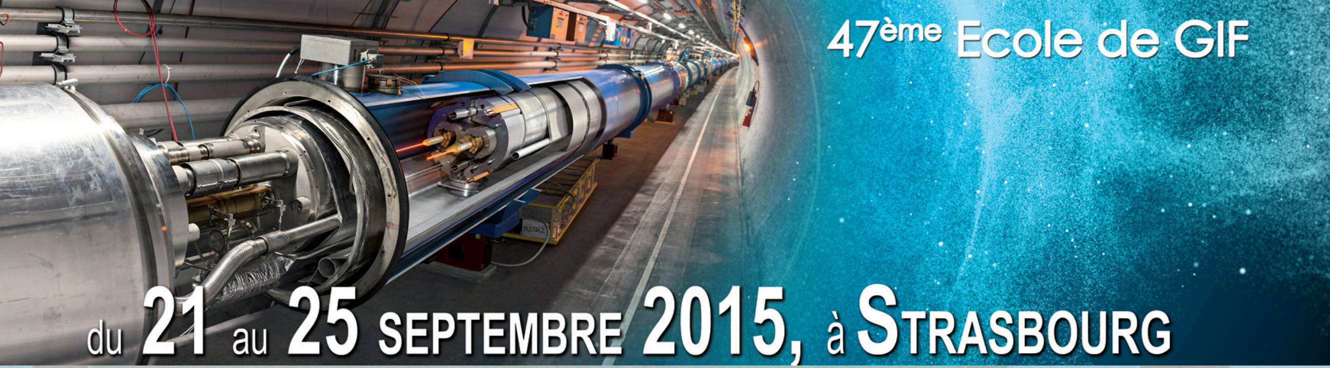

Quel futur pour le Modèle Standard après la découverte du HIGGS ?

Programme :

- Introduction au Modèle Standard
- Higgs : Aspects théoriques
- Higgs et physique électrofaible : aspects expérimentaux
- Physique du quark top
- Au-delà du Modèle Standard et
- Table ronde sur les collisionneurs du futur
- Saveurs et mesures hors collisionneurs

Flavour and non accelerator physics

I. Ripp-Baudot
IPHC Strasbourg

Course outline

- Course on « Flavour and non accelerator physics » ? Vaste topic!
  ➛ subjective selection: focus on few examples of precision measurements performed in the quark and charged lepton sectors & experimental point of view.

  - Introduction,
  - Neutron electric dipole moment,
  - Muon anomalous magnetic moment,
  - Charged lepton (μ) flavour violating decays,
  - K decays,
  - τ, B and D decays.

  ➛ Looking for Beyond Standard Model physics with nev to GeV particle physics.

- You may also refer to:
  - Gif 2010 Saveurs Lourdes,
  - Gif 2011 Neutrinos,
  - top quark physics treated in a dedicated course in this year Ecole de Gif 2015.

Course outline

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PART I

- Introduction,
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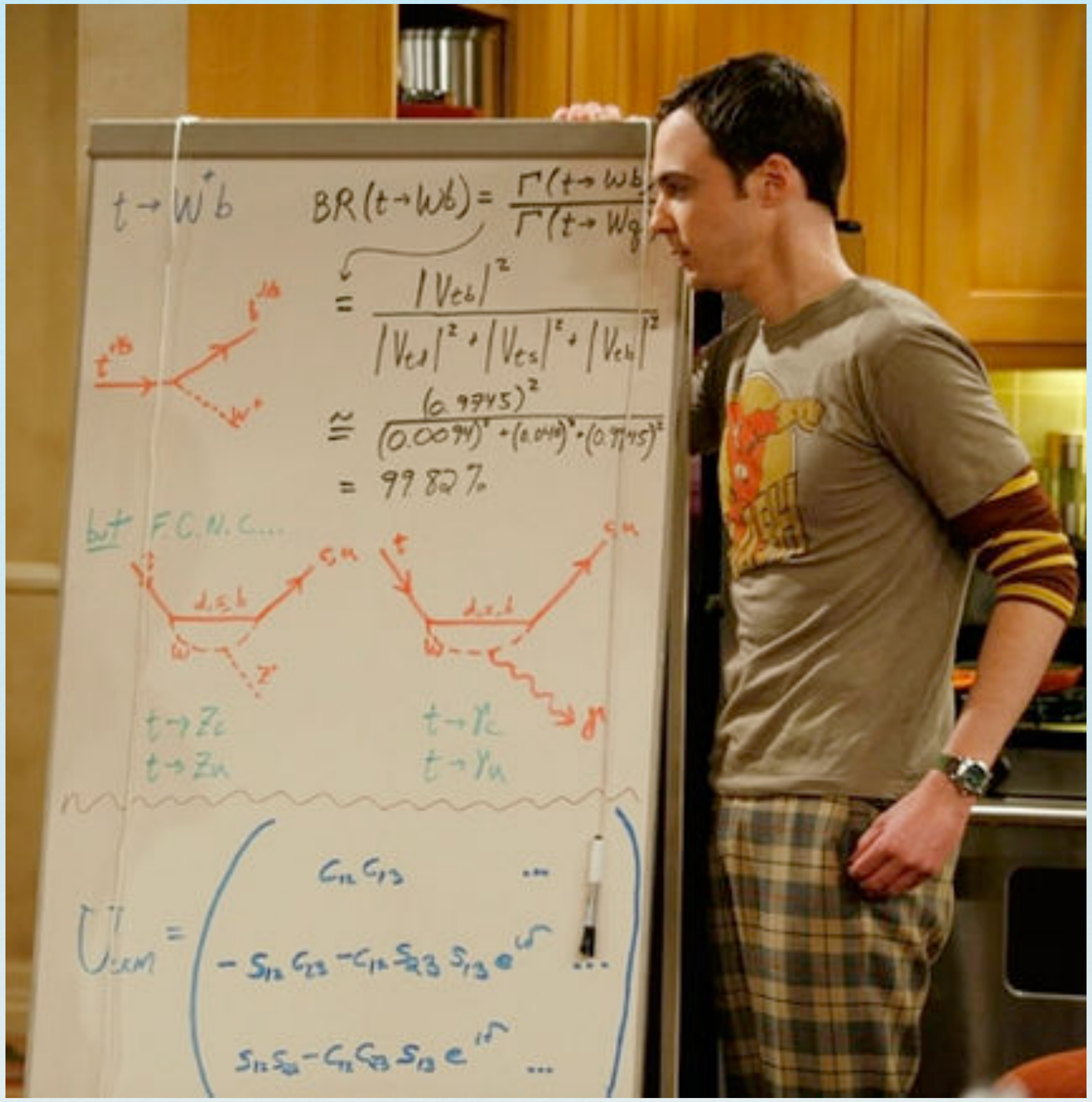
Introduction : outline

- The CKM matrix:
  - the Cabibbo mixing,
  - FCNC and GIM,
  - the CKM matrix,
  - Wolfenstein parametrisation,
  - unitarity triangles.
- Mysteries of the SM:
  - baryogenesis,
  - flavour changing,
  - quarks and leptons,
  - quark masses.
- Status of the SM,
- The quantum path.



Introduction: the Cabibbo mixing

- Discovery of strange particle decays (1946-1949): V^0, hyperons and K^0.
  Introduction of a new quantum number by Gell-Mann and Nishijima in 1954: Strangeness, conserved in strong interactions but violated in weak interactions.

- Existence of quarks (u, d and s) proposed by Gell-Mann and Zweig in 1963.
  Observation in late 60s at SLAC.

- N. Cabibbo proposes in 1963 that quarks involved in a weak process are not physics eigenstates, in order to account for suppressed $\Delta S = 1$ transitions w.r.t. $\Delta S = 0$:

$$d' = \cos\theta_C \, d + \sin\theta_C \, s$$

flavour eigenstate: involved in weak interactions (d')

physics eigenstates: involved in electromagnetic and strong interactions (d, s)

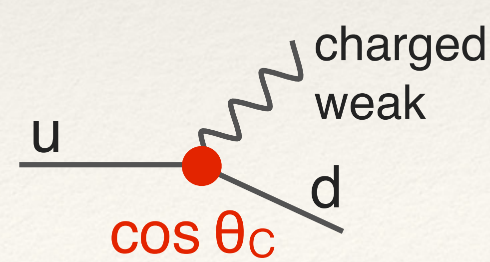
The weak charged current is given by: $J_\mu^{charged} = \bar{u} \, \gamma_\mu \, (1-\gamma_5) \, (\cos\theta_C \, d + \sin\theta_C \, s)$,

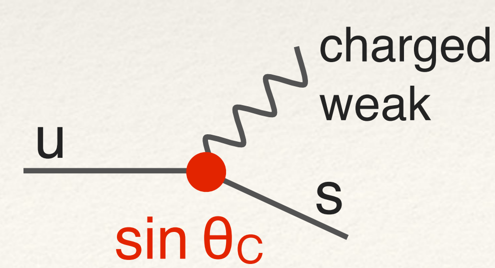
while the orthogonal combination: $s' = [\, -\sin\theta_C \, d + \cos\theta_C \, s \,]$ remains uncoupled.

➛ 1 unique real parameter $\theta_C \sim 13°$ is enough to describe the change of basis.

$\Delta S = 0$ transitions are proportional to $\cos^2\theta_C \sim 1$,

while $\Delta S = 1$ transitions are $\sim \sin^2\theta_C$.





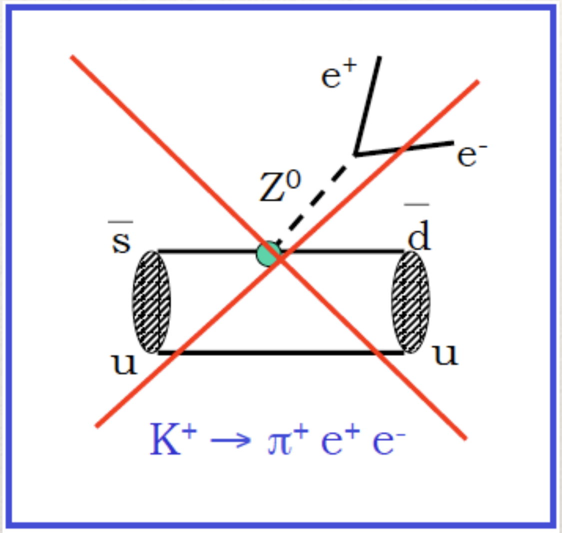
Introduction: FCNC and GIM

- Issue because the Cabibbo mixing enables FCNC processes:

$$J_\mu^{\text{neutral}} = \bar{u}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,u + (\cos\theta_C\,\bar{d} + \sin\theta_C\,\bar{s})\,\gamma_\mu\,(g_v - g_a\gamma_5)\,(\cos\theta_C\,d + \sin\theta_C\,s)$$

$$= \bar{u}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,u + \cos^2\theta_C\,\bar{d}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,d + \sin^2\theta_C\,\bar{s}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,s$$

$$+ \cos\theta_C\,\sin\theta_C\,(\,\bar{d}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,s + \bar{s}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,d\,)$$



would imply existence of FCNC
Flavour Changing Neutral Current
➛ never observed

- The GIM mechanism: in 1970, Glashow, Iliopoulos and Maiani propose the existence of the charm quark to get rid of possible FCNC transitions.
The charm quark is coupled to the linear combination $s' = [\,-\sin\theta_C\,d + \cos\theta_C\,s\,]$

$$J_\mu^{\text{neutral}} = \bar{u}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,u + \bar{d}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,d + \bar{c}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,c + \bar{s}\,\gamma_\mu\,(g_v - g_a\gamma_5)\,s$$

Discovery of the $J/\psi = (c\bar{c})$ in 1974 in e^+e^- collisions at SLAC and in a fixed target experiment at BNL.

Introduction: the CKM matrix (1)

- In 1973, Kobayashi and Maskawa propose to introduce a 3rd doublet of quarks to account for CP violation in weak interactions (observed in $K^0_L \to \pi\pi$ decays by Christenson, Cronin, Fitch and Turlay in 1964).

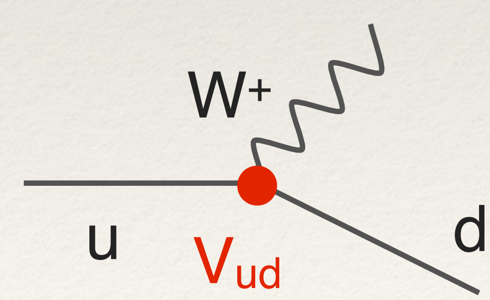
  ➛ 3 $SU(2)_L$ doublets: $\begin{pmatrix} u \\ d' \end{pmatrix}_L \begin{pmatrix} c \\ s' \end{pmatrix}_L \begin{pmatrix} t \\ b' \end{pmatrix}_L$

  Discovery of the $\Upsilon = (b\bar{b})$ in 1977 in a fixed experiment at FNAL, and of the top quark in $p\bar{p}$ collisions in 1995 at FNAL.

  ➛ generalisation to 3 SU(2) doublets of the Cabibbo mixing: the CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{weak} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{mass}$$

  ➛ flavour changing through charged weak interaction:



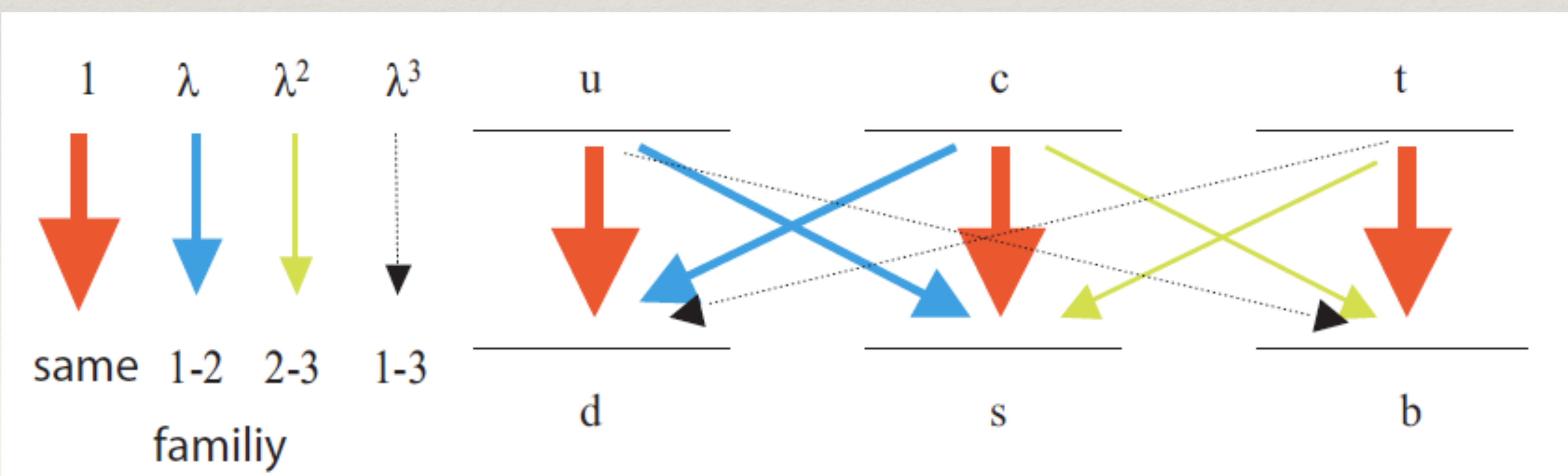
Introduction: the CKM matrix (2)

- The CKM matrix is complex of dim 3×3
  ➣ 9 elements $|V_{ij}|\exp(-i\phi_{ij})$, described by 18 parameters:
  - the unitarity relation $V V^{\dagger} = Id$ implies 3^2 relations between the matrix elements;
  - 5 relative phases among the quarks out of 6 can be redefined w/o changing the Lagrangien.

  ➣ only 4 parameters remain independent: 3 real rotation angles + 1 CP-violating phase.

- Comment: with 2 families of quarks only (Cabibbo mixing), there is no CP-violating phase. Kobayashi and Maskawa understood that CPV can only be generated with ≥ 3 families.

- Experimentally observed hierarchy between the 9 modules of the matrix elements:



$$V \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Introduction: the Wolfenstein parametrisation

- Wolfenstein (phenomenological) parametrisation of the CKM matrix with parameters: A, λ, ρ and η.
  Parameters can be determined from a global fit to all available measurements and imposing unitarity: $\lambda = 0.22537 \pm 0.00061$.

  Expansion up to λ^3 to handle Belle / BaBar measurements (mainly CP violation measurements):

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

  Expansion at order λ^5 needed to compare to more precise LHCb and Belle II measurements (search for beyond standard model physics):

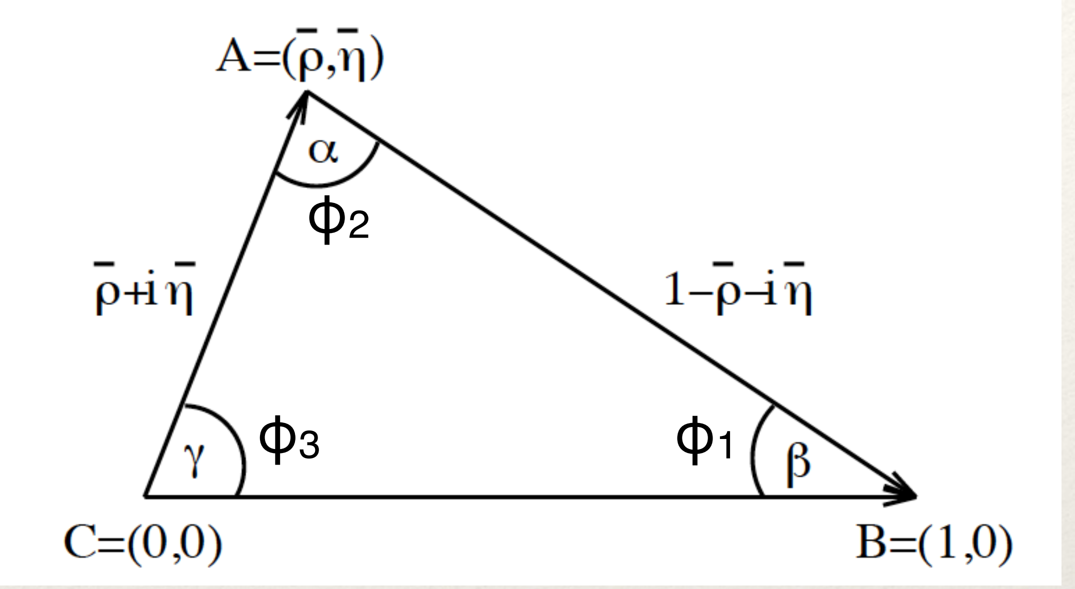
$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{A^2\lambda^5}{2}(1-2\rho) - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2}-\lambda^4(\frac{1}{8}+\frac{A^2}{2}) & A\lambda^2 \\ A\lambda^3\left[1-(1-\frac{\lambda^2}{2})(\rho+i\eta)\right] & -A\lambda^2(1-\frac{\lambda^2}{2})\left[1+\lambda^2(\rho+i\eta)\right] & 1-\frac{A^2\lambda^4}{2} \end{pmatrix} + \mathcal{O}(\lambda^6).$$

Introduction: unitarity triangles (1)

The 6 non diagonal unitarity relations

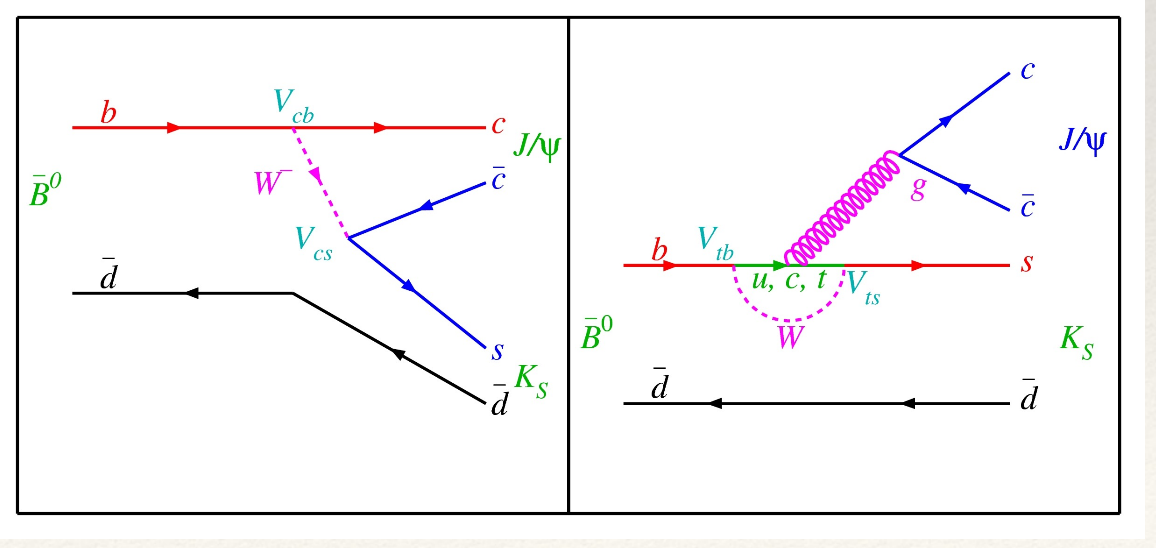
s-d	$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0$	$\lambda \ \lambda \ \lambda^5$
b-d	$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$	$\lambda^3 \ \lambda^3 \ \lambda^3$
b-s	$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0$	$\lambda^4 \ \lambda^2 \ \lambda^2$
t-u	$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$	$\lambda^3 \ \lambda^3 \ \lambda^3$
t-c	$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0$	$\lambda^4 \ \lambda^2 \ \lambda^2$
c-u	$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$	$\lambda \ \lambda \ \lambda^5$

The b-d unitarity triangle



Triangle surface = 0 ⇔ CPV = 0.

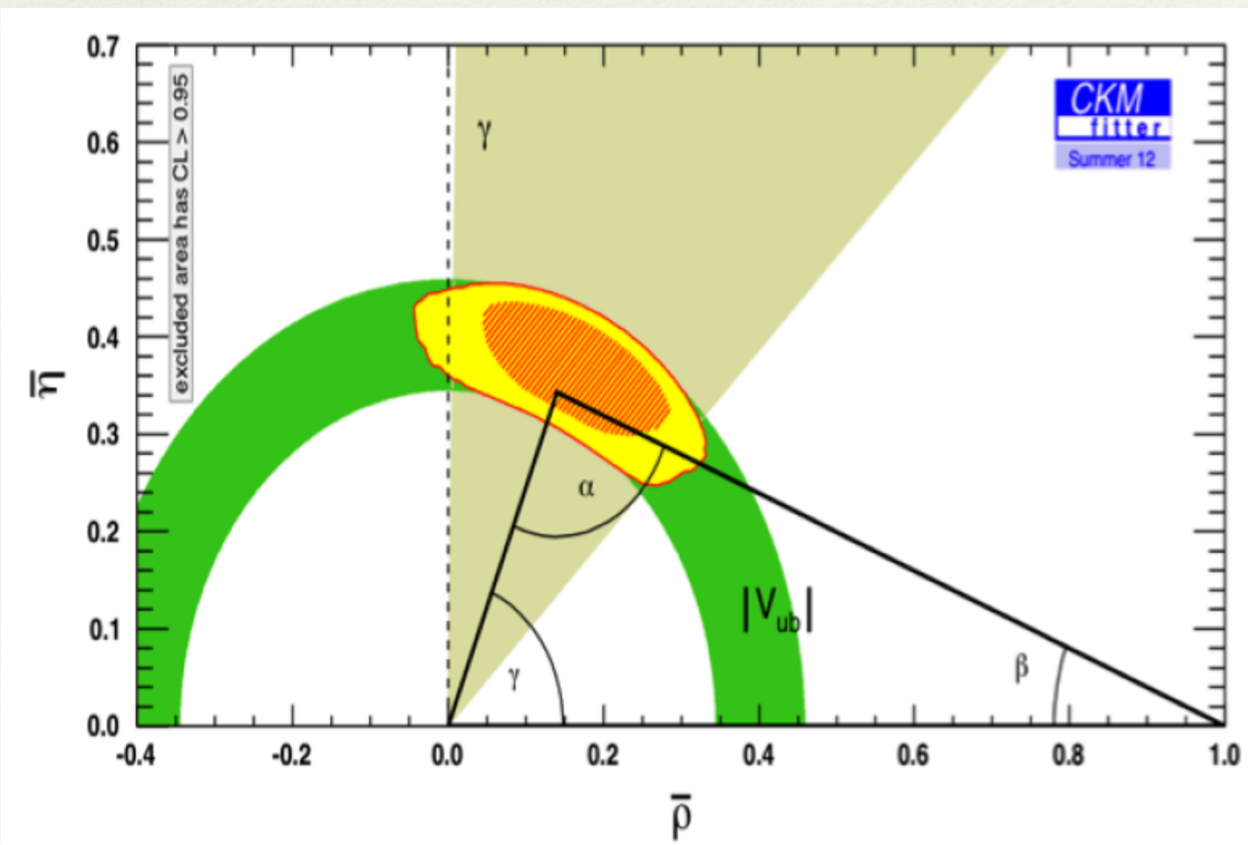
- Measurement of the b-d unitarity triangle leads to the complete determination of the CKM matrix.
  To search for physics beyond the SM:
  - Redundant measurements of all 6 triangles
    (most of them are ~ flat: less easy):
    coherence w.r.t. SM predictions, only 1 phase
    ➛ all 6 triangles feature the same area.
  - Compare tree with higher order processes
    (sensitive to unknown particles contributions).



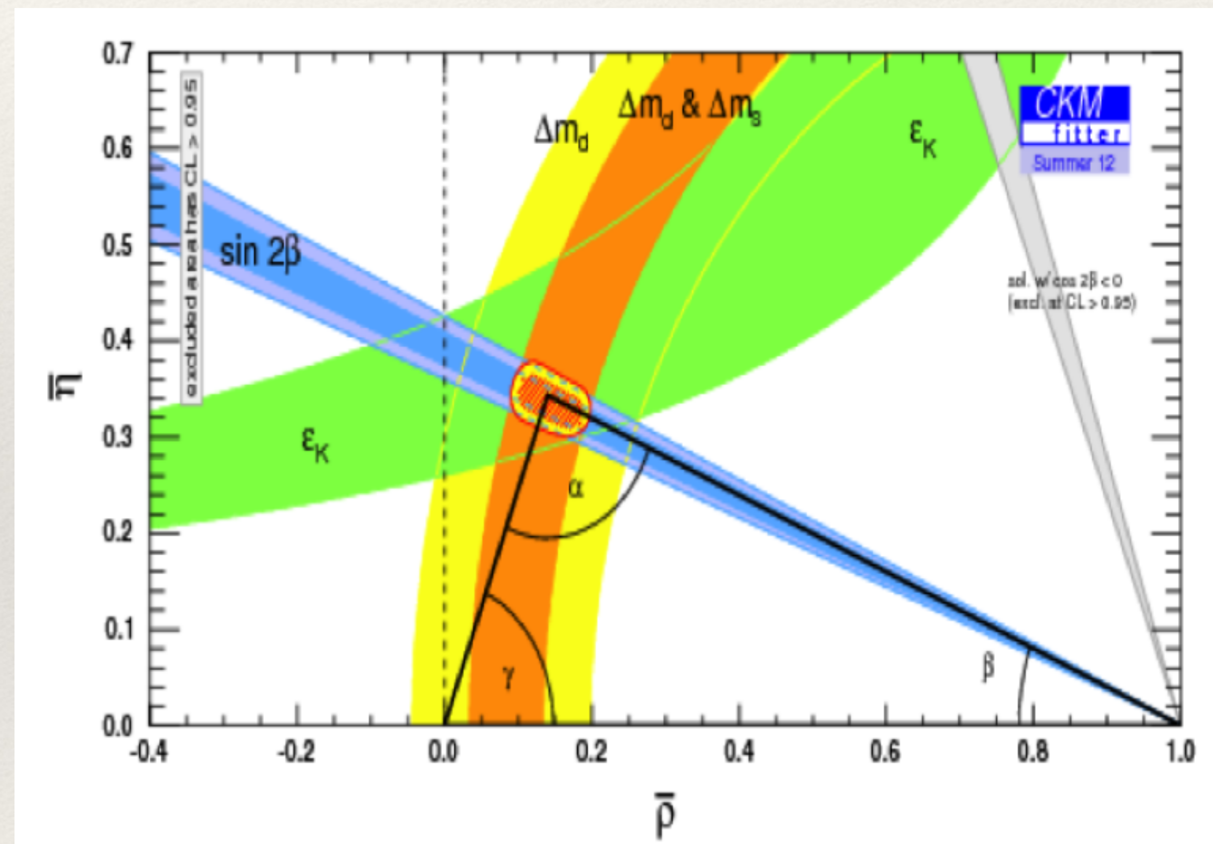
Introduction: unitarity triangles (2)

constraints on the b-d unitarity triangle from:

tree-level amplitudes,
i.e. Flavour Changing Charged Currents



loop-mediated amplitudes,
i.e. ΔF=2 Flavour Changing Neutral Currents



[http://ckmfitter.in2p3.fr]

Currently, all measurements are in agreement with the SM relations.

Introduction: baryon/anti-baryon asymmetry

- Observed baryon/anti-baryon asymmetry in the universe today: $\Delta n_B / n_\gamma \sim 6 \times 10^{-10}$
  The early universe is expected to be symmetric (i.e. $\Delta n_B = 0$), then an imbalance between matter and anti-matter is produced, satisfying Sakharov conditions.
  Baryogenesis scenerio: the imbalance occurs during the electroweak phase $\Lambda \approx$ TeV.
  Leptogenesis (heavy Majorana neutrino): at very high energy $\Lambda \approx 10^{15}$ TeV (exp. test difficult).

- Sakharov conditions (1967):

  1) Baryon number violation:
     ➛ possible in the SM with sphalerons and violation of B and L, but B-L is conserved.
     Baryons are transformed in anti-leptons and vice-versa.

  2) C and CP symmetries violation:
     ➛ at least one more CP violating phase is needed in addition to the CKM one.
     SM with one unique CPV phase allows: $\Delta n_B/n_\gamma \approx 10^{-18}$.

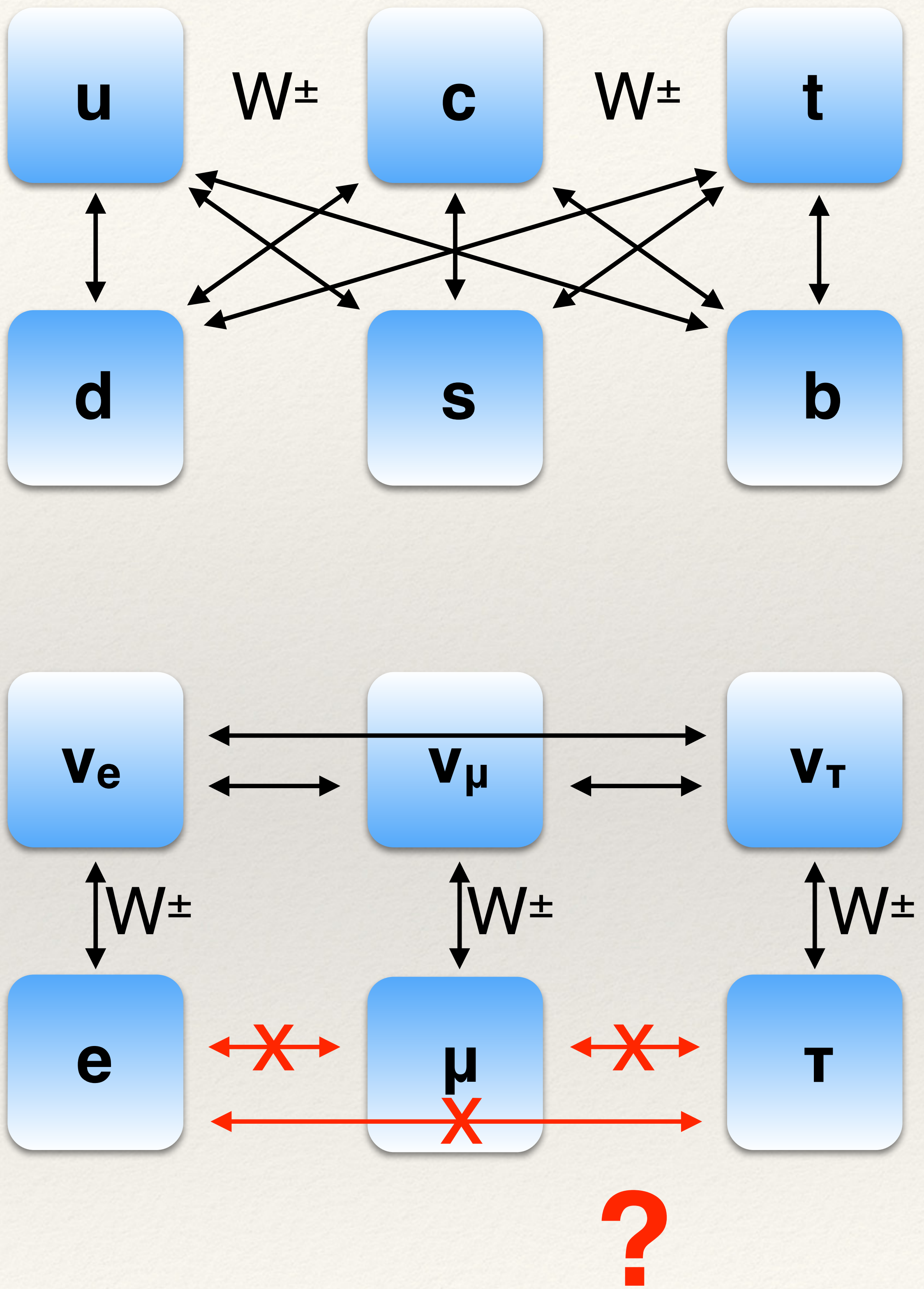
  3) Interactions out of thermal equilibrium:
     ➛ baryogenesis within the SM requires electroweak symmetry breaking be a first-order phase transition.
     Constrains $M_H \sim< 40$ GeV/c^2, or requires an extended scalar sector (introducing new CPV phases).

Introduction: flavour changing

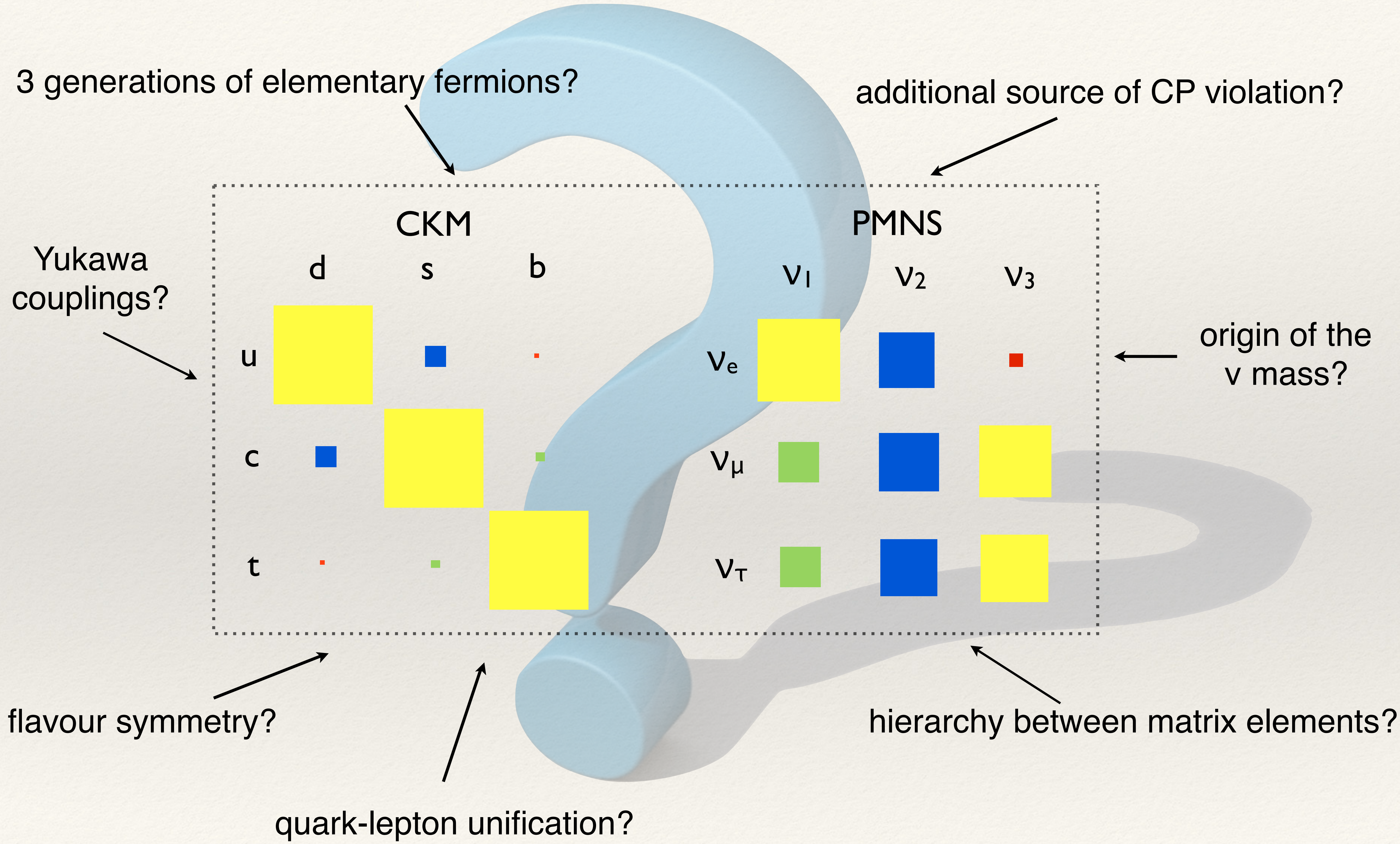
"who ordered that?"

(by I. Rabbi according to [Phys.Rept. 532 (2013) 27-64])

- Still lots of unknown from the lepton sector: CP-violating parameters, mass hierarachy.
- The observed neutrino flavour violation implies that charged lepton flavour violating processes also occur at least at loop level, but their rates depend on the BSM physics.
- Neutrino oscillation does not necessarily imply that total lepton number L is violated (Dirac vs. Majorana neutrinos).
  Indeed, B is conserved in the SM though individual quark flavour numbers are violated by charged weak interaction.



Introduction: quarks and leptons



Introduction: quark masses

- The Yukawa interaction couples the Higgs field to the quarks:

$$\mathcal{L}_Y^{quarks} = -Y_d \bar{q}_L H d_R - Y_u \bar{q}_L \tilde{H} u_R + h.c.$$

q_L: 3 generations of left-handed SU(2) doublets of quarks
d_R: 3 right-handed singlets
H: SU(2) Higgs doublet
$Y_{d,u}$: adimensional 3×3 complex matrices of Yukawa couplings

- After spontaneous symmetry breaking, the Yukawa interaction gives rise to quark masses:

$\mathcal{L}_{mass}^{quarks} = \bar{d}_L M_d d_R + \bar{u}_L M_u u_R + h.c.$ where $M_d = (v.e.v./\sqrt{2})\, Y_d$ and $M_u = (v.e.v./\sqrt{2})\, Y_u$,

with: $d^0_{L,R} = D_{L,R}\, d_{L,R}$
and: $u^0_{L,R} = U_{L,R}\, u_{L,R}$

($u^0_{L,R}$: mass eigenstates; $u_{L,R}$: flavour eigenstates)

and the diagonal 3×3 physical mass matrices:
$M_d(diag.) = D_L M_d D_R^{-1}$
$M_u(diag.) = U_L M_u U_R^{-1}$

➢ The charged weak current written with mass eigenstates: $J^\mu(W) = \bar{u}^0_L\, U_L \gamma^\mu D_L^{-1}\, d^0_L$

with: $U_L D_L^{-1} = V_{CKM}$

no mixing in neutral weak current, since $U_L U_L^{-1} = Id$:

$$J^\mu(Z) = \bar{u}^0_L\, U_L \gamma^\mu U_L^{-1}\, u^0_L = \bar{u}^0_L \gamma^\mu u^0_L$$

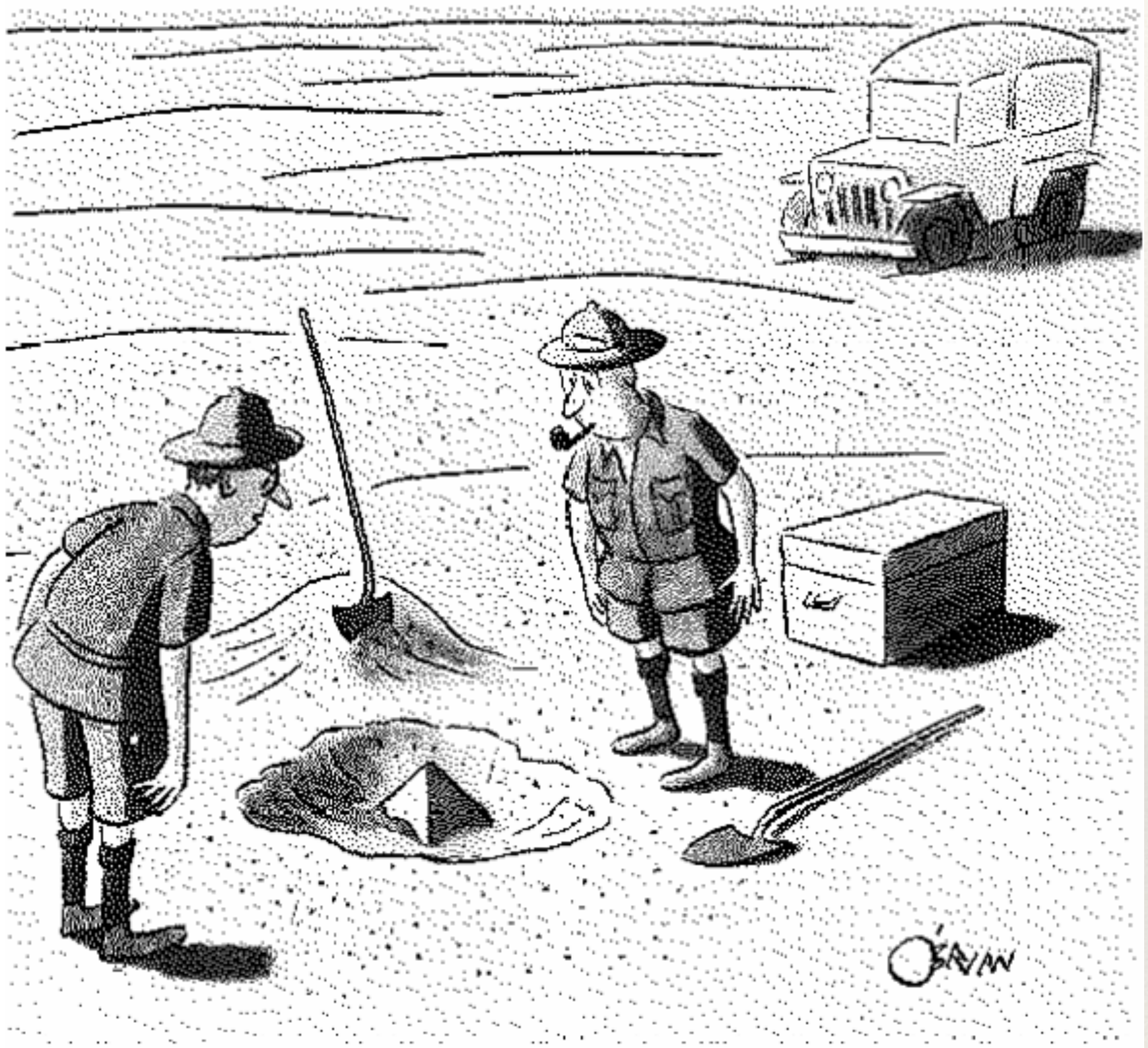
The Yukawa interactions of the Higgs field with the fermion fields are the only source breaking the global flavour symmetry of the SM (the gauge sector is flavour symmetric).
Minimal Flavour Violation principle: this remains also true BSM.

Introduction: status of the SM

- Beyond SM physics: what physics? at what energy? Few experimental indications, e.g.:
  - (neutral) lepton flavour is violated,
  - origin of neutrino masses?
  - additional source of CPV exists,
  - dark matter exists,
  - dark energy exists.

- Few puzzling ~3σ smoking guns from precision measurements, mainly in the flavour sector:
  - muon g-2,
  - $\sin^2\theta_W$,
  - $B \rightarrow \tau\nu$,
  - $B \rightarrow D^{(*)}\tau\nu$,
  - angular $B^0 \rightarrow K^{0*}\mu\mu$ distribution,
  - …

➛ mainly based on one unique, statistically limited and finally non conclusive measurement.

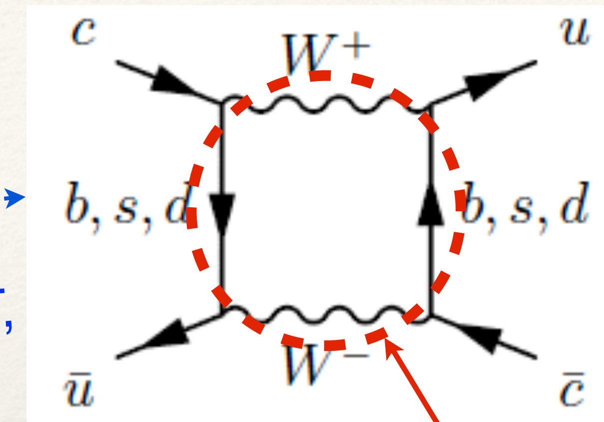


"This could be the discovery of the century. Depending, of course, on how far down it goes."

Introduction: the quantum path (1)

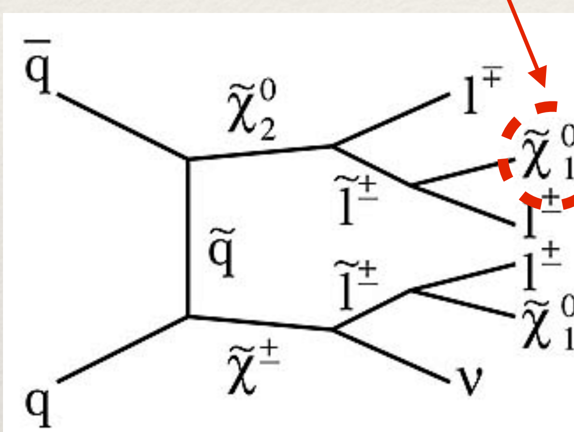
- Observed manifestations of Beyond SM physics do not indicate any energy scale.
- Finding and understanding new physics will not be easy!
  ➛ pursue a global effort relying on different programs:
  - the quantum path (mainly at intensity frontier),
  - the relativistic path (mainly at energy frontier).

LHCb, Belle II, nEDM, COMET, etc.



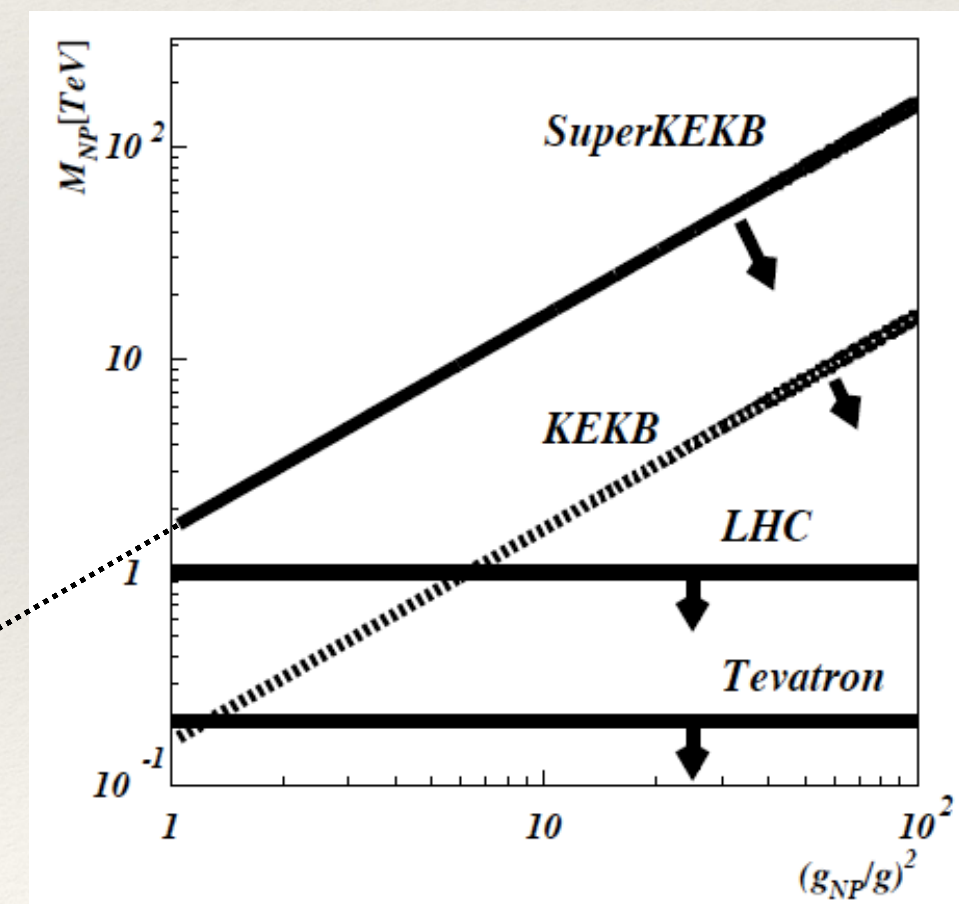
new physics?

new physics?



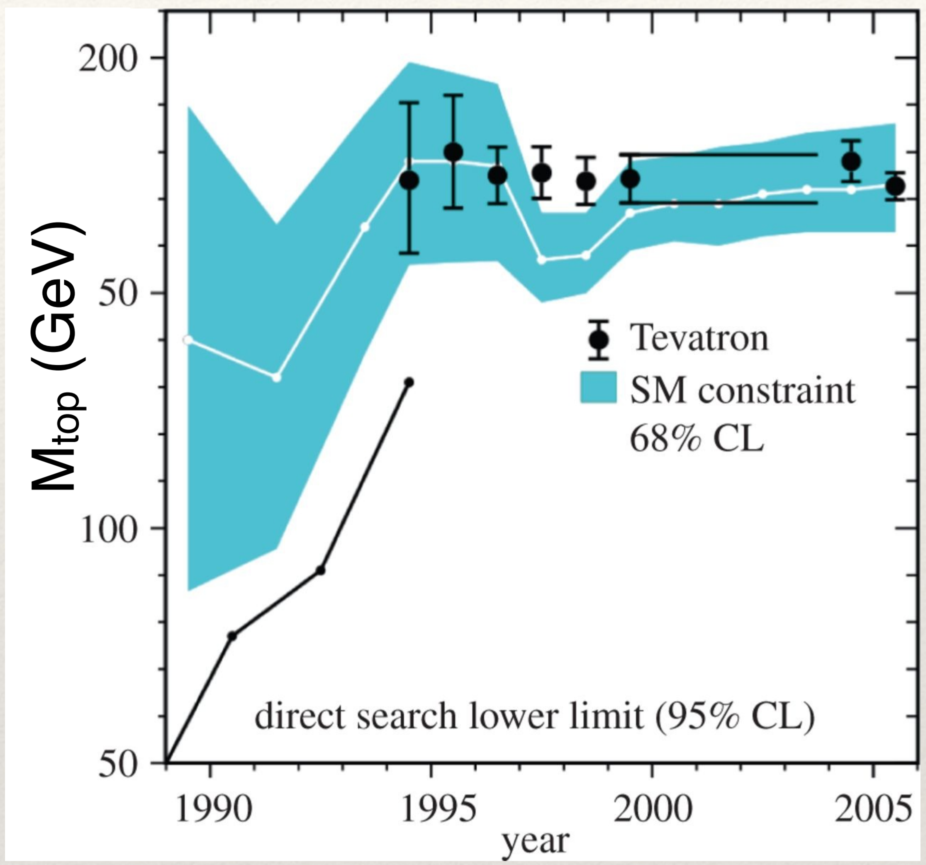
ATLAS, CMS, CAST, etc.

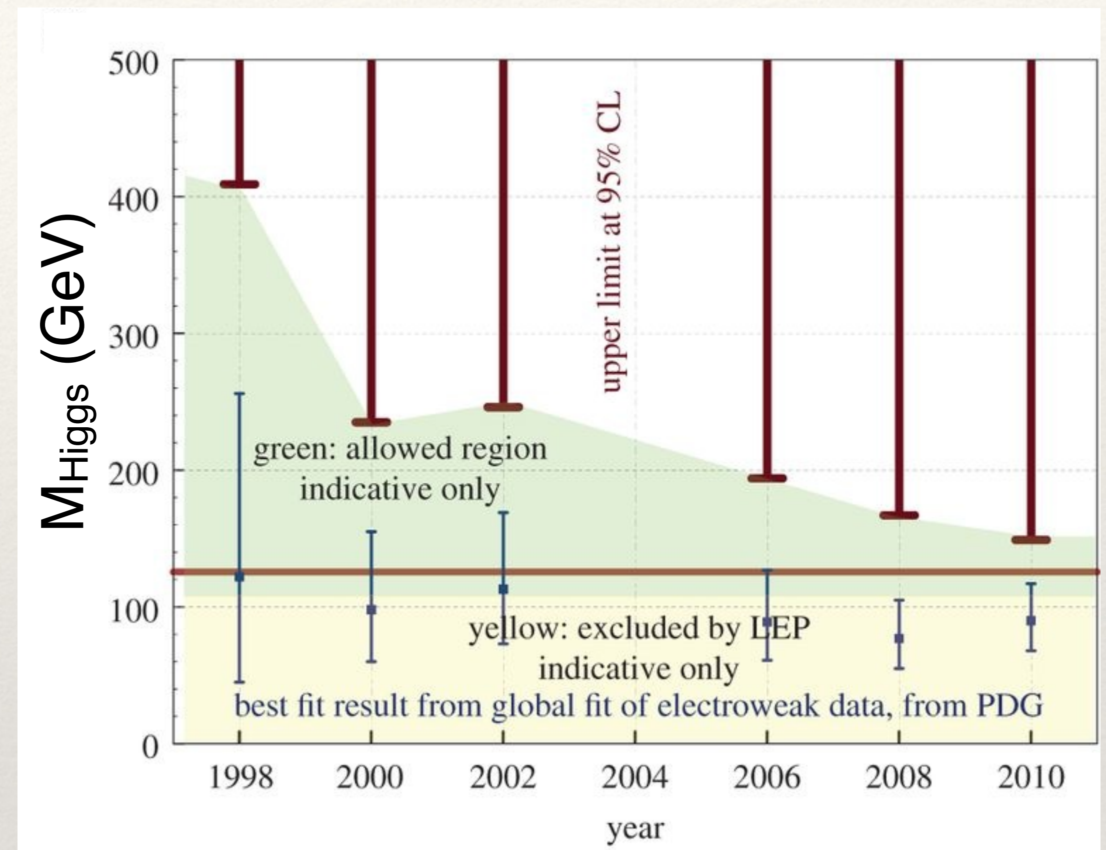
- Flavour physics is a powerful tool to search for NP, potentially sensitive to a much higher NP scale than LHC.
- Moreover: precision measurements are sensitive to very light new particles:
  - very light Higgs,
  - dark photon,
  - light dark matter.

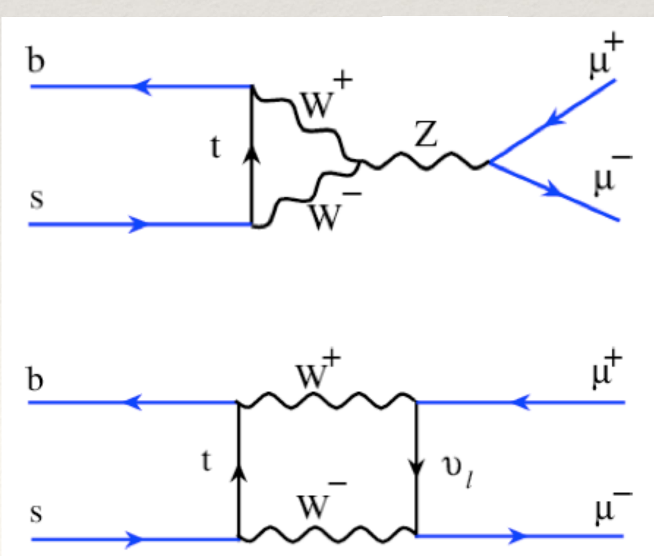


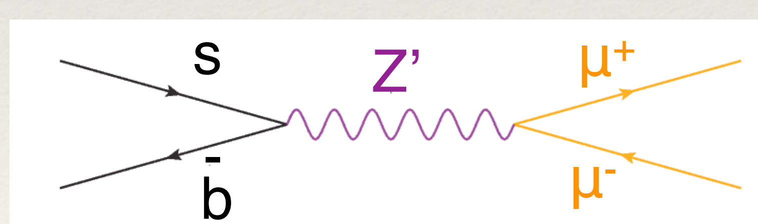
Introduction: the quantum path (2)

- In the past HEP history, quantum corrections and Flavour Changing processes enabled key progresses: existence of the charm quark, of the 3rd quark family, top mass, Higgs mass, …









Measurements of FCNC

➣ Excellent sensitivity to NP but requires:
- very high statistics,
- very precise experiments,
- very precise theoretical predictions.

Introduction: the quantum path (3)

- First way to look for BSM physics: by measuring lots of observables with good sensitivity to NP, depending on the BSM theory.

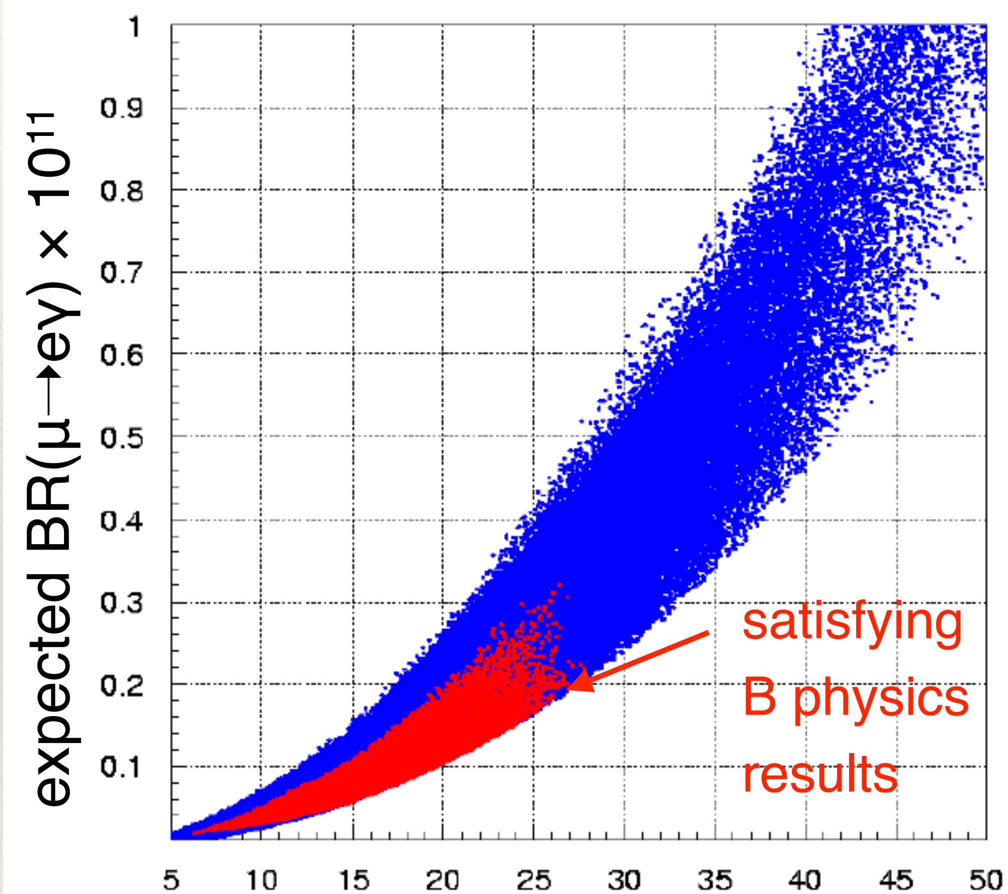
DNA of flavour physics effects on BSM theories

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

[Nucl.Phys. B830 (2010) 17-94]

[Phys.Rev. D75 (2007) 115019]



expected $\Delta a_\mu \times 10^{10}$

$= (g_\mu^{BSM} - g_\mu^{BSM}) / 2 \times 10^{10}$

Introduction: the quantum path (4)

- Second way: assuming that SM is extended with new d.o.f. arising at higher energy, analyse the possible NP effects using a generic effective-theory.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g_{NP}}{\Lambda^2} O^{(6)}\text{(SM fields)} + \ldots$$

coupling constant

NP scale: $\Lambda \sim M_{NP}$

NP contributions are known to be very small:

- either Λ is very high,
- or g_{NP} is very weak,
- or both!

[Ann.Rev.Nucl.Part.Sci. 60 (2010) 355]

Bounds on dim-6 $\Delta F = 2$ operators:

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

➢ Constraints from quark-flavour physics on NP energy scale: $\Lambda > 10^3$ TeV, considering $g_{NP} \sim 1$, and new particles at the TeV scale imply non generic flavour structure of any BSM theory.

N.B.: constraints from charged lepton flavour violating decays: $\Lambda > 10^5$ TeV.

Neutron electric dipole moment: outline

- Definition of nEDM
- SM prediction
- The PQ symmetry and the strong CP problem
- The CAST experiment at CERN
- Physics motivation
- Experimental constraints
- Principle of the nEDM measurement
- Ultra Cold Neutrons
- The nEDM experiment at PSI
- Outlook

nEDM: definition

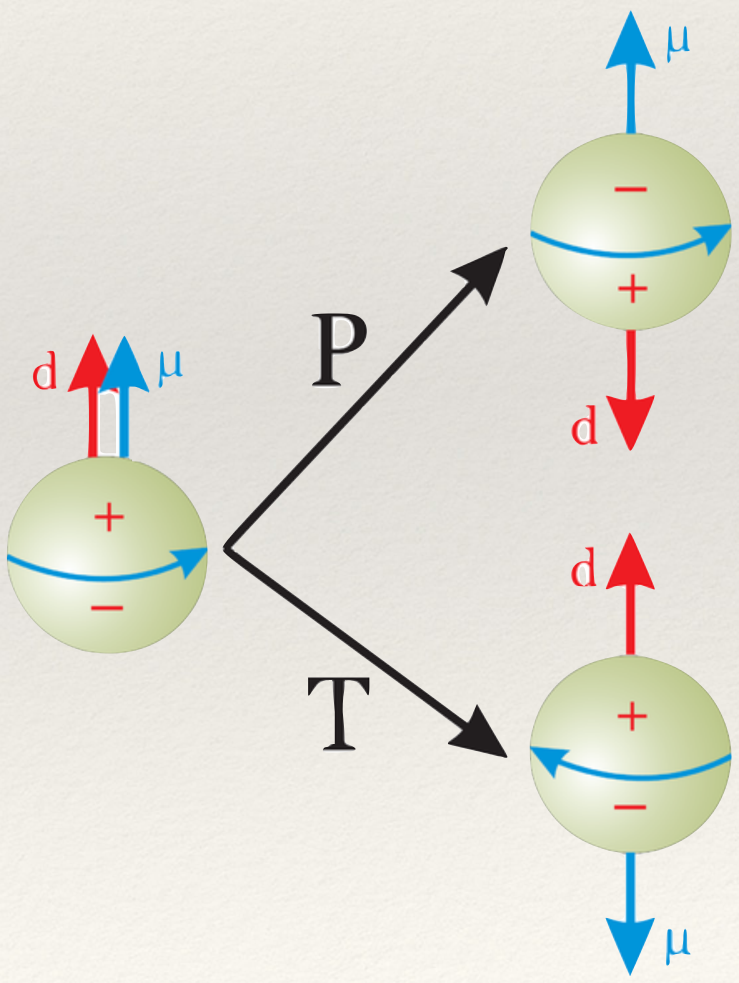
- Neutron Electric Dipole Moment: measure of the separation of + and - electrical charges.

  Intrinsic vector quantity: $\vec{d}_n = d_n \frac{\vec{J}}{J}$ (cf. Wigner-Eckart)

- EDM measured in various systems of very different scales: elementary particles (e-, μ), nucleons (n, p), nuclei, atoms (Hg, Xe, Ra,…), molecules (YbF, ThO,…).
  Imply different fields and technologies. More complicated with composite or charged particles.

- Transformations under P and T symmetries:

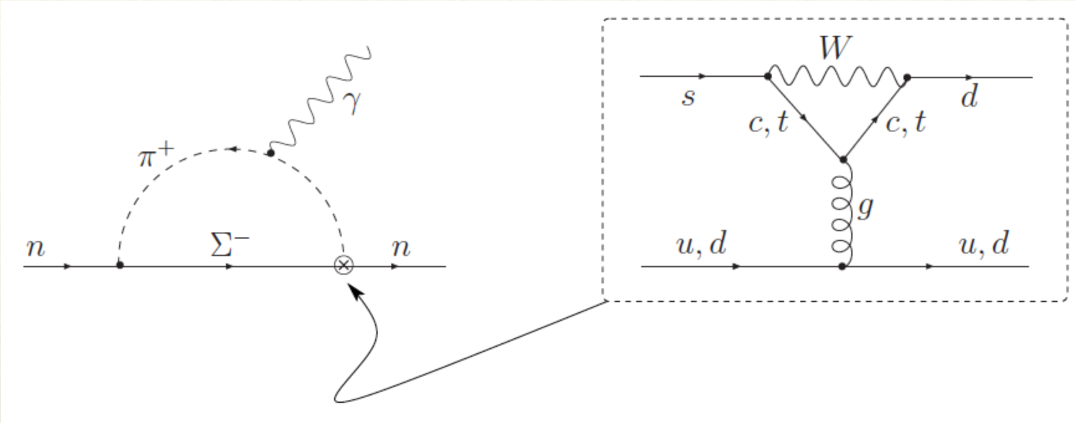
Observable	P symmetry	T symmetry
position $\vec{r}$	$-\vec{r}$	$\vec{r}$
time t	t	-t
momentum $\vec{p}$	$-\vec{p}$	$-\vec{p}$
angular momentum $\vec{J}$	$\vec{J}$	$-\vec{J}$
EDM $\vec{d}$	$-\vec{d}$	$\vec{d}$



nEDM: SM prediction

- $\vec{d}_n$ not conserved under T and P ➛ EDM ≠ 0 implies P, T and therefore CP violations.
  In the SM: CPV is small, observed in the quark sector.

SM prediction: $d_n \sim 10^{-31}$ - 10^{-32} e cm.



- Theoretically, also CPV in strong interactions:
  A priori 2 sources of CPV: θ_{QCD} (QCD vacuum angle) and θ_{chir} (chiral phase of quark fields)
  ➛ free parameters, with $\theta_{QCD} \in [0, 2\pi]$.

  Fine tuning needed to compensate these 2 terms in the Lagrangian (strong CP problem) :

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{n_f\, g^2\, \theta_{QCD}}{32\,\pi^2} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}\, \left(i\gamma^\mu D_\mu - m e^{i\theta_{chir}\gamma_5} \right) \psi$$

  Finally it was shown that no CPV is induced with θ_{chir} [Phys.Lett. B573 (2003) 109], the fine tuning problem turns to be a problem of naturarlity: why $\theta_{QCD} \sim 0$?

nEDM: PQ symmetry and strong CP problem

- The PQ symmetry (Peccei & Quinn) :

  additional global U(1) symmetry, spontaneously broken, to get rid of CPV terms in the strong interaction Lagrangian.

  ➛ existence of an axion = associated Goldstone boson ("photon-like"):
  neutral, very light, very weakly interacting ➛ dark matter candidate.

  Cosmological constraints: $m_{axion} \approx 1$ µeV - 100 meV.
  This means: PQ symmetry broken at an energy scale $f_a > 10^3$ TeV.

- Axions searched for a long time by several experiments using various technologies (radio-frequencies, strong magnetic fields, lasers, …), sensitive to different mass scales.

➛ Example of an experiment searching for axions:
CAST at CERN

CAST, the CERN Axion Solar Telescope

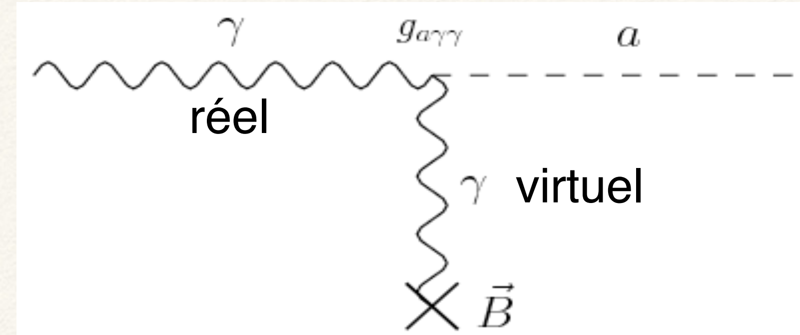
- CAST experiment at CERN since 2003:

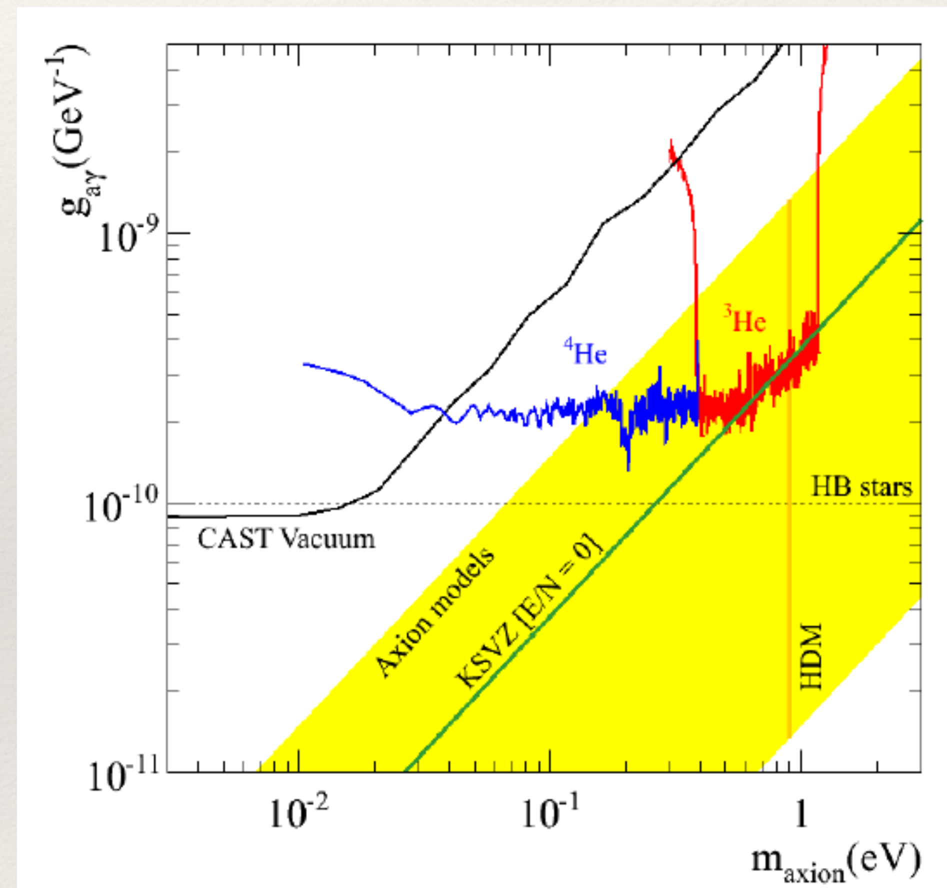
  Search for axions produced in the 🌞 (E ~ keV).

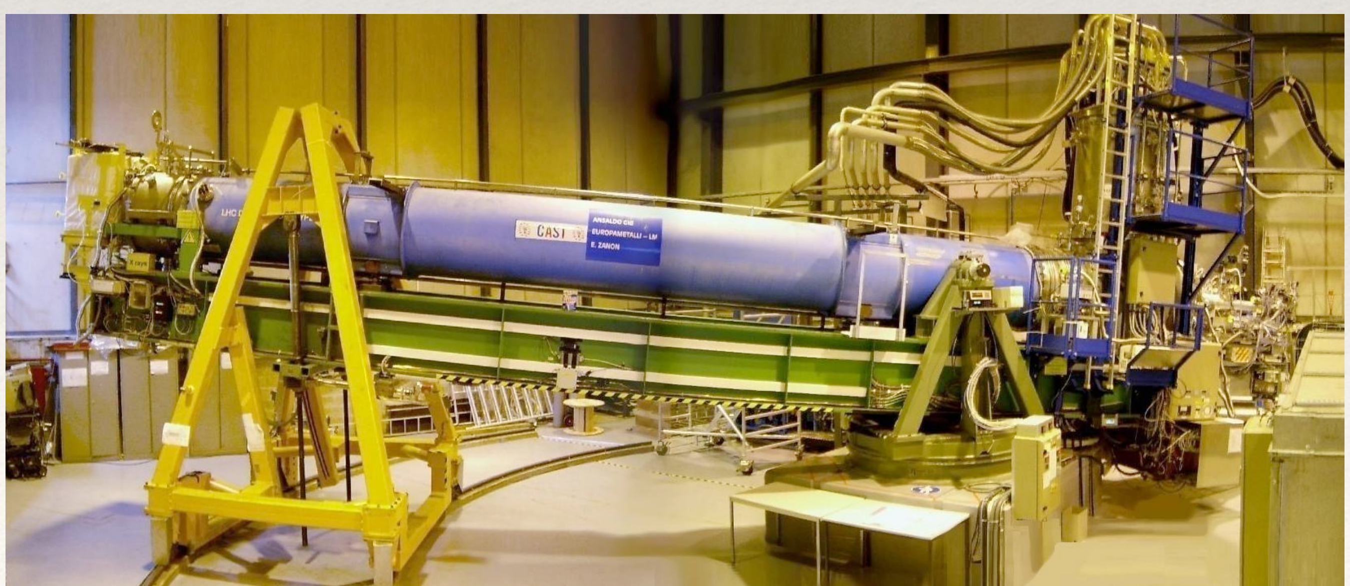
  Detection of axion-γ interaction in a magnetic field (Primakoff effect).

  Conversion axion-γγ ∝ $(B_T \times \text{magnet length})^2$

- Helioscope = an X-ray focusing telescope in front of an LHC prototype superconducting dipole magnet (10 m, 9 T).
  Signal: an excess of detected X-rays when pointing at the 🌞.







f_a = E scale of the symmetry breaking

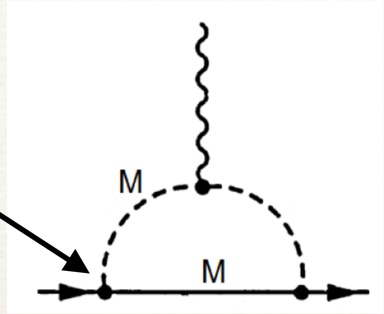
mass: $m_a \propto 1 / f_a$,

aγγ coupling: $g_{a\gamma} \propto 1 / f_a$.

nEDM: physics motivation

- Measured value EDM ≠ 0 would reveal a new source of CPV, i.e. physics beyond the SM.

CPV at the vertex, induced by the coupling to a new particle



➛ 1 loop BSM diagram leading to EDM ≠ 0

- Several theoretical BSM scenarios predict significant enhancement of nEDM value:

BSM theoretical predictions: $d_n \sim 10^{-25}$ - 10^{-28} e cm.

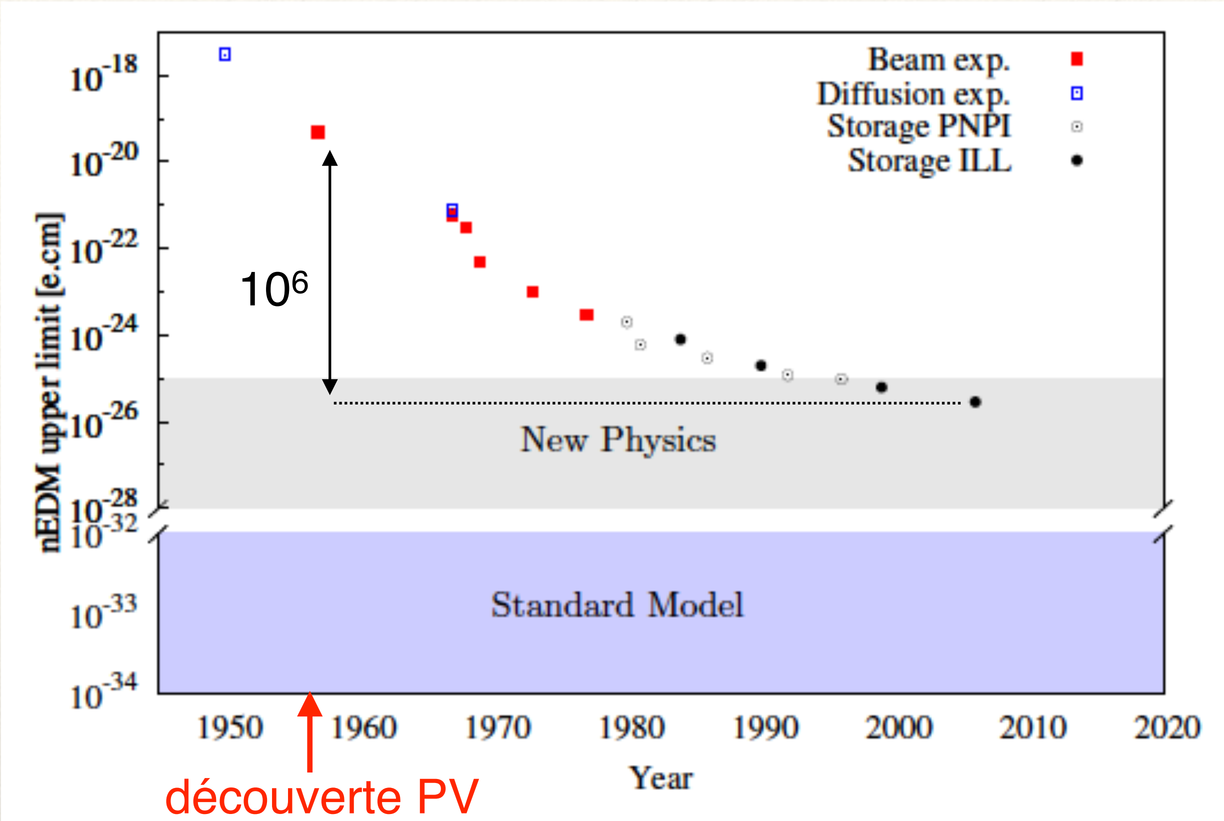
  - Supersymmetry: CPV phases in sparticle mass matrices (physics eigenstates mixing). nEDM measurement leads to efficient constraints on the BSM proposed theories: heavy sparticles, small phases, compensations needed between several terms.
  - Existence of a 4th generation of quarks: generalisation of the CKM matrix to a dim. 4×4 matrix, leading to 2 more CPV phases.
  - Electroweak baryogenesis: additional CPV phase due to an extended scalar sector.

nEDM: experimental constraint

- First measurements: thermal neutrons (Ramsey *et al.*, 1957, @ORNL reactor, USA).
  Then cold neutrons, from beams until 1977
  ➛ sensitivity limited to 3×10^{-24}
  due to neutron speed ($\vec{v} \times \vec{E}$ effect).

- Best limits: based on Ultra Cold Neutrons (since 1980 @PNPI St Petersbourg).

- Current experimental constraint:
  (OILL = RAL-Sussex detector @ILL Grenoble)



$d_n < 2.9 \times 10^{-26}$ e cm, CL = 90 %. [PRL 97 (2006) 131801]

Sensitivity is statistically limited.

Limit scaled up to compare to the size of the Earth: separation of electrical + et - charge c.o.g. by less than a human haar (~ $o(10)$ µm) w.r.t. Ø = 40 000 km.

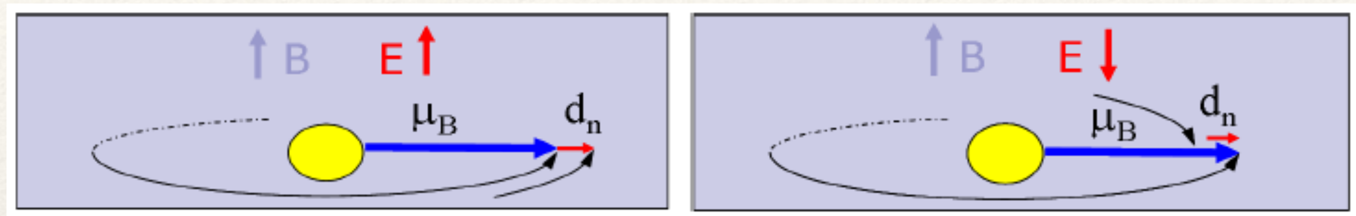
➛ Electroweak contribution to nEDM is not experimentally accessible today.

➛ A measured nEDM ≠ 0 value is an unambiguous manifestation of BSM physics.

➛ θ_{QCD} is constrained < 10^{-10} rad by the experimental limit on d_n. [PRD 19 (1979) 2227]
The Strong CP problem is the consequence of the nEDM measurement.

nEDM: principle of the measurement

- Measurement based on the Larmor precession of the neutron spin while placed in static $\vec{B}$ and $\vec{E}$ fields, first // (+) and then anti-// (-).
  Hamiltonian to describe the interaction of the neutron with $\vec{E}$ and $\vec{B}$: $H = -(\vec{\mu}_n \cdot \vec{B} + \vec{d}_n \cdot \vec{E})$

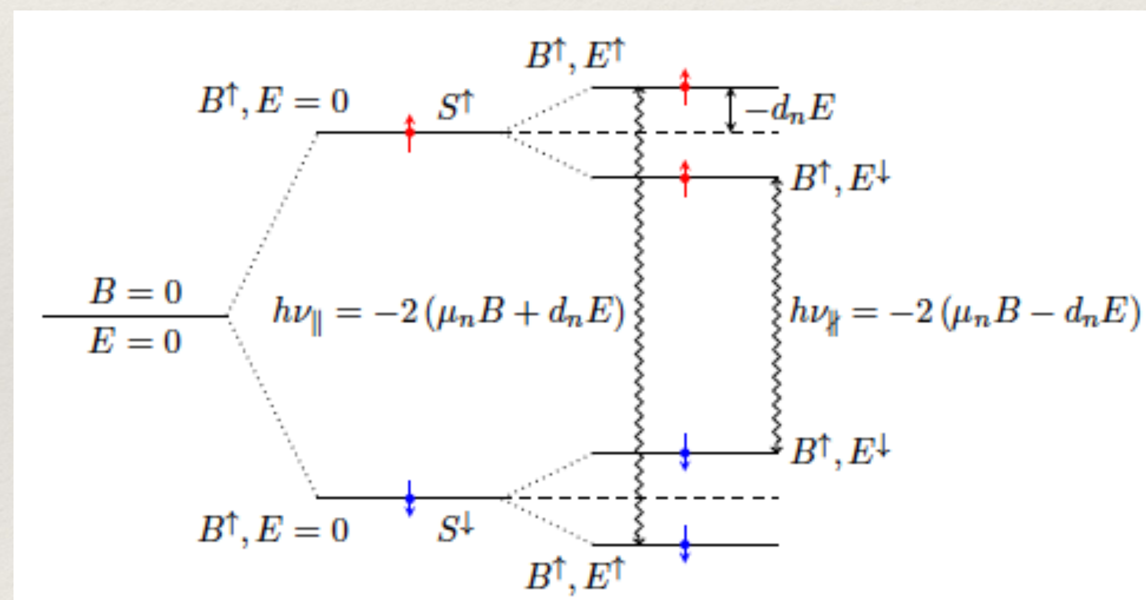


- Precession frequencies $\nu_{\pm}$ corresponding respectively to + and - field configurations:

$$\text{Energy}_{\pm} = h\nu_{\pm} = 2\,(\mu_n B \pm d_n E)$$

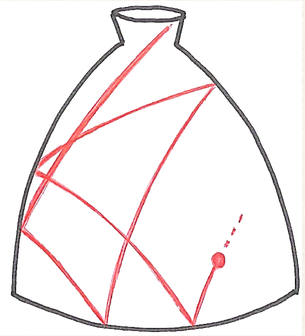
➛ $$d_n = \frac{h\,(\nu_{\parallel} - \nu_{\nparallel}) - 2\mu_n\,(B_{\parallel} - B_{\nparallel})}{2\,(E_{\parallel} + E_{\nparallel})}$$

➛ $$d_n = h\,(\nu_{\parallel} - \nu_{\nparallel}) / 4E$$



- Main difficulties:
  - B field stability between the 2 field configurations // and anti-// : dominant systematics.
    Additional term $2\mu_n(B_{\parallel} - B_{\nparallel})$ to be taken into account in d_n if the B field varies.
  - Difference $(\nu_{\parallel} - \nu_{\nparallel}) < 60$ nHz, very small.

nEDM: UCN (1)



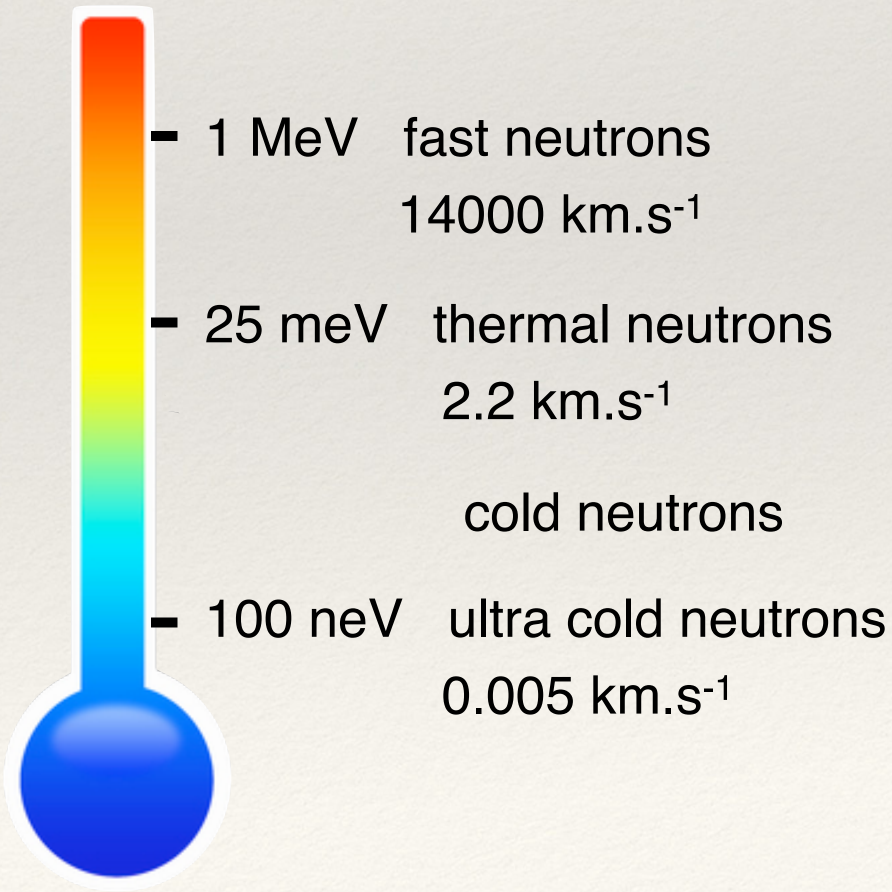
- Neutron: massive and neutral particle, with long lifetime (~15 min).
  Production: reactor, spallation source.

- Bouncing neutrons:
  if moving slowly enough, neutrons are reflected when striking the surface of a material, with energy E and incident θ angle such as:

  $\sin\theta < \sqrt{(V_F / E)}$. V_F = Fermi potential (property of the material).
  If $V_F < 0$, the material is transparent to neutrons.

- Ultra Cold Neutrons:
  $E \sim 100$ neV, $v < 10$ m.s^{-1}.

  ➛ the neutron is always reflected ∀ θ:
  storage possible, easy guidance in tubes.
  Confinement time governed by the neutron lifetime and by the wall absorption coefficient.



nEDM: UCN (2)

- Several experiments based on UCN test fundamental laws and search for BSM physics, e.g. with following measurements:
  - EDM,
  - quantum states in a gravitational potential,
  - β decay properties (V_{ud}),
  - mirror neutron oscillation, …

  World community amounts to ~ 200 physicists.
  France: LPC Caen, LPSC Grenoble.

- Mesurement of nEDM: breakthrough ~ 1980 thanks to UCN.

  Several experiments are about to start:

  targeted sensitivities <~10^{-27} e.cm at the horizon 2020-2025.

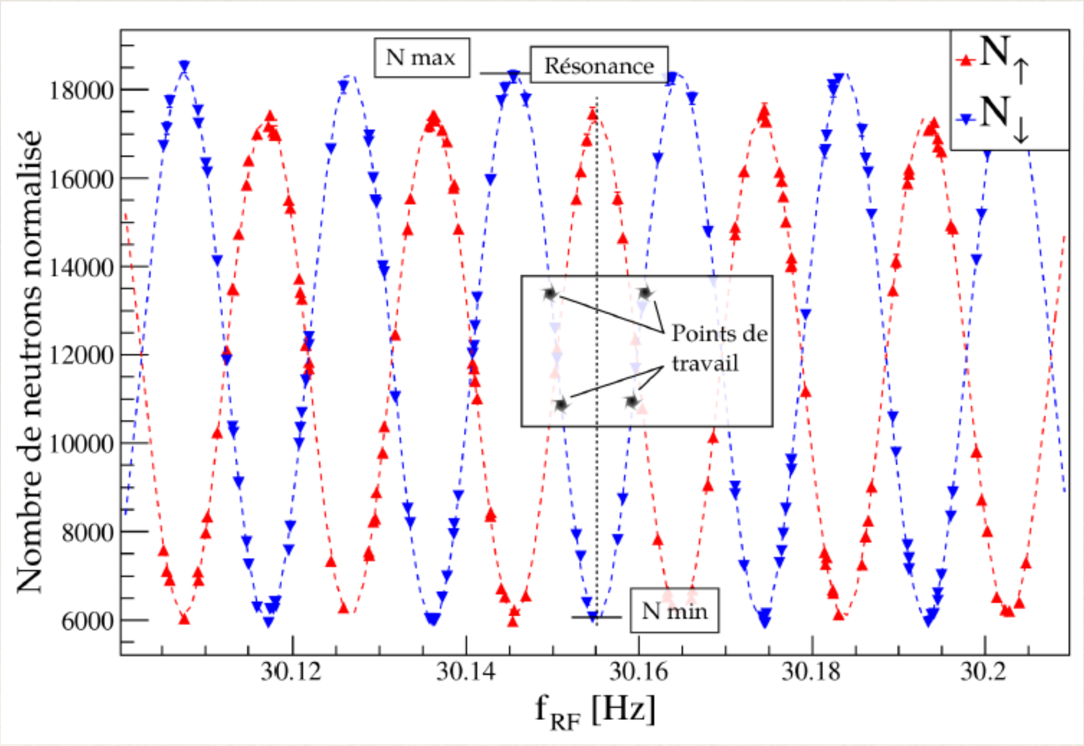
➛ Following slides :
example of the nEDM experiment @PSI

nEDM: the nEDM experiment @PSI (1)

- OILL experiment moved from ILL to PSI in 2009 to increase the neutron density.
  Proton beam ➛ hits a target ➛ spallation (10 neutrons / proton collision) ➛ feeds an UCN source.

- Measurement of the Larmor frequency based on Ramsey's separate oscillating fields method: production of the interference pattern. The RF frequency is detuned to perform counting rate measurements. The precession frequency is extracted from the fit to the interference pattern.

Ramsey's interference pattern
(PSI, after 50 s of free precession, August 2012)



Statistical accuracy: $\sigma_{stat} \sim \frac{1}{T\,E\,\alpha\sqrt{N}}$

where E = electric field amplitude
N = # of detected neutrons
T = free precession time
α = visibility of the central fringe
(depends on polarisation rate and on B magn. field homogeneity)

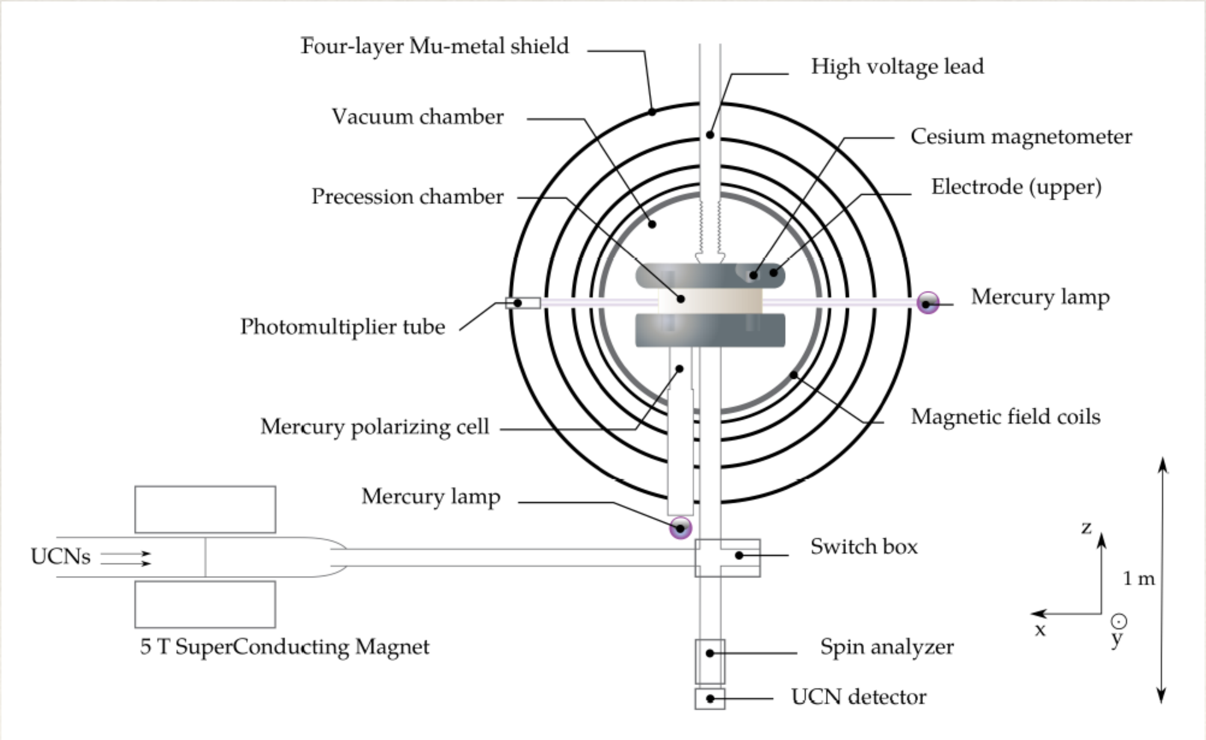
➛ each has to be as high as possible

Strategy: very homogeneous and weak B = 1 μT magnetic field,
very high E = 10 kV.cm^{-1} electric field.

nEDM: the nEDM experiment @PSI (2)

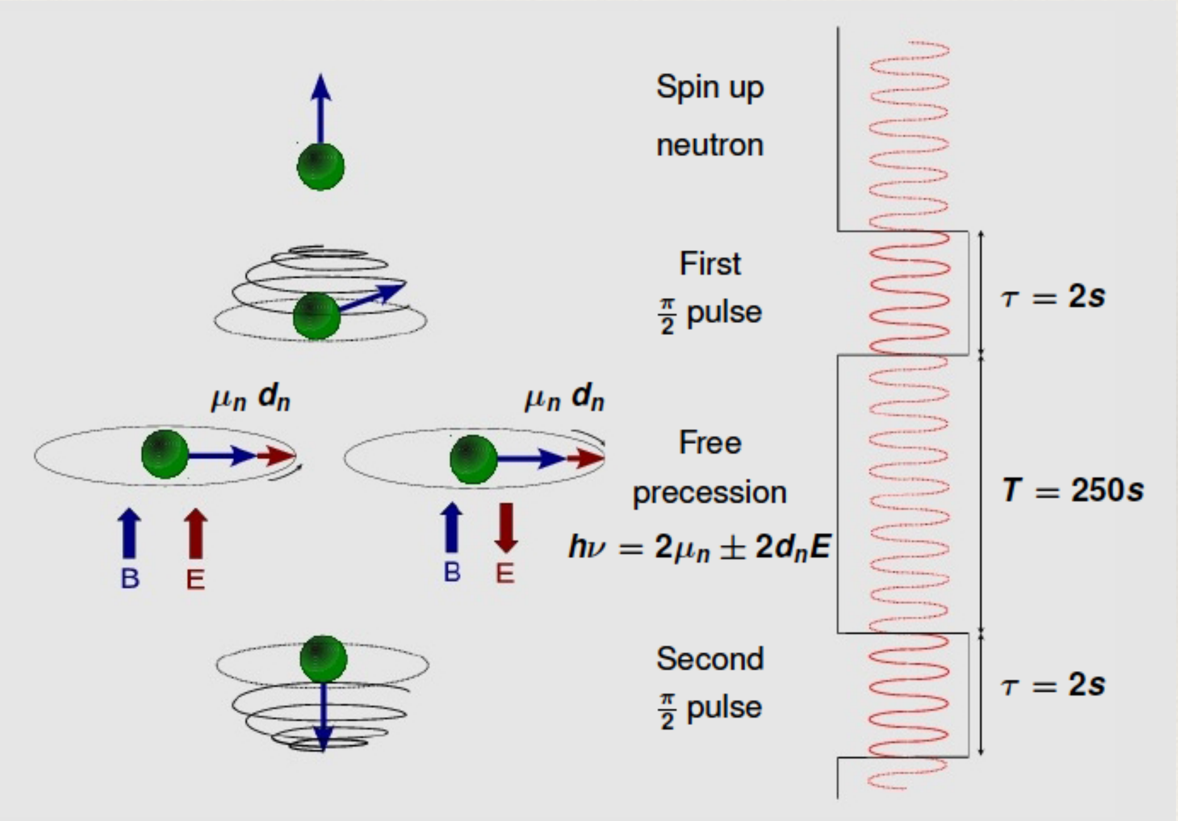
- Polarisation (~100 %) of UCN by traversing the supra 5 T magnet.
- Transport of UCN towards the precession chambre with guides (featuring a high Fermi potential).
- Storage of UCN in the precession chambre (Fermi potential 8x higher, 80 % of UCN are stored). Production of the electric field E (top electrode connected to the high voltage).
- Production of the main magnetic field B (1 µT, // z): coil wound around the vacuum tank.
- Stabilisation of the B magn. field: static (shields) and dynamic (compensating coils).

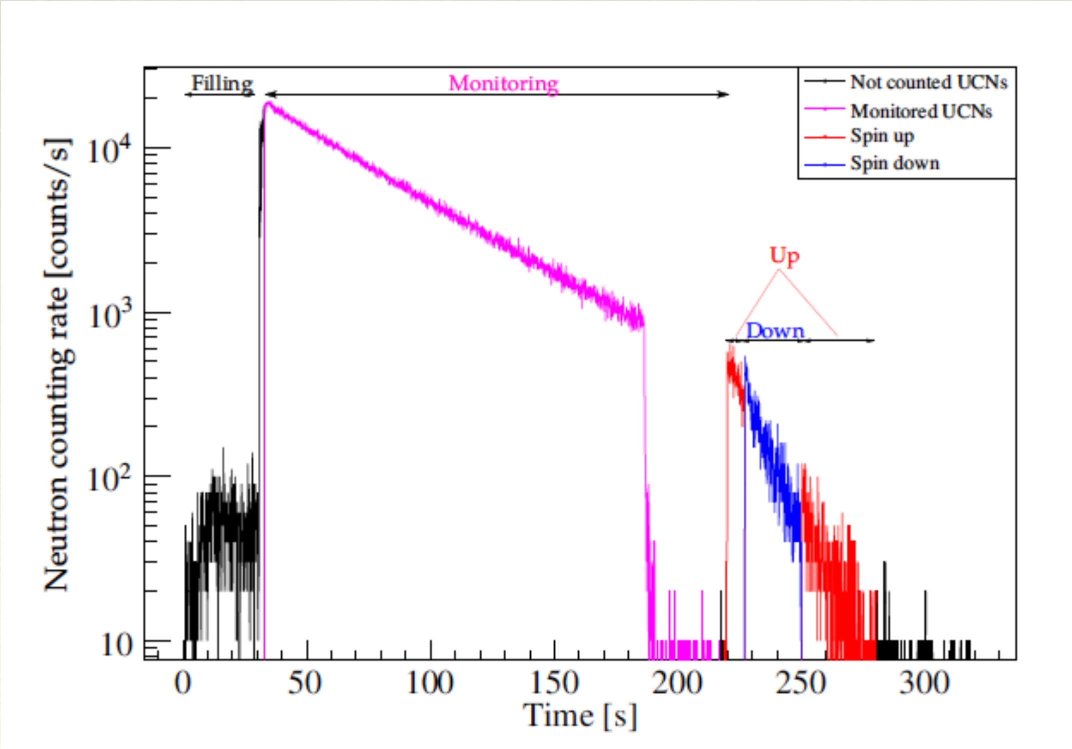
  Final relative homogeneity $\Delta B \sim 10^{-4}$-10^{-3}.
- B magnetic field monitoring:
  - Hg co-magnetometer inside the volume to compensate for the B variations ~300 fT. Induces a systematic effect (field gradient).
  - Cs magnetometer outside the volume: B gradient control.



nEDM: the nEDM experiment @PSI (3)

- UCN are filled during 8 s into the vessel, every 800 s by the beam.
- UCN detection: UCN fall (gravitation) down to the detector. Measurement lasts $< \tau_{neutron}$.
  Detector = 2 glass scintillator layers for background identification (γ and Čerenkov in light guides).
  One layer is ^{6}Li-doped : $^{6}Li + n \rightarrow \alpha + {}^{3}T + 4.78$ MeV.
- Spin analysis: counting of spin-up and spin-down neutrons.
  - Magnetised Fe layer: only UCN with spin anti-// with magnetisation are able to cross.
  - Spin-flipper: to count the other spin state.
  - Sequential counting: 8 s spin up + 25 s spin down + 17s spin up.





nEDM: outlook

- nEDM measurements are currently limited by:
  - UCN density,
  - systematics related to the $\vec{B}$ magnetic field spatial and time homogeneity.

- 4 experiments dedicated to nEDM measurements based on UCN, all at the R&D stage:
  @FRM-2 (reactor), München ; @RCNP-TRIUMF, Vancouver ; @SNS-ORNL, Oak Ridge ; @PSI, Villigen.

  ↳ Use 2 precession chambers:

  - improved statistics: better UCN production, higher V_F of storage materials ➛ more UCN are stored;
  - the same $\vec{B}$ field is used in the 2 $\vec{E}$ vs. $\vec{B}$ field configurations (↑↑ and ↑↓), (+ improved magnetometers, + improved shielding).

➛ Future limits <~ 10^{-27} expected at the horizon 2020-2025:
- If no signal observed with such a sensitivity: electroweak baryogenesis is unlikely.
- If $d_n \neq 0$ measured: it is a discovery of a new source of CPV, beyond the SM.

Muon anomalous magnetic moment: outline

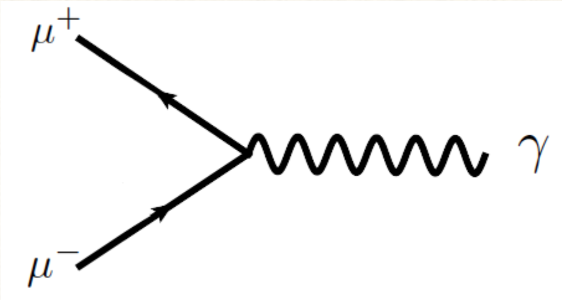
- Definition of the anomaly a_μ
- SM prediction
- Measurement principle
- The BNL E821 experiment
- Discrepancy with the prediction
- Sensitivity to BSM
- Outlook: the FNAL E989 and J-PARC E34 experiments

muon (g-2): definition

- Muon magnetic moment: $\vec{M} = g_\mu \frac{e}{2m_\mu} \vec{S}$

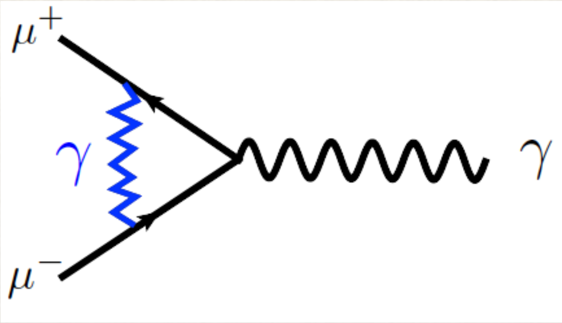
  with the gyromagnetic ratio (a.k.a. Landé g-factor) :

  $g_\mu = 2$ as predicted from the Dirac equation.



- Anomalous magnetic moment: quantum corrections lead to deviations w.r.t. $g_\mu = 2$, quantified by the so called « anomaly » a_μ:

$$a_\mu = \frac{g_\mu - 2}{2}$$

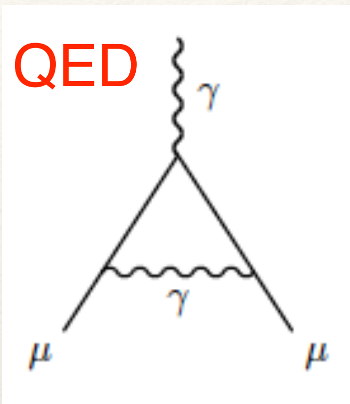


➛ the measurement of a_μ is sensitive to possible contributions of new unknown particles to quantum corrections.

- The measurement of a_μ enables to test the SM with very high precision:
  - accurate theoretical prediction: current relative precision $\sim 0.42 \times 10^{-6}$,
  - precision measurement: current relative precision $\sim 0.54 \times 10^{-6}$.

muon (g-2): SM prediction

- SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had} = 116\,591\,803\,(1)\,(42)\,(26) \times 10^{-11}$ (EW) (Had)

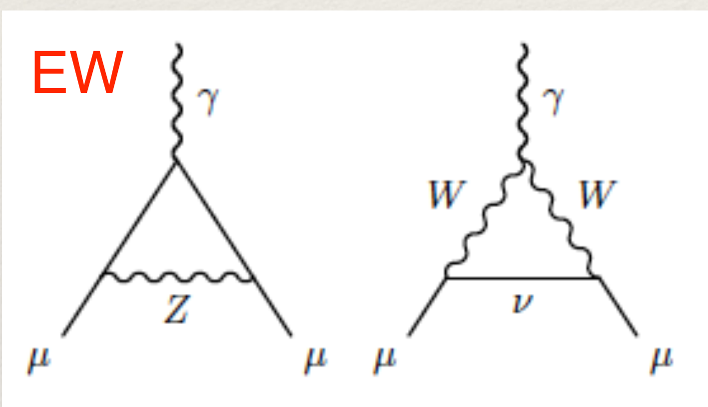


QED: calculation including γ, e, μ and τ loops up to order $(\alpha/\pi)^5$:

[12 672 diagrams at order α^5]

$a_\mu^{QED} = 116\,584\,718.95(0.08) \times 10^{-11}$ ➛ 99.99 % of a_μ

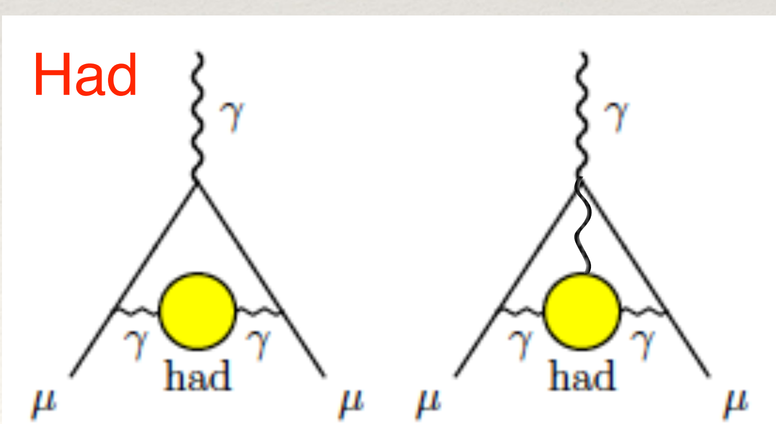
Uncertainty dominated by accuracy on α.



EW: calculation including $W^\pm$, Z and H loops up to 2 loops:

contributions are suppressed by at least $\frac{\alpha}{\pi}\,\frac{m_\mu^2}{M_W^2} \sim 4 \times 10^{-9}$

$a_\mu^{EW} = 153.6(1.0) \times 10^{-11}$



[had.vac.pol.] [l-b-l]

Had: main uncertainty, expected to decrease in near future (new exp. measurements and Lattice QCD progress).

Non perturbative regime, needs experimental inputs:

$\sigma(e^+e^- \rightarrow \text{hadrons})$ or τ-decays for the "vacuum polarisation" contribution and modelisations for the "light-by-light" contribution.

$a_\mu^{Had} = 6923(42)(3) \times 10^{-11}$ [had.vac.pol.] et $7(26) \times 10^{-11}$ [l-b-l]

muon (g-2): measurement principle

- Polarised muons circulating in a storage ring, in magnetic and electric transverse and uniforme fields ($\vec{\beta}\cdot\vec{E} = \vec{\beta}\cdot\vec{B} = 0$):
  - spin Larmor precession, with rate ω_S.
  - Thomas precession with frequency ω_C (relativistic correction).
- ➛ mesurement of a_μ by calculating the difference $\omega_a = \omega_S - \omega_C$.

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\left(\vec{\beta}\times\frac{\vec{E}}{c}\right) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

$$\vec{d}_\mu = \eta\left(\frac{q}{2mc}\right)\vec{S}$$

BNL E821, FNAL E989 :

The spin oscillation does not depend on the electric E field by choosing the “magic γ” value: p = 3.09 GeV ➛ $\gamma^2 - 1 = 1 / a_\mu$.

Assume that you know the value a_μ first.

J-PARC E34 :

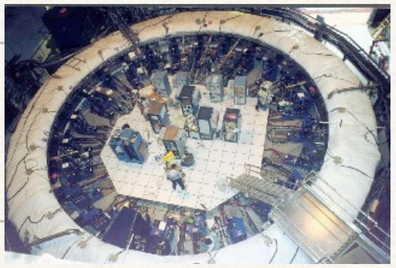
Eliminate the E field dependence: E = 0

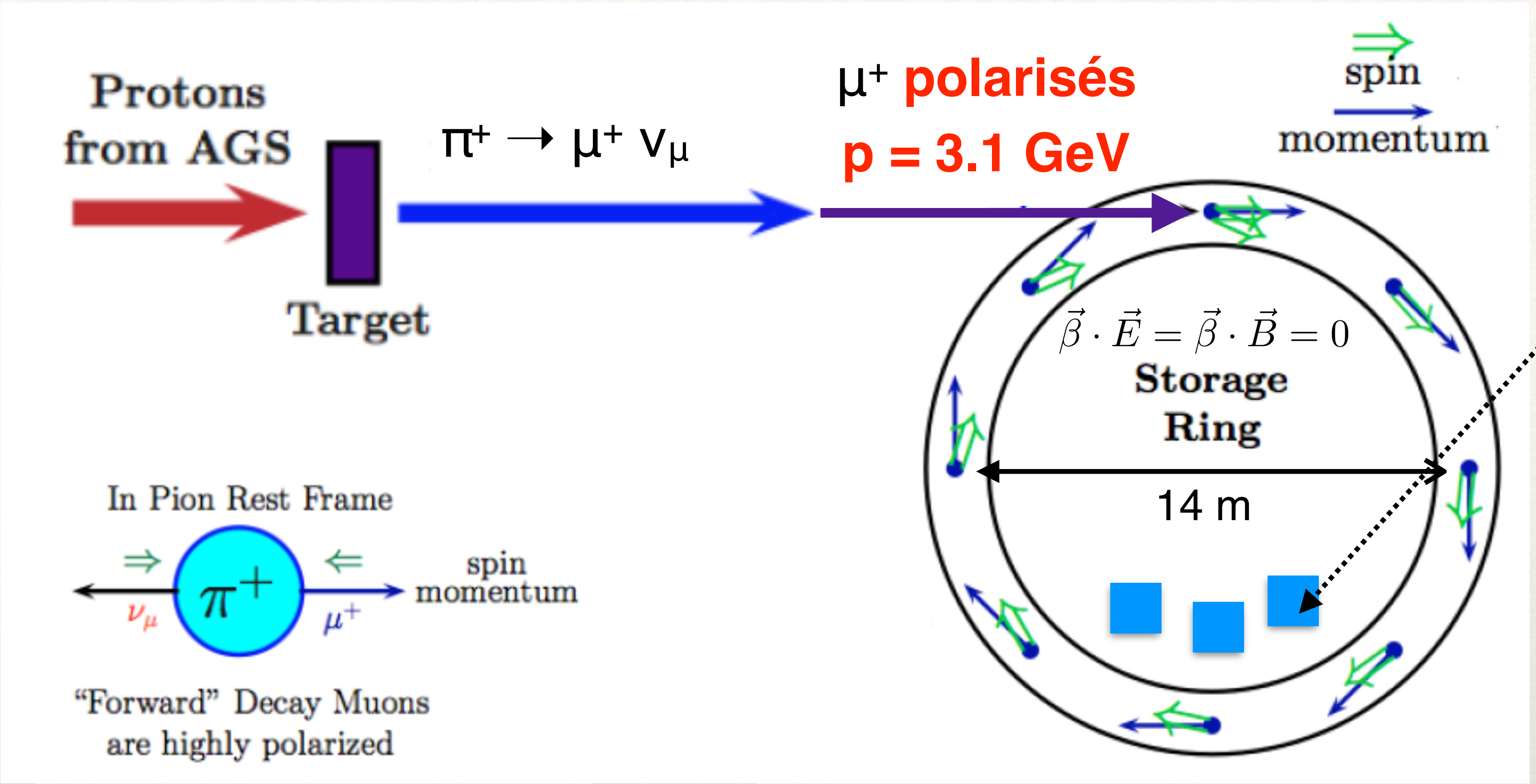
- Muon electric dipole moment $d_\mu = (-0.1 \pm 0.9)\times 10^{-19}$ e cm, is very small and can be neglected:

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

➛ measurement of a_μ = measurements of the B magnetic field and of the spin precession frequency ω_a (spin direction as a function of time).

muon (g-2): the BNL E821 experiment (1)





24 calorimeters along the storage ring, measuring:

- e^- time of arrival,
- e^- energy.

- If $a_\mu = g - 2 = 0$ ➛ $\omega_a = 0 = \omega_S - \omega_C$, i.e. identical spin precession and cyclotron frequencies.

  If $a_\mu \neq 0$: during the revolution, the muon polarisation varies as ~ a_μ.

  The μ spin axis change is 12° w.r.t. the μ momentum after each revolution.

- The μ observed lifetime ~ 64.5 μs. One revolution lasts ~ 149 ns.

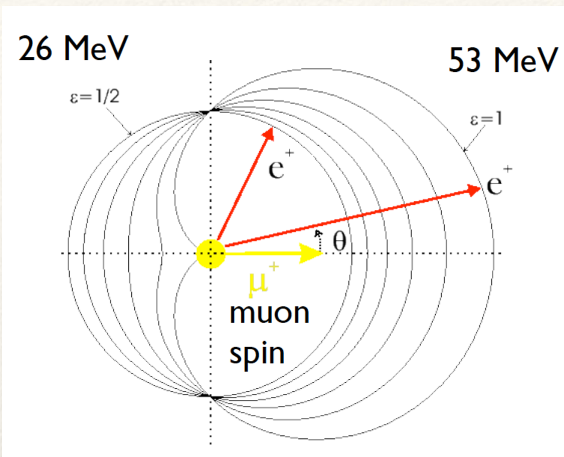
  After several revolutions: $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

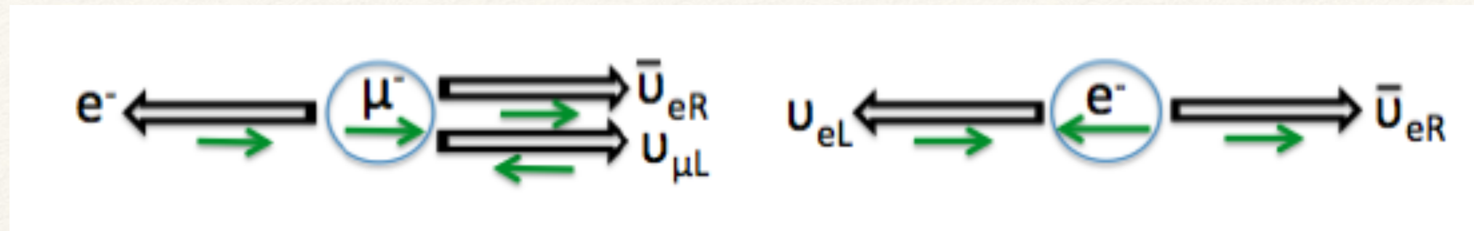
  In the μ rest frame, e^- is emitted with direction depending on E_e and on the μ spin orientation.

  The highest energy electrons are emitted in the direction of the muon spin, while the lower-energy electrons are emitted in the opposite direction.

muon (g-2): the BNL E821 experiment (2)

μ rest frame: $E_{e-,\,max} = m_\mu c^2 / 2 = 53$ MeV $E_{e-,\,min} = 0$



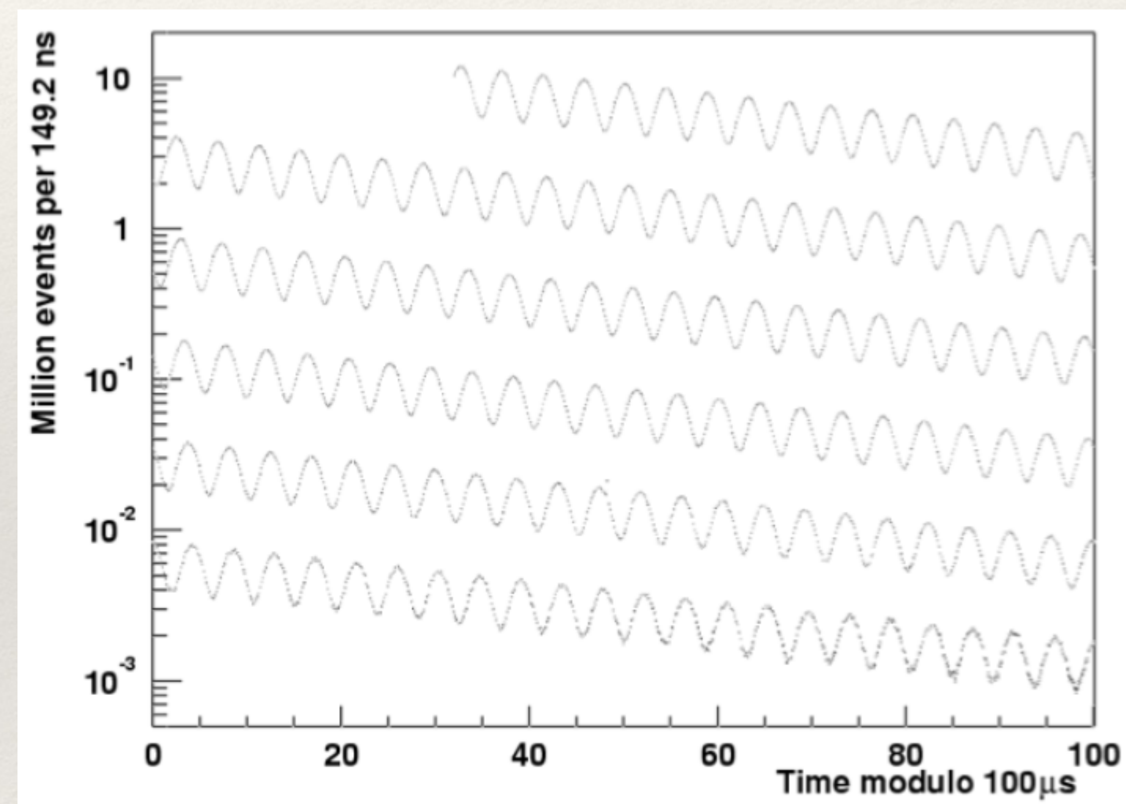


$$N(t, E_{th}) = N_0(E_{th})\ \exp(-\frac{t}{\tau_\mu})\ f(\sin(\omega_a t))$$

\# of detected e^-

If all e^- are detected

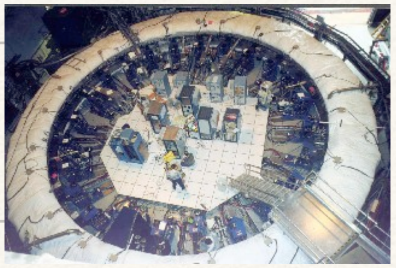
e^- with $E_\mu > E_{th}$ are detected



3.6×10^9 e^- detected with $E_{th} > 1.8$ GeV (BNL E821 2001 data).

➛ measurement of ω_a from the fit of the curve $N(t,E_{th})$.

muon (g-2): the BNL E821 experiment (3)



- Measurement of the B magnetic field (very homogeneous): accuracy ~ 0.01×10^{-6}.
  Mapping of B along the storage ring and monitoring as a function of time with NMR probes to measure the Larmor frequency ω_p of protons (water samples) placed in the same field:

  $\omega_p = g_p B$, with g_p = proton gyromagnetic ratio: $\vec{\mu}_p = g_p \vec{S}$ ➛ $B = \omega_p / 2\mu_p$.

➛ $$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

- Final measurement of the muon (g-2) at BNL E821 (with agreement between μ^- and μ^+ measured values): $a_\mu = (116\ 592\ 089\ (54)_{stat}\ (33)_{syst}\ (63)_{tot}) \times 10^{-11}$

statistically limited

- Betatron oscillation (μ orbit): $\vec{\beta} \cdot \vec{E} = \vec{\beta} \cdot \vec{B} = 0$ not totally true.
  ➛ main systematic, from the measurement of ω_a.

- Water samples (protons) not exactly placed on the same orbit as muons (offset): second main systematic, from the measurement of ω_p.

muon (g-2): measurement vs. prediction (1)

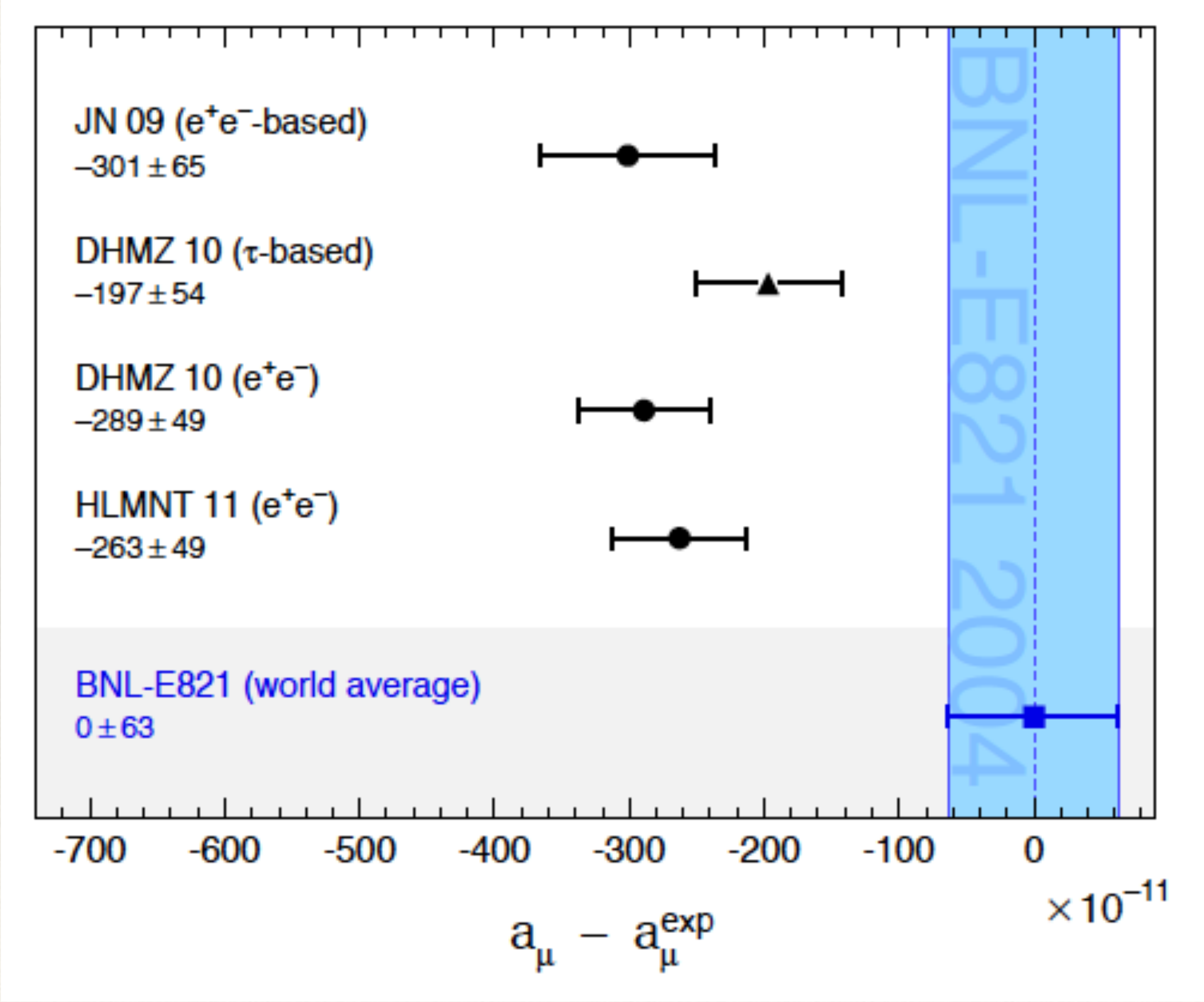
- Comparison of the measured value with its prediction:

$$\Delta a_\mu = a_\mu\,(\text{exp}) - a_\mu\,(\text{SM}) = (29 \pm 8) \times 10^{-10}$$

➢ ~3.6 σ discrepancy between exp. measurement and SM prediction.

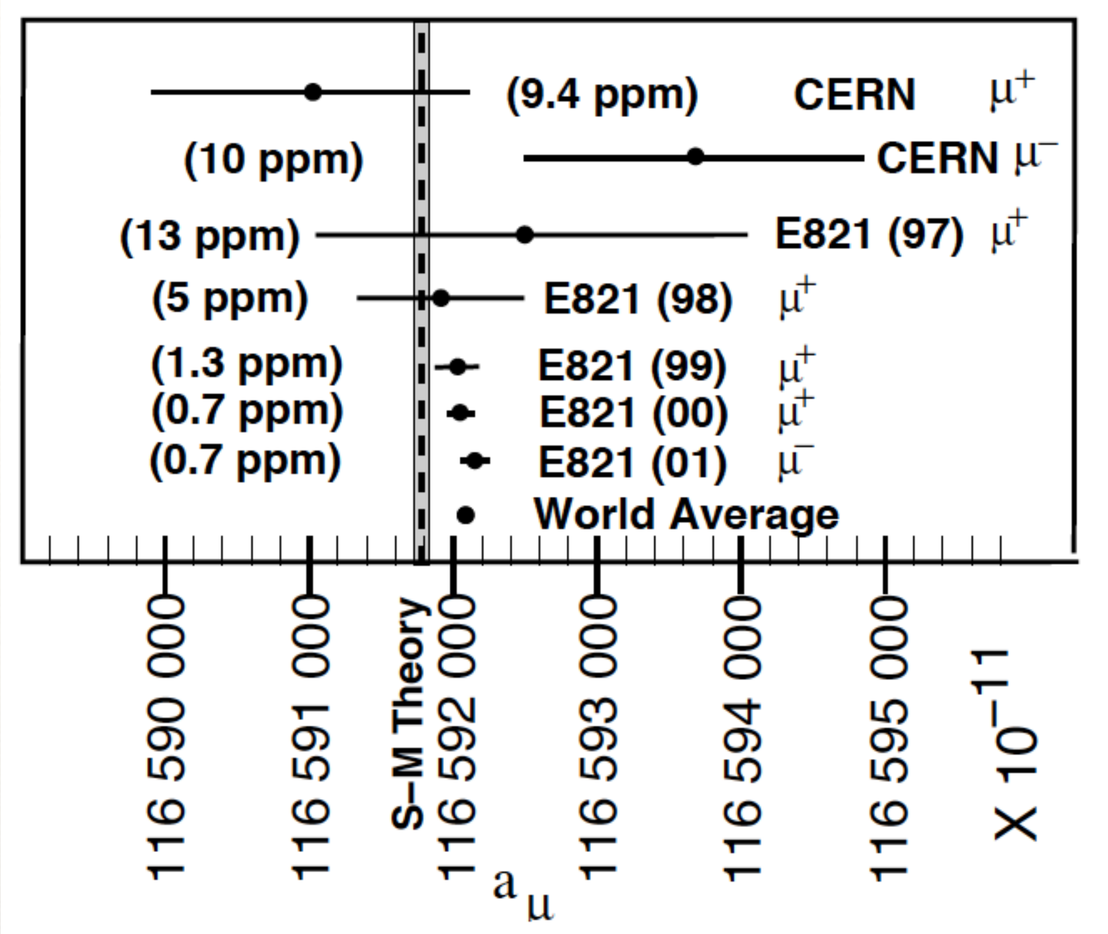
- What explanation?
  - Theoretical issue?
    Hadronic contributions in quantum corrections are difficult to estimate.
  - New particle forgotten contributions?

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had} + a_\mu^{NP}$$



muon (g-2): measurement vs. prediction (2)

- What explanation [cont[d]]?
  - Experimental issue?
    Measurement preformed by
    one unique experiment!



➛ Motivation to perform:

- improved theoretical calculations
  (Lattice QCD + VEPP-2000 and BES-III results),
- new measurements of a_μ with improved accuracy
  w.r.t. BNL E821 and based on different techniques:
  FNAL E989 and J-PARC E34.

Targeted experimental accuracy: 0.1 - 0.14 $\times 10^{-6}$ (improvement by a factor of 4)

➛ reach a discovery > 5 σ aind strongly constraint BSM theories?

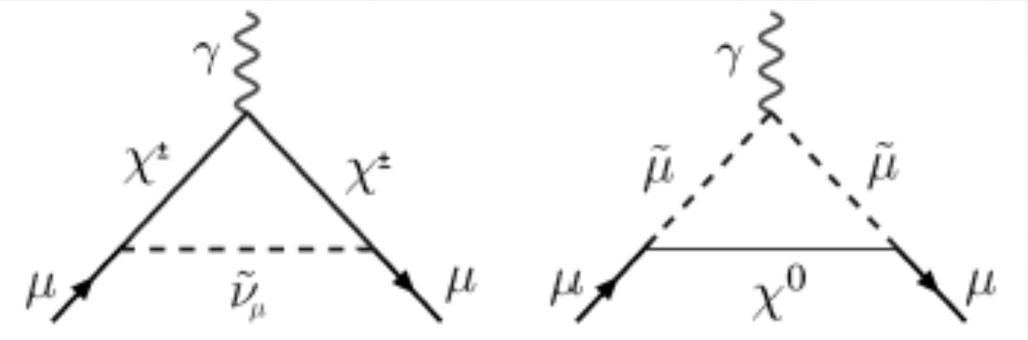
muon (g-2): sensitivity to BSM physics

- All lepton (g-2) are sensitive to beyond SM physics occuring at scale M_{NP} (with coupling g_{NP}):

$$\text{sensitivity to NP} \quad \delta a_\mu \sim \frac{g_{NP}^2}{g_{EW}^2} \frac{m_{lepton}^2}{M_{NP}^2}$$

  - Electron (g-2) is measured with a better experimental precision than μ (g-2), however μ provides a better sensitivity to NP than electron, by a factor ~ 4×10^4.
  - Sensitivity from μ (g-2) up to NP mass scale ~ TeV.

- New susy particles may contribute to g-2 through loops:



$$a_\mu^{SUSY} \sim \text{sign}(\mu) \times 130 \times 10^{-11} \times \frac{(100\ \text{GeV})^2}{(m_{SUSY})^2} \tan\beta$$

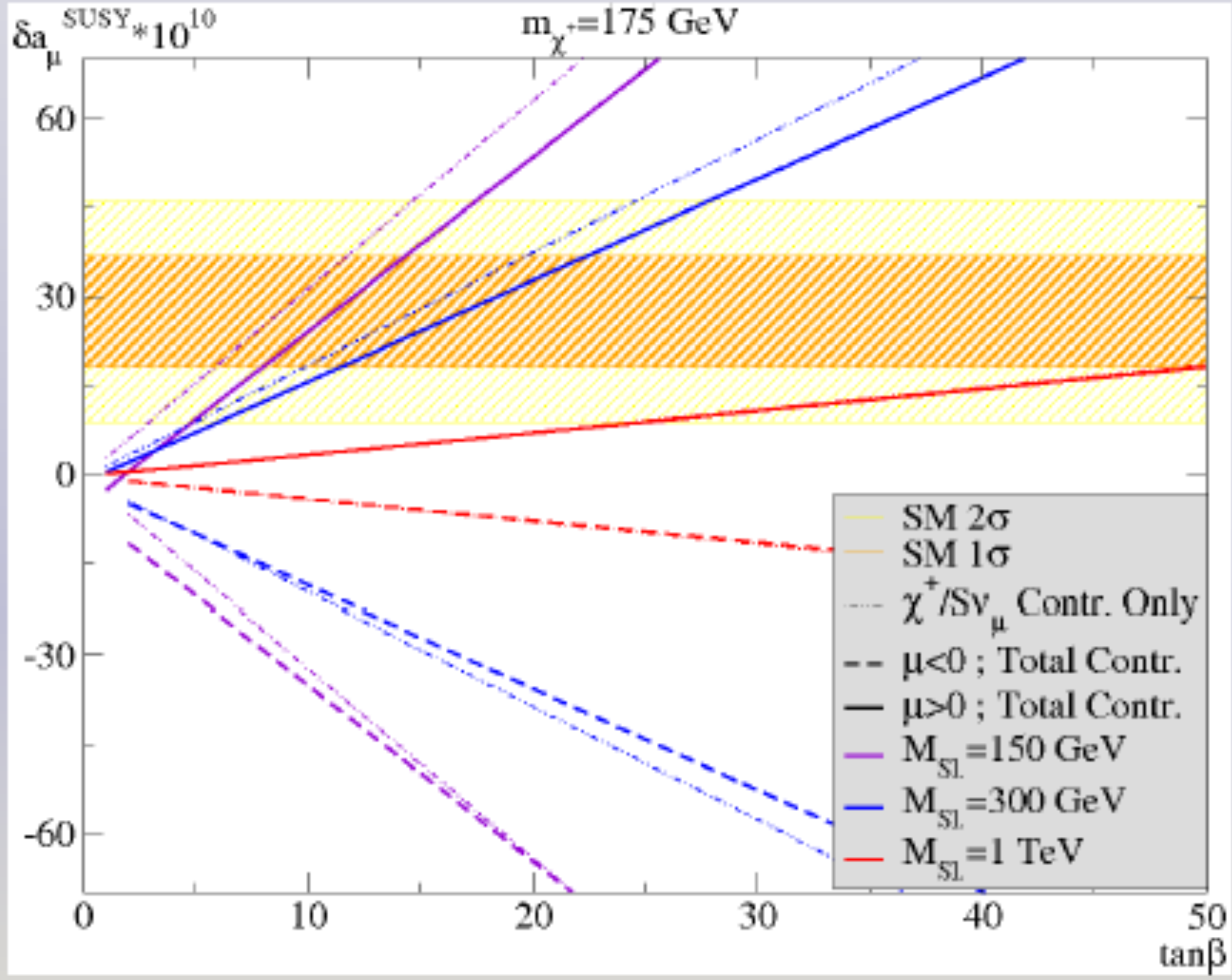
➢ m_{SUSY} ~ 100-500 GeV could explain the discrepancy, with tan β ~ 3-40 and sign(μ) >0.

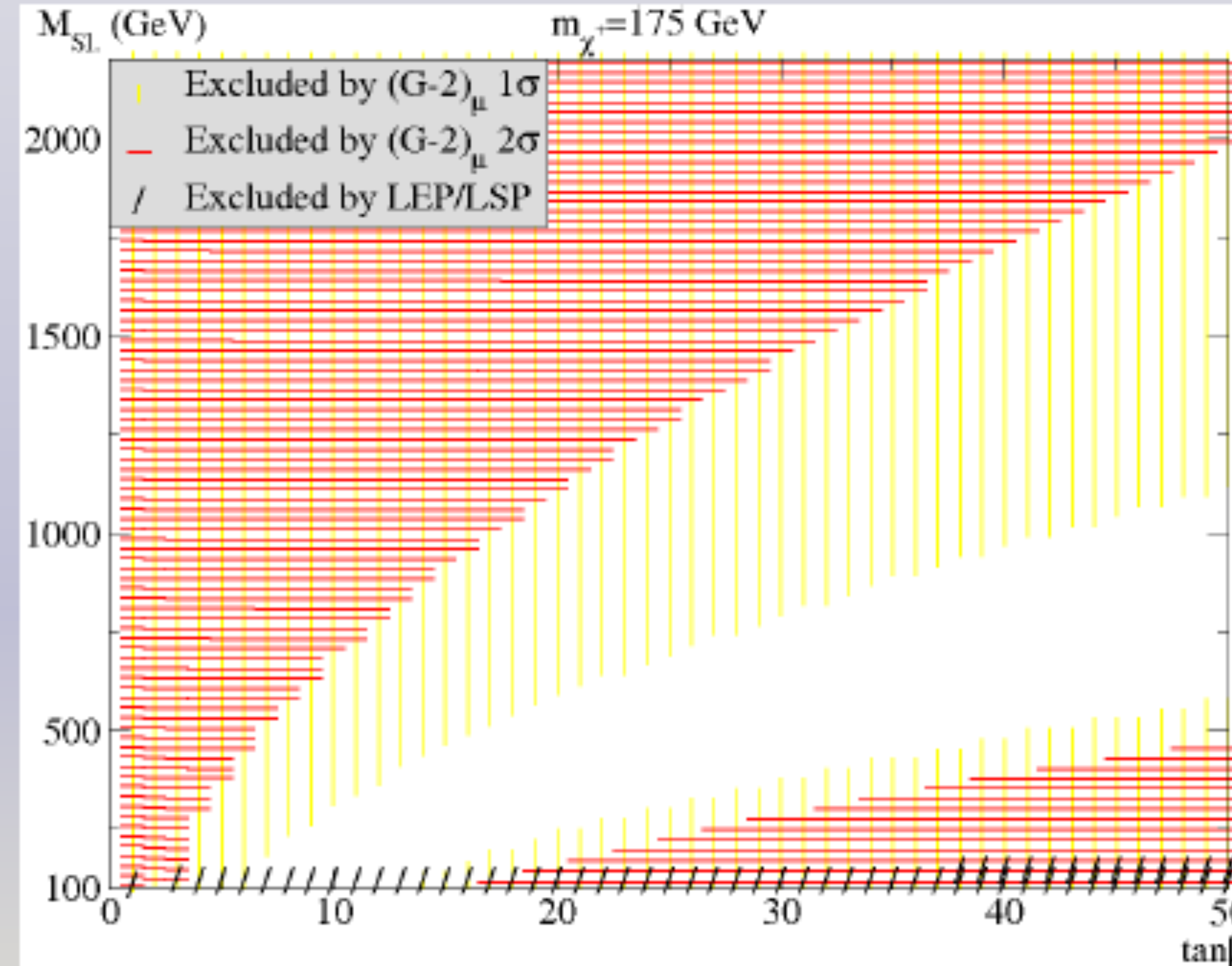
- Contribution of a dark photon Z':

$$a_\mu^{\text{dark photon}} \sim \frac{\alpha}{2\pi} \varepsilon^2 F(m_{Z'}/m_\mu)$$

➢ a dark photon with $m_{Z'}$ ~ 10-100 MeV and coupling $\varepsilon \sim 10^{-3}$ could explain the discrepancy.

Constraints on the MSSM parameter space



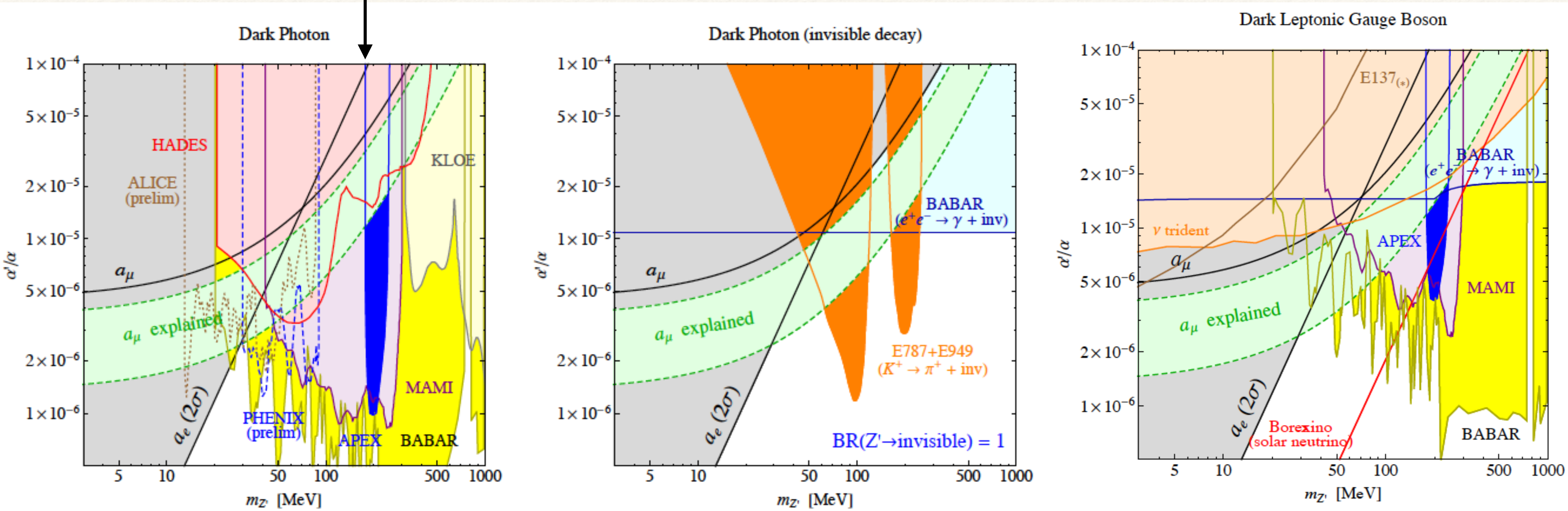


- Chargino/Slepton loop tends to be dominant;
- Effect $\propto Y_\mu \propto \tan\beta$;
- $\mu > 0$ required;
- Light binos can also have significant effect.

Conclusion: The 3σ deviation can be reproduced provided SUSY particles are sufficiently light / $\tan\beta$ is large.

muon (g-2): constraints on the dark photon

BR(Z’→e^+e^-) = 1



BR(Z’ → ℓ ℓ) ≈ 1

Search for a dilepton resonance.

BR(Z’ → invisible) = BR (Z’ → DM) = 1

Hypothesis: Light Dark Matter with $m_{DM} < M_{Z'} / 2$.

Search for missing energy.

BR(Z’ → quarks) = 0

Assume LDM,

but BR(Z’ → νν) ≠ 0.

➢ The measured value of muon (g-2) excludes almost all theories including a Dark Photon. Still possible in case of very Light Dark Matter and $M_{Z'} \sim 50$ MeV, $\varepsilon' \sim 10^{-3}$.

muon (g-2): outlook at FNAL E989 and J-PARC E34 (1)

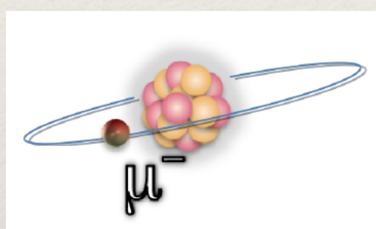
- In order to be able to conclude on BNL E821 (g-2) measurement:
  systematics have to be decreased (➛ syst ~ 0.1×10^{-6}) and μ statistics has to be significantly increased (➛ stat ~ 0.1×10^{-6}).
  Currently under construction: 2 experiments, FNAL E989 (US) and J-PARC E34 (Japan), based on different techniques ➛ different systematics.

- **FNAL E989 experiment:** upgrade of BNL E821.
  - Reuse parts from BNL E821 which were well understood: storage ring, B magnetic field measurement devices.
  - Identify where a new approach is needed to reach the targeted syst. level: contamination of the μ beam by π is decreased by a factor of 20 ; new calorimeters (SiPM read out: the B field is not perturbated) ; tracking within the storage ring (in vacuum) to monitor the μ betatron oscillation.
  - Move the experiment at FNAL at the Tevatron anti-p accelerator: statistics of μ stored /hour × 6. Measurement performed only with μ^+.
  - Expected start of data taking end of 2017.

g−2 Collaboration Meeting November 2014

muon g-2: outlook at FNAL E989 and J-PARC E34 (2)

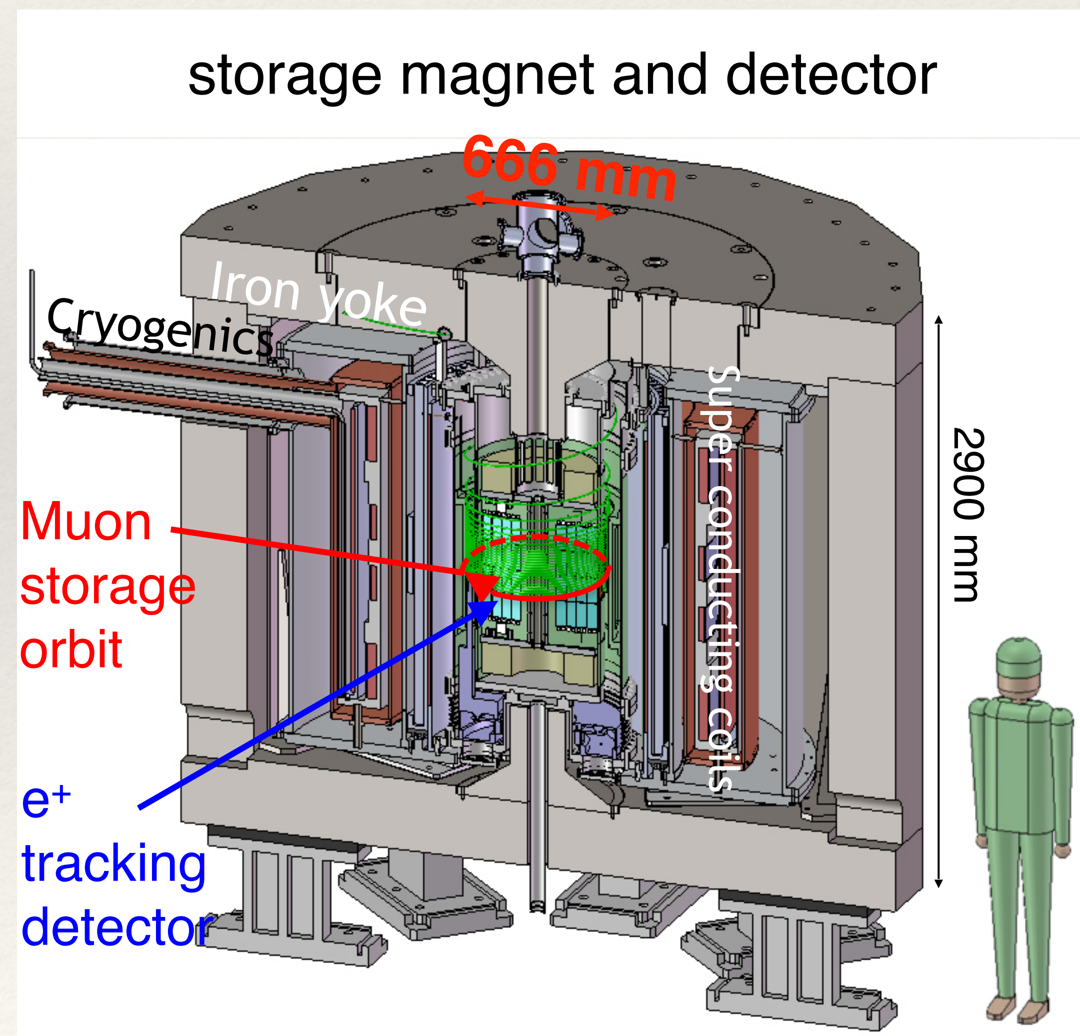
- **J-PARC E34 experiment:** different technique w.r.t BNL E821.
  - Measurement performed only with μ^+.
  - Production of "surface muons": π decay at rest ➛ 100 % polarised μ + unique momentum (2-body decay $\pi^+ \to \mu^+ \nu_\mu$): $p_\mu \sim 30$ MeV.
  - Since electric field $E = 0$ to eliminate the $\vec{\beta} \times \vec{E}$ term in ω_a: how to focus muons? Ultra Cold Muons ($p_\mu \sim 3$ keV) by producing and then ionising (w/ Laser) muonium μ^+e^- atoms.



Then μ are re-accelerated up to $p_\mu \sim 300$ MeV
➛ production of a μ focused beam with $\Delta p_T/p_T \sim 3$ keV / 300 MeV $\sim 10^{-5}$.

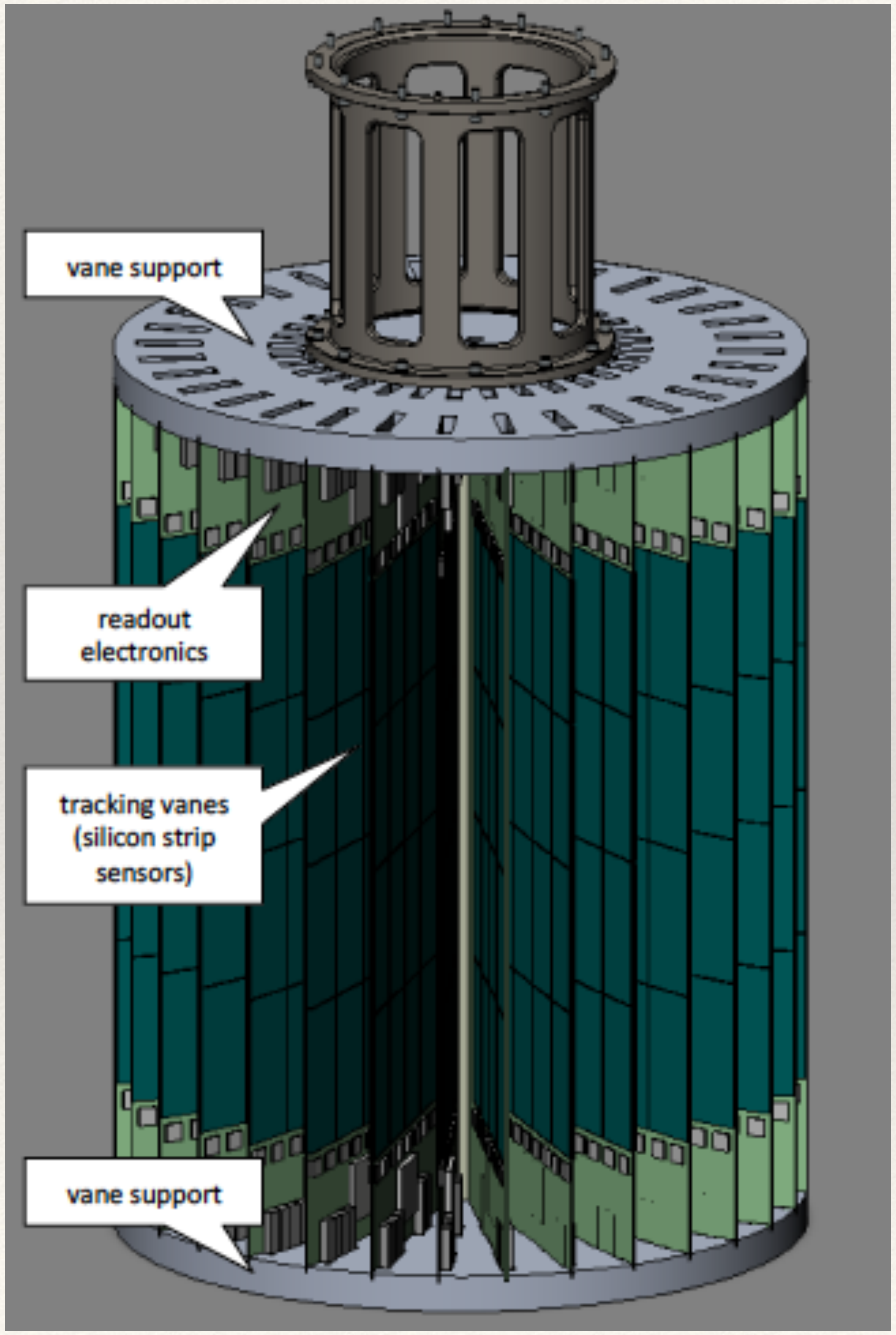
Low efficiency of this process:
4×10^{15} protons ➛ 10^4 thermalised μ^+.

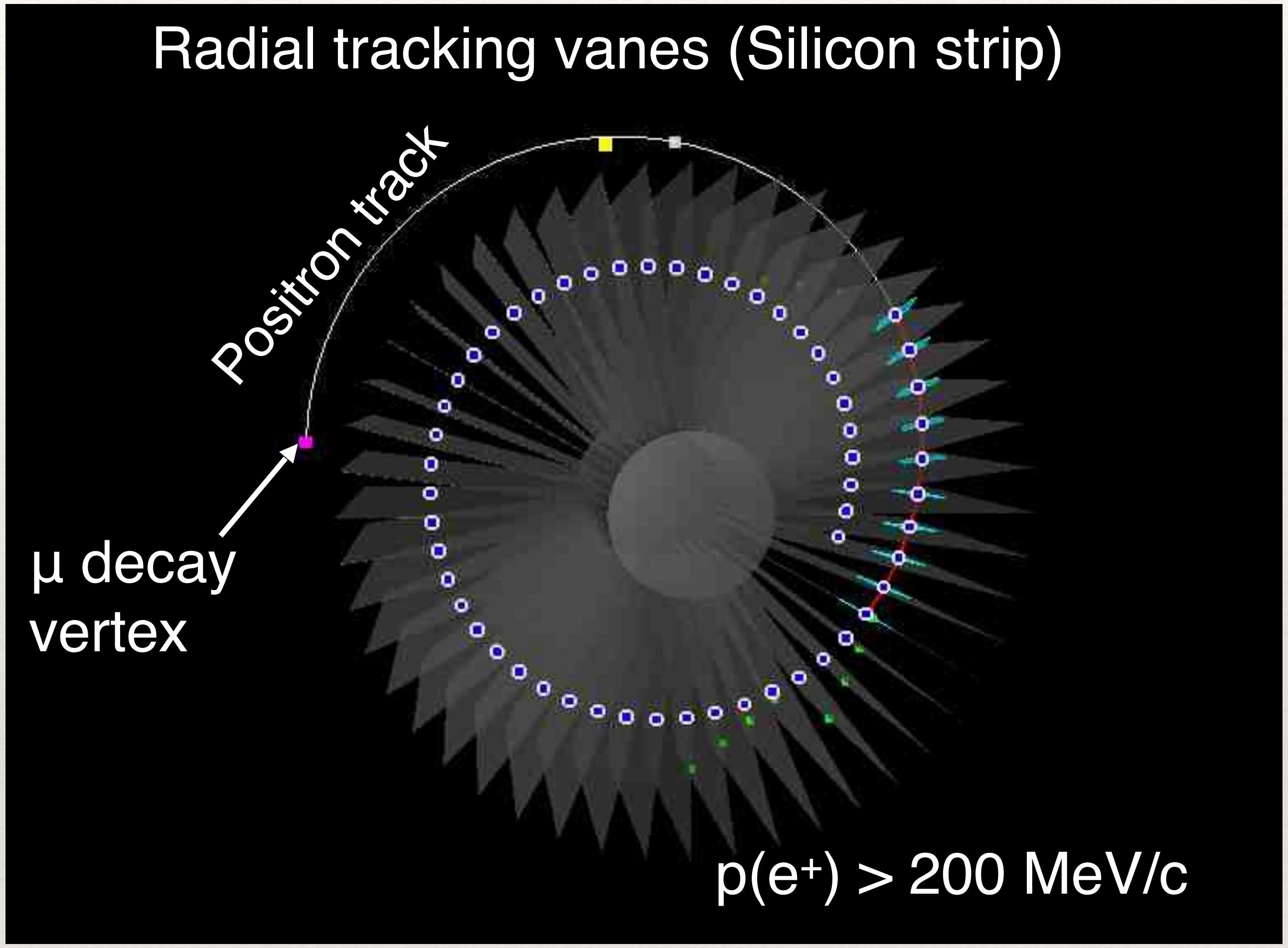
  - Storage of μ^+ in a very compact region: better control of the B field.



muon g-2: outlook at FNAL E989 and J-PARC E34 (3)

- Positron energy, angle and arriving time (in time coincidence with the pulsed p beam to limit the background) are measured in Silicon strip detectors.





- Contribution of IN2P3 (LPNHE Paris) to J-PARC E34, in particular to the tracking effort:
  - Caracterisation of Silicon detectors.
  - Track reconstruction algorithm.

Course outline

- Course on « Flavour and non accelerator physics » ? Vaste topic!

  ➛ subjective selection: focus on few examples of precision measurements performed in the quark and charged lepton sectors & experimental point of view.

- Introduction,
- Neutron electric dipole moment,
- Muon anomalous magnetic moment,
- Charged lepton (μ) flavour violating decays,
- K decays,
- τ, B and D decays.

PART II (Charged lepton (μ) flavour violating decays; K decays; τ, B and D decays)

➛ Looking for Beyond Standard Model physics with nev to GeV particle physics.

- You may also refer to:
  - Gif 2010 Saveurs Lourdes,
  - Gif 2011 Neutrinos,
  - top quark physics treated in a dedicated course in this year Ecole de Gif 2015.

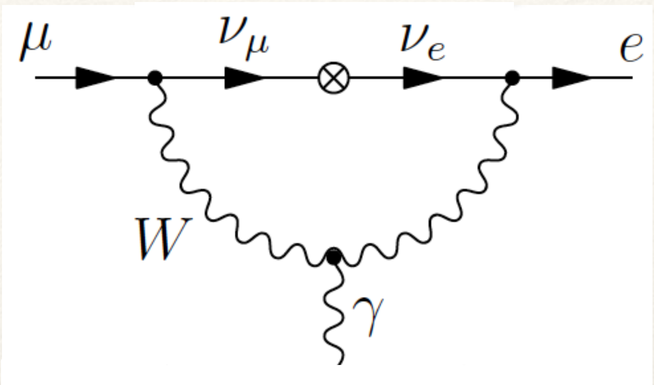
Charged lepton (μ) flavour violation: outline

- cLFV decays: SM and BSM predictions
- Muon vs. tau decays
- Search μ LFV channels
- Sensitivity to New Physics
- Search for $\mu \to e \gamma$ and the MEG experiment
- Search for $\mu \to e\, e\, e$ and the Mu3e experiment
- Search for $\mu \to e$ conversion and the Mu2e and COMET experiments
- Outlook

cLFV: SM and BSM predictions

- In the SM including ν oscillations, charged Lepton Flavour Violation possible in loop diagrams:

$$\Gamma(\mu \to e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left(\frac{\alpha}{2\pi}\right) \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)$$



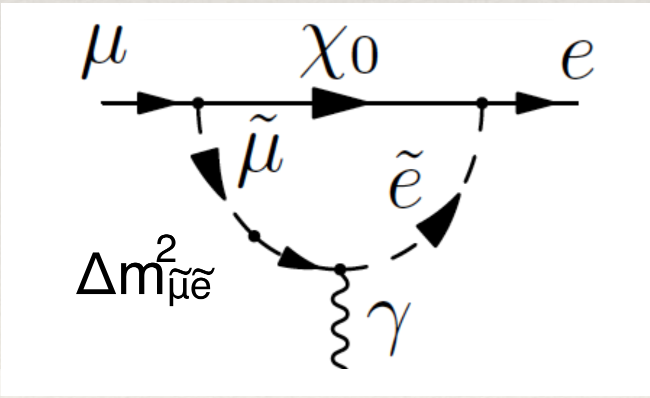
➛ cLFV transition suppressed ~ $(\Delta m_\nu^2/M_W^2)^2$ making cLFV undetectably small in the SM:

e.g.: BR(μ → eγ) < 10^{-50}.

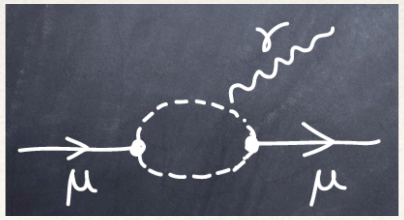
- BSM scenarios enhance cLFV rates up to BR ~ 10^{-11}, within experimental reach.

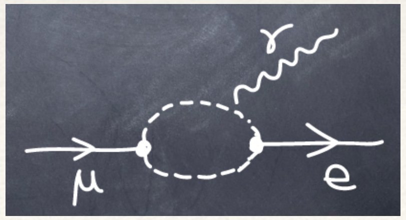
- SM prediction relies on eweak calculation only: theoretically very clean, no uncertainty from SM prediction (≠ quark FCNC).

  ➛ observation of cLFV would be an unambiguous signal of NP. Upper bounds constrain very efficiently BSM scenarios.



complementarity:
μ g-2 vs. μ → μγ.





cLFV: muon vs. tau decays

Muons

- Intense continuous or pulsed beams can be achieved,
- Long lived particle,
- Simple final states.

➛ single "small" experiments dedicated to a given μ decay channel.

Following slides: MEG, Mu3e, COMET, Mu3e.

Taus

- Intensity: no τ beam,
  production of ~15 $\tau^+ \tau^-$/sec (@PEP-II and KEKB),
  will become > 700 $\tau^+ \tau^-$/sec @SuperKEKB in e^+e^- collisions,
  to be compared to: 10^8 μ /sec (@PSI),
  next generation of experiments aim at 10^{11}-10^{12} μ /sec,
- Short lived particle,
- Many complicated hadronic and leptonic decay channels,

➛ need a more complicated detector at a collider, taking advantage of the large τ production cross-section ($\sigma_{\tau\tau} \sim \sigma_{bb} \sim \sigma_{cc} \sim 1$ nb).

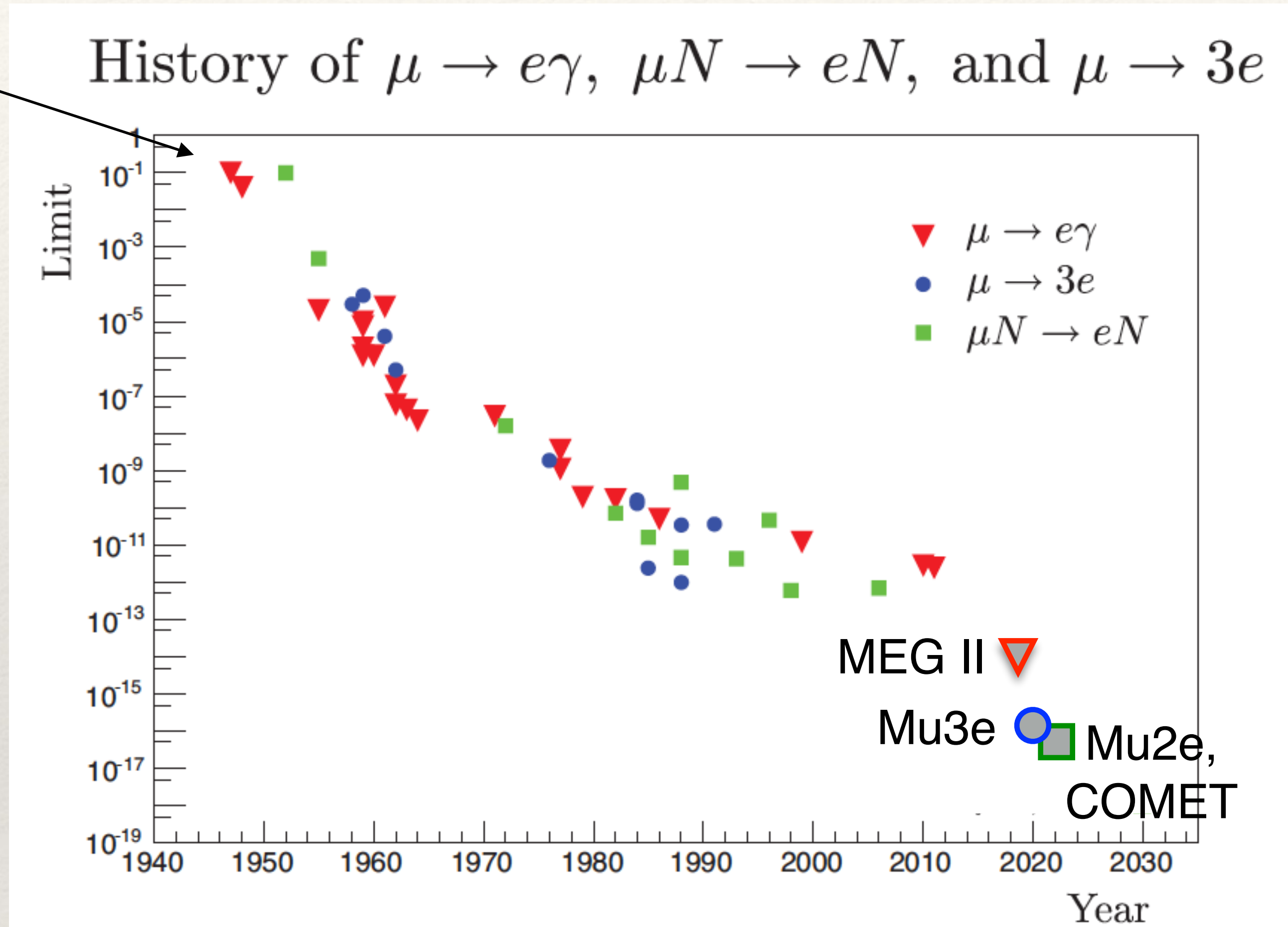
τ decays will be treated in a dedicated section together with B and D decays at Belle II.

Different correlations between FCNC rates according to the considered BSM scenario:

➛ important to measure as many τ and μ channels as possible.

cLFV: search channels

- μ FCNC decays ($\Delta L = 1$) provide the most stringent constraints on BSM scenarios:
  $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to eN$ (conversion within the nucleus).



- $BR(\mu \to eee) < 1.0 \times 10^{-12}$
  CL = 90 % (SINDRUM @PSI)
  [Nucl. Phys. B, 299, 1 (1988)]

- $BR(\mu \to e$ conv. in Au$) < 7 \times 10^{-13}$
  CL = 90 % (SINDRUM II @PSI)
  [Eur. Phys. J. C, 47, 227 (2006)]

- $BR(\mu \to e\gamma) < 5.7 \times 10^{-13}$
  CL = 90 % (MEG @PSI)
  [Nucl.Part.Phys.Proc. 260 (2015) 147-150]

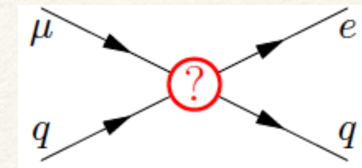
- Very challenging measurements: the best limit on $\mu \to eee$ was obtained 25 years ago.

- cLFV μ decay rates are also constrained by:
  - muonium oscillations $\mu^+ e^- \leftrightarrow \mu^- e^+$
  - rare K decay searches: $K_L \to e^\pm \mu^\pm$ and $K \to \pi e^\pm \mu^\pm$.

cLFV: sensitivity to New Physics

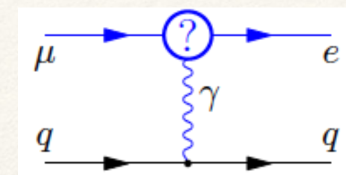
- Effective model with 2 parameters:
  - coupling ratio κ = $\frac{\text{contact terms}}{\text{dipole terms}}$
  - mass scale Λ of NP.

$$\frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}$$



very massive new V bosons, leptoquarks

$$\frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}$$



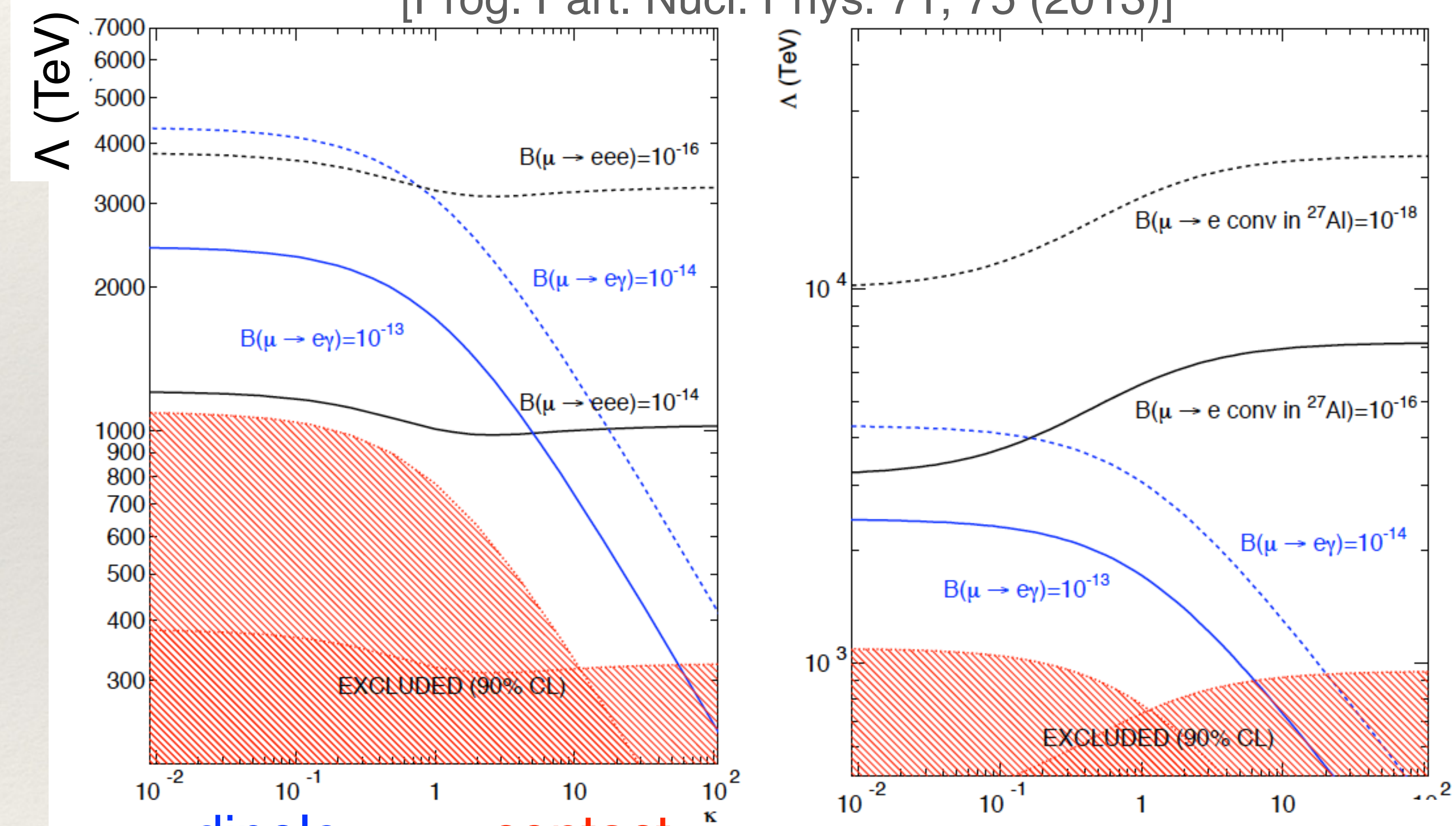
radiative loop contributions

- μ → e conv. experiments outperform other channels.

  But positive signal of μ → e conv. does not allow to measure either K or Λ, only a function of the two.

  ➛ combination of various measurements (g-2, cLFV decays, …) needed.

[Prog. Part. Nucl. Phys. 71, 75 (2013)]



dipole term

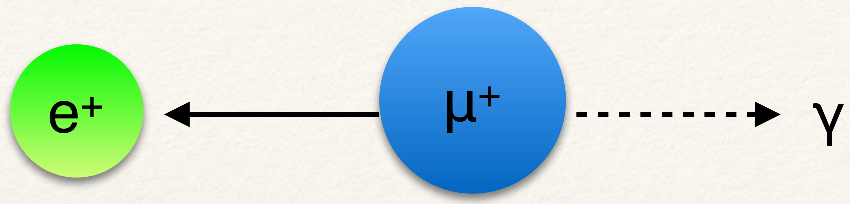
contact term

K

- Current limits probe Λ ~ 1000 TeV and next generation of experiments will probe Λ ~ 10^4 TeV.

cLFV: search for $\mu \to e\gamma$

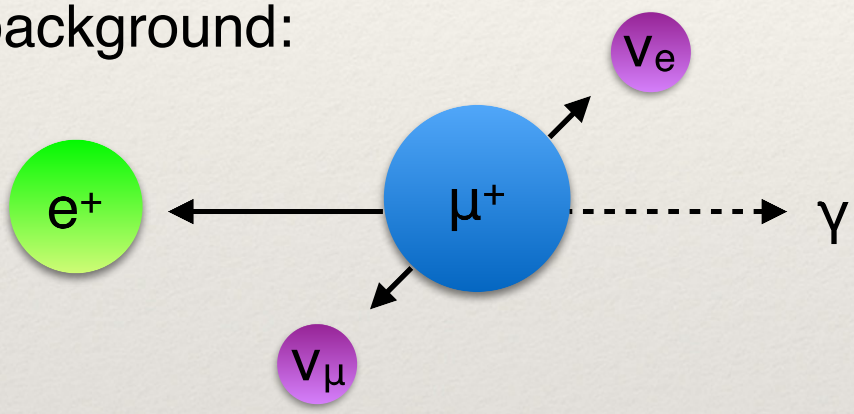
$\mu \to e\gamma$ signal:



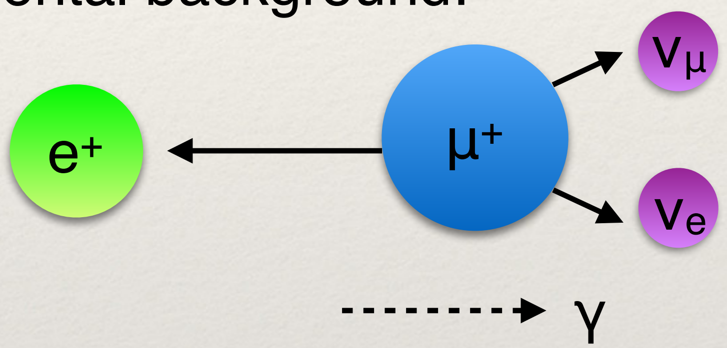
2-body decay:

- $E_e = E_\gamma = 52.8$ MeV
- $\theta_{e\gamma} = 180°$
- e-γ time coincidence

Physics background:



Accidental background:



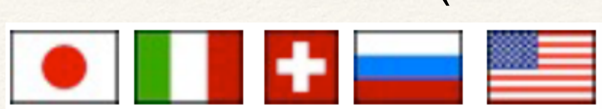
Dominant

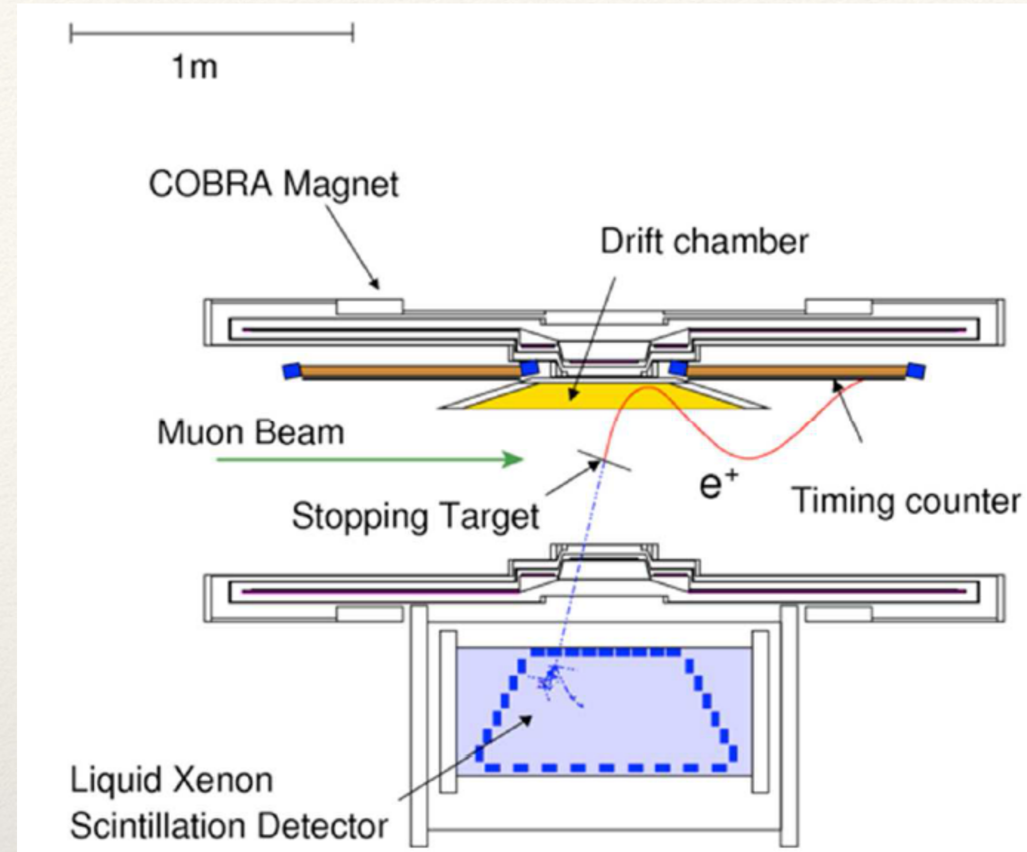
➛ exp. sensitivity limited by accidental coincidences, determined by exp. performances:

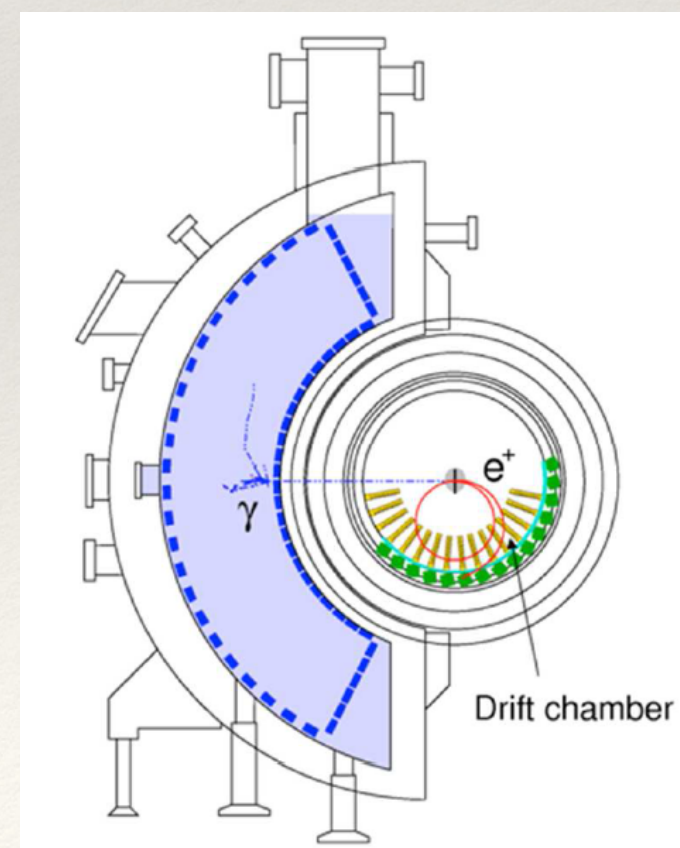
- Accidental background ~ (beam rate)^2: use Direct Current beam,
  (not pulsed: too high intensity increases coincidence),
- Detector featuring good spatial, time and E resolution, operational at very high rate.
  5 observables: E_e, E_γ, $t_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$.

cLFV: the MEG experiment at PSI

- Current best limit from 2009-2011 data analysis:
  $BR(\mu \to e\gamma) < 5.7\times10^{-13}$ C.L. = 90 %
  [Phys. Rev. Lett. 110 (2013) 20, 201801]
  2012 and 2013 data analysis on-going
  (expected improvement by a factor 1.5).
- World's most intense DC μ beam from PSI: 10^8 μ/sec.
  Stopping target: μ^+ decay at rest (surface muons).
- γ detection: L-Xe calorimeter (900 l = world's largest).
- Cobra gradient field magnet: track radius does not depend on incident angle at 52.8 MeV.
- Upgrade MEG II key points:
  - Targeted sensitivity: $BR(\mu \to e\gamma) \sim 5 \times 10^{-14}$
    after running 2016-2019.
  - e^+ detection: low mass drift chamber 1.17 ‰ X_0 (p_e)
    + fast plastic scintillator + SiPM 30 ps ($t_{e\gamma}$).
- Collaboration: ~65 collaborators (5 countries, 14 institutes).

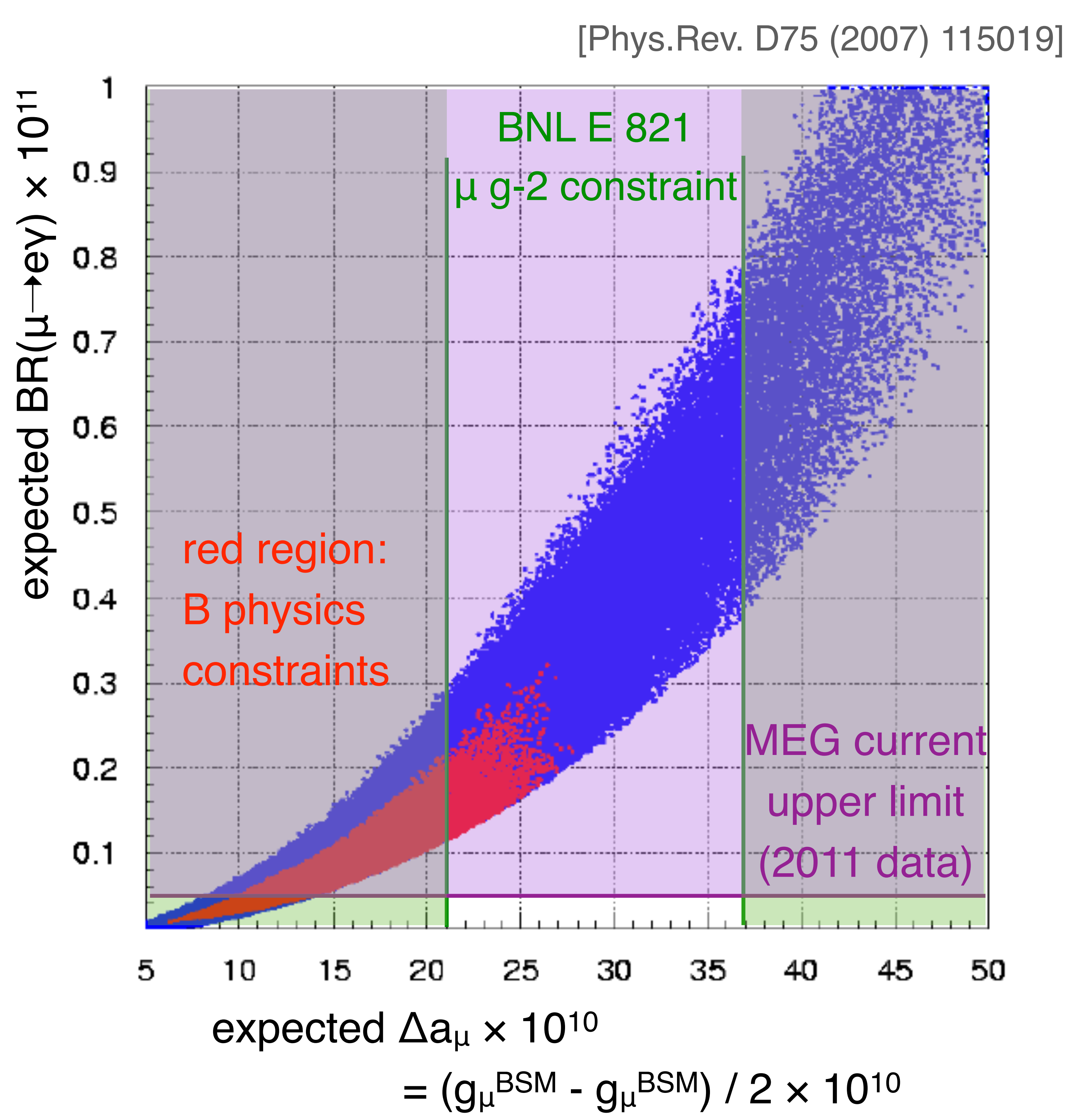






cLFV: impact of MEG results

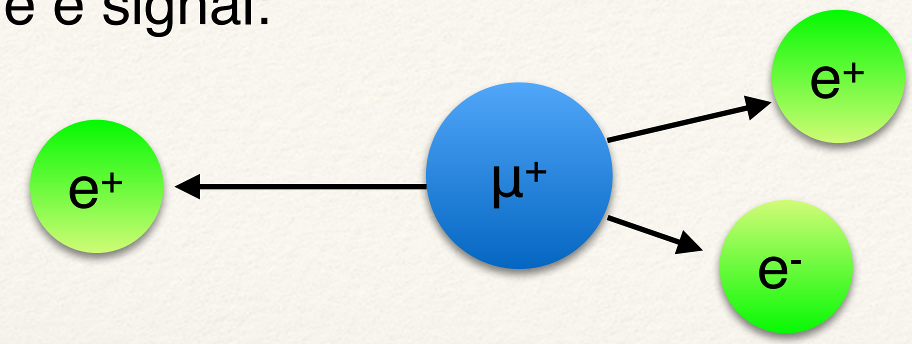
Example:
MSSM - GUT
with large tanβ



If muon g-2 discrepency is real: either $\Lambda > 1000$ TeV or flavour violation on NP is very small.

cLFV: search for $\mu \rightarrow e\ e\ e$

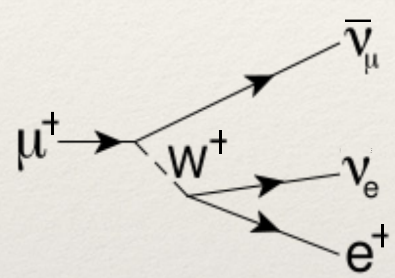
$\mu \rightarrow e\ e\ e$ signal:



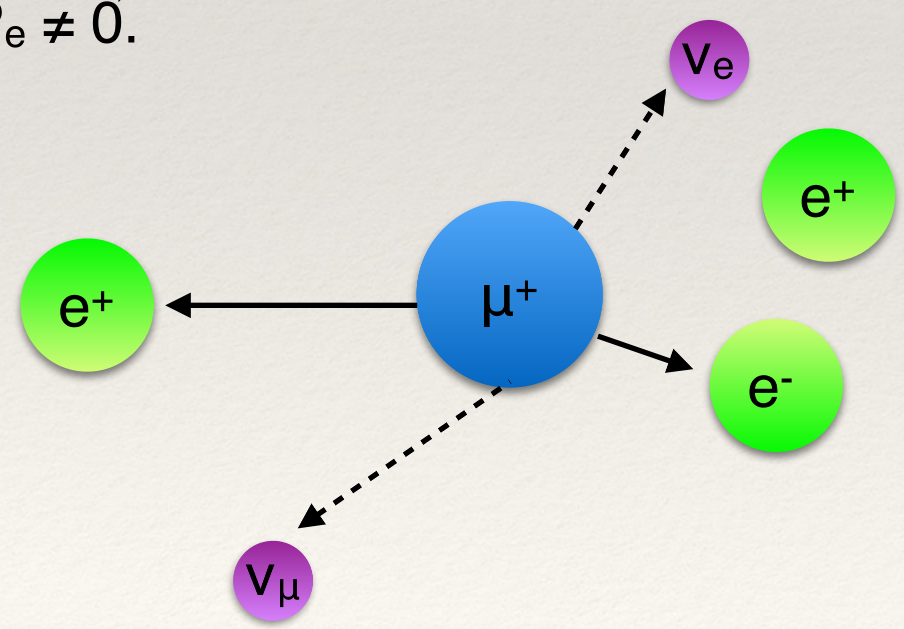
- Coplanarity
- Common vertex
- $\Sigma E_e = m_\mu$
- $\Sigma \vec{P}_e = \vec{0}$
- e^+-e^+-e^- time coincidence

Physics background:

$\mu \rightarrow e\ e\ e\ \nu\ \nu$



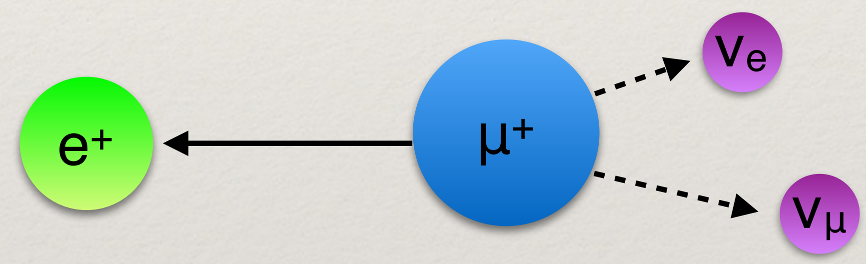
Reduced by excellent momentum resolution:
$\Sigma \vec{P}_e \neq \vec{0}$.

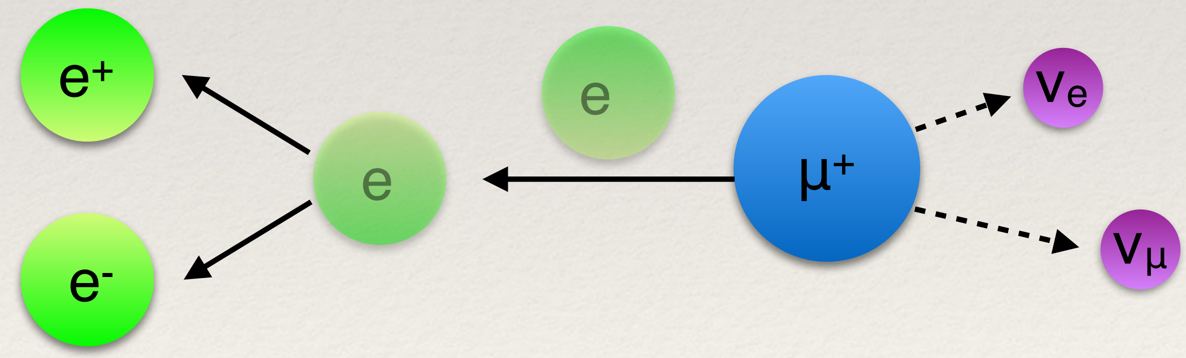


Accidental background:

$\mu^+ \rightarrow e^+\ \nu\ \nu$

$\mu^+ \rightarrow e^+\ \nu\ \nu$ & $e^+\ e^- \rightarrow e^+\ e^-$





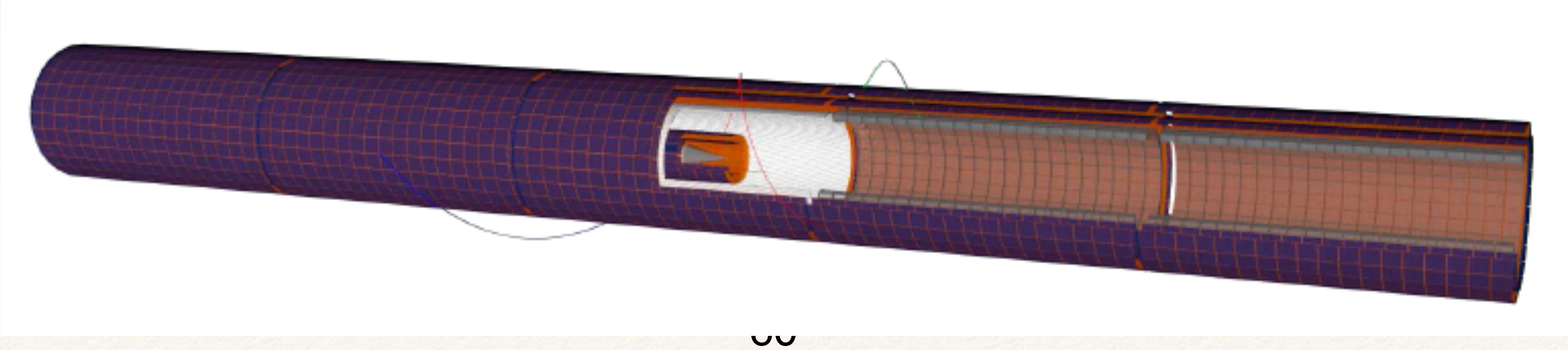
Reduced by excellent momentum, vertexing and time resolution

cLFV: the Mu3e experiment at PSI (1)

- Data taking starting in 2017, several stages of upgrades.
  Ultimate targeted sensitivity in ~2020:
  $BR(\mu \to eee) < 10^{-16}$ C.L. = 90 %,
  i.e. improvement × 10^4 w.r.t. current best bound (SINDRUM @PSI).

- Technological breakthrough enabling to improve SINDRUM limit:
  - New μ beam line providing > 10^9 μ /sec (installation > 2019).
  - Excellent momentum resolution for soft (few 10 MeV) particles with detectors able to cope with particle rates > 10^7 cm^2 s^{-1}, featuring excellent vertexing and time resolutions to reduce the accidental background below 10^{-16}.

    ➛ 2 double layers equipped with 275×10^6 HV-CMOS monolithic 80×80 μm^2 pixels + 1 T magnetic field: 100 ns time-stamp, continuous read-out, Si thinned down to < 50 μm, no cooling.
    Total material budget = 1 ‰ X_0 /layer.
  - Timing with scintillating fibers (1 ns) and scintillating tiles (100 ps).

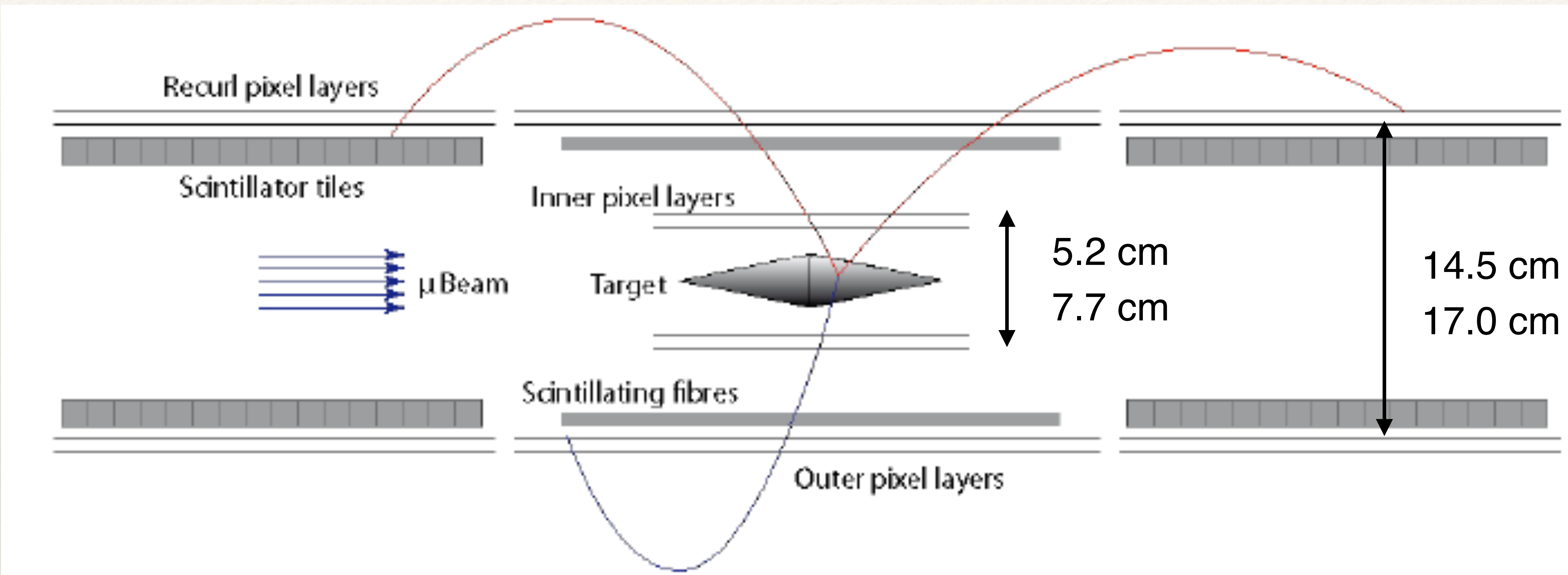


cLFV: the Mu3e experiment at PSI (2)

12 cm

2017

2018



5.2 cm
7.7 cm

14.5 cm
17.0 cm

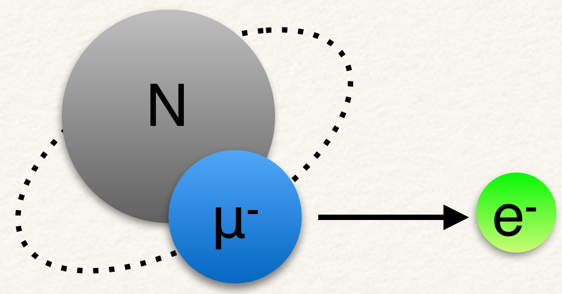
36 cm

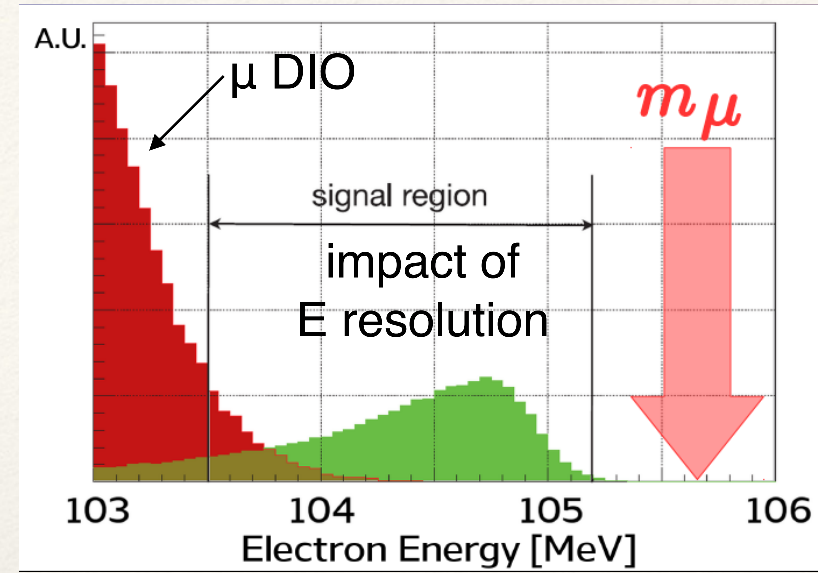
~ 100 cm and more (+ 36 cm ×2 with further upgrade ~2020)

cLFV: search for μ → e conversion

$\mu\,(A,Z) \rightarrow e\,(A, Z)$ signal:

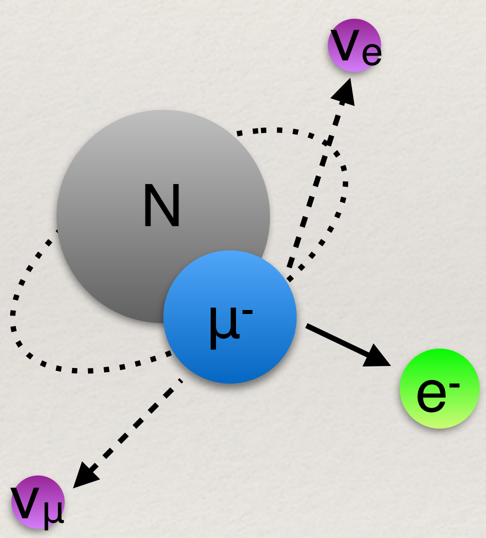
- ν-less, single mono-energetic e^-:
  $E_e = m_\mu - B_\mu - E_{recoil} \sim 105$ MeV
- $Z_{ini} = Z_{final}$





Dominant background:

μ Decay in orbit $\mu\,(A, Z) \rightarrow e\;\nu\;\nu\,(A, Z)$



Contiunous E_e spectrum with a long tail < m_μ .

+ other backgrounds:

- Physics, e.g.: radiative muon capture
  $\mu\,(A,Z) \rightarrow \nu_\mu\,\gamma\,(A, Z-1)$, etc.
- Beam related, e.g.: beam e^-, π or μ decay in flight, radiative π nuclear capture, etc.
- Others, e.g.: cosmic rays, fake tracks, etc.

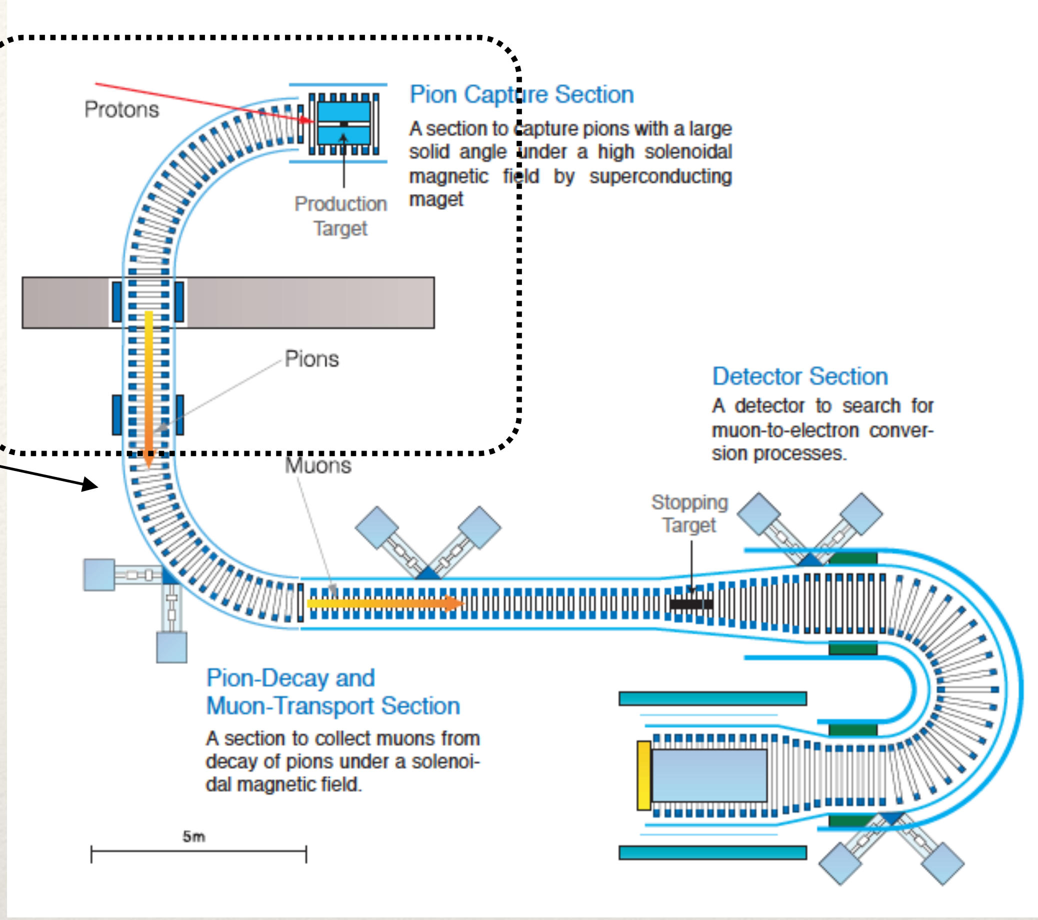
➛ Experimental sensitivity limited by beam quality:

- Wait until pion decays,
- Use pulsed beam.

cLFV: the COMET experiment at J-PARC

- COMET (E21) staged approach:
  - Phase 1 target: BR(μ→e conv. in Al) < 7×10^{-15} (90 % CL) after run 2016-2017,
  - Phase 2 target: < 6×10^{-17} after run 2020-2021, i.e. improvement × 10^4 w.r.t. current best bound (SINDRUM @PSI with DC μ beam).

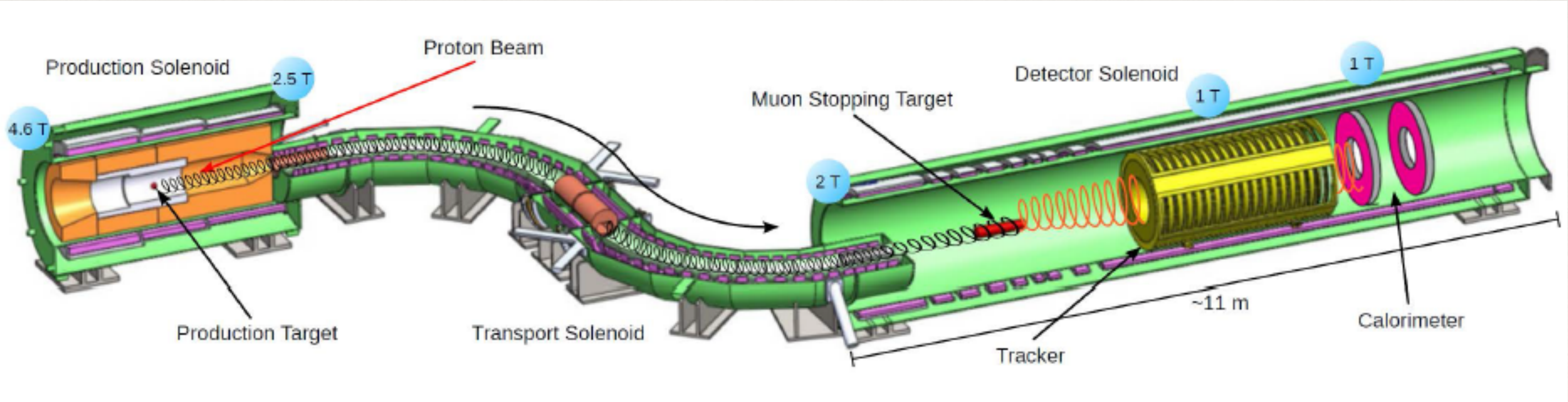
stopping target here



- Experimental setup:
  - Pulsed proton beam from J-PARC main accelerator: 10^{11} μ /sec stopped on Al target to form muonic-atoms. Lifetime of muonic-Al: 864 s.
  - C-shaped superconducting solenoid 3 T for μ beamline: > 20 m long to wait for π→μ decays. C-shaped solenoid for electron transport.
    ➛ Spectrometer solenoids enable momentum and charge selection: low-p μ^- and high-p e^-.
  - e^- detector: straw-tubes tracker (5 disk x-y stations in vacuum and B = 1 T) and LYSO crystals calorimeter (E_e, p-id and trigger).
- COMET collaboration: 179 collaborators (~30 FTE), 32 institutes, 13 countries (IN2P3 is member).

cLFV: the Mu2e experiment at FNAL

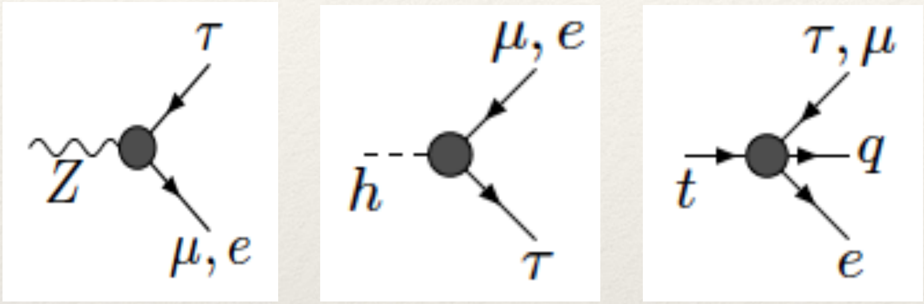
- Targeted sensitivity: BR($\mu \to e$ conv. in Al) < 2×10^{-17} (C.L. = 90 %) in 2023 with a 3-year run.
- Experimental setup:
  - Pulsed proton beam from recycled Tevatron.
  - S-shaped μ beamline: > 13 m long to wait for $\pi \to \mu$ decays. Selection of low-p μ^- and π^-.
  - e^- transport: straight solenoid (no e^- momentum selection at this stage).
  - e^- detector: 28 stations of straw-tubes tracker in vacuum, and 2 BaF2 crystal disks (E_e, p-id and trigger). Detector inner-radius is empty to select high-p_T e^- and to reject background (μ that did not stop in target, e^- from μ DIO) to be able to cope with the high track rate.



cLFV: outlook

- Limited sensitivity to cLFV decays @LHC,
  but only place where Z, H and top are produced on mass shell.

  e.g.: BR($Z \to \mu\, e$) < 7.5×10^{-7} C.L. = 95 %. [ATLAS, arXiv:1408.5774]
  Unlikely to see Z, $h \to \mu\, e$ at LHC following MEG results.



- Search for $\mu \to e\gamma$ and $\mu \to eee$ limited by accidental background:
  increases with μ beam intensity
  ➢ currently scheduled experiments may be the final ones during a long time.

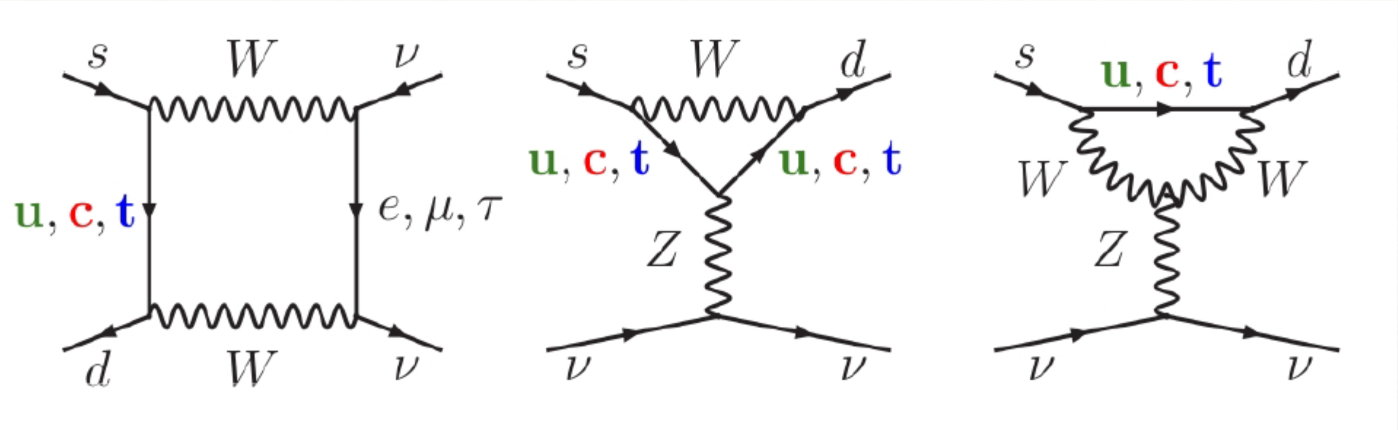
  Whereas no identified limitation so far to improve sensitivity to $\mu \to e$ conversion in muonic atoms: e.g. BR < 10^{-18} may be accessible with the Project X facility at FNAL.

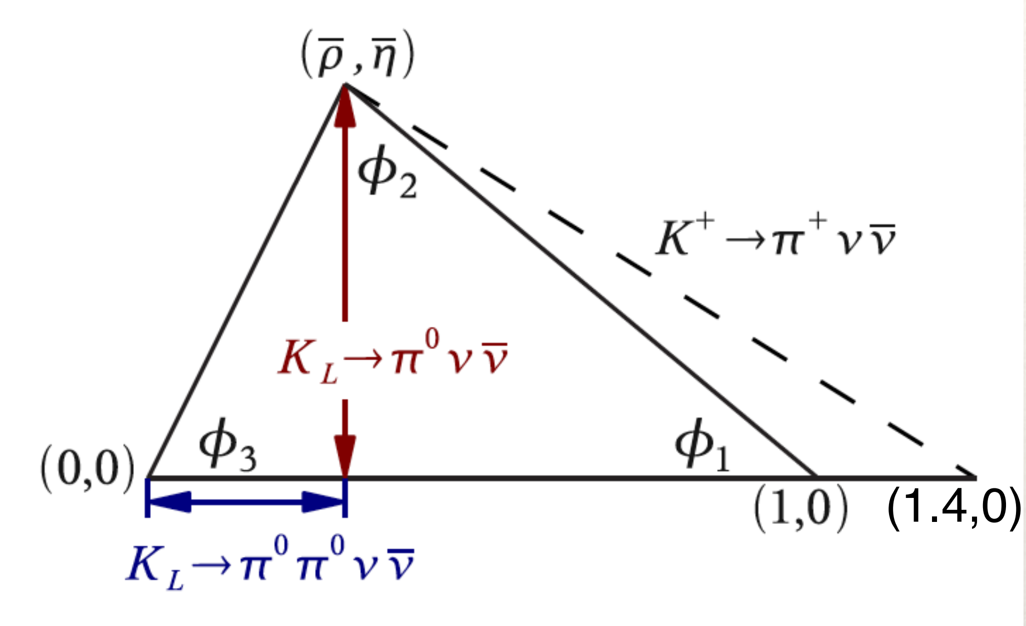
Kaon decays: outline

- Looking for NP with kaons
- SM predictions of $K \rightarrow \pi\nu\nu$ Branching Ratios
- The $K^+ \rightarrow \pi^+ \nu \nu$ decay and the NA62 experiment
- The $K_L \rightarrow \pi^0 \nu \nu$ decay and the KOTO experiment

Kaons: looking for NP with kaons (1)

- $K^+ \to \pi^+ \nu\nu$ (CP conserving) and $K_L \to \pi^0 \nu\nu$ (direct CP violating) very rare FCNC decays are dominated by short distances box and Z-penguin diagrams.





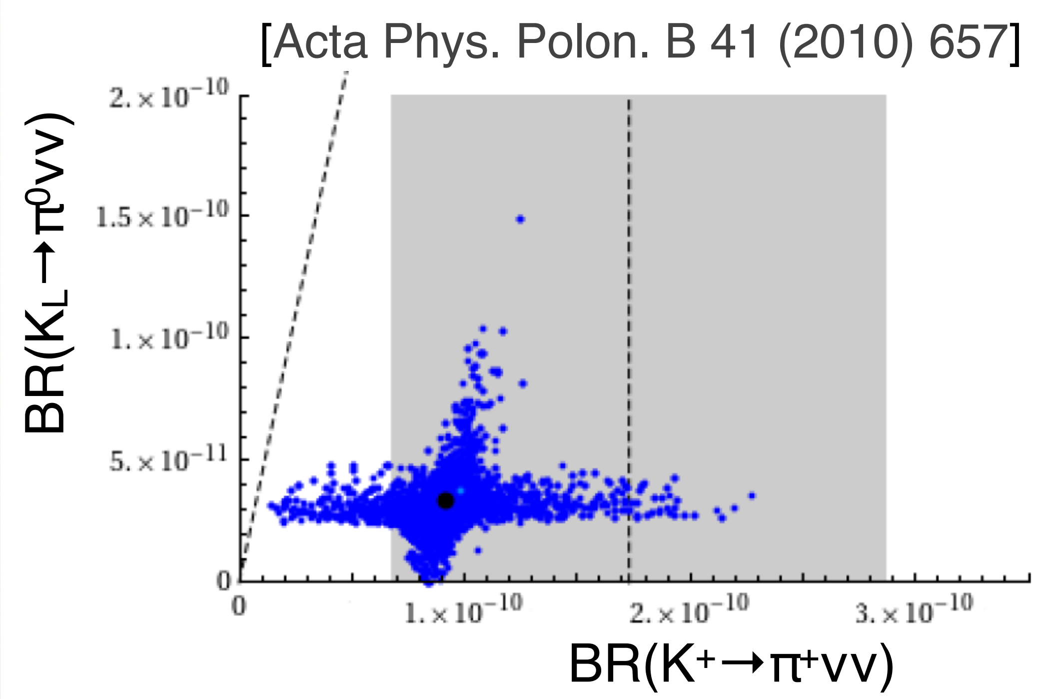
➛ Short distances (i.e. precise SM prediction) ⊗ loop suppressed process
= promising place to look for NP.

- ε'/ε is also very sensitive to NP contributions, but suffers from large hadronic uncertainties: accurate prediction of SM and BSM theory values difficult.

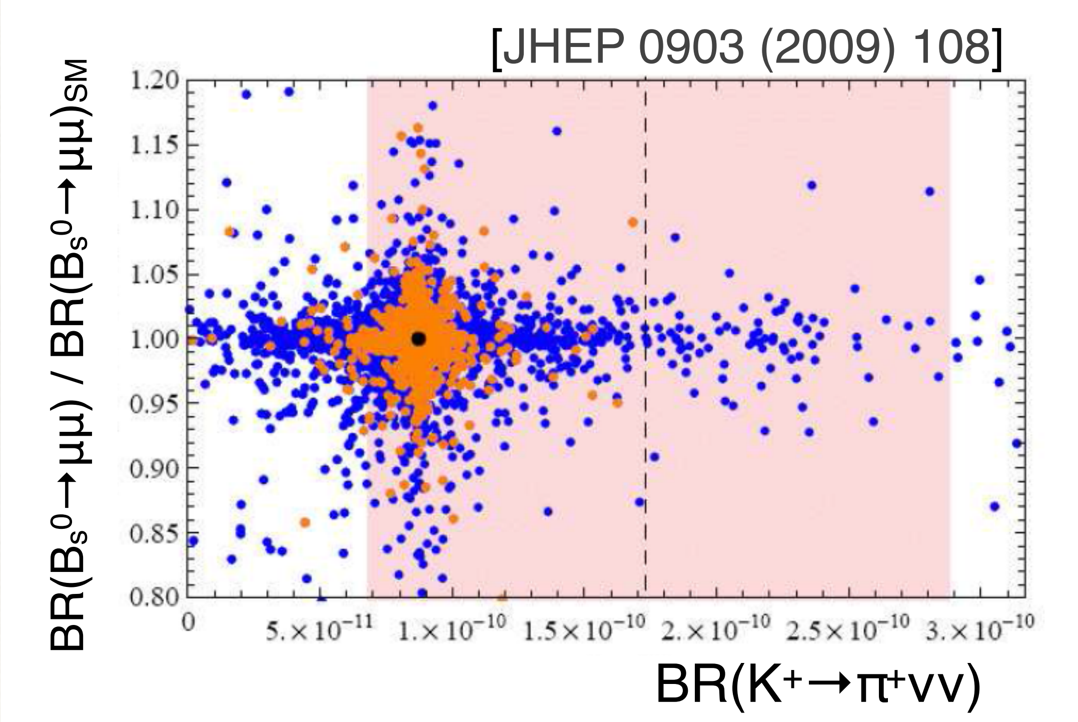
- Also: look for K decays violating lepton flavour and lepton number conservation, for heavy neutrinos produced in K decays, …

Kaons: looking for NP with kaons (2)

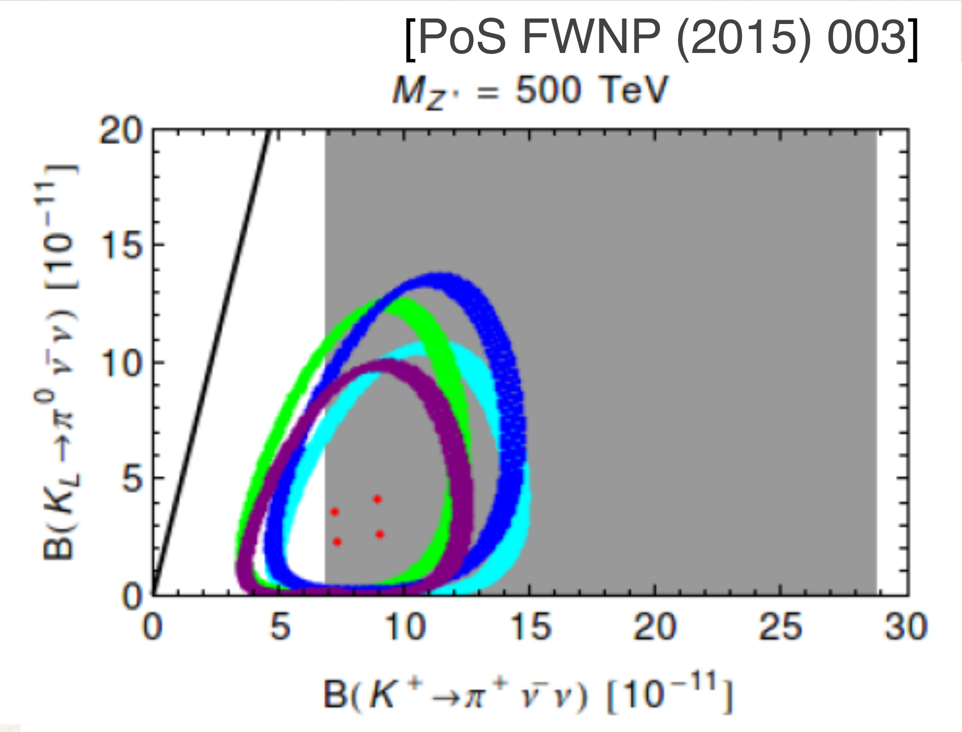
- $K \to \pi \nu\nu$ decays are a powerful tool not only to discover NP but also to distinguish among different models: thanks to predicted correlation factors between different observables: $BR(K^+ \to \pi^+ \nu\nu)$, $BR(K_L \to \pi^0 \nu\nu)$, ε'/ε, $BR(B_{s,d} \to \mu\mu)$, …



Littlest Higgs model with T Parity



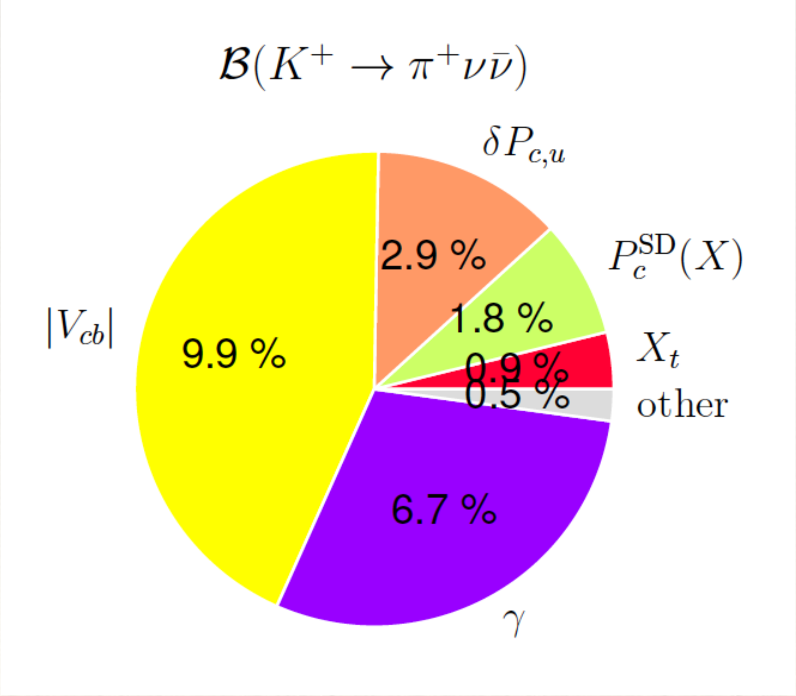
Custodial Randall-Sundrum

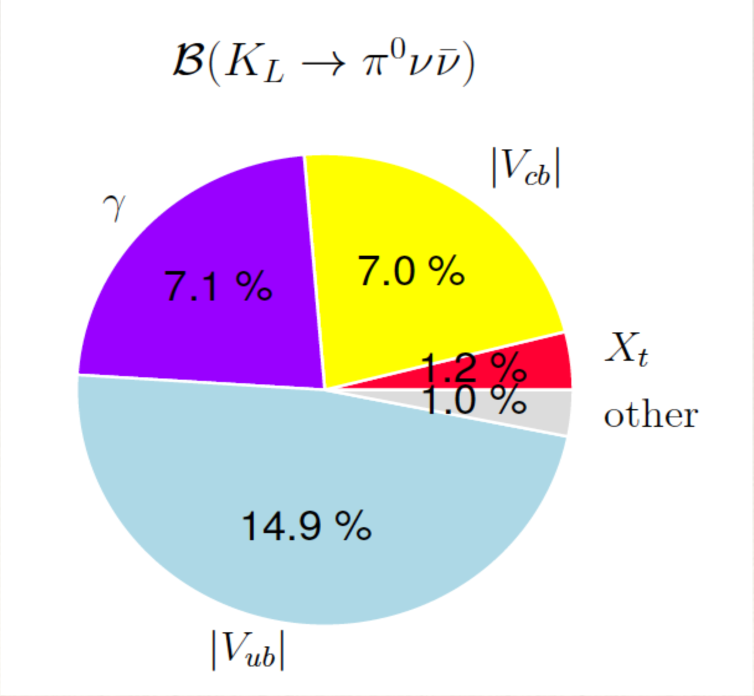


Z' model

Kaons: SM prediction of BR(K→πνν) (1)

- Precision of the SM predictions of K→πνν Branching Ratios:
  - Theoretical uncertainty ~ 2-6 % on the SM prediction: unique in quark flavour physics!
    Including NNLO QCD and NLO EW corrections to top and charm contributions.
    Hadronic corrections tested with the well measured K^+_{e3} $K^+ \to \pi^0 e^+ \nu$ decay (BR ~ 5 %).
  - But total error on the predicted BR dominated by uncertainty on CKM parameters (a.k.a. parametric uncertainties): $|V_{ub}|$, $|V_{cb}|$, γ.
    Issue of current discrepancy between inclusive and exclusive V_{ub} and V_{cb} tree-level measurements: need Belle II data to clarify.
  - Correlation between observables (e.g. $K^+ \to \pi^+ \nu\nu$ and $B_s \to \mu\mu$ BR) is less dependent on CKM inputs.





[arXiv:1507.08672]

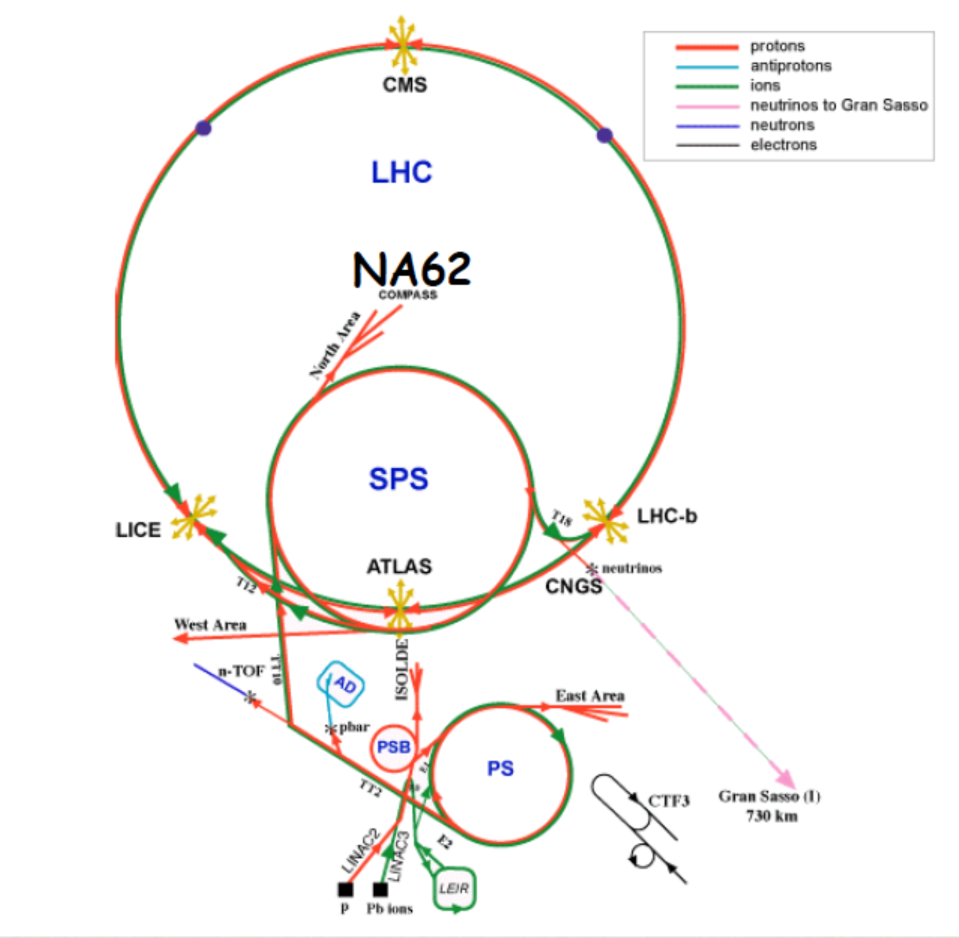
Kaons: SM prediction of BR($K \to \pi\nu\nu$) (2)

- Assuming no NP at eweak scale and using only tree-level measurements of CKM elements to predict SM values [arXiv:1507.08672] :
  - BR($K^+ \to \pi^+\nu\nu$) = $(8.4 \pm 1.0) \times 10^{-11}$,
  - BR($K_L \to \pi^0\nu\nu$) = $(3.4 \pm 0.6) \times 10^{-11}$.
- Improvement by about a factor of 2 in accuracy can be achieved using CKM parameters extracted from $\Delta F=2$ loop-level observable measurements (ε_K, $\Delta m_{s,d}$, $\sin 2\beta_{\psi K_S}$), assuming nothing else exists but SM.
  But in case of theory/experimental discrepancy, we do not know whether it is due to NP manifestation in CKM parameters or in $K \to \pi\nu\nu$! [arXiv:1503.02693]

- This theoretical precision can be compared to the current experimental precision:
  - BR($K^+ \to \pi^+\nu\nu$) = $(17.3\ \ {+11.5}\ \ {-10.5}) \times 10^{-11}$ measured at BNL based on 7 candidates,
    [E949 collaboration, Phys.Rev.Lett. 101 (2008) 191802, Phys. Rev. D 79, 092004 (2009)]
  - BR($K_L \to \pi^0\nu\nu$) $< 2.6 \times 10^{-8}$ C.L. = 90 % measured at J-PARC (KOTO pilot run).
    [E391a collaboration, PoS ICHEP2010 (2010) 289]
- Two experiments plan to measure BR($K \to \pi\nu\nu$) at the 10 % level at the horizon 2020: KOTO at J-PARC and NA62 at CERN.

Kaons: the NA62 experiment at CERN (1)

- NA62 is a fixed target experiment: 400 GeV SPS protons on a Be target, producing a hadron beam with ~ 6 % of K^+. Selection of direction and momentum p = 75 GeV. Detect K^+ decay in flight.



- Physics program:
  - 1997-2001: ε'/ε (NA48)
  - 2002: rare K_S decays (NA48/1)
  - 2003-2004: CP asymmetry in K decays (NA48/2)
  - 2007-2008: Lepton universality
    $R_K = \Gamma(K^+ \to e^+ \nu_e) / \Gamma(K^+ \to \mu^+ \nu_\mu)$
    (NA62 with NA48 detector)
  - 2014: commissioning of NA62 to measure $K^+ \to \pi^+ \nu\nu$
  - 2015-2019 (LS2): NA62 data taking started end of June.

- Target: ~10 % uncertainty on BR($K^+ \to \pi^+ \nu\nu$), i.e. ~100 $K^+ \to \pi^+ \nu\nu$ decays.
  Since BR ~ 10^{-11} ➛ need to detect ~10^{13} K^+ decays.

Kaons: the NA62 experiment at CERN (2)

- Experimental strategy: huge background from K decays, redundant background rejection by a factor of 10^{12} needed, based on:
  - kinematical selection,
  - veto (extra γ),
  - trigger (K-π timing),
  - particle identification (π-μ and π-e separation).

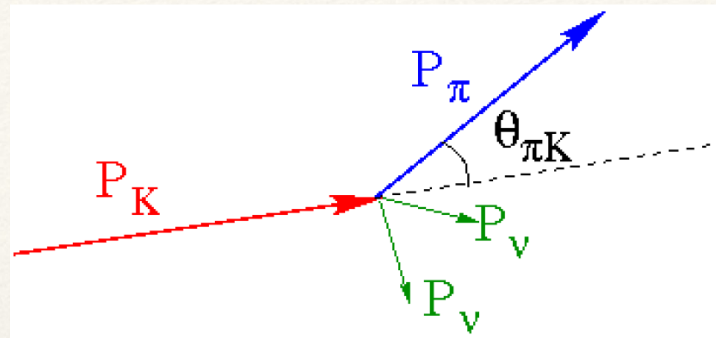
Decay	BR	rejection method
$\mu^+\nu$ (Kμ2)	63.5%	π-μ separation
$\pi^+\pi^0$ (Kπ2)	20.7%	extra γ
$\pi^+\pi^+\pi^-$	5.6%	extra track
$\pi^0 e^+\nu$ (Ke3)	5.1%	π-e sep. extra γ
$\pi^0\mu^+\nu$ (Kμ3)	3.3%	π-μ sep. extra γ
$\pi^+\pi^0\pi^0$	1.8%	extra γ

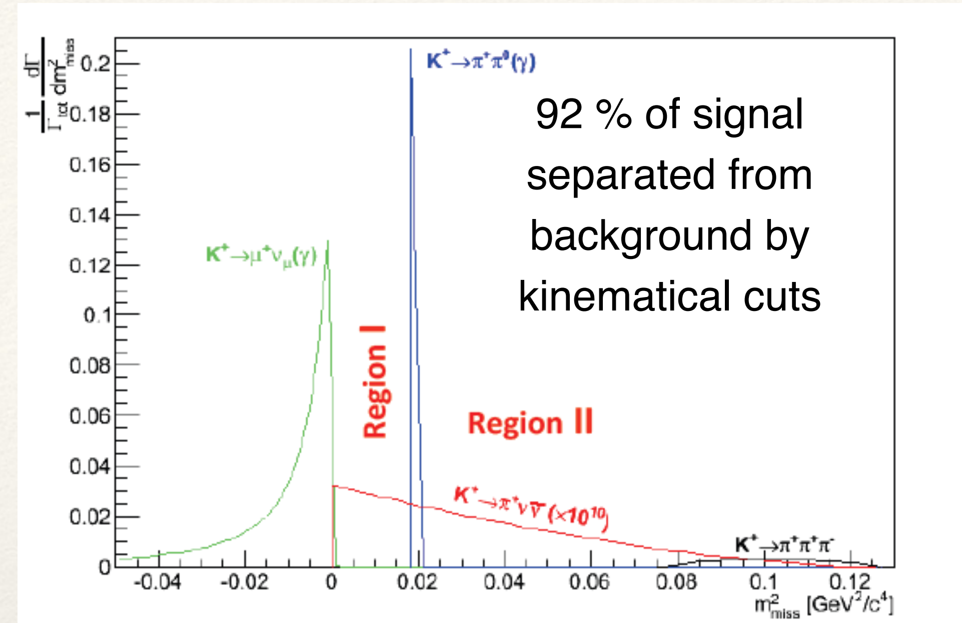
Decay	BR	rejection method
$\mu^+\nu\gamma$ (Kμ2γ)	0.62%	π-μ sep. extra γ
$\pi^+\pi^0\gamma$	2.7×10^{-4}	
$\pi^+\pi^- e^+\nu$ (Ke4)	4.1×10^{-5}	
$\pi^0\pi^0 e^+\nu$ (Ke400)	2.2×10^{-5}	
$e^+\nu$ (Ke2)	1.5×10^{-5}	
$\pi^+\pi^-\mu^+\nu$ (Kμ4)	1.4×10^{-5}	

Kaons: the NA62 experiment at CERN (3)

- Kinematical selection: measurement of p_π in GTK (Si pixel) and p_K in STRAW

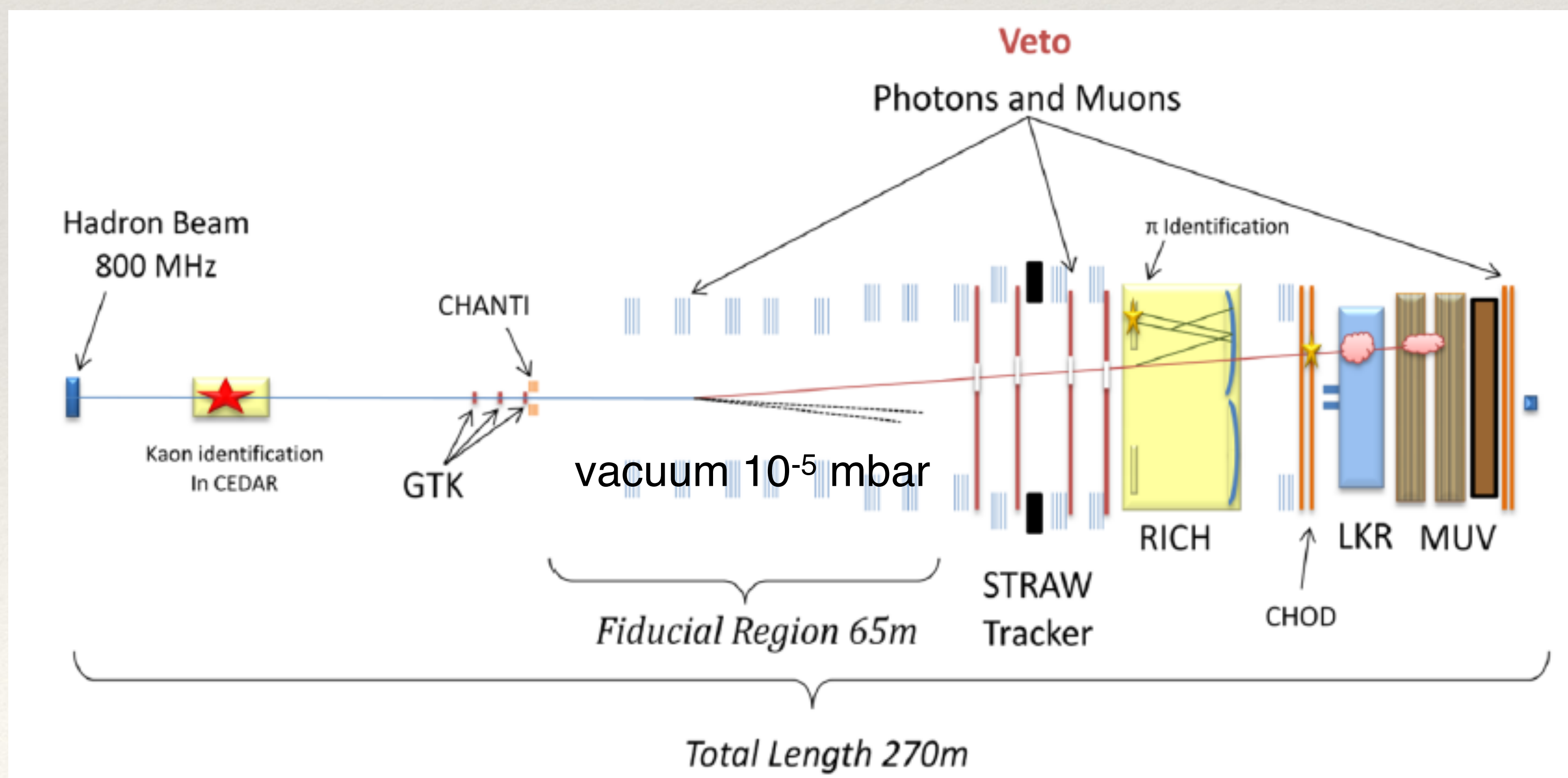
  ➛ $M^2_{MISS} = (P_K - P_\pi)^2$, used to identify regions with lower background level.





- Veto against additional γ or μ: LAV (lead glass Cerenkov), IRC and SAC (small angle shashlik calorimeters), CHANTI and CHOD (scintillators), LKr (cryogenic Liquid Kripton calorimeter), MUV (Fe/scintillators sandwich).

- Particle identification: Kaon-id for incoming particle in CEDAR (N_2 Cerenkov) and Pion-id for outgoing particle (Ne RICH).



Kaons: the NA62 experiment at CERN (4)

- Many major K^+ decay modes produce π^0, in particular $BR(K^+ \to \pi^+\pi^0) \sim 20.7$ %:
  ~10^{12} π^0 will be produced in vacuum in NA62, in addition to ~10^{13} K^+
  - ➢ NA62 will also be able to improve upper limits by factors of 10-10^3 on cLFV and LNV in K^+ and π^0 decays.

Mode	Upper limit (90% CL)	Experiment	
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL E777/E865	2005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL E865	2000
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL E865	2000
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL E865	2000
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	2011
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	1976
$K^+ \to e^-\nu\mu^+\mu^+$	no data		
$\pi^0 \to \mu^\pm e^\mp$	3.6×10^{-10}	KTeV	2008

[Nucl.Phys.Proc.Suppl. 248-250 (2014) 58-63]

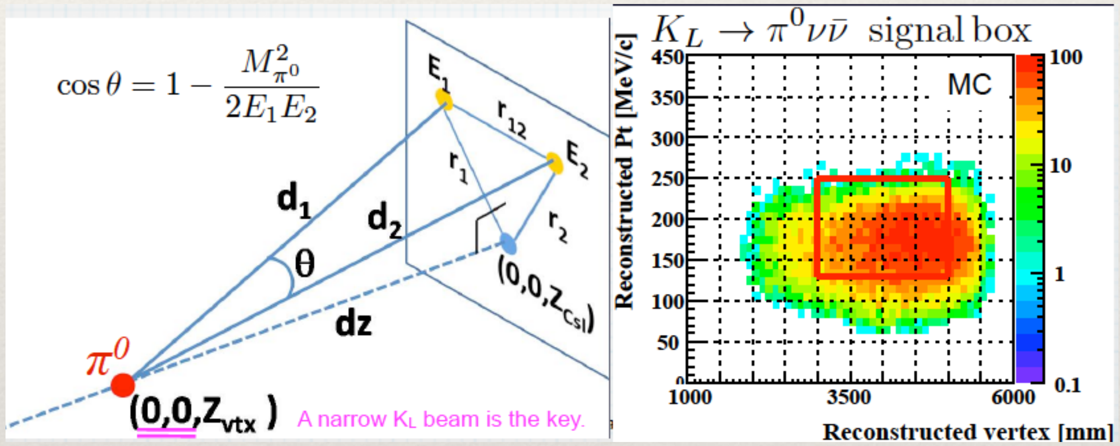
Kaons: the KOTO experiment at J-PARC (1)

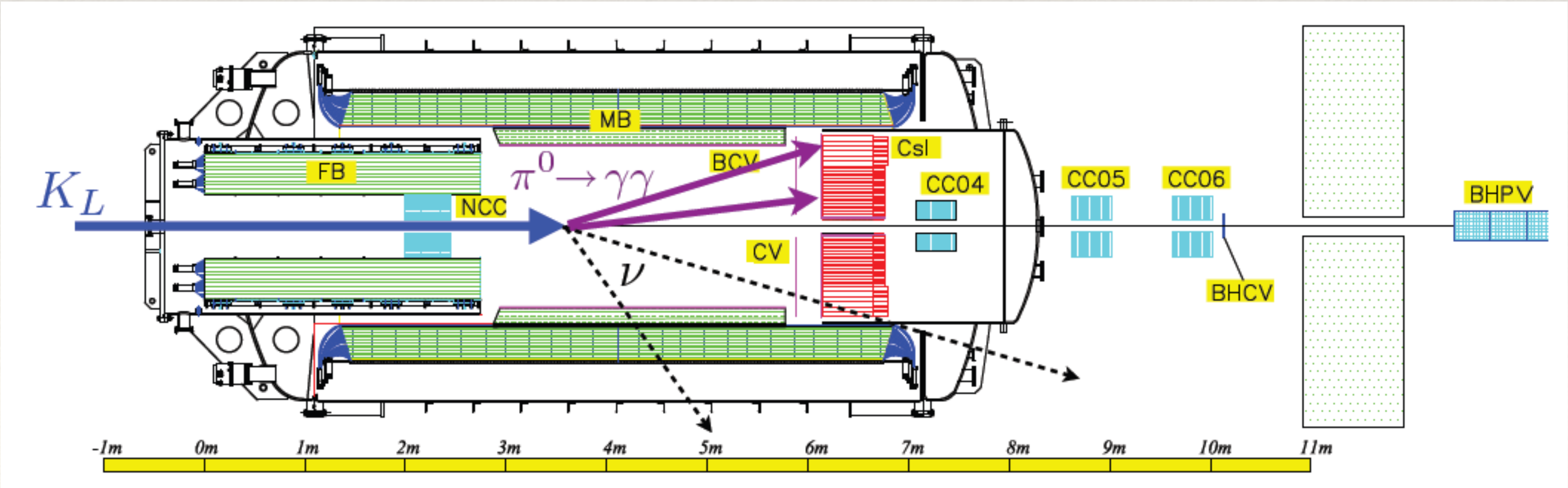
- KOTO is a fixed target experiment: 30 GeV p from J-PARC Main Ring on a target composed of Ni disks, producing K_L with average p = 2.1 GeV.

- Staged experiment:
  - 2005 pilot run with KEK-E391a (12 GeV protons from KEK synchrotron): $BR(K_L \rightarrow \pi^0 \nu\nu) < 2.6 \times 10^{-8}$ [E391a collaboration, PoS ICHEP2010 (2010) 289], improved the FNAL-KTeV limit (2000) by a factor of 20.
  - 2018 J-PARC-KOTO step 1: targeted sensitivity BR ~ 10^{-11} (SM prediction), detecting a few (~4) $K_L \rightarrow \pi^0 \nu\nu$ events in 3-4 years, with S/N~2. KEK beamline is moved to J-PARC and E-391 detector is upgraded.
    - 2011-2013: delays due to earthquake + J-PARC radiation accident.
    - May 2015: data taking resumed, sensitivity will reach the GN limit ~10^{-9} end of 2015.
  - > 2020 KOTO step 2: targeted sensitivity ~10 % on BR, detecting 100 $K_L \rightarrow \pi^0 \nu\nu$ events with S/N~5 (larger detector: 15 m long, higher beam power 400 kW).

Kaons: the KOTO experiment at J-PARC (2)

- Experimental strategy:
  - Main background from $K_L \to \pi^0\pi^0$ (BR = 8.6×10^{-4}) where 2γ are missed: need background suppression by a factor > 10^{-8}.
    ➛ Ask for 2γ with high $p_T(\gamma\gamma)$ and VETO everything else: calorimeter (CsI from FNAL-KTeV) + hermetic veto detectors (Pb and plastic scintillators, aerogel Cerenkov counters).
  - Most detectors are in vacuum to avoid producing π^0 by neutron interactions with residual gas and to avoid absorbing the γ before being detected.
  - P_{KL} and p_π are not measured.
    But $p_T(\pi^0)$ is calculated assuming that the K_L decay vertex is at the center of the beam
    ➛ use small K_L beam size.



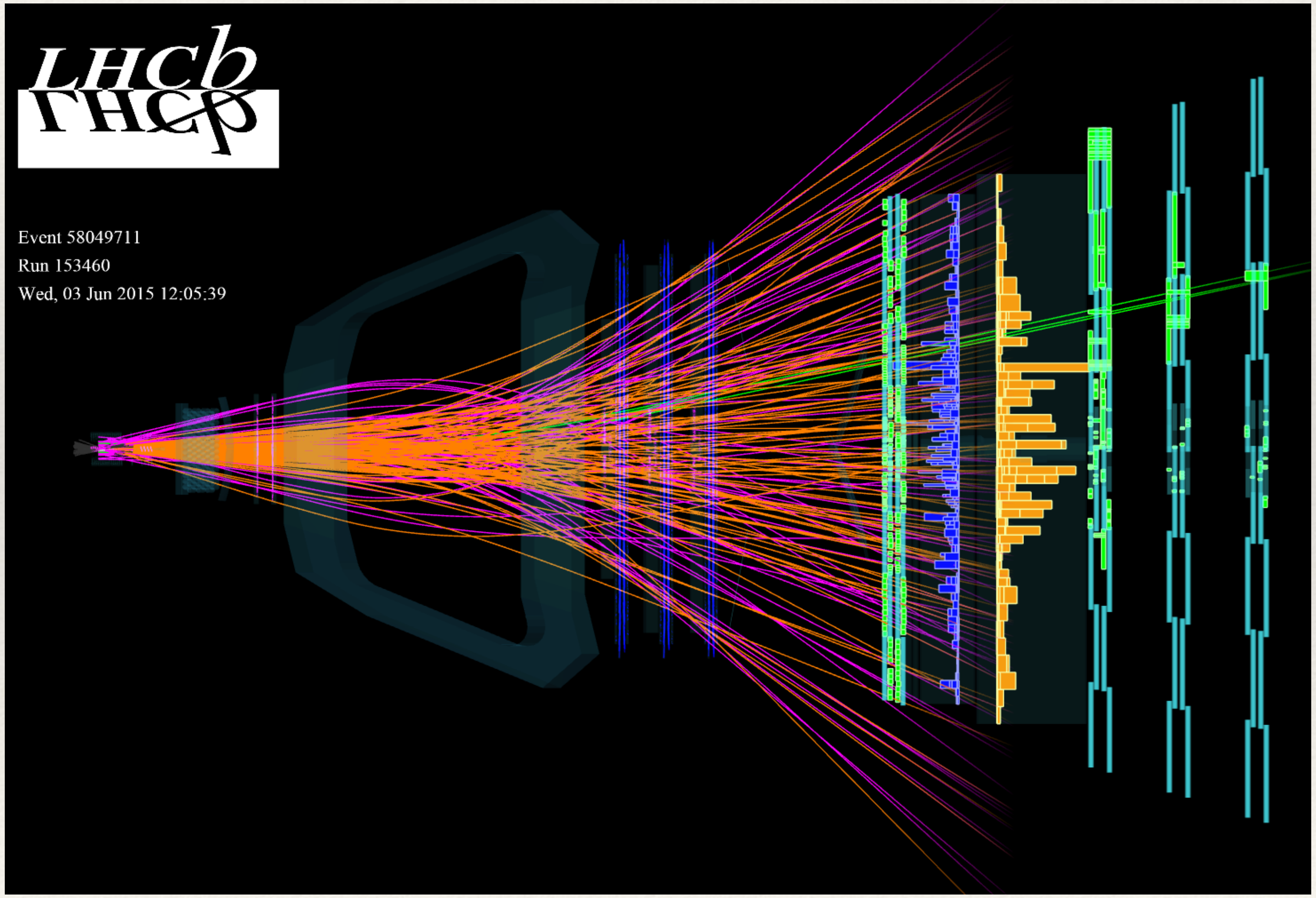


τ, B and D decays:outline

- τ, B and D production in LHCb and SuperKEKB
- The SuperKEKB collider
- τ, B and D rare decays
- The $B \to D^* \tau \nu_\tau$ decay:
  - results from BaBar, Belle and LHCB
  - Prospects
  - $B \to D^* \tau \nu$ and $B \to \tau\ \nu$
- τ cLFV decays
- Conclusion and outlooks

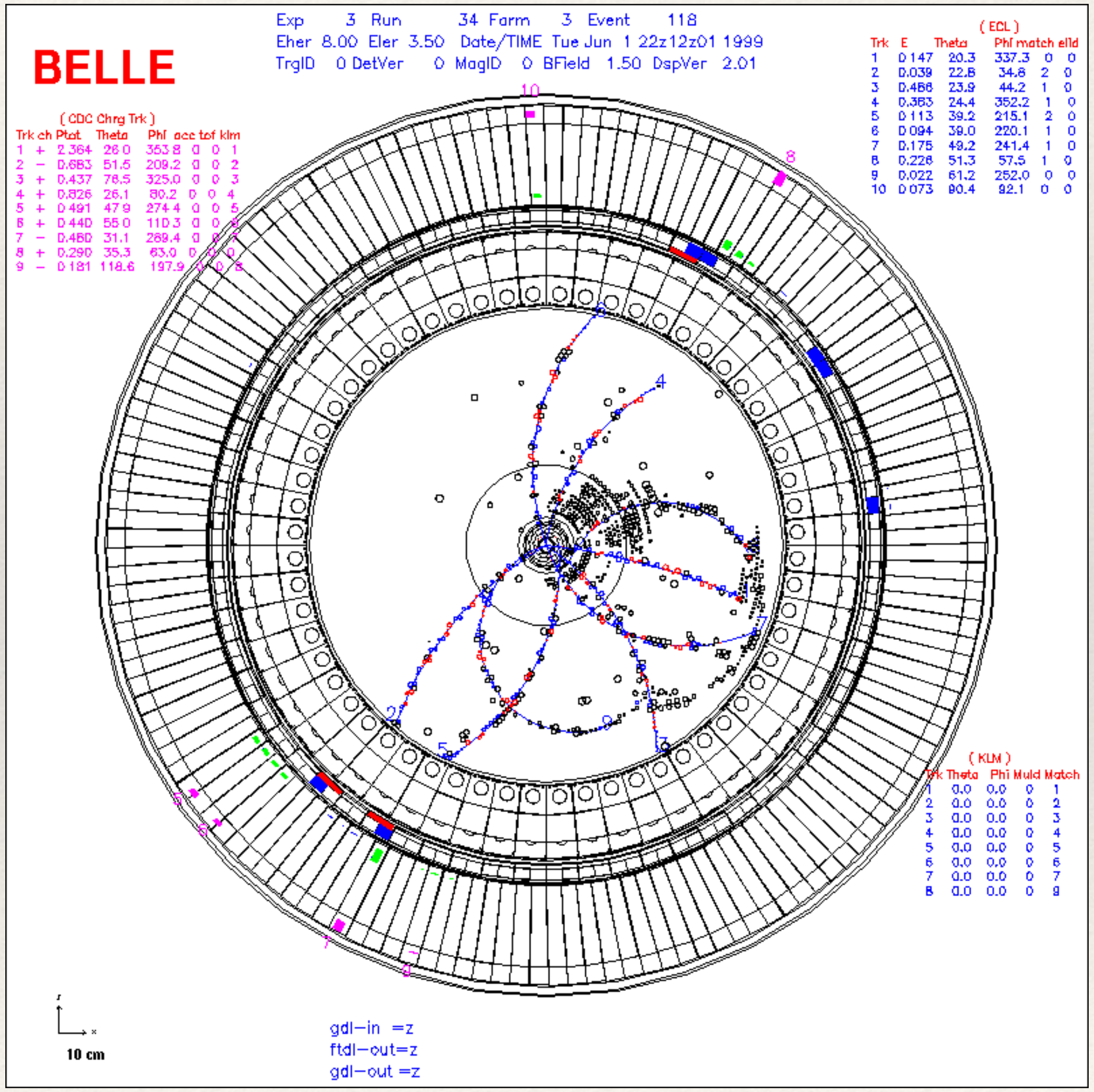
τ, B and D decays: in LHCb

- In LHCb @$\sqrt{s}$ = 14 TeV, luminosity = 1.5×10^{34} cm^{-2} s^{-1} × very large cross sections:
  - $\sigma_{bb} \sim 530$ µb, $\sigma_{cc} \sim 7\times\sigma_{bb}$, and prolific source of τ with $\sigma_{\tau} \sim 0.1$ mb, but τ mainly originating from D_s and X_b decays.
  - Acceptance: only < 0.3 σ_b within $1.8 < \eta < 4.9$.
  - Trigger selection.
  - Very high pile-up rate.
  - Hadronisation
    ➛ no quantum correlation.
  - Flavour tagging power:
    $\varepsilon D^2 \sim 5$ %.
  - All species of B baryons are produced.
  - High boost:
    B mean decay length ~ 1 cm.



τ, B and D decays: in Belle II

- At SuperKEKB: very high luminosity $L = 0.8\times10^{36}$ cm^{-2} s^{-1} $\times$ cross sections at $\sqrt{s} = M_{Y(4S)}$:
  - $\sigma_{bb} \sim \sigma_{cc} \sim \sigma_{\tau\tau} \sim 1$ nb.
    In addition to that, τ and X_c baryons also produced from B (and D for τ) decays.
  - Large acceptance 17°-150°.
  - No pile-up but machine background induced by nanobeams.
  - $Y(4S) \to B^0B^0$, B^+B^-, no hadronisation
    ➛ quantum correlation between mesons.
  - Flavour tagging power: $\varepsilon D^2 \sim 30$ %.
  - B^0_s meson can only be produced at $Y(5S)$ c.o.m. energy with reduced luminosity.
  - Boost: $\beta\gamma = 0.28$
    ➛ B mean decay length ~ 140 μm.

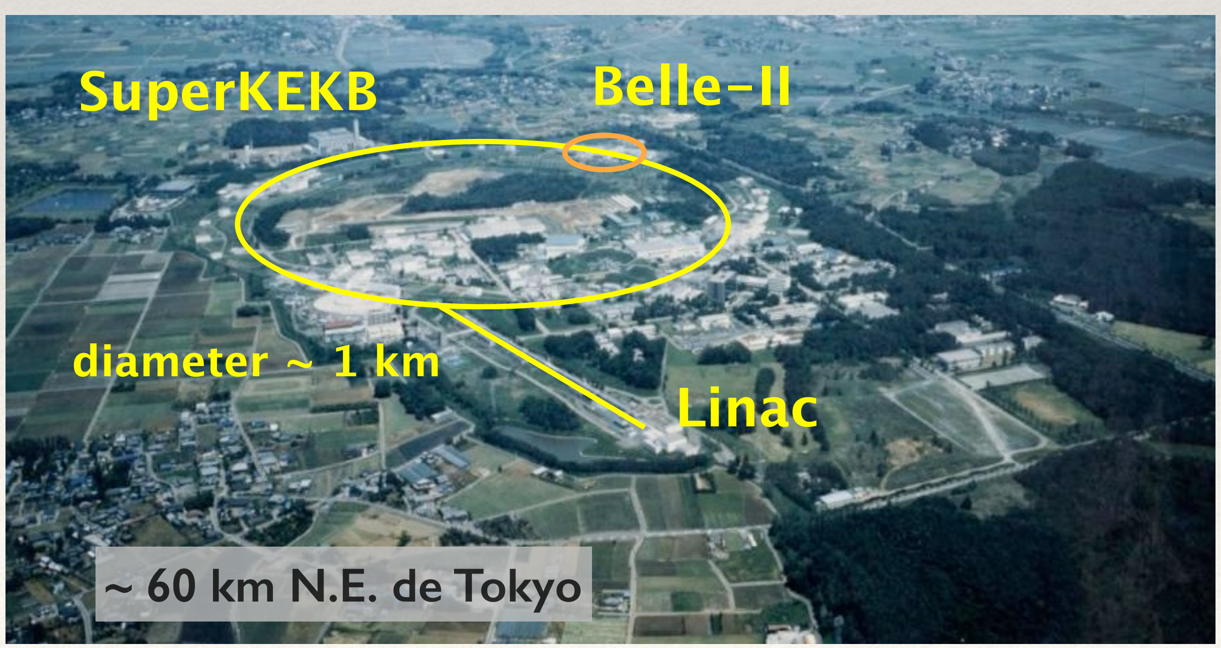


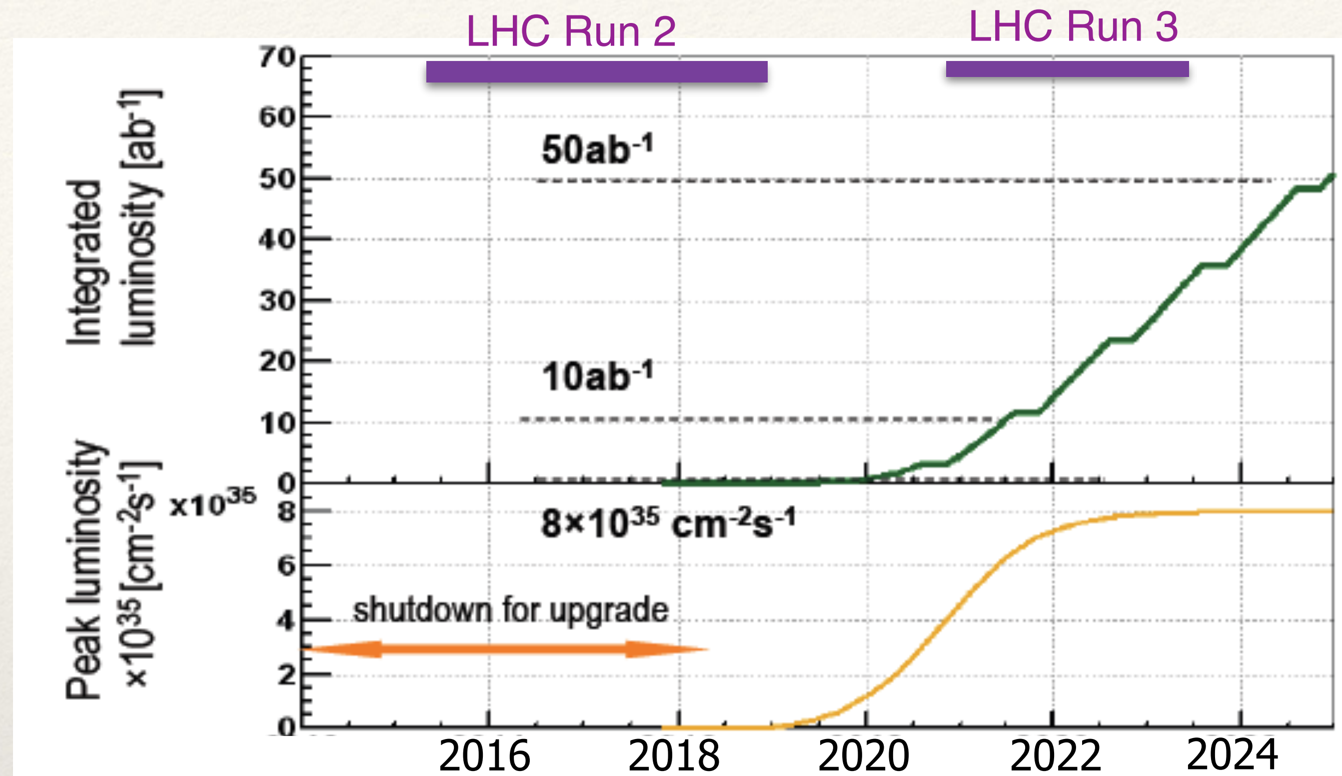
➛ LHCb-Run3 with 50 fb^{-1} and Belle II with 50 ab^{-1} are both super-B-D-τ Factories, with complementary skills.

τ, B and D decays: the SuperKEKB collider

- Asymmetric beams: e^- 7 GeV - e^+ 4 GeV.
  Collisions with $E_{c.m.}$ around $M_{Y(4S)}$ and $M_{Y(5S)}$.
- Increased beam currents: ~2×KEKB
  moderately to limit background.
- Nano-scale beam transverse size:
  ~KEKB/20 in y, $\sigma_x \times \sigma_y \sim 10\ \mu m \times 60\ nm$.
- Large crossing angle:
  22 mrad (KEKB) → 83 mrad (SuperKEKB)

➛ Instantaneous luminosité x40:
$0.8 \times 10^{36}\ cm^{-2}\ s^{-1}$





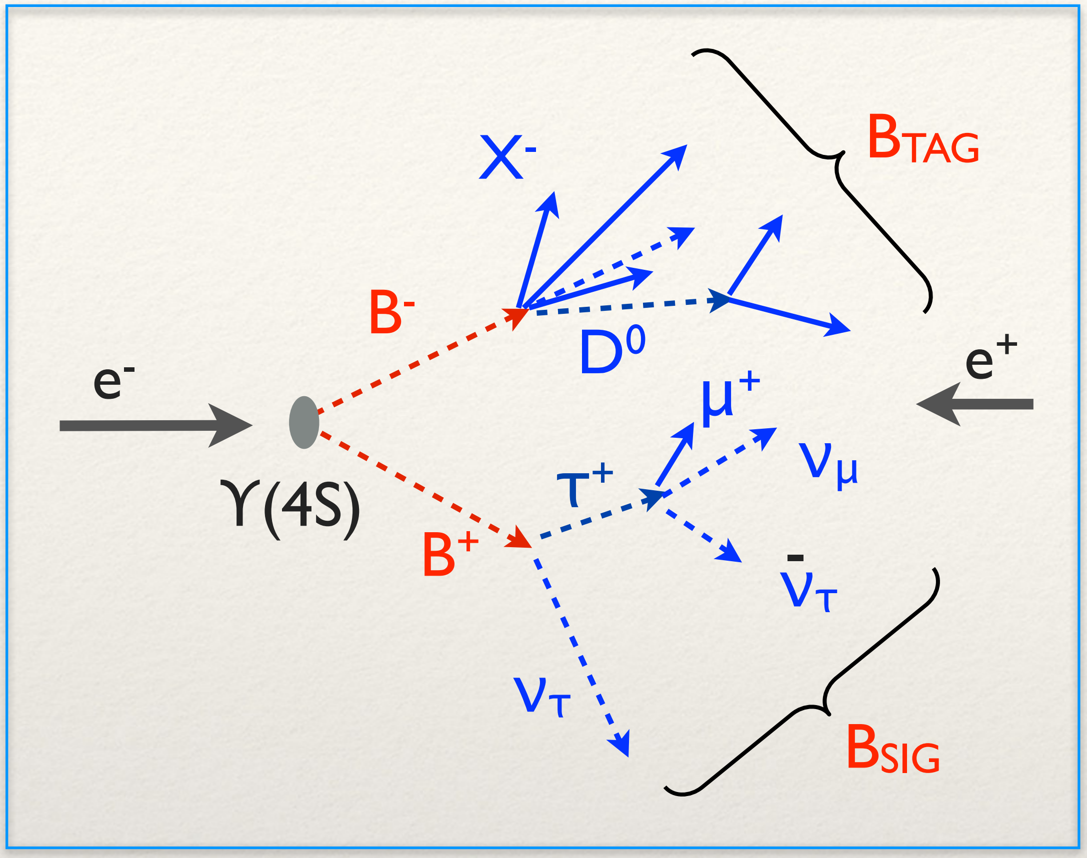
Early 2016: BEAST II collider commissioning until $10^{34}\ cm^{-2}\ s^{-1}$ reached.

October 2018: start of data taking

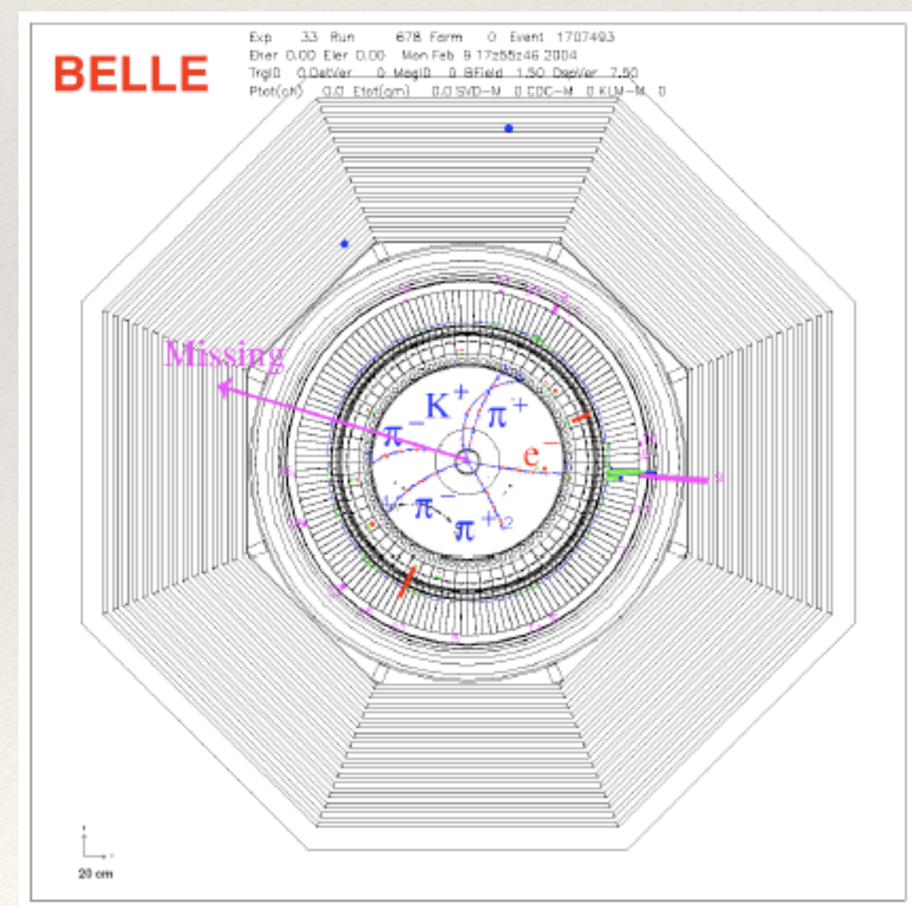
End of 2021: 10 ab^{-1} on tape

Mid 2024: 50 ab^{-1} on tape

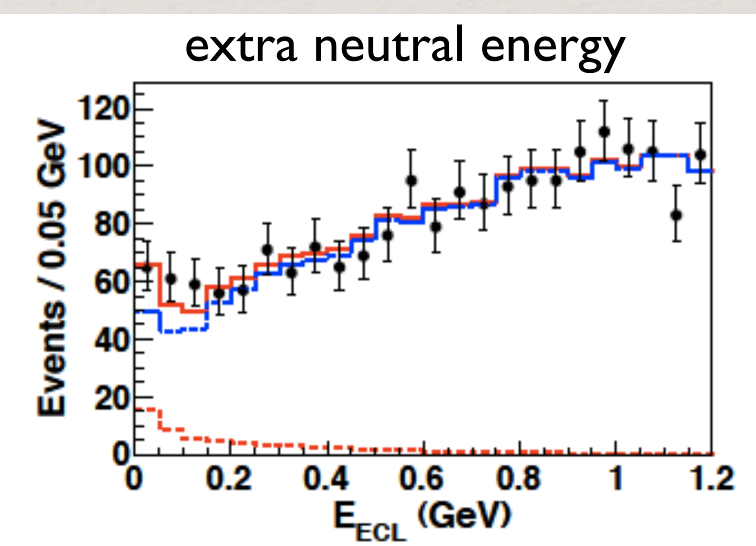
τ, B and D decays: Belle II assets

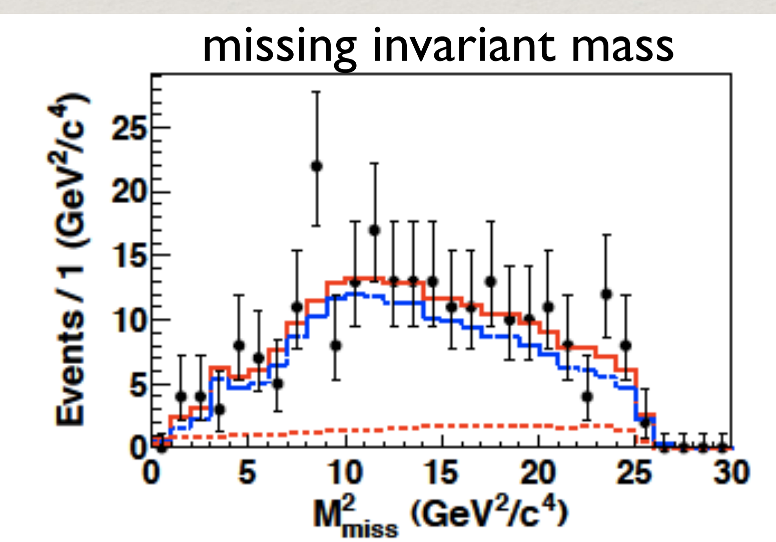


- Event 'simple' topology: only B_{TAG} and B_{SIG}.
  ➛ good ability to study inclusive decays, producing neutrals (γ, π^0, K_L^0) or missing energy (ν).
- B_{TAG} and B_{SIG} are quantum correlated:
  ➛ good performance of flavour tagging.
- Reduced boost and improved particle-id (w.r.t. Belle):
  ➛ increased acceptance.



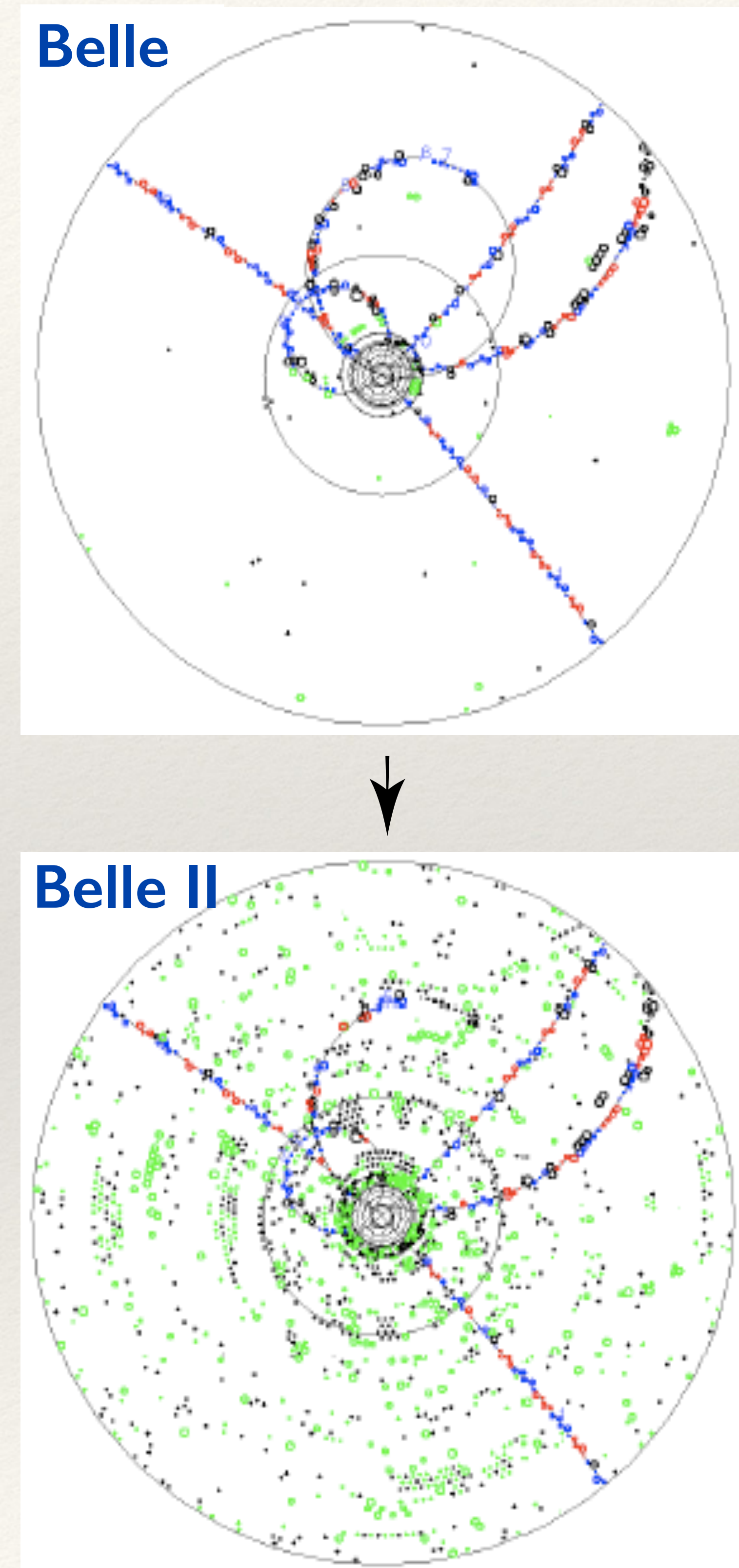
- Example:
  signal: $B^- \rightarrow \tau^- \bar{\nu} \rightarrow (e^- \nu \bar{\nu}) \bar{\nu}$ tag: $B^+ \rightarrow \bar{D}^0 \pi^+ \rightarrow (K^+ \pi^- \pi^+ \pi^-) \pi^+$



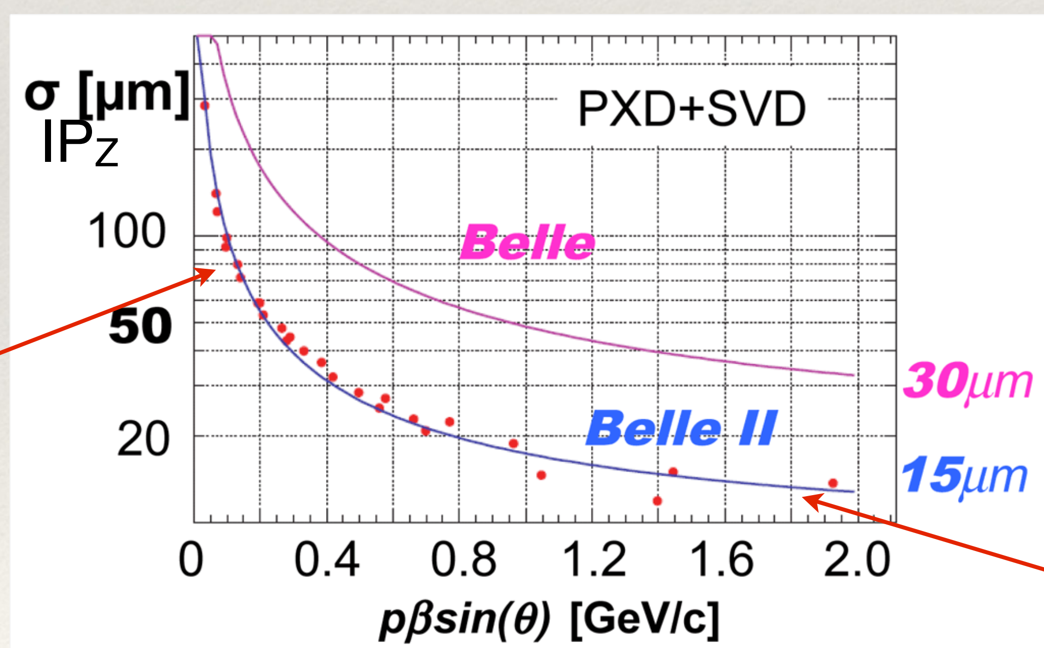


τ, B and D decays: Belle II difficulties

- Very high rate of machine induced background:
  - High radiation level: may damage the detectors,
  - High occupancy rate: impact track and energy reconstruction.
- Lower beam asymmetry $\beta\gamma = 0.28$ (was 0.42 @KEKB):
  impact on flight time resolution: lower Δz and degraded $\sigma(\Delta t)$.
  Therapy (upgrade w.r.t. Belle inner tracker):
  - beam pipe radius is reduced to 1 cm,
  - beam spot is reduced with nano-beams.
  - 2 innermost pixelated layers are added.
    Strips do not stand the machine induced background occupancy rate.



low material budget



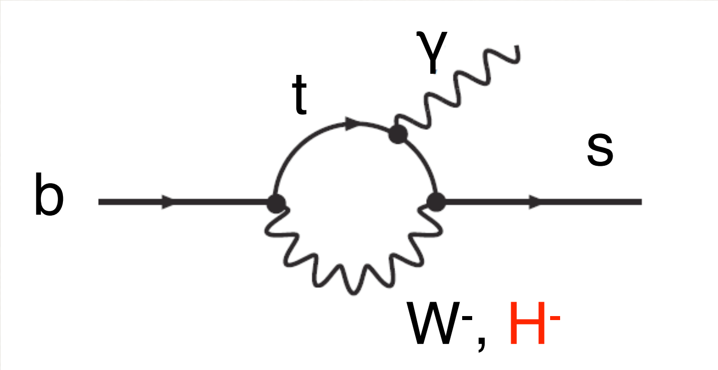
innermost layers closer to the collision point

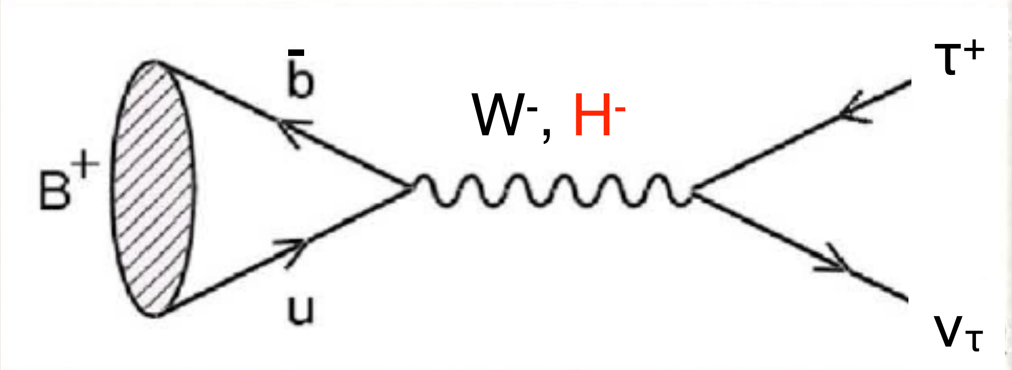
➛ Expected resolution on Δt expected to be improved ×2.

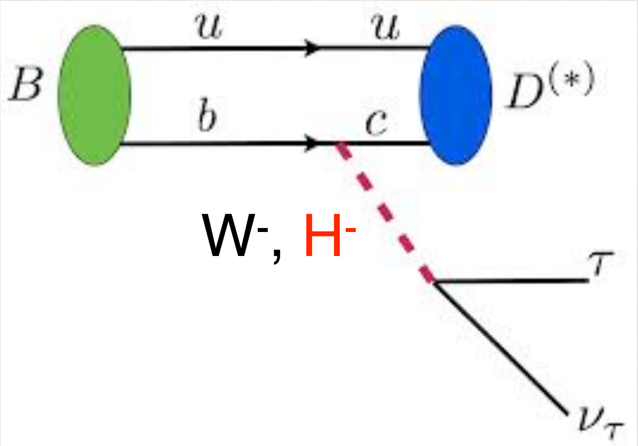
τ, B and D decays: rare decays in Belle II

- Search for highly suppressed decay modes in the SM:
  observation is an unambiguous sign of NP discovery.
  Some of the Belle II golden channels:
  - $B^+ \to \tau^+\nu$, $B^+ \to \mu^+\nu$, $B \to K^{(*)}\nu\bar{\nu}$
  - $b \to s\nu\bar{\nu}$, $b \to s\gamma$, $b \to s\ell\ell$
  - $D^0 \to \ell\ell$, $D^0 \to \gamma\gamma$
  - $B_s^0 \to \gamma\gamma$
  - $\tau \to \ell\gamma$, $\tau \to 3\ell$

<u>H^+ couplings</u>:
- $B \to \tau\nu$: H-b-u
- $B \to D^*\tau\nu$: H-b-c
- LHC: H-b-t





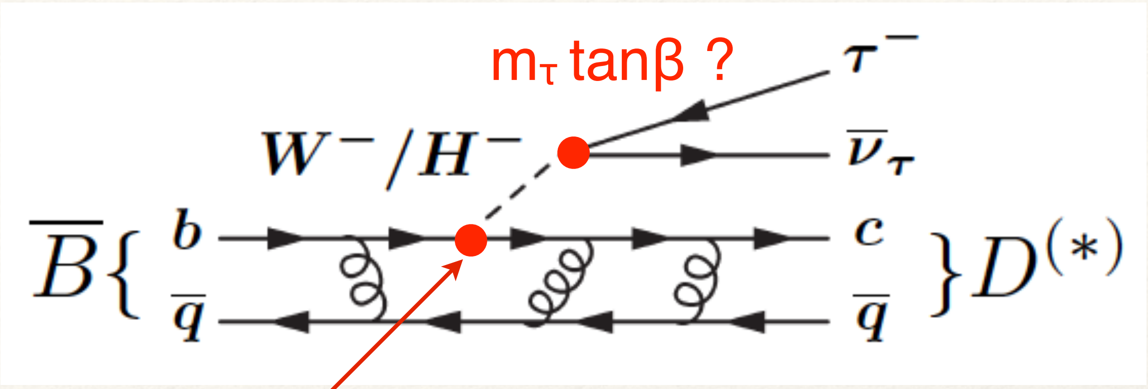


- Very precise measurements of very precisely predicted BR in the SM:
  any discrepancy should be an unambiguous sign of NP discovery.
  One of the Belle II golden channels:
  - $B \to D^{(*)}\tau^+\nu$.

exotic penguin

τ, B and D decays: $B \to D^{(*)}\tau\nu$ decay

- $B \to D^{(*)}\tau\nu$ decays particularly sensitive to an H^+ contribution at the level of a tree diagram.



- SM predictions of these BR suffer from QCD effects (few % level) and $|V_{cb}|$ uncertainty. (cf. discussion on $K \to \pi\nu\nu$ BR predictions).

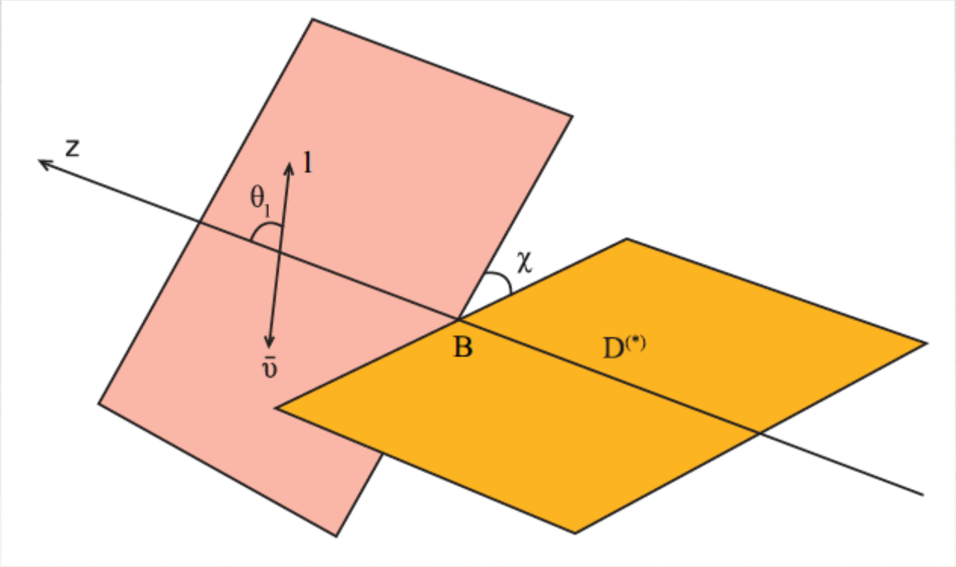
- To get rid of theoretical uncertainties, measurement of the following BR ratio:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

considering only purely leptonic τ decays to cancel further some detection efficiencies.

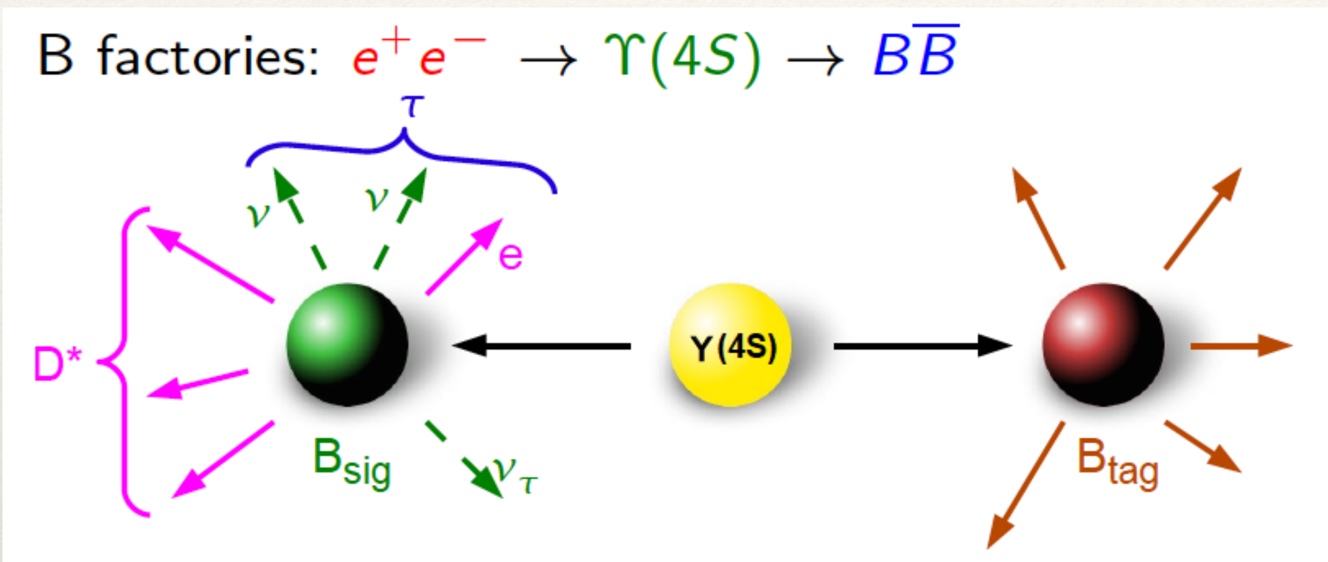
- $B \to D^{(*)}\ell\nu$ decays can be precisely measured: e.g. $BR(B^- \to D^0 \ell^- \nu) = (2.27 \pm 0.11)$ %. Theoretically: only phase space and helicity suppression effects.

- Additional observables help clarifying the NP structure: (τ and) D^* polarizations, q^2 distribution, …



τ, B and D decays: reconstruction of $B \to D^{(*)}\tau\nu$

- Experimentally challenging due to 3 neutrinos in the final state.
  First exclusive observation of $b \to c\tau\nu$ transition by Belle in 2007 (5.2σ):
  $BR(B^0 \to D^{*-}\tau\nu) = (2.02\ ^{+0.40}_{-0.37}\ (stat) \pm 0.37\ (syst))\ \%$.



- At a Flavour Factory, reconstruction of B_{TAG}:
  - Selection of BB events and reduction of continuum (uu, dd, ss, cc) background.
  - Obtain kinematic constraints on B_{SIG} momentum: $\vec{p}_{SIG} = -\vec{p}_{TAG}$
  - Small efficiency $< 10^{-2}$.

B_{TAG} fully reconstructed in hadronic decays. Many (>> 1000) exclusive modes used.

B_{TAG} reconstructed in semi-leptonic modes: $D^{(*)}\ell\nu$.

B_{TAG} reconstructed inclusively (all remaining tracks but B_{SIG}) or partially (charged lepton).

τ, B and D decays: $B \to D^{(*)}\tau\nu$ from BaBar (1)

- BaBar measurement based on full data set: 471×10^6 BB.

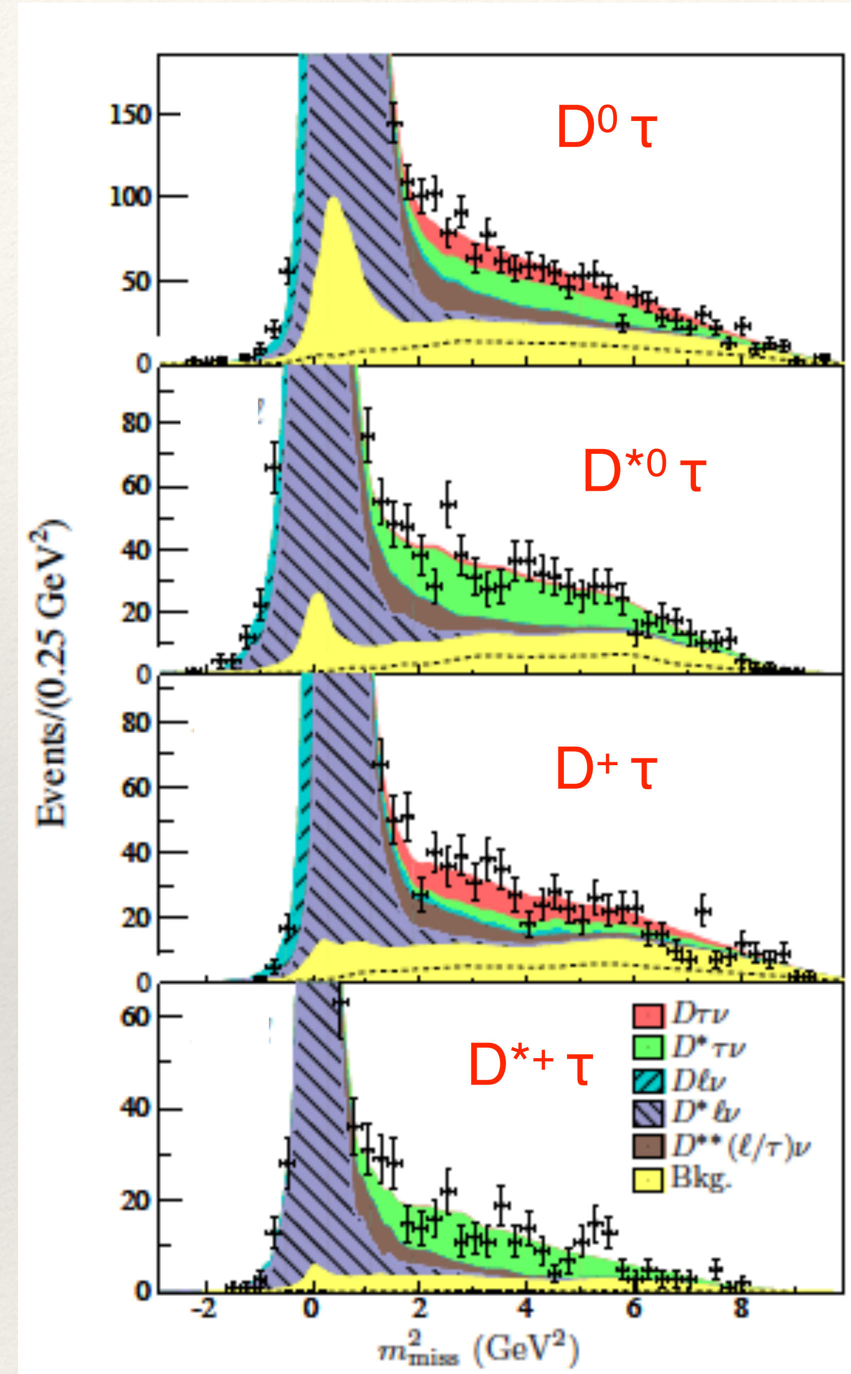
  Semi-exclusive hadronic B_{TAG} reconstruction

  (1680 different $B_{TAG} \to X_c X^{\pm}$ decay modes)

  + (loose) charged lepton selection in the remaining tracks

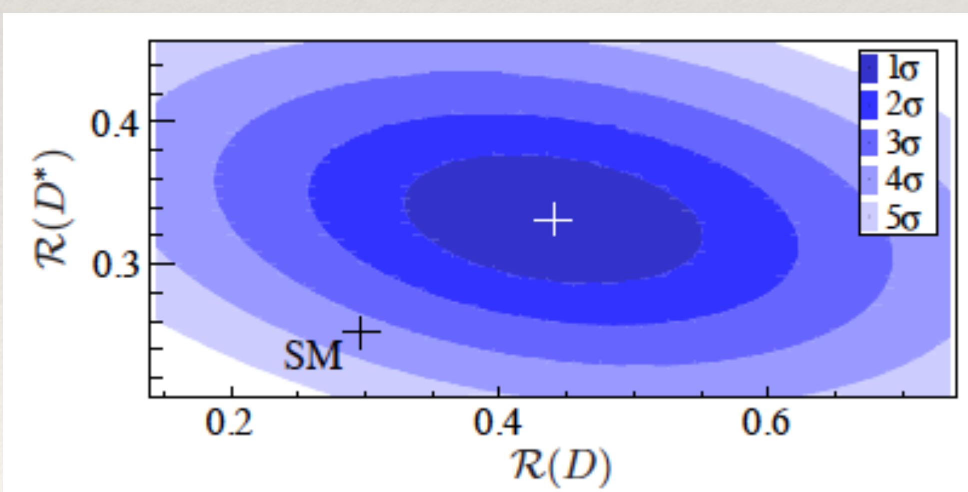
  + kinematic cuts ➛ low purity, depending on the channel.

  Final selection improved with help of a BDT.



SM prediction:		BaBar measurement:
0.297 ± 0.017	2.0σ ⟷	R(D) = 0.440 ± 0.058 (stat) ± 0.042 (syst)
0.252 ± 0.003	2.7σ ⟷	R(D*) = 0.332 ± 0.024 (stat) ± 0.018 (syst)

[Phys.Rev. D85 (2012), 094025] [Phys.Rev. D88 (2013) 7, 072012]



global: 3.4σ disagreement with the SM prediction

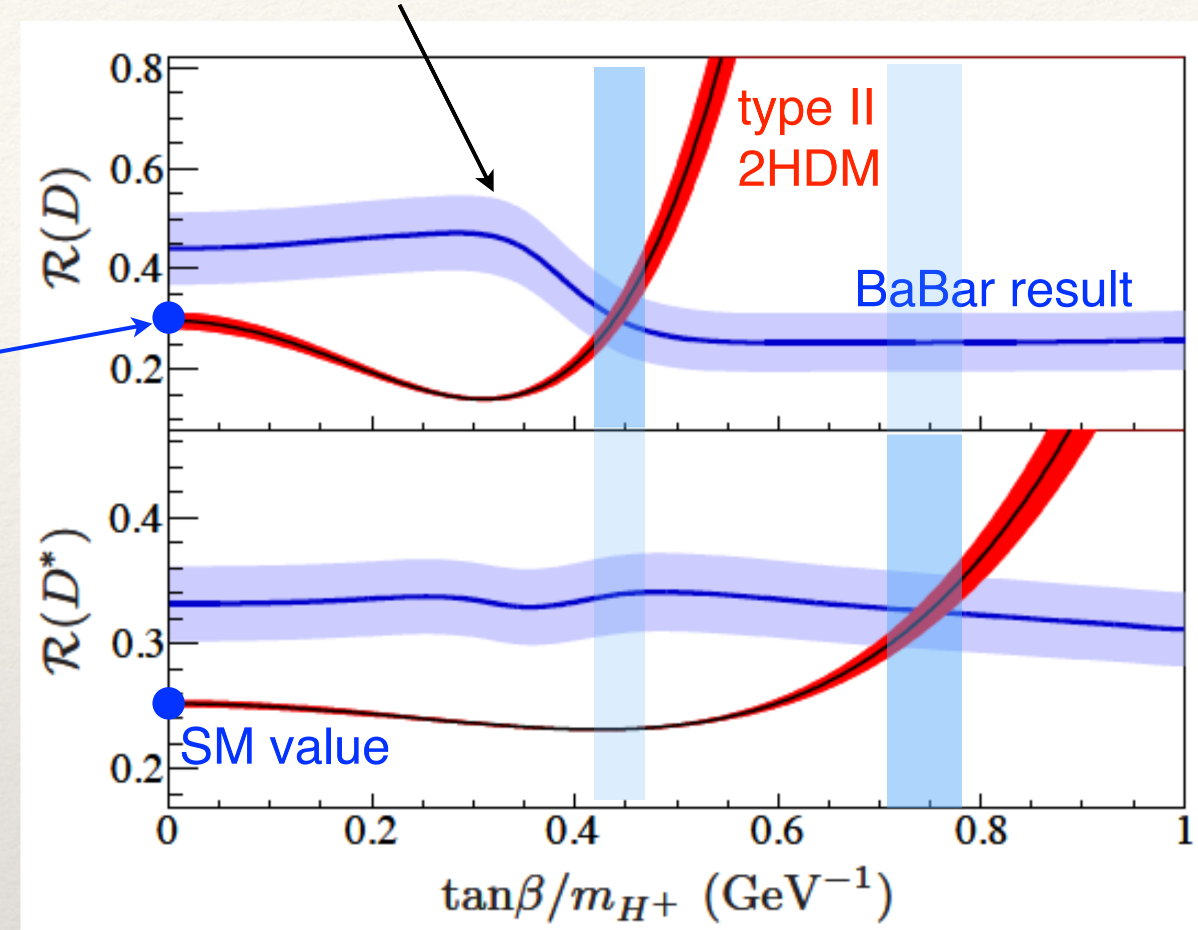
τ, B and D decays: $B \to D^{(*)}\tau\nu$ from BaBar (2)

- Predictions by type II 2HDM:
  - significant impact from H^+ on R(D),
  - smaller effect on $R(D^*)$,

  due to D* spin.

(acceptance variations)

SM value



- Extracted from R(D) measurement: $\tan\beta/m_{H+} = 0.44 \pm 0.02\ \mathrm{GeV}^{-1}$,
- Extracted from $R(D^*)$ measurement: $\tan\beta/m_{H+} = 0.75 \pm 0.04\ \mathrm{GeV}^{-1}$.

➛ type II 2HDM H^+ excluded with C.L. = 99.8 % in the $\tan\beta$-m_{H+} parameter space

More general H^+ models (e.g. type III), or non-scalar NP contributions are still allowed (spin 1 favoured by observed q^2 distributions).

τ, B and D decays: adding $B\to D^{(*)}\tau\nu$ from Belle

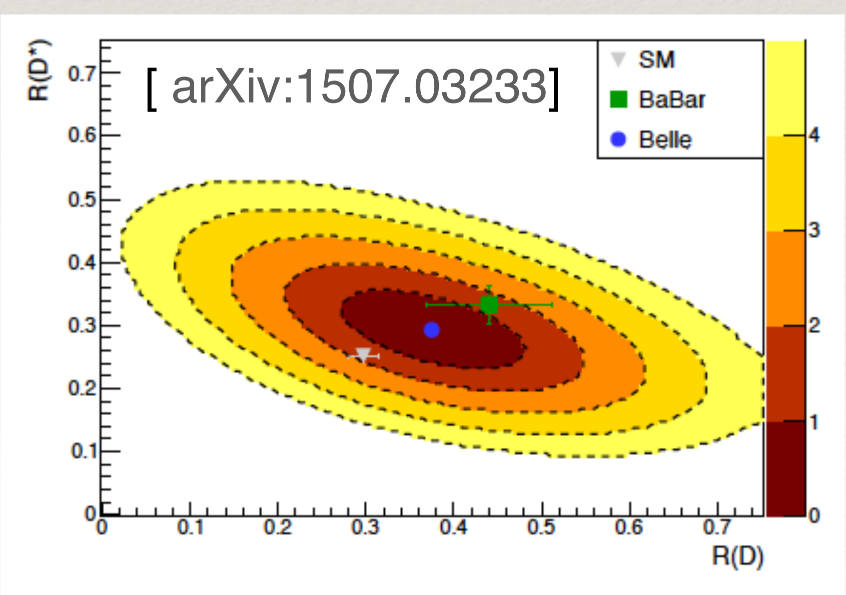
- 2 different analyses in Belle: exclusive and inclusive tags, based on the full dataset 711 fb^{-1}.
- Inclusive tags: start by reconstructing B_{SIG}, (including also $\tau\to\pi^+\nu$, $\rho\nu$), then B_{TAG} = left overt tracks and energy clusters. Signal selection based mostly on B_{TAG} variables.

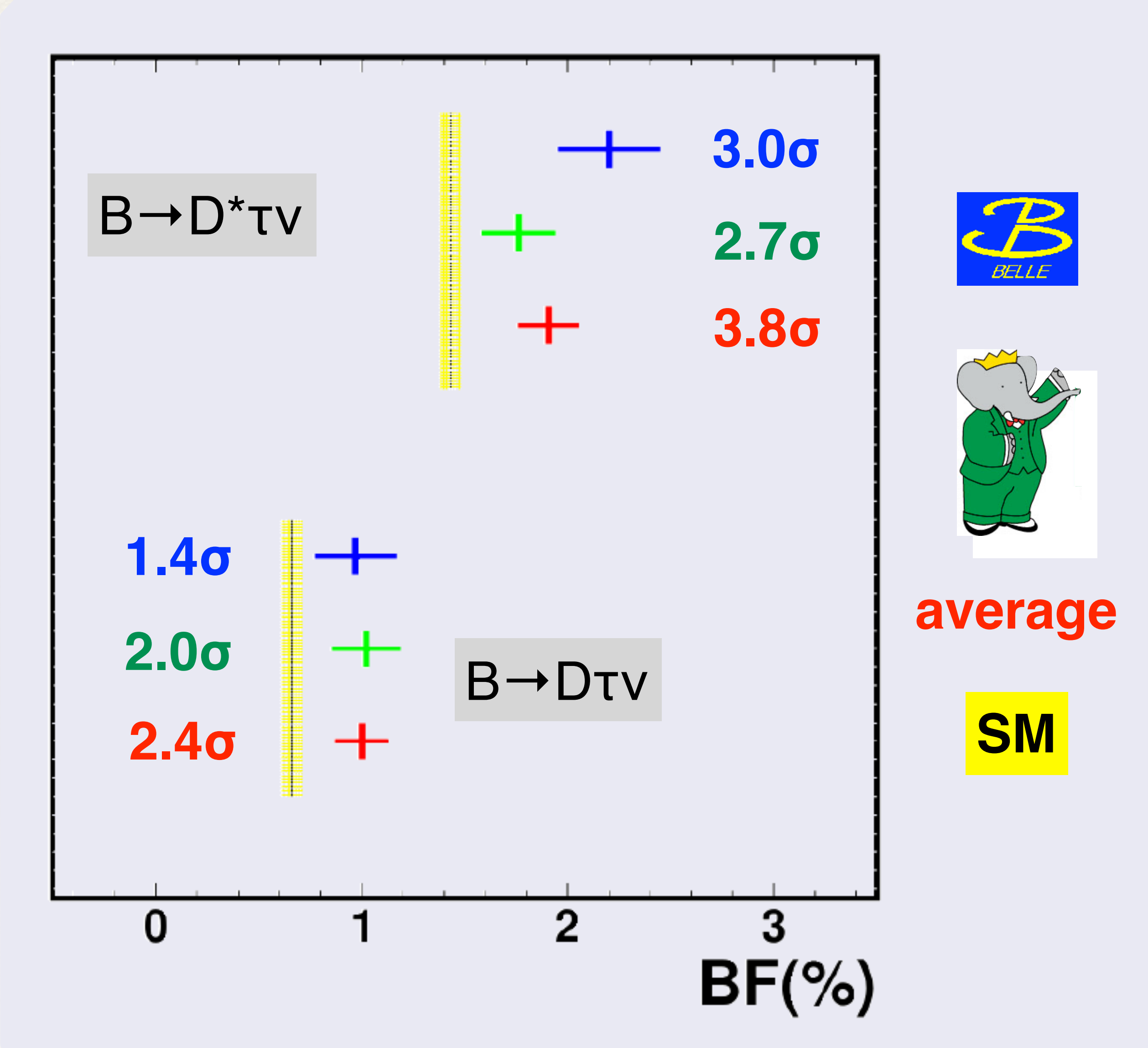
➢ combined R(D), R(D*) excess in Belle: 3.3σ. [from A. Božek @KEK-FF2013 Workshop]

➢ systematic excess, observed in all individual channel (B^0, B^+, D, D* / inclusive or exclusive tags), by BaBar and Belle.

Global discrepancy with SM rises up to ~4.8σ.

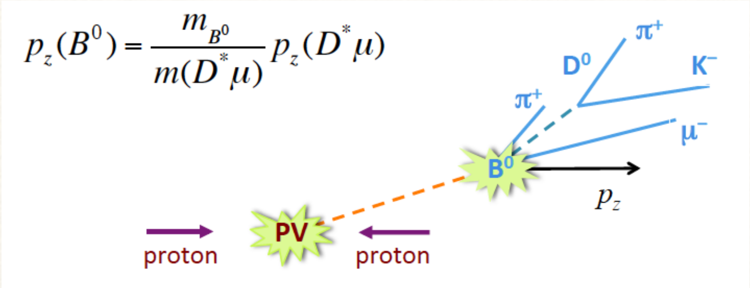
- Updated result from Belle in 2015 using only leptonic tau decays: better agreement with SM.





τ, B and D decays: B→D(*)τν from LHCb

- Precise measurement of BR(B→D(*)τν) unfeasible at LHC due to multiple ν in the final state. No kinematic constraints as at B-Factories, and huge background.

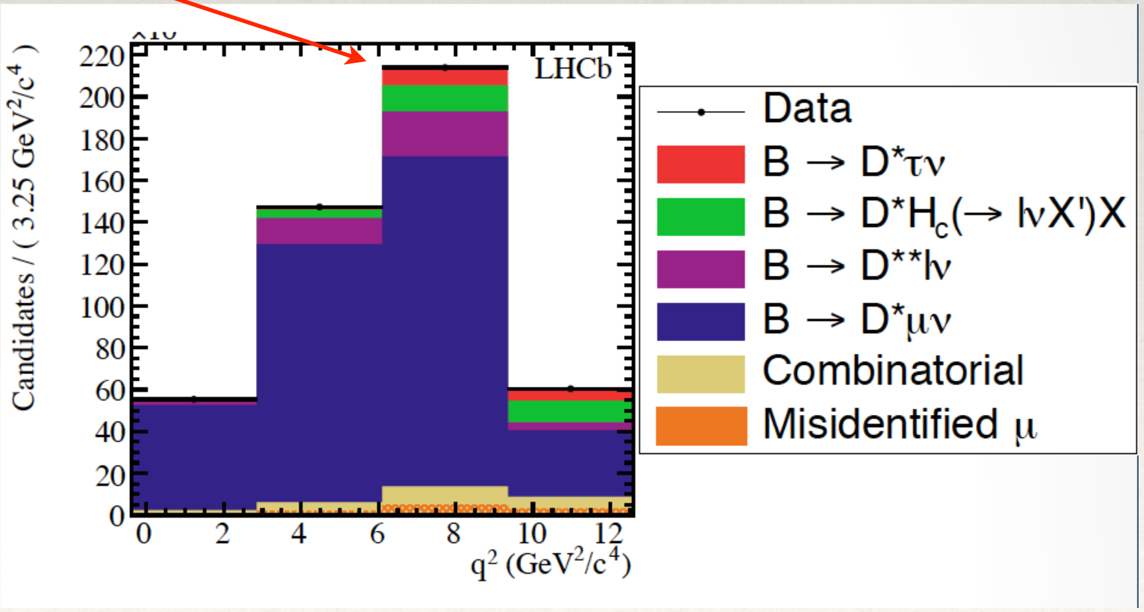


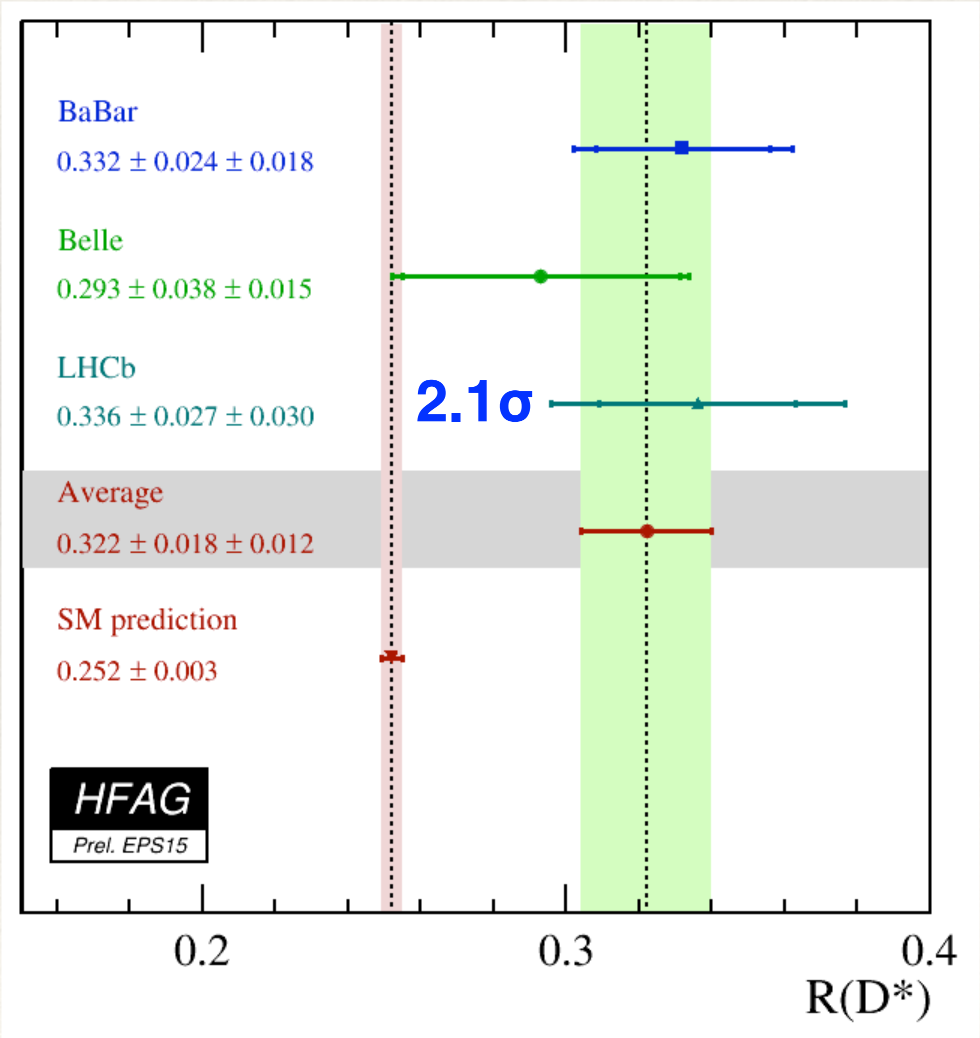
- Feasible: measurement of R(D*) with τ→μνν decays (17.4 %).

- Reconstruction of the B rest frame: B momentum unknown, B flight direction known (from primary and decay vertices), p_Z(B) approximated.

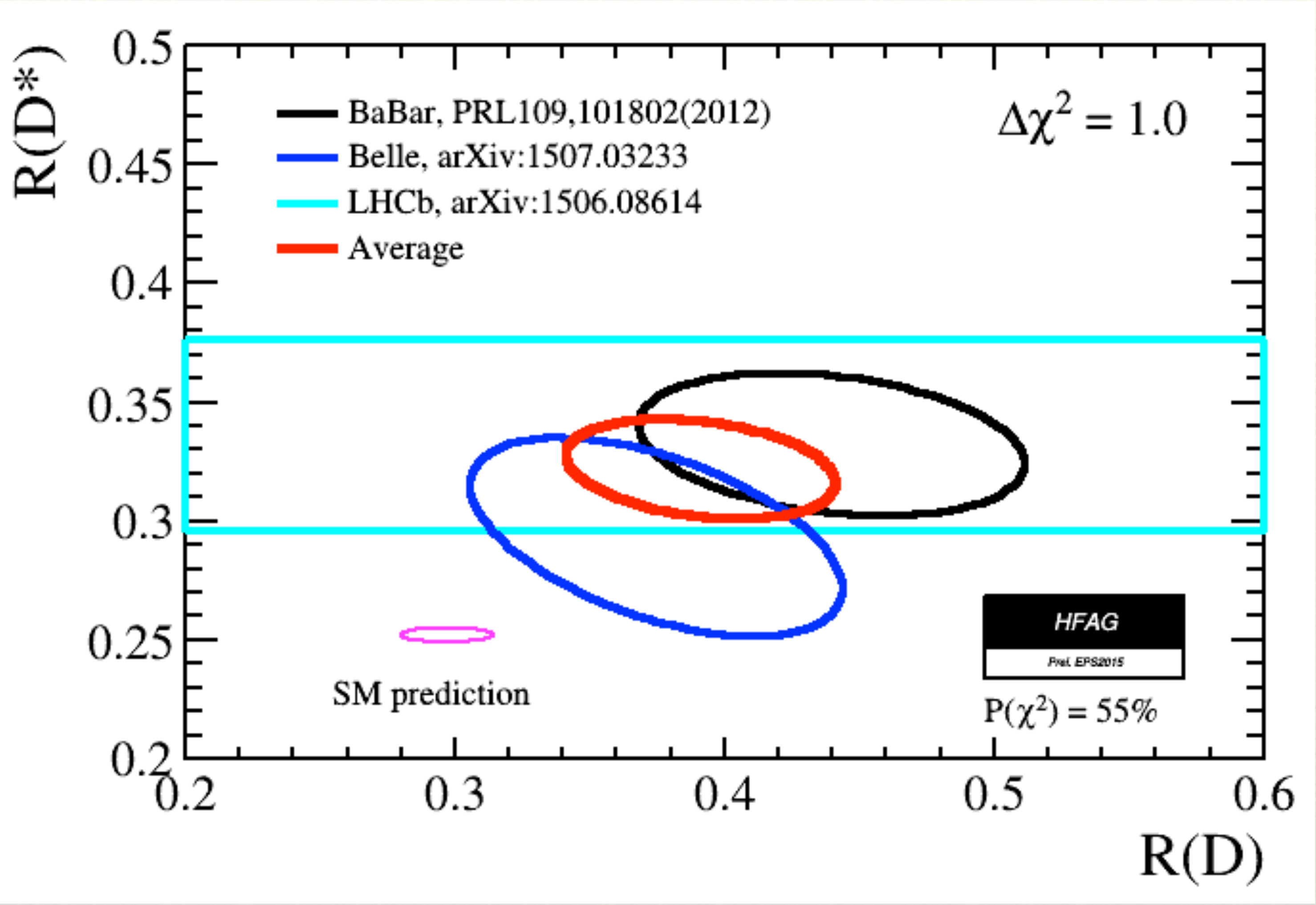
First LHCb results presented at EPS-2015 based on 3 fb^{-1} of Run I data @ 7, 8 TeV, show a 2.1σ excess with SM expectation.

signal





τ, B and D decays: $B\to D^{(*)}\tau\nu$ status and prospects



Global discrepancy with SM ~ 3.9σ.

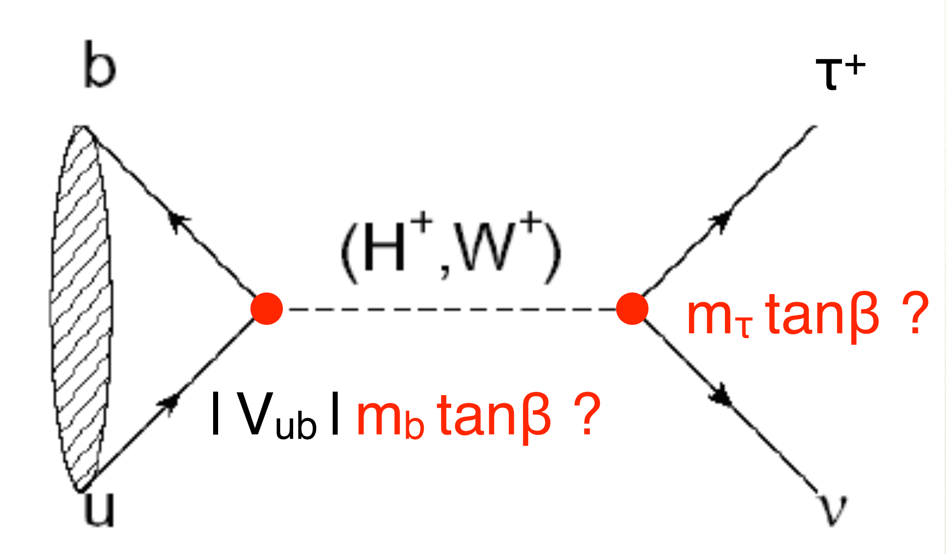
2HDM seems to be excluded by these results, but $R(D^{(*)})$ is also a sensitive probe to other BSM theories.

Need Belle II to improve precision on this measurement.

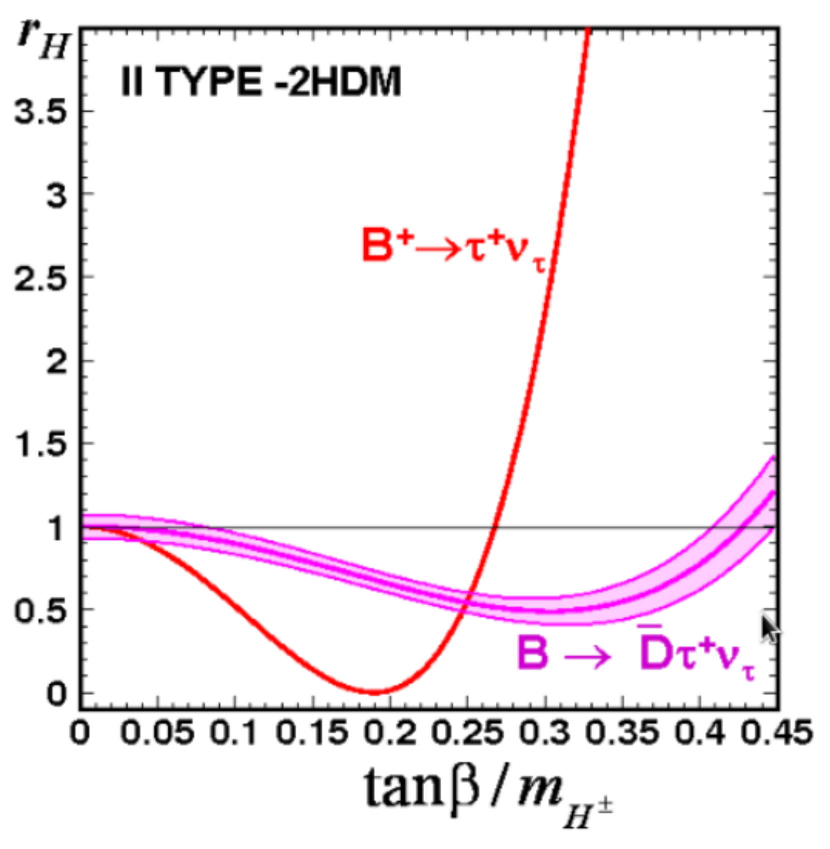
- What can be done in Belle II:
  - Total uncertainty on R(D) and R(D*) can be reduced by a factor > 5.
    If D** background is better understood: reduction by another factor of 2.
  - Measurement of different kinematic distributions: q^2, angular distributions, …
  - Individual BR can be precisely measured: uncertainty reduced by a factor of ~5.

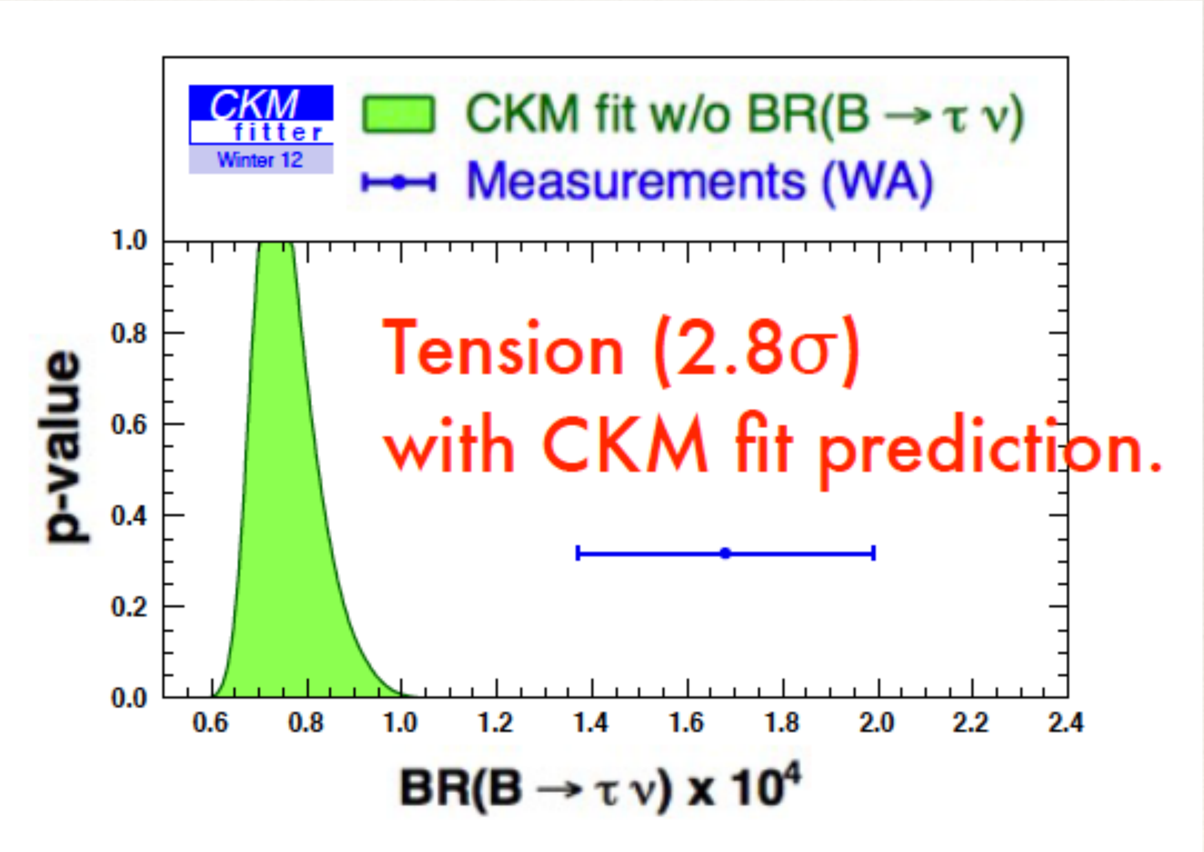
τ, B and D decays: $B \to D^{(*)}\tau\nu \otimes B \to \tau\nu$

- $B \to \tau\nu$ decays also particularly sensitive to an H^+ contribution at the level of tree diagram.
  (as it is the case of all decays including $\tau\nu$)
  Tree diagram, but rather rare ~ 10^{-4}.
- $B \to \tau\nu$ can only be measured at B-Factories.
- Modification factor r_H, e.g. of 2HDM:



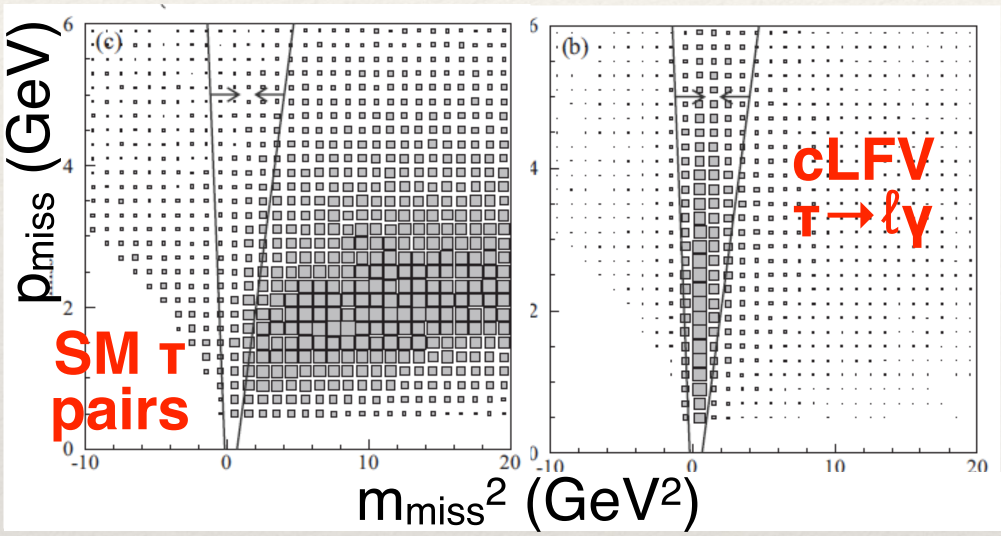
$$r_H = \frac{BR_{SM+NP}}{BR_{SM}} = \left(1 - \frac{m_B^2}{m_H^2}\,tan^2\beta\right)^2$$

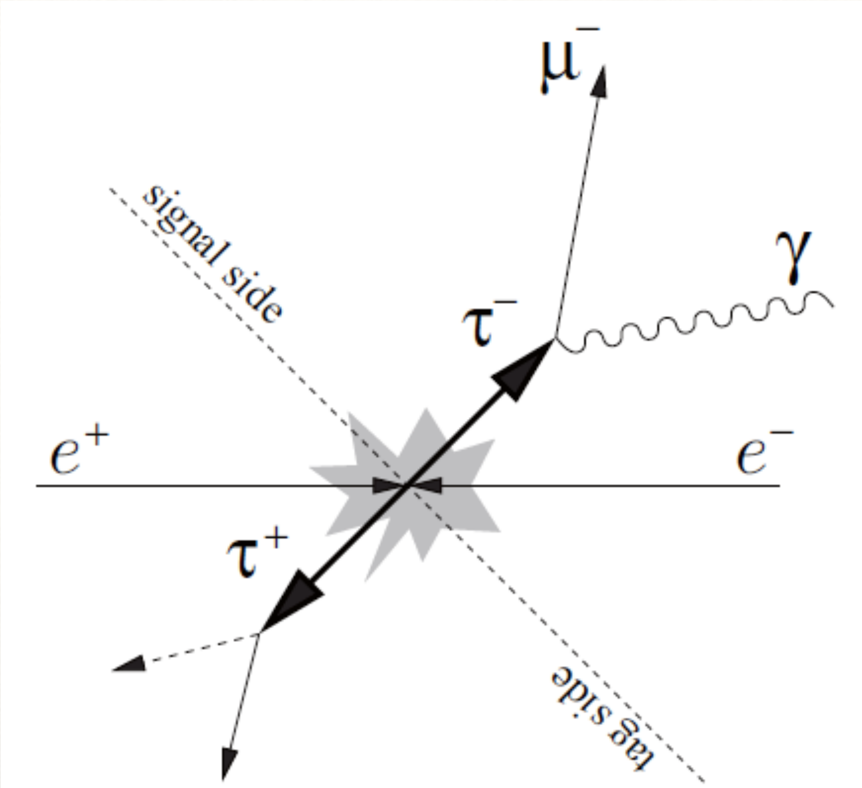




τ, B and D decays: τ cLFV decays (1)

- cLFV τ decays can be mainly searched at SuperKEKB, where signal is very clean:
  - $\tau \to 3\ell$, ℓ(P, S, V) channels: upper limits improve ~ 1/lumi,
  - $\tau \to \ell\gamma$ channels: upper limits improve ~ $1/\sqrt{\text{lumi}}$, because background free analyses.



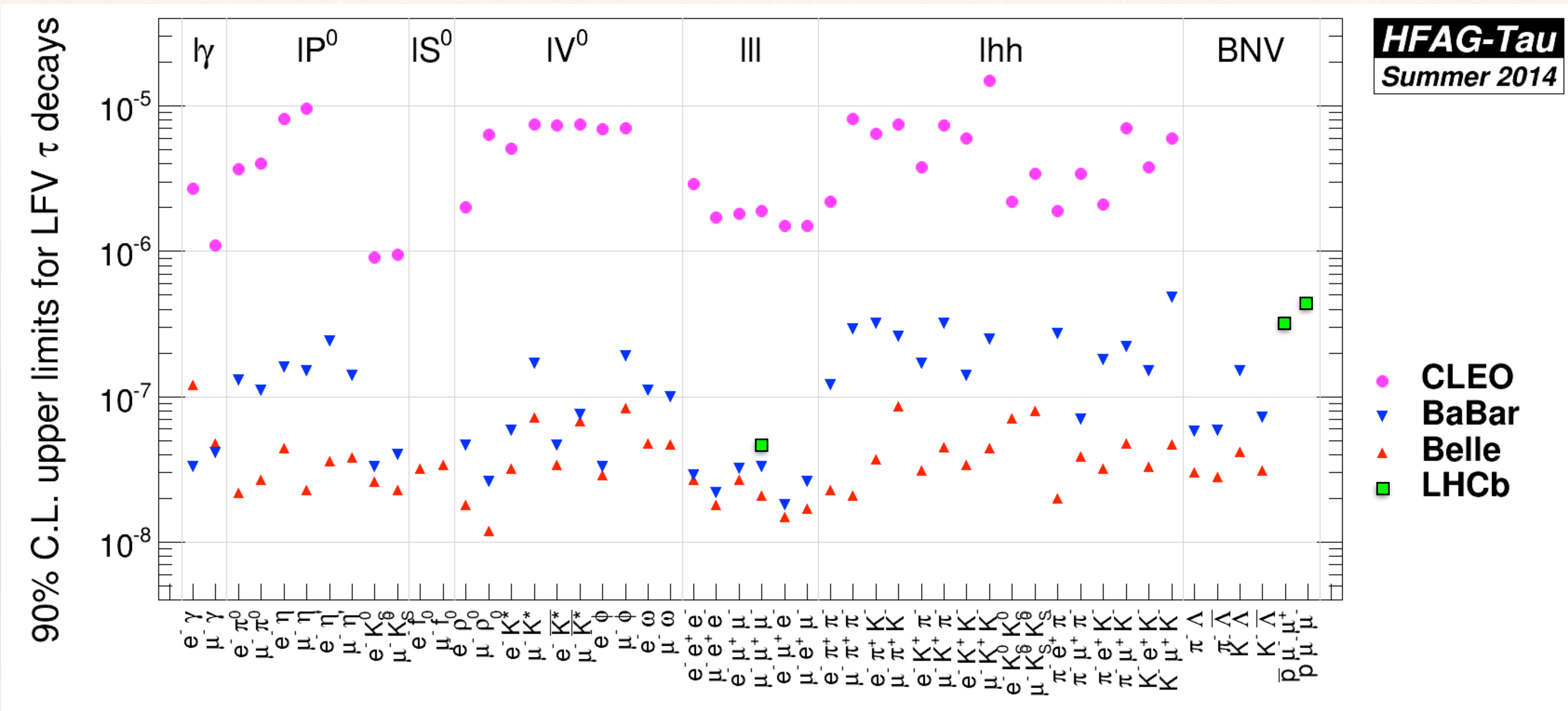


process	present limit	future	
$\tau \to e\gamma$	$<3.3 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super KEKB
$\tau \to eee$	$<3.4 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super KEKB
$\tau \to \mu\gamma$	$<4.4 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super KEKB
$\tau \to \mu\mu\mu$	$<2.1 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	super KEKB/LHCb

Reminder:
the correlation with cLFV μ decays is particularly powerful to constraint NP models.

τ, B and D decays: τ cLFV decays (2)

A huge amount of channels can be investigated!



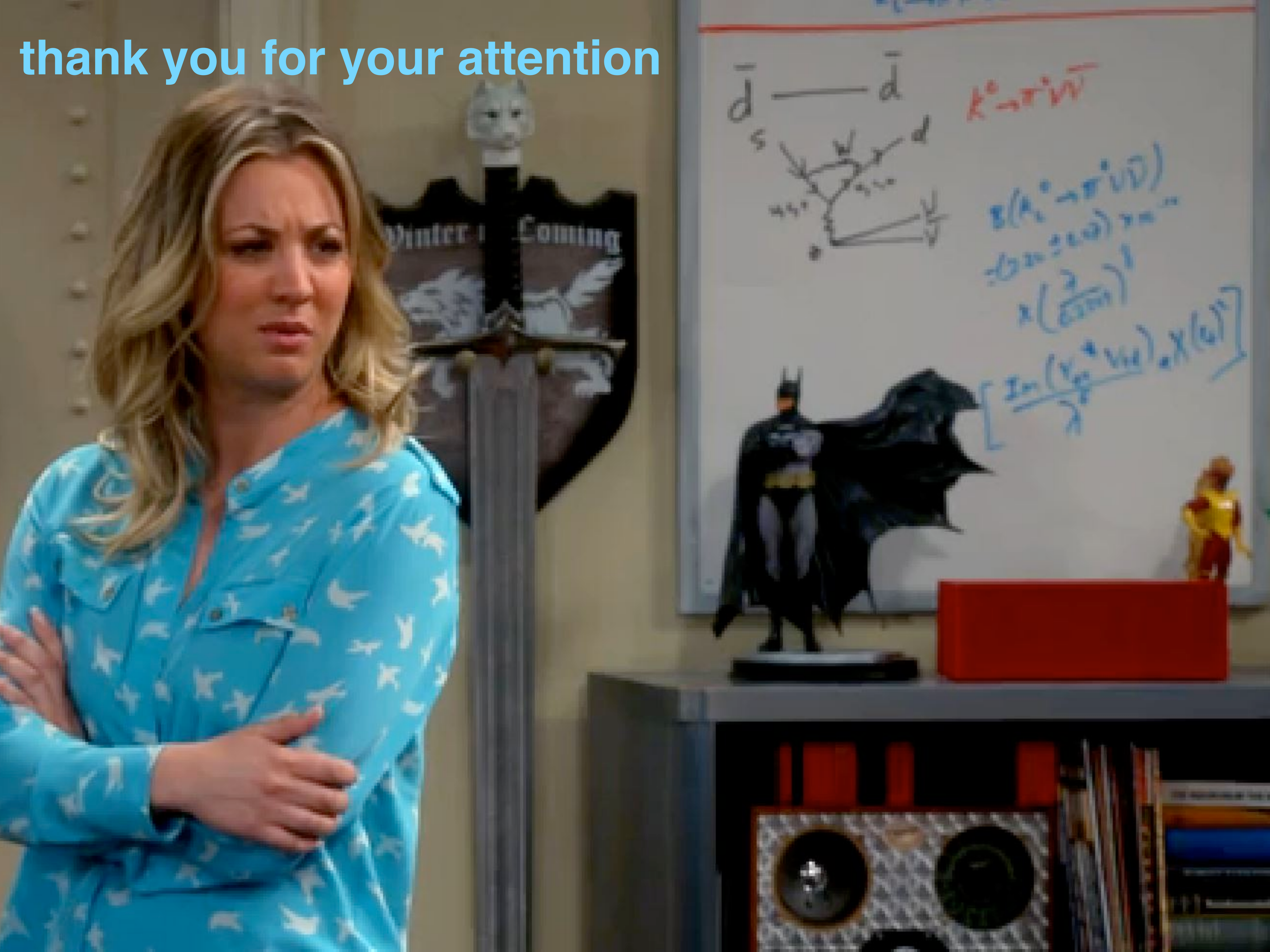
τ, B and D decays: conclusion and outlooks

- B, D and τ decays provide sensitive probes to discover and constraint BSM physics.
- LHC (in particular Run 3) and SuperKEKB will be prolific sources of τ leptons and B, D mesons:
  - SuperKEKB will start commissioning in a few months and data taking in 2018. It will be the most intense collider in the world, delivering 50 ab^{-1} to the Belle II experiment in ~ 2024.
  - LHC-Run 3 will start in 2021 and deliver 50 fb^{-1} to the LHCb experiment at ~ the same time.
- Belle II will play a crucial role, in a complementary way to LHCb (with different assets) and all the experiments also looking for indirect quantum manifestations of NP, as those reported in this course.

Conclusion

- An exciting program of sensitive searches at the intensity frontier is awaiting us, made possible thanks to significant progresses in accelerator and detector technologies.
- Flavour physics and precision measurements at low energies may be the only way to reach the Zeptouniverse (10 TeV and above, 10^{-21} m) in the next decade. If the scale of NP is not under experimental reach, it is a powerful tool to constrain NP models.
- The actual conclusion is that a variety of approaches is needed to address the question of BSM, as well with experiments at the energy frontier, at the intensity frontier and at the cosmic frontier.
  The key word of this course is complementarity: not only the sensitivity to NP is enhanced, but also it is the only way to understand the structure of NP and the flavour-breaking pattern once NP is discovered.
- IN2P3 laboratories are participating to several experiments discussed in this course:
  - neutron EDM @nEDM, PSI: LPC Caen, LPSC Grenoble
  - muon cLFV decay @COMET, J-PARC: LPNHE Paris
  - tau cLFV and B, D decays @ Belle II, KEK : IPHC Strasbourg, LAL Orsay

thank you for your attention



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    - EPS Conference on HEP 2015, July 2015, Vienna, Austria.

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Main sources and origin of figures (3)

- cLFV:
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  - Prog.Part.Nucl.Phys. 71 (2013) 75-92, A. de Gouvea and P. Vogel, Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model.
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additional material

Introduction: “DNA” of flavour physics

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

[Nucl.Phys. B830 (2010) 17-94]

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

Introduction: the quantum path

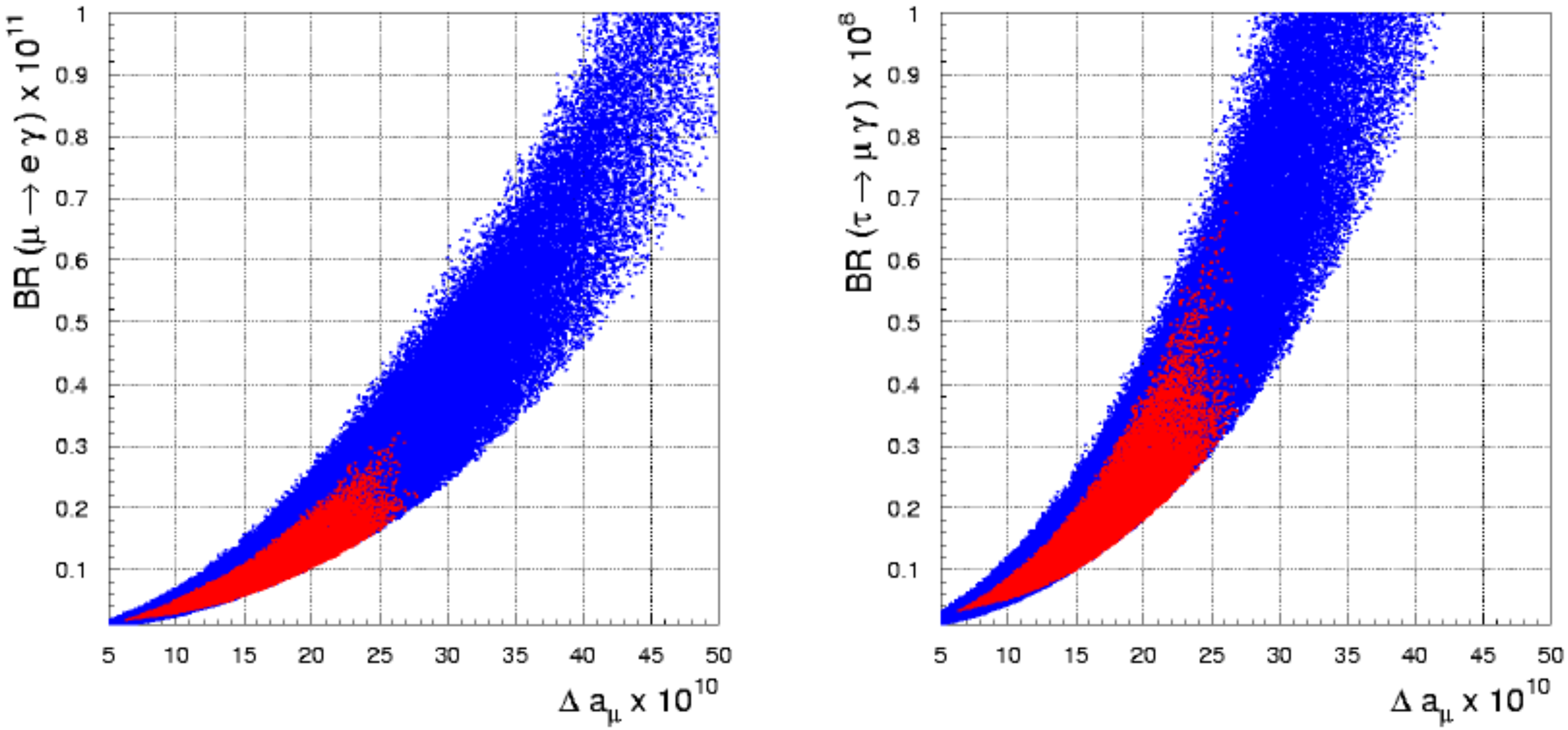


Figure 6: Expectations for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ vs. $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$, assuming $|\delta_{LL}^{12}| = 10^{-4}$ and $|\delta_{LL}^{23}| = 10^{-2}$. The plots have been obtained employing the following ranges: 300 GeV $\leq M_{\tilde{\ell}} \leq$ 600 GeV, 200 GeV $\leq M_2 \leq$ 1000 GeV, 500 GeV $\leq \mu \leq$ 1000 GeV, $10 \leq \tan\beta \leq 50$, and setting $A_U = -1$ TeV, $M_{\tilde{q}} = 1.5$ TeV. Moreover, the GUT relations $M_2 \approx 2M_1$ and $M_3 \approx 6M_1$ are assumed. The red areas correspond to points within the funnel region which satisfy the B-physics constraints listed in Section 3.2 [$\mathcal{B}(B_s \to \mu^+\mu^-) < 8 \times 10^{-8}$, $1.01 < R_{Bs\gamma} < 1.24$, $0.8 < R_{B\tau\nu} < 0.9$, $\Delta M_{B_s} = 17.35 \pm 0.25$ ps^{-1}].

[Phys.Rev. D75 (2007) 115019]

muon (g-2): comparison of experiments

	BNL-E821	Fermilab	J-PARC
Muon momentum	*3.09 GeV/c*		*0.3 GeV/c*
gamma	*29.3*		*3*
Storage field	*B=1.45 T*		*3.0 T*
Focusing field	*Electric quad*		*Very weak magnetic*
# of detected μ+ decays	*5.0E9*	*1.8E11*	*1.5E12*
# of detected μ- decays	*3.6E9*	*-*	*-*
Target Precision (stat)	*0.46 ppm*	*0.1 ppm*	*0.1 ppm*
Spin flip	*No*	*No*	*Yes*

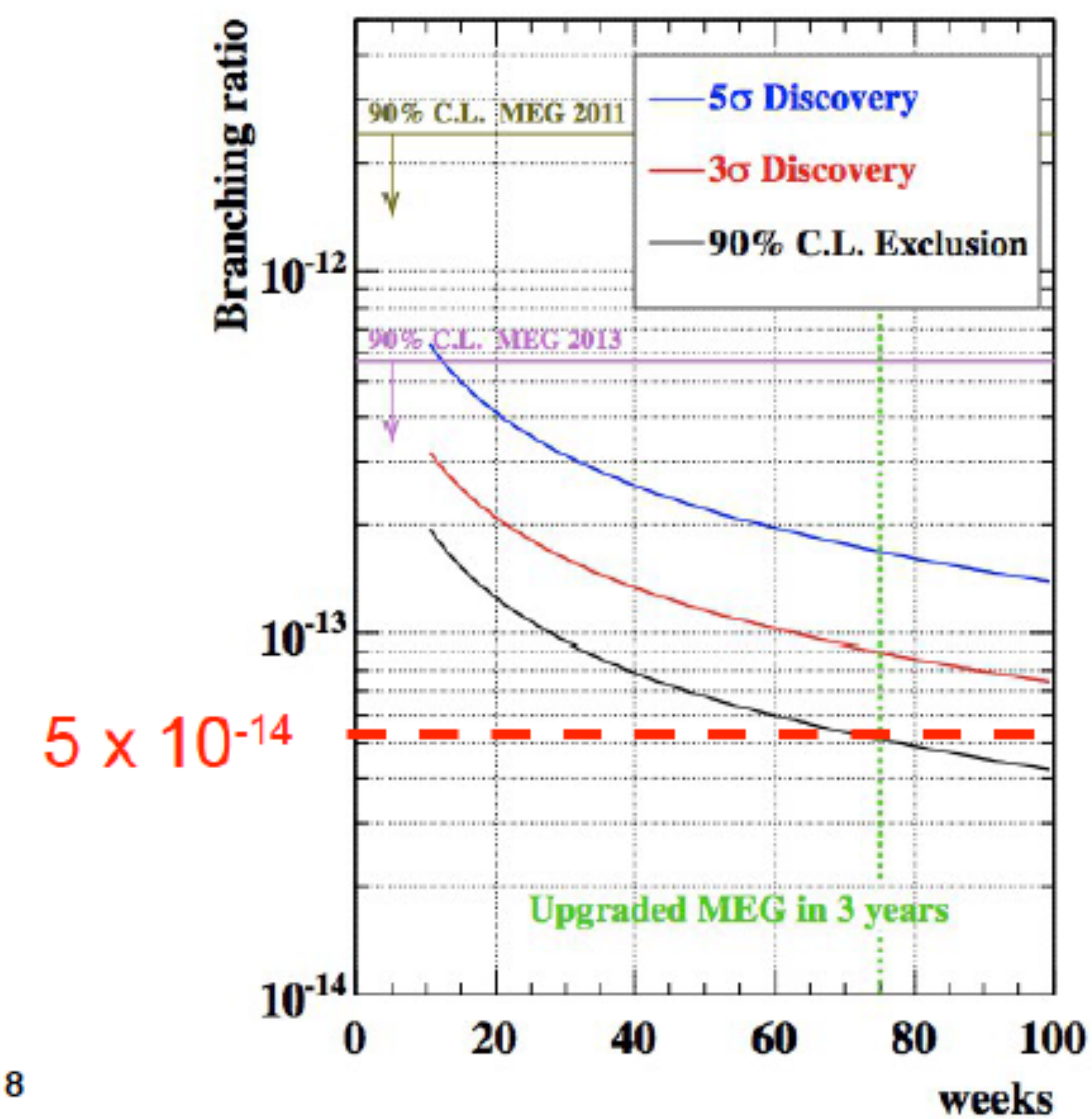
T. Mibe, SSP2015, Victoria, June 11, 2015.

MEG upgrade: MEG II

MEG upgrade

An improvement of an order of magnitude is expected on the sensitivity

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88



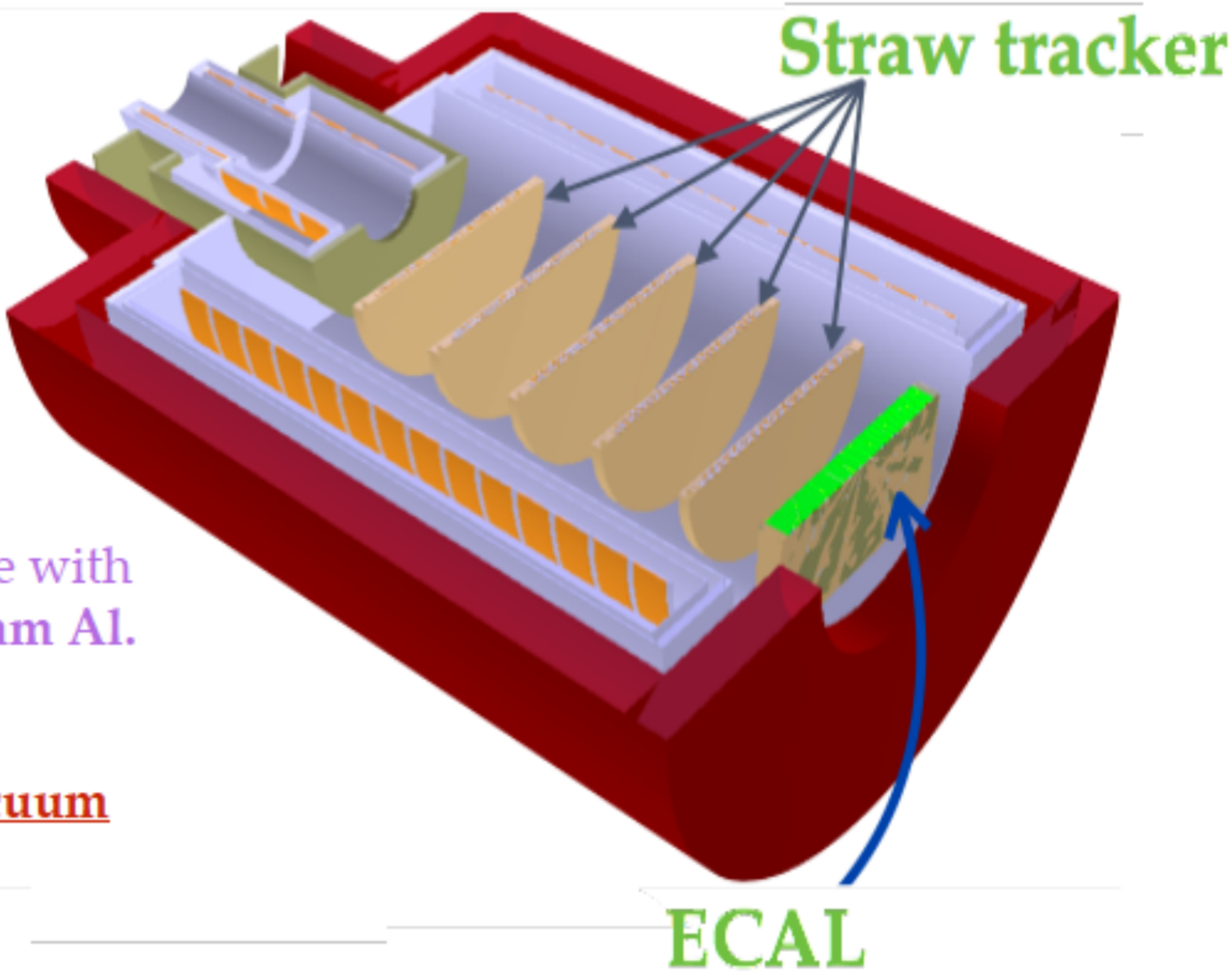
E. Ripiccini, Tau2014, Aachen, September 17, 2014.

The COMET detector

16

Electron Detector (Tracker + Calorimeter)

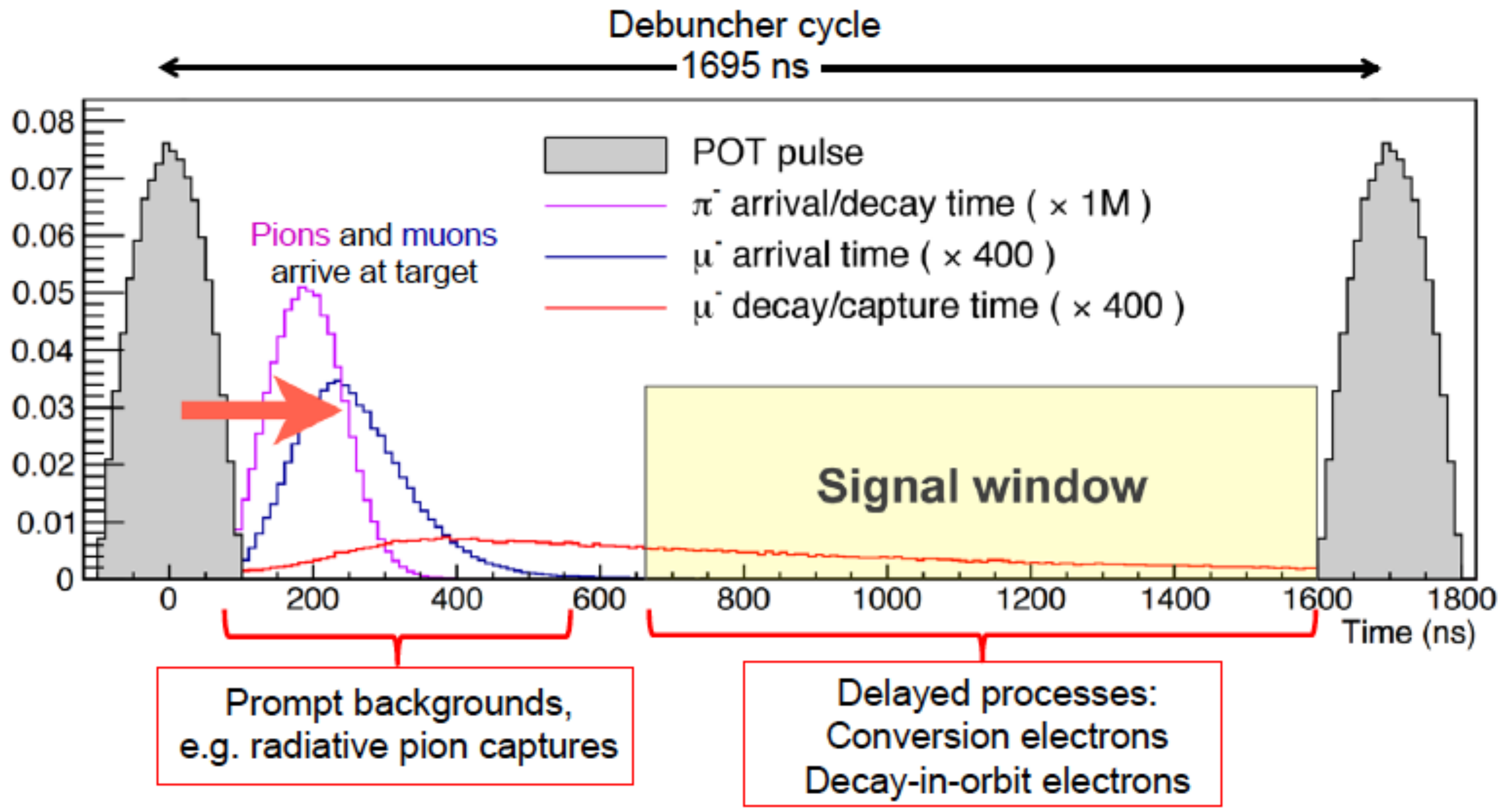
- Rate ≲ 800 kHz
- **Straw-tube tracker to measure electron mom.**
  - 5 stations (super-layers)
  - $\sigma_P < 200$ keV / c
    - 4 planes / super-layer
    - 5 mm diameter straw-tube with **12 μm thick Mylar & 70 nm Al.**
    - **different for phase-I**
  - **should be operational in vacuum**
  - <200μm spacial resolution



- **Crystal calorimeter for trigger (ECAL)**
  - LYSO crystal + APDs

Mu2e Timing Structure

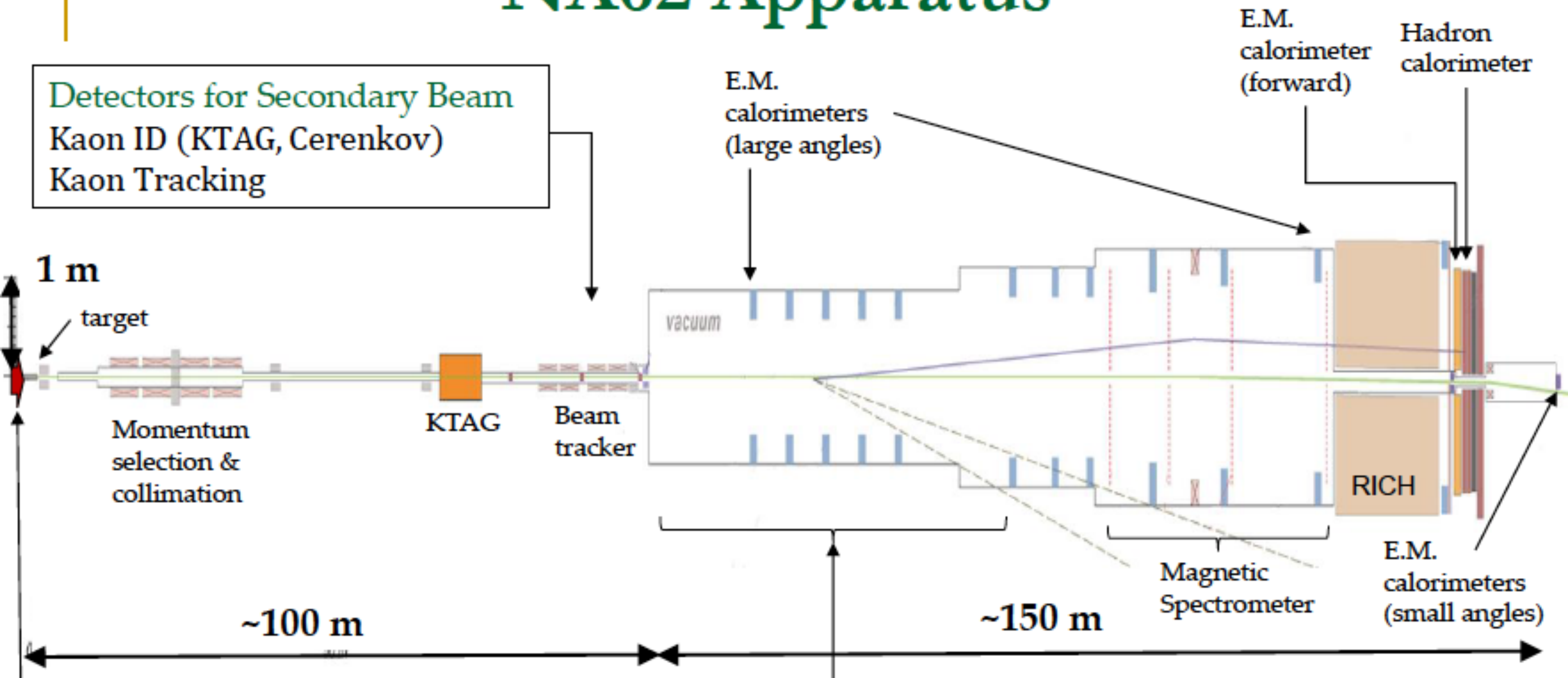
- FNAL accelerator complex and Mu2e timing structure:



- Utilize the pulsed structure of the proton beam and the lifetime of muonic atoms to suppress prompt backgrounds

NA62 Apparatus

Detectors for Secondary Beam
Kaon ID (KTAG, Cerenkov)
Kaon Tracking



SPS proton
400 GeV
10^{12} p/s

Secondary Beam
$p = 75$ GeV/c
$\Delta p/p \sim 1\%$
X,Y Divergence < 100 μrad
$K(6\%), \pi(70\%), p(23\%)$
750 MHz
Beam size: 6.0 × 2.7 cm²

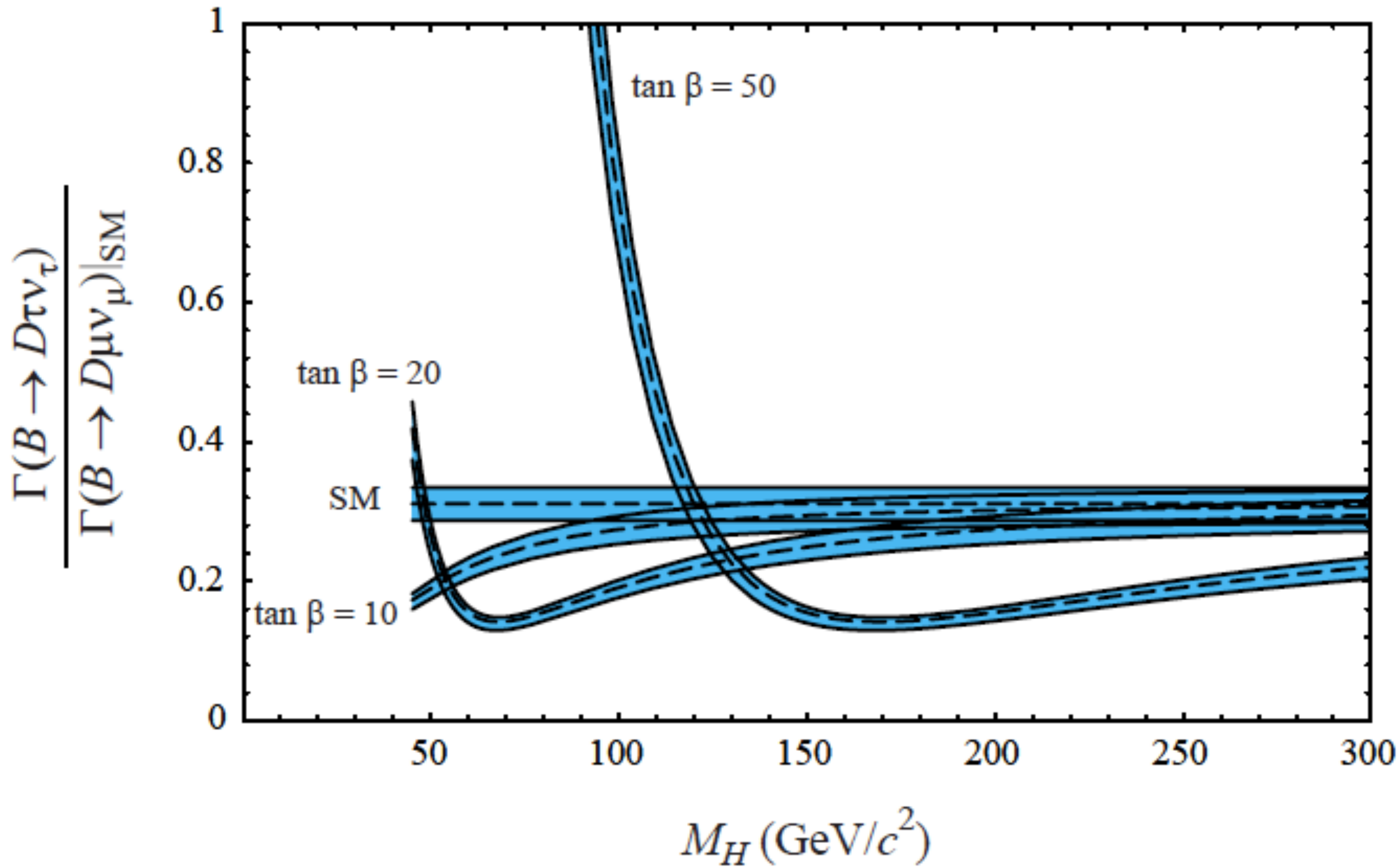
Kaon Decay
~5 MHz
$4.5 \times 10^{12}/year$
60 m length
10^{-6} mbar vacuum

Detectors for decay products
Charged particle tracking
Charged particle Time Stamping
Photon detection
Charged particle ID
Pion and muon identification

Further NA62 K Physics Program

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	5.9×10^{-11} $m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h,\nu_h\to\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

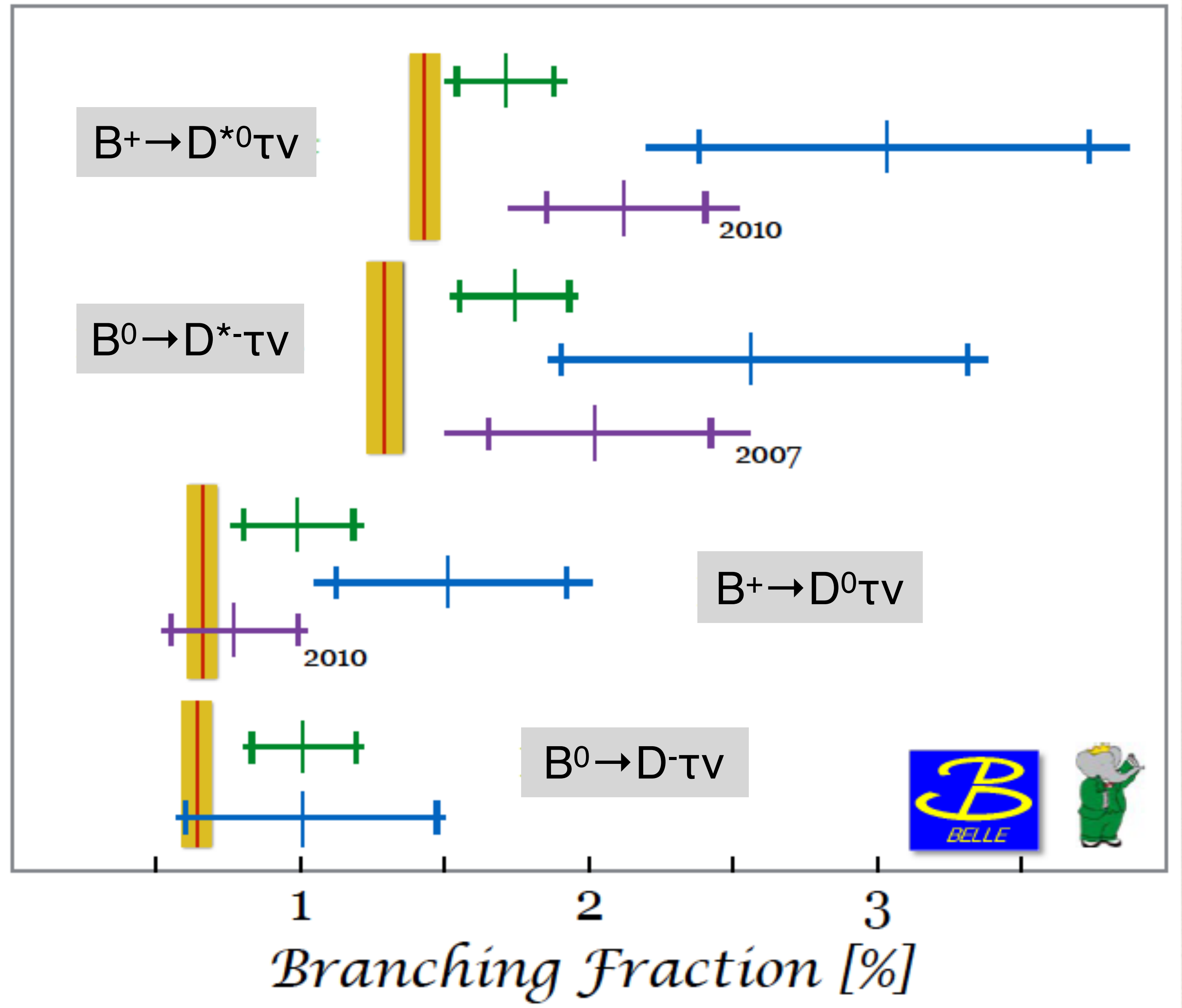
τ, B and D decays: B → D$^{(*)}$τν decays



τ, B and D decays: adding BR($B \to D^{(*)} \tau \nu$) from Belle 2013

$R(D) = 0.430 \pm 0.091$
$R(D^*) = 0.405 \pm 0.047$

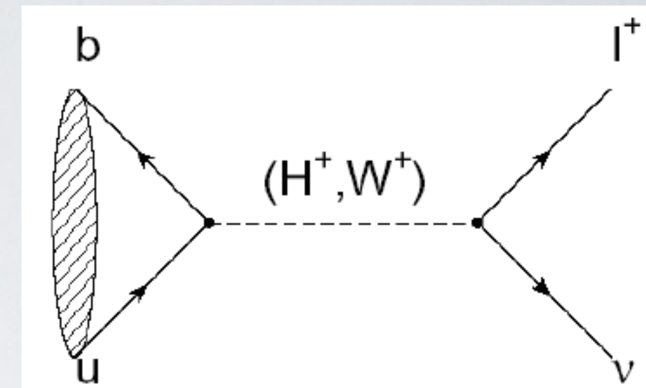
SM deviations:
R(D): 1.4σ
R(D*): 3.0σ
Combined: 3.3σ



Rare B → τν decay

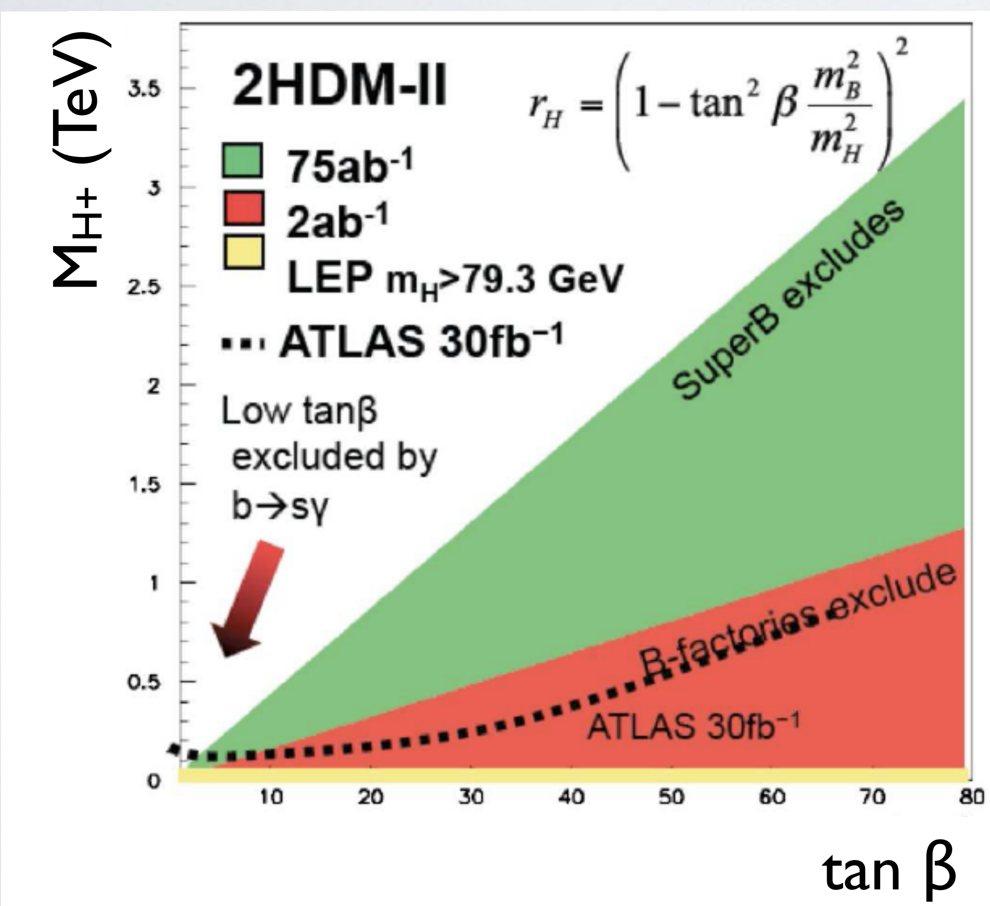
- Current discrepancy between experiment and prediction:

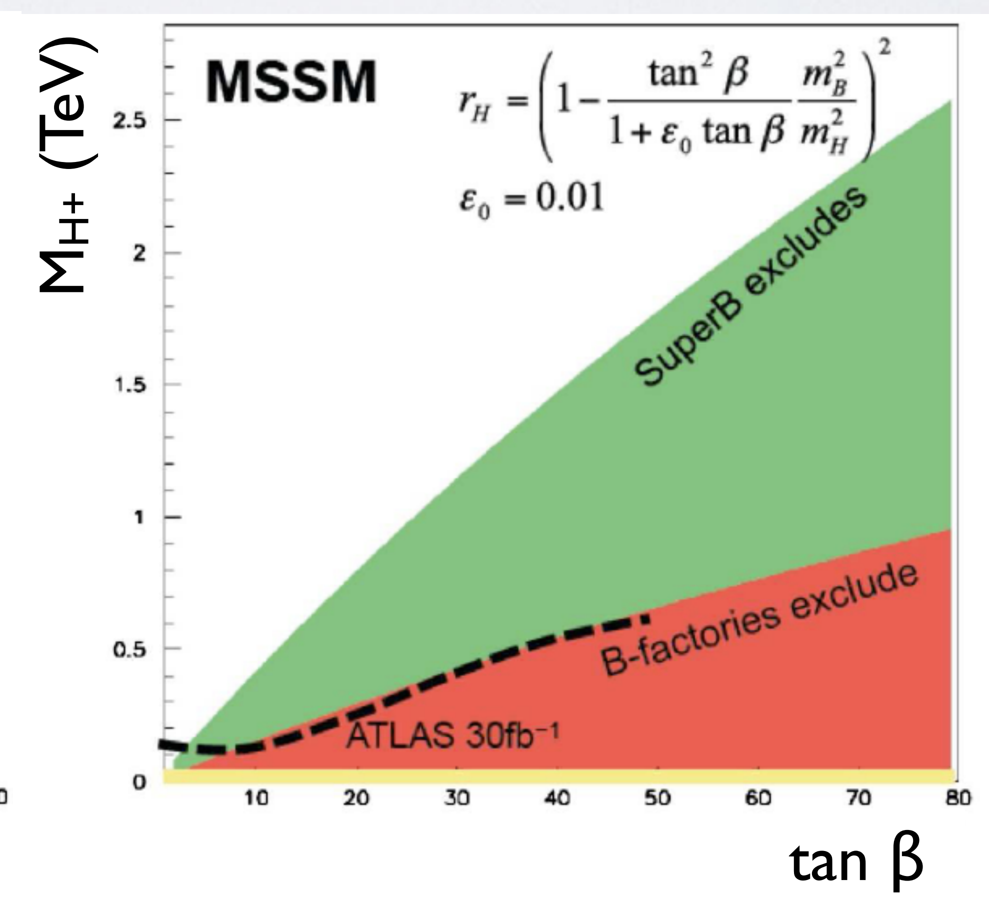
B.R.($B^+ \to \tau^+\nu$) W.A. measurement:	SM prediction through CKM global fit:
$(1.67 \pm 0.30)\times10^{-4}$	$(0.879 \pm 0.084)\times10^{-4}$



but also Belle 2012: $(0.72 \pm 0.29)\times10^{-4}$ (hadronic tag)

$$r_H = \frac{\mathcal{B}_{SM+NP}}{\mathcal{B}_{SM}}$$





~3% precision possible on B.R. in SM with Super B (currently 20%). Also $B \to \mu^+\nu$.

Les triangles d'unitarité

- Amélioration de la précision globale sur CKM de ~10 % → ~1 %:
  - Recherche d'une nouvelle source de violation de CP.
  - Limitation principale de nombreuses recherches de NP dans le secteur des saveurs : cf. $K \to \pi\nu\bar{\nu}$, $\sin 2\beta$ vs. ε_K UT fits, …
  - Identification d'une contribution de NP : comparer contraintes des processus à l'ordre de l'arbre et boucles.

$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0 \qquad \lambda \; \lambda \; \lambda^5$$

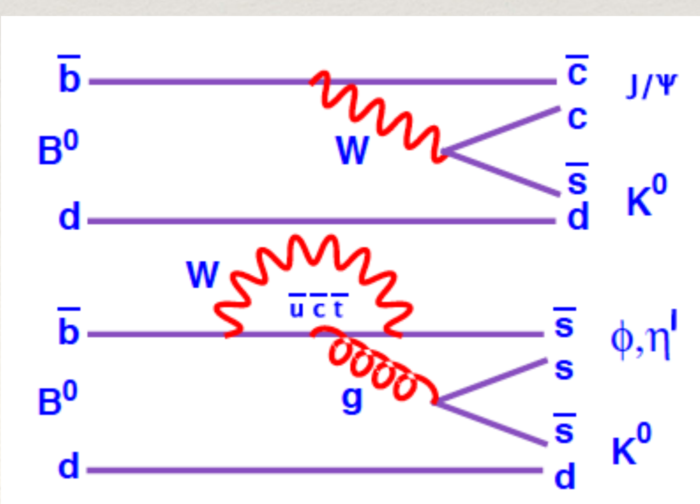
$$\boxed{V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0} \qquad \lambda^3 \; \lambda^3 \; \lambda^3$$

$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0 \qquad \lambda^4 \; \lambda^2 \; \lambda^2$$

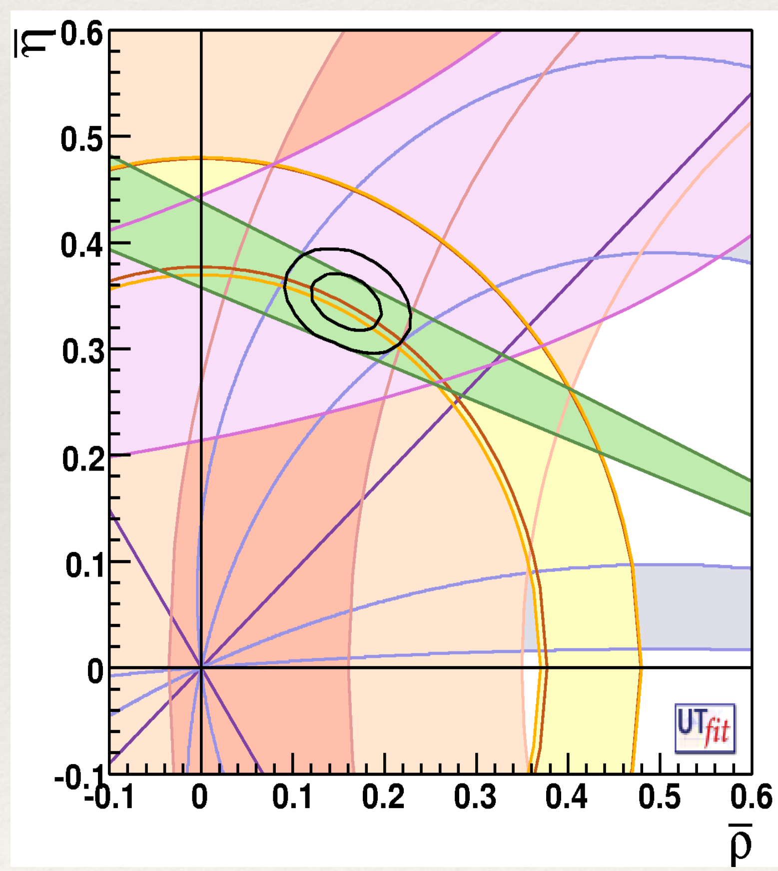
$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 \qquad \lambda^3 \; \lambda^3 \; \lambda^3$$

$$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0 \qquad \lambda^4 \; \lambda^2 \; \lambda^2$$

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \qquad \lambda \; \lambda \; \lambda^5$$



aujourd'hui (1 ab^{-1})

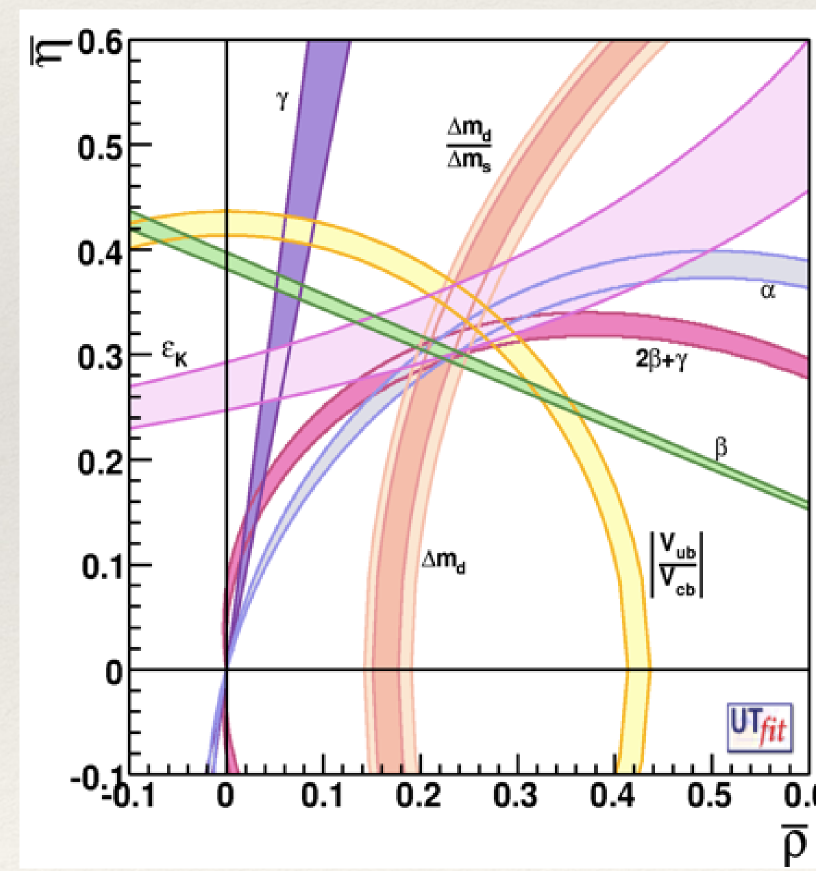


$\bar{\rho} = 0.163 \pm 0.028$

$\bar{\eta} = 0.344 \pm 0.016$

avec 50 ab^{-1}

+ améliorations de Lattice QCD



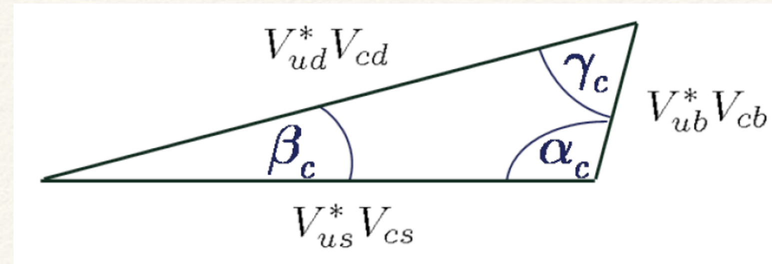
$\delta\bar{\rho}/\bar{\rho} \sim 3.4$ %

$\delta\bar{\eta}/\bar{\eta} \sim 1.5$ %

Violation de CP dans le charme

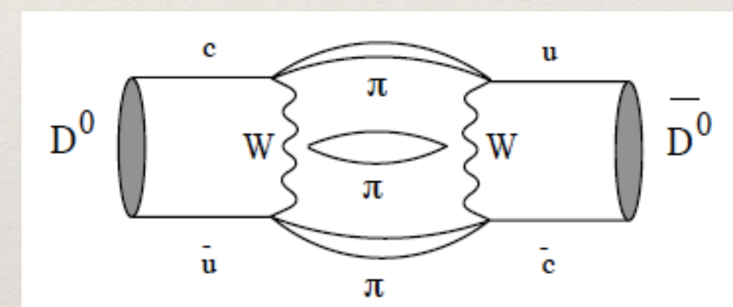
- Mesure du UT *cu* :

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$$



prediction du fit CKM :
$\beta_c = (0.0350 \pm 0.0001)°$

- Mesure importante :
  - Excès observé de CPV directe dans les désintégrations du D^0 par LHCb en 2011
    (aussi par CDF et Belle, résultats non concluants de LHCb en 2013)
  - Asymétrie matière/anti-matière : phase supplémentaire de CPV nécessaire ;
  - Seul système oscillant testant le couplage NP-quarks down.



- Prédiction théorique difficile : contributions à longues distances.

- Belle II vs. LHCb :
  - LHCb : statistique supérieure mais bruit de fond plus important, efficacité de trigger moins élevée, critères de sélection et de trigger dépendant du temps.
  - Belle II : résolution temporelle moins bonne (collisions avec faible boost).
    Analyse particulièrement sensible à la diffusion multiple.
    Mesure nécessitant une bonne reconstruction des faibles impulsions et des vertex de désintégration des D^0.

Complementarity between Belle II and LHCb

- no results (red)
- moderate precision (yellow)
- precise (blue)
- very precise (green)

	observable	current ~ 1 ab	LHCb 2017 ~ 5 fb	Belle II 2022 50 ab	LHCb upgrade 50 fb	theory
τ decays	τ → μγ	moderate precision	moderate precision	very precise	moderate precision	very precise
	τ → eγ	moderate precision	moderate precision	very precise	moderate precision	very precise
B^0, B^+ decays	B → τν, μν	moderate precision	no results	precise	no results	precise
	B	no results	no results	very precise	no results	very precise
	S in B	moderate precision	no results	very precise	no results	moderate precision
	S (other penguins)	moderate precision	moderate precision	very precise	precise	moderate precision
	A_{CP}	precise	moderate precision	very precise	moderate precision	very precise
	BR(B	precise	moderate precision	very precise	moderate precision	moderate precision
	BR(B	moderate precision	no results	very precise	no results	very precise
	BR(B	moderate precision	precise	very precise: K^* e e	very precise: K^* μ μ	moderate precision
B_s^0 decays	B_s	no results	precise	no results	very precise	very precise
	β_s	no results	precise	no results	very precise	very precise
	B_s	no results	no results	precise	no results	very precise
	a_{sl}	no results	precise	very precise	very precise	very precise
Charm	mixing param.	moderate precision	precise	very precise	very precise	very precise
	CP violation	no results	precise	very precise	very precise	very precise
Electroweak	sin	no results	no results	very precise	no results	very precise
	sin	very precise	precise	no results	very precise	moderate precision
CKM	α (ϕ	precise	precise	very precise	precise	moderate precision
	β (ϕ	precise	precise	very precise	very precise	very precise
	B_d	moderate precision	no results	very precise	no results	very precise
	B_s	no results	moderate precision	no results	precise	very precise
	γ (ϕ	moderate precision	precise	very precise	very precise	very precise
	lVubl inclusive	precise	moderate precision	very precise	precise	precise
	lVubl exclusive	precise	moderate precision	very precise	precise	precise
	lVcbl inclusive	precise	moderate precision	very precise	precise	precise
	lVcbl exclusive	precise	moderate precision	very precise	precise	precise