

# Journée de Physique de la SFP. Quelle stratégie pour demain ??

## La physique des saveurs

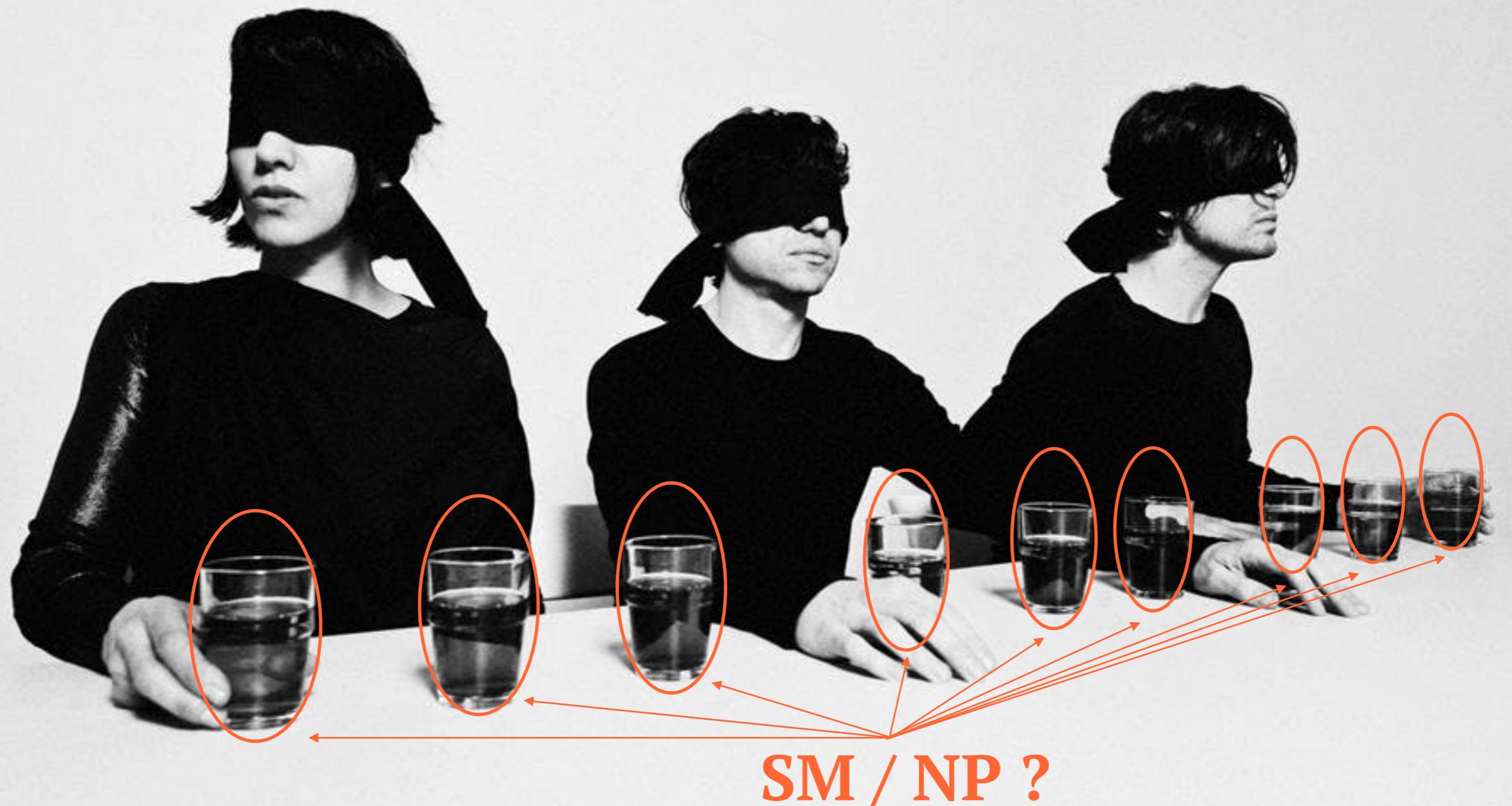


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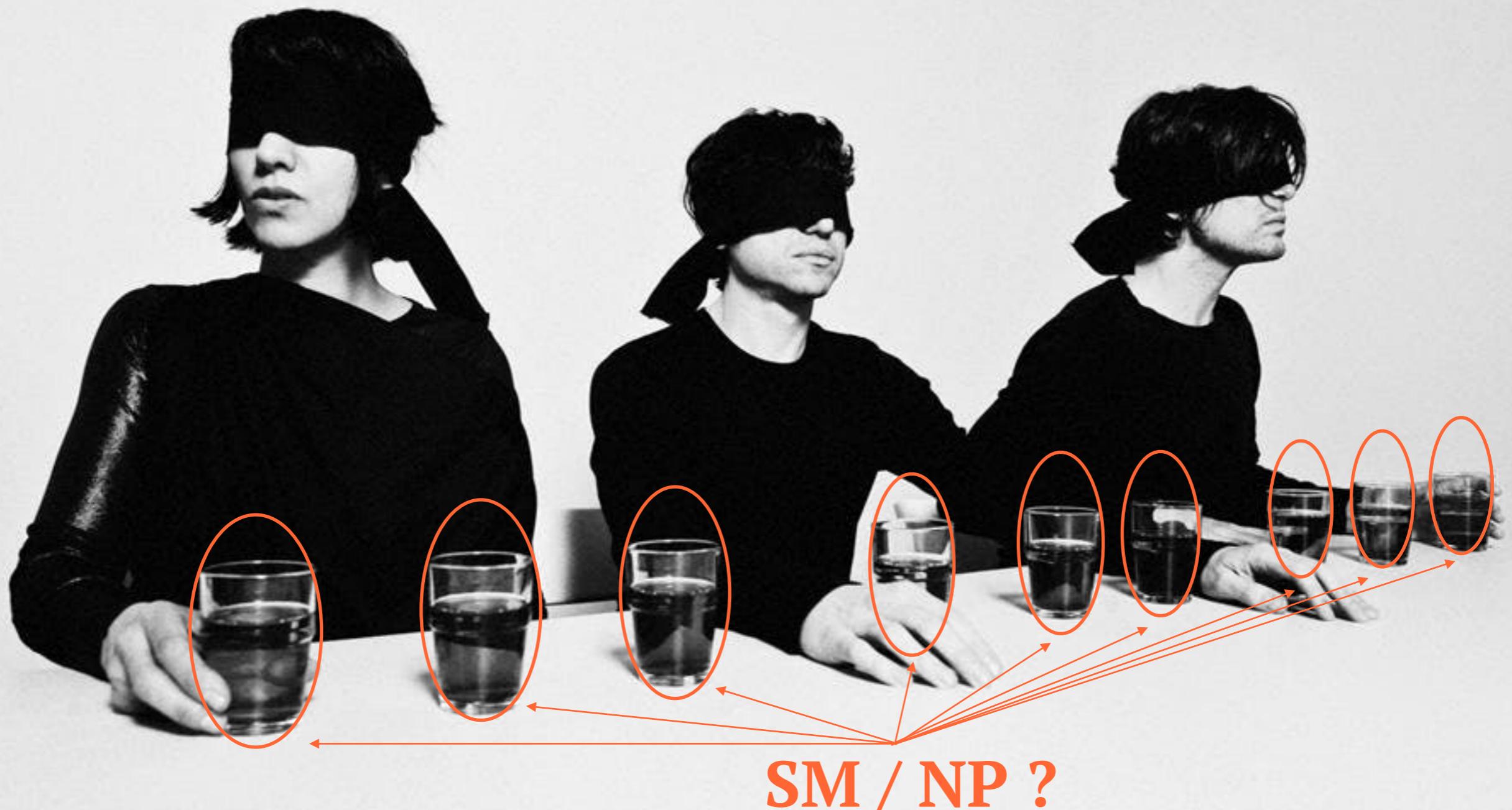
# Journée de Physique de la SFP. Quelle stratégie pour demain ??

## La physique des saveurs



# Journée de Physique de la SFP. Quelle stratégie pour demain ??

## La physique des saveurs

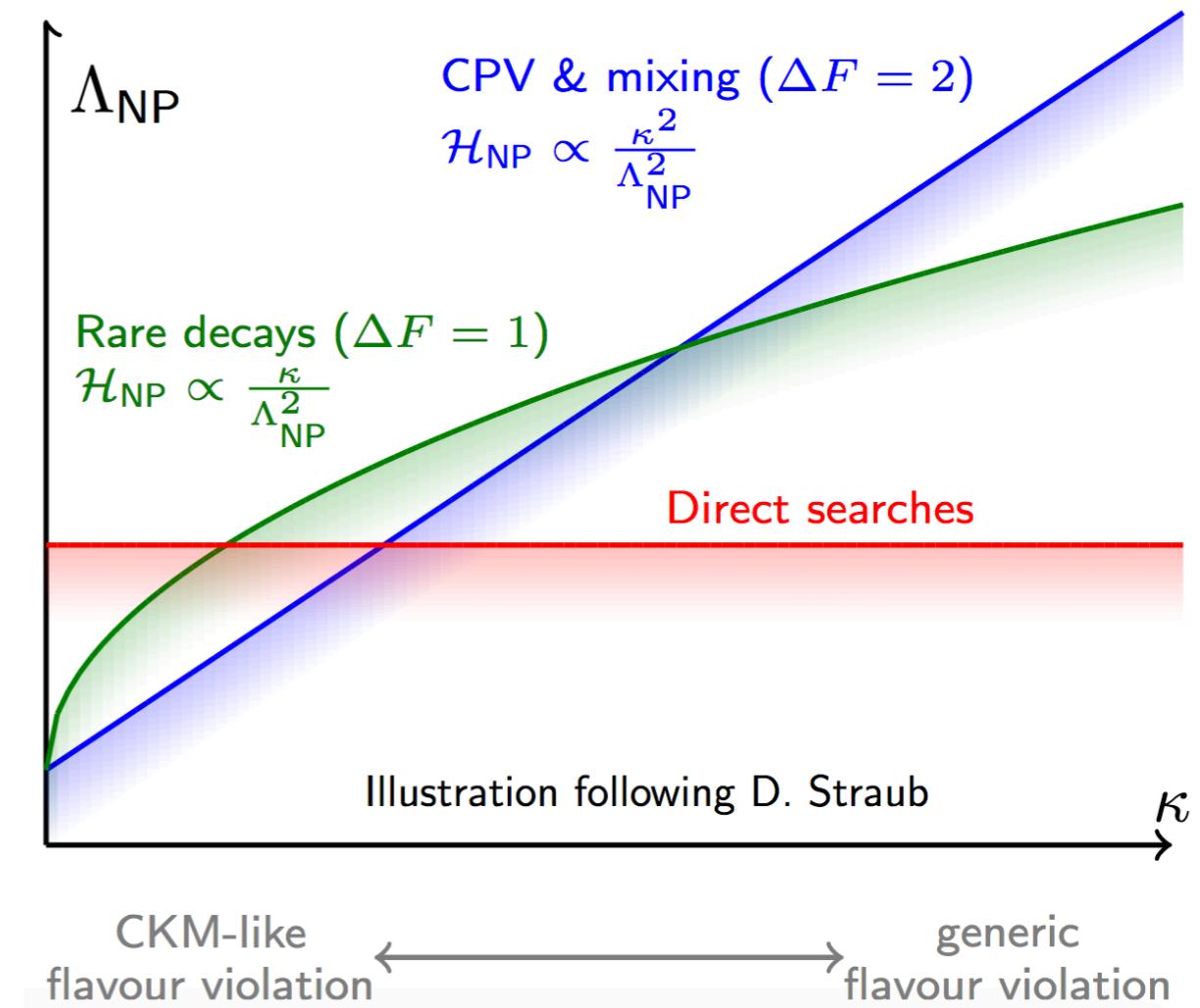
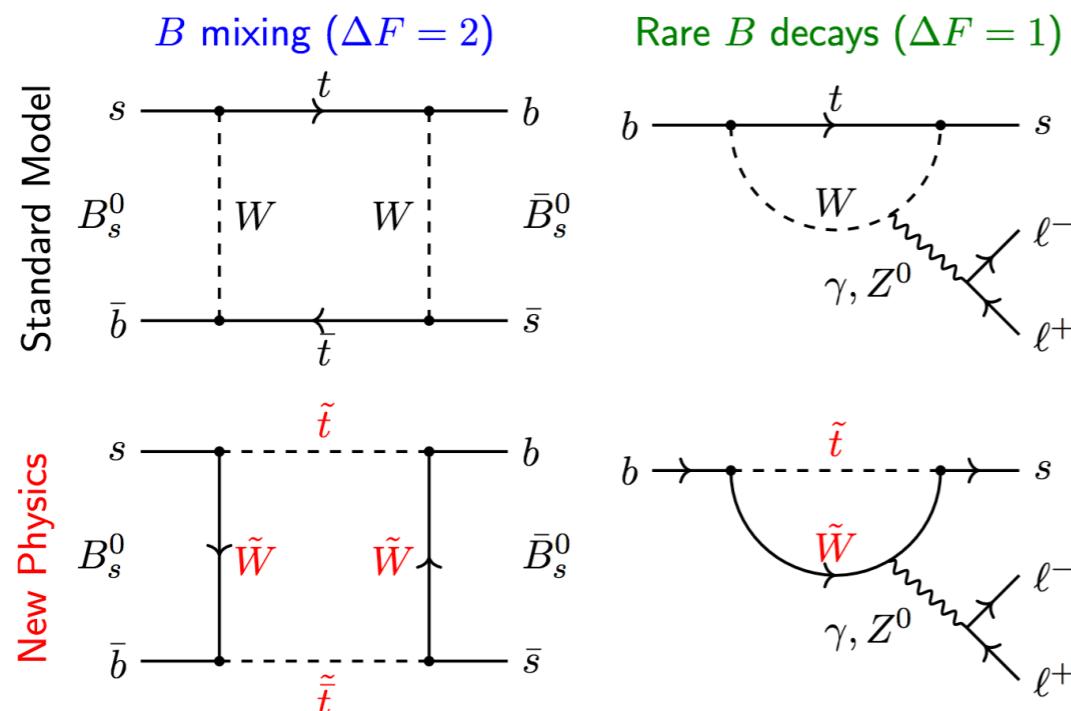


**Need to measure many observables using complementary detectors!**

# Bounds on New Flavour Physics

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\kappa_n}{\Lambda_{\text{NP}}^2} \mathcal{O}_n$$

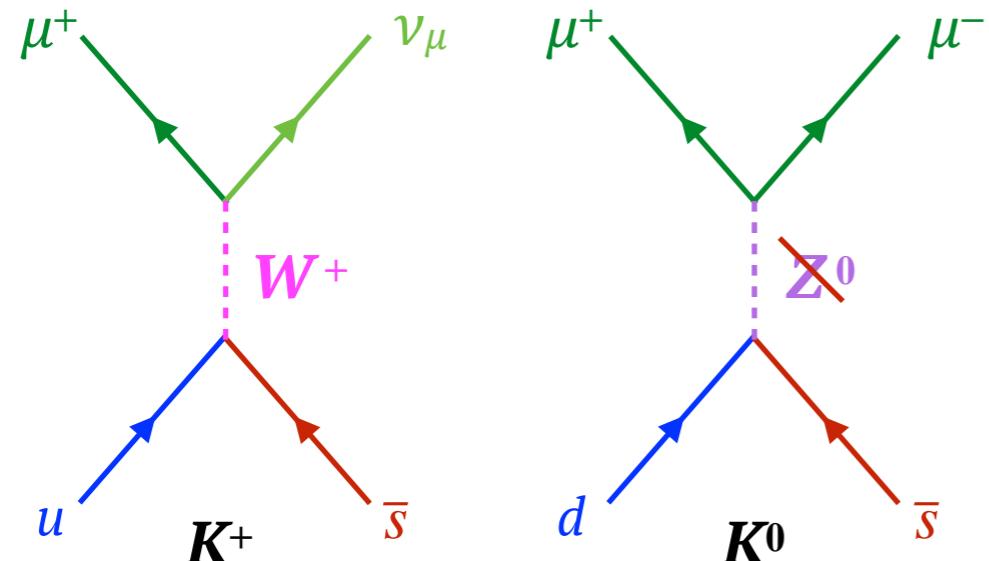
- Virtual production of new particles:** probe very high energy scale, beyond the energy available in the accelerator



- Generic flavour structure [ $\kappa \sim \mathcal{O}(1)$ ] ruled out at the TeV scale**
- $\Lambda_{\text{NP}} \sim 1$  TeV requires  $\kappa$  to inherit the strong SM suppressions (GIM)**

# Back to the future

- Historically, **indirect observations** of “new physics” has often been the portal to infer properties of heavy particles before experiments with sufficient energy to produce them.
  - Kaon semileptonic branching fractions: 1970

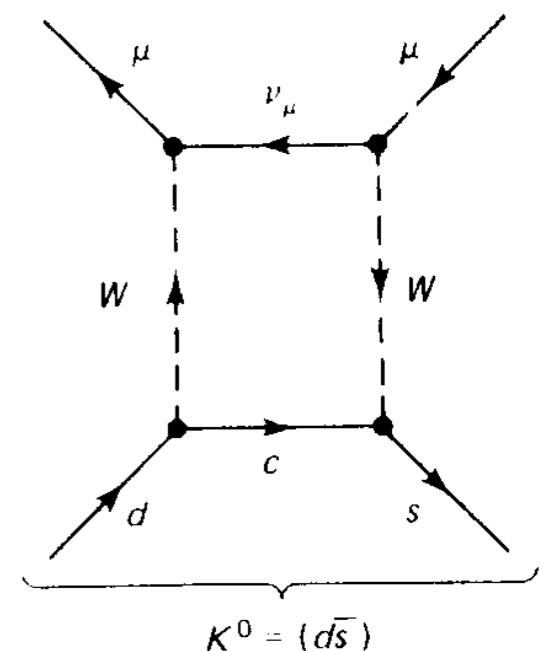


$$\frac{\mathcal{B}(K^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(K^+ \rightarrow \mu^+ \nu_\mu)} = \frac{7 \times 10^{-9}}{0.64} \simeq 10^{-8}$$

## ► Solution proposed by Glashow, Iliopoulos, Maiani (GIM):

- No flavour changing neutral current (FCNC)
- FCNC are suppressed by loop diagrams
- **charm quark prediction**

→ **Discovery of the  $J/\psi$  at SLAC and Brookhaven in 1974**



# Back to the future

- Observation of  $CP$  violation in kaons: 1964

In 1973 Kobayashi and Maskawa proposed an explanation based on the existence of at least 3 generations of quarks

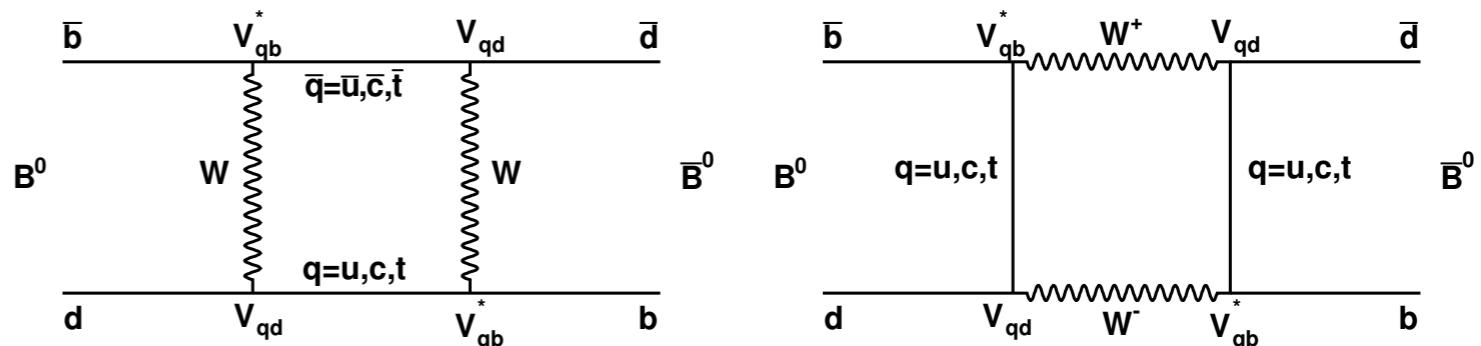
→ **discovery of the Upsilon at Fermilab in 1977**

- $B$  meson mixing: 1987

In 1987, the Argus experiment measured:

$$\Delta m_B \sim 0.00002 \times \left( \frac{m_t}{\text{GeV}/c^2} \right)^2 \text{ ps}^{-1}$$
$$\sim 0.5 \text{ ps}^{-1}$$

→  $m_t > 50 \text{ GeV}/c^2$

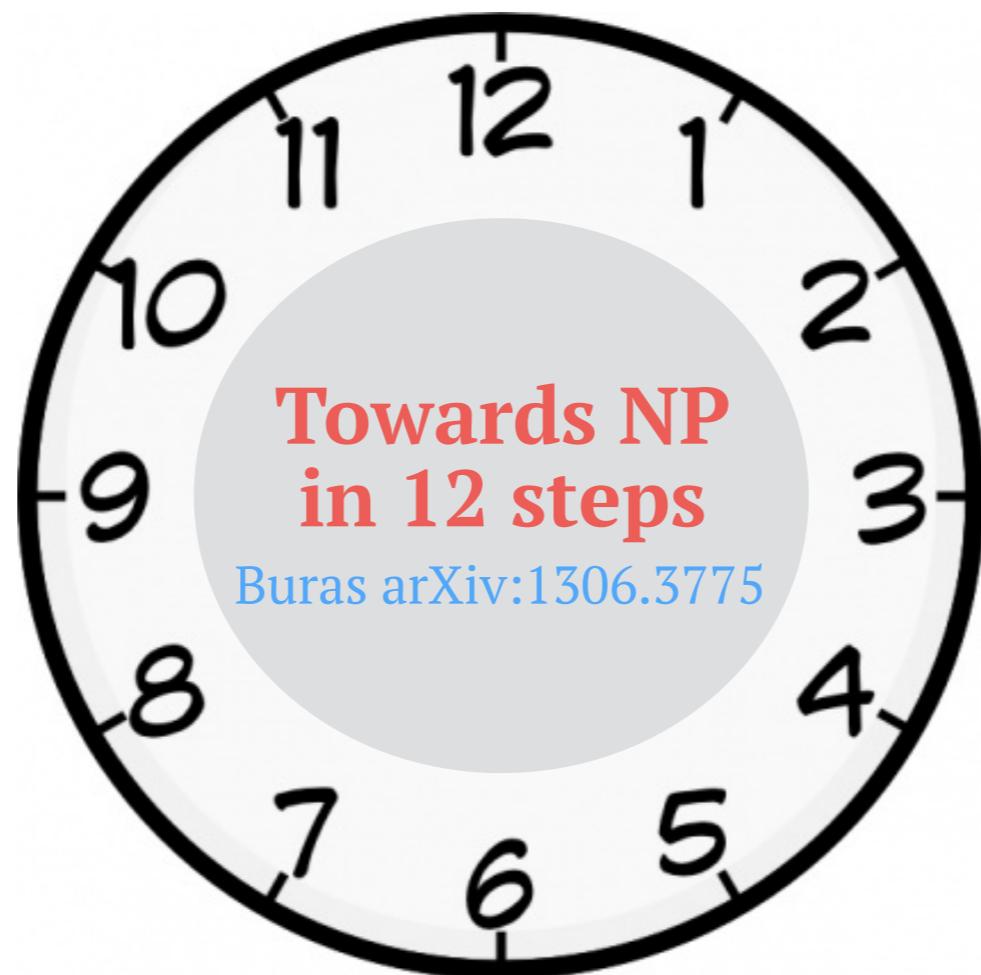


First hint that the yet unseen top quark was much heavier than expected!

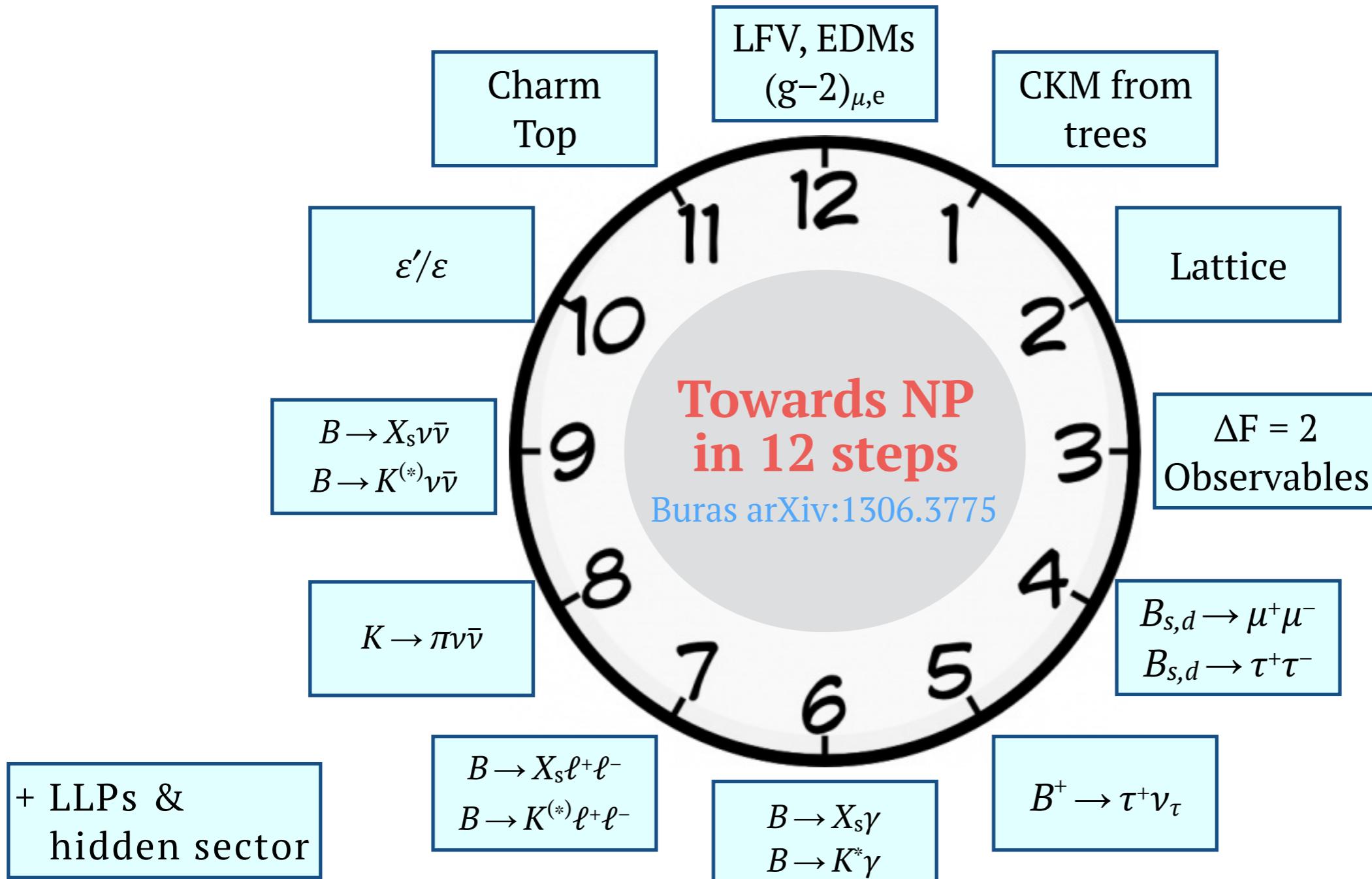
**Discovered in 1995 at the Tevatron:**

$$m_t = 173.21 \pm 0.51 \pm 0.71 \text{ GeV}/c^2$$

# Landscape & objectives

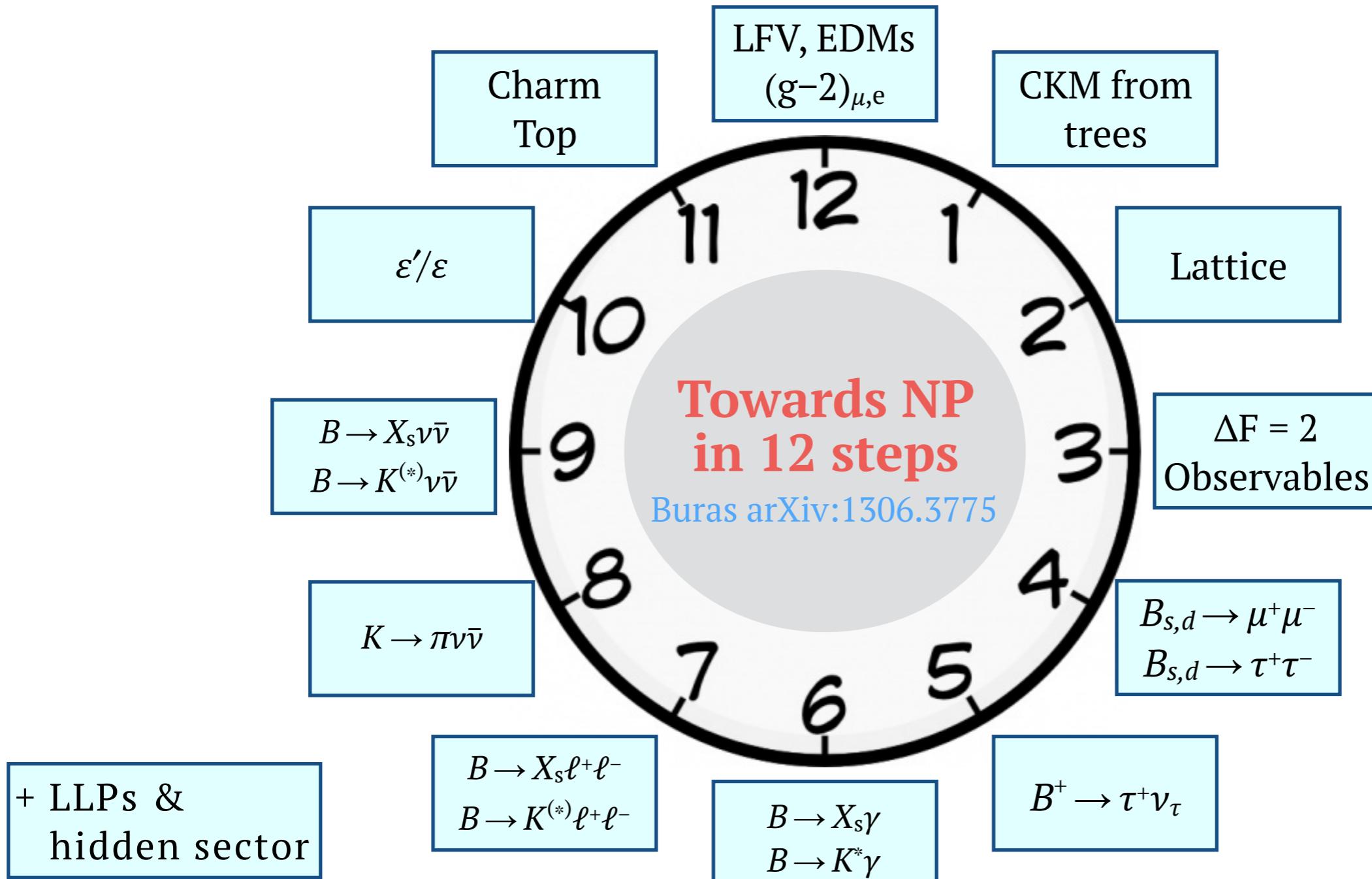


# Landscape & objectives



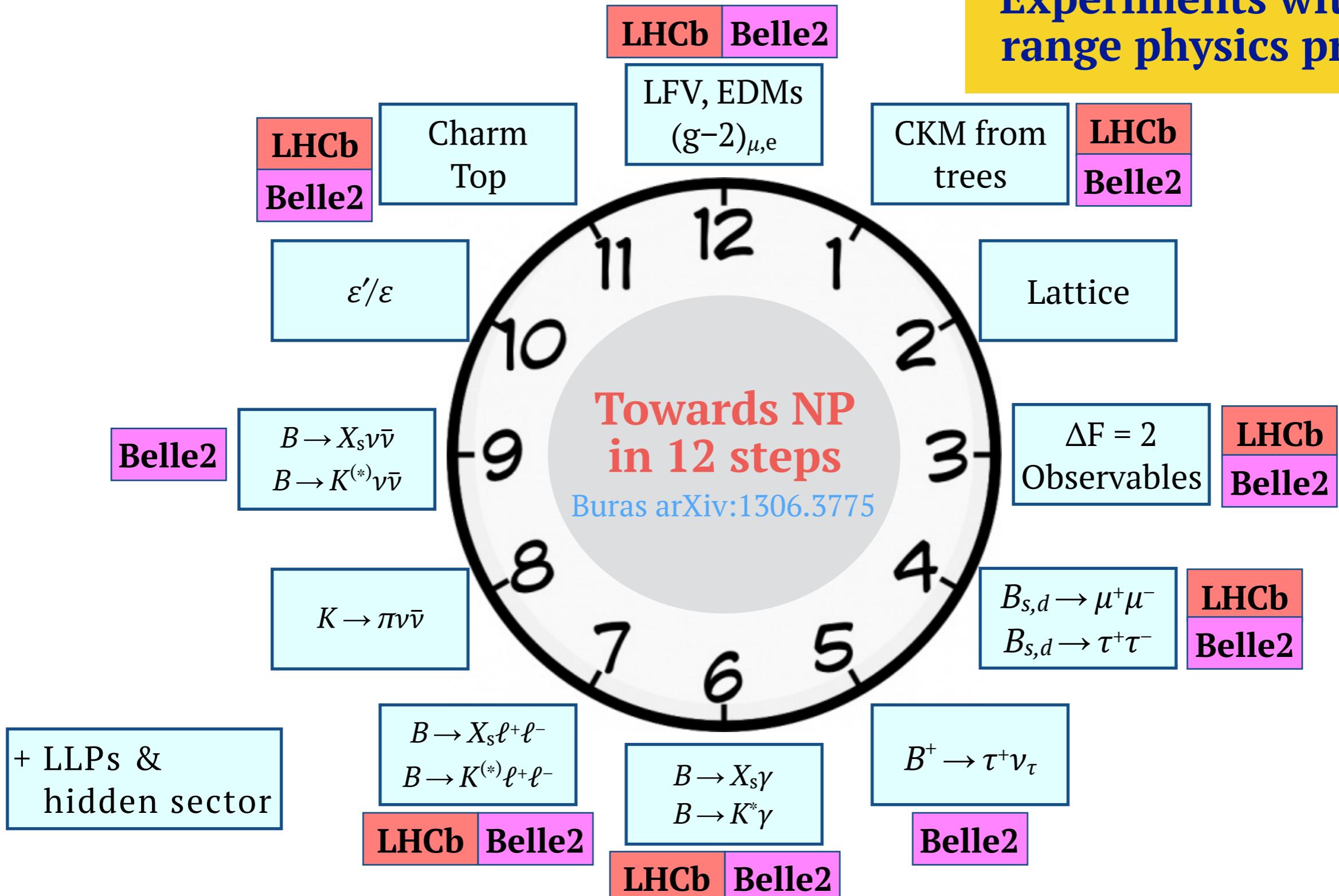
# Landscape & objectives

Correlations between observables is extremely powerful to constrain NP models!



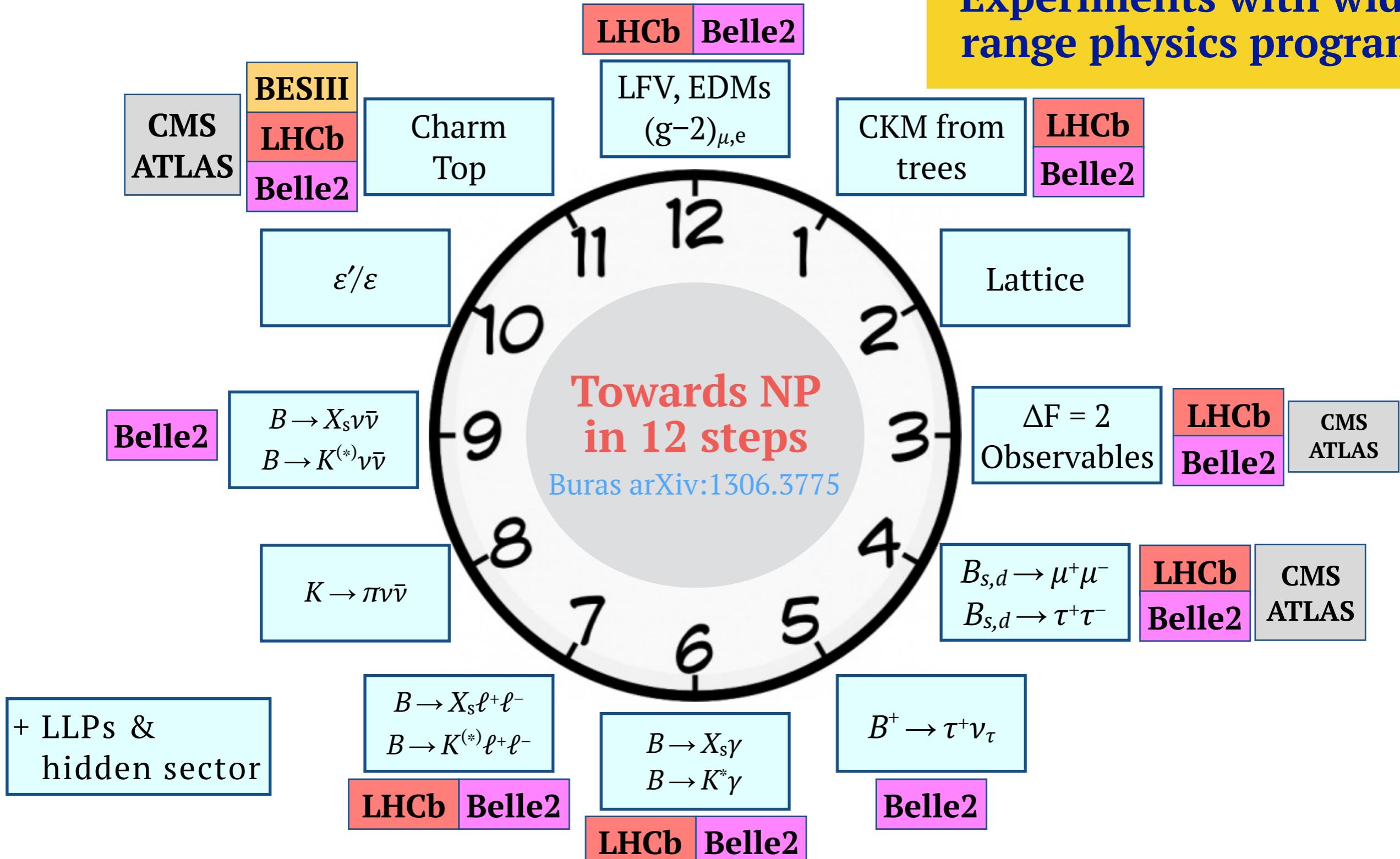
# Landscape & objectives

Experiments with wide range physics program



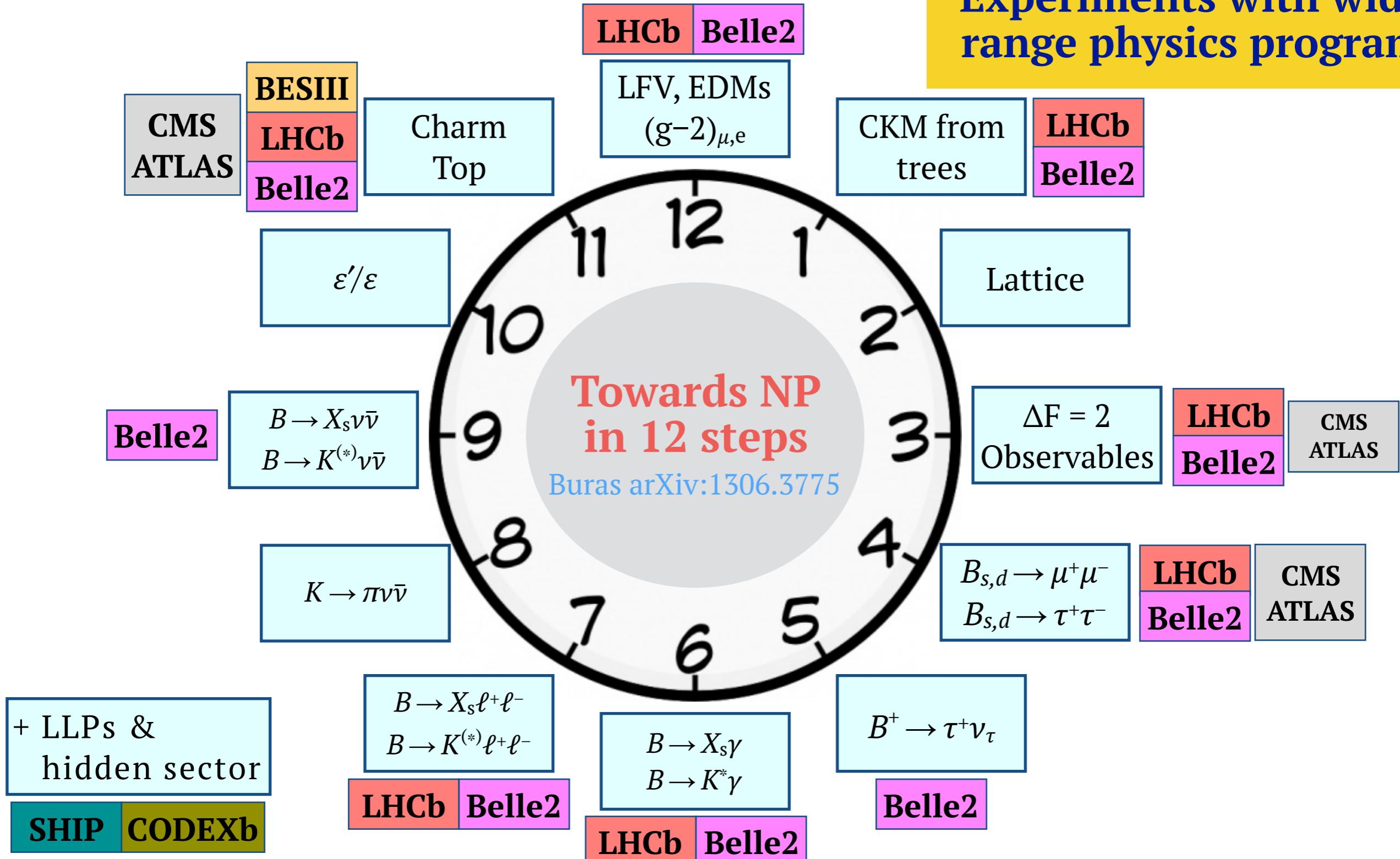
# Landscape & objectives

Experiments with wide range physics program

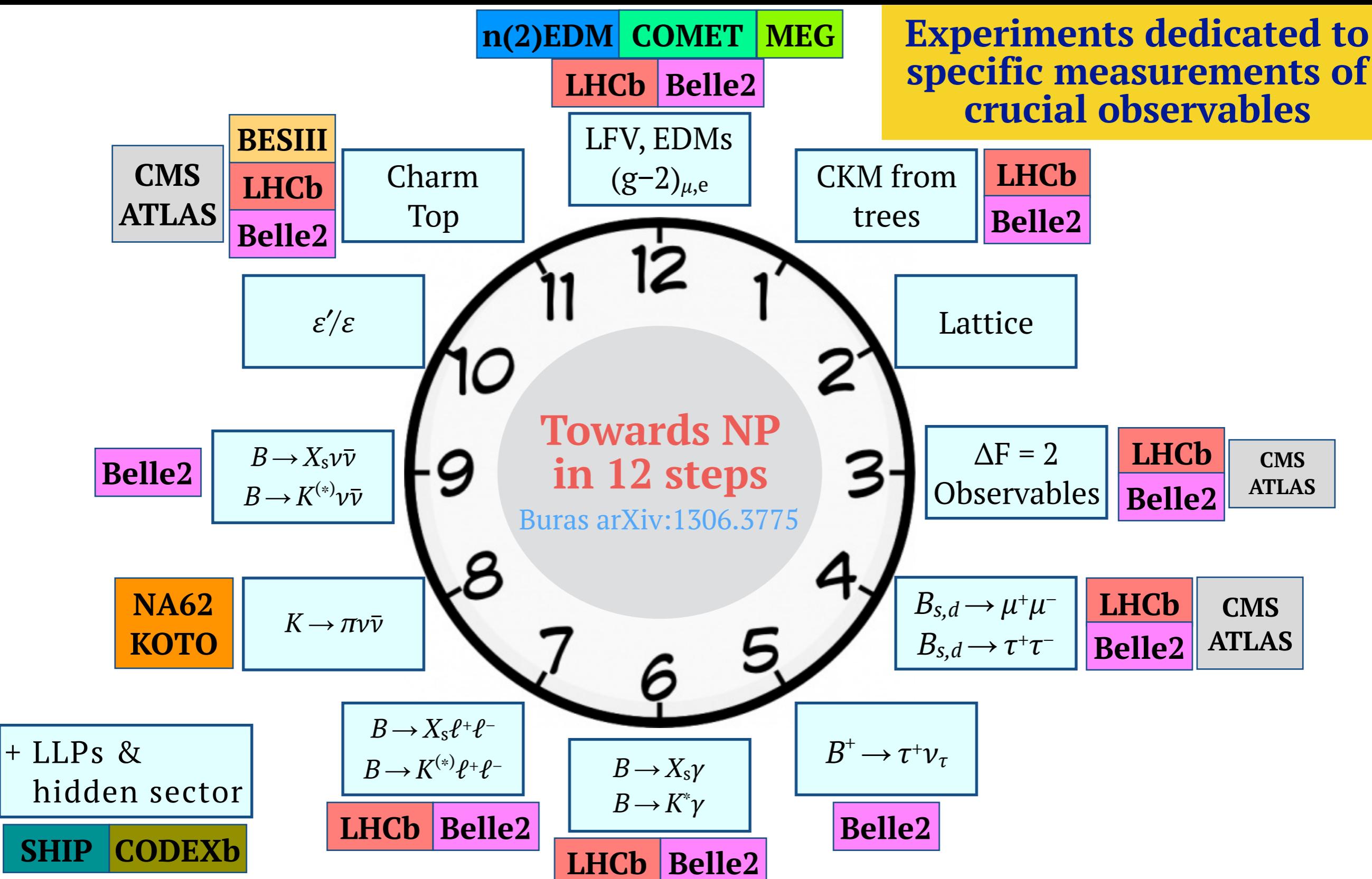


# Landscape & objectives

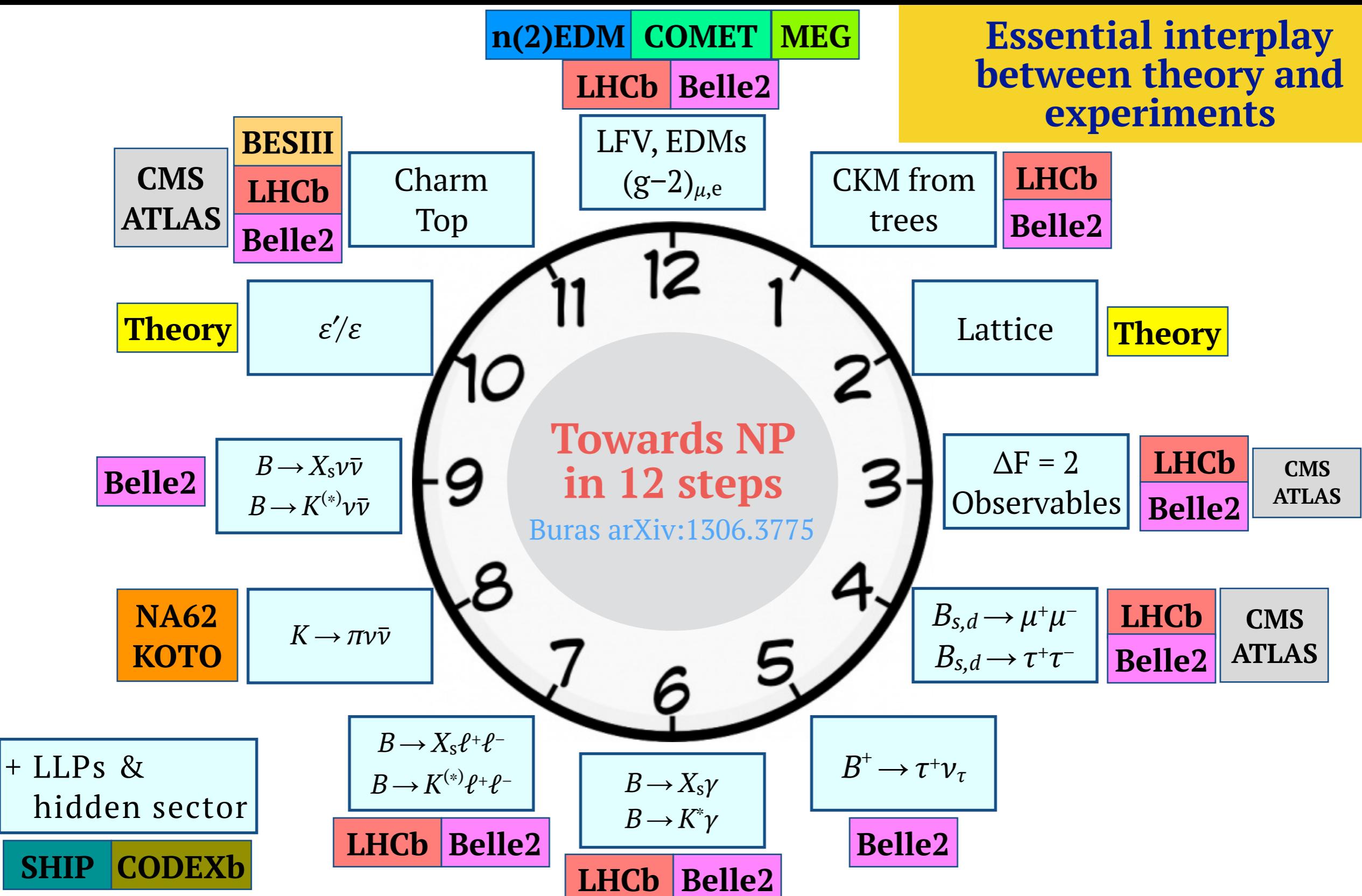
Experiments with wide range physics program



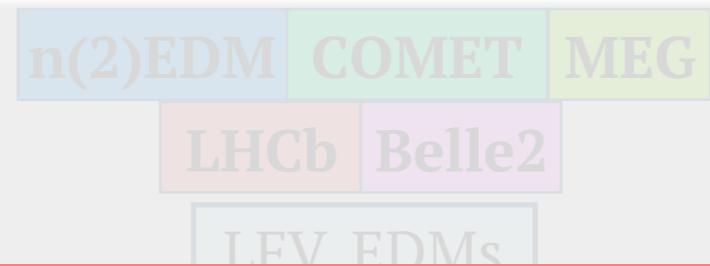
# Landscape & objectives



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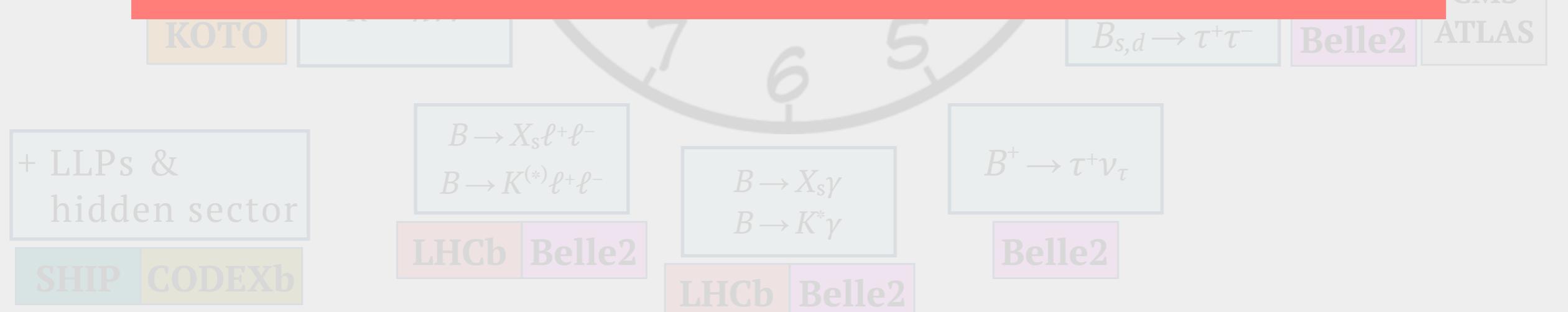


# Landscape & objectives



## DISCLAIMER:

Due to time constraints,  
will concentrate on a (biased)  
selection of flavour physics topics



## GDR-InF input for the European Strategy for Particle Physics

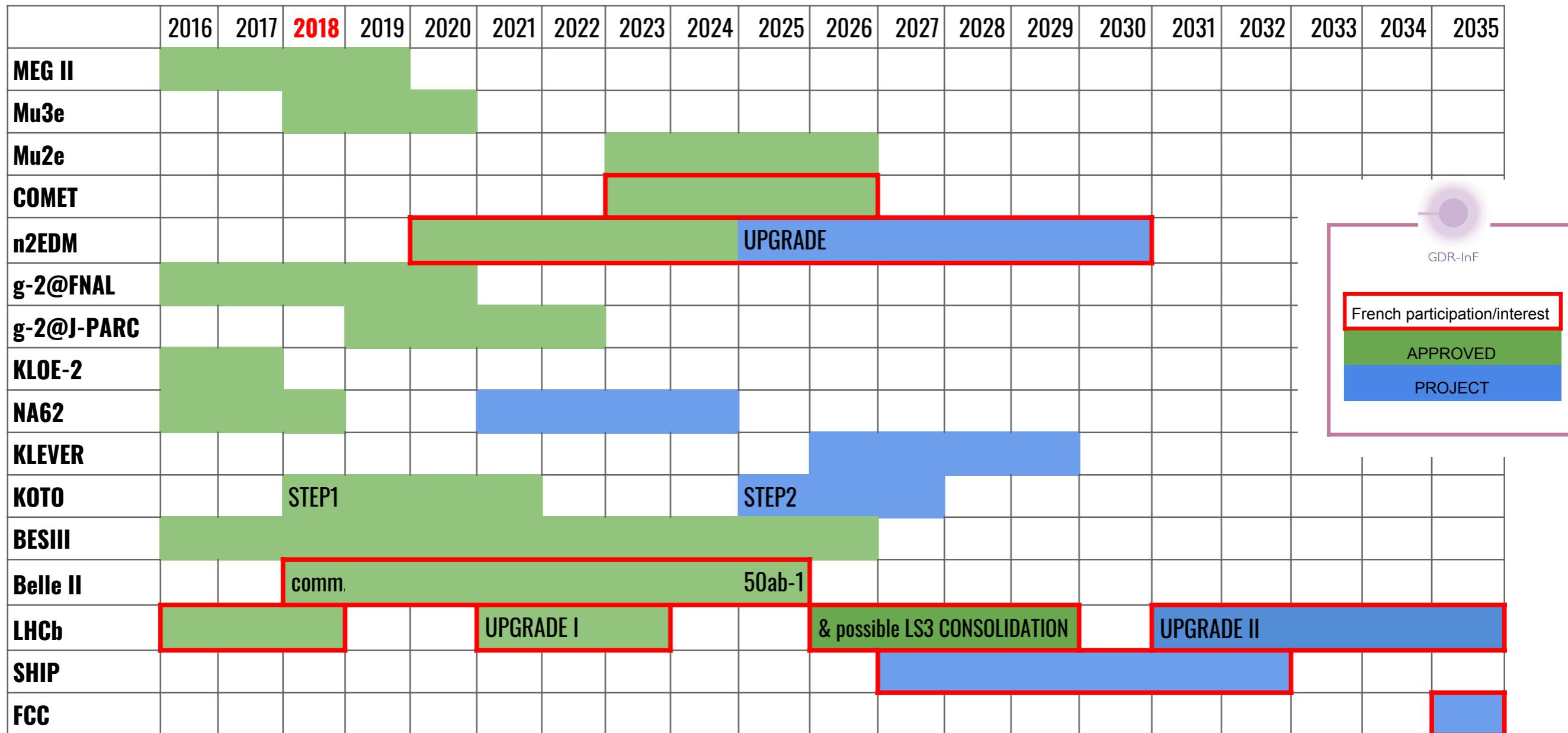
The GDR Intensity Frontier  
31-08-2018

Research at the intensity frontier allows the detection and interpretation of signs of new physics using large datasets of some of the rarest processes in nature. If new particles are found by direct searches, then indirect tests are needed to study the new physics structure and couplings. If on the other hand no direct evidence for new physics is found in collisions, which has been the case so far at the LHC, higher scales and/or smaller couplings can be probed by experiments at the intensity frontier. Lately the case for the intensity frontier has further been strengthened by several anomalies observed in measurements of rare B decays, the anomalous magnetic moment of the muon and the proton radius.

The GDR-InF, gathering the French community working on the intensity frontier, supports an experimental strategy based on two complementary pillars: large facilities with a wide physics program (LHC, SuperKEKB, HL-LHC, beam dump experiments at SPS, ILC and FCC) and experiments dedicated to specific measurements of crucial observables (EDM, g-2, LFV experiments). This document provides an overview of the experiments in which the GDR-InF physicists are involved, and that we wish to see endorsed by the European Strategy for Particle Physics (ESPP). Members of the GDR-InF currently produce high level physics results with running experiments and perform detector developments to prepare the future ones. Experiments with no involvement in the GDR-InF experimental community, but which are recognized as crucial for the field are also mentioned. Finally, the GDR-InF underlines the interplay between theory and experiments to be supported as part of the strategy.

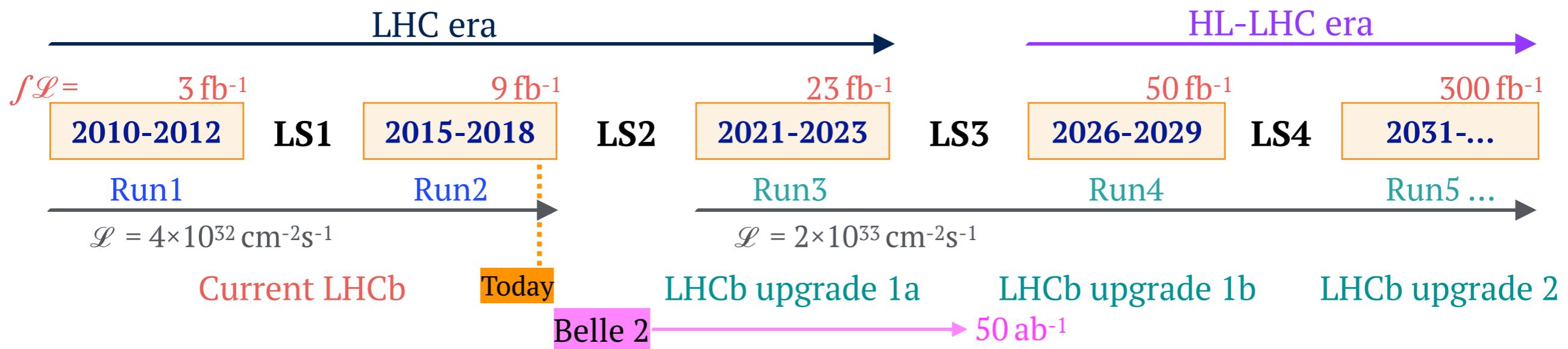
[full document]

# Experiments & timescales



# Wide physics program experiments

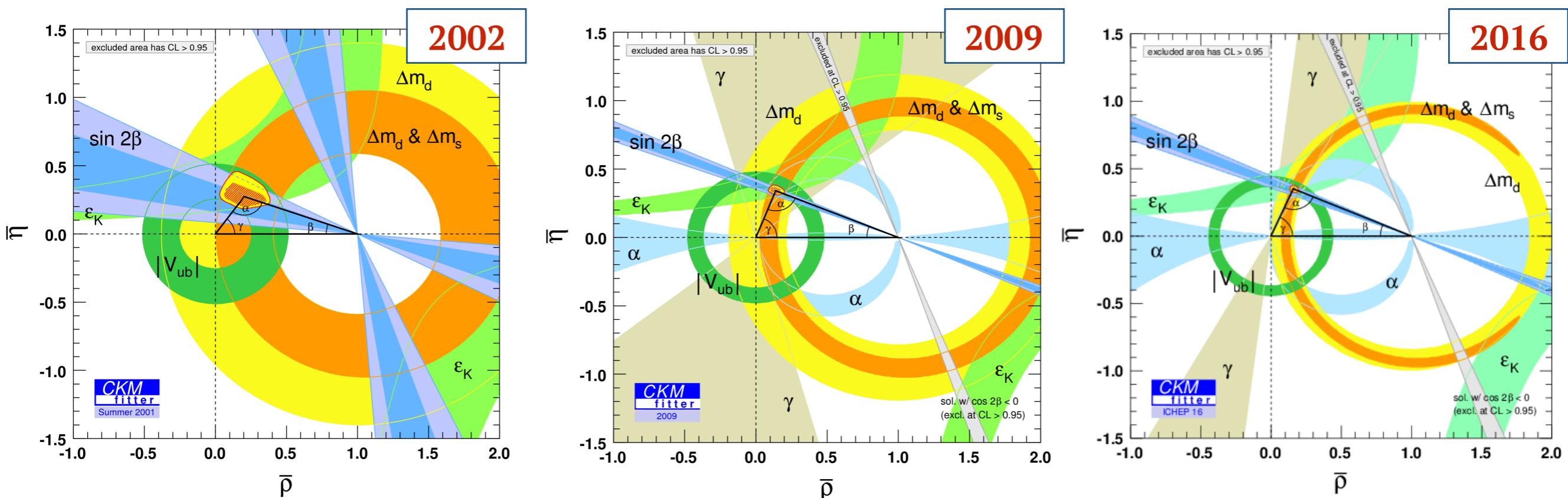
- LHCb (+Upgrades) and Belle2 major running experiments in the next decade:



- ▶ **Belle II** will dominate measurements of final states with **missing energy, multiple photons and of inclusive decays**
- ▶ **LHCb Upgrades** will dominate measurements with **charged particles** in final states with the possibility to access **all  $b$ -hadron decays**  
→ **important complementarity!**

# CKM precision measurements

- Huge success in the last 20 years from CLEO, LEP, Tevatron,  $B$ -factories & LHCb drawing a consistant SM-like CKM picture:

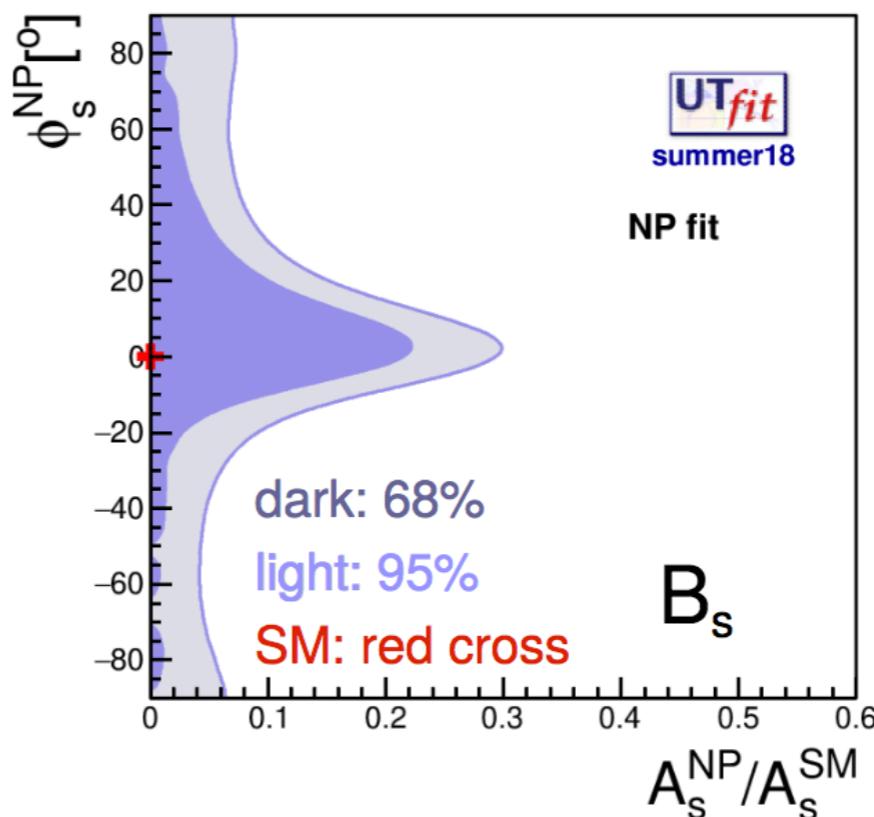
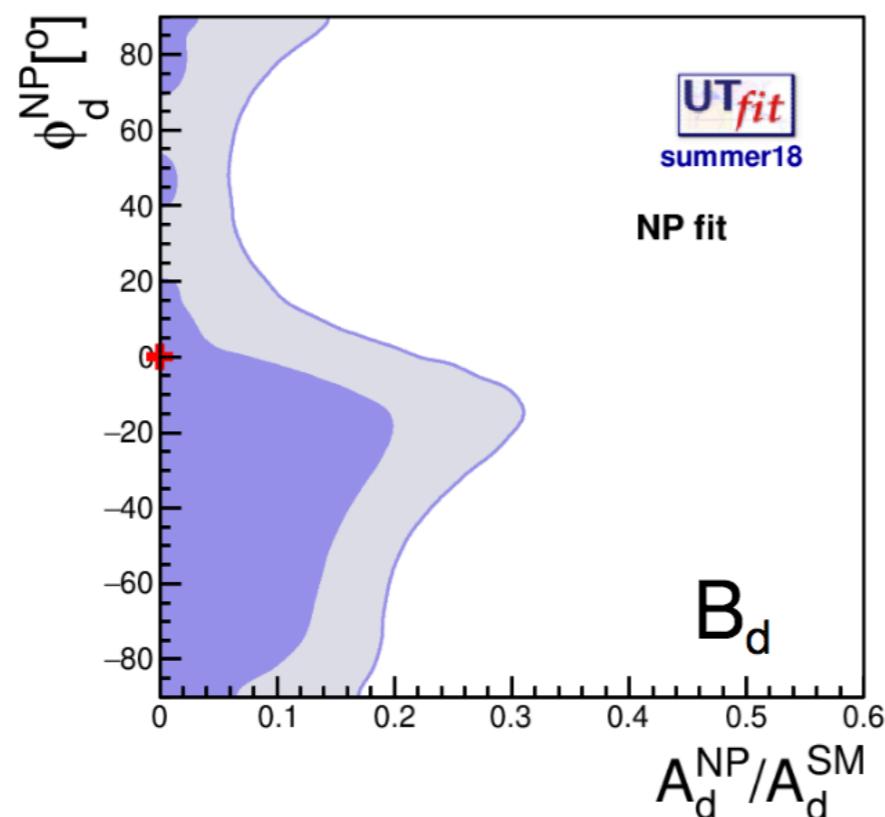


# CKM precision measurements

- From Marcella Bona @ CKM2018:

## NP parameter results

$$A_q = \left( 1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})} \right) A_q^{SM} e^{2i\phi_q^{SM}}$$



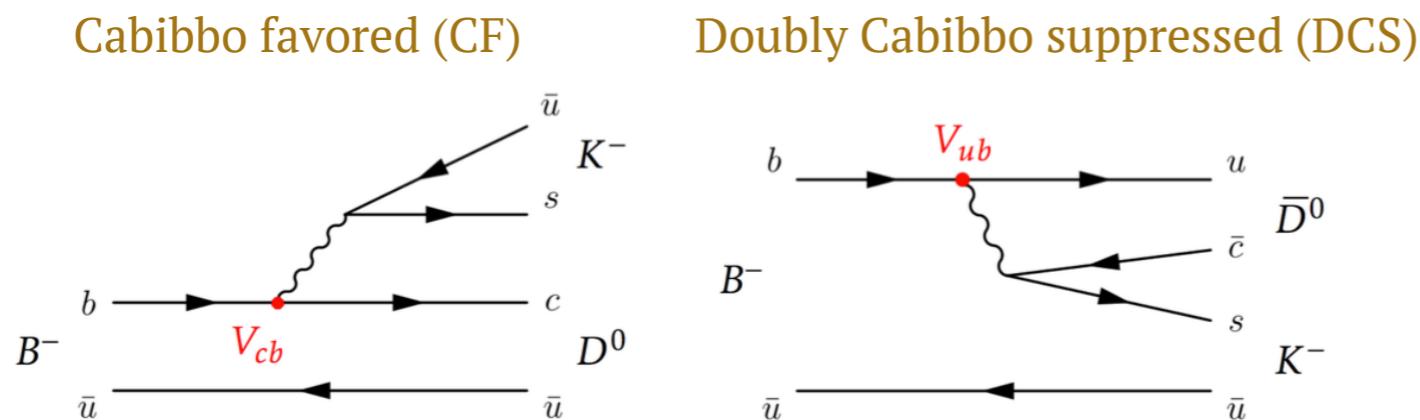
The ratio of NP/SM amplitudes is:

< 18% @68% prob. (30% @95%) in  $B_d$  mixing

< 20% @68% prob. (30% @95%) in  $B_s$  mixing

# $\gamma$ measurements

- Use tree decays of  $B^\pm \rightarrow DK^\pm$  which lead to the same final state with interference between  $D^0 - \bar{D}^0$  decays to the same final state



- Combination of results from several modes using different experimental methods:

- **GLW:** CP-even final states

[PLB 265 (1991) 172]

[PLB 253 (1991) 483]

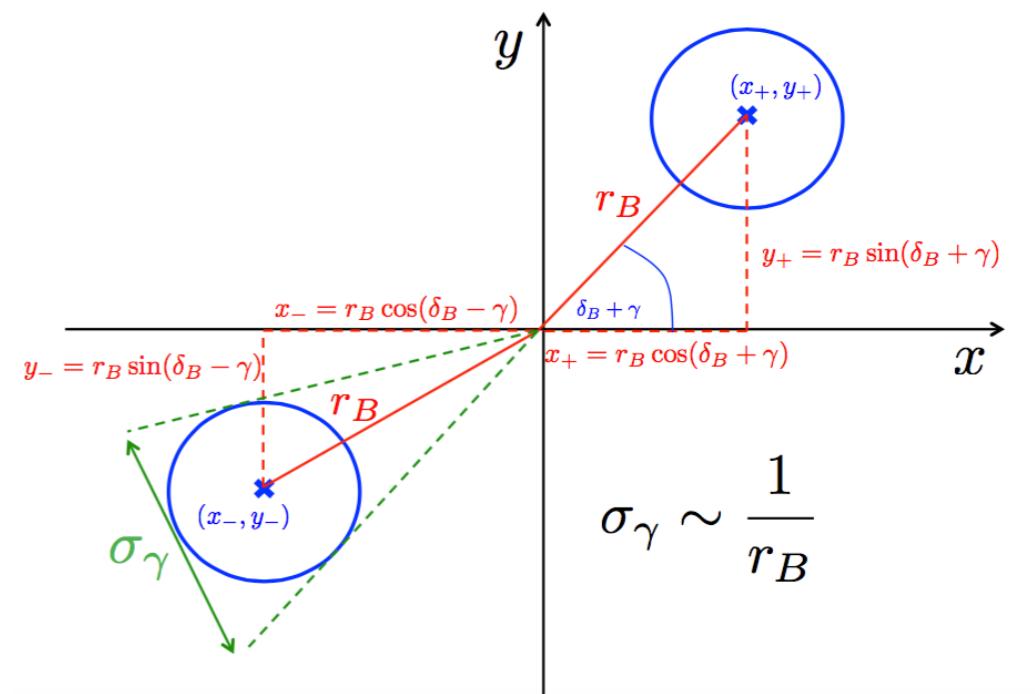
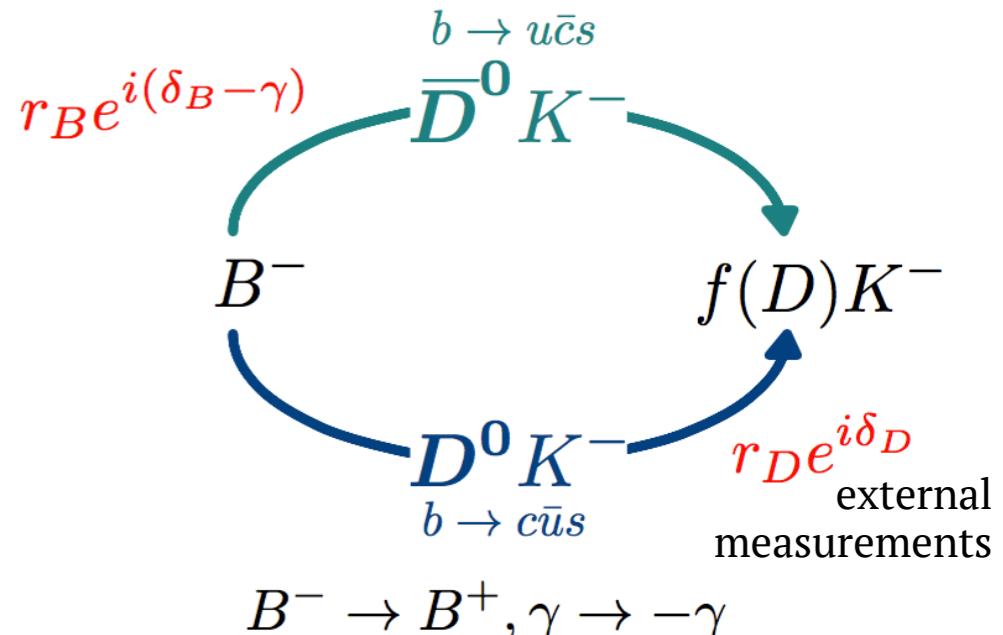
- **ADS:** CF or DCS final states

[PRL 78, 3257 (1997)]

[PRD 63 (2001) 036005]

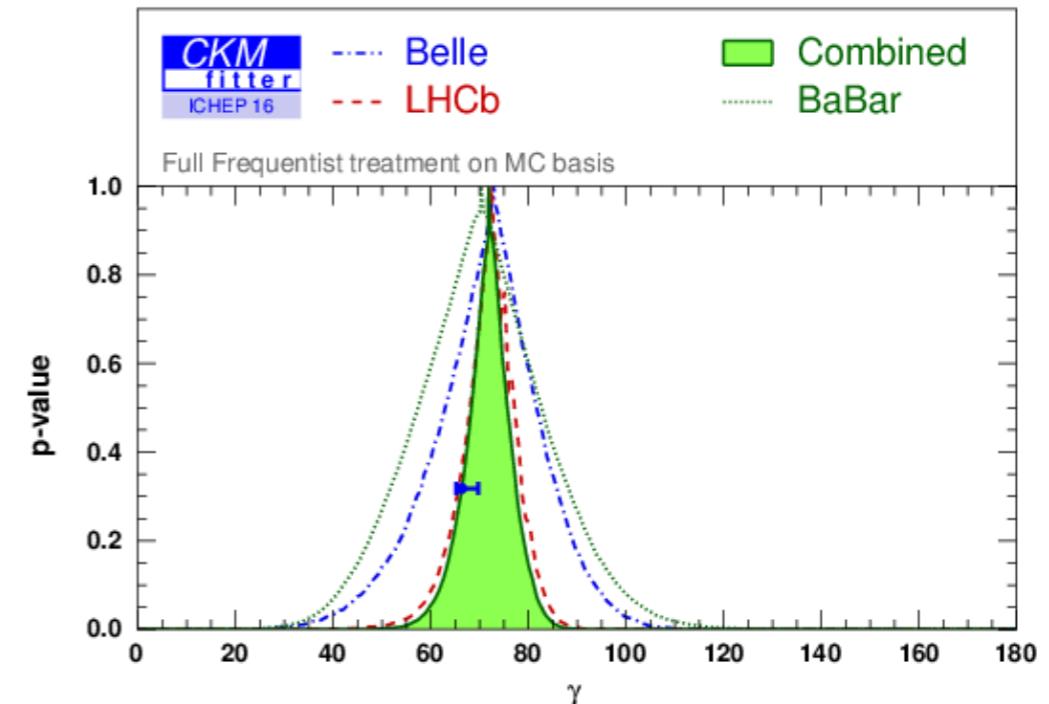
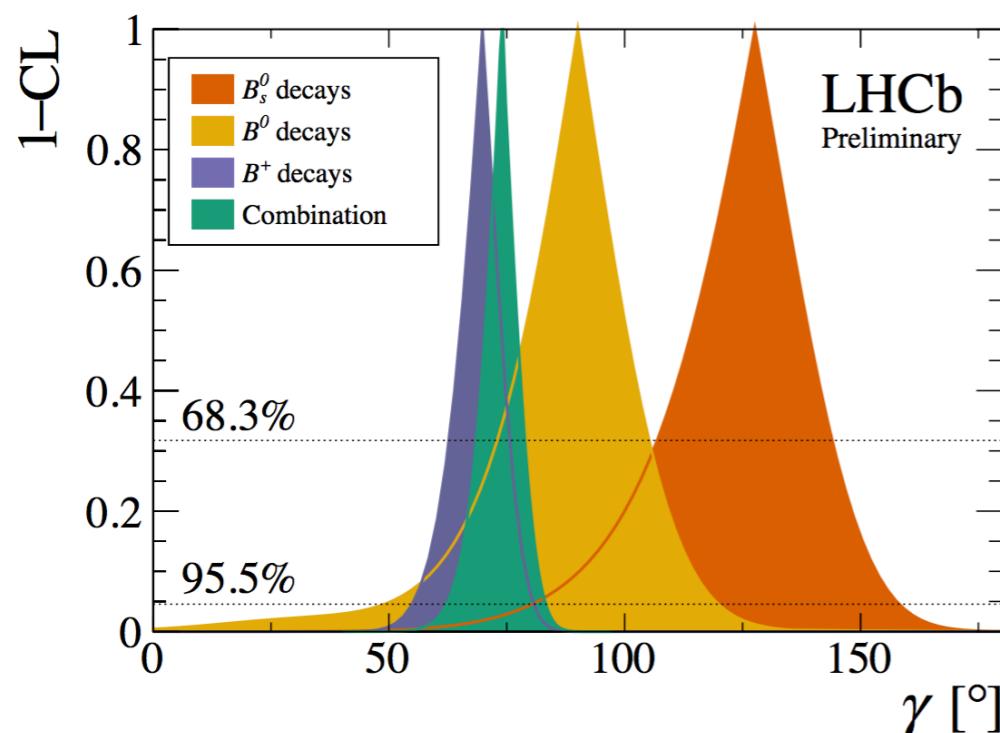
- **GGSZ:** 3 body final states

[PRD 68 (2003) 054018]



# $\gamma$ measurements

- World average currently dominated by LHCb combination (~16 measurements)



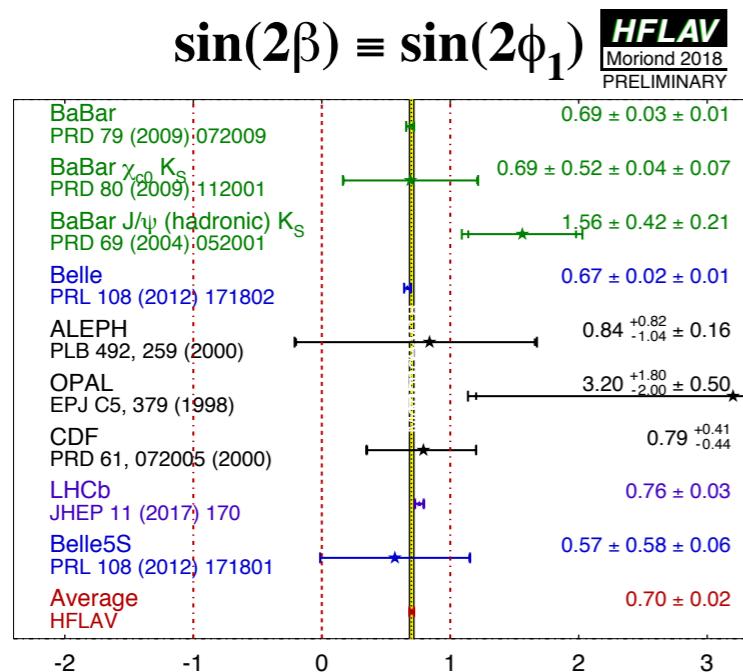
- LHCb combination:
- World average:
- Slight tension with loop-determination:

$$\begin{aligned} \gamma &= (74.0^{+5.0}_{-5.8})^\circ \quad [\text{LHCb-CONF-2018-002}] \\ \gamma &= (73.5^{+4.2}_{-5.1})^\circ \quad [\text{HFLAV}] \\ \gamma &= (65.6^{+1.0}_{-3.4})^\circ \quad [\text{CKMFitter}] \end{aligned}$$

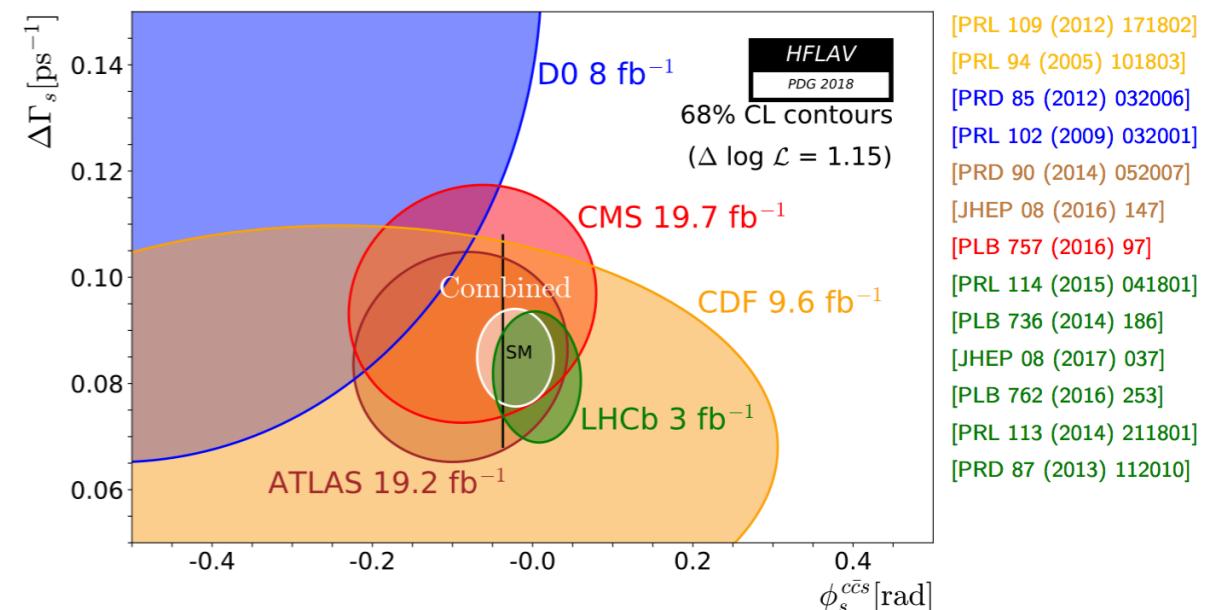
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
$\gamma$ , with $B_s^0 \rightarrow D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
$\gamma$ , all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°

# Interference in mixing & decay

$B^0 - \bar{B}^0$  mixing phase:  $\phi_d$



$B_s^0 - \bar{B}_s^0$  mixing phase:  $\phi_s$



► Golden mode:  $B^0 \rightarrow J/\psi K_S^0$

$$\phi_{d,J/\psi K_S^0}^{\text{eff}} = [42.2 \pm 1.5]^\circ \text{ [HFLAV]}$$

$$\phi_d^{\text{SM}} = [47.8 \pm 2.6]^\circ \text{ [CKMFitter]}$$

► Golden mode:  $B_s^0 \rightarrow J/\psi \phi$

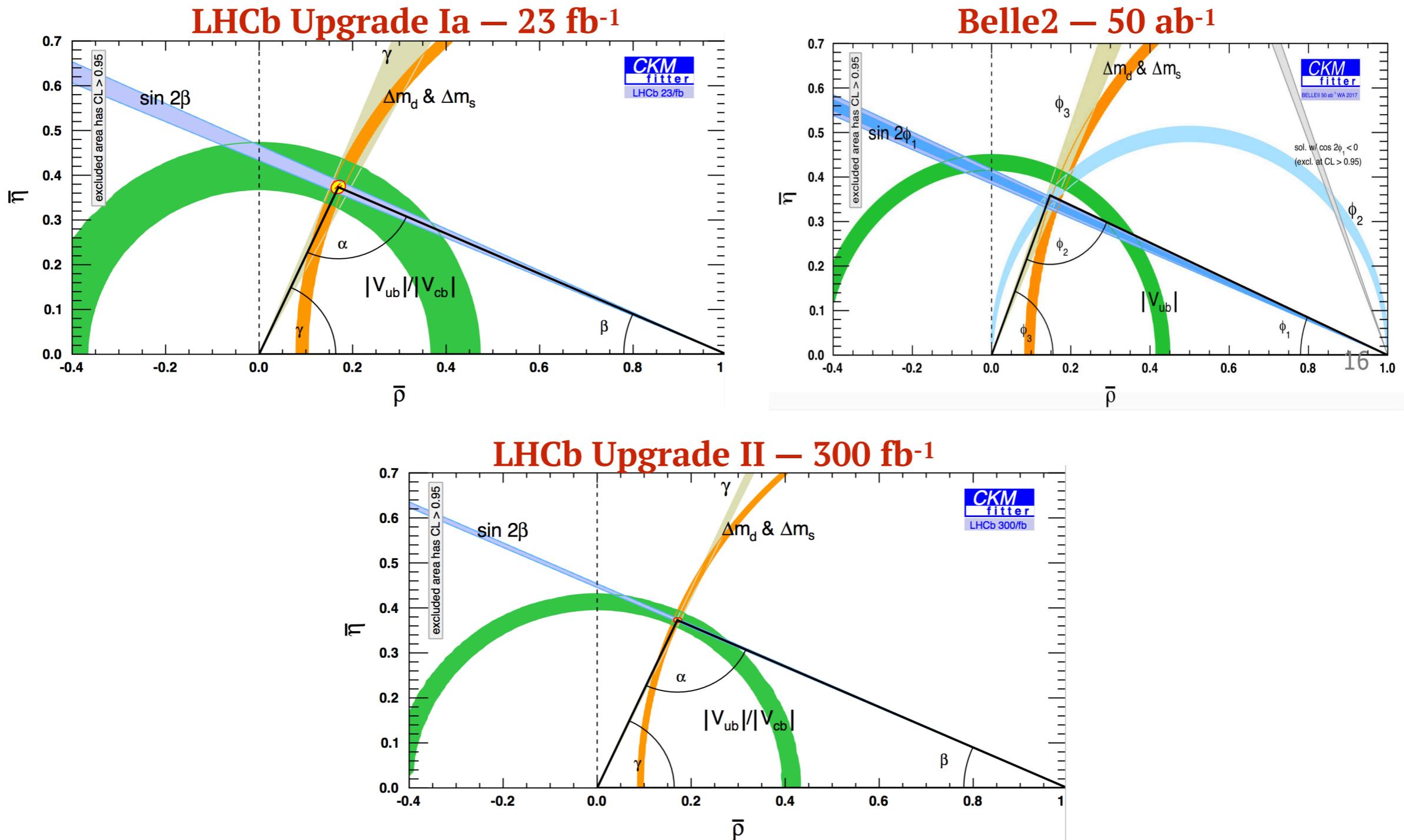
$$\phi_{s,c\bar{s}s}^{\text{eff}} = -0.021 \pm 0.031 \text{ rad [HFLAV]}$$

$$\phi_s^{\text{SM}} = -0.037 \pm 0.001 \text{ rad [CKMFitter]}$$

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
$\sin 2\beta$ , with $B^0 \rightarrow J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003
$\phi_s$ , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad
$\phi_s$ , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$ , with $B_s^0 \rightarrow \phi \phi$	154 mrad [94]	39 mrad	–	11 mrad

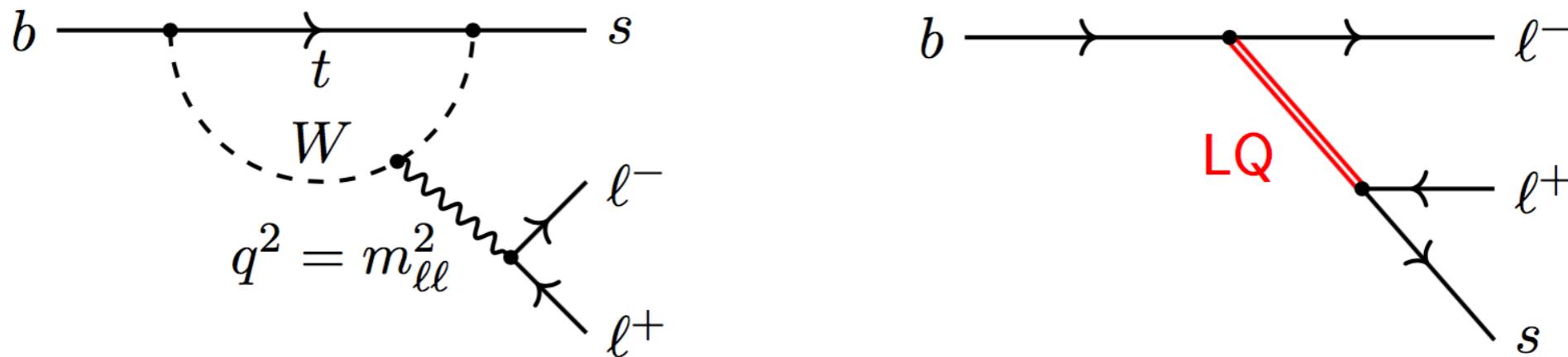
# CKM precision measurements

- Toward the very-high precision era:



# Flavour anomalies: @ loop

- Flavour Changing Neutral Currents (FCNCs) forbidden at tree level in the SM and only occur as loop-suppressed  $\Rightarrow$  typical exclusive BF  $\sim 10^{-5}$
- NP can contribute, affect decay rates and angular distributions



- Model independent description in effective field theory (EFT):

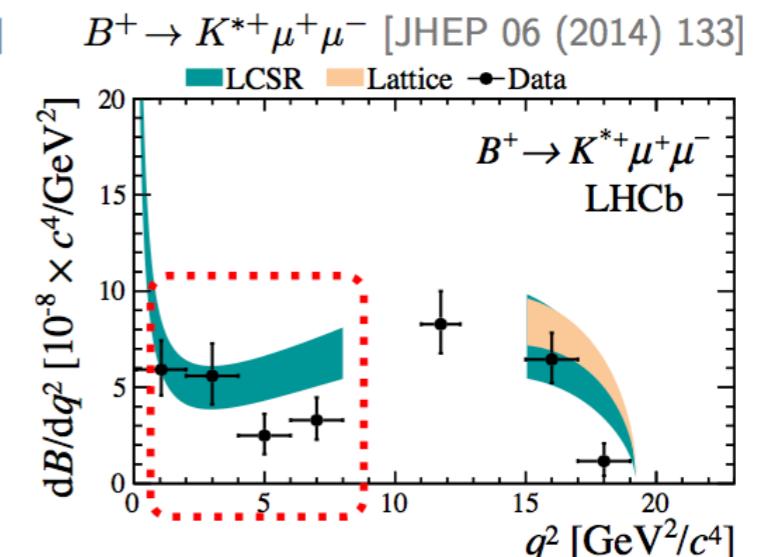
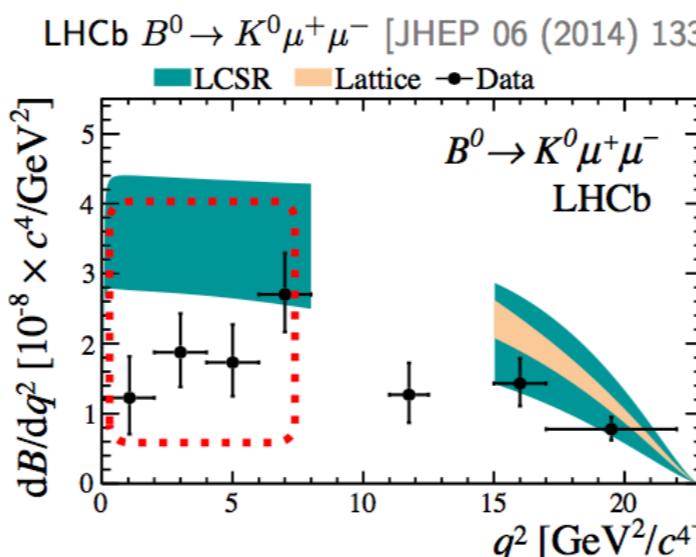
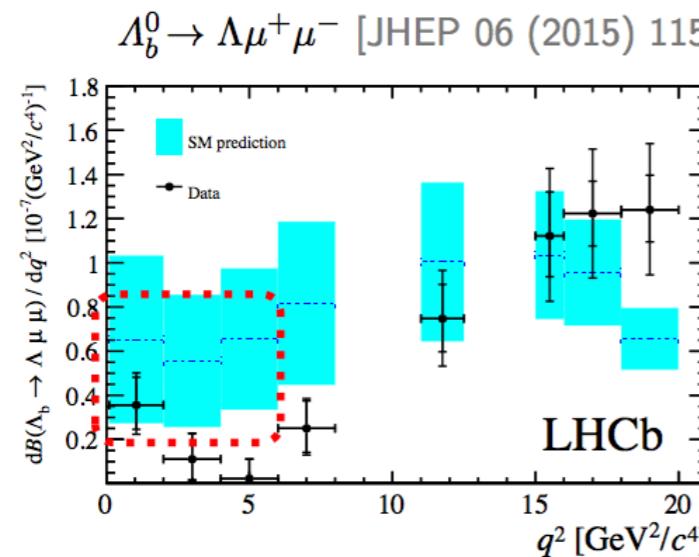
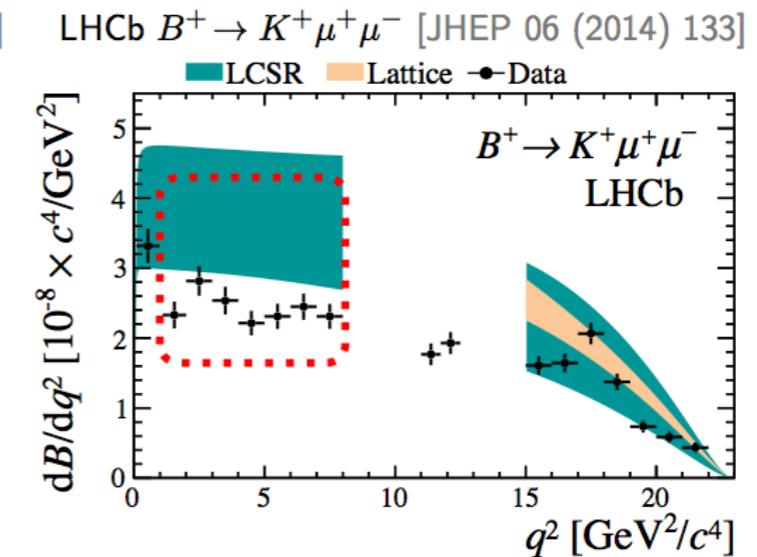
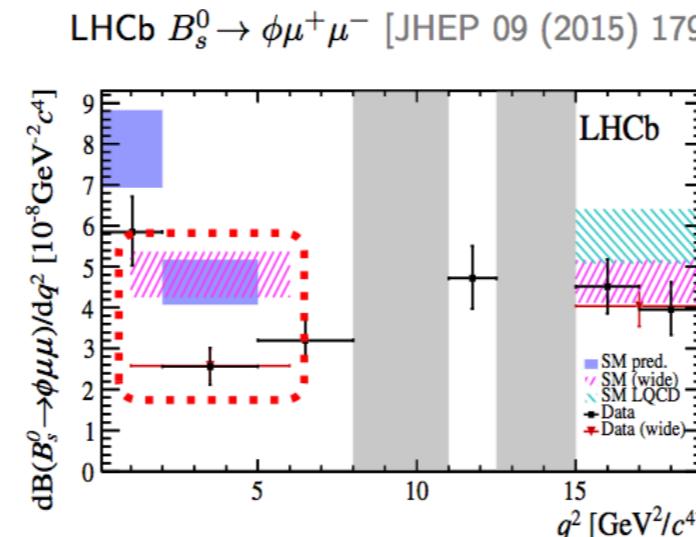
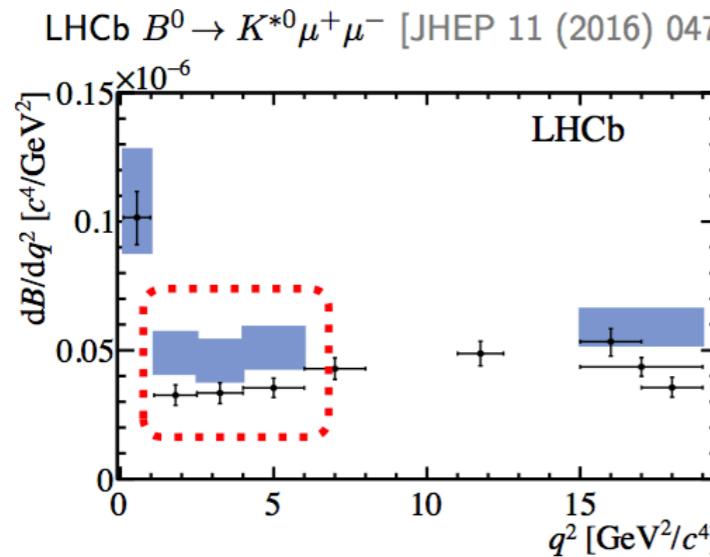
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + \frac{\kappa}{\Lambda_{\text{NP}}^2} \mathcal{O}$$

Local operator  $\mathcal{O}_i$   
Wilson coefficient ("effective coupling")  $C_i$   
NP coupling  $\kappa$   
NP scale  $\Lambda_{\text{NP}}^2$

$i = 1, 2$	Tree
$i = 3 - 6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

# Flavour anomalies: @ loop

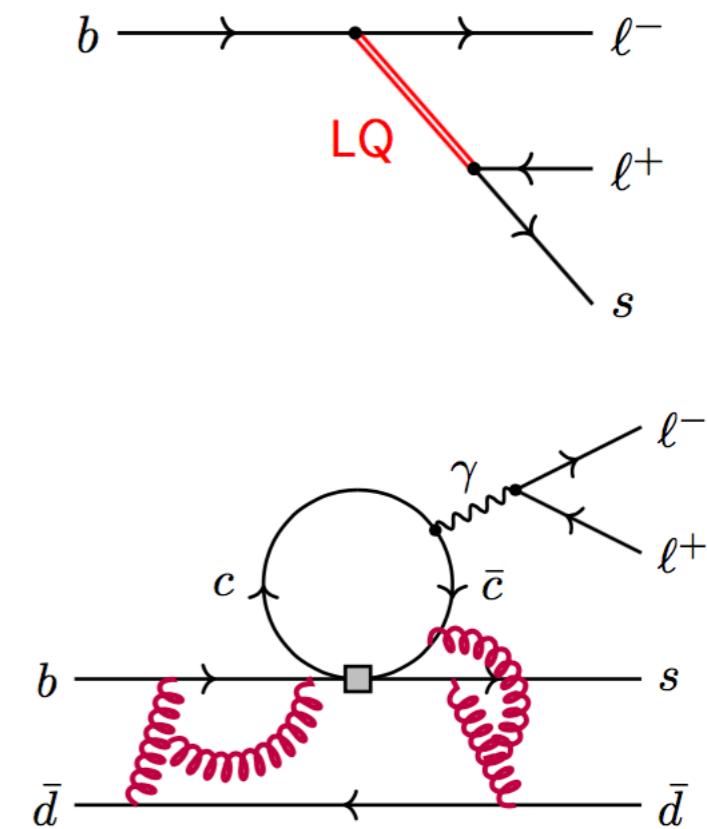
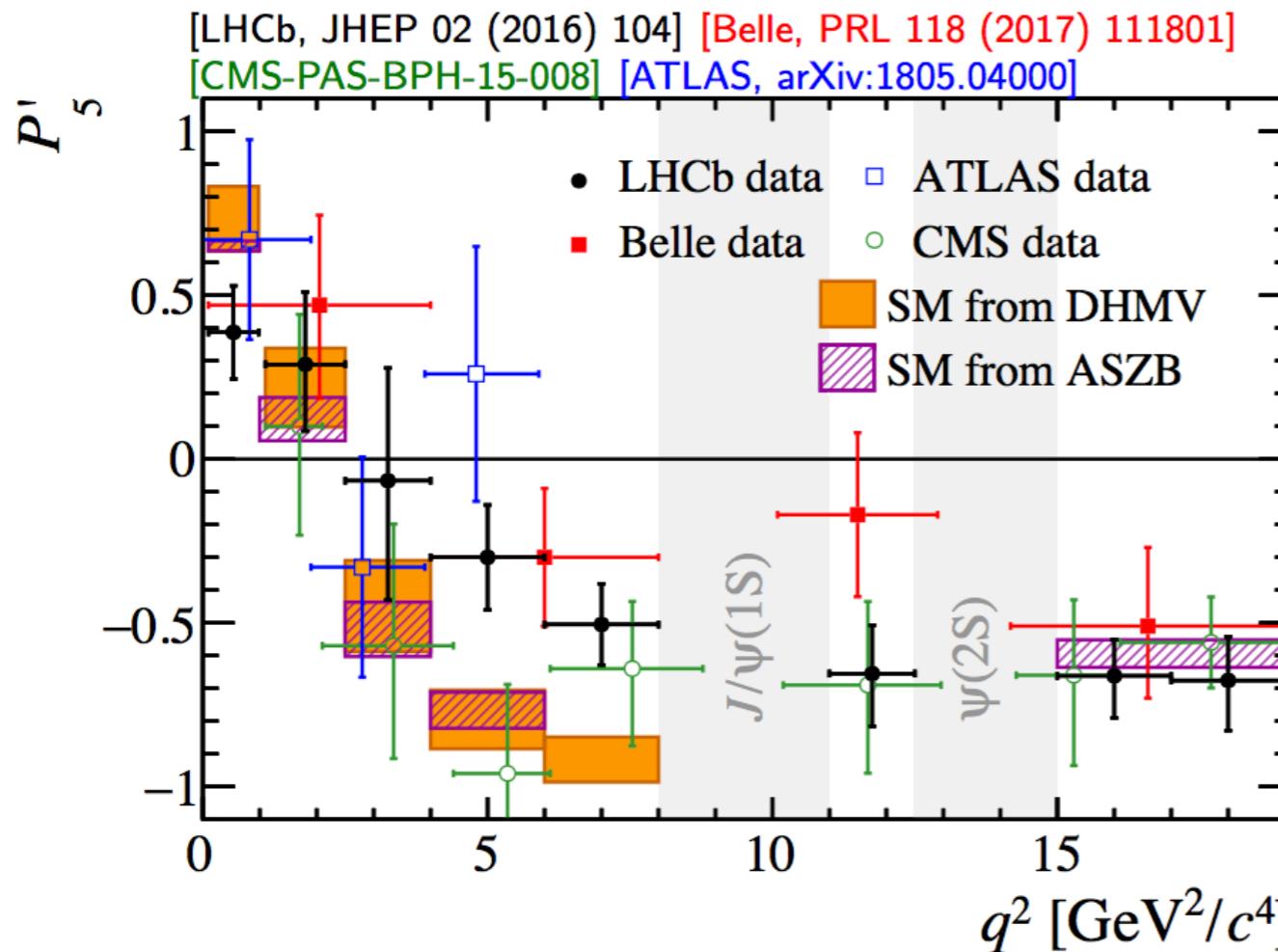
- Branching fractions of rare  $b \rightarrow s\mu^+\mu^-$  decays



- Data consistently below SM predictions
- Sizeable hadronic theory uncertainties
- Tensions at **1–3 $\sigma$**  level

# Flavour anomalies: @ loop

- Angular distributions of  $b \rightarrow s\mu^+\mu^-$  decays



- Local tensions (**2.8  $\sigma$**  and **3.0  $\sigma$** ) in  $q^2$  bins [4.0, 6.0] and [6.0, 8.0]  $\text{GeV}^2/\text{c}^4$  for  $P'_5$
- Significances depend on hadronic charm-loop uncertainties

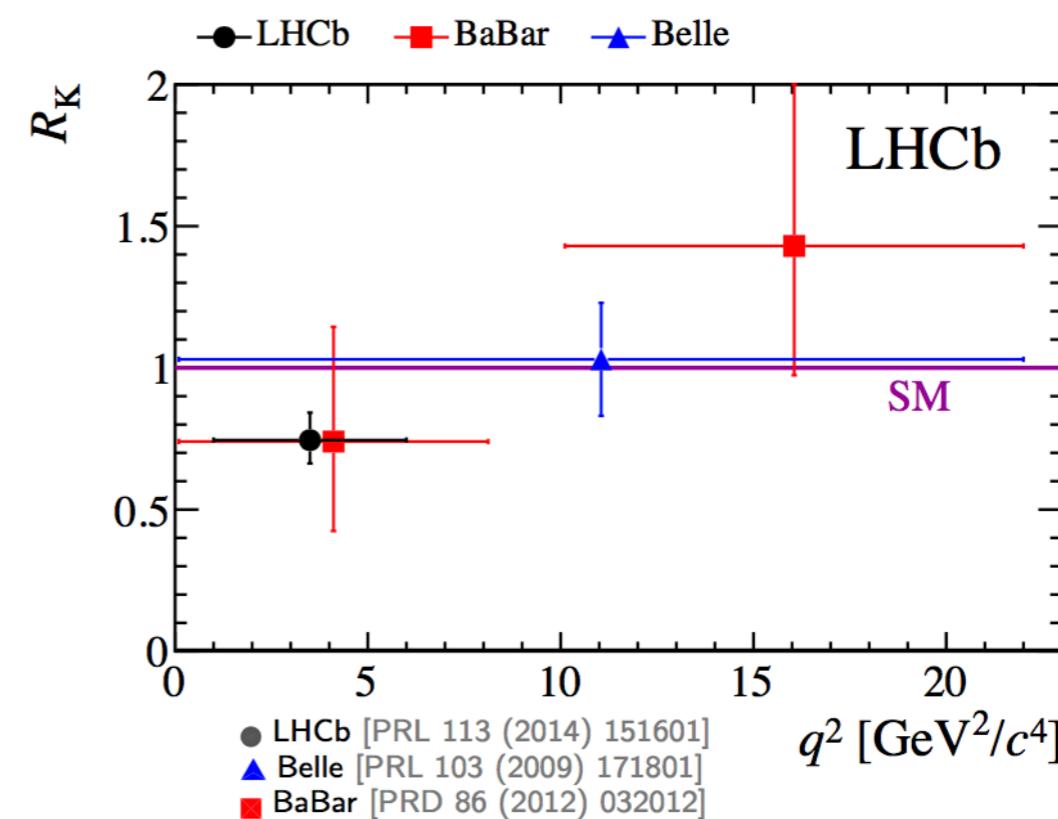
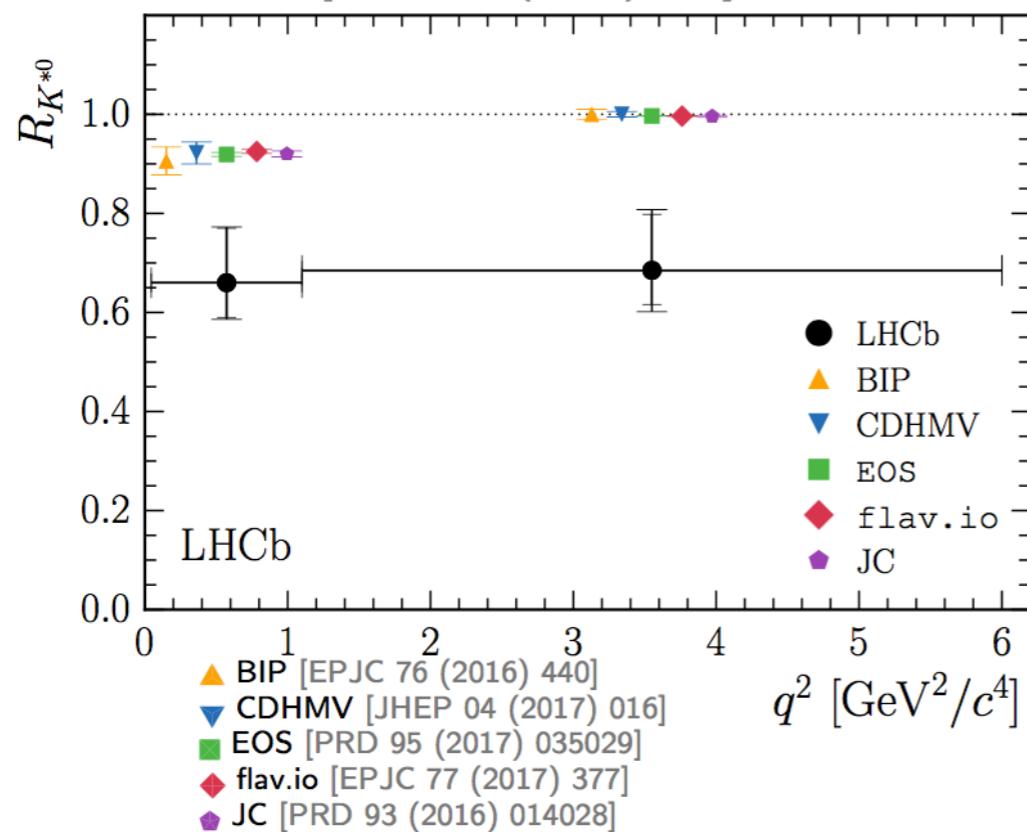
# Flavour anomalies: @ loop

- Lepton Flavour Universality tests  $R_{K^*}$  and  $R_K$

- Unlike  $P'_5$  very robust SM prediction:

$$R_X = \int \frac{d\Gamma(B \rightarrow X \mu^+ \mu^-)}{dq^2} dq^2 / \int \frac{d\Gamma(B \rightarrow X e^+ e^-)}{dq^2} dq^2 \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(1\%) \quad [\text{EPJC 76 (2016) 8,440}]$$

[JHEP 08 (2017) 055]

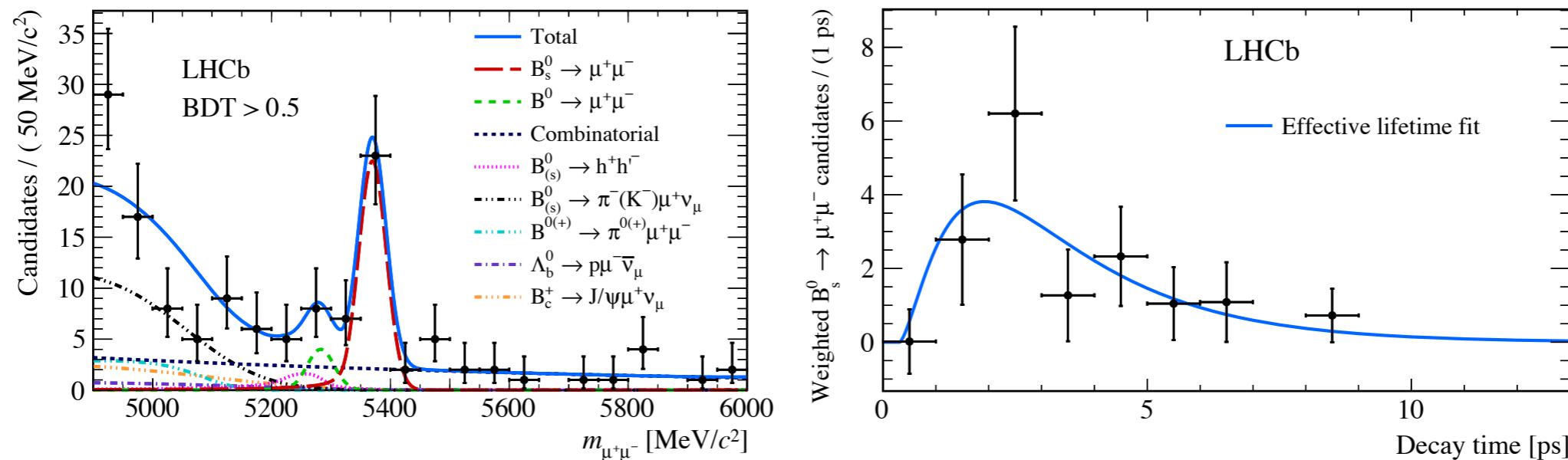


- Local tensions **2.1–2.6  $\sigma$**  depending on  $q^2$  bin
- LHCb updates of  $R_{K^*}$  and  $R_K$  with Run 2 data in preparation, as well as other  $R_X$
- LHCb upgrades and Belle2 will allow unprecedented precision (@ % level)

# Flavour anomalies: @ loop SM like

- But also non-anomalous results, with strong constraints on NP models

- The very rare decay  $B_s^0 \rightarrow \mu^+ \mu^-$

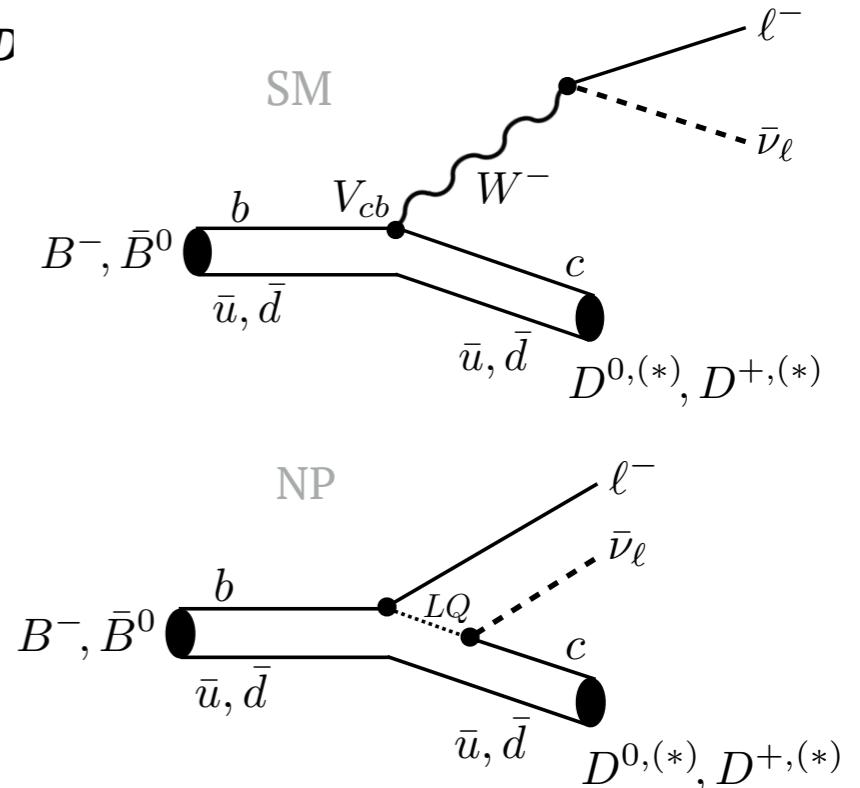
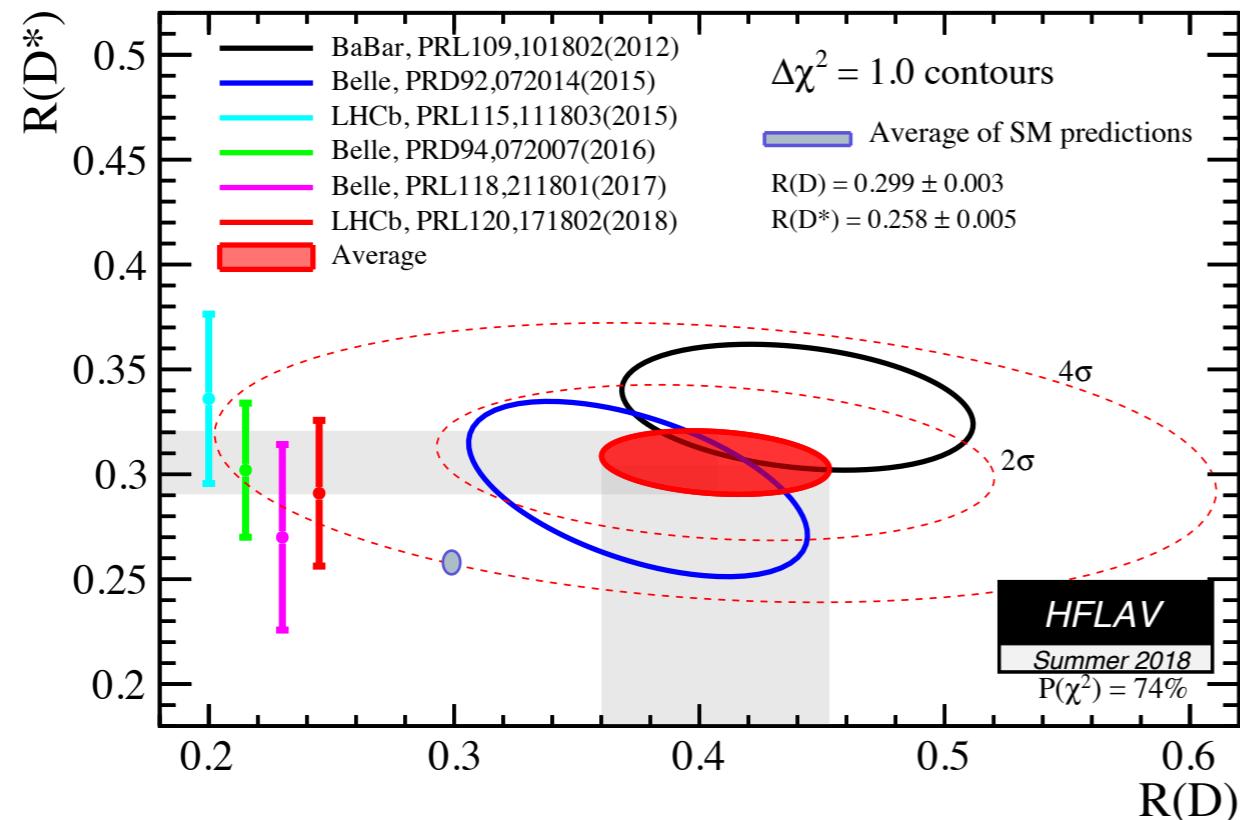


- First observation of  $B_s^0 \rightarrow \mu^+ \mu^-$  ( $7.8\sigma$ ) by single experiment with  $4.4 \text{ fb}^{-1}$  of data (incl.  $1.4 \text{ fb}^{-1}$  Run 2) by LHCb [PRL 118 (2017) 191801]:
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6 {}^{+0.3}_{-0.2}) \times 10^{-9} \quad \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.5 {}^{+1.2}_{-1.0} {}^{+0.2}_{-0.1}) \times 10^{-10}$$
- First eff. lifetime meas.  $\tau(B_s^0 \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$  as complementary probe

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–

# Flavour anomalies: @ tree

- LFU tests in semileptonic  $b \rightarrow c\ell\nu$  decays:  $R_{D^*}$  and  $R_D$



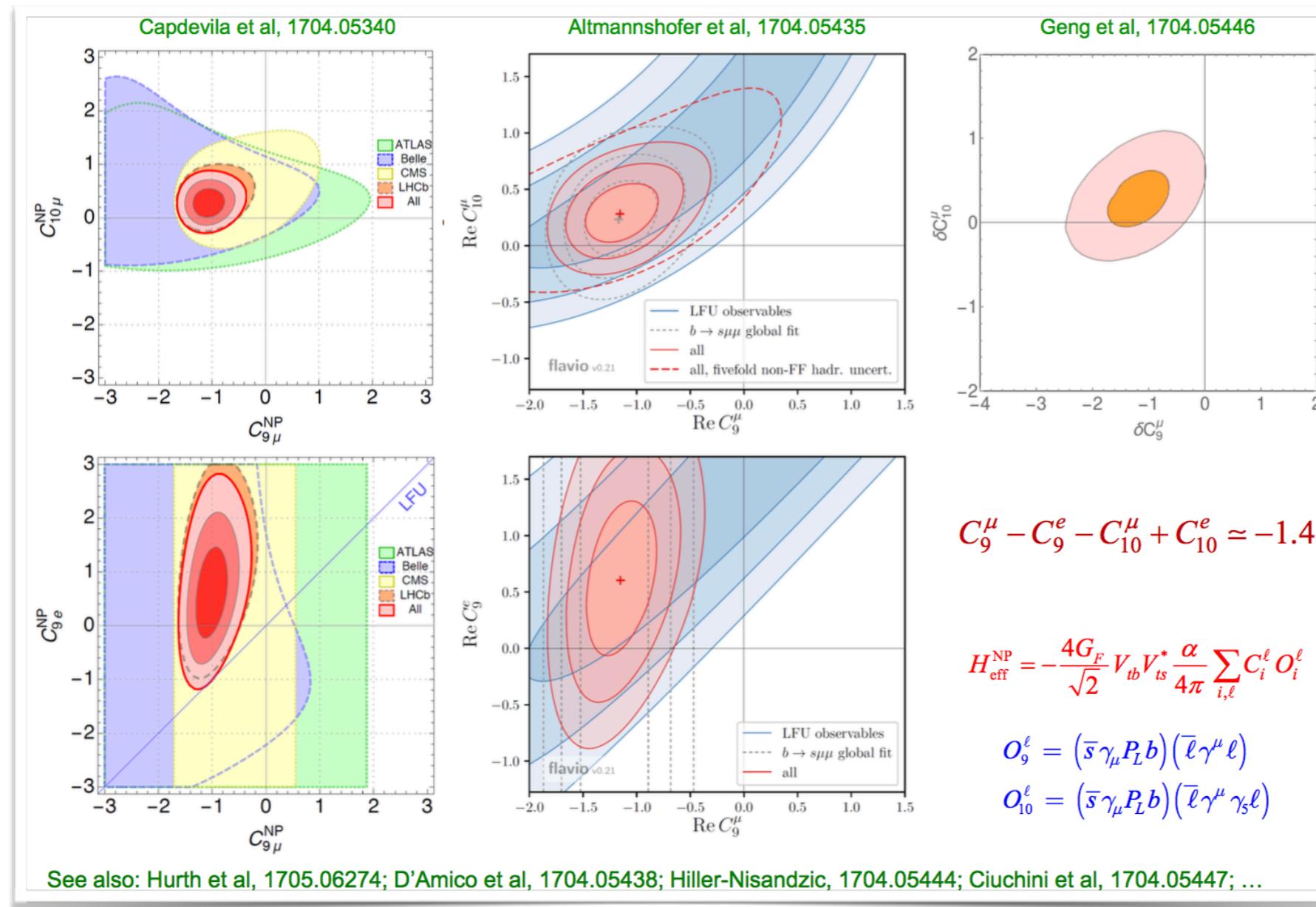
- Modified coupling in particular possible to third generation  $\tau$
- All measurements see excess wrt. SM prediction: **combined tension  $\sim 3.8\sigma$**
- LHCb Run 2 updates ongoing, additional  $b$ -hadron modes in preparation ( $B_s^0, B_c^+, \Lambda_b^0, \dots$ )
- LHCb Upgrades and Belle2 will allow angular analysis to determine spin structure of NP

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002
$R(J/\psi)$	0.24 [220]	0.071	–	0.02

# Flavour anomalies: interpretations

- EFT approach, a major tool:

- Starting from SM (or extensions) and integrating out heavy/energetic degrees of freedom
- Several global fits of recent experimental results performed, all in good agreement suggesting large deviation in vector operator coupling  $C_9$



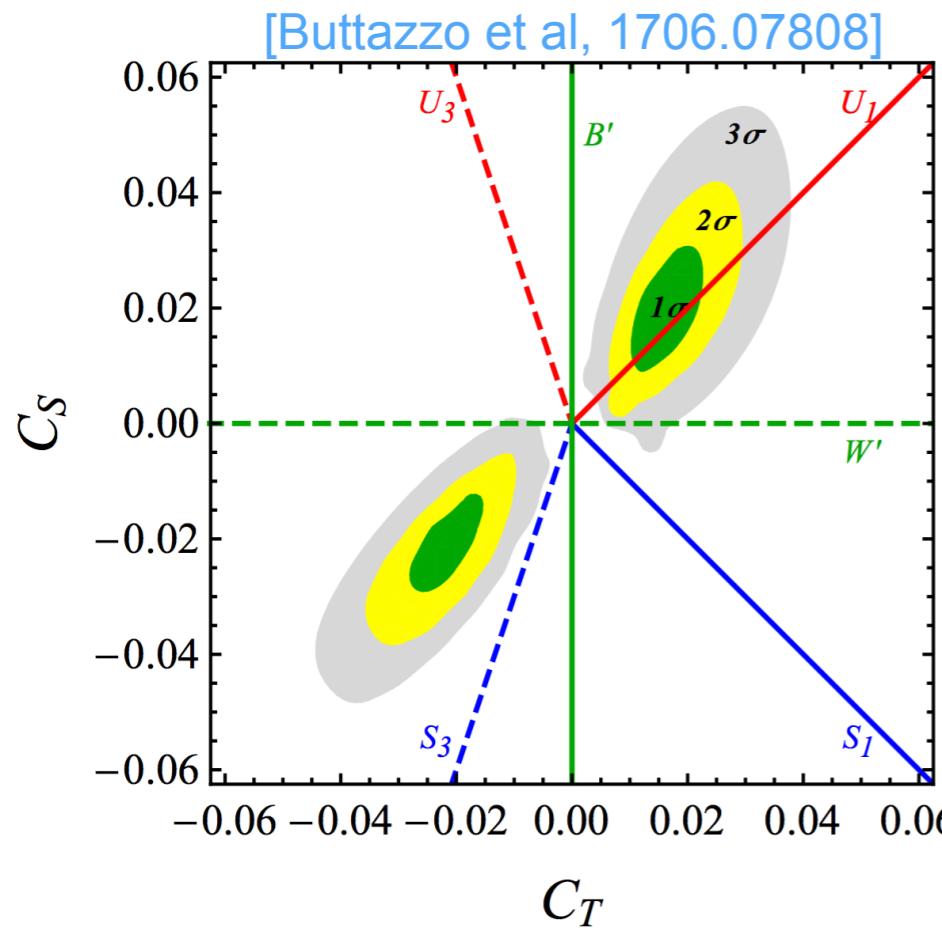
From Alberto Pich @ LHCb implication workshop 2018

# Flavour anomalies: interpretations

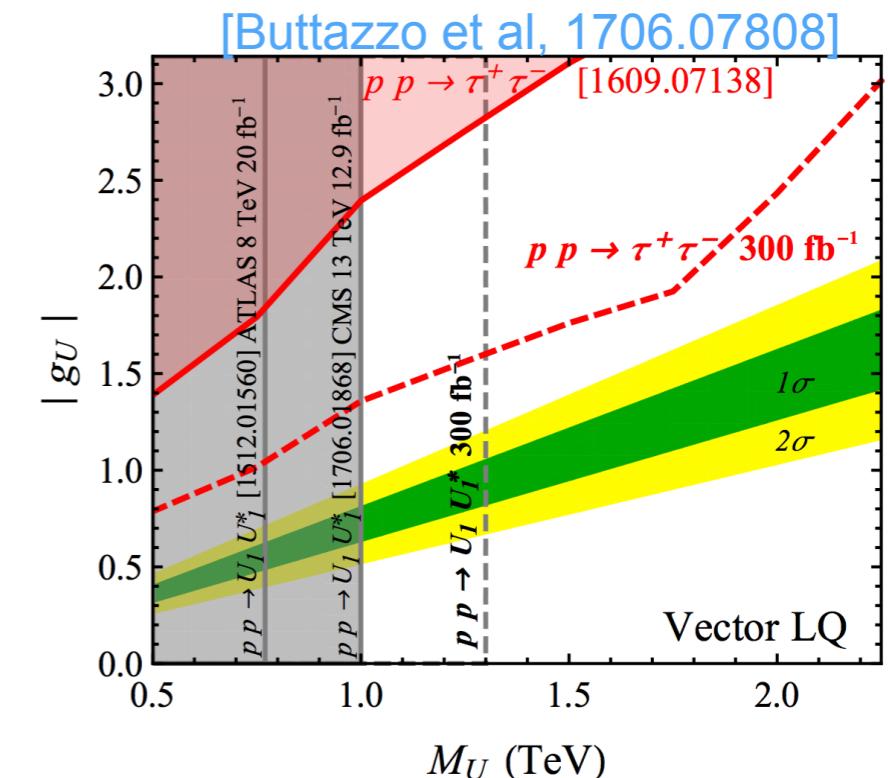
- EFT approach, a major tool:

- Possible NP candidates: “The Return of the LeptoQuark”

[Angelescu et al, 1808.08179]



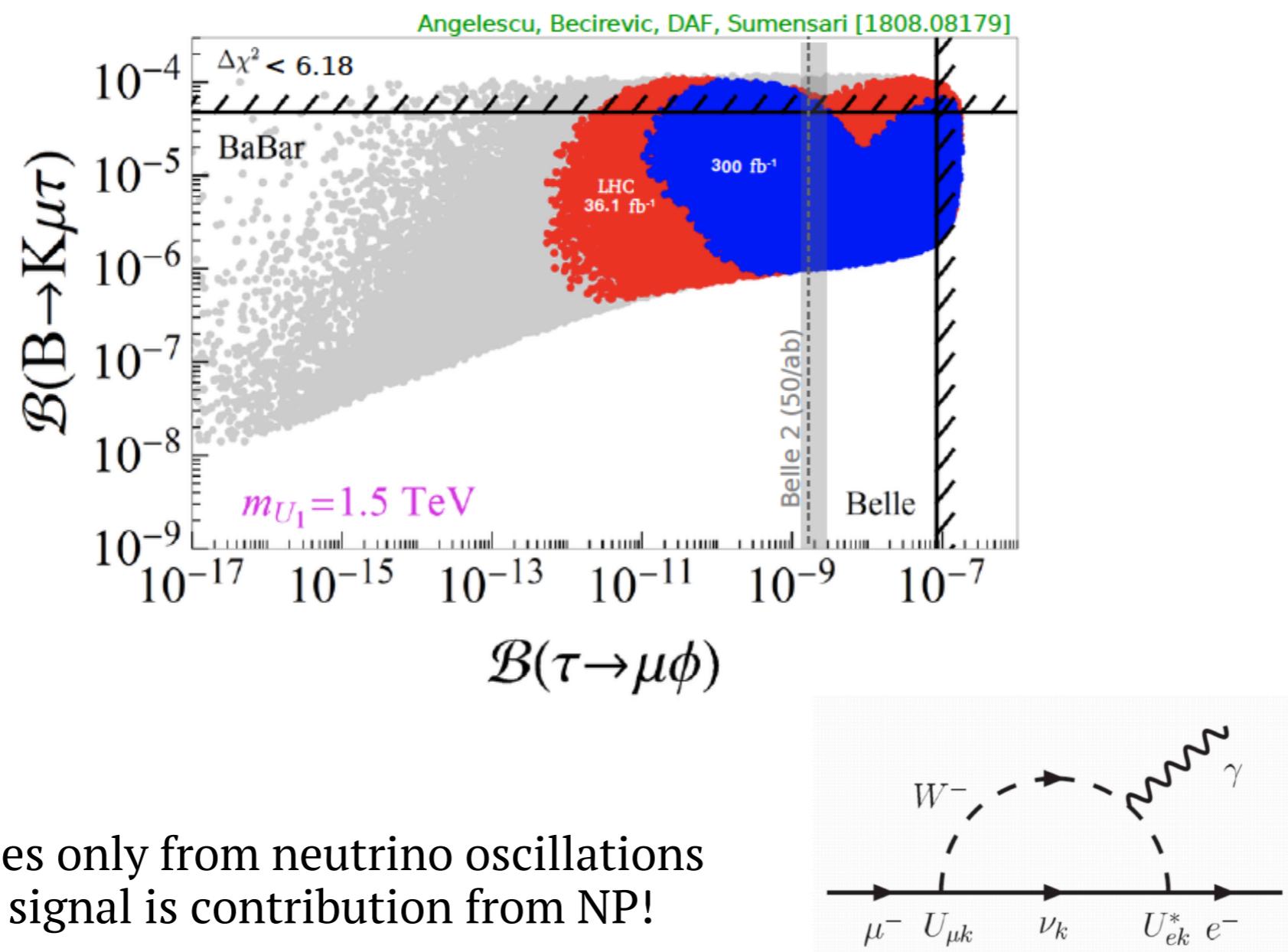
	Model	$R_{K(*)}$	$R_{D(*)}$	$R_{K(*)} \& R_{D(*)}$
Scalars	$S_1 = (3, 1)_{-1/3}$	✗	✓	✗
	$R_2 = (3, 2)_{7/6}$	✗	✓	✗
Vector	$\tilde{R}_2 = (3, 2)_{1/6}$	✗	✗	✗
	$S_3 = (3, 3)_{-1/3}$	✓	✗	✗
$U$	$U_1 = (3, 1)_{2/3}$	✓	✓	✓
	$U_3 = (3, 3)_{2/3}$	✓	✗	✗



- Disfavours colourless vectors ( $W'$ , $Z'$ ) and coloured scalars ( $S_1$ , $S_3$  leptoquarks) + high  $p_T$  constraints
- Favours  $U_1$  vector leptoquark, which also passes direct LHC production limits

# LFV in charged leptons

- LFU models often imply Lepton Flavor Violation (LFV):
  - Allowed regions from direct search of  $U_1$  leptoquark @LHC and bounds from cLFV searches



# LFV in charged leptons

- cLFV tau decays:

- Belle2 is also a tau factory:  $O(10^{10})$  tau pairs produced @ $50\text{ ab}^{-1}$ 
  - Full event reconstruction allows to tag signal from other side  $\tau$

Radiative decay:

$$\tau \rightarrow \ell \gamma$$

3-body decays:

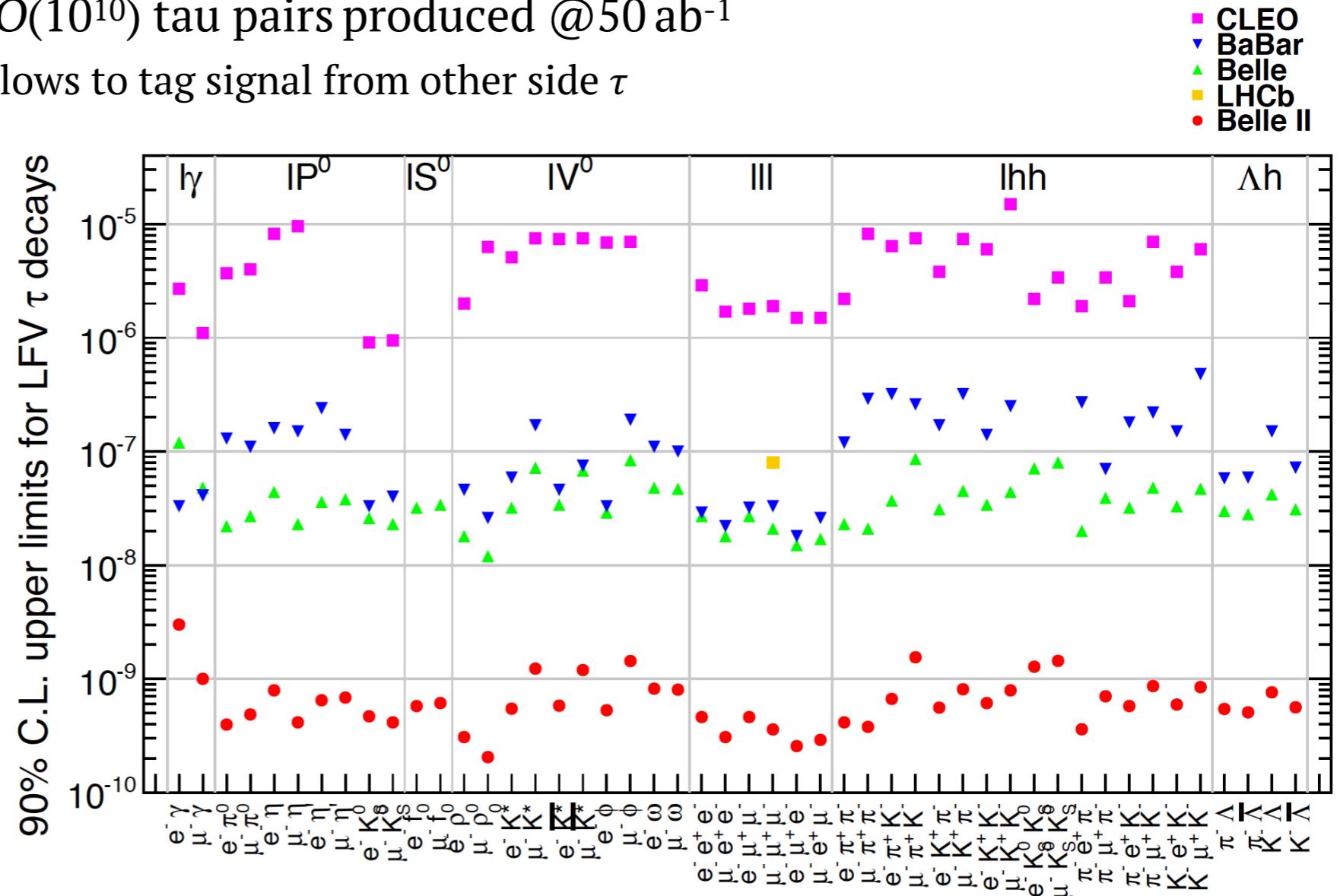
$$\tau \rightarrow \ell_i \ell_j \ell_k$$

Meson(s) & charged lepton:

$$\tau \rightarrow \ell h ; \tau \rightarrow \ell h_i h_j$$

cLFV exotic modes:

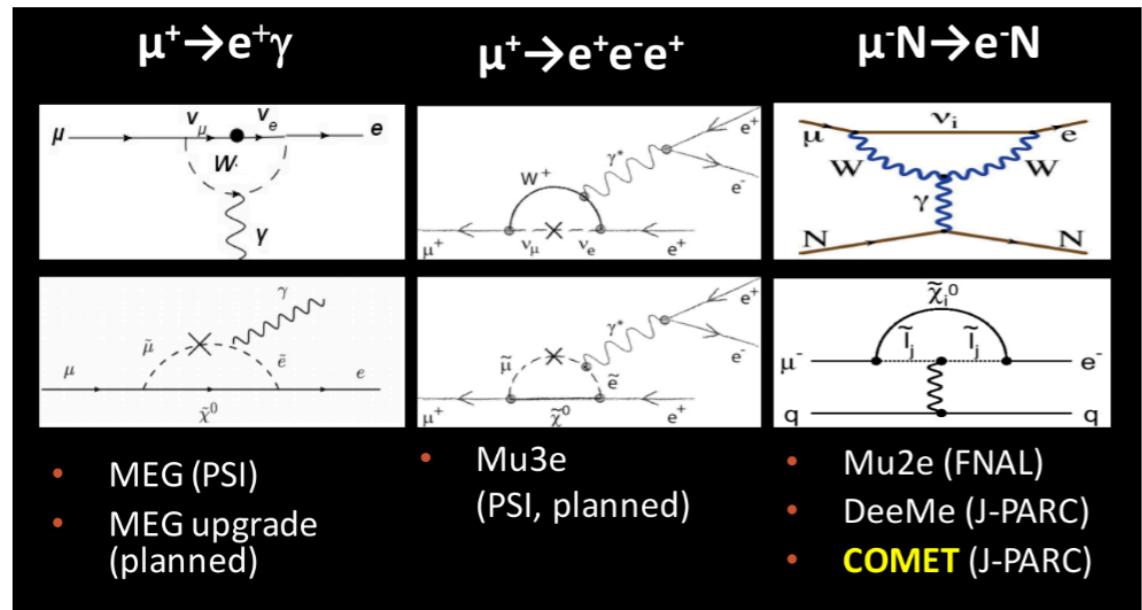
$$\tau \rightarrow \ell h_i h_j ; \tau \rightarrow p \mu \mu$$



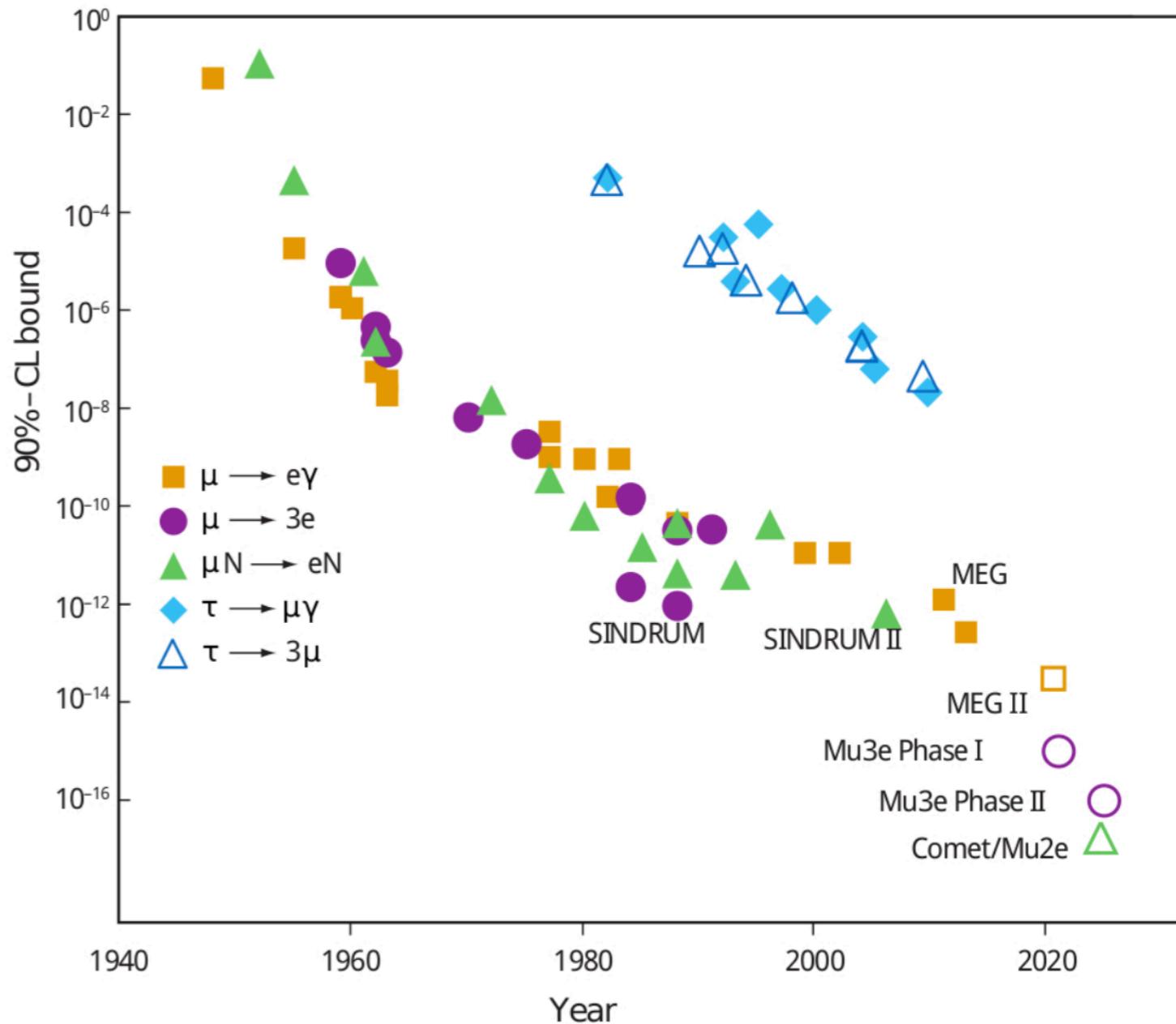
- **Belle2: two orders of magnitude improvement on current bounds on multiple cLFV processes**

# LFV in charged leptons

- cLFV in muons: dedicated experiments



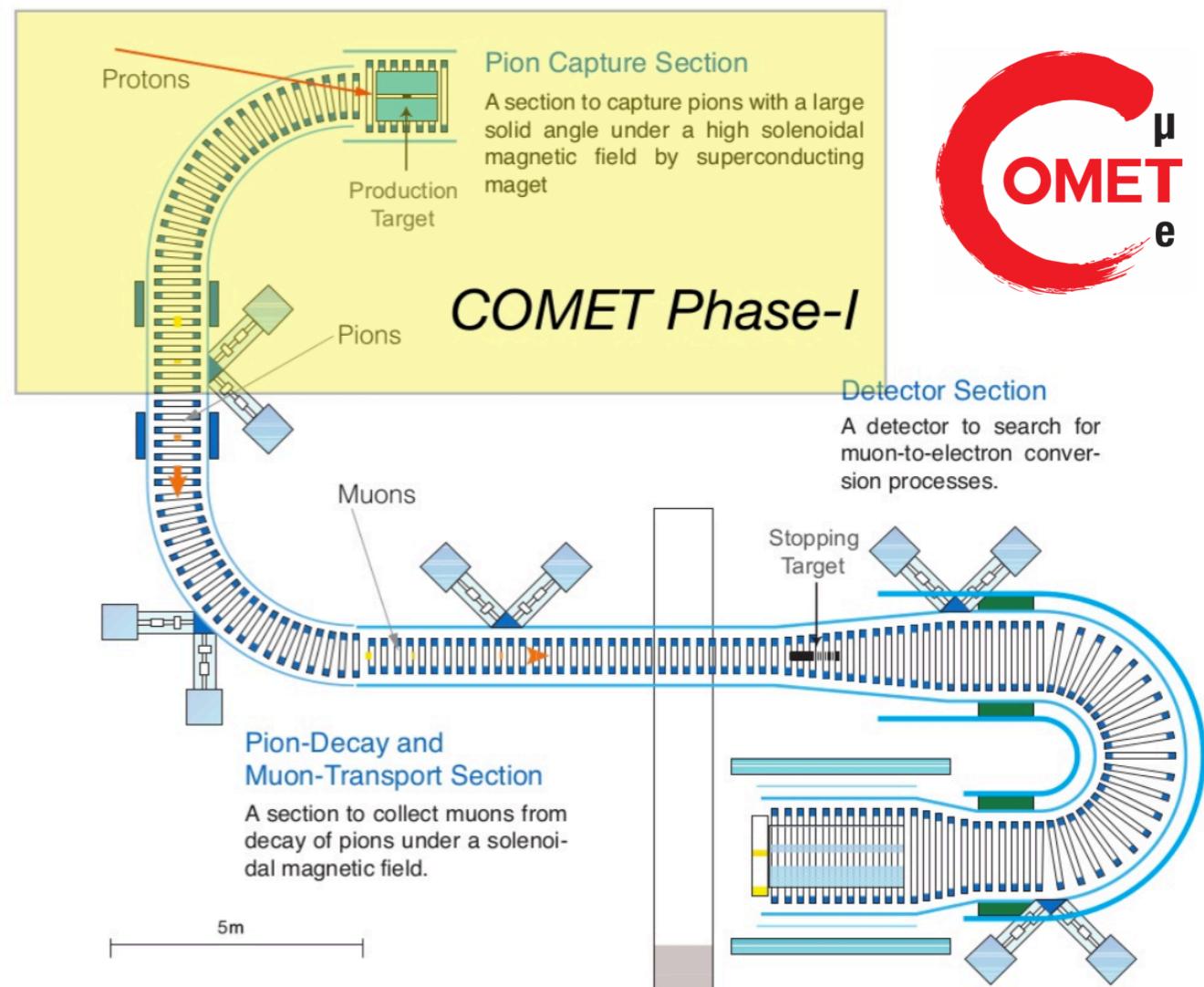
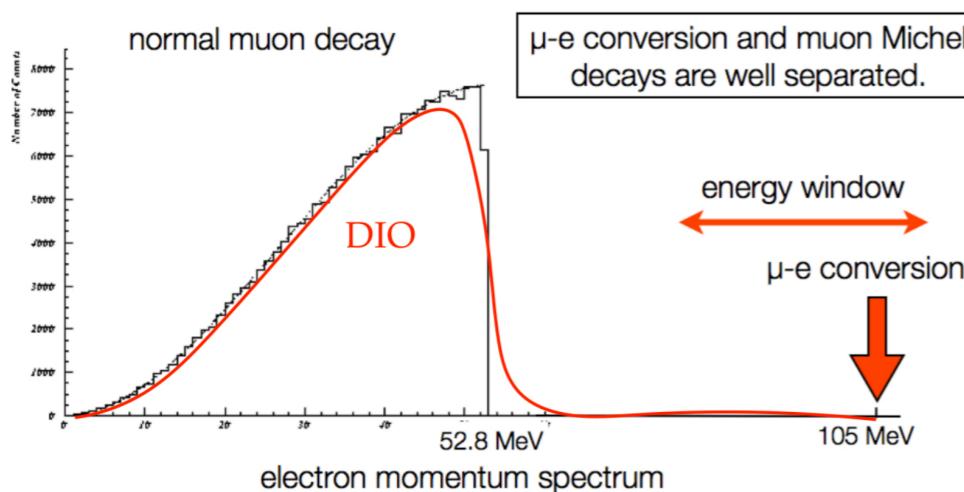
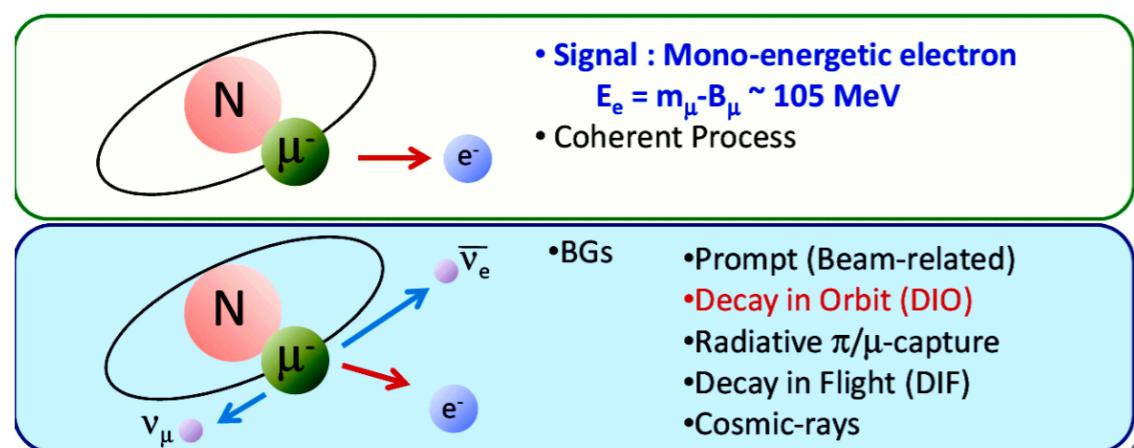
Process	Experiment	Limit
$\text{BR}(\mu^+ \rightarrow e^+ \gamma)$	MEG('13)	$4.2 \cdot 10^{-13}$
	MEG-II( $\geq$ '20) at PSI	$4 \cdot 10^{-14}$
$\text{BR}(\mu^+ \rightarrow eee)$	SINDRUM('88)	$10^{-12}$
	Mu3e Phase I( $\geq$ '20) at PSI	$2 \cdot 10^{-15}$
$R(\mu \rightarrow e : \text{Au})$ $R(\mu \rightarrow e : \text{Al})$	SINDRUM-II('06)	$7 \cdot 10^{-3}$
	COMET-PhaseI( $\simeq$ '20)	$3 \cdot 10^{-15}$
$R(\mu \rightarrow e : \text{Ti})$	COMET-PhaseII( $>$ '20)	$3 \cdot 10^{-17}$
	Mu2e( $\geq$ '20)	$7.5 \cdot 10^{-17}$
	PRISM( $>$ '20)	$O(10^{-18})$



Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]

# LFV in charged leptons

- cLFV in muonic atoms:  $\mu - e$  conversion

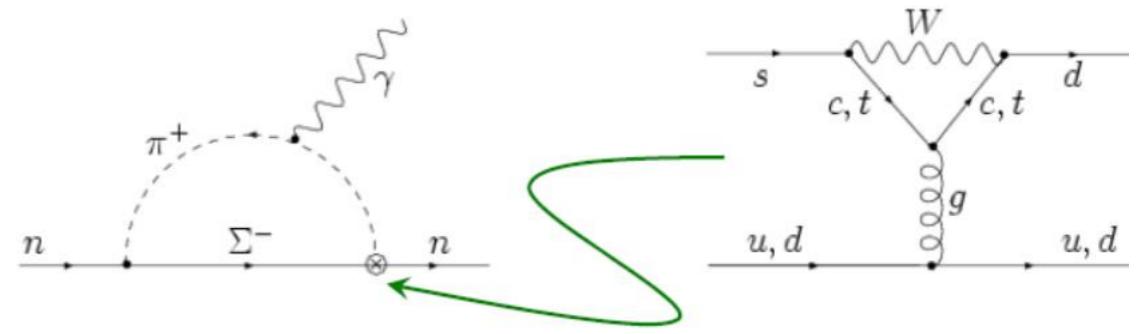


- Staging approach: Phase I to achieve  $10^{-15}$  sensitivity and then Phase II (increased beam intensity & final detector) to achieve  $10^{-17}$  sensitivity

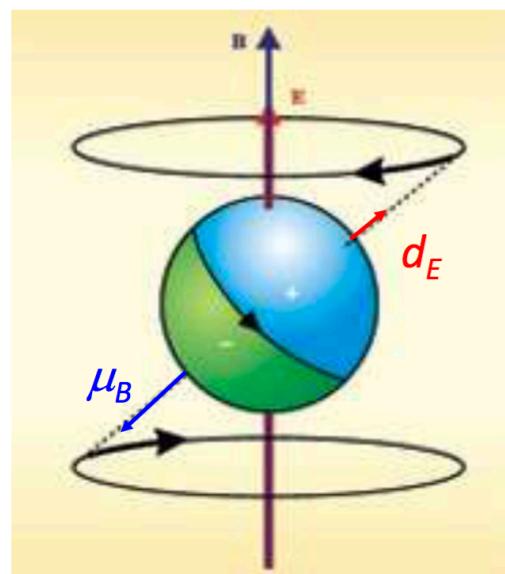
# Neutron EDM

- New sources of CP violation needed to explain baryonic asymmetry of the Universe
- Particle with non-zero permanent Electric Dipole Moment (EDM) violates P & T, thus CP under CPT conservation

- In SM  $d_n(\text{CKM}) \sim 10^{-32} \text{ e.cm}$
  - Current experimental limit  $d_n < \sim 10^{-26} \text{ e.cm}$
- ⇒ large discovery potential



- Nuclear Magnetic Resonance technique:



Apply static  $B$ ,  $E \parallel B$   
Look for  $\Delta\omega$  on reversal of  $E$

$$H = -(\mu \vec{B} + d_n \vec{E}) \cdot \frac{\vec{S}}{|S|}$$

Larmor precession

$$\omega_B = -\frac{2\mu_B B}{\hbar}$$

Additional precession  
due to EDM

$$\omega_E = \frac{2d_n E}{\hbar}$$

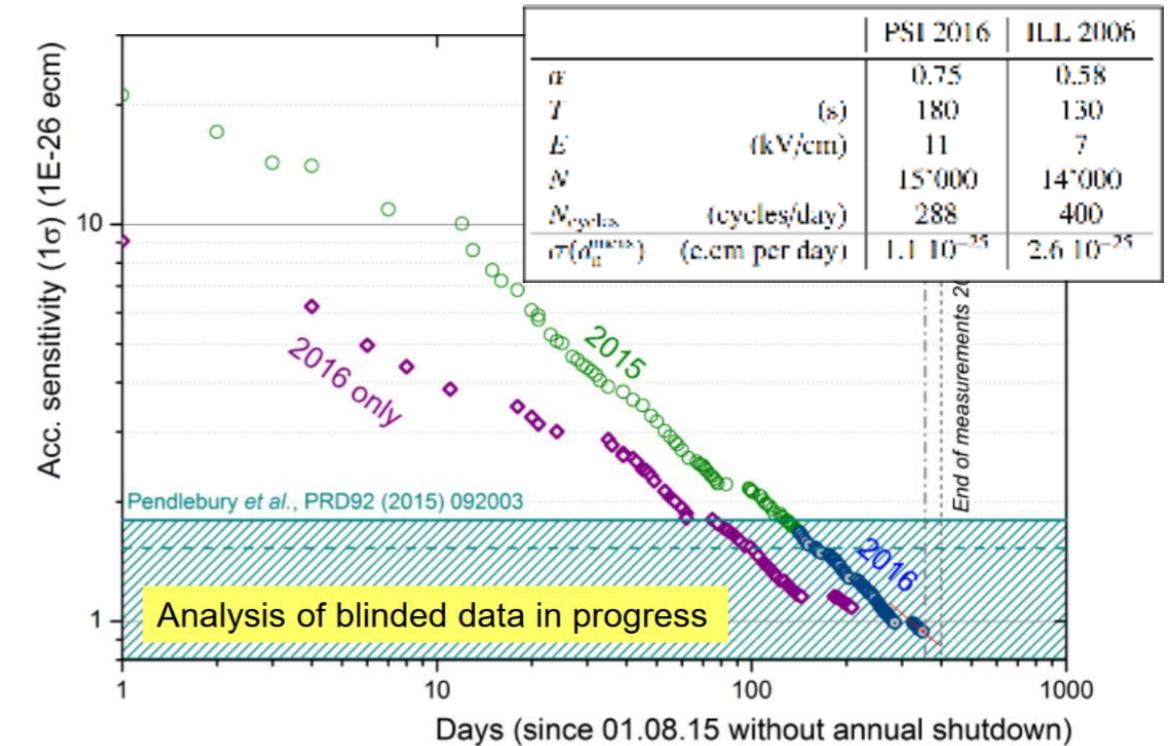
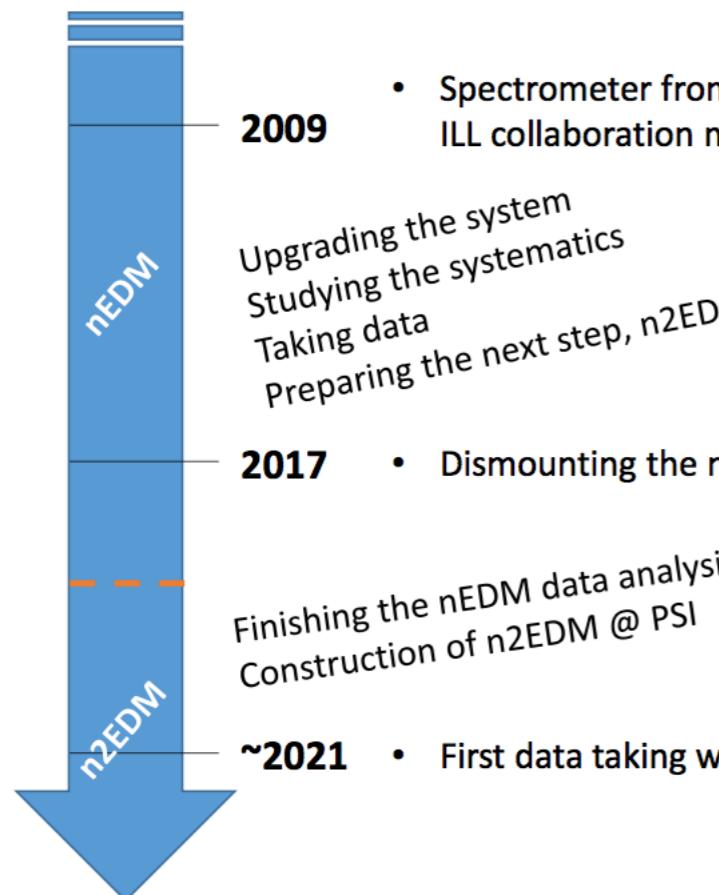
$$\omega_{E \parallel B} - \omega_{E \text{anti-} \parallel B} \equiv \Delta\omega = \frac{4d_n E}{\hbar}$$

Figure: Physics Today 56 6 (2003) 33

# Neutron EDM

- nEDM & n2EDM @ PSI

- Using Ultra Cold Neutrons (trapped)
  - T close to  $\tau$ (neutron)
- Main challenges:
  - Number of neutrons
  - B field stability ( $\sim 0.03$  pT) / uniformity ( $\sim$ pT)



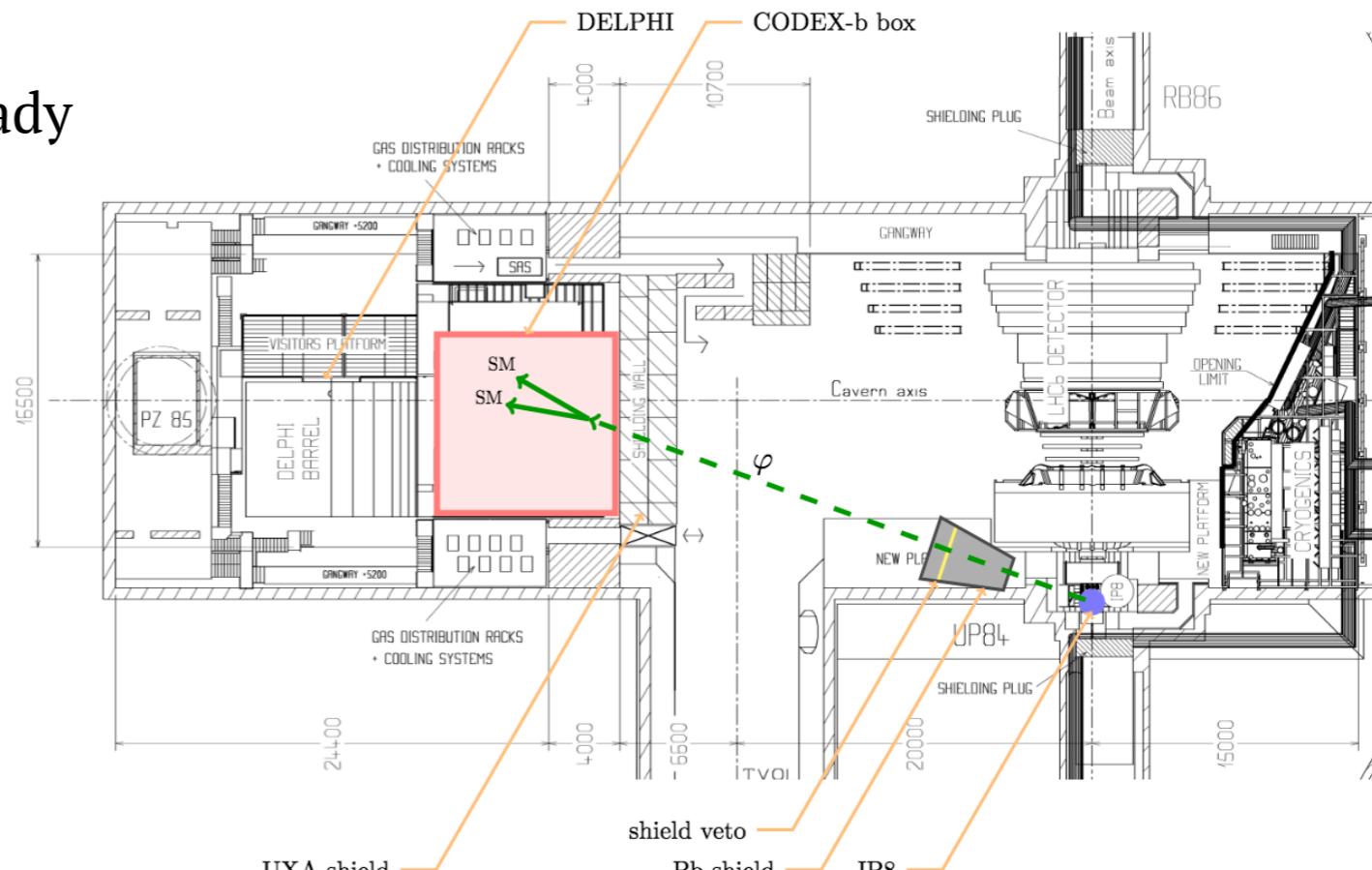
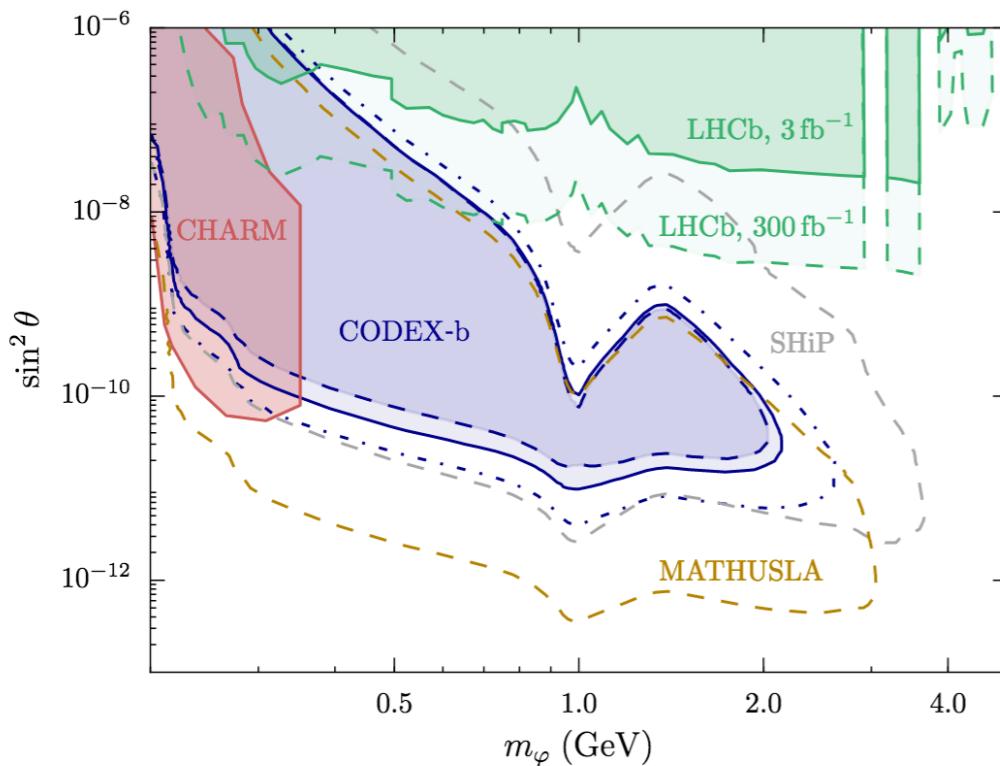
$$\sigma(d_n) = \frac{\hbar}{2\alpha|E|T \sqrt{N}}$$

	nEDM 2016	n2EDM baseline
diameter (cm)	47	80
$\alpha$	0.75	0.8
$E$ (kV/cm)	11	15
$T$ (s)	180	180
$N$ (per cycle)	15'000	121'000
$\sigma(d_n)$ (per day)	$11 \times 10^{-26} e \text{ cm}$	$2.6 \times 10^{-26} e \text{ cm}$
$\sigma(d_n)$ (total)	$9.8 \times 10^{-27} e \text{ cm}$	$1.1 \times 10^{-27} e \text{ cm}$

# LLPs & hidden sector

- Compact Detector for Exotics at LHCb (CODEX-b): [Proposal, arxiv:1708.09395]

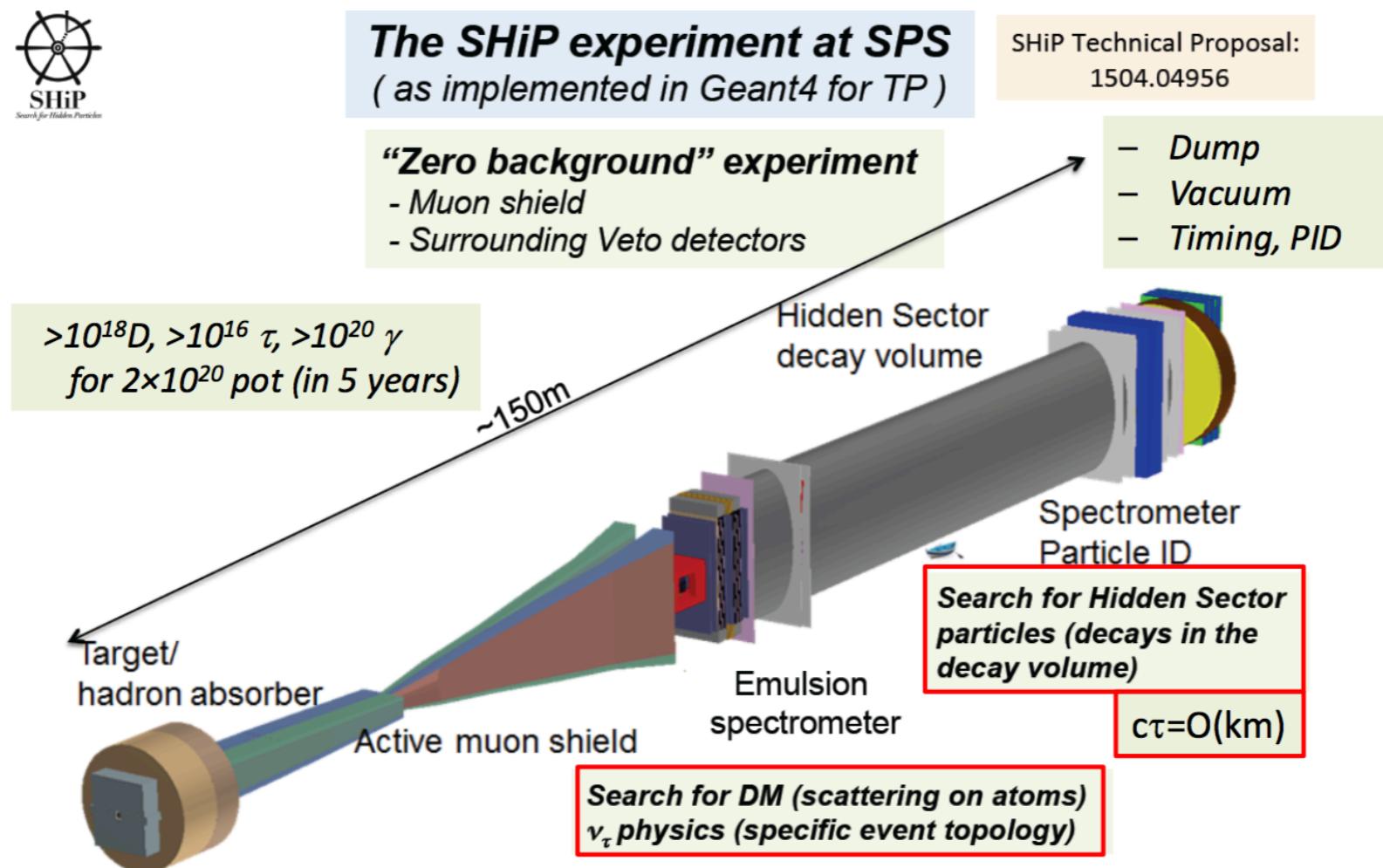
- ▶ LLPs predicted by many NP models
- ▶ ATLAS, CMS (high  $p_T$ ) LHCb (softer  $p_T$ ) already providing limits on such particles
- ▶ CODEX-b is particularly interesting for 1GeV LLPs, such as
  - dark photons
  - light CP-even scalar,  $\varphi$ , that mixes with the Higgs ( $\theta \ll 1$ )



- ▶ Other proposals such as MATHUSLA
    - Above ATLAS (on the ground)
    - much larger decay volume (x100) wrt CODEX-b
- [arxiv:1606.06298]

# LLPs & hidden sector

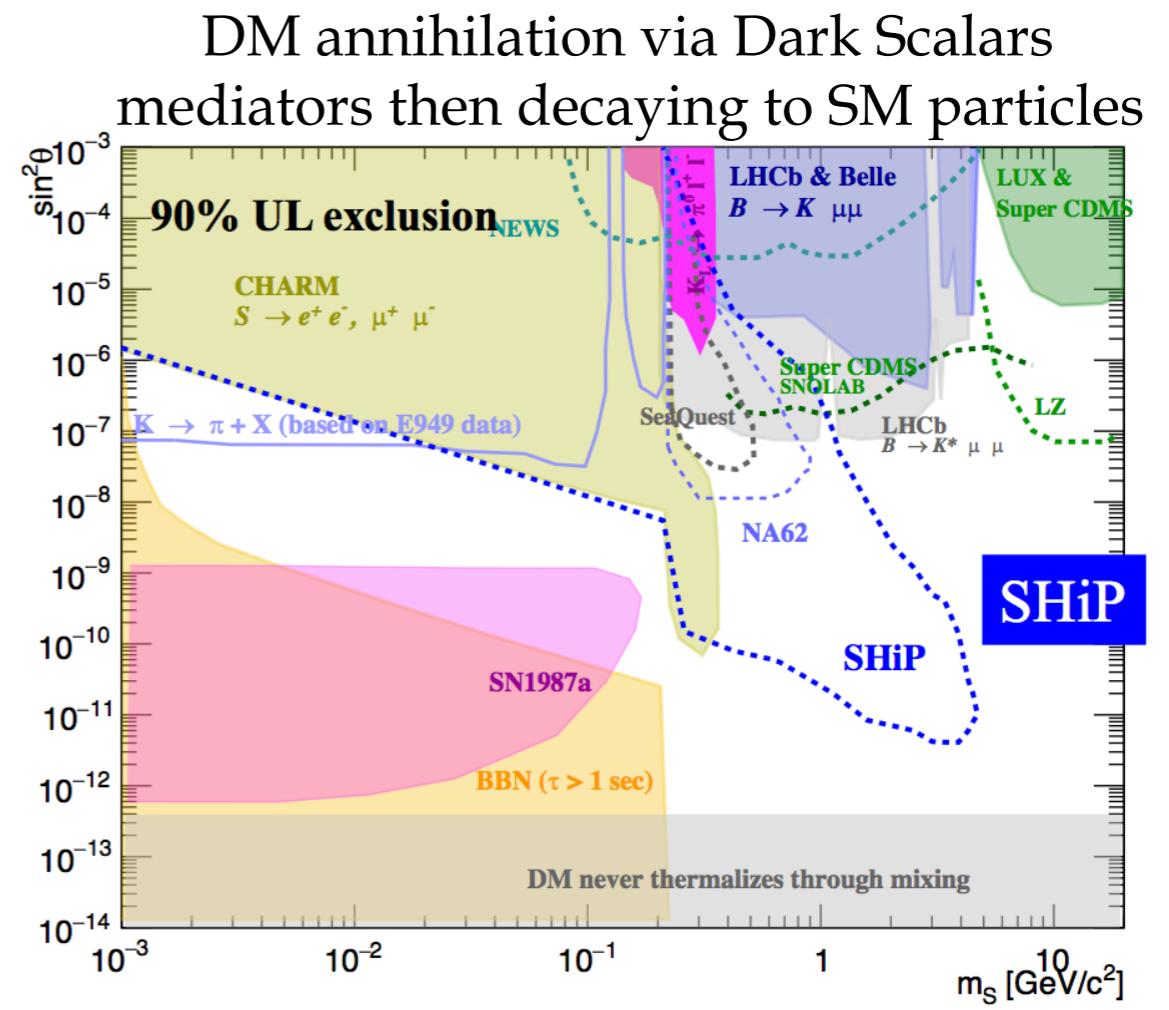
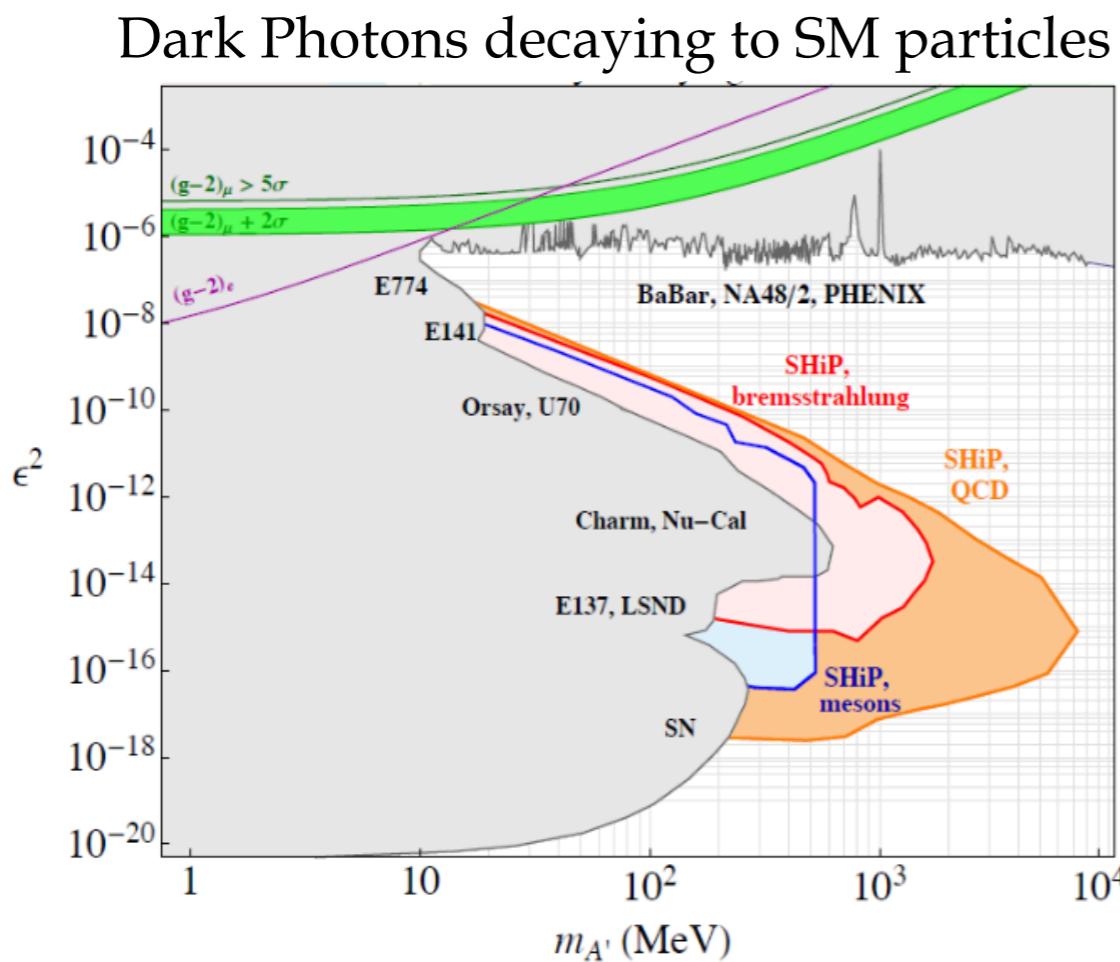
- Search for Hidden Particles (SHiP):
  - General purpose detector at the new beam dump facility at the SPS in >2026



- Hidden particles have very feeble couplings, hence they are (very) long-lived:
  - The 60m-long, in-vacuum SHiP decay volume allows us to be sensitive to extremely low couplings
- Hidden particles from D and B decays have large  $p_T$ :
  - SHiP large geometrical acceptance maximizes detection of decay products

# LLPs & hidden sector

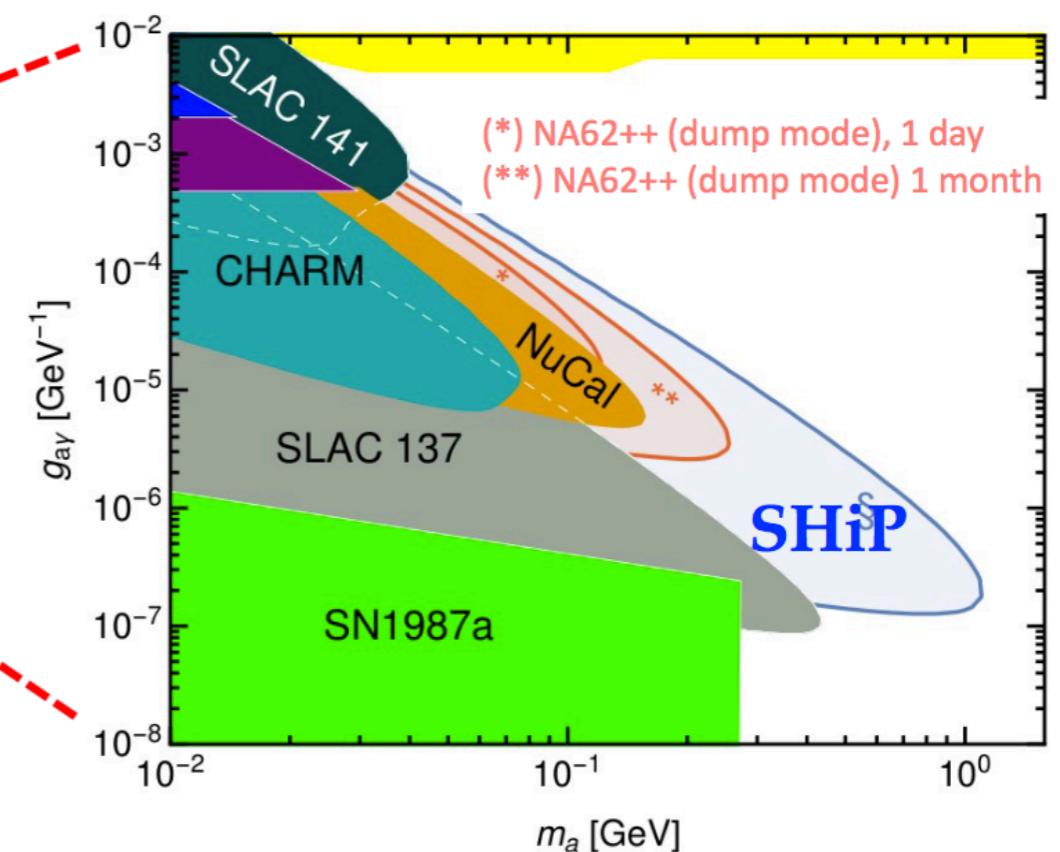
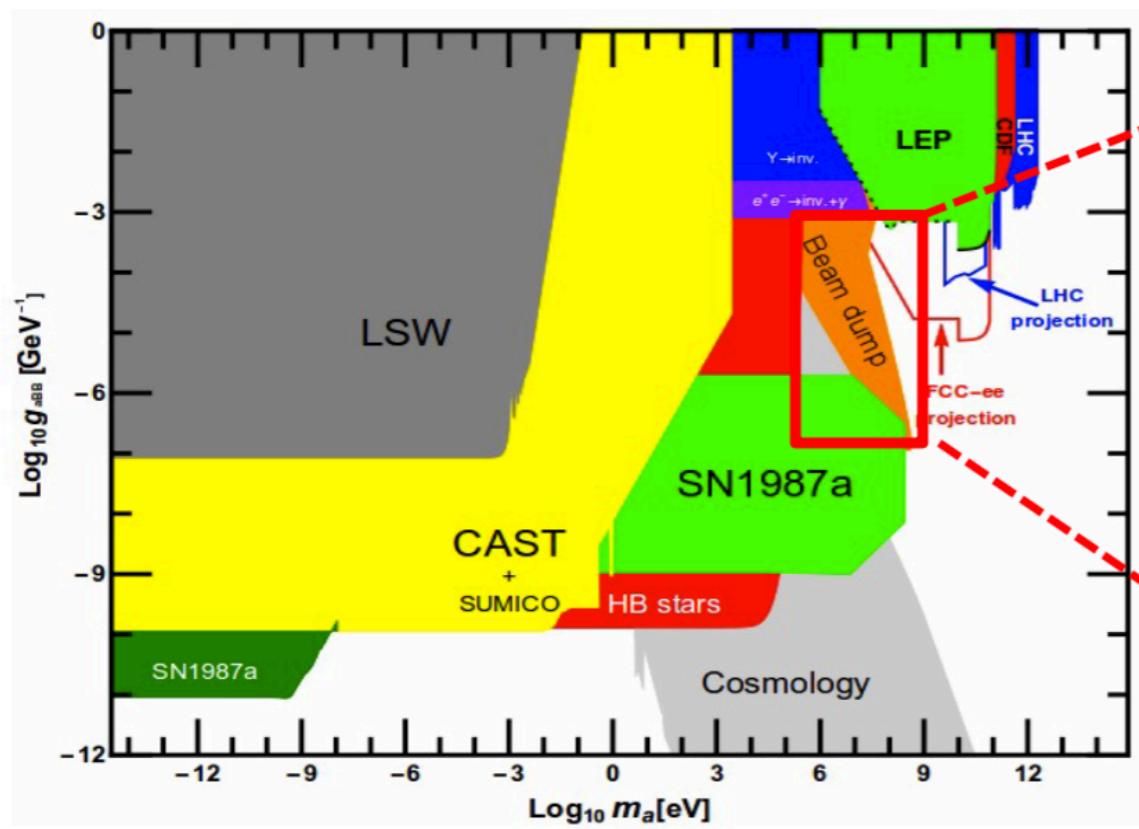
- Search for Hidden Particles (SHiP):
  - General purpose detector at the new beam dump facility at the SPS in >2026
  - Wide physics program, such as
    - Light Dark Matter mediators
      - Dark (Pseudo)-Scalars;
      - Dark Photons



# LLPs & hidden sector

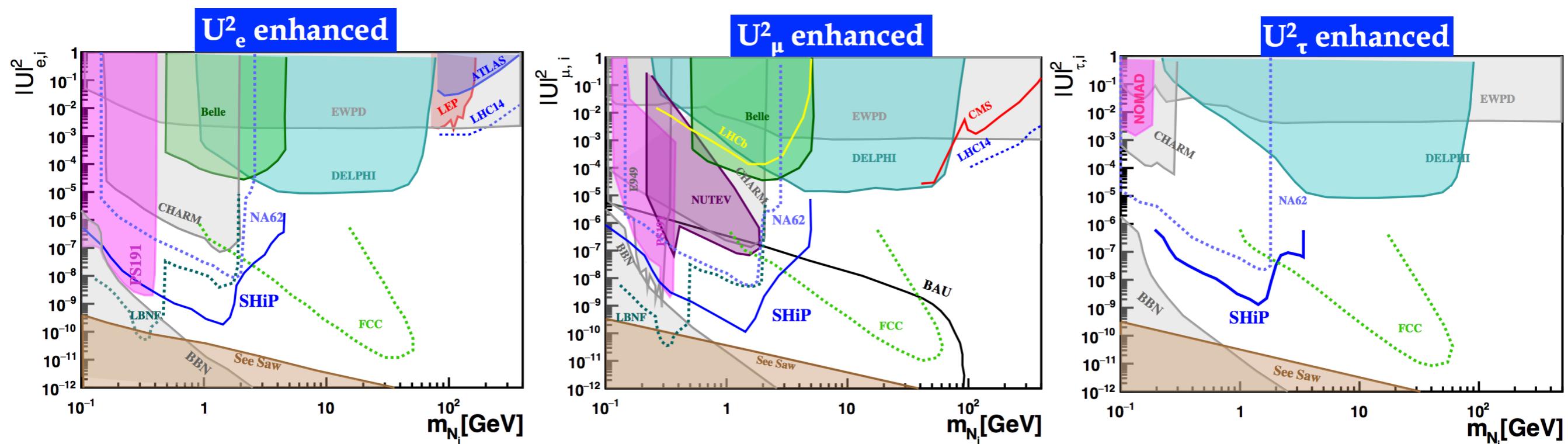
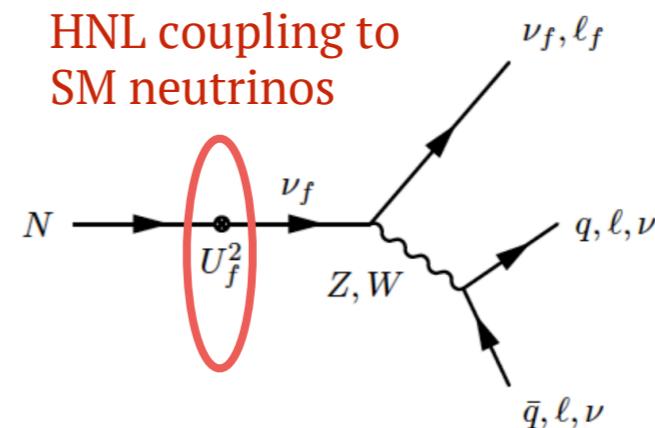
- Search for Hidden Particles (SHIP):
  - General purpose detector at the new beam dump facility at the SPS in >2026
  - Wide physics program, such as
    - Light Dark Matter mediators
      - Dark (Pseudo)-Scalars;
      - Dark Photons
    - Axion Like Particles

ALP decaying to a photon pair



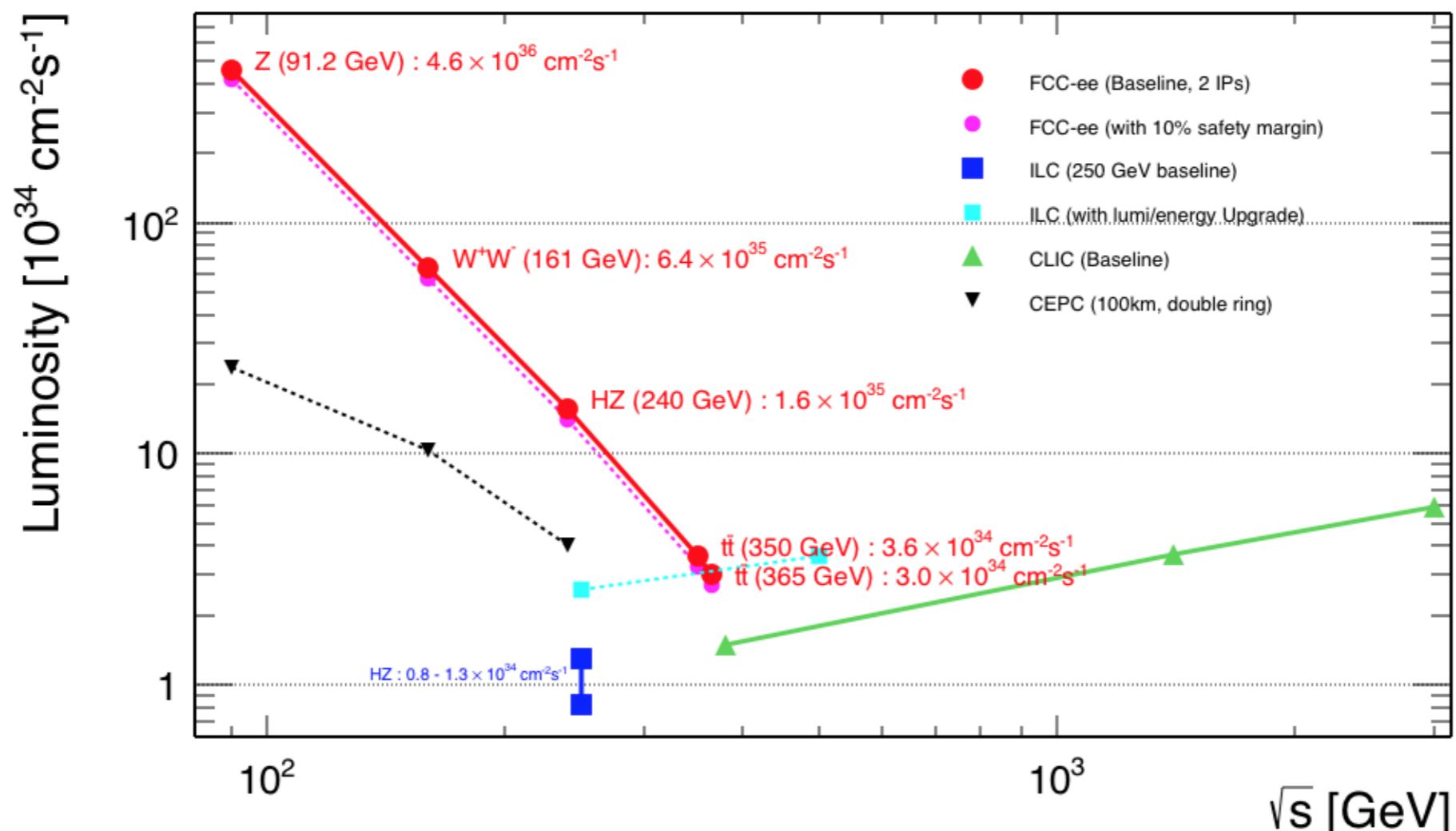
# LLPs & hidden sector

- Search for Hidden Particles (SHIP):
  - General purpose detector at the new beam dump facility at the SPS in >2026
  - Wide physics program, such as
    - **Light Dark Matter mediators**
      - Dark (Pseudo)-Scalars;
      - Dark Photons
    - **Axion Like Particles**
    - **Heavy Neutral Leptons**

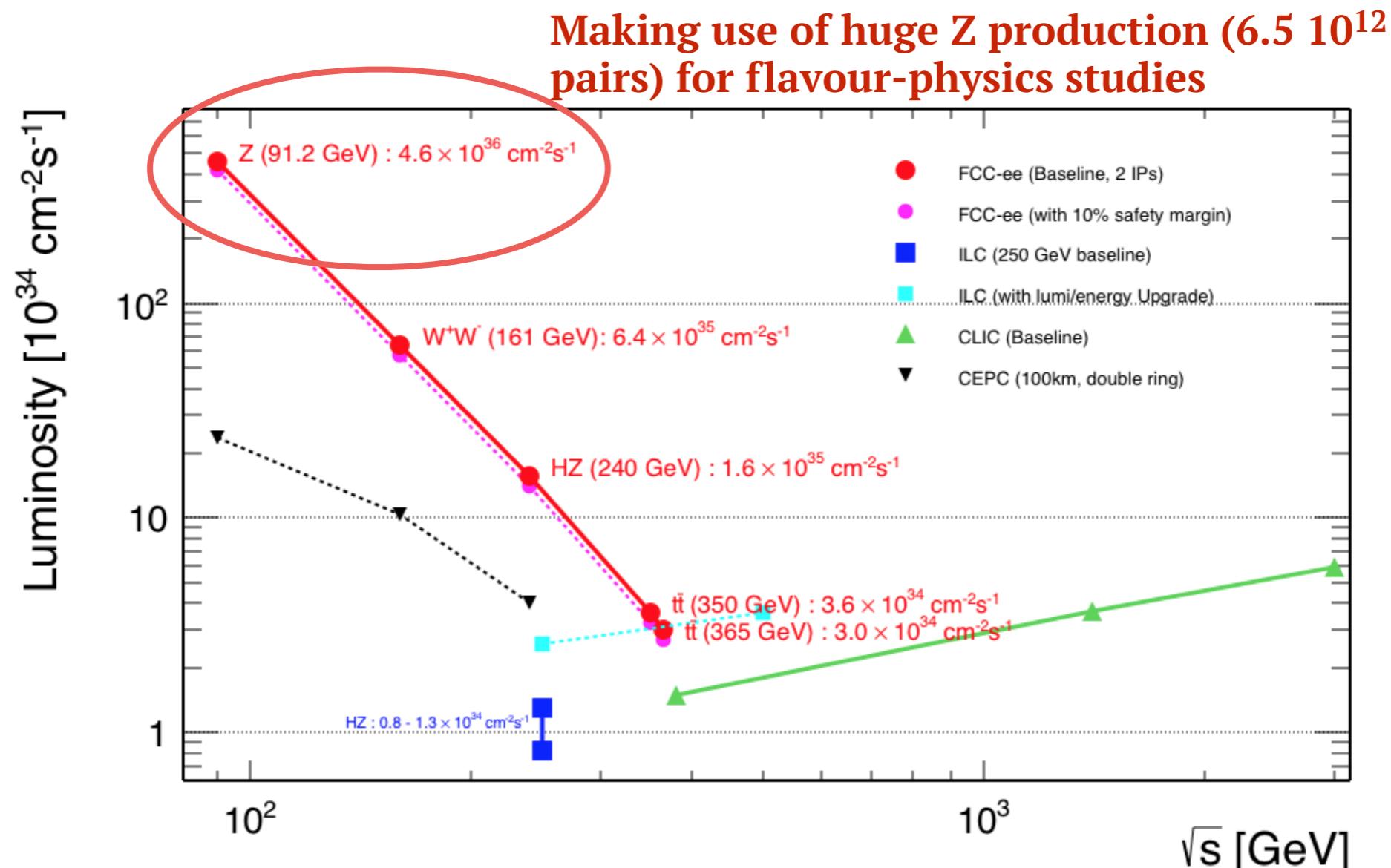


# FCC

- Will only discuss physics opportunity in the context of a FCC-ee machine



- Will only discuss physics opportunity in the context of a FCC-ee machine



- Comparison of accumulated b-hadrons in two ee machines

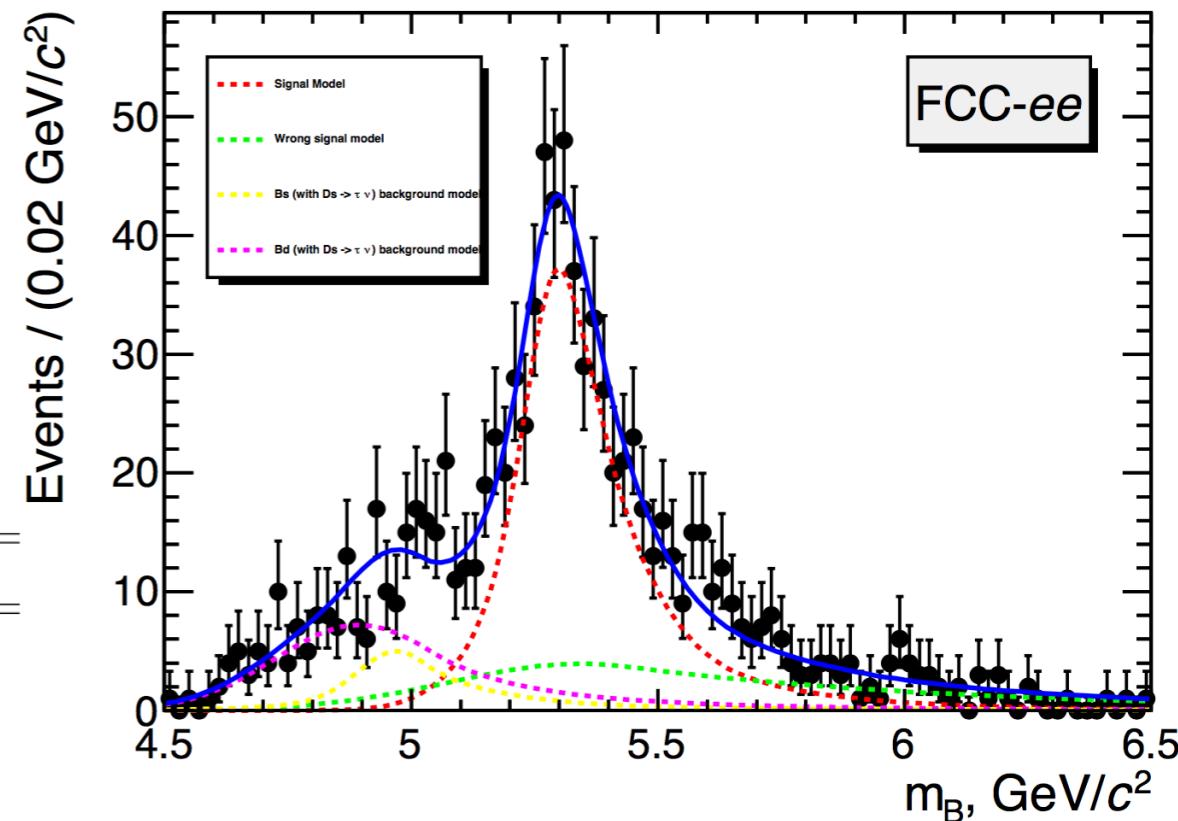
Particle production ( $10^9$ )	$B^0 / \bar{B}^0$	$B^+ / B^-$	$B_s^0 / \bar{B}_s^0$	$\Lambda_b / \bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	1000	1000	250	250	550	170

- FCC-ee ideal to study for instance:

- LFV in Z decays
- BSM in  $\Delta F = 2$  transitions
- **Unique access to the decay  $B \rightarrow K^*\tau^+\tau^-$**

- Using 3-prong  $\tau$  decay
- partial reconstruction technique to solve the kinematics of the decay
- angular analysis would allow tremendous constraints on NP models

Decay mode	$B^0 \rightarrow K^*(892)e^+e^-$	$B^0 \rightarrow K^*(892)\tau^+\tau^-$	$B_s(B^0) \rightarrow \mu^+\mu^-$
Belle II	$\sim 2\,000$	$\sim 10$	n/a (5)
LHCb Run I	150	-	$\sim 15$ (-)
LHCb Upgrade	$\sim 5\,000$	-	$\sim 500$ (50)
FCC-ee	$\sim 200\,000$	$\sim 1\,000$	$\sim 1\,000$ (100)



# Summary

- Flavour physics is at the heart of the SM and has demonstrated in the past to be a powerful tool to look for NP
- Up to now no unambiguous NP signal emerged...but tensions are present
  - ▶ several complementary observables are needed (benefiting from their correlations)
  - ▶ both **experimental** (LHCb, Belle II, but also GPD, NA62, BESIII,...) and **theoretical** improvements (Lattice QCD, LCSR) are needed!
- The absence of positive results is also very helpful in the search of NP
  - ▶ many NP scenarios are now strongly constrained!
- Many new exciting results are expected in the coming years!

# Additional material

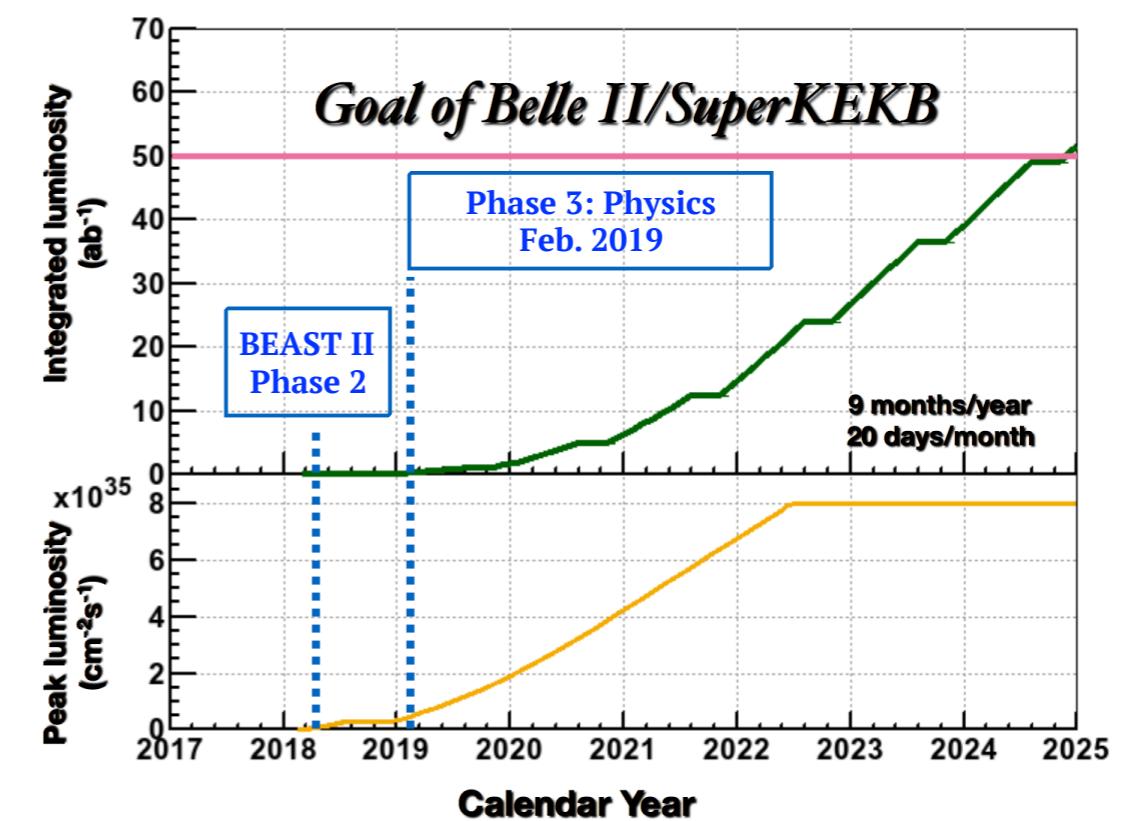
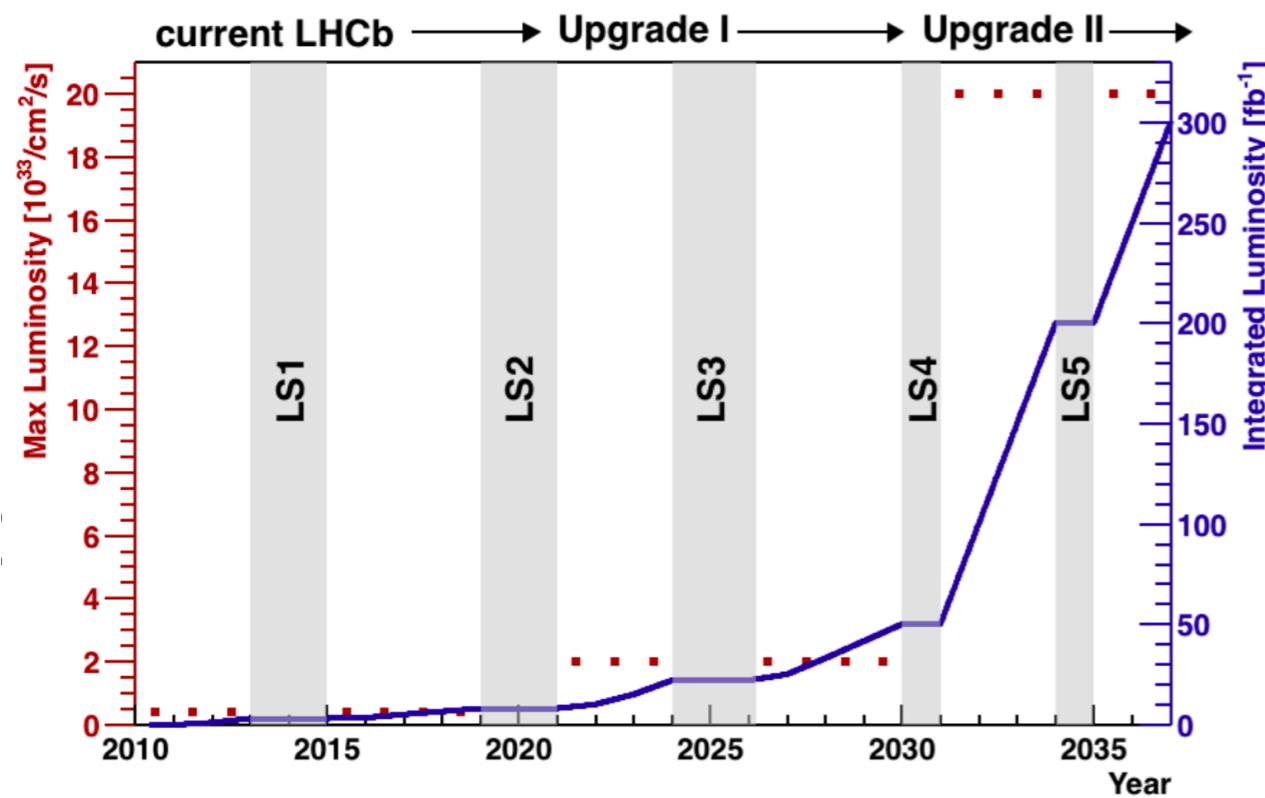


# LHCb and Belle2

- Wide and highly complementary physics program

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
<b>EW Penguins</b>					
$R_K$ ( $1 < q^2 < 6 \text{ GeV}^2 c^4$ )	0.1 [274]	0.025	0.036	0.007	–
$R_{K^*}$ ( $1 < q^2 < 6 \text{ GeV}^2 c^4$ )	0.1 [275]	0.031	0.032	0.008	–
$R_\phi, R_{pK}, R_\pi$	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
<b>CKM tests</b>					
$\gamma$ , with $B_s^0 \rightarrow D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
$\gamma$ , all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$ , with $B^0 \rightarrow J/\psi K_s^0$	0.04 [609]	0.011	0.005	0.003	–
$\phi_s$ , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
$\phi_s$ , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$ , with $B_s^0 \rightarrow \phi \phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a_{sl}^s$	$33 \times 10^{-4}$ [211]	$10 \times 10^{-4}$	–	$3 \times 10^{-4}$	–
$ V_{ub} / V_{cb} $	6% [201]	3%	1%	1%	–
<b><math>B_s^0, B^0 \rightarrow \mu^+ \mu^-</math></b>					
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
<b><math>b \rightarrow c \ell^- \bar{\nu}_l</math> LUV studies</b>					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
<b>Charm</b>					
$\Delta A_{CP}(KK - \pi\pi)$	$8.5 \times 10^{-4}$ [613]	$1.7 \times 10^{-4}$	$5.4 \times 10^{-4}$	$3.0 \times 10^{-5}$	–
$A_\Gamma (\approx x \sin \phi)$	$2.8 \times 10^{-4}$ [240]	$4.3 \times 10^{-5}$	$3.5 \times 10^{-4}$	$1.0 \times 10^{-5}$	–
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	$13 \times 10^{-4}$ [228]	$3.2 \times 10^{-4}$	$4.6 \times 10^{-4}$	$8.0 \times 10^{-5}$	–
$x \sin \phi$ from multibody decays	–	$(K3\pi) 4.0 \times 10^{-5}$	$(K_s^0 \pi\pi) 1.2 \times 10^{-4}$	$(K3\pi) 8.0 \times 10^{-6}$	–

# LHCb and Belle2



# LHCb and Belle2

- LHCb versus *B* factories (naive/rough comparison)

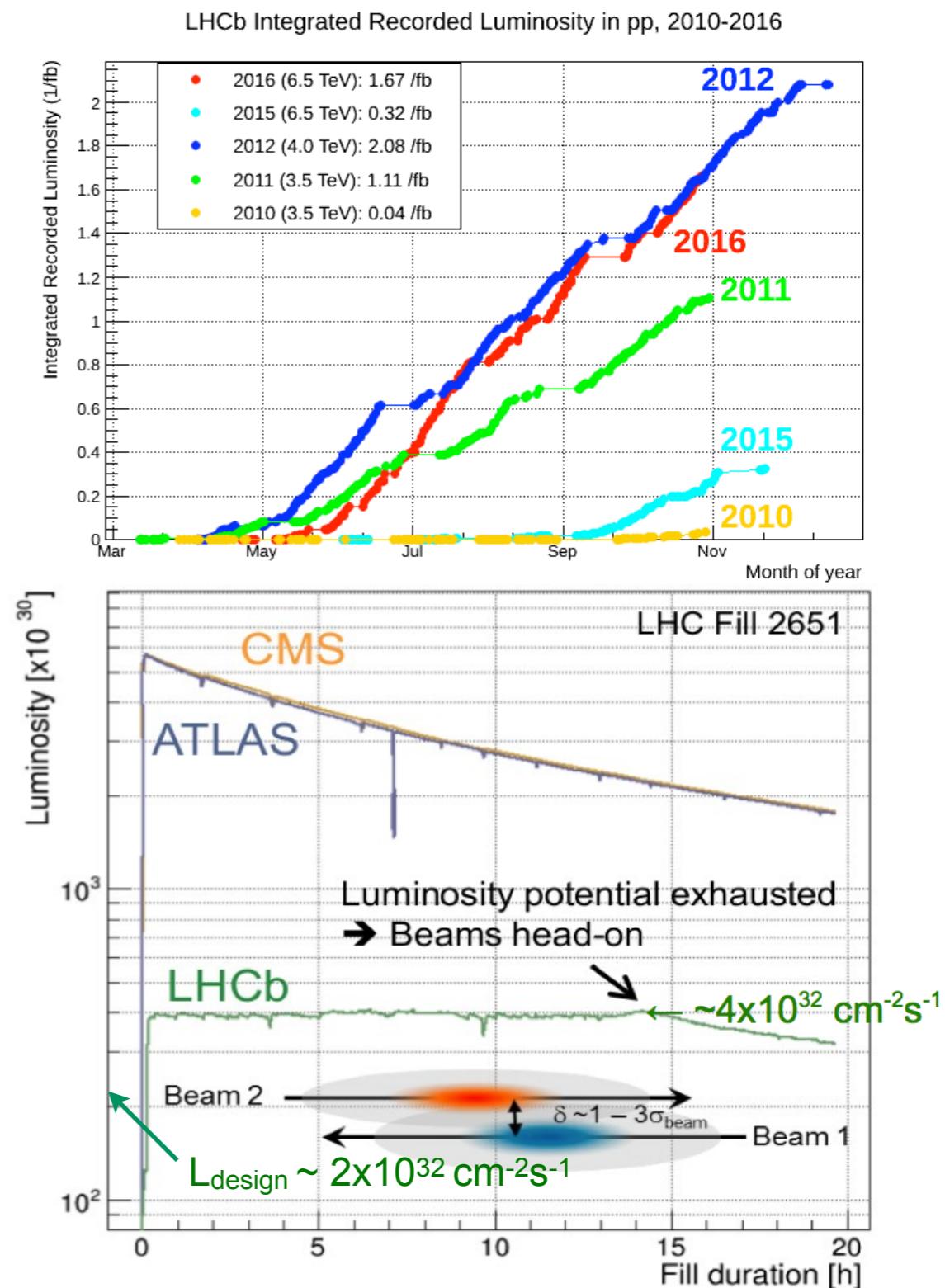
	<i>B</i> factories	LHCb
Statistics	:(	:)
Cleanliness	:)	:(
heavy flavour hadrons produced	$B^+, B^0$ , dedicated run for $B_s$ , charm	$B^+, B^0, B_s, B_c$ , baryons, and lot of charm
neutrino modes	:)	:(
Trigger bias	:)	:(
$\mu / e$ modes	:( / :)	:) / :(

- ▶ Some measurements can only be done by *B* factories or LHCb  
→ important complementarity!
- ▶ Cross-check and competition for common measurements

# The LHCb experiment

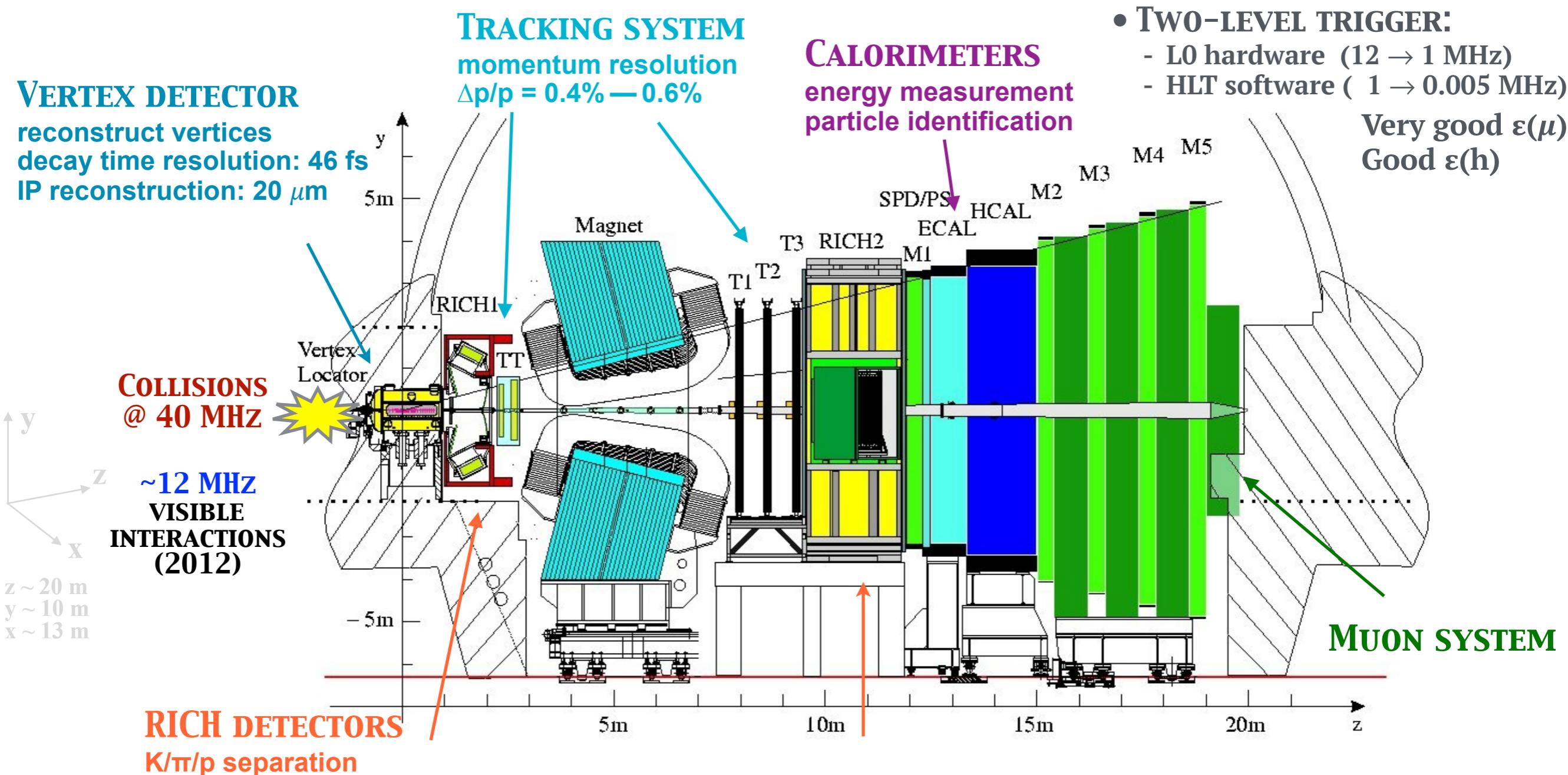
## Physics performances – Run I

- **Integrated luminosity**
  - **1  $\text{fb}^{-1}$  @ 7 TeV (2011)**
  - **2  $\text{fb}^{-1}$  @ 8 TeV (2012)**
  - **2  $\text{fb}^{-1}$  @ 13 TeV (2015+2016)**
- **Excellent LHCb performances**
  - > 99% detector channels working
  - > 99% collected data good for analysis
  - Stable operations with  $L \sim 2 \times L_{\text{design}}$
- **luminosity leveling**
  - Displaced pp beams
  - Constant running conditions
  - **Lower instantaneous luminosity**
  - Lower pile-up
  - Better tracking and PID performances

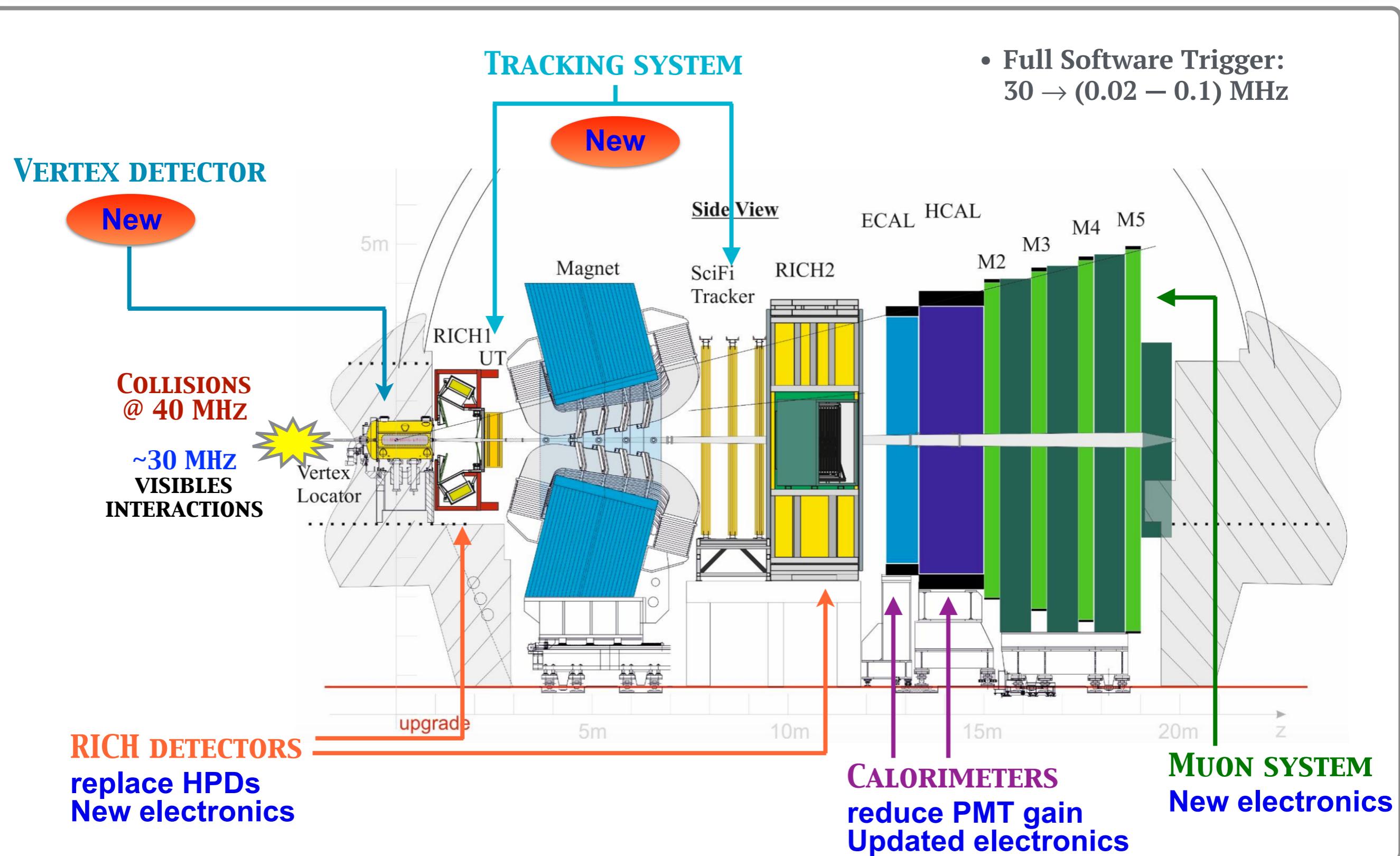


# The LHCb detector

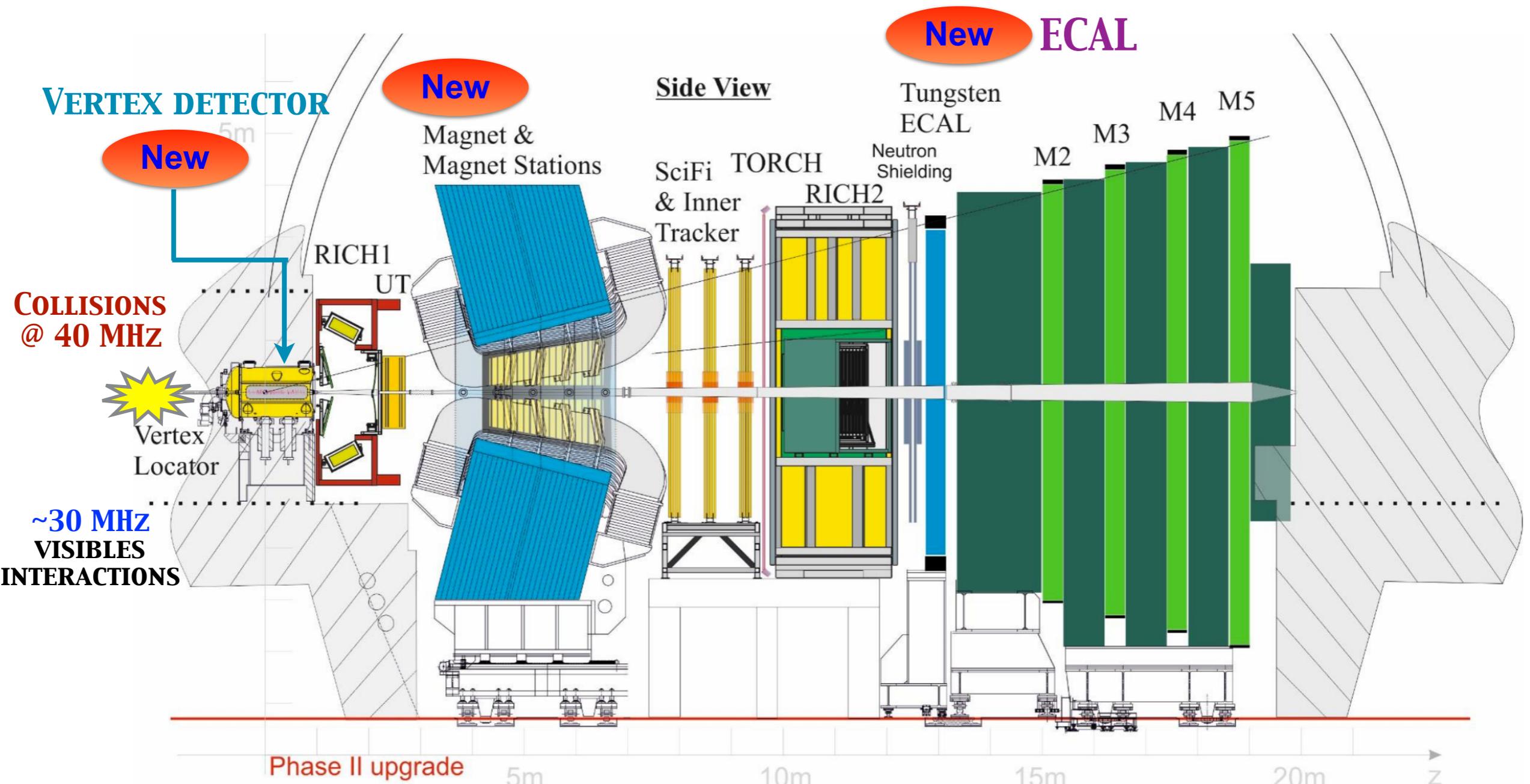
- Forward General-Purpose Detector at the LHC
- ~30 % of heavy quark production cross-section with just 4% of solid angle



# The LHCb Upgrade Phase-I

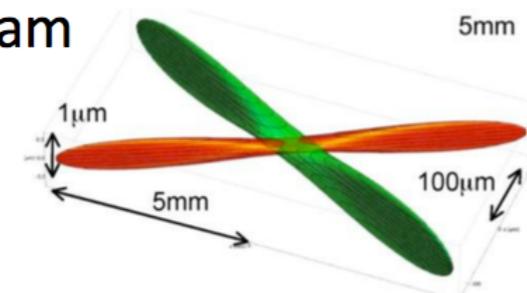


# The LHCb Upgrade Phase-II

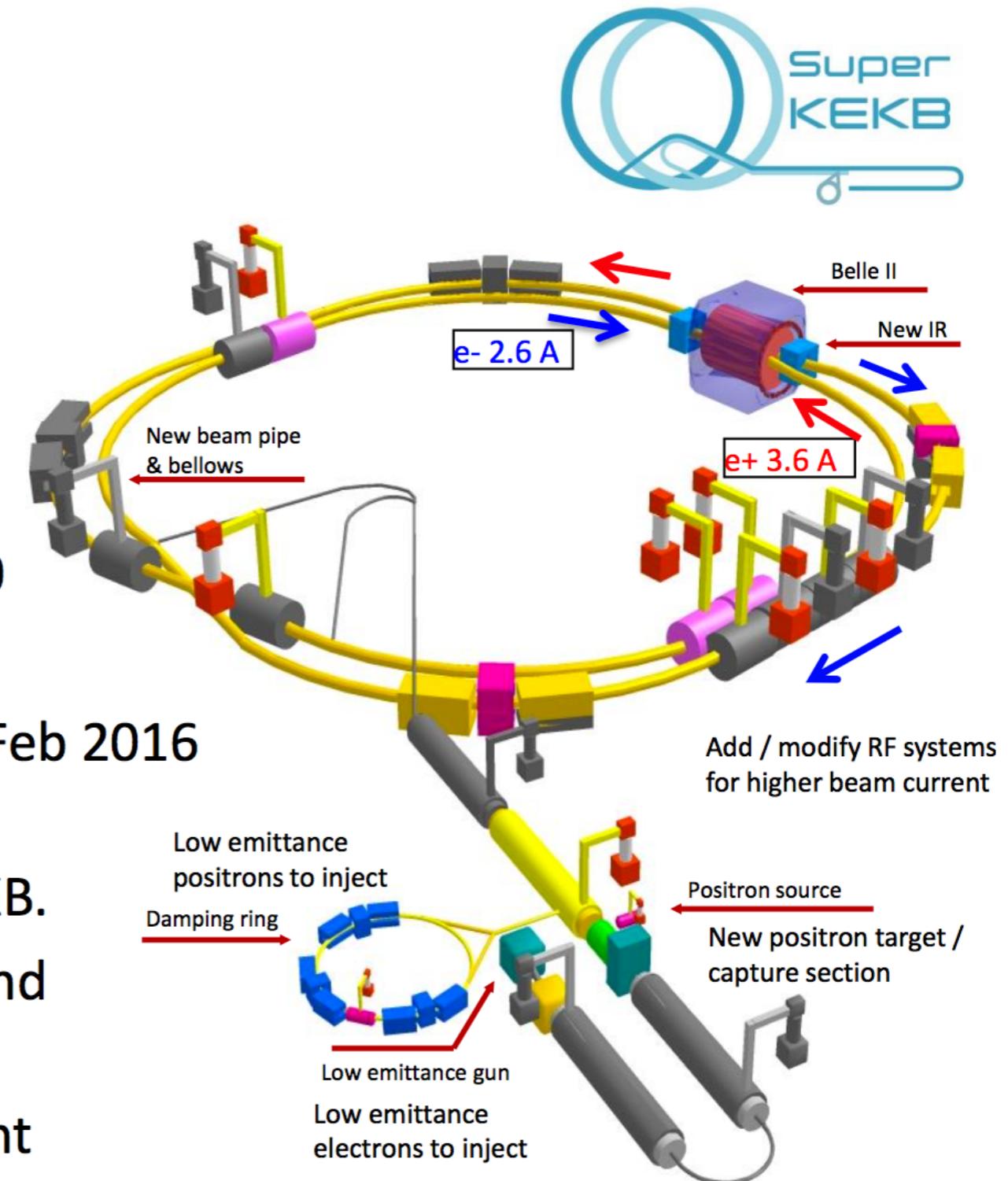


# SUPER KEKB

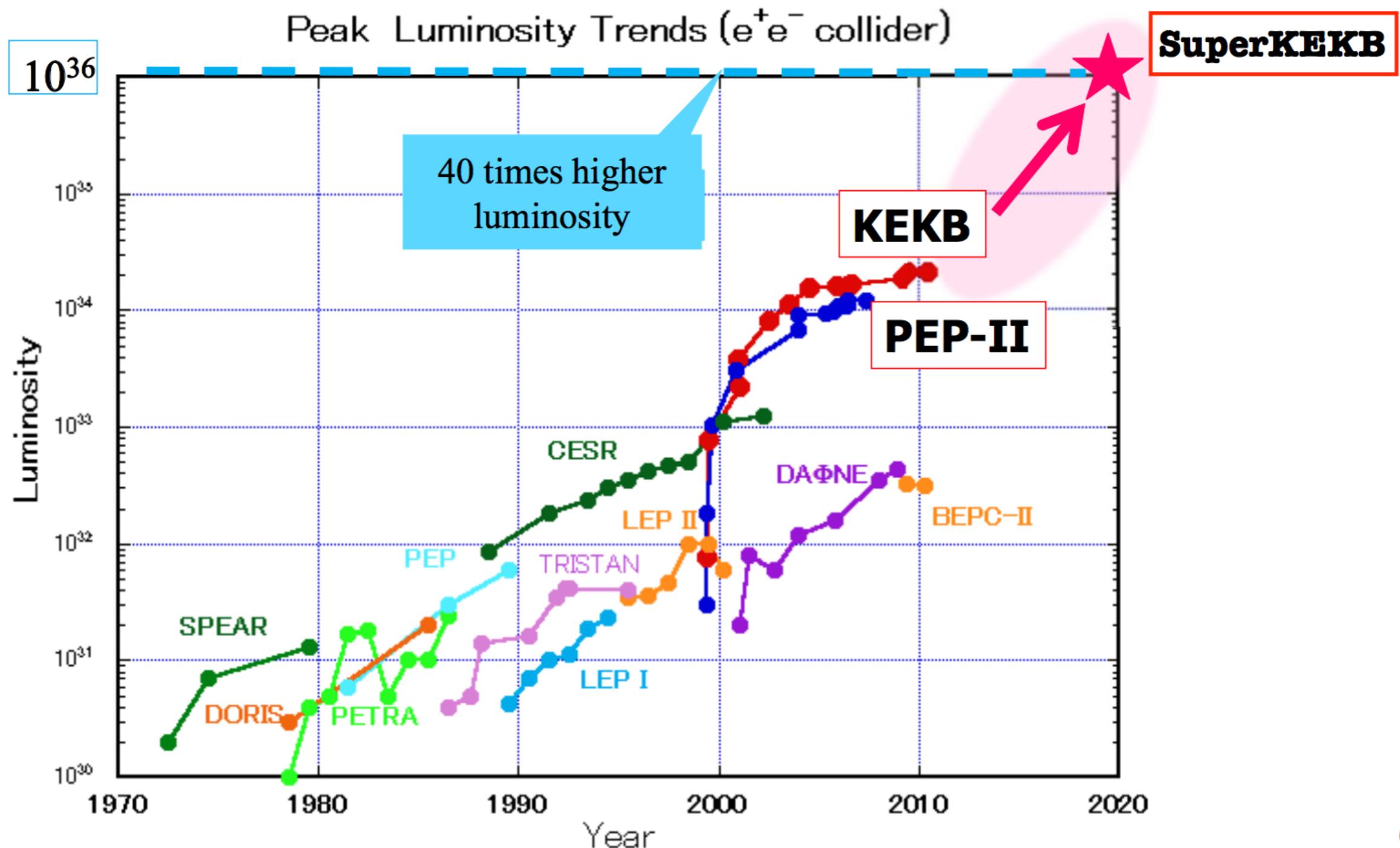
Nano-beam scheme



- **40 times higher luminosity**
  - Focus on small  $\beta^*_y$  :  $\times 20$
  - Increase in current :  $\times 2$
- First tunings was achieved Feb 2016
- Beam background is also 40 times higher than at KEKB.
  - Reduce by collimators and shielding
  - Background measurement

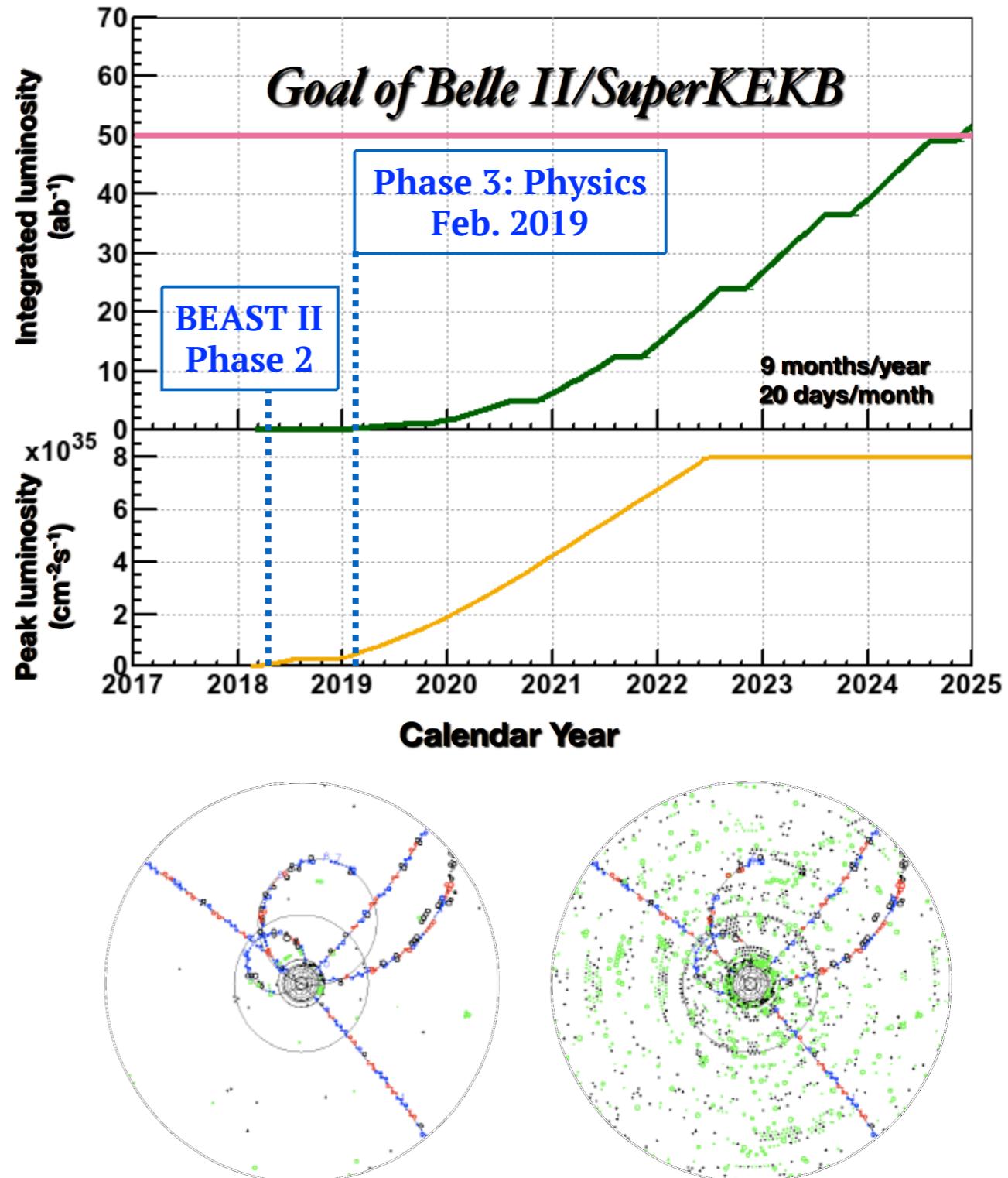


# SUPER KEKB

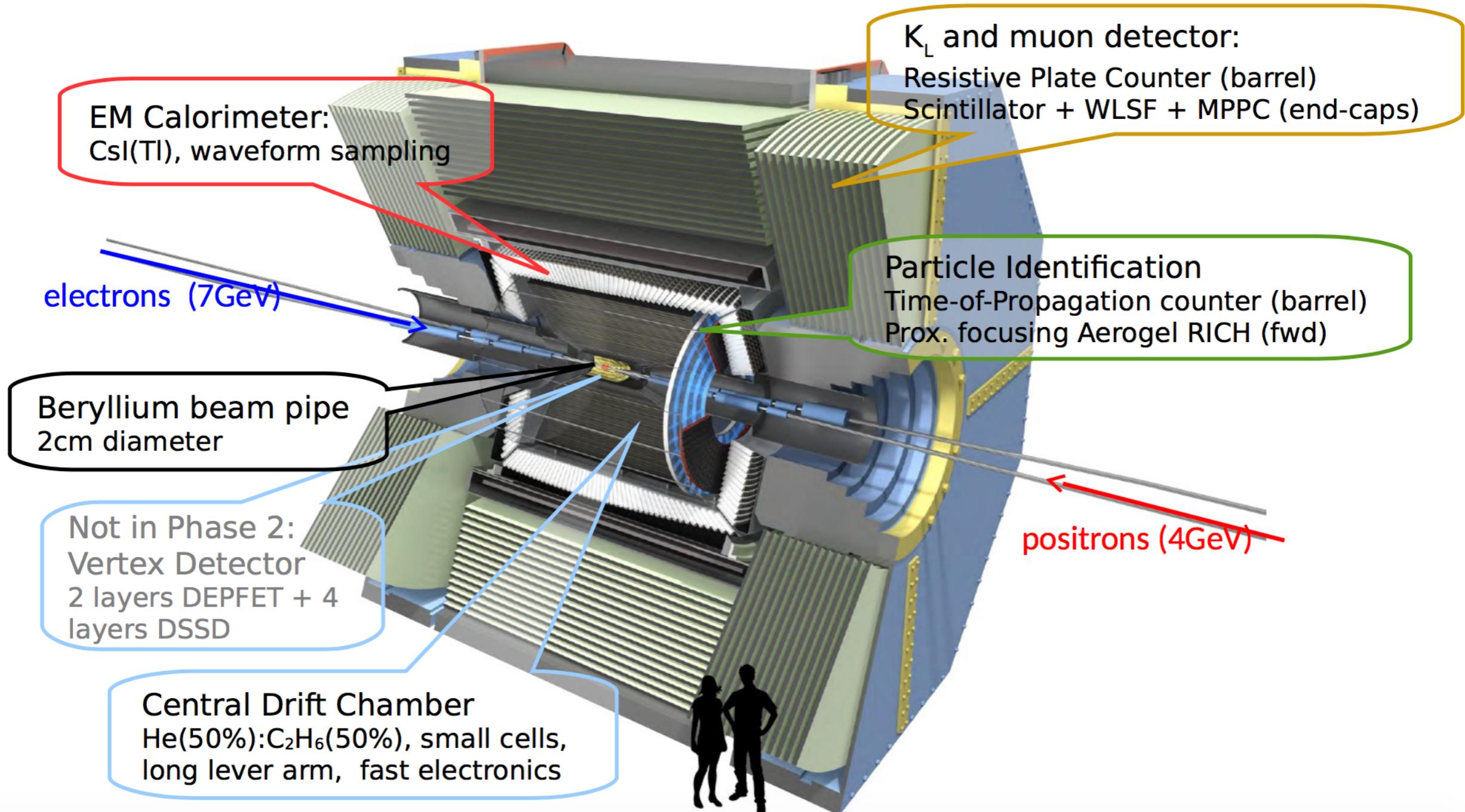


## Frontière en intensité

- Belle II @ SuperKEKB :
  - ▶ **50 ab<sup>-1</sup> en 5 ans (10 ab<sup>-1</sup>/an) ( $\times 50 f\mathcal{L}$ )**
  - ▶ **Complémentarité avec LHCb:**
    - mesures **inclusives**  
 $B \rightarrow X_S \gamma, B \rightarrow X_S \ell \ell, \dots$
    - modes avec **énergie manquante**  
 $B \rightarrow \tau \nu, B \rightarrow D^{(*)} \tau \nu, B \rightarrow K^* \nu \nu, \tau \text{ decays} \dots$
    - modes **neutres**  
 $B \rightarrow \gamma \gamma, B \rightarrow K_S^0 \pi^0 \gamma, B \rightarrow K_S^0 \pi^- \pi^+ \gamma \dots$
  - ▶ **Défi majeur**
    - Luminosité instantanée  **$\times 40$**
    - Contrôle des **bruits de fonds machine**  
**phase 1 : 2016**  
**phase 2 : mars → juillet 2018**



# Belle II overview



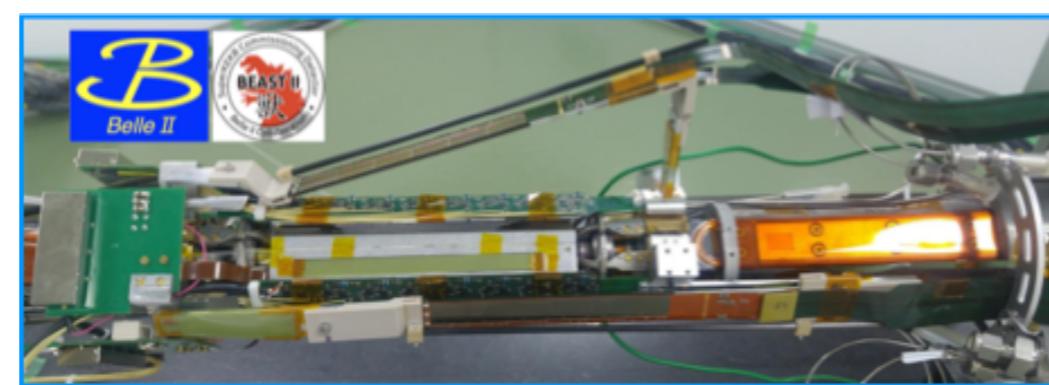
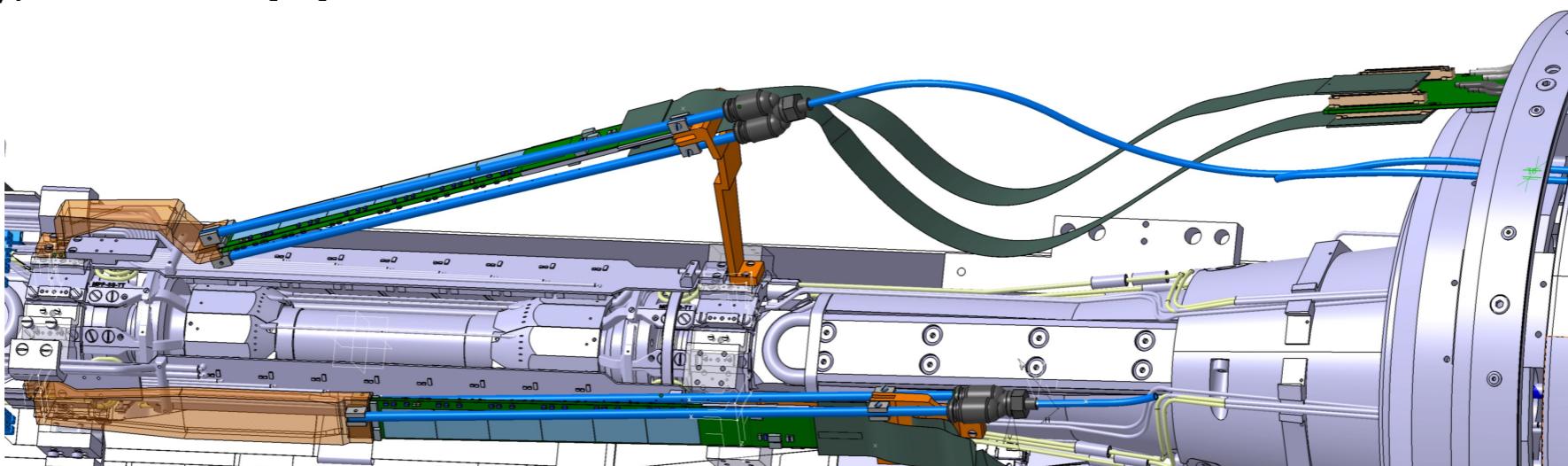
## BEAST II

- **PLUME (developed @ IPHC):**

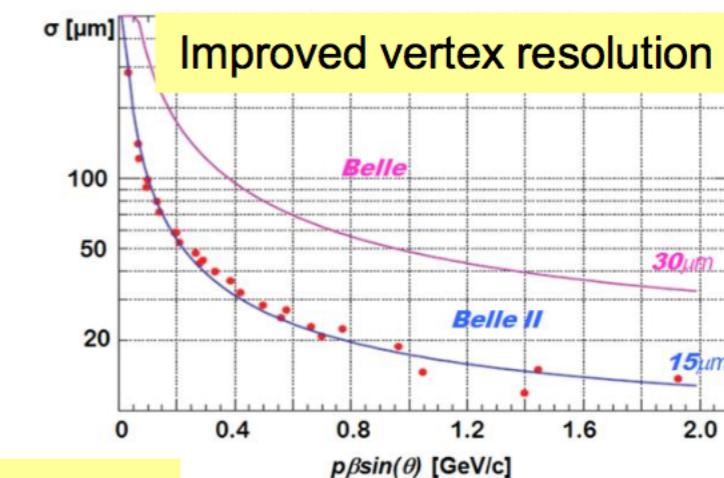
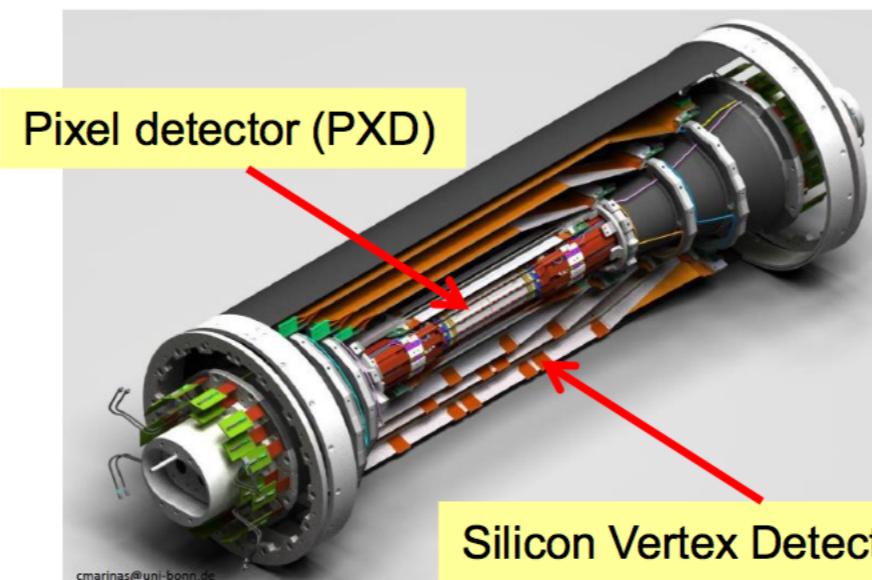
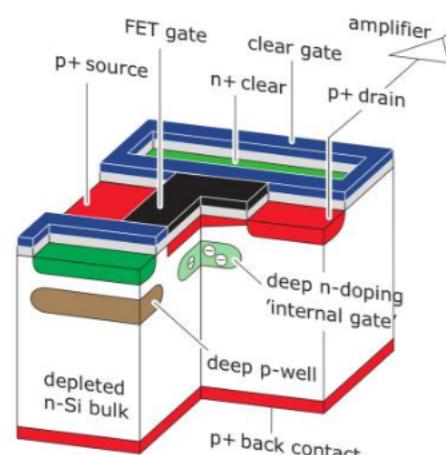
- Standalone mini-tracker: unique information on machine induced background
- CMOS detector of  $16 \times 10^6$  pixels
- Very light self-stiffened detector: 0.4% of  $X_0$

**2 CMOS ladders around the beam pipe:**

- one inclined: scan background in the whole vertex detector radius range.
- one  $\sim //$  to beam pipe: fit of helix tracks.



# Vertex detector (VXD)



Pixel detector (PXD):

- 2 layers of  $75 \times 75 \mu m^2$  pixels at  $r=1.4$  and  $2.4$  cm
- DEPFET technology (DEPleted P-channel Field Effect Transistor)
- produced by Max Planck HLL in Munich
- PXD alone generates 2 GB/s output

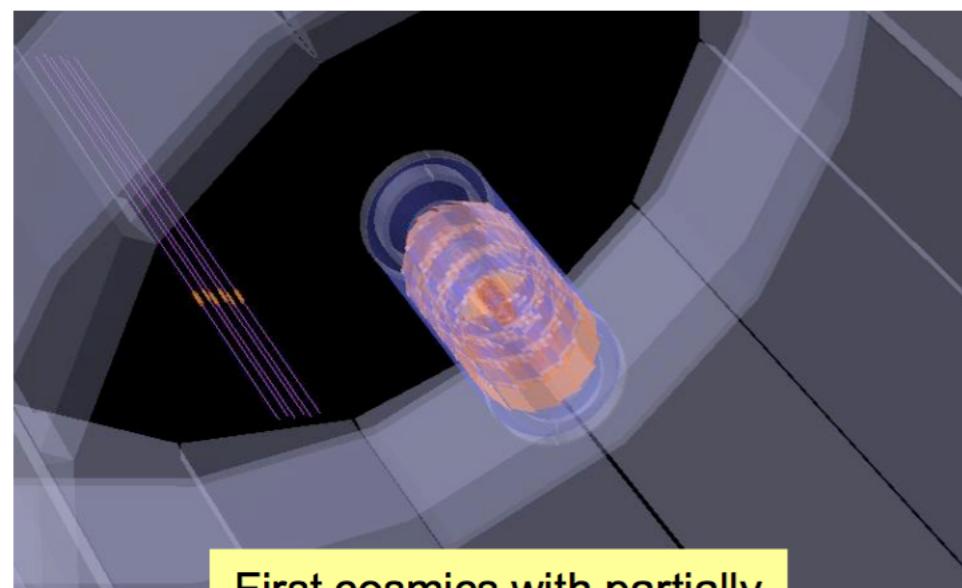
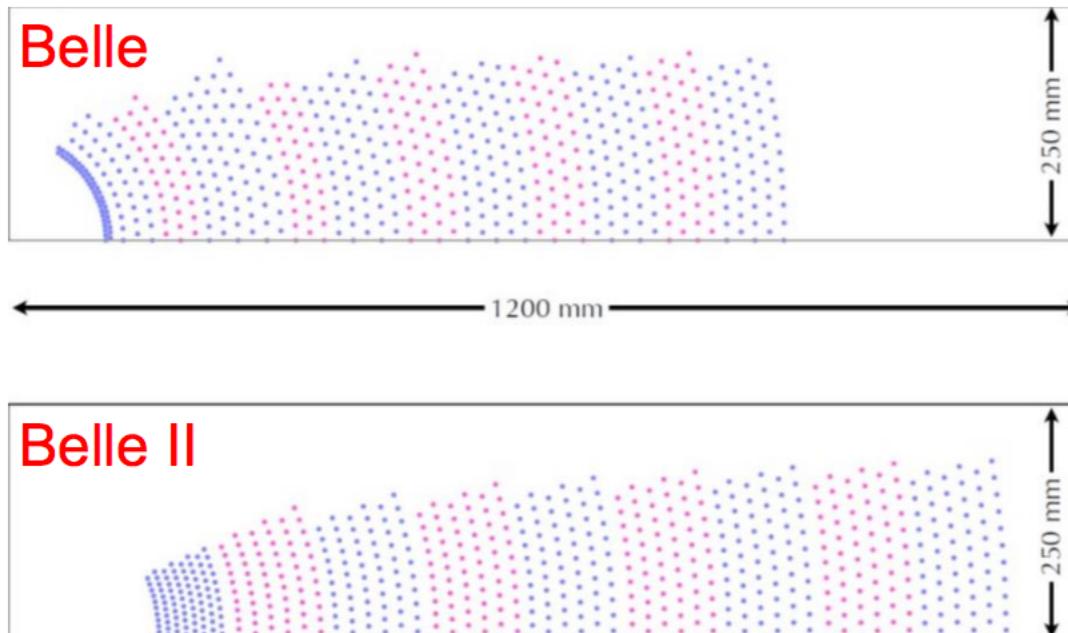
Silicon Vertex Detector (SVD):

- 4 layers of DSSD (Double Sided Silicon Strip Detectors)
- covers full Belle 2 angular acceptance

→ PXD and SVD greatly improve vertex resolution (important for time-dep. CPV)



# Central Drift Chamber (CDC)

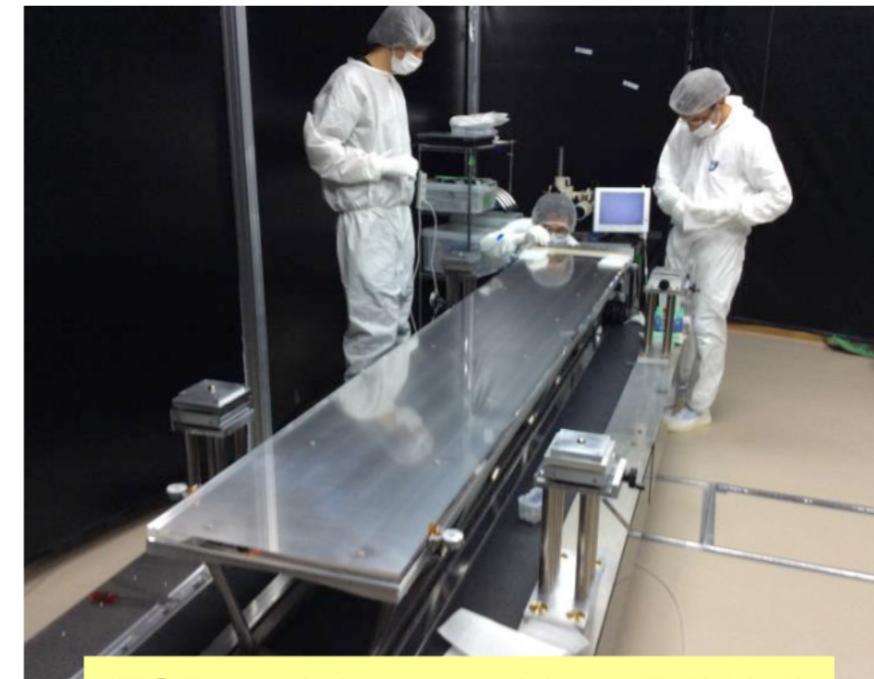
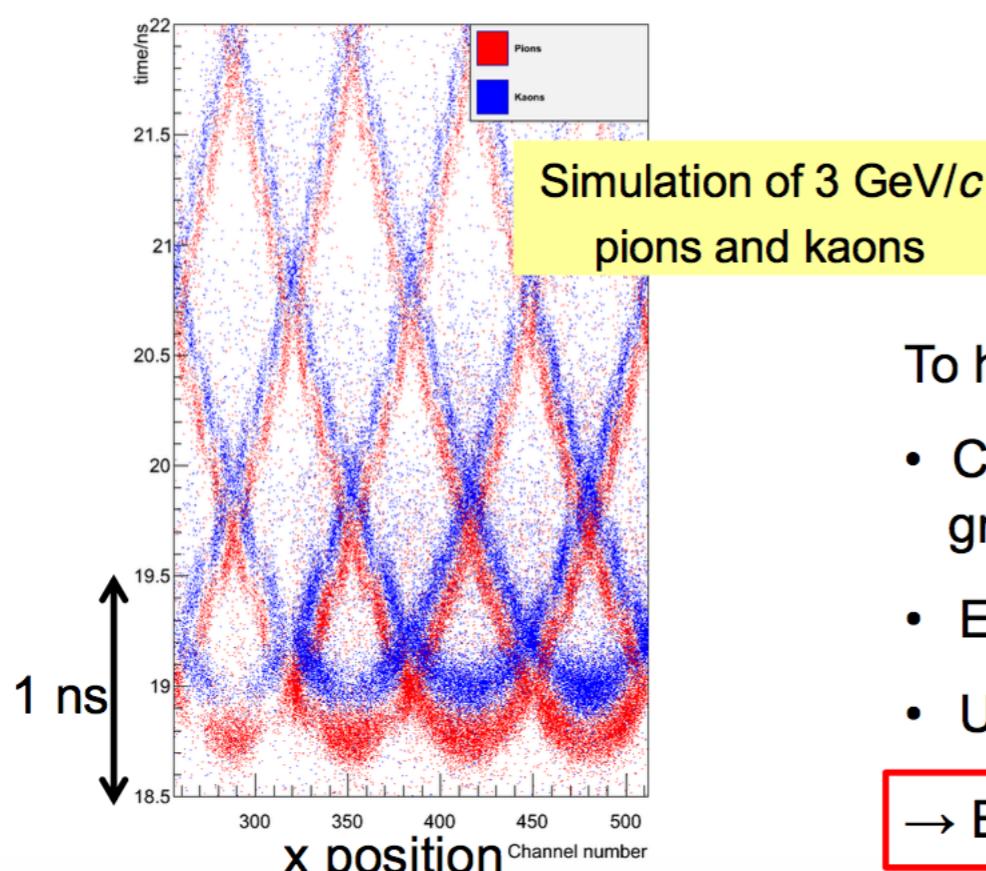
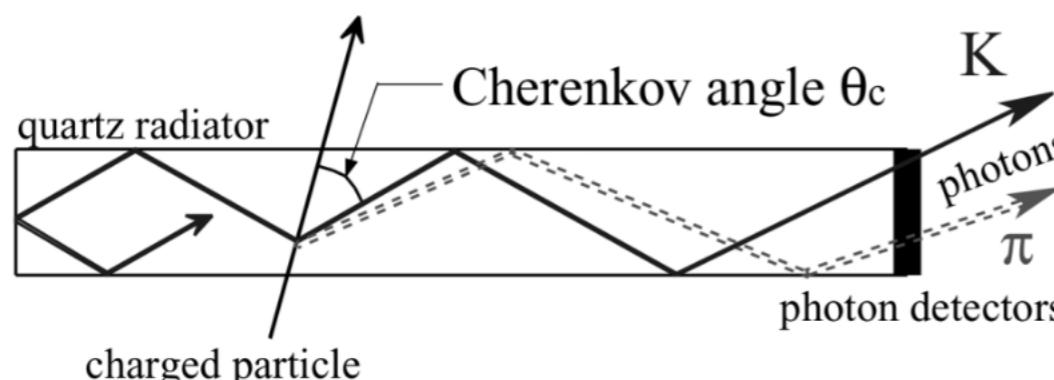


Central drift chamber (CDC):

- Belle II has only one PID system  
→ More space for tracking
- Belle II drift chamber has larger radius than Belle's  
→ Improvement in momentum resolution
- New fast electronics to handle higher trigger rates  
at reduced dead times

# PID barrel: Time Of Propagation (TOP)

An imaging time of propagation (iTOP) detector measures time and position of Cherenkov photons from charged tracks:



iTOP module assembly at Fuji Hall

To have good K/π separation, the iTOP requires:

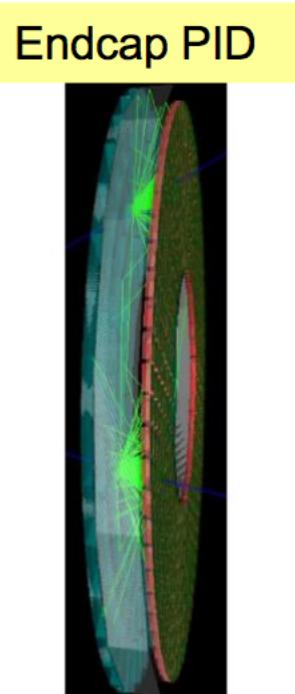
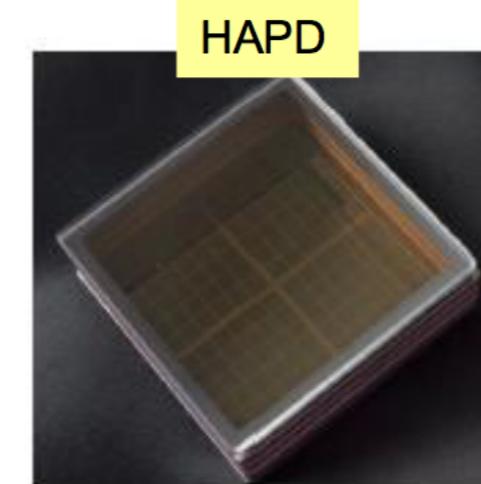
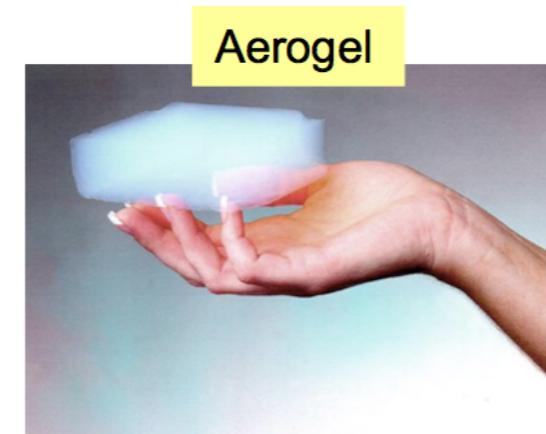
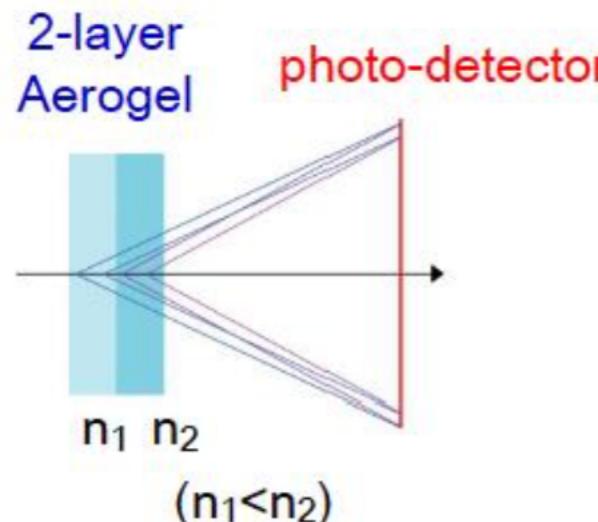
- Capability to count single photons with O(1mm) granularity
- Excellent time resolution of O(100 ps)
- Usage of MCP-PMTs and new waveform sampling

→ Expect significantly better K/π separation than at Belle



# PID endcaps: Aerogel (ARICH)

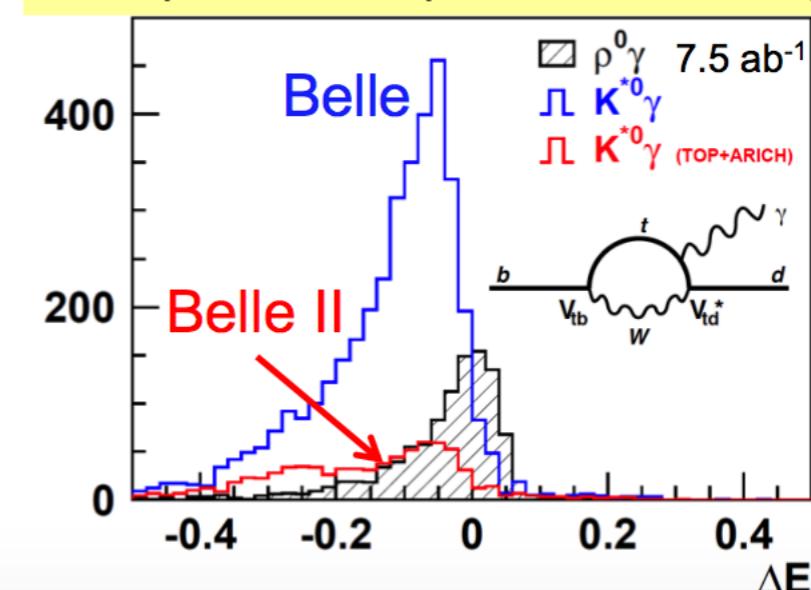
In the forward region, an aerogel ring imaging Cherenkov (ARICH) detector is used for PID:



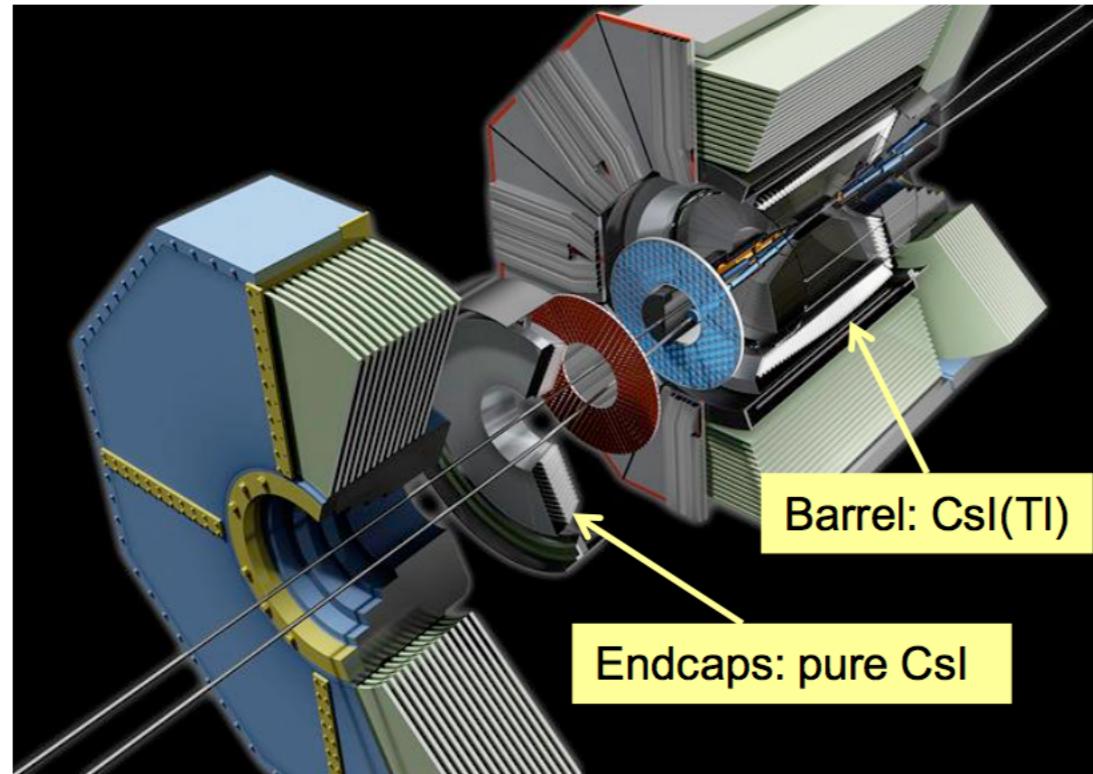
Aerogel ring imaging Cherenkov detector:

- Radiator of 2-layer aerogel [NIM A548, 383 (2005)]
- Usage of multiple radiators with different  $n$  increases photo statistics w/o degrading resolution
- Photo detection by 420 hybrid avalanche photo detectors (HAPD), each with 144 channels

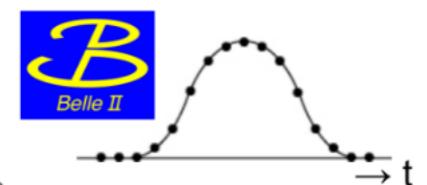
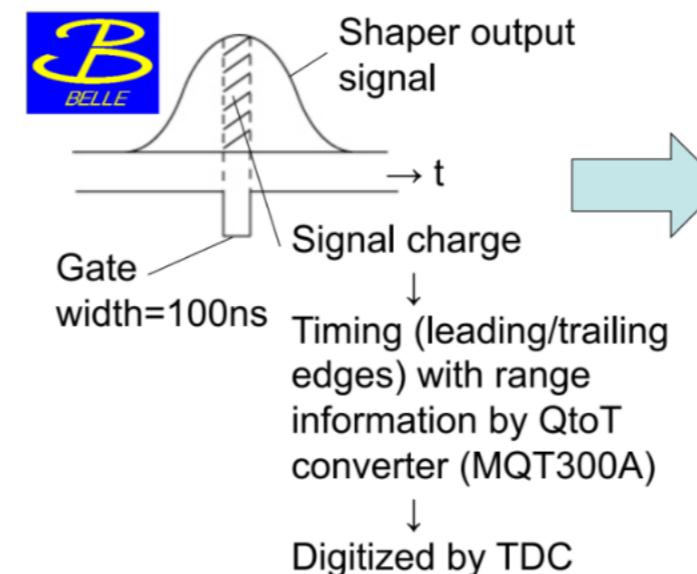
Example of PID improvement for  $B^0 \rightarrow \rho^0 \gamma$



# Electromagnetic Calorimeter : (ECL)

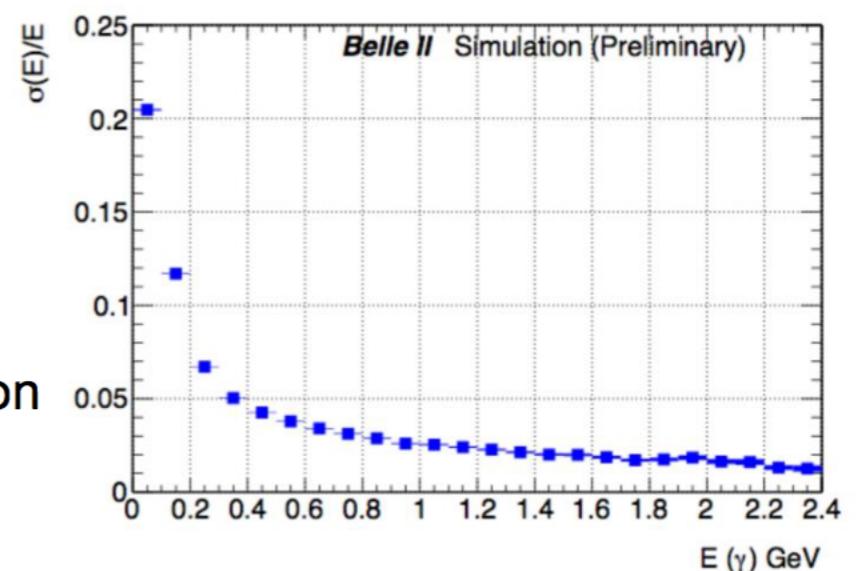


## Waveform analysis



1.76MHz, 18bits digitizer,  
waveform fit to get energy  
and timing (i.e. Digital  
Signal Processing)

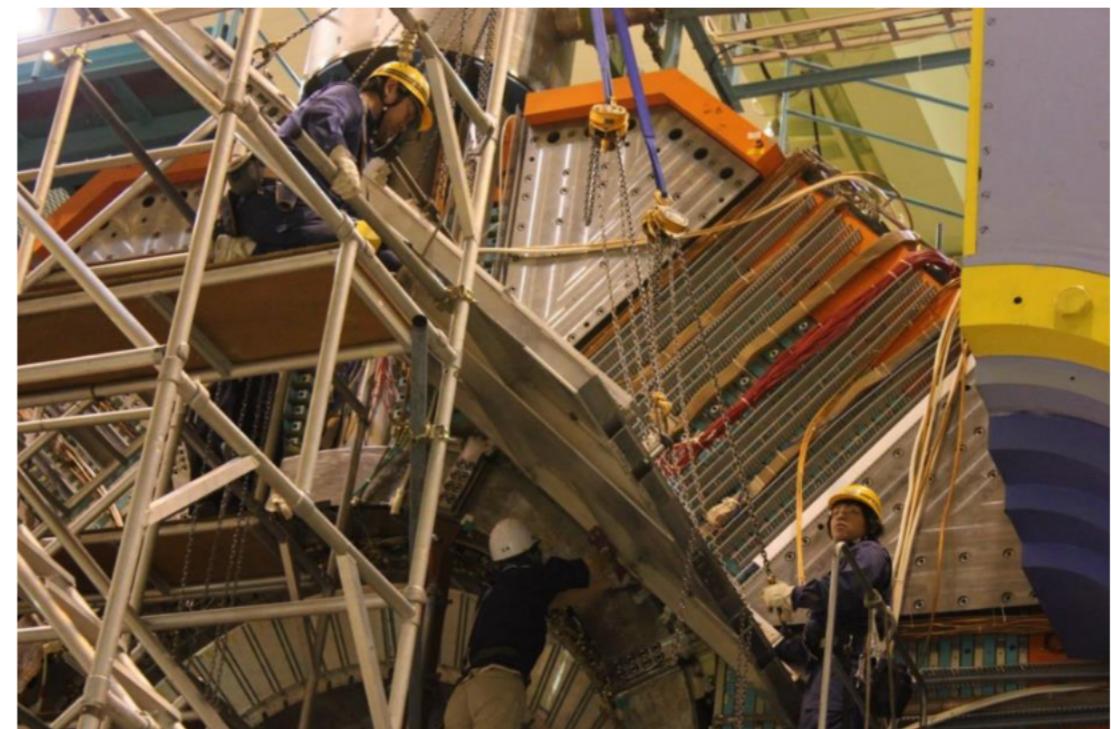
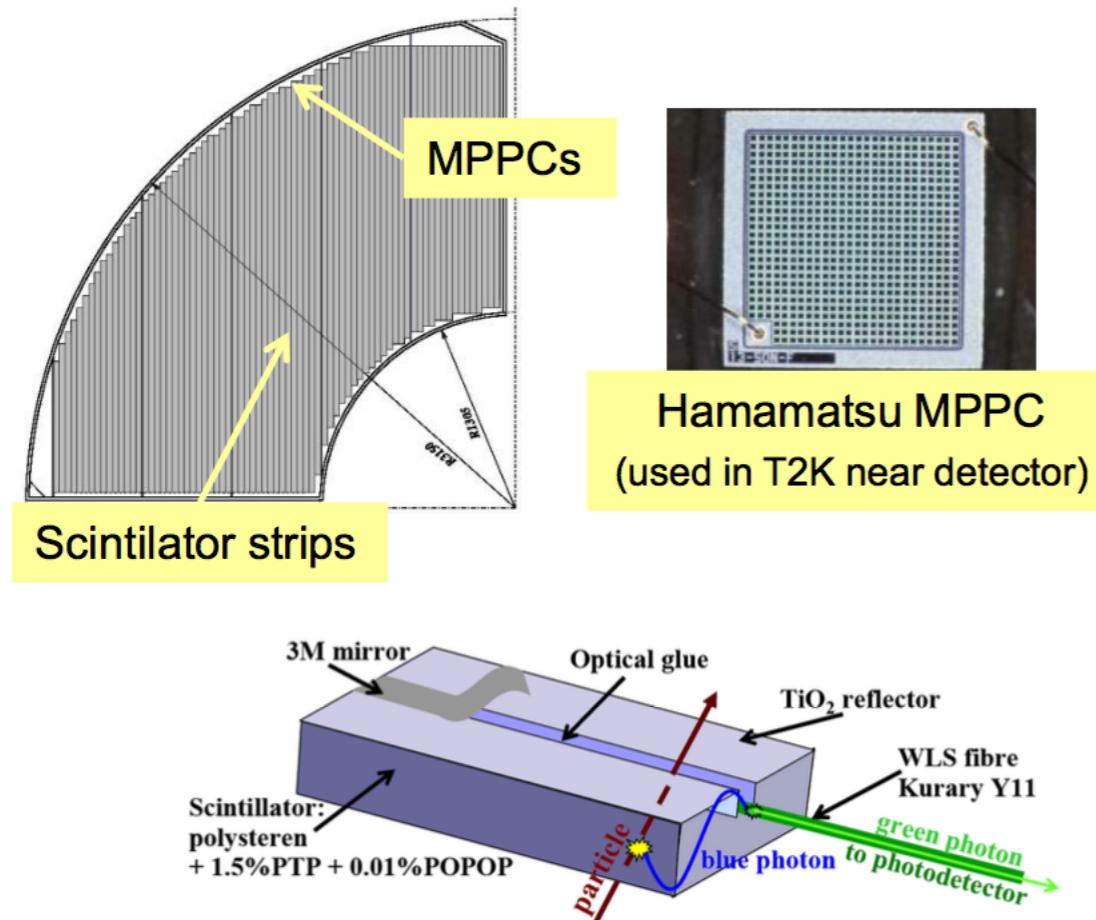
Reduction factors;  
×7 BG showers  
×1.5~2 pileup noise



## Electromagnetic calorimeter (ECL):

- Higher luminosity is challenging for the ECL with respect to radiation hardness and background levels
- Pure CsI in endcaps enable for fast timing + bkg. suppression
- Full waveform analysis for barrel and endcap readouts

# K<sub>L</sub> and Muon detector : (KLM)

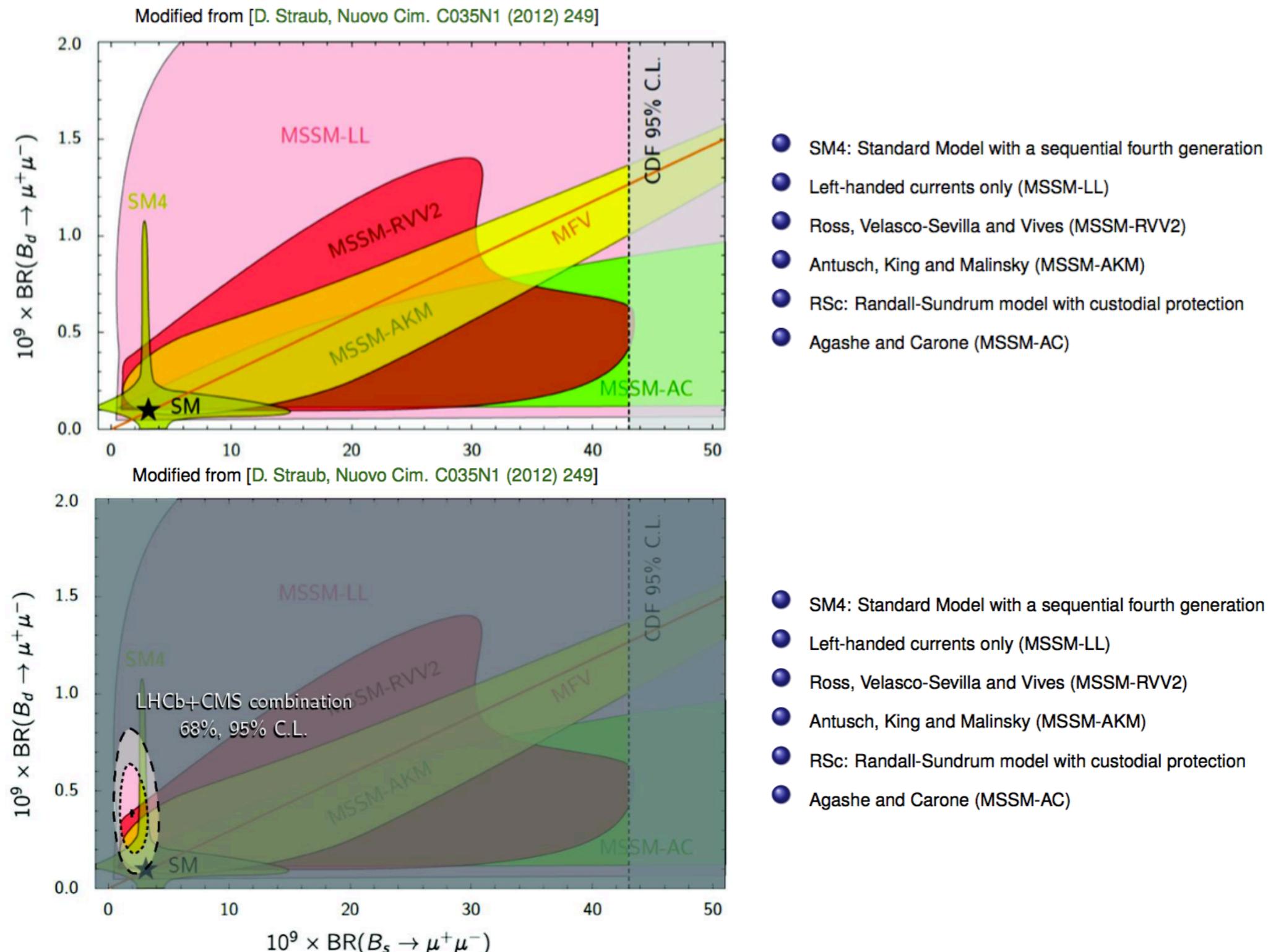


## K<sub>L</sub> and muon detector (KLM):

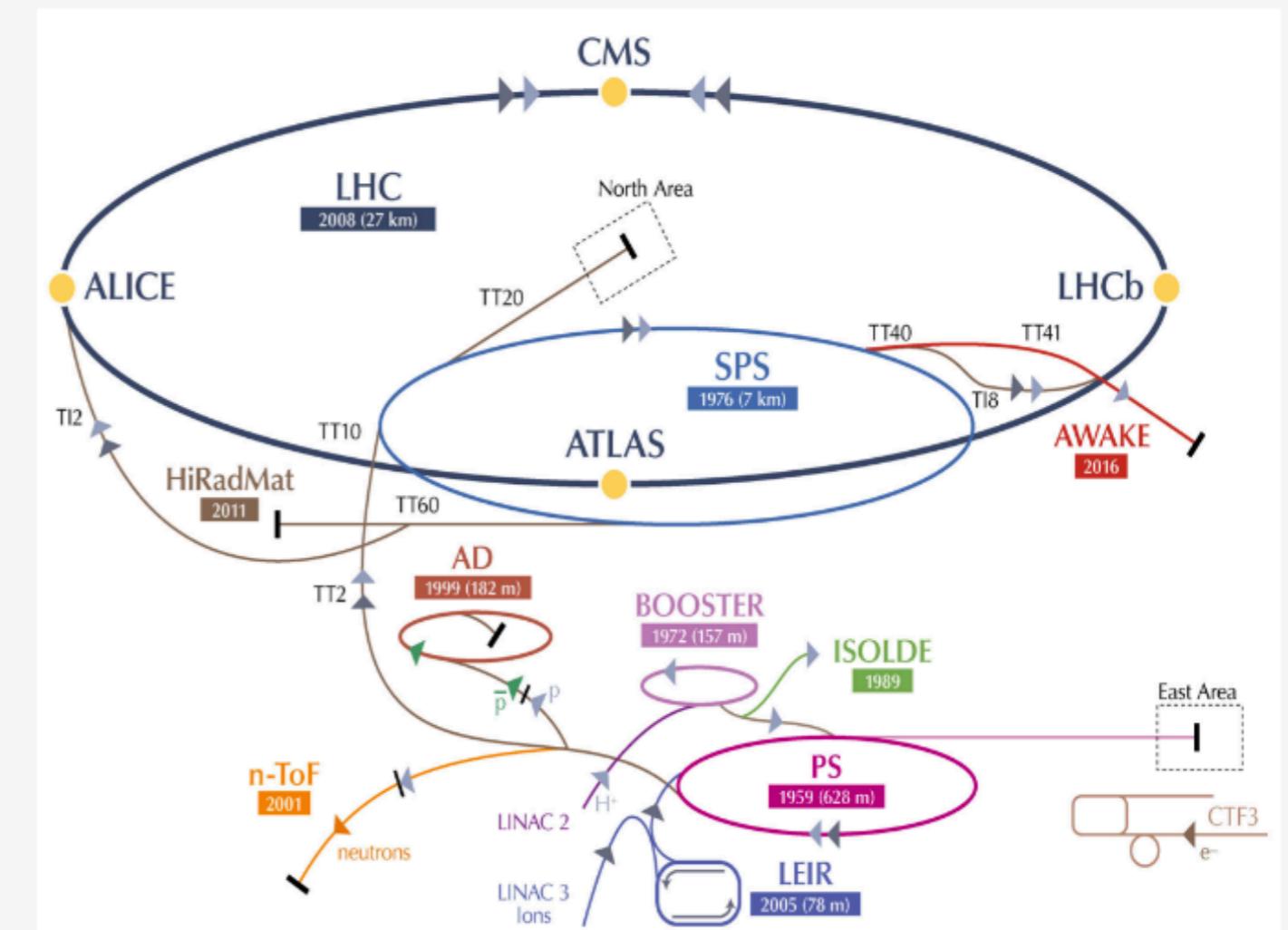
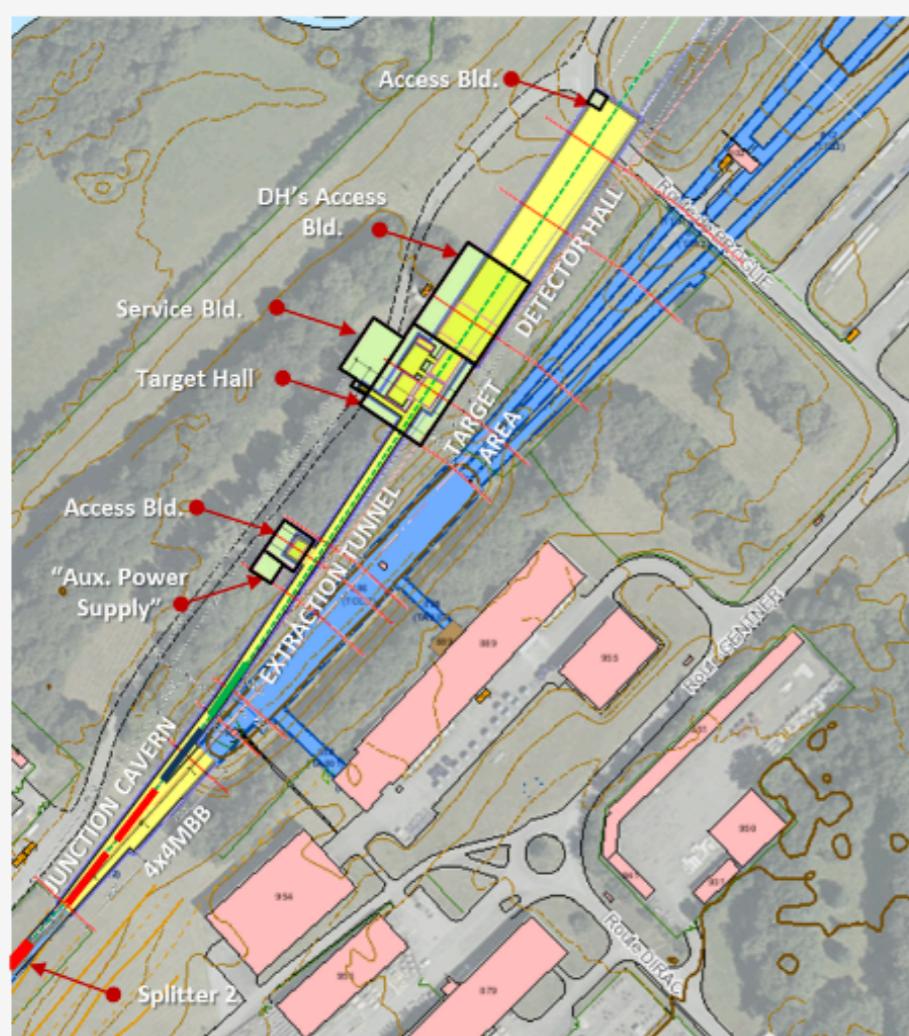
- Belle used resistive plate chambers (RPCs) to detect K<sub>L</sub> and to identify muons
- RPCs are not efficient at the Belle II background levels
- Endcap and inner barrel RPC layers are replaced by scintillators readout by MPPCs



# $B_s^0/B^0 \rightarrow \mu^+\mu^-$ & NP constraints



## SHIP



- 400 GeV protons
- $4 \cdot 10^{13}$  pot/spill (every 7 s)
  - ▷  $2 \cdot 10^{20}$  pot in 5 years

## Decay of hidden particles



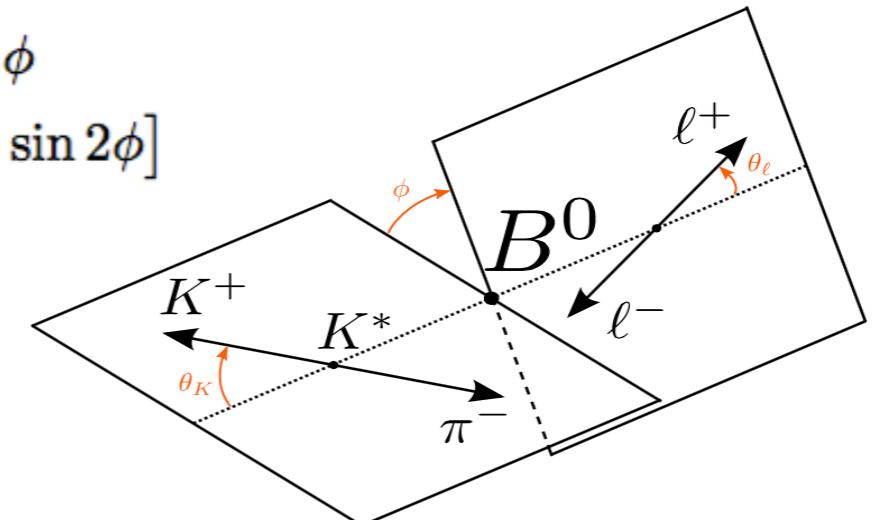
- Large decay volume followed by spectrometer, calorimeter, PID
- Shielding from SM particles: hadron absorber and veto detectors

# Angular analysis of $B \rightarrow K^* \ell^+ \ell^-$ decays

- Decay fully described by three helicity angles  $\Omega = (\theta_\ell, \theta_K, \phi)$  and  $q^2 = m_{\ell\ell}^2$

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\ + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

- Angular observables,  $F_L, A_{FB}, S_i$  appearing in the full decay rate are combinations of  $K^*$  amplitudes depending on WC  $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$  and form factors (FF)
- Large part of theory uncertainty due to hadronic FF
- Introduced the  $P'_i$  observables, less dependent on FF:



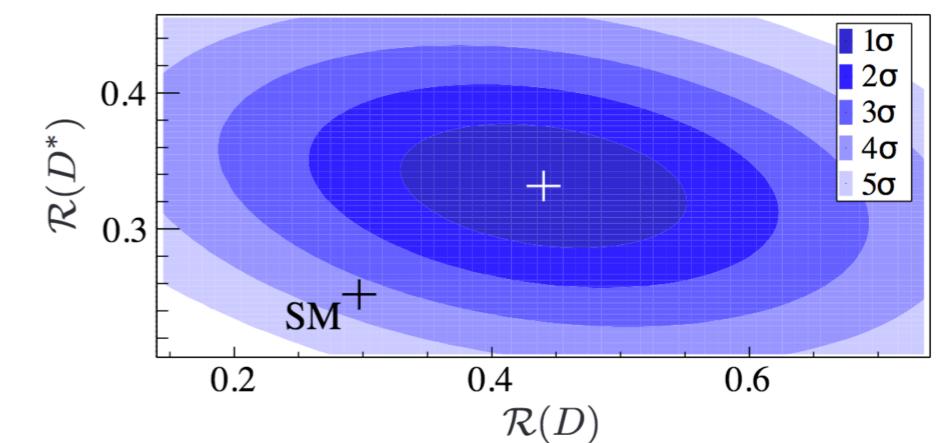
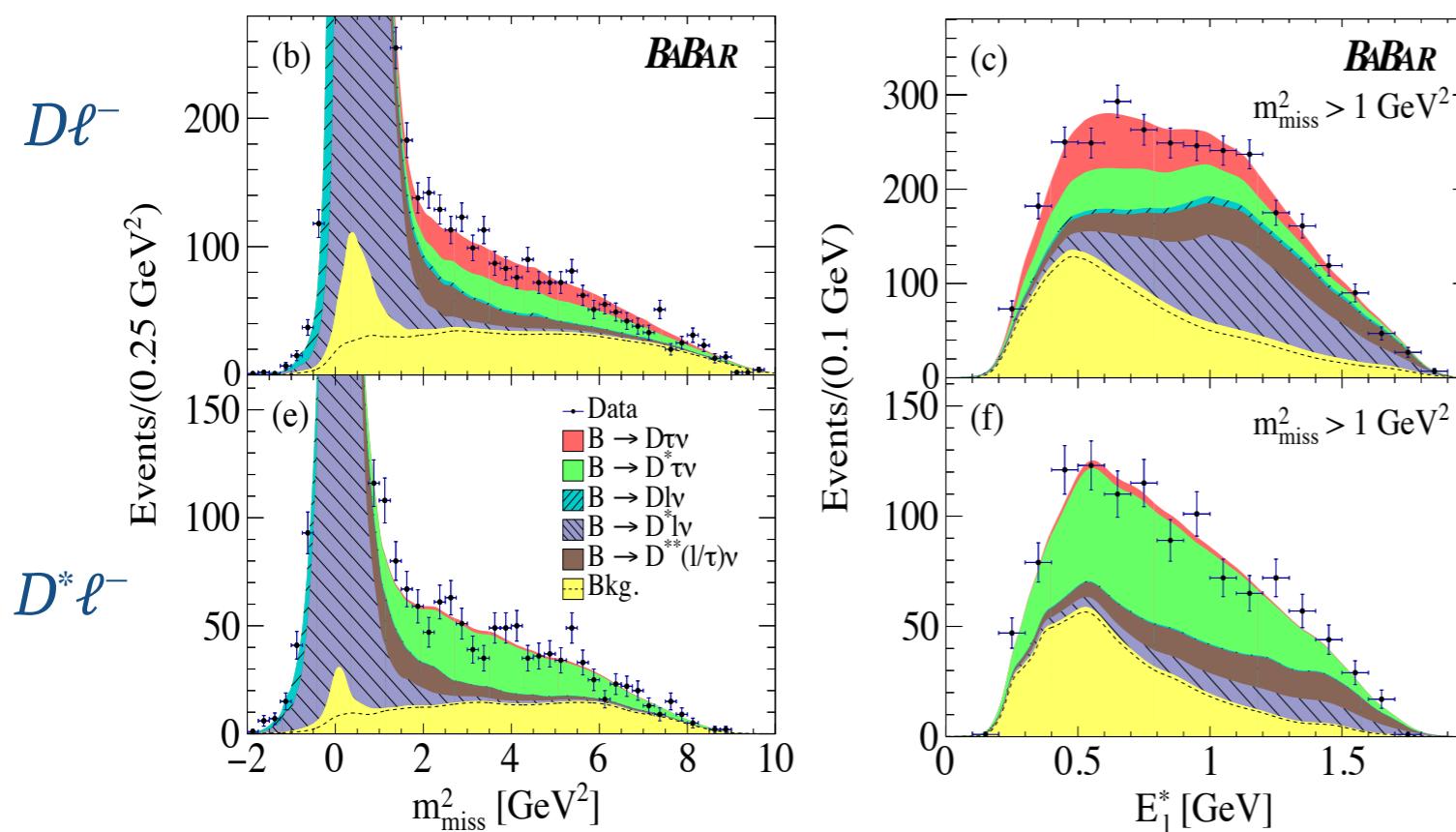
Also for  $B^+$  decays with  $K_S^0$  or  $\pi^0$

$$P_2 = -\frac{2}{3} \frac{A_{FB}}{(1 - F_L)} \quad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}} \quad P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}$$

[S. Descotes-Genon et al., JHEP, 05 (2013) 137]

- In a nutshell:

- ▶ hadronic tag of the other  $B \Rightarrow$  access missing mass ( $m_{\text{miss}}^2$ )
- ▶ beam constraints variables used to enhance S/B
- ▶ tau reconstructed in  $\tau \rightarrow \ell \nu \bar{\nu}$ ,  $\ell = \{\text{e}, \mu\}$
- ▶  $D$  meson reconstructed in  $D \rightarrow 2h(3h)$ ,  $h = \{h^0, h^+\}$
- ▶  $R_{D^{(*)}}$  measured from 2D fit to  $m_{\text{miss}}^2$  and  $E_\ell^*$

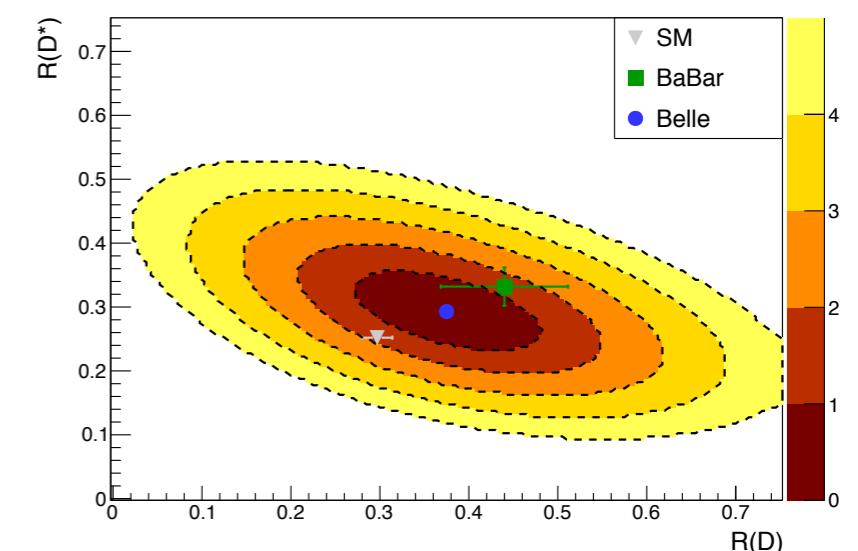
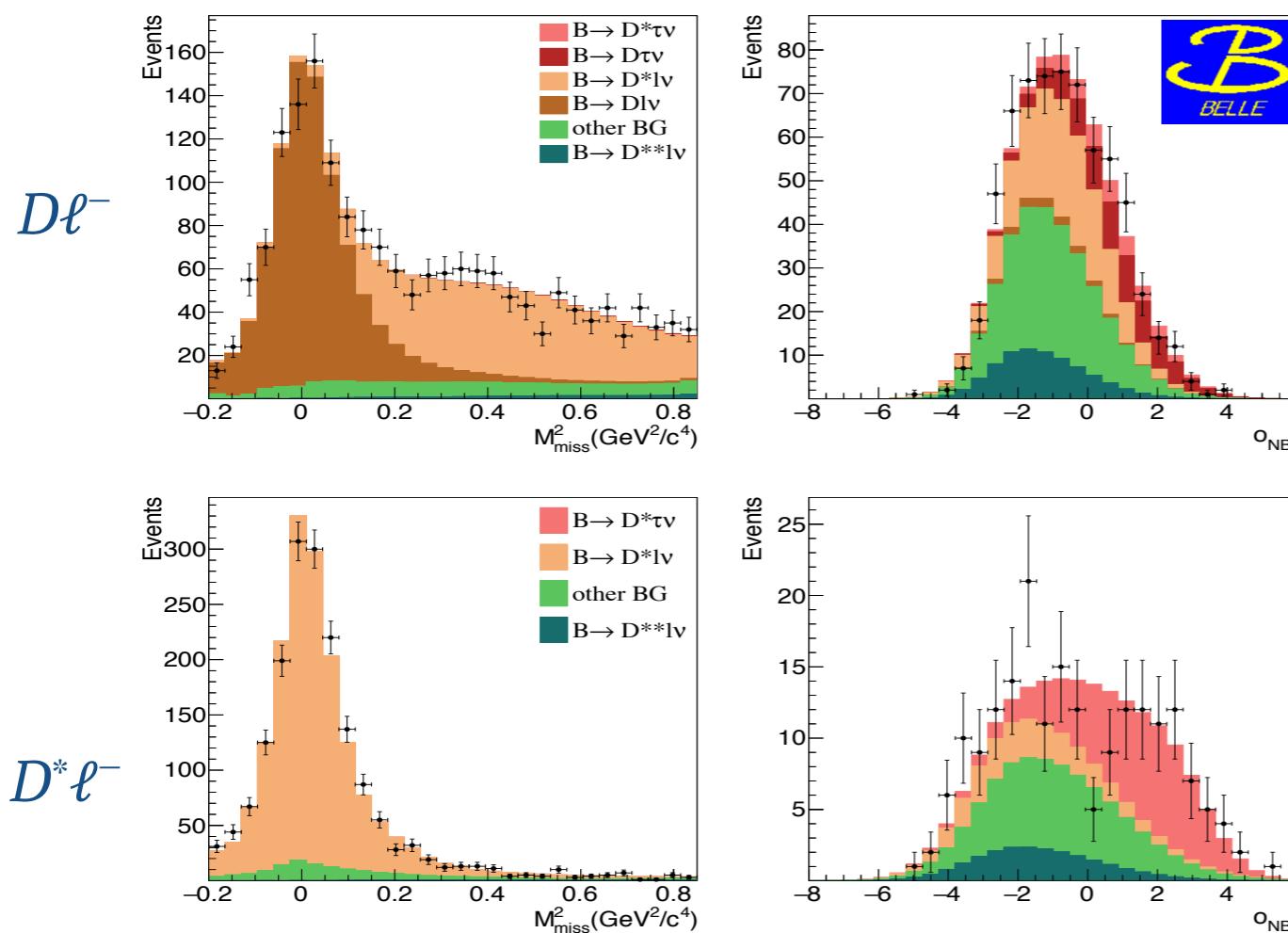


$R_D = 0.440 \pm 0.072$ 
 $R_{D^*} = 0.332 \pm 0.030$

Statistically limited and  
systematics dominated by  
knowledge of the shapes

- In a nutshell:

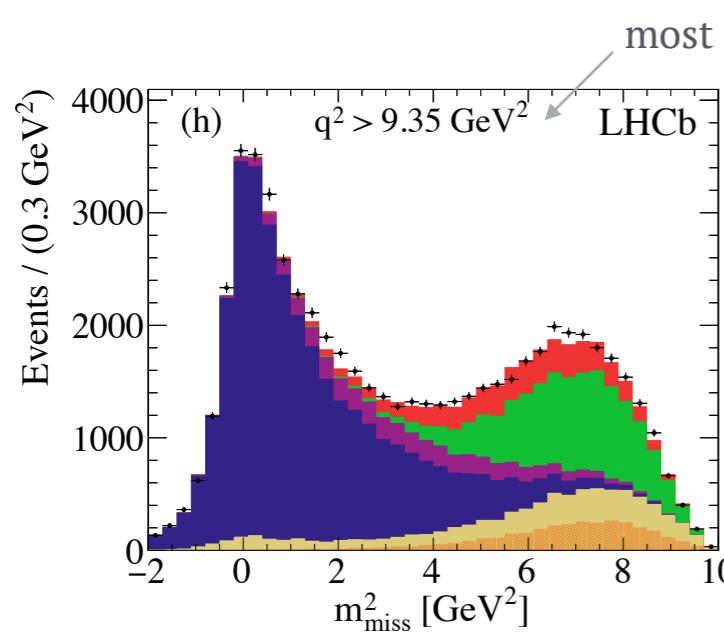
- ▶ hadronic (HT) and semileptonic (ST) tagging of the other B
- ▶ beam constraints variables used to enhance S/B
- ▶ tau reconstructed in  $\tau \rightarrow \ell \nu \bar{\nu}$ ,  $\ell = \{e, \mu\}$
- ▶  $D$  meson reconstructed in  $D \rightarrow 2h(3h)$ ,  $h = \{h^0, h^+\}$
- ▶  $R_{D^{(*)}}$  measured from 2D fit to  $m_{\text{miss}}^2$  and NN output



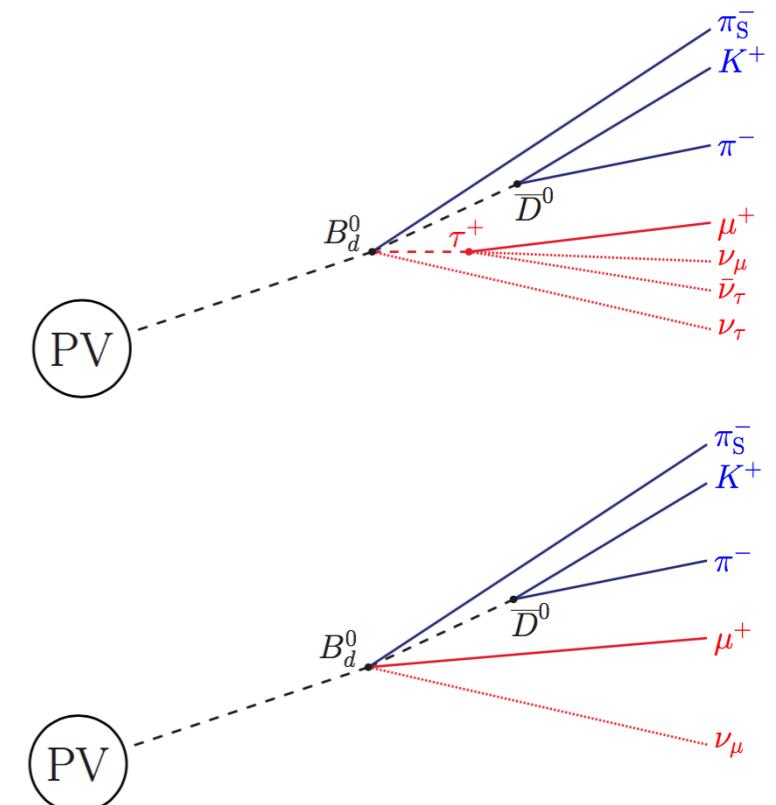
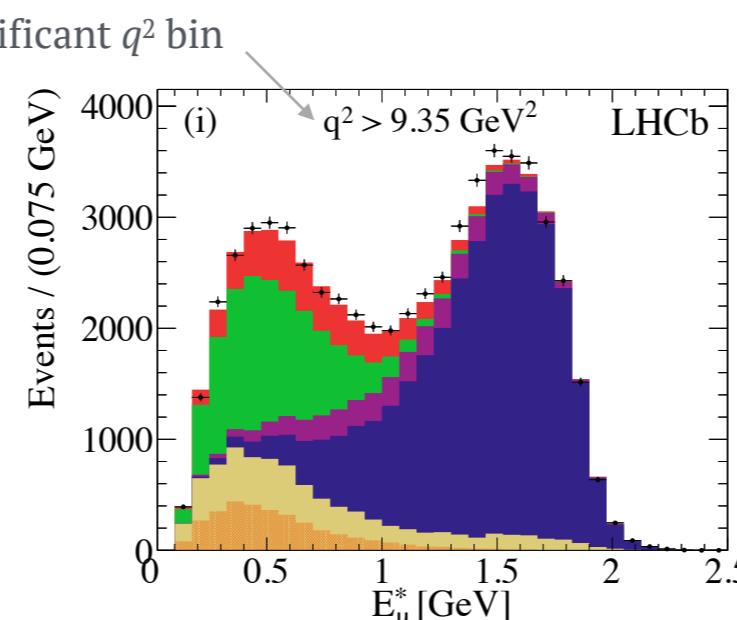
HT	$R_D = 0.375 \pm 0.069$
ST	$R_{D^*} = 0.293 \pm 0.041$
	$R_{D^*} = 0.302 \pm 0.032$

Statistically limited

- Experimentally very challenging!
  - both initial and final states not constrained
- In a nutshell:
  - tau reconstructed only in  $\tau \rightarrow \mu\nu\nu$
  - $D^*$  reconstructed only in  $D^{*+} \rightarrow D^0 [K^-\pi^+] \pi^+$
  - $R_{D^*}$  measured from 3D fit to  $m_{\text{miss}}^2$ ,  $E_\mu^*$  and  $q^2 = m_{\ell\nu}^2$



— Data		
<span style="color:red">█</span> $B \rightarrow D^*\tau\nu$	<span style="color:green">█</span> $B \rightarrow D^*H_c(\rightarrow l\nu X)X$	<span style="color:yellow">█</span> Combinatorial
<span style="color:blue">█</span> $B \rightarrow D^*\mu\nu$	<span style="color:magenta">█</span> $B \rightarrow D^{**}l\nu$	<span style="color:orange">█</span> Misidentified $\mu$

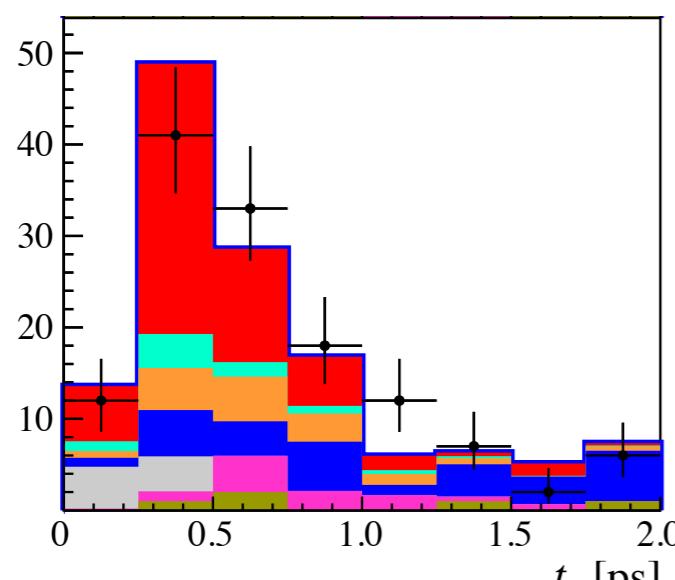
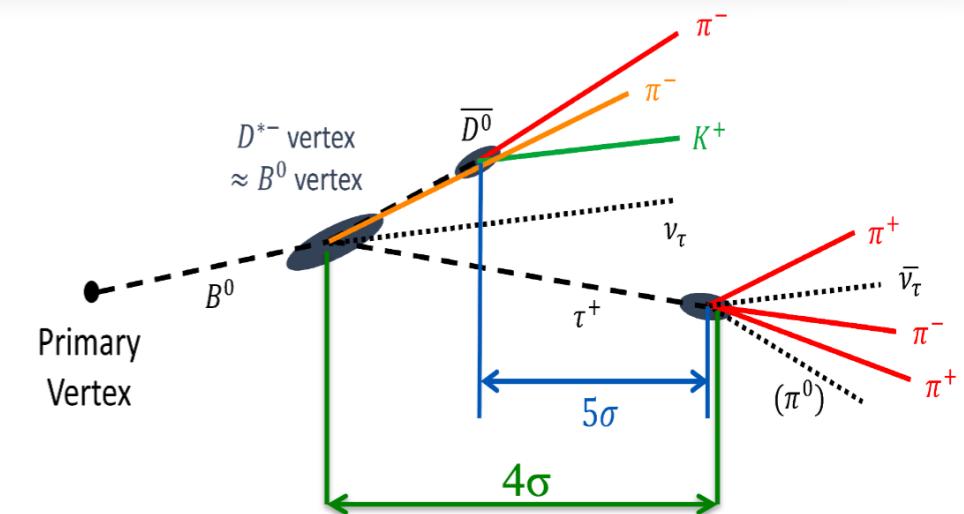


$$R_{D^*} = 0.336 \pm 0.040$$

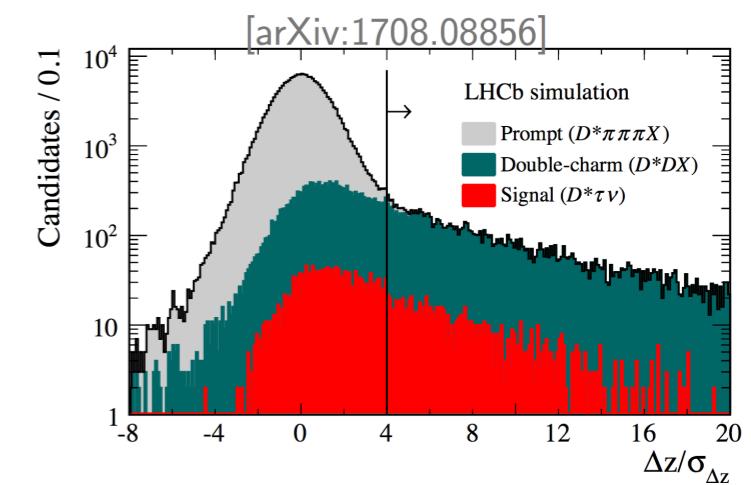
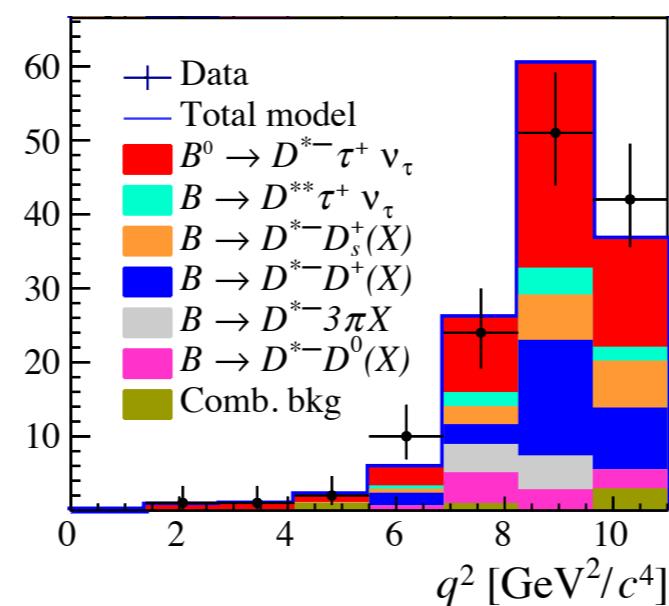
Systematically limited,  
dominated by size of simulated  
samples for templates

# $R_{D^*}$ in LHCb

- Experimentally very challenging!
  - both initial and final states not constrained
- In a nutshell:
  - tau reconstructed only in  $\tau \rightarrow \pi\pi\pi\nu$
  - fully hadronic final state:  $D^{*+} \rightarrow D^0 [K^-\pi^+] \pi^+$
  - Normalise to  $B \rightarrow D^{*-}\pi^+\pi^+\pi^-$  and use  $\mathcal{B}(B \rightarrow D^*\mu\nu)$  from  $B$  factories
  - $R_{D^*}$  measured from 3D fit to  $\tau$  decay time, BDT and  $q^2$



bin with highest BDT value (signal enhanced)



$$R_{D^*} = 0.286 \pm 0.038$$

Systematically limited,  
dominated by knowledge of  
 $\mathcal{B}(B \rightarrow D^*\mu\nu)$

# Tau polarisation

- Experimentally very challenging!

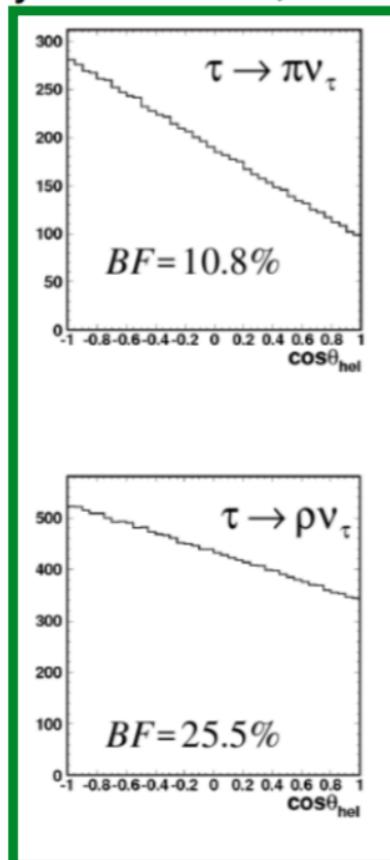
- ▶  $\cos \theta_{hel}(\tau)$  distribution in (quasi)2-body decays  $\tau \rightarrow M\nu_\tau$
- ▶  $\tau$  polarization measurement based on  $\cos \theta_{hel}(\tau)$  distribution:

$$\frac{d\Gamma}{d \cos \theta_{hel}(\tau)} \sim \frac{1}{2}(1 + \alpha P_\tau \cos \theta_{hel}(\tau))$$

- ▶ **SM:  $P_\tau \approx -0.5$**
- ▶ leptonic  $\tau$  decays not useful;

for  $J_M = 0$

$$\alpha = 1$$



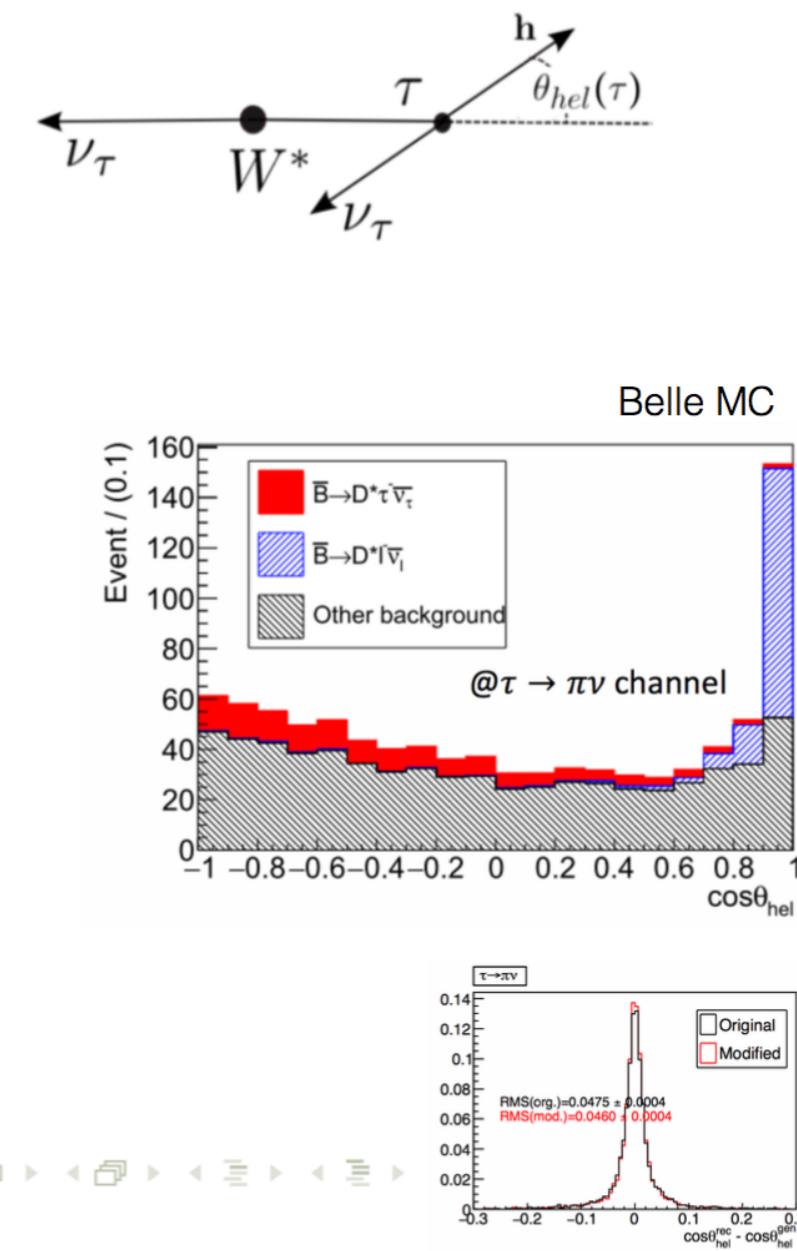
best sensitivity

for  $J_M = 1$

$$\alpha = \frac{m_\tau^2 - m_M^2}{m_\tau^2 + m_M^2}$$

$$\alpha = 0.45 \text{ for } \tau \rightarrow \rho \nu$$

$$\alpha = 0.12 \text{ for } \tau \rightarrow a_1 \nu$$



# Tau polarisation

- Belle results:

$$R(D^*) = 0.270 \pm 0.035(\text{stat.})^{+0.028}_{-0.025}(\text{syst.}),$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})^{+0.21}_{-0.16}(\text{syst.}).$$

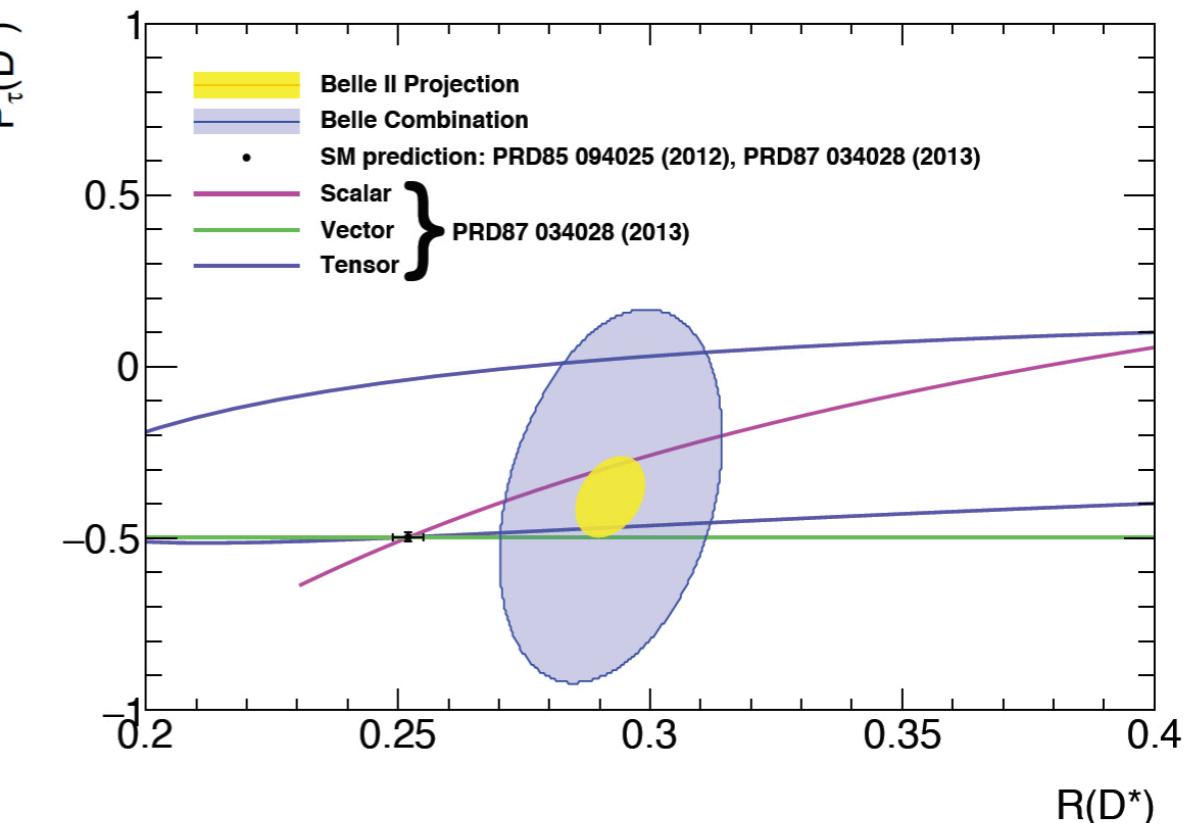
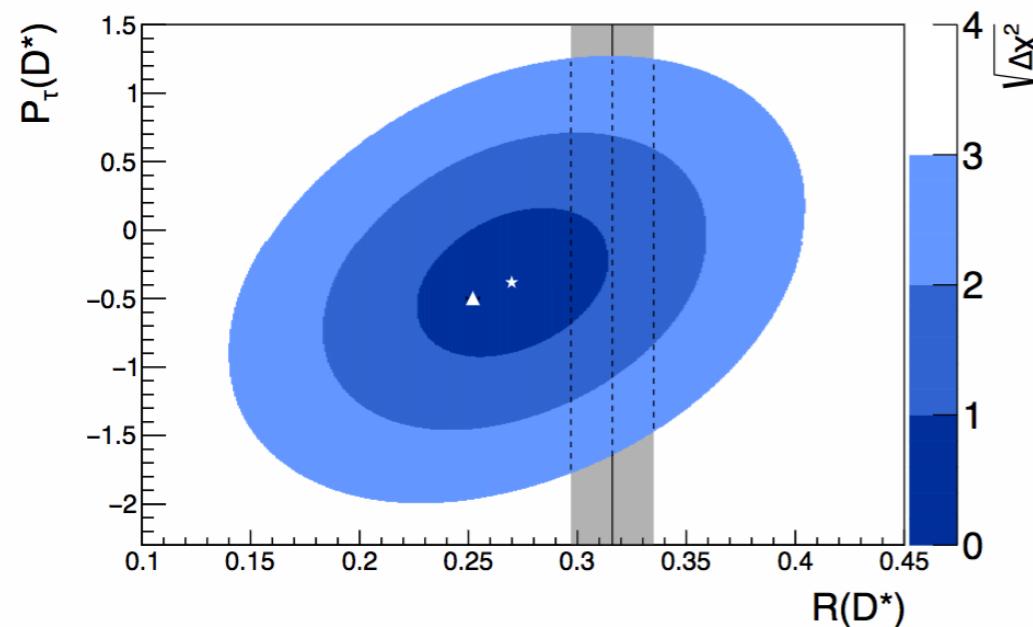


FIG. 2. Comparison of our result (star for the best-fit value and  $1\sigma$ ,  $2\sigma$ ,  $3\sigma$  contours) with the SM prediction [22, 24] (triangle). The shaded vertical band shows the world average [19] without our result.

*Belle: Phys. Rev. Lett. 118, 211801 (2017)*

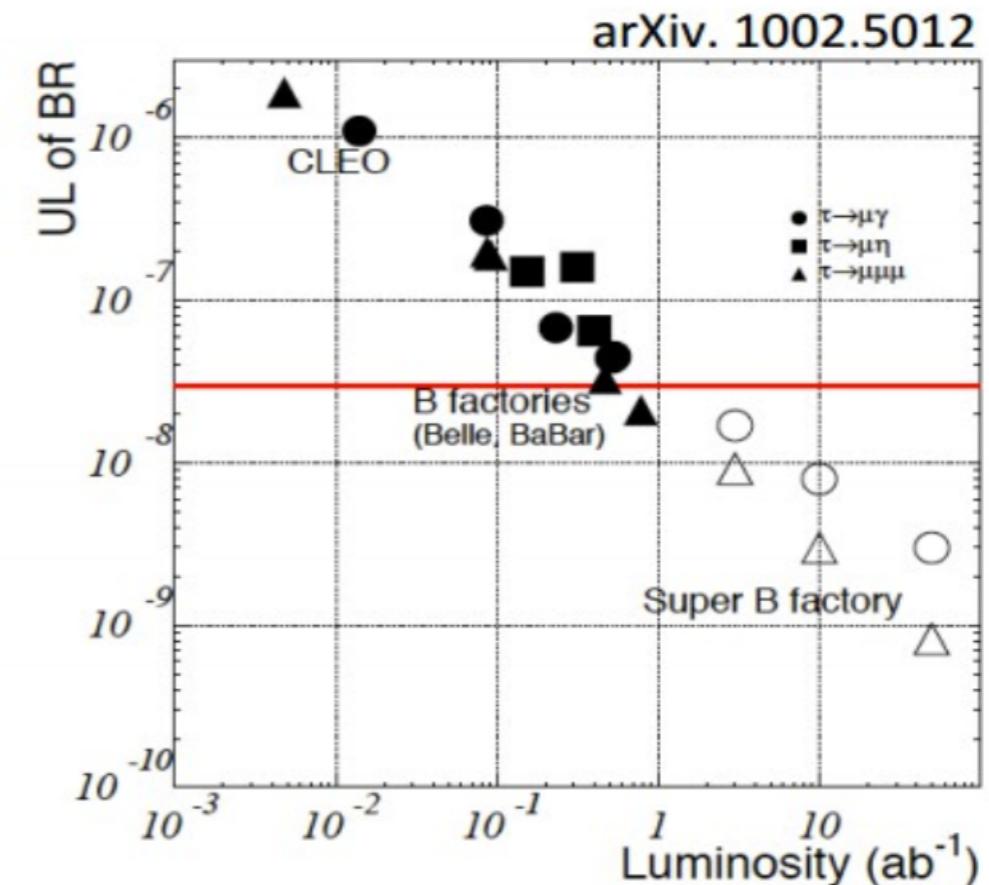
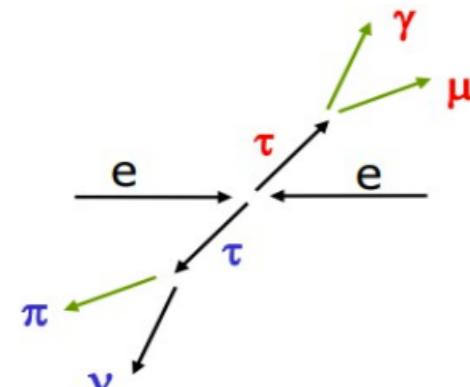
# Tau LFV

$\tau \rightarrow \mu\gamma$

main background from  $e e \rightarrow \mu\mu\gamma_{\text{ISR}}$   
possible to reduce sensitivity by a factor  $\sim 7$

$\tau \rightarrow \mu\mu\mu$

very clean mode  
possible to reduce sensitivity by a factor of 50



	$\mathcal{B}(\tau \rightarrow \mu\gamma)$	$\mathcal{B}(\tau \rightarrow \mu\mu\mu)$	
mSUGRA+seesaw	$10^{-7}$	$10^{-9}$	PRD 66(2002) 115013
SUSY+SO(10)	$10^{-8}$	$10^{-10}$	PRD 68(2003) 033012
SM+seesaw	$10^{-9}$	$10^{-10}$	PRD 66(2002) 034008
Non-Universal Z'	$10^{-9}$	$10^{-8}$	PLB 547(2002) 252
SUSY+Higgs	$10^{-10}$	$10^{-7}$	PLB 566(2003) 217

# FCC

- Will only discuss physics opportunity in the context of a FCC-ee machine

