Forbidden Processes

journées de prospectives de l'IN2P3 – GT01

Benoit Clément (with the help of A. Teixeira and G. Pignol)

What are forbidden processes

Observables for which the **SM expected value** is

- zero
- much smaller that experimental sensitivity (multiloop SM contribution)

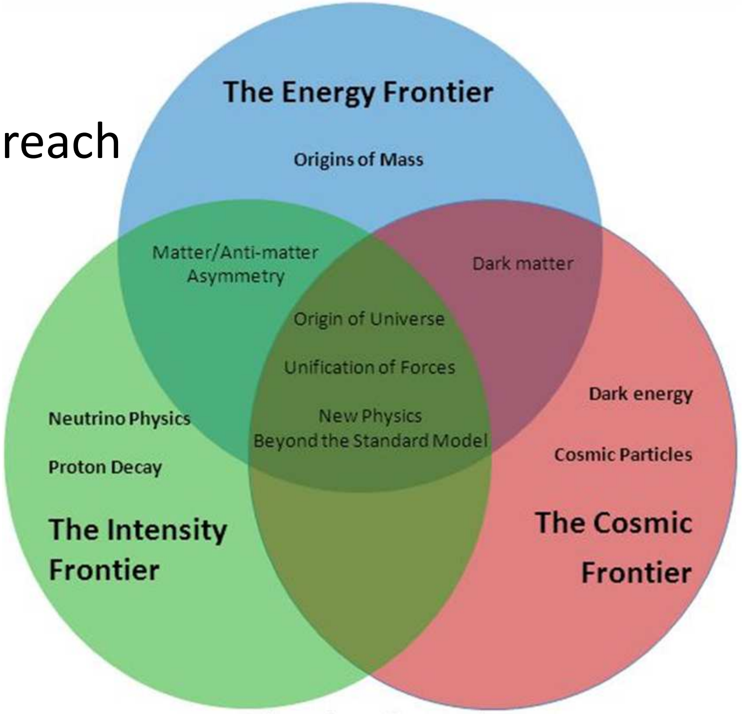
BSM contribution through 1 or 2 loops
can sensitive to New Physics scales beyond collider reach

Rare processes : Intensity frontier

Any non zero measurement is a signature of new physics

→no SM background

Any zero measurement can exclude some models



Physics Frontiers

Focus on non collider experiment

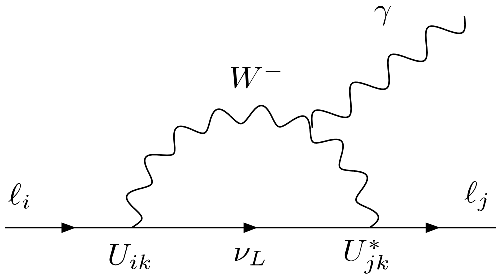
Lepton flavour violation : $\mu^- \to e^-\gamma, \mu^- N \to e^- N, \quad \mu^- \to e^- e^- e^+$,…
Spin ½ particle electric dipole moments : neutron, proton, electron, atoms…)
also : $0\nu\beta\beta$, neutron oscillations, proton decay…

Charged Lepton Flavour Violation

New Physics in the lepton sector: neutrino oscillations reflect violation of lepton flavour in the neutral lepton sector

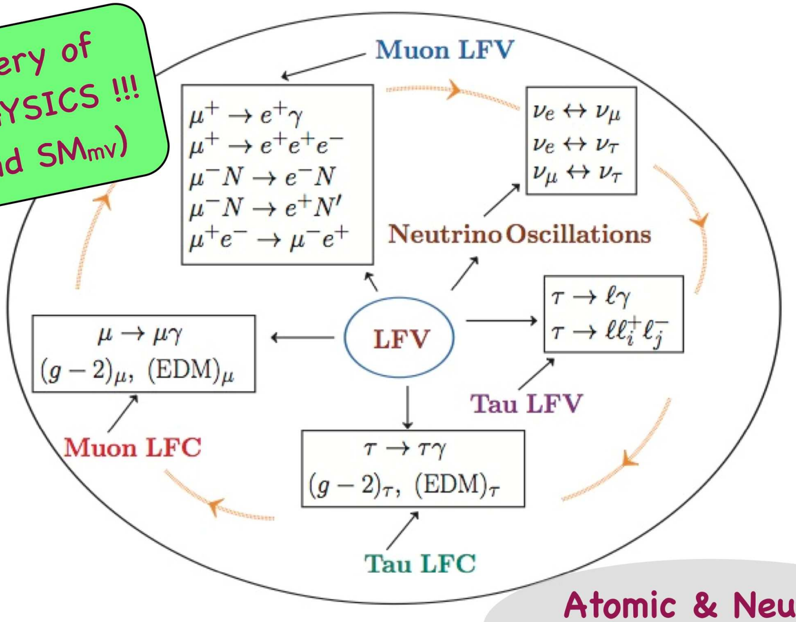
(1st laboratory discovery on New Physics!)

Minimal SM to accommodate neutrino oscillations: SM + ν_R & lepton number conservation (i.e. Dirac neutrino masses)
cLFV transitions are possible, but hugely suppressed by tiny m_ν



$$BR(\mu \to e\gamma) \propto \left|\sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W}\right|^2 \approx 10^{-54}$$

Discovery of
NEW PHYSICS !!!
(beyond SM$_{m\nu}$)


Muon LFV

$\mu^+ \to e^+\gamma$
$\mu^+ \to e^+e^+e^-$
$\mu^- N \to e^- N$
$\mu^- N \to e^+ N'$
$\mu^+e^- \to \mu^-e^+$

$\nu_e \leftrightarrow \nu_\mu$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_\mu \leftrightarrow \nu_\tau$

Neutrino Oscillations

LFV

$\mu \to \mu\gamma$
$(g-2)_\mu$, $(\mathrm{EDM})_\mu$

Muon LFC

$\tau \to \ell\gamma$
$\tau \to \ell\ell^+_i\ell^-_j$

Tau LFV

$\tau \to \tau\gamma$
$(g-2)_\tau$, $(\mathrm{EDM})_\tau$

Tau LFC

Atomic & Neutron
EDM

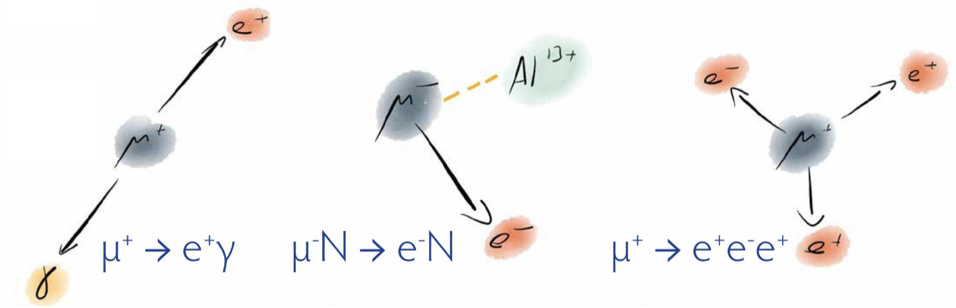
Rare processes searched for at **high-intensities**
⇒ **NP discovery** (possibly before LHC)
⇒ **Complementary** information to direct searches
⇒ Sensitive to **scales beyond collider reach...**

Muons as probe of cLFV

Versatile, abundantly produced, offer many experimental advantages

Past & current searches: very good bounds!

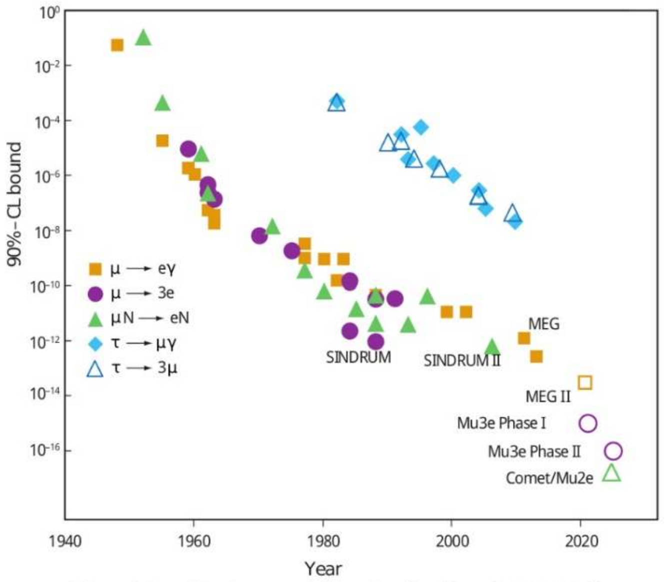
3 golden channels:



radiative decays
MEGII @ PSI

conversion in nuclei
COMET@J-PARC, Mu2e@FNAL

3-body decays
Mu3e @ PSI



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

Requirements: **very high intensity beams @ PSI, J-PARC, FNAL**

Detectors with very good resolution and background rejection

Background control (including physics and accidental backgrounds, machine effects, cosmic rays and badly reconstructed tracks)

Comparison between **μ → eγ** and **μ – e conversion**

	Background	Challenge	Beam Intensity	Beam type
μ → eγ	accidentals	detector resolution	limited	continuous
μ – e	beam	beam background	no limit	pulsed

BSM sources of cLFV

Model independent (effective approach) $\mathcal{L}^{eff} = \mathcal{L}^{SM} + \sum_{n\geq 5}\frac{1}{\Lambda^{n-4}}\mathcal{C}^{n}(g, Y, \dots)\,\mathcal{O}^{n}(l, q, H, \gamma, \dots)$

Cast observable in terms of effective couplings and NP scale

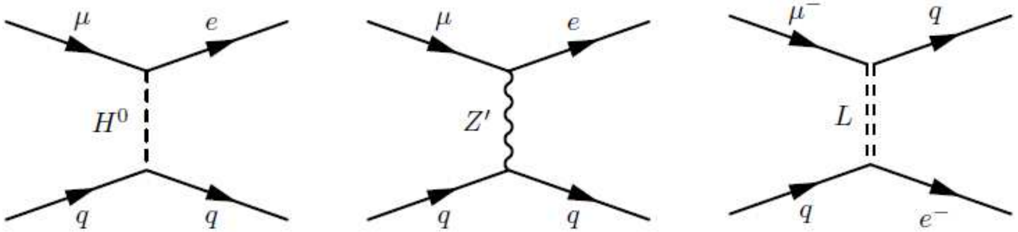
Apply experimental bounds to constrain Wilson coefficient (dim 6) C_{ij}^{6}

- * infer sensitivity of a process to C_{ij}^{6}
- * hints on scale Λ by taking naïve limits (C_{ij}^{6}=1)

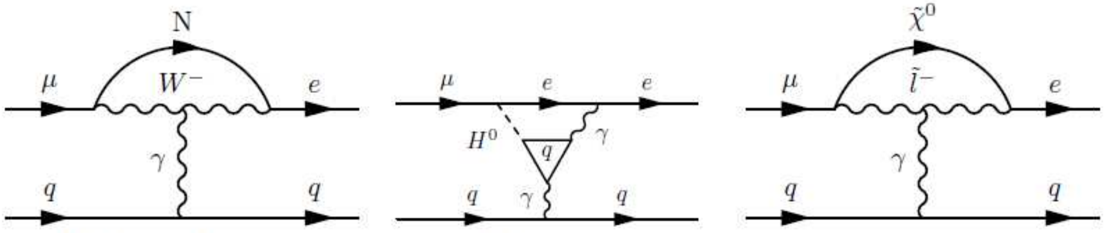
Observable	present bound	future sensitivity
$\mu \to e\gamma$	4.2×10^{-13} [MEG]	4×10^{-14} [MEG II]
(dipole)	$\Lambda \geq \mathcal{O}(10^{4}$ TeV)	$\Lambda \geq \mathcal{O}(2 \times 10^{4}$ TeV)
$\mu \to 3e$	10^{-12} [SINDRUM]	10^{-16} [Mu3e]
(dipole,4f)	$\Lambda \geq \mathcal{O}(500$ TeV)	$\Lambda \geq \mathcal{O}(5000$ TeV)
$\mu - e$	7×10^{-13} [SINDRUM]	10^{-17} [COMET, Mu2e]
(dipole | 4f)	$\Lambda \geq \mathcal{O}(300 \,\vert\, 10^{3}$ TeV)	$\Lambda \geq \mathcal{O}(5 \times 10^{3} \,\vert\, 10^{4}$ TeV)

Or look at specific (well-motivated) models of New Physics:

Exemple of processes generating μ^{-} to e^{-} conversion in nuclei



(a) Exotic Higgs (b) Z-prime (c) Leptoquarks



(d) Heavy Neutrinos (e) Exotic Higgs (f) Supersymmetry

Muon-electron conversion in nuclei

Muonic atoms : 1s bound state formed when μ^- stopped in target

SM allowed processes:

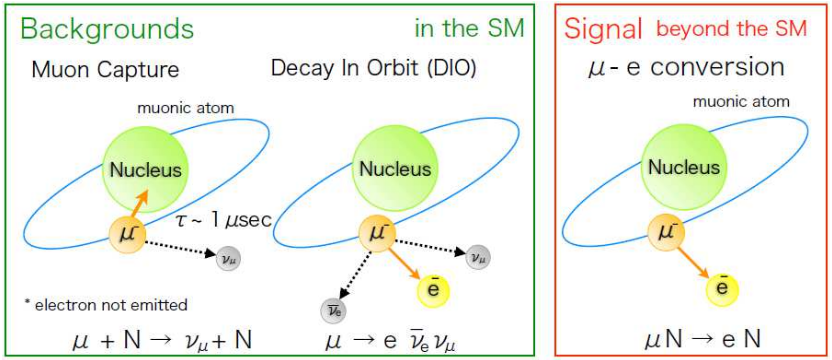
decay in orbit (DIO) $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ (3 body)

nuclear capture $\mu^- + (A,Z) \rightarrow \nu_\mu + (A, Z-1)$

cLFV BSM process :

$\mu^- - e^-$ conversion: $\boldsymbol{\mu^- + (A,Z) \rightarrow e^- + (A,Z)}$

Coherent process, spin-independent rate ∝ Z^2



Event signature: **single mono-energetic electron**

$$E_{\mu e}^{N} = m_\mu - E_B(A,Z) - E_R(A,Z)$$

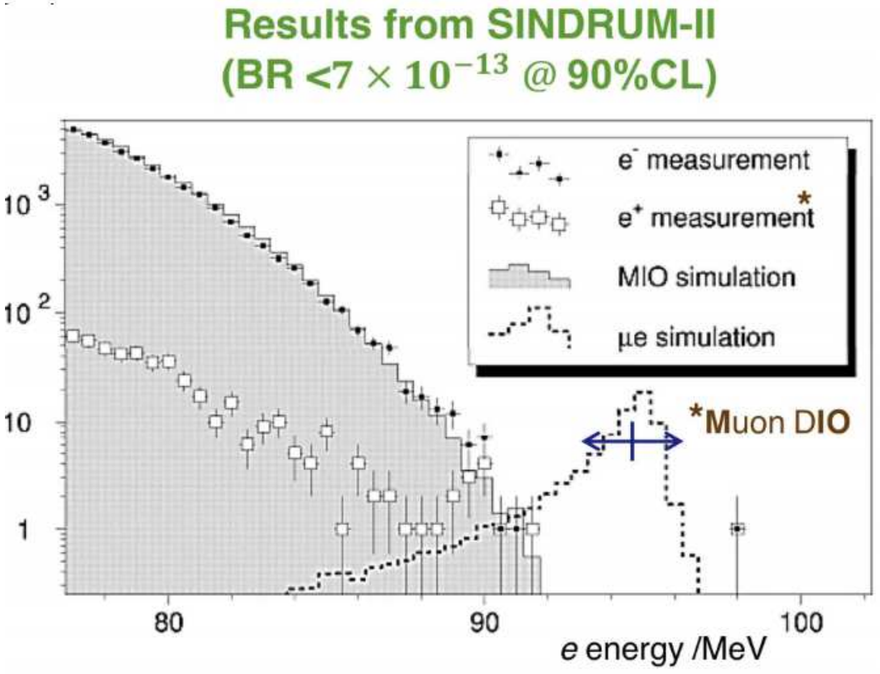
$$E_R = \frac{\left(m_\mu - E_B(A,Z)\right)^2}{2m_N}$$

$$E_{\mu e}^{Al,Pb,Ti} \approx \mathcal{O}(100\ \text{MeV})$$

Current bounds:

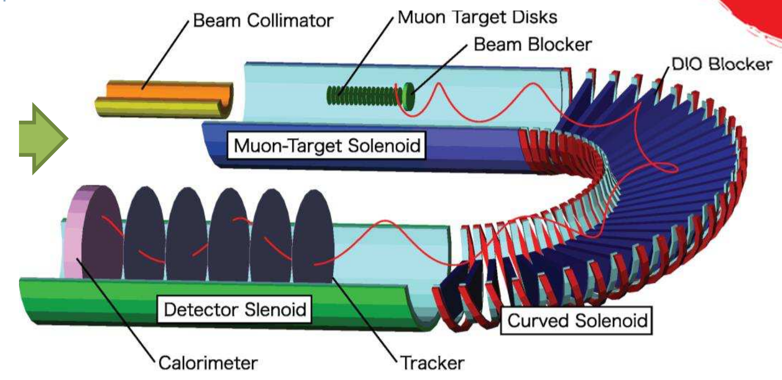
obtained for Gold nuclei (SINDRUM II @ PSI)

$CR(\mu - e, Au) < 7 \times 10^{-13}$



COMET : COherent Muon to Electron Transition

@ J-PARC



- **8 GeV 56 kW** **proton beam**
- Thick **target** with **1~2 hadron interaction lengths**
- Powerful capture magnet: **5 T**
- Expected muon yield: $\mathbf{10^{11}}$ **muon/s** (10^{8} μ/s at PSI)


arXiv:1812.09018v2 [physics.ins-det] 26 Nov 2019

COMET Phase-I Technical Design Report

The COMET Collaboration: R. Abramishvili[10], G. Adamov[10,16], R. R. Akhmetshin[3,29], A. Allin[22], J. C. Angélique[4], V. Anishchik[1], M. Aoki[30], D. Aznabayev[14], I. Bagaturia[10], G. Ban[4], Y. Ban[31], D. Bauer[11], D. Baygarashev[14], A. E. Bondar[3,29], C. Cârloganu[8], B. Carniol[4], T. T. Chau[30], J. K. Chen[35], S. J. Chen[27], Y. E. Cheung[27], W. da Silva[34], P. D. Dauncey[11], C. Densham[32], G. Devidze[36], P. Dornan[11], A. Drutskoy[22,25], V. Duginov[16], Y. Eguchi[30], L. B. Epshteyn[3,29,28], P. Evtoukhovich[16,2], S. Fayer[11], G. V. Fedotovich[3,29], M. Finger Jr[6], M. Finger[6], Y. Fujii[26], Y. Fukao[18], J. L. Gabriel[4], P. Gay[8], E. Gillies[11], D. N. Grigoriev[3,29,28], K. Gritsay[16], V. H. Hai[40], E. Hamada[18], I. H. Hashim[24], S. Hashimoto[20], O. Hayashi[30], T. Hayashi[30], T. Hiasa[30], Z. A. Ibrahim[24], Y. Igarashi[18], F. V. Ignatov[3,29], M. Iio[18], K. Ishibashi[20], A. Issadykov[14], T. Itahashi[30], A. Jansen[38], X. S. Jiang[13], P. Jonsson[11], T. Kachelhoffer[5], V. Kalinnikov[16], E. Kaneva[16], F. Kapusta[34], H. Katayama[30], K. Kawagoe[20], R. Kawashima[20], N. Kazak[2], V. F. Kazanin[3,29], O. Kemularia[10], A. Khvedelidze[16,10], M. Koike[39], T. Kormoll[38], G. A. Kozlov[16], A. N. Kozyrev[3,29], M. Kravchenko[16,1], B. Krikler[11], G. Kumsiashvili[30], Y. Kuno[30], Y. Kuriyama[19], Y. Kurochkin[2], A. Kurup[11], B. Lagrange[11,19], J. Lai[30], M. J. Lee[12], H. B. Li[13,7], R. P. Litchfield[11], W. G. Li[13], T. Loan[40], D. Lomidze[10], I. Lomidze[10], P. Loveridge[32], G. Macharashvili[36], Y. Makida[18], Y. J. Mao[31], O. Markin[22,25], Y. Matsuda[30], A. Melkadze[10], A. Melnik[2], T. Mibe[18], S. Mihara[18], N. Miyamoto[30], Y. Miyazaki[20], F. Mohamad Idris[24], K. A. Mohamed Kamal Azmi[24], A. Moiseenko[16], M. Moritsu[18], Y. Mori[19], T. Motoishi[30], H. Nakai[30], Y. Nakai[20], T. Nakamoto[18], Y. Nakamura[30], Y. Nakatsugawa[13], Y. Nakazawa[30], J. Nash[26], H. Natori[12], V. Niess[8], M. Nioradze[36], H. Nishiguchi[18], K. Noguchi[20], T. Numao[37], J. O'Dell[32], T. Ogitsu[18], S. Ohta[30], K. Oishi[20], K. Okamoto[30], T. Okamura[18], K. Okinaka[30], C. Omori[18], T. Ota[23], J. Pasternak[11], A. Paulau[2,16], D. Picters[30], V. Ponariadov[1], G. Quémener[4], A. A. Ruban[3,29], V. Rusinov[22,25], B. Sabirov[16], H. Sakamoto[30], P. Sarin[15], K. Sasaki[18], A. Sato[30], J. Sato[33], Y. K. Semertzidis[12,17], N. Shigyo[20], Dz. Shoukavy[2], M. Slunecka[6], D. Stöckinger[38], M. Sugano[18], T. Tachimoto[30], T. Takayanagi[30], M. Tanaka[18], J. Tang[35], C. V. Tao[40], A. M. Teixeira[8], Y. Tevzadze[*36], T. Thanh[40], J. Tojo[20], S. S. Tolmachev[3,29], M. Tomasek[9], M. Tomizawa[18], T. Toriashvili[10], H. Trang[40], I. Trekov[36], Z. Tsamalaidze[16,10], N. Tsverava[16,10], T. Uchida[18], Y. Uchida[11], K. Ueno[18], E. Velicheva[16], A. Volkov[16], V. Vrba[9], W. A. T. Wan Abdullah[24], P. Warin-Charpentier[34], M. L. Wong[30], T. S. Wong[30], C. Wu[13,27,30], T. Y. Xing[13,7], H. Yamaguchi[18], A. Yamamoto[18], M. Yamanaka[21], T. Yamane[30], Y. Yang[20], T. Yano[30], W. C. Yao[30], B. Yeo[17], H. Yoshida[30], M. Yoshida[18], T. Yoshioka[20], Y. Yuan[13], Yu. V. Yudin[3,29], M. V. Zdorovets[14], J. Zhang[13], Y. Zhang[13], and K. Zuber[38]

COMET Collaboration: **over 200 people from 40+ Institutes in 17 countries!** (and still growing!)

COMET spokesperson: **Y. Kuno (Osaka Univ.)**

COMET-France: **approved end 2018**

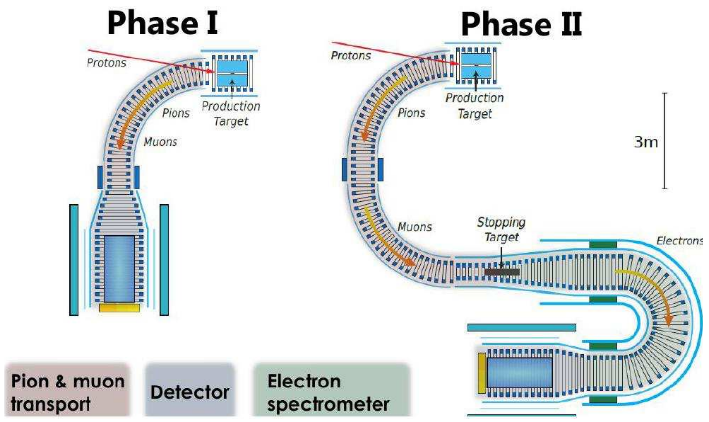
Participation from IP2I-Lyon, LPC-Clermont, LPNHE-Paris, LPC-Caen and CCIN2P3

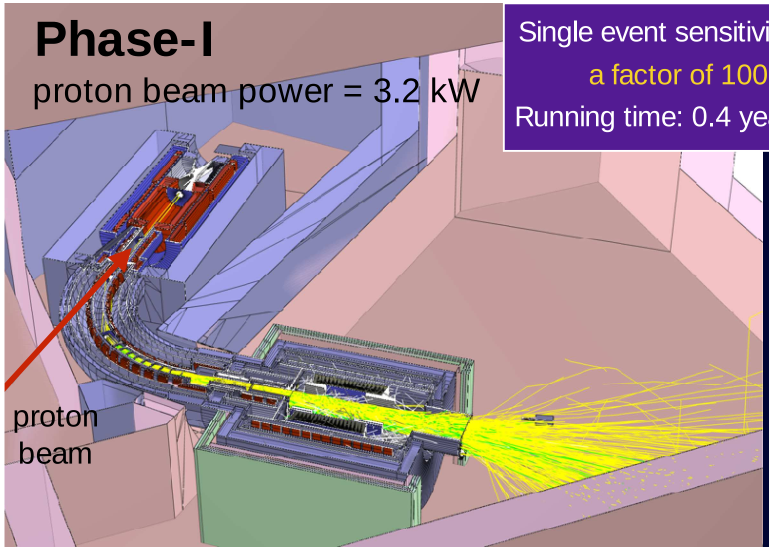
COMET : phases I and II

Different detectors for both phases

Phase-I : CyDet (Cylindrical Drift Chamber and a Cherenkov Trigger Hodoscope) provides **triggering, tracking, momentum measurement and PID**

Directly **measure muon beam** with **prototypes of Phase II detector** (preparation of Phase II)





Phase-I

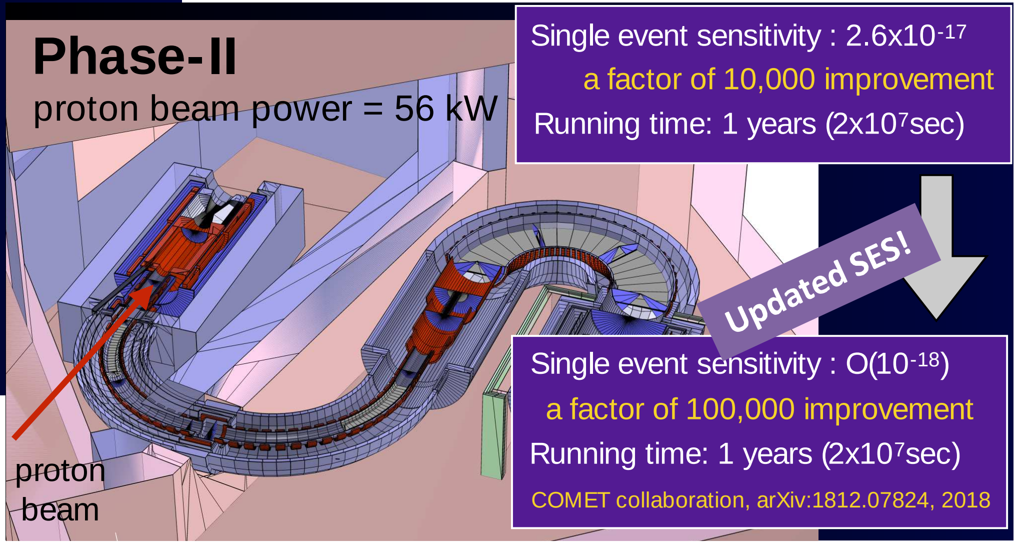
proton beam power = 3.2 kW

proton beam

Single event sensitivity : 2×10^{-15}

a factor of 100 improvement

Running time: 0.4 years (1.2×10^{7}s)



Phase-II

proton beam power = 56 kW

proton beam

Single event sensitivity : 2.6×10^{-17}

a factor of 10,000 improvement

Running time: 1 years (2×10^{7}sec)

Updated SES!

Single event sensitivity : $O(10^{-18})$

a factor of 100,000 improvement

Running time: 1 years (2×10^{7}sec)

COMET collaboration, arXiv:1812.07824, 2018

Phase-II :

Straw tracker for momentum measurement
- operating in vacuum
  - 12 µm thin straws

Electromagnetic calorimeter for triggering, TOF measurement and PID

IN2P3 Contribution to Phase-I

- ➢ **Data analysis**

- ➢ **Software developments:**
  - tracking : original algorithm implementation & use of GPUs
  - simulation of the background induced by atmospheric muons.
  - estimation of radiation yields at sub-detector level with MCNPX and PHITS

- ➢ **Hardware contribution to the Cosmic Ray Veto:**
  - design of the CRV based on GRPCs
  - construction and validation of a CRV module based on GRPCs (resolutions, dead time, efficiency, stability, radiation hardness, etc)

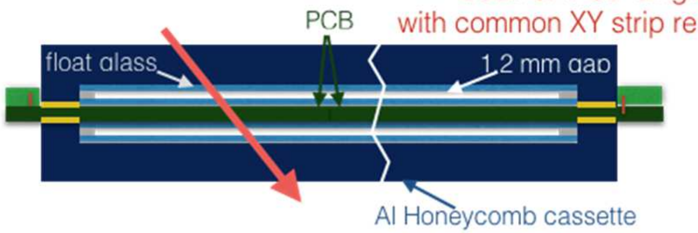
- ➢ **Computing@CCIN2P3**: Data Storage and Users Management

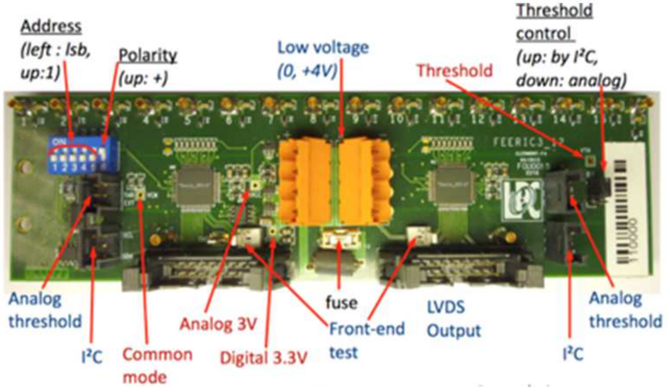
Cosmic Ray Veto

- **Scintillator slabs** with embedded WLS-fibres and SiPM readout
- **Resistive Plate Chambers (RPC)** read out with XY strips and Feeric ASIC (LPC/ALICE design)

  in the highest neutron yield areas

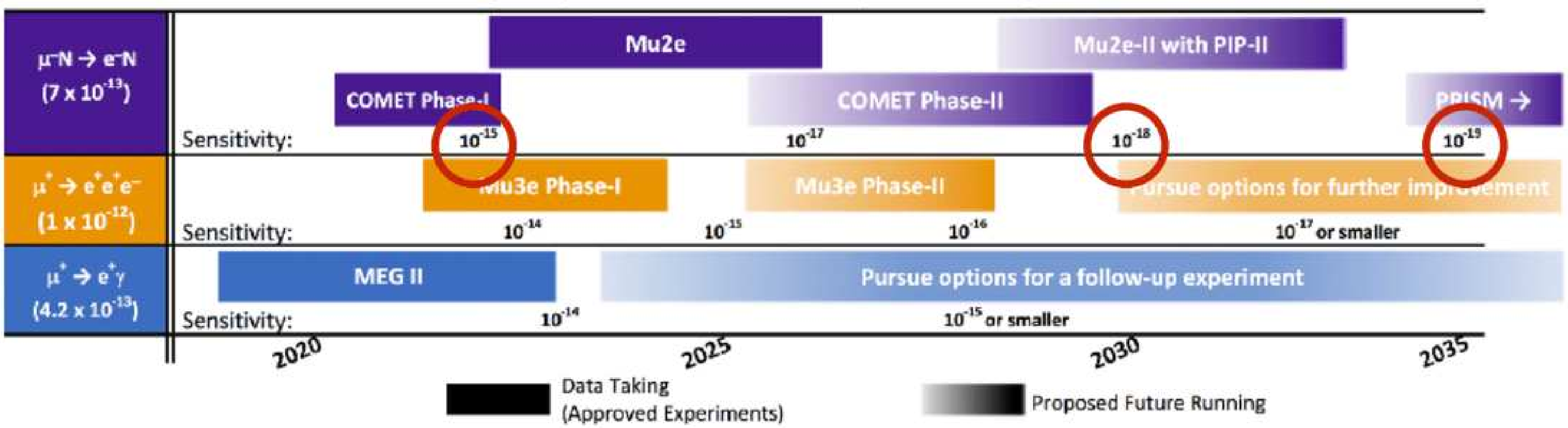
a GRPC module (1900x600 mm^2):
deux GRPCs single-gap
with common XY strip readout

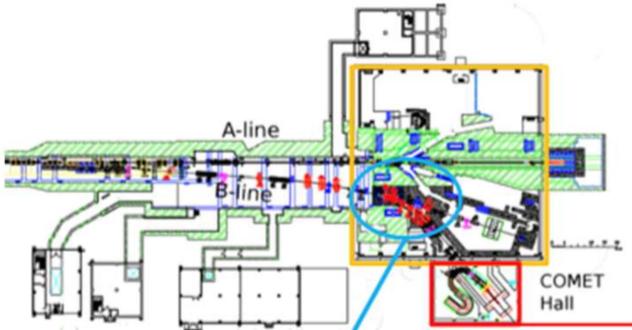


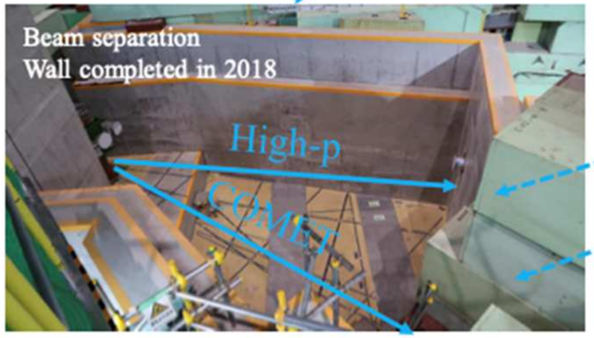


FE board for a GRPC module, with two Feeric ASICs

cLVF experiments time scale





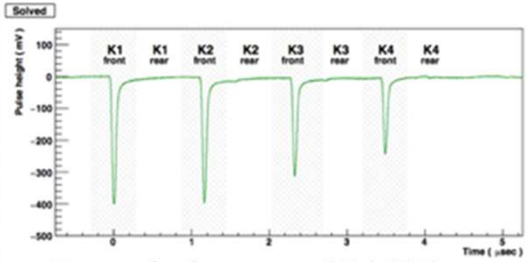

Beam separation
Wall completed in 2018


COMET Experimental Hall
Constructed in 2015


Installation Yard in 2015


Experiment Room in 2019

2 magnets will be moved to Hadron Hall



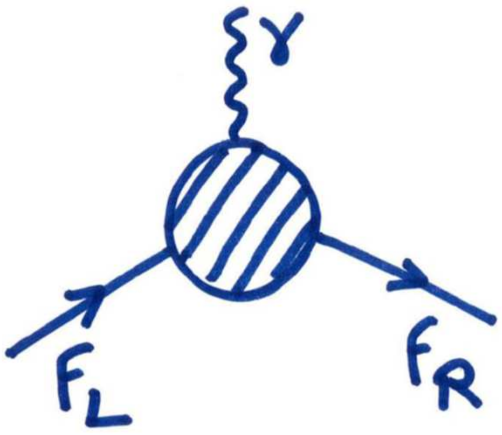
Beam extinction measured Feb 2019

Electric dipole moments

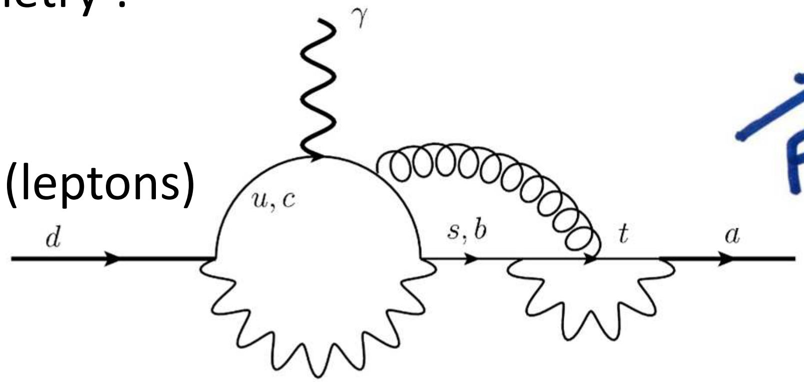
For theoricist

C**P**-violating term in the EM current : $\mathcal{L}_{int} = \boldsymbol{i}\frac{d}{2}\bar{\psi}F_{\mu\nu}\sigma^{\mu\nu}\boldsymbol{\gamma^5}\psi$

Important for Baryon asymmetry !



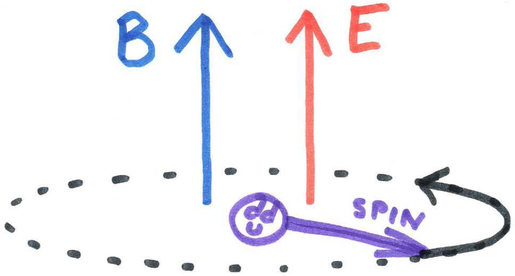
In standard model :
only through 3 (quarks) or 4 (leptons)
loops EW diagrams



For the experimentalist

At low energy (non relativistic limit): $\mathcal{L}_{int} = -\boldsymbol{\vec{d}}.\boldsymbol{\vec{E}} = \boldsymbol{d}\hat{\vec{J}}.\boldsymbol{\vec{E}}$

Coupling between the **Spin** and an external **Electric Field**



Change in Larmor frequency if B and E fields are (anti)paralell

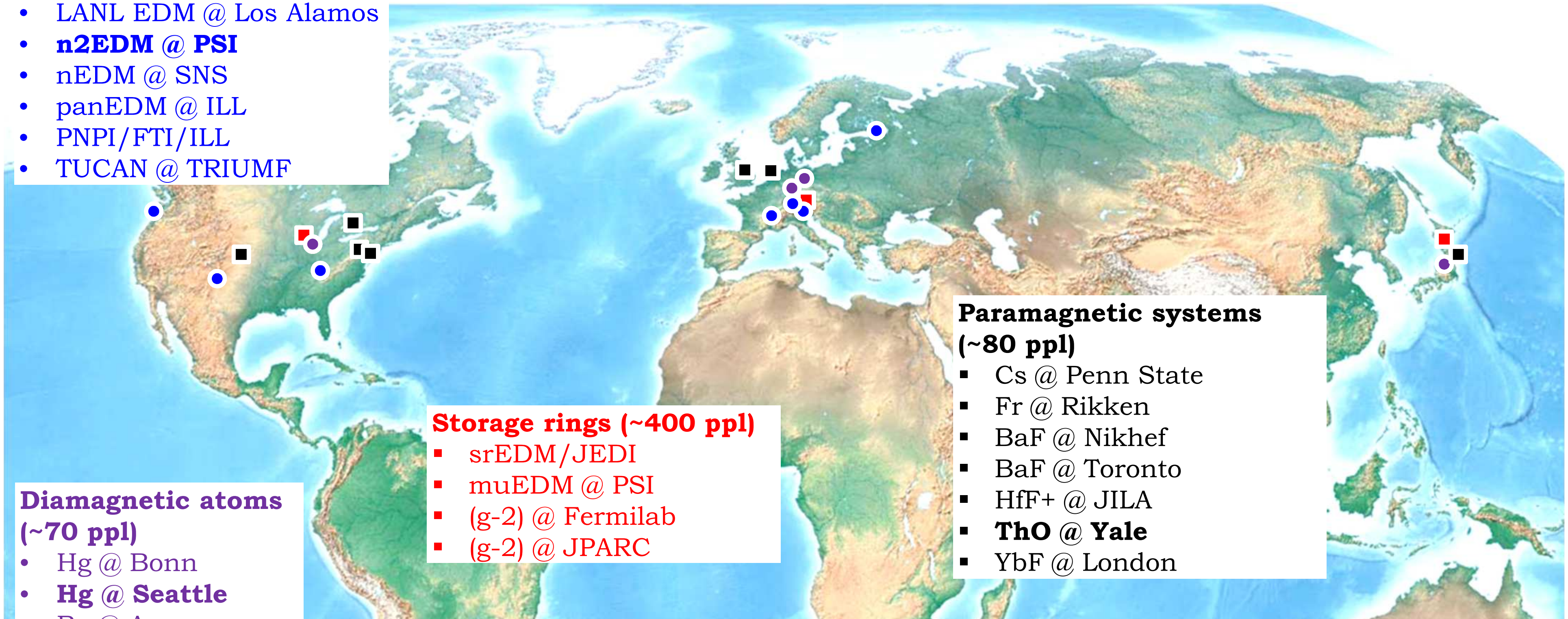
$$2\pi f = \frac{2\mu}{\hbar}B \pm \frac{2d}{\hbar}|E| \qquad f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar}d\,E$$

$$d_n < 1.8 \times 10^{-26}\ e\ \mathrm{cm}\ \ (\mathrm{PSI, 2020})$$

$$d_e < 1 \times 10^{-29}\ e\ \mathrm{cm}\quad (\mathrm{Yale, Harvard, 2018})$$

EDMs in the world

www.psi.ch/en/nedm/edms-world-wide



Neutrons (~200 ppl)

- Beam EDM @ Berne
- LANL EDM @ Los Alamos
- **n2EDM @ PSI**
- nEDM @ SNS
- panEDM @ ILL
- PNPI/FTI/ILL
- TUCAN @ TRIUMF

Diamagnetic atoms (~70 ppl)

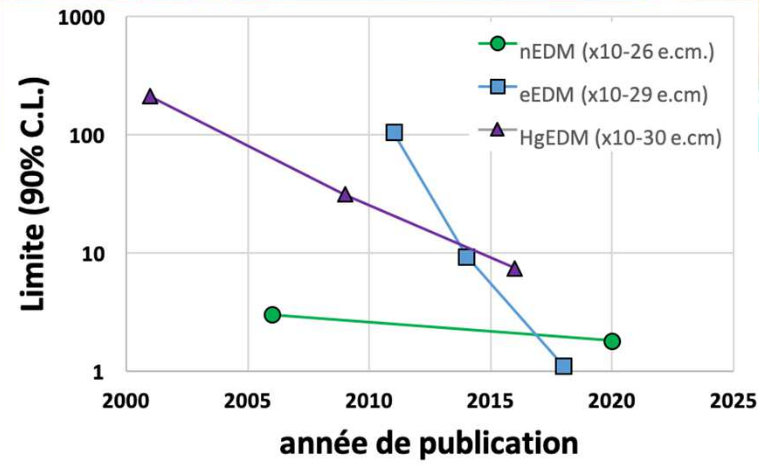
- Hg @ Bonn
- **Hg @ Seattle**
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Rikken

Storage rings (~400 ppl)

- srEDM/JEDI
- muEDM @ PSI
- (g-2) @ Fermilab
- (g-2) @ JPARC

Paramagnetic systems (~80 ppl)

- Cs @ Penn State
- Fr @ Rikken
- BaF @ Nikhef
- BaF @ Toronto
- HfF+ @ JILA
- **ThO @ Yale**
- YbF @ London



At IN2P3 : only neutron EDM in the nEMD/n2EDM@PSI collaboration

LPC Caen : 1PR+1MCF

LPSC Grenoble : 2 MCF + 1 DR

Beyond SM contribution

SM contribution through EW loops : $d_n \approx 10^{-33} e$ cm

The QCD contribution : $\mathcal{L} = \frac{\alpha}{8\pi}\theta\, G^{\mu\nu}\widetilde{G_{\mu\nu}}$

$d_n \approx \theta \times 10^{-16}\ e$ cm

$\rightarrow \theta < 10^{-10}$

« Strong CP problem »

No known mechanism to reduce θ to (nearly?) zero -> axions ?

One loop contribution : for example MSSM contains ~40 CP violating imaginary parameters…

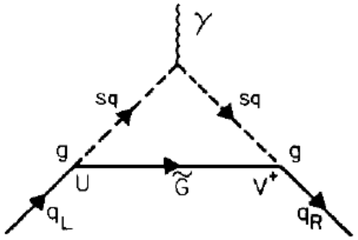


Fig. 2. One-loop diagram which may contribute to d_n in a softly broken susy model.

Ellis, Ferrara, Nanopoulos, PLB ***114*** *(1982).*

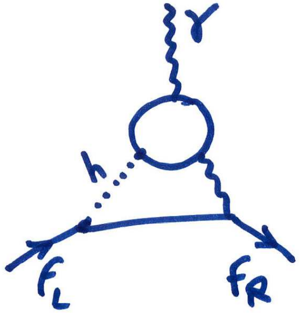
EDM induced by soft mass terms for squarks and gluinos

$$d_n \approx e\frac{\alpha}{4\pi}\frac{m_q}{M_{CPV}^2} \approx \left(\frac{1\ \mathrm{TeV}}{M_{CPV}}\right)^2 \times 10^{-25}\ e\ \mathrm{cm}$$

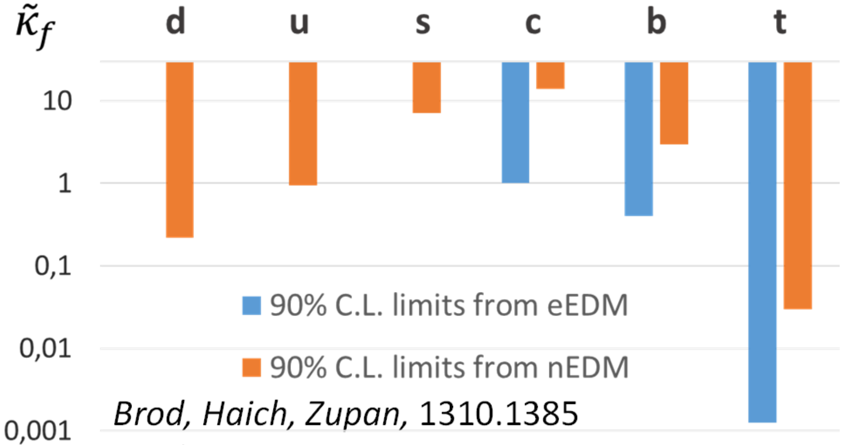
Two loops contribution :

Modified Higgs Yukawa coupling:

$$\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\ \bar{f}\gamma_5 f h\right)$$



Barr, Zee, PRL ***65*** *(1990)*



Brod, Haich, Zupan, 1310.1385

Brod, Stamou, 1810.12303

Brod, Skodras, 1811.05480

Computing nEDM on the lattice

Going from quarks EDMs to the neutron EDM is **low energy QCD**

Current efforts to compute it in the framework of Lattice QCD using dimension 5 and 6 CP violating extension of the QCD lagrangien :

$$\mathcal{L}_{QCD} + \underbrace{i\theta G_{\mu\nu}\tilde{G}_{\mu\nu}}_{\theta\text{-term}} + \underbrace{i\sum_q d_q^{\gamma}\bar{q}\sigma^{\mu\nu}\tilde{F}_{\mu\nu}q}_{\text{Quarks EDM}} + \underbrace{i\sum_q d_q^{G}\bar{q}\,\sigma^{\mu\nu}\tilde{G}_{\mu\nu}q}_{\text{Quarks chromoEDM}} + \underbrace{d_G f^{abc}\, G_{\mu\nu}^{a}\tilde{G}^{\nu\beta,b}\, G_{\beta}^{\mu,c}}_{\text{Weinberg operator}}$$

Imaginary nature of CP violating terms pose specific problems and conventional Markov Chain Monte Carlo methods cannot be used

need to develop new techniques

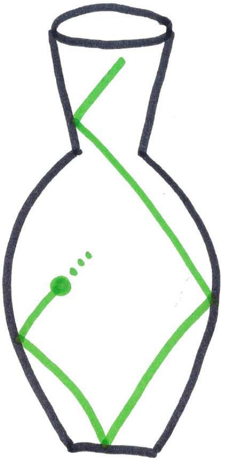
Neutron EDMs in the world

Based on **ultra cold neutron storage** (all but one)

Neutron production : spallation or nuclear reactor + thermalisation + inelastic cooling (He-II or solid D_2)

Room temperature experiments : UCN need to be produced (source) then extracted/guided to the experimental chamber

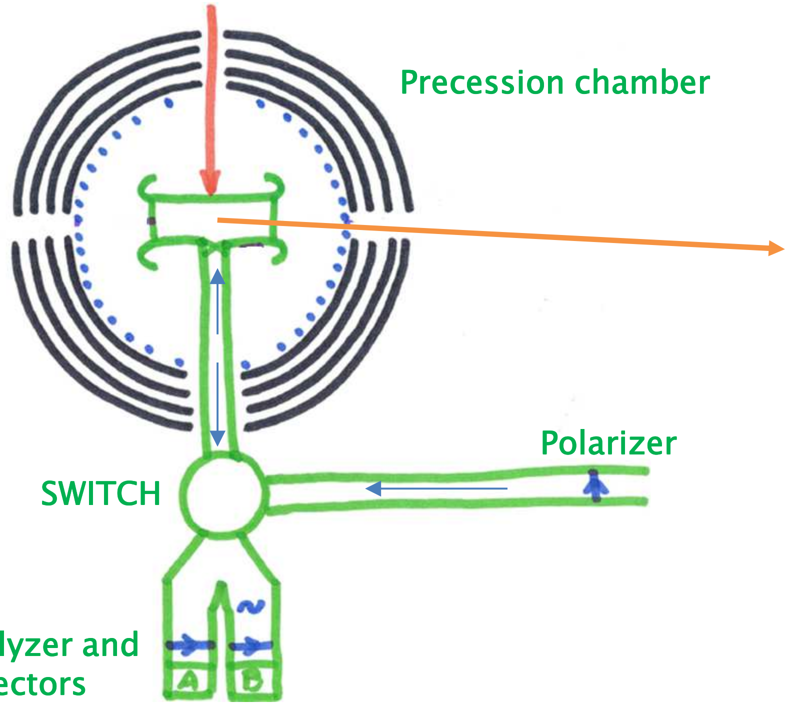
Cryogenic experiments : UCN production and EDM measurement takes place at the same place (in superfluid helium at 1K…)

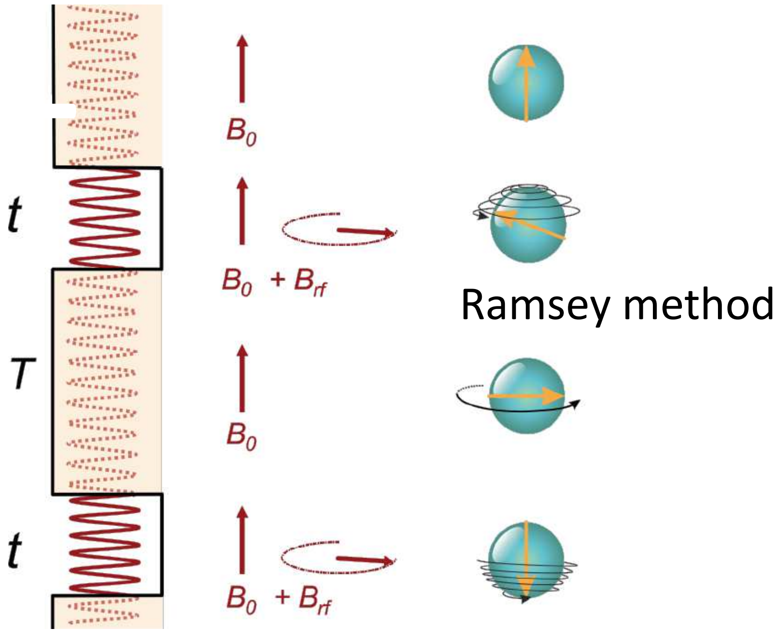


Place	Neutron source	Concept	Stage/Readiness
SNS	Spallation + UCN production in situ	Cryogenic double chamber with helium comagnetometers	« large scale integration » phase
PSI	Spallation + sD2 UCN source	n2EDM: double Ramsey chamber with mercury comagnetometers	Source running, experiment under construction
LANL	Spallation + sD2 UCN source	double Ramsey chamber with mercury comagnetometers	Source running, experiment in design phase
TRIUMF	Spallation + superfluid He UCN source	double Ramsey chamber	Source under construction, experiment in conceptual phase
ILL	Reactor + superfluid He UCN source	panEDM: double Ramsey chamber, no comagnetometers	Source and experiment under construction
PNPI	WWR-M reactor + inpile superfluid He UCN source	Getting a really high density of UCNs	Source under construction
ESS	Spallation + Cold neutron beam	100m double beam + time of flight	Demonstration phase, small prototype operational @ ILL

Room temperature UCN experiments aiming at a precision of $\approx \mathbf{1\times 10^{-27}}\,e\,\mathbf{cm}$

How to measure nEDM



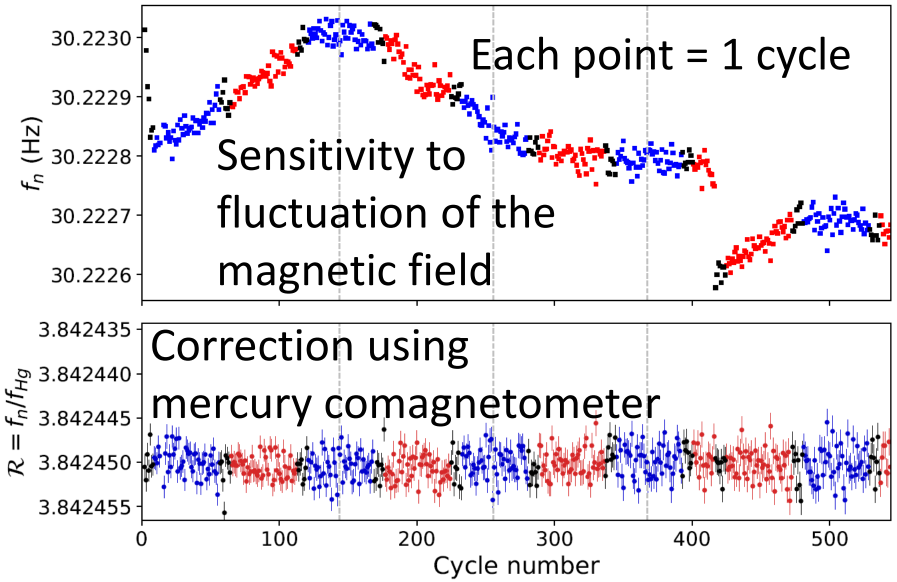


Count neutrons in ↑ and ↓ spin states
Relate asymmetry to precession frequency

Of course many extra subtleties and corrections are needed…

Statistical sensitivity: $\sigma_{d_n} = \frac{\hbar}{2\,\alpha\,E\,T\,\sqrt{N}}$

1 cycle : $T \approx 180s, N = 5000$ to 15000


Each point = 1 cycle

Sensitivity to fluctuation of the magnetic field

Correction using mercury comagnetometer

nEDM and n2EDM @ PSI

$$d_n < 3 \times 10^{-26}\ e.cm$$

$$d_n = \left(-0.2 \pm 1.5_{stat} \pm 1.0_{syst}\right) \times 10^{-26}\ \mathrm{ecm}$$

1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012

ILL data production

RAL/Sussex collaboration

Transfer at PSI (new UCN source)
Various upgrade
New collaboration : nEDM

New appartus : n2EDM

PSI data

n2EDM installation and comissionning

n2EDM data…

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

$$d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{syst}\right) \times 10^{-26}\ \mathrm{ecm}$$

$$d_n < 1.8 \times 10^{-26}\ e.cm$$

Abel et al., PRL 124 081803 (2020)

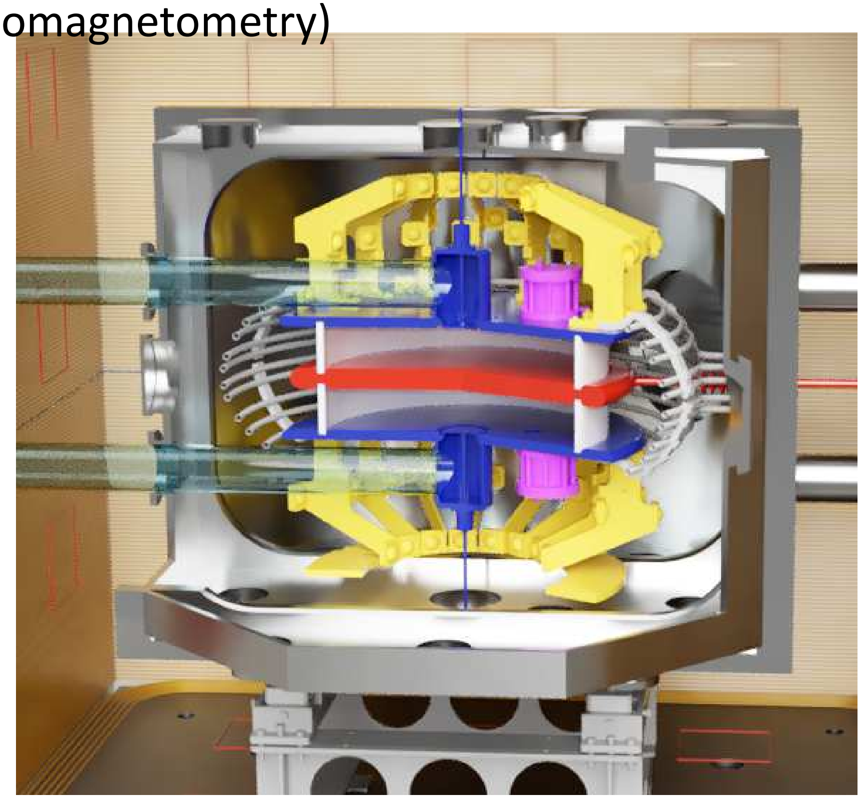
n2EDM @ PSI

The nEDM collaboration has demonstrated its capacity to control systematic effects at a few $\mathbf{10 \times 10^{-27}}$ $\boldsymbol{e}$cm

Further improvement for n2EDM :

Control of the magnetic field homogeneity and measurement : improved systematiccs

- Colossal magnetic shield (6 mu-metal layers, $5 \times 5 \times 5\ \mathrm{m}^3$), shielding factor 100000
- Dual chamber apparatus : simultaneous measurement of both field configuration
- Advanced magnetometry (external and comagnetometry)



Increase the statistics

- 5 year data taking
- Larger chambers

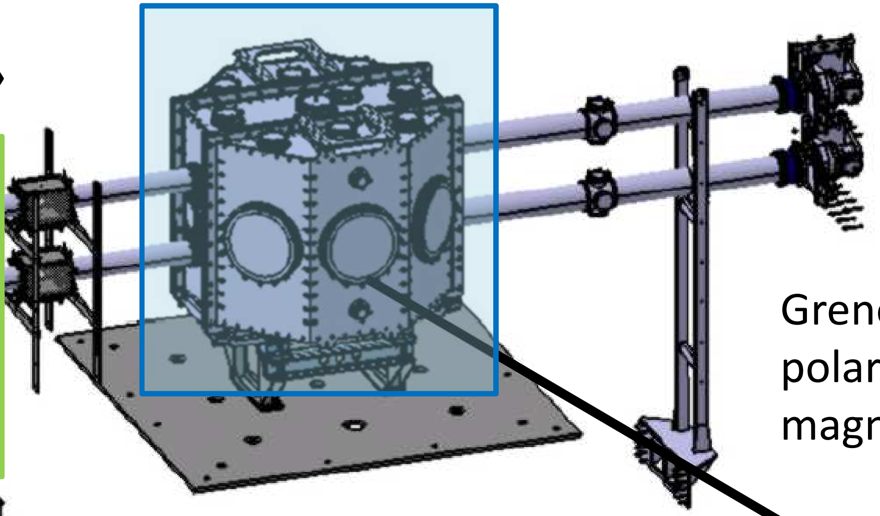
Possible further improvement :
« magic field » to compensate
Systematic vxE effect in comagnetometer
G.Pignol 1812.01420

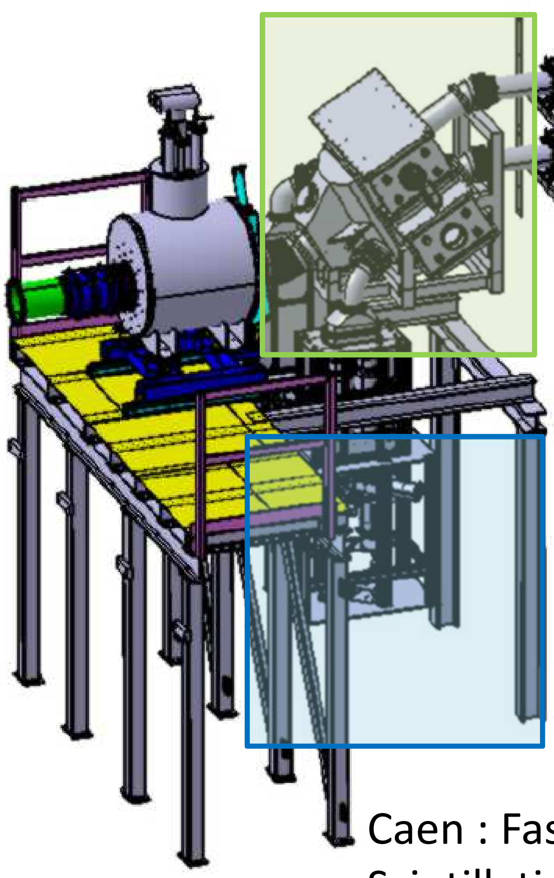
IN2P3 contribution

For n2EDM, French contribution financed mostly through : ANR (Th. Lefort) + ERC (G.Pignol)
Continue in our field of expertise of nEDM : Magnetic field coils, detectors, Hg magnetometry and data analysis

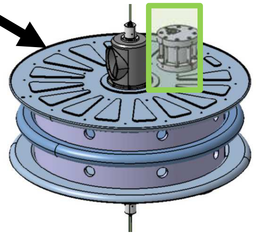
Caen : Vacuum chamber

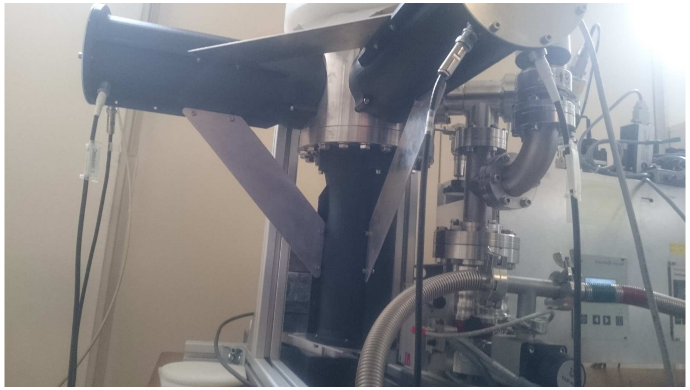
Grenoble : Neutron distribution « switch »





Grenoble : Hg polarisation and magnetometry

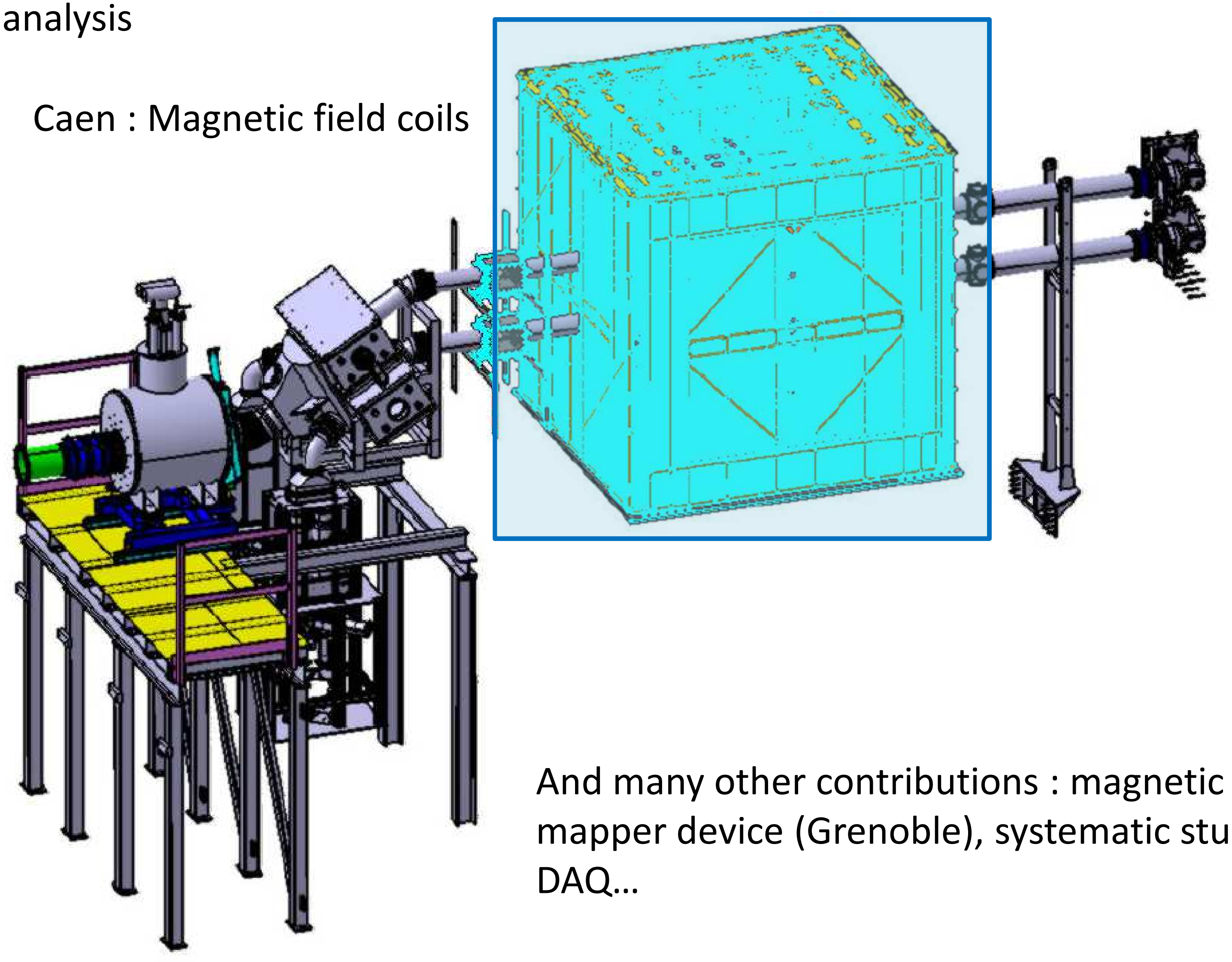




Caen : Fast (500kHz) and efficient UCN detectors
Scintillation in 3He

IN2P3 contribution

For n2EDM, French contribution financed mostly through : ANR (Th. Lefort) + ERC (G.Pignol)
Continue in our field of expertise of nEDM : Magnetic field coils, detectors, Hg magnetometry and data analysis



Caen : Magnetic field coils

And many other contributions : magnetic field mapper device (Grenoble), systematic studies, DAQ…

Summary and conclusion

Forbidden processes :

Interesting window into BSM Physics
Complementarity with direct searches

In France :

Small community with both theoricists (phenomenology, effective theories, lattice QCD) and experimentalists.

Two main experimental projects supported by IN2P3

COMET : charged lepton flavour violation
n2EDM : neutron electric dipole moment

Experiments with timescale spanning the coming decade and beyond!

Extra material

❑ COMET experiment: muon-electron conversion and more!

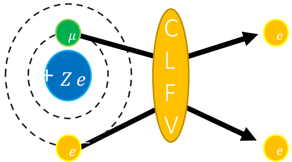
COMET offers the possibility to study further

cLFV observables (Coulomb enhanced $\mu^- e^- \to e^- e^-$ decay),
LNV decays ($\mu^- + (A,Z) \to e^+ + (A, Z-2)^*$) and
even search for light exotics ($\mu^- \to e^- X$)

- $\mu^- N_Z \to e^+ N_{Z-2}$: Lepton number violation (LNV)
  - Current limits: $\mu^- Ti \to e^+ Ca(gs) \le 1.7 \times 10^{-12}$
    $\mu^- Ti \to e^+ Ca(ex) \le 3.6 \times 10^{-12}$
  - Can improve with a proper target

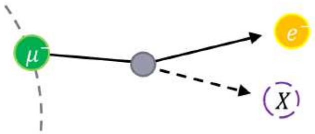
Phys. Lett. B422 (1998)
Phys. Lett. B764 (2017)
Phys. Rev. D96 (2017)

- $\mu^- e^- \to e^- e^-$: μ^- and e^- overlap proportional to Z^3



Phys. Rev. Lett. 105 (2010)
Phys. Rev. D93 (2016) 076006
Phys. Rev. D97 (2018) 015017

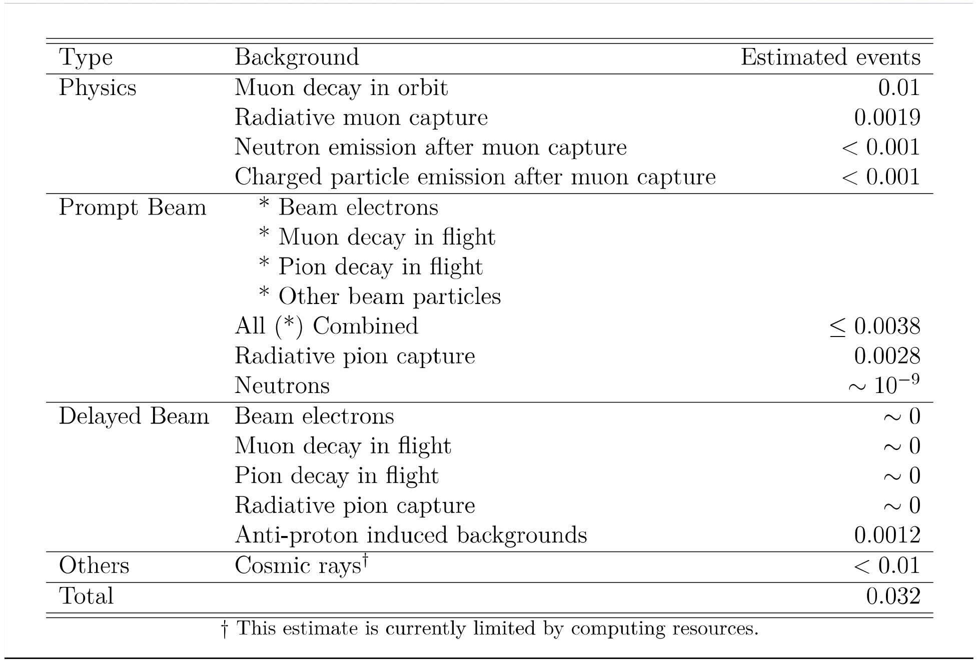
- $\mu^- \to e^- X$: X can be a new light boson, axion, etc.
  - feasibility being studied in COMET



Phys. Rev. D79. 055023 (2009)
Phys. Rev. D84. 113010 (2011)

❑ COMET experiment: COherent Muon to Electron Transition

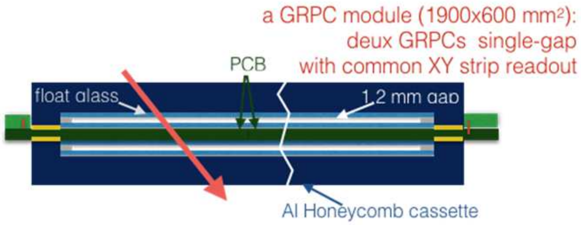
COMET: Phase I – backgrounds and Cosmic Ray Veto

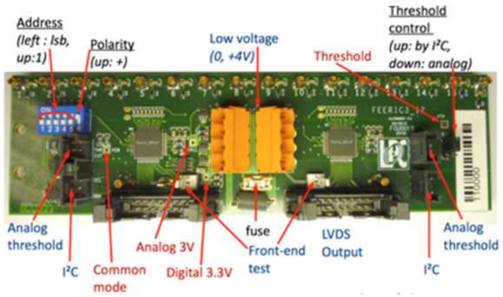


Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

- **Scintillator slabs** with embedded WLS-fibres and SiPM readout
- **Resistive Plate Chambers (RPC)** read out with XY strips and Feeric ASIC (LPC/ALICE design) in the highest neutron yield areas

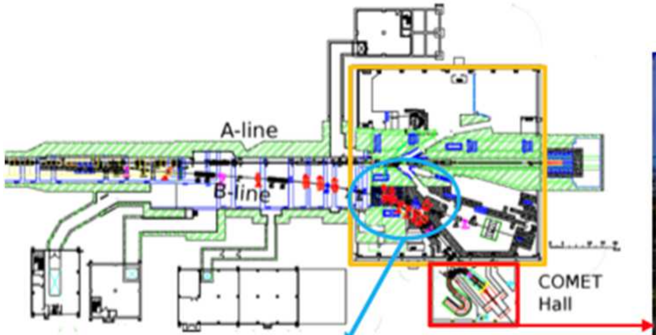


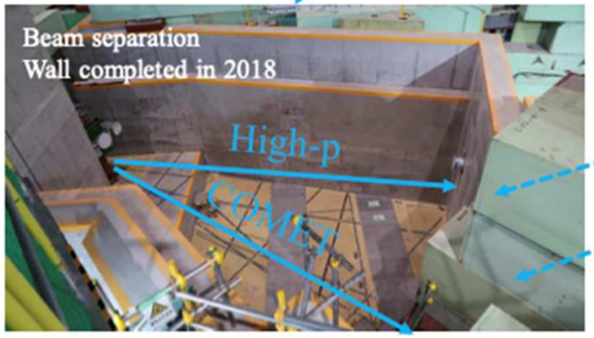


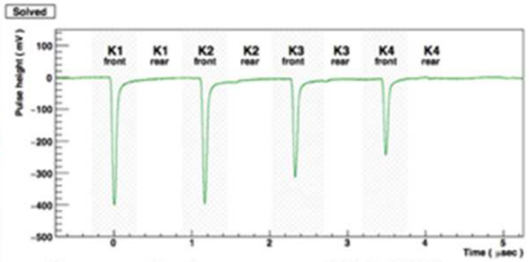
FE board for a GRPC module, with two Ferric ASICs

❑ COMET experiment: COherent Muon to Electron Transition

COMET: Phase I (status end 2019)







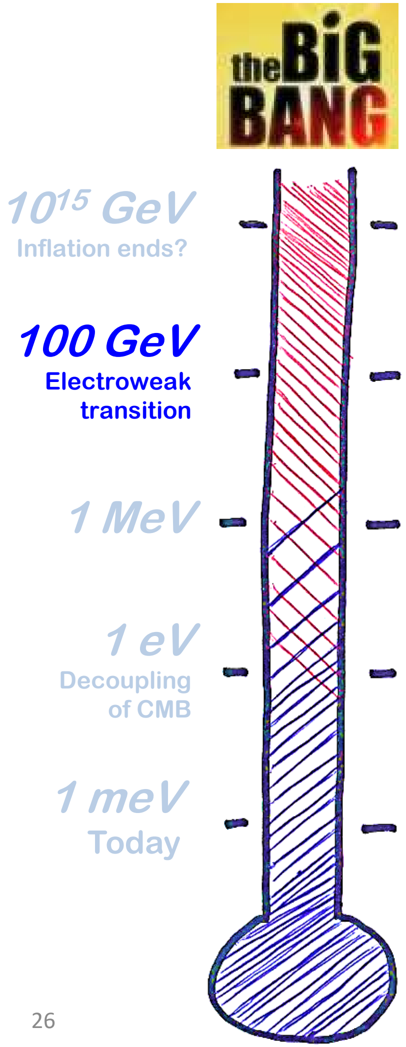
Beam extinction measured Feb 2019

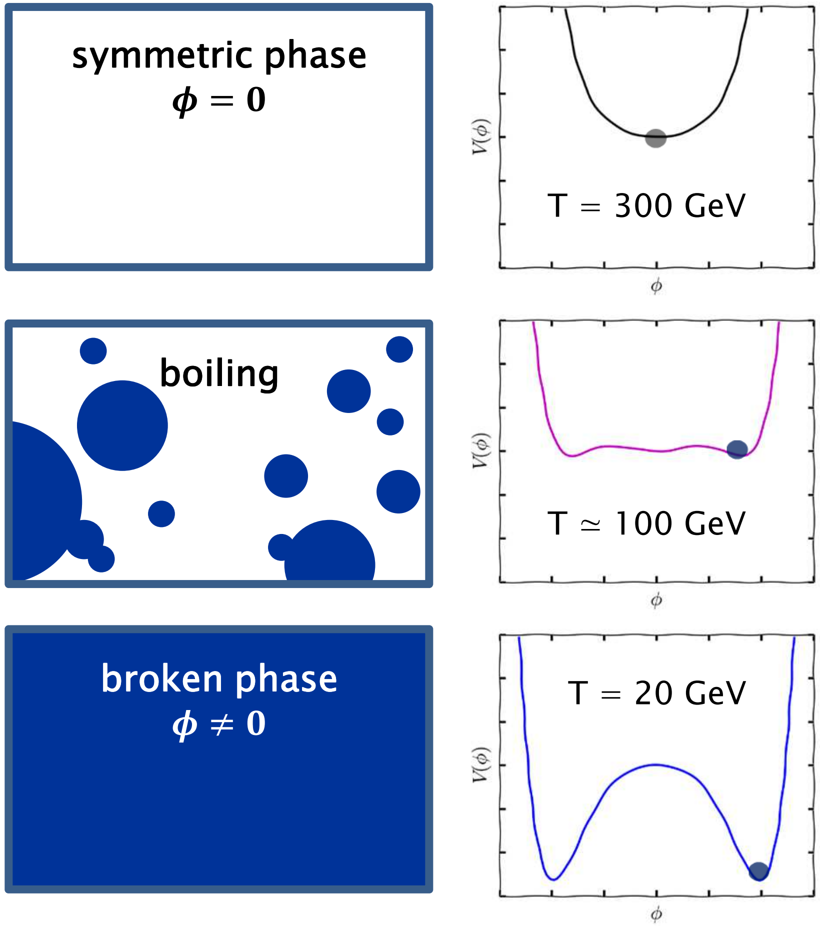
COMET facility: ready before end **2022**

CDC calibration with atmospheric muons: **ongoing**

First beam muons expected end **2022**

Electroweak baryogenesis?





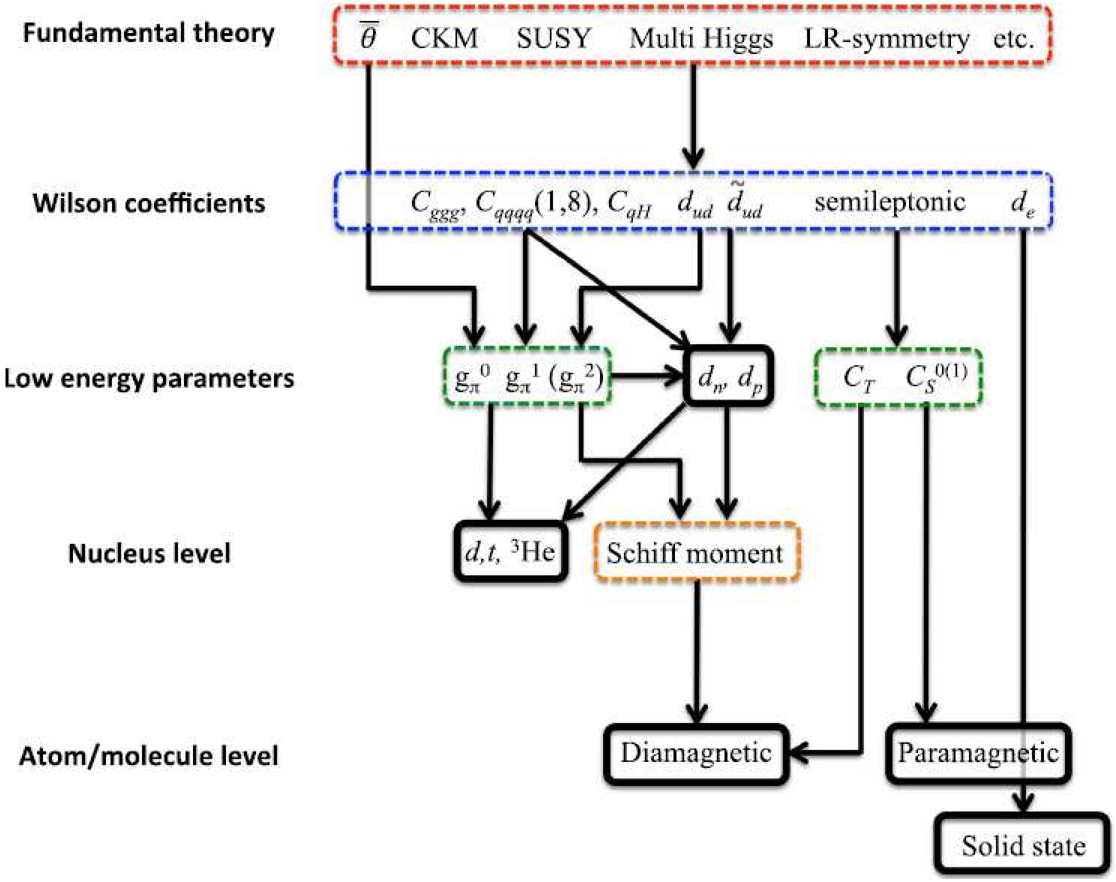
Sakharov's Baryogenesis recipe (1967)

- Baryon number not conserved
- Universe out of equilibrium
- **Violation of CP symmetry**

>> EDMs

Current EDM bound constrains many scenarios of BSM electroweak baryogenesis

Energy scale ladder



Fundamental theory

$\overline{\theta}$ CKM SUSY Multi Higgs LR-symmetry etc.

Wilson coefficients

C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} d_{ud} $\tilde{d}_{ud}$ semileptonic d_e

Low energy parameters

g_π^0 g_π^1 (g_π^2)

d_n, d_p

C_T $C_S^{0(1)}$

Nucleus level

$d, t,$ ^{3}He

Schiff moment

Atom/molecule level

Diamagnetic

Paramagnetic

Solid state