Dipole Moments and Lepton Flavour Violation

- Introduction
- Dipole Moments
  - EDM
  - Muon g-2
- Lepton Flavour Violation
- Lepton Flavour Universality
- Summary

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2017 ICFA Seminar
Nov. 6th-9th, 2017, Ottawa, Canada

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- I apologise that I can't cover all the experiments for this topic just because of the limited time.

- Many thanks for materials and information provided by

  D. Hertzog, T. Mibe, S. Mihara, H. Nishiguchi, A. Papa, N. Saito, Y. Sakemi, A. Schoening

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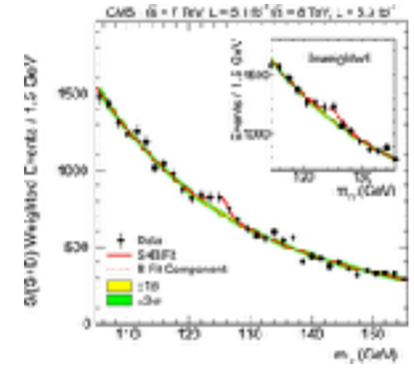
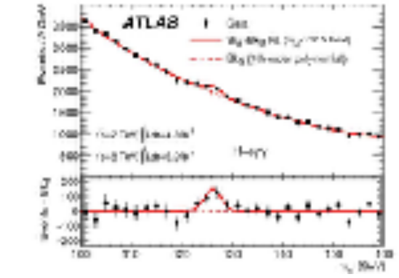
Where Are We?



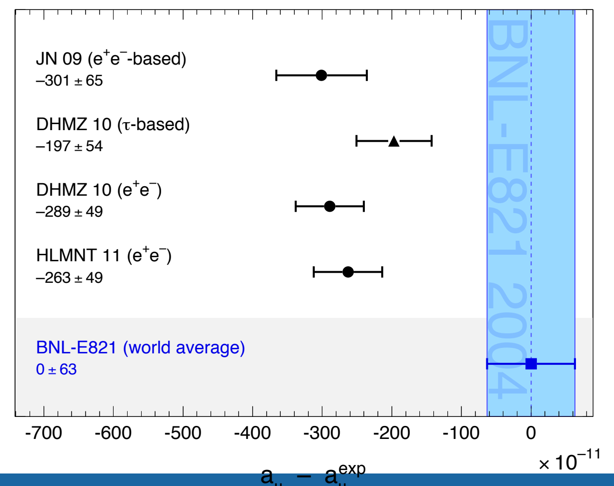
The Nobel Prize in Physics 2013

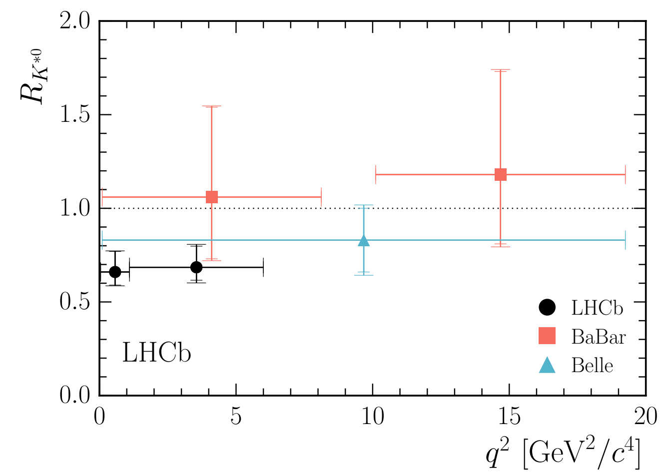
Photo: A. Mahmoud
François Englert

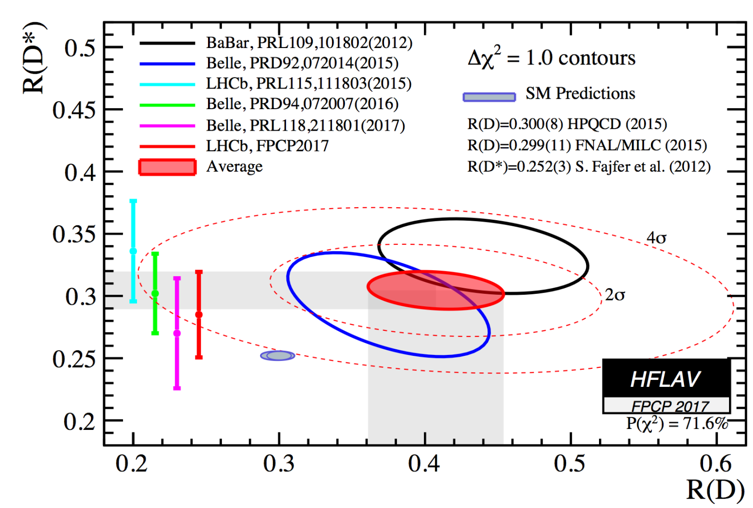
Photo: A. Mahmoud
Peter W. Higgs



- **Looks (a little) different from what we expected**
  - Higgs boson with a mass of 125GeV discovered at LHC in 2012
  - Non-observation of supersymmetry
- **On the other hand, obviously, the Standard Model (SM) is not satisfactory**
- **We should tackle the problem with different approaches including high precision probes at low energies such as**
  - Electric Dipole Moment (EDM)
  - Magnetic Dipole Moment (MDM)
  - Lepton Flavour Violation (LFV)
  - Lepton Flavour Universality Violation (LFUV)
- **Note that there are some interesting hints of deviation from SM in the low energy phenomena**

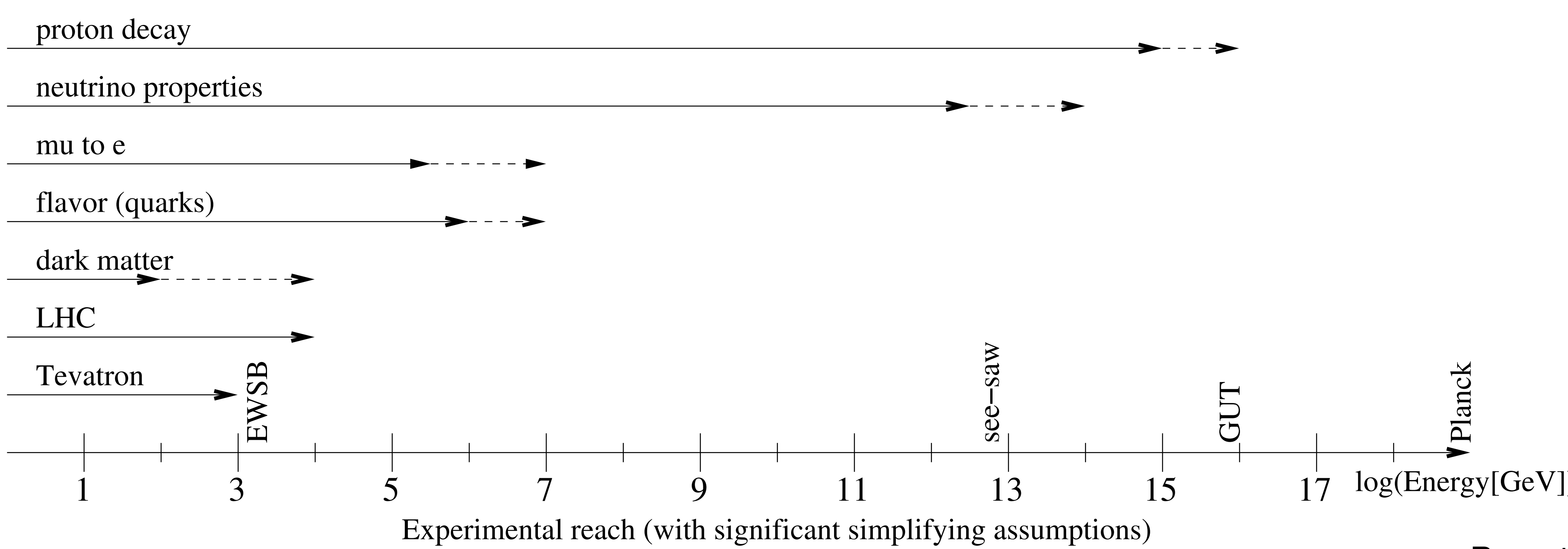






Why to Take These Approaches?

- **Large contribution expected from new physics**
- **SM contribution strongly suppressed (No SM background)**
- **Complementary to energy frontier experiments**
  - Colourless particles not strongly constrained by LHC
  - Physics at very high energy scale beyond LHC reach is accessible
  - Direct study on flavour structure of new physics
- **Large samples available with high intensity accelerator**
  - μ (PSI, TRIUMF, J-PARC, Fermilab)
  - τ ((Super)KEKB, PEP-II, LHC)
- **Development of technologies to enable sensitive experiments**



Report from Snowmass 2013

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

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

W.Altmannshofer et al., Nucl. Phys. B 830(2010)17

Low energy probes have broad sensitivities to BSM models

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Electric Dipole Moment (EDM)

- **EDM: Separation of particle charge along angular momentum axis**
  - Non-zero EDM violates both P (parity symmetry) and T (time-reversal symmetry).
  - Also violates CP (C: charge conjugation), assuming CPT conservation
- **New large source of CP violation (CPV) is required to explain matter-antimatter asymmetry in the universe**
  - EDM induced by SM (electroweak) CPV is too small and far beyond experimental reach
  - Possible large enhancement of EDM by new physics

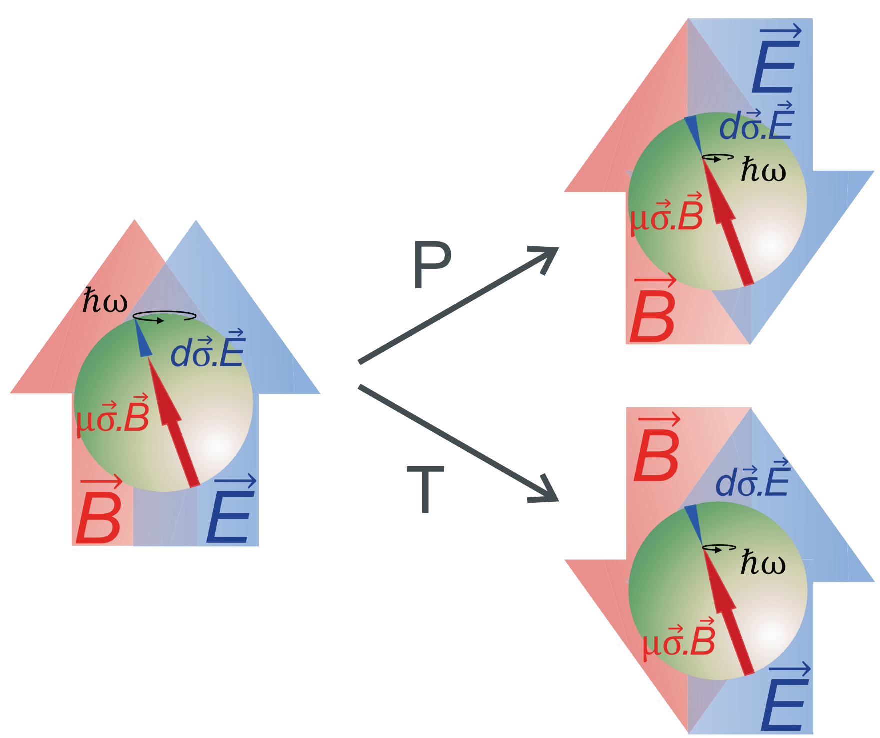
$$d_e^{\mathrm{CKM}} \sim 10^{-38}\,\mathrm{e\text{-}cm}$$

→Physics motivation of EDM search

- New physics
- New CPV source

$$H = -(\mu \vec{J}\cdot\vec{B} + d\vec{J}\cdot\vec{E})/J$$

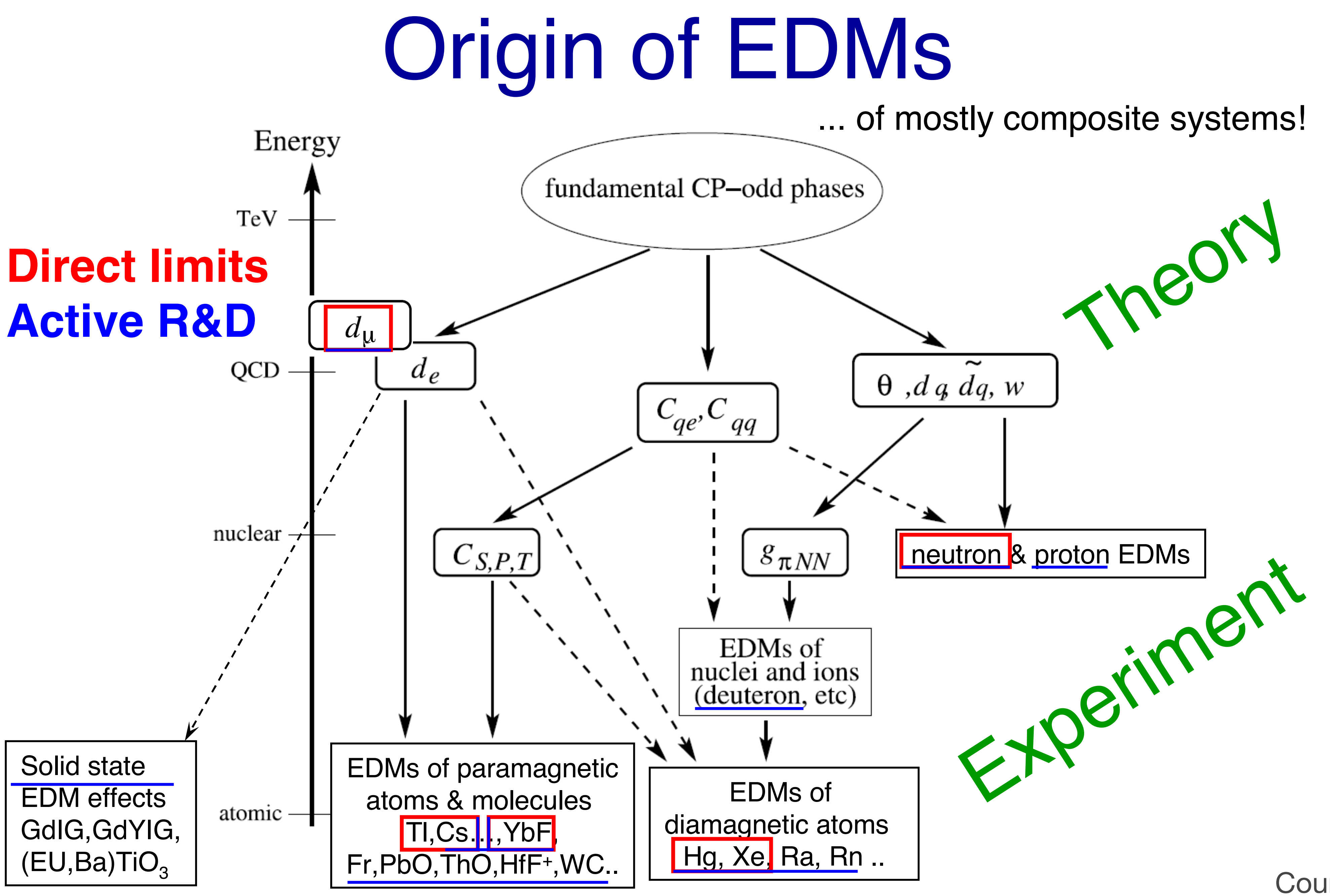
	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-



Courtesy of P. Schmidt-Wellenburg

EDM Experimental Approaches

- **Various systems (neutron, muon, atom, molecules,…) are utilised**
  - Different approaches to study different CPV parameters

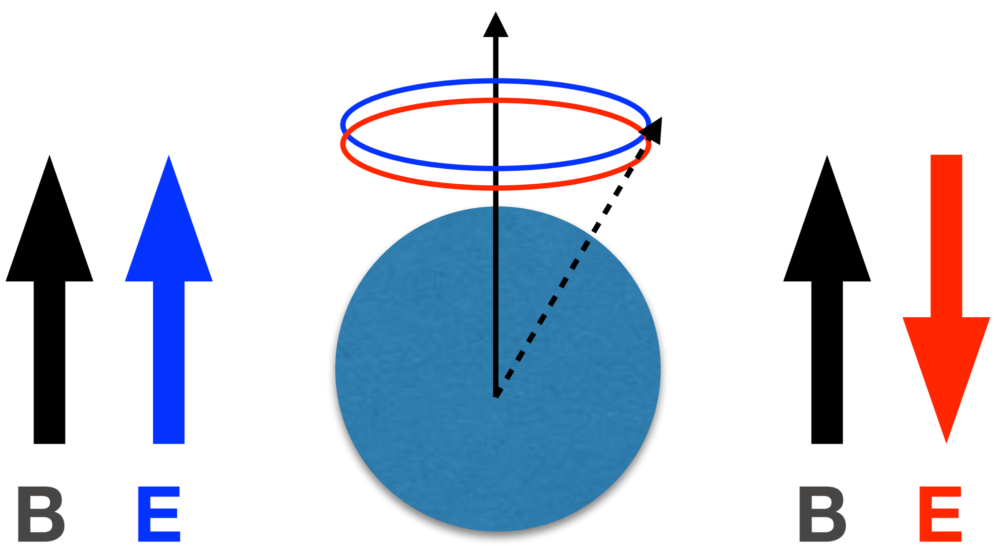


Courtesy of K. Kirch

Adapted from:
Pospelov, Ritz, Ann. Phys. 318 (2005) 119
M. Raidal et al., Eur. Phys. J. C 57 (2008) 13

EDM How to Measure EDM?

- **Common approach**
  - Apply small but well-controlled B-field for spin precession
  - Apply strong E-field
  - Measure Larmor frequency shift in splitting of magnetic sub-levels



$$h\nu_{\uparrow\uparrow} = 2(\mu \cdot B + d \cdot E)$$
$$h\nu_{\uparrow\downarrow} = 2(\mu \cdot B - d \cdot E)$$

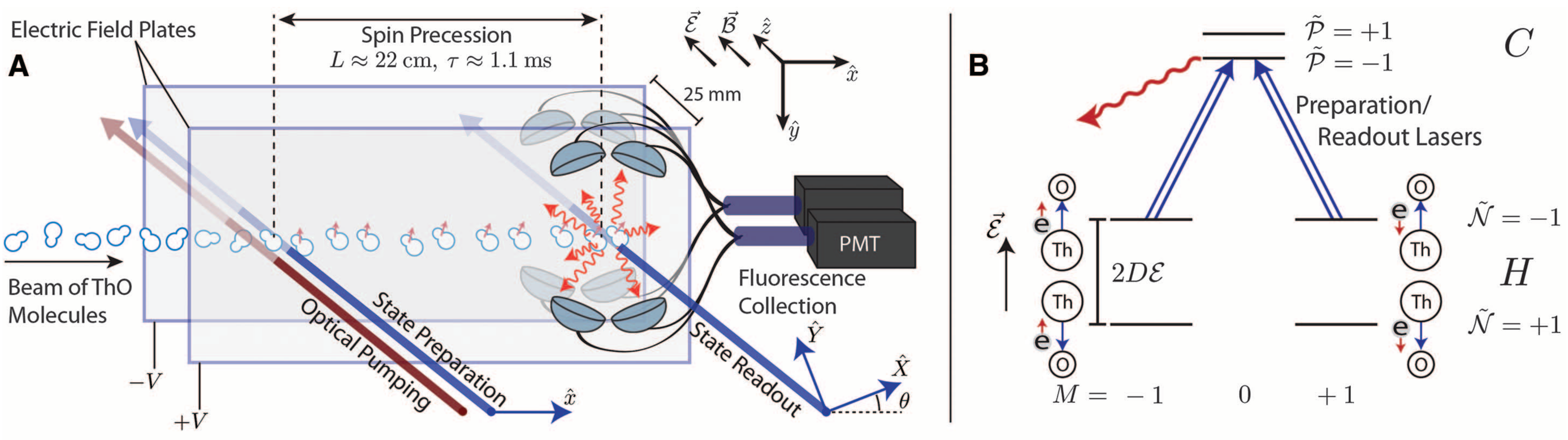
$$\Rightarrow \quad h\Delta\nu = 4d \cdot E$$

Sensitivity $$\delta d \propto \frac{1}{K \cdot p \cdot E \cdot \sqrt{N \cdot \tau \cdot T}}$$

- K: Enhancement factor
- p: Polarisation
- E: Electric field
- N: # of particles
- τ: Lifetime of system
- T: Measurement time

EDM Paramagnetic Atoms and Molecules

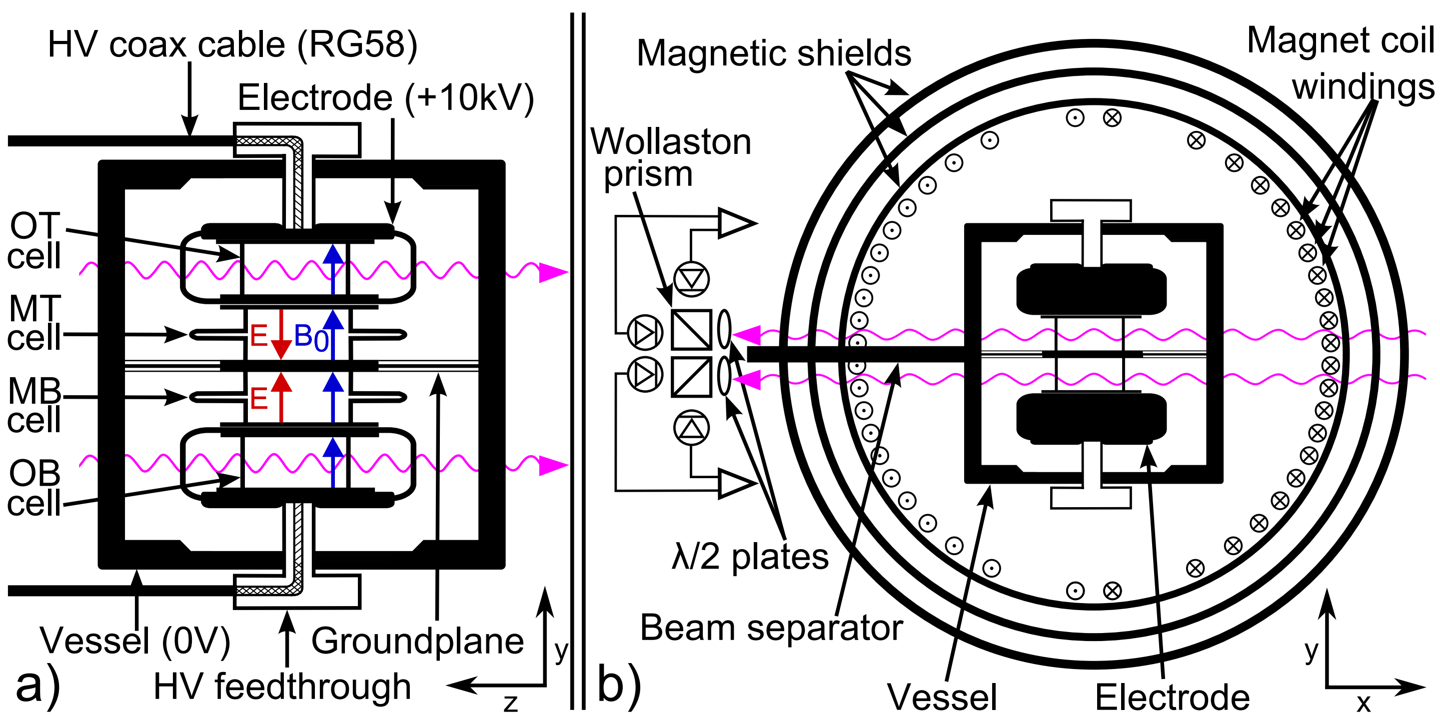
- Tl, Cs, Fr, YbF, PbO, ThO, HfF^+, WC, …
- Sensitive to electron EDM
- Large enhancement factor $\sim 10Z^3\alpha^2$ for paramagnetic atoms
- Additional enhancement by large internal electric field ($\gtrsim$10GV/cm) for polar molecules
  - Even further enhancement with combined polar molecule Fr-Sr
- Best upper limit on electron EDM
  - $|d_e|<8.7\times10^{-29}$ e-cm (90% C.L.)



J. Baron et al. (ACME), Science 343(2014)269

EDM Diamagnetic Atoms

- **Most sensitive to P, T-odd nuclear force**
- **d_{Hg}=~$10^{-3}d_q^c$ (chromo EDM of quark): suppression by Schiff-moment of ~10^3**
- **Hg, Xe, Ra, Rn,…**
- **$|d_{Hg\text{-}199}|<7.4\times10^{-30}$ e-cm (95%C.L.)→ Best EDM limit to date!**
  - Limiting various CPV parameters



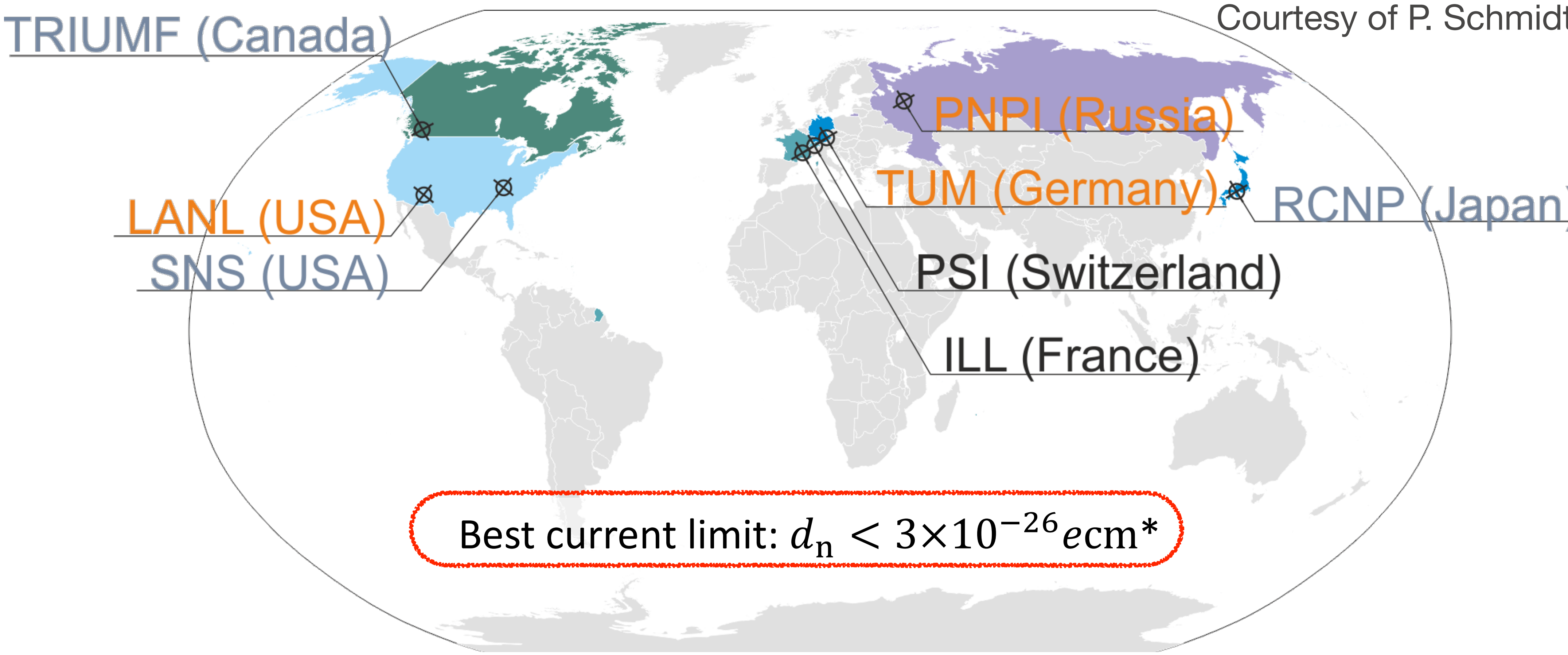
B. Graner et al., PRL 116(2016)161601

Parameter	system	95% u.l.
d_e	ThO	9.2×10^{-29} e-cm
C_S	ThO	8.6×10^{-9}
C_T	^{199}Hg	3.6×10^{-10}
$\bar{g}_\pi^0$	^{199}Hg	3.8×10^{-12}
$\bar{g}_\pi^0$	neutron	2.2×10^{-12}
$\bar{g}_\pi^1$	^{199}Hg	3.8×10^{-13}
$\bar{g}_\pi^1$	TlF	4.1×10^{-10}
$\bar{g}_\pi^2$	^{199}Hg	2.6×10^{-11}
d_n^{sr}	neutron	3.3×10^{-26} e-cm
d_p^{sr}	TlF	8.7×10^{-23} e-cm
d_p^{sr}	^{199}Hg	2.0×10^{-25} e-cm
Other parameters		
d_d	$\approx 3/4 d_n$	2.5×10^{-26} e-cm
$\bar{\theta}$	$\approx \bar{g}_\pi^0/(0.02)$	1.9×10^{-10}
$\tilde{d}_d-\tilde{d}_u$	$5\times10^{-15}\bar{g}_\pi^1$ e-cm	2×10^{-27} e-cm

T. Chupp et al., arXiv:1710.02504v1

EDM Neutron

Courtesy of P. Schmidt-Wellenburg



Best current limit: $d_n < 3\times10^{-26} e\text{cm}$*

- PNPI: Measurement at ILL concluded – and published $d_n < 5.5\times10^{-26} e\text{cm}$**
  UCN source equipment ready for WWR-M reactor
- PSI: data-taking concluded – analysis ongoing, setup of new apparatus
- TRIUMF/RCNP/KEK: construction of new source for TRIUMF
- SNS: UCN source & experiment are one apparatus, construction of half/scale prototypes, finalization of design → Start of measurements in 2023
- TUM: Experiment moves to ILL to new source “SuperSUN” → Start 2020
- LANL: UCN source upgrade finished: factor 3 increase – construction of Ramsey apparatus

- **Modest improvement expected in next years (PSI-nEDM, PNPI-UCN nEDM at ILL)**
- **×10 improvement (~10^{-27} e-cm) expected in next 5 years**
- **Also aiming at ultimate goal down to ~10^{-28} e-cm**

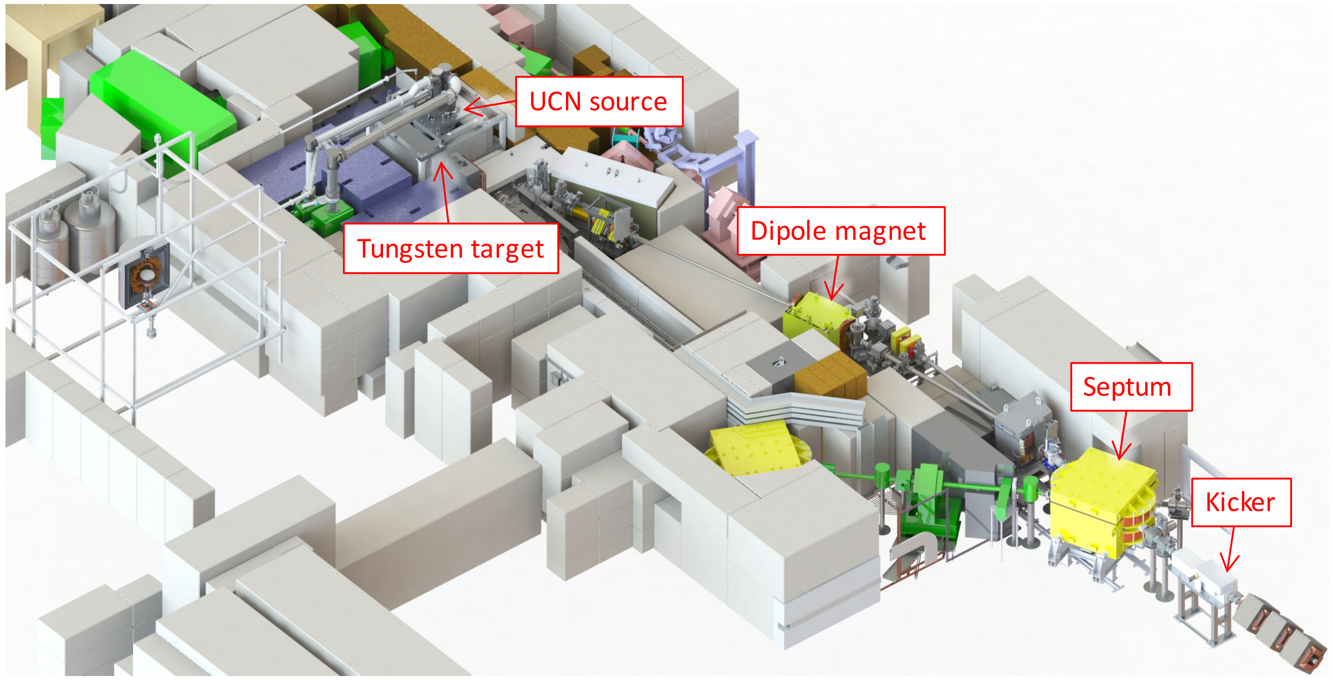
*J.M. Pendlebury et al., PRD 92 (2015) 092003

PHYSICAL REVIEW C **92, 055501 (2015)

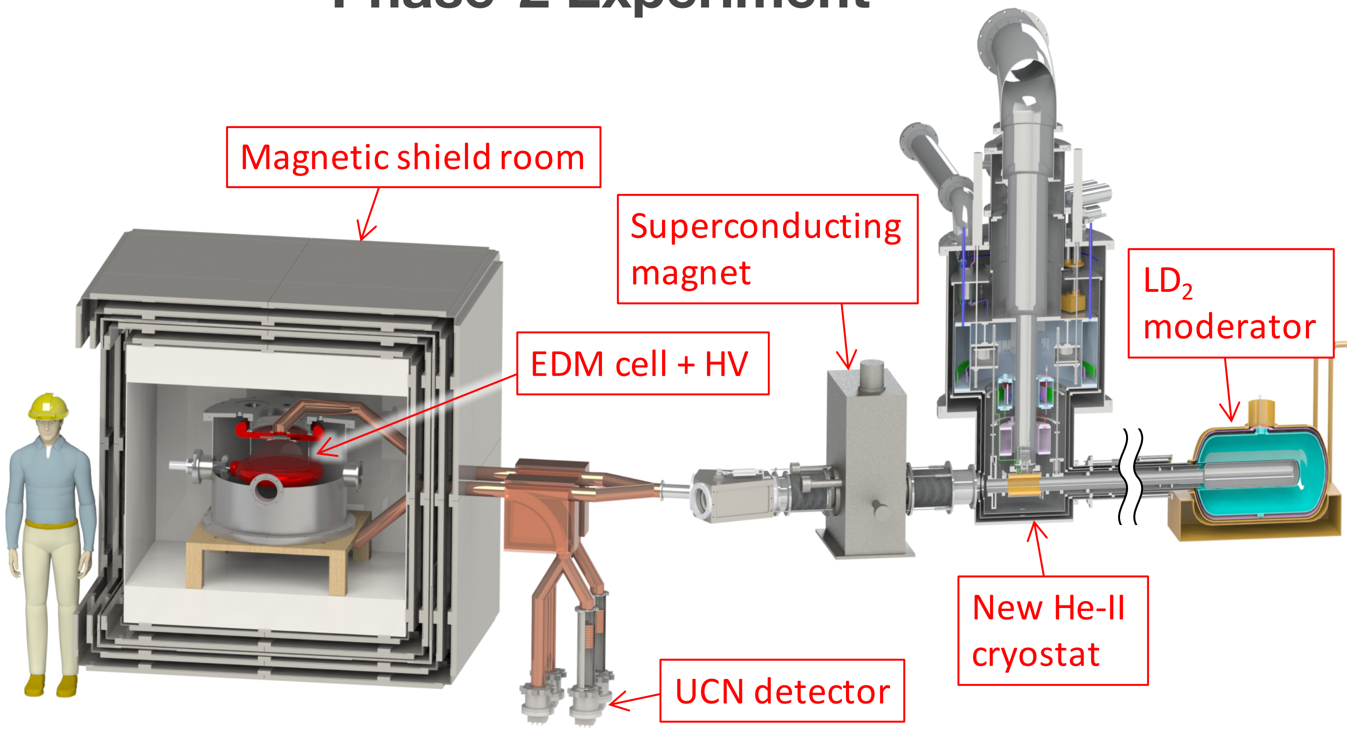
EDM Japan-Canada nEDM

- **New ultra cold neutron (UCN) beam line constructed at TRIUMF**
- **Phase 1**
  - UCN source and EDM apparatus moved from Japan
  - Start in 2018
- **Phase 2**
  - Target sensitivity: $d_n < 10^{-27}$ e-cm
  - Start in 2020

New UCN beam line at TRIUMF



Phase-2 Experiment

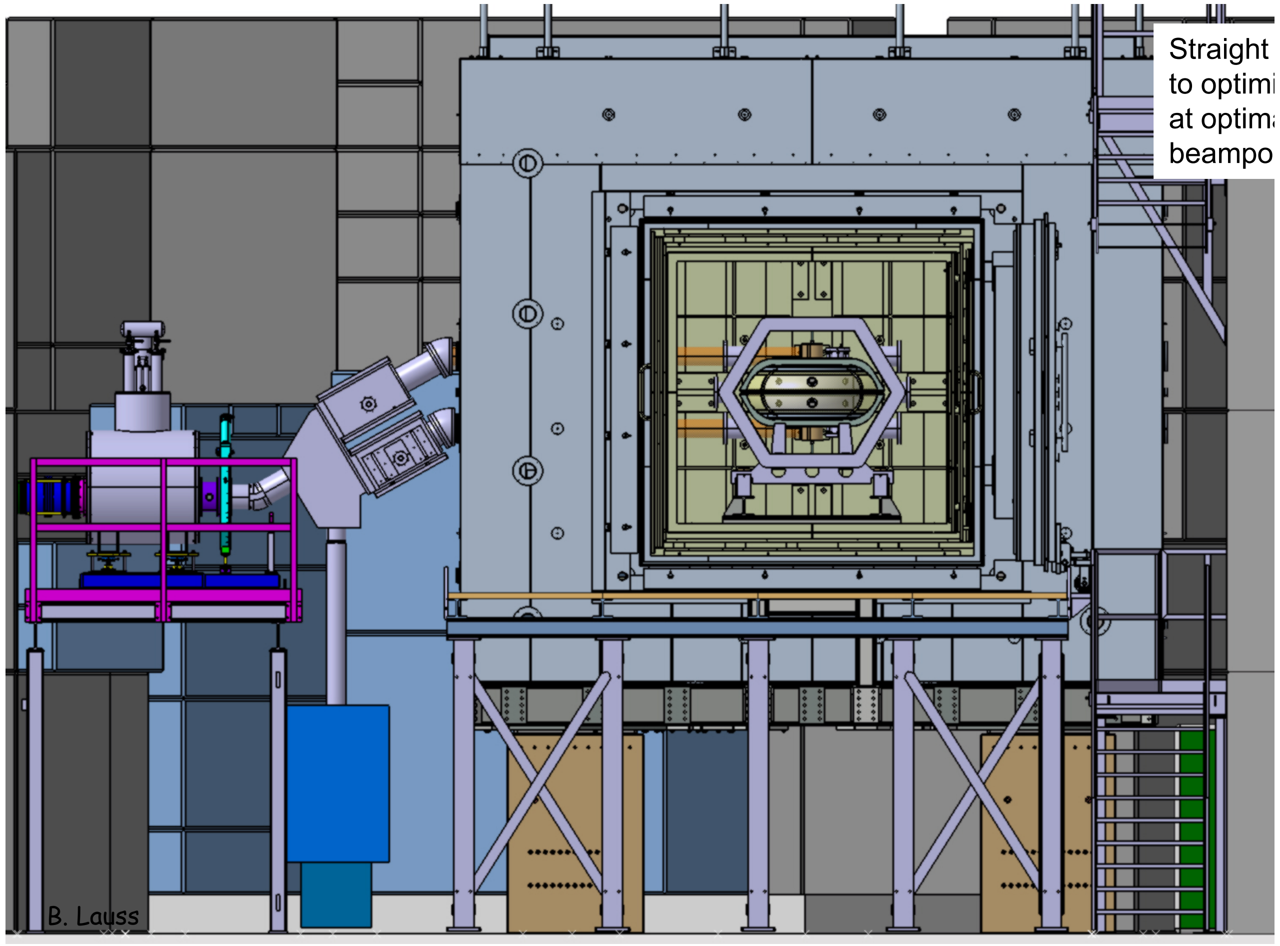


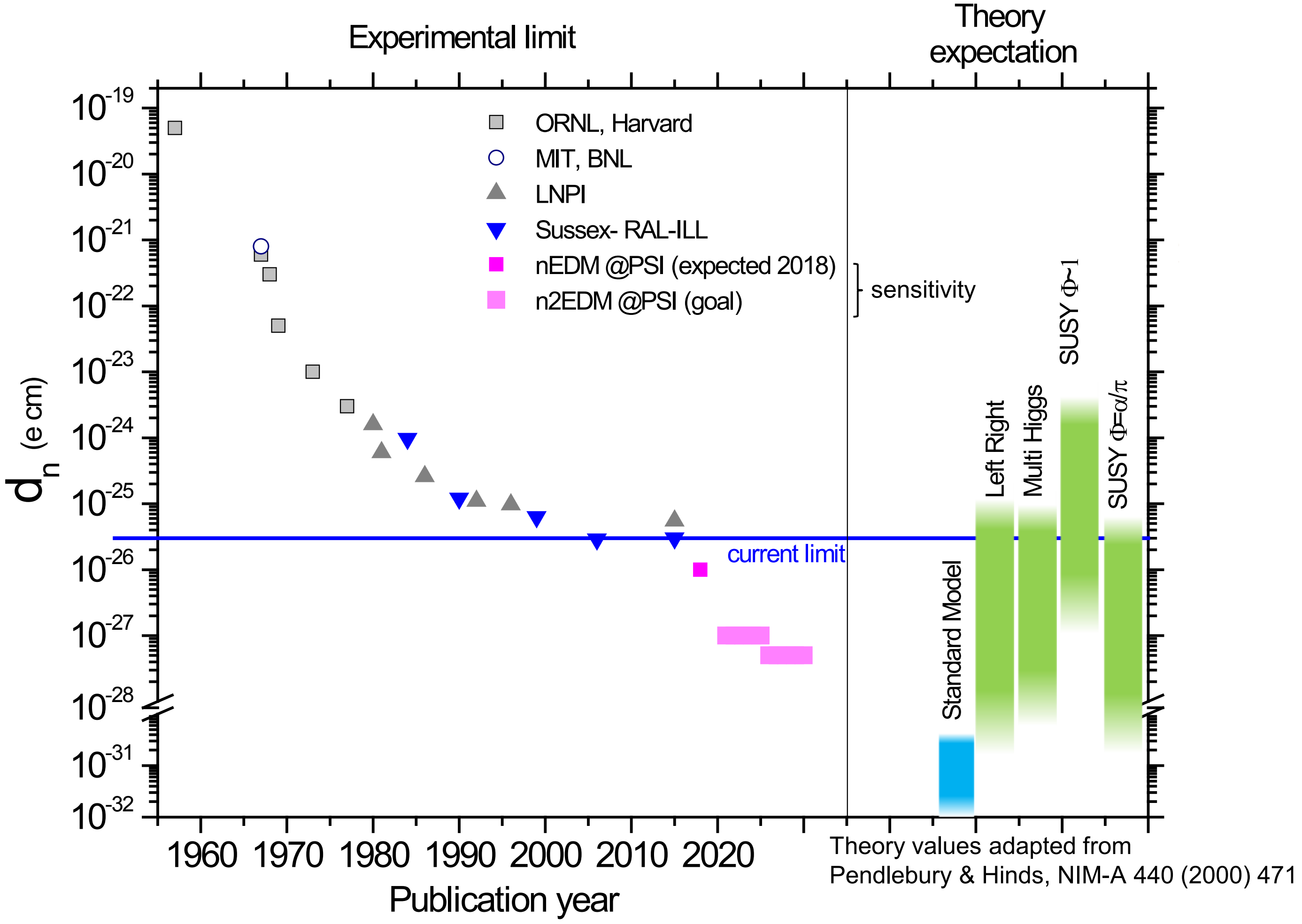
T. Kikawa, nEDM Workshop 2017

EDM PSI-nEDM

- **Data-taking completed**
- **Preparation for new apparatus (n2EDM) has been started**
  - ×10 sensitivity: $d_n < 1\times10^{-27}$ e-cm in 500-days DAQ
  - Data-taking will start in 2020

n2EDM

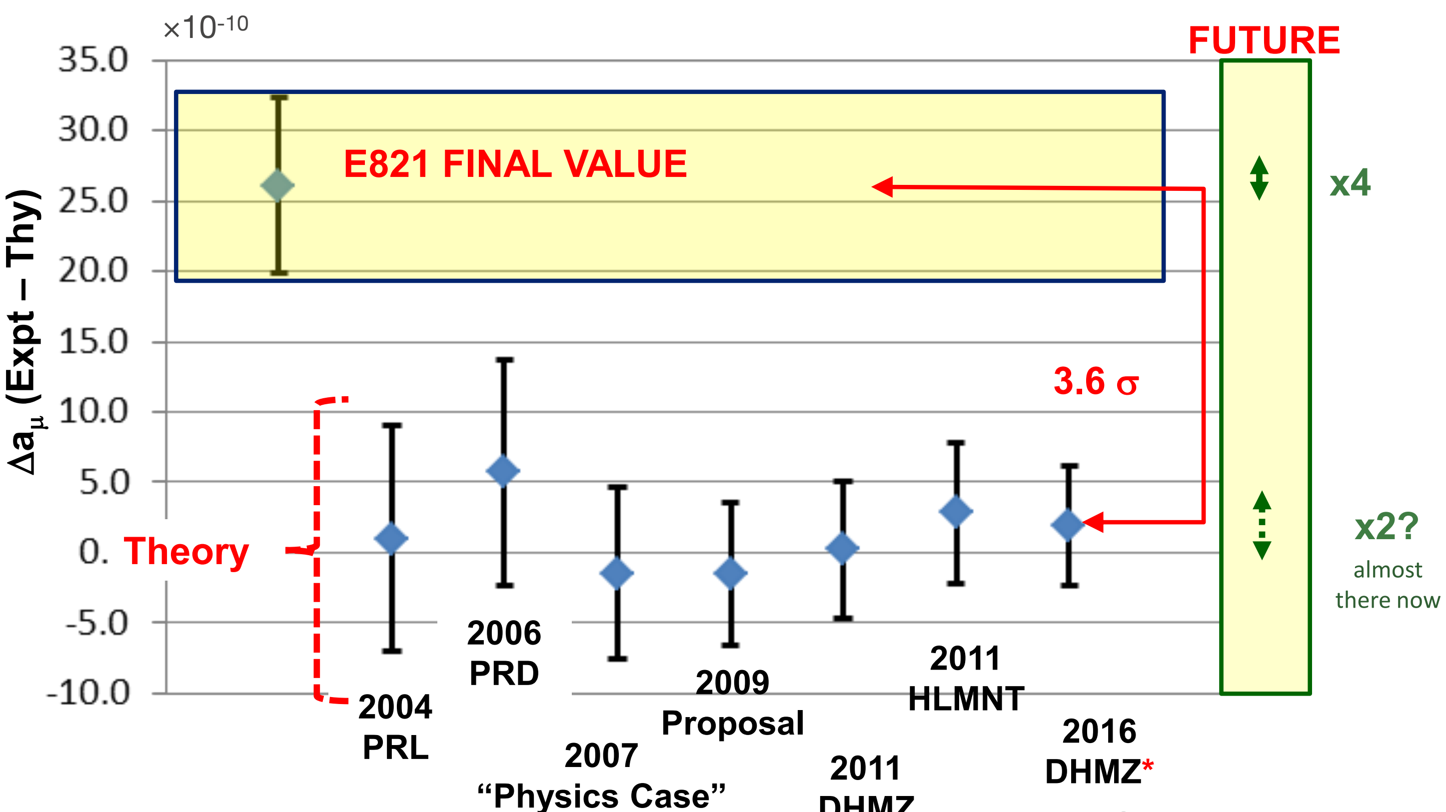




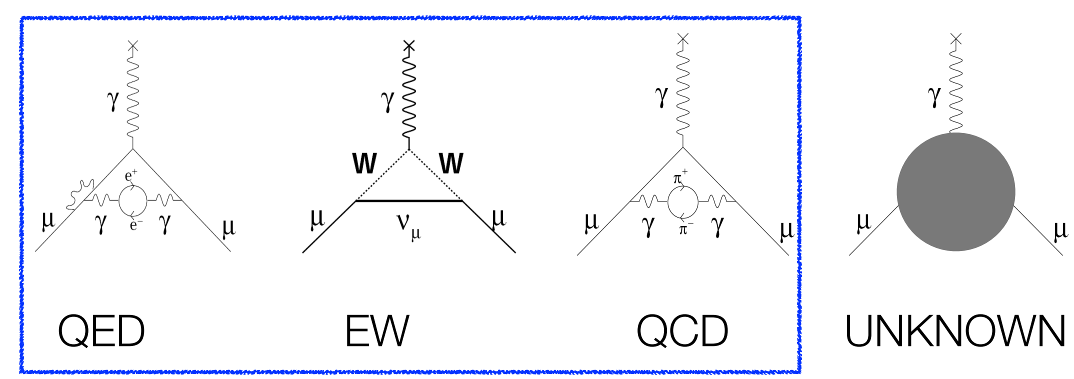
B. Lauss, nEDM Workshop 2017

muon g-2

- **muon anomalous magnetic moment** $a = \frac{g-2}{2}$ $\vec{\mu} = g\frac{Qe}{2m}\vec{s}$
  - In SM, a=0 at tree level and a≠0 due to radiative corrections
  - Further corrections could be induced by new physics
- **A long-standing anomaly**
  - E821(BNL) results on a_μ : 3.6σ deviation from SM prediction
  - Effect of new physics?
- **Two experiments are in preparation to test BNL results with improved precision (FNAL/E989, J-PARC/E34)**



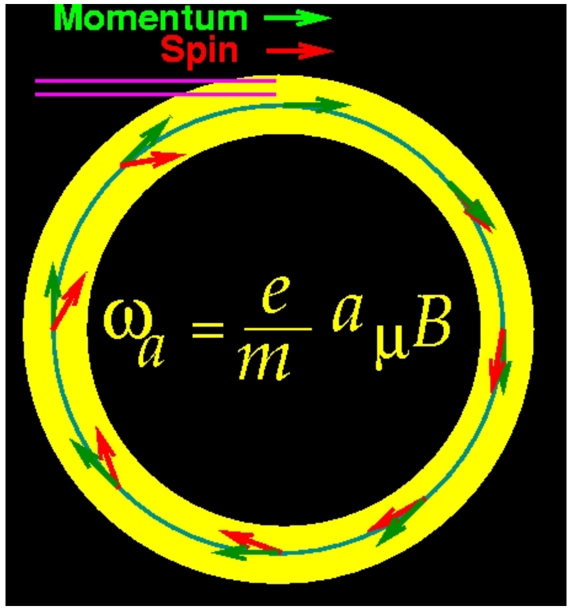
SM contributions



Courtesy of D. Hertzog

muon g-2 Experimental Method

- **Muon g-2 and EDM measurement**



In uniform magnetic field, muon spin rotates ahead of momentum due to $g-2 \neq 0$

general form of spin precession vector:

EDM → η

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

BNL E821 approach
γ=30 (P=3 GeV/c)

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

FNAL E989

J-PARC approach
E = 0 at any γ

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

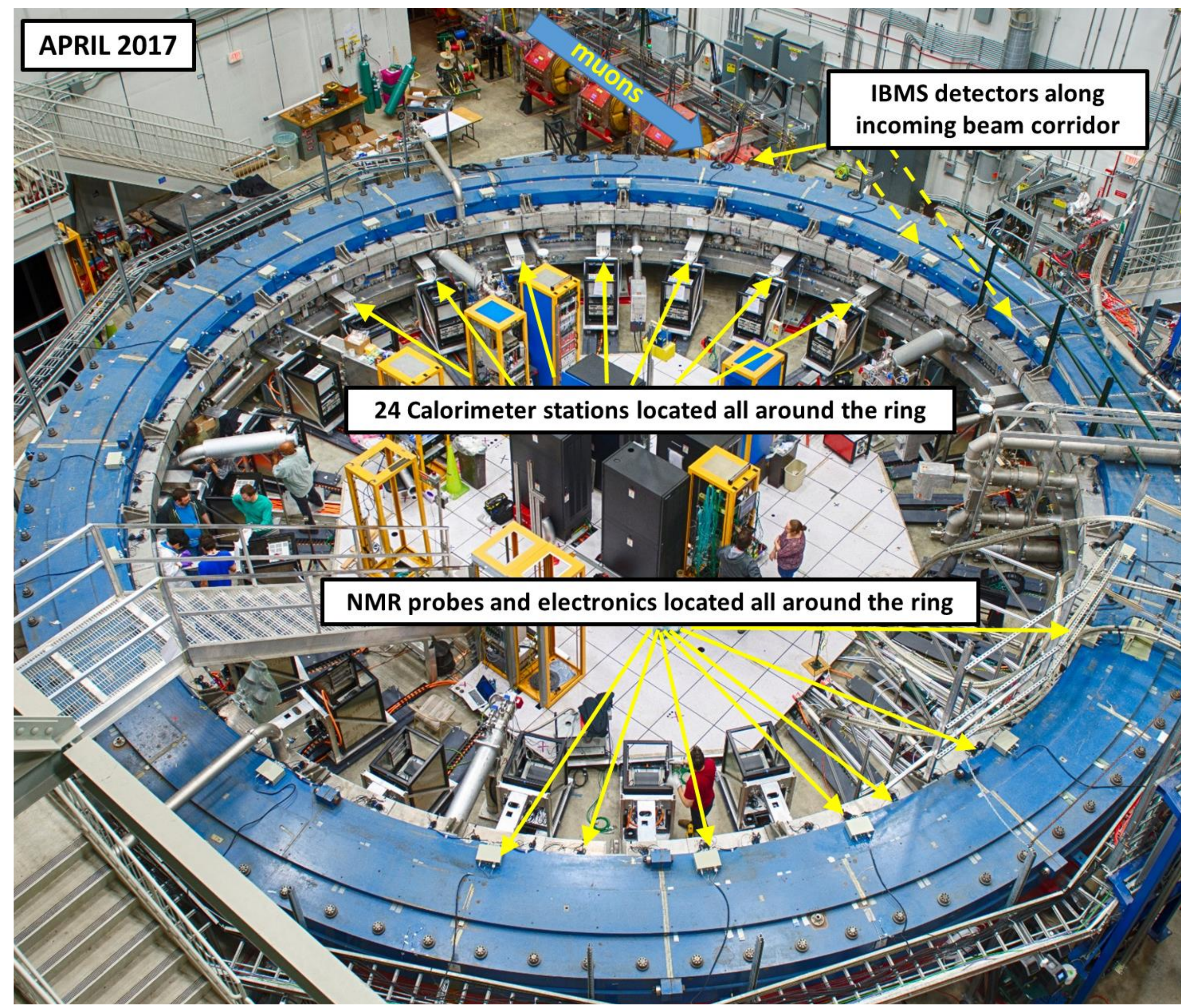
J-PARC E34

Courtesy of T. Mibe

muon g-2 FNAL E989

- **Goal**
  - ×21 statistics, ×3 lower systematics (0.46ppm → 0.14ppm) w.r.t. BNL results
  - ×10-30 sensitivity to muon EDM
- **Experiment is fully built!**

Electromagnet of E821 moved from BNL to FNAL



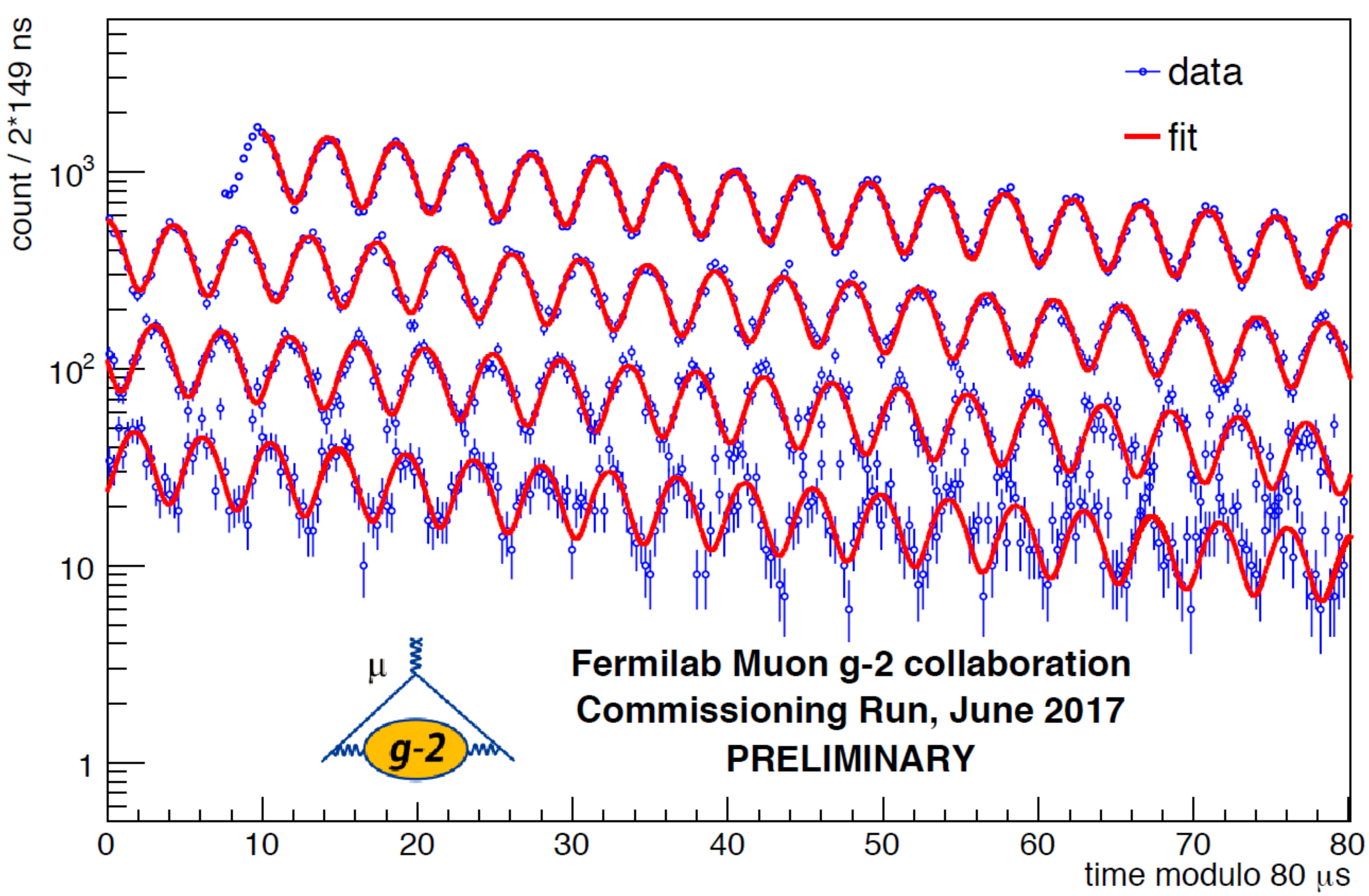
J. Holzbauer, NuFACT 2017

Courtesy of D. Hertzog

muon g-2 FNAL E989

- **Commissioning has been started!**
  - All instrumentation works quite well
  - First "wiggle plots" have been produced
    - Spin precession vs. time on top of muon life-time
- **Acquire physics data with ×1-3 BNL statistics for this year's running**

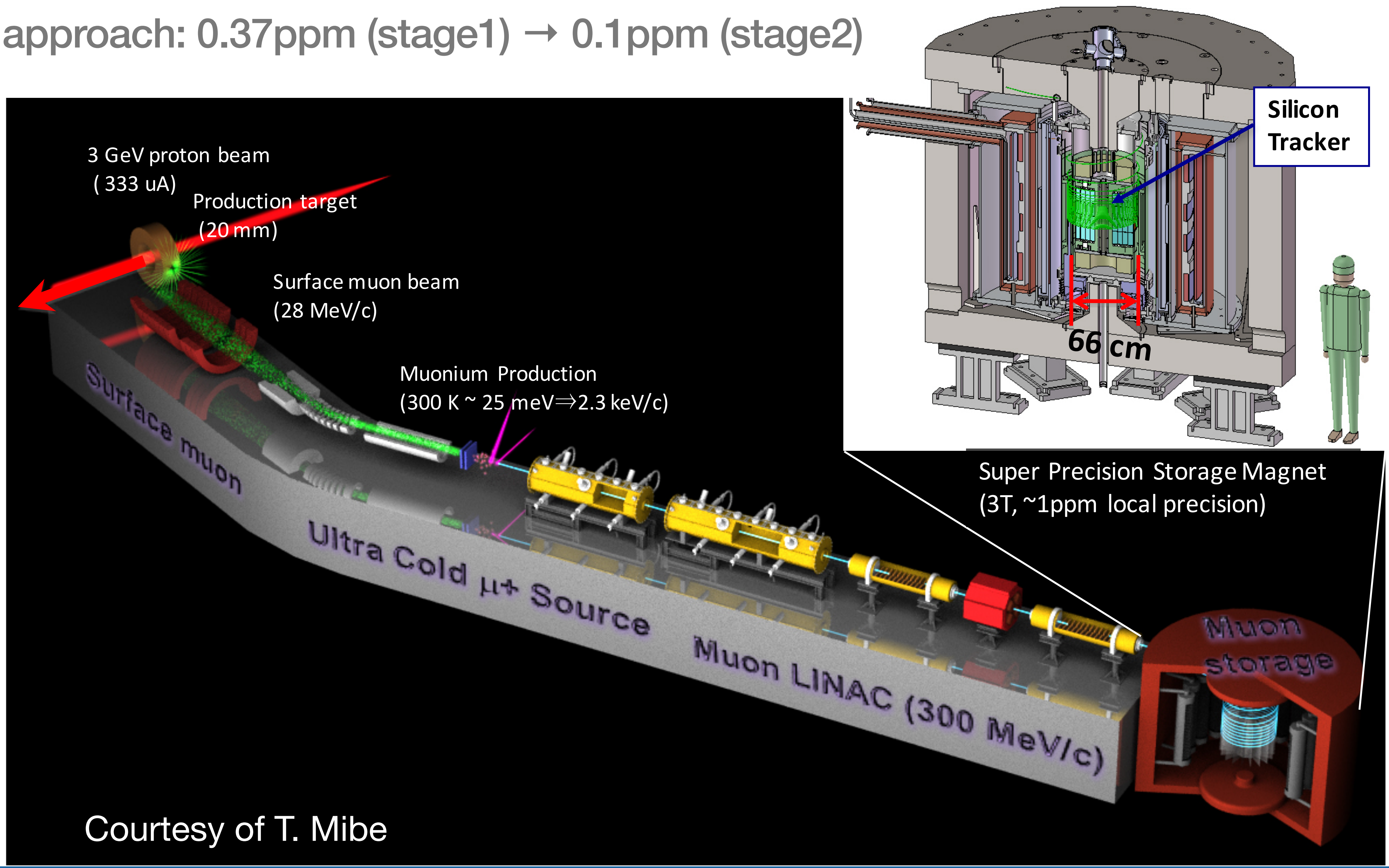
Number of high energy positrons as a function of time



Courtesy of D. Hertzog

muon g-2 J-PARC E34

- **Muon g-2/EDM Experiment at J-PARC (E34)**
  - Storage of ultra cold muon beam with super-low emittance
  - Completely different approach w.r.t. BNL/FANL experiments
  - Staging approach: 0.37ppm (stage1) → 0.1ppm (stage2)

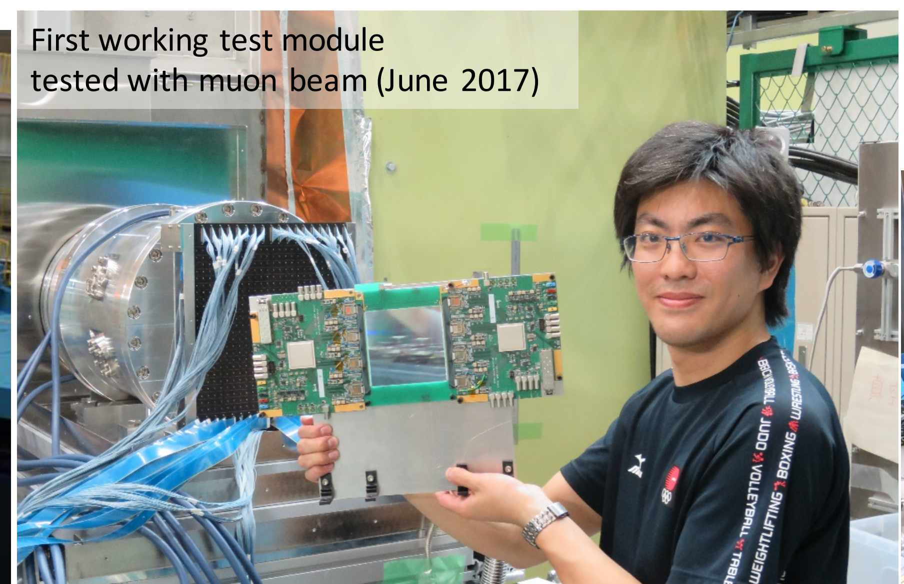


muon g-2 J-PARC E34

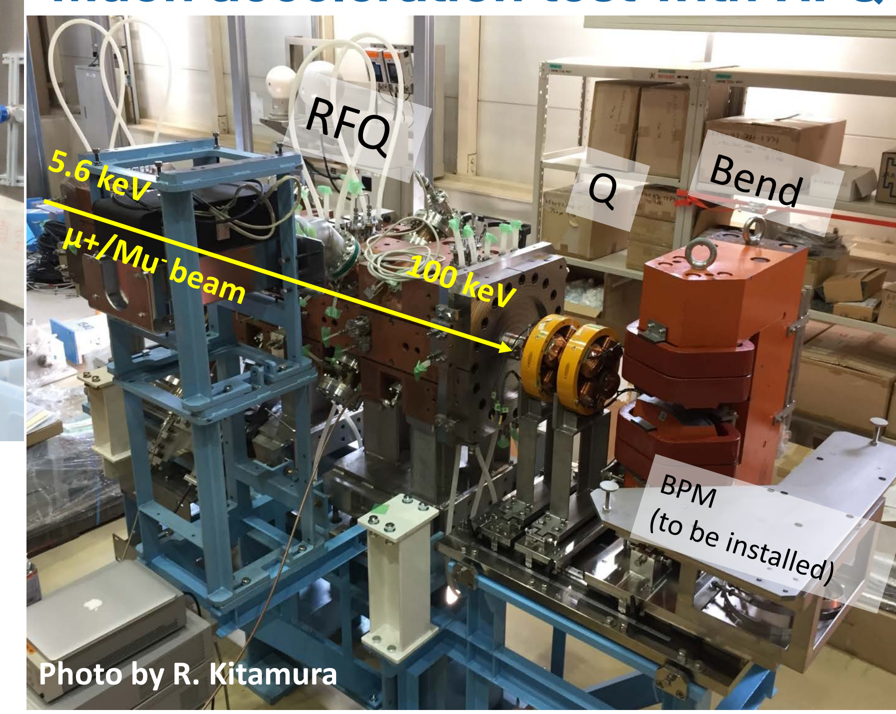
- **Good progress in R&D**
  - Surface muon beam, muonium production, muon acceleration, detectors,…
- **Moving from R&D phase to construction phase**
  - 4 years for construction once budget/resource is available

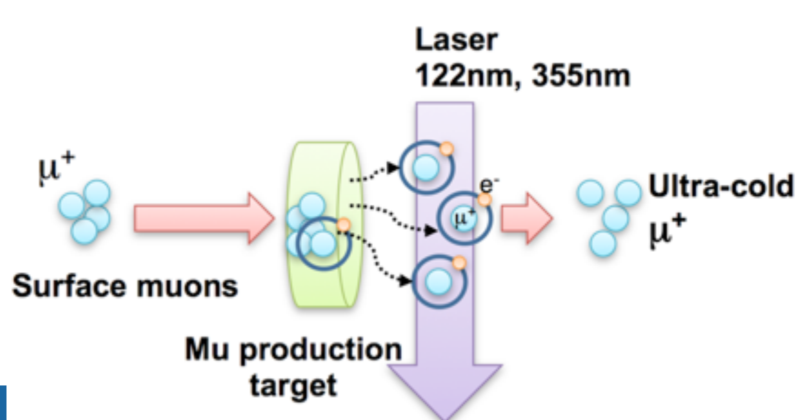
H-line construction

Positron tracker

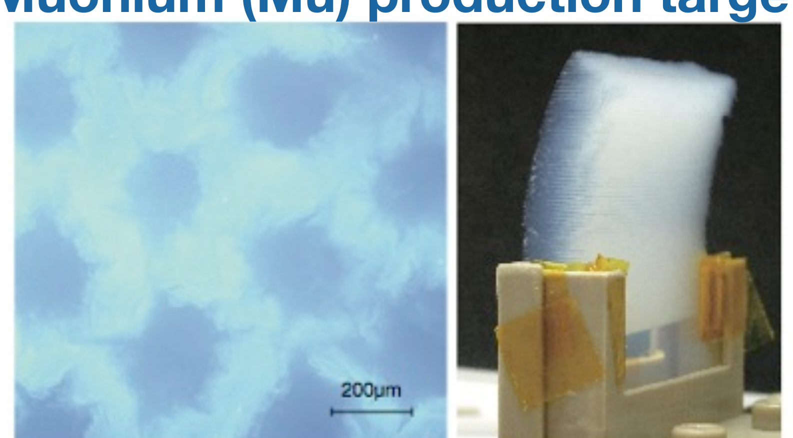


Muon acceleration test with RFQ





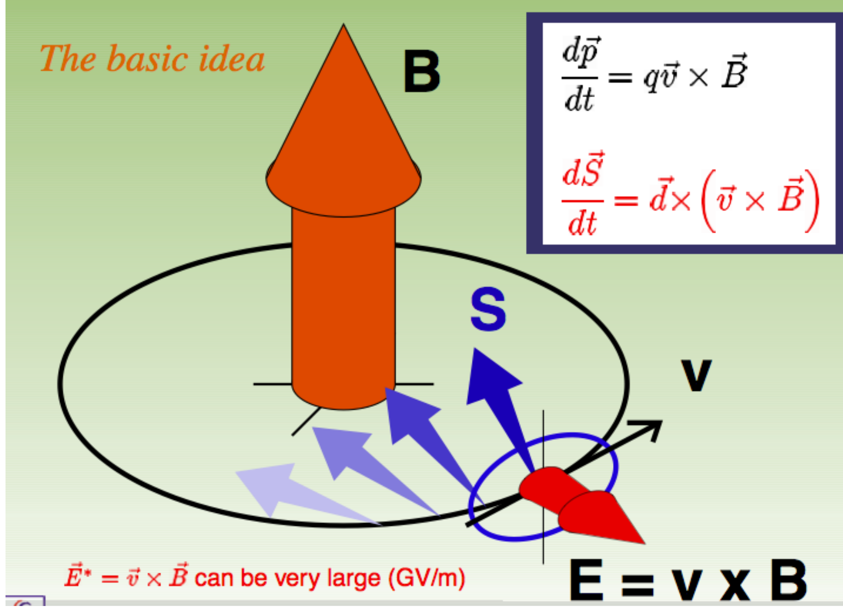
Muonium (Mu) production target



G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01

Courtesy of T. Mibe

EDM Storage Rings



- Angular frequency of muon spin precession with EDM

$$\vec{\omega} = -\frac{e}{m}\left\{ a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right\} \qquad d_\mu = \frac{\eta}{2}\left(\frac{e\hbar}{2mc}\right)$$

=0

- Motional electric field at muon's rest frame can be very large (~GV/m).

$$\vec{E}^* = \gamma c \vec{\beta} \times \vec{B}$$

- Turn off *g*-2 precession with momentum lower than "magic momentum" and a radial electric field
  - $1/(\beta^2\gamma^2) \gg a$
  - $E = E_0 \approx aBc\beta\gamma^2$

particle (units)	J	a	$\lvert\vec{p}\rvert$ (GeV/c)	γ	$\lvert\vec{B}\rvert$ (T)	$\lvert\vec{E}\rvert$ (kV/cm)	$\lvert\vec{E}'\rvert/\gamma$ (kV/cm)	R (m)	σ_d^{goal} (e cm)	Ref.
$\mu^\pm$	1/2	+0.00117	3.094	29.3	1.45	0	4300	7.11	10^{-21}	E989
			0.3	3.0	3.0	0	8500	0.333	10^{-21}	E34
			0.5	5.0	0.25	22	760	7	10^{-24}	srEDM
			0.125	1.57	1	6.7	2300	0.42	10^{-24}	PSI
p^+	1/2	+1.79285	0.7007	1.248	0	80	80	52.3	10^{-29}	srEDM
			0.7007	1.248	0	140	140	30	10^{-29}	JEDI
d^+	1	−0.14299	1.0	1.13	0.5	120	580	8.4	10^{-29}	srEDM
			1.000	1.13	0.135	33	160	30	10^{-29}	JEDI
$^3He^{++}$	1/2	−4.18415	1.211	1.09	0.042	140	89	30	10^{-29}	JEDI

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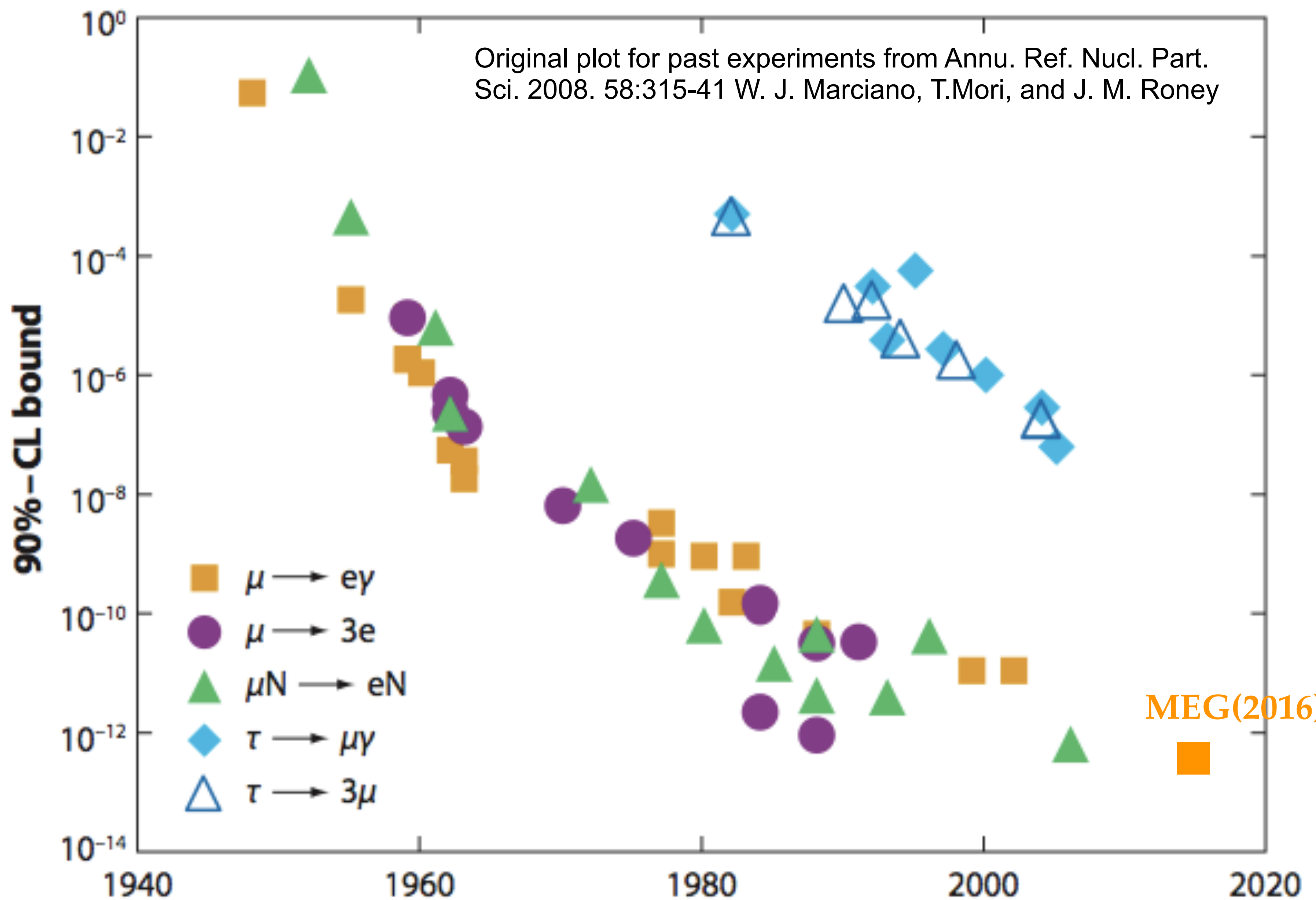
cLFV Search History

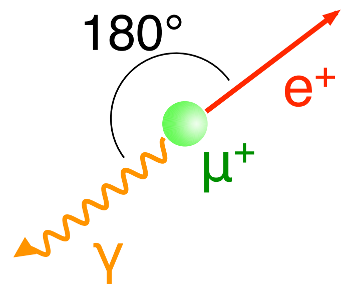


For SUSY
$\mathcal{R}(\mu Al \to eAl)/\mathcal{B}(\mu \to e\gamma) = 2.6\times10^{-3}$
$\mathcal{B}(\mu \to 3e)/\mathcal{B}(\mu \to e\gamma) = 6\times10^{-3}$

Getting sensitive enough to explore new physics!

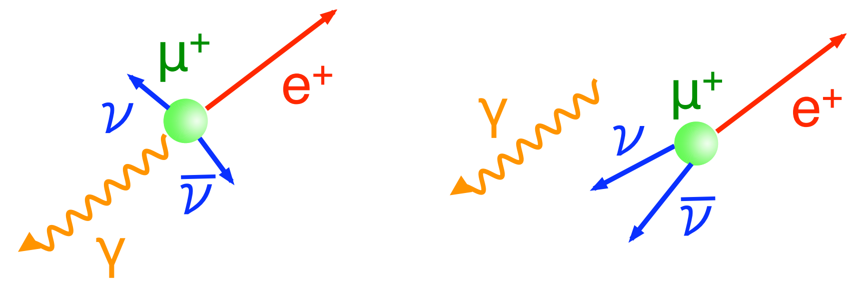
$\mu^+ \rightarrow e^+\gamma$

- **Signal**
  - Back-to-back
  - Mono-energetic
    - E_e=52.8MeV
    - E_γ=52.8MeV
  - Coincident in time

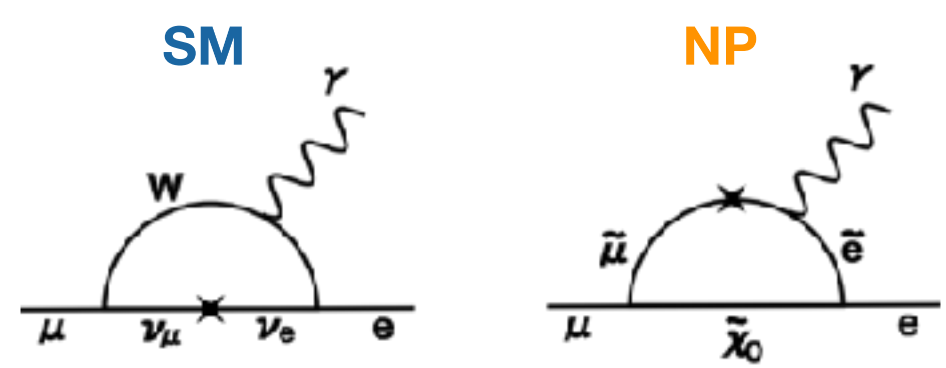


- **Background**
  - Prompt background: μ→eγνν
  - "Accidental" overlap: μ→eνν + γ

Predominant



- **SM contribution negligibly small ($\mathcal{B}$~10^{-54})**
- **Possible enhancement of new physics contribution within reach of state-of-art experiment**
- **Requirements for sensitive μ→eγ search**
  - **High intensity continuous muon beam**
  - **Good detectors**
    - Precise measurements of energy, timing and angle both for e and γ
    - Operational at high rate environment (stability and pileups…)

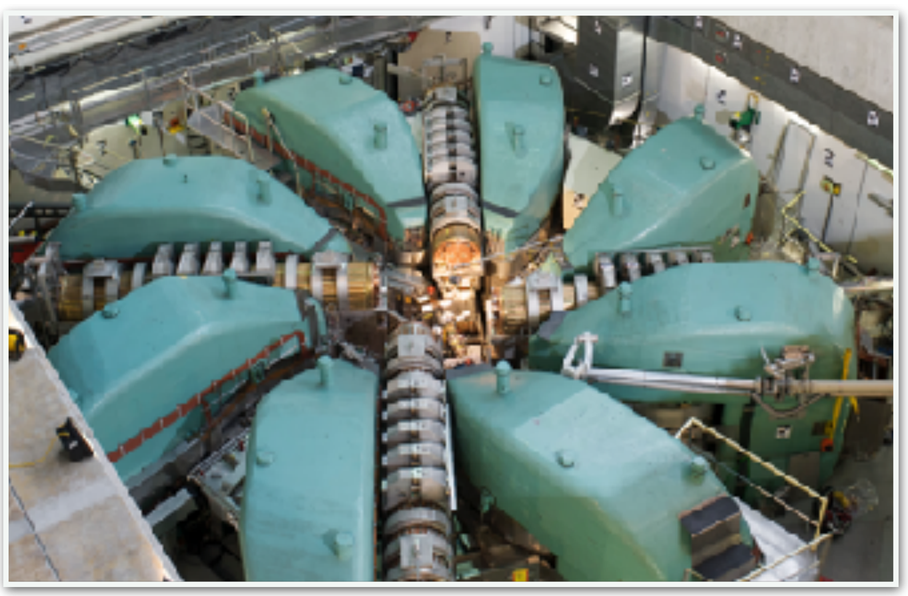


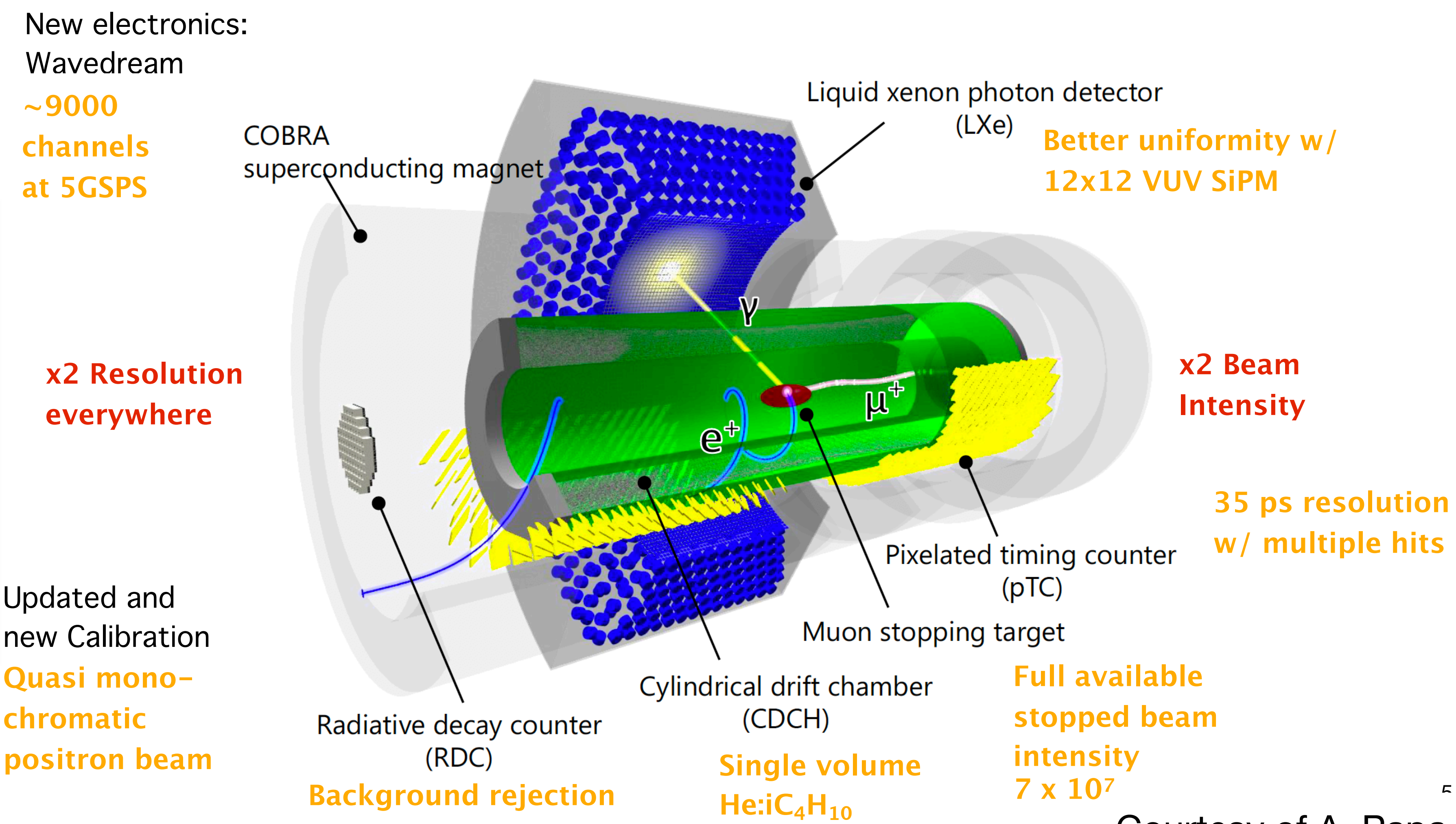
- **Current bound**
  - **$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2\times10^{-13}$ (90%C.L.) (MEG in 2016)**

MEG II

- **Leading LFV experiment, looking for μ→eγ**
  - Current bound: $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2\times10^{-13}$ (90%C.L.) (MEG in 2016)
  - **MEG upgrade (MEG II) with a projected sensitivity of ~5×10^{-14} in preparation.**
- **MEG II detectors with significantly improved performance**
  - Much higher resolutions and efficiencies for both photon and positron detectors
  - Twice or higher μ intensity, fully exploiting world's most intense DC μ-beam at PSI up to ~10^8 μ^+ beam

590MeV ring cyclotron @PSI

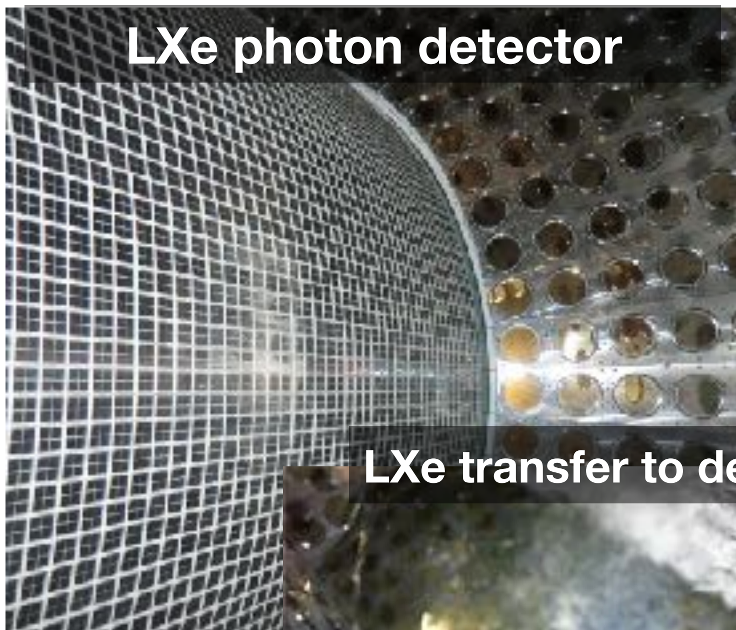


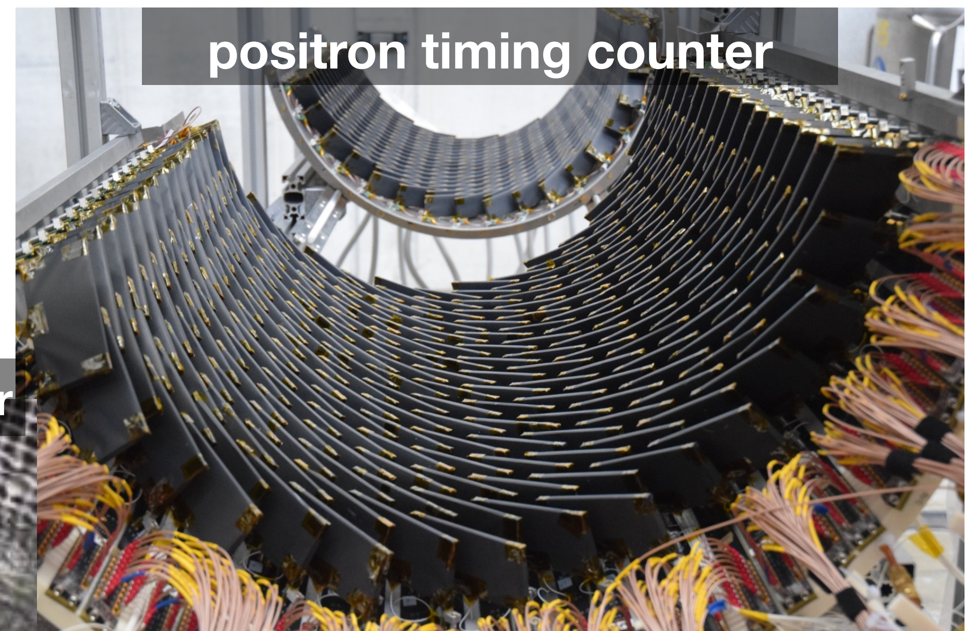


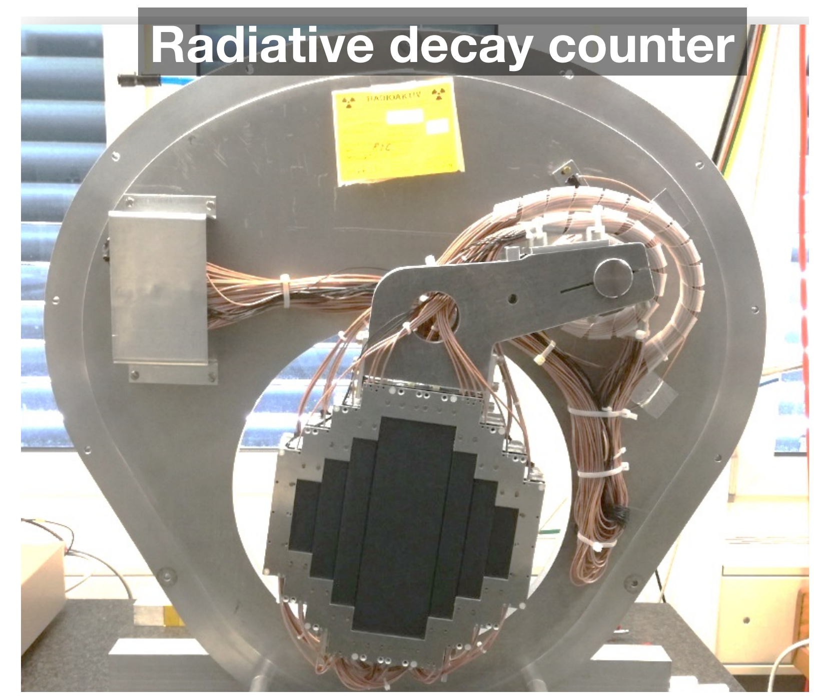
Courtesy of A. Papa

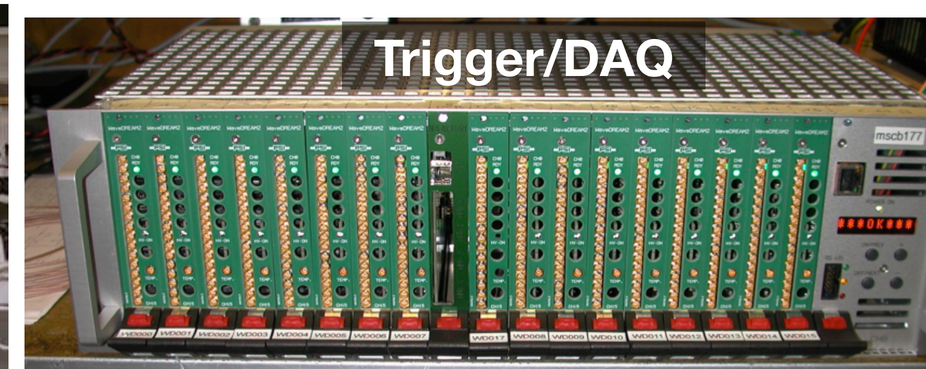
MEG II Status

- Detector commissioning in progress
- Full engineering run with all sub-detectors will start in 2018, which will be followed by physics run



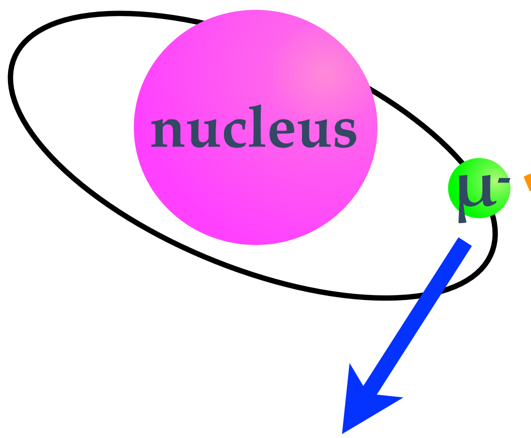






μ-N→e-N (μ--e- conversion)

1s-state in a muonic atom



Beyond standard model

μ-e conversion

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

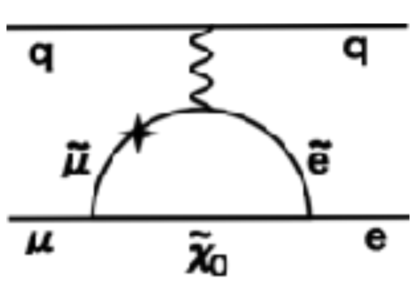
Standard model

Muon decay in orbit (DIO)

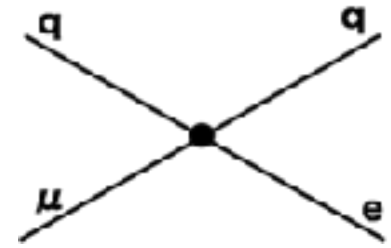
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Nuclear muon capture

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



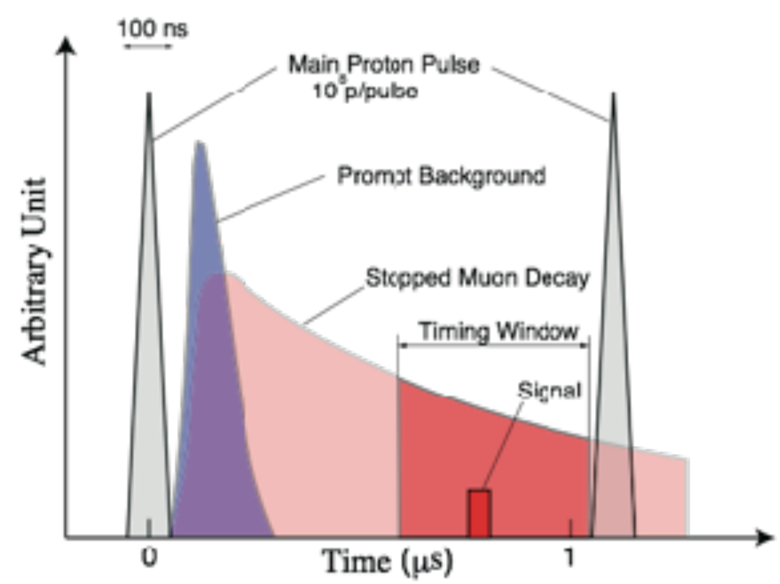
Photonic



Non-photonic

- **Signal**
  - **A mono-energetic electron**
    - $E_e = m_\mu - B_\mu \sim 105$MeV
    - Muonic atom lifetime (~1μs for Al target)→delayed measurement
- **Background**
  - Muon decay in orbit (DIO), beam related, cosmic-ray,…
  - **No accidentals!**
- Best limit: 7×10^{-13} (SINDRUM II)

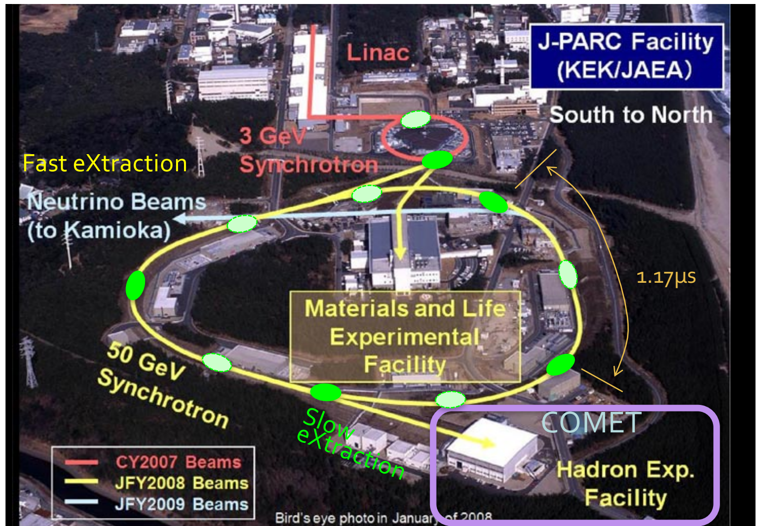
Delayed measurement to avoid beam related BG



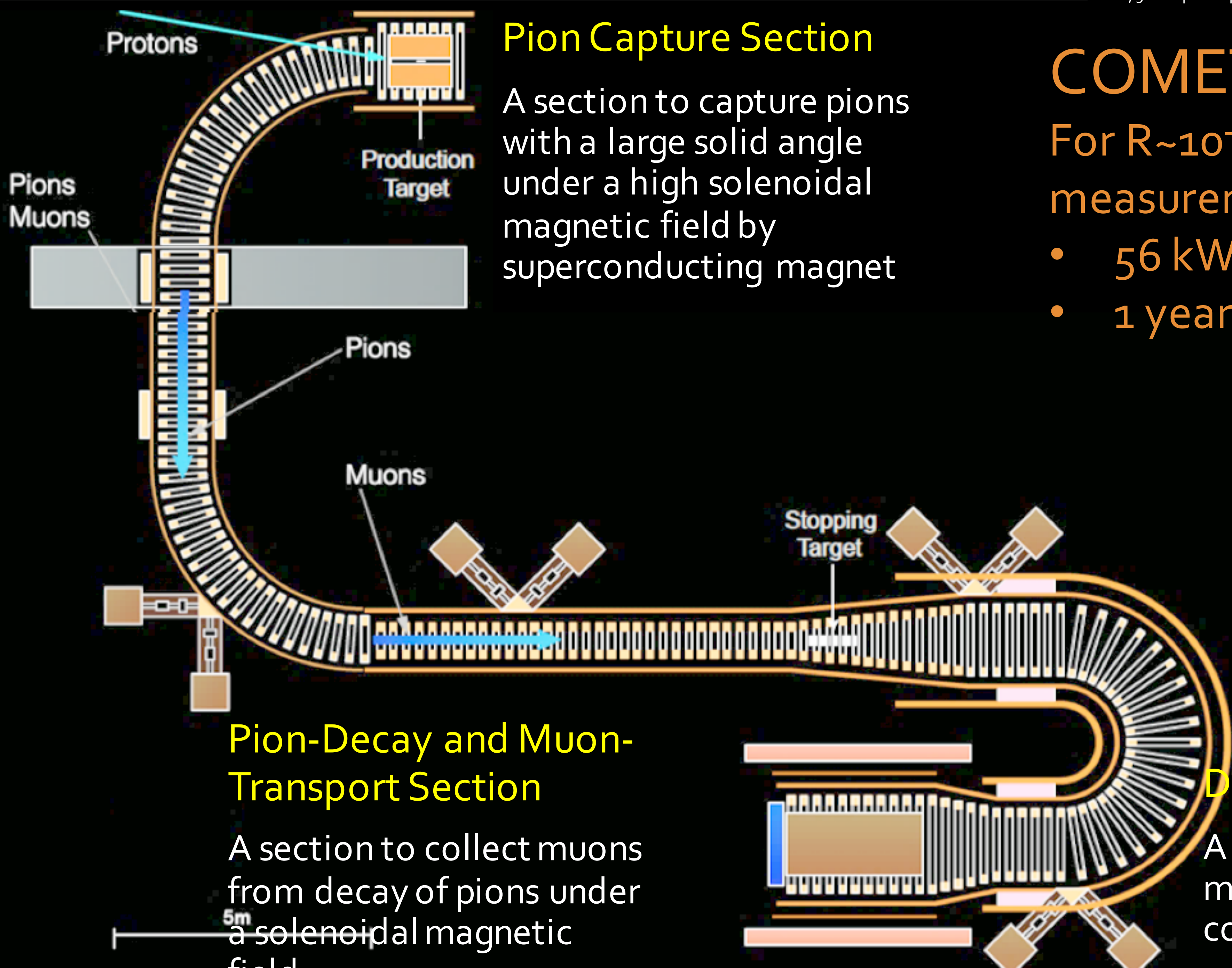
- **Advantages**
  - Sensitive to both photonic and non-photonic processes
  - Delayed measurement with pulsed beam to reduce beam related BG
  - Target dependence to discriminate interaction types
- **Challenges**
  - Need high intensity and hight purity pulsed μ-beam of $O(10^{11})$ μ/s
- **COMET@J-PARC, Mu2e@Fermilab, DeeMe@J-PARC**

μ⁻N→e⁻N COMET@J-PARC

- **Staging approach @COMET**
  - **Phase-I**: SES 3×10^{-15} (~5 month) + beam BG study
  - **Phase-II**: SES 2.6×10^{-17} (~1year)



8GeV, 3.2kW pulsed proton beam in Phase-I, 4/9 (or 3/9) buckets filled in MR



Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet

COMET Phase-II

For R~10^{-17} muon conversion measurement

- 56 kW proton beam
- 1 year DAQ

Pion-Decay and Muon-Transport Section

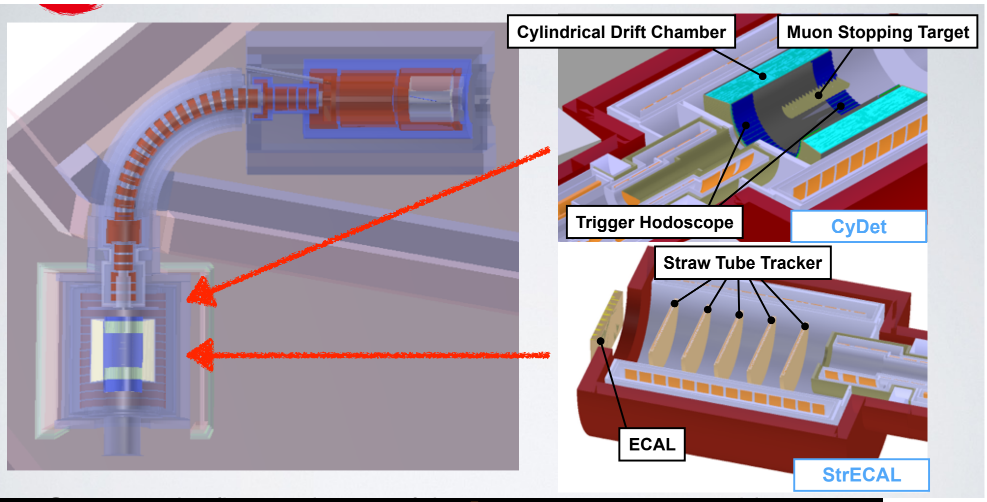
A section to collect muons from decay of pions under a solenoidal magnetic field.

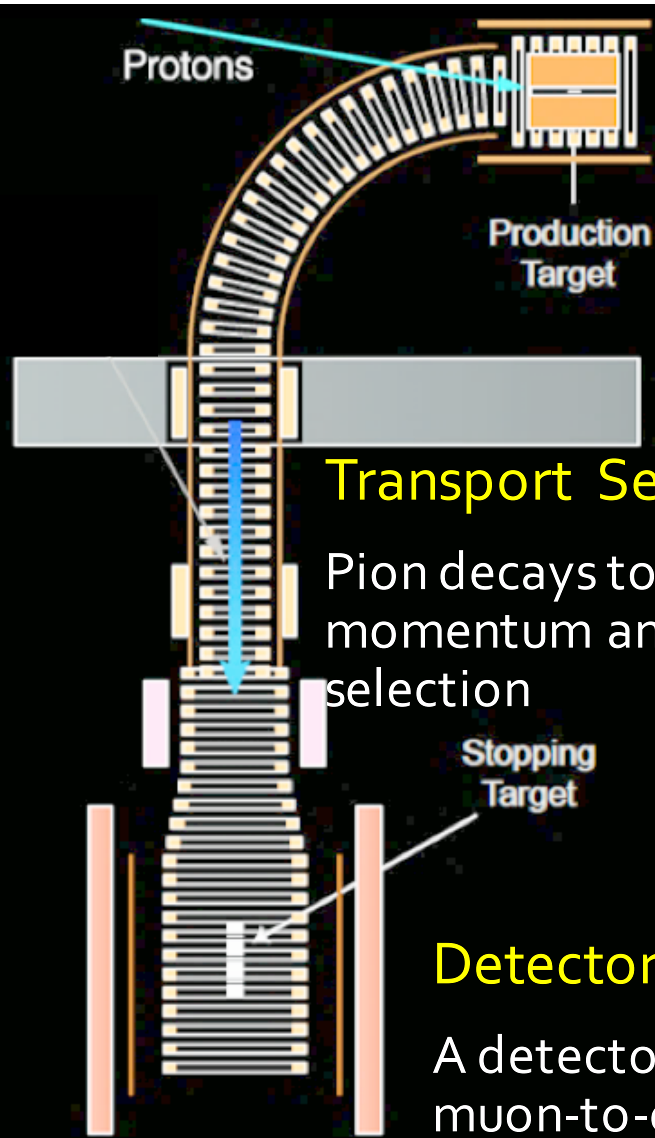
Detector Section

A detector to search for muon-to-electron conversion process

μ-N→e-N COMET Phase-I

- μ-N→e-N search with modest sensitivity (SES 3×10^{-15}) using CyDet
- Beam BG study in final operation mode with StrECAL





Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet

Transport Section

Pion decays to muon, with momentum and charge selection

Detector Section

A detector to search for muon-to-electron conversion process

COMET Phase-II

For $R\sim10^{-17}$ muon conversion measurement

- 56 kW proton beam
- 1 year DAQ

COMET-Phase-I

For BG measurement, $R\sim10^{-15}$ muon conversion

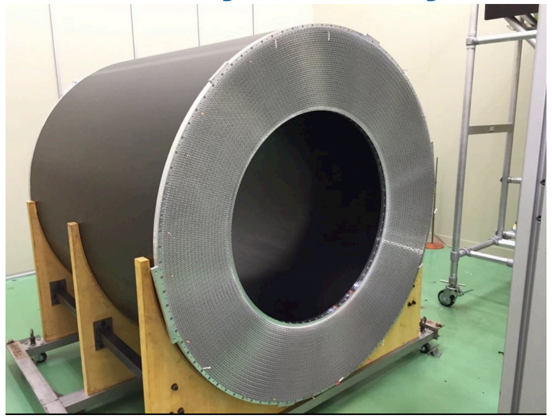
- 3.2kW proton beam
- Half year DAQ

μ-N→e-N COMET Status

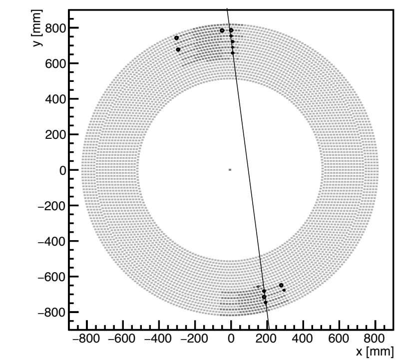
- **Stage-2 approval of Phase-I (fully funded, beam will be delivered)**
  - **Physics data-taking will start in 2019** though it depends on budget allocation
  - 5-month data-taking to reach ~10^{-15}
- **Phase-II physics data-taking in 2021-2022**
  - 1-year data-taking to reach ~10^{-17}

M. J. Lee, NuFACT 2017

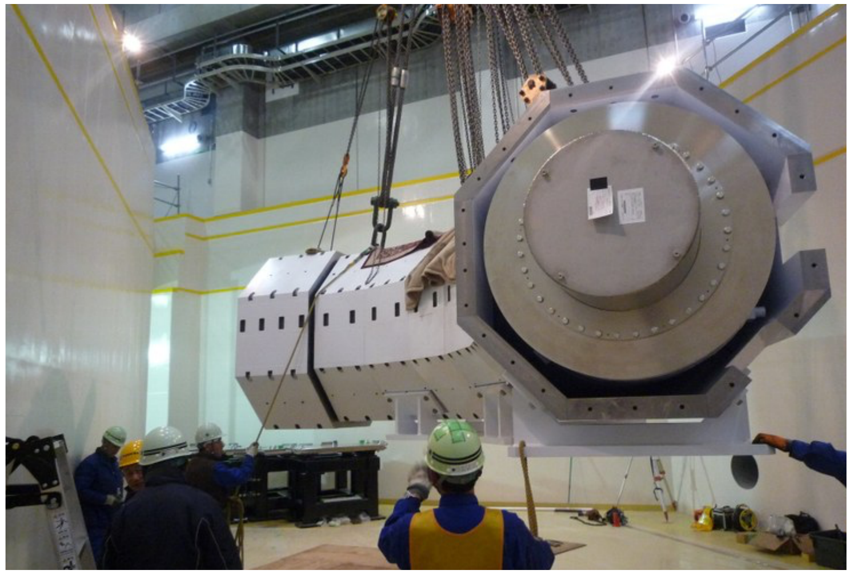
CDC for CyDet: ready



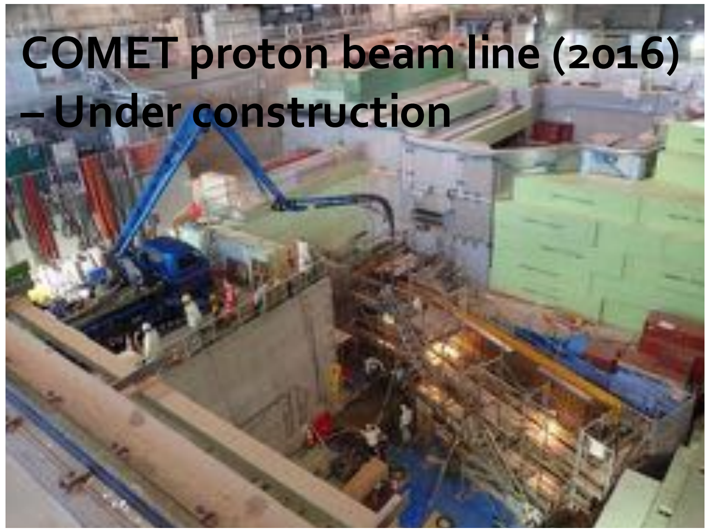
CDC CR test

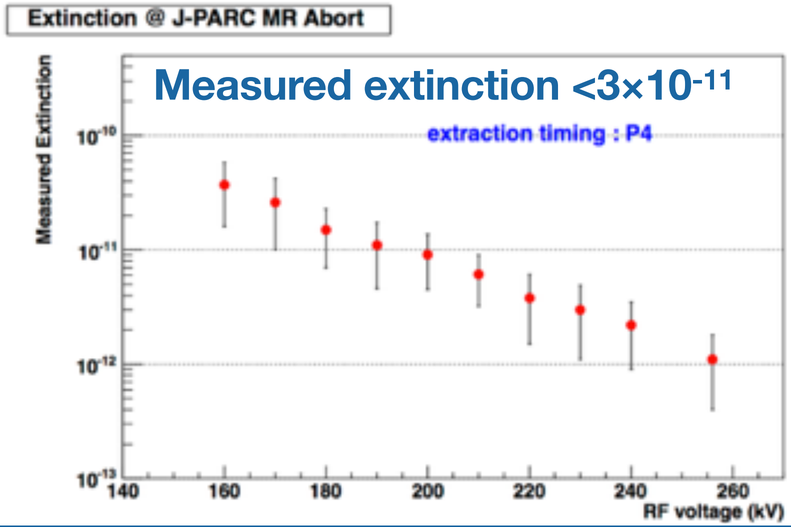


Transport solenoid: ready

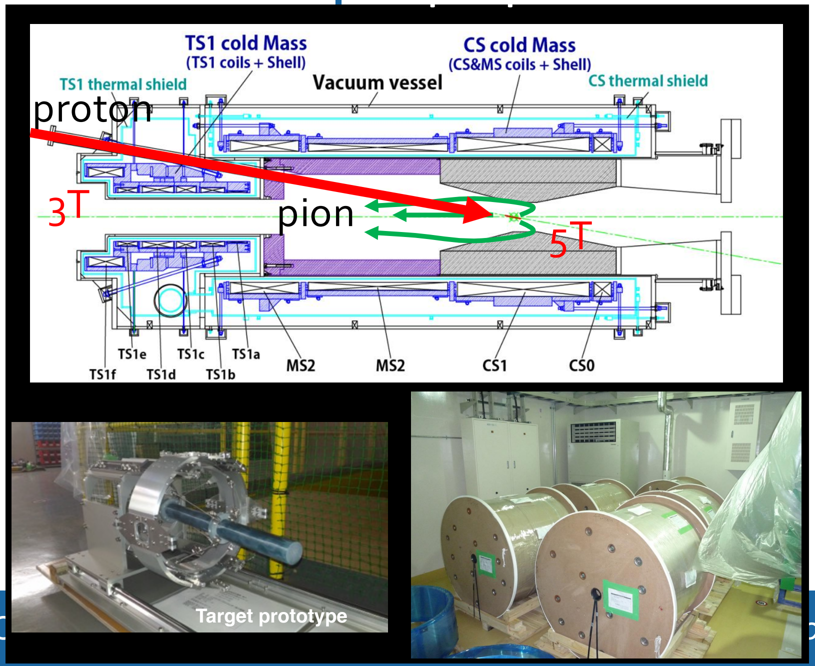


COMET proton beam line under construction

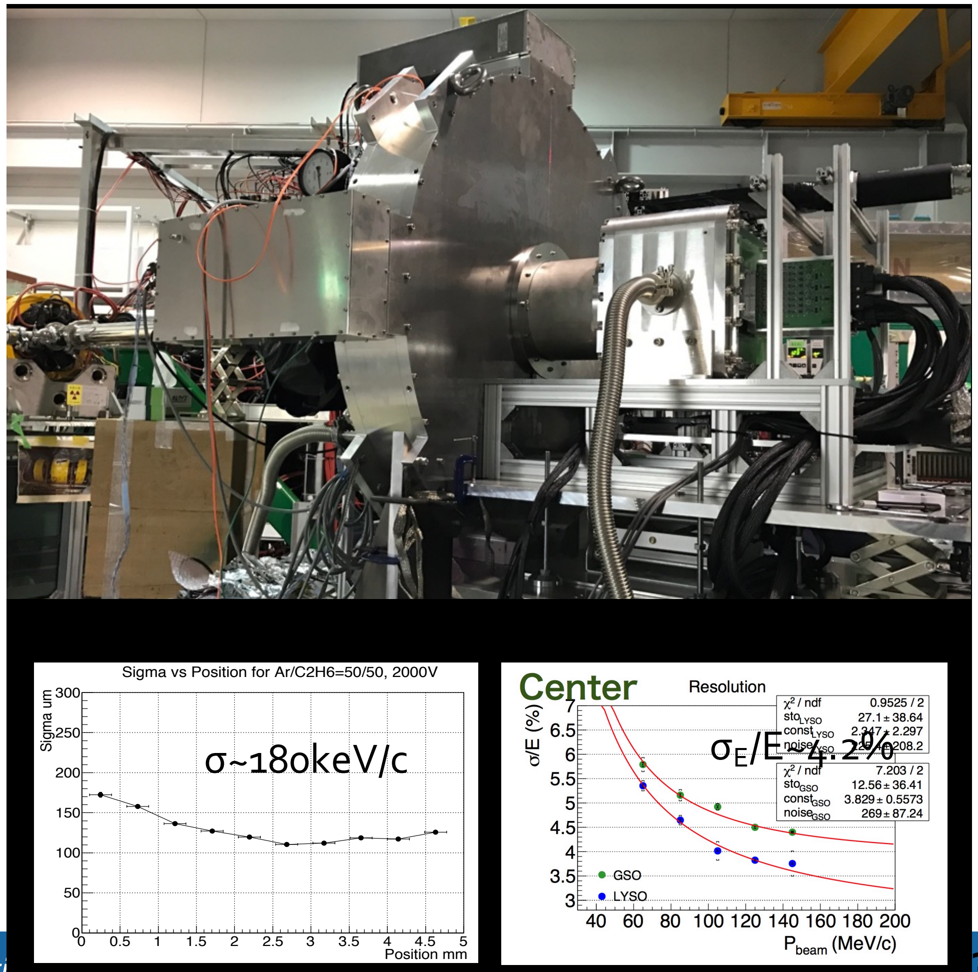




Pion capture solenoid

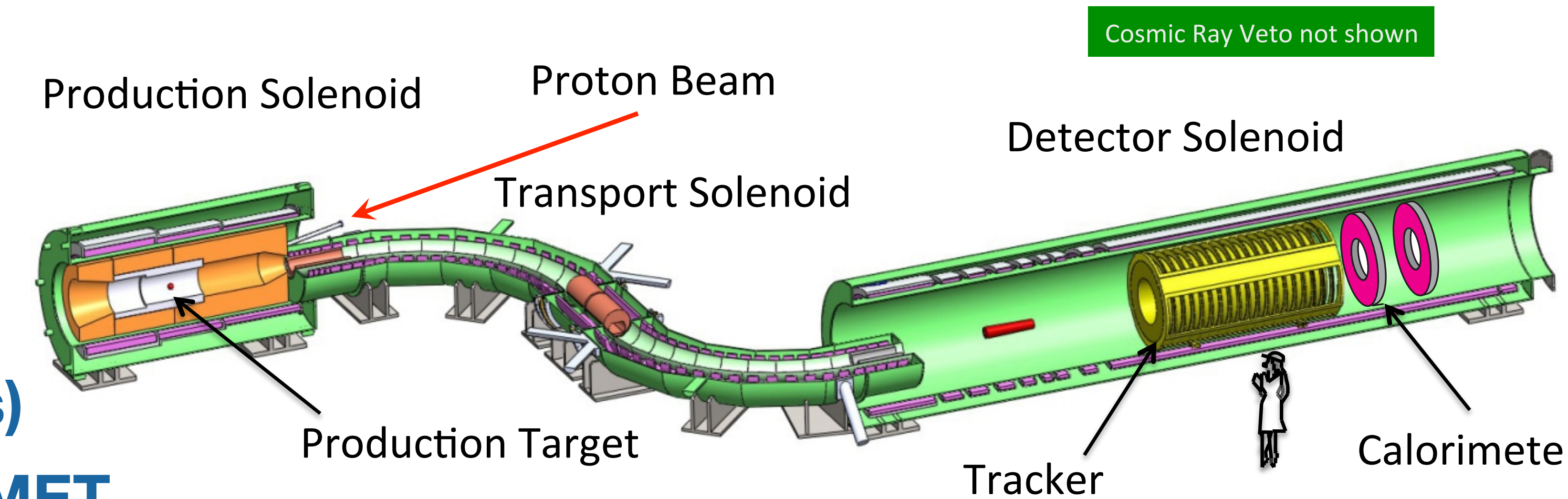


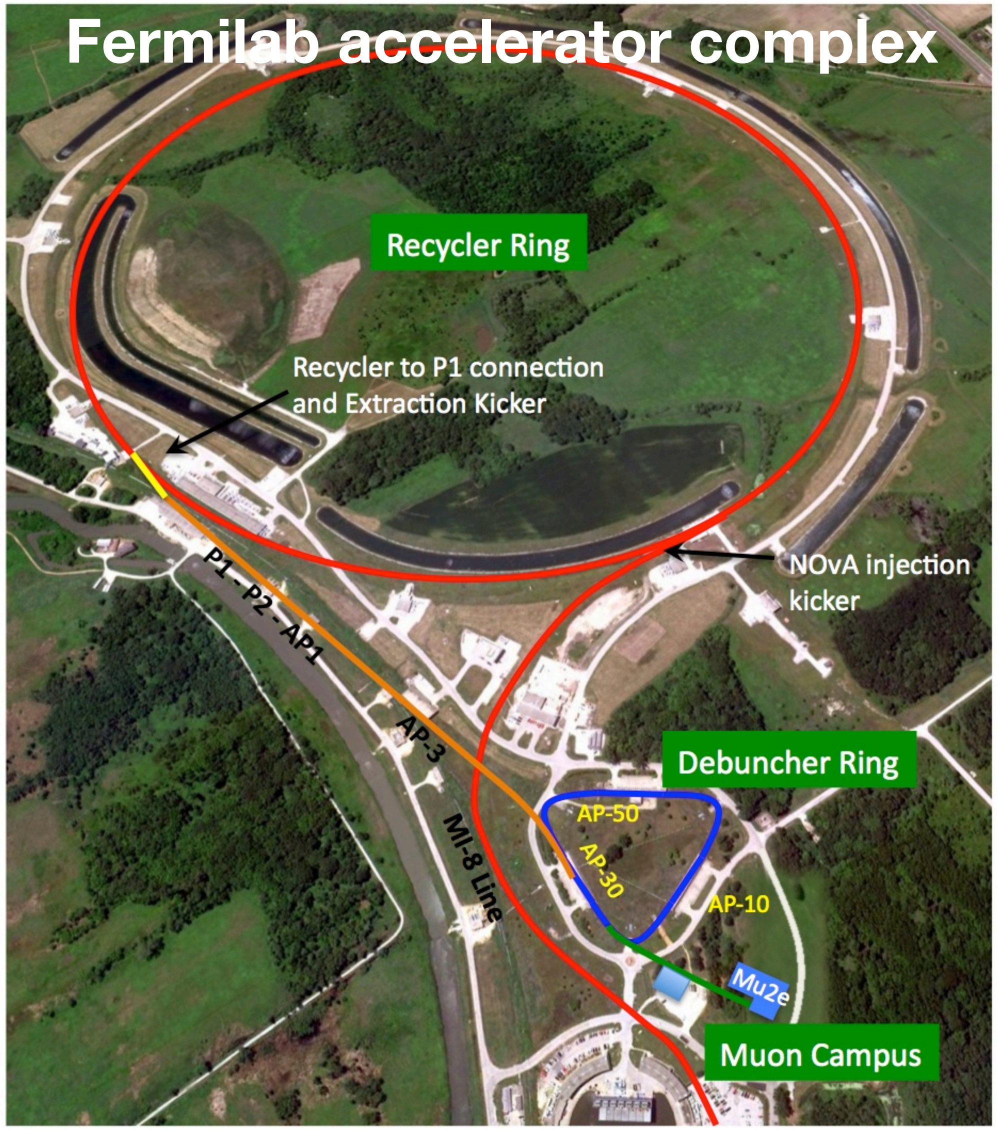
StrECAL Integrated beam test



$\mu^- N \to e^- N$ Mu2e@Fermilab

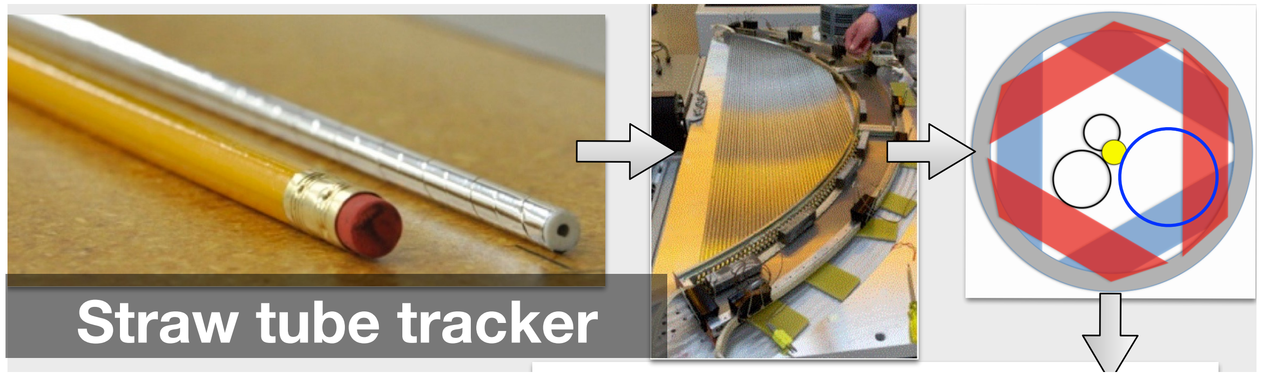
- **Target S.E.S.: 3×10^{-17}**
- **Existing Recycler and Debuncher at Fermilab (8GeV, 8kW, rebunched@1695ns)**
- **Important differences w.r.t. COMET**
  - S-shape transport solenoid
    - COMET: C-shape
  - Positrons can also be measured→different process $\mu^- N \to e^+ N'$
    - COMET: electron only
  - Muon stopping target in detector solenoid
    - COMET: detector after electron transport solenoid → lower detector hit rate
  - No conflict with NOvA experiment
    - COMET can't share the beam with other experiments.
  - No phased approach
    - COMET: $\sim10^{-15}$@phase-I (105days) →$\sim10^{-17}$@phase-II (1year)

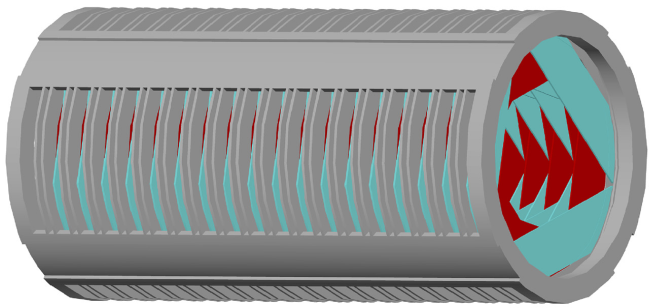




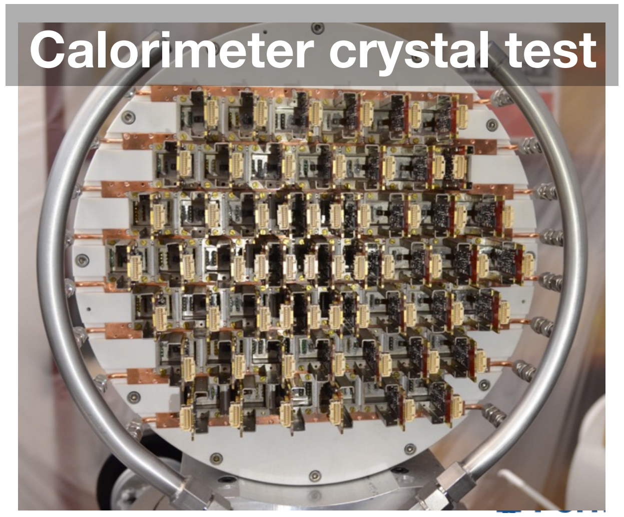
μ⁻N→e⁻N Mu2e@Fermilab

- Mu2e building completed
- Production of solenoid coils underway
- Beam line under construction
- Starting production for detector elements
- Commissioning in 2021
- Data taking in 2022-2024





Accelerator work ~50% complete; solenoid work ~60% complete

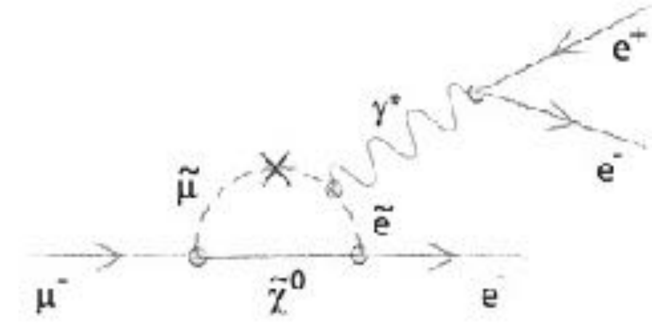


E. C. Dukes, NuFACT 2017

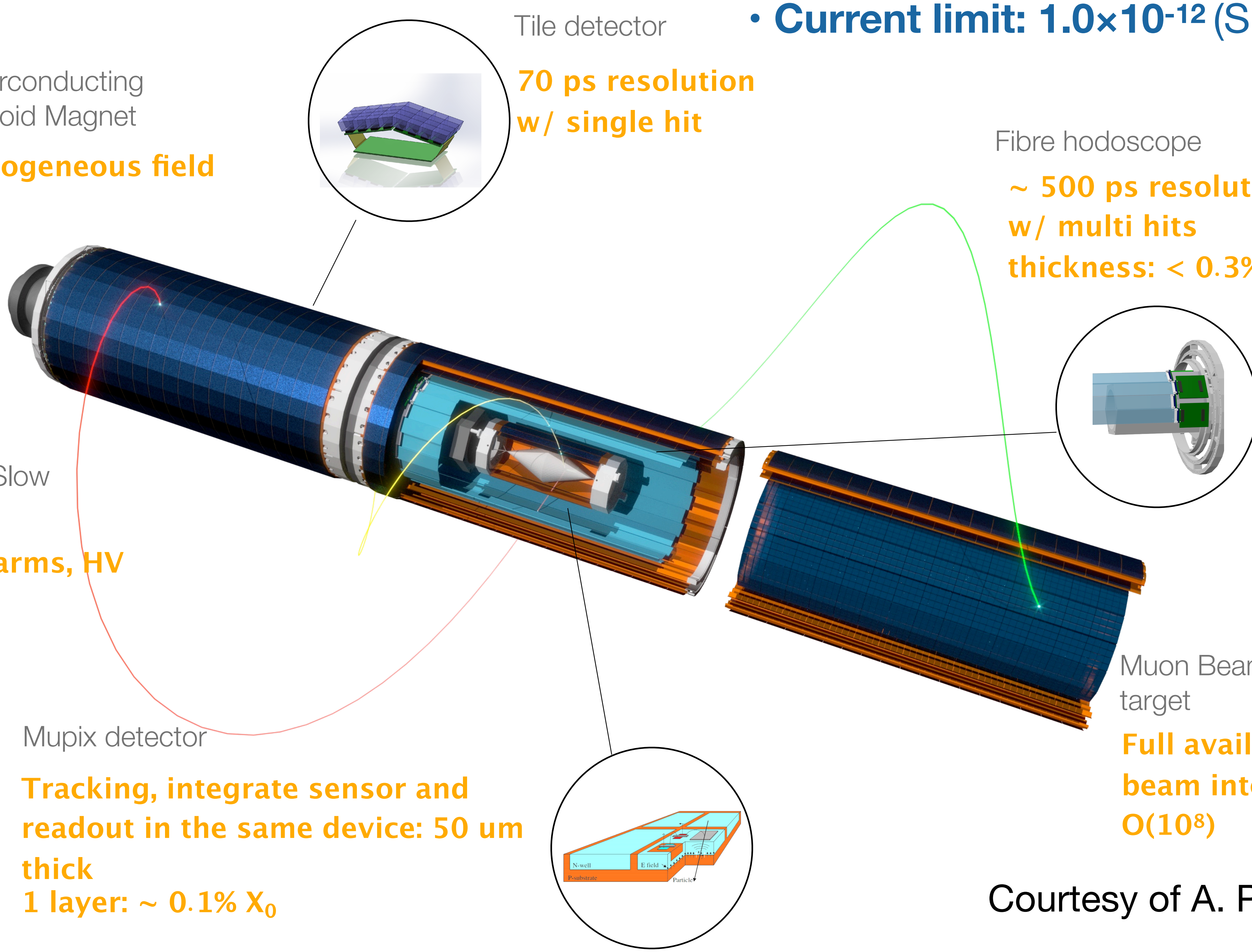
$\mu^+ \rightarrow e^+e^-e^+$ Mu3e@PSI

- **Mu3e @PSI**
  - πE5@PSI for phase-I (shared by MEG)
  - ~10^8 μ^+/s on hollow double cone target
  - Thin silicon pixel tracker (HV-MAPS)
  - Scintillating fibre/tile detector for timing

- **μ→eee signal**
  - $E = m_\mu$
  - $\Sigma p_i = 0$
  - Same vertex



- **Background**
  - Accidentals
  - Radiative decay
- **Current limit: 1.0×10^{-12}** (SINDRUM)

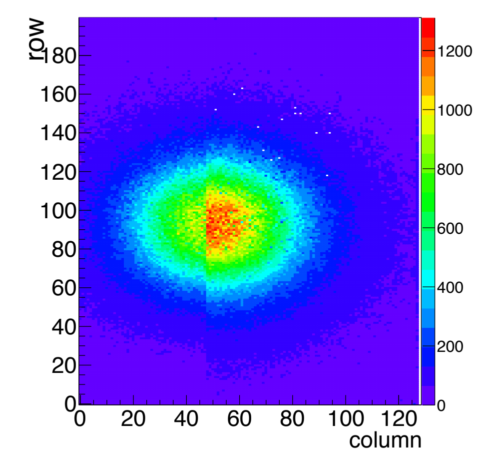


Courtesy of A. Papa

$\mu^+ \rightarrow e^+e^-e^+$ Mu3e Status

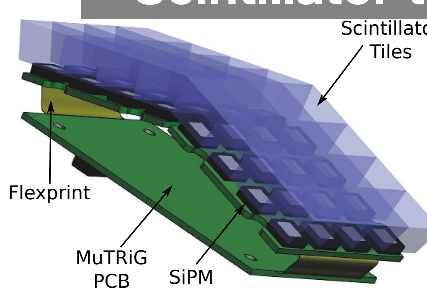
- **Phase I**
  - **Sensitivity goal: 2×10^{-15}** (300days DAQ)
  - πE5 beam line at PSI with 10^8 μ^+/s
  - Detector R&D completed and construction in preparation
  - Technical design report to be published soon
  - Full engineering run expected in 2019
- **Phase II**
  - **Sensitivity goal: 10^{-16}**
  - Need higher intensity muon beam up to 10^9 μ^+/s (HiMB project @PSI)

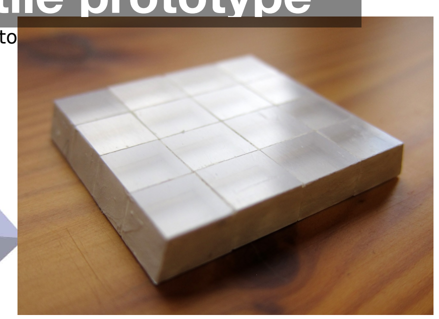
Mupix8 (First large prototype 2×1cm² for Si tracker)



Preliminary hitmap of a Sr-90 source

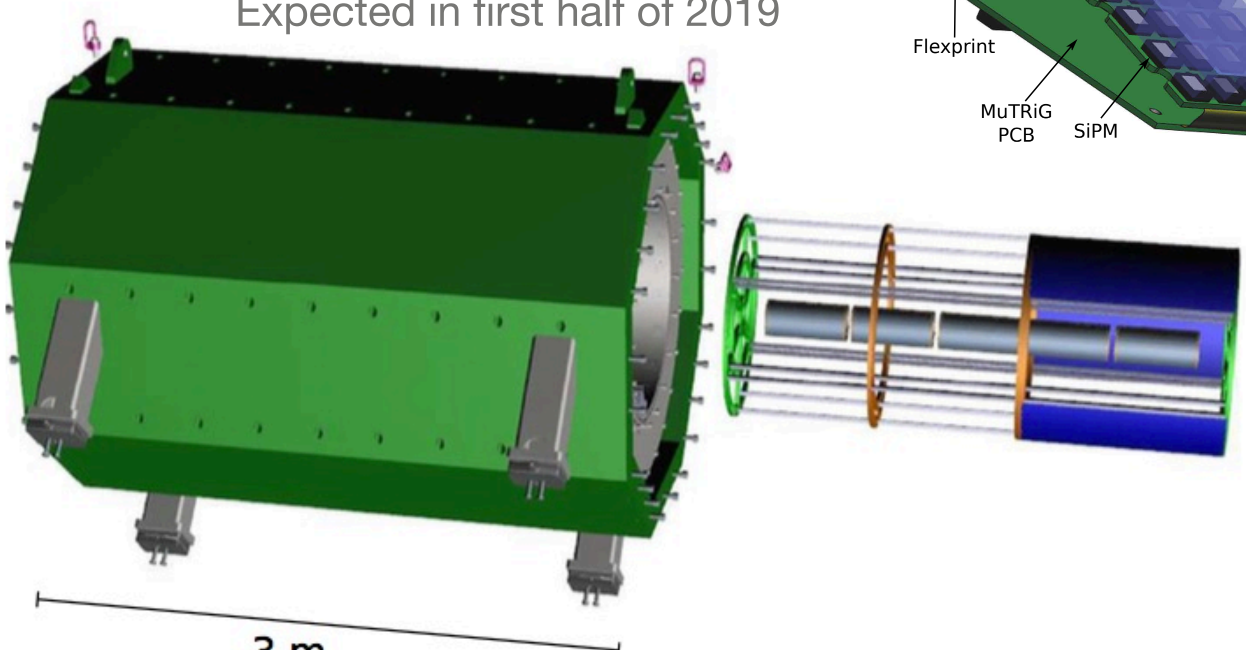
Scintillator tile prototype

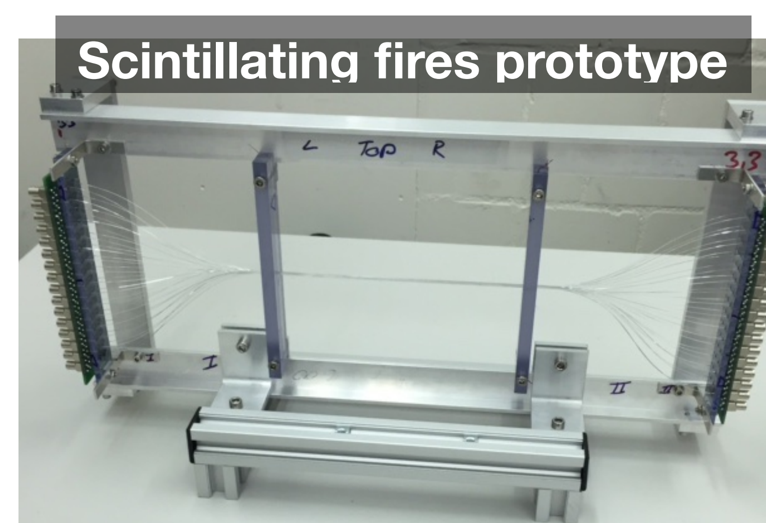




Mu3e Magnet

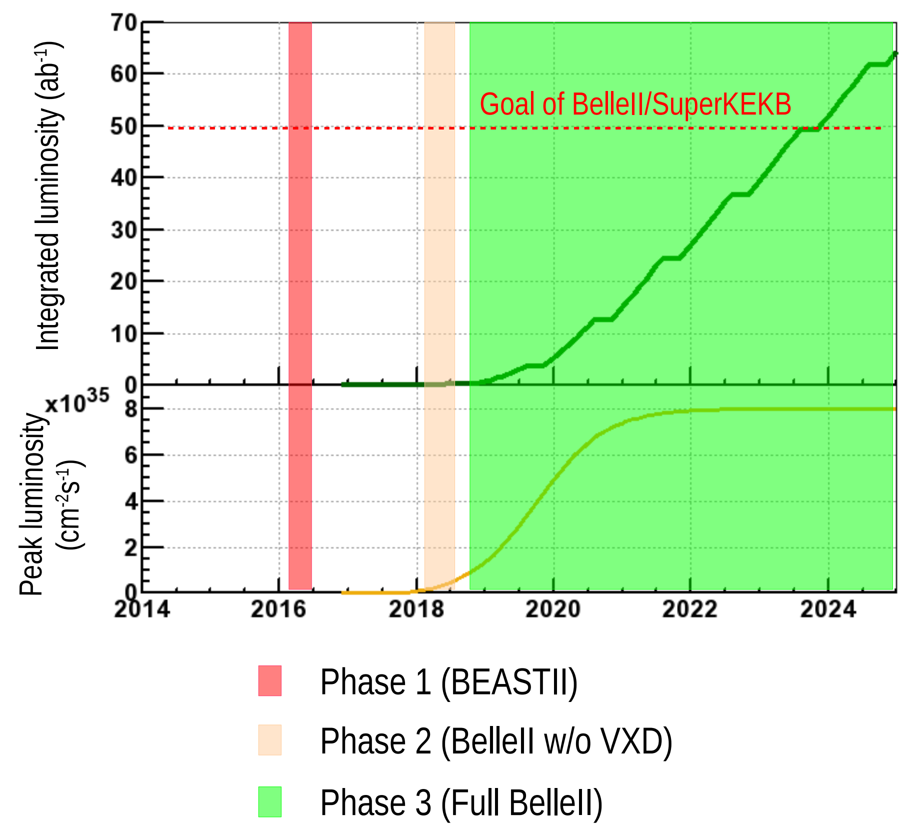
Expected in first half of 2019

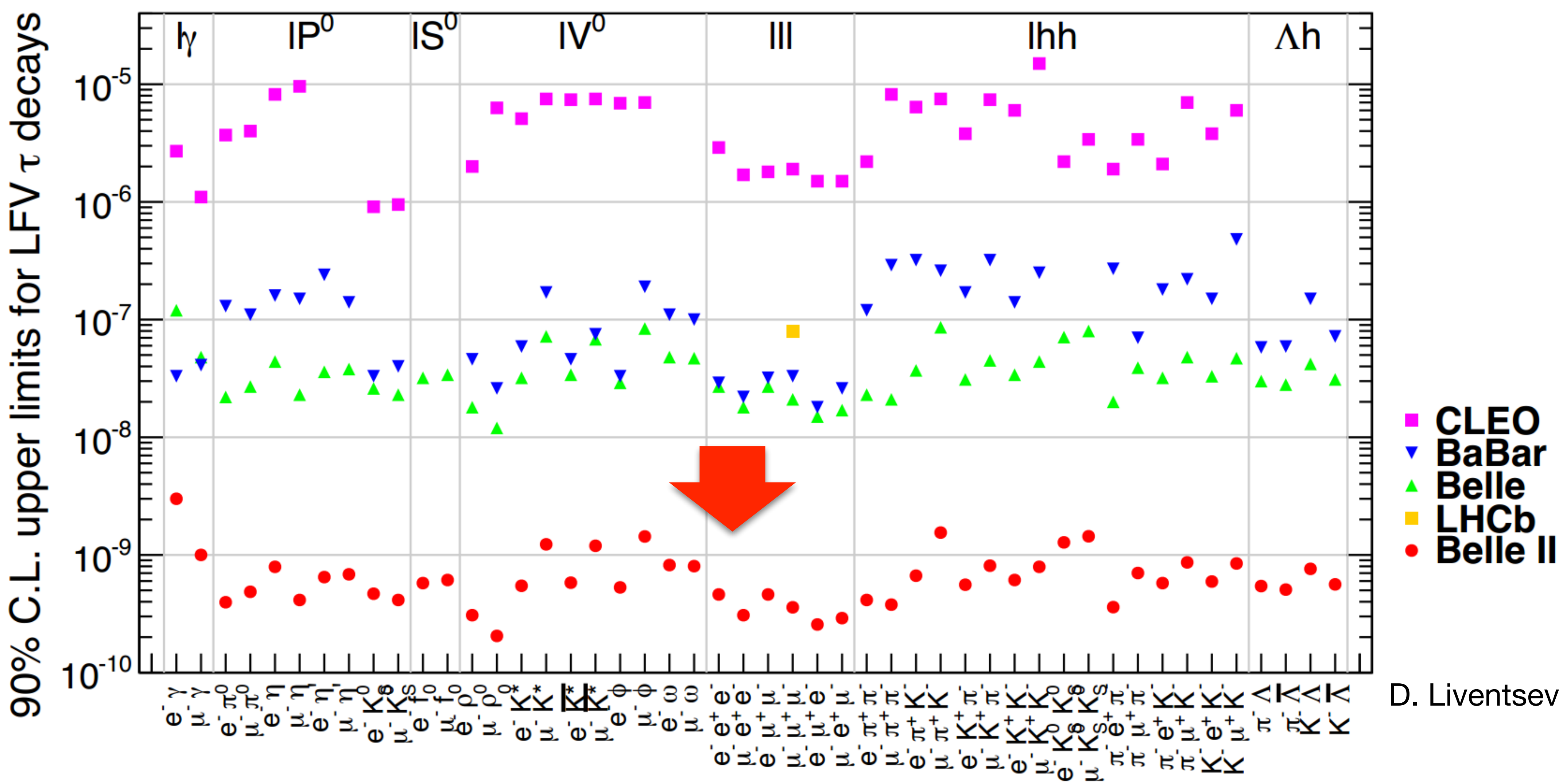




LFV τ Decays

- **10^9 τ-pairs collected at Belle/BaBar**
  - 48 channels of LFV τ-decays studied down to $O(10^{-8})$ sensitivity
  - Similar results from LHCb
- **$O(10^{11})$ τ-pairs will be collected by Belle II at SuperKEKB**
- **Sensitivity**
  - **τ→μγ: $O(10^{-(8\text{-}9)})$** BG dominated
  - **τ→lll, τ→l+meson: $O(10^{-(9\text{-}10)})$** still clean





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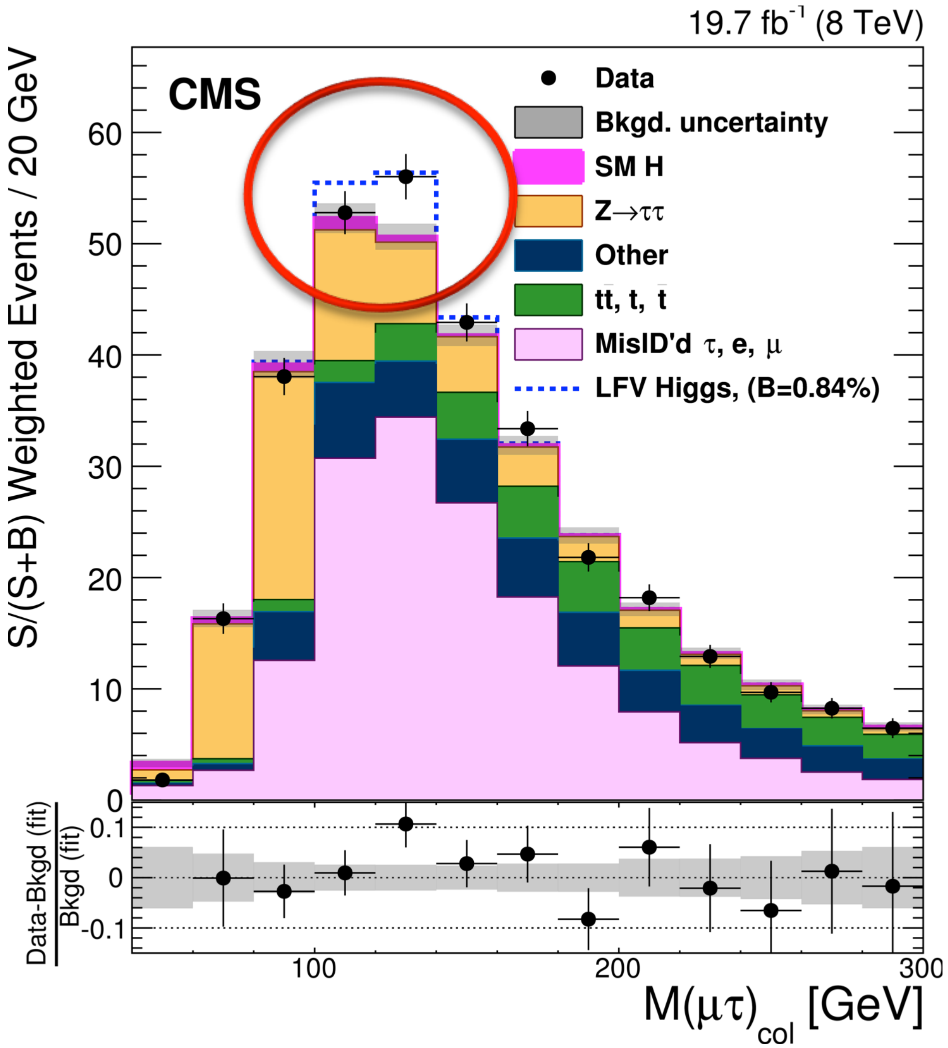
cLFV Searches LHC

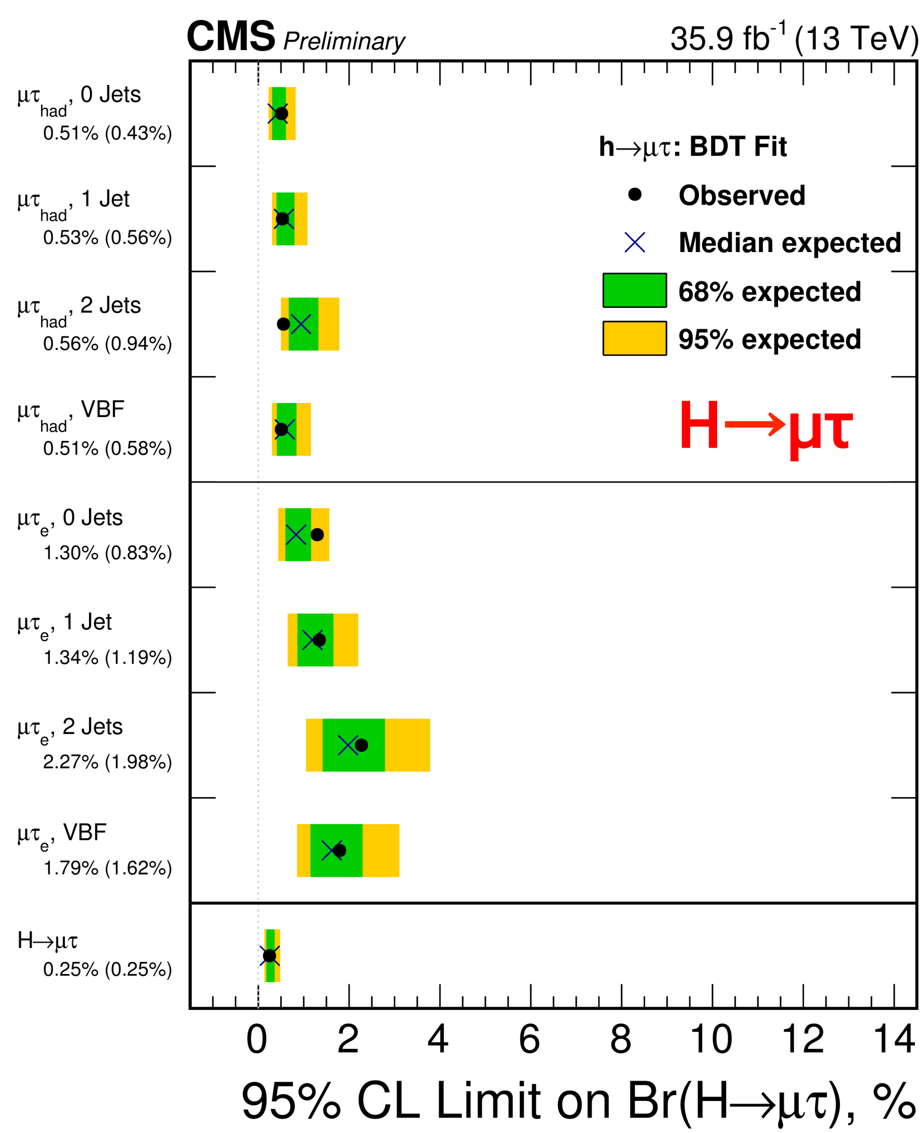
- **H→μe/μτ/eτ, Z→μe/μτ/eτ (CMS/ATLAS)**
  - N.B. decay to μe strongly constrained by μ-LFV experiments
- **Small excess (~2.4σ) in H→μτ in 8TeV data at CMS**

  →Excluded by 2016 data with improved analysis Br(H→μe)<0.25% (0.25% exp.)

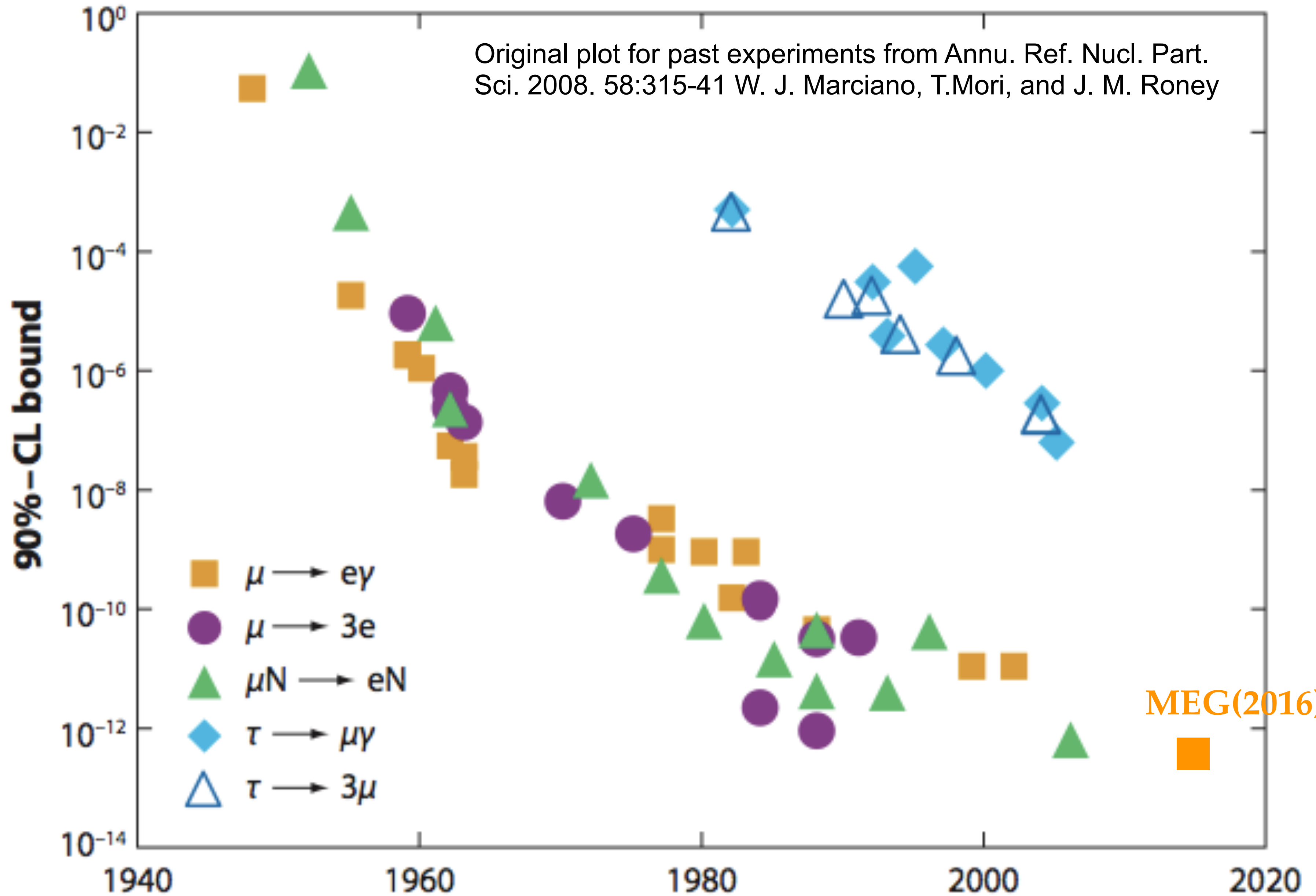
PLB 749(2015)337



CMS PAS HIG-17-001

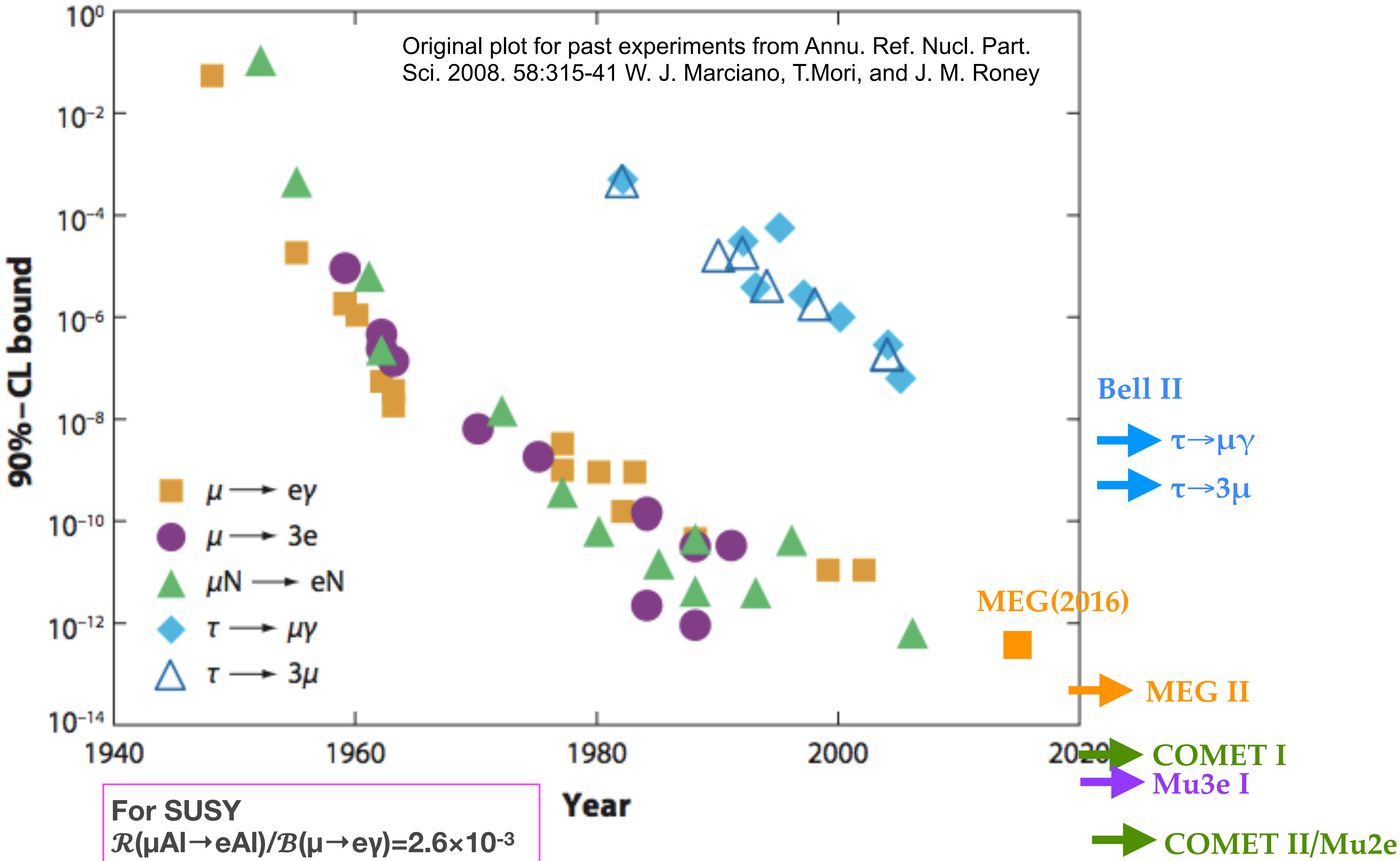


cLFV Searches Perspectives



For SUSY
$\mathcal{R}(\mu Al \to eAl)/\mathcal{B}(\mu \to e\gamma) = 2.6\times10^{-3}$
$\mathcal{B}(\mu \to 3e)/\mathcal{B}(\mu \to e\gamma) = 6\times10^{-3}$

cLFV Searches Perspectives



For SUSY
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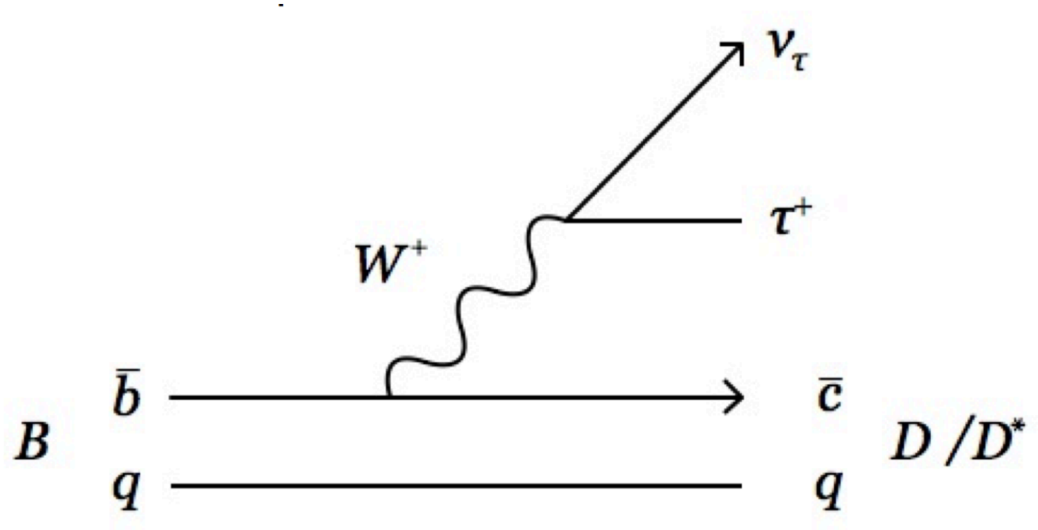
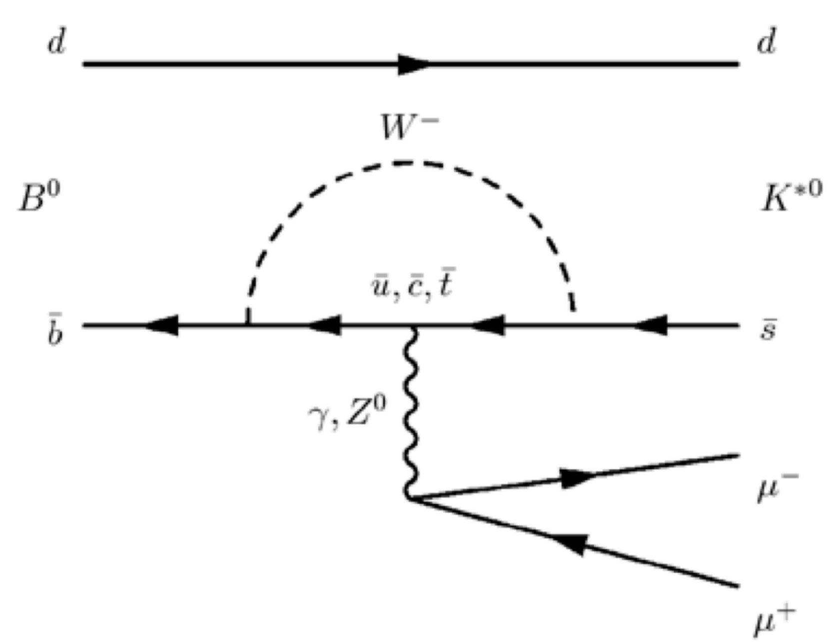
A lot of new results coming in next decade!

- Introduction
- Dipole Moments
  - EDM
  - Muon g-2
- Lepton Flavour Violation
- **Lepton Flavour Universality**
- Summary

Lepton Flavour Universality

- **In SM, couplings of leptons to gauge bosons do not depend on lepton flavours**
  - **Lepton Flavour Universality (LFU)**
  - Any observation of LFU violation = Unambiguous evidence of new physics!
- **Some hints of deviation from SM predictions in recently measured semi-leptonic B-meson decays.**
  - $B \to K^{(*)} l^+ l^-$, $B \to D^{(*)} l \nu$
  - $R(D^{(*)})$, $R(K^{(*)})$, **Angular observable** P_5'
  - Experimental and theoretical uncertainties greatly suppressed by taking ratio

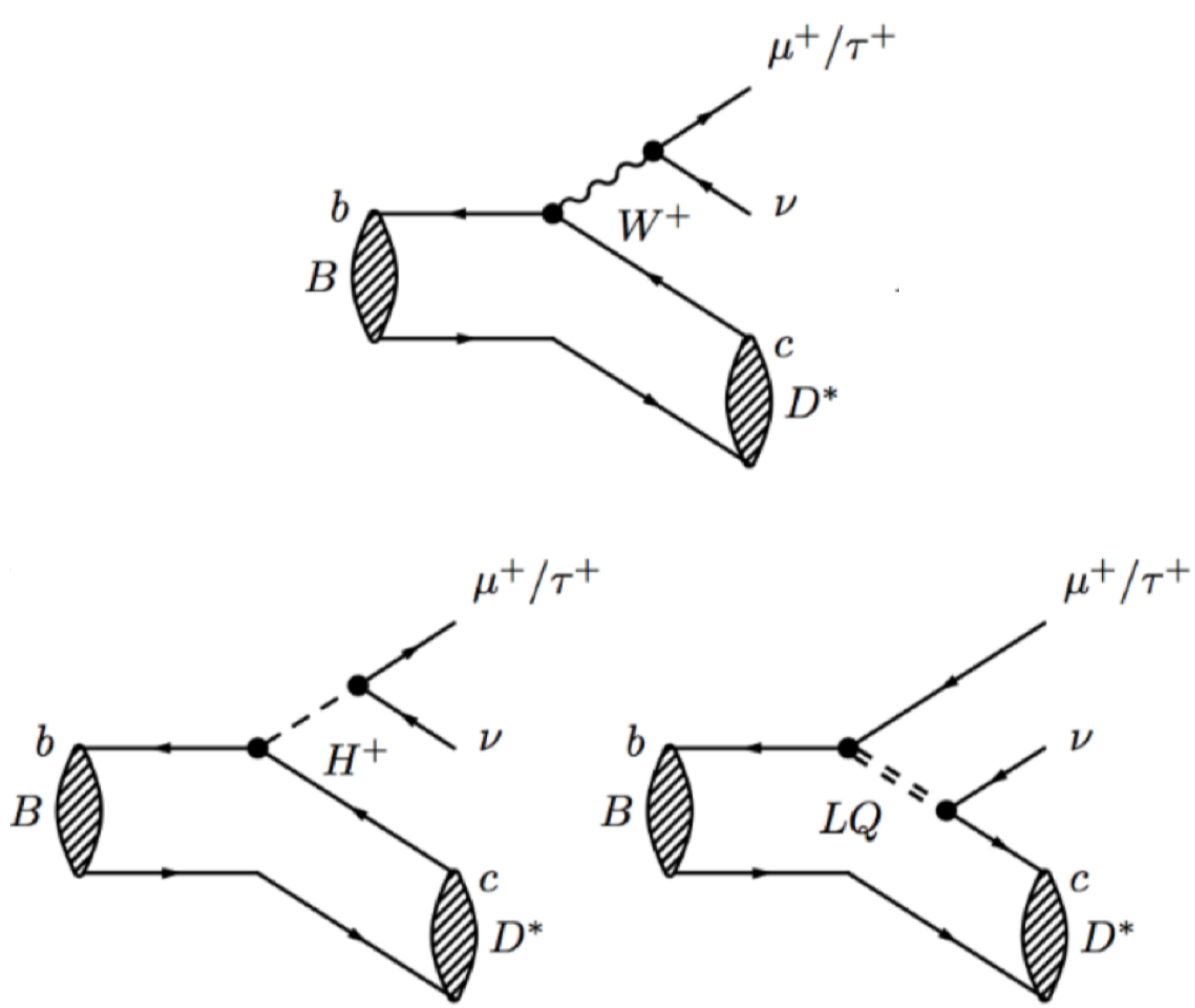


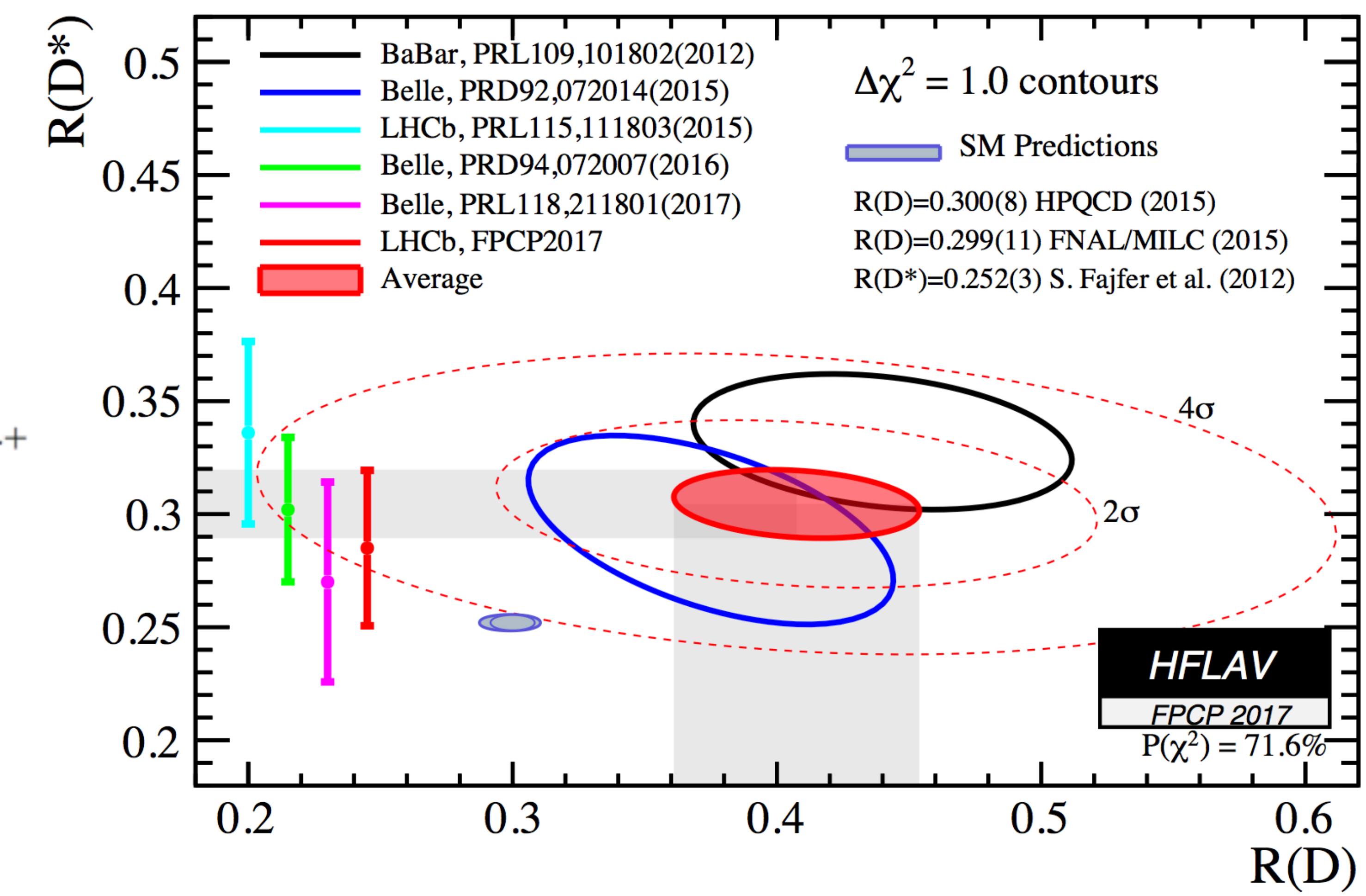


R(D^(*))

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

- **Test LFU at semi-leptonic decay $B \to D^{(*)}l\nu$**
  - Experimental and theoretical uncertainty greatly suppressed by taking ratio
- **4.1σ deviation from SM in combination of $R(D)$ and $R(D^*)$**

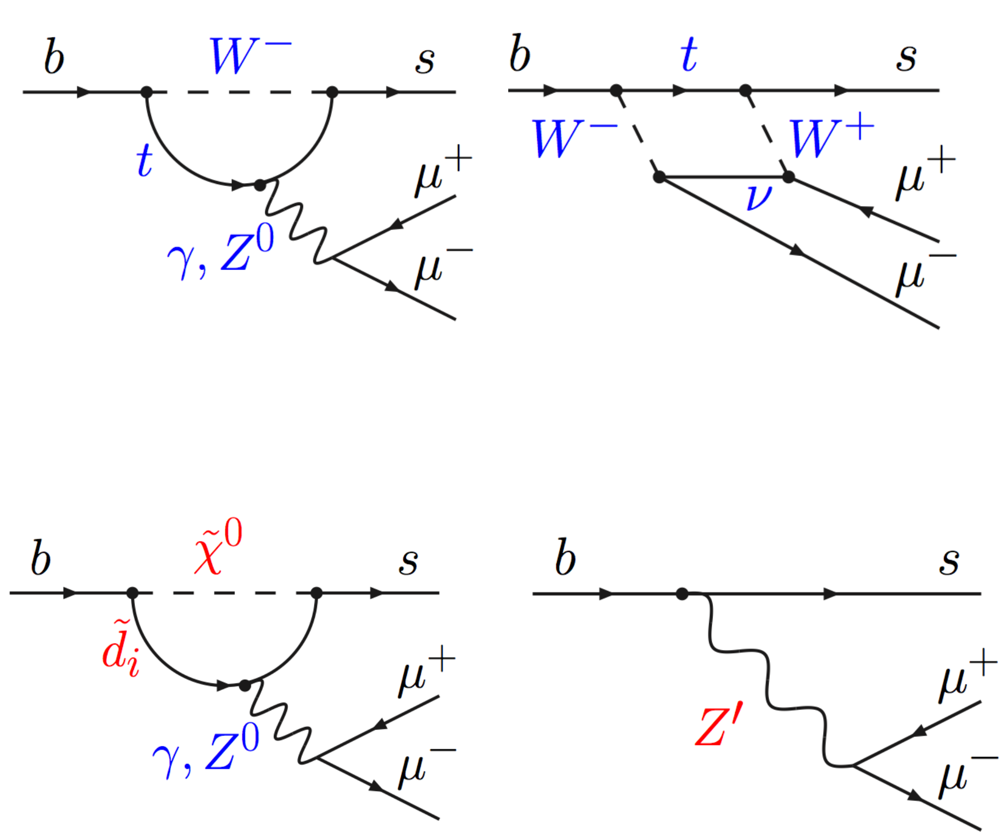


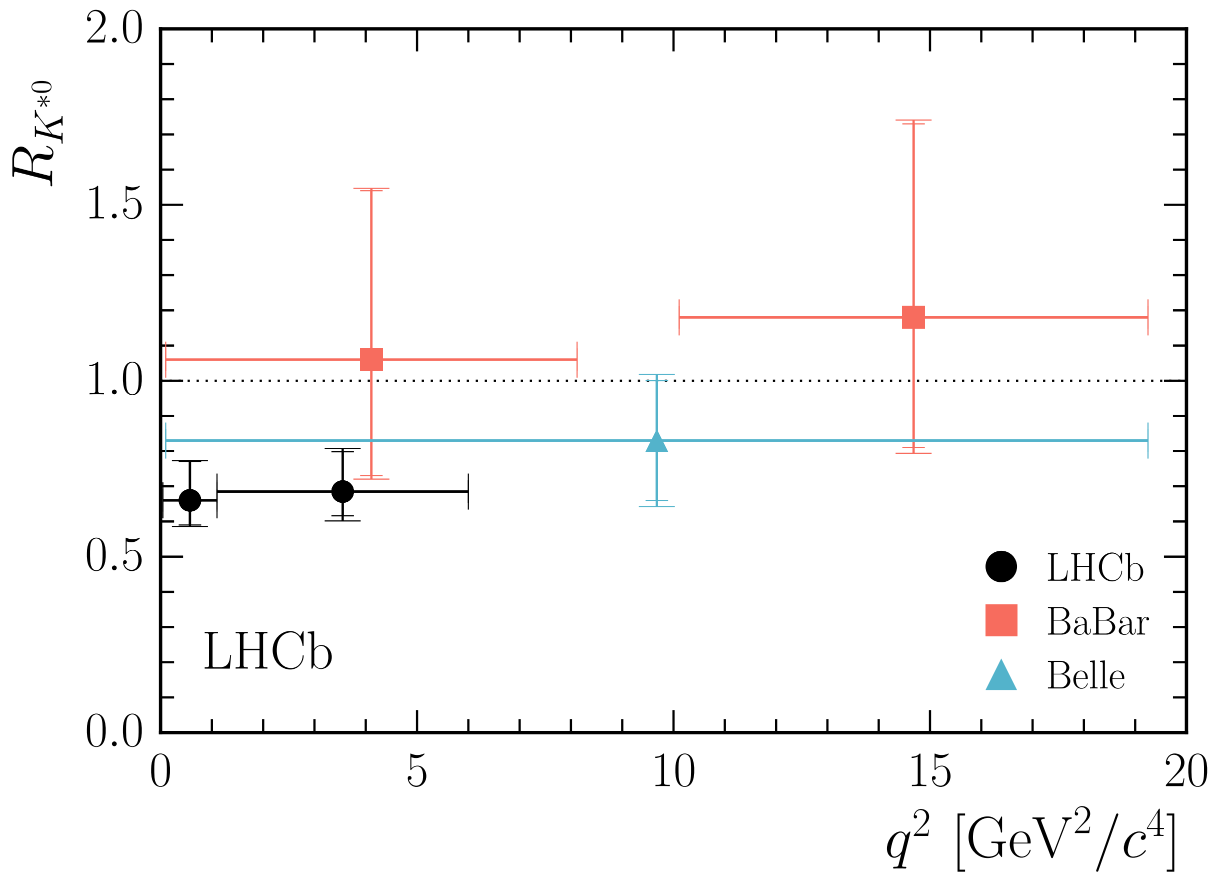


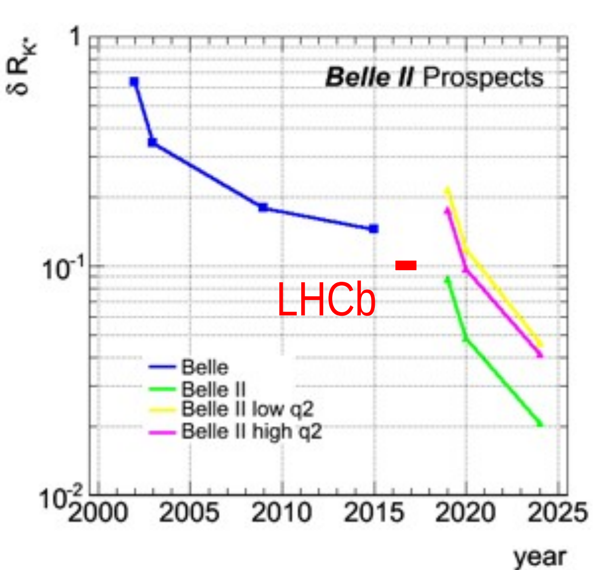
R(K(*))

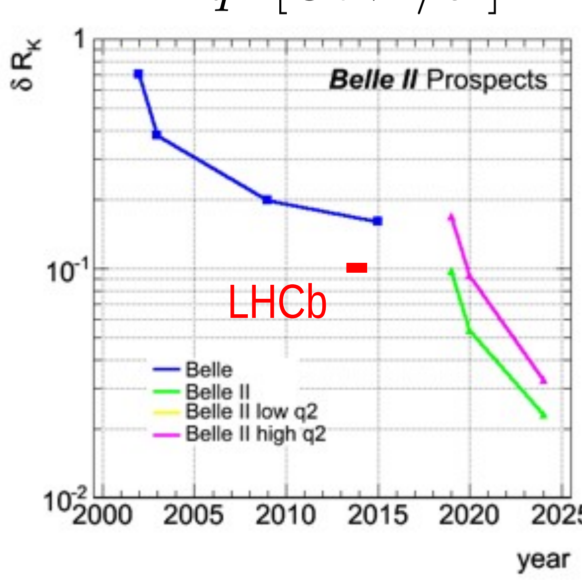
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- **Test LFU at semi-leptonic decay $B \to K^{(*)}l^+l^-$**
  - **Very precise SM prediction in double ratio**
- **LHCb: 2.1-2.3σ (2.4-2.5σ) deviation from SM in low (central) q²** (JHEP 08(2017)55)









D. Liventsev NuFACT 2017

Summary

- **High precision probes at low energies such as dipole moments, LFV and LFUV are powerful tools to hunt for new physics beyond Standard Model**
  - Very high mass scale beyond LHC reach can be explored
  - Physics motivations higher than ever with non-discovery of new physics at LHC
- **Already constraining new physics with some interesting hints of deviation from SM and significant improvements expected in the next 5-10 years**
  - Let’s see how the tensions will develop
  - Good chance of discovery(ies)
- **“Discovery” is not the end of the story!**
  - Possibility to pin-down new physics model from “pattern” measured in multiple probes

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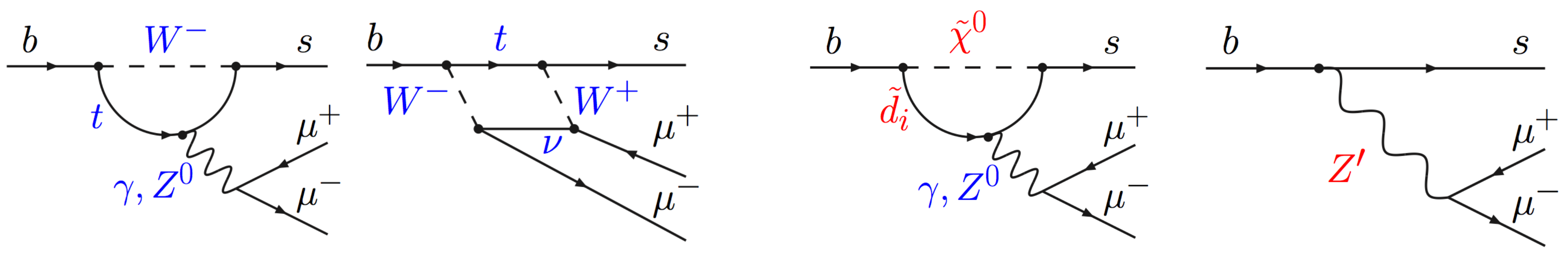
The next decade is going to be really exciting!!

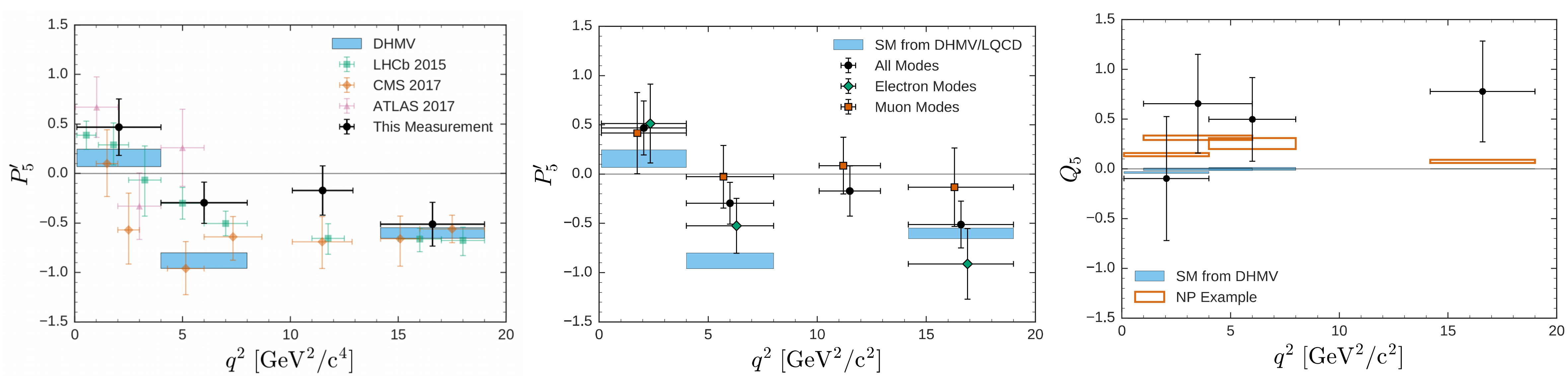
Thank you for your attention!

P_5' in $b \to sll$

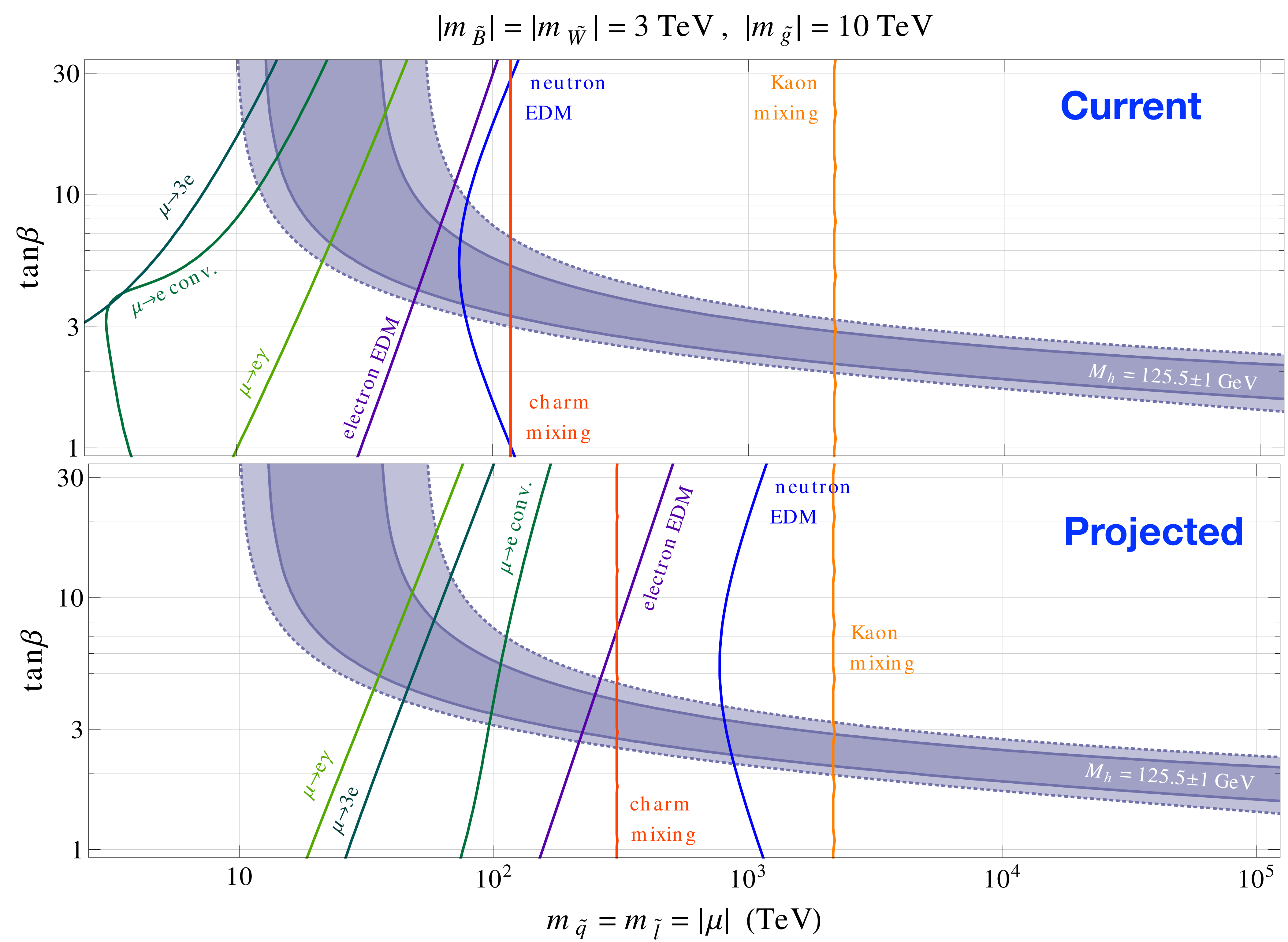


- 3.4σ (LHCb), 2.1σ (Belle) deviation from SM in $P_5{}'$ in $4<q^2<8$ GeV²
- Belle also compared $b \longrightarrow see$ and $b \longrightarrow s\mu\mu$
- 2.6σ deviation for $P_5{}'^{\,\mu}$ versus 1.3σ deviation for $P_5{}'^{\,e}$
- Also seen in $Q_5 = P_5{}'^{\,\mu} - P_5{}'^{\,e}$ (= 0 in SM)

PRL 118, 111801 (2017)



Reach of Low Energy Probes



arXiv:1308.3653v4

EDM Limits History

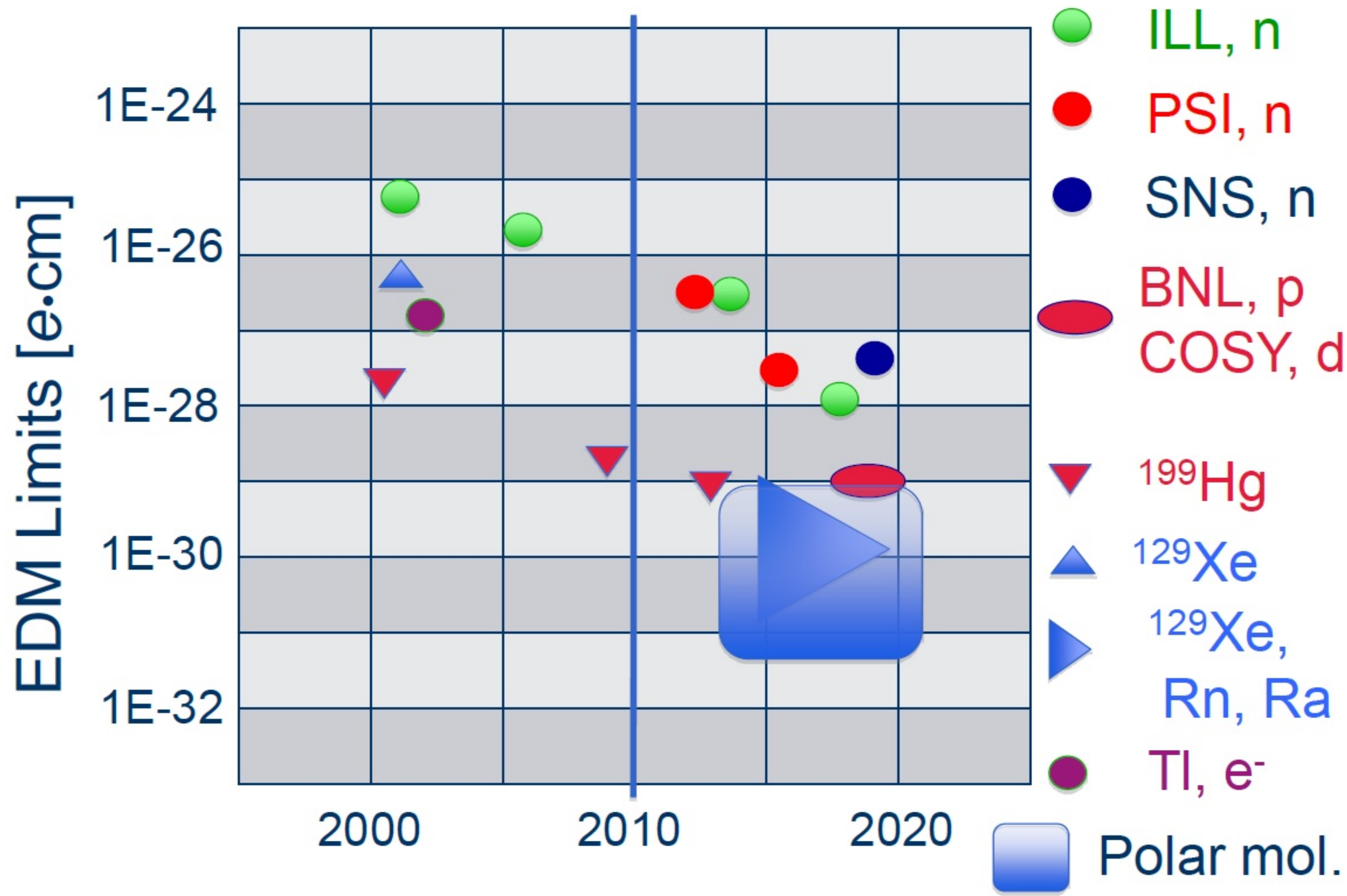


Figure 7. The past experimental sensitivity as well as the expected sensitivity of several experimental methods is shown here. The various electron EDM efforts have a similar goal as the Xe, Rn and Ra efforts and at approximately the same time period. The physics reach of the different systems varies. At present, the physics limits are dominated mostly by the ^{199}Hg, but also ^{205}Tl (at 1.6×10^{-27} $e\cdot$cm for the electron, see text) and neutron EDM results.

Yannis K Semertzidis 2011 *J. Phys.: Conf. Ser.* **335** 012012

cLFV

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to\mu^-\mu^+\mu^-)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to\mu^-e^+e^-)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to\mu^-\mu^+\mu^-)}{Br(\tau^-\to\mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

M.Blanke et al., Acta Phys.Polon.B41(2010)657

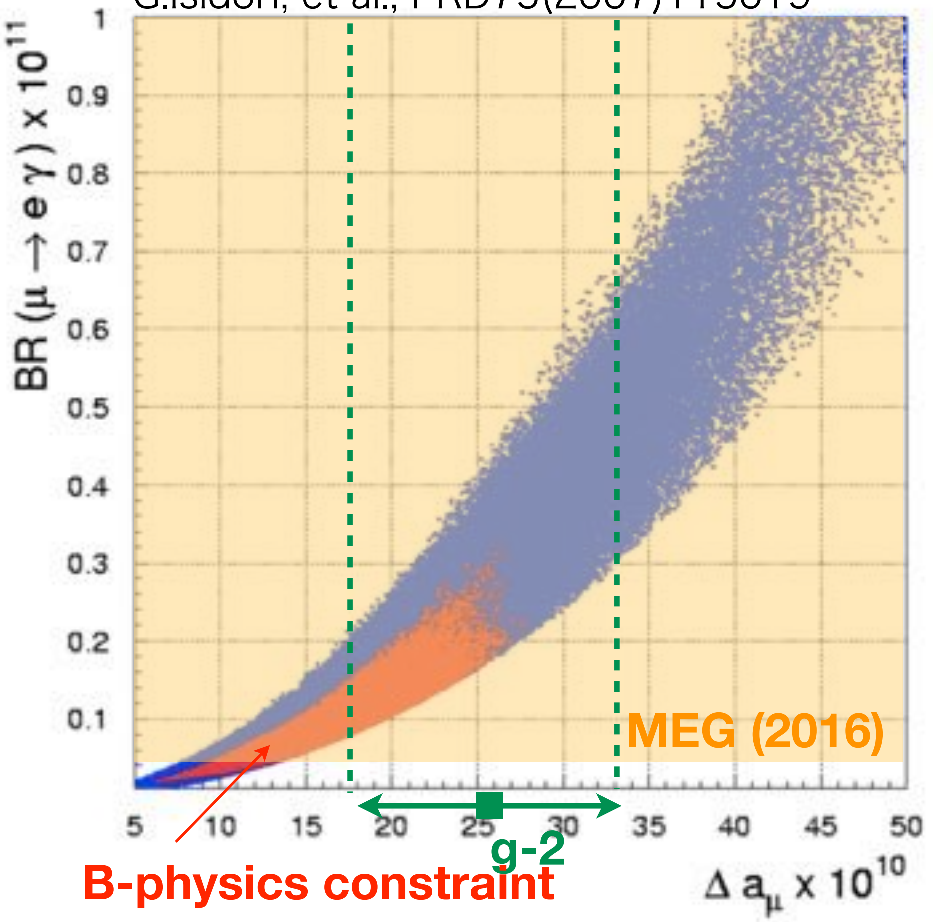
Correlation btw cLFV processes strongly depends on BSM models

→possibility to discriminate BSM models after discovery

cLFV Searches Strongly Constrain NP!

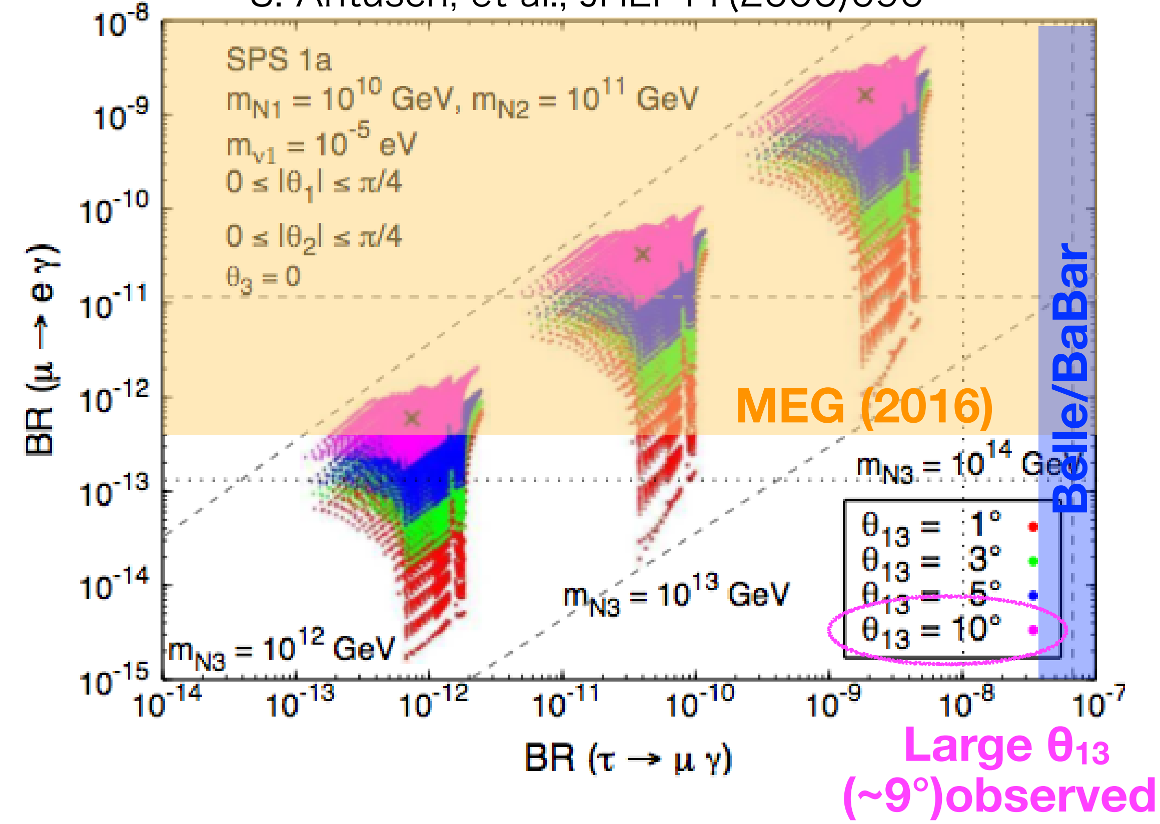
SUSY-GUT

G.Isidori, et al., PRD75(2007)115019

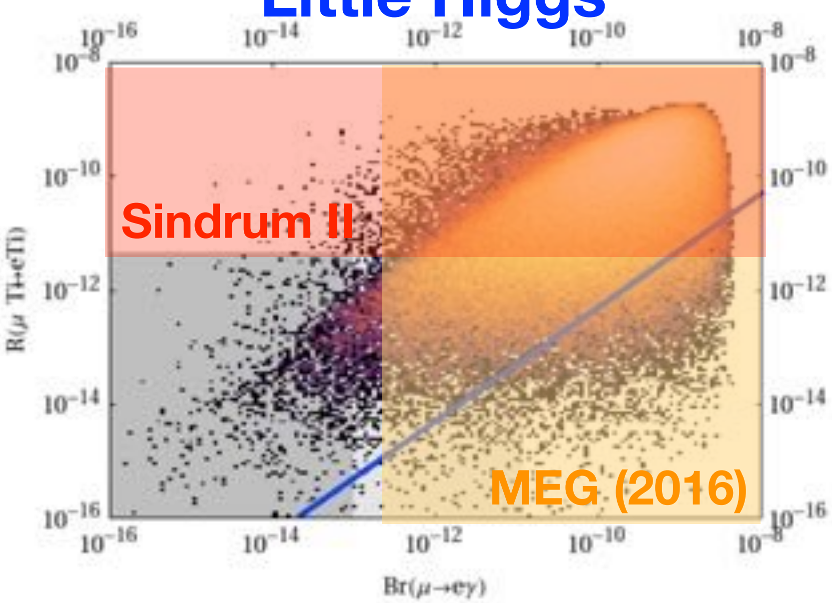


SUSY-Seesaw

S. Antusch, et al., JHEP11(2006)090



Little Higgs



M.Blanke et al., Acta Phys.Polon.B41(2010)657

Extra dimensions