New Physics with Muons

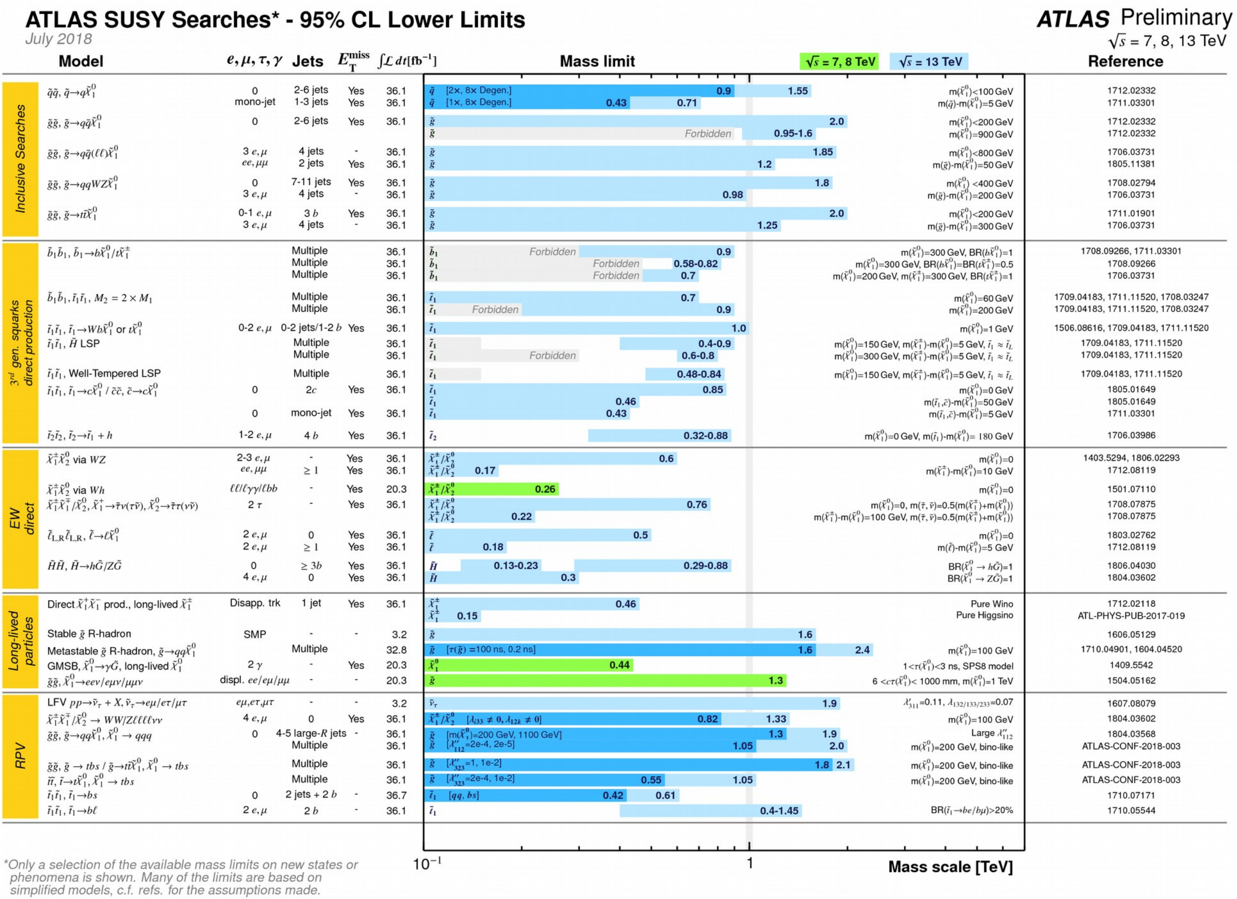
Gavin Hesketh
YETI 2019
7/1/19

UCL

New physics must exist:

- dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, gravity….

…but where is it??



…or: where is the New Physics?

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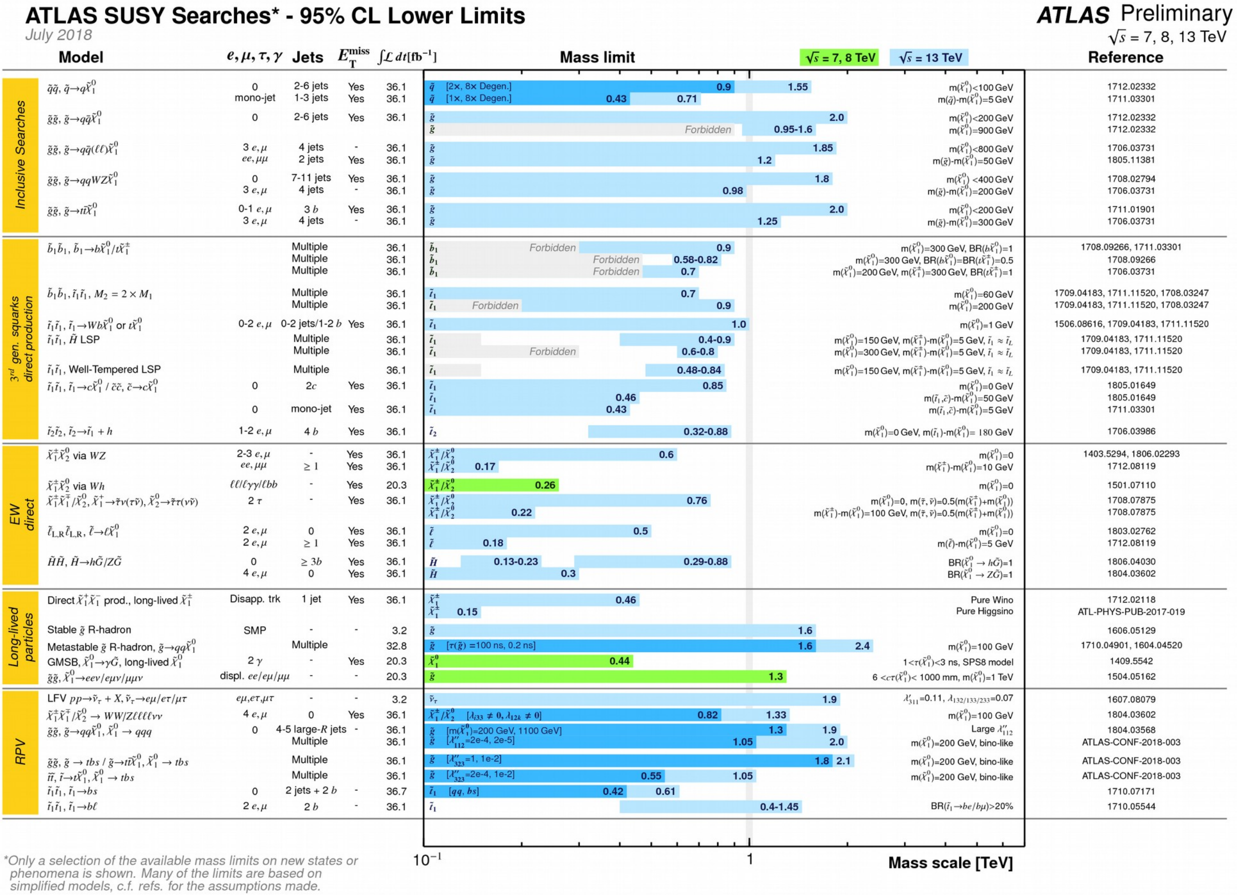


Surprises from the lepton sector:

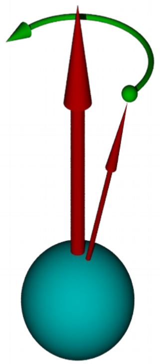
- neutrino masses
- some ~3σ effects: R(K), R(D)
- 3.8σ effect in muon g-2

So, how do we learn more?

- Fermilab Muon g-2
- Mu3e

…+several other experiments

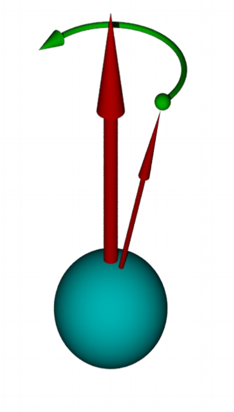
Precise measurements vs precise calculations



Larmor Precession:

- the magnetic moment of a particle rotates around a B-field

$$\omega_s = \frac{g\,qB}{2\,m} \quad = \frac{(2 + 2a)\,qB}{2 \qquad m}$$



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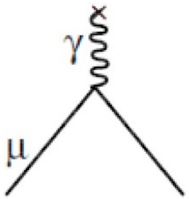
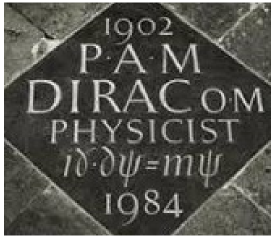
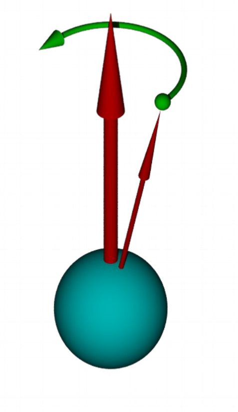
The magnetic moment of charged leptons:

- exactly 2 at tree level (Dirac's prediction)







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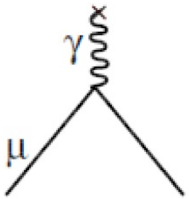
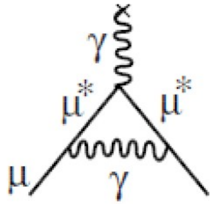
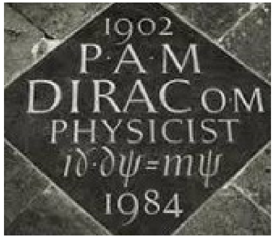




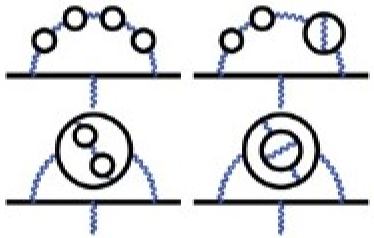


- first loop calculated by Schwinger in 1948

$$g = 2 + \alpha/2\pi + ...$$

- state of the art: *O(5) in QED*

12,762 diagrams! arXiv:1712.06060



For electons, a determined by QED loops

A recent measurement of α

$1/\alpha = 137.035999046(27)$

Science, 13 Apr 2018: Vol. 360, Issue 6385, pp. 191-195

→ new prediction of $a_e = 0.00115965218161(23)$

compared to measured $a_e = 0.00115965218073(28)$

PRD 97(2018)036001, PRL 100(2008)120801

→ ***2.5σ difference***

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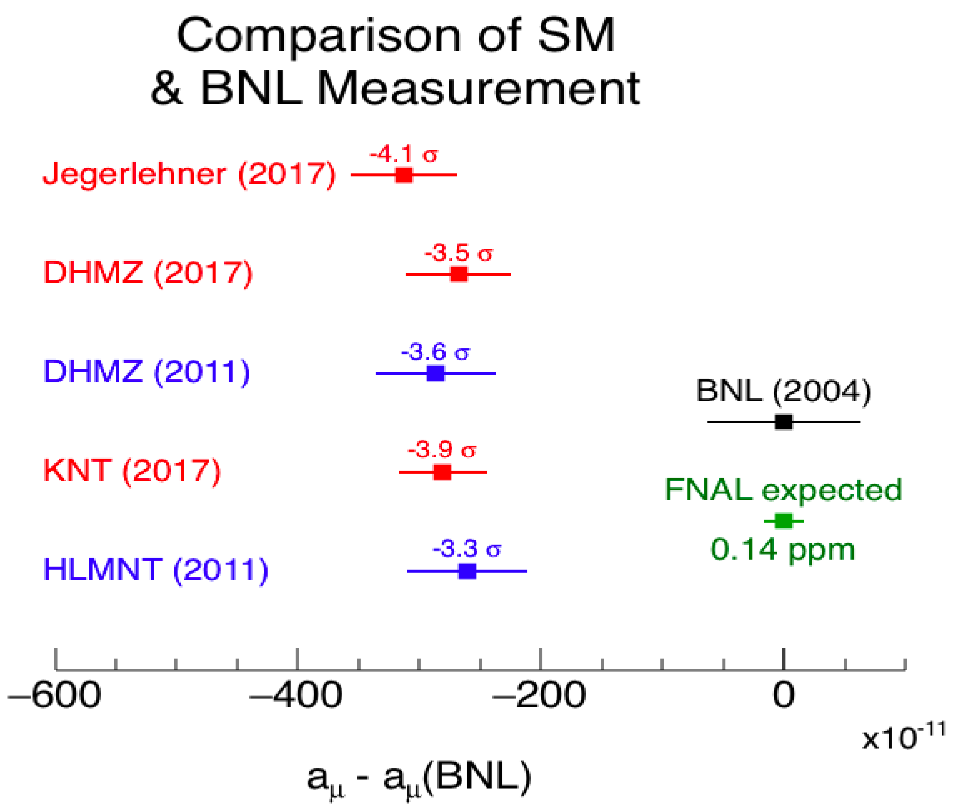
For muons:

- larger muon mass → QCD and EWK loops contribute
- a long-standing disagreement with experiment:
  - a = 0.00116592089(63) (measured)
  - a ~ 0.00116591821(36) (prediction)

PRD 73(2006)072003, KNT18, PRD97, 114025

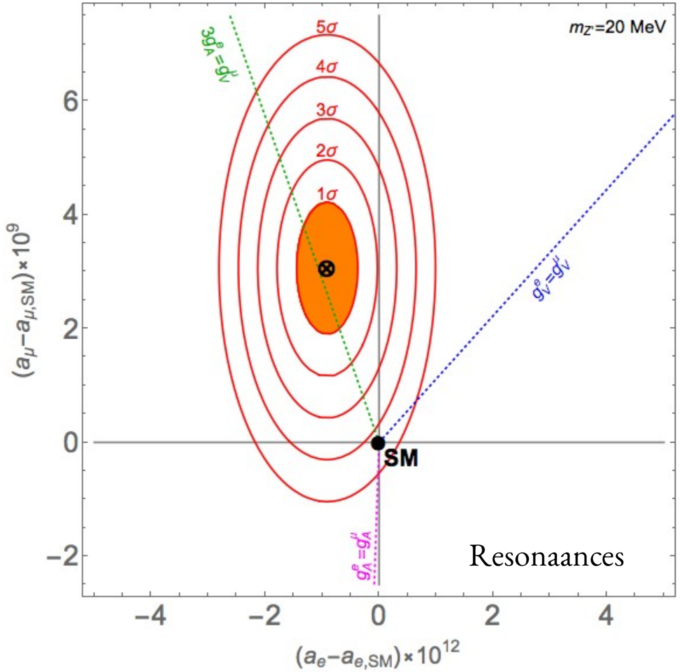
→ ***3.7σ difference***



Electron and muon discrepancies in opposite directions…

…so a lepton-flavour violating dark photon..?

…a model with a large muon EDM..?
- arXiv:1807.11484



Resonaances

"Follow that ambulance!"

UCL

Electron and muon discrepancies in opposite directions...

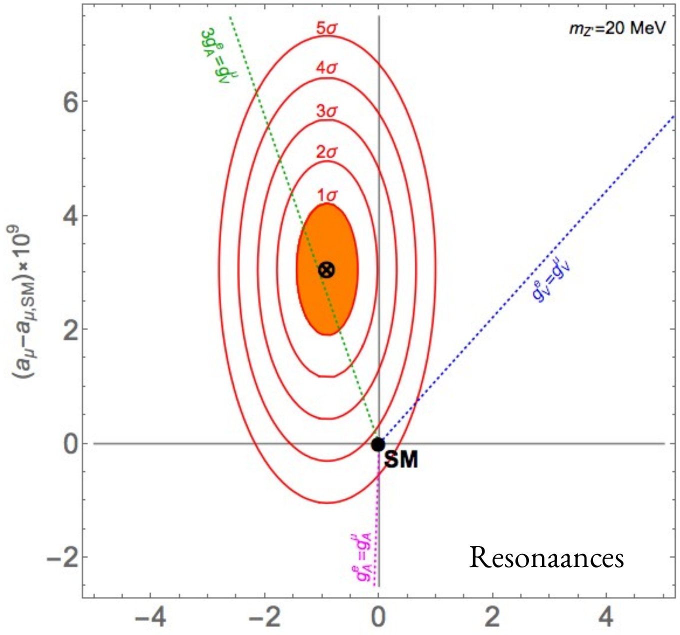
...so a lepton-flavour violating dark photon..?

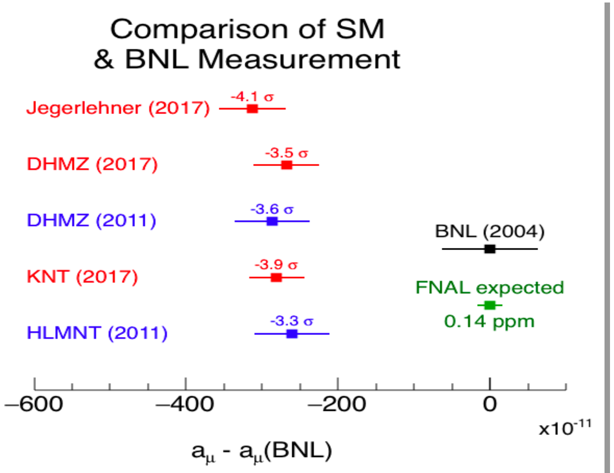
...a model with a large muon EDM..?
- arXiv:1807.11484

...or experimental effects..?

Fermilab Muon g-2 experiment:
- factor 4 improvement over BNL result
- should resolve (at 5-10σ level) or resolve muon discrepancy

34 institutes, 185 collaborators
UK: Lancaster, Liverpool, Manchester, UCL





GIZMODO

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PHYSICS

Why Particle Physicists Are Excited About This Mysterious Inconsistency

Ryan F. Mandelbaum
7/03/18 1:30pm
Filed to: PARTICLE PHYSICS

48.3K 10 9

Forbes

6,854 views | Sep 8, 2018, 10:00am

Ask Ethan: Does The Measurement Of The Muon's Magnetic Moment Break The Standard Model?

Ethan Siegel Senior Contributor
Starts With A Bang Senior Contributor
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The Universe is out there, waiting for you to discover it.

FRONTLINE

DISPATCHES
Demonetisation still hurts

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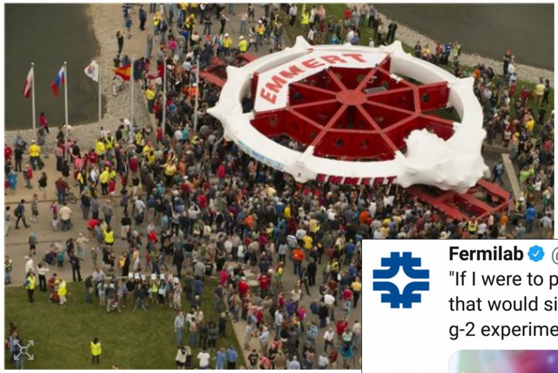
PARTICLES AND INTERACTIONS | RESEARCH UPDATE

Has the muon magnetic moment mystery been solved?

02 Feb 2018 Hamish Johnston



Gravitational effect: the g-2 magnet arrives at Fermilab to be i… experiment

Science

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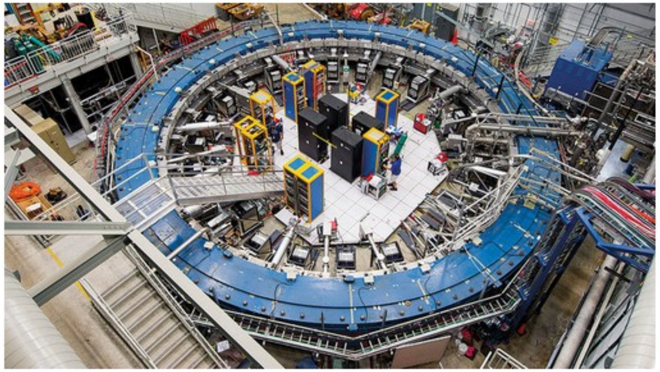


The magnetism of muons is measured as the short-lived particles circulate in a 700-ton ring. FERMILAB

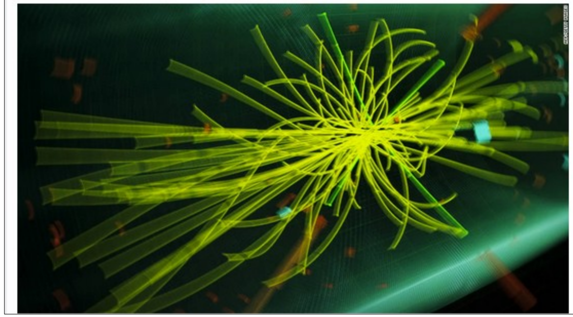
Renewed measurements of muon's magnetism could open door to new physics

By Adrian Cho | Jan. 25, 2018 , 12:00 PM

CNN Home

Scientific breakthrough could be as simple as measuring the wobble of a muon

By Don Lincoln
Updated 1648 GMT (0048 HKT) February 13, 2018

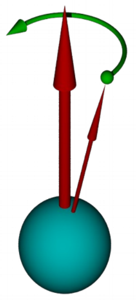


Fermilab @Fermilab · 3h
"If I were to put my money on something that would signal new physics, it's the g-2 experiment at Fermilab."

We Asked Celeb Physicist Brian Cox About Flat Earth Conspiracies, the …
gizmodo.com

Put muons in a magnetic field, measure precession frequency

$$\omega_s = \frac{g}{2}\frac{qB}{m} = \frac{(2 + 2a)}{2}\frac{qB}{m}$$



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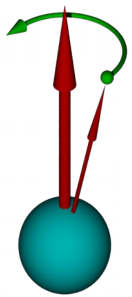
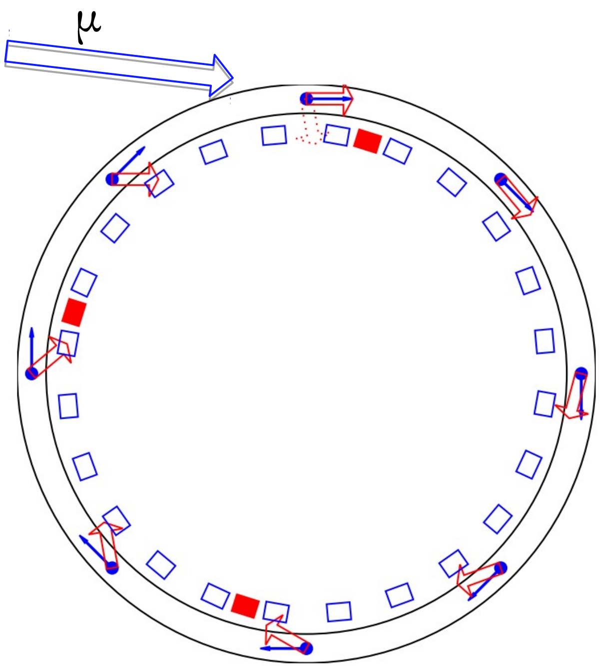


Use a circular magnetic storage ring (7.1 m radius)

Cyclotron frequency: $\omega_c = \frac{qB}{m} \rightarrow \omega_a = \omega_s - \omega_c = a\frac{qB}{m}$



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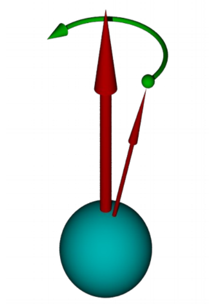

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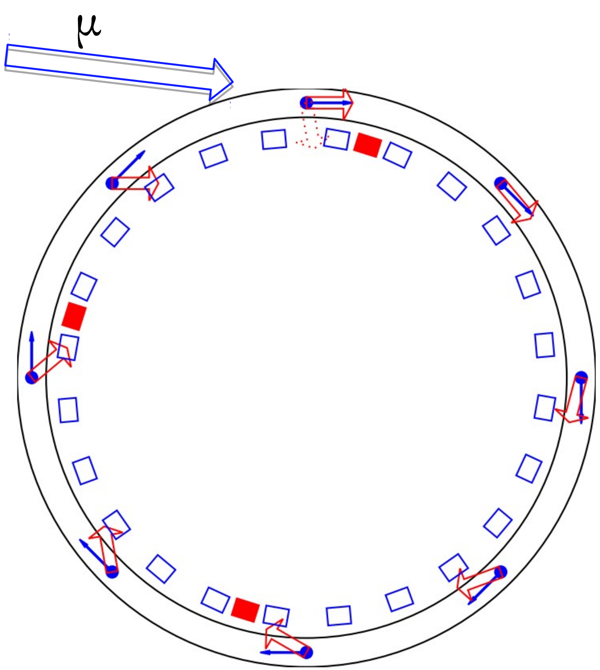
Use "magic momentum" 3.09 GeV

$$\omega_a = -\frac{q}{m}\left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\beta \times E}{c}\right]$$

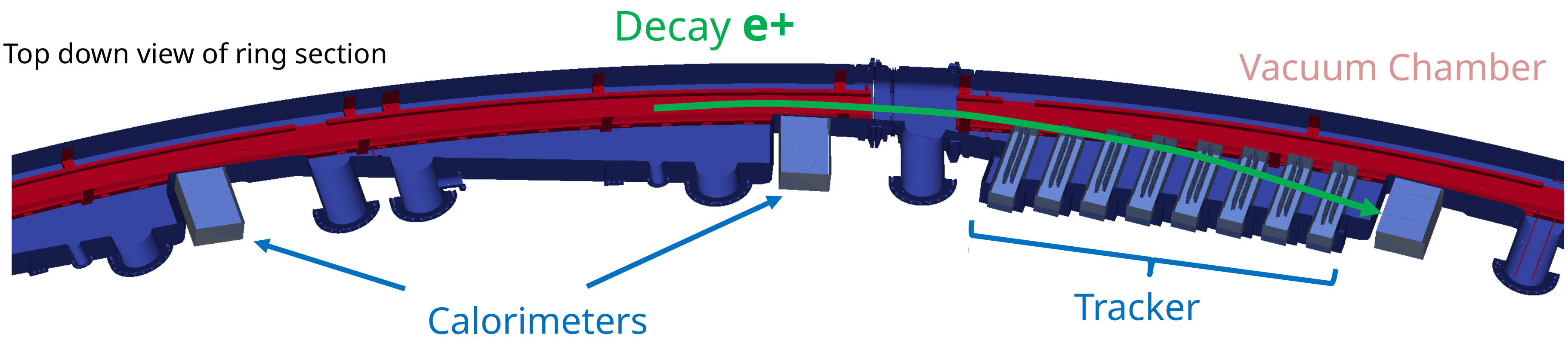
Actually measure ratio of two frequencies:

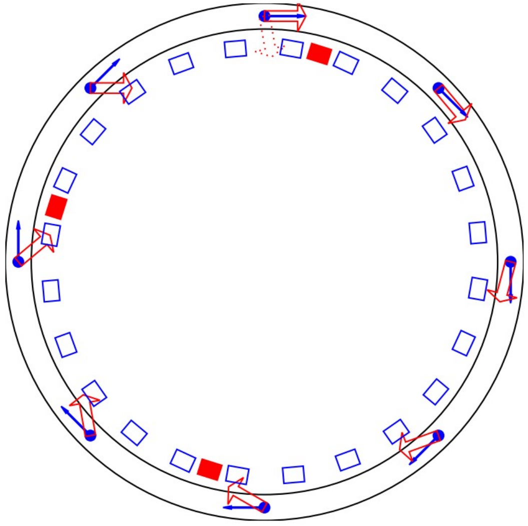
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

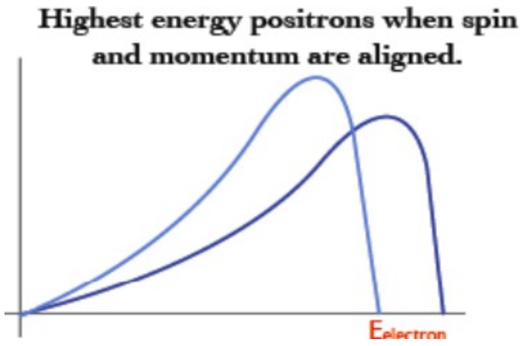
3ppb 22ppb 0.0003ppb

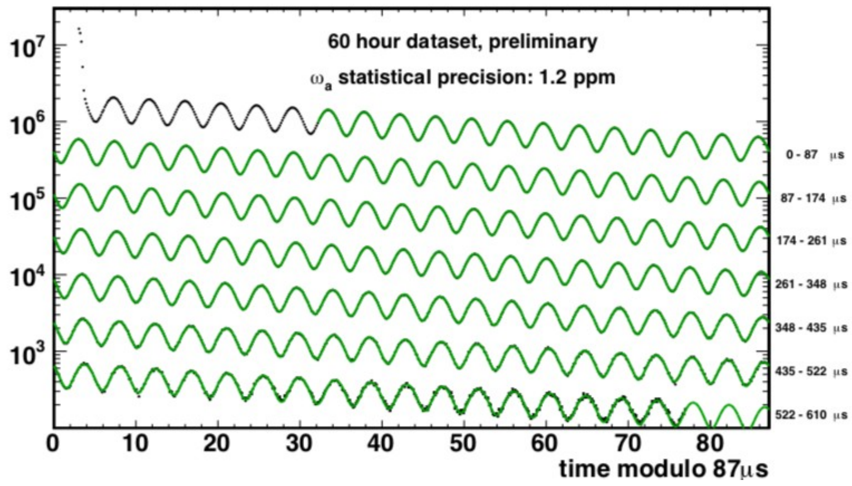


Wiggle plots







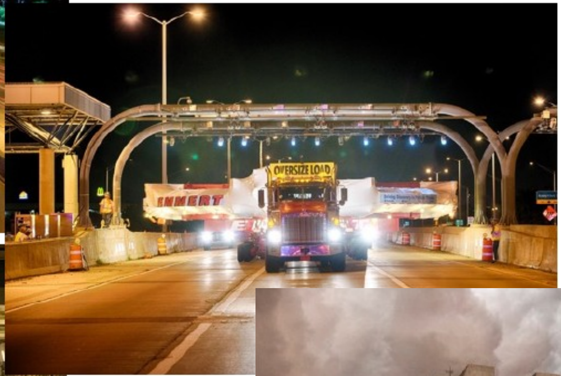


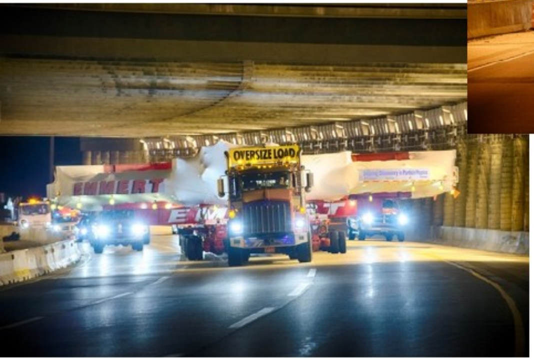
A long journey

BNL → FNAL

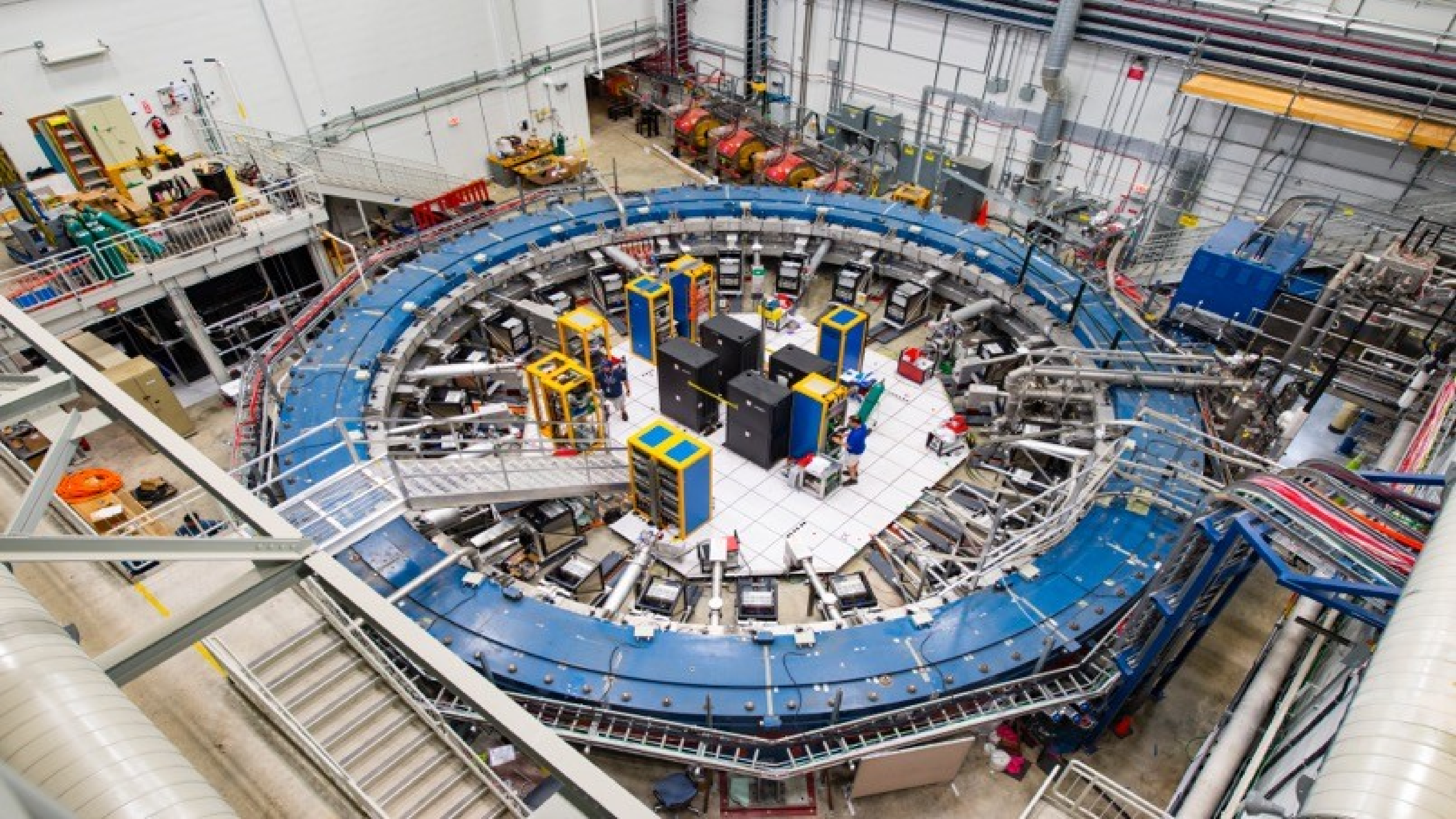
[50 (stat) + 33 (syst) → 11 (stat) + 11 (syst)] x 10^{-11}

BNL magnet moved to Fermilab in 2013
- higher intensity, cleaner beam
- new trackers & calorimeters
- lots more stats





22 June → 26 July 2013

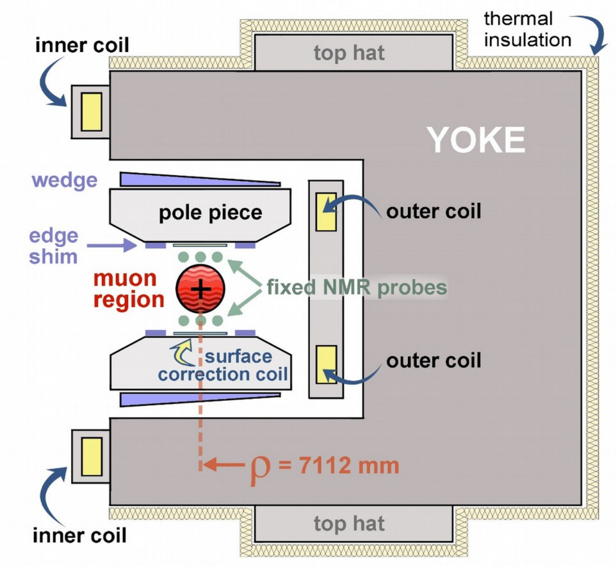


B-field

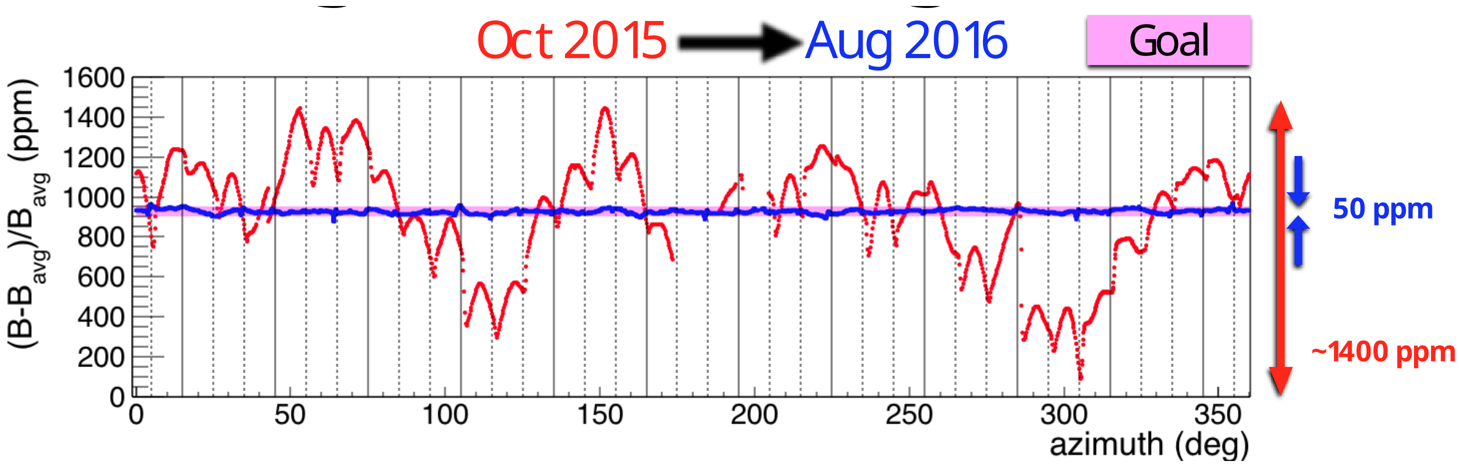
$$\omega_a = a \frac{qB}{m}$$

Need highly uniform B-field around the storage ring

- magnetic field was shimmed to high precision
- constantly monitored using NMR probes



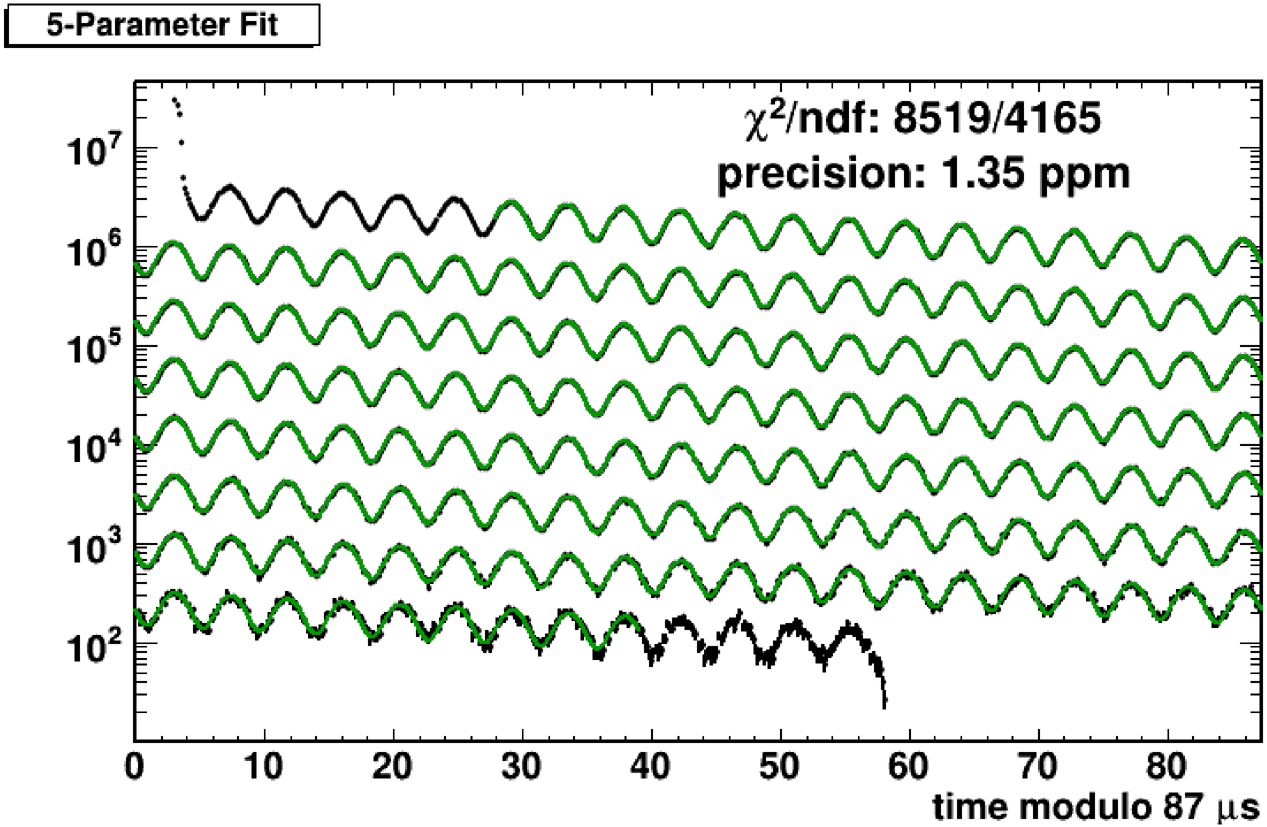
g-2 Magnet in Cross Section



B-field uniformity 3x better than BNL (2x was the goal)

Simplest fit: 5 parameters

- exponential decay (2 parameters)
- with a superimposed sine wave (3 parameters)

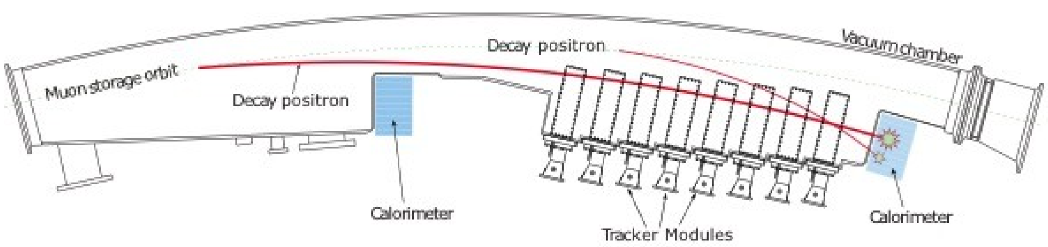


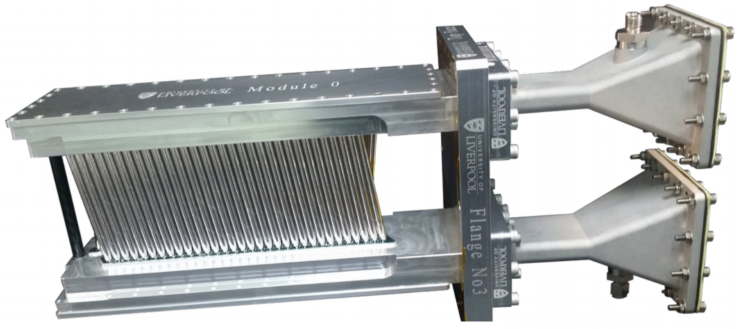
New Trackers

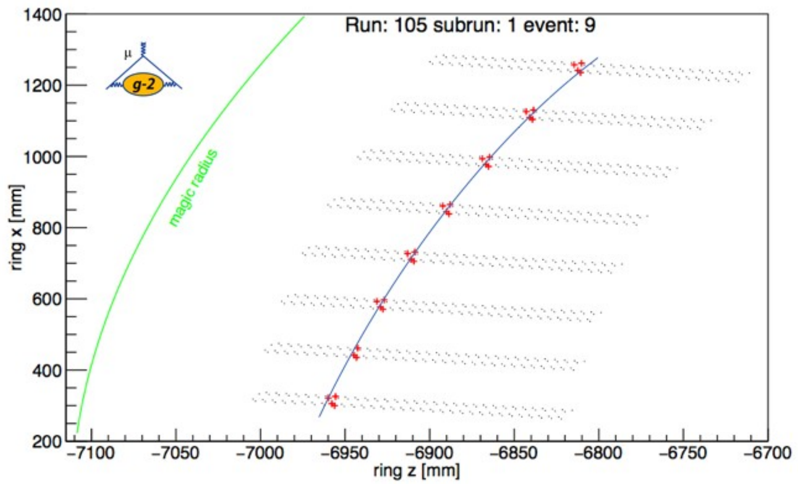
Main positron energy measurement made using 24 calorimeters

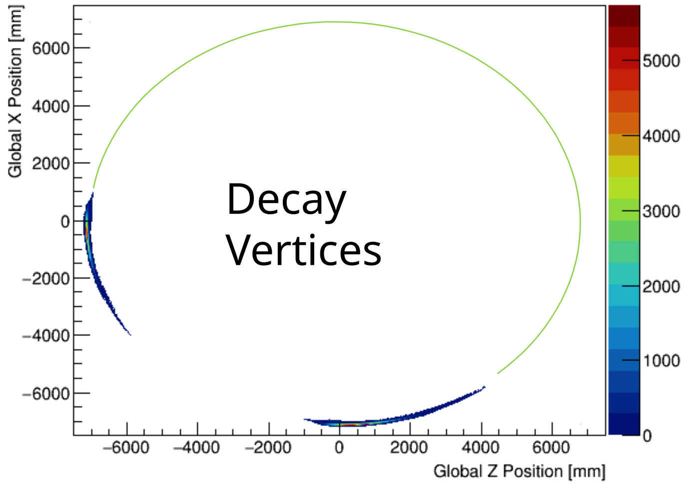
- fast response lead-flouride Cherenkov crystals (9x6 array, each crystal 25x25x140mm)
- resolution 2.3% at 3 GeV

UK contributed new tracking detectors in front of two calorimeters





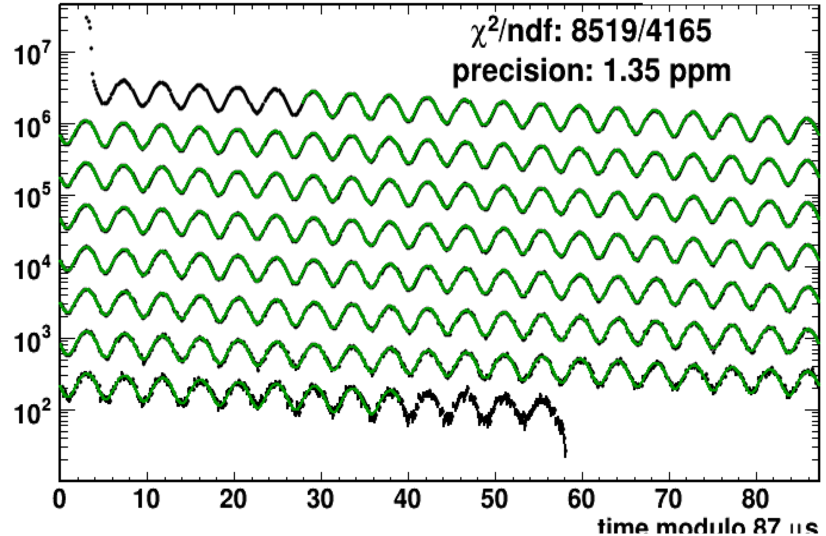


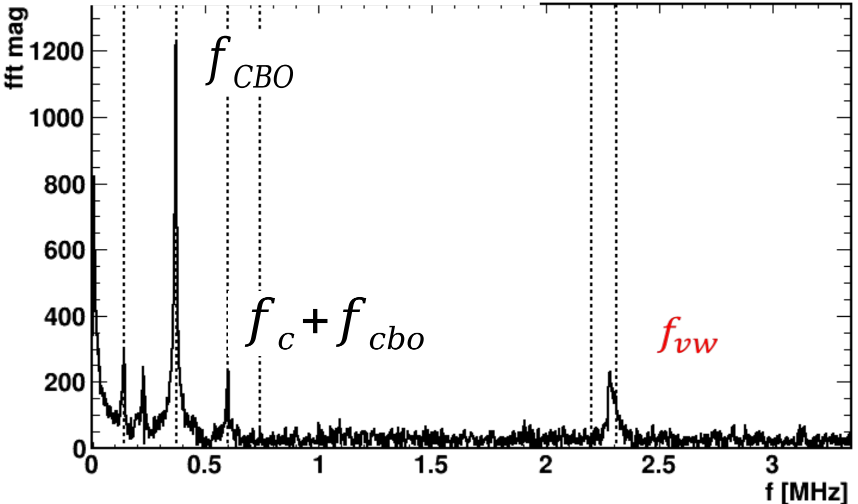


Beam position

beam position video

Improved Wiggle





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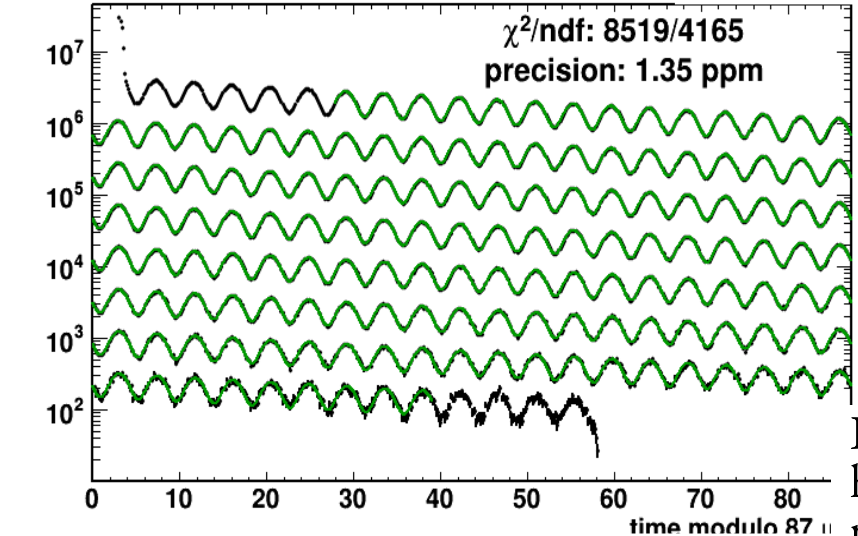
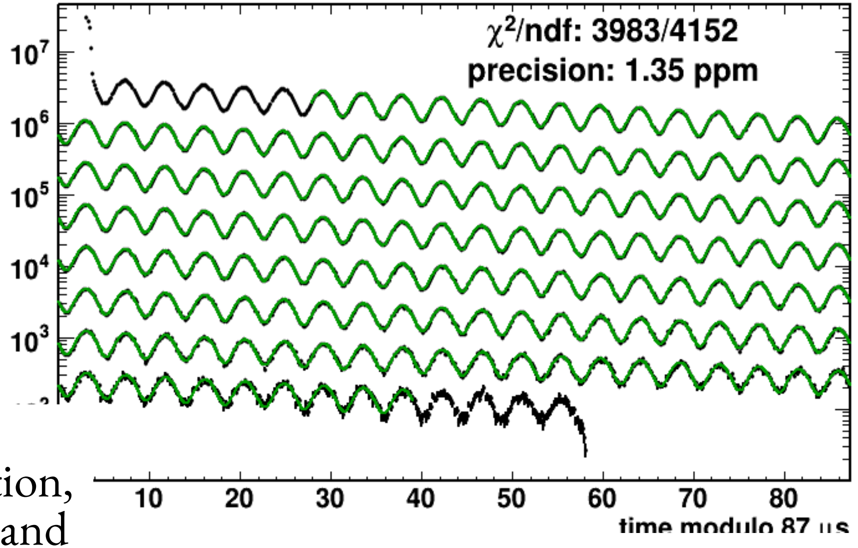
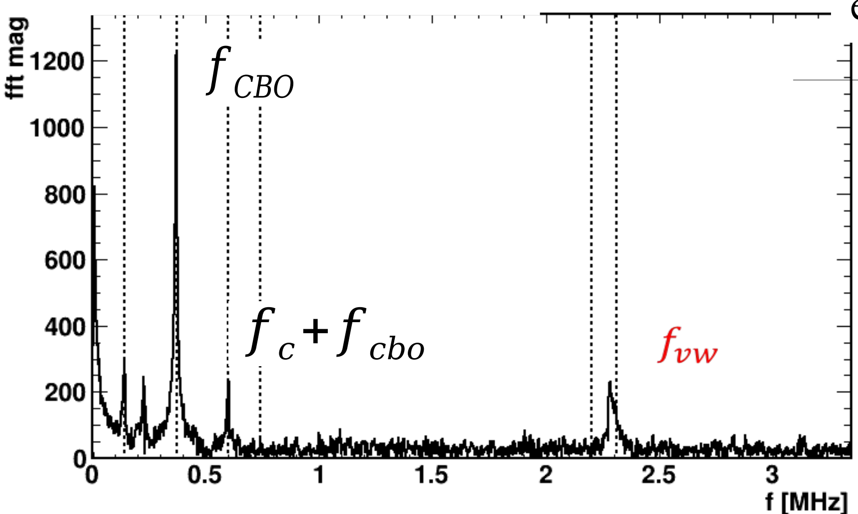
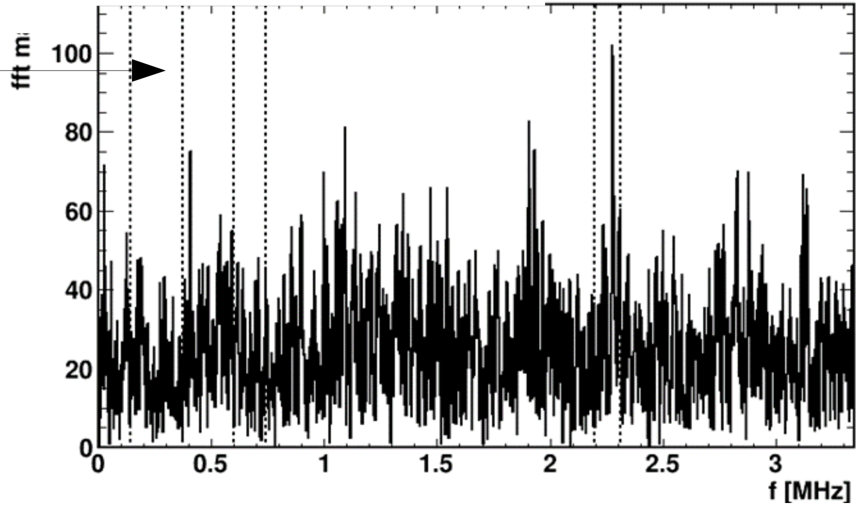




Include vertical and horizontal beam motion, pile-up, muon losses and energy scale



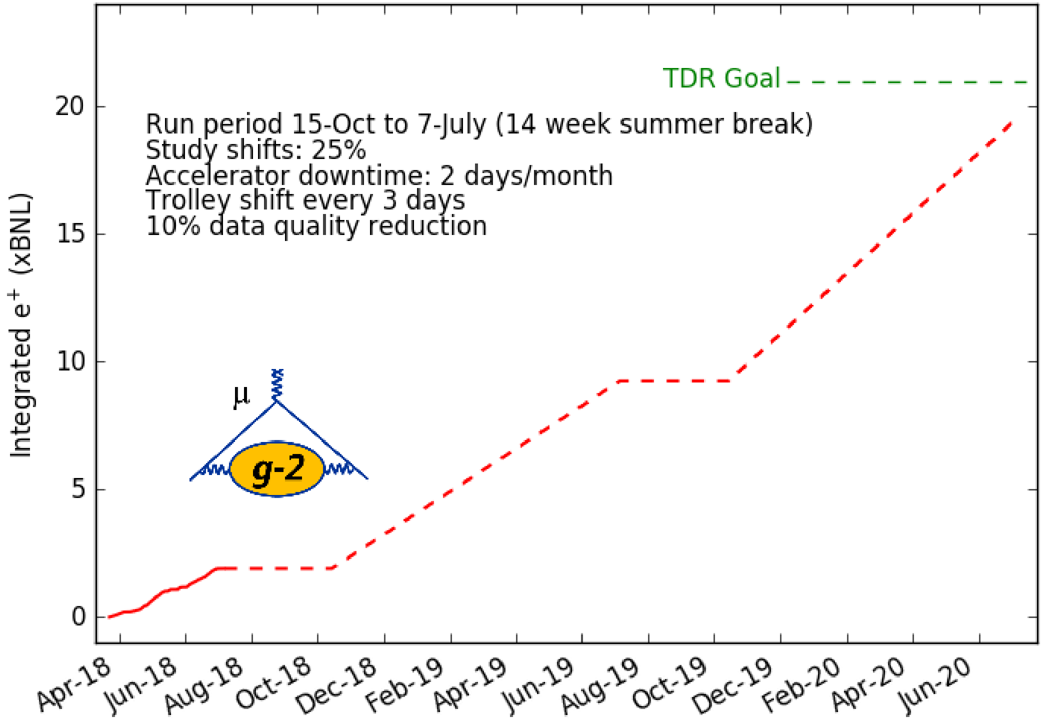


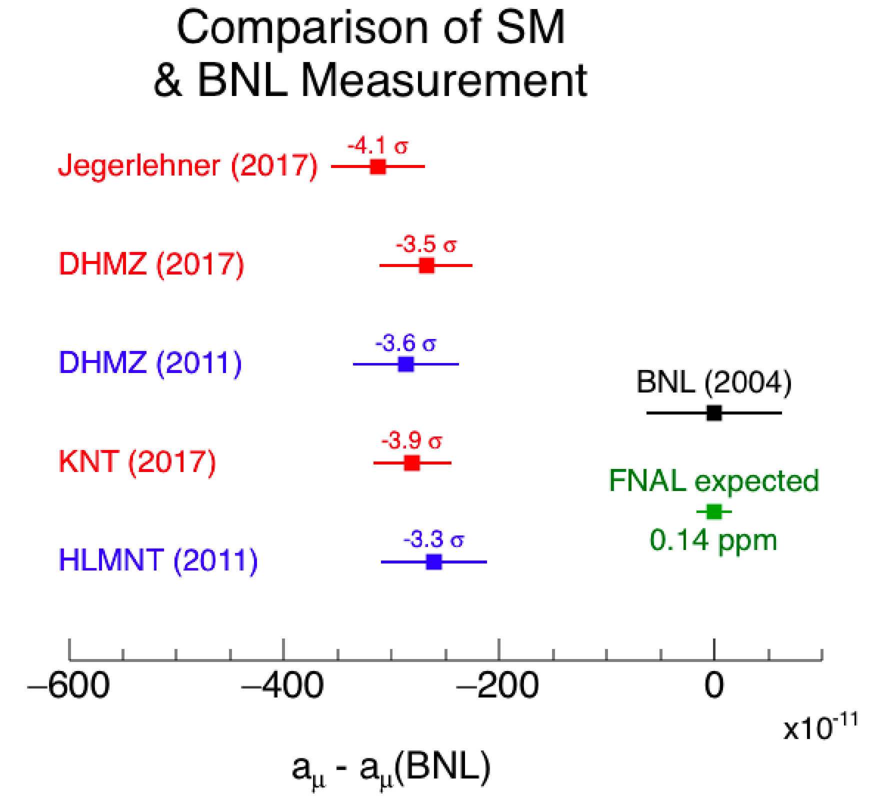
First data-taking run complete:

- 5 months running, > 2x Brookhaven stats (took 5 years!)
- publish in 2019

Runs in 2019/20 will accumulate ~20 x BNL

→ could push significance to ~5-10σ



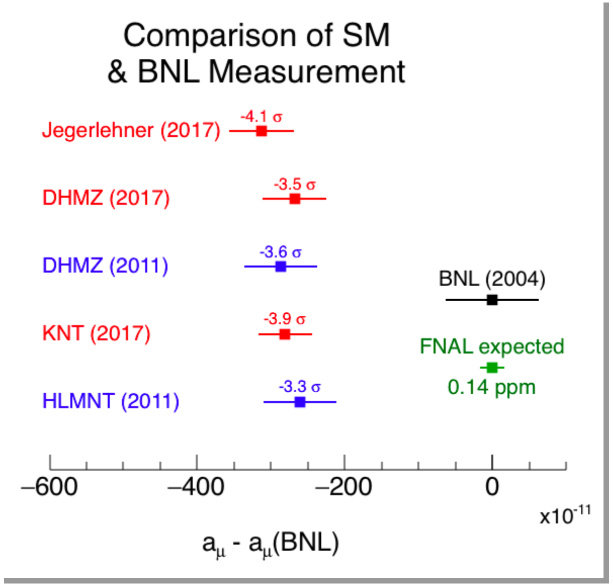


What will it mean..?

Planned g-2 experiment at J-PARC

- provide completely independent measurement

How about the theory?



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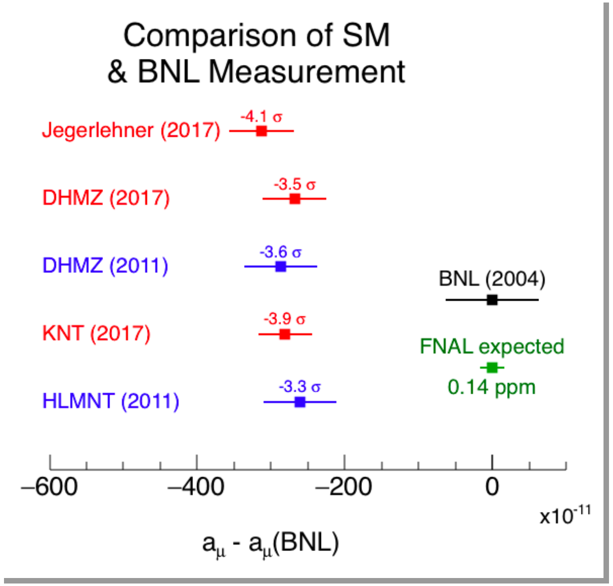
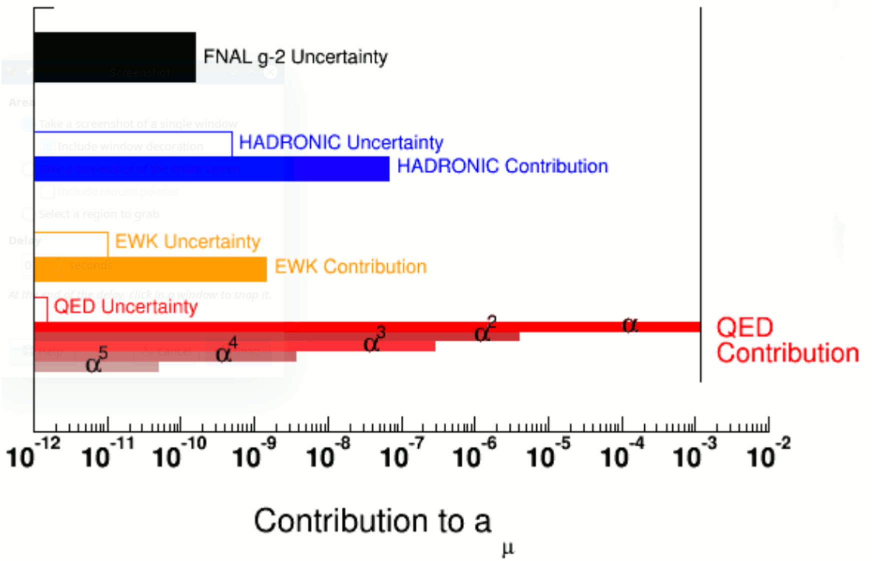
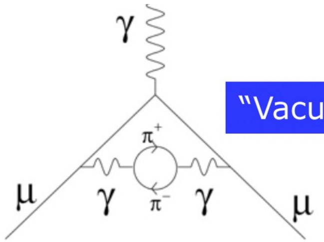
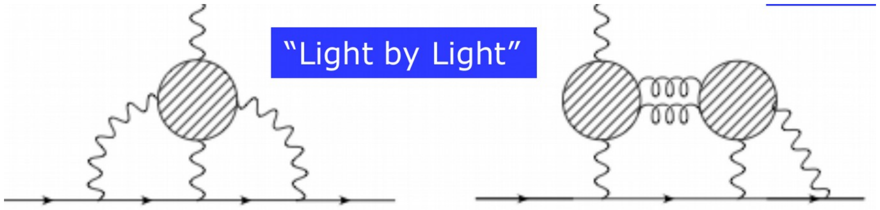






"Vacuum Polarisation"



g-2 theory

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

[T. Blum et al., arXiv:1311.2198]

→ need x2 improvement to keep up with experiment

Muon g-2 Theory Initiative underway
https://indico.fnal.gov/event/13795/

Lattice starting to contribute to LBL & HVP

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Lattice starting to contribute to LBL & HVP

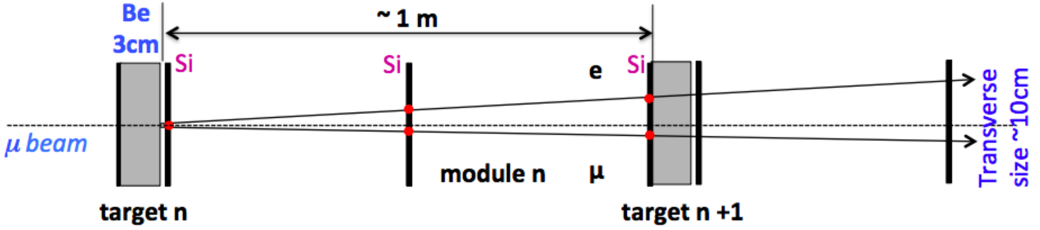
MUonE experiment @ CERN:

- space-like (free of resonances) e-mu scattering
  - basically a 150 GeV muon structure-function experiment
  - -> new, independent input to ***HVP*** calculations (used ee→hadrons to date)

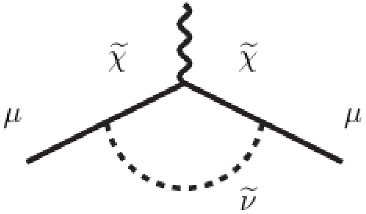
Schedule:

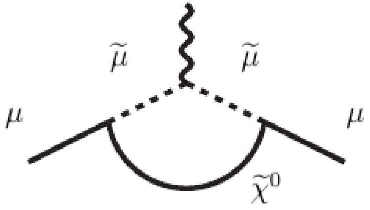
2018: 2 modules in CERN M2 Beam Line
2019: LOI to SPSC
2020/1: construction & installation
2021/2: start data taking (for 2 years)

Up to 20 Be targets + Si detectors
downstream calorimeters + muon PID



g-2: new physics?





$$a_\mu^{\mathrm{SUSY}} \simeq sgn(\mu)\, 130 \times 10^{-11}\, \tan\beta \left(\frac{100\,\mathrm{GeV}}{\Lambda_{\mathrm{SUSY}}}\right)^2$$

SUSY?

- *Needs $\mu>0$, 'light' SUSY-scale Λ and/or large tan β*
    - ...excluded by LHC for simplest (like CMSSM)
    - causes large χ^2 in simultaneous SUSY-fits with LHC data and g-2
- *However, SUSY does not have to be minimal*
    - could have large mass splittings (with lighter sleptons), be hadrophobic/leptophilic

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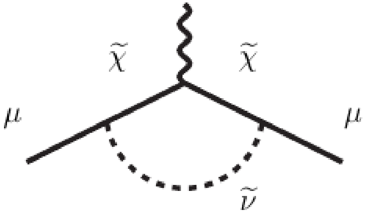

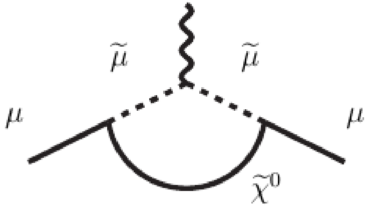

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Many other ideas out there, eg:

- 2 Higgs doublet model, Stockinger et al., JHEP 1701 (2017) 007
- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016)
    - single new scalar could solve g-2, B-factory anomalies and still satisfy limits from LEP and LHC...
- axion-like particle contributing like π^0 in HLBL Marciano et al, PRD 94 (2016) 115033
- inevitably, a dark photon eg Feng et al, PRL 117 (2016) 071803

If the discrepancy goes away, will set tight limits on these new physics scenarios

See Thomas Teubner's talk at the UK HEP Forum, Nov 2018

It may not be the clear sign of new physics we wanted...
...but it may be the sign we get!

…so..?

It may not be the clear sign of new physics we wanted…
…but it may be the sign we get!

To identify the new physics model, need to determine
- couplings
- quantum numbers
- mass

Continued non-observation at the LHC will rule out some scenarios
…but need other observations to pin this down.

→ EDMs
→ cLFV experiments

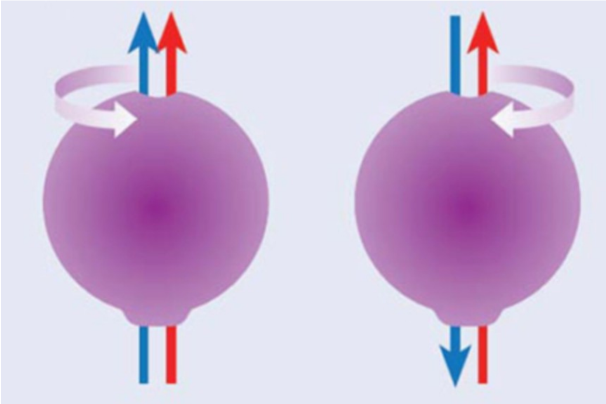
Further clues

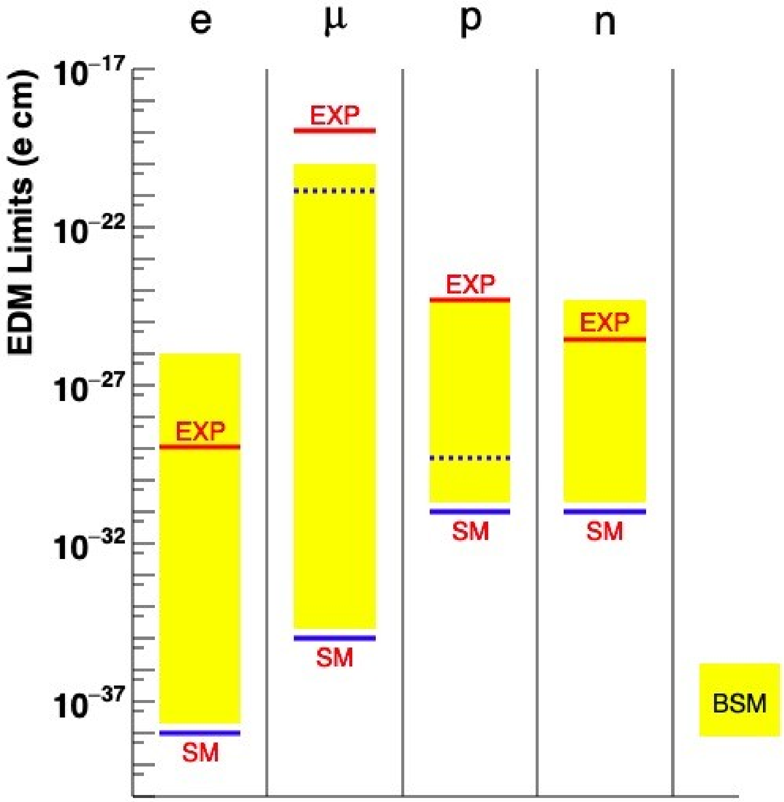
Fundamental particles can also have an EDM

→ zero in SM, slightly non-zero due to loops

$$\vec{d} = \eta \frac{Qe}{2mc} \vec{s} \qquad \vec{\mu} = g \frac{e}{2mc} \vec{s}$$

Existence of EDM → additional source of CP violation





A non-zero muon EDM would lead to out-of-plane precession

- can be measured using trackers

→ 100x improvement in limit from Fermilab g-2

- an upgrade would push limit further…

Proton EDM

The proton EDM can be measured using similar techniques to g-2

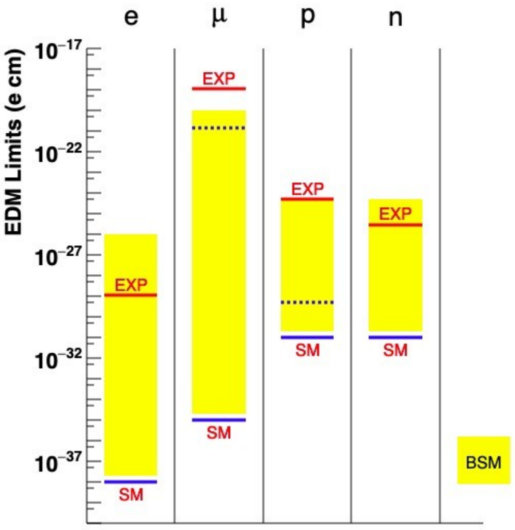
- but use all electric storage ring

$$\omega_a = \frac{e}{mc}\left[\left(a_\mu - \frac{1}{\gamma^2+1}\right)\vec{\beta}\times\vec{E}\right]$$

cancels completely using p = 0.7 GeV

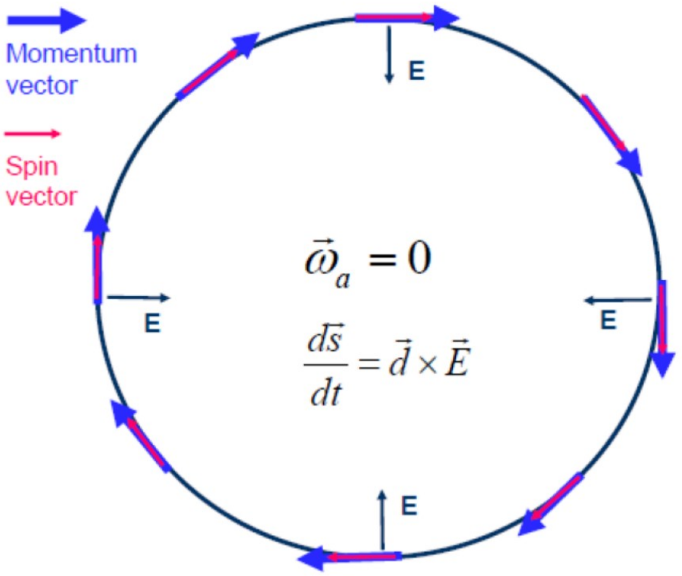
$$\omega_\eta = -\eta\frac{Qe}{2m}\frac{\vec{E}}{c}$$

leaves precession due to EDM



Part "Physics Beyond Colliders" programme
→ expect 5 orders of magnitude in limit.

Development work ongoing at Juelich.



Many BSM models include charged lepton flavour violation

- leptoquarks, compositeness, Higgs doublets, heavy neutrinos…

…or invoke it for leptogenesis of matter-antimatter asymmetry

Heavy mediator → low rate process

- *a la* beta decay with the massive W boson

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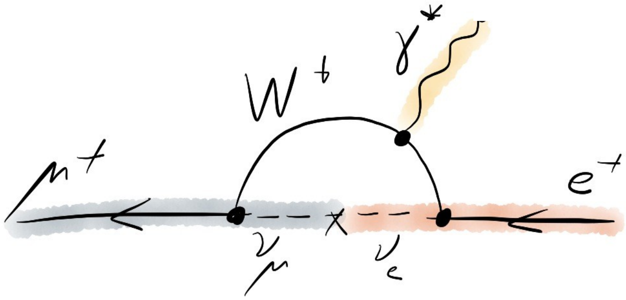
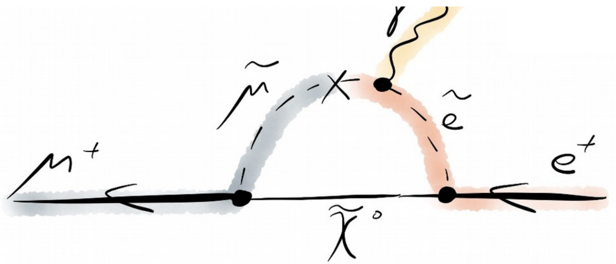




Neutrino oscillations violate lepton flavour conservation

→ techincally possible in charged lepton sector

…but suppressed by ~10^{-50}

Put one of these models in a loop, rate may increase…

There is no "floor"!

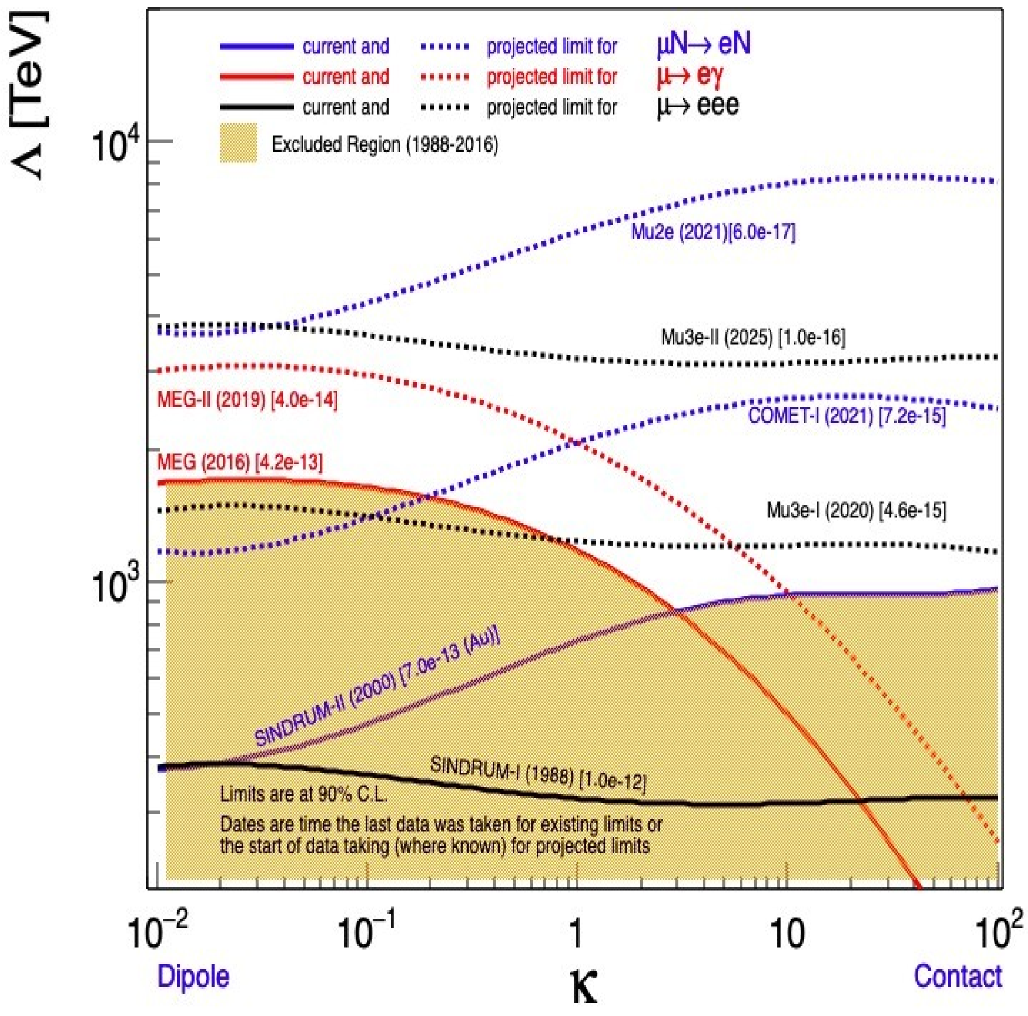
- current limits ~10^{-12}
- sensitivity purely experimental limitation

→ any observation of cLFV is new physics!

Effective Lagrangian
de Gouvea & Vogel, arXiv 1303.4097

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$

$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c..$$



Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

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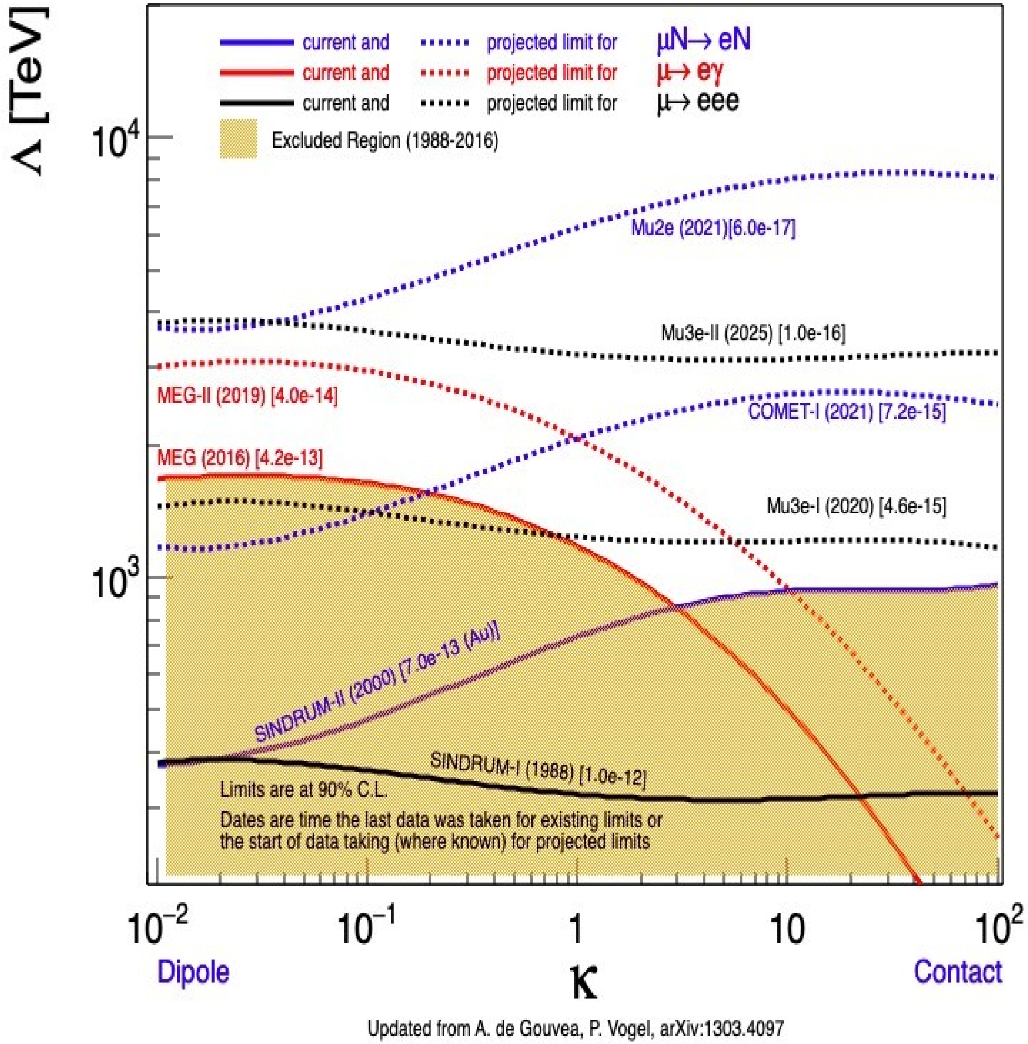
Next generation experiments can reach BSM physics at masses of 10,000 TeV
...the LHC direct reach is ~10 TeV

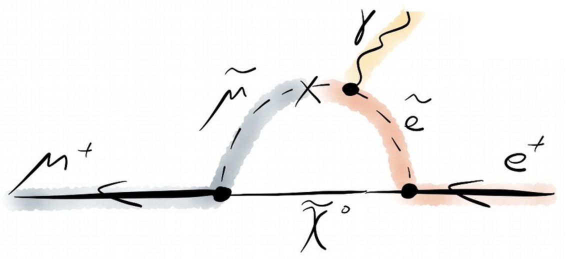
Can help resolve model dependency in g-2:

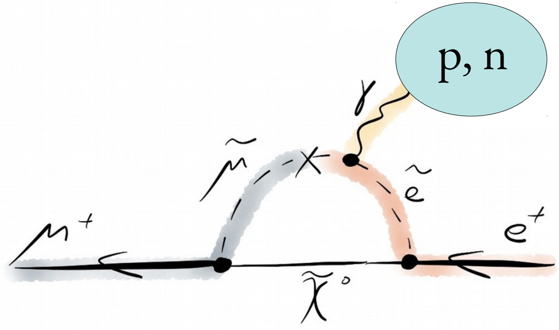
$$\text{Rate (CLFV)} \sim g^2 \times \theta_{e\mu}^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$

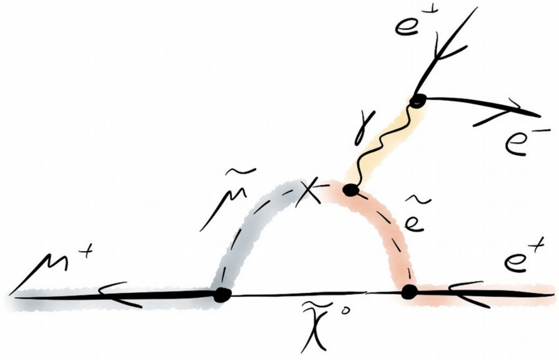
$$a_\mu \sim g^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$



cLFV







MEG-II @ PSI:
- physics in 2019
- aiming for x10 on limit
  → 10^{-14} with 3 years running

11 institutes, 75 collaborators
- *no UK involvement*

Mu2e @ FNAL
- starting 2022 (after g-2)
- aiming for $x10^4$ on limit
  → 10^{-17} with ~4/5 years running

  COMET @ J-PARC similar

40 institutes, 242 collaborators
- Liverpool, Manchester, UCL

Mu3e @ PSI
- phase 1 (2020) & 2 (2025)
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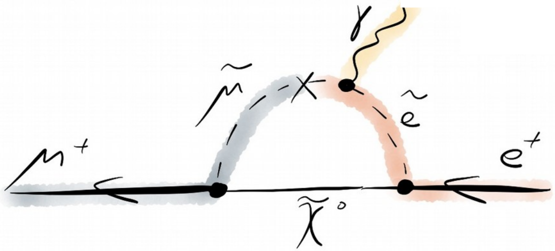

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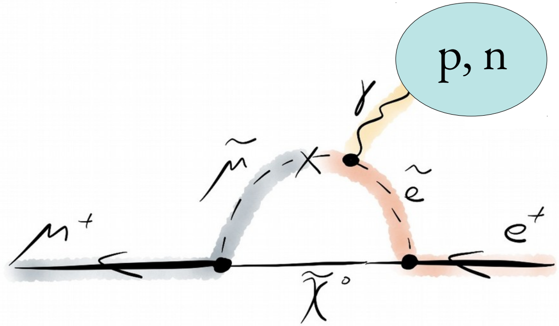

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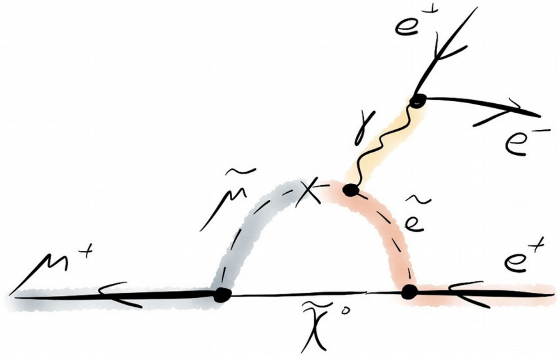

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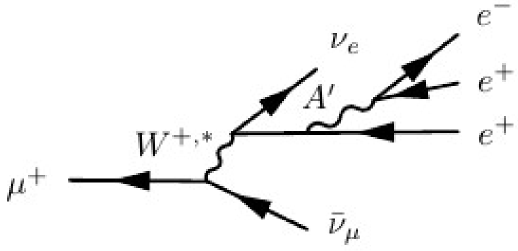
The coming 5 years sees a step-change in sensitivity to cLFV!

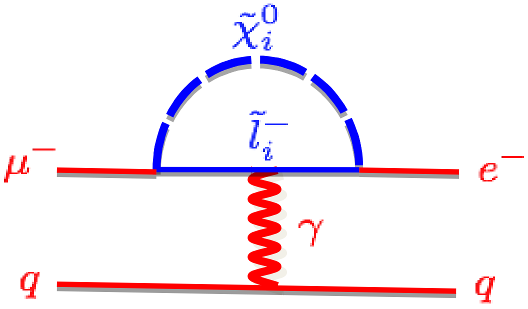
Complementary experiments:

- Mu2e involves quark and lepton couplings
- Mu3e purely leptonic, can also search for dark photons etc



Searching for one cLFV interaction in 10^{16} muon decays
...looking for one specific grain of sand...

$\mu N \rightarrow eN$

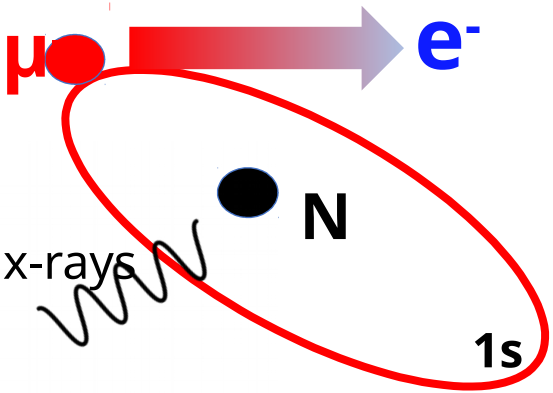


Stop muons on an Al target

- x-ray emission from capture → normalisation

Signal of neutrino-less conversion:

mono-energetic electron



$$E_e = m_\mu - E_{bind} - E_{recoil}$$
$$= 105.67 - 0.47 - 0.22\ MeV$$
$$= \mathbf{104.98\ MeV}$$

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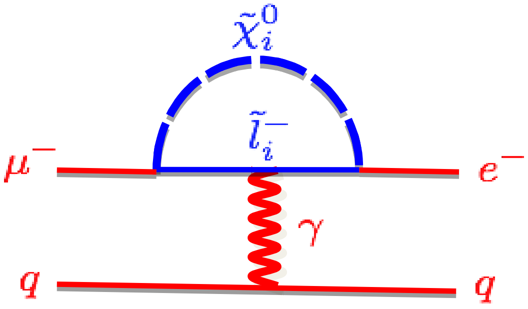

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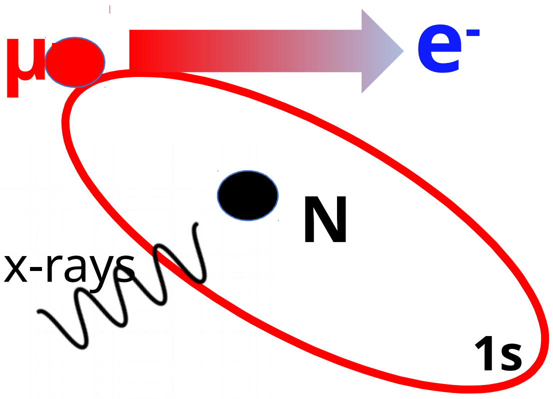

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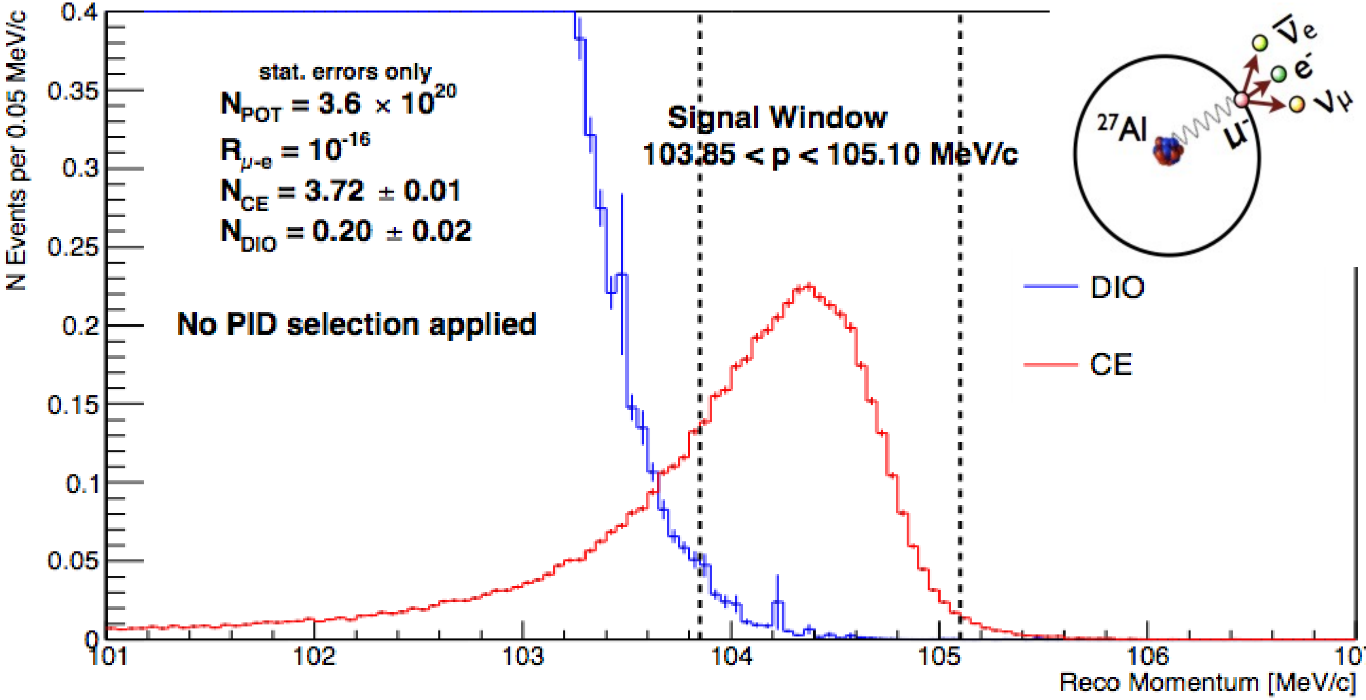
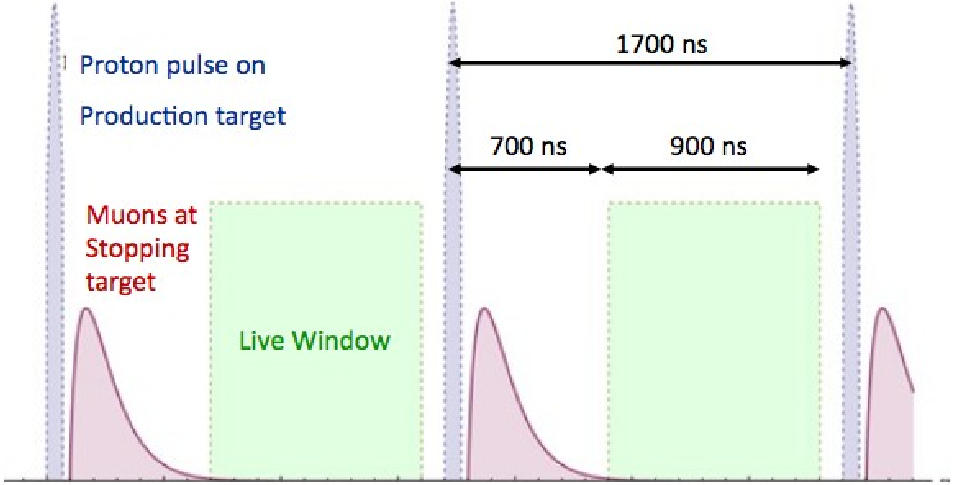
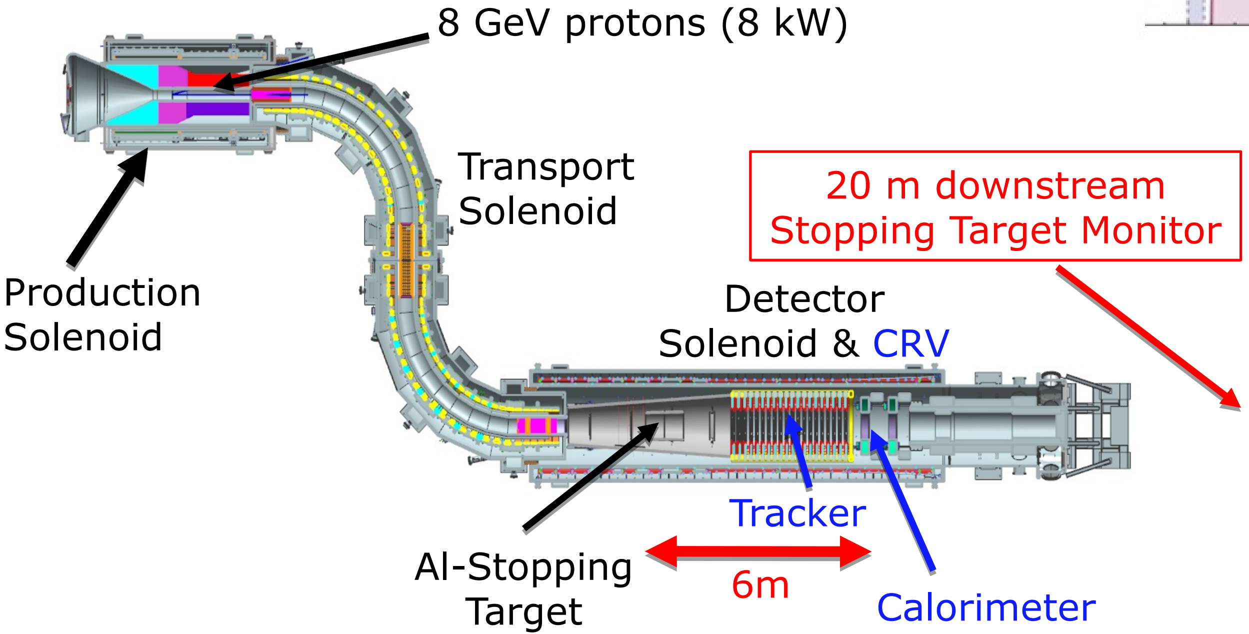


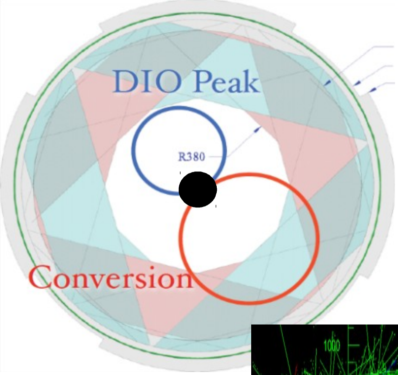
Prompt backgrounds
(radiative nuclear capture, d.i.f., pions, protons).
- Curved solenoid transport channel
- Pulsed beam strong extinction factor (<10^{-9})

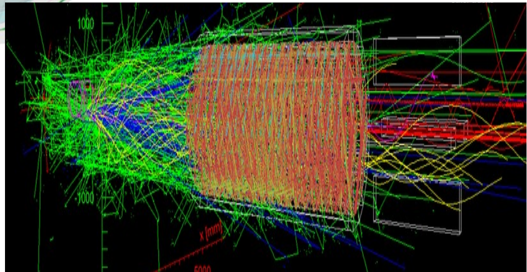
Cosmics: cosmic veto detector

Muon decay in orbit ($\mu N \rightarrow e\nu\nu N$)
- precise momentum resolution



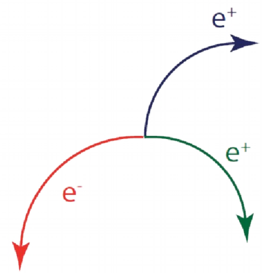


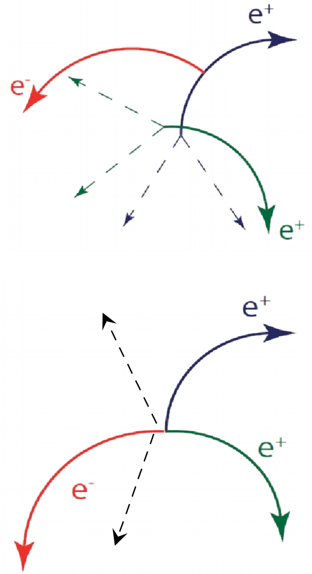


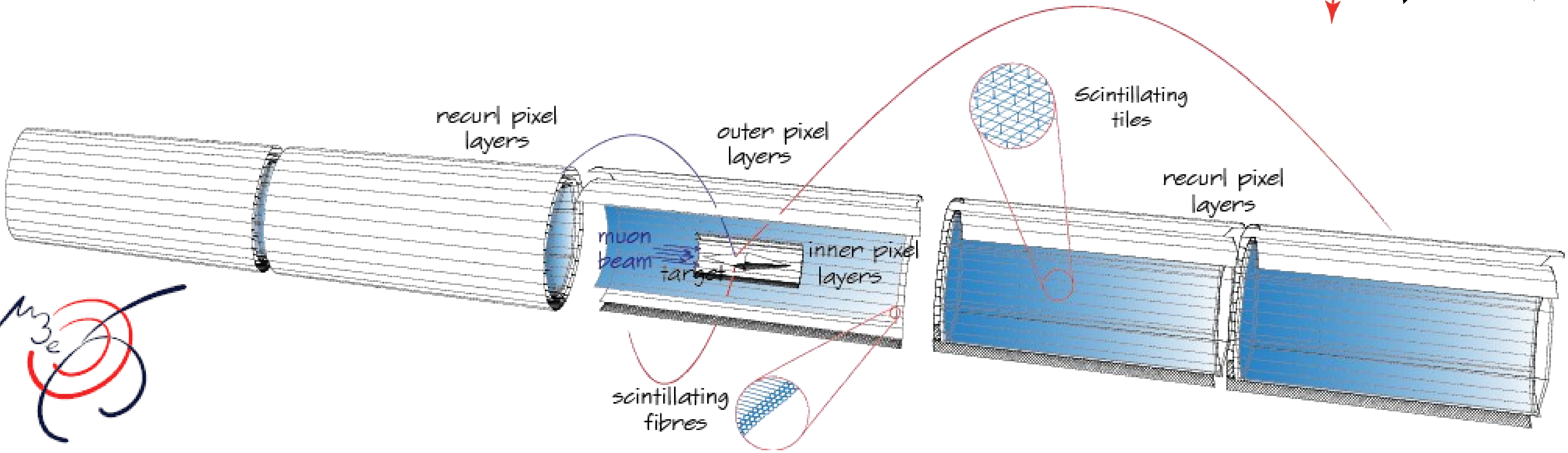


Mu3e @ PSI

DC beam of up to 10^{10} μ/s on target, triggerless DAQ.







Mu3e @ PSI

DC beam of up to 10^{10} μ/s on target, triggerless DAQ.

Combinatorics, Michel decay + photon conversion:

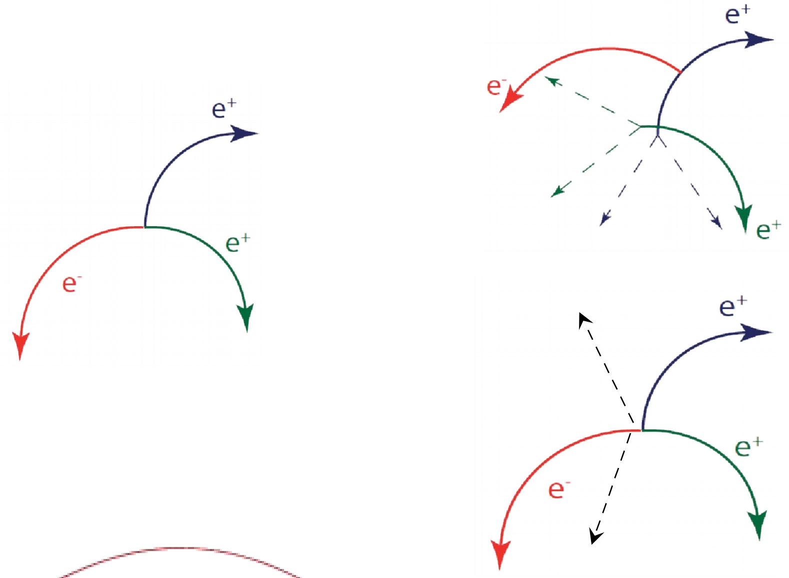
- Scintillating fibres (1ns) and tiles (100ps)
- vertex resolution 200 μm

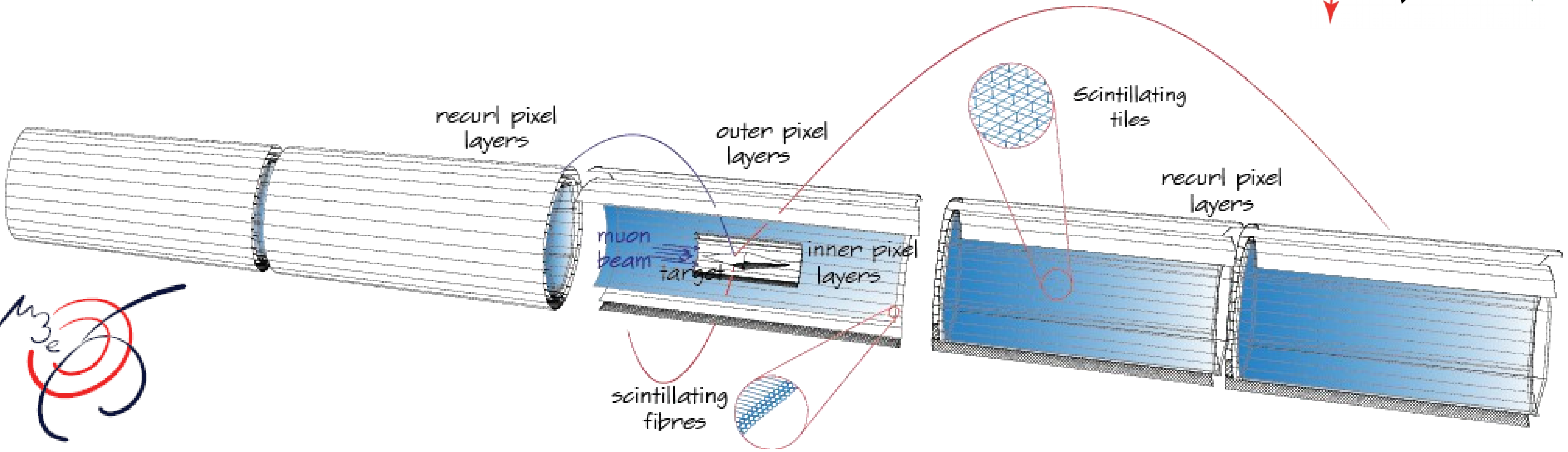
Michel decay + internal conversion

- momentum resolution 0.5 MeV

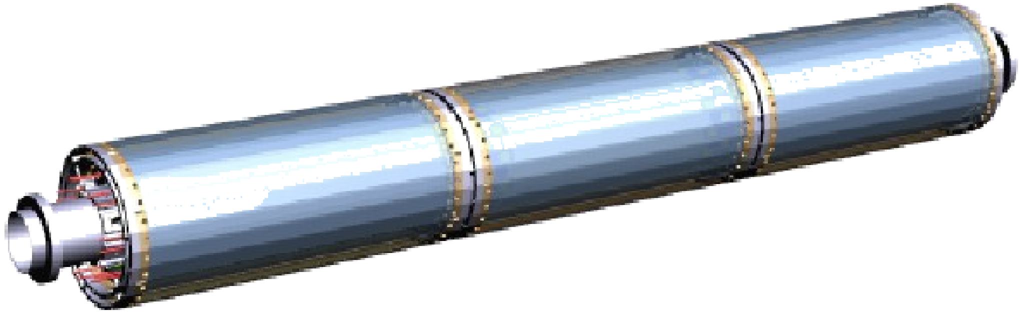
Recurling tracks in 1T field,

scattering dominated regime (E<53 MeV)





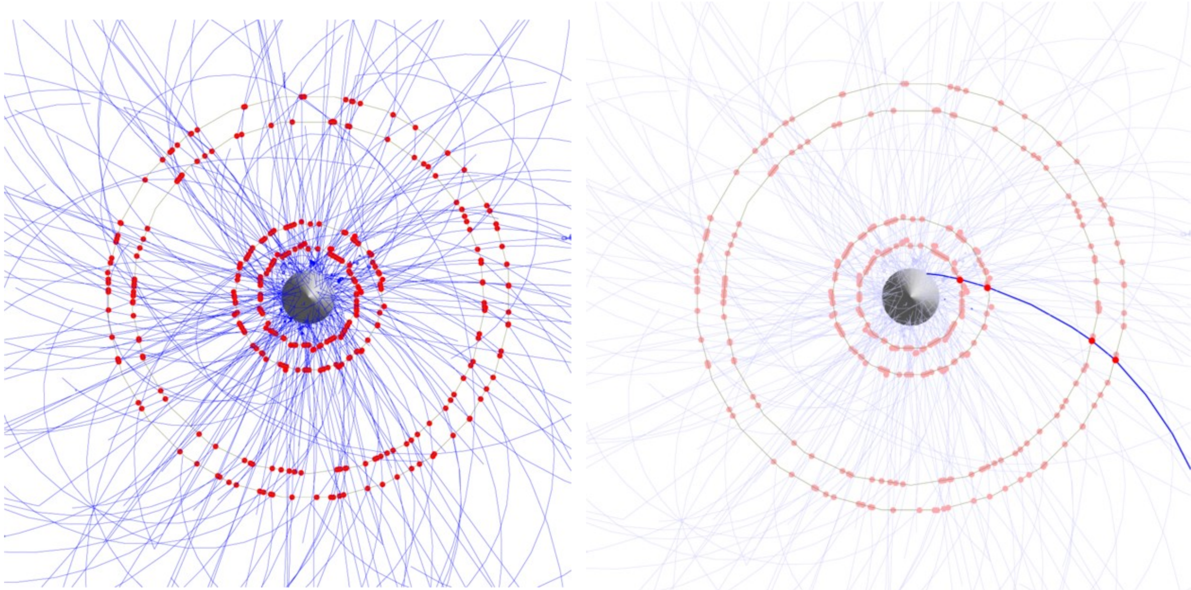
1.1 m² pixel tracker
- first HV-CMOS tracker in particle physics!



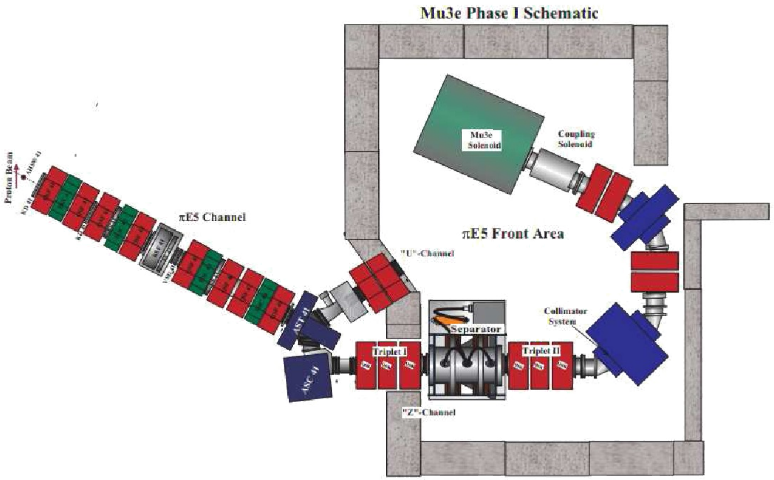
Material budget critical:
- 50 µm HV-MAPS
- 25 µm support
- 25 µm flex-print
- 12 µm aluminium traces
- 10 µm adhesive

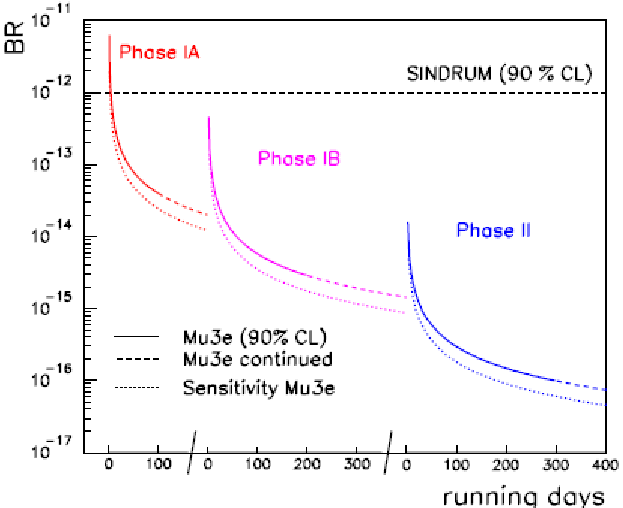
→ 0.1% X_0 per tracking layer

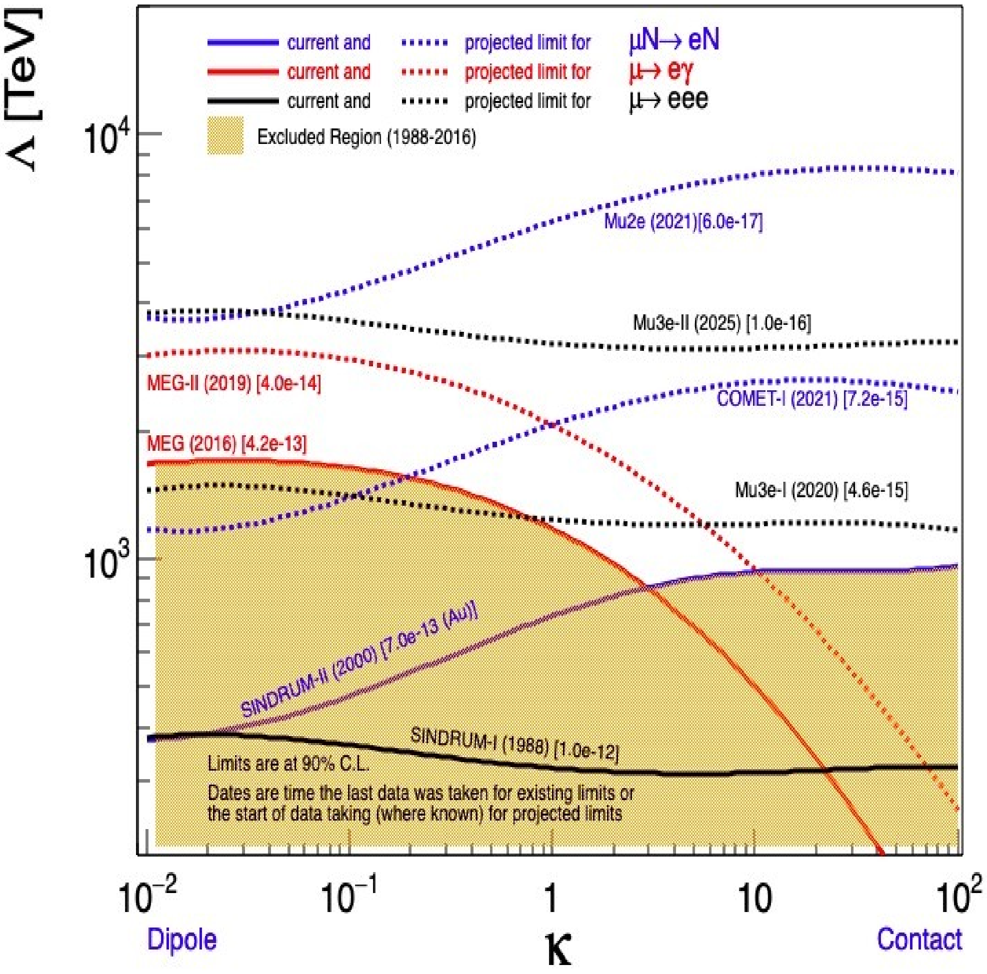
Timing detectors reduce combinatorics
- tracking on GPUs to keep up with muon rate



Currently under construction, first data 2020







Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

Conclusion

New physics must be out there… but where?

→ reach further through loops, with high precision measurements

Muon physics complements and extends major research themes:

- BSM searches, CPV in the lepton sector and leptogenesis of matter-antimatter asymmetry

g-2:

- first publication in 2019, running for 2 more years, 20x BNL stats.
- options for extended / upgraded running, and follow-on measurements incl EDM

cLFV:

- Mu2e and Mu3e aiming for 10^4 improvement in sensitivity over current limits
    - probe mass scales up to ~10^4 TeV
- complementary physics, and complementary to g-2

Going to be an exciting few years!

We may need new ideas and new experiments to really identify new physics

- this is a great time to be joining the field!