New Physics with Muons

g-2, Mu3e and more

Gavin Hesketh
University of Birmingham
30/1/19

...or: where is the New Physics?

New physics must exist:
- dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino masses, strong CP, gravity....

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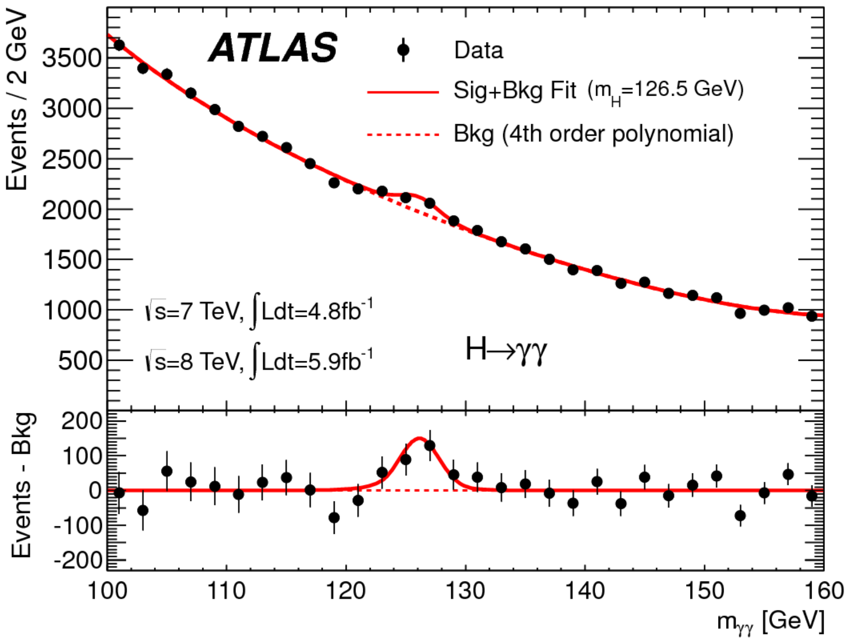

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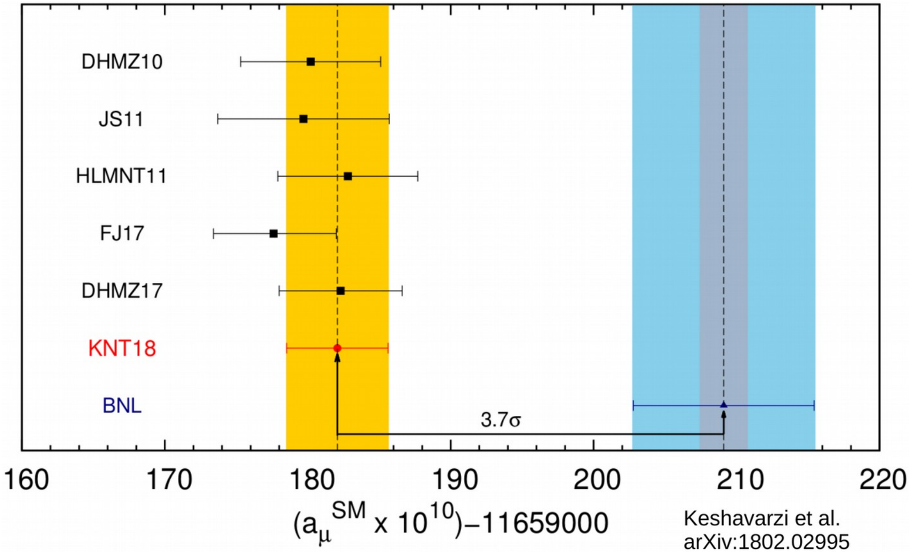
There have been some surprises from the lepton sector:
- neutrino masses
- proton radius puzzle
- some ~3σ effects from semi-leptonic hadron decays, R(K), R(D)
- 3.7σ effect in muon g-2



Keshavarzi et al.
arXiv:1802.02995

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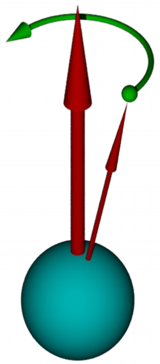
If there is some new physics in a loop, muons are a good tool:
- m_μ^2/m_e^2 ~ 42000: muons much more sensitive to new physics
- stable enough to capture and store

Today:
- Fermilab Muon g-2
- Mu3e

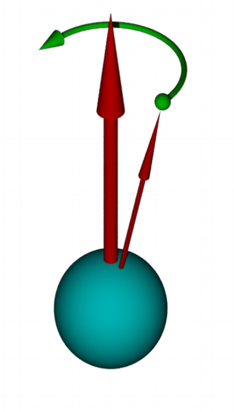
  … + a few other experiments



Spin Precession:

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

$$\omega_s = \frac{gqB}{2m}$$



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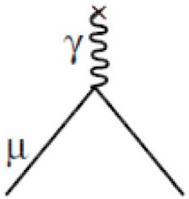
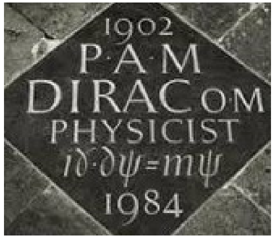
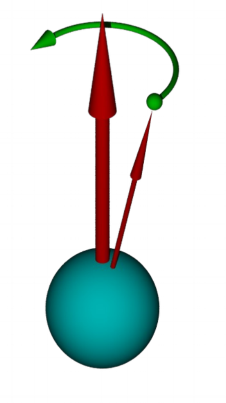
The magnetic moment of charged leptons:

- exactly 2 at tree level (Dirac)







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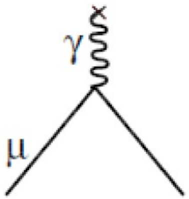
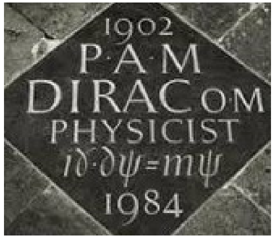
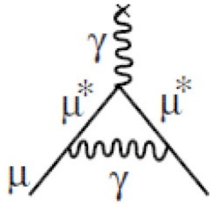
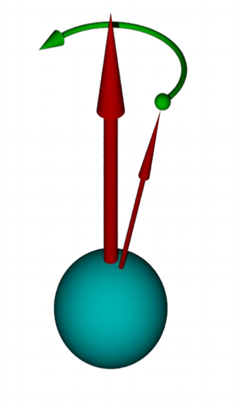




- first loop calculated by Schwinger in 1948

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





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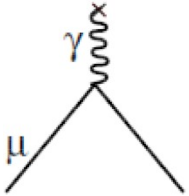

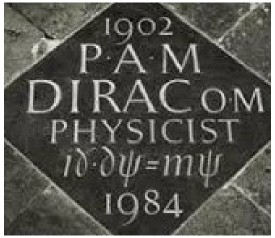

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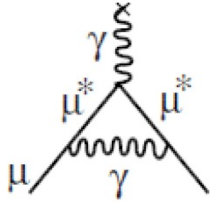
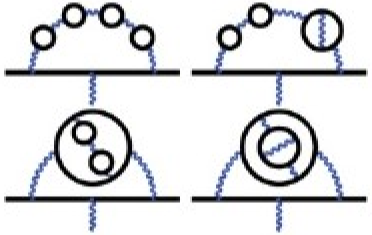


- state of the art: ***O(5) in QED***
  12,672 diagrams!
  arXiv:1712.06060



For electrons, a completely determined by QED

→ only depends on α

Recent measurement of α

$1/\alpha = 137.035999046(27)$

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

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

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Compared to measured: $a_e = 0.00115965218073(28)$

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

→ ***2.5σ difference***

"Follow that ambulance!"

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For muons:

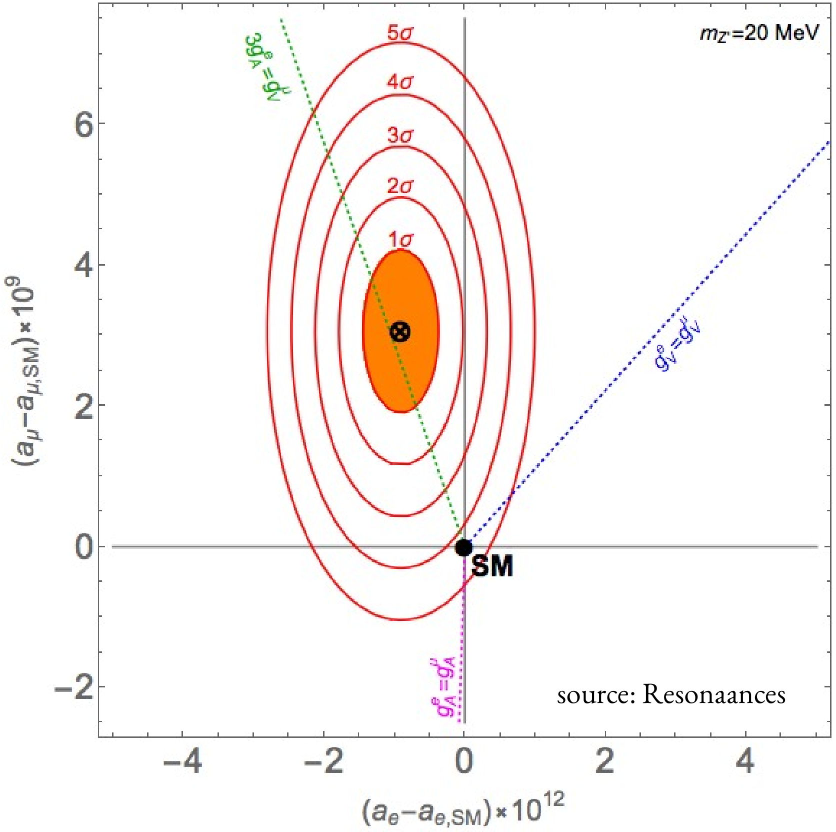
- larger muon mass → QCD and EWK loops contribute
- a long-standing disagreement with experiment:

a_μ = 0.00116592089(63) (measured)

a_μ ~ 0.00116591821(36) (prediction)

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

→ 3.7σ difference



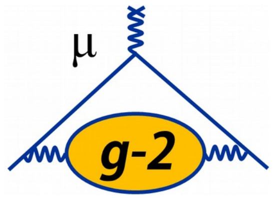
source: Resonaances

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

...a model with a large muon EDM..?

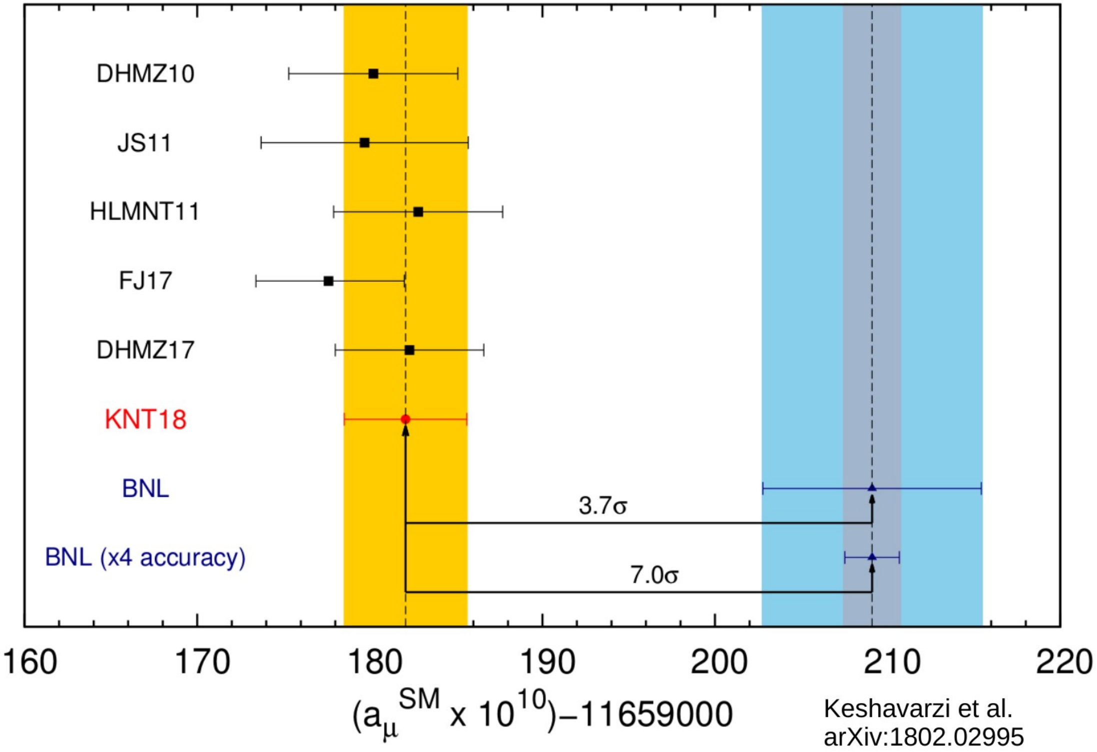
arXiv:1807.11484

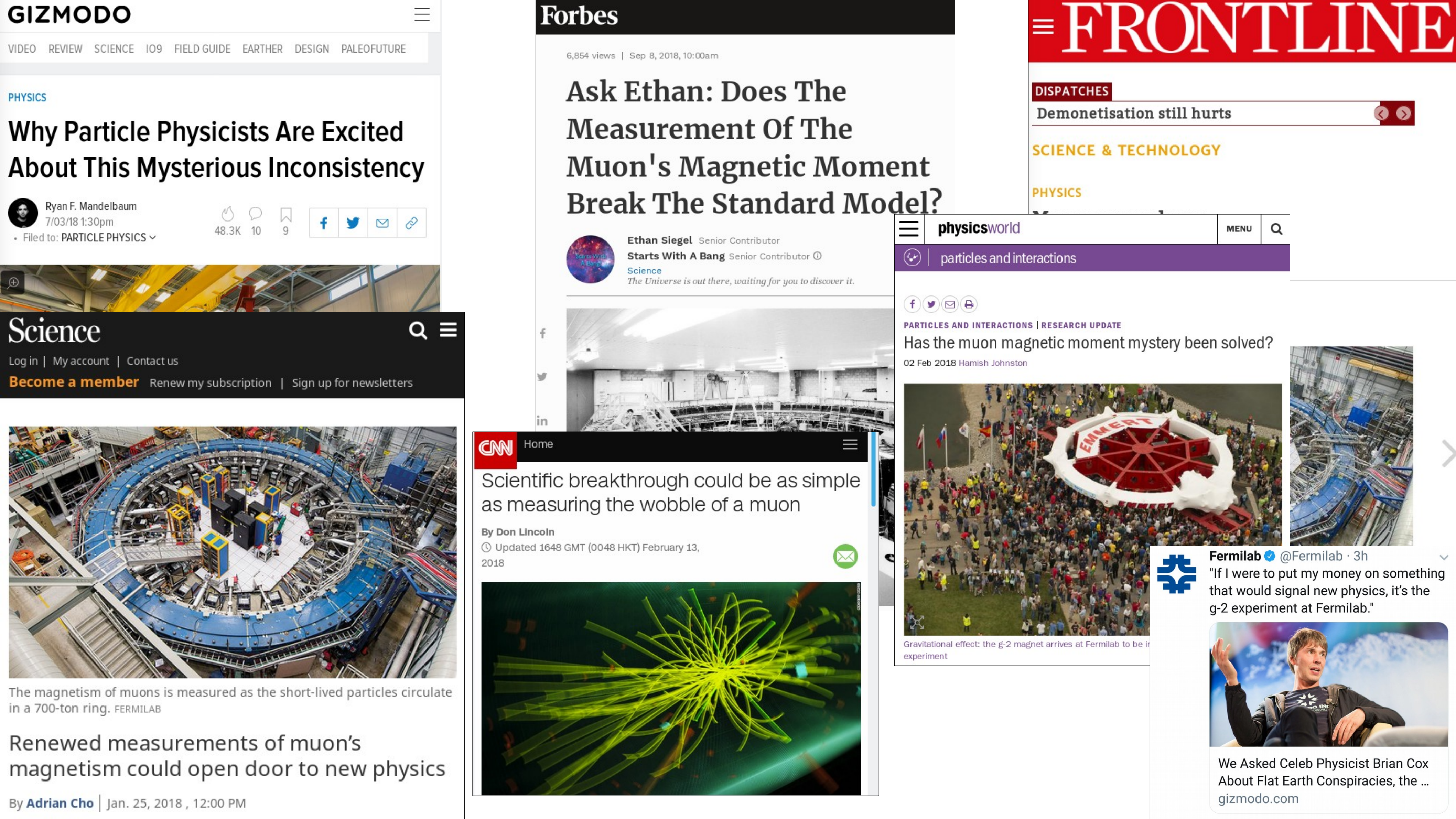
Fermilab Muon g-2 experiment (E989)
- factor 4 improvement over BNL (E821) result
  - precision of 140 ppb



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

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

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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.
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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
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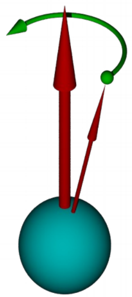
The magnetism of muons is measured as the short-lived particles circulate in a 700-ton ring. FERMILAB
Renewed measurements of muon's magnetism could open door to new physics
By Adrian Cho | Jan. 25, 2018 , 12:00 PM
CNN Home
Scientific breakthrough could be as simple as measuring the wobble of a muon
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

Measuring Muon g-2

Put muons in a magnetic field, measure precession frequency

$$\omega_s = \frac{gqB}{2m} = \frac{(2 + 2a_\mu)}{2}\frac{qB}{m}$$



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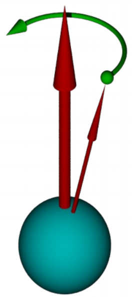

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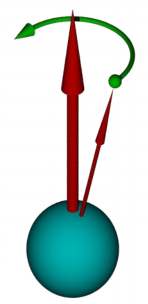
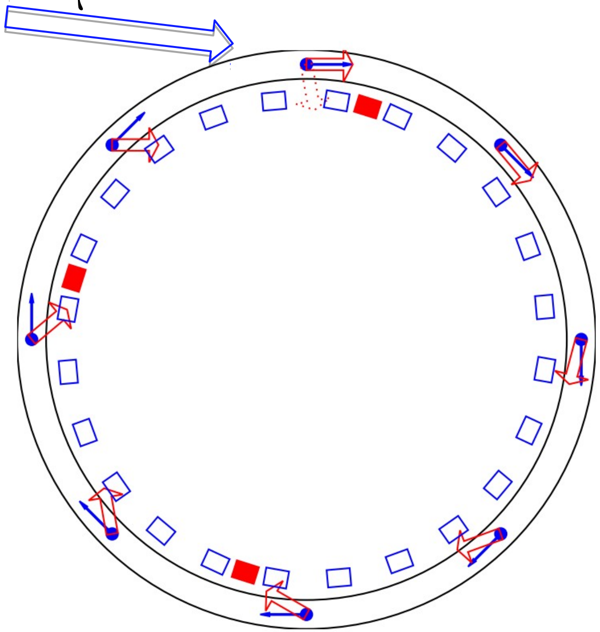


$$\boxed{\omega_s = \frac{gqB}{2\,m} = (1 + a_\mu)\frac{qB}{m}}$$

Muons decay…

→ Use a circular magnetic storage ring (7.1 m radius)



Cyclotron frequency:

$$\omega_c = \frac{qB}{m} \quad \Rightarrow \quad \boxed{\omega_a = \omega_s - \omega_c = a_\mu \frac{qB}{m}}$$

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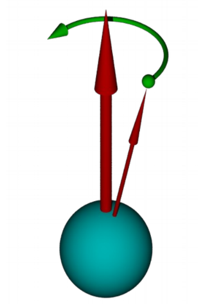

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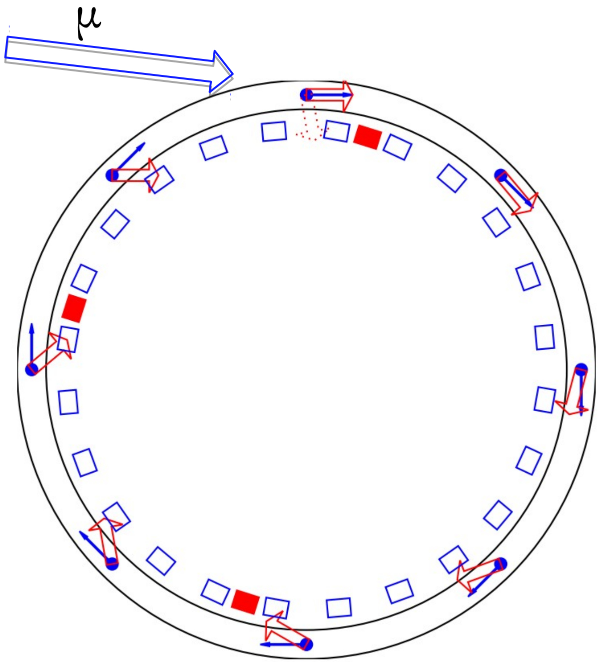

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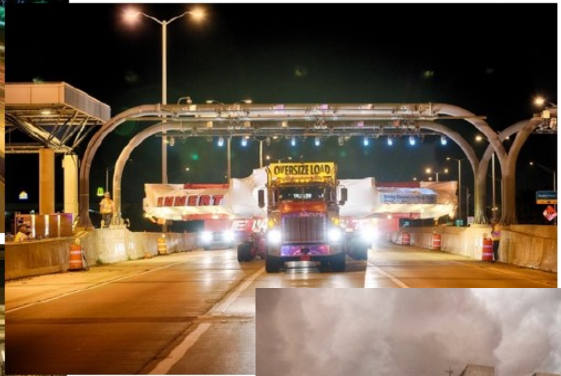
Use "magic momentum" 3.09 GeV

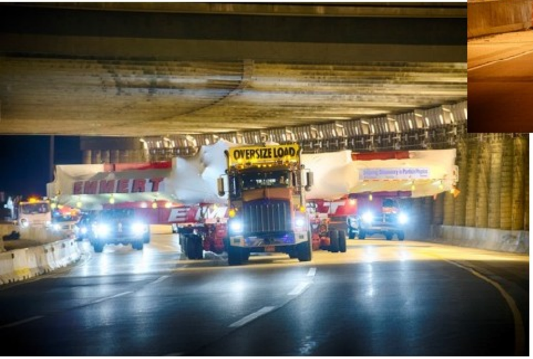
$$\omega_a = -\frac{q}{m}\left[a_\mu B - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\beta \times E}{c}}\right]$$

A long journey

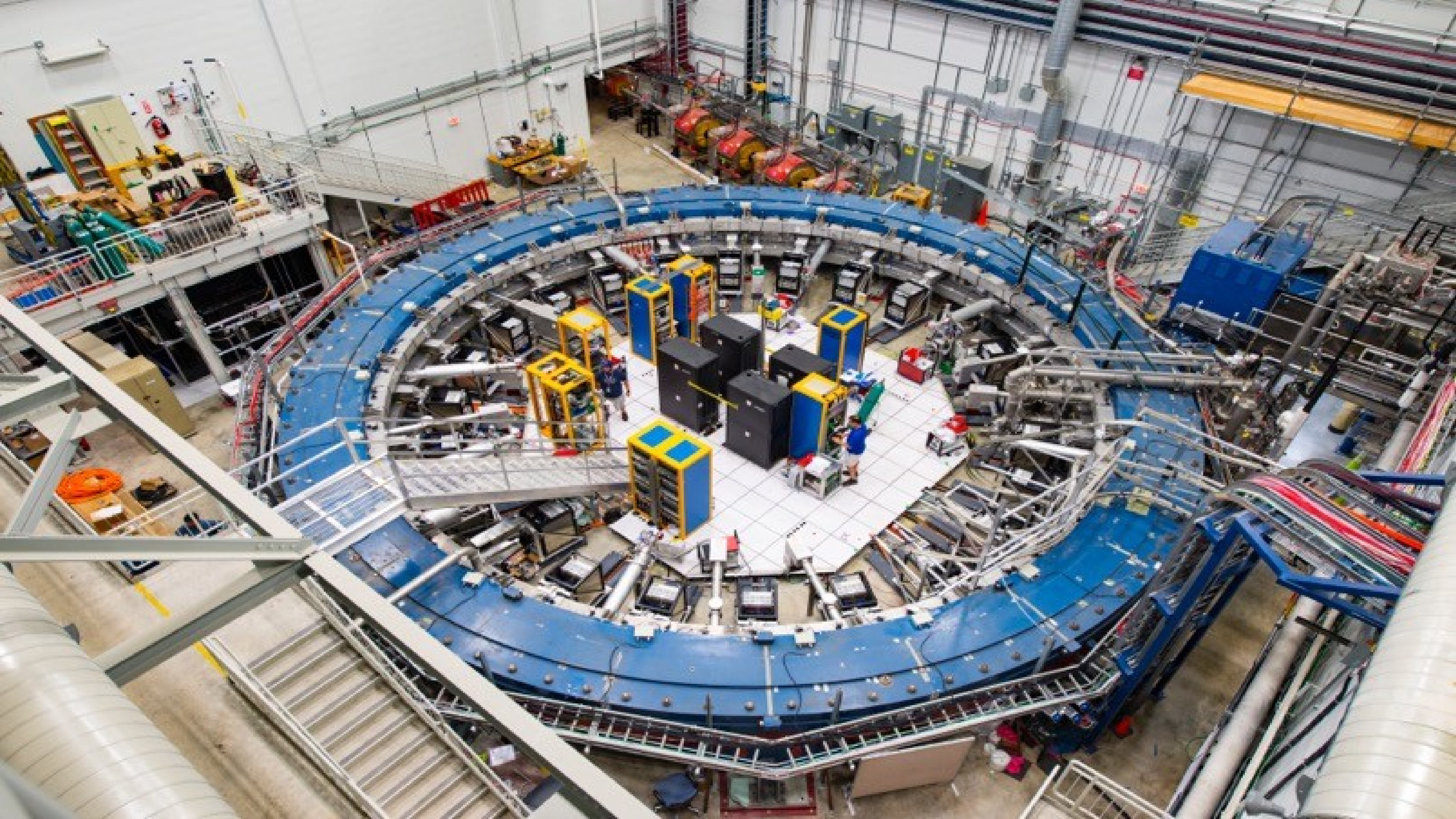
BNL magnet moved to Fermilab in 2013

- new trackers & calorimeters
- higher intensity, cleaner beam → more stats

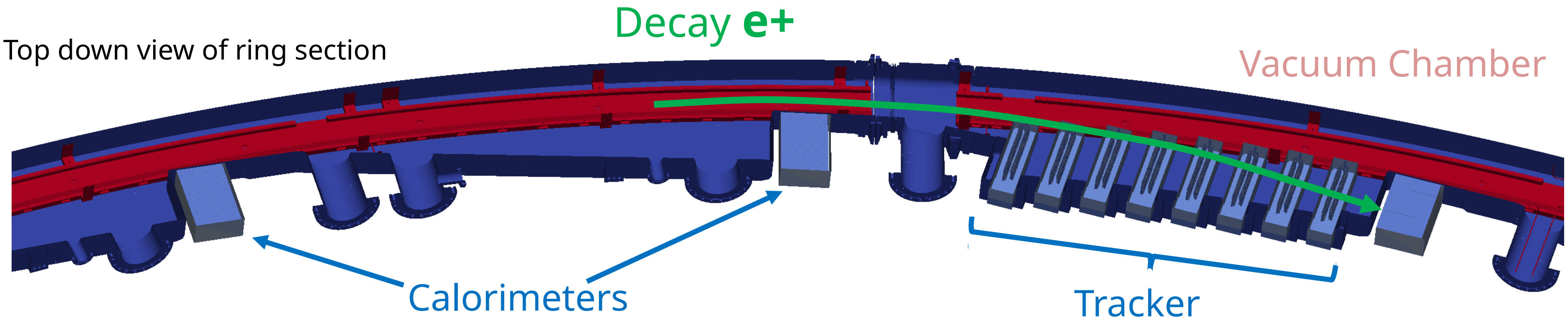




22 June → 26 July 2013



Wiggle plots



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

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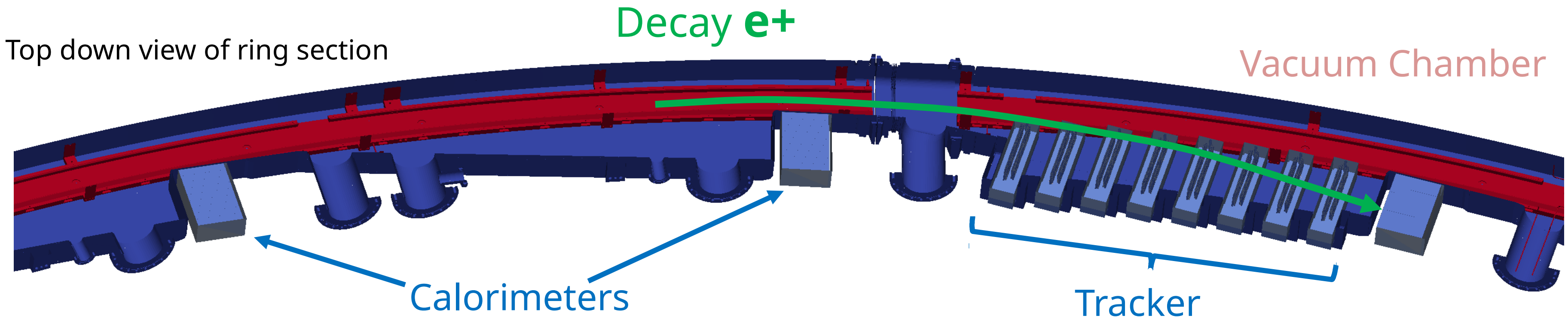

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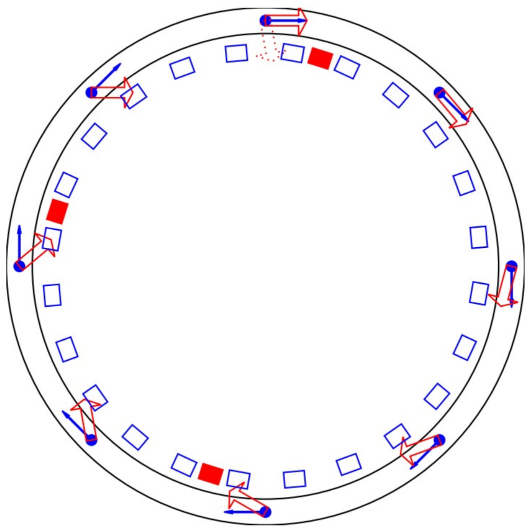

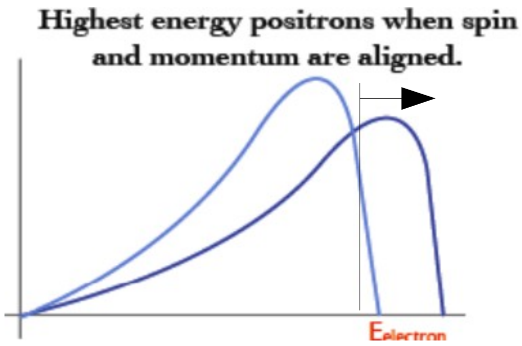

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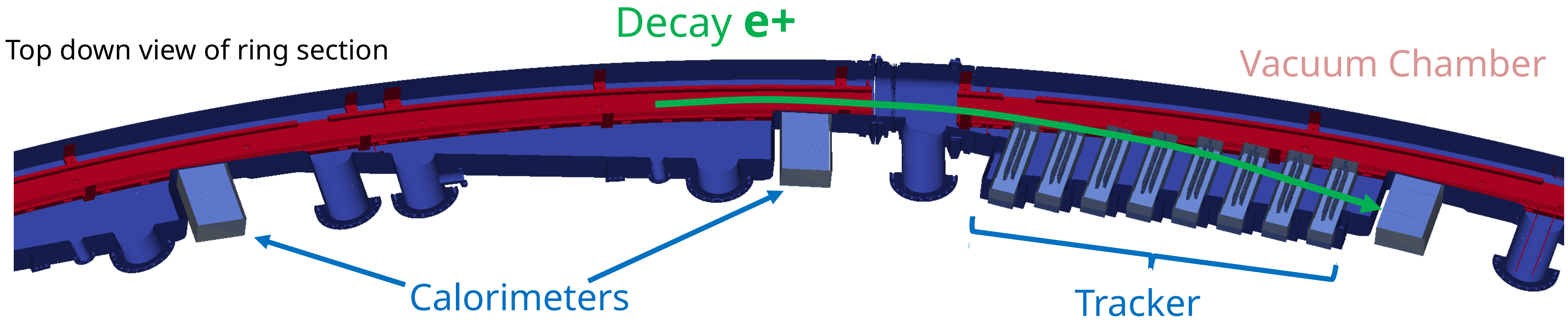

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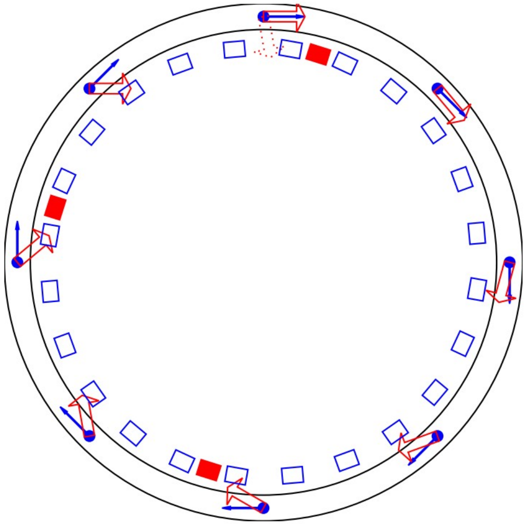
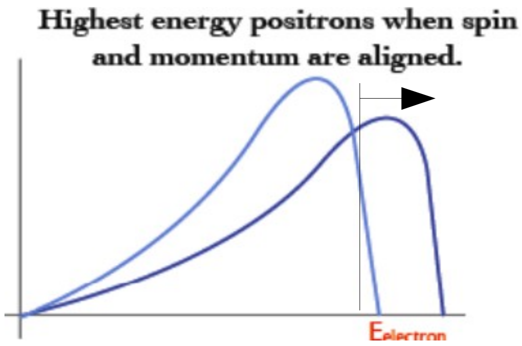
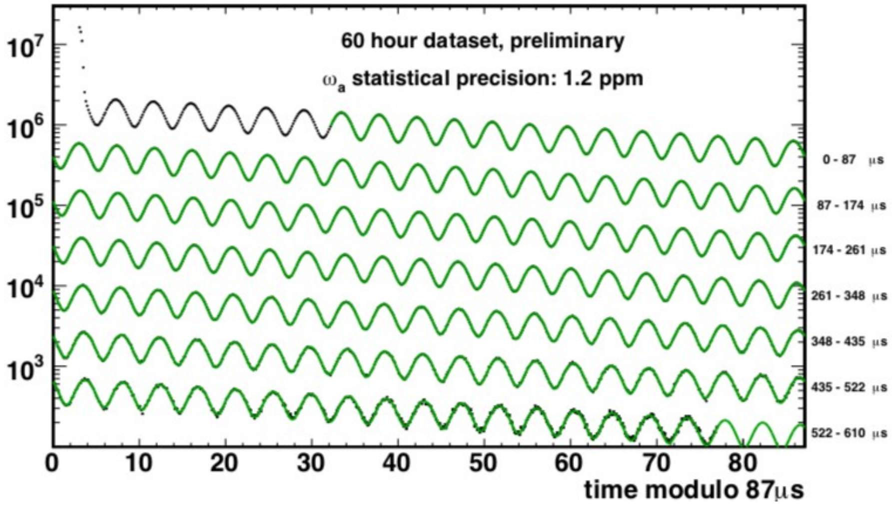




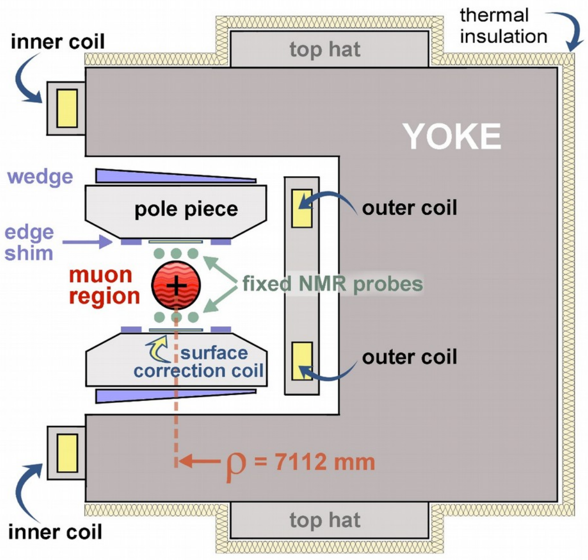


B-field

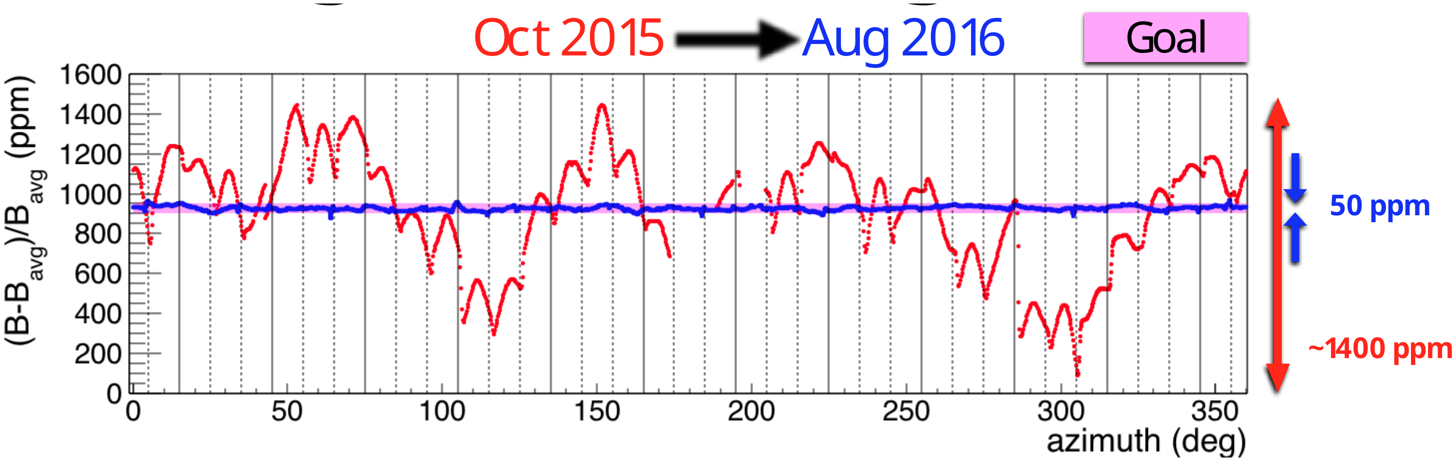
$$\omega_a = \frac{a\,qB}{m}$$

Need highly uniform B-field around the storage ring

- magnetic field was shimmed to high precision
- monitored using NMR probes
  - plunge probes and trolley runs

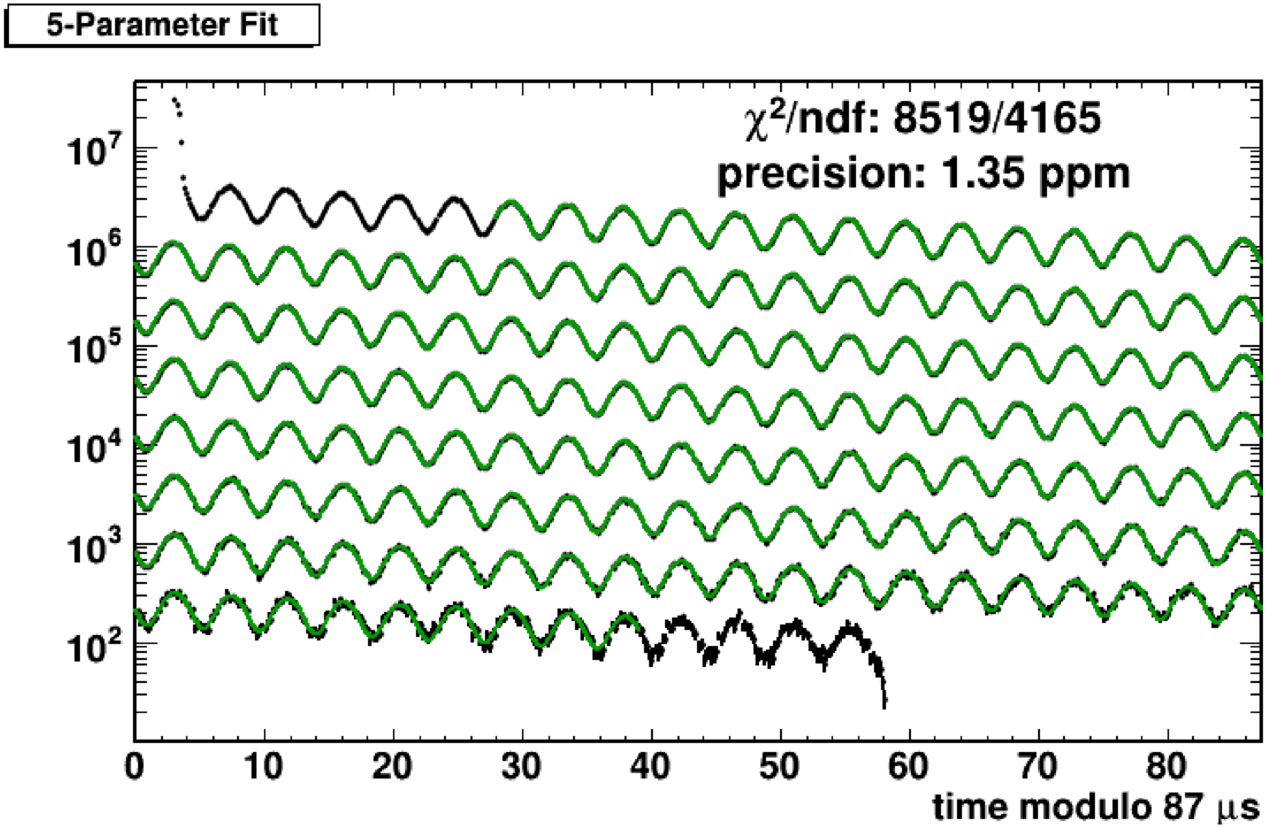


g-2 Magnet in Cross Section



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

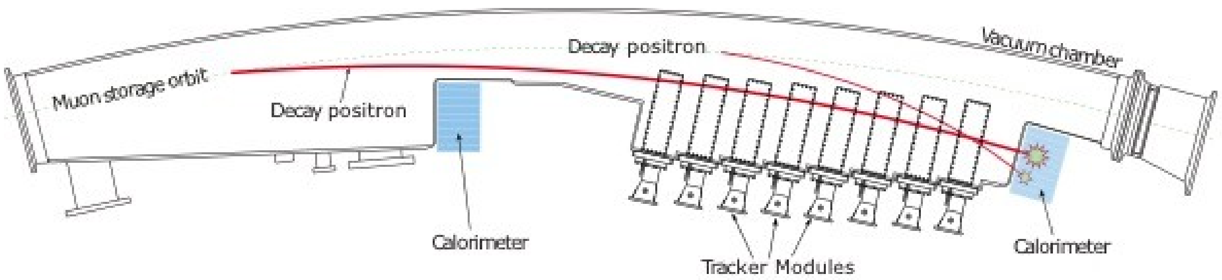
Simplest fit: 5 parameters
- exponential decay (2 parameters)
- with a superimposed sine wave (3 parameters)

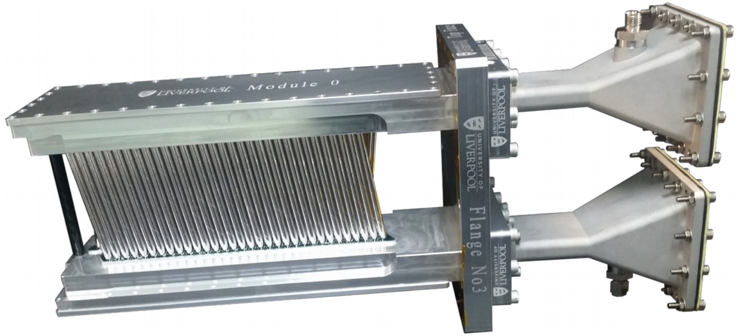


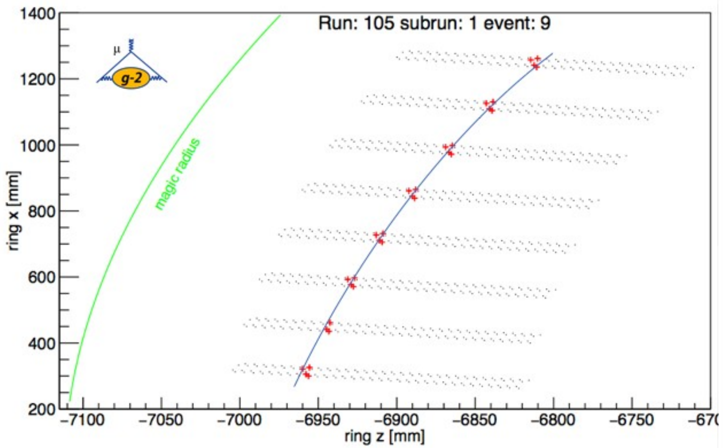
New Trackers

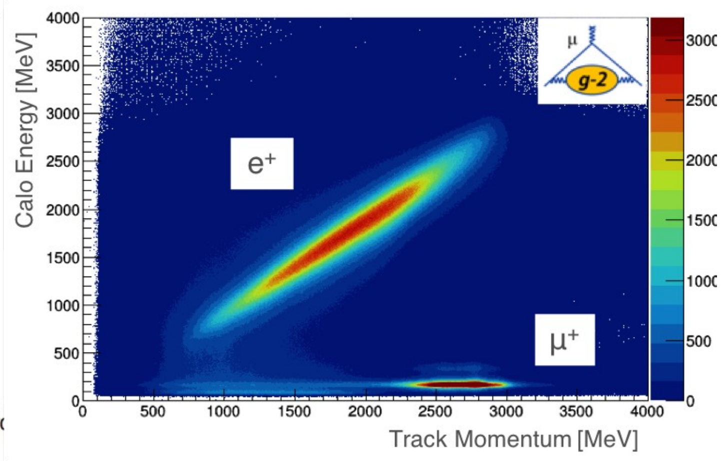
UK contributed new tracking detectors in front of two calorimeters

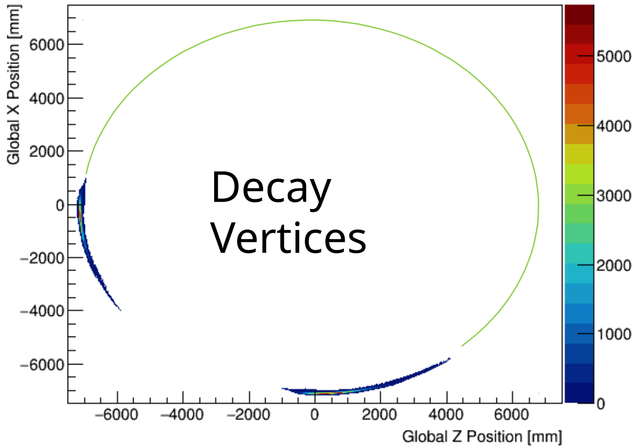
- 8 modules, 4 rows (2 x stereo) per module, 32 straws per row





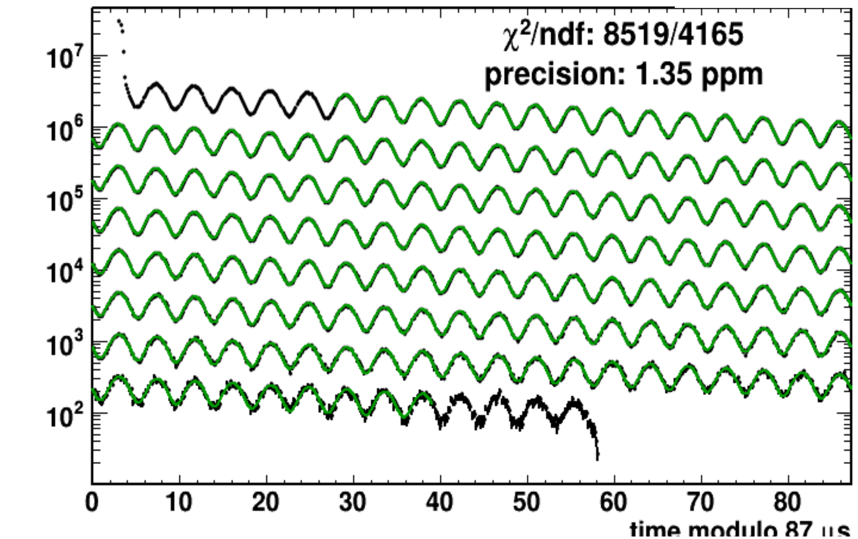


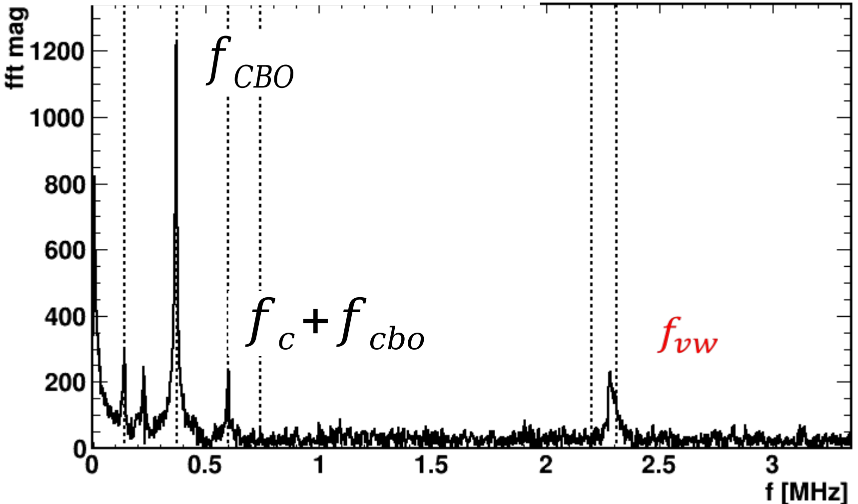




Beam position

Improved Wiggle





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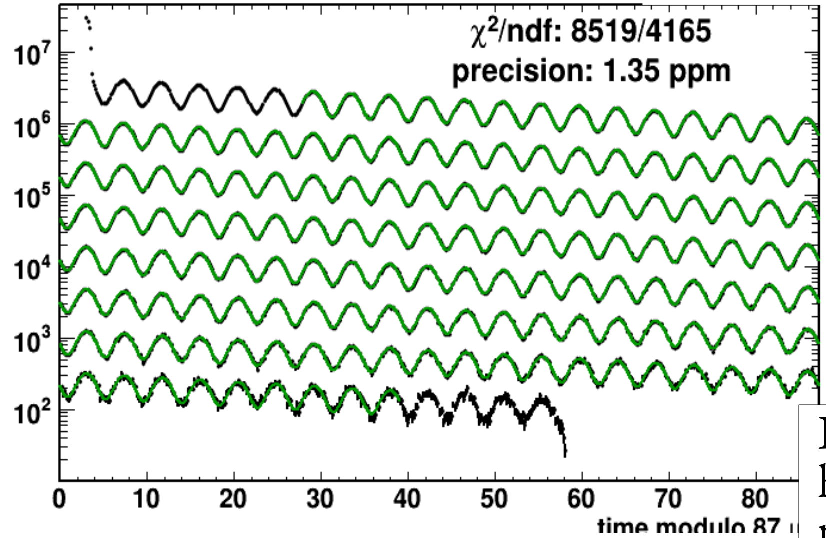
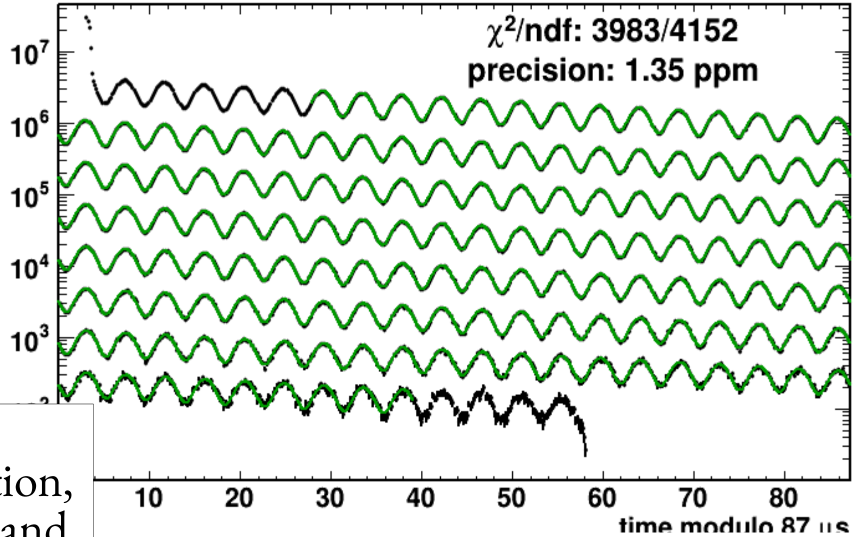
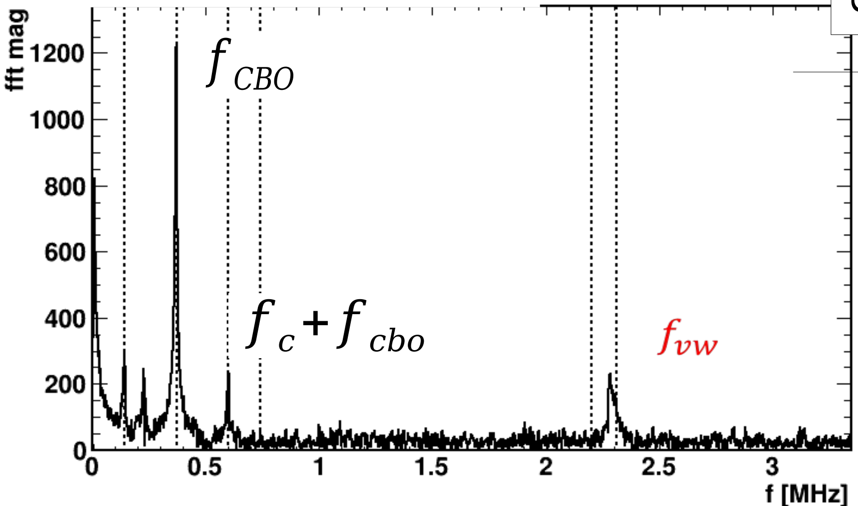
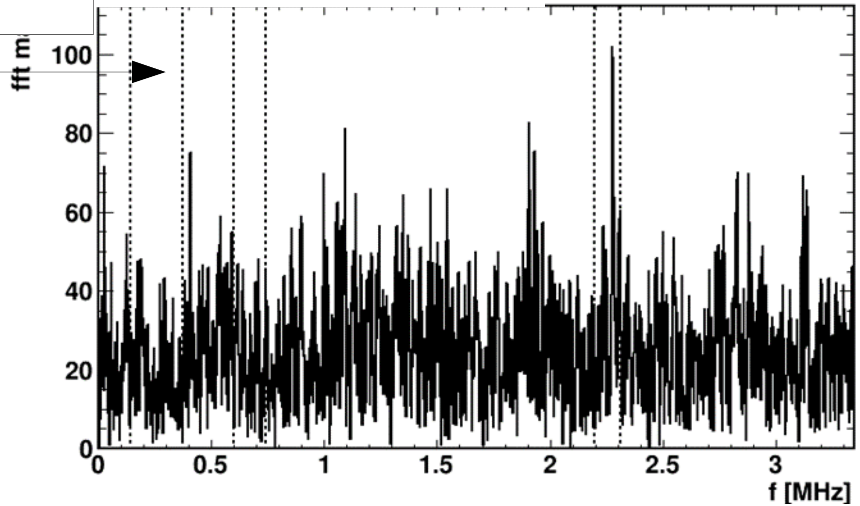




Include vertical and horizontal beam motion, pile-up, muon losses and energy scale





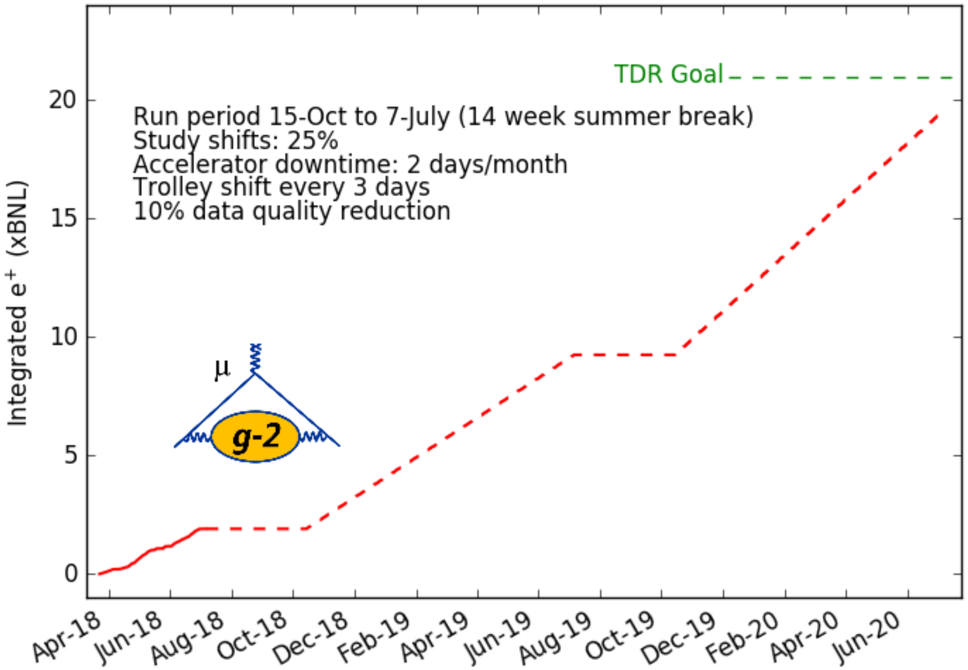
Status

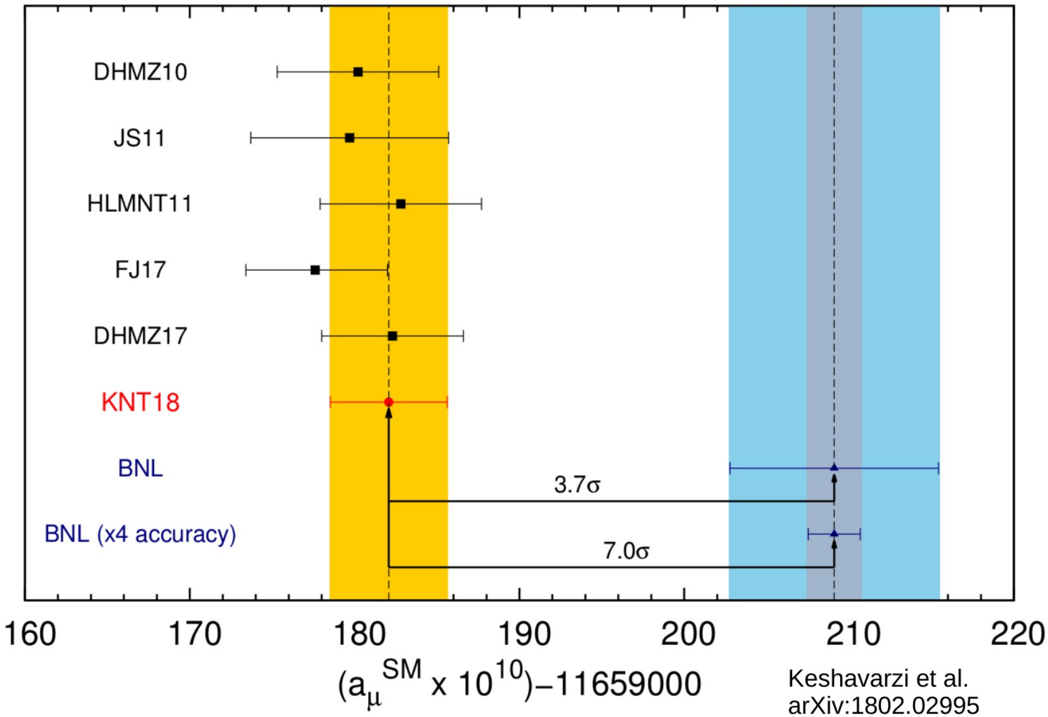
First data-taking run complete:

- 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





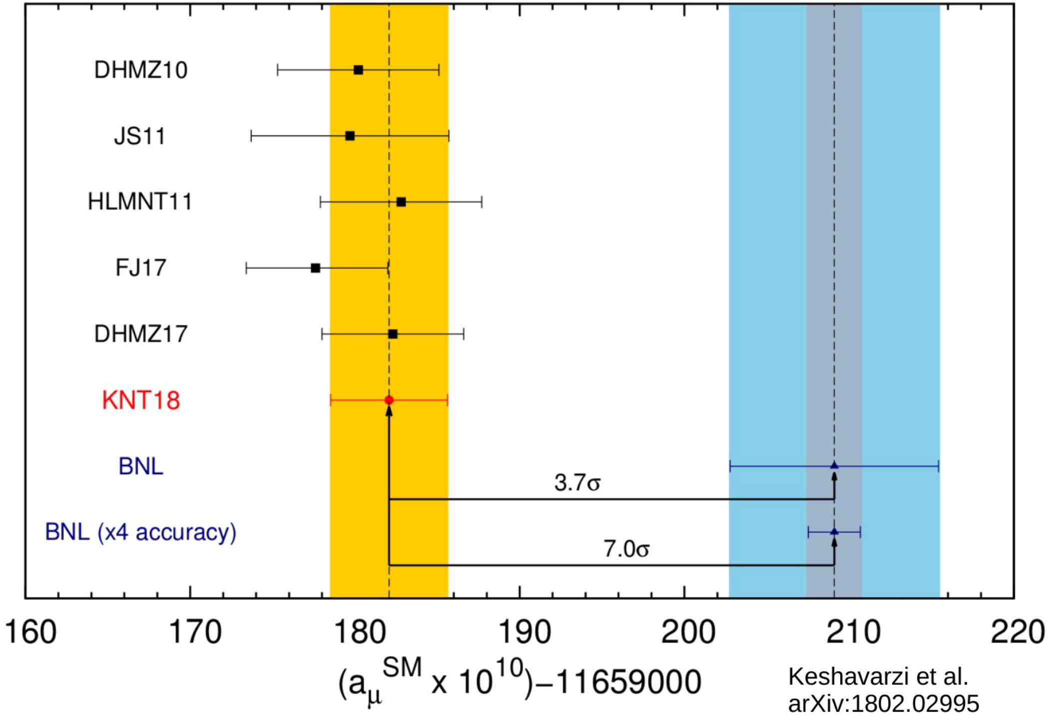
Keshavarzi et al.
arXiv:1802.02995

What would it mean..?

Further experimental confirmation?

→ *Planned g-2 experiment at J-PARC*

- different techniques, different systematics



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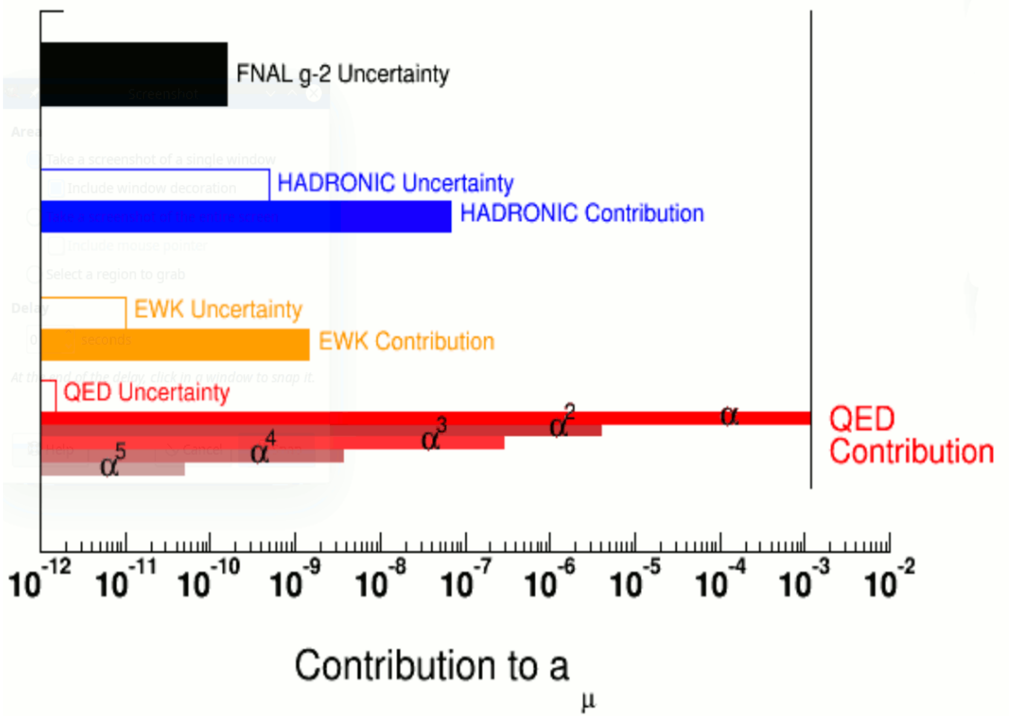

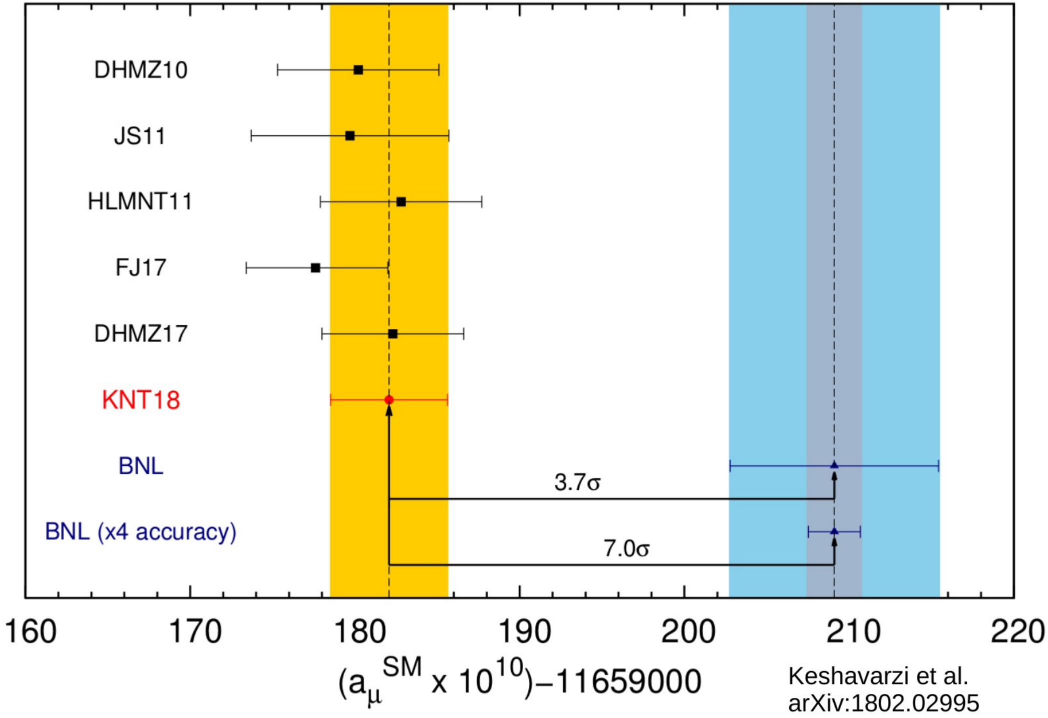

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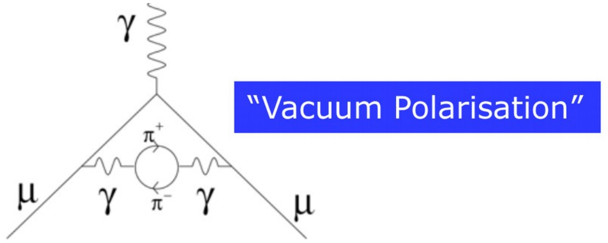

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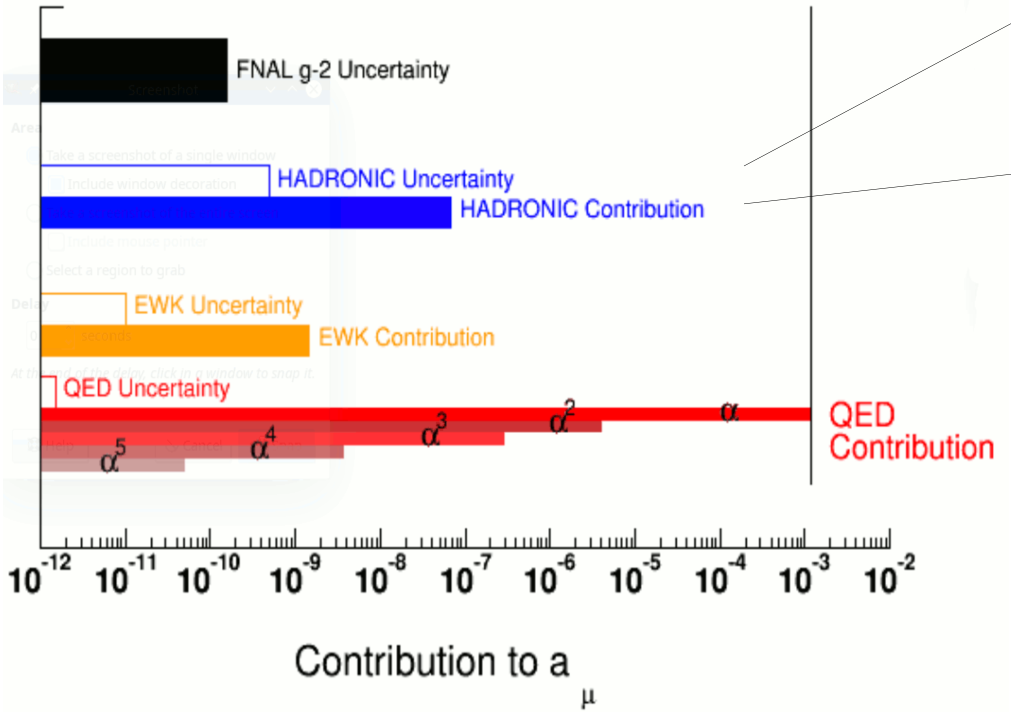
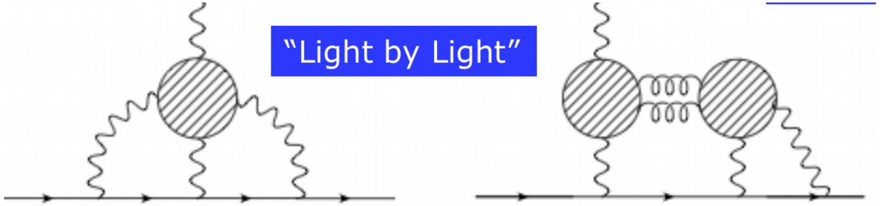




Low energy QCD...

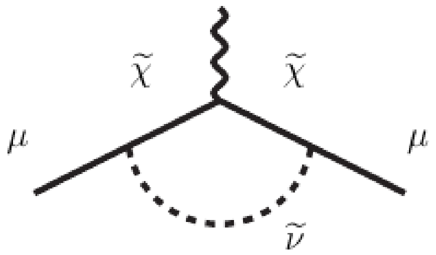
- *need experimental input*
    - proposed MUonE experiment at CERN

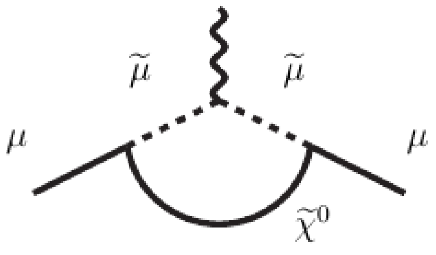
...or lattice calculations

Muon g-2 theory initiative underway:

https://indico.him.uni-mainz.de/event/11/overview

g-2: new physics?





SUSY?

- Needs μ>0, 'light' SUSY-scale (Λ) and/or large tan β

...already ruled out by the LHC?

- However, SUSY does not have to be minimal

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

Many other ideas out there, eg:

- 1 TeV Leptoquark Bauer + Neubert, PRL 116 (2016)
- 2 Higgs doublet model Stockinger et al., JHEP 1701 (2017) 007
- axion-like particle Marciano et al, PRD 94 (2016) 115033
- 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 also Thomas Teubner's talk at the UK HEP Forum, Nov 2018

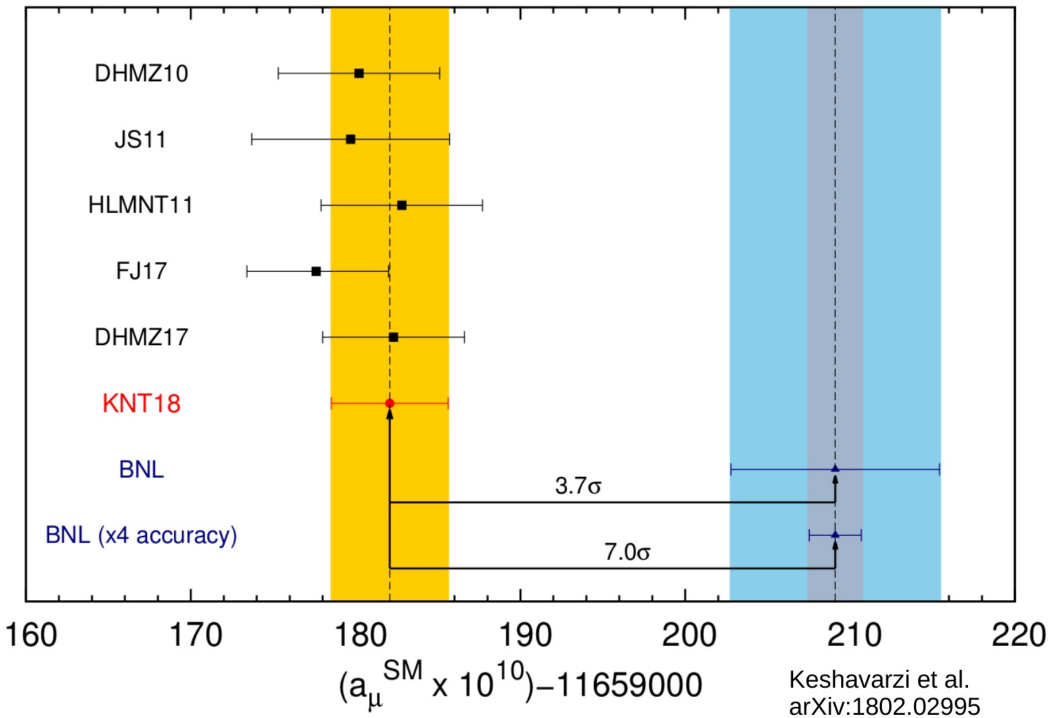
What would it mean..?

It may not be the clear sign of new physics we wanted...

- complementary measurements needed to resolve model dependency.

→ *EDM experiments*

→ *cLFV experiments*



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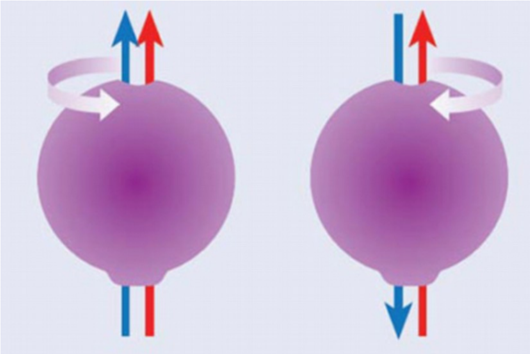
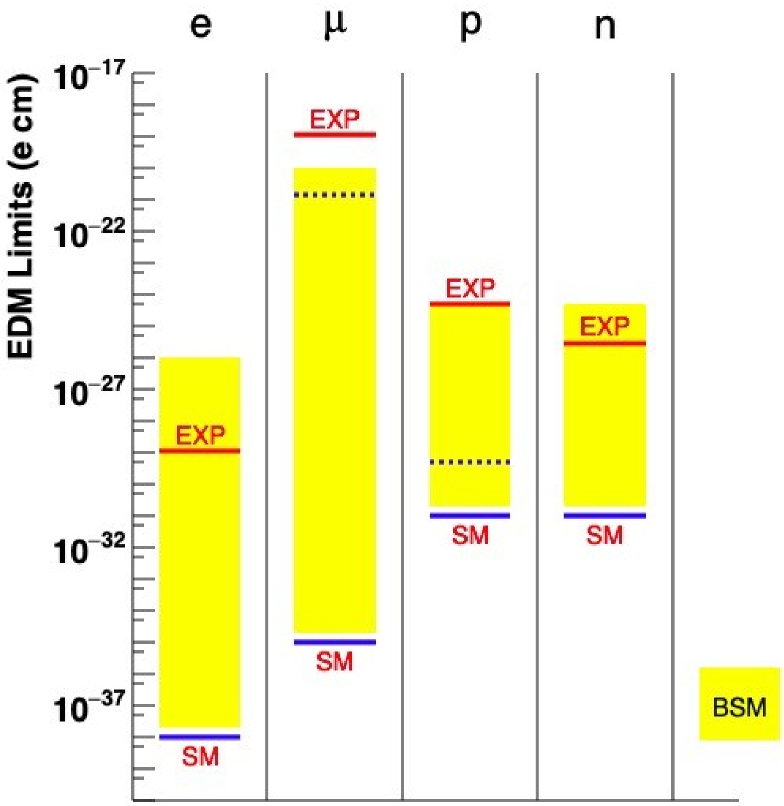
Further clues: EDMs

Fundamental particles can also have an EDM
- zero in SM (slight shift due to loops)
- more significant shifts with BSM 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



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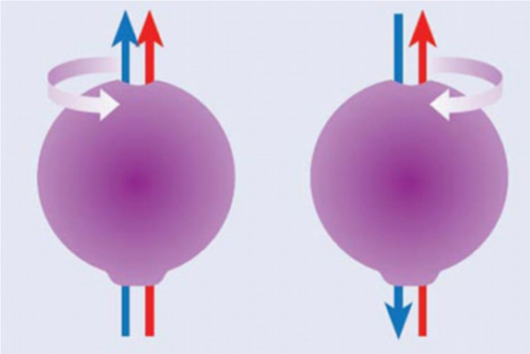

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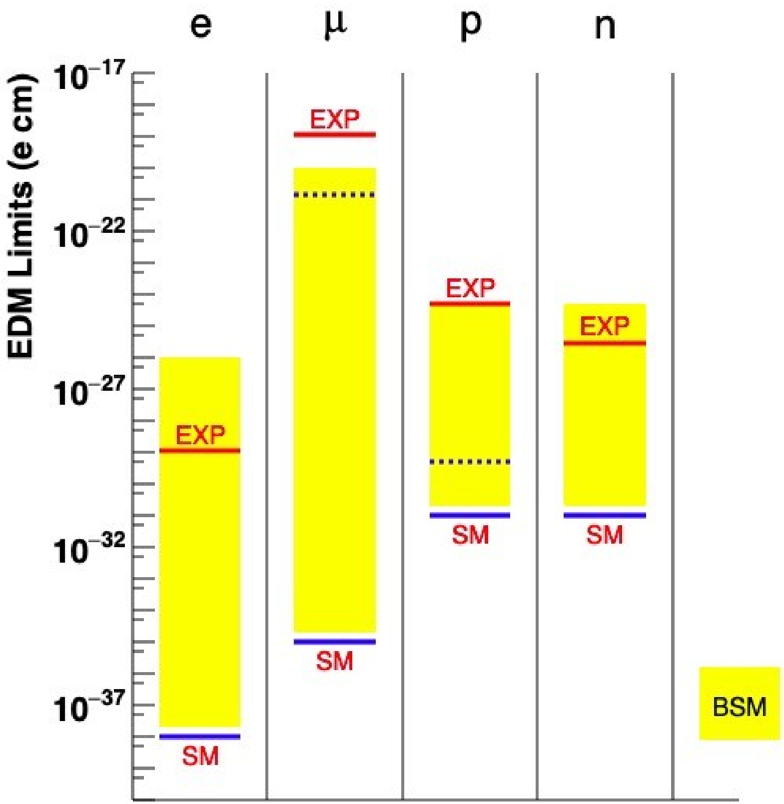
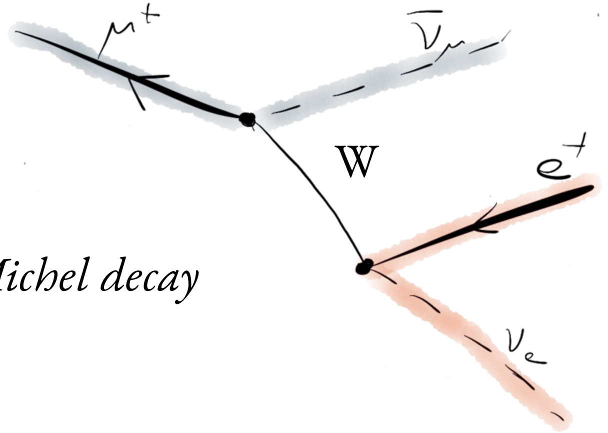


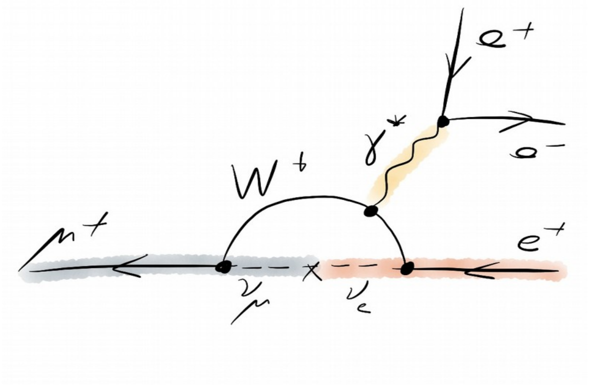
A non-zero muon EDM would lead to out-of-plane precession
→ 100x improvement in limit from Fermilab g-2
- an upgrade would push limit further…

Development work for proton EDM ring underway
- part of CERN's "*Physics Beyond Colliders*" programme.

Charged Lepton Flavour Violation



Michel decay



CLFV decay

Neutrino oscillations violate lepton flavour conservation
→ technically possible in charged lepton sector
...but suppressed by ~10^{-50}

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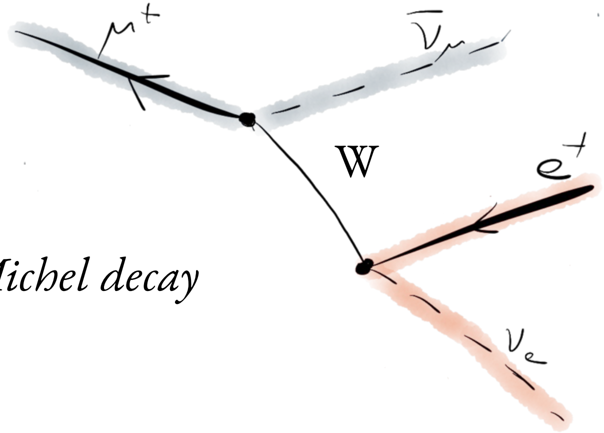

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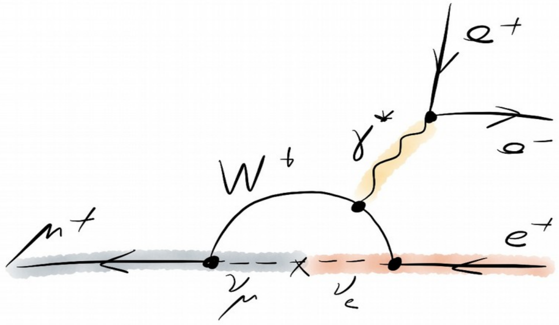

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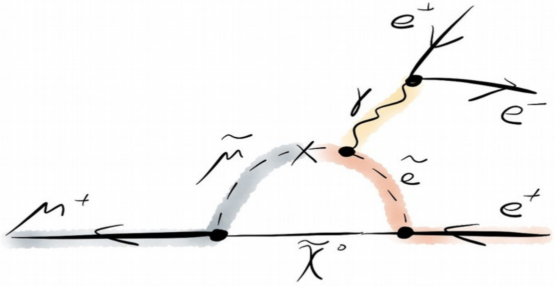

Neutrino oscillations violate lepton flavour conservation
→ technically possible in charged lepton sector
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Put BSM physics in the loop → increase the rate

Any observation of cLFV is new physics!

Many BSM models include charged lepton flavour violation

- leptoquarks, compositeness, Higgs doublets, heavy neutrinos…

…or invoke it for leptogenesis of matter-antimatter asymmetry

CLFV

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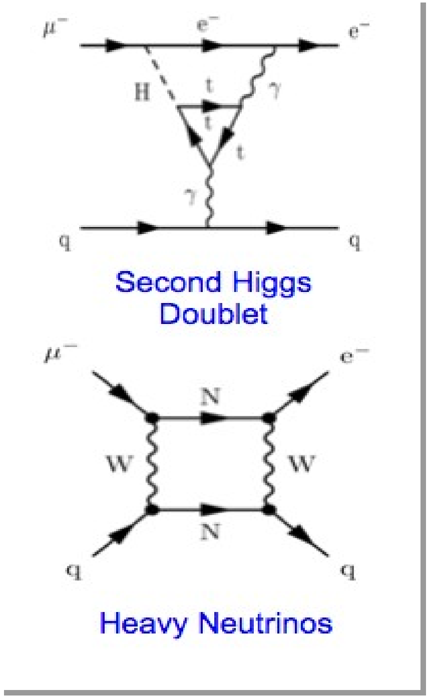
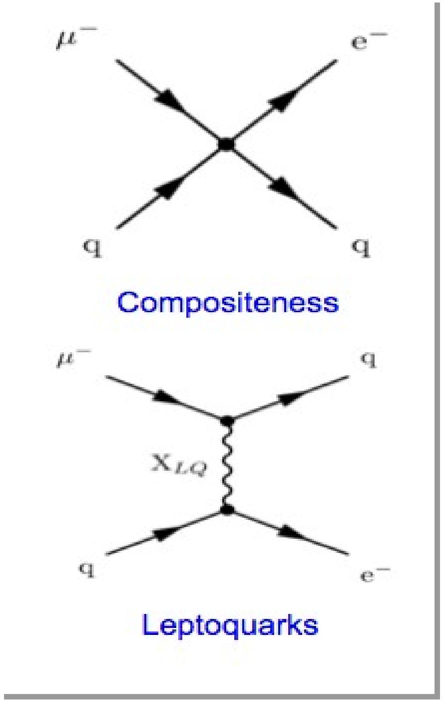
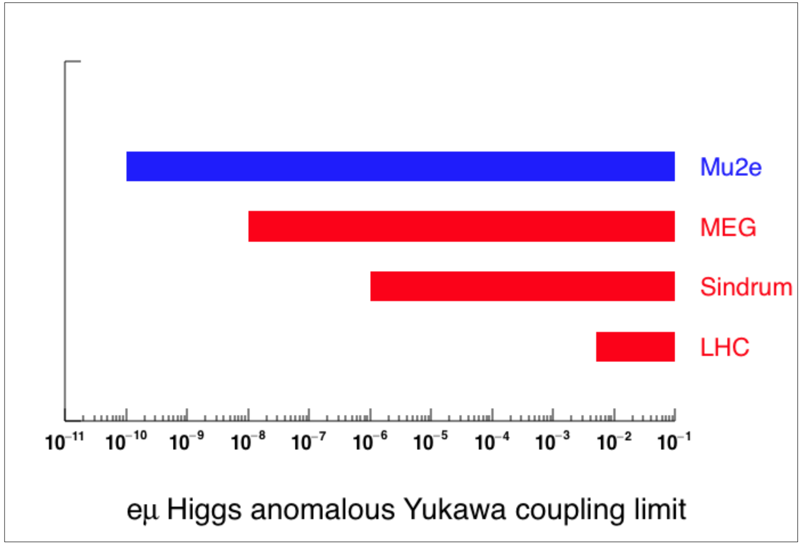






Probe LQ masses up to 300 TeV
cf 1 (120) TeV at HL-LHC (LHCb)

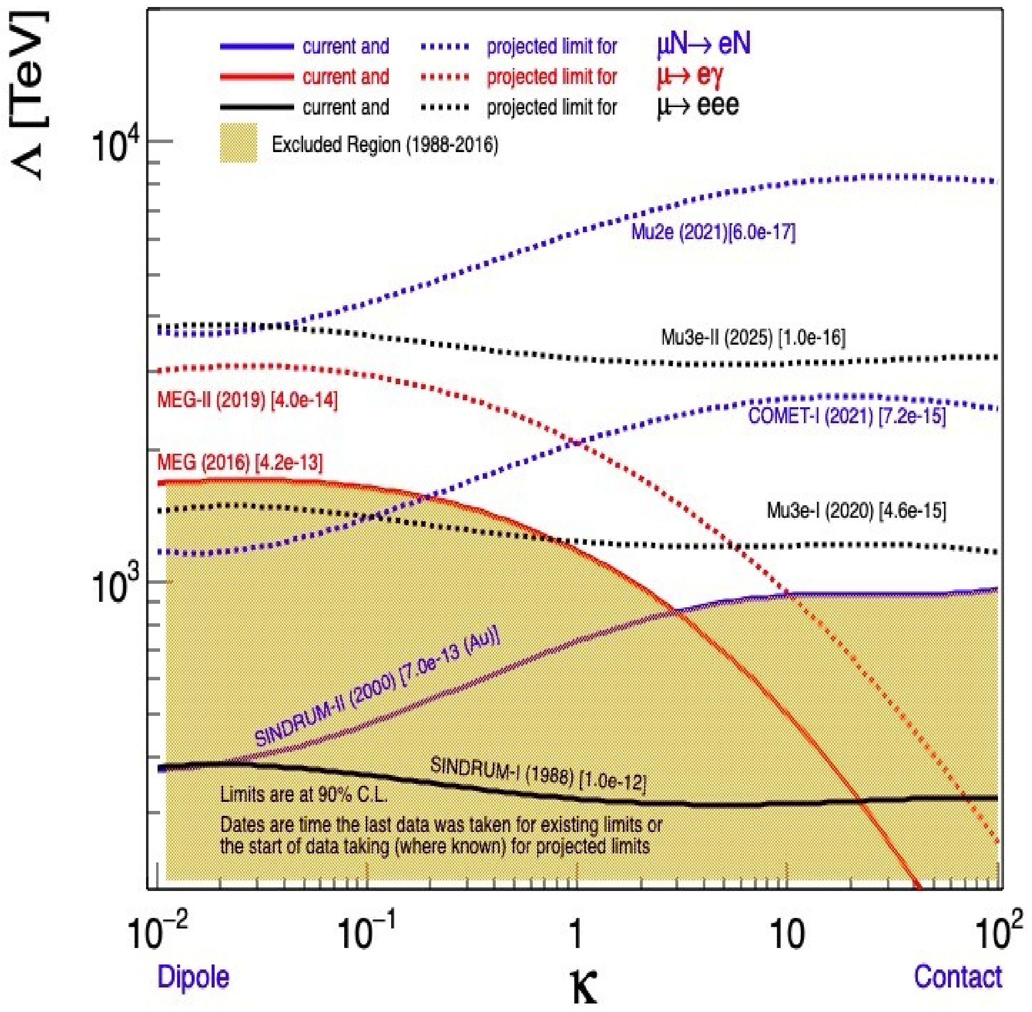
Sensitivity to flavour-violating Higgs couplings

CLFV

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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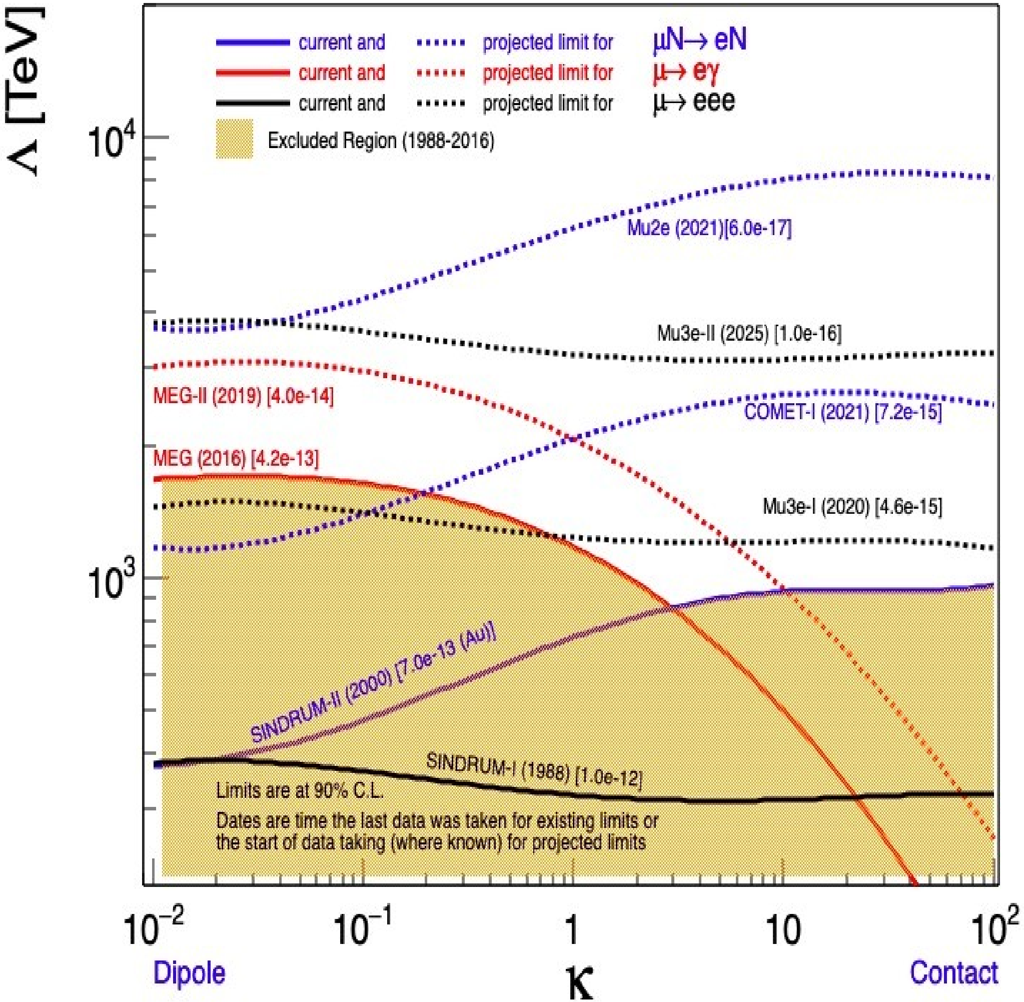
Step-change in sensitivity in coming years

...probing mass scales up to 10,000 TeV

Can help resolve model dependency in g-2:

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

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



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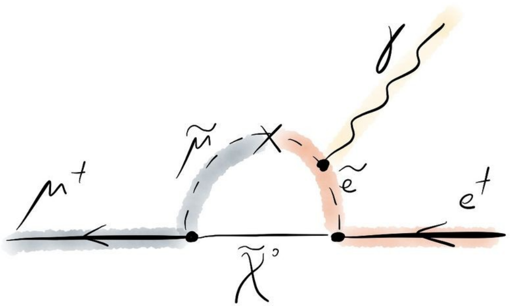


MEG-II @ PSI:

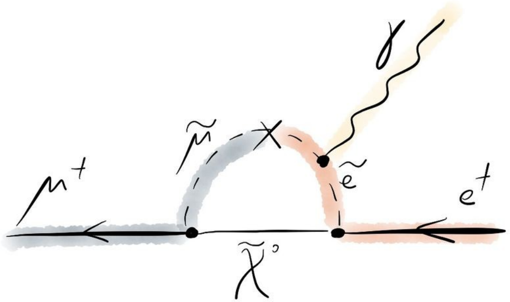
- physics in 2019
- x10 on limit

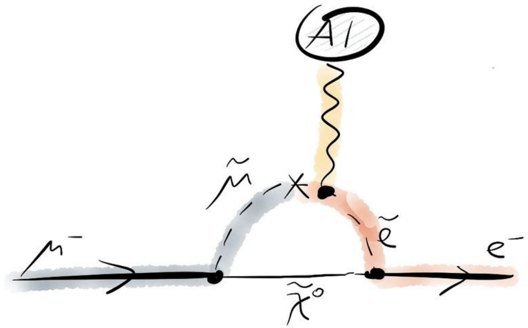
→ 10^{-14} after 3 years

11 institutes, 75 collaborators

- no UK involvement

CLFV





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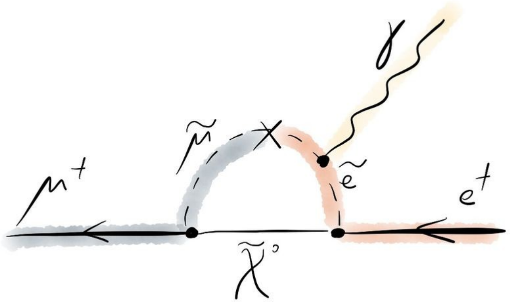
Mu2e @ FNAL
- starting 2022 (after g-2)
- x10^{4} on limit

→ 10^{-17} after ~4/5 years

40 institutes, 242 collaborators
- Liverpool, Manchester, RAL, UCL

COMET @ J-PARC similar (Imperial)

CLFV



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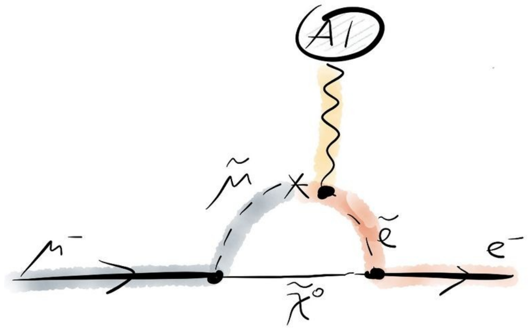

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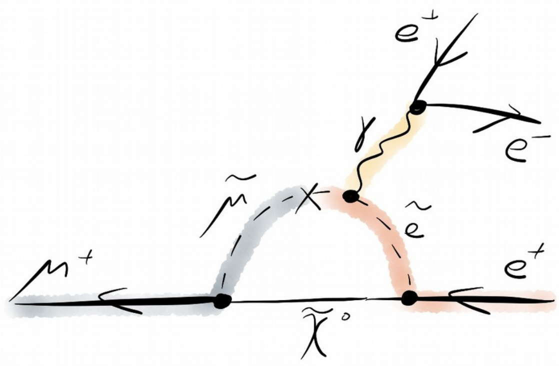

Mu3e @ PSI
- phase 1 (2020) & 2 (2025)
- x10^4 on limit
  → 10^{-16} after phase 2

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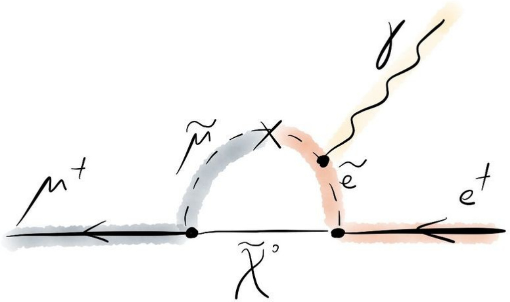

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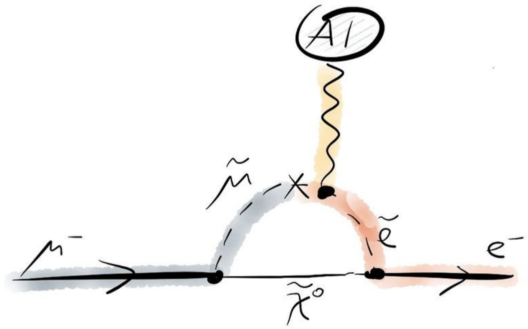

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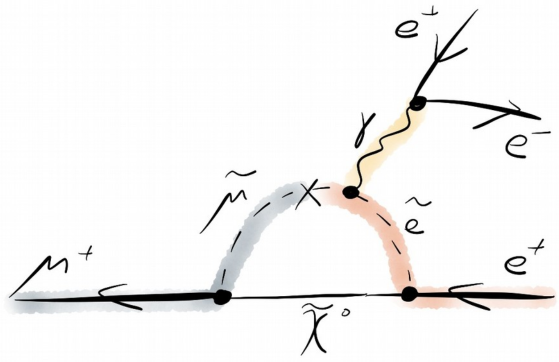

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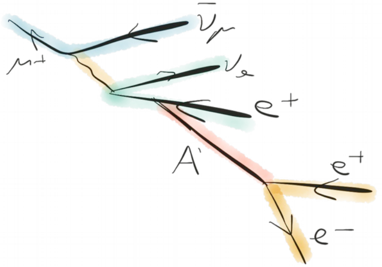
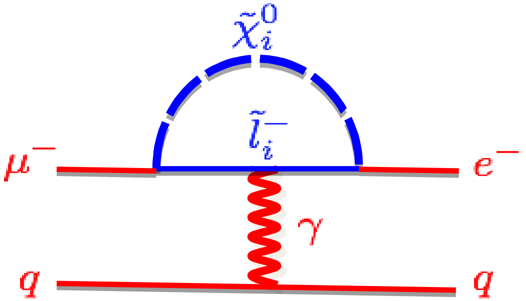
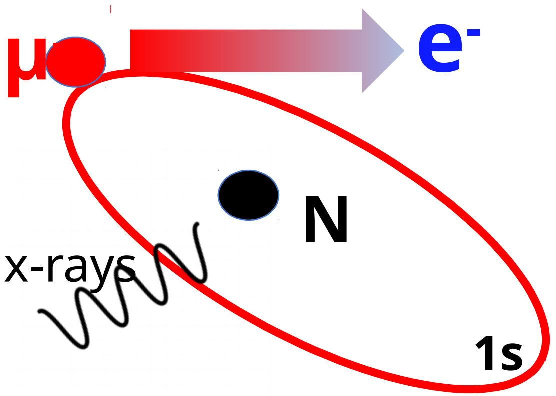
Complementary experiments:
- Mu2e involves quark and lepton couplings
- Mu3e purely leptonic, can also search for dark photons etc




One CLFV interaction in 10^{16} muon decays is like…
looking for one specific grain of sand

$\mu N \rightarrow eN$





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

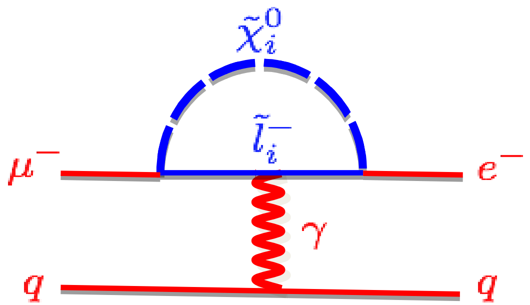
Stop muons on an Al target

- x-ray emission from capture → normalisation

Signal of neutrino-less conversion:

mono-energetic electron

$\mu N \rightarrow eN$



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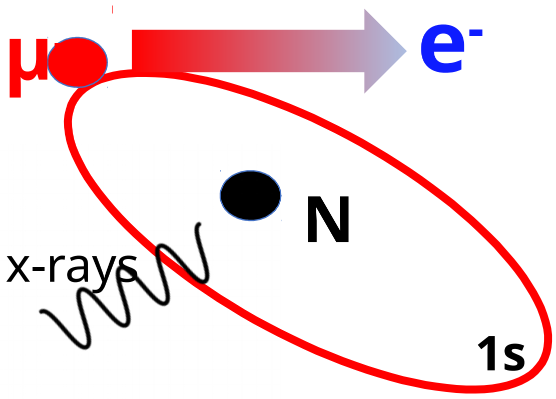

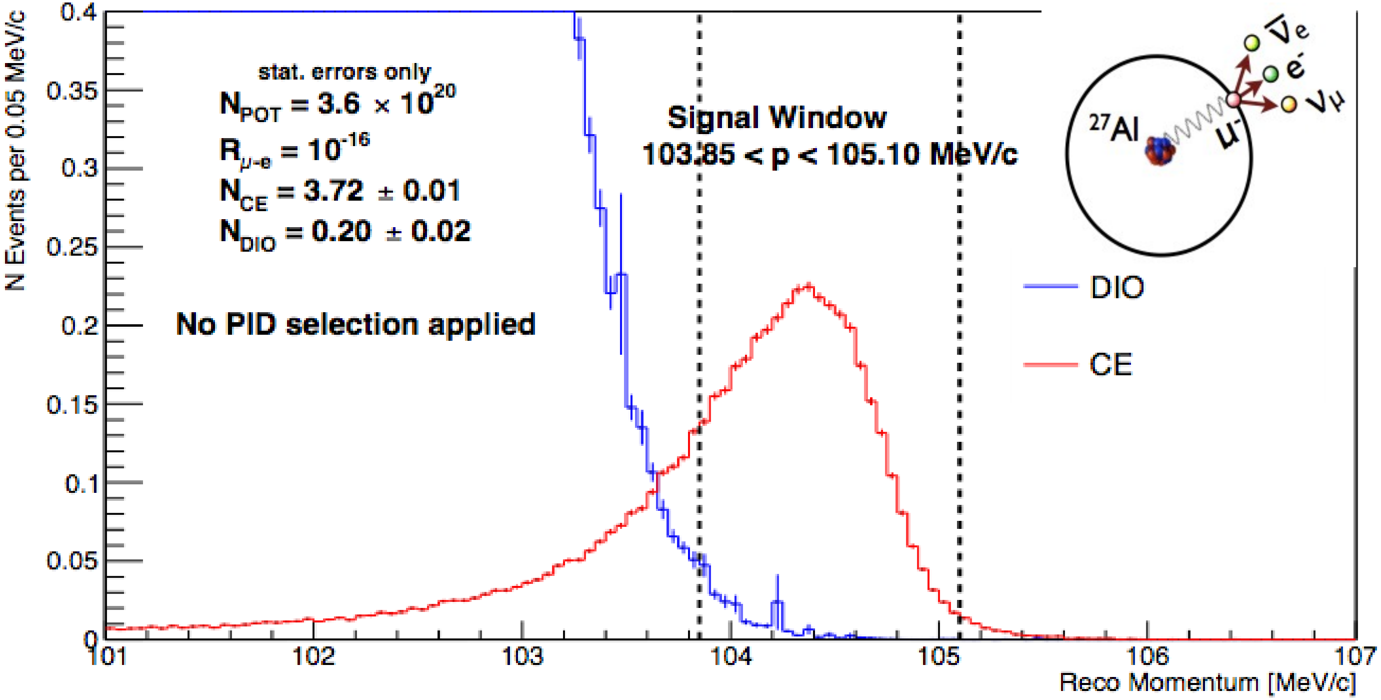

$$
\begin{aligned}
E_e &= m_\mu - E_{bind} - E_{recoil} \\
&= 105.67 - 0.47 - 0.22\ MeV \\
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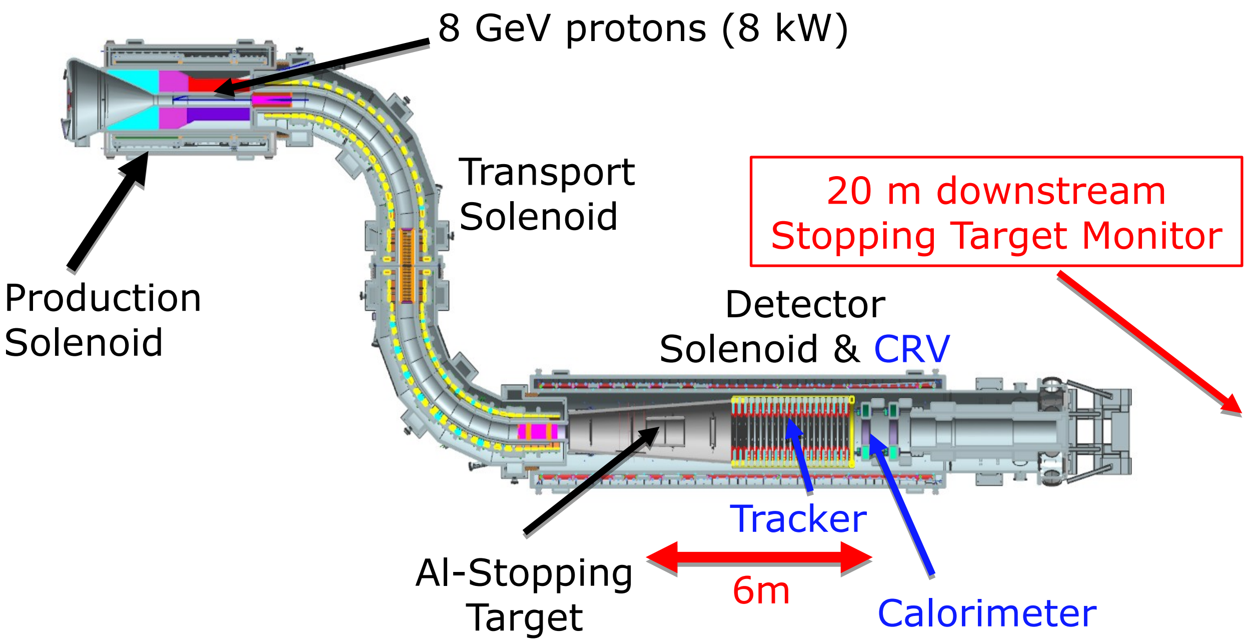
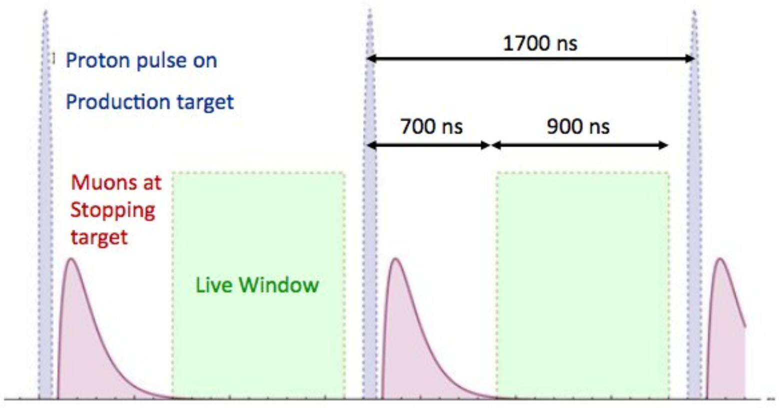
$$

Mu2e





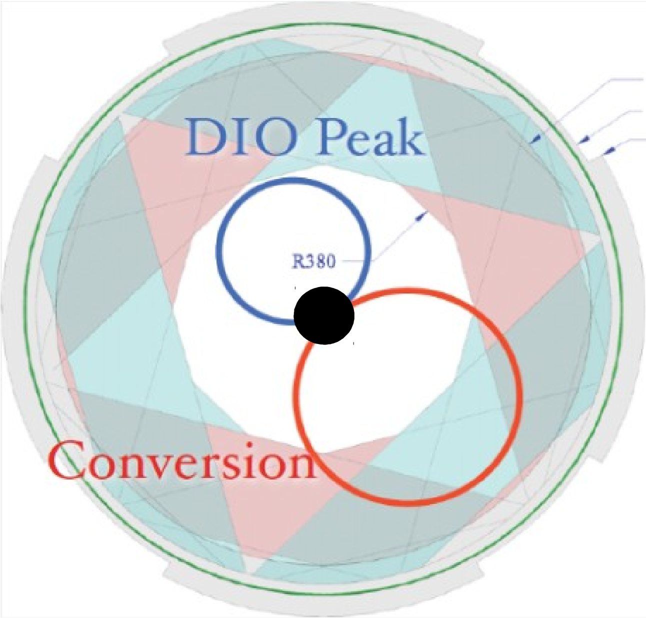
Prompt backgrounds
(radiative nuclear capture, d.i.f., pions, protons).
- Curved solenoid transport channel
- Pulsed beam with strong extinction factor ($<10^{-9}$)

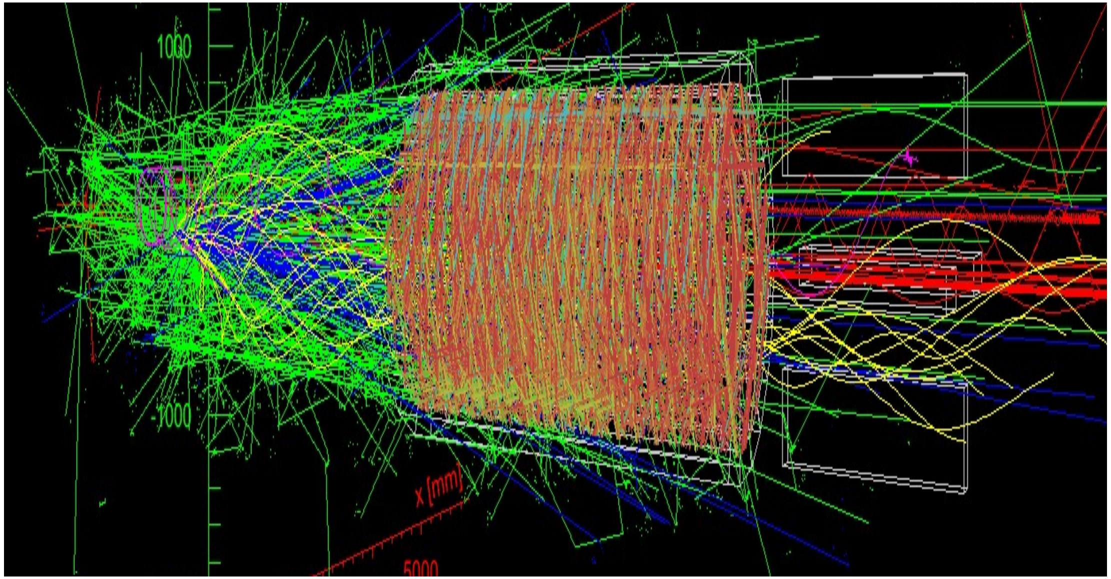
Cosmics: cosmic veto detector

Mu2e

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

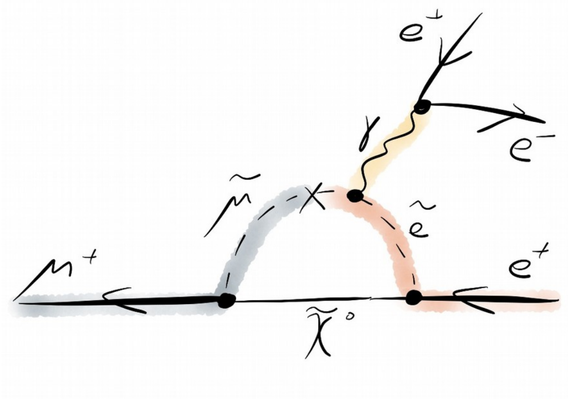
Straw tracker (similar to g-2 trackers)
- hollow cylinder design



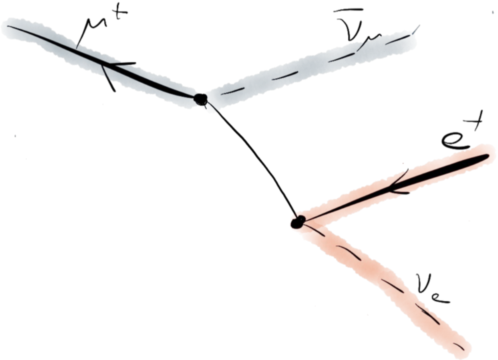


Mu2e will follow g-2
- uses same beamline at Fermilab Muon Campus
- first beam 2020, data-taking through 2025

Possible upgrade using PIP-II beam
→ further factor of 10 on the limit
arXiv:1802.02599

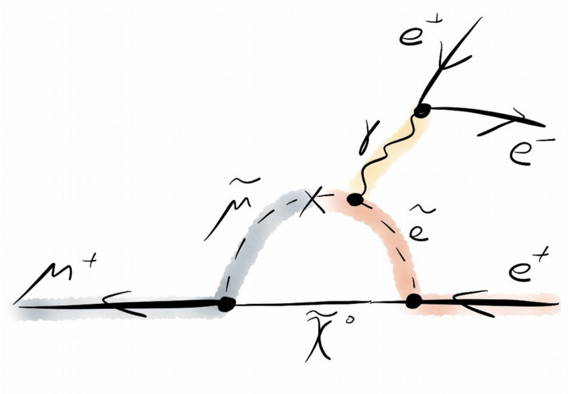


Signal



Michel Decay

Michel Decay + Conversion



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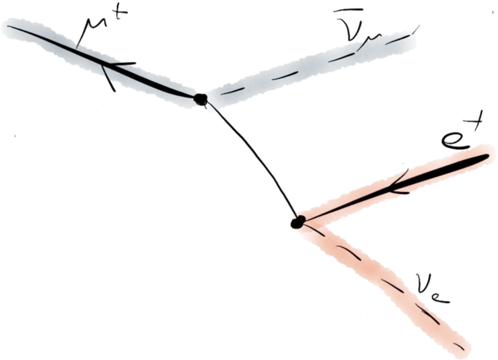

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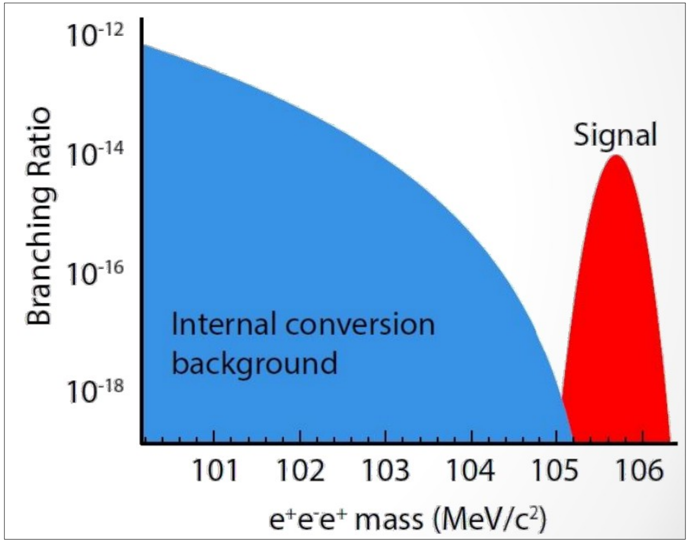
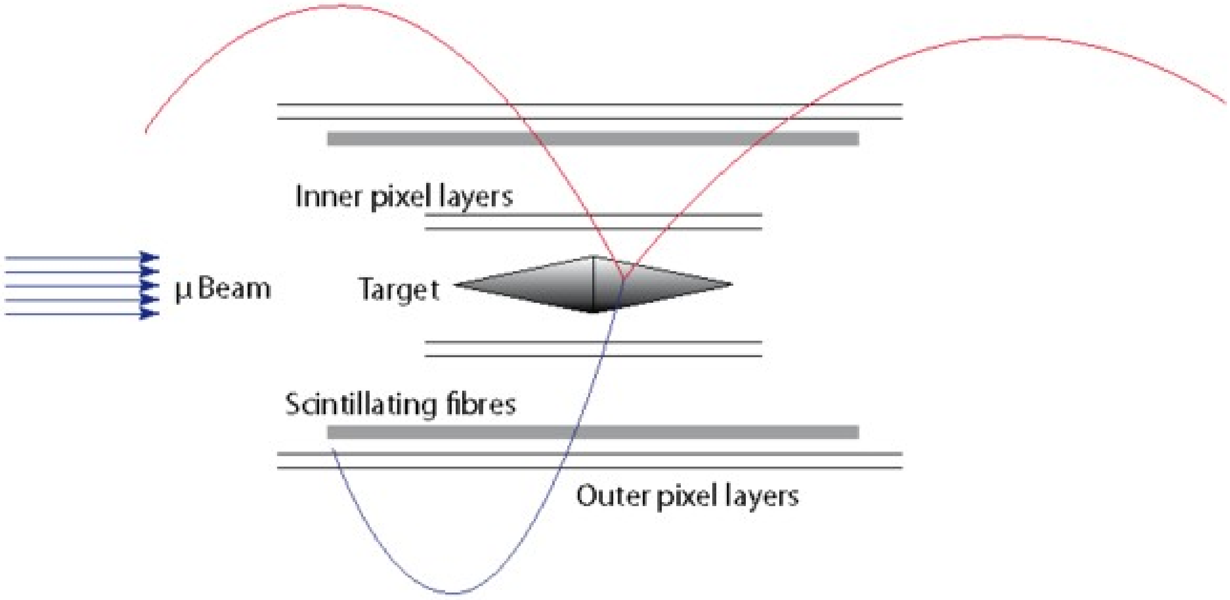


μ^- **DECAY MODES**		Fraction (Γ_i/Γ)
$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$
$e^- \overline{\nu}_e \nu_\mu \gamma$	[d]	$(6.0\pm0.5) \times 10^{-8}$
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[e]	$(3.4\pm0.4) \times 10^{-5}$

Mu3e @ PSI
DC beam of up to 10^{10} μ/s on target, triggerless DAQ.

Photon conversion:
- vertex resolution 200 μm
- Scintillating fibres (<1ns)

Internal conversion
- momentum resolution 0.5 MeV
  ...in the scattering-dominated regime (E<53 MeV)



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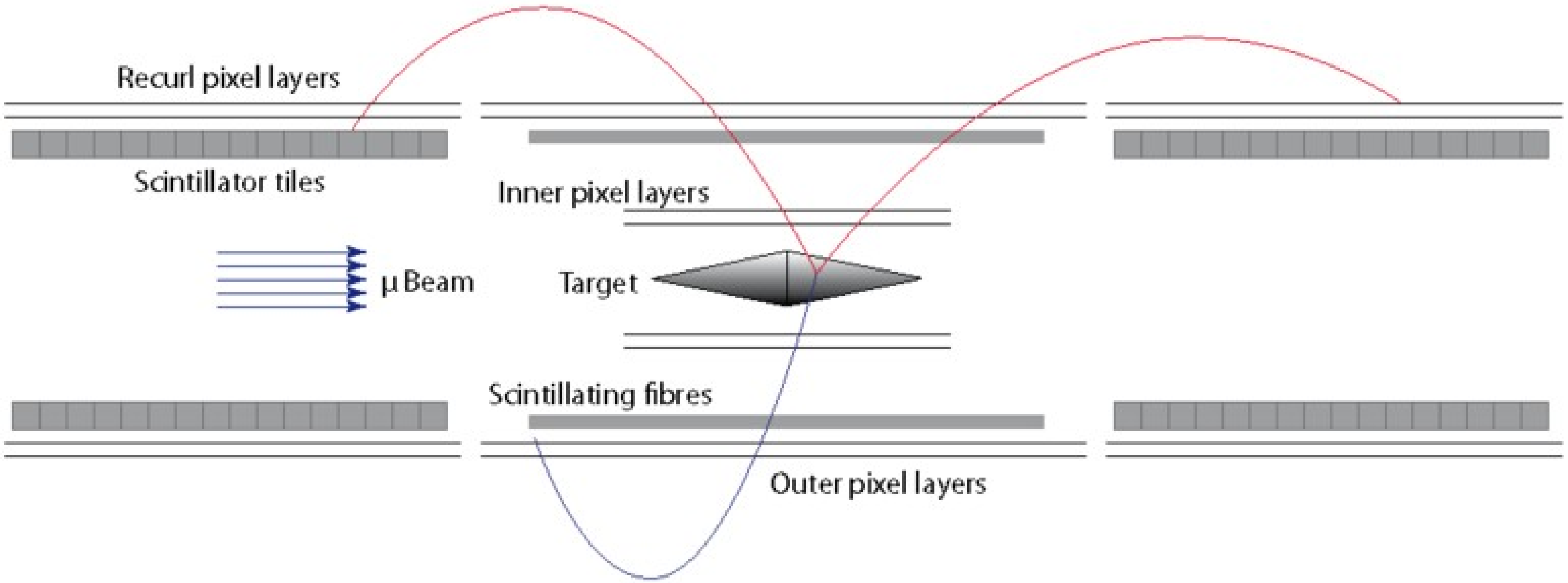
Photon conversion:

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

Internal conversion

- momentum resolution 0.5 MeV

 ...in the scattering-dominated regime (E<53 MeV)

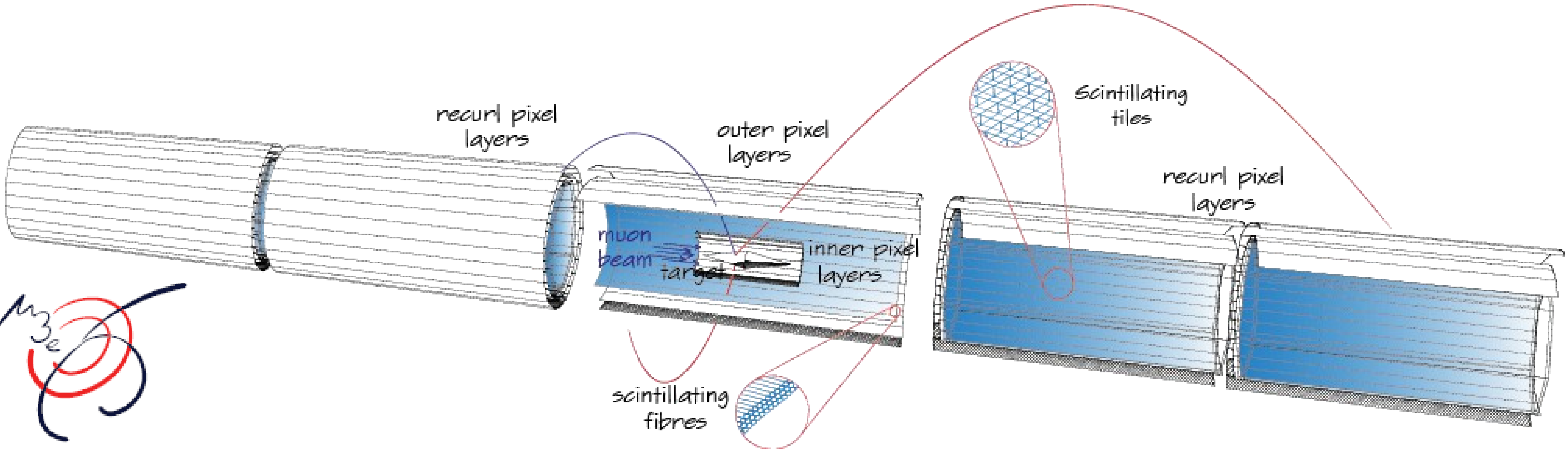


Mu3e @ PSI
DC beam of up to 10^{10} μ/s on target, triggerless DAQ.

Photon conversion:
- vertex resolution 200 μm
- Scintillating fibres (<1ns) and tiles (<100ps)

Internal conversion
- momentum resolution 0.5 MeV

 ...in the scattering-dominated regime (E<53 MeV)



Mu3e Pixel Detectors

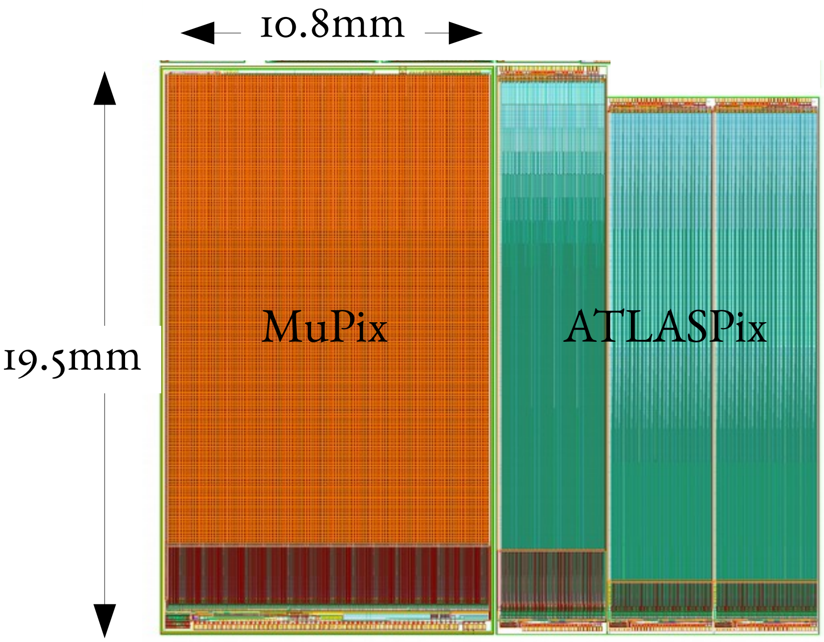
1.1 m² pixel tracker

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

→ 0.1% X_0 per tracking layer

MuPix8 development:
- 81x80 µm pixels, 128x200 pixels per chip
    - 178 M channels for Phase 1.
- 1.25 Gbit/s serial data outputs
- ~210mW/cm² power consumption

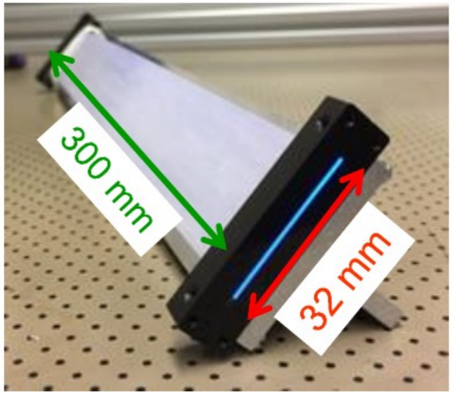
Test-beam results:
- >99.5% efficiency
- noise rate per pixel ~0.2 Hz
- time resolution ~14.5 ns
- measured track residuals ~ 35µm ($80/\sqrt{12} = 23$ µm)



Mu3e Timing Detectors

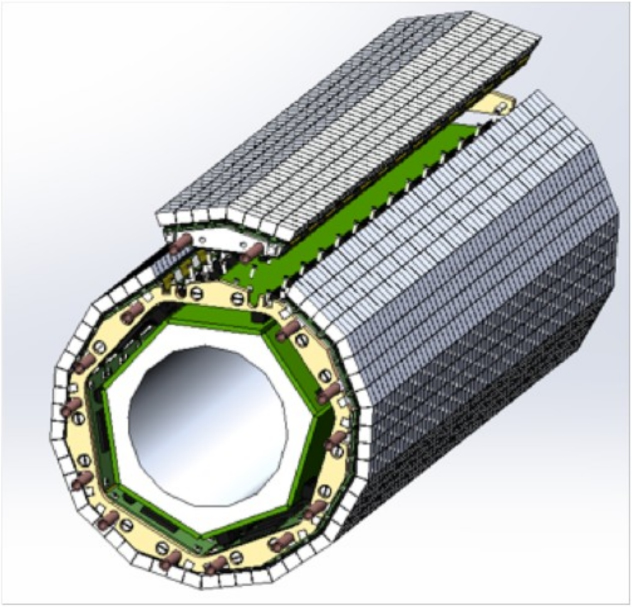
Fibre ribbons in central barrel:

- 4 layers of ~250μm
- 12 x SiPM arrays (LHCb type)
- time resolution <400ps on prototype

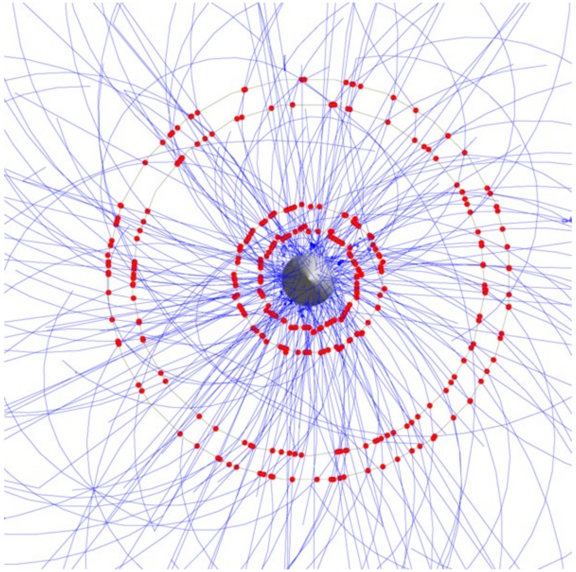


Scintillating tiles in the recurl stations:

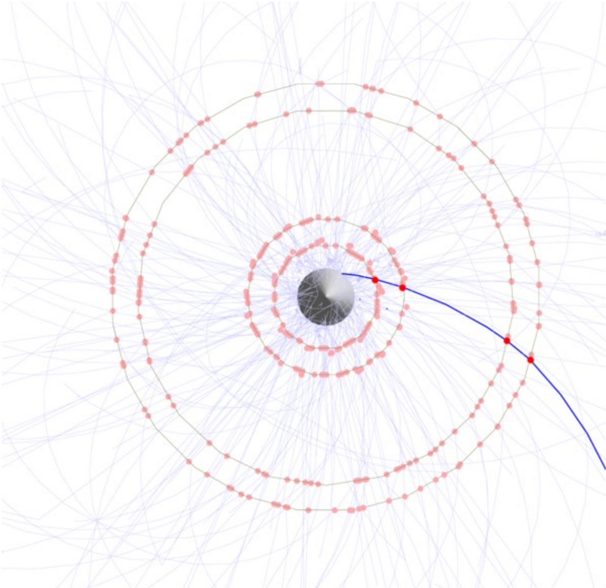
- 6.5x6.5x5 mm^3
- total of 6272 channels in Phase 1
- resolution of ~35ps from prototype



50 ns



1 ns



Mu3e DAQ

Mu3e will run a triggerless DAQ

- occupancy up to 5.2 MHz per sensor
- max bandwidth 740 Mbit/s (x4 requirement)

→ data output up to 1 TB/s (phase 2)

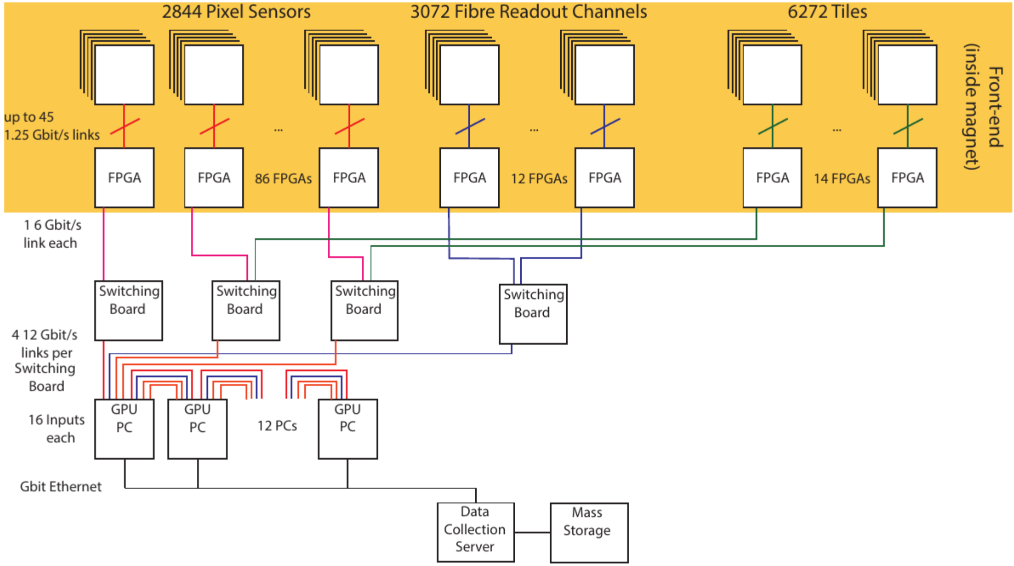
Need to find and fit billions of tracks per second...

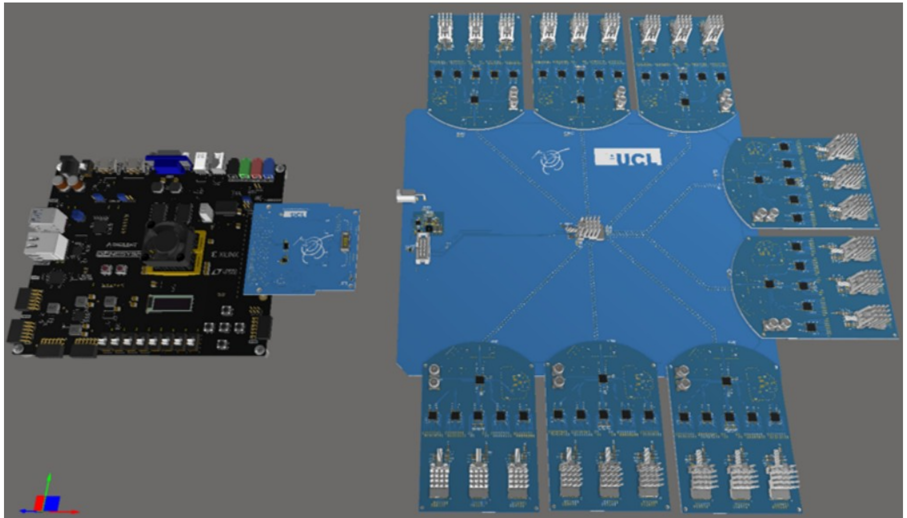
→ *Online event reconstruction on GPU farm*

~50 GPUs

- data reduction of ~1000

→ output 50-100MB/s

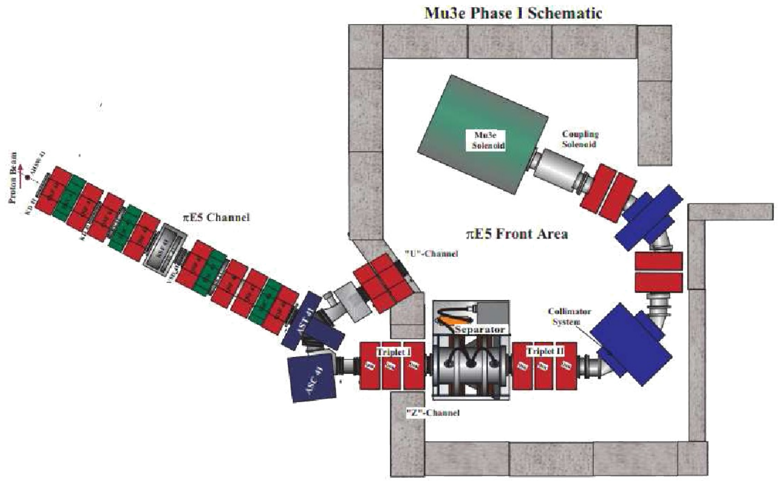


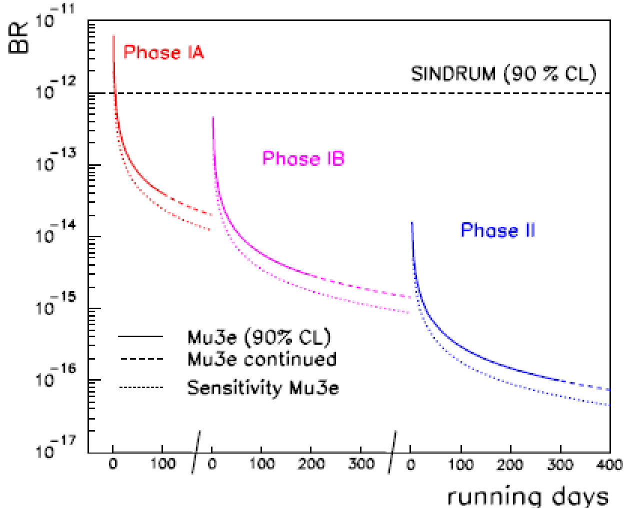


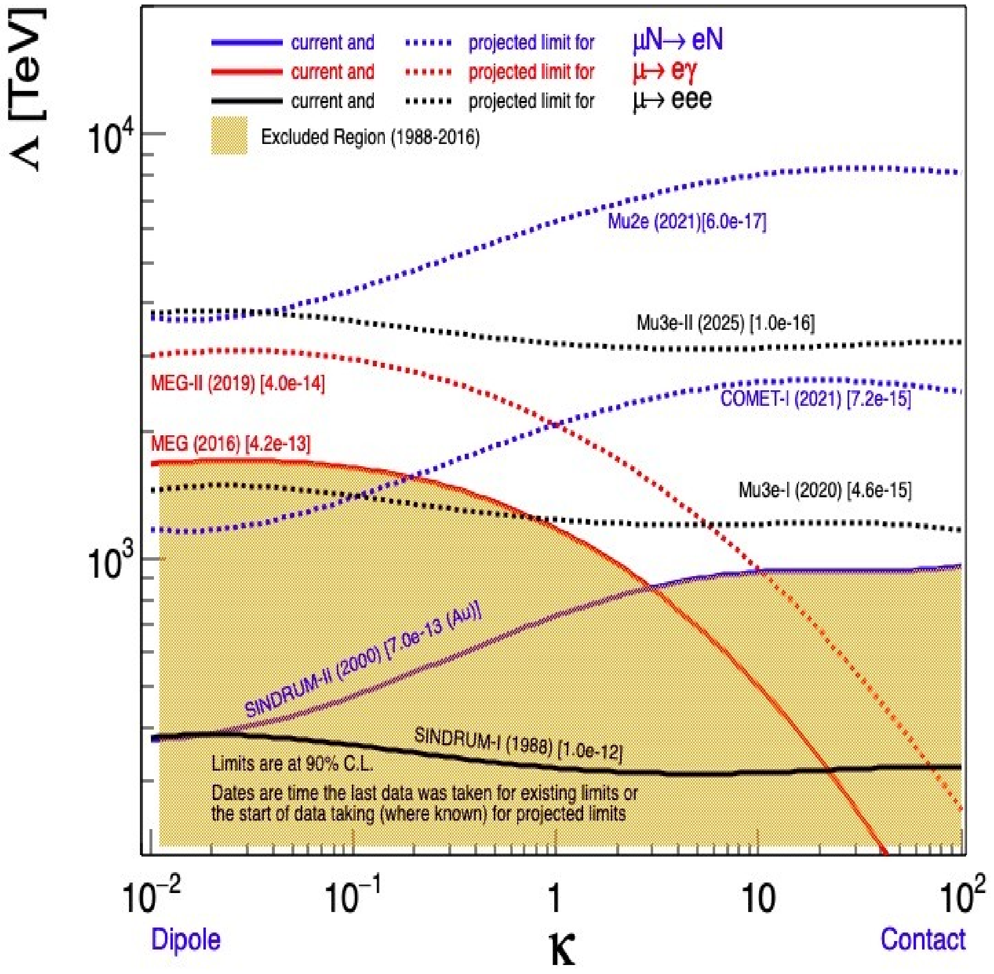
At UCL we are developing the clock & control system

- optical transmission of:
  - clock signal to frontends
  - control signals (start run, reset, ...)
- active splitting using Firefly connectors

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 planned in 2019, running for 2 more years to reach 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!

~~ *fin* ~~

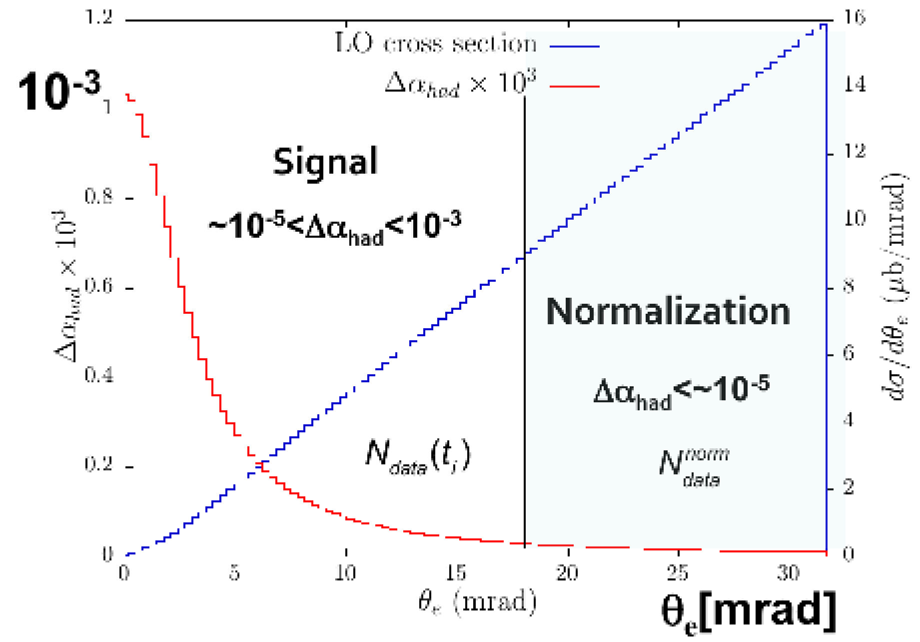
MUonE

Theory limited by hadronic LO corrections, a_μ^{HNLO}

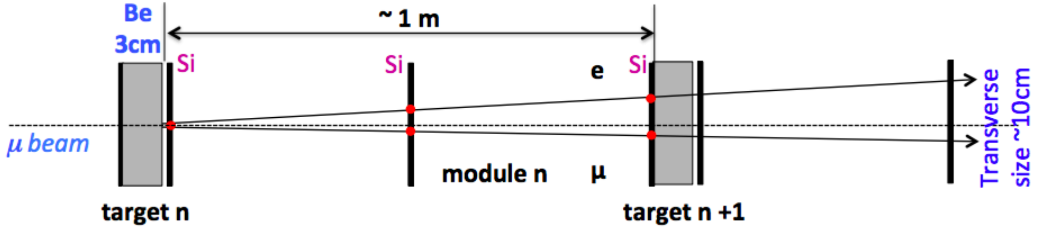
Traditional calculation from ee→hadrons
→ need x2 improvement to keep up with g-2

MUonE will measure space-like region:
→ scattering of high energy mu (150 GeV) on e

$$\boxed{a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}(t(x))dx}$$



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



Schedule:
2017: test beam at CERN H8 Beam Line
2019: LOI to SPSC
2020/1: construction & installation
2022/4: (after LHC LS2) start data taking

g-2 theory

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{EW}$$

	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]

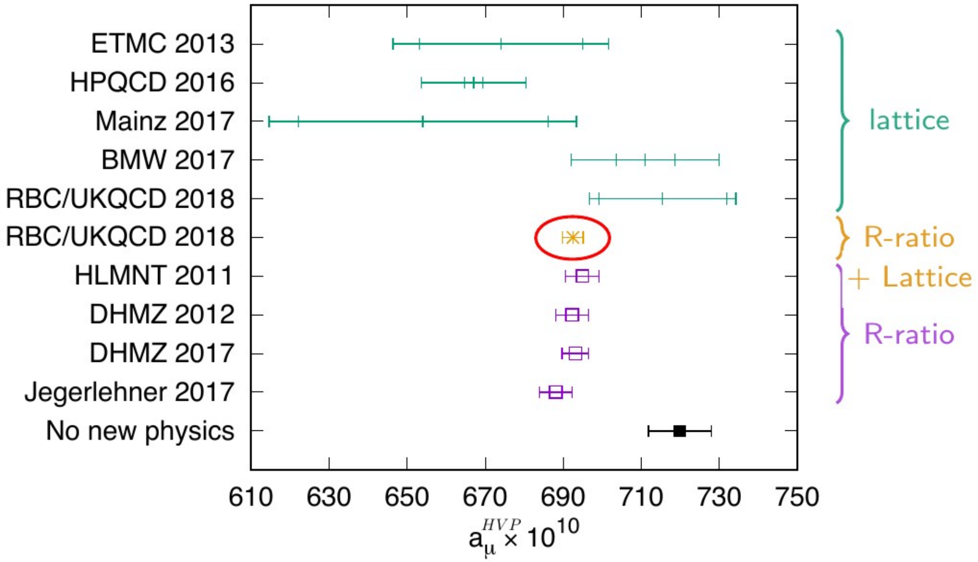
→ *need x2 improvement to keep up with experiment*

Muon g-2 Theory Initiative underway
https://wwwth.kph.uni-mainz.de/g-2/

Lattice starting to contribute to LBL & HVP
T. Blum et al., arXiv:1801.07224

HVP calculated using dispersion relation plus experimental data from ee→hadrons
→ MUonE will improve experimental input

See Phiala Shanahan's talk at ICHEP
https://indico.cern.ch/event/686555/timetable/#20180711



3ppb

22ppb

0.0003ppb

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

Category	E821 [ppb]	E989 Improvement Plans	E989 [ppb]
Gain changes	120	• Better laser calibration • Low-energy threshold	20
Pileup	80	• Recording low-energy samples • Segmented Calorimeters	40
Lost muons	90	• Better collimation in ring	20
CBO	70	• Higher n value • Better match of beamline to ring	< 30
E and pitch corrections	50	• Improved tracker • High precision storage ring simulation	30
Total	180	**Quadrature Sum for $\delta\omega_a$ (syst.)**	70

Detector Team

Ring Team

Detector Team