Imperial College London

Charged lepton flavor experiments

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IOP HEPP 2018, Bristol

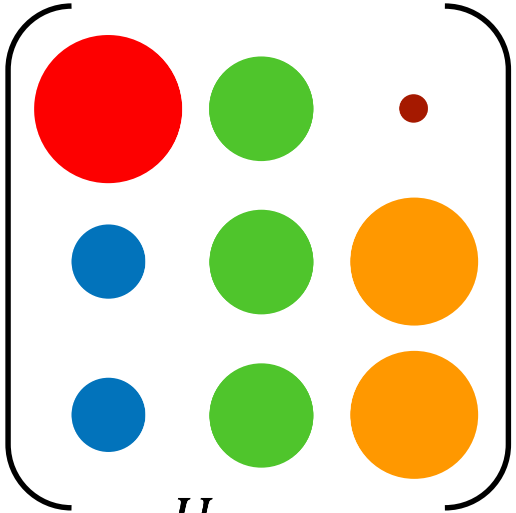
Lepton flavor

Very simple in the Standard Model

- 3 LH weak doublets + 3 weak RH singlets
- No neutrino masses
- So label everything by $\ell^{\pm}$ Higgs couplings (aka masses)
- Go home early [23rd August 1998]

But the SM is not correct. Neutrinos do have masses!

- We don't know how they get it, but
  we now have another basis to work in.
- And it looks nothing like the $\ell^{\pm}$ basis ▶



U_{PMNS}

Conclusion:

There is little reason to suppose the $\ell^{\pm}$ mass basis would be used by new physics either.

Adding new physics

Consider 2 possible types of flavour structure for new interactions:

1. Aligns with mass states (e, μ, τ), but couple differently to each (like mass terms). How can we detect this?
   - SM doesn't predict masses, but does predict how masses affect magnetic moments. **Check this → $\boldsymbol{g-2}$**
2. Does not align to mass states (like neutrino mixing): (Almost) inevitably gives rise to flavour changing effective operators
   - Look for flavor transitions without neutrinos → $\boldsymbol{\mu \to e\gamma}$**,** $\boldsymbol{\mu N \to eN}$**,** $\boldsymbol{\mu \to eee}$ etc

$g_\mu - 2$:

$g-2$ (FNAL) and $g-2$ (J-PARC)

“The big move” - the Brookhaven ring arrives at Fermilab

Anomalous magnetic moment

Magnetic moment of spin-½ fermions:

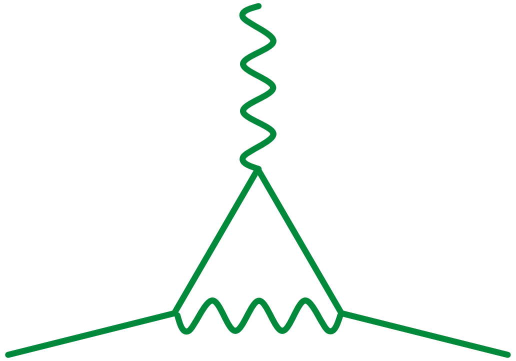
$$\boldsymbol{\mu}_f = g_f \frac{q}{2m_f} \boldsymbol{s}$$

The Dirac equation gives $g_f = 2$.

Further 'anomalous' corrections $a_f = \frac{1}{2}\left(g_f - 2\right)$ arise from QFT.

Expand with perturbation theory: 1st order QED term by Schwinger:

$$\frac{g_f}{2} \simeq 1 + \boldsymbol{\frac{\alpha}{2\pi}} + \cdots$$



More corrections

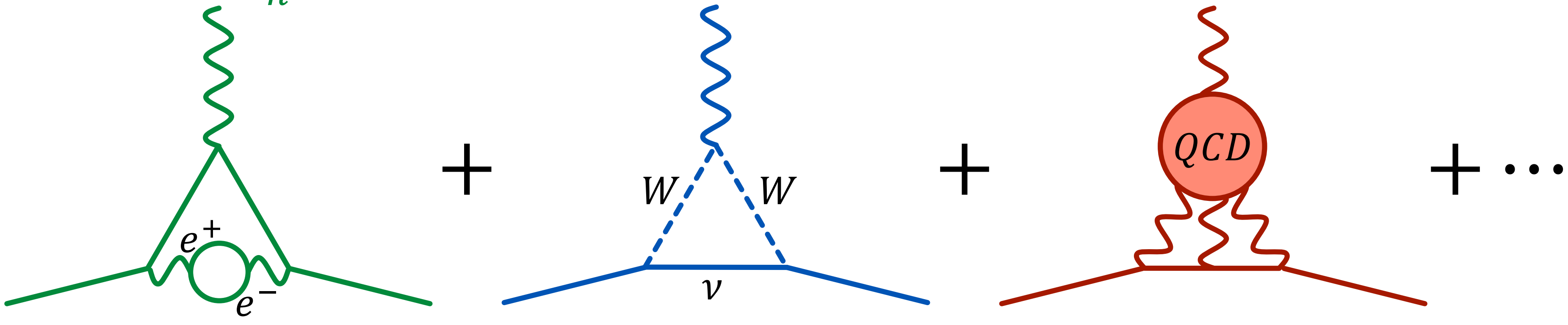
Since we can measure g very precisely, we need lots of terms in the anomalous part:

$$a = 1 + \Delta a_{\text{QED}} + \Delta a_{\text{EW}} + \Delta a_{\text{Had}} \ (+\Delta a_{\text{BSM}}?)$$

And, for example,

$$\Delta a_{\text{QED}} = \sum_n C_n \left(\frac{\alpha}{\pi}\right)^n$$

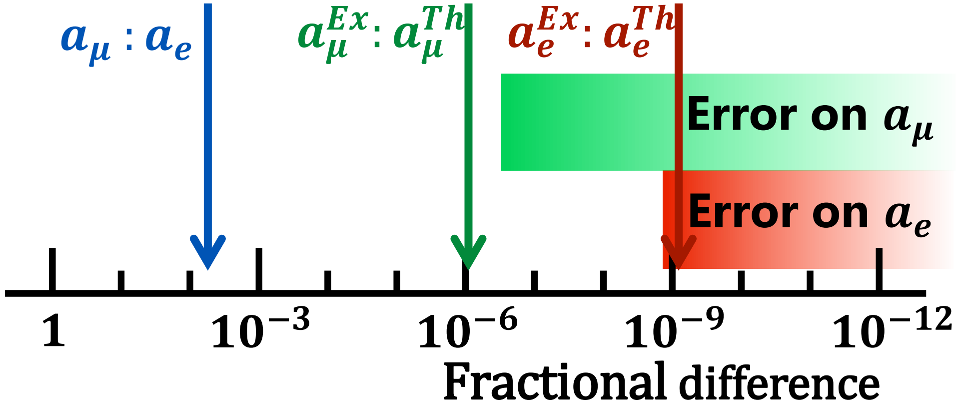
$$\frac{g_f}{2} \simeq 1 + \sum_n^{(4)} C_n \left(\frac{\alpha}{\pi}\right)^n \quad + \quad \Delta a_{\text{EW}} \quad + \quad \Delta a_{\text{Had}}$$



Discrepancy

Corrections depend on **flavor**

For a_e, theory and experiment famously agree to 9 s.f.

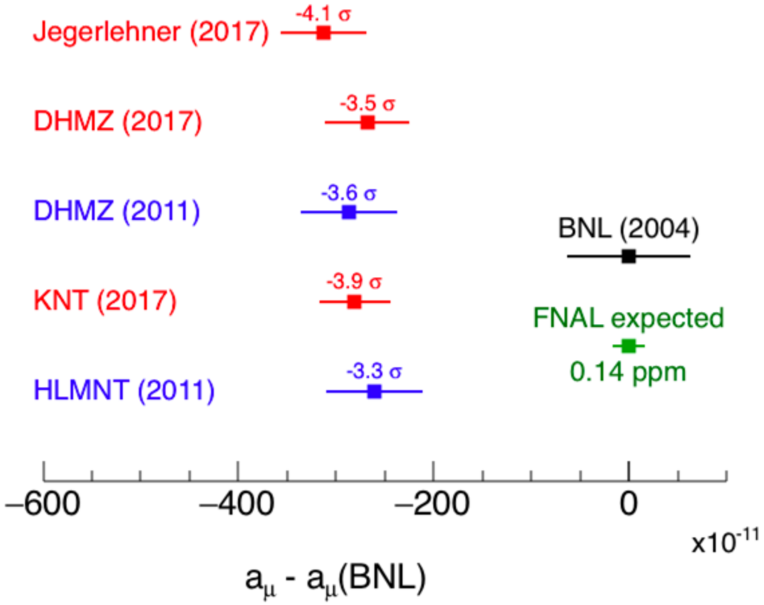


For a_μ things are not quite so good:

- Estimated error 200× larger
- But not as large as the discrepancy

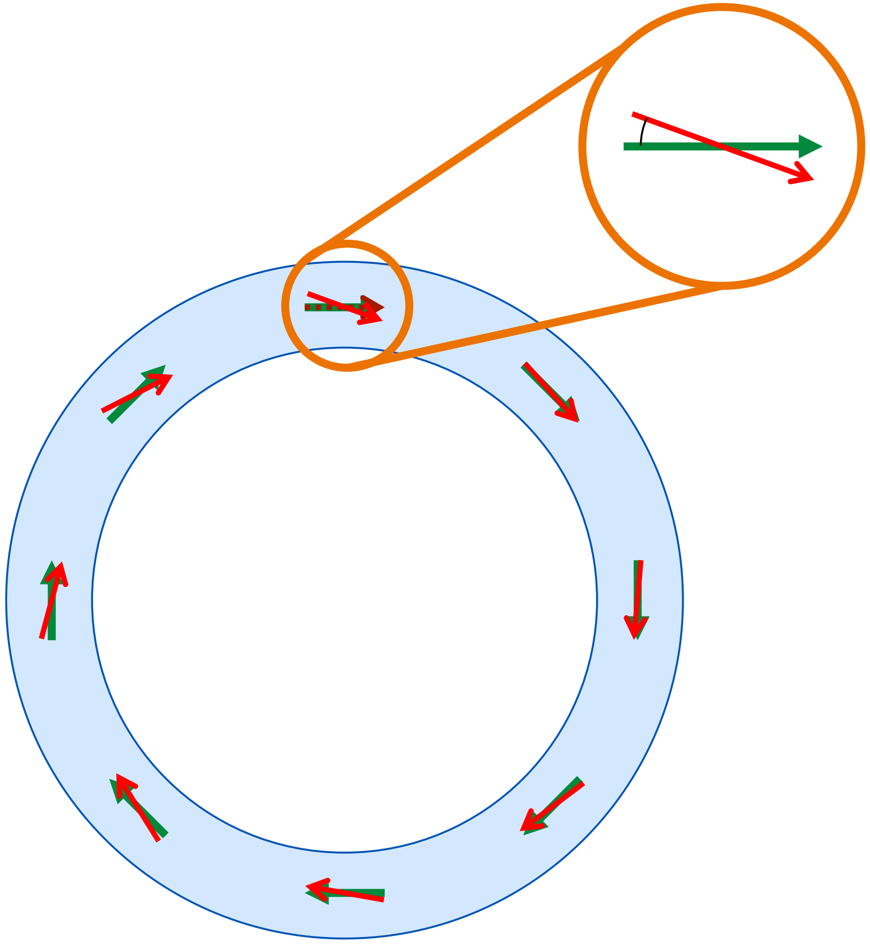
Theoretical error is shrinking.

- Now better than previous measurement (BNL), but dominate after new measurement at FNAL



Measurement of $g_\mu - 2$

$$\boldsymbol{\omega}_a = \boldsymbol{\omega}_s - \boldsymbol{\omega}_c = -\frac{q}{m\mu}\left[a_\mu \boldsymbol{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{\simeq 0 \text{ at } \gamma = 29.3 \; (p \simeq 3\mathrm{GeV/c})} \frac{\boldsymbol{\beta} \times \boldsymbol{E}}{c}\right]$$



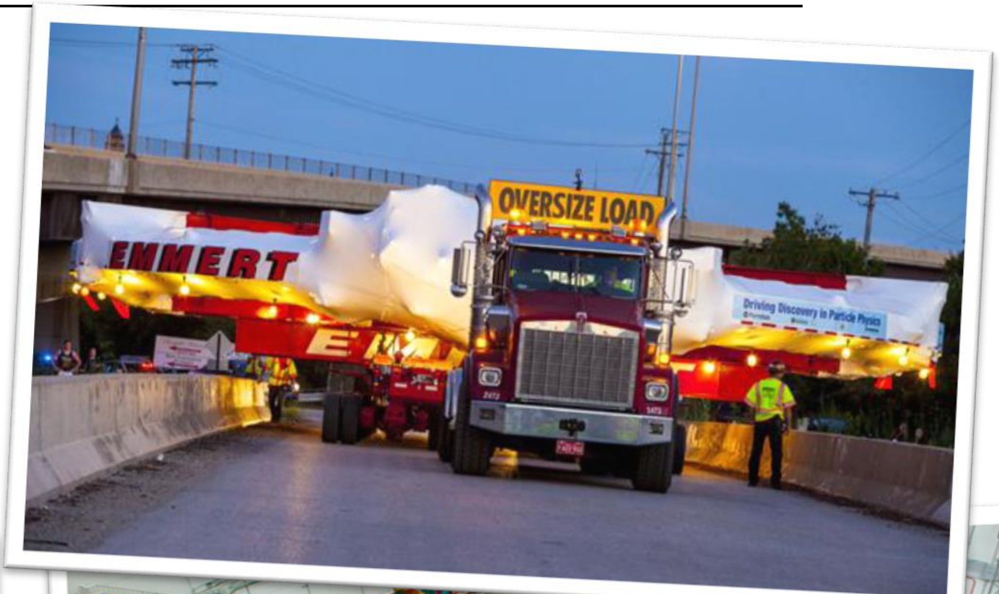
Inject polarised μ^+ into Penning trap

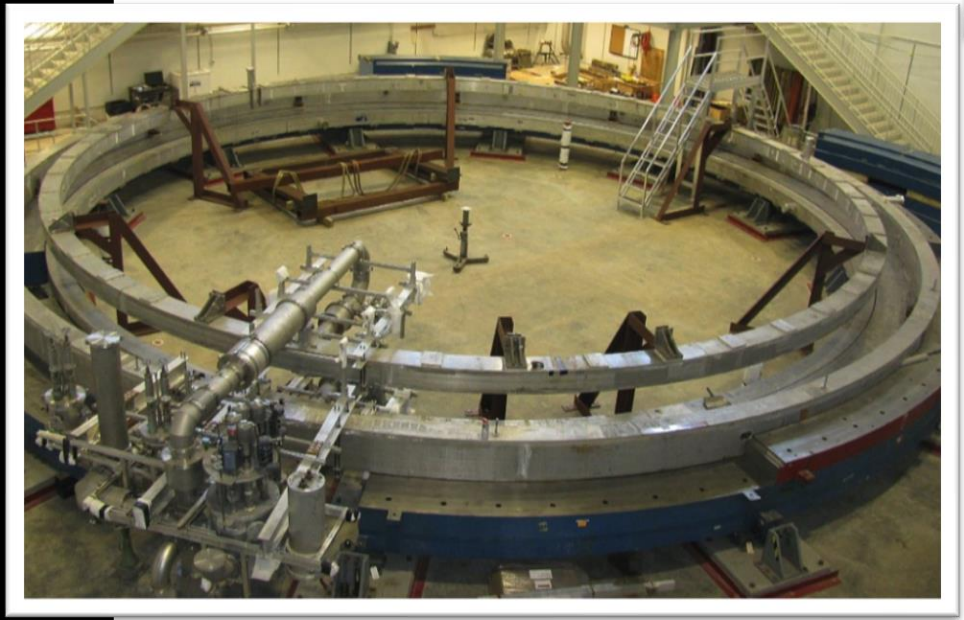
- Spin precession and momentum rotation get out of alignment at frequency ω_a
- Energy and rate of positrons in decay depends on $\boldsymbol{s} \cdot \boldsymbol{p}$

Therefore **can see oscillation at $\boldsymbol{\omega}_a$ in rate of high-energy e^+**

g – 2 at FNAL

Refurbish the most recent (BNL) experiment with **more muons**, **more detectors**, and **better control of systematics**

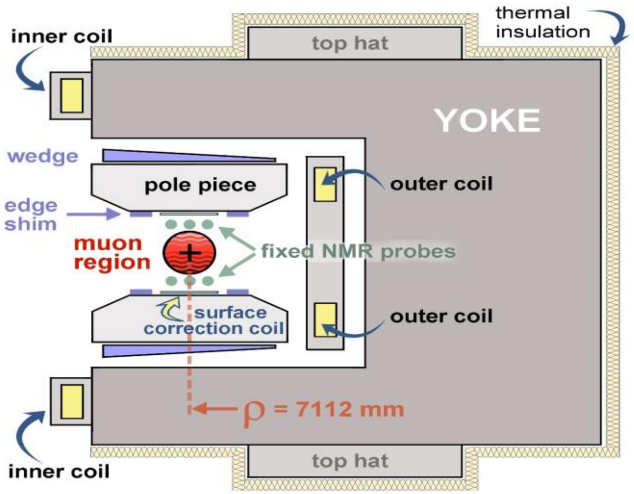




Upgrades since BNL


Straw trackers [UK]

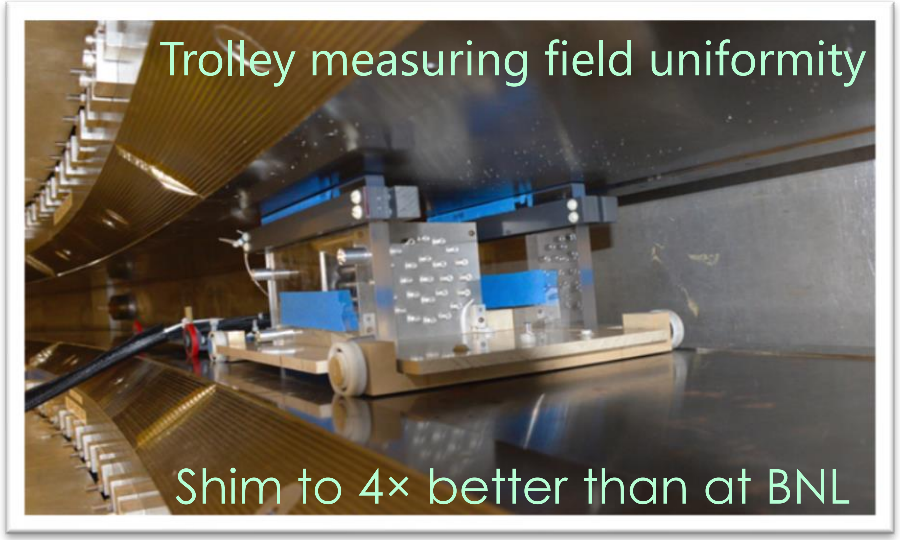
monitor beam position



g-2 Magnet in Cross Section

Repurpose the $\overline{p}$ source at Fermilab as a pion decay ring.

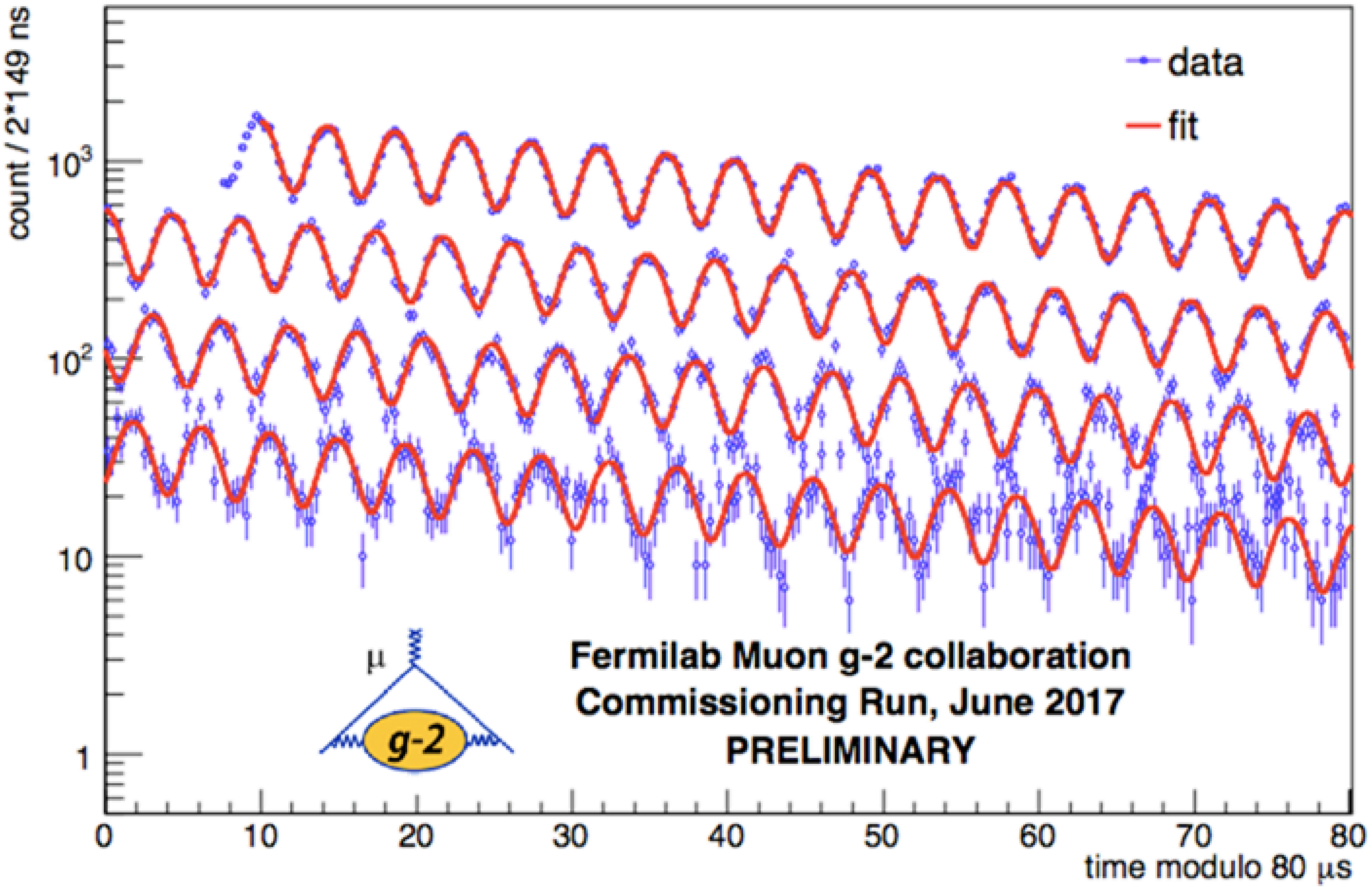
- More muons overall (20×BNL), but lower bunch intensity
- Cleaner bunches with lower pion contamination.


Trolley measuring field uniformity

Shim to 4× better than at BNL

Et voilà !

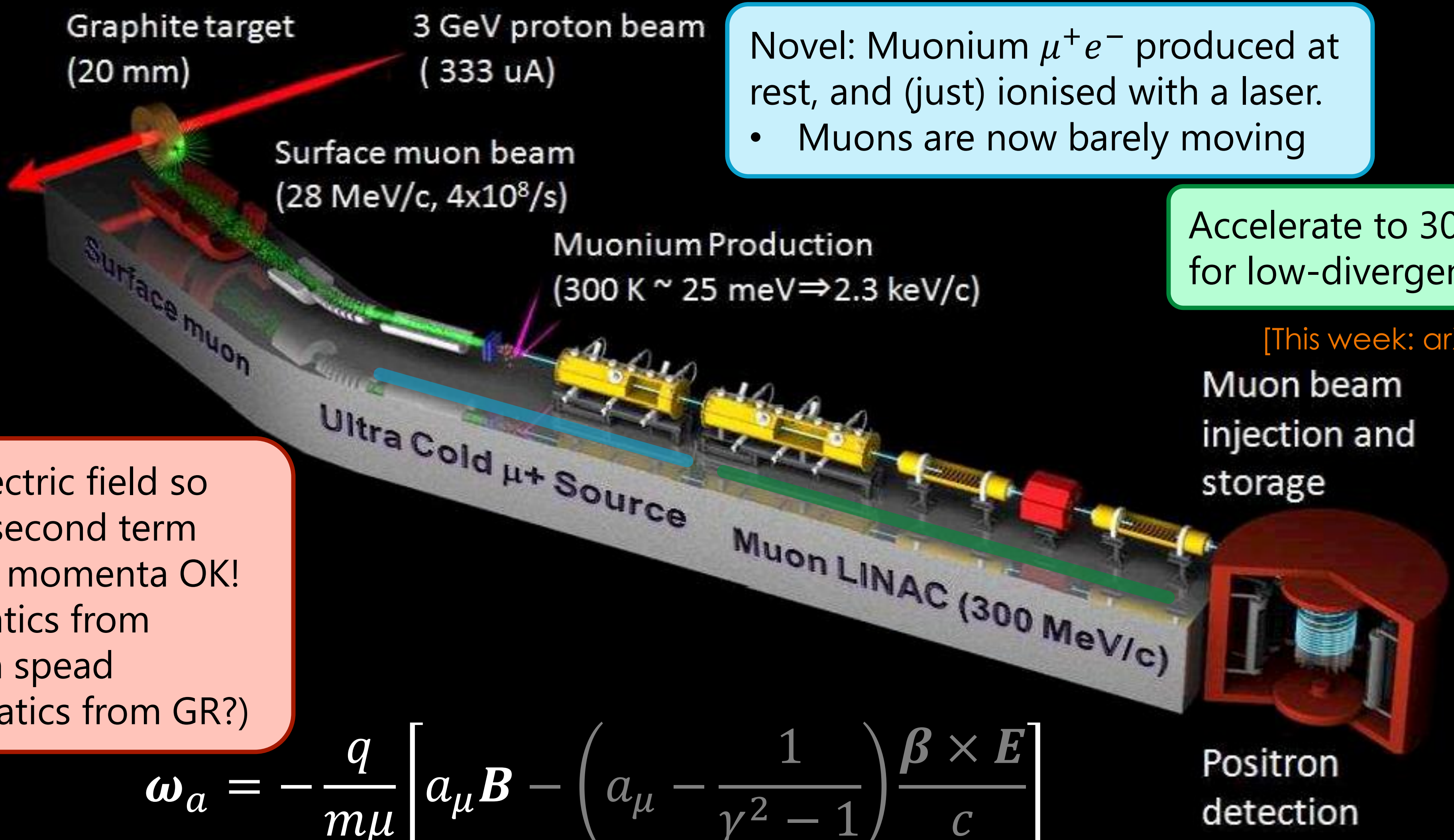
Number of high energy positrons as a function of time



BNL-sized dataset expected by this summer.

Full (20×BNL) dataset by 2020 → 0.14 p.p.m

JPARC $g_\mu - 2$



Novel: Muonium $\mu^+ e^-$ produced at rest, and (just) ionised with a laser.

- Muons are now barely moving

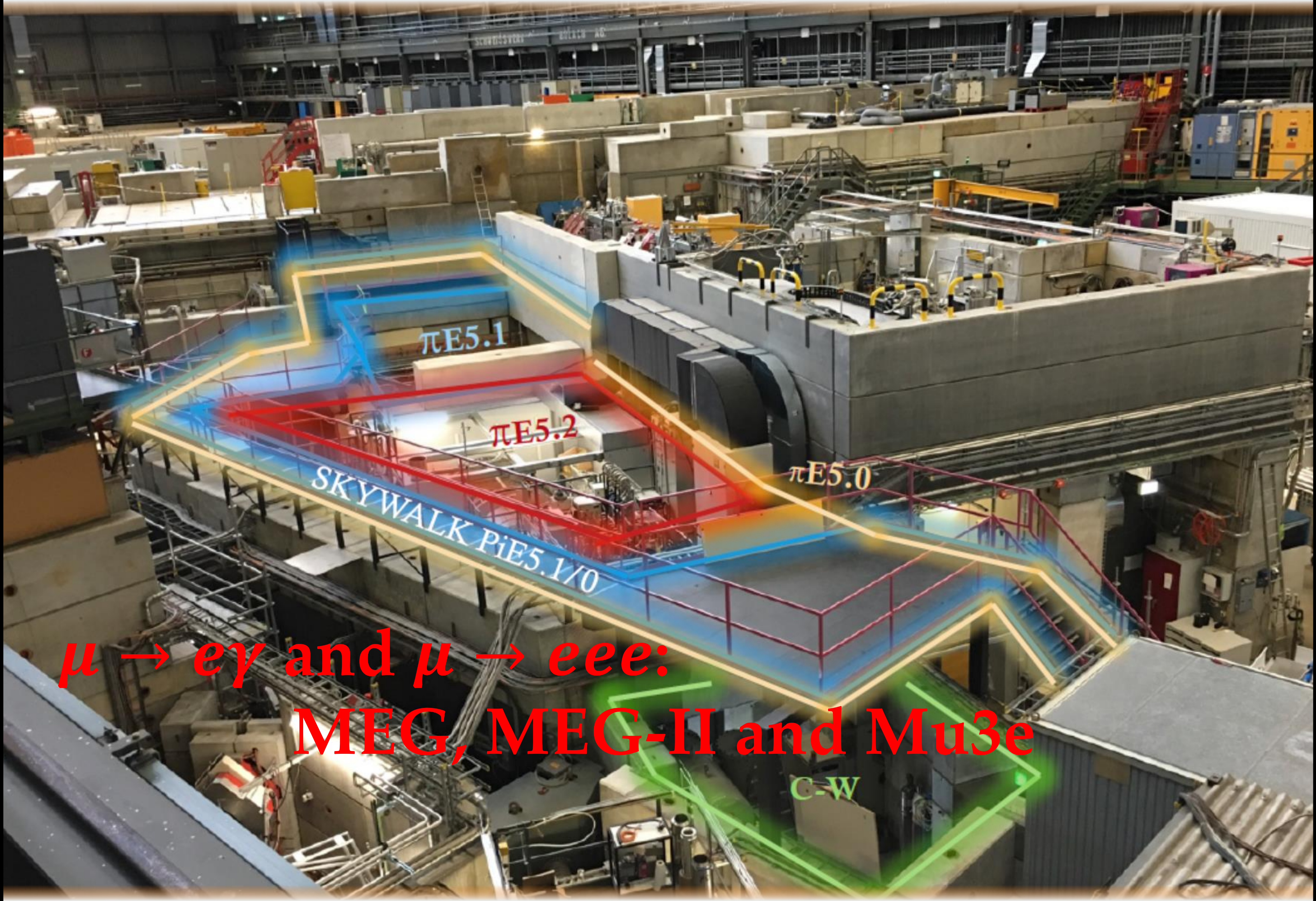
Accelerate to 300MeV/c for low-divergence beam

[This week: arXiv:1803.07891]

Don’t need electric field so eliminate the second term
→ Non-magic momenta OK!
→ No systematics from momentum spead
→ (No systematics from GR?)

NMR sized magnet is easier to get uniformity

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

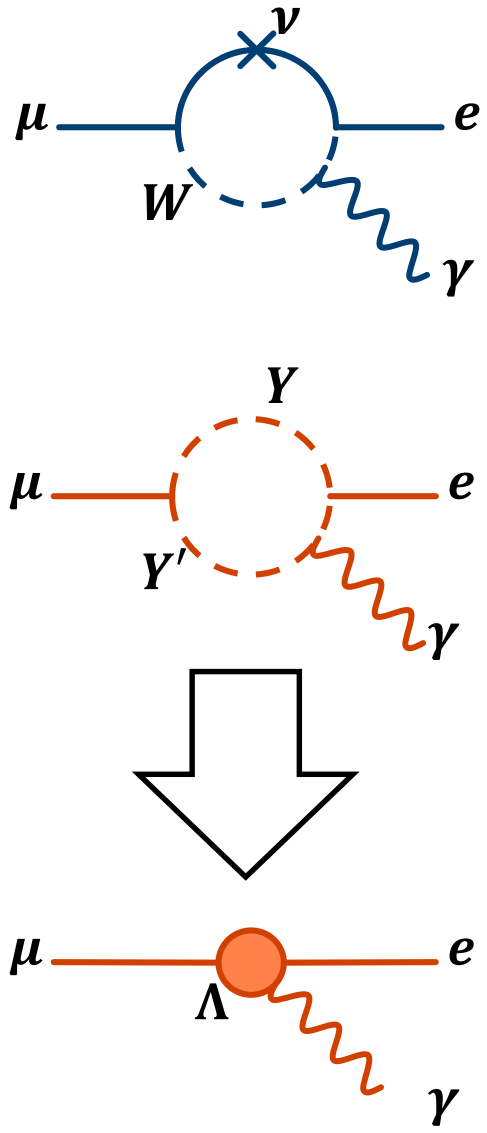


$\mu \to e\gamma$ and $\mu \to eee$:

MEG, MEG-II and Mu3e

The πE5 area at PSI – home to MEG and Mu3e

$\ell \rightarrow \ell'$ transitions



In the **ν+SM**, lepton flavour transitions are supressed by $\mathcal{O}(10^{-54})$ because of the mass disparity between the W and neutrino.

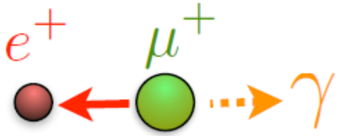
This is 'accidental'; **new physics** that doesn't go via light neutrino states is not suppressed.

Therefore can search for *effective operators* with extremely large mass scales:

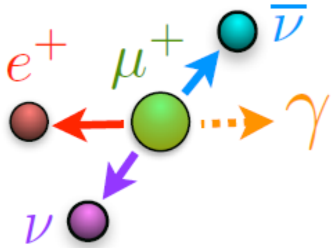
- No symmetry forbids this - it's even predicted by the ν+SM
- But **SM background is tiny** (~40 orders of magnitude below current limits)
- Almost all BSM models produce large enhancement, unless *deliberately* excluded.

Principles of a $\mu \rightarrow e\gamma$ search

Use target to stop μ^+, which decay at rest

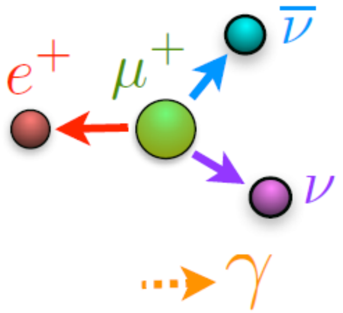


✓



✗

radiative decay



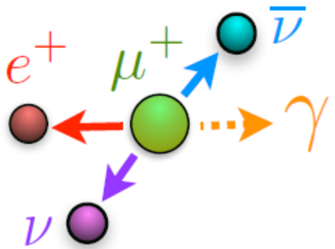
✗

accidental γ

Then 2-body decay should have:

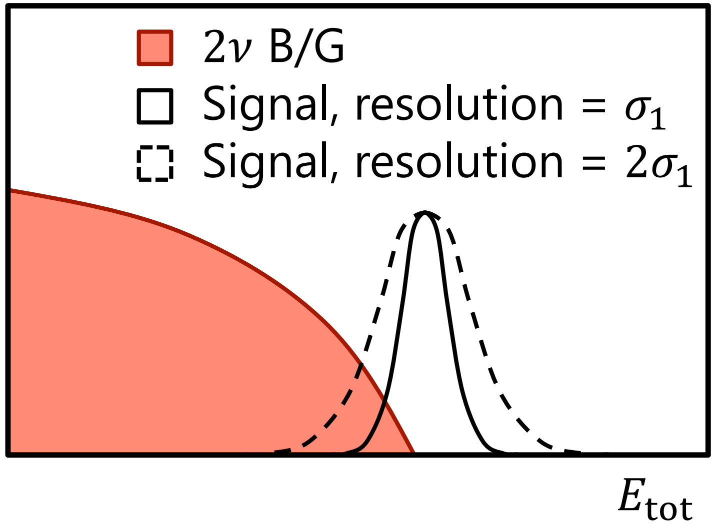
- **Back-to-back e^+ and γ**
  - Measure angles $\theta_{e\gamma}$ and $\phi_{e\gamma}$
- $\mathbf{E_e = E_\gamma = 52.8\ MeV}$
  - Measure energies E_e and E_γ
- **Coincident timing**
  - Measure time difference $t_{e\gamma}$

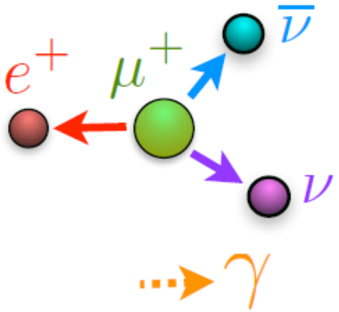
Remarks on backgrounds



In MEG and the other lepton flavor experiments there is pretty generally a SM equivalent process adding two neutrinos.

- A falling background that ends when neutrinos are at rest
- Minimise it by improving energy resolution.
- Requirement common to all experiments of this type





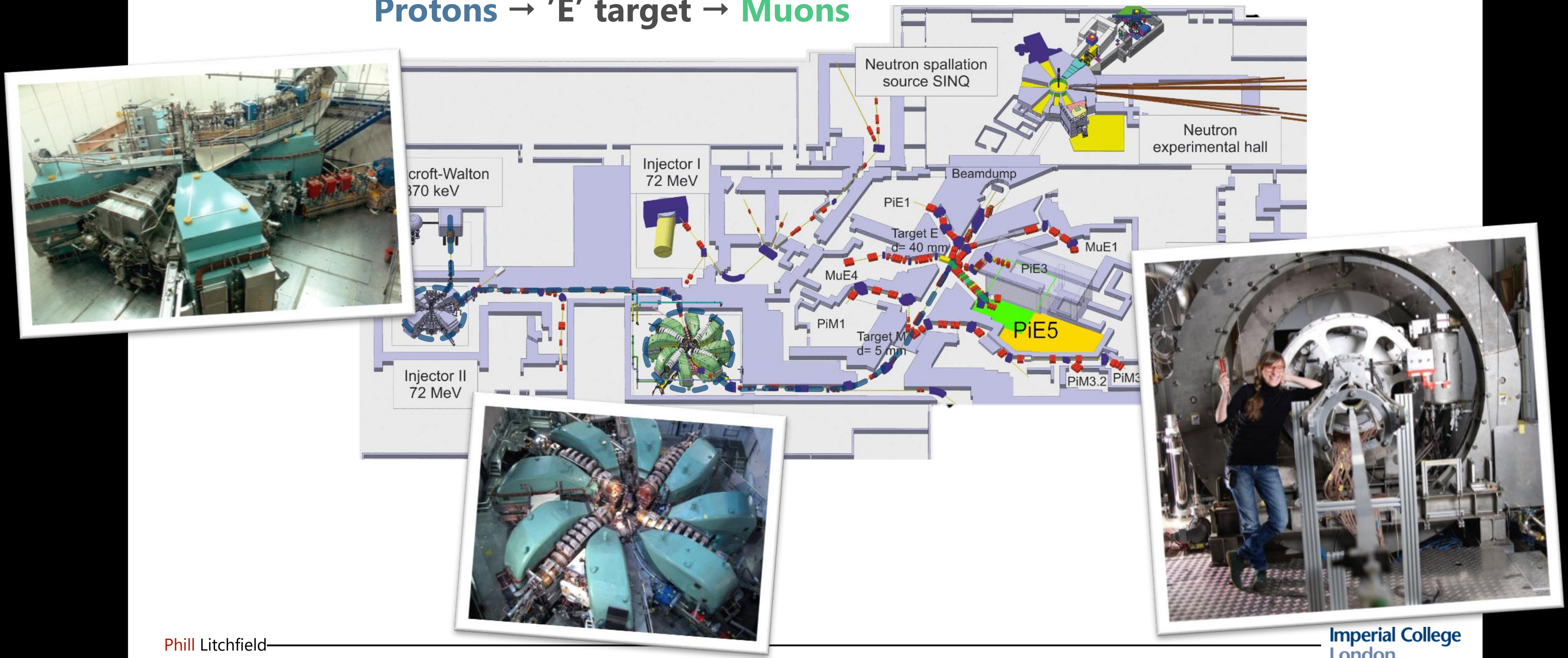
Also: Any *coincidence* measurement benefits from muons being spread out in time:

- Prefer DC beams (at cyclotrons)

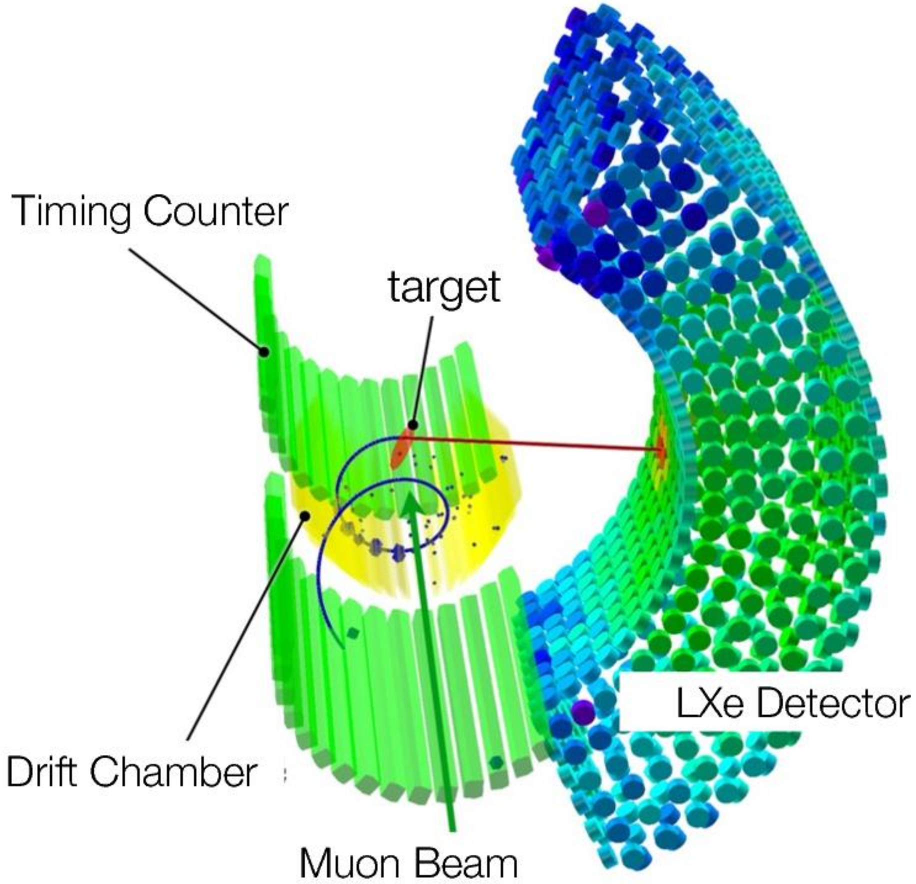
MEG at PSI

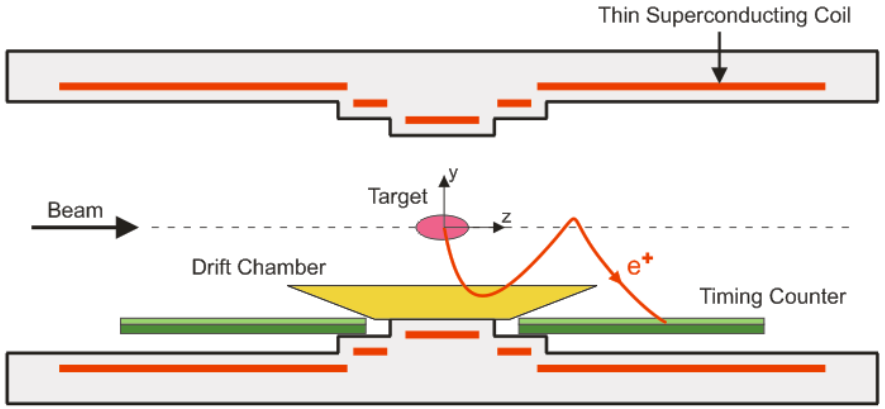
- DC muon beam from cyclotron ($10^7 \sim 10^8\ \mu/s$ at PiE5)
- Muons from low momentum pions: $p_\mu\ =\ 29\ \mathrm{MeV}/c$

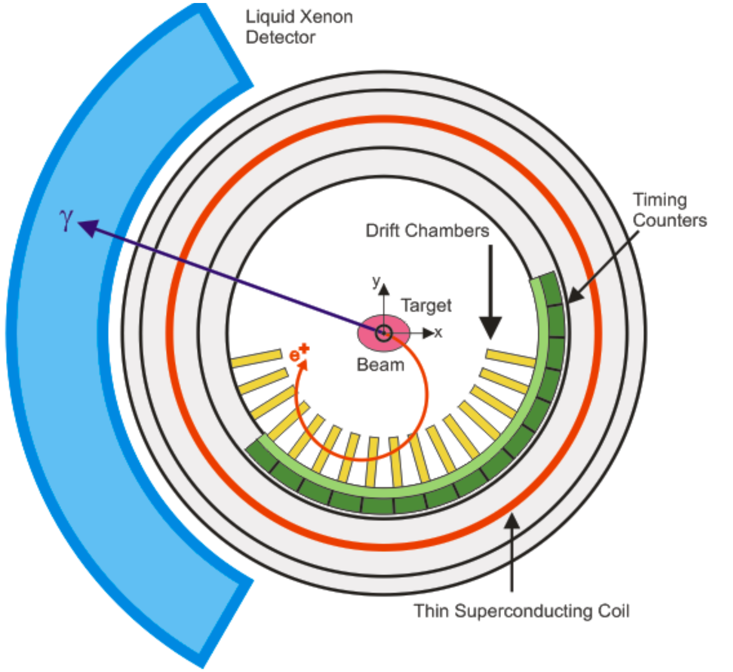
Protons → 'E' target → **Muons**



MEG in operation



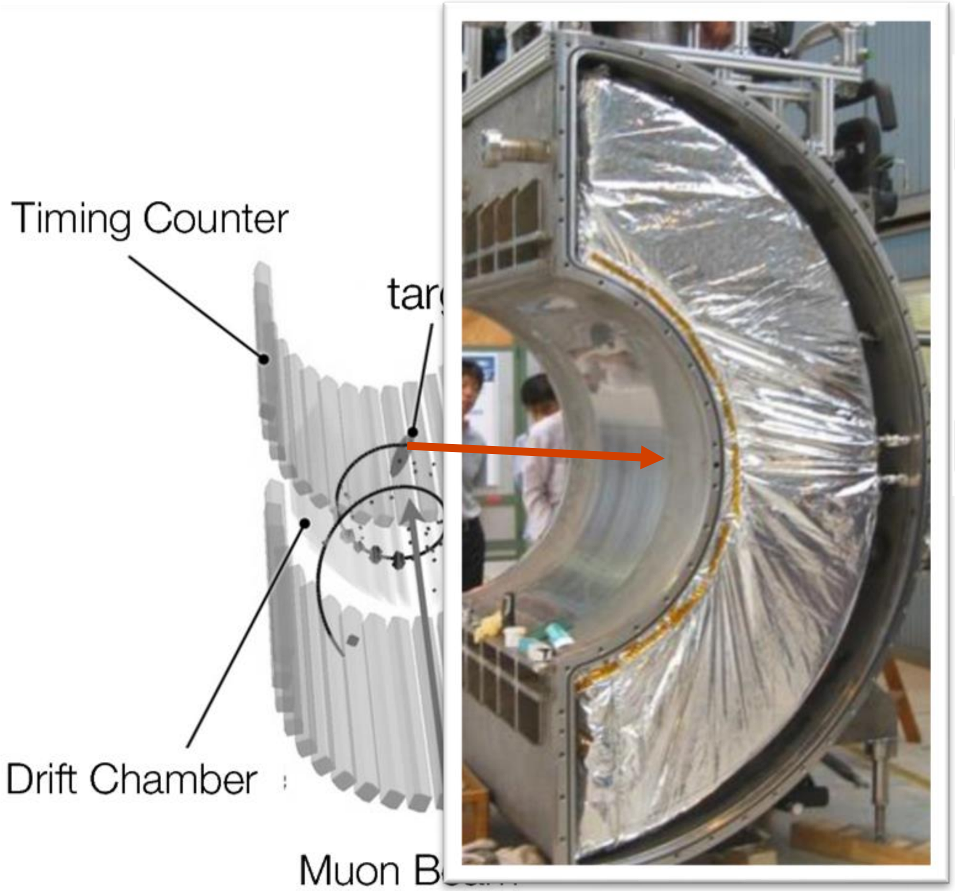


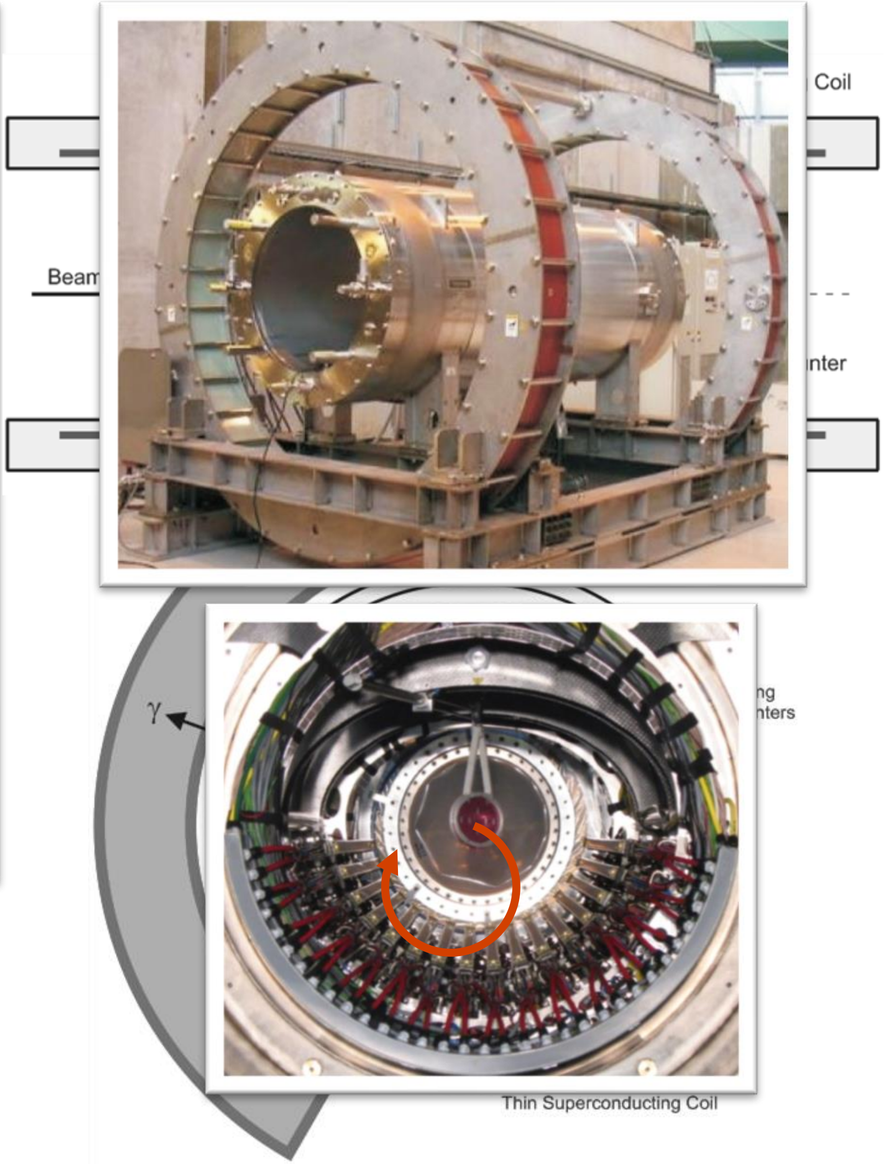


Highlights:

- 900-litre LXe calorimeter
- Very fancy COBRA solenoid

MEG in operation





Highlights:

- 900-litre LXe calorimeter
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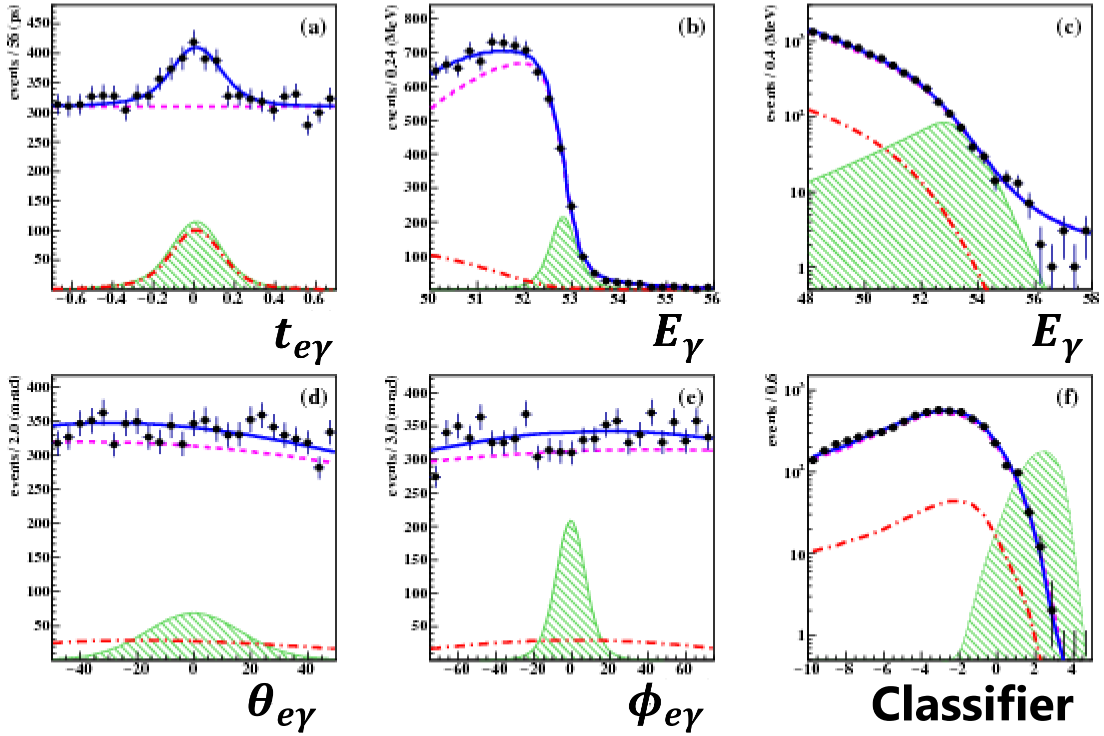
MEG Results



Signal @ 100x limit

Radiative decays

Accidental coincidence

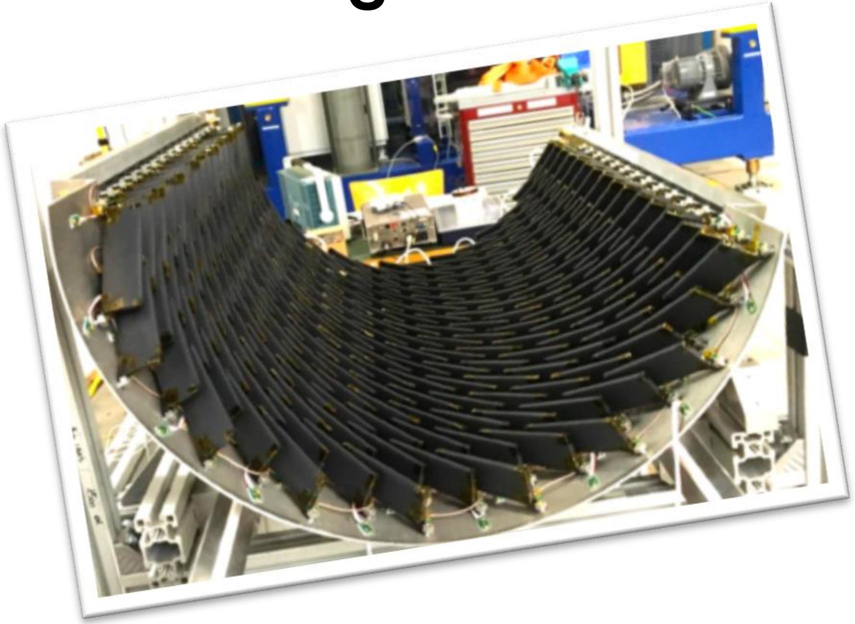
Variables combined into multivariate classifier

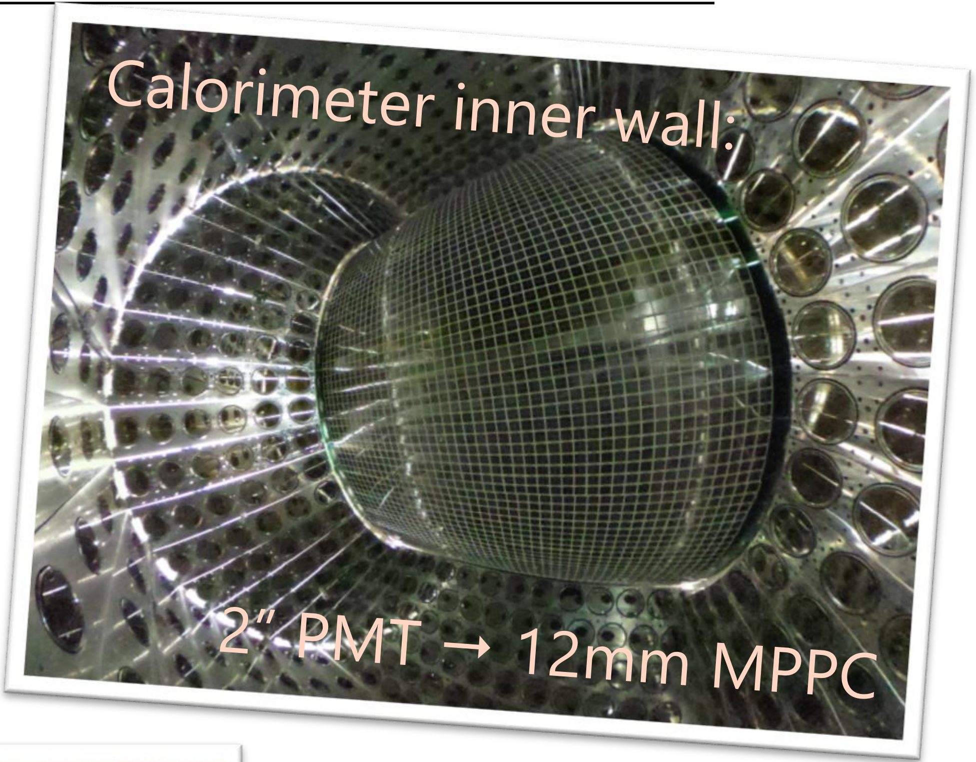
Final results (2017):

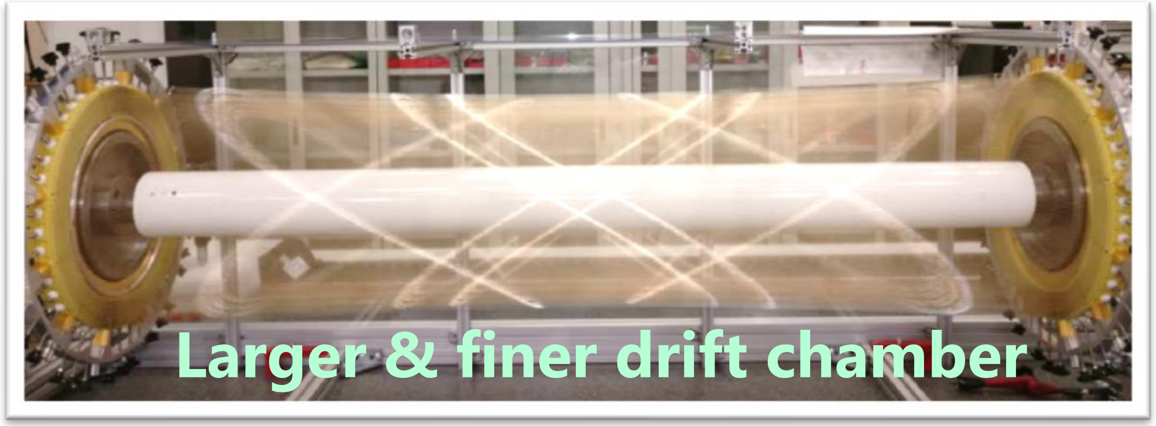
- **Didn’t see anything.**
- $\mathrm{Br}(\mu \to e\gamma) \leq 4.2 \times 10^{-13}$
  - Improved limit by ~30 over previous expriment (MEGA)

The Future: MEG-II

Tiled timing counter







+ DAQ upgrades

× 2 beam intensity

Aim for ×10 sensitivity

Mu3e at PSI

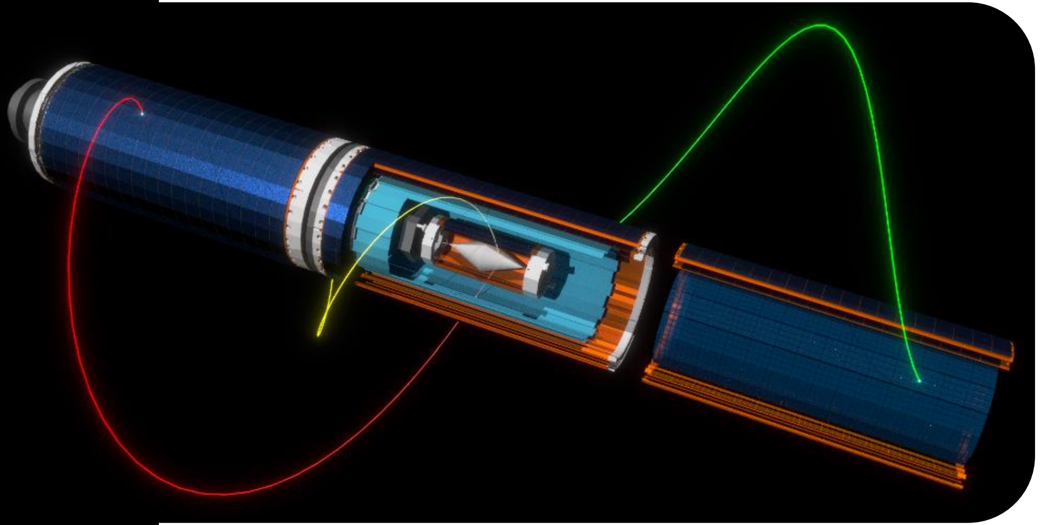
Looking for $\mu^+ \rightarrow e^+e^+e^-$, (hence the name.)

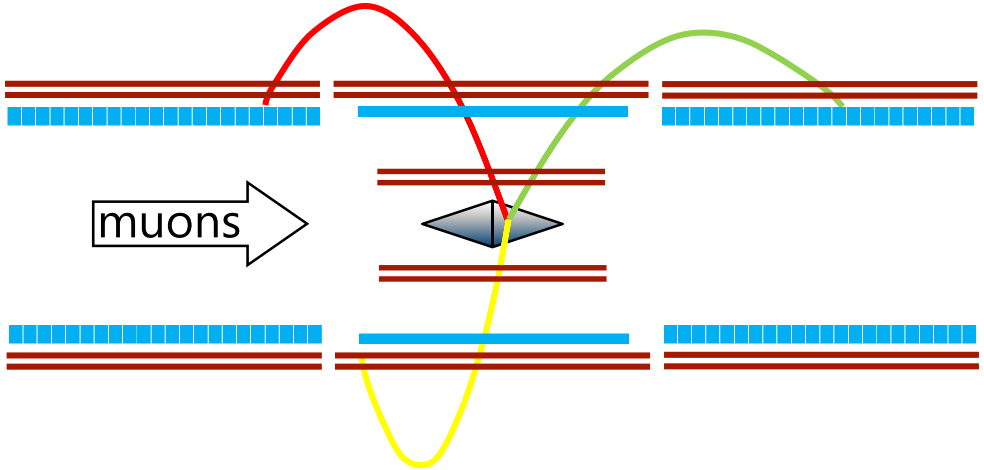
Can relate to $\mu \rightarrow e\gamma$ by SM conversion $\gamma \rightarrow ee$ but **direct process is also available** for (some) BSM operators

Principle is quite similar to $\mu \rightarrow e\gamma$:

- Use μ^+ at rest in minimal target
- Look for coincidence in **time** & **space**
- Need excellent **momentum resolution** (the ν-at-rest B/G again)
- Backgrounds from accidental coincidence
  - Again, want DC muon beam; so go to PSI
  - New Compact Muon beam at PiE5 (shared with MEG-II)

Mu3e detector

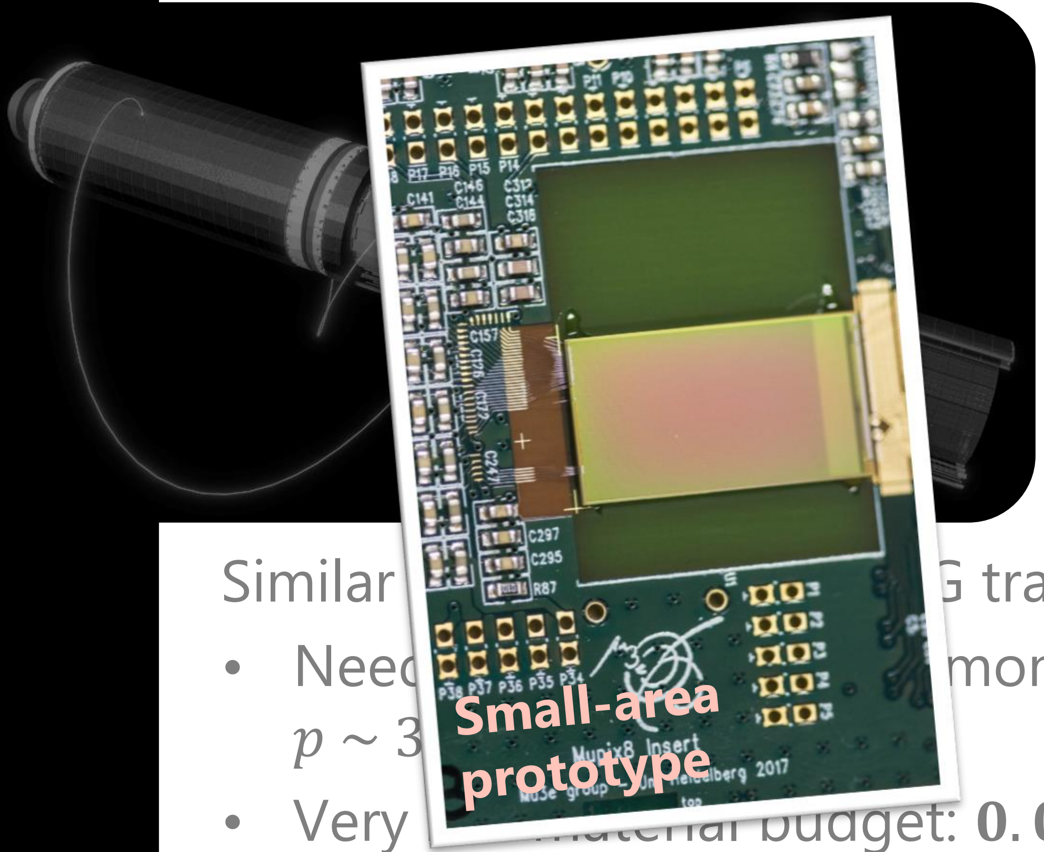




Similar requirements to MEG tracker [but 2π azumith]:

- Need good position and momentum resolution for electrons with $p \sim 30 \mathrm{MeV}/c$
- Very low material budget: $\mathbf{0.001}\ \boldsymbol{X_0}$ per layer
- Small scale: 18cm diameter → high radiation.
- Design uses novel pixel (HV-MAPS) sensors supported on an ultra-light (Kapton) frame

Mu3e detector



Similar … G tracker …

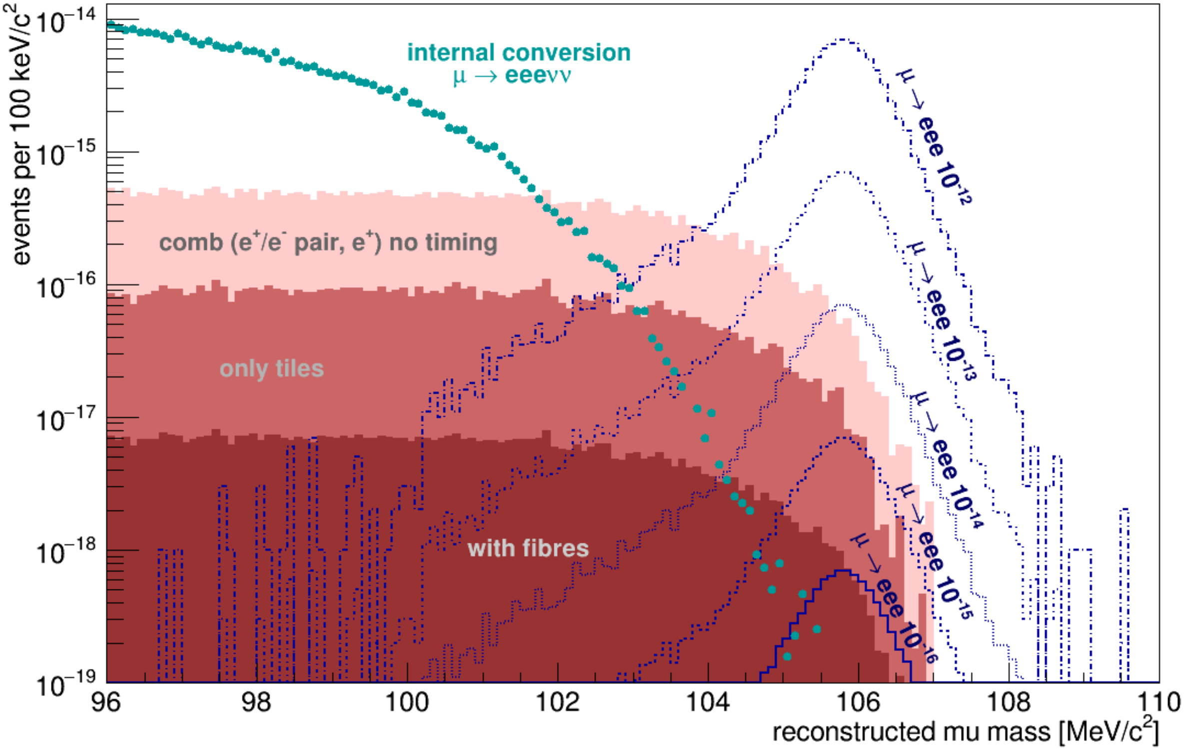
- Need … momentu… with $p \sim 3$…
- Very … material budget: $\mathbf{0.001\ X_0}$ per layer
- Small scale: 18cm diameter → high radiation.
- Design uses novel pixel (HV-MAPS) sensors supported on an ultra-light (Kapton) frame

Projected sensitivity

Need to supress accidental/combinatoric background to reach desired sensitivity

- Include scintillator fibre and tile detectors for timing
- Eliminate combinatoric B/G

Sensitivity goal:
BR($\mu \to eee$)
down to $\mathcal{O}(10^{-16})$



$\mu N \rightarrow eN$:

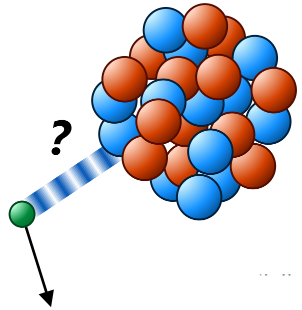
COMET and Mu2e

Lowering the 1st COMET transport solenoid into place

Muon conversion

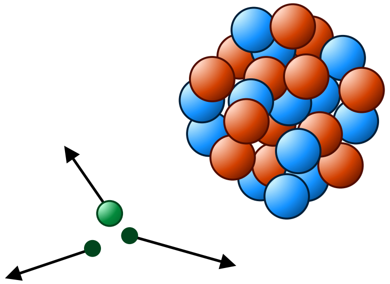
μ^- allowed to stop in suitable target → will capture to atomic $1s_\mu$

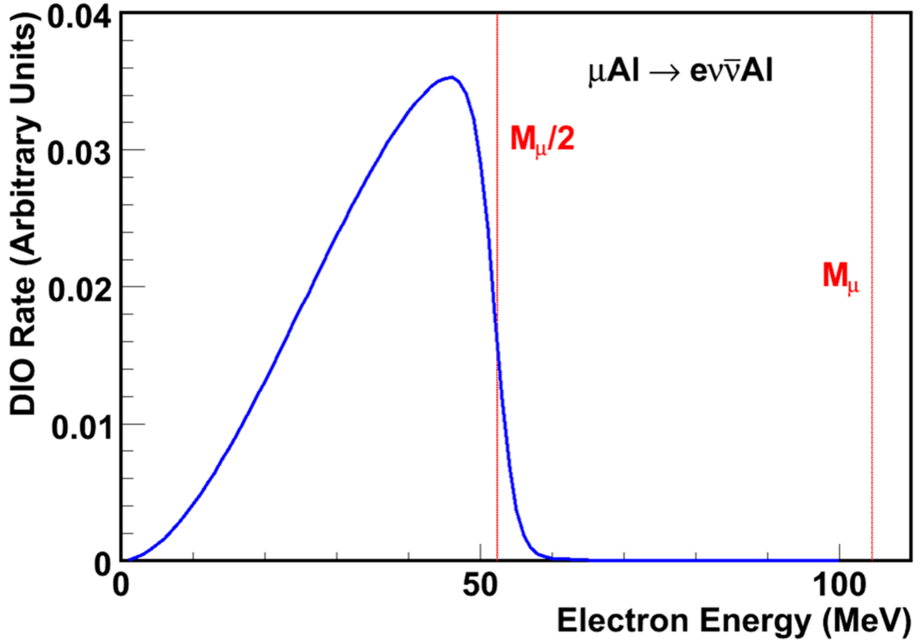
- Both experiments use **Aluminium**
- Conversion from 1s orbital: $\mu N \rightarrow eN$ gives a ***mono-energetic electron*** at 105MeV ($\approx m_\mu - B^\mu_{1s}$)



‘Normal’ Decay-in-orbit is a background to be avoided

(Tail up to 105MeV is tiny, but non-zero)





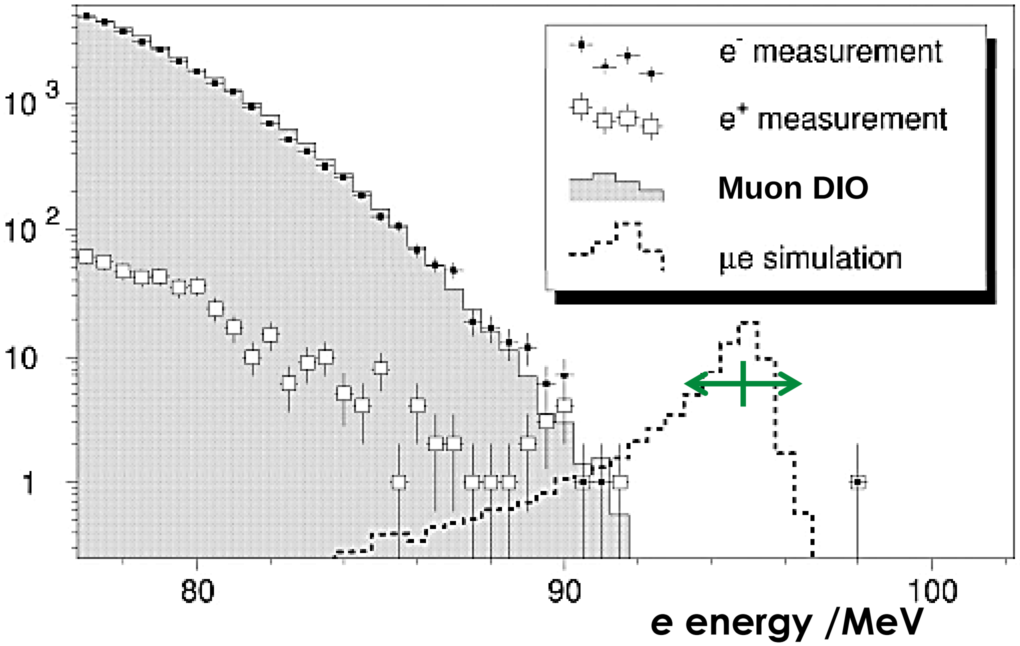
Backgrounds

Three main background processes:

- **Decay in orbit** ▶ **Energy resolution!**
- **Decay in flight**: Electrons from energetic free muons can be boosted to 105MeV.
  - Momentum selection so only slow muons in beam

SINDRUM-II (BR <7×10^{-13} @ 90%CL)

[Eur.Phys.J. C47 (2006) 337-346]



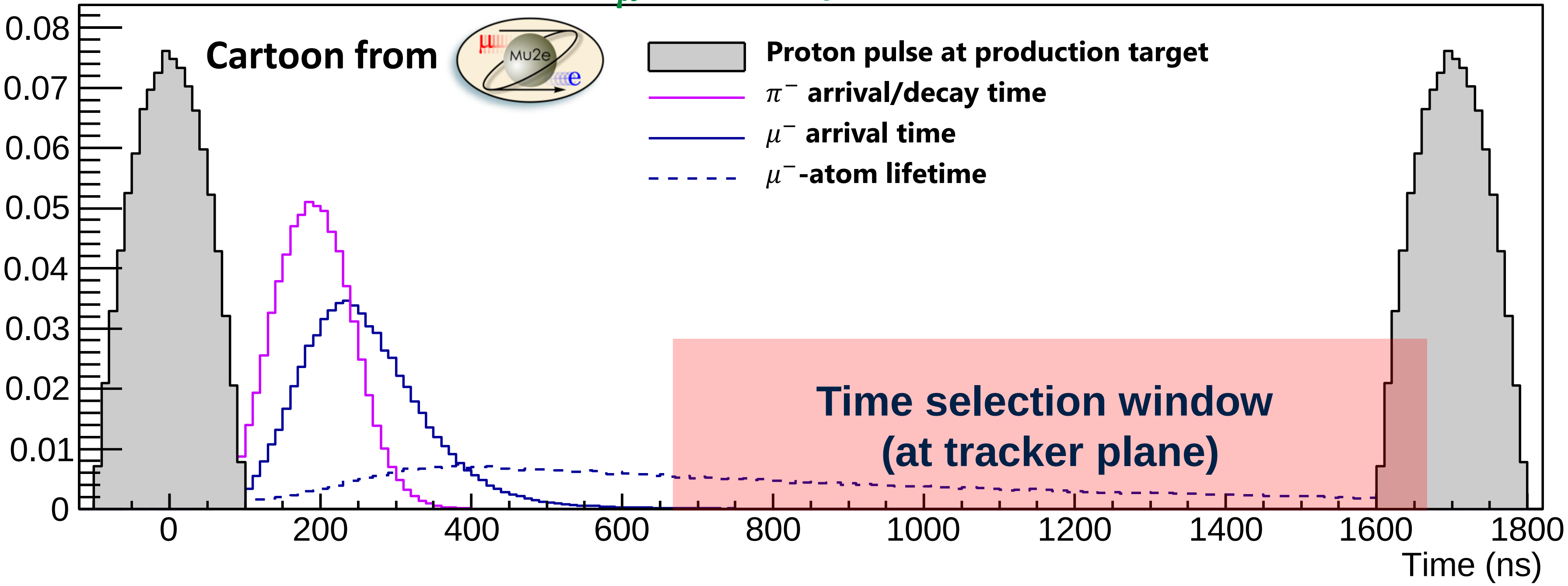
- **Beam backgrounds**: Significant number of prompt e^- and π^- produced by beam.
  - *Easy (in principle) solution: Bunch the muons and wait it out*
  - Possible because there is no combinatoric B/G

Waiting out the beam

Naïvely, this sounds easy, but…

- High intensity pulsed muon beams are uncommon → new facilities (J-PARC, FNAL muon campus)
- Require on interbunch gaps to be *extremely* free of particles
- Need $\boldsymbol{\tau_\mu} \gg \boldsymbol{\sigma_{\mathrm{Pulse}}}$ so choose stopping targets with long lifetime

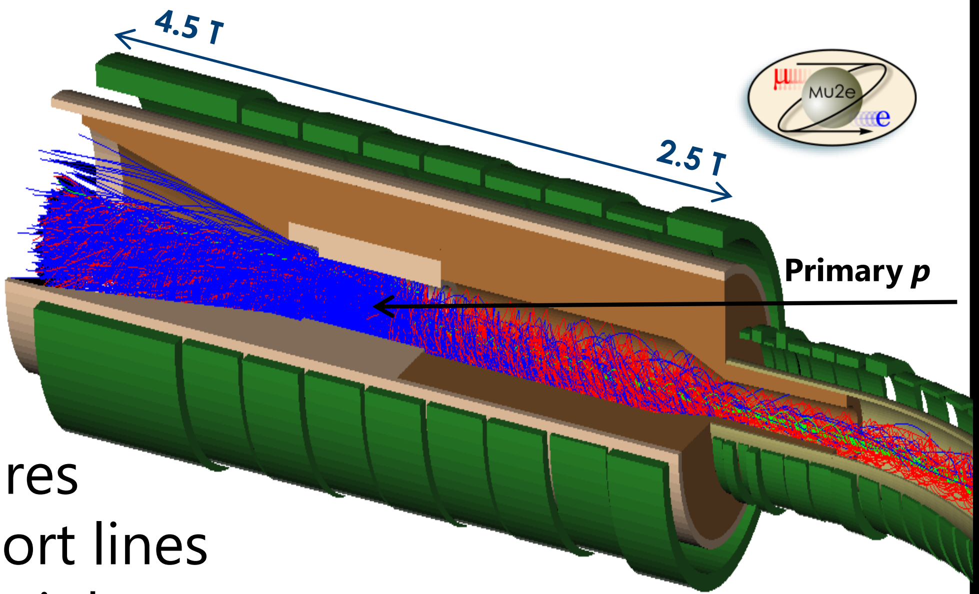
Al ($Z = 13, \tau_\mu = 0.88\mu s$) is ideal



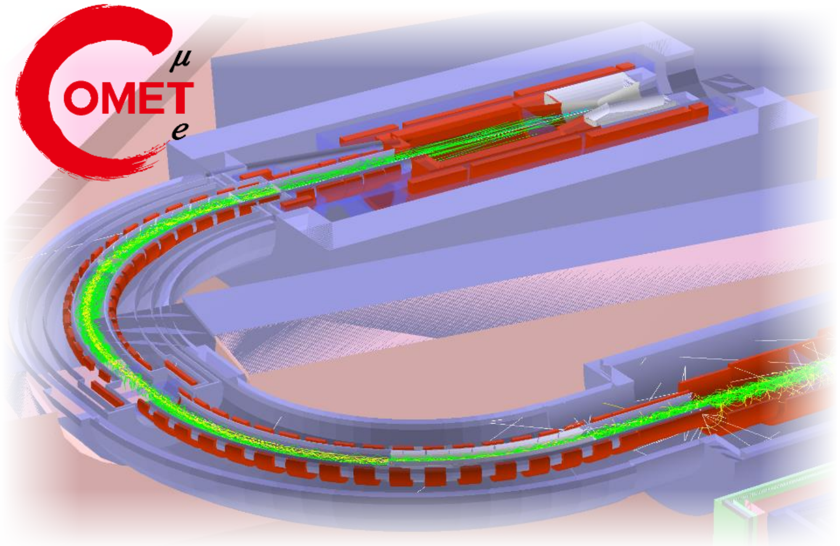
Muon source

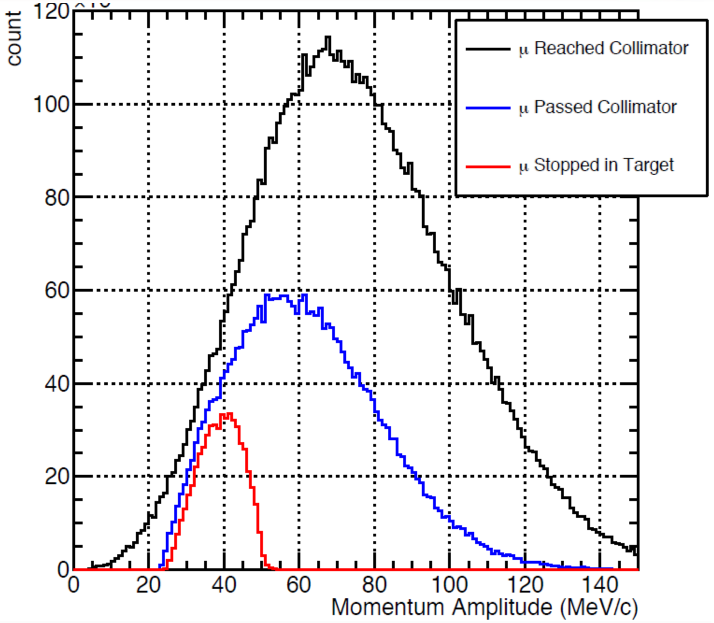
Main driver of sensitivity: Need lots of low energy muons!

- Use dedicated high-power *pulsed* proton beam lines (~8 GeV to limit $\overline{p}$ production)
- Resonant slow extraction onto pion production target
- Collect *backward*-going pions with capture solenoid
- Pions decay to muons en-route to stopping target.
- Many neutrons produced, requires careful shielding. Curved transport lines helps to eliminate direct line-of-sight.



Muon transport

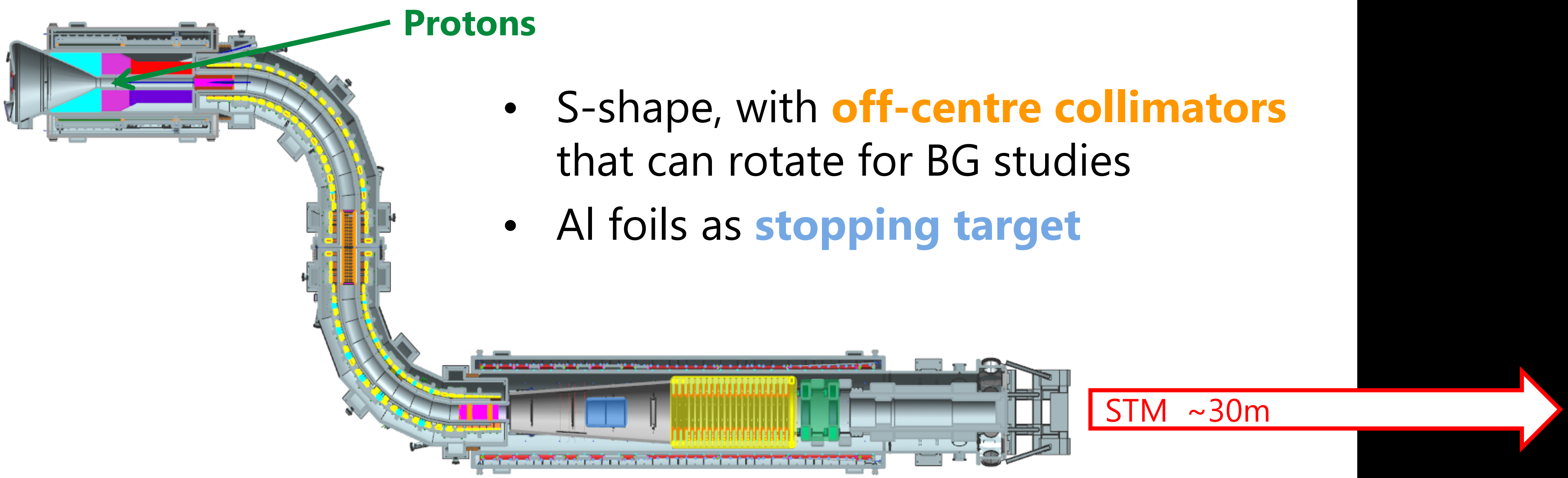




Muon transport is a **curved solenoid**

- Particles are channelled in **spiral paths [solenoid]**, which naturally tend **up/down [curvature]** depending on momentum and charge.
- Gives **charge sign and momentum selection**, enhanced by using a collimator.
- Use to eliminate high momentum muons, and other particles.

Mu2e overview



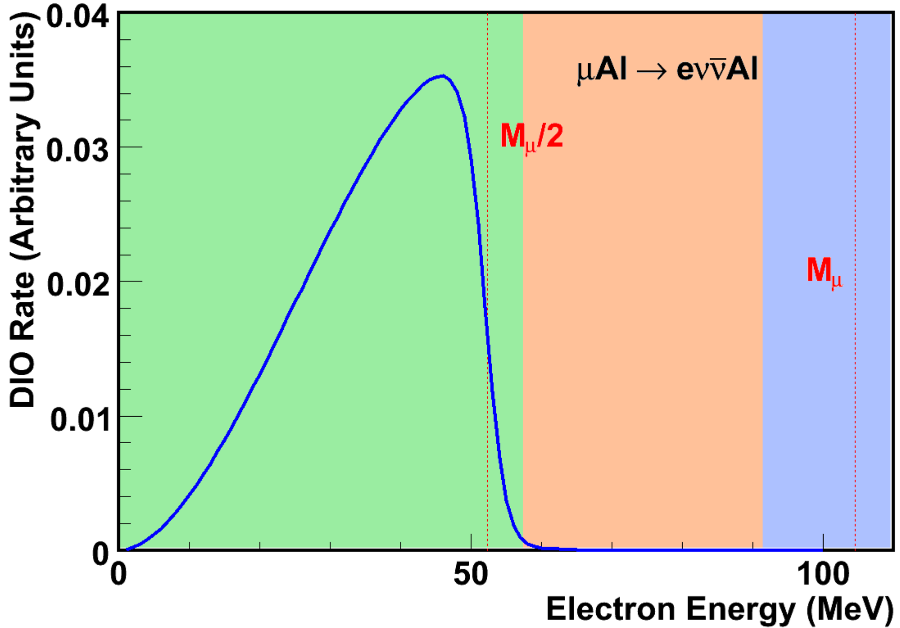
- S-shape, with **off-centre collimators** that can rotate for BG studies
- Al foils as **stopping target**

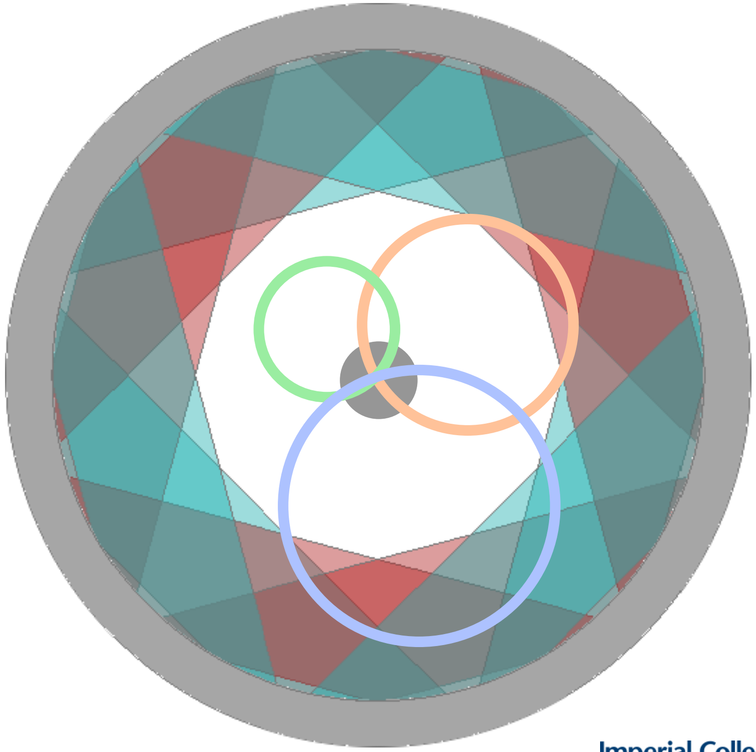
Target & detector surrounded by large aperture solenoid for (105MeV) electron transport

- Electrons spiral from target to ring-shaped **straw tracker** and **EM calorimeter**
- Downstream **Stopping Target Monitor** [UK] monitors muonic X-rays, for normalisation of muon capture rate

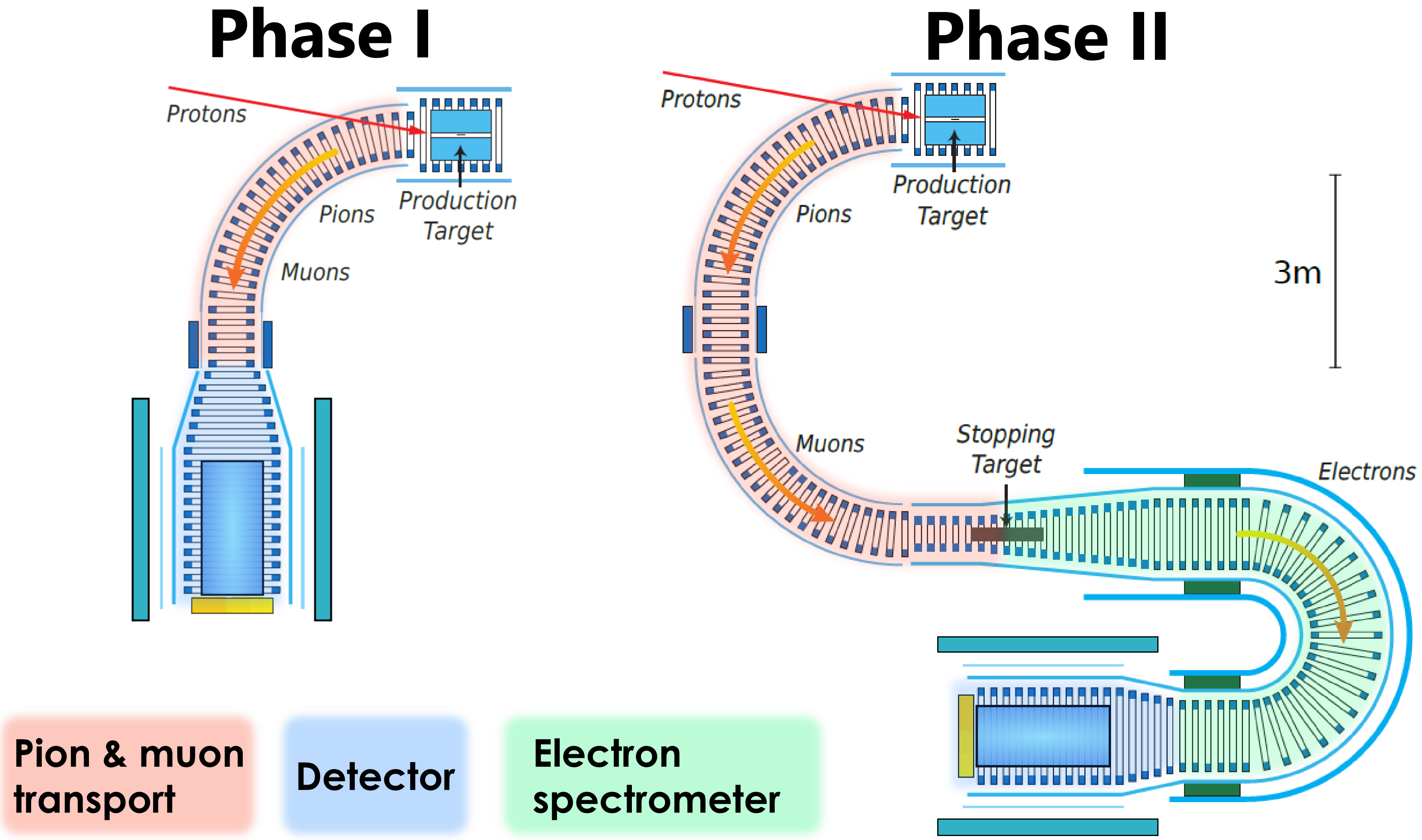
Mu2e detectors

- Straw tube tracker and high-resolution crystal calorimeter
- Inner radius of 380mm corresponds to $p_T \sim 60\text{MeV}/c$
- ‘Complete’ tracks in straws need $p_T > 90\text{MeV}/c$
- Centre has occupancy $\mathcal{O}(1)$ from Michel-like decays…
  - …and subject to even larger prompt pulse





COMET, Phase I and II



Phase I

Phase II

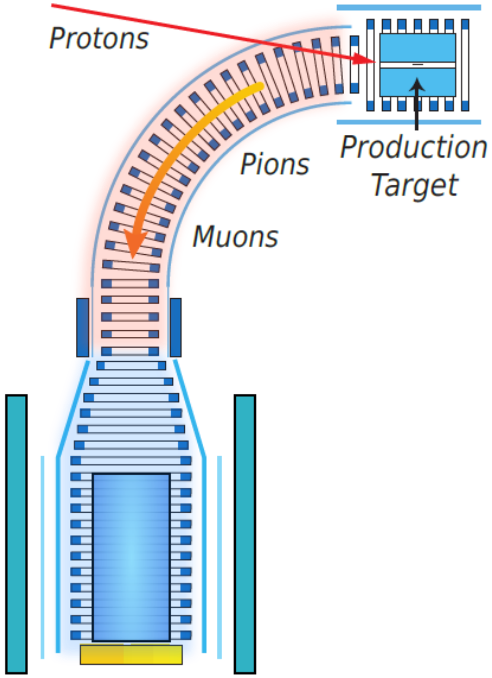
COMET: Phase-I

Dual purpose:

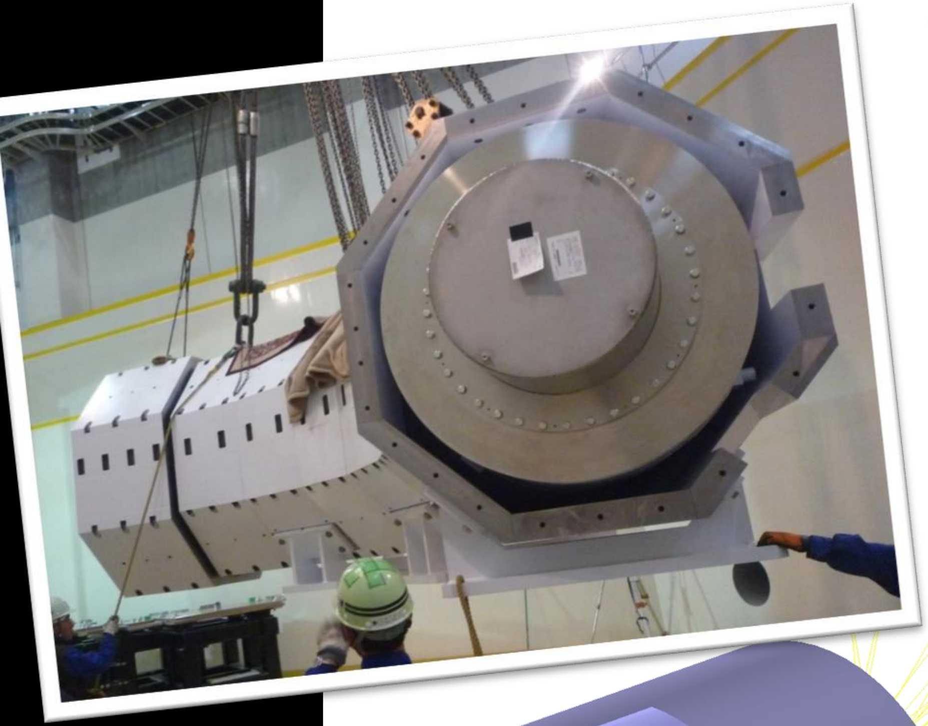
- Characterise beam transport and secondary pion yield
- Make an intermediate-sensitivity measurement

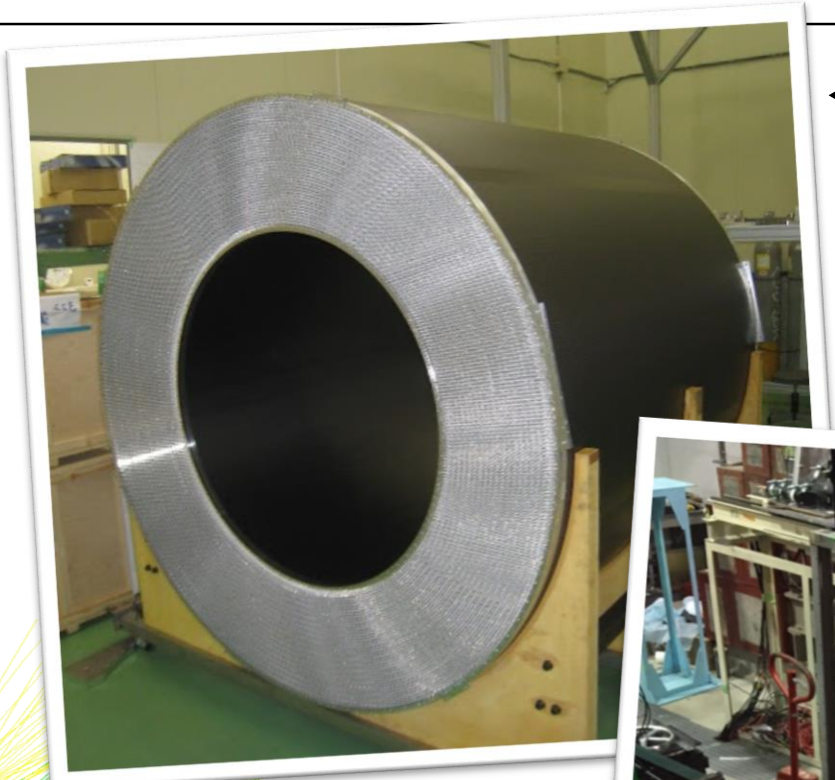
Features:

- Shorter 90° transport and decay line
- Dipole compensation to keep desired momentum band horizontal
- Use **Cylindrical Drift Chamber** to make $\mu N \rightarrow eN$ measurement.
- Swap for centre-covering **Straw Tube** and LYSO **crystal calorimeter** for beam measurements (at lower intensity)

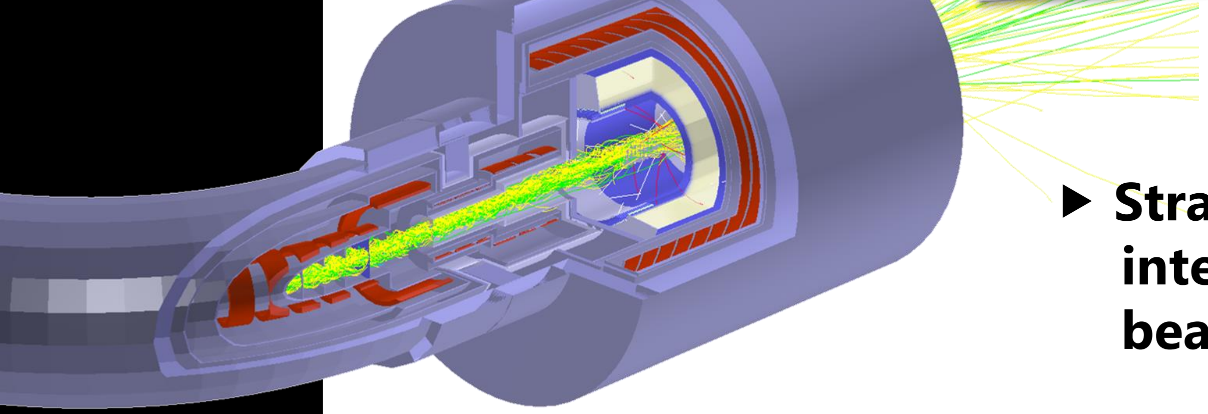


COMET photos

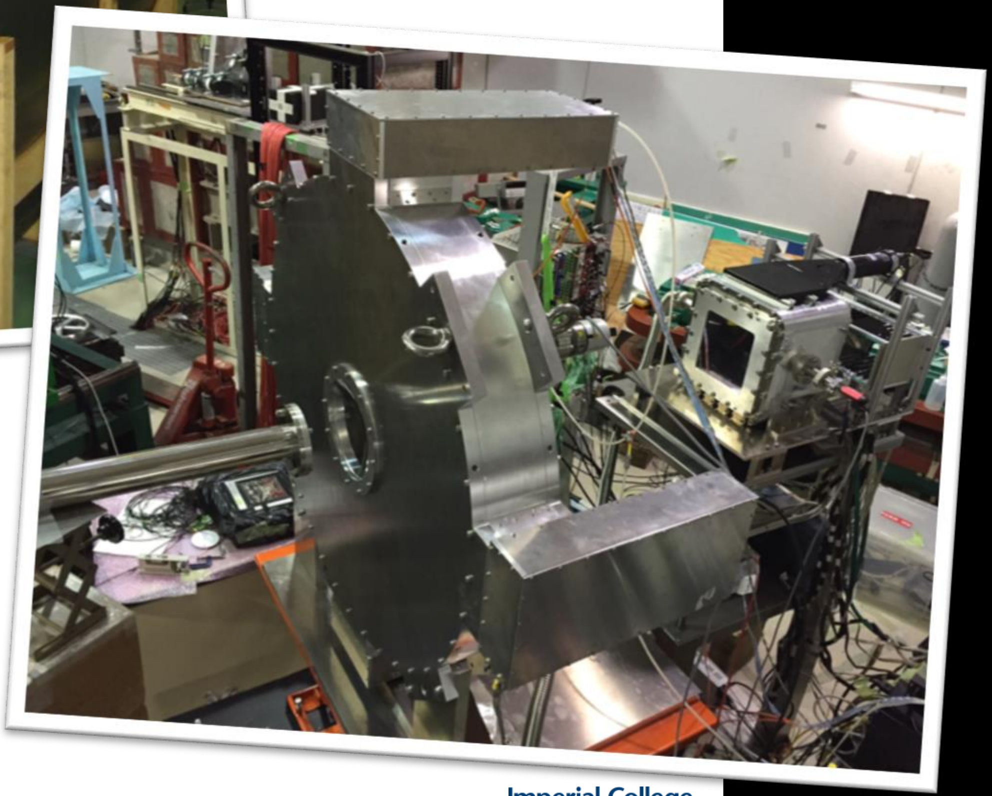




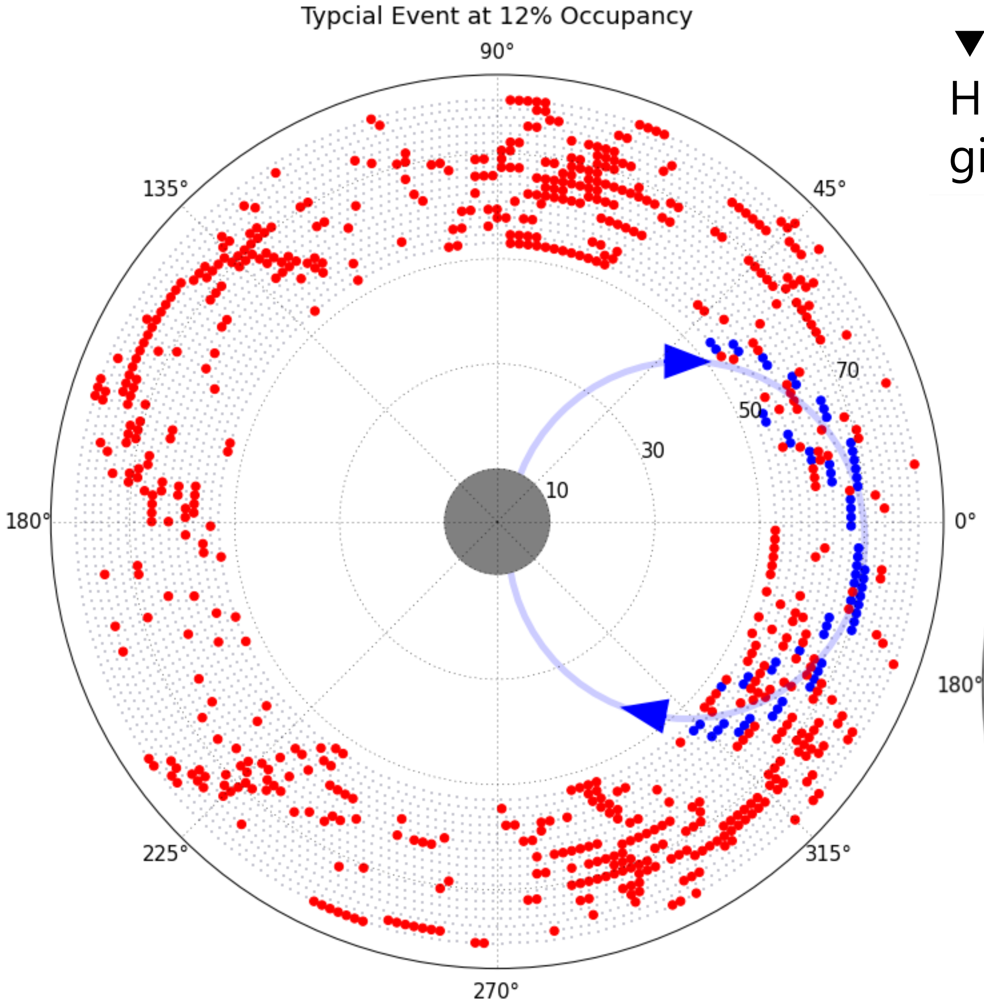
- Drift chamber before wiring for CR test



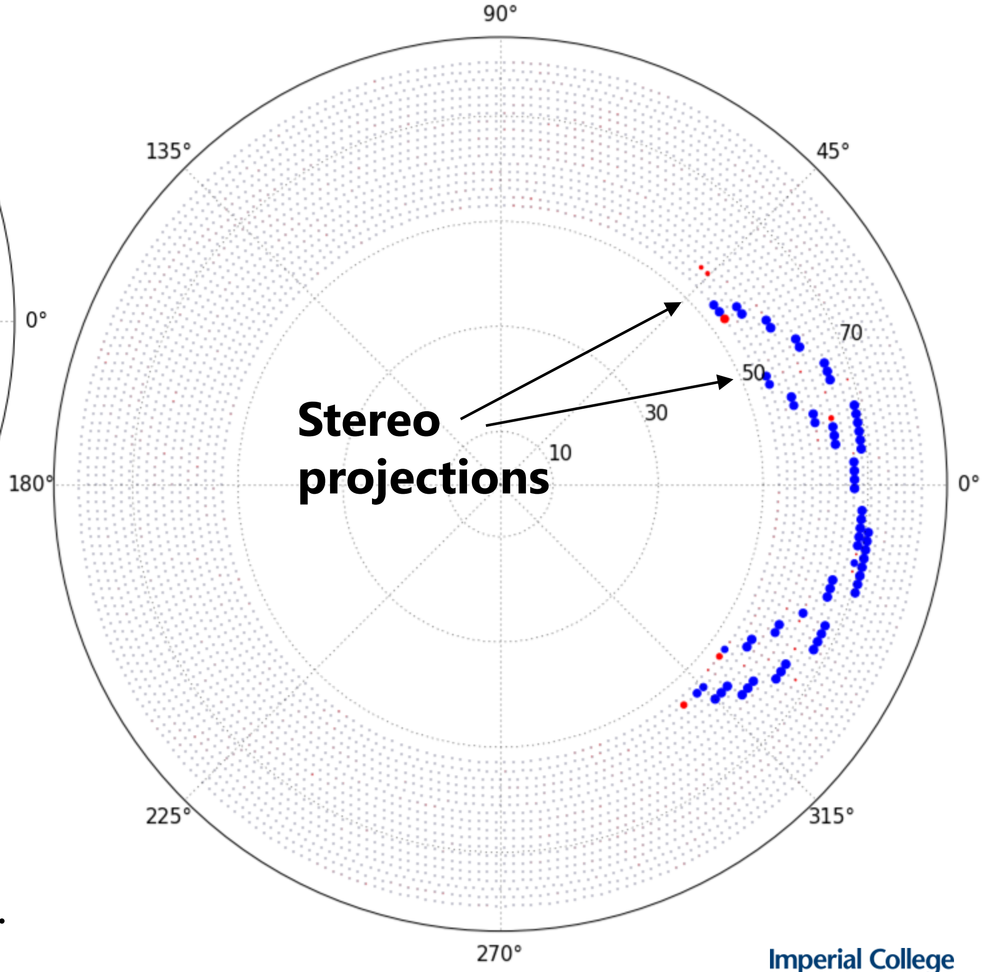
- Straw & ECal integrated beam test



CyDet reconstruction [UK]



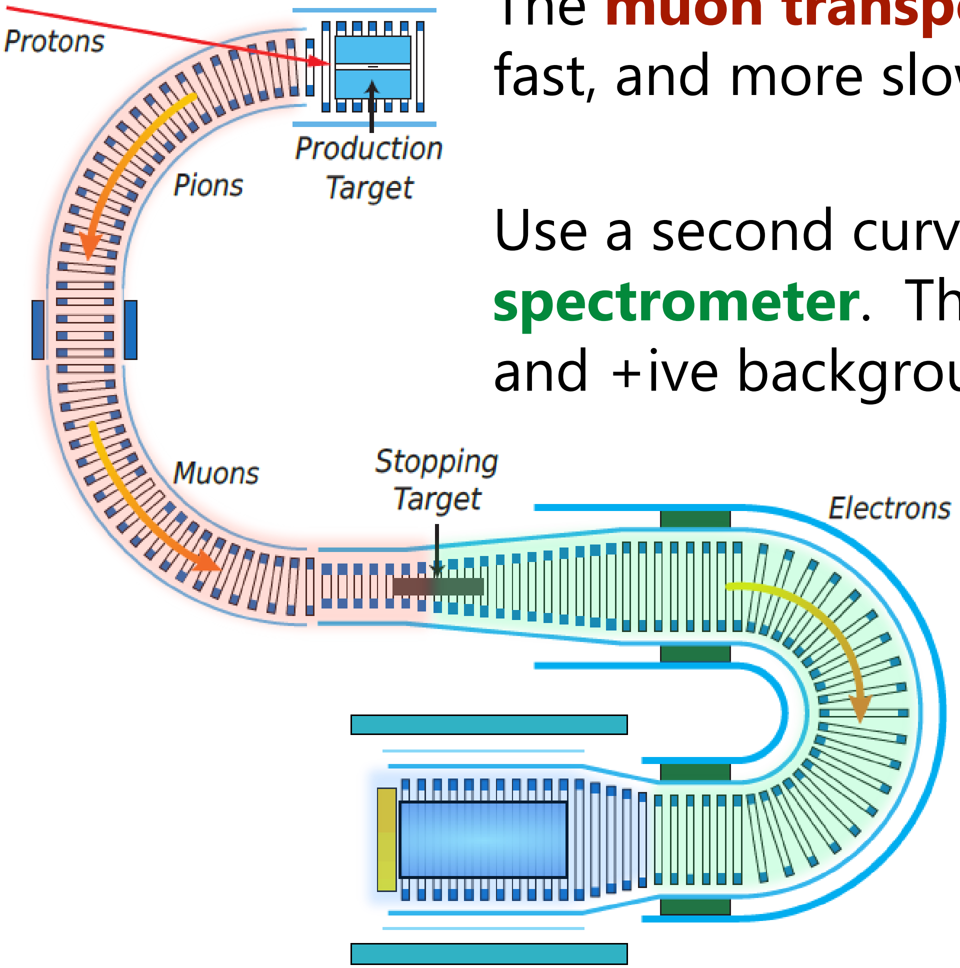
▼ **Signal** tracks picked out using Hough transform based discriminator, then given to Kalman filter for reconstruction.



Stereo projections

▲ Most **background** hits are rejected based on timing, charge, & local features.

COMET: Phase II



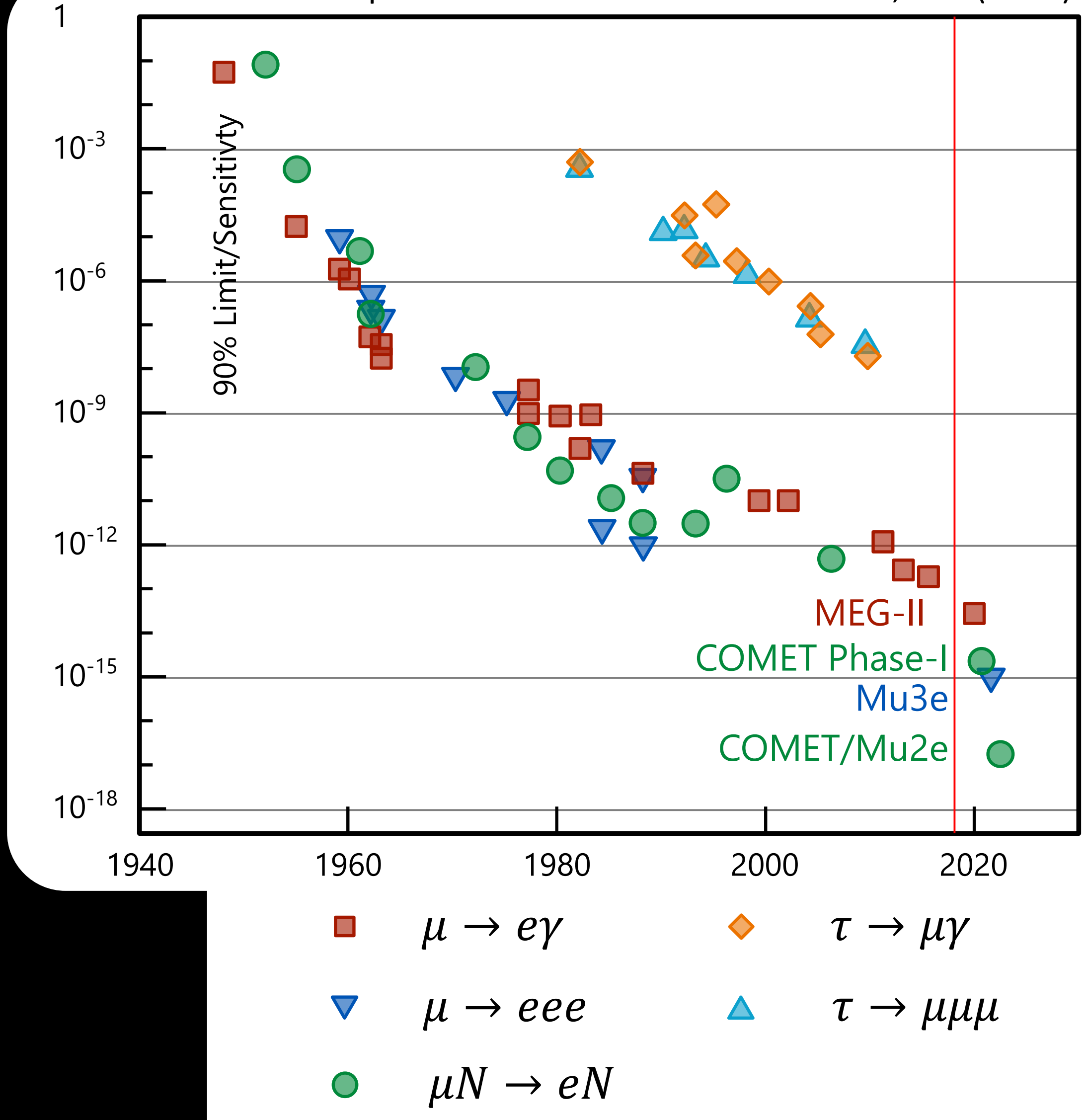
Full sensitivity version of experiment

The **muon transport** extended to **180°** for fewer fast, and more slow muons

Use a second curved solenoid as an **electron spectrometer**. This filters out 'low' momentum and +ive backgrounds, and reduces beam flash

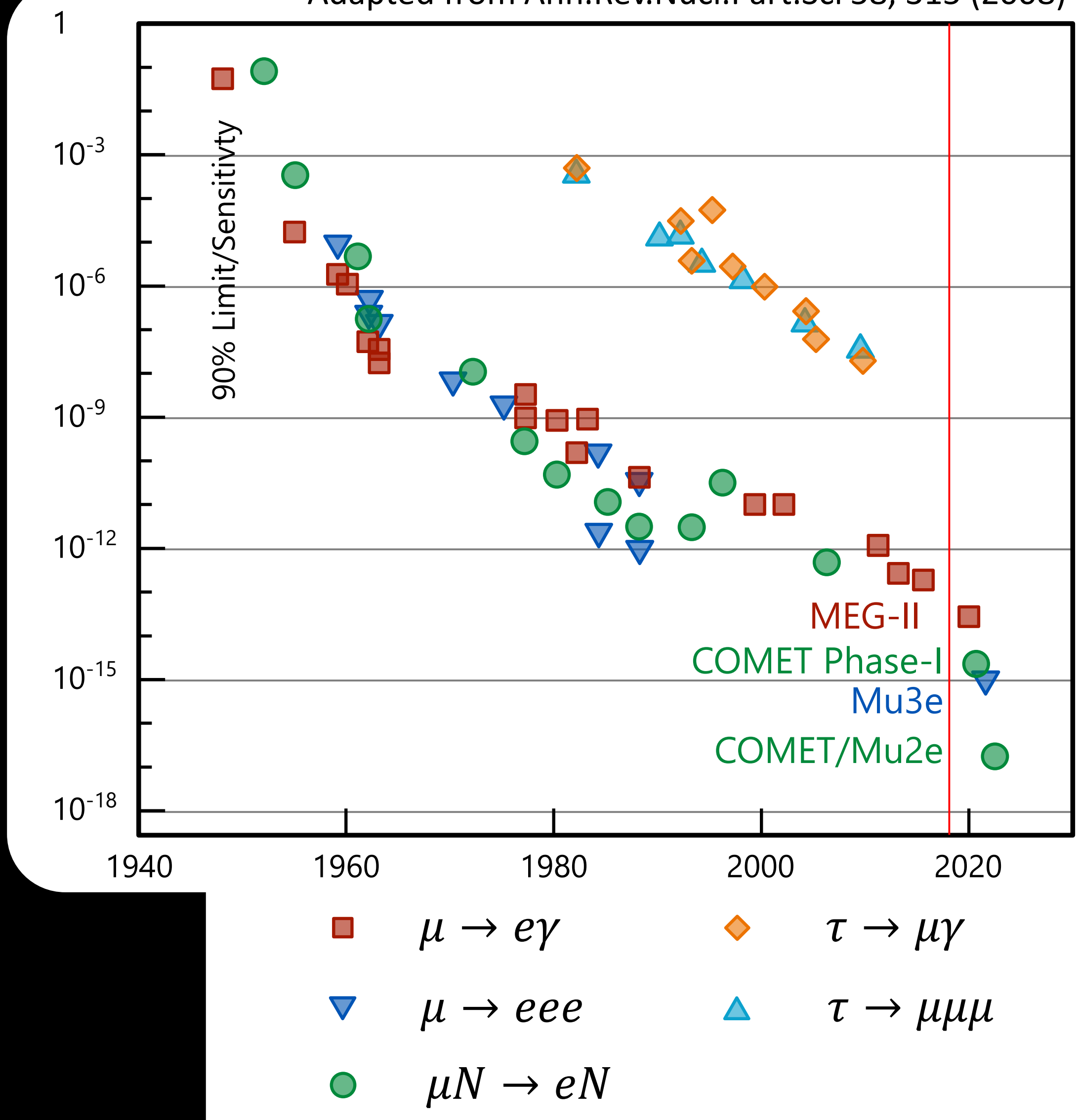
Final detector is **tracker / EM calorimeter** (like Mu2e and Phase-I) but *full plane* – possible because of the spectrometer.

Summary



Adapted from Ann.Rev.Nucl.Part.Sci 58, 315 (2008)

Summary



Adapted from Ann.Rev.Nucl.Part.Sci 58, 315 (2008)

SM assumed that flavour structure of the lepton sector was trivial.

- Neutrino oscillations blew that wide open. We must catch up!

***g-2* anomaly** has become gradually bigger over time.

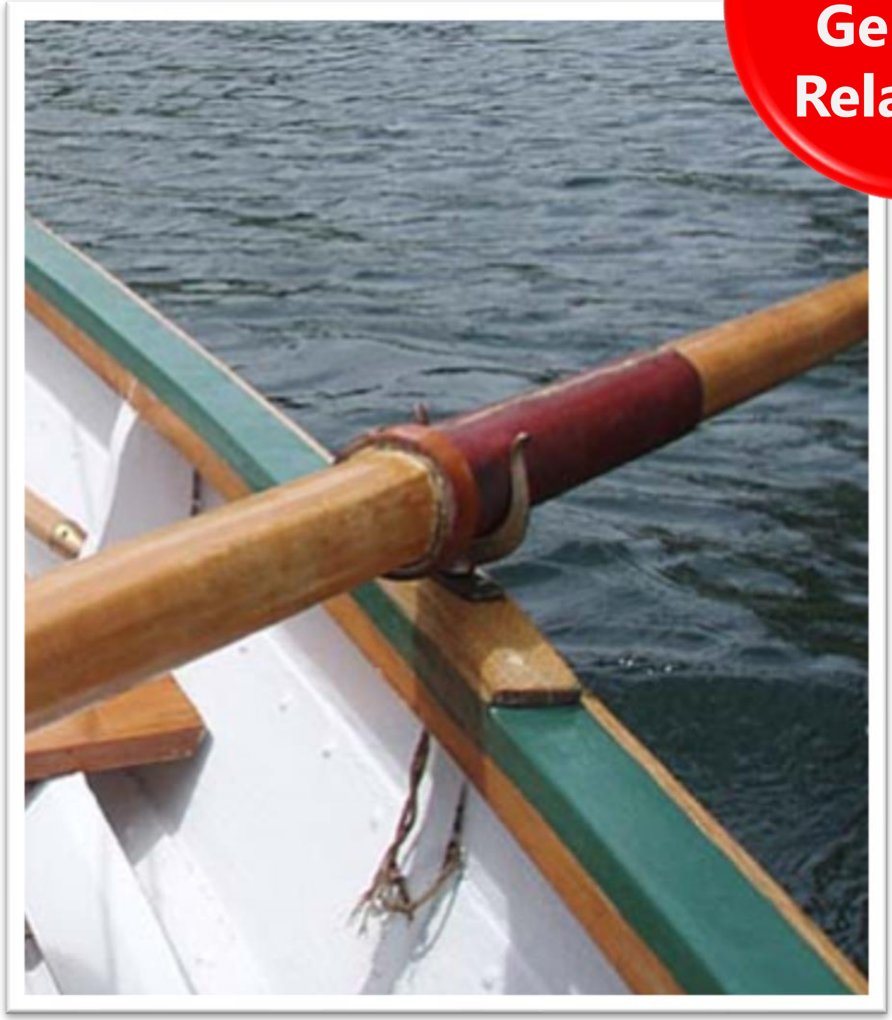
- New experiment(s) will seek to confirm it, starting ~2020

Charged Lepton Flavour Violation is having a slight renaissance.

- Several new experiments in multiple channels, driven by new beam and detector technologies.

Any questions?

Ask
Me About
General
Relativity



Reconstructed reaction of a g-2 collaborator to GR papers

Reserves

GR corrections to g-2?

Ask me about general relativity

“Post-Newtonian effects of Dirac particle in curved spacetime”

arXiv: 1801.10244; 1801.10245; 1801.10246

[Caveat: I have barely skimmed the papers]

3rd paper posits that a previously unrecognised *general-relativity* (!) correction would explain the g-2 anomaly. But…

$$\boldsymbol{\omega}_a = \boldsymbol{\omega}_s - \boldsymbol{\omega}_c = -\frac{q}{m\mu}\left[a_\mu \boldsymbol{B} - \boxed{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta} \times \boldsymbol{E}}{c}}\right]$$

- As I understand it, g-2 response is that the correction only affects **boxed term**, so is $\mathcal{O}(10^{-3})$ smaller than assumed by authors
- Theorists on blogs also suggest the correction depends on absolute potential, not potential differences [so must be wrong]

I don’t know enough to judge on either of these two criticisms

More corrections

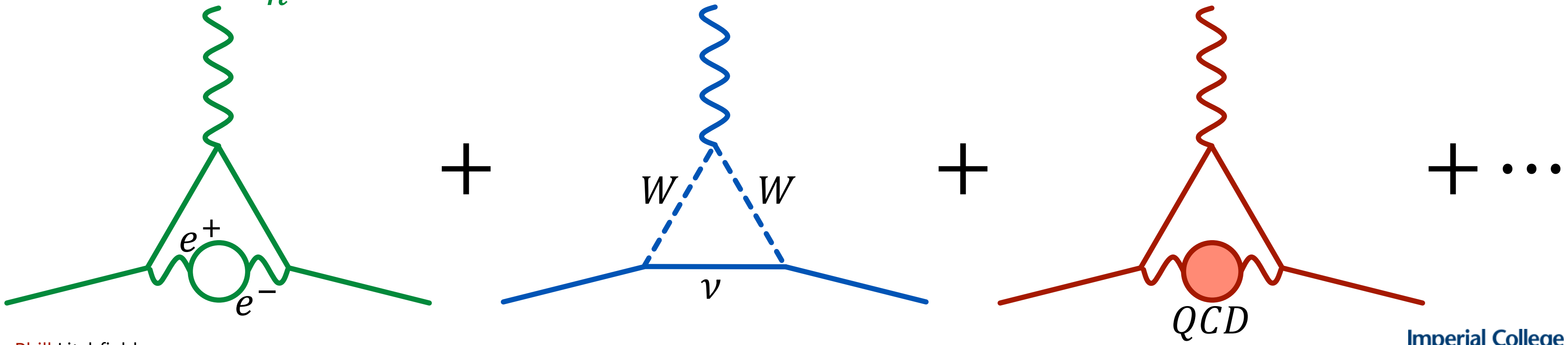
Since we can measure g very precisely, we need lots of terms in the anomalous part:

$$a = 1 + \Delta a_{\mathrm{QED}} + \Delta a_{\mathrm{EW}} + \Delta a_{\mathrm{Had}}\ (+\Delta a_{\mathrm{BSM}}?)$$

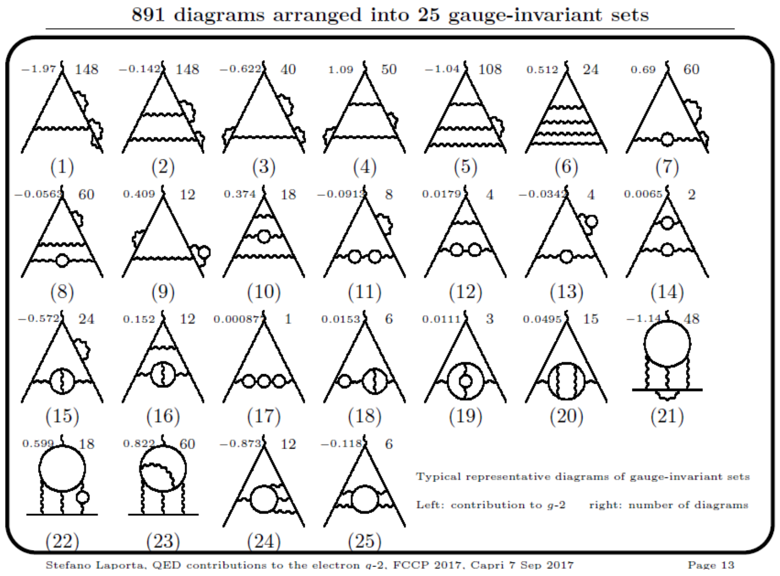
And, for example,

$$\Delta a_{\mathrm{QED}} = \sum_{n} C_n \left(\frac{\alpha}{\pi}\right)^n$$

$$\frac{g_f}{2} \simeq 1 + \sum_{n}^{(4)} C_n \left(\frac{\alpha}{\pi}\right)^n \quad + \quad \Delta a_{\mathrm{EW}} \quad + \quad \Delta a_{\mathrm{Had}}$$



Theoretical work (on a_μ)

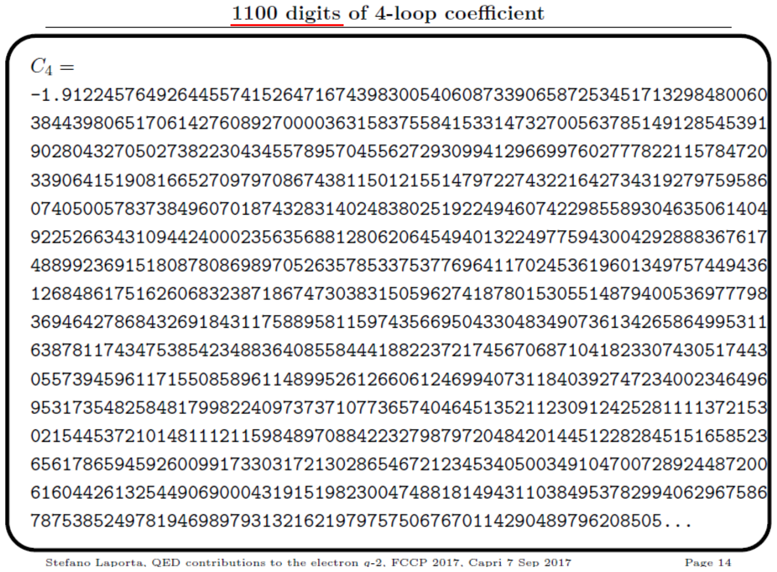


891 diagrams arranged into 25 gauge-invariant sets

Typical representative diagrams of gauge-invariant sets

Left: contribution to g-2 right: number of diagrams

Stefano Laporta, QED contributions to the electron g-2, FCCP 2017, Capri 7 Sep 2017 Page 13



1100 digits of 4-loop coefficient

$C_4 =$

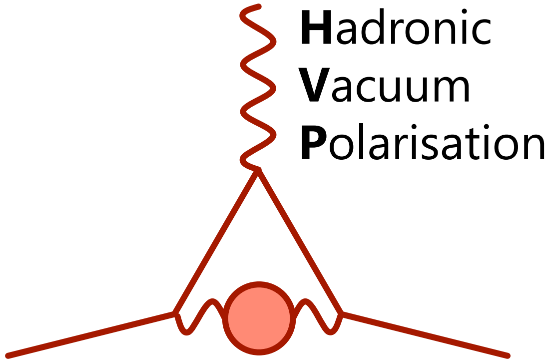
```
-1.912245764926445574152647167439830054060873390658725345171329848006
0384439806517061427608927000036315837558415331473270056378514912854539
1902804327050273822304345578957045562729309941296699760277782211578472
0339064151908166527097970867438115012155147972274322164273431927975958
6074050057837384960701874328314024838025192249460742298558930463506140
4922526634310944240002356356881280620645494013224977594300429288836761
7488992369151808780869897052635785337537769641170245361960134975744943
6126848617516260683238718674730383150596274187801530551487940053697779
8369464278684326918431175889581159743566950433048349073613426586499531
1638781174347538542348836408558444188223721745670687104182330743051744
3055739459611715508589611489952612660612469940731184039274723400234649
6953173548258481799822409737371077365740464513521123091242528111137215
3021544537210148111211598489708842232798797204842014451228284515165852
3656178659459260099173303172130286546721234534050034910470072892448720
0616044261325449069000431915198230047488181494311038495378299406296758
6787538524978194698979313216219797575067670114290489796208505...
```

Stefano Laporta, QED contributions to the electron g-2, FCCP 2017, Capri 7 Sep 2017 Page 14

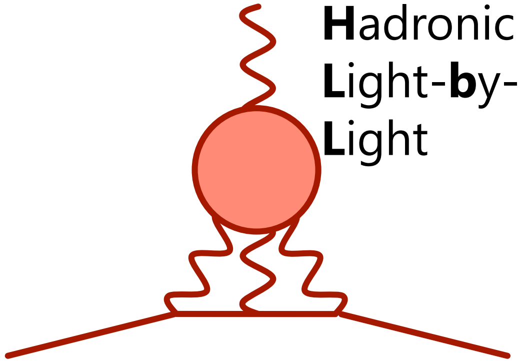
◀ QED component calculated to 4th order… should be enough for the time being

As *always*, the hard part is QCD

- But many recent improvements from Lattice calculations, new theoretical insight…



Hadronic
Vacuum
Polarisation

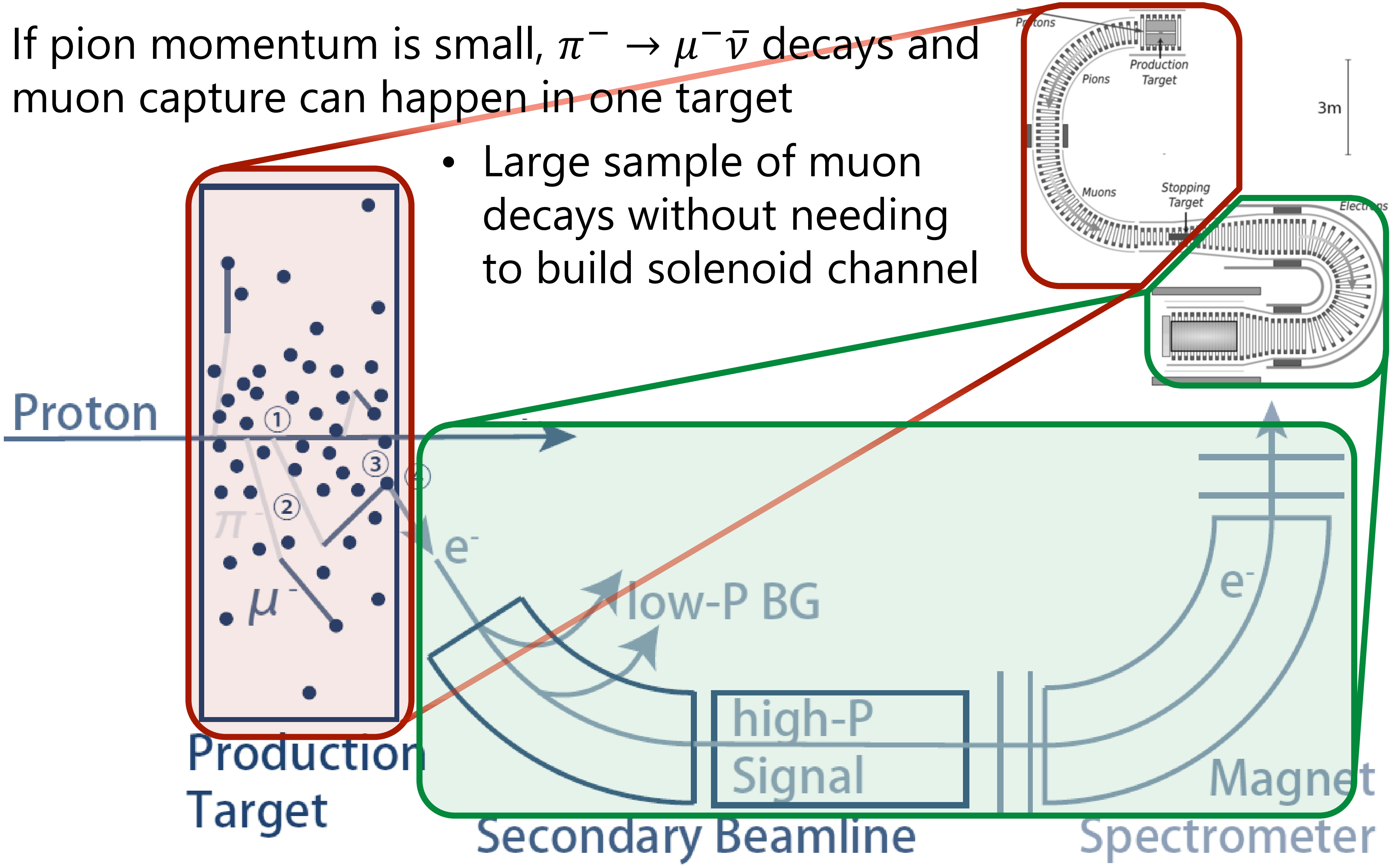


Hadronic
Light-**by**-
Light

DeeMe concept

If pion momentum is small, $\pi^- \rightarrow \mu^- \bar{\nu}$ decays and muon capture can happen in one target

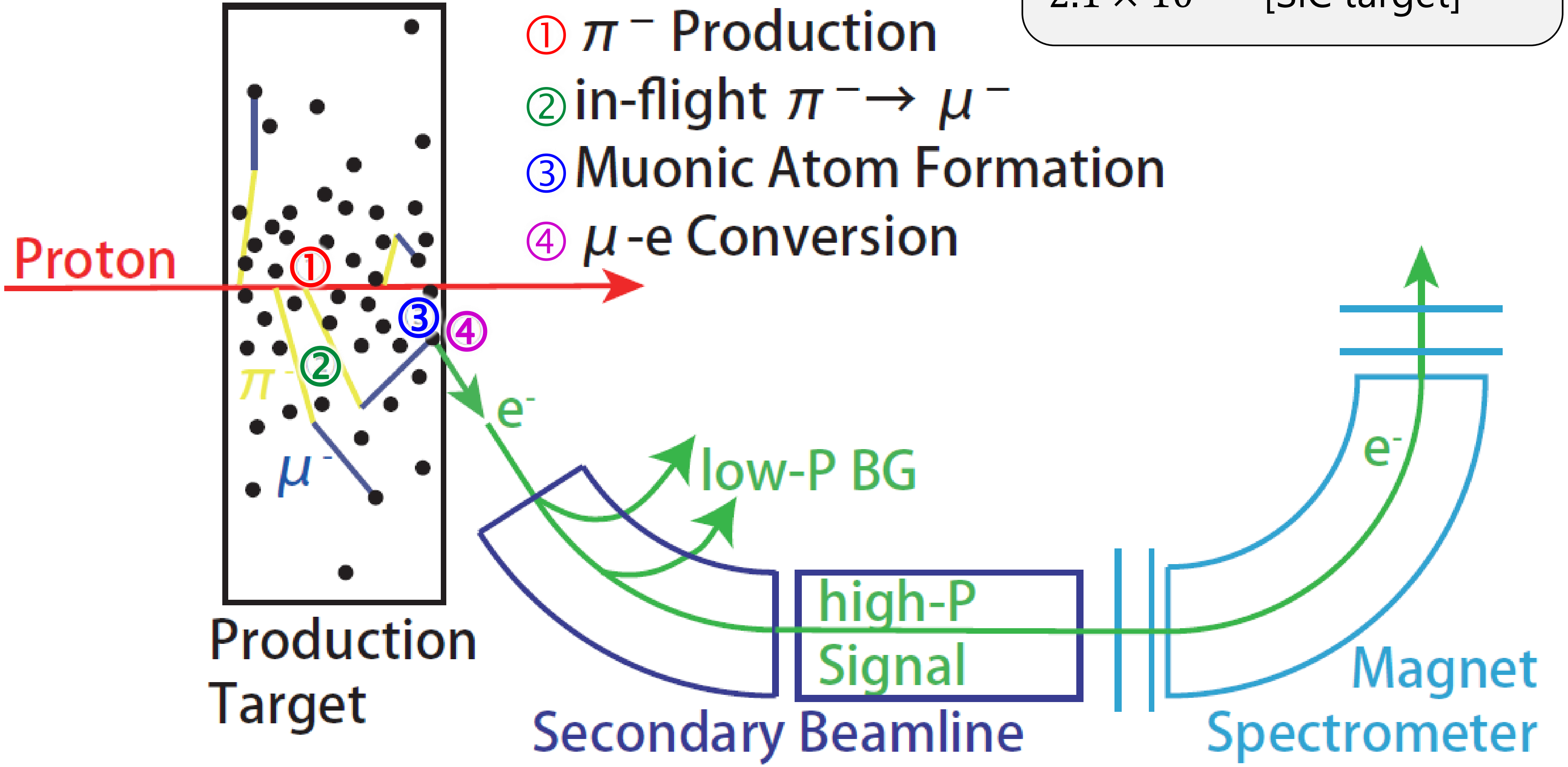
- Large sample of muon decays without needing to build solenoid channel



DeMee design & goals

- **Study DIO tail** (see Nagao-san's poster)
- **$\mu - e$ conversion**

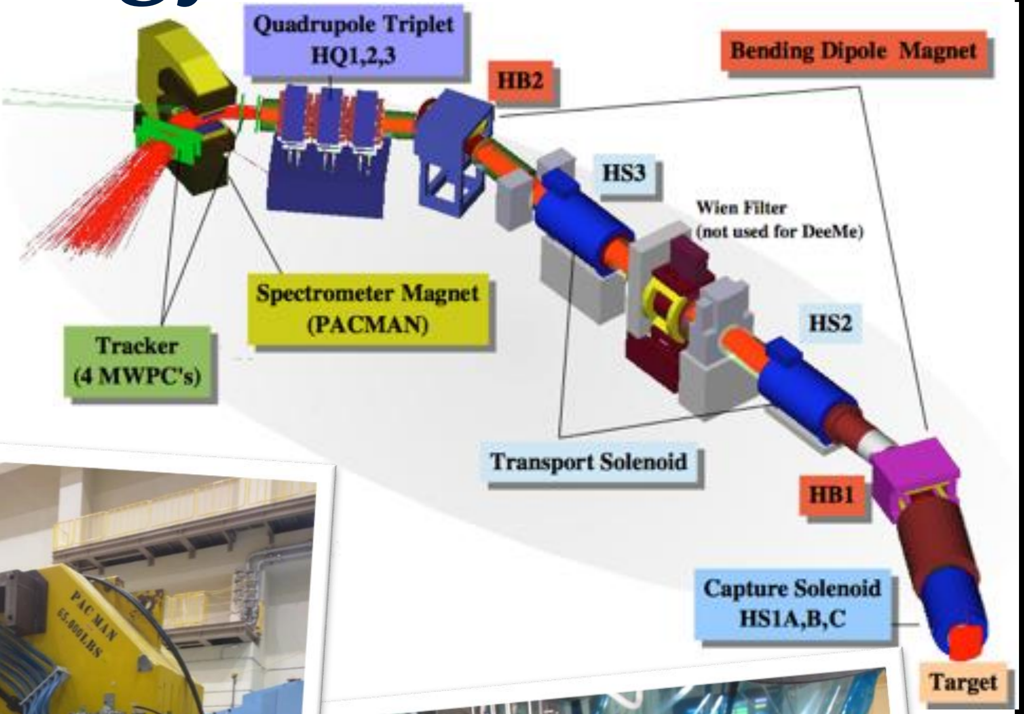
$\mu - e$ 1 year S.E.S.
1.2×10^{-13} [Carbon target]
2.1×10^{-14} [SiC target]



DeeMe in MUSE H-line (Technology)

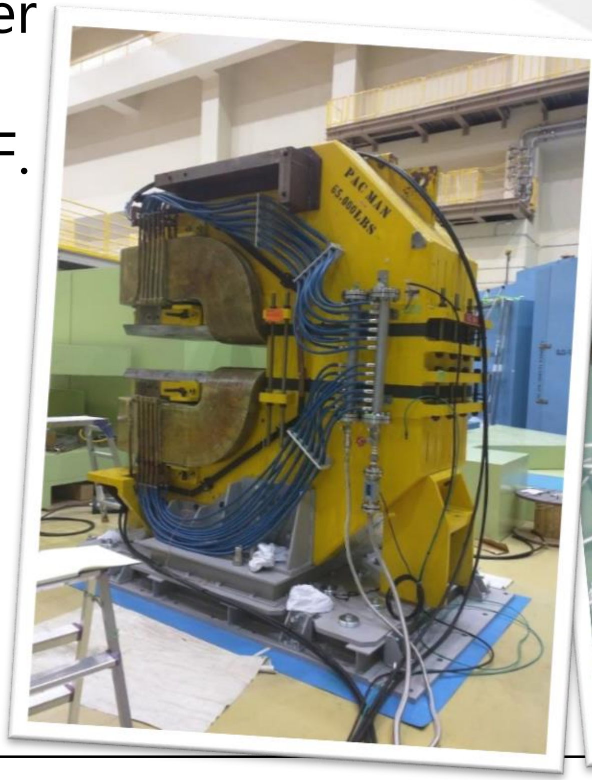
Prompt burst would cause big problems for normal MWPC

- Develop fast-switched MWPC. (see Teshima-san's poster)

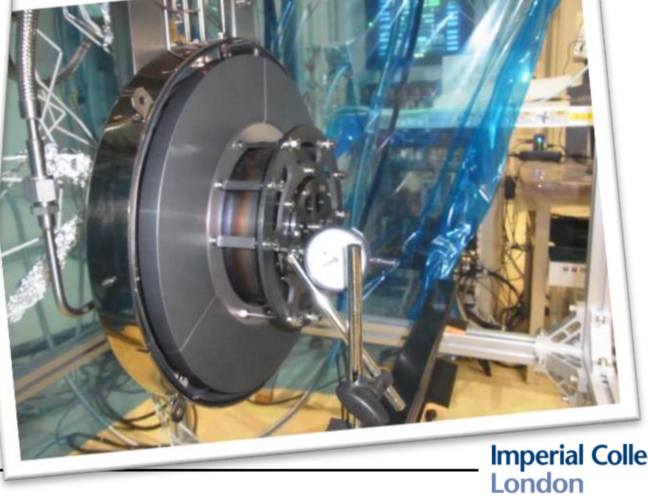


PACMAN spectrometer magnet from PIENU experiment @ TRIUMF.

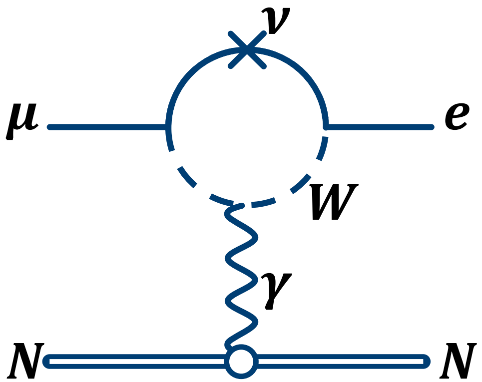
- B = **0.4T** at centre. For 105MeV, gives a **70°** bend.



Prototype of rotating SiC target fabricated, updating design.



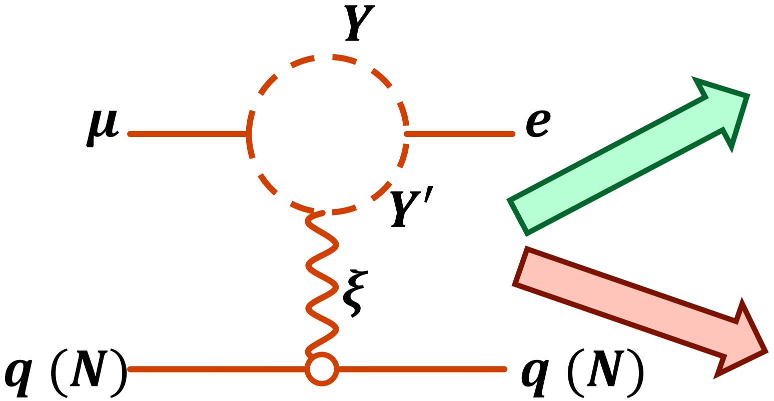
μ to e conversion



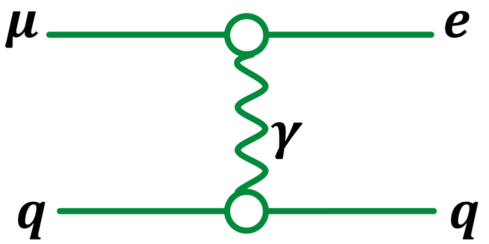
SM $\mu - e$ conversion

In the **SM** $\mu N \to e N$ is supressed by $O(10^{-54})$ because of the mass disparity between the W and neutrino.

This is 'accidental'; **new physics** scenarios typically give CLFV much higher than SM.

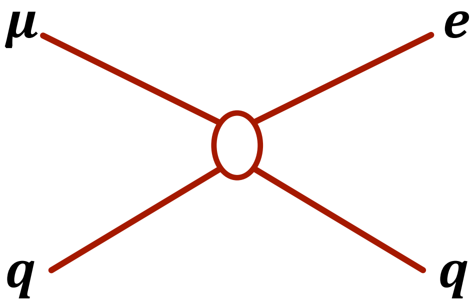


NP $\mu - e$ conversion



Dipole coupling

$$\mathcal{L}_{\mathrm{d}} \sim \frac{m_\mu}{\Lambda^2}\, \bar{\mu}\sigma_{\mu\nu} e \cdot F^{\mu\nu}$$



Four-fermion coupling

$$\mathcal{L}_4 \sim \frac{1}{\Lambda^2}\, \bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q$$

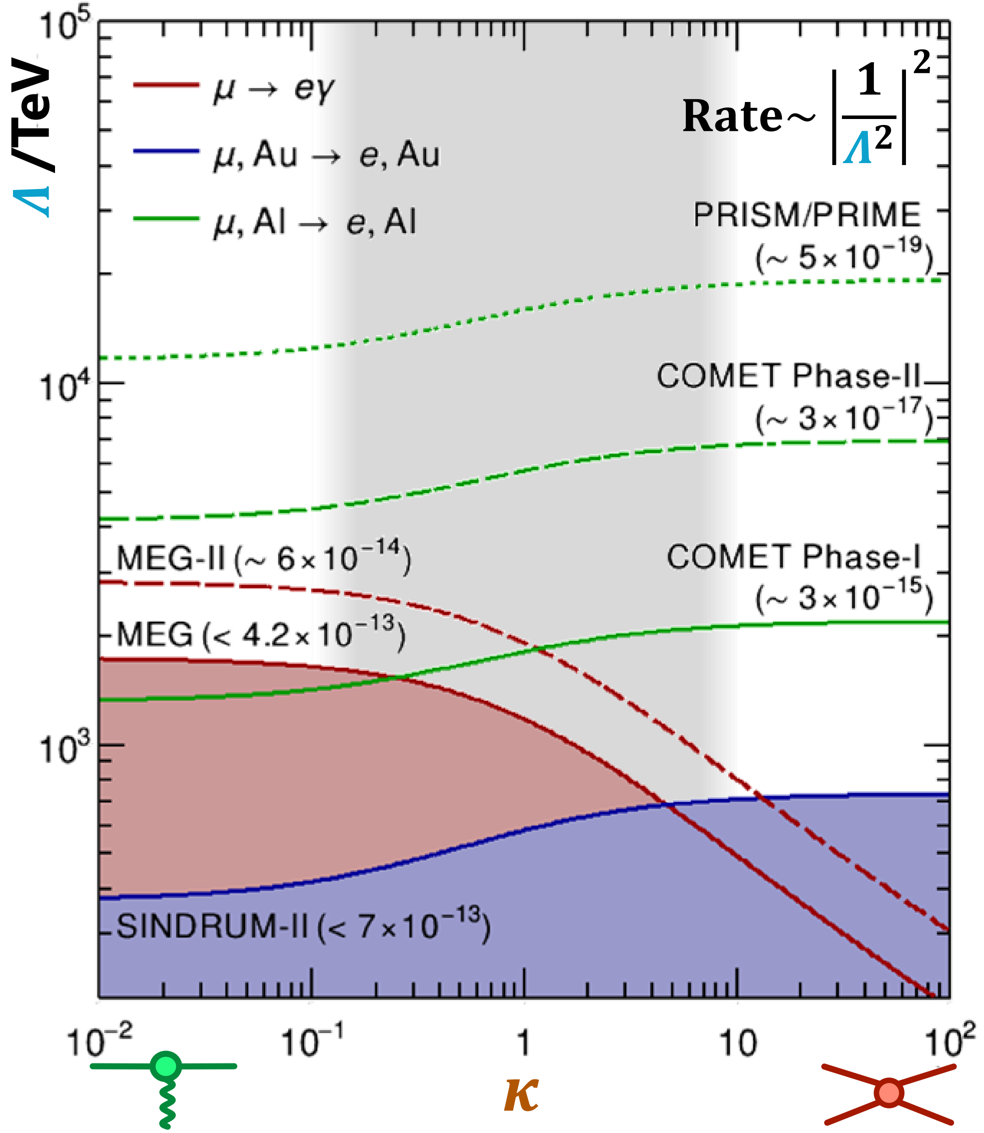
$$\mathcal{L} = \frac{1}{1+\kappa}\mathcal{L}_d + \frac{\kappa}{1+\kappa}\mathcal{L}_4$$

A giant leap…

For the full COMET experiment sensitivity improvement over SINDRUM-II is **4 orders of magnitude.**

MC of background processes [especially '*tails*'] may not be good enough for optimal design

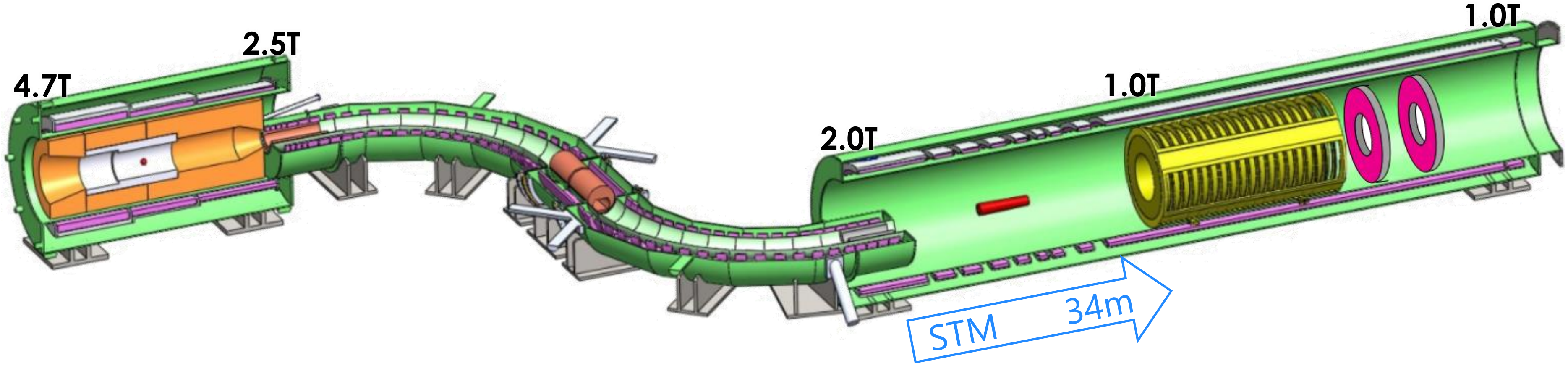
- Intermediate-scale experiment can measure background sources and inform design.
- Can still do competitive physics with a smaller apparatus



Include in COMET programme:

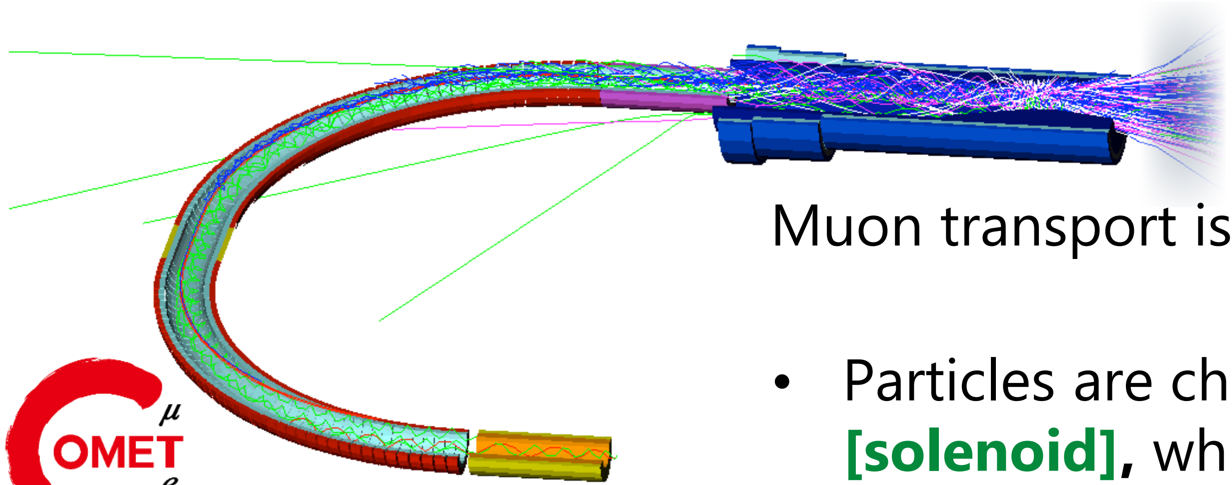
COMET Phase-I

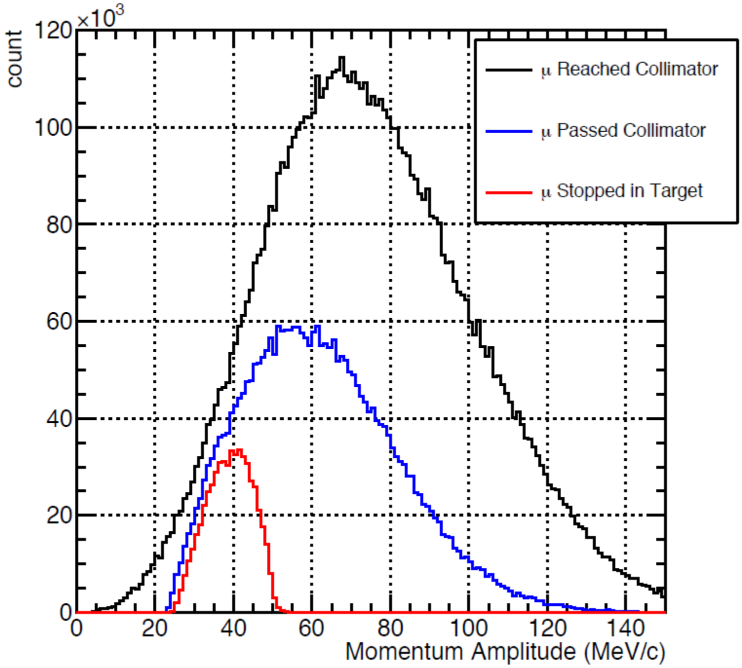
Mu2e overview



- S-shape and off-centre collimators that can rotate for BG studies
- Stopping **target** is 17 × 0.2mm Al foils
- Target & detector surrounded by large aperture solenoid for (105MeV) electron transport
- Electrons spiral from target to ring shaped **tracker** and **EM calorimeter**
- Downstream **Stopping Target Monitor** [UK] monitors muonic X-rays, for normalisation of muon capture rate

Muon transport





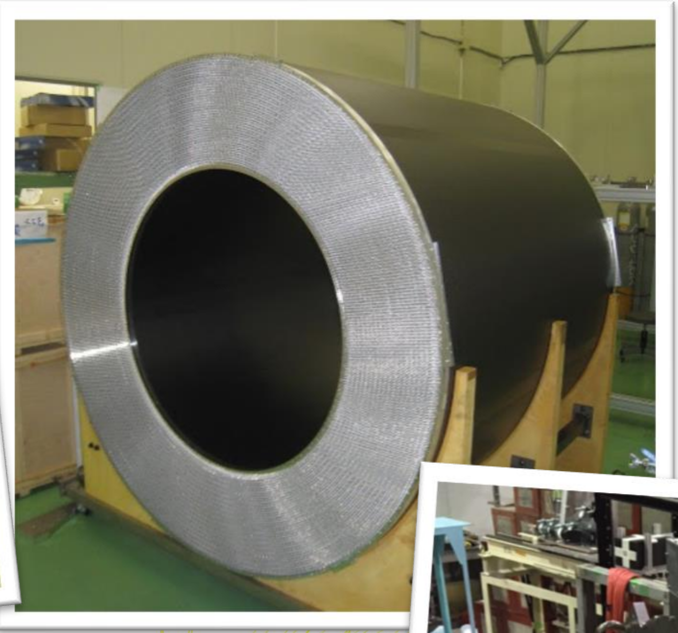
Muon transport is a **curved solenoid**

- Particles are channelled in **spiral paths [solenoid]**, which naturally tend **up/down [curvature]** depending on momentum and charge.
- Gives **charge sign and momentum selection**, enhanced by using a collimator.
- Use to eliminate high momentum muons, and other particles.

Mu2e photos

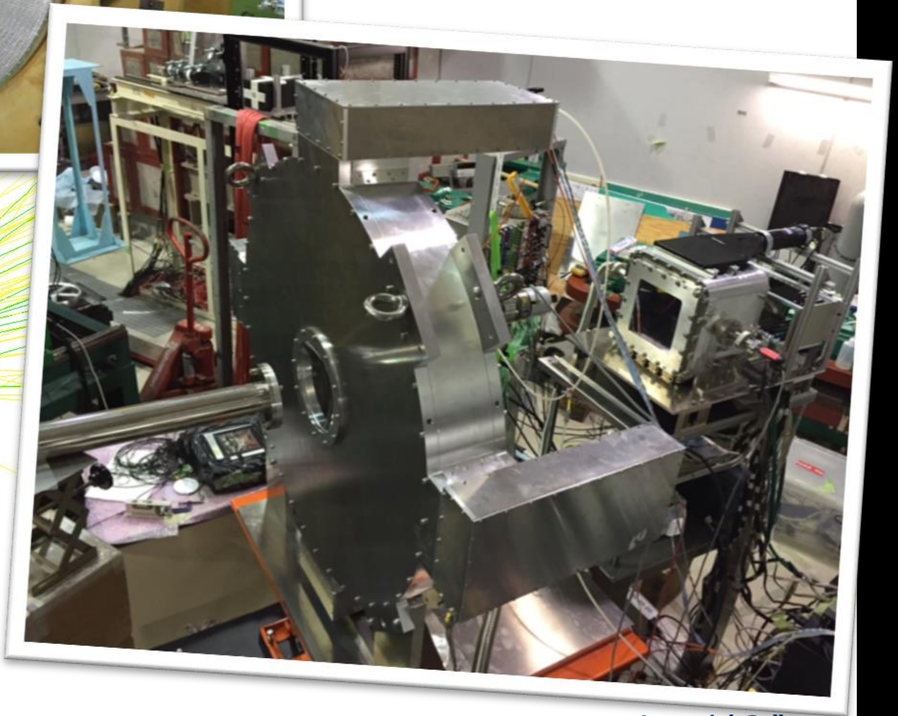
COMET photos

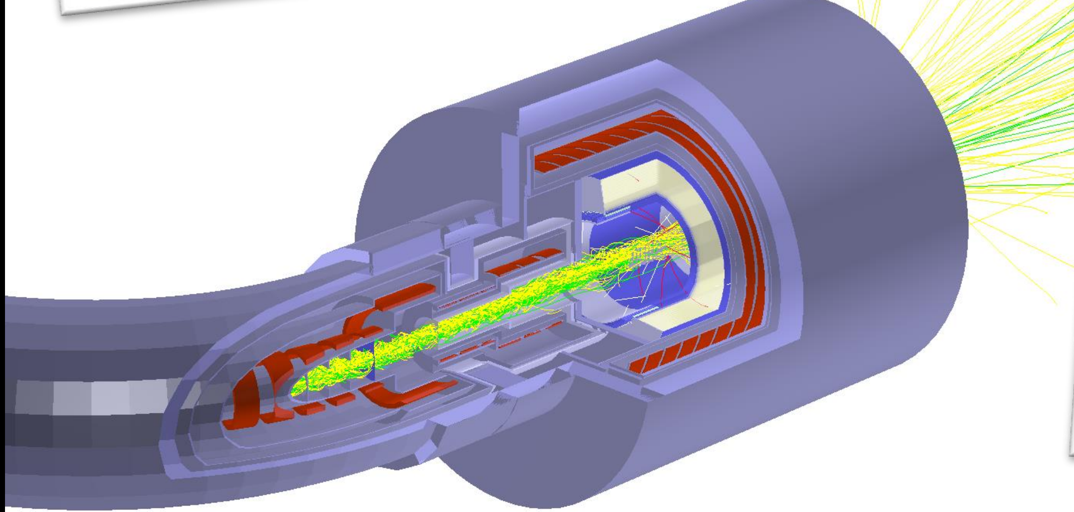
▼ Magnets laid-out for switchyard



◀ Drift chamber before wiring for CR test

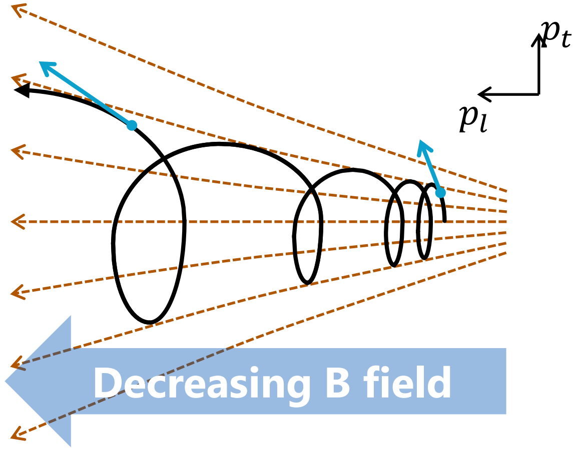
▼ Straw & ECal integration test

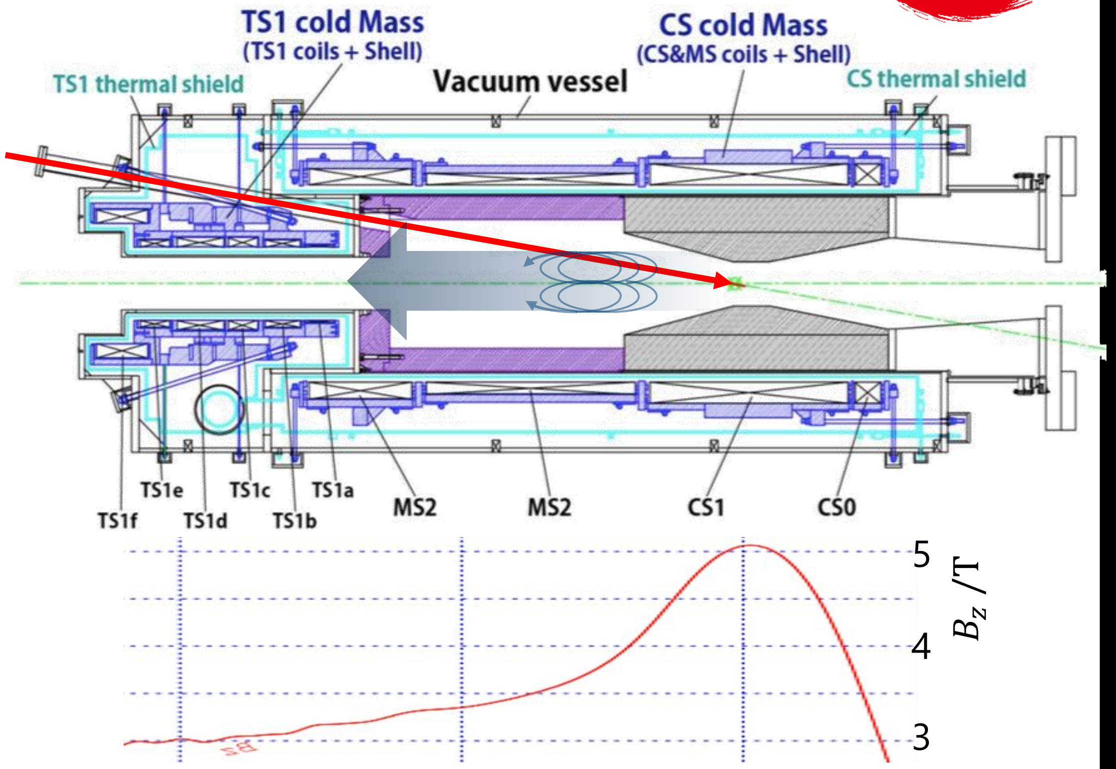




Muon source

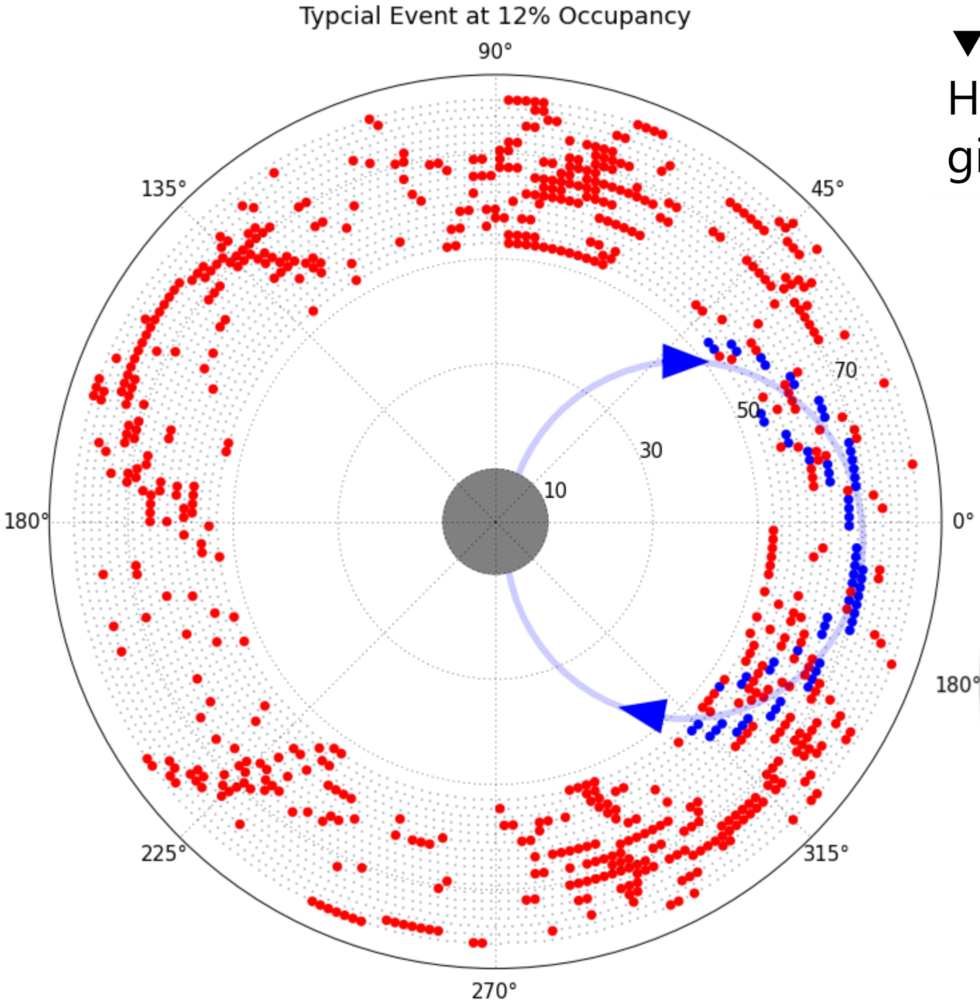
- Collect ***backward*-going pions** with capture solenoid
- Maximise field at target to give larger aperture angle





- Pions decay to muons en-route to stopping target.
- Many neutrons produced, requires careful shielding. The curved transport line helps to eliminate direct line-of sight.

CyDet reconstruction



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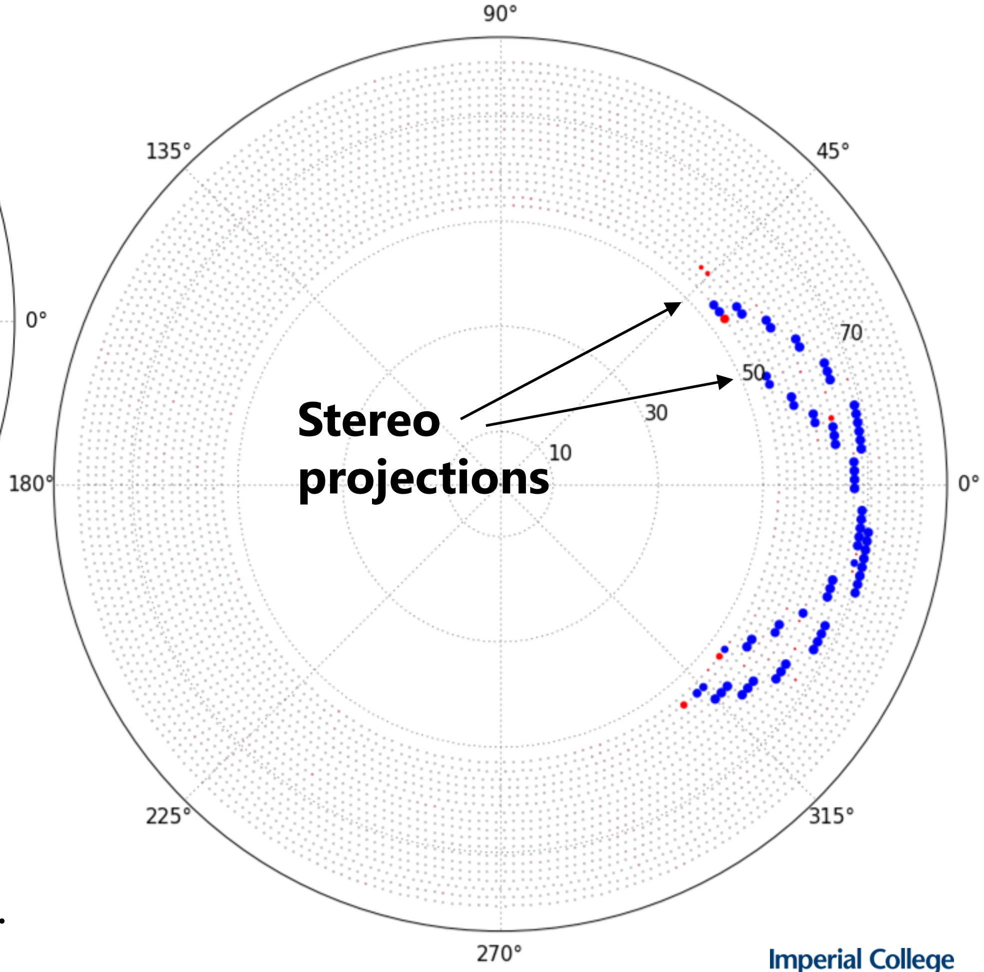
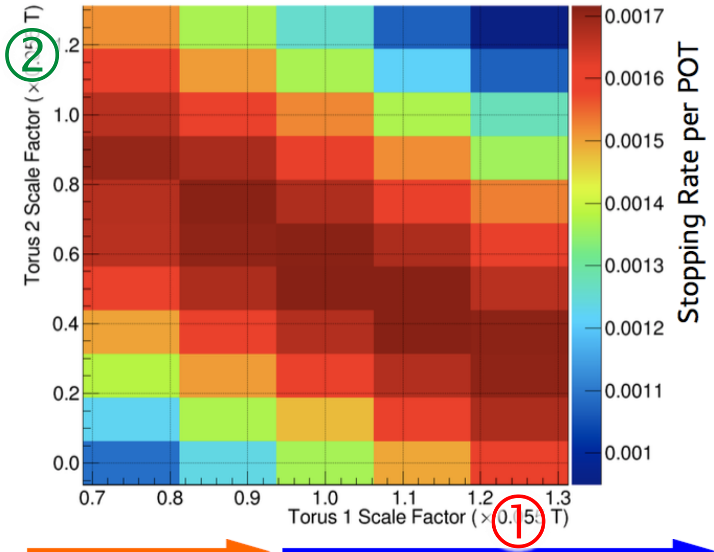


Stereo projections

▲ Most **background** hits are rejected based on timing, charge, & local features.

Phase II beamline optimisation

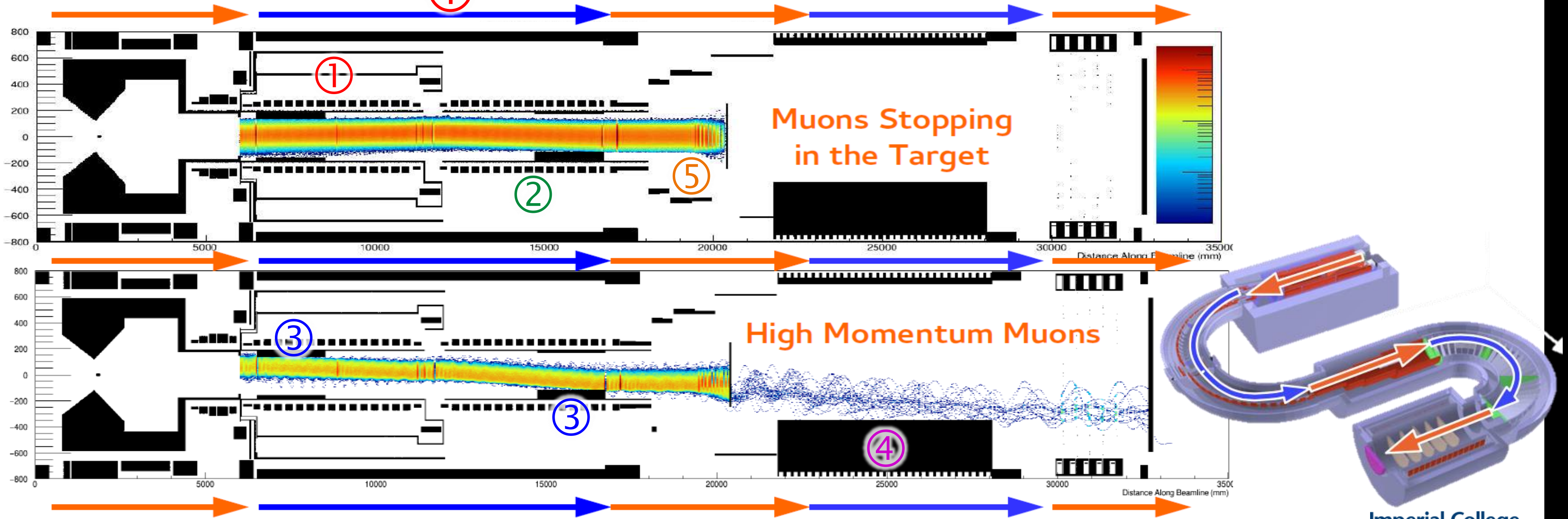


In parallel with Phase I construction, Phase II design is being optimised using integrated COMET simulation. Examples:

① ② Correcting dipole field strength

③ ④ Collimator positions

⑤ Target position & shape



Sensitivity

Expressed in terms of $\mathcal{R} = \frac{\Gamma(\mu N \to e N)}{\Gamma(\mu N \to \nu N')}$

Define single event sensitivity (S.E.S.):

Value of $\mathcal{R}$ s.t. mean expectation is 1 signal event.

$$\therefore \text{S.E.S.} = \frac{1}{N_\mu \cdot g \cdot f \cdot A} \quad \text{where:}$$

$g = 0.9$ prob. for N to remain in ground state

$f = 0.61$ fraction of nuclear capture $(1 - P_{\text{DIO}})$

In phase-1:

$N_\mu = 1.5 \times 10^{16}$ number of stopped muons

$A = 4.1\%$ is the signal acceptance

- Dominated by geometric (18%) and time (30%) acceptance.
- Selection for B/G of 0.03 events