Muon Experiments

Mark Lancaster
UCL

Precision Experiments

arXiv.org > hep-ph > arXiv:1302.3794

High Energy Physics – Phenomenology

Higgs Precision (Higgcision) Era begins

30 %

arXiv.org > hep-ph > arXiv:1212.2355

High Energy Physics – Phenomenology

Precise charm–quark mass from deep–inelastic scattering

4 %

arXiv.org > hep-ex > arXiv:1212.4012

High Energy Physics – Experiment

Precision Measurement of the Ratio of the Charged Kaon Leptonic Decay Rates

0.4 %

arXiv.org > hep-ex > arXiv:1304.6865

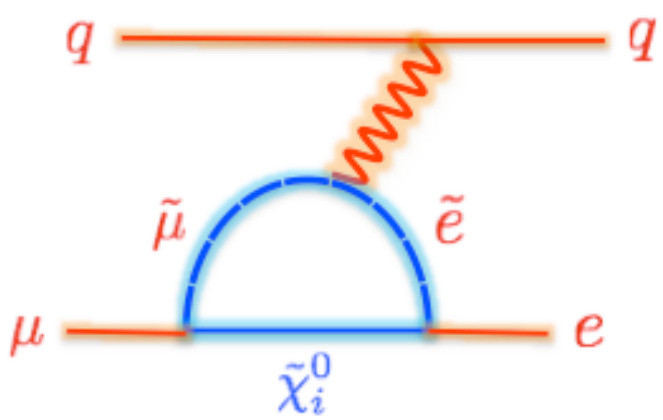
High Energy Physics – Experiment

Precision measurement of D meson mass differences

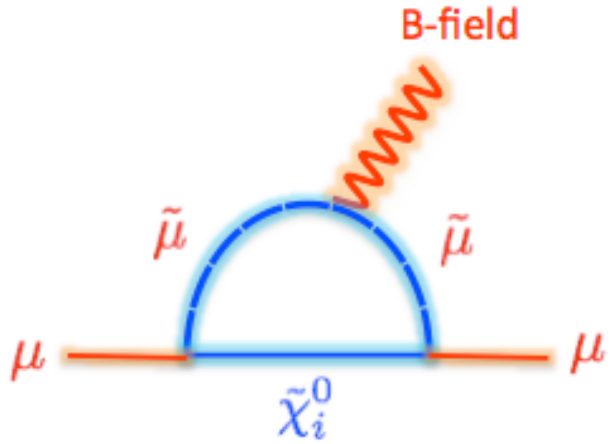
0.05%

500 ppm

Precision Muon Experiments



BSM SUSY interaction for neutrinoless muon to electron conversion



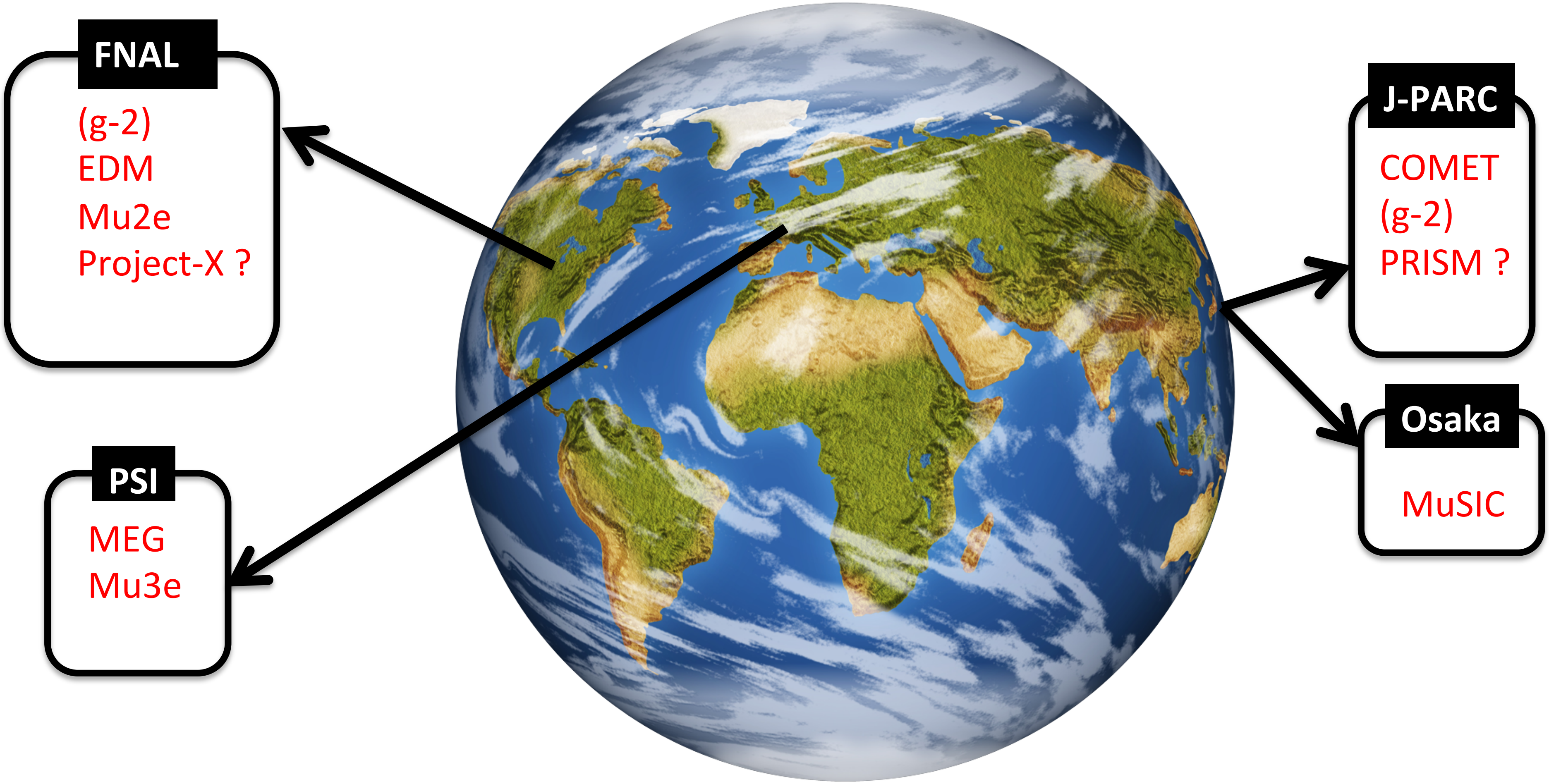
BSM SUSY interaction contributing to g-2

Discuss two classes of experiments, epitomising the intensity frontier:

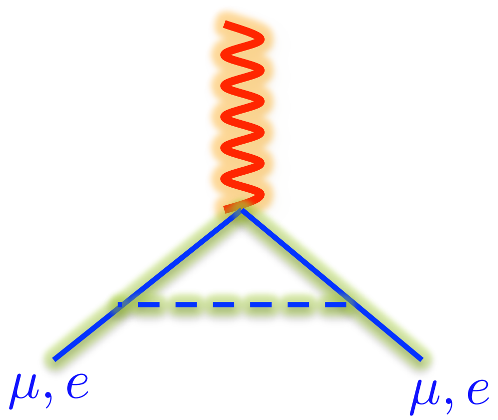
1. **Rarity** : processes with essentially zero SM cross section
   - look for a handful of events
2. **Precision** : muon measurements that are predicted v. precisely in SM
   - measure billions of events to achieve high precision and look for discrepancy e.g. muon magnetic moment.

Renaissance in this field

Due to the recent availability of higher power proton sources & construction of dedicated muon beamlines



Why Muons (and taus)



New physics as: $\left(\frac{m_\ell}{M_{\mathrm{NEW}}}\right)^2$

Therefore we should do muons and taus but …

Ecce Gabrielse

QED (5th order) at 13th dp.

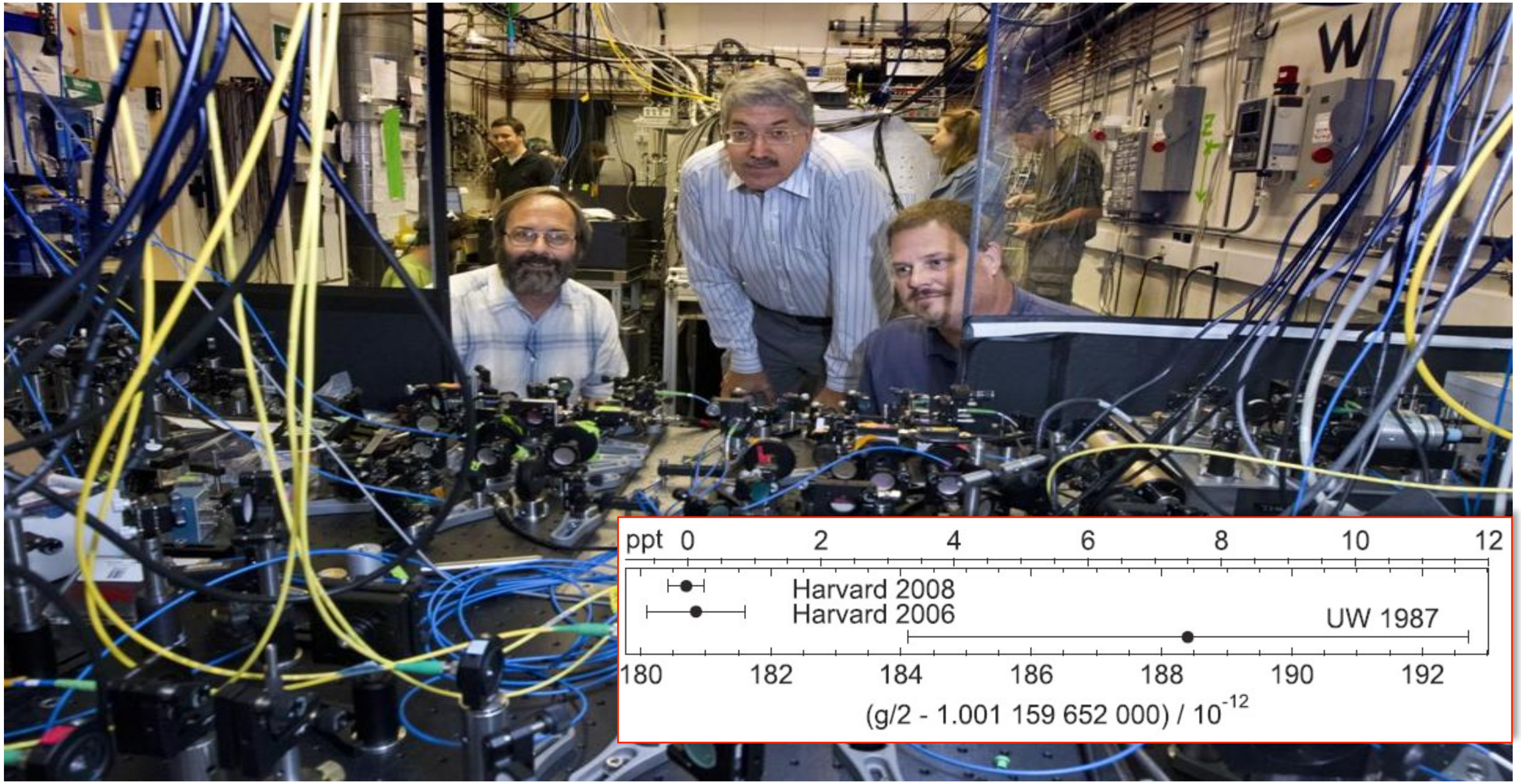
$$g - 2 = 0.00231930436146 \pm 0.00000000000056$$

Hadronic at 12th dp.

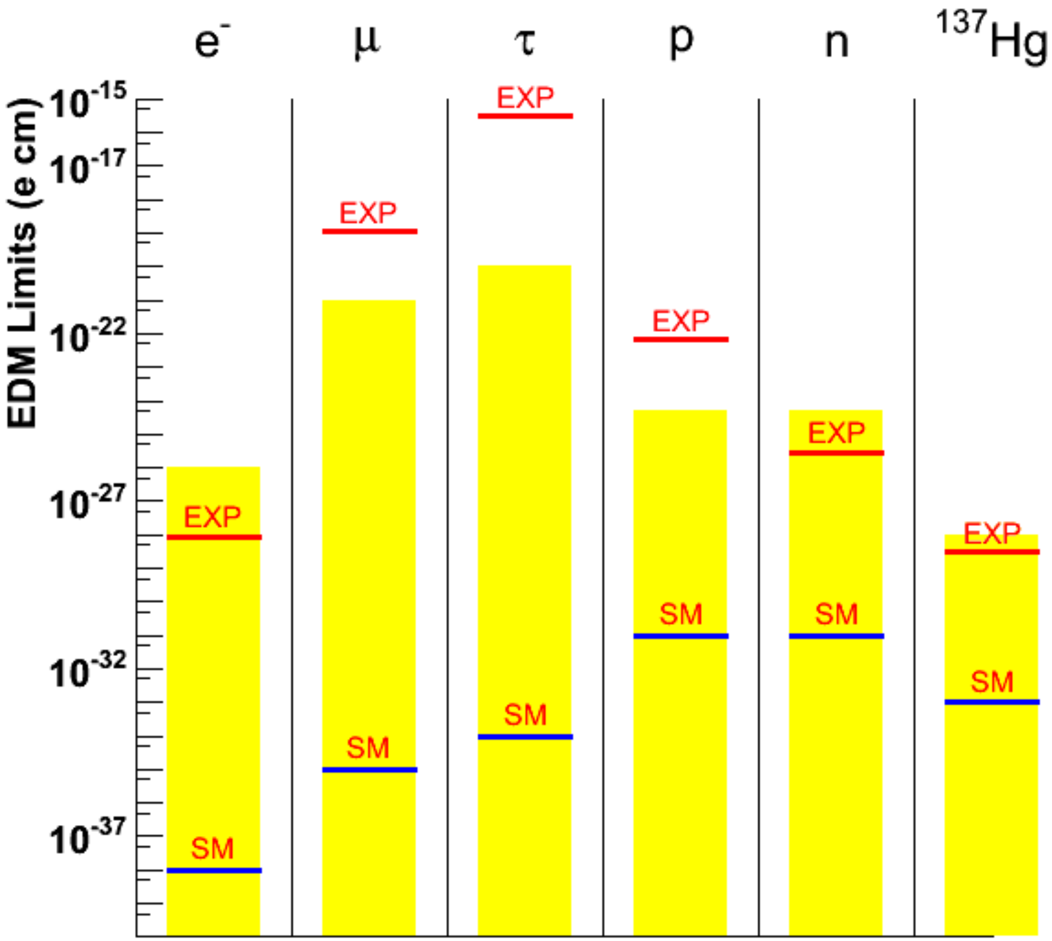
Electron Magnetic Moment

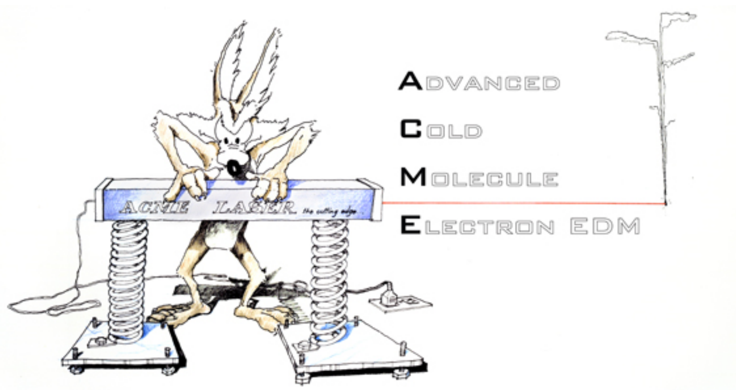
Measured to 3 parts in 10^{13} !!!

Physics reach of this is limited by precision in α_{EM} but this is expected to improve significantly in the near future



Electric Dipole Moment





In last month approx factor ~ 10 improvement in electron EDM limit

$$\frac{\mu_{\overline{p}}}{\mu_p} = -1.000000 \pm 0.000005 \quad (5\text{ppm})$$

Muonic Hydrogen

Published online 7 July 2010 | Nature | doi:10.1038/news.2010.337

News

The proton shrinks in size

Tiny change in radius has huge implications.

Geoff Brumfiel

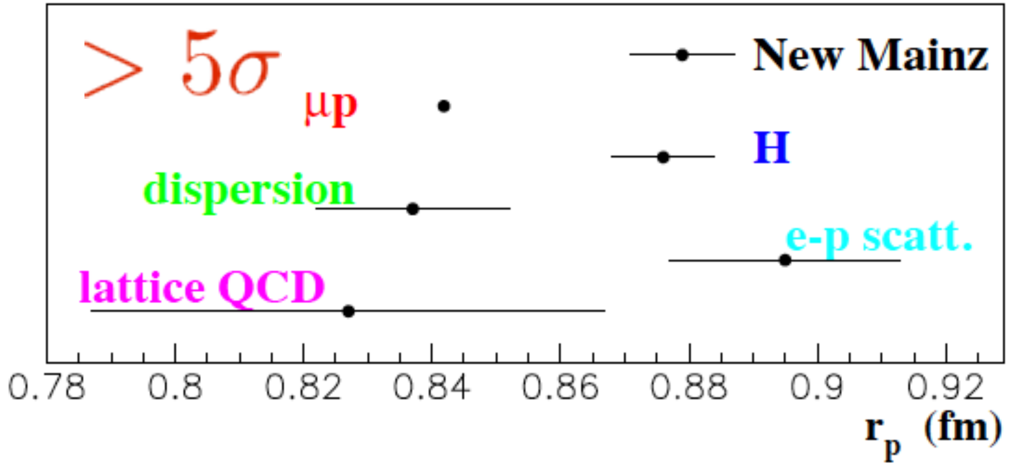
The proton seems to be 0.00000000000003 millimetres smaller than researchers previously thought, according to work published in today's issue of *Nature*[1].

Measurements with las
revealed that the proto
touch smaller than predicted by current theories.

PSI / F. Reiser

The difference is so infinitesimal that it might defy belief that anyone, even physicists, would care. But the new measurements could mean that there is a gap in existing theories of quantum mechanics. "It's a very serious discrepancy," says Ingo Sick, a physicist at the University of Basel in Switzerland, who has tried to reconcile the finding with four decades of previous measurements. "There is really something seriously wrong someplace."

Muonic hydrogen
- originally missed it !



Rp = 0.84184 (67) fm (muons)
Rp = 0.8768 (69) fm (electrons)

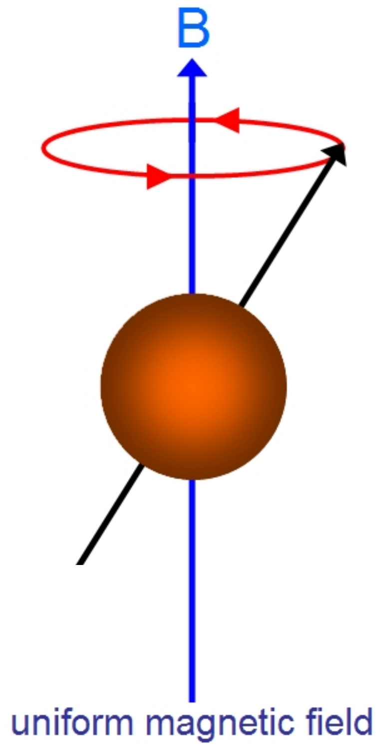
$$\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0346 r_p^3 \quad \text{meV}$$

Muon Magnetic Moment (g-2)

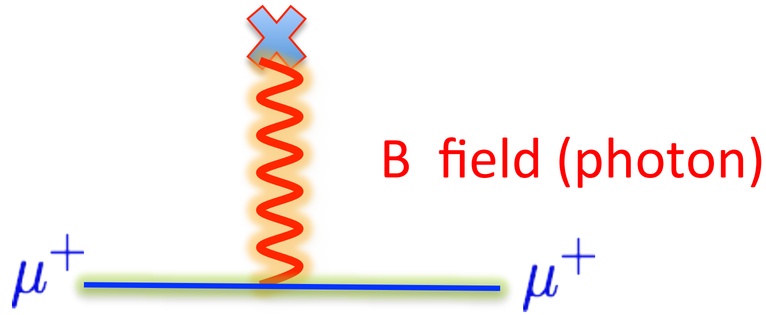
$$\vec{\mu} = g\frac{Qe}{2m}\vec{s}$$

Interaction between
magnetic moment (spin) with B-field.

$$\vec{\mu} \times \vec{B}$$



Spin **precesses** around B at
a frequency determined by “g”



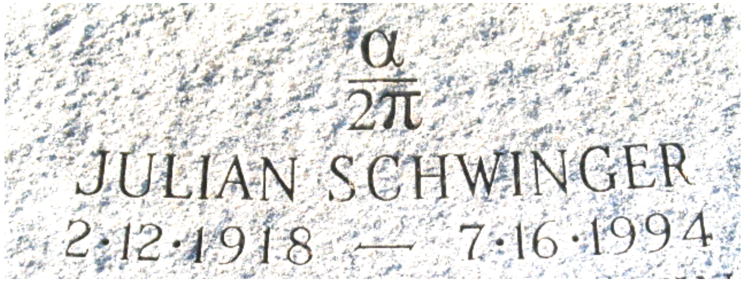
“Anomalous” contribution

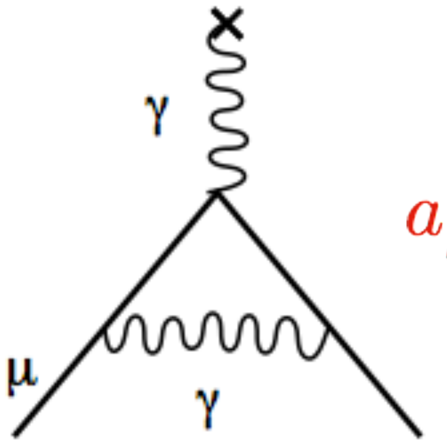
Additional “loop” interactions give **a non g=2 contribution**

$$a_\mu = \left(\frac{g-2}{2}\right)$$

This is the so-called anomalous contribution

These interactions flip the chirality of the muon

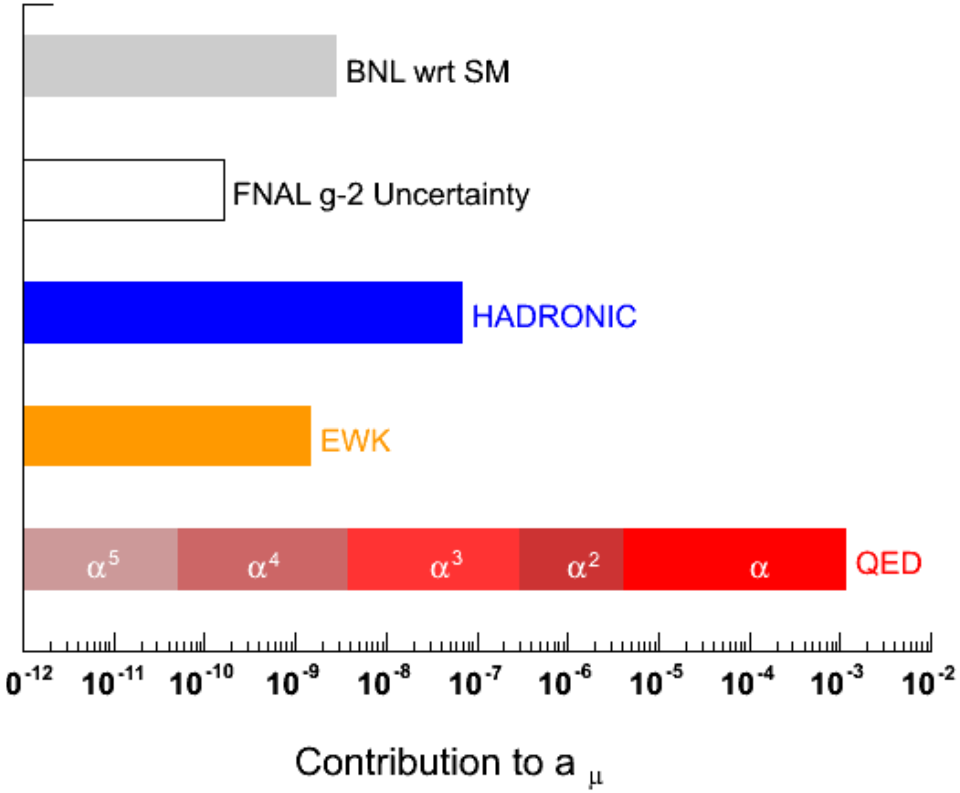


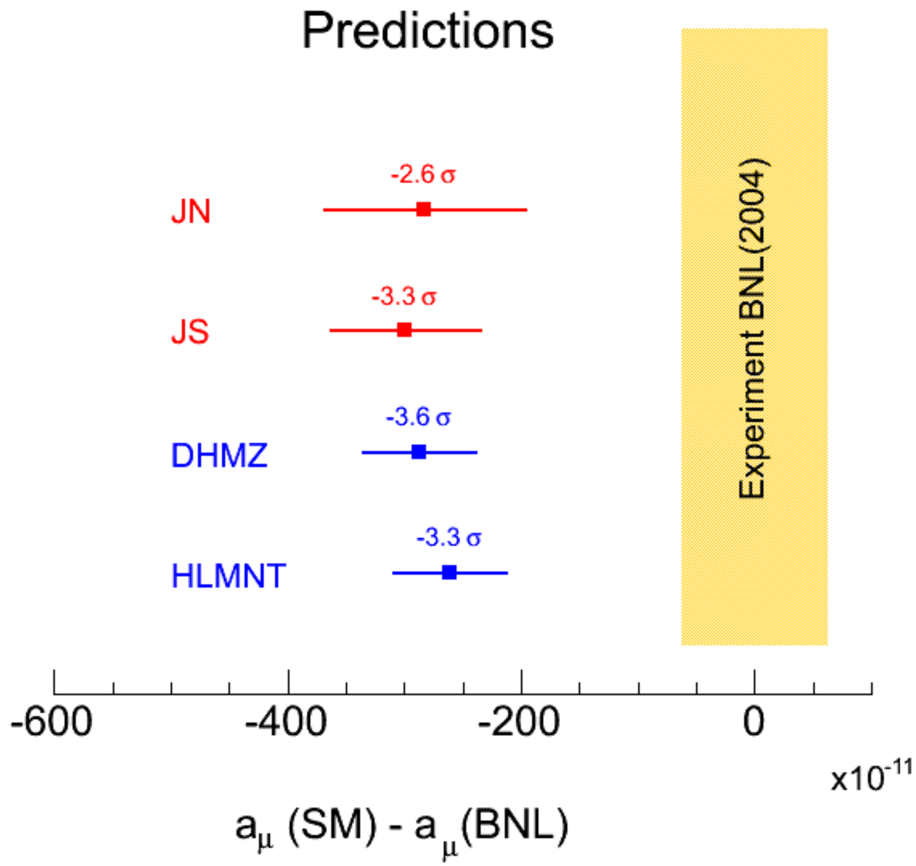


$$a_\mu = \frac{\alpha}{2\pi} = 0.00116\ 140980$$

$$= 0.00116\ 591792\ \text{(SM all loops)}$$

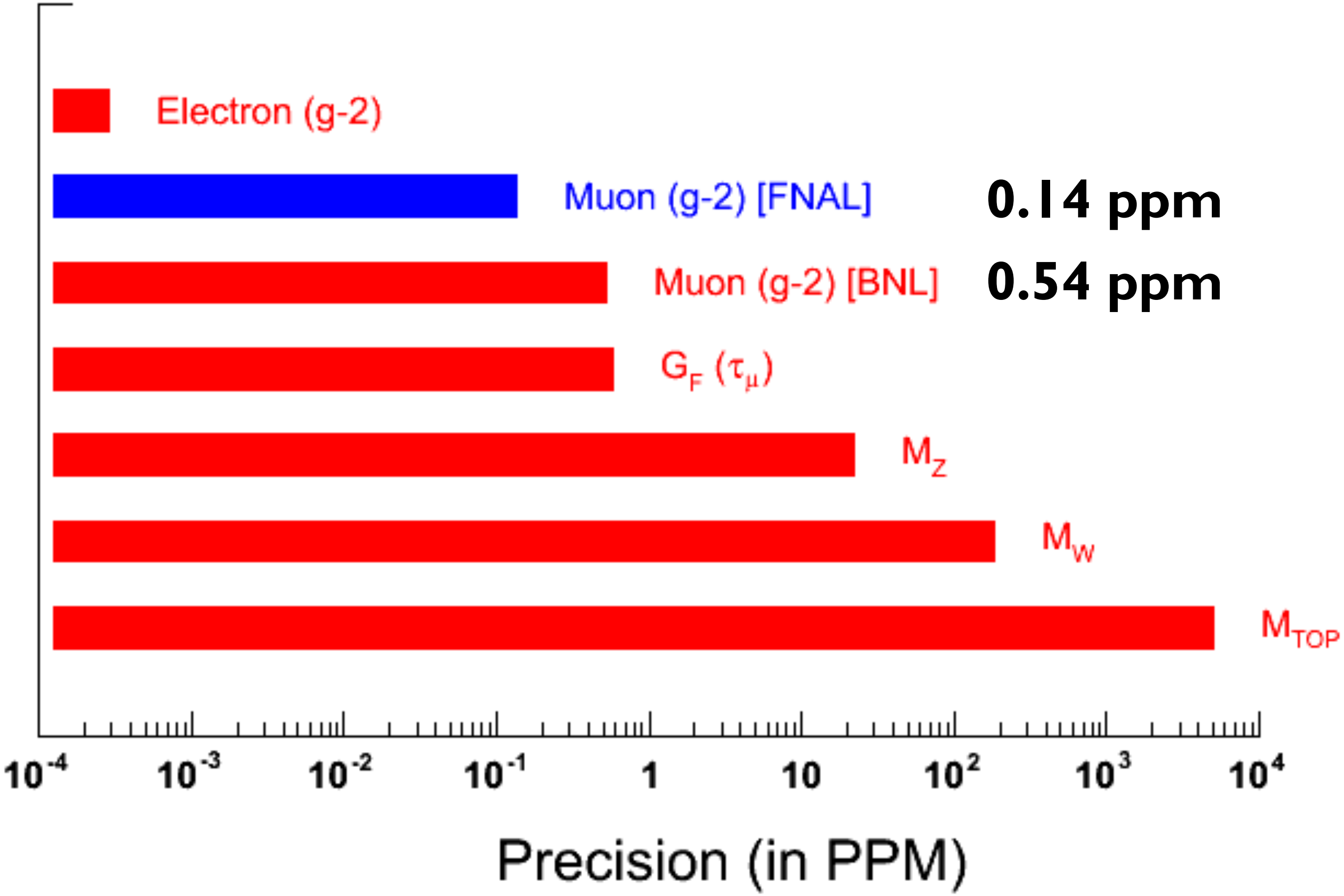
SM contribution





Muon g-2

Muon g-2 is most precisely measured quantity at an accelerator



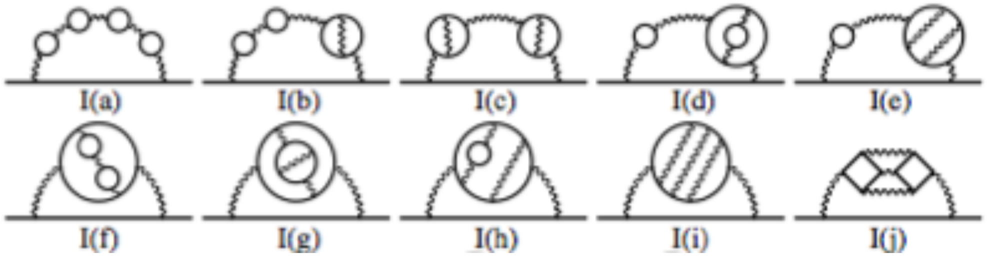
0.14 ppm

0.54 ppm

“We don’t know the SM value well enough”

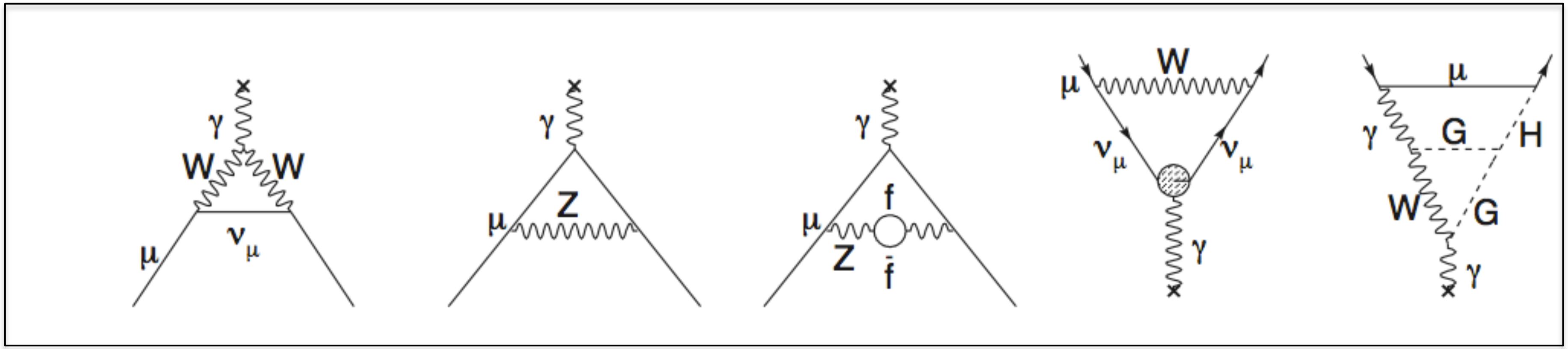
5-loop QED calculation (arxiv 1205.5370) : May 2012.

0.0003 ppm accuracy



2-loop electroweak calculation (arxiv 1306.5546) : June 2013

0.01 ppm accuracy

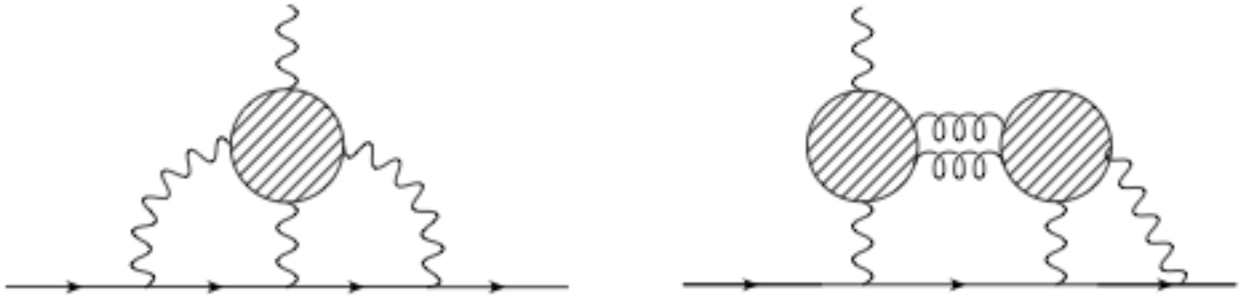


SM Hadronic Contribution

Hadronic Vacuum Polarisation (HVP)

0.36 ppm

Hadronic Light-by-Light (HLBL)

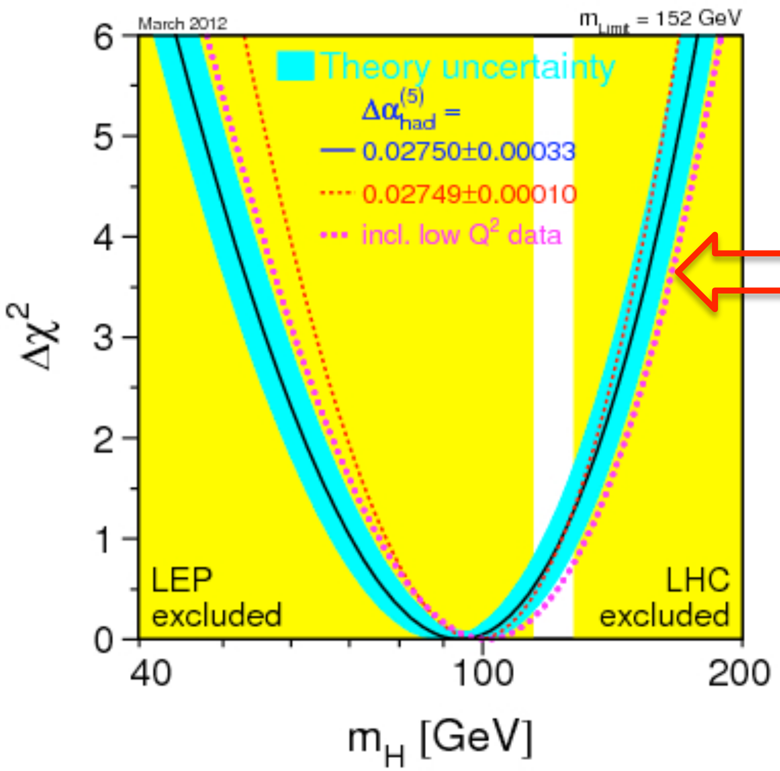


0.22 ppm

Reducing this 0.42 ppm to ensure 0.14 ppm FNAL measurement has maximum impact is now a subject of much work : expect O(50%) improvement.

Is this hadronic estimate reliable ?

97% of the hadronic estimate is **data-driven** and it can now be cross checked by the measured Higgs Mass



$$a_\mu^{\mathrm{HVP(LO)}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\boxed{\sigma(s)}ds$$

$$\Delta\alpha^{(5)}_{\mathrm{HAD}}(M_Z) = \frac{M_Z^2}{4\alpha\pi^2}P\int_{4m_\pi^2}^{\infty}\frac{\boxed{\sigma(s)}}{M_Z^2 - s}ds$$

This HVP value (+ other EWK data) gives

$$M_H = 94^{+29}_{-34}\ \mathrm{GeV}$$

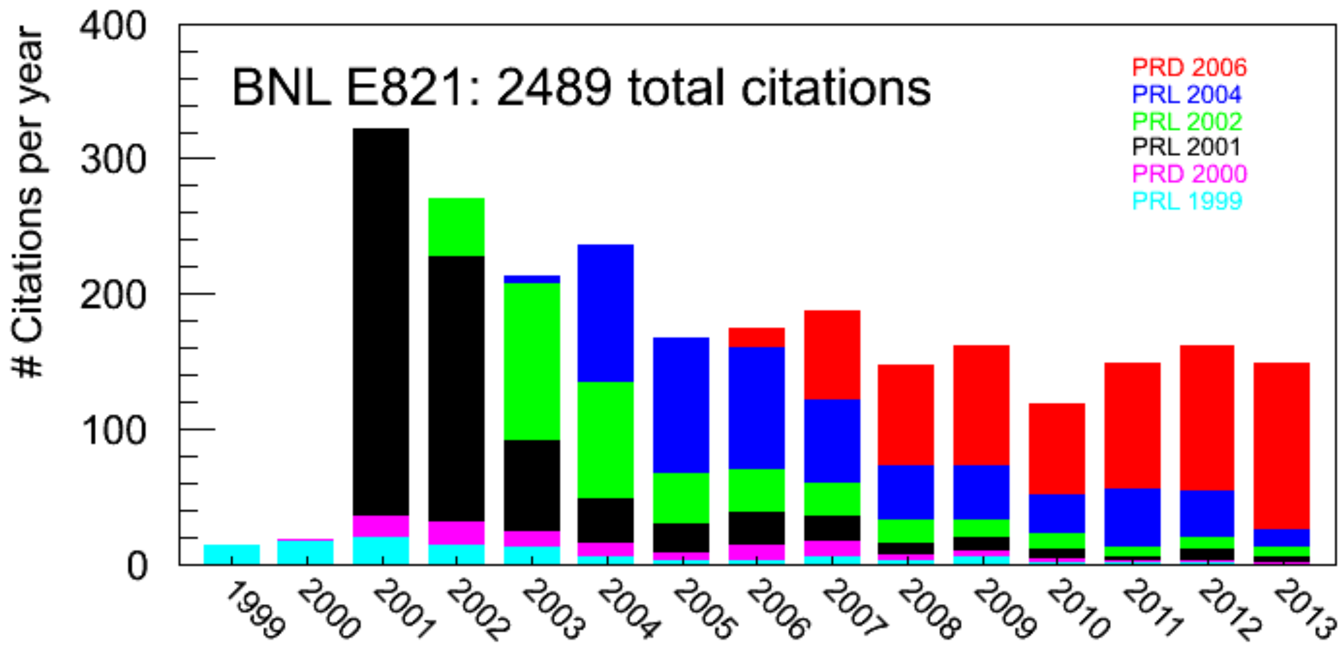
Assume HVP is wrong by 6 σ (so BNL = SM)

$$M_H = 68^{+29}_{-34}\ \mathrm{GeV}$$

Use M_H = 125 GeV for HVP **increases significance** of BNL discrepancy wrt SM

Theoretical Interest in result

BNL (g-2) paper(s) is the 2nd most cited paper in experimental particle physics



Renewed interest after Higgs and null-SUSY results at the LHC

Theoretical Landscape

Measurement probes much of the same TeV-scale BSM landscape as LHC.

Large +ve anomaly wrt SM

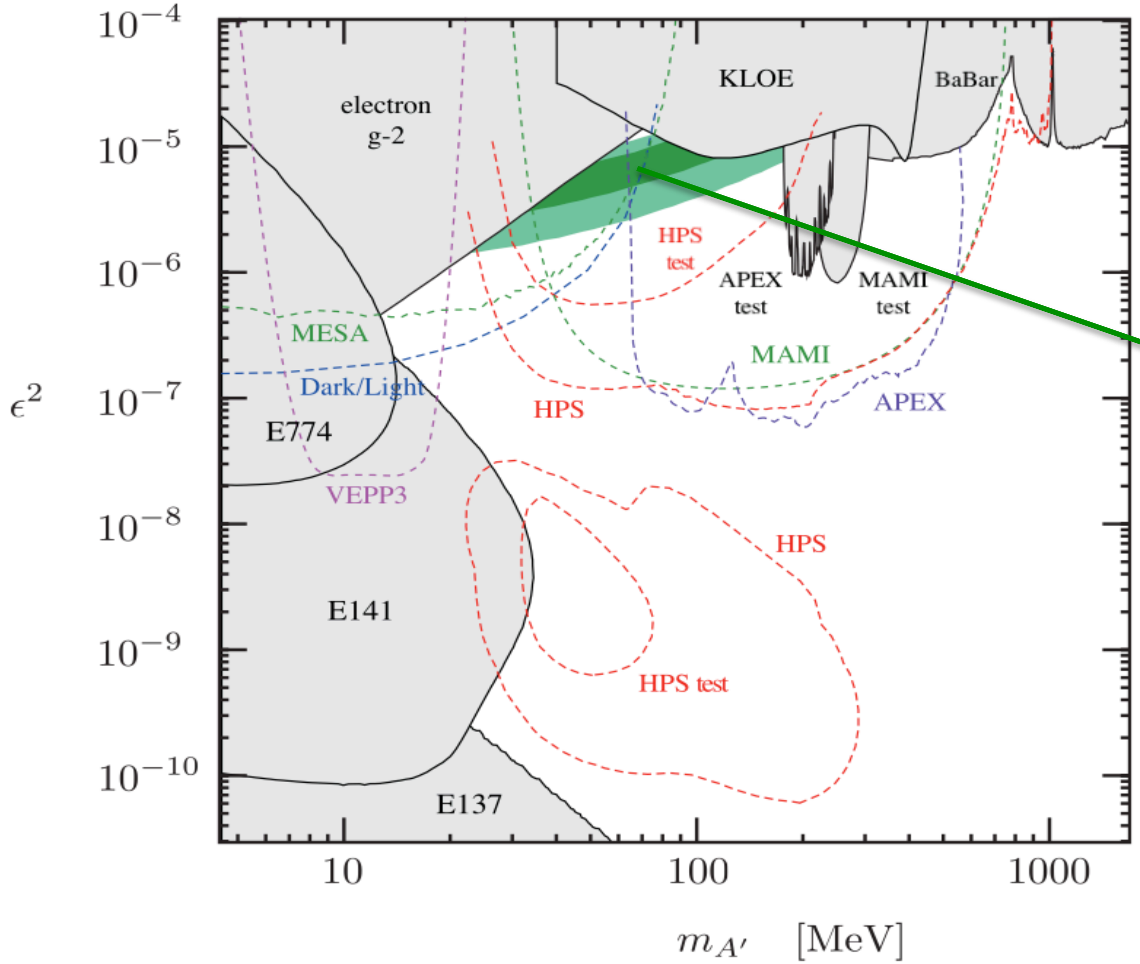
Extended technicolor (fermion masses)

SUSY (natural, gauge-mediated, compressed), RS ED

Z', W', Little Higgs, Universal ED

Value consistent with SM

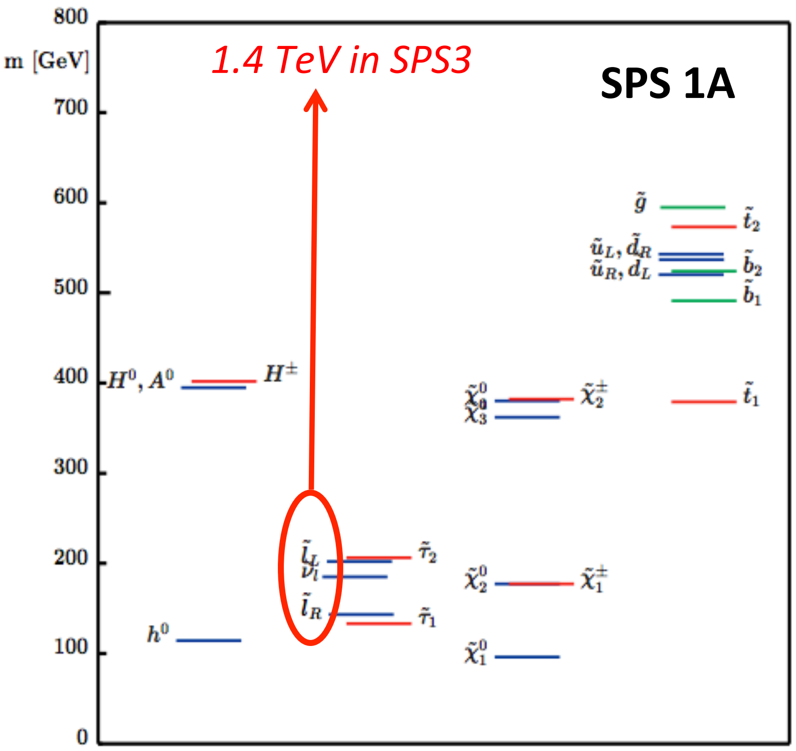
But also low-mass physics below LHC's reach



Dark photon contribution of 280±80 x 10^{-11} to a_{μ}

SUSY

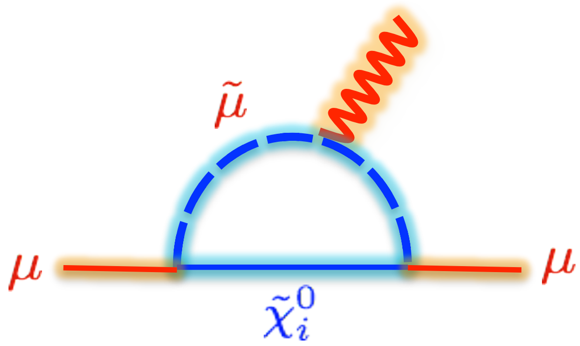
Many pre-LHC "models" ruled out solely by squark and gluino limits



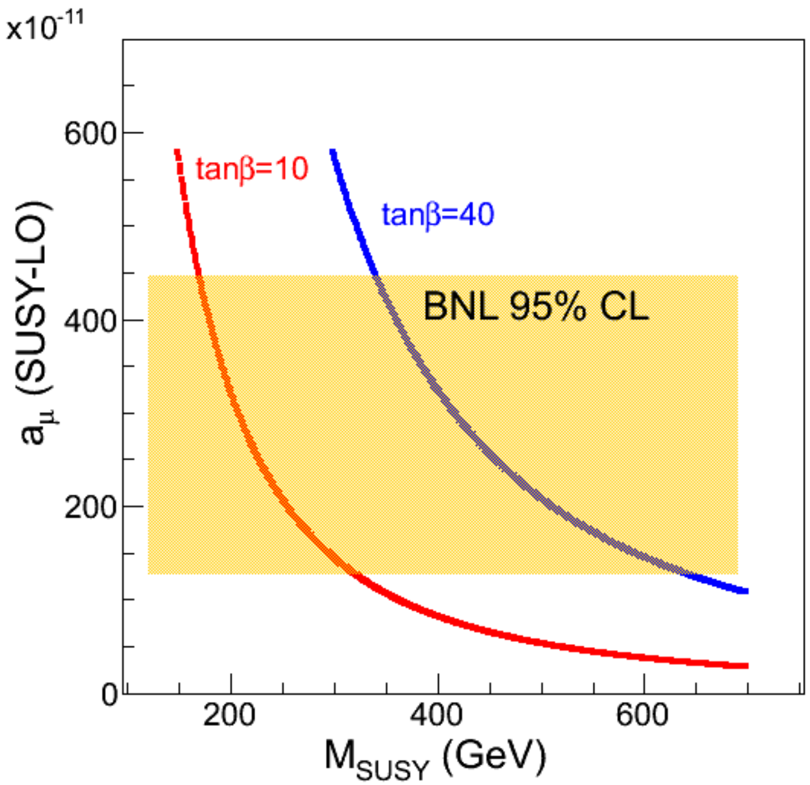
"Looking to (SUSY) models with ***a different connection between the coloured and uncoloured sector****, not only seems timely now, but mandatory."*

John Ellis et al., arxiv:1207.7315

LHC constraints on neutralino-slepton are comparatively weak.



SUSY



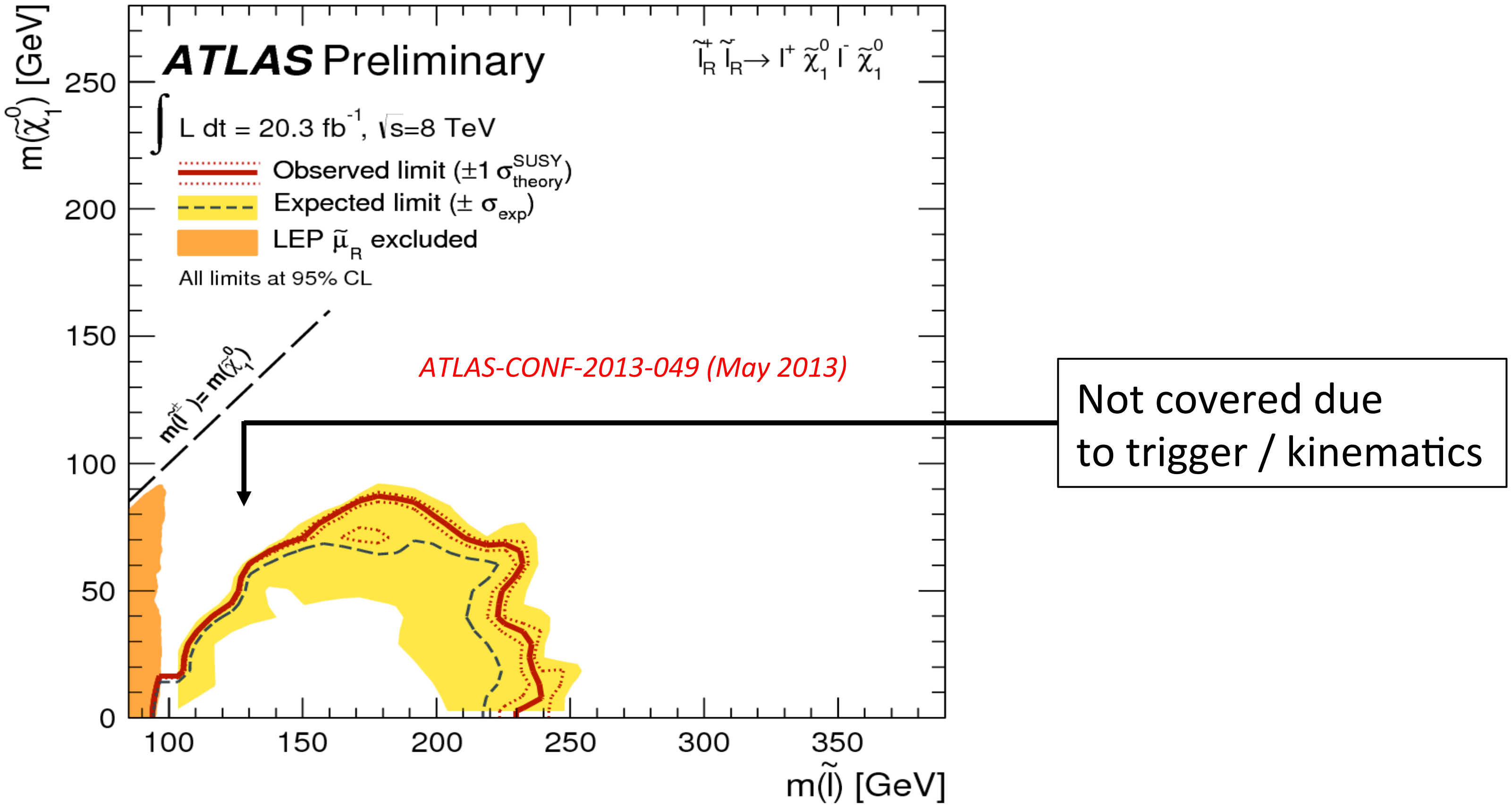
At 95% CL current BNL a_μ favours smuon masses of 200 – 700 GeV

Also unambiguously defines μ (Higgsino mass term) to be positive

A measurement with < 100 x 10^{-11} different wrt to SM would put non-coloured SUSY in similar mass region to squarks/gluinos

a_μ measurement + LHC smuon mass allows an accurate determination of tan β

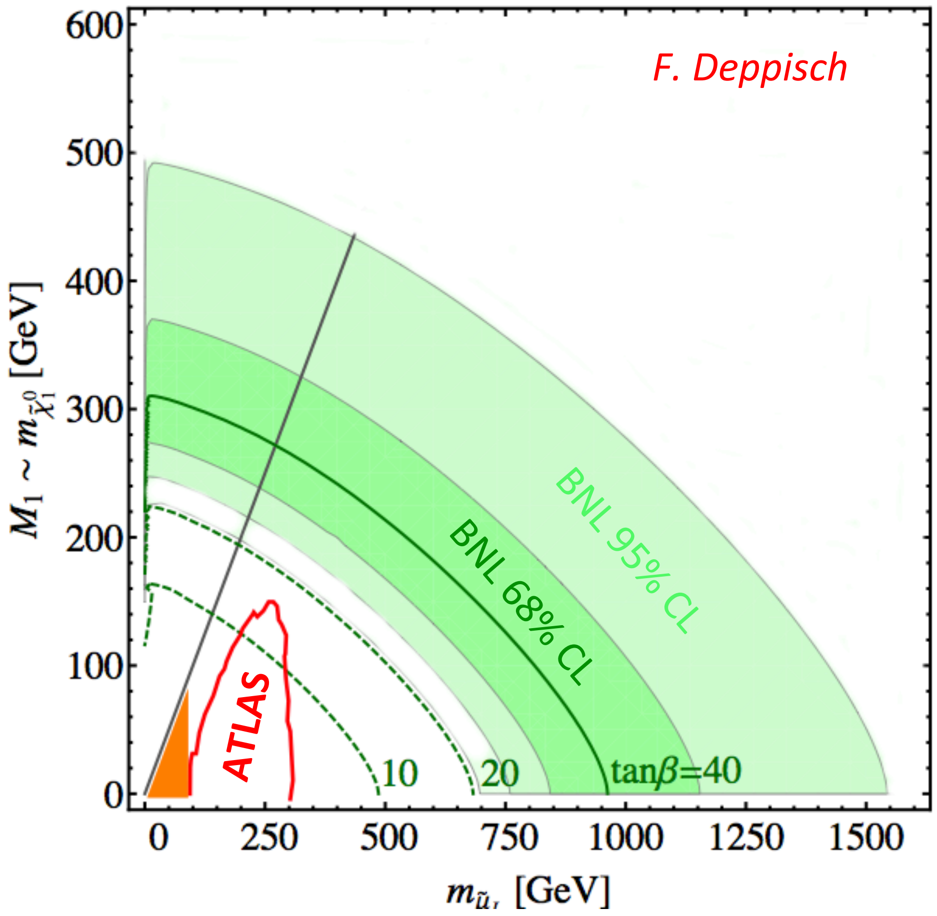
LHC slepton limits



Much of phase space giving large a_μ is not covered by LHC

Constraints beyond LHC

$$M_2 = \mu = 2M_1, m_{\tilde{\mu}_R} \gg m_{\tilde{\mu}_L}$$

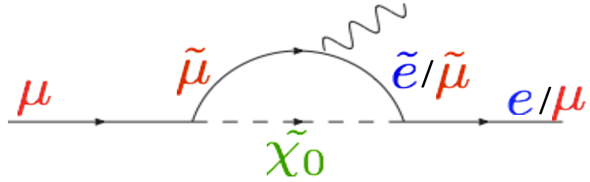


(g-2) probes/constrains additional phase space beyond LHC

Need both g-2 and CLFV

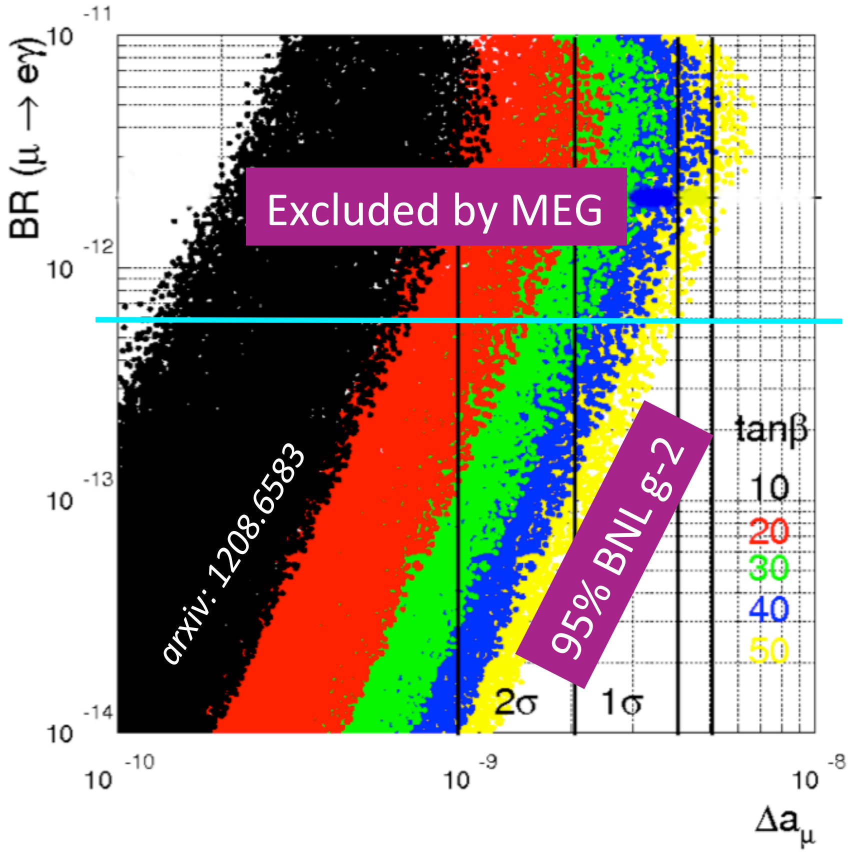
For BSM dipole interactions e.g. SUSY

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



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

But no theoretical motivation for any particular $\theta_{e\mu}$ value.



Need **both** measurements to resolve model degeneracy

The g-2 Measurement

"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known" : Pauli

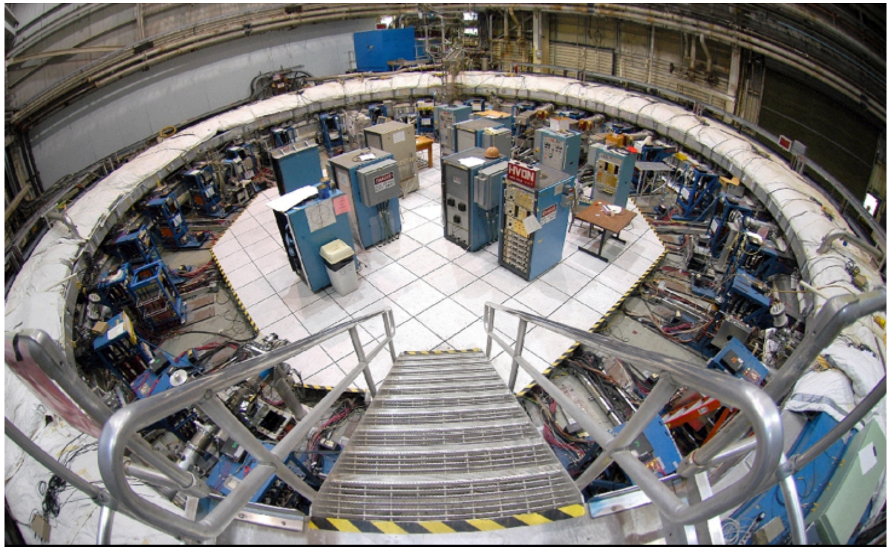
Otto Stern Wolfgang Pauli

"No experiment is so dumb, that it should not be tried" : Gerlach

Evidence for proton structure in 1933 from its magnetic moment.

FNAL g-2

1. Use established technique (& apparatus)
2. Increase # muons by factor of 21
3. Reduce systematics by factor of 3



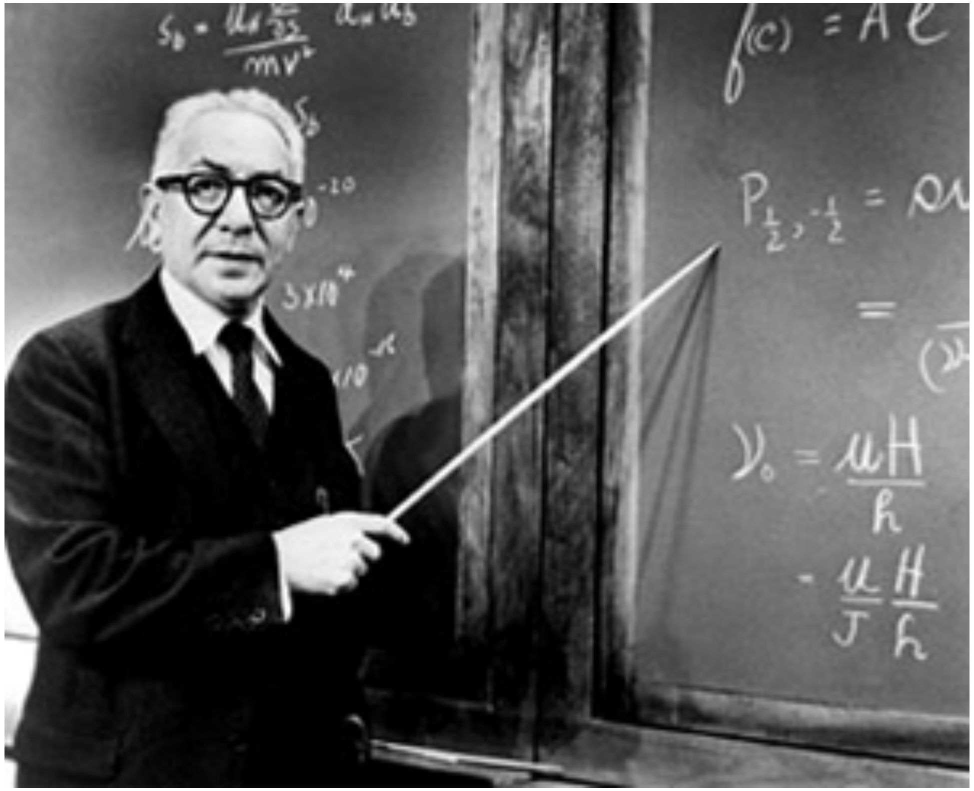
$$\mathrm{BNL} \rightarrow \mathrm{FNAL}$$

$$[54\ (\mathrm{stat.}) \oplus 33\ (\mathrm{syst.}) \rightarrow 11\ (\mathrm{stat.}) \oplus 11\ (\mathrm{syst.})] \times 10^{-11}$$

$$0.54\ \mathrm{ppm} \rightarrow 0.14\ \mathrm{ppm}$$

Data taking to begin April 2016

Frequency



"Never measure anything but frequency"

I. Rabi

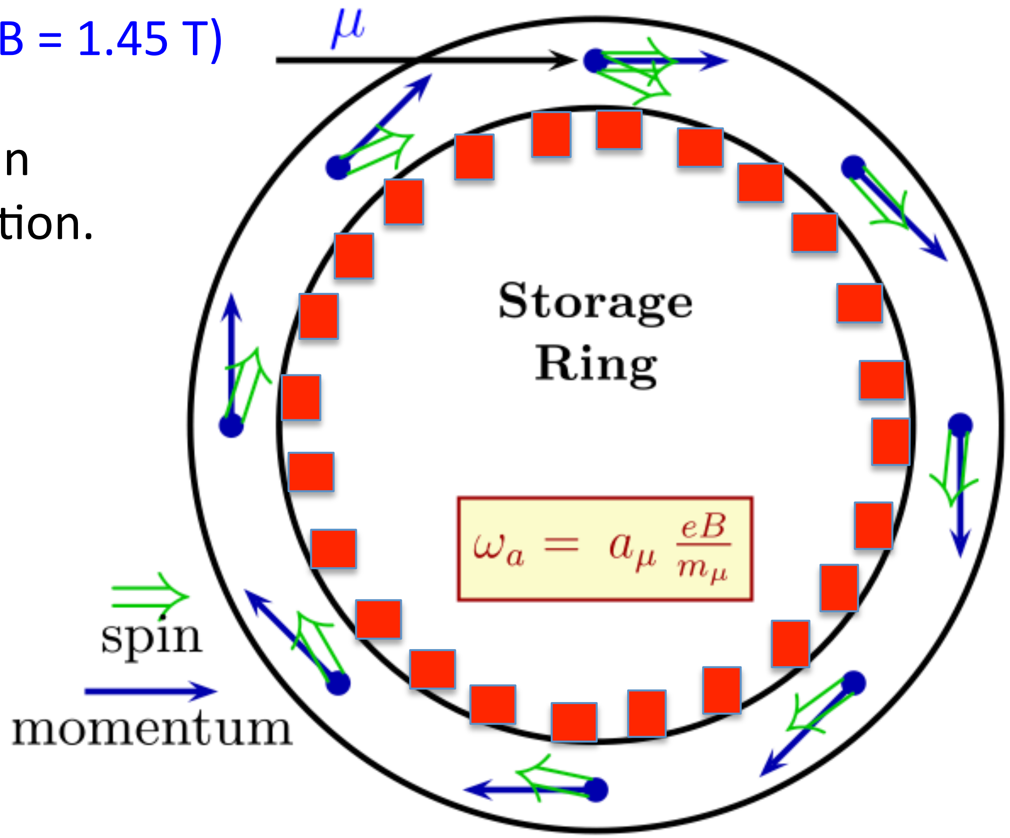
$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

Experimental Technique

Inject muons into a storage ring (B = 1.45 T)

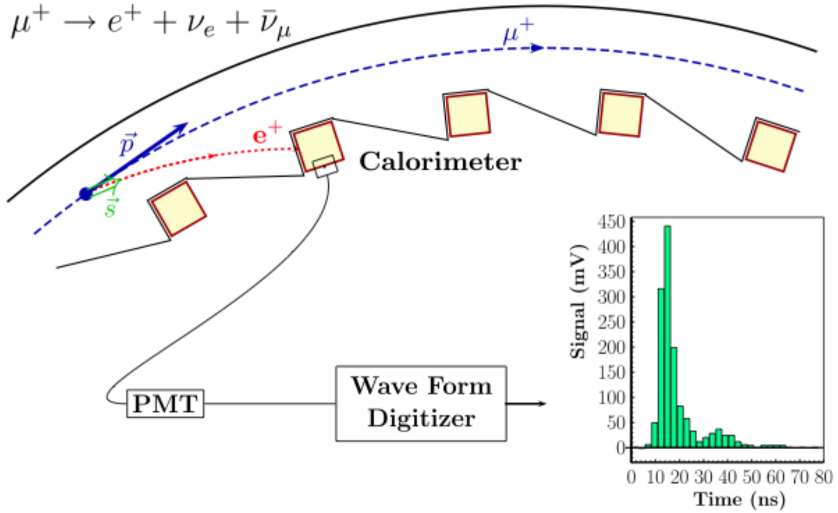
Measure rate of precession of spin with respect to momentum direction.

Exploit property that direction of e^+ from μ^+ decay is strongly (anti)correlated with μ^+ spin for highest energy e^+



1. **Measure e^+ with E > 1.9 GeV in 24 calorimeters vs t (30 μs after injection)**
2. **Measure B field to a precision of 0.07 ppm**

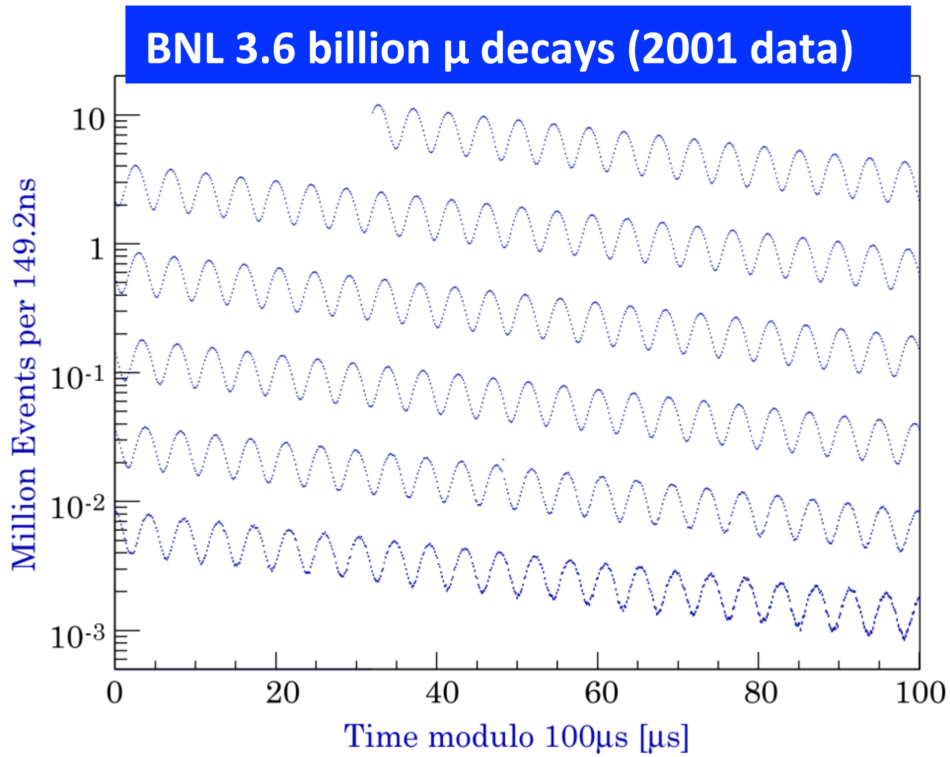
The data



$$N(t) = N_0 \exp(-t/\gamma\tau_\mu)\left[1 - A\cos(\omega_a t + \phi)\right]$$

A, ϕ : known functions of e^+ energy

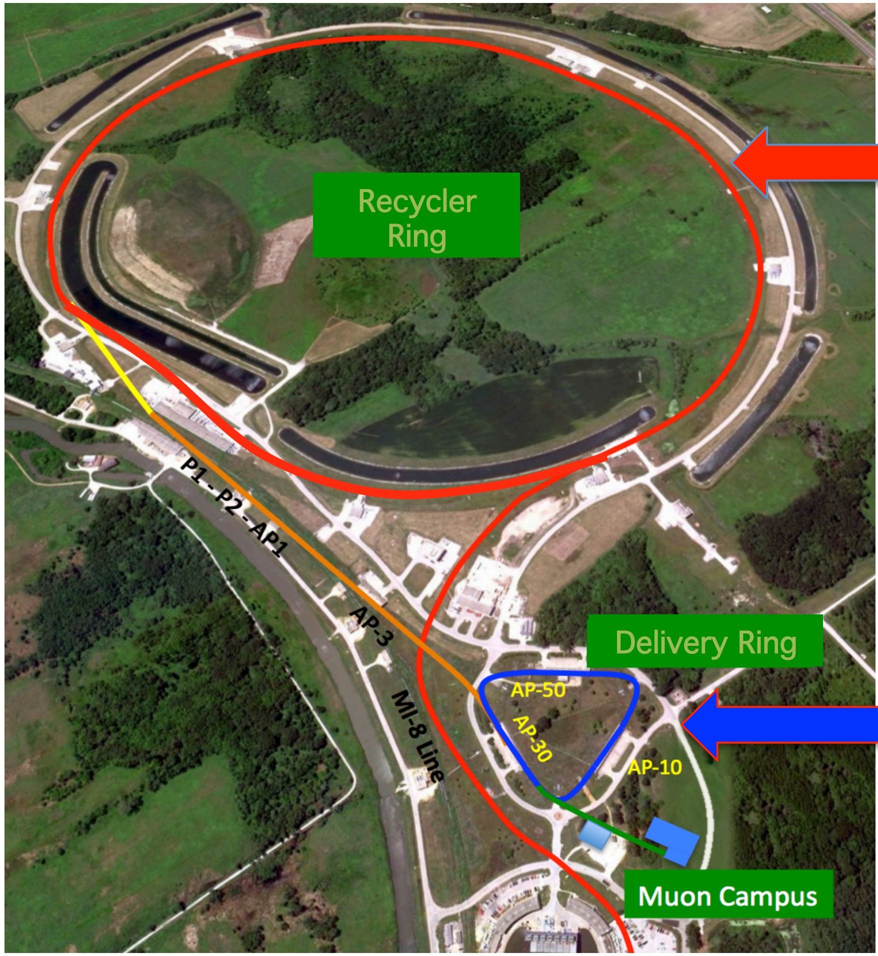
$$\omega_a = a_\mu \frac{eB}{m_\mu}$$



4 Key Improvements over BNL experiment

1. **Accelerator before storage ring**

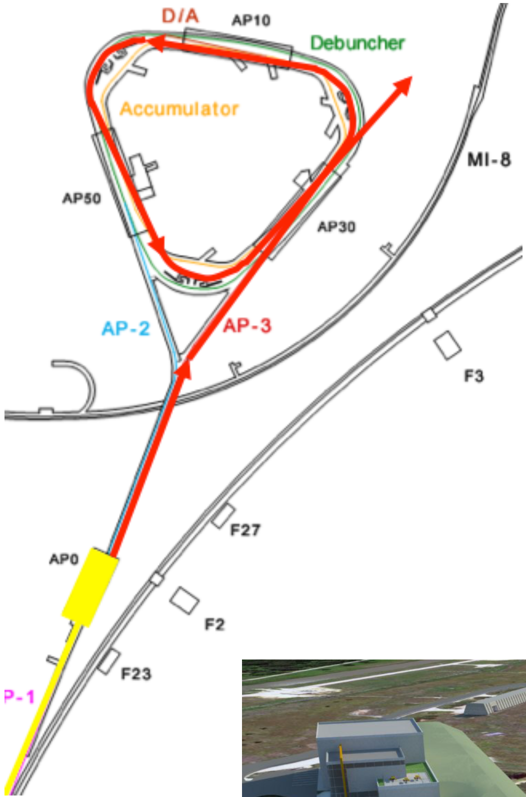
   More muons at lower inst. rate with much reduced pion contamination

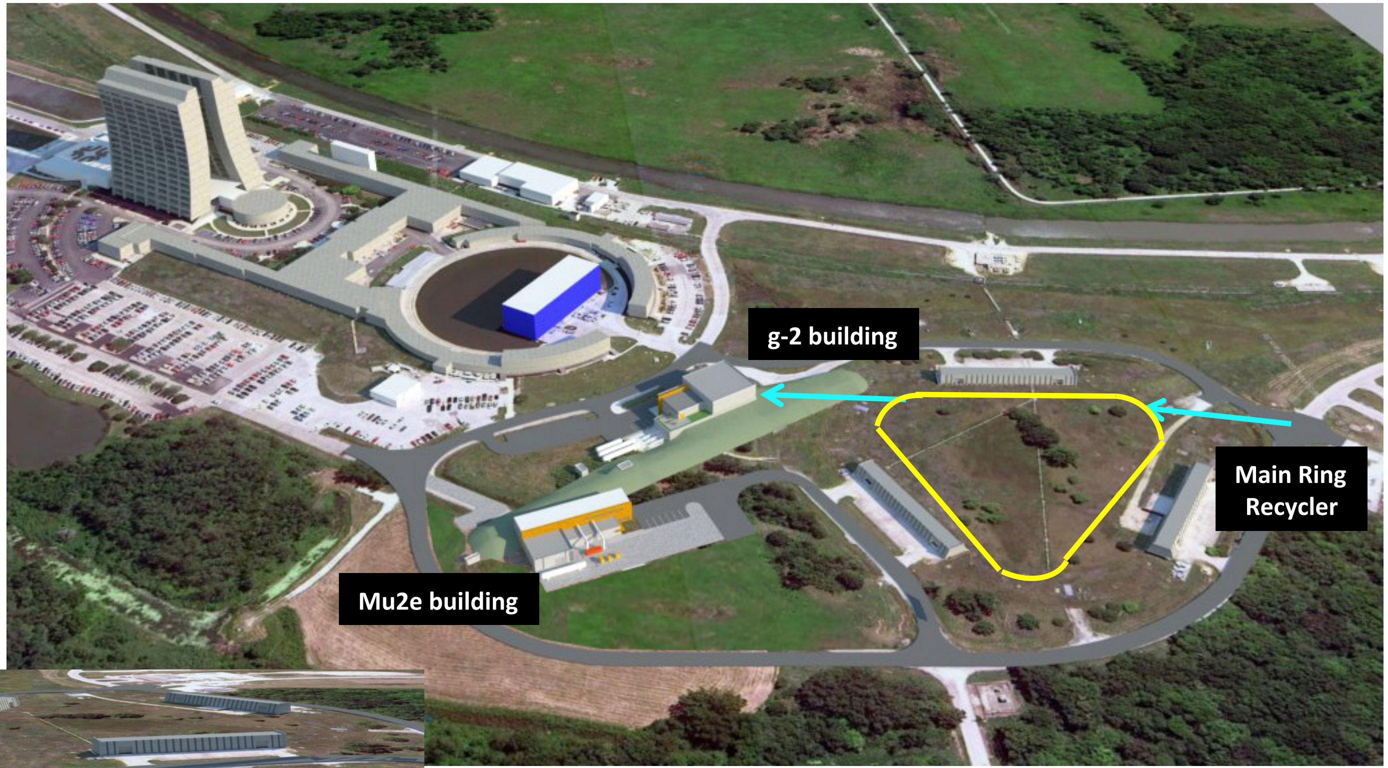


Proton accelerator mods completed since needed for NoVa.

Pbar accelerator complex being re-configured to provide muons.

Improvements over BNL experiment



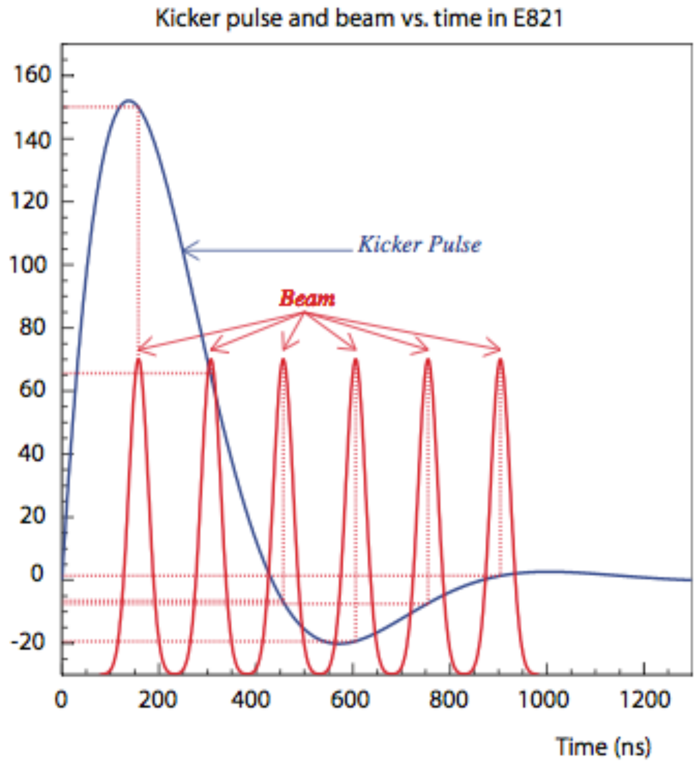


Muon campus

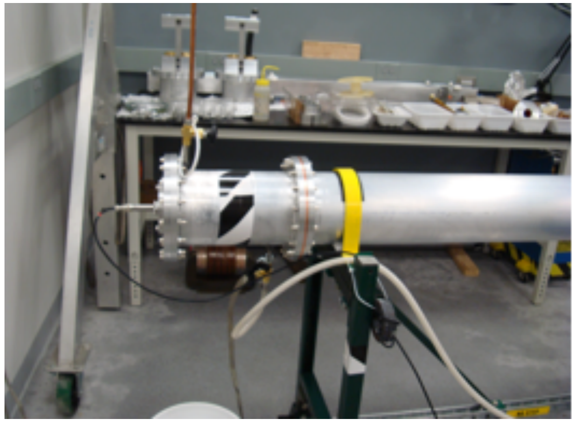
Building ready for kit in April 2014

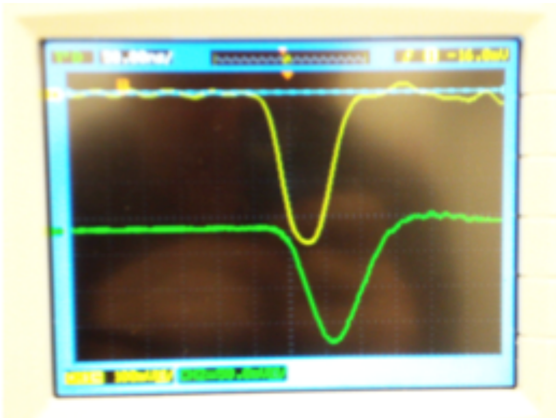
Improvements

2. New inflector magnet, better kicker, better CBO damping



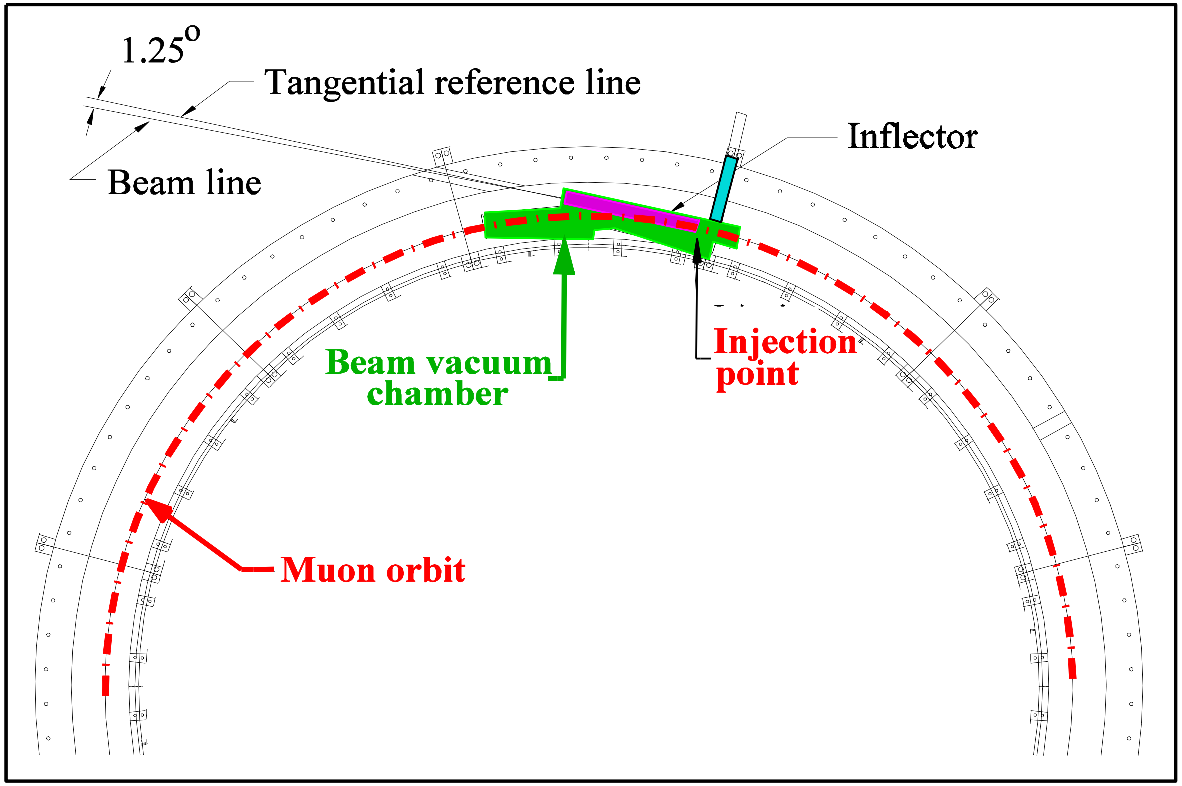
Kicker use Blumlein triaxial transmission line to reduce kick to < 100 ns.

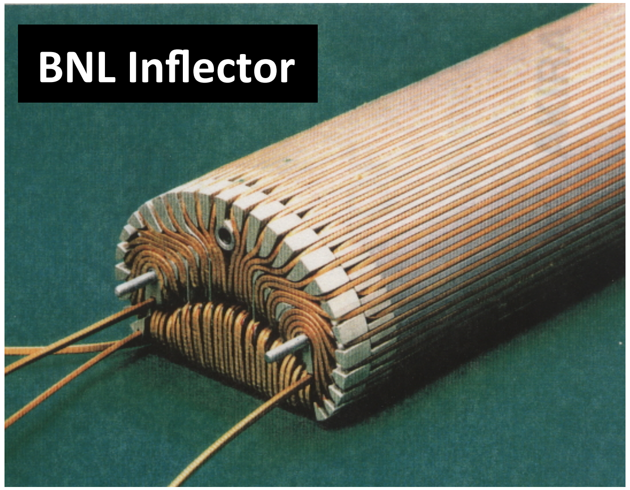




- coupled with improved beam modeling

Inflector





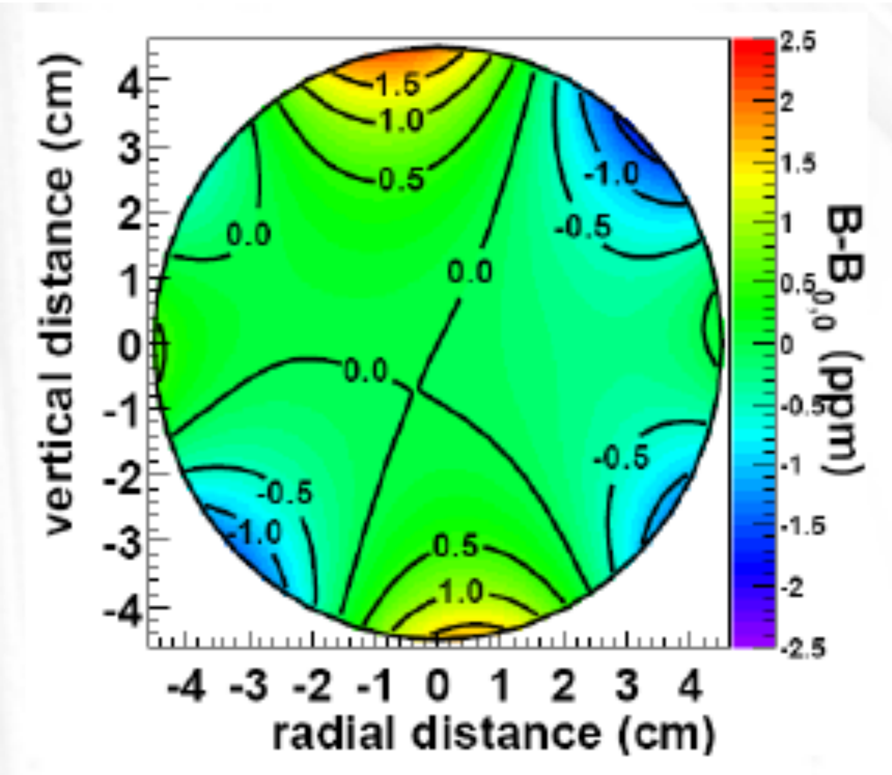
1.7m superconducting magnet with superconducting flux shield

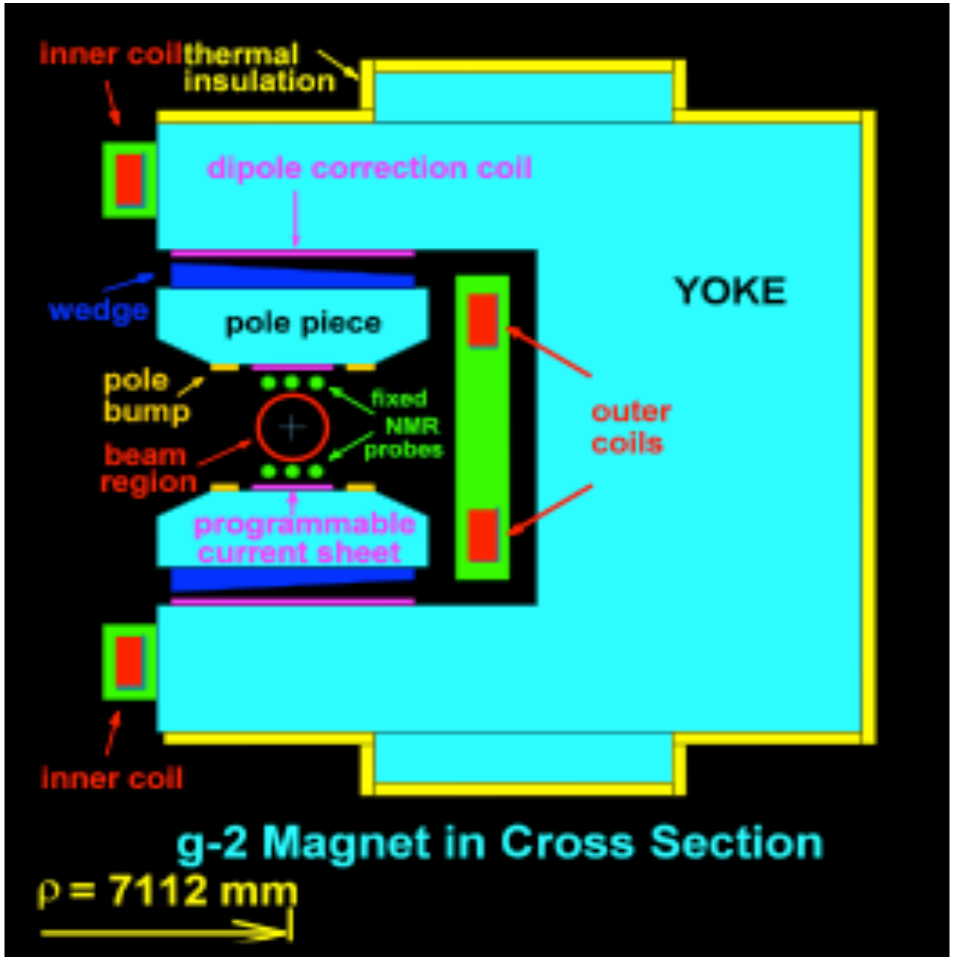
Cancels main storage ring B-field by providing “cancelling” field BUT only at the injection point

This will be replaced with a new “open-end” design that increases muon acceptance and orbit stability over BNL experiment.

Improvements

3. B-field : uniformity and calibration will be improved



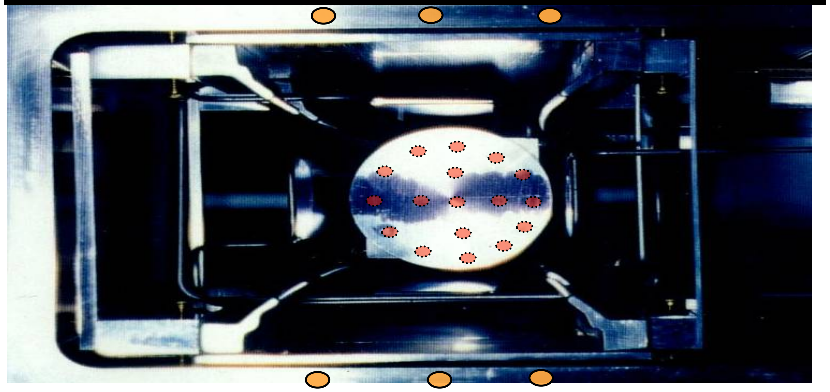


Additional field shimming,
more frequent field mapping.

B-field improvements

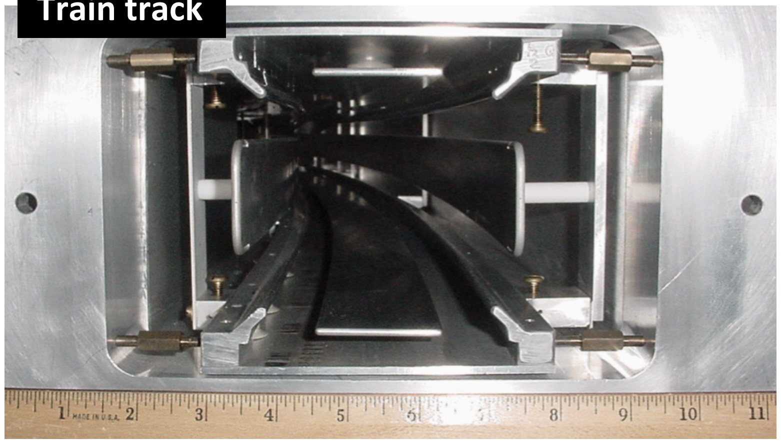
$H_2$0-based ref. NMR probe -> ^{3}He

378 fixed NMR probes in vacuum tank walls



17 movable NMR probes on a trolley

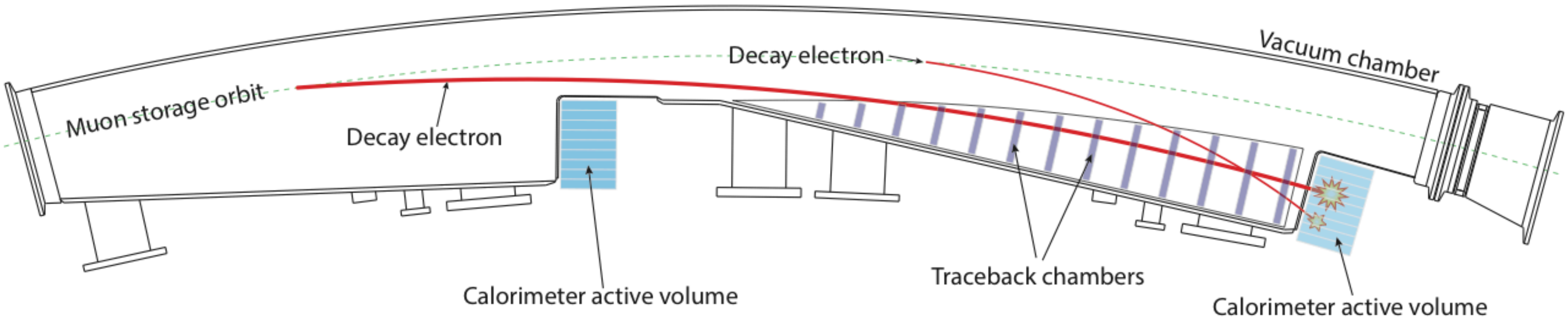
Train track



Improvements

4. New detectors: improved stability, better handling of pileup

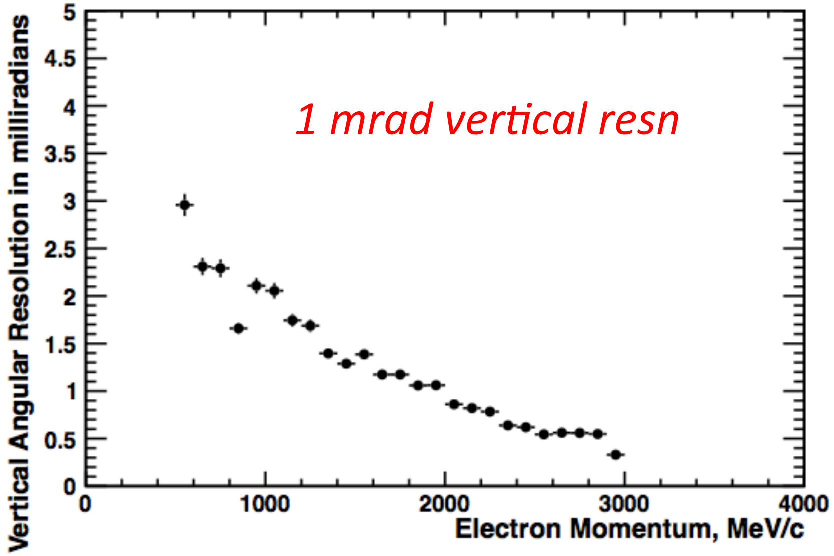
- Improved tracking (straws in vacuum)
- New segmented calorimeter
- New calibration system



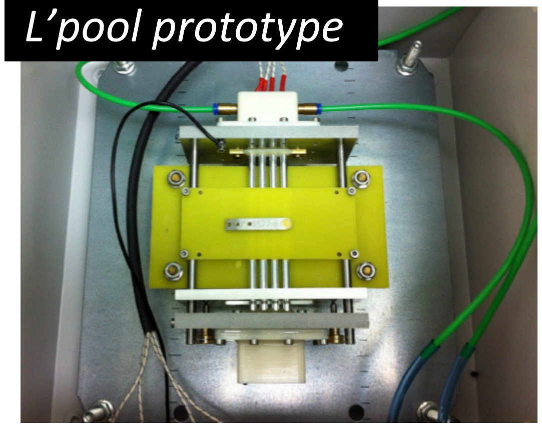
Straws provide beam profile, calorimeter pileup corrections & calibration and **muon EDM….**

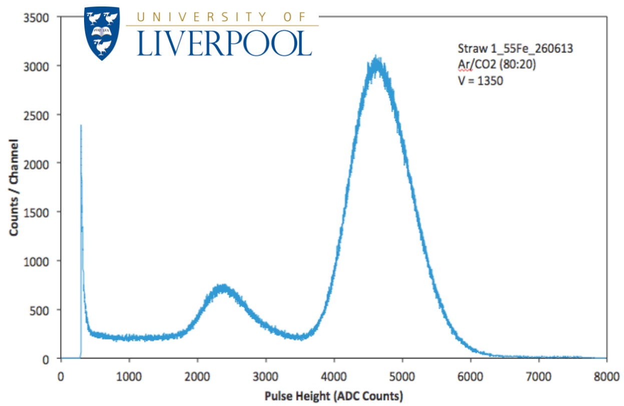
- low mass, non-magnetic in primary vacuum
- 11 (0.1% X_0) stations each with UV plane : 1216 straws

Tracker ?



L'pool prototype

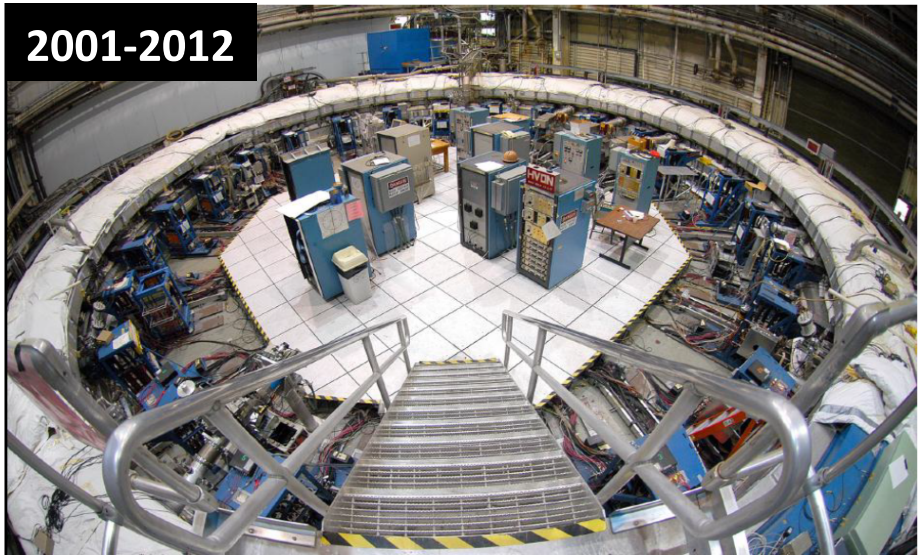


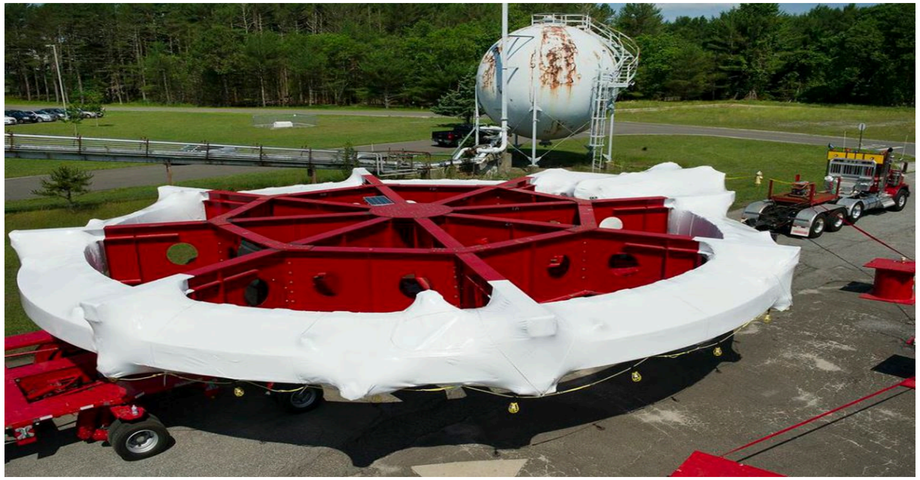


UNIVERSITY OF LIVERPOOL

The journey

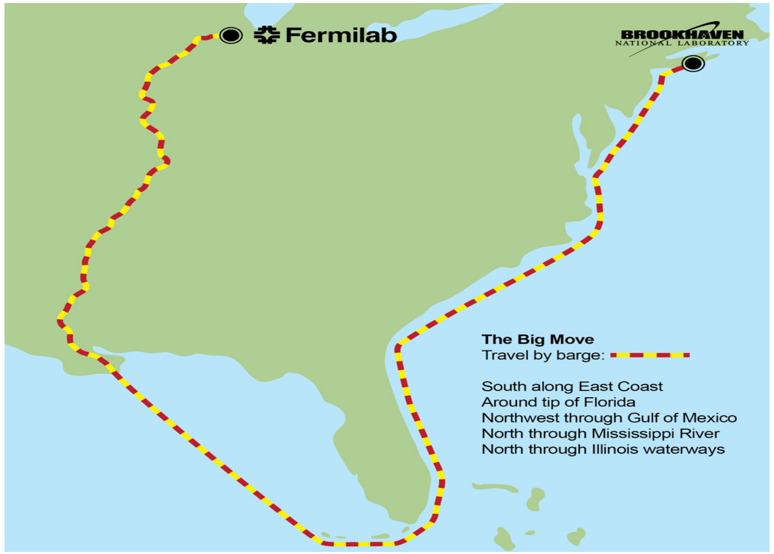
2001-2012





June 24 2013

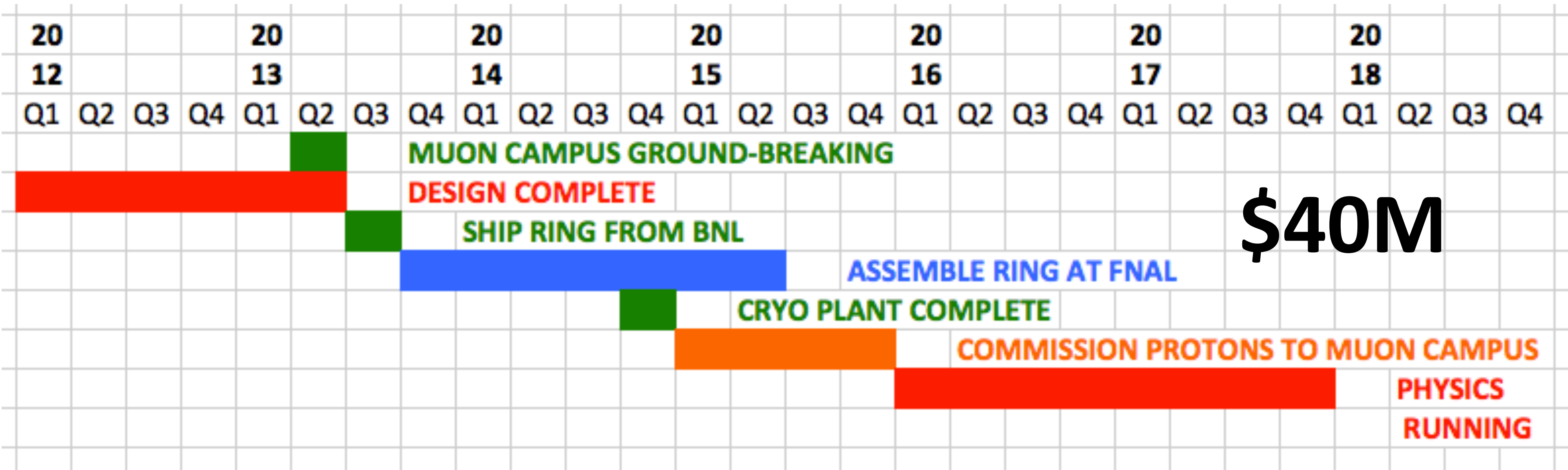
The journey


Fermilab
BROOKHAVEN
NATIONAL LABORATORY
The Big Move
Travel by barge:
South along East Coast
Around tip of Florida
Northwest through Gulf of Mexico
North through Mississippi River
North through Illinois waterways


Muon g-2

Arrived safely in Fermilab in mid July

Timeline



80 collaborators in 16 US institutes + 30 (Germany, Netherlands, China, Russia, Italy, UK)

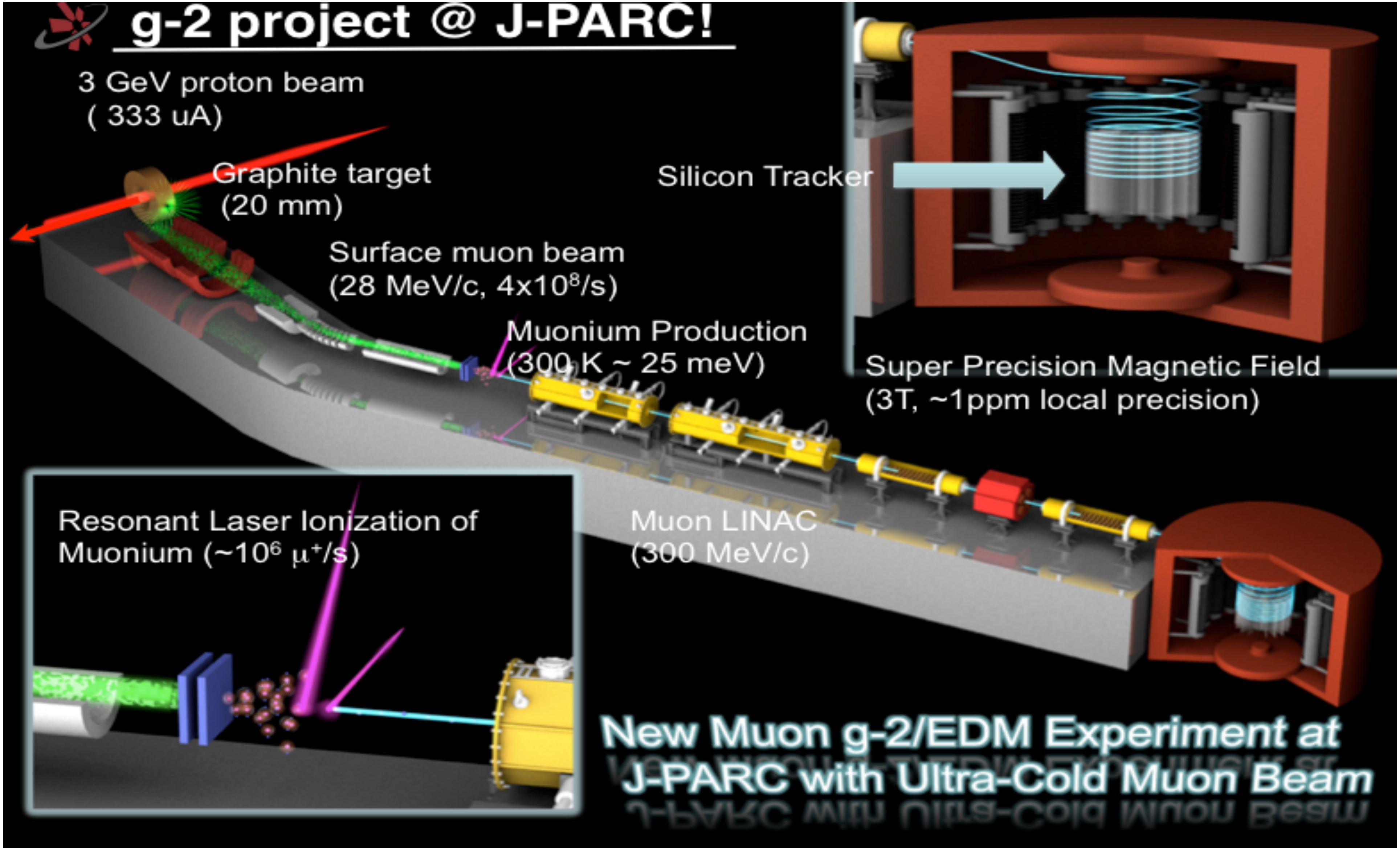
J-PARC Muon g-2

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

FNAL/BNL approach : use magic γ (29.3), p = 3.09 GeV muons.

J-PARC proposal : use E ~ 0
: ultra-cold muons (low β)
: larger (and more uniform) B (3T MRI magnet)

J-PARC Muon g-2



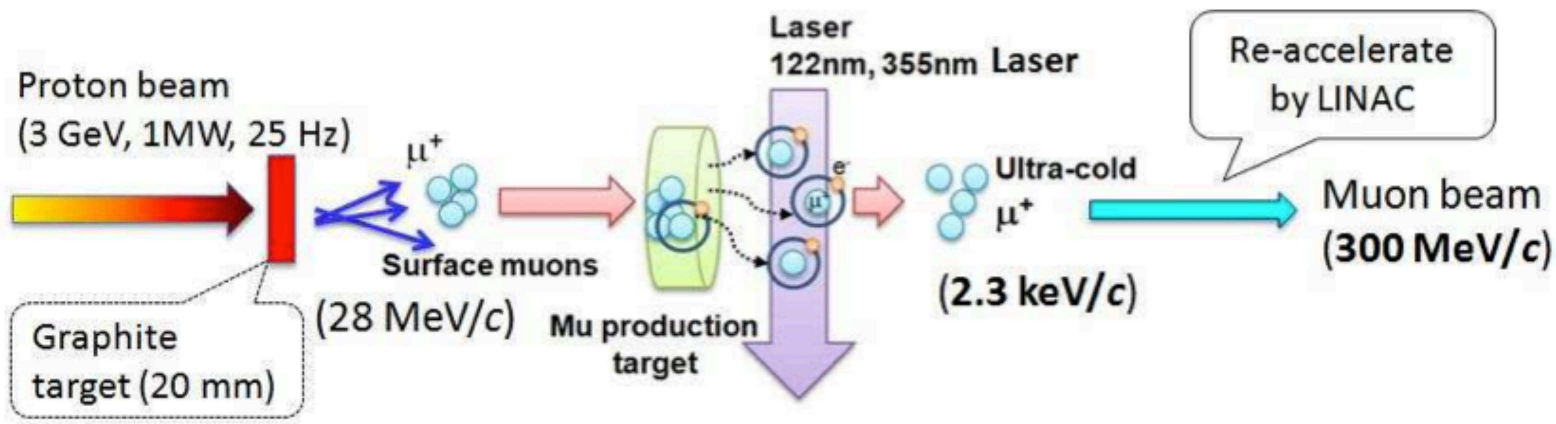
J-PARC g-2 : Several Challenges

Getting a sufficient rate of ultra cold muons (require 10^6 /sec and 10^{12} e^+)

Avoiding pile-up issues in detector with the high rate

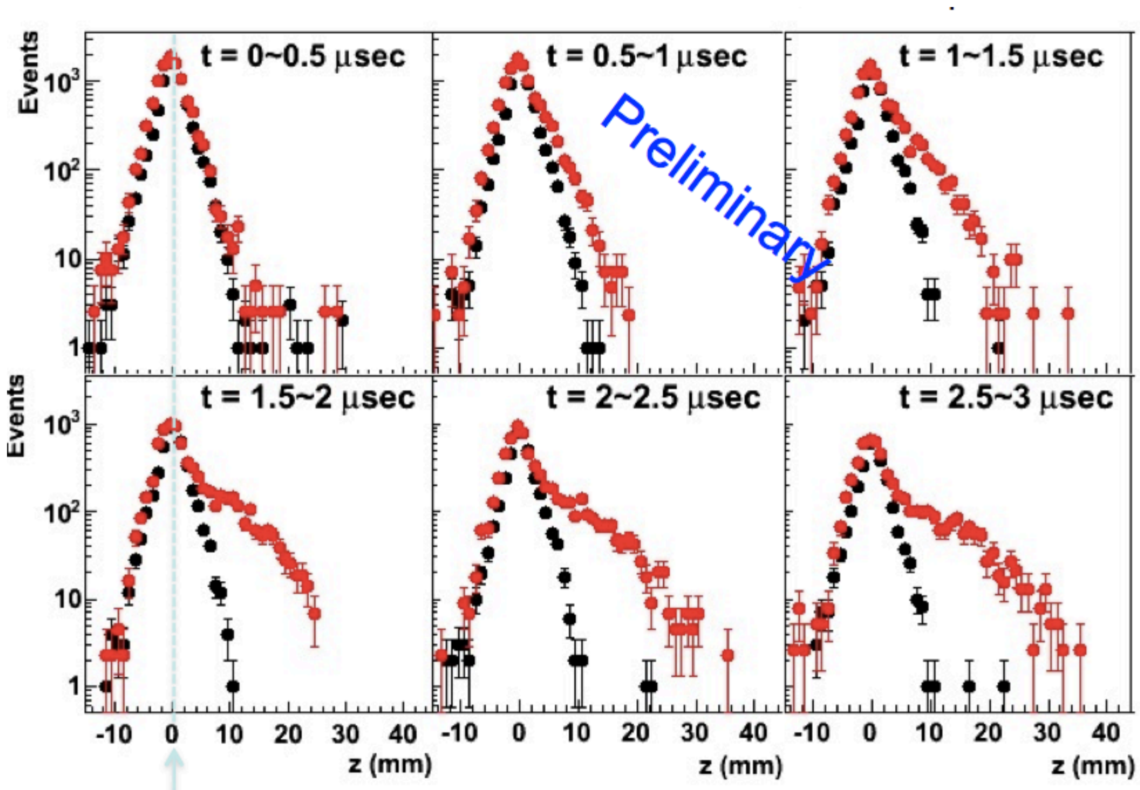
Achieving v. small vertical beam divergence : $\Delta p_T/p_T = 10^{-5}$

Requires advances in "muonium" production
- target materials e.g. nano-structured SiO_2
- lasers (pulsed 100 μJ VUV) to ionise muonium (x100)



JPARC g-2

R & D continuing on cold muon yield and ionisation efficiency



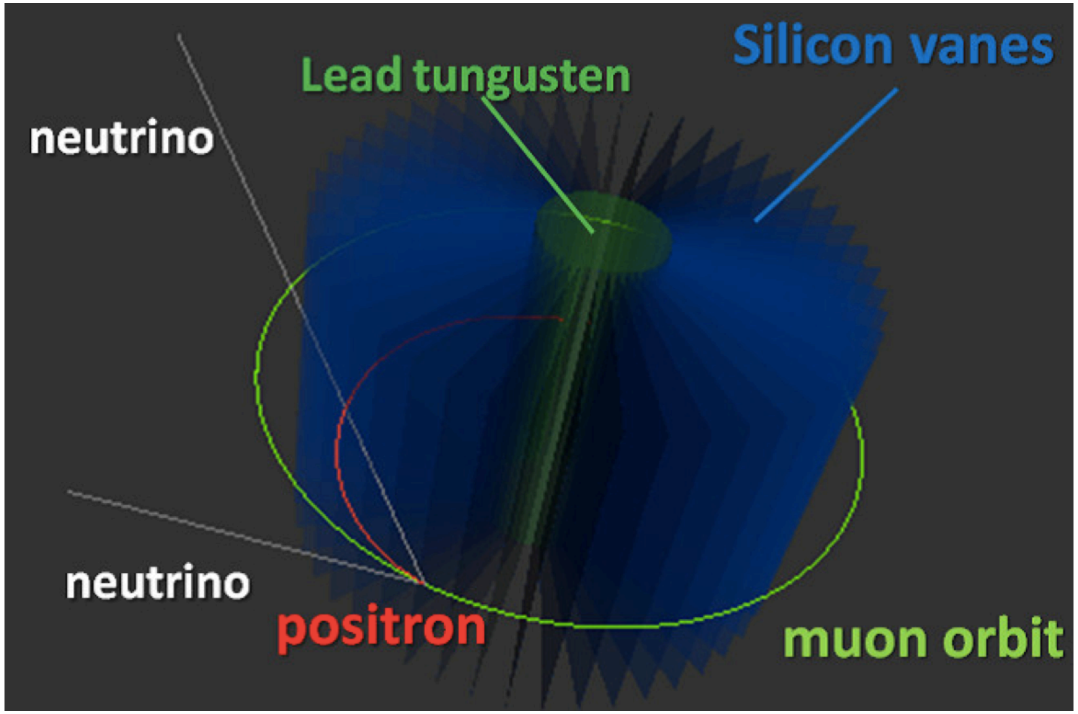
Potential to achieve same precision as FNAL **<u>with very different systematics</u>** but likely on a timescale after the FNAL experiment.

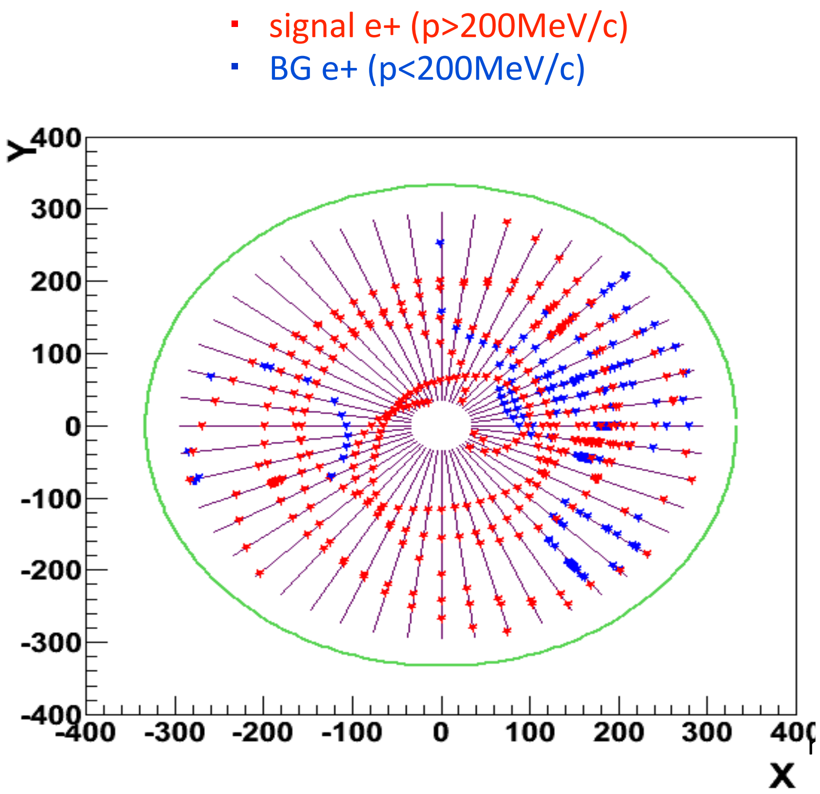
JPARC g-2 Silicon Tracker

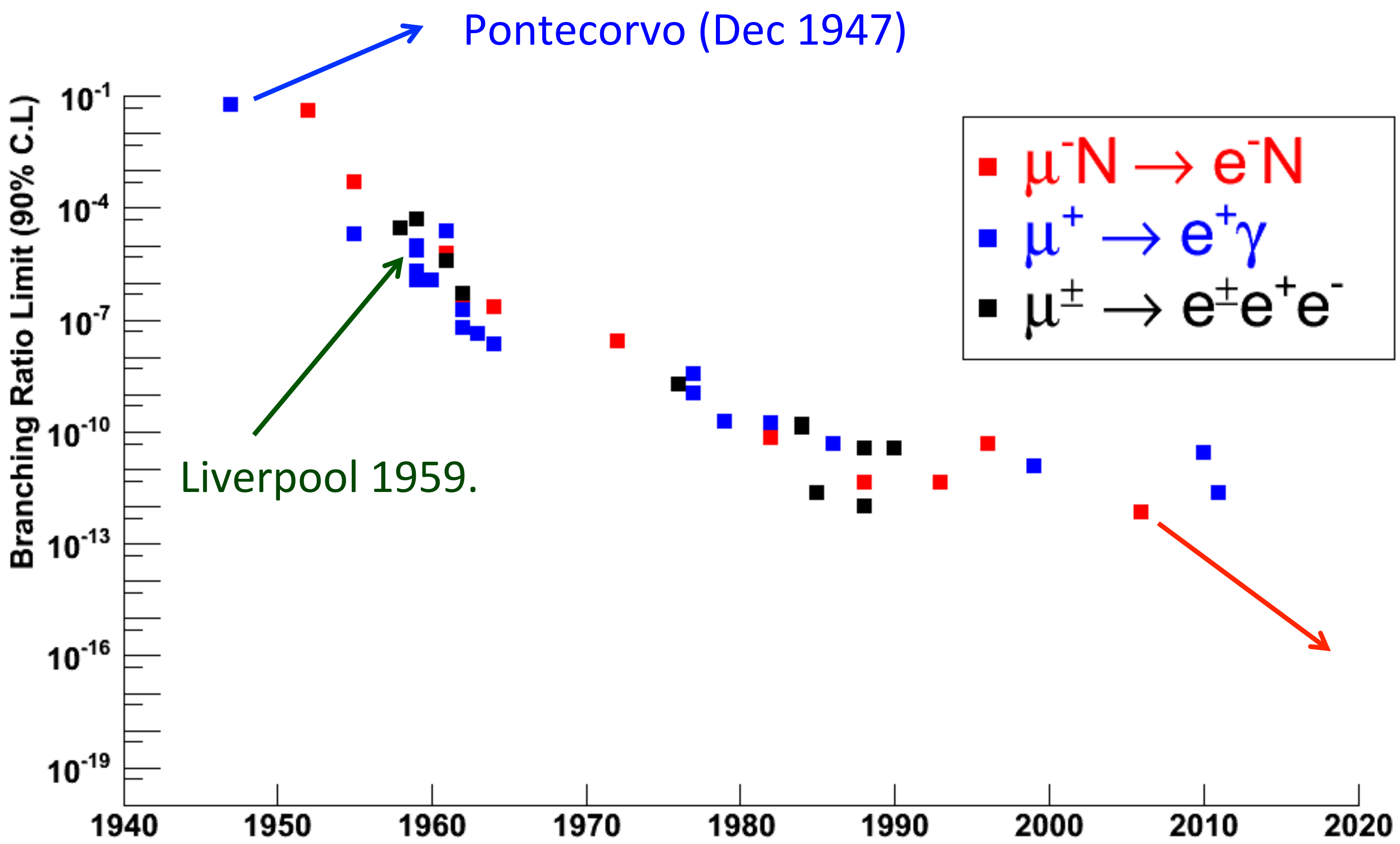
High granularity Silicon vane tracker (exploiting (Super)KEKB electronics))

Event rate : 1 MHz

Need to reconstruct e+ track from lots of hits, particularly for earliest events.

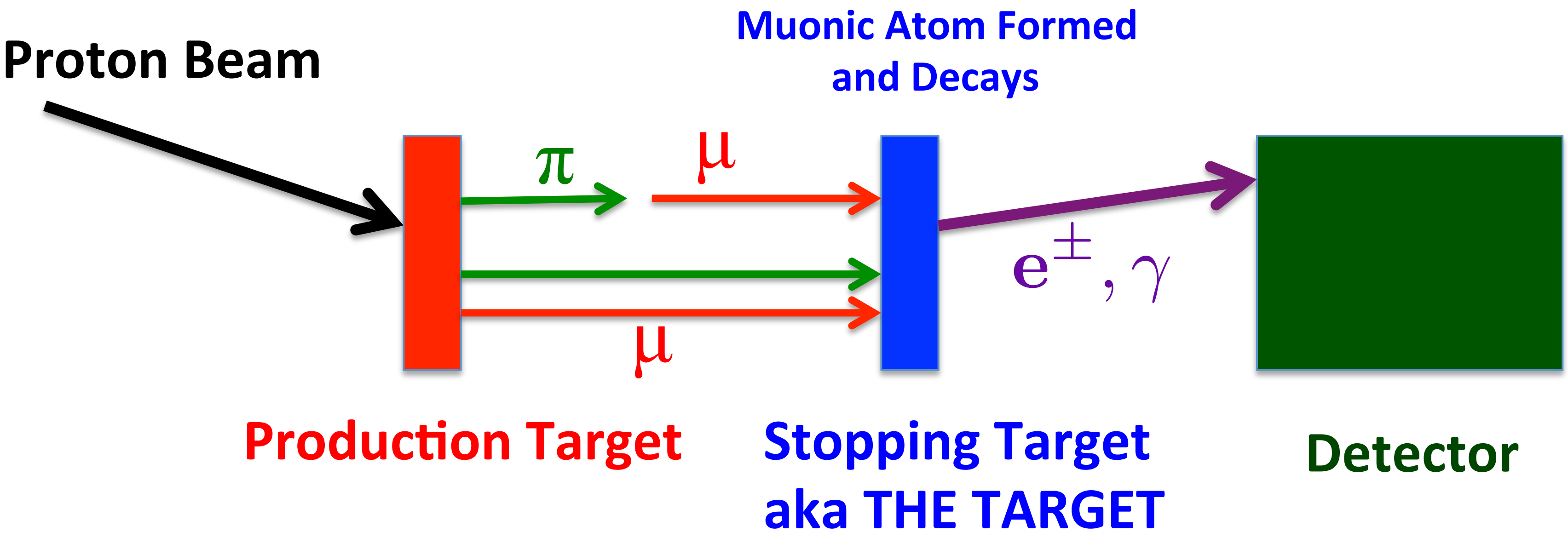




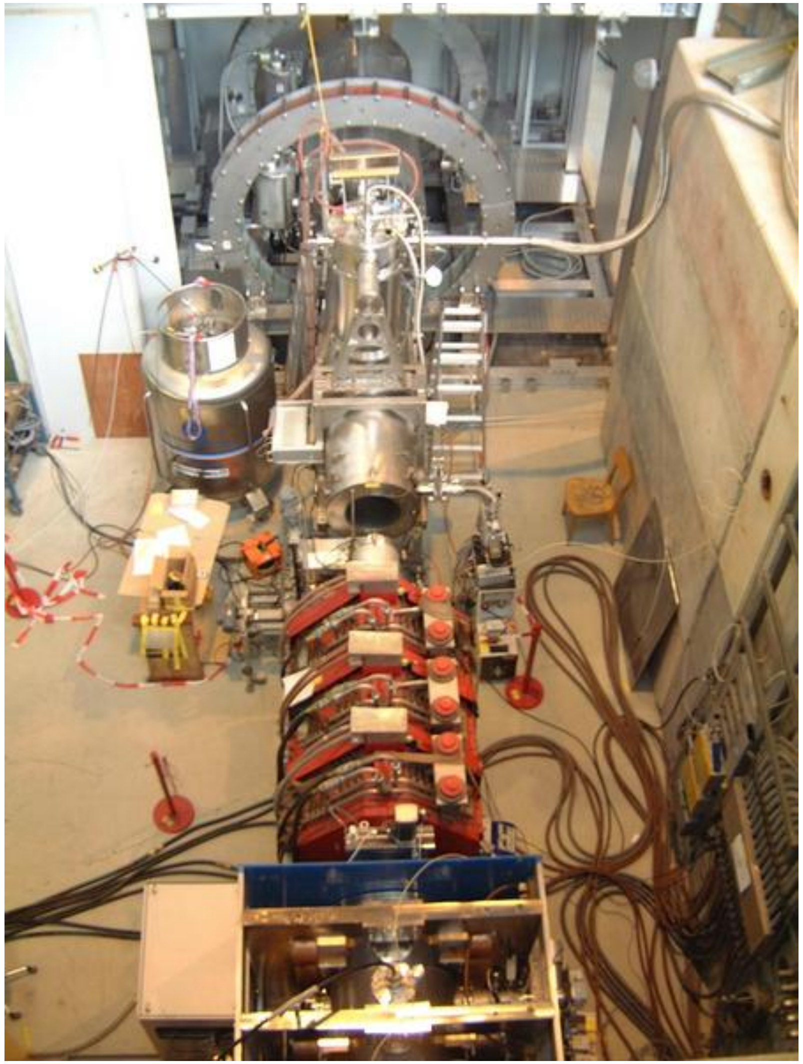


Factor of 10-10,000 improvements in sensitivity in near future.

Experimental Technique

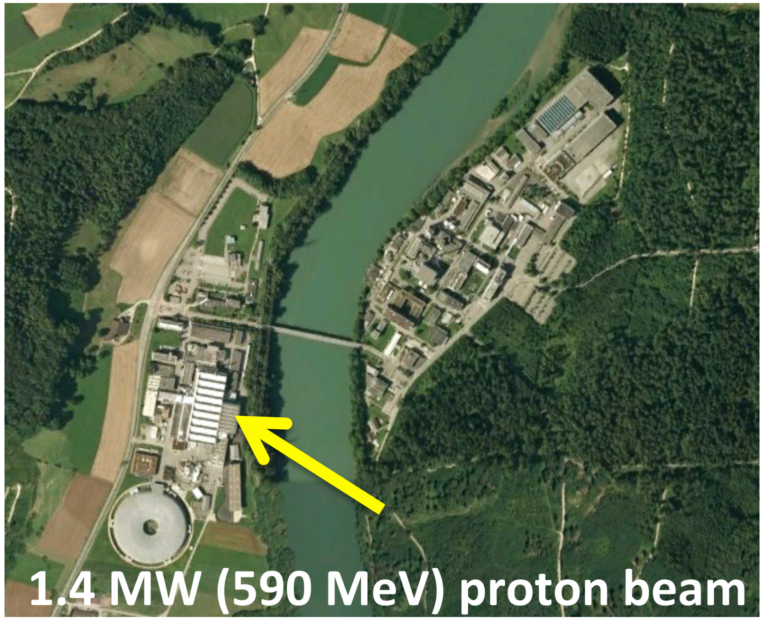


Apply symmetries, translations, rotations, ...



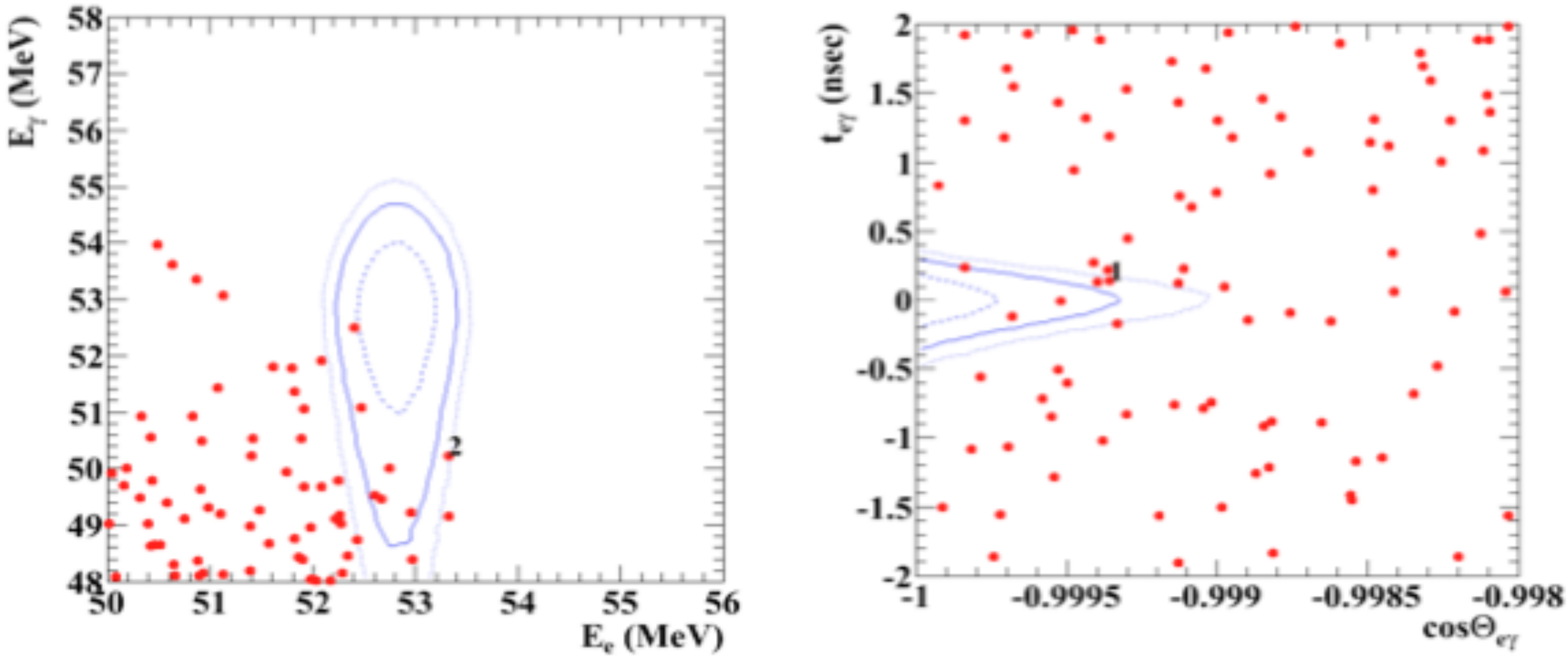
PSI (Zurich/Switzerland) Facility

3×10^{7} “stopped” $\mu+$/sec

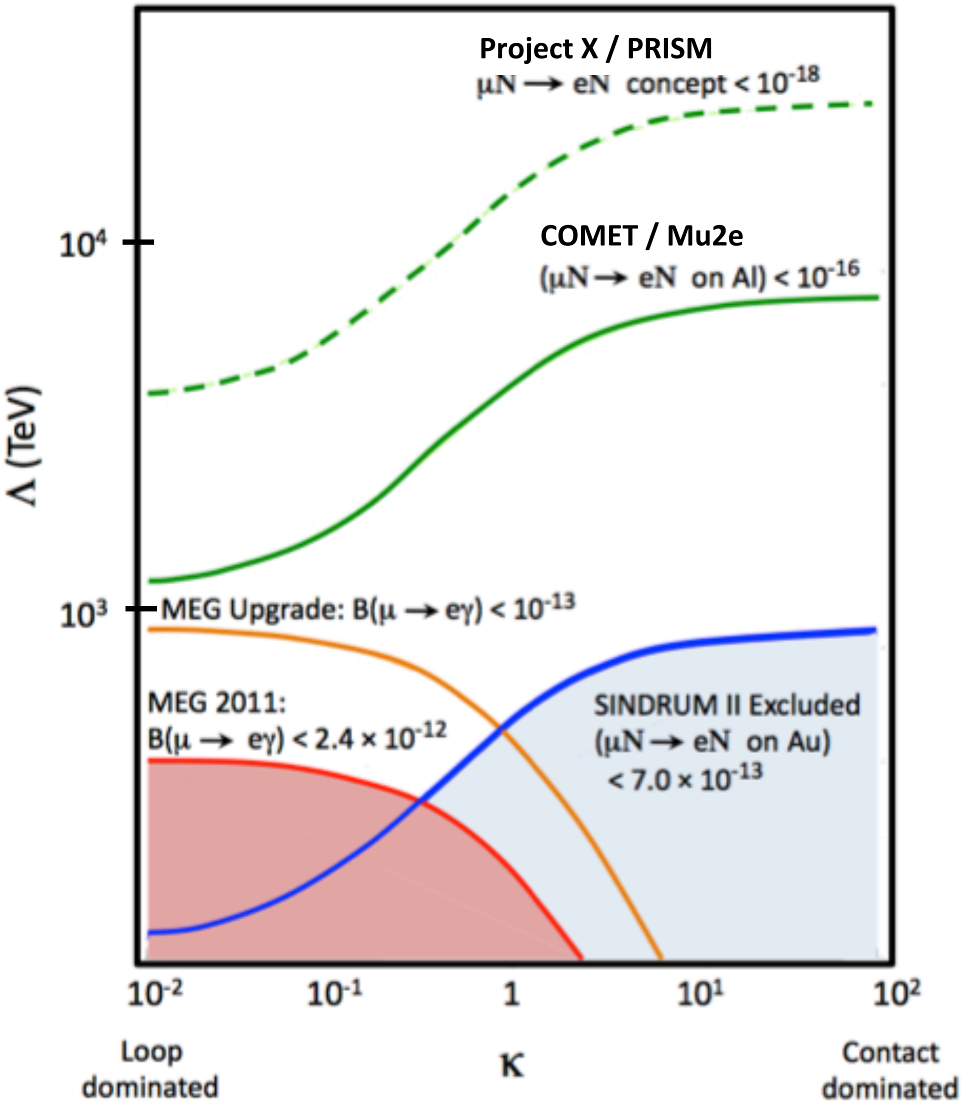


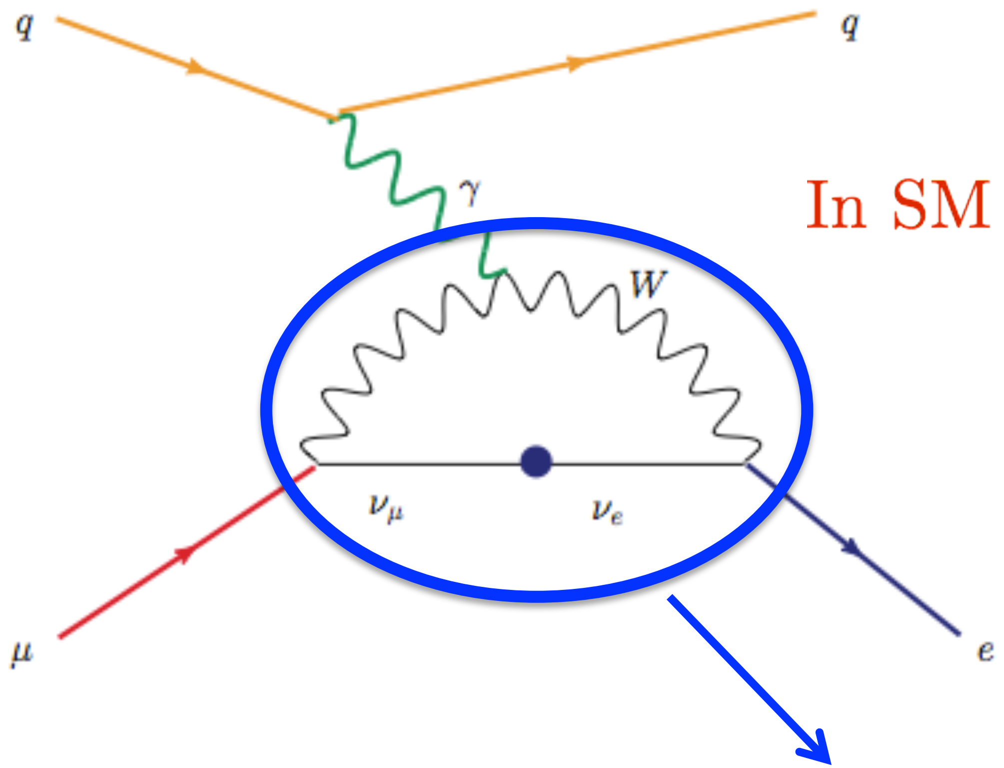
MEG Sensitivity Determined By

MEG present limit on $\mu \rightarrow e\gamma$ is 6 x10^{-13}. It is aiming to get to 5x10^{-14}



Ultimate reach provided by μ to e conversion



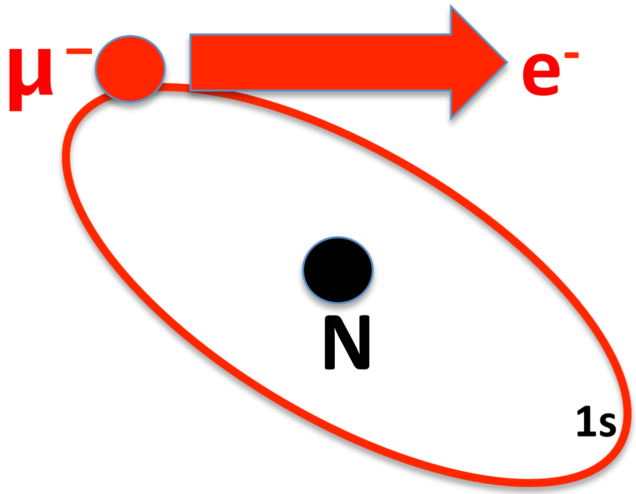


In SM : $\mathcal{O}\left(\frac{m_\nu}{M_W}\right)^4 \approx 10^{-50}$

In BSM : $\mathcal{O}(10^{-12 \to 50})$

Most BSM models predict rates larger than 10^{-20}

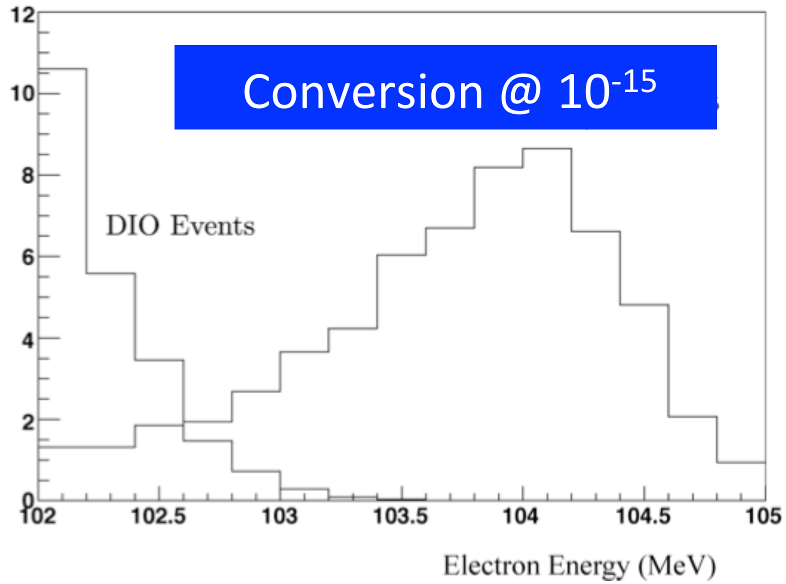
Muon to Electron Conversion



$$\mu^+ \to e^+ \gamma$$

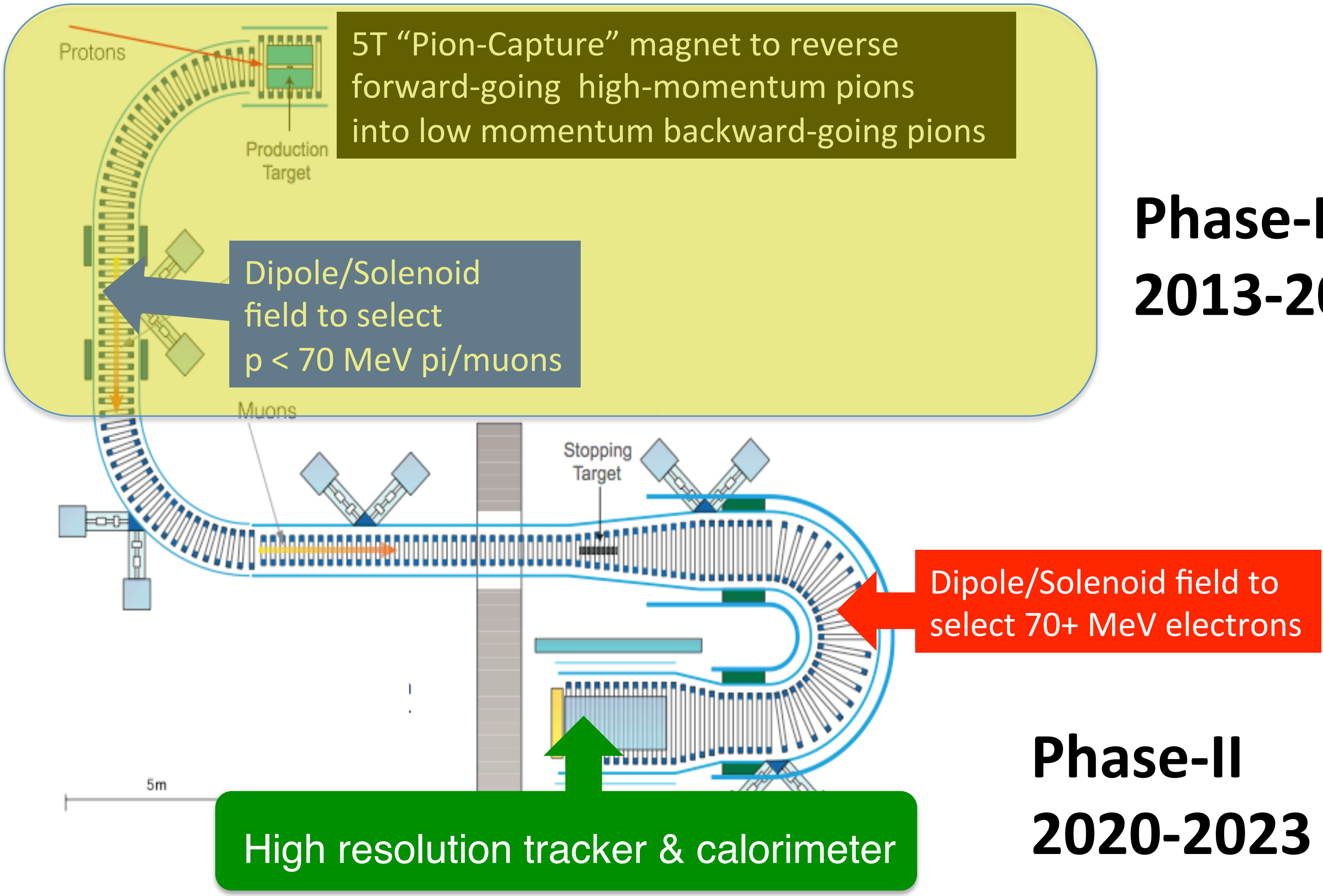
$$\mu^+ \to e^+ e^- e^+$$

Suffer, at the highest rates,
from accidental backgrounds that scale as $R(\mu)^2$



The "conversion process" has a simple one particle signature. Ee ~ m_μ
(>> Ee from free muon decay).

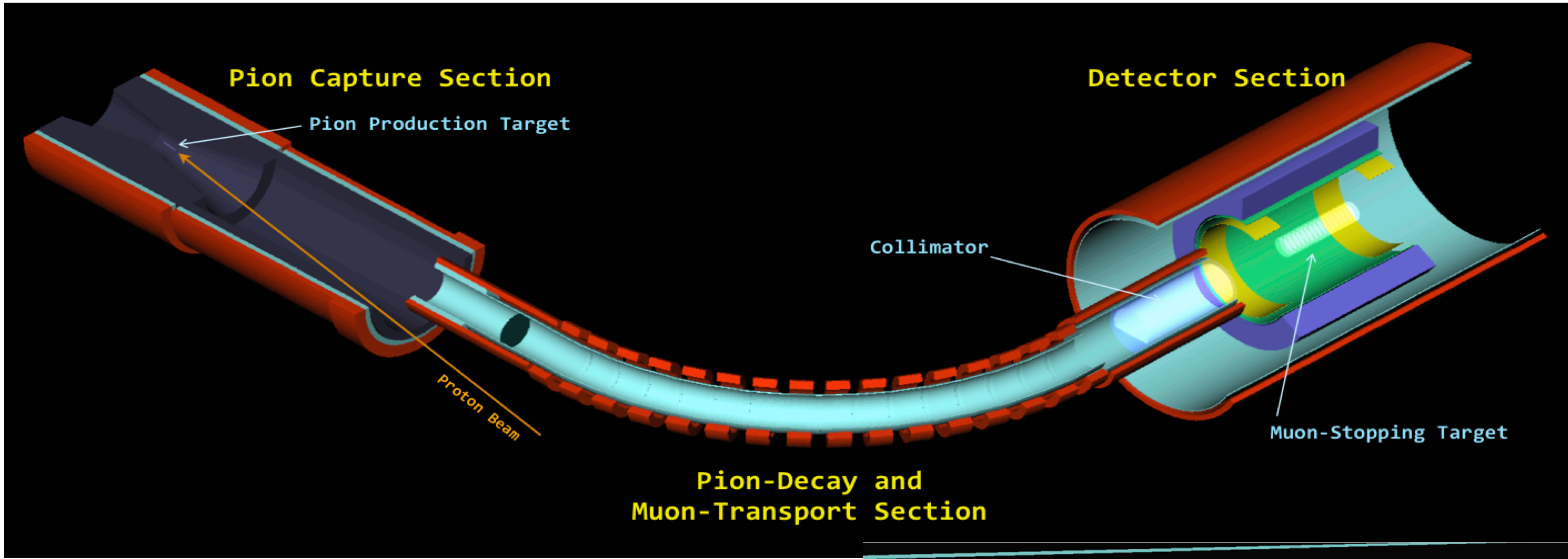
Arguably best route to highest sensitivity at high muon rates.

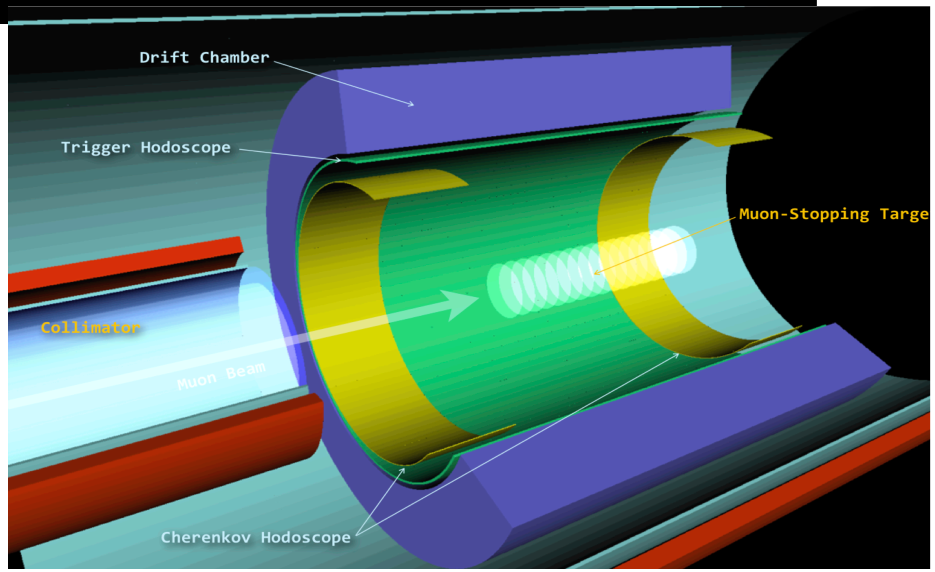


Phase-I
2013-2017

Phase-II
2020-2023

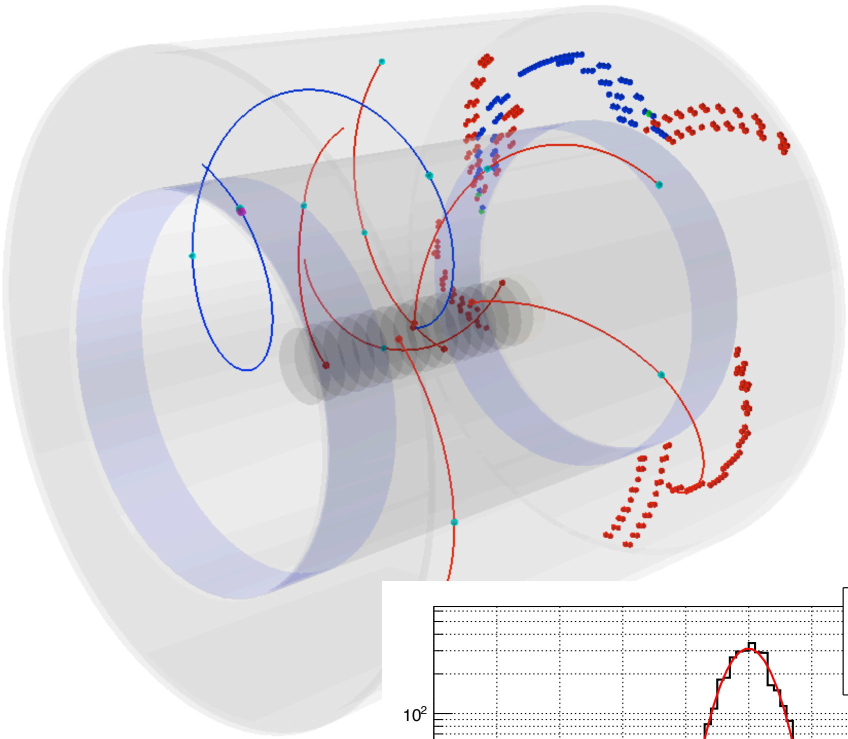
COMET Phase-I



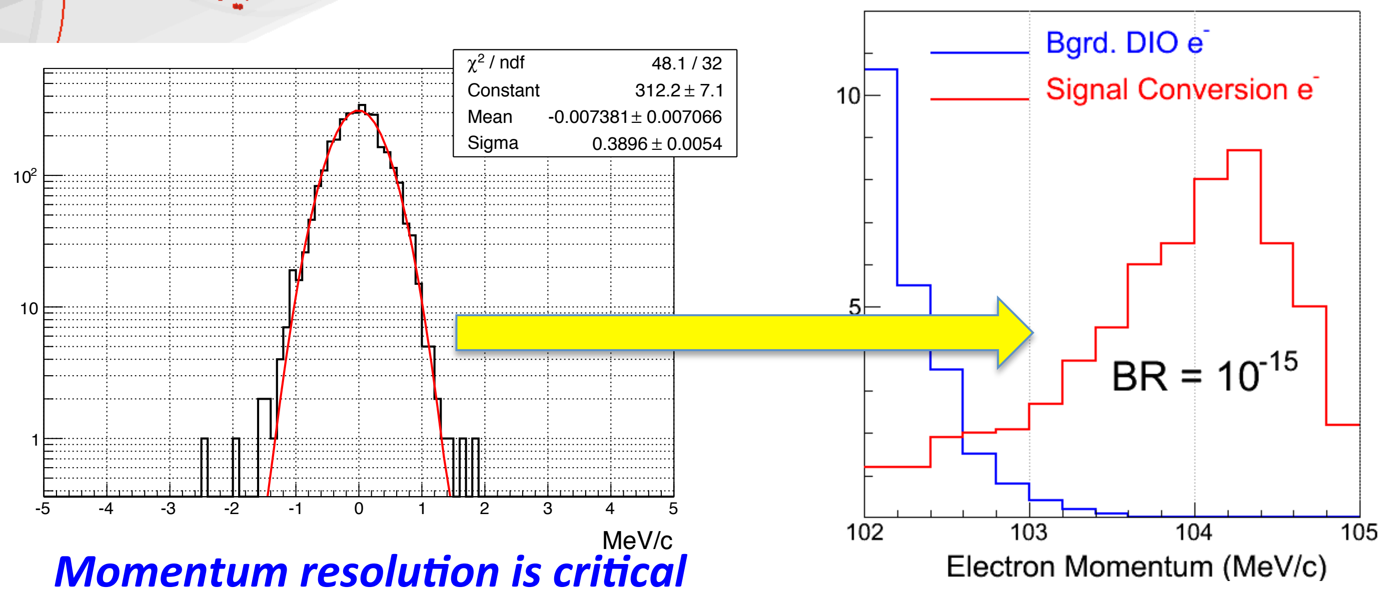


Cylindrical detector has higher acceptance but poorer resolution compared to transverse/phase-II detector

Detector Optimisation

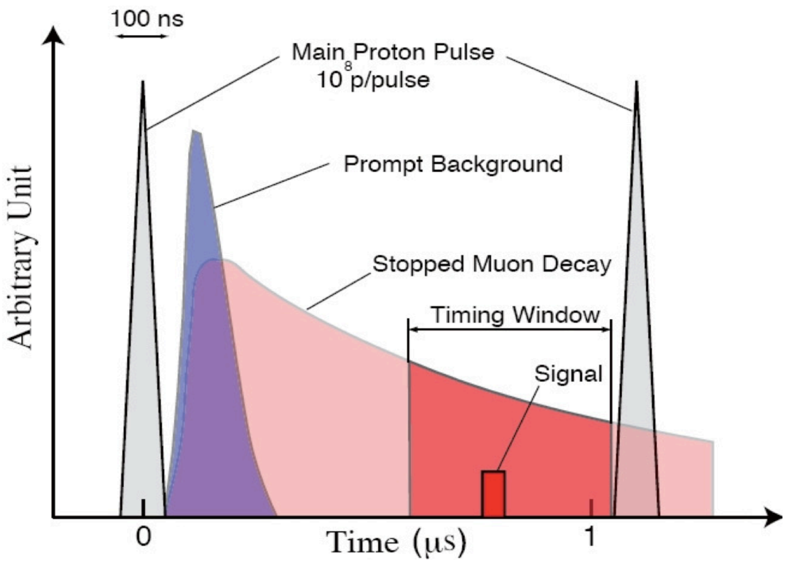


Commissioning detector in 2016

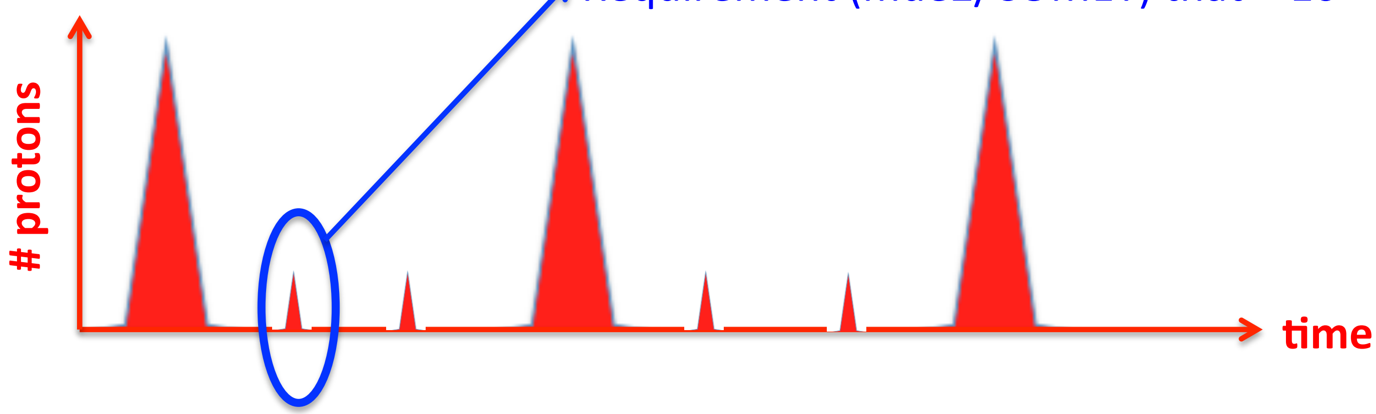


Momentum resolution is critical

Challenges : Proton Extinction/ "After protons"

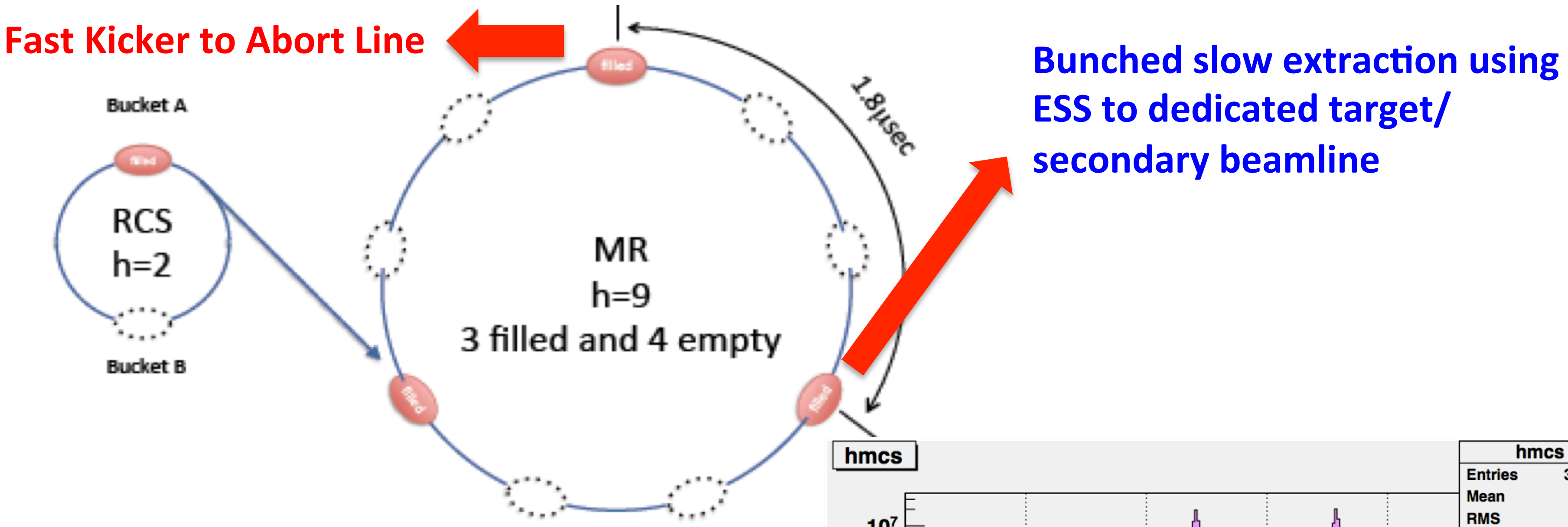


Require that between proton pulses there are no rogue proton pules that could produce a "prompt" background

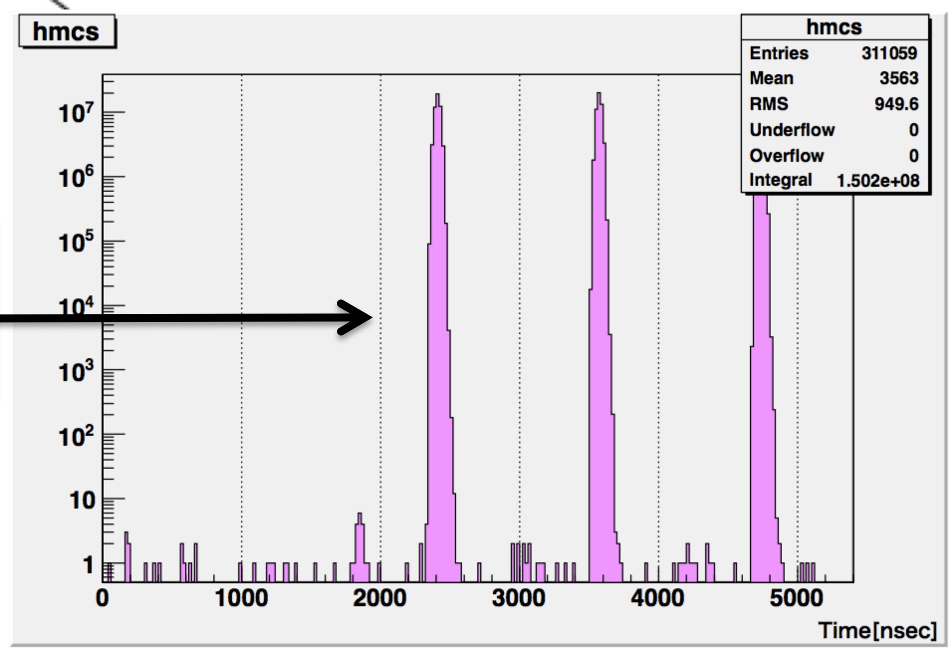


AC dipole/collimator system kicks out the out-of-time particles

COMET : Extinction Studies



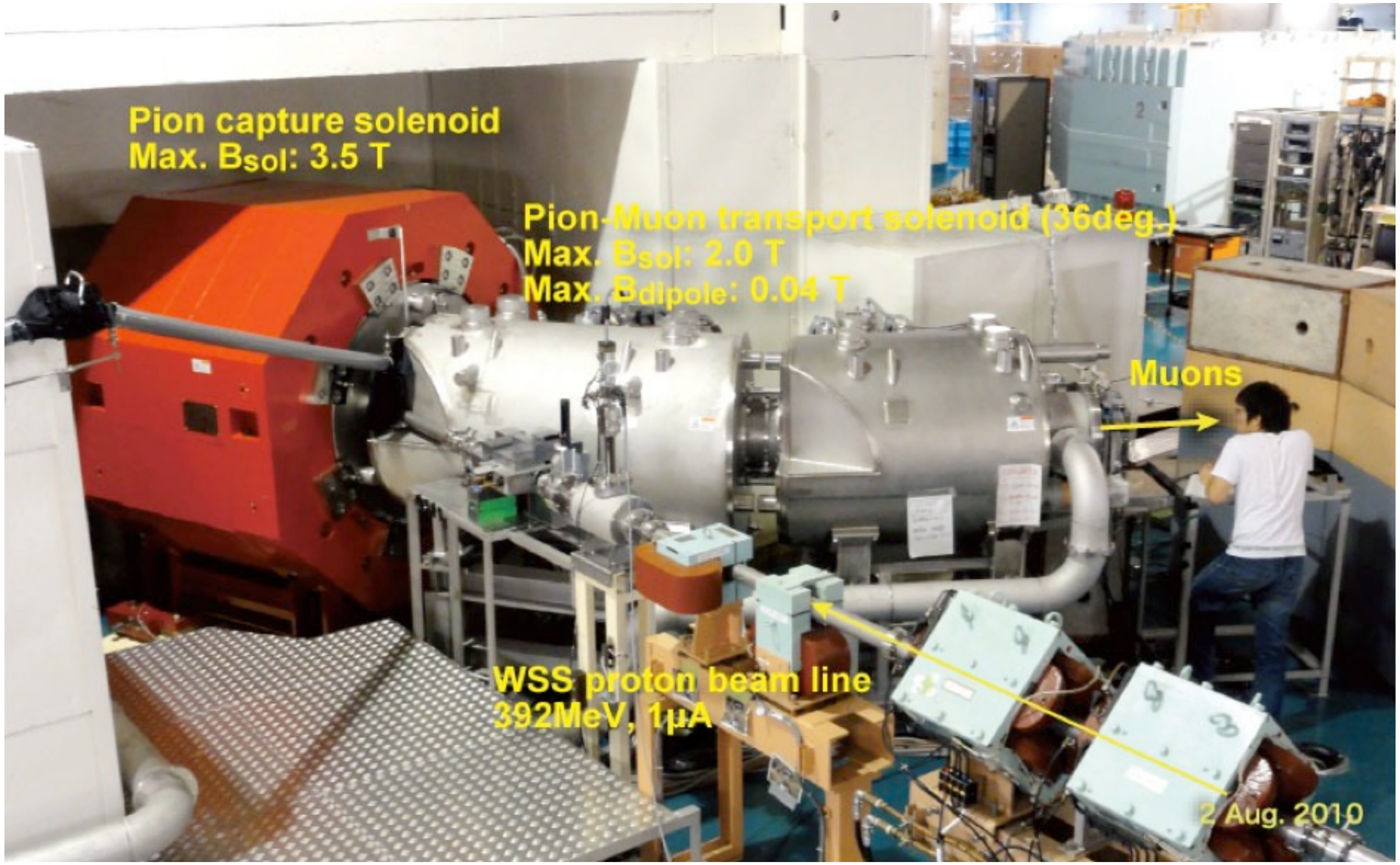
Extinction level of **(5.4 ± 0.6) × 10^{-7}** measured at secondary J-PARC beam line and O(10^{-7}) at abort line



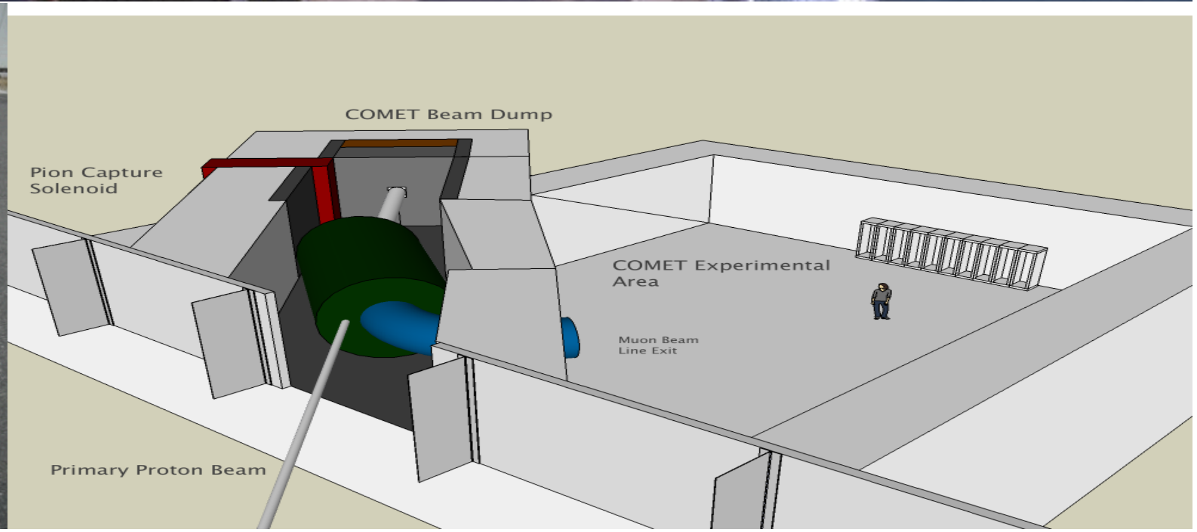
And additional O(10^{-6}) from double kick injection into MR

MUSIC @ Osaka

Utilising prototype pion production environment for COMET



Construction of beamline has begun



Conclusion

It's clear that the path to a credible BSM theory isn't as smooth as some had anticipated.

We need to cast the net wide to establish a credible BSM theory.

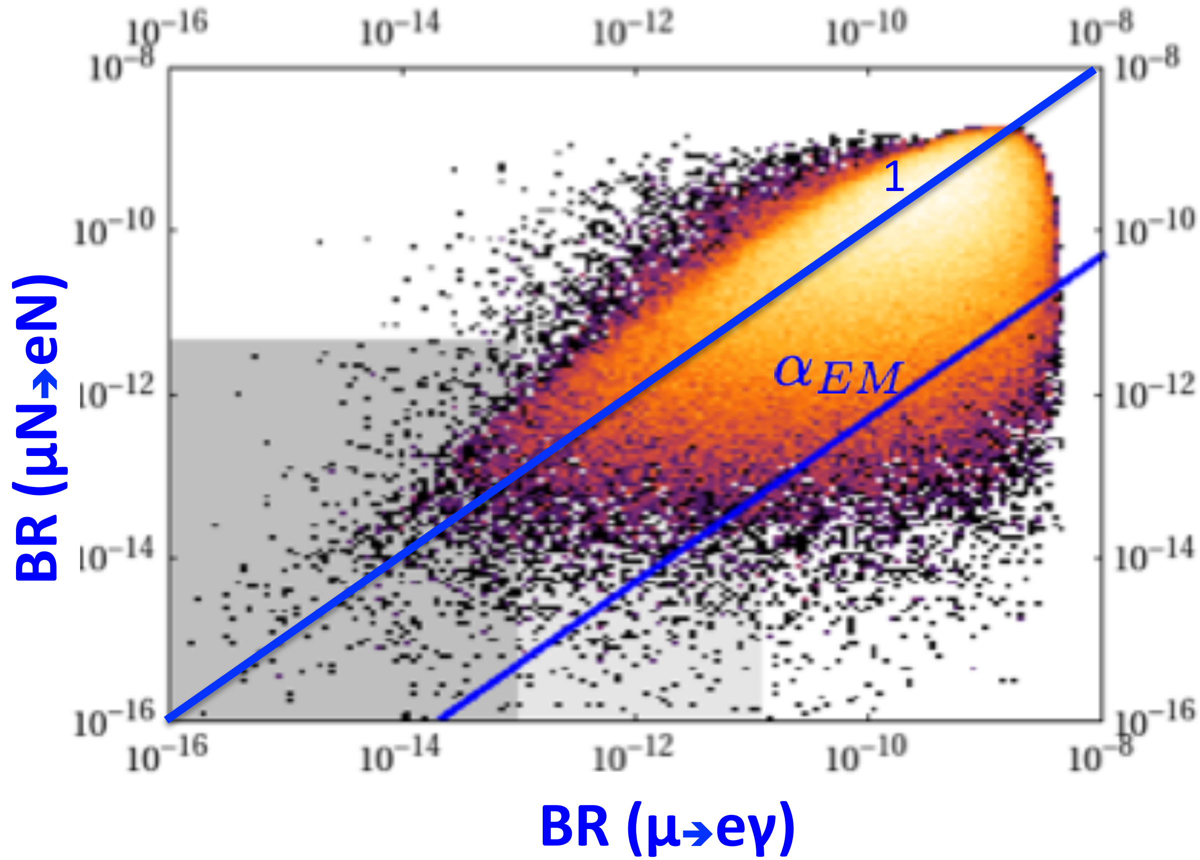
Muon experiments : g-2 and CLFV will be critical in establishing (or not) integrity of BSM models in concert with the LHC : particular the non-coloured sector + BSM that flips chirality.

Bother COMET and g-2 expect to take data in 2016.

BACKUP

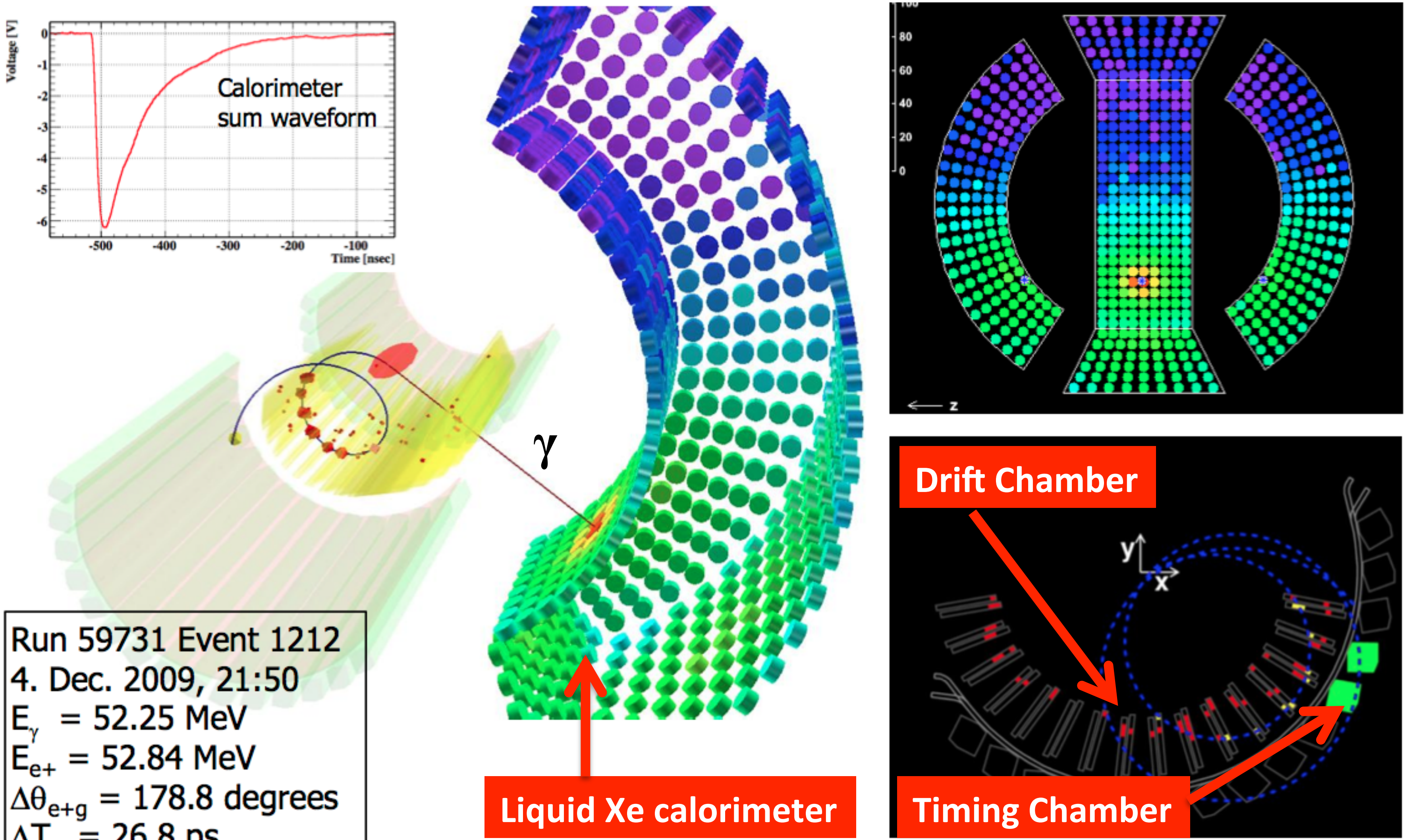
Process Ratios are Model Dependent

In general in BSM models $\frac{BR(\mu N \rightarrow eN)}{BR(\mu \rightarrow e\gamma)} = \mathcal{O}(\alpha_{EM})$ but not always…



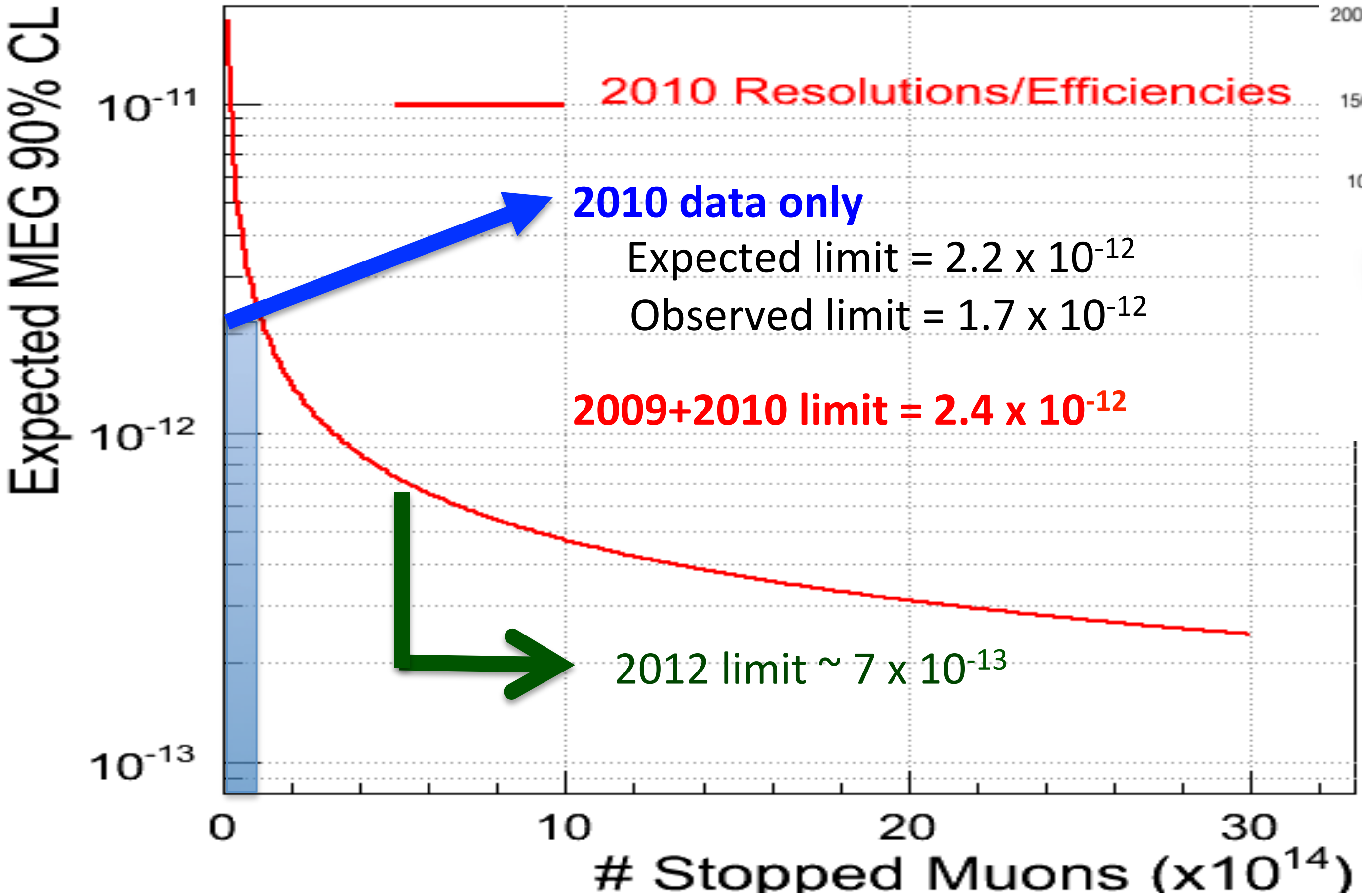
e.g. "Littlest Higgs model" with T-parity (LHT) *Blanke et al, Acta Phys.Polon.B41:657,2010*

MEG Experiment

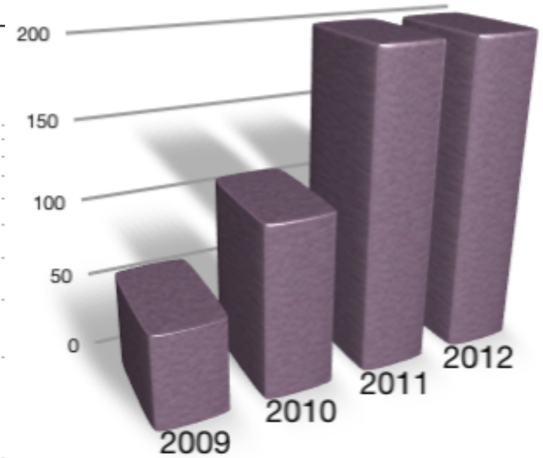


Run 59731 Event 1212
4. Dec. 2009, 21:50
E_γ = 52.25 MeV
E_{e+} = 52.84 MeV
$\Delta\theta_{e+g}$ = 178.8 degrees
$\Delta T_{e\gamma}$ = 26.8 ps

MEG Sensitivity

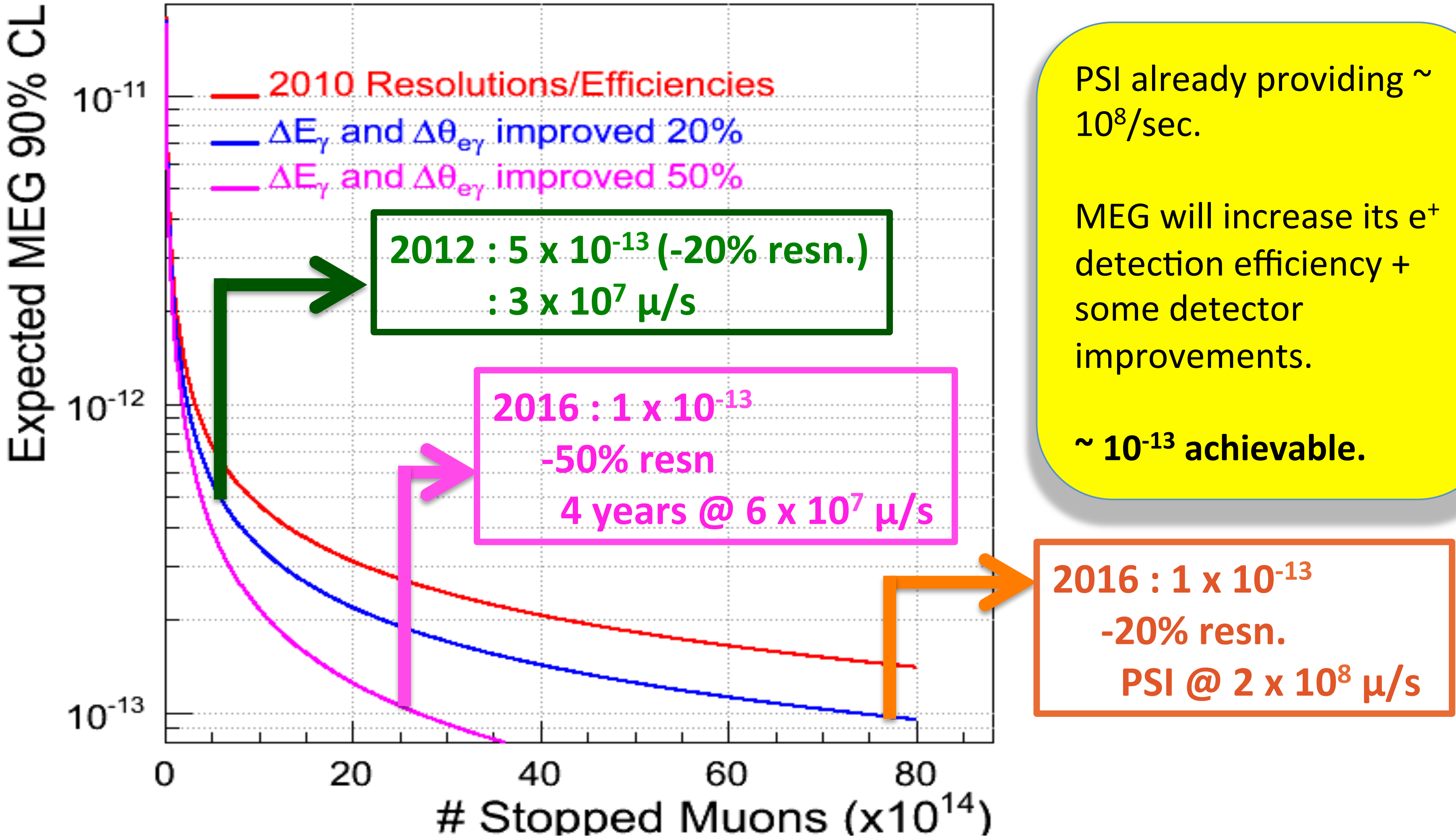


μ on Target x 10^{12}



MEG : 2013-2016

Assume 10^7 sec running per year for 2013-2016.

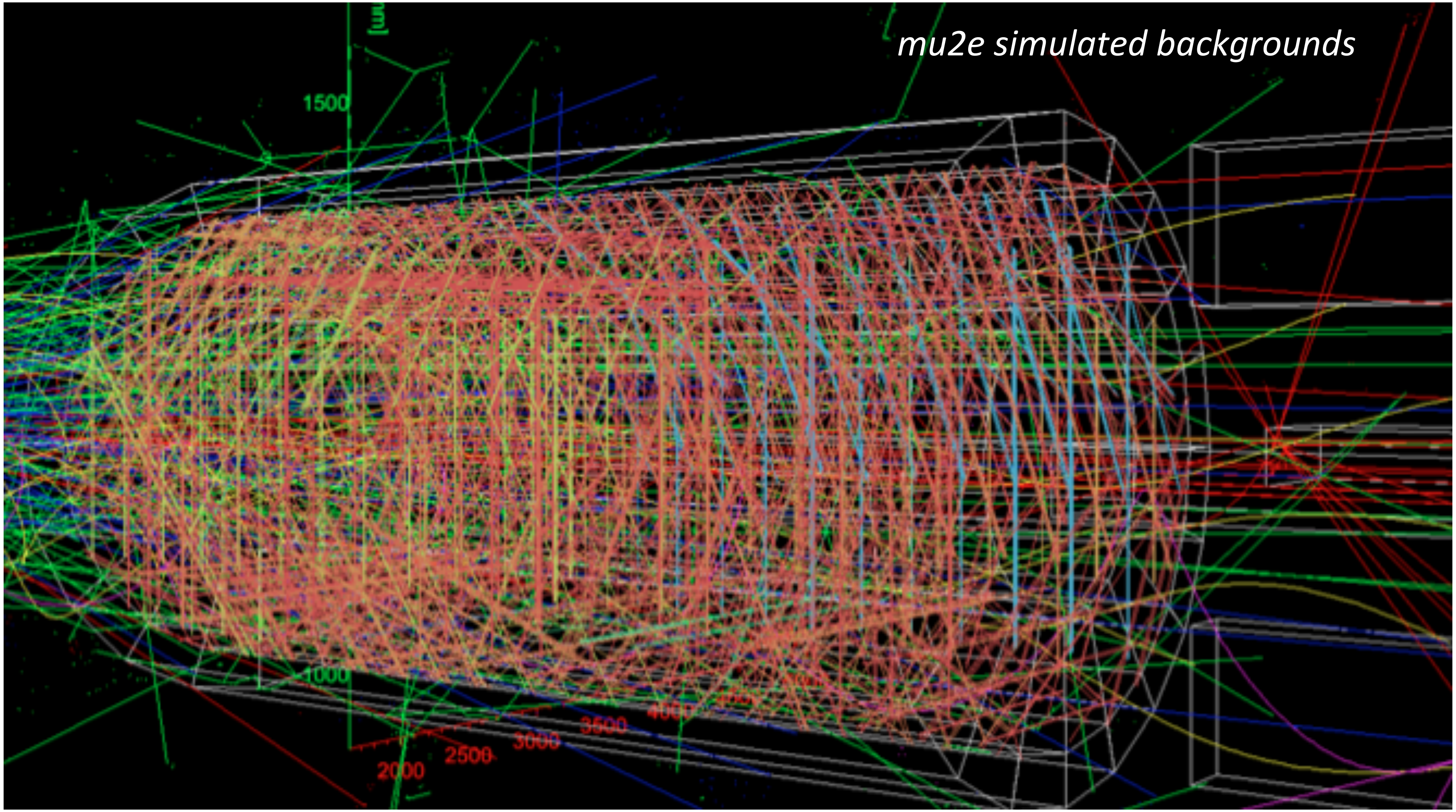


PSI already providing ~ 10^8/sec.

MEG will increase its e^+ detection efficiency + some detector improvements.

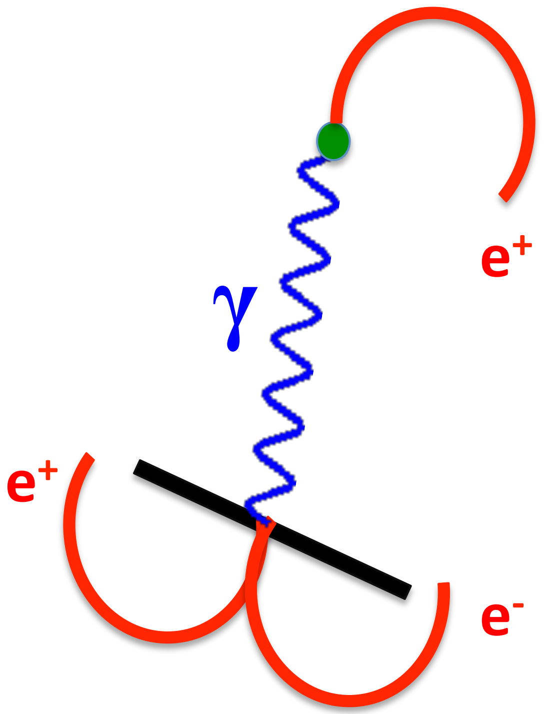
~ 10^{-13} achievable.

Challenges : High Rates in Detector



Below 10^{-13} needs new detector

- E_γ, $\Theta_{e\gamma}$ resolution and pile-up are limiting factors particularly at high μ intensities
- Another option to achieve reduced sensitivity is to have a "track-only" analysis.



Conversion point and event vertex defined by precision tracking.

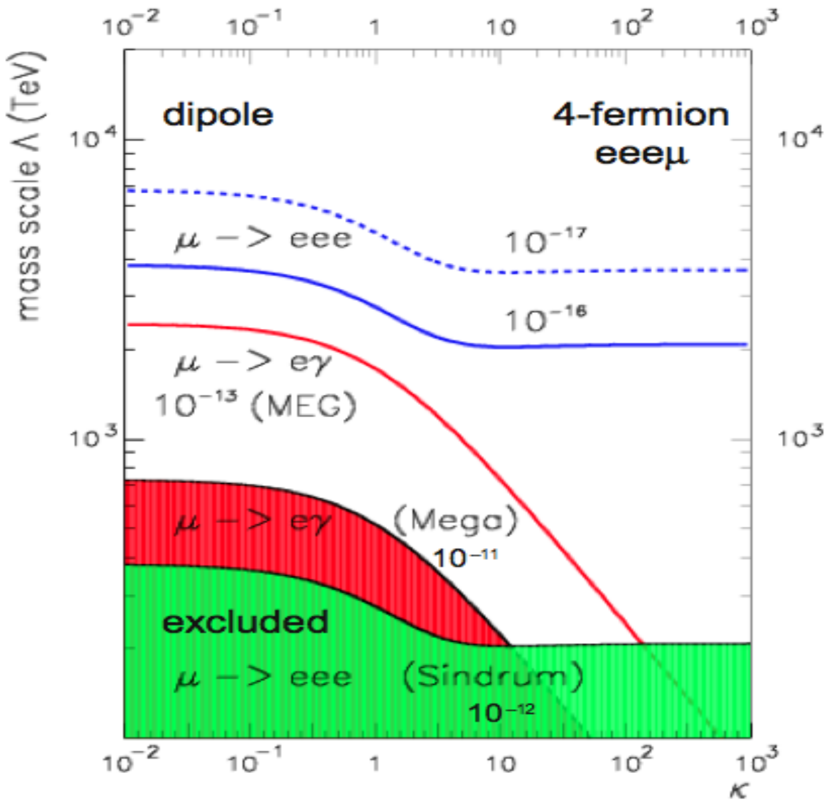
Optimise material thickness to optimise rate reduction vs resolution degradation.

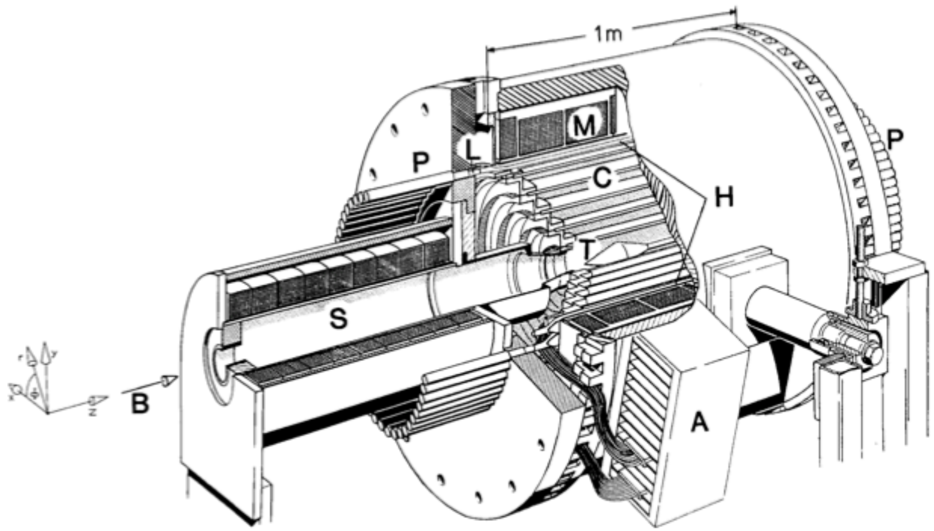
MEGA (LANL:1990s) used this approach & achieved
$\Delta\theta_{e\gamma}$ = 33 mrad vs 52 mrad in MEG and
ΔE_γ = 1.7 - 3% vs 4.5 - 5.6% (MEG).

However these resolutions need to be achieved in high pile-up environment.

μ→eee

Current state of the art is 1988 with **limit @ 10^{-12}**





Sindrum-I @ PSI

Given MEG results (@ 10^{-13}) this only begins to get interesting at 10^{-14} (e.g LHT models) BUT ideally would like to get to 10^{-16}

Same issues as μ→eγ

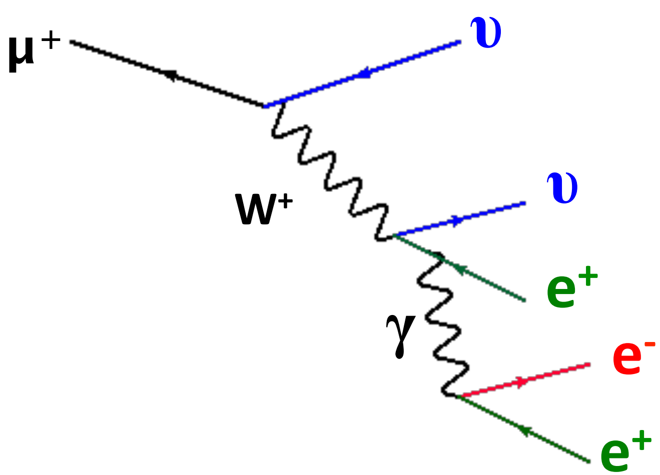
- accidental/pile-up backgrounds : $(R\mu/D)^2$ – so DC beam required.

Issue as go to v. high rates

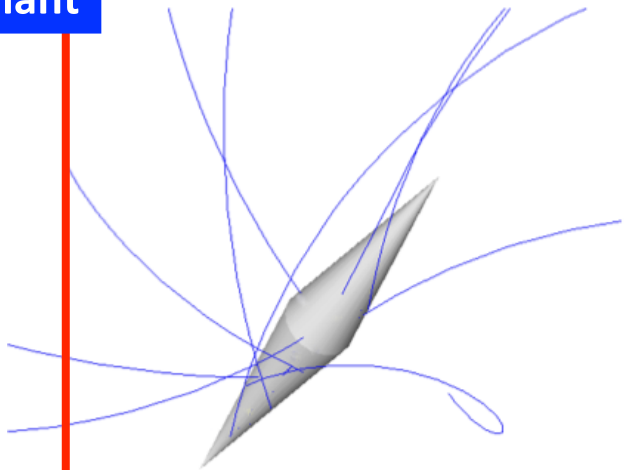
Two μ+ decays and fake e- (Bhaba scattering, γ conversion)

- irreducible background : Rμ

Dominant



BR = 3×10^{-5}



As with μ→eγ the solution is resolution, resolution, resolution…

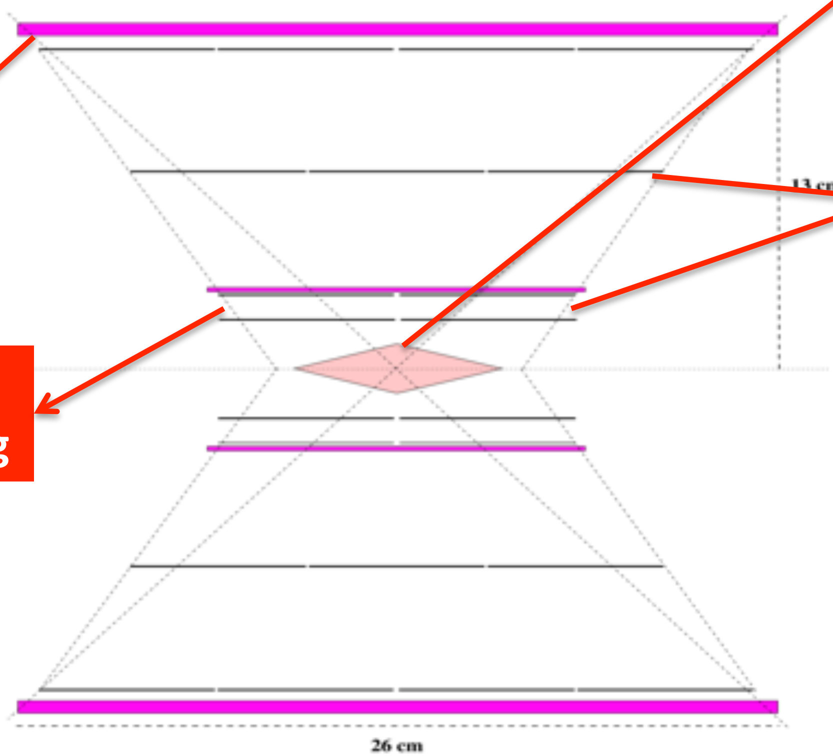
Mu3e Proposal at PSI

Improve MS-resolution by using v. thin (~ 40μm) HV-MAPS pixel silicon layers

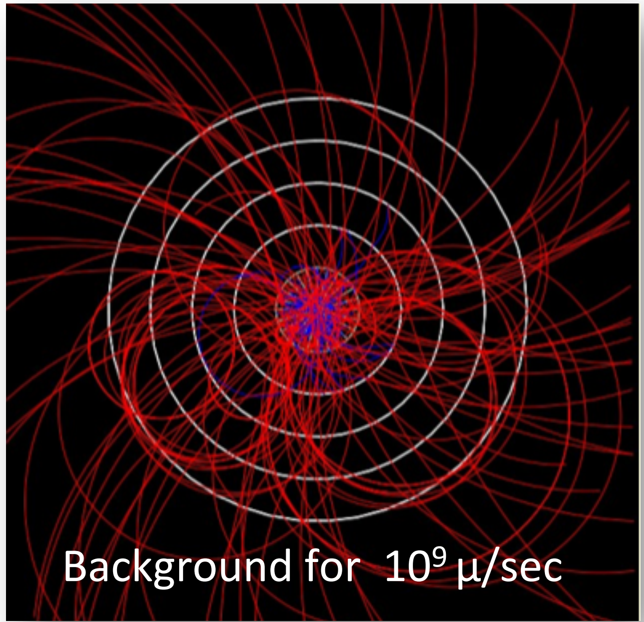
$\sigma(\theta)_{MS}$ = 5 mrad (c.f. SINDRUM-I : 28 mrad)

Hollow double cone target

Very thin silicon sensors for precision momentum and vertexing



Scintillating Fibers for precision timing



Background for 10^9 μ/sec

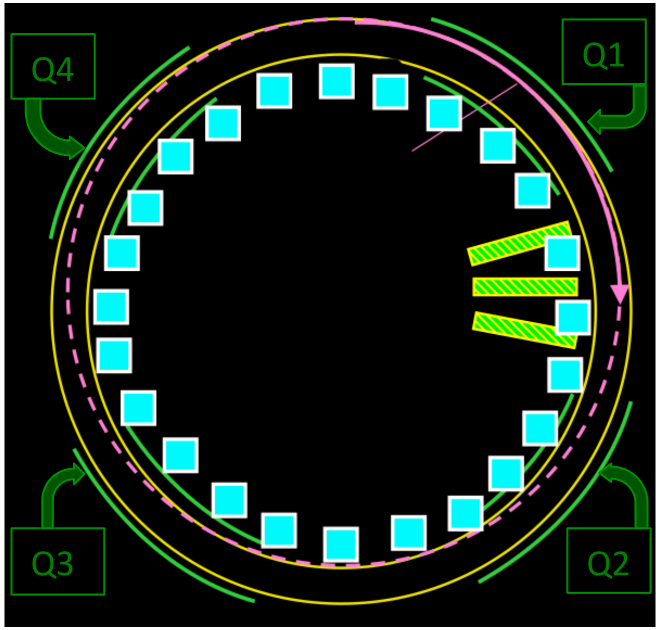
Aiming to achieve 10^{-16}

Experimental Technique

But particle trajectory in B-field is a spiral and need E-field to keep in orbit

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

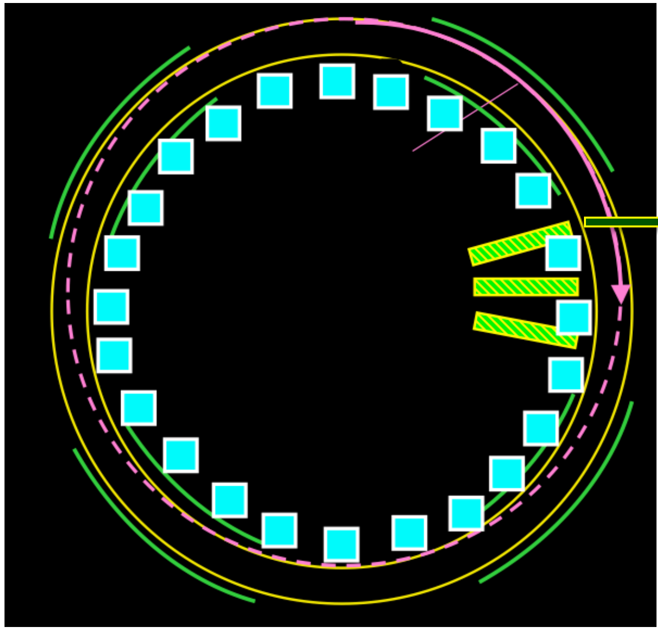
4 electric quadrupoles for focussing

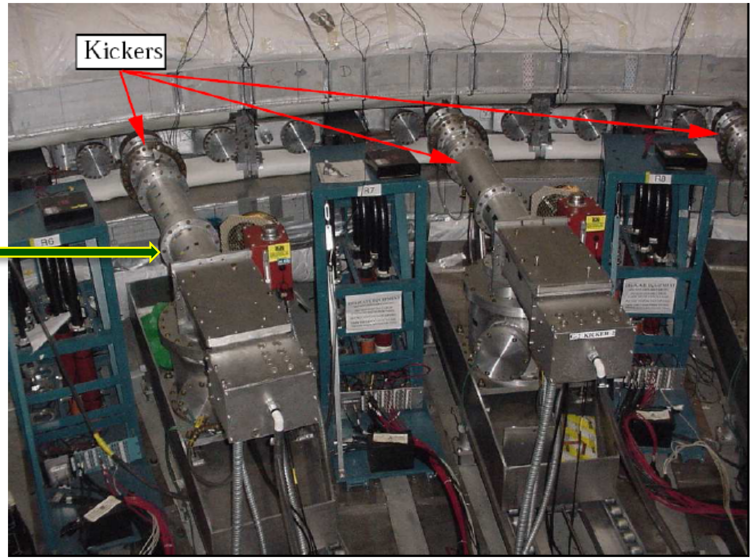


Cancel the E-field contribution by judicious choice of γ : the "magic momentum" : 3.094 GeV

Kicker

3 kickers to put beam "on orbit"

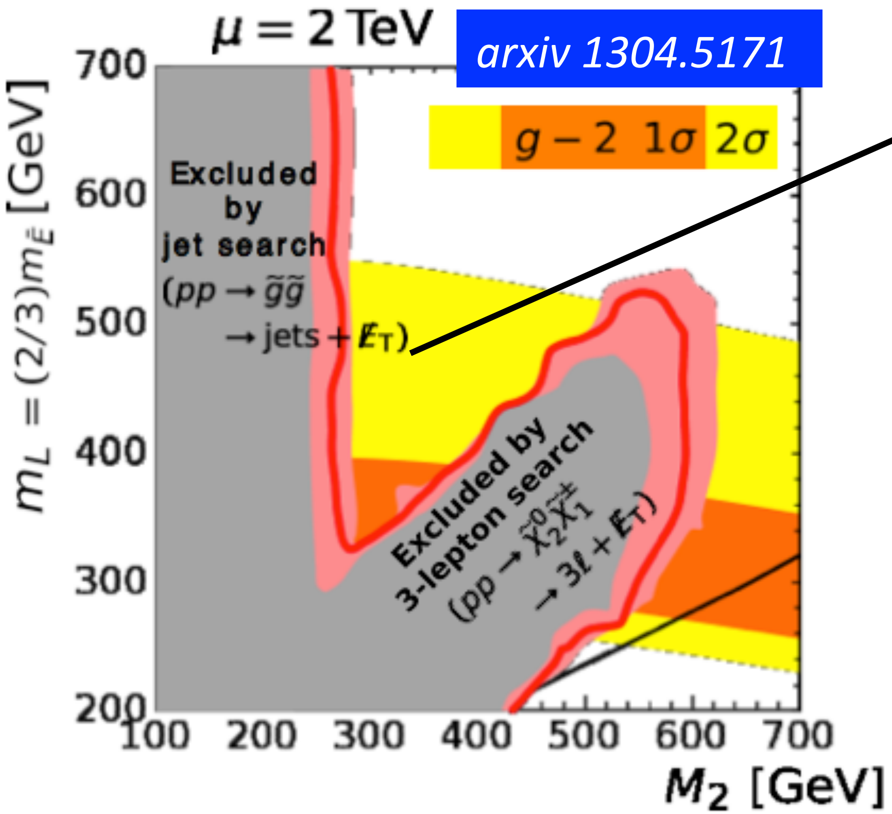




These are being replaced to have a "kick" over a smaller time period to produce a more stable beam.

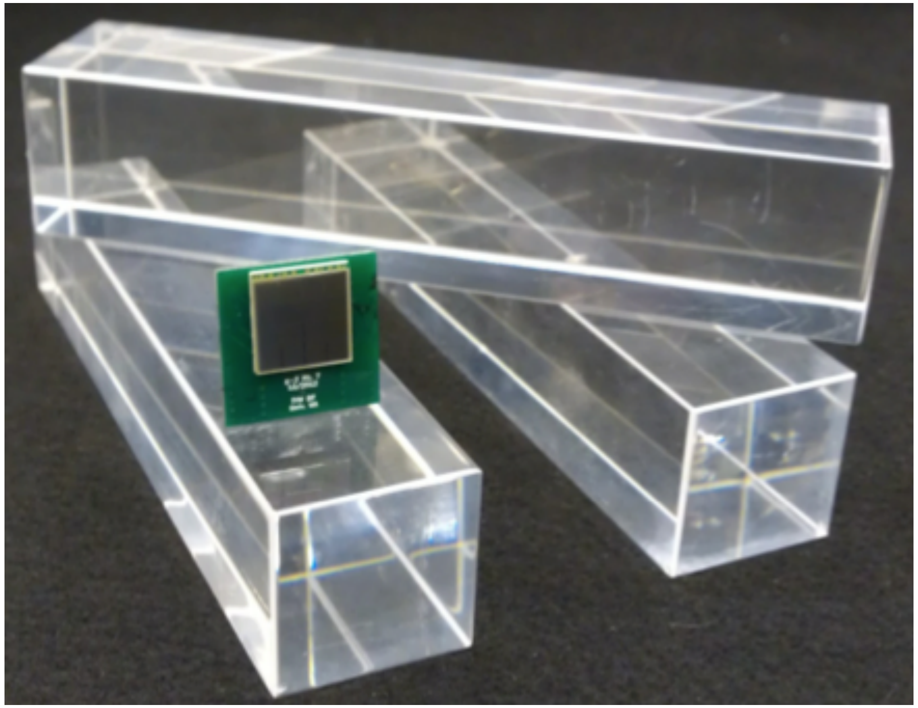
Constraints beyond LHC

Model with heavy squarks and gluinos respecting LHC limits



Large (BNL) a_μ not covered at LHC

Detector improvements



PbF_2 + 16-channel MPCC

Straw tracker

- **coupled with improved detector modeling**

NATURE | NEWS

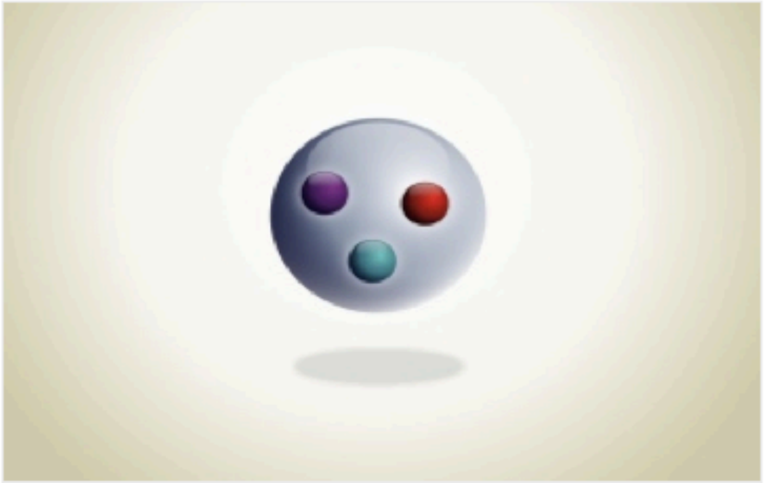
Shrunken proton baffles scientists

Researchers perplexed by conflicting measurements.

Geoff Brumfiel

24 January 2013

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.



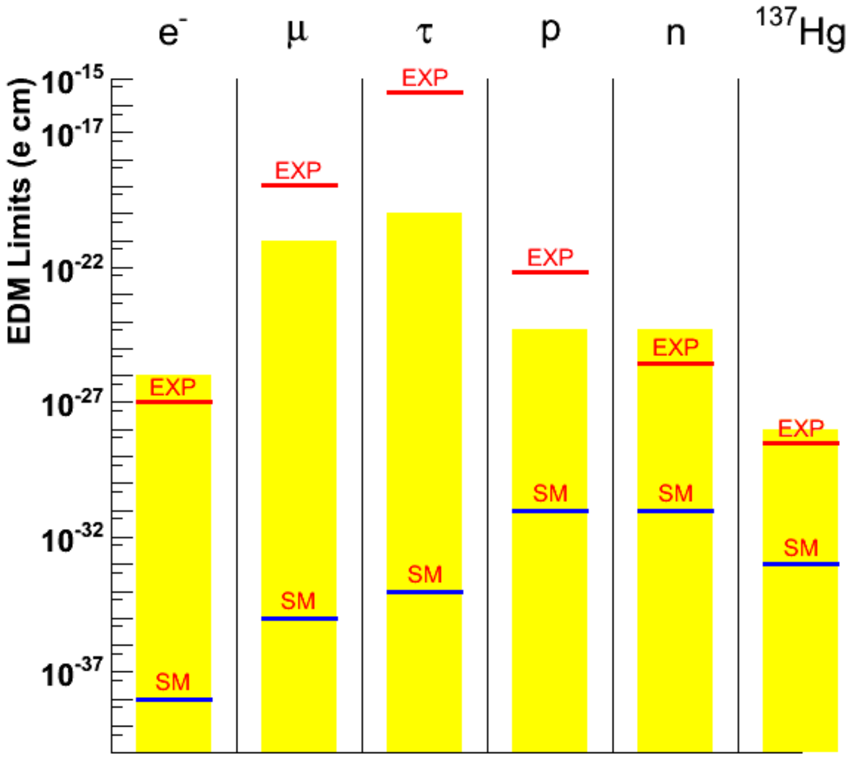
The proton's three quarks are (mostly) confined within a region 0.87 femtometres wide — or is it 0.84?

WESLEY FERNANDES

An experiment published today in *Science*[1] only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

Muon EDM

Essentially zero in SM : any observation is new physics



Muon is the only 2nd flav. gen. measurement. and it's free of nuclear / molecular effects

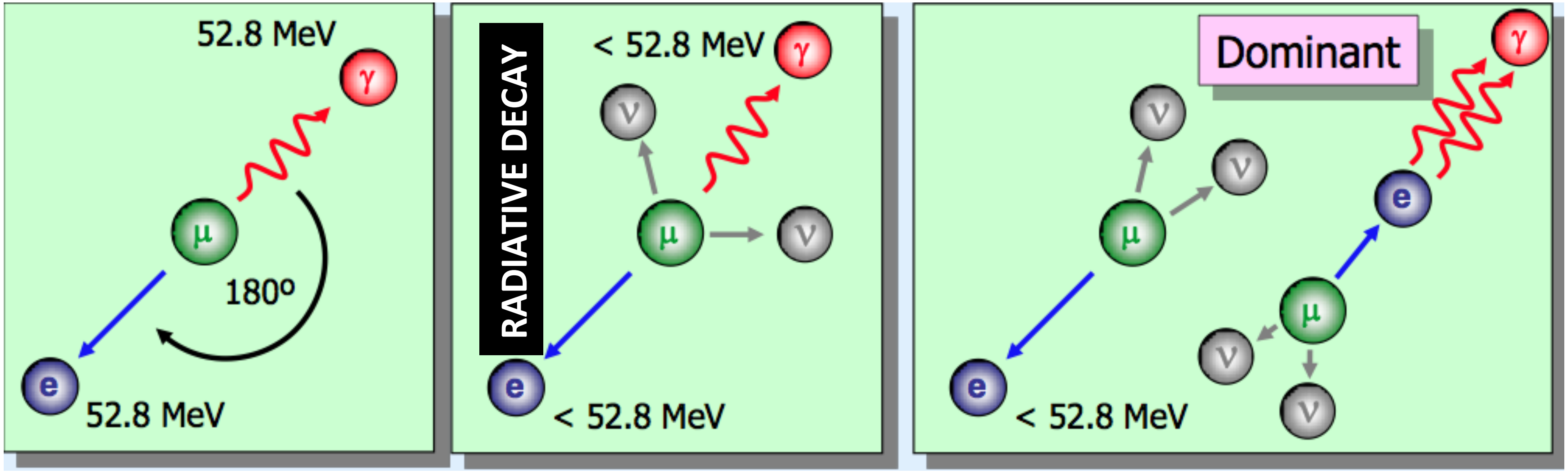
BNL limit is 1.8 x 10^{-19}

Can quickly be improved by x10 and ultimately x100 to 10^{-21}

If there are non mass-scaling BSM effects then 10^{-21} becomes competitive

Measurement can only be performed using the tracking detectors

MEG Experiment



Signal

Prompt Background

Accidental Background

$E_\gamma = E_{e+} = 52.8$ MeV

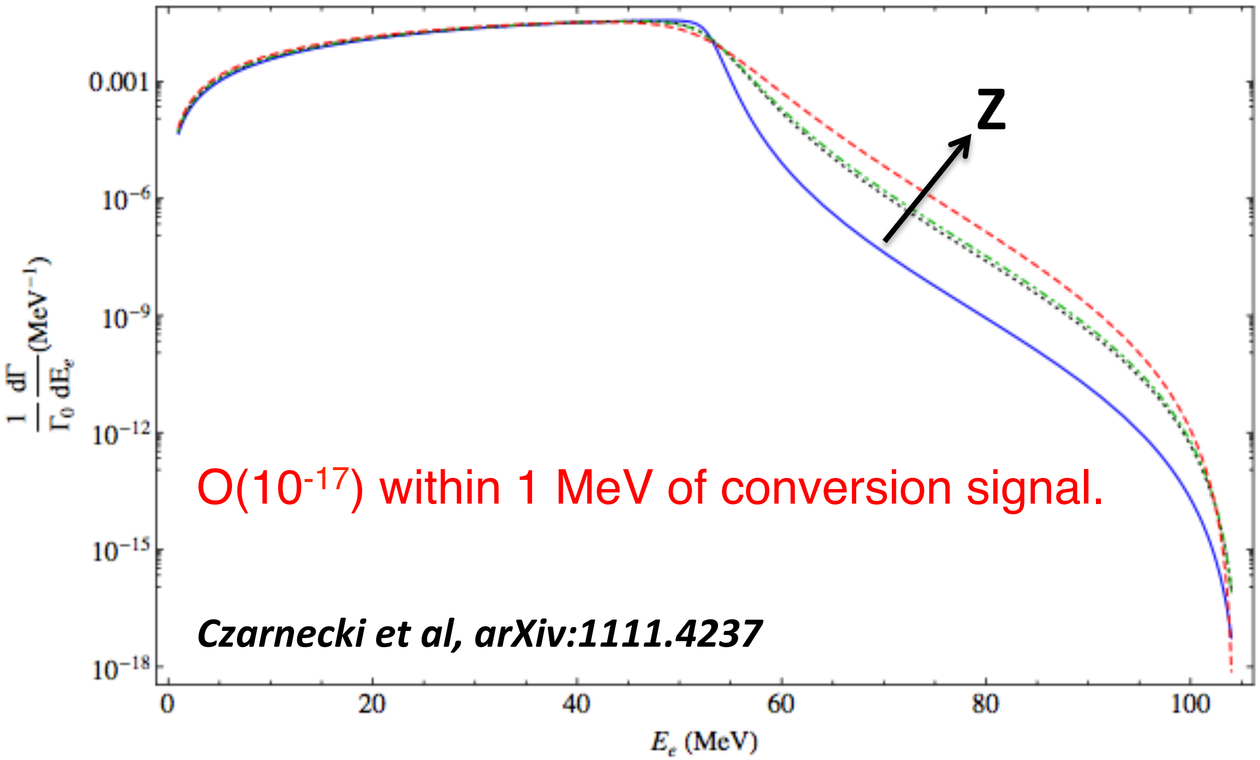
$\theta_{\gamma e} = 180^0$

γ and e^+ in time

μN→eN Backgrounds

Two pertinent backgrounds

1. Decay in orbit (**DIO**) of stopped muon. In atom gives electrons beyond the free-muon 53 MeV end-point.



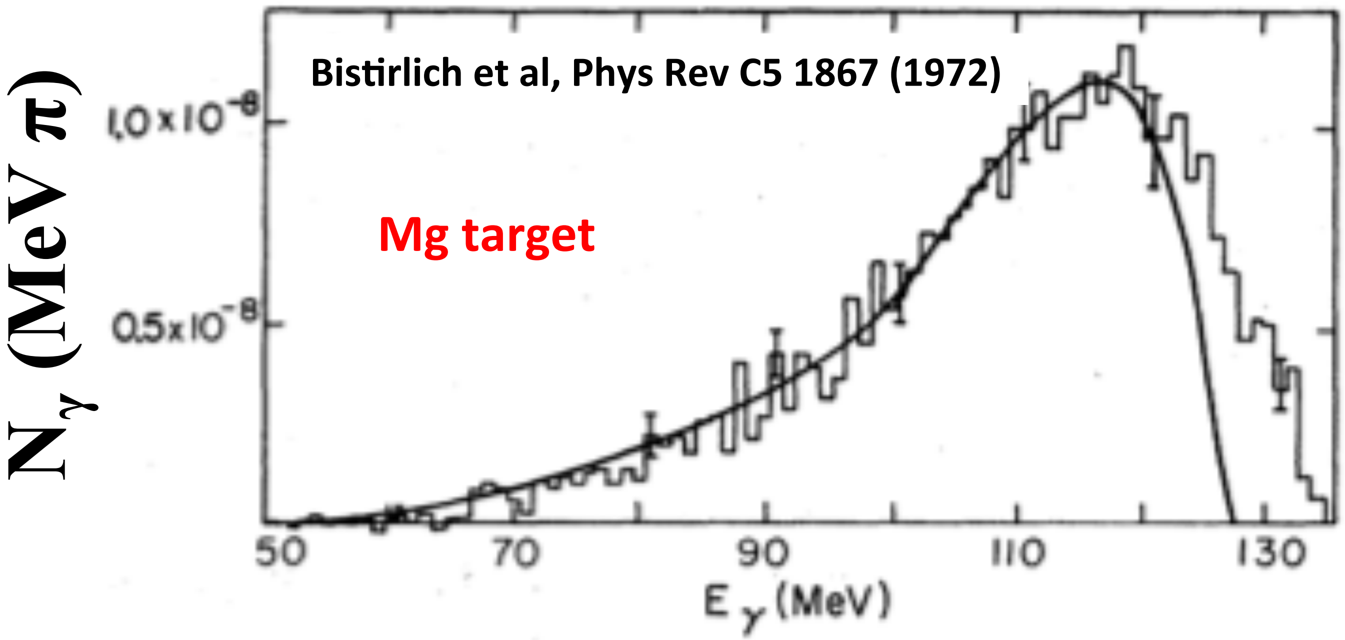
Controlled by detector resolution AND energy loss prior to detector.

Need FWHM < 1 MeV

2. Radiative Pion Capture (RPC)

$\pi^- N \rightarrow \gamma N^*$ and $\gamma \rightarrow e^+ e^-$ External conversion

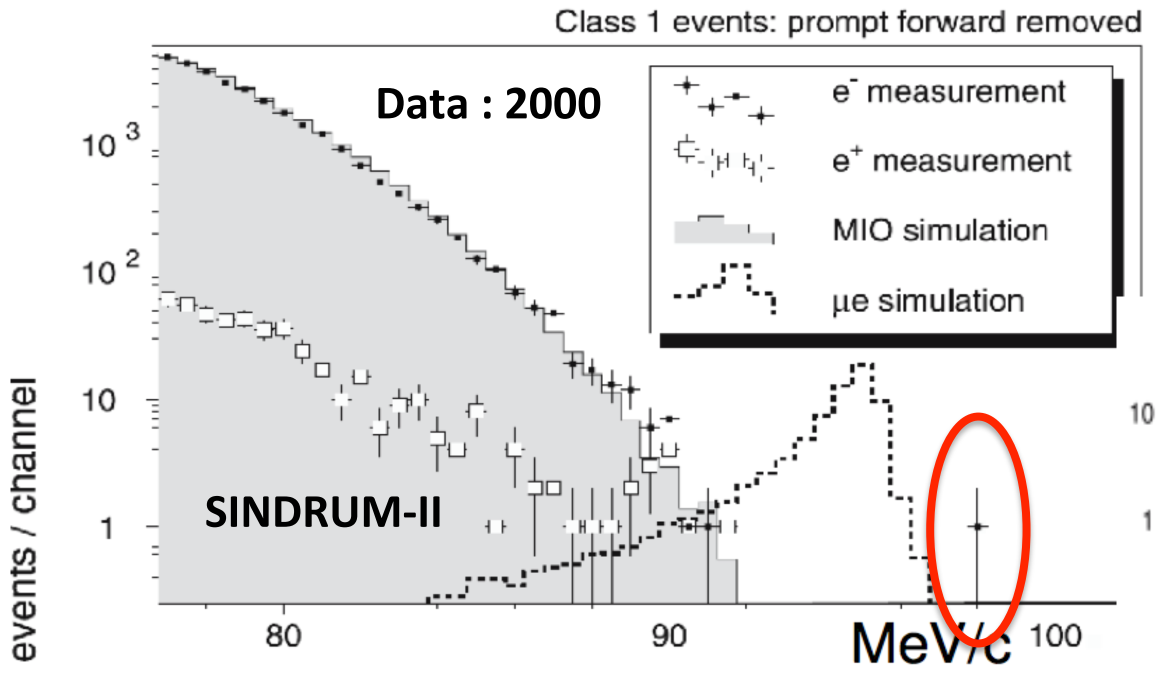
$\pi^- \mathrm{N} \rightarrow e^+ e^- N$ Internal conversion

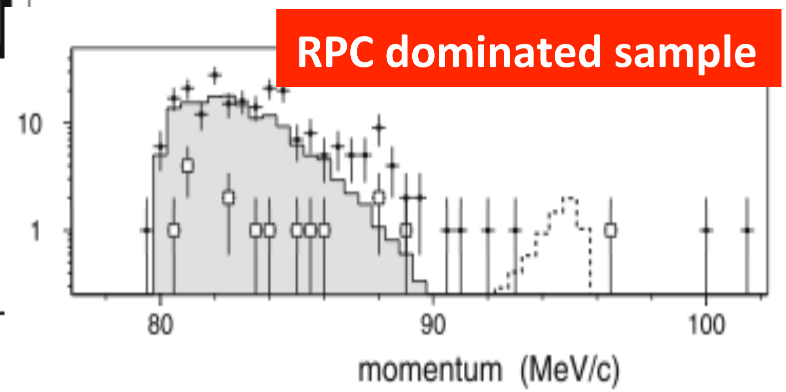


Suppress by reducing # pions on target : wait, stop them, veto them
- beamline and accelerator are the constraint.

Muon to Electron Conversion

Current best measurement (SINDRUM-II @ PSI) used 8mm of CH_2 to reduce pion (RPC) contamination to 1 in 10^9 π reaching target

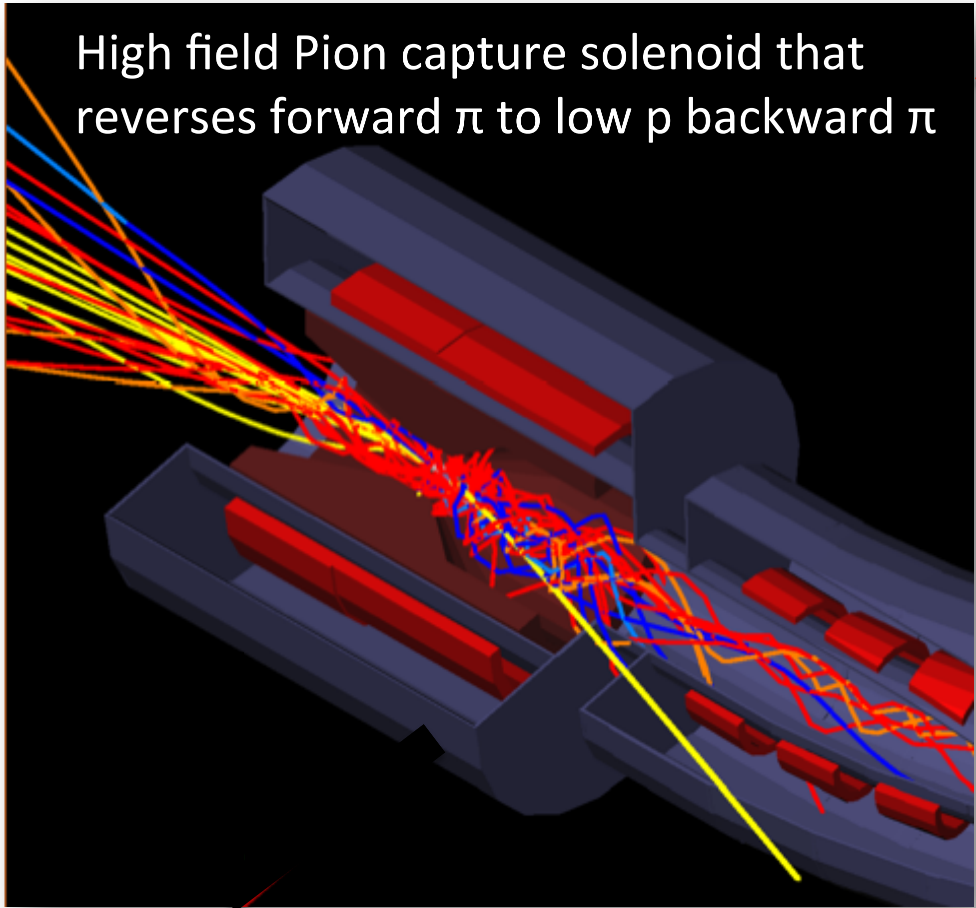




Limit : 7 x 10^{-13} (Gold target).

Challenges : Stopped Muon Yield

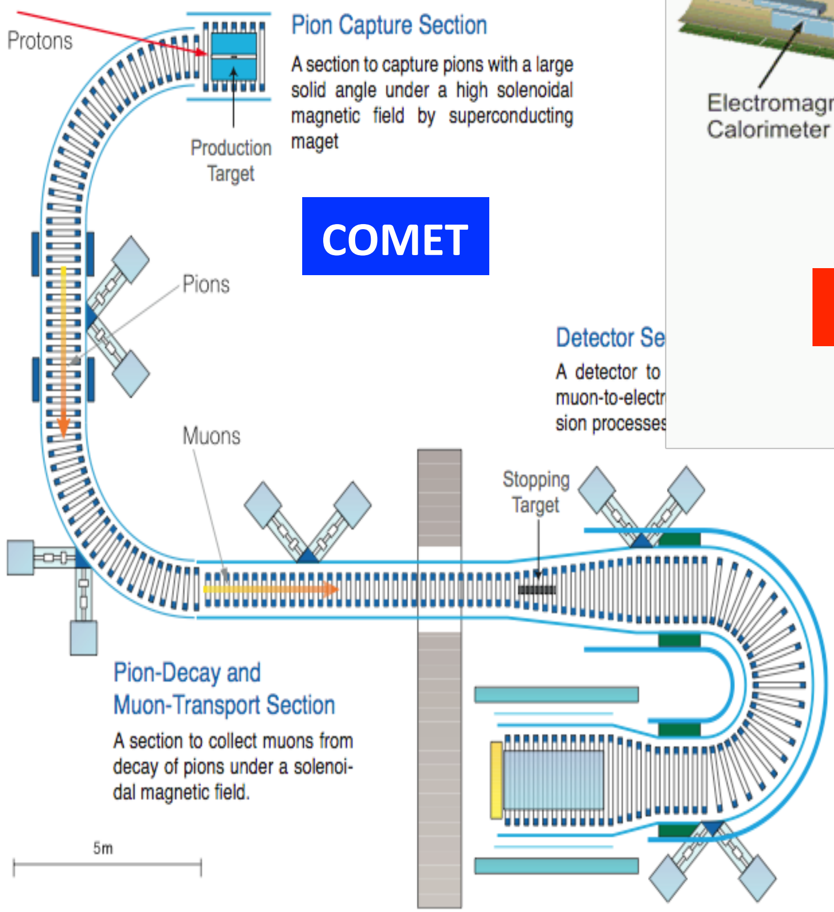
Increases yield by O(1000) - method successfully demonstrated at MUSIC in Osaka in 2010

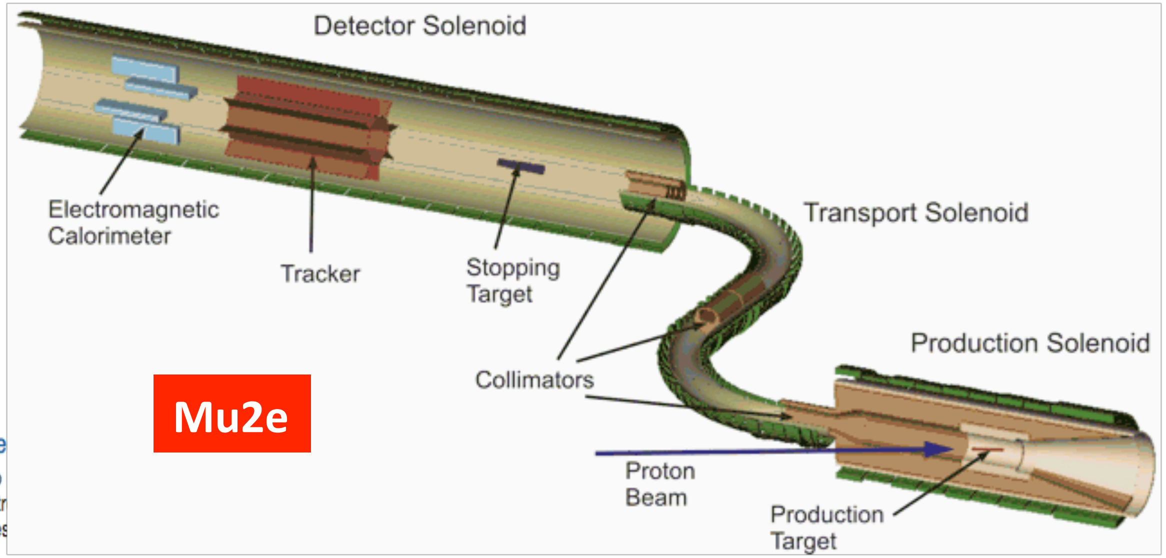


Transport solenoids that select low p (< 50 MeV) muons and reject high p particles **before** the stopping target.

COMET/Mu2e : 6x10^{-17}

Sensitivity reach physics wise is at least x10 that of upgraded MEG.





COMET : 10^{18} μ/yr (CDR) with lower acceptance & requirement of dedicated running vs Mu2e 4.5 x 10^{17} μ/yr (CD0) and concurrent Noυa running

Beyond COMET/Mu2E

Strategy depends somewhat on whether signal is seen or not.

If signal is seen

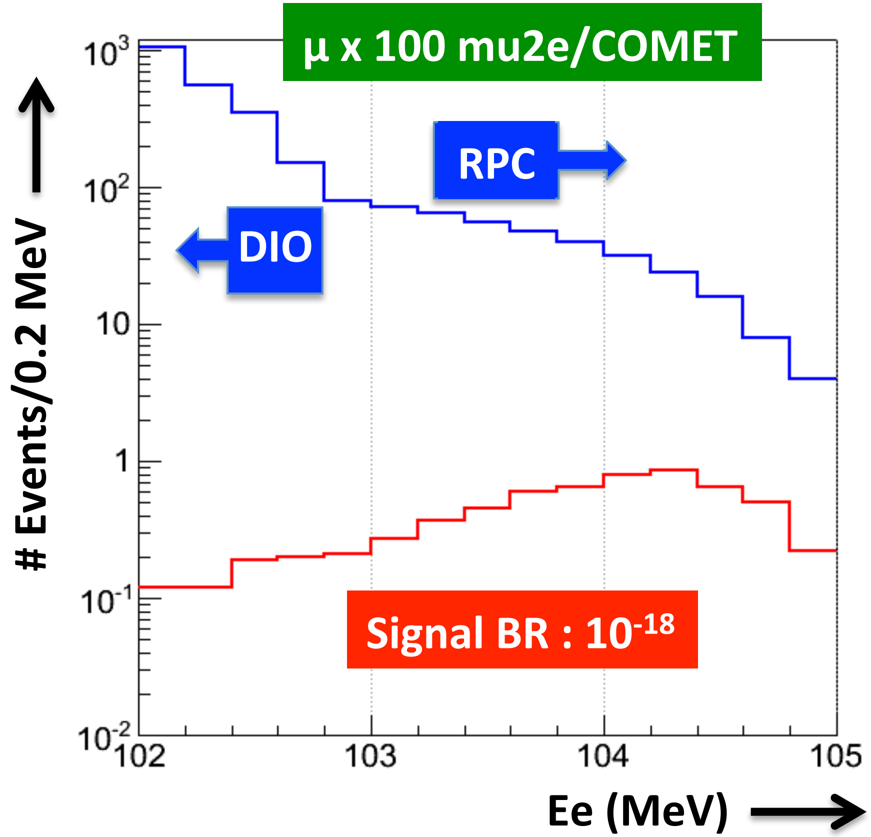
- **run with high-Z target** to elucidate the underlying physics

If no signal seen

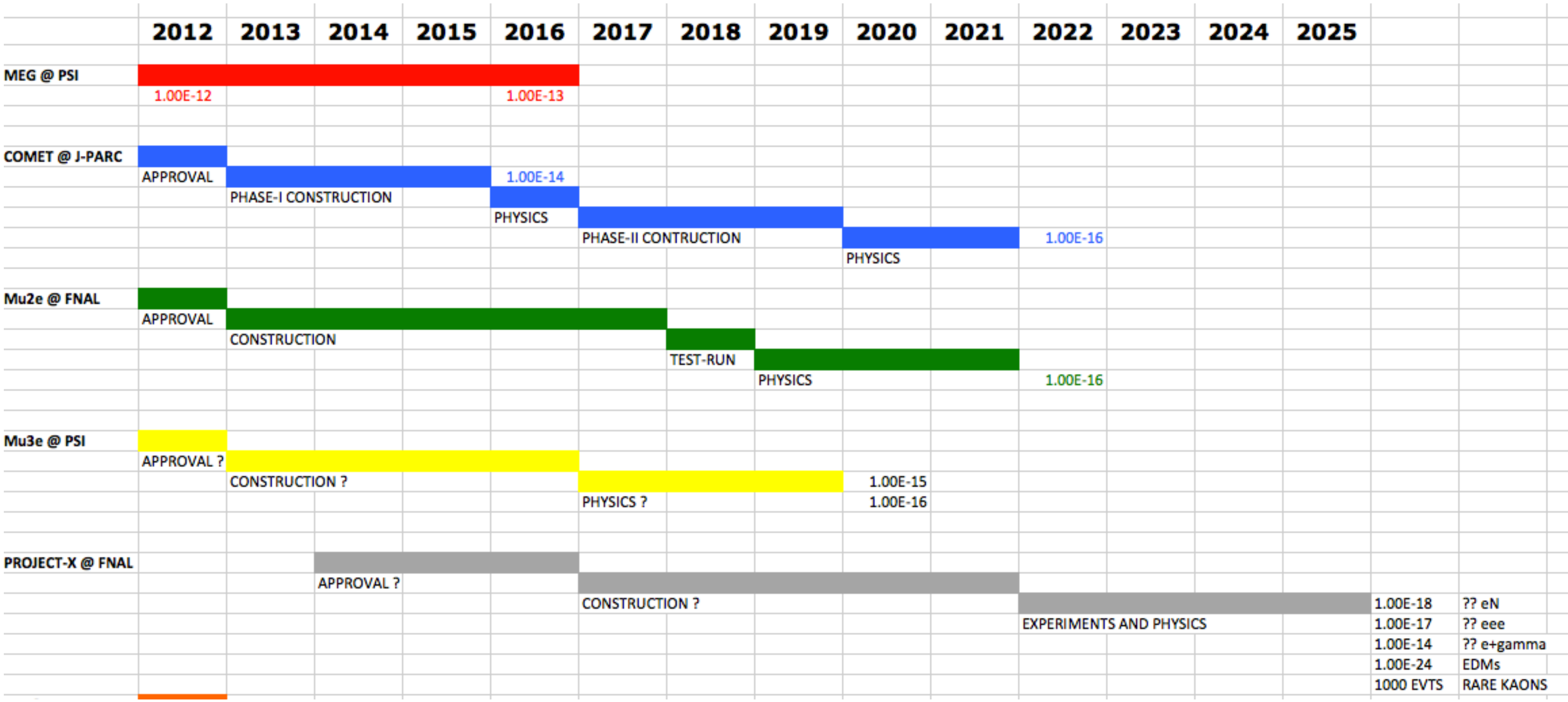
- push sensitivity down to $O(10^{-18})$

Very challenging requires many of the ideas being explored for NF/muon collider.

- muon momentum selection
- muon cooling (FFAG/helical channel)

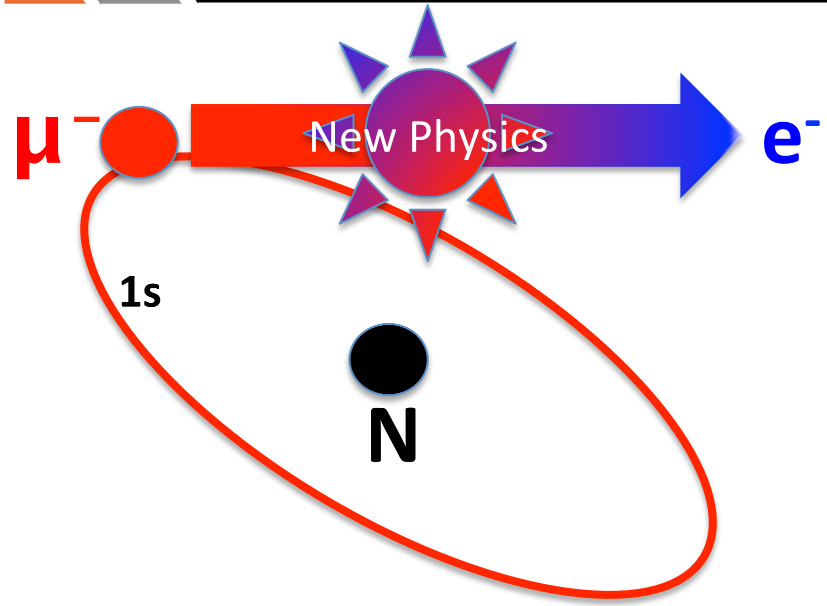


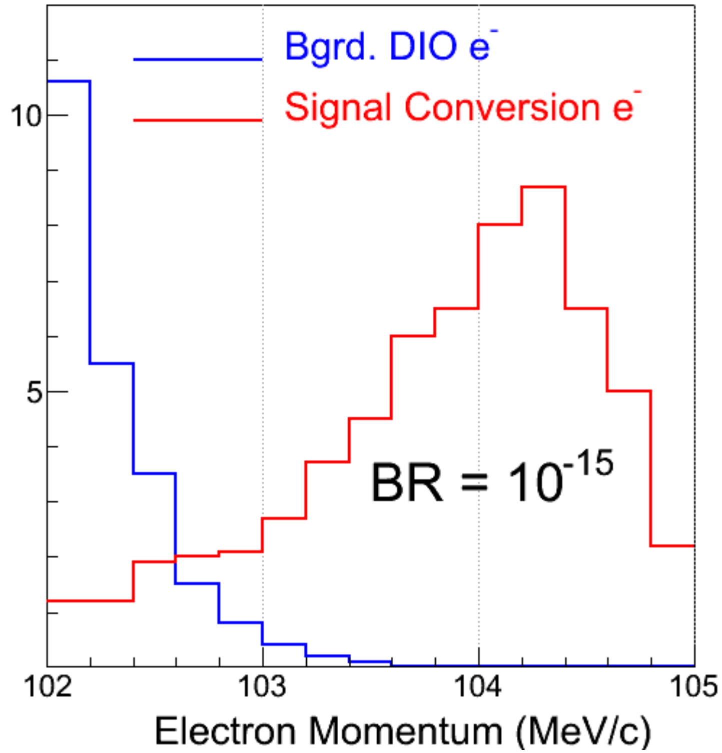
Where are we now / timescales ?



COMET unlike Mu2e will be constructed in two phases with 1st data in 2016/17.

What we hope to see



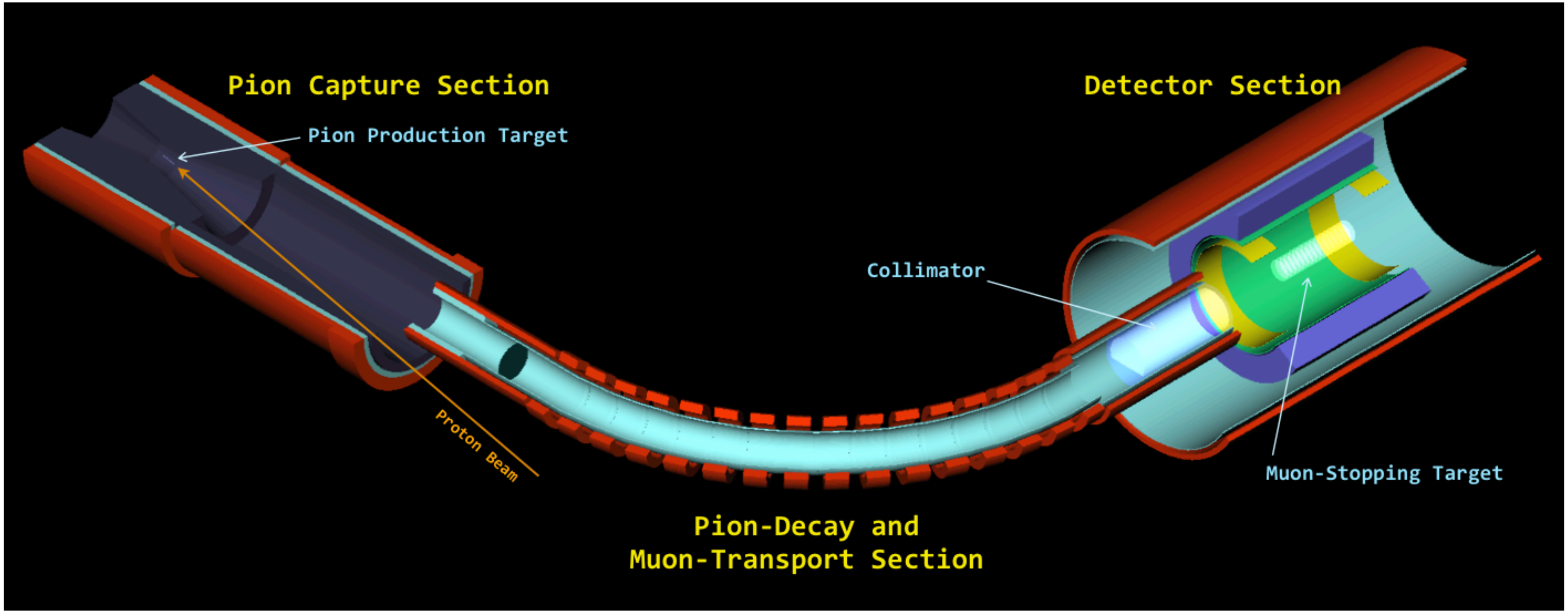


Coherent (all nucleons recoil) neutrinoless transition of 1s-μ to e⁻

$$\boxed{E_\mathrm{e} = m_\mu - E_\mathrm{b} - E_\mathrm{rec}}$$

Simple signature of single electron with energy ~ 105 MeV

Phase-I Beamline and detector



PhD student : Optimise the beamline design: collimators, proton absorbers

Quantify and optimise the physics sensitivity.

Commission the detectors

Test beam measurements

At PSI (and possibly Osaka)

To measure the particle types and fluxes when a muon is captured by nucleus
 - crucial to understanding backgrounds to the conversion process

Trackers

Crucial to achieve systematic error goal

0.10 ppm is **total** systematic error budget

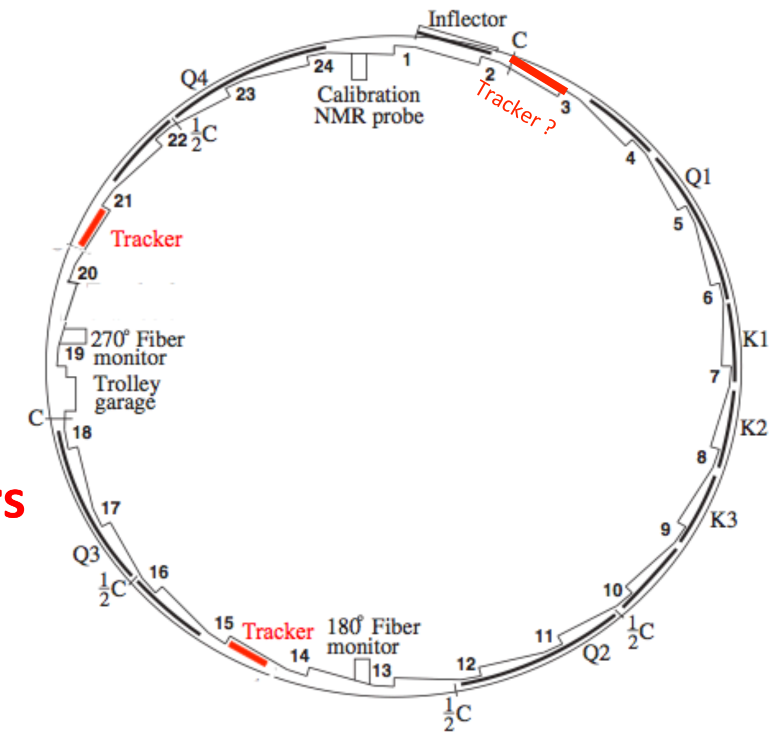
0.07 ppm : B field

$\oplus$

0.07 ppm : frequency measurement

0.06 ppm of this 0.07 ppm needs trackers

BNL	*FNAL*	*Systematic*
0.03	0.02	Beam Profile
0.05	0.03	E-field & pitch Correction
0.08	0.04	Pileup
0.12	0.02	Calorimeter Calibration



Need at least two to measure beam profile in 64 μs