Muon Physics around the world and at the Intensity Frontier - Part 2

Peter Winter

Argonne National Laboratory

So far on...

So far

- Got to know the muon
- Muon beams (surface versus cloud) and typical beamlines
- We have learned about the two things a muon usually does:

  Decay: $\mu \to e\nu_e\nu_\mu$

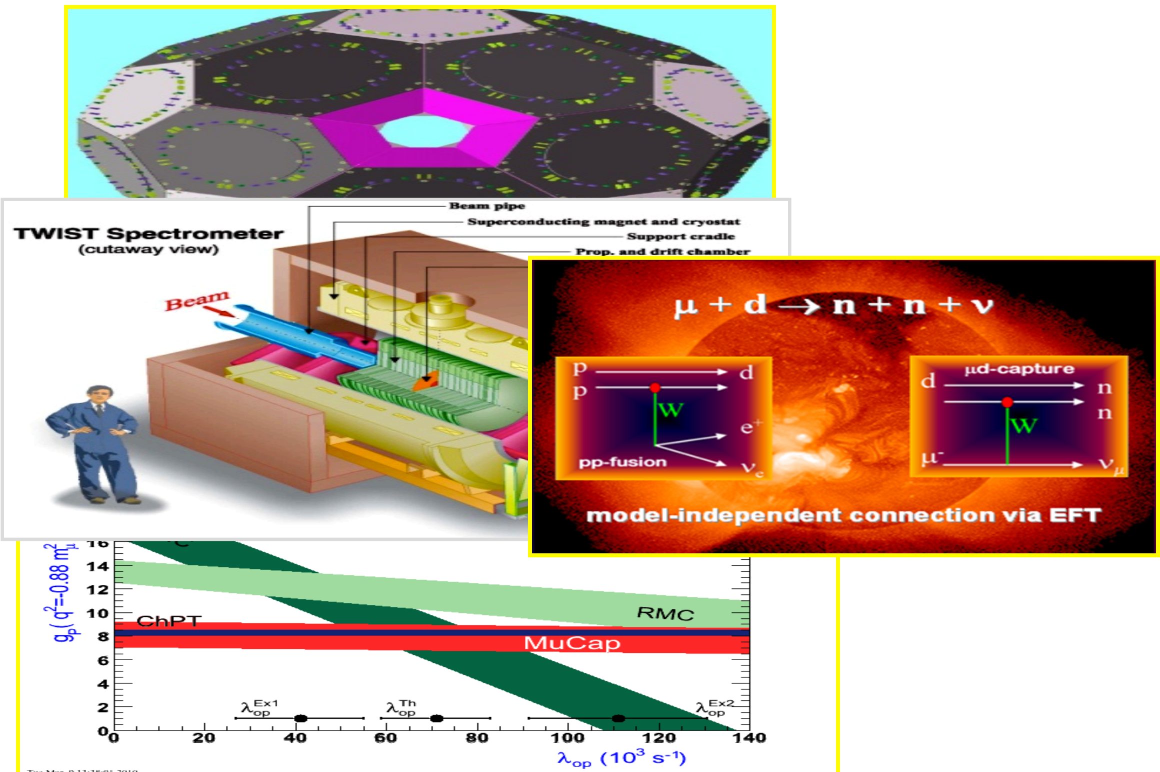
  Capture: $\mu^- p \to n\nu$

- A tour of experiments measuring parameters within the SM:
  - TWIST: Michel parameters (also probes BSM)
  - Muonic lamb shift: Proton charge radiusß
  - MuLan: τ_μ, G_F
  - MuCap: g_P
  - MuSun: L_{1A}/d_R

General timeline

All time ranges are only approximate. But it gives a good feeling for the length of these experiments!

2000 2005 2010 2015 2020 2025



Different categories of muon experiments

1. Measurement of Standard Model parameters:
   - Masses: **M_Z M_W M_H m_b m_t m_e m_u m_v …**
   - Couplings: α_{QED} α_{Strong} G_F G_{grav}
   - Structure of interactions: $SU(3)_C \times SU(2)_L \times U(1)_Y$

2. Search for Physics Beyond the Standard Model:
   - TWIST: Michel Parameters ρ, δ, η, $P_\mu \xi$
   - Charged Lepton Flavor violation MEG, Mu2e, μ3e
   - Physics Beyond the SM: Muon g-2, μEDM

TODAY

3. Applied material research:
   - Muon spin Resonance (muSR) to probe magnetic properties

… and now:

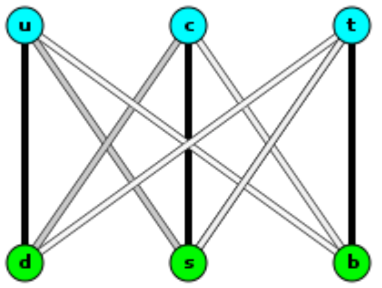
Overview

- The Muon and the Big Picture
- Muon Beams
- Recent Muon Experiments
  - TWIST, Muon Spin Resonance, Lamb shift, **MuLan, MuCap/MuSun**
- Muons at Fermilab and the Intensity Frontier
  - CLFV: **MEG** ($\mu^+ \rightarrow e^+\gamma$), μ3e, **Mu2e**, COMET
  - **New g-2**
  - Future Muon experiments with Project-X

Charged lepton flavor violation: General introduction

- The Cabibbo-Kobayashi–Maskawa tells us that there is flavor change in the **quark** sector:

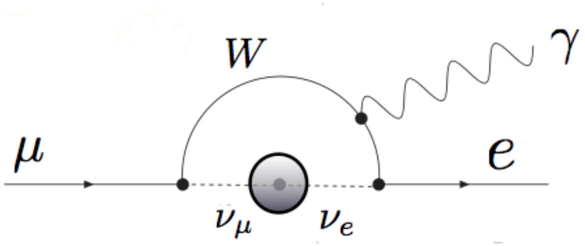
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$



- Is there flavor change in the **lepton** sector?
  YES, neutrinos oscillate
- So is there Charged Lepton Flavor Violation (CLFV) in the SM?
  Yes but it is extremely small! (see next slide)
- Since CLFV is pretty much absent in the SM, it is an ideal probe to search for New Physics

Charged lepton flavor violation in the SM

- Neutrino oscillation allows for CLFV in the SM via:

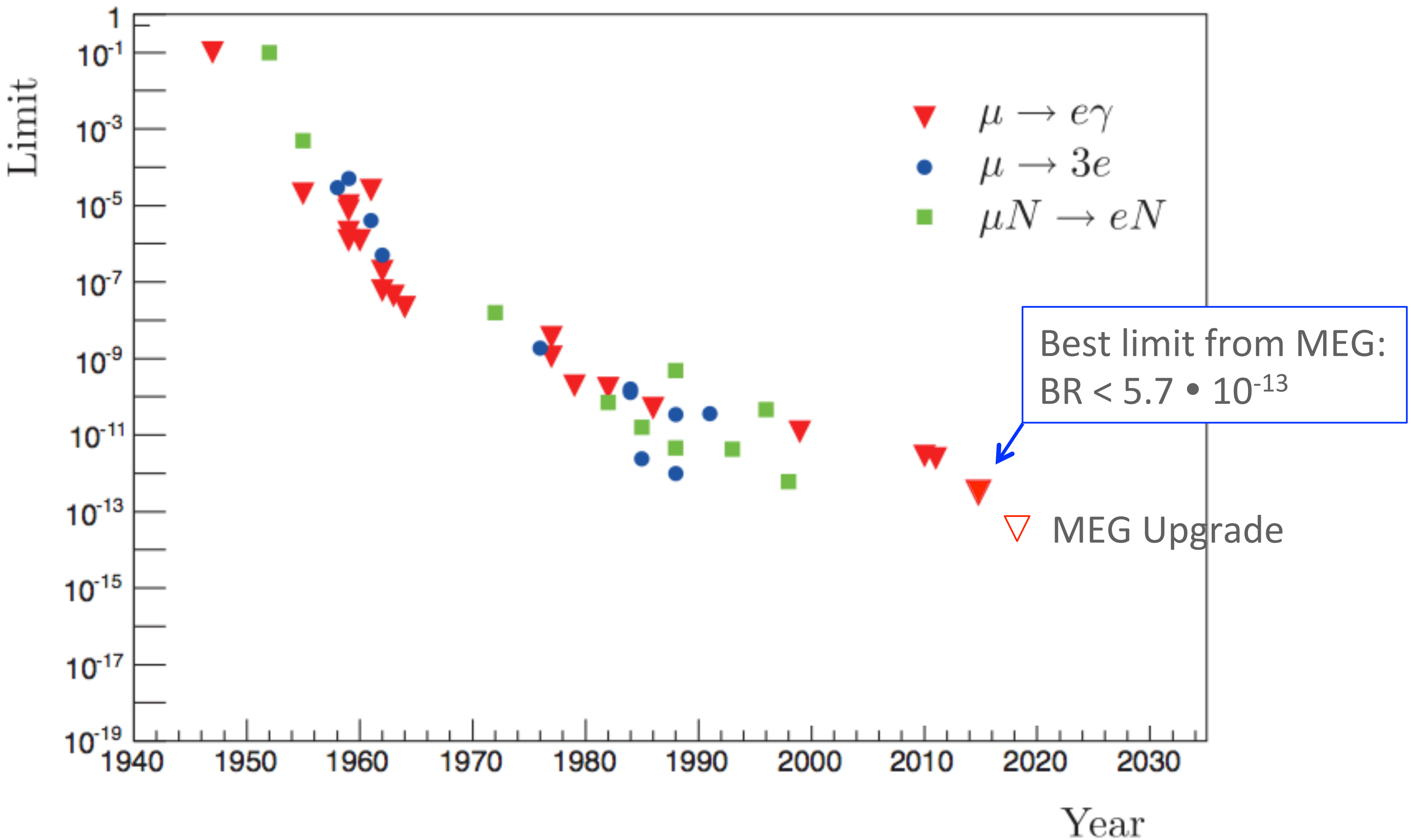


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

Good luck ever measuring that!

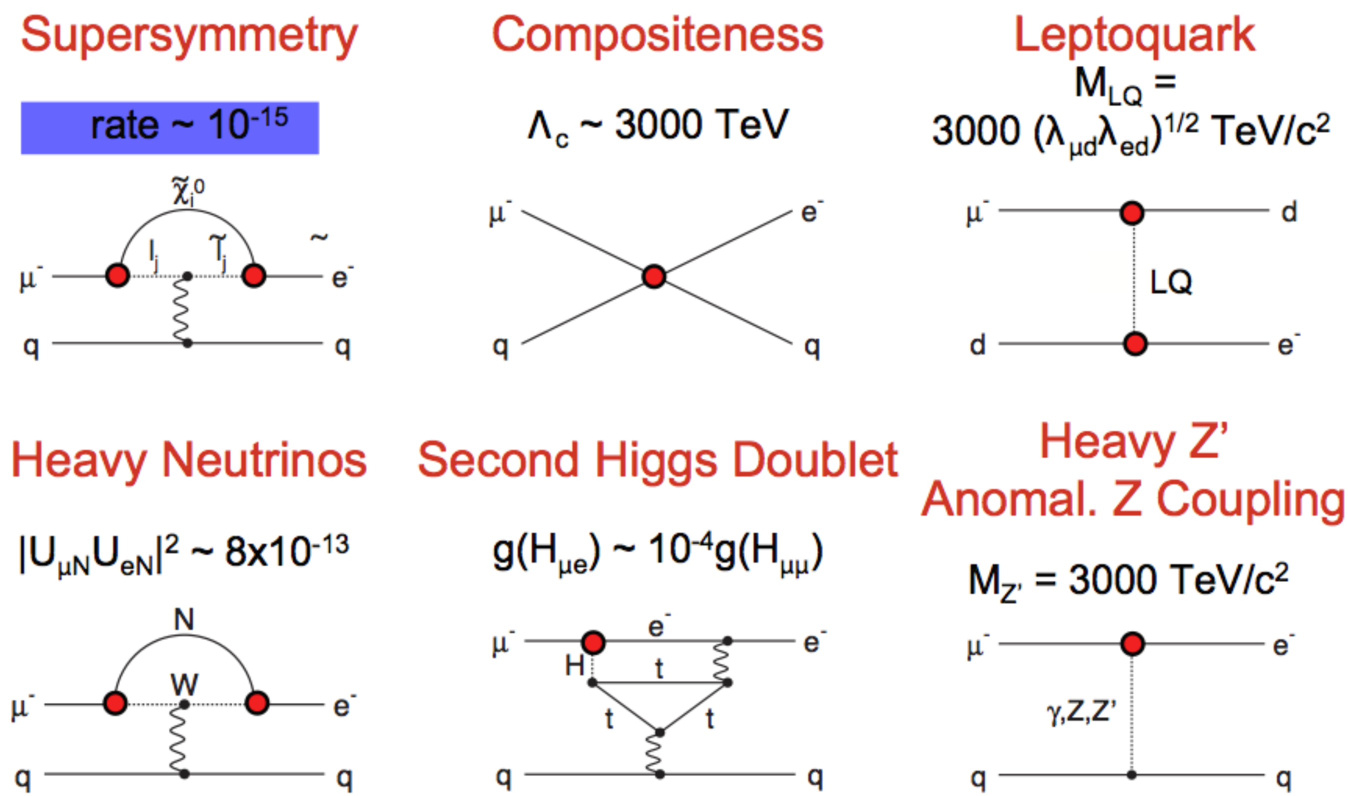
- Three golden channels in the muon sector:
  - $\mu^+ \to e^+ \gamma$
  - $\mu^+ \to e^+ e^+ e^-$
  - $\mu^- N \to e^- N$
- Tau channels also interesting but current limits not as strong since experimentally more challenging (10^{10} μ/s >> 10^{10} τ/year)

CLFV experimental searches: Status



CLFV in extensions to the SM

- Many extensions to the Standard Model can generate sizeable CLFV



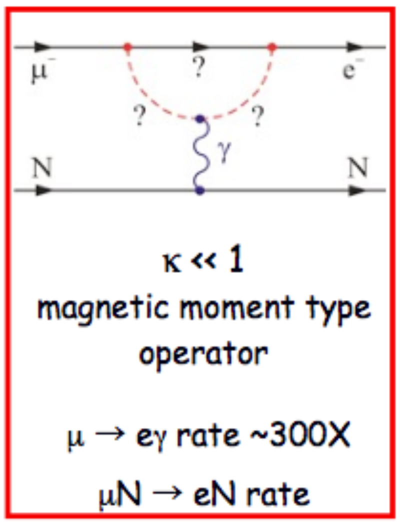
also see Flavour physics of leptons and dipole moments, arXiv:0801.1826
and Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126

Model independent parametrization of CLFV

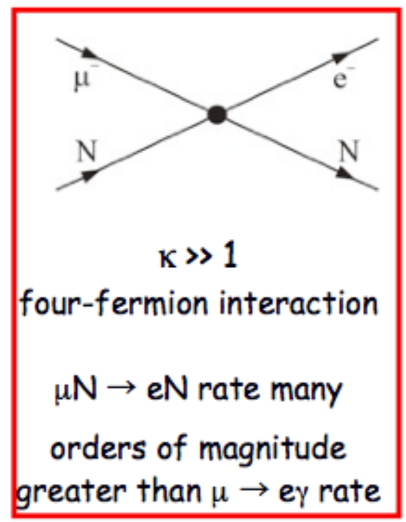
- Add effective CLFV operators to the Lagrangian:

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

Loop diagrams



Contact diagrams

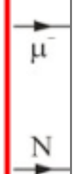


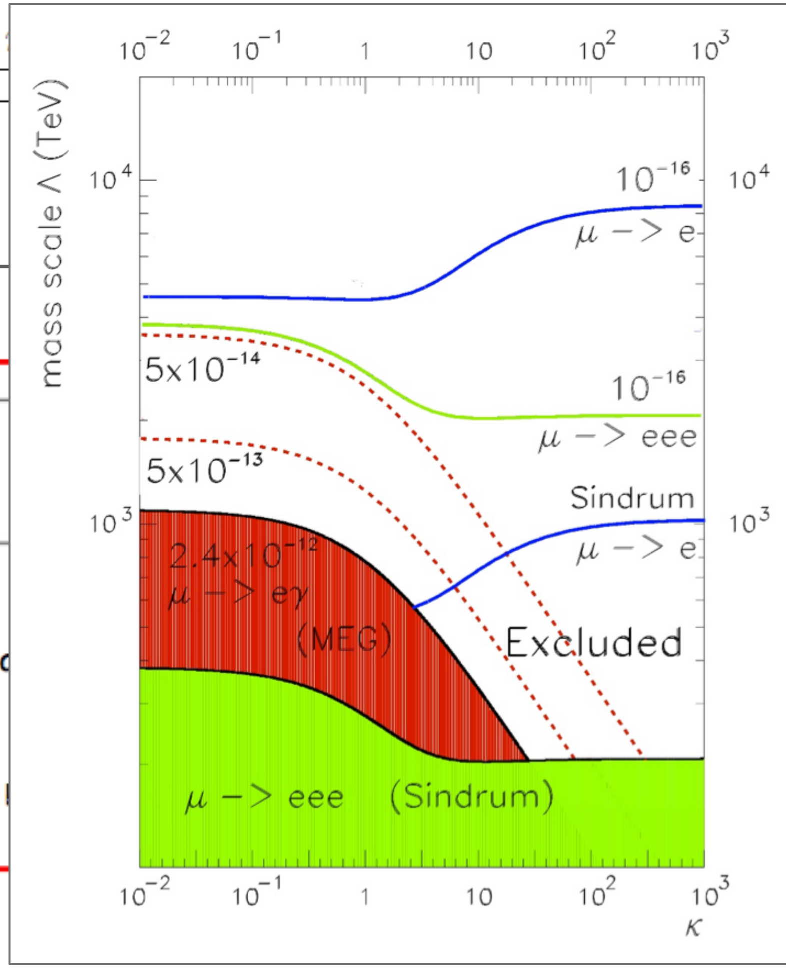
Λ is the mass scale of the new physics

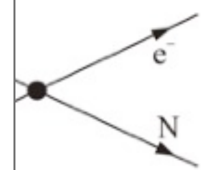
Model independent parametrization of CLFV

$\mathcal{L}_{\mathrm{CLFV}} = \frac{\quad}{(\kappa \; \ldots}$ … $(\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$

L … diagrams







mo…

…> 1
…n interaction
…rate many
…magnitude
…n μ → eγ rate

The 3 golden channels: A comparison

	$\mu^+ \rightarrow e^+ \gamma$ $\mu^+ \rightarrow e^+ e^+ e^-$	$\mu^- N \rightarrow e^- N$
Difference in the decay channels?	Electron and γ energies $\leq$53 MeV	Monoenergetic 105 MeV electron
Main backgound channels?	Accidental backgrounds proportional to the beam rate R^2	Out of time beam
Beam structure requirements	Continuous beam to have $R_{max} = R_{average}$	Pulsed beam with good extinction

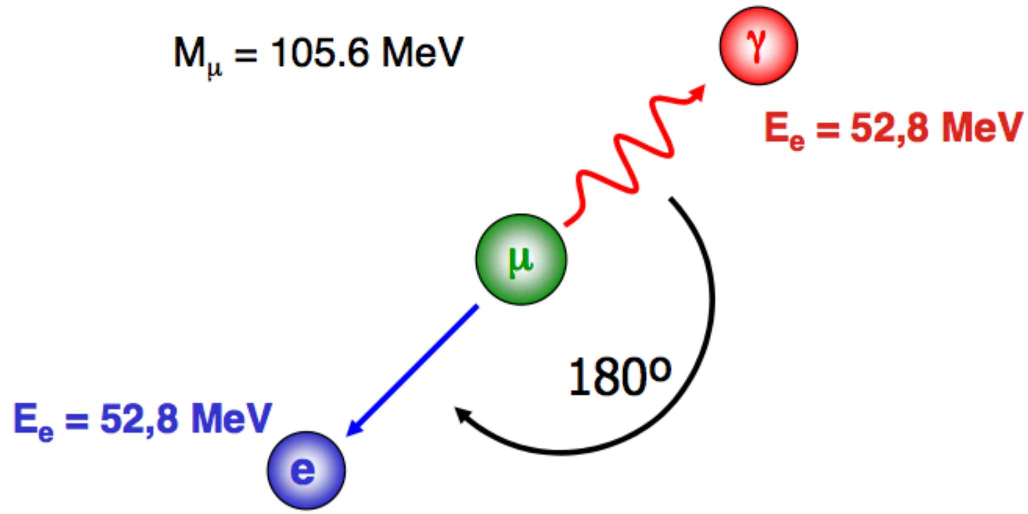
CLFV experiments: Current and future

- MEG ($\mu^+ \rightarrow e^+ \gamma$) at PSI
- μ3e ($\mu^+ \rightarrow e^+ e^+ e^-$) at PSI

- Mu2e ($\mu^- N \rightarrow e^- N$) at Fermilab

MEG ($\mu^+ \rightarrow e^+ \gamma$): Event signature

$\mu \rightarrow e\,\gamma$ event signature:
(muon decay at rest)



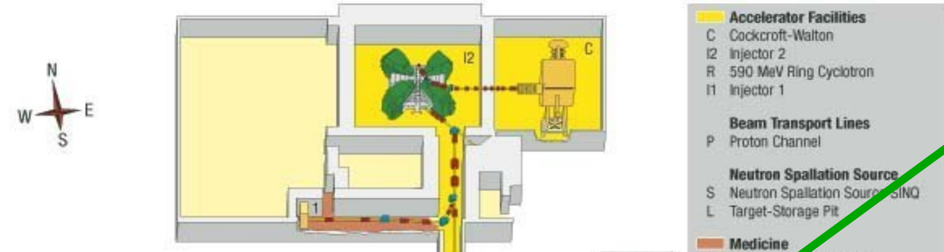
requirement:

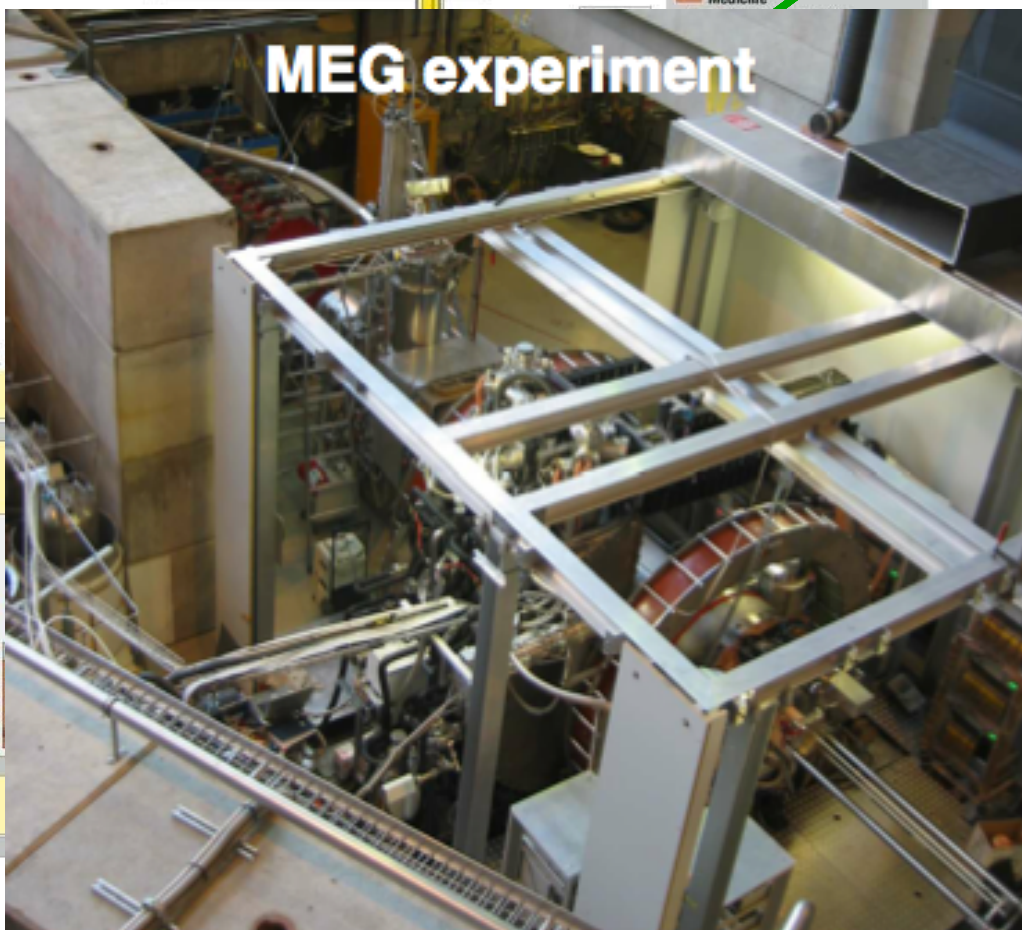
- high-rate, low-p μ-beam → surface μ-beam at PSI

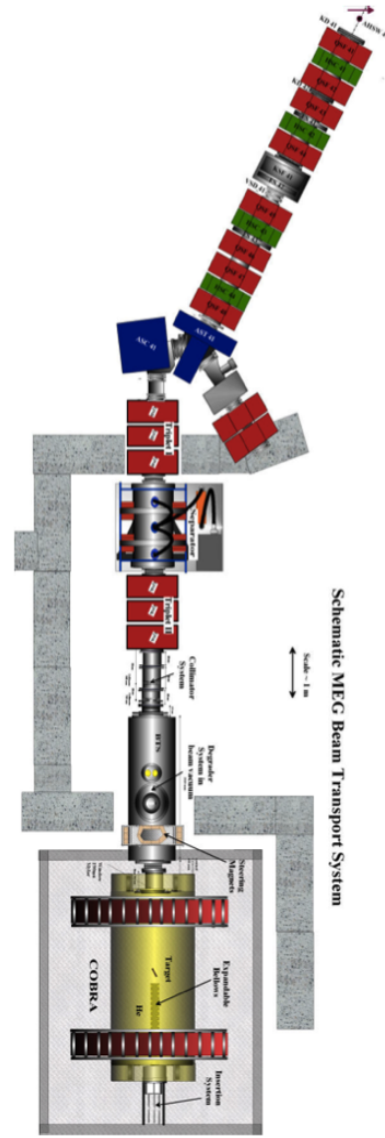
detector:

- $E_e = E_\gamma = 52.8$ MeV → energy resolution
- $\theta_{\gamma e} = 180^\circ$ → spatial resolution
- e and γ coincident in time → timing resolution, pile-up rejection

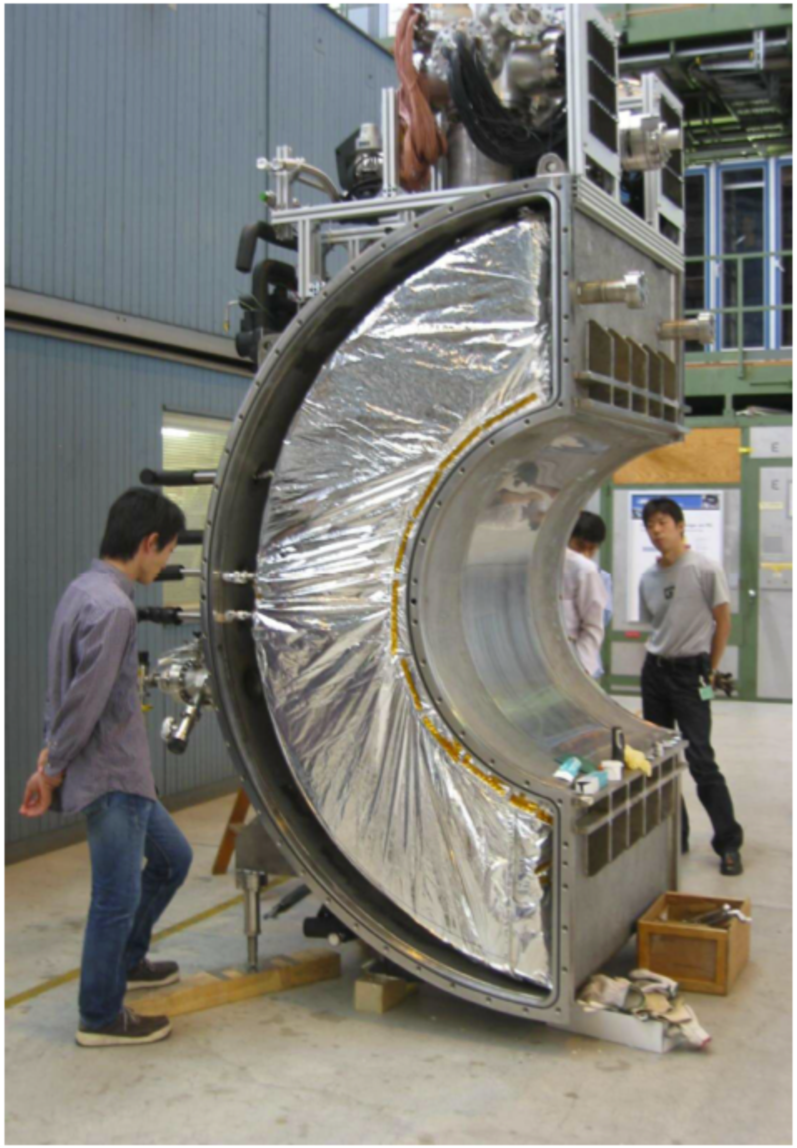
MEG detector at PSI

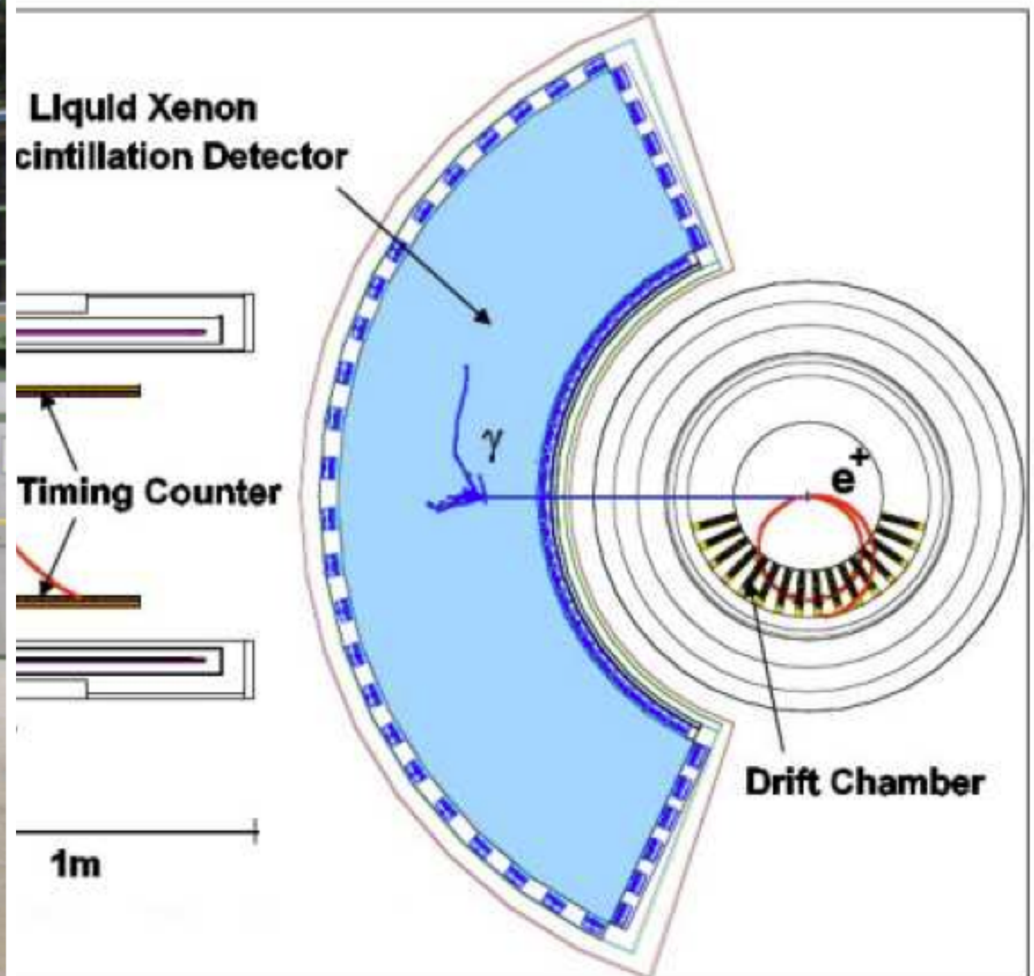






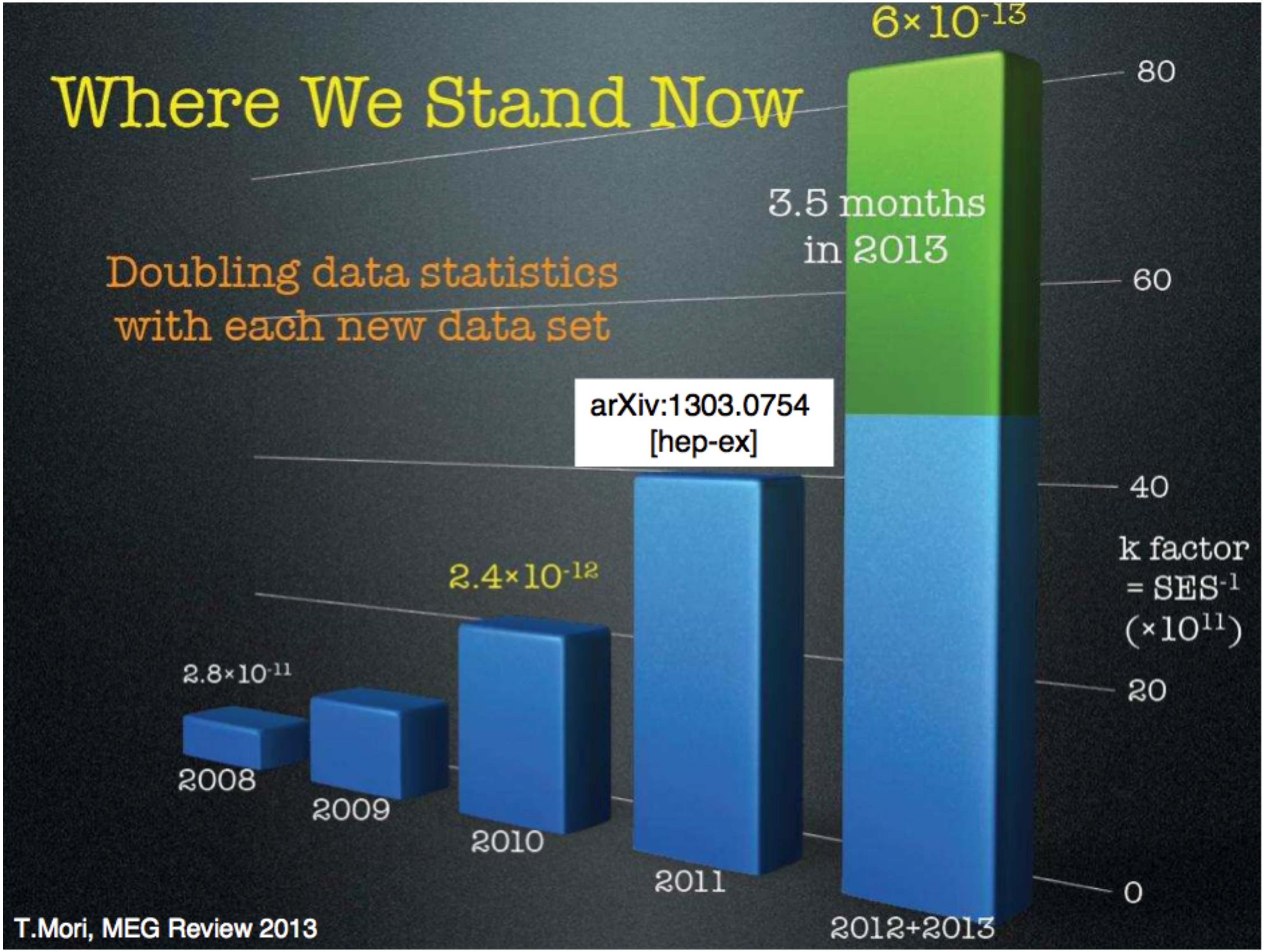
MEG detector at PSI





PAUL SCHERRER INSTITUT

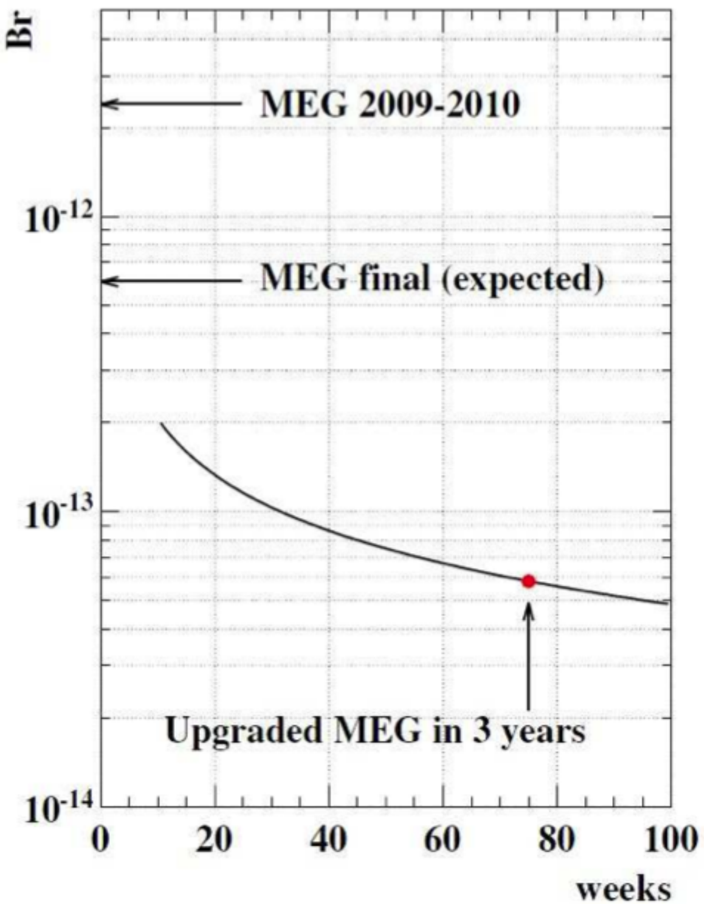
MEG current status



MEG upgrade

TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88
muon rate	$3.3\text{x}10^7$/sec	$7\text{x}10^7$/sec

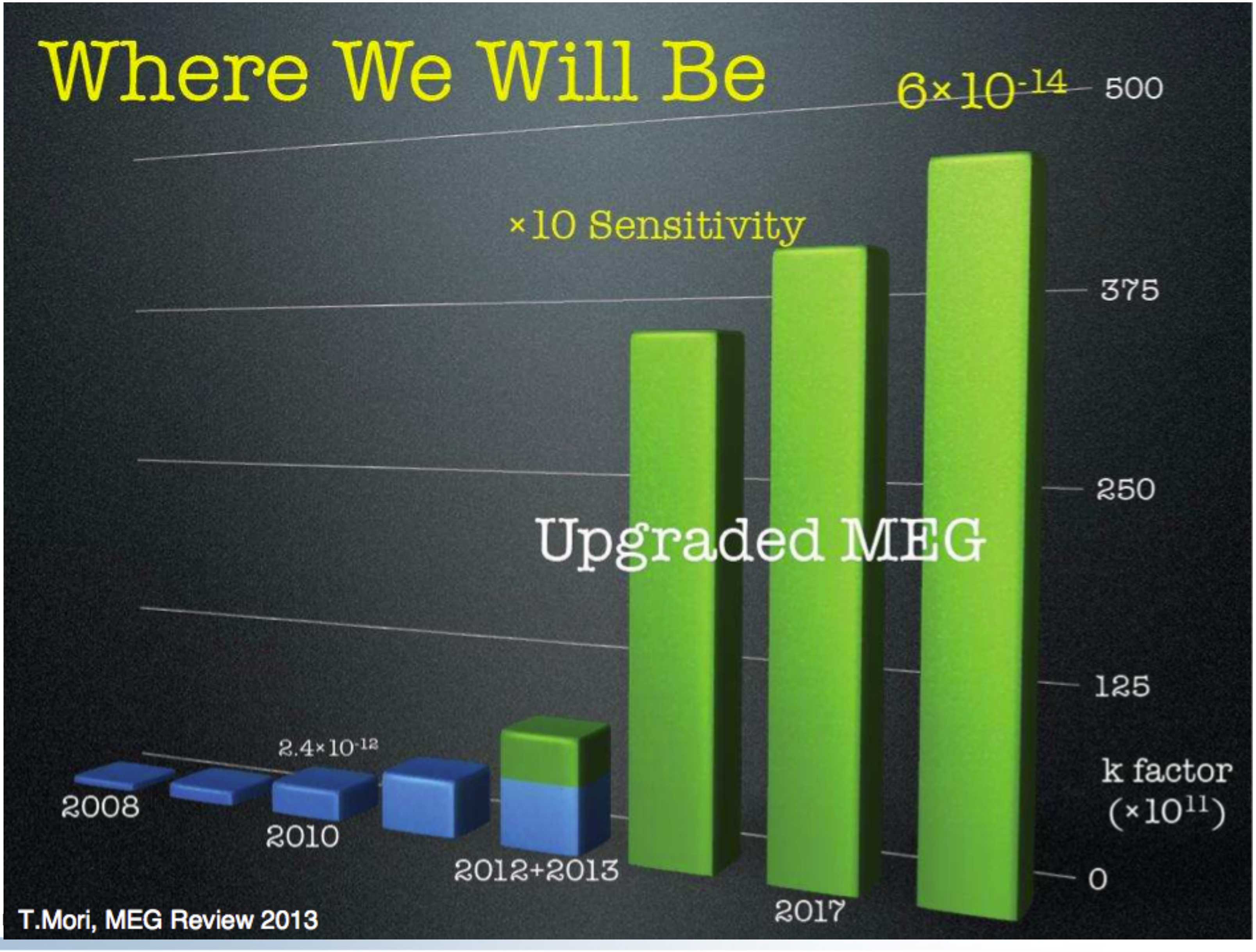


T.Mori, MEG Review 2013

MEG upgrade all about improving resolution:

- thinner target
- single colume drift chambers
- new timing counter
- SiPM readout for LXe calo

MEG upgrade

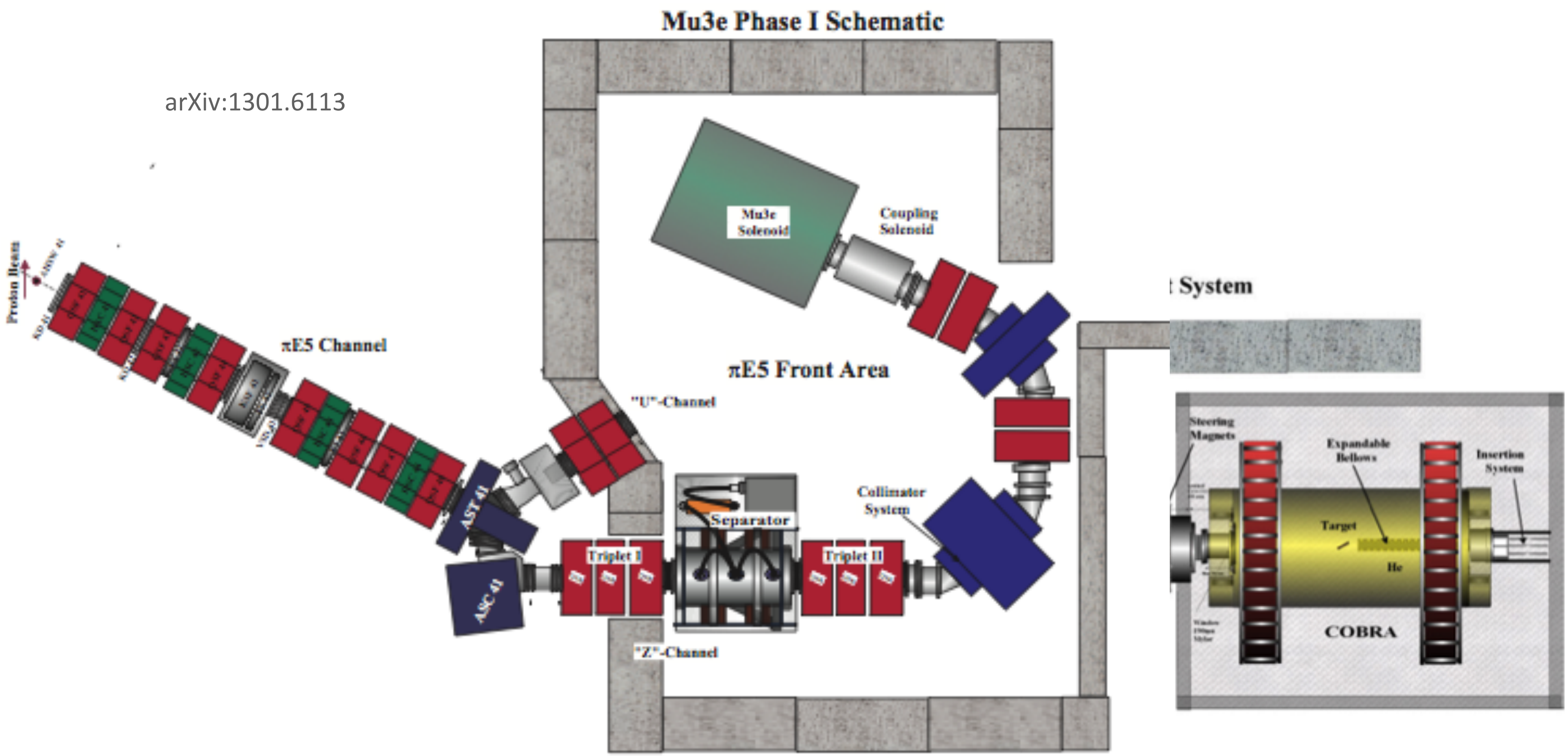


Where We Will Be
6×10-14
500
×10 Sensitivity
375
250
Upgraded MEG
125
k factor
(×10¹¹)
0
2.4×10-12
2008
2010
2012+2013
2017
T.Mori, MEG Review 2013

Proposal: $\mu^+ \rightarrow e^+ e^+ e^-$

- Measure this channel to probe down to 10^{-16}
- Share πE5 beamline with MEG to probe 10^{-15} in Stage 1
- Stage 2 in High Intensity Muon Beamline (see yesterday) to reach 10^{-16}

arXiv:1301.6113



Future muon program at Fermilab

- The shutdown of the tevatron opens new possibilties

- Accelerator improvement plan in progress to deliver high intensity proton beam
- Repurposing anti-proton target to generate muon beams

Fermilab accelerator improvements

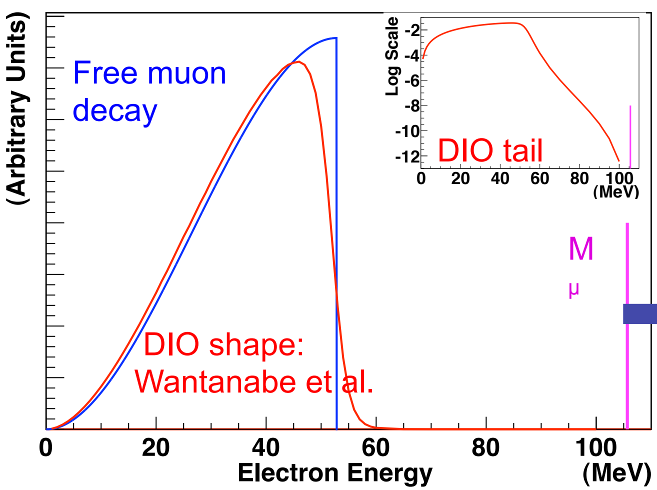
o meet g-2 and Mu2e

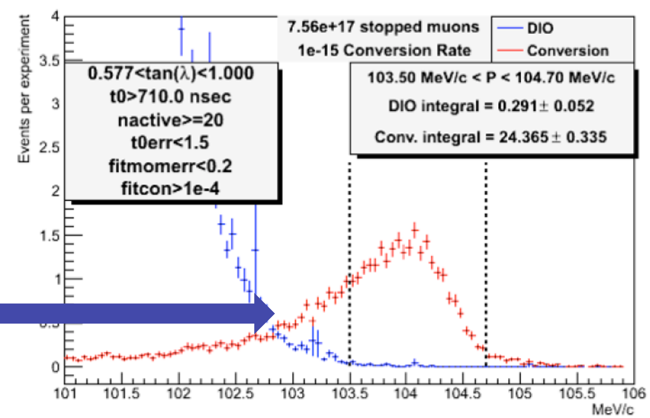
for custom muon

Mu2e concept*

* Somewhat similar project COMET built in Japan

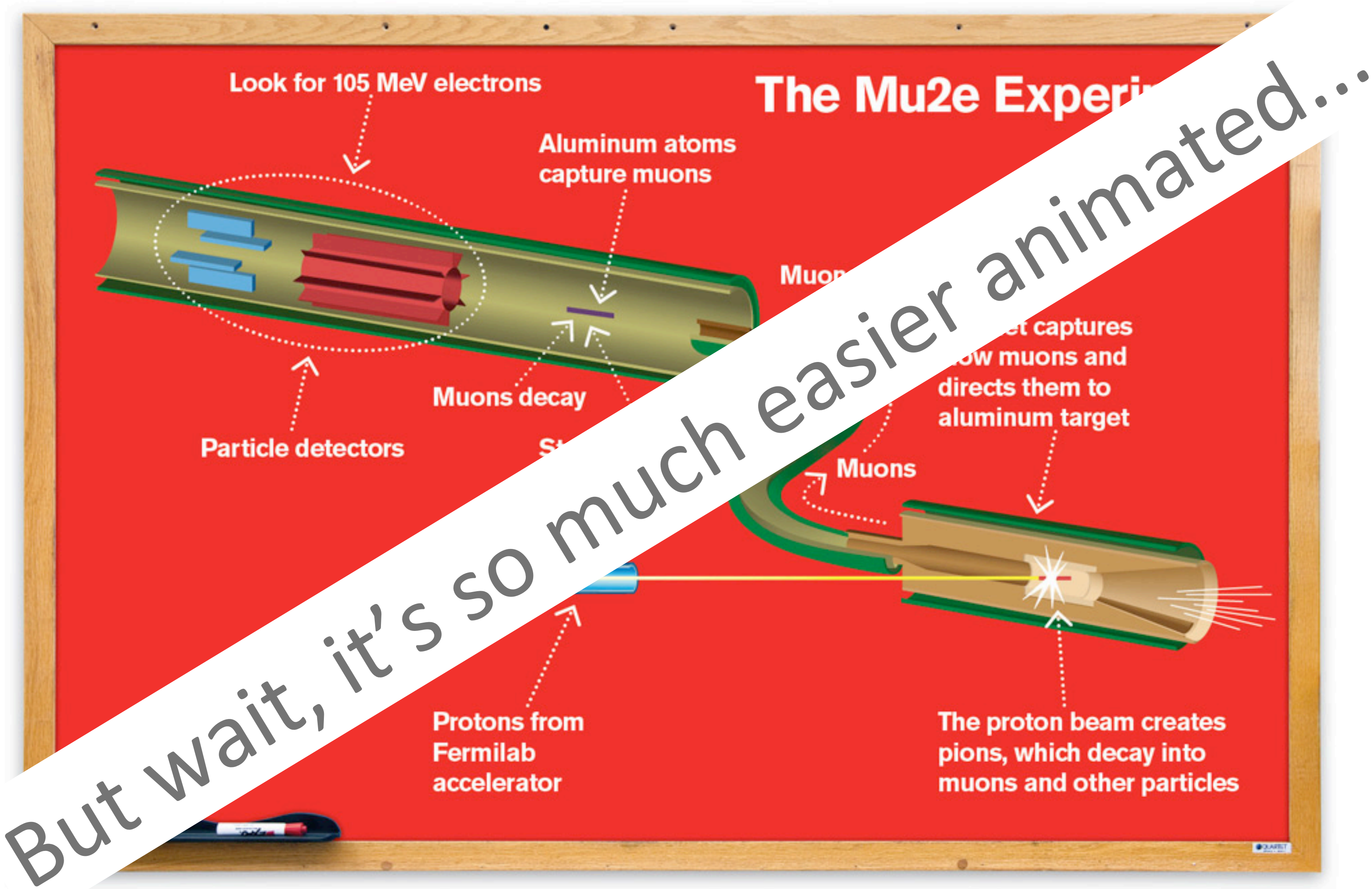
- Produce muons and stop them in target where they form μ^-Al:
  - 40% decay in orbit (DIO)
  - 60% will capture (protons, neutrons, αs, ... emitted)
- Look for mono-energetic ~105 MeV electron from μ^- Al → e^- Al
- Avoid any fake backgrounds





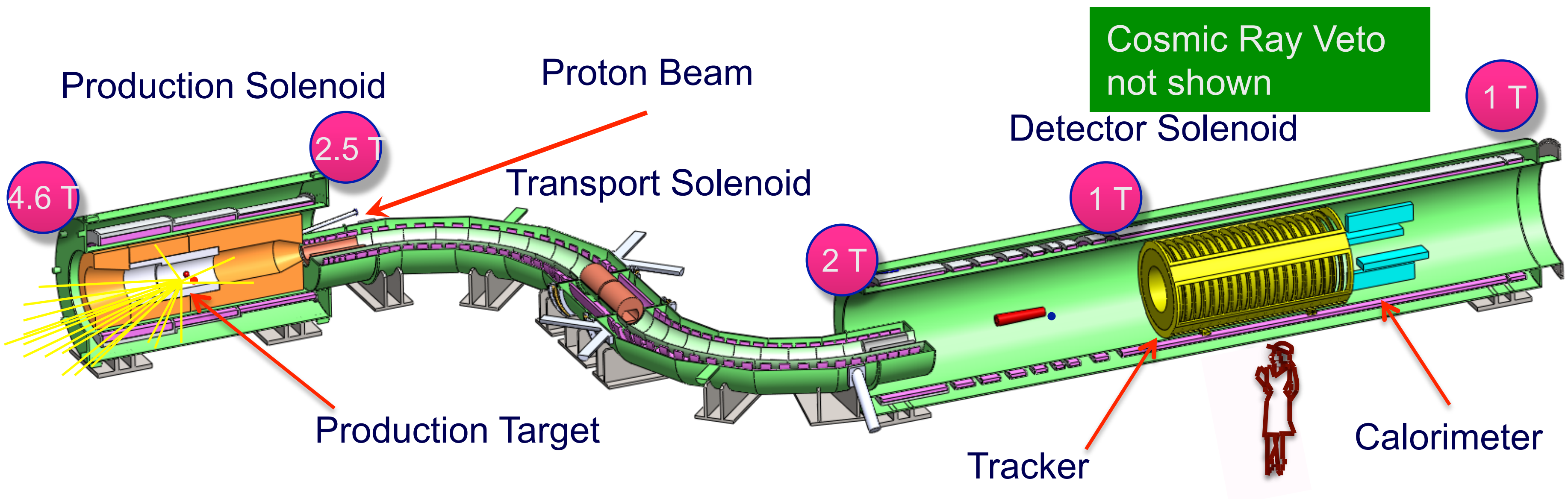
Resolution at 105 MeV matters!

Mu2e on the whiteboard



Mu2e experimental concept

This experiment is in R&D and Pre-Construction Mode with CD1 approval

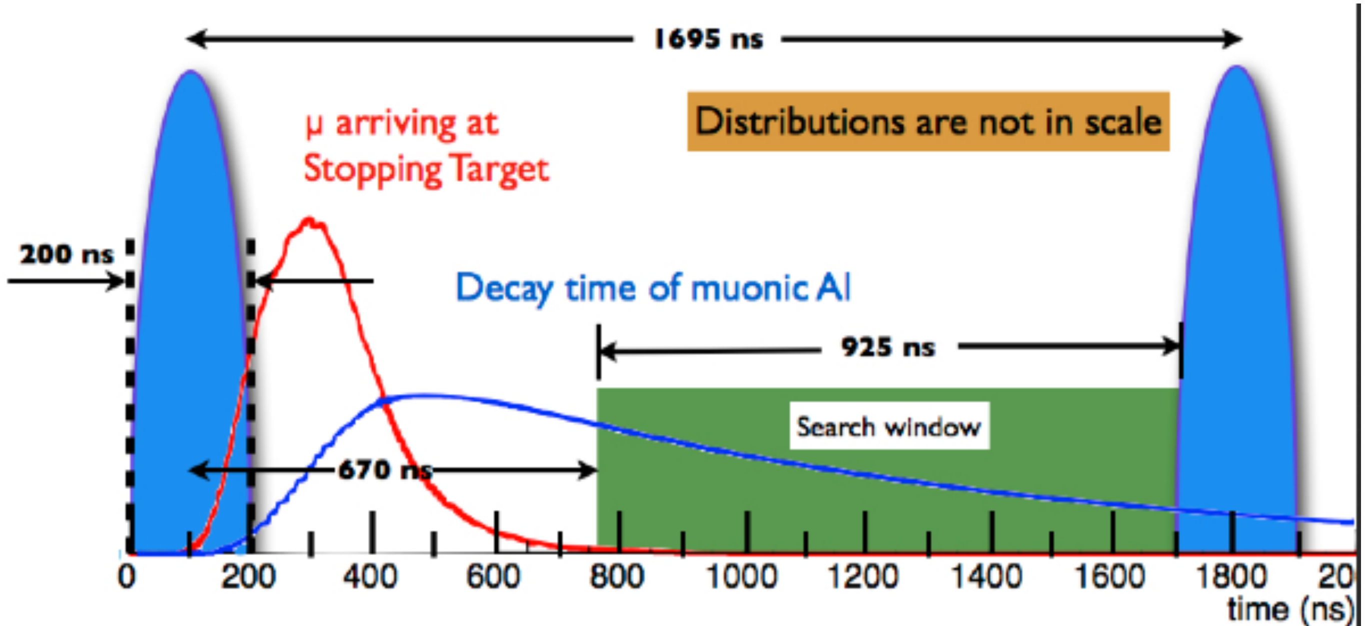


From R. Ray

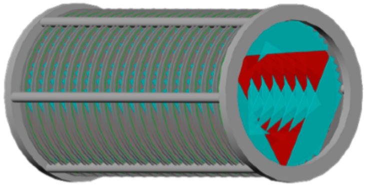
Mu2e: Pulsed beam for background reduction

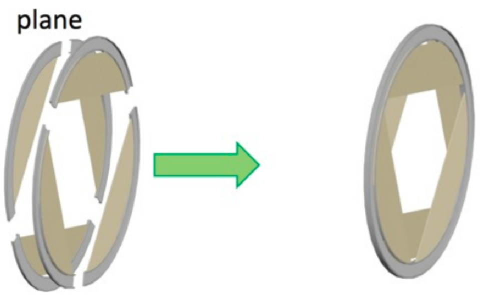
Fermilab

- Beam electrons, μ and π produce backgrounds:
  - Decay in flight $\mu^- \rightarrow e^- \nu_e \nu_\mu$
  - $\pi^- N \rightarrow \gamma N'$ and then $\gamma N \rightarrow e^- e^+ N$
- Solution:
  1. Narrow 200 ns proton pulse with no more protons after that
  2. Wait ~700 ns until all beam background is gone (pions decay fast)
  3. Measure for 900 ns to detect 105 MeV electrons



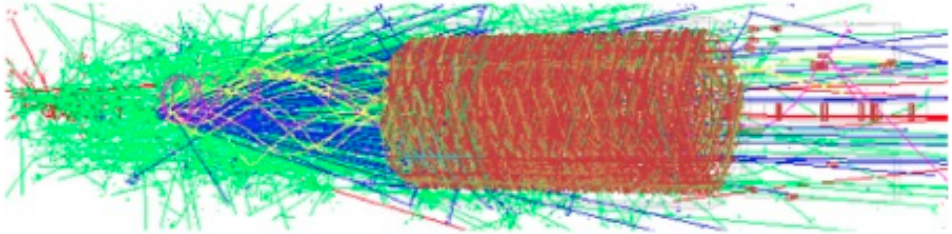
Mu2e: straw tracker and track finding



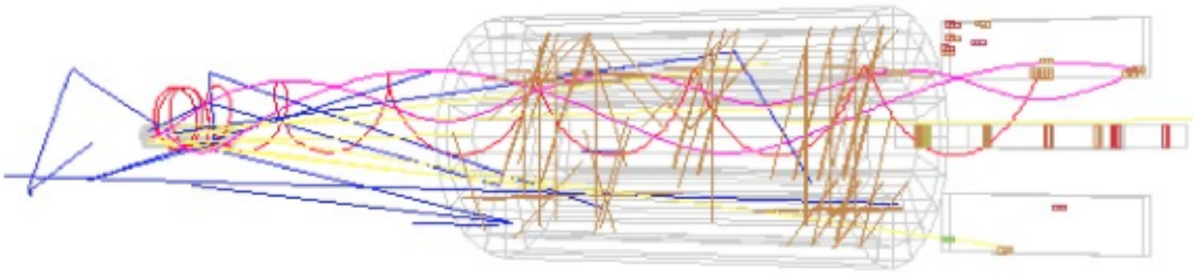


- 21,600 straws in vacuum (5mm diameter, 15 micron Mylar walls)
- Electronics and frame at outer radius
- Self supporting panels form planes

All tracks in search window after one proton pulse



All tracks in 50 ns time window: still a challenge to find the red track



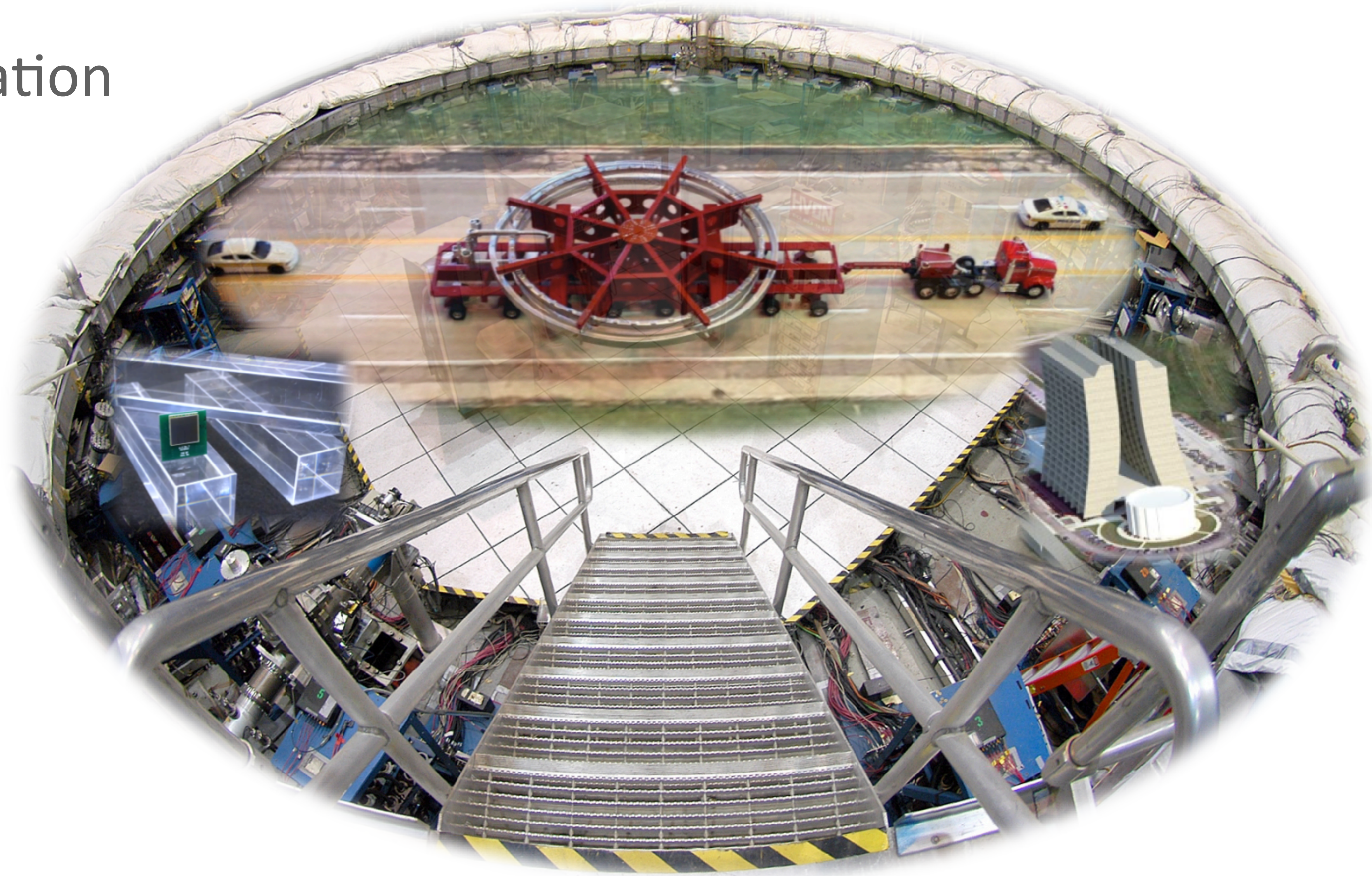
Mu2e background and goal

Background	Size	Uncertainty	Source of Uncertainty
Muon Decay-In-Orbit	0.22	± 0.06	Acceptance and Energy Loss Modeling
Antiproton RPC	0.10	± 0.05	Cross-Section and Acceptance
Cosmic Rays	0.05	± 0.05	Statistics of Sample
Radiative Pion Capture	0.03	± 0.007	Acceptance and Reconstruction
Muon Decay-in-Flight	0.01	± 0.003	Cross-Section, Acceptance and Modeling
Pion Decay-in-Flight	0.003	± 0.0015	same
Beam Electrons	0.0006	± 0.0003	same
Radiative Muon Capture	$< 2 \times 10^{-6}$	—	Calculation
Sum	0.41	± 0.08	**Added in Quadrature**

- 3 years to get 3.6 x 10^{20} protons (8kW proton beam)
- Estimate is a total of 0.41 background events
- Goal: Single event sensitivity < 2 x 10^{-17}
- If for example $R_{\mu e} = 10^{-15}$: Mu2e would see 40 events

The new g-2 experiment at FNAL

- Motivation
- Experimental technique
- Muon g-2 at Fermilab

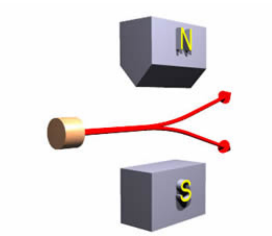


Let's enter the stage of g-2...

A primer: Magnetic moments

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

- Classical current loop in B field: g = 1
- Stern-Gerlach and atomic spectr.: g ≈ 2

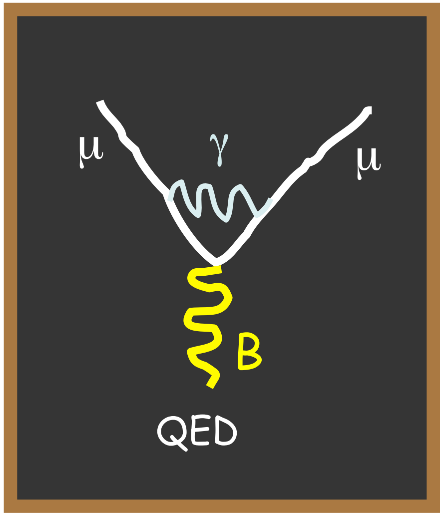


- Dirac theory of elem. spin ½ particle: g ≡ 2
- Kusch and Foley:

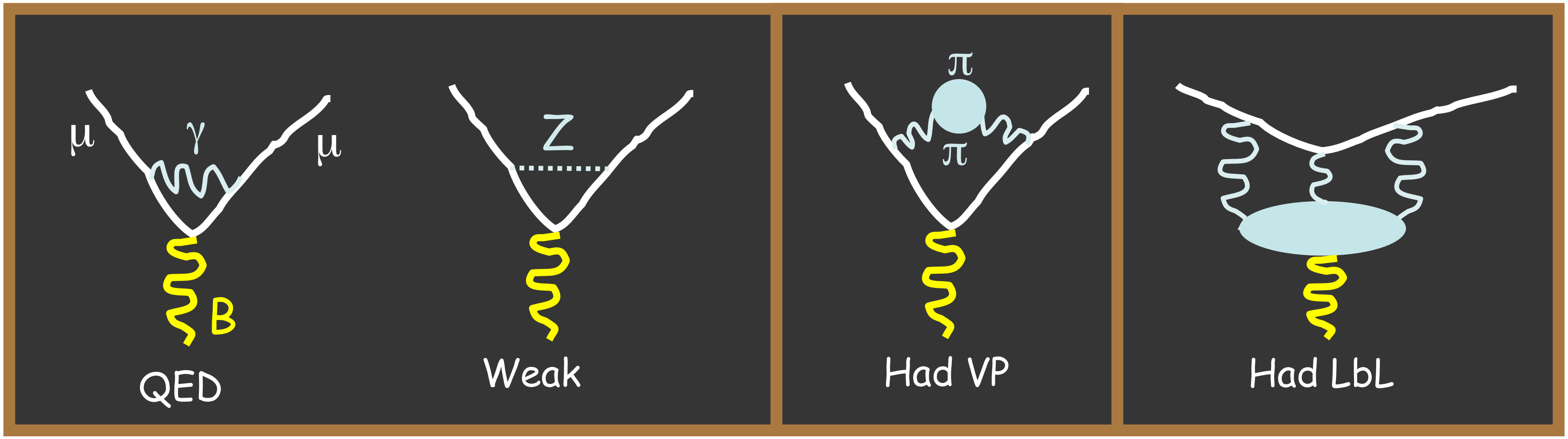
$$g_e = 2.00238(6) \neq 2$$

- Schwinger's blackboard:

$$g_e = 2 + \alpha/\pi = 2.00232$$



g-2 on the Standard Model blackboard



Known well beyond current experimental precision

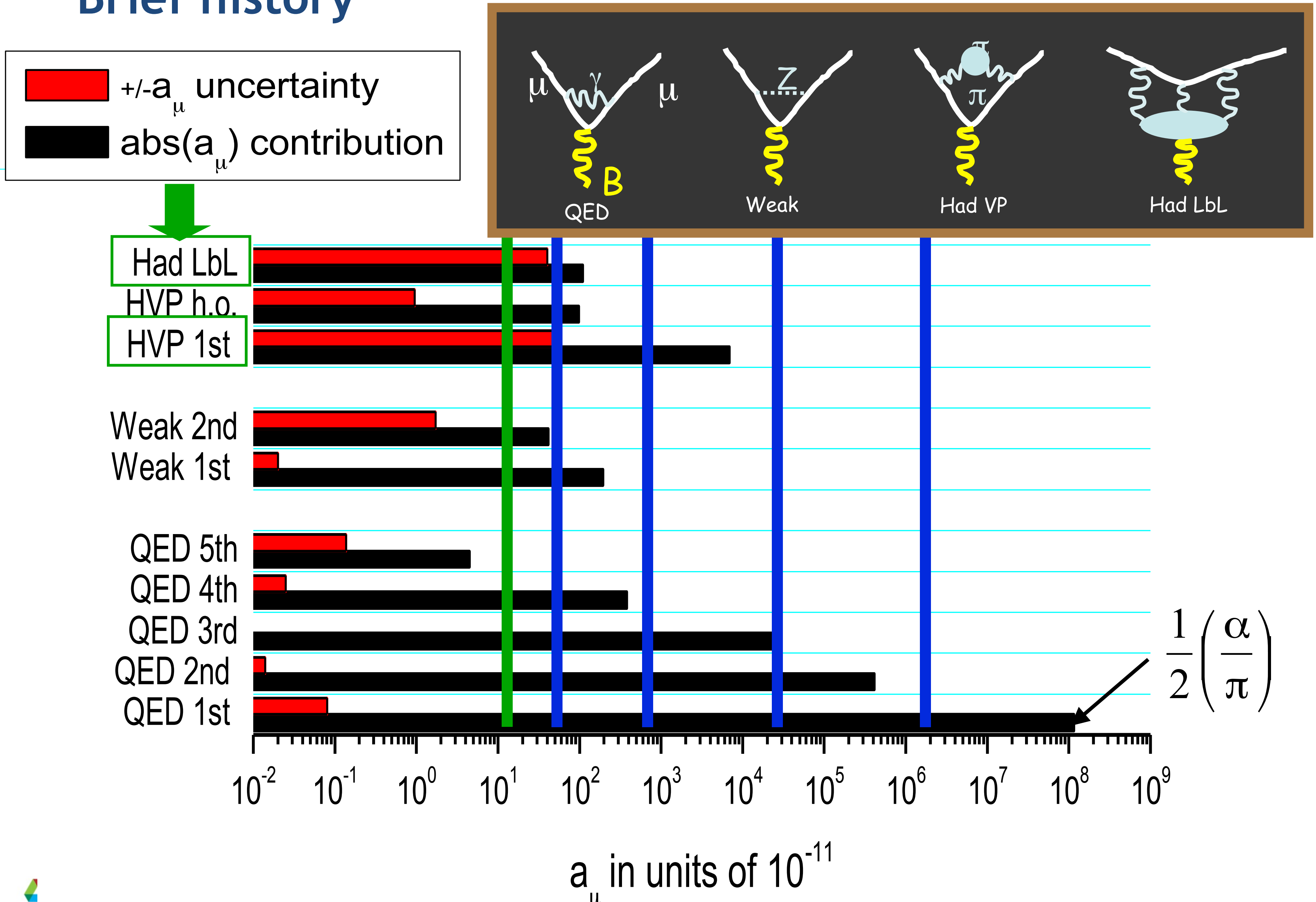
Known slightly better than current experimental precision – needs work

Anomalous magnetic moment: $a_\mu = (g_\mu - 2)/2$

$$a_\mu^{Expt.} = a_\mu^{SM} + a_\mu^{New\ Physics}$$

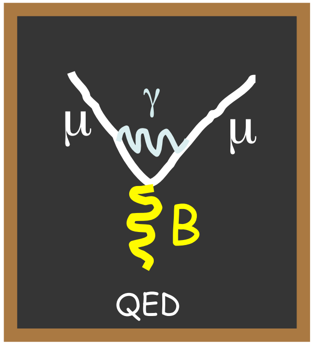
- Enhanced sensitivity $(m_\mu / m_e)^2 \approx 43{,}000$!
- Muon lives long enough (2.2 μs) !

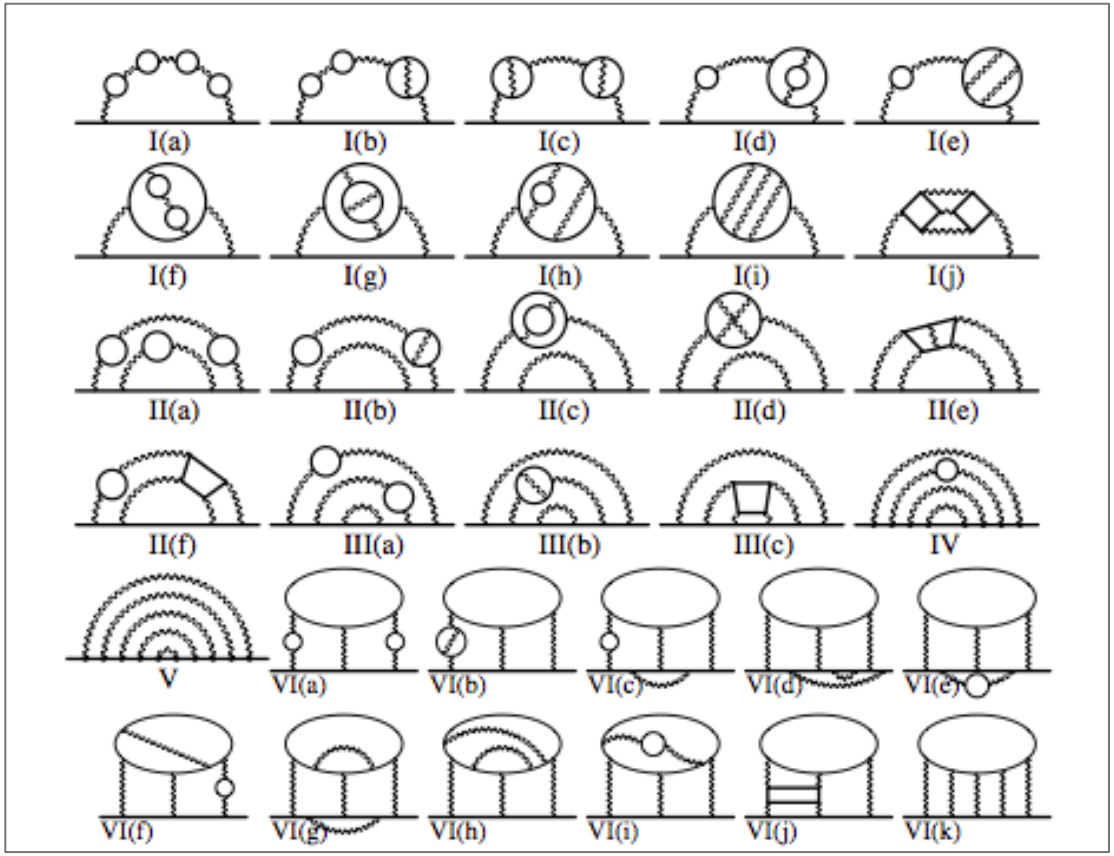
Brief history



QED calculated to 10th order

Some of the thousands of diagrams contributing to a_μ at 10th order:



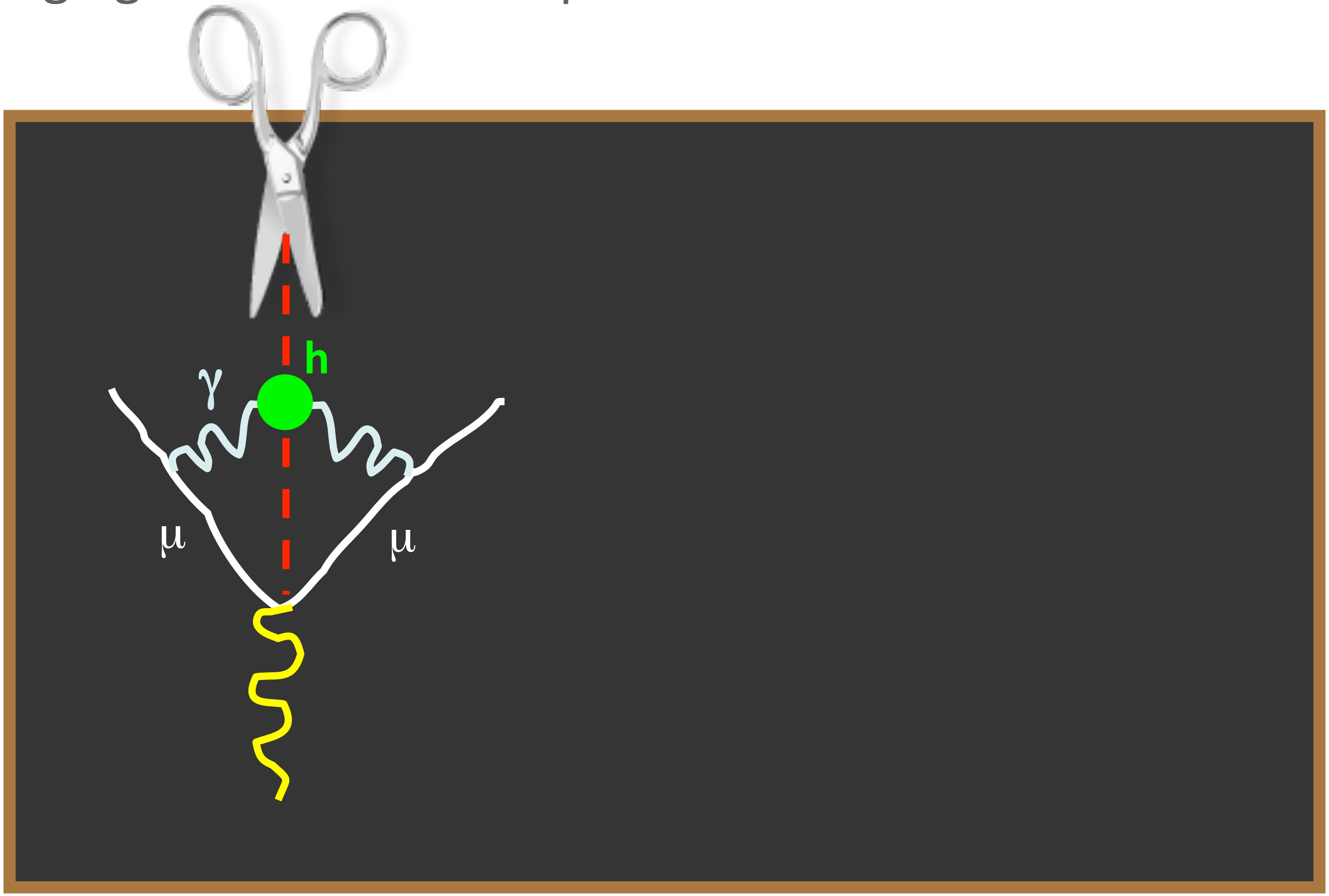


T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, Phys. Rev. Lett. 109, 111808 (2012)

Warning: Professional calculator at work. Do not attempt at home!

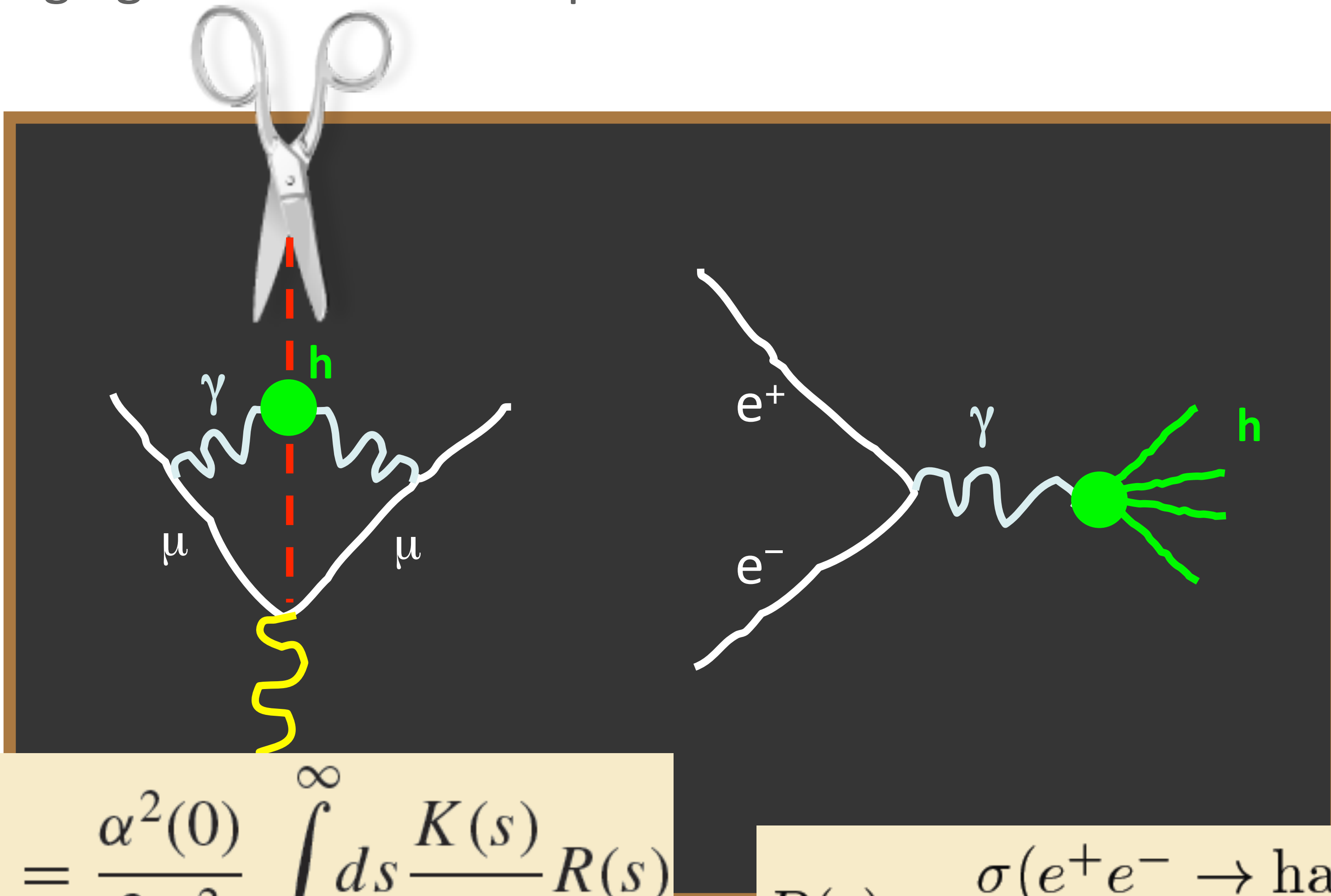
Hadronic vacuum polarization

Challenging but can link to experimental data!



Hadronic vacuum polarization

Challenging but can link to experimental data!



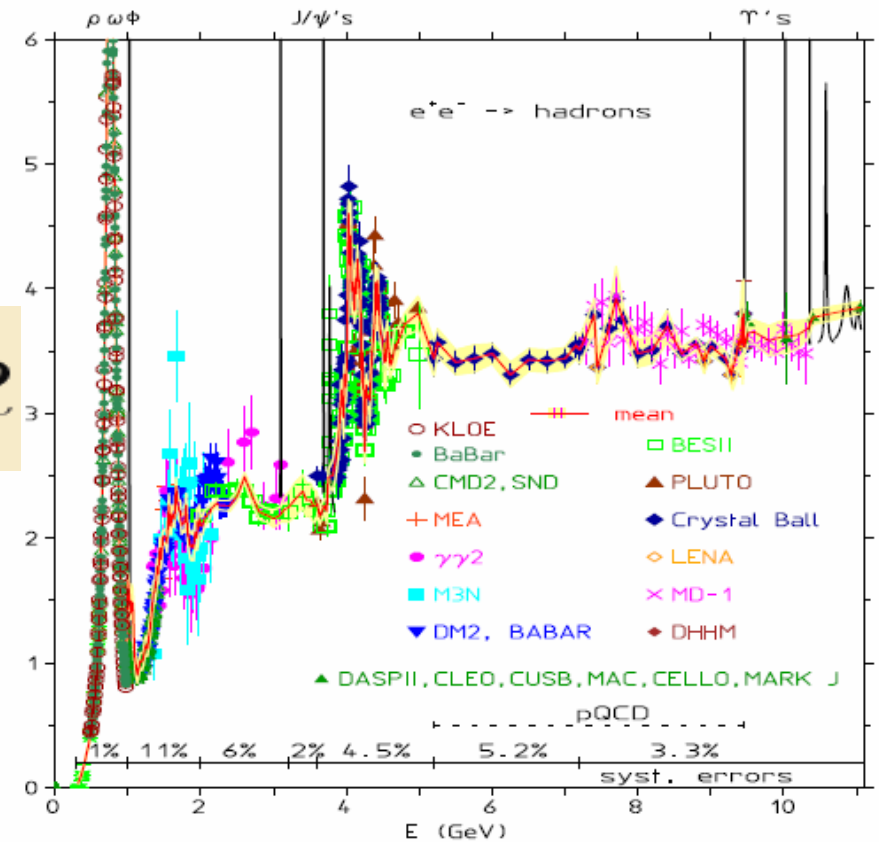
$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mathrm{muons})}$$

Hadronic vacuum polarization

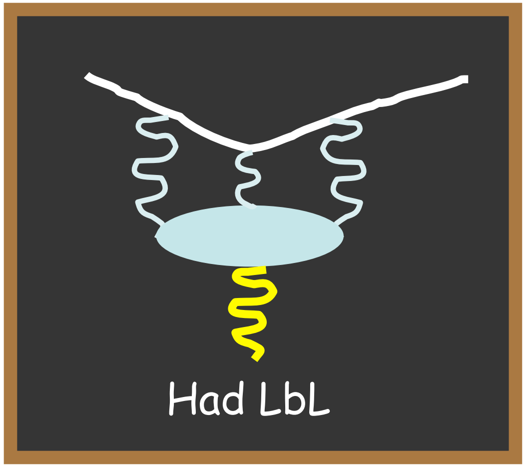
$$a_\mu^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

R



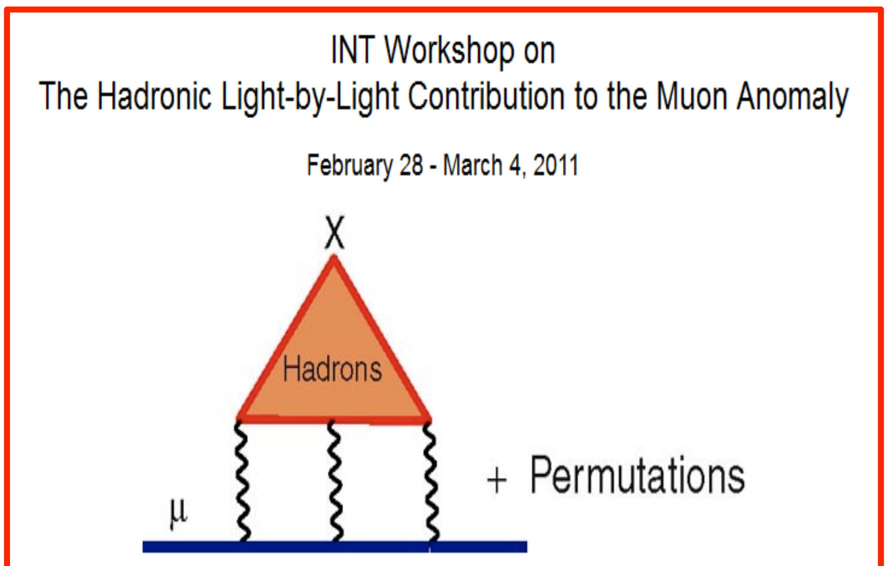
- A lot of precision data already available from many experiments
- Future improvements from VEP-2000, KLOE, BaBar, Belle, BES-III, ...

Hadronic Light-by-Light



Needs to be evaluated by theory

1. Model dependent calculations
2. Lattice-QCD is progressing (both for HVP and HLbL)
3. Some indirect data from KLOE to constrain models



$a_\mu(\mathrm{HLbL}) = (105 \pm 26) \times 10^{-11}$

Hadronic contributions to the muon anomalous magnetic moment: Strategies for improvements of the accuracy of the theoretical predictions
Mar 31 - Apr 4, 2014
Coordinater: F. Jegerlehner

Current status of a_μ in Standard Model

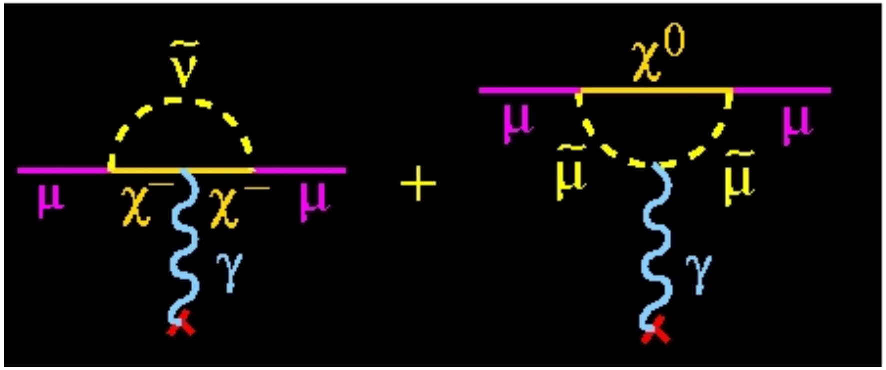
	Value (x 10^{-11})
QED	116 584 718.951 ± 0.009 ± 0.019 ± 0.007 ± 0.077
HVP (lo)	6949 ± 42
HVP (ho)	-98.4 ± 0.7
HLBL	105 ± 26
EQ	154 ± 1
Total SM	116 591 802 ± 49

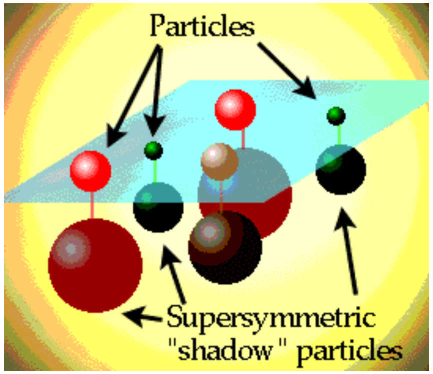
$$a_\mu^{\text{Expt.}} - a_\mu^{\text{SM}} = (260 \pm 78) \times 10^{-11} \quad (3.3\ \sigma)$$

- New E989 experiment will reduce experimental uncertainty by a factor of 4 to 16 x 10^{-11} (0.14 ppm)
- If current discrepancy remains this would yield >5σ
- Together with theory improvements could give >8σ

What about the new physics?

One example: SUSY



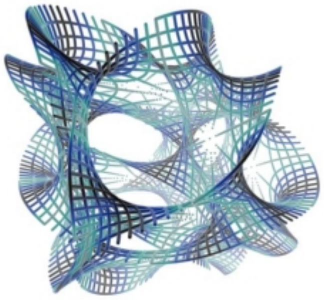


$$a_\mu(\mathrm{SUSY}) \simeq (\mathrm{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

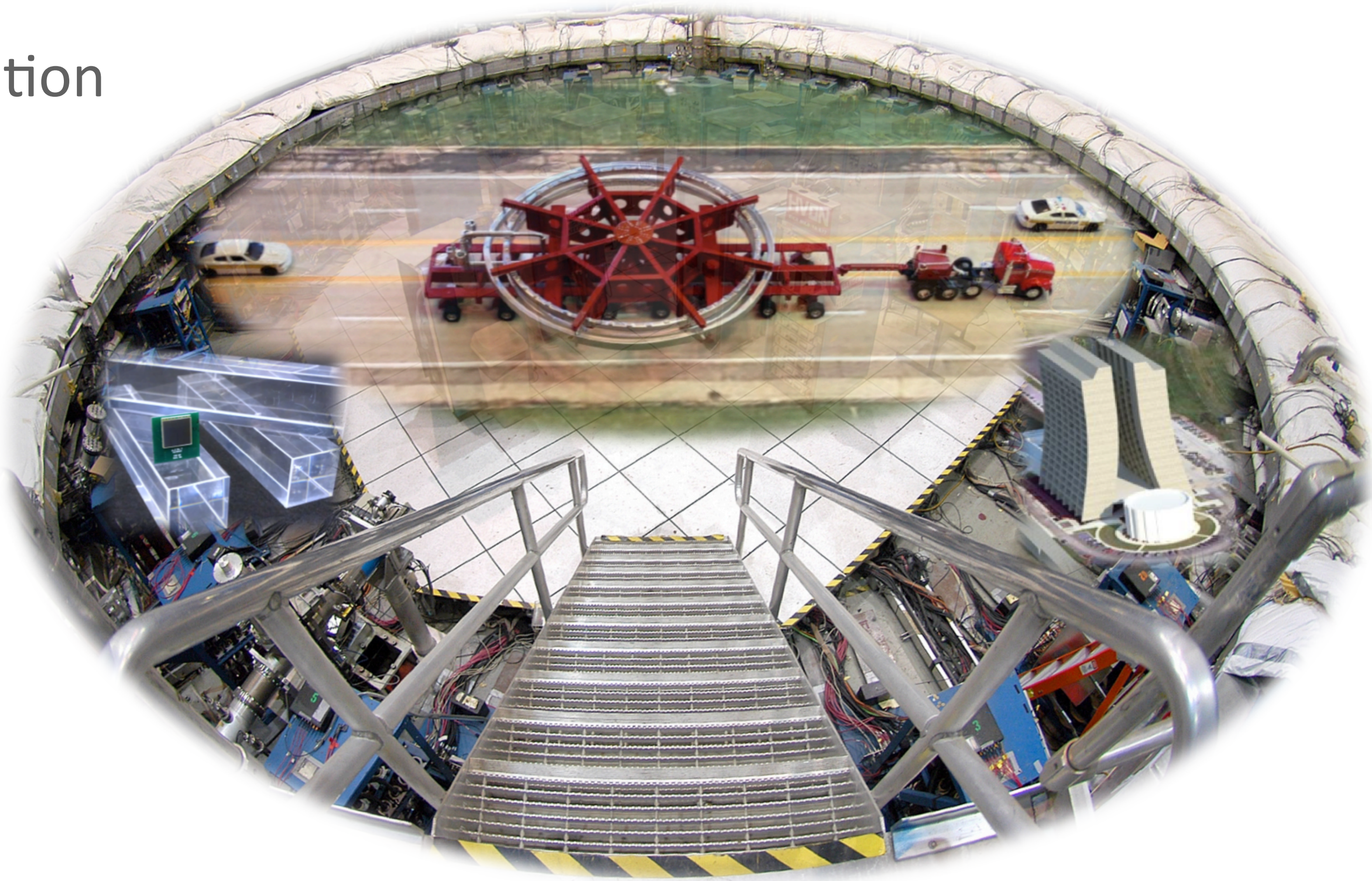
Another example: Universal Extra Dimensions (1 UED)

$$a_\mu(1\ \mathrm{UED}) \approx -13 \times 10^{-11}$$



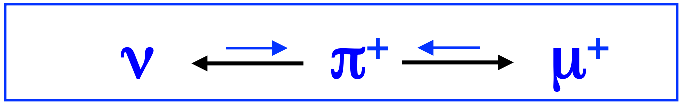
Outlook

- Motivation
- Experimental technique



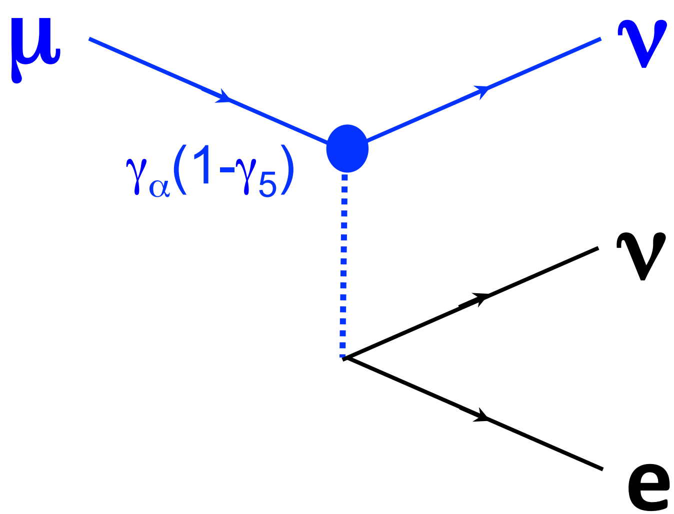
Remember: Two important ingredients

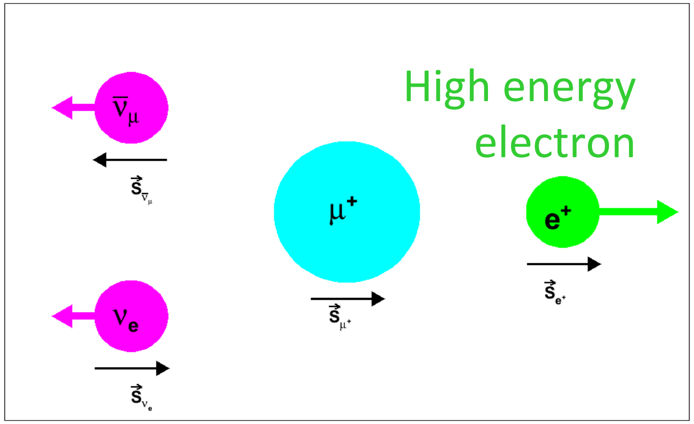
1. Polarized muons from pion decay



2. Muon decay is self-analyzing

$$\mu \rightarrow e\,\nu\,\nu$$





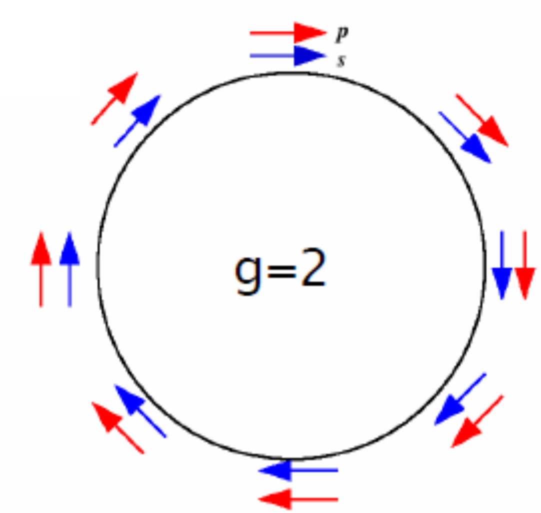
Muons in a storage ring

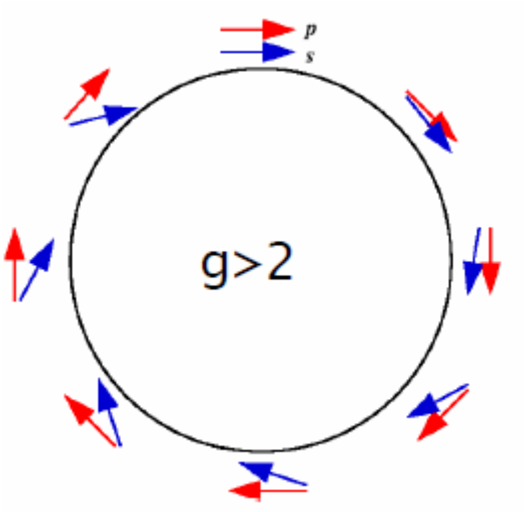
Cyclotron frequency ω_C: $$\omega_c = \frac{e}{m\,\gamma} B$$

Spin precession frequency ω_S: $$\omega_S = \frac{e}{m\,\gamma} B\,(1 + \gamma\, a_\mu)$$

Larmor + Thomas precession

$$\omega_a = \omega_S - \omega_C = e/m\ \mathbf{a_\mu}\ B$$





Muons in a storage ring

$$\omega_a = e/m\, a_\mu\, B$$

Measuring the anomalous moment a_μ requires both

1. the spin precession frequency ω_a
2. the magnetic field **B**

We can rewrite this to:

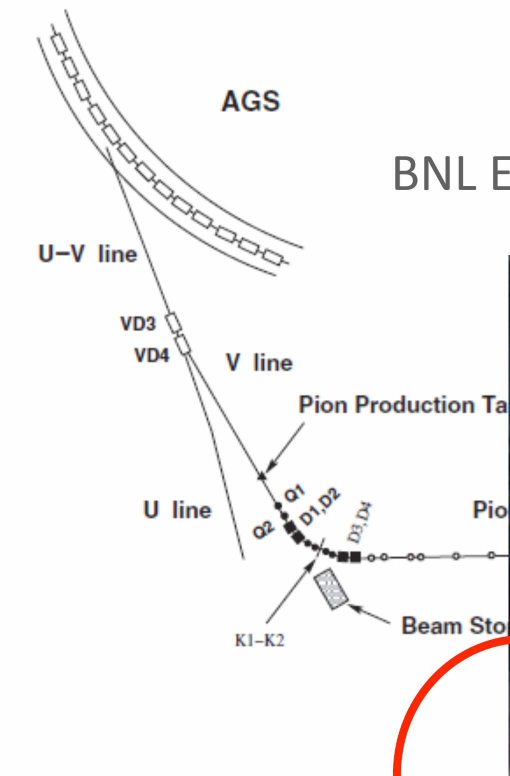
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

ω_p: Proton Larmor frequency measured in the same B field

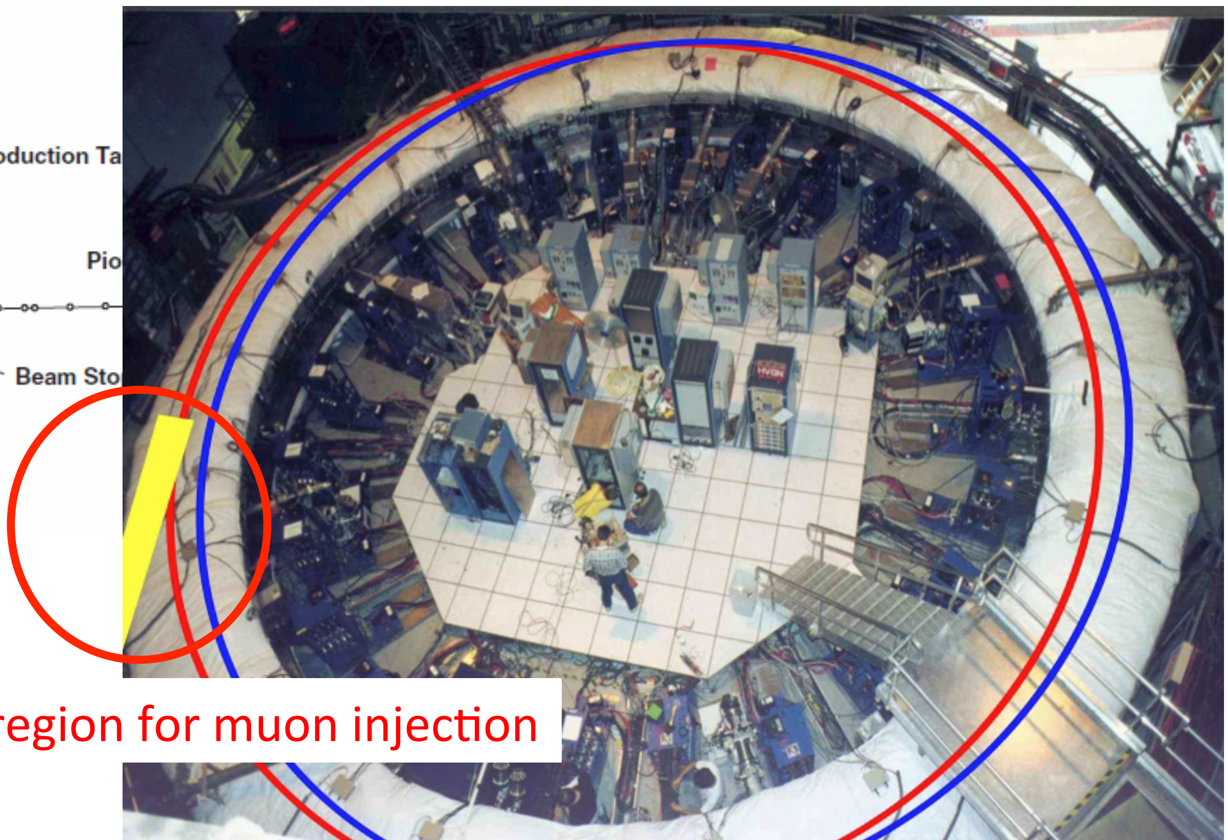
ω_a: Spin precession frequency measured with decay positrons

μ_μ/μ_p: Ratio known from muonium hyperfine measurement

Muon injection and kicker

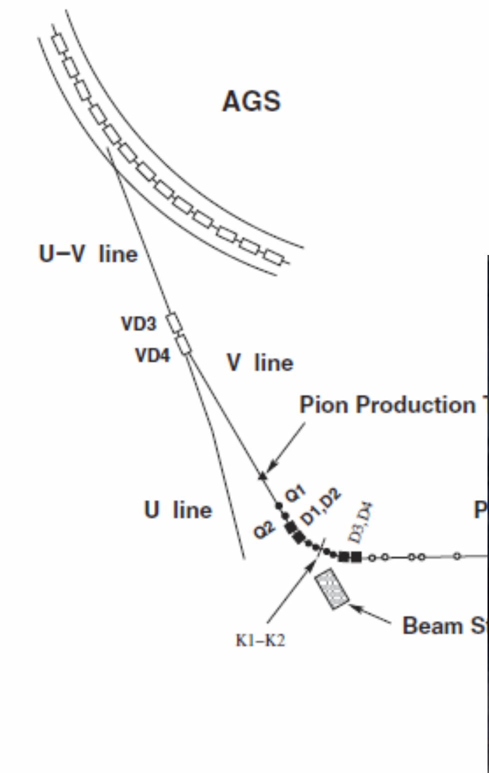


BNL E821

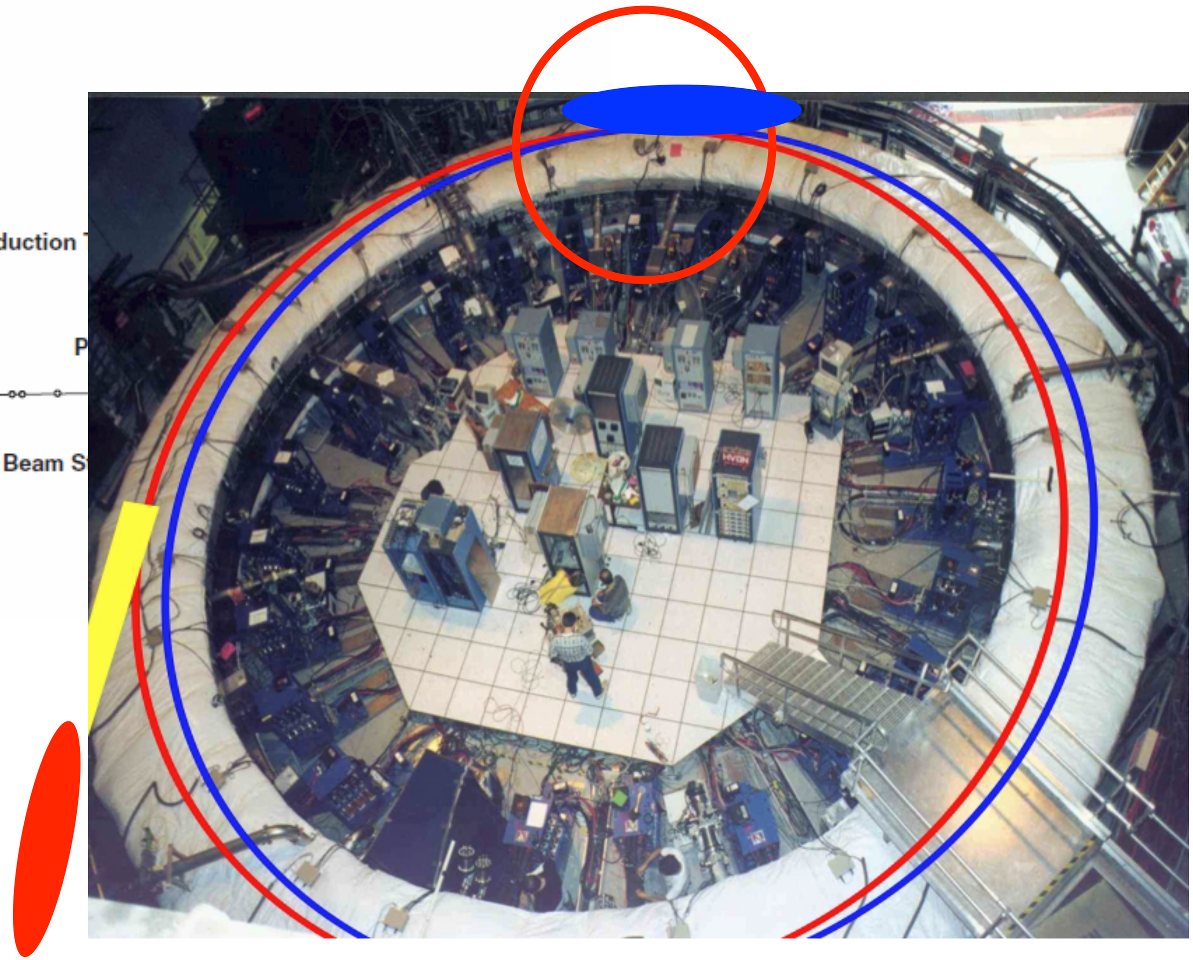


Need field free region for muon injection

Muon injection and kicker



Need to kick muons to bring on stable orbit



Vertical focusing with electrostatic quadrupoles

Fermilab

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

Term vanishes at magic momentum!

E field introduces new term

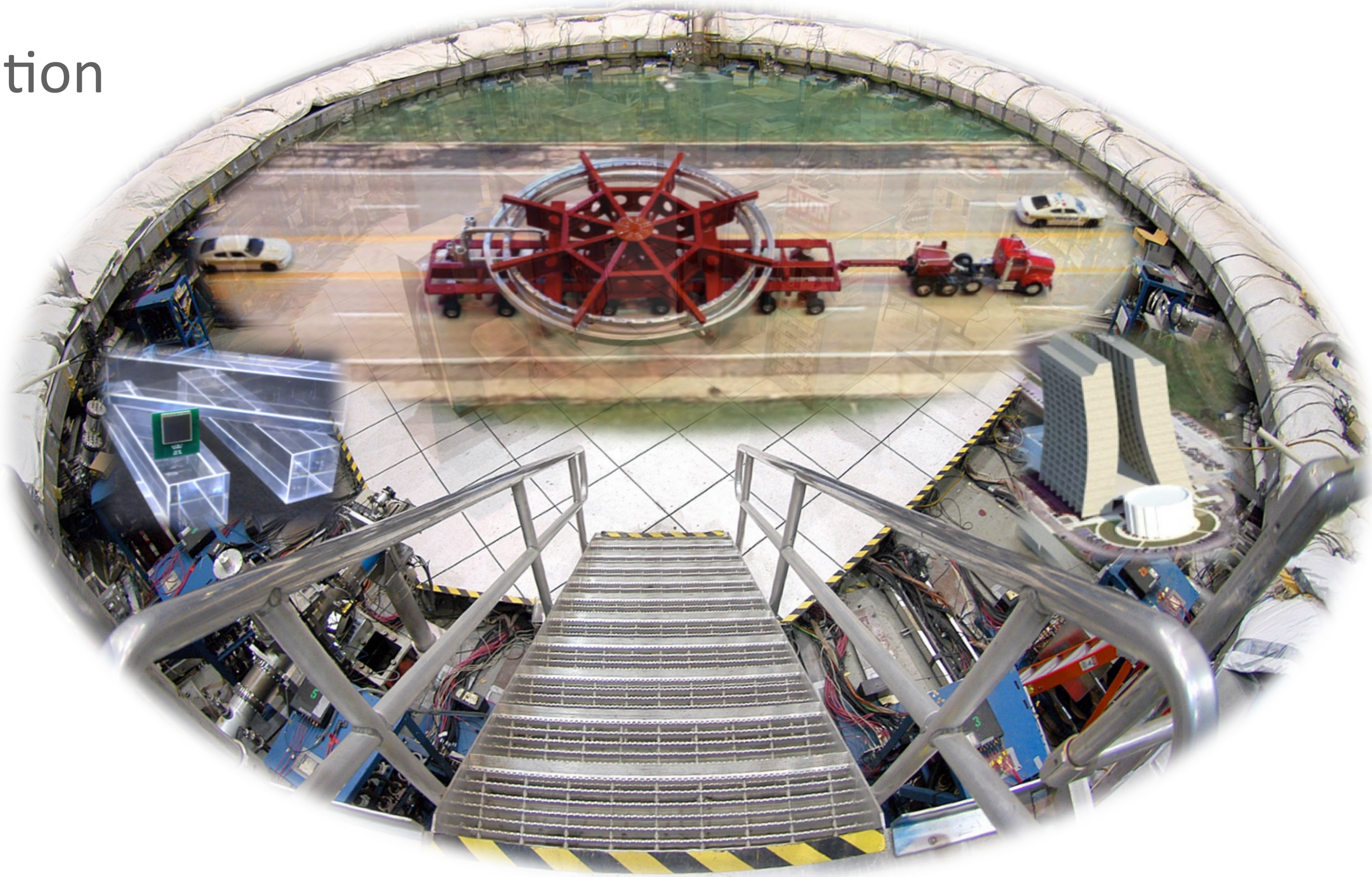
Solution

Magic momentum with $\gamma = 29.3$ ($p = 3.09$ GeV/c)

So far we have polarized stored muons in the ring.
But how are we going to measure ω_a and **B** at Fermilab?

Outlook

- Motivation
- Experimental technique
- Muon g-2 at Fermilab



Roadmap from BNL E821 to E989 at Fermilab

1. Bring storage ring from Long Island to the Midwest
2. Use Fermilab infrastructure to get **20 times more muons** for statistical error of **0.1 ppm**
3. Upgrade and build new systems to reduce systematics to **0.07 ppm** for both ω_a and **B**
4. Overall improvement by factor of 4 to **0.14 ppm**

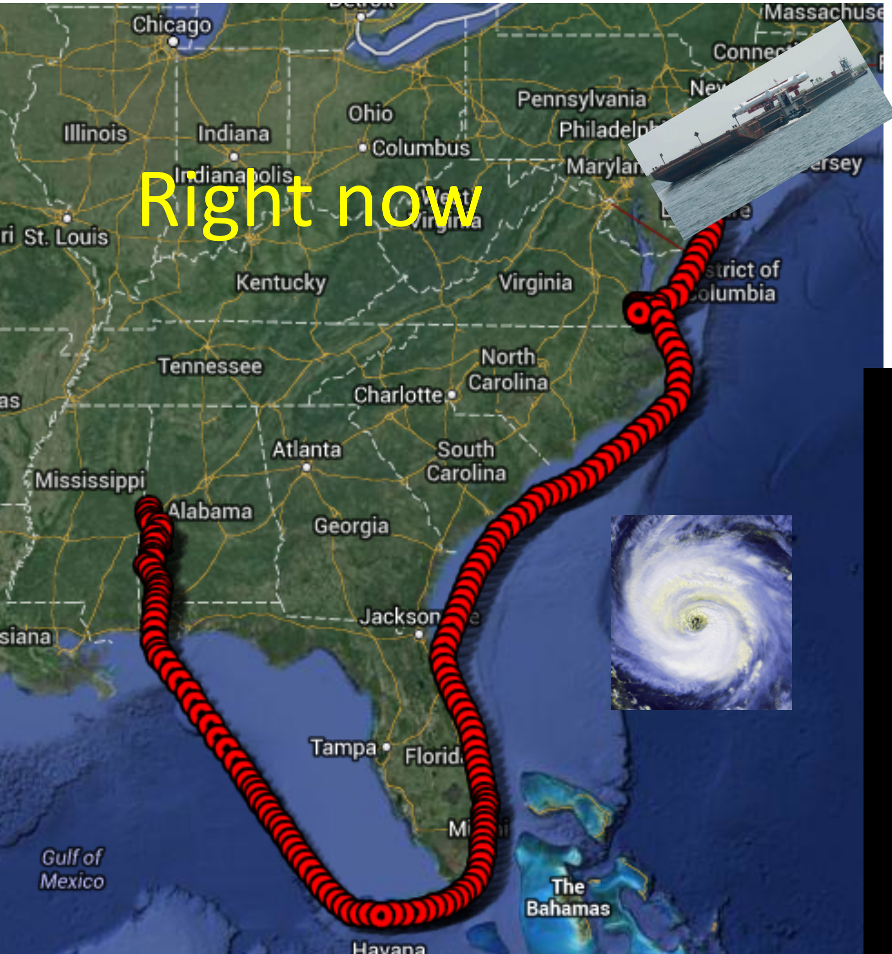
Transporting the ring to Fermilab

Fermilab

Transporting the ring to Fermilab

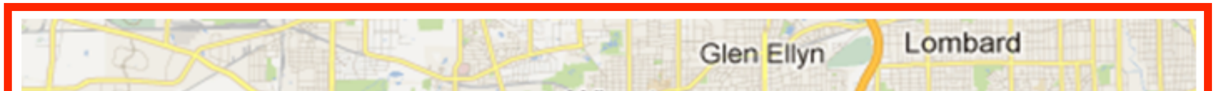
Transporting the ring to Fermilab

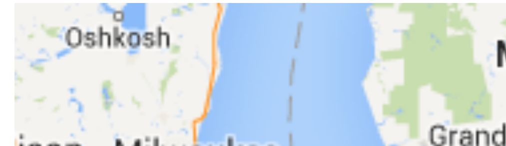
Transporting the ring to Fermilab



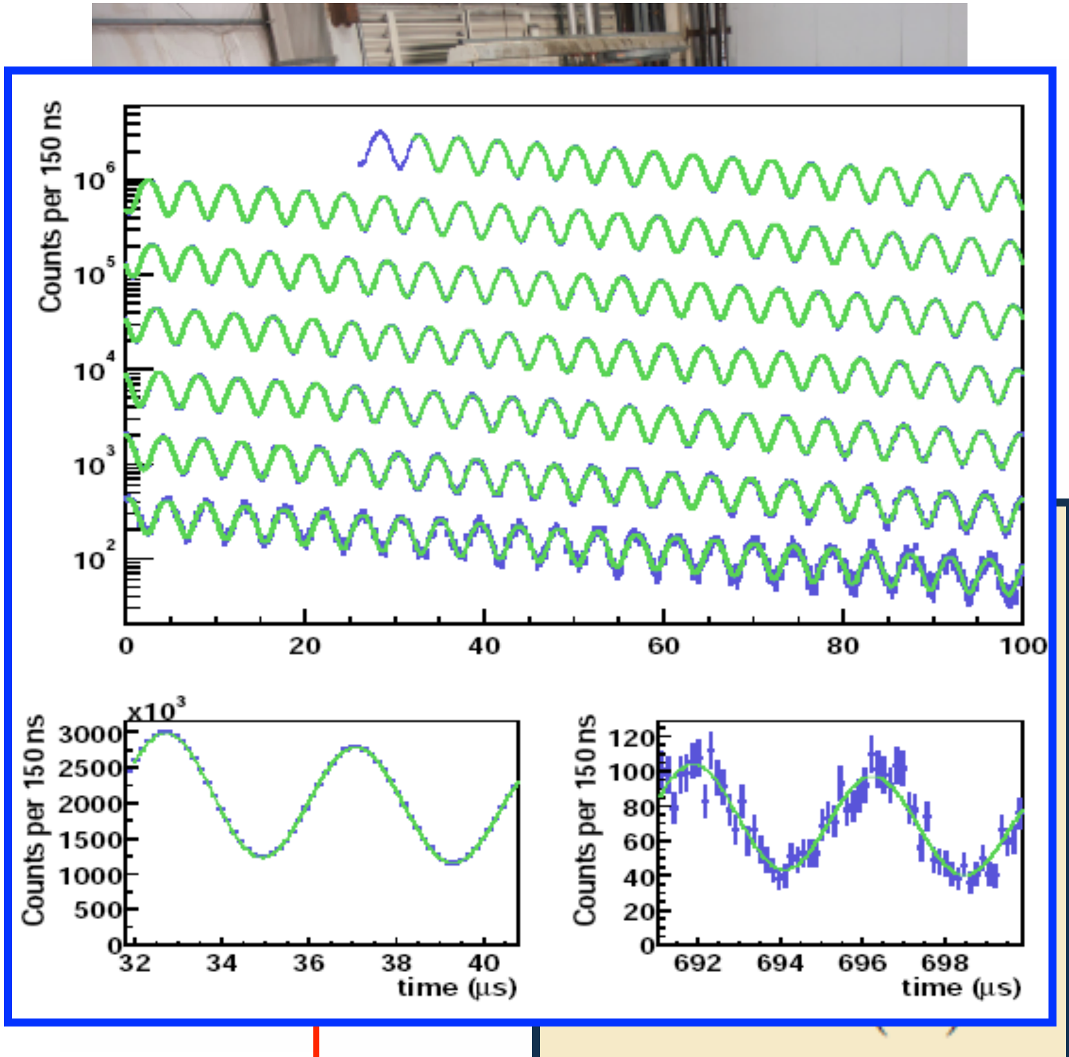
Movie credit: Volodya Tishchenko (BNL)

Transporting the ring to Fermilab





Measuring the spin precession frequency ω_a

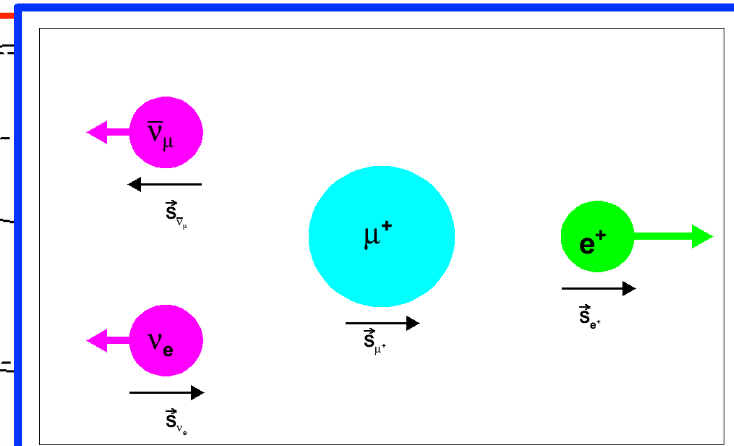


24 calorimeter stations

Scallop vacuum chamber

Full waveform digitized

Fit time spectrum of positrons with E > 1.8 GeV



Remember from yesterday: high energy positron carries spin information!

Improvements for measurement of ω_a

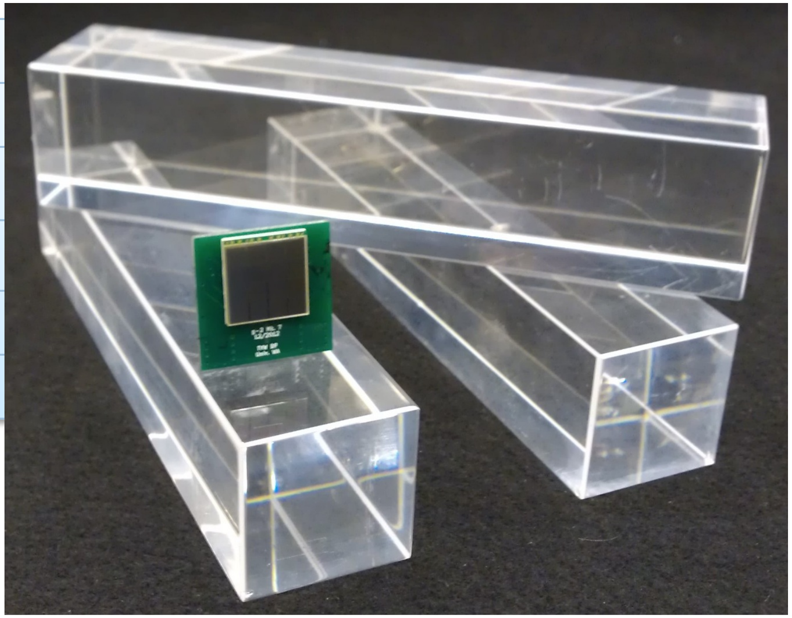
E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long be	
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

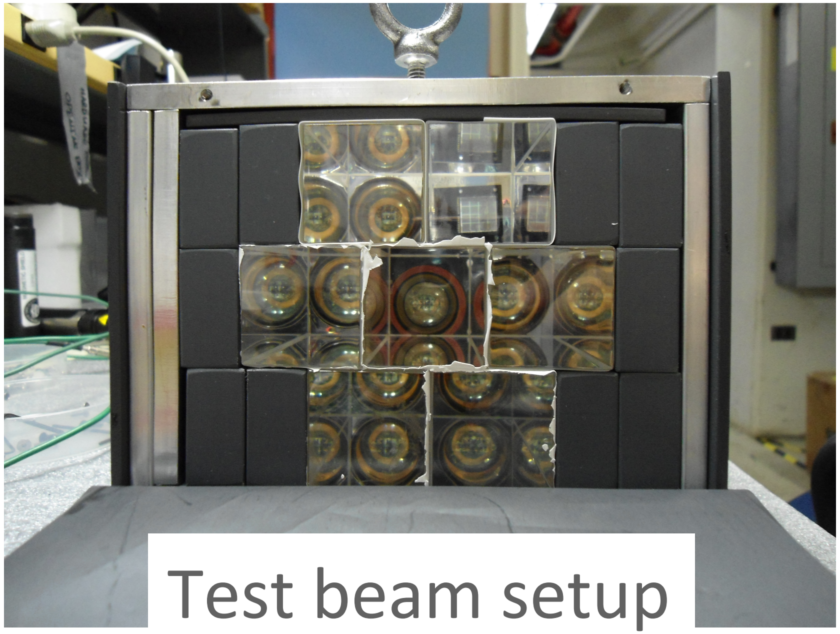
Let me just highlight the electron calorimeter

- New kicker to increase muon storage and better beam dynamics
- Upgrade quadrupoles for better beam dynamics
- Two in-vacuum straw trackers for measuring beam motion and muon EDM
- New 500 MSPS digitization and DAQ
- ...

New calorimeter: PbF_2 Cerenkov with SiPM

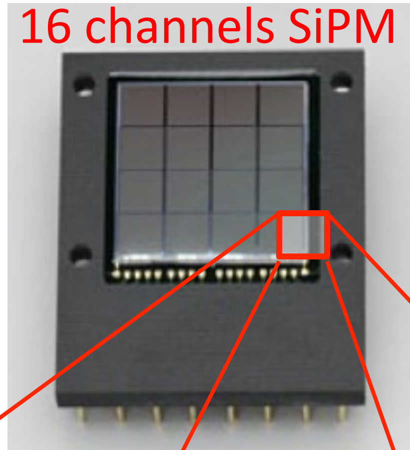
Size	2.5 x 2.5 cm
Thickness	14 cm (> 15 X_0)
Segmentation	6 x 9
Radiation length	0.93 cm
Moliere radius R_M	2.2 cm
Moliere radius R_M (Cerenkov)	1.8 cm

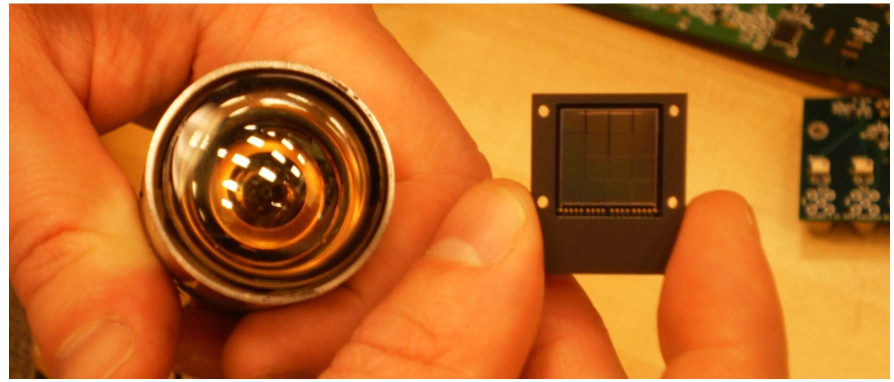




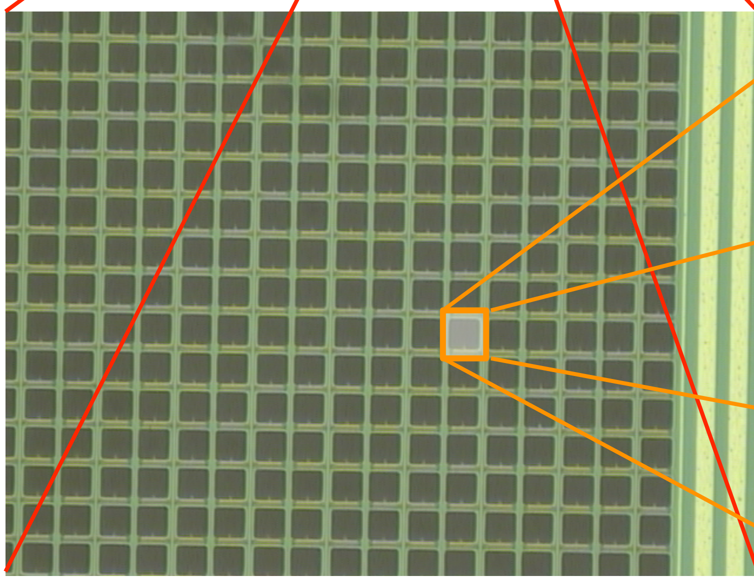
- PbF2 is dense
- Segmentation helps with pileup
- SiPM operate in magnetic fields
- Need very stable bias voltage

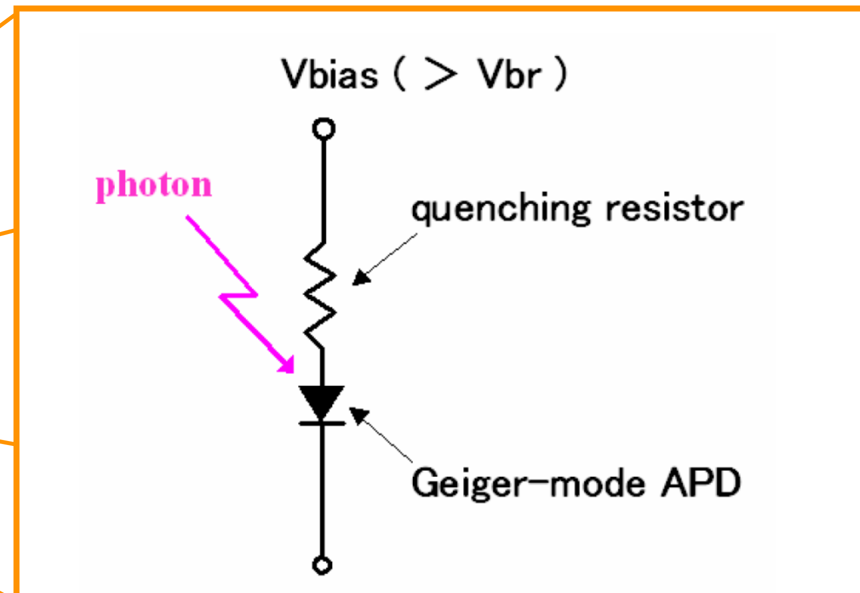
Everybody uses SiPMs today, so what are they?



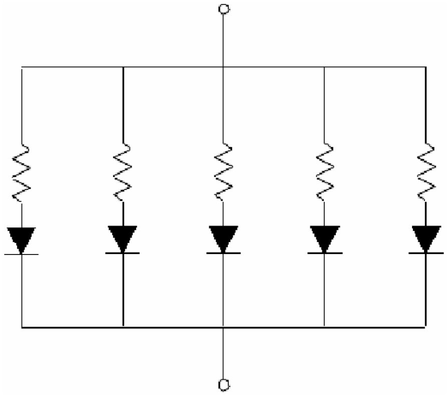


Size comparison with 1-inch photomultiplier left





Everybody uses SiPMs today, so what are they?

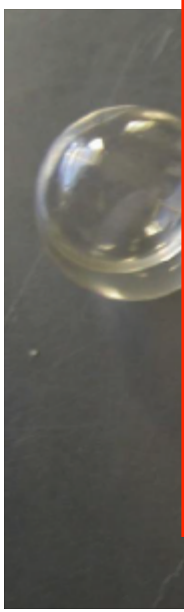


SiPMs are:

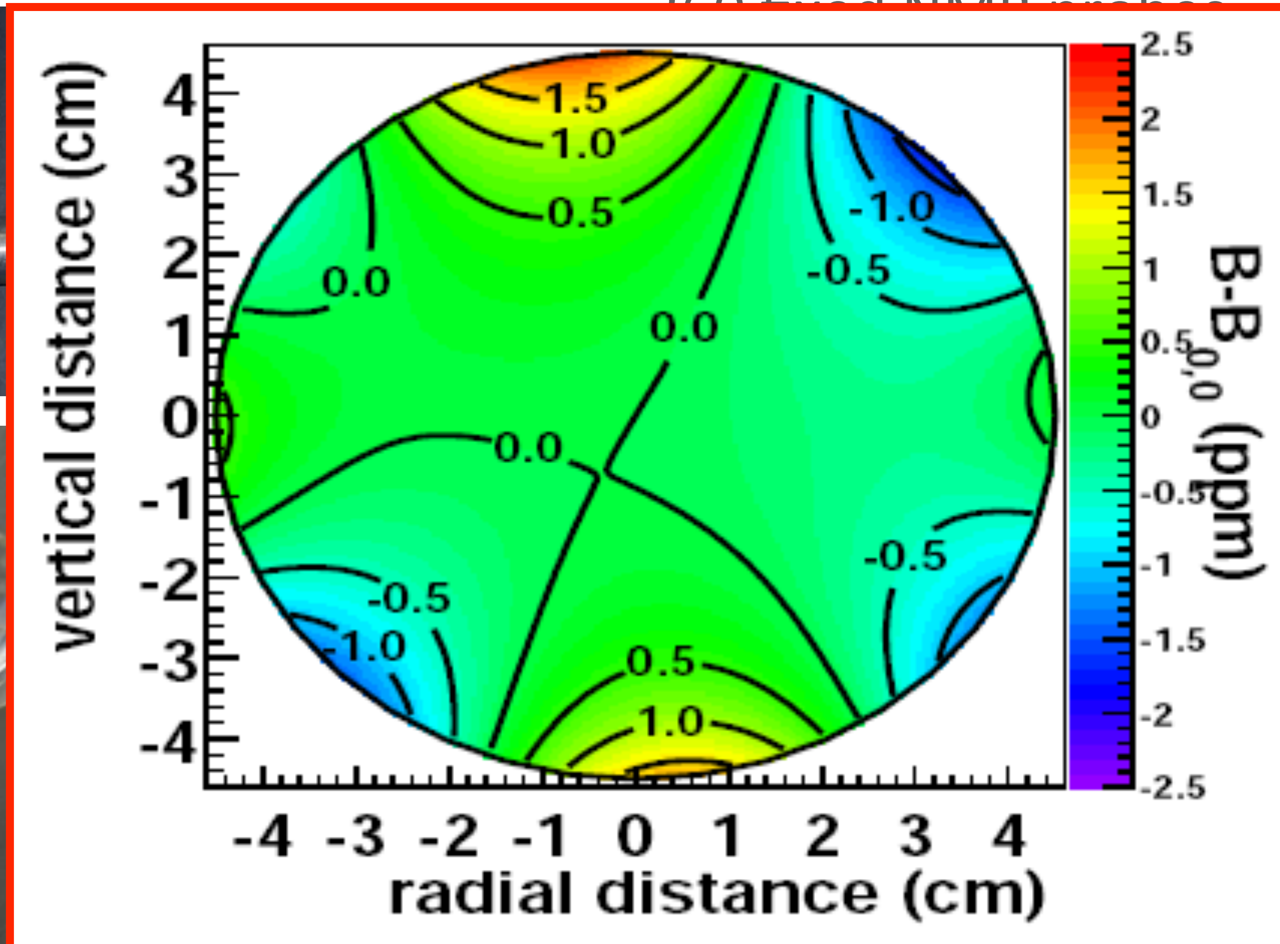
- a series of individual Geiger mode diodes (57,600 for the example)
- very easy to handle: compact, low bias voltage (< 70V)
- robust (don't burn like PMTs in bright light)
- immune to magnetic fields (PMTs need shielding)
- relatively cheap these days

Measuring the B field

Absolute calibration probe



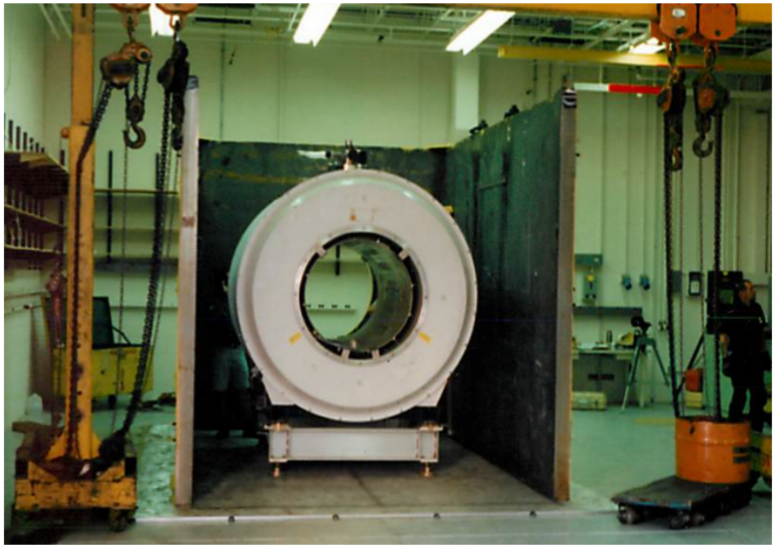
360 fixed NMR probes

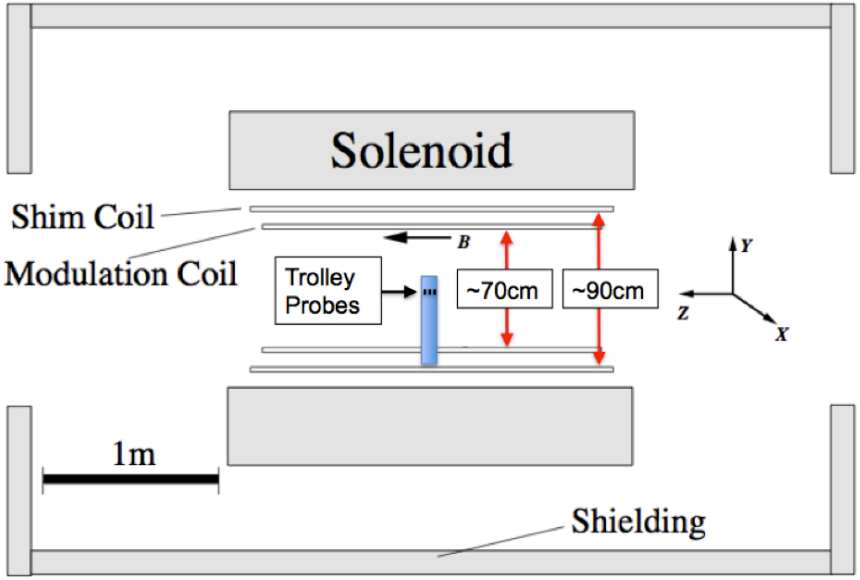


rolley to
imuthal

Improvements for measuring the B field in E989

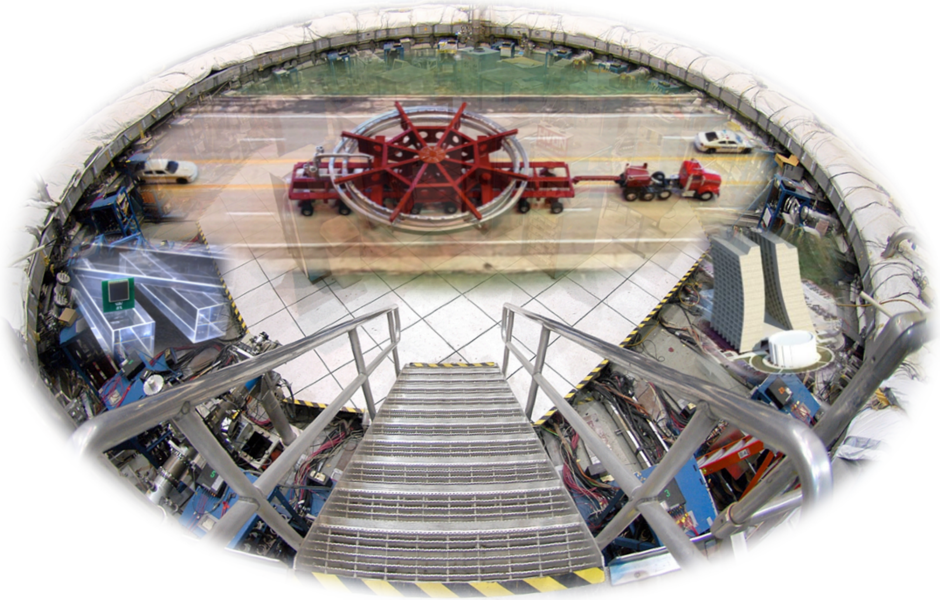
- Refurbish most of the existing NMR probes and equipment
- Add full waveform digitization of NMR signal
- Improve homogeneity of field with passive and active shims
- Better temperature control in new building
- Careful studies of systematic uncertainties with homogeneous and stable solenoid test magnet shipped to FNAL



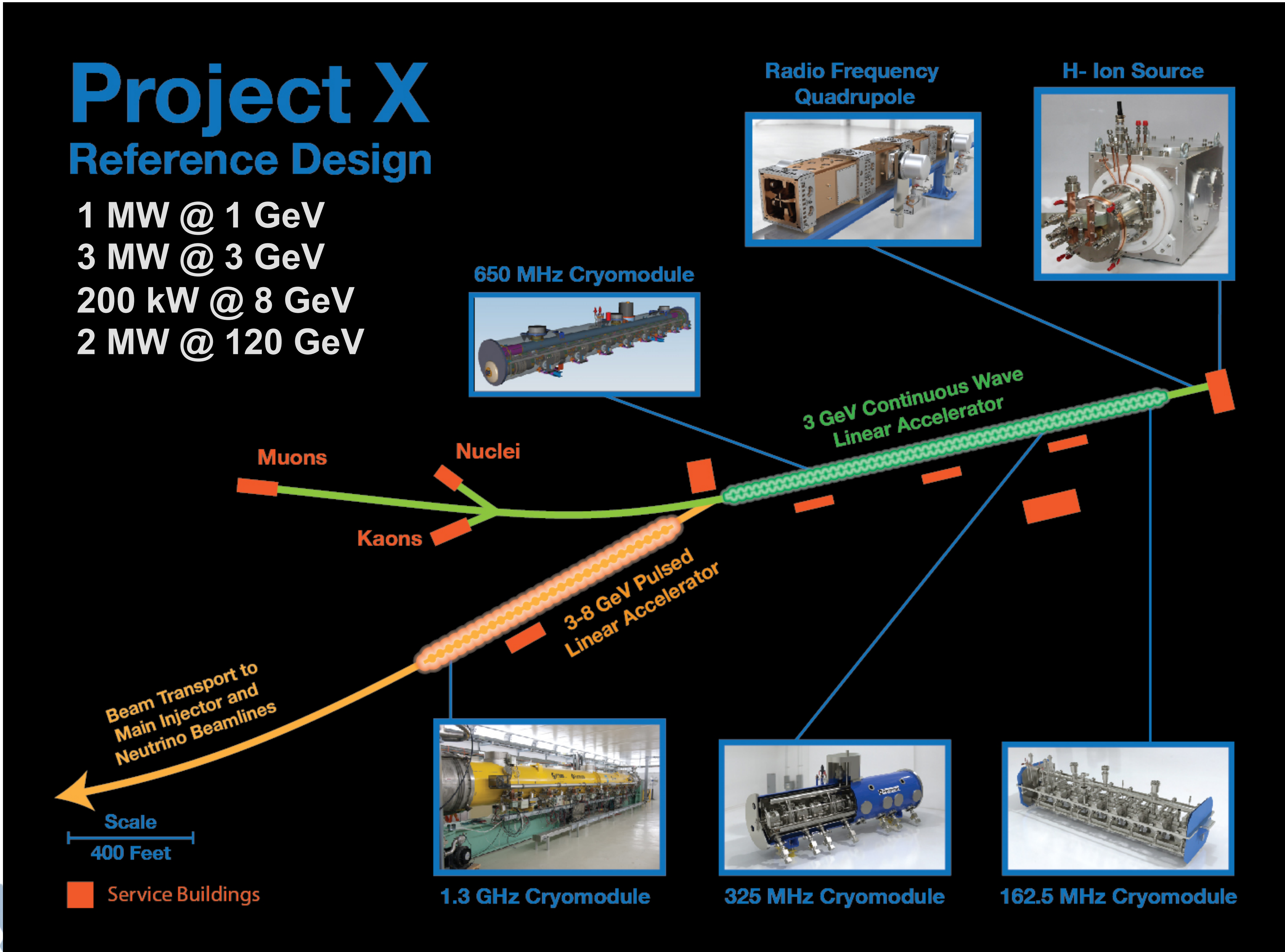


Summary

- Future E989 result will improve uncertainty by a factor of 4 to 0.14 ppm
- Many upgrades in accelerator, beamlines and detectors
- Active collaboration with balanced mix of former E821 and new members
- Textbook experiment with a well motivated physics case complementary to direct searches of BSM
- It's a great experiment to get involved NOW!



Looking into the future: Project X



Project X: Performance goals

Linac		
Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current (1/3 GeV)	2/1	mA
Linac pulse rate	CW	
Beam Power to 1 GeV program	1000	kW
Beam Power to 3 GeV program	2870	kW
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	4.3	msec
Cycles to Recycler/MI	6	
Particles per cycle to Recycler/MI	2.7×10^{13}	
Beam Power	340	kW
Beam Power to 8 GeV program	170	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.2	sec
Particles per cycle	1.5×10^{14}	
Beam Power at 120 GeV	2400	kW

simultaneous

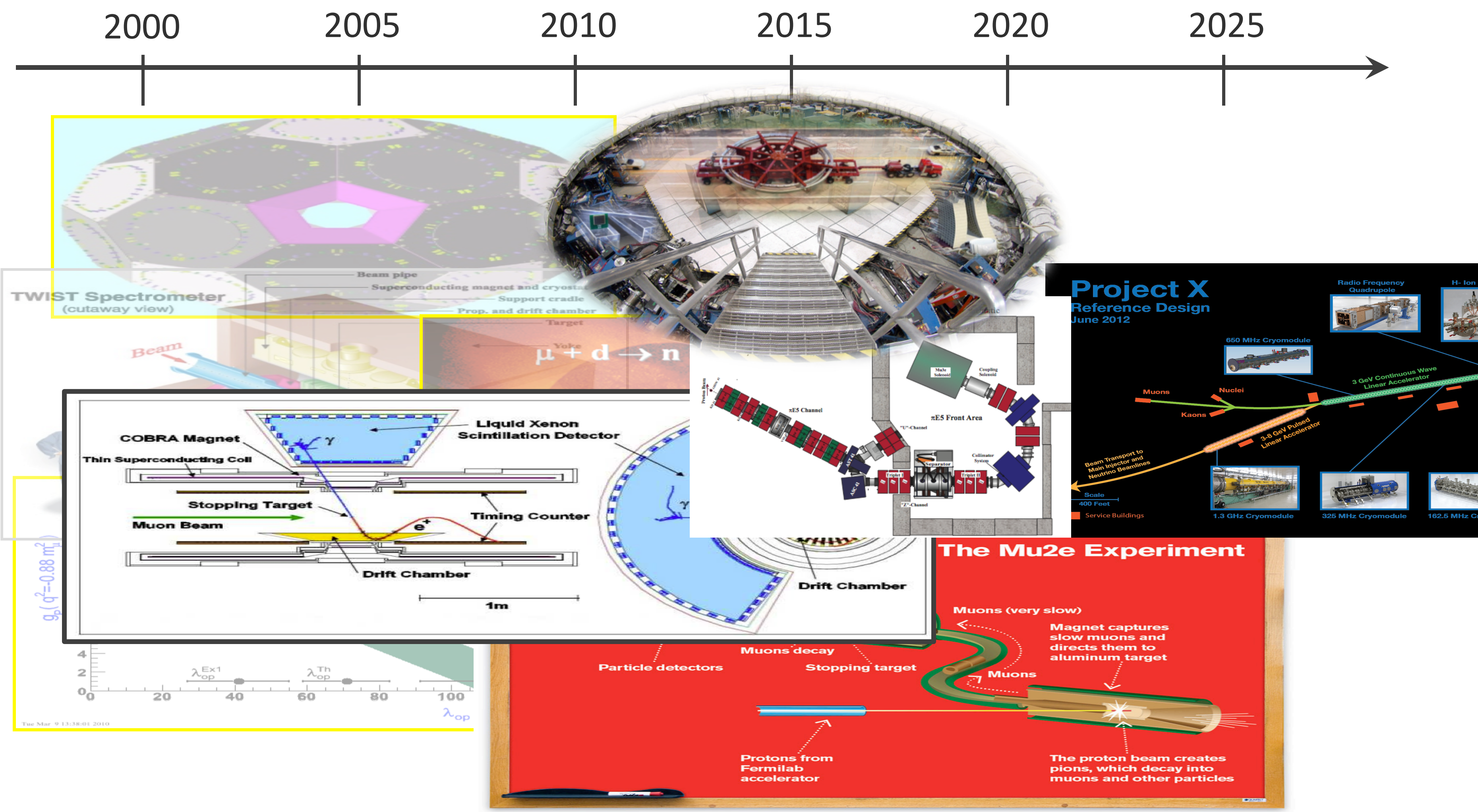
Muon experiments in the Project X era

Muon community developing new ideas for the future like at upcoming Snowmass:

- Mu2e-X: Increase sensitivity by ~10 with more beam power from Project-X
- $\mu^+ \rightarrow e^+ \gamma$ with Project-X and photon-conversion ($\gamma \rightarrow e^+e^-$) would possibly allow to go beyond MEG upgrade goal
- Increased Project-X beam power would allow to run g-2 with μ^- which has lower production yields
- Search for Muon Electric Dipole Moment
- Muonium oscillation ($\mu^+ e^- \rightarrow \mu^- e^+$)
- ...

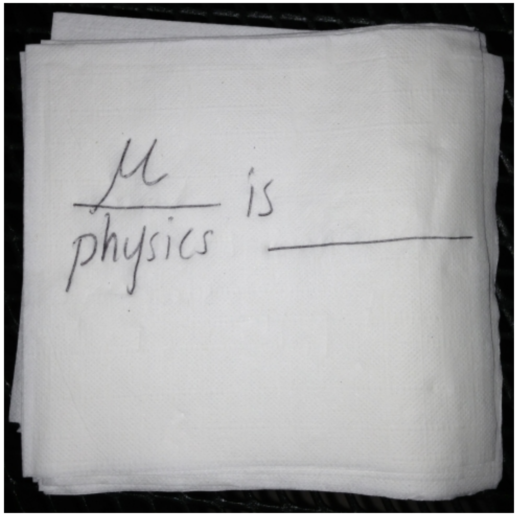
General timeline

All time ranges are only approximate. But it gives a good feeling for the length of these experiments!



Summary #1: What non physicists think

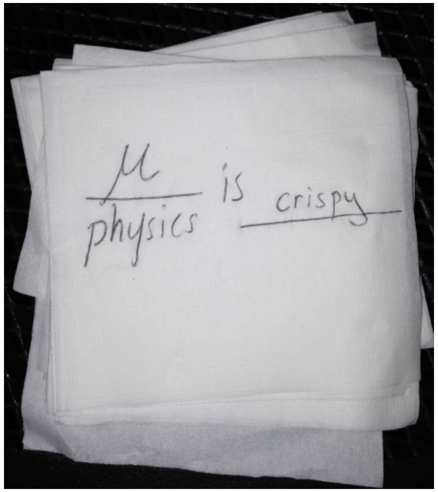
- I asked several non physicists to fill out

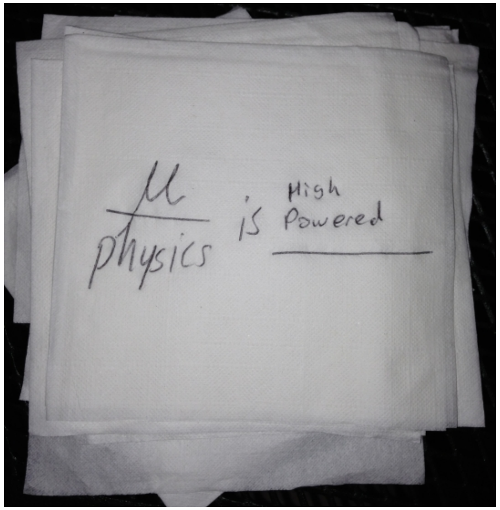


*Yes these are bar napkins!

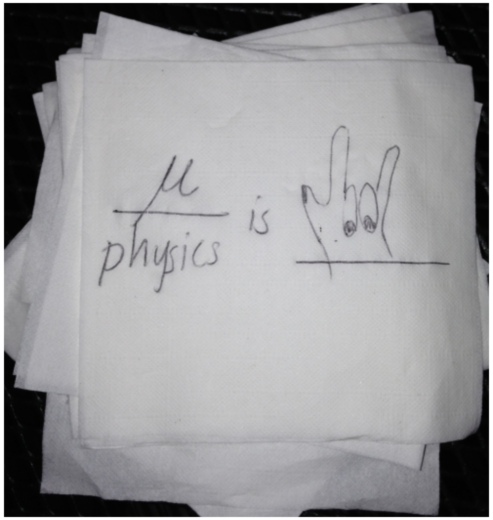
Summary #1: What non physicists think

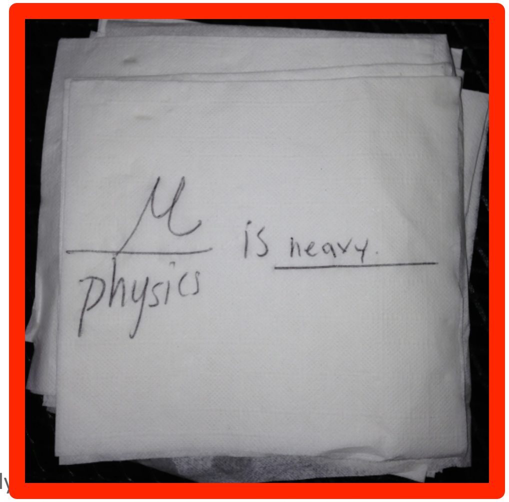
- And here is what they said:





I hope you weren't left with these impressions!!



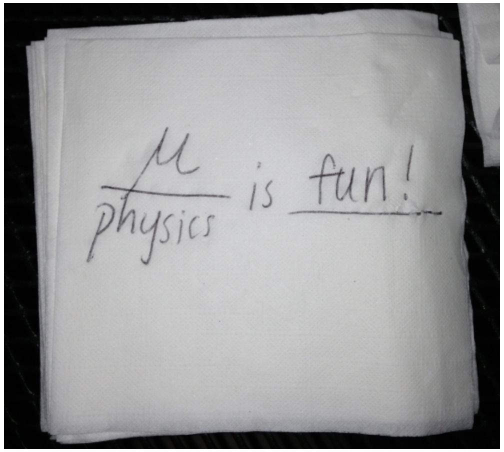


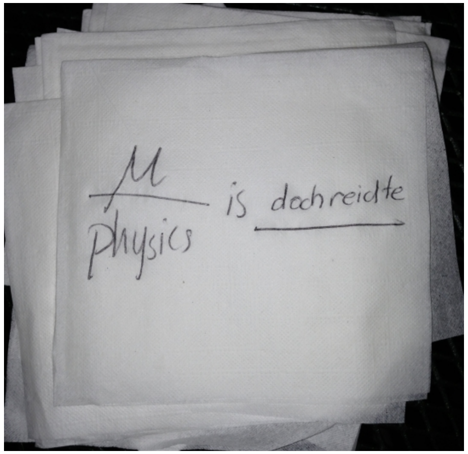
Summary #2: Muon physics

But I hope you really learned that muon physics is

- very diverse in the physics reach (SM parameters, BSM physics, material science, ...)
- all about parts-per-million precision these days
- complementary to direct searches (like at the LHC)
- a field with a vibrant future

And hopefully everyone can agree that:





incredible in Irish