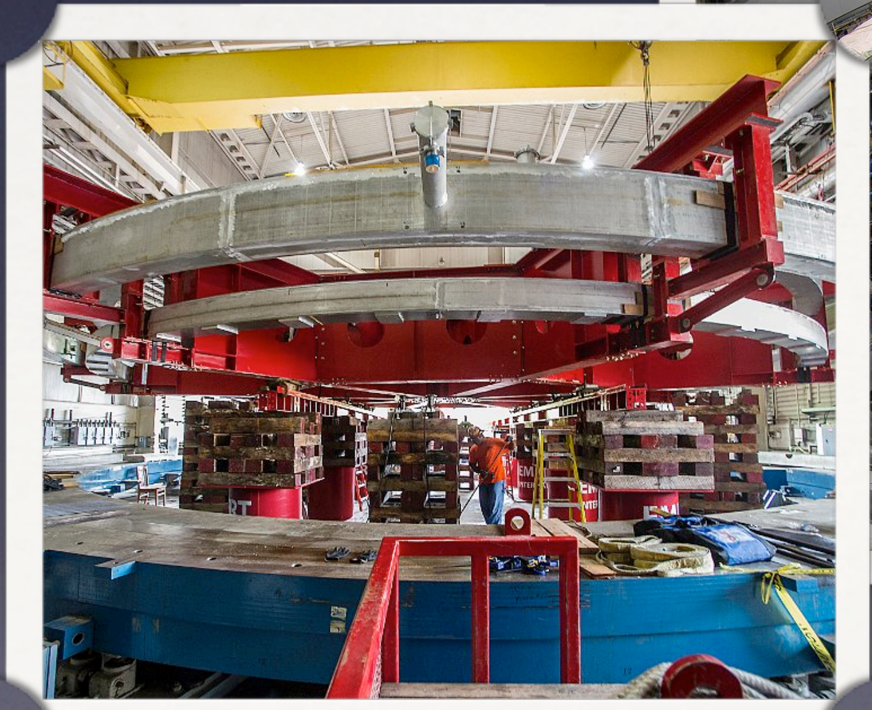
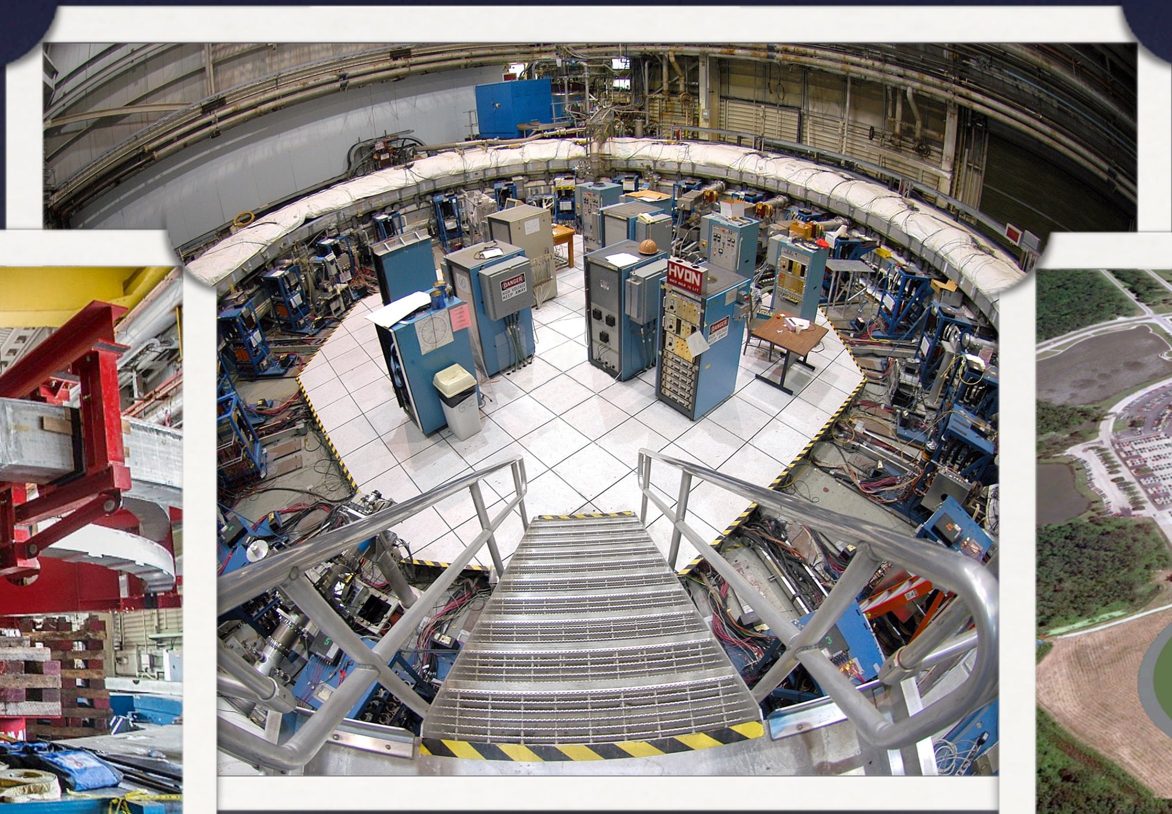
Taking the Muon for a Spin

The Fermilab "Muon g-2" Experiment

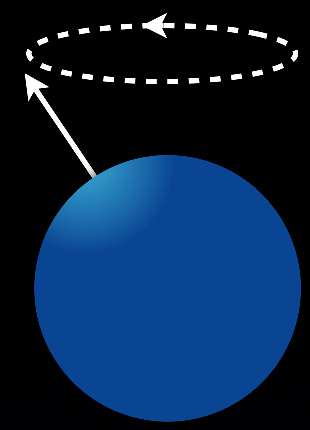
Lawrence Gibbons

Cornell University





The goal:

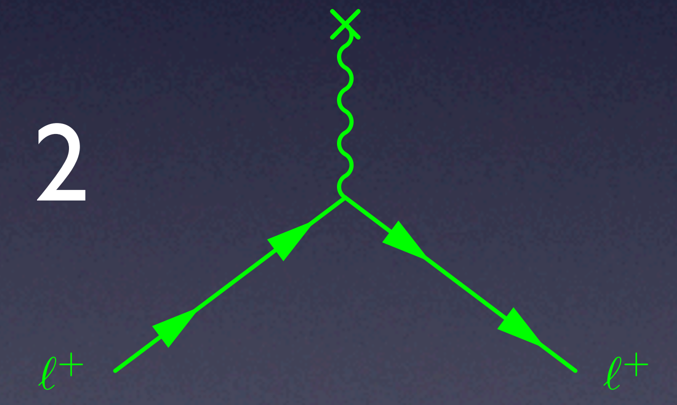


The muon anomalous magnetic moment (a_μ) to 0.14 ppm via spin precession

$$a_\mu = \frac{g-2}{2}$$

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

Dirac, relativistic QM (ie, tree level): g = 2

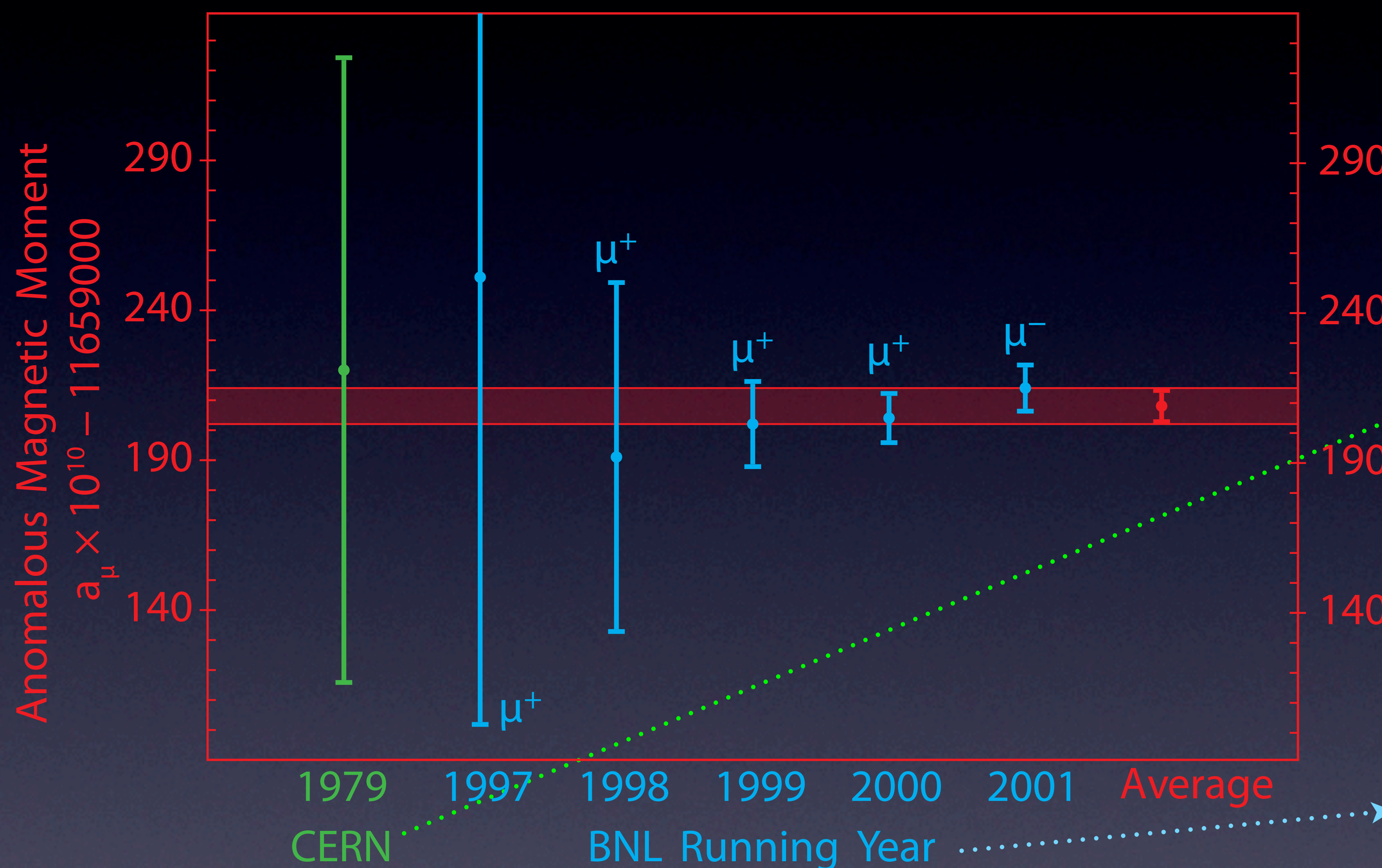


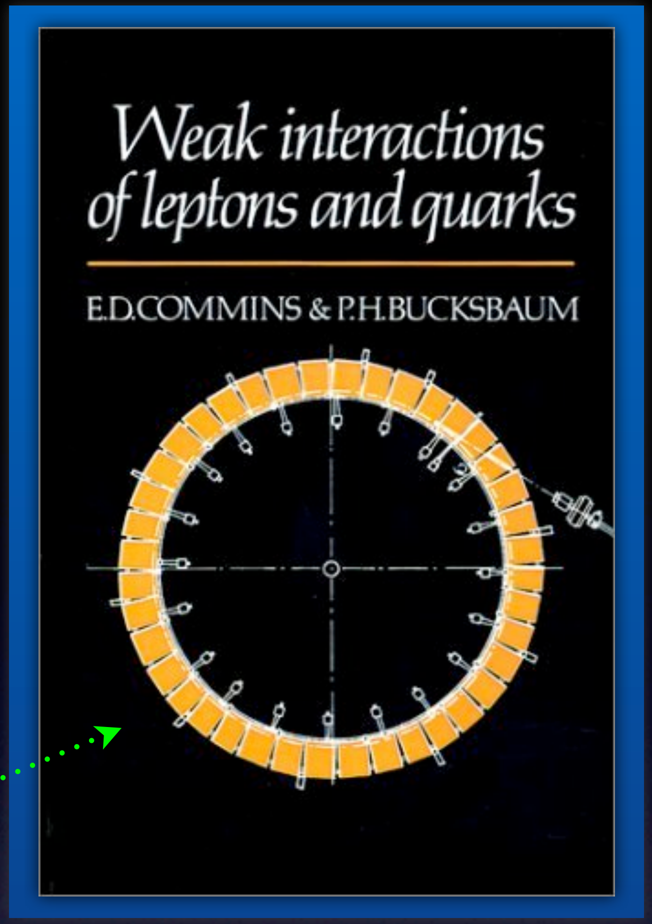
Loop corrections: $a_\mu > 0$

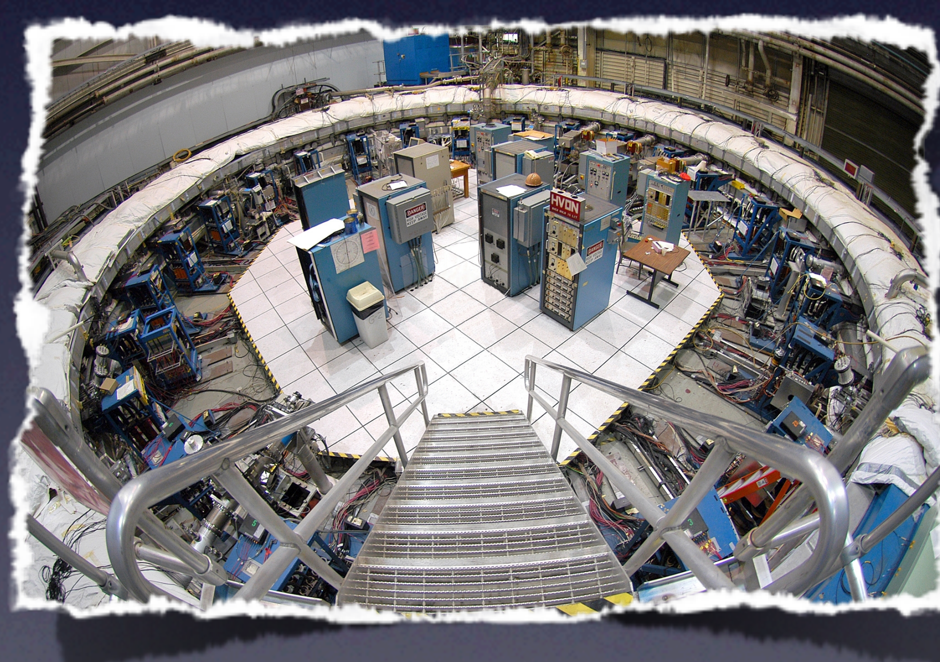
a_μ receives contributions

- ☑ from all SM particles
- ☑ from Beyond SM particles

The status of a_μ:



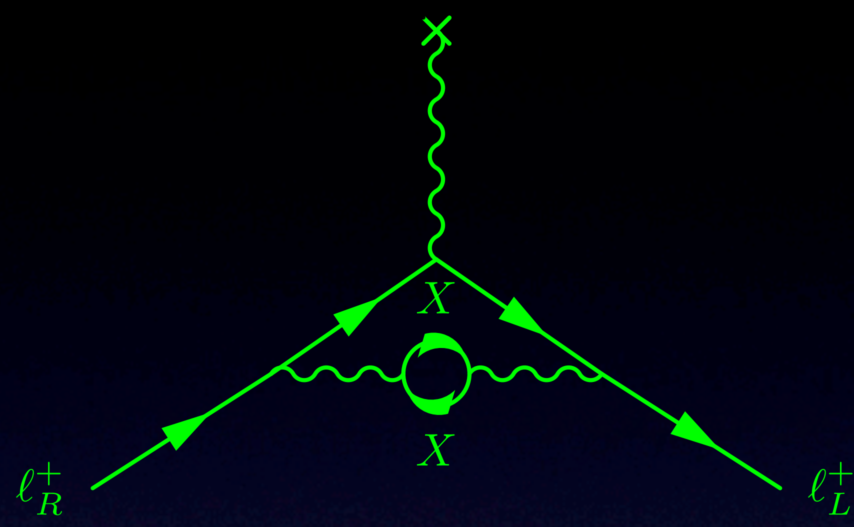


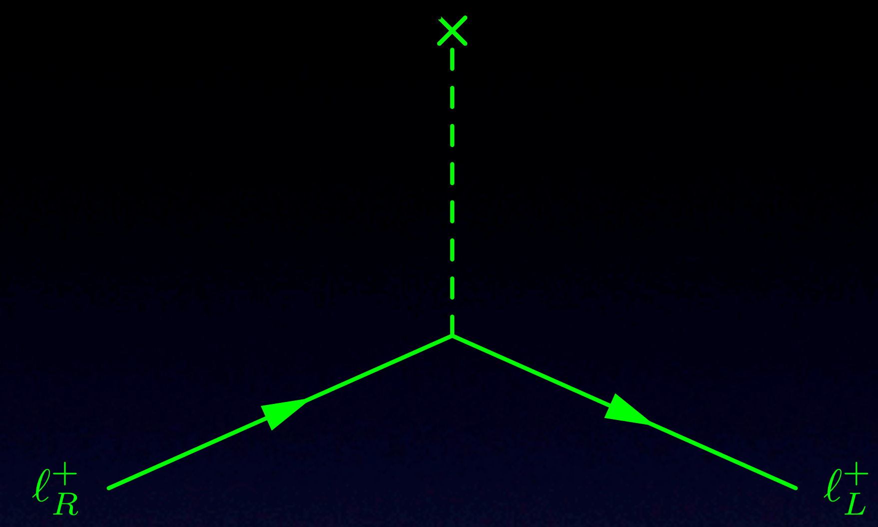


$$a_\mu = 11\ 659\ 208.0(5.4)(3.3) \times 10^{-10} \quad [0.54 \text{ ppm}]$$

Bennet *et al*, PRD 73072003 (2006)

Why improve a_μ





...when $a_e = 1159652180.73(28) \times 10^{-12}$ (0.3 ppb)?

Hanneke, Fogwell, and Gabrielse, PRL 100, 120801 (2008)

Magnetic moment: interaction flips helicity

→ a_ℓ sensitivity scales like $(m_\ell/m_X)^2$

→ $(m_\mu/m_e)^2$ → 40,000x increase in sensitivity

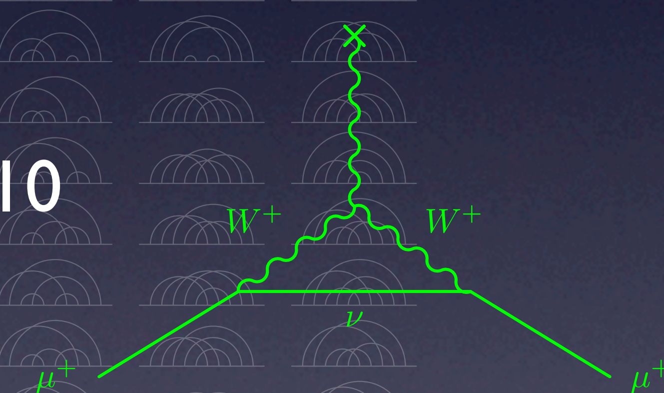
- must know SM corrections)-:
- Beyond SM sensitivity!

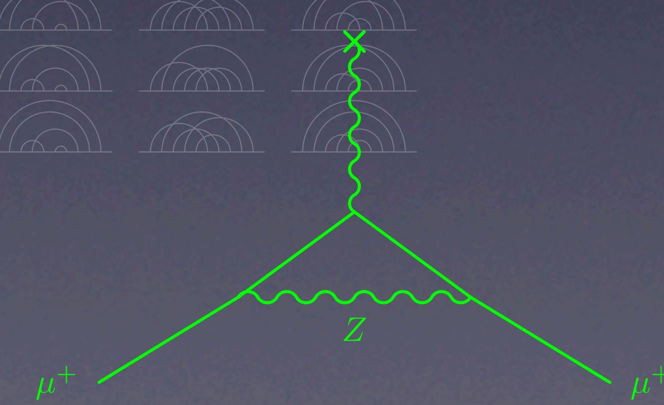
compensates for 1000x reduced precision (-:

The spin on a_μ

Standard Model Evaluation of a_μ

- QED: $a_\mu(\text{QED}) = 11\ 658\ 471.8951(80) \times 10^{-10}$
  - $O([\alpha/\pi]^5)$ Aoyama, Hayakawa, Kinoshita and Nio, PRL 109, 111808
  - 12,000+ diagrams!
  - far better than we need
- Electroweak: $a_\mu(\text{EW}) = 15.4(2) \times 10^{-10}$
  - probing EW was E821's goal
  - to 2 loops

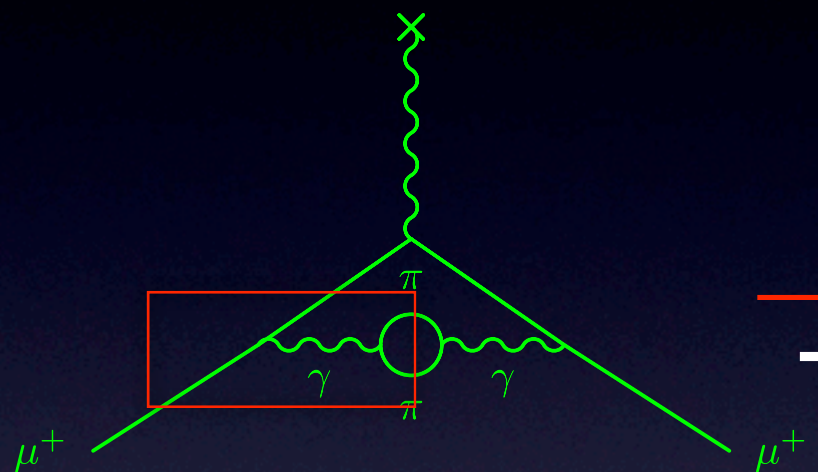




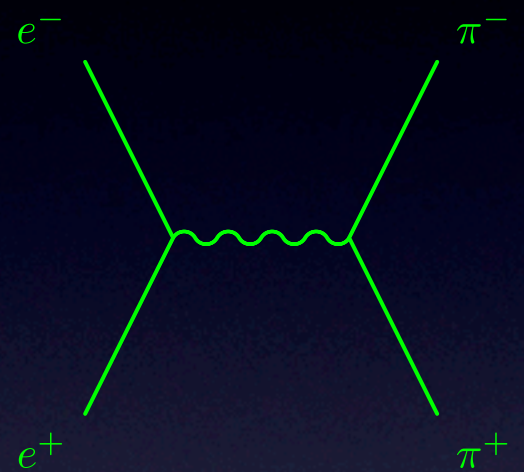
and...

...hadronic contributions

Hadronic Vacuum polarization (LO and NLO)



optical theorem
+ analyticity



$$a_\mu(HVP, LO) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2} ds \frac{R(s)\hat{K}(s)}{s^2}$$

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

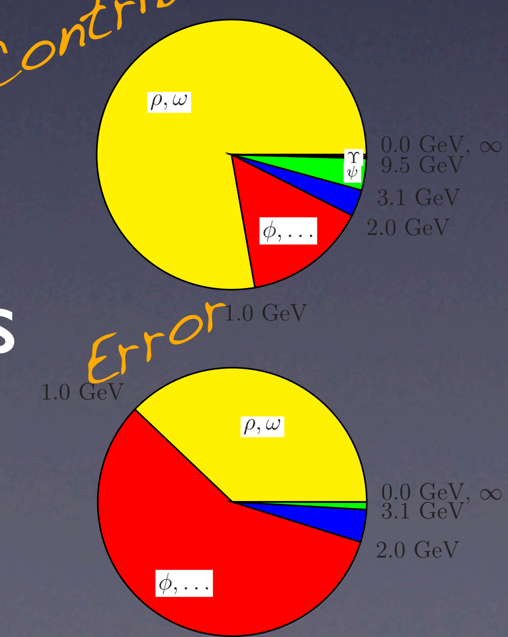
measured (low s) or pQCD (high s)

Slowly varying: 0.63 → 1

heavily weights to low E_{CM}

Jegerlehner, Nyffeler
Phys Rept 477, 1 (2009)

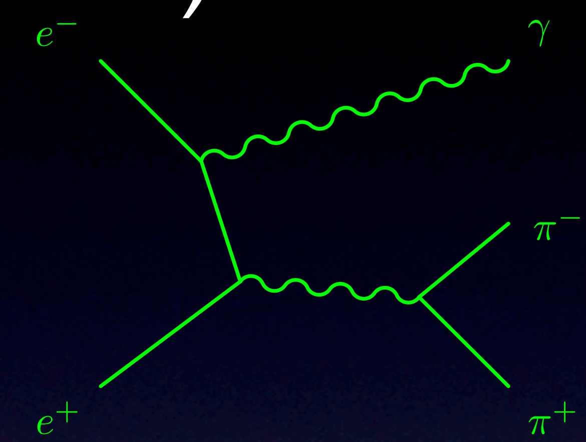
Contribution

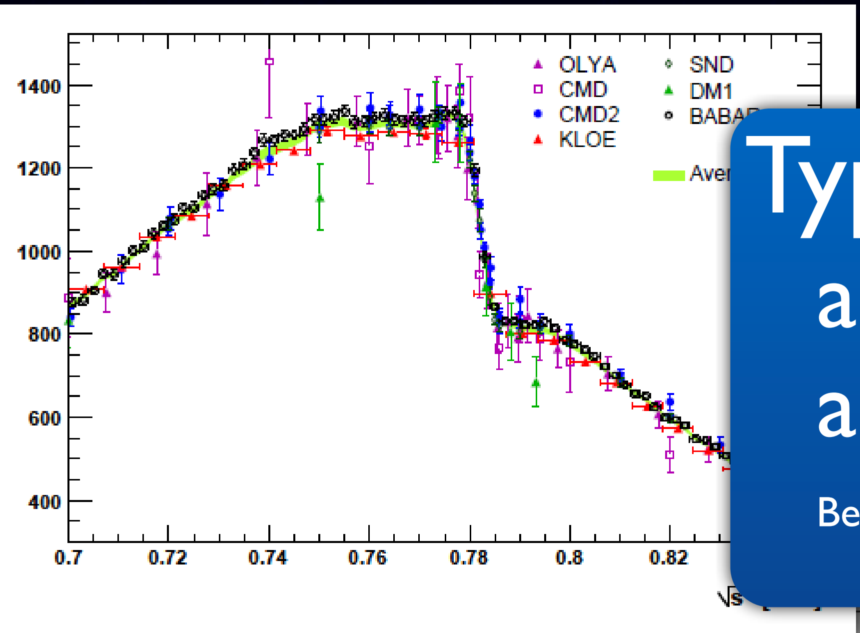


...hadronic contributions

Hadronic Vacuum Polarization (LO and NLO)

many new and anticipated inputs:



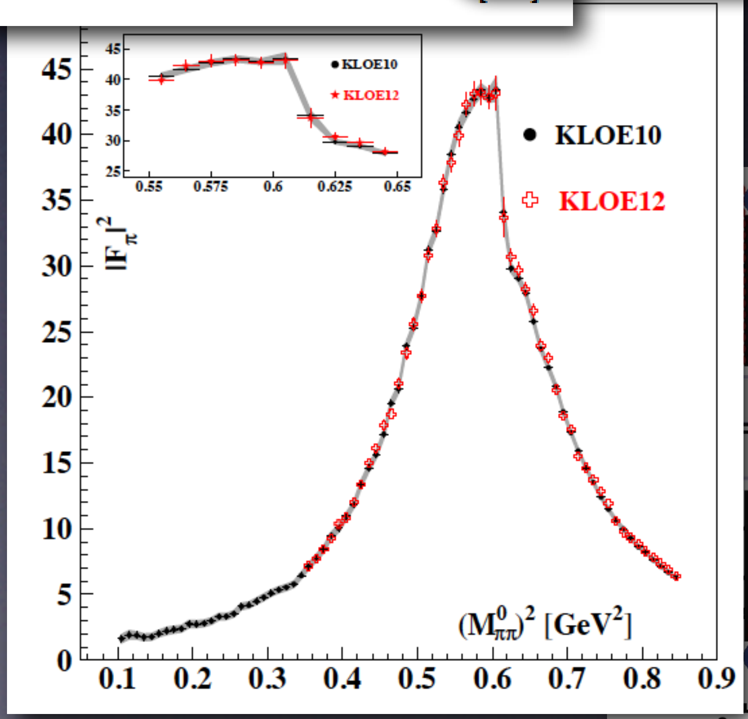


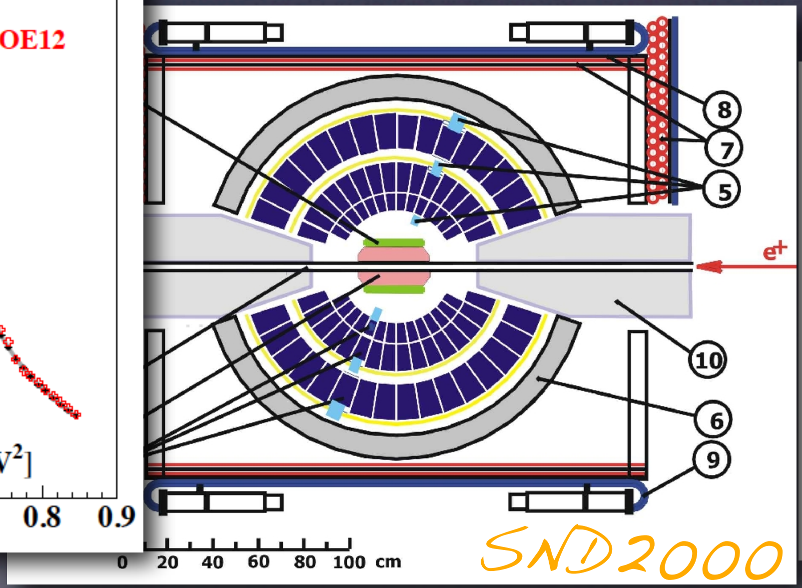
Typical result:

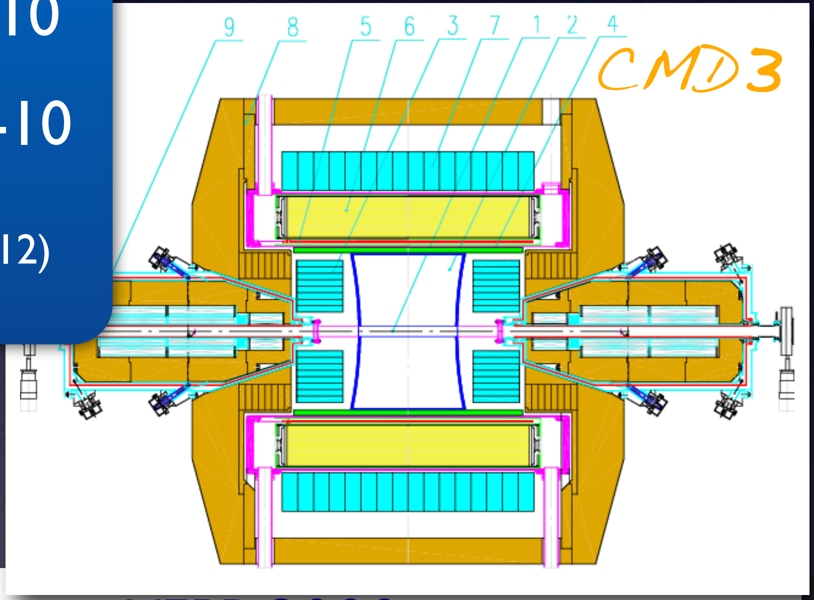
$a_\mu(\mathrm{HVP,LO}) = 685.8(4.6) \times 10^{-10}$

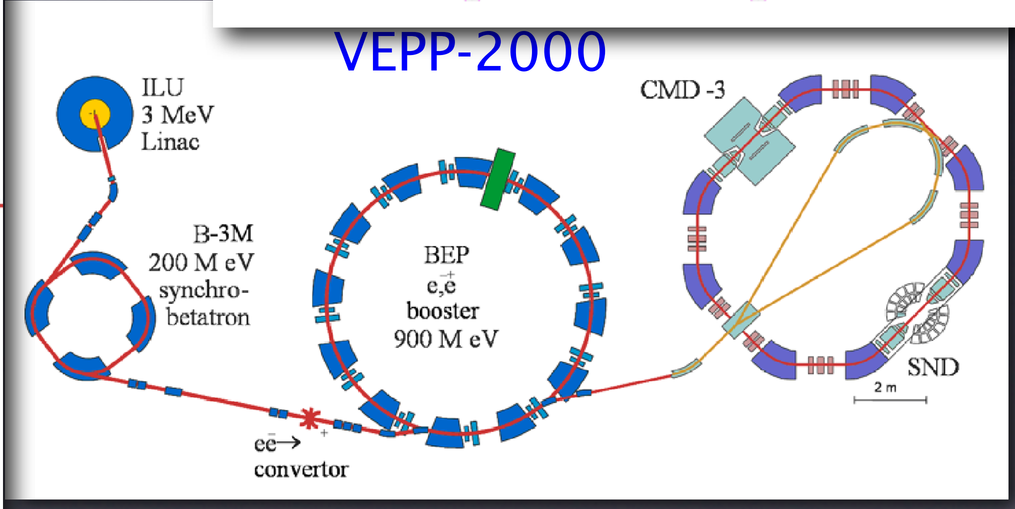
$a_\mu(\mathrm{HVP,NLO}) = -9.98(10) \times 10^{-10}$

Benayouna, Davida, DelBuonoa, Jegerlehner, EPJ C72, 1848 (2012)

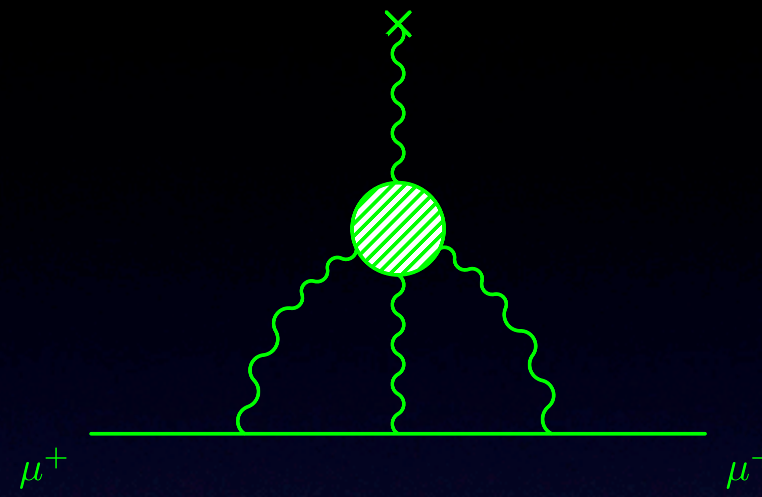






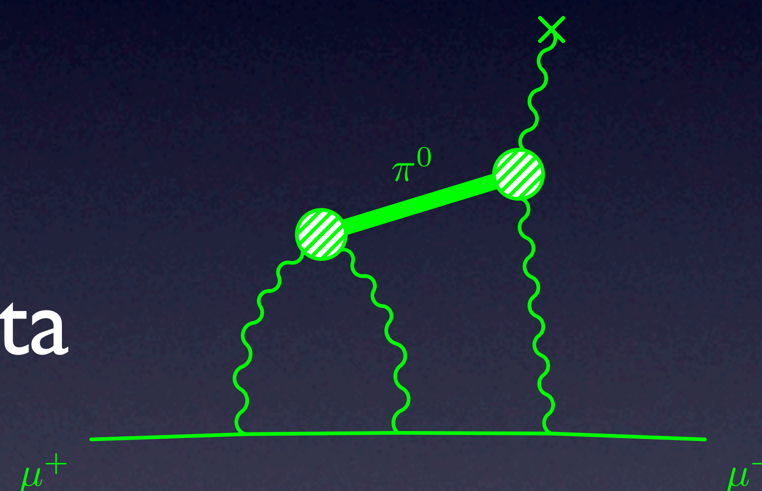


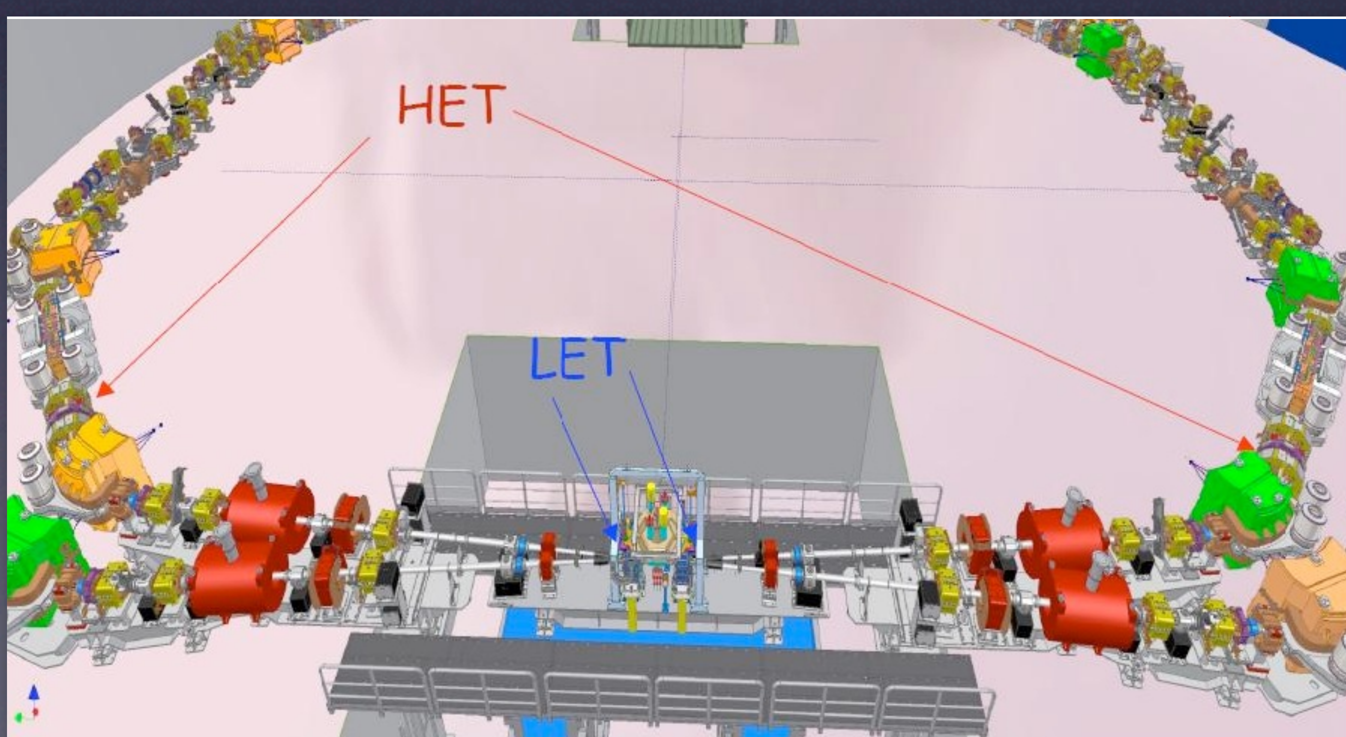
...hadronic contributions



Hadronic light by light

- nonperturbative, but higher order
- estimated via modeling + e.g., 2-photon data
  - will soon be dominant uncertainty
- KLOE-2 will constrain with new $\gamma^*\gamma^*$ data at low Q^2





a_μ(HLxL) = 11.6(4.0) x 10^{-10}
Prades, de Rafael, Vainshtein

- size ~ NLO HVP
- lattice calculations under way (10% in '17 feasible)

Combining it all...

- experiment vs SM

  $\Delta a_\mu \sim (33 - 38) \pm 8.3$

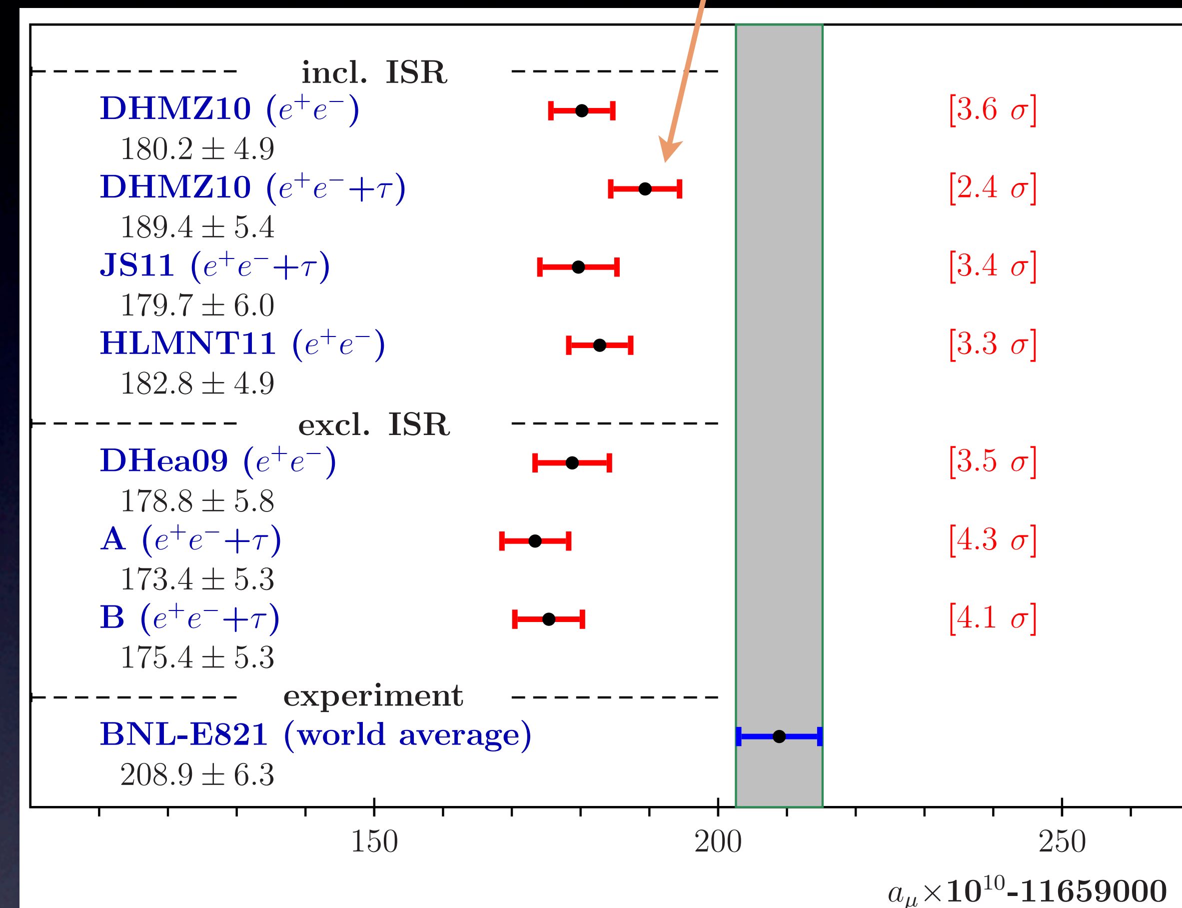
- **deviation remains > 3.5 σ**
- $\Delta a_\mu > 2 \cdot a_\mu^{EW}$!
  - If new physics, why haven't we seen it?
- a_μ sensitive to *ratio*

  coupling / mass scale

Coupling ≪ G_F
(hidden sectors)

Masses ≫ M_Z

No ρ-γ mixing correction in τ data

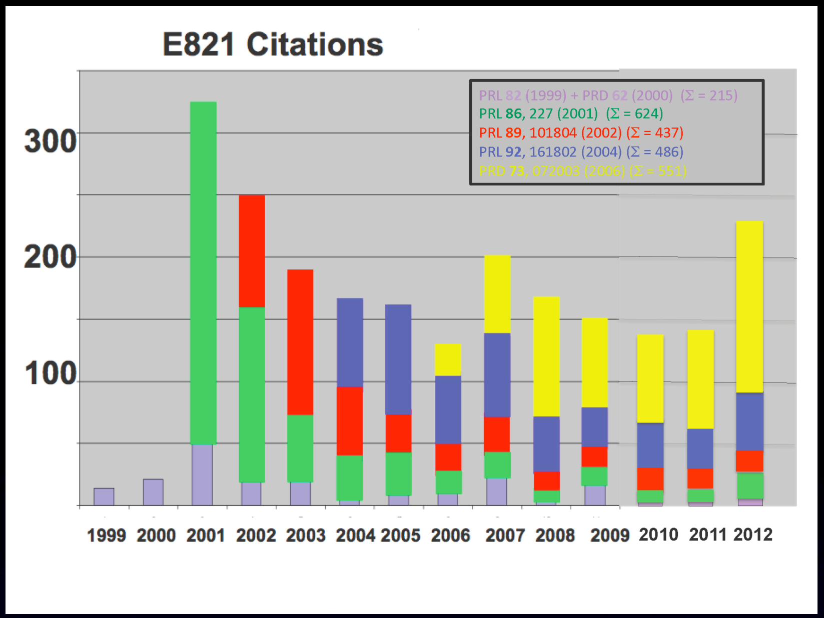


Good agreement among various a_μ^{SM} assessments

Benayouna, Davida, DelBuonoa, Jegerlehner, EPJ C72, 1848 (2012)

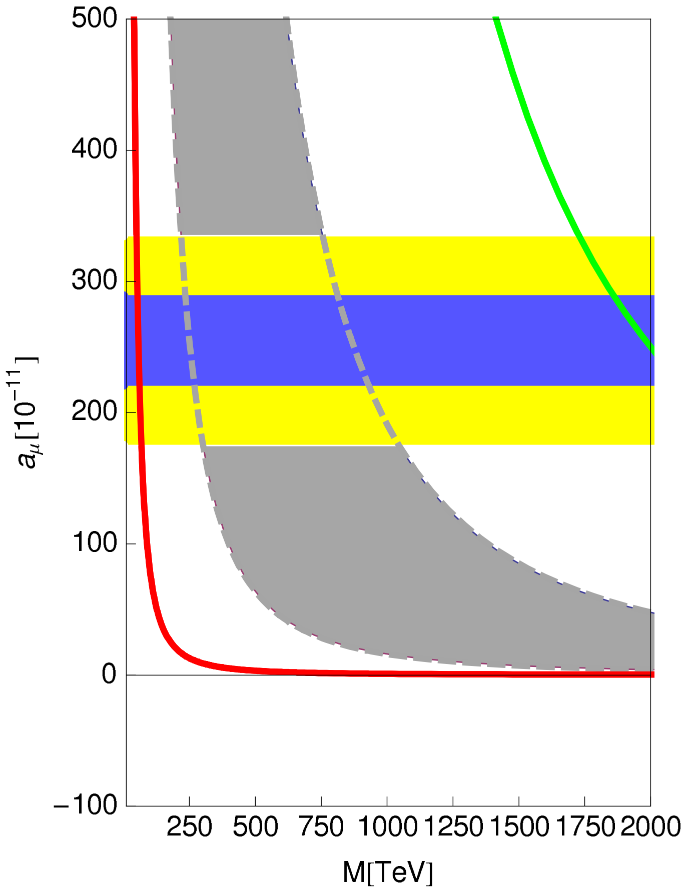
Outlook (5.1 → 3) x 10^{-10} on prediction circa 2017

Beyond Standard Model



generally: $\delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$

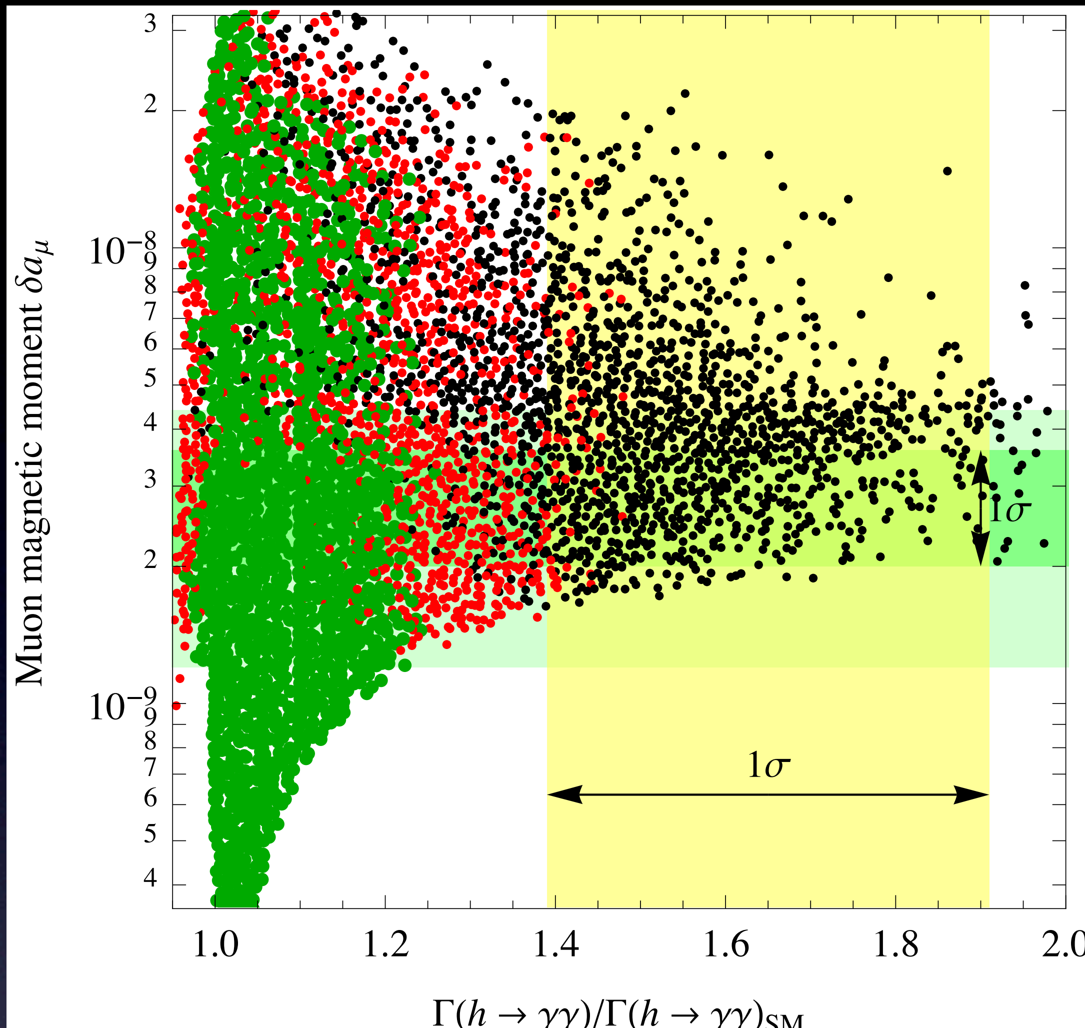
classify new physics: C **very** model-dependent



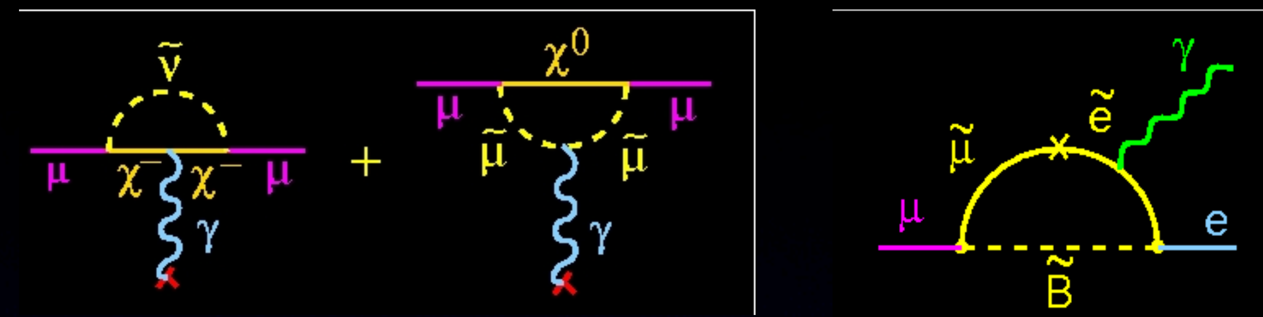
$\mathcal{O}(1)$	radiative muon mass generation . . . [Czarnecki,Marciano '01]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry (tan β), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c). . . [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT). . .

Stockinger

LHC and g-2

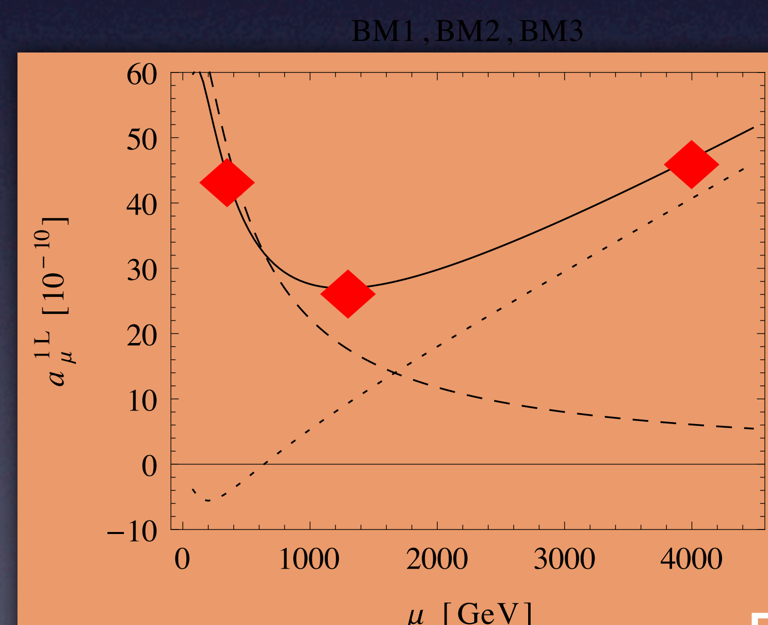


Giudice, Paradisi, Strumia 2012
(SUSY w/ light staus)



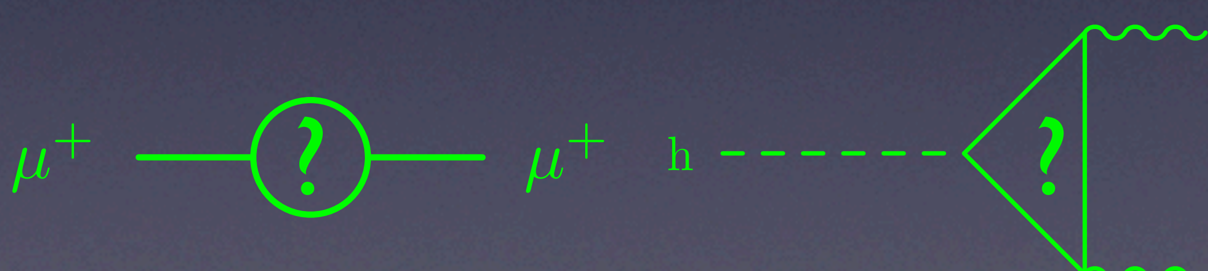
$$\Delta a_\mu \approx 150\times 10^{-10}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2}{\mu M_{\mathrm{wino}}}\right)$$

$$\Delta a_\mu \approx 15\times 10^{-10}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2}{m^2_{\tilde\mu L}m^2_{\tilde\mu R}/\mu M_{\mathrm{bino}}}\right)$$



	BM1	BM2	BM3	BM4
μ[GeV]	350	1300	4000	−160
$\tan\beta$	40	40	40	50
M_1[GeV]	150	150	150	140
M_2[GeV]	300	300	300	2000
M_E[GeV]	400	400	400	200
M_L[GeV]	400	400	400	2000
$a_\mu^{1L}[10^{-10}]$	44.02	26.95	46.78	15.98

Fargnoli et al, 1309.0980



Contributions affect both a_μ and h→ γγ

Split spectra, large Higgsino Mass, …

➡ consistent w/ LHC, large a_μ contrib's

Taking the muon for a spin

Fermilab E989 “Muon g - 2”

Goal:

a_μ to < 0.14 ppm

BNL E821 stat’s limited

bring collaboration

+ its experience

+ its ring to FNAL

Deliver 21x the μ’s

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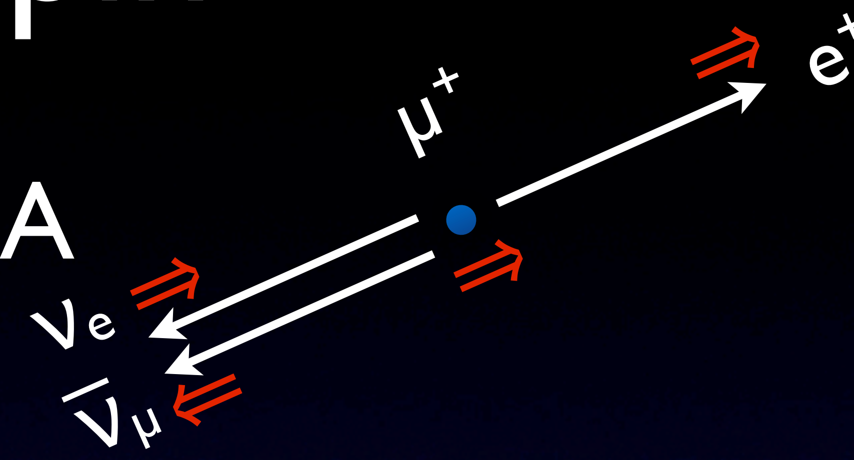

The principles: motion in B field, V-A

- cyclotron: $\omega_C = B\dfrac{e}{m_\mu c}\dfrac{1}{\gamma}$
- spin precession: $\omega_s = B\dfrac{g_\mu}{2}\dfrac{e}{m_\mu c} + B\dfrac{e}{m_\mu c}\left(\dfrac{1}{\gamma} - 1\right)$

Larmor　　　　Thomas

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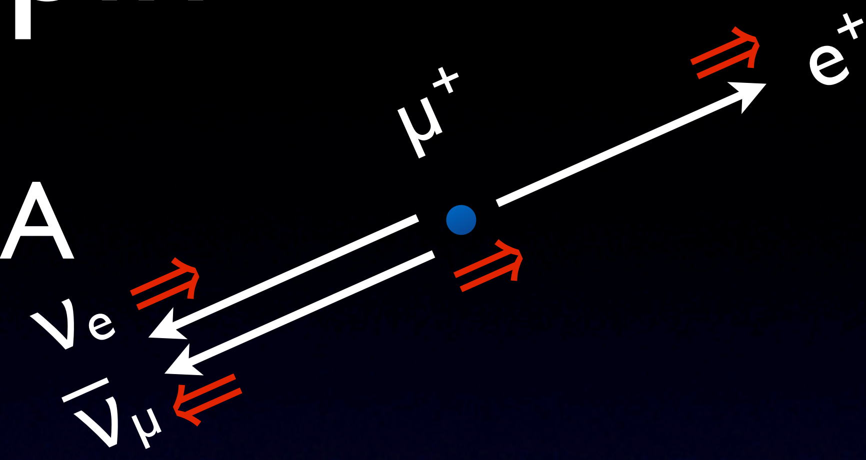

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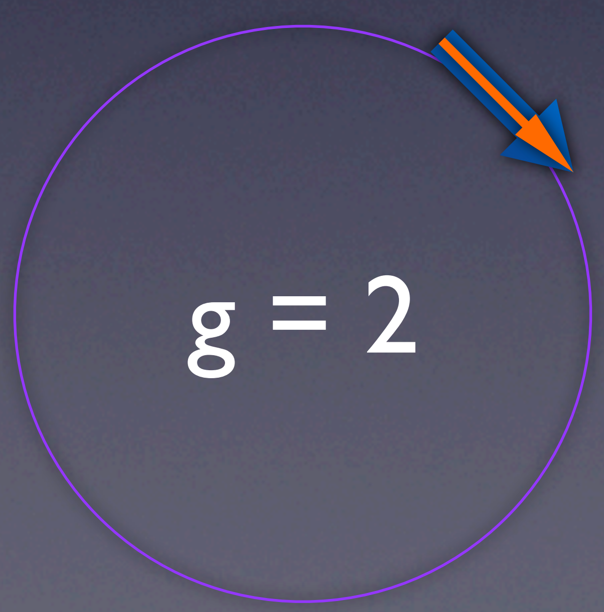

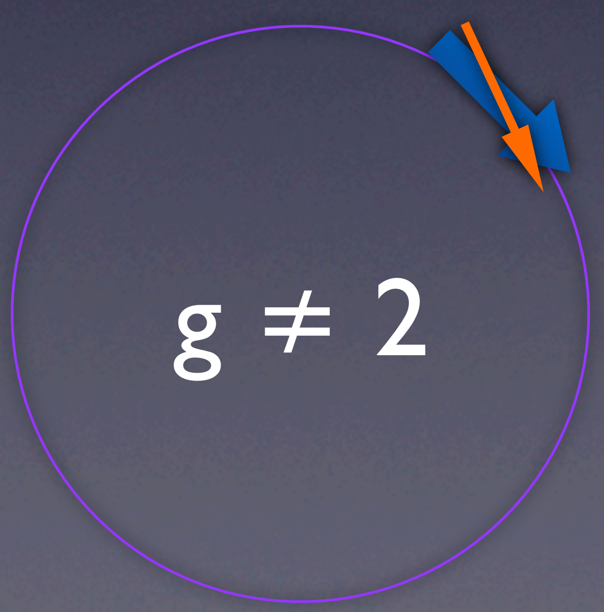

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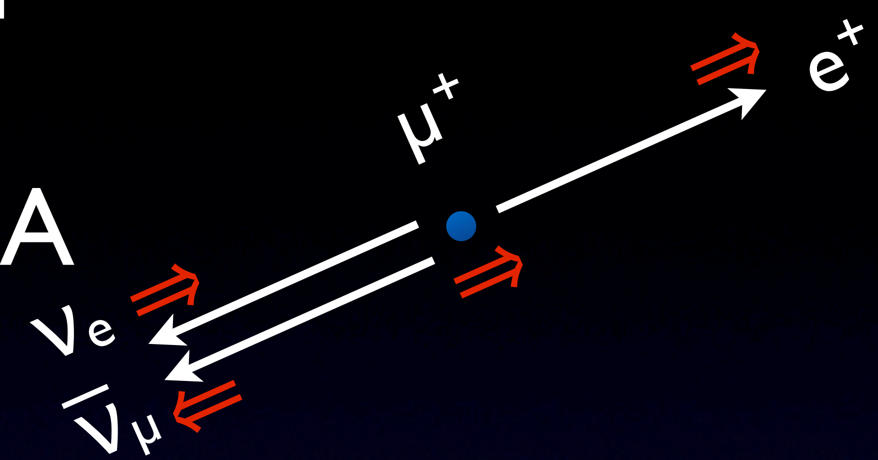

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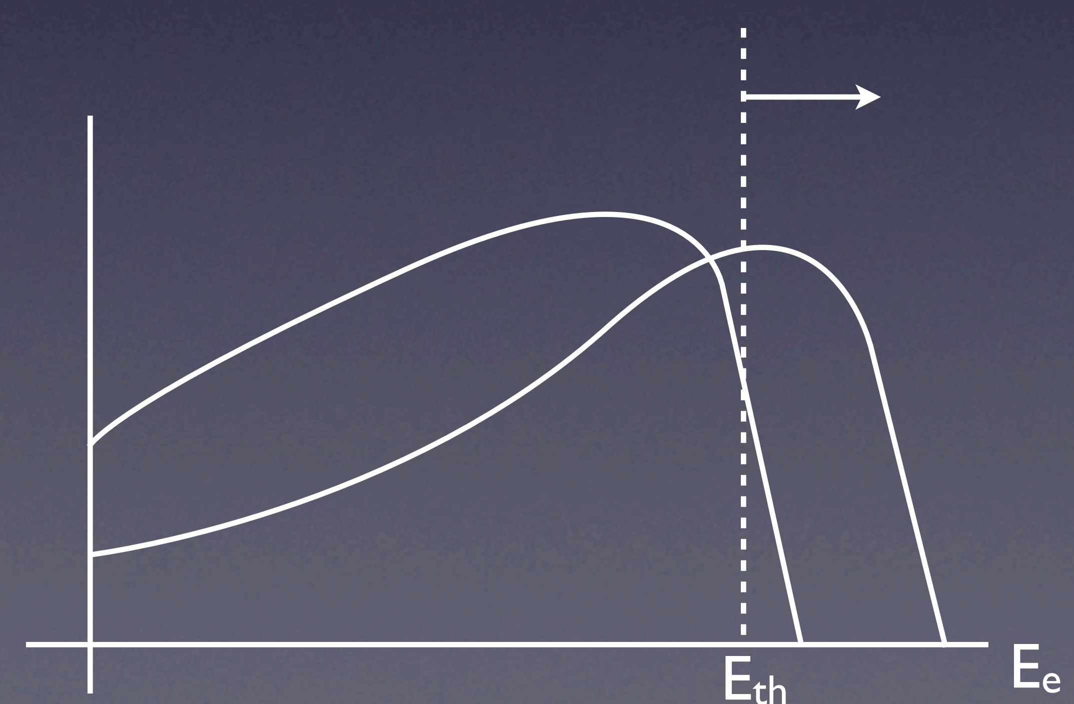
  Larmor Thomas
- relative precession:

ω_a $$\omega_s - \omega_C = B\frac{e}{m_\mu c}\left(\frac{g_\mu}{2} - 1\right)$$

a_μ!



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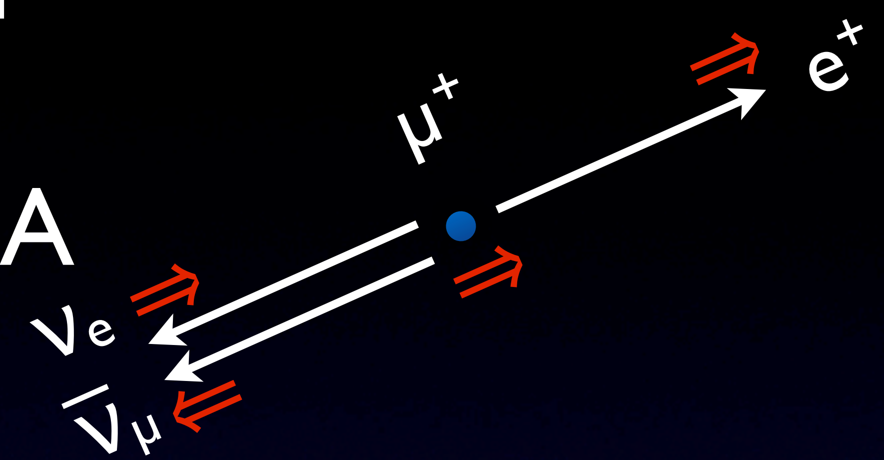

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Larmor Thomas

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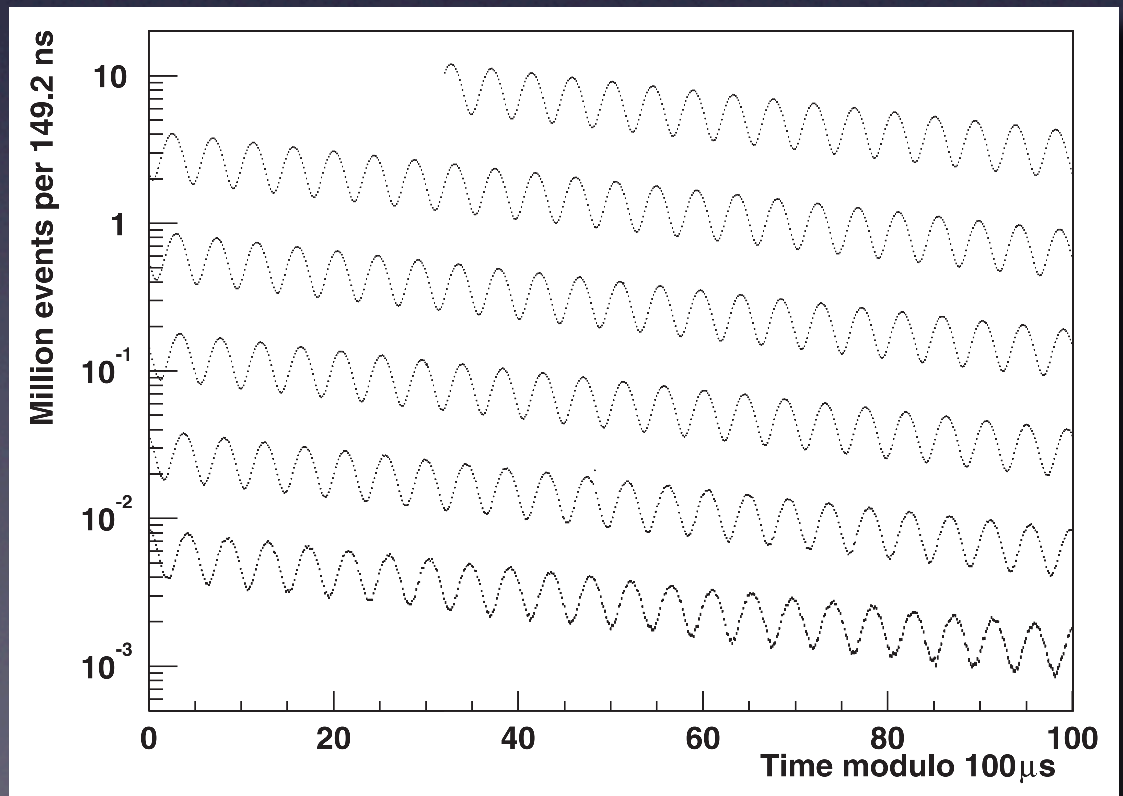
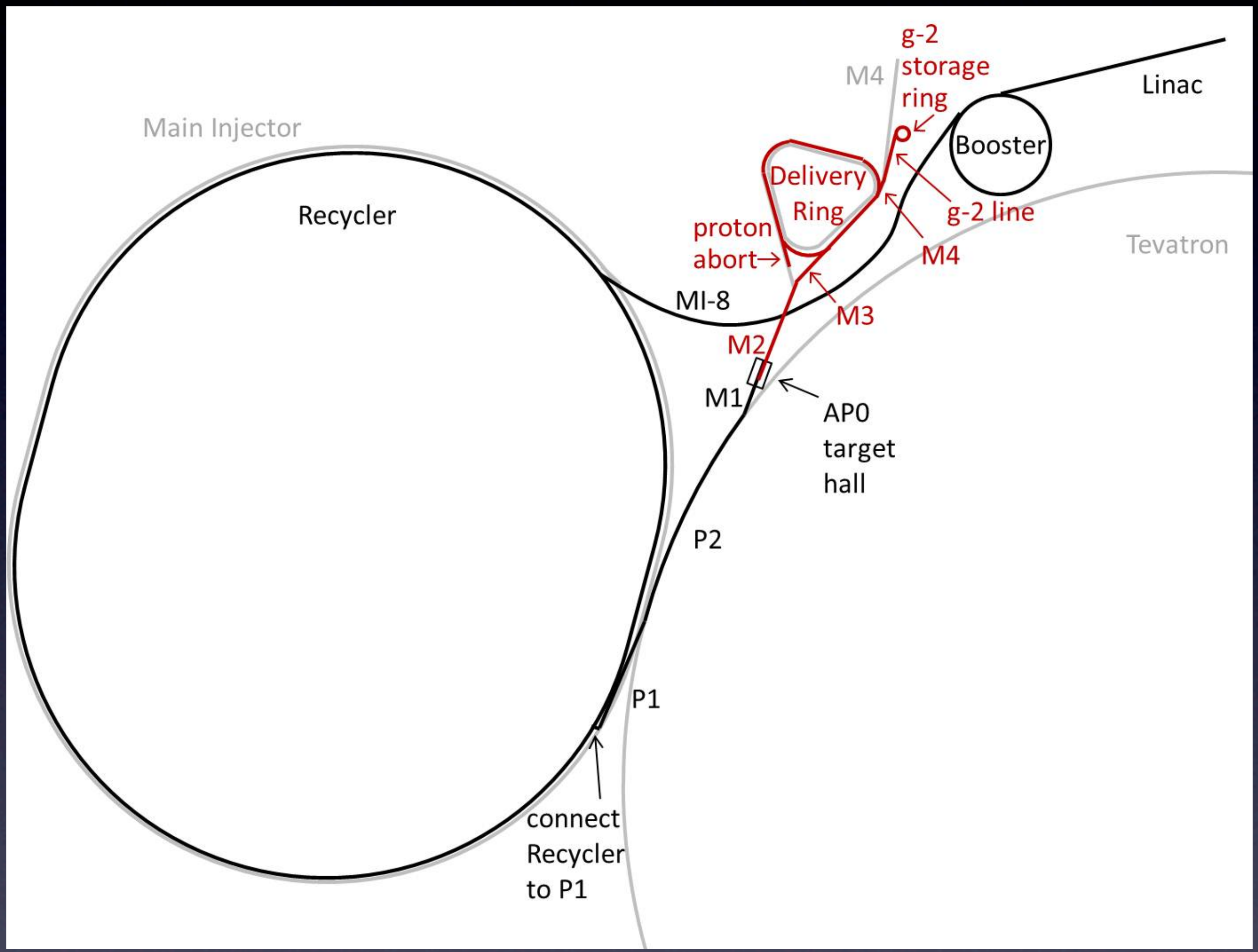
a_μ!



Taking the muon for a spin

Producing 21x the muons:



parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

- ☑ ~12x μ / proton yield
- ☑ ~3x repetition rate:

$\Rightarrow$ only ~3-5x BNL instantaneous rate and ~1 year of protons

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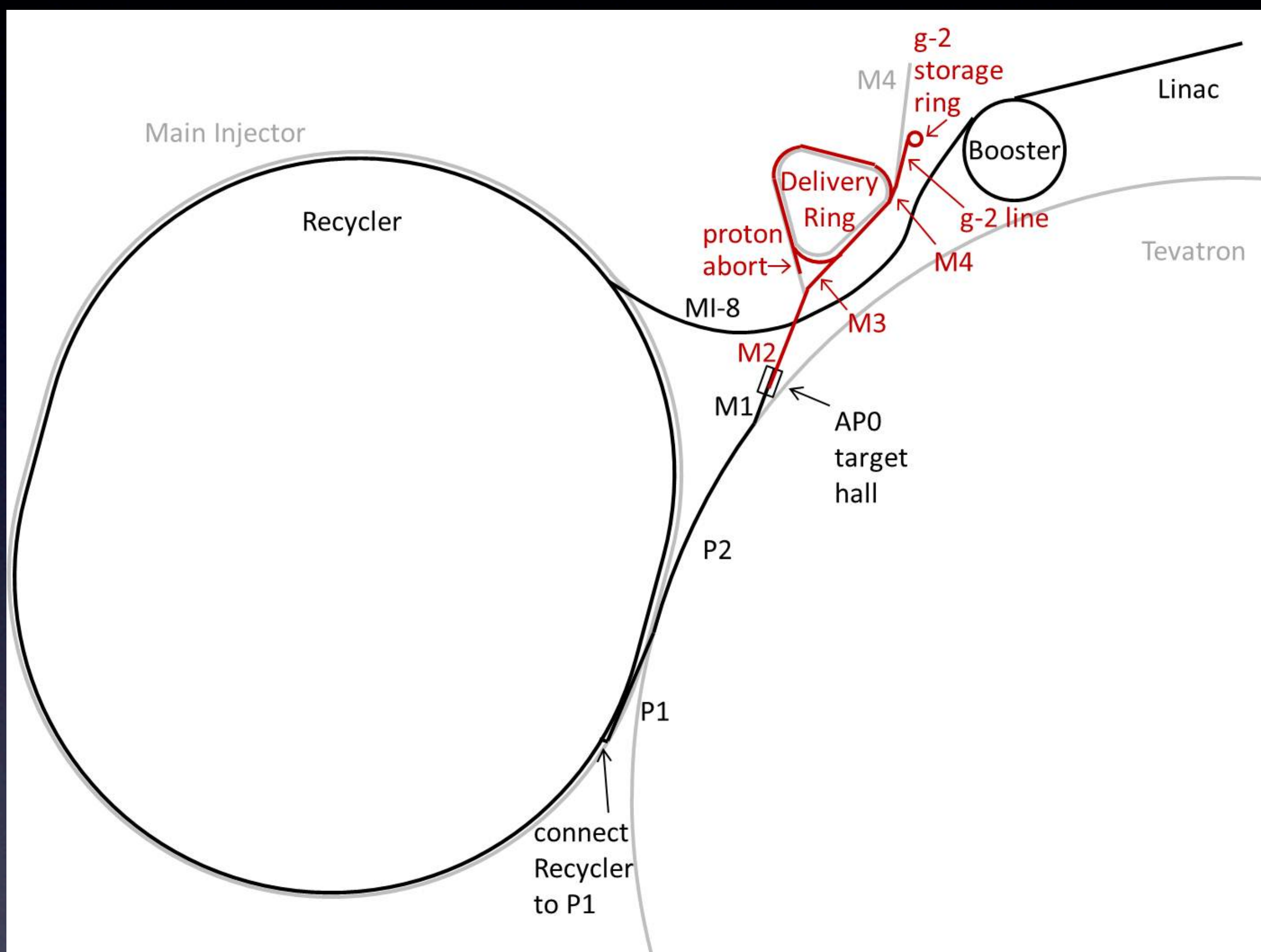

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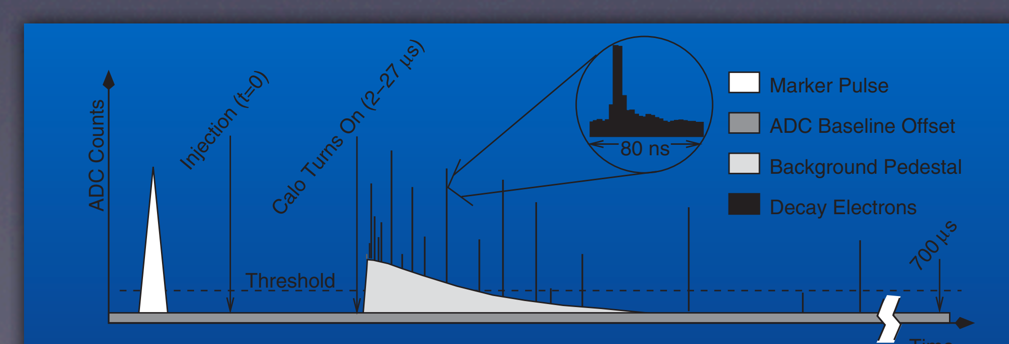
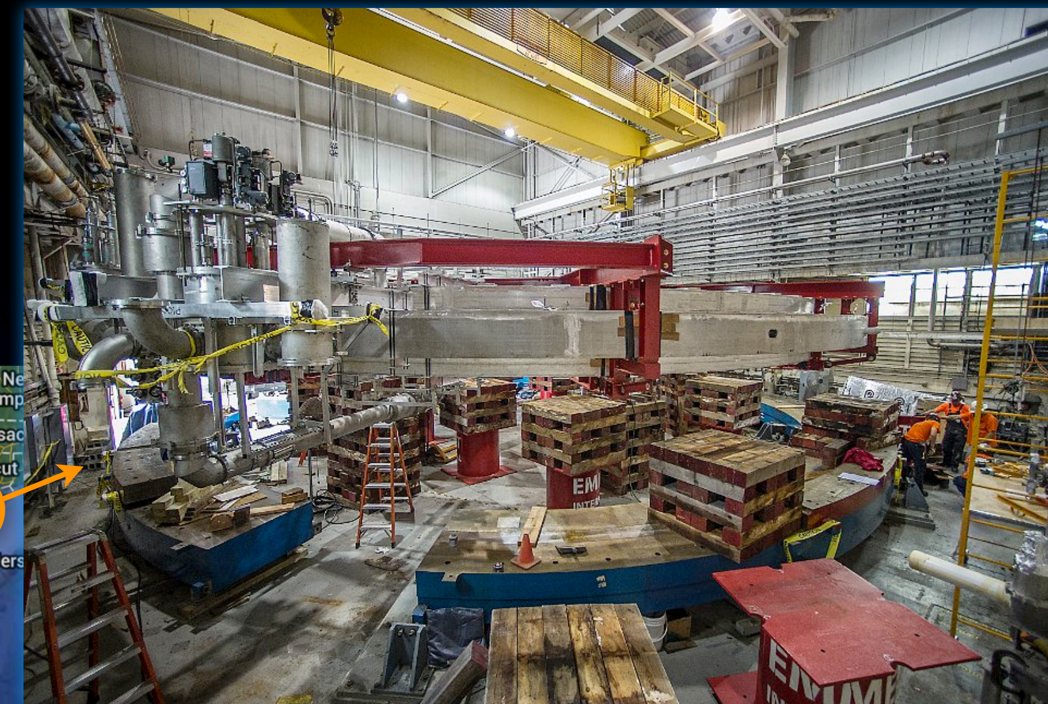
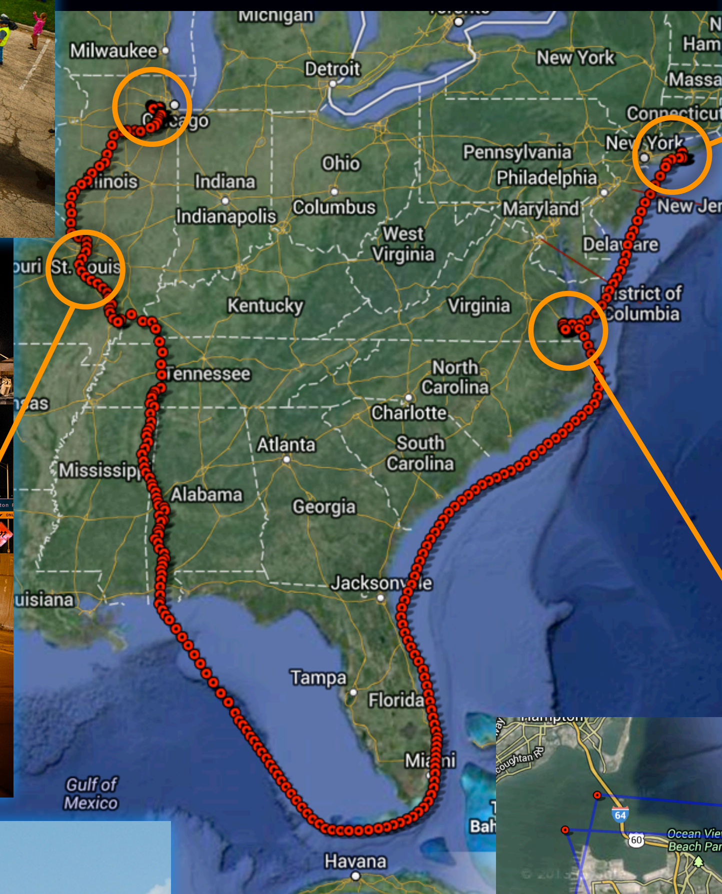
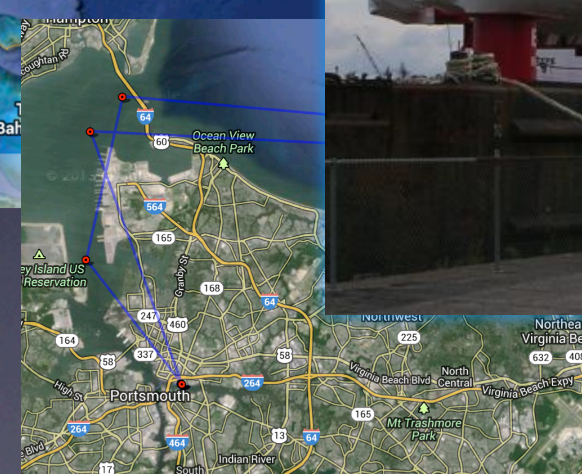
Side benefit:
reduced hadronic flash = improved systematics!



Taking the ring for a spin







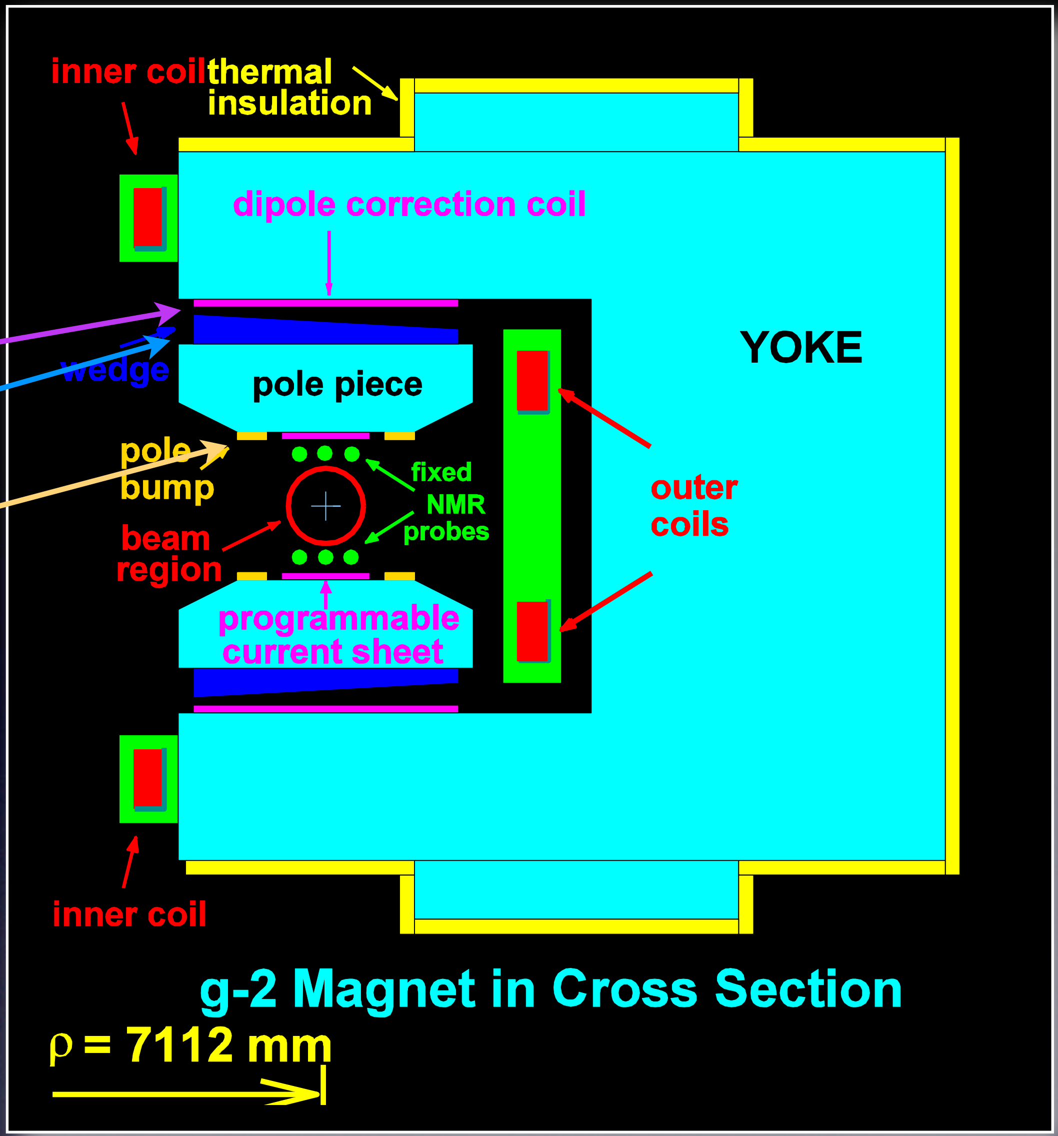
15 m diameter

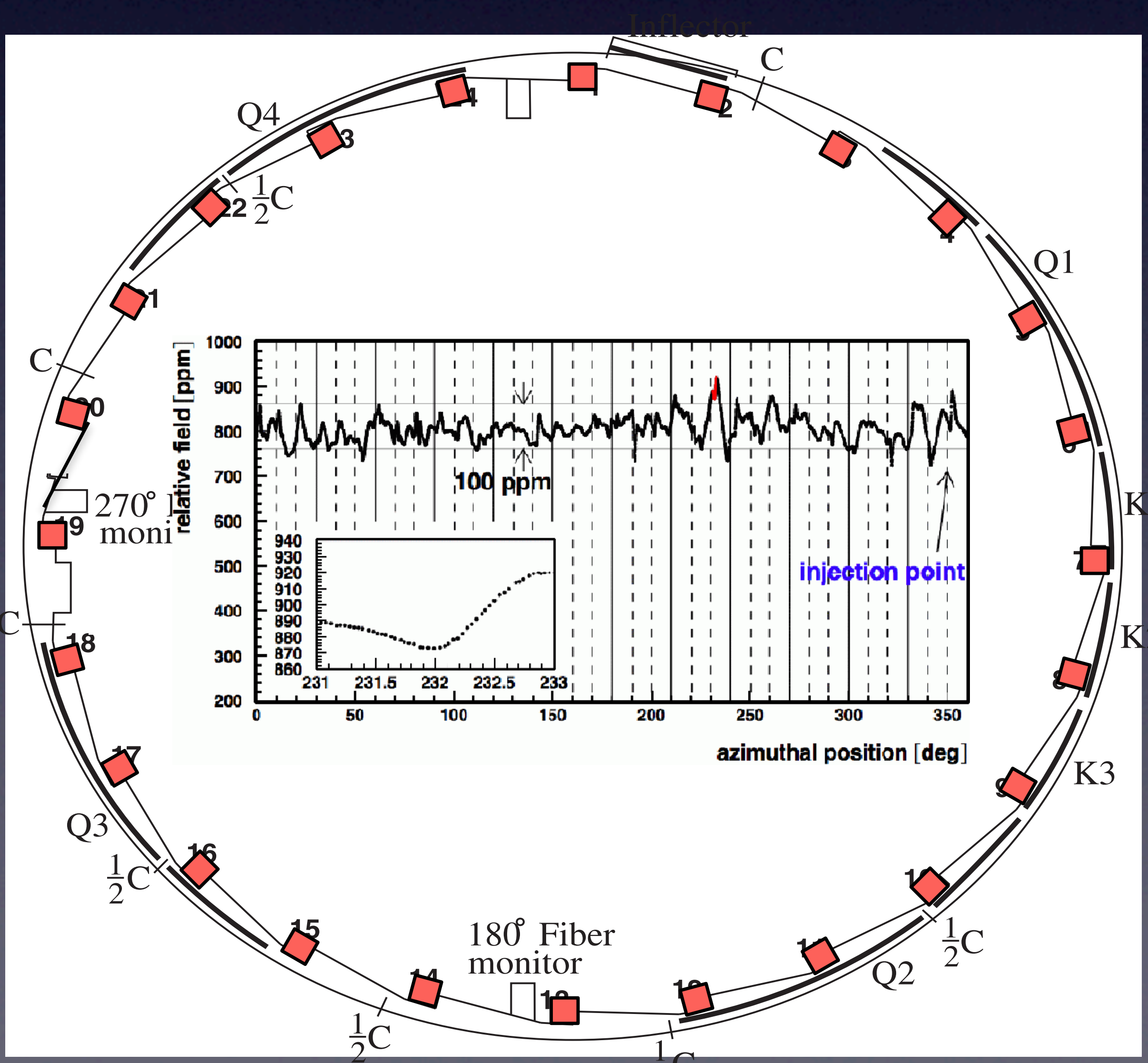
1 mm vertical flex tolerance

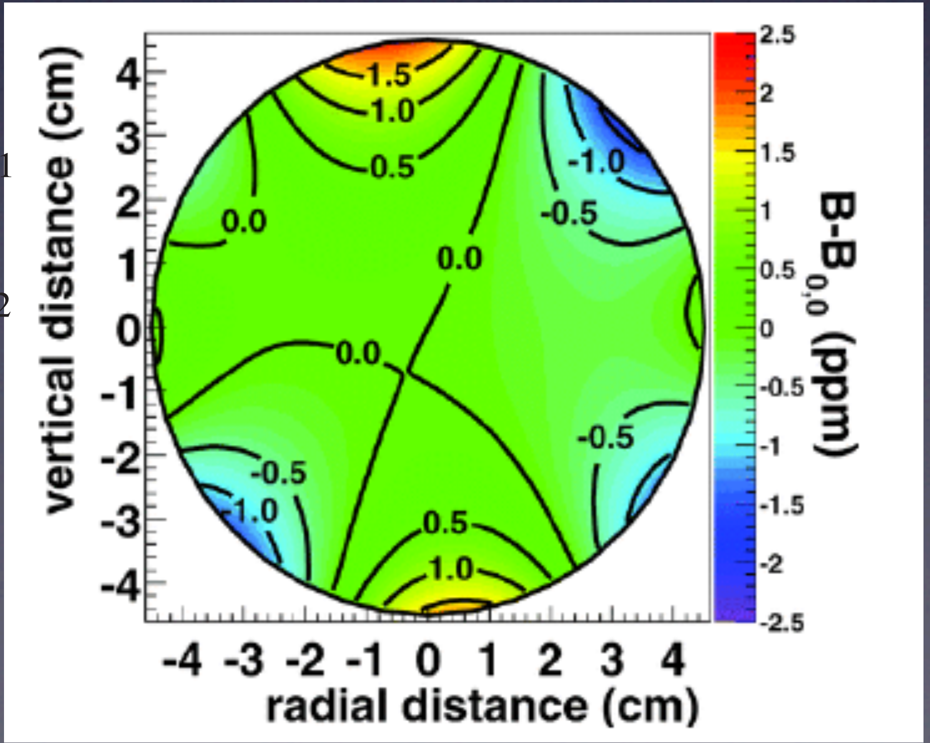
The precision B field

~1 year to shim, independently,

- dipole
- quadrupole
- sextupole







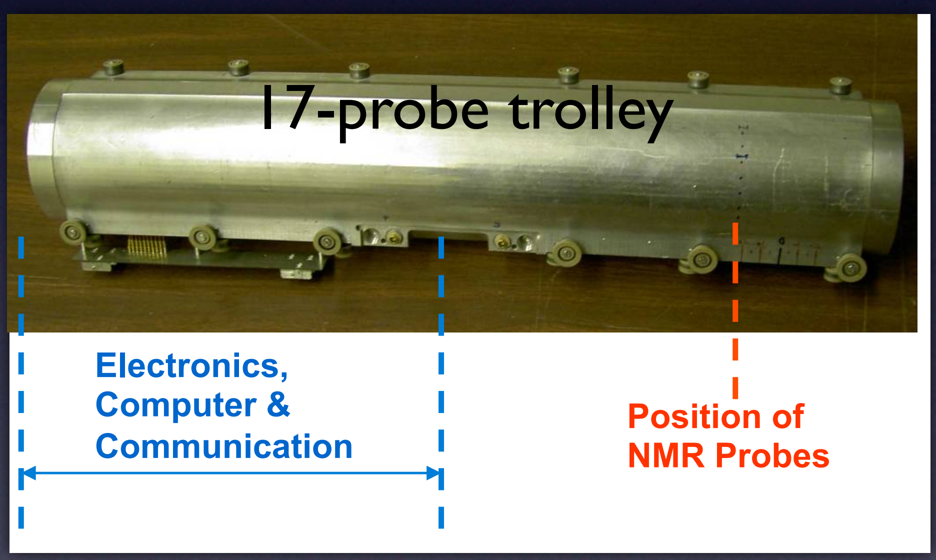
E821: ppm uniformity $\langle B \rangle_{ring}$ over beam

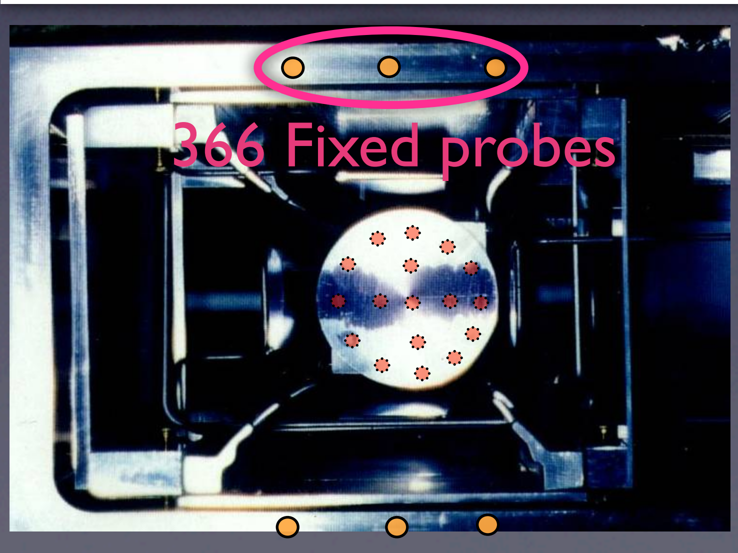
The precision B field

Measurement + calibration of B:

- Pulsed NMR with free-induction decay yields proton Larmor precession ω_p *in same B field*
- Muon hyperfine normalizes (30 ppb)

Absolute calibration: spherical water sample





Improvement highlights

- Extensive Opera modeling of B
- Improved building temp. control (±1°C)
- Improved shimming:
  - ½ BNL gradient
  - Improved uniformity
- Improved magnet insulation
- Improved absolute calibration process
- More fixed probes
- Improved trolley position accuracy

0.17 ppm → 0.07 ppm uncertainty

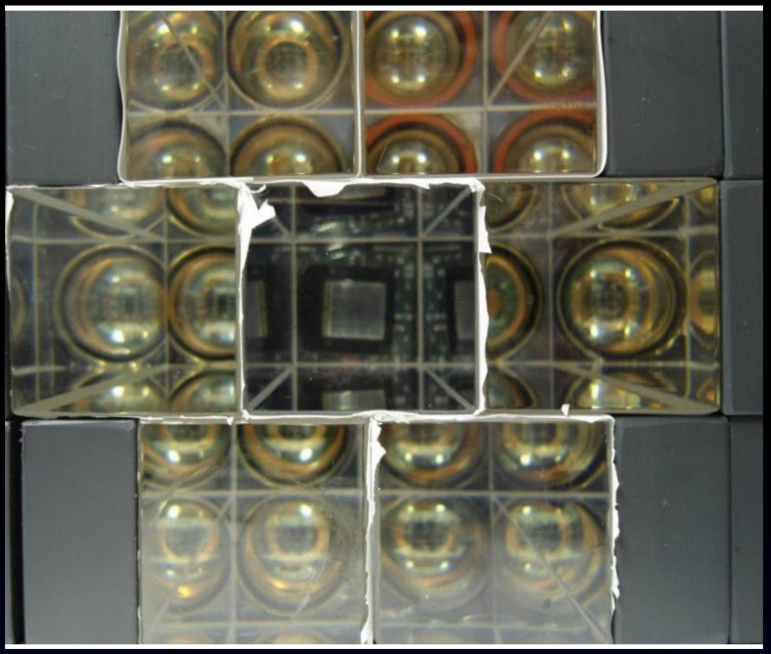
Measuring ω_a

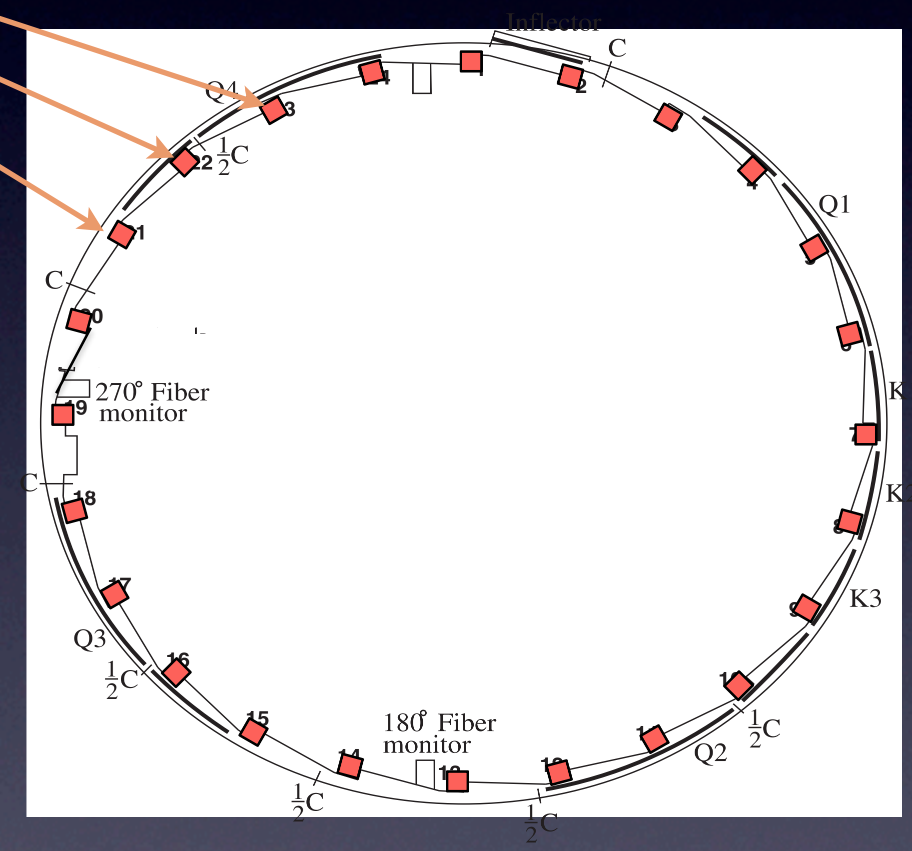
24 Calorimetry stations (E and t)

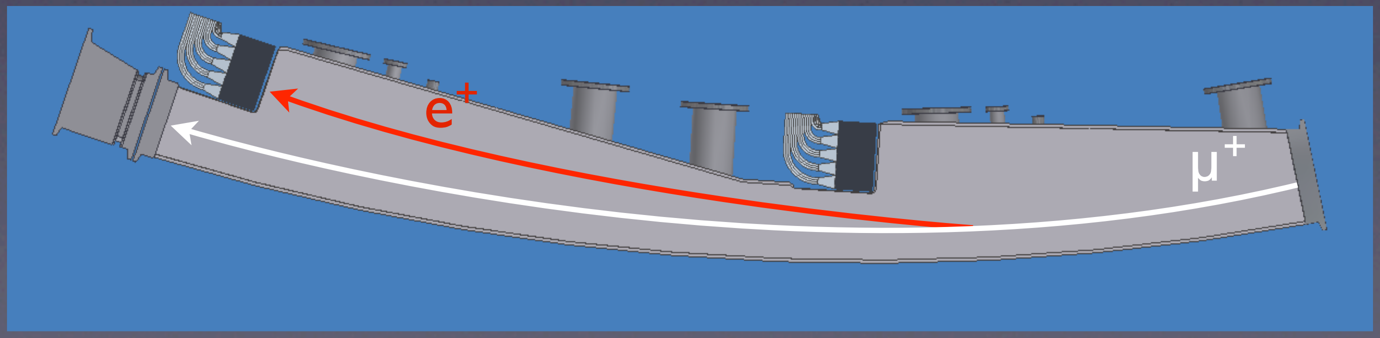
- 9x6 (2.5x2.5) cm PbF_2 array (X_0 = 0.93 cm)
- Silicon Photomultipliers
- 500 MSPS waveform digitizers

Improvements over E821

- Improved gain control and laser monitoring
- Pileup suppression via segmentation
- entire μ fill digitized, transferred to DAQ
    - opens new analysis methods
    - better gain systematic control
- reduced pion "flash"





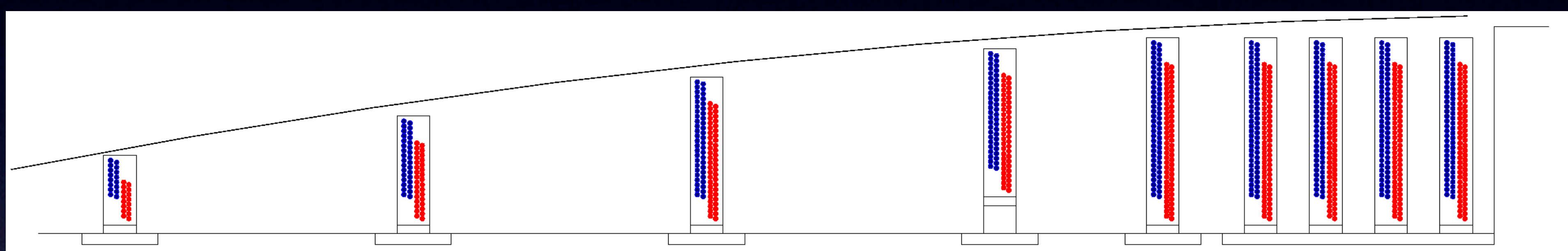


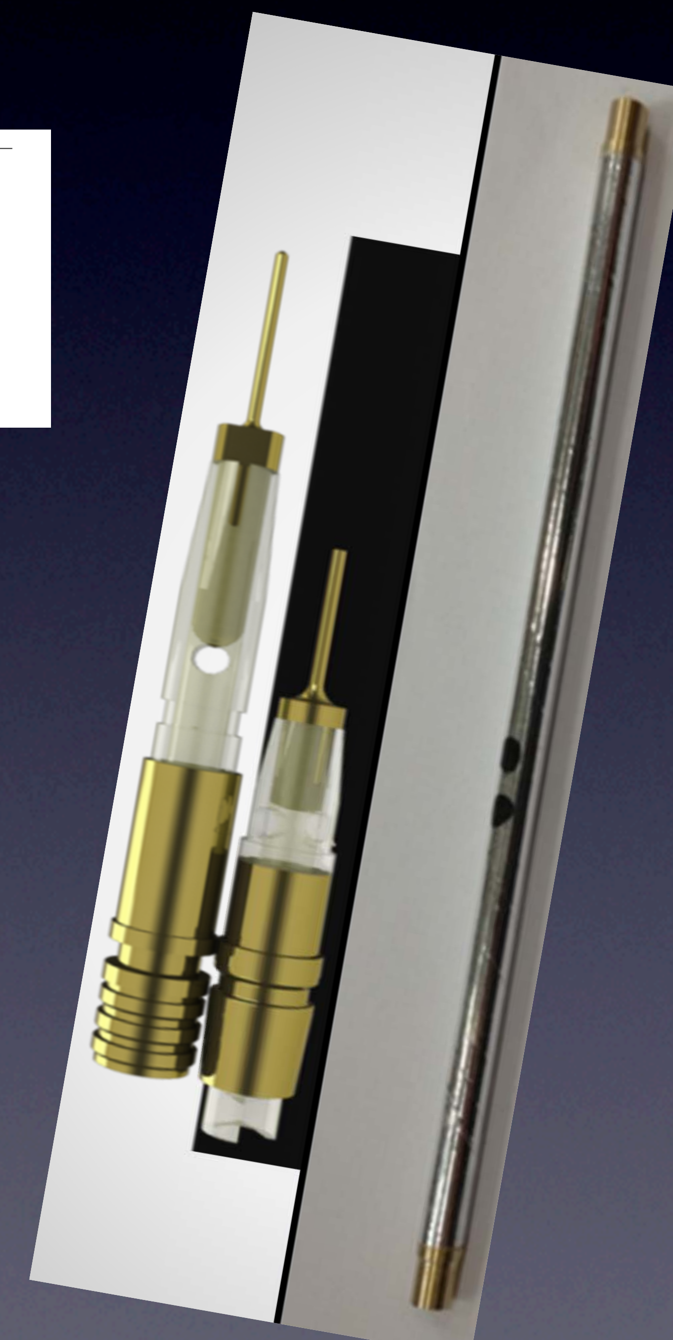
ω_a systematics:

0.18 → 0.07 ppm

Tracking

Straw tubes in vacuum in front of 2 PbF_2 arrays





N. Pohlman

- stereo angle: ±7.5° fom vertical
- Improved diagnostics
    - identify pileup sample
    - identify lost muon sample
    - E/p calibration
- muon EDM measurement (tips precession plane)
    - $d_\mu < 1.8\times10^{-19}$ e-cm → few 10^{-21}

Summary / Status

Expected beam + incremental measurement improvements:

➡ a_μ to ± 0.1(stat) ± 0.07 (ω_p) ± 0.07 (ω_a)

Detector funding in hand

- NSF Major Research Instrumentation for calo+daq
- DOE Early Career for straw chambers

Ring has been transferred BNL → Fermilab

DOE Critical Decision - 1 review next week

- proceed to technical design
- technically-driven schedule: beam in 2016
- funding-driven schedule: beam in 2017-2018 (?)