The muon g-2 experiment at Fermilab

VULCANO Workshop 2018

Marco Incagli – INFN Pisa

"g-2" : a precision test of Standard Model

$$\vec{\mu}_P = -g_P \frac{e}{2m_P} \vec{S}$$

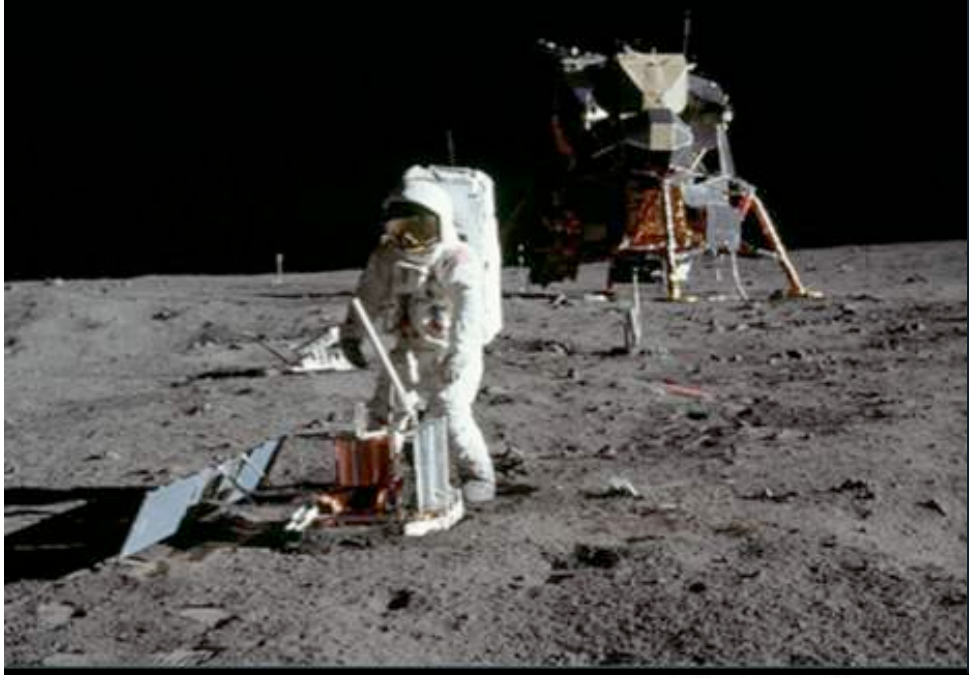
$$a_P = \frac{g_P - 2}{2}$$

$$a_\mu = (11\ 659\ 181.7 \pm 4.2) \times 10^{-10}$$

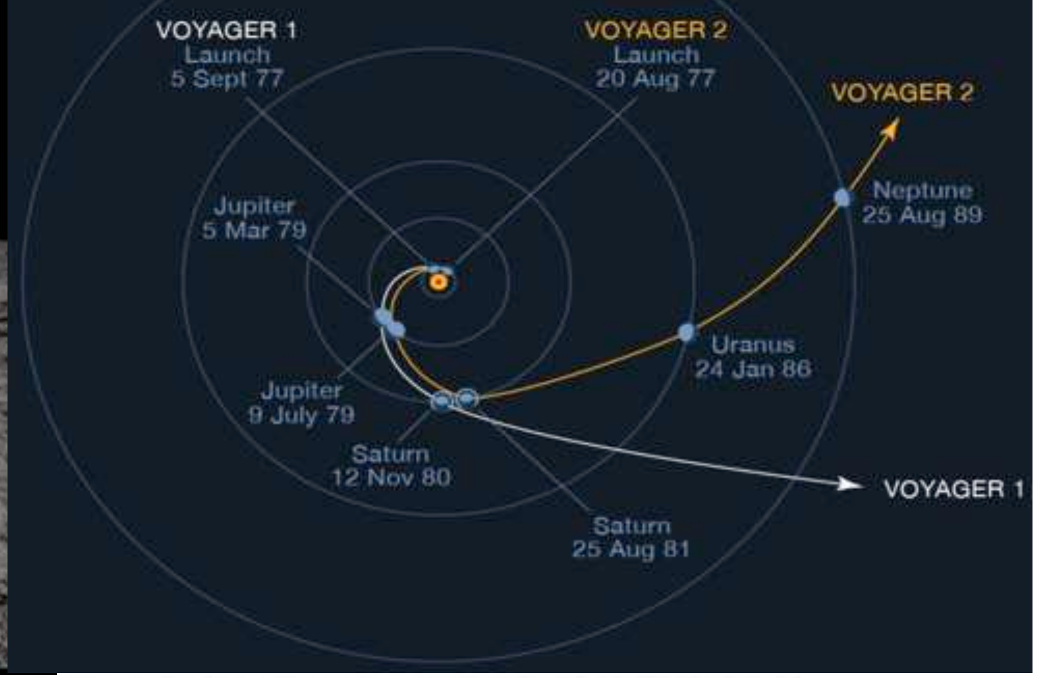
- ***g_P*** : proportionality between spin and magnetic moment for particle P
- ***a_P*** : anomalous magnetic moment
- ***a_P*** = 0 at tree level (*purely Dirac particle*)

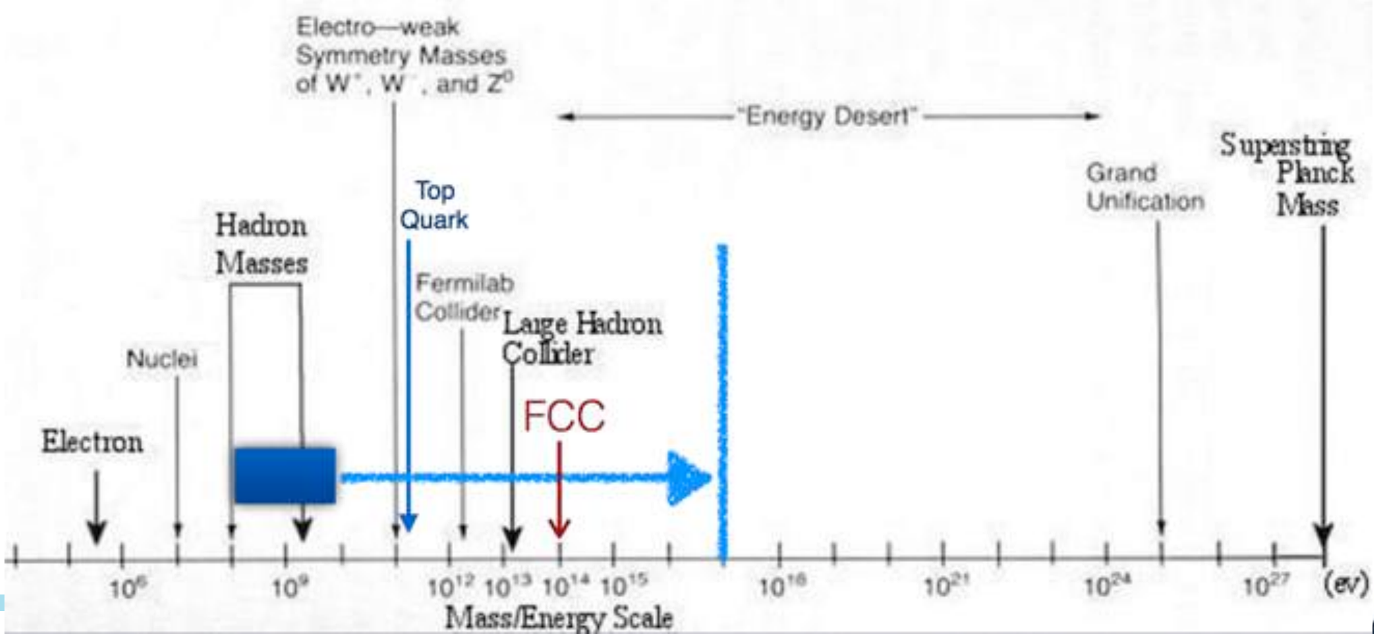
- The measurement of "g-2" or, more correctly, of the ***anomalous magnetic moment a_μ***, allows
  – for a precise test of the Standard Model
  – to look for New Physics

HIGH ENERGY: systematic search



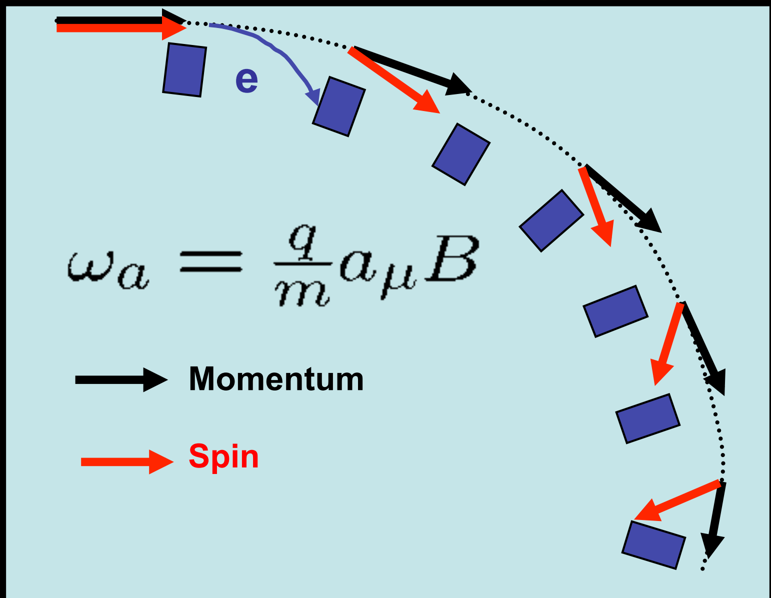
HIGH PRECISION: launching probes





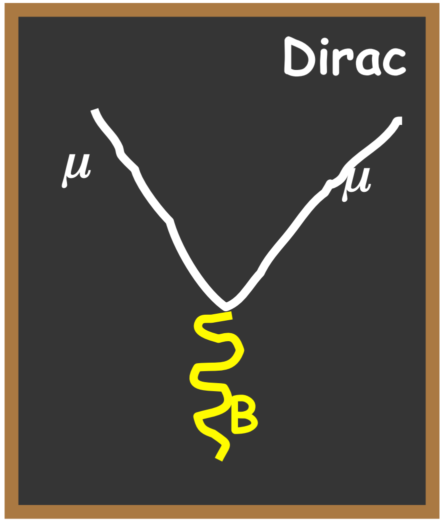
Today's probe

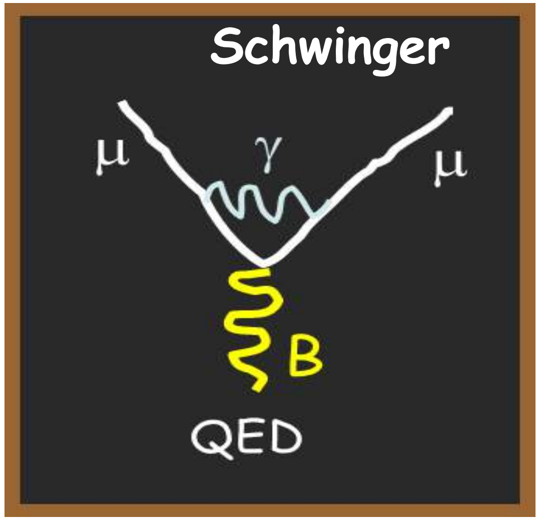
- The Muon's Anomalous Magnetic Moment



Contributions to a_μ

$$a_\mu \quad = \quad 0 \quad + \quad \alpha/2\pi \quad + \quad ....$$





1948 , first big success of QED :

$a^{exp} = 0.00118 \pm 0.00003$ Kush & Foley

$a^{the} = \alpha/2\pi = 0.00116$ Schwinger

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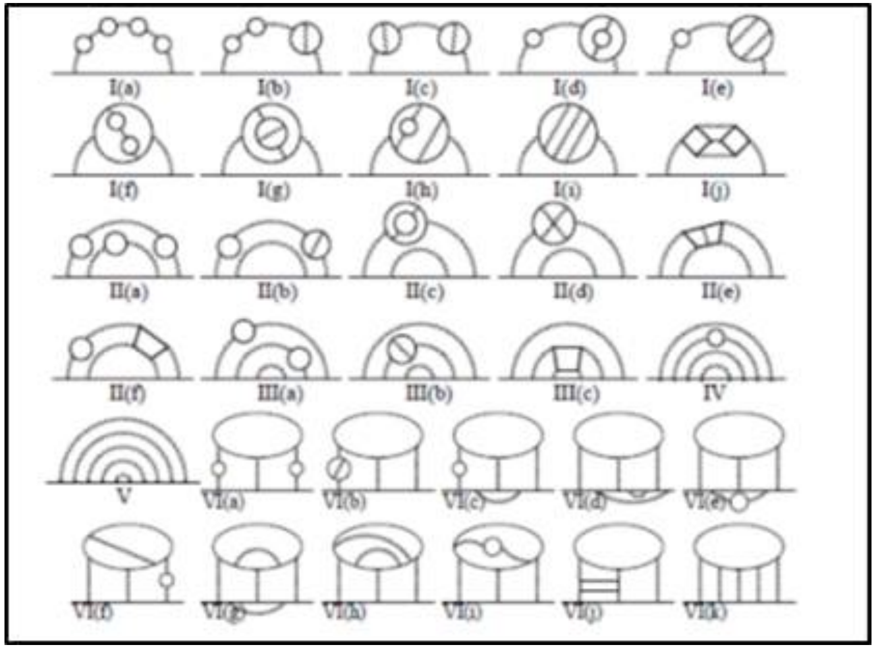
Contributions to a_μ

$$a_\mu = 0 + \alpha/2\pi + QED^* + \ ....$$

QED 1st Order	116140973.301
QED 2nd Order	413217.621
QED 3rd Order	30141.902
QED 4th Order	380.807
QED 5th Order	4.483



Presently: QED thru tenth-order terms (12,672 diagrams)

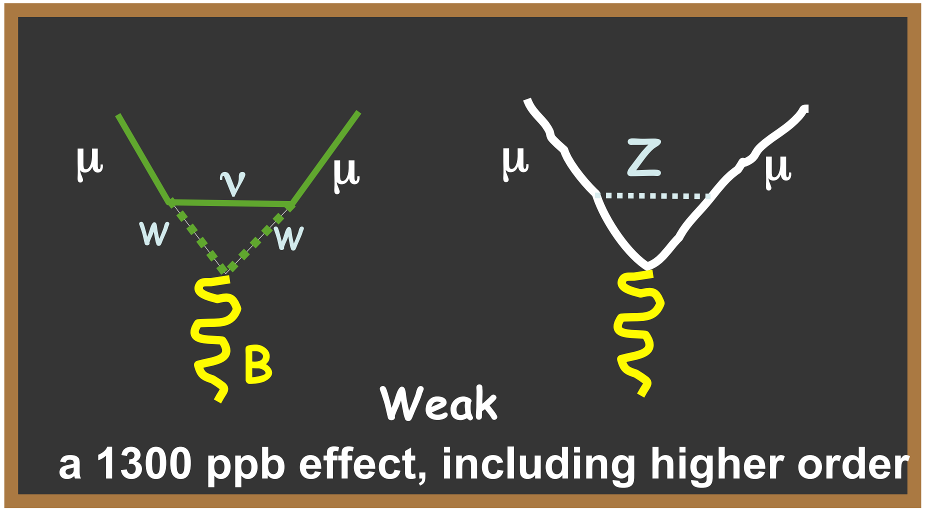
Revised and Improved Value of the QED Tenth-Order Electron Anomalous Magnetic Moment

Tatsumi Aoyama,[1,2] Toichiro Kinoshita,[3,4] and Makiko Nio[2]

(Dated: December 19, 2017)

Contributions to a_μ

$$a_\mu \quad = \quad 0 \; + \alpha/2\pi + QED^* + \; EW + \quad ....$$

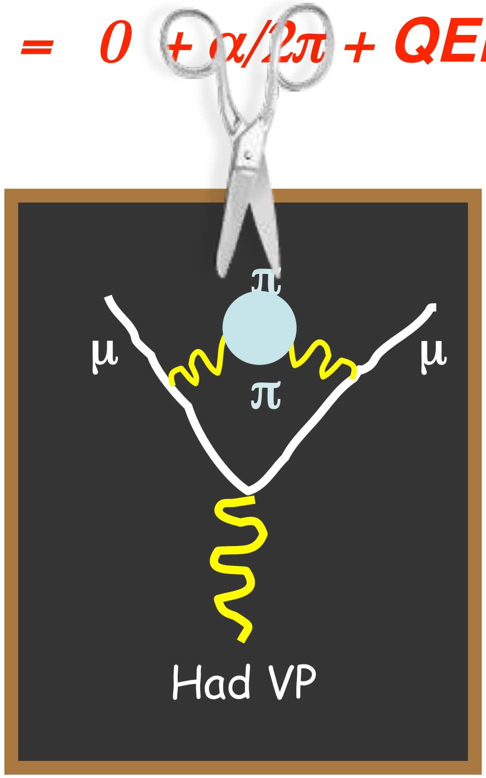


Well known now, but not an easy calculation

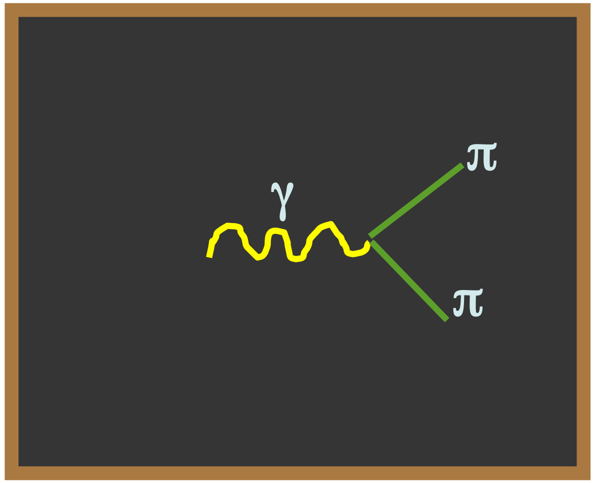
Weak 1st Order	194.820
Weak 2nd Order	-41.760
	x 10^{-11}

Contributions to a_μ

$$a_\mu = 0 + \alpha/2\pi + QED^* + EW + HLO + ...$$



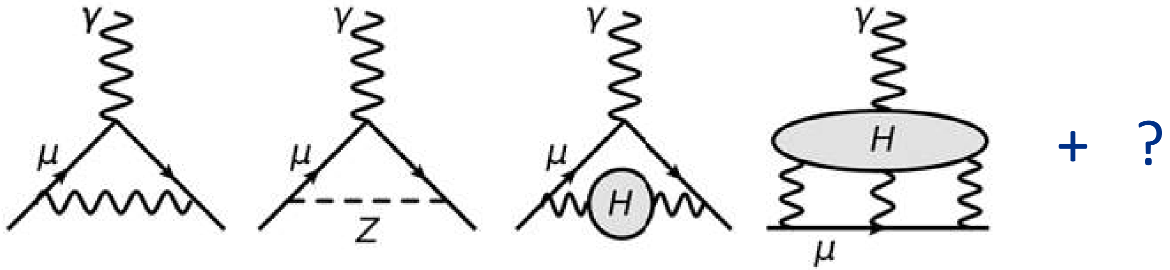
HLO = Hadronic Leading Order



This contribution can be exactly linked to experimental data

1. **Cut diagram down middle**
2. **Looks like $\gamma > \pi\pi$**
3. **Dispersion relation connects $e^+e^- > \pi\pi$ cross section measurement to 1st-order Hadron Vacuum Polarization**

Contributions to a_μ

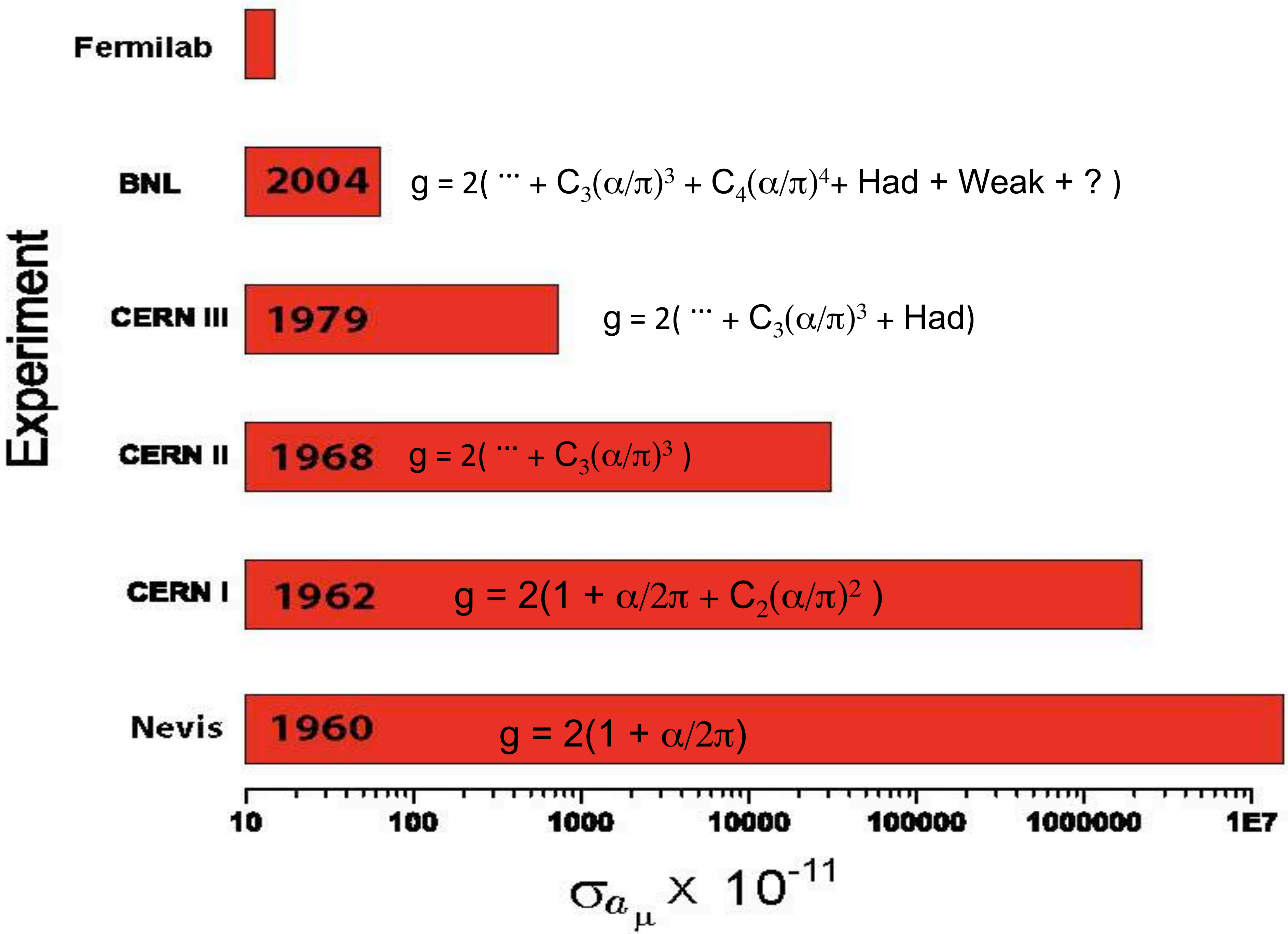


QED	Weak	HLO	HLbL	New Physics.
Known	Known	Data	Models/Lattice	?

HLbL = Hadronic Light by Light = Hadronic higher order

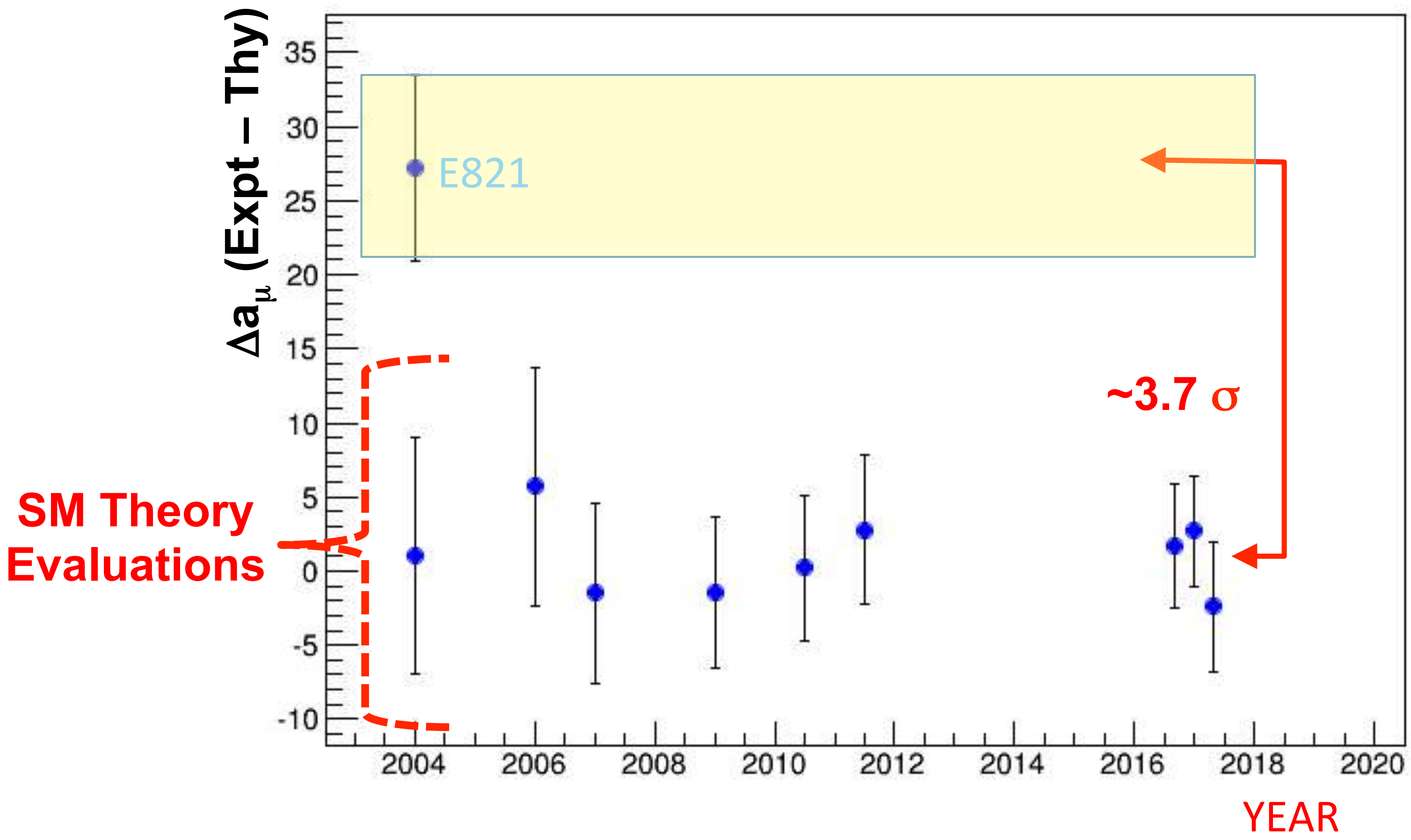
	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$

BNL E821 δa_μ(Expt) = ± 6.3


Fermilab
BNL
2004
g = 2(··· + C3(α/π)3 + C4(α/π)4+ Had + Weak + ?)
CERN III
1979
g = 2(··· + C3(α/π)3 + Had)
CERN II
1968
g = 2(··· + C3(α/π)3)
CERN I
1962
g = 2(1 + α/2π + C2(α/π)2)
Nevis
1960
g = 2(1 + α/2π)
Experiment
10
100
1000
10000
100000
1000000
1E7
σaμ X 10-11

The “g-2 Test” has continued to point to something interesting

E821 = BNL experiment



Sensitivity to new physics at the TeV scale!

Very generally New Physics contributions to a_μ take the form:

$$a_\mu^{NP} \approx C \times \frac{m_\mu^2}{M^2}$$

New Physics coupling (→ C)

New Physics Mass scale (→ M)

a_μ is a flavor and CP conserving, chirality flipping loop induced quantity.

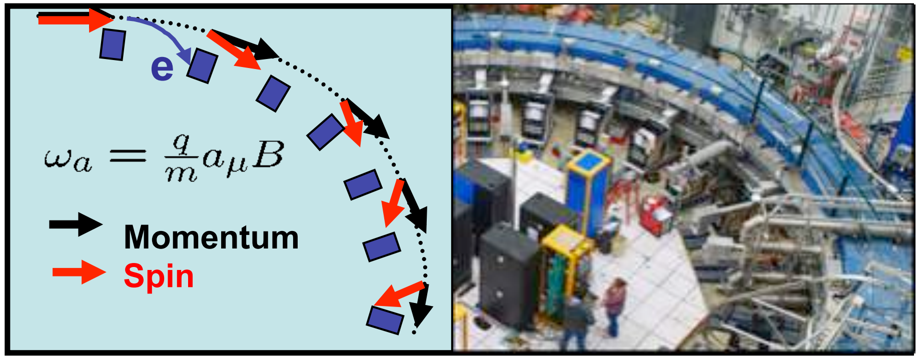
e.g.: in SUSY it is sensitive to charginos and sleptons. LHC direct searches are sensitive to squarks and gluinos.

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \frac{m_\mu^2}{M^2} \tan\beta$$

Ratio of the vacuum expectation value for the two Higgs doublets* (5-50) (→ $\tan\beta$)

* JHEP11(2014)058

The Fundamental Experimental Principle



- Difference between spin precession and cyclotron motion for a muon (charged particle with spin) in a magnetic field*:

$$\omega_a = \omega_s - \omega_c = g\frac{e}{2m}B - \frac{e}{m}B = a_\mu \frac{e}{m}B$$

*$\mathbf{s}$ and $\mathbf{p}$ are assumed to be in a plane perpendicular to $\mathbf{B}$

- simple classical calculation;
- the relativistic approach provides the same result!

The Fundamental Experimental Principle

- To keep the muon beam focused, **electrostatic quadrupoles** are used
- The ***E*** *field* modifies the frequence as follows:

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

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Magic $\gamma \sim 29.3$

- By choosing a *"Magic γ"* of $\gamma = 29.3$, corresponding to a muon momentum of 3.1 GeV, the electric field contribution cancels out (...at least at first order!)

The Fundamental Experimental Principle

- To keep the muon beam focused, **electrostatic quadrupoles** are used
- The ***E*** *field* modifies the frequence as follows:

Get a_μ

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

Measure these

Magic $\gamma \sim 29.3$

- By choosing a *"Magic γ"* of $\gamma=29.3$, corresponding to a muon momentum of 3.1 GeV, the electric field contribution cancels out (...at least at first order!)

Side Note:
g-2 is, in part, also an EDM experiment

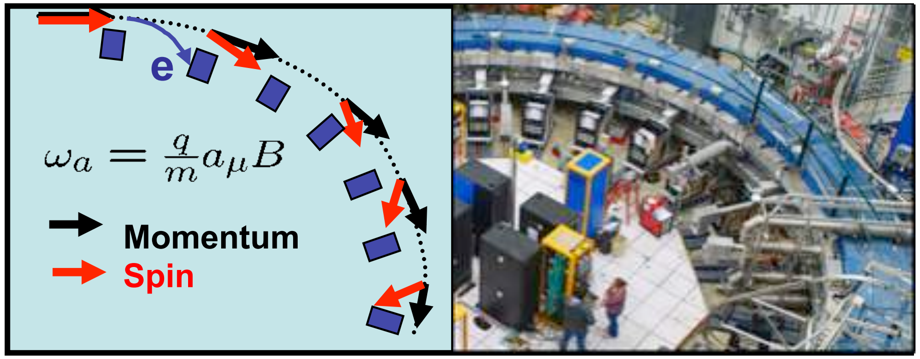
- A muon Electric Dipole Moment (EDM) would give an additional contribution to the spin rotation:

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

$$\vec{\omega}_{net} = \vec{\omega}_a + \vec{\omega}_{EDM}$$

- An η term would result in a *out of plane* spin precession
- In the frame of **Standard Model**, where only 1 CP violating phase exists, η is strongly suppressed
- This is not the case for **supersimmetry**, where *many CP violating phases exist*

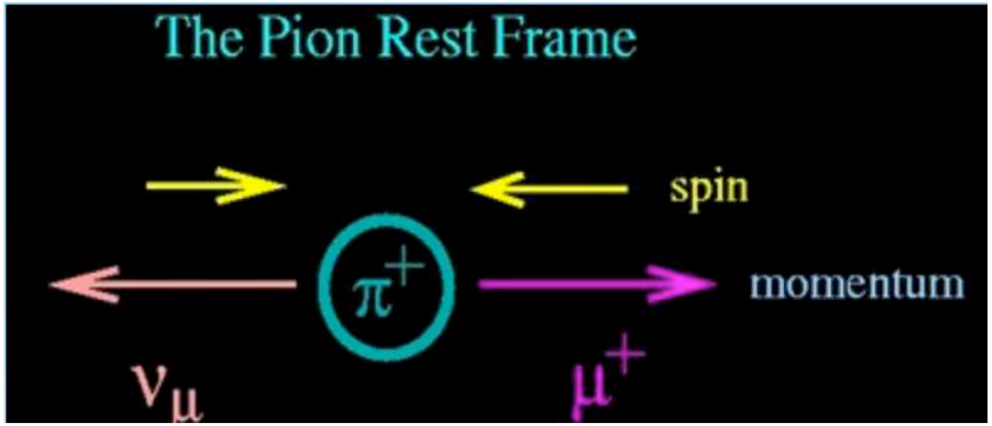
The Fundamental Experimental Principle



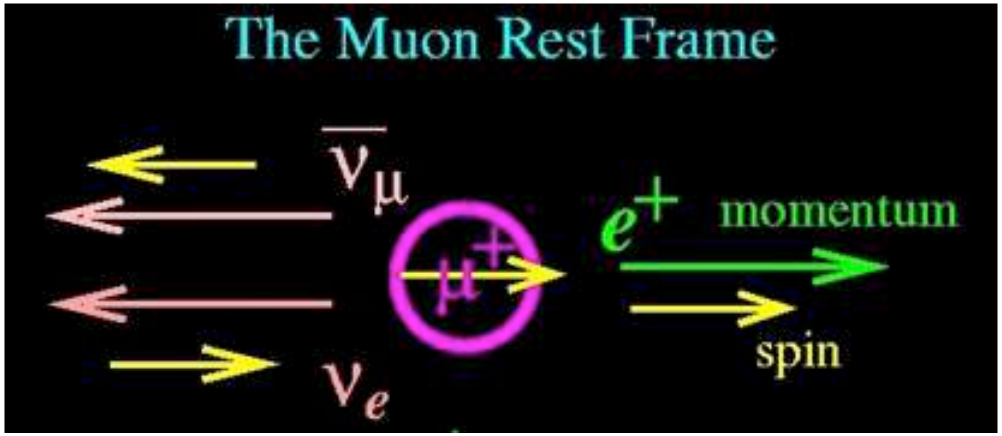
- To measure the *Spin precession with respect to the particle momentum (ω_a)*, two ingredients are needed:
  - a polarized muon beam
  - a way to measure muon Spin as a function of time (= a polarizer)

Polarization

- Use V-A structure of weak decays to build a polarized beam...



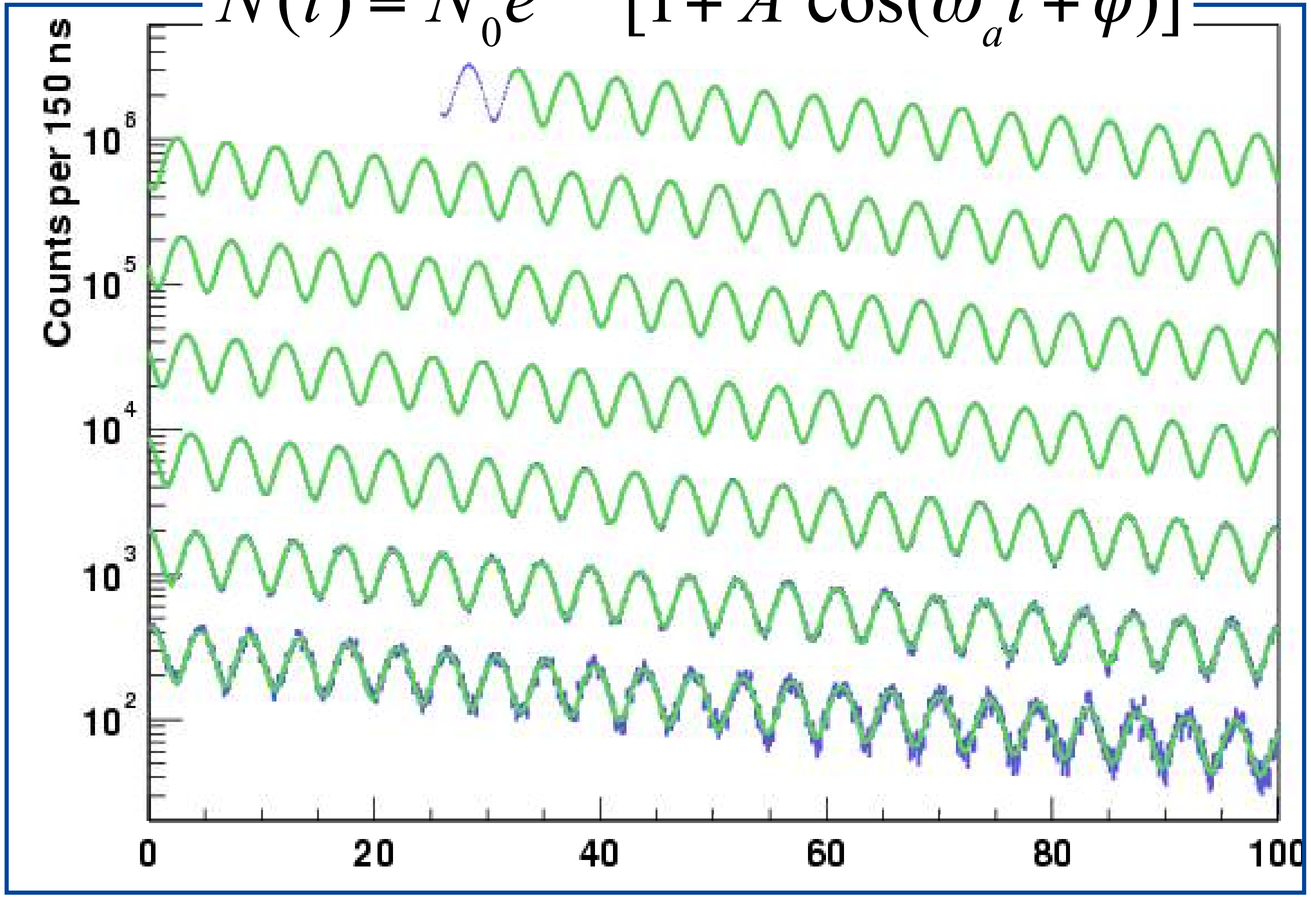
- ... and to measure muon polarization



Measuring the spin precession

- The number of observed positrons from muon decay oscillates with the ω_a frequency due to spin precession

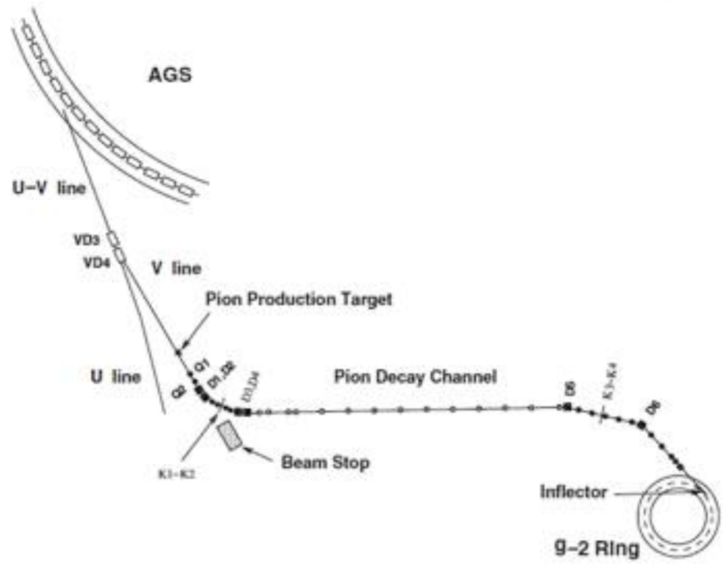
$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$



time (μsec)

- exponential decay modulated by spin precession
- note that the x-axis "wraps up" every 100 μsec for a total of 700msec, corresponding to 11 muon lifetimes

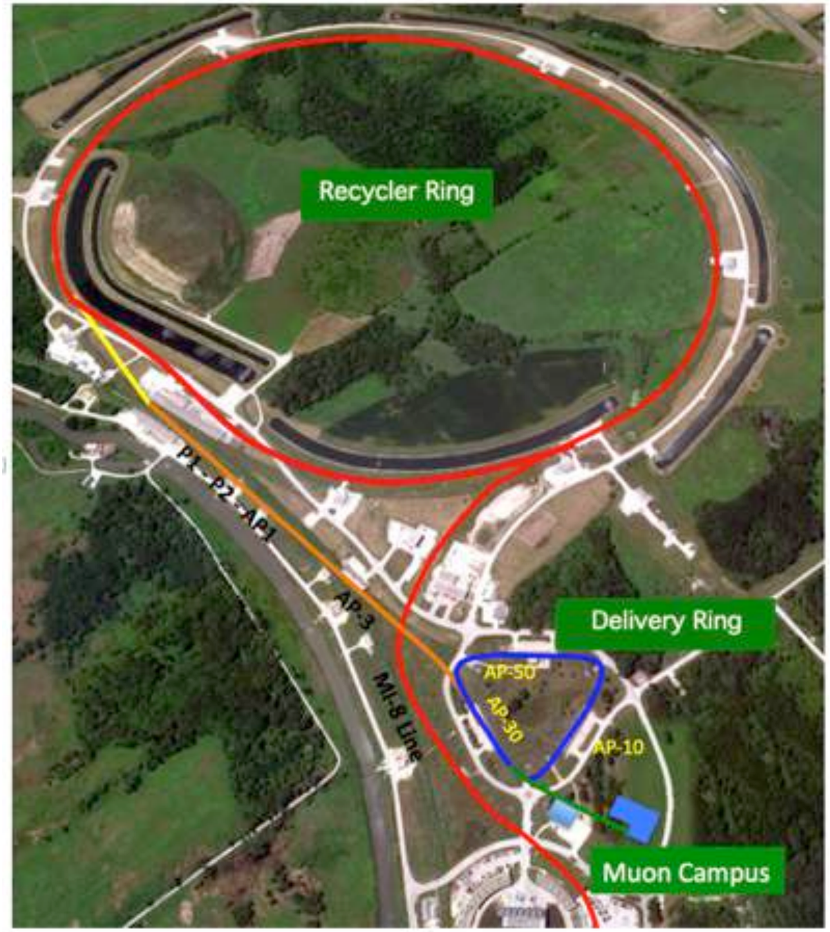
Beam: BNL



24 GeV/c proton beam

The pion decay channel is **80 m** and the ring diameter is 14.1 m. Most m are thrown away to minimize pion content of the beam. $\pi/\mu \simeq 1{:}1$, big source of background

Fermilab



8 GeV/c proton beam from Booster

The pion decay channel is ≃ **2 km**, No pions left

Analyzed Events: **9×10^{9}**

E989 **goal: 2×10^{11}**

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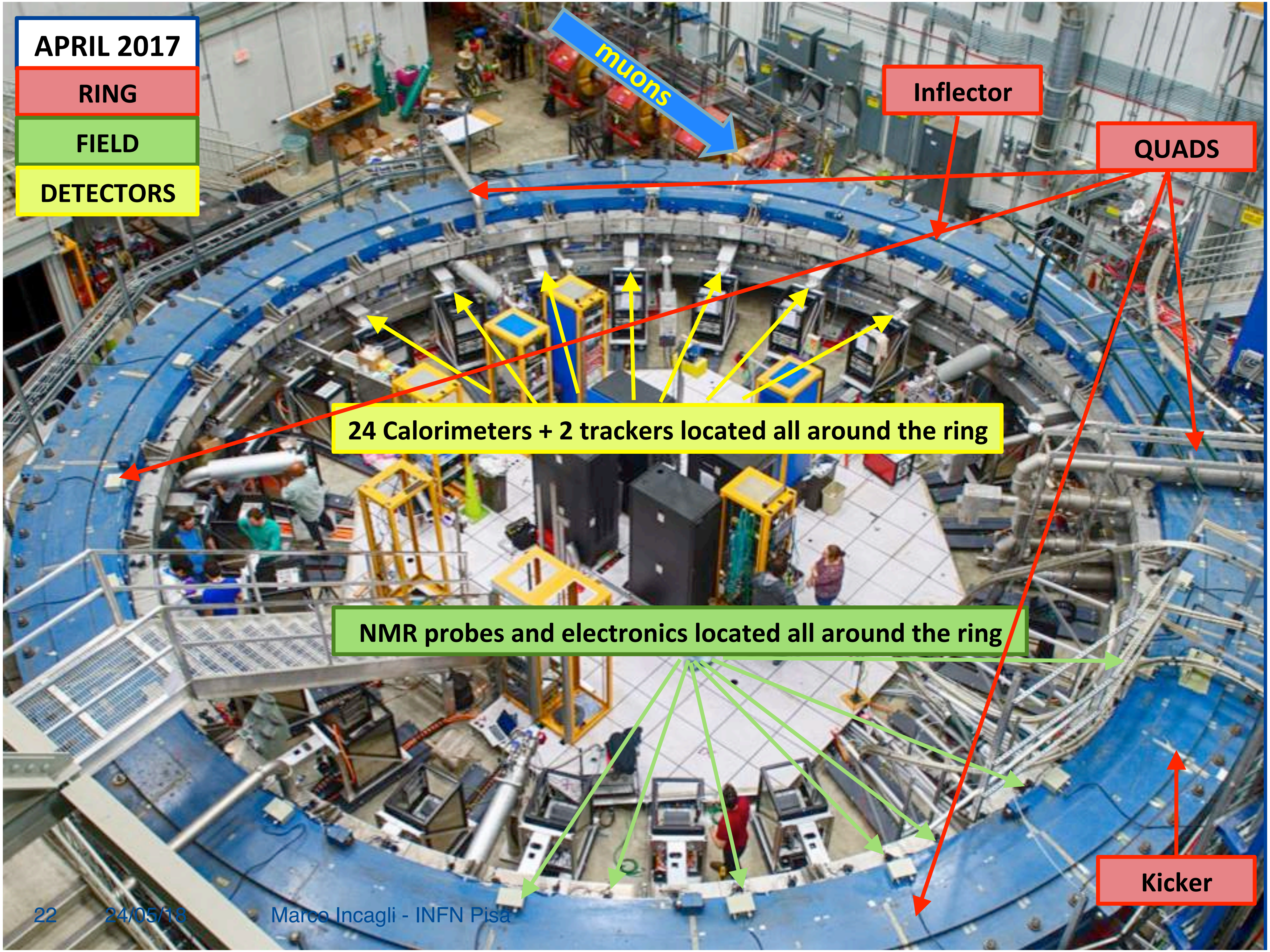

APRIL 2017
RING
FIELD
DETECTORS
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

A formal way to write this looks like

- Expressing the magnetic field in terms of the *free proton precession* ω_p, a_μ can be written as:

$$a_\mu(\text{Expt}) = \frac{g_e}{2}\frac{\omega_a}{\omega_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

0.001519270384(12) [8 ppb]

206.768 2843(52) **[25 ppb]**

We will measure these two frequencies and report the Ratio $\boldsymbol{R_\mu}$

In previous experiment $\boldsymbol{R_\mu}$ *= 0.003 707 206 4(2 0)*[0.54 ppm]

Requirements for a better measurement

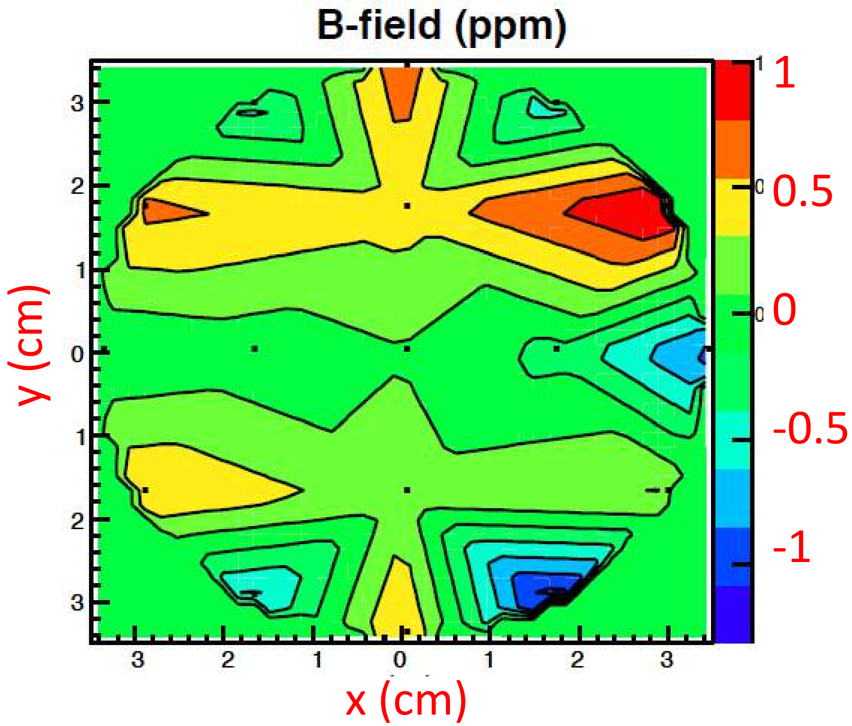
1. Store More Muons
   - ~20 x BNL in statistics … (→100 ppb)

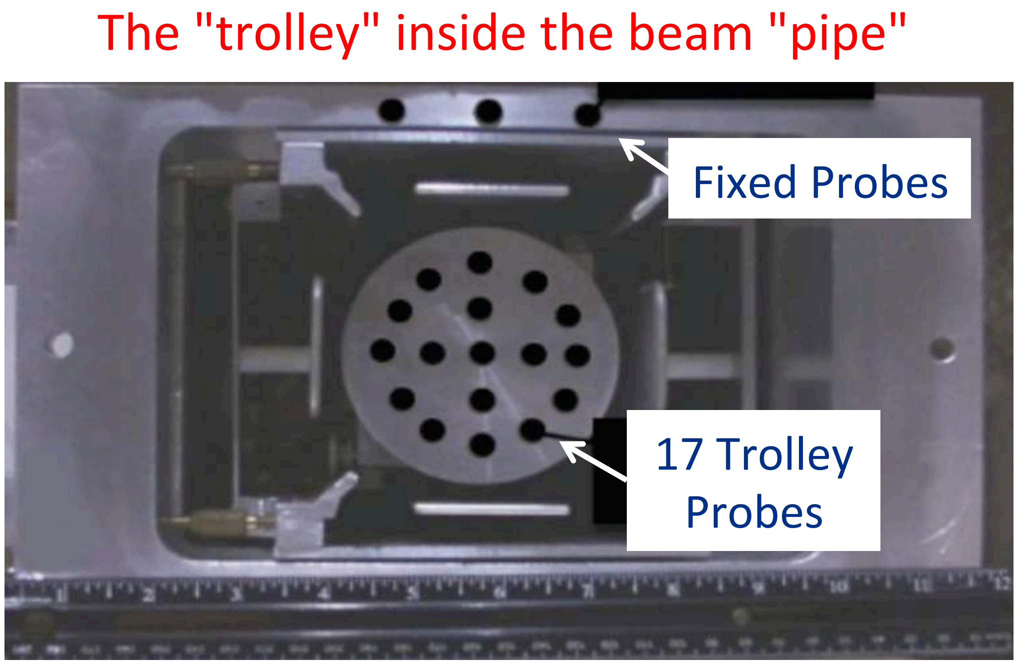
2. Prepare A More Uniform Magnetic Field
   - Goal: 3 x better and more carefully measured (→70 ppb)

3. Improve the Precession Frequency Measurement
   - All new instrumentation with high-fidelity recording of muon decays by many systems (→70 ppb)

To measure the Field, ω_p we start with the BNL magnet but improve its field uniformity

Field is measured using protons NMR





- A ***Trolley*** runs inside the beam pipe to map periodically the field by a set of pNMR probes : 1 run of ~3h is performed every 3d
- A set of 378 fixed probes are located in 72 locations in azimuth

Systematics on ω_a

- The goal of the Fermilab experiment is to reduce the systematic error on ω_a ***180→70 ppb***
  - ➢ Improved Calorimeters
  - ➢ New Laser control system
  - ➢ New Tracker

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

Key element:

Laser

Calo + Laser

Calo + Laser

Inflector + Kicker

Tracker

Systematics on ω_a

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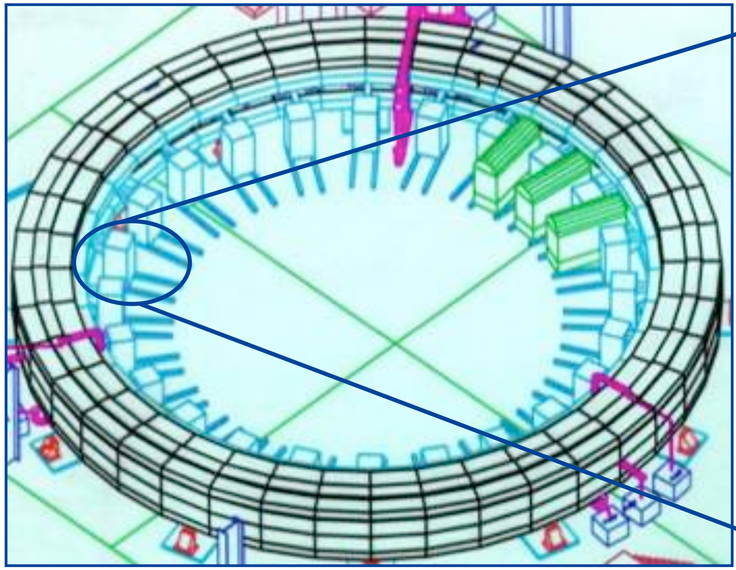
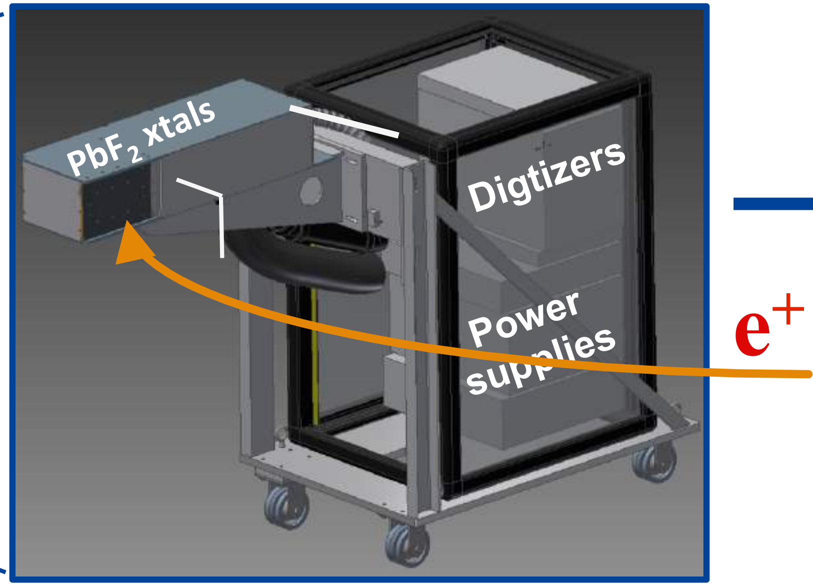
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]	Key element:
Gain changes	120	Better laser calibration low-energy threshold	20	Laser (Largest improvement)
Pileup	80	Low-energy samples recorded calorimeter segmentation	40	Calo + Laser
Lost muons	90	Better collimation in ring	20	Calo + Laser
CBO	70	Higher n value (frequency) Better match of beamline to ring	< 30	Inflector + Kicker
E and pitch	50	Improved tracker Precise storage ring simulations	30	Tracker
Total	180	Quadrature sum	70	

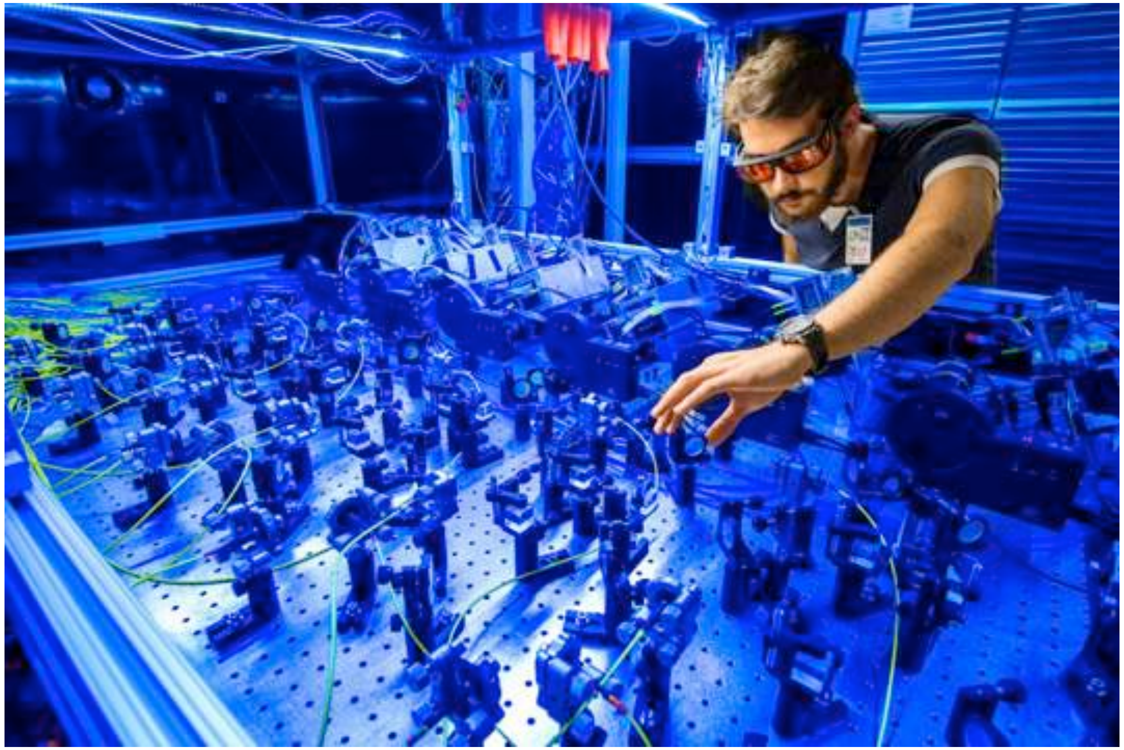
The new calorimeter

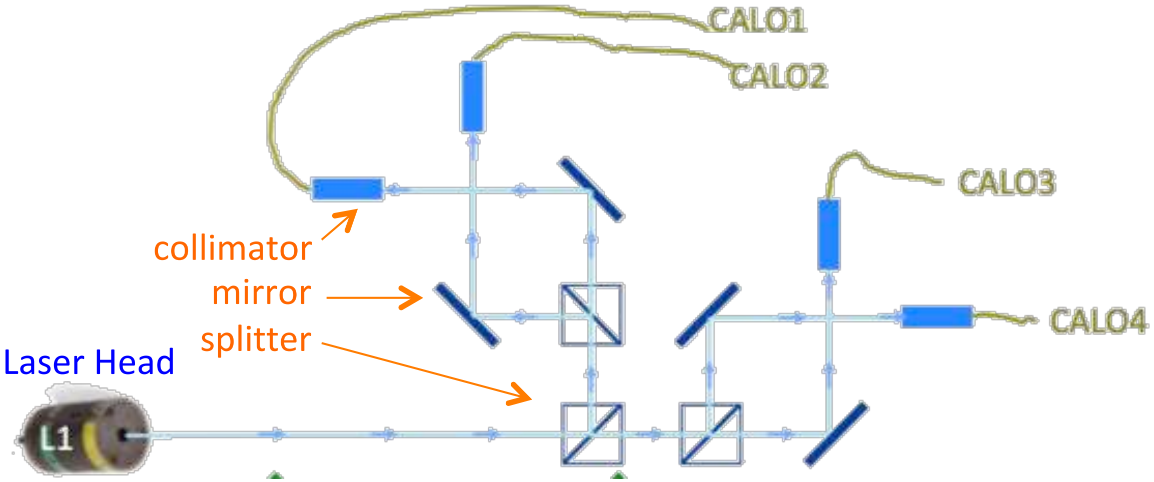




Segmented array of PbF_2 crystals to reduce pileup (was one full block in BNL exp. E821)

The Laser energy-time calibration system

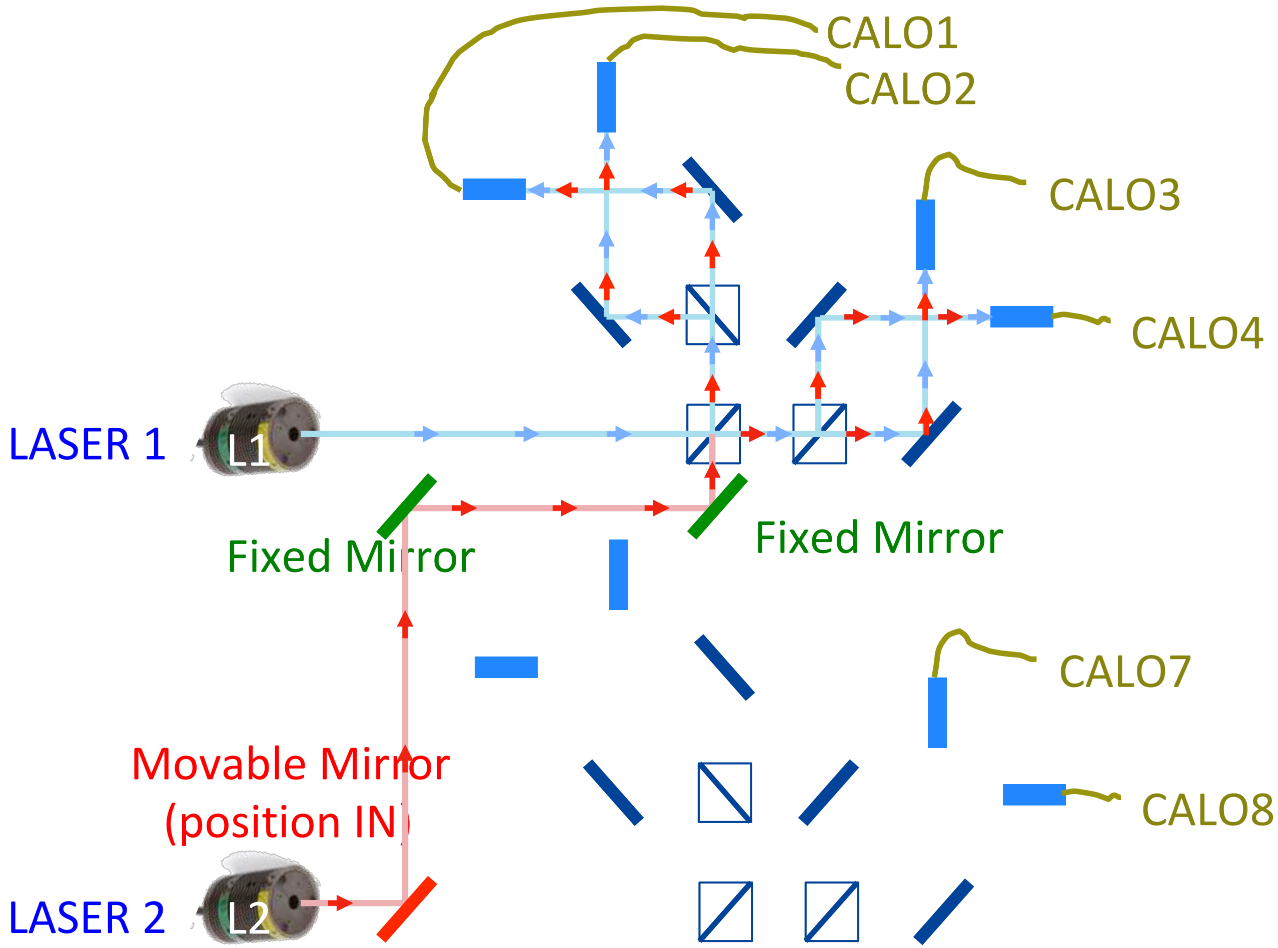




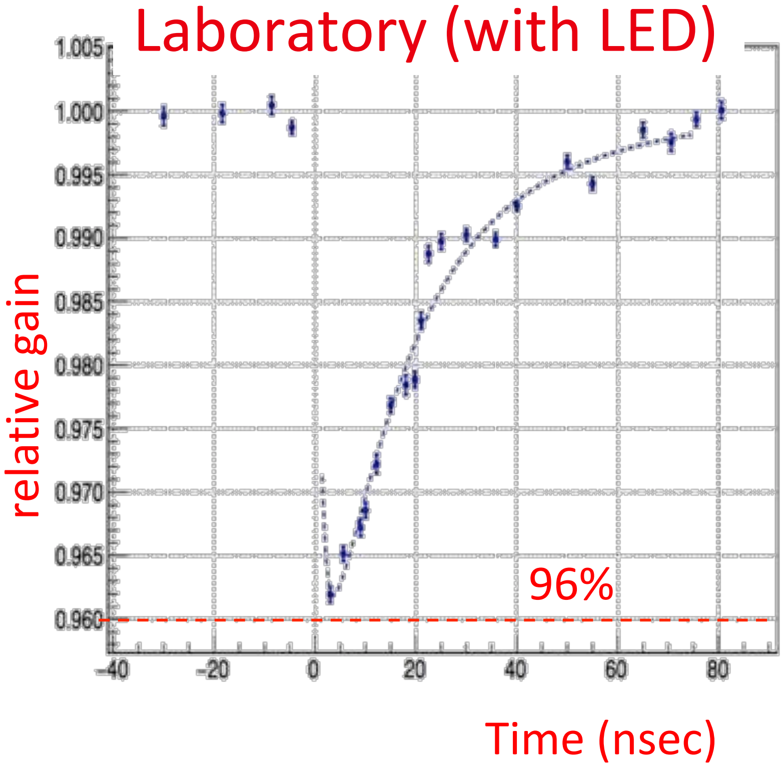
- State-of-the-art Laser-based calibration system
- 6 laser each one calibrating 4 calorimeters
- GAIN stability established to ~few x 10^{-4}
- SYNC pulse before beam injection provides time synchronization
- To keep laser stability at 10^{-4} level → fraction of laser light sent to redundant monitoring system

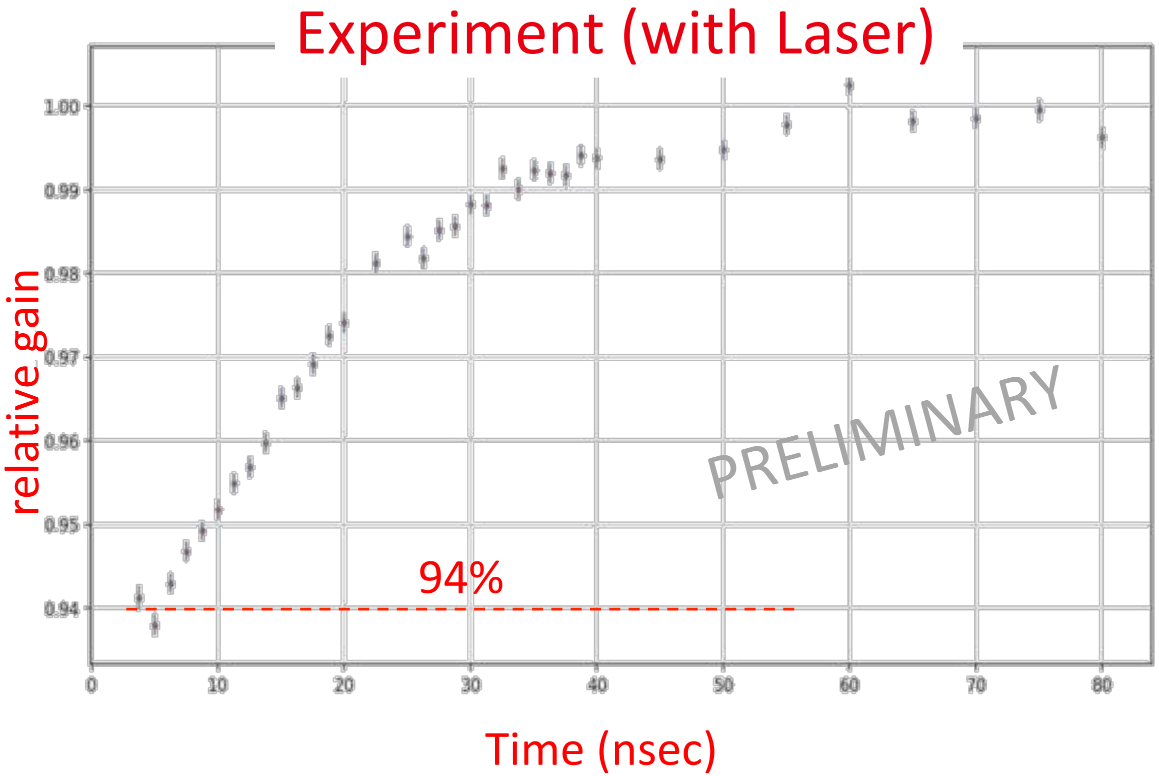
Example: measuring pile up effect

- To measure CALO response to consecutive hits (pile up) two laser pulses are sent into the same calorimeters



Calorimeter response to close positrons





- The calorimeter response is not 1 for two close hits (<40nsec)
- Systematic effect: pile up is more probable in the first part of the fill (muon life time ~64 μsec)
- With the Laser, all 1296 channels can be routinely measured

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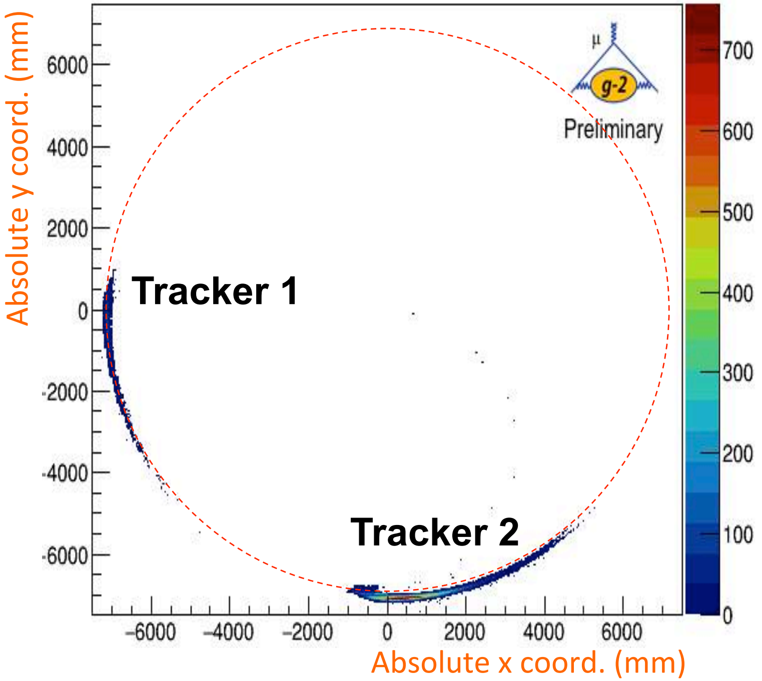
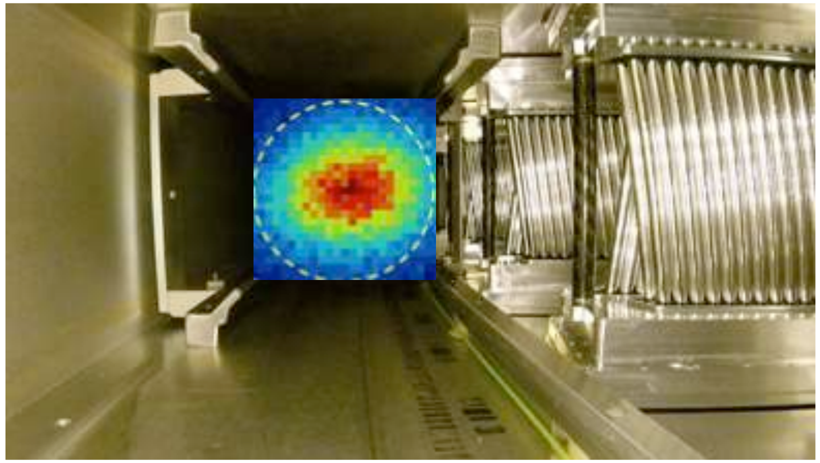
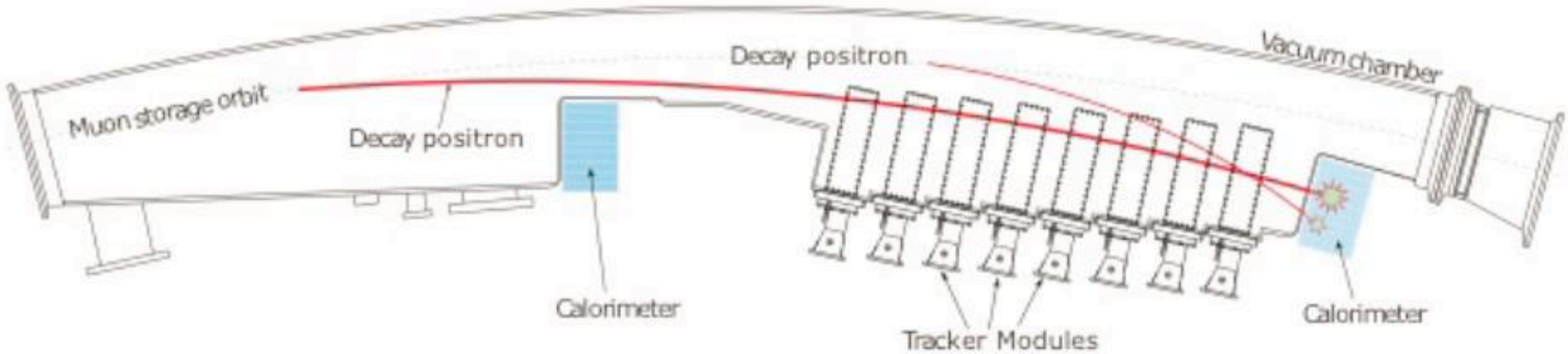
In-vacuum Straw Tracker determines Muon Distribution → limits on EDM via out of plane precession







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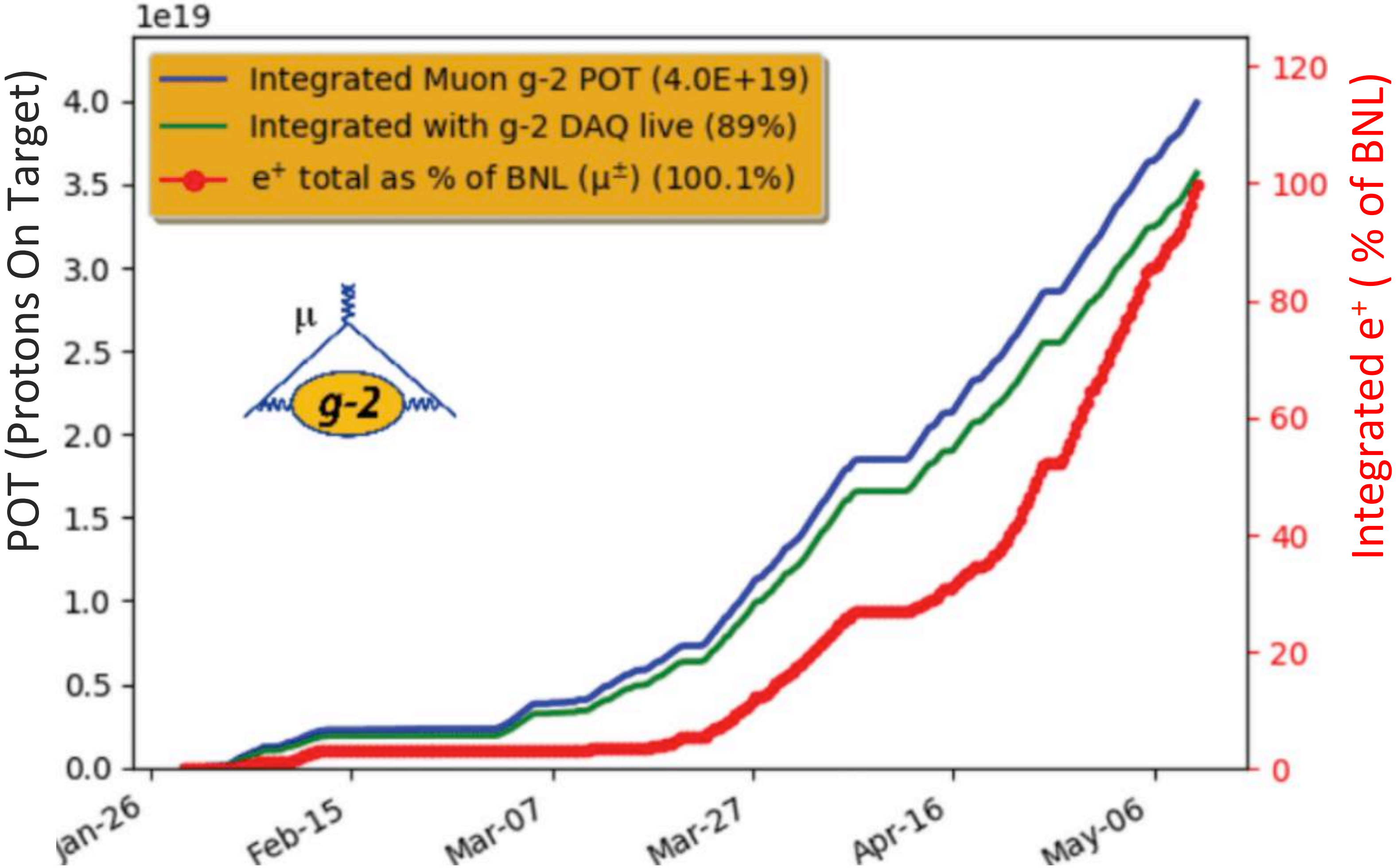
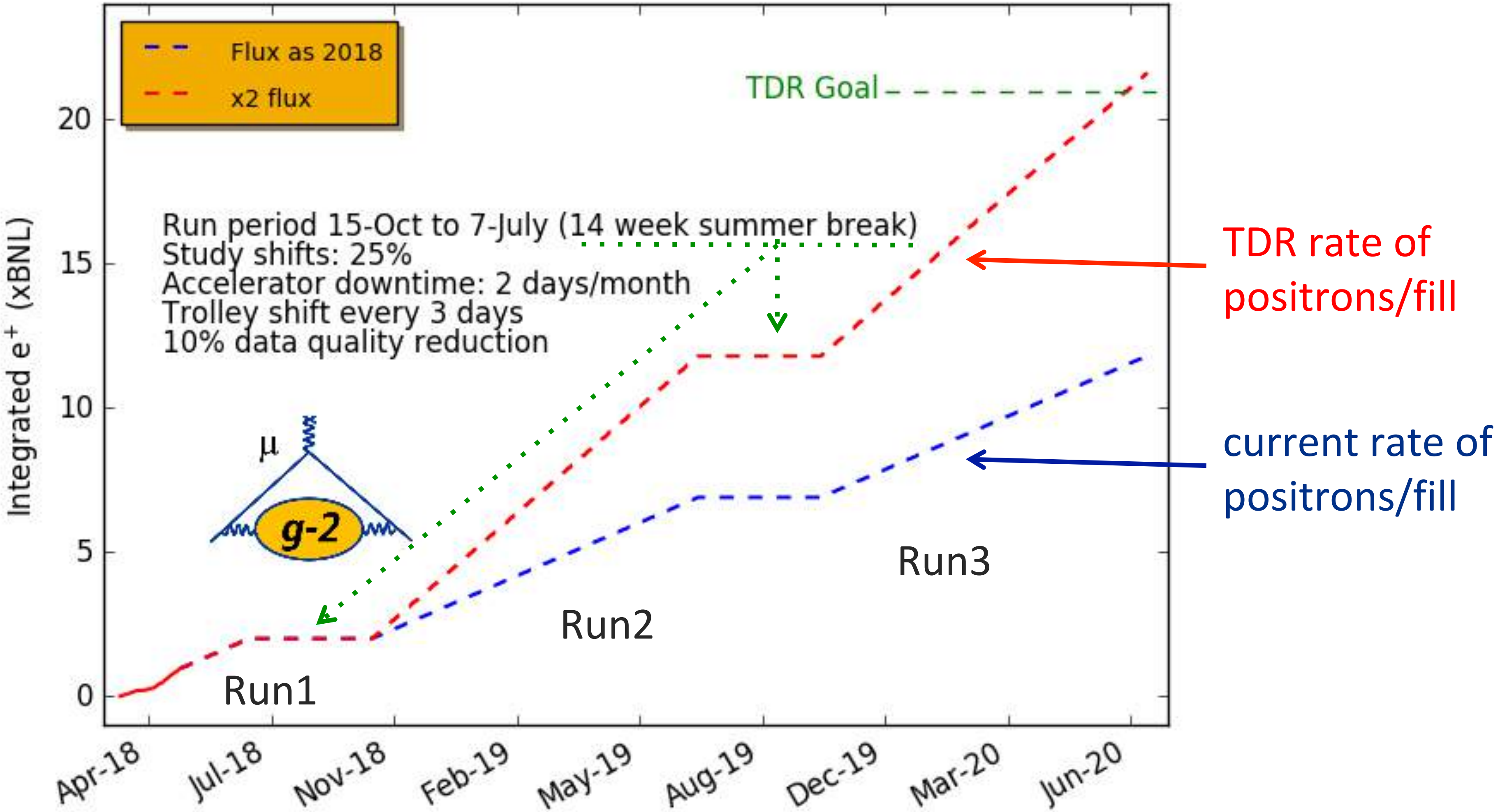
Data taking just started …



- BNL statistics reached on May 10!
- NOTE: <u>this is a rough proxy of BNL statistics</u>

Run1 + Run2 + Run3 ~ 20*BNL (statistics)

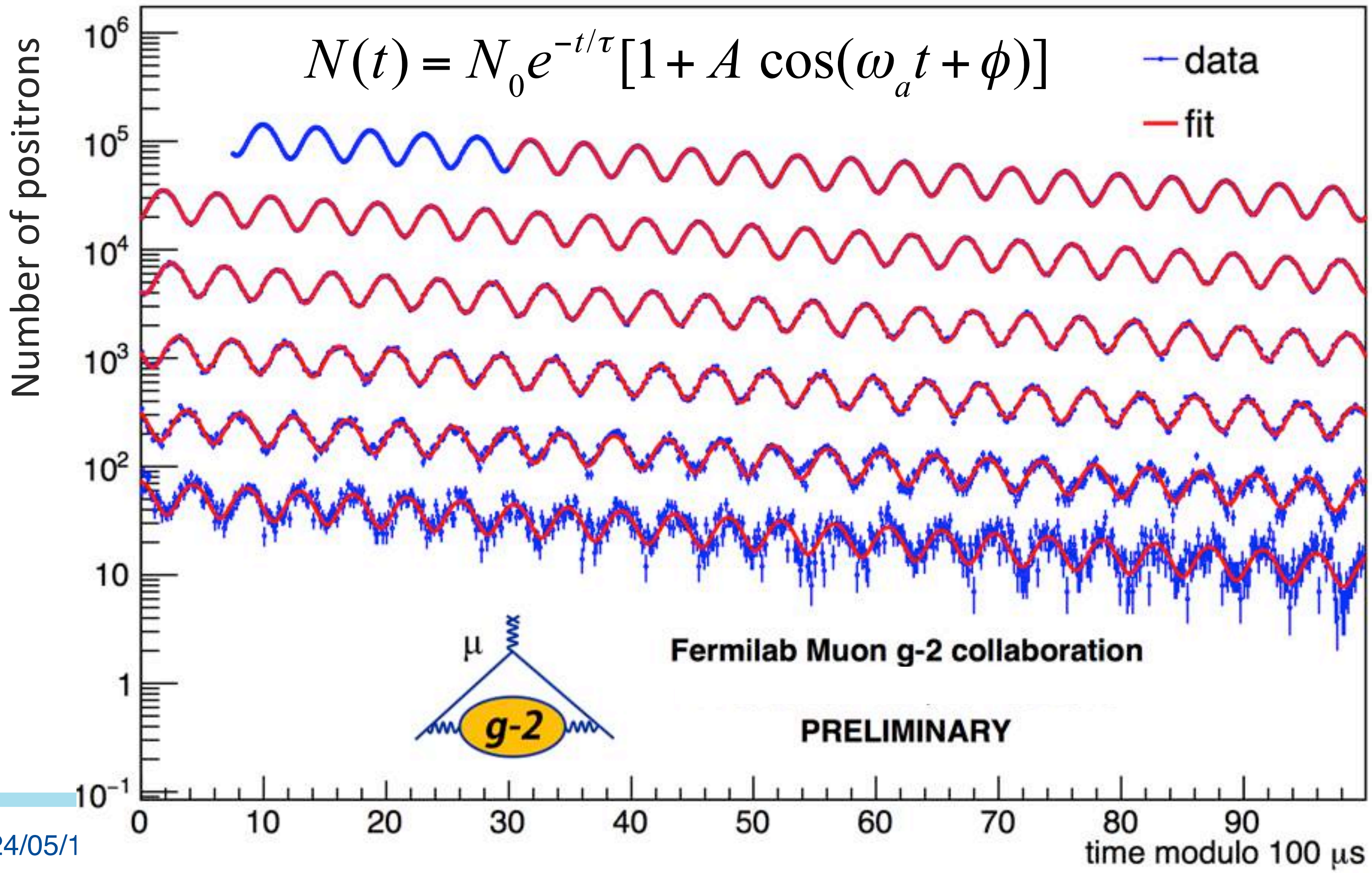


Summer 2018 → path to higher flux

- Several improvements foreseen for this summer, each contributing to increase the stored muons by 10-30%
- Accelerator upgrades
  - faster switching between MuonCampus-BeamTest
  - New target
  - Add wedges for beam momentum compaction
- Ring upgrades
  - Kicker : key upgrade for improving quality of stored beam
  - Quads : fix instabilities which cause Quads to run at HV lower than BNL (20kV vs 25kV)
  - Inflector : install new inflector

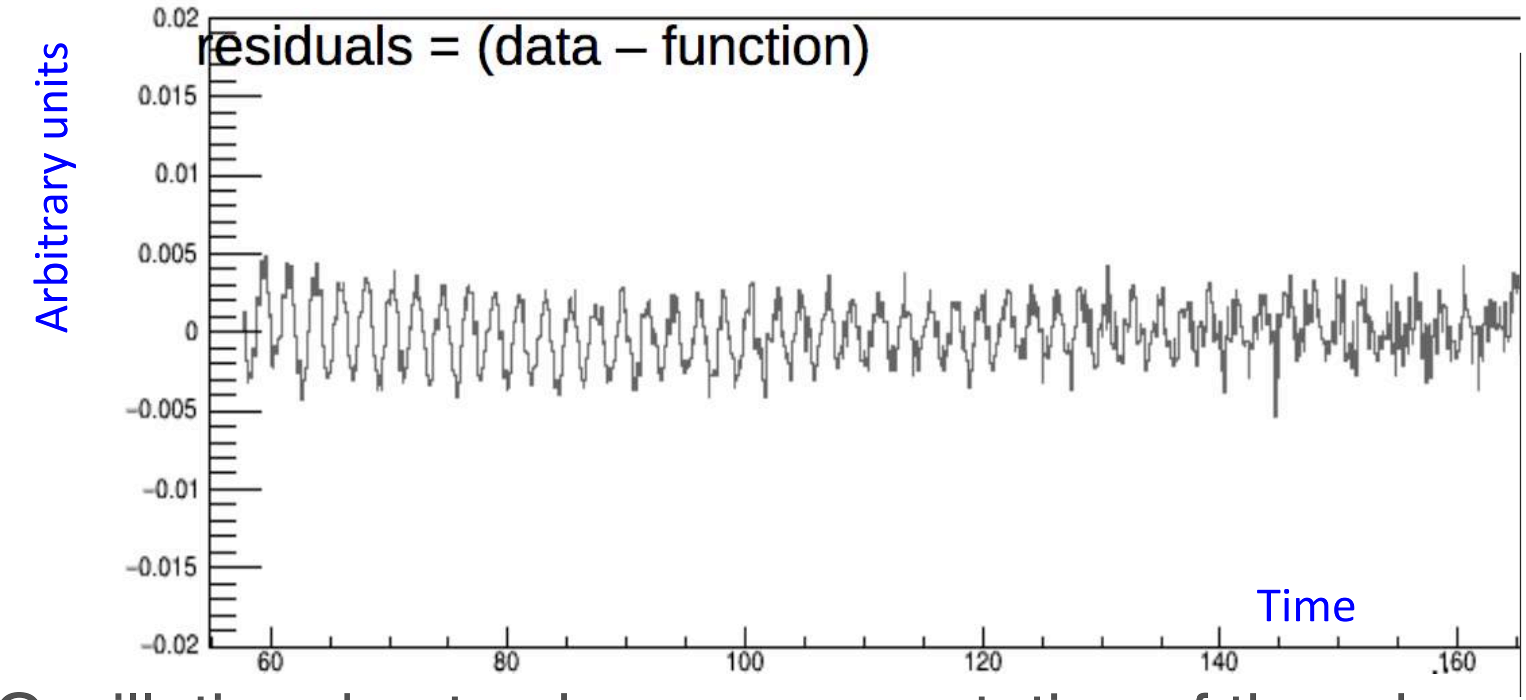
First look at data

- Number of positrons as a function of time : oscillation due to spin precession
- 5 parameters fit; good but ....



... but systematic effects are behind the corner

- plot of residuals :

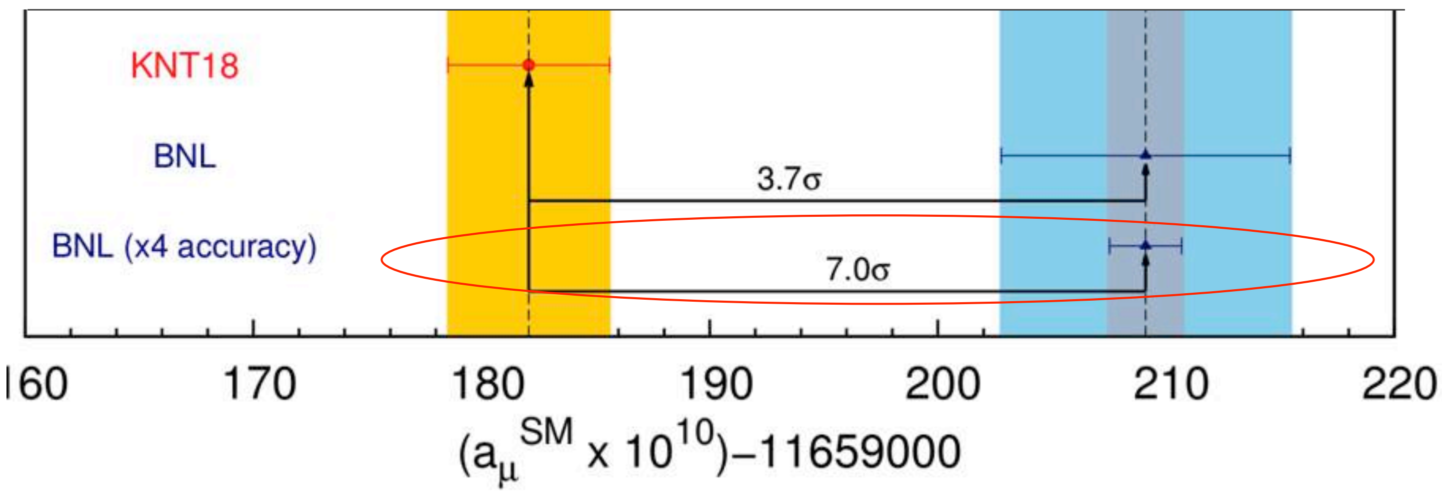


- Oscillation due to phase space rotation of the μ beam
- Well known effect → to be corrected
- Many other such effects exist !

→ at least 1 year to have systematics under control at ~0.2 ppm

Summary

- g-2 is taking data: 1xBNL statistics already collected !
- goal:
  - publish next year a result with an error compatible with previous experiment → first check of central value
  - reduce by a factor of 2 in 2020
  - reduce by a factor of 4 in 2021
- If central value holds ... it starts to become interesting



BACKUP SLIDES

Scientific collaboration

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- UT Austin
- Virginia
- Washington

- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma 2
- Trieste
- Udine

China
- Shanghai

Germany
- Dresden

Russia
- JINR/Dubna
- Novosibirsk

England
- Lancaster
- Liverpool
- University College London

Korea
- CAPP/IBS
- KAIST

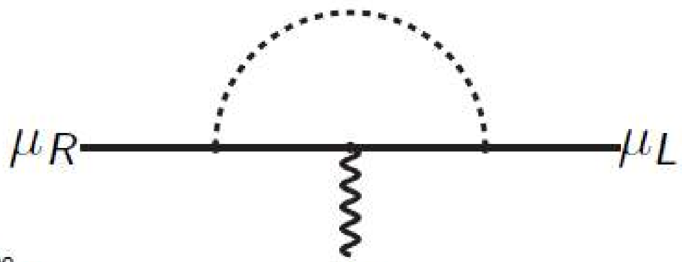
INFN Istituto Nazionale di Fisica Nucleare

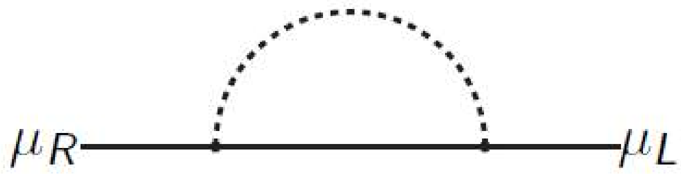
What could it mean if Expt ≠ Theory at > 5σ?

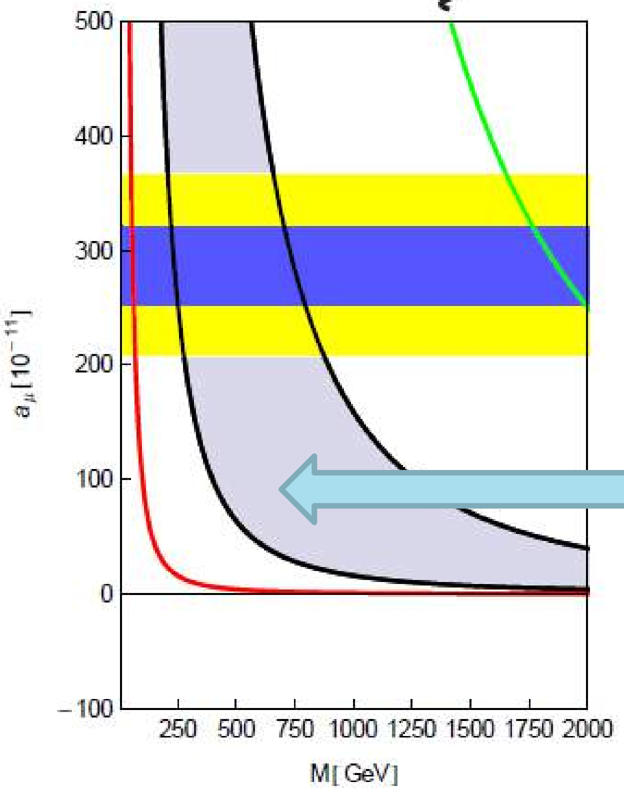
Generically, "loop effects" couple to the muon mass and moment in

$\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2$

$C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$





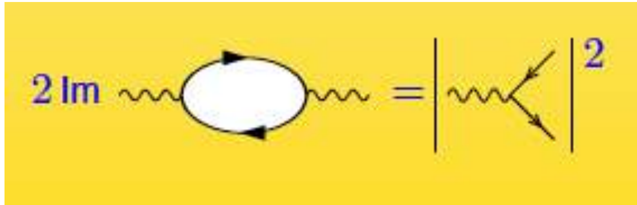


$\mathcal{O}(1)$	radiative muon mass generation . . . [Czarnecki,Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry (tan β) vectorlike fermions . . .
$\mathcal{O}(\frac{\alpha}{4\pi})$	SM: Z, W. New physics: $Z', W'\ldots$
$< \frac{\alpha}{4\pi}$	2-Higgs doublet model, dark photon .

Following Czarnecki, Marciano, and Stockinger

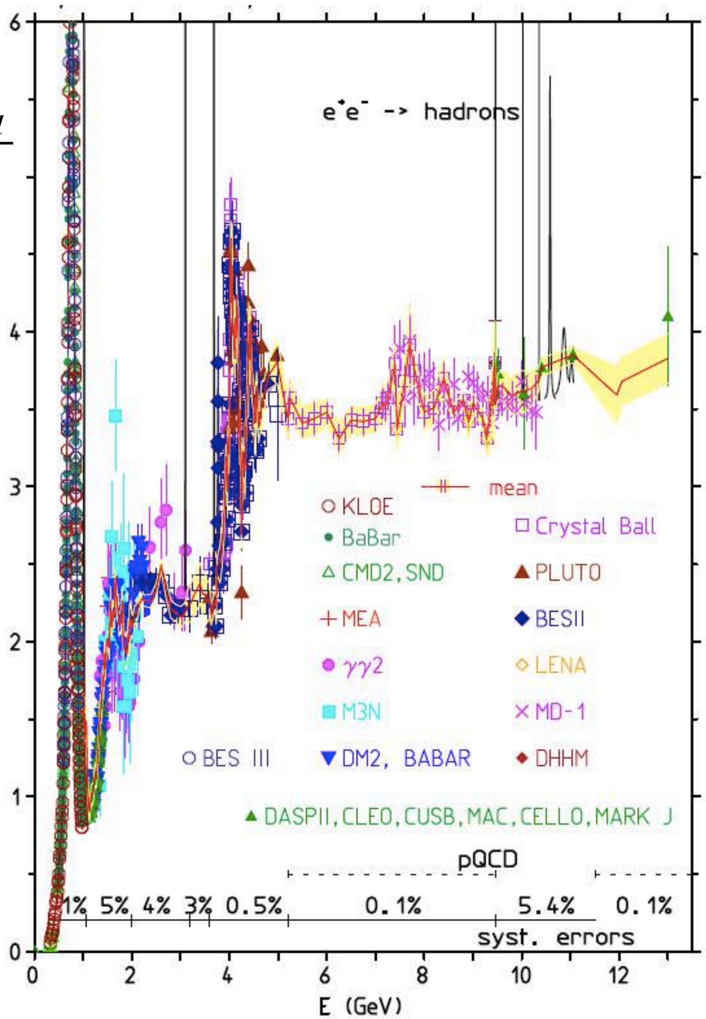
a_μ^{HLO} calculation, traditional way: time-like data

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty}\sigma_{e^+e^-\to hadr}(s)K(s)\,ds$$



$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s}$$

$$R = \frac{\sigma_{had}}{\sigma^0_{\mu\mu}}$$

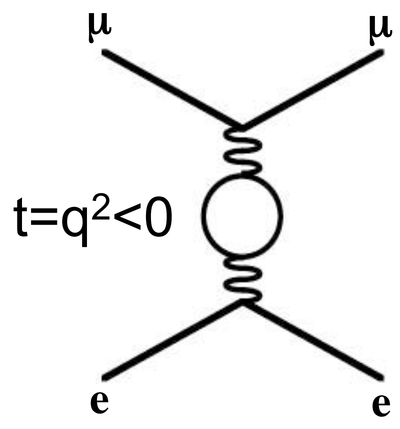


- $\sigma(s)$ measured in the s-channel
- collection of many experimental results
- large fluctuations with large resonances and steps
- published error ~0.6% (update presented in TAU16)

a_μ^{HLO} = (692.3±4.2)10^{-10} (DHMZ)

a_μ^{HAD} from μ + e → μ + e scattering

- NEW IDEA: measure $\mathbf{a}_\mu^{HAD}$ using *μe→μe* in the t-channel instead of ee→ππ !
- INTEREST of the measurement:
  - a single experiment can cover almost all the phase space
  - systematics completely different with respect to s-channel data
  - theoretical interpretation is not easy (NNLO terms are needed) but more straightforward than for s-channel



$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2$$

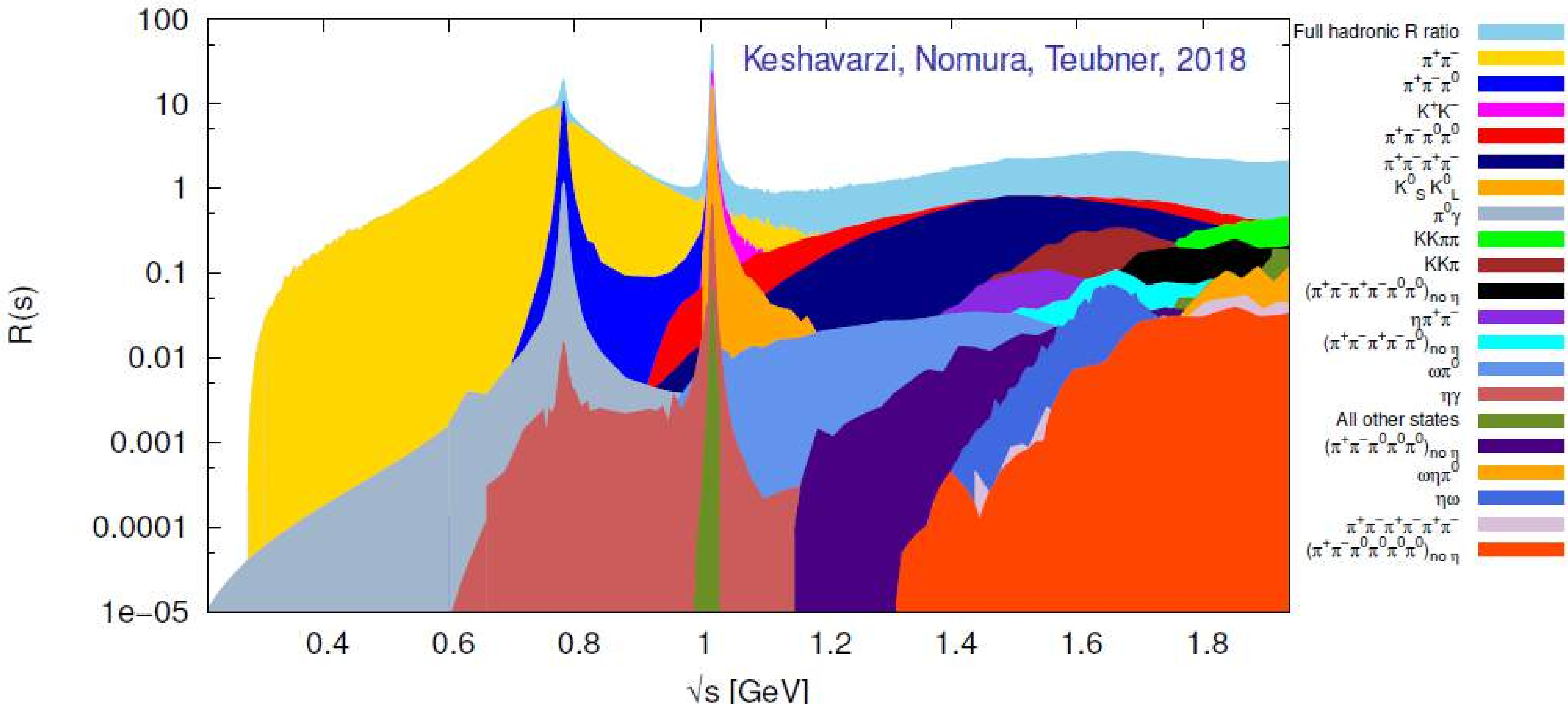
$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha_{LEP}(t)-\Delta\alpha_{HAD}(t)}$$

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

$$t = \frac{x^2 m_\mu}{x-1} < 0; \quad (0 \le x < 1);$$

(x = 0 ↑ t=0; x → 1 ↑ t=-∞)

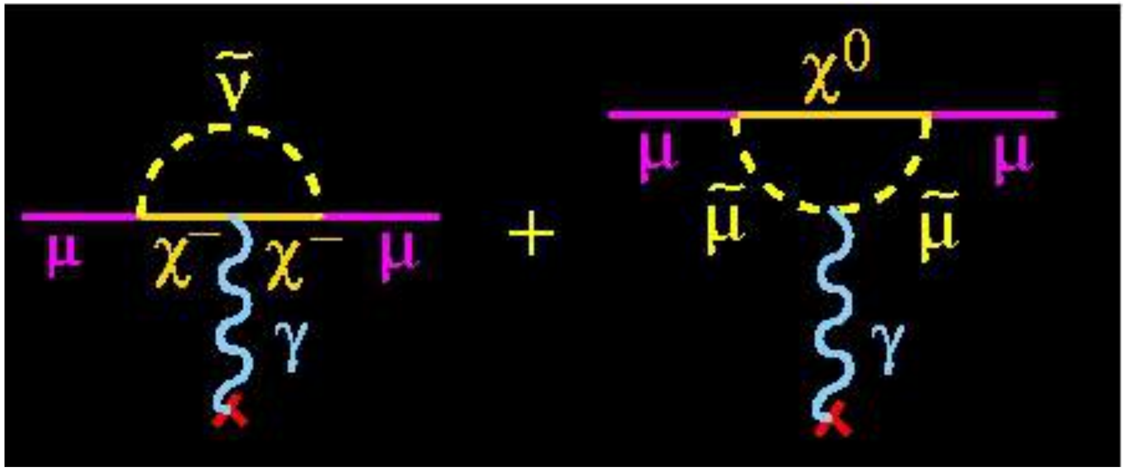
The cross sections scan a wide range in energy



Latest **comprehensive compilation of all th**e world's data, obtaining:

$$a_\mu^{\exp} - a_\mu^{SM} = 268.5 \pm 72.4 \qquad [3.7\sigma]$$

The attractive idea: SUSY



Difficulty to measure at the LHC

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\ \mathrm{GeV}}{M_{SUSY}} \right)^2 \tan\beta\ \mathrm{sign}(\mu)$$

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