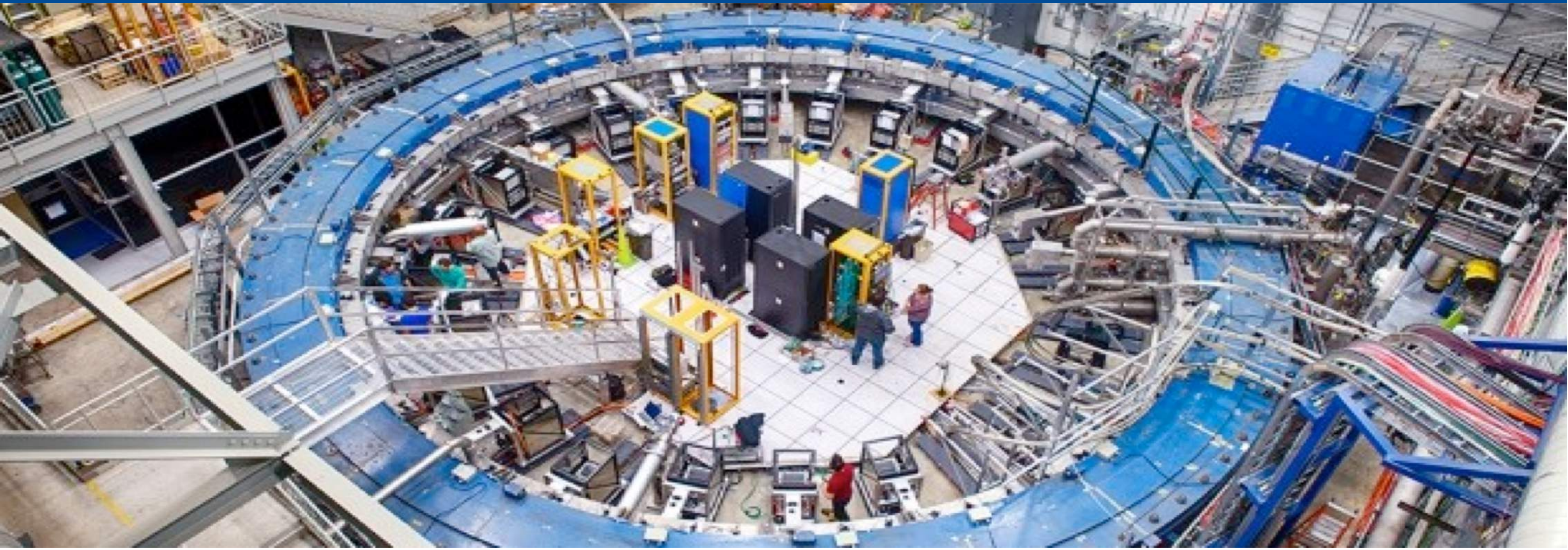


The muon g-2 experiment at Fermilab

European Physical Society (EPS) – July 2019

Marco Incagli – INFN Pisa

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

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

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

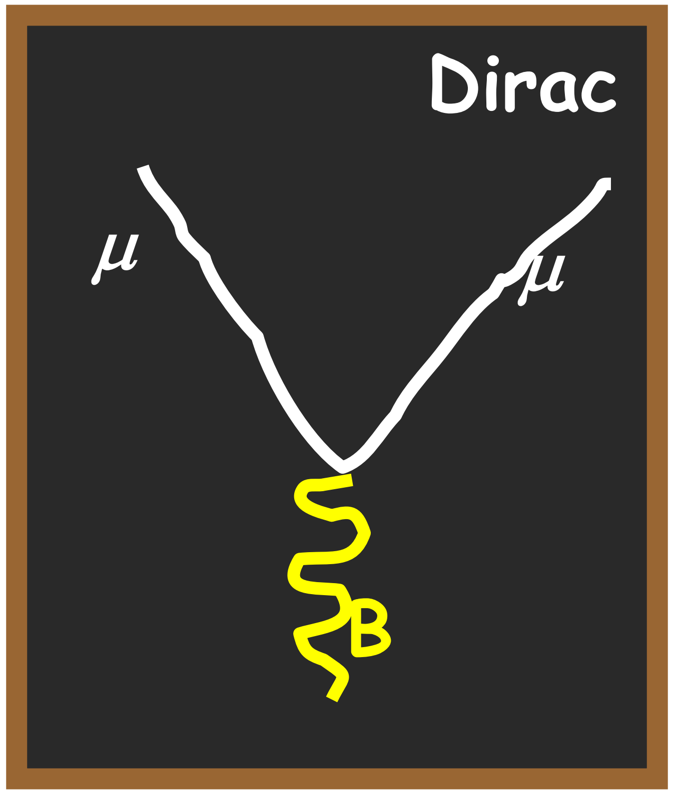
$$a_\mu = (11\,659\,181.7 \pm 4.2) \times 10^{-10}$$

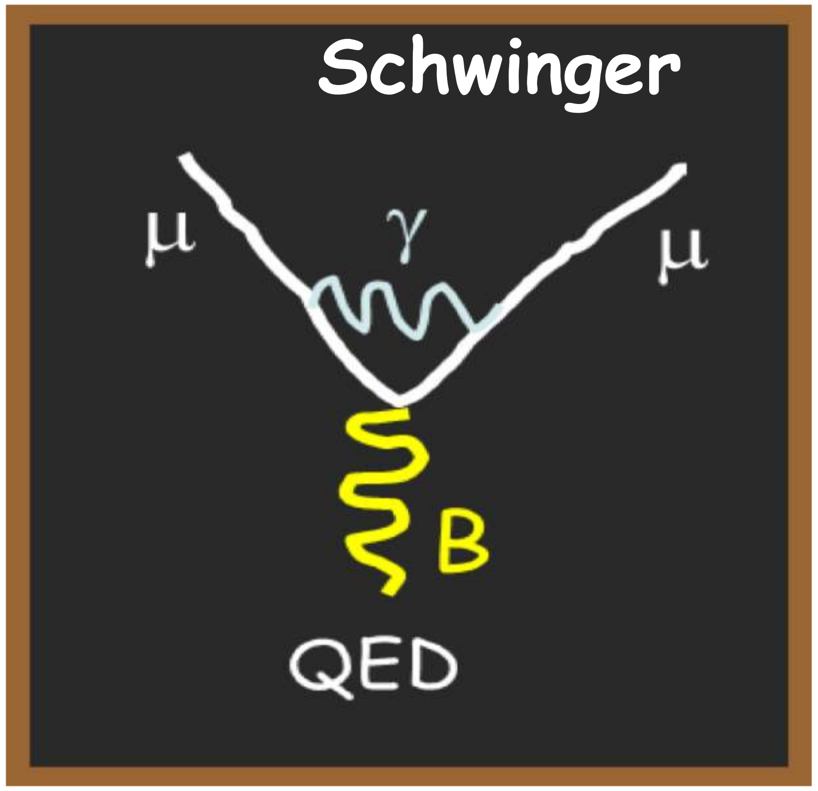
- ***g_P*** : proportionality between spin and magnetic moment for particle P
- ***a_P*** : anomalous magnetic moment
- ***a_P*** = 0 at tree level (*purely Dirac particle*)

- 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

Contributions to a_μ

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



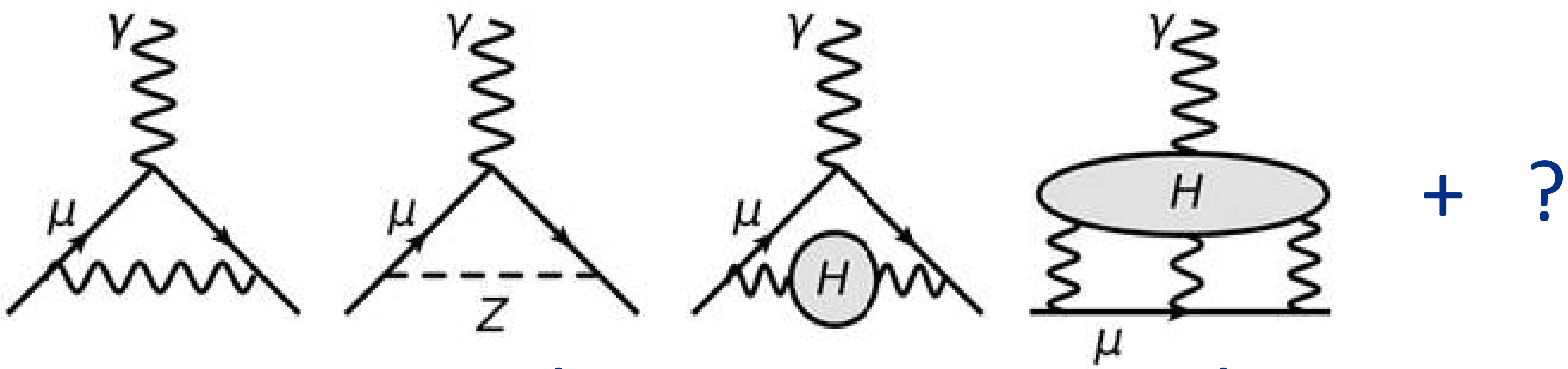


1948 , first big success of QED :

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

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

Contributions to a_μ

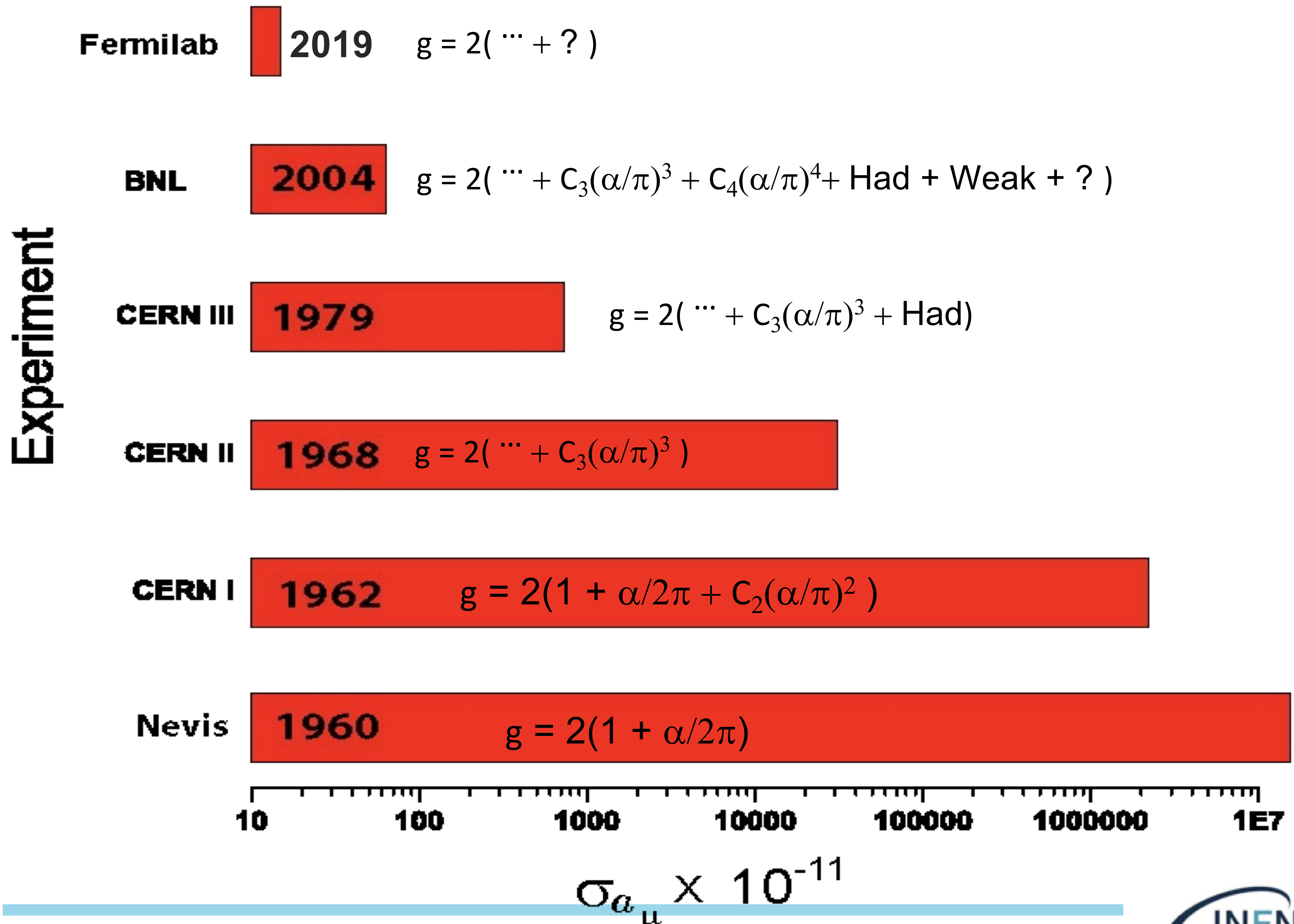


QED — Known | Weak — Known | HLO — Data | HLbL — Models/Lattice | New Physics. — ?

HLbL = Hadronic Light by Light = Hadronic higher order

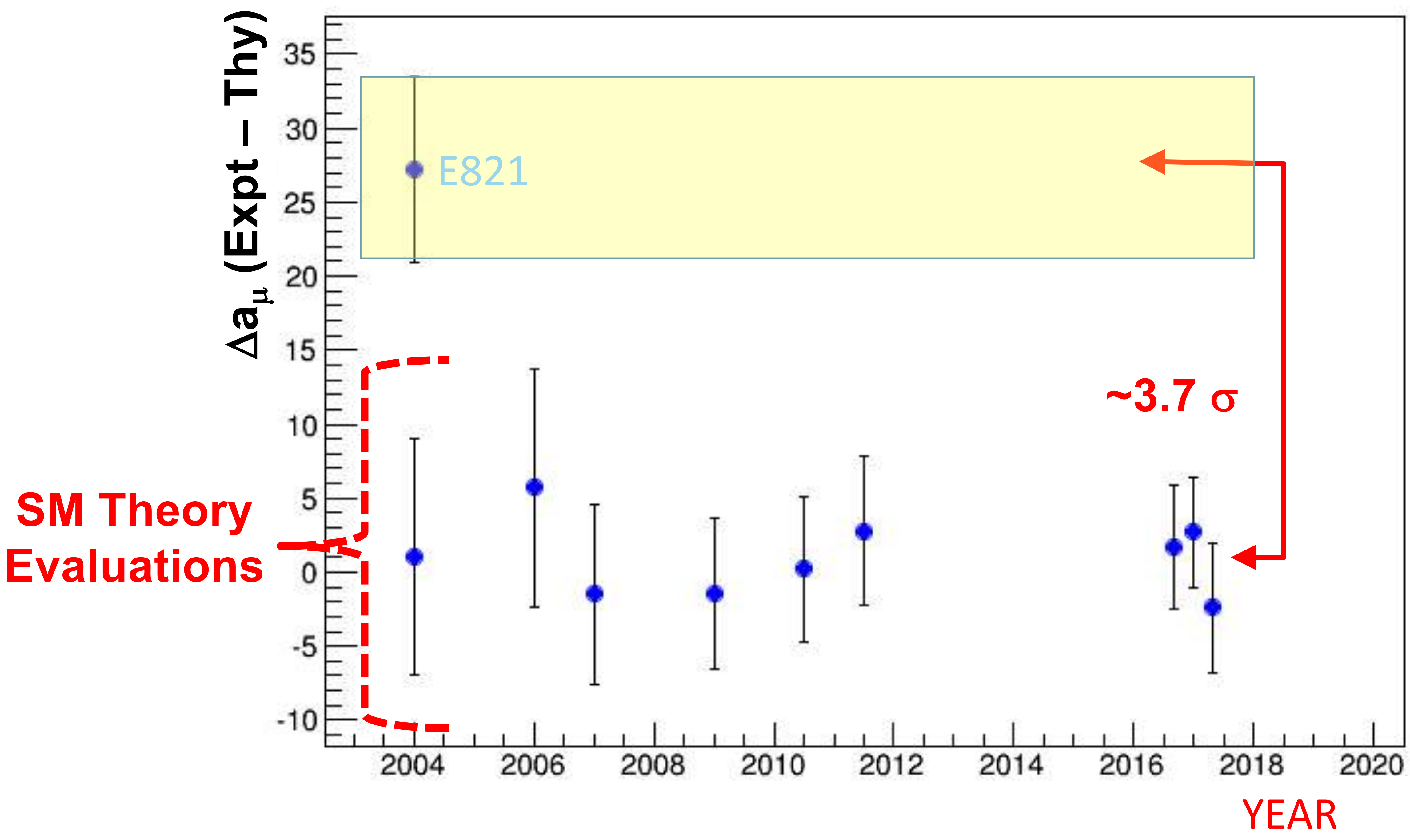
	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$

- theoretical error comparable with experimental one:
  E821 @BNL δa_μ(Expt) = ± 6.3 (10^{-10} units)


Experiment
Fermilab
2019
g = 2(⋯ + ?)
BNL
2004
g = 2(⋯ + $C_3(\alpha/\pi)^3$ + $C_4(\alpha/\pi)^4$+ Had + Weak + ?)
CERN III
1979
g = 2(⋯ + $C_3(\alpha/\pi)^3$ + Had)
CERN II
1968
g = 2(⋯ + $C_3(\alpha/\pi)^3$)
CERN I
1962
g = 2(1 + $\alpha/2\pi$ + $C_2(\alpha/\pi)^2$)
Nevis
1960
g = 2(1 + $\alpha/2\pi$)
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$

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

New Physics Mass scale

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

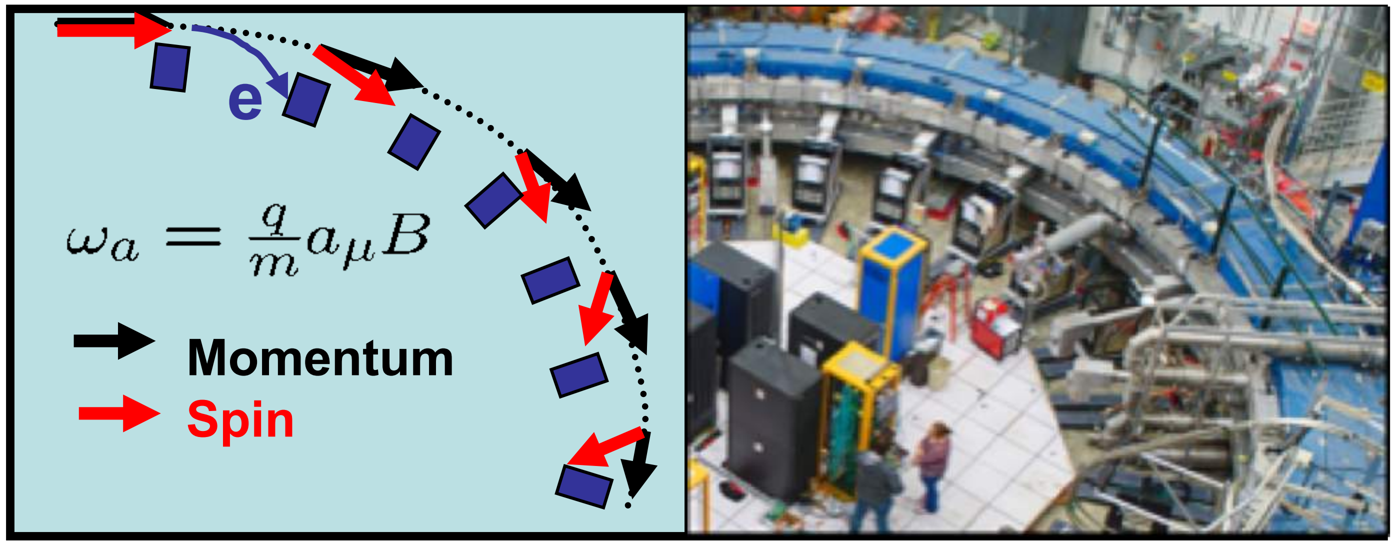
e.g.: in SUSY it is sensitive to charginos and sleptons. LHC direct searches are sensitive to squarks and gluinos.

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

Ratio of the vacuum expectation value for the two Higgs doublets* (5-50)

* 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*:

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

***s** and **p** are assumed to be in a plane perpendicular to **B**

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

The basic (ideal) equation

- Inverting the previous simple (ideal) equation:

$$a_\mu = \frac{m_\mu}{e}\frac{\omega_a}{B} = \frac{g_p}{2}\frac{m_\mu}{m_p}\frac{\omega_a}{\omega_p} = \frac{R_\mu}{\lambda - R_\mu} \quad ; \quad R_\mu = \frac{\omega_a}{\omega_p} \; , \quad \lambda = \frac{\mu_\mu}{\mu_p}$$

- The B-field is expressed in terms of the proton precession ω_p (measured by NMR probes inserted in the ring)
- a_μ is proportional to the *ratio of muon to proton precession in the same magnetic dipole field*
  - ω_a (muon precession) : particle physics techniques
  - ω_p (proton precession) : nuclear physics techiniques

Effects of Beam Dynamics

- The *full equation* is more complex and corrections due to radial (x_e) and vertical (y) beam amplitude and shape are needed

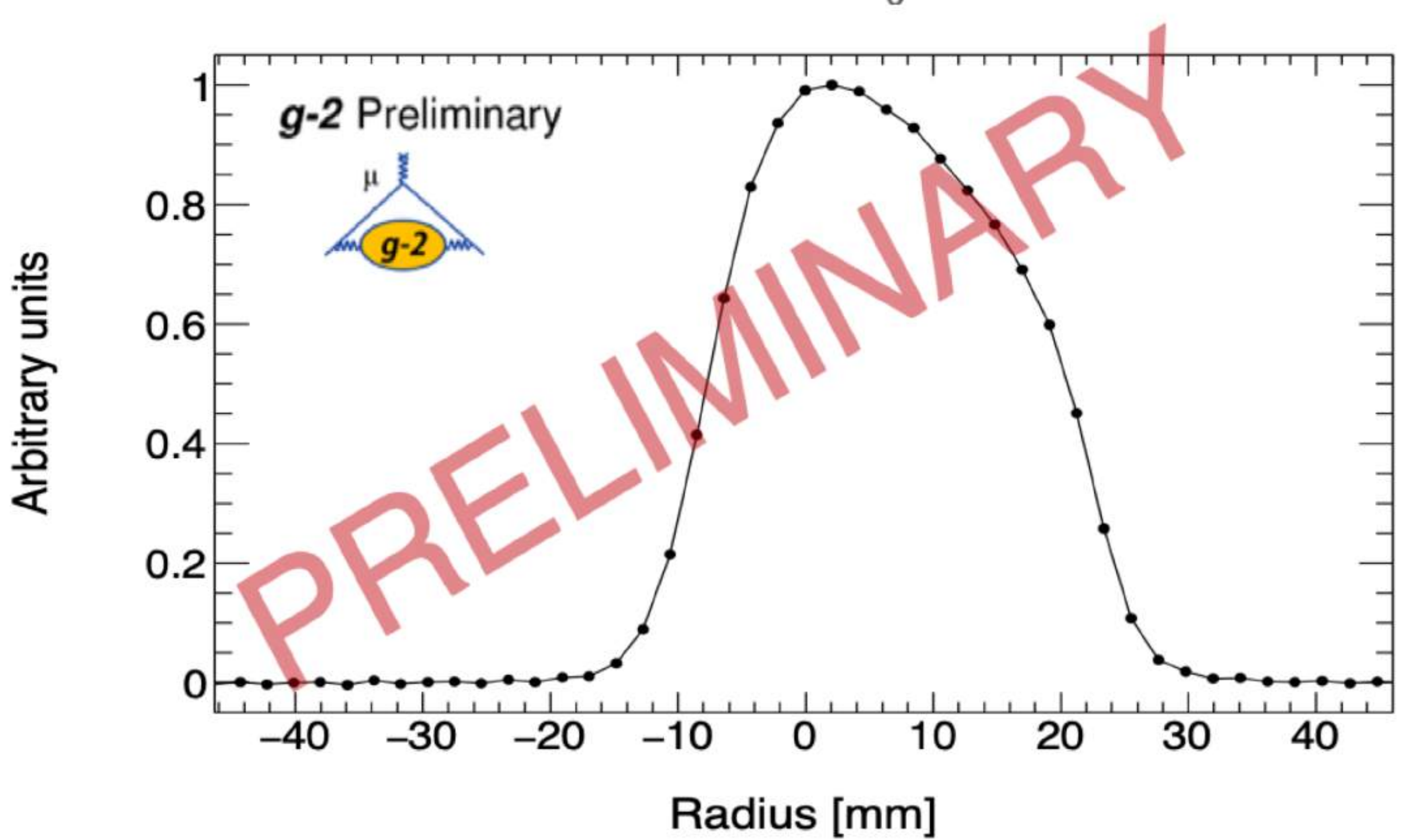
$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{mc}\left[a_\mu \vec{B} - \boxed{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}} - \boxed{a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}}\right]$$

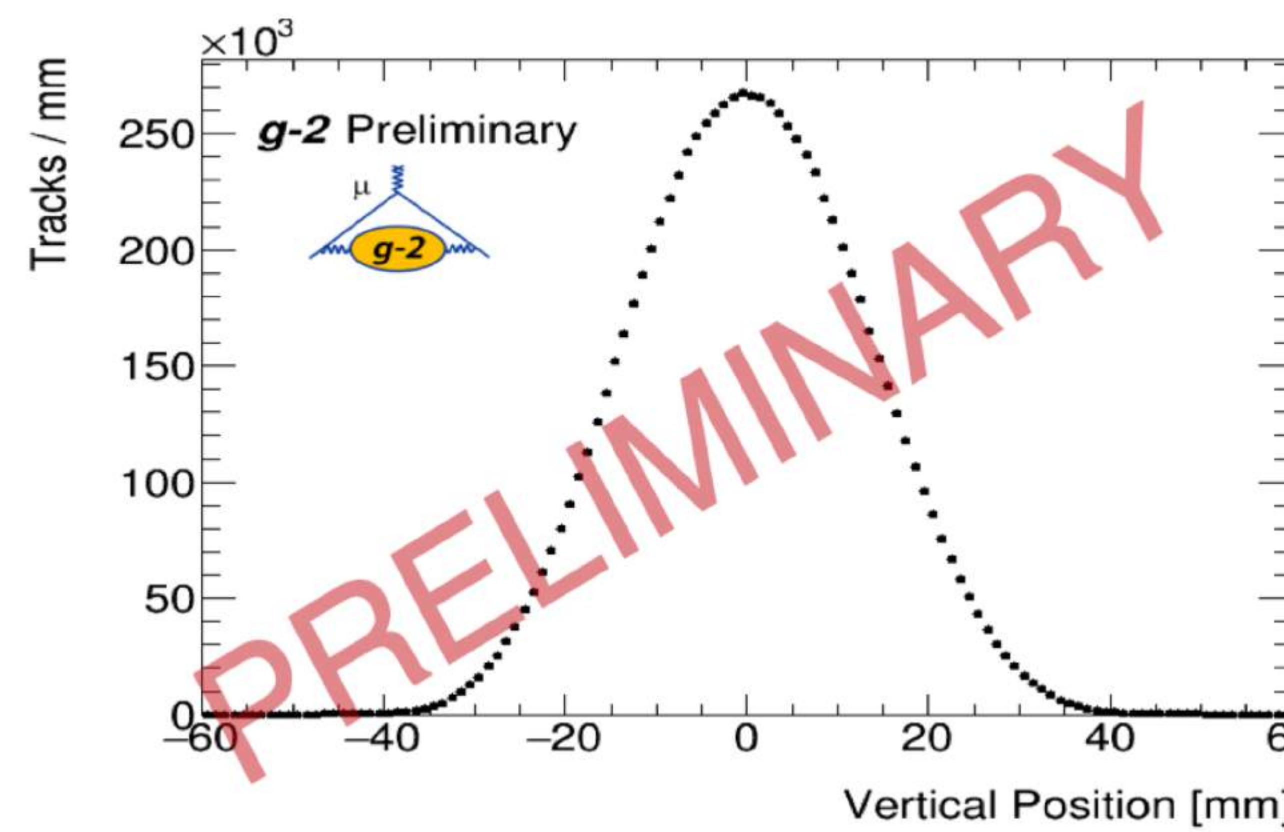
- Running at γ_{magic}=29.3 (p_μ=3.094 GeV/c) this coefficient is null
- Because of beam spread → E-field Correction

- Vertical beam oscillations, field felt by the muons is reduced → Pitch Correction

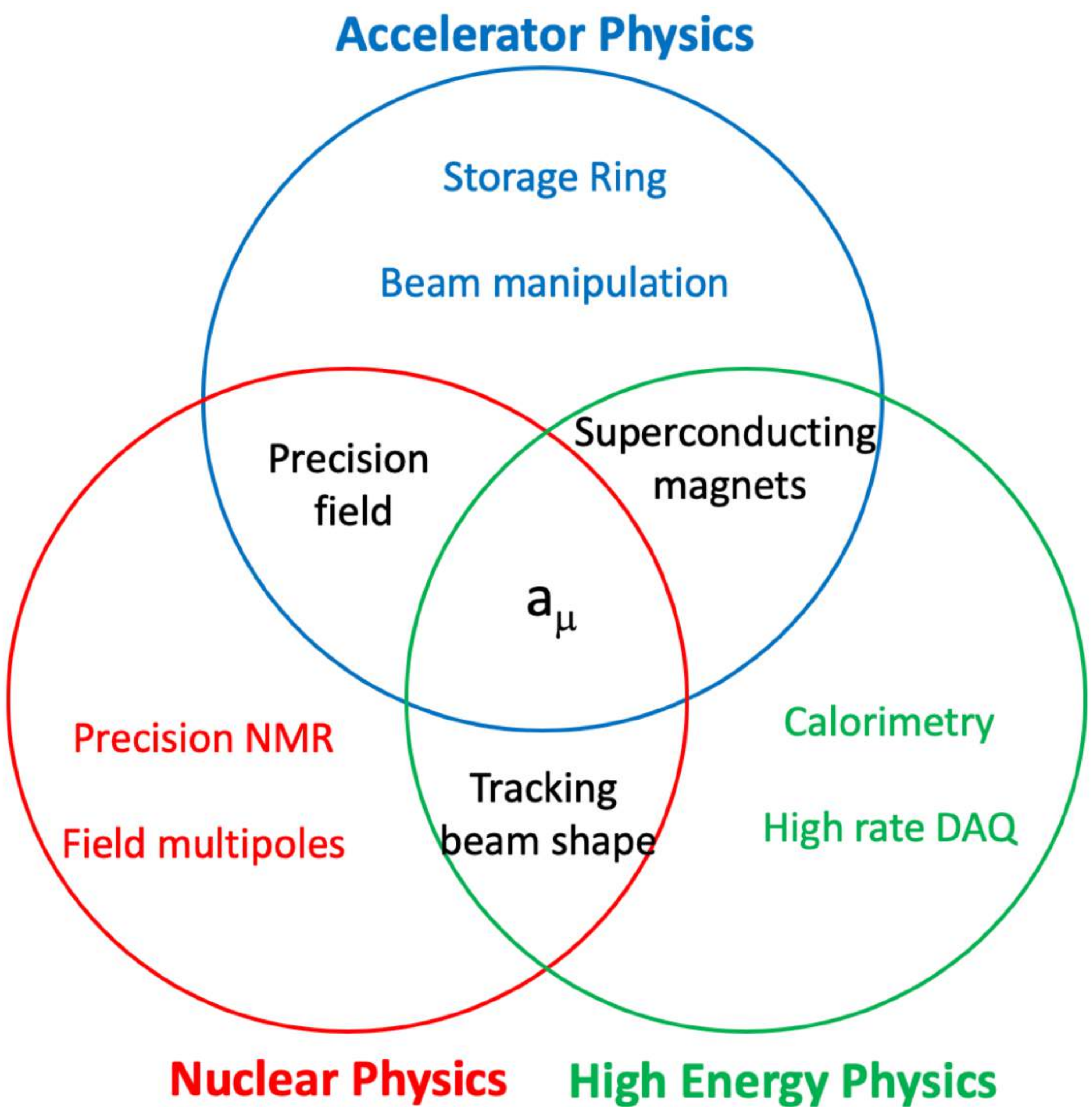
$$C_E = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

$$C_P = \frac{\Delta\omega_a}{\omega_a} = -\frac{n}{2R_0^2}\langle y^2\rangle$$

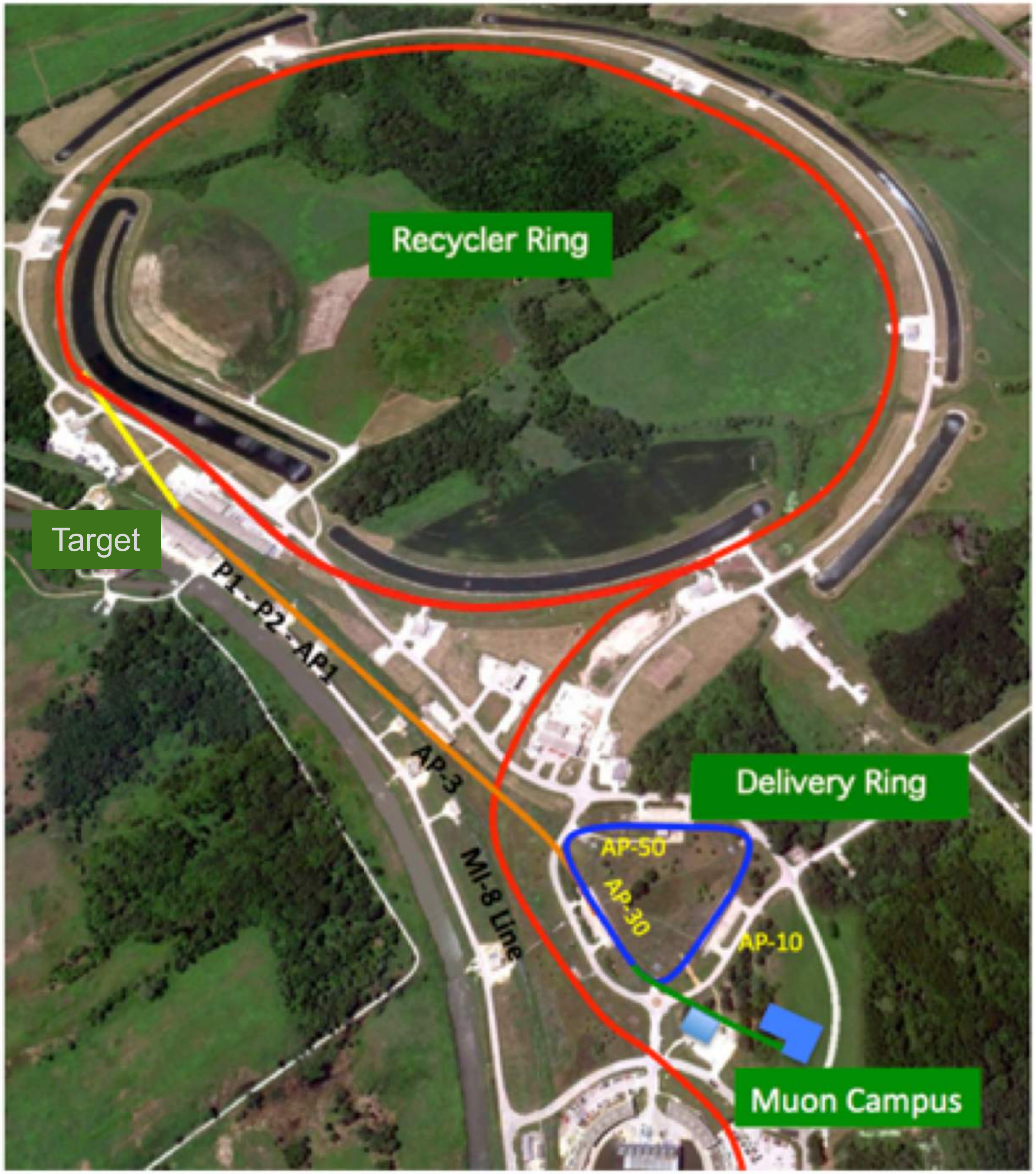




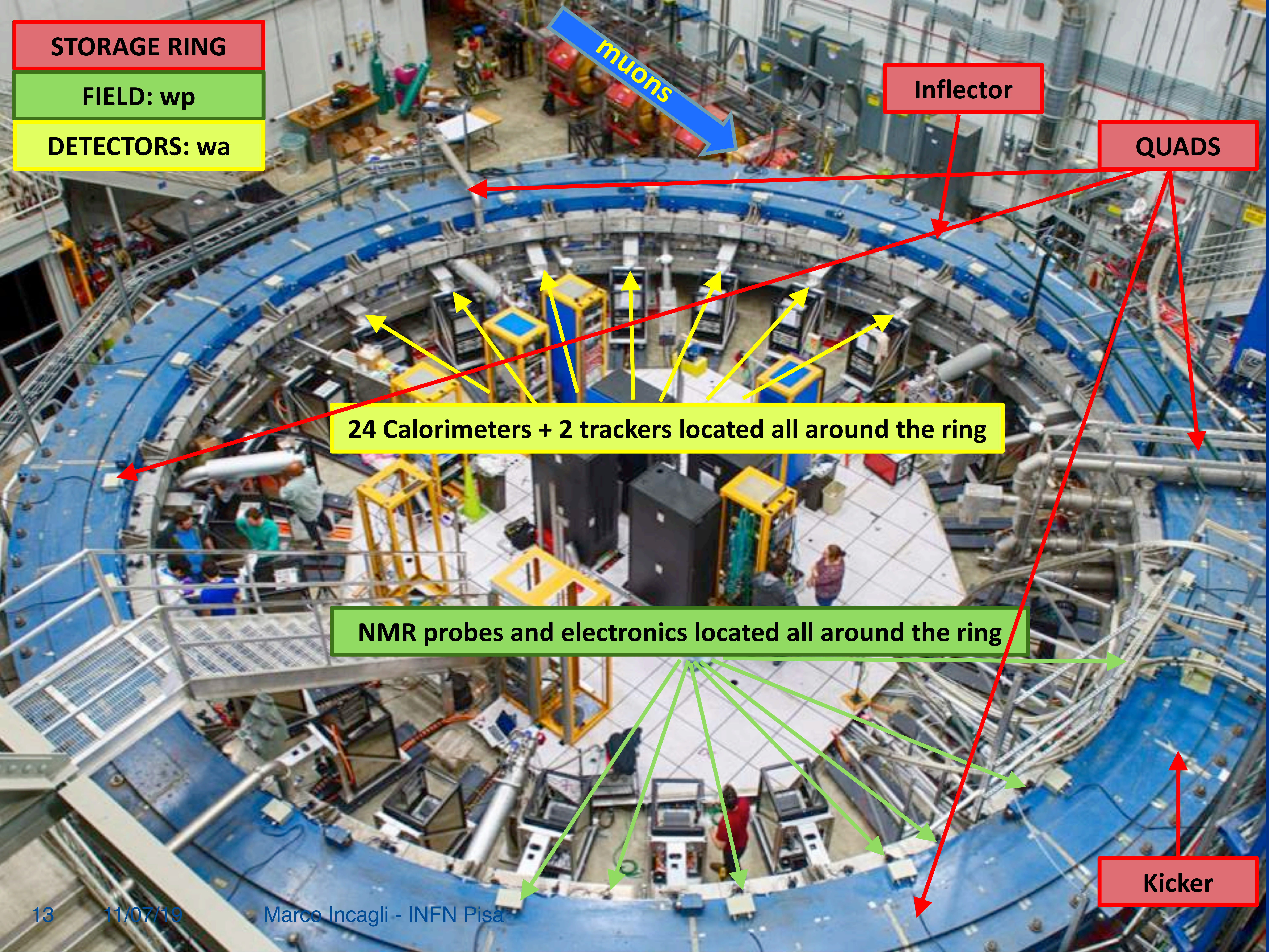
- Three different communities converging to measure a_μ



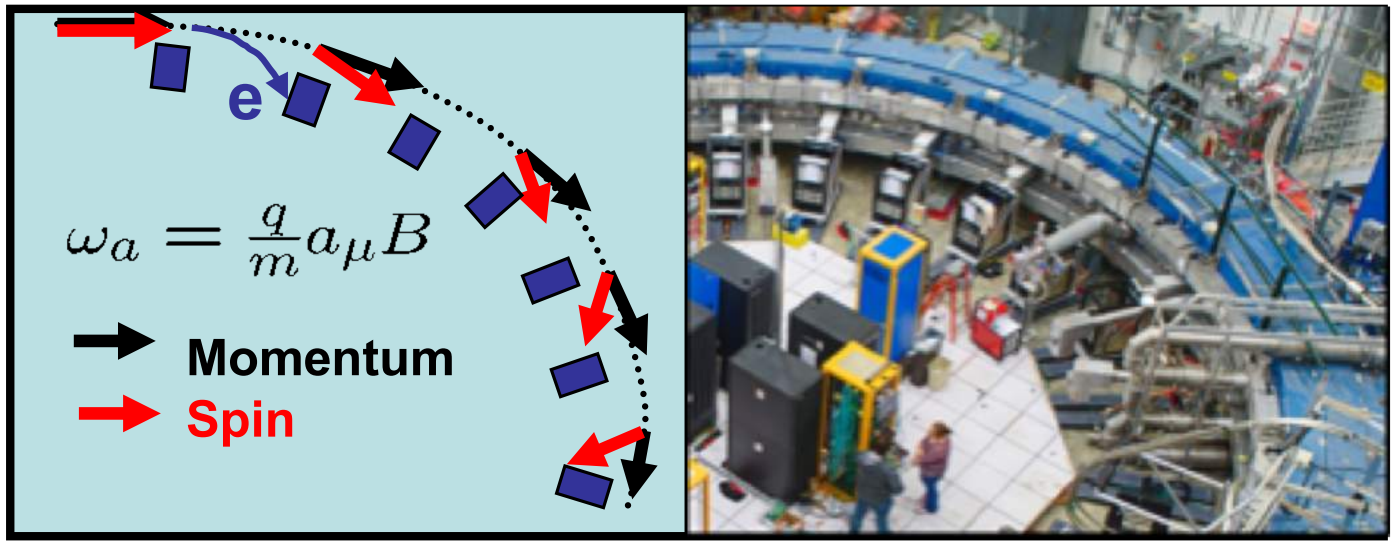
The accelerator complex : Fermilab



- 8 GeV/c proton beam from Booster to Recycler Ring
- protons hit target and 3.1 GeV/c pions are selected
- pions decay in the Delivery Ring ≃ **2 km**
- muons are sent to the "Muon Campus" where "*g-2*" and "*Mu2e*" experiments are located
- (cannot run together!)


STORAGE RING
FIELD: wp
DETECTORS: wa
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

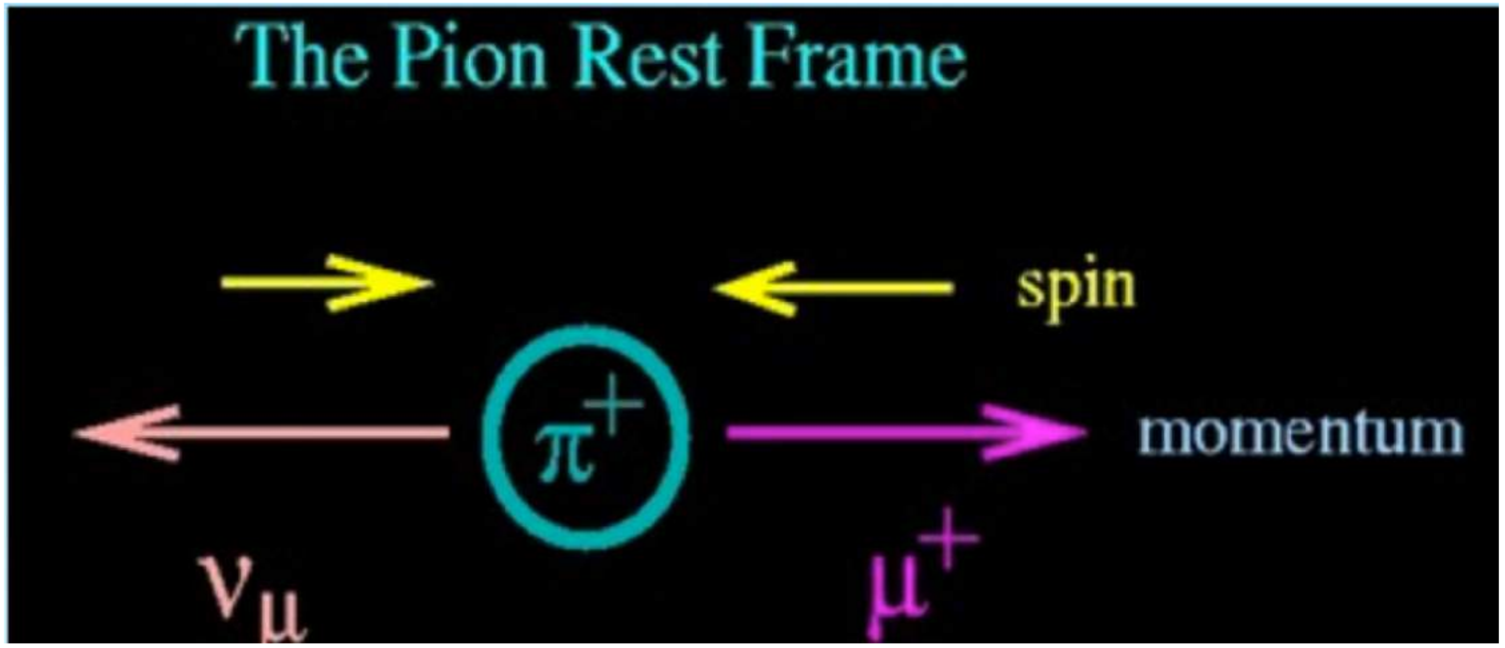
How to measure ω_a



- 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 polarimeter)

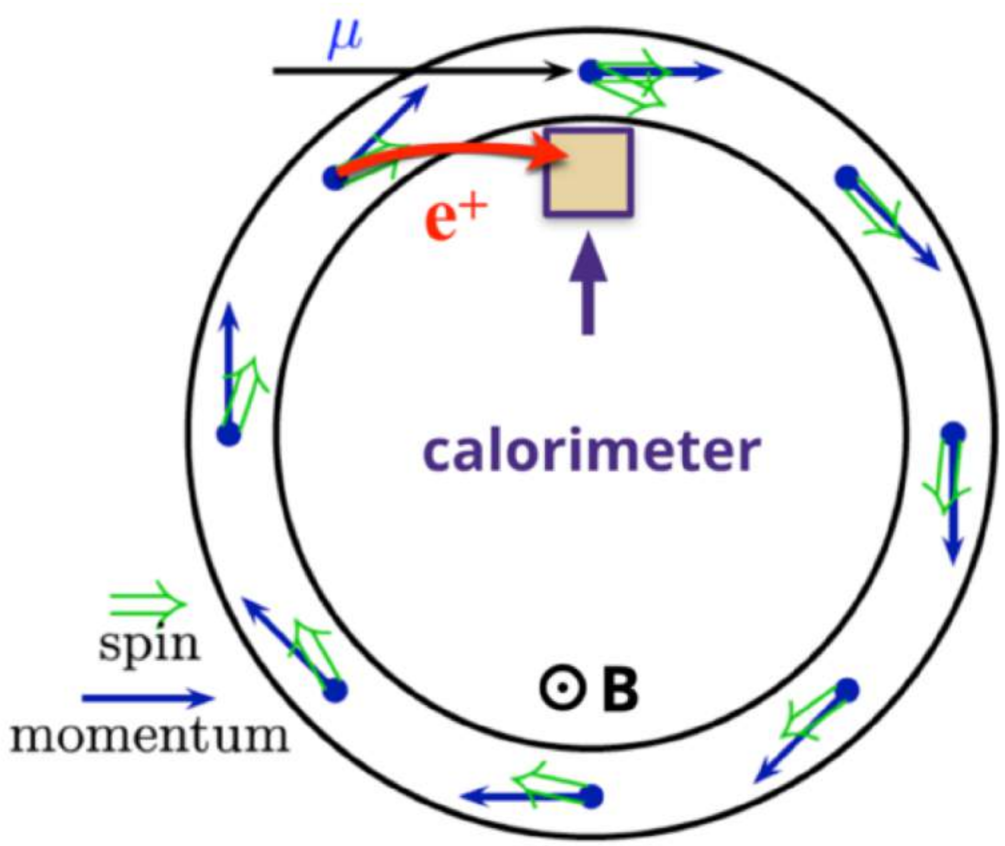
Polarization of incoming muons

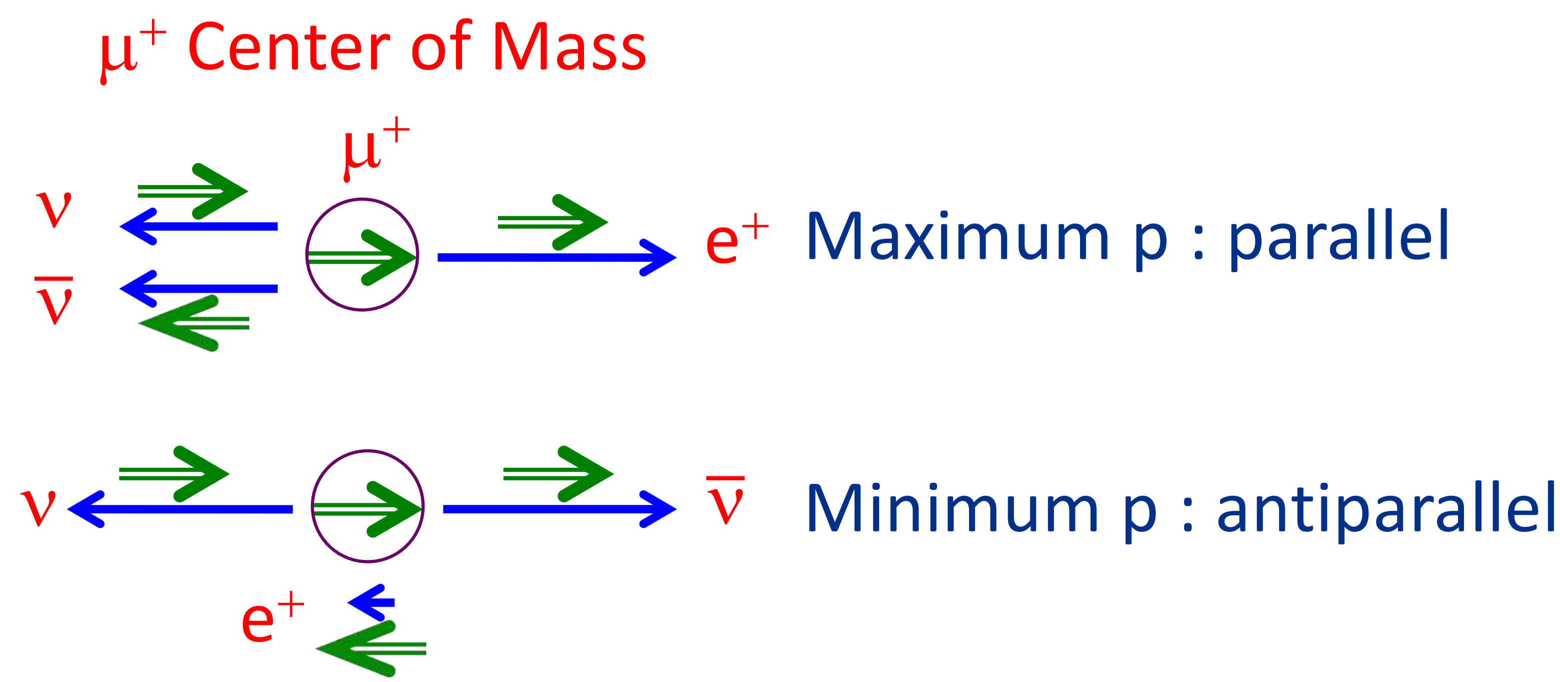
- Use V-A structure of weak current to build a polarized beam...



- Selecting 3.094 GeV/c muons from 3.11 GeV/c pion decays yields a muon beam with a net polarization of about 95% (see g-2 TDR for details)

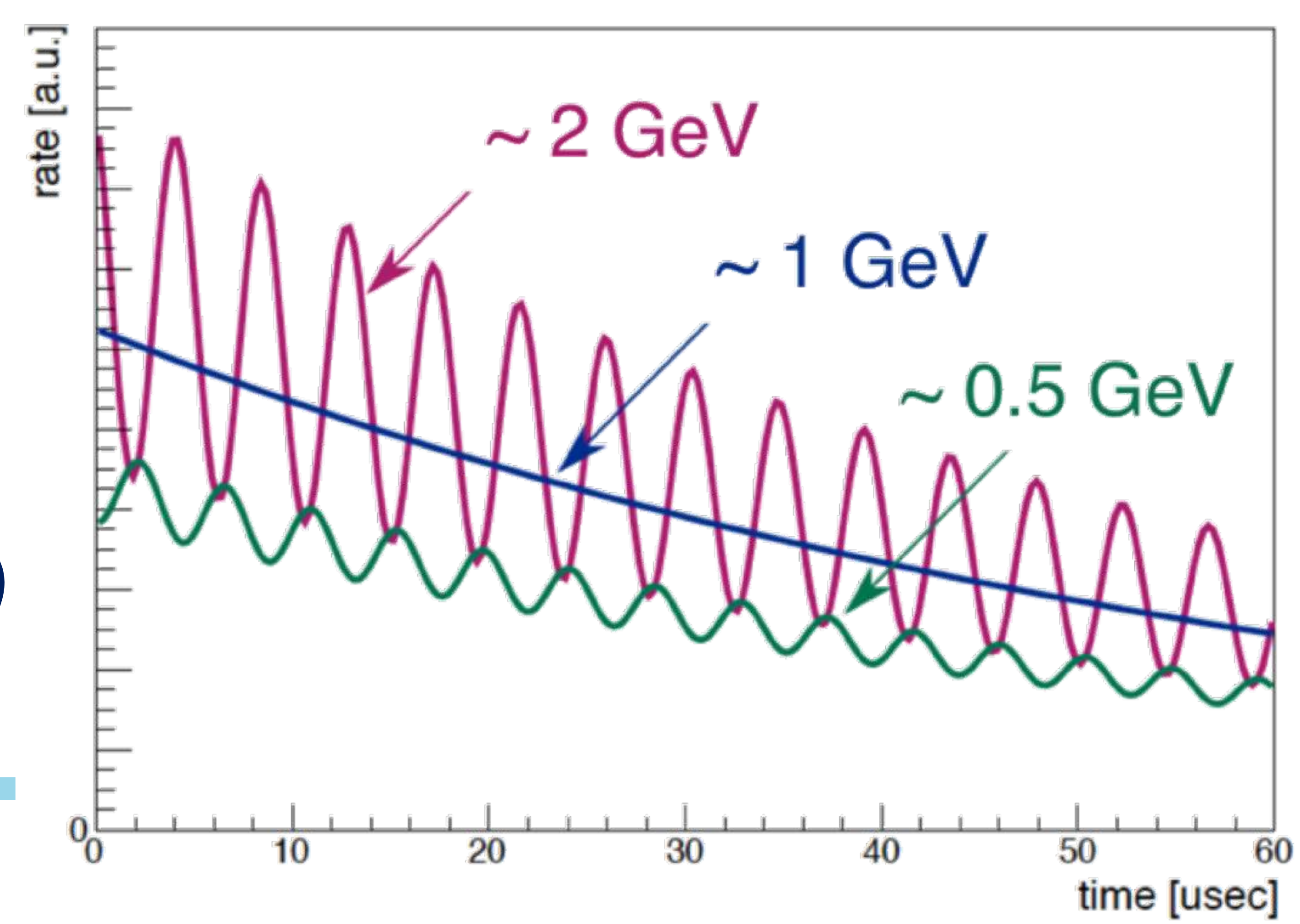
Polarimeter: muon decay





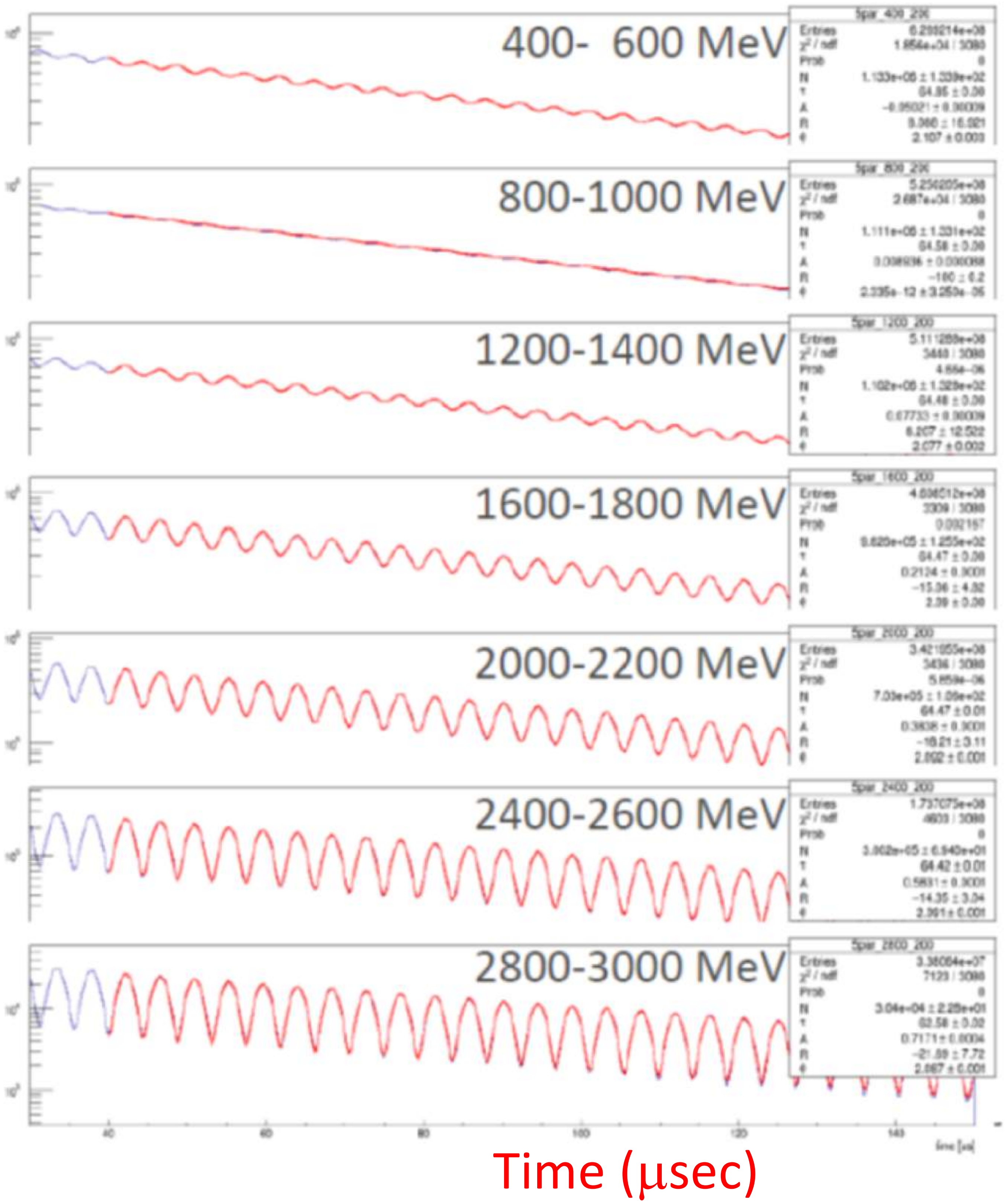
$$N(t) = N_0 e^{-t/\tau}\left(1 + A\cos(\omega_a t + \varphi)\right)$$

- *positron emission direction is correlated with muon spin*
- the number of observed positrons oscillates with an amplitude A(E) depending on e+ *momentum*: ***the Asymmetry A(E) can be positive, null or negative***



Nuber of positrons vs time: analysis methods

$$N_{ideal}(t) = N_0 \exp(-t/\tau_{\mu}) \, [1 + A\cos(\omega_a t + \varphi)]$$



- **T-method** (time integrated) : count all positrons with E>1.7GeV → reference method («*Wiggle plot*»)
- **E-method** (Energy binned) : fit each energy slice, combine the resulting values for ω_a
- **A-method** (Asymmetry weighted) : weight each event with its own asymmetry A(E)
- **R-method** (Ratio) → backup
- **Q-method** (Charge) → backup

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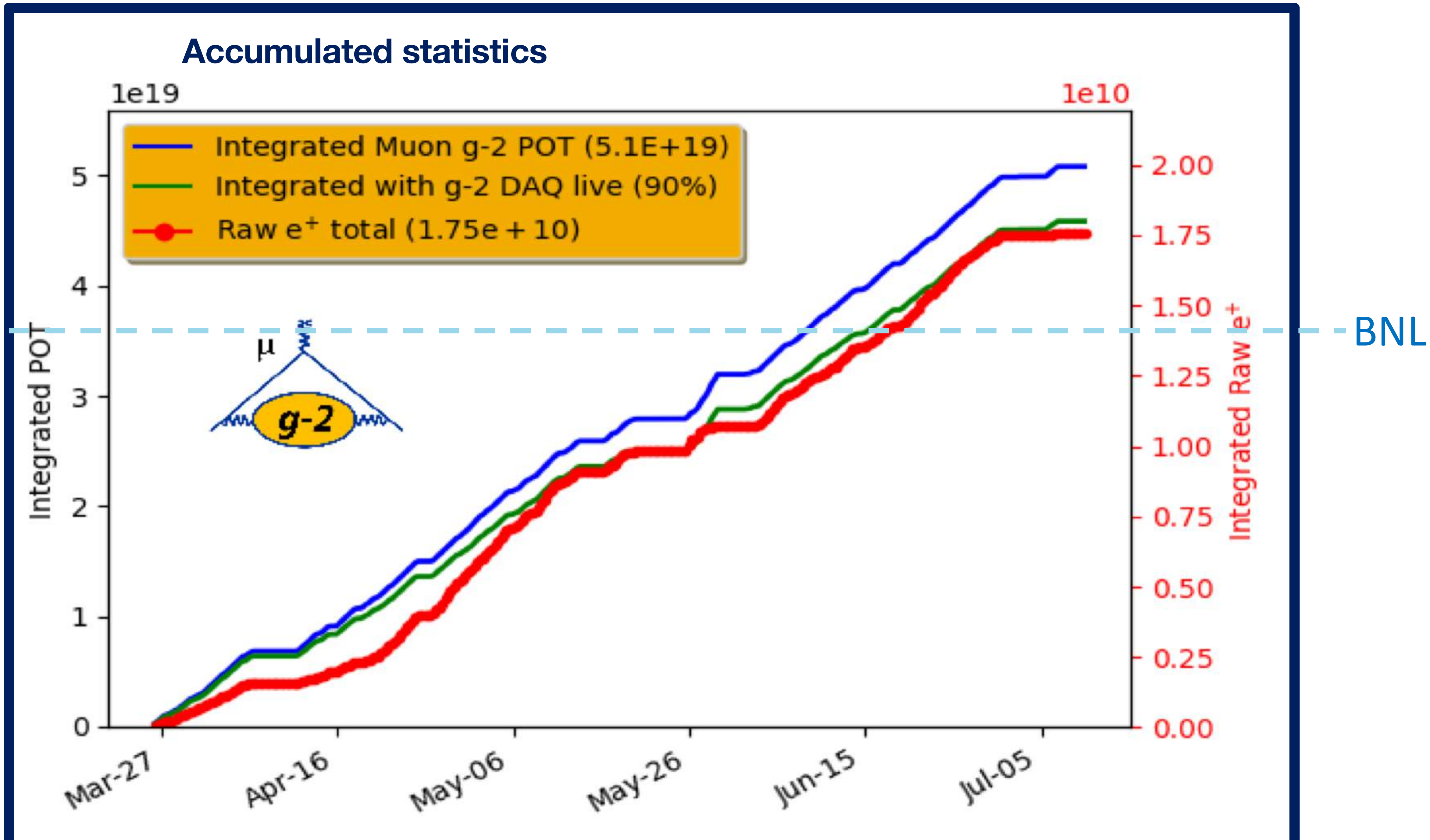
The wa analysis strategy

- 6 groups perform an independent analysis by using different *Reconstruction algorythms* and different *Fit methods*
- The result of the fit is *blinded* (=hidden)
- A dataset corresponding to *~10% of BNL* has been *relatively unblinded*

Team	Reconstruction	Analysis
CU (Cornell)	East	T,E
UW (Washington)	West	T,A
Europa (Italy+UK)	West/Europa	T,A
SJTU (Shangai)	West	T,E
BU (Boston)	West	T,R
Uky (Kentucky)	Q	Q

Run 1 Overview

- Data taking period: April—July 2018
- Accumulated statistics corresponding to ~1.3 times the previous BNL experiment: **$\delta\omega_a$(stat) ~ 400 ppb (BNL $\delta\omega_a$(stat) ~ 460 ppb)**



Run 1 Overview

- In Run1, data have been taken in different Quadrupole and Kicker settings, while optimizing Storage Ring operations
- Run2 data are much more uniform
- Six datasets identified, for a total of *~10 Billion* positrons:

Name	Date acquired	Quad n	Kicker [kV]	Positrons
60 hour	22-25 / 4	0.108	128-132	1.0B
High Kick	26/4 - 2/5	0.120	136-138	1.2B
9 day	4-12 / 5	0.120	128-132	2.4B
Low Kick	17-19 / 5	0.120	123-127	1.2B
Superlow Kick	2-6 / 6	0.108	117-119	0.5B
End Game	6-29 / 6	0.108	122-127	4.0B

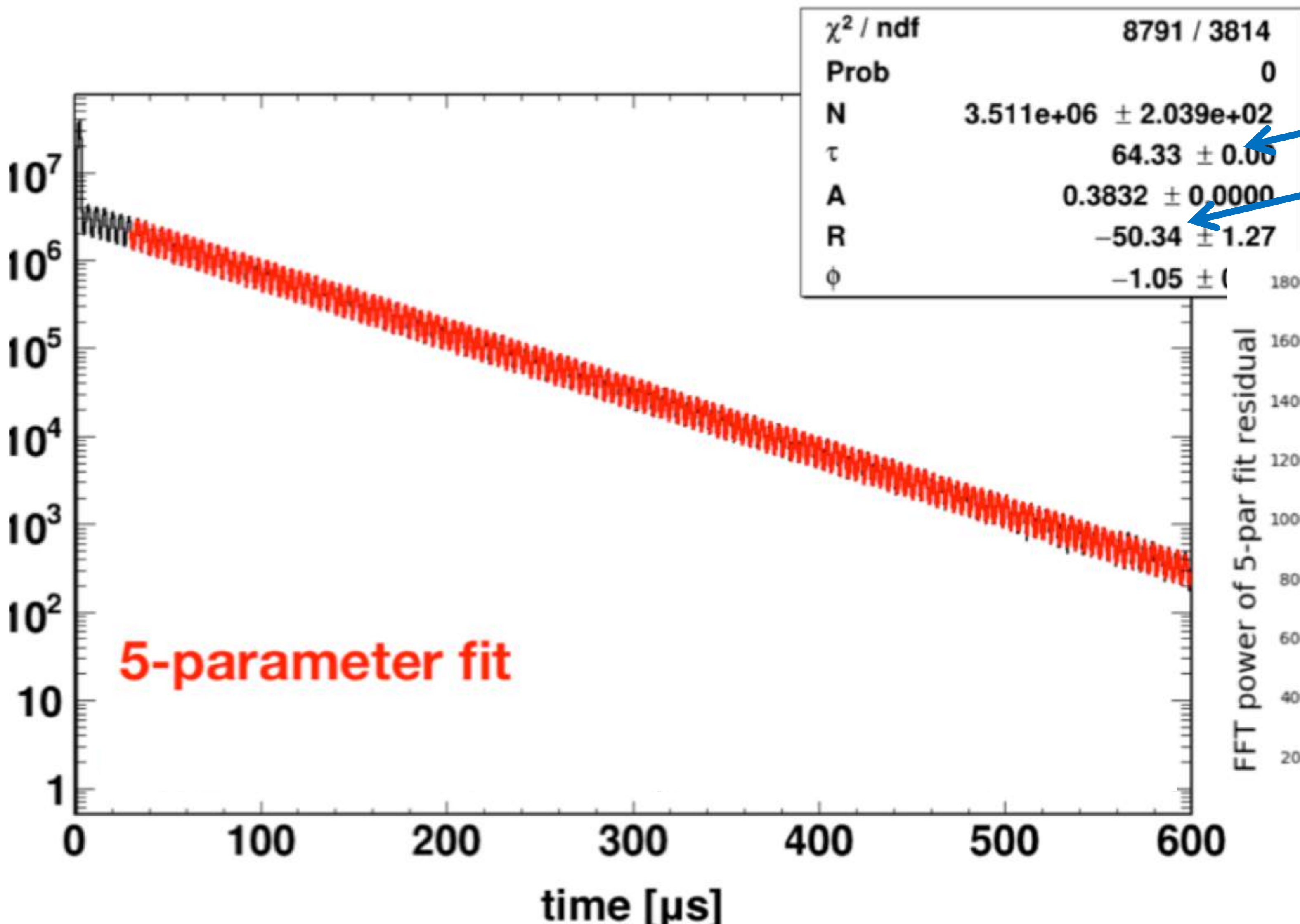
Relative unblinding

The 60h dataset: 5-par fit

- Simple (ideal) positron oscillation:

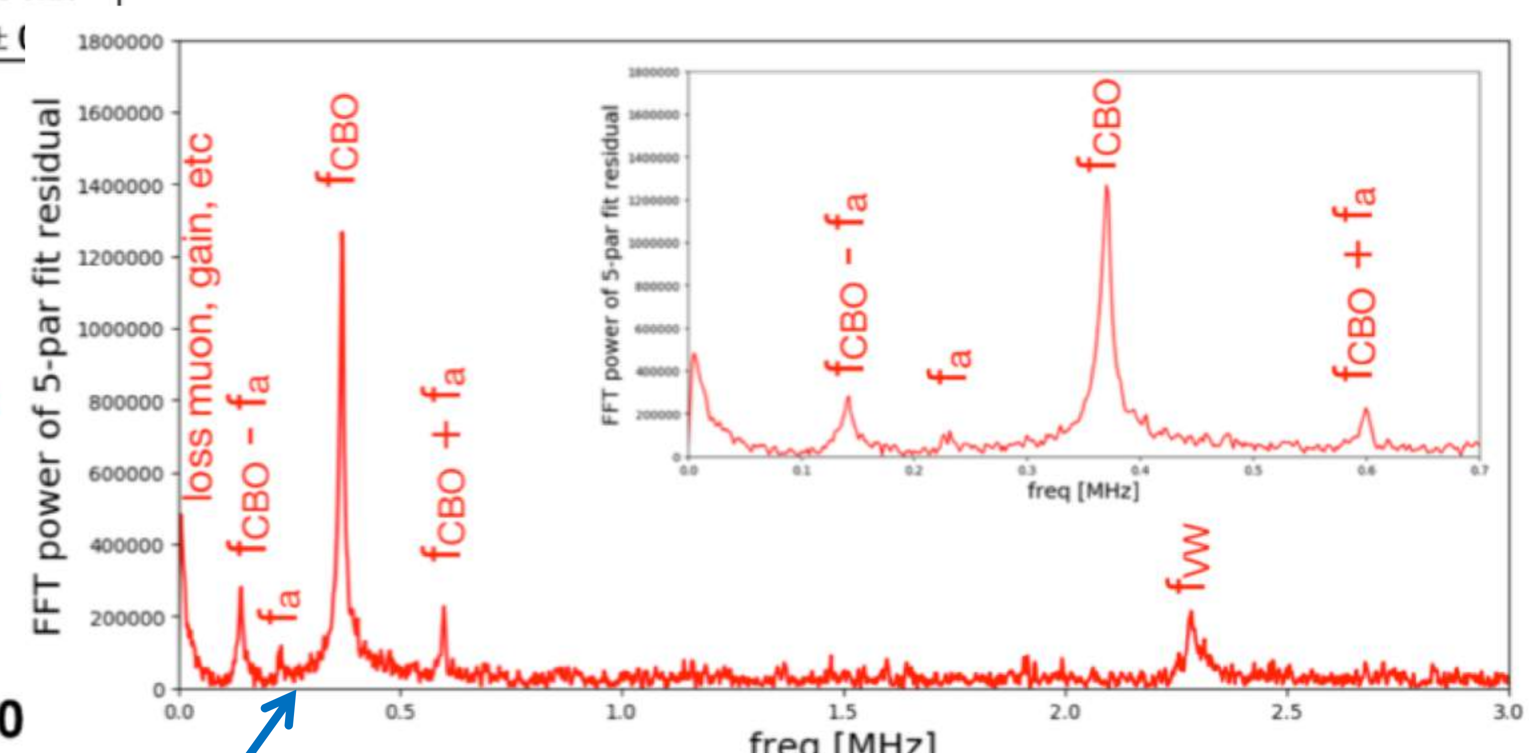
$$N_{ideal}(t) = N_0 \exp(-t/\tau_\mu)\,[1 + A\cos(\omega_a t + \varphi)]$$

- This simple fit is clearly not sufficient and well defined resonances are observed in the residuals



muon lifetime: τ_μ = 64.35 µsec

NOTE: blinding on ω_a!

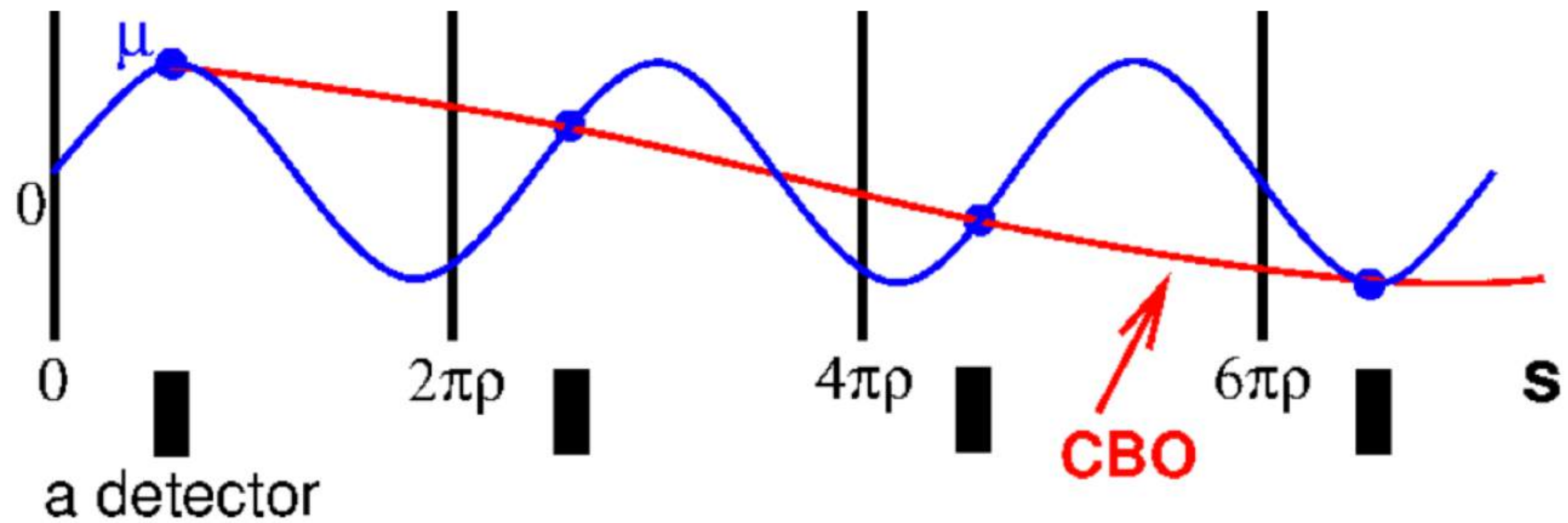


RESIDUALS (in frequency space)

Structure in residual: Beam Oscillations

- Coherent Betatron Oscillations (CBO) sampled by each detector at one point around the ring

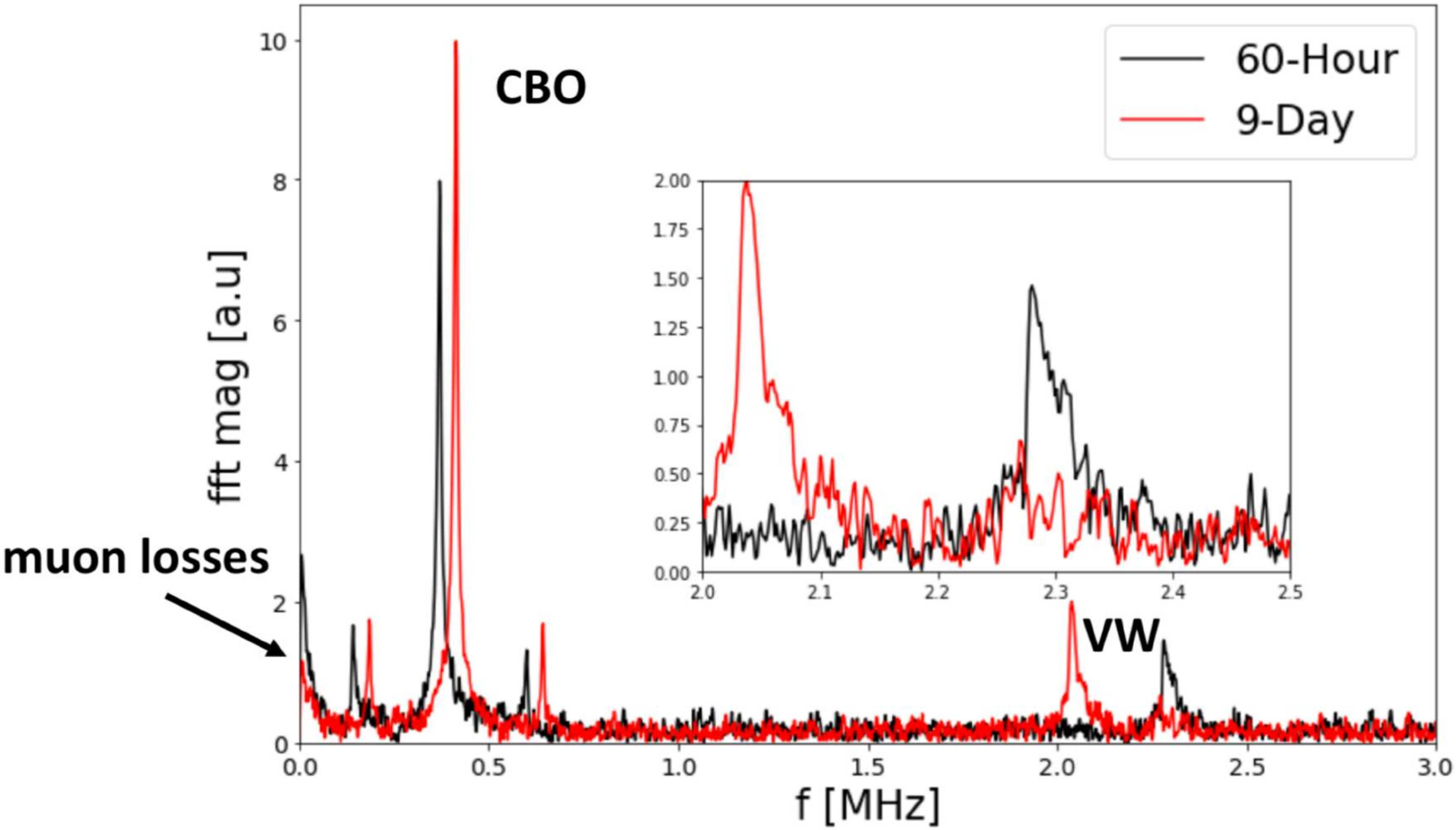
$$\lambda_{\mathrm{CBO}} \simeq \text{ 14 turns}$$



- Beating effect: the frequency measured by any one detector is $f_{CBO} = f_C - f_x$ (much smaller than both individual freqs)
- Similar effect in vertical direction

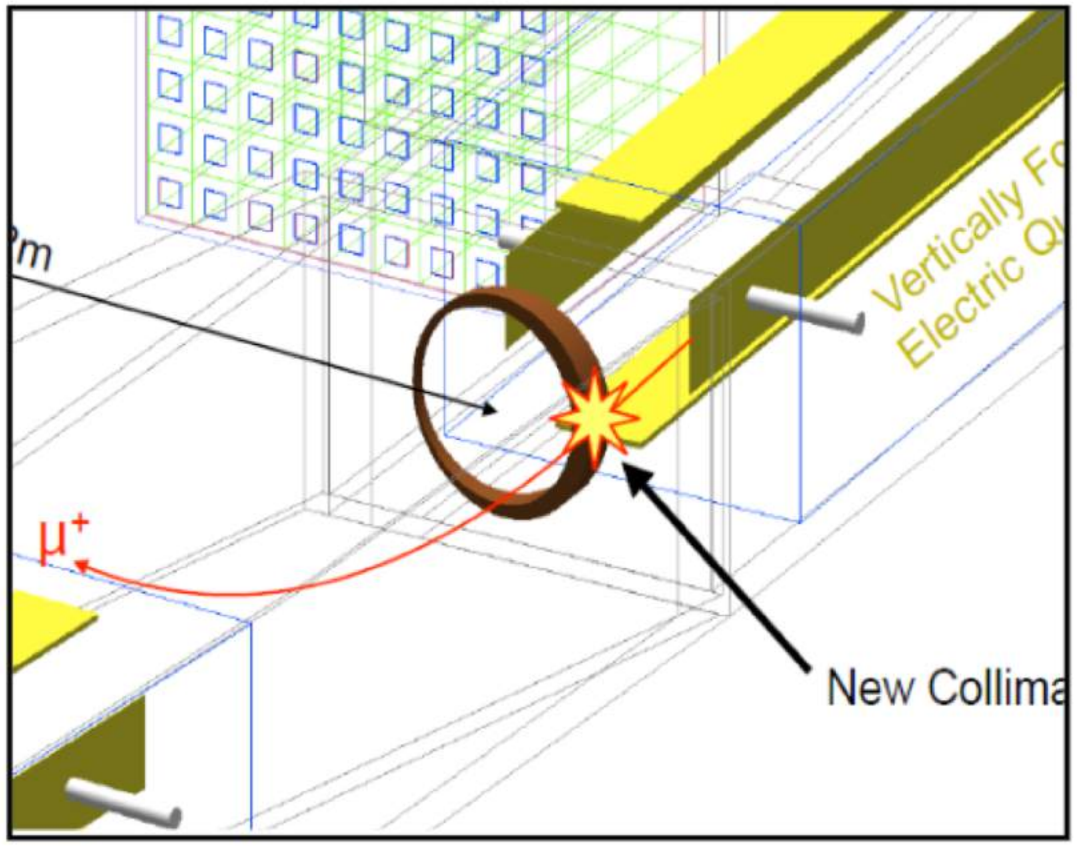
Residuals for two datasets

- The betatron oscillations depend on the beam parameters → different for each Run1 dataset: to be fitted separately

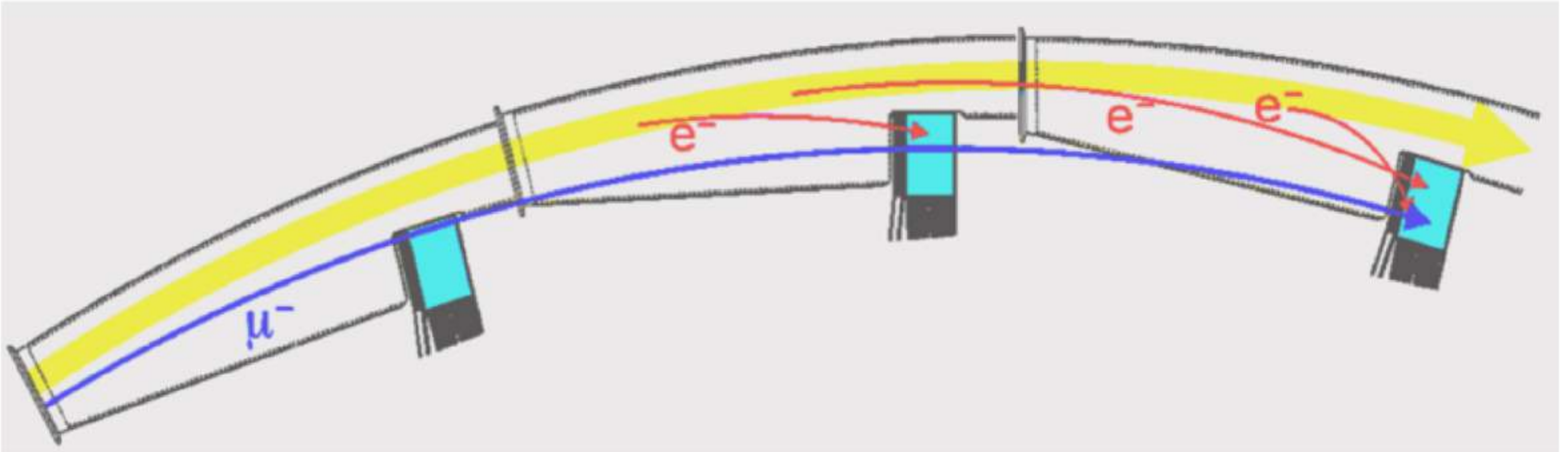


Distorting muon life time: lost muons

- Muons at the border of the beam phase space hit the collimators and bend (tipically) inward
- This happens mostly in the first microseconds, distorting muon exponential decay



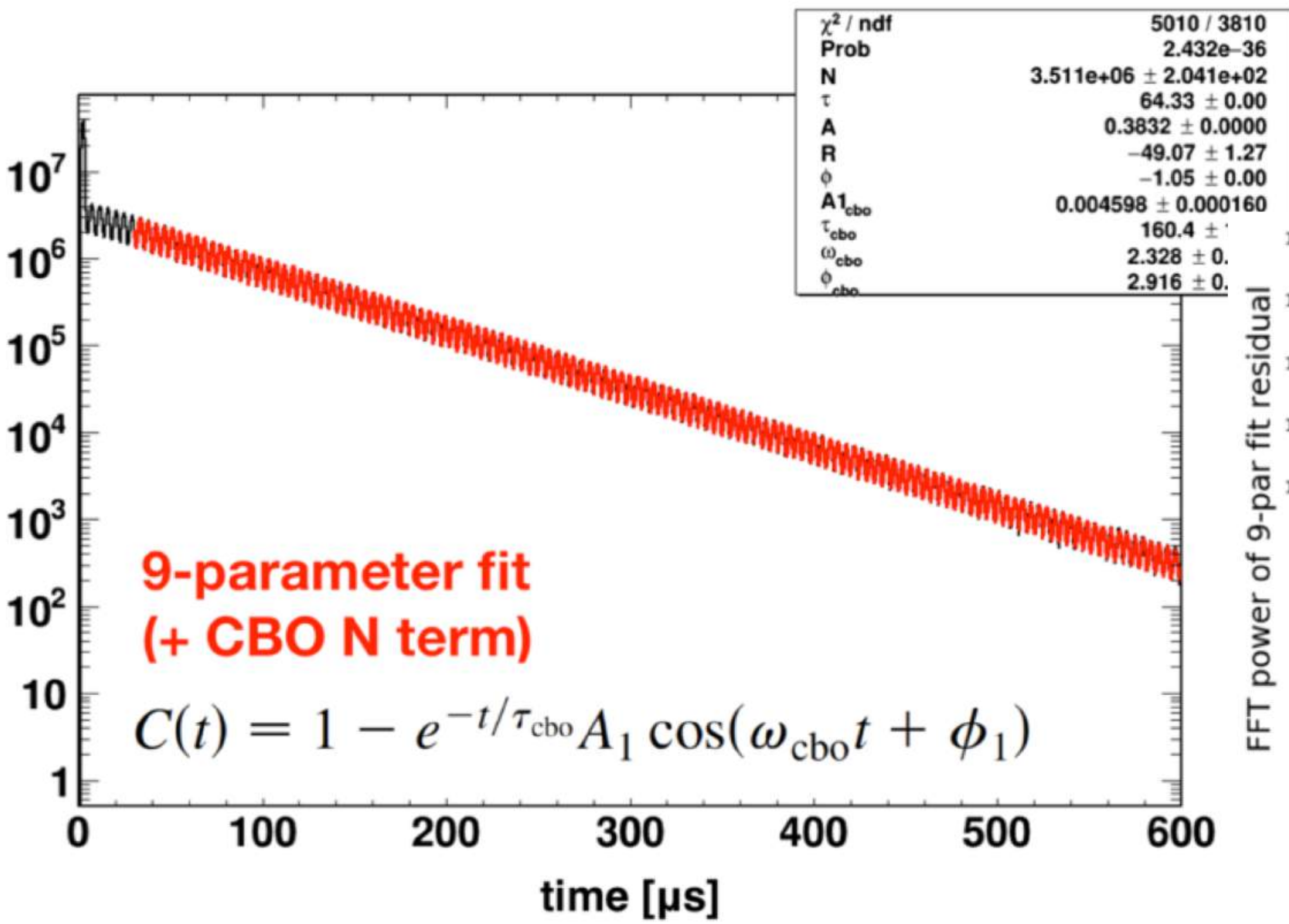
$$N(t) = N_0 \boxed{e^{-t/\tau} \cdot \Lambda(t)} \cdot \left(1 + A \cos(\omega_a t + \varphi)\right)$$

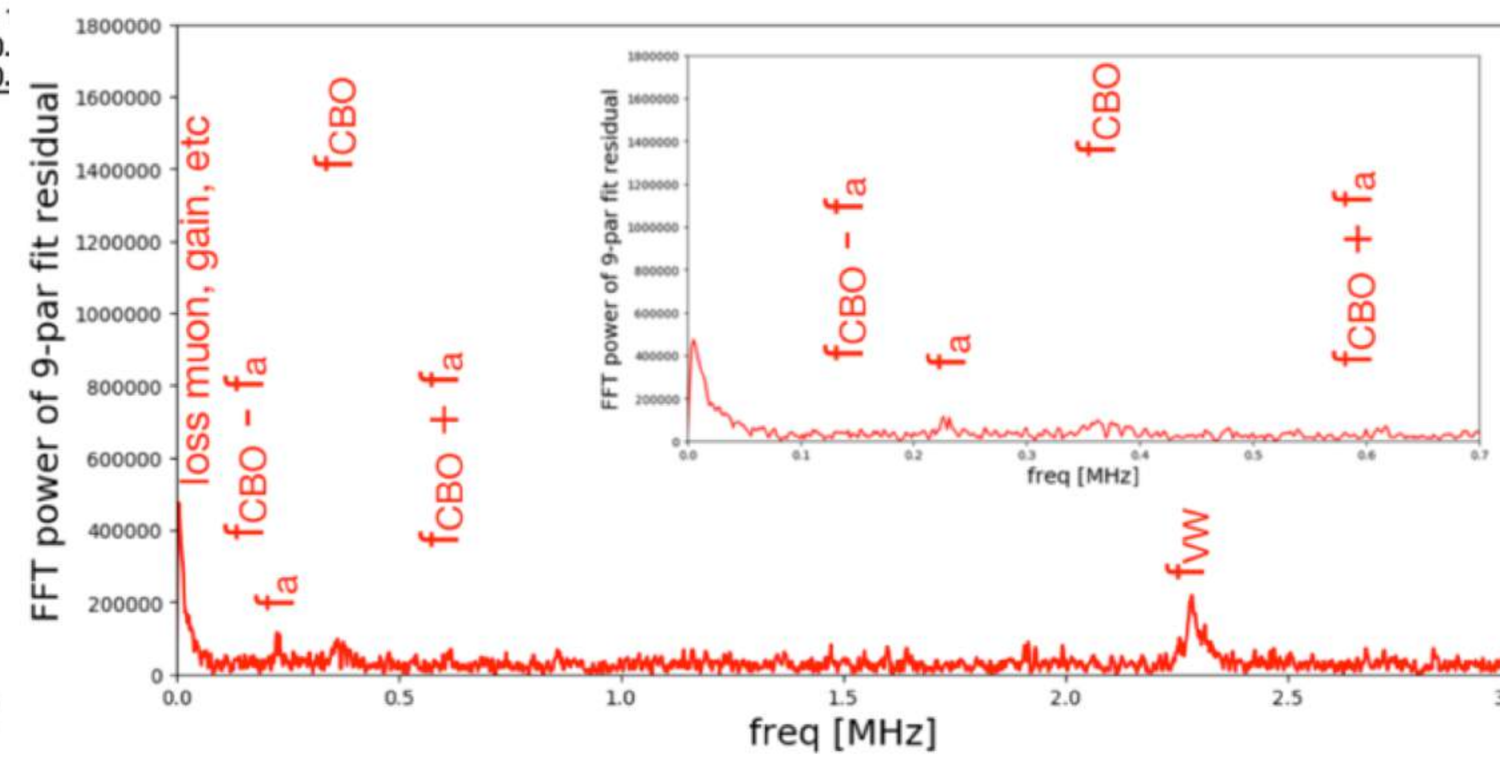


- ***Lost muons*** identified as MIPs in 2 or 3 consecutive calorimeters with Δt ~ 6.2 nsec

9-par fit

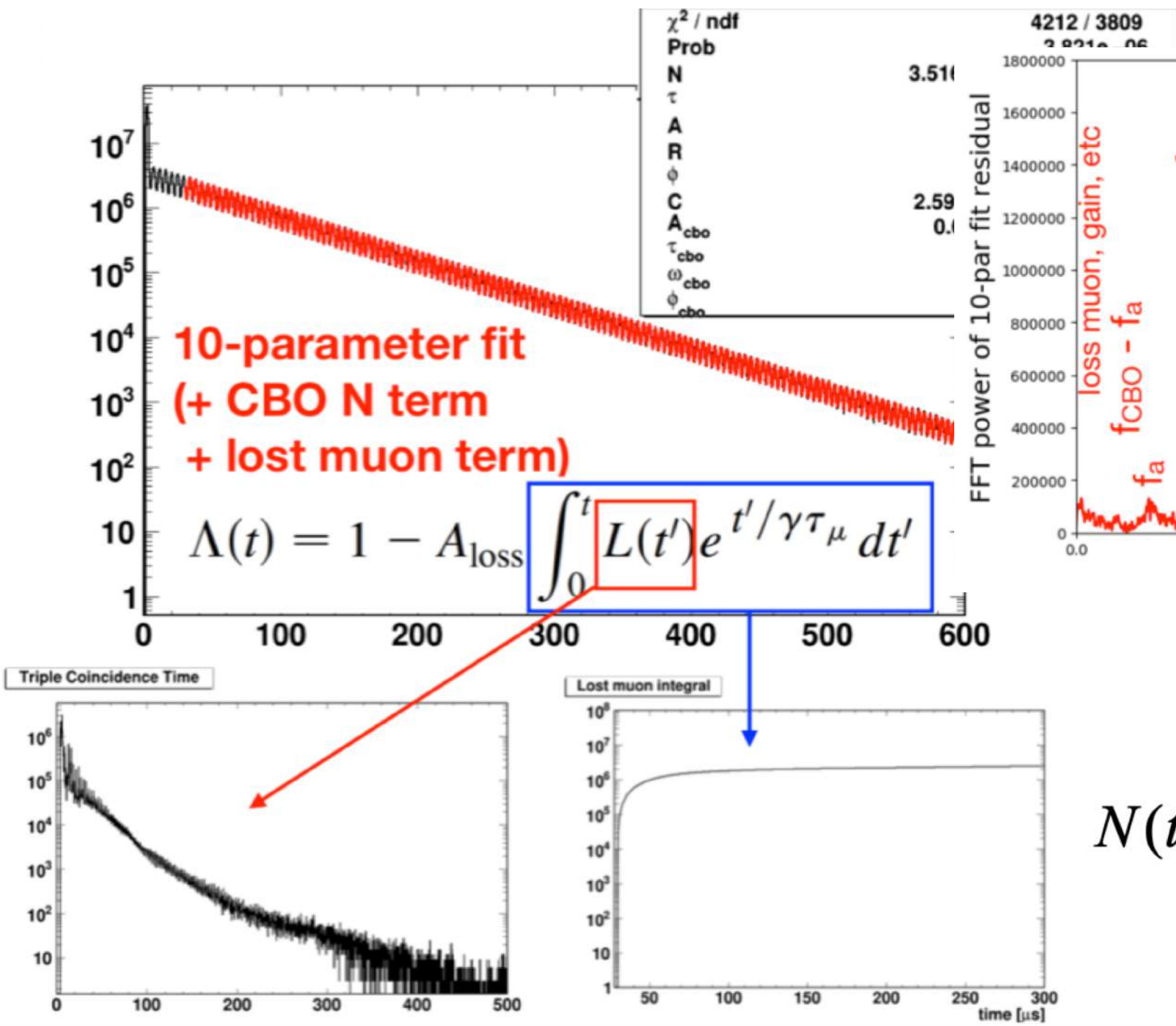
- The effect of Coherent Betatron Oscillation is parametrized as a factor with similar structure as the muon modulated decay

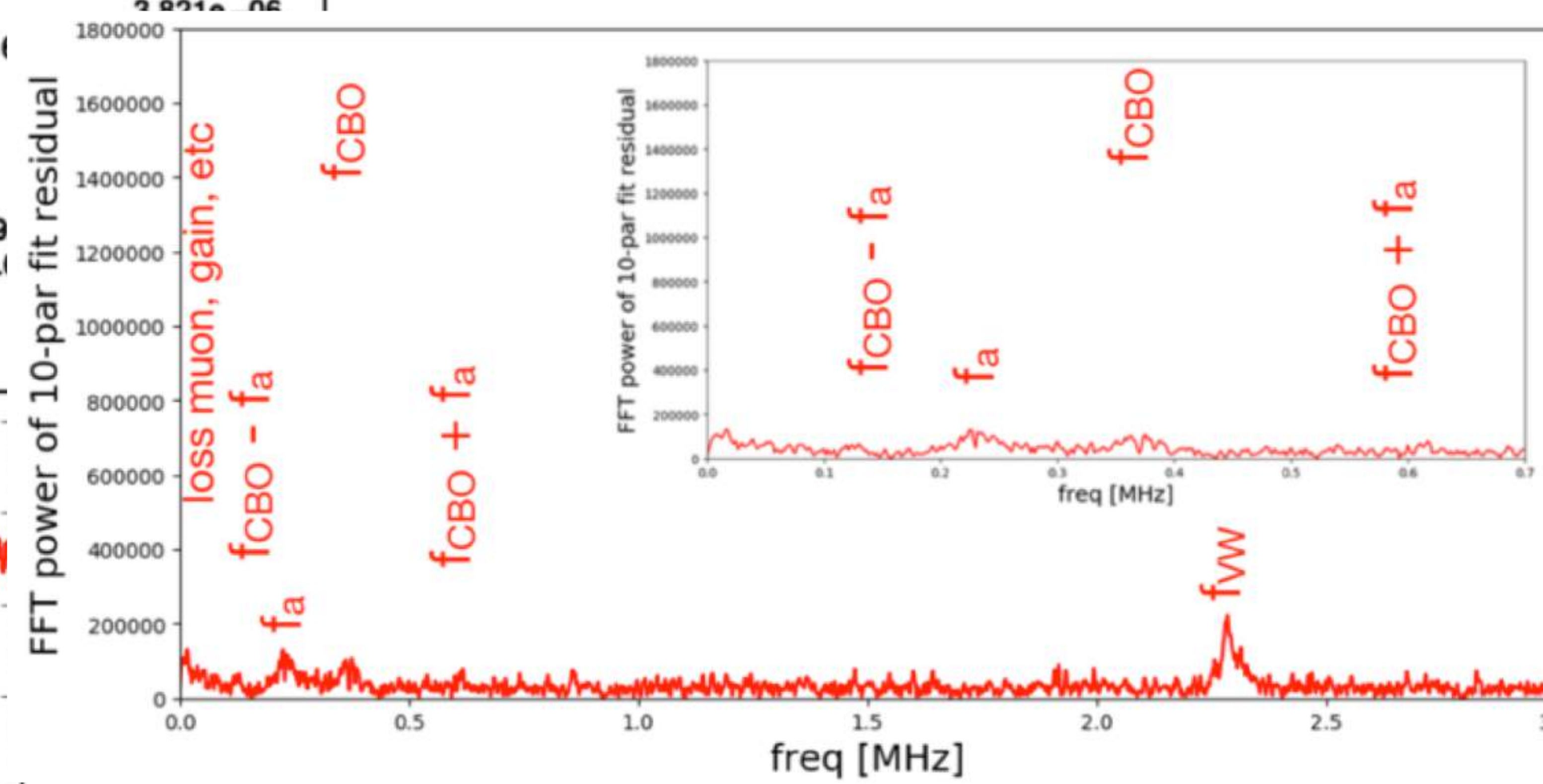




10-par fit: adding lost muons

- Including the *lost muons* term removes the peak at *f=0* in the FFT plot



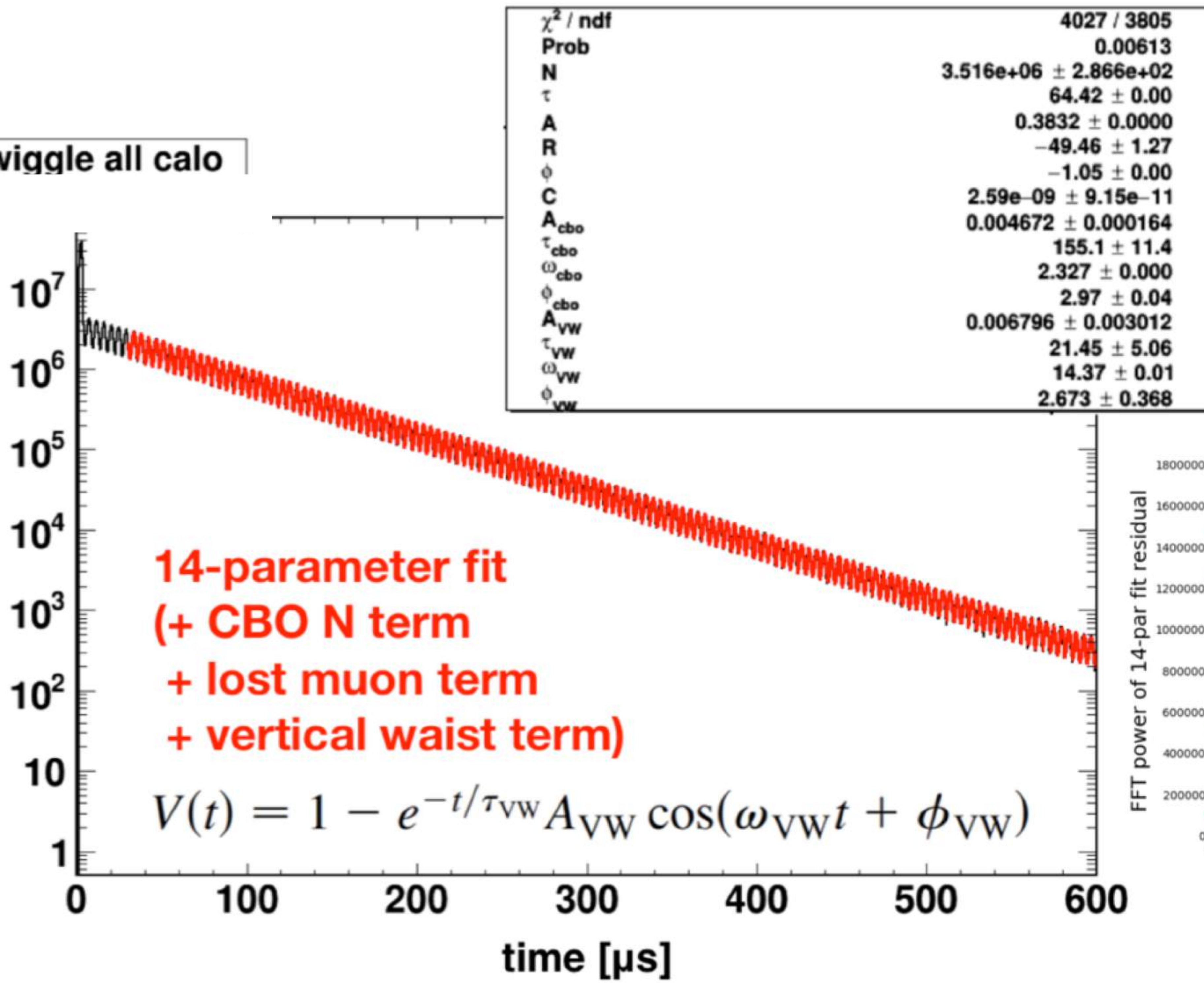


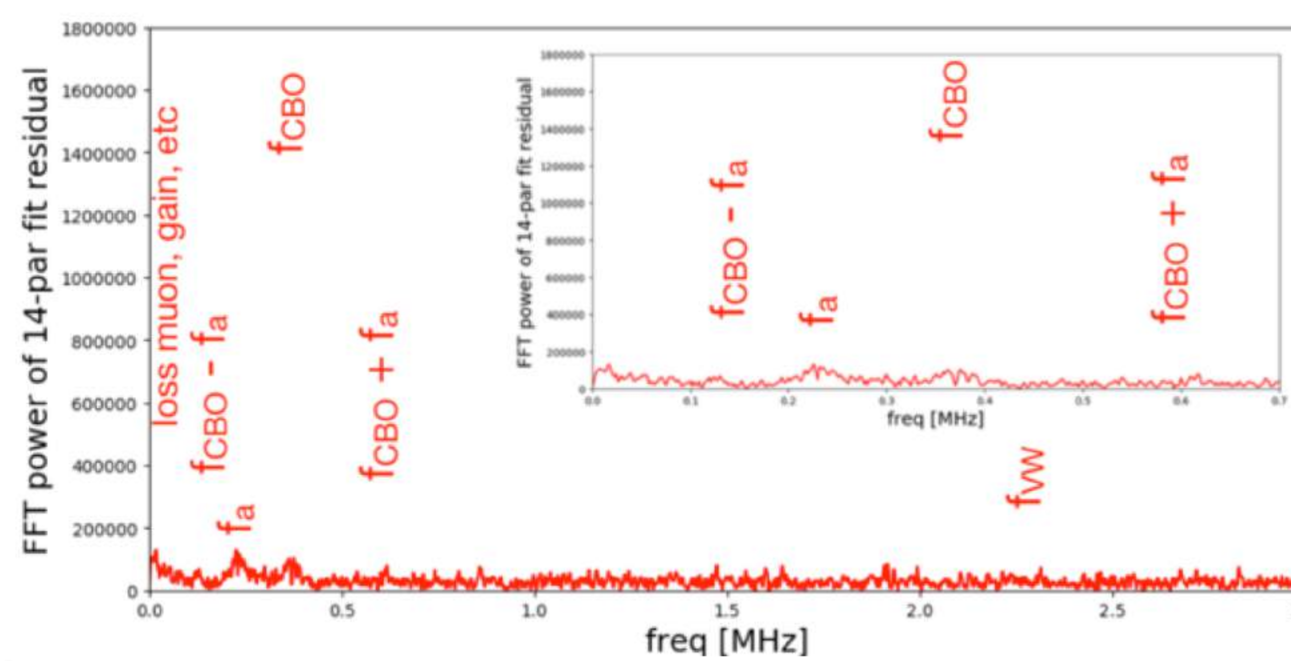
$$N(t) = N_0 \boxed{e^{-t/\tau} \cdot \Lambda(t)} \cdot \left(1 + A\cos(\omega_a t + \varphi)\right)$$

14-par fit: adding vertical oscillation

60 hour

- Vertical oscillations (*vertical waist*) parametrized as an exponential term times an oscillation





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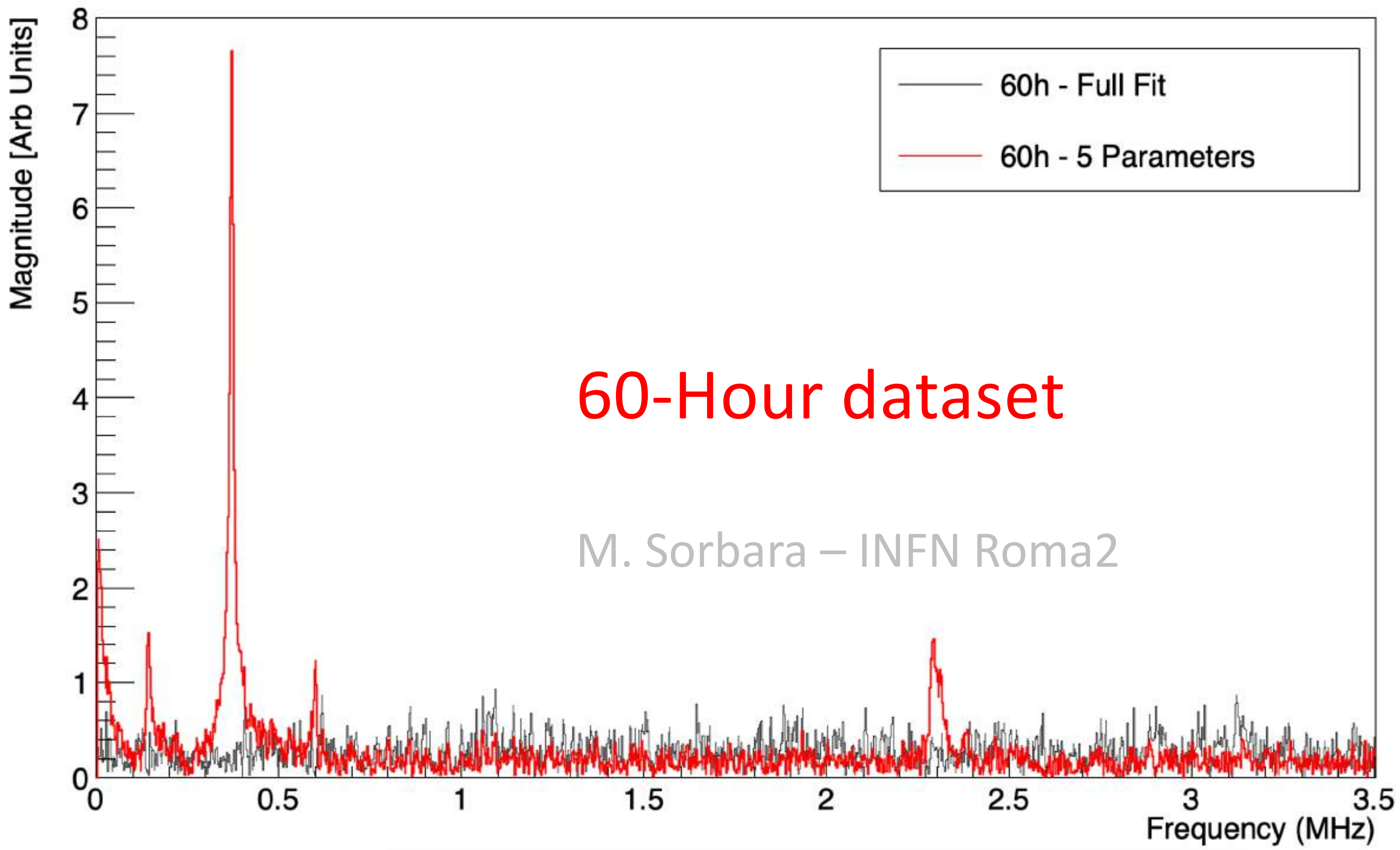
Full fit on 2 datasets

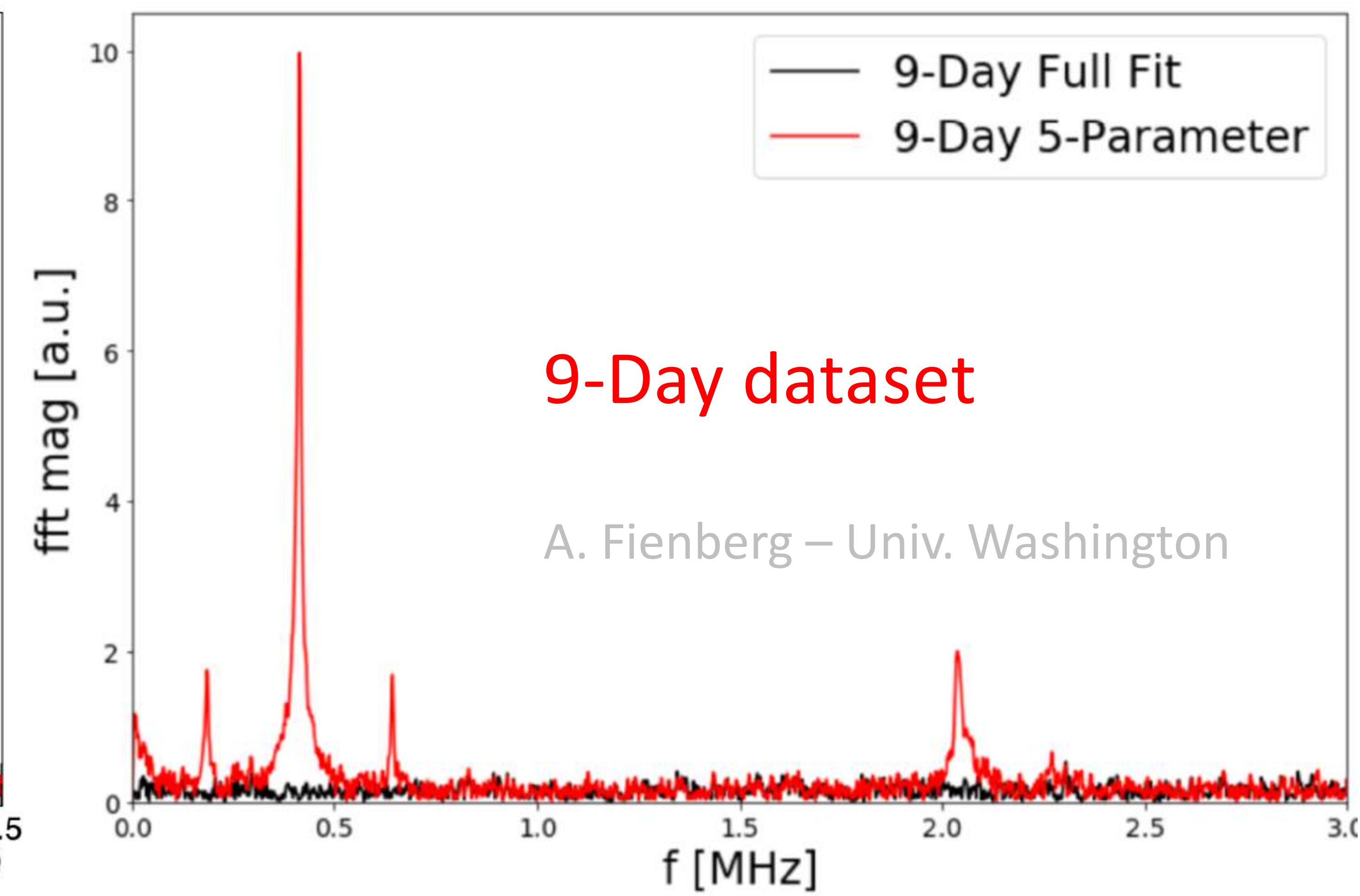
- Presented at the last «g-2 Physics Week» (Elba Island, Italy, May 27-31, 2019)
- Results by 2 groups; similar by other analyzers → next slides



1.0×10^9 positrons

1.34 ppm precision

χ^2/ndf = 3451/3467



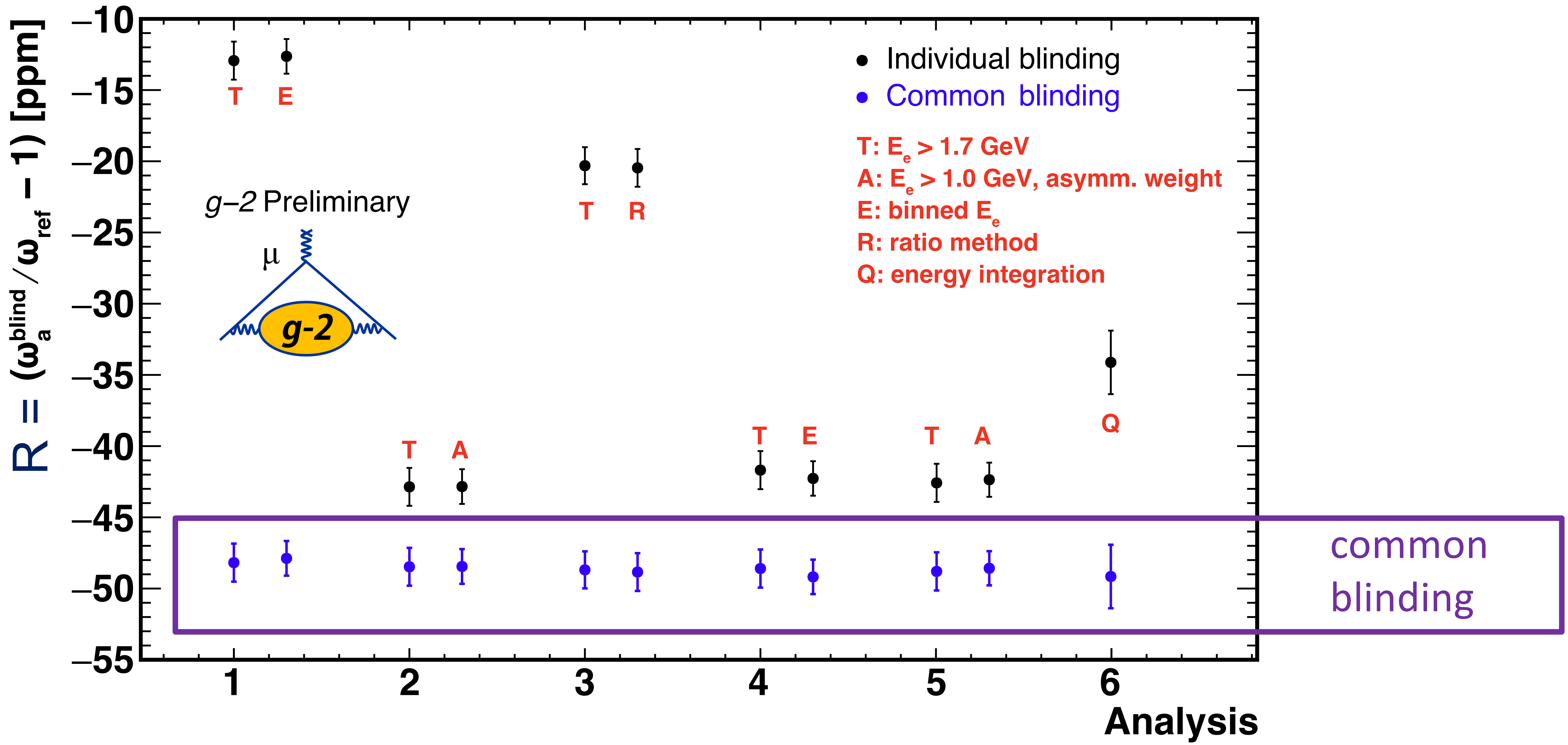
2.3×10^9 positrons

0.88 ppm precision

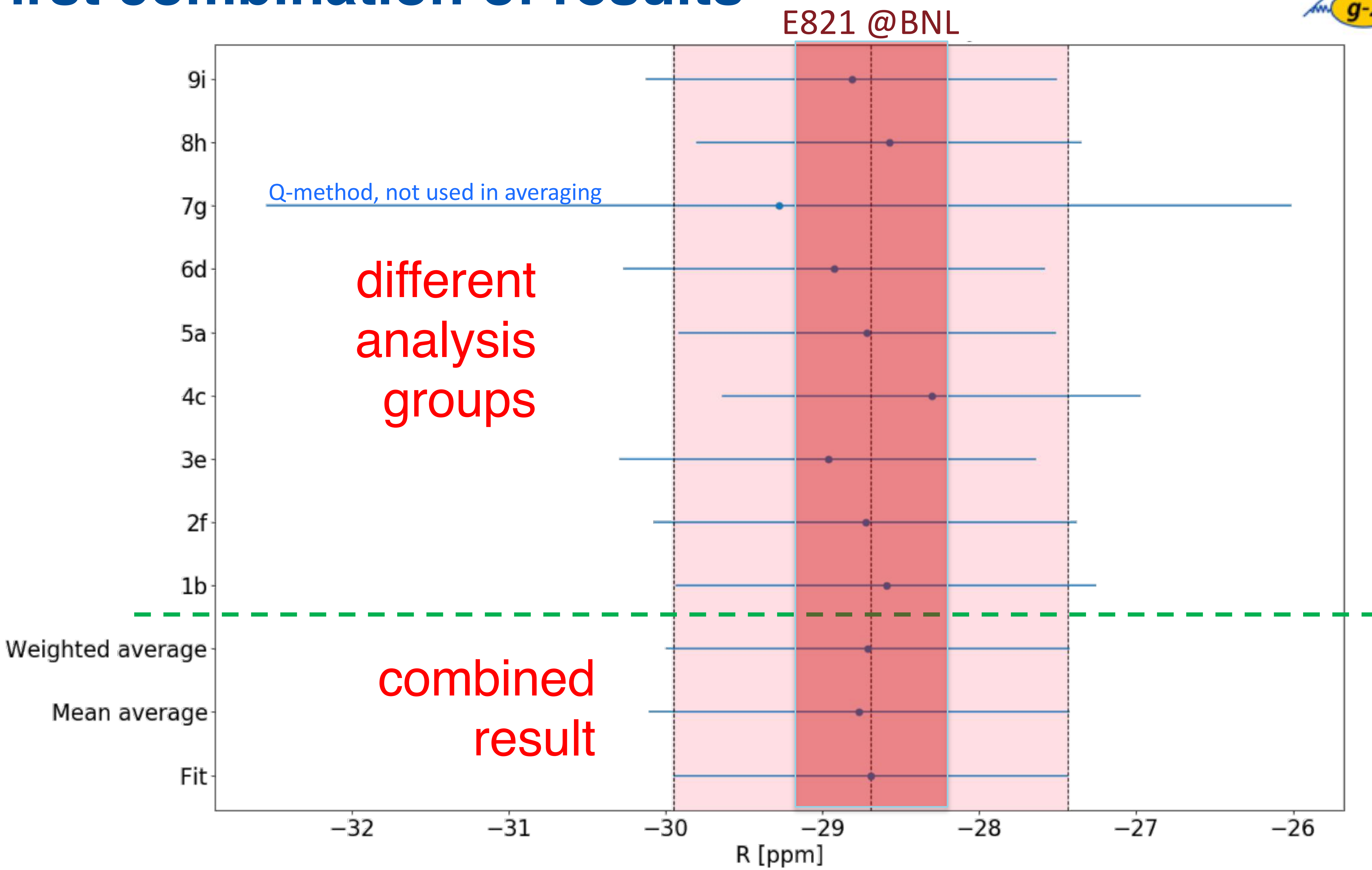
$$\frac{\chi^2}{ndf} = 4161/4133$$

First combination of results

- Results on wa for the first dataset (the 60-Hour ~ 10% BNL) have been compared among analyzers by applying a *common blinding procedure*



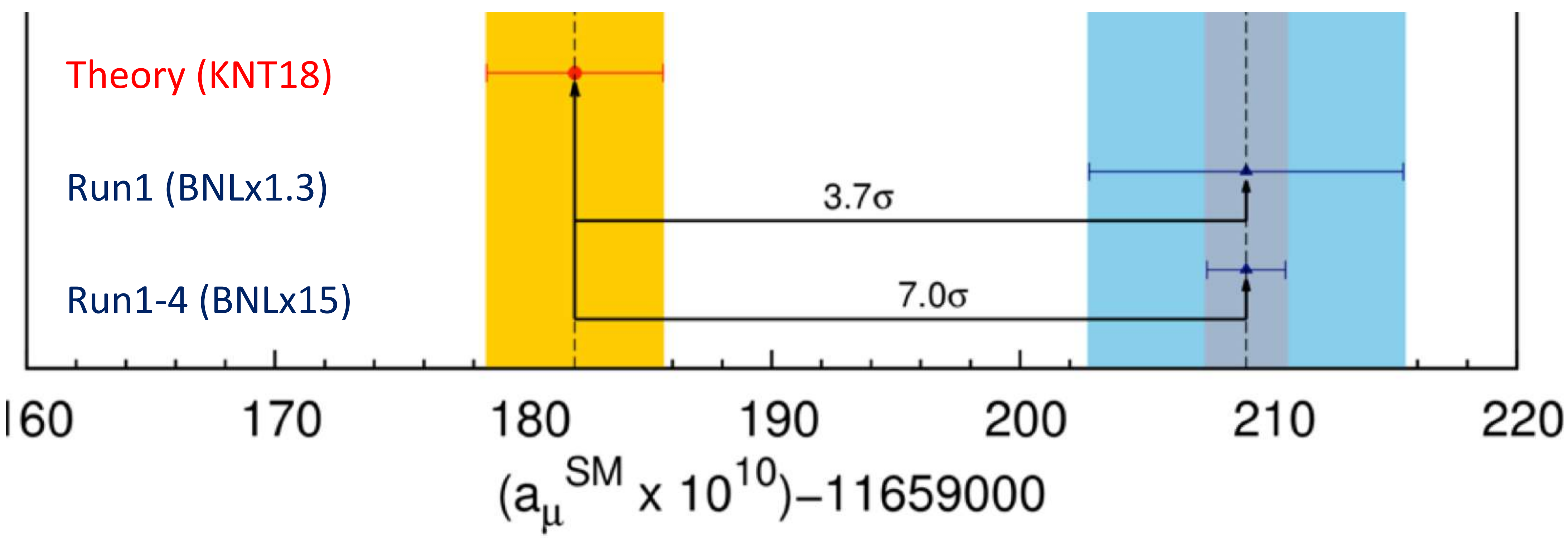
First combination of results



$\delta\omega_a/\omega_a$ (0.1 x BNL) = 1.23 ppm ; central value *blinded*

The (next) future …

- Confirming *E821@BNL* central value, even with the same error, is extremely important! → Run1
- At the end of Run4 (2021), with a statistics ~15 times BNL, the discrepancy can become significant, *assuming central value holds!*



Summary & Outlook

- Analysis of Run1 going on
- Expected total error $\delta\omega_a/\omega_a$ (Run1) ~ 0.5 ppm, similar to BNL one: *important check of central value*
- 6 datasets to be fitted independently
- Publication expected by calendar year 2019 ...

- ... Run2 (apr-jul 2019) provided 2.2 additional «BNL equivalent», with more stable beam conditions
- Waiting for this new data to be processed and studied implies a delay in the publication of ~1 year
- Decision will be taken in September 2019

THANKS

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

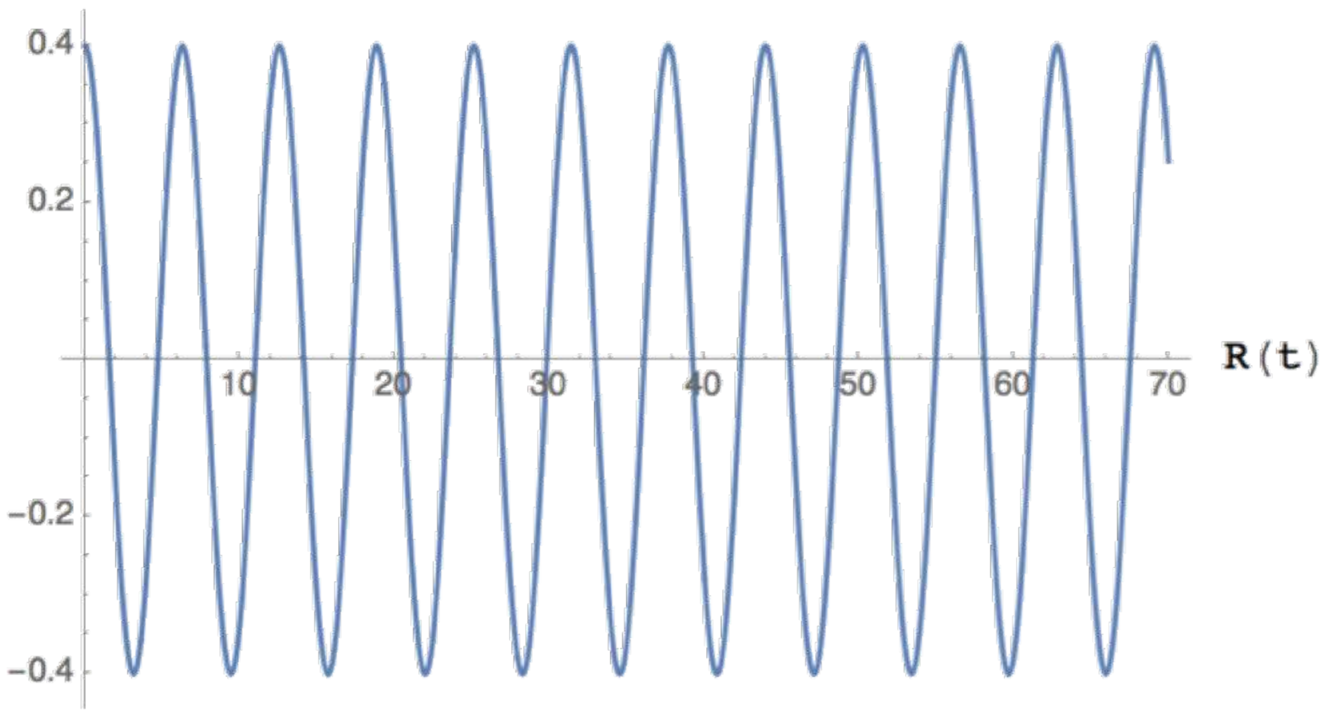
Inflector + Kicker

Tracker

R-method (Ratio)

- Ratio method: randomly split dataset in 2 subsets shifted by ±half a g-2 period
- Build combinations of the 2 subsets which eliminates the exponential behaviour and leaves just a sinusoidal term

$$u^{\pm}(t) = N(t \pm \mathrm{T}/2) = N_0 e^{-t/\tau \mp T/2\tau}\left(1 + A\cos(\omega_a t \pm \omega_a \frac{T}{2} + \varphi)\right)$$



$$U(t) = u^{+}(t) + u^{-}(t)$$

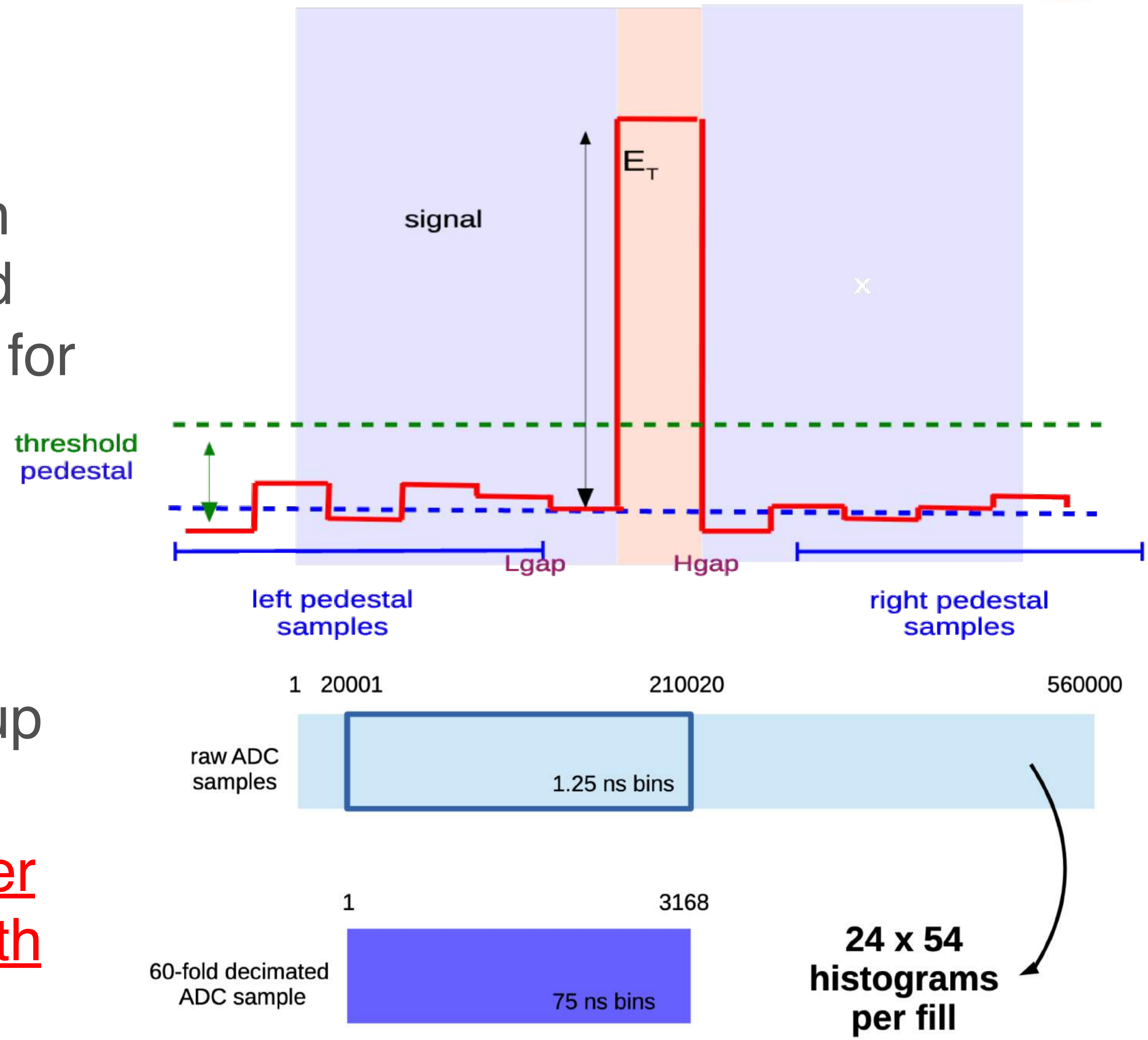
$$R(t) = \frac{N(t) - U(t)}{N(t) + U(t)}$$

$$R(t) = A\cos(\omega_a t + \phi) - \frac{1}{16}\left(\frac{T}{\gamma\tau}\right)^2 + (h.o.)$$

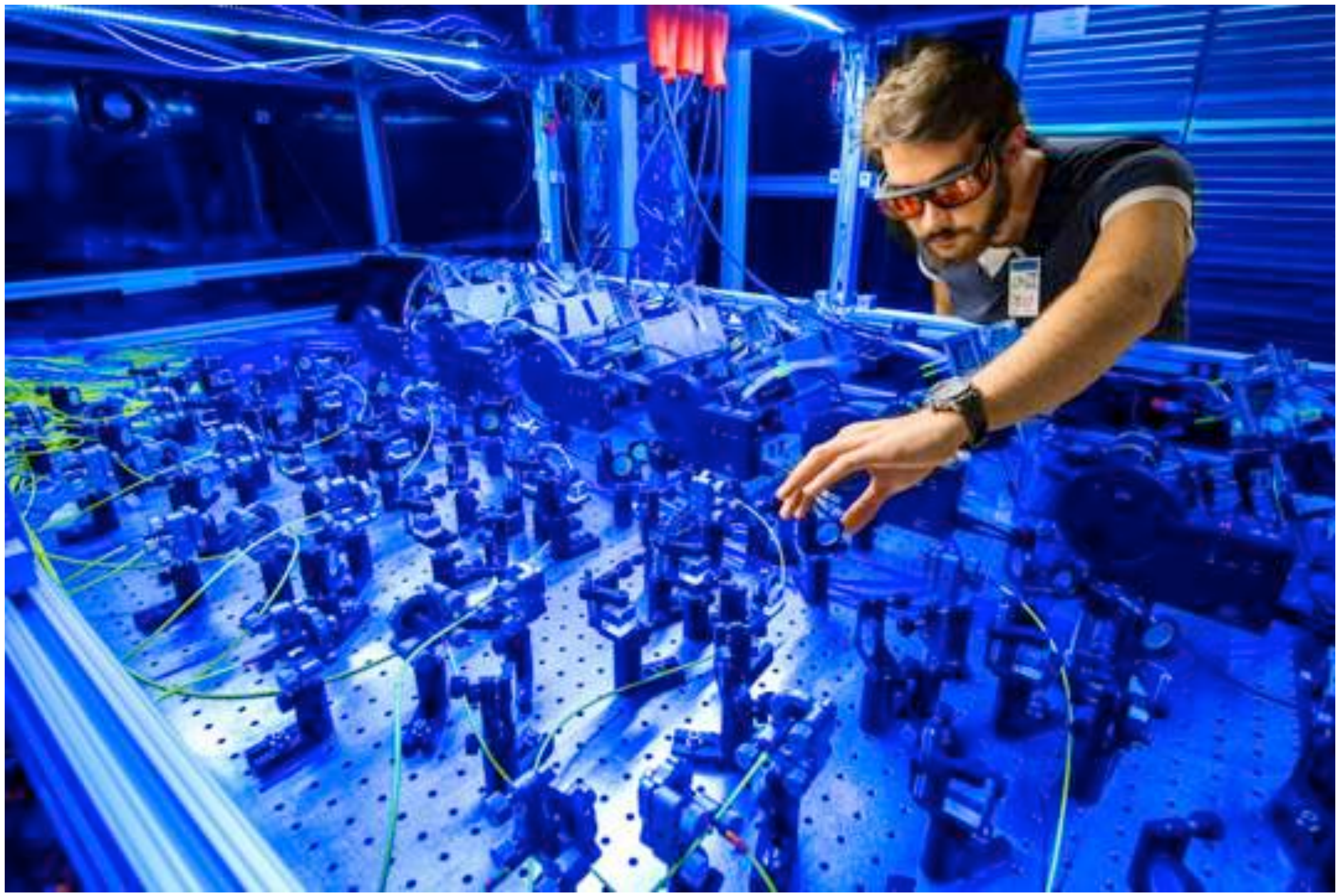
3 parameters fit: less sensitive to slow effects which divide out

Q-method

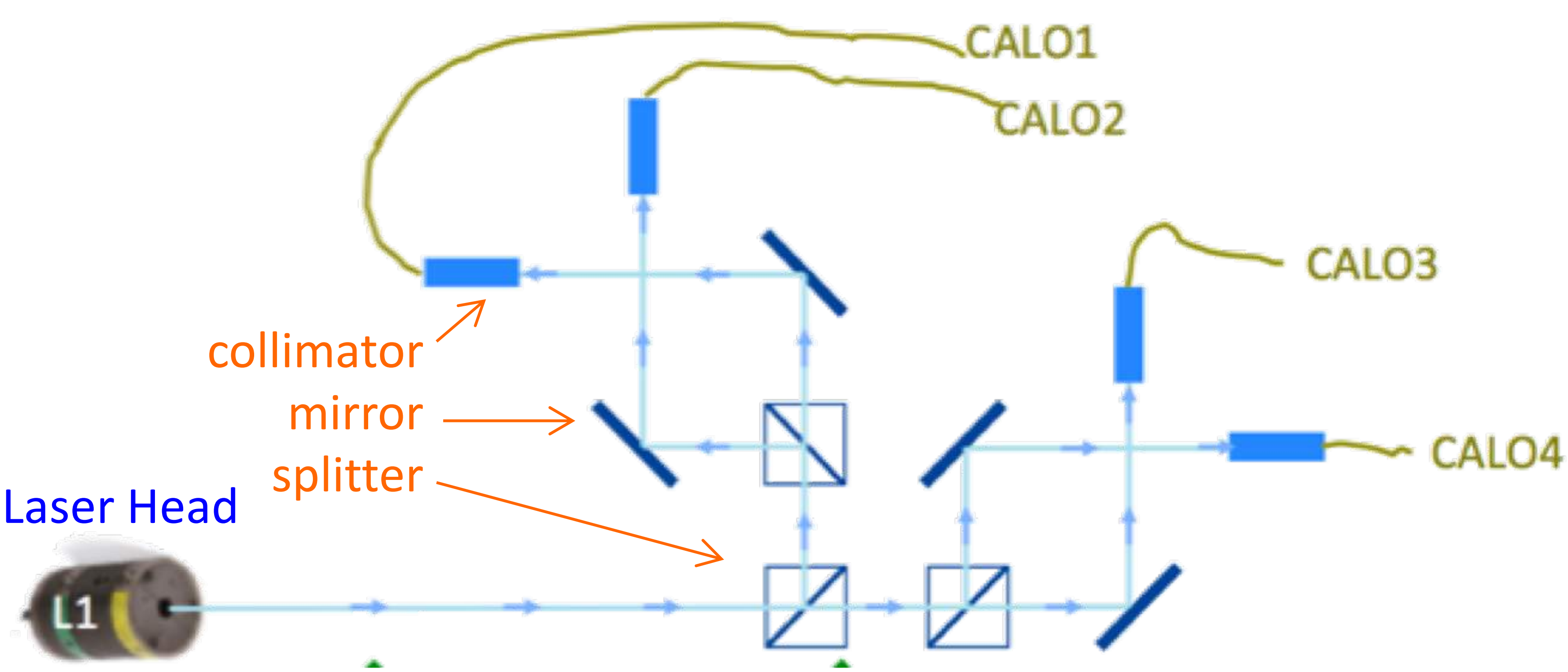
- No clustering: just integrate energy above threshold (in theory no threshold should be applied) for each crystal
- To reduce the amount of data stored offline, time bins are summed up in groups of 60
- <u>The total energy per event fluctuates with ω_a frequency</u>



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



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

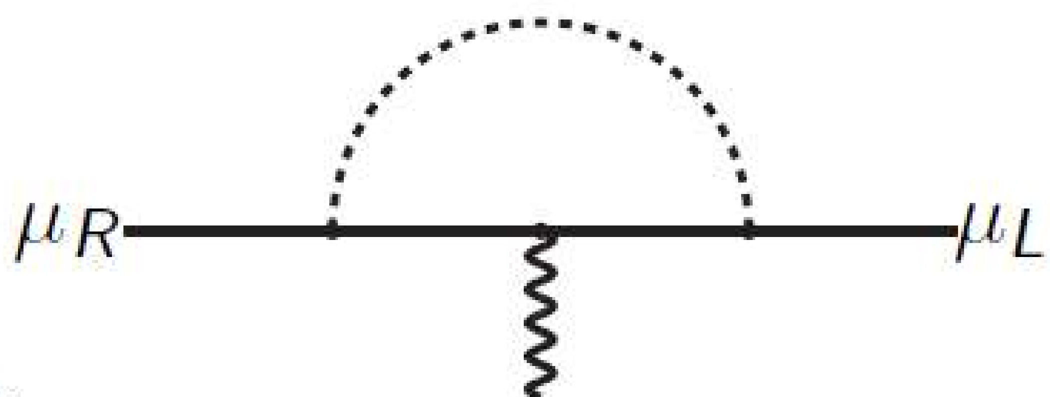
England
- Lancaster
- Liverpool
- University College London

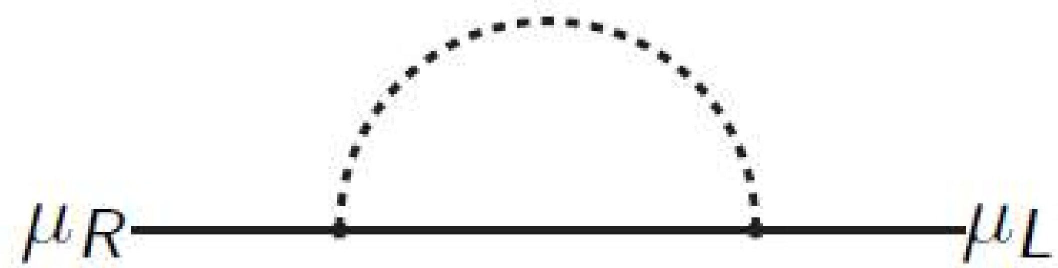
Korea
- CAPP/IBS
- KAIST

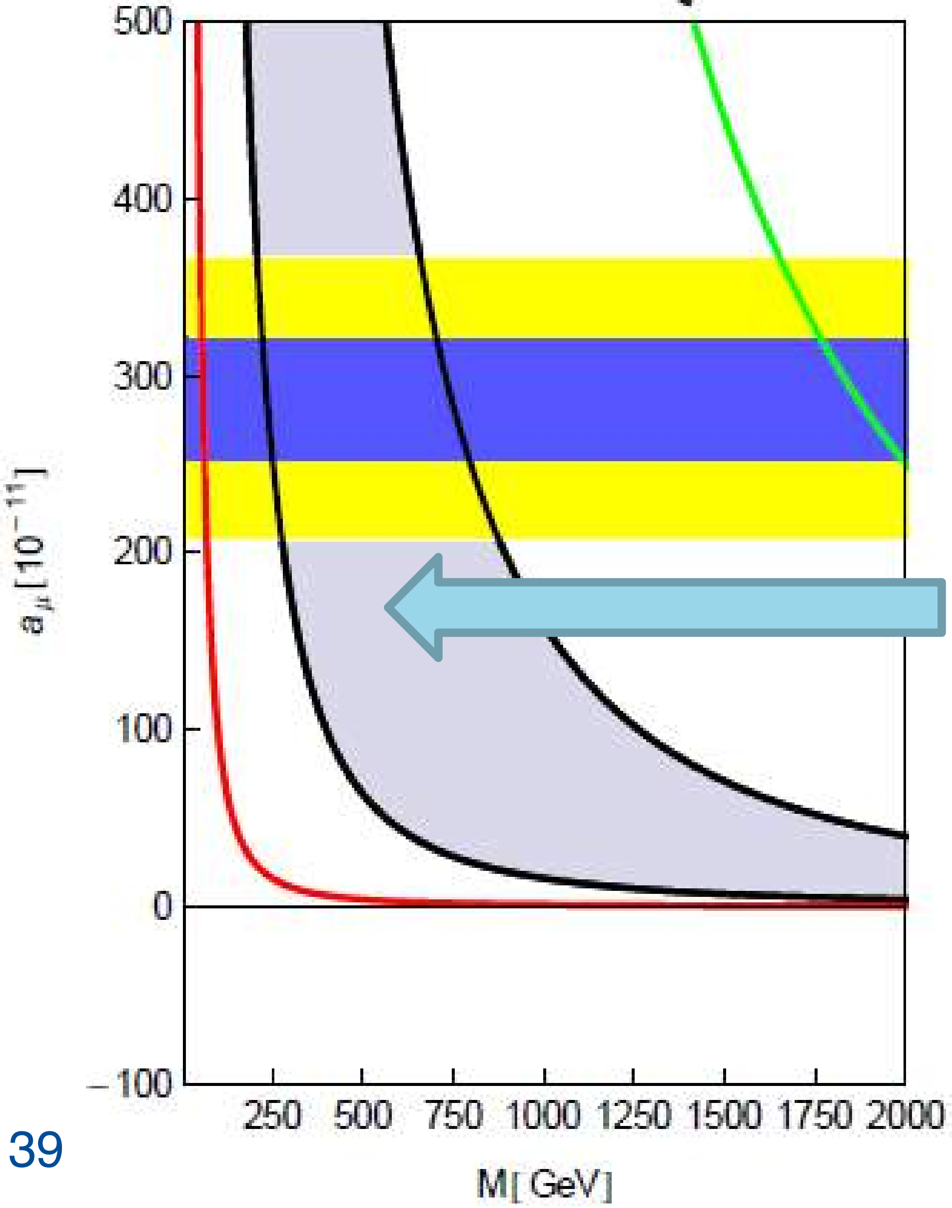
What could it mean if Expt ≠ Theory at > 5σ?

Generically, "loop effects" couple to the muon **mass** and **moment** in similar fashion, characterized by a coupling, ***C***

$$\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2 \qquad\qquad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$



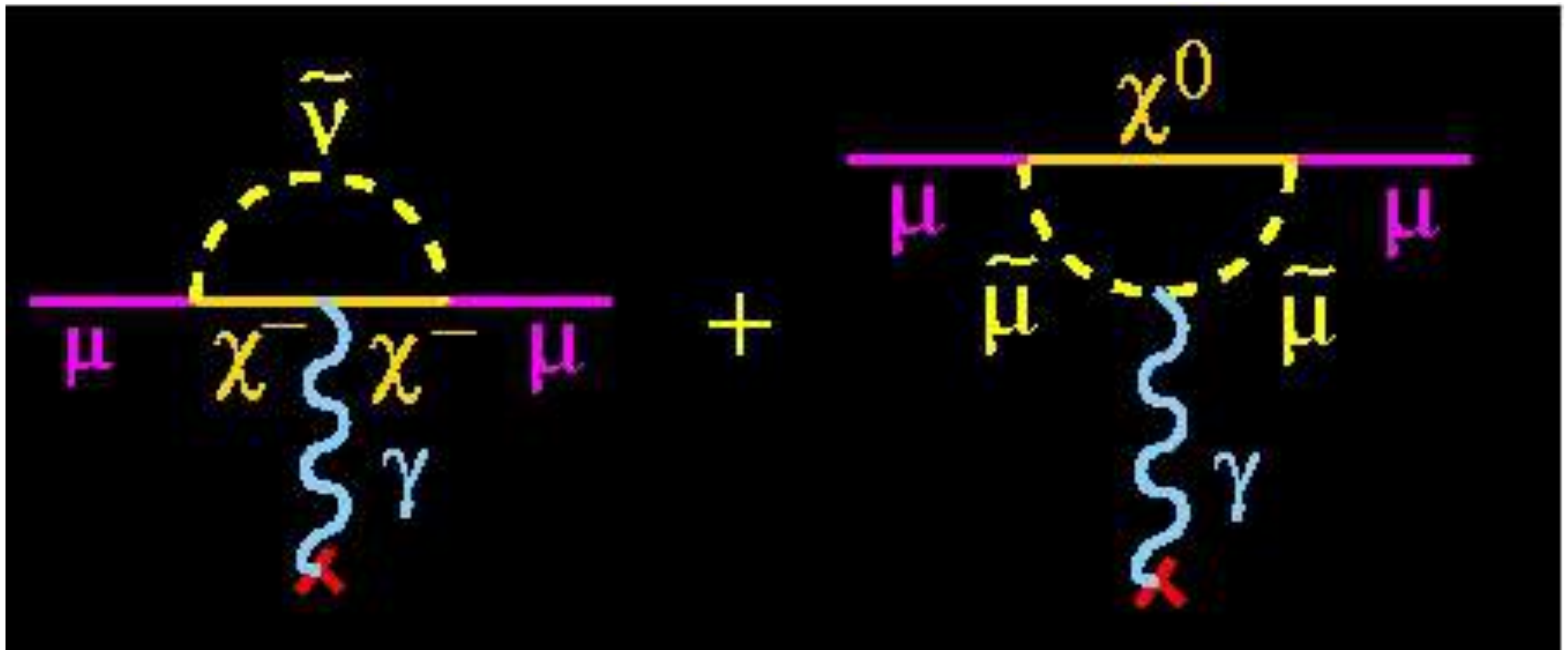




$\mathcal{O}(1)$	radiative muon mass generation . . . [Czarnecki,Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry ($\tan\beta$) vectorlike fermions . . .
$\mathcal{O}(\frac{\alpha}{4\pi})$	SM: Z, W. New physics: $Z', W'\ldots$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

Following Czarnecki, Marciano, and Stockinger

The attractive idea: SUSY



Difficulty to measure at the LHC

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