Pileup Systematic Studies in The Fermilab Muon g-2 Experiment

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New Perspectives
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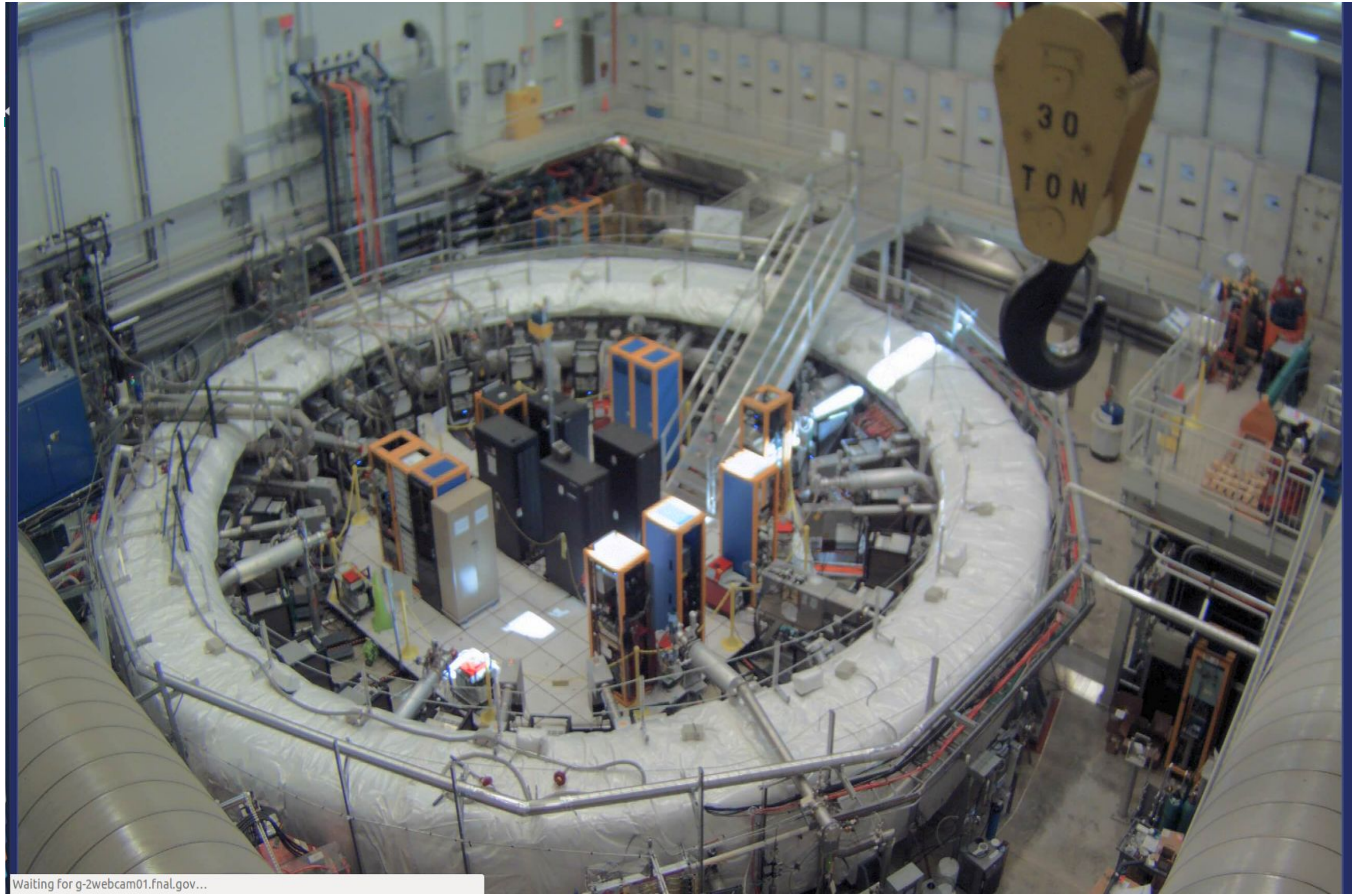
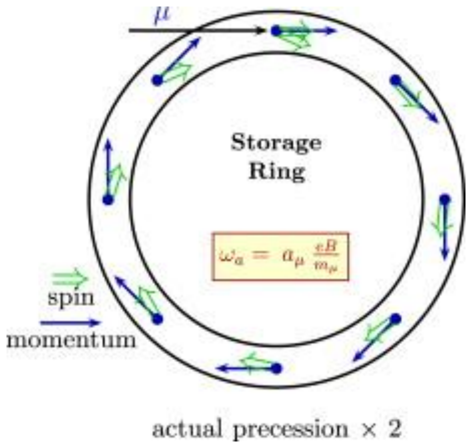
(On behalf of the Muon g-2 Collaboration)

Muon g-2 Experimental Hall at Fermilab



Measurement of a_μ

- Muon Cyclotron frequency : $\omega_c = \frac{eB}{\gamma mc}$
- Muon spin precession frequency : $\omega_s = g_\mu \frac{eB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$
- Experimentally measured :
  - Anomalous precession frequency: $\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$ (Ideally)
  - Magnetic field: $2\hbar\boldsymbol{\omega_p} = 2\boldsymbol{\mu_p}|\mathbf{B}|$

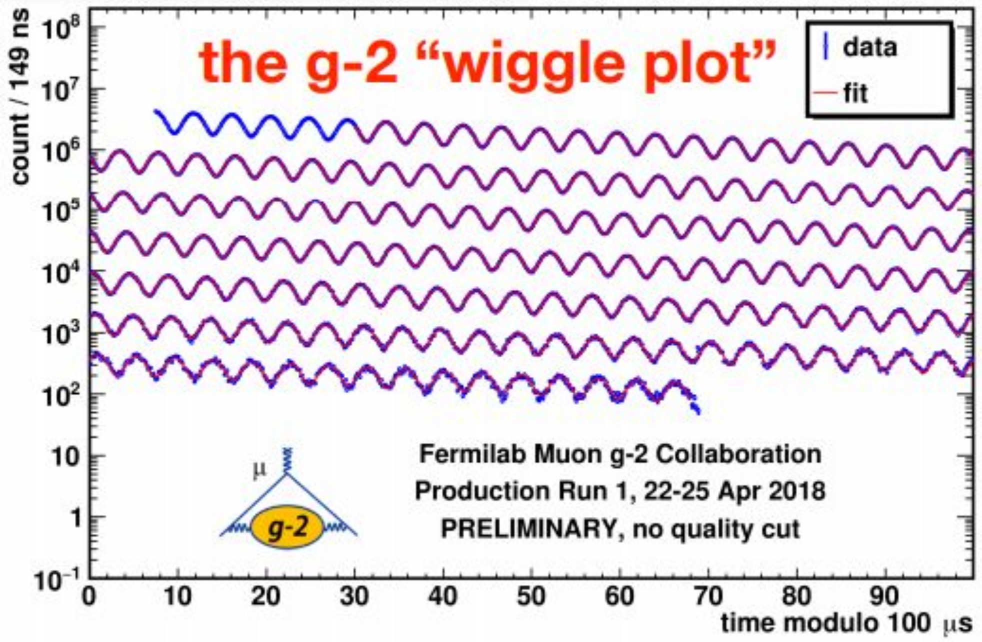


For more details: Jason Hempstead (Muon g-2 in 10 minutes)

Extracting ω_a (Using Threshold Method)

- Highest-energy e^+ emitted preferentially along muon spin (Energy Cut > 1.7 GeV)

- Results in sinusoidally-oscillating arrival time of these e^+ in calorimeters



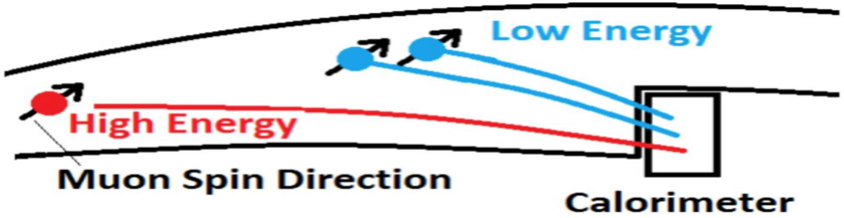
$$N(t) = N_0(t)e^{-t/\tau}[1 + A(t)cos(\omega_a t + \phi(t))]$$

More precise this time!

- Increase the statistics by a factor of 21 and reduce systematics by a factor of ~ 3 w.r.t BNL experiment

ω_a Goal: Factor of 3 Improvement		
Category	E821 (ppb)	E989 Goal (ppb)
Gain Changes	120	20
Lost Muons	90	20
Pileup	80	40
Horizontal CBO	70	< 30
E-field/pitch	110	30
Quadrature Sum	**214**	**70**

Pileup events

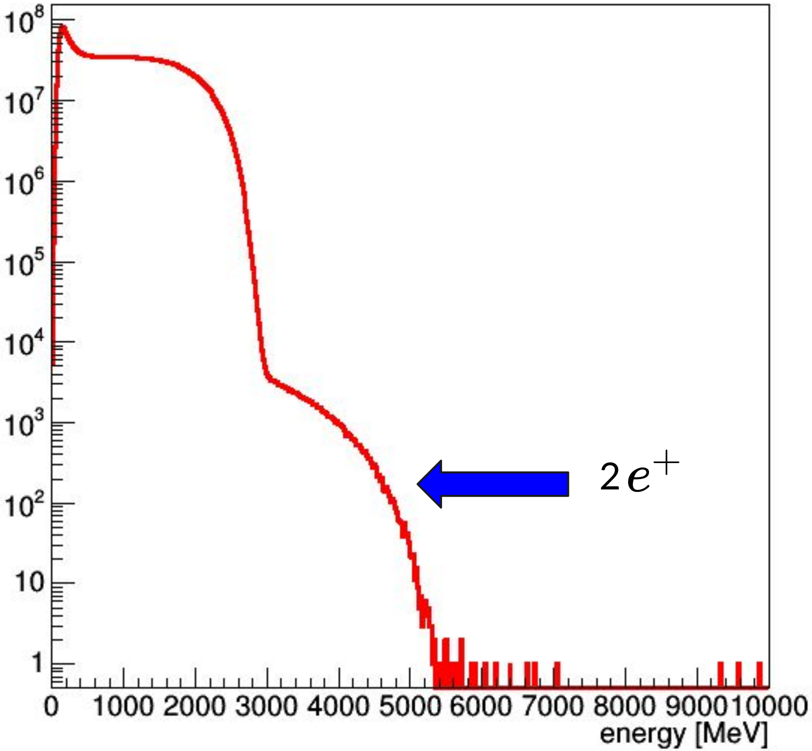


Two (or more) decay positrons hit a calorimeter too close in space and time

The overlapping pulses are treated as a single pulse of higher energy(pileup events)

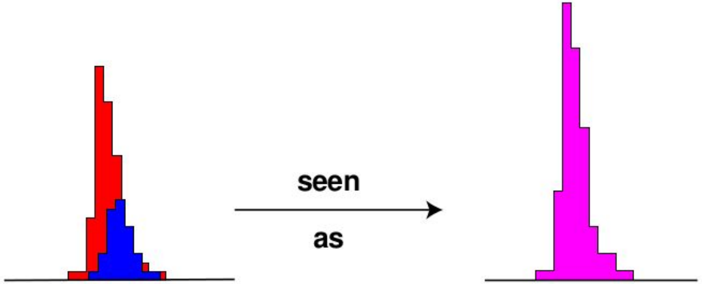
Pileup events distort the time (carries a different g-2 phase) and energy spectra

Energy spectra from all detectors

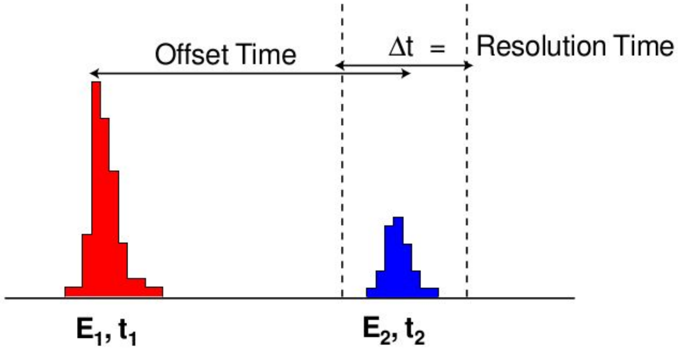


Evidence of two or more overlapping events

Pileup construction



Pileup: Overlapping pulses cannot be resolved

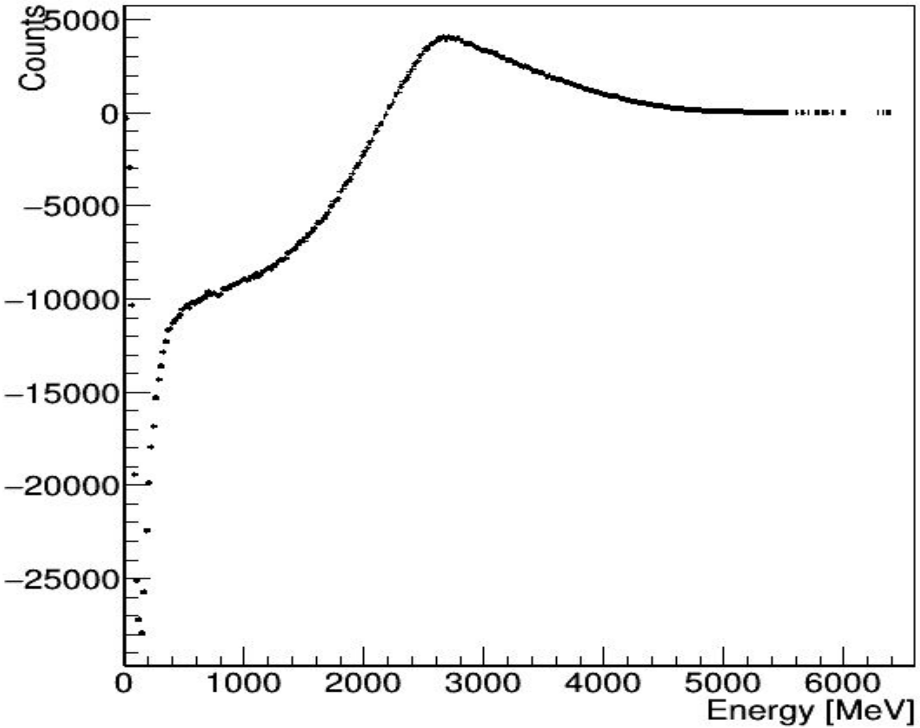


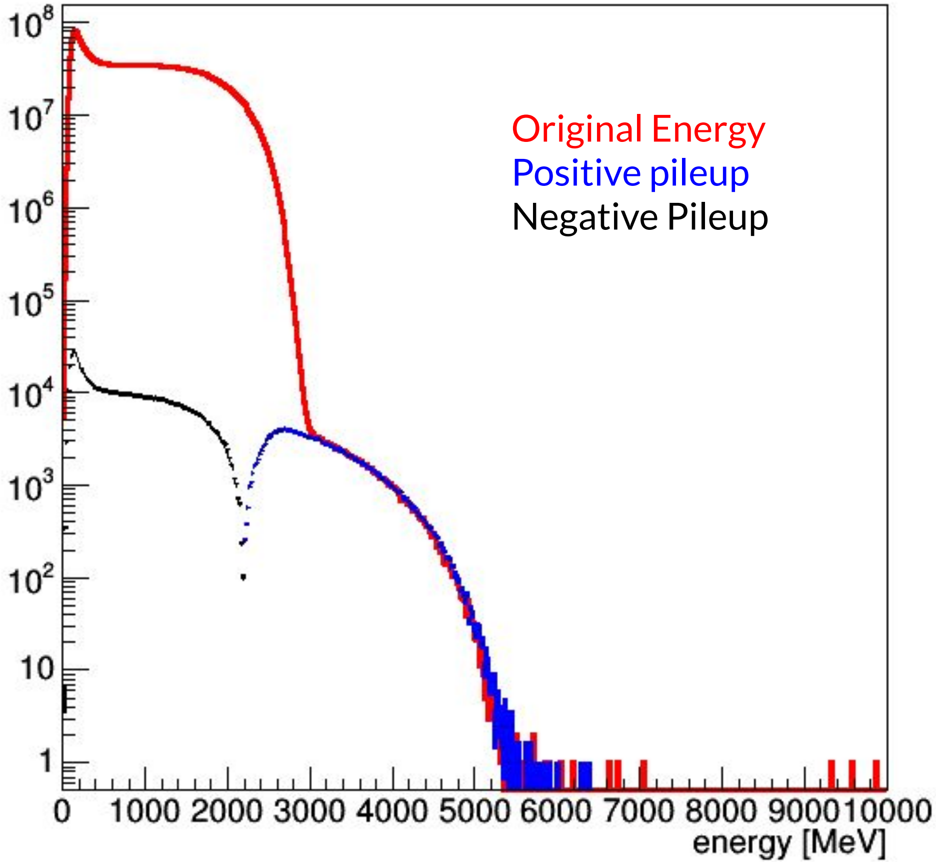
Probability of having overlapping pulses is the same as having pulses separated by a small offset time (~10 ns)

- ❖ Form doublets by looking in "shadow" windows for shadow pulses
- ❖ The energy of the doublet is $E_D = C(E_1, E_2) \times (E_1 + E_2)$
- ❖ The time of the doublets are approximated as $T_D = \frac{(t_1+t_2)}{2}$
- ❖ Pileup spectrum = Doublets-Singlets

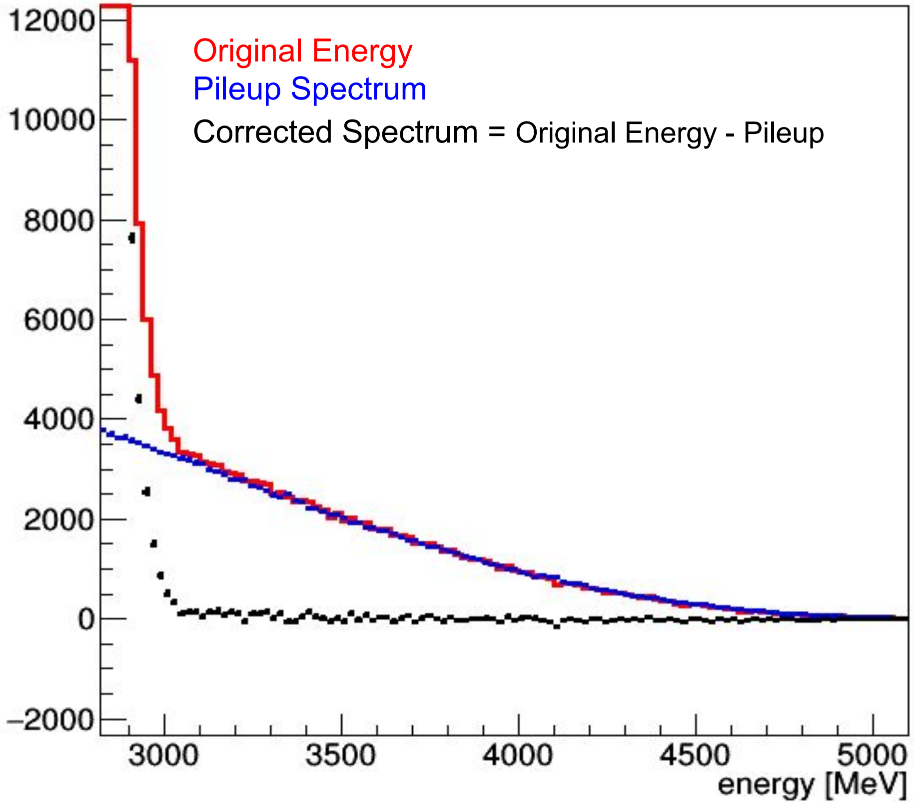
Pileup construction

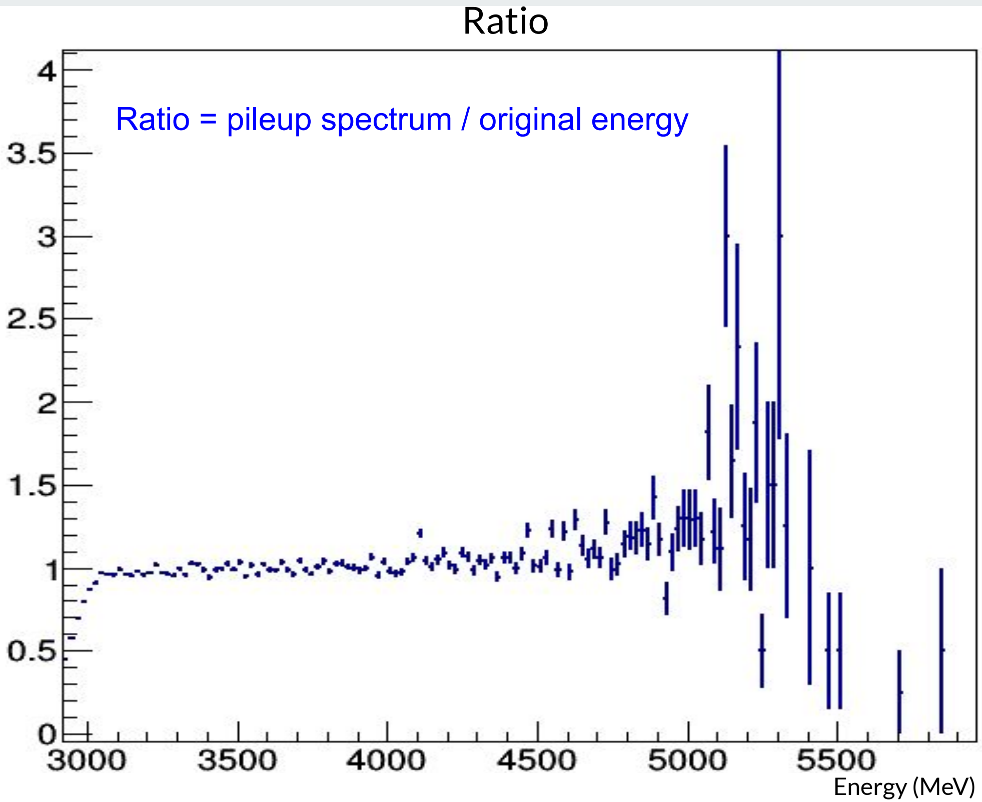
Pileup energy spectrum = Doublets - Singlets





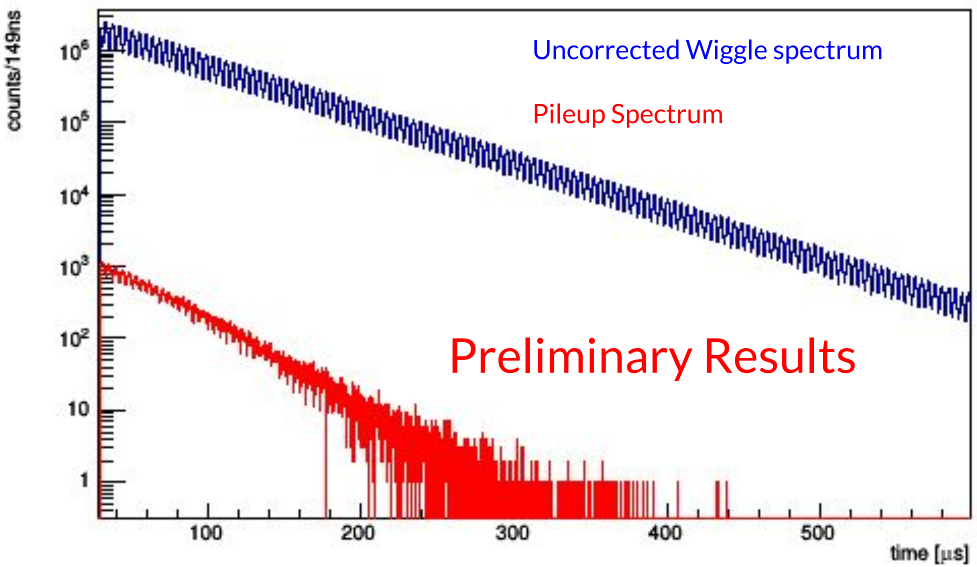
Pileup Correction

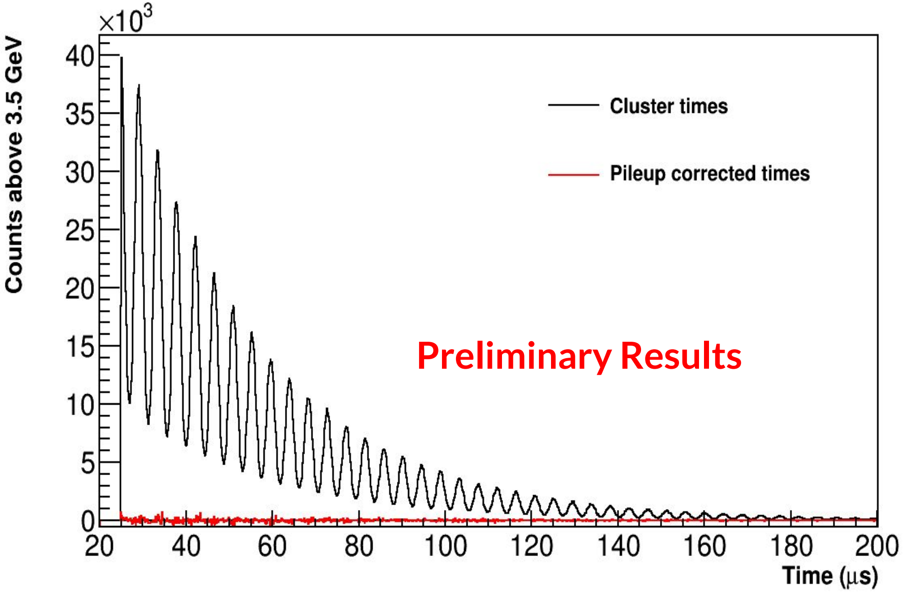




- Ratio -> Consistent with 1 if constructed correctly
- Higher order pileup contamination around 5 GeV

Pileup Time Spectra



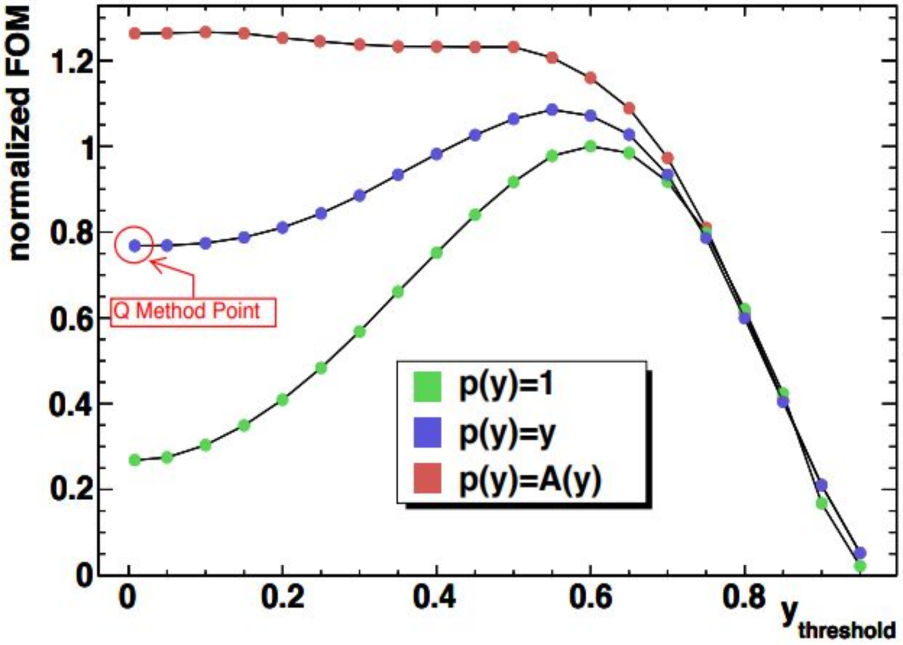


Conclusion

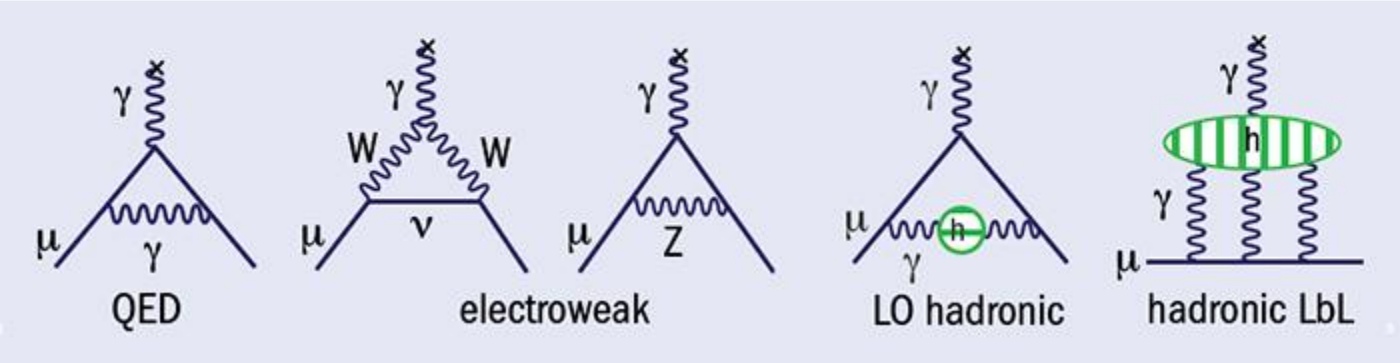
- Muon g-2 experiment has completed run 1 and we are currently analyzing the data
- Pileup is one of the most important source of systematic uncertainties to the anomalous spin precession frequency measurement
- Next step is to evaluate the systematic uncertainty coming from the Pileup events and finally estimate the error

Backup

Why 1.7 GeV

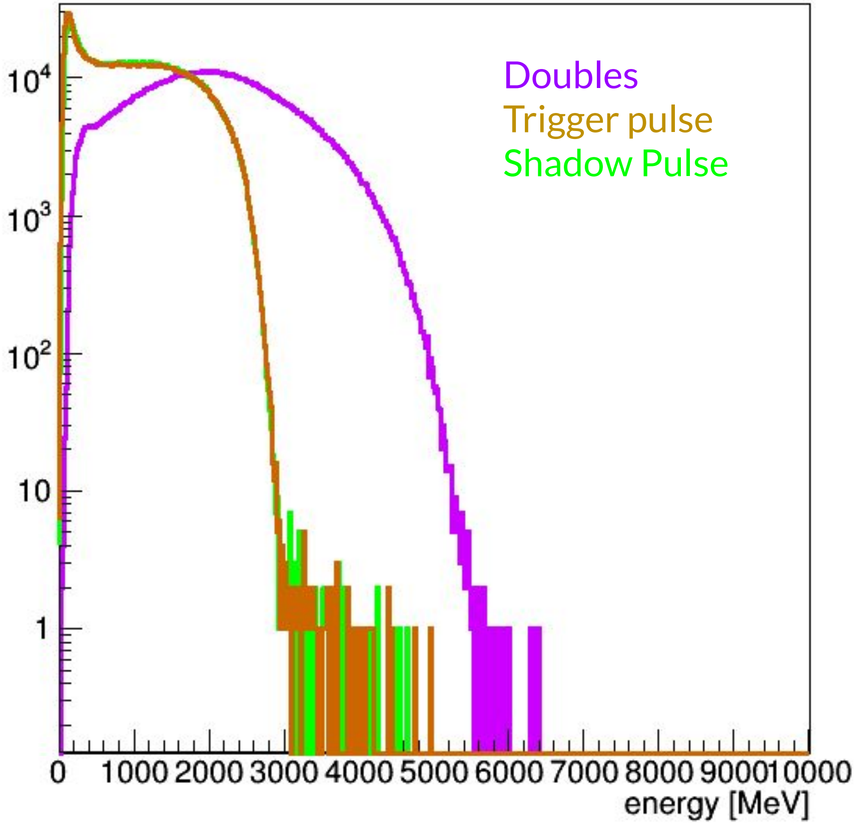


SM Contributions



QED correction: by far the largest one....well understood
EW contribution: the uncertainty is much smaller than the hadronic sector
Hadronic sector: The uncertainty is dominated by the hadronic contribution and challenges the Theory community

Doubles and single energy spectra



Measurement of a_μ

In E821 $\mathcal{R}_\mu(\mathrm{E821}) = 0.003\,707\,206\,4(2\,0)$ **(0.54 ppm)**

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{<\omega_p>}}{\frac{\mu_e}{\mu_p}}$$

Get from CODATA [1]:

$g_e = 2.00231930436182(52)$(0.00026 ppb)

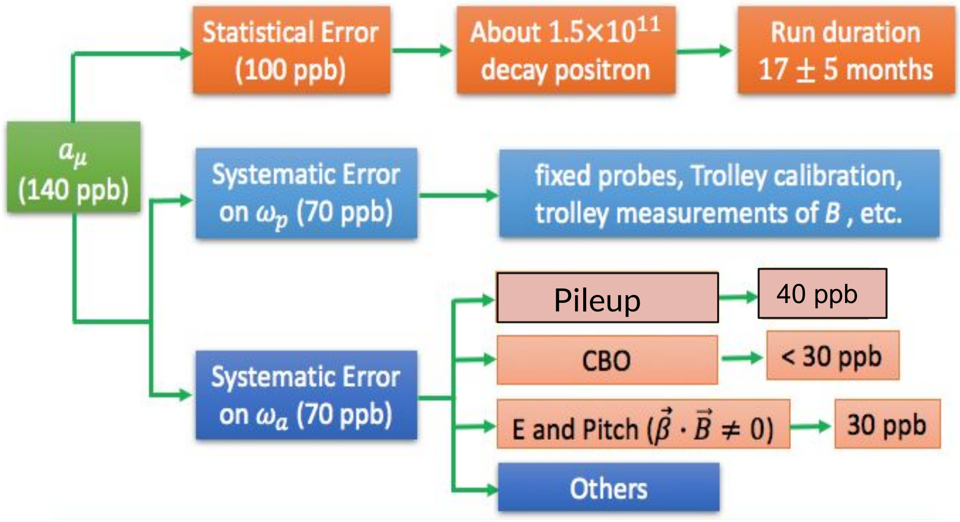
$m\mu/me = 206.7682826(46)$ (22 ppb)

$\mu e/\mu p = -658.2106866(20)$(3.0 ppb)

[1]. P. J. Mohr, D. B. Newell and B. N. Taylor, Rev. Mod. Phys.**88**, no. 3, 035009 (2016), doi:10.1103/RevModPhys.88.035009 [arXiv:1507.07956 [physics.atom-ph]]

More Precise this time!

Increase the statistics by a factor of 21 and reduce systematics by a factor of ~ 3 w.r.t BNL experiment



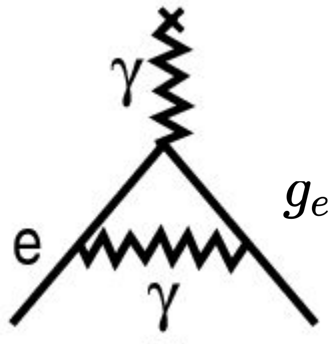
More Statistics

Better uniform magnetic field

Much smaller systematic errors

What is g?

- A charged elementary particle with half-integer intrinsic spin has magnetic dipole moment aligned with its spin : $\boldsymbol{\mu} = g\frac{Qe}{2m}\mathbf{S}$
- According to Dirac's theory $g = 2$
- 1947: Schwinger showed...the lowest order radiative correction to the electron spin magnetic moment results in $\boldsymbol{\mu} = 2(1 + \mathrm{a_l})\frac{\mathrm{Qe}}{\mathrm{2m}}\mathbf{S}, \quad \mathrm{a_l} = \frac{\mathrm{g_l} - 2}{2}$



g_e = 2.00238(6)

Schwinger term describing 1st order electron self-interaction

Agreed well with the experiments and that is how we build confidence in new physics model

Pileup Time Spectra Construction

E_{th} = 1.7 GeV

Chart of Doublets	$E_1 < E_{th}$	$E_1 > E_{th}$
$E_2 < E_{th}$	$N_1(+1)$	$N_2(0)$
$E_2 > E_{th}$	$N_3(0)$	$N_4(-1)$

N_i **: number of pileup events**

- N_i > 1.7 GeV (threshold)
- For N1 : gain a count in the time spectrum
- For N4 : lose a count, because both singlets were above threshold
- N2 , N3 : no net change of counts (only one singlet > 1.7 GeV)

Why measure a_μ?

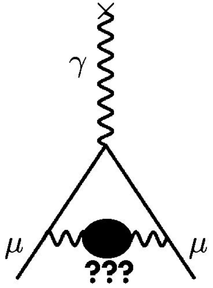
- ❖ Contributions to a_μ come from all sectors of the Standard Model
- ❖ Greater than 3σ between the BNL measurement and current theory prediction
- ❖ Sensitive to many new models

Status Quo

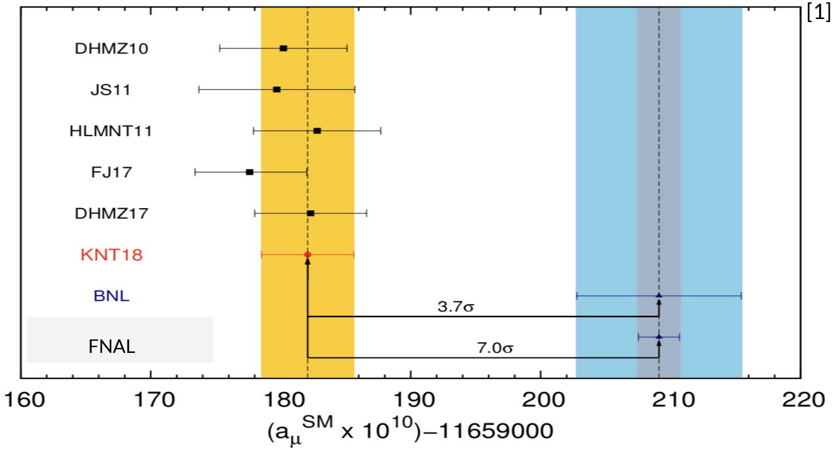
$$a_\mu^{SM} = 11659182.05(3.56) \times 10^{-10}$$ (Theory Total)

$$a_\mu^{exp} = 11659208.9(6.3) \times 10^{-10}$$ (World average)

$$a_\mu^{exp} - a_\mu^{SM} = 27.05(7.26) \times 10^{-10} > 3\sigma$$ discrepancy



Physics BSM?
Hint of New Physics?



[1]

0.54 ppm (BNL) → 0.14 ppm (FNAL Goal)

[1] KNT2018, arXiv:1802.02995v1 [hep-ph]