Muon Anomalies and Their Future Investigations

Fermilab
Muon Department Journal Club

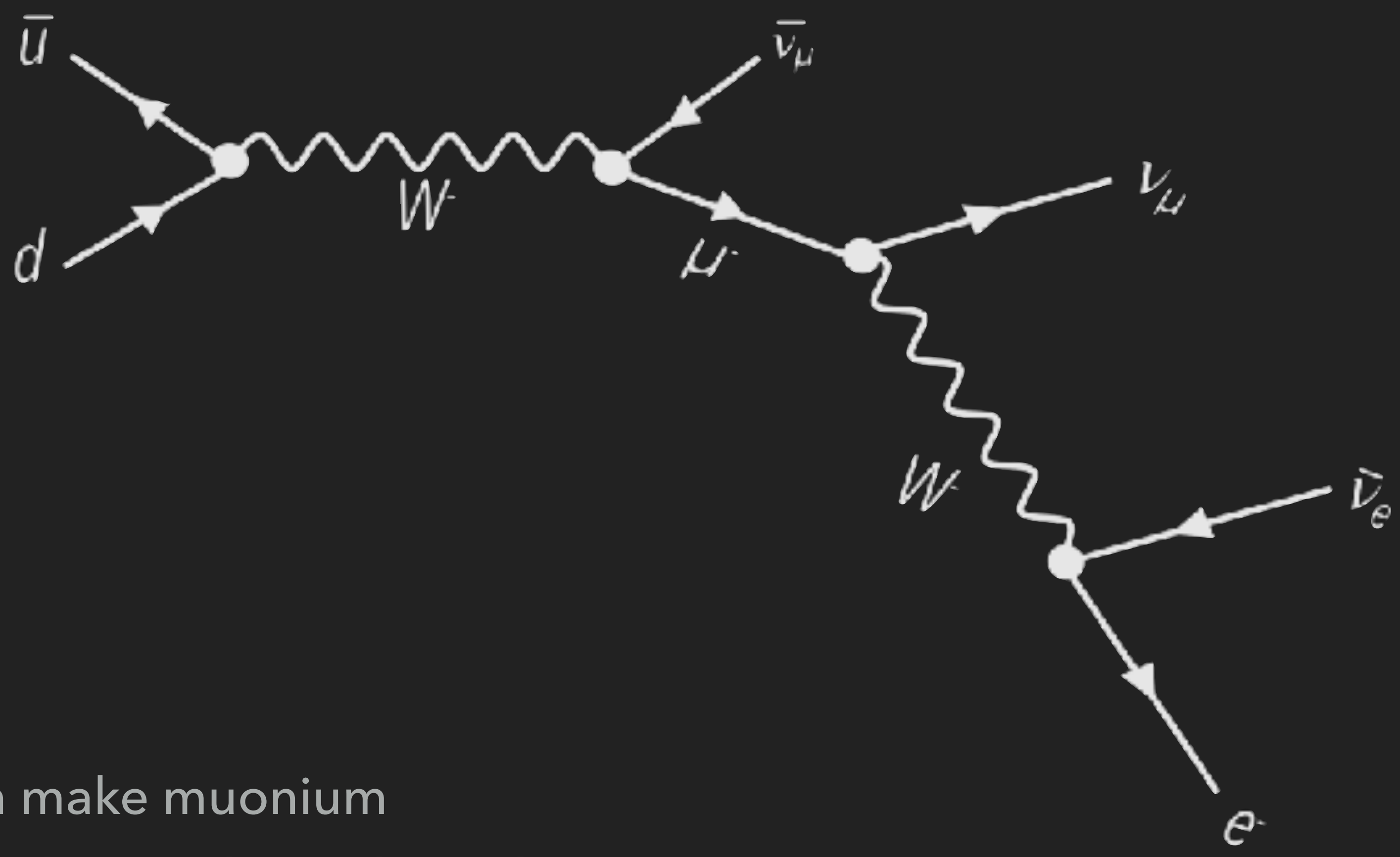
Jason Bono, Fermilab
April 9, 2018

Muons

- A few nice properties
- A historical perspective
- Anomalies and Future Investigations
  - The Proton Radius Puzzle
  - The Muon anomalous magnetic moment
  - Hints of Lepton Flavor Non-Universality in B decays
  - Searches for Charged Lepton Flavor Violation
  - Extra: Muons and The Great Pyramid of Giza

Jason Bono, jbono@fnal.gov

Why We Like Muons



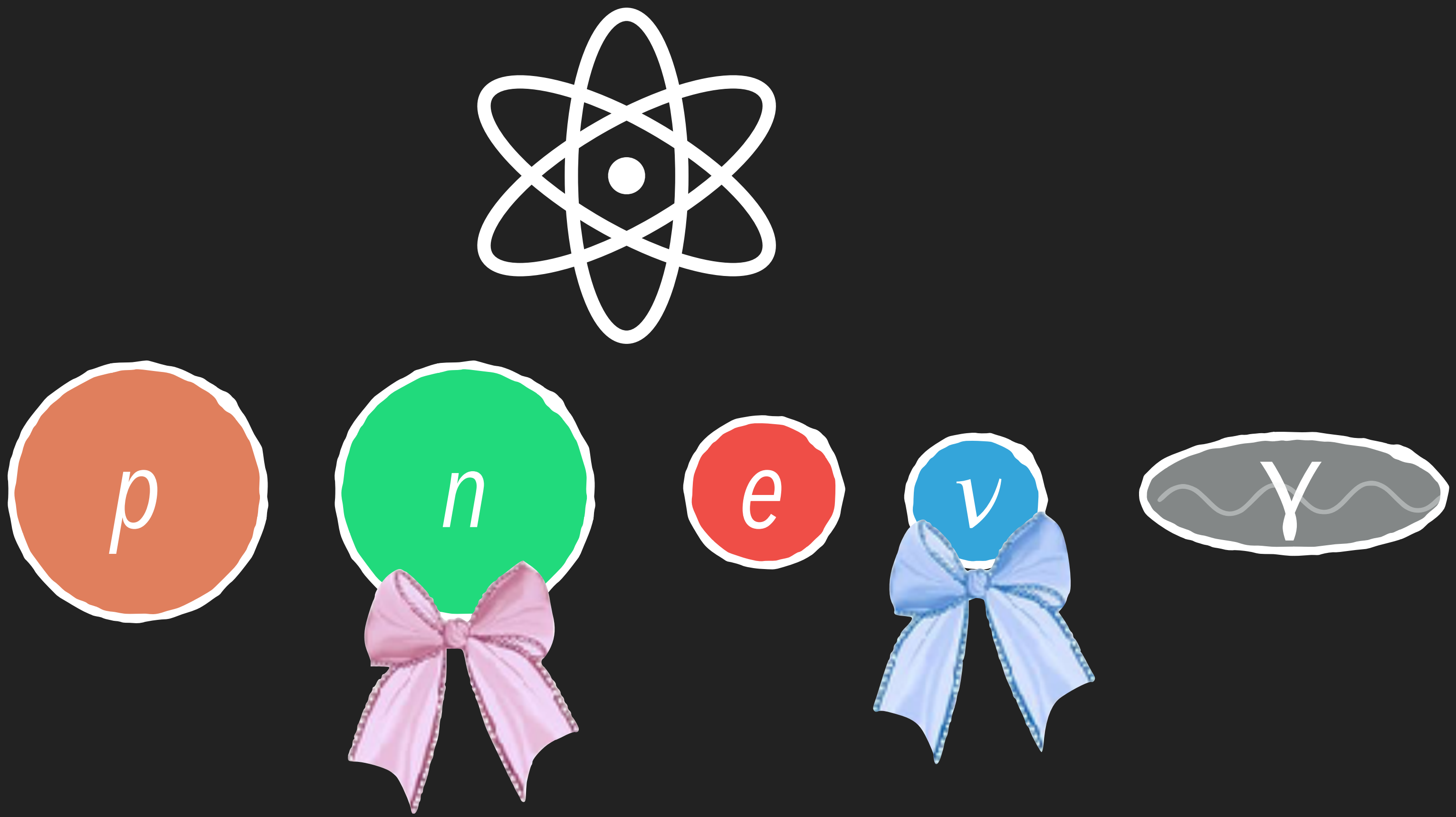
- They’re easy to produce
  - Natural product of pion’s weak decay
    - Helicity suppression of electrons
  - Come out 100% polarized
- They’re charged
  - Can be contained with EM fields
  - Can be detected directly
  - Can μ^- can make muonic atoms, and μ^+ can make muonium
- They’re much heavier than the electron, but lighter than the pion
  - Access to virtual effects on high mass scales
  - No hadronic decay
  - Lifetime of 2.2 μs: Long enough to study interaction, short enough to study decay
  - Penetrating: most abundant charged cosmic ray at sea level (~10K/s·m^2)
- They don’t participate in the strong interaction
  - Interactions subject to precise theoretical predictions
  - Decay is “self analyzing” and contains an easily detectable electron

Muons offer a unique combination of theoretical “Cleanness,” experimental sensitivity, and New Physics reach

Jason Bono, jbono@fnal.gov

Nuclear Physics from 1930–1934

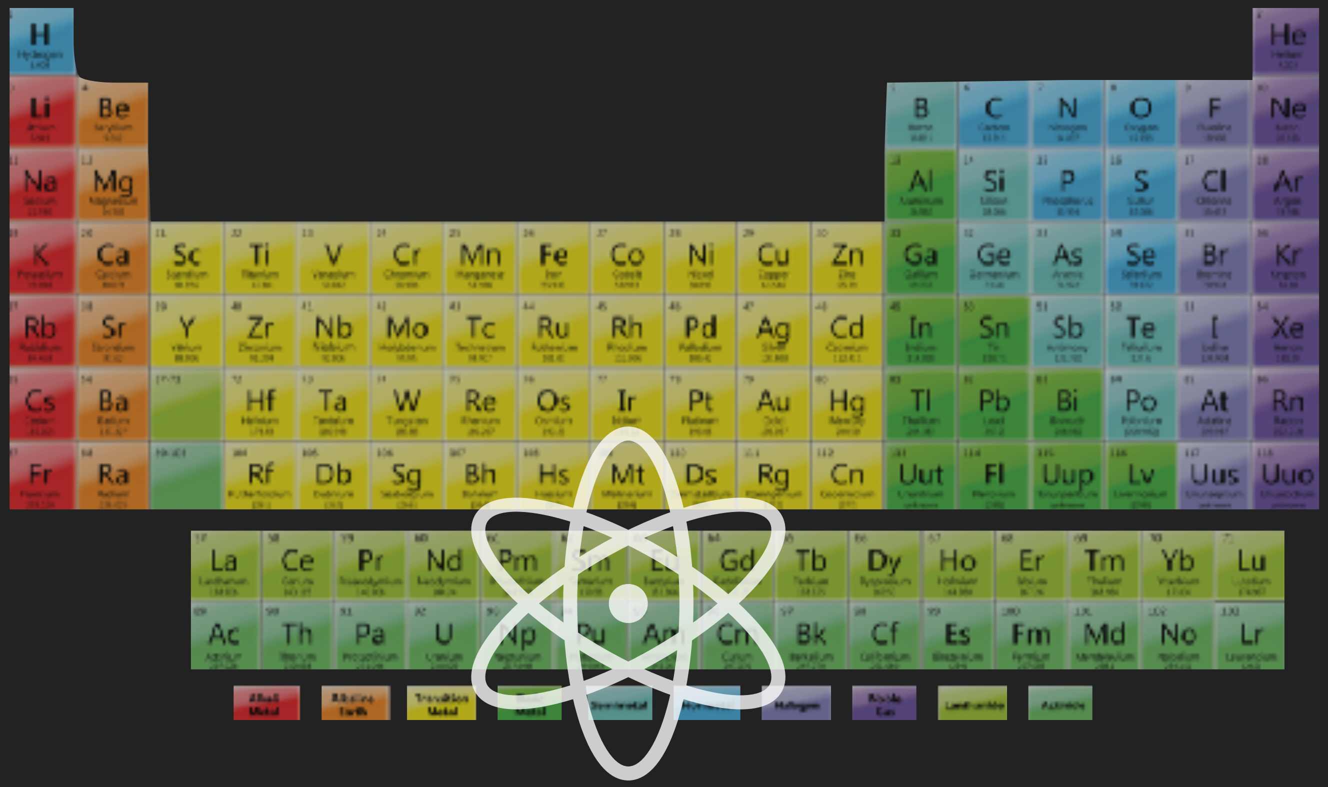
- Two new particles arrive on the scene!
  - A low/no mass neutrino is invoked by Pauli
    - to save the fundamental conservation laws in β-decay
  - The neutron is discovered
    - The proton-neutron model of nucleus arrives
    - Fermi proposed that nuclear β-decay is a result of $n \to p\ e\ \nu$



Jason Bono, jbono@fnal.gov

All Is Well

- Rutherford's atomic model and nuclear theory are successful
  - By far the best theories, so far, of elements & particles

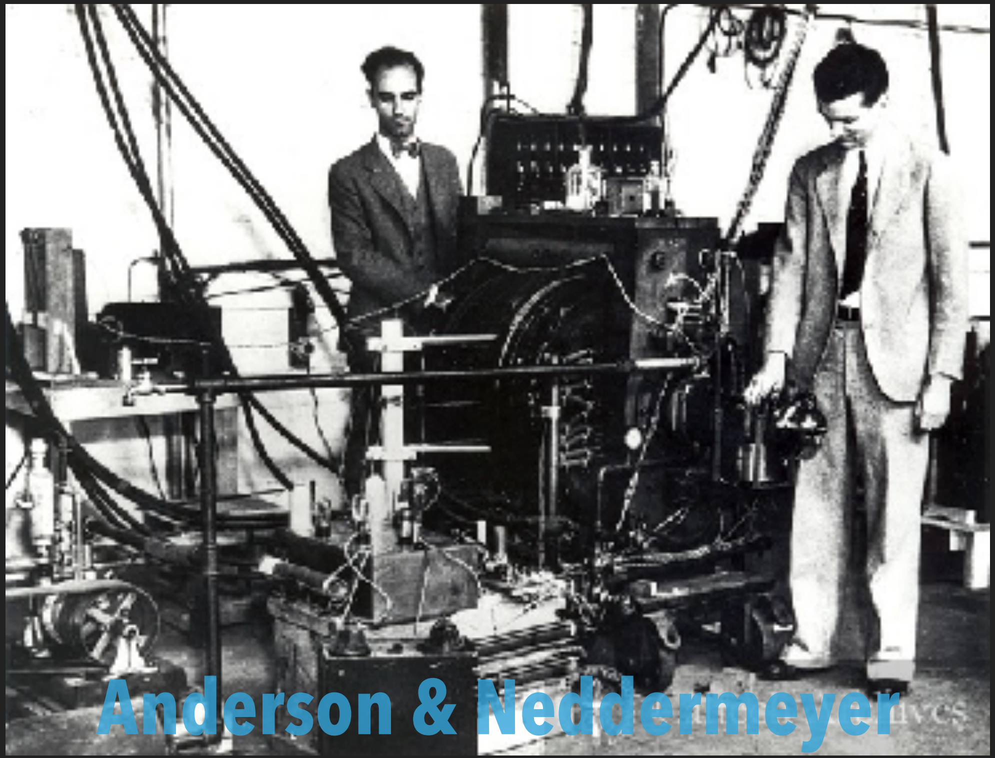


Meanwhile…

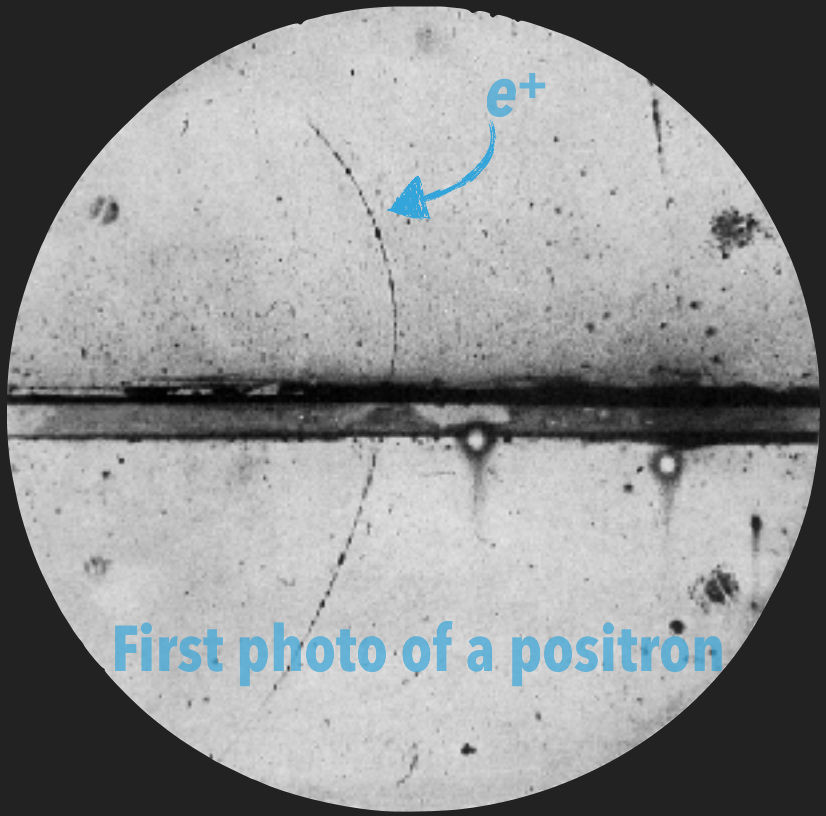
Jason Bono, jbono@fnal.gov

More Success

- 1931: Dirac predicts the positron
  - A hole in the infinite sea of negative energy electrons
- 1932: Anderson and Neddermeyer discover the positron in cosmic rays
  - Using a cloud chamber in a strong magnetic field
  - Totally unaware of Dirac's prediction!



Anderson & Neddermeyer

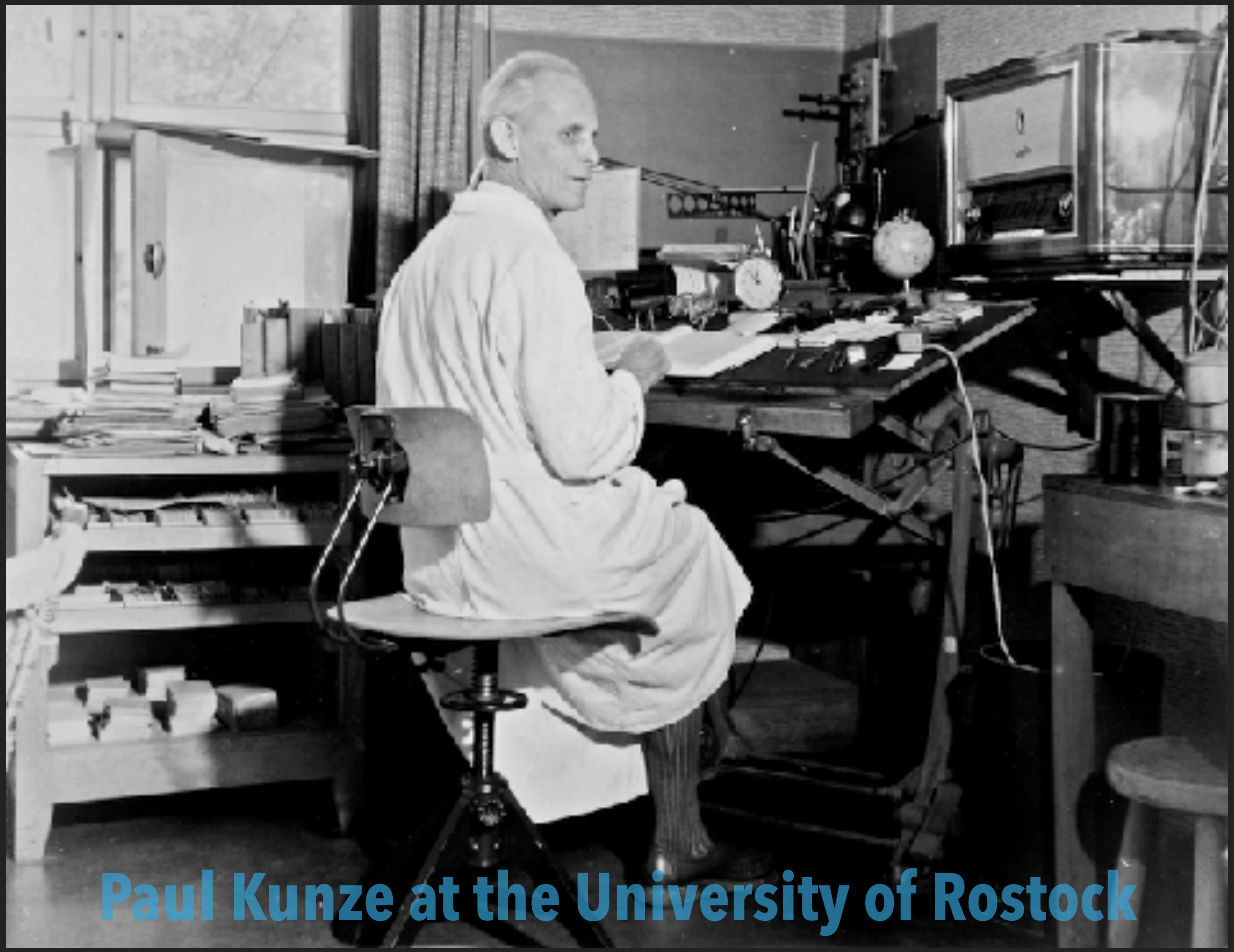


First photo of a positron

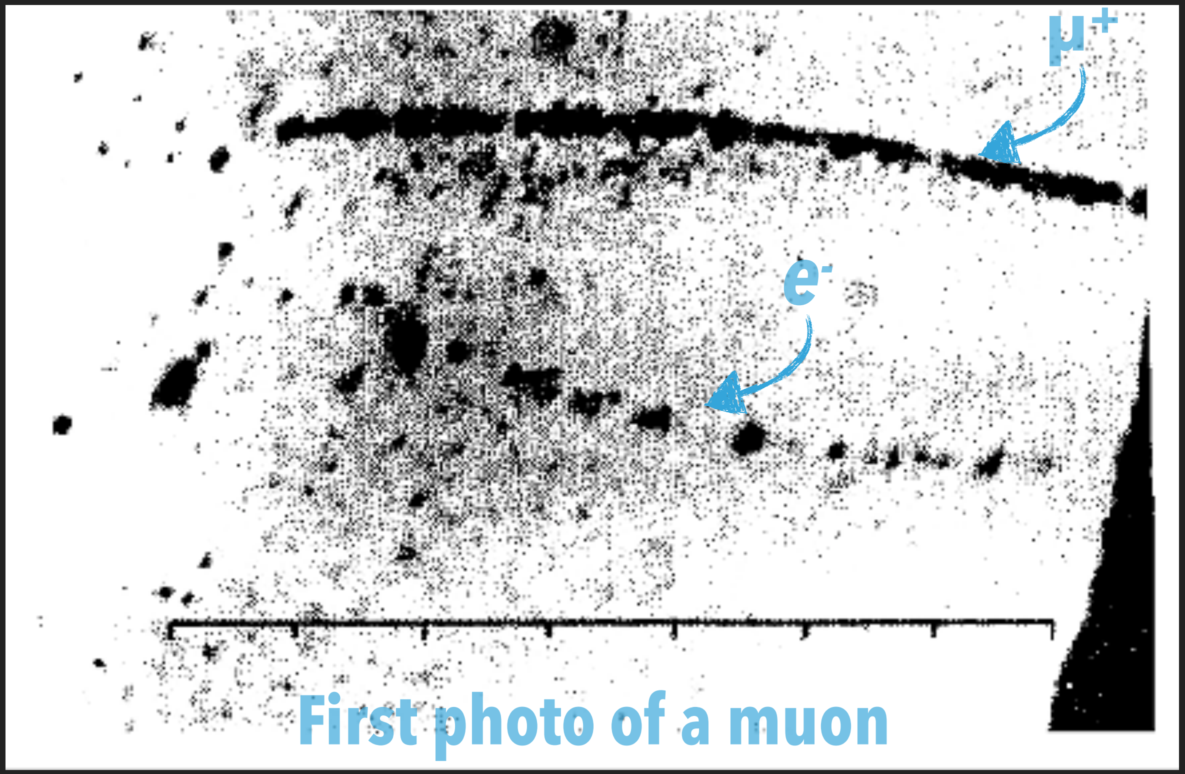
Jason Bono, jbono@fnal.gov

A Particle "of uncertain nature" Appears

- 1933: Kunze publishes the first observation of a muon
  - "The nature of this particle is unknown; for a proton, it does not ionize enough, and for a positive electron, the ionization is too strong"



Paul Kunze at the University of Rostock



First photo of a muon

Next, cosmic rays get more interesting…

Jason Bono, jbono@fnal.gov

The Mu-Meson

- 1934: To explain the cohesion of the nucleus, Yukawa predicts a “meson”
  - Conserved force carriers gives long distance forces; $F(r) \sim 1/r^2$
  - Let the force carriers decay! $N(r) = N_0 \exp(-(\alpha/v)r) \rightarrow F(r) \sim \exp(-\lambda r)/r^2$
  - Expect the meson to have $m \sim 200 \cdot m_e$
- 1935: J.C. Street narrows in on Kunze’s bizarre particle
  - Identifies individual, highly penetrating, charged particles, at sea level
  - Are these electrons that somehow penetrate? “Red” and “green” electrons are spoken of
  - Or does quantum theory break down at higher energies?
- 1936: Three groups independently conclude that the penetrating particle is a new one, and of intermediate mass between the electron and proton.
  - The Caltech group published first, and are credited with the discovery of the the “mu-meson”
- 1937: Yukawa-meson = mu-meson
  - Whops… Idea not abandoned till a decade later!
    - Observed that the mu-meson doesn’t feel the nuclear force
    - Discovered the pi-meson: observed $\pi \rightarrow \mu \nu$

A decade passes…

Jason Bono, jbono@fnal.gov

A Heavy Electron?

Isidor I. Rabi
@RabiNMR

The muon: who ordered that !?

1:23 AM - 20 Jun 1937 · Embed this Tweet

Image by Roni Harnik

- When it became clear that the the pion and muon were distinct, Rabi is said to have asked, about the latter, “Who ordered that?”
- 1948: The muon is not an excited electron
  - μ → eγ excluded as a major decay mode
  - What is going on?
  - We still don’t know, and we’re still searching

Soon after, nuclear physics splits, and a new field, HEP, appears

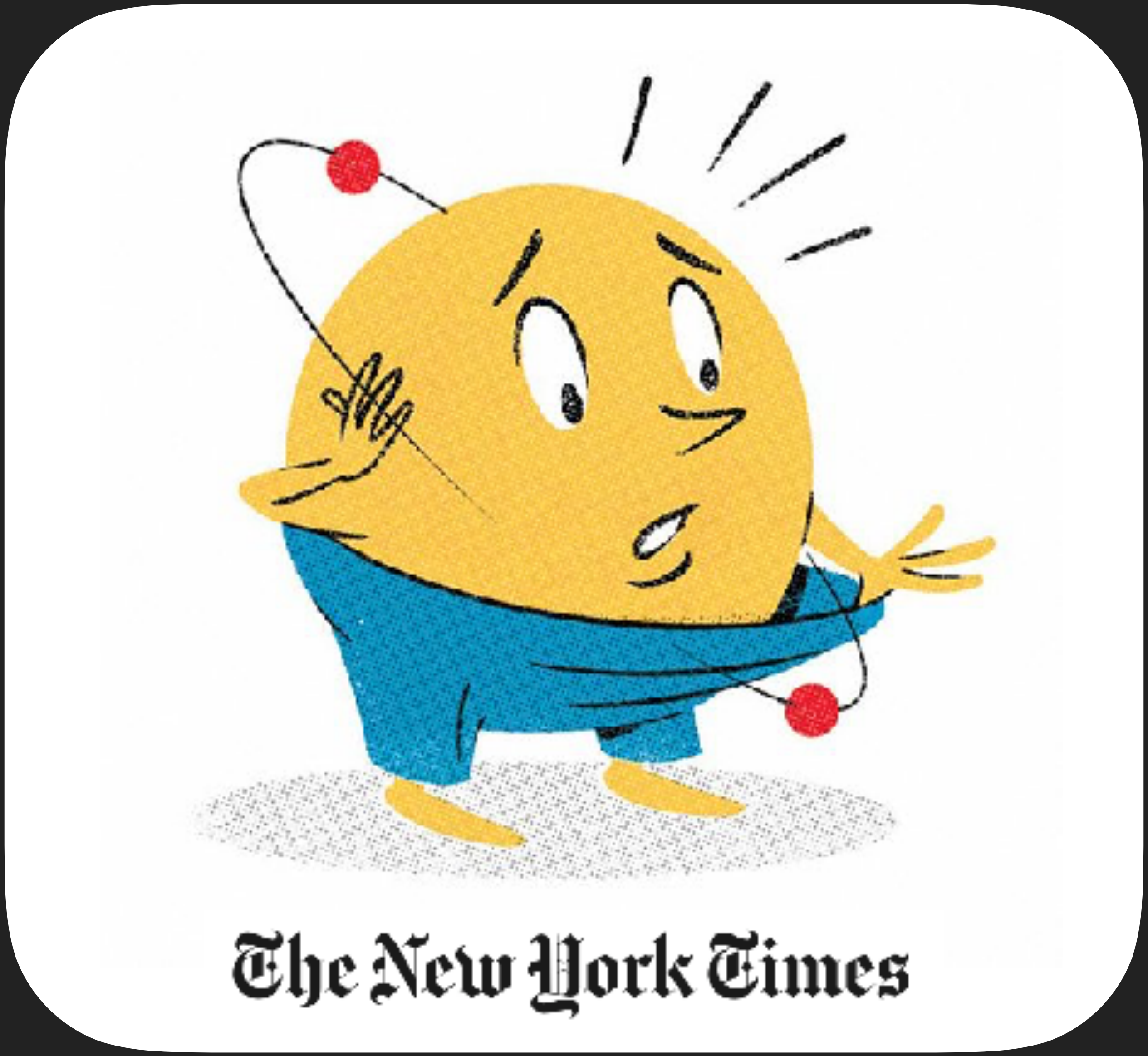
Jason Bono, jbono@fnal.gov

The Muon Has Since Provided:

- The birth of HEP
- The first evidence for particle generations
- The decisive test of time dilation
- The best determination of the Fermi constant
  - Quantifying the universal strength of weak interactions
  - Through precision lifetime measurements
- First hint of weak universality
- The coupe de gras for universal parity conservation
  - Through anisotropies in muon decay
  - Preceded by the Theta-Tau Puzzle, and Lee and Yang's proposed solution, in which parity is violated in the weak interaction
- The conclusion that $\nu_e \neq \nu_\mu$
  - BR($\mu \rightarrow e\gamma$) < 10-4 ➜ the electron does not absorb the neutrino emitted by the muon in $\mu \rightarrow e\nu\nu$
- Precision tests of V-A theory
  - Through the muon's decay angle/energy distributions
- The most precise measurement of the proton radius
  - Through energy splitting in muonic hydrogen
  - Anomalous results! Stay tuned
- Arguably the best direct evidence for physics beyond the current SM

Are Recent Muon Measurements Pointing to New Physics?

The Proton Radius Puzzle



The Proton Radius Puzzle

- The proton's charge radius, r_p, is defined as the RMS of its charge distribution
- Laser spectroscopy of Hydrogen has long been used to measure physical constants such as R_∞ and r_p
  - R_∞ , the Rydberg constant, is the wavenumber of the lowest energy photon capable of ionizing hydrogen

$$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

- The Lamb shift, L_{1S}, contains dependence on r_p
  - It's the splitting between L=0 and L=1 orbital angular momentum states
  - L=0 has penetration to the nucleus, so its energy is raised due to finite nuclear size, more so than the L=1 state
- One can extract both terms with two transitions

Jason Bono, jbono@fnal.gov

The Proton Radius Puzzle

- The proton's charge radius, r_p, is defined as the RMS of its charge distribution
- Laser spectroscopy of Hydrogen has long been used to measure physical constants such as R_∞ and r_p
    - R_∞, the Rydberg constant, is the wavenumber of the lowest energy photon capable of ionizing hydrogen

$$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

- The Lamb shift, L_{1S}, contains dependence on r_p
    - It's the splitting between L=0 and L=1 orbital angular momentum states
    - L=0 has penetration to the nucleus, so its energy is raised due to finite nuclear size, more so than the L=1 state
- One can extract both terms with two transitions
- Additionally, electron proton scattering has been used extensively to measure r_p
    - Differential cross section ➜ electric (and magnetic) form factor
    - Typically extrapolate the slope of the electric form factor, from low Q^2, down to $Q^2=0$

$$G_E(Q^2) = 1 + \sum_{n>0} \frac{(-1)^n}{(2n+1)!} < r^{2n} > Q^{2n}$$

$$r_p \equiv \sqrt{< r^2 >} = \left(-6 \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \bigg|_{Q^2=0} \right)^{1/2}$$

Jason Bono, jbono@fnal.gov

The Proton Radius Puzzle

- The proton's charge radius, r_p, is defined as the RMS of its charge distribution
- Laser spectroscopy of Hydrogen has long been used to measure physical constants such as R_∞ and r_p
  - R_∞, the Rydberg constant, is the wavenumber of the lowest energy photon capable of ionizing hydrogen

Both methods have generally agreed

$$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

- The Lamb shift, L_{1S}, contains dependence on r_p
  - It's the splitting between L=0 and L=1 orbital angular momentum states
  - L=0 has penetration to the nucleus, so its energy is raised due to finite nuclear size, more so than the L=1 state
- One can extract both terms with two transitions
- Additionally, electron proton scattering has been used extensively to measure r_p
  - Differential cross section ➜ electric (and magnetic) form factor
  - Typically extrapolate the slope of the electric form factor at low Q^2 down to $Q^2=0$

$$G_E(Q^2) = 1 + \sum_{n>0} \frac{(-1)^n}{(2n+1)!} < r^{2n} > Q^{2n}$$

$$r_p \equiv \sqrt{< r^2 >} = \left(-6 \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\bigg|_{Q^2=0} \right)^{1/2}$$

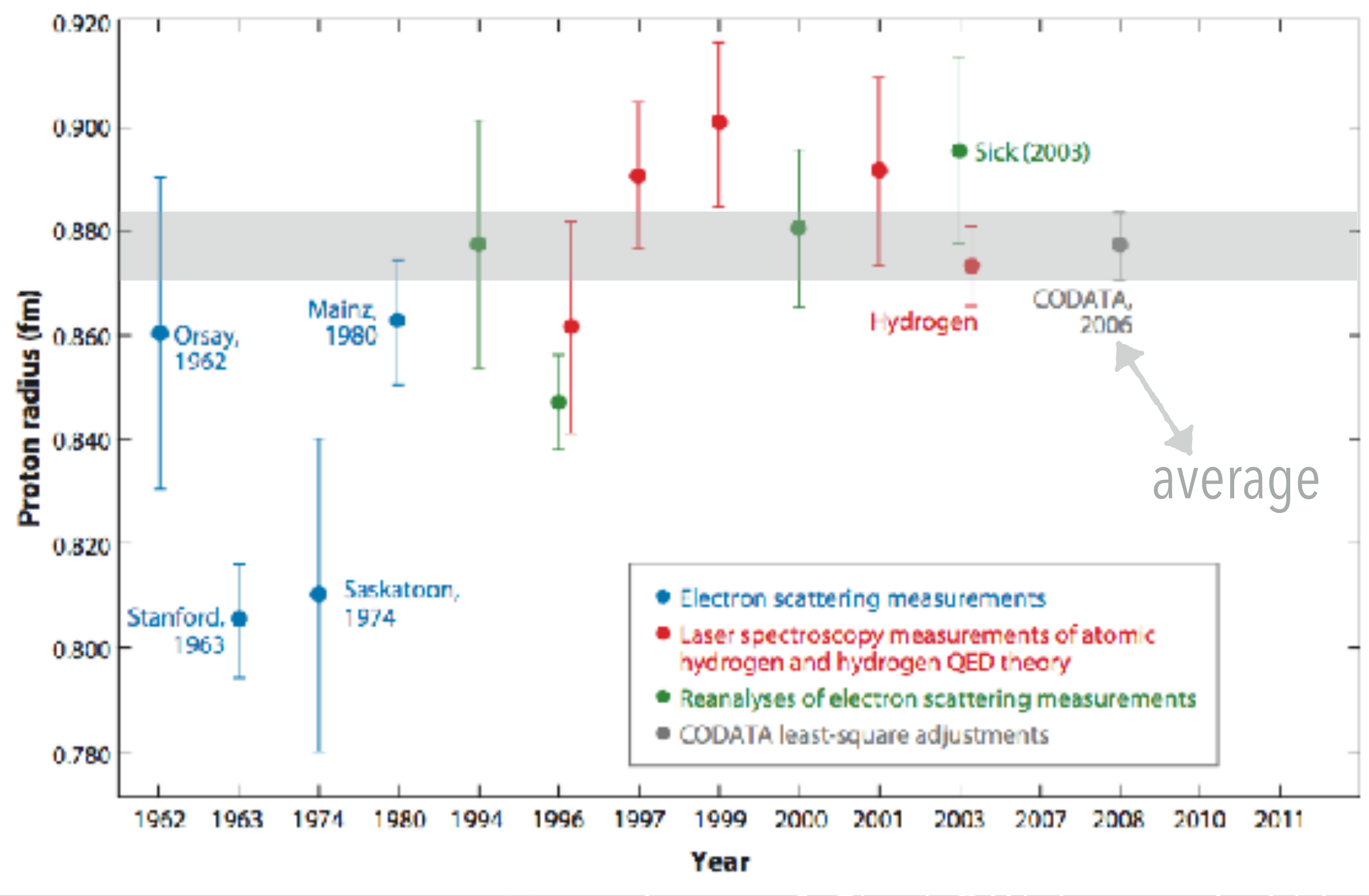
Jason Bono, jbono@fnal.gov

The Proton Radius Puzzle

- The proton's charge radius, r_p, is defined as the RMS of its charge distribution
- Laser spectroscopy of Hydrogen has long been used to measure physical constants such as R_∞ and r_p
  - R_∞, the Rydberg constant, is the wavenumber of the lowest energy photon capable of ionizing hydrogen

Both methods have generally agreed

$$E(nS) \approx -\frac{R_\infty}{\quad} + \frac{L_{1S}}{\quad}$$



average

- The Lamb shi
  - It's the splitti
  - L=0 has pen ze, more so than the L=1 state
- One can extr
- Additionally, to measure r_p
  - Differential c
  - Typically ext =0

$$r_p \equiv \sqrt{< r^2 >} = \left(-6\frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\bigg|_{Q^2=0} \right)^{1/2}$$

CREMA (Charge Radius Experiment With Muonic Atoms)

- 2010: Study muonic hydrogen to dramatically increase precision of r_p
  - The Bohr radius is reduced by a factor of 200
  - The Lamb shift is exaggerated by $\mathcal{O}$(10^7)
  - Finite nuclear size effects in energy transitions are enhanced by a factor of 100!
    - ~2% for of the total lamb shift for 2S-2P!
- Achieved, in one measurement, 10x better precision than the all of the world's electron data combined

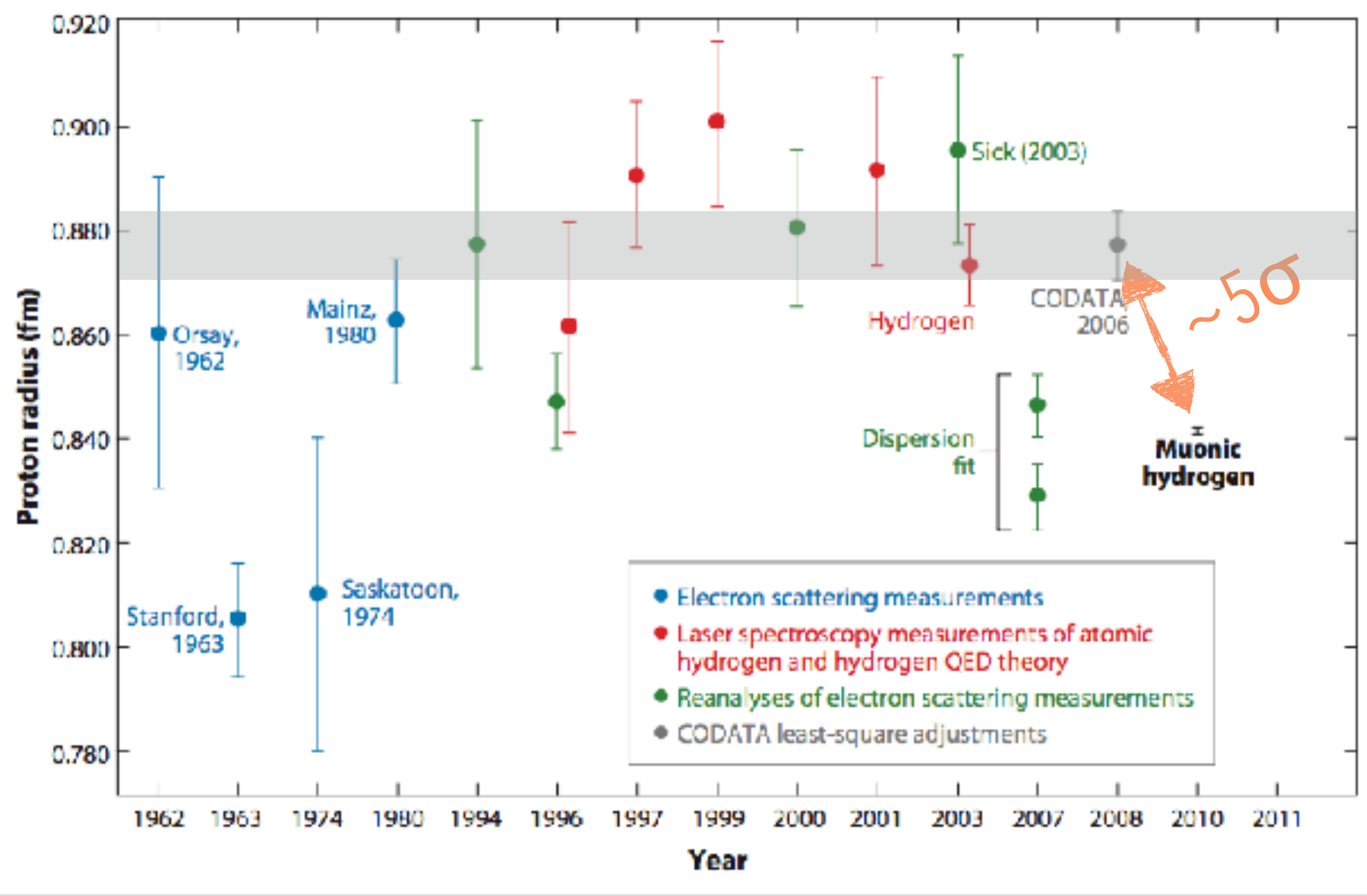
$$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

Jason Bono, jbono@fnal.gov

CREMA (Charge Radius Experiment With Muonic Atoms)

$$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

- 2010: Study muonic hydrogen to dramatically increase precision of r_p



DOI: 10.1146/annurev-nucl-102212-170627

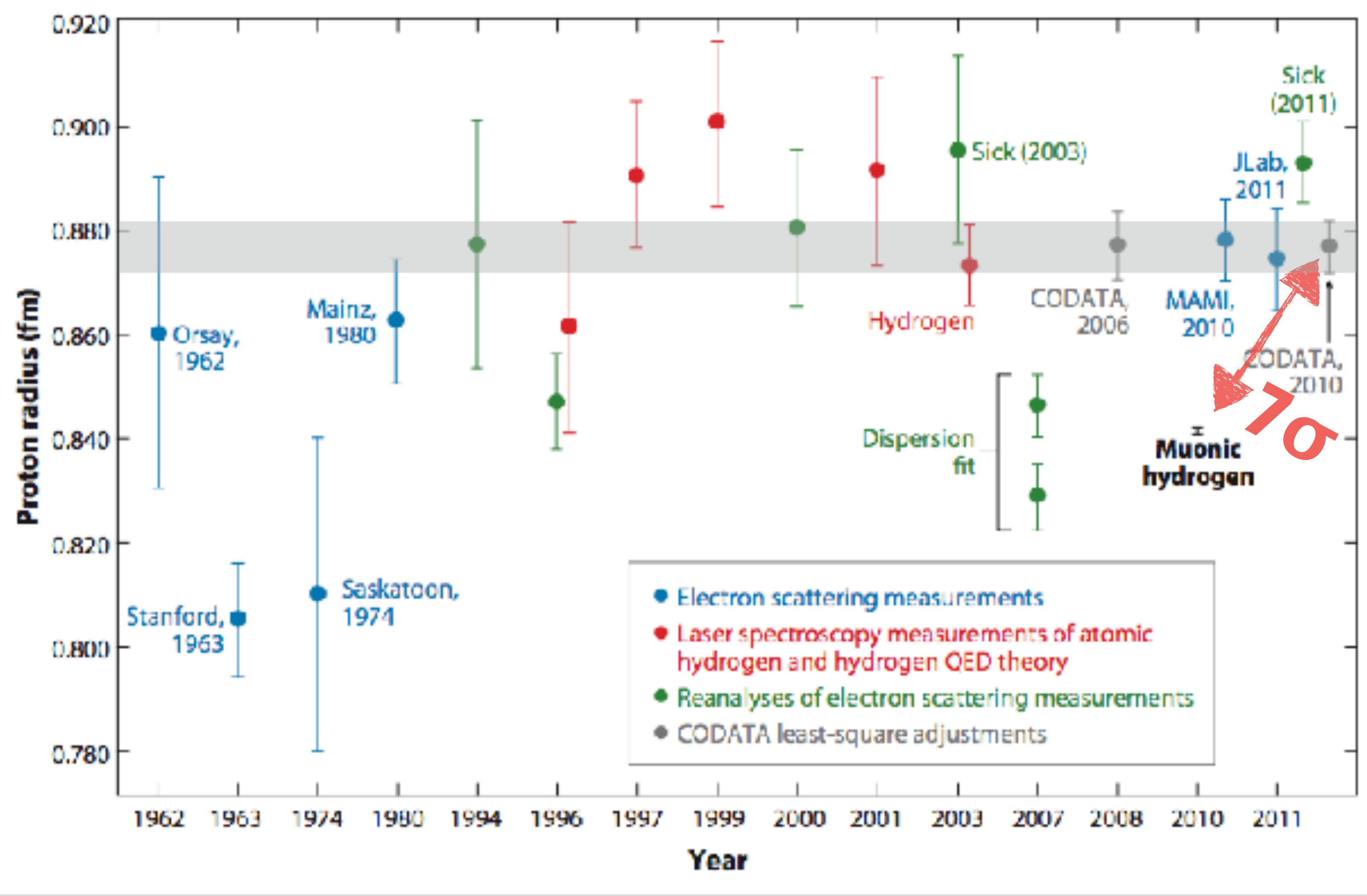
The experiment "shrunk" the proton radius by ~4%

Jason Bono, jbono@fnal.gov

CREMA (Charge Radius Experiment With Muonic Atoms)

$$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

- 2010: Study muonic hydrogen to dramatically increase precision of r_p



DOI: 10.1146/annurev-nucl-102212-170627

Subsequent electron measurements worsened the discrepancy

Possible Explanations

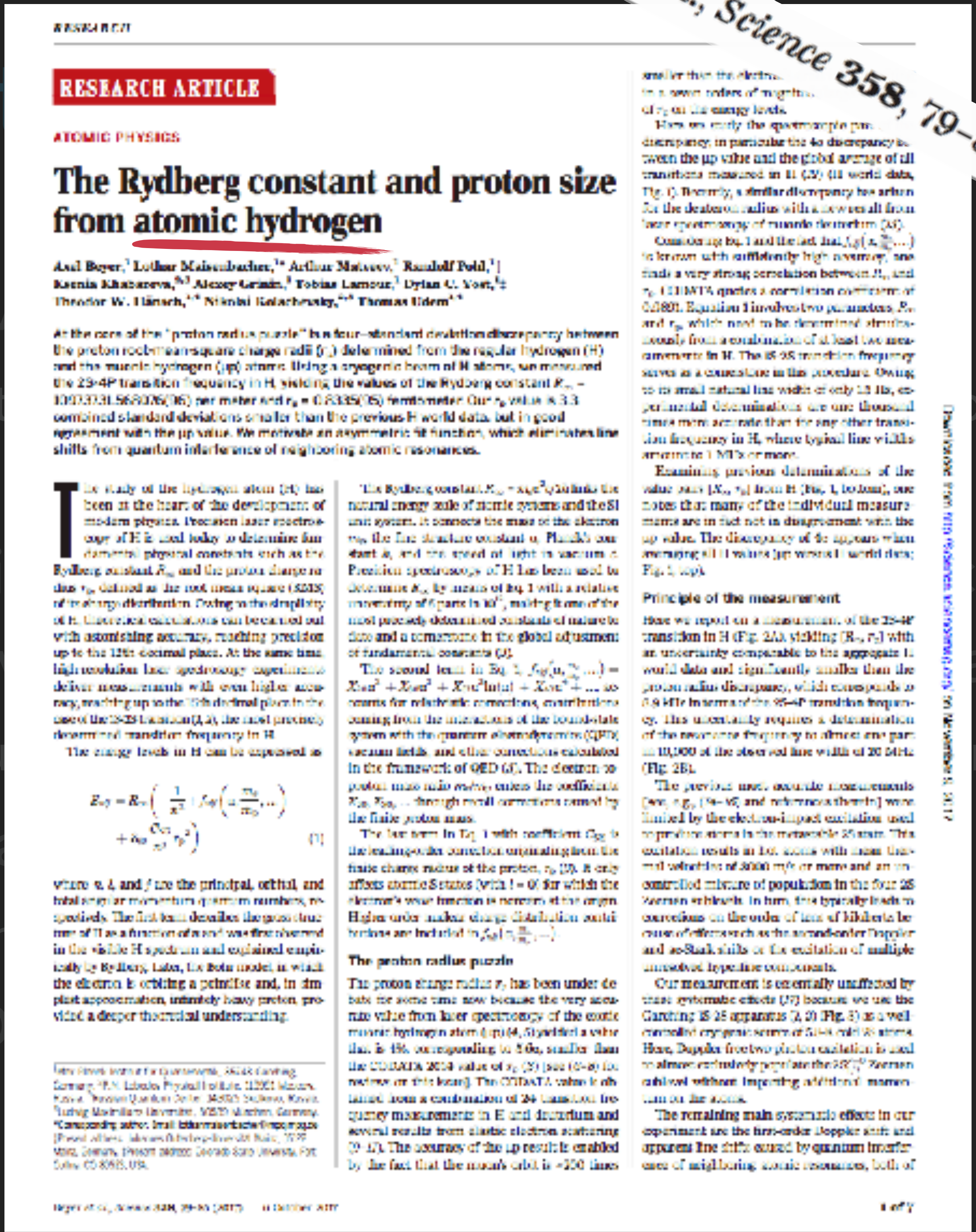
- Lepton non universality?
  - Past experiments have compared e-p and μ-p interactions, with no discrepancies
- Have the majority (or all) of laser spectroscopy and electron scattering experiments have much larger error bars than stated?
  - All relevant results have been triple checked by independent groups!
- Finite proton mass effect for muonic H?
  - This has recently been shown to be small
- Flaws with QCD calculations for atomic H?

Results from a few weeks ago may provide a clue

Jason Bono, jbono@fnal.gov

Possible Explana

- Lepton non univ
  - Past experiment ons, with no discrepancies
- Have the majori tron scattering experiments ha ated?
  - All relevant resu ndent groups!
- Finite proton ma
  - This has been sh
- Flaws with QCD



RESEARCH ARTICLE

ATOMIC PHYSICS

The Rydberg constant and proton size from atomic hydrogen

Axel Beyer,[1] Lothar Maisenbacher,[1*] Arthur Matveev,[1] Randolf Pohl,[1†] Ksenia Khabarova,[2,3] Alexey Grinin,[1] Tobias Lamour,[1] Dylan C. Yost,[1‡] Theodor W. Hänsch,[1,4] Nikolai Kolachevsky,[2,3] Thomas Udem[1,4]

At the core of the "proton radius puzzle" is a four–standard deviation discrepancy between the proton root-mean-square charge radii (r_p) determined from the regular hydrogen (H) and the muonic hydrogen (µp) atoms. Using a cryogenic beam of H atoms, we measured the 2S-4P transition frequency in H, yielding the values of the Rydberg constant R_∞ = 10973731.568076(96) per meter and r_p = 0.8335(95) femtometer. Our r_p value is 3.3 combined standard deviations smaller than the previous H world data, but in good agreement with the µp value. We motivate an asymmetric fit function, which eliminates line shifts from quantum interference of neighboring atomic resonances.

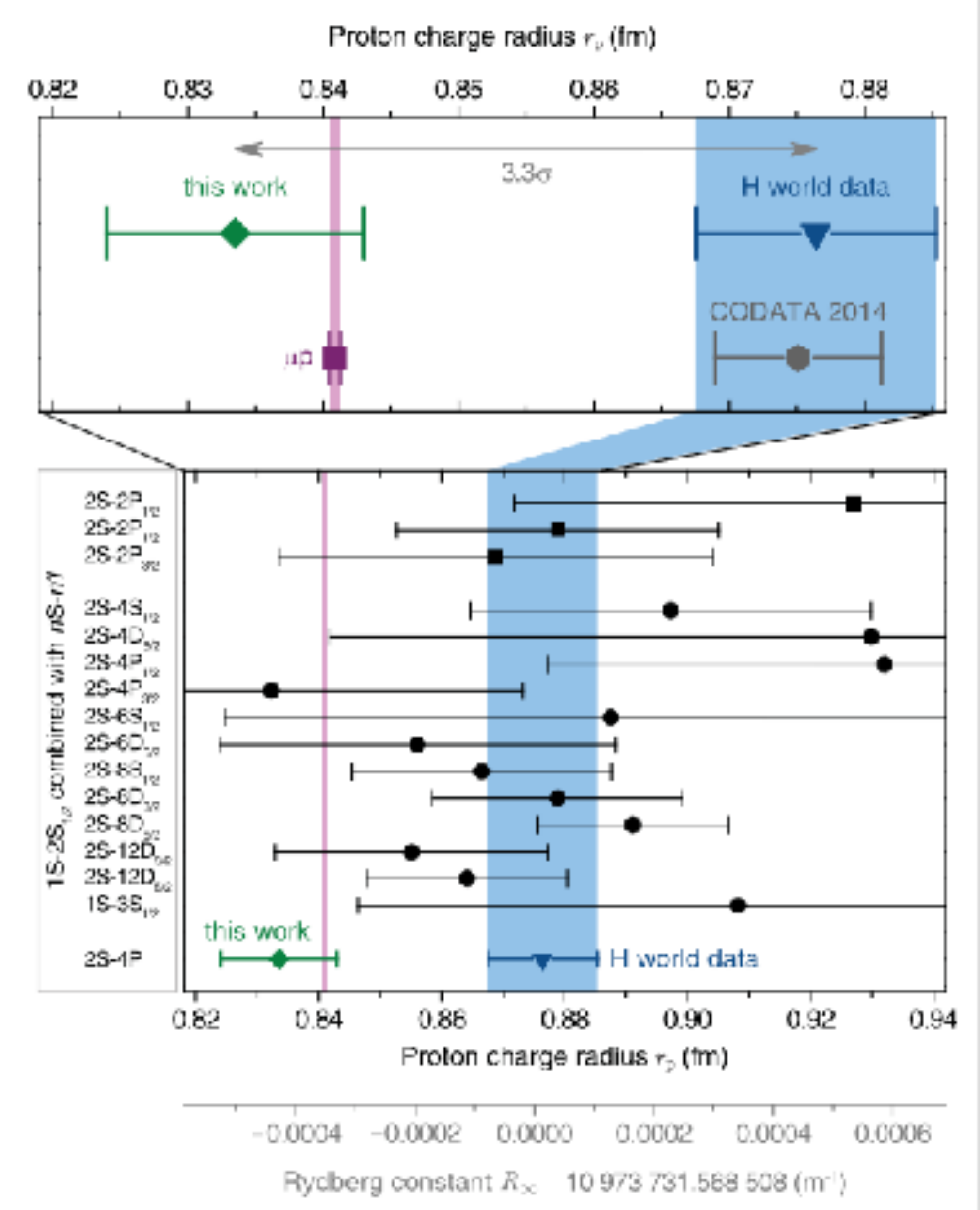
Beyer *et al.*, *Science* **358**, 79–85 (2017)

6 October 2017

Results from a few weeks ago may provide a clue

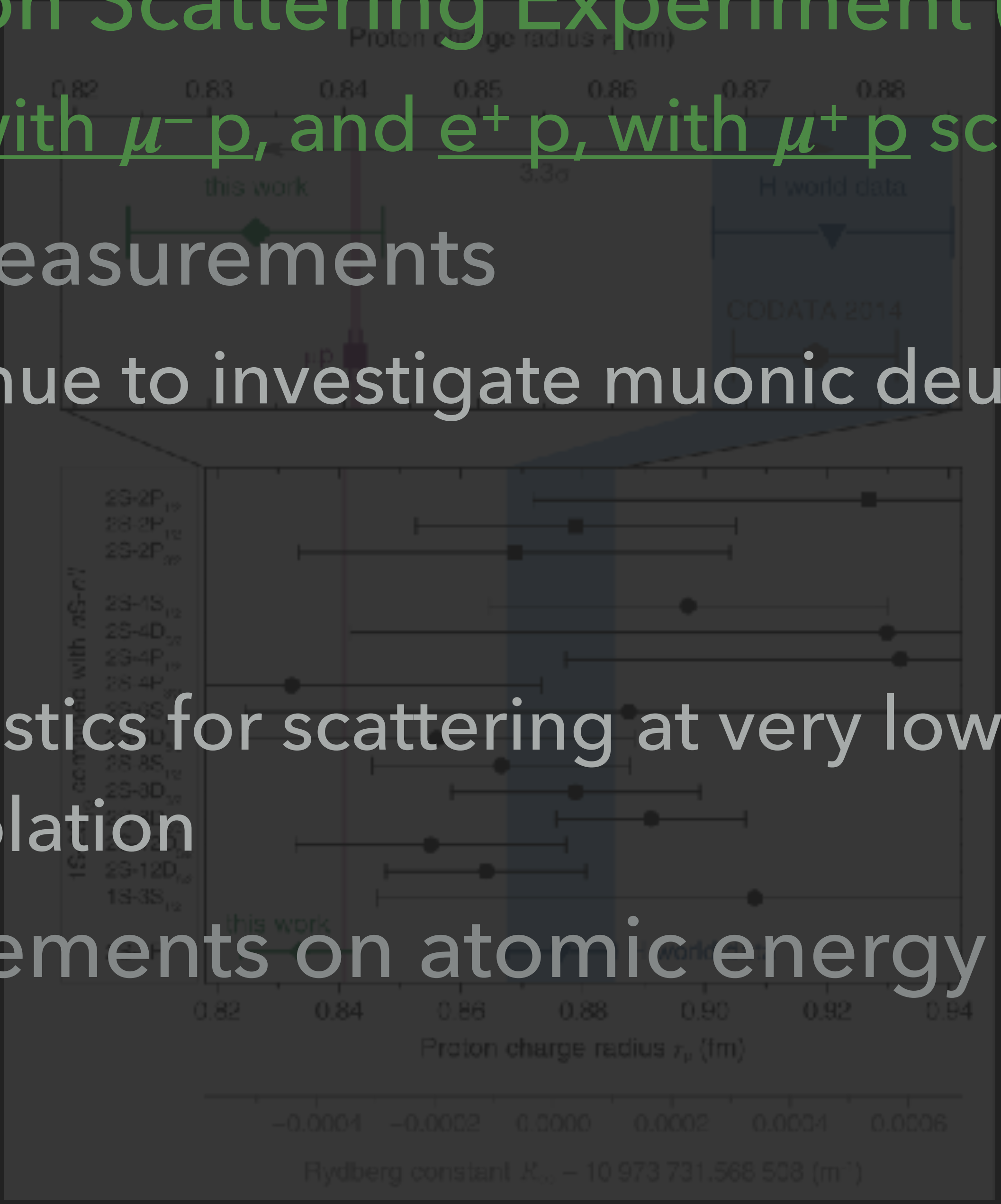
The Proton Radius Puzzle

- New result using electrons
- Most precise spectroscopy measurement to date using atomic hydrogen
    - Agreement with the muonic hydrogen results



Plot of Rydberg constant is nearly identical, hence the double axes

Looking Forward



- The Muon Proton Scattering Experiment (MUSE) @ PSI
  - Compare e^--p with μ^- p, and e^+ p, with μ^+ p scattering
- New CREMA measurements
  - Have/will continue to investigate muonic deuterium and muonic-ionic-helium
- PRad @ Jlab
  - Will collect statistics for scattering at very low scattering Q^2 for reliable extrapolation
- Various improvements on atomic energy level splitting measurements

The muonic measurements have revealed something, but we don't know what, yet

The Muon's Anomalous Magnetic Moment

The g-factor

- A particle's magnetic moment is coupled to its spin by its gyromagnetic ratio:

$$\vec{\mu} = \mathrm{g}\frac{e}{2mc}\vec{S}$$

- For a Dirac particle,

$$\mathrm{g} = 2$$

- The anomalous component of the magnetic moment comes in internal structure, and from vacuum fluctuations from everything, known and unknown, that couples, either directly or indirectly, the the system in question

$$a = \frac{g-2}{2}$$

Sensitive to a wide range of phenomena

Jason Bono, jbono@fnal.gov

The g-factor

- A particle's magnetic moment is coupled to its spin by its gyromagnetic ratio:

$$\vec{\mu} = \mathrm{g}\frac{e}{2mc}\vec{S}$$

- For a Dirac particle,

$$\mathrm{g} = 2$$

- E.g. the magnetic moments of nucleons:

$$\mathrm{g}_p \approx 5.6 \neq 2$$
$$\mathrm{g}_n \approx -3.8 \neq 0$$

→ Internal Structure

- E.g. the magnetic moment of the electron

$$\mathrm{g}_e^{\mathrm{exp}}/2 = 1.00115965218073(28)$$
$$\mathrm{g}_e^{\mathrm{QED}}/2 = 1.00115965218164\,3(764)$$

→ Independent measurement of α
QED corrections work!

Phys. Rev. Lett. 100, 120801 (2008)

Jason Bono, jbono@fnal.gov

The g-factor

e

- \+ Easy to produce and stable
  - ➡ measured to 0.28 parts per trillion!
- \- Small mass
  - ➡ Low sensitivity to new physics
  - ➡ Clean calculations

μ

- \+ Abundant from pion decays
- \+ 200 times the mass of the electron
  - ➡ ~40,000 times the sensitivity to new physics
- ± Unstable
  - ➡ Utilize the decay
- \+ long lifetime of 2.2 us
  - ➡ Sufficient time to interact with external magnetic field

τ

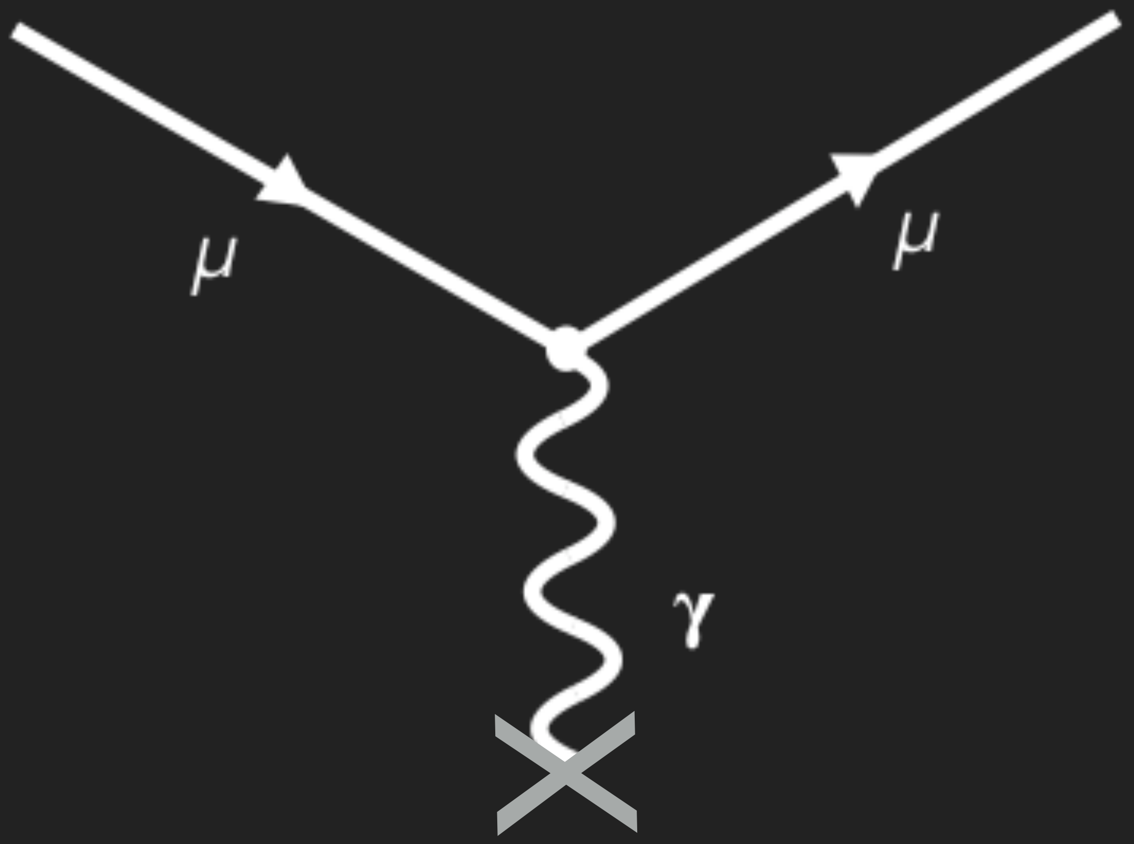
- \+ 17 times the muon mass
  - ➡ More sensitivity!
- \- Disproportionally difficult to produce
- \- Short lifetime, ~0.29 ps

Jason Bono, jbono@fnal.gov

The Muon's g-factor

$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu c}\vec{S}$$

Dirac: $g_\mu = 2$



Jason Bono, jbono@fnal.gov

The Muon's g-factor

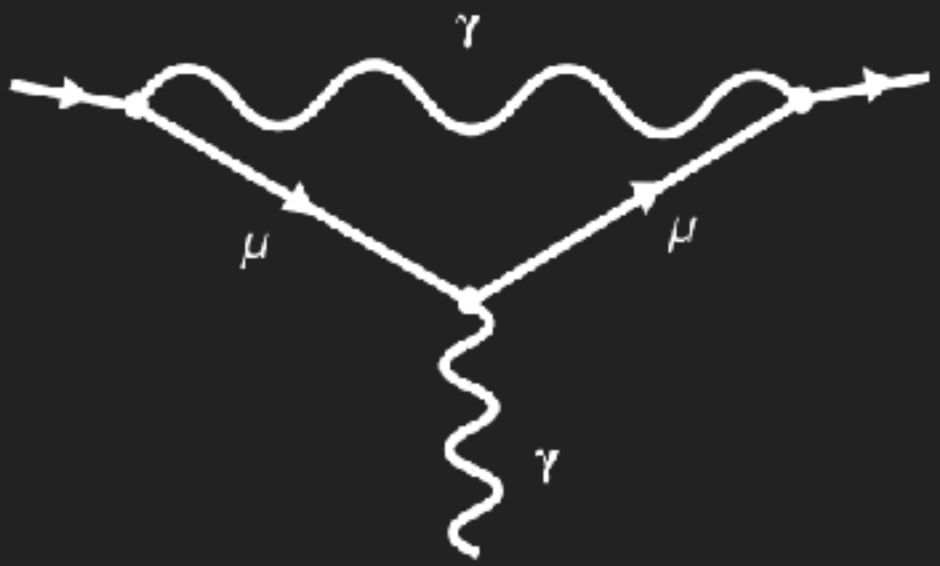
$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu c}\vec{S}$$

Dirac: $g_\mu = 2$

+

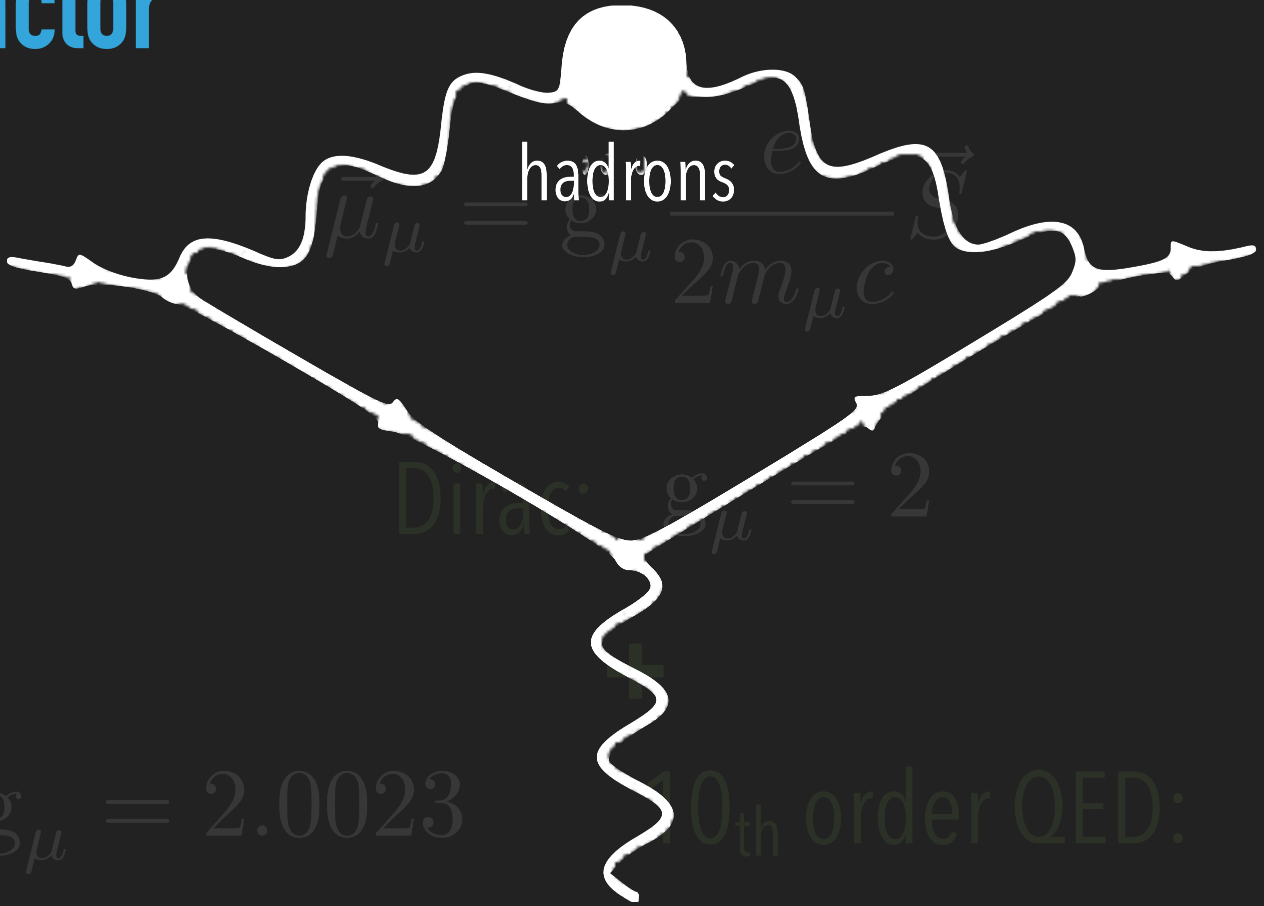
1st order QED: $g_\mu = 2.0023$

10th order QED: $g_\mu = 2.002331$



Jason Bono, jbono@fnal.gov

The Muon's g-factor



$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu c}\vec{S}$$

Dirac: $g_\mu = 2$

+

1st order QED: $g_\mu = 2.0023$

10th order QED: $g_\mu = 2.002331$

+

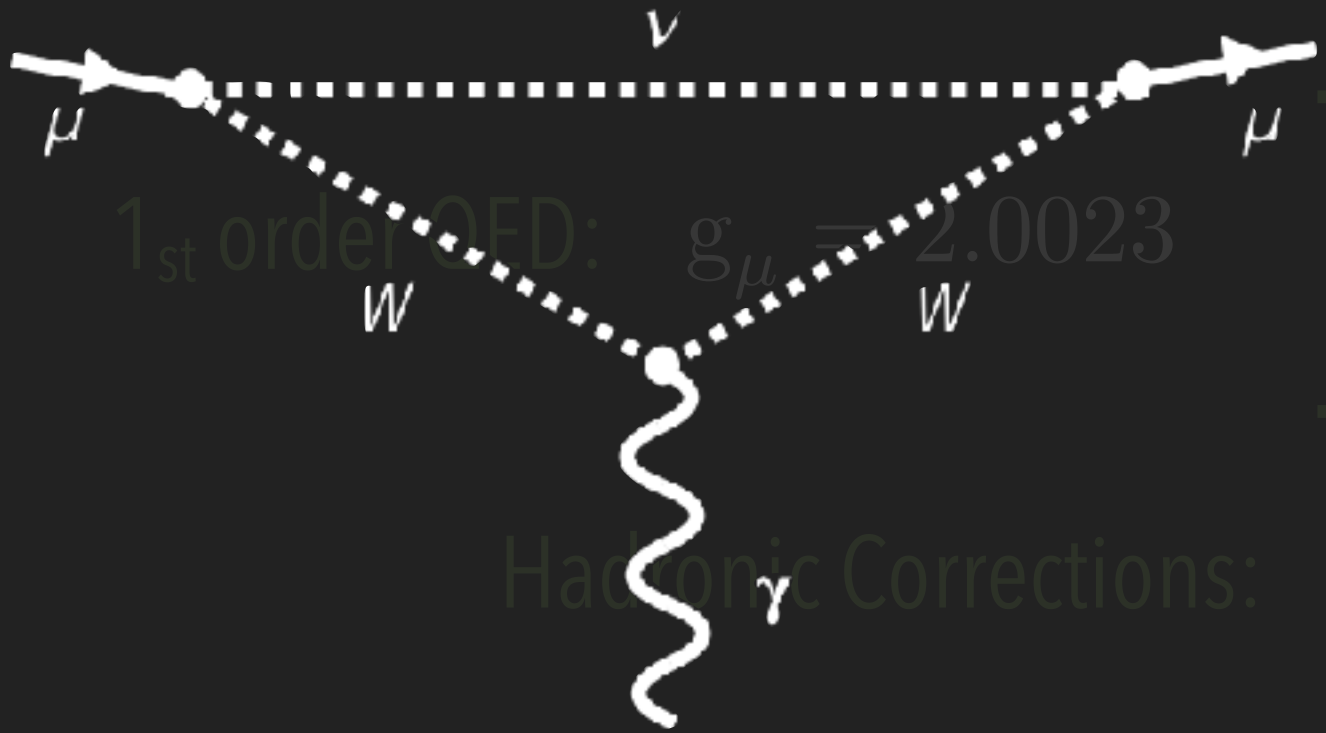
Hadronic Corrections: $g_\mu = 2.00233184$

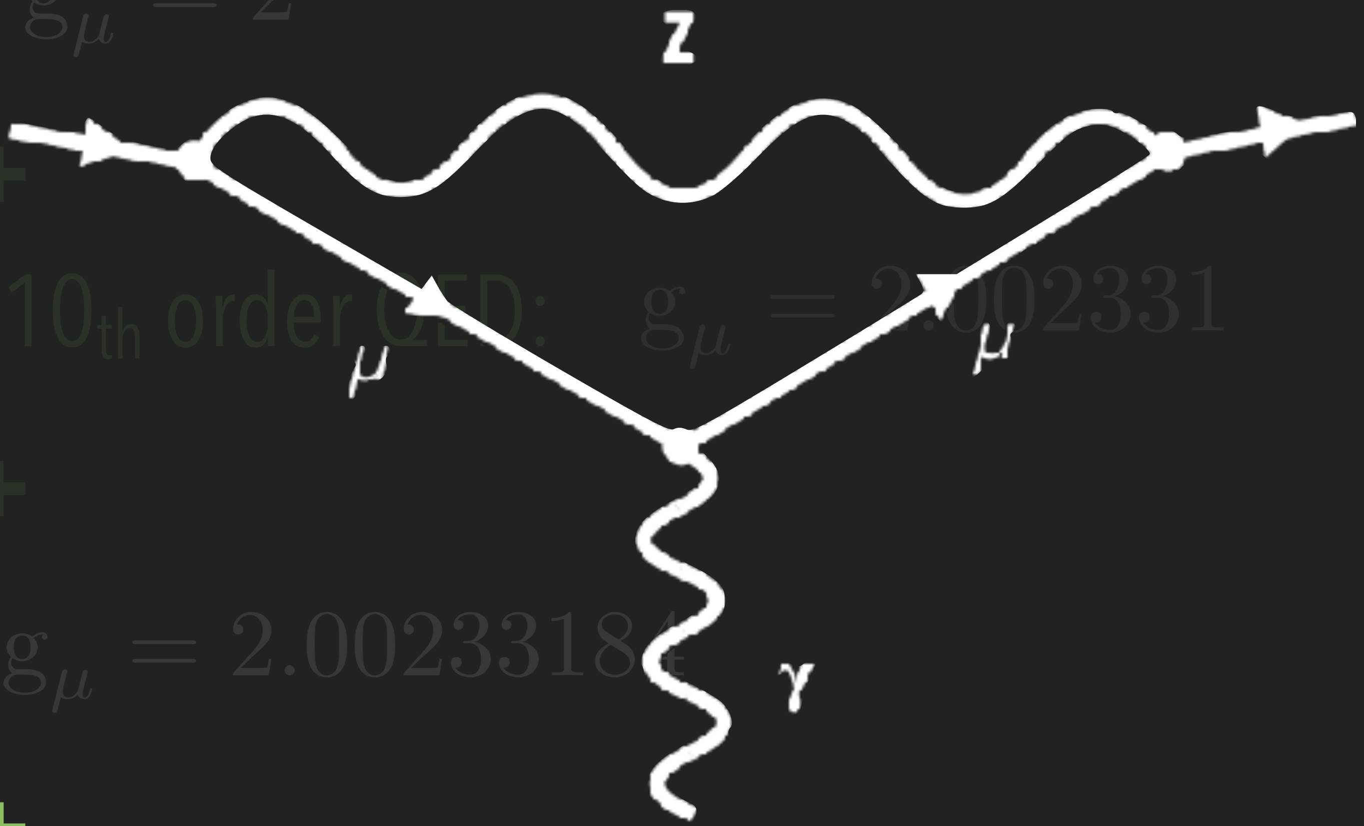
Jason Bono, jbono@fnal.gov

The Muon's g-factor

$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu c}\vec{S}$$

Dirac: $g_\mu = 2$





\+

1st order QED: $g_\mu = 2.0023$

10th order QED: $g_\mu = 2.002331$

\+

Hadronic Corrections: $g_\mu = 2.00233184$

\+

Electroweak Corrections: $g_\mu = 2.00233184178$

Jason Bono, jbono@fnal.gov

The Muon's g-factor

$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu c}\vec{S}$$

Dirac: $g_\mu = 2$

+

1st order QED: $g_\mu = 2.0023$

10th order QED: $g_\mu = 2.002331$

+

Hadronic Corrections: $g_\mu = 2.00233184$

+

Electroweak Corrections: $g_\mu = 2.00233184178$

Jason Bono, jbono@fnal.gov

The Muon's g-factor

$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu c}\vec{S}$$

Dirac: $g_\mu = 2$

+

1_{st} order QED: $g_\mu = 2.0023$

10_{th} order QED: $g_\mu = 2.002331$

+

Hadronic Corrections: $g_\mu = 2.00233184$

+

Electroweak Corrections: $g_\mu = 2.00233184178$

Jason Bono, jbono@fnal.gov

The Muon's Anomalous Magnetic Moment

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

Theory (420 ppb)

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Hadron}} = (11,659,182.8 \pm 4.9) \cdot 10^{-10}$$

Hagiwara *et al.* J. Phys. G38 085003 (2011)

Experiment (540 ppb)

$$a_\mu^{\mathrm{EXP}} = 116,592,089(63) \cdot 10^{-11}$$

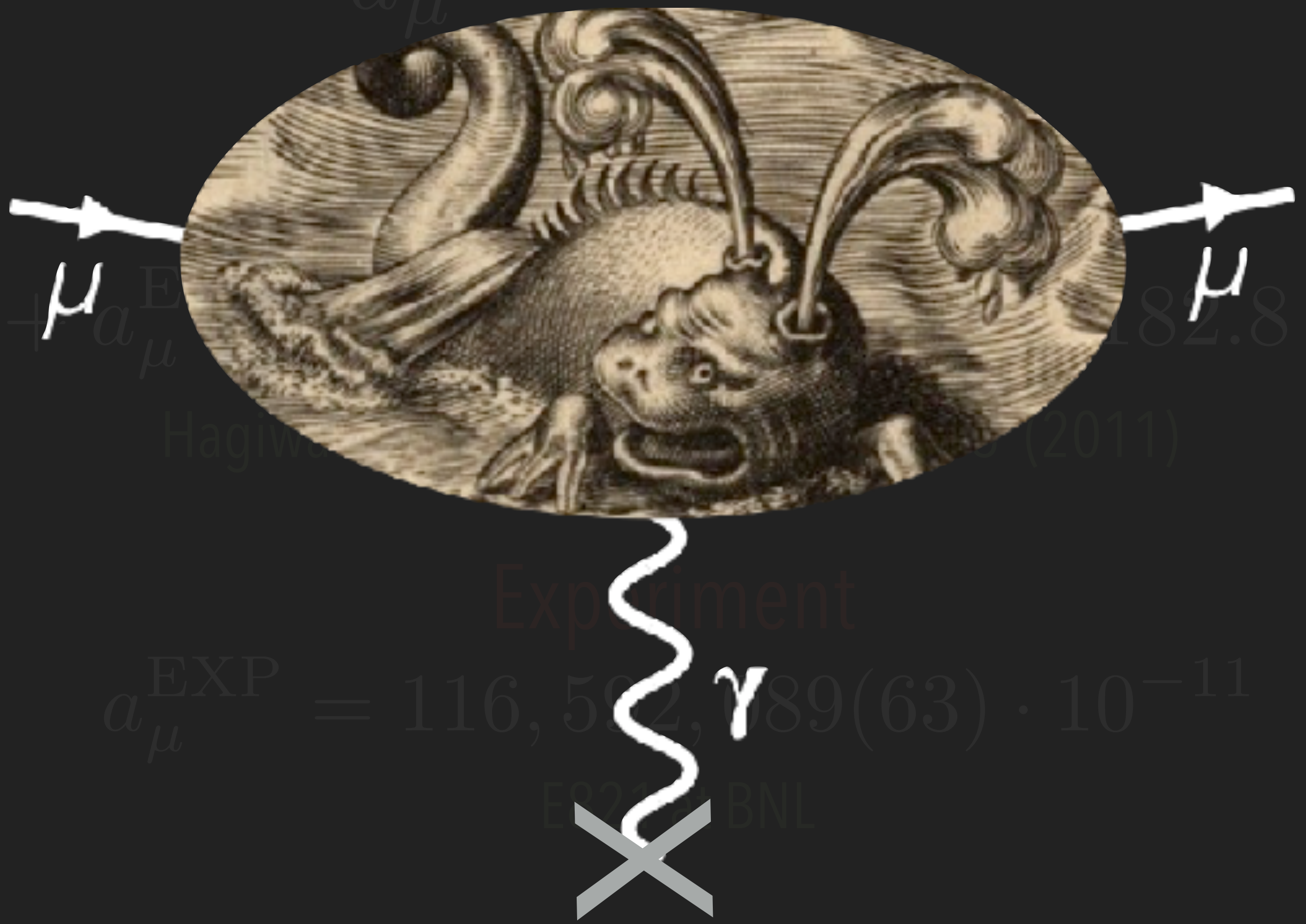
2004: E821 @ BNL

3.3 σ discrepancy

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

Jason Bono, jbono@fnal.gov

BLN's E821 was in uncharted territory. Did they see the effects of something new?



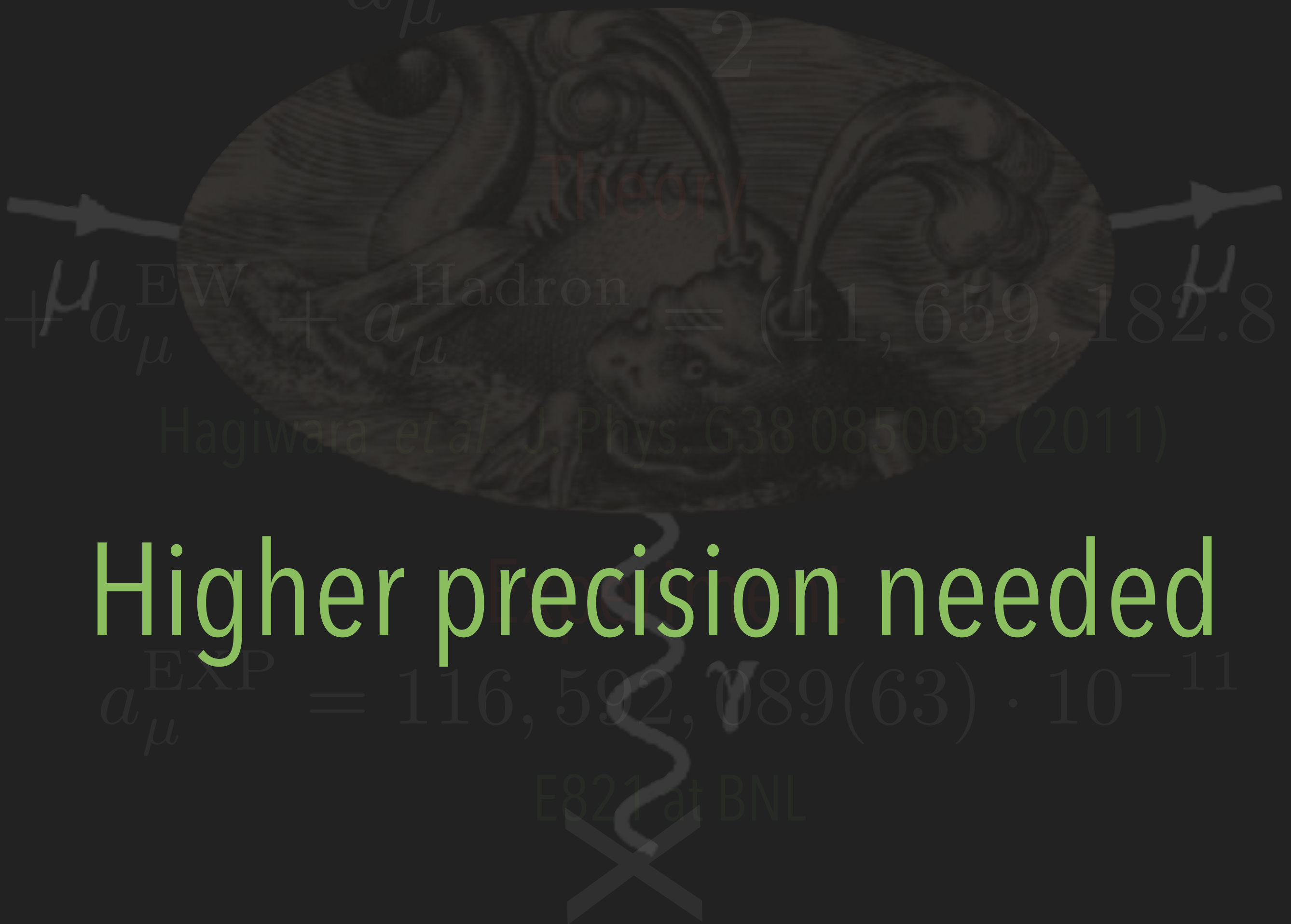
3.3 σ discrepancy

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

Jason Bono, jbono@fnal.gov

Did BLN's E821 See Beyond the Standard Model?

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



$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Hadron}} = (11,659,182.8 \pm 4.9) \cdot 10^{-10}$$

Hagiwara *et al.* J. Phys. G38 085003 (2011)

Higher precision needed

$$a_\mu^{\mathrm{EXP}} = 116,592,089(63) \cdot 10^{-11}$$

E821 at BNL

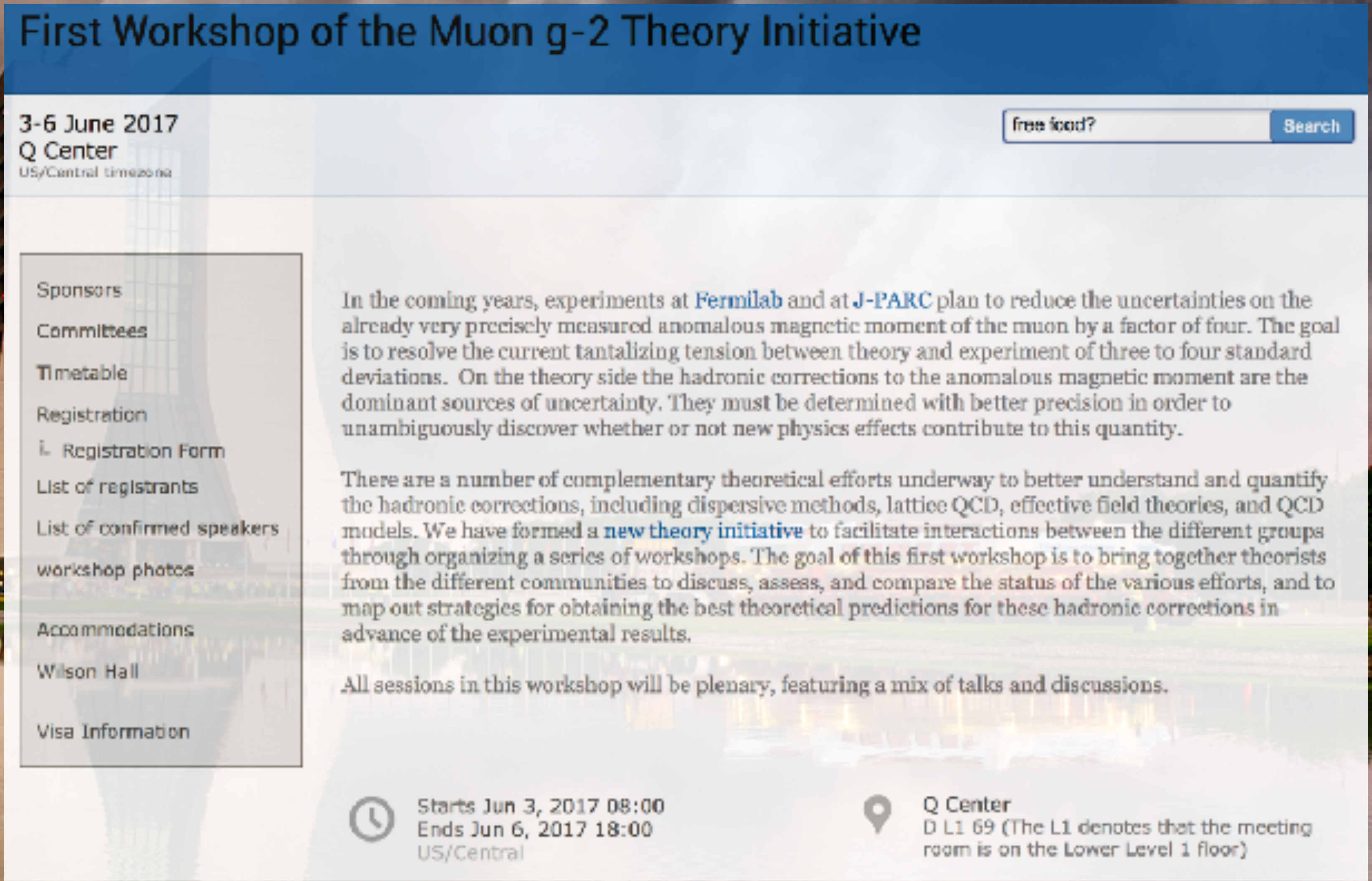
3.3 σ discrepancy

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

Jason Bono, jbono@fnal.gov

Delivery of BNL's muon storage ring to Fermilab

A vigorous global theory effort



First Workshop of the Muon g-2 Theory Initiative

3-6 June 2017
Q Center
US/Central timezone

In the coming years, experiments at Fermilab and at J-PARC plan to reduce the uncertainties on the already very precisely measured anomalous magnetic moment of the muon by a factor of four. The goal is to resolve the current tantalizing tension between theory and experiment of three to four standard deviations. On the theory side the hadronic corrections to the anomalous magnetic moment are the dominant sources of uncertainty. They must be determined with better precision in order to unambiguously discover whether or not new physics effects contribute to this quantity.

There are a number of complementary theoretical efforts underway to better understand and quantify the hadronic corrections, including dispersive methods, lattice QCD, effective field theories, and QCD models. We have formed a new theory initiative to facilitate interactions between the different groups through organizing a series of workshops. The goal of this first workshop is to bring together theorists from the different communities to discuss, assess, and compare the status of the various efforts, and to map out strategies for obtaining the best theoretical predictions for these hadronic corrections in advance of the experimental results.

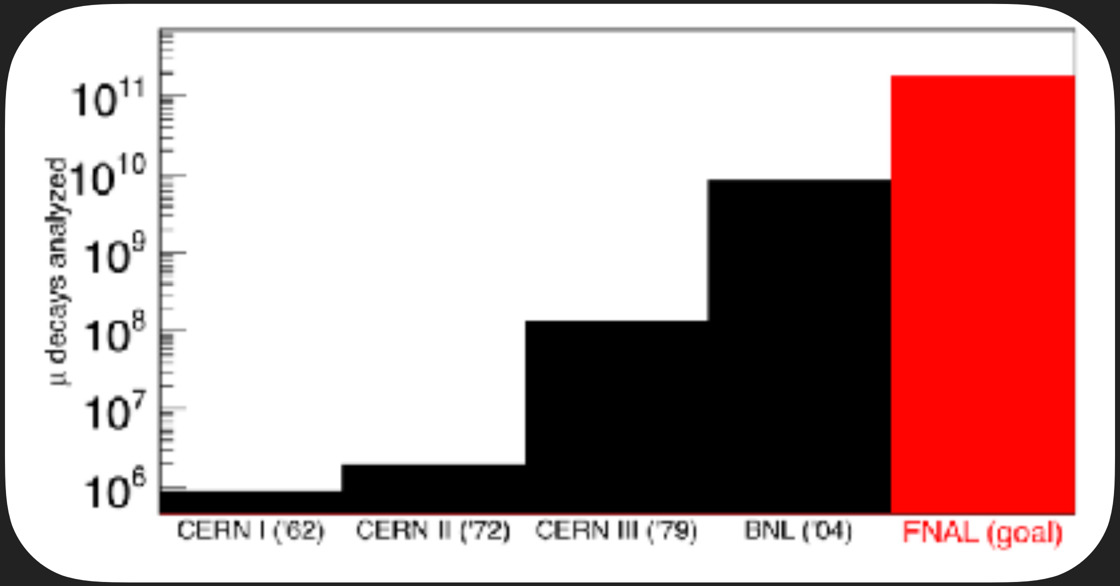
All sessions in this workshop will be plenary, featuring a mix of talks and discussions.

Starts Jun 3, 2017 08:00
Ends Jun 6, 2017 18:00
US/Central

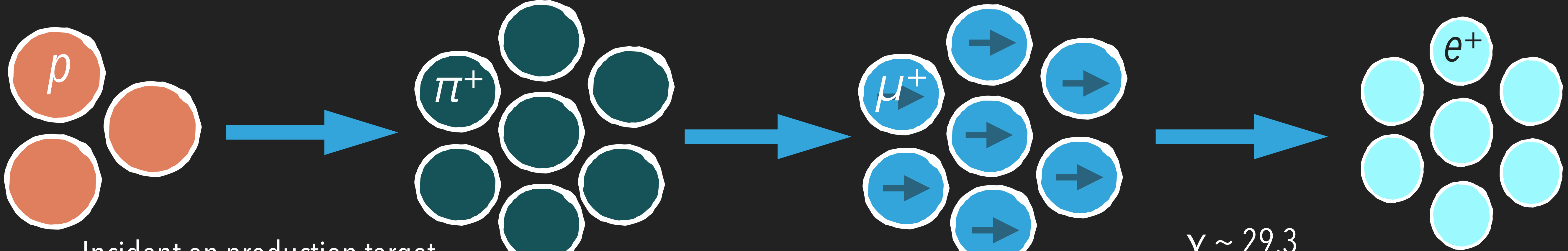
Q Center
D L1 69 (The L1 denotes that the meeting room is on the Lower Level 1 floor)

Higher Precision on the Way

- A new muon beamline at FNAL will deliver 21x the statistics as in E821
  - As well as reduced 3x systematic uncertainty from B field uniformity
  - Overall 4 fold improvement: 540 ppb @ BNL →140 ppb @ FNAL
- First physics run to begin this month!
  - Should be the highest statistics dataset in a few months
- Theory expected to improved by a factor of 2 on experiments timescale
  - If central values remain the same:
    - ~5σ discrepancy if theory does not improve
    - ~7-8σ discrepancy if theory improves as expected



Jason Bono, jbono@fnal.gov



8 GeV proton beam

Incident on production target, select pions

Pions in the delivery ring, wait out decay

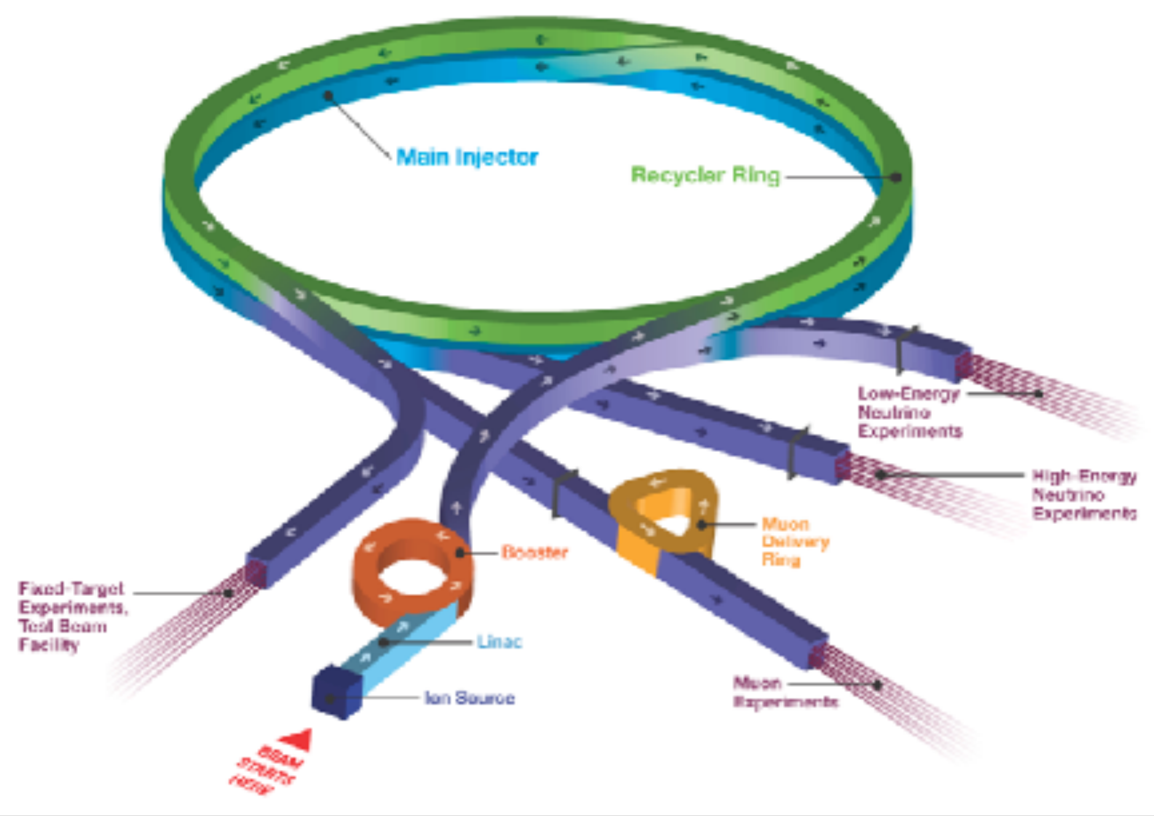
Select "forward going" muons

~3 GeV, polarized muons kicked into the storage ring, which has a uniform 1.45 T B-field. Vertical confinement by electric quadrupoles

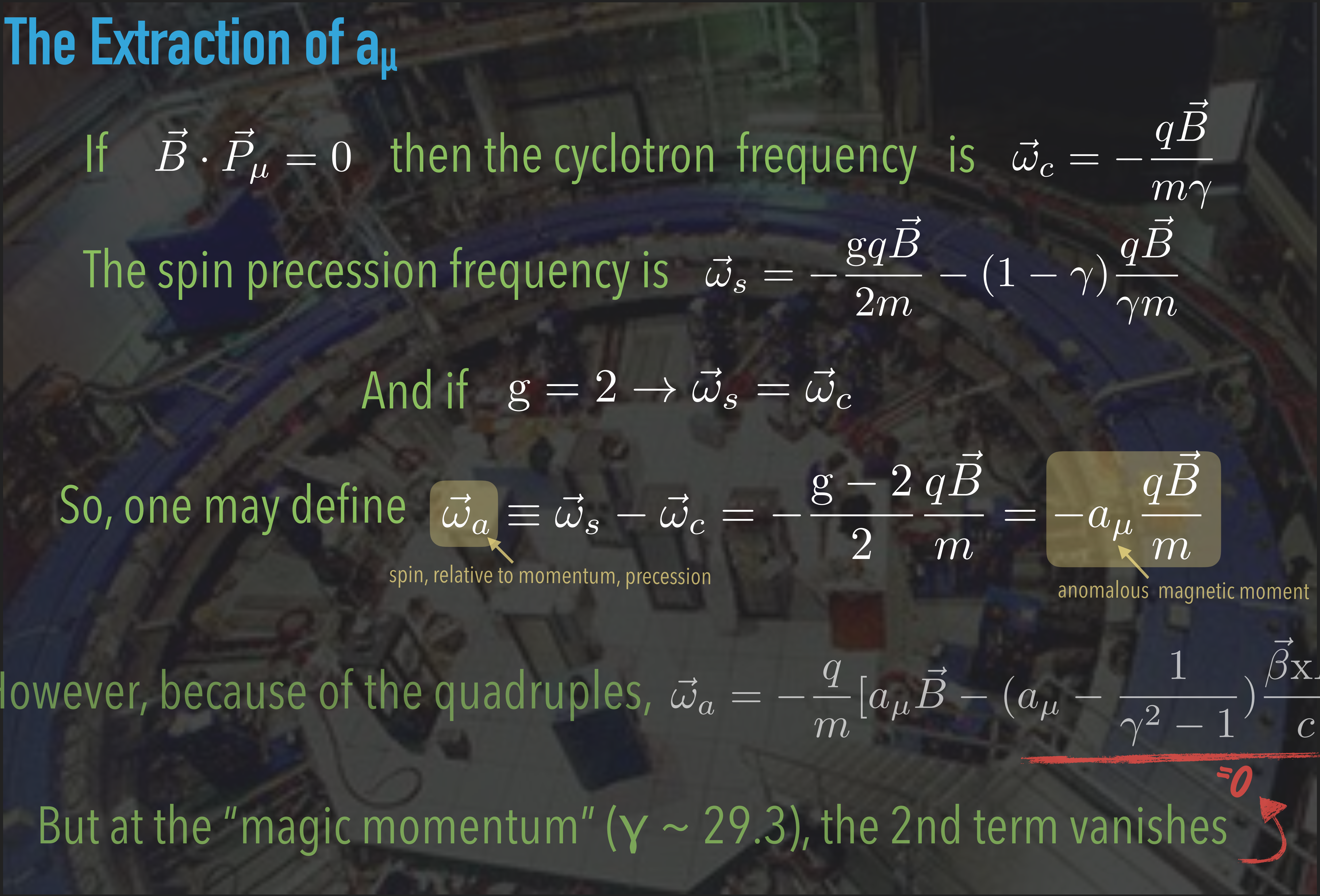
$\gamma \sim 29.3$

lifetime: $2.2\ \mu s \rightarrow 64.4\ \mu s$

Anisotropic positions detected



The Extraction of a_μ



If $\vec{B}\cdot\vec{P}_\mu = 0$ then the cyclotron frequency is $\vec{\omega}_c = -\frac{q\vec{B}}{m\gamma}$

The spin precession frequency is $\vec{\omega}_s = -\frac{\mathrm{g}q\vec{B}}{2m} - (1-\gamma)\frac{q\vec{B}}{\gamma m}$

And if $\mathrm{g} = 2 \rightarrow \vec{\omega}_s = \vec{\omega}_c$

So, one may define $\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{\mathrm{g}-2}{2}\frac{q\vec{B}}{m} = -a_\mu\frac{q\vec{B}}{m}$

spin, relative to momentum, precession

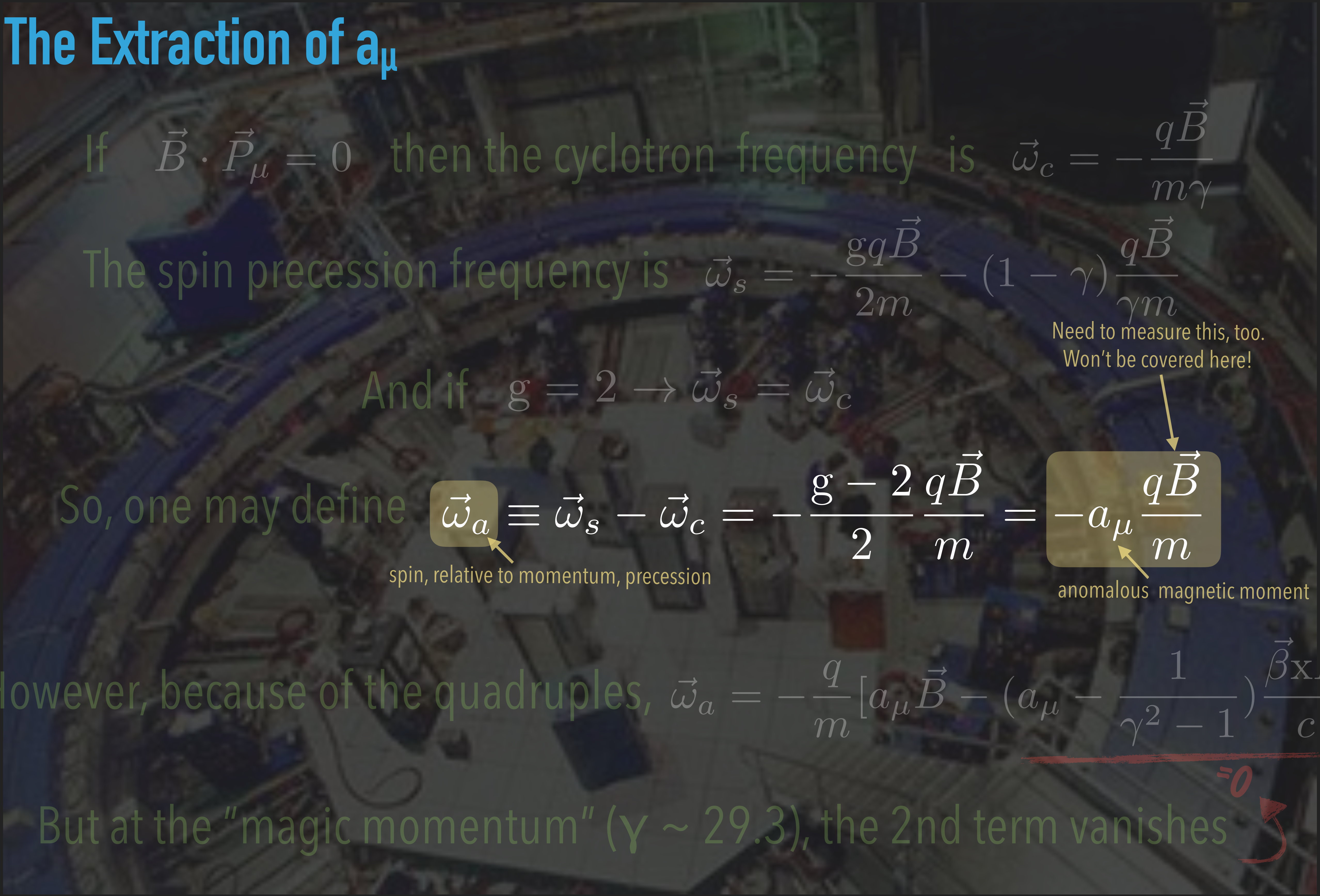
anomalous magnetic moment

However, because of the quadruples, $\vec{\omega}_a = -\frac{q}{m}[a_\mu\vec{B} - \underbrace{(a_\mu - \frac{1}{\gamma^2-1})\frac{\vec{\beta}\mathrm{x}\vec{E}}{c}}_{=0}]$

But at the "magic momentum" (γ ~ 29.3), the 2nd term vanishes

Jason Bono, jbono@fnal.gov

The Extraction of a_μ



If $\vec{B} \cdot \vec{P}_\mu = 0$ then the cyclotron frequency is $\vec{\omega}_c = -\frac{q\vec{B}}{m\gamma}$

The spin precession frequency is $\vec{\omega}_s = -\frac{gq\vec{B}}{2m} - (1-\gamma)\frac{q\vec{B}}{\gamma m}$

Need to measure this, too.
Won't be covered here!

And if $g = 2 \rightarrow \vec{\omega}_s = \vec{\omega}_c$

So, one may define $\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{g-2}{2}\frac{q\vec{B}}{m} = -a_\mu \frac{q\vec{B}}{m}$

spin, relative to momentum, precession

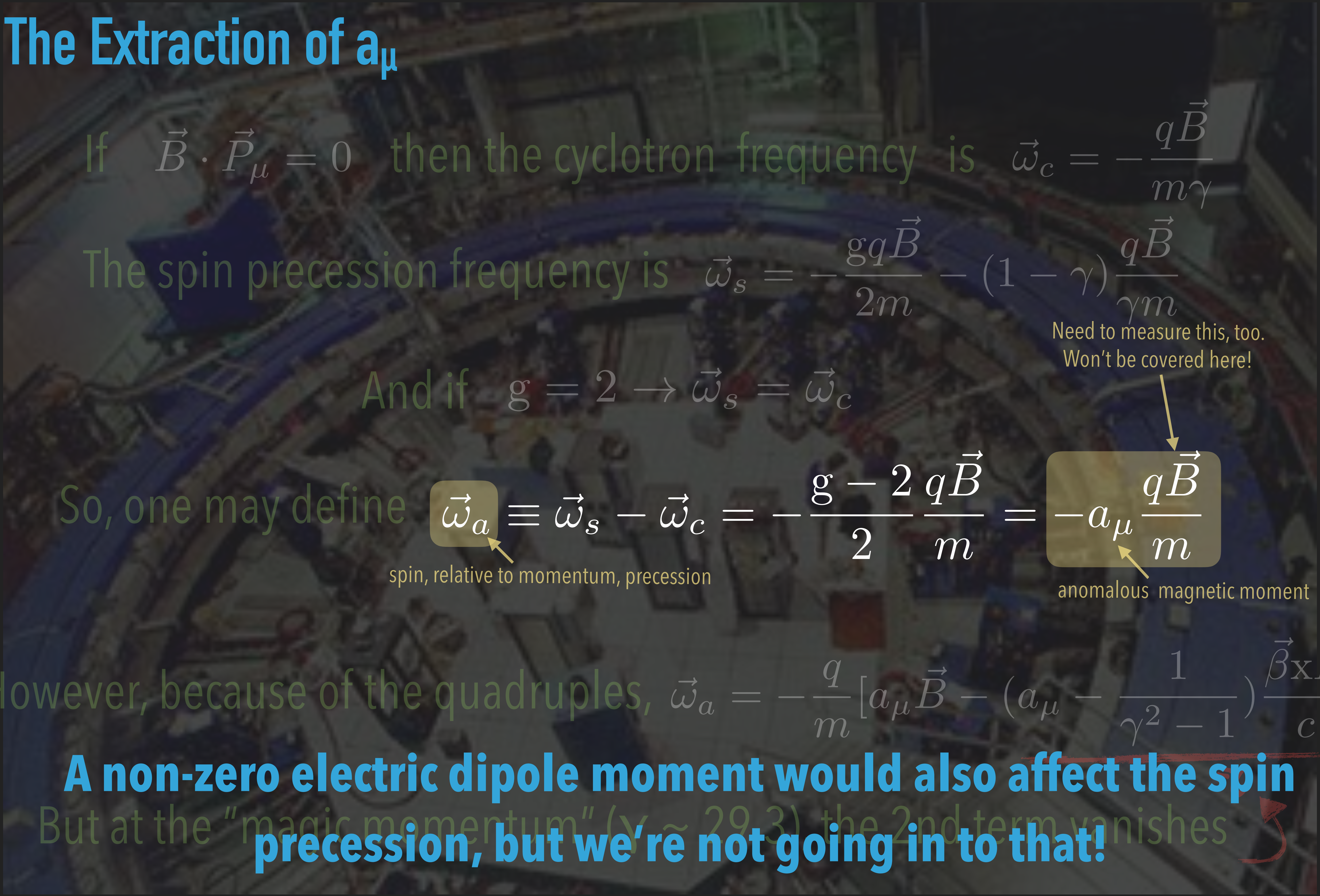
anomalous magnetic moment

However, because of the quadruples, $\vec{\omega}_a = -\frac{q}{m}[a_\mu \vec{B} - \underbrace{(a_\mu - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} x \vec{E}}{c}}_{=0}]$

But at the "magic momentum" ($\gamma \sim 29.3$), the 2nd term vanishes

Jason Bono, jbono@fnal.gov

The Extraction of a_μ



If $\vec{B}\cdot\vec{P}_\mu = 0$ then the cyclotron frequency is $\vec{\omega}_c = -\frac{q\vec{B}}{m\gamma}$

The spin precession frequency is $\vec{\omega}_s = -\frac{gq\vec{B}}{2m} - (1-\gamma)\frac{q\vec{B}}{\gamma m}$

Need to measure this, too.
Won't be covered here!

And if $g = 2 \rightarrow \vec{\omega}_s = \vec{\omega}_c$

So, one may define $\boxed{\vec{\omega}_a} \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{g-2}{2}\frac{q\vec{B}}{m} = \boxed{-a_\mu \frac{q\vec{B}}{m}}$

spin, relative to momentum, precession

anomalous magnetic moment

However, because of the quadruples, $\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\mathrm{x}\vec{E}}{c}\right]$

But at the "magic momentum" ($\gamma \approx 29.3$) the 2nd term vanishes

A non-zero electric dipole moment would also affect the spin precession, but we're not going in to that!

Jason Bono, jbono@fnal.gov

The Extraction of ω_a

- ω_a is the difference between the ensemble averaged muon spin precession and cyclotron frequencies
- In the CM frame, muon spin direction is correlated with positron angle
- In the lab frame (as well as the CM frame), the positron energy is correlated with it’s angle relative to the muon spin

The Extraction of ω_a

- ω_a is the difference between the ensemble averaged muon spin precession and cyclotron frequencies
- In the CM frame, muon spin direction is correlated with positron angle
- In the lab frame (as well as the CM frame), the positron energy is correlated with it's angle relative to the muon spin
  - Maximal energy when positron momentum and muon spin are parallel

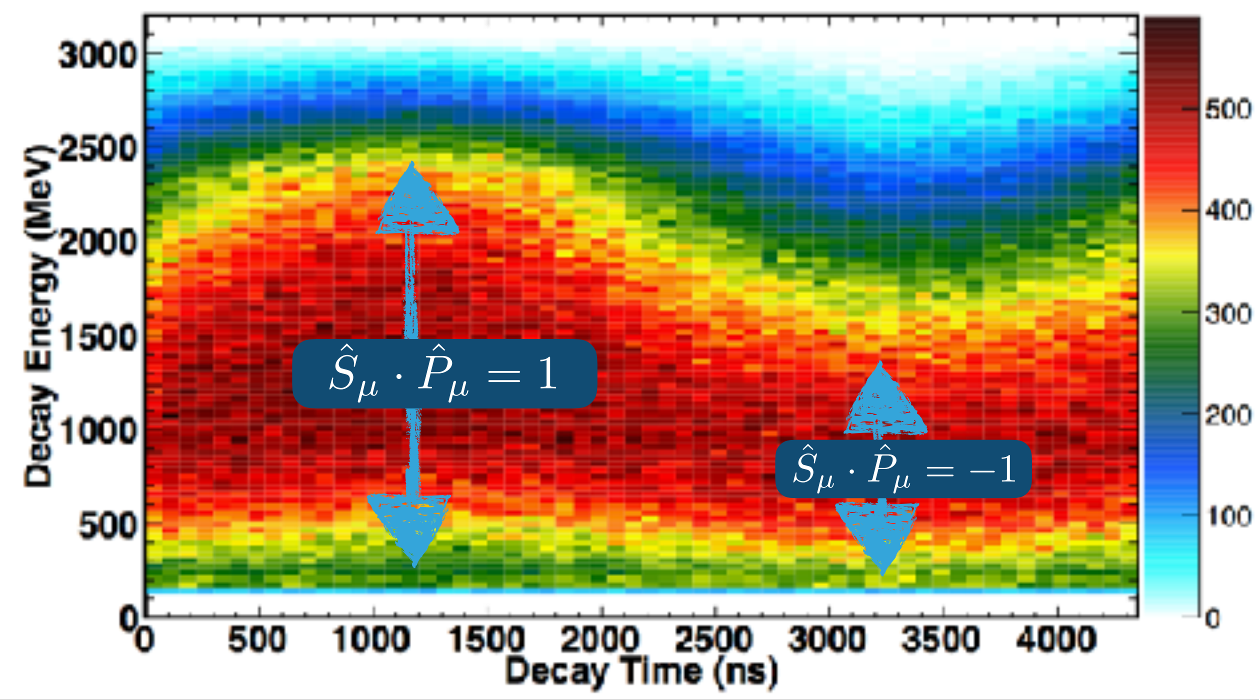
$$E_{e,\text{lab}} = \gamma(E_{e,\text{CM}} + \beta P_{e,\text{CM}} \cos\theta_{\text{CM}}) \approx \gamma E_{e,\text{CM}}(1 + \cos\theta_{\text{CM}})$$

Jason Bono, jbono@fnal.gov

The Extraction of ω_a

- ω_a is the difference between the ensemble averaged muon spin precession and cyclotron frequencies
- In the CM frame, muon spin direction is correlated with positron angle
- In the lab frame (as well as the CM frame), the positron energy is correlated with it's angle relative to the muon spin
  - Maximal energy when positron momentum and muon spin are parallel

$$E_{e,\mathrm{lab}} = \gamma(E_{e,\mathrm{CM}} + \beta P_{e,\mathrm{CM}} \cos\theta_{\mathrm{CM}}) \approx \gamma E_{e,\mathrm{CM}}(1 + \cos\theta_{\mathrm{CM}})$$

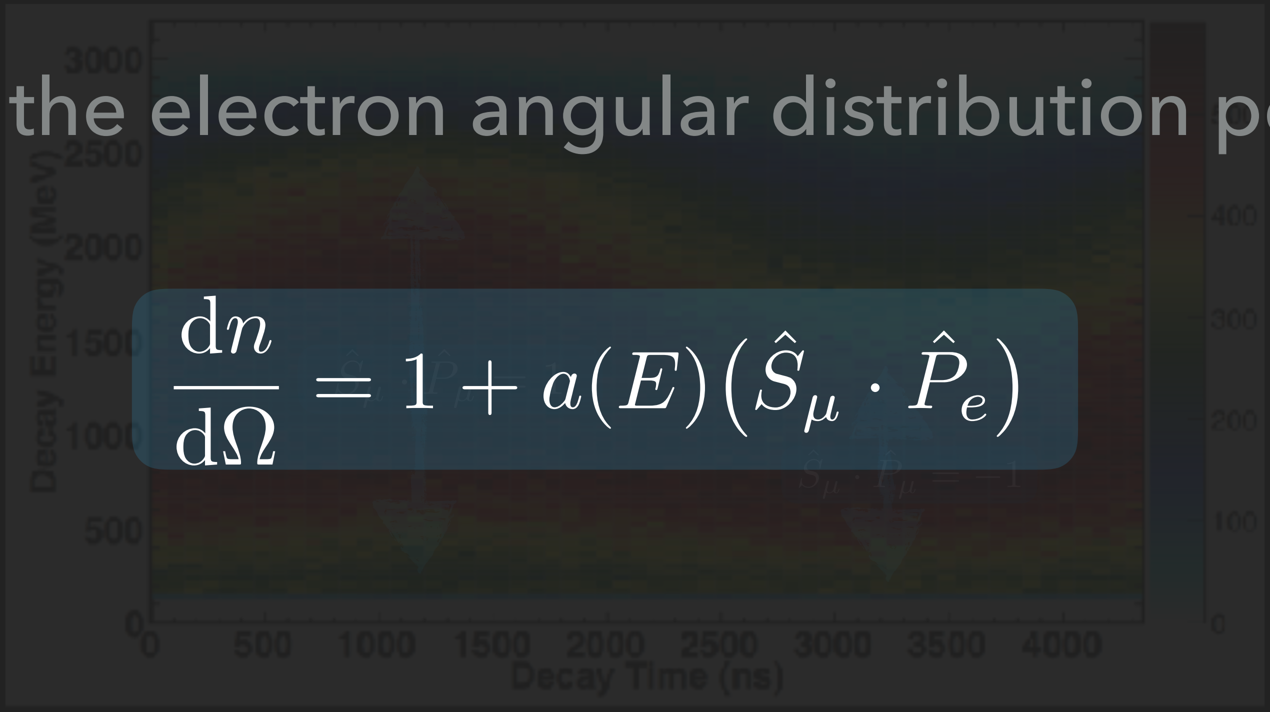


Jason Bono, jbono@fnal.gov

The Extraction of ω_a

- ω_a is the difference between the ensemble averaged muon spin precession and cyclotron frequencies
- In the CM frame, muon spin direction is correlated with positron angle
- In the lab frame (as well as the CM frame), the positron energy is correlated with it's angle relative to the muon spin
  - Maximal energy when positron momentum and muon spin are parallel

$$E_{e,\mathrm{lab}} = \gamma(E_{e,\mathrm{CM}} + \beta P_{e,\mathrm{CM}} \cos\theta_{\mathrm{CM}}) \approx \gamma E_{e,\mathrm{CM}}(1 + \cos\theta_{\mathrm{CM}})$$

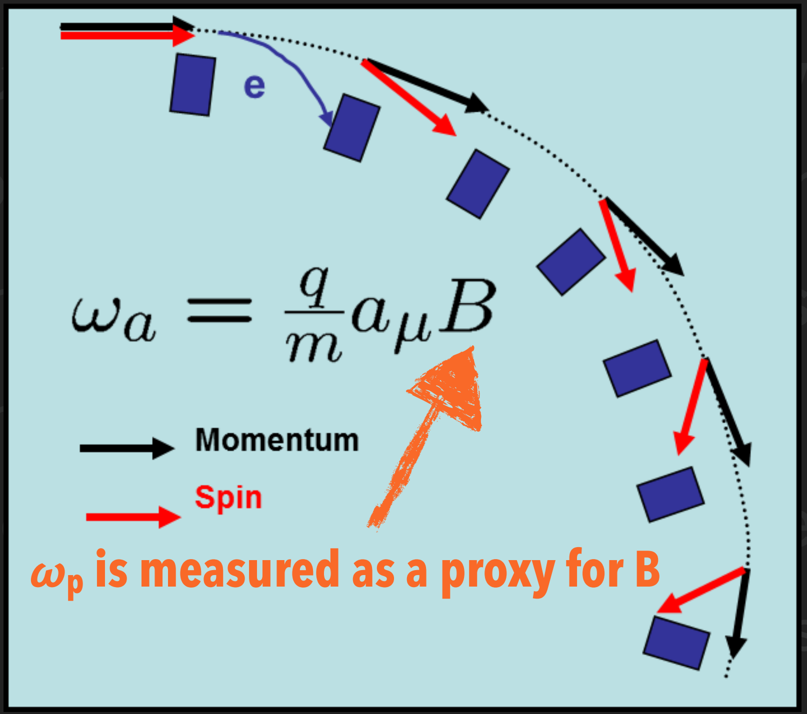


- Also note that the electron angular distribution peaks for parallel alignment:

$$\frac{\mathrm{d}n}{\mathrm{d}\Omega} = 1 + a(E)(\hat{S}_\mu \cdot \hat{P}_e)$$

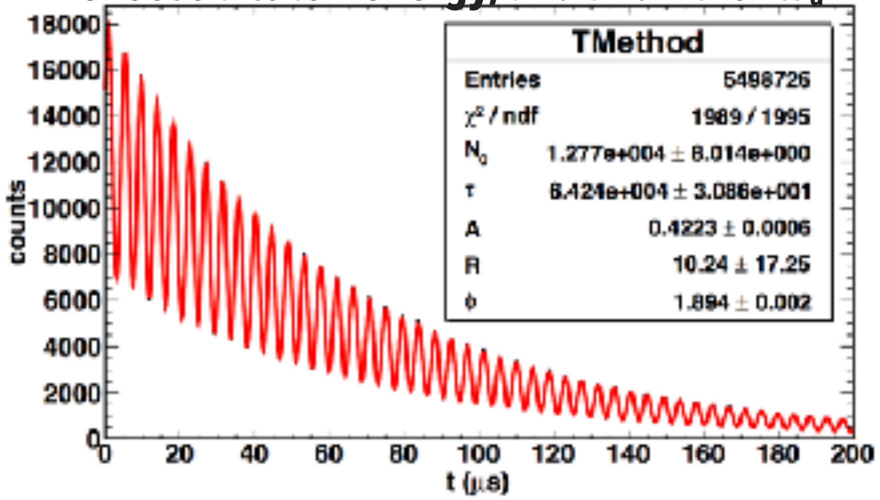
Jason Bono, jbono@fnal.gov

The Extraction of ω_a



The "wiggle plot"

Choose a cutoff energy, and and fit for ω_a!

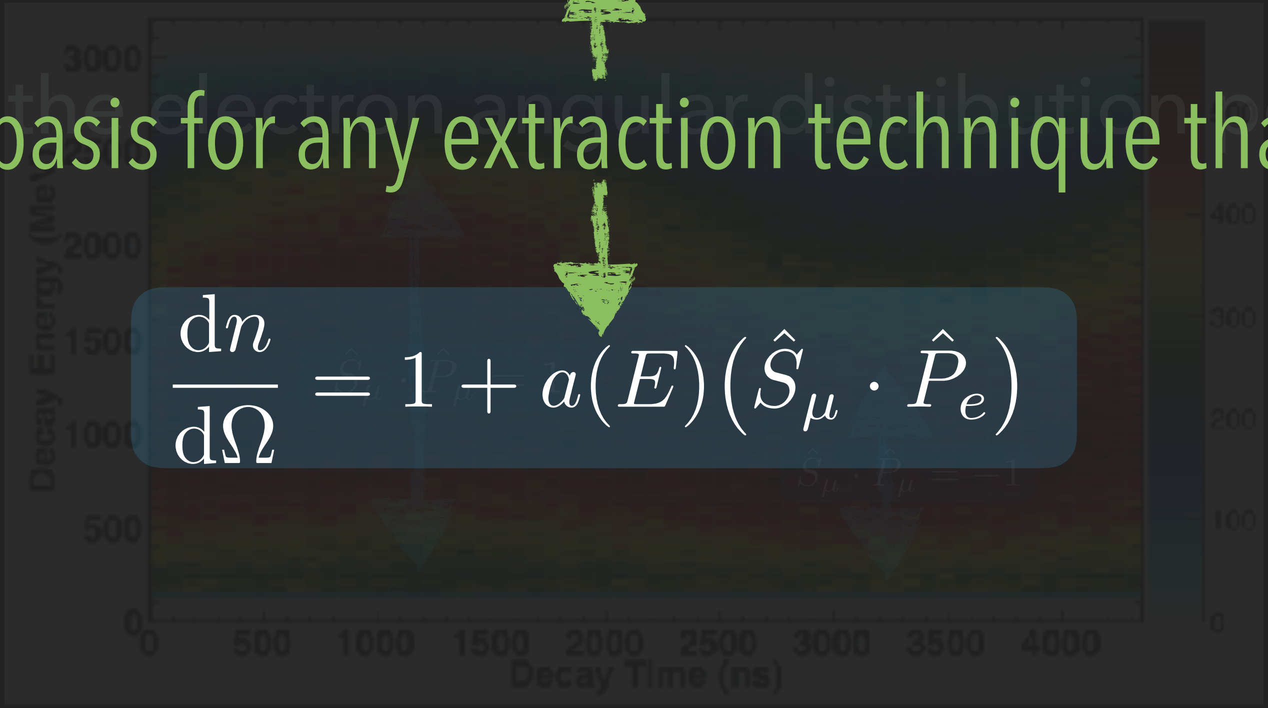


One could just plot number of event with equal weighting, as above. Or, one could weight the probability according to energy. Many possibilities!

$$E_{e,\text{lab}} = \gamma(E_{e,\text{CM}} + \beta P_{e,\text{CM}} \cos\theta_{\text{CM}}) \approx \gamma E_{e,\text{CM}}(1 + \cos\theta_{\text{CM}})$$

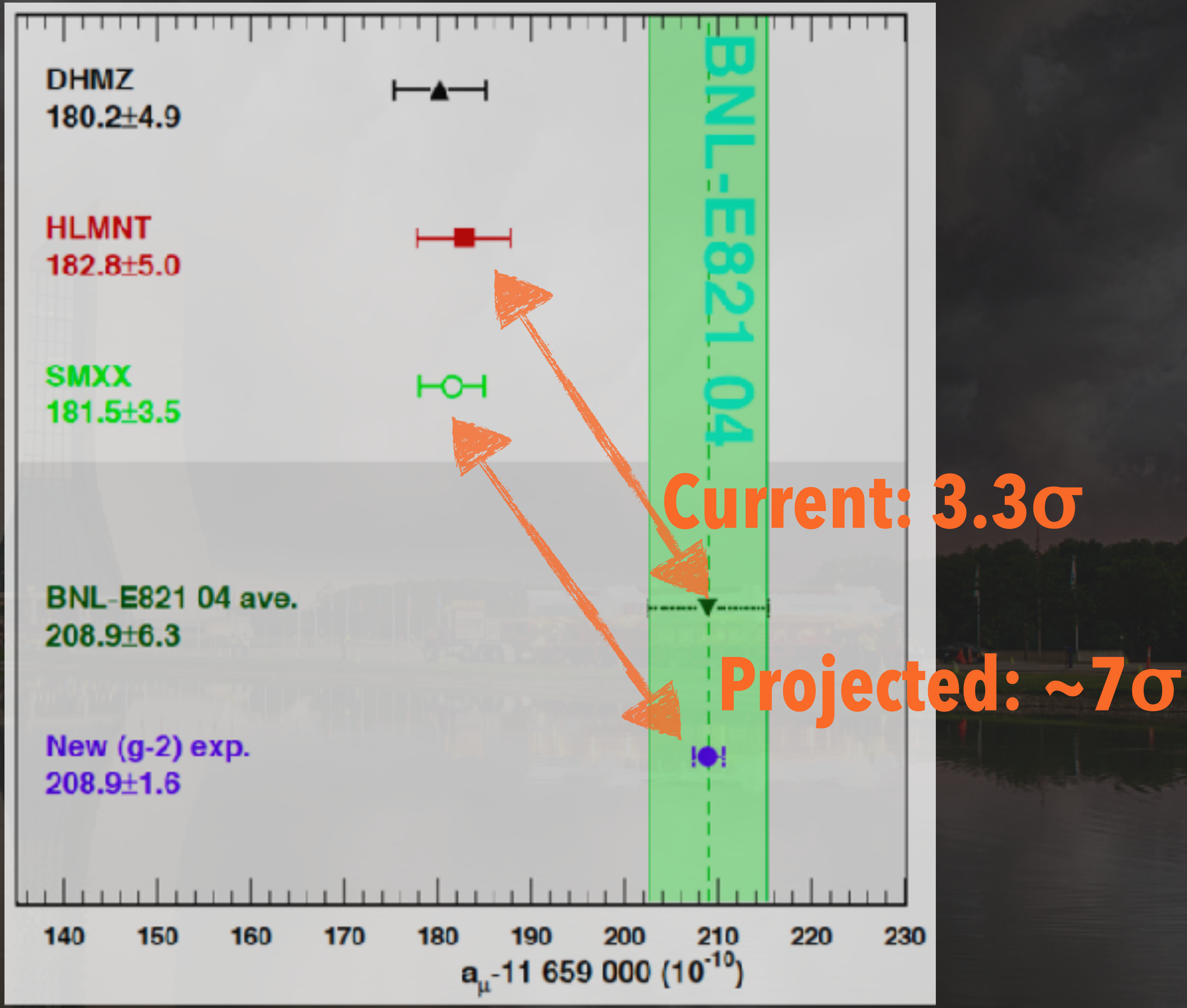
These form the basis for any extraction technique that will be used

Also note that the electron angular distribution peaks for parallel alignment:



$$\frac{\mathrm{d}n}{\mathrm{d}\Omega} = 1 + a(E)(\hat{S}_\mu \cdot \hat{P}_e)$$

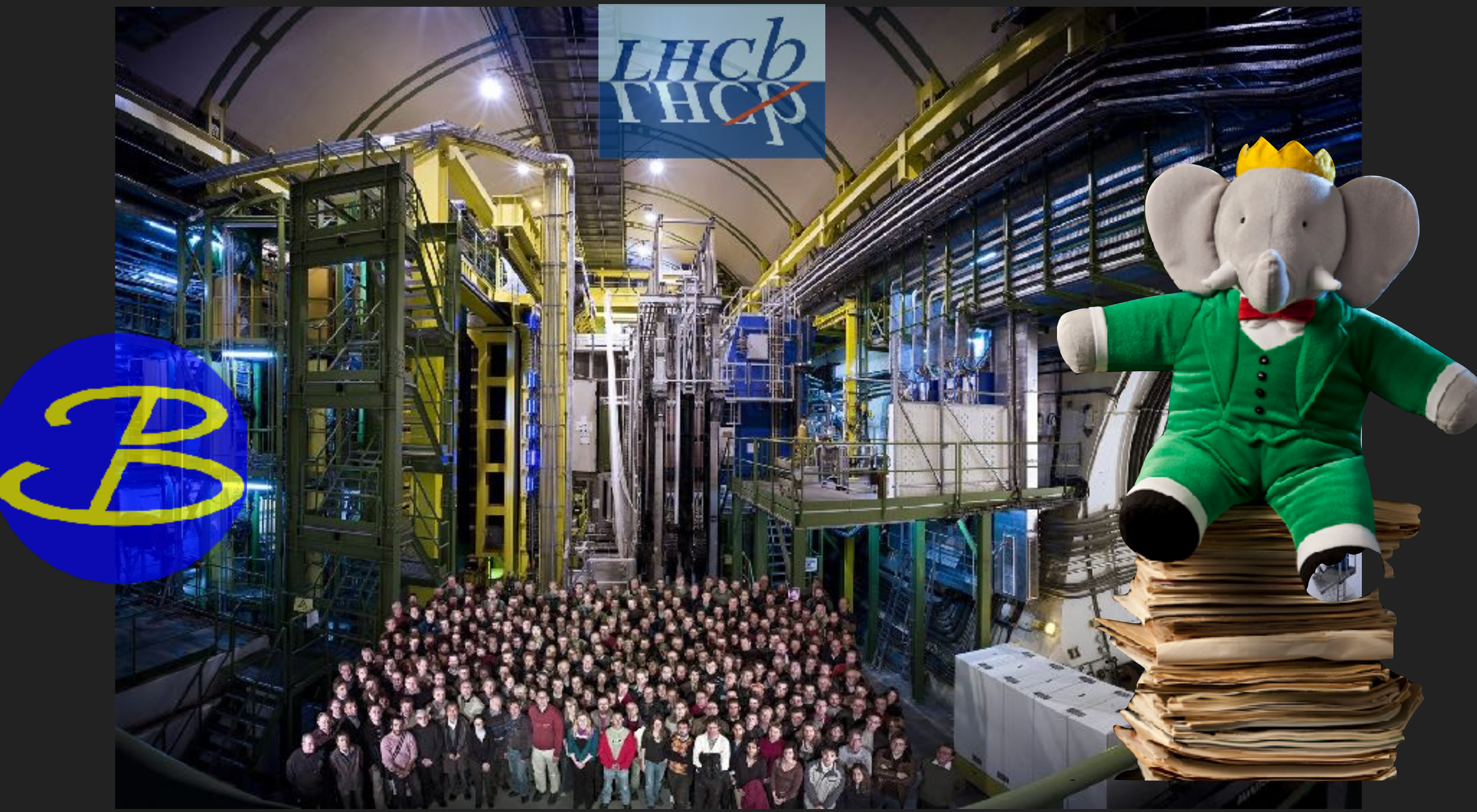
Jason Bono, jbono@fnal.gov



Stay tuned in the coming months for preliminary results!

Jason Bono, jbono@fnal.gov

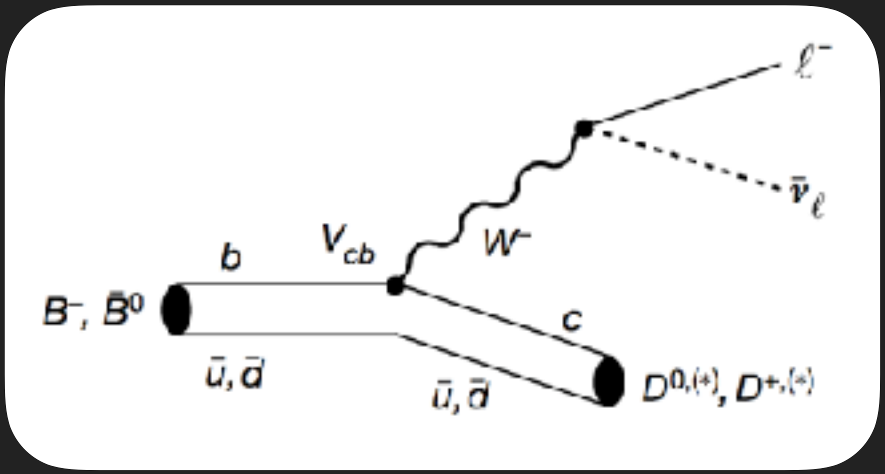
Hints of Lepton Flavor Non-Universality in B decays



Semi-Leptonic B-Meson Decays

- Lepton Universality: e, μ, and τ differ only by their masses
  - Identical coupling constants
- In semi-leptonic decays of B mesons, both e *and* μ can be treated as massless [1]
  - Therefore expect identical rates and kinematics of the decay for either lepton in the final state
- The mass of the τ must be accounted for [1]
  - $m_\tau \sim 1777$ MeV ~ 17 x m_μ
  - hadronic effects
- These decays are well understood in the SM, and so can be used to probe for new phenomena

$$\mathcal{B}(\bar{B} \to D l^- \bar{\nu}_l)$$



[1] Z. Phys. C - Particles and Fields 46, 93-109 (1990)

Jason Bono, jbono@fnal.gov

Semi-Leptonic B-Meson Decays

- SM predictions for the semi-leptonic B branching ratios:
  - Small suppression for τ in the final state

$$\mathcal{R}_{D^*}^{SM} = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* e^- \bar{\nu}_e)} = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* \mu^- \bar{\nu}_\mu)} = 0.252 \pm 0.003$$

$$\mathcal{R}_{D}^{SM} = \frac{\mathcal{B}(\bar{B} \to D \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D e^- \bar{\nu}_e)} = \frac{\mathcal{B}(\bar{B} \to D \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D \mu^- \bar{\nu}_\mu)} = 0.300 \pm 0.008$$

Semi-Leptonic B-Meson Decays

- SM predictions for the semi-leptonic B branching ratios:
  - Small suppression for τ in the final state

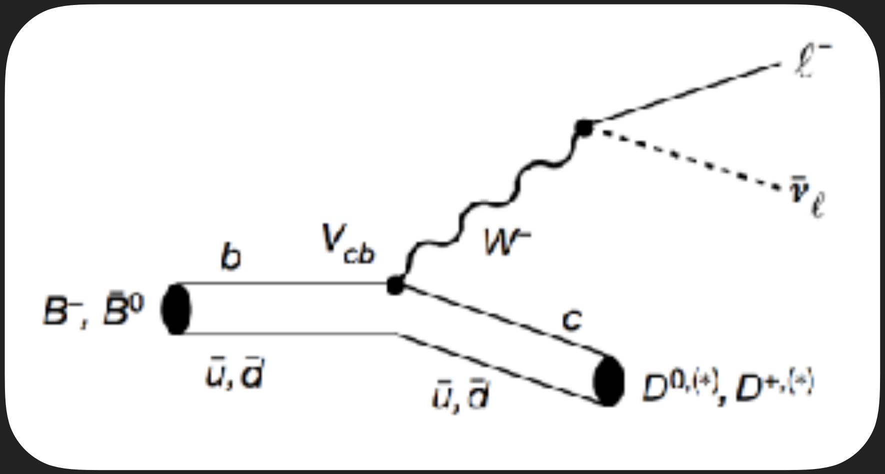
$$\mathcal{R}_{D^*}^{SM} = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* e^- \bar{\nu}_e)} = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* \mu^- \bar{\nu}_\mu)} = 0.252 \pm 0.003$$

$$\mathcal{R}_{D}^{SM} = \frac{\mathcal{B}(\bar{B} \to D \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D e^- \bar{\nu}_e)} = \frac{\mathcal{B}(\bar{B} \to D \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D \mu^- \bar{\nu}_\mu)} = 0.300 \pm 0.008$$

- These ratios have been measured in $p\bar{p}$ and e^+e^- production
  - BaBar & Belle: ~10 GeV lepton collider data collected from 1999 to ~2010
  - LHCb: 7-8 TeV hadron collider data collected from 2008 to 2012

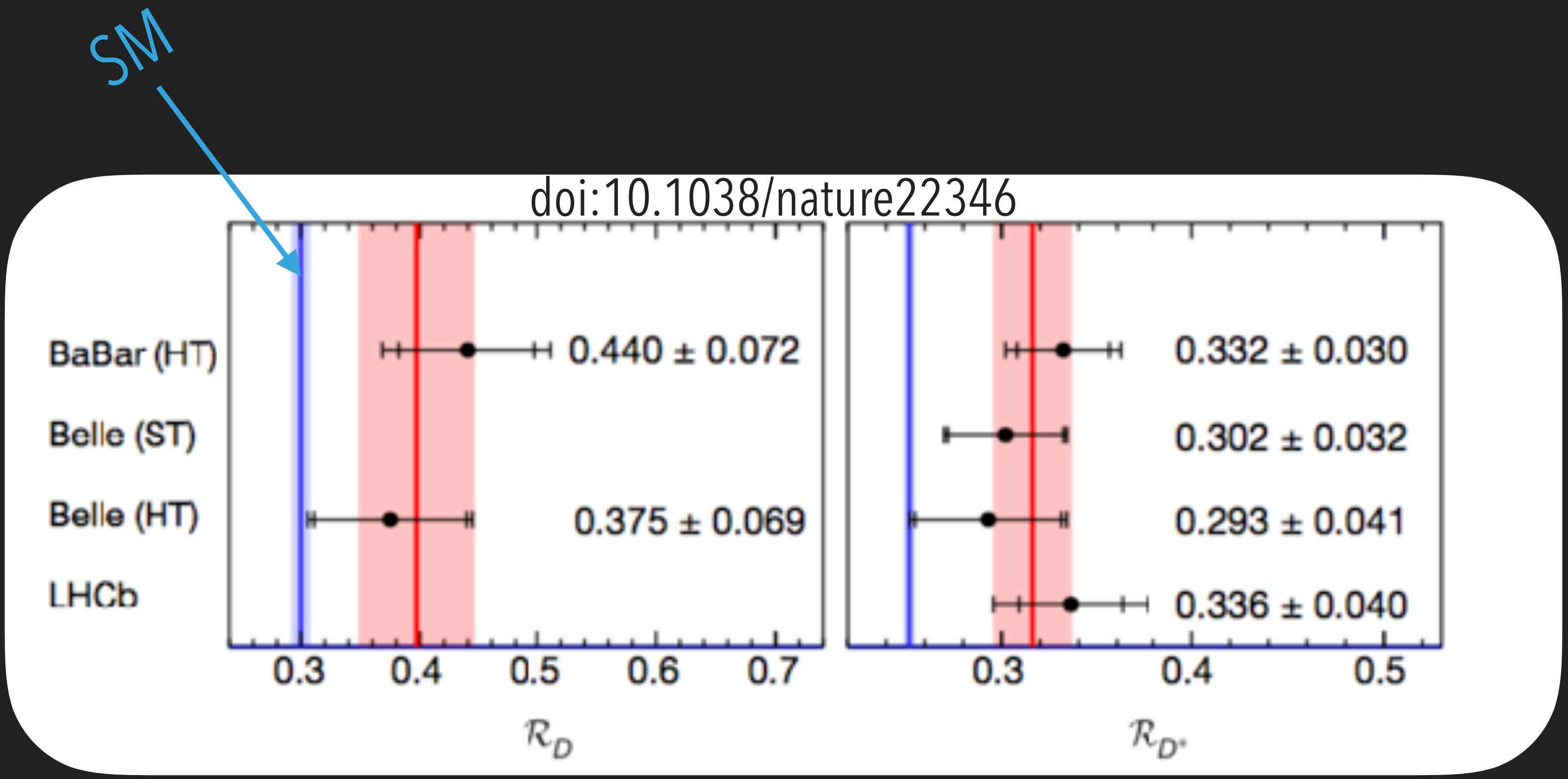
B-Meson Measurements

- All analyses fit to m^2_{miss}, E_ℓ, and q^2
  - The invariant mass squared of all undetected particles, lepton energy in the B rest frame, and invariant mass squared of the $\ell\nu$ system
- BaBar and Belle require B_{tag}, $D^{(*)}$ and ℓ in the final state
  - Hadronic B tagging algorithm
  - Semileptonic B tagging algorithm
- Similarly for LHCb



B-Meson Measurements

- All analyses fit to m^2_{miss}, E_ℓ, and q^2
  - The invariant mass squared of all undetected particles, lepton energy in the B rest frame, and invariant mass squared of the $\ell\nu$ system
- BaBar and Belle require B_{tag}, $D^{(*)}$ and ℓ in the final state
  - HT: Hadronic B tagging algorithm
  - ST: Semileptonic B tagging algorithm
- Similarly for LHCb

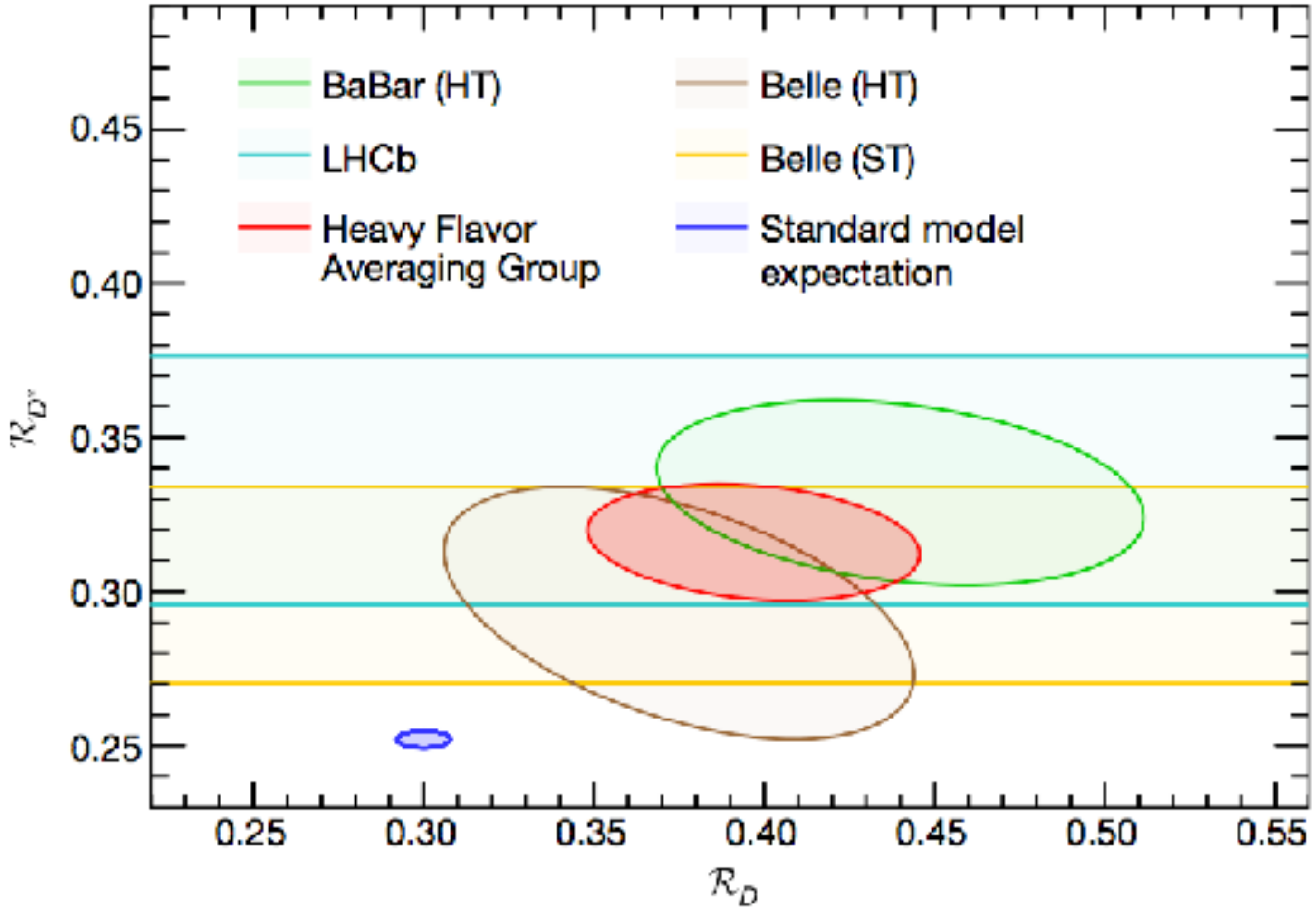


SM

doi:10.1038/nature22346

B-Meson Measurements

doi:10.1038/nature22346



Accounting for correlations, the combined discrepancies from R_D and R_{D^*} gives ~4σ

Jason Bono, jbono@fnal.gov

B-Meson Measurements

- Similarly, can test lepton universality with a kaon in the final state

$$\mathcal{R}_K^{SM} = \frac{\mathcal{B}(\bar{B} \to K^+ \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\bar{B} \to K^+ e^- \bar{\nu}_e)} \approx 1$$

- These ratios have been measured in $p\bar{p}$ and e^+e^- production
  - BaBar, Belle & CDF had large error bars, results consistent with the SM
  - LHCb produced a better measurement: Phys. Rev. Lett. 113, 151601 (2014)

B-Meson Measurements

- Similarly, can test lepton universality with a kaon in the final state

$$\mathcal{R}_K^{SM} = \frac{\mathcal{B}(\bar{B} \to K^+ \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\bar{B} \to K^+ e^- \bar{\nu}_e)} \approx 1$$

$$\mathcal{R}_K^{\mathrm{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

A 2.6σ departure from unity

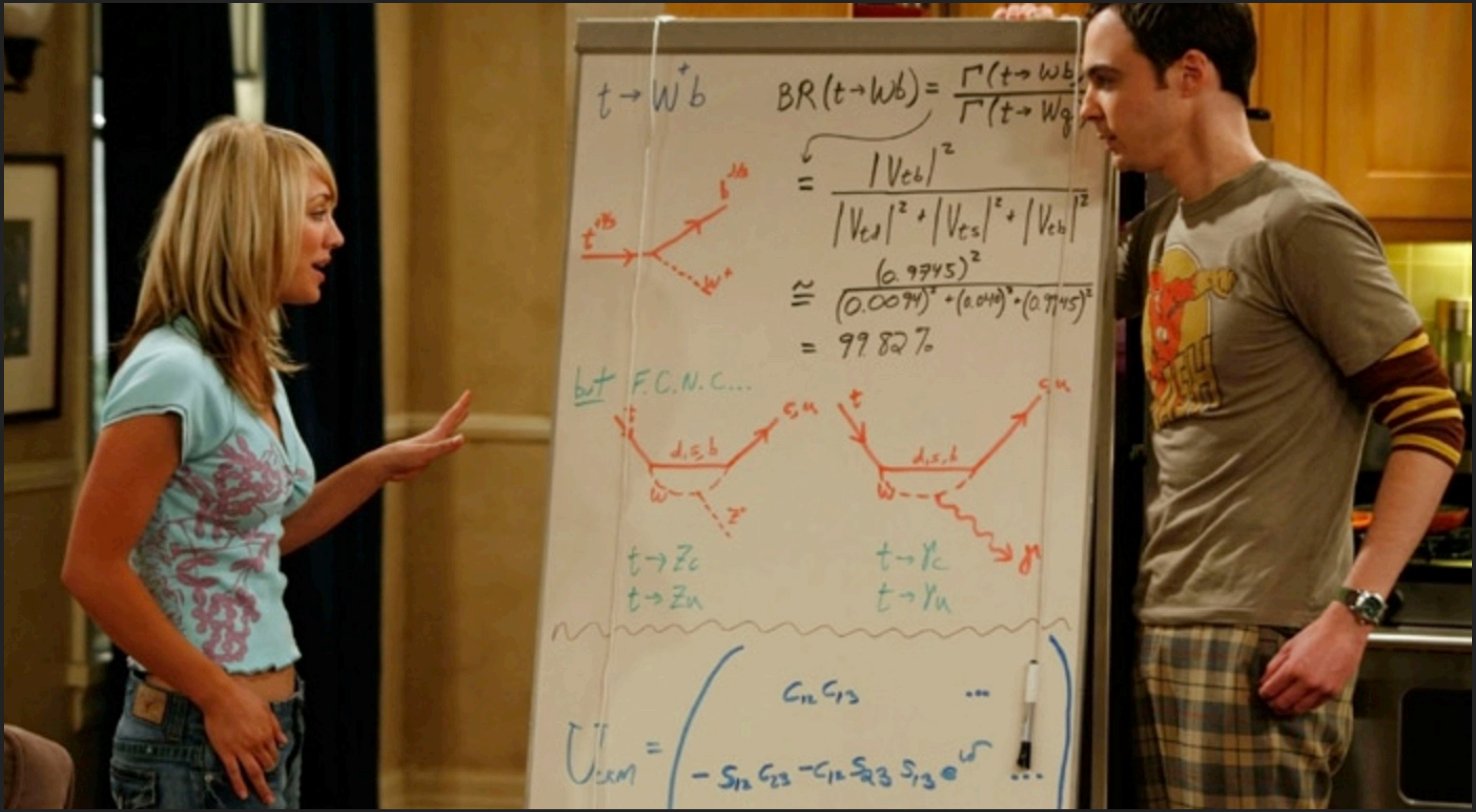
Jason Bono, jbono@fnal.gov

B-Meson Measurements

- SM discrepancies in $R_{D(*)}$ from three independent experiments
  - Adds up to 4σ departure
- SM discrepancy in R_K from LHCb
  - 2.6σ departure
- Could be seeing the effects of a new interaction that breaks lepton flavor universality
  - A new vector boson, W'^-, with different couplings for different quarks and leptons?
  - A scalar, i.e. charged Higgs, H^- ?
  - Leptoquarks?
- No conclusion yet
  - Underestimated experimental uncertainties?
  - SM predictions lacking some ordinary ingredient?
  - Awaiting Belle II and the LHCb upgrade

Jason Bono, jbono@fnal.gov

Searches for Charged Lepton Flavor Violation



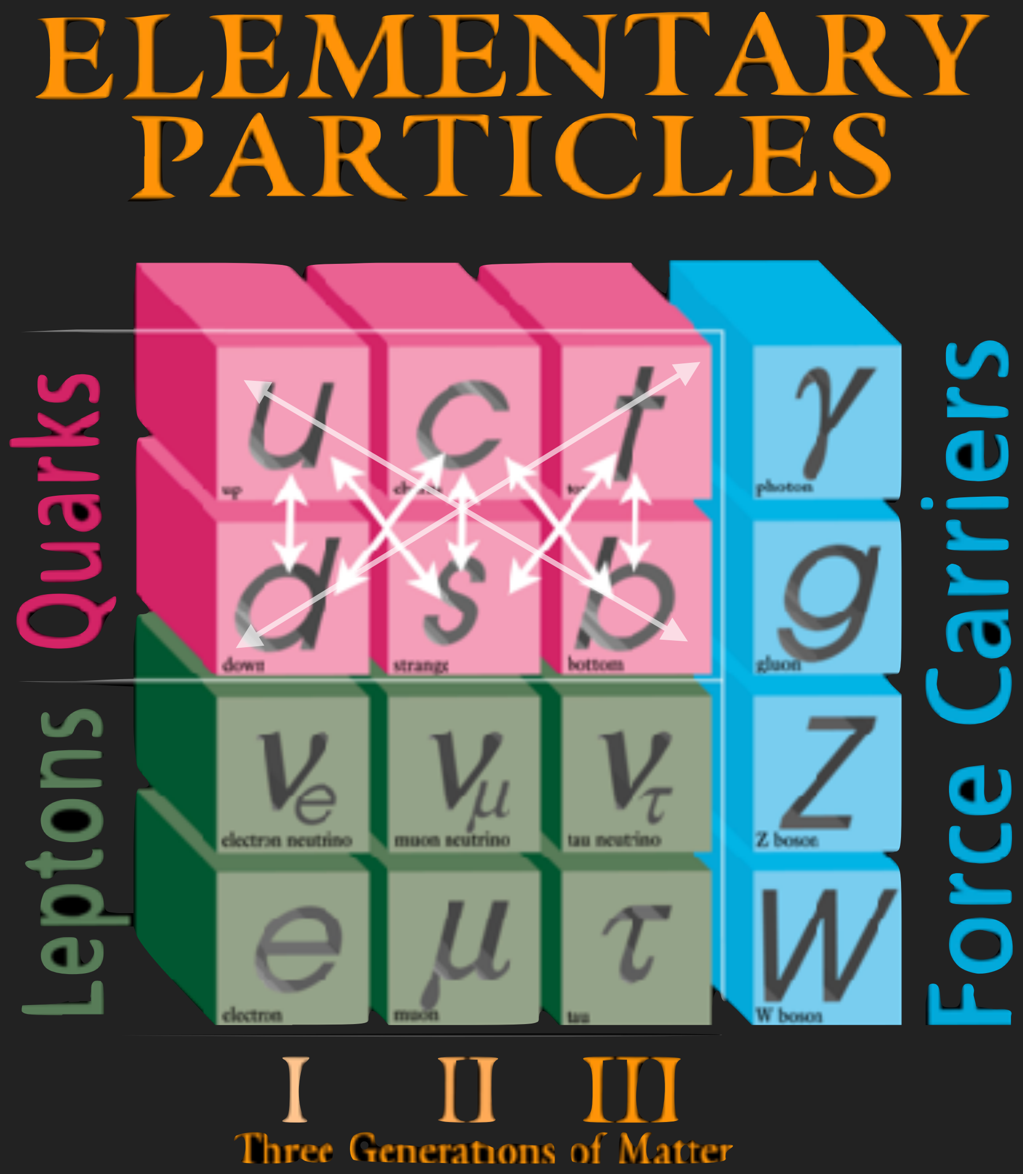
Charged Lepton Flavor Violation

- The recent anomalies in the lepton sector certainly add to the excitement of looking for Charged Lepton Flavor Violation (CLFV)
- But these searches have always been interesting!
  - Recall the role that the early muon experiments had in piecing together the SM

Jason Bono, jbono@fnal.gov

Flavor Violation in the SM

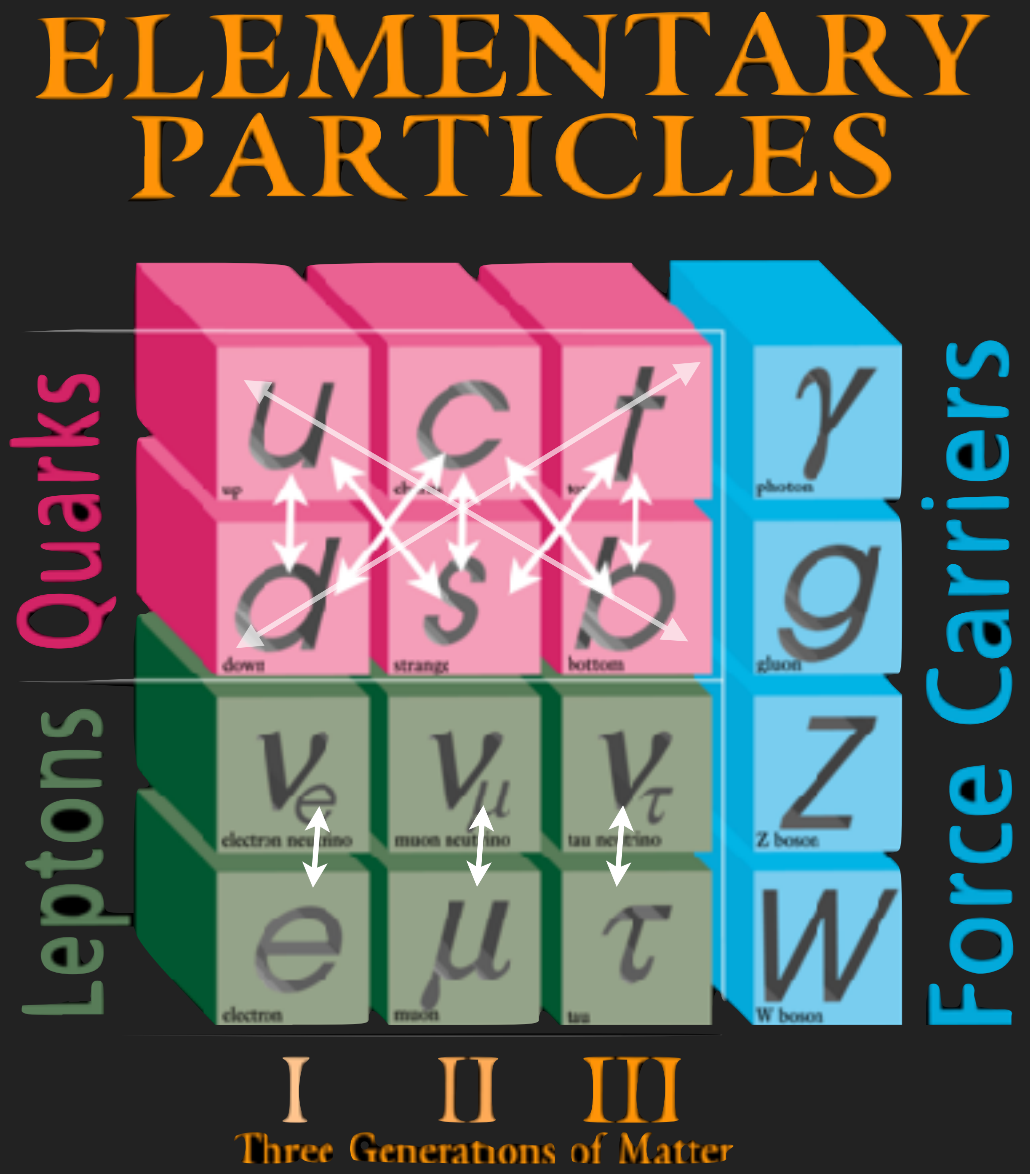
- The quarks commit Flavor Violation
  - They mix via the *W*

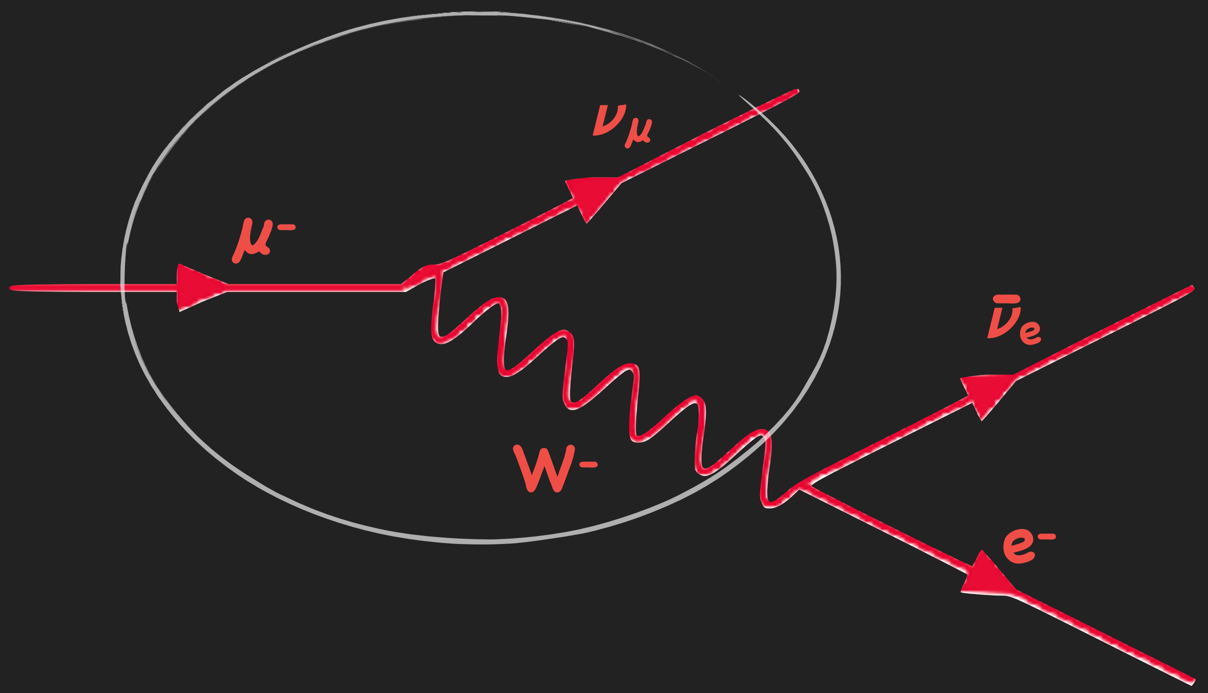


Jason Bono, jbono@fnal.gov

Flavor Violation in the SM

- The quarks commit Flavor Violation
  - They mix via the *W*
- The neutrinos can change into their partners (and vice versa)

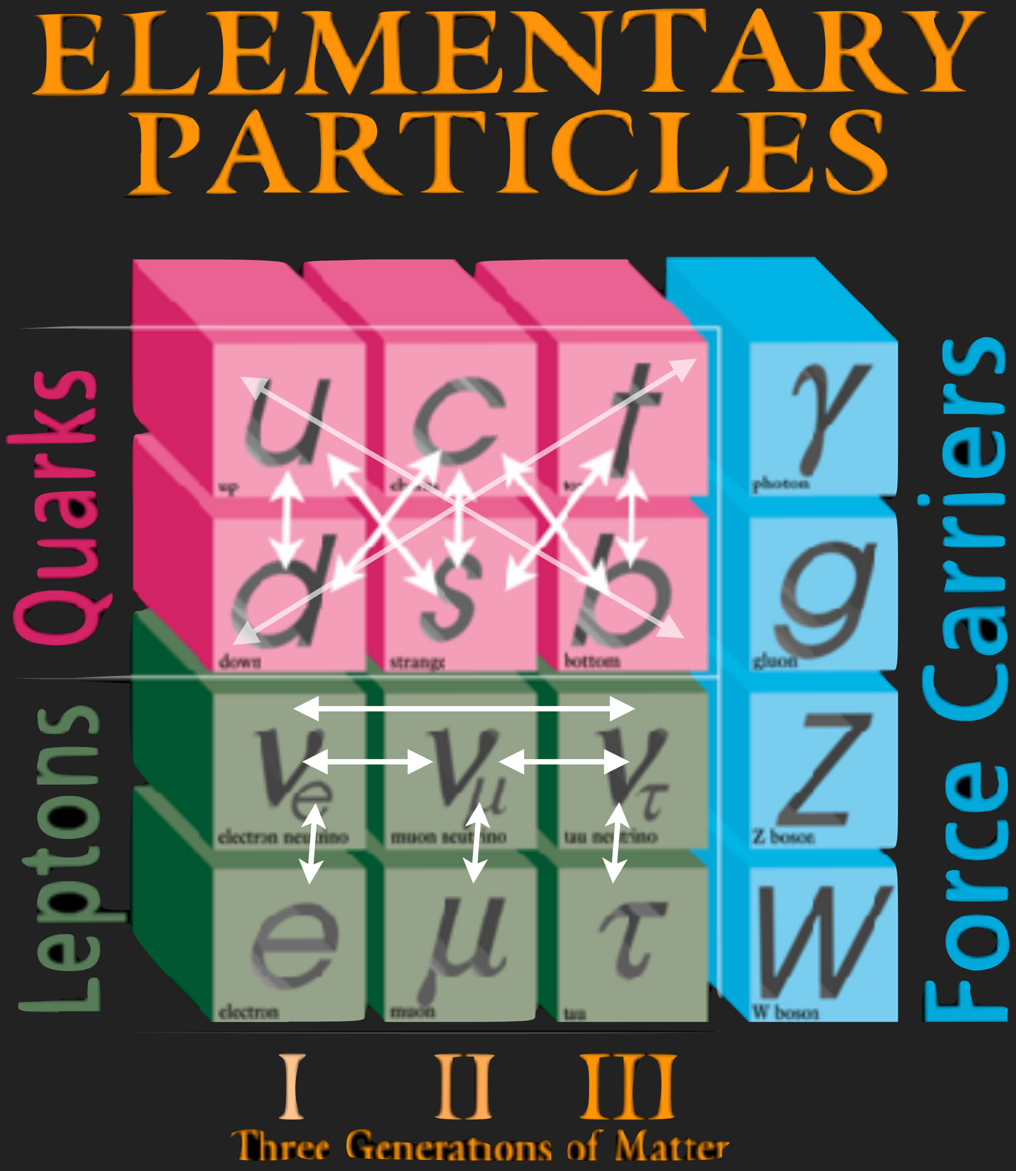




Jason Bono, jbono@fnal.gov

Flavor Violation in the SM

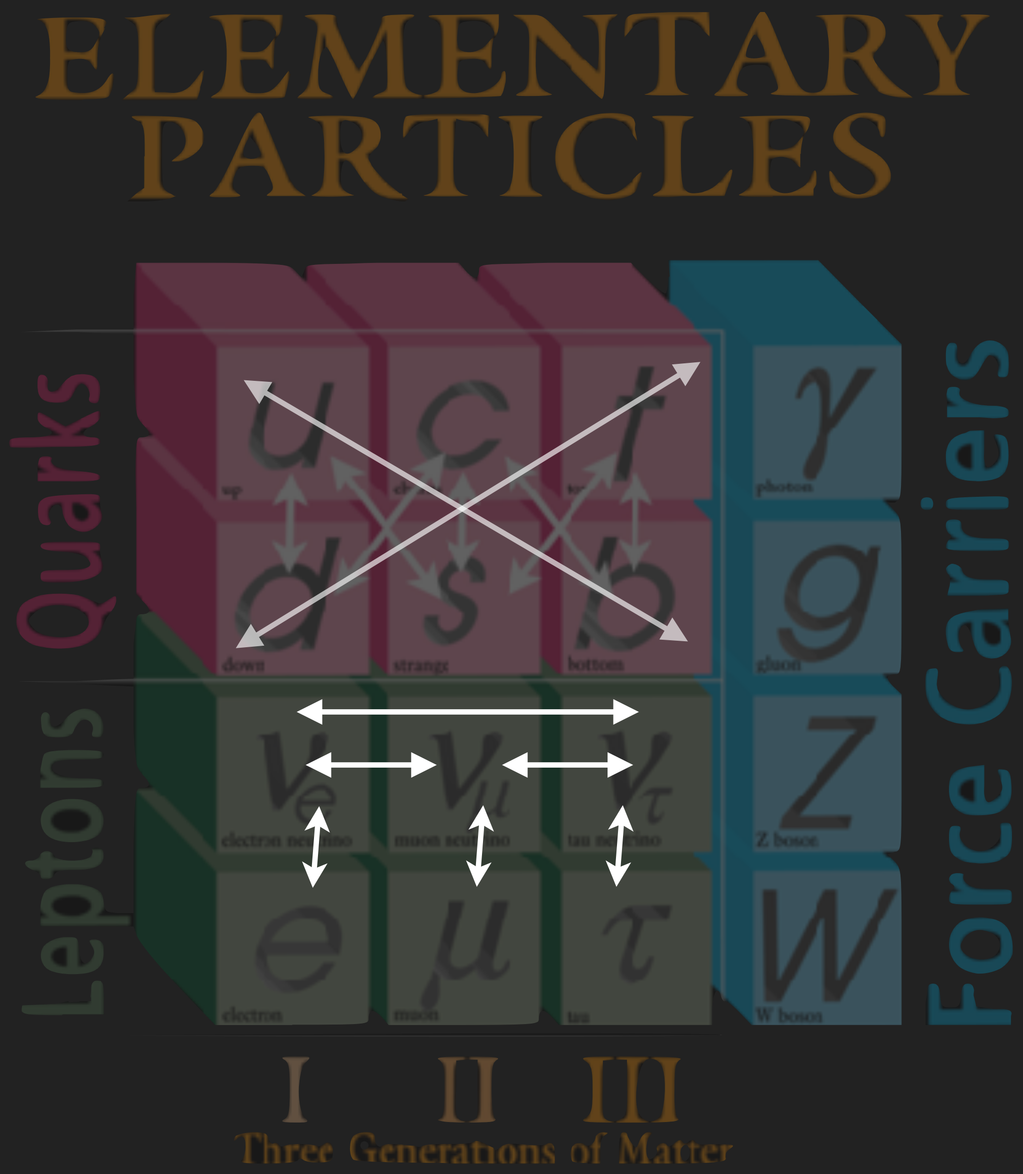
- The quarks commit Flavor Violation
  - They mix via the *W*
- The neutrinos can change into their partners (and vice versa)
- And the neutrinos also mix!



Jason Bono, jbono@fnal.gov

Flavor Violation in the SM

- The quarks commit Flavor Violation
  - They mix via the *W*
- The neutrinos can change into their partners (and vice versa)
- And the neutrinos also mix!

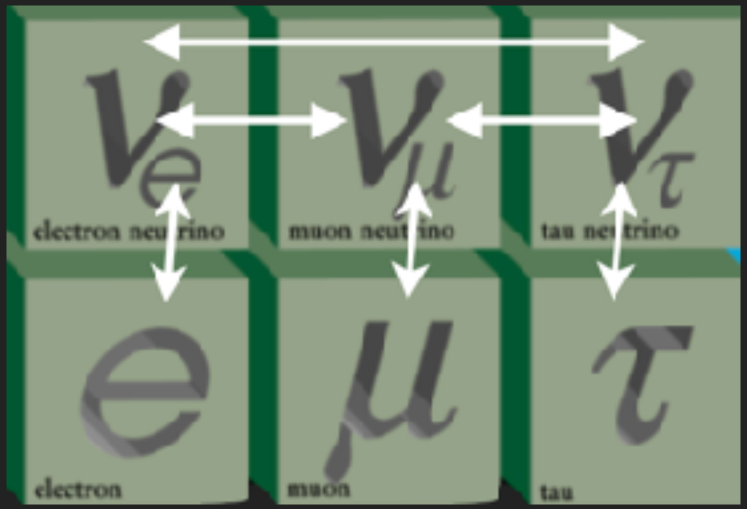


What's going on with the charged leptons?

Jason Bono, jbono@fnal.gov

CLFV in the Standard Model

- All CLFV processes are dynamically suppressed in the SM
  - it’s impossible to proceed through SM interactions without violating deeper conservation laws



But neutrino mixing implies an encouraging fact…

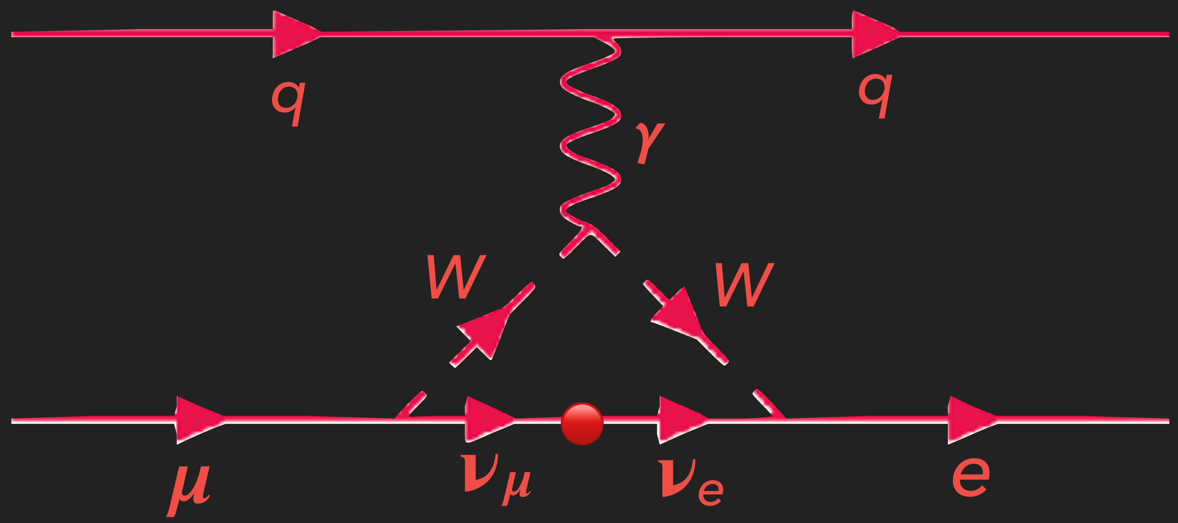
Jason Bono, jbono@fnal.gov

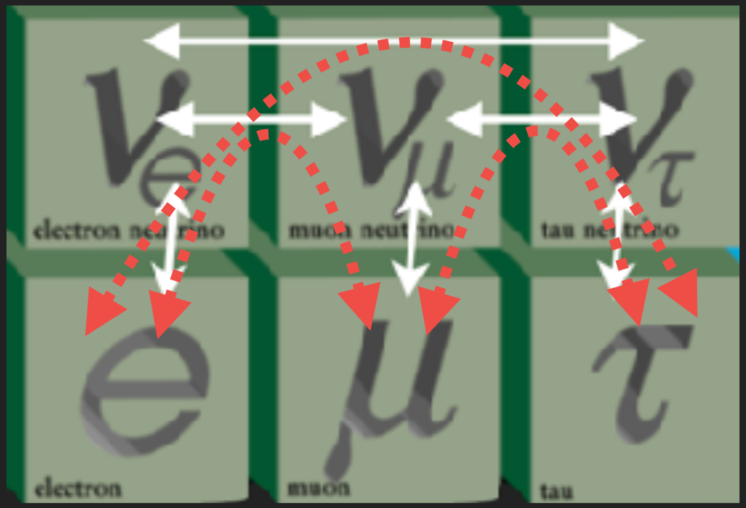
CLVF Must Occur

- Neutrino oscillations *require* CLFV on some level

e.g. $$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{il}}{M_W^2}\right|^2 \quad 10^{-54}$$

- But that level is tiny, because all SM CLFV processes involve loops with *W* and ***ν***



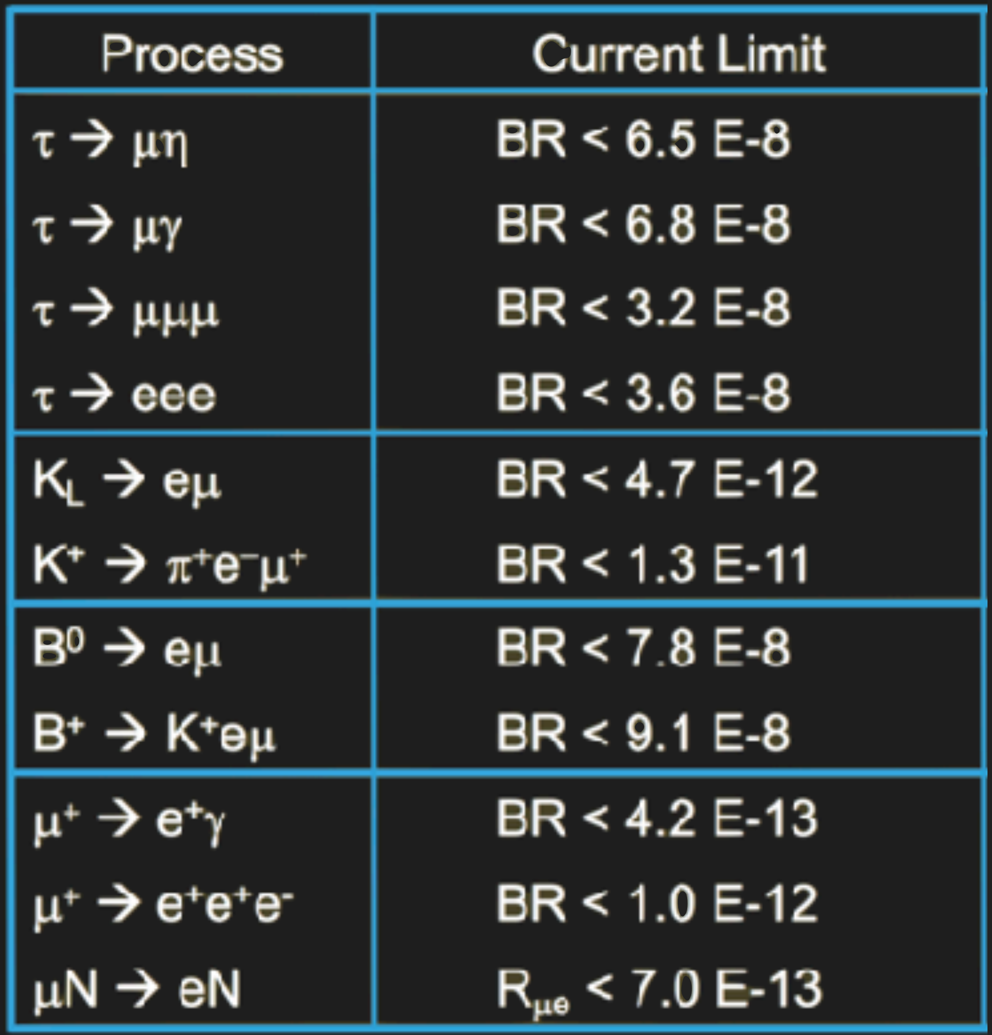


Charged lepton flavor is not an exact symmetry in our universe, so there's no formal reason for new phenomena to feature it.

Furthermore, if CLFV is observed, it's physics beyond the standard model, unequivocally

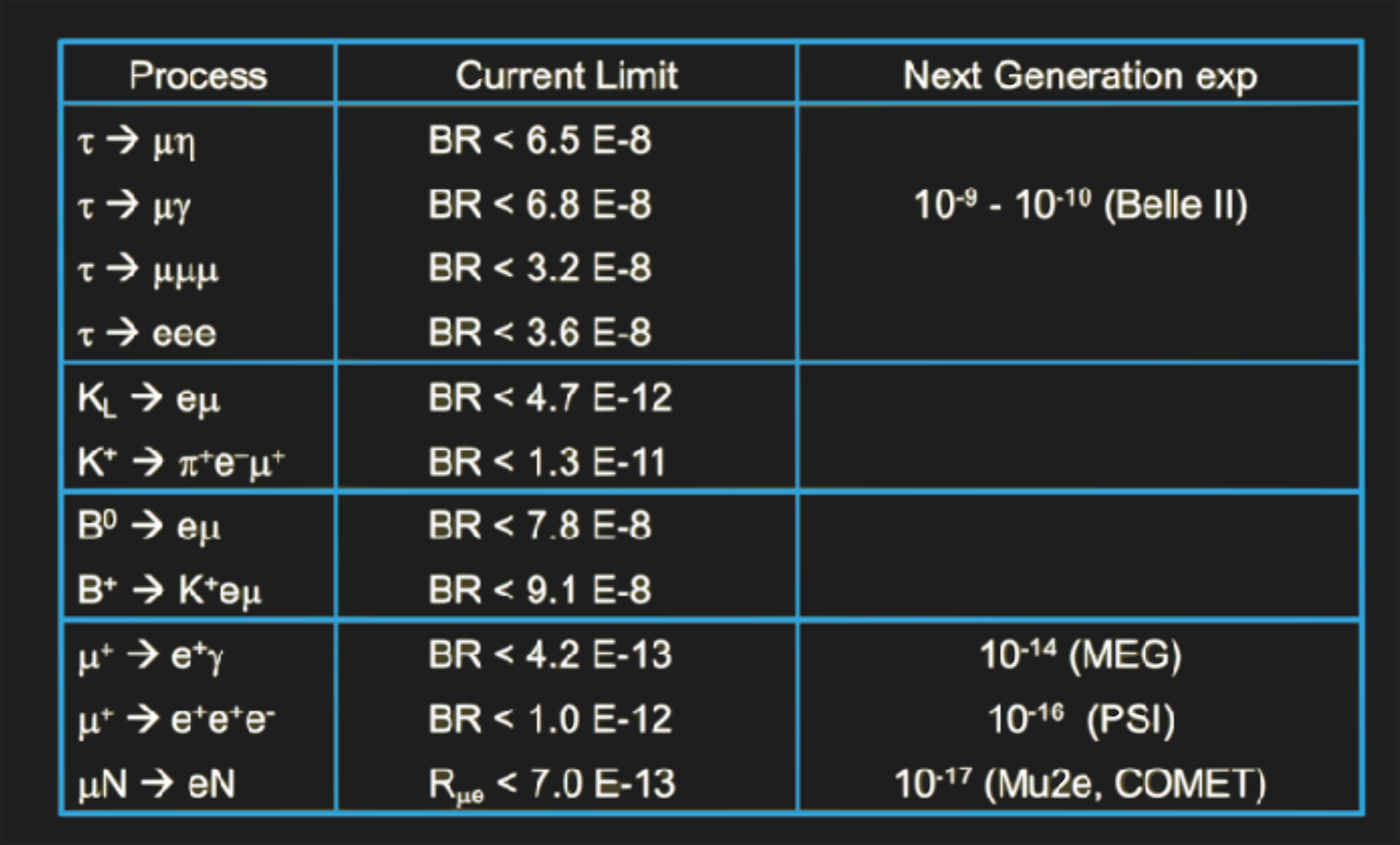
Jason Bono, jbono@fnal.gov

CLFV Searches



Process	Current Limit
$\tau \to \mu\eta$	BR < 6.5 E-8
$\tau \to \mu\gamma$	BR < 6.8 E-8
$\tau \to \mu\mu\mu$	BR < 3.2 E-8
$\tau \to eee$	BR < 3.6 E-8
$K_L \to e\mu$	BR < 4.7 E-12
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11
$B^0 \to e\mu$	BR < 7.8 E-8
$B^+ \to K^+ e\mu$	BR < 9.1 E-8
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13

CLFV Searches

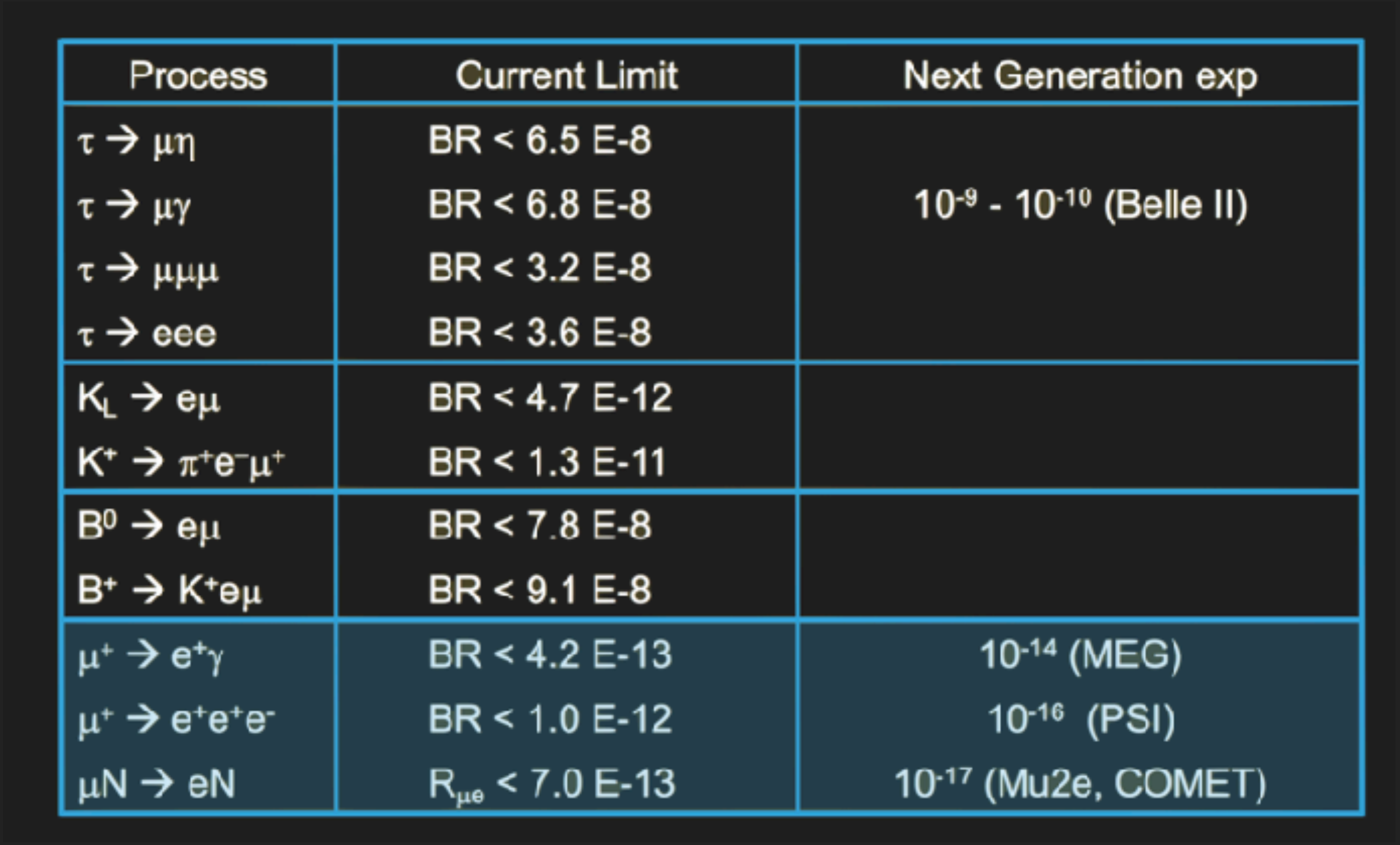


Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

Next generation experiments will bring us a ~1-4 orders of magnitude increase in sensitivity

Jason Bono, jbono@fnal.gov

CLFV Searches



Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

Muons, with their relative ease of production, long lifetime, large mass, and simple decay, offer the best combination of access to new physics and experimental sensitivity

Jason Bono, jbono@fnal.gov

Many Muon Searches Planned

$$\mu \rightarrow e\gamma$$

The oldest search

$$\mu N \rightarrow eN$$

μ*-e* conversion. Extremely sensitive searches to come!

$$\mu \rightarrow eee$$

Excellent complimentary to above

$$\mu^- N \rightarrow e^+ N(Z-2)$$

Lepton *number* *violation* can also be searched for by the ***μ****-e* conversion experiments!

$$\mu^- e^- \rightarrow e^- e^-$$

Likely won't be searched for until CLFV is observed
Limits come from ***μ***→eee

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

Muonium-antimuonium conversion. Best limit is from the 90s. Nothing new planned yet! (to my knowledge)

Jason Bono, jbono@fnal.gov

A Long History of CLFV Searches With Muons

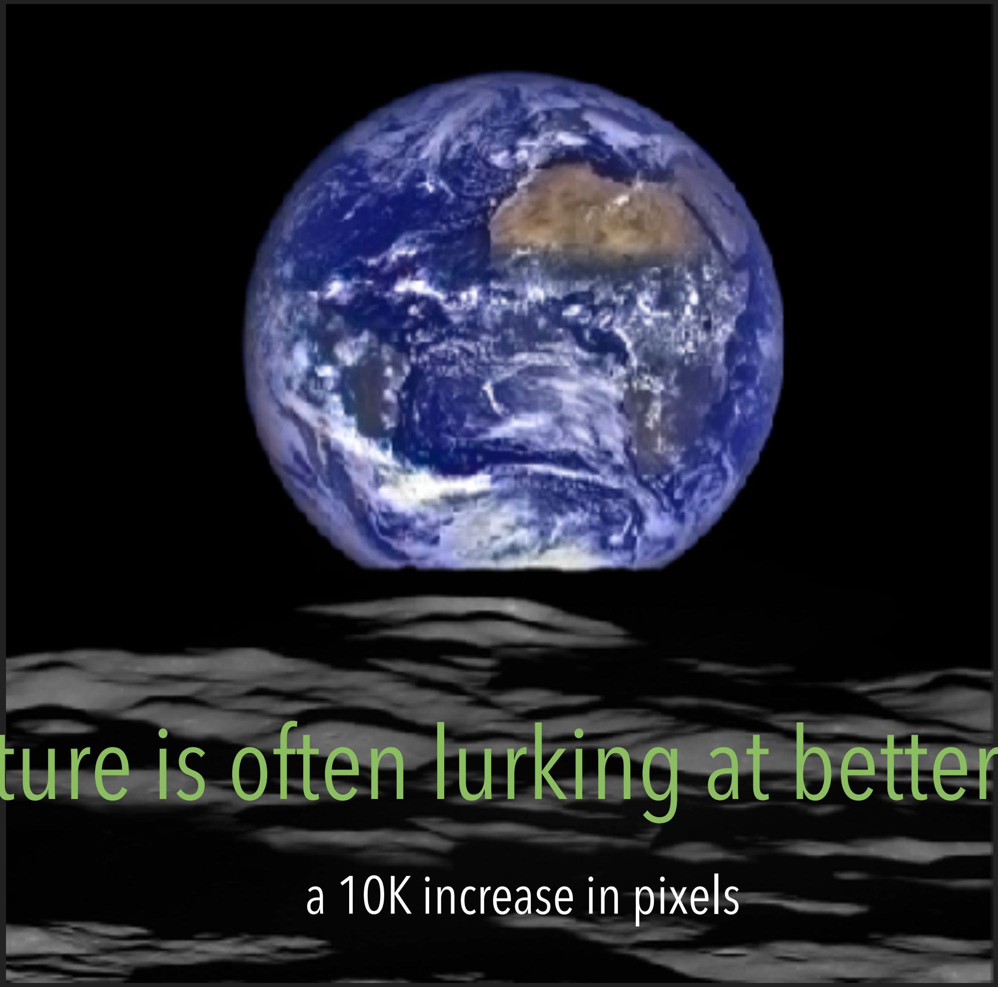
- Despite nearly eight decades of searching, it's never been observed

Why continue to search?

Thanks to Nina Hazen, NYC

A 10 to 10000 Fold Leap In Sensitivity

- Leading New Physics models predict CLFV rates to be within reach
- The next generation of rare muon decay searches, with their revolutionary sensitivity, will ultimately help guide future experimental and theoretical developments in HEP



Hidden structure is often lurking at better "resolution"

a 10K increase in pixels

A 10 to 10000 Fold Leap In Sensitivity

- Leading New Physics models predict CLFV rates to be within reach
- The next generation of rare muon decay searches, with their revolutionary sensitivity, will ultimately help guide future experimental and theoretical developments in HE

The Adventure of Silver Blaze

From Wikipedia, the free encyclopedia

For the 1937 film, see Silver Blaze (1937 film). For the 1977 film, see Silver Blaze (1977 film).

"**Silver Blaze**", one of the 56 Sherlock Holmes short stories written by British author Sir Arthur Conan Doyle, is c

ranked "Silver Blaze" 13th in a list of his 19 favourite Sherlock Holmes stories.[1]

One of the most popular Sherlock Holmes short stories, "Silver Blaze" focuses on the disappearance of the epor

on the apparent murder of its trainer. The tale is distinguished by its atmospheric Dartmoor setting and late-Victc

plotting, hinging on the "curious incident of the dog in the night-time:"

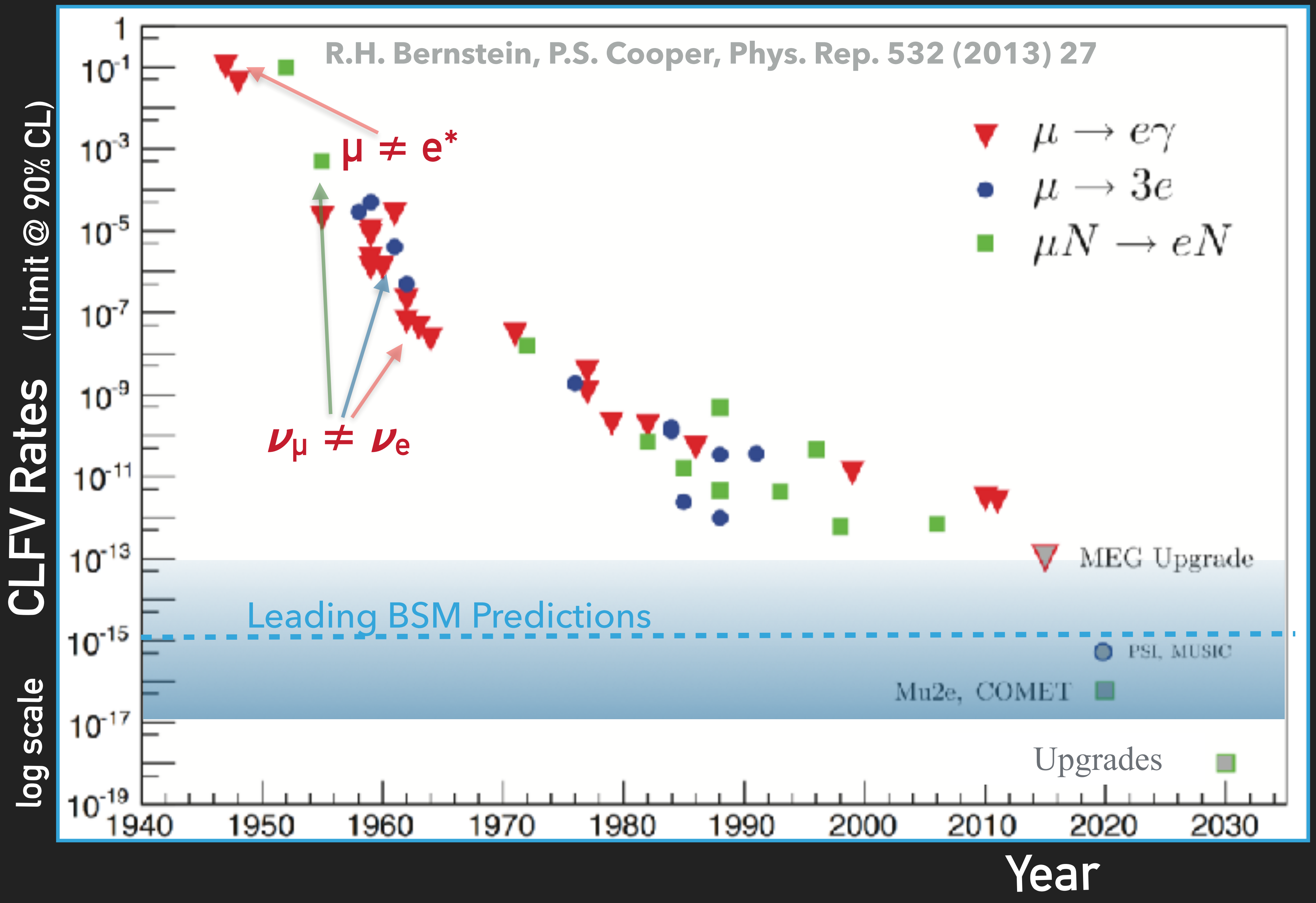
> Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"
> Holmes: "To the curious incident of the dog in the night-time."
> Gregory: "The dog did nothing in the night-time."
> Holmes: "That was the curious incident."[2]

Hidden structure is often lurking at better "resolution"

And if it isn't, that's also interesting!

Jason Bono, jbono@fnal.gov

A History of Searches for CLFV Muon Decays



R.H. Bernstein, P.S. Cooper, Phys. Rep. 532 (2013) 27

Breaking Through the Plateau… And Beyond the SM?

Jason Bono, jbono@fnal.gov

The Future of Muon CLFV Searches

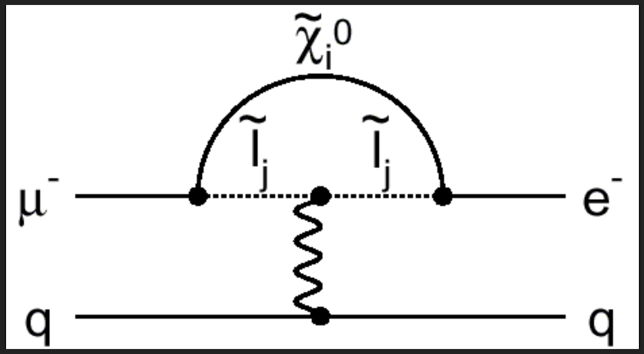
Breaking Through the Plateau… And Beyond the SM?

Jason Bono, jbono@fnal.gov

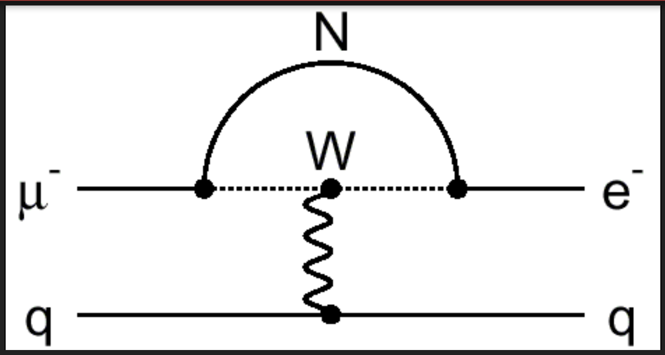
Effective CLFV Lagrangian: de Gouvea, A., and P. Vogel (2013)

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$

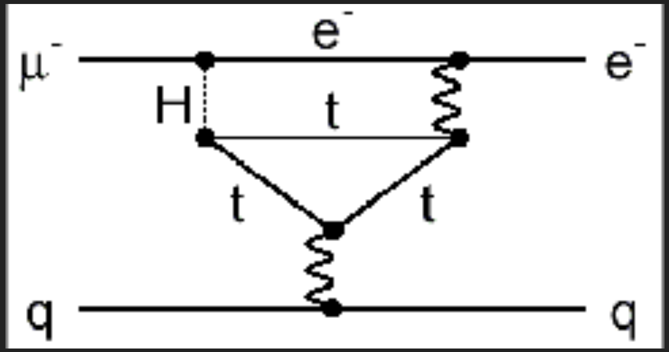
Magnetic moment type operator



Supersymmetry

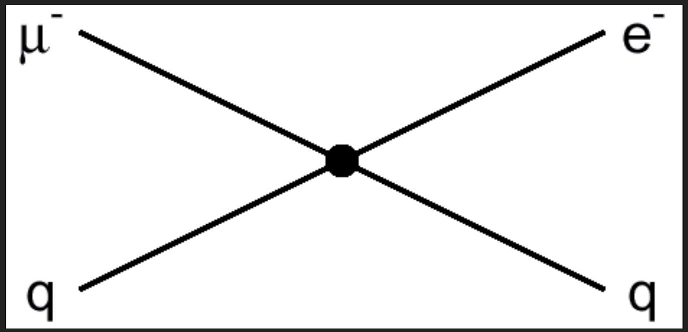


Heavy neutrinos

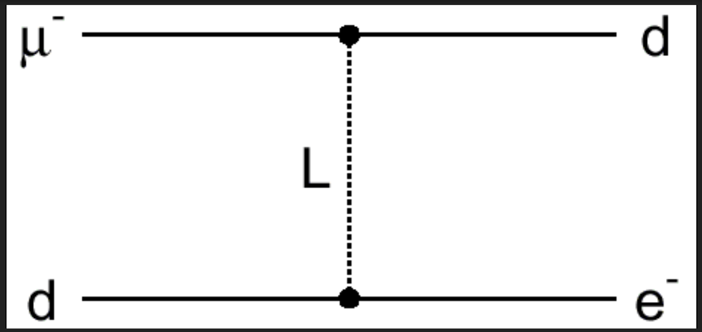


Two Higgs doublets

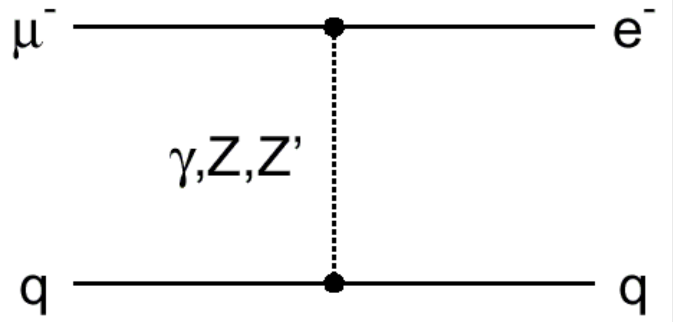
Contact term operator



Compositeness



Leptoquarks

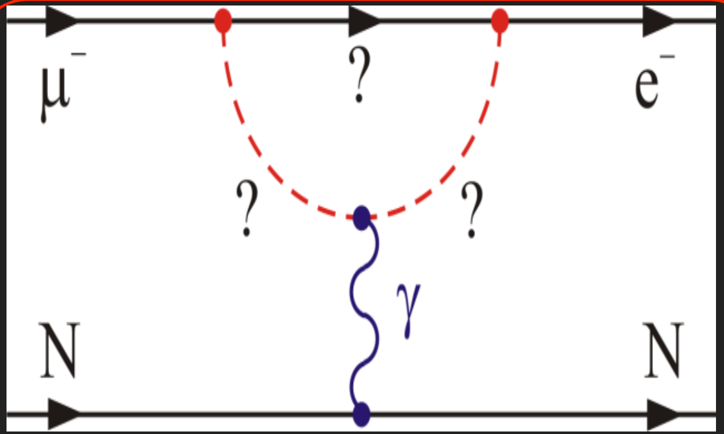


New heavy bosons / anomalous coupling

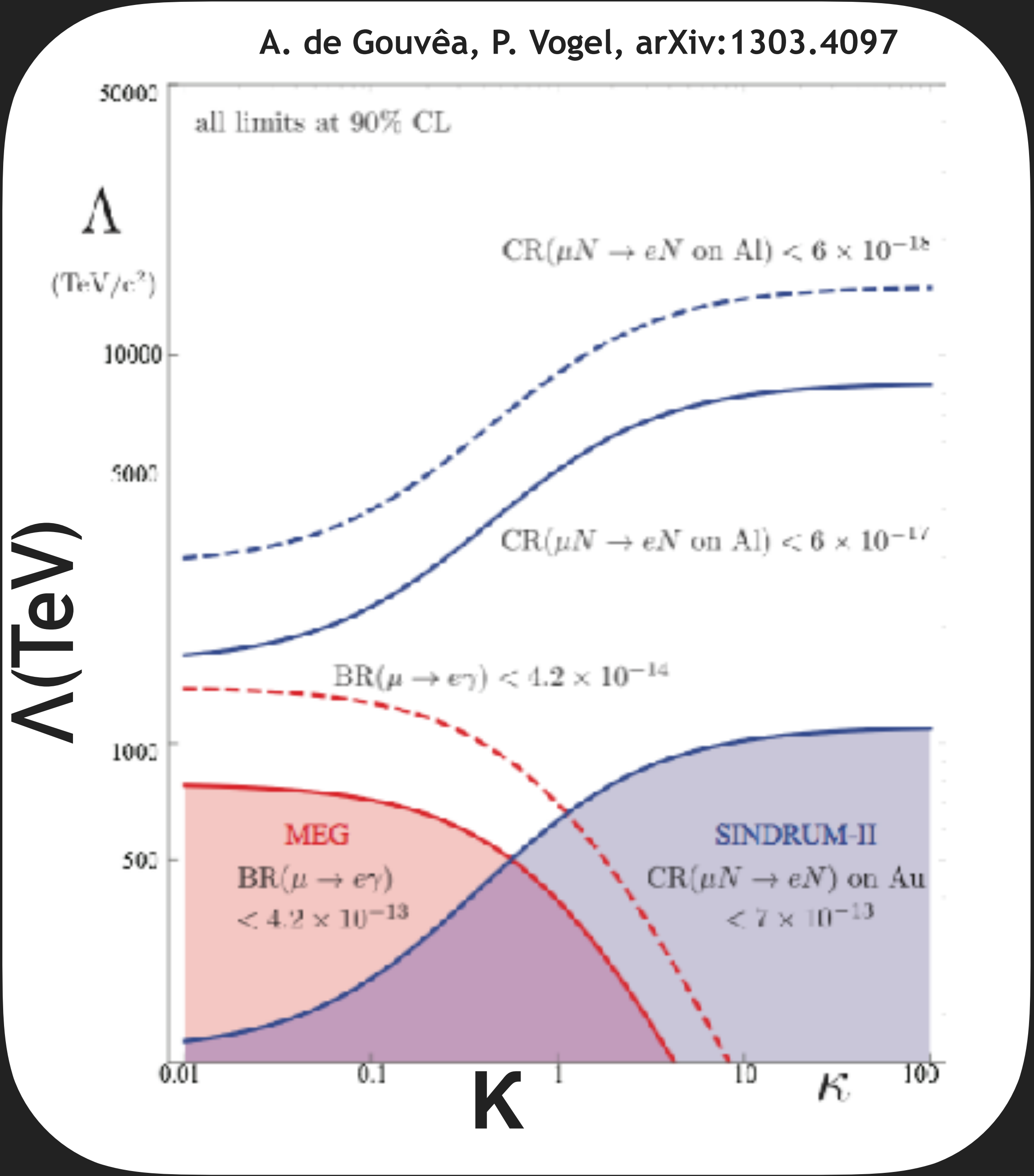
Jason Bono, jbono@fnal.gov

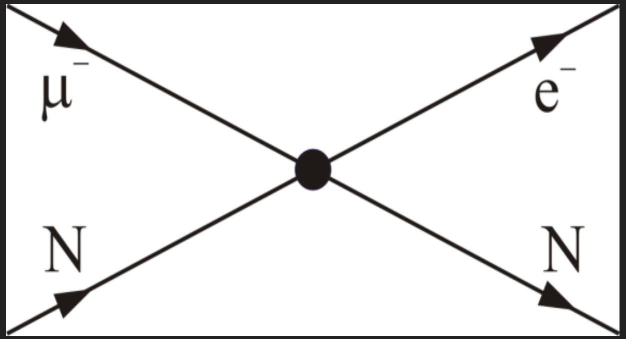
Effective CLFV Lagrangian: de Gouvea, A., and P. Vogel (2013)

$$\boldsymbol{L} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$



κ << 1


A. de Gouvêa, P. Vogel, arXiv:1303.4097



κ >> 1

Loop dominated

Contact dominated

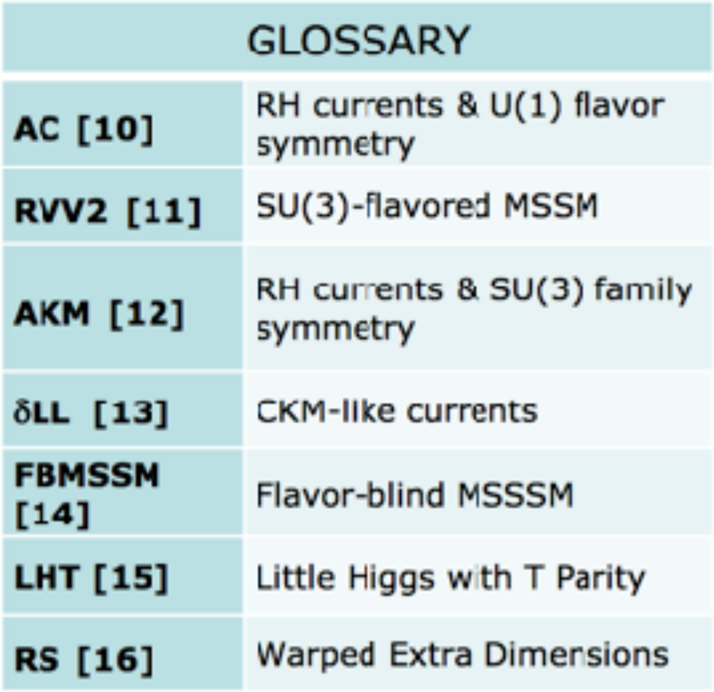
Jason Bono, jbono@fnal.gov

Observables and a Handful of New Physics Models

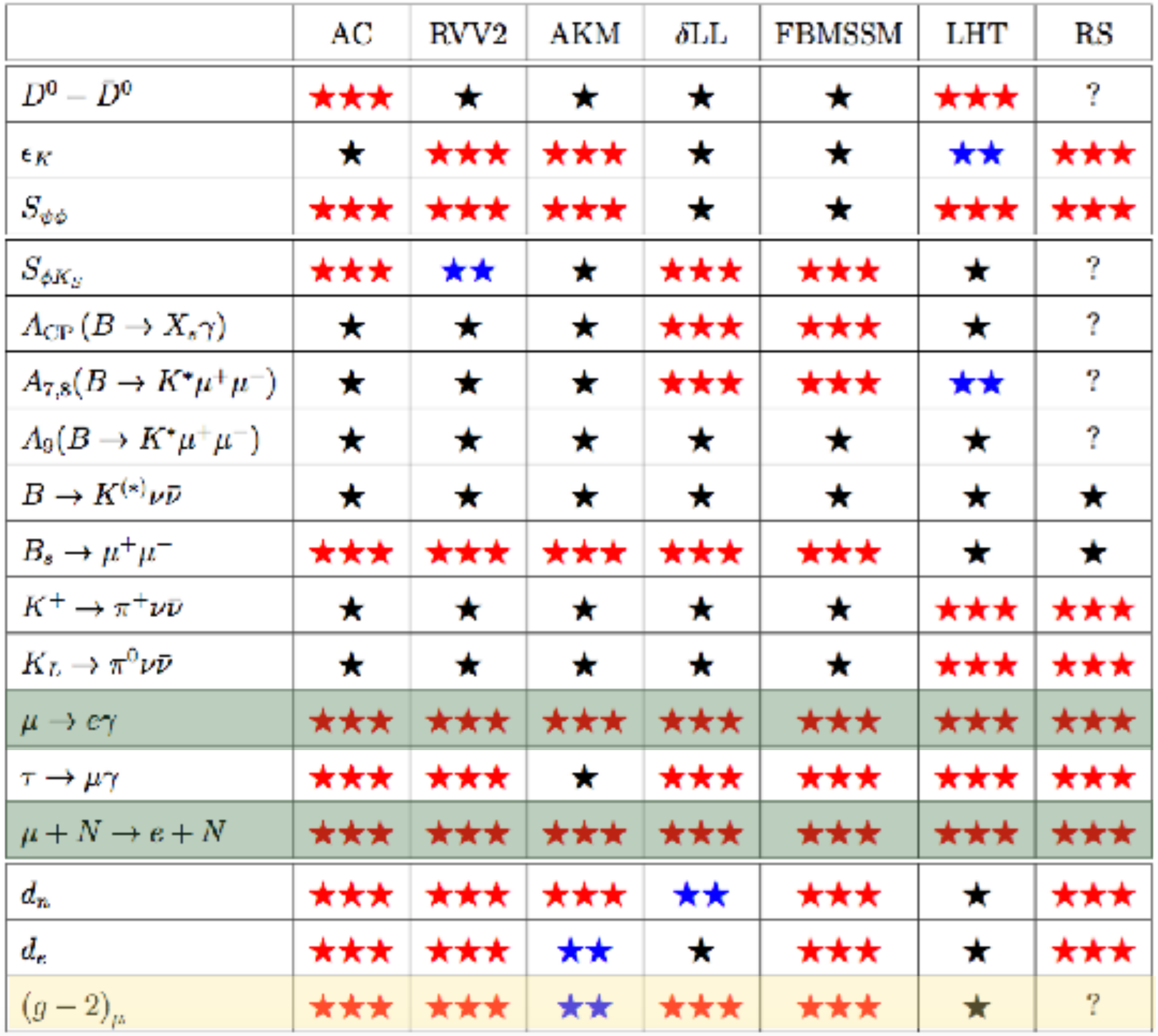
★ Vanishingly small effects

★★ Moderate, but visible effects

★★★ Large effects



GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions



	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Altmannshofer, Buras, *et al*, **Nucl.Phys.B830:17-94, 2010**

Jason Bono, jbono@fnal.gov

Observables and a Handful of New Physics Models

★ Vanishingly small effects

★★ Moderate, but visible effects

★★★ Large effects

GLOSSARY	
AC [10]	RH curre symmetr
RVV2 [11]	SU(3)-flav
AKM [12]	RH currents & symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parit
RS [16]	Warped Extra Dimensions

	AC	RVV2	[illegible]	[illegible]	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	[illegible]	[illegible]	[illegible]	★	★★★	?
ϵ_K	[illegible]	[illegible]	[illegible]	[illegible]	★	★★	★★★
$S_{\psi\phi}$	[illegible]	[illegible]	[illegible]	[illegible]	★	★★★	★★★
$S_{\phi K}$	[illegible]	[illegible]	[illegible]	[illegible]	★★★	★	?
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	★	?
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	★★	?
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	★	★	?
[illegible]	[illegible]	[illegible]	[illegible]	★	★	★	★
[illegible]	[illegible]	[illegible]	★★★	★★★	★★★	★	★
[illegible]	[illegible]	[illegible]	★	★	★	★★★	★★★
[illegible]	[illegible]	★	★	★	★	★★★	★★★
[illegible]	★★★	★★★	★★★	★★★	★★★	★★★	★★★
[illegible]	★★★	★★★	★	★★★	★★★	★★★	★★★
$\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Altmannshofer, Buras, *et al.* **Nucl.Phys.B830:17-94, 2010**

Check out the theory reviews:

Y. Kuno, Y. Okada, 2001

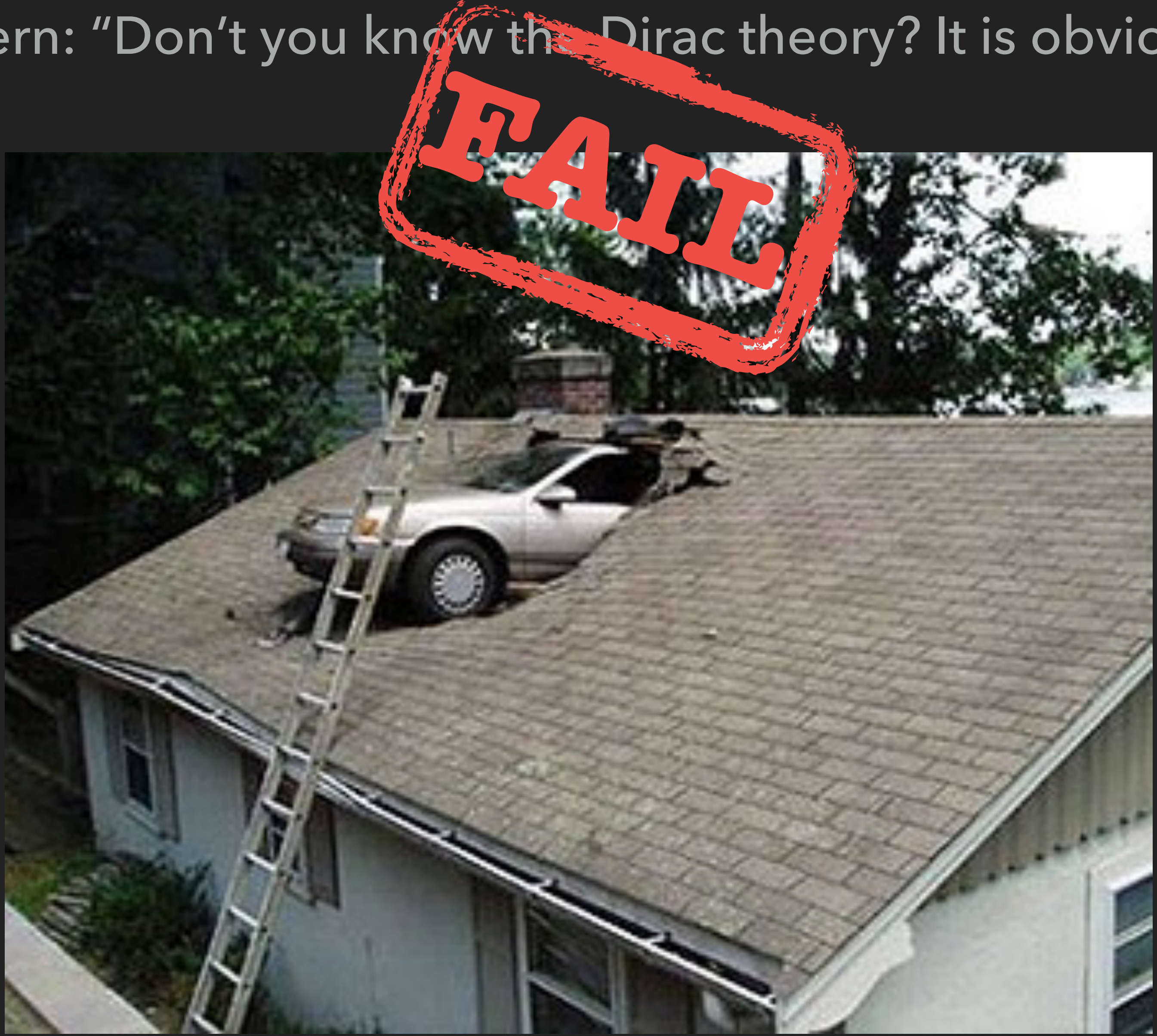
M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013

Jason Bono, jbono@fnal.gov

- Precision searches and measurements needn’t be theoretically motivated
  - Recall the discovery of the muon!
  - Or, Pauli to Stern: “Don’t you know the Dirac theory? It is obvious that g_p=2.”

- Precision searches and measurements needn't be theoretically motivated
  - Recall the discovery of the muon!
  - Or, Pauli to Stern: "Don't you know the Dirac theory? It is obvious that $g_p=2$."

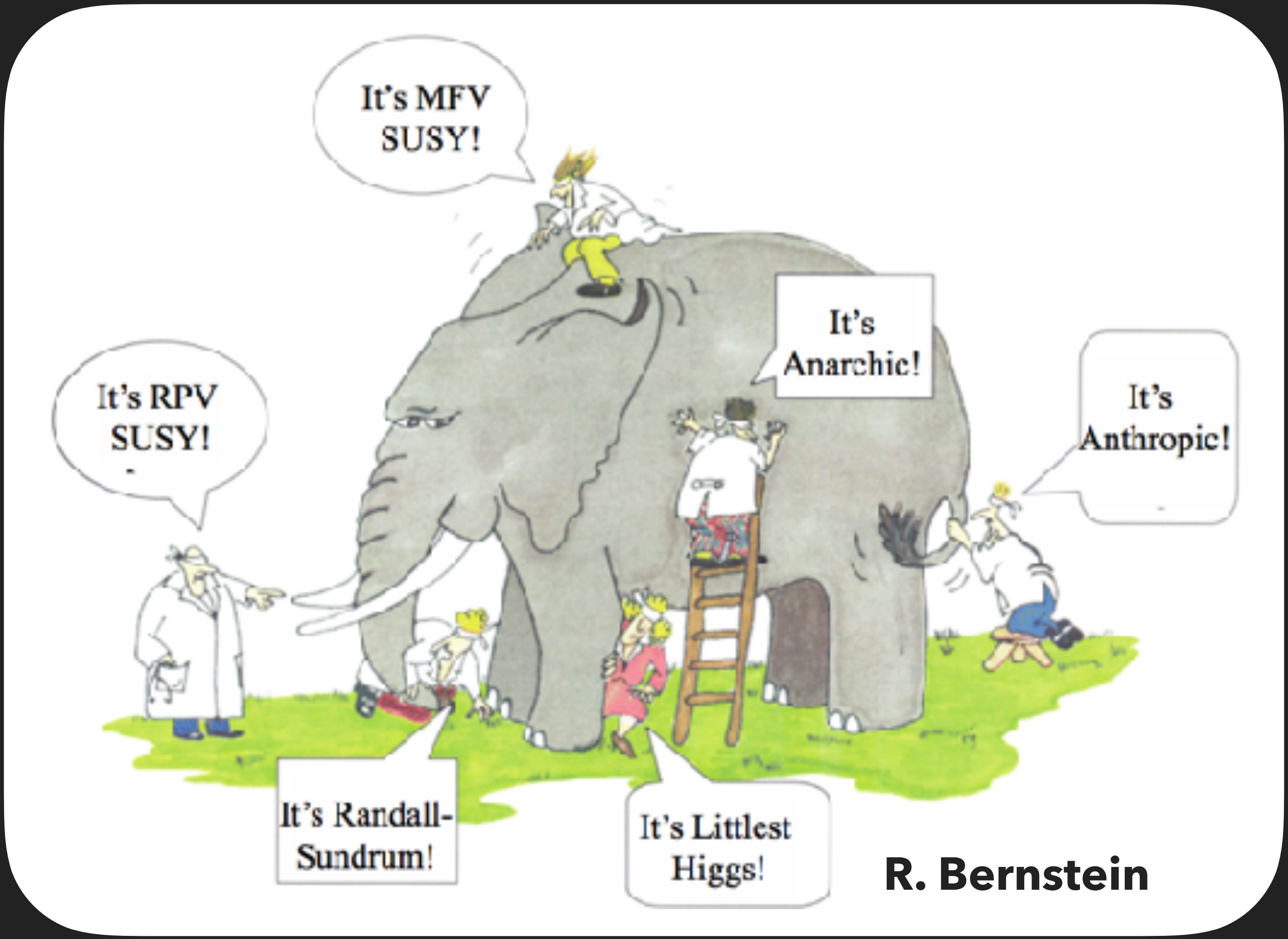


Luckily for Stern, he didn't listen

Jason Bono, jbono@fnal.gov

Complementarity

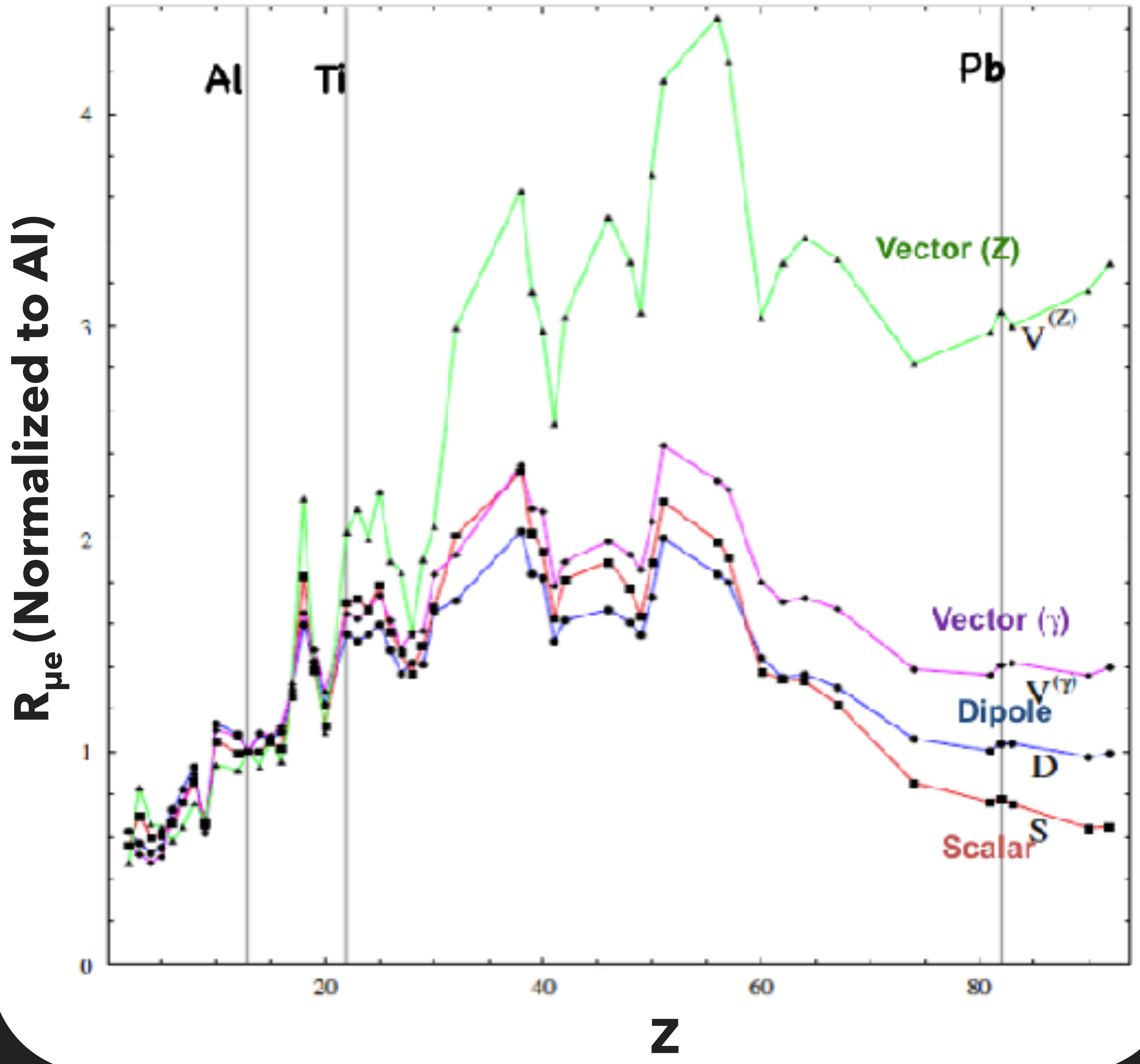
- If BSM physics is seen in CLFV searches or elsewhere, the complementarity between measurements will be crucial for discerning its nature



Conversion Experiments With Various Nuclei

- Can begin to distinguish models by changing target material

Cirigliano, V., R. Kitano, Y. Okada, and P. Tuzon (2009), Phys. Rev. D 80, 013002, arXiv:0904.0957 [hep-ph]



Jason Bono, jbono@fnal.gov

Results in the years to come!

Jason Bono, jbono@fnal.gov

Muons and The Great Pyramid of Giza

Muons and The Great Pyramid of Giza

published two weeks ago:

nature Accelerated Article Preview

LETTER

doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima, Mitsuaki Kuno, Akira Nishio, Nobuko Kitagawa, Yuta Manabe, Masaki Moto, Fumihiko Takasaki, Hirofumi Fujii, Kotaro Satoh, Hideyo Kodama, Kohei Hayashi, Shigeru Odaka, Sébastien Procureur, David Attié, Simon Bouteille, Denis Calvet, Christopher Filosa, Patrick Magnier, Irakli Mandjavidze, Marc Riallot, Benoit Marini, Pierre Gable, Yoshikatsu Date, Makiko Sugiura, Yasser Elshayeb, Tamer Elnady, Mustapha Ezzy, Emmanuel Guerriero, Vincent Steiger, Nicolas Serikoff, Jean-Baptiste Mouret, Bernard Charlès, Hany Helal and Mehdi Tayoubi

"We have been very surprised to discover something so big—a big anomaly"

Not quite the type of anomaly that we've been talking about, but that's ok!

The Great Pyramid of Giza

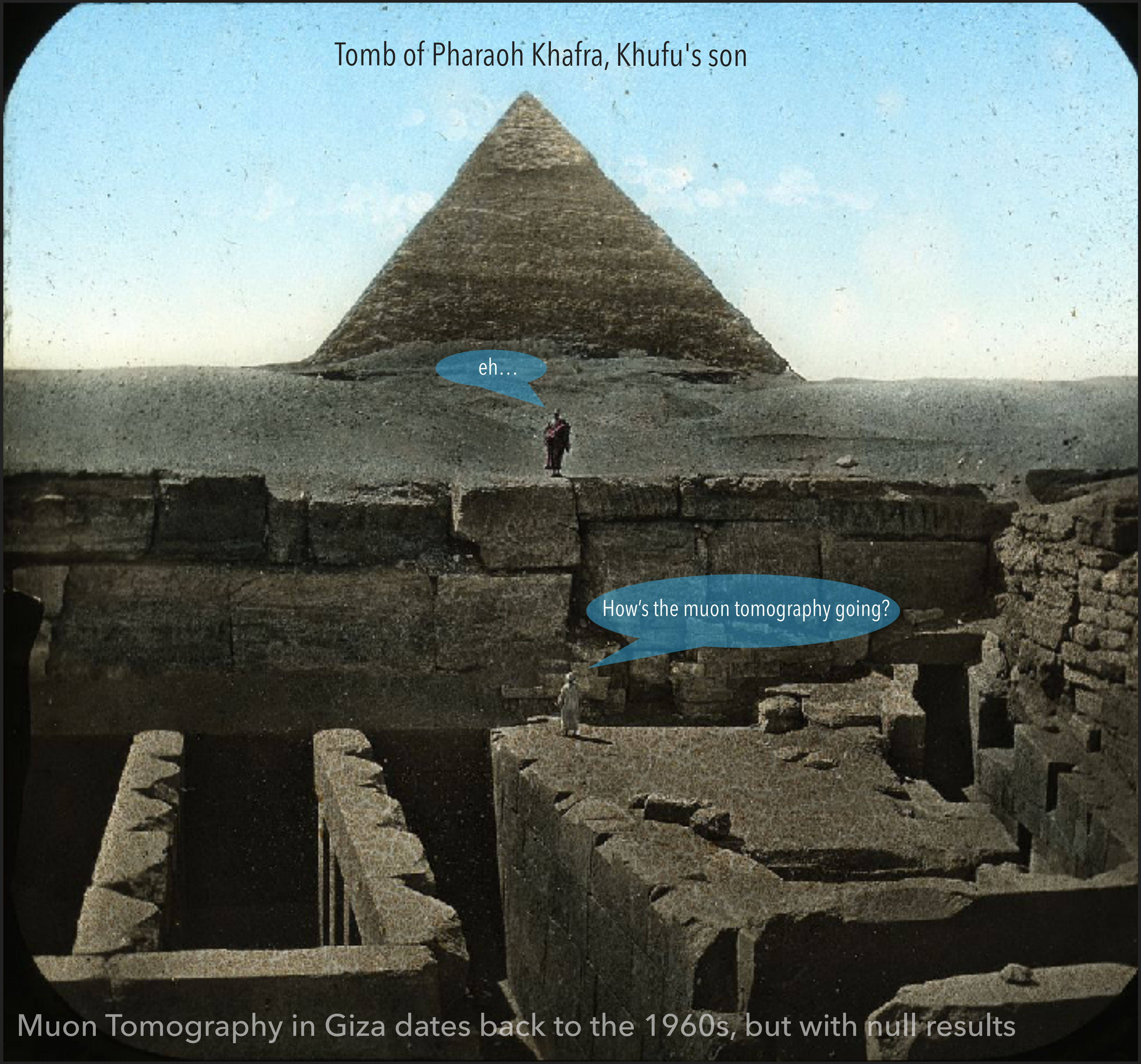
- The oldest of the six "pyramids of Giza"
  - Built more than 4.5 millennia ago, as a Mausoleum for the fourth dynasty Egyptian Pharaoh Khufu
- The oldest and only standing of the Seven Wonders of the Ancient World
- Was the world's tallest man-made structure for nearly four millennia (135x230 m)
  - The finishing of the pyramid marked the end of an "period of experimentation"
  - Subsequently, conventions of visual art became fixed, and architecture simplified
- Has a comparatively complex internal architecture
  - But the most complete account of construction is from Herodotus, two millennia later!

Jason Bono, jbono@fnal.gov

The Technique: Cosmic Ray Muon Tomography

- 10K cosmic muons per square meter per minute, at sea level
  - About 1% of pass though the Great Pyramid
  - Weeks or months of data collection
- Get muon flux and momentum angular distribution:
  - Three independent muon detection methods:
    - Nuclear emulsion films, argon based detectors, scintillating hodoscopes
- Obtain angular mass distribution from absorption and deflection
  - Radial component requires multiple detection locations
- Because it's passive, it's gaining use in a variety of applications
  - Volcanos -> imaging interior -> predict eruptions
  - Fukushima -> image the reactor core mass distribution -> safe dismantling
  - Non proliferation -> no artificial radiation dose on humans, nuclear warheads, or other sensitive materials -> easy to enforce -> slow the spread of nuclear weapons
  - And, of course, pyramids
    - Use in Giza dates back to the 1960s (*Science* **167** (3919), 832-839)

Muons and The Great Pyramid of Giza



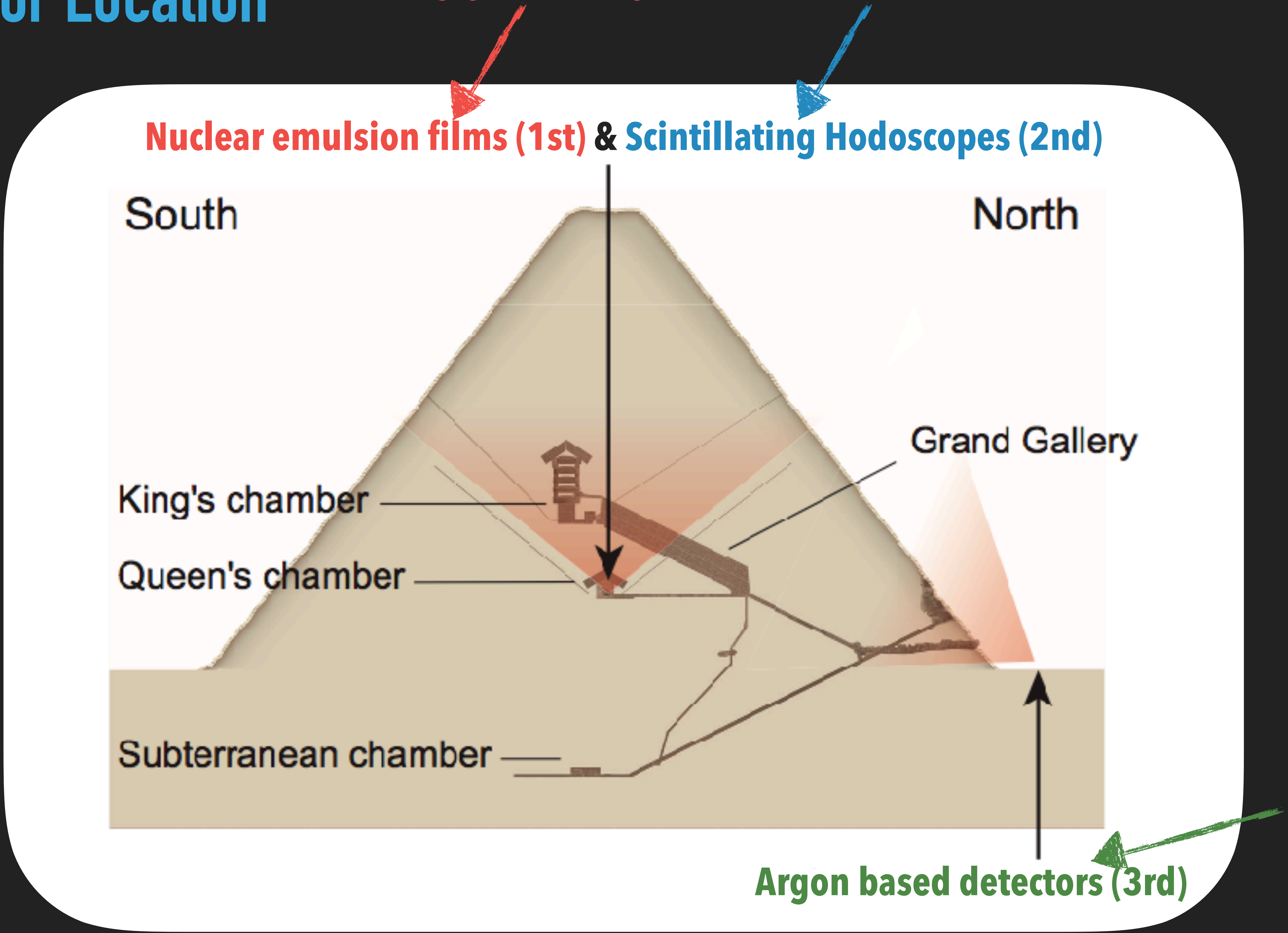
Muon Tomography in Giza dates back to the 1960s, but with null results

Jason Bono, jbono@fnal.gov

Detector Location

Nagoya University

KEK



Nuclear emulsion films (1st) & Scintillating Hodoscopes (2nd)

CEA

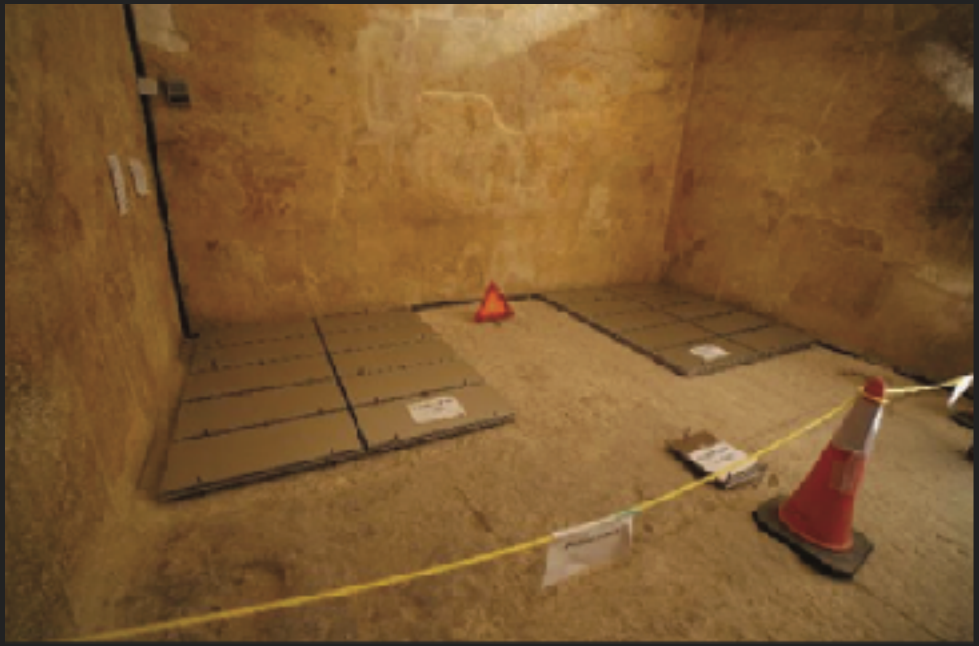
Argon based detectors (3rd)

Jason Bono, jbono@fnal.gov

Muons and The Great Pyramid of Giza

Nagoya University

Nuclear emulsion films in the Queen's chamber



- 8 m^2 of double sided 70 μm film
- 3D tracks: ~1 μm & 1.8 mrad
- 2 sets, 10 m separated horizontally for stereo imaging of detected structures

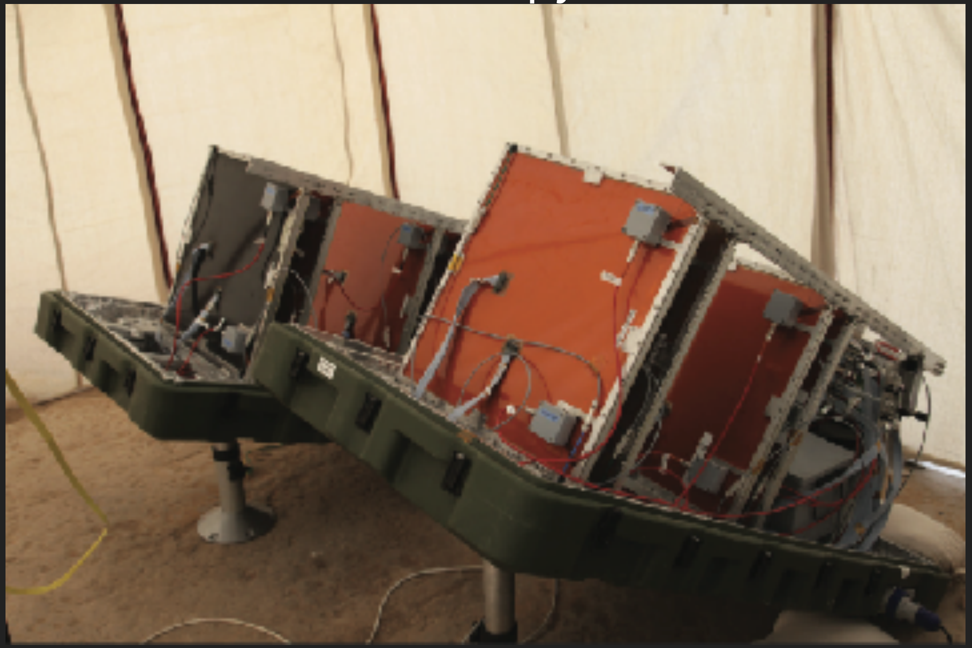
KEK

Scintillating hodoscopes in the Queen's chamber

- 4 scintillating layers in 2 orthogonal sets
- 120, 1 cm^2 bars in a layer
- 2 units separated vertically by 1m
  - trade off between angular acceptance and angular resolution

CEA

Argon based detectors outside the pyramid



- 4, 50x50 cm micro-pattern gas detectors
- require coincidence in 3 out of 4
- Gets solid angles of tracks
  - No mention of track resolution in paper
- No stereo imaging of structures

Jason Bono, jbono@fnal.gov

KEK
Scintillating hodoscopes in the
Queen's chamber

Nagoya University
Nuclear emulsion films in the
Queen's chamber

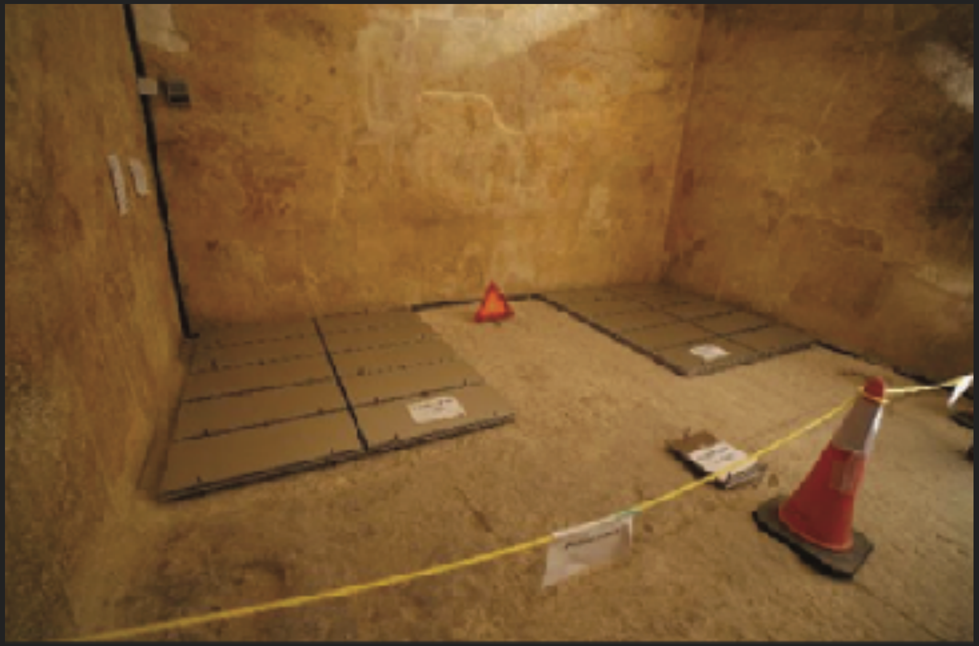
CEA
Argon based detectors
outside the pyramid

Subtract Monte Carlo simulations, using the pyramid's known internal structure (~1 cm resolution), from data collected since 2015

Jason Bono, jbono@fnal.gov

Nagoya University

Nuclear emulsion films in the Queen's chamber



Found an excess coming from above the grand gallery

~8 m high × 30 m long × 1-2 m wide

KEK

Scintillating hodoscopes in the Queen's chamber

CEA

Argon based detectors outside the pyramid

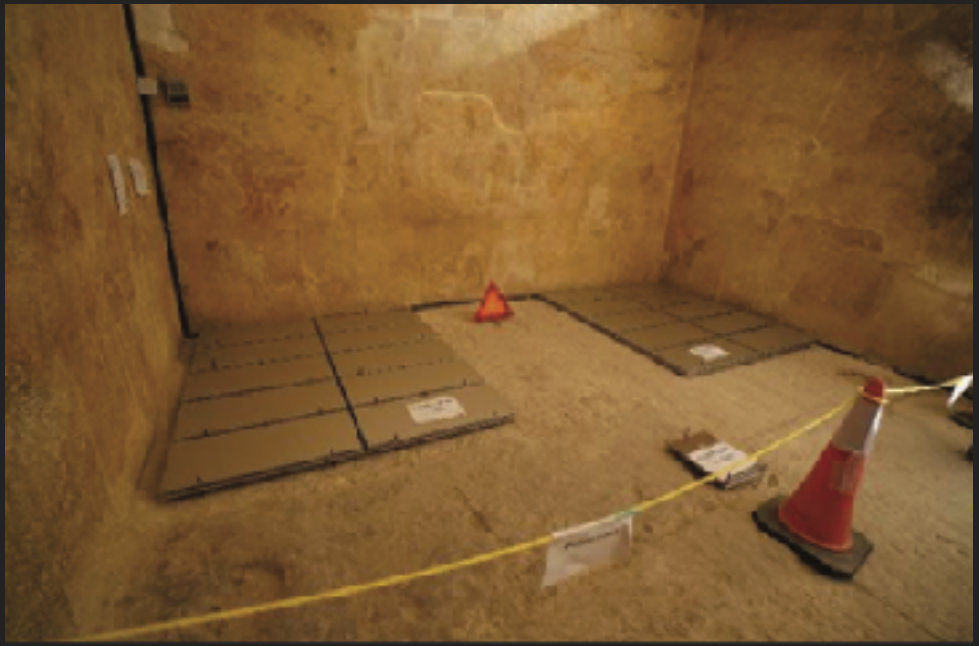
Jason Bono, jbono@fnal.gov

KEK

Scintillating hodoscopes in the Queen's chamber

Nagoya University

Nuclear emulsion films in the Queen's chamber



CEA

Argon based detectors outside the pyramid

Found an excess coming from above the grand gallery

~8 m high × 30 m long × 1-2 m wide

Saw a similar excess

Jason Bono, jbono@fnal.gov

KEK

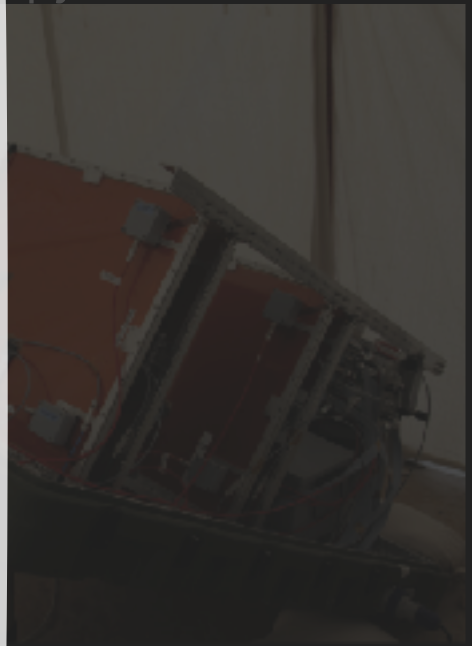
Scintillating hodoscopes in the Queen's chamber

Nagoya University

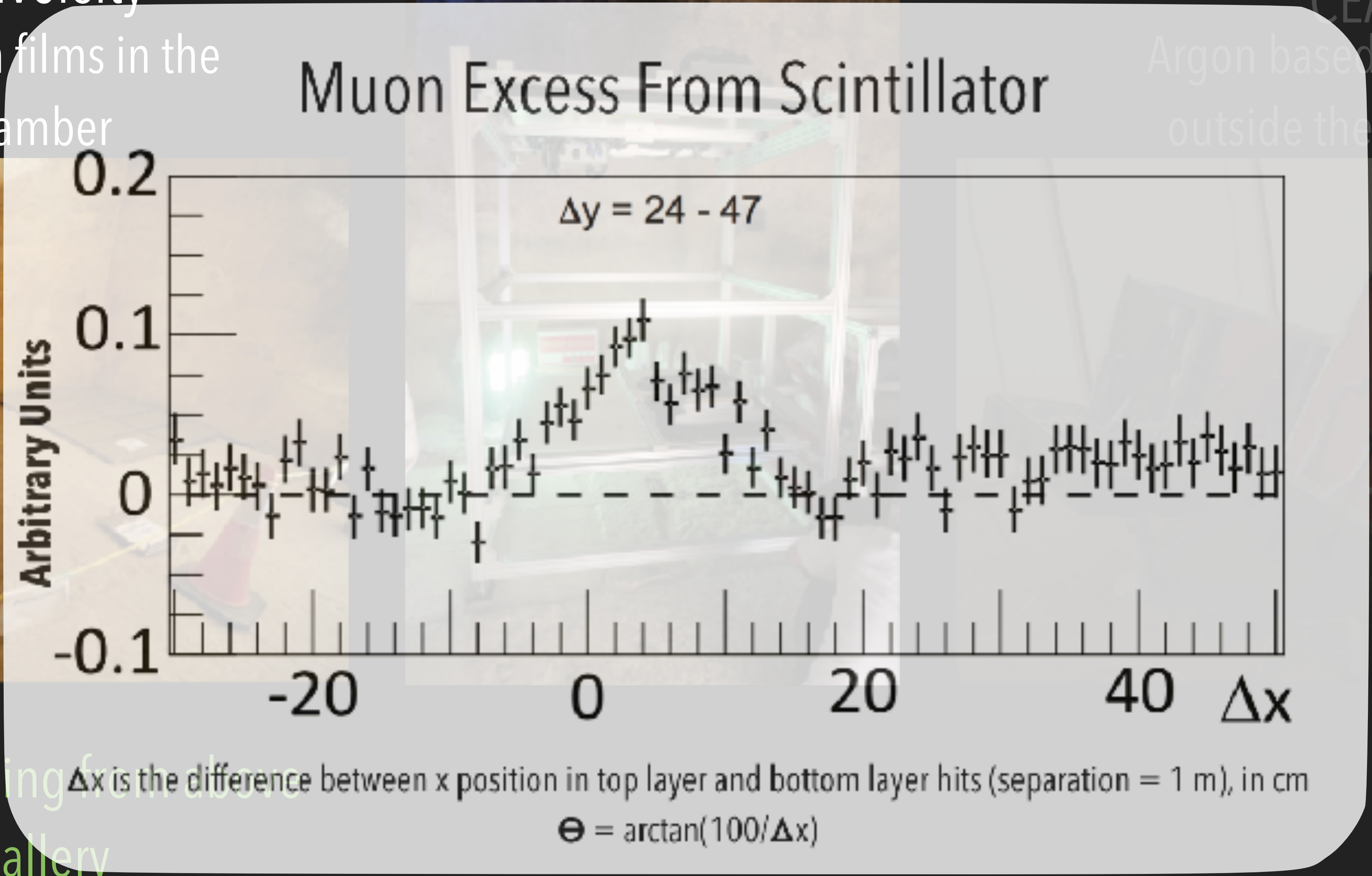
Nuclear emulsion films in the Queen's chamber

CEA

Argon based detectors outside the pyramid



Muon Excess From Scintillator



Δx is the difference between x position in top layer and bottom layer hits (separation = 1 m), in cm

ϴ = arctan(100/Δx)

Found an excess coming from above the grand gallery

~8 m high × 30 m long × 1-2 m wide

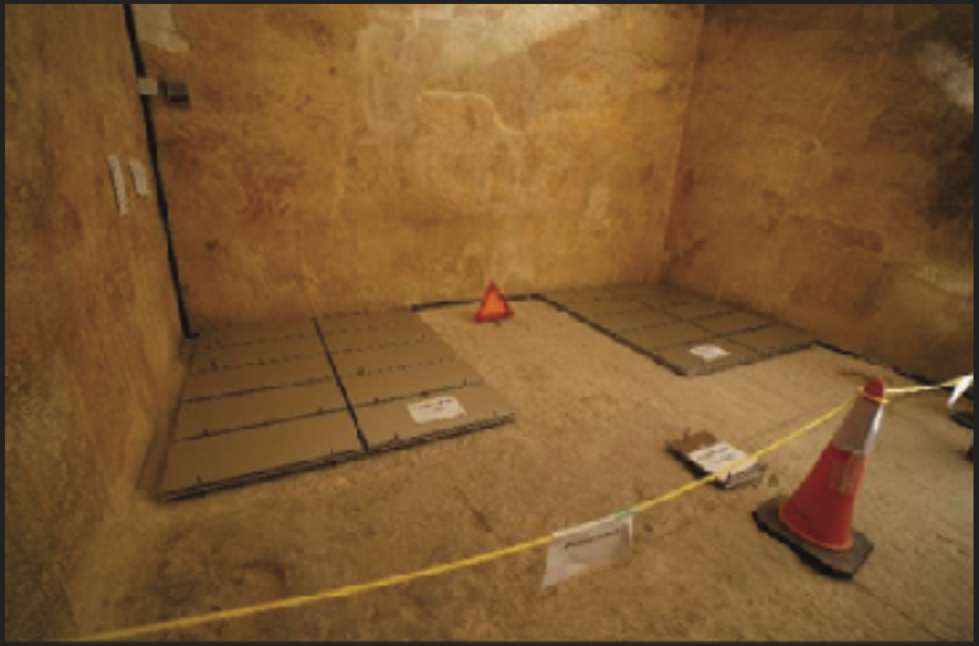
Saw a similar excess

Jason Bono, jbono@fnal.gov

Muons and The Great Pyramid of Giza

Nagoya University

Nuclear emulsion films in the Queen's chamber



Found an excess coming from above the grand gallery

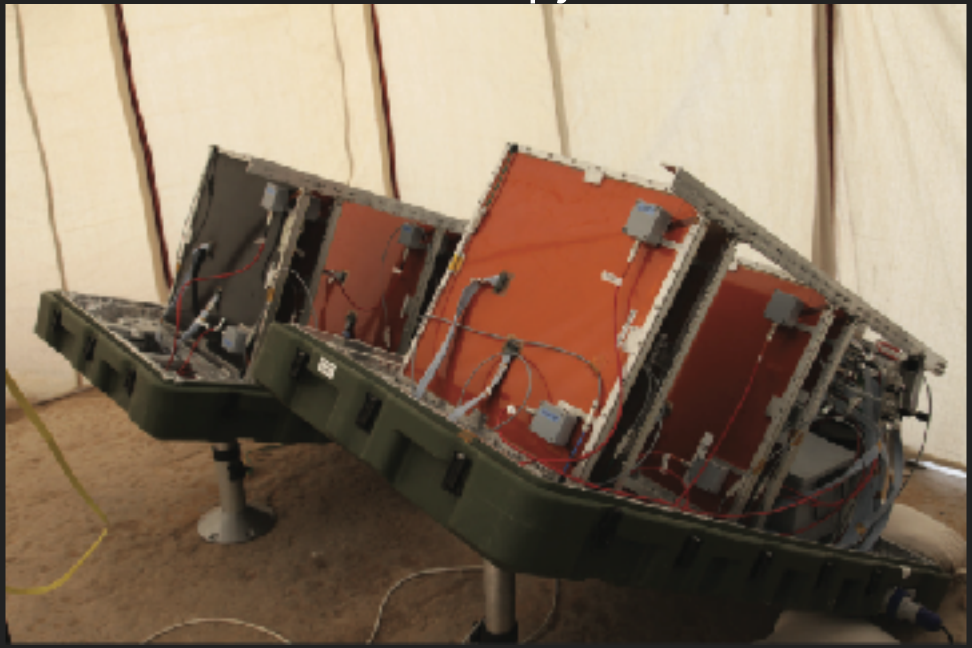
KEK

Scintillating hodoscopes in the Queen's chamber

Saw a similar excess

CEA

Argon based detectors outside the pyramid

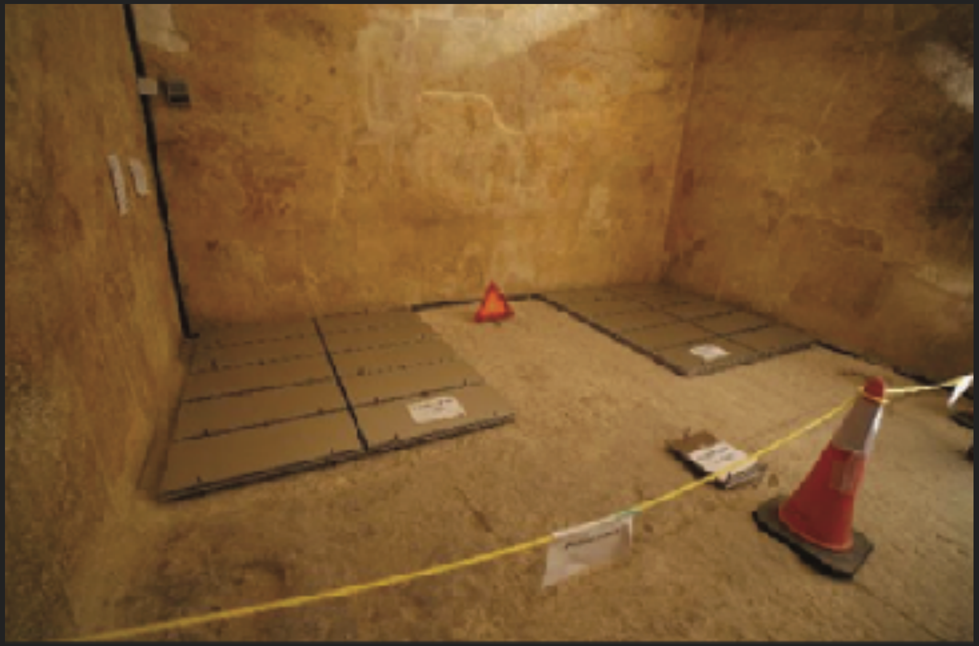


Saw the same excess, projected onto a different plane

Jason Bono, jbono@fnal.gov

Nagoya University

Nuclear emulsion films in the Queen's chamber



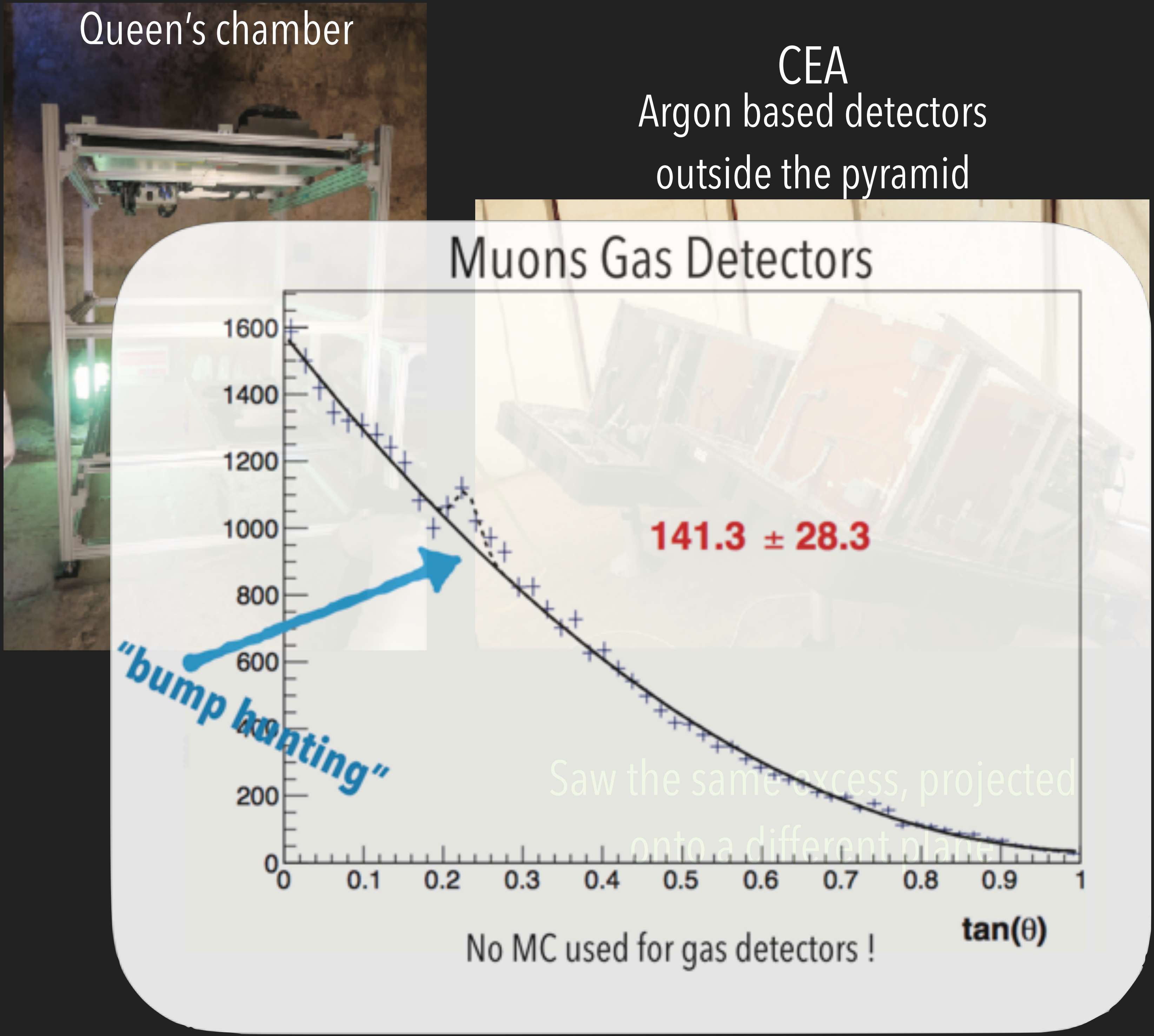
Found an excess coming from above the grand gallery

KEK

Scintillating hodoscopes in the Queen's chamber

CEA

Argon based detectors outside the pyramid



Saw the same excess, projected onto a different plane

No MC used for gas detectors !

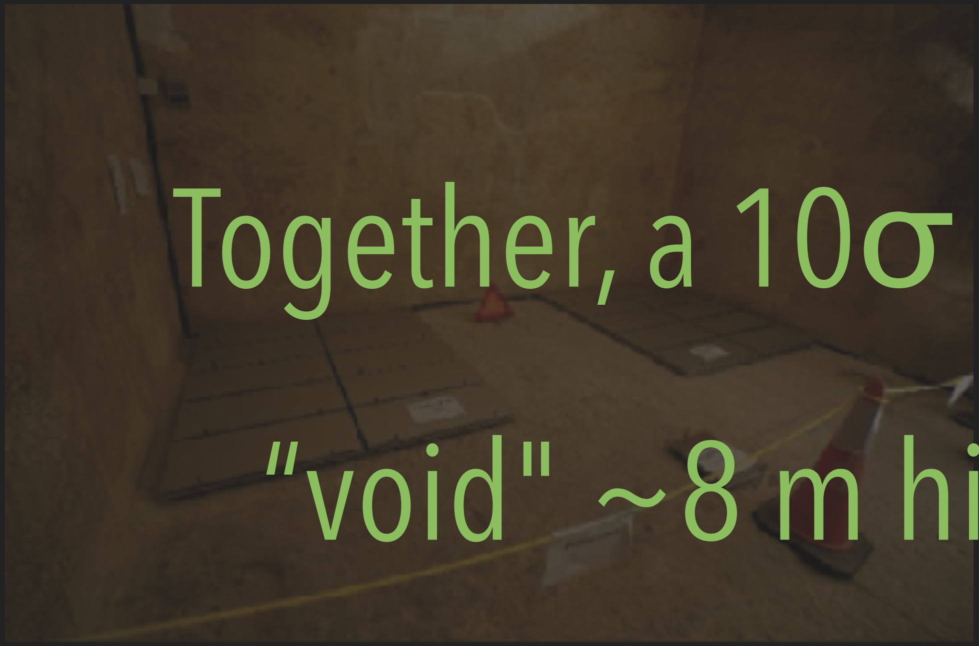
Saw a similar excess

Jason Bono, jbono@fnal.gov

Muons and The Great Pyramid of Giza

Nagoya University

Nuclear emulsion films in the Queen’s chamber



Found an excess coming from above the grand gallery

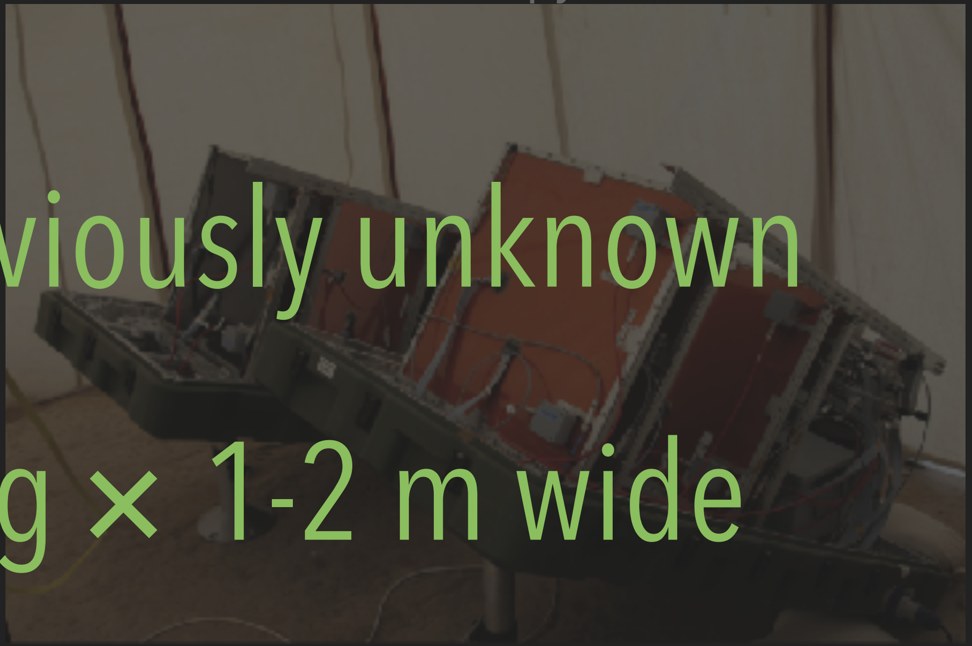
KEK

Scintillating hodoscopes in the Queen’s chamber

Saw a similar excess

CEA

Argon based detectors outside the pyramid



Saw a similar excess, projected onto a different plane

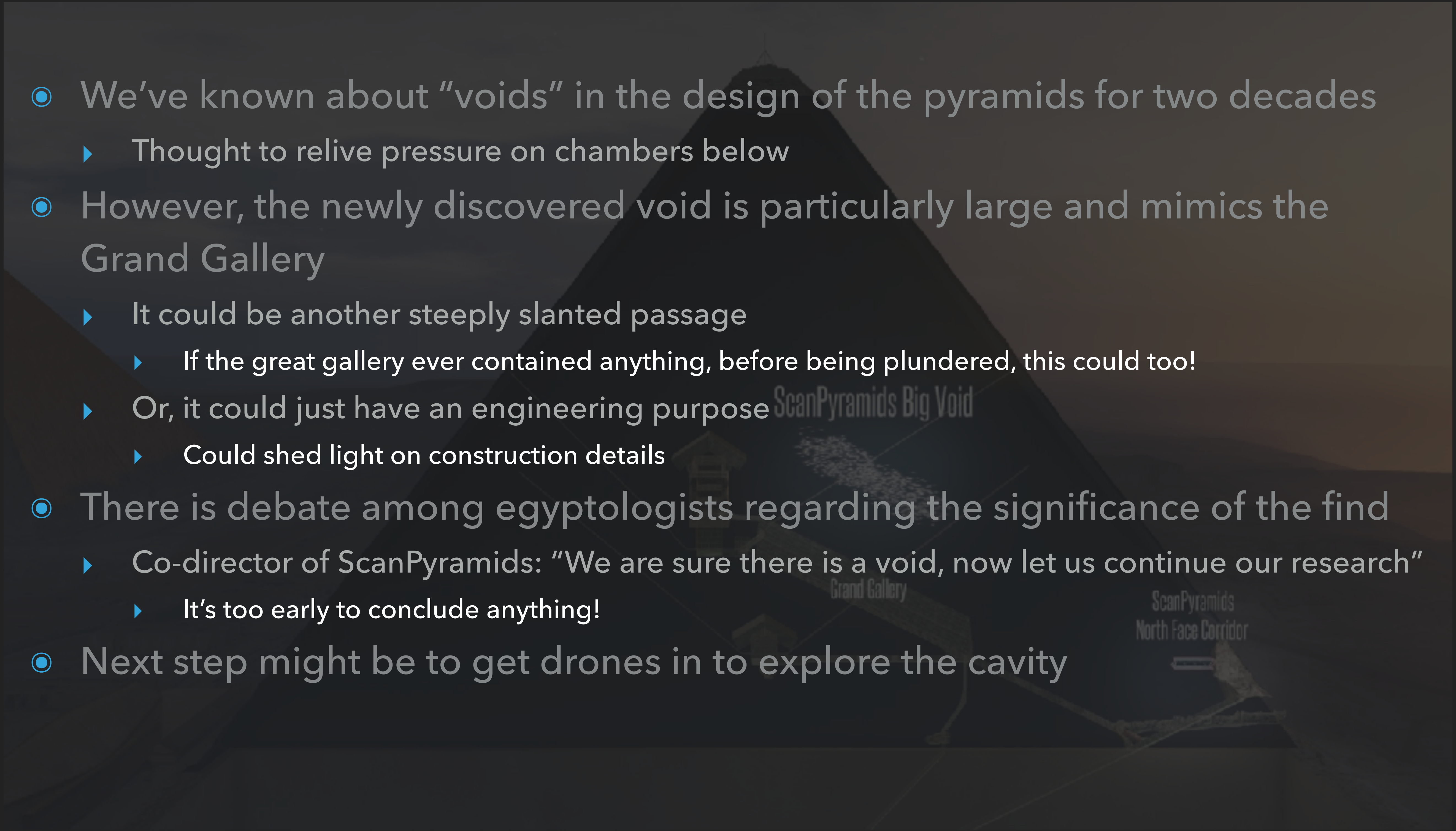
Together, a 10σ signal for a previously unknown “void" ~8 m high × 30 m long × 1-2 m wide

Jason Bono, jbono@fnal.gov

Muons and The Great Pyramid of Giza

Jason Bono, jbono@fnal.gov

The Archeological Significance



- We’ve known about “voids” in the design of the pyramids for two decades
  - Thought to relive pressure on chambers below
- However, the newly discovered void is particularly large and mimics the Grand Gallery
  - It could be another steeply slanted passage
    - If the great gallery ever contained anything, before being plundered, this could too!
  - Or, it could just have an engineering purpose
    - Could shed light on construction details
- There is debate among egyptologists regarding the significance of the find
  - Co-director of ScanPyramids: “We are sure there is a void, now let us continue our research”
    - It’s too early to conclude anything!
- Next step might be to get drones in to explore the cavity

Jason Bono, jbono@fnal.gov

Muons

- ~~A few nice properties~~
- ~~A historical perspective~~
- ~~Anomalies and Future Investigations~~
    - ~~The Proton Radius Puzzle~~
    - ~~The Muon anomalous magnetic moment~~
    - ~~Hints of Lepton Flavor Non-Universality in B decays~~
    - ~~Searches for Charged Lepton Flavor Violation~~
    - ~~Extra: Muons and The Great Pyramid of Giza~~

Thank you!