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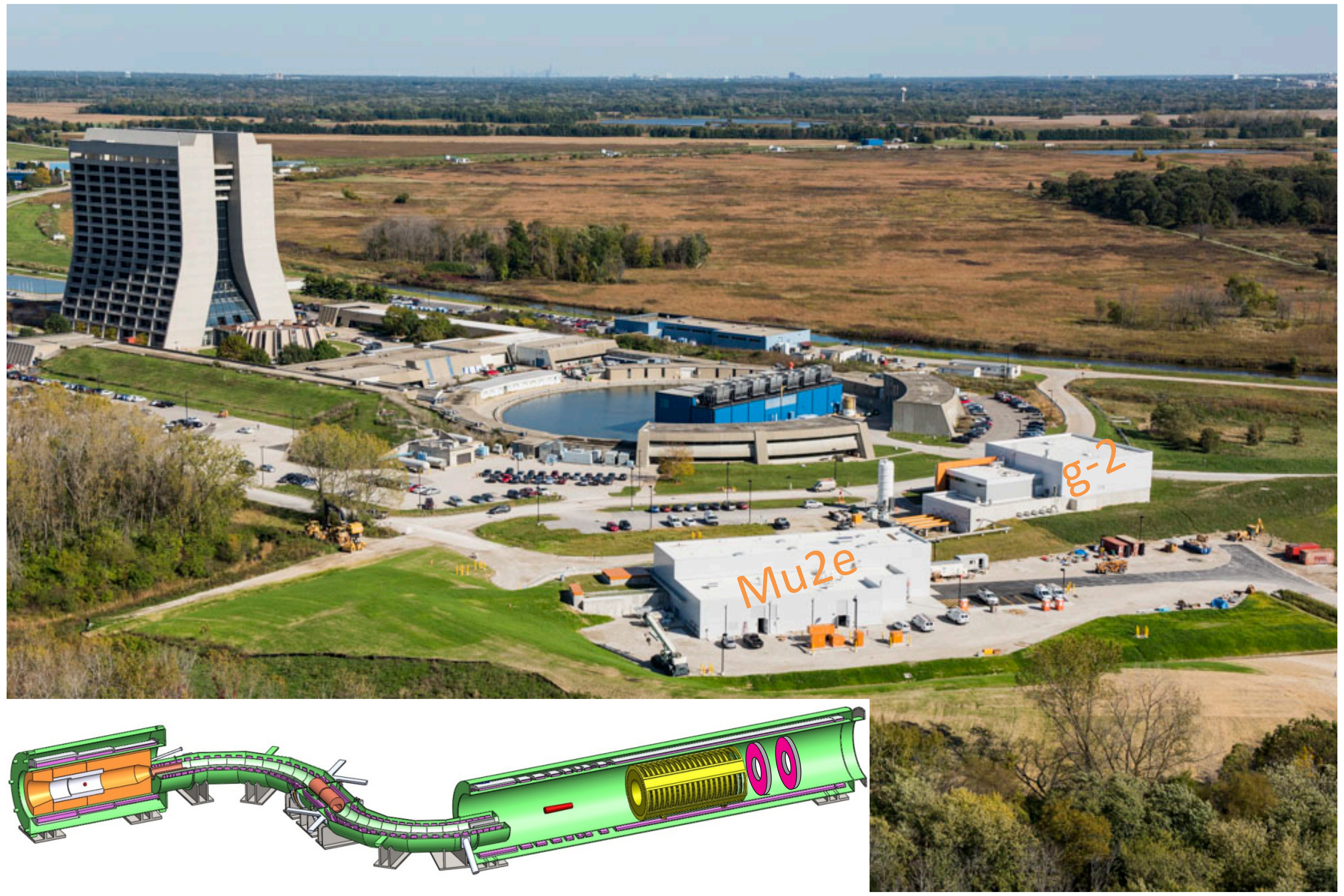
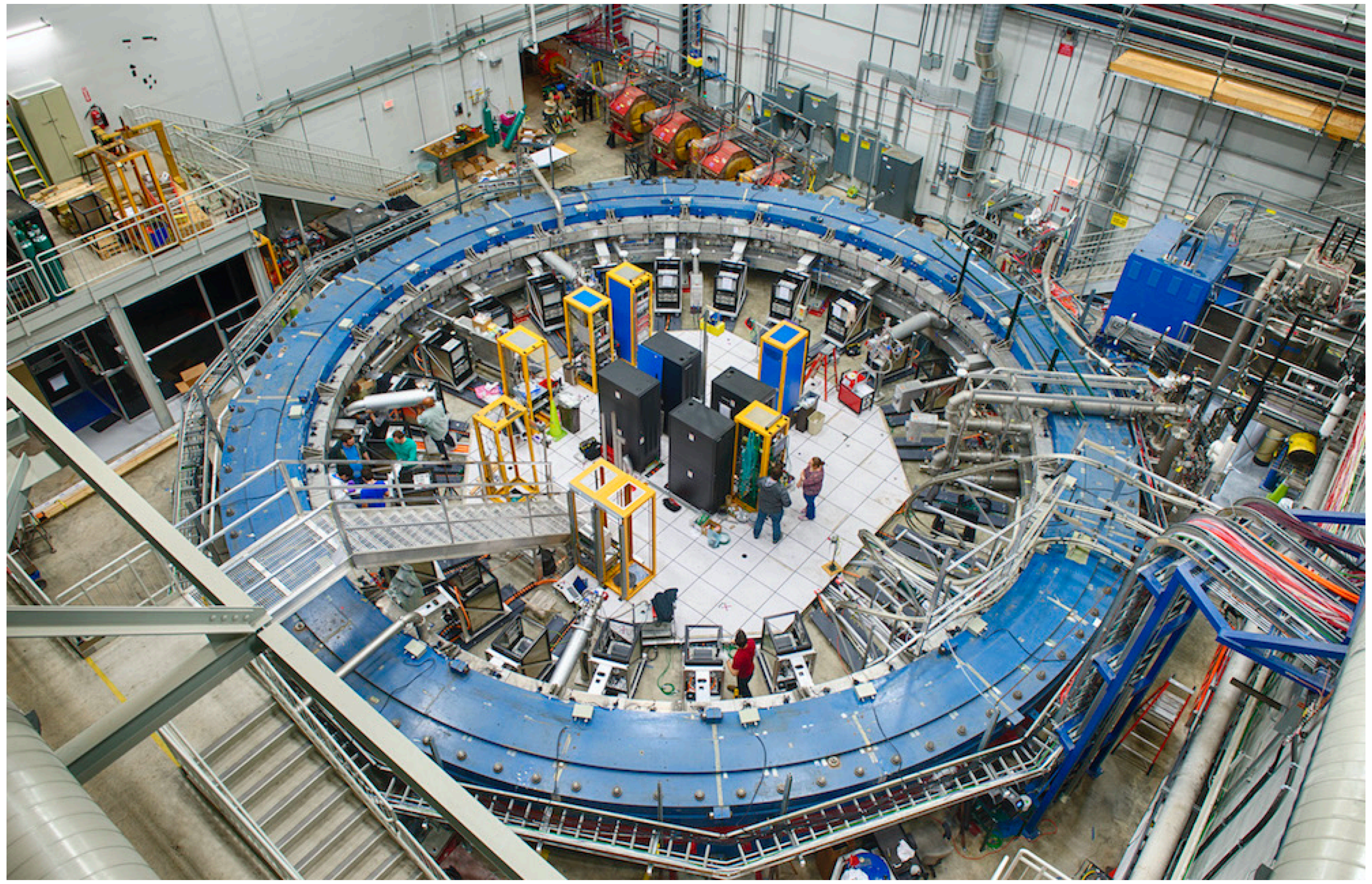




Muon Physics at Fermilab

Saskia Charity

Fermilab Summer Student Lecture Series

Aug 1 2019

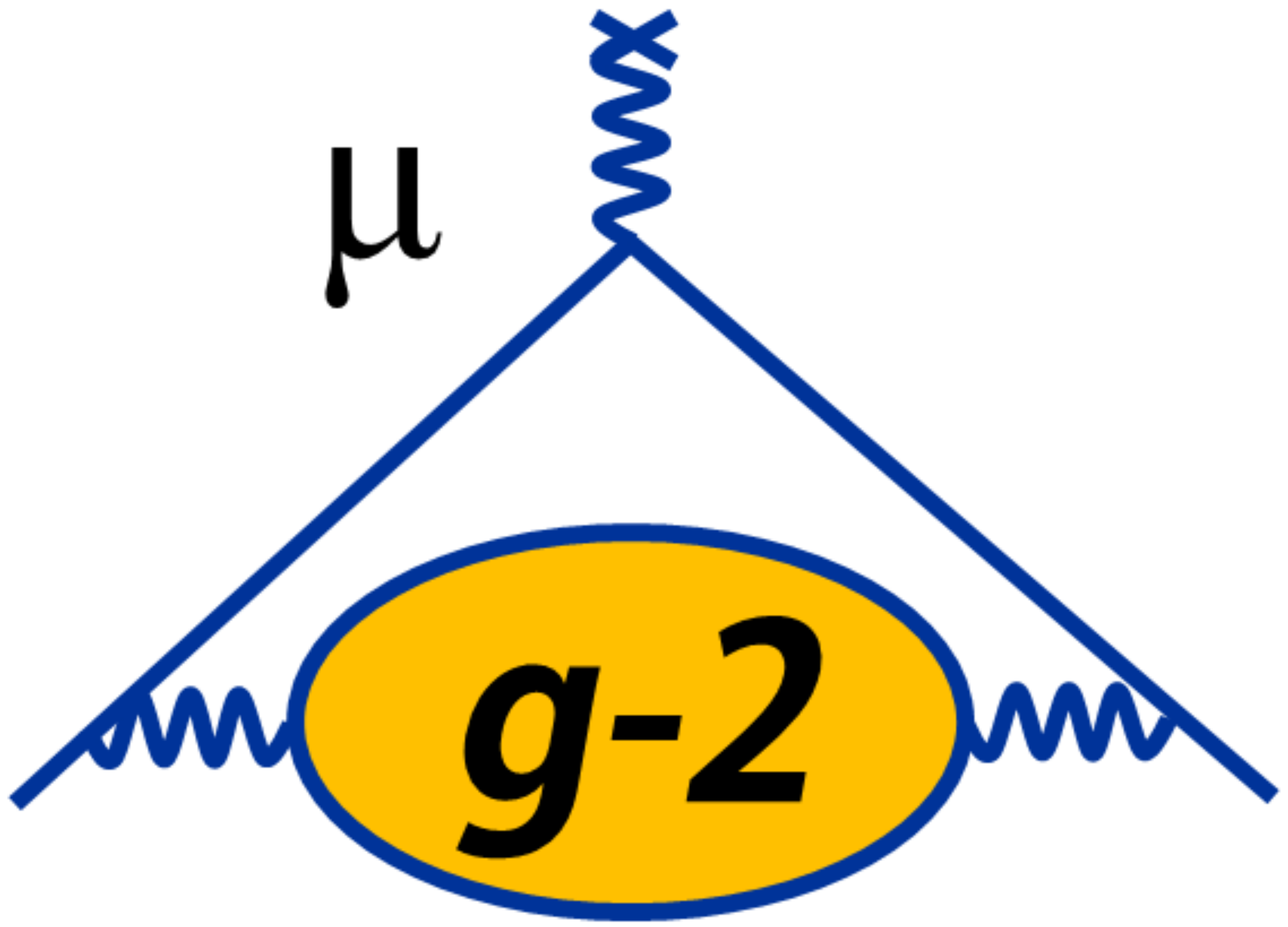
Outline

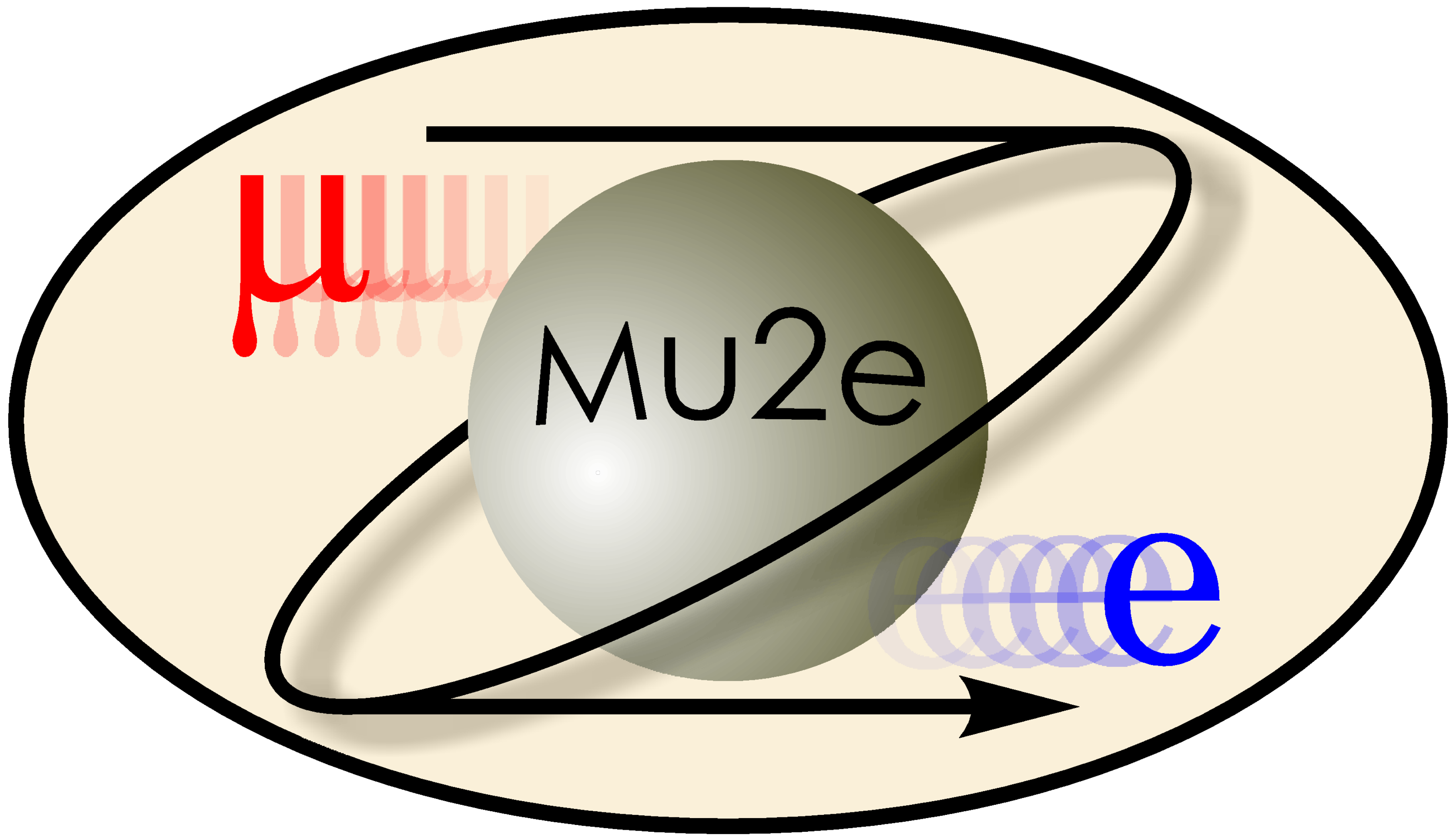
- Quick introduction to muon physics at Fermilab
- History of muons and the Standard Model
- Muon properties
- The mu2e experiment at Fermilab
- The g-2 experiment at Fermilab
- Summary and questions

Muon Physics at Fermilab

- Muons are my favorite particle, and I hope by the end of this talk, they will be yours!

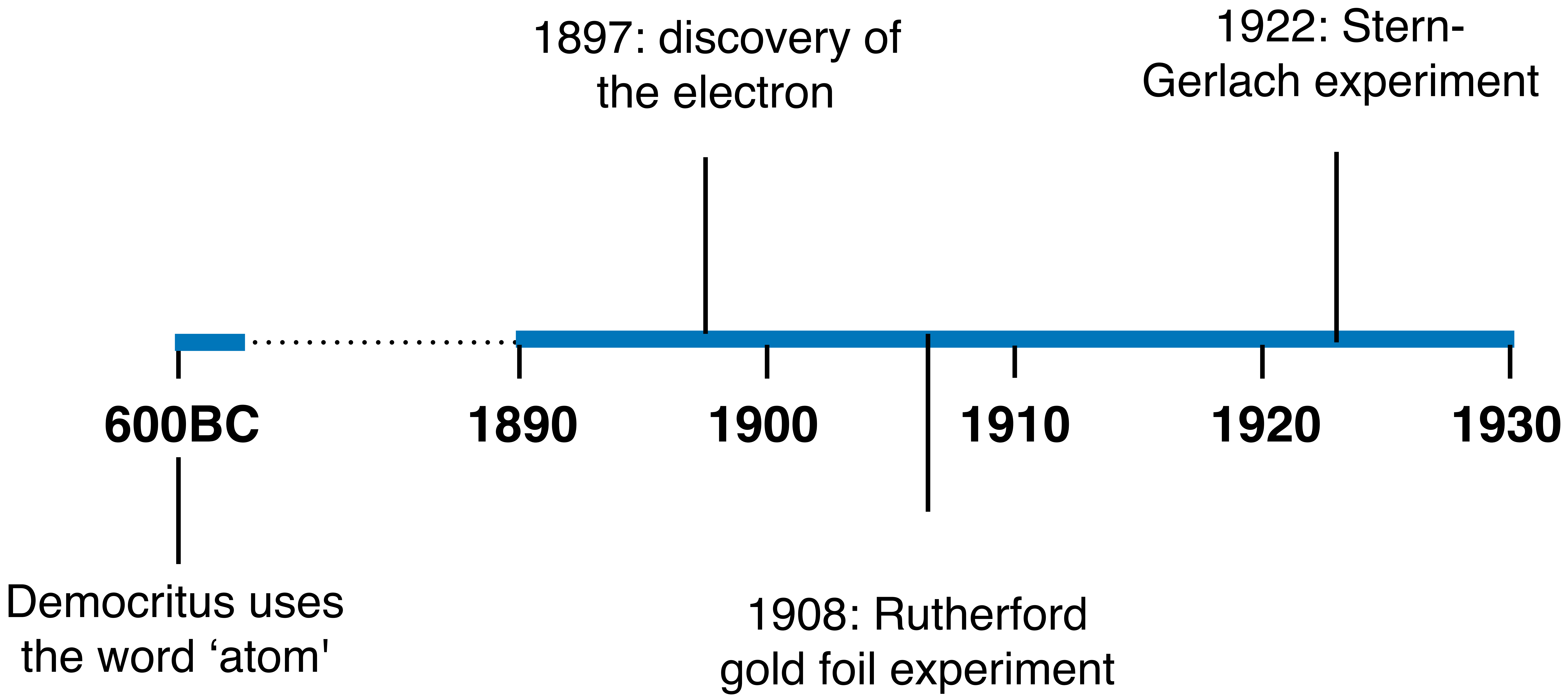
- Two experiments at Fermilab: g-2 and mu2e





- **Aim for this talk: be able to explain these logos!**

History of muons and the Standard Model



The 1930s — a big decade for muons

Dirac predicts positrons

Kunze observes a new particle of ‘uncertain nature’

J.C. Street identifies penetrating particles at sea level

1930 1931 1932 1933 1934 1935 1936

Anderson and Neddermeyer observe positrons

Yukawa predicts a ‘meson’ of mass ~200m_e

Confirmed observation of new particle: call it the ‘mu-meson'

The idea that the ‘mu-meson’ was the Yukawa meson persisted for 10 more years

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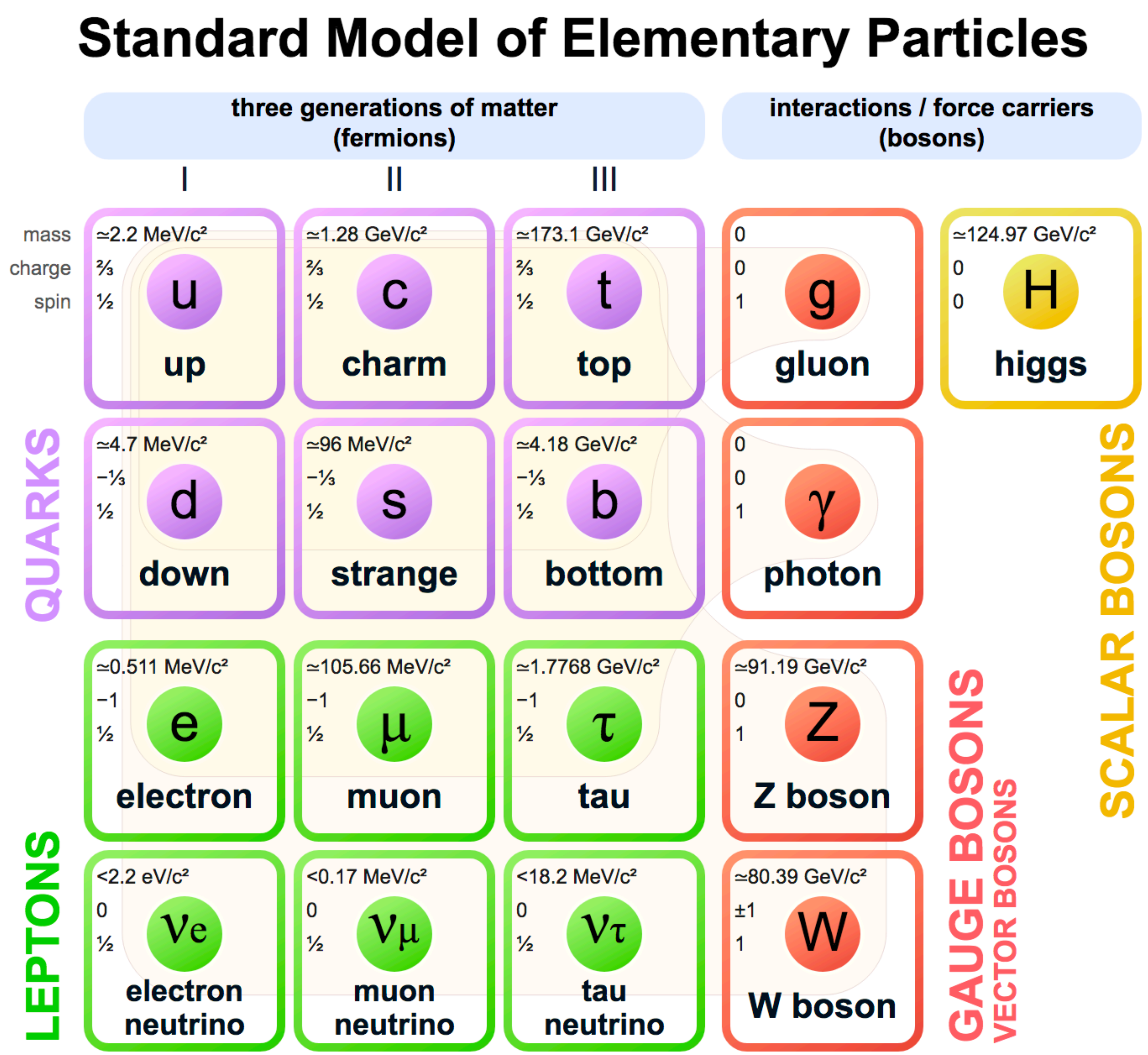
Muons vs ‘Yukawa mesons’

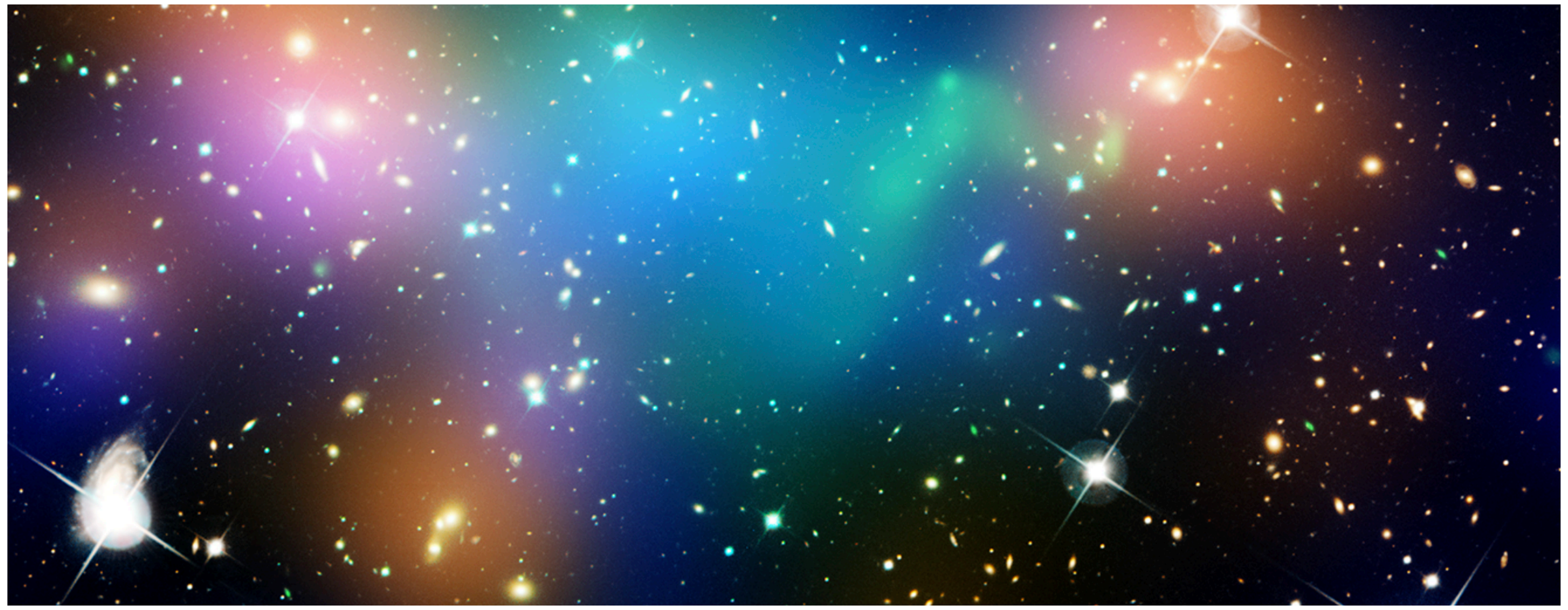
- Yukawa’s meson was determined to be the pi-meson (pion) in 1947
- Carries nuclear force — can’t be the mu-meson
- More mesons were discovered in accelerators, and the ‘mu-meson’ didn’t behave like any of them, either
- Pion decay to a muon + neutrino was observed, settling the muon’s identity crisis
- The muon is just like an electron, but it's heavier
    - First instance of the concept of ‘generations of matter’
    - What is going on? “Who ordered that?”

Muons in the Standard Model

- Today, we are used to the idea that there are 3 generations, or flavors, of leptons and quarks
- As of 2012, all predicted SM particles have been observed
- But this is not the end of the story



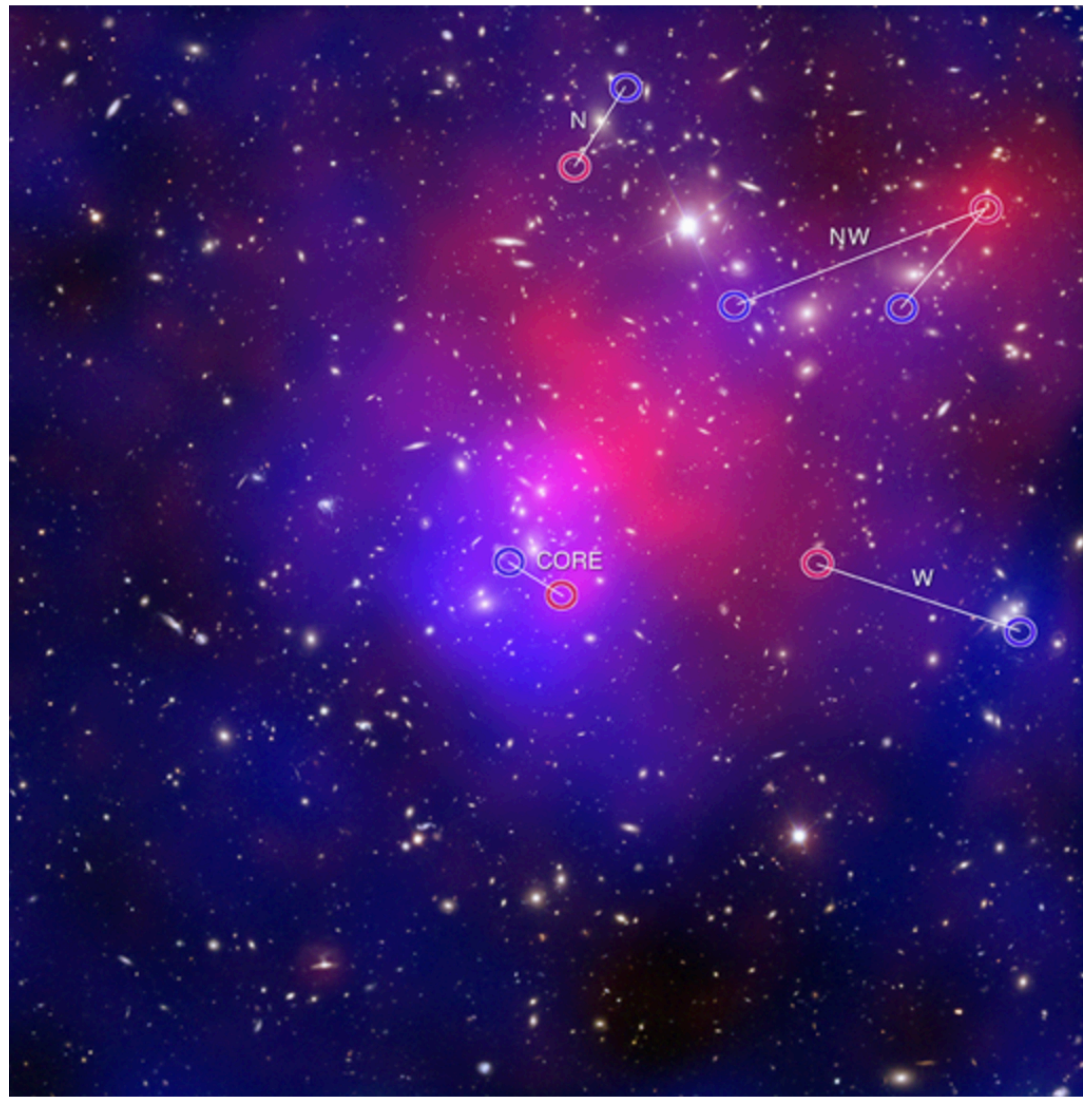
Evidence for physics beyond the SM



Why is the universe expanding so quickly?

Dark energy?

Why is there anything rather than nothing?



5x more mass than expected

What is dark matter?

Where is all the antimatter?

Why is the Higgs so light?

Why are neutrinos so weird?

How can we answer these questions?

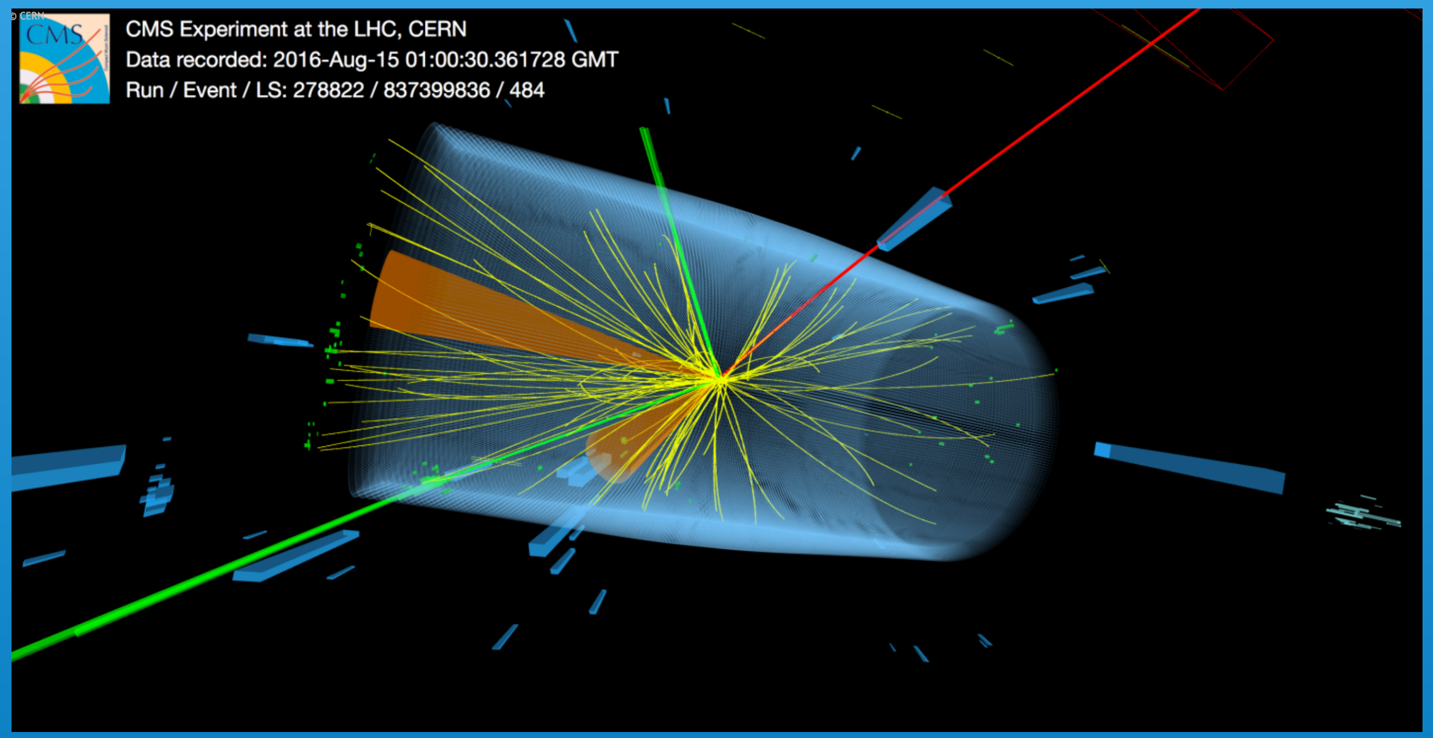
- How do we go about finding all this missing mass/energy/antimatter?
- One approach is to build a big accelerator (LHC, Tevatron) and hope we see the missing particles directly using very sensitive detectors — ‘General Purpose Detectors’
- I really hope this succeeds — but so far, no luck…
- We need complementary searches to help find the missing particles
- What else can we try?

Energy, precision and intensity

- We can think of the program of particle physics as being divided into three types of search

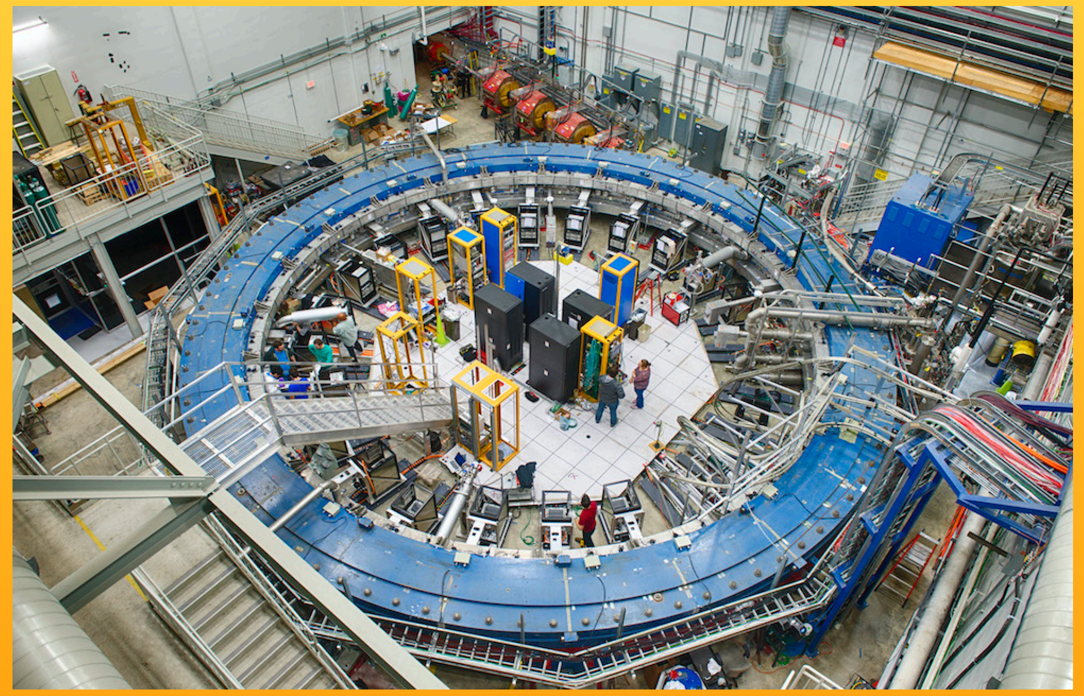
High energy

Collide particles at high energies to try and make new ones



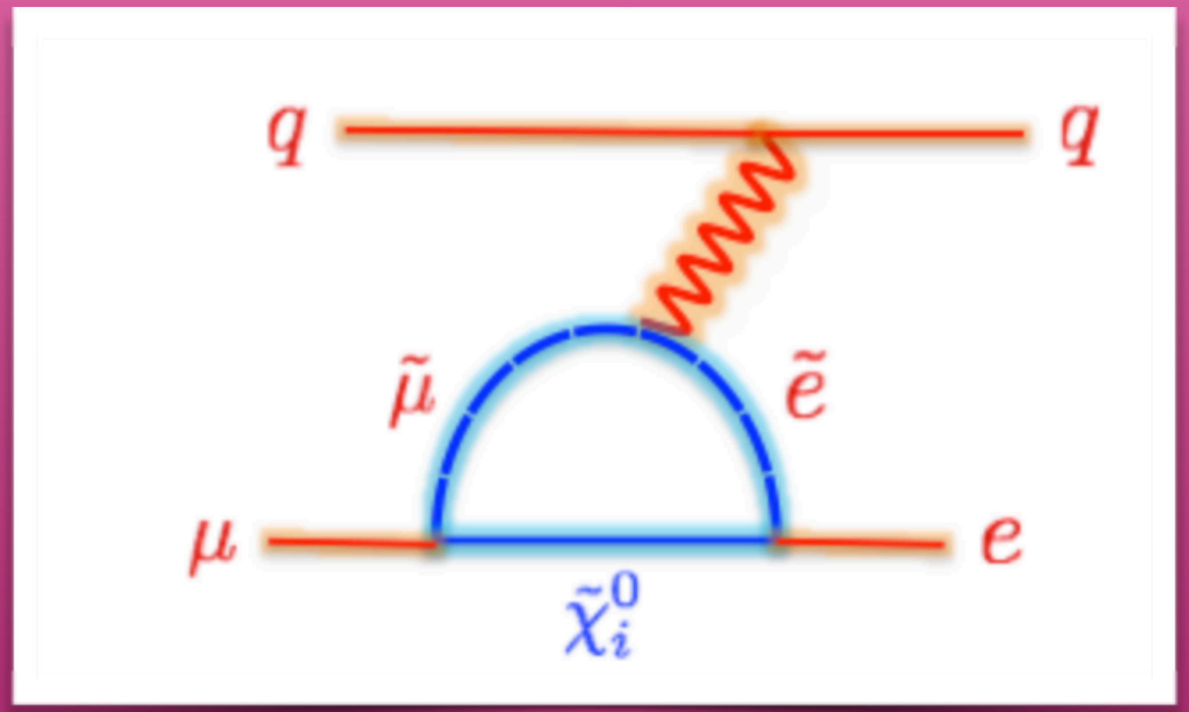
High precision

Use the SM to make precise predictions — compare with very precise measurements



High intensity

Look for very rare processes that are completely (or close to) forbidden in the SM



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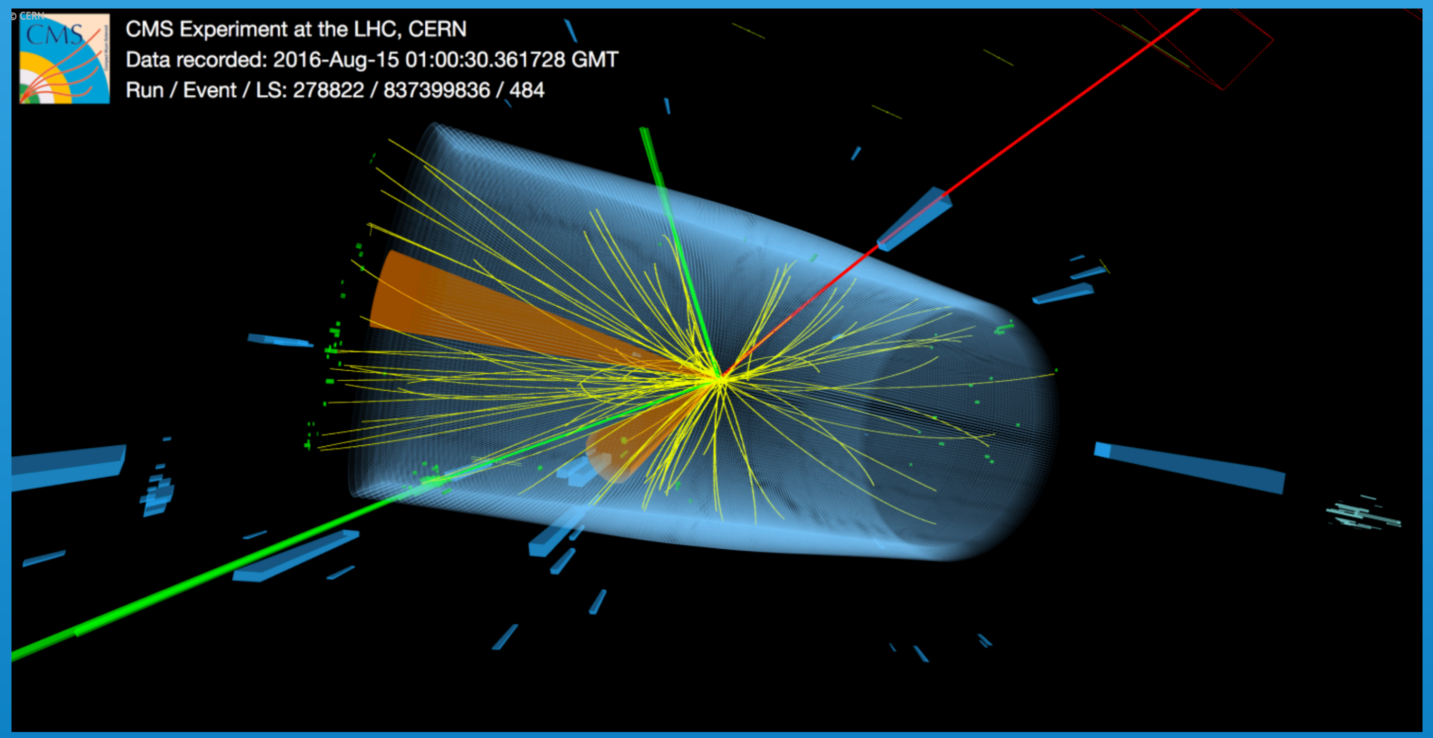

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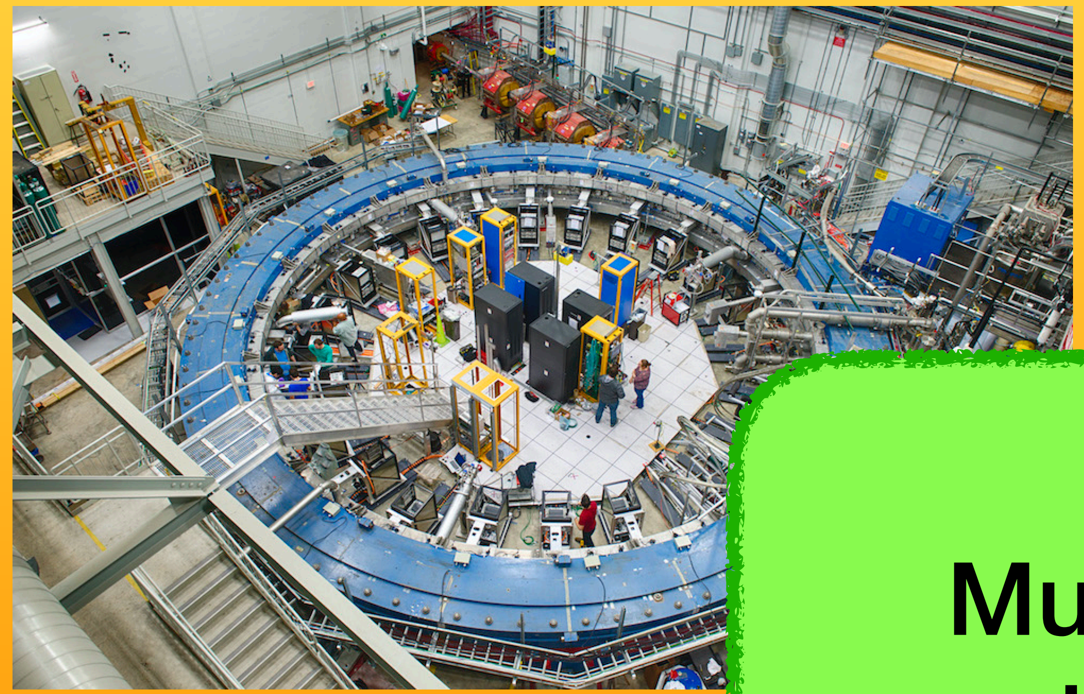

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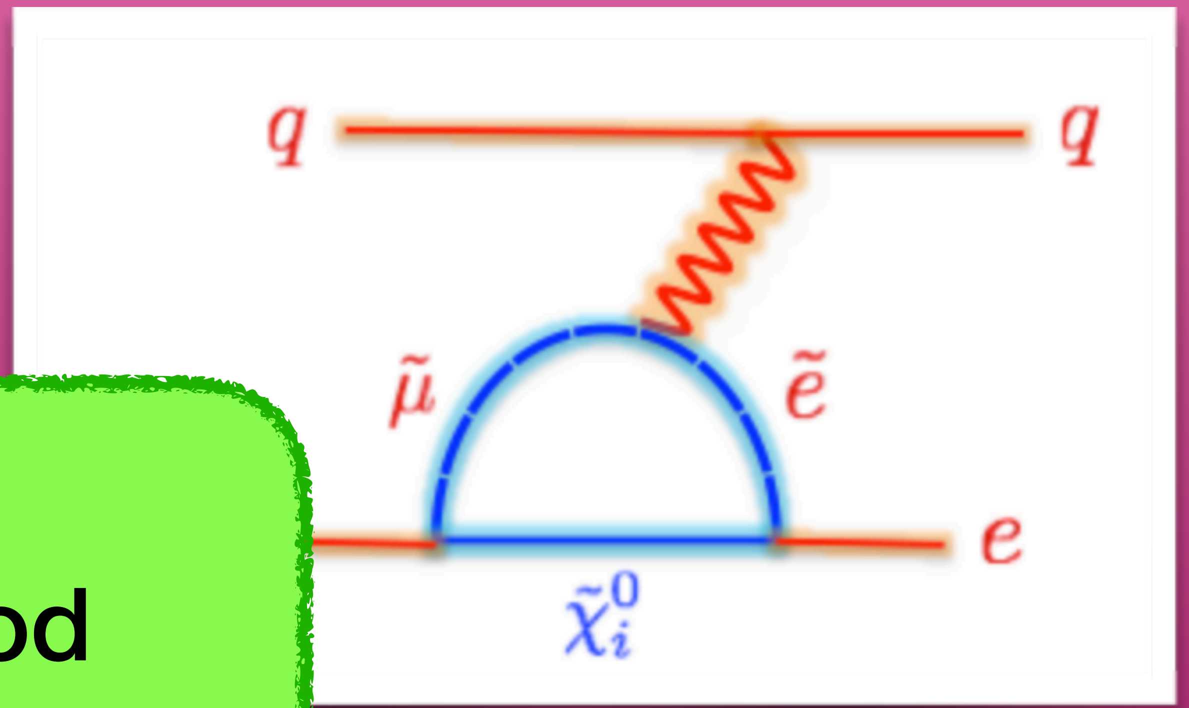

Muons are good candidates for these two types!

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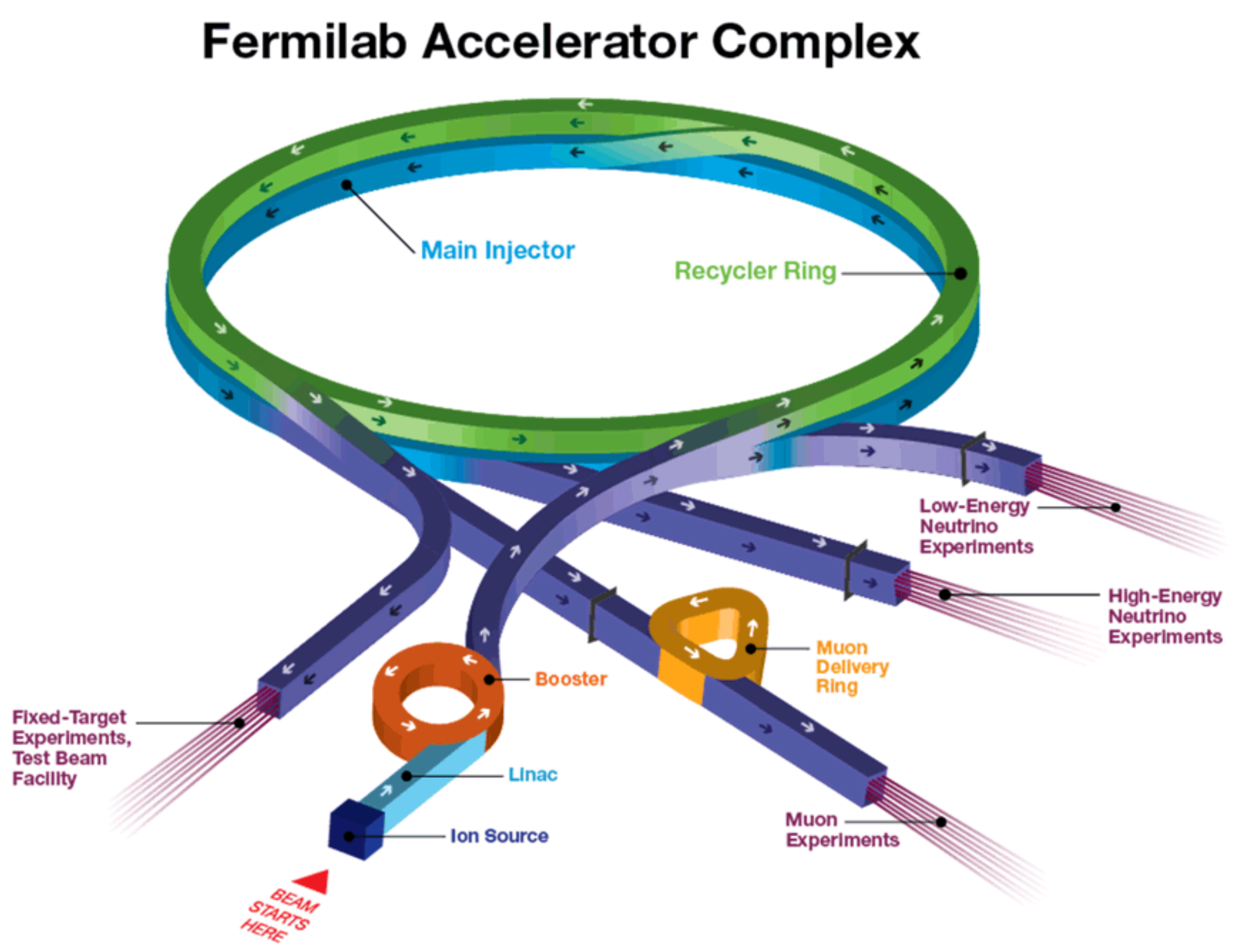
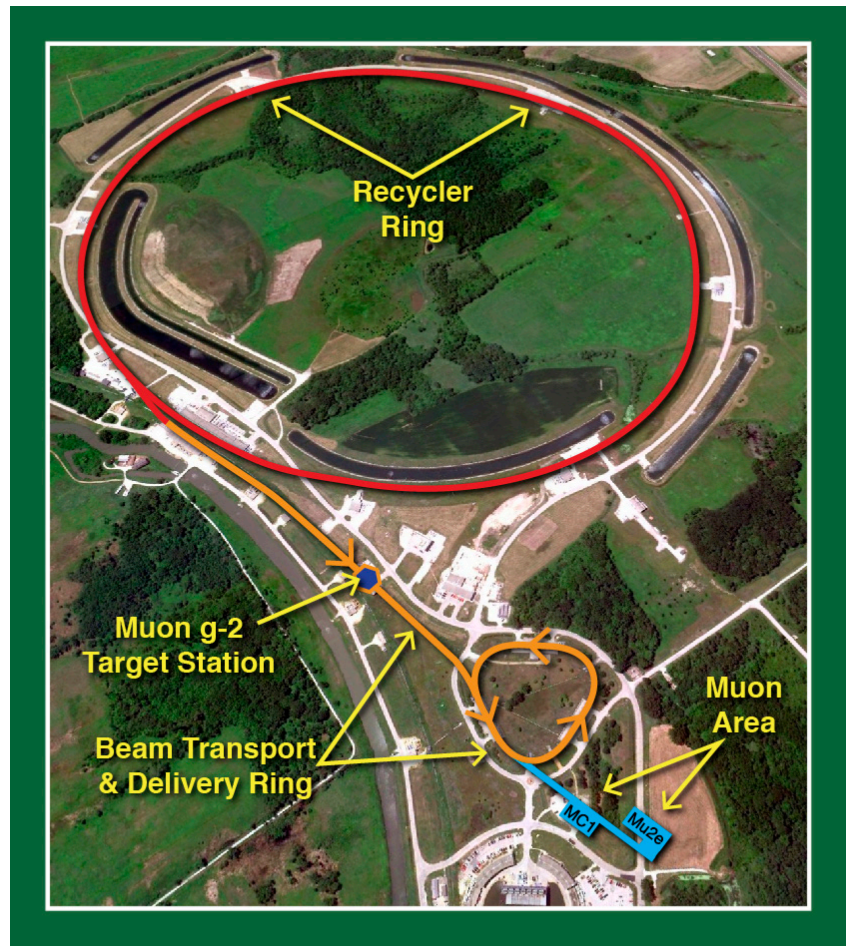
Why muons?

- Muons have a number of interesting properties that make them good candidates for testing the Standard Model
- They are easy to produce from pion decays: > 99.9% of pions decay to muon + neutrino
- They are naturally polarized
- They are charged
- They live for long enough to study their behavior, but short enough to study their decay
- They're heavier than electrons, but not too heavy
- We'll go into these features in more detail as we discuss the experiments.

Muon production at Fermilab





- Protons accelerated to 8 GeV in booster
- Protons collide with target —> pions produced
- Pions go round delivery ring many times to allow time for them all to decay to muons
- Muons directed to g-2 and mu2e

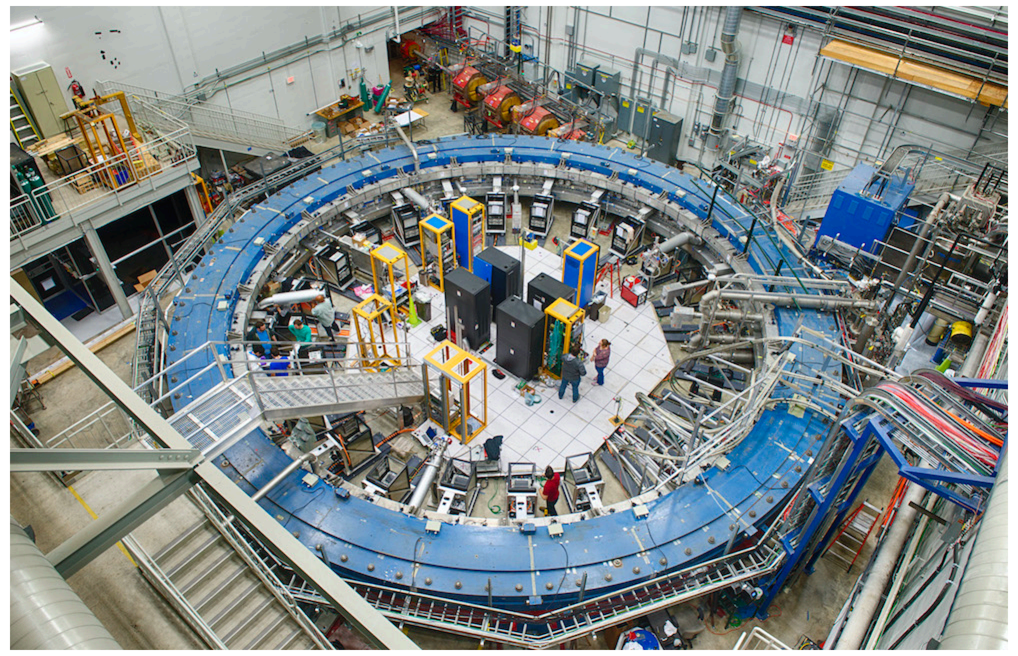
target

protons

pions

delivery ring

muons



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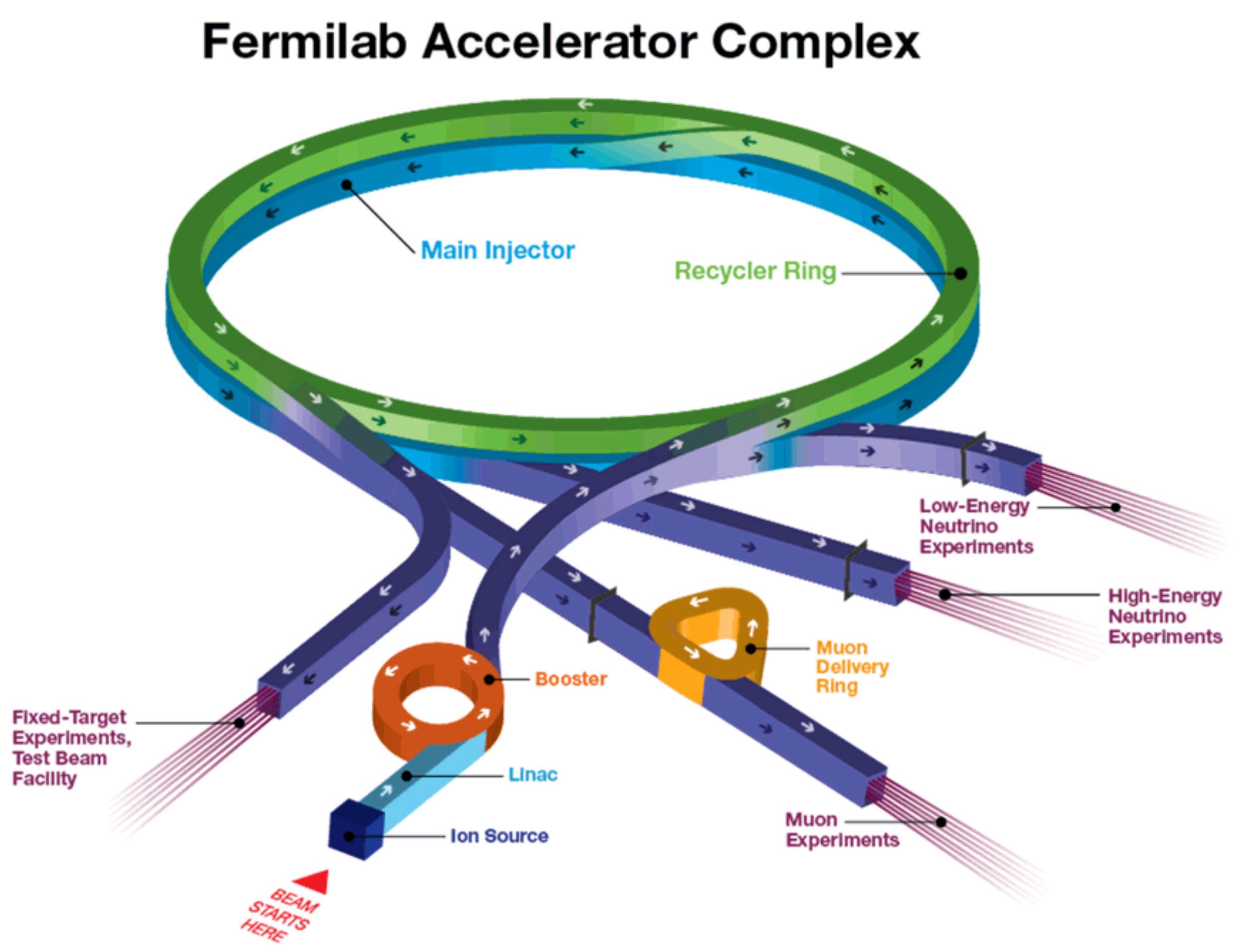

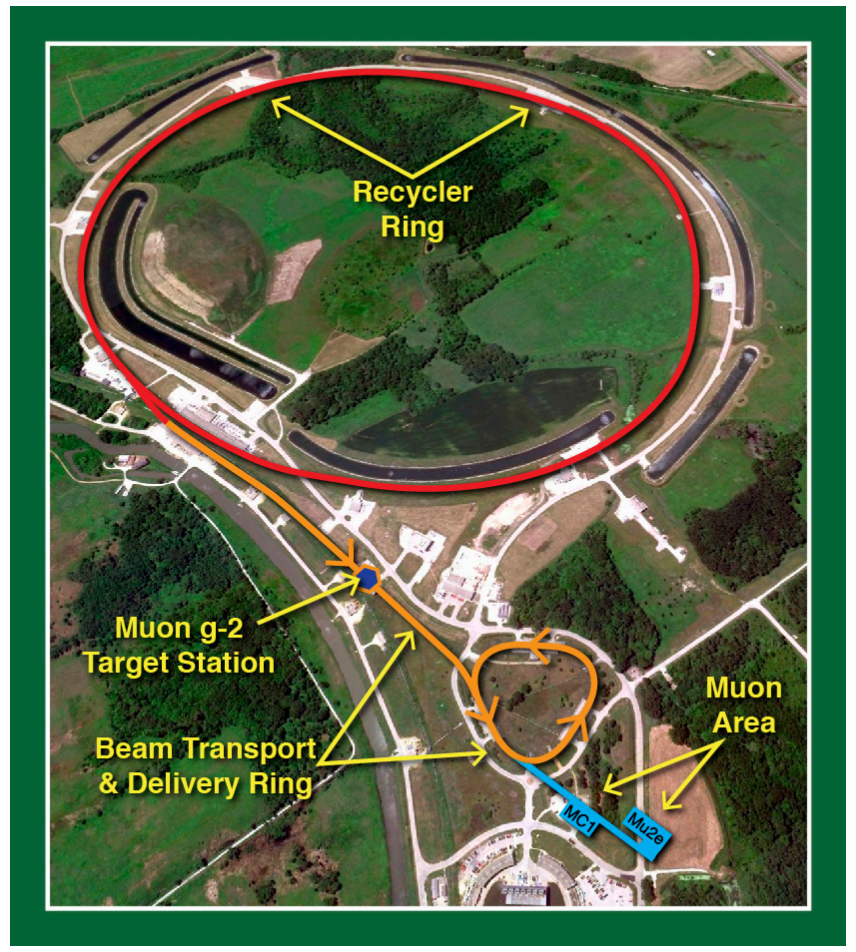

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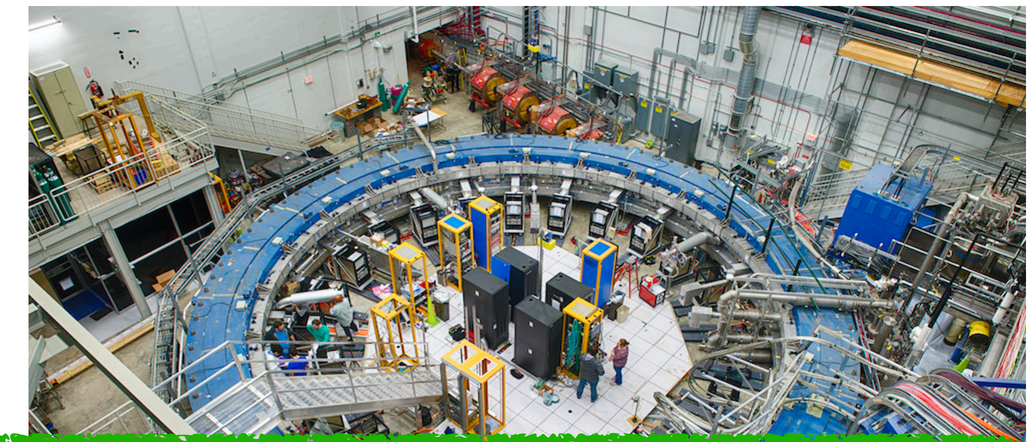
target

protons → | → pions →

delivery ring

muons →



What's special about these muons?

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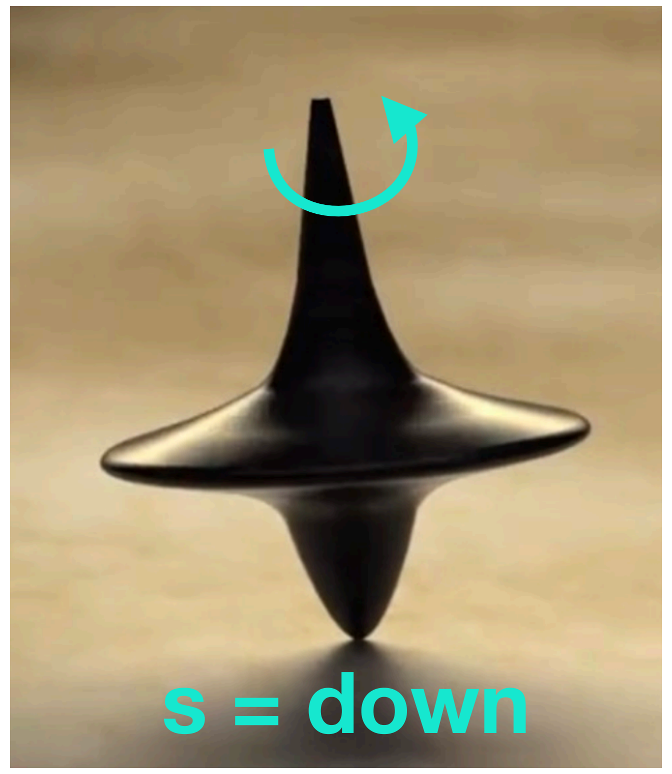
Parity violation and polarization

What is a polarized muon beam?

- The muons produced from pion decays are polarized
- This means their spin direction is aligned with their momentum
- Spin is the key concept that underpins the g-2 experiment — we'll come back to it later
- We can think of particles with spin just like a spinning top, rotating about an axis
- The direction of the spin determines its designation as spin 'up' (+) or spin 'down' (-)



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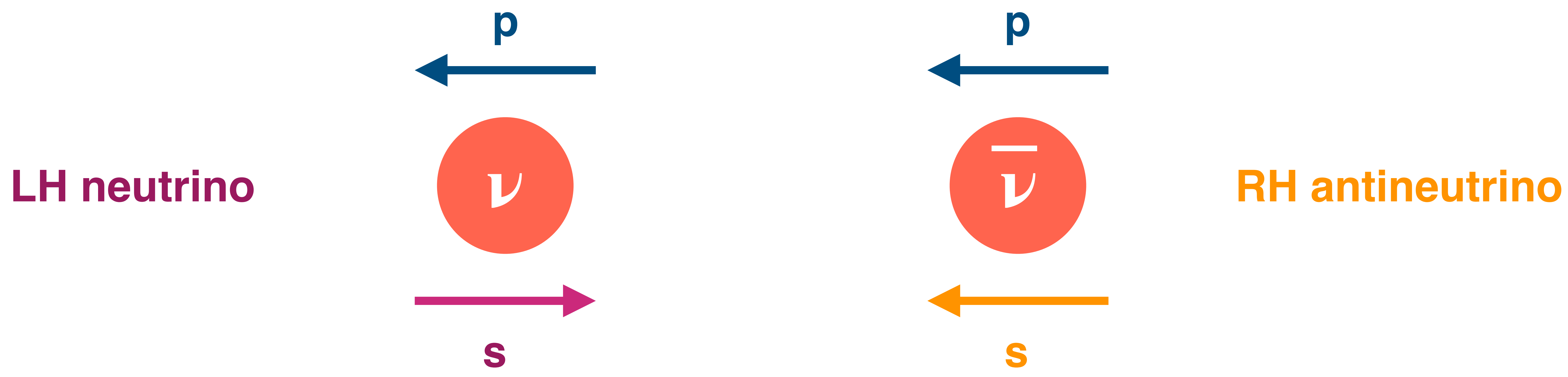
What is a polarized muon beam?

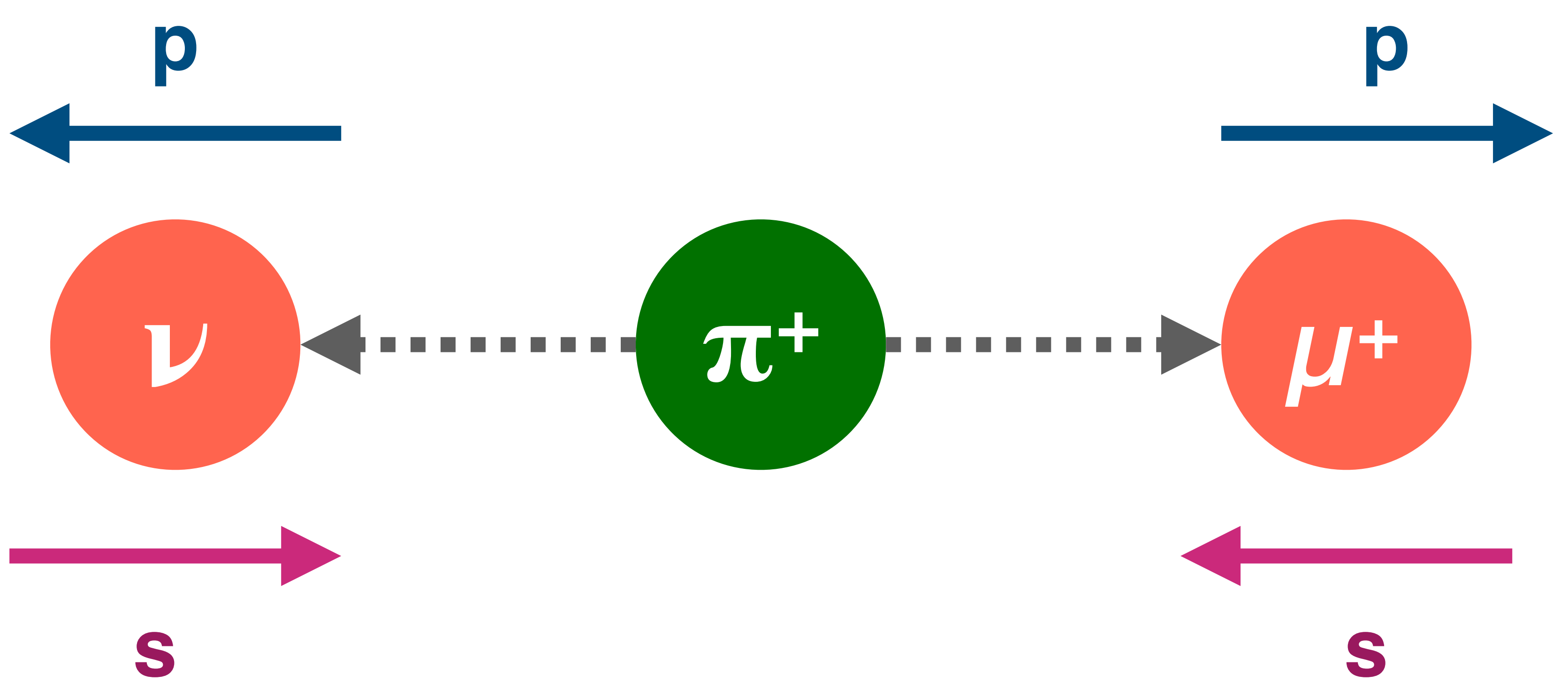
- The direction of a particle's spin relative to its momentum is important
- Particles with parallel spin and momentum vectors are right-handed (RH)
- Particles with antiparallel spin and momentum vectors are left-handed (LH)
- In the SM, neutrinos are always LH, and antineutrinos are always RH
  - This is a consequence of them being almost massless
- What does this mean for pion decay?



Producing polarized muons from pion decays

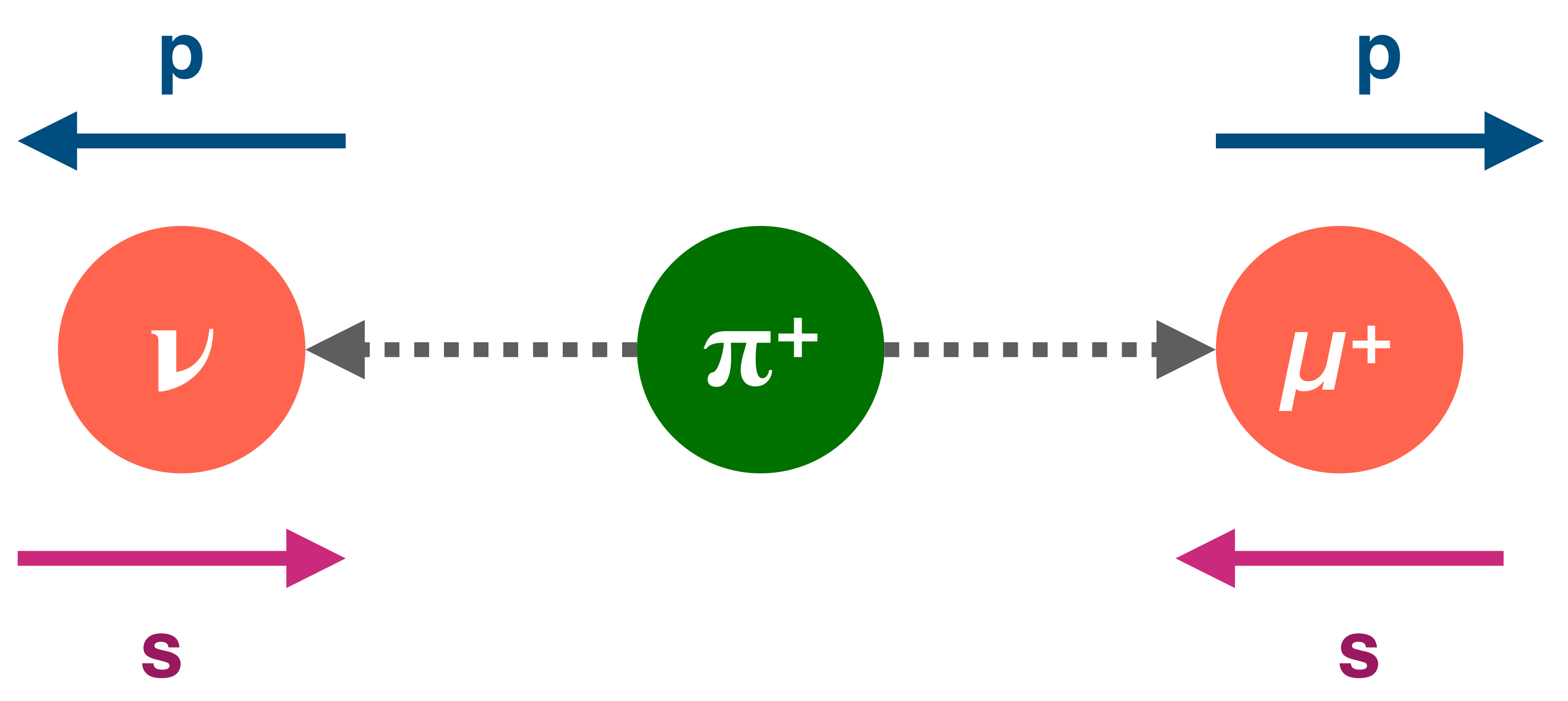
- Pions are spin-0, and in the pion rest frame, have momentum p=0

- To conserve momentum, the neutrino and muon must be emitted in opposite directions



Producing polarized muons from pion decays

- Pions are spin-0, and in the pion rest frame, have momentum p=0
- To conserve momentum, the neutrino and muon must be emitted in opposite directions
- Spin (full name 'spin angular momentum') must also be conserved
- In the SM, neutrinos are always LH, and antineutrinos are always RH
- So all muons produced in this decay must also be LH!



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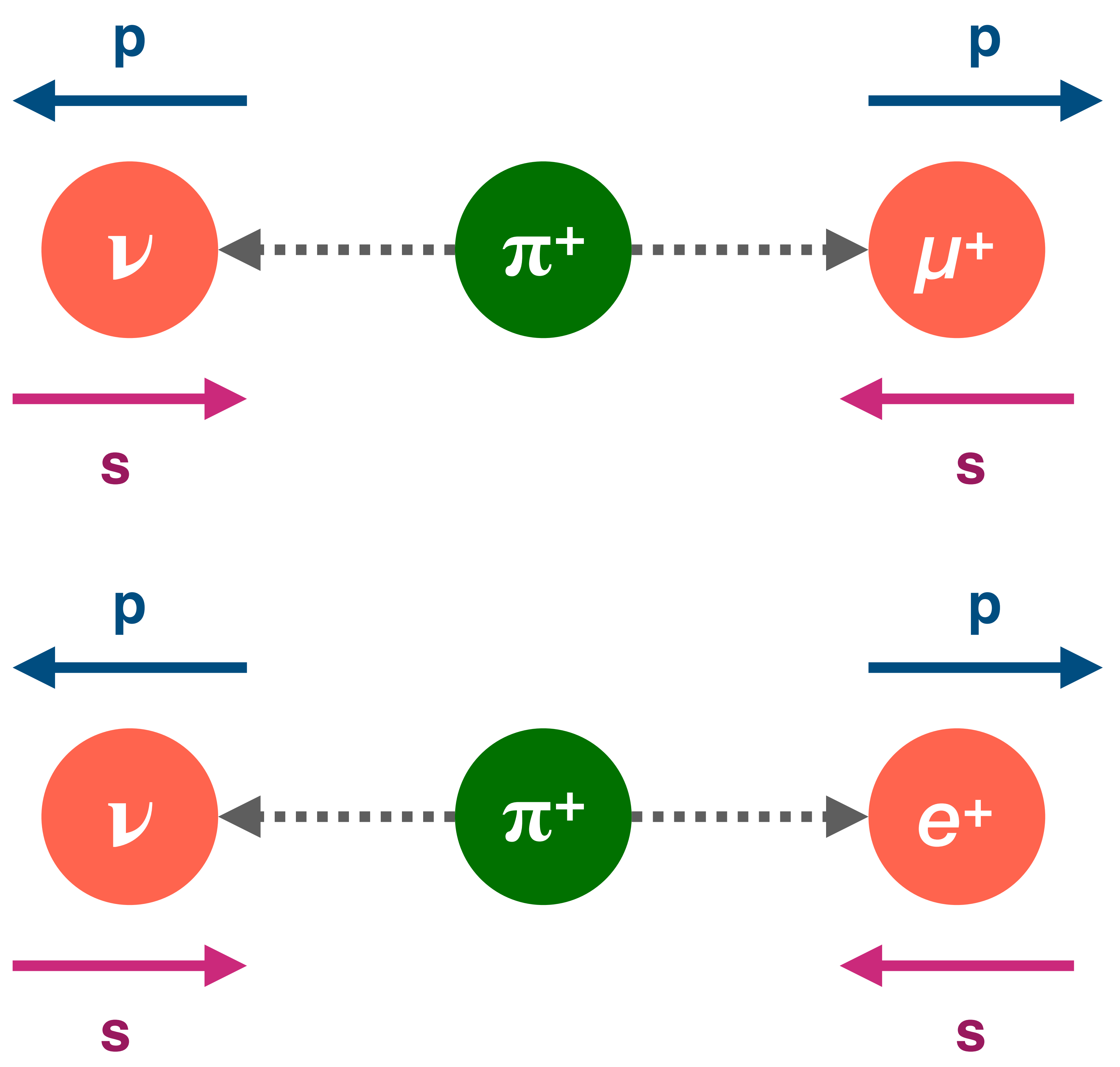
What about electrons?

- Pions can also decay to electrons
- Remember that the reason neutrinos have to be LH is because they are (nearly) massless
- Muons are heavier and don't have this constraint — they can be either LH or RH
- Electrons are nearly massless — they really want to be LH
- Positive pions produce positrons (e+) and so they want to be RH
- But conservation laws require them to be LH and so the e+ are very unhappy!



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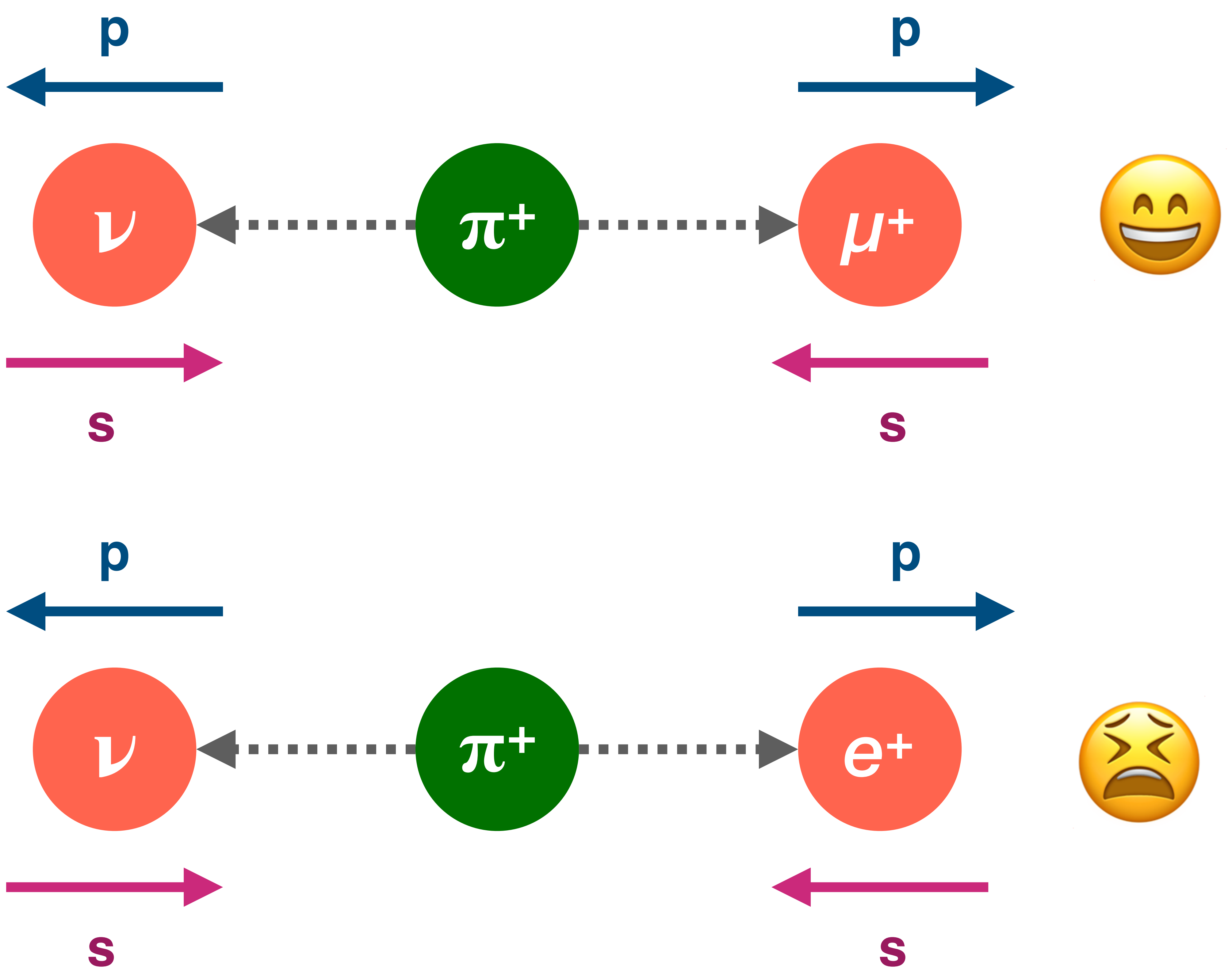


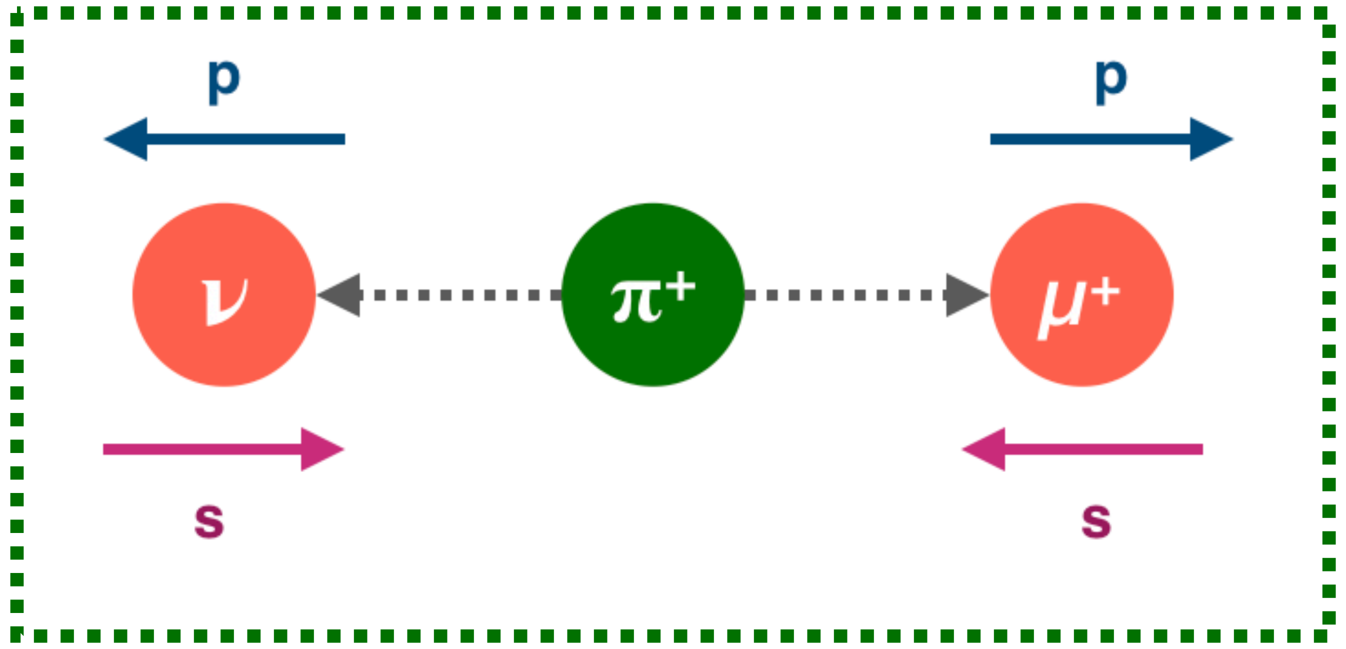
Pions decay to muons >99.9% of the time because decays to e+ are *suppressed*

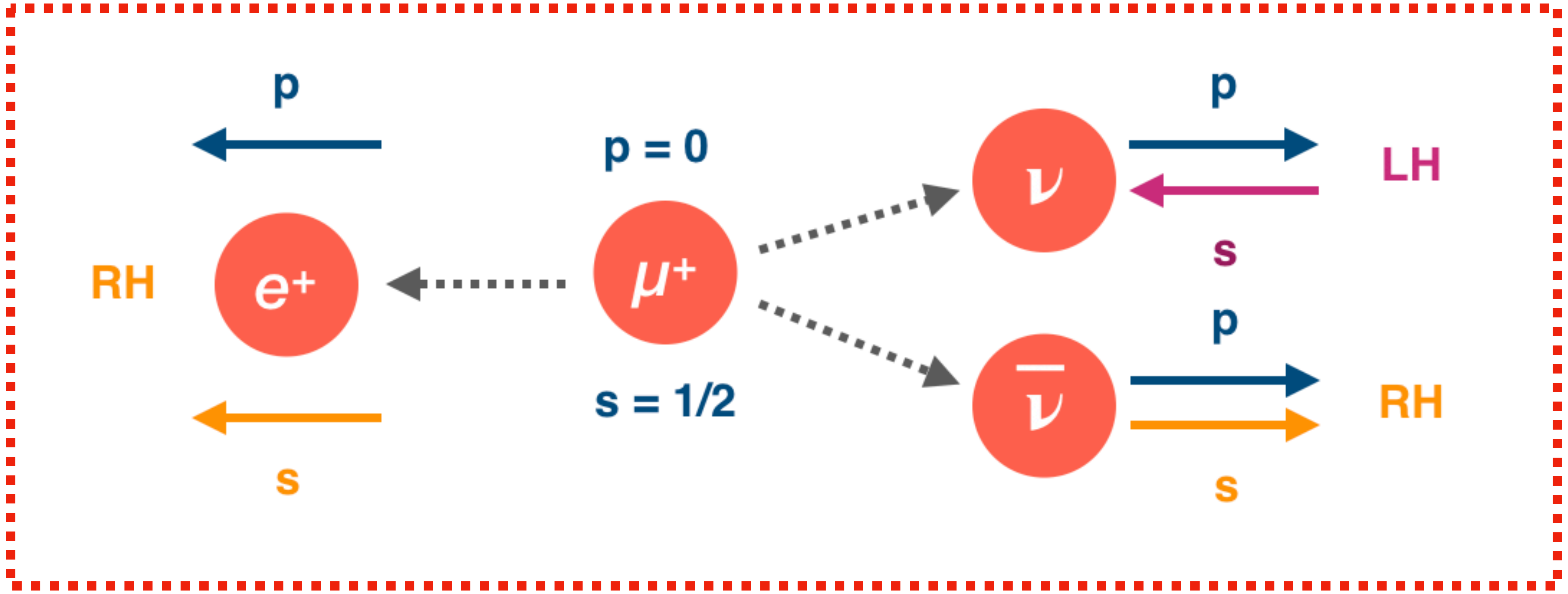
What about muon decays?

- The ability to produce a beam of muons with the same polarization is really useful — thanks, parity violation!

- It turns out the same logic applies for muon decays, and parity violation helps us once again.

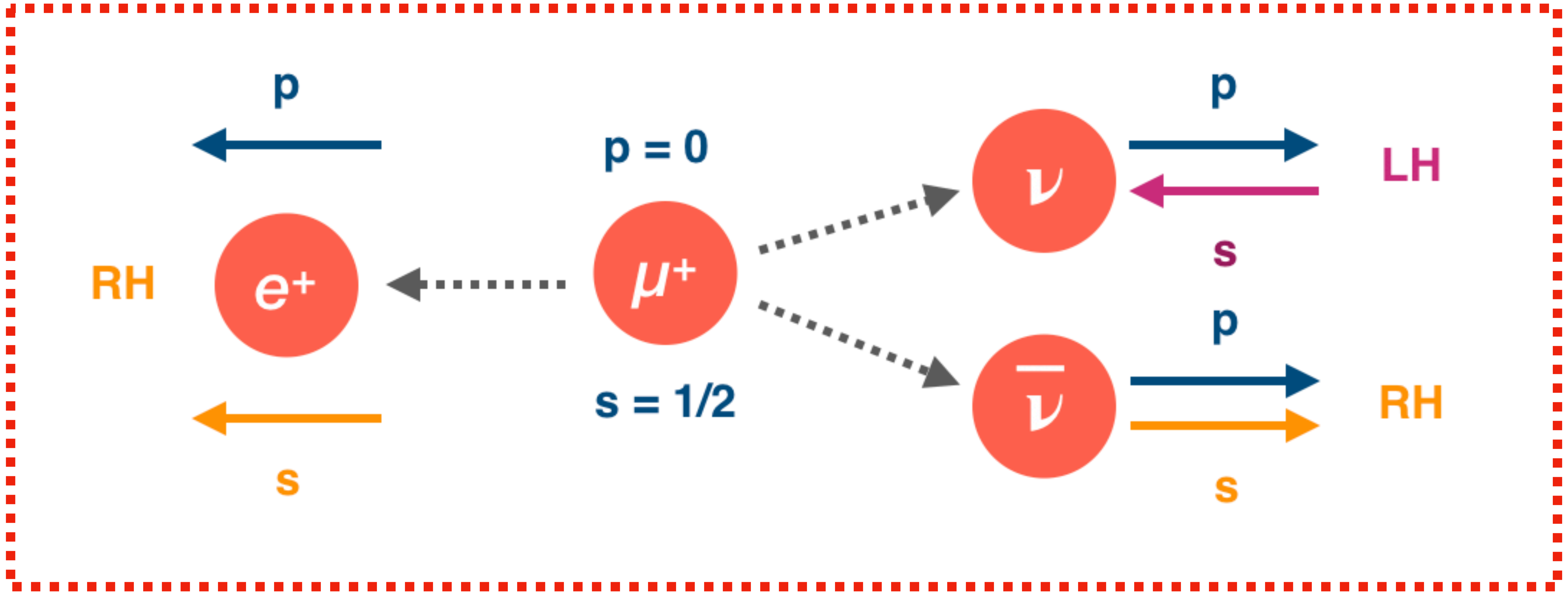
- To think about this, we need to move from the pion rest frame into the muon rest frame.





‘Self-analyzing’ muon decays

What can we learn by measuring the muon spin direction?



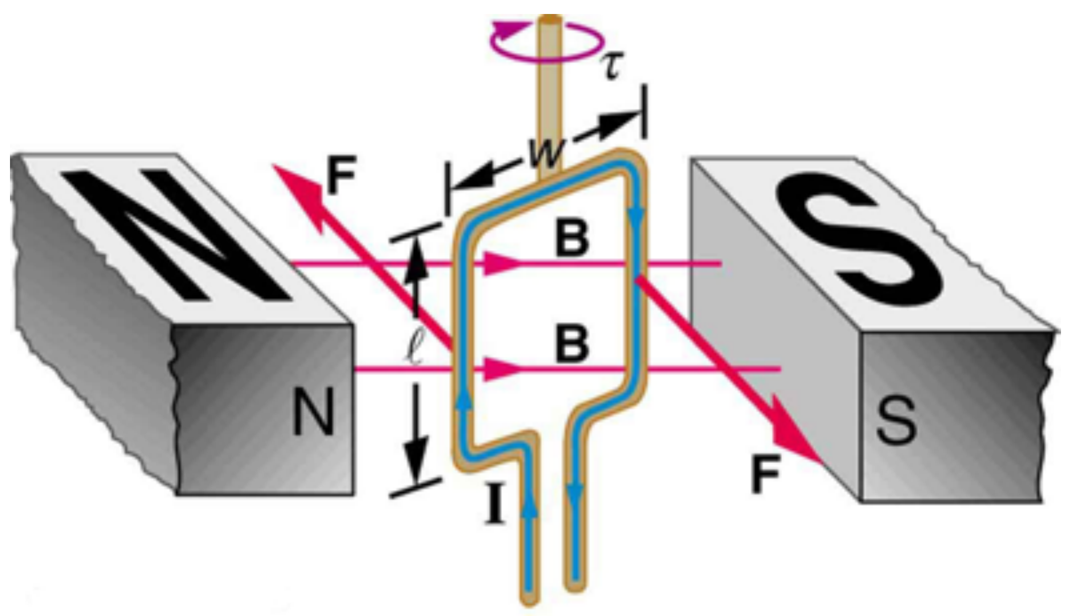
The e+ ‘carries’ the spin of its parent muon

We can infer the spin direction of muons by measuring the emitted positrons…

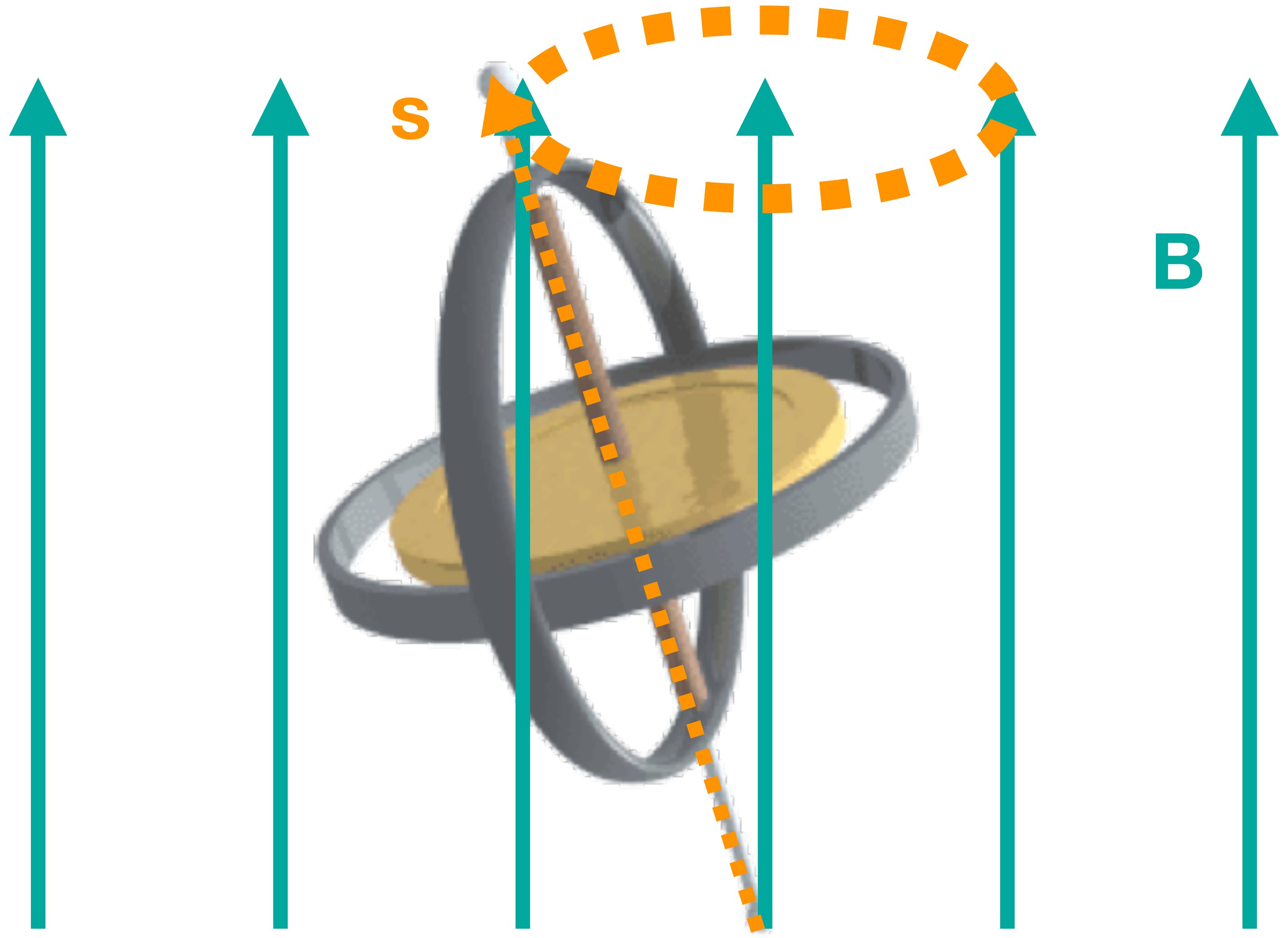
Spin precession and magnetic moments

Spin precession in a magnetic field

- Particles with spin (e.g. leptons) will **precess** when they are in the presence of a magnetic (B) field : this is called **Larmor precession**



- Classical analogy: current loop between two bar magnets
- The lepton will behave just like a spinning top with its spin vector precessing about the B-field direction



- We define the magnetic moment, μ:

$$\boldsymbol{\mu} = g\frac{q}{2m}\boldsymbol{s}$$

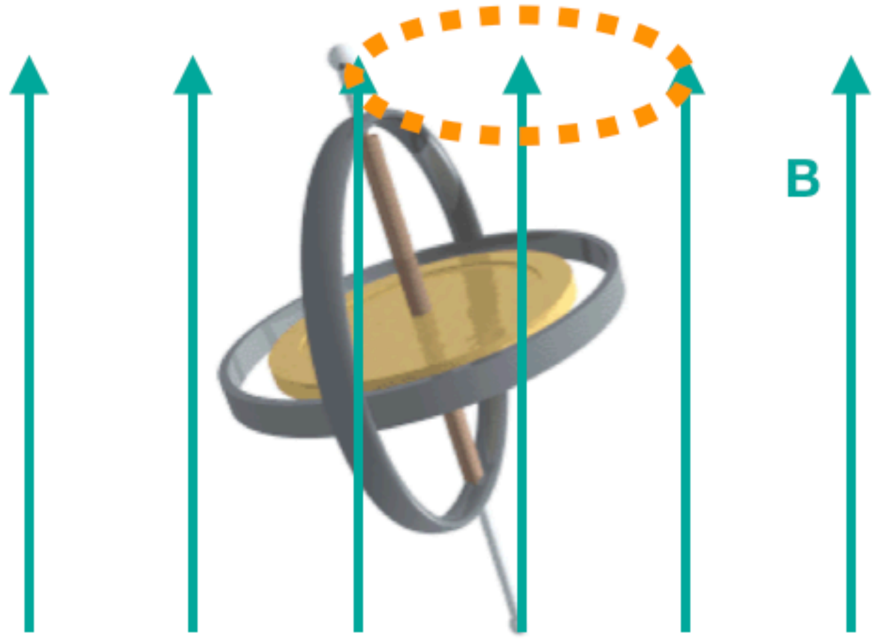
charge

spin

mass

what's g?

Lande g-factor



magnetic moment

$$\boldsymbol{\mu} = g\frac{q}{2m}\mathbf{s}$$

spin precession frequency

$$\omega_s = g\frac{eB}{2m}$$

- In this expression, *g* is called the Lande g-factor, or gyromagnetic ratio
- It is a dimensionless number (no units) that parameterizes the relationship between the particle's magnetic moment and its spin
- Describes the size of μ and how quickly the spin will precess
- What is the value of *g*? Good question!

g = ?

$$\omega_s = g\frac{eB}{2m}$$

- Classical description: g = 1
- After discovery of spin (Stern-Gerlach experiment), Dirac predicted that g = 2 for a charged spin 1/2 particle (e.g. charged leptons, protons)
- This means its spin would precess twice as fast. Measure ω to measure size of *g*
- In 1933, Frisch, Stern and Estermann measured *g* of proton = 5.5 !
- And in 1934, *g* of neutron = -3.8 ! It's not even charged!
- Explanation: neutron has substructure (udd) — charged quarks have magnetic moments that give the neutron a net magnetic moment

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Case closed: g=2 for fundamental charged spin-1/2 particles

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- This mean
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- In 1933, Fr
- And in 193

Case closed: g=2 for fundamental charged spin-1/2 particles

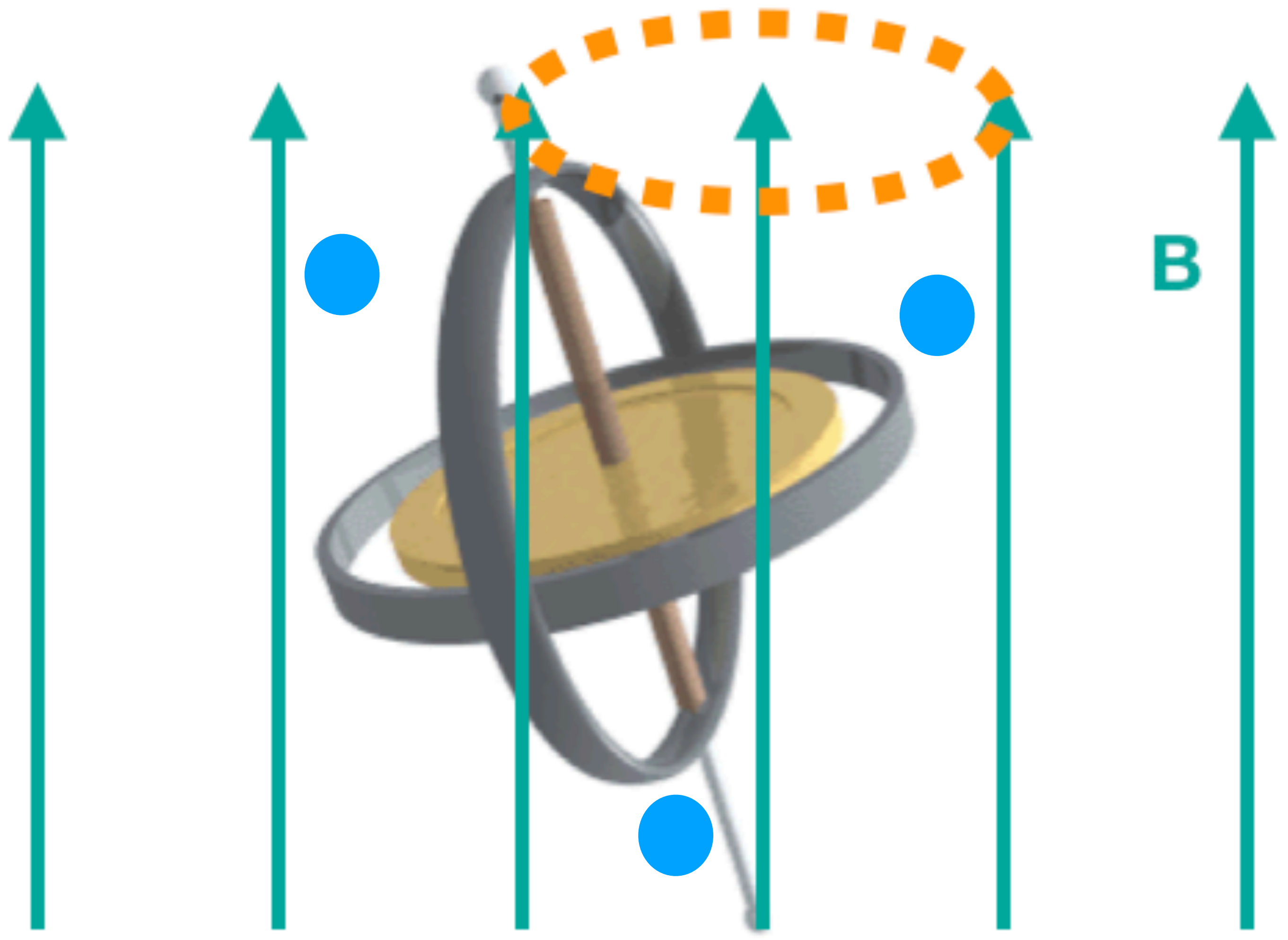
Until 1947, when Kusch and Foley measured $g = 2.00238(6)$…

What's going on?

- Explanation: neutron has substructure (udd) — charged quarks have magnetic moments that give the neutron a net magnetic moment

Vacuum interactions

- In nature, particles are never truly alone
- Virtual particles continually fluctuate in and out of ‘the vacuum’
- Muons, electrons and all other particles can interact with these virtual particles
- The heavier the particle, the higher the number of ways it can interact
- Effectively, the virtual particles screen the magnetic field experienced by the particle, changing the value of g



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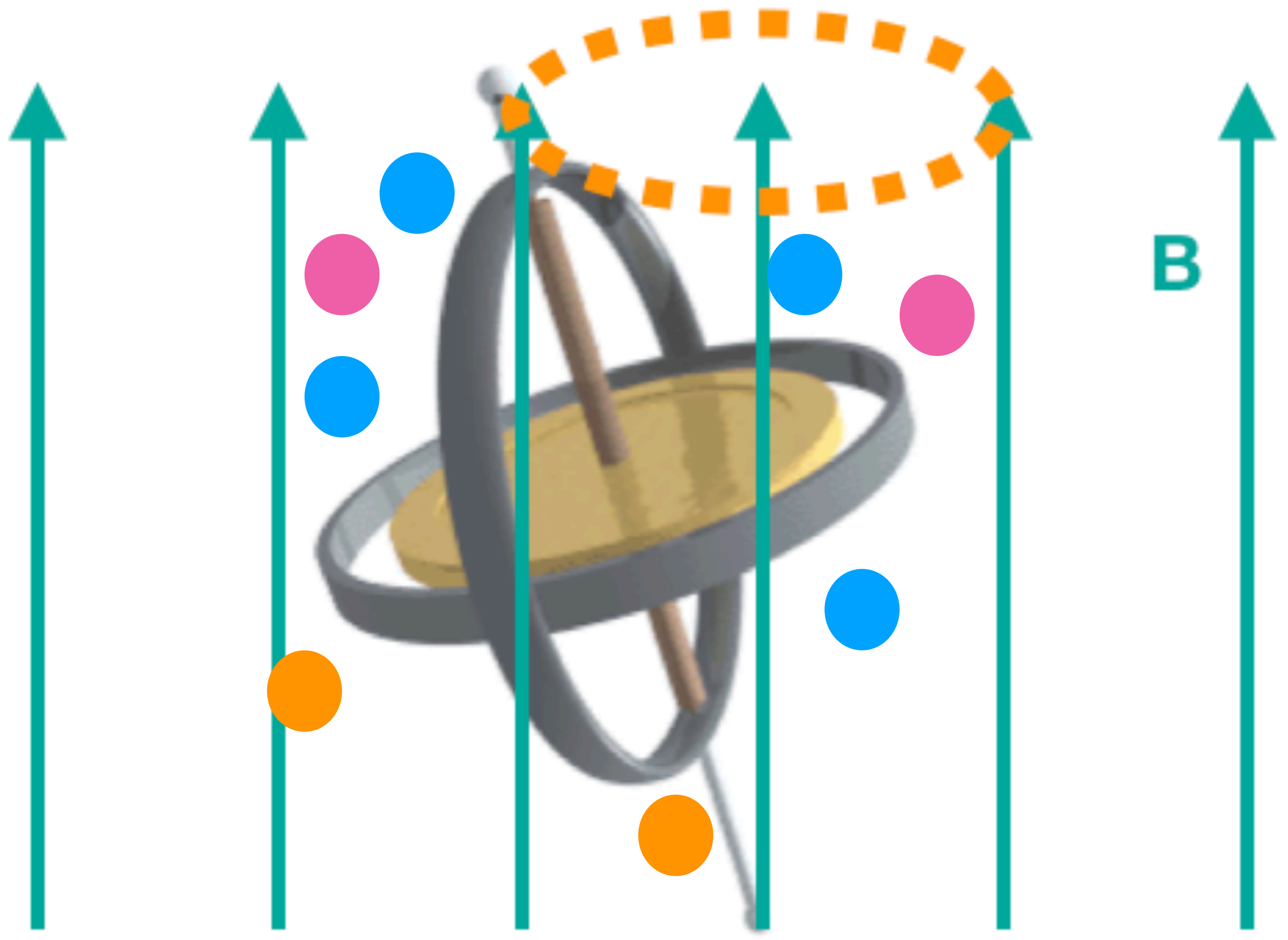

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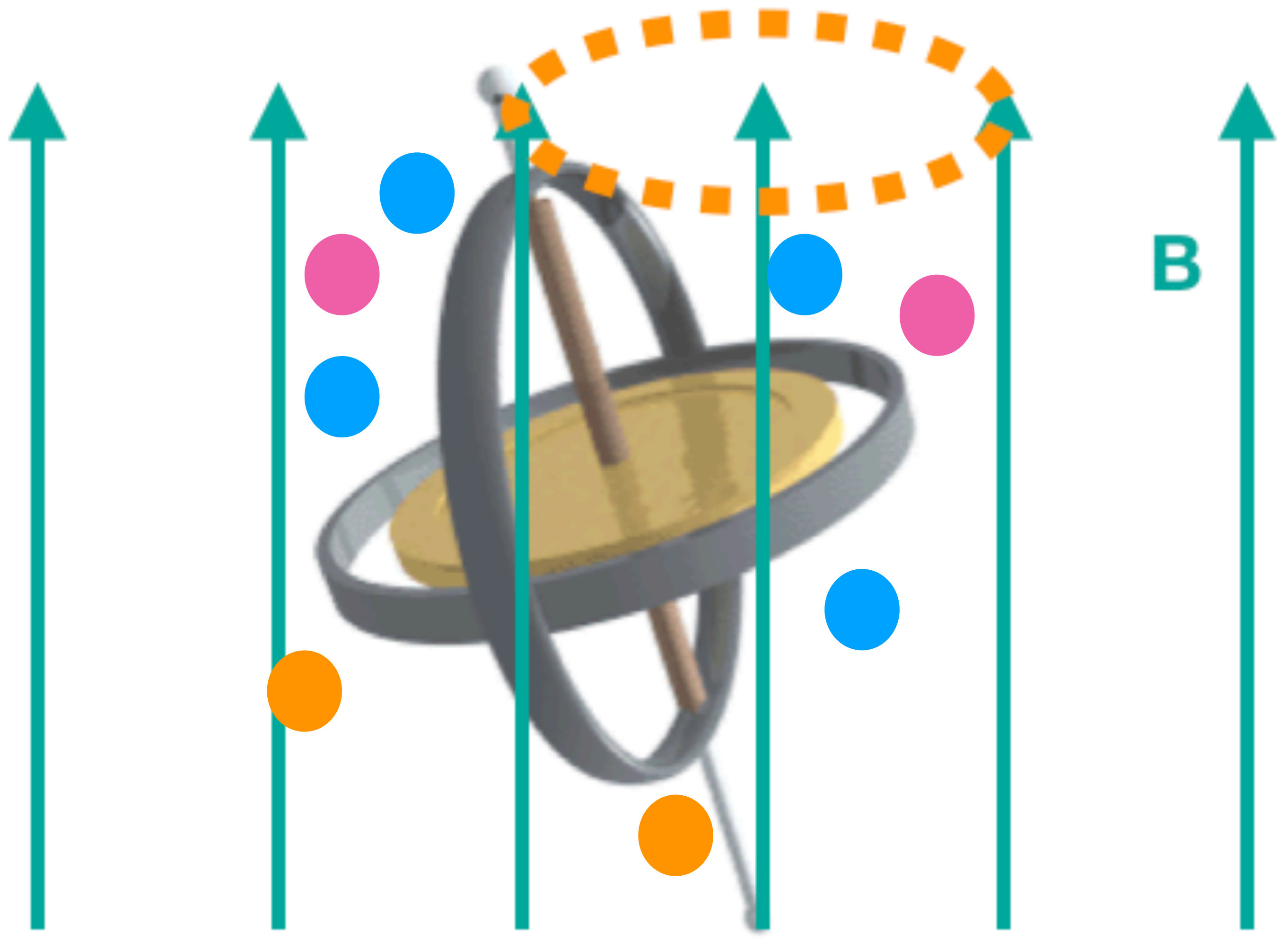
How much do vacuum interactions change g?

- Schwinger used the rapidly developing field of QED to predict the how much these interactions would change *g*



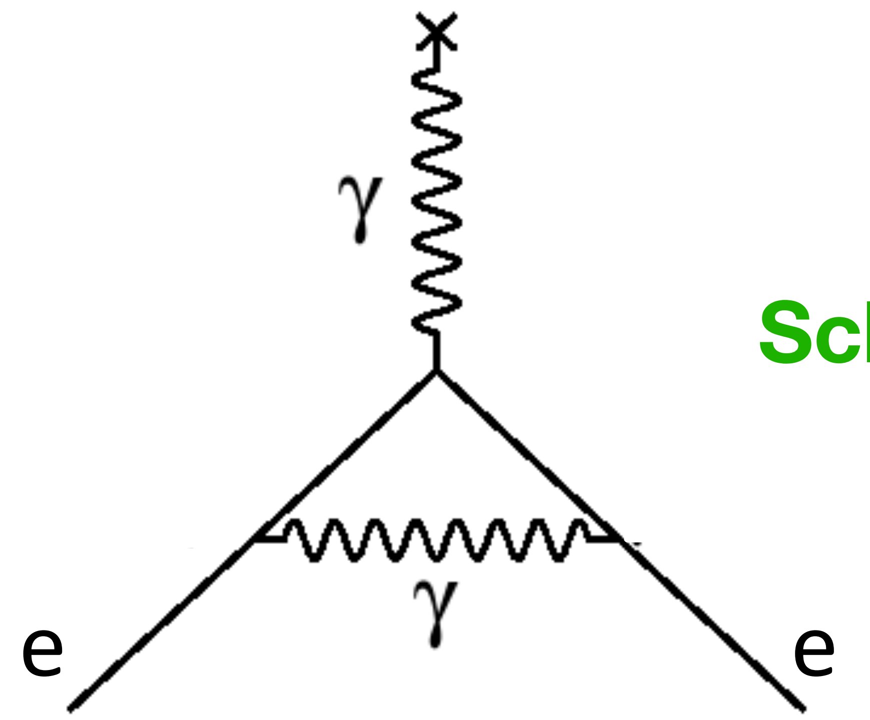
$$\mu = (1 + a)\frac{q\hbar}{2m} \qquad a = \frac{g-2}{2}$$

Dirac term

Schwinger term

$$g \approx 2\left(1 + \frac{\alpha}{2\pi}\right) \approx 2.00232$$

Agrees with experiment!



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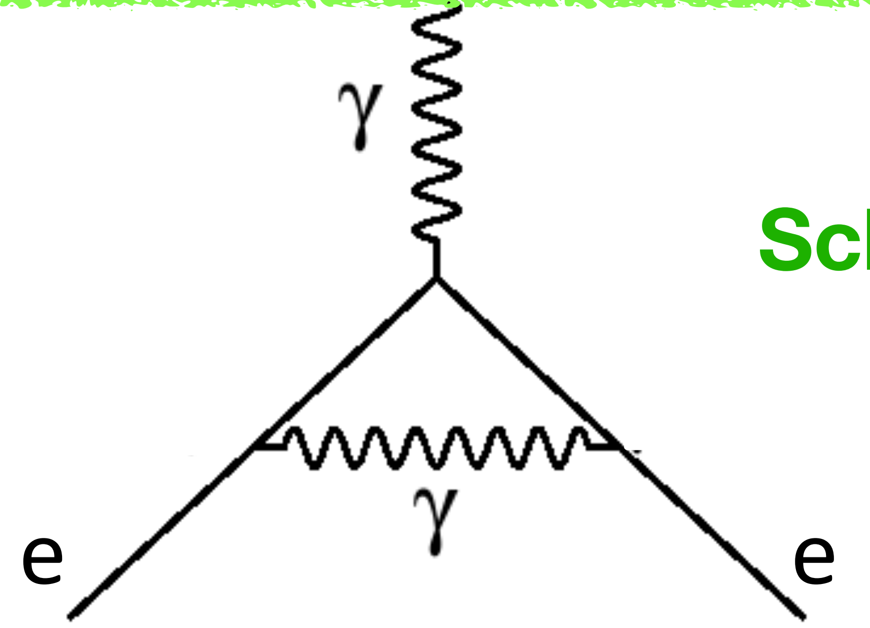

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Not just one correction…

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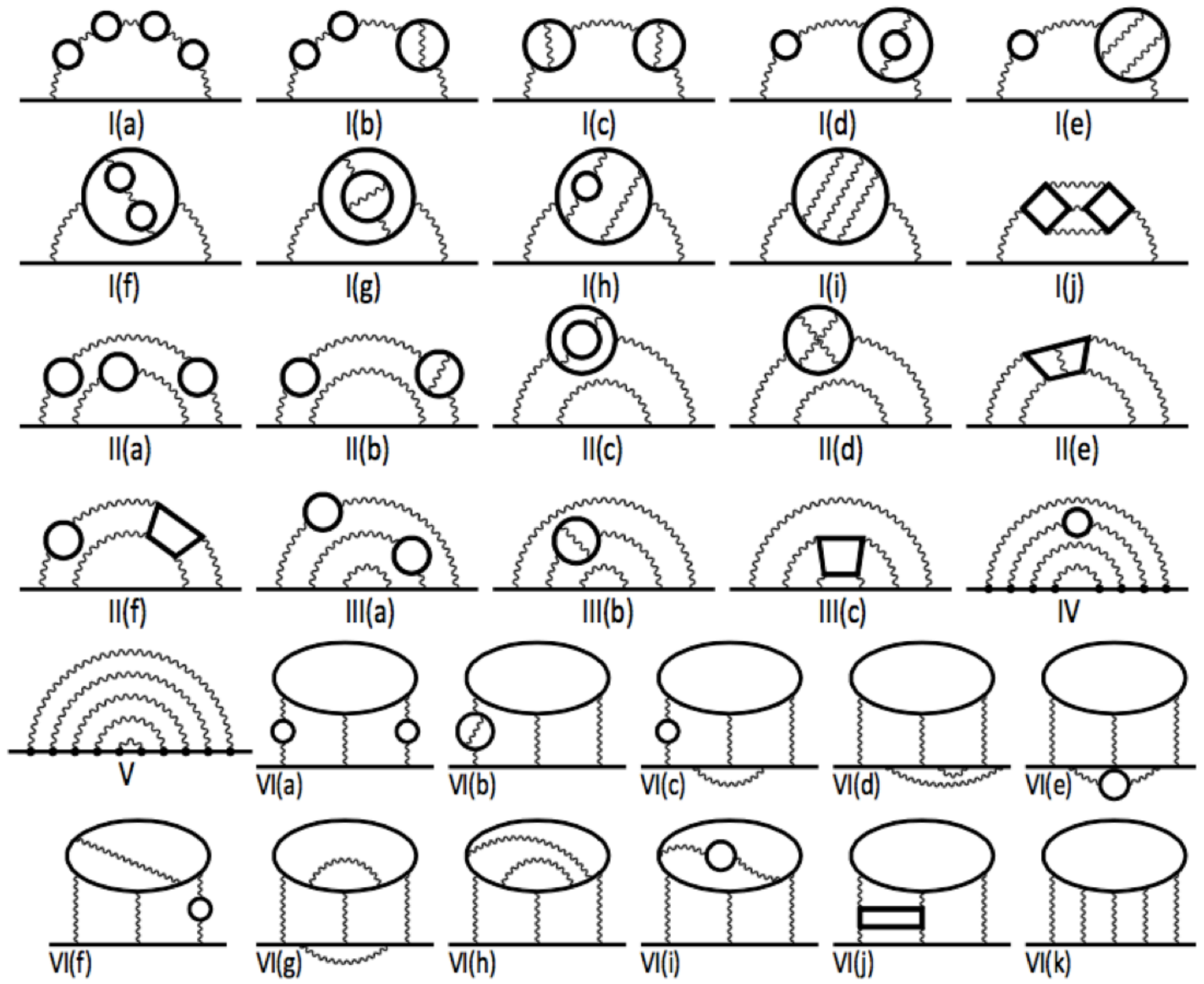
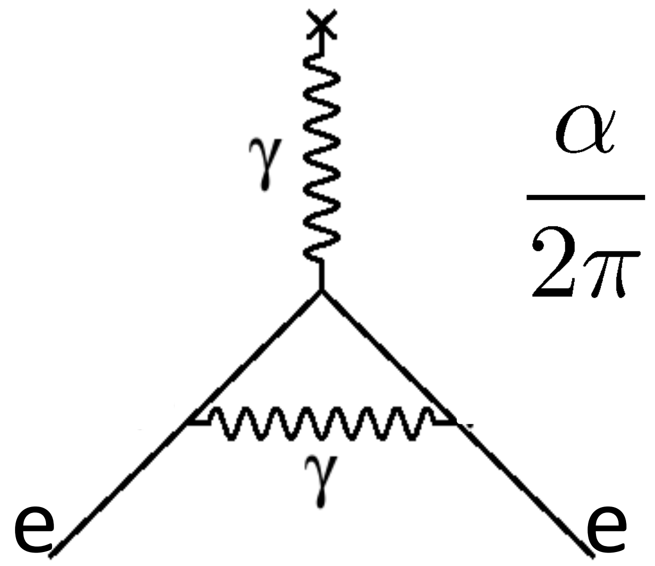


12672 QED diagrams!

- For electrons, QED tells the full story
- SM prediction of a_e agrees with experiment at ppt level!
- Muons are more complicated because they are heavier
- Sensitivity to other types of interaction scales as $\left(\frac{m_\mu}{m_e}\right)^2$

g = 2.00232

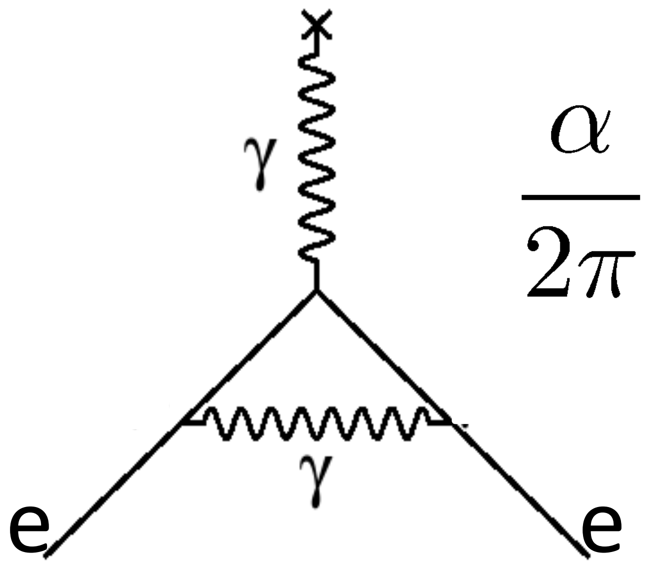
Schwinger: QED (1st order)



$$\frac{\alpha}{2\pi} = 0.00232$$

$g = 2.0023238$

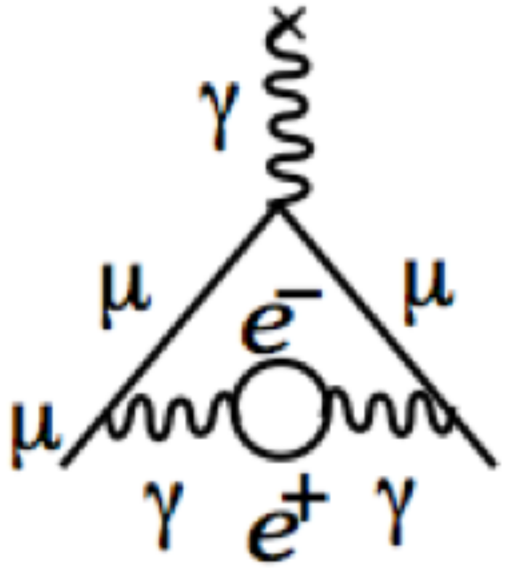
Schwinger: QED (1st order)



$$\frac{\alpha}{2\pi} = 0.00232$$

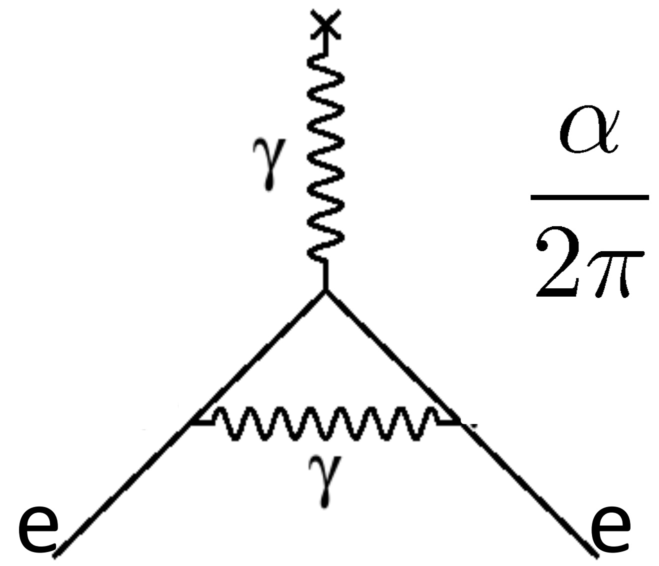
Kinoshita et. al. : QED (up to 10th order)

12,672 x



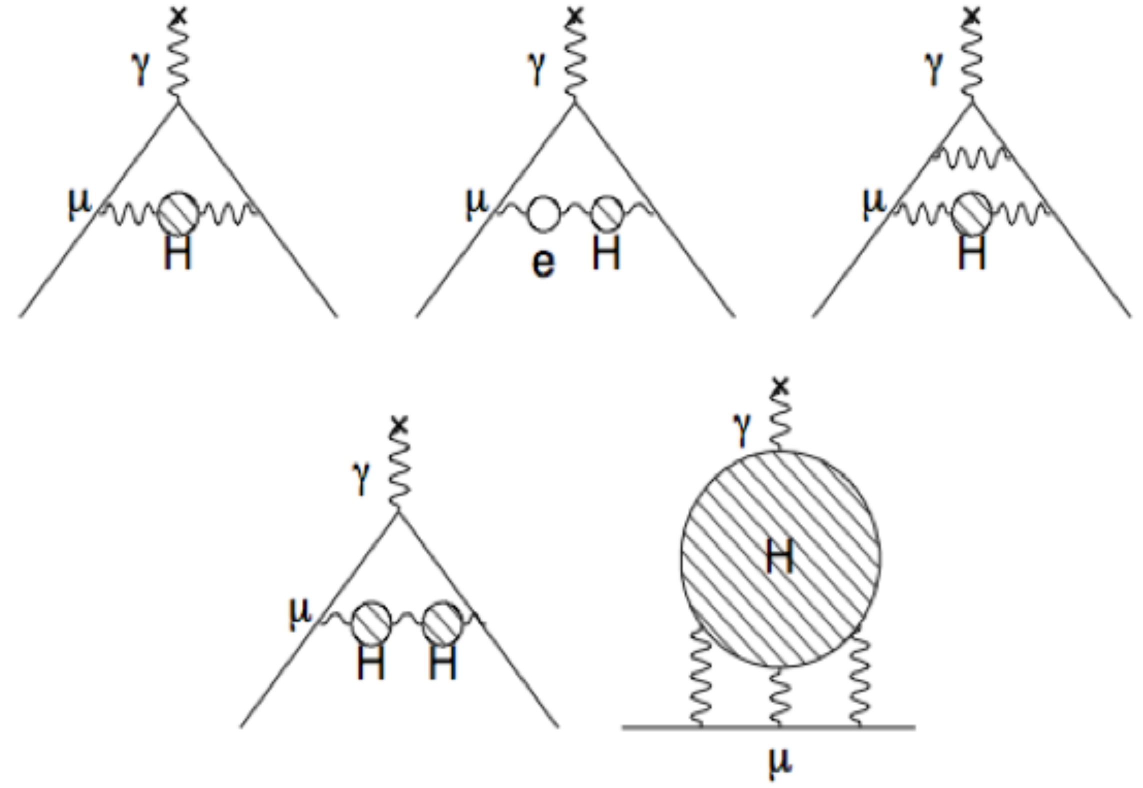
$g = 2.002323884$

Schwinger: QED (1st order)



$$\frac{\alpha}{2\pi} = 0.00232$$

Hadronic – dominant uncertainty on prediction



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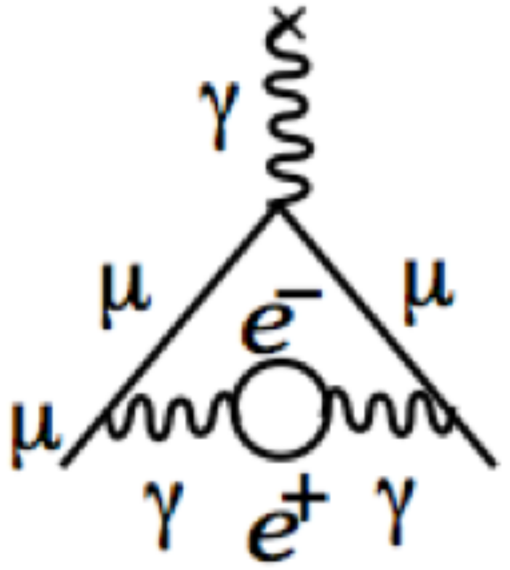
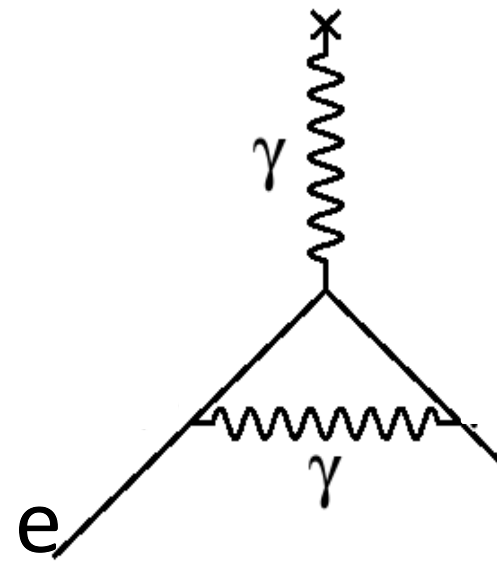


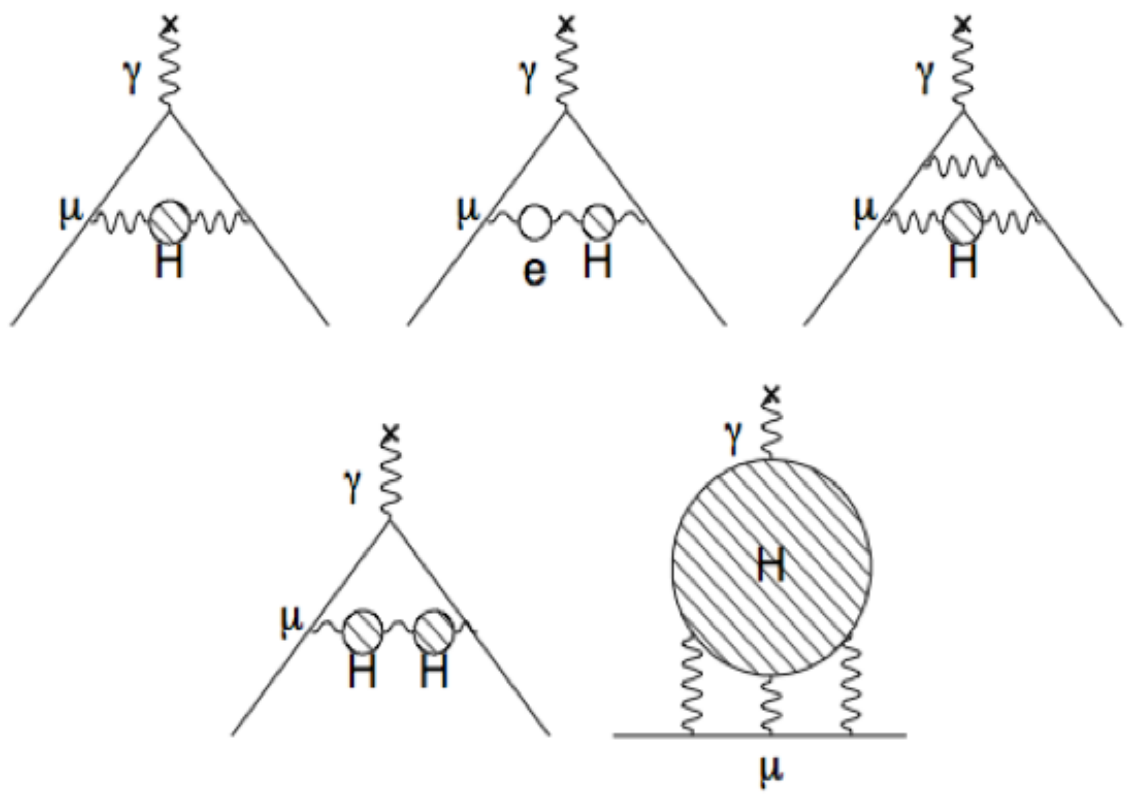
g = 2.0023238417

Schwinger: QED (1st order)



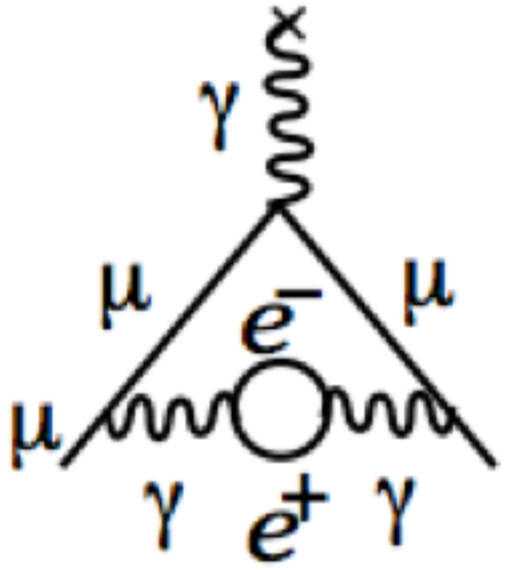
$$\frac{\alpha}{2\pi} = 0.00232$$

Hadronic – dominant uncertainty on prediction

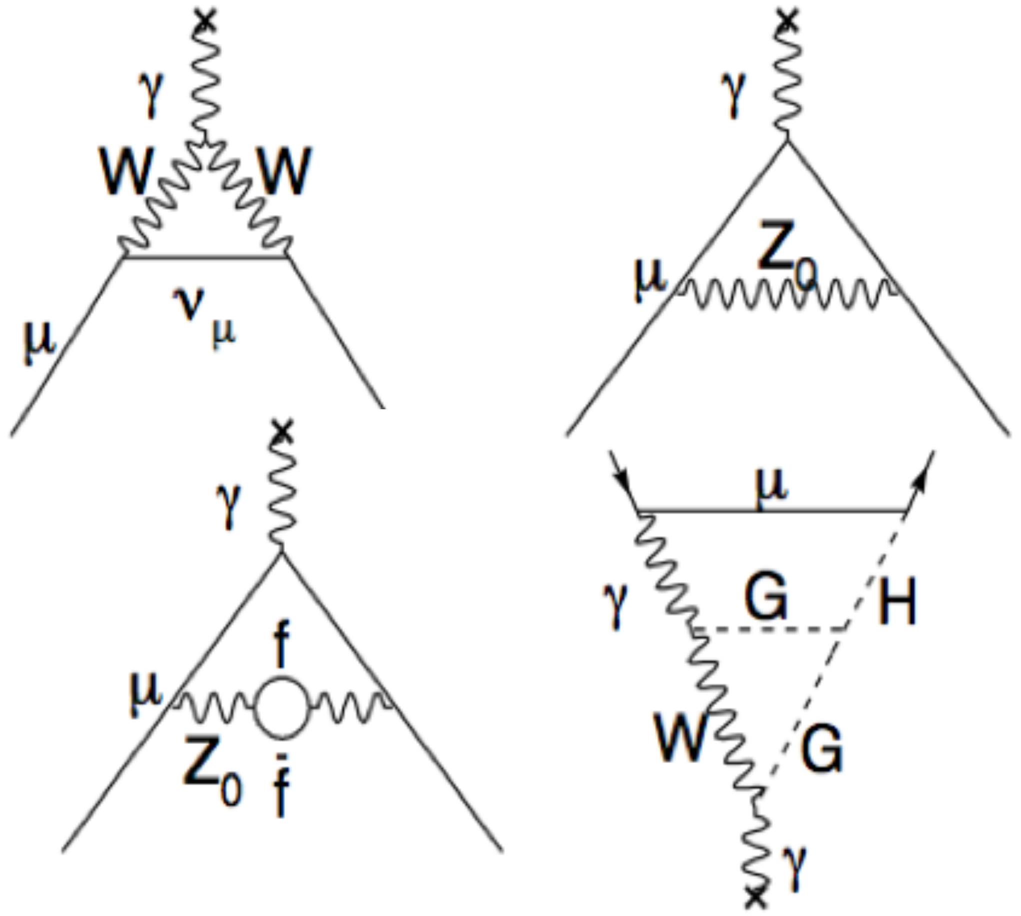


Kinoshita et. al. : QED (up to 10th order)

12,672 x



Electroweak



$g = 2.0023323884178(126)$

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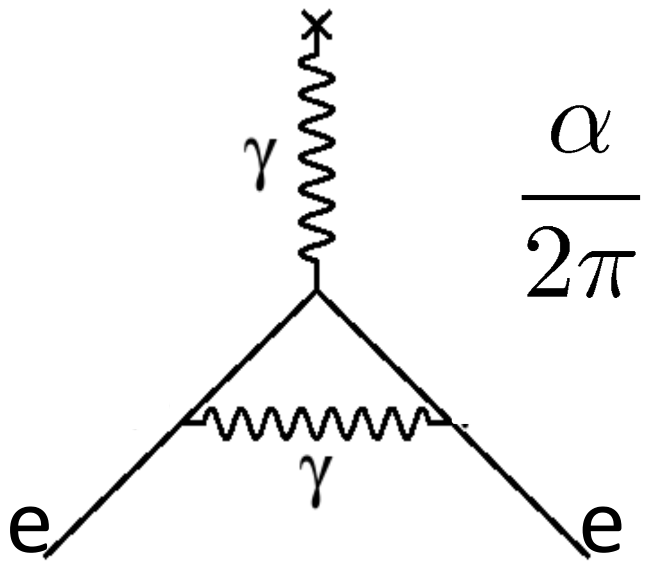

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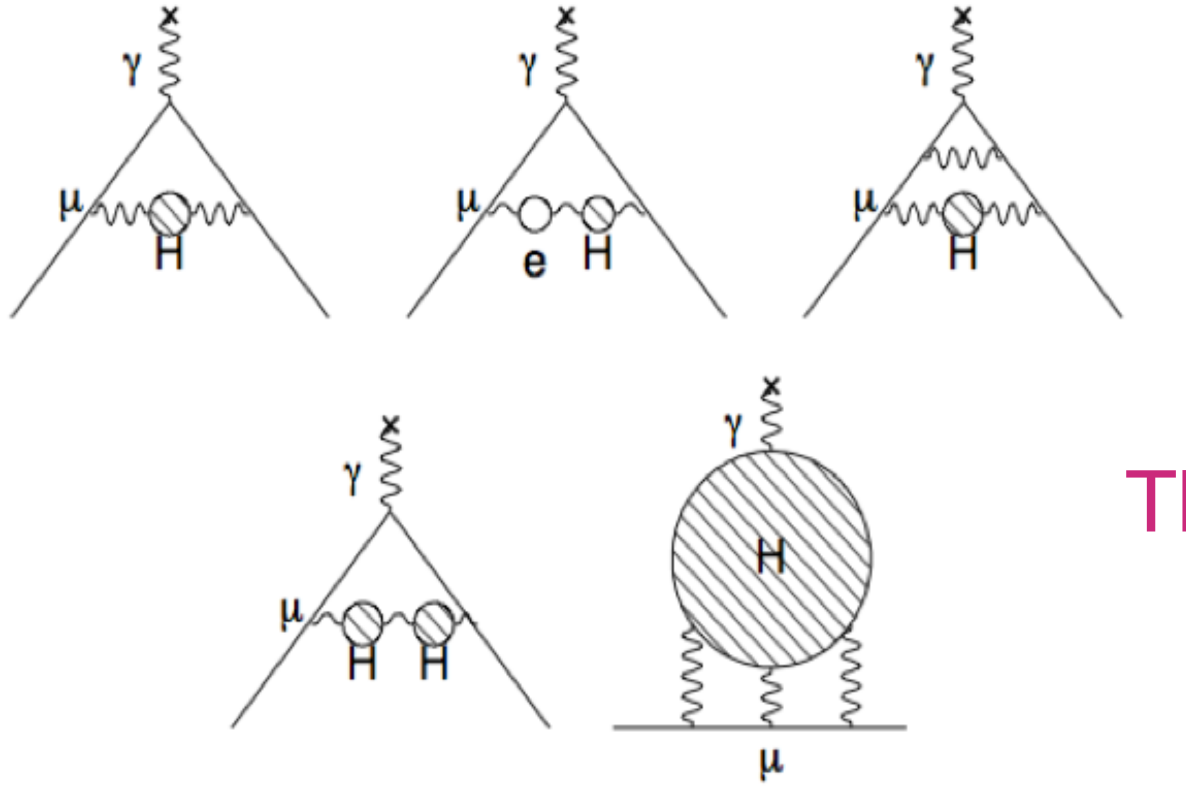

???

Theorists are working to reduce uncertainty by a factor of 2

Kinoshita et. al. : QED (up to 10th order)

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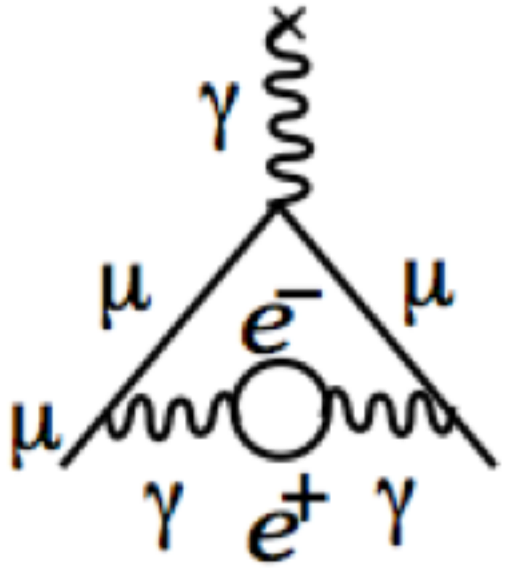

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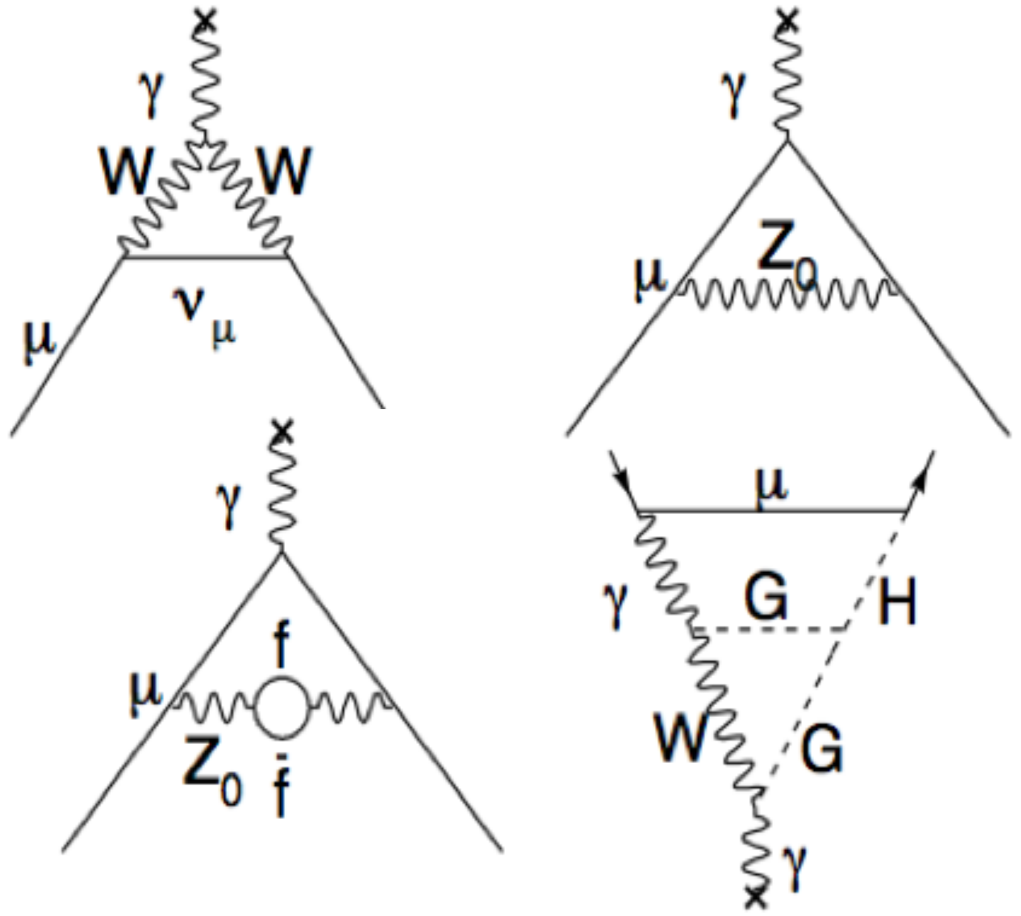

Fermilab

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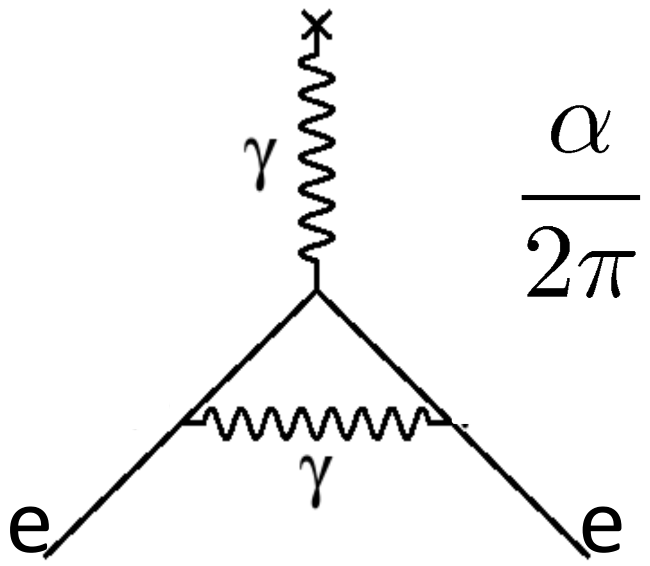

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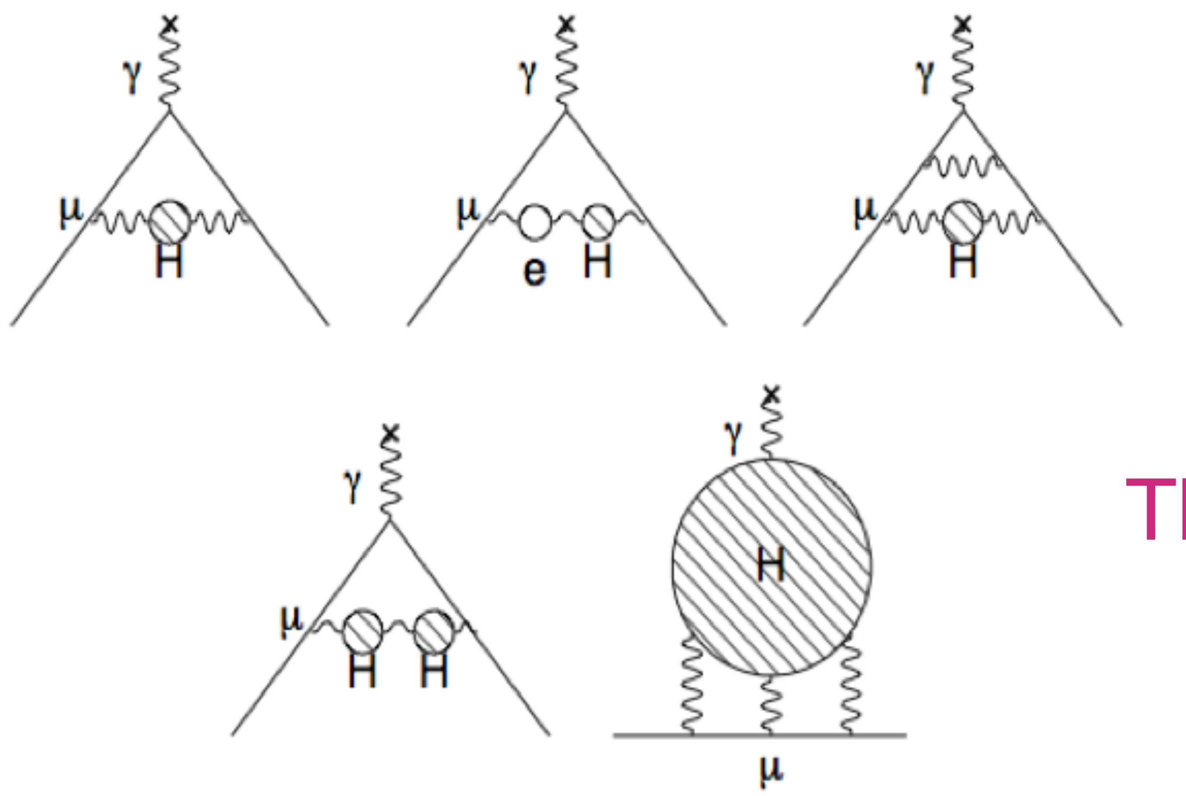

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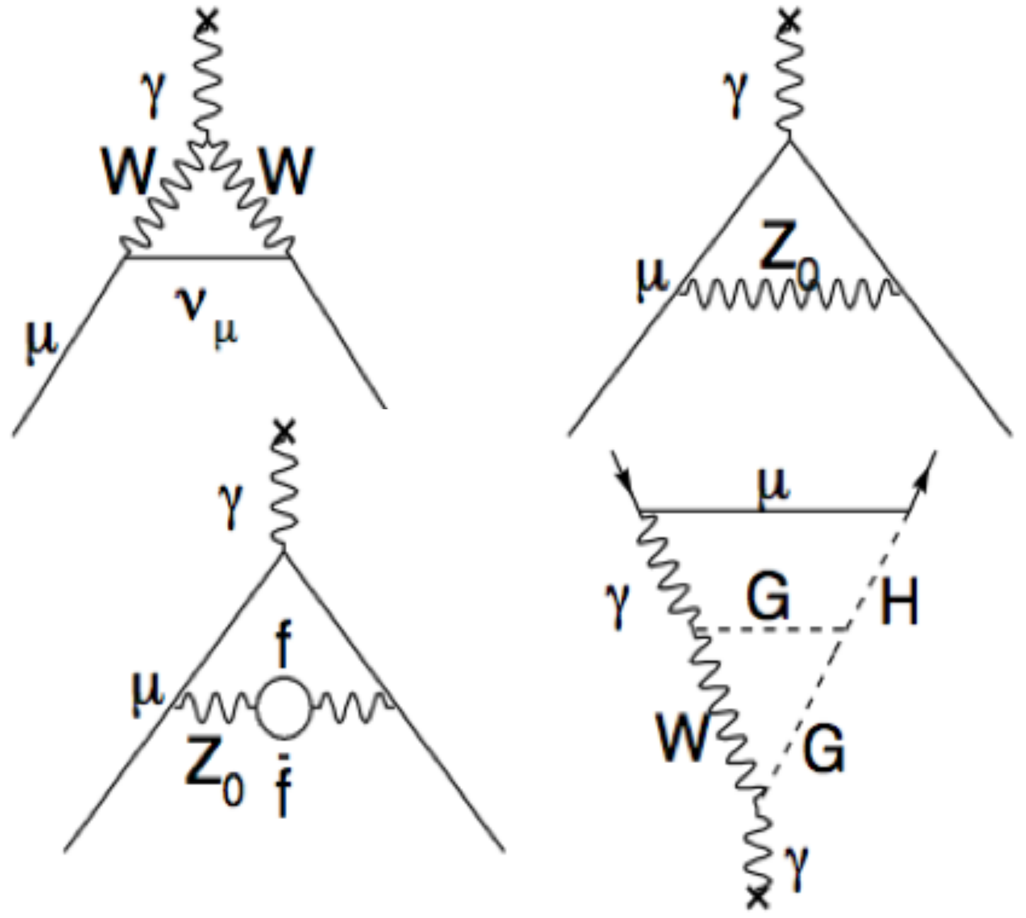

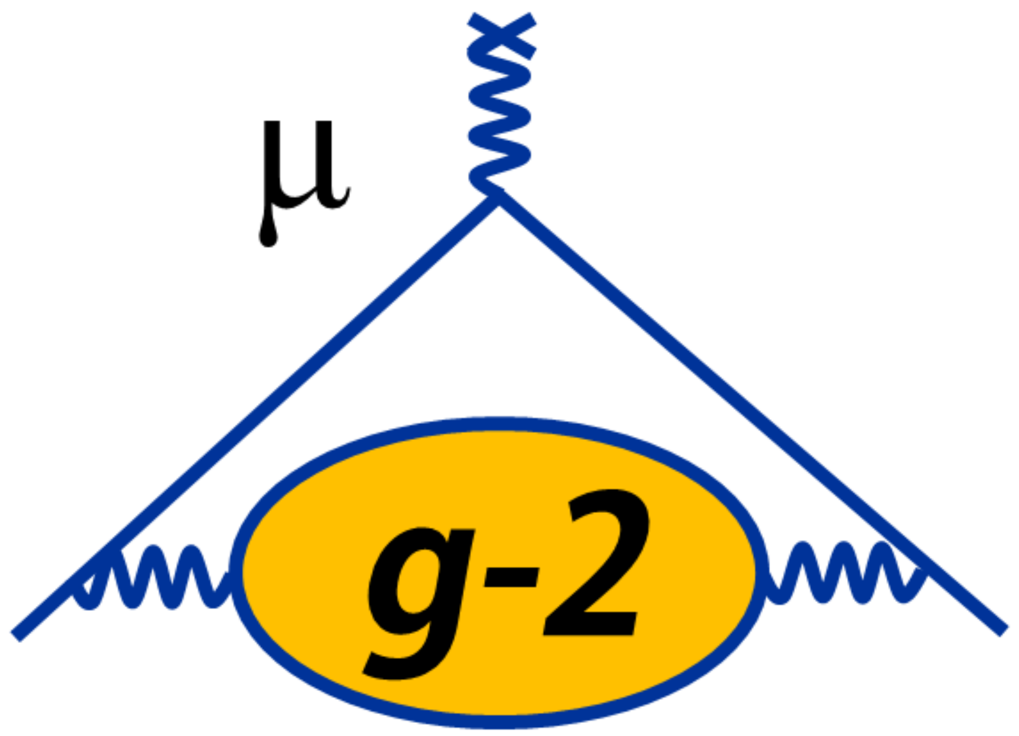

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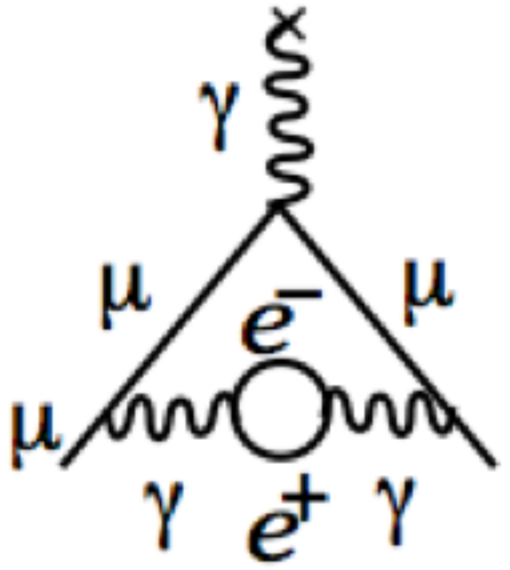


Fermilab

Comparing the numbers

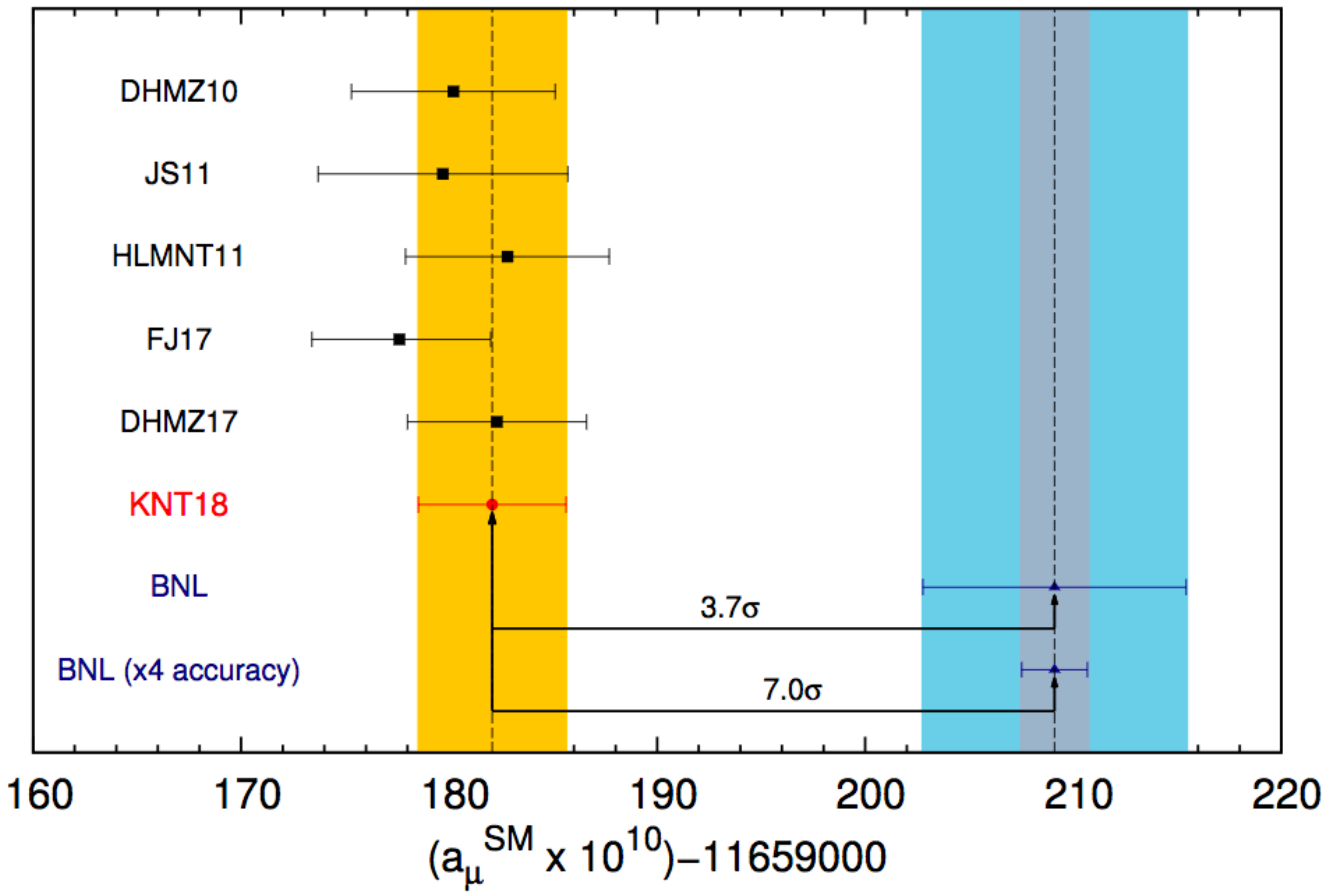
- Current best measurement of g comes from the Brookhaven g-2 experiment

$$a_\mu^{exp} = 116\,592\,089\,(54)_{st}\,(33)_{sy}\,(63)_{tot} \times 10^{-11}$$

- It's different from the theory by around 3 – 4 σ!

- This measurement caused an international sensation — it's the second-most cited publication in the field of particle physics!

- How can it be different? What's missing from the theory?



Fermilab

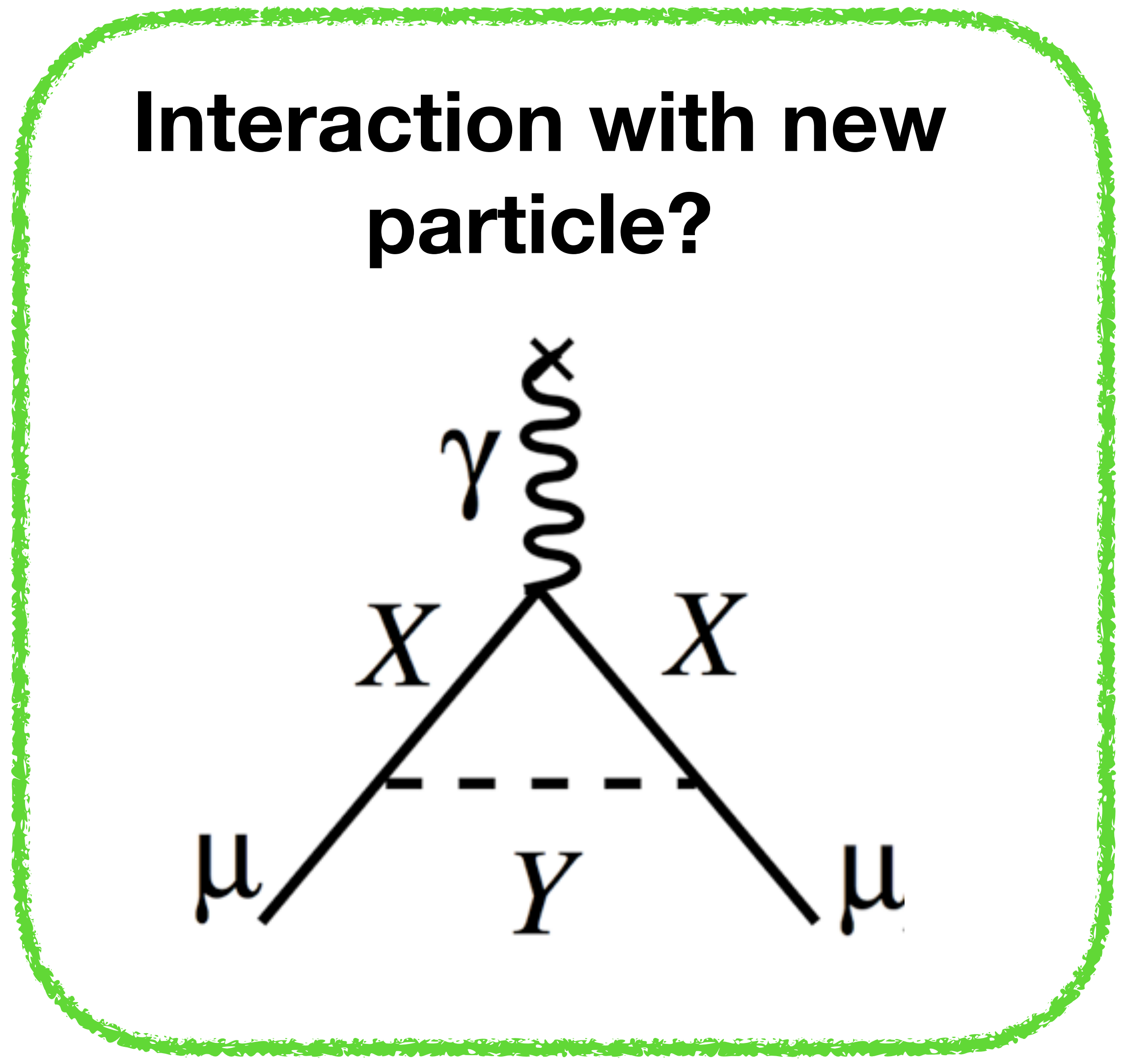
Comparing the numbers

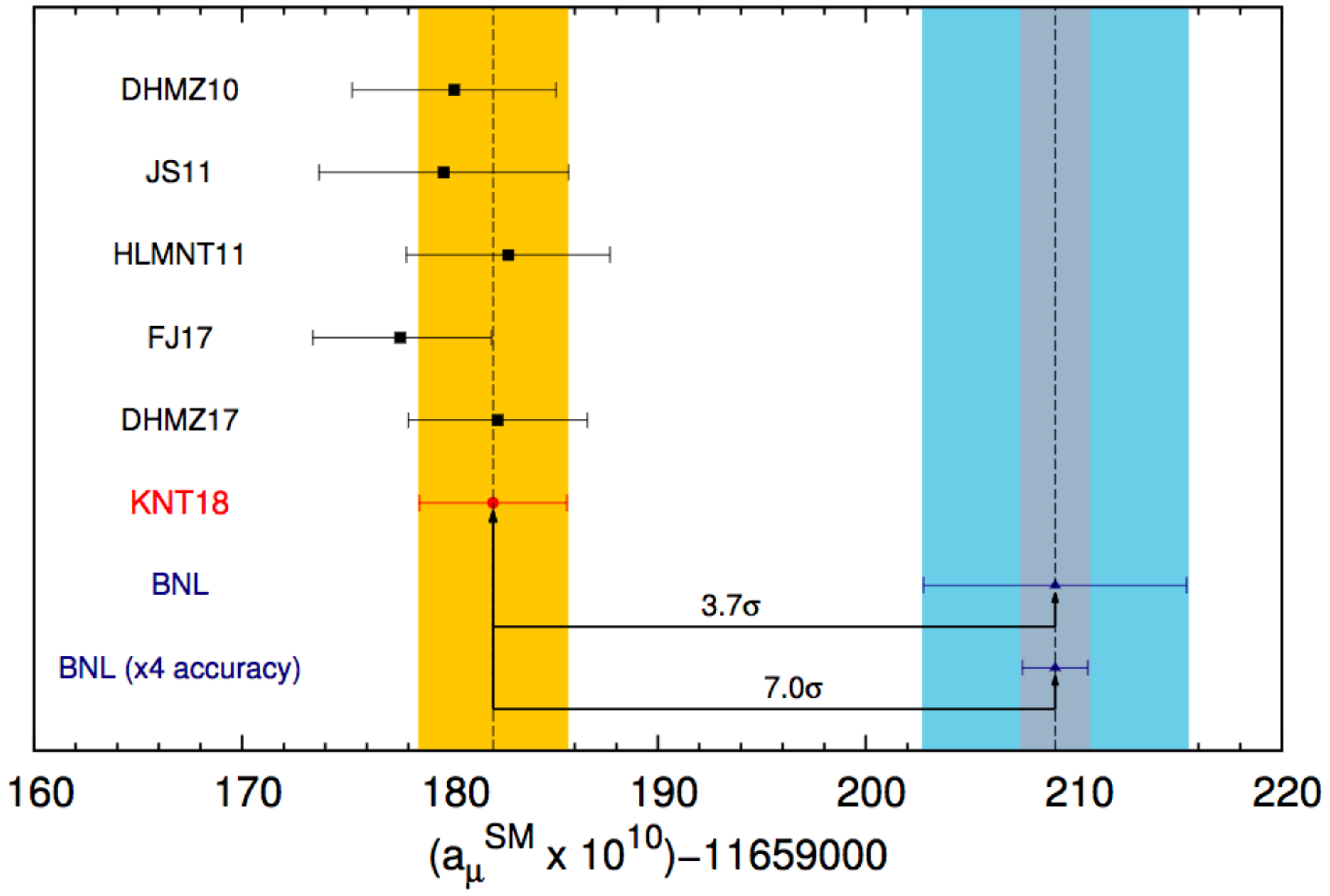
- The reason this discrepancy is so exciting is that the only way theorists think it could happen is if non-SM particles were interacting with the muon

- The size of the discrepancy could tell us about the mass range of new particles — focus the broad searches at colliders more precisely

- But, we can't be sure — need 5σ for discovery

- We need to reduce the error bars to compare more conclusively





We need more muons!

- Best way to get smaller error bars — higher statistics!

$$a_\mu^{exp} = 116\,592\,089\,(54)_{st}\,(33)_{sy}\,(63)_{tot} \times 10^{-11}$$

- We need 21x as much data as the Brookhaven experiment
- Move the experiment to Fermilab for its muon beam

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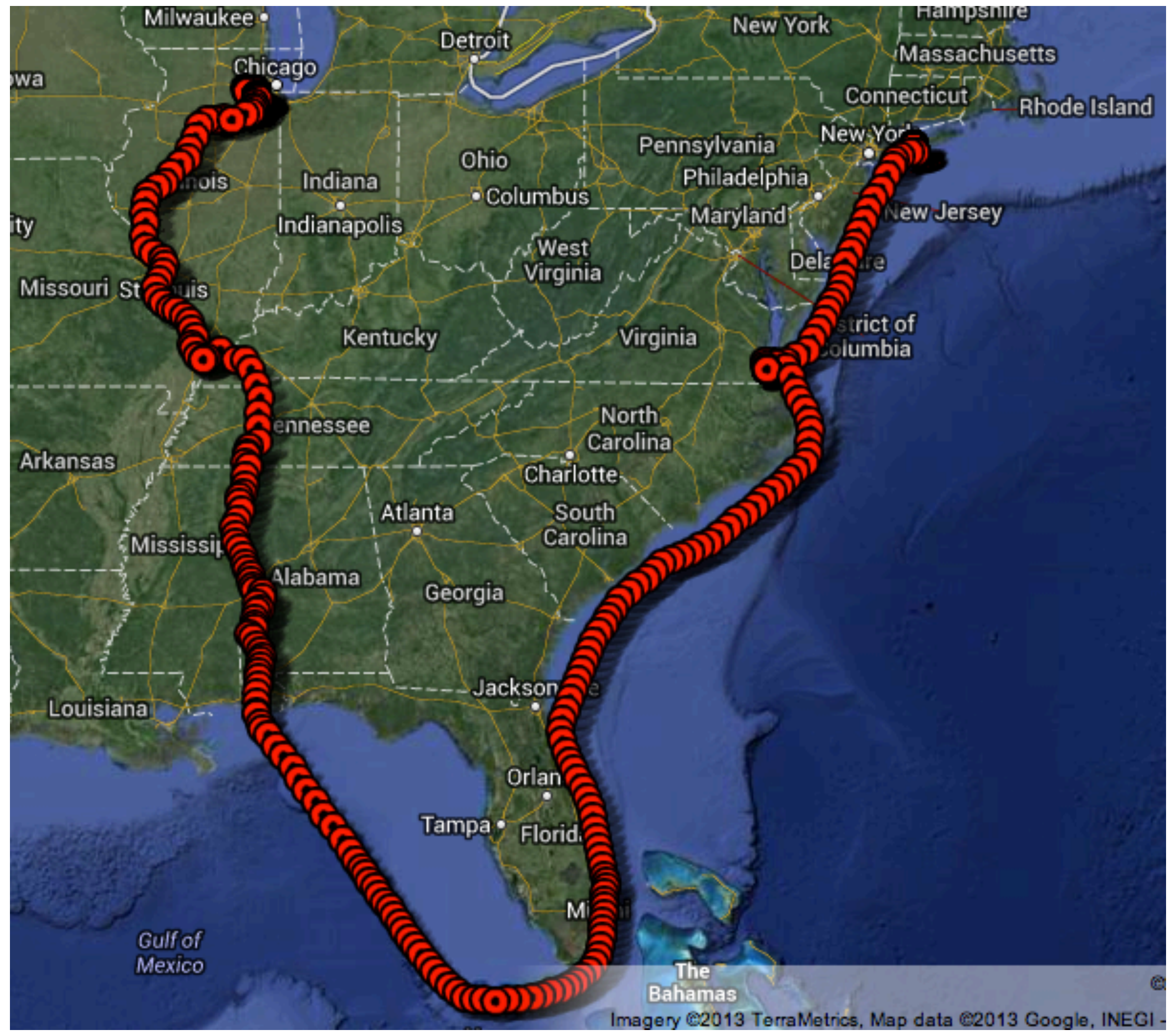

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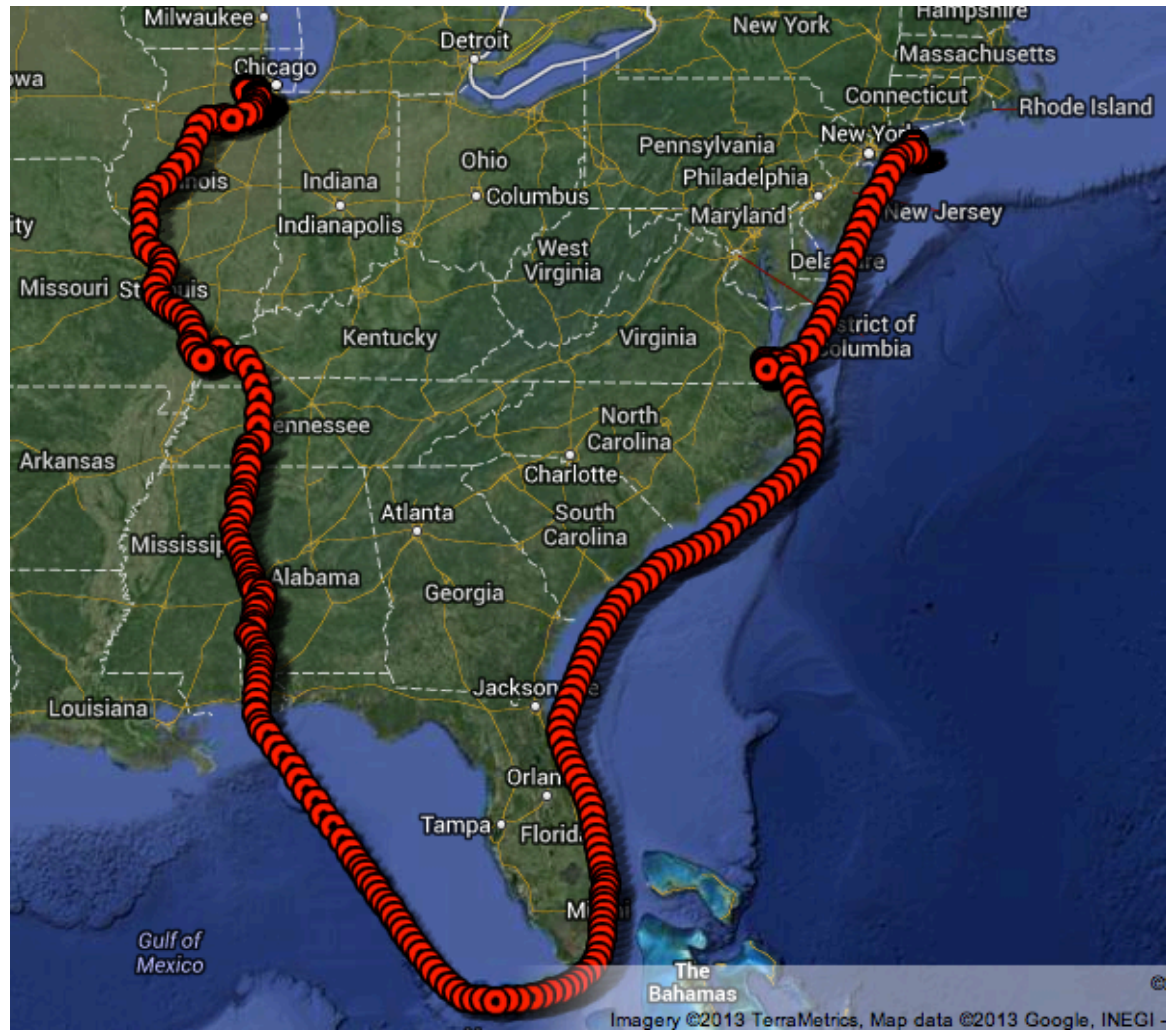
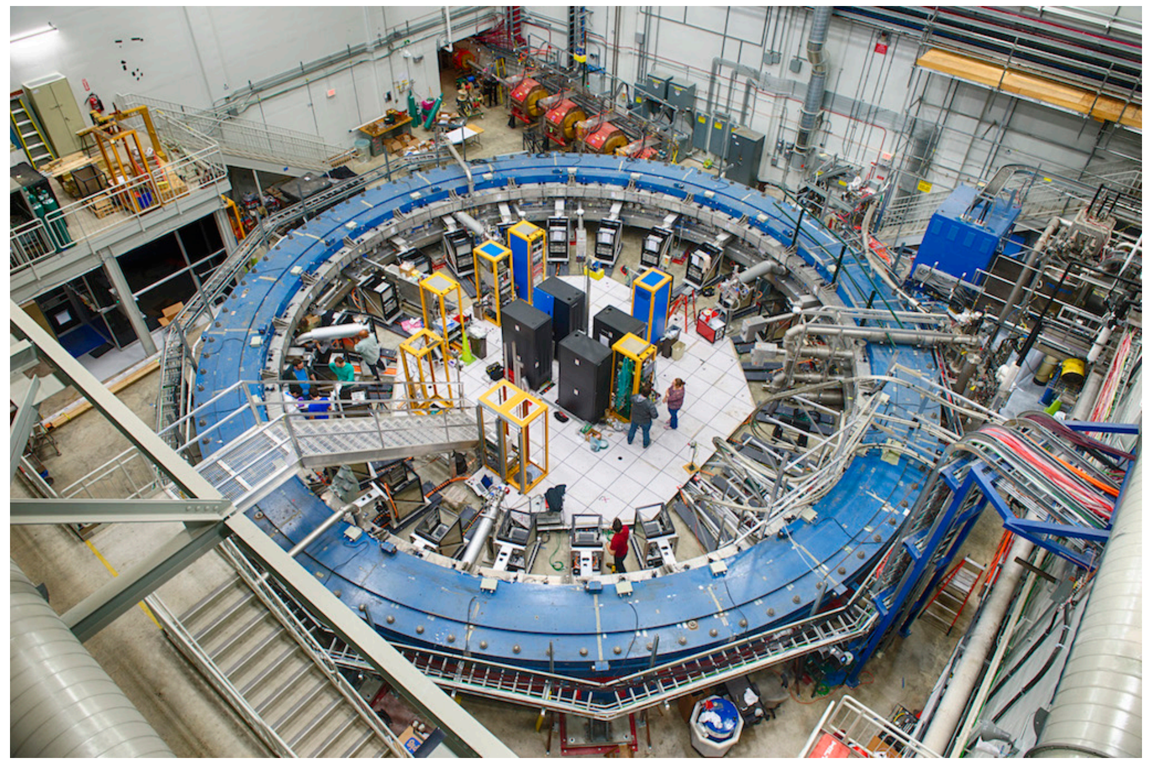


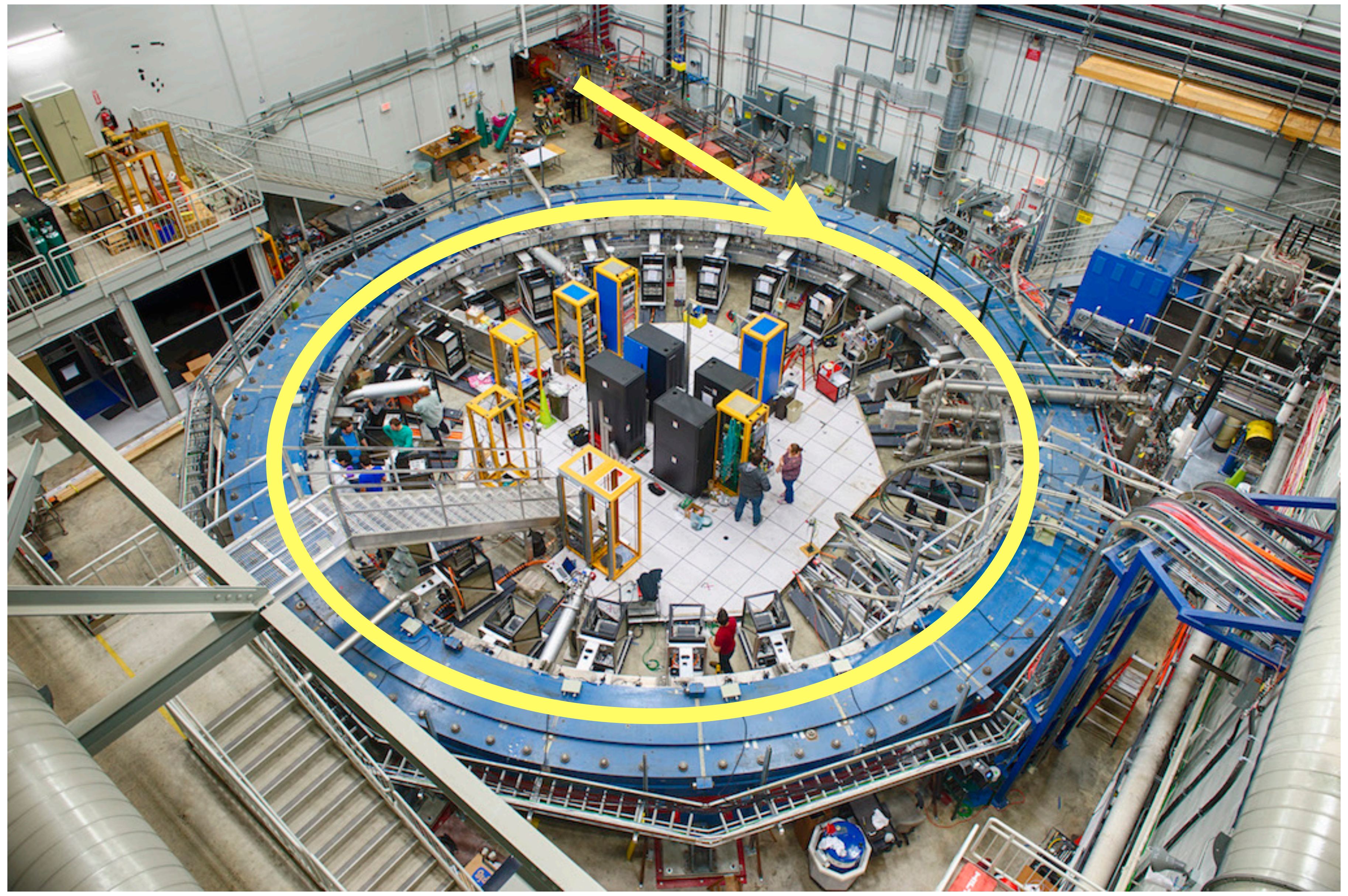


Fermilab

The Fermilab muon g-2 experiment

g-2 experimental principle

- Inject a beam of polarized muons into a magnetic storage ring
- Magnetic field is vertically aligned — very very precisely
- Muon circulates around storage ring hundreds of times
- A muon takes 149 ns to go around once
- Boosted lifetime is 64 μs (thanks, Special Relativity!)



g-2 experimental principle

- The circulating muon is described by two frequencies
- At injection, muon spin is aligned with its momentum (polarized beam)
- The muon circulates around the ring with frequency ω_c
- The spin vector precesses around the B field with frequency ω_s
- Difference between the two depends directly on anomalous magnetic moment

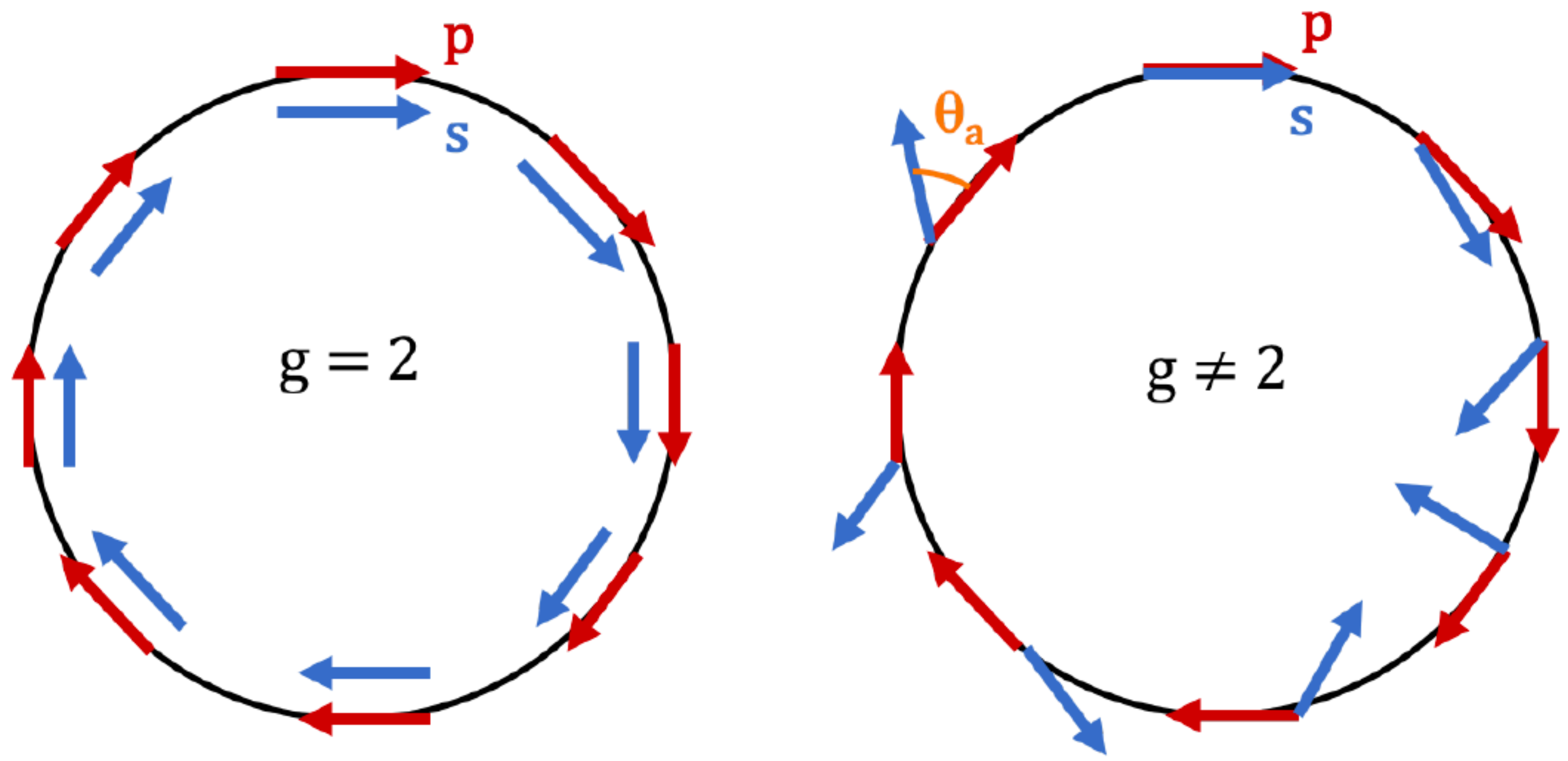
$$\omega_a = \omega_s - \omega_c = \left(\frac{g}{2} - 1\right)\frac{eB}{m} = a_\mu \frac{eB}{m}$$

Cyclotron frequency

$$\omega_c = \frac{eB}{m}$$

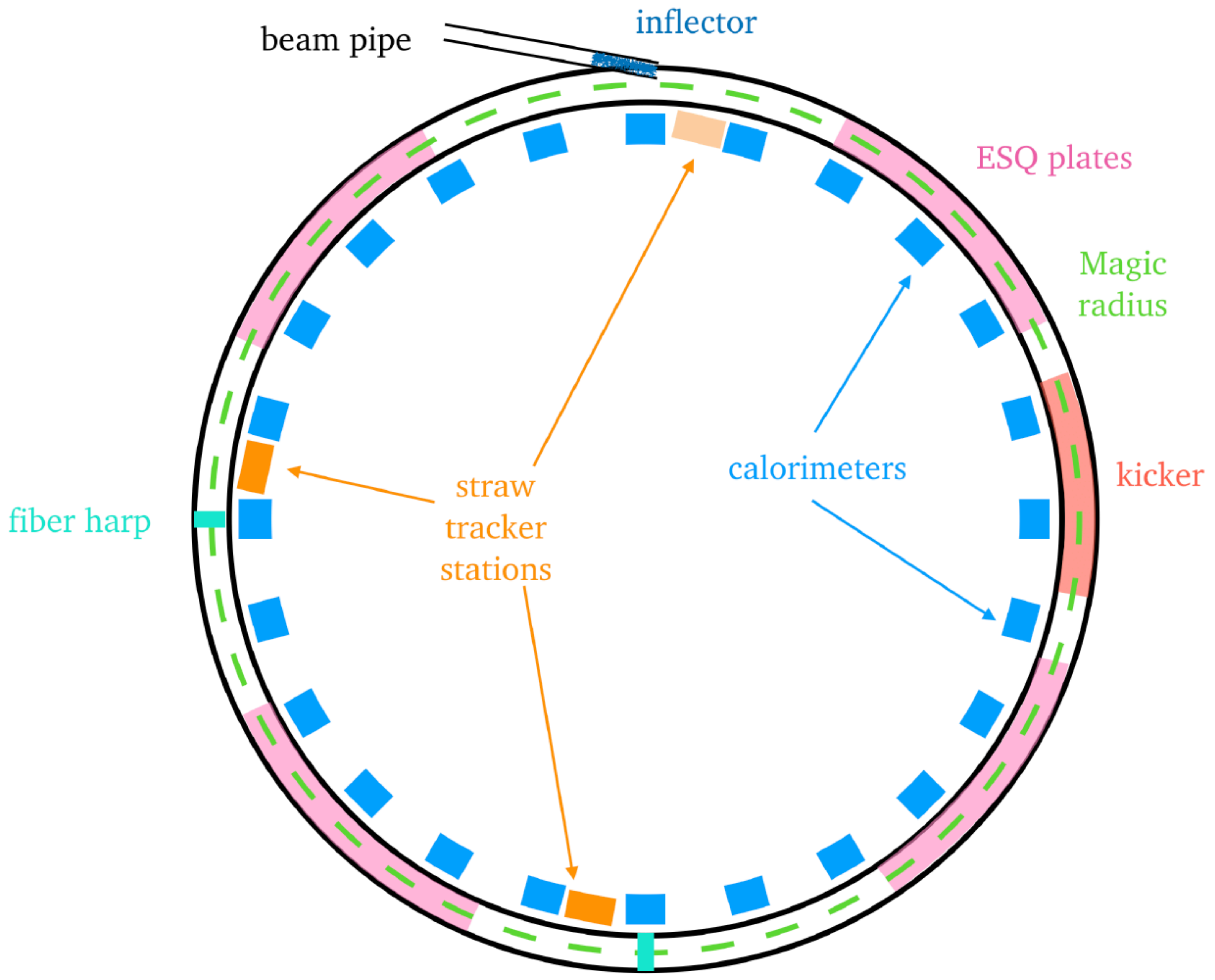
Larmor frequency

$$\omega_s = g\frac{eB}{2m}$$

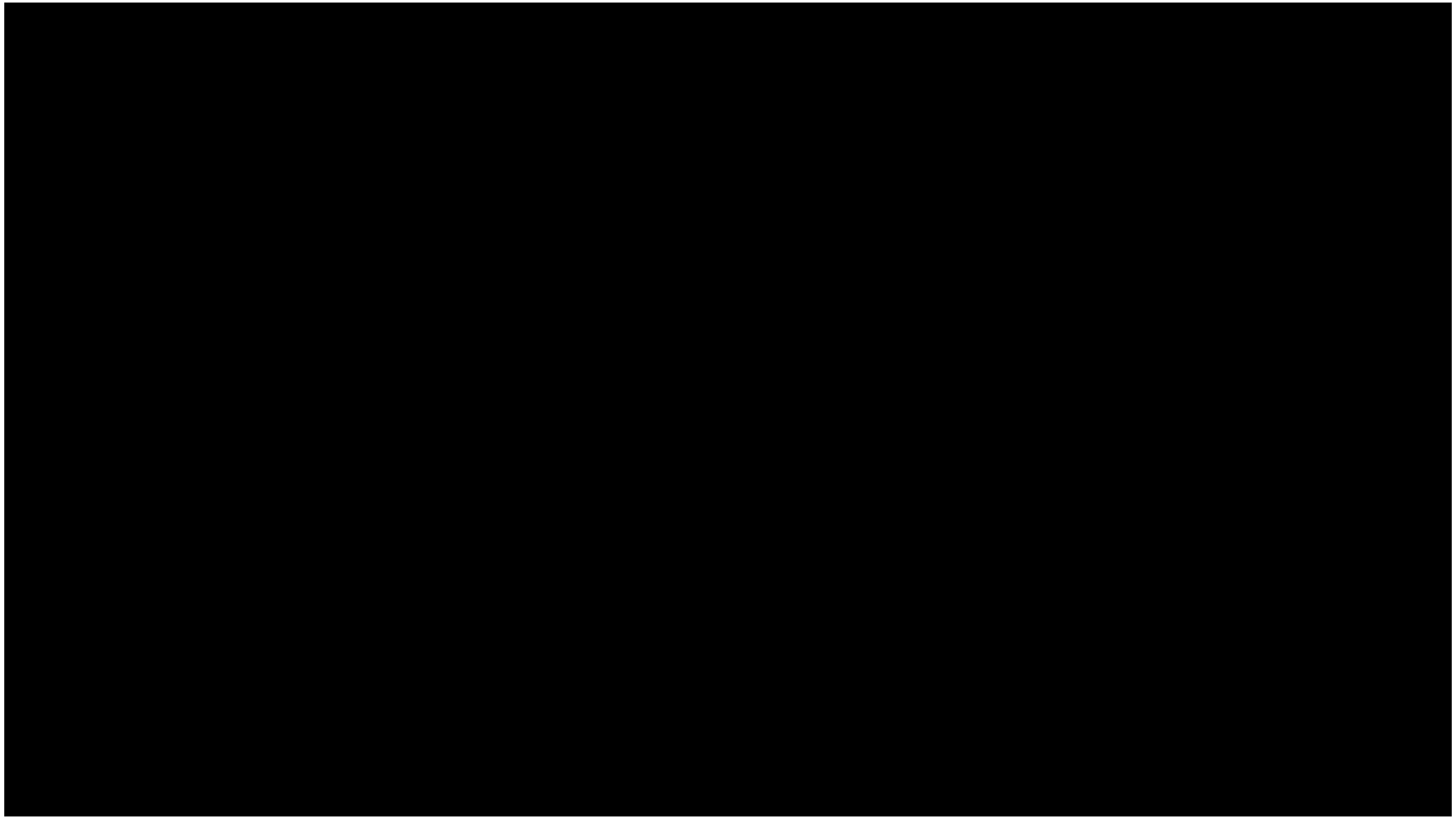


Measuring ω_a

- When they enter the ring, all muons have spin pointing the same way (fully polarized beam)
- At some random time they will spontaneously decay to e+
- The emitted e+ have lower momentum than the parent muons, so they curl into the center of the ring
- Detect the decay e+ with calorimeter detectors (measure the energy and time of arrival of the incident particle)



Inside the storage ring



Inside the storage ring

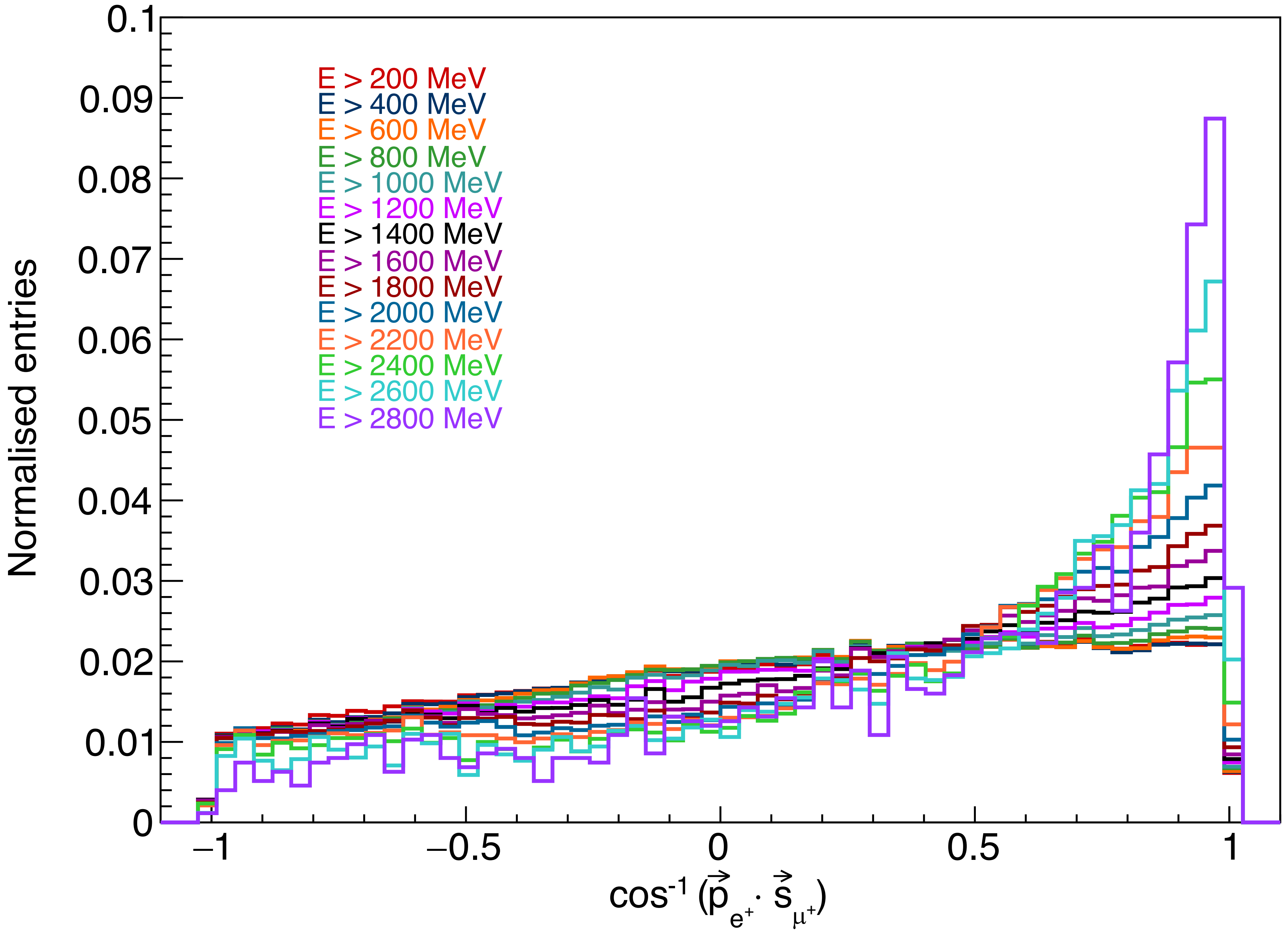
Measuring ω_a

- Two important features of muon decay enable us to measure ω_a directly

1: Decay positrons are preferentially emitted in the direction of the muon spin

2: Momentum of the decay positrons is correlated with their emission direction

- Highest energy positrons have the strongest correlation between their momentum and spin directions



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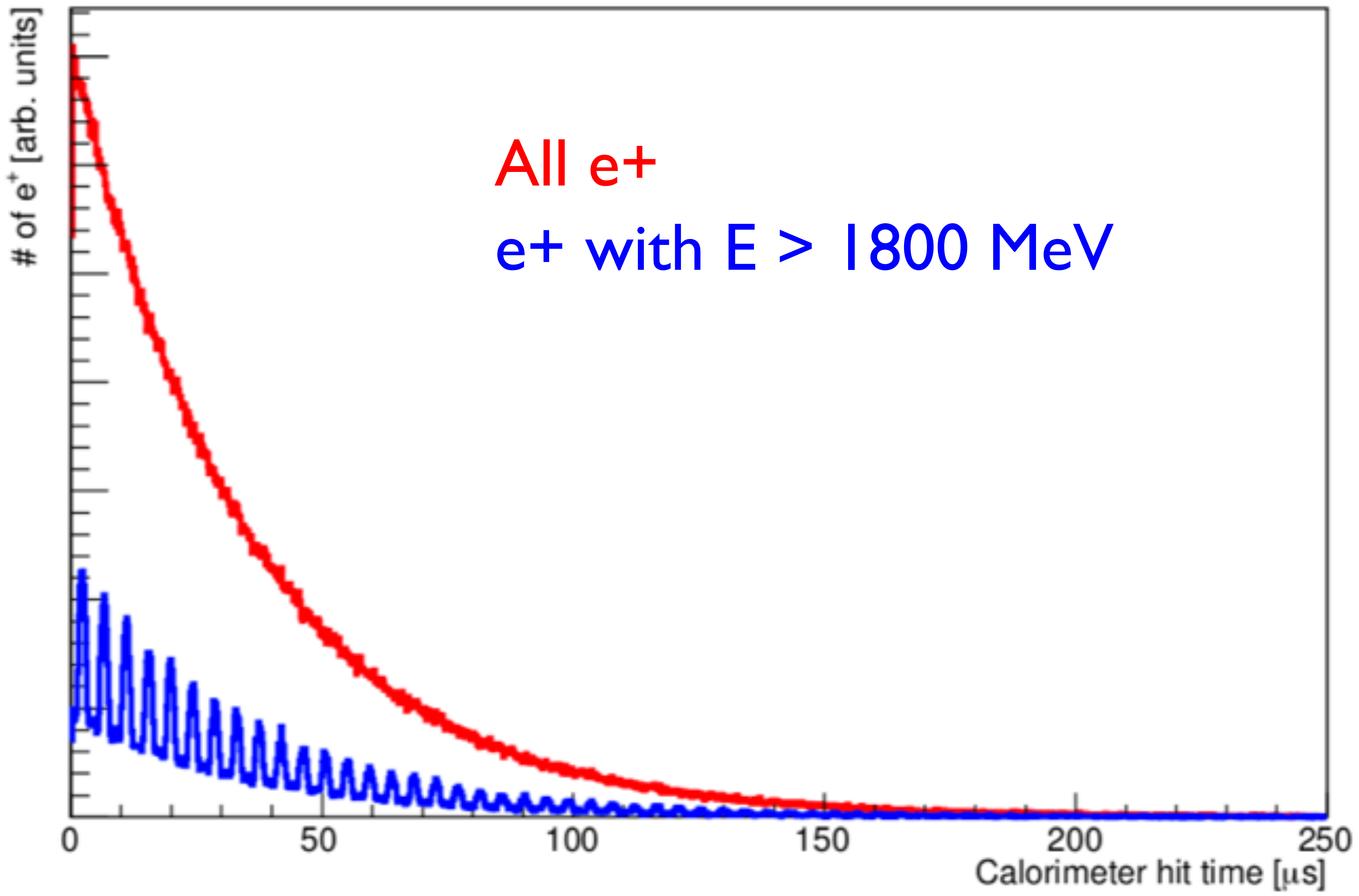
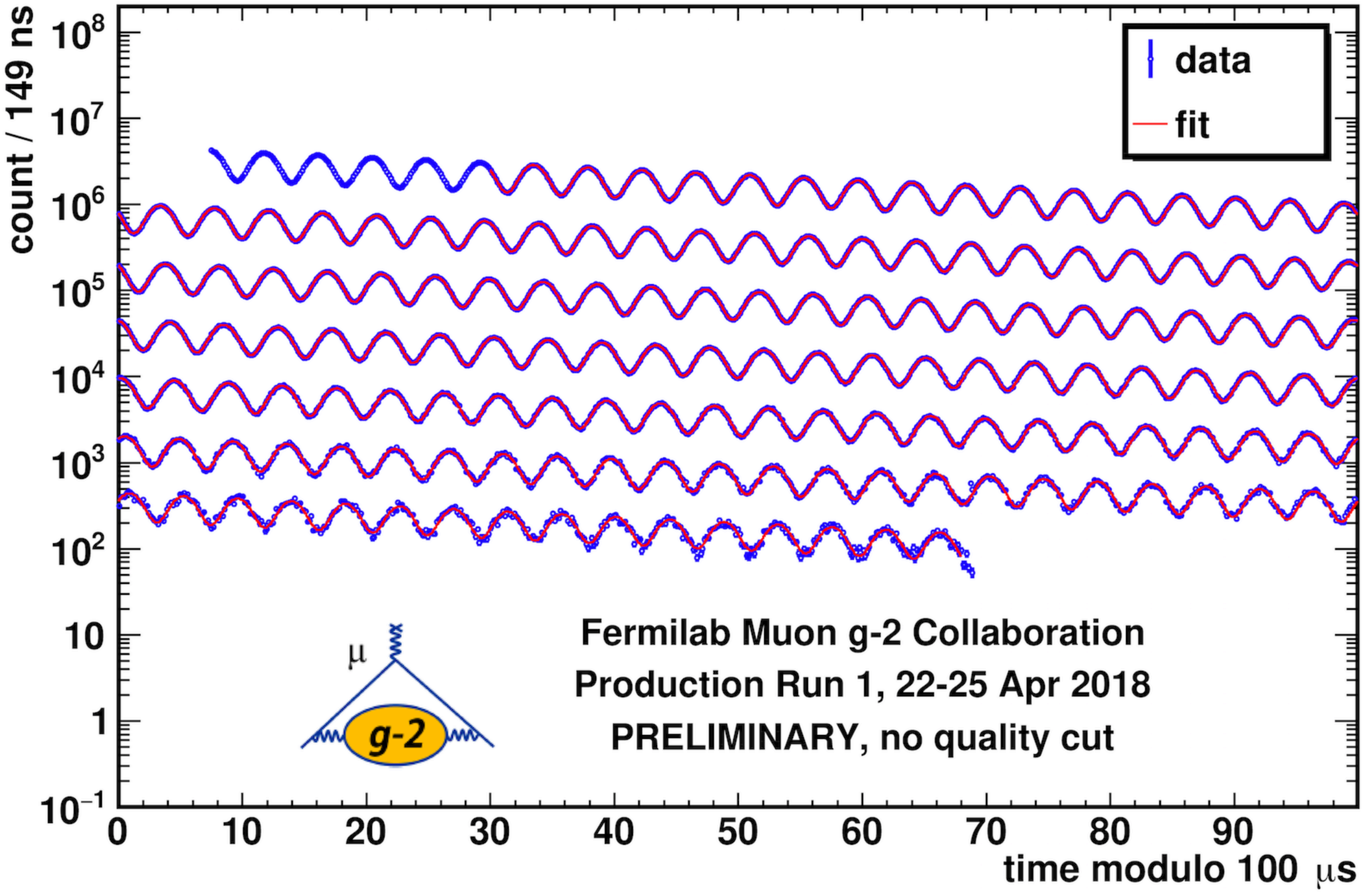
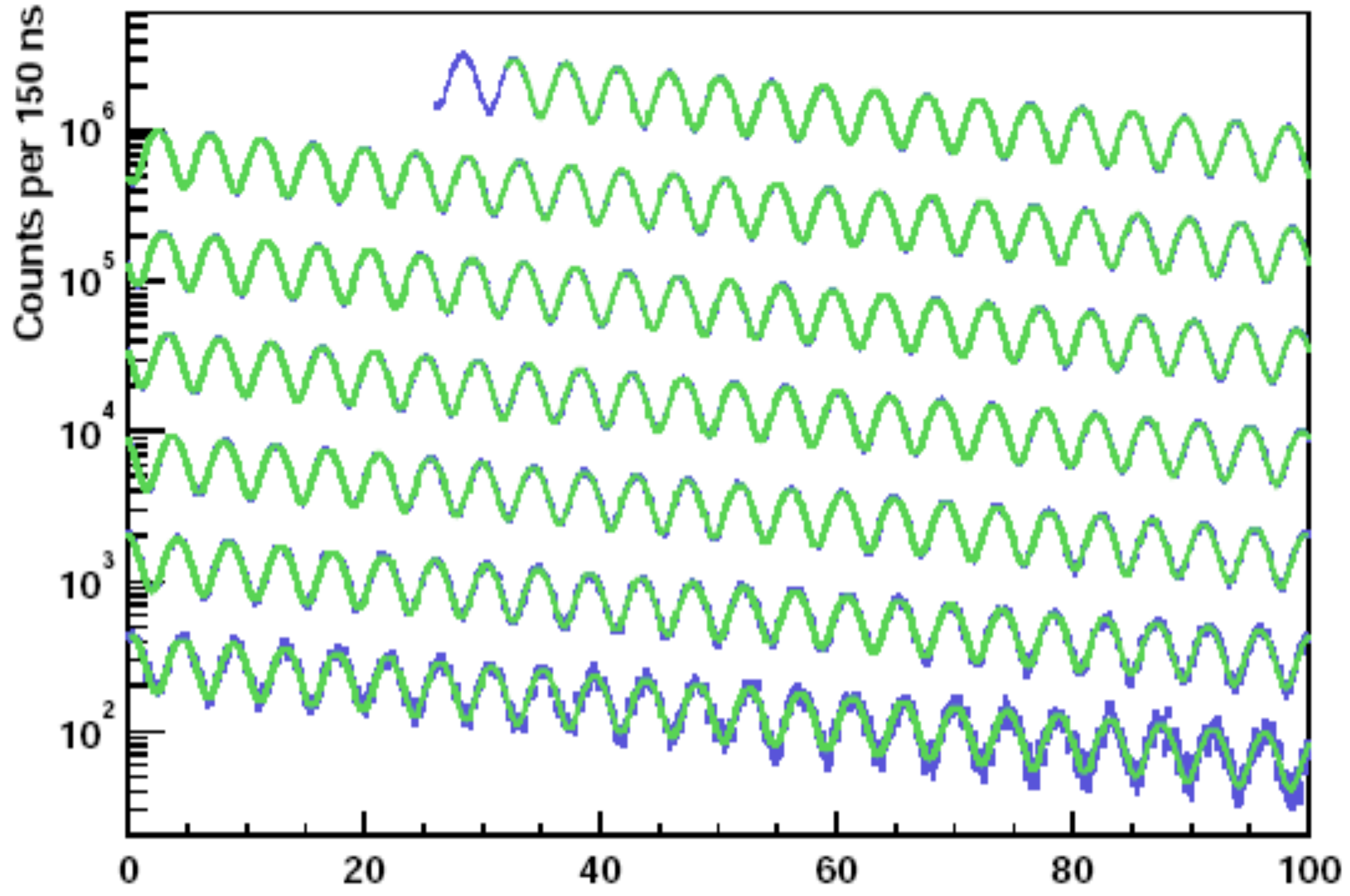
- Highest energy positrons have the strongest correlation between their momentum and spin directions

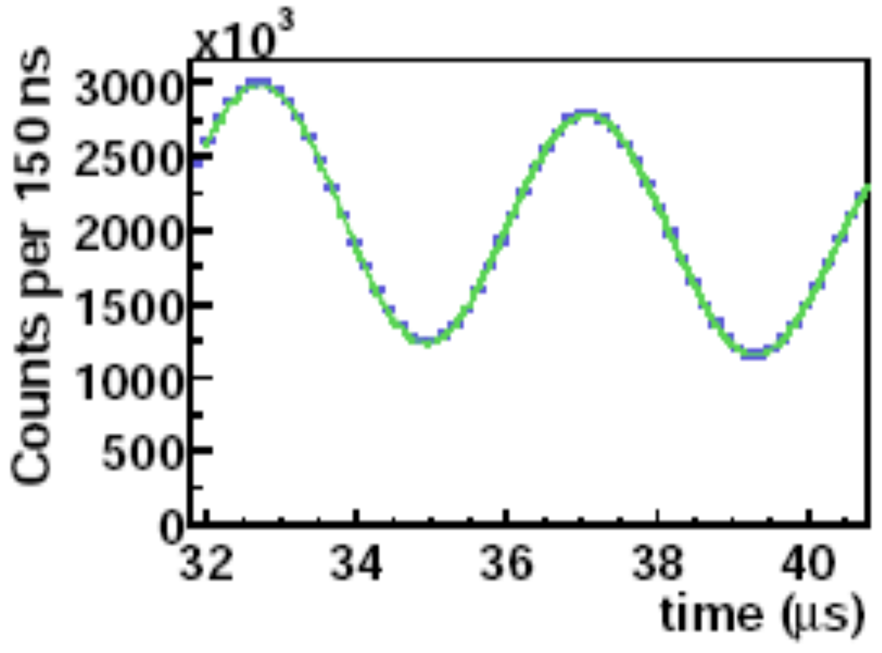
- Number of high energy positrons entering the detectors will vary as a function of time

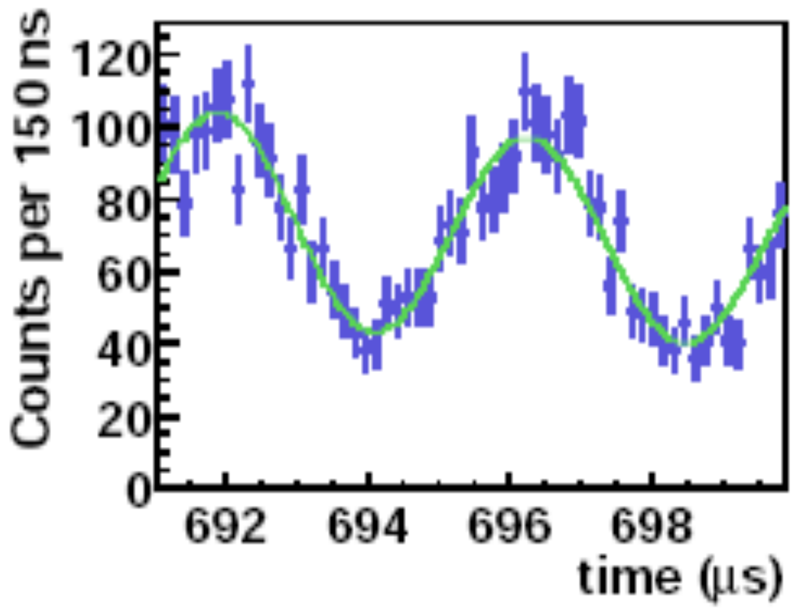


The Wiggle Plot



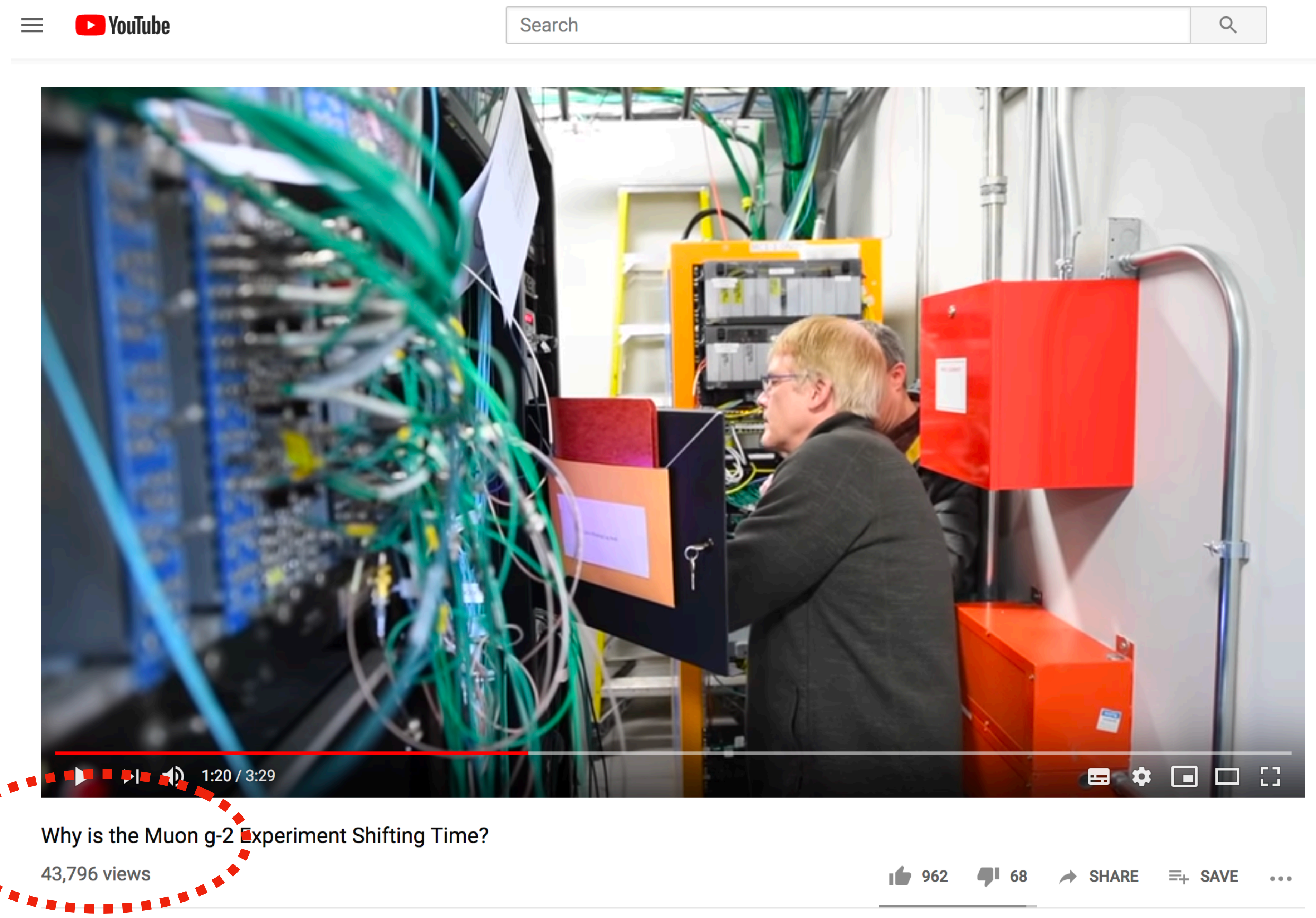






What's the answer?!?!

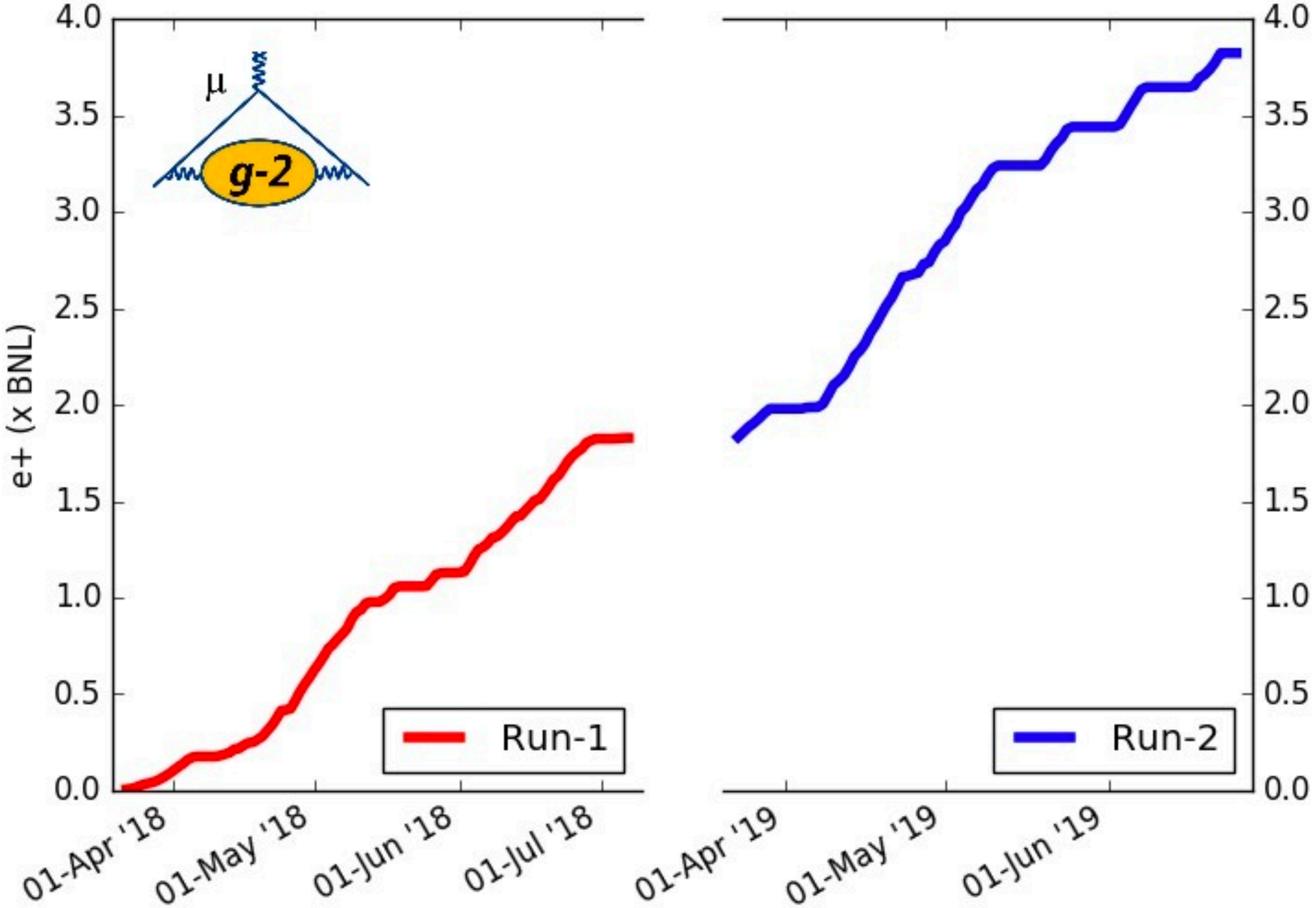
- We don't know yet!
- One of the great things about measuring frequency is that it's clear (in principle) -- just fit the wiggle and get the number
- But this is a problem if you know what you want the number to be!
- Solution: **blind the clock**
- We won't know the answer until we 'unblind' — it will be an exciting moment!



Fermilab

Watch this space

- The g-2 experiment has just finished run 2
- In run 1 (2018) we took 2x the data of the Brookhaven experiment
- After run 2, total data collected = 4x Brookhaven experiment!
- Publication of run 1 data expected later this year
- If the mean value is the same as the Brookhaven number, we'll know that once we've taken full dataset that we'll see a >5σ discrepancy!



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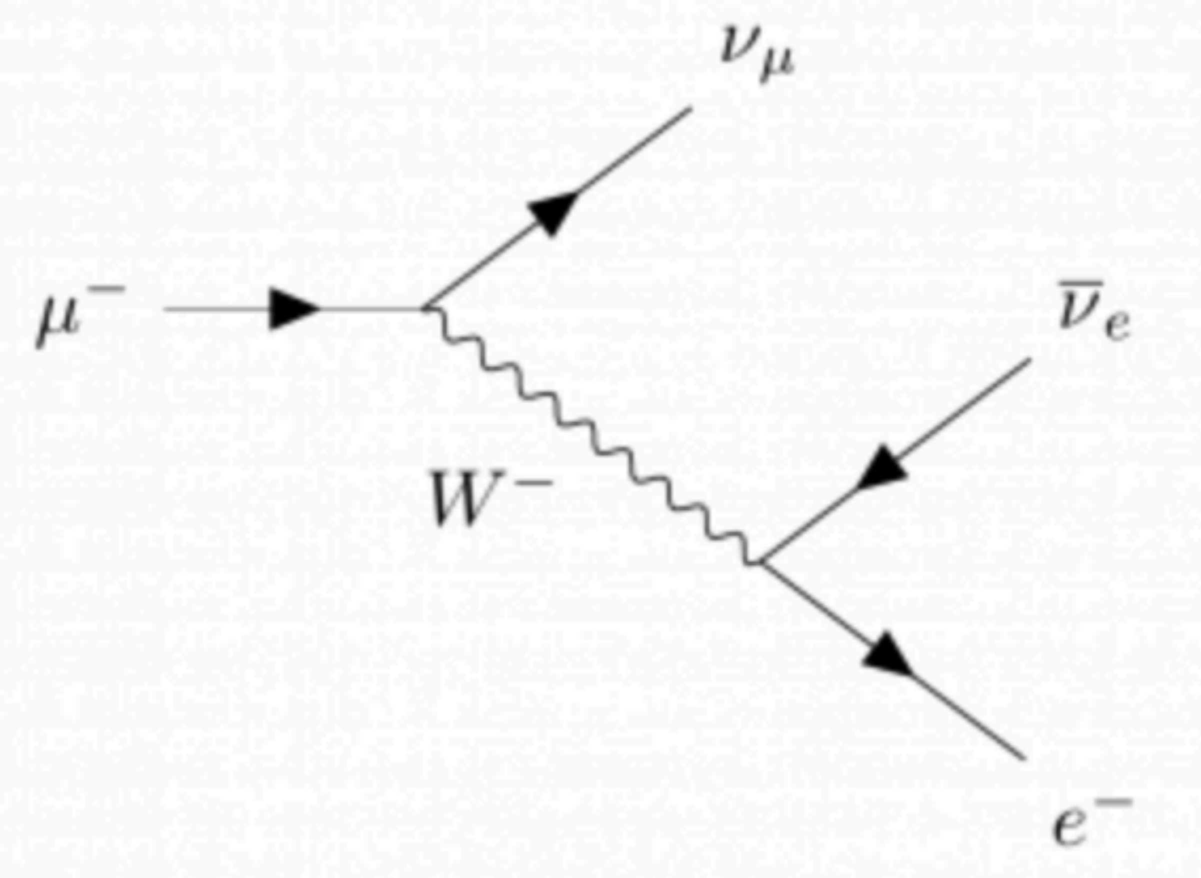
Celebrity status!

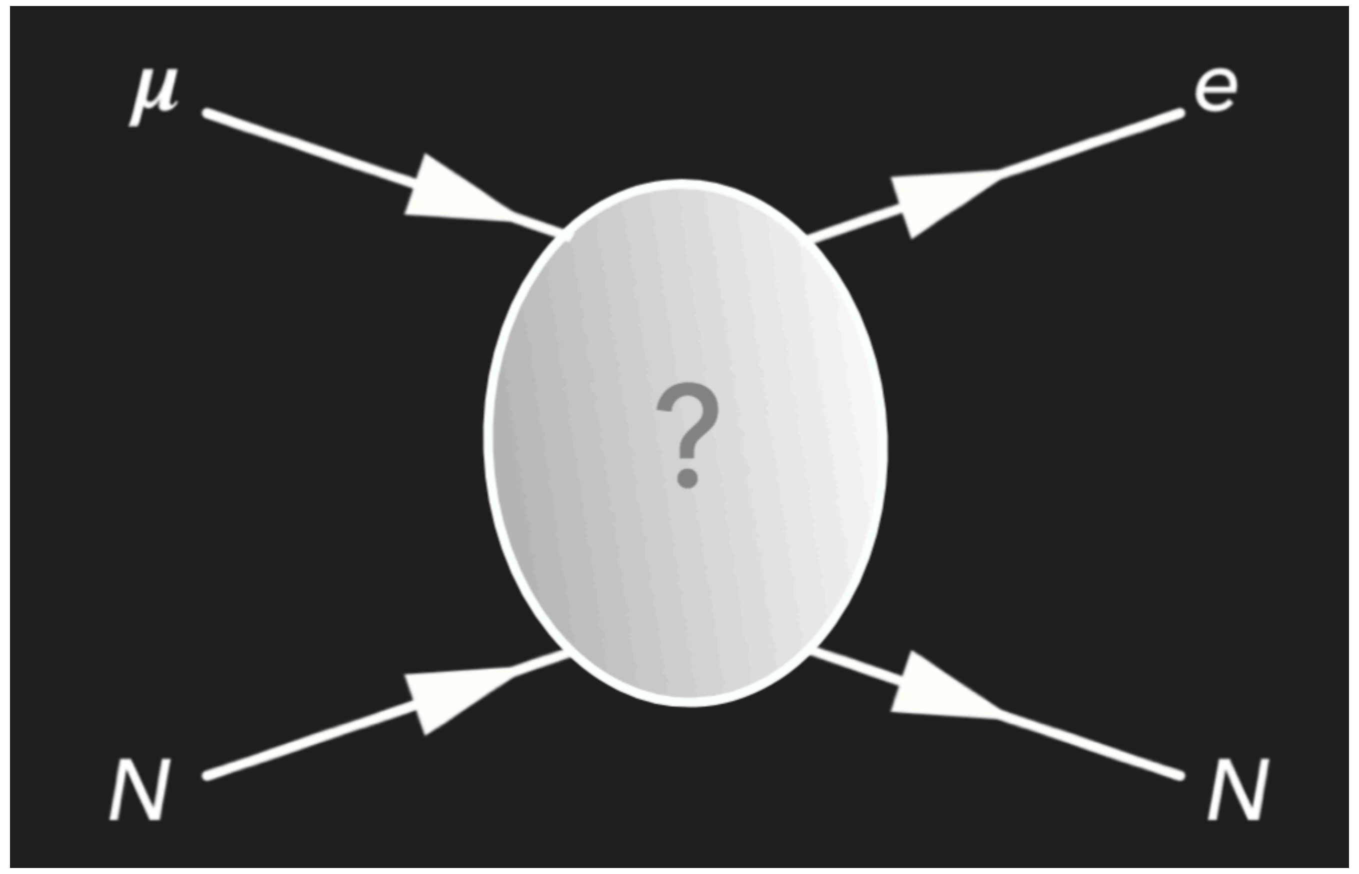
Celebrity physicist Prof. Brian Cox:
“If I were to put my money on something that would signal new physics, it’s the g-2 experiment at Fermilab.” !!

Charged Lepton Flavor Violation: the mu2e experiment

Charged lepton flavor violation

- After the g-2 experiment finishes running (2021) the mu2e experiment will begin
- Aim: **look for conversion of a muon to an electron**





e ⟷ ? ⟷ μ ⟷ ? ⟷ τ

m_e = 0.511 MeV
τ_e = stable

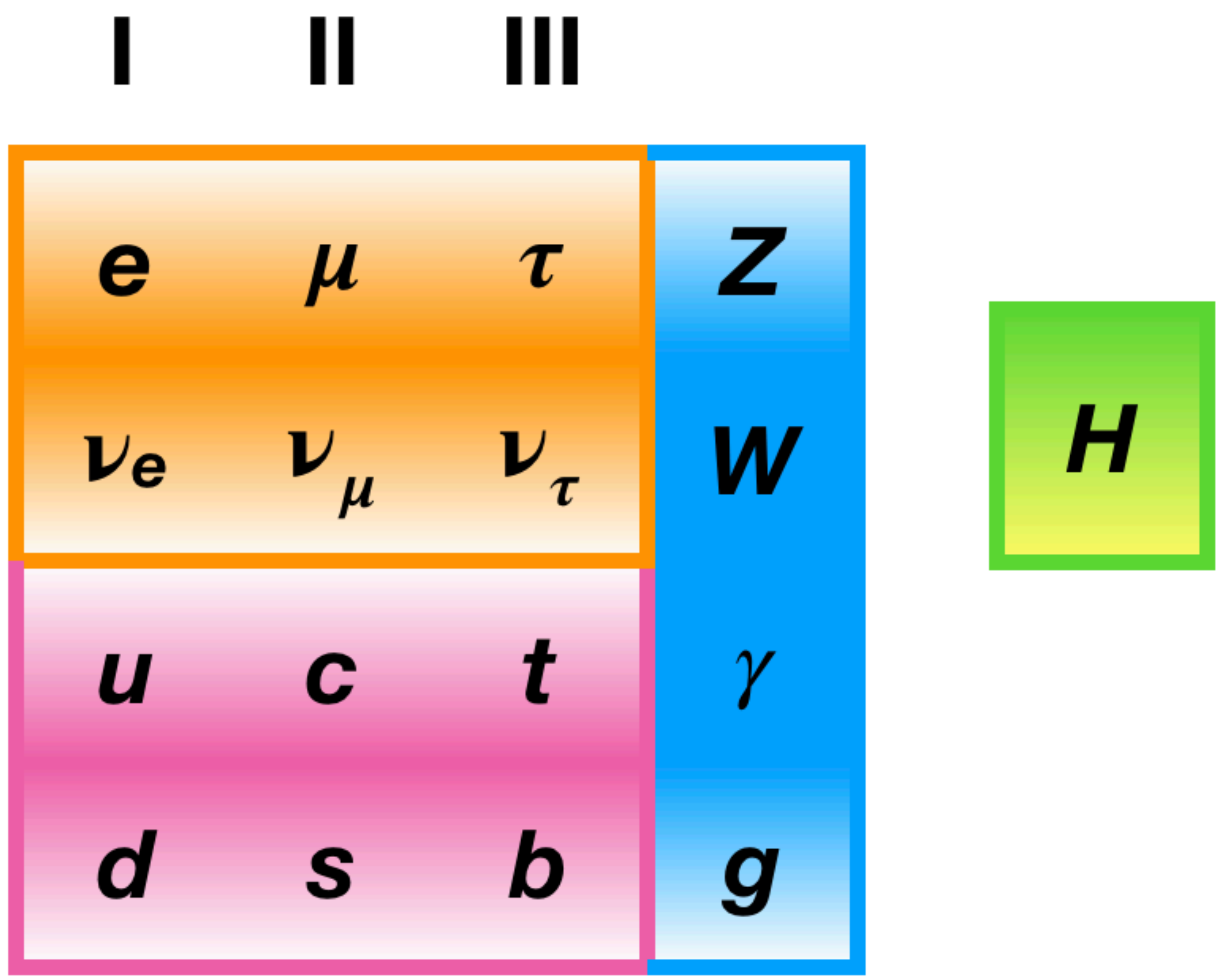
m_μ = 105 MeV
τ_μ = 2.2 μs

m_τ = 1777 MeV
τ_τ = 2.9 e-13 s

Fermilab

Flavor violation in the Standard Model

- We have seen quarks commit flavor violation
- Neutrinos can change flavor too — called ‘neutrino oscillations’
- Flavor violation between charged leptons is heavily suppressed in the SM — forbidden by conservation laws



- There must be some level of CLFV in the SM to allow neutrino oscillations, but that level is really tiny
- Probability goes as $\left(\frac{M_W}{M_\nu}\right)^4$ — M_ν really tiny so SM interaction unmeasurable
- But if it could happen via a new BSM particle with higher mass than the neutrino, muon to electron conversion might happen at a measurable rate

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Any observation of CLFV is a definite sign of new physics!

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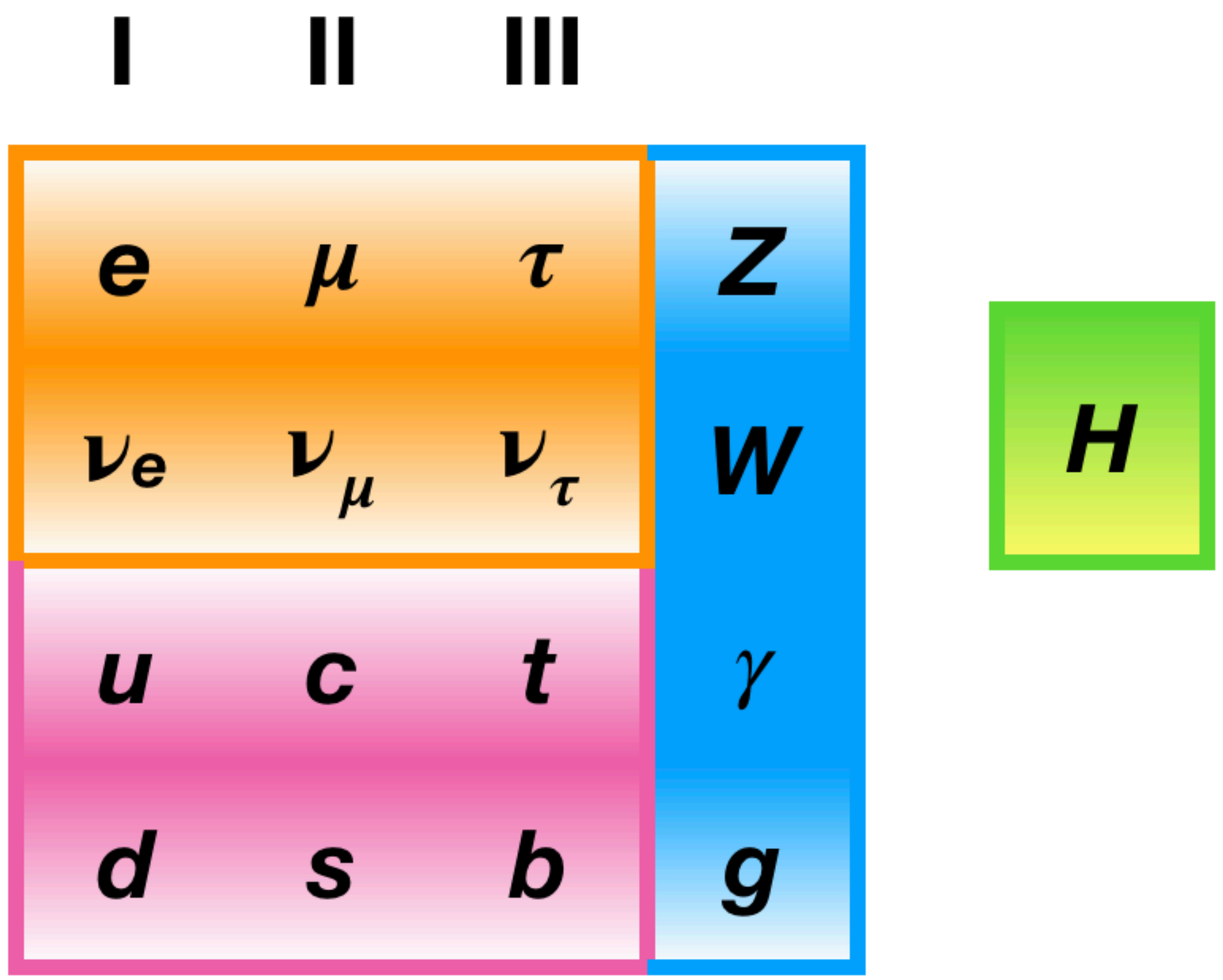

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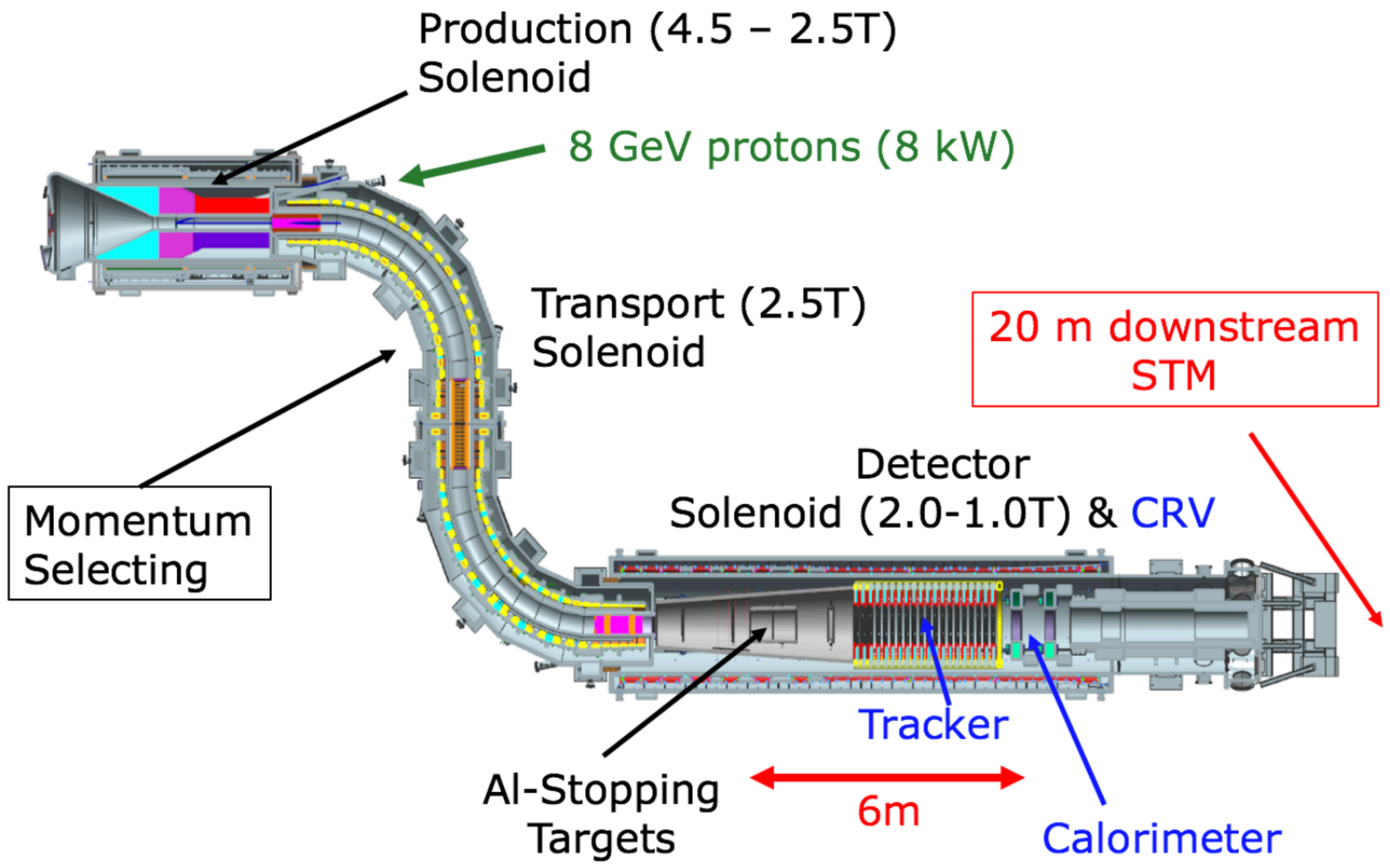
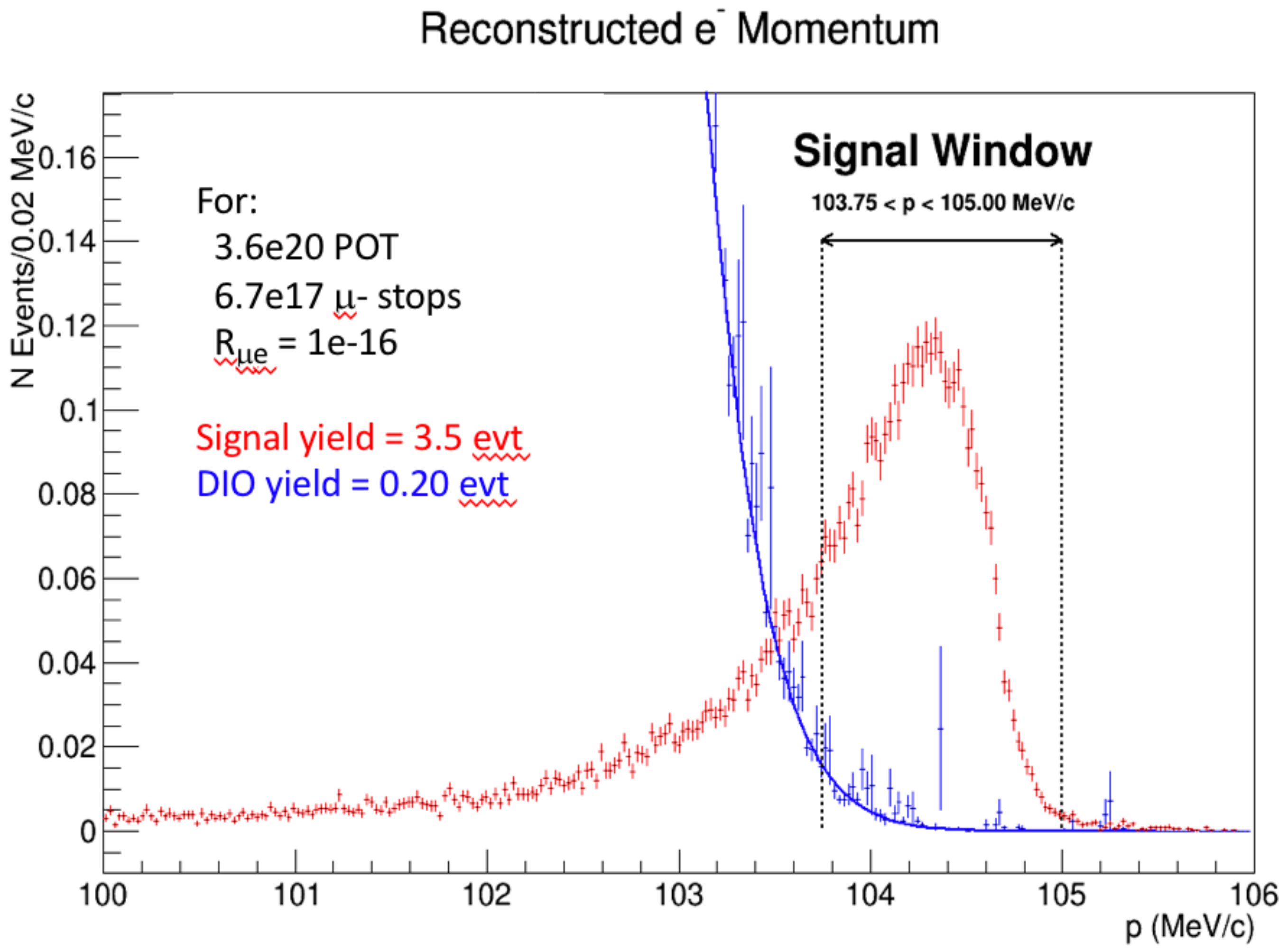
The mu2e experiment

- Search for CLFV through coherent neutrinoless conversion of muon to electron in the field of a nucleus: **eN —> μN**
- Require single event sensitivity as low as 10^{-17}
- Muons stopped in Al disks ('stopping targets')
- Need to stop 10^{18} muons total





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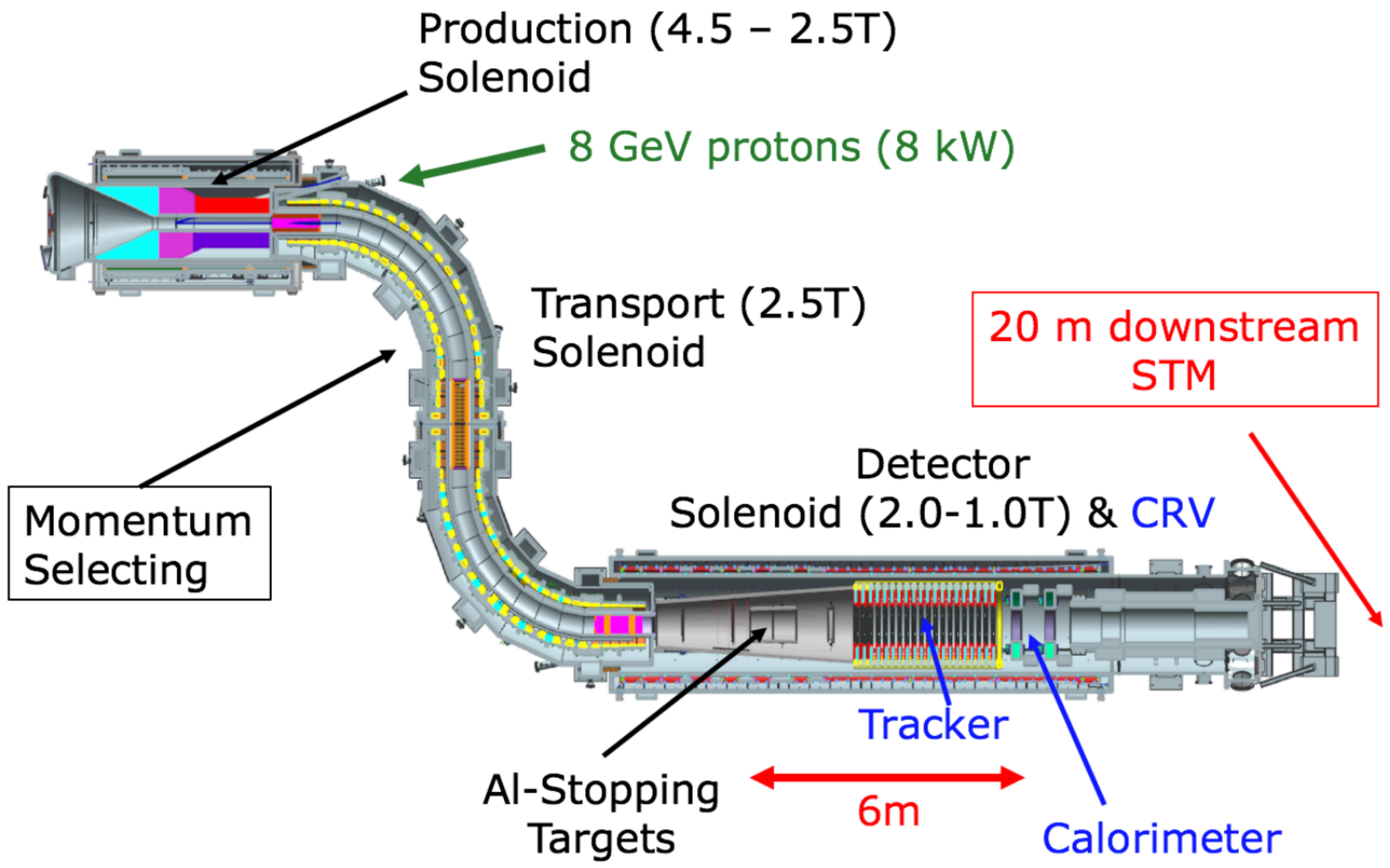
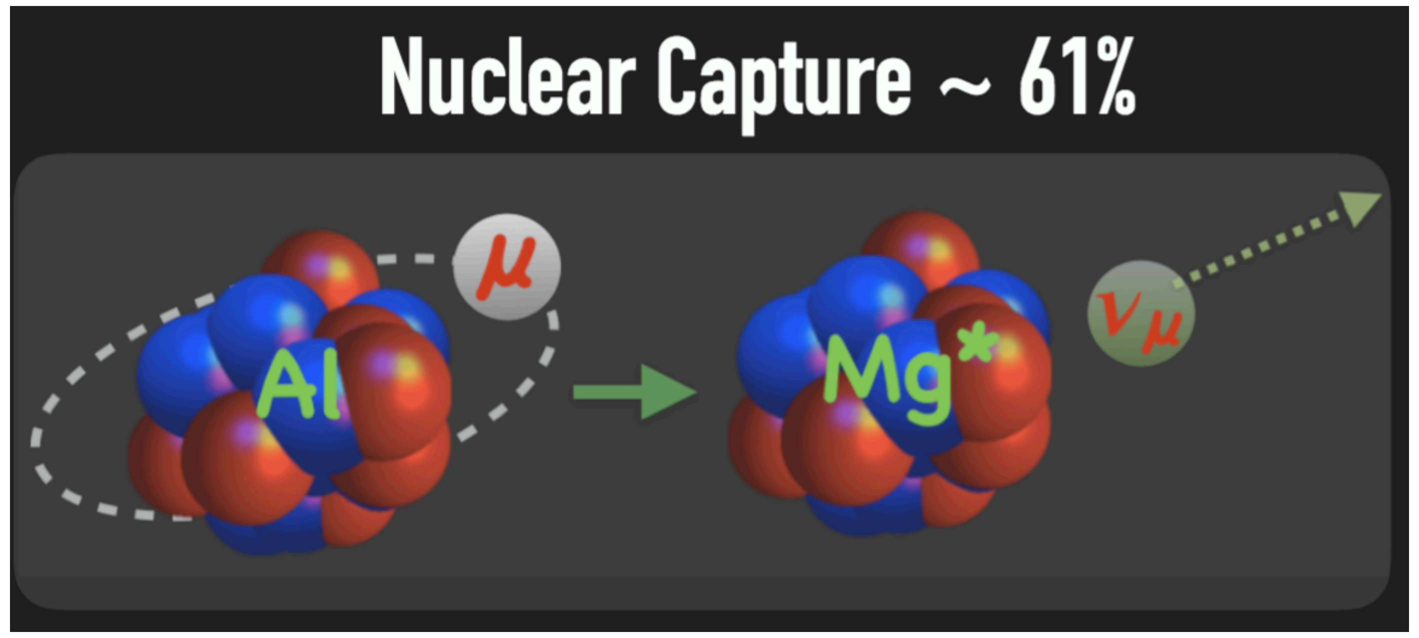
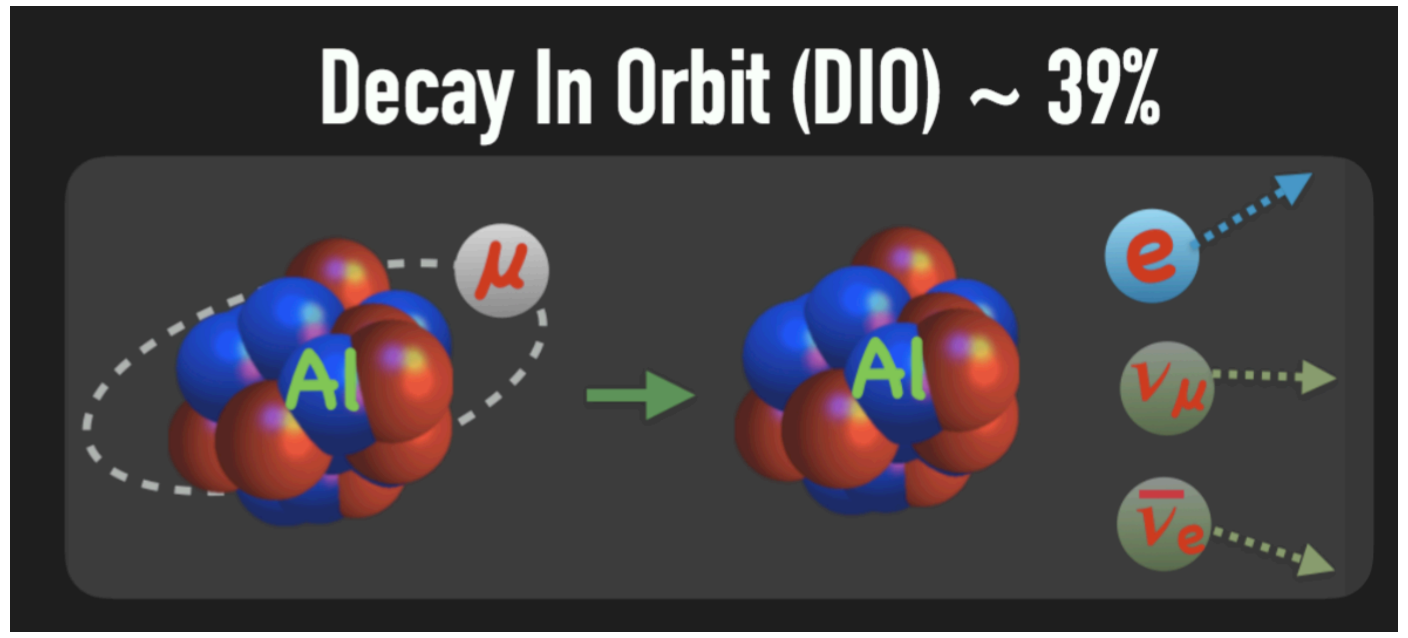
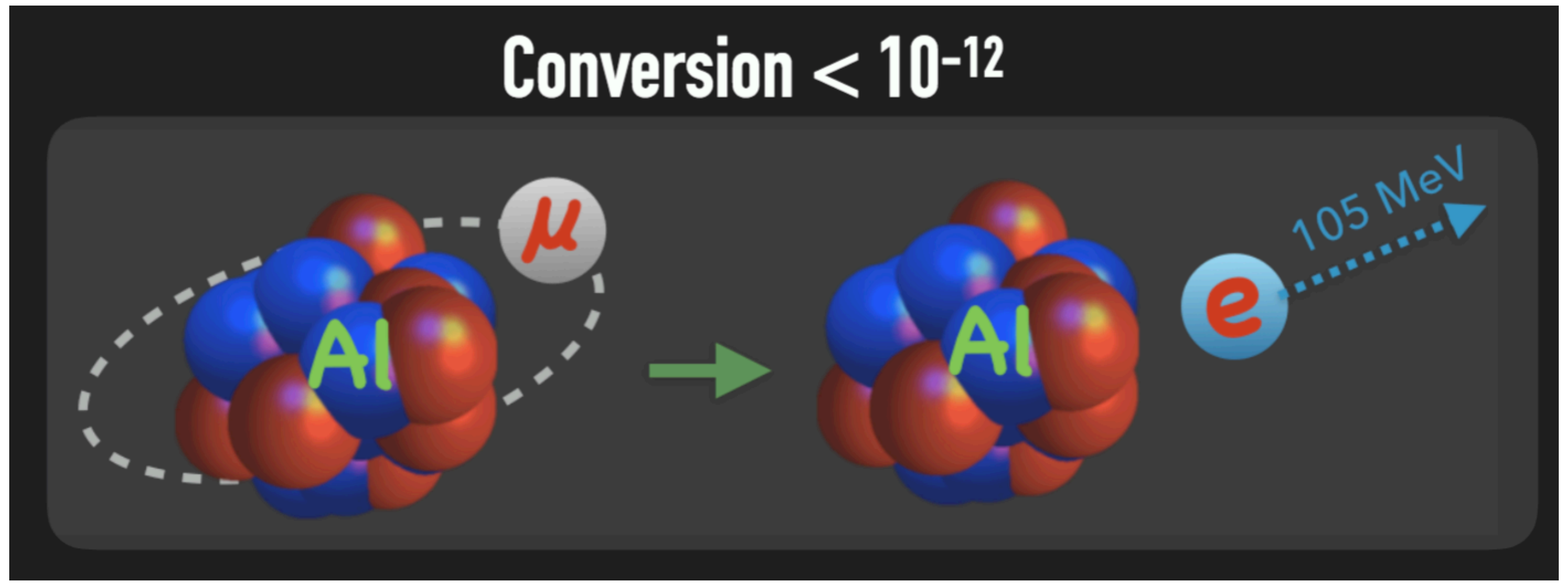
The mu2e experiment

- Once stopped, muon can either:
  - decay from the 1s atomic orbit — release two neutrinos and an electron
  - be captured by the nucleus — release protons, photons and neutrinos
  - **Convert to an electron with no byproducts**









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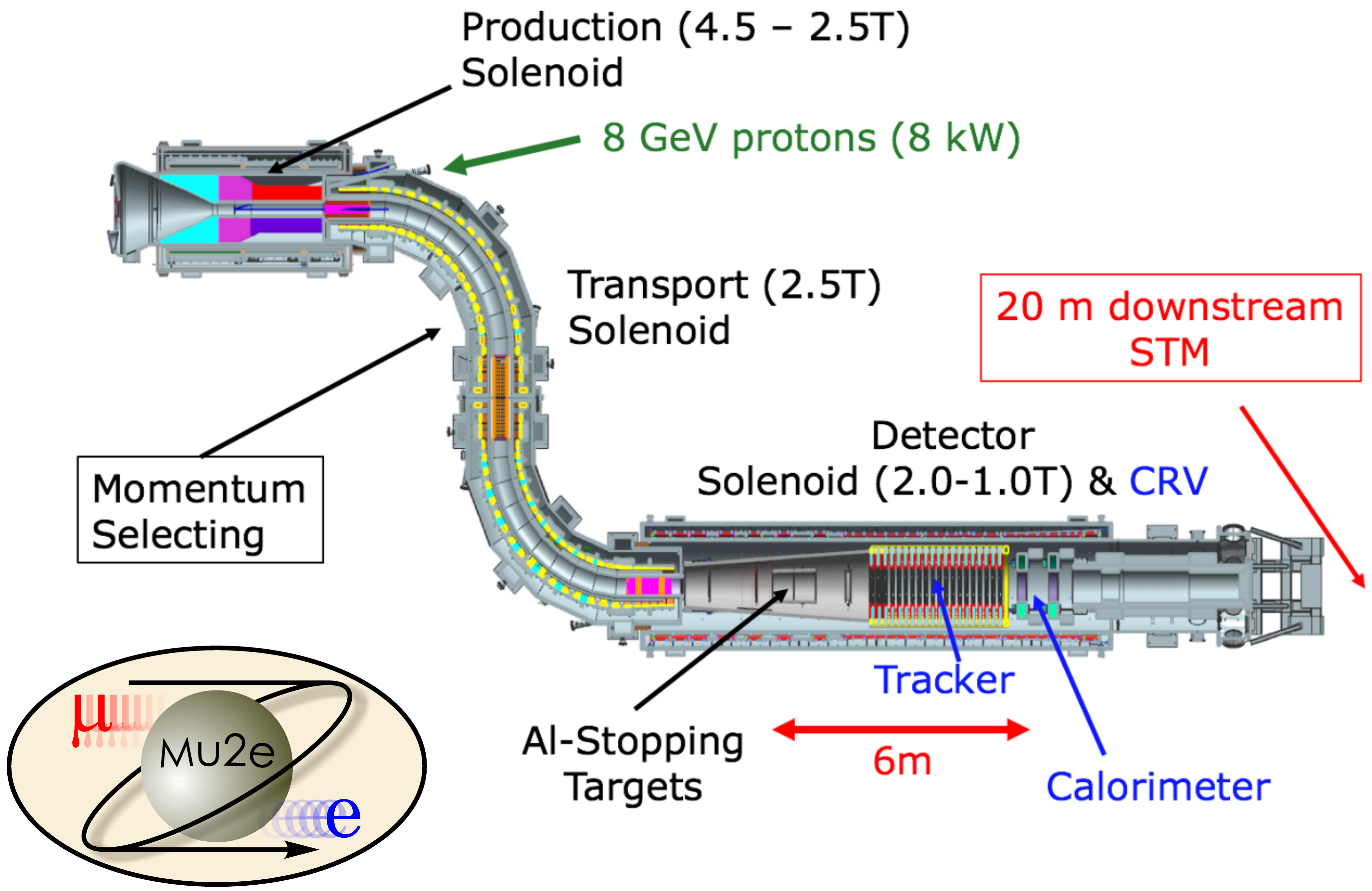
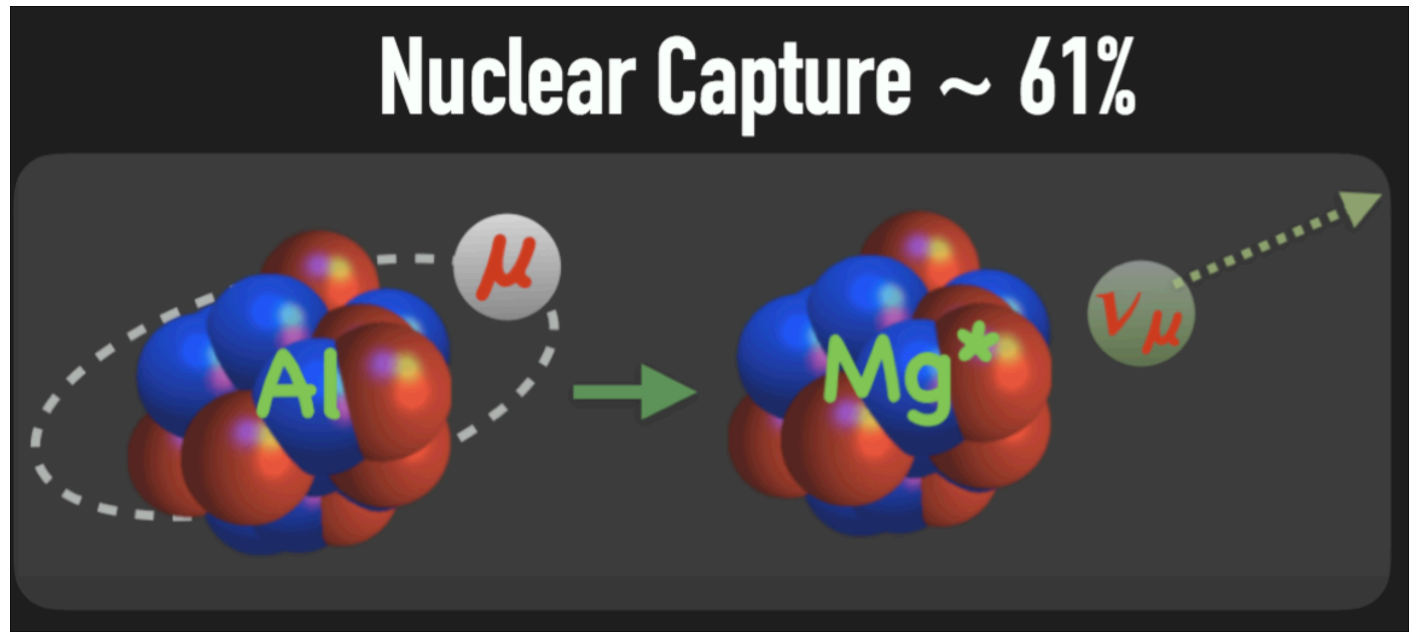
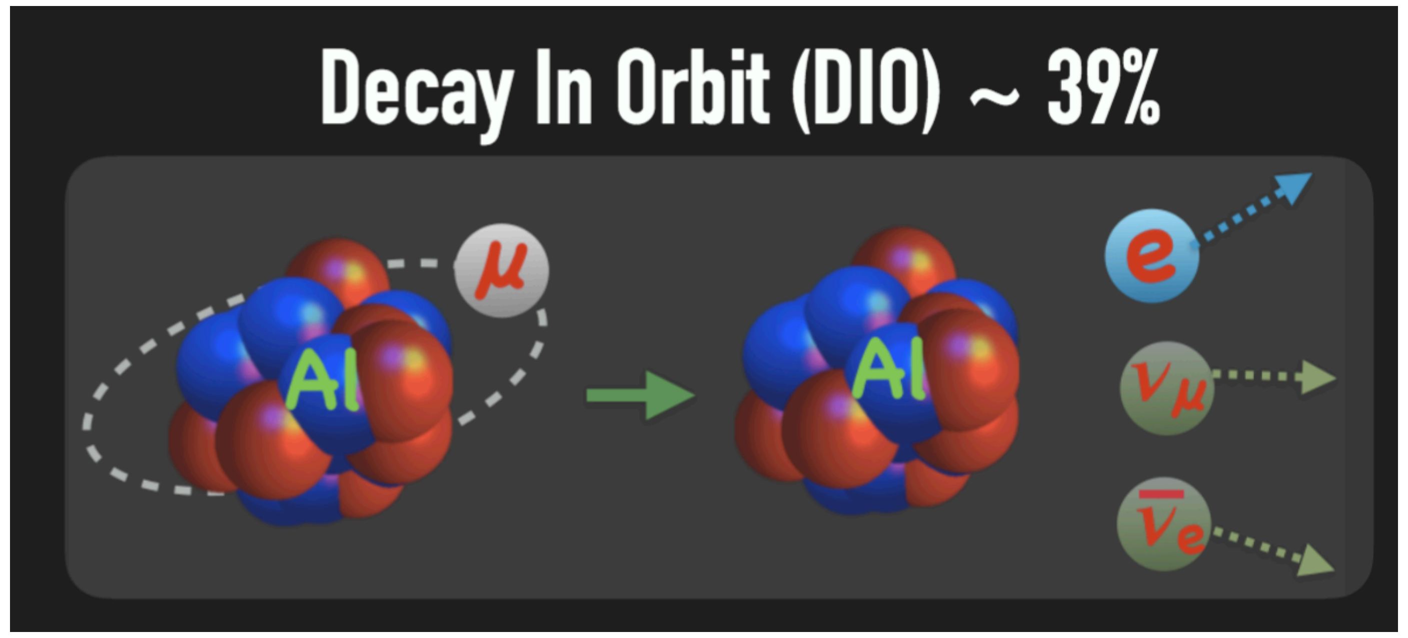
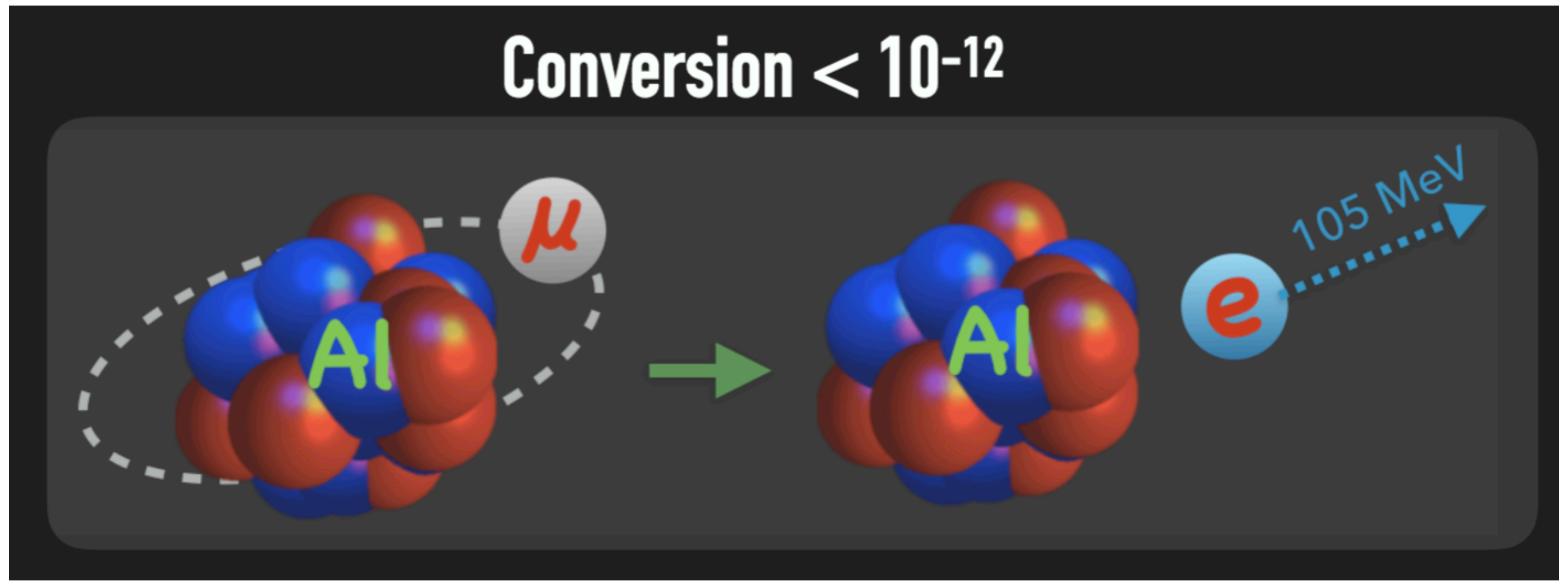


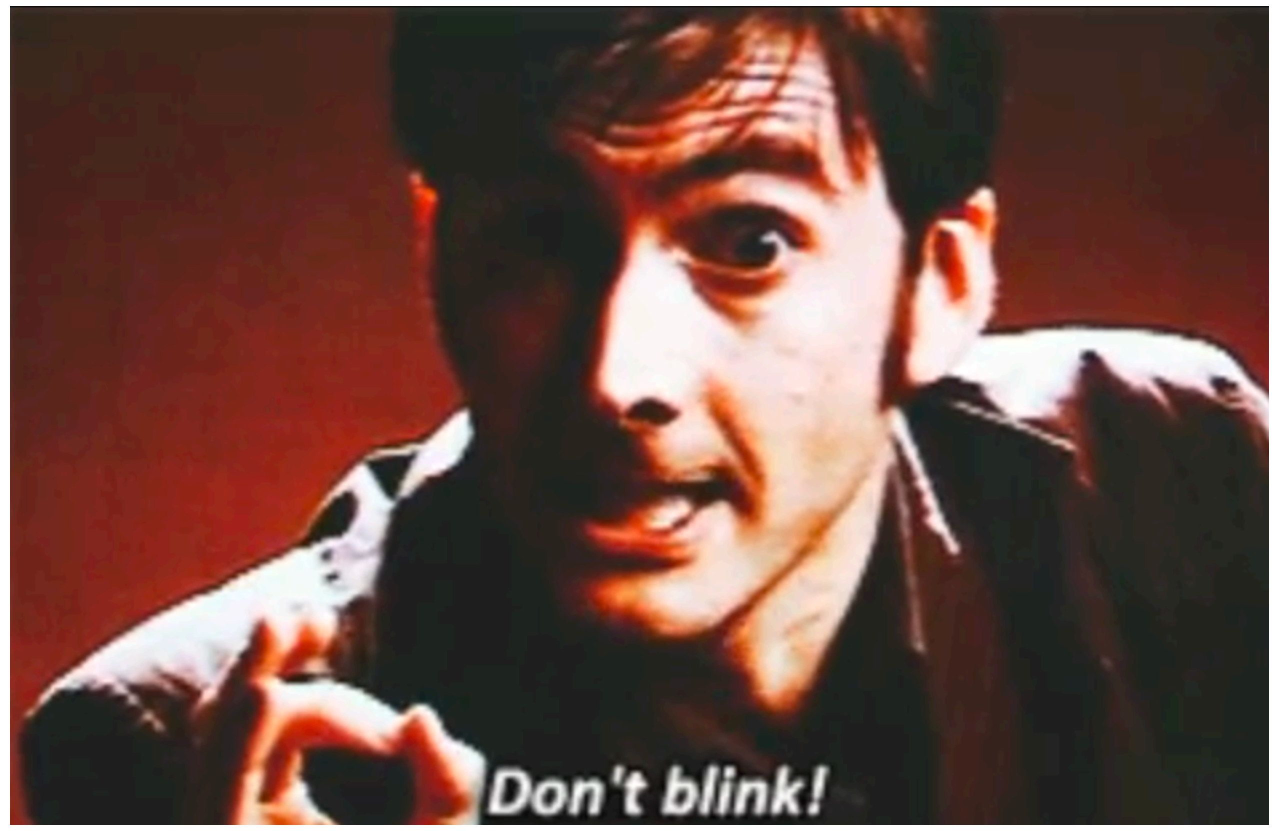






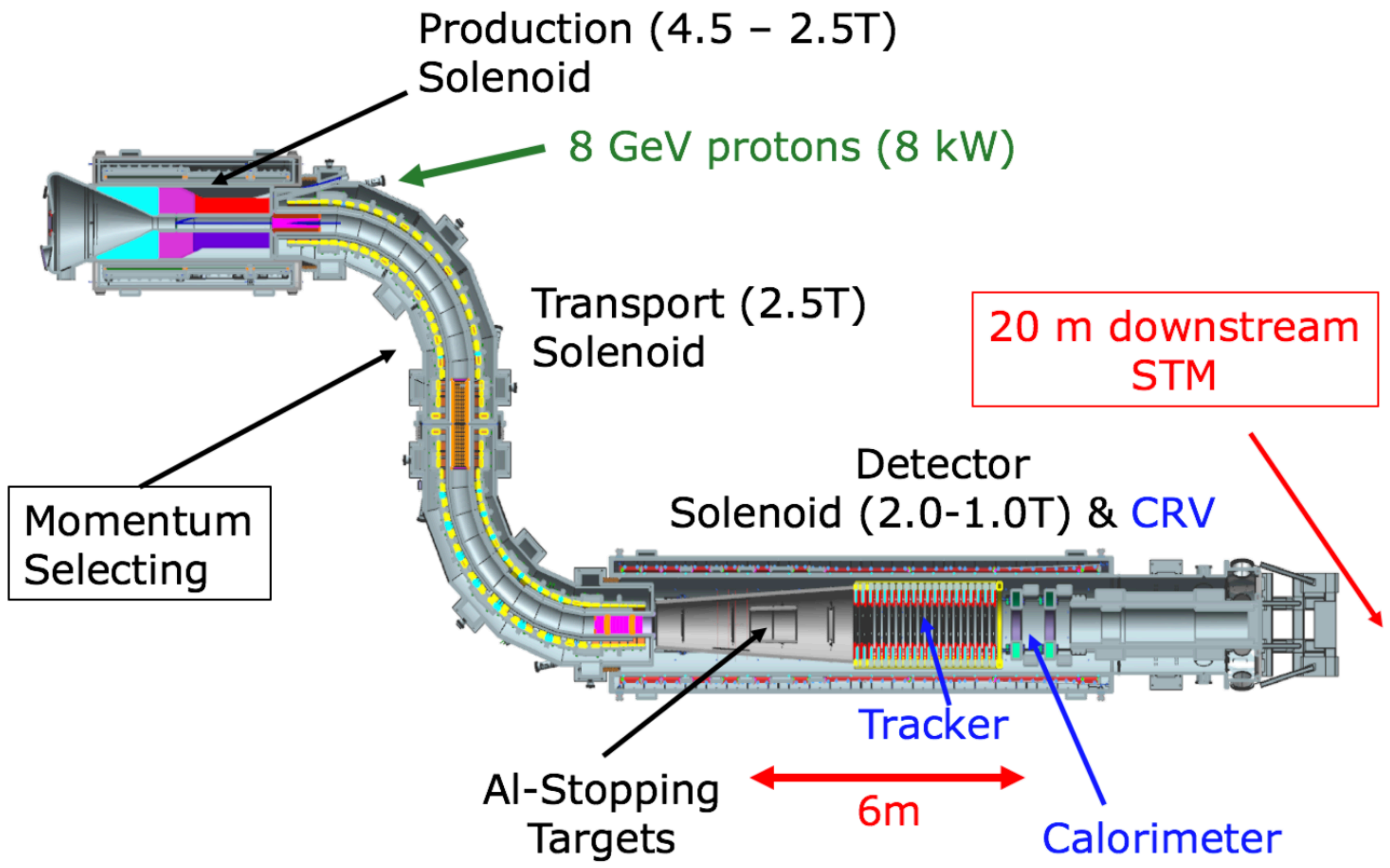
A needle in a very large haystack

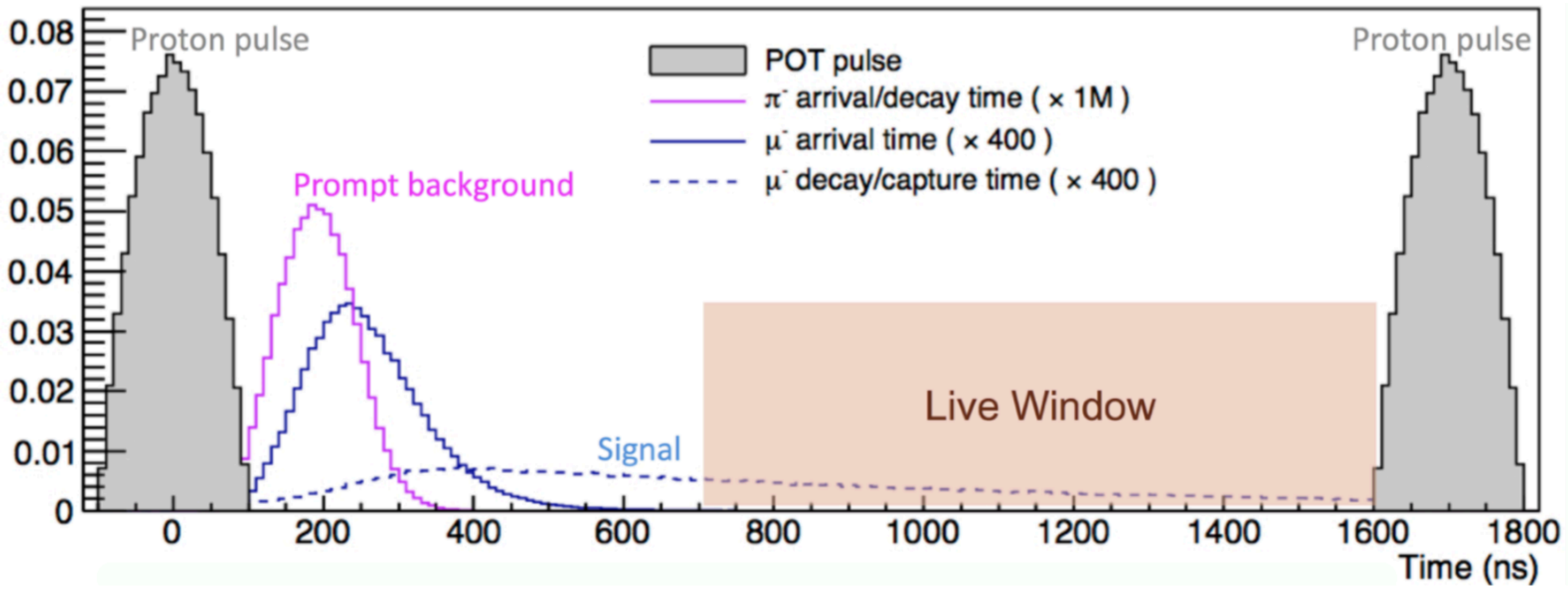
- To reach the required sensitivity, we need the hottest muon beam in the world — 10^{10} muons per second
- Looking for one event in 10^{18} — **this is like looking for one grain of sand out of all the grains of sand in the world !!!!!**
- Require incredibly sensitive detectors with maximum possible efficiency — don't want to miss any events at all! Don’t blink!



How to find that grain of sand

- Some key ideas to make it possible to be sure we didn't miss any signal events
- 'S-shaped' magnet called transport solenoid — eliminate line-of-sight transport of protons and neutrons, select low-momentum muons only
- Minimize scattering — everything lives in vacuum, detector is ultra low-mass
- Pulsed beam with extinction — only look at a time without big backgrounds
- Veto cosmic rays — of the 10^9 cosmic rays a day, one per day would look like signal !

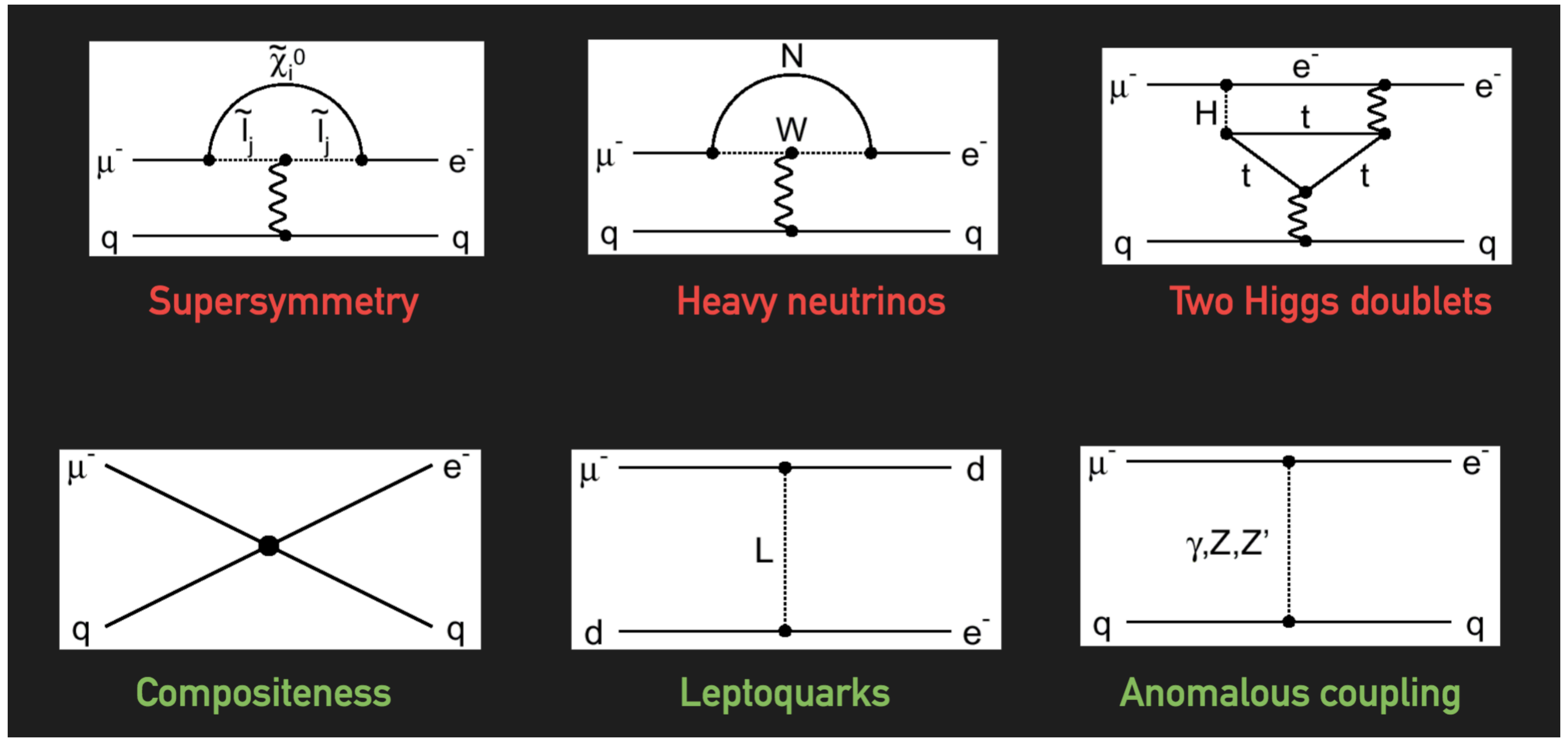




The Future

Muons to the rescue!

- Particle physics is heading towards a crisis if we don't see something new soon
- We know the SM is incomplete — but it keeps passing all its tests!
- The two muon experiments at Fermilab provide different windows to look for new physics
- Both g-2 and mu2e can probe a huge variety of BSM models!



BSM models allowing measurable mu2e signal

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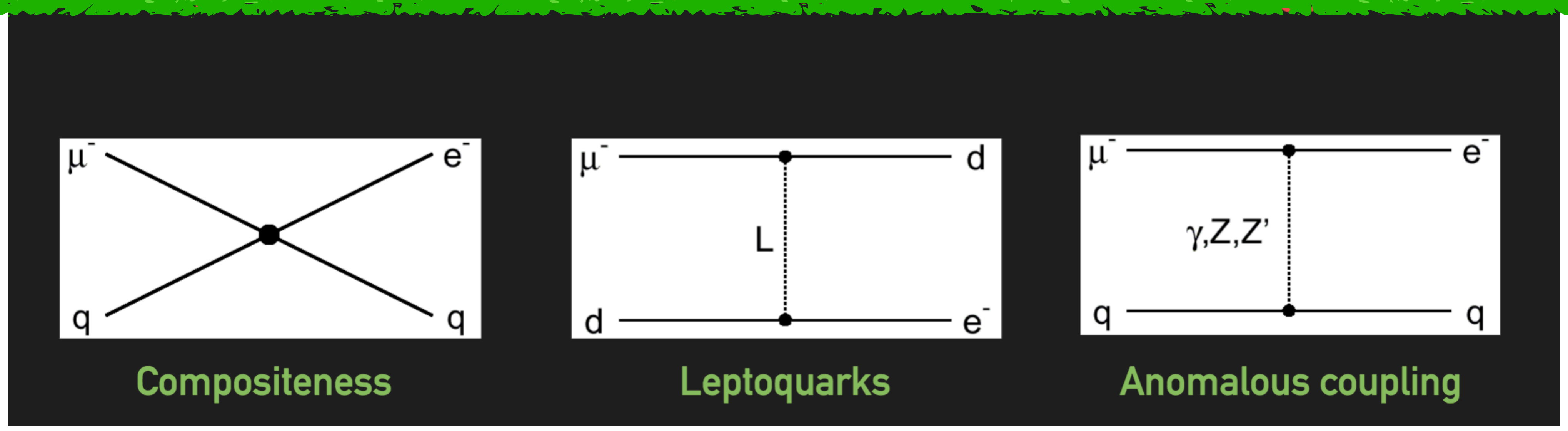
Muon physics at Fermilab is at the forefront of the worldwide search for new physics

Look out for publications in the near future!



BSM models allowing measurable mu2e signal

Thanks!

Thanks for listening!
Any questions?

Acknowledgements: Thanks to Jason Bono, Manolis Kargiantoulakis, Chris Polly and Mark Lancaster for some pictures and plots in this talk. Thanks Adam Lyon and Will Turner for the movie!

Backups

Measuring ω_a

- Two important features of muon decay enable us to measure ω_a directly

1: Decay positrons are preferentially emitted in the direction of the muon spin