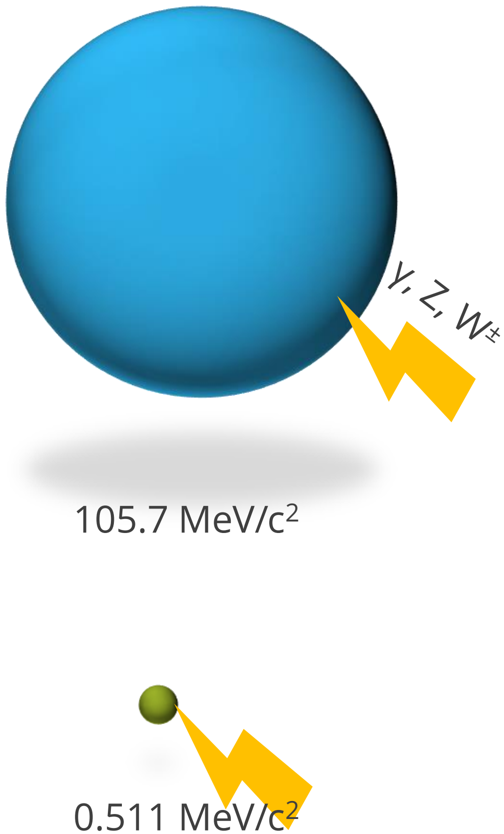
Particle physics with muons

with my personal bias…

Yusuke UCHIYAMA
ICEPP, the University of Tokyo

Int. Conf. on the Physics of the Two Infinities
March 30, 2023
@ Kyoto University

The Muon



2^{nd}-gen. charged lepton

Replica of electron but with 200 times larger mass

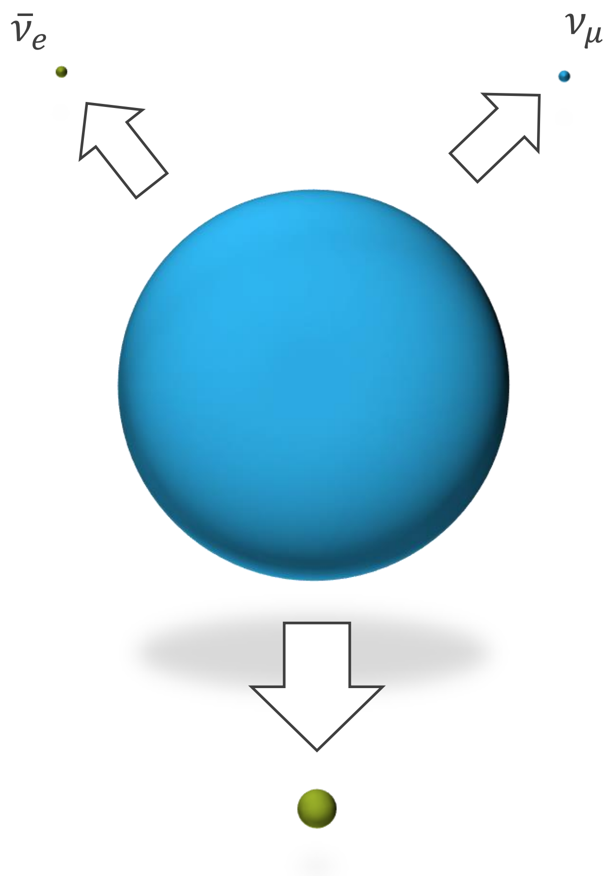
Only Higgs Yukawa coupling distinguishes e/μ.

- Gauge interactions don't (Gauge symmetry)
- Lepton Flavor Universality

We still don't know why it exists

- after 86 years from the discovery.
- *"Who ordered that?"* (Rabi)

Muons decay weakly



The first unstable elementary particle

- The beginning of flavor physics

Muons decay only via weak interaction

Lifetime: 2.2 μs

- Long enough to manipulate and make beam

Determines Fermi constant (G_F)

- One of the most fundamental parameters of SM
- MuLan experiment @ PSI (2013) 510 ppb

Discovery of the muon opened modern particle physics.

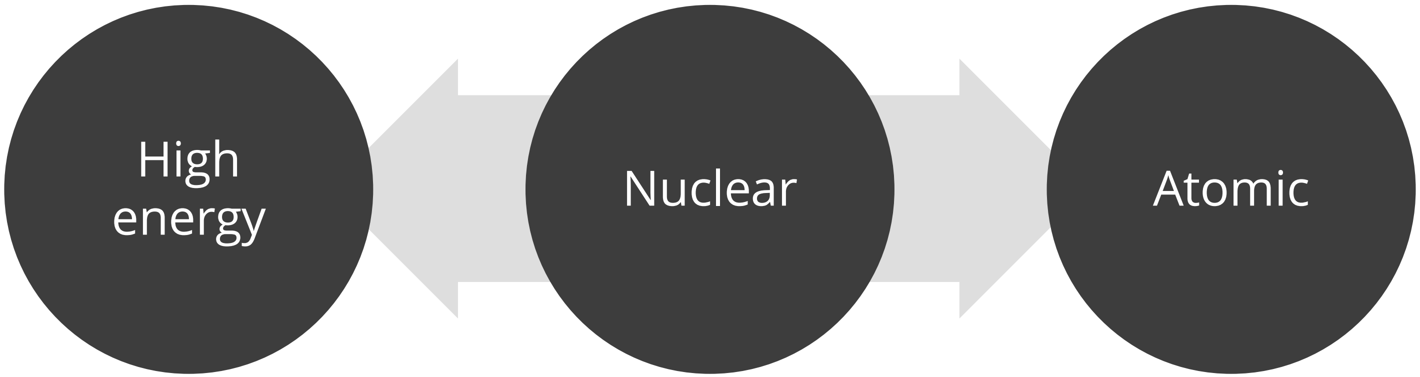
Studies of its properties played an essential role to establish SM.

Is it a legacy physics?

— No. It’s still active, even hottest now!

Particle physics with muons

Synergies in physics & experimental techniques



+ other science
material, chemistry, biology, archeology, etc.

Three keywords

High precision measurements
Fight against systematics

Rare process searches
Fight with backgrounds

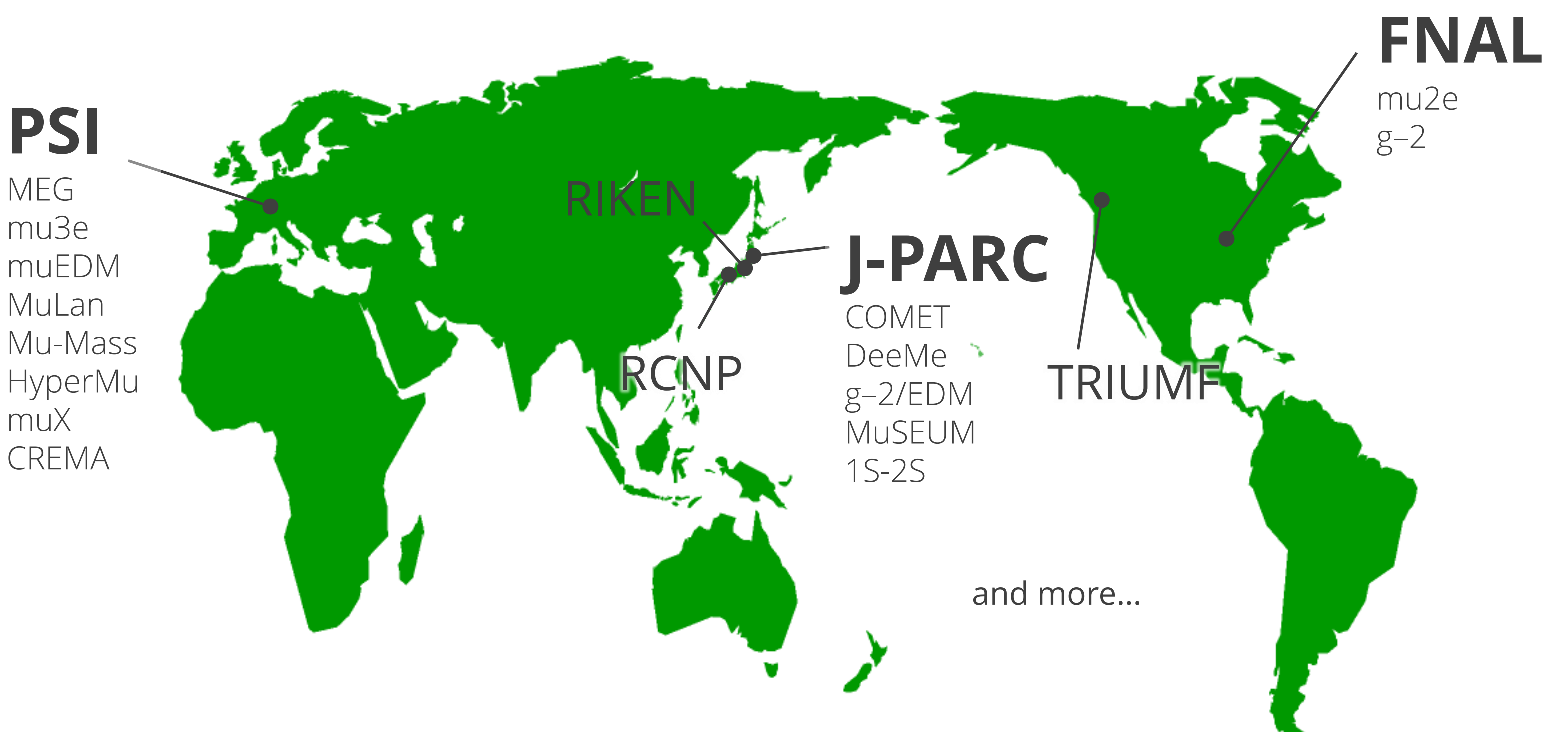
High intensity muon beams

Muon sources in the world

μ± are produced from π± decay

π± are produced by hitting protons to a target, so μ± are tertiary beam.
Therefore, high-power proton accelerators become muon factories.

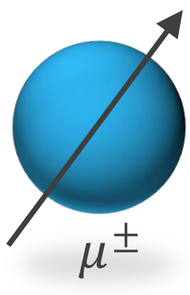
Maximum intensity: 10^8 s^{-1} (now) → $10^{10–11}$ s^{-1} (in near future)



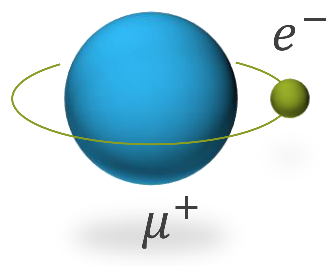
Leading meson/muon factories

Unique experimental systems

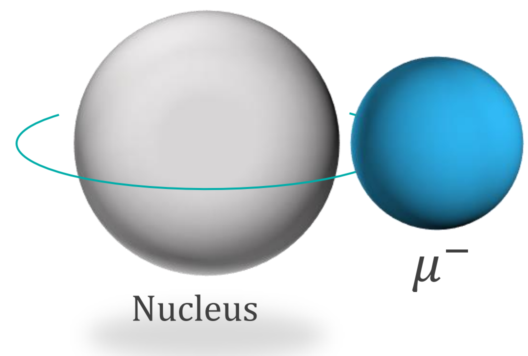
Free muon



Muonium (Mu)



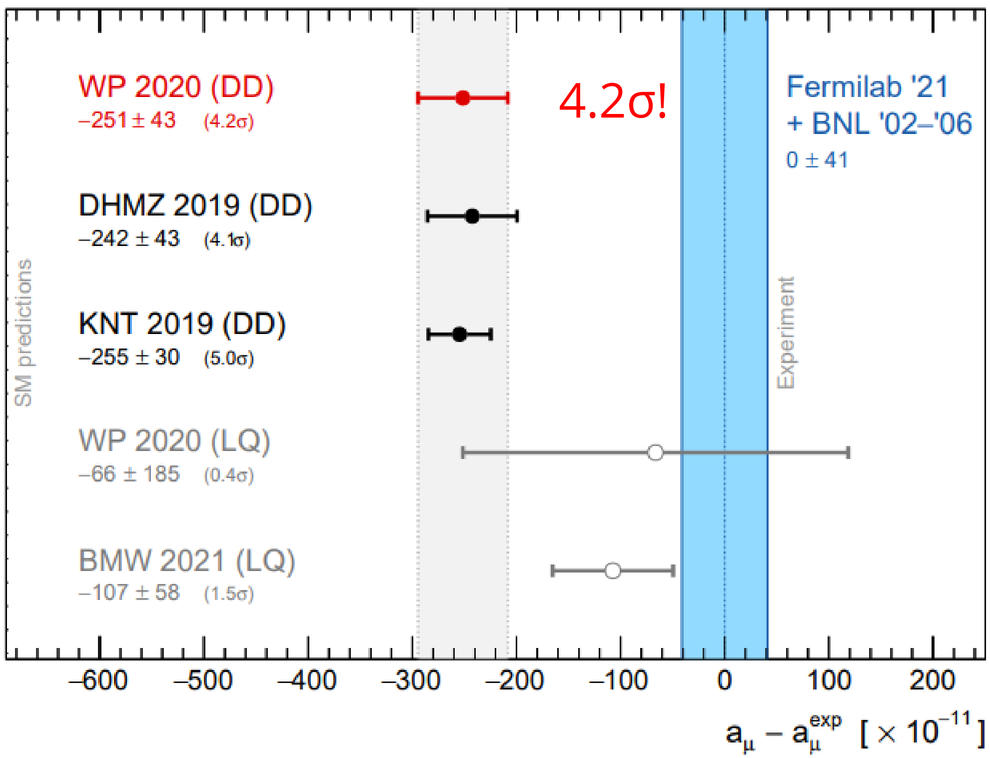
Muonic atom



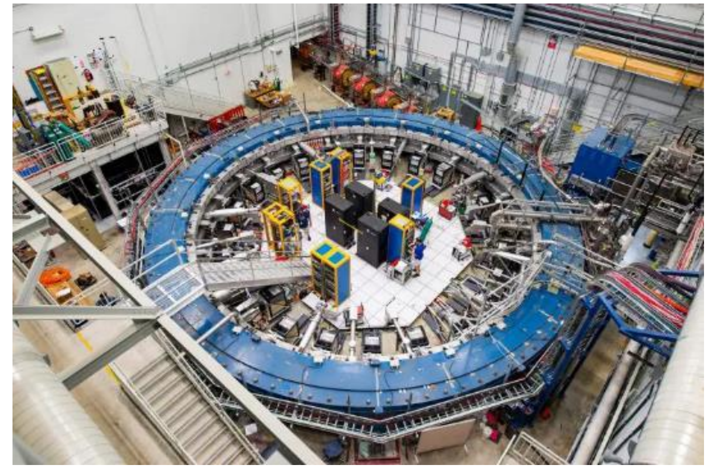
Exotic “hydrogens/atoms”

Anomaly in anomaly: $g_\mu - 2$

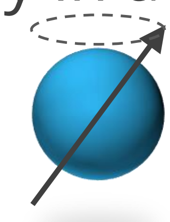
20-year long outstanding anomaly



New experiment @ FNAL confirmed the previous experimental result (2021). 350 ppb



Measure spin precession frequency in a B field: ω_a



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

0

We are not confident that the anomaly is a signature of NP.

- Theoretical uncertainties (hadronic), especially in view of recent lattice results.
- Unknown experimental systematic errors.

Crosscheck by independent experiments is necessary

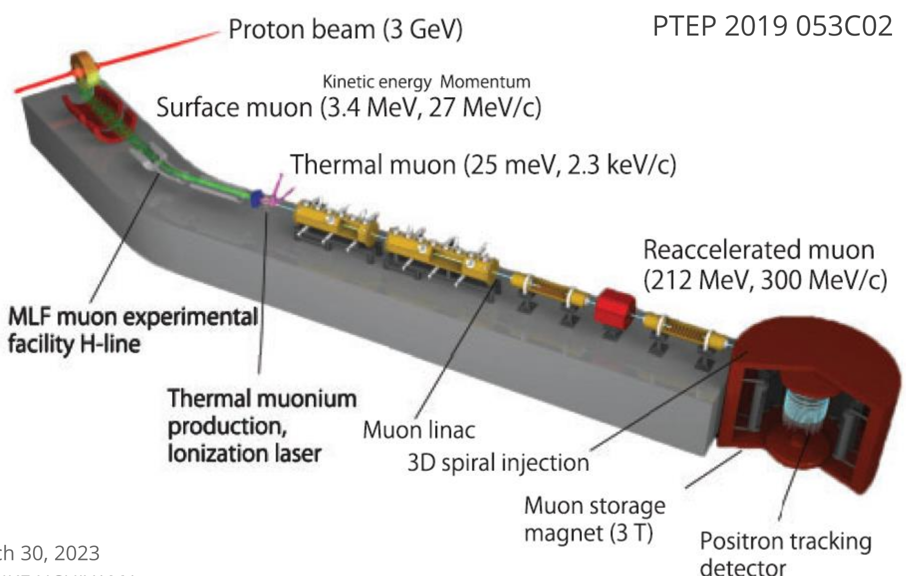
- with different technique.
- → a new experiment at J-PARC (muon g-2/EDM), starting from 2028.

It is important to conclude even if it ends with systematic error

- because it has been a strong guidance for both theoretical and experimental research.

Will we be confident if it is confirmed?

PTEP 2019 053C02

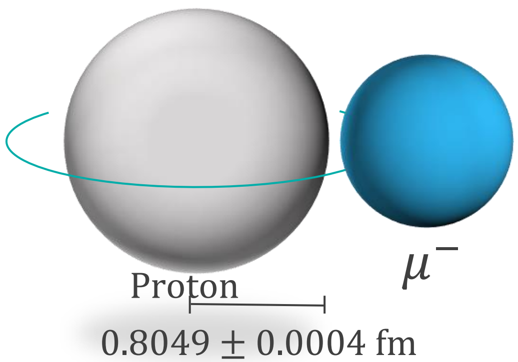


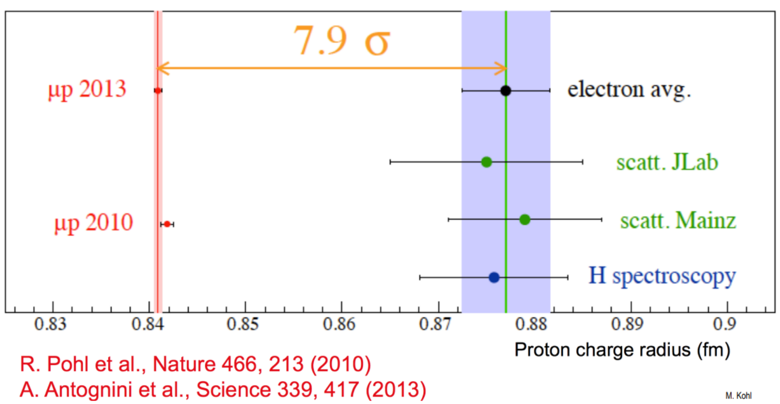
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\cancel{\vec{E}}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\cancel{\vec{E}}}{c}\right)\right]$$

- Low emittance μ^+ beam
- with muon cooling by muonium laser-ionization
- and muon acceleration.
- No need of electric field, avoid magic momentum.
- Measure EDM at the same time.

Goal: 450 ppb (stat.) + 70 ppb (sys.)

Muonic atom





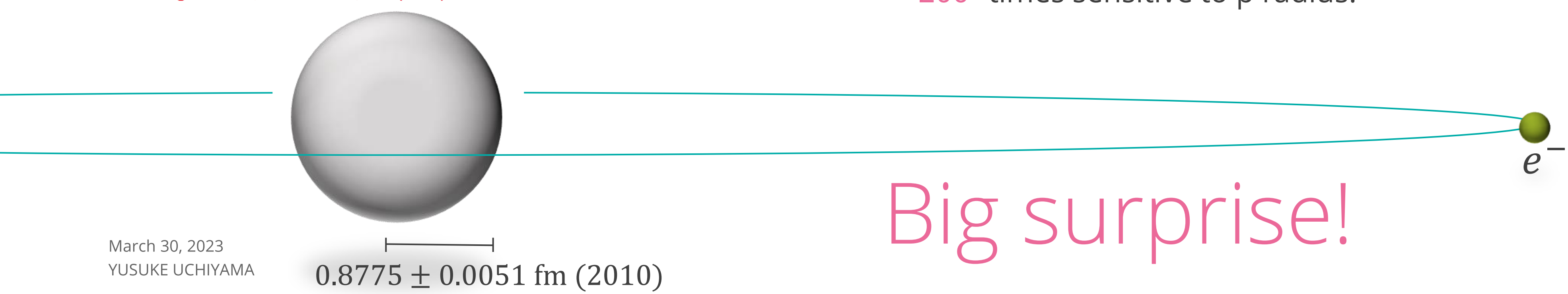
Precise measurements of energy levels in muonic hydrogen

- Strict test of QED.
- 200 heavier → orbit much closer to nucleus.

Proton charge radius

- Hydrogen spectroscopy (atomic phys) + e-p scattering (nuclear/particle phys)
- New measurements with Lamb shift (2S–2P) in muonic hydrogen at PSI.
- Much more precise & accurate than with e.

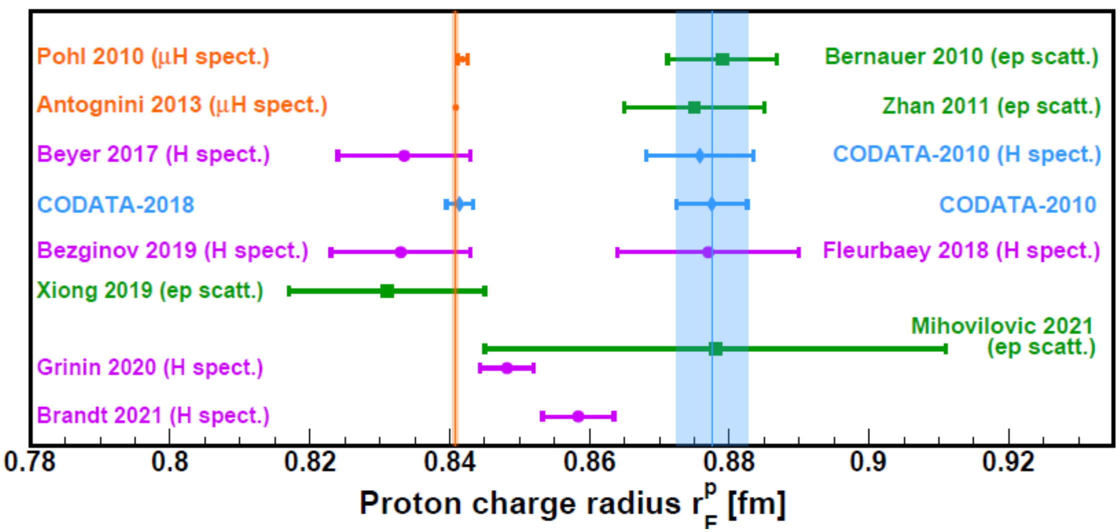
Bohr radius 200 times smaller,
200^3 times sensitive to p radius!



Big surprise!

Recent status

W. Xiong, C. Peng, arXiv:2302.1381



PDG 2022

However, reflecting the new electronic measurements, the 2018 CODATA, TIESINGA 21, recommended value is 0.8414(19) fm, and the puzzle appears to be resolved.

Experts don't consider it fully resolved until
they understand how and where these differences come from.

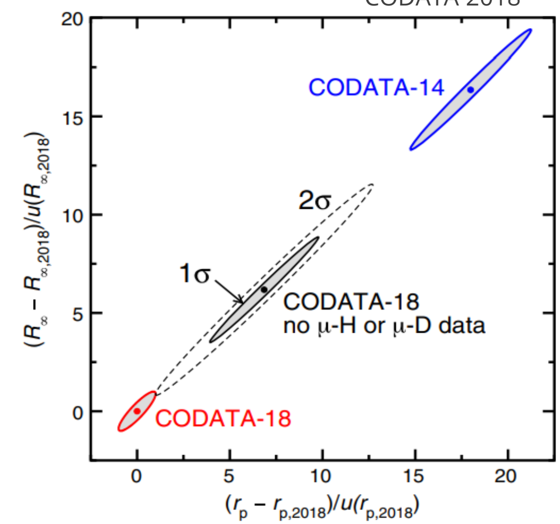
Proton radius puzzle is now somehow solved.

- New experiments & analyses reproduced the results with muonic hydrogen.
- Remind us the importance of experiments with different system.

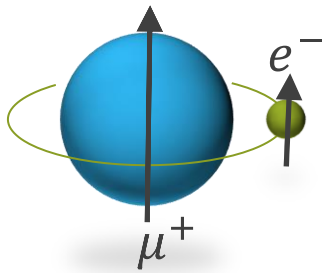
- Input to the determination of Rydberg constant (R_∞),
- which is now the 2nd most precise constant to date.

1.9×10^{-3} ppb

CODATA 2018

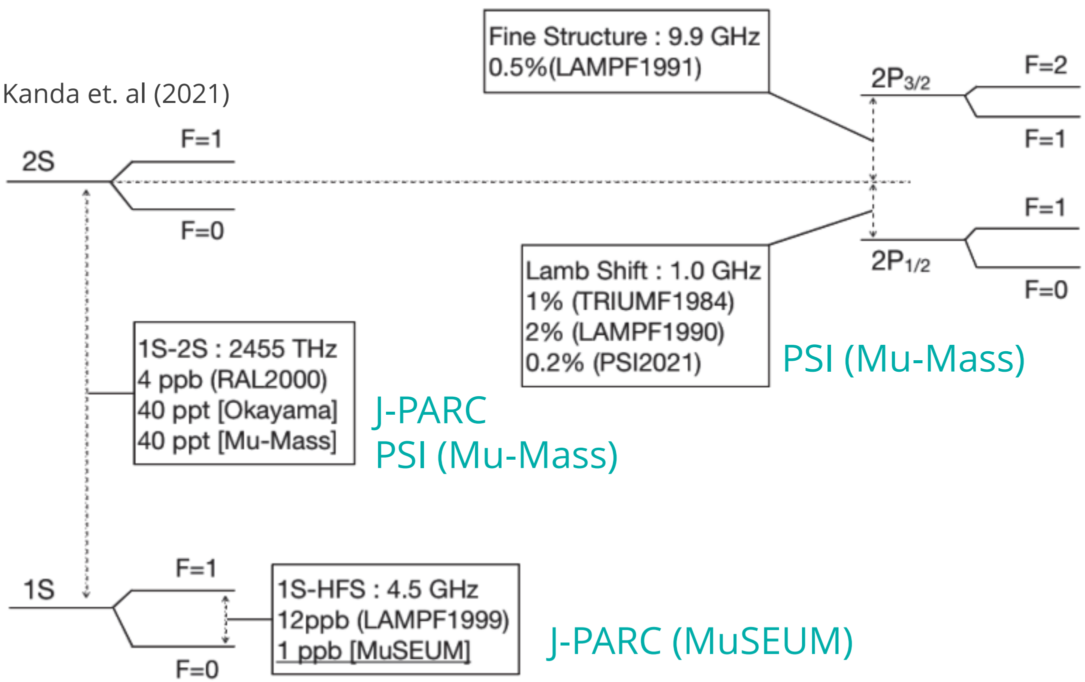


Muonium



Pure leptonic "hydrogen"

- Enable precise test of electro-weak.
- Free from form factor (finite size) of proton.
- Measure energy levels
- with laser spectroscopy developed in atomic physics.



High precision measurements are now possible

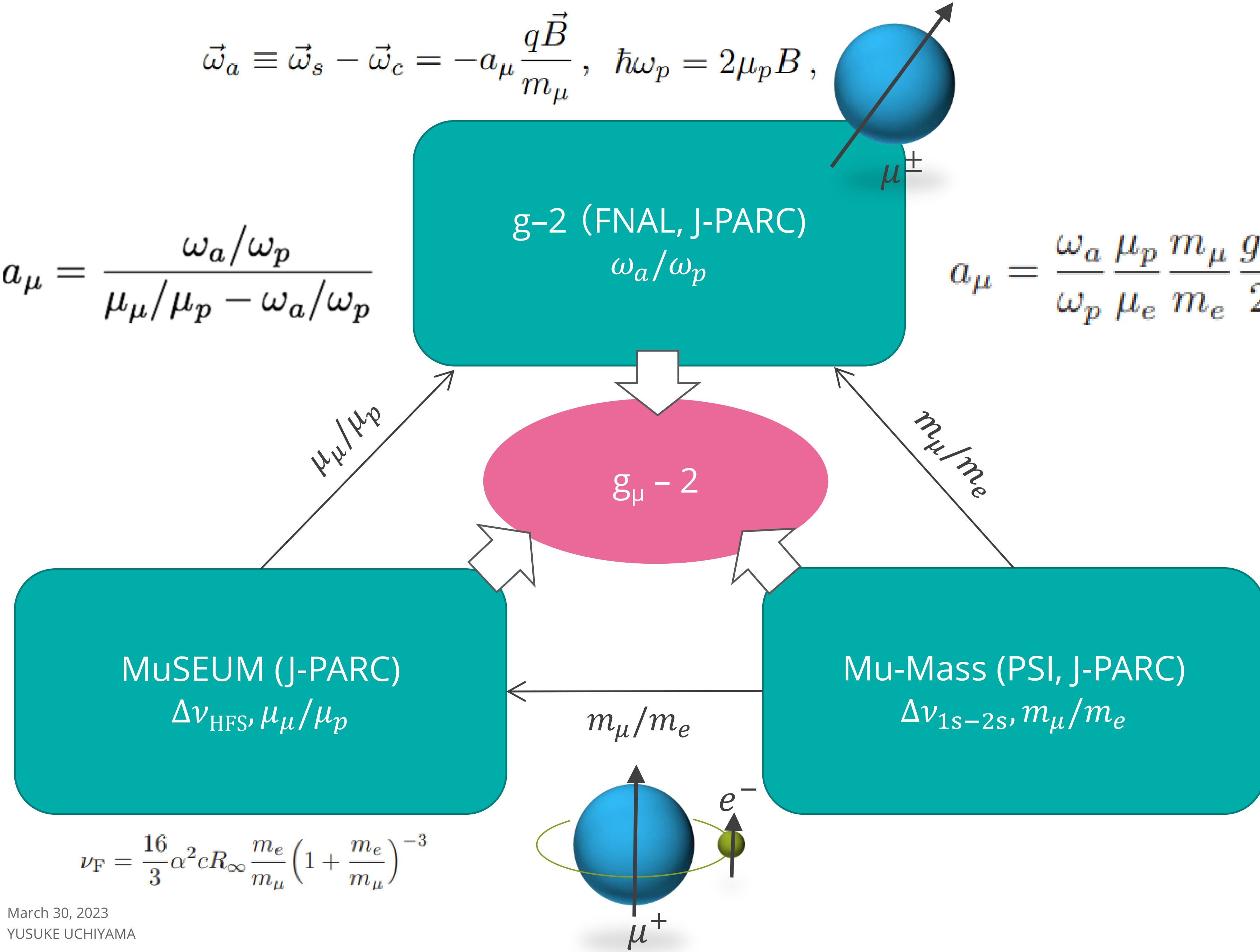
- with high-intensity muon beams
- and advanced laser technologies.

- (Alternative) determination of fundamental physics constants: α, R_∞, m_μ
- Precise test of QED.

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -a_\mu \frac{q\vec{B}}{m_\mu}\,, \quad \hbar\omega_p = 2\mu_p B\,,$$

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

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



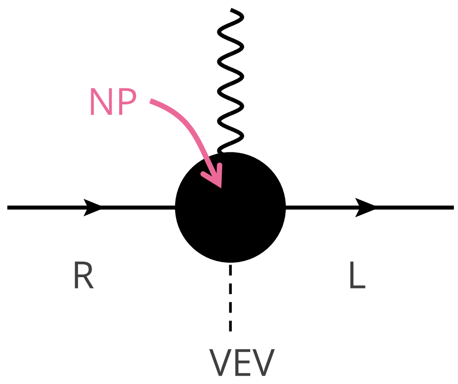
$$\nu_{\rm F} = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$

Relation b/w g-2, EDM, & μ→eγ

Interaction of muon with photon

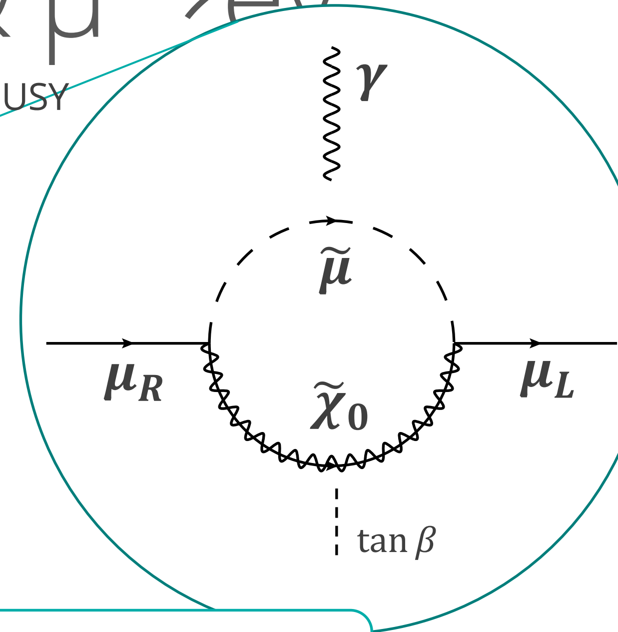
In effective field theory, new physics contributes model independently via Dim.6 dipole operator

modifies dipole moments



Relation b/w g-2, EDM, & μ→eγ

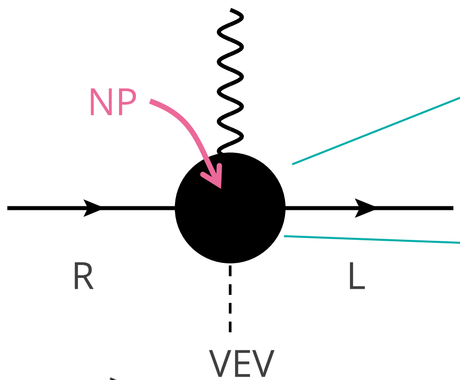
e.g. SUSY



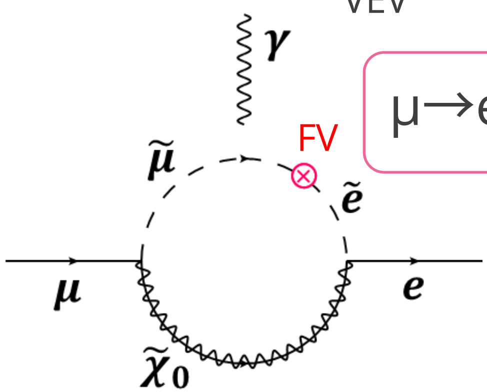
Interaction of muon with photon

In effective field theory, new physics contributes model independently via Dim.6 dipole operator

modifies dipole moments

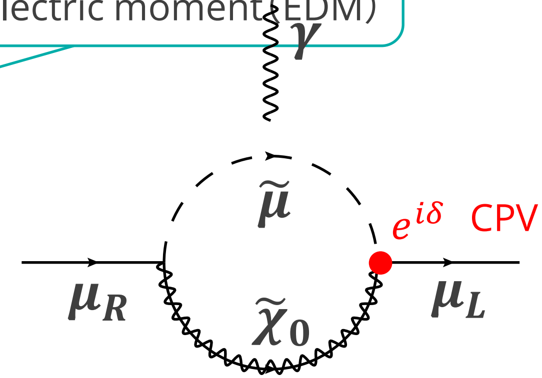


Real: magnetic moment (g−2)
Imaginary: electric moment (EDM)



μ→eγ

$$\begin{pmatrix} m_{\tilde{e}\tilde{e}} & m_{\tilde{e}\tilde{\mu}} & m_{\tilde{e}\tilde{\tau}} \\ m_{\tilde{\mu}\tilde{e}} & m_{\tilde{\mu}\tilde{\mu}} & m_{\tilde{\mu}\tilde{\tau}} \\ m_{\tilde{\tau}\tilde{e}} & m_{\tilde{\tau}\tilde{\mu}} & m_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$



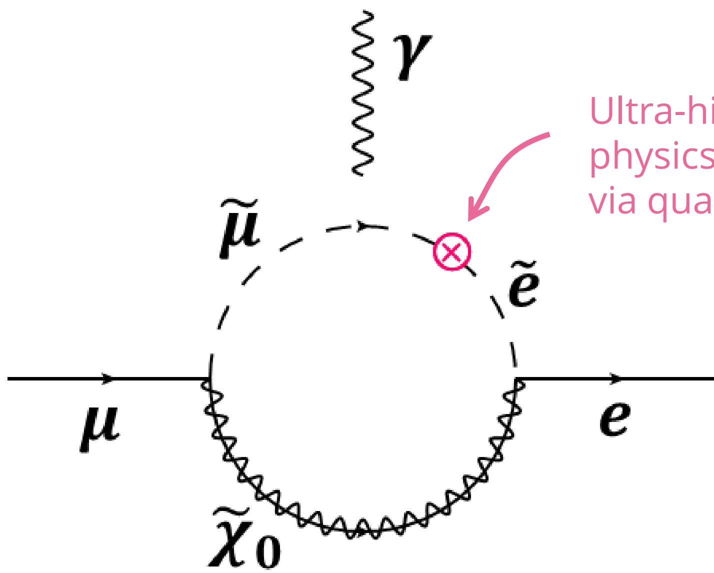
Slepton mass-matrix is in general not diagonalized together with that for leptons

Flavor violating processes are of particular interesting.

Why?

1. provides definitive evidence for NP when discovered (unlike g–2)
   via “forbidden” decay searches

2. connects to ultra-high energy physics



Ultra-high energy physics here via quantum corrections ← source of FV exists in what we already know.

Ultra-high scale
~10^{16} GeV

Inflation

Origin of matter

ν_R

GUT

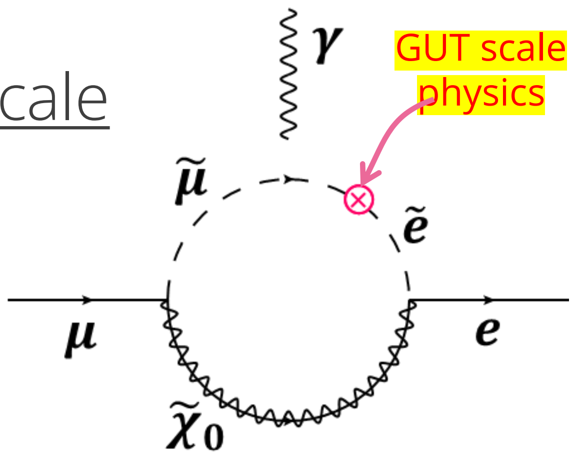
Neutrino mass

Flavor violation from neutrino Yukawa

Flavor violation from quark Yukawa

Force unification
Matter unification
Charge quantization

TeV scale



SUSY

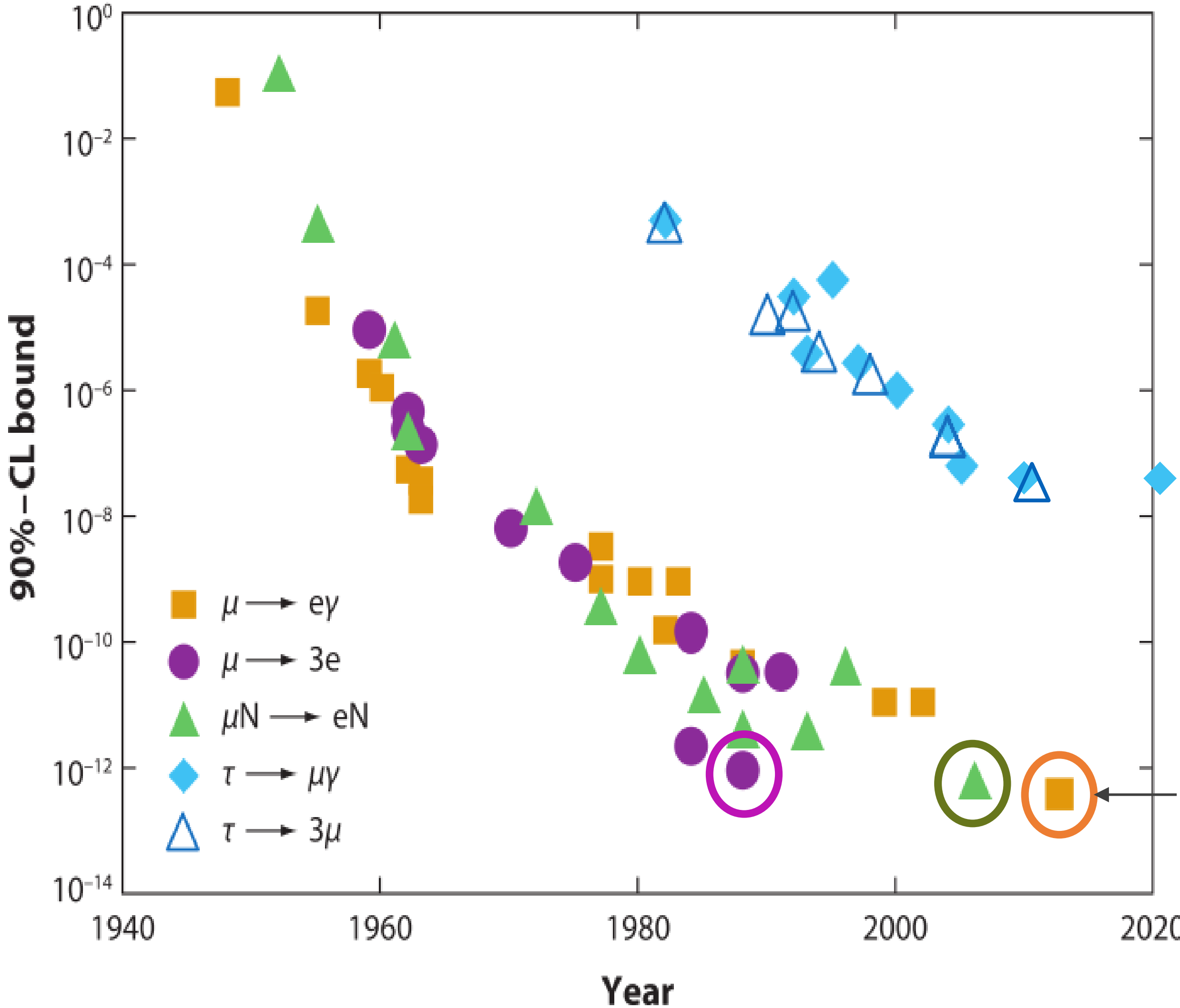
Unify symmetries in space-time & internal
Dark matter
Solve hierarchy problem

Low scale

CLFV $B(\mu \rightarrow e\gamma) \sim 10^{-12} - 10^{-15}$

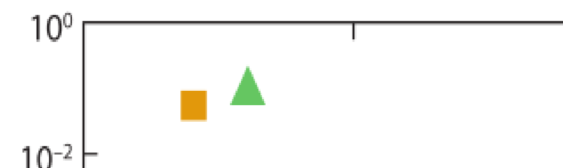
Create a new vison of “elementary particle & Universe” with muon decays

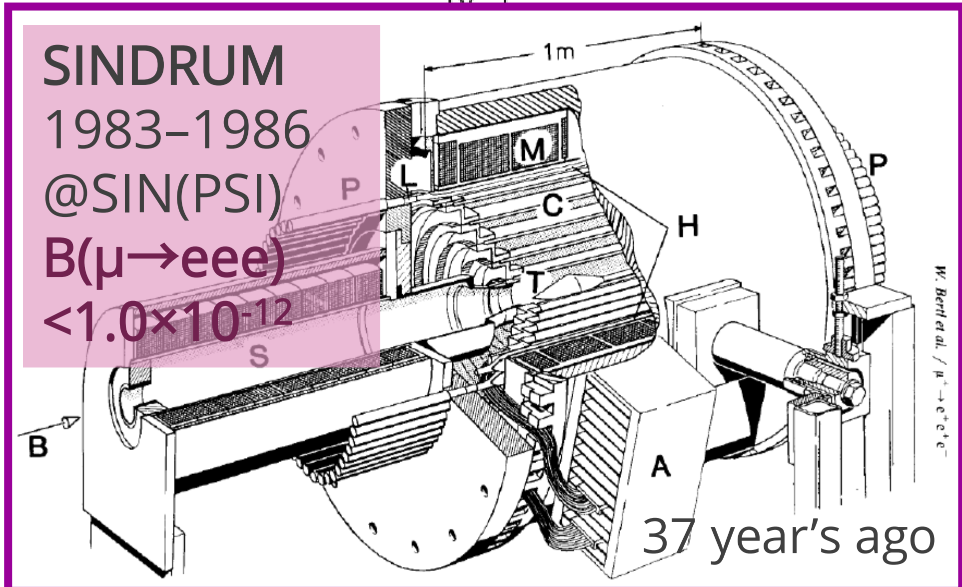
CLFV search history



The tiniest upper limit for any particle's BR
$<4.3\times10^{-4}$ ppb

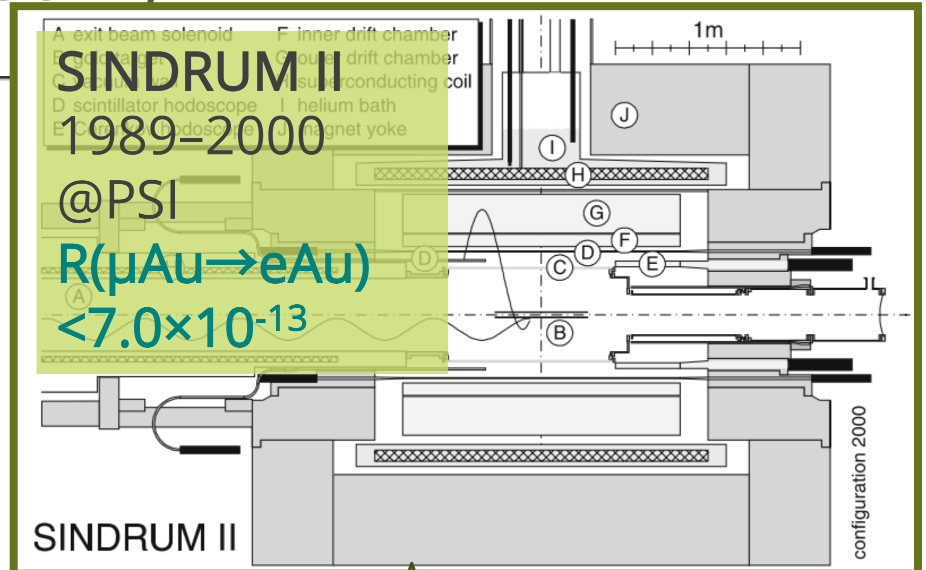
CLFV search history



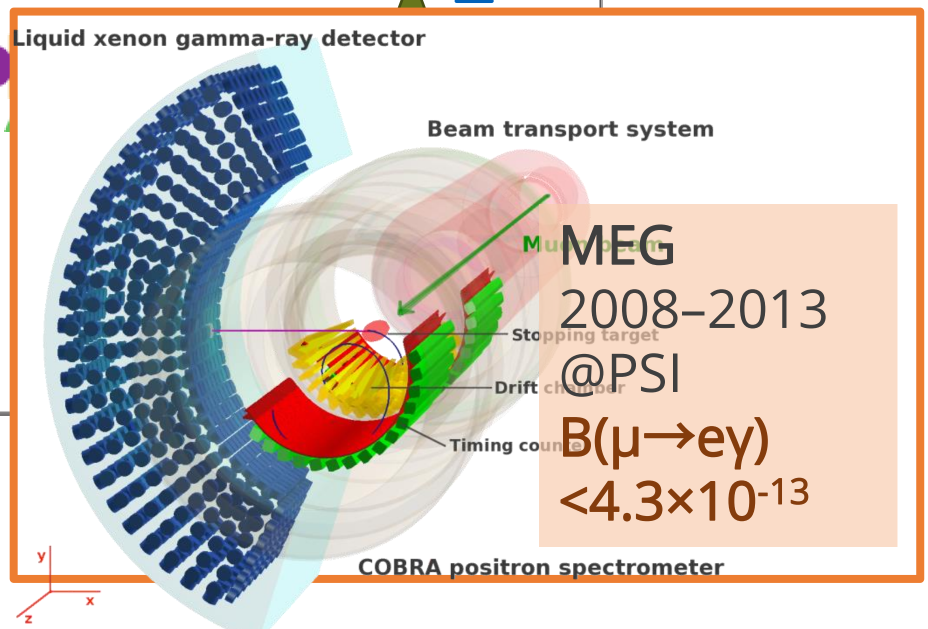


SINDRUM
1983–1986
@SIN(PSI)
B(μ→eee)
$<1.0\times10^{-12}$

37 year's ago



SINDRUM II
1989–2000
@PSI
R(μAu→eAu)
$<7.0\times10^{-13}$

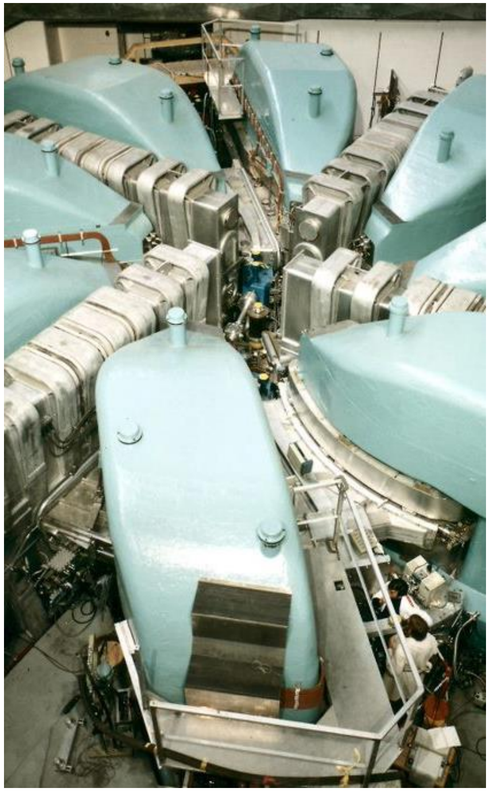


MEG
2008–2013
@PSI
B(μ→eγ)
$<4.3\times10^{-13}$

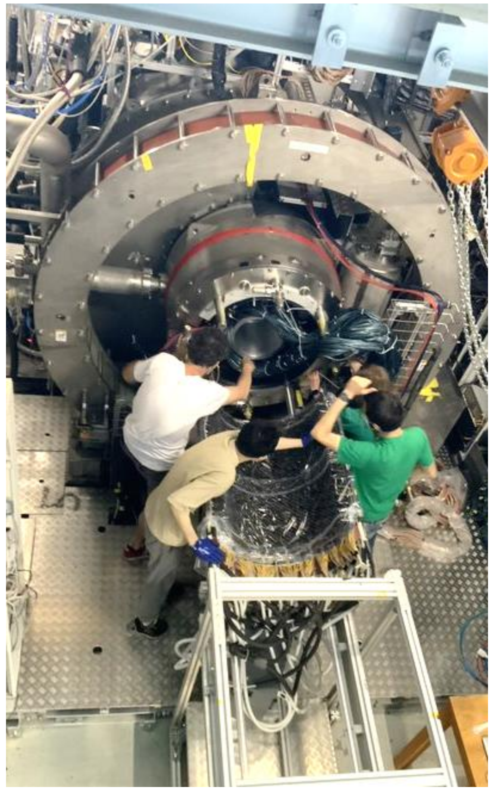
μLFV→
PSI!!

The MEG II experiment

the only ongoing μLFV experiment now

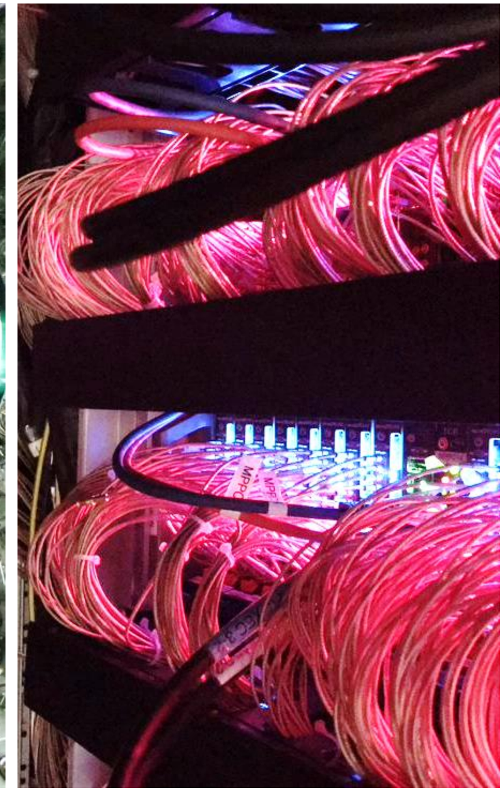


1.4 MW 590-MeV proton ring cyclotron, providing world's most intense DC muon beam



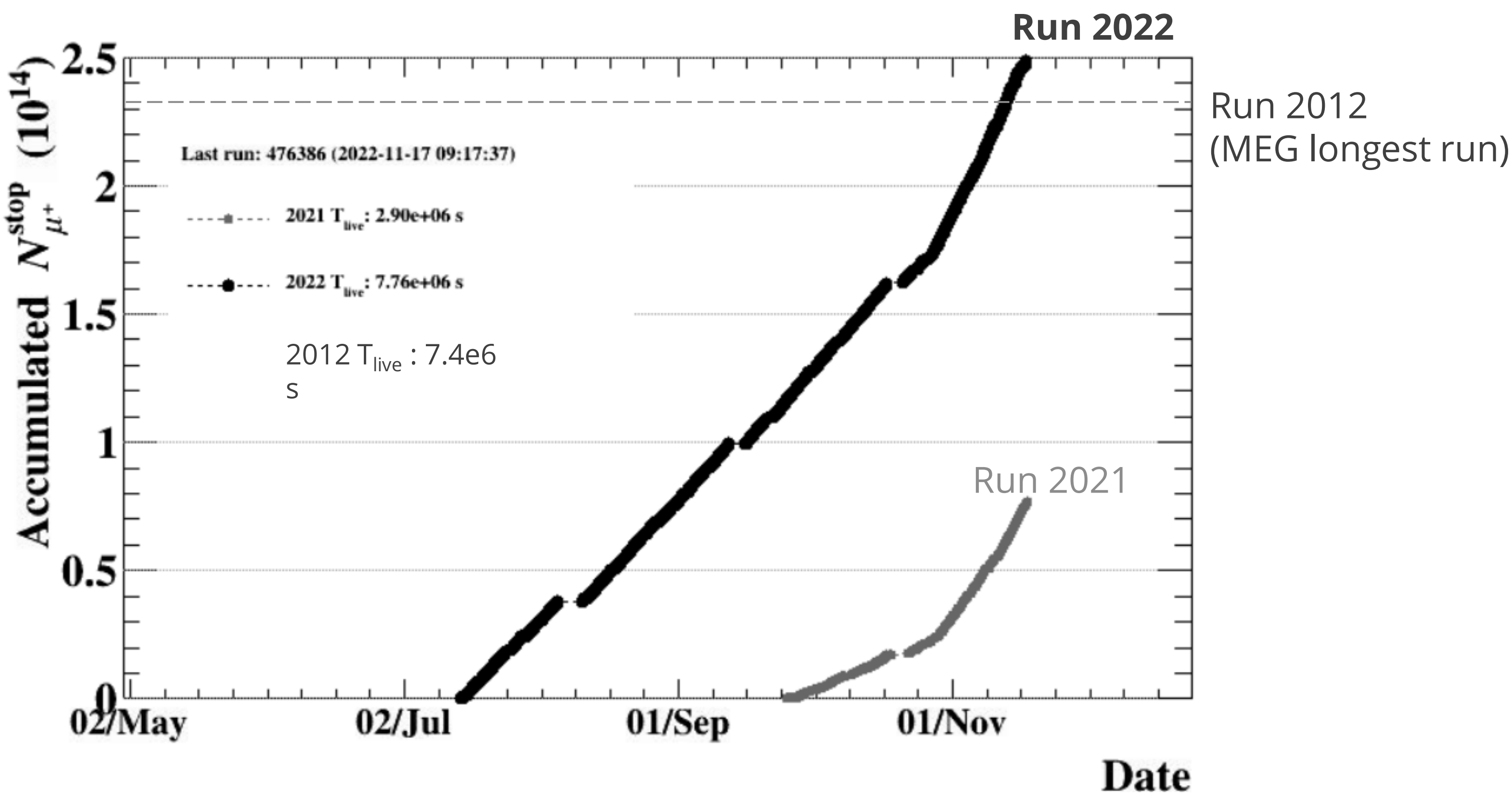
10^8 s^{-1} beamline, gradient field SC solenoid, high-rate capable low-mass e^+ detectors

LXe scintillation photon detector with VUV sensitive photo-sensors, a pioneer work of LXe detectors



Integrated trigger & DAQ system to record waveform data @ 1.4 GSPS, with trigger rate of <30 Hz.

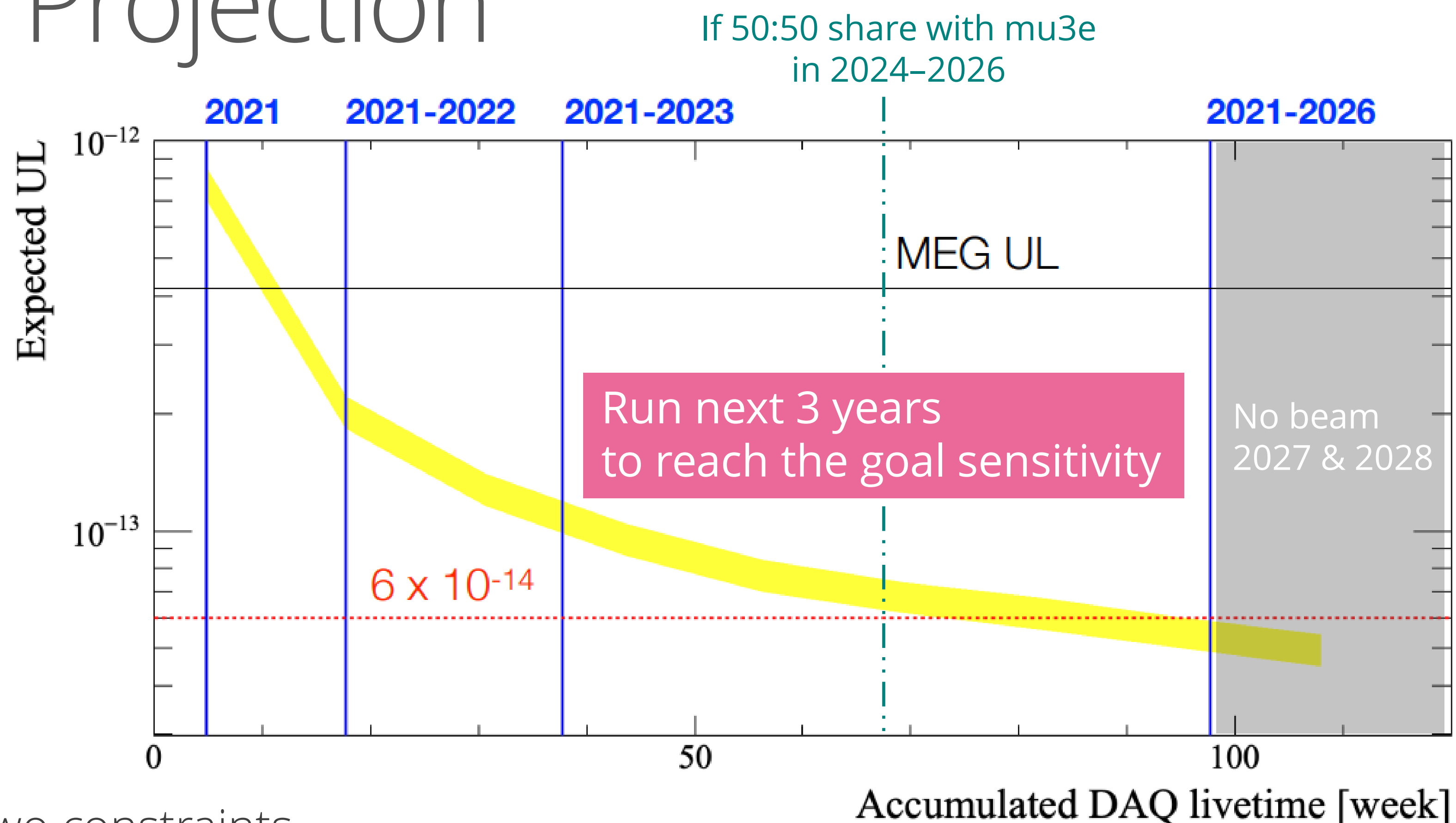
MEG II started in 2021



2021: pilot run → 1st result foreseen in this summer.

2022: 1st long production run → ×2.5 better sensitivity than MEG

Projection

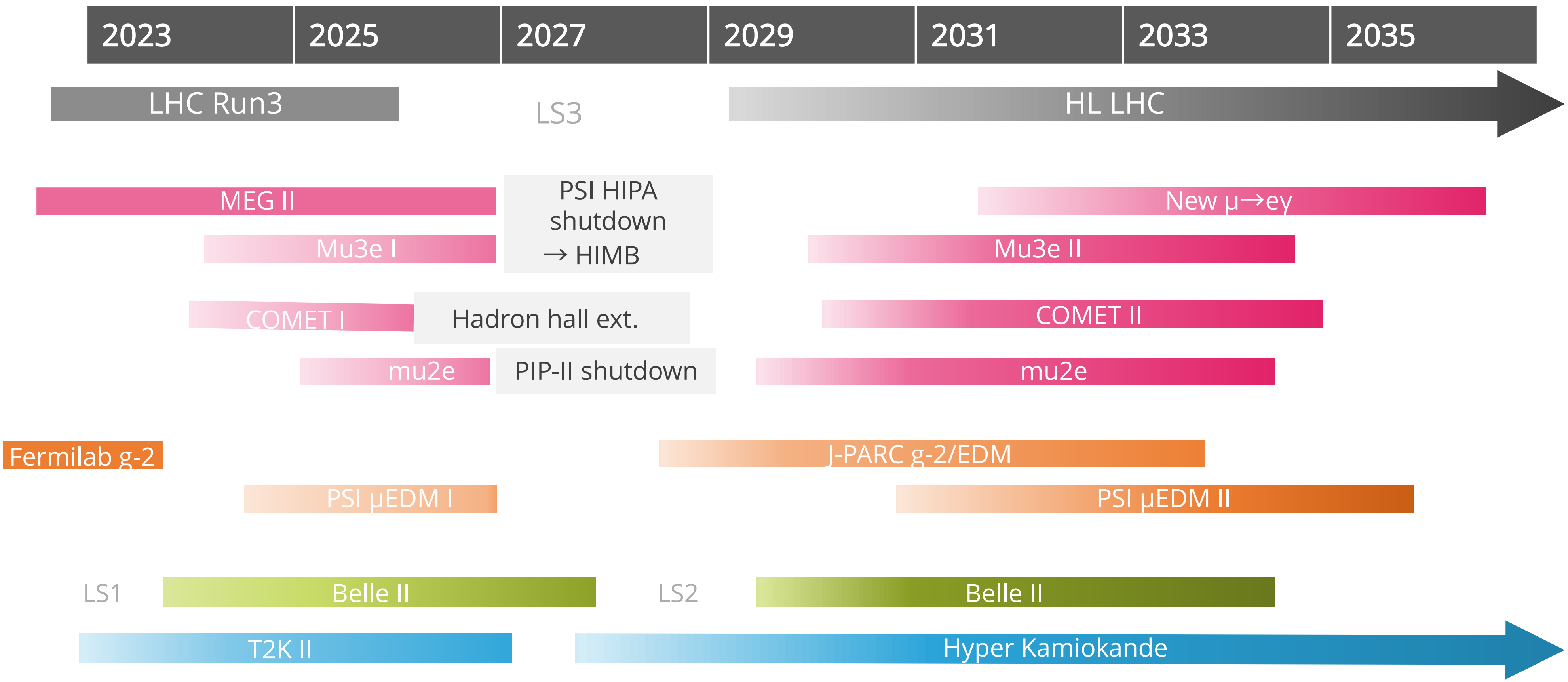


<u>Two constraints</u>

1. **Long shutdown in 2027–2028 planned**
   to build a new high-intensity muon beamline (10^{10} s^{-1})
2. **Share πE5 beamline with mu3e**
   once they get ready. They also conduct phase I experiment before the shutdown…

Next decade

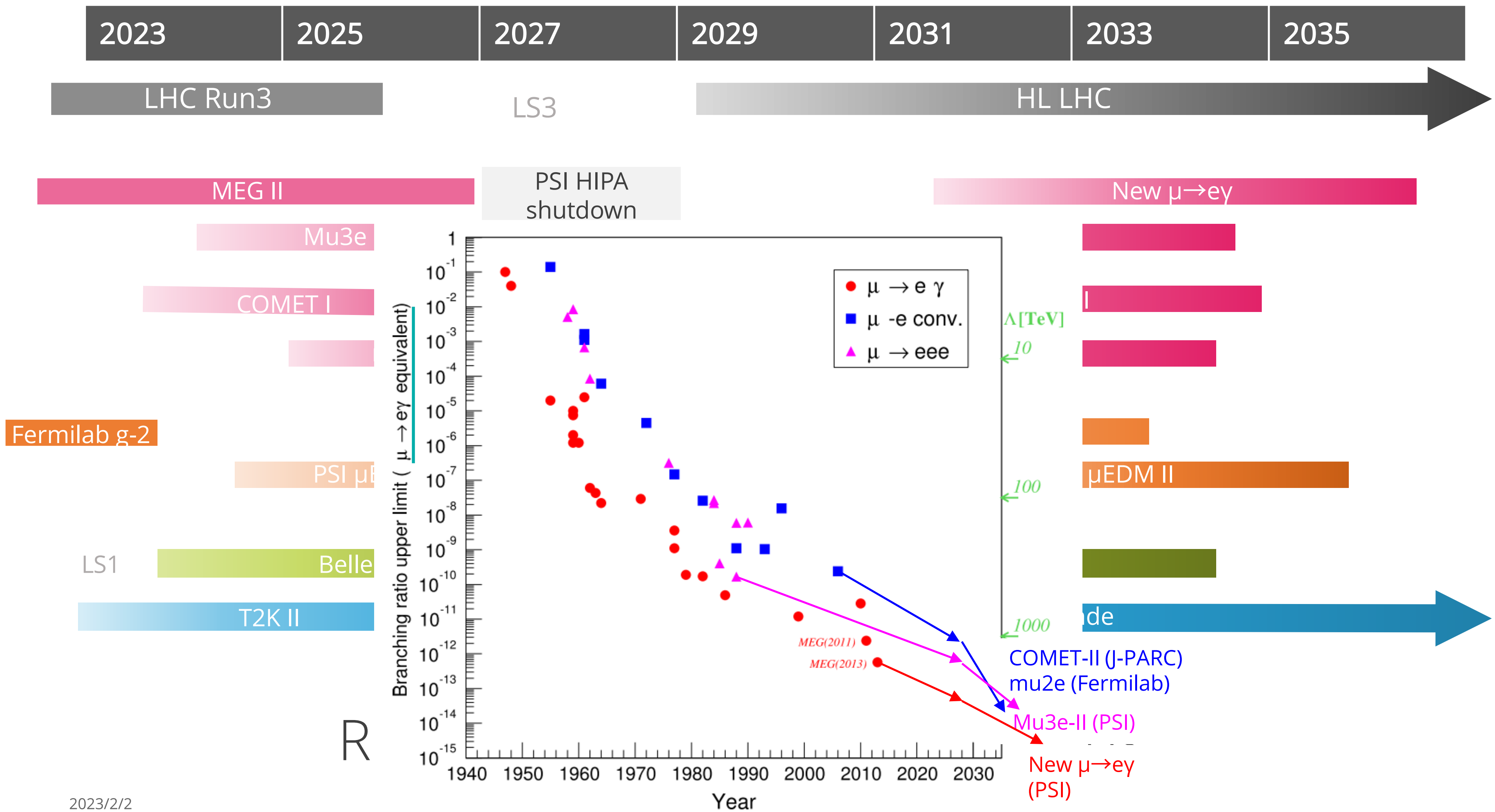
Include my perspective



Rich programs in 2020s – 2030s

Next decade

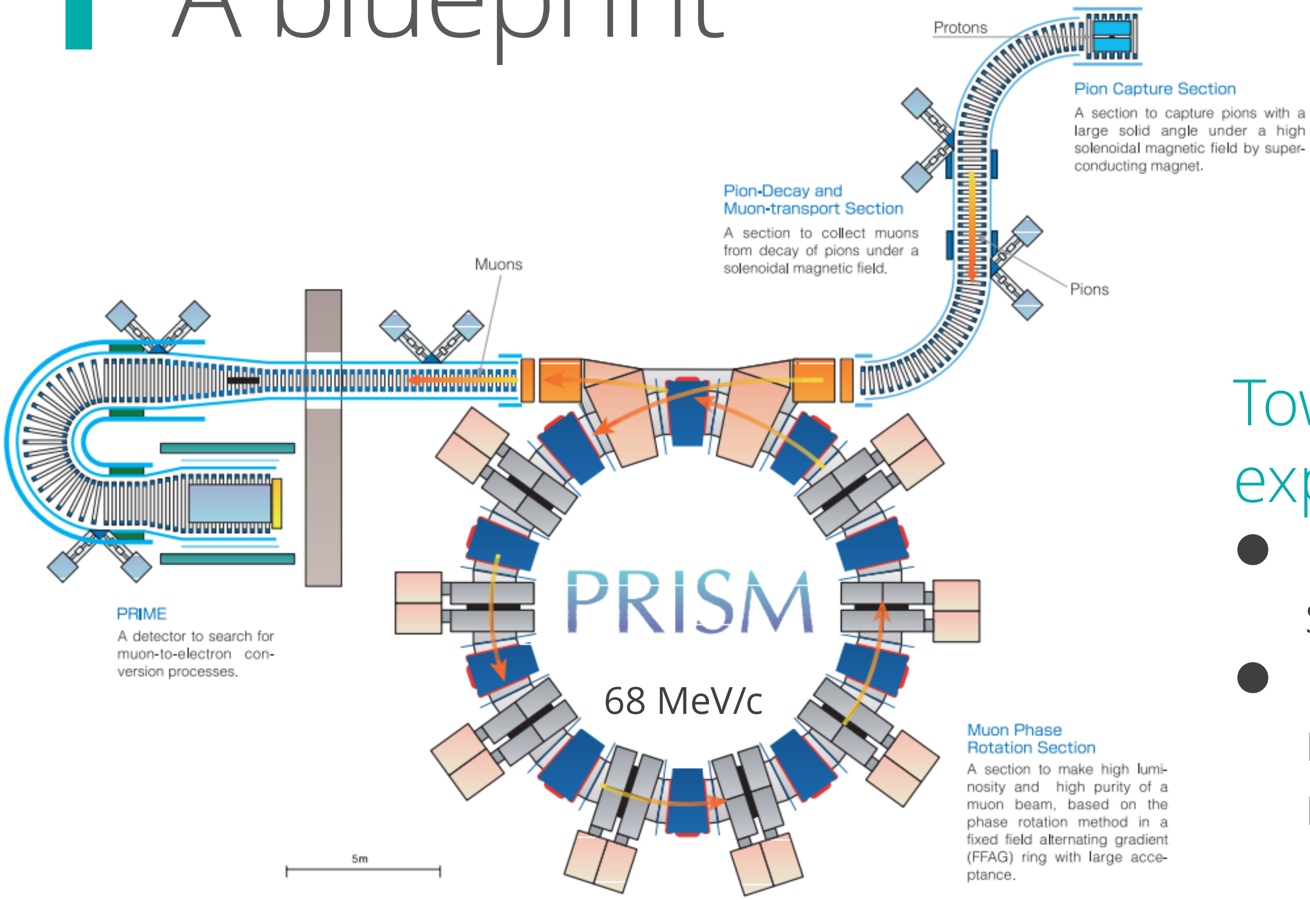
Include my perspective

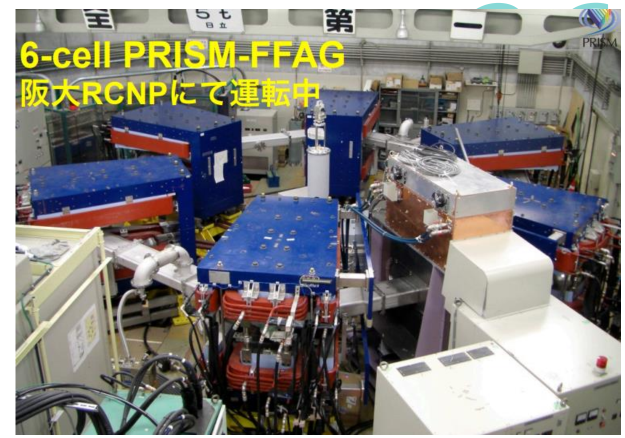


What about far future?

Manipulation of muons will be a key in 2040s particle physics personal

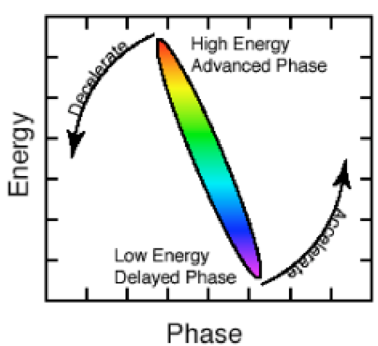
A blueprint

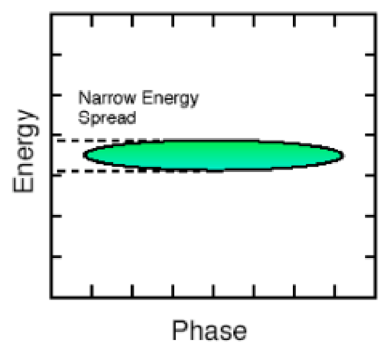




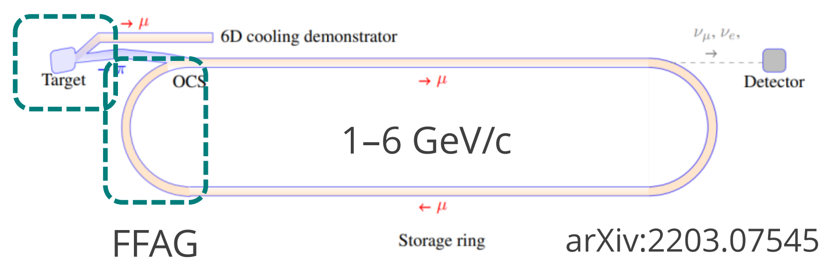
Towards an ultimate CLFV experiment O(10^{-18})

- FFAG-based phase rotating storage ring
- High intensity (10^{12} s^{-1}), monochromatic, high purity muon beam





Technical synergy with νSTORM



FFAG

arXiv:2203.07545

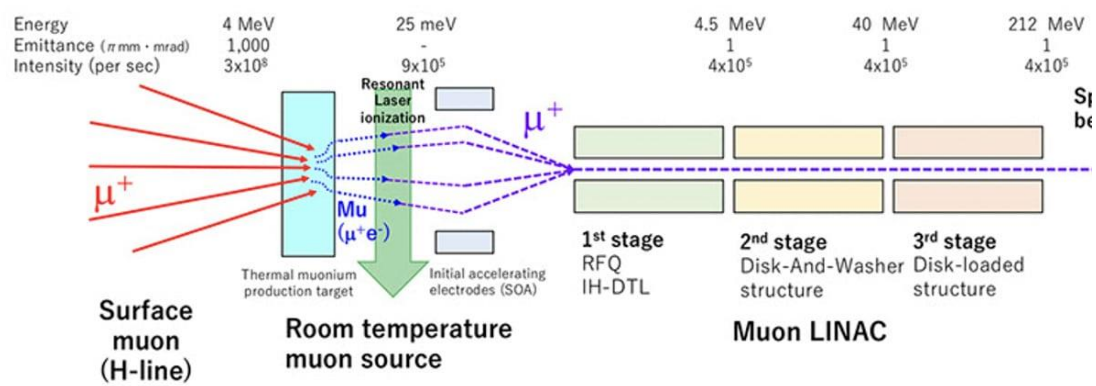
Worldwide interest and efforts for muon colliders

- However, technically not mature.
- Japanese contribution to MC is behind, but we have advanced technologies
  - High-power proton driver (J-PARC)
  - COMET will establish pion capture technique → 10^{11} s^{-1} beam
  - g-2/EDM will establish low emittance μ⁺ beam with muonium-ionization cooling and muon acceleration for the first time in the world
  - FFAG technologies may fit to fast acceleration

→ collider with μ^+

Y. Fukao

H. Iinuma



A new idea of μ^+e^- collider: μTRISTAN

- as a Higgs factory $\sqrt{s} = 346$ GeV
- a realistic design
- earlier realization than $\mu^+\mu^-$

PTEP 2022 053B02

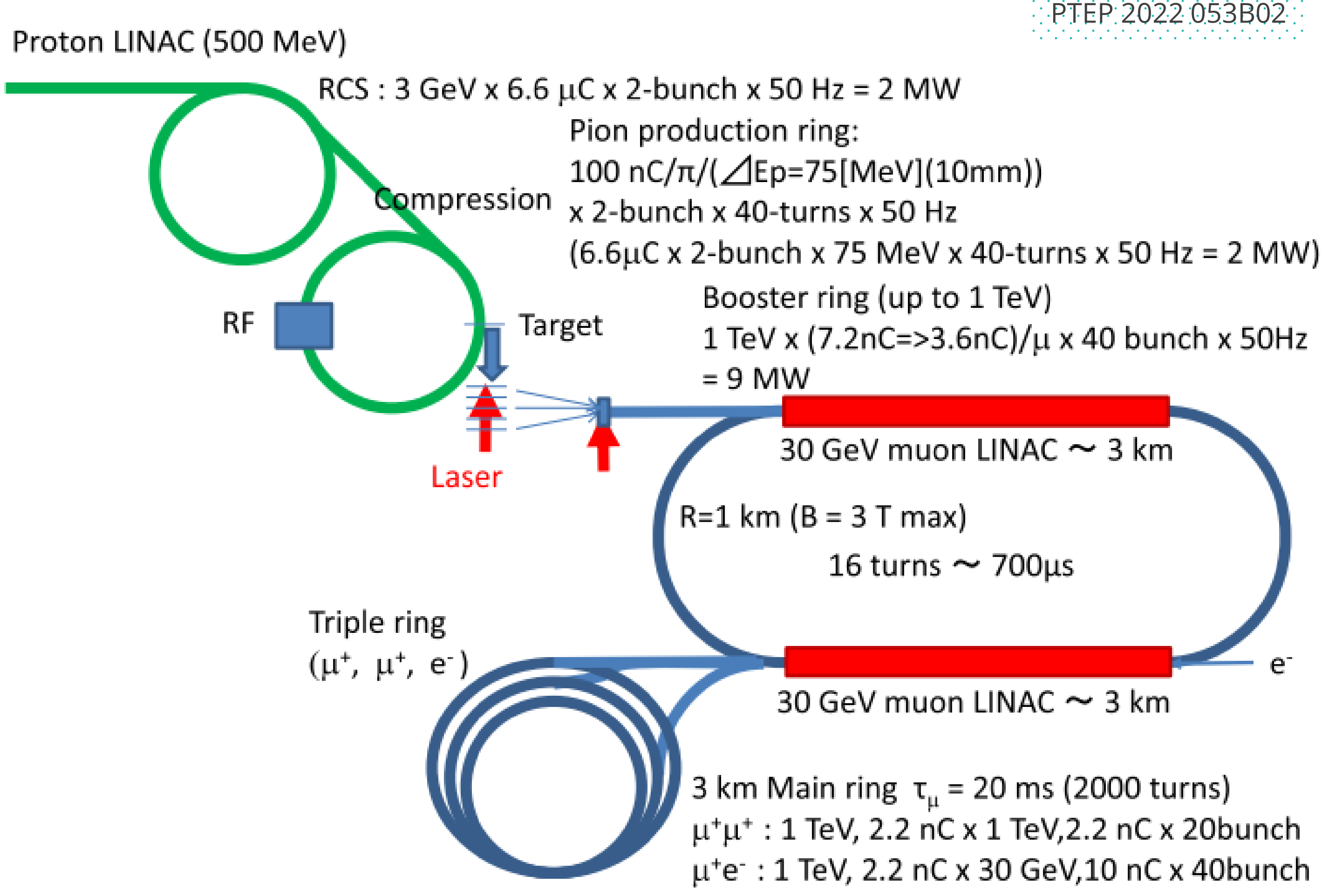


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

As a pre step, start with ν-factory (only ν_e&$\bar{\nu}_\mu$) with 5 GeV?

Conclusions

Muons have played an essential role in modern physics (SM) in its 86-year history

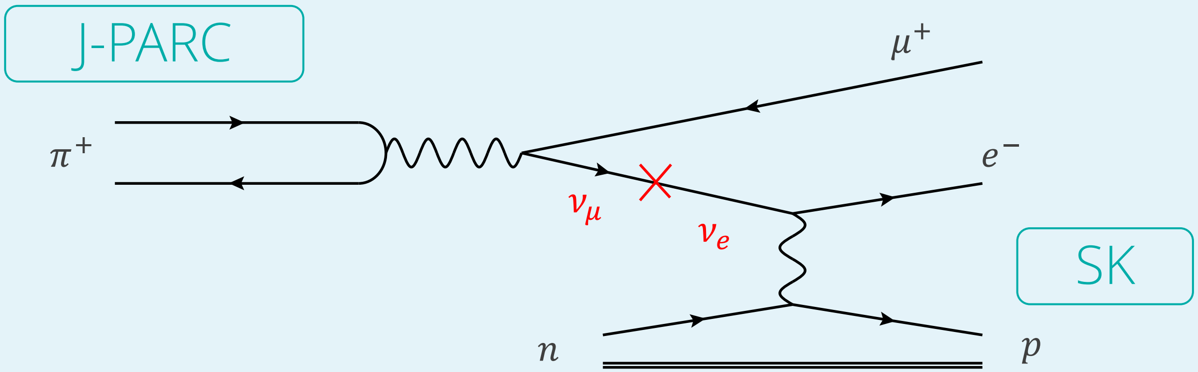
Providing the most fundamental (G_F) & most precise (R_∞) parameters in SM.

Today & next decade would be the hottest period of particle physics with muons

New experiments in J-Parc (& lattice QCD) will conclude the $g-2$ anomaly.
New CLFV experiments in the world would discover evidence for NP.
So, CLFV & LFUV would be key probes for NP.

New technologies to manipulate muons would be the key of high-energy & particle physics in 2040s (or even earlier)

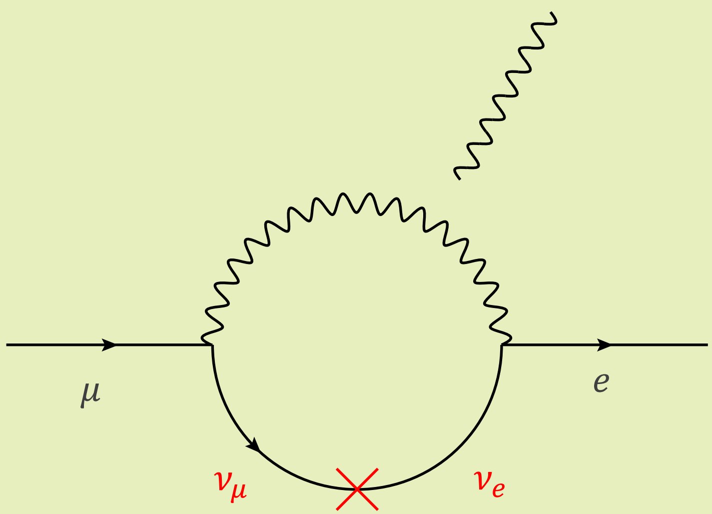
CLFV processes in SM



$\boldsymbol{\pi^+ n \rightarrow \mu^+ e^- p}$

$L_e = 0$, $L_\mu = 0$ → $L_e = 1$, $L_\mu = -1$

CLFV!!



$\boldsymbol{\mu \rightarrow e\gamma}$

$L_e = 0$, $L_\mu = 1$ → $L_e = 1$, $L_\mu = 0$

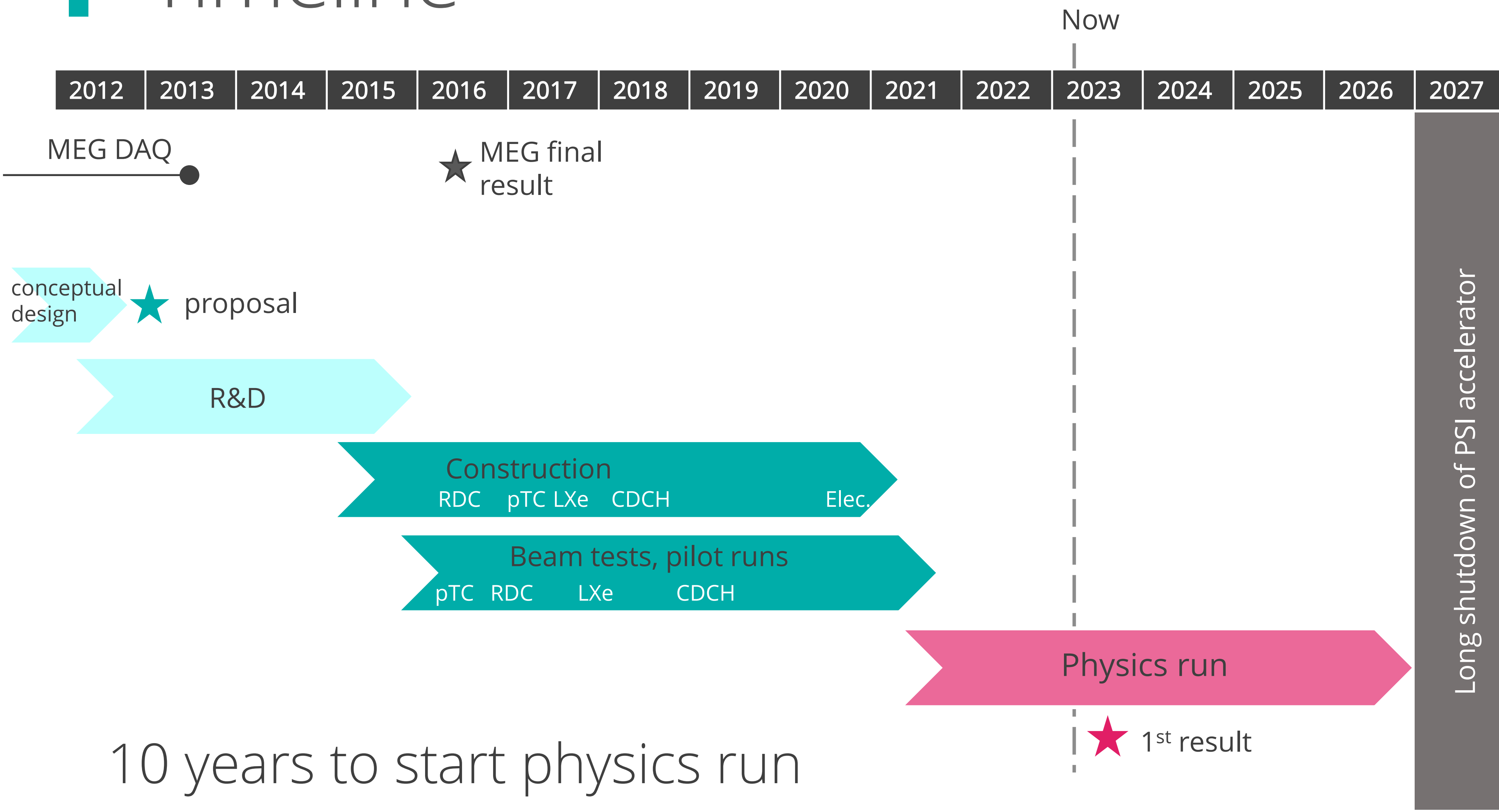
$$\frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

Just too small probability
due to mysteriously tiny neutrino masses

Impossible to be observed

If observed, definitive evidence for NP

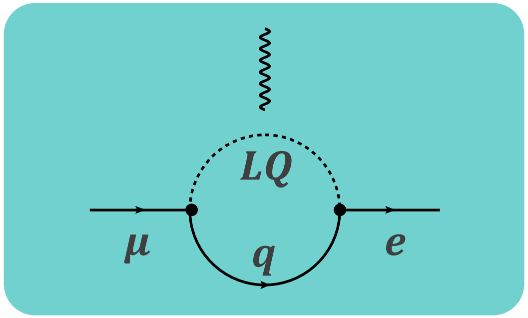
Timeline

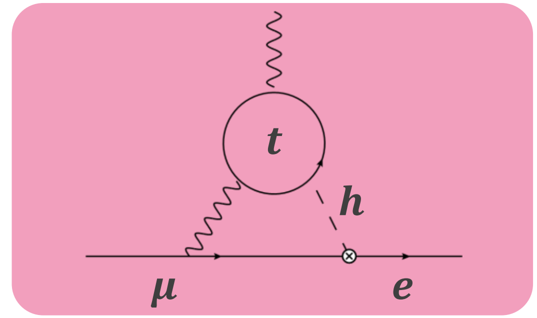


10 years to start physics run

bottom-up

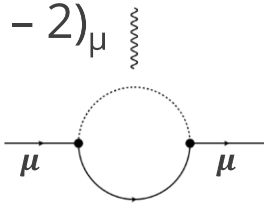
Other reasons



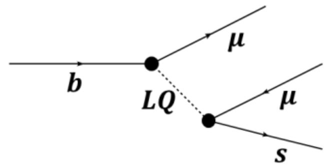


two-loop

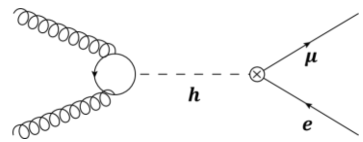
$(g-2)_\mu$



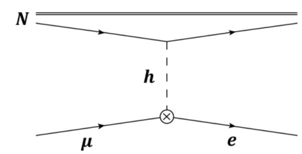
LHCb



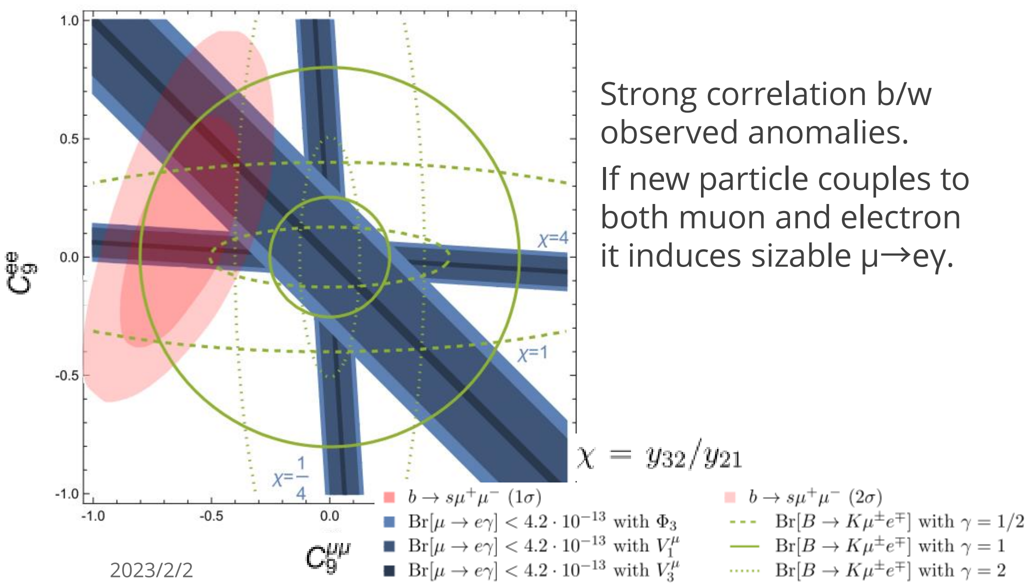
CMS



mu2e/COMET



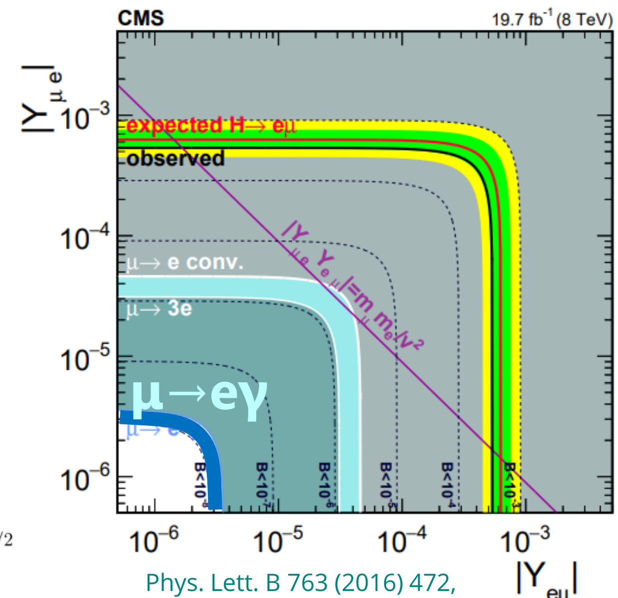
tree



Phys. Rev. D 97 (2018) 015019

Strong correlation b/w observed anomalies.

If new particle couples to both muon and electron it induces sizable μ→eγ.



Phys. Lett. B 763 (2016) 472,
JHEP 03 (2013) 026

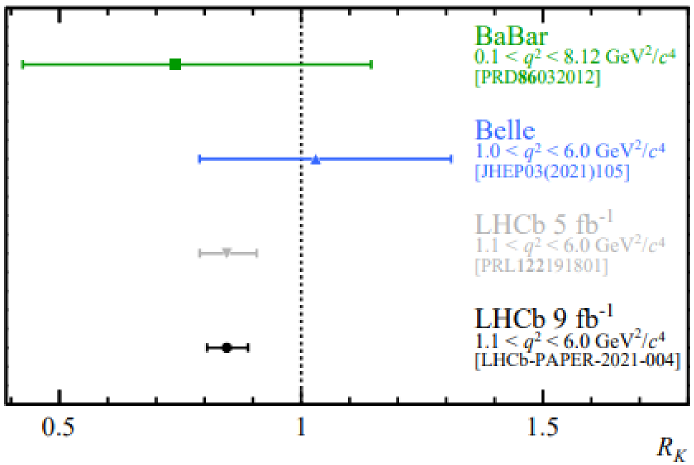
Limit on μ→eγ provides the most stringent limit on the LFV Higgs decay

BR(h→μe) $\lesssim 10^{-8}$

(CMS limit:
BR(h→μe) $< 3.5\times10^{-4}$)

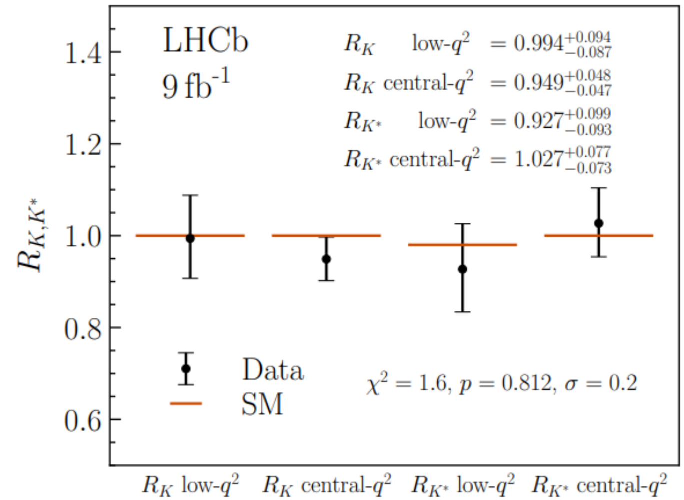
Recent news

> 3σ discrepancy found !!!!

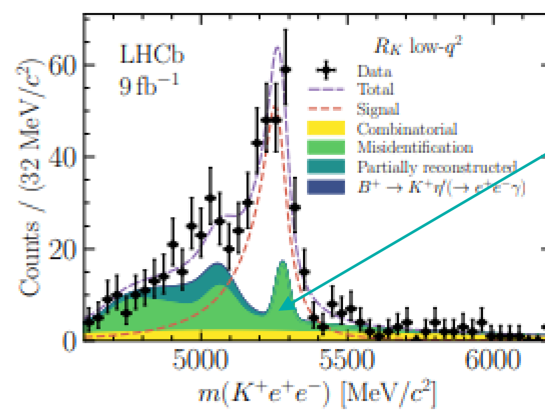


Nature Physics 18, (2022) 277-282
545 citations (← many theories to explain this anomaly)

Turned out to be just systematic error



arXiv:2212.09153



Peaking BG unconsidered in the old analysis

Surely it is the way for science to go, but

Flavor physics is now put to test.

(Lots of "anomalies" appeared and disappeared not only in flavor physics.)

We need conclusive experiments

Different processes

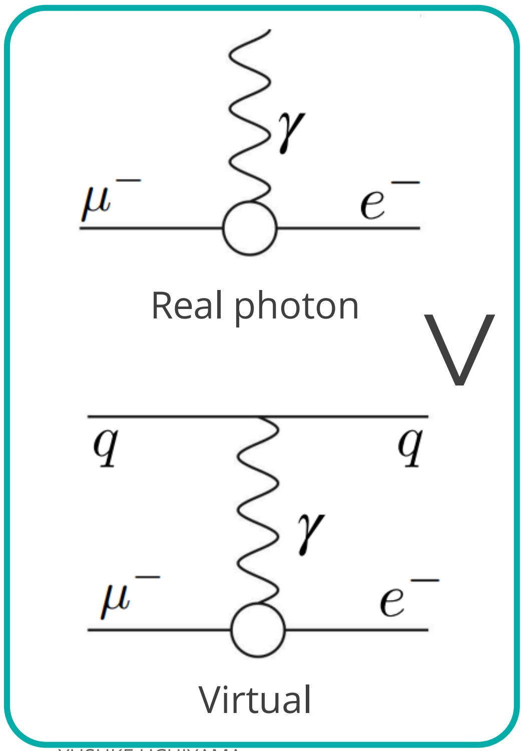
Why search different channels

- Sensitive to different physics behind
- Different requirements for experiments
- Test/confirmation for the other experiments
- Identify physics once discovered in a channel
- Competition

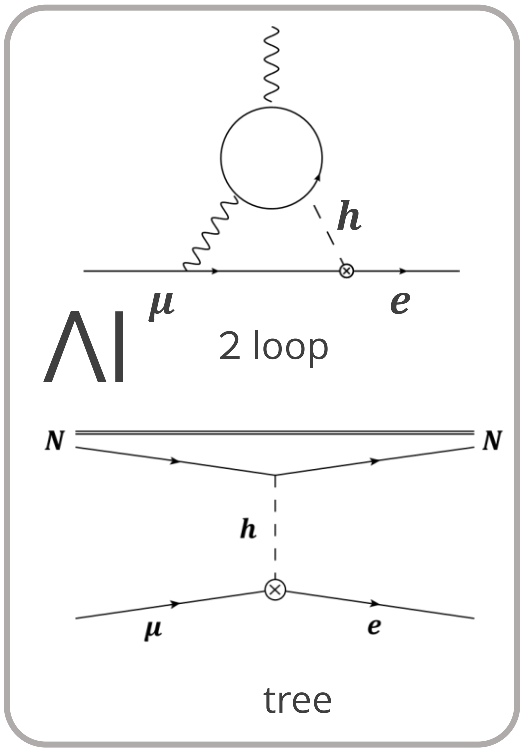
What are you interested in?
What are available technologies?

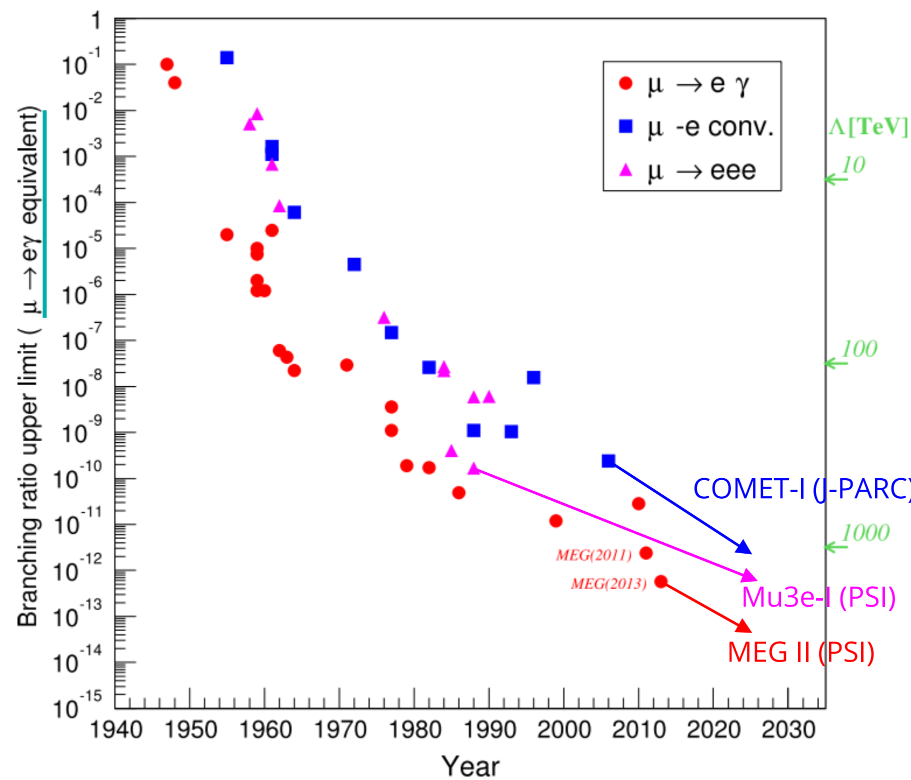
So far, μ→eγ has always leaded.

SUSY-GUT case

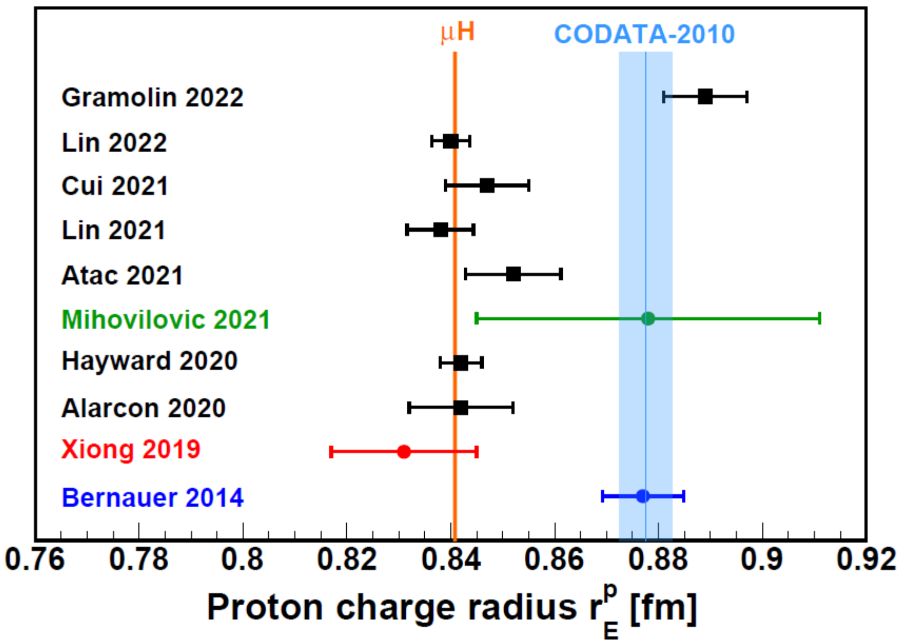


Higgs case

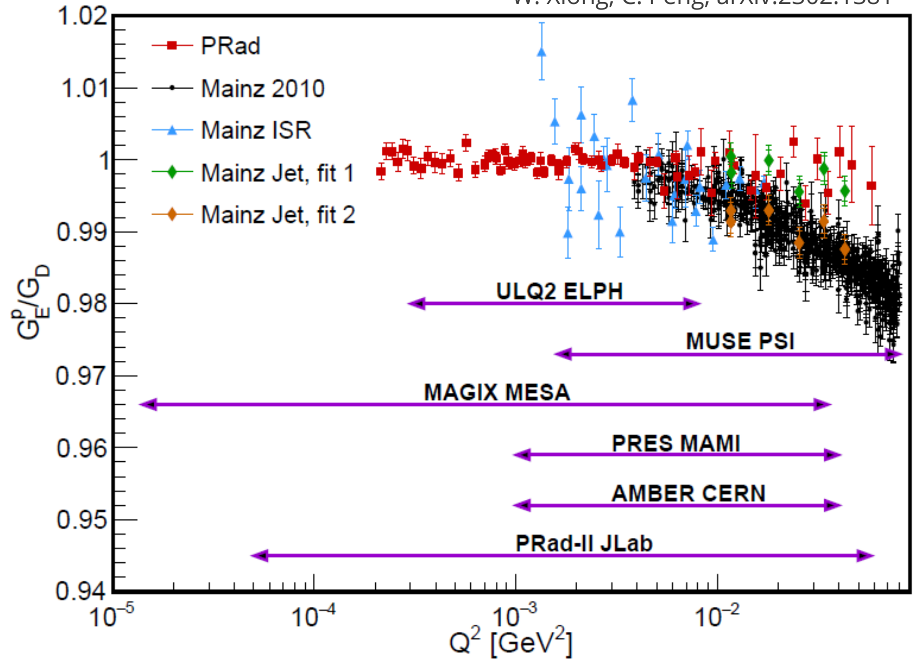




W. Xiong, C. Peng, arXiv:2302.1381



W. Xiong, C. Peng, arXiv:2302.1381



Y. Mori, NuFact03