Lepton Flavour Experiments

— ICFA Seminar 2023 —

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KEK / J-PARC

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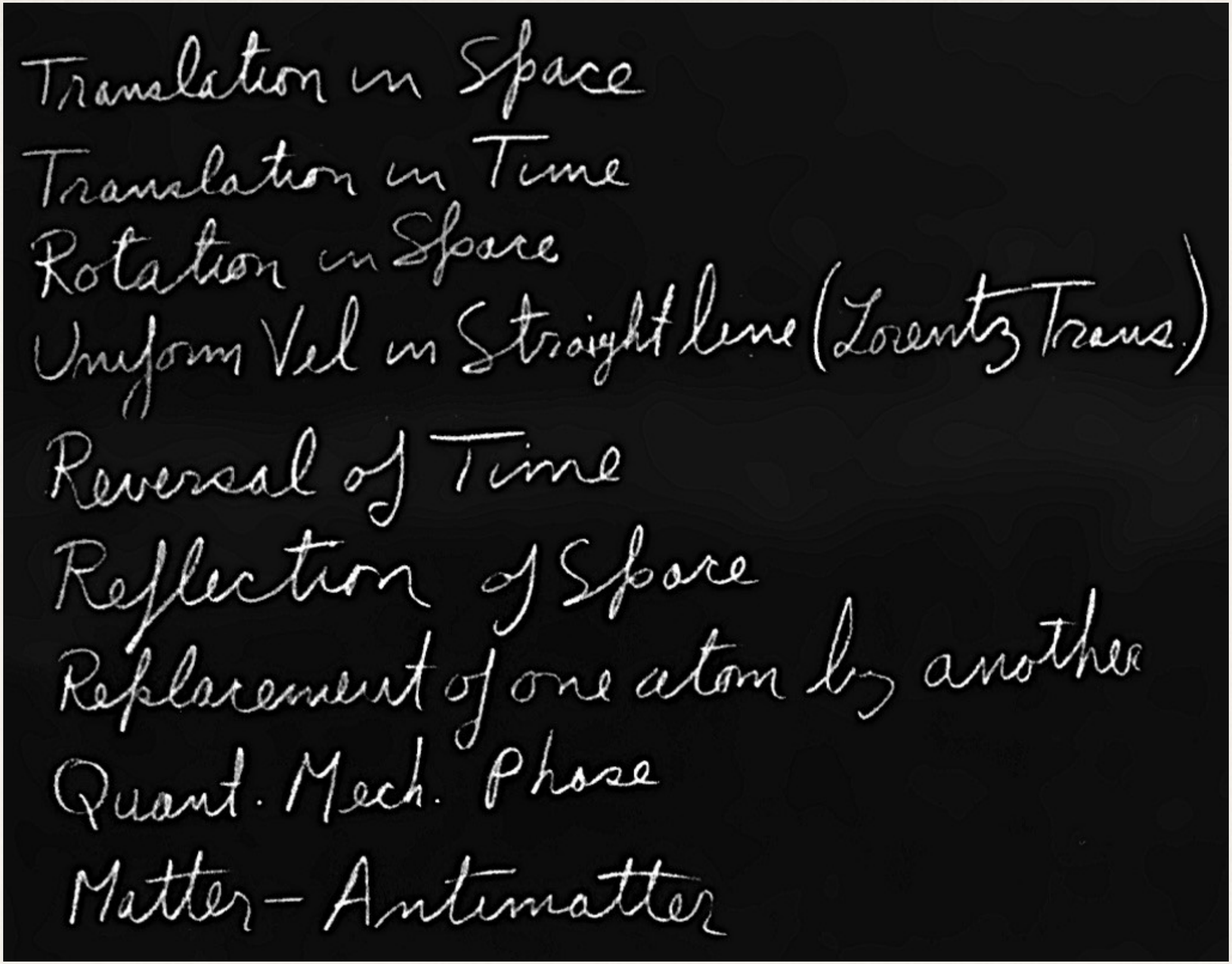
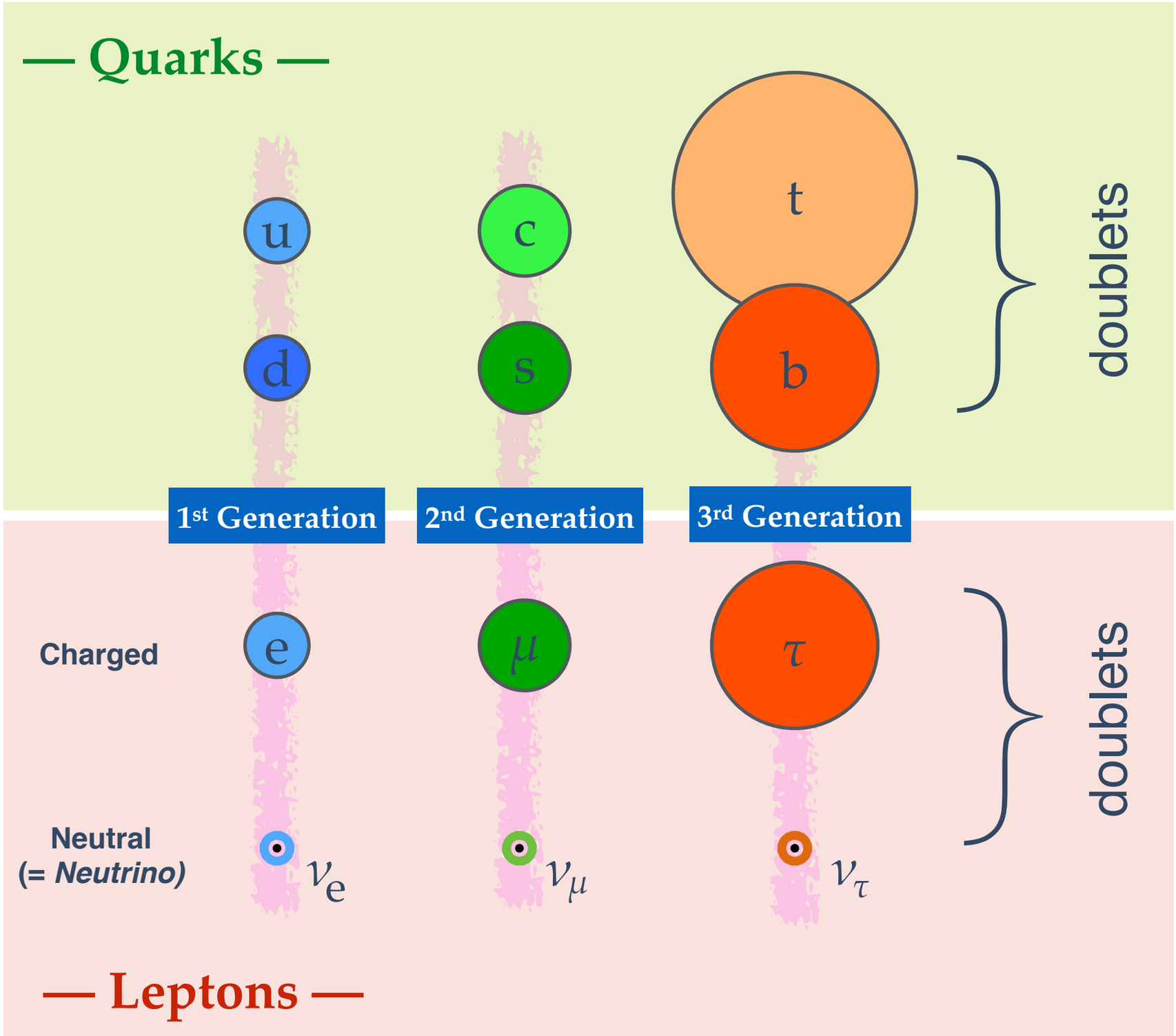


Symmetry in Physical Laws *from "Feynman Lectures"*

The "*Flavour Symmetry*" of Elementary Particle

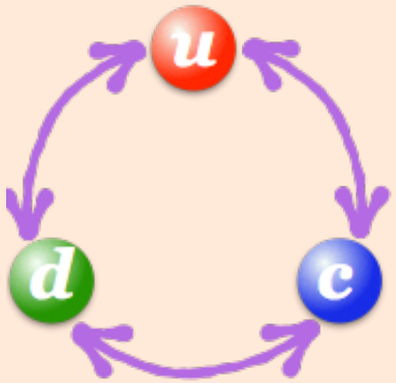


- **Fermion**
  - Quarks & Leptons
  - 6 Flavours
- Introduced due to new symmetry
- Symmetry violations have been observed in "Quarks" and "Nuetrinos"

The "*Flavour Symmetry*" of Elementary Particle

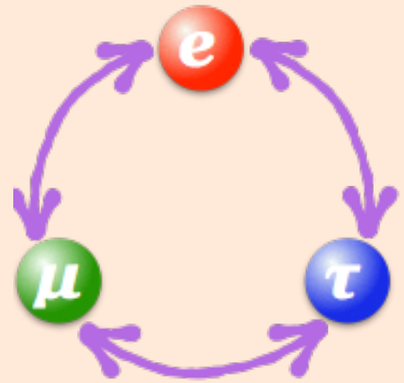
— Quarks —

Quarks



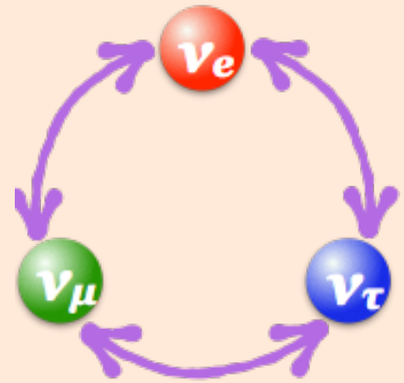
- Known as CKM, Found in B-Factories. Nobel Prize in 2008

(Charged) Leptons

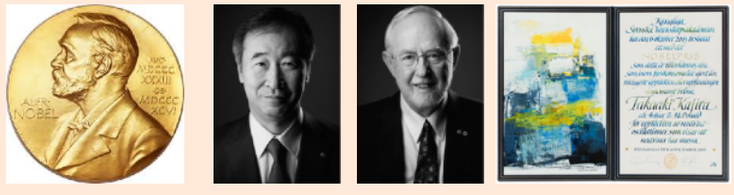


WANTED !!

(Neutral) Leptons



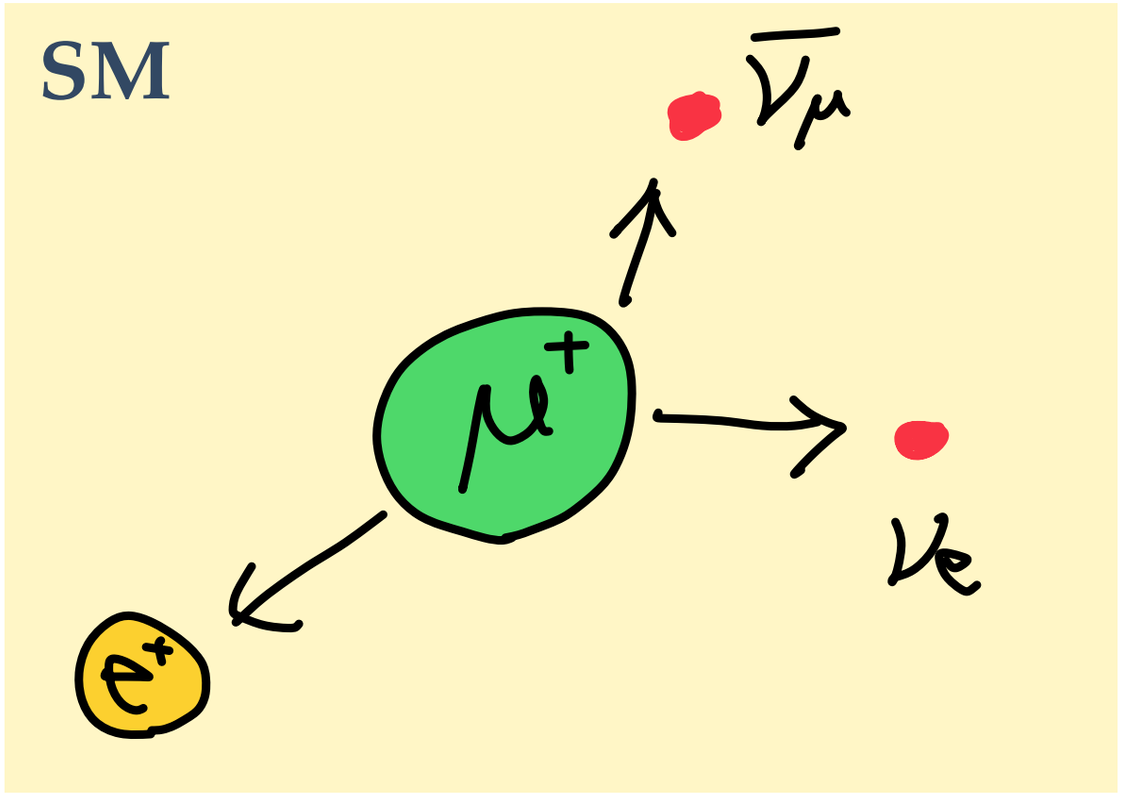
- Observed in Solar Neutrino Oscillation. Nobel Prize in 2015

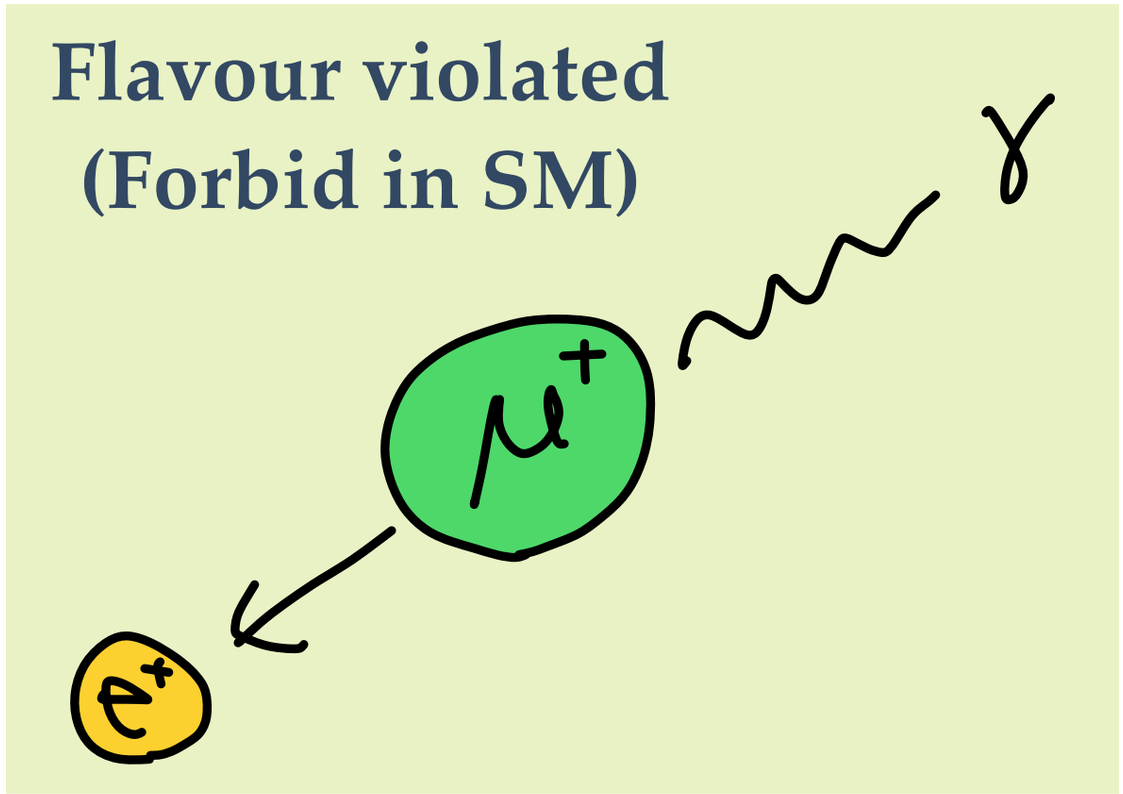


— Leptons —

Lepton Flavour Violation among Charged Leptons

- ***eg*. Muon Lepton Flavour Violating Decay**





$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2 \quad \Rightarrow \quad \mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

$B(\mu \to e\gamma)$ in SM w/ m_ν assumption
→ **< 10^{-54}** due to tiny ν-mass

$B(\mu \to e\gamma)$ in New Physics (NP)
Naturally causable at **10^{-17} ~ 10^{-13}**

Lepton Flavour Violation among Charged Leptons

✓ Flavour mixing in "Quarks" and "Neutrinos", Possible in SM

✓ Already confirmed experimentally

✓ Flavour mixing in "Charged Leptons", Not possible in SM (Unmeasurable), Only possible in NP

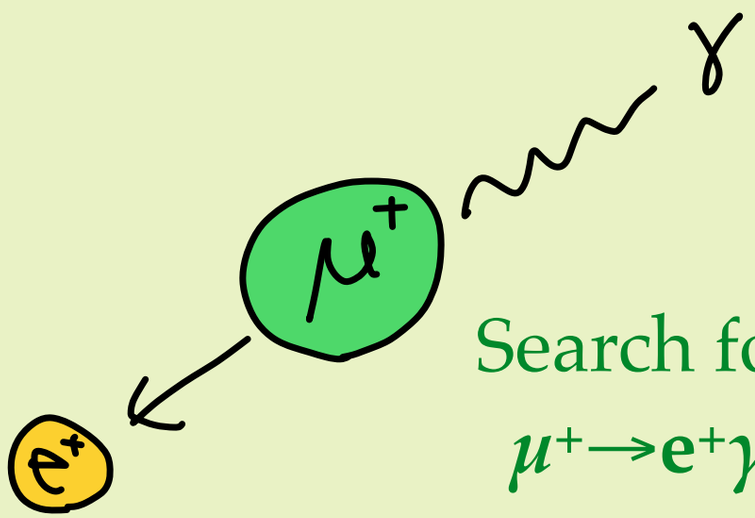
✓ Never been observed

➡ Unambiguous evidence of New Physics !!

➡ Even higher energy scale physics than LHC is accessible by searching for smaller BR.

Decay Searches

- **Most major channels to search for muon LFV decay**

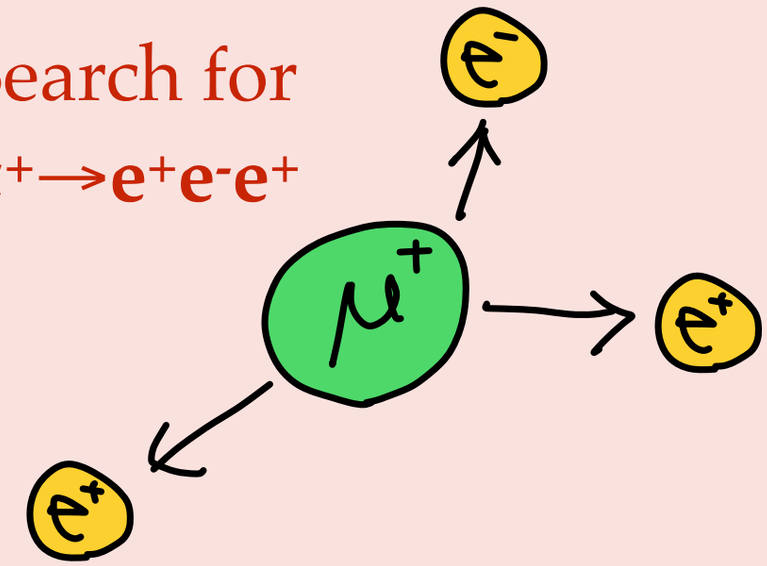


Search for
$\mu^+ \to e^+\gamma$

BG dominated by Accidental Overlaps

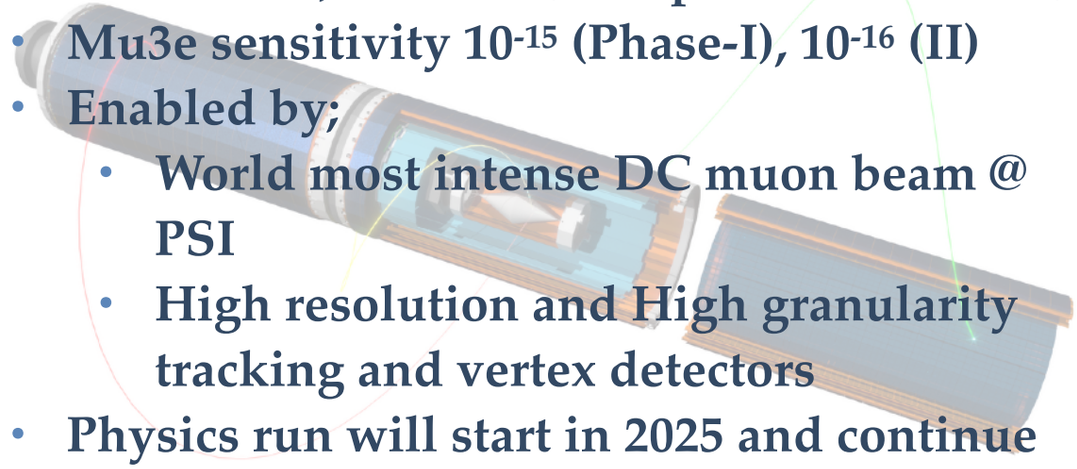
DC-beam Suitable

Search for
$\mu^+ \to e^+e^-e^+$



- MEG II (PSI), Successor to MEG(2009-2013)
- MEG set the current UL, < 4.2×10^{-13} (90CL)
- MEG II sensitivity ~ 6×10^{-14}
- Enabled by;
  - World most intense DC muon beam @ PSI
  - High resolution detectors; Liquid xenon gamma-ray detector, gradient B-field and low-mass e^+ spectrometer, *etc.*
- Physics run started in 2021, and expect to continue data taking by 2026

- Mu3e (PSI)
- Present UL, 1.0×10^{-12} (No update since 1988)
- Mu3e sensitivity 10^{-15} (Phase-I), 10^{-16} (II)
- Enabled by;
  - World most intense DC muon beam @ PSI
  - High resolution and High granularity tracking and vertex detectors
- Physics run will start in 2025 and continue by 2026 (Phase-I), & achieve final sensitivity after muon beam upgrade (Phase-II)

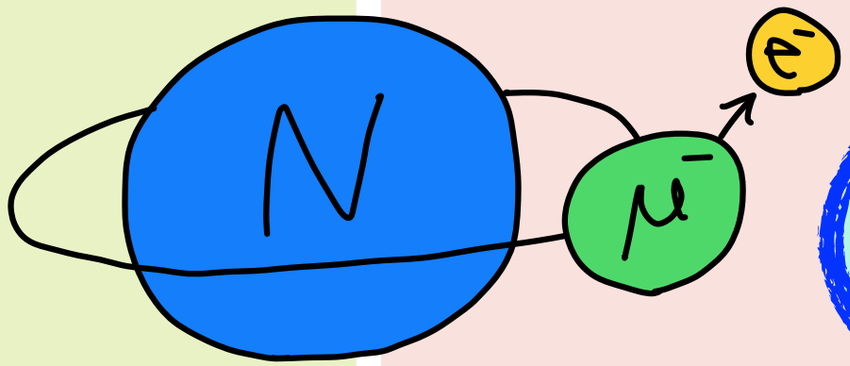


Conversion Searches

- **Most promising channel to search for muon LFV process in near future**

Search for $\mu^- N \rightarrow e^- N$

Coherent μ^- to e^- conversion from a muonic atom that captures μ^- instead of e^-



- **COMET (J-PARC)**
- **Enabled by;**
  - **Very intensive pulsed muon beam**
  - **Long/Curved solenoid to suppress BG**
  - **Low mass / high reso. e^- spectrometer**
- **Staged approach; Phase-I searches for mu-e conv w/ sensitivity of 10^{-15}, and perform beam measurement incl. BG. Then Phase-II will search mu-e w/ full sensitivity of 10^{-17}.**
- **Phase-I will be ready by 2025 and start physics run in 2026.**

BG dominated by primary-proton related

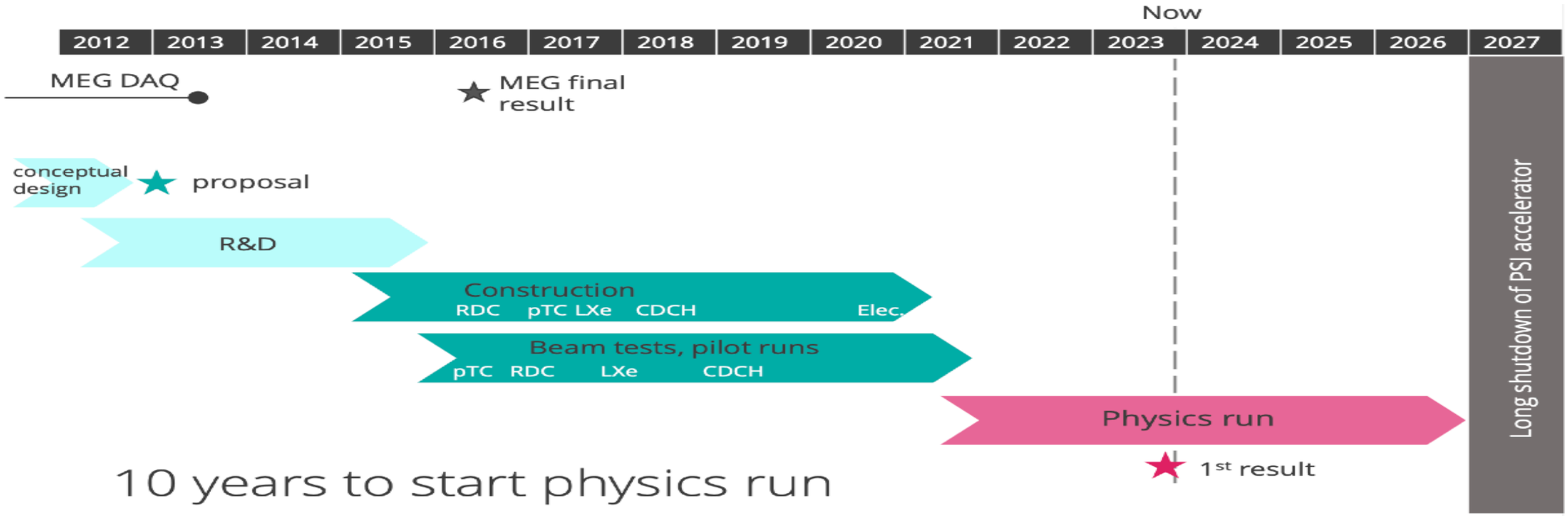
Pulse-beam Suitable

- **Mu2e (FNAL)**
- **Enabled by;**
  - **Similar concept to COMET**

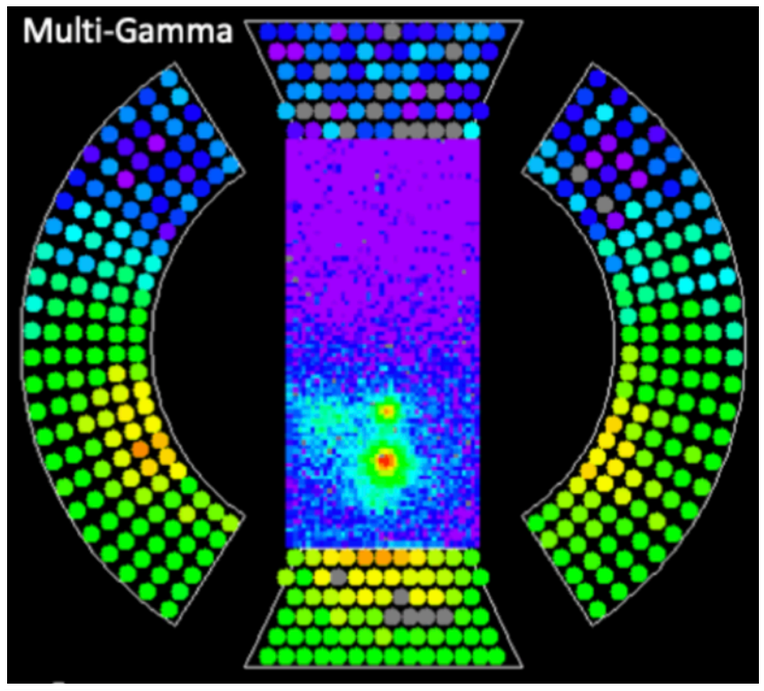
  (Originate from same experiment; MECO)
  - **But beam handling is different**
- **Searches for mu-e conv w/o staged approach**
- **Expects 2.4×10^{-16} by Run1 (starts in 2026) and x10 sensitivity in 2029.**
- **Mu2e-II will follow, after 2030, with a new linac and alternative targets.**

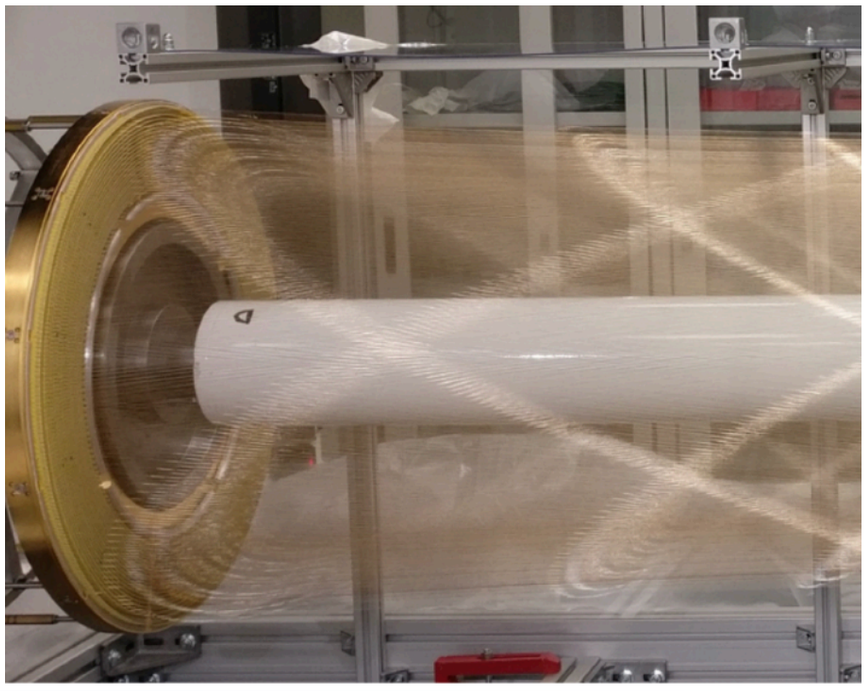
Latest Update — MEG II, Status —

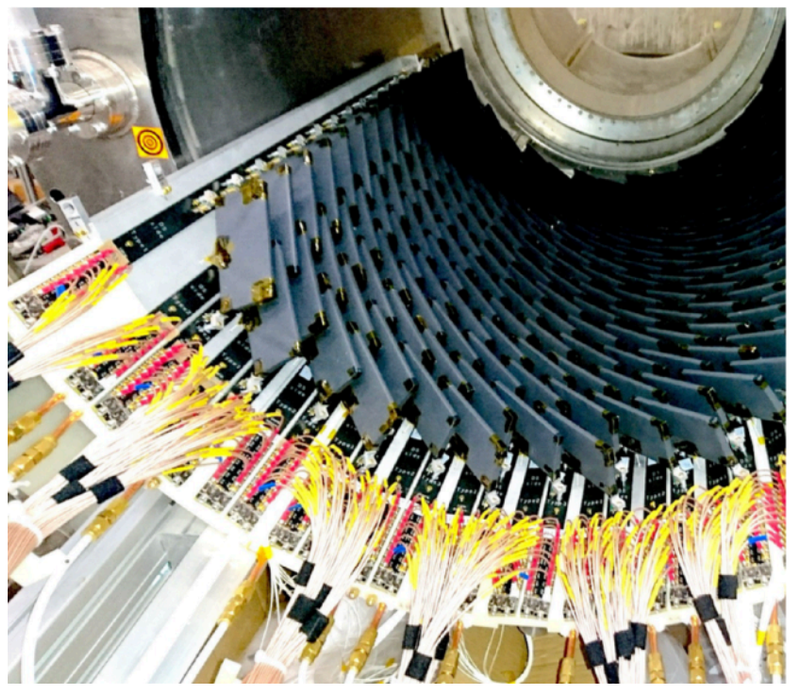
- **MEG II finally resumed the physics-run after a 10-year upgrade period.**



10 years to start physics run



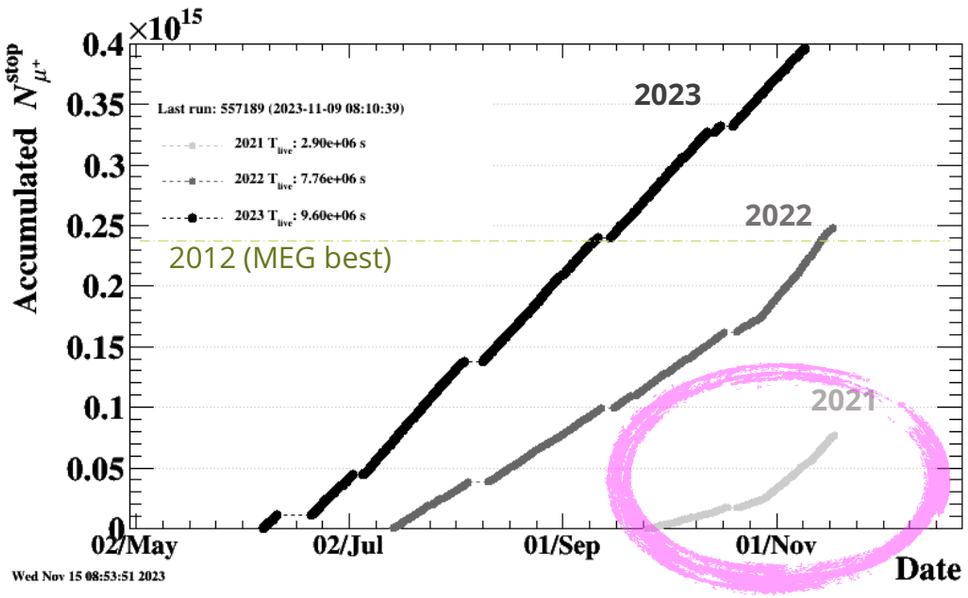


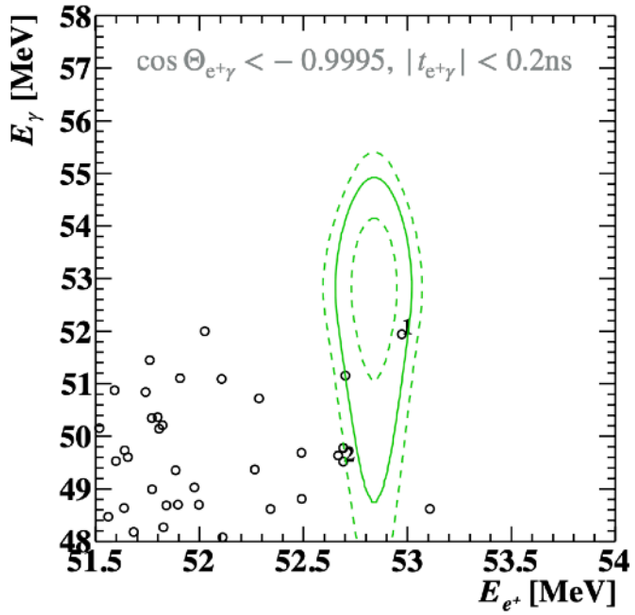


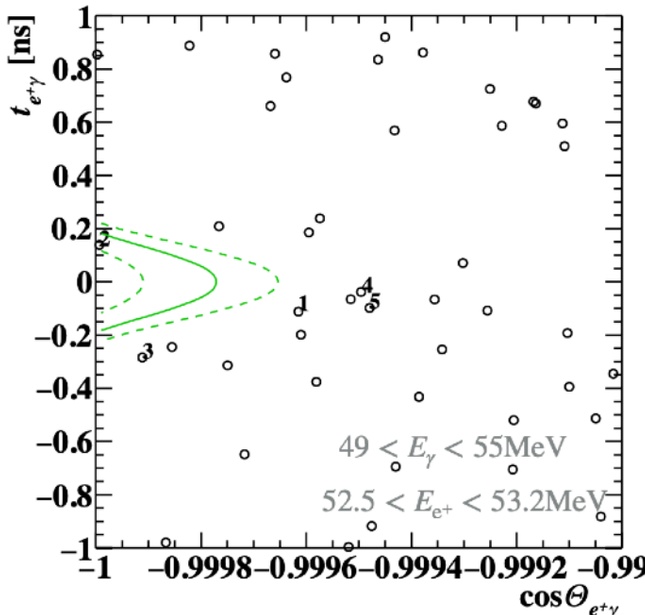
Latest Update — MEG II, First Result —

- **MEG II is running from 2021**
- **The 1st result have been published just last month !**

Unblinded 2021 Data







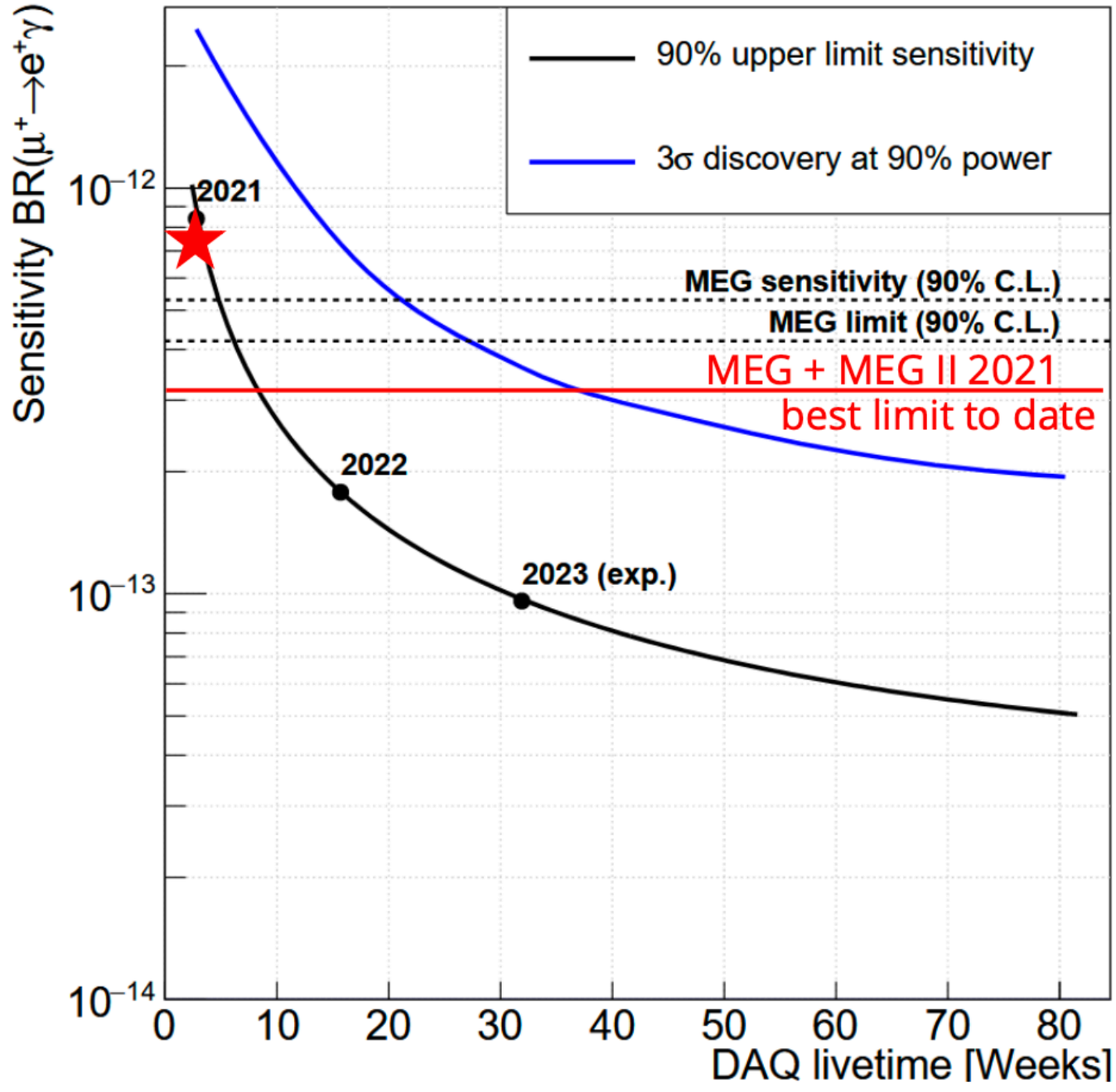
- **Only 7 weeks of physics run in 2021 = Almost equivalent to MEG data**
- **No excess of events over the expected background is observed**
  - **Upper Limit (90CL), $\mathcal{B}(\mu^+\to e^+\gamma) < 7.5 \times 10^{-13}$, *c.f.* MEG result : $< 4.2 \times 10^{-13}$**
  - **Combined (MEG II 2021 + MEG): $\mathcal{B}(\mu^+\to e^+\gamma) < 3.1 \times 10^{-13}$ (90% C.L.)**

The most stringent limit to date !

Immediate Outlook (1) — MEG-II —

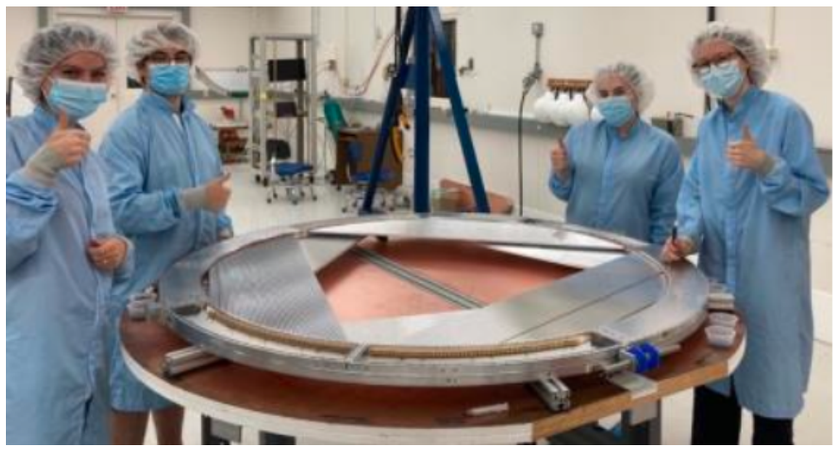
- Latest release (2021 data) is just 10% of MEG II data taken already for 2021-2023.
- Next release (2022 data) is planned in spring 2024.
- Results are expected to be updated one after another from next year onwards.
- MEG II will continue data-taking by 2026
  - Expected goal : 6×10^{-14}
  - PSI schedules a long shut-down 2027-2028 to upgrade beam line (100-times muon intensity: **HiMB**)

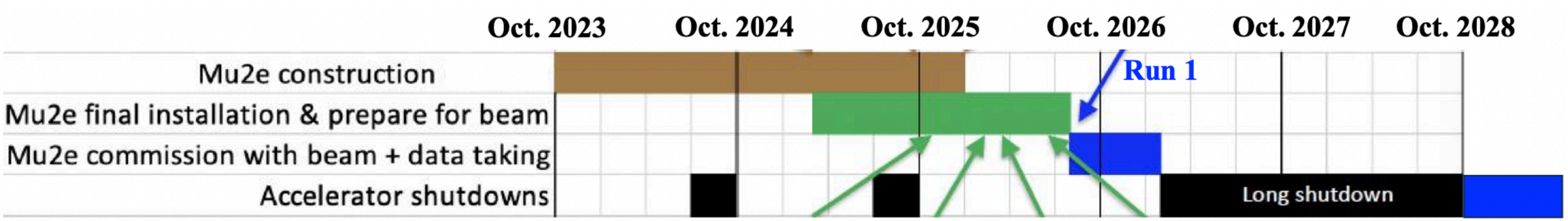
Time to consider new experiment that can handle 100x beam



Immediate Outlook (2) — Mu2e / COMET / Mu3e —

- **Preparations for 3 experiments (Mu2e, COMET, Mu3e) are in the final stage**



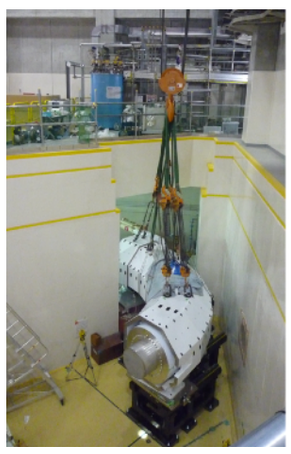


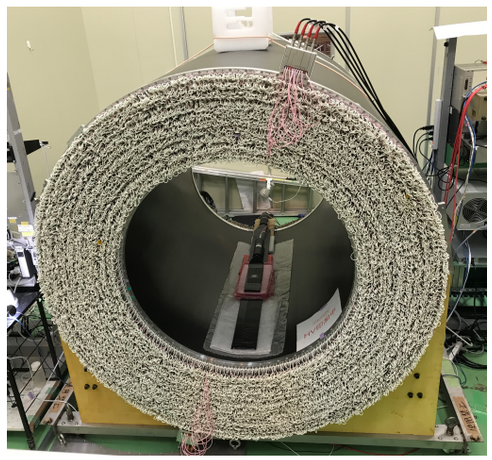
Critical path item: Detector solenoids
Scheduled delivery: mid 2024
Data taking begins: 2026

- **Detector and Super-conducting Solenoid construction, on going.**
- **Detector Solenoid, Delivery in mid 2024**
- **Run1 (2.4×10^{-14}) in 2026, Run2(10x sensitivity) after long shutdown**

Immediate Outlook (3) — Mu2e / COMET / Mu3e —

- **Preparations for 3 experiments (Mu2e, COMET, Mu3e) are in the final stage**



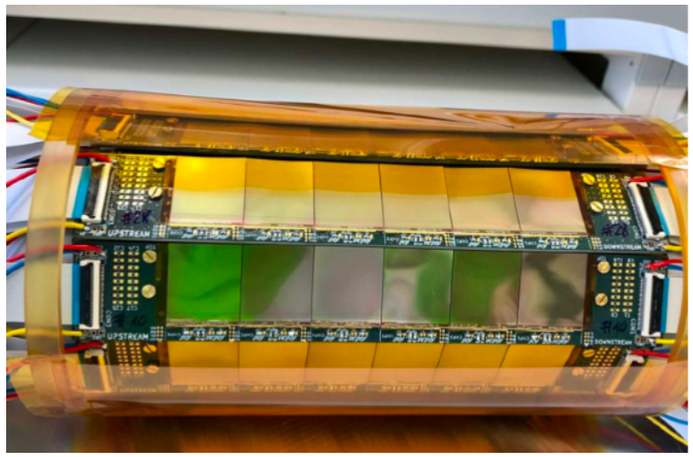


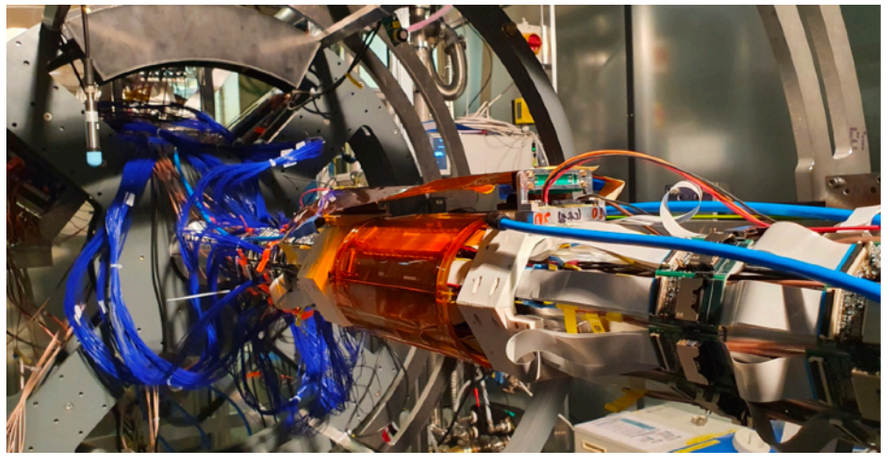
	JFY2023	JFY2024	JFY2025	JFY2026	JFY2027
Detector for mu-e Search			★ Ready		
Detector for beam measurement			★ Ready		
Beam line construction			Magnet Installation	Shield ★	
Engineering & Physics Runs				Eng	Physics Run

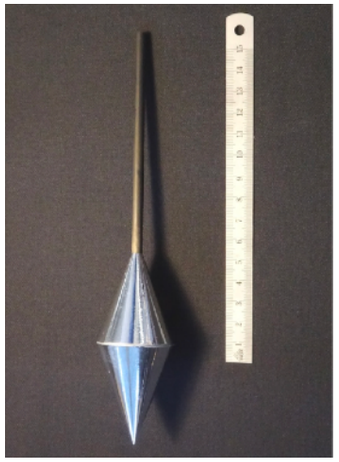
- **Two detectors, for physics and BG, Ongoing and will be ready in 2025**
- **Beam-line commissioning w/ low-intensity proton beam, completed**
- **Pion Capture and Detector Solenoids, will be installed in 2026**
- **Engineering/Physics Runs are expected to start in 2025-2026, after radiation shield construction which leaves uncertainty in schedule.**

Immediate Outlook (4) — Mu2e / COMET / Mu3e —

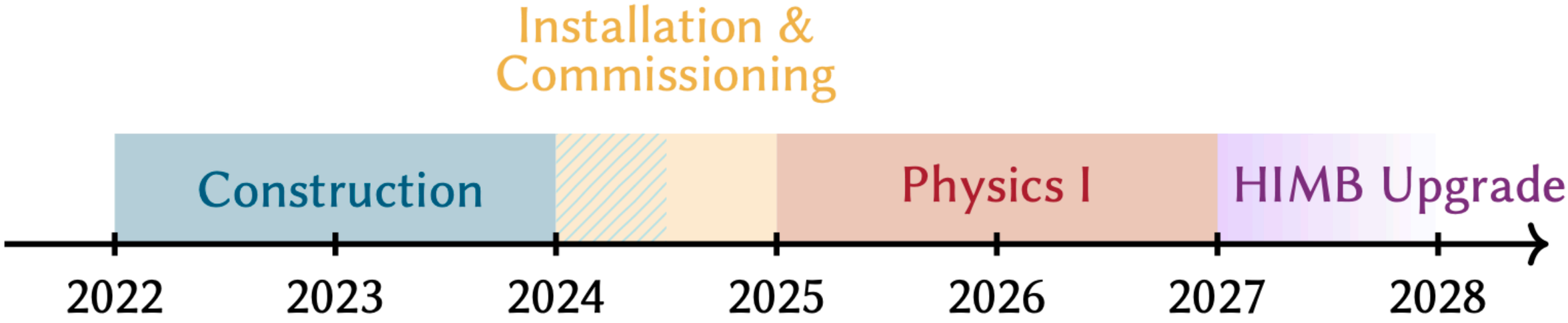
- **Preparations for 3 experiments (Mu2e, COMET, Mu3e) are in the final stage**





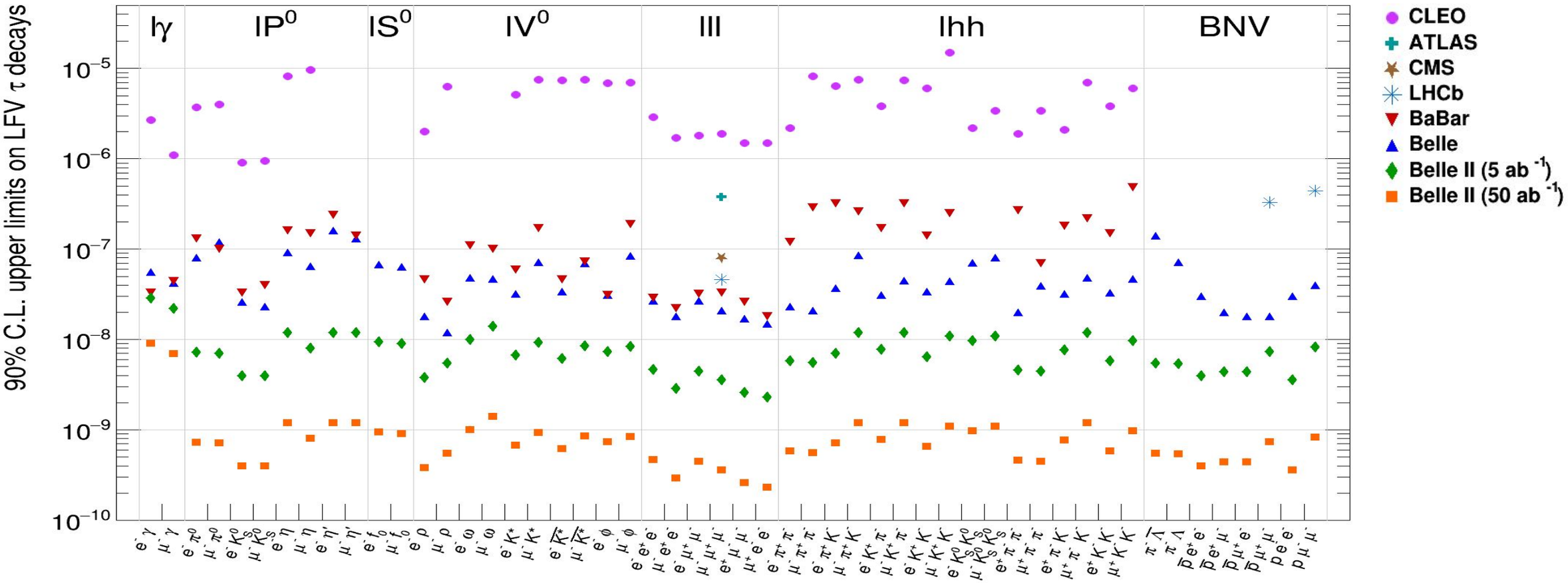


- **Detector development, completed. Construction, ongoing.**
- **Installation/commissioning in 2024, and Physics run (Phase-I, 10^{-15}) expected in 2025-2026 by PSI HiMB upgrade (Same as MEG-II). Needs to share secondary beam-line (πE5) with MEG-II.**



Tau Lepton Flavour Violation Experiments

- **Attractive to search for cLFV at e^+e^- collider**
- **Many channels, Valuable inputs for New Physics Considerations**



- **So far, Belle and BaBar experiments performed so many searches**

Tau Lepton Flavour Violation Experiments

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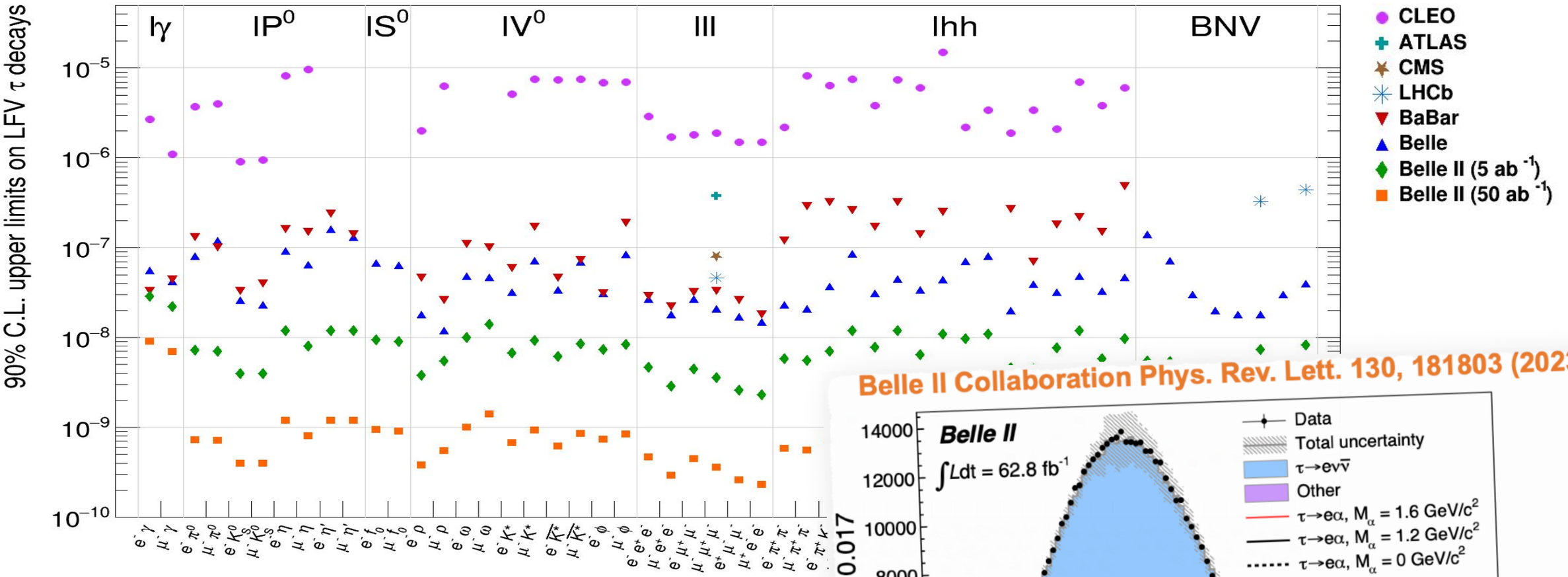
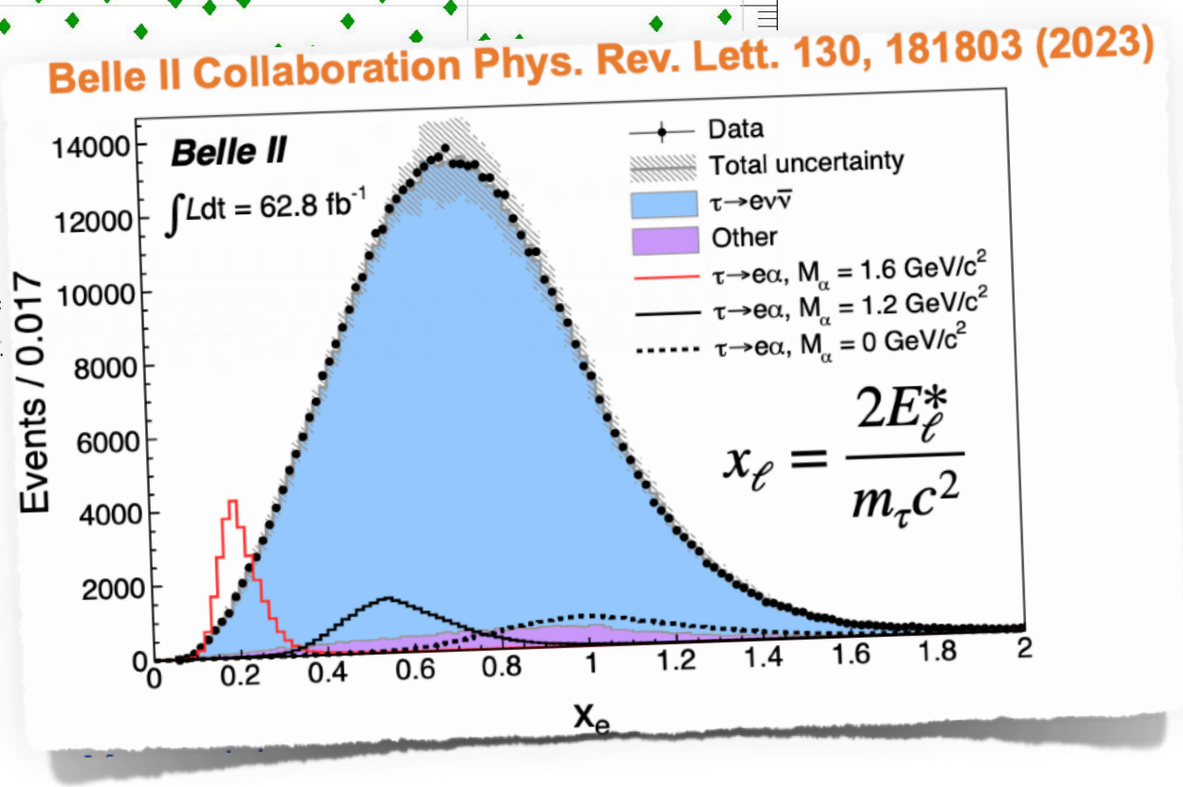


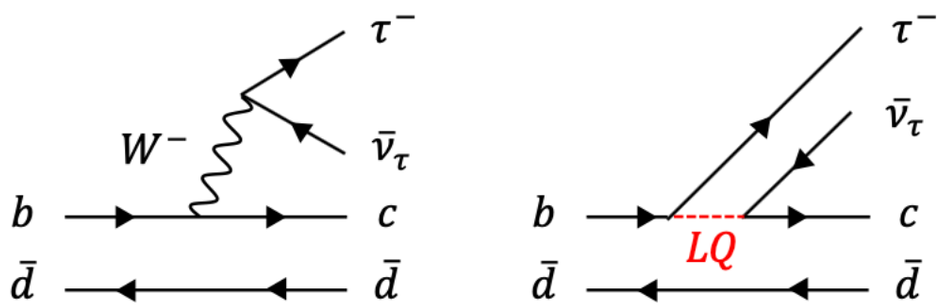
- **So far, Belle and BaBar experiments performed so many searches**
- **Belle II updated $B(\tau\to e\alpha)$ & $B(\tau\to\mu\alpha)$ recently (α = invisible boson)**
- **Belle II / LHCb opening up a new era**

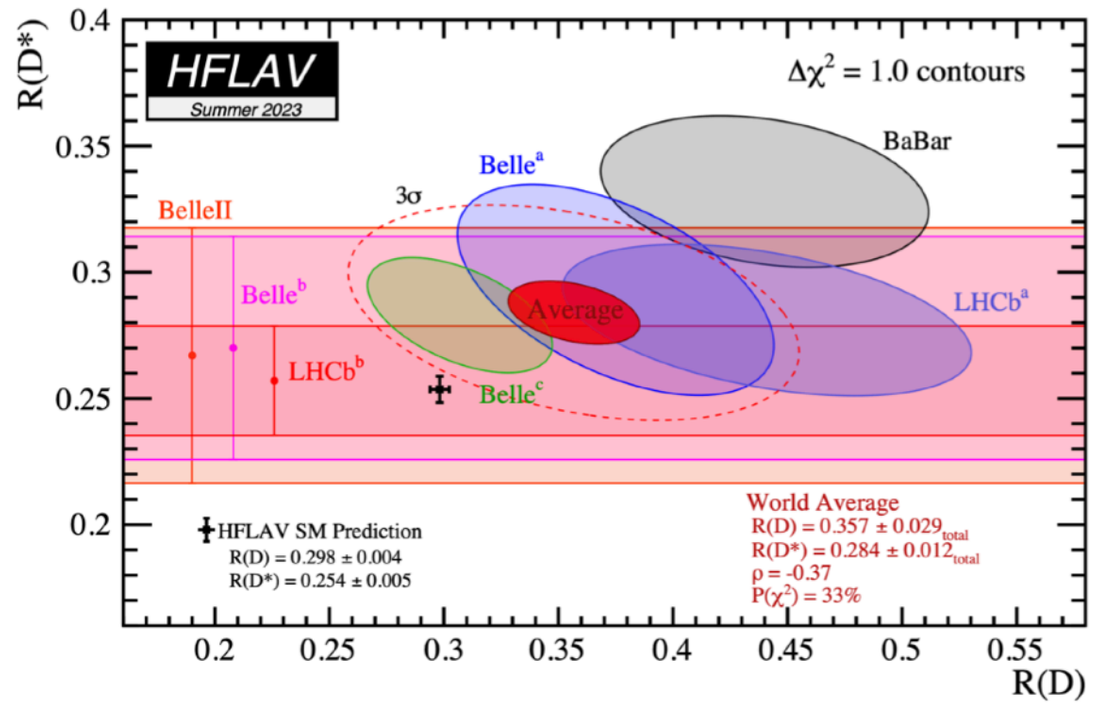


Tests of Lepton Universality

- **Anomalies in $b \to c$ Decays**
- **The BaBar, Belle and LHCb have observed excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays in $R(D^{(*)})$ measurements by 3.2σ in the SM**

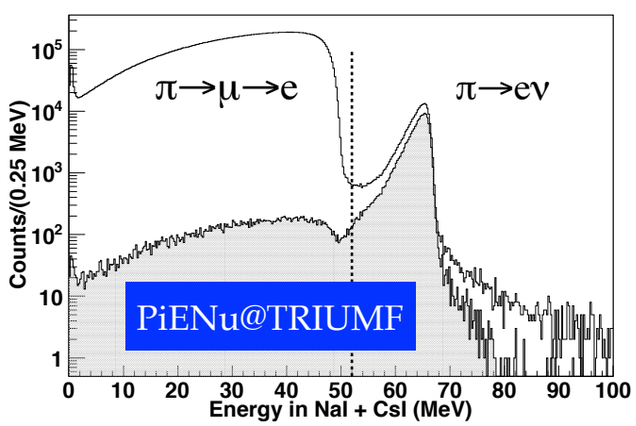
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}, (\ell = e \text{ or } \mu)$$

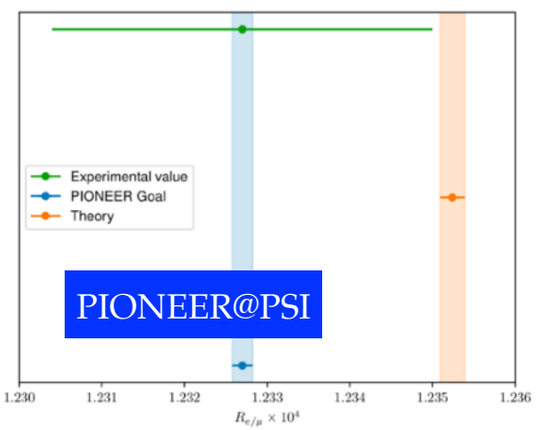




- **Updated !! by Belle II; Consistent w/ SM prediction and *HFLAV* average.**
  - **The new *HFLAV* average increases the tension with the SM from 3.2σ to 3.3σ**

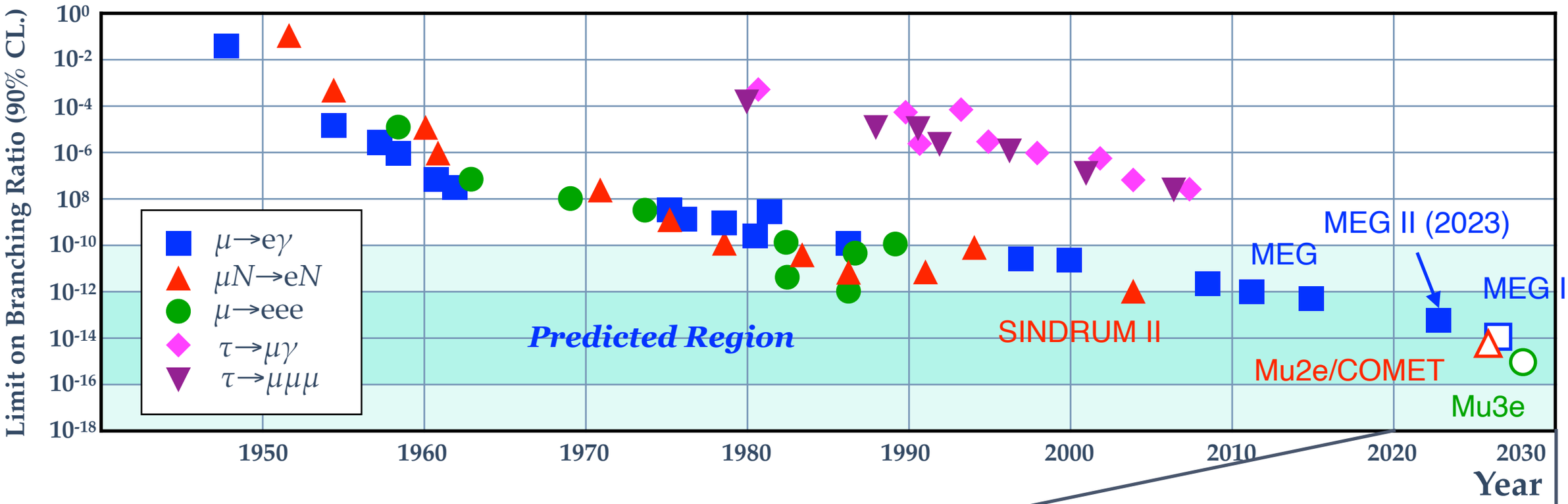
- **Lepton Flavour Experiments have high affinity w/ tests of Lepton Universality**
  - **τ LFV Search → Test w/ $R(D^*)$**
  - **μ LFV Search → Test w/ $B(\pi \to e\nu)$**





Future Prospects

- **Time evolution of Charged LFV Search, from long time ago to future**

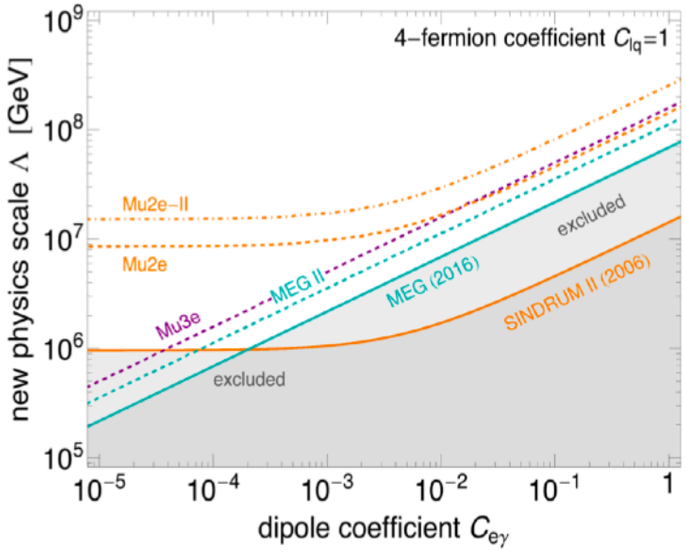


- **Outlook for the 2020s**

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
MEG II (PSI)			Physics Run								
Mu2e (FNAL)							Run1			Run2	
COMET (J-PARC)							Phase-I				?
Mu3e (PSI)						Phase-I				Phase-II	

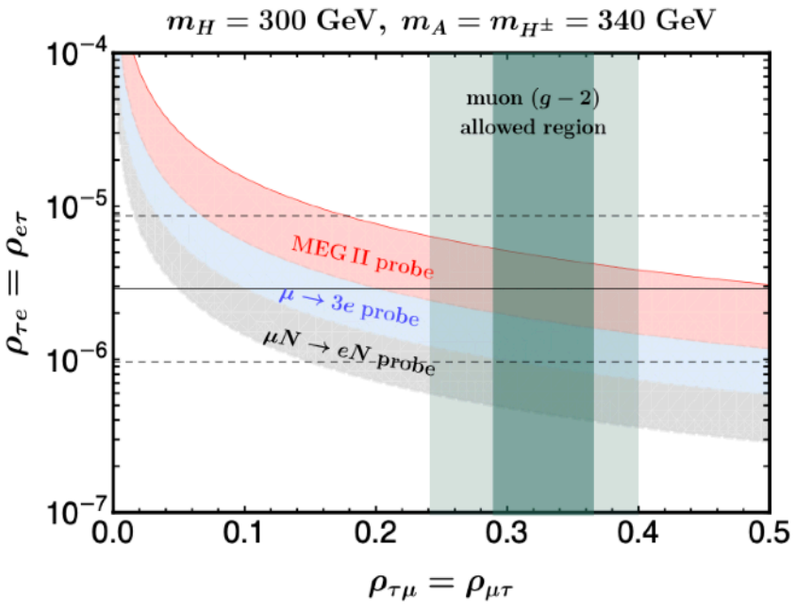
Further Future Prospects (1) — Theoretical Aspects —

- **Whether cLFV is observed or not, there is a strong case to be made for further improving sensitivity, or for examining the process on additional target materials → Further upgrades incl Accelerator is under consideration !!**



Can Seek Very High Energy World

Even Λ>10^3TeV accessible

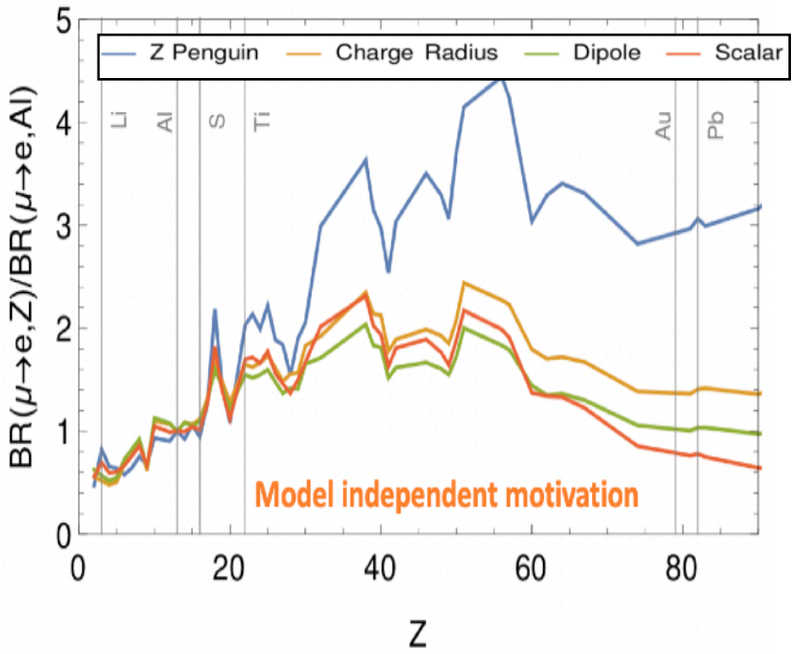


Synergy w/ $(g\text{-}2)_\mu$ in New Physics

LFV has strong correlation w/ g-2

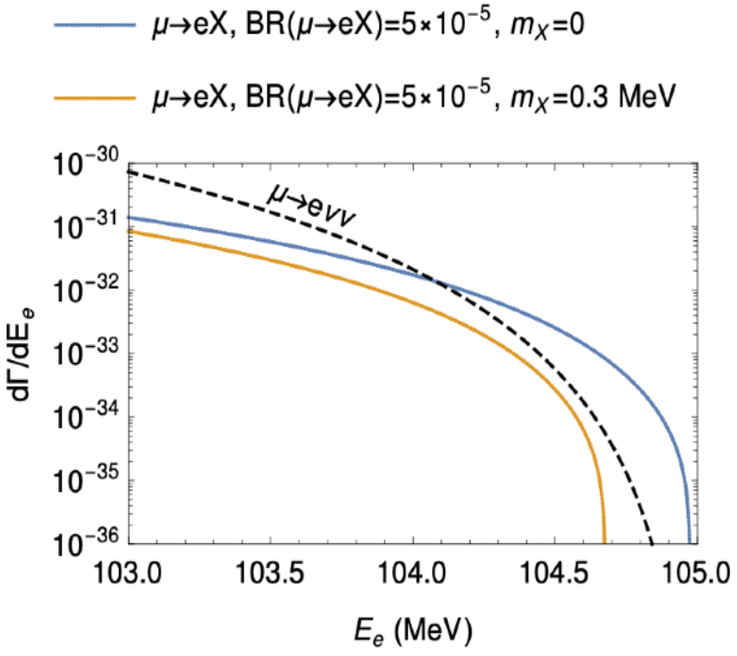
Important inputs to NP Model Studies

eg. Nuclear dependence of μ-e conversion



Even unknown phenomenon

Invisible boson can be investigated

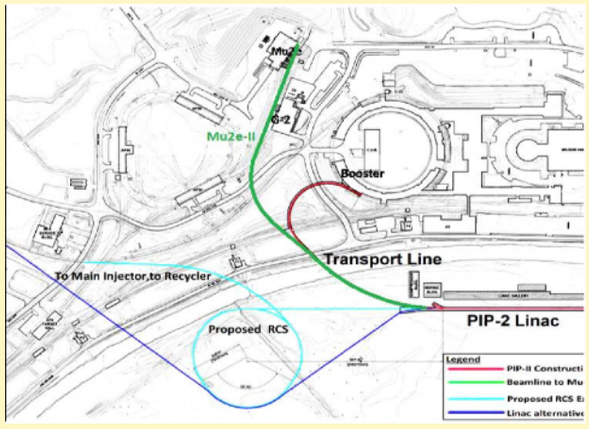


Further Future Prospects (2) — w/ Stronger Beam —

- **Whether cLFV is observed or not, there is a strong case to be made for further improving sensitivity, or for examining the process on additional target materials → Further upgrades incl Accelerator is under consideration**

>2030, FNAL

Mu2e-II, based on PIP-II Linac



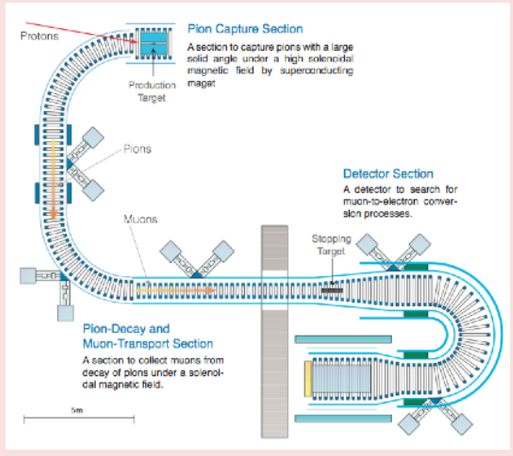
Beam power improve
8kW → 100kW !!

So many challenges are under consideration

Aims 2 x 10^{-18}

>2030, J-PARC

COMET Phase-II



Beam power improve
3kW → 56kW !!

Detector R&D, OK
Only radiation issue

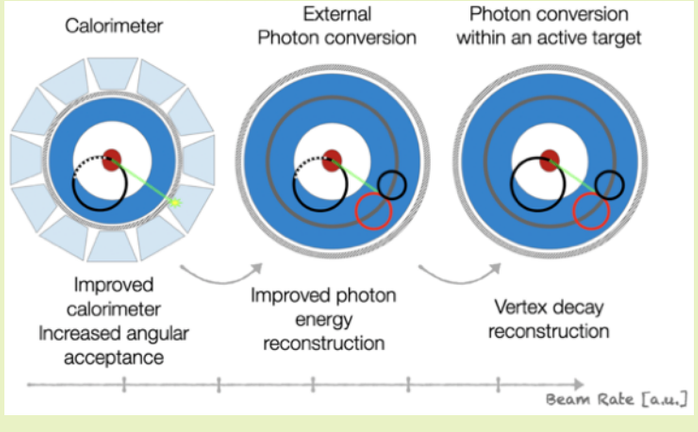
Aims 1 x 10^{-17}

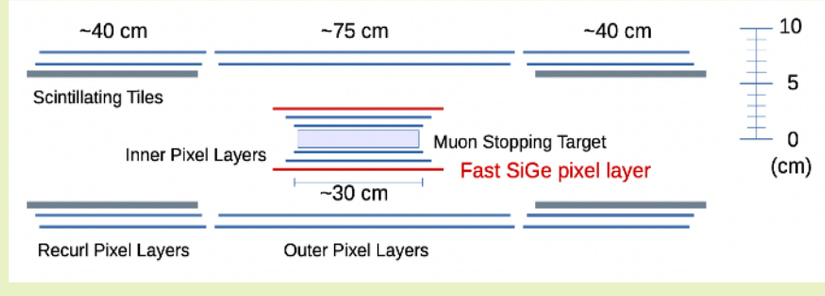
>2029, PSI

MEG III(?) and Mu3e Phase-II, based on HiMB

New Target
100x muon !

1st beam
in mid 2028



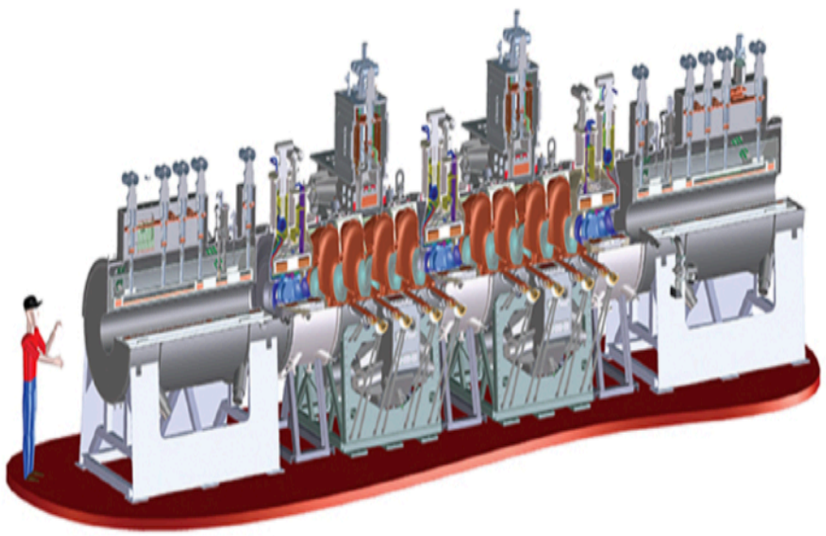


MEG II and Mu3e considering their upgrades, key = rate capability

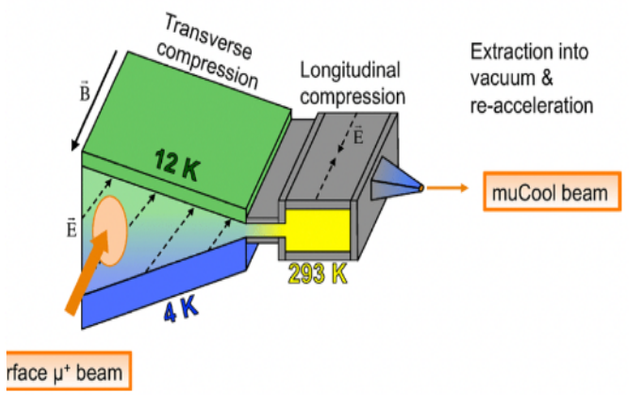
Expected starts in ~2030

Further Future Prospects (3) — Brand-New Technologies —

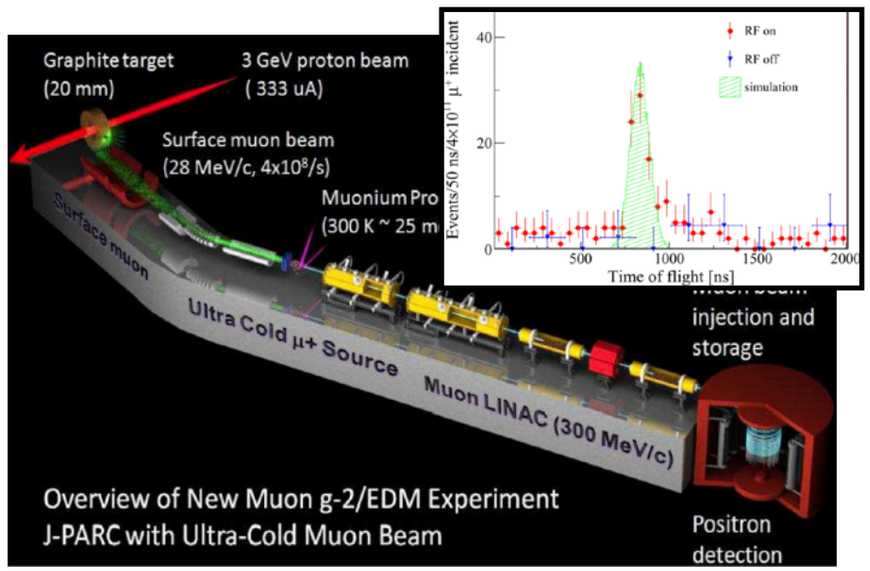
- ***"Muon Cooling"*, One of the most interesting key item for next decade (important)**



MICE, based on **ionization cooling**

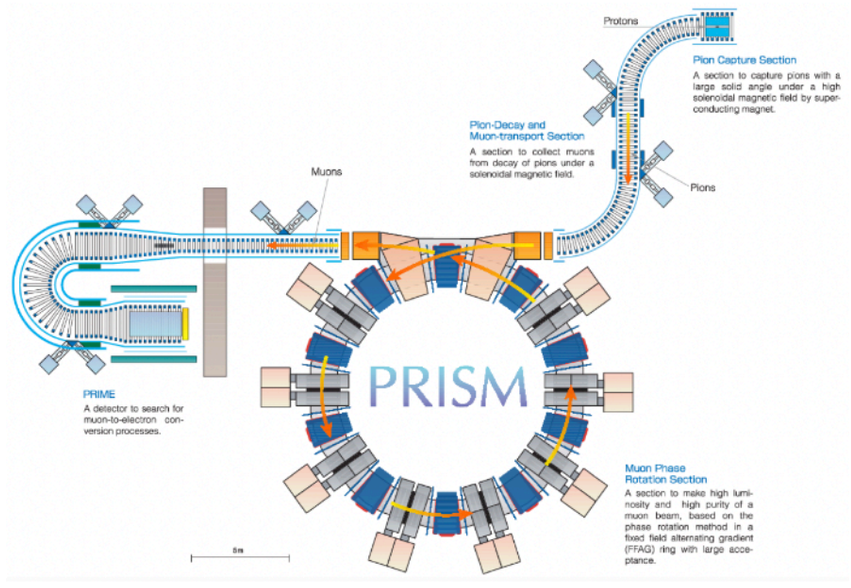


muCool, based on gaseous **phase space compression**



J-PARC muon g-2/EDM, based on **Muonium re-acceleration**

- **Attractive also for muon LFV experiments**



PRISM, based on **muon phase-rotation**

PRIME, New generation mu-e conversion experiment using PRISM beam

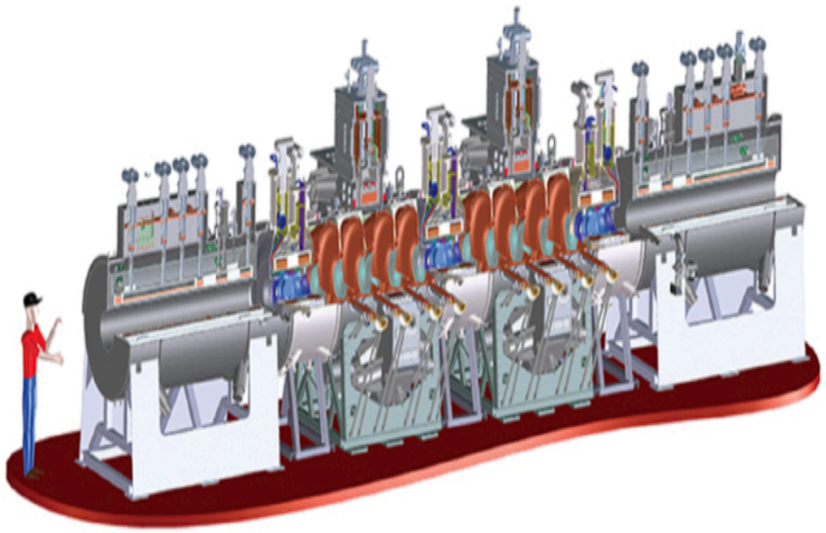
Thanks to cooled beam, achievable even better sensitivity than 10^{-18}

- **Muon phase-rotation is also a kind of *"Muon Cooling"***

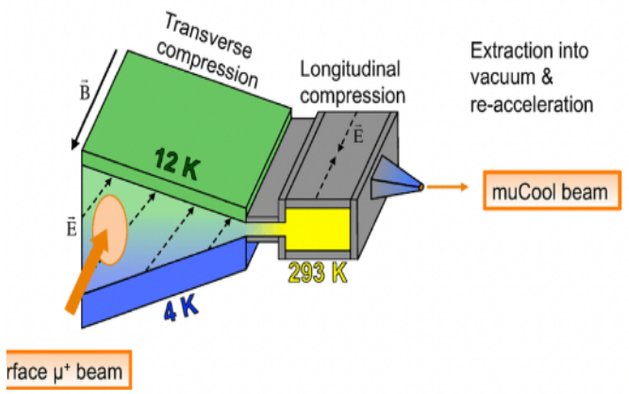
➡ **Muon Cooling is becoming a Reality**

Further Future Prospects (3) — Brand-New Technologies —

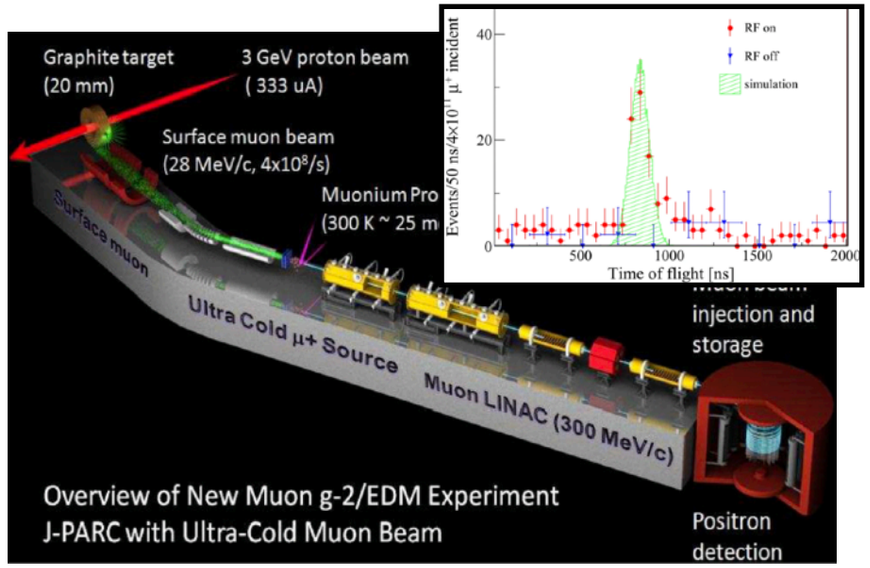
- ***"Muon Cooling"*, One of the most interesting key item for next decade (important)**



MICE, based on **ionization cooling**

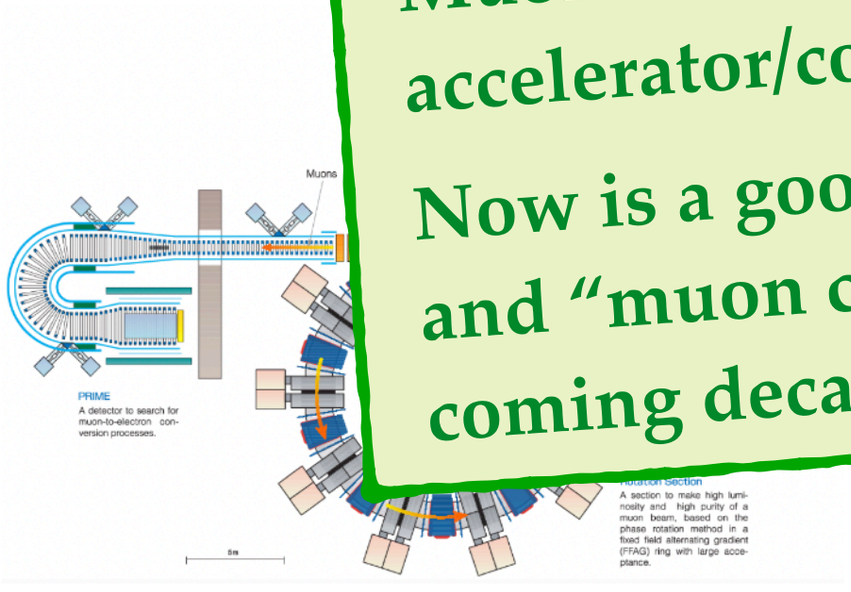


muCool, based on gaseous



J-PARC muon g-2/EDM

- **Attractive a**



Muon cooling is one of the key components of muon accelerator/collider development.

Now is a good time to further consider "ν-factory" and "muon collider" with LFV synergies for the coming decades.

"Muon Cooling"

➡ **Muon Cooling is becoming a Reality**

— Conclusions —

- **Charged Lepton Flavour Violation = Clear evidence of New Physics BSM**
  - **Muon is one of the best probe to explore New Physics.**
    - ***eg.*** $\mu^+ \to e^+\gamma$, $\mu^- N \to e^- N$, $\mu^+ \to e^+e^-e^+$, ***et al.***
    - **MEG II, Mu2e, COMET, Mu3e, *et al.***
  - **Tau LFV has many channels to provide valuable inputs.**
    - **Belle II, LHCb *et.al.***
  - **Synergy with precision tests on Lepton Universality**

- **Within the coming decade…**
  - **In particular later half of 2020's, many experimental results are expected. Should be fruitful period.**
  - **Upgrades of the current experiment including accelerator/beam-line upgrade will start → Important whether cLFV is observed or not, there is a strong case to be made for further improving sensitivity.**

- **Further future…**
  - **The synergistic effect with muon cooling will open up a new era of LFV experiments and make further dreams come true with the ν-factory/ muon collider!** (just my personal perspective…)