42ND INTERNATIONAL CONFERENCE
ON
HIGH ENERGY PHYSICS

18-24 July 2024

Lepton Flavor Physics & EDM

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Kobayashi-Maskawa Institute (KMI)
Nagoya University

Belle II

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

FlaP
Flavor Physics International Research Center
フレーバー物理学国際研究センター

NAGOYA
UNIVERSITY

Talk Outline

- Introduction
- Muon g-2 (+EDM)
  - Experimental status
  - Theoretical prediction
- Muon cLFV programs
- Tau physics at Belle II
- EDM dedicated exp's in 1 page
- Summary

Special thanks to;
L. Bernhard, R. Bernstein, S. Kawasaki, T. Mibe, S. Miscetti, H. Nishiguchi, W. Ootani, A. Schöning, Y. Seiya, P. Winter & many Belle II collaborators
for very useful inputs to prepare this talk

and also to speakers in parallel sessions

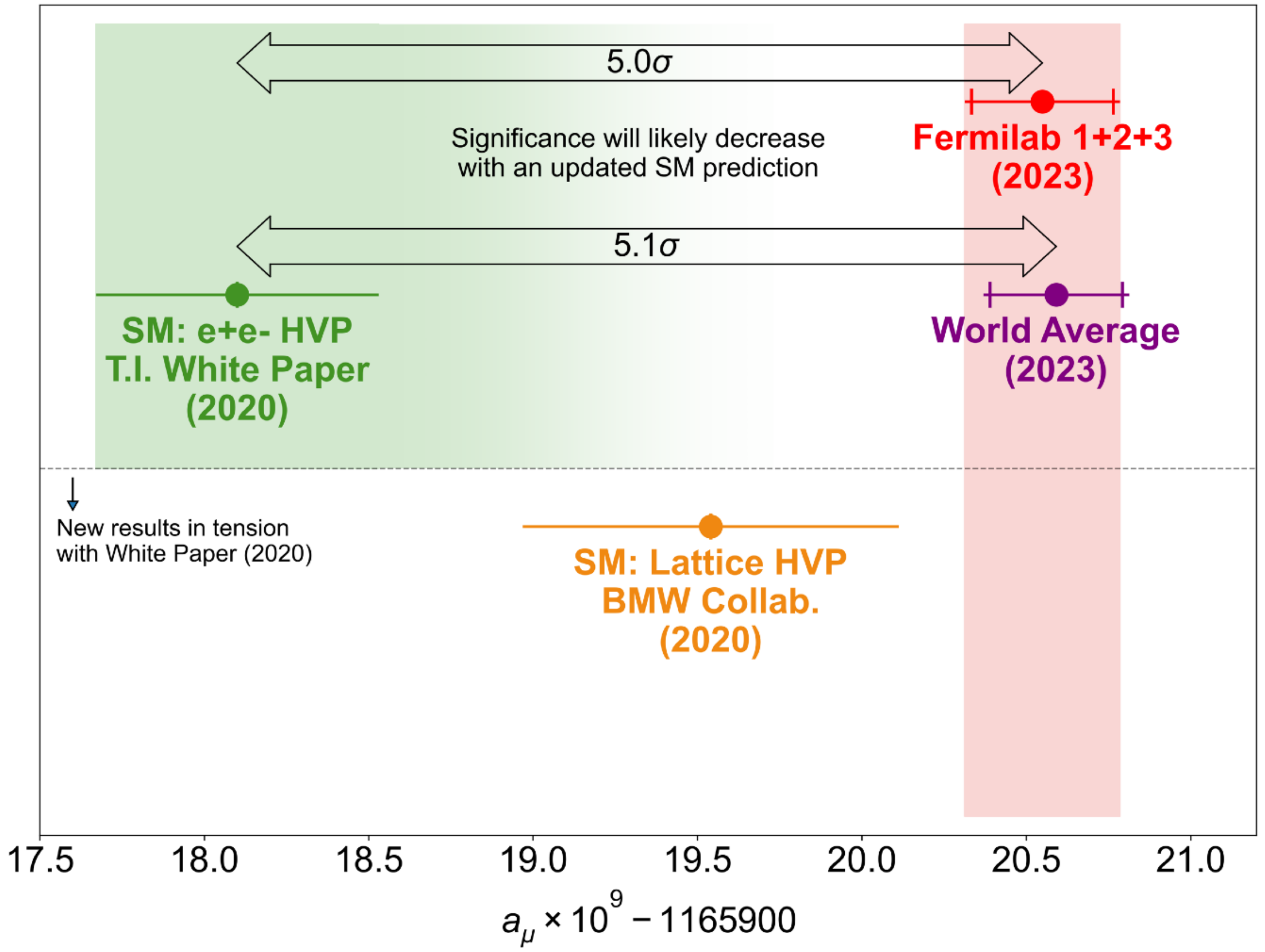
Sorry, if I miss any …

Apology;
My talk cannot cover or is very brief for EDM measurements and cannot cover LFV in meson decays.

Flavor Anomalies

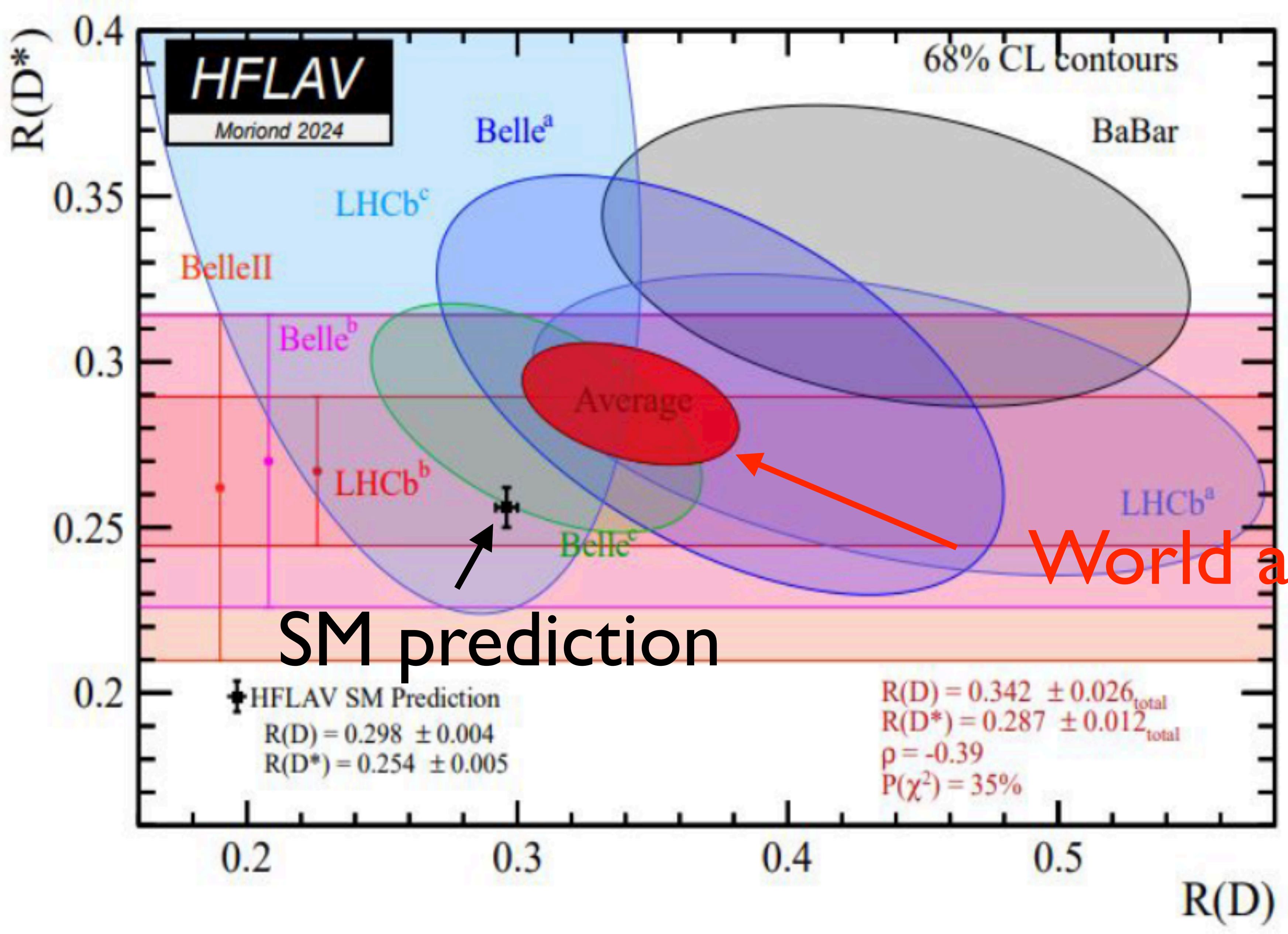
There is still no indication of physics Beyond the Standard Model (BSM) at LHC.
Flavor physics experiments play important roles.

"Muon g-2 anomaly"



"B anomalies"

e.g.; Test of lepton-flavor-universality w/ B semileptonic decays



SM prediction

World average (HFLAV 2024)

>3σ deviation

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

$$(\ell = e, \mu)$$

Leptons *are key probes to search for BSM Physics!*

Role of Lepton Flavor Physics & EDM

- **cLFV**: (almost) background free from the SM → clear signature of BSM
- **EDM**: $\not{C}\not{P}$ observable → new source of $\not{C}\not{P}$ at high-energy scale relevant to BAU

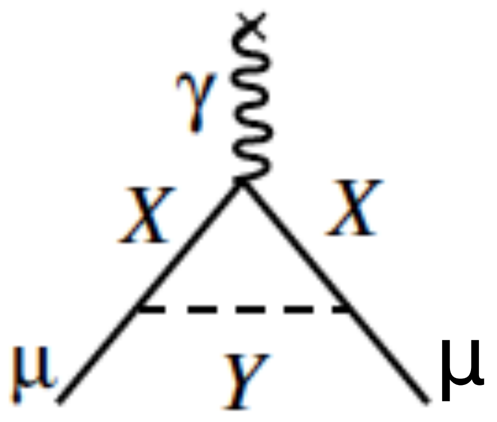
Baryon Asymmetry of the Universe

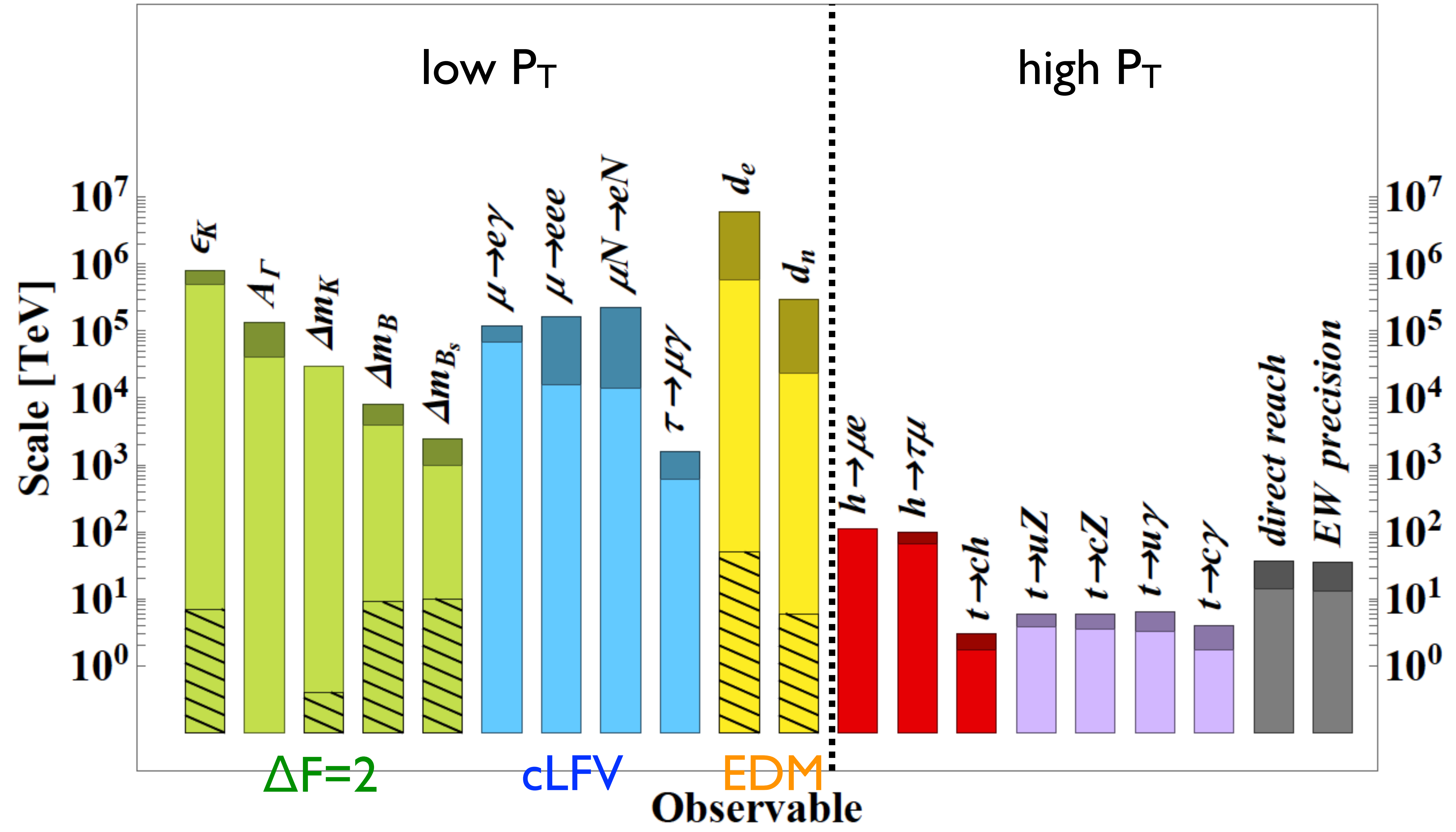
Both have sensitivities to the very high energy scale; $10^{3\text{-}7}$ TeV!

- **g-2**:

Flavor-diagonal observable

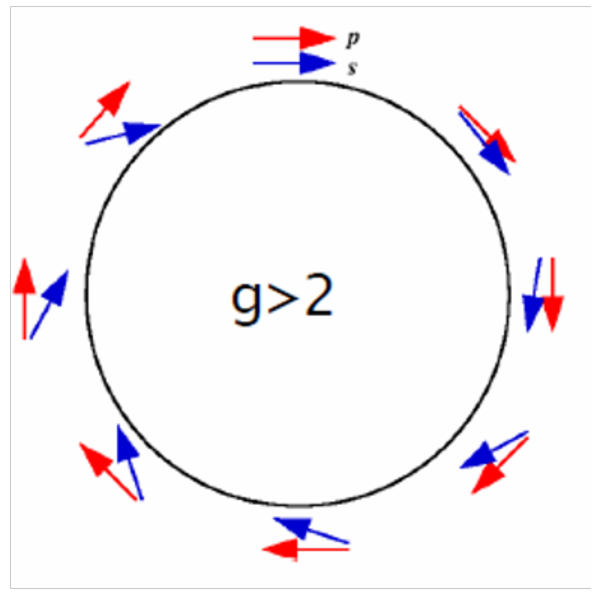
→ mass-scale of unknown particles.





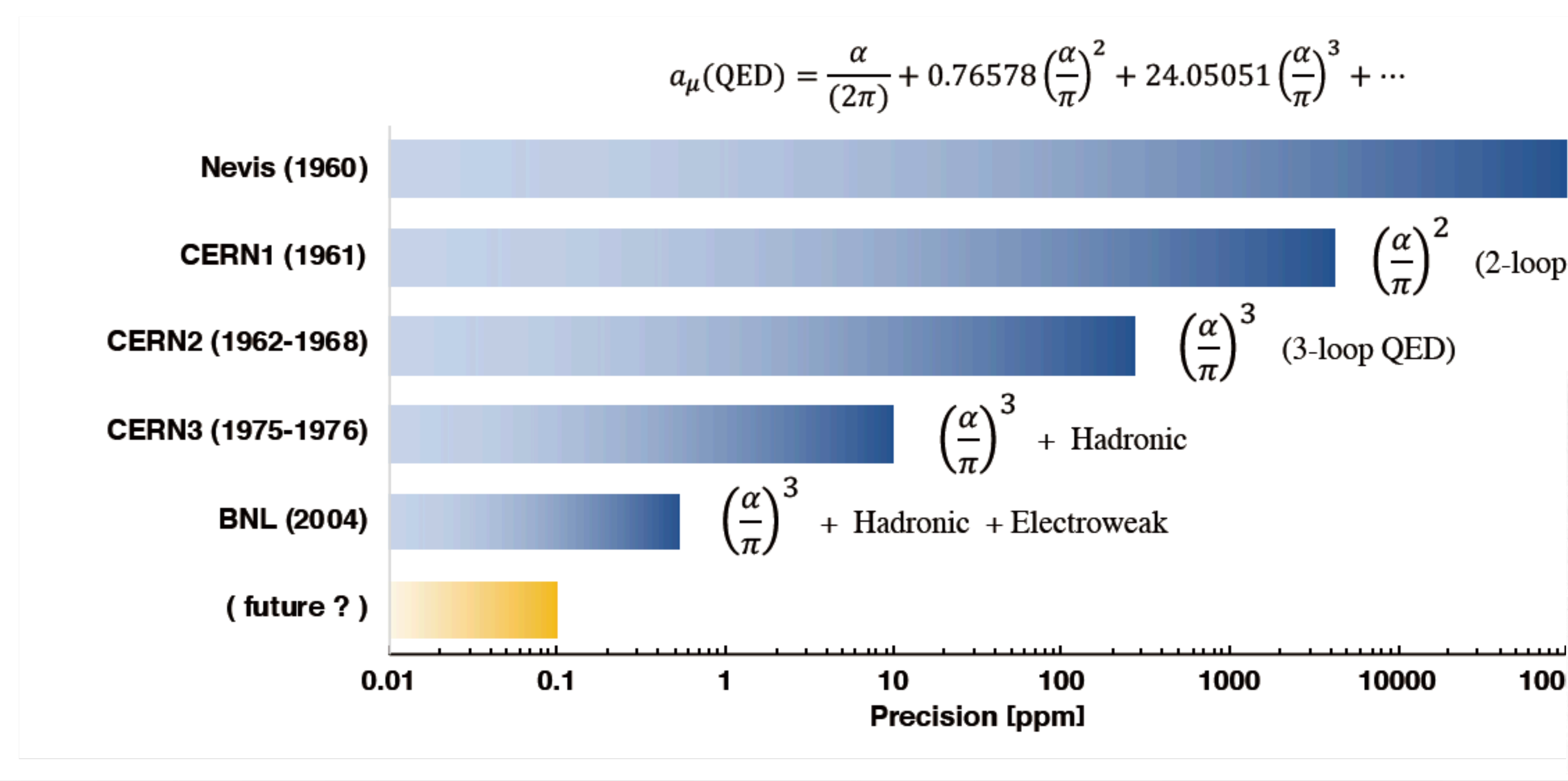
Mass (energy) reach of flavor observables
(Physics Briefing Book, arXiv:1910.11775)

Muon g-2 Experiments

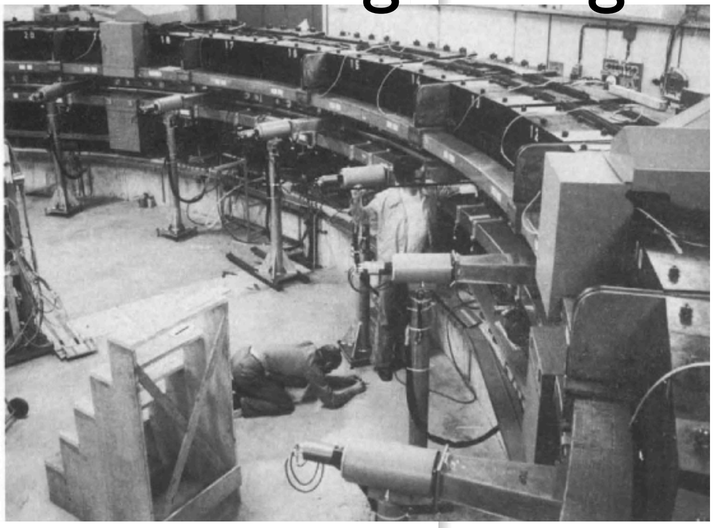


Spin precession by g-2 $\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$

Long history in step-by-step improvement to test the quantum corrections by QED, Hadronic, Electroweak, …



CERN3 g-2 ring



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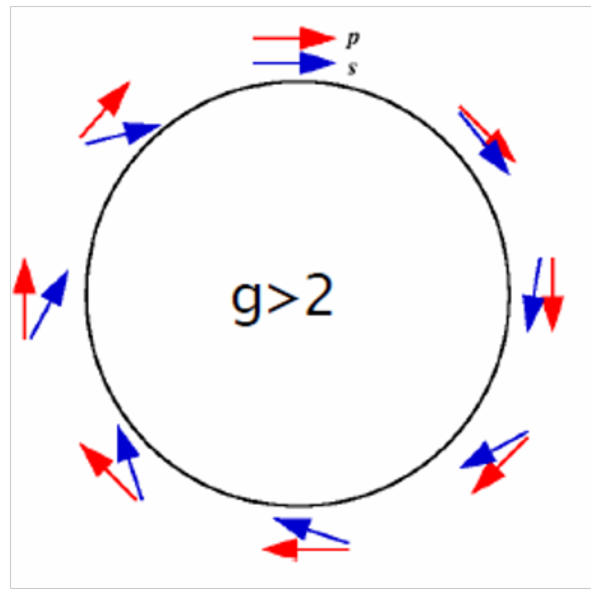

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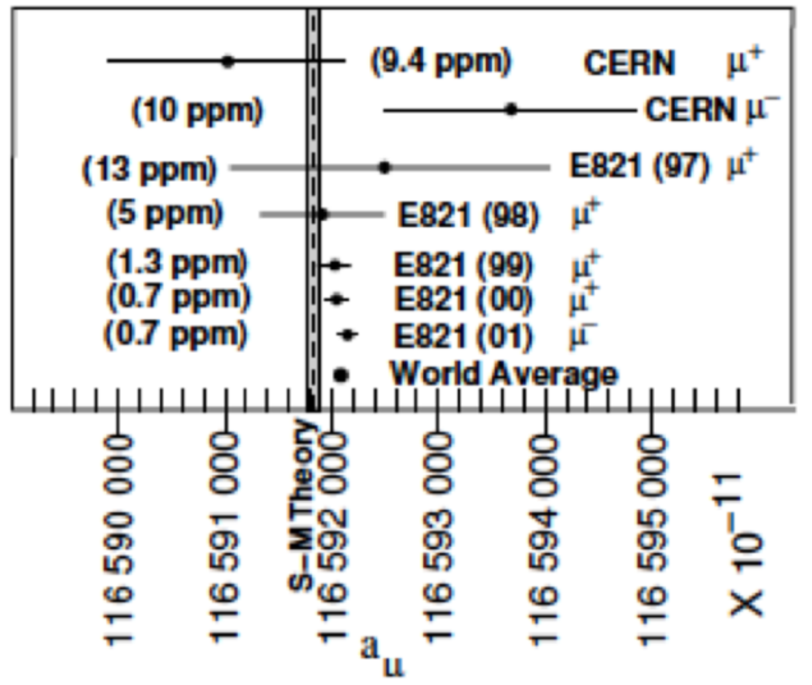

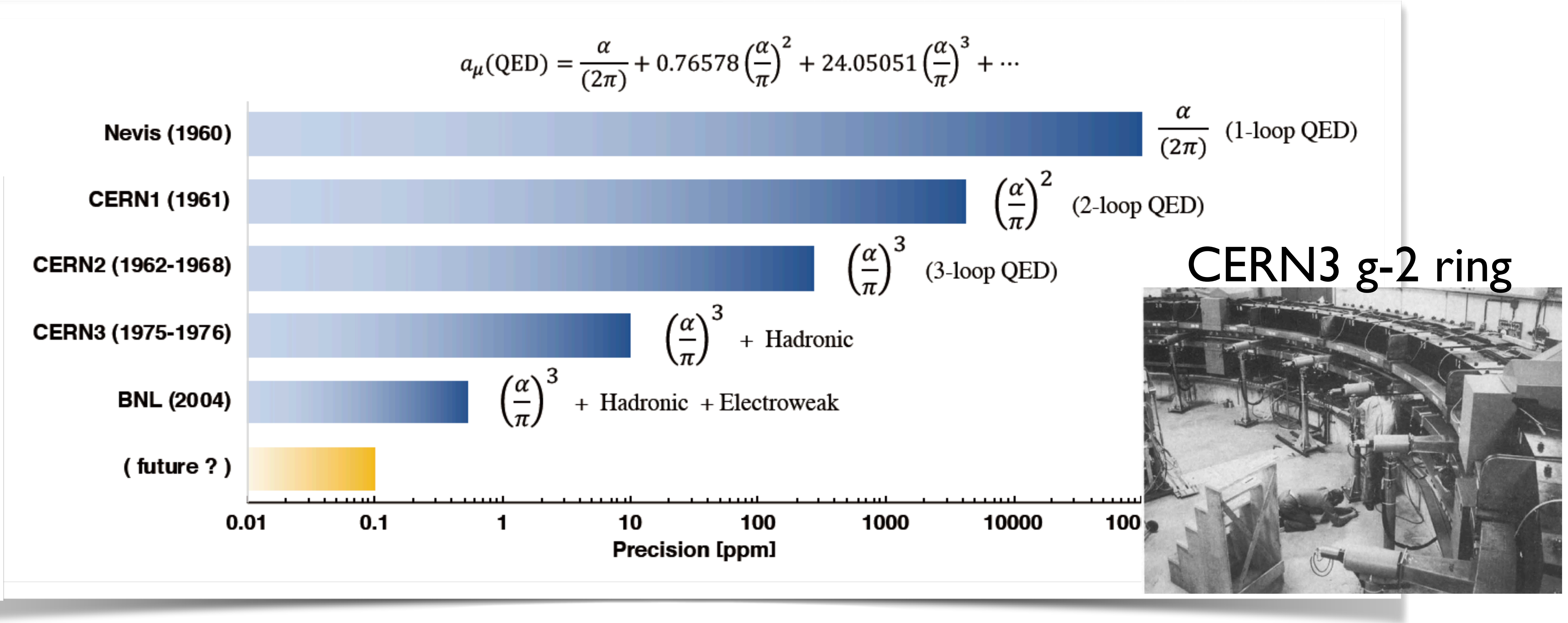

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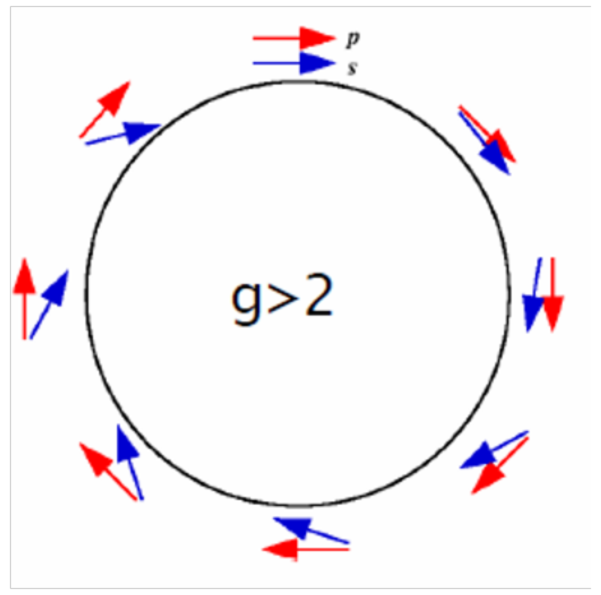

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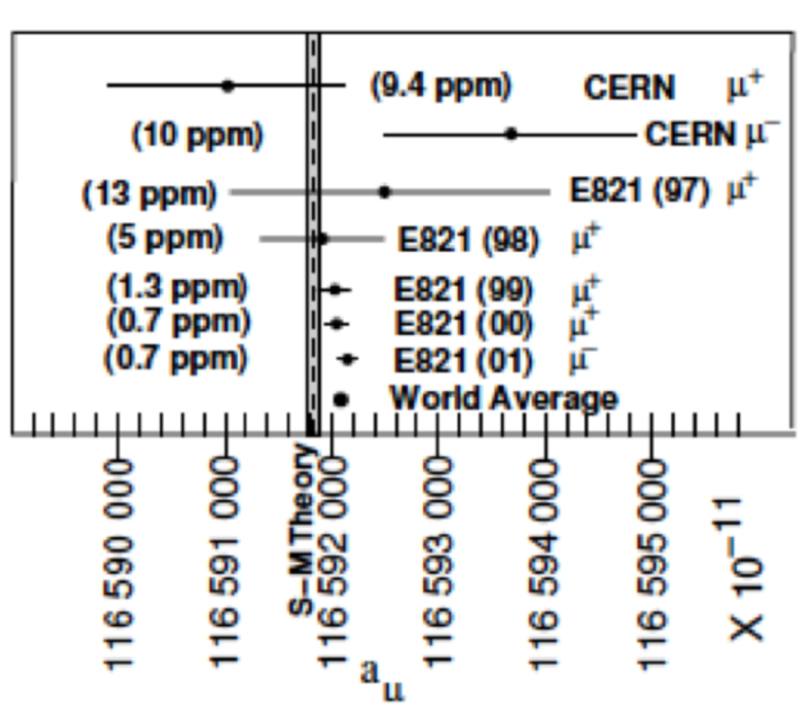

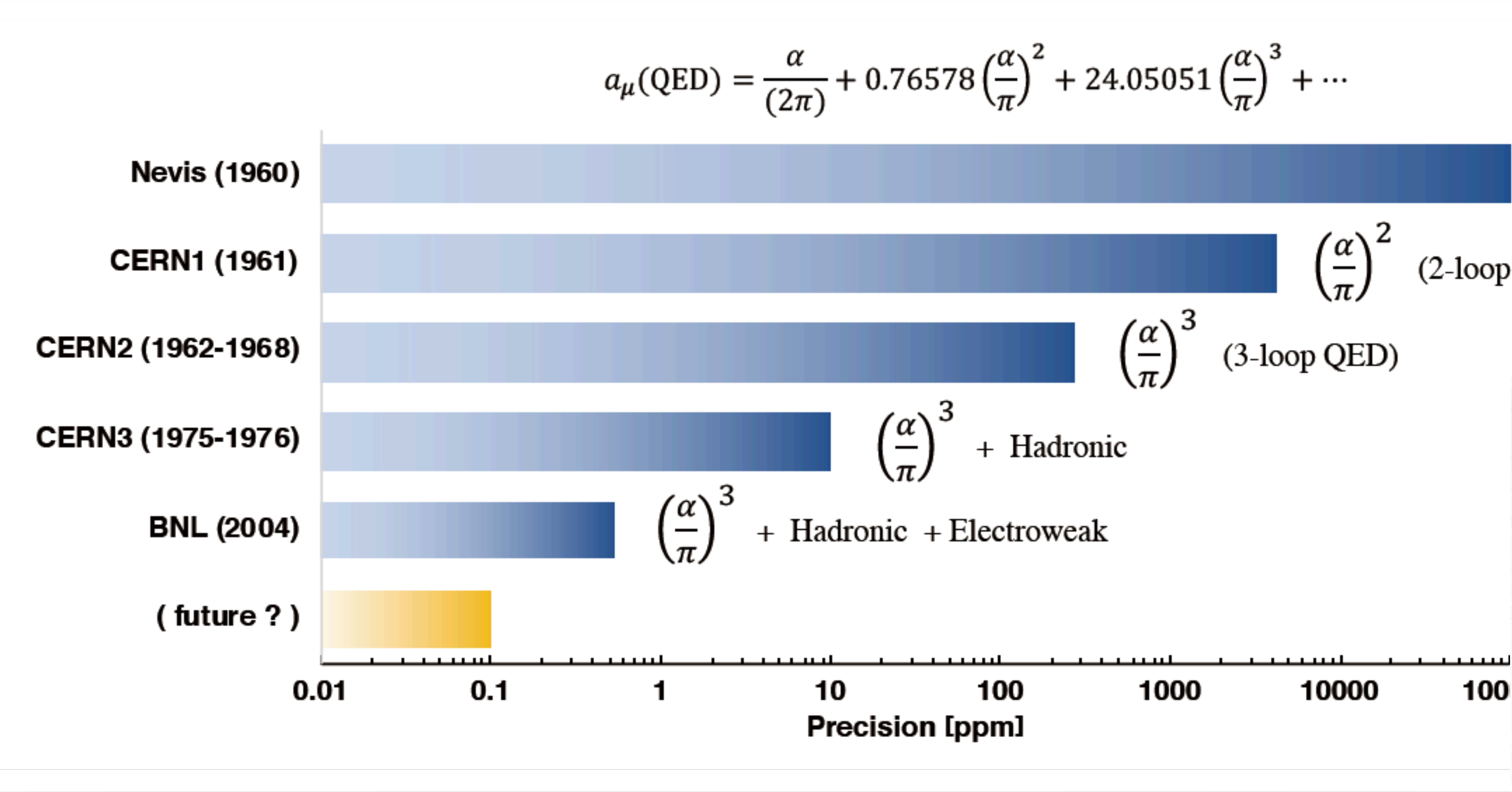

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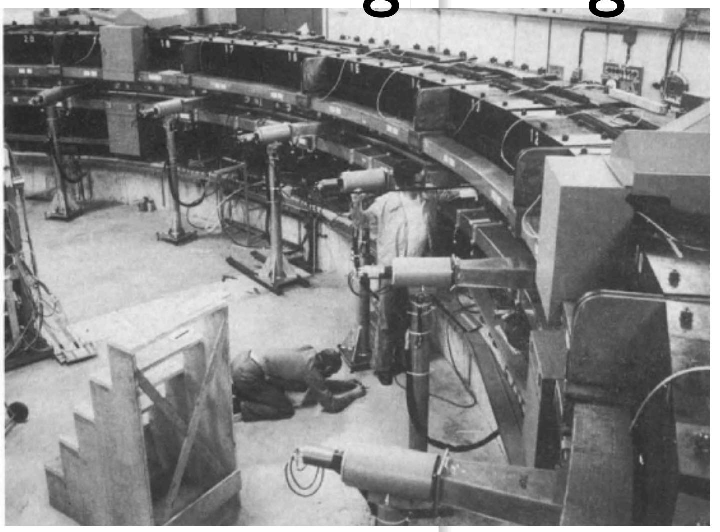
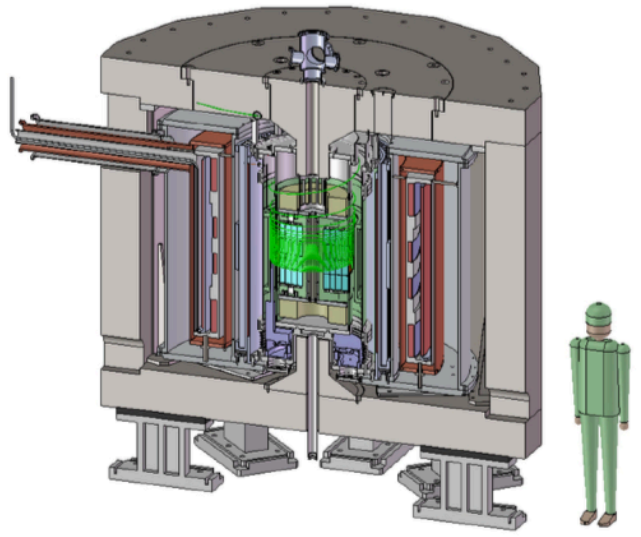


Experiments in this decade

E989 (Fermilab)

E34 (J-PARC)



	E989 @ Fermilab	E34 @ J-PARC
Beam	Magic-momentum (p = 3.094 GeV/C)	Ultra-cold muon beam (p = 300 MeV/c)
Polarization	P ≈ 97%	P_{max} = 50%
Magnet	Storage ring (7m radius)	MRI-like solenoid ($r_{storage}$ = 33cm)
B-field	1.45 Tesla	3 Tesla
B-field gradients	Try to eliminate	Small gradients for focusing
E-field	Electrostatic quadrupole	None
Current sensitivity goal	140 ppb	~400 ppb (possibly 100 ppb)

Muon g-2 at Fermilab

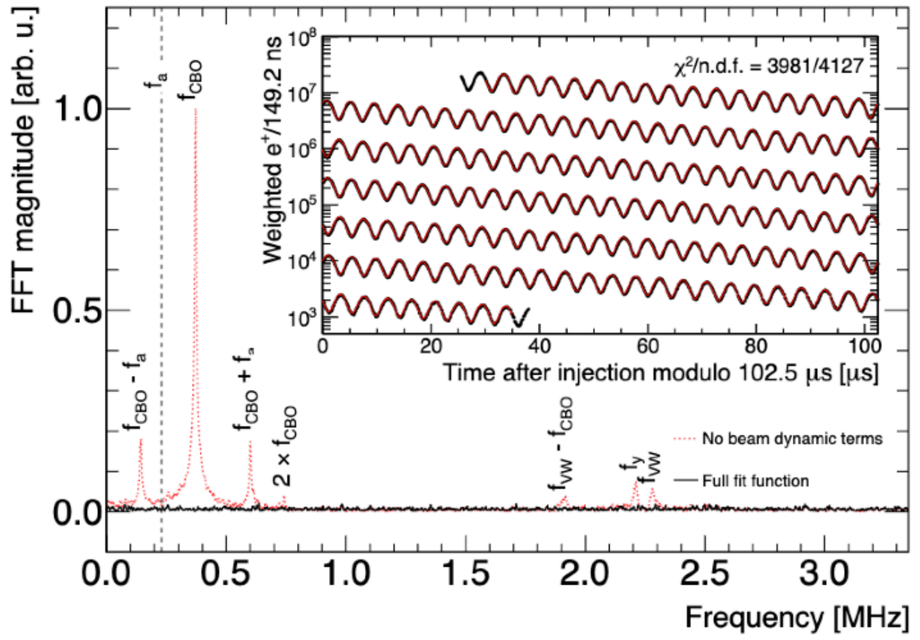
Kim Siang Khaw
Lorenzo Cotrozzi
Alberto Luisiani

Design Goals;

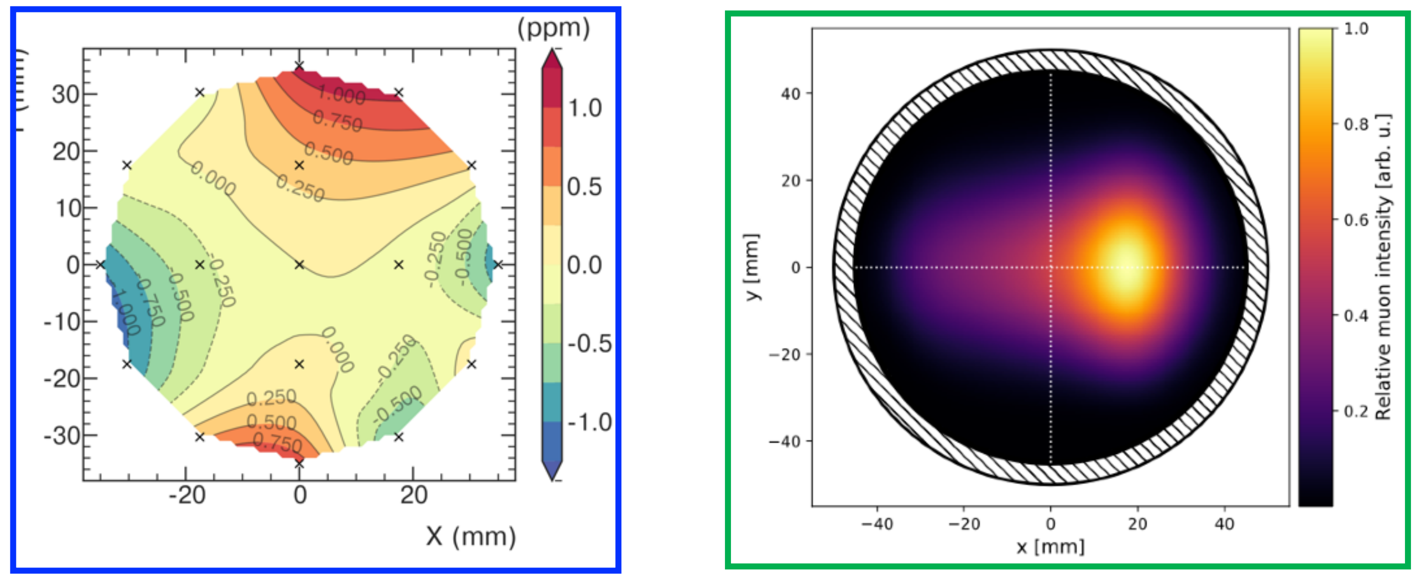
- Statistical uncertainty of 100 ppb by using Fermilab accelerator to get muons 21 times more than Brookhaven.
- Total systematic uncertainty of 100 ppb by reducing systematic uncertainty for both ωa and B to 70 ppb with improved hardware.
- Measure **a_μ** with four-fold improved precision of **140 ppb**

g-2 ring moved from Brookhaven to Fermilab

g-2 frequency measurement



Magnetic field weighted by muon distribution



Accurate field mapping & field tracking

muon distribution extracted by trackers

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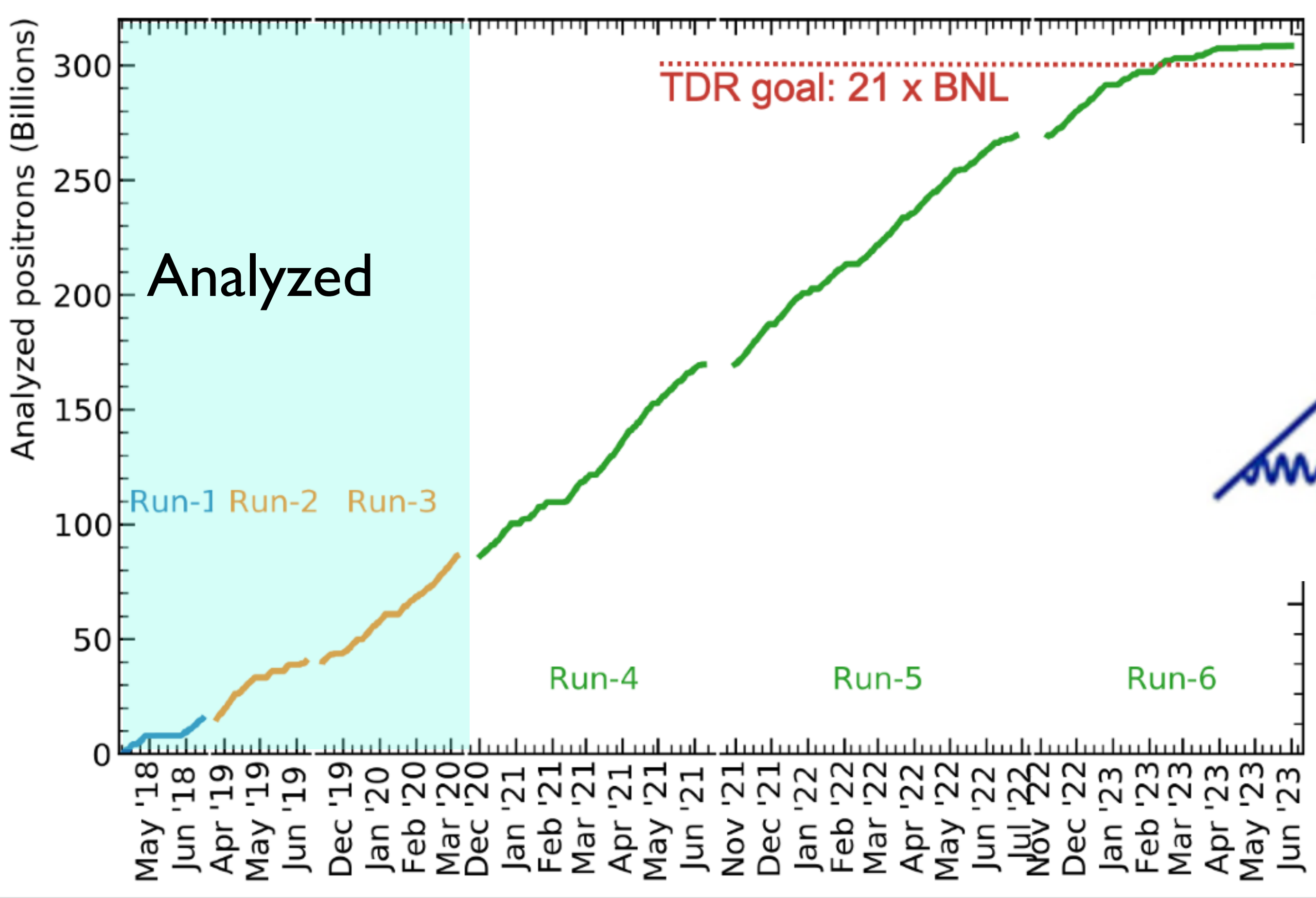

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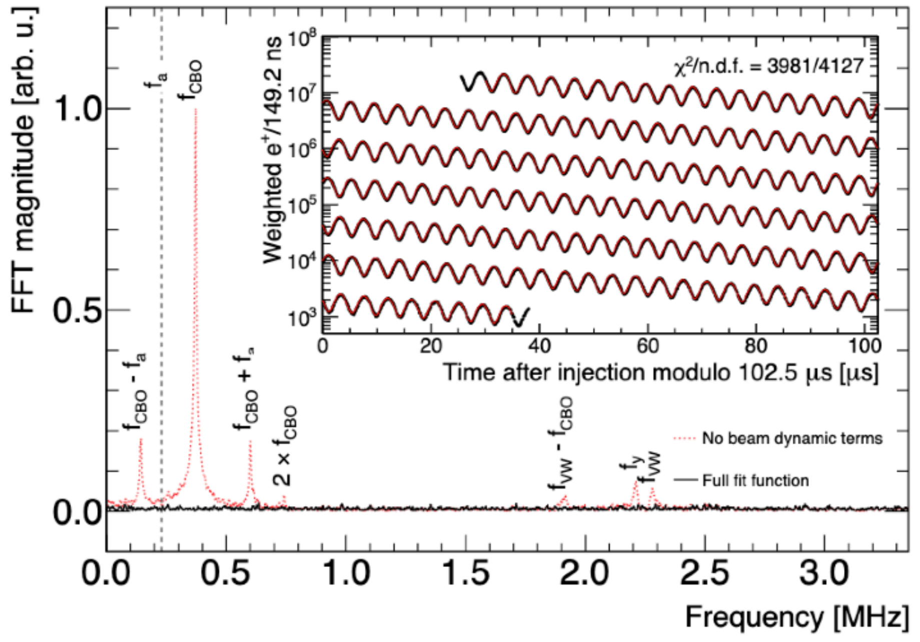

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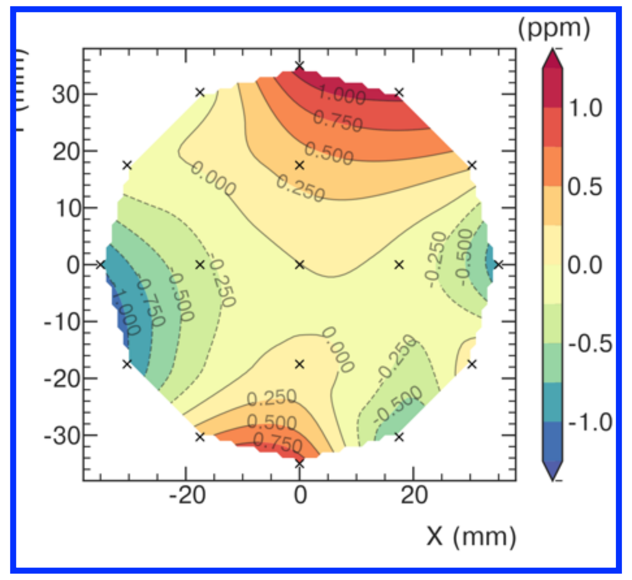

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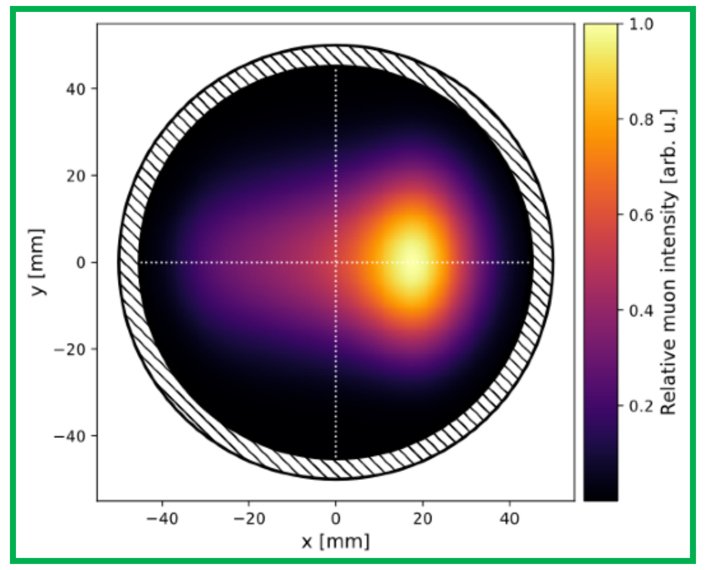

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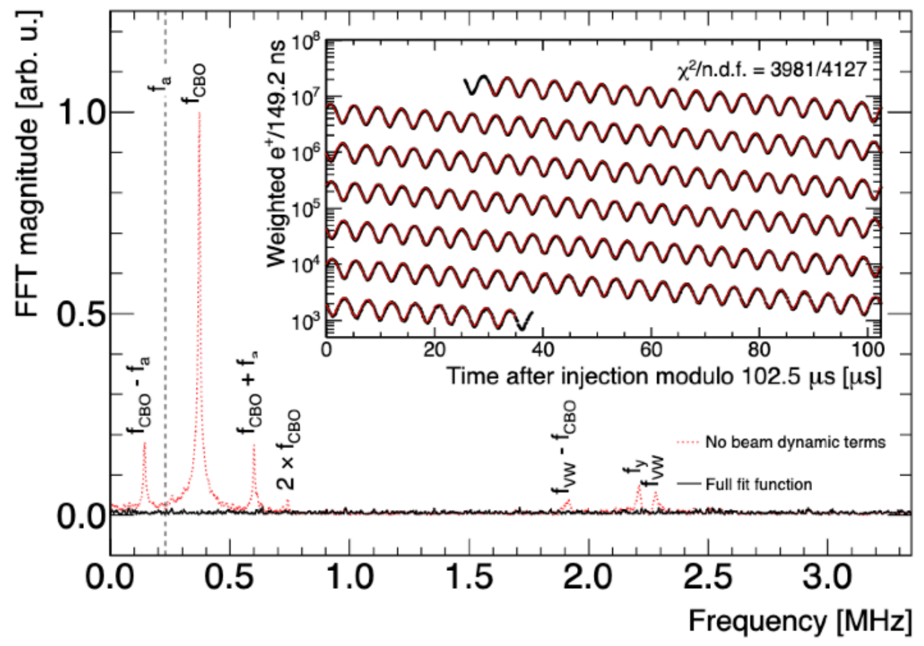

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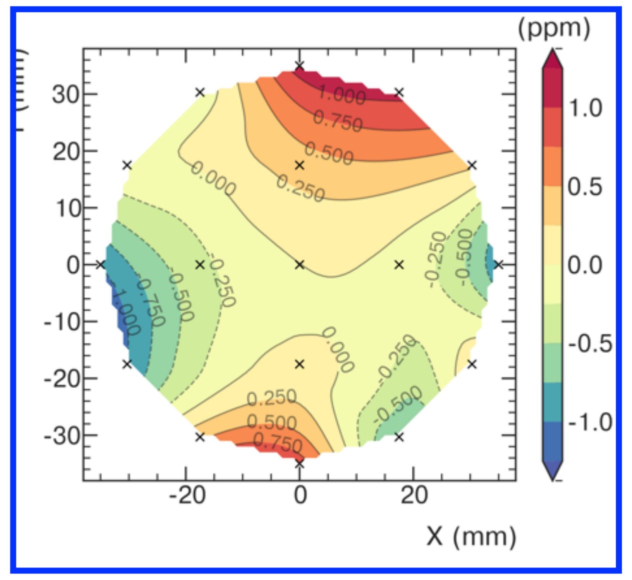

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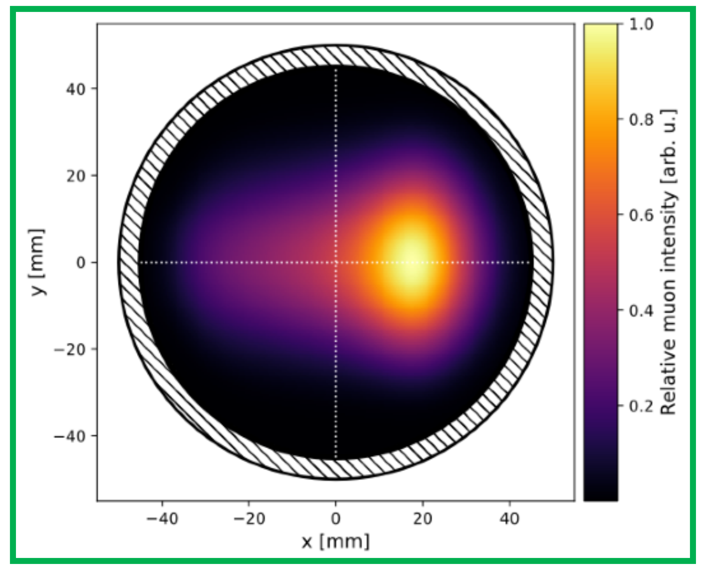

muon distribution extracted by trackers

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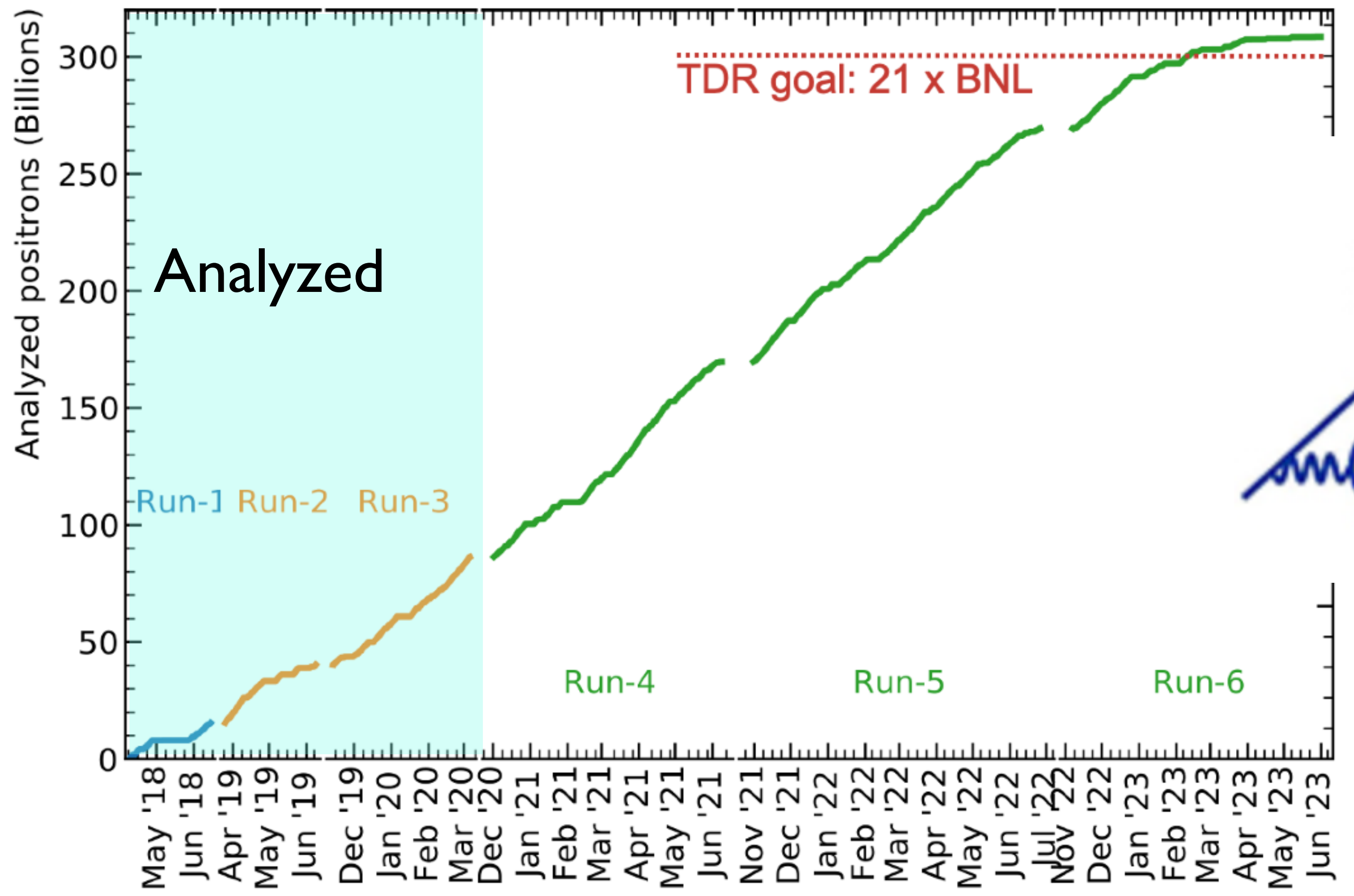
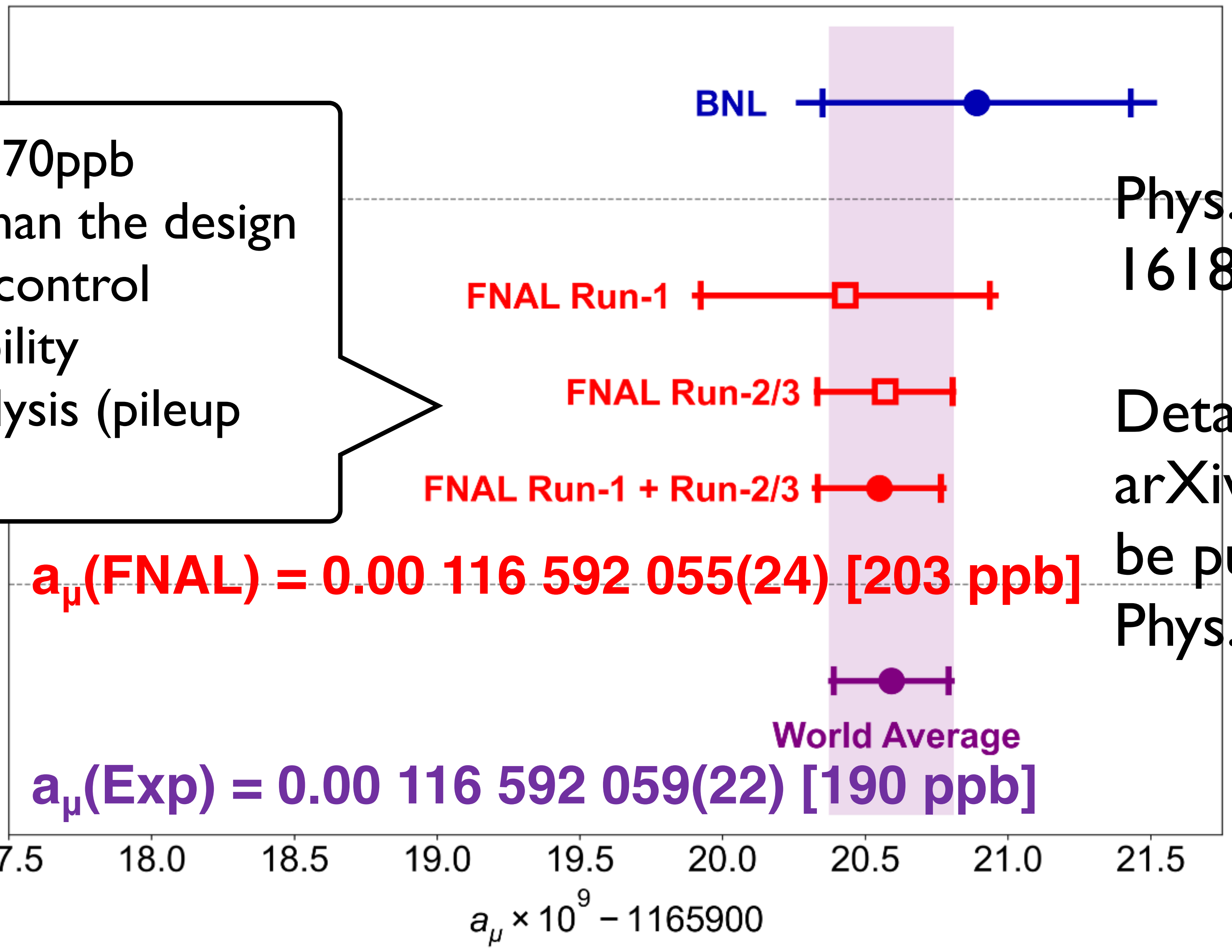


Run-2/3 Δsyst.=70ppb already better than the design

- Temperature control
- Mag. field stability
- Improved analysis (pileup correction)



a_μ(FNAL) = 0.00 116 592 055(24) [203 ppb]

a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

Phys. Rev. Lett. 131, 161802 (2023)

Detailed report; arXiv:2402.15410 to be published on Phys. Rev. D

EDM sensitivity ~10^{-21}e cm by searching for up/down asymmetry out of phase with ω_a

Current best limit from BNL: $|d_\mu| < 1.8 \times 10^{-19}$ ecm (95%CL)

Muon g-2 /EDM at J-PARC

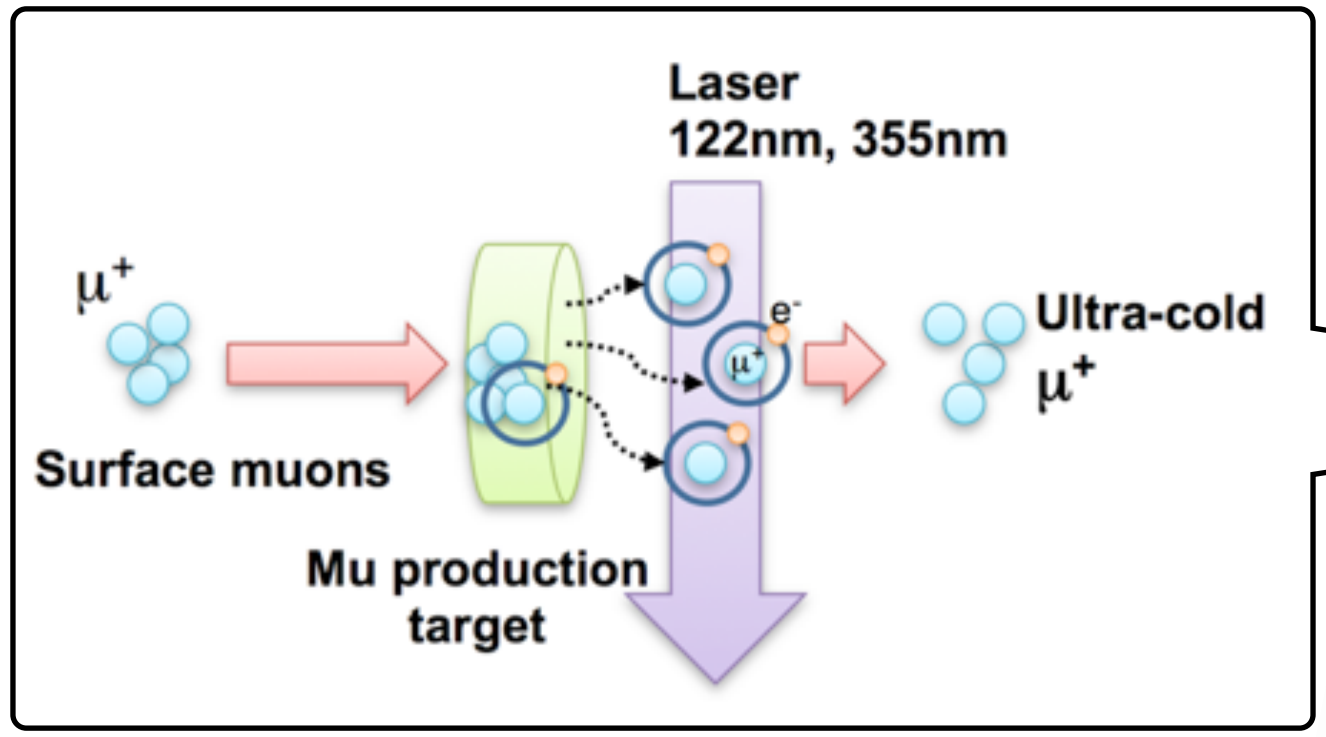
https://g-2.kek.jp

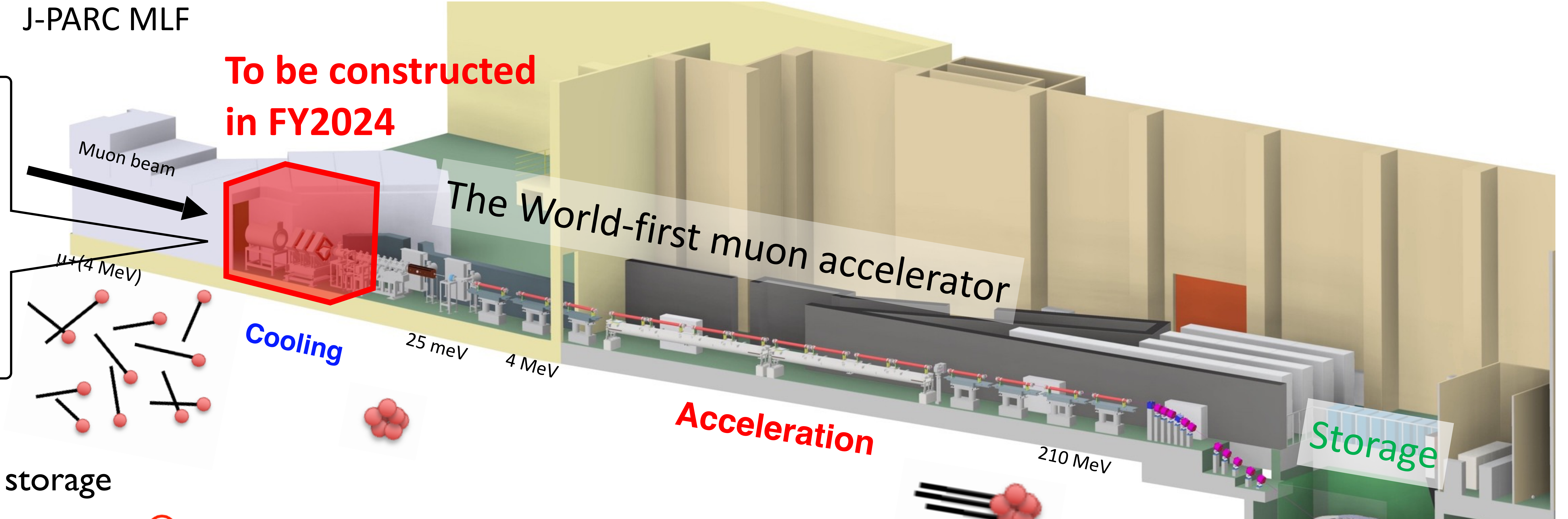
New approach to measure the muon g-2 and EDM at the J-PARC facility

Prog. Theor. Exp. Phys. 2019, 053C02 (2019)

- low emittance muon beam (1/1000) by cooling and re-acceleration
- no strong focusing (1/1000) & good injection efficiency (x10)
- Compact storage magnet (1/20)

⇒ *Independent measurement of g-2 to test BNL/FNAL results with different systematic uncertainty*





To be constructed in FY2024

The World-first muon accelerator

No focusing electrode (E=0) in the storage

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{=0}\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \underbrace{\frac{\vec{E}}{c}}_{=0}\right)\right]$$

Expected sensitivity (2 year running)

	Δstat	Δsyst
g-2	450 ppb	70 ppb
EDM	1.5×10^{-21} e・cm	0.4×10^{-21} e・cm

Aiming at data taking from 2028.

World-first Acceleration of Positive Muon!

Test of muon cooling + re-acceleration
at MLF S2 beam line

2024.05.23
https://j-parc.jp/c/en/press-release/2024/05/23001341.html

World's first cooling and acceleration of muon
- The first muon accelerator finally coming to a reality. -

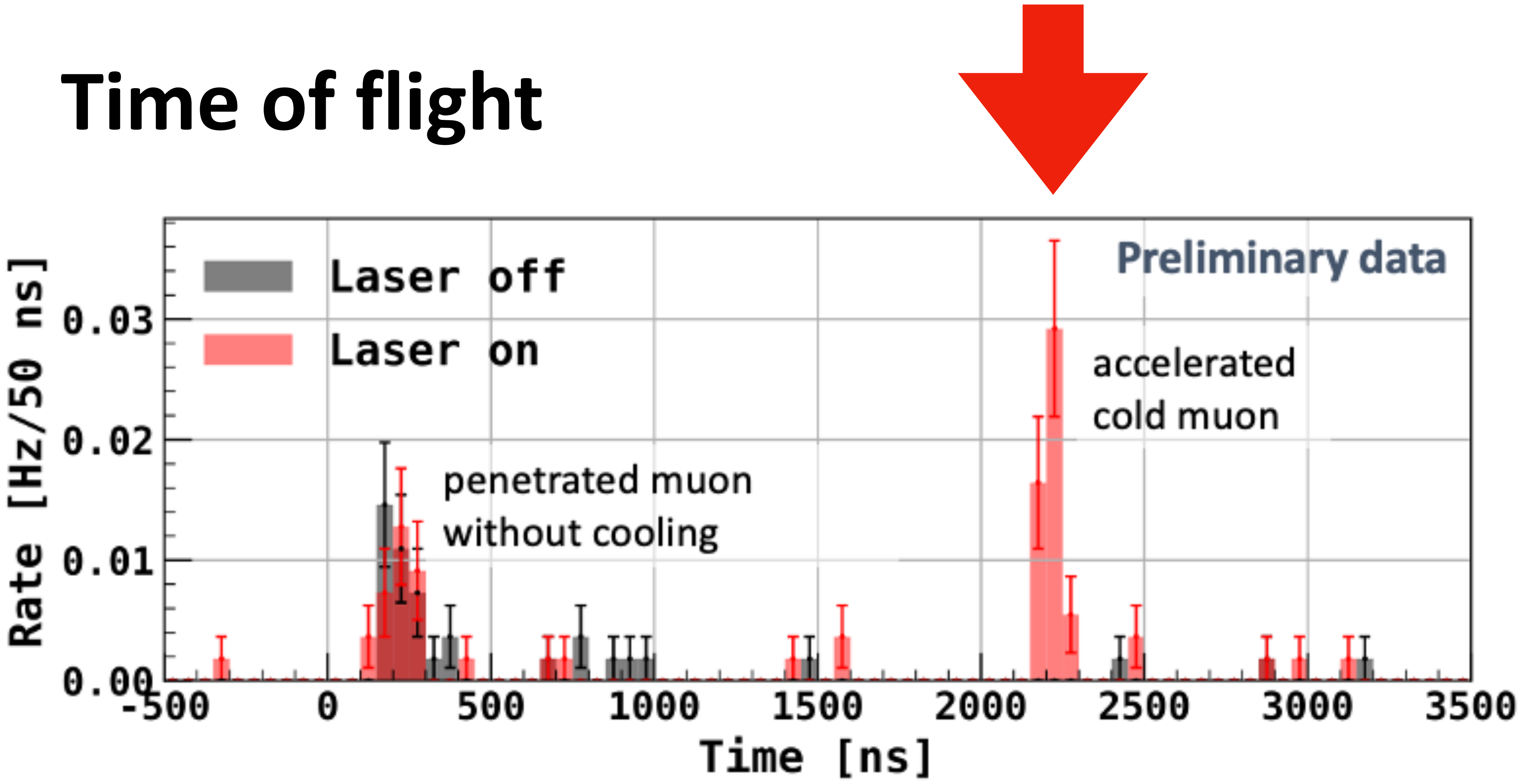
World's first cooling and acceleration of muon

A muon is an elementary particle like an electron. Muons were first discovered in 1936 as cosmic rays falling from the sky. Natural muons originated from cosmic rays have been used to see through the interior of large and/or thick objects, such as pyramids. Presently, muons can be produced in much higher intensity using accelerators for the use of various research and applications.

https://www.interactions.org

World first The experimental set up for muon cooling and acceleration at J-PARC. A beam of antimatter muons enters the apparatus from the right. Credit: J-PARC

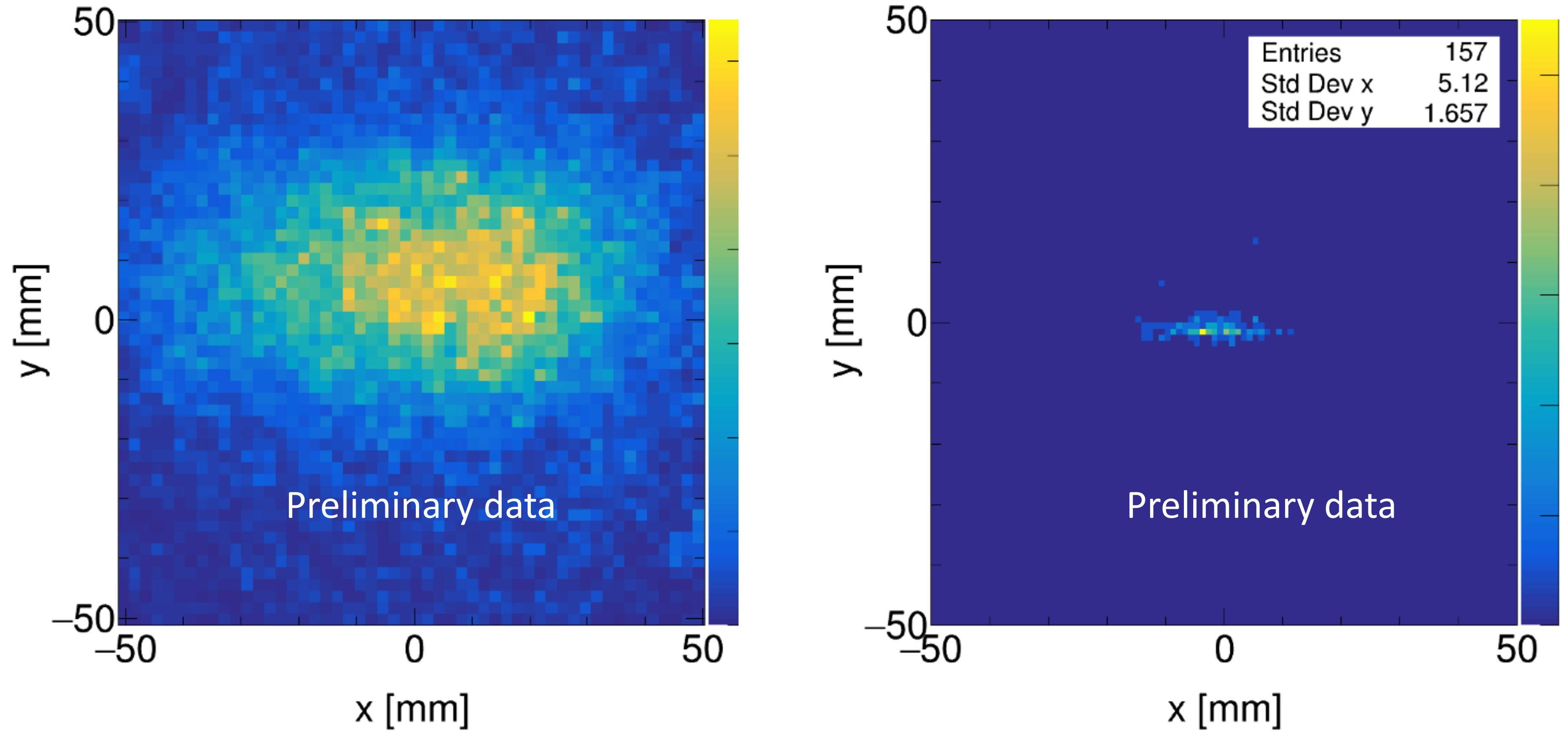
Time of flight



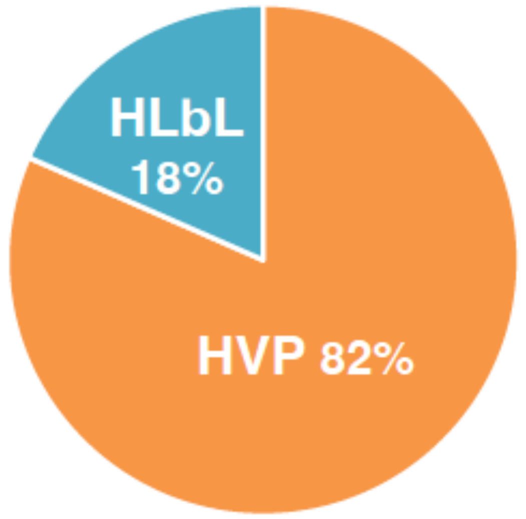
Beam profiles

before cooling

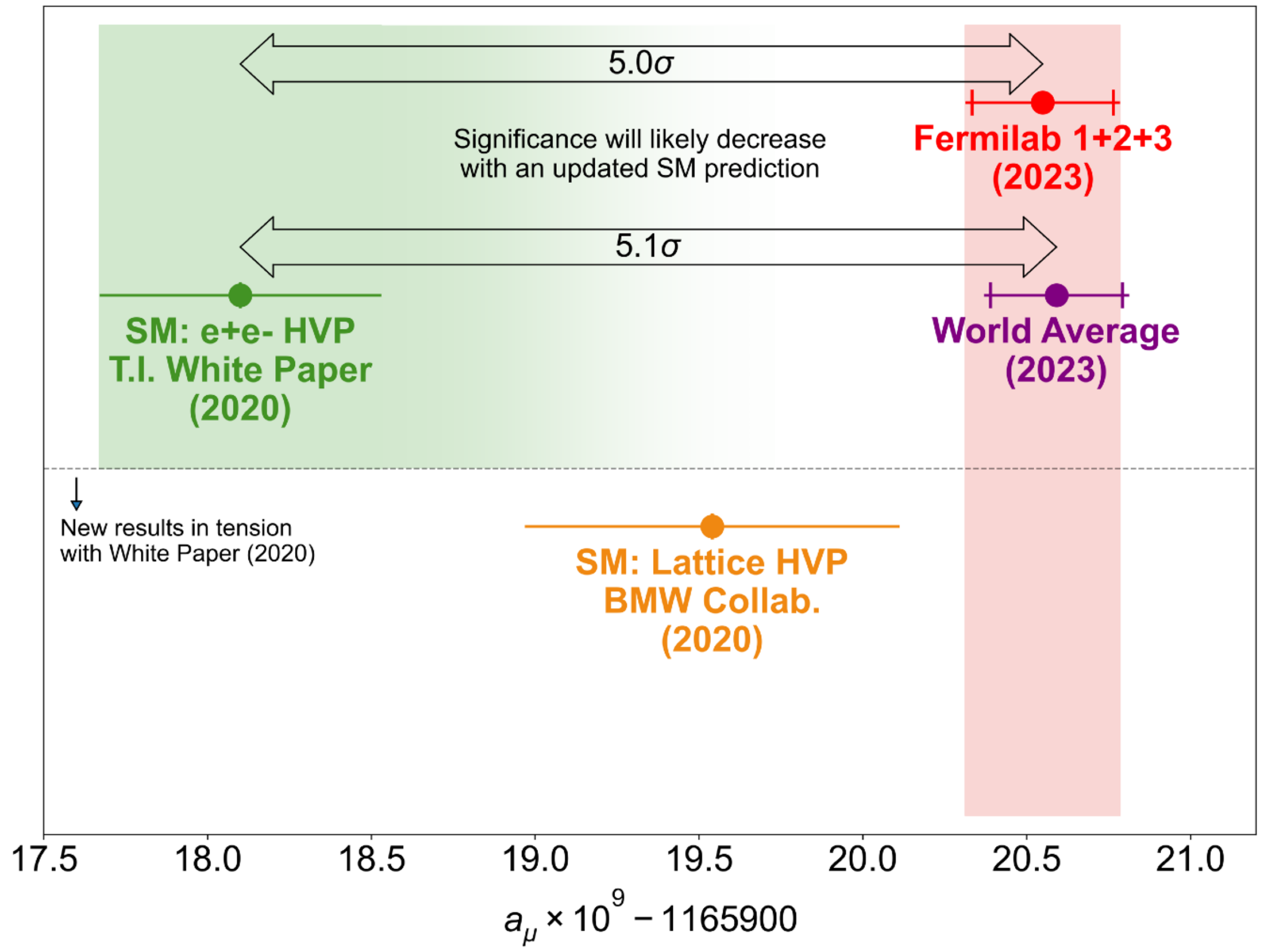
after cooling & accel.



Reference SM Predictions



- Hadronic Vacuum Polarization (HVP) is the dominant error source.
- Tension between two approaches; Dispersive and Lattice



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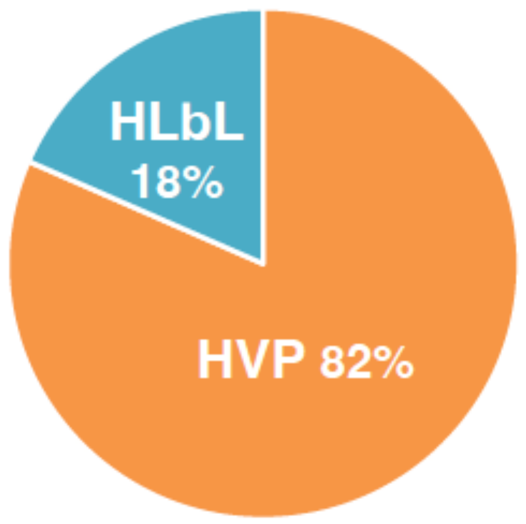

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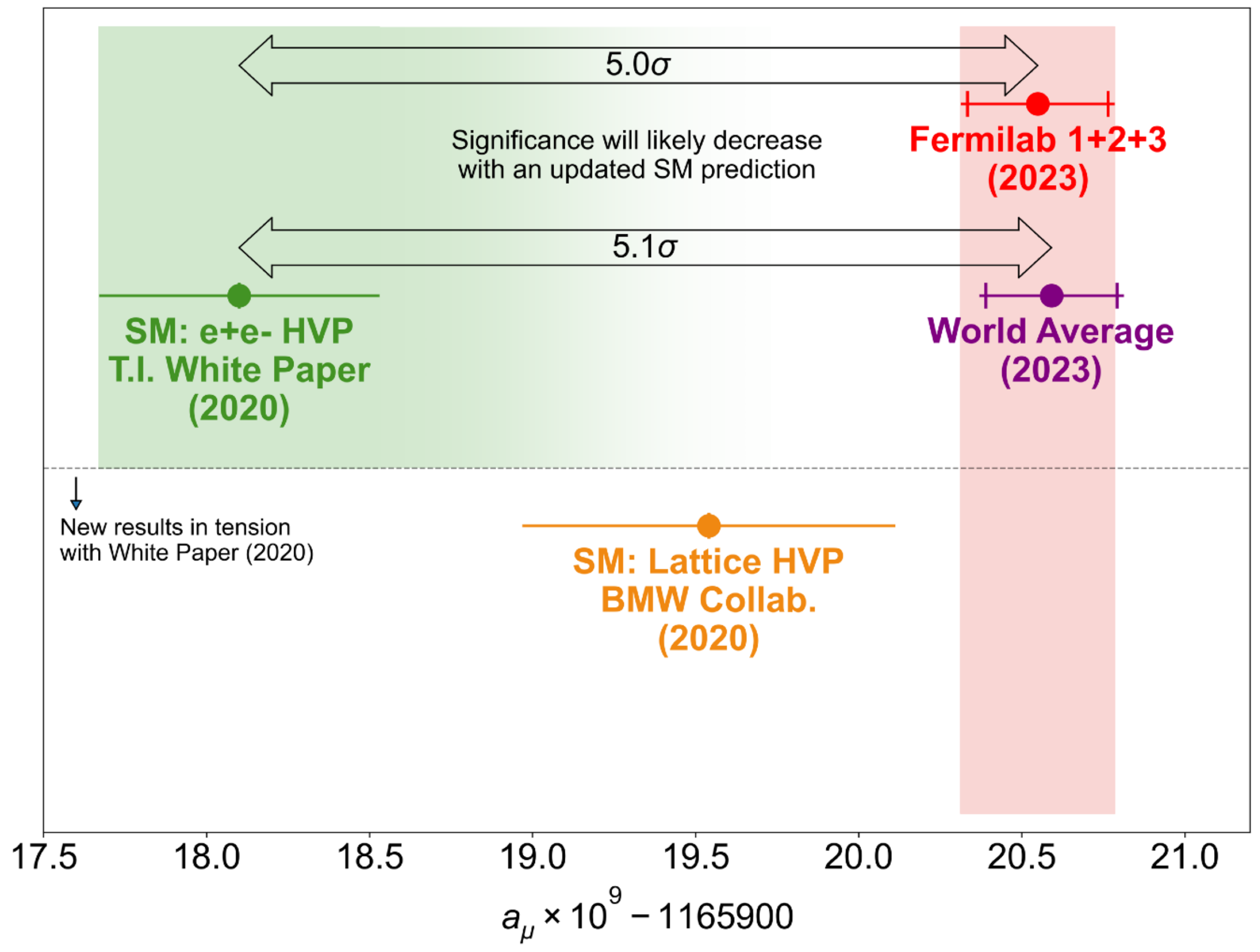
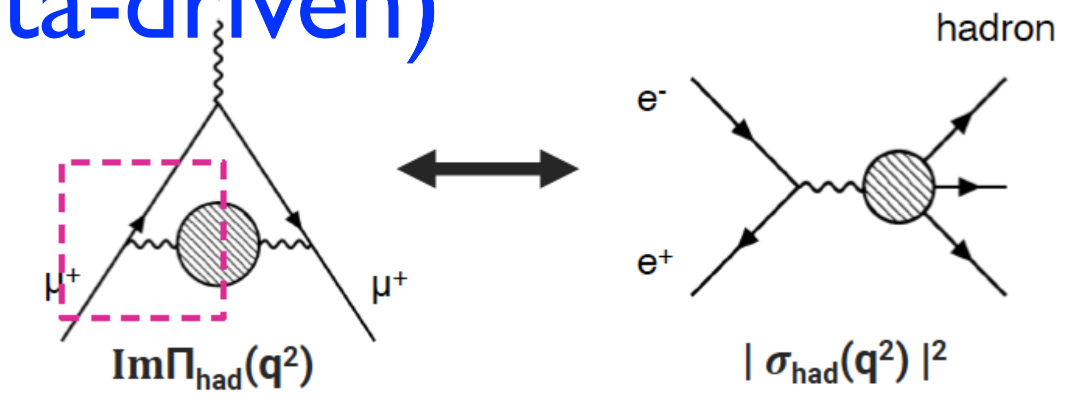
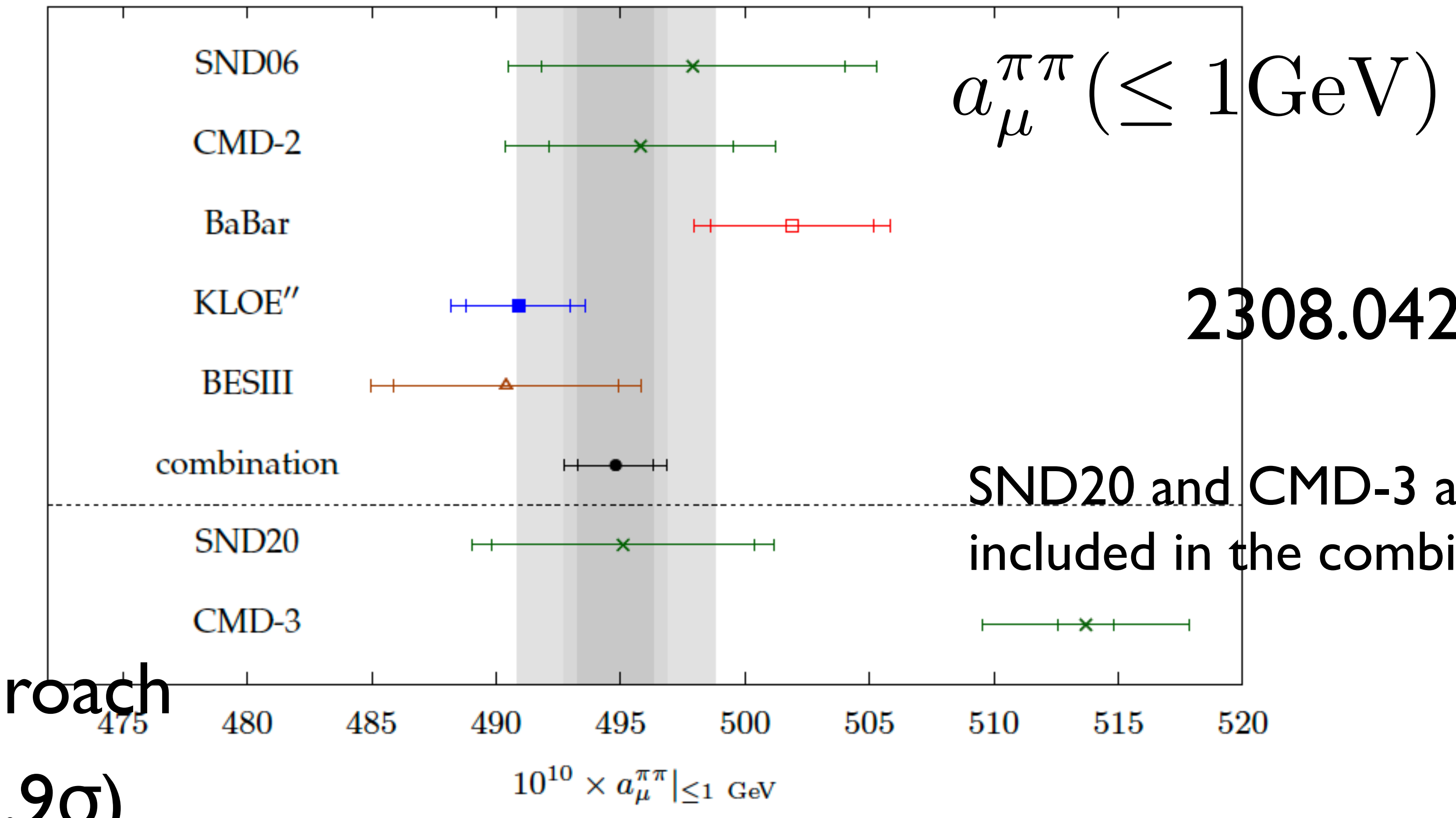


Dispersive approach (data-driven)





2308.04217

SND20 and CMD-3 are not included in the combination

T.I. White Paper (2020) takes this approach

Tension between BaBar and KLOE (2.9σ)

& more tension between CMD-3 (2.2/5.1σ w.r.t. BaBar/KLOE)

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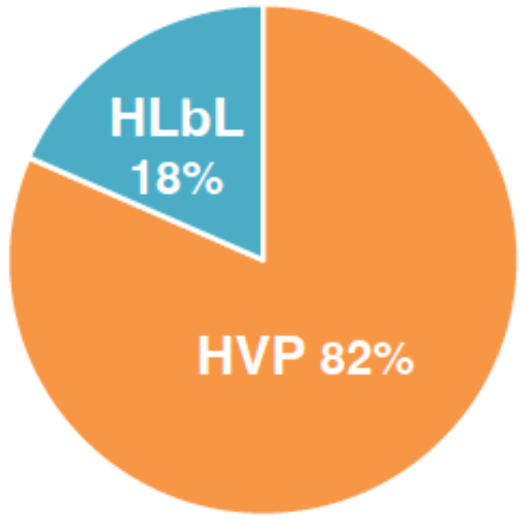

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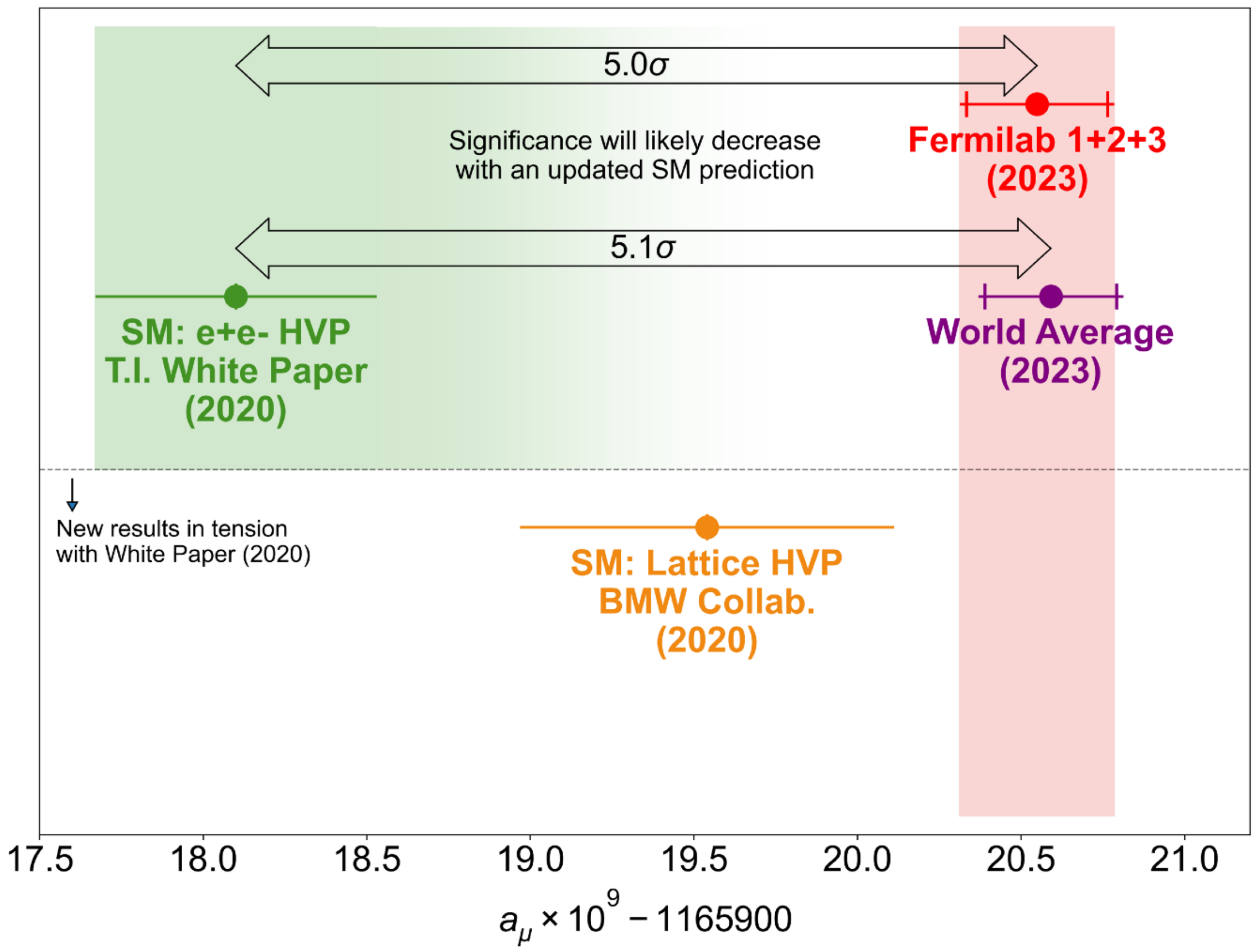

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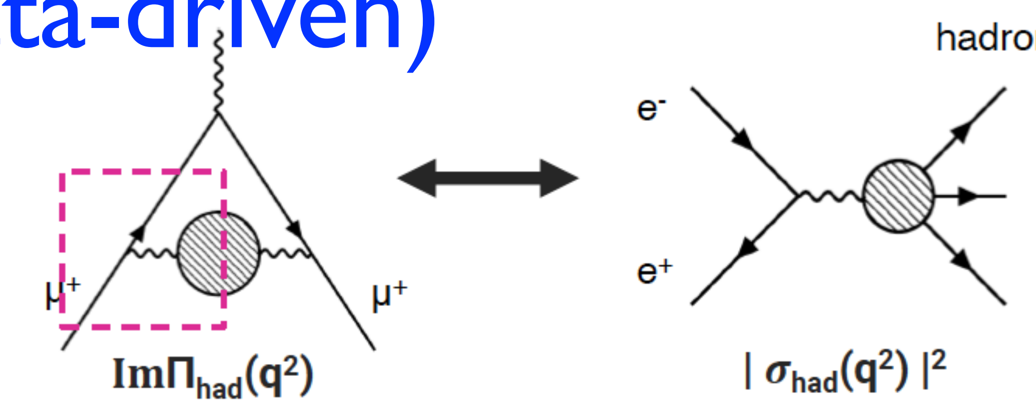

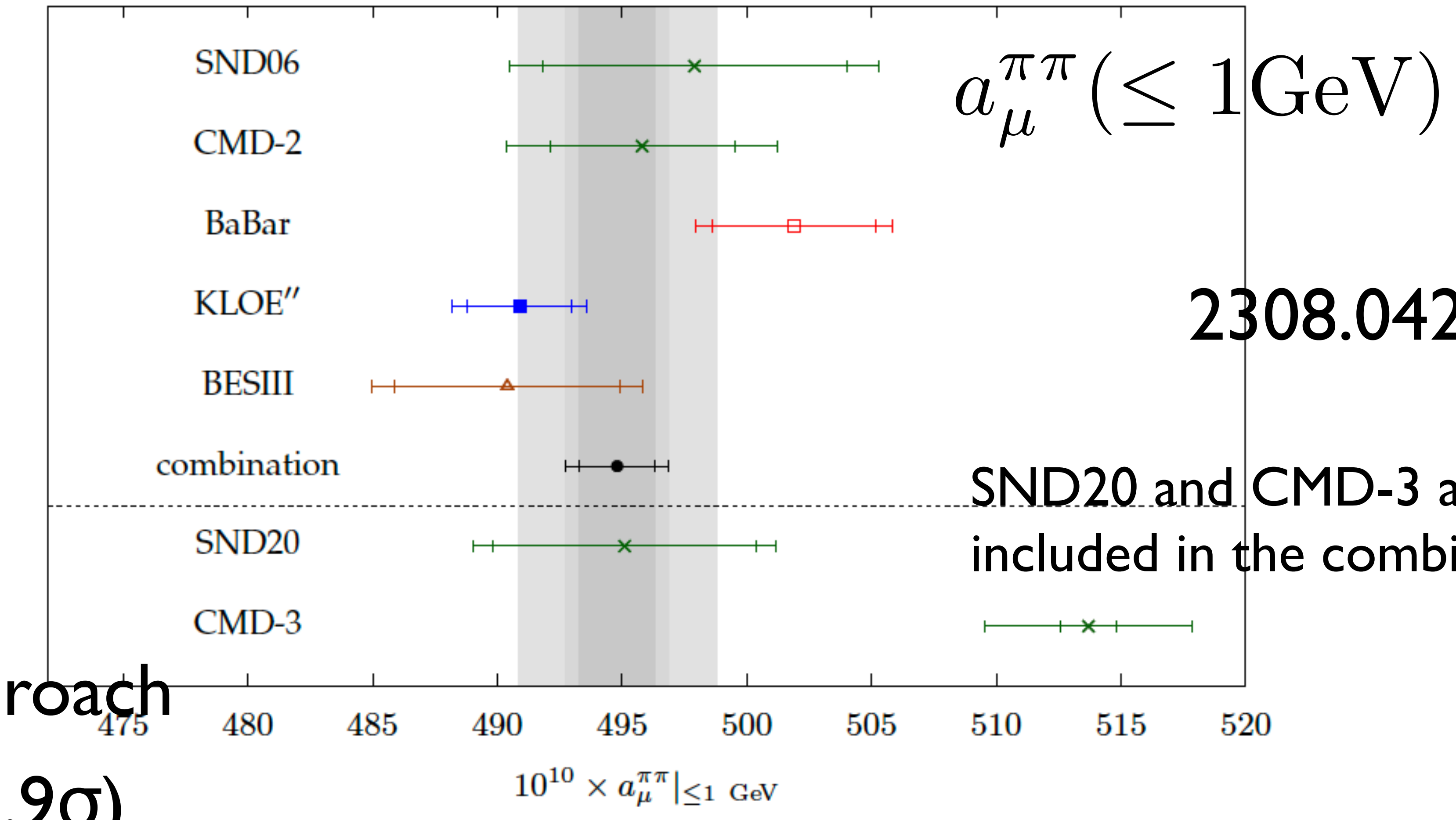

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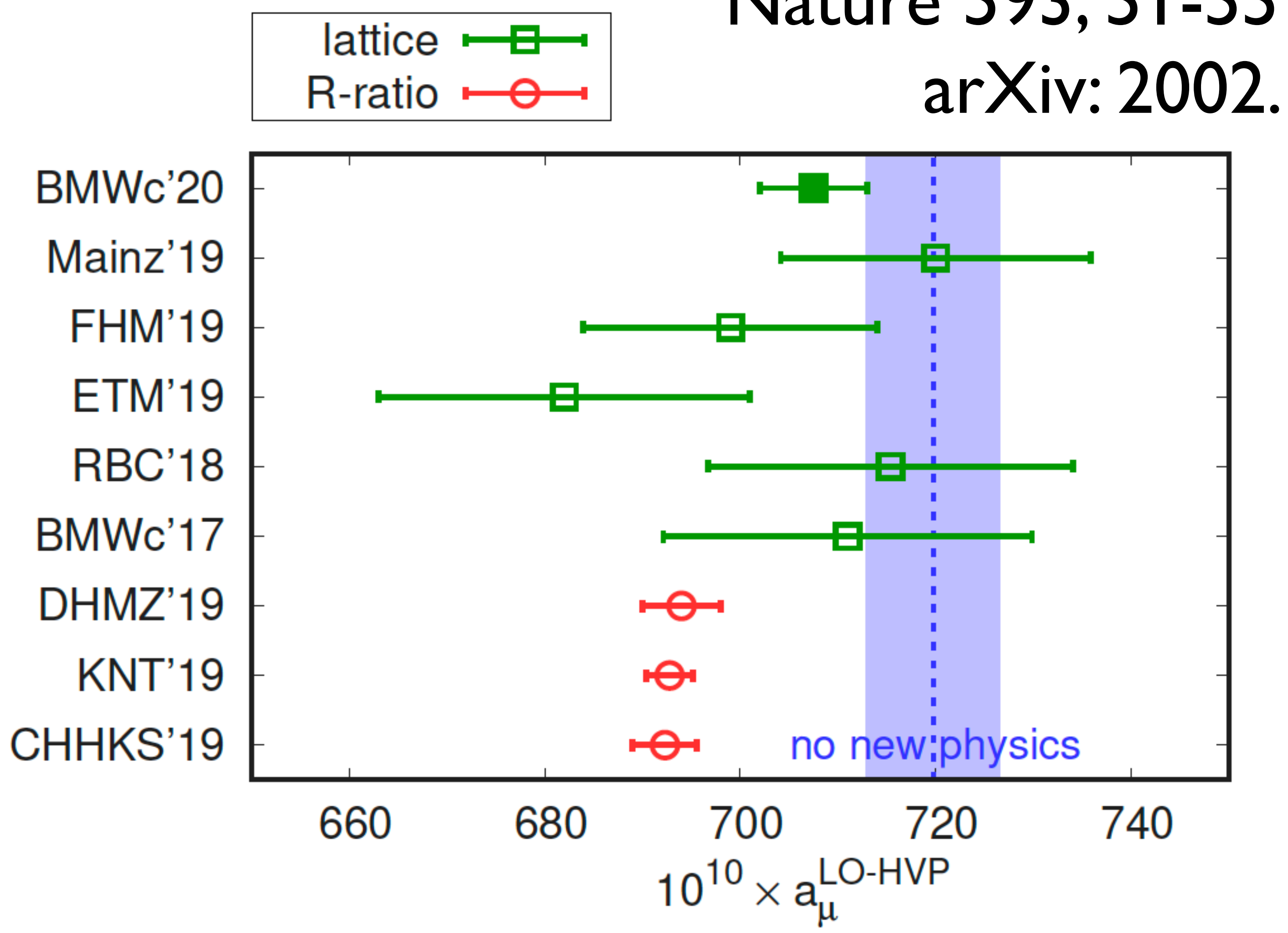
Lattice approach

Finite size, lattice spacing, large computing

Recent lattice calculation (e.g.;BMW20) achieved comparable error and gives prediction closer to exp.

Nature 593, 51-55 (2021)
arXiv: 2002.12347



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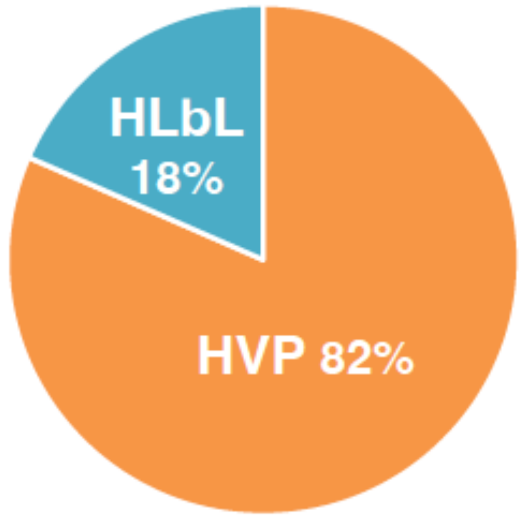

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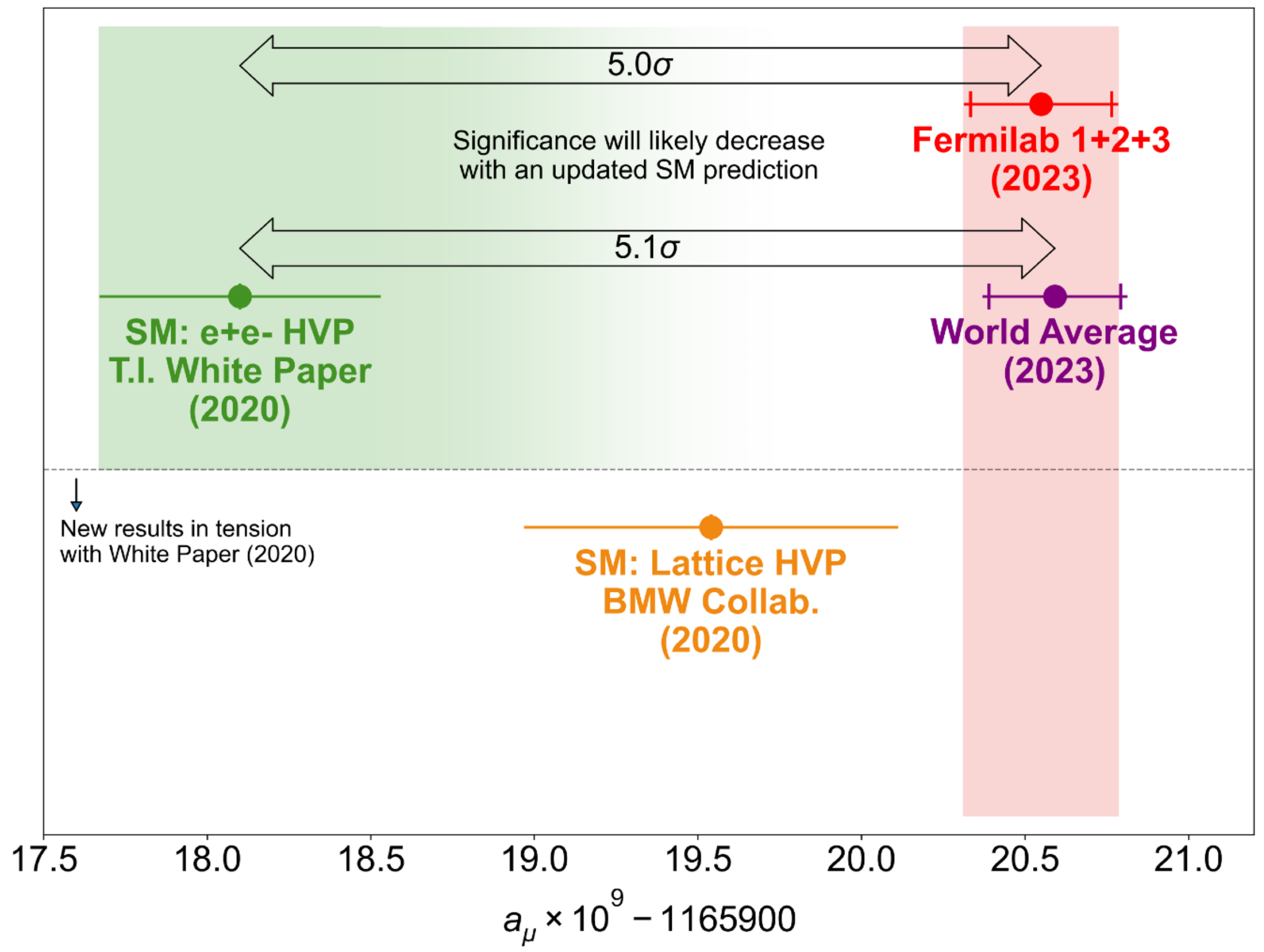

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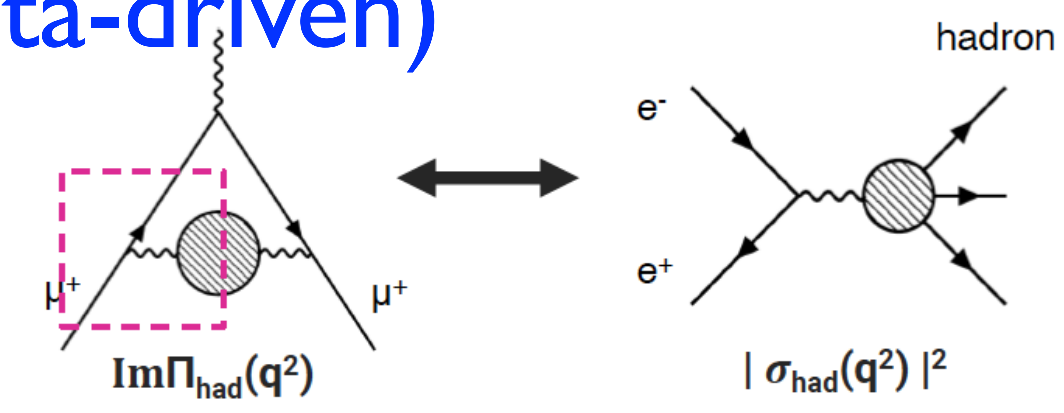

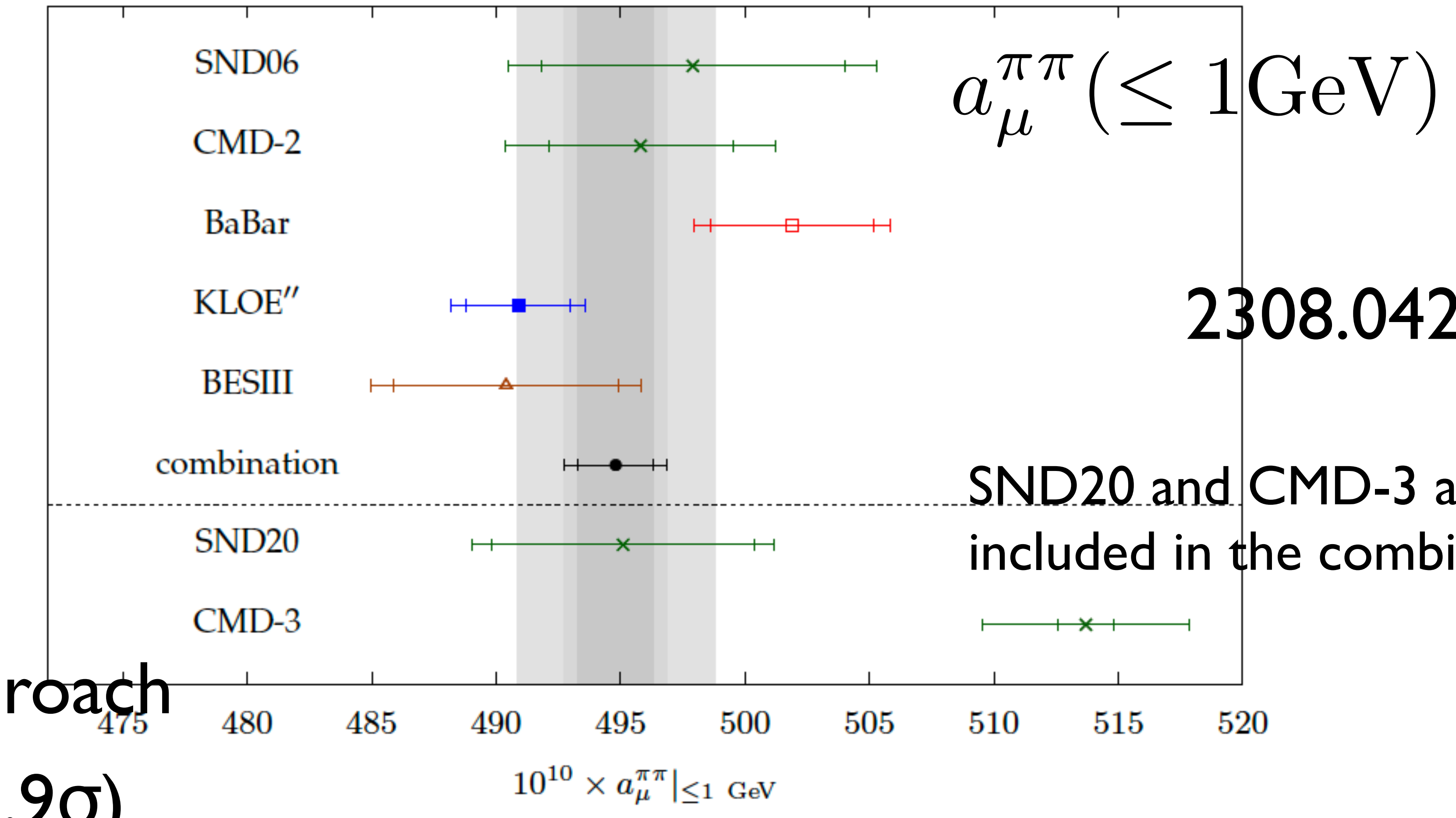

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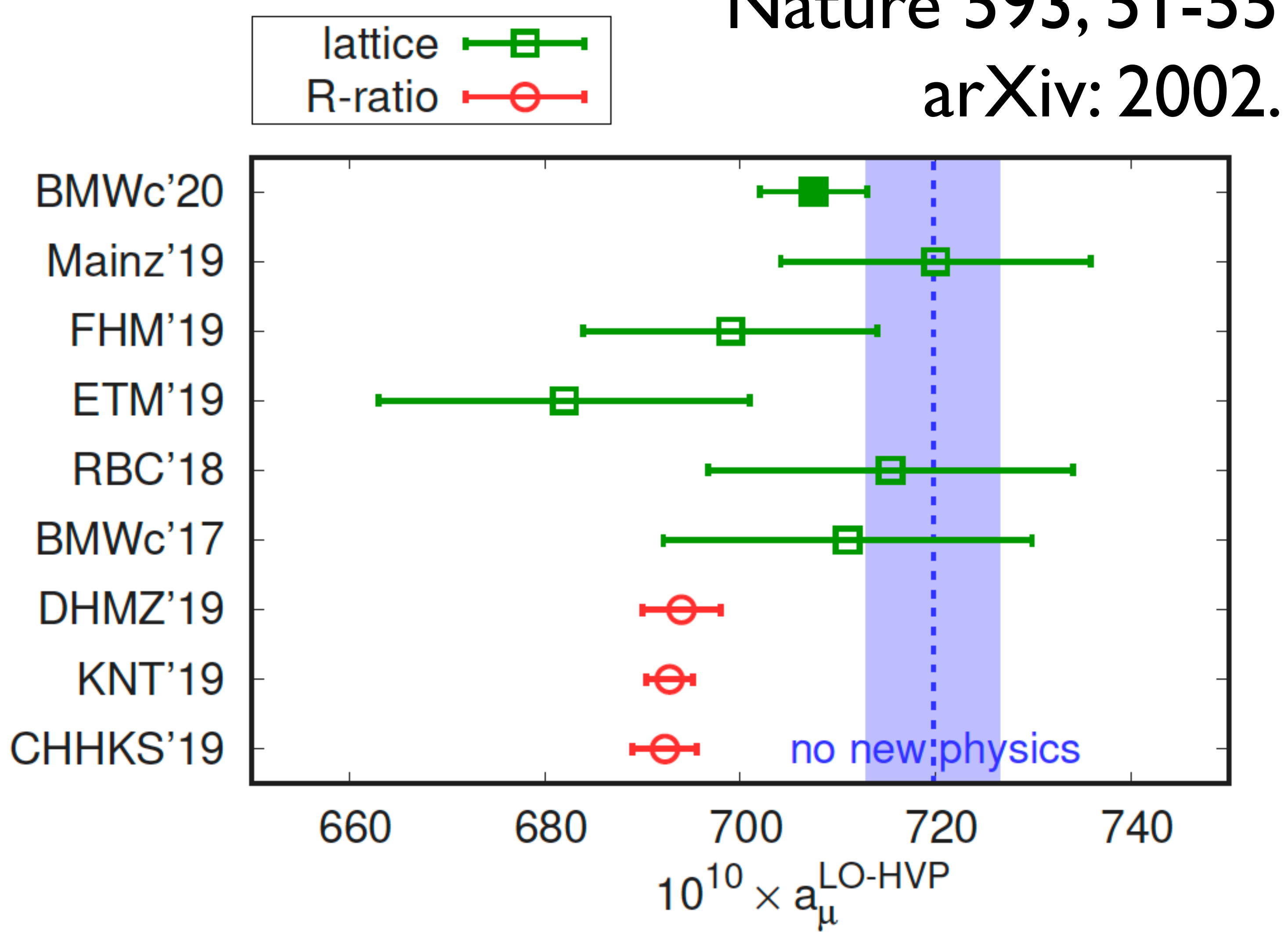
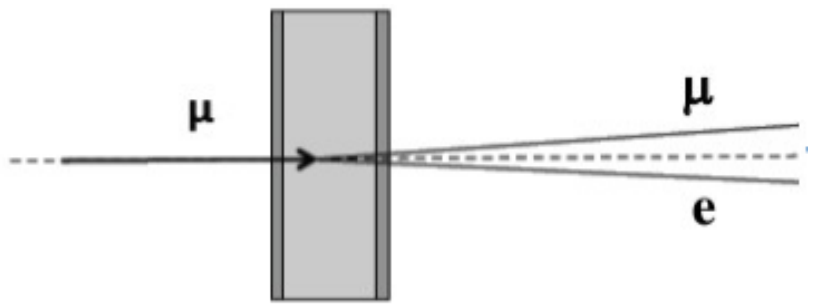


Another approach by MUonE

A new independent evaluation of a_μ^{HLO} by μe → μe differential cross section



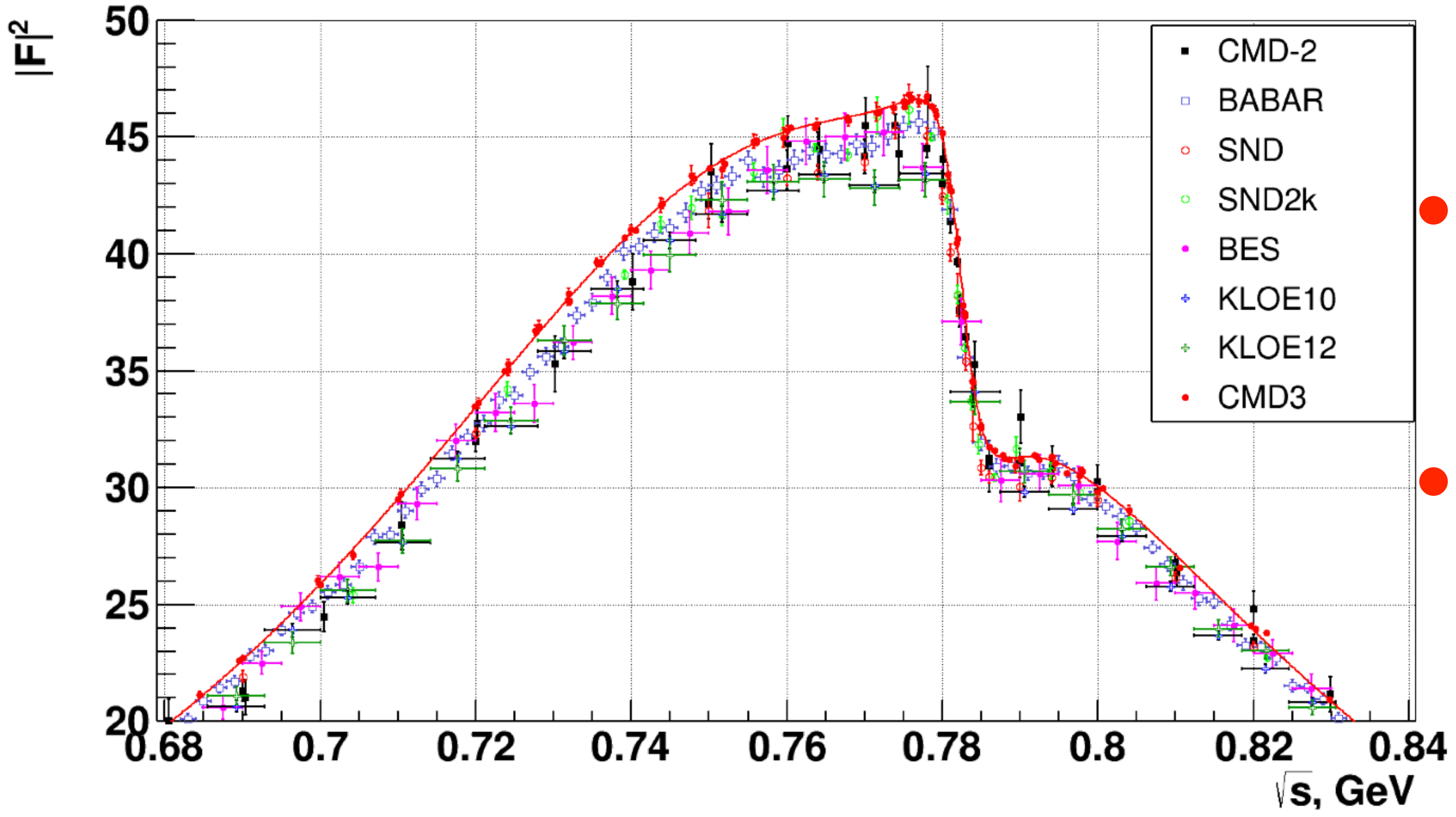
Test runs in 2023-2024 → Technical proposal for 4-week run in 2025

Eugenia Spedicato

Recent $e^+e^- \rightarrow \pi^+\pi^-$ Results

CMD-3 at VEPP-2000 e^+e^- collider

- Scanning E_{CM} = 0.32-2 GeV
- Better detector performance
- Larger statistics (x30 CMD-2)

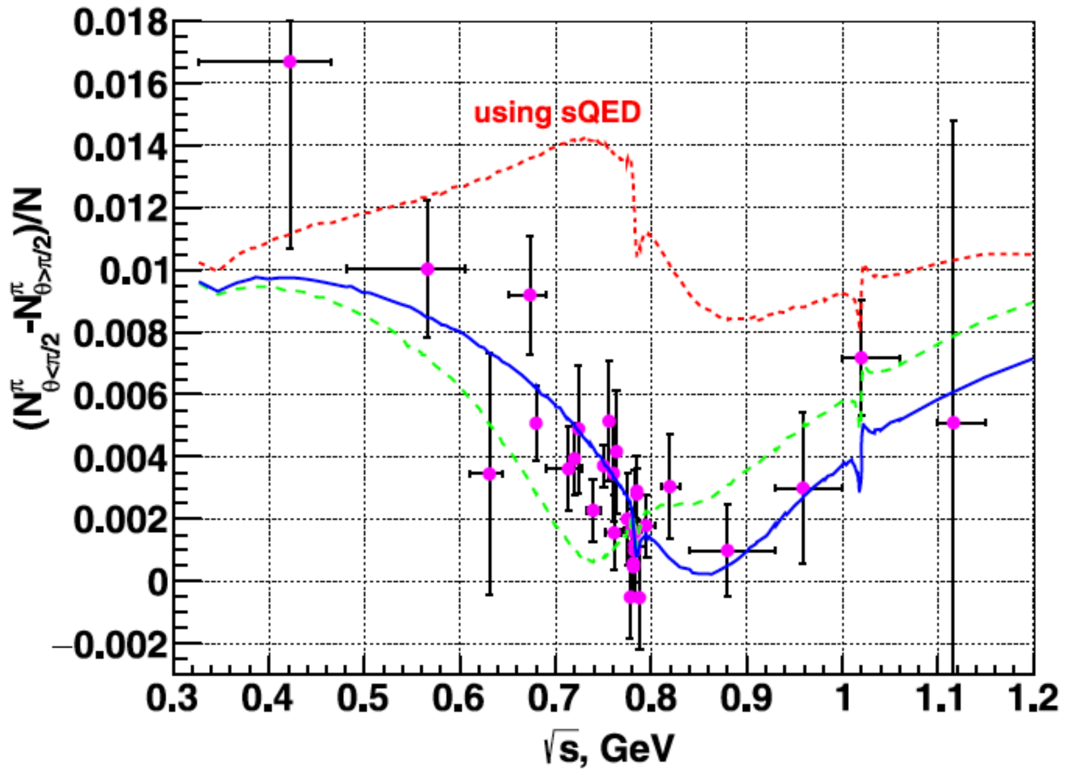


- *Statistical precision is a few times better than other experiments*
- *Cross section is higher by ~2-5%.*

Forward-backward charge asymmetry

→Better fiducial volume determination

→Better radiative correction modeling



Phys. Rev. D109, 112002 (2024)

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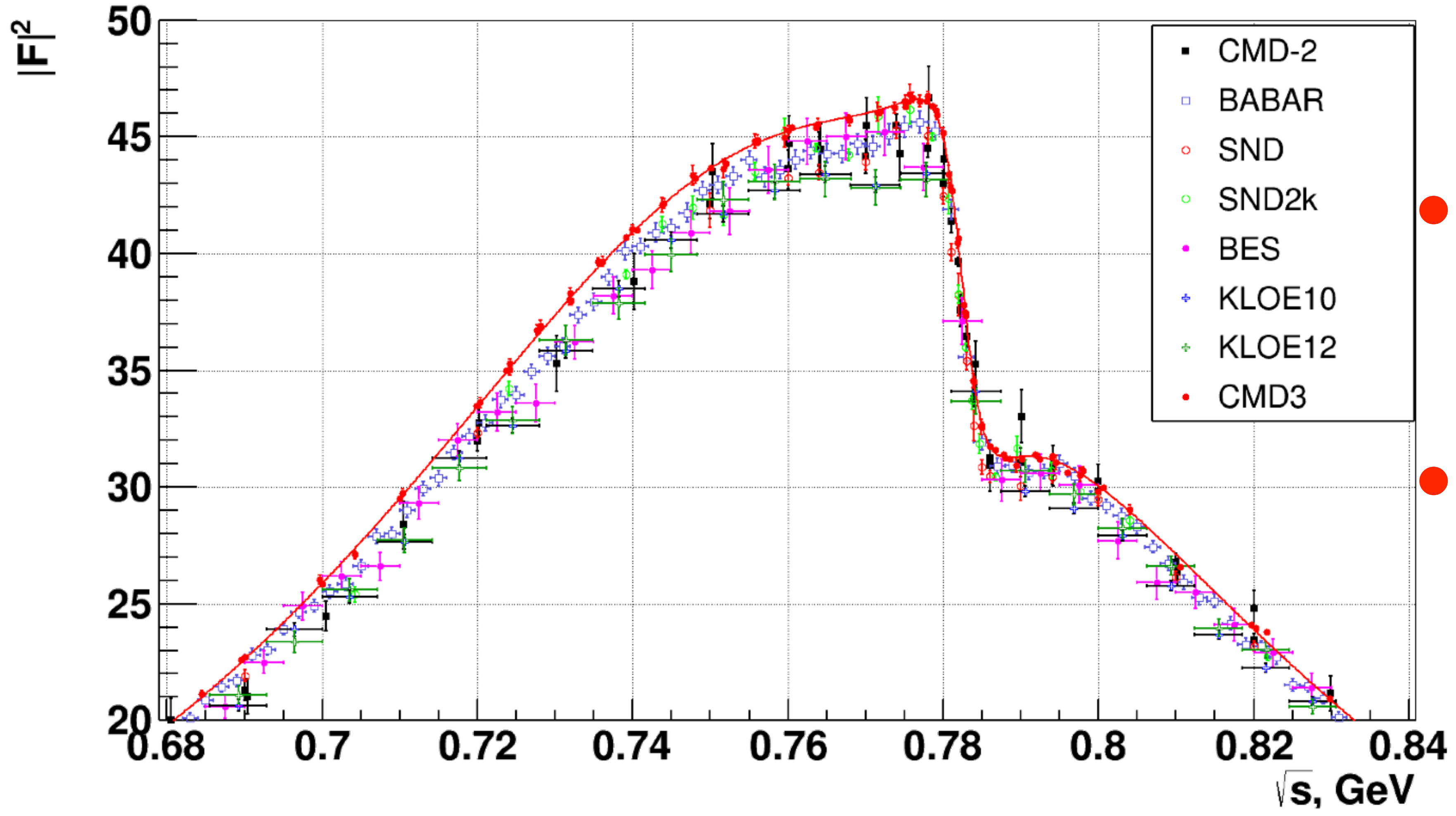

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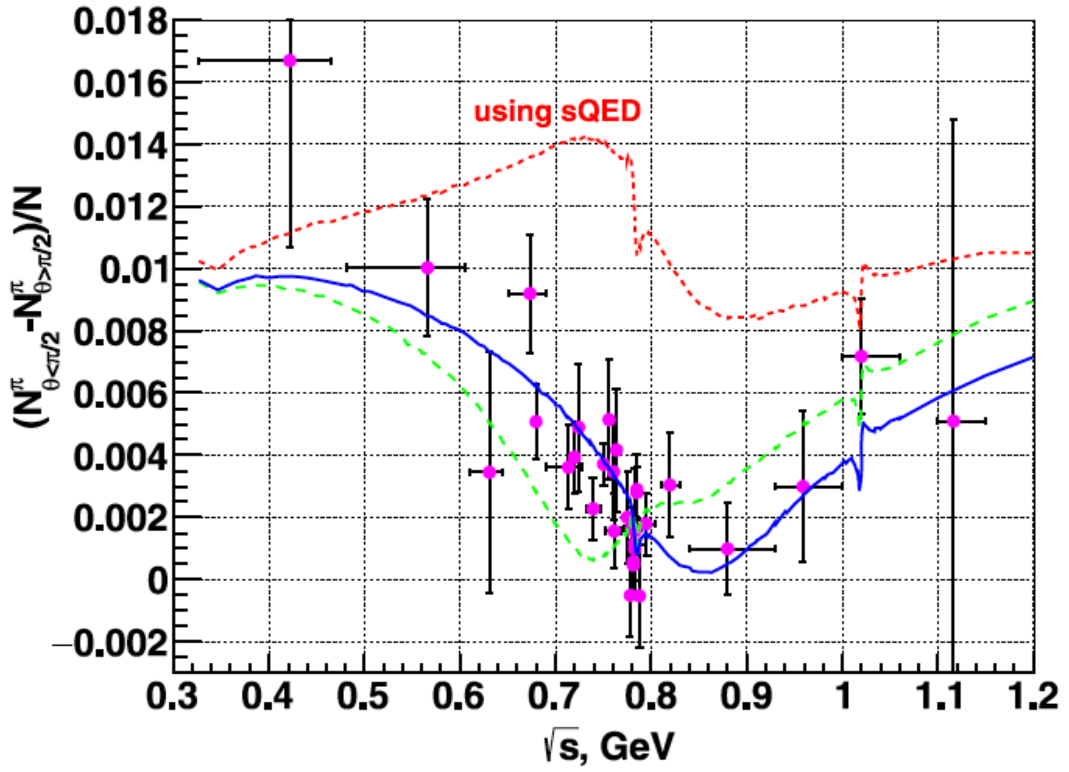


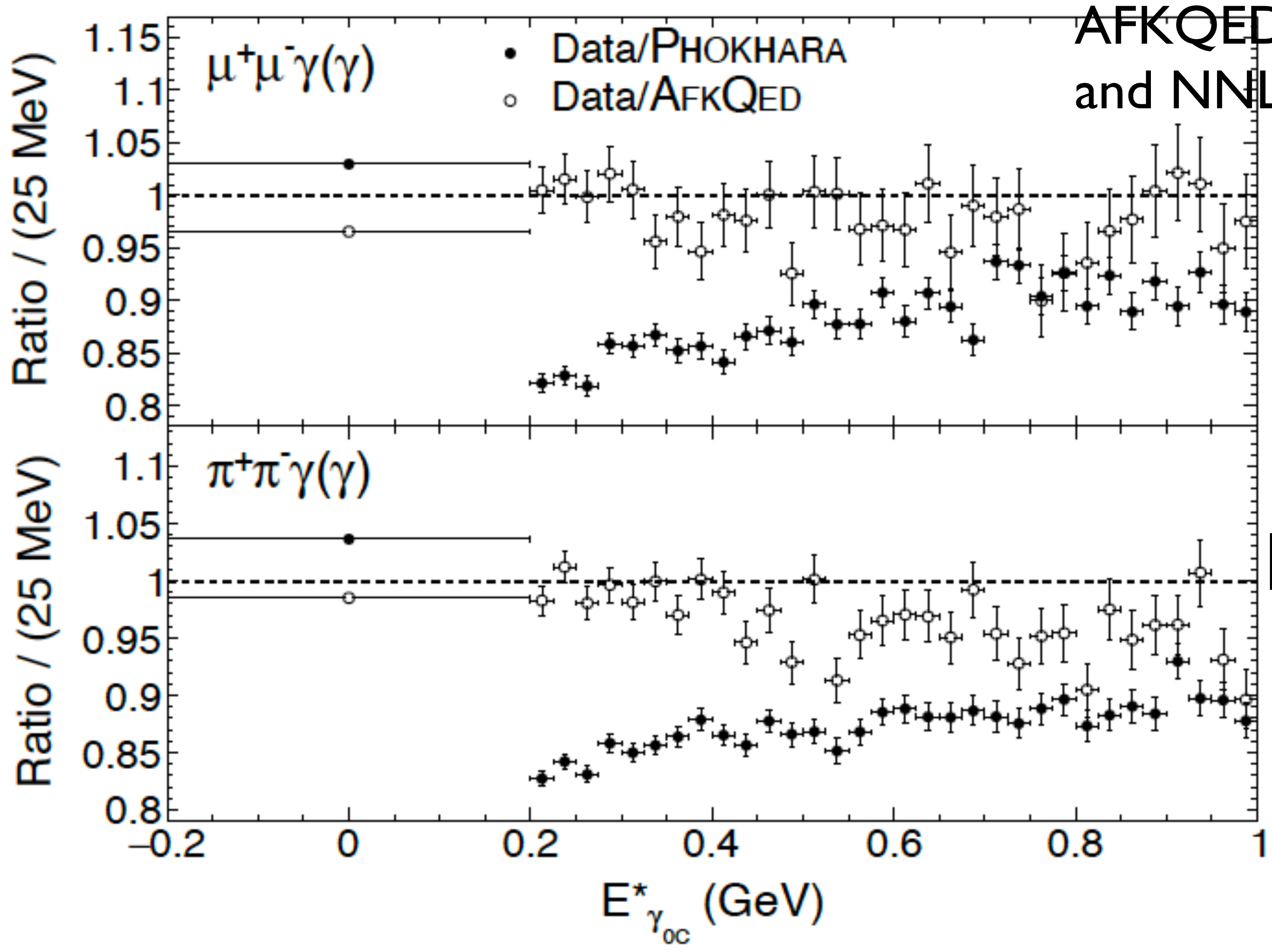
BaBar: measurement of additional radiation in $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow \pi^+\pi^-\gamma$

Bogdan Malaescu

Higher-order radiative processes

- NLO: $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$ and $e^+e^- \rightarrow \pi^+\pi^-\gamma\gamma$
- NNLO: $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma\gamma$ and $e^+e^- \rightarrow \pi^+\pi^-\gamma\gamma\gamma$

affect ISR measurements if MC generator does not correctly account these contributions.



PHOKHARA limited to NLO

AFKQED includes both NLO and NNLO

Phys. Rev. D 108, L111103 (2023)

Radiative corrections need to be better understood and accounted in analyses!

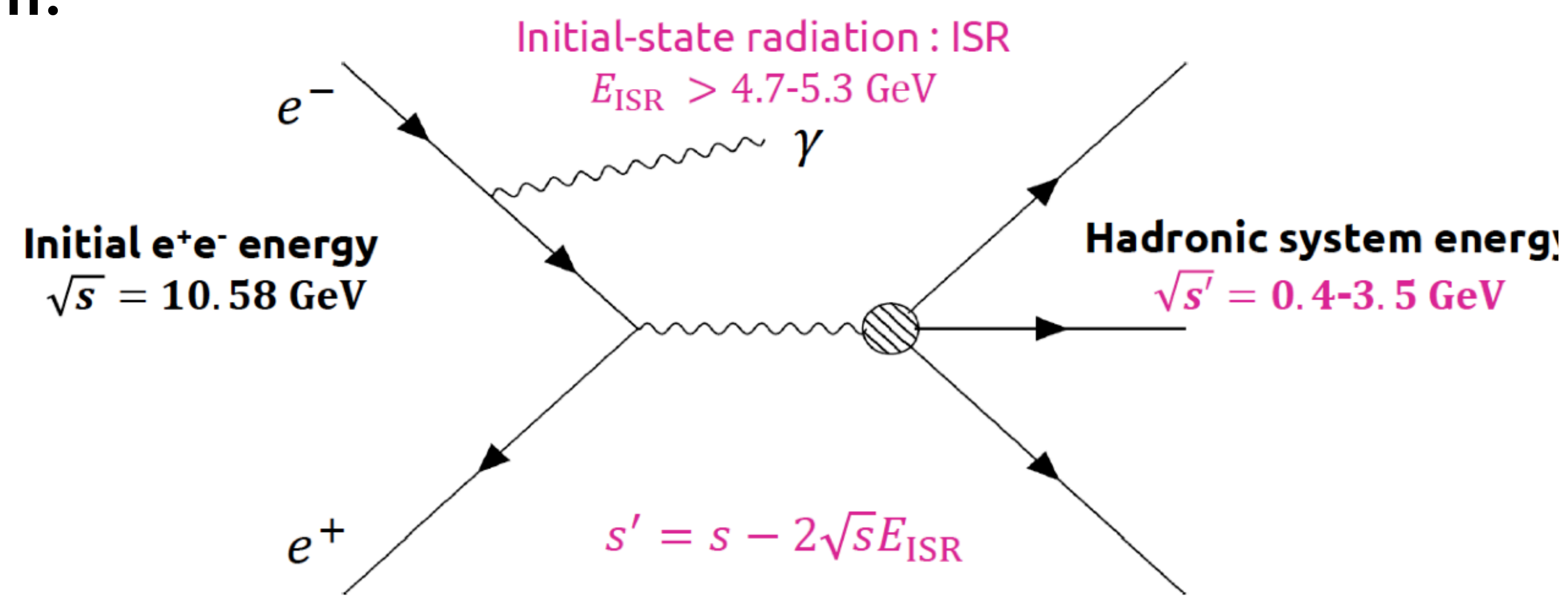
William J. Torres Bobaailla

$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ by Belle II

arXiv: 2404.04915

Yuki Sue

- e^+e^- cross-section measurement w/ ISR method in progress at Belle II.
  - Good trigger efficiency confirmed
- Released the first result for $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ with 2.2% error
  - The largest uncertainty arises from the MC generator (1.2%)
- The results are about 2.5σ higher than BaBar and global fit.



Initial-state radiation : ISR

$E_{\mathrm{ISR}} > 4.7$-5.3 GeV

γ

e^-

e^+

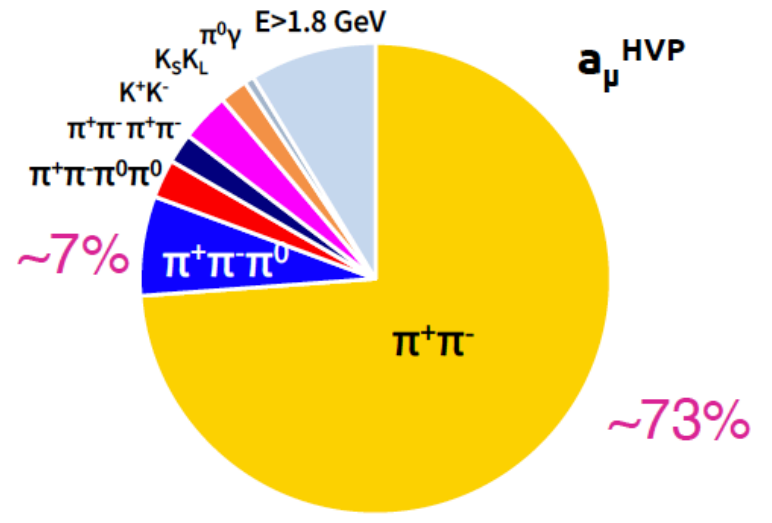
Initial e^+e^- energy

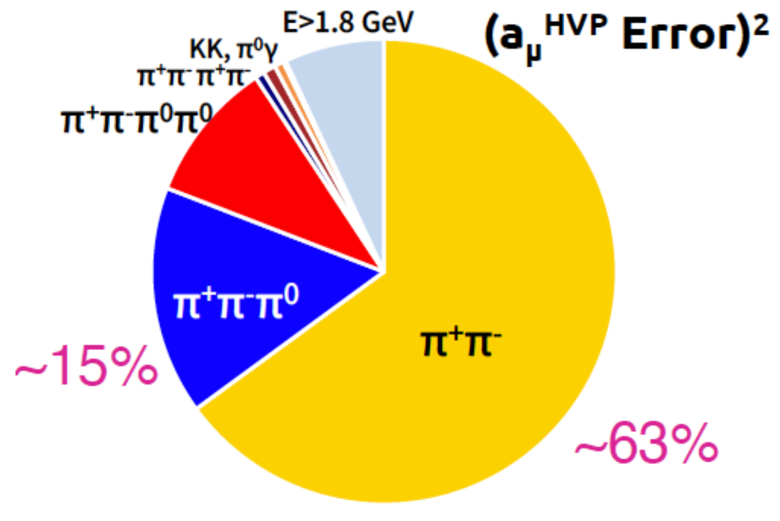
$\sqrt{s} = 10.58$ GeV

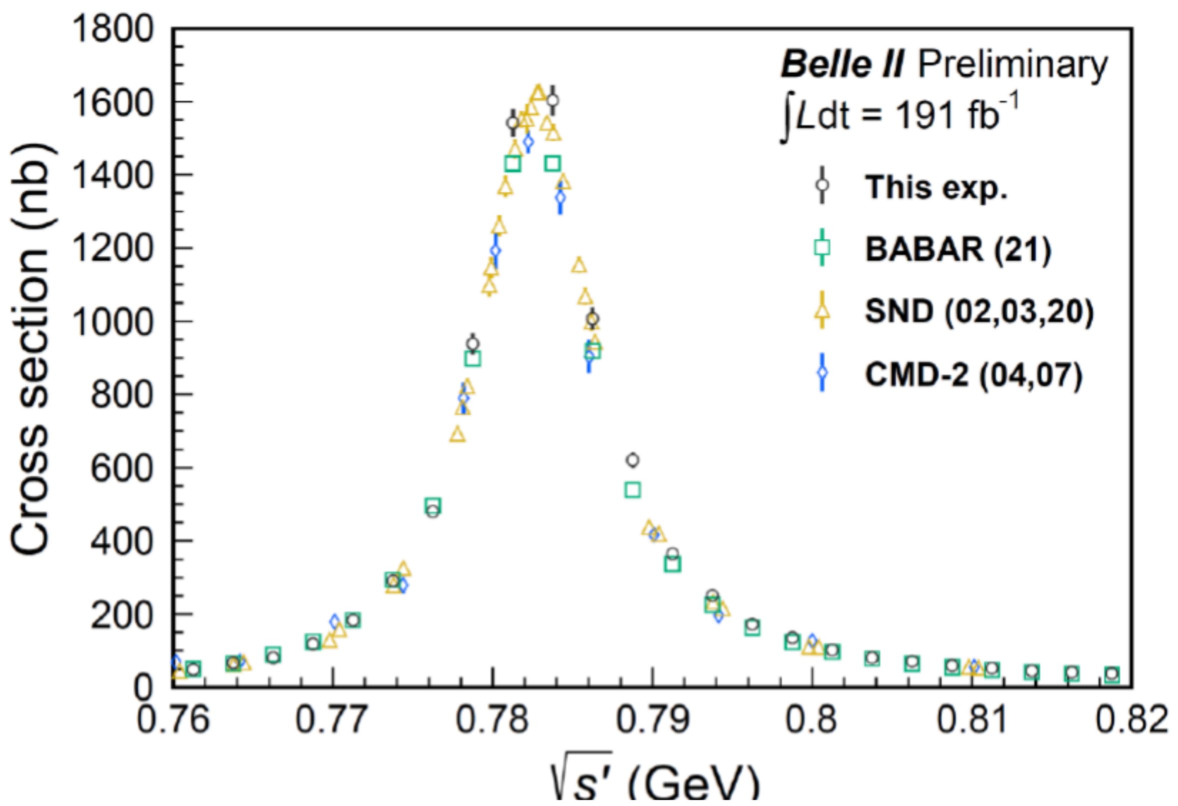
Hadronic system energ

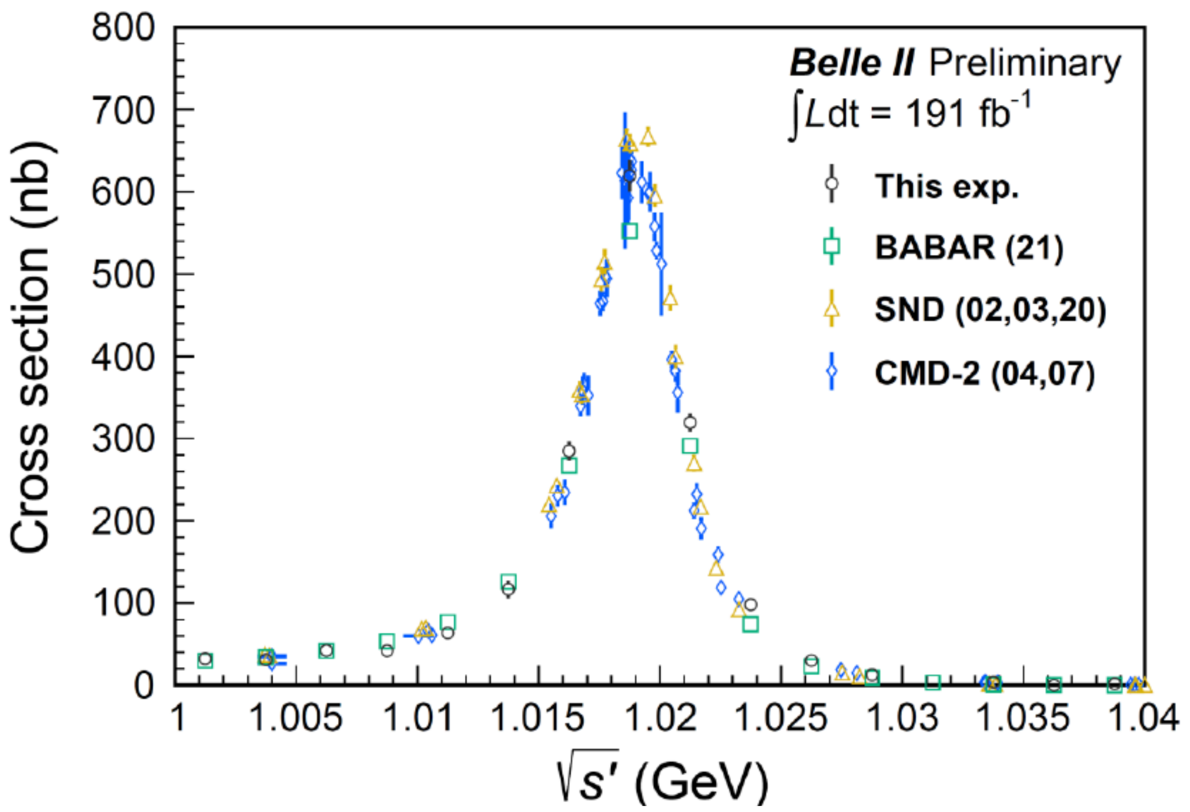
$\sqrt{s'} = 0.4$-3.5 GeV

$s' = s - 2\sqrt{s}E_{\mathrm{ISR}}$



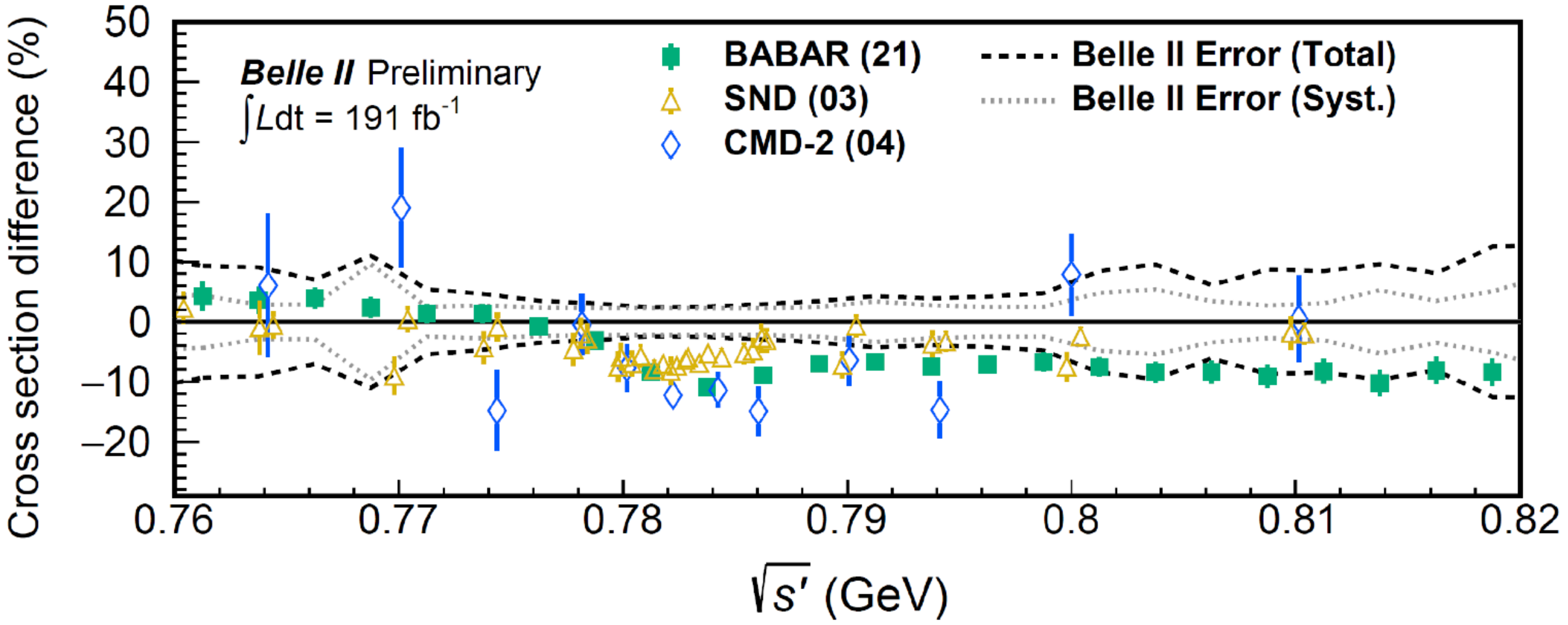






$$a_\mu^{\mathrm{LO,HVP},3\pi}(0.62\text{-}1.8\ \mathrm{GeV}) = \left(48.91 \pm 0.25_{\mathrm{stat}} \pm 1.07_{\mathrm{syst}}\right) \times 10^{-10}$$

	$a_\mu(3\pi)\times10^{10}$	Difference$\times10^{10}$
BABAR alone [PRD104 11 (2021)]	45.86 ± 0.14 ± 0.58	3.2±1.3 (6.9%)
Global fit [JHEP08 208 (2023)]	45.91 ± 0.37 ± 0.38	3.0±1.2 (6.5%)



- Next: $e^+e^- \rightarrow \pi^+\pi^-$ w/ target precision: 0.5% of $a_\mu(2\pi)$

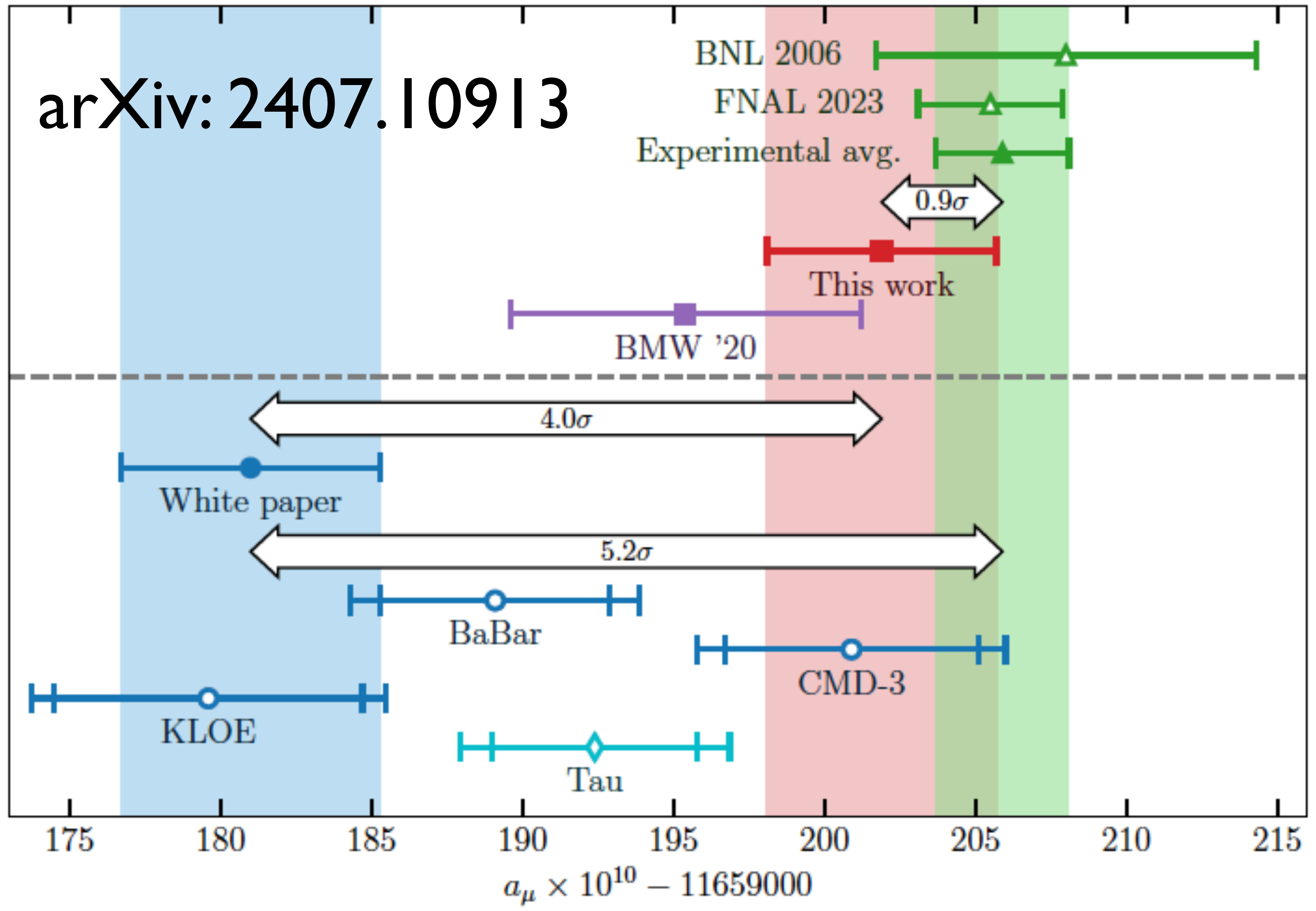
Belle II has joined this important community-wide activity

Stay Tuned!

New Result by BMW (+ e^+e^- data)

Zoltan Fodor

- 40% Reduction of uncertainties w.r.t. BMW20 by
  - Finer lattices → more accurate continuum extrapolation
- Also include a small, long-distance contribution obtained using input from e^+e^- data where they all agree
- Difference from measurement of a_μ by only 0.9σ.



arXiv: 2407.10913

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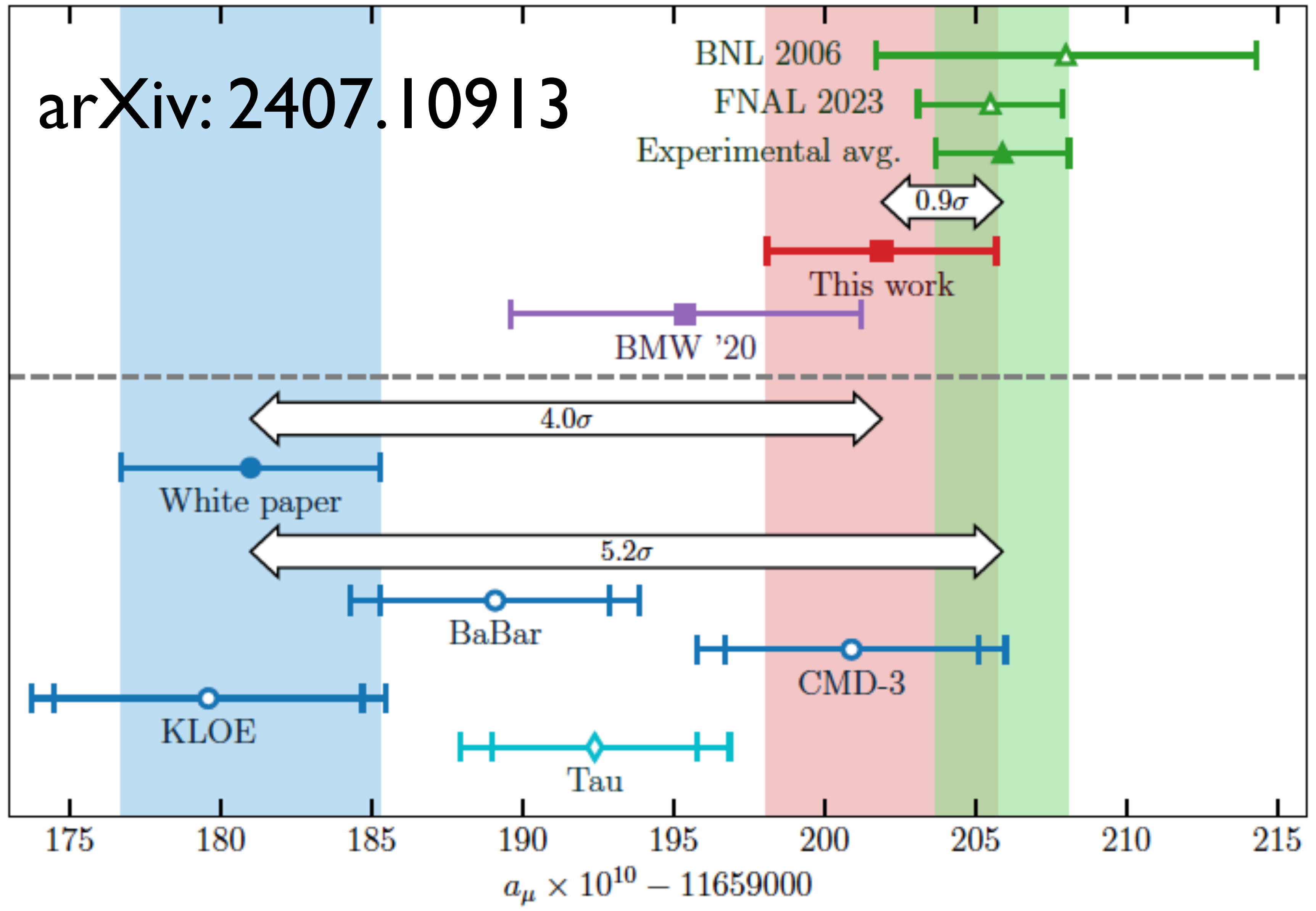


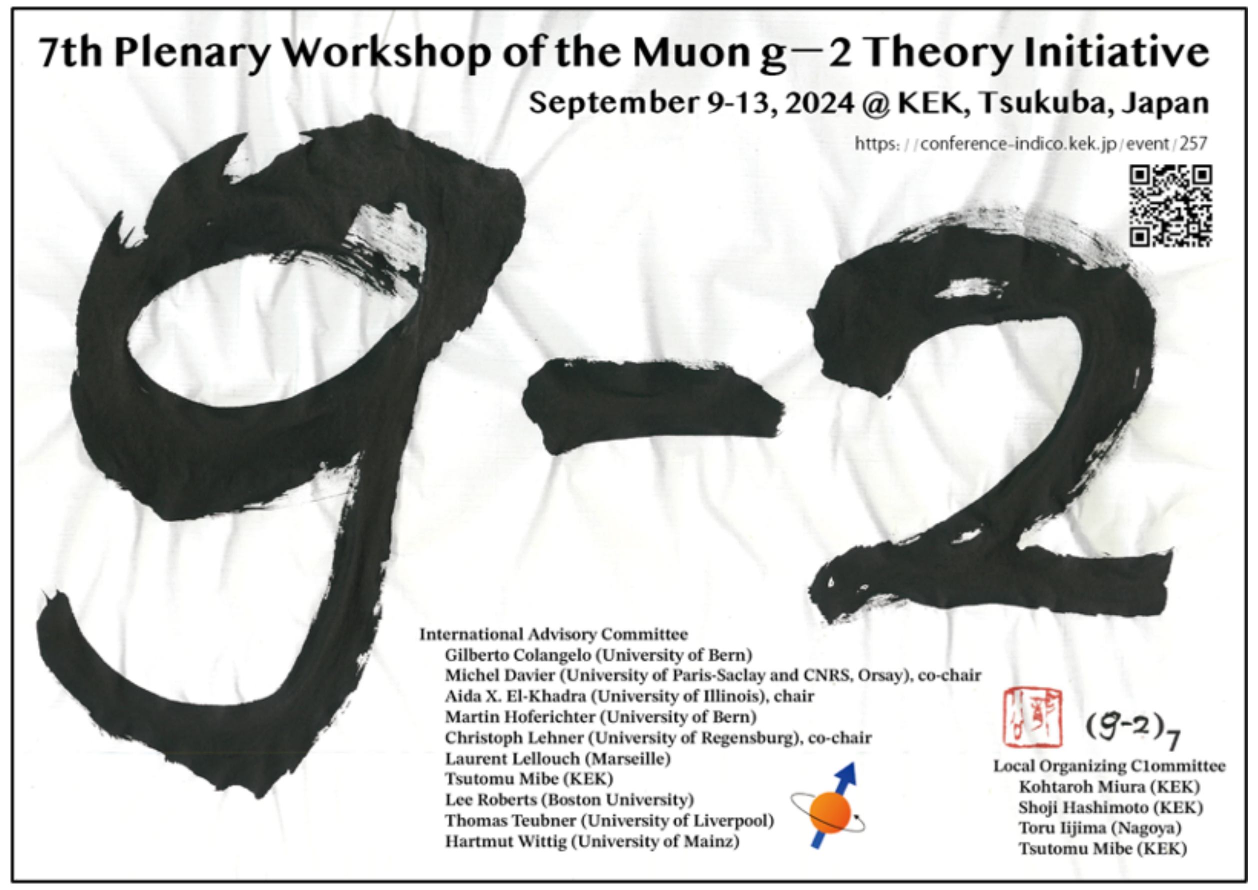
Need more studies & discussions

- Other lattice results ?
- Difference between e+e- experiments (+ tau data) ?
- MC generators ?
- HLbL ?
- MUonE ?

7th Plenary Workshop of the muon g-2 Theory Initiative
September 9-13, 2024 at KEK

https://conference-indico.kek.jp/event/257

Registration deadline extended to July 31.



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International Advisory Committee
Gilberto Colangelo (University of Bern)
Michel Davier (University of Paris-Saclay and CNRS, Orsay), co-chair
Aida X. El-Khadra (University of Illinois), chair
Martin Hoferichter (University of Bern)
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Hartmut Wittig (University of Mainz)

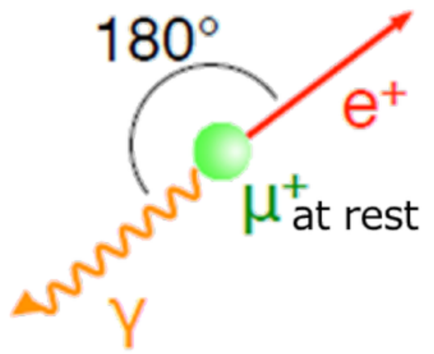
Local Organizing C1ommittee
Kohtaroh Miura (KEK)
Shoji Hashimoto (KEK)
Toru Iijima (Nagoya)
Tsutomu Mibe (KEK)

CLFV in Muon Decays

μ+ → e+ γ

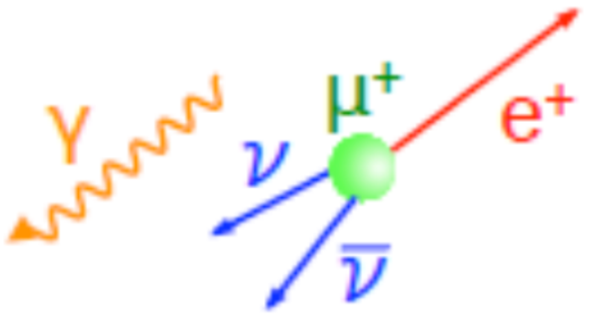
Signals

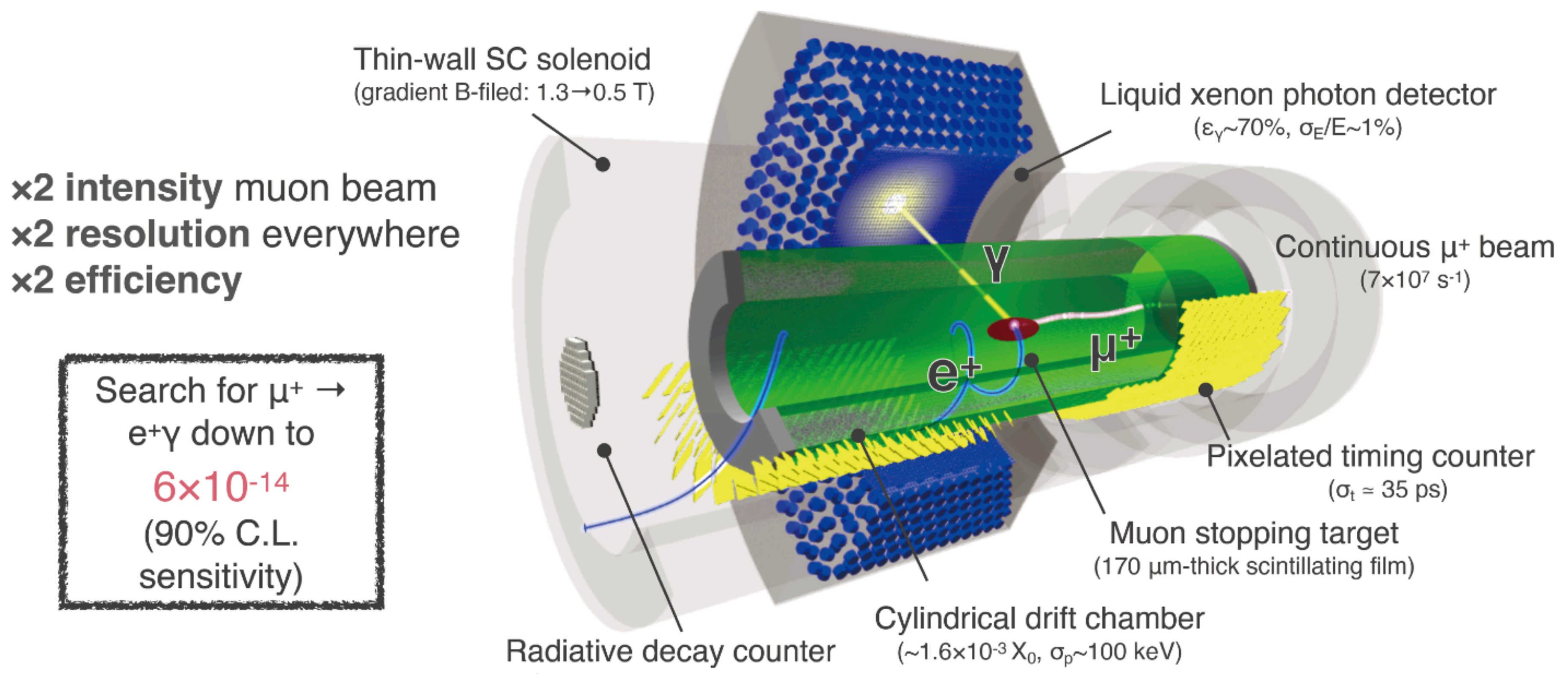
- Mono-energetic $m_e = m_\gamma = m_\mu/2 = 52.8 MeV$
- Angle $\theta_{e\gamma} = 180^\circ$
- Time coincidence $\Delta t_{e\gamma}$



Backgrounds

- physics background $\mu^+ \to e^+ \nu \bar{\nu} \gamma$
- accidental background $\mu^+ \to e^+ \nu \bar{\nu}, \;\; + \gamma$





EPJ-C **78** (2018) 380

MEG(2009-2013) set UL<4.2×10^{-13} (90%CL)

MEGII sensitivity: 6×10^{-14}

Alessandro Bravar

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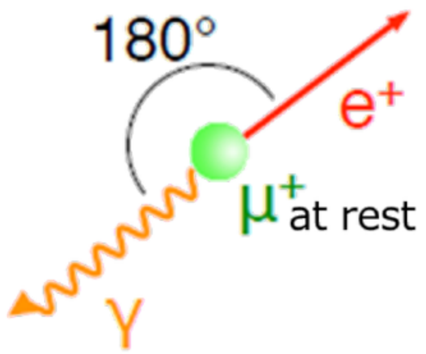

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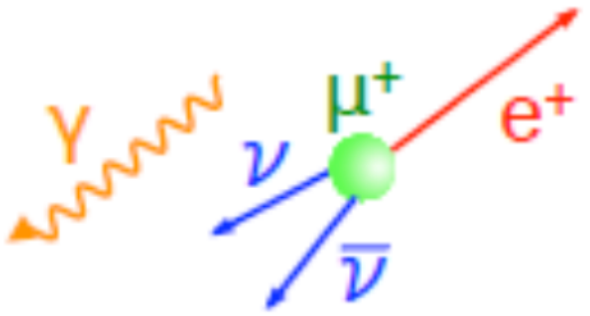

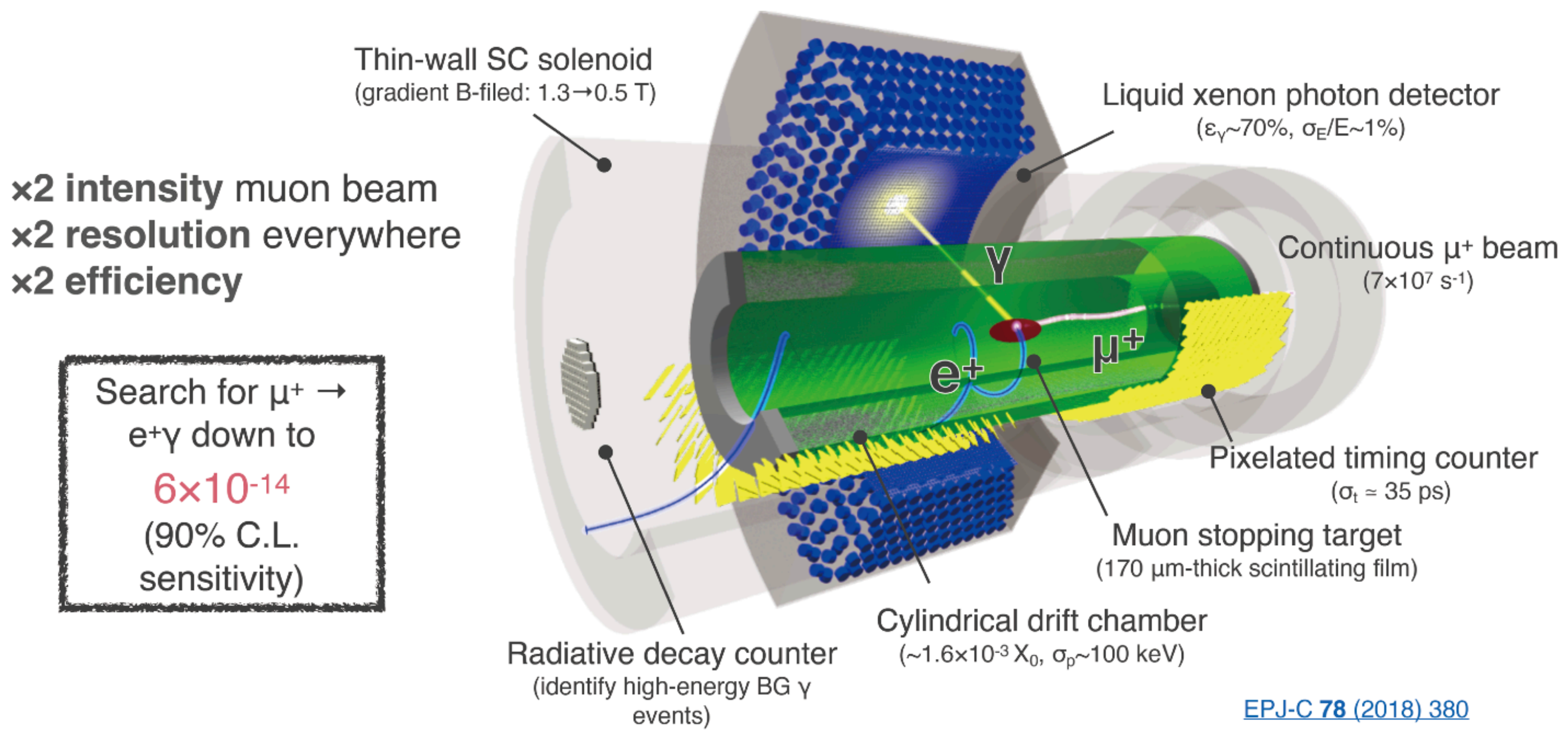

×2 intensity muon beam
×2 resolution everywhere
×2 efficiency

Search for $\mu^+ \to e^+\gamma$ down to 6×10^{-14} (90% C.L. sensitivity)

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MEGII sensitivity: 6×10^{-14}

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

Signals

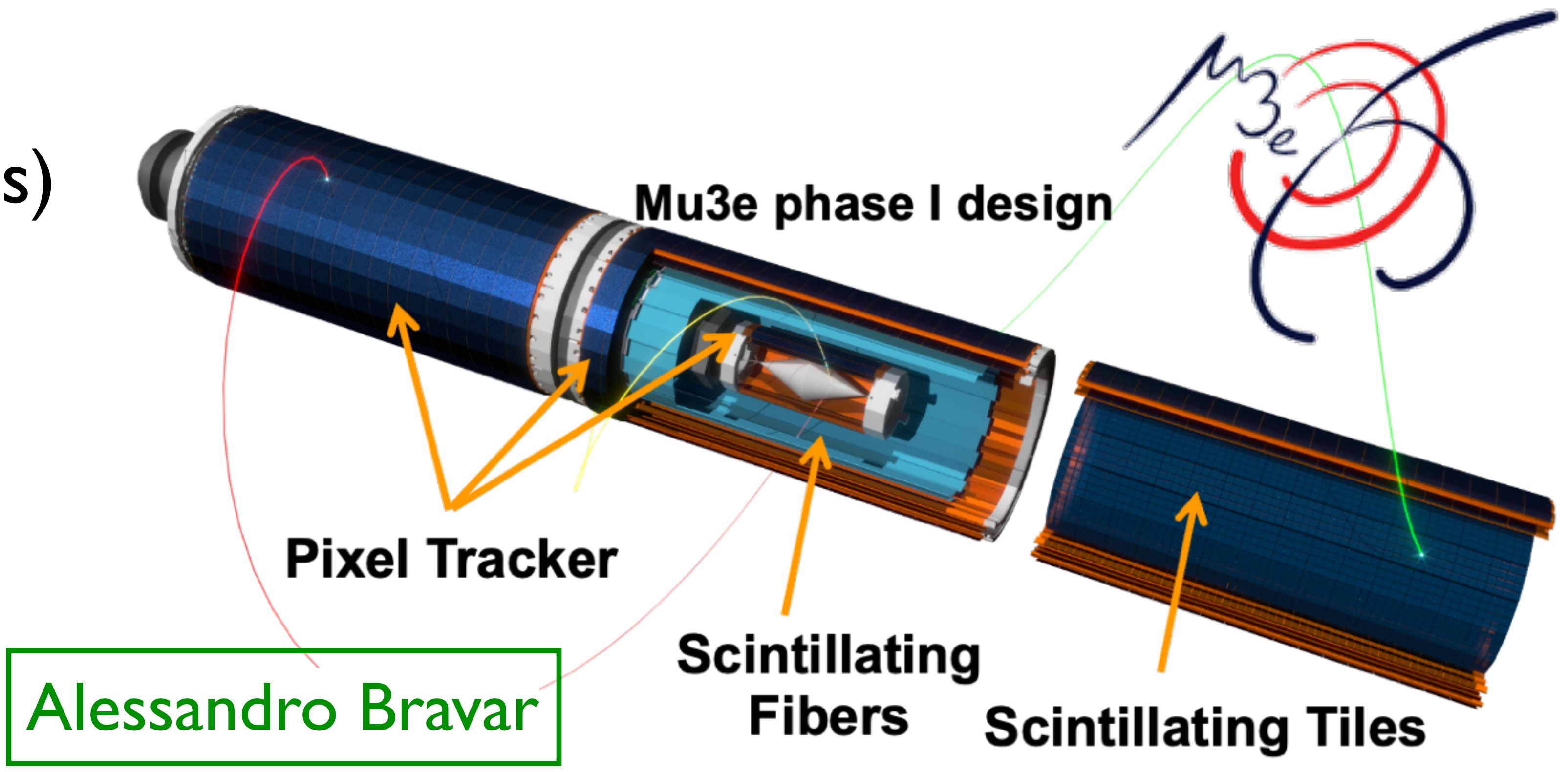
- 3-body kiematics

Backgrounds

- Accidental coincidences of tracks from Michel decays + Bhabha scattering
- Radiative decays with internal conversion: $\mu^+ \to e^+ \nu \bar{\nu}\, \gamma (\to e^+ e^-)$

- High rate capability (>10^9 muon/s)
- Good resolution
  - Vertex < 200 μ m
  - Time < 100 ps
  - Momentum < 0.5 MeV/c

→ extremely low material budget



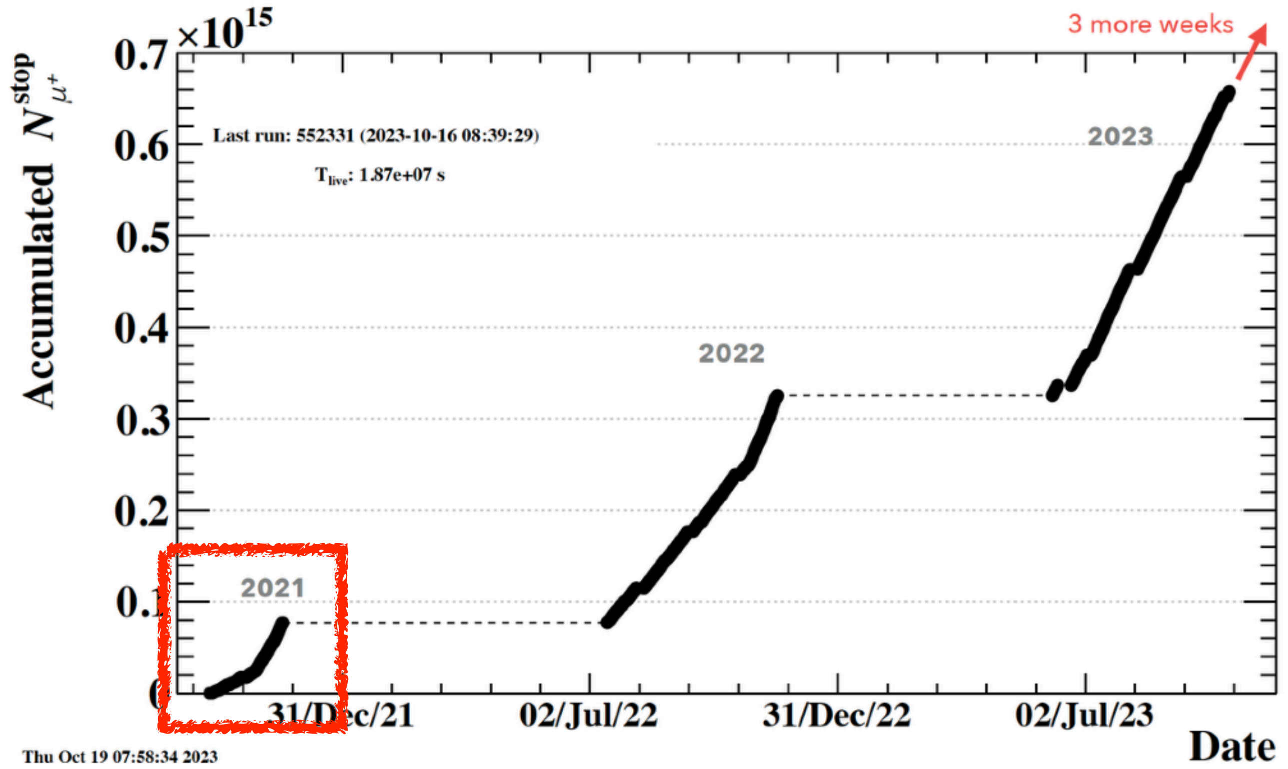
Alessandro Bravar

Current limit <10^{-12} (SINDRUM 1986)
Mu3e sensitivity < 5×10^{-15} (phaseI at PiE5) → 10^{-16} (phase II at HiMB)

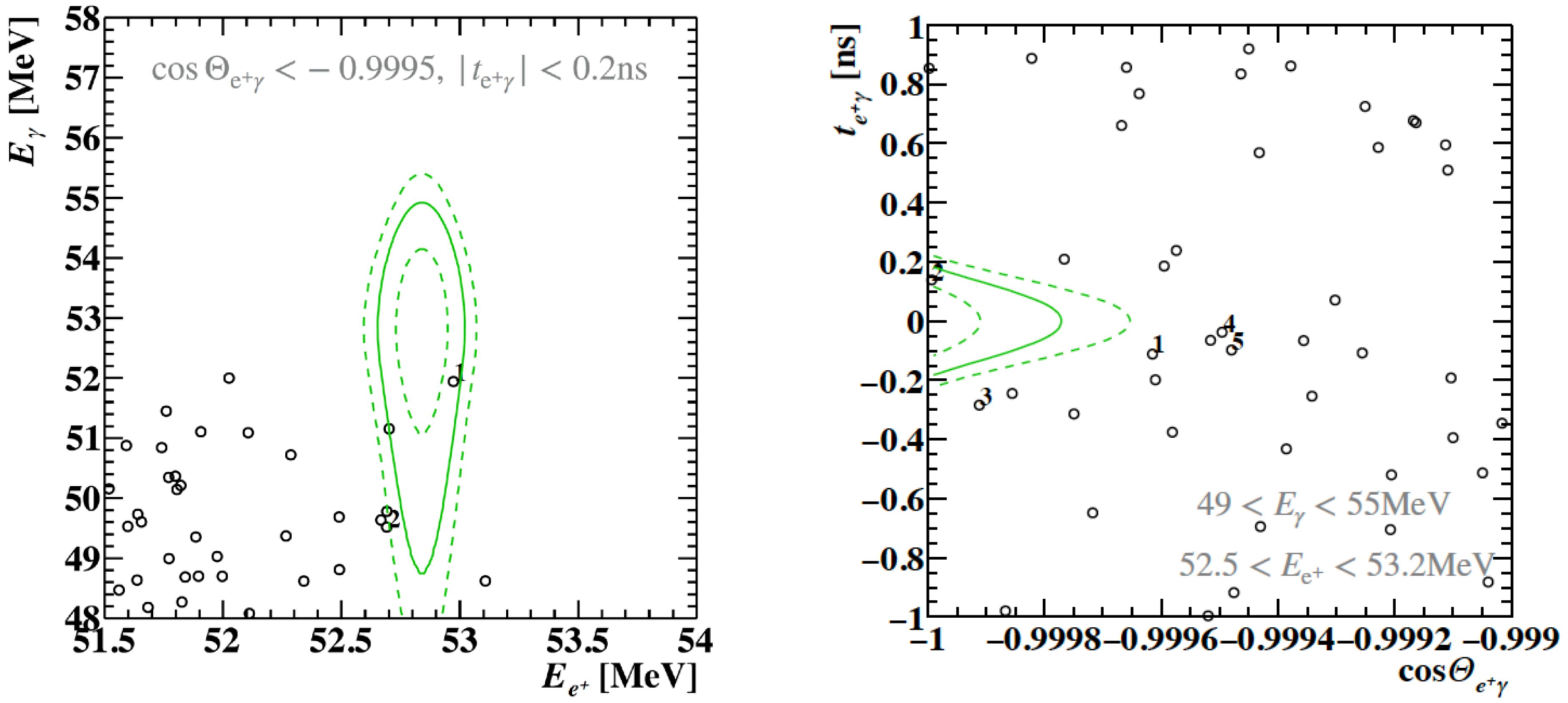
DC beam at PSI has advantage to suppress accidental backgrounds in these searches

MEG II First Results & Outlook

MEG II is running since 2021



7 weeks of physics run in 2021
= almost equivalent to MEG data



Euro. Phys. J.C(2024)84:216

No excess of events over the expected background observed.

Upper limit (90%C.L): $\mathcal{B}(\mu^+ \to e^+\gamma) < 7.5 \times 10^{-13}$

Combined (MEG II 2021 + MEG): $\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13} (90\%\text{C.L.})$

The most stringent limit to date.

MEG II First Results & Outlook

Wataru Ootani

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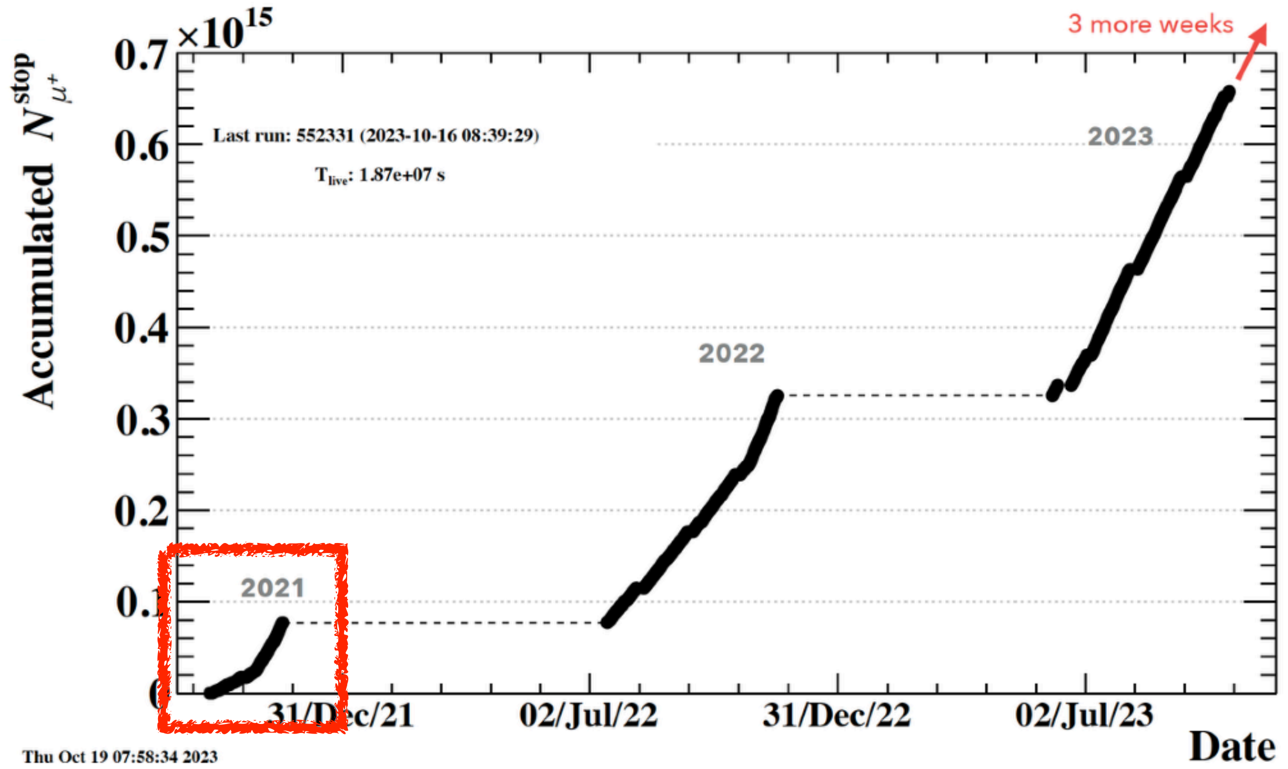

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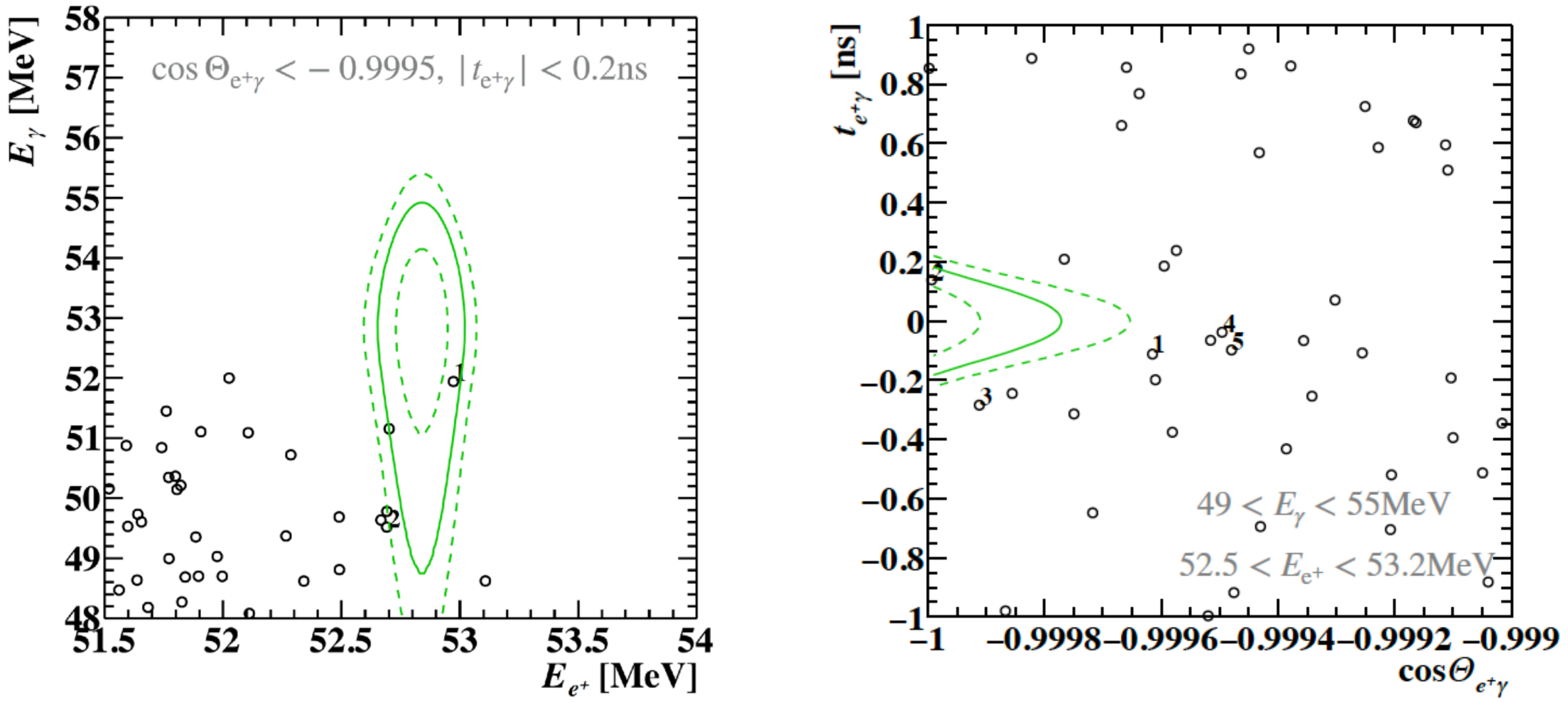
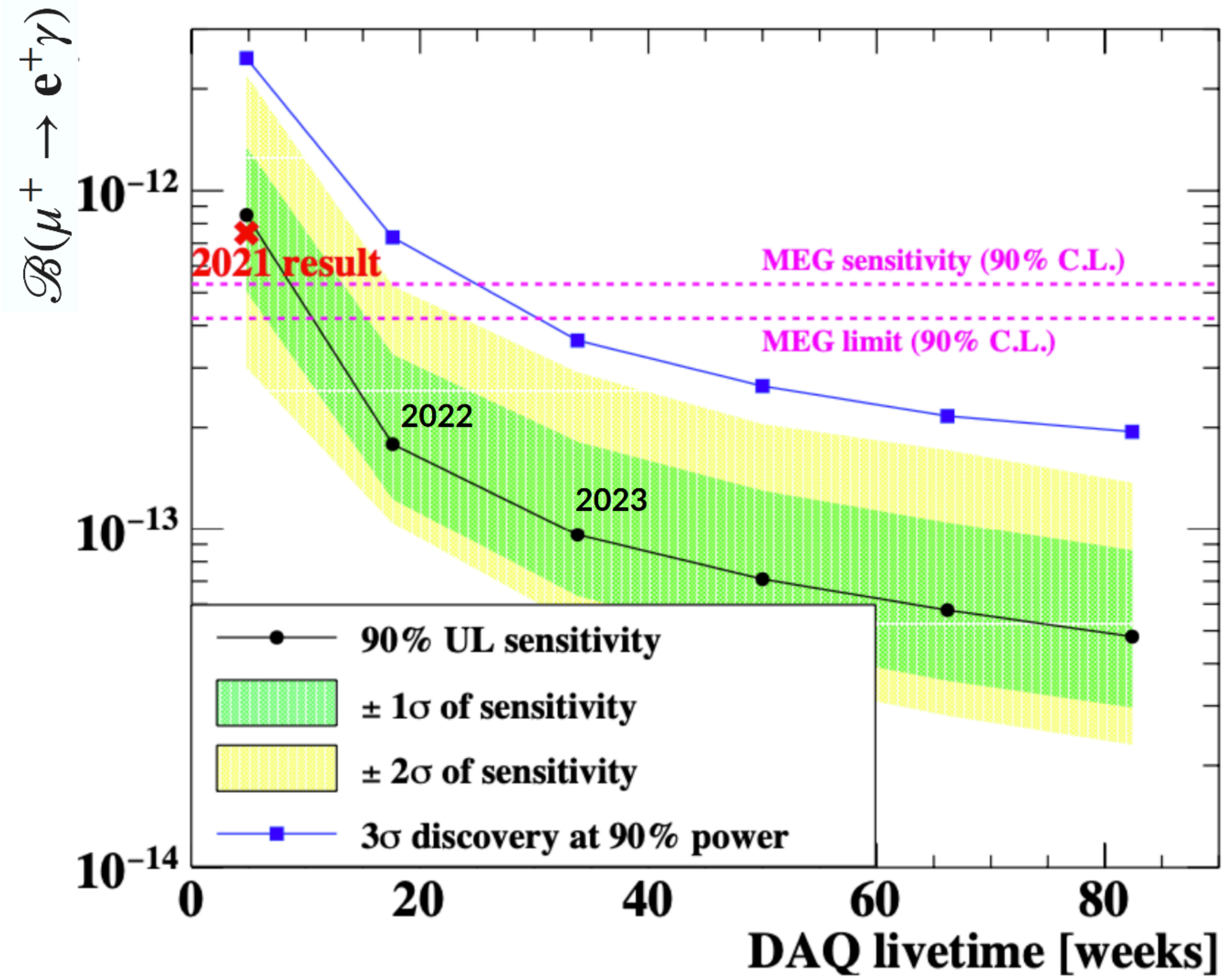


Euro. Phys. J.C(2024)84:216

- Latest release (2021 data) is just 10% of data taken by 2023.
- Next release (2022 data) is coming soon.
- MEG II will continue data-taking till PSI accelerator shutdown in 2027
  - Expected goal: 6×10^{-14}
  - PSI schedules a long shut-down in 2027-2028 to upgrade the beam line to provide x100 muon intensity: HiMB.



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Status of μ-N→e-N Conversion

Hajime Nishiguchi

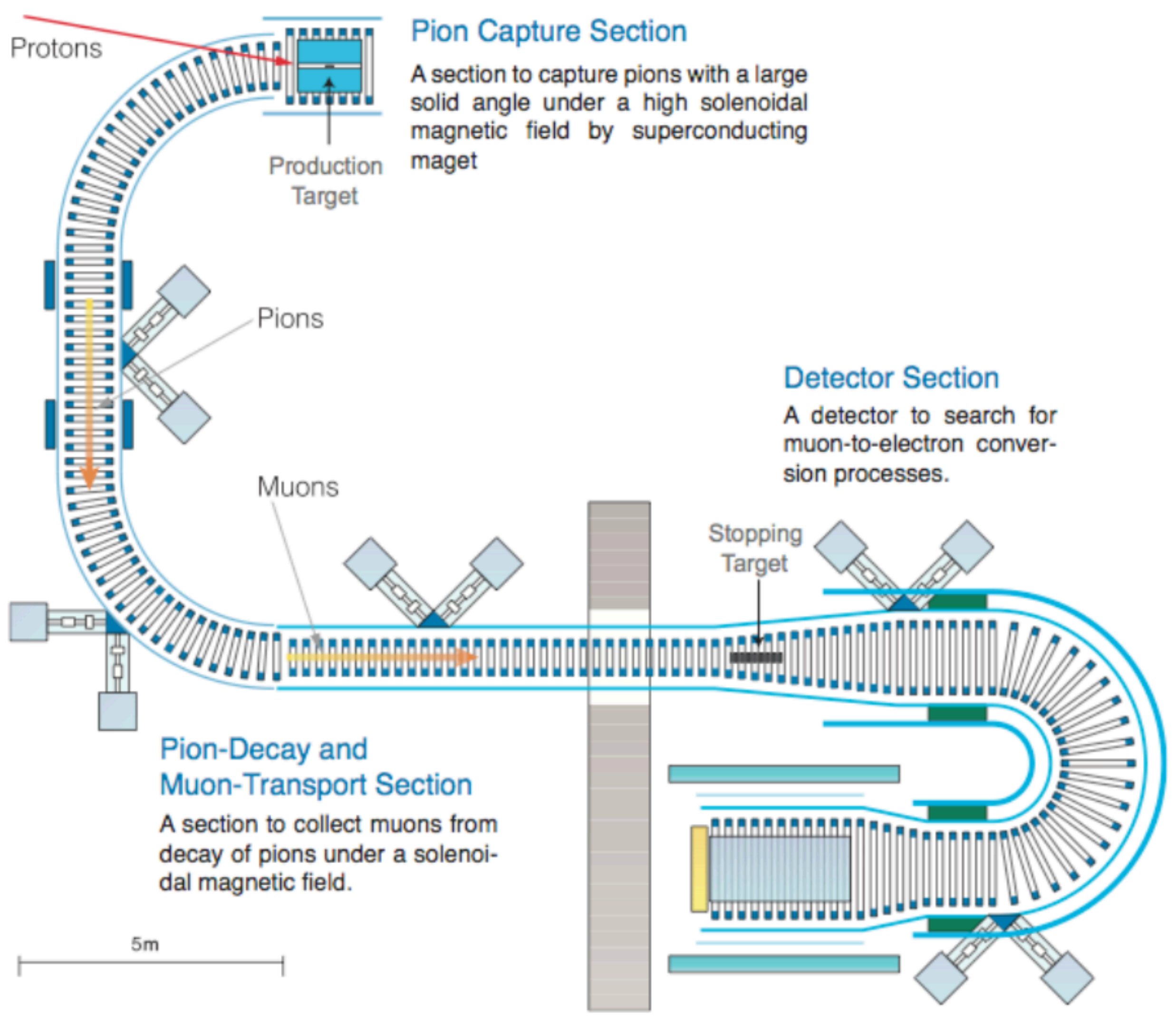
COMET at J-PARC

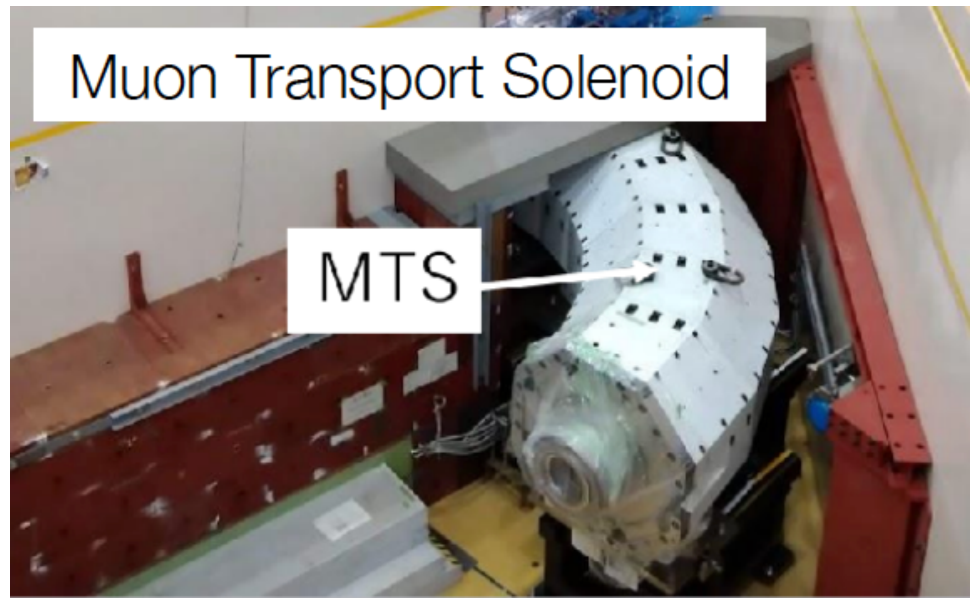
Phase-I

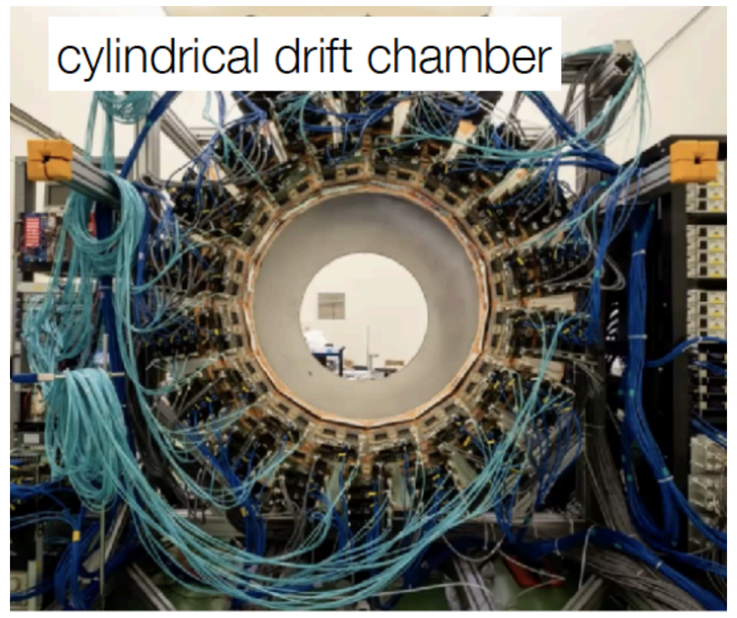
- Construct up to 90° bend and place detector.
- Engineering run in 2025/2026
- Intermediate sensitivity: O(10^{-15})

Phase-II (>2030)

- Complete all transport.
- Full sensitivity: O(10^{-17})







DeeMe at J-PARC MLF

- S.E.S ~ 10^{-13} (carbon, 1 year)
- μ- produced and stopped in C target
- Detector commissioning started
- Start physics run after fixing the fake track issue

Mu2e at Fermilab

Run I

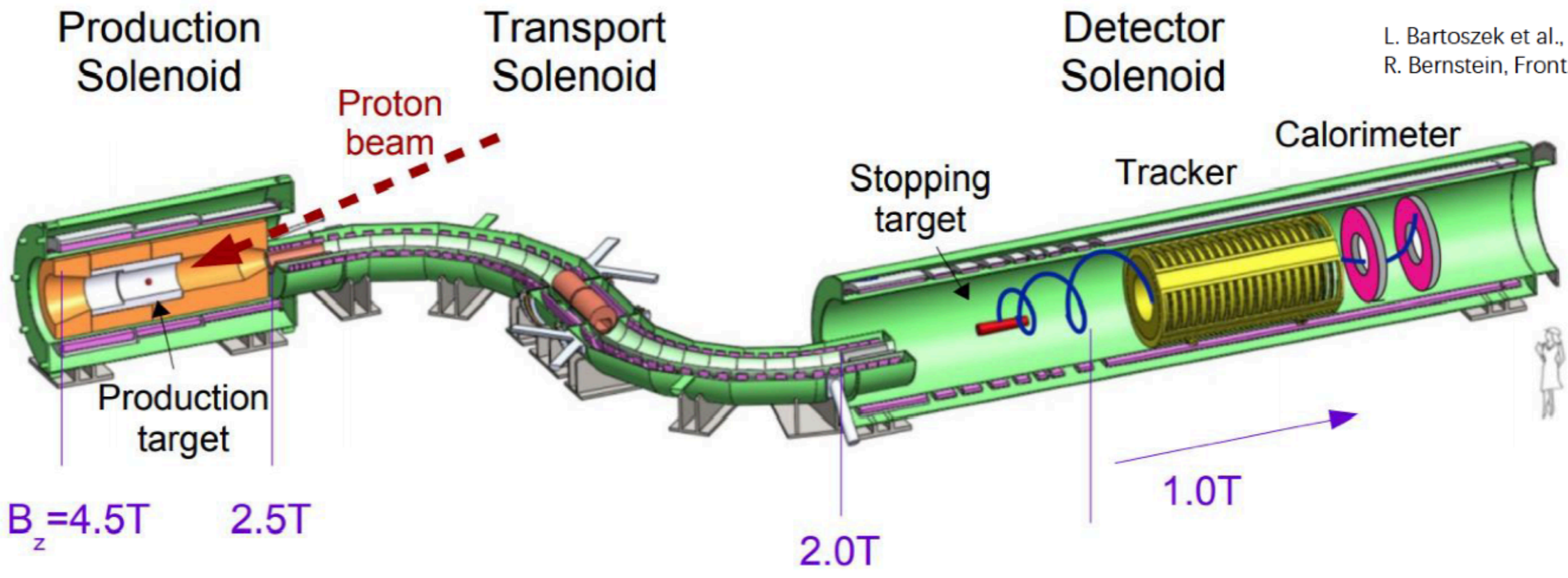
- expect to start in 2027 and continue the beginning of PIP-II/LBNF long shutdown
- ~10^{3} improvement over SINDRUM-II

Run II

- Full data set by mid-2030s

→ < 8×10^{-17} @ 90%CL

Sphie Charlotte Middleton
Sridhar Tripathy
Fabio Happacher



A schematic view of the Mu2e experiment (not including the Cosmic Ray Veto)

L. Bartoszek et al., arXic:15
R. Bernstein, Front. Phyis. 7

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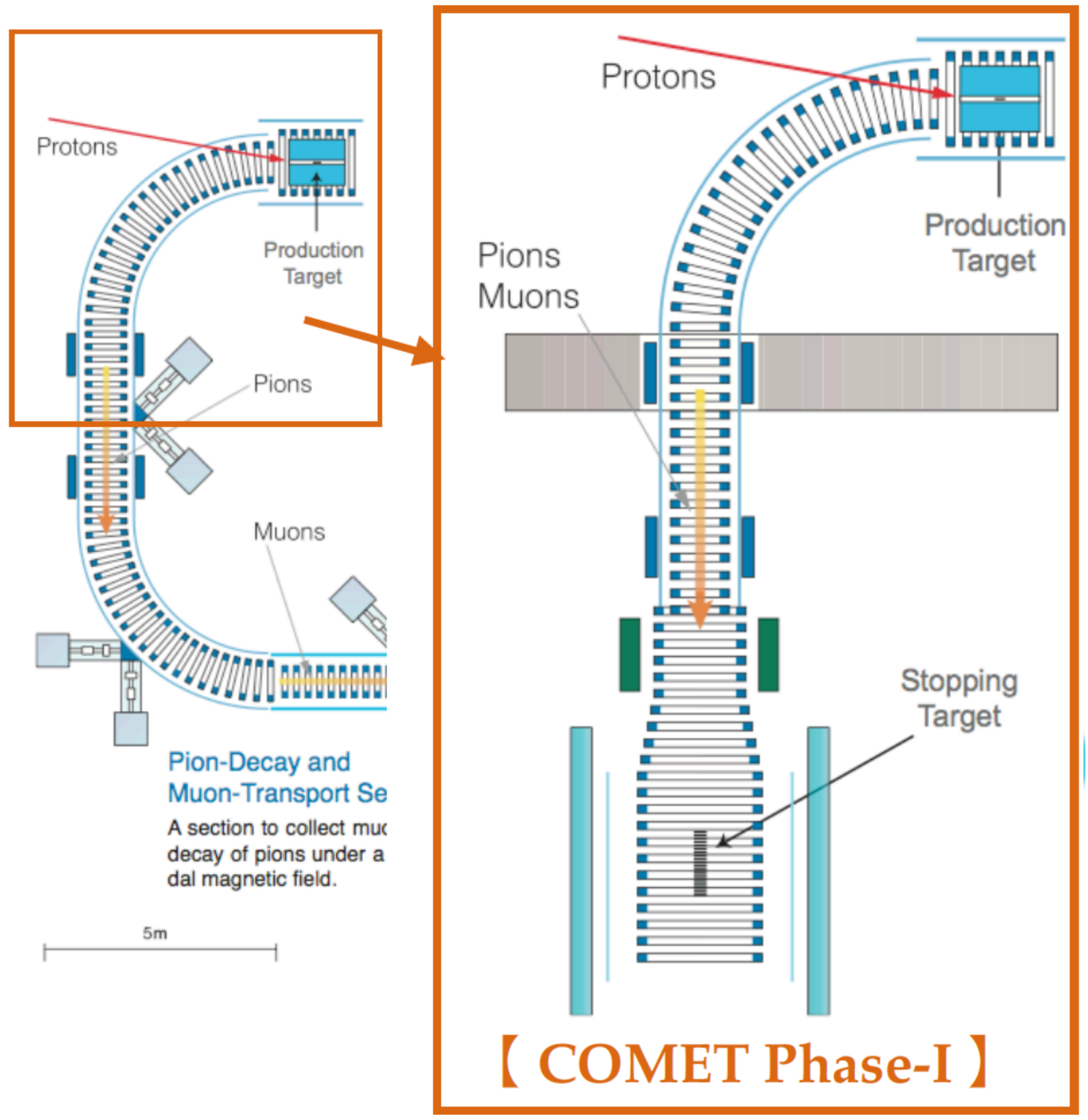
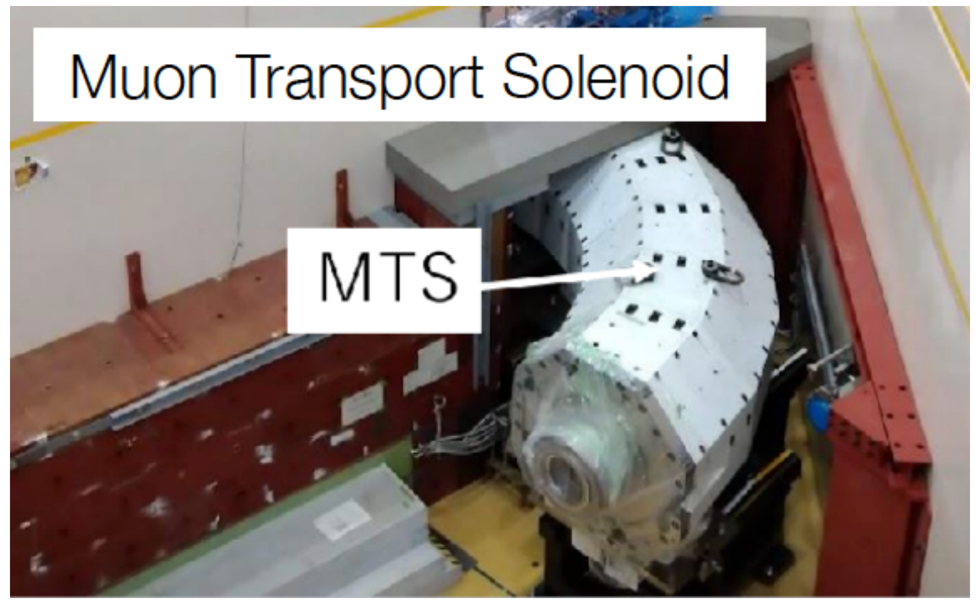
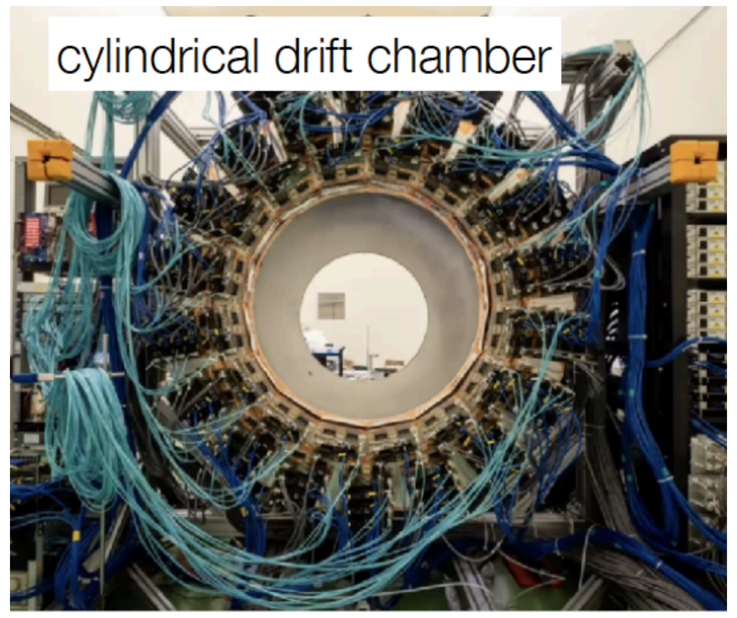




Muon Transport Solenoid

First beam in
COMET Phase-alpha

February 11th, 2023



cylindrical drift chamber

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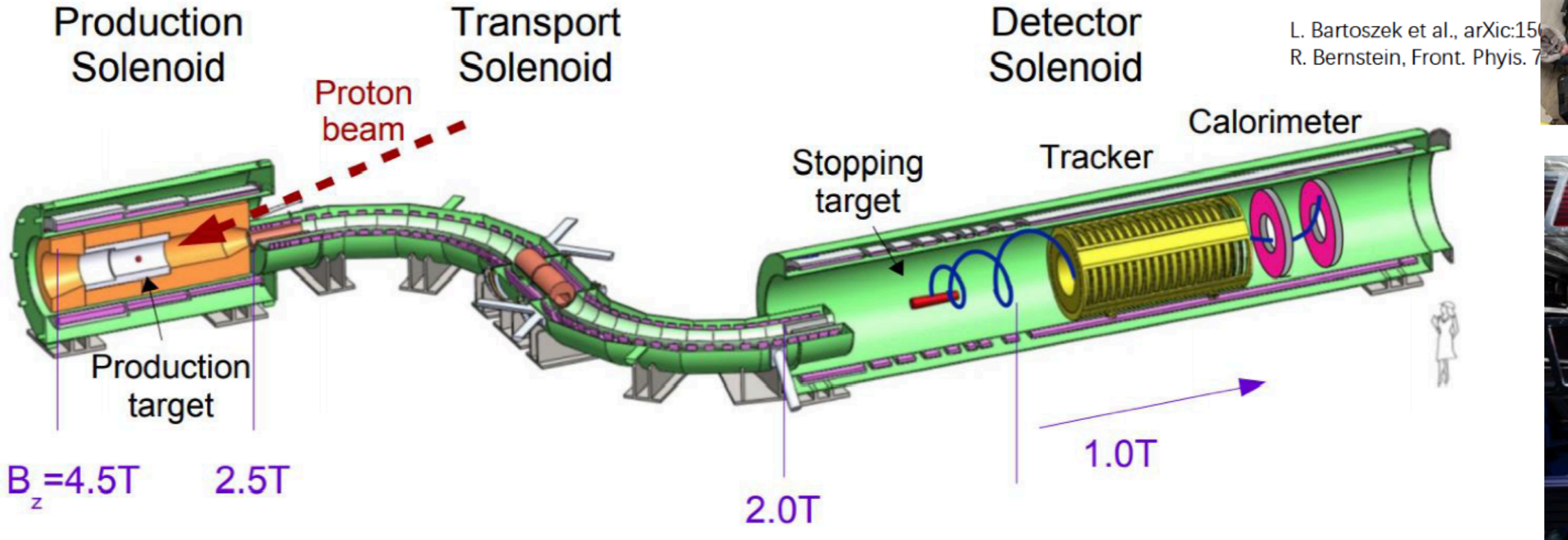

L. Bartoszek et al., arXic:15
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Transport Solenoid

Tracker planes

Calorimeter disks

CRV modules

Tau Physics at Belle II/SuperKEKB

Plans to collect 50 ab^{-1} of e^+e^- collision data at and near Υ(4S);

- 7 GeV e^- (HER) x 4 GeV e^+ (LER)
- “Nano beam scheme”

→ x30 higher luminosity than KEKB

K. Shibata

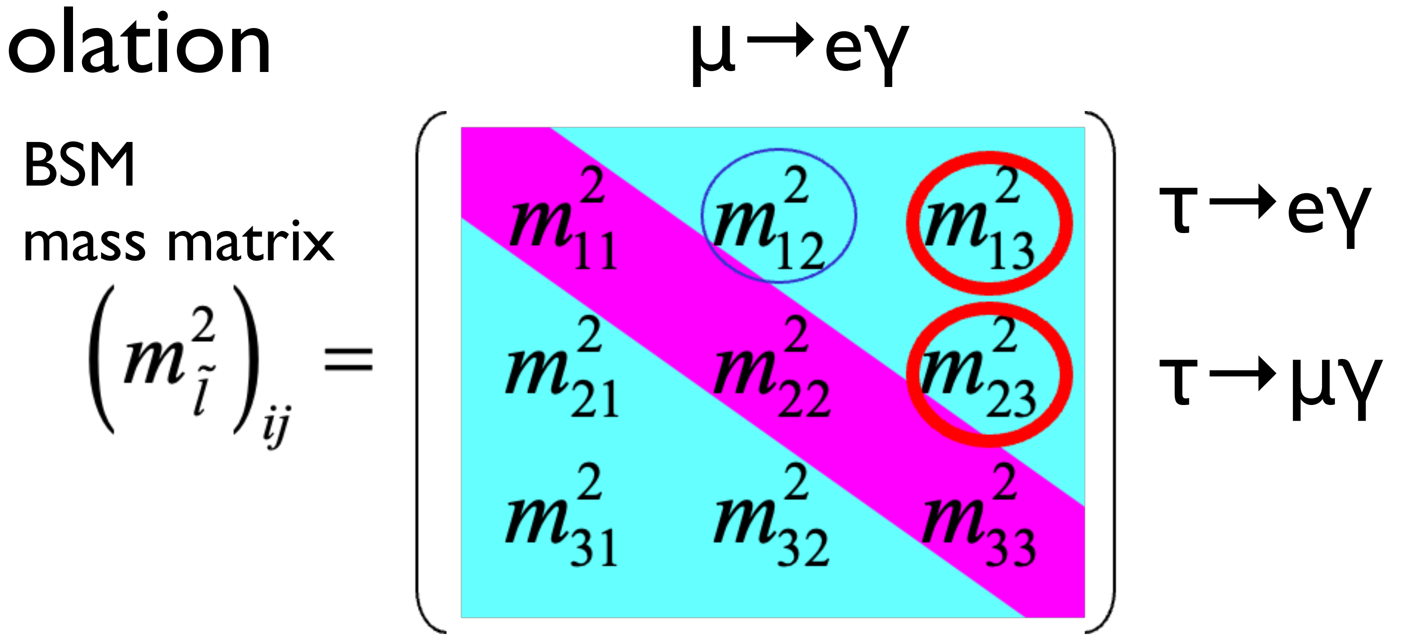
$$\sigma(e^+e^- \to \Upsilon(4S)) = 1.05[\text{nb}]$$
$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92[\text{nb}]$$

Super B factory
= “Super τ factory”

Tau is the heaviest charged lepton

- Sensitive to BSM physics
  - Lepton Flavor Violation

Complementary
to muon cLFV



$$\left(m_{\tilde{l}}^2\right)_{ij} = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

  - CP violation, EDM, Lepton Universality
- Also provide precise SM test

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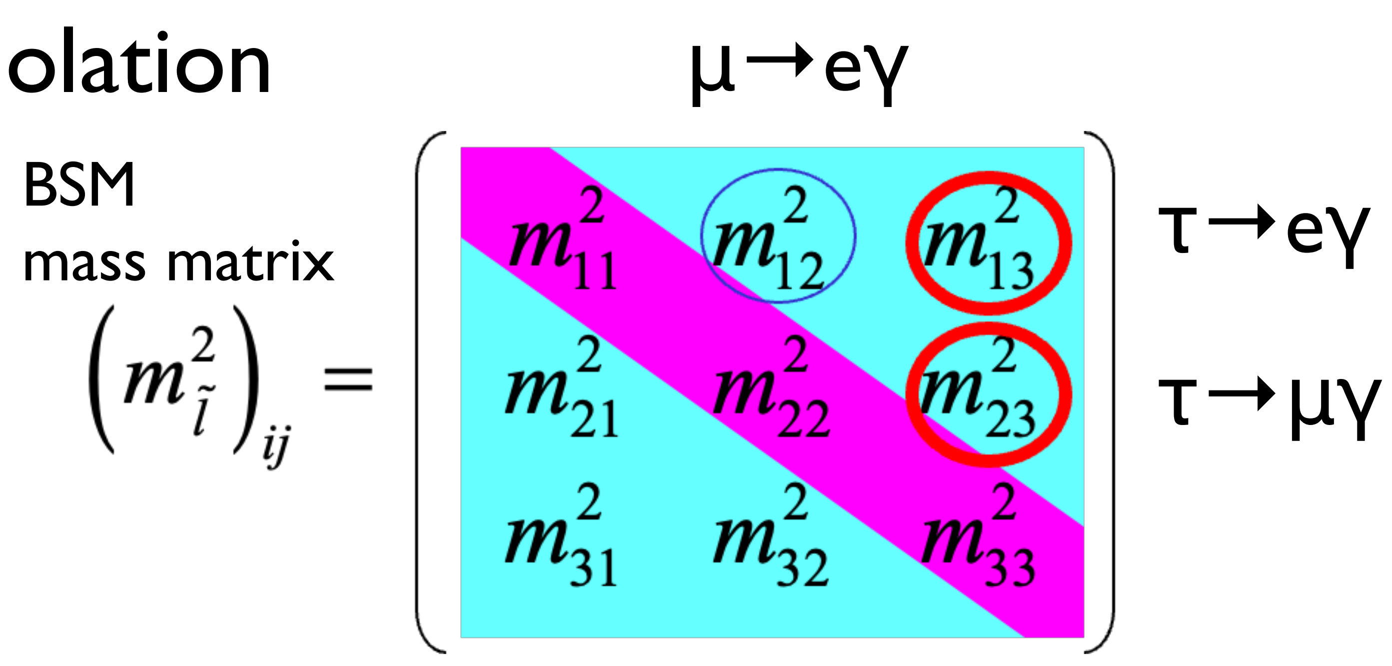


Complementary to muon cLFV

BSM mass matrix

μ→eγ

$$\left(m^2_{\tilde{l}}\right)_{ij} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

τ→eγ

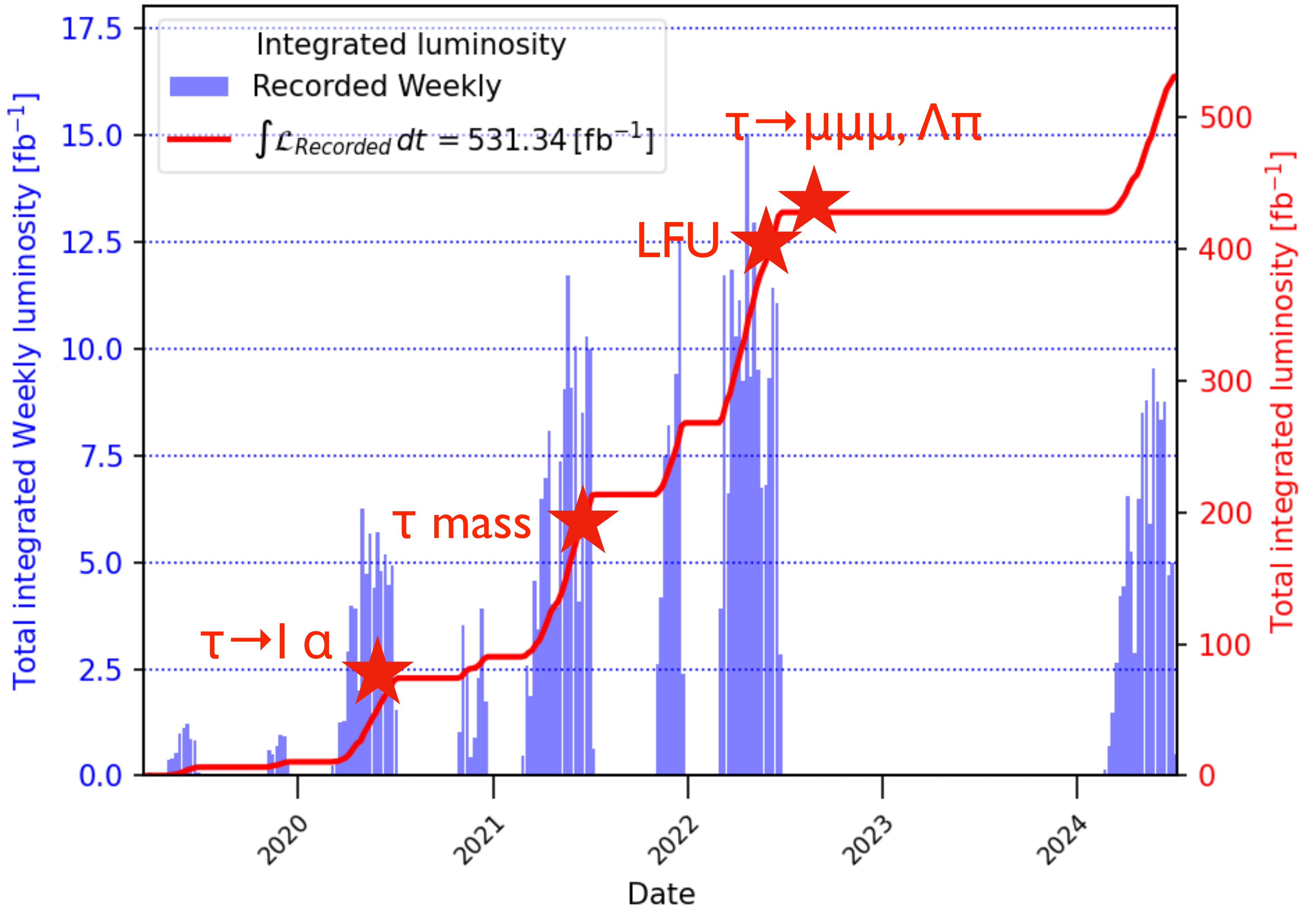
τ→μγ

  - CP violation, EDM, Lepton Universality
- Also provide precise SM test

Technical challenge

- Low-multiplicity trigger in high luminosity environment
- Improved vertex resolution, particle ID, neutral clusters detection, …
- Analysis techniques based on machine learning.

Belle II integrated luminosity by summer 2024



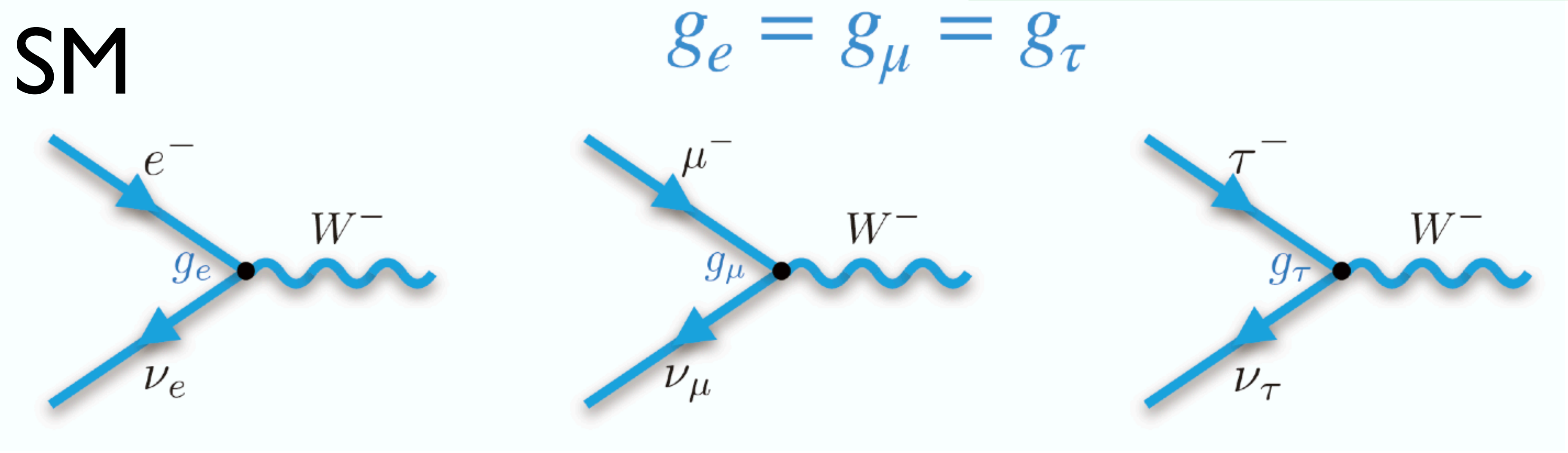
Test of Lepton-Flavor-Universality in τ decays

Gianluca Inguglia

The coupling of leptons to W boson is flavor-independent in SM

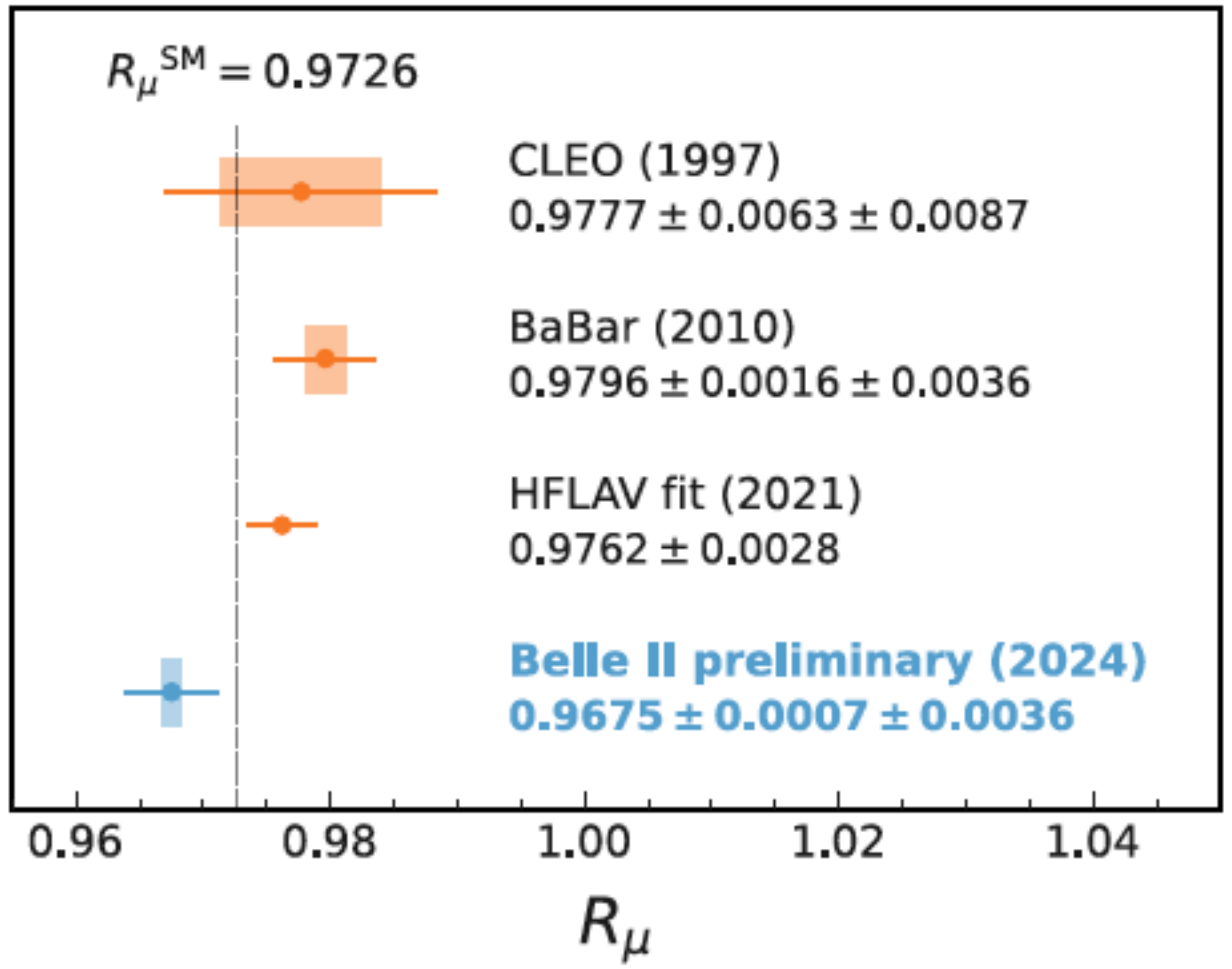
→ Identical lepton interaction rates involving e, μ or τ

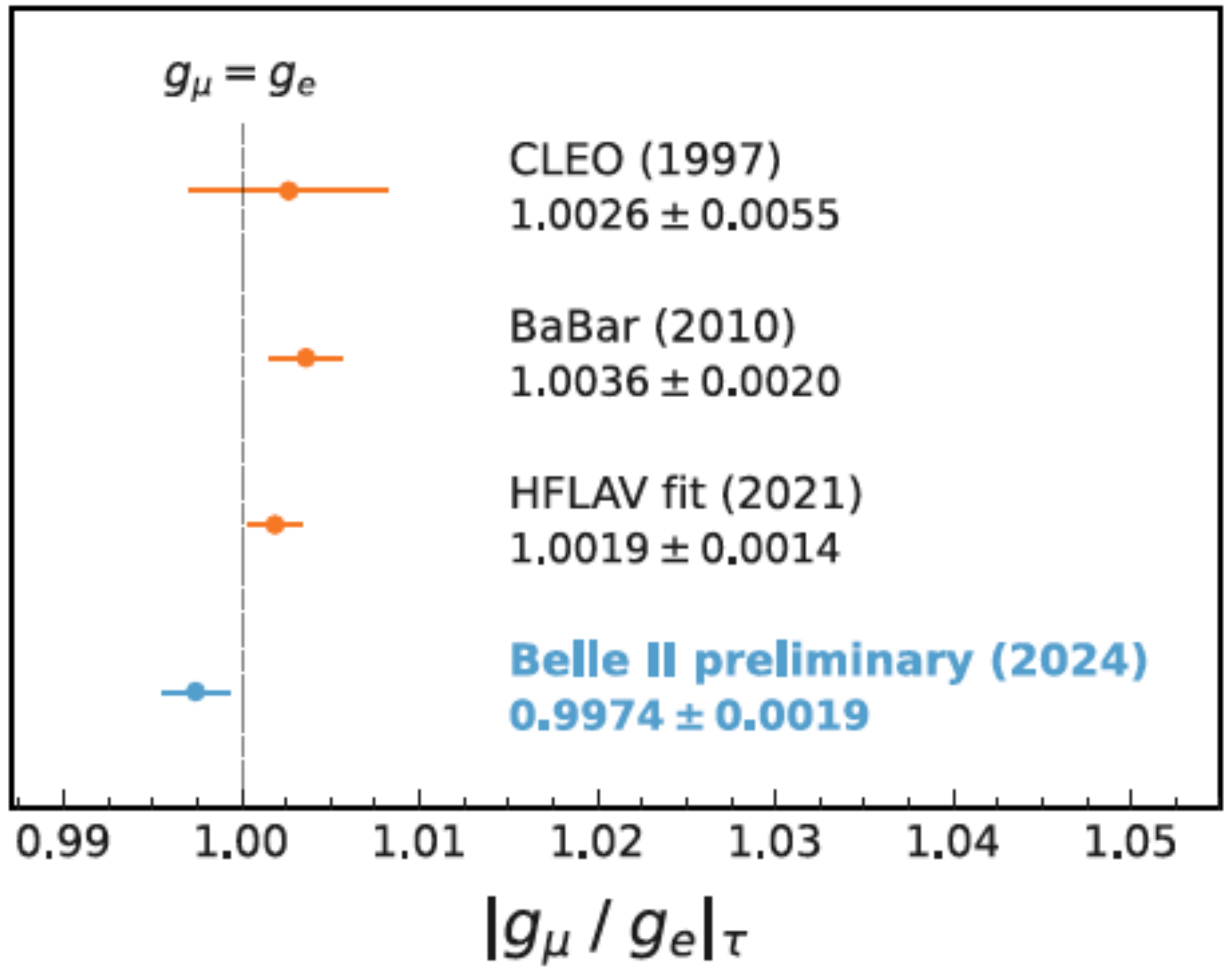
→ Test of μ-e universality in τ decays



$$R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \overset{\text{SM}}{=} 0.9726$$

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\text{SM}}{=} 1$$





arXiv:2405.14625

The most precise test of e-μ universality in τ decays from a single measurement

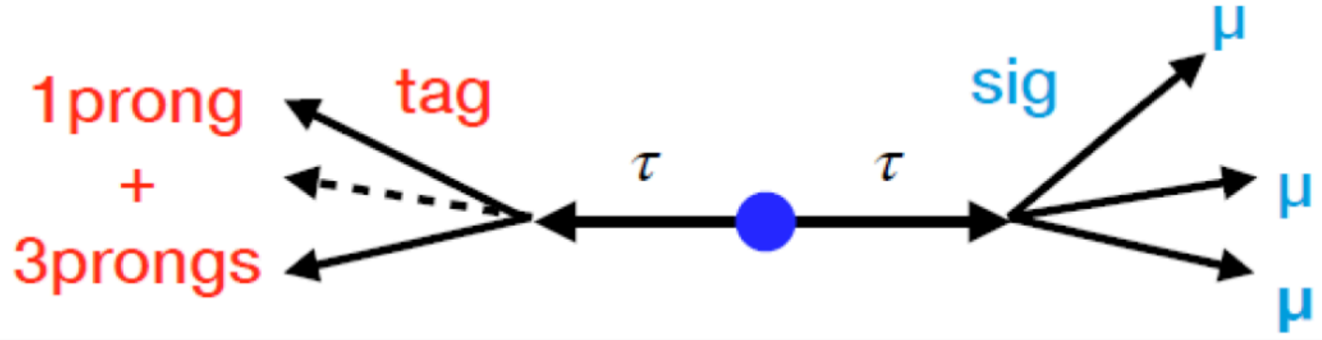
Consistent with the SM prediction at the level of 1.4 σ

Search for $\tau \to \mu\,\mu\,\mu$

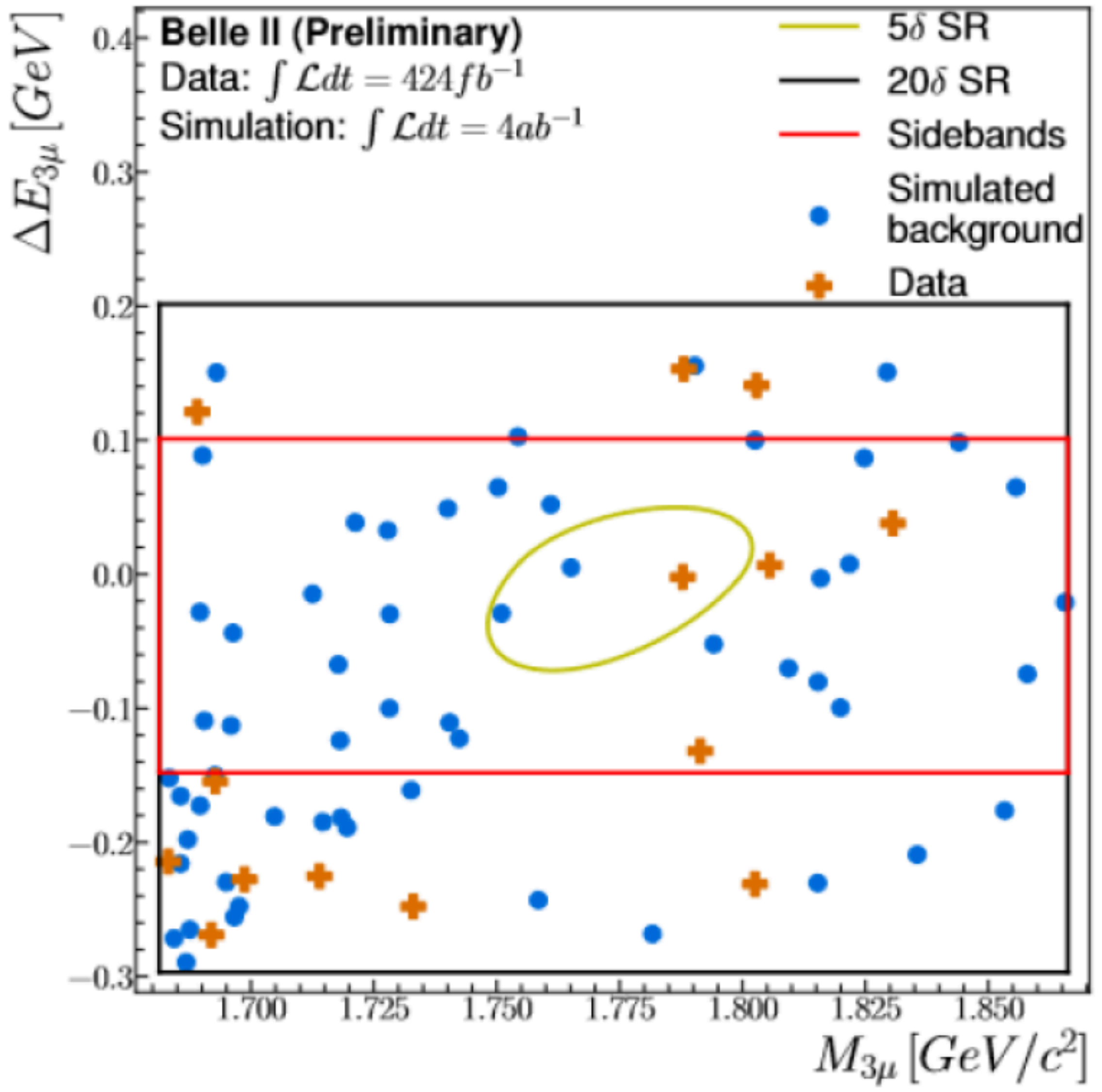
Wenzhe Li

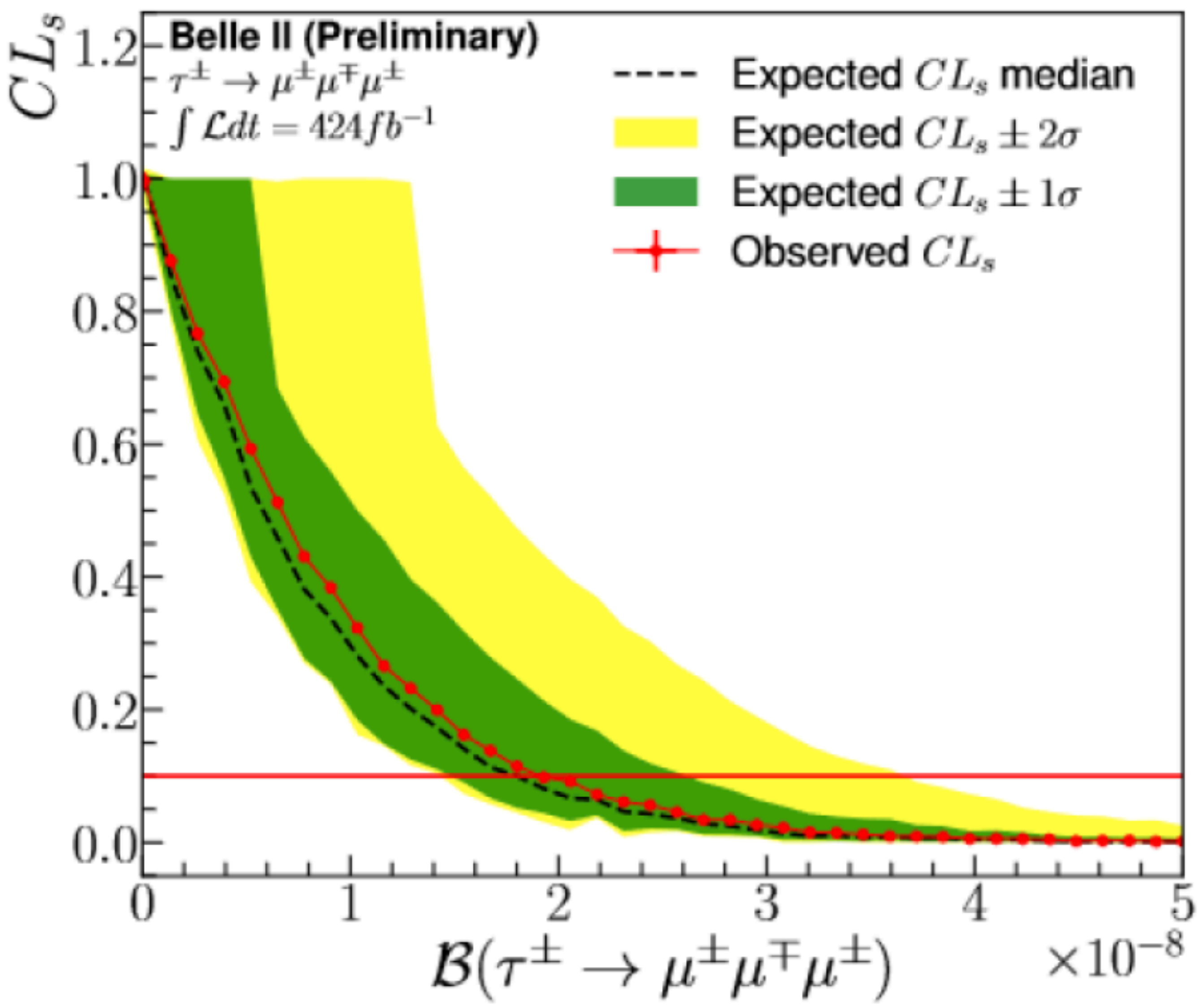
arXiv:2405.07386

- Previous results from Belle: 2.1×10^{-8} at 90% CL with 782 fb^{-1}
- Tag side: 1-track τ decays
- Belle II analysis explores
  - Inclusion of 1 x 3 and 3 x 3 topologies
  - Selection and background rejection using BDT



- Signal: efficiency: 20.4% (2.7 × Belle efficiency);
- Number of expected BG: 0.5;
- 1 event observed inside the SR;
- $\mathcal{B}(\tau \to 3\mu) < 1.9 \times 10^{-8}$ at 90% C.L.;





	UL at 90% C.L. on $\mathcal{B}(\tau \to 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L} = 20.3\ \mathrm{fb}^{-1}$)
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0\ \mathrm{fb}^{-1}$)
CMS	2.9×10^{-8} ($\mathcal{L} = 131\ \mathrm{fb}^{-1}$)
Belle	2.1×10^{-8} ($\mathcal{L} = 782\ \mathrm{fb}^{-1}$)
BaBar	3.3×10^{-8} ($\mathcal{L} = 486\ \mathrm{fb}^{-1}$)
Belle II	1.9×10^{-8} ($\mathcal{L} = 424\ \mathrm{fb}^{-1}$)

Chiara Rovelli

Recent result by CMS
Phys. Lett. B853
(2024) 138633

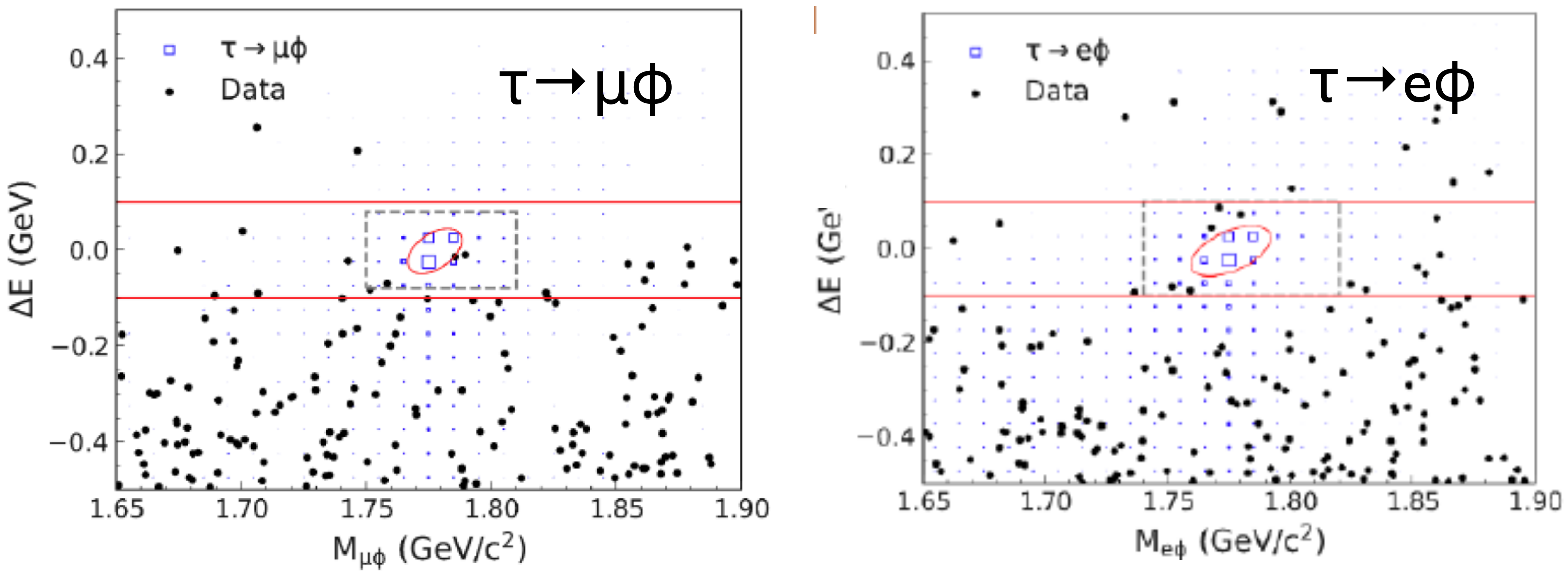
The world best limit!

Search for τ→lV^0 at Belle/Belle II

Wenzhe Li

Update w/ full Bele data set of 980 fb^{-1}

- More decay modes in the tag side
- V^0 = ρ, ω, ϕ, K^{*0} and K^{*0}
- Further suppress τ→3πν and ee→qq with BDT



$$\mathcal{B}(\tau \to eV^0) < (1.7\sim2.4) \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu V^0) < (1.7\sim4.3) \times 10^{-8}$$

World leading results

JHEP 2023, 118 (2023)

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}_{\rm obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm\rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm\rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm\phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3
$\tau^\pm \to e^\pm\phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0
$\tau^\pm \to \mu^\pm\omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9
$\tau^\pm \to e^\pm\omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7

World leading results

Belle II explores also untagged inclusive reconstruction

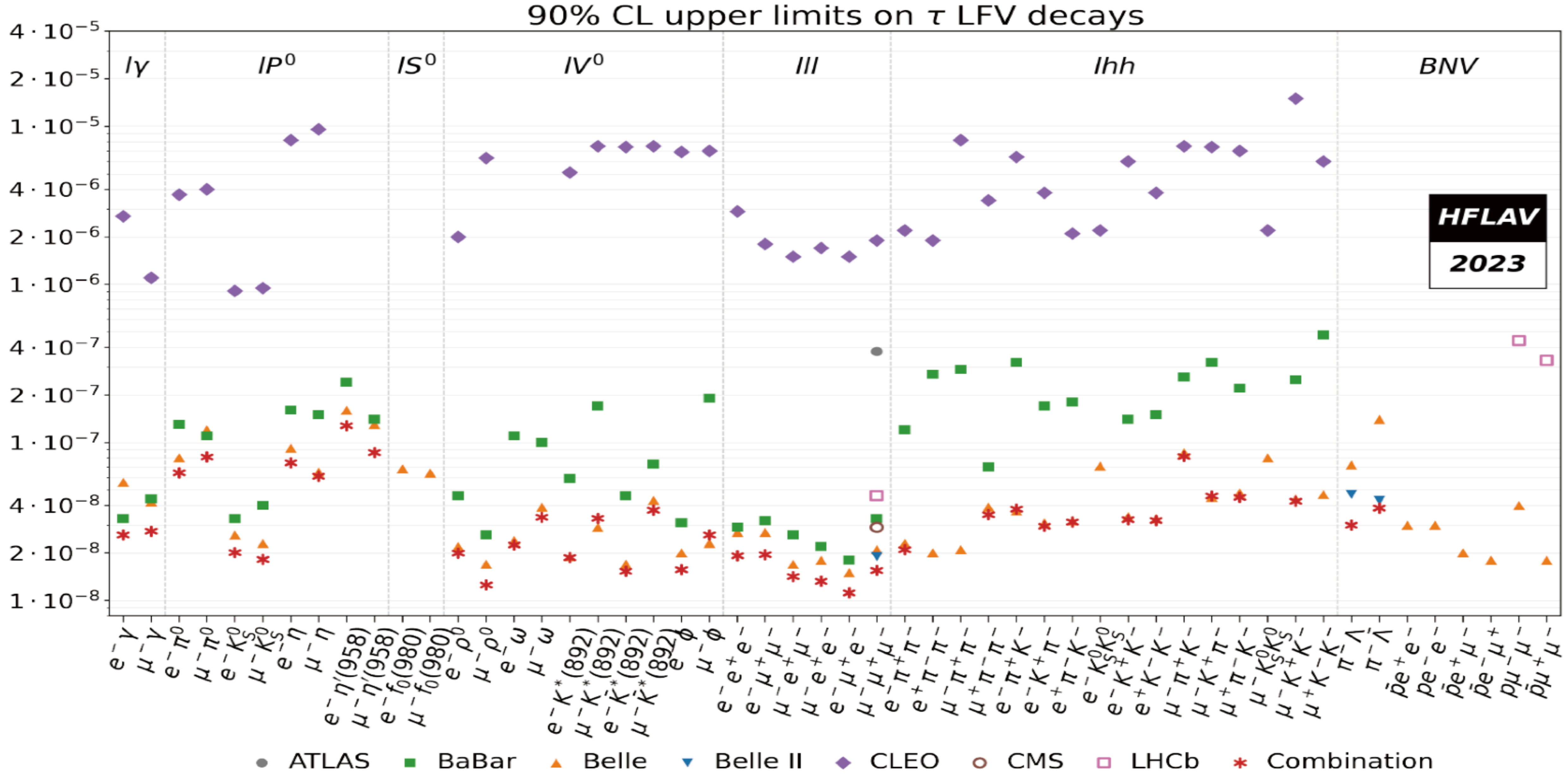
- higher signal efficiency (16% higher)
- Background rejection with preselection and BDT

$$\mathcal{B}(\tau \to e\phi) < 23 \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu\phi) < 9.7 \times 10^{-8}$$

190 fb^{-1}
90% CL

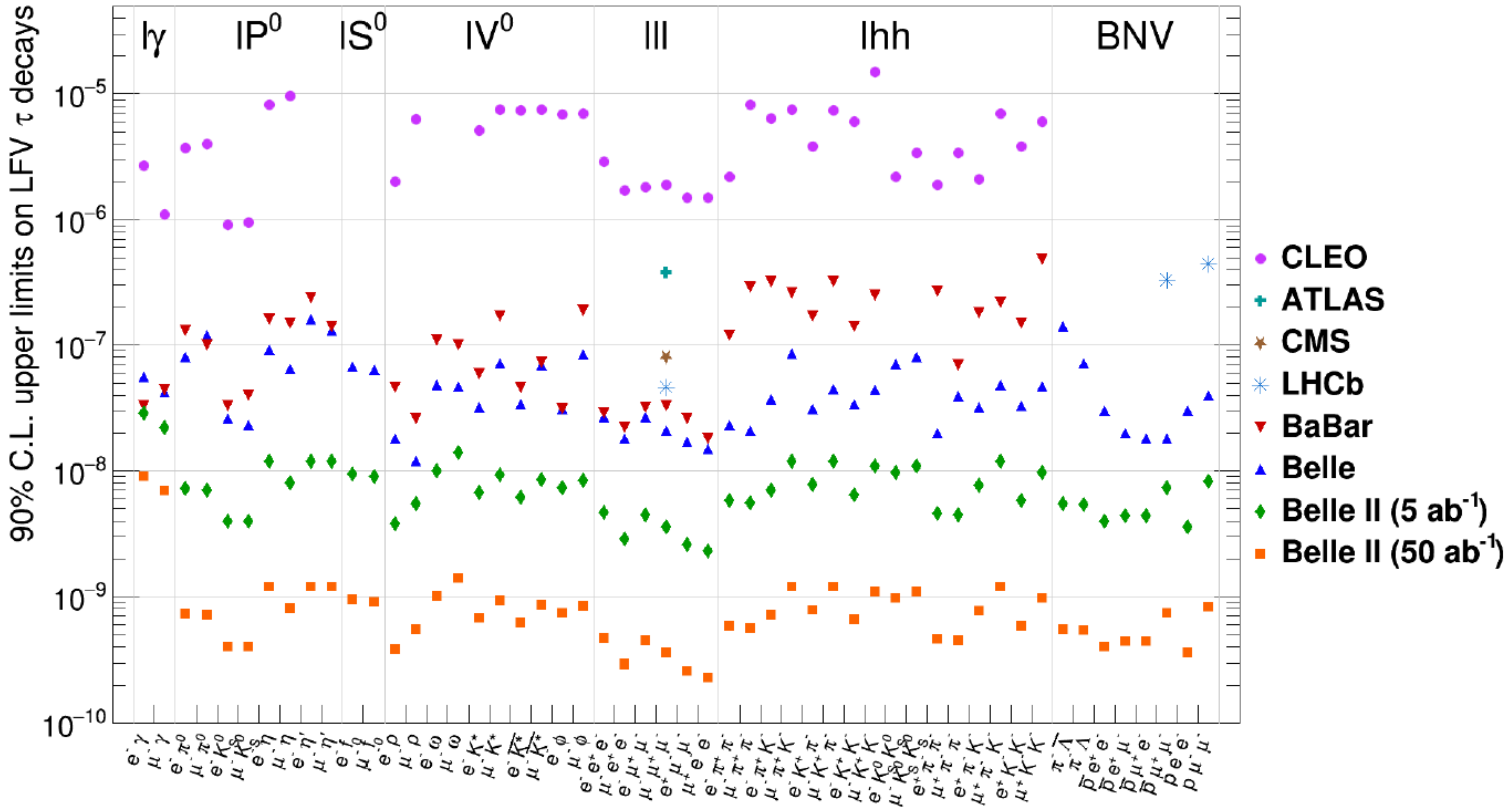
Tau Physics Prospects

Tau LFV decays



Tau Physics Prospects

Tau LFV decays



Belle II will push the sensitivity down to $O(10^{-9\rightarrow 10})$ at 5 → 50 ab^{-1}

Tau Physics Prospects

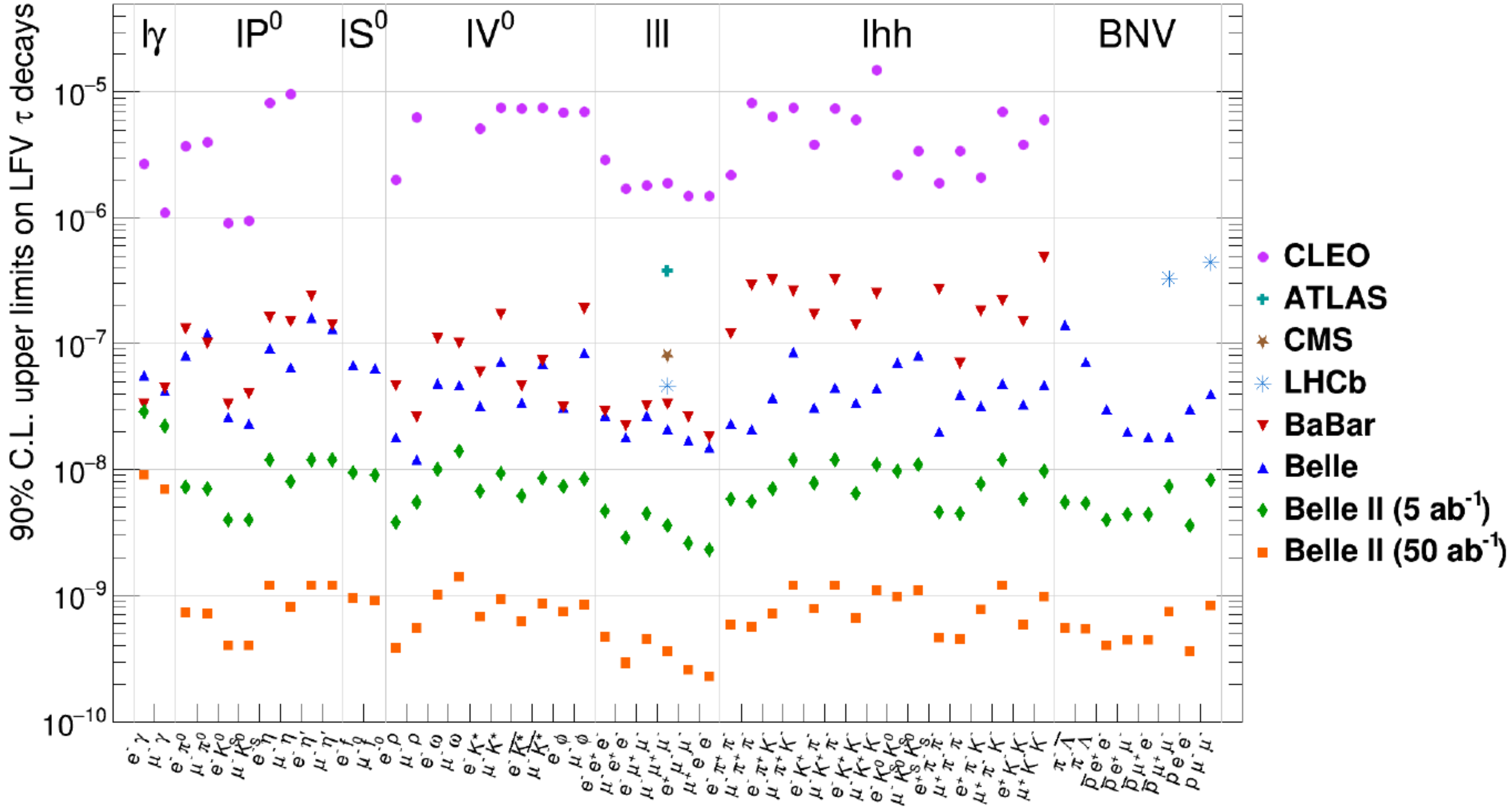
pp →ττ by CMS

$\rightarrow a_\tau = 0.0009^{+0.0032}_{-0.0031}$

$\rightarrow |d_\tau| < 1.7 \times 10^{-17} e \cdot \mathrm{cm} (68\%)$

Izaak Neutelings

Tau LFV decays



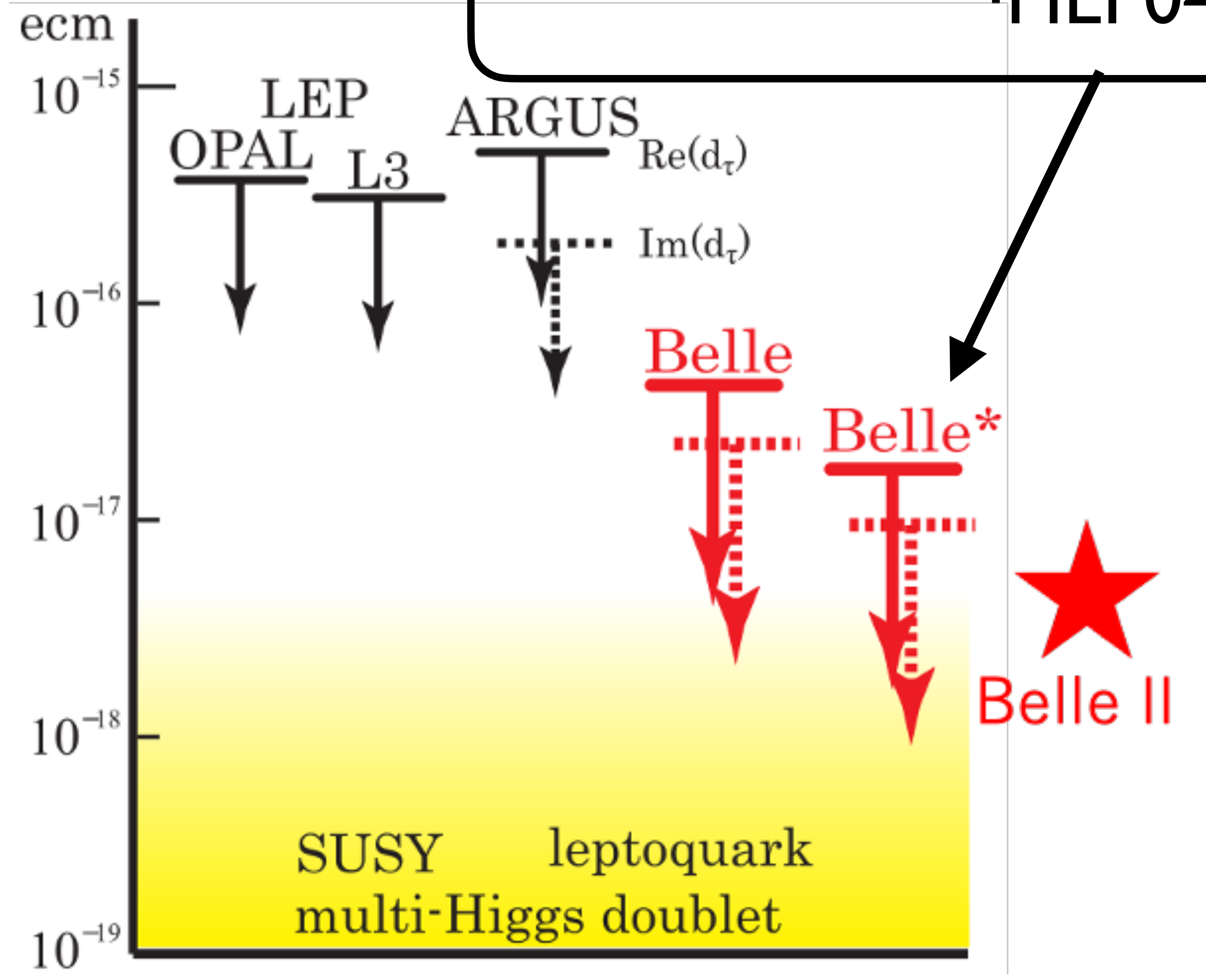
Tau EDM

Belle (833fb⁻¹)

$\mathrm{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17} e \cdot cm$

$\mathrm{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17} e \cdot cm$

JHEP04(2022)110



Tau g-2 at "Chiral Belle"

Mike Roney

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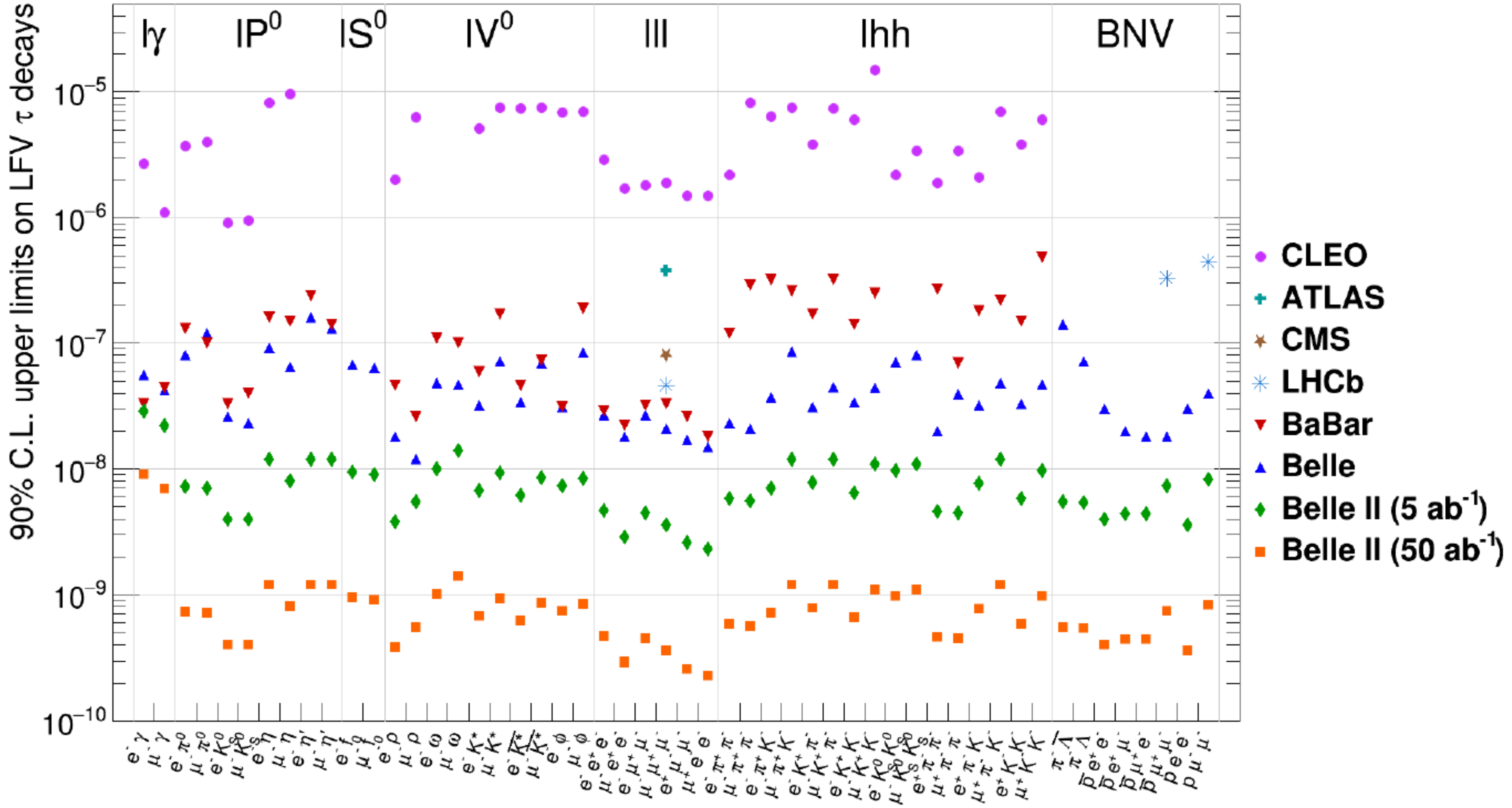

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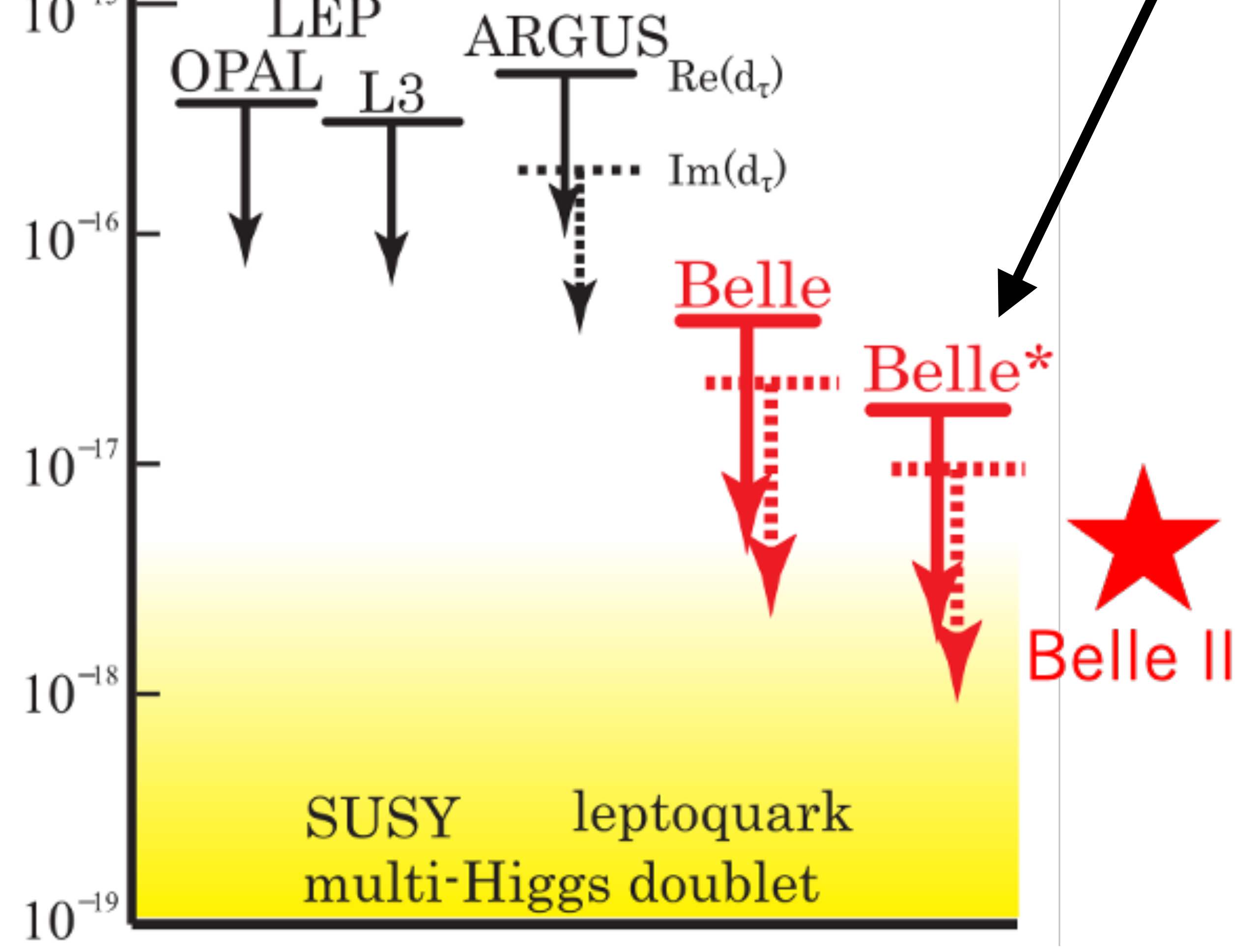
JHEP04(2022)110



Tau g-2 at "Chiral Belle"

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Belle II will push the sensitivity down to O($10^{-9\rightarrow10}$) at 5 → 50 ab^{-1}

Opportunities also at LHC→HL-LHC (LHCb, ATLAS, CMS) proposed future facilities; Super τ-c factory, FCC-ee, CEPC

Worldwide Efforts for EDM

Electron

- New bound by the HfF⁺ molecule at JILA (Colorado, NIST)

$$d_e = (-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-30} e\,\text{cm}$$
$$d_e < 4.1 \times 10^{-30} e\,\text{cm}(90\%\,\text{CL})$$

- ThO by ACME (Havard, Northwestern, Yale)

Muon

- MuEDM at PSI
- Spin-frozen method to achieve O(10^{-23}) e cm

Francesco Renga

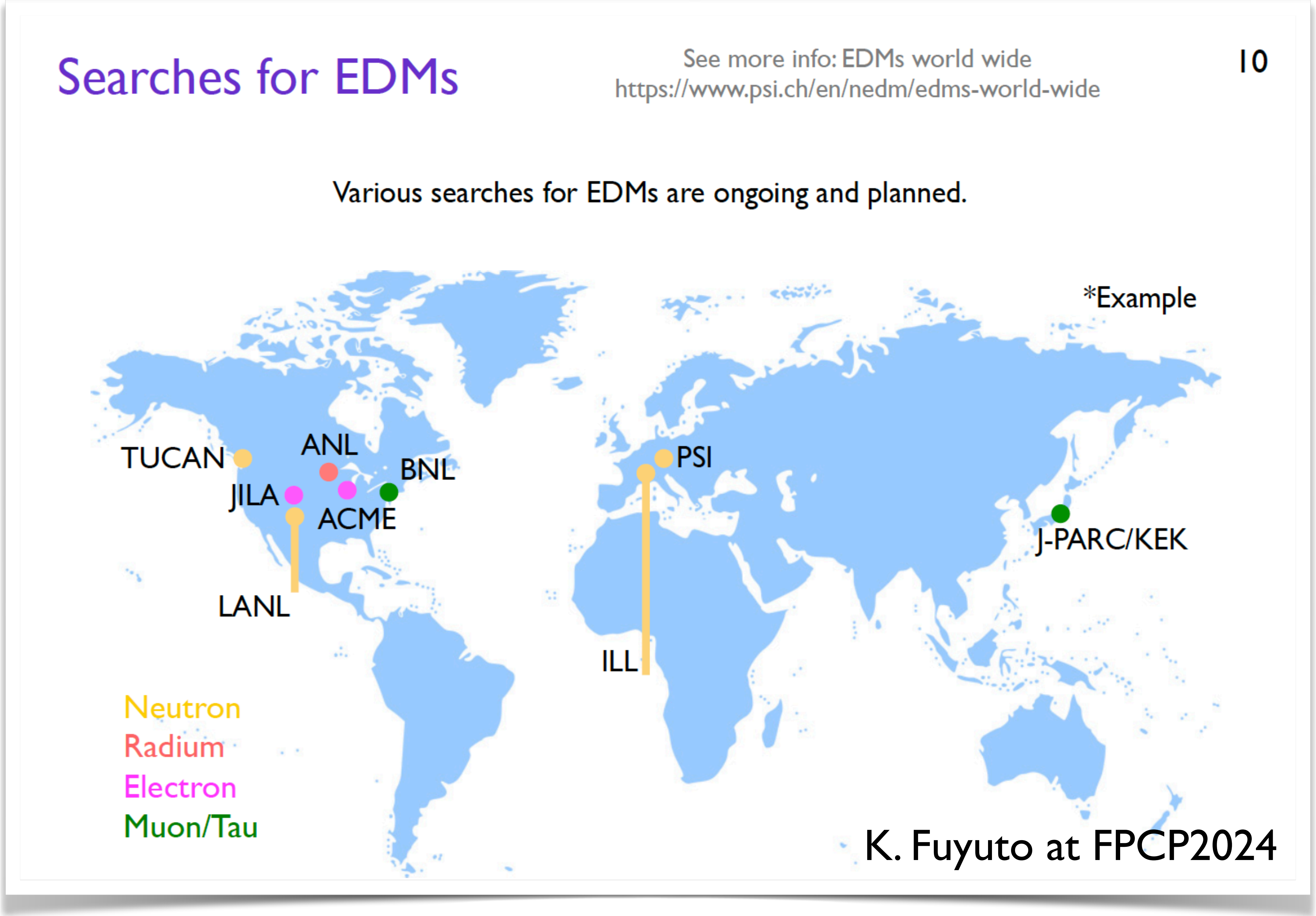
Neutron

- PSI, ILL, SNS, LANL, TRIUMF ~O(10^{-27}) e cm

&More (ongoing, planned and proposed)

- Diamagnetic atoms (Hg, Ra, Xe)
- Molecules
- Proton (strorage ring)

Alex Keshavarzi



Searches for EDMs

See more info: EDMs world wide
https://www.psi.ch/en/nedm/edms-world-wide

10

Various searches for EDMs are ongoing and planned.

K. Fuyuto at FPCP2024

Worldwide Efforts for EDM

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See Science 381 (2023) 6653

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mass scale for new CPV source

$$M/g \geq 40\,\mathrm{TeV}/\alpha^{1/2}$$

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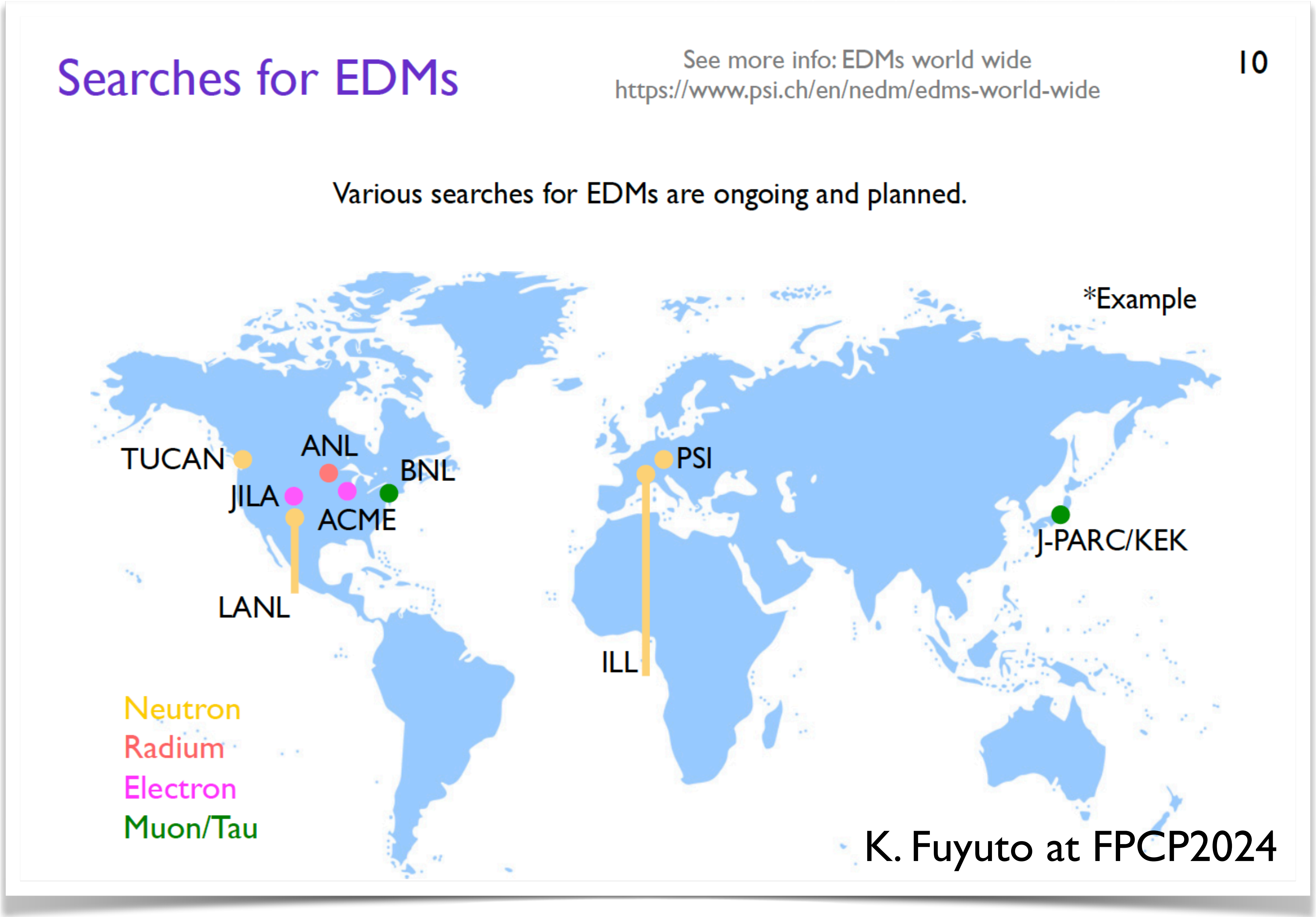

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Summary

- Lepton flavor physics and EDM are important to find BSM physics at high energy scale.
- "Anomaly" found in the muon anomalous magnetic moment could be clue to BSM, but requires verification by other experiments based on different technique, i.e.; J-PARC muon g-2/EDM and also clarification of the SM prediction
- Rich muon LFV programs in progress at J-PARC (COMET, DeeMe), PSI (MEG II, Mu3e) and Fermilab (Mu2e).
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Many challenges are in progress and interesting results will come in 2025~ and 2030's!

Gambaro (がんばろう) !! & Stay Tuned!!!

Thank you!

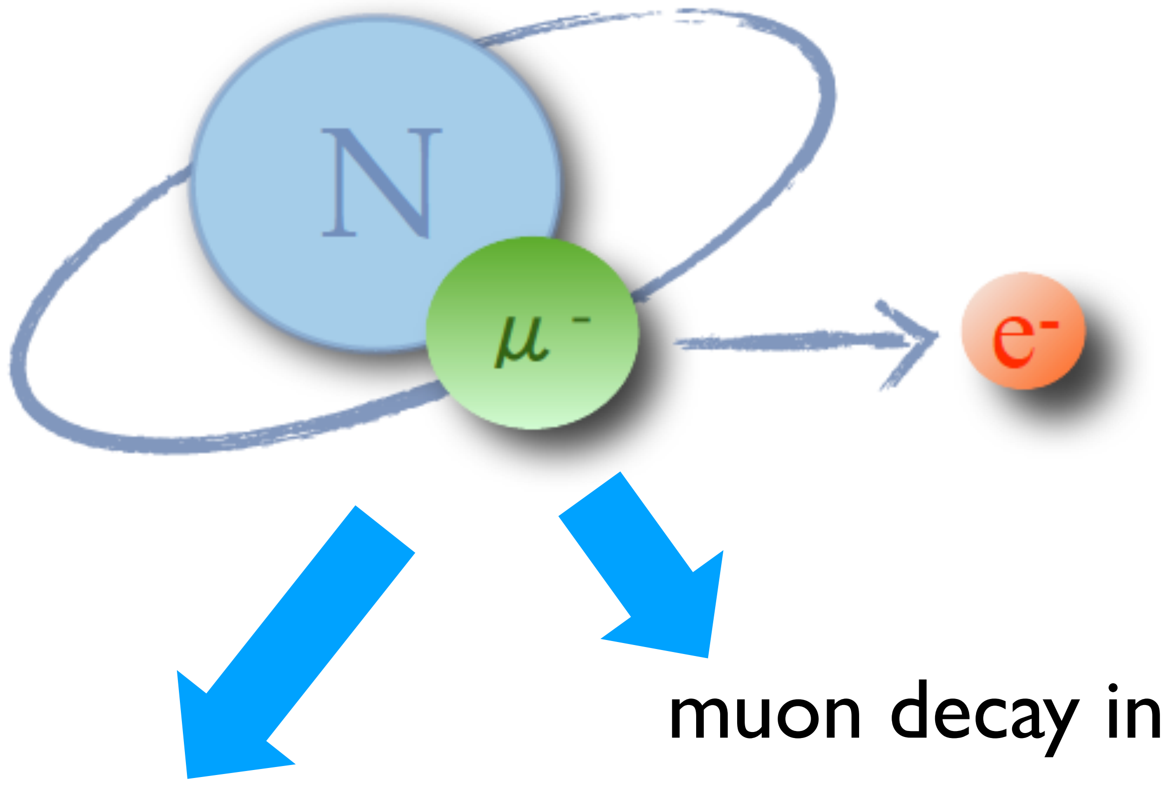
Backup

Search for μ-N→e-N

"Muon-to-Electron Conversion in Munic Atom (μ-N → e- N)"

- One of the most prominent process of muon LFV

$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$$

Signals:

a mono-energetic electron

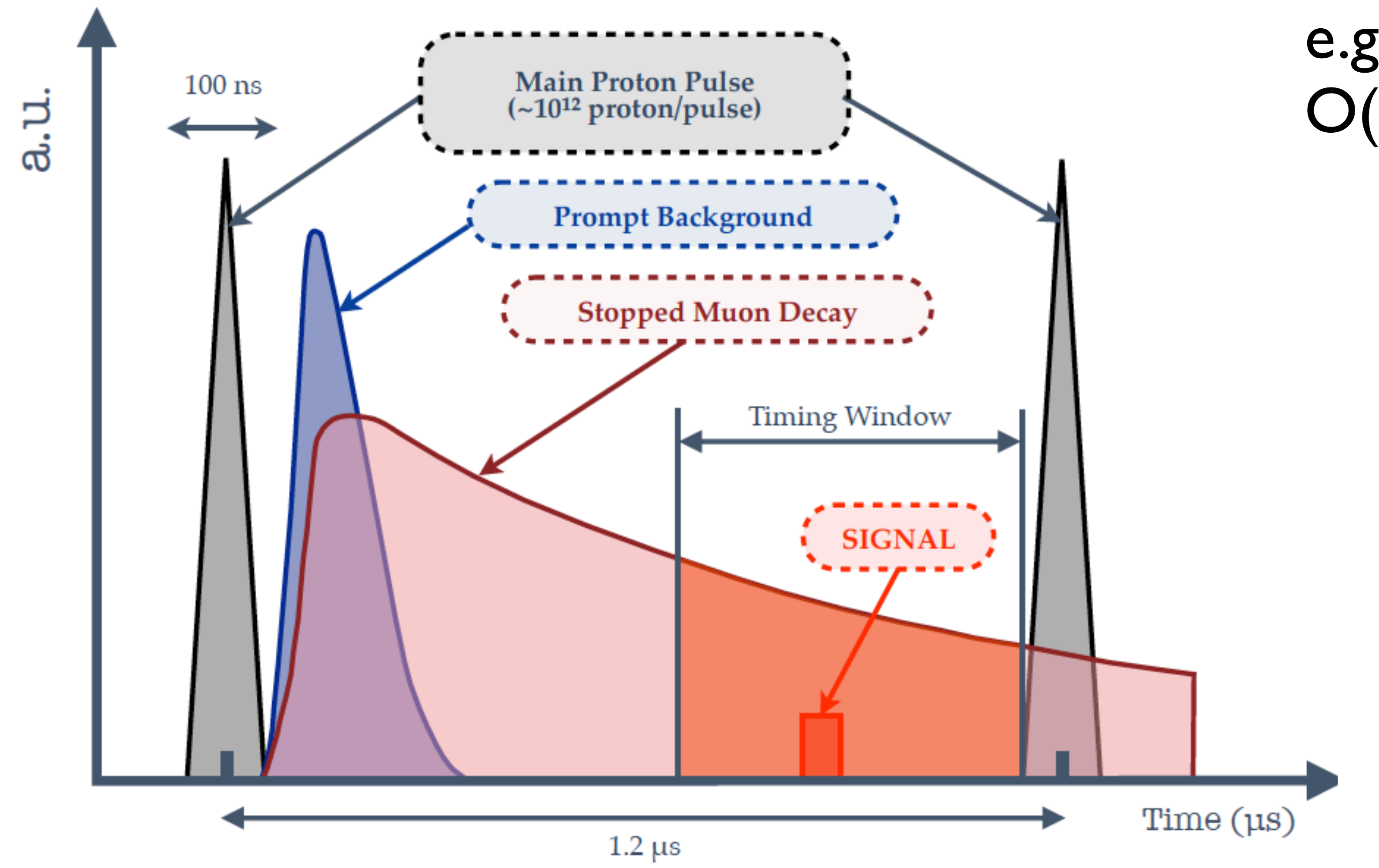
$$E_e \approx m_\mu - E_{bound\,\mu} - E_{recoil} \approx 105\,\mathrm{MeV}$$

Backgrounds:

- Physics backgrounds
- Beam-related backgrounds
- Cosmic-ray induced

Extinction is essential

$$\text{Extinction} = \frac{\text{\# of leaked protons in between bunches}}{\text{\# of filled protons in main bunches}}$$



e.g.; Excellent extinction O(10^{-12})-O(10^{-11}) in MR confirmed at J-PARC