PREN 2023 Workshop, Mainz, June 26-30, 2023

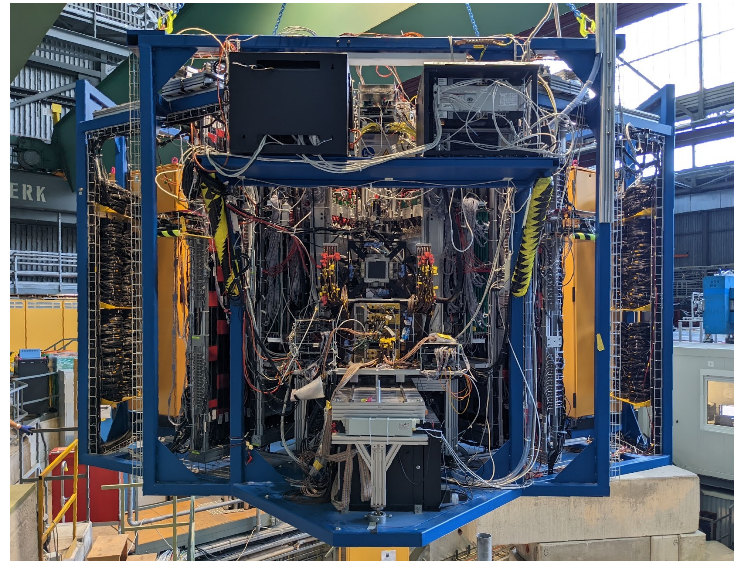
Tests of μ-e universality

Michael Kohl <kohlm@jlab.org> *

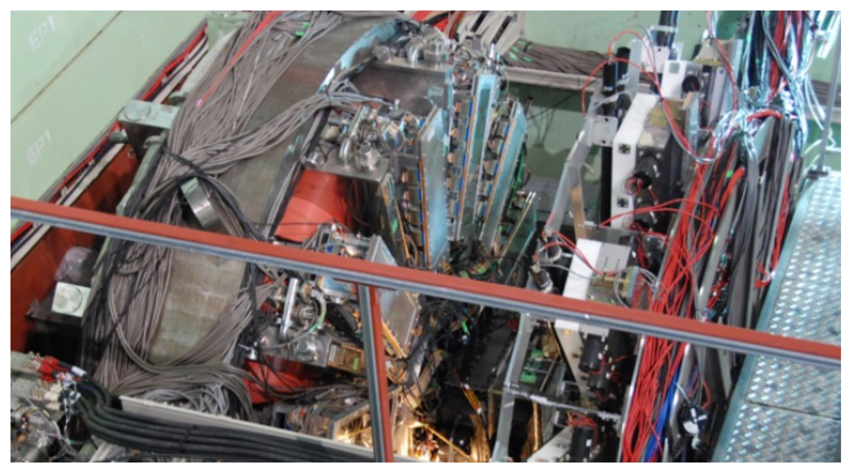
Hampton University, Hampton, VA 23668
Jefferson Laboratory, Newport News, VA 23606

* **Supported by NSF PHY-1812402 and PHY-2113436, and by DOE DE-SC0013941**

Outline



- τ-μ universality
  - B decays
- μ-e universality
  - B decays
  - g_μ-2
  - Proton radius puzzle: MUSE
  - Kaon decays: TREK/E36



Limits of lepton universality (until 2021)

- **e, μ, and τ: Different masses, same gauge couplings**
- **Lepton universality has been rather well established at 10^{-3} – 10^{-2} level**
- **Summary by A. Pich, arXiv:1201.0537v1 [hep-ph] (2012)**

	$\Gamma_{\tau\to\nu_\tau e\bar\nu_e}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar\nu_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar\nu_\mu}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to\mu\bar\nu_\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0007 ± 0.0022	0.992 ± 0.004	0.982 ± 0.008	1.032 ± 0.012

	$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\tau\to\nu_\tau e\bar\nu_e}$	$\Gamma_{\pi\to\mu\bar\nu_\mu}/\Gamma_{\pi\to e\bar\nu_e}$	$\Gamma_{K\to\mu\bar\nu_\mu}/\Gamma_{K\to e\bar\nu_e}$	$\Gamma_{K\to\pi\mu\bar\nu_\mu}/\Gamma_{K\to\pi e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	1.0018 ± 0.0014	1.0021 ± 0.0016	0.998 ± 0.002	1.001 ± 0.002

	$\Gamma_{W\to\mu\bar\nu_\mu}/\Gamma_{W\to e\bar\nu_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	0.991 ± 0.009	$\lvert g_\tau/g_e\rvert$	1.0016 ± 0.0021	1.023 ± 0.011

- **Couplings to *W* and *Z*^{0} (LEP-II [PDG 2010])**

$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}(W\to\tau\bar\nu_\tau)}{\mathrm{BR}(W\to e\bar\nu_e)+\mathrm{BR}(W\to\mu\bar\nu_\mu)} = 1.055(23)$$

2.4σ dev.

- **Belle, Babar, LHCb (HFLAV 2019)**

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

3.6σ dev.

- **LHCb (March 2021)**

$BR(B^+\to K^+\mu^+\mu^-) / BR(B^+\to K^+e^+e^-) = 0.846^{+0.042}_{-0.039}{}^{+0.013}_{-0.012}$

3.1σ dev.

- **Muon anomalous mag. moment (Apr 2021)** $a_\mu = 116\,592\,061(41)\times10^{-11}$ **4.2σ dev.**

- **Proton charge radius puzzle (since 2010)**

r_e (μH) = 0.84087 ± 0.00039 fm, r_e (CODATA2014) = 0.8751 ± 0.0061 fm

5.6σ dev.

Limits of lepton universality (2023)

- e, μ, and τ: Different masses, same gauge couplings
- Lepton universality has been rather well established at $10^{-3} – 10^{-2}$ level
- Summary by A. Pich, arXiv:1201.0537v1 [hep-ph] (2012)

	$\Gamma_{\tau\to\nu_\tau e\bar\nu_e}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar\nu_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar\nu_\mu}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to\mu\bar\nu_\mu}$
$\vert g_\tau/g_\mu\vert$	1.0007 ± 0.0022	0.992 ± 0.004	0.982 ± 0.008	1.032 ± 0.012

	$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\tau\to\nu_\tau e\bar\nu_e}$	$\Gamma_{\pi\to\mu\bar\nu_\mu}/\Gamma_{\pi\to e\bar\nu_e}$	$\Gamma_{K\to\mu\bar\nu_\mu}/\Gamma_{K\to e\bar\nu_e}$	$\Gamma_{K\to\pi\mu\bar\nu_\mu}/\Gamma_{K\to\pi e\bar\nu_e}$
$\vert g_\mu/g_e\vert$	1.0018 ± 0.0014	1.0021 ± 0.0016	0.998 ± 0.002	1.001 ± 0.002

	$\Gamma_{W\to\mu\bar\nu_\mu}/\Gamma_{W\to e\bar\nu_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to e\bar\nu_e}$
$\vert g_\mu/g_e\vert$	0.991 ± 0.009	$\vert g_\tau/g_e\vert$	1.0016 ± 0.0021	1.023 ± 0.011

- Couplings to *W* and *Z*⁰ (LEP-II [PDG 2010])

$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W\to\tau\,\bar\nu_\tau)}{\mathrm{BR}\,(W\to e\,\bar\nu_e)+\mathrm{BR}\,(W\to\mu\,\bar\nu_\mu)} = 1.055(23)$$

2.4σ dev.

- Belle, Babar, LHCb (Oct 2022+Mar 2023)

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

3.2σ dev.

- LHCb (Dec 2022)
  $R(K^{(+,*)})$ ~ 1.0; dR ~ 0.05-0.10

<1σ dev.

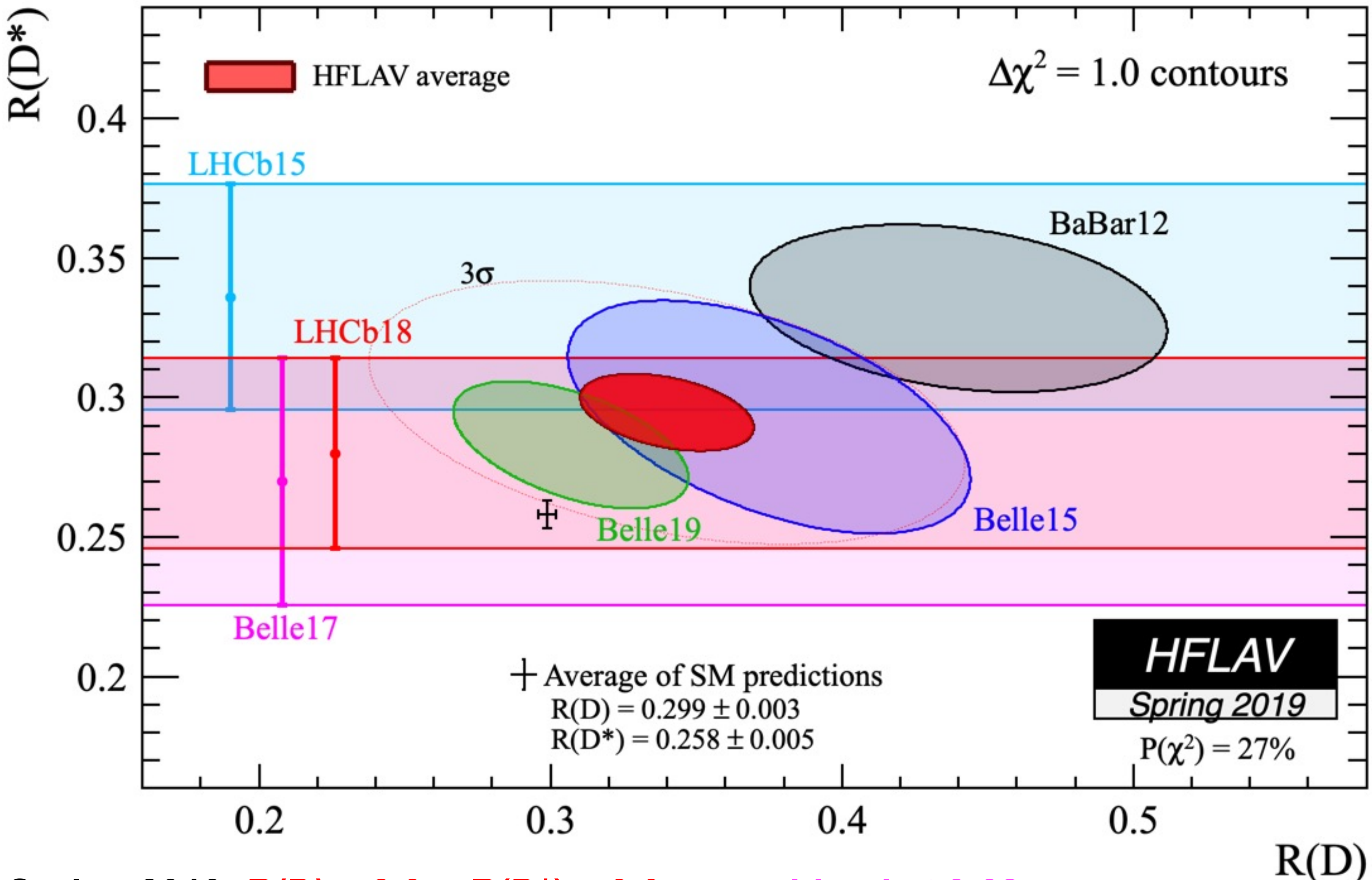
- Muon anomalous mag. moment (Apr 2021) $a_\mu = 116\,592\,061(41)\times10^{-11}$

4.2σ dev.

- Proton charge radius puzzle (June 2021)
  r_e (μH) = 0.84087 ± 0.00039 fm, r_e (CODATA2018) = 0.8414(19) fm

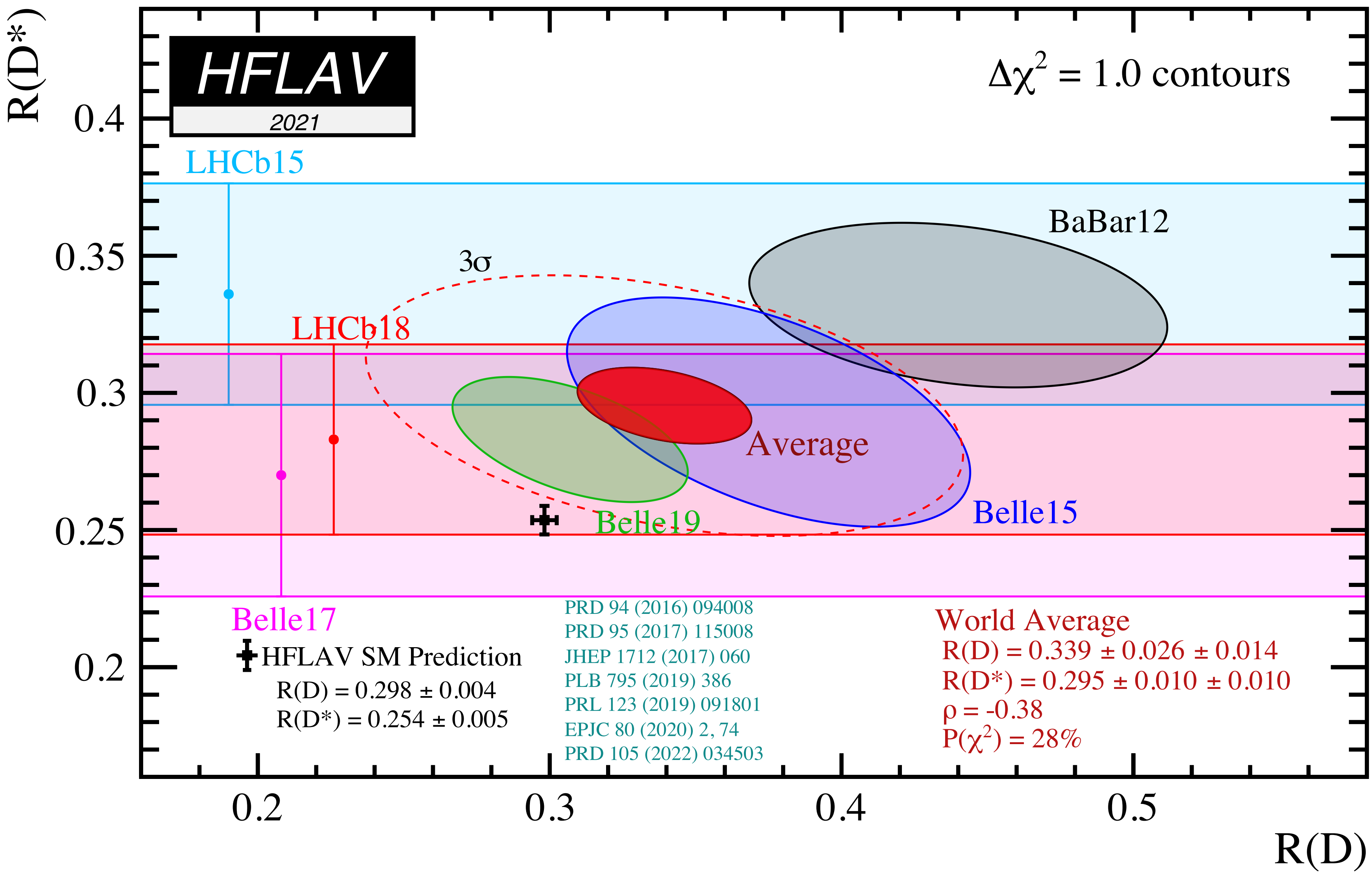
? 5.6σ dev. ?

Lepton non-universality in B-decays (τ-μ)



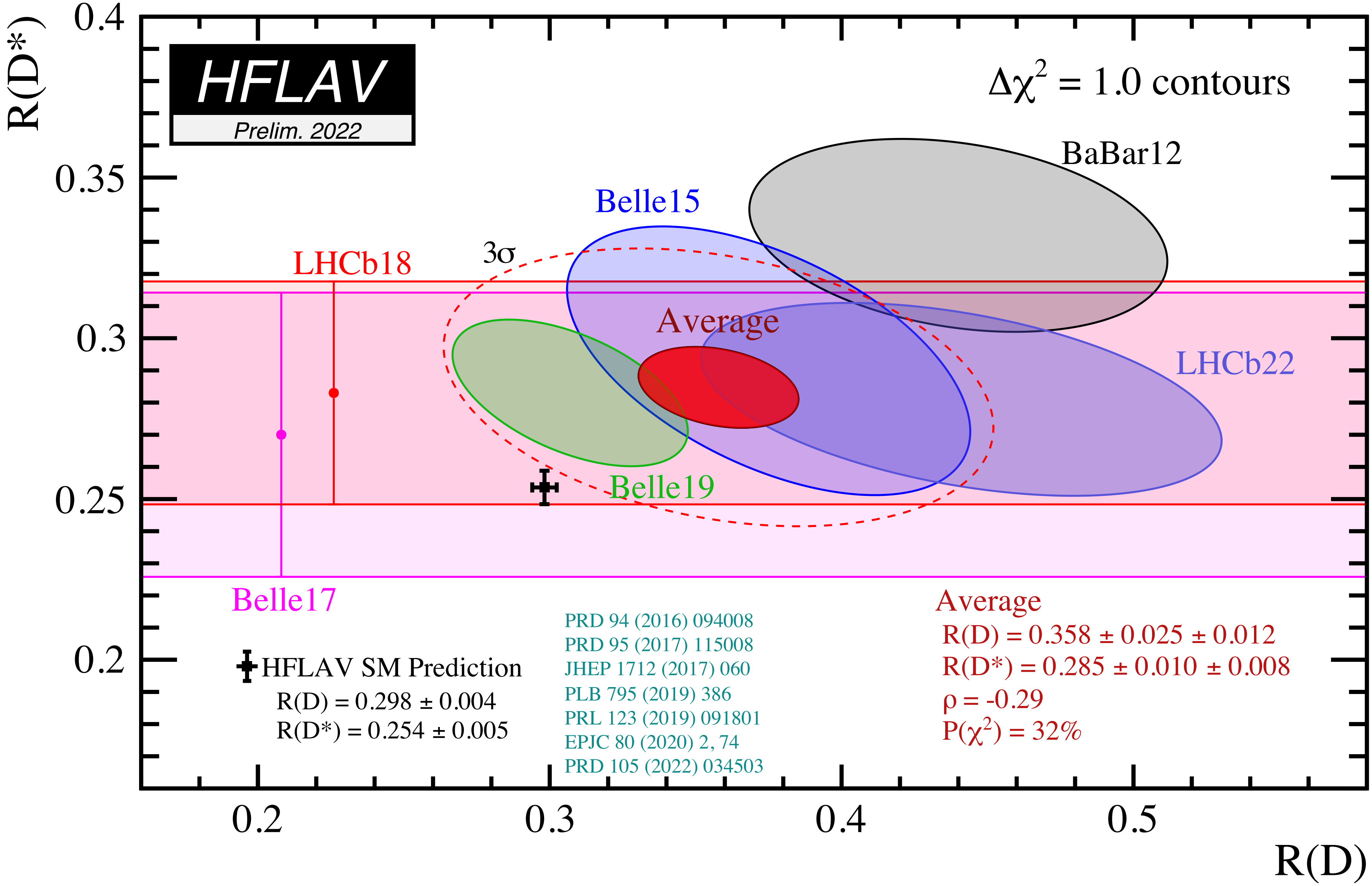
- **Spring 2019: R(D) ~ 2.3σ, R(D*) ~ 3.0σ; combined at 3.62σ**

Lepton non-universality in B-decays (τ-μ)



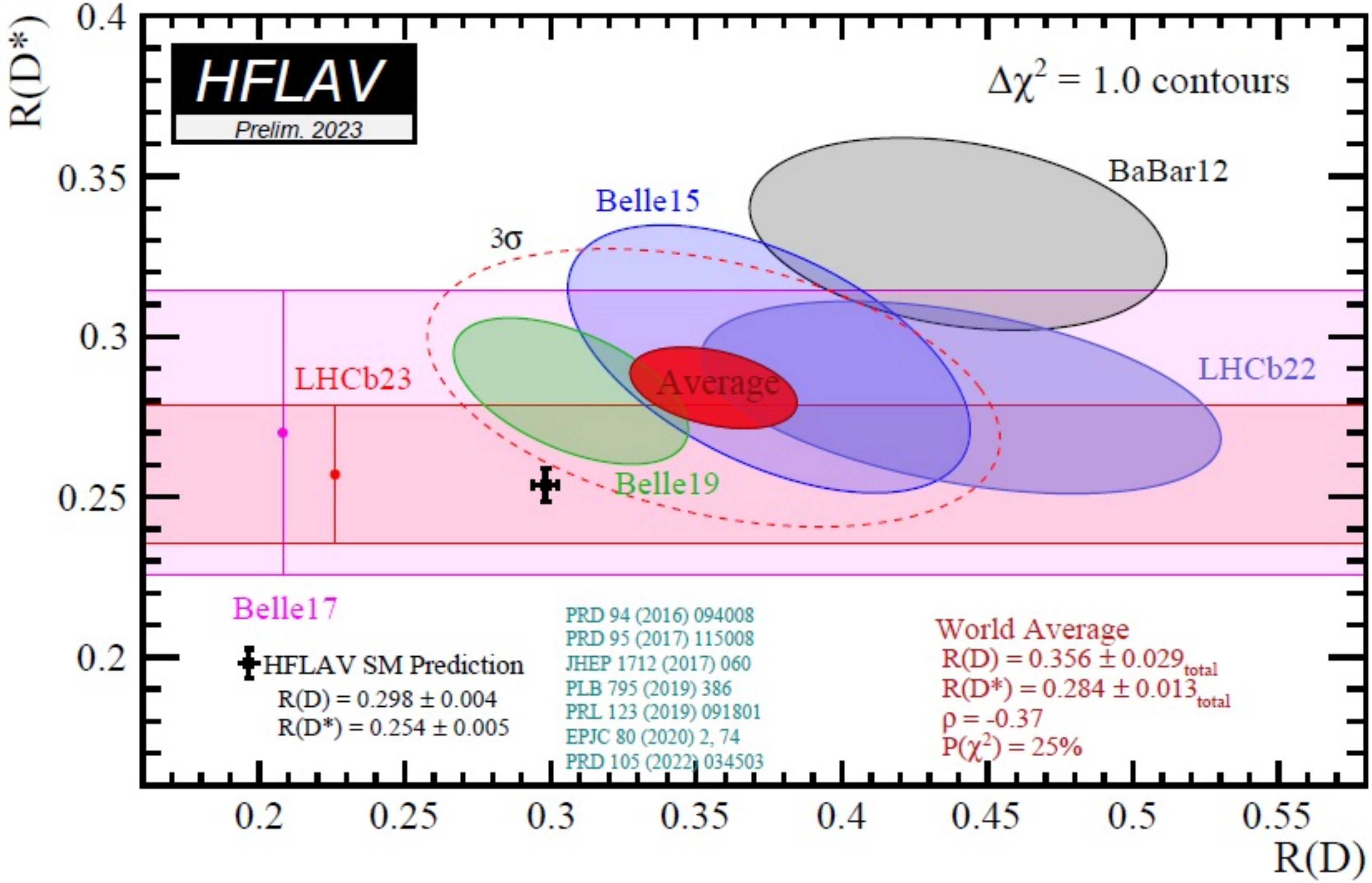
- **2021: R(D), R(D*) ~ combined at 3.3σ**

Lepton non-universality in B-decays (τ-μ)



- **Oct. 2022: R(D), R(D*) ~ combined at 3.2σ**

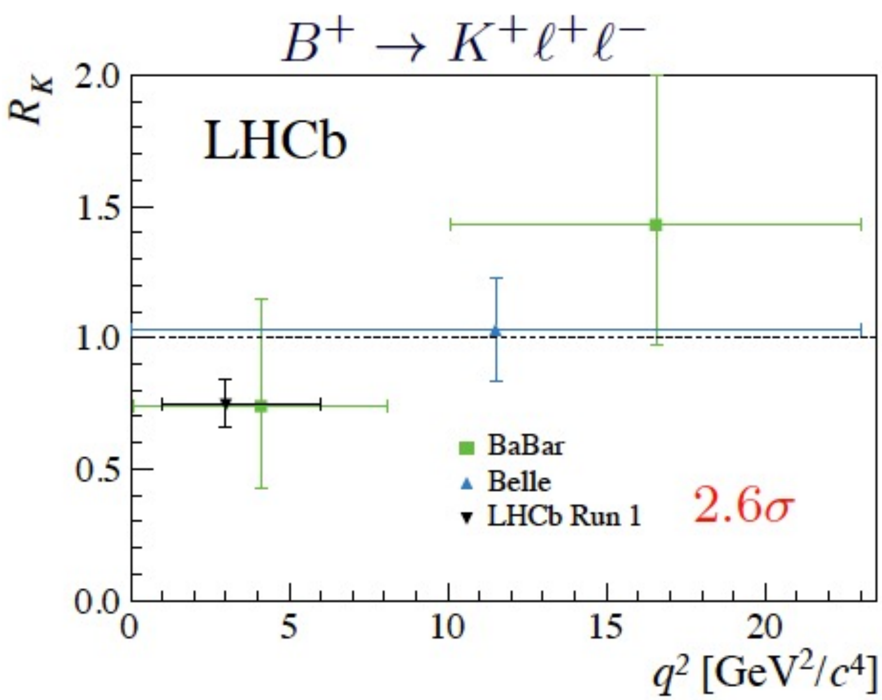
Lepton non-universality in B-decays (τ-μ)

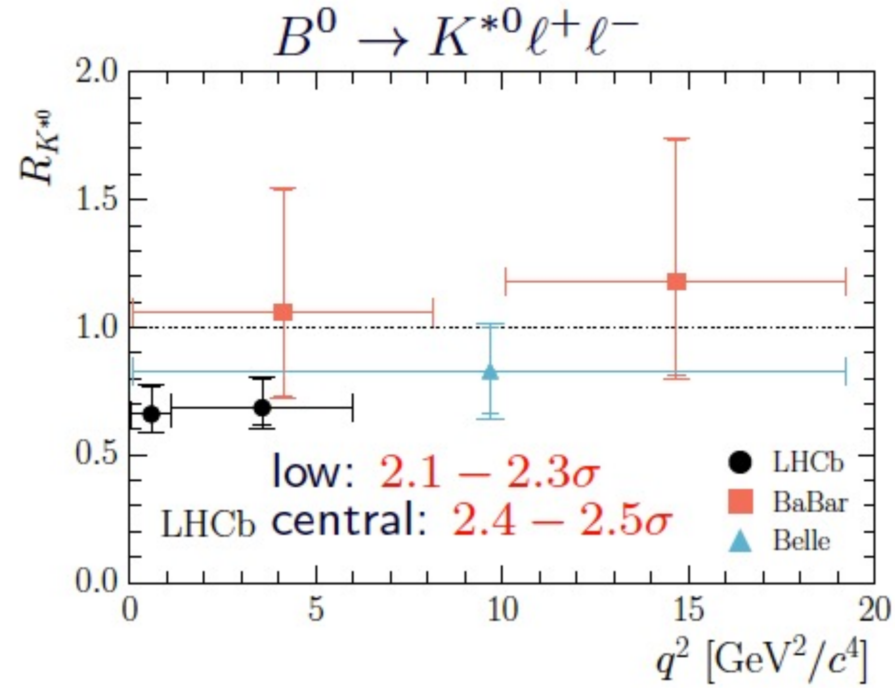


- **2023: R(D), R(D*) incl. hadronic-τ decays ~ combined at 3.2σ**

Lepton non-universality in B-decays (μ-e)

- **LHCb: $R(K^{(+,*)}) = \Gamma(B^{(+,0)} \rightarrow K^{(+,*)} \mu^+\mu^-) / \Gamma(B^{(+,0)} \rightarrow K^{(+,*)} e^+e^-)$**
- **Summer 2018: $R(K^{(+,*)})$ different from SM at the 2.5σ level**





[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

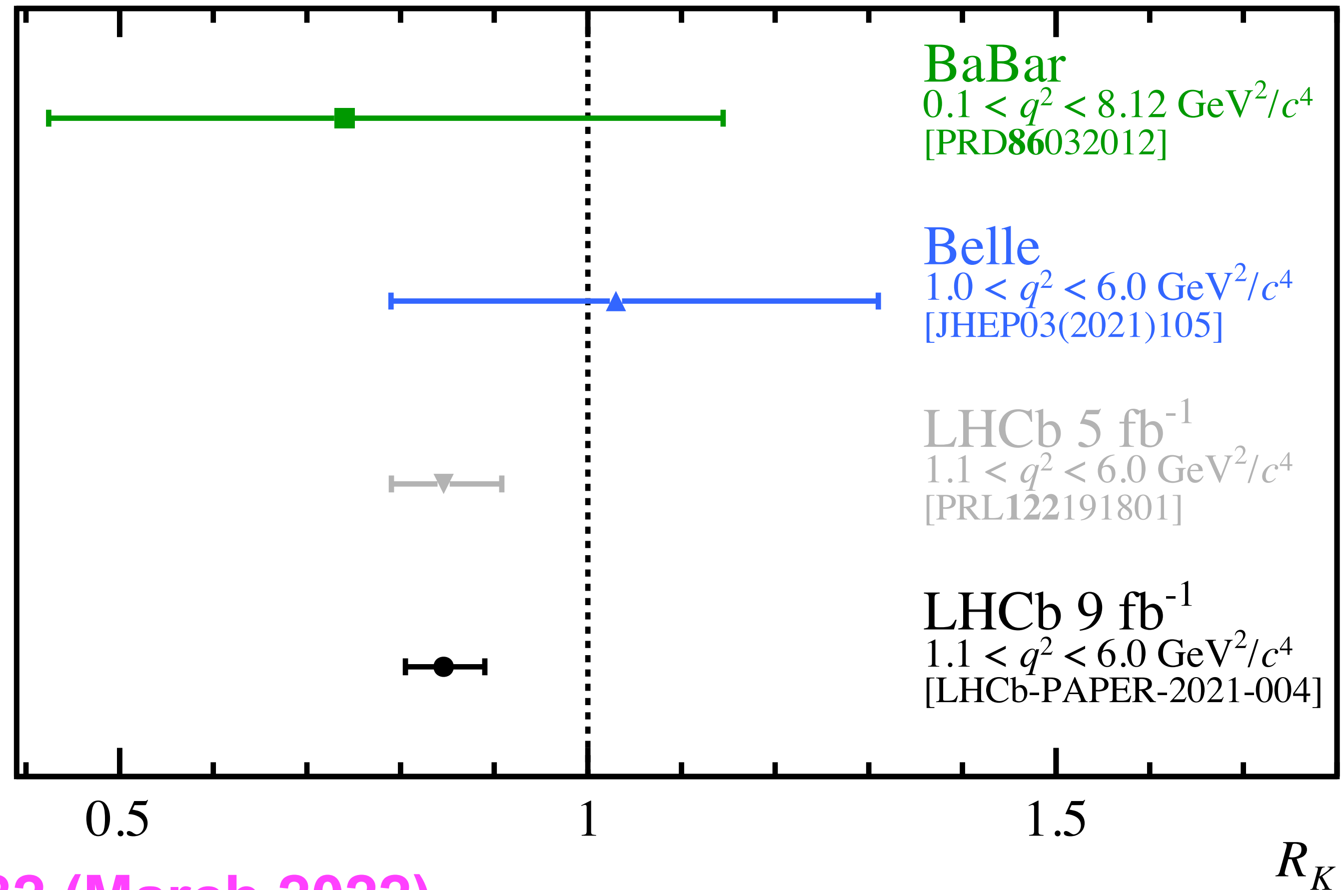
Lepton non-universality in B-decays (μ-e)

- LHCb: $R(K^+) = \Gamma(B^+ \to K^+ \mu^+\mu^-) / \Gamma(B^+ \to K^+ e^+e^-)$
- Spring 2021: $R(K^+)$ different from SM at 3.1σ level

[LHCb, PRL 113 (2014) 151601]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

R. Aaji, PRL 122, 191801 (2019)

Full Run1 + Run2
arXiv:2103.11769

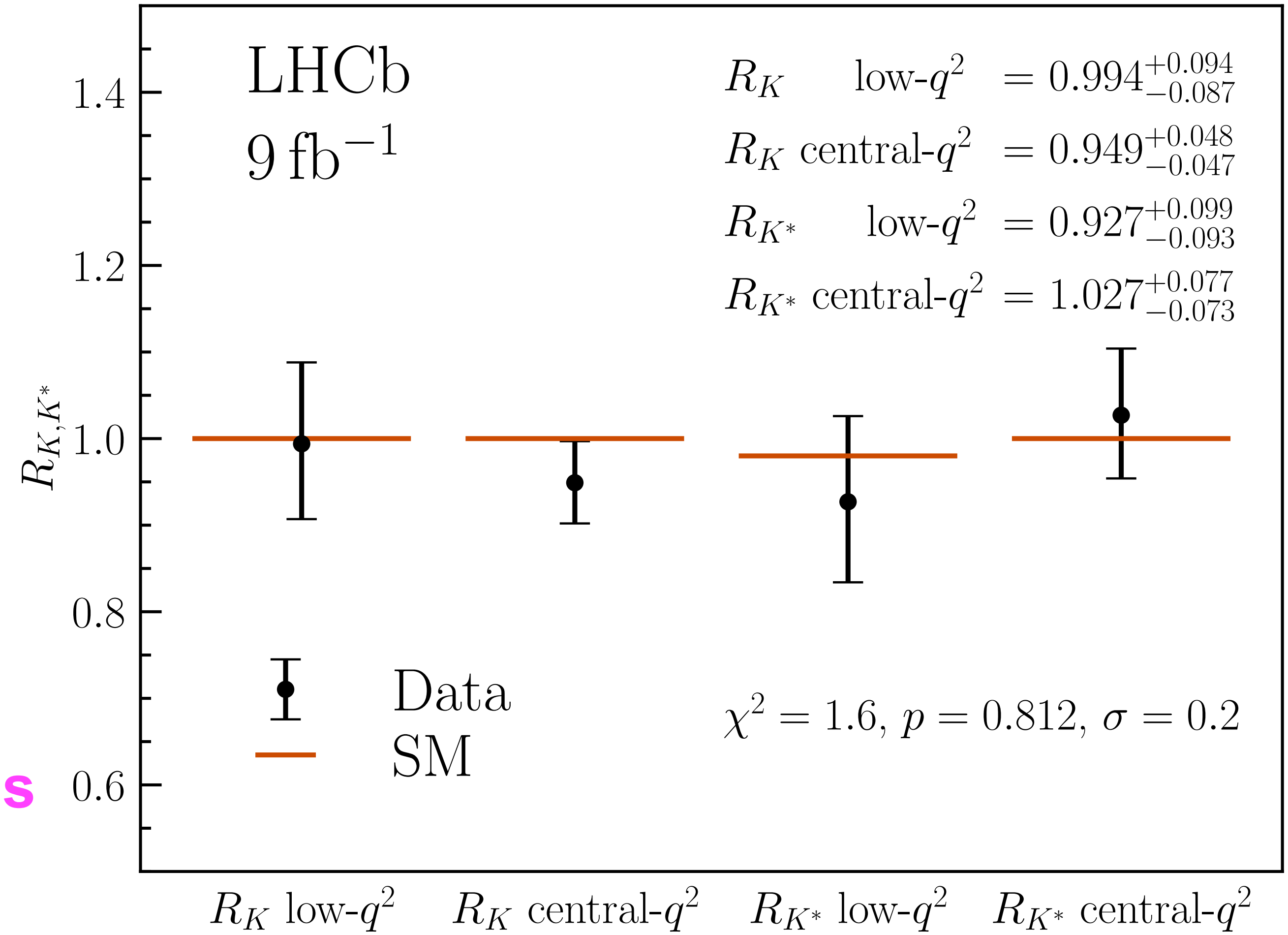


Nature 18, 277–282 (March 2022)

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$$

Lepton non-universality in B-decays (μ-e)

- LHCb: $R(K^{(+,*)}) = \Gamma(B^{(+,0)} \rightarrow K^{(+,*)} \mu^+\mu^-) / \Gamma(B^{(+,0)} \rightarrow K^{(+,*)} e^+e^-)$
- **December 2022:** $R(K^{(+,*)})$ consistent with Standard Model

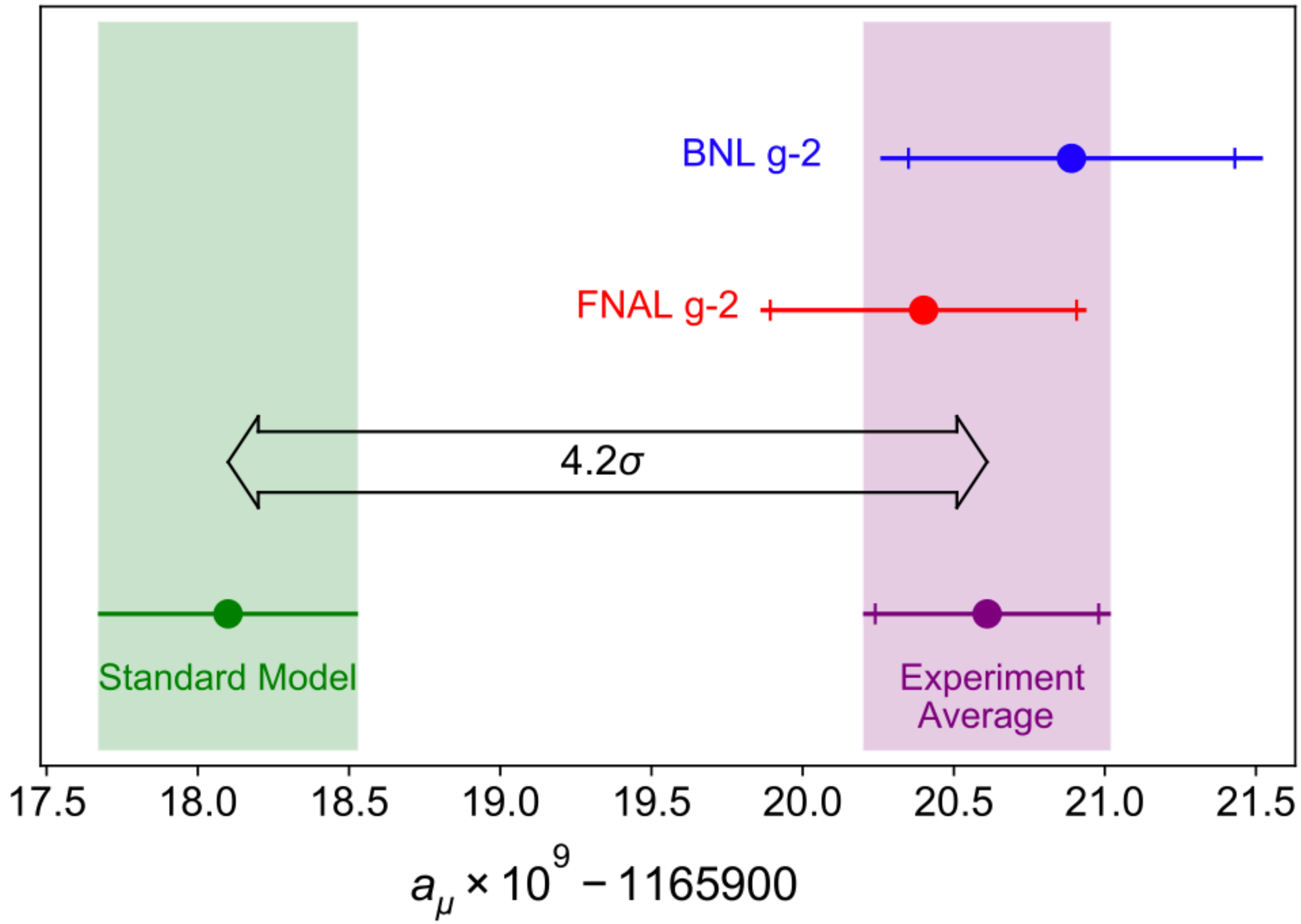


Full Run1 + Run2

arXiv:2212.09153

Supersedes previous results!

Lepton non-universality: Muon g-2



The Muon g-2 Collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, arXiv: 2104.03281

Blinded analysis. Expect smaller errors in the future.

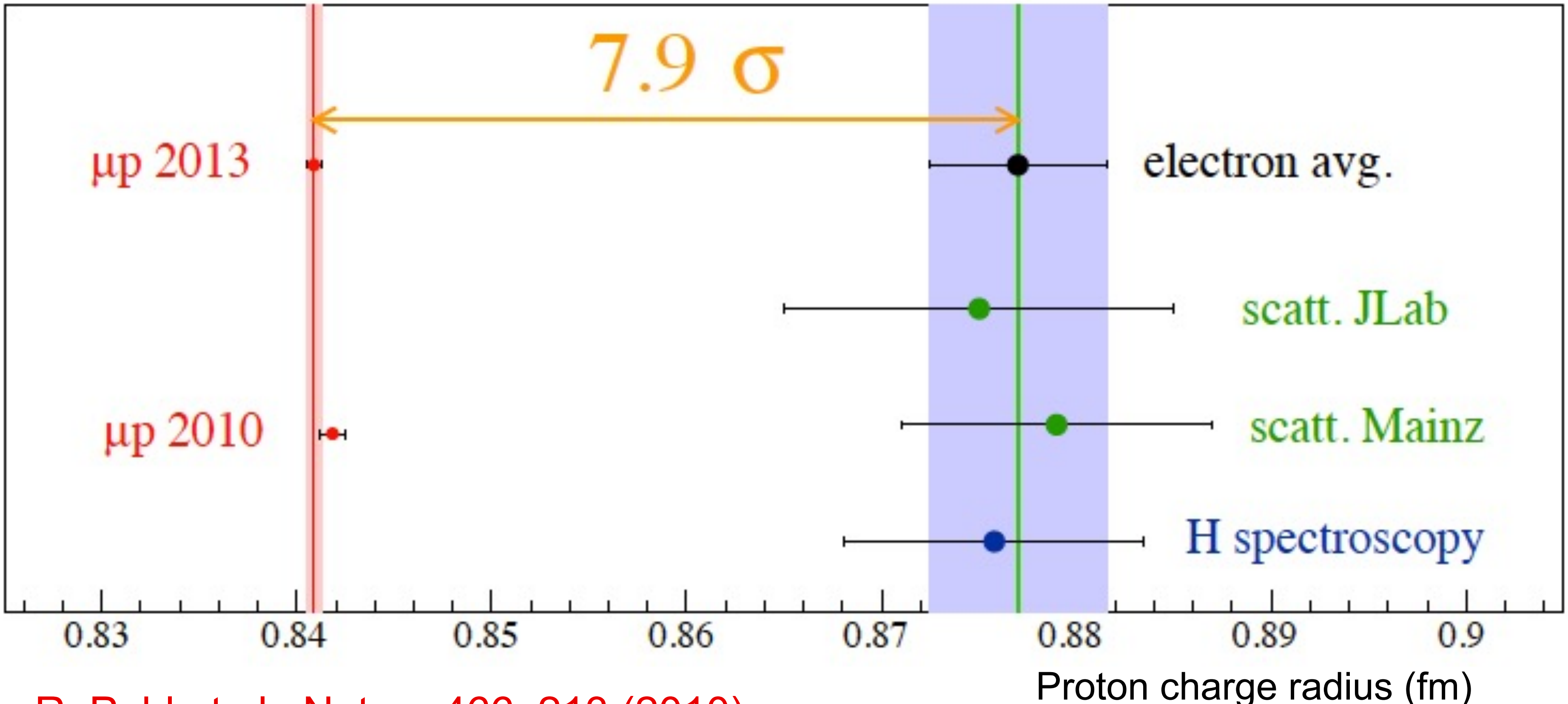
Huge theory effort: Hadr. vac. pol., light-by-light scatt.; Lattice QCD

The proton radius puzzle in 2010/2013

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)

muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)

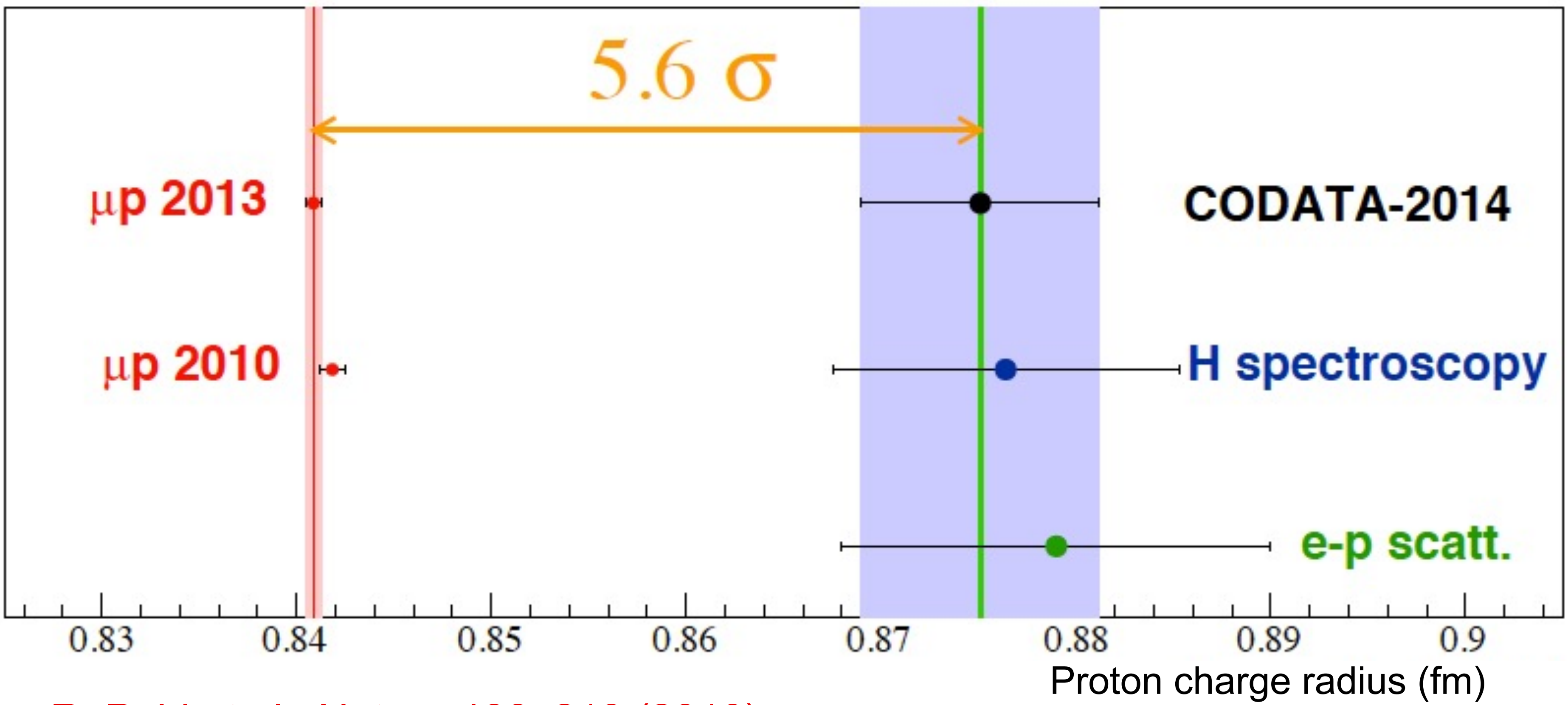
A. Antognini et al., Science 339, 417 (2013)

The proton radius puzzle in 2016

The proton rms charge radius measured with

electrons: (0.8751 ± 0.0061) fm **(CODATA2014)**

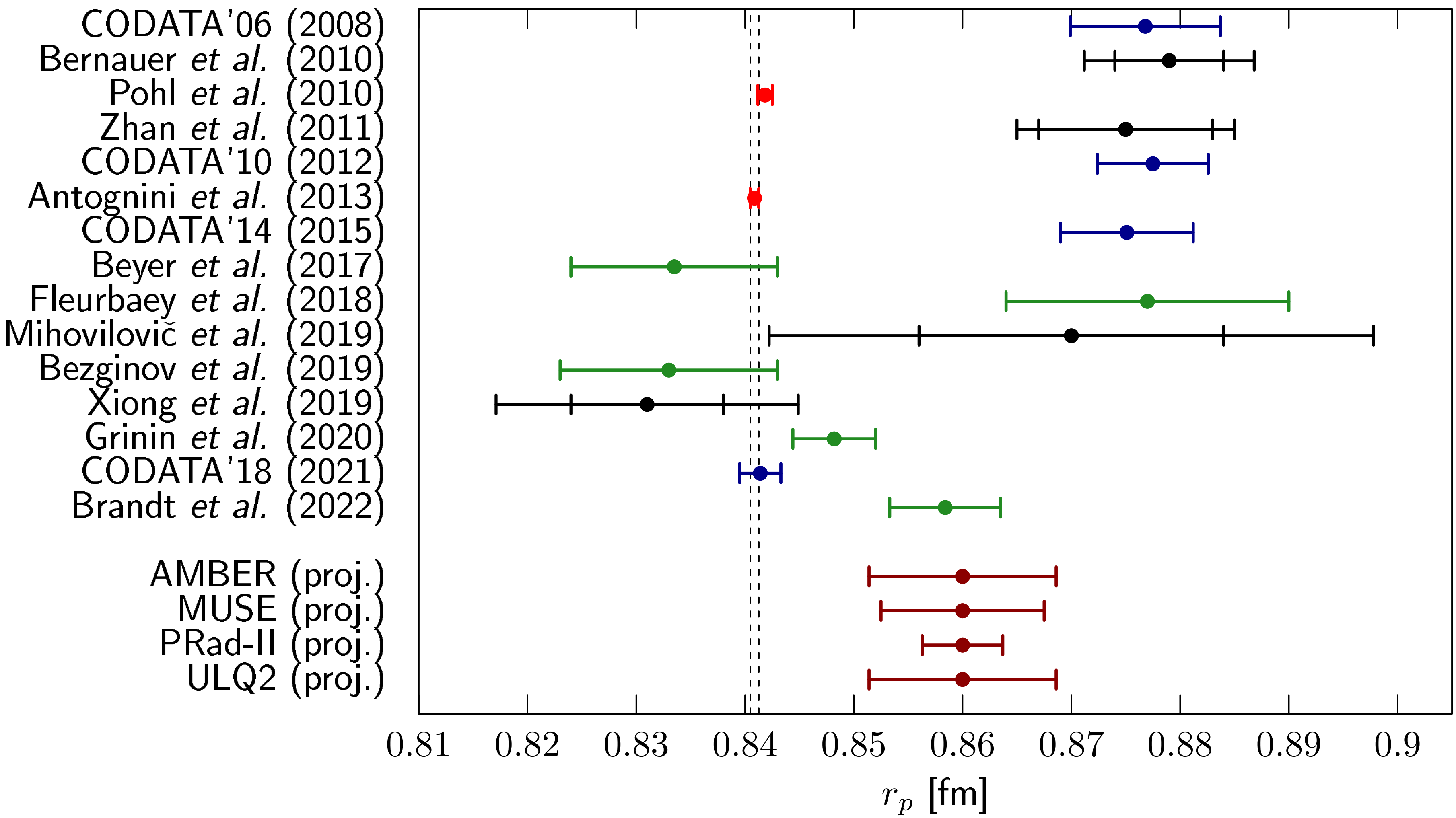
muons: (0.8409 ± 0.0004) fm



R. Pohl et al., Nature 466, 213 (2010)

A. Antognini et al., Science 339, 417 (2013)

The proton radius puzzle in 2023



Red = μp spectroscopy
Black = ep scattering
Green = ep spectroscopy
Blue = CODATA
Dark-red = Future scattering

Plot: courtesy by J. Bernauer

Motivation for μp scattering

Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84184 ± 0.00067
0.84087 ± 0.00039

Electron scattering

0.8770 ± 0.0060

Scattering

Muon scattering
???

Idea for MUSE developed by R. Gilman, G. Miller, and M.K. at PINAN2011, Morocco

MUSE timeline and status

- Proton radius puzzle not solved in 2023 – 13 years later
- Lepton non-universality in the center of beyond-SM effects

- MUSE first proposed in 2012, PAC-approved in 2013
- R&D program with NSF, BSF, and DOE support 2014 – 2016

- Technical design report November 2015
- Collaborative funding proposal to NSF in Nov 2015: Mid-scale
- NSF technical review February 2016

- Target conceptual design March 2016
- MOU with PSI April 2016
- Project management review May 2016 → award recommendation!

- Funding for construction has begun in fall 2016
- Construction and commissioning of MUSE 2016-2022
- Initial scattering data collected in Fall 2021 and Fall 2022

- Data taking for 12 calendar months – 5 months in 2023 ongoing

MUSE experiment layout

- **Beam particle tracking**
- **Liquid hydrogen target**
- **Scattered lepton detected**

Measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering

p = 115, 153, 210 MeV/c

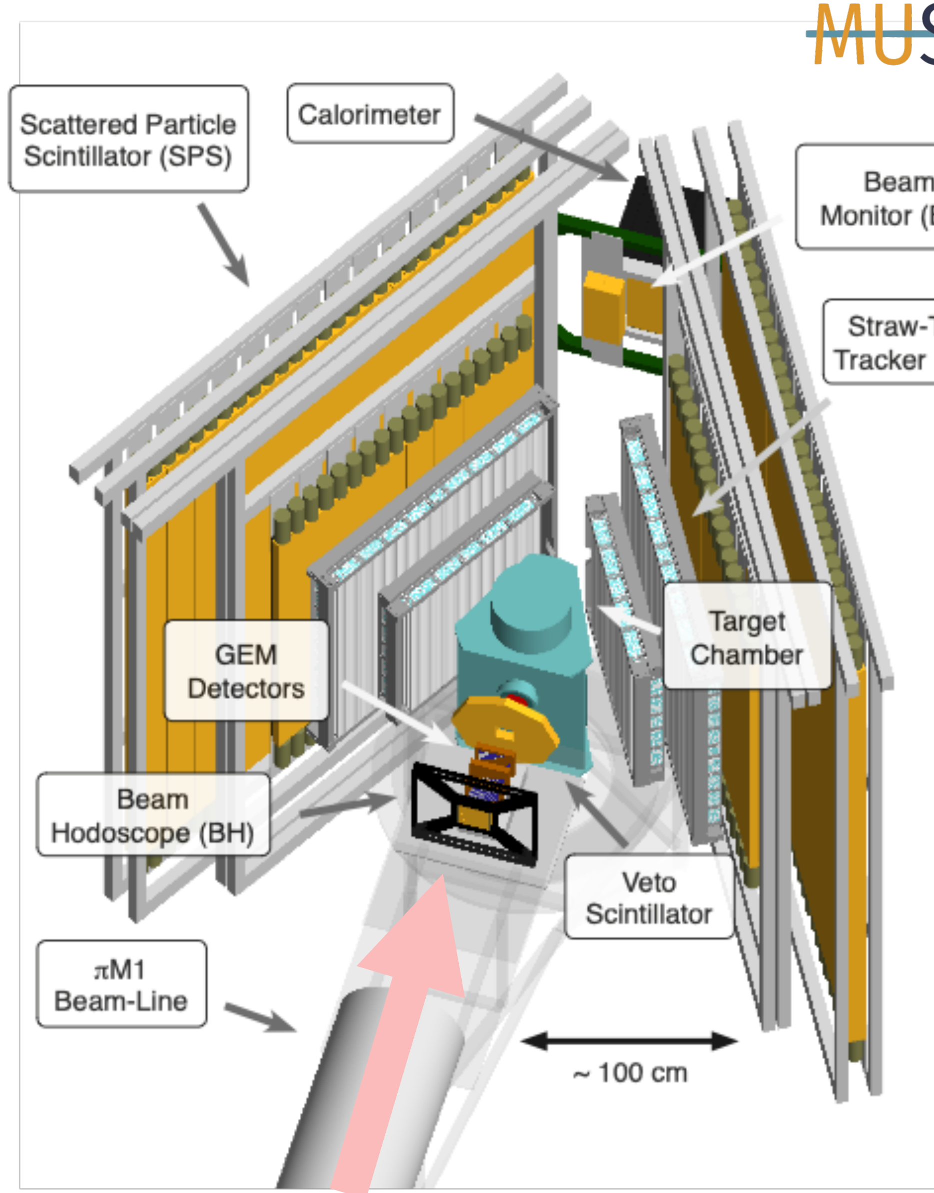
θ = 20° to 100°

Q^2 = 0.002 - 0.07 $(GeV/c)^2$

ε = 0.256 - 0.94

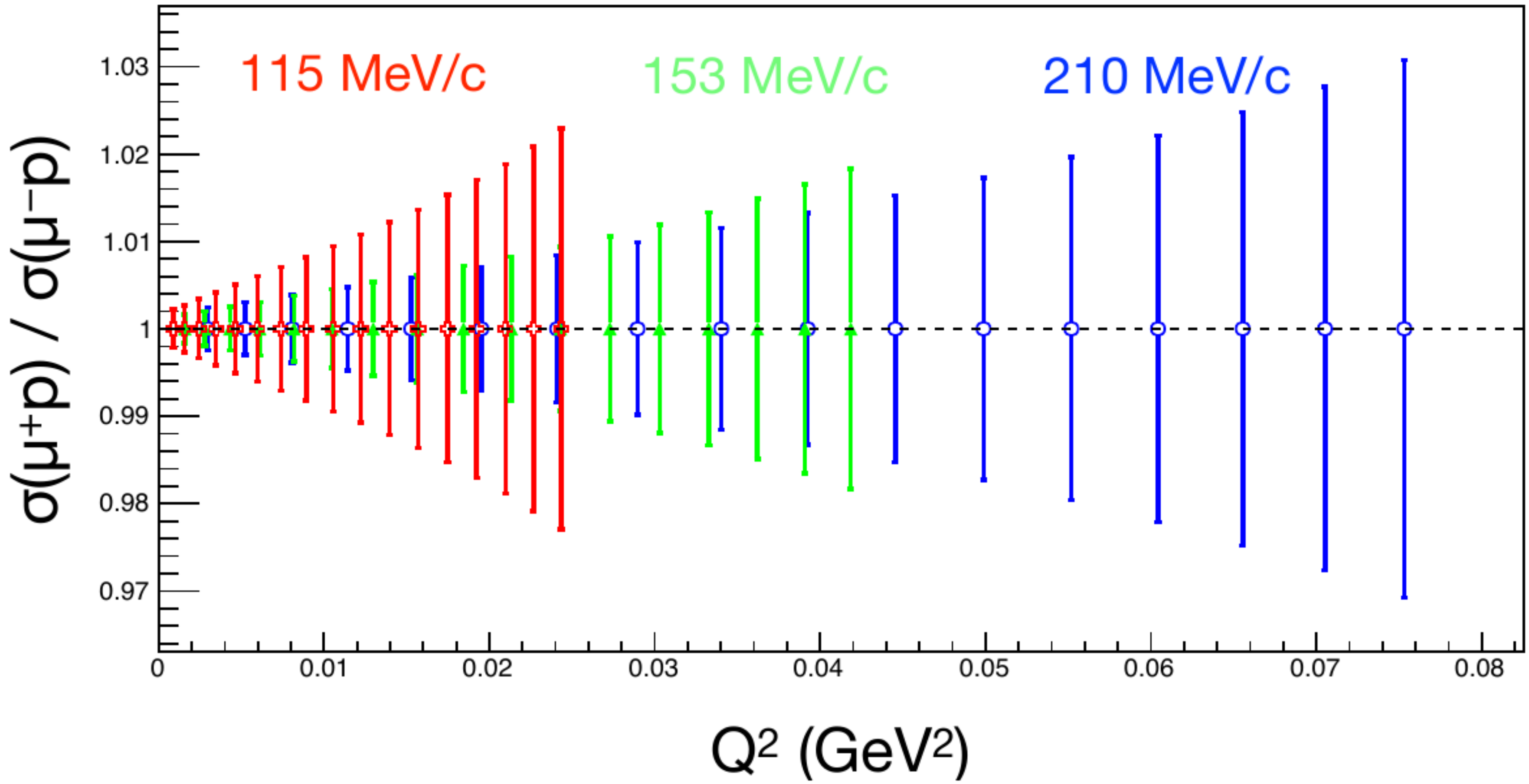
Challenges

- Secondary beam with π background – PID in trigger
- Non-magnetic spectrometer
- Background from Møller scattering and muon decay in flight



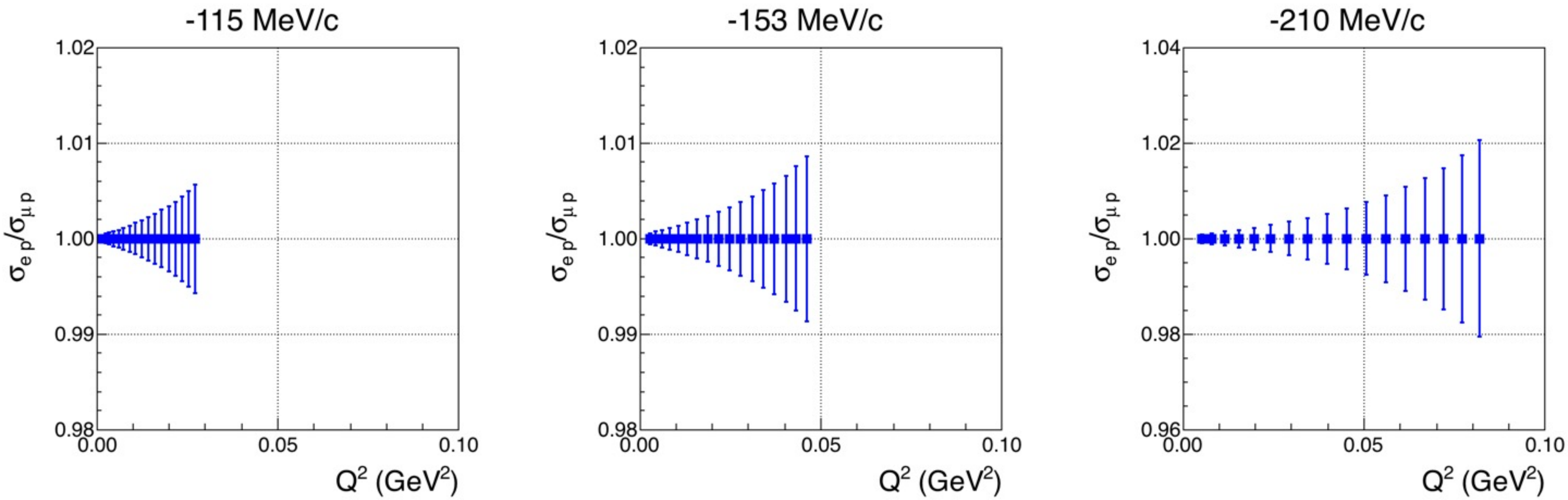
e/π/μ

MUSE: expected precision for TPE (muons)



- **Investigation of e+/e-, μ+/μ-**
- **Direct measurement of 2-photon effects**
- **TPE for muons could be sizable; for e+/e- expect sub-percent**

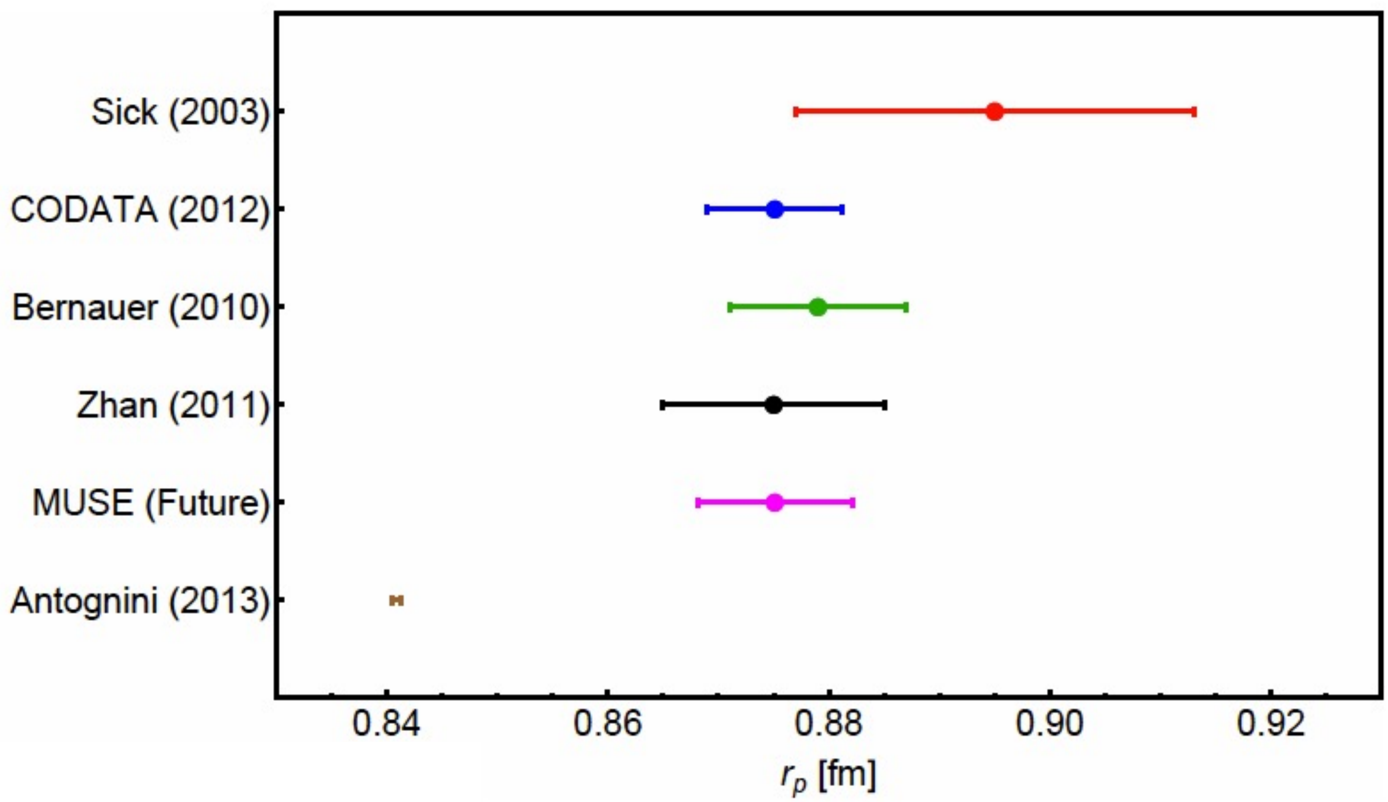
MUSE: expected precision for LU ratio



- **Comparison of ep and μp cross section statistical uncertainty, systematic better than 0.5%**
- ***The MUon Scattering Experiment at PSI (MUSE),*** **MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]**

MUSE: expected precision for charge radius

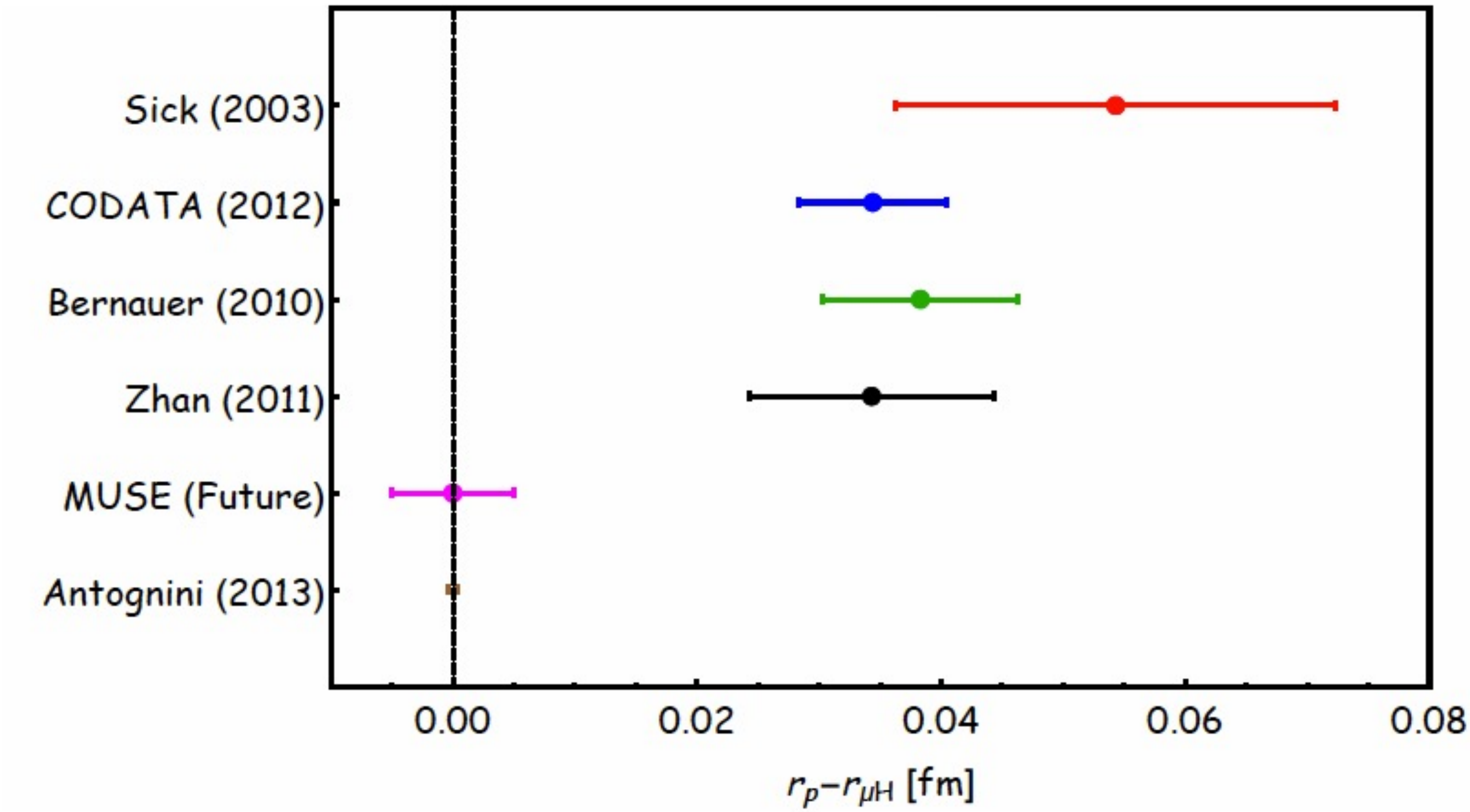
- **Cross sections** to <1% stat. for backward μ, <<1% for e and forward μ
  Absolute 2%, point-to-point relative uncertainties **few x10^{-3}**
- **Individual radius extractions** from $e^{\pm}$, $\mu^{\pm}$ each to **0.010 fm**
- Compare $e^{\pm}p$ and $\mu^{\pm}p$ for TPE. Charge-average to eliminate TPE.
- From e/μ xsec ratios: extract **e-μ radius difference** with minimal truncation error to **0.0045 fm or ~8σ** (1st-order fits)
- If no difference, extract **combined radius to 0.007 fm** (2nd-order fit)



MUSE: expected precision for radius diff.

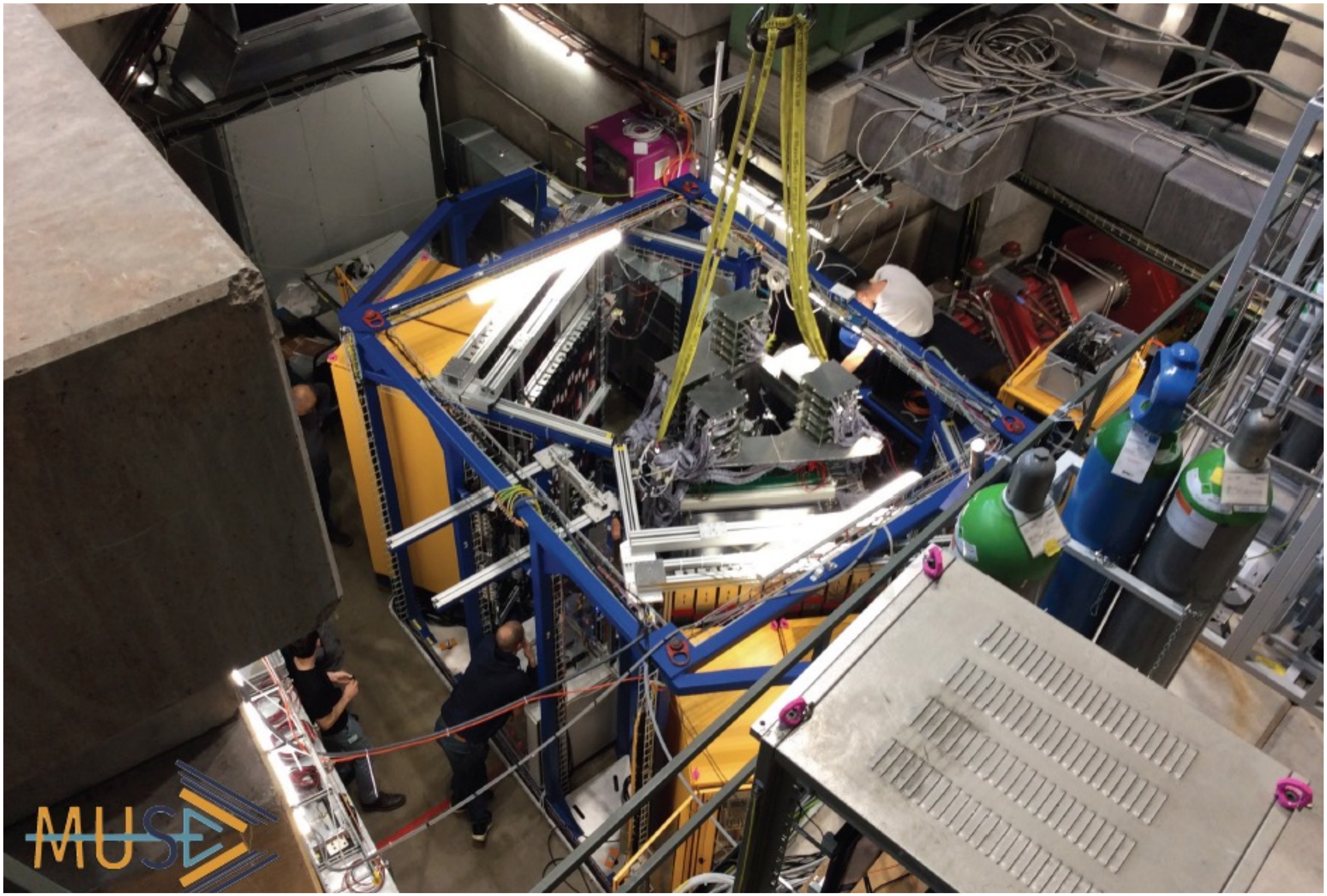
- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiment: Cancel in e+/e-, μ+/μ-, and μ/e comparisons
- R_e-R_μ = 0.034±0.006 fm (5.6σ), **MUSE: δ(R_e-R_μ) = 0.0045 fm (7.6σ)**

MUSE suited to verify 5.6σ effect (CODATA2014) with 7.6σ significance



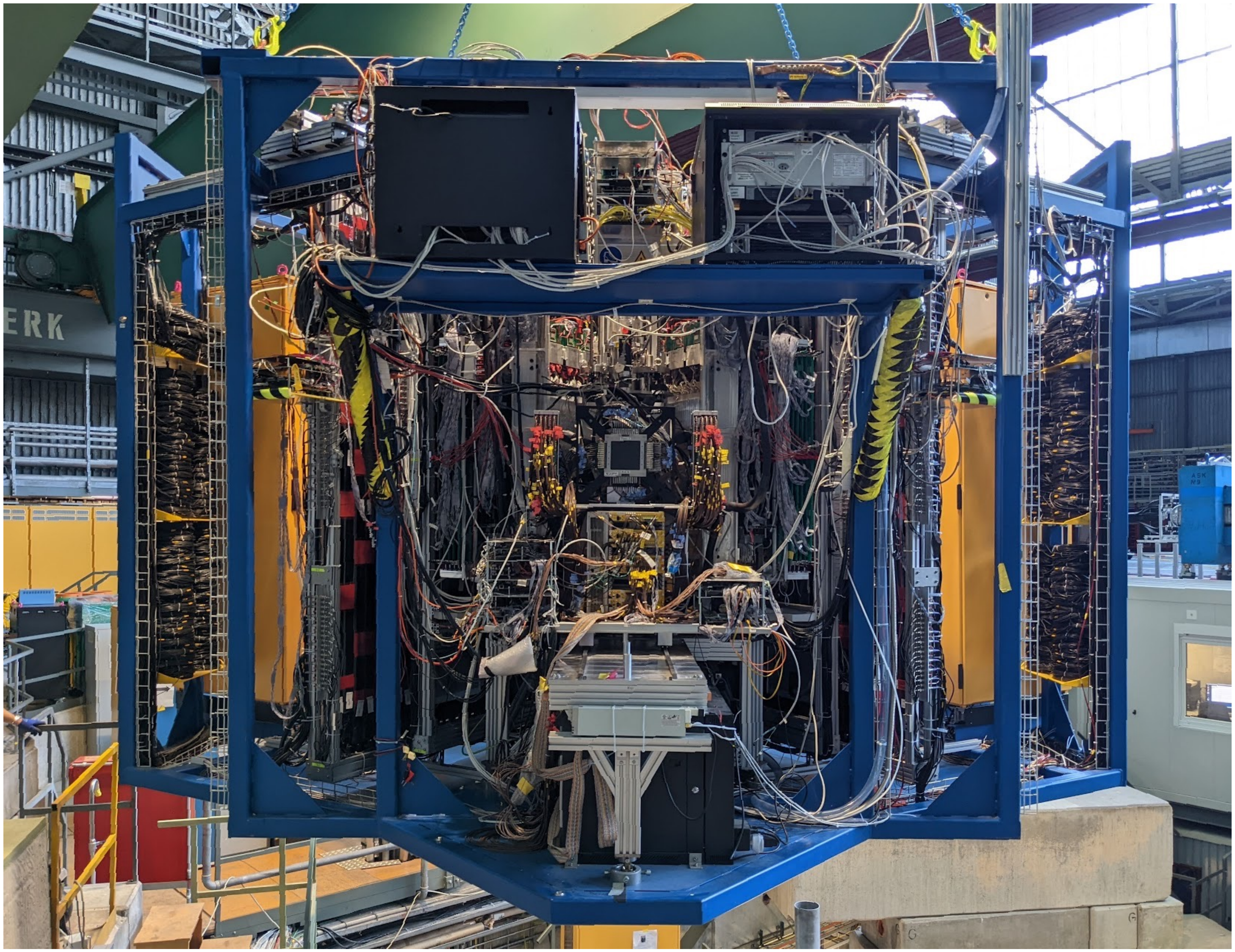
2018-2022 installation and commissioning

Dec. 2018: Assembly complete; Summer/fall 2019: Initial commissioning
Fall 2020/Spring 2021: Commissioning cont'd under Covid-19 constraints
From Fall 2022: Start production data for 12 beam months over ~2 years



2023-2025: production data taking

Dec. 2018: Assembly complete; Summer/fall 2019: Initial commissioning
Fall 2020/Spring 2021: Commissioning cont'd under Covid-19 constraints
From Fall 2022: Start production data for 12 beam months over ~2 years



MUon Scattering Experiment – MUSE

72 MUSE collaborators from 25 institutions in 5 countries:

A. Afanasev, A. Akmal, A. Atencio, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, K. Bailey, N. Benmouna, J. Bernauer, W.J. Briscoe, T. Cao, D. Cioffi, E. Cline, D. Cohen, E.O. Cohen, C. Collicott, K. Deiters, J. Diefenbach, S. Dogra, E.J. Downie, I. Fernando, A. Flannery, T. Gautam, D. Ghosal, R. Gilman, A. Golossanov, R. Gothe, D. Higinbotham, J. Hirschman, D. Hornidge, Y. Ilieva, N. Kalantarians, M.J. Kim, M. Kohl, O. Koshchii, G. Korcyl, K. Korcyl, B. Krusche, I. Lavrukhin, L. Li, J. Lichtenstadt, W. Lin, A. Liyanage, W. Lorenzon, K.E. Mesick, Z. Meziani, P. M. Murthy, J. Nazeer, T. O'Connor, P. Or, T. Patel, E. Piasetzky, R. Ransome, R. Raymond, D. Reggiani, H. Reid, P.E. Reimer, A. Richter, G. Ron, P. Roy, T. Rostomyan, P. Salabura, A. Sarty, Y. Shamai, N. Sparveris, S. Strauch, N. Steinberg, V. Sulkosky, A.S. Tadepalli, M. Taragin, and N. Wuerfel

PAUL SCHERRER INSTITUT

George Washington University, Montgomery College, Argonne National Lab, Temple University, Duquesne University, Stony Brook University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, University of Basel, Paul Scherrer Institute, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of South Carolina, Jefferson Lab, Massachusetts Institute of Technology, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University (April 2020)

TREK

- **Lepton non-universality?**
- **TREK Program**
  - **E06: Search for Time Reversal Symmetry Violation**
  - **E36: Test of Lepton Universality**
  - **Search for Heavy Neutrinos**
  - **Search for Light Bosons**

  (E36, Heavy Neutrinos, Light Bosons: Lower intensity)
- **TREK Apparatus**
- **Status**

E36 data taking completed in 2015 !

http://trek.kek.jp

TREK (E36/E06) collaboration

~30 collaborators

Spokespeople:
M.K., S. Shimizu

CANADA

University of British Columbia
Department of Physics and Astronomy

TRIUMF

USA

University of South Carolina
Department of Physics and Astronomy

University of Iowa
Department of Physics

Hampton University
Department of Physics

JAPAN

Osaka University
Department of Physics

Chiba University
Department of Physics

Rikkyo University
Department of Physics

High Energy Accelerator Research Organization (KEK)
Institute of Particle and Nuclear Studies

RUSSIA

Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)

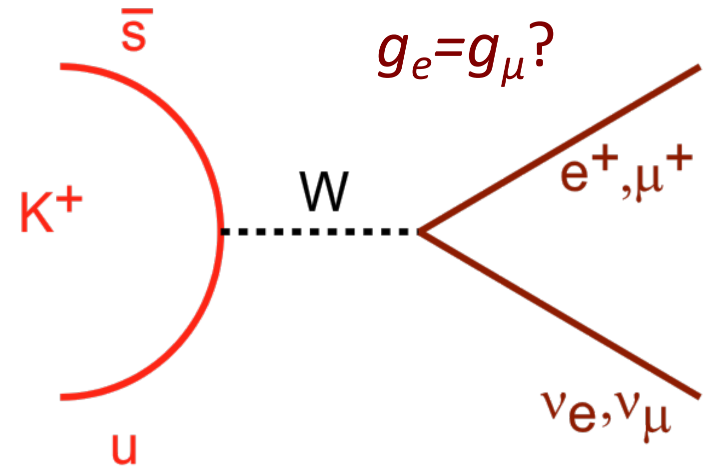
Timeline of TREK E06 and E36

- 2006: E06 (T-violation) Proposal (PAC1)
- 2009: J-PARC PS and HF start operating
- 2010: E36 (LFU/HNS) Proposal (PAC10)
- 2011: E36 stage-1 recommended (PAC11)
- 2012: E36 stage-1 approved (PAC15)
- 2013: E36 stage-2 recommended (PAC17)
- 2014: E36 stage-2 approved (PAC18)
- Detector preparation November 2014 – April 2015
- First commissioning run April 8 (24) – May 7, 2015
- Second commissioning run June 3 – 26, 2015
- Implemented improvements in summer 2015
- Production run October 14 – November 24, 2015
- Run extended until December 18, 2015
- 2016-2023: Analysis in progress and first results

Lepton universality in Standard Model K_{l2}

Standard Model:

- $$\Gamma(K_{l2}) = g_l^2 \frac{G^2}{8\pi} f_K^2 m_K m_l^2 \left(1 - \frac{m_l^2}{m_K^2}\right)^2$$



- **In the ratio of $\Gamma(K_{e2})$ to $\Gamma(K_{\mu 2})$, hadronic form factors are cancelled**

- $$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta_r)$$

helicity suppression *radiative correction (Internal Brems.)*

- **Strong helicity suppression of the electronic channel enhances sensitivity to effects beyond the SM**

- **Highly precise SM value**
  R_K^{SM}= (2.477±0.001) x 10^{-5} with δ_r = -0.036; (→ $\delta R_K/R_K$=0.04%)
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

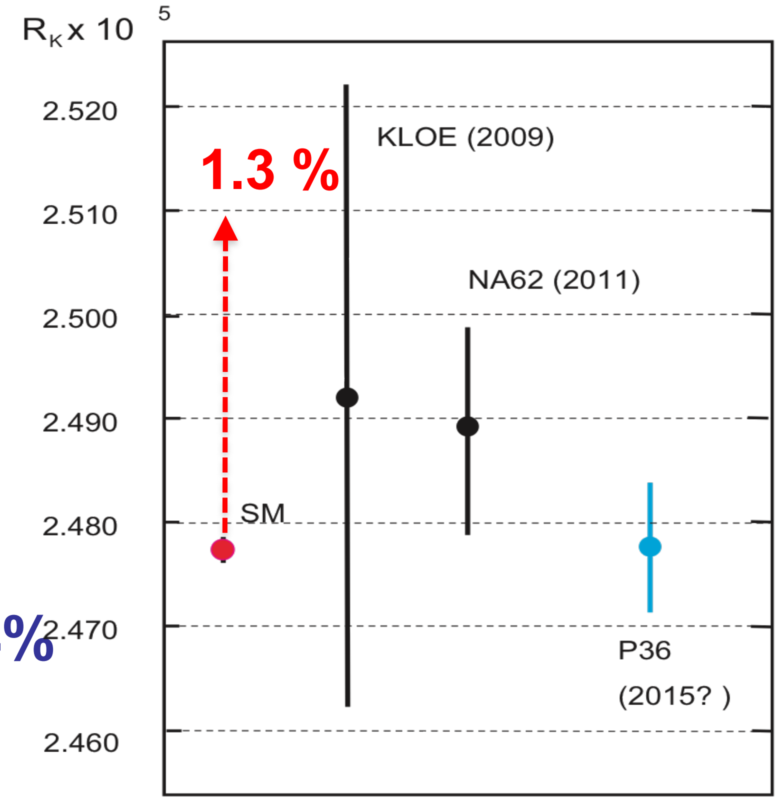
Experimental status of R_K

- **Highly precise SM value**
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$ (with $\delta_r = -0.036$), $\delta R_K/R_K = 0.04\%$
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

- **KLOE @ DAΦNE (in-flight decay)**
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
  F. Ambrosino et al., Eur. Phys. J. C64, 627 (2009)

- **NA62 @ CERN-SPS (in-flight decay)**
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
  C. Lazzeroni et al., PLB719, 105 (2013)

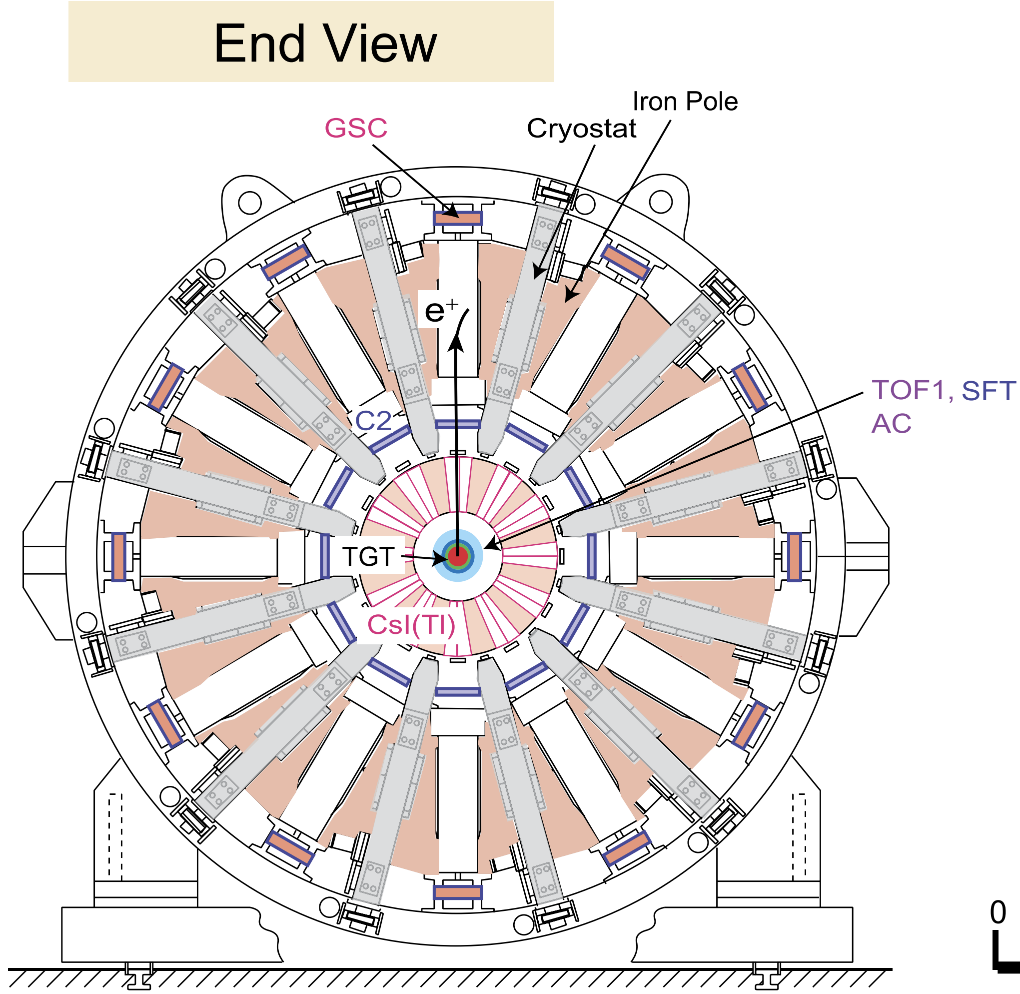
- **World average (2012)**
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$

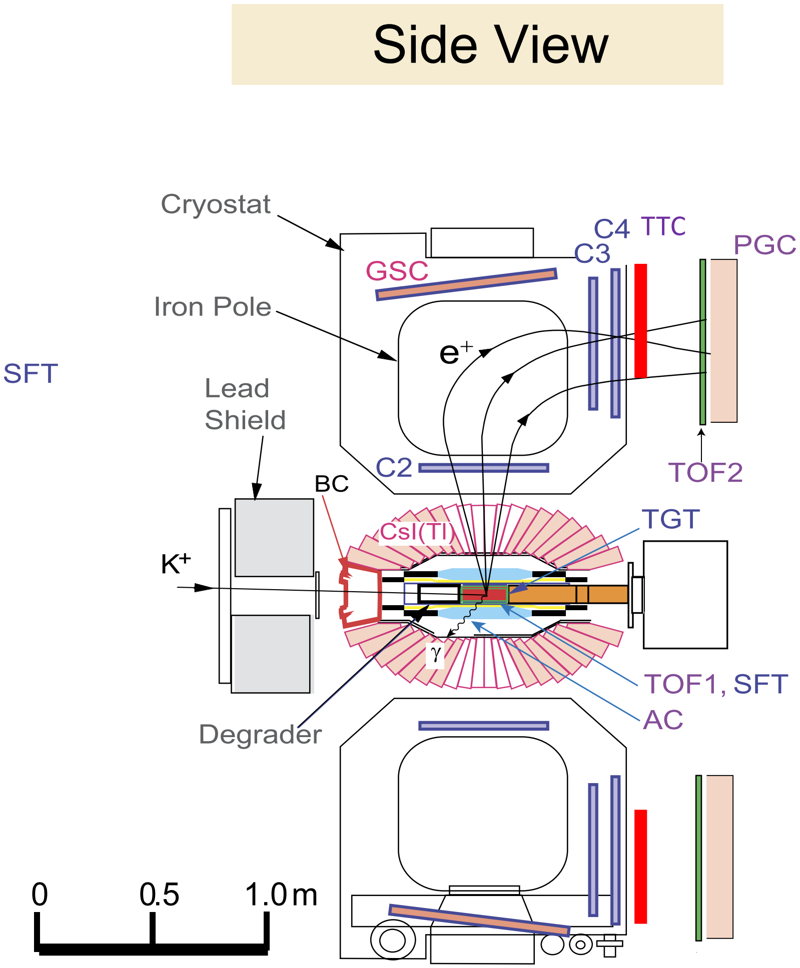


- **Dominant systematics:**
  - **In-flight-decay experiments: kinematics overlap**
  - **E36 stopped K^+: detector acceptance and target**
  - **E36 complementary to in-flight experiments**

- **E36 orig. goal: $\delta R_K / R_K = \pm$ 0.2% (stat) $\pm$ 0.15% (sys) [0.25% tot.]**

The TREK apparatus for E36





Modest upgrade of KEK-PS E246

Stopped K^+
- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target (TGT)

Tracking (π,μ,e)
- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)
- TGT, TOF1,2, TTC

PID
- TOF2-TOF1 (TOF)
- Aerogel Ch. (AC)
- Pb glass (PGC)

Gamma
- CsI(Tl)
- Gap scintillators (GSC)

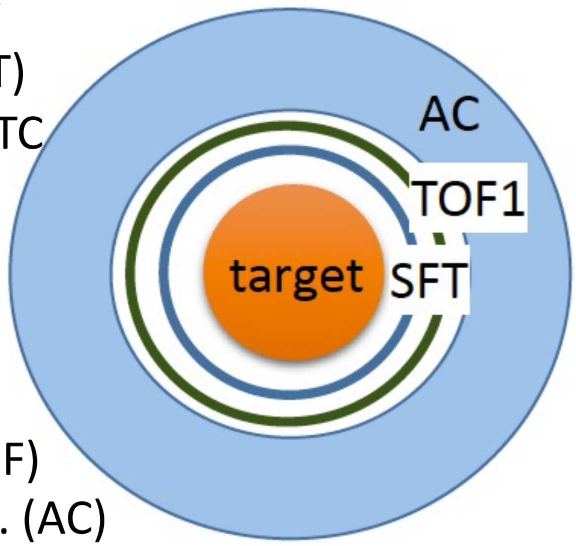
The TREK apparatus for E36

Stopped K^+
- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target

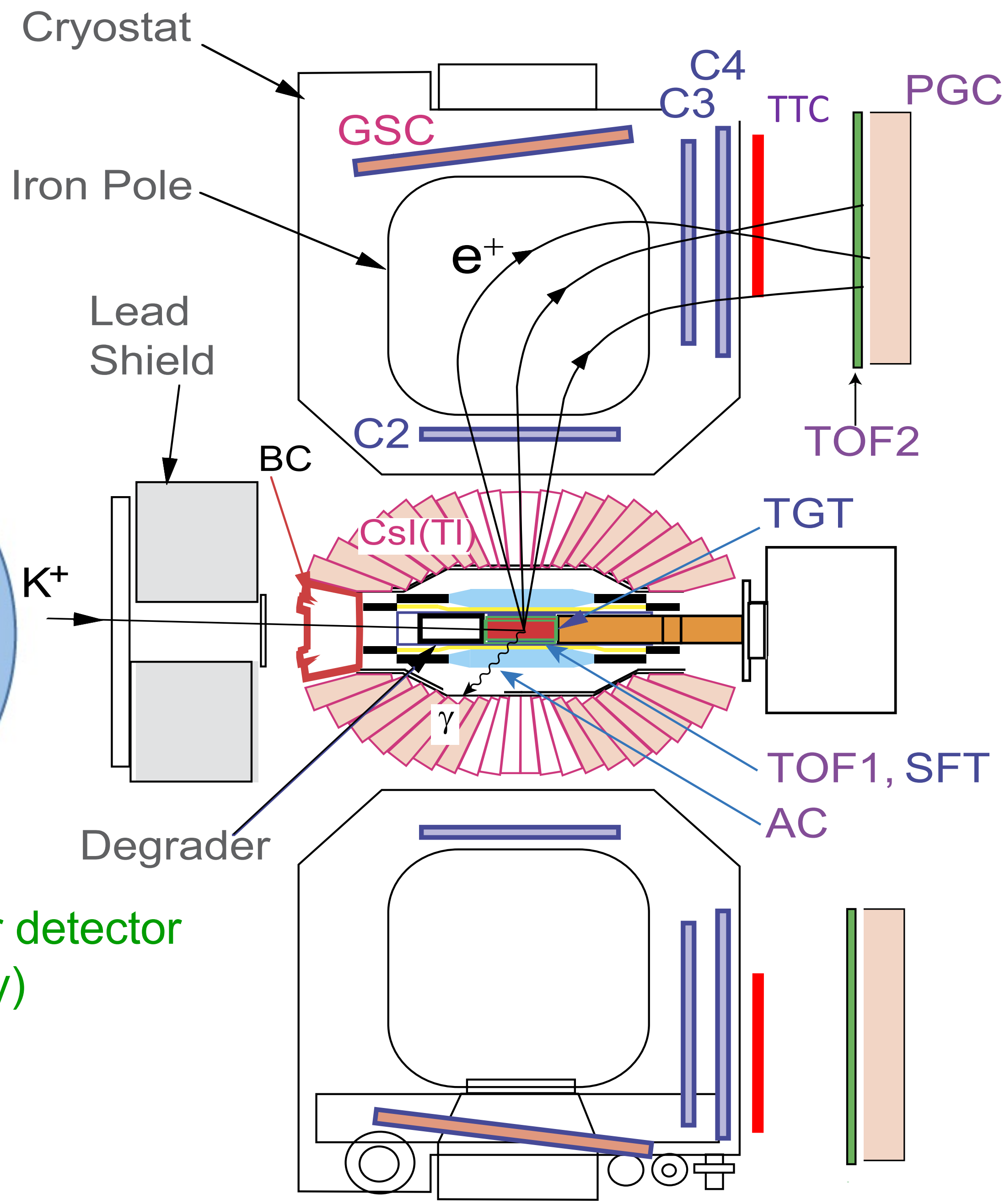
Tracking (π,μ,e)
- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)
- TGT, TOF, TTC

PID
- TOF1,2 (TOF)
- Aerogel Ch. (AC)
- Pb glass (PGC)

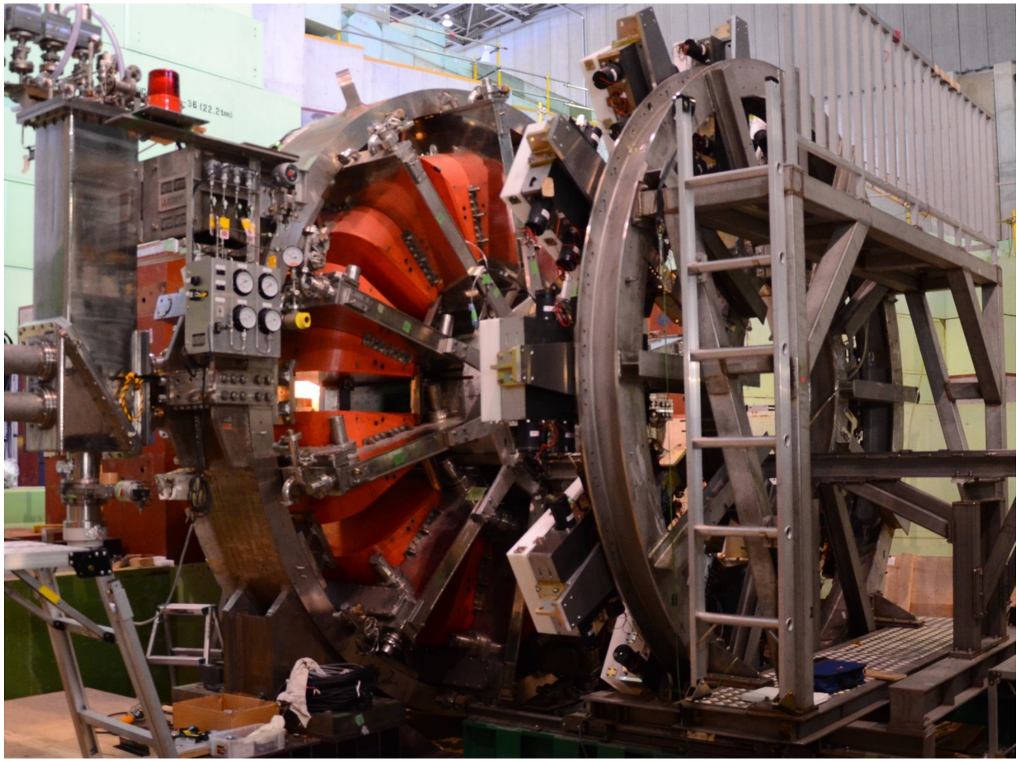
Gamma
- CsI(Tl)
- Gap scintillators (GSC)

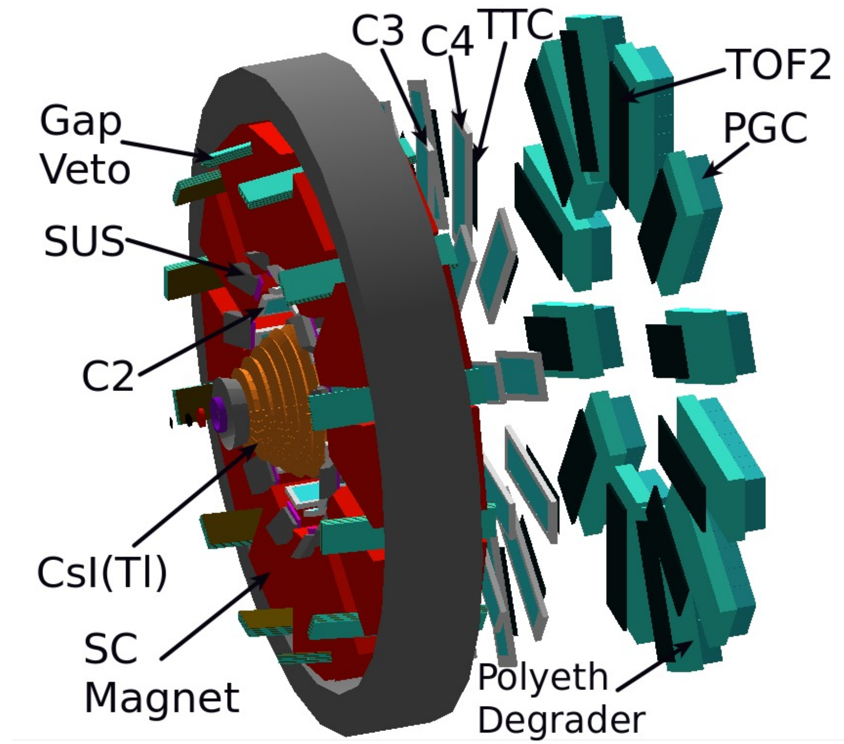


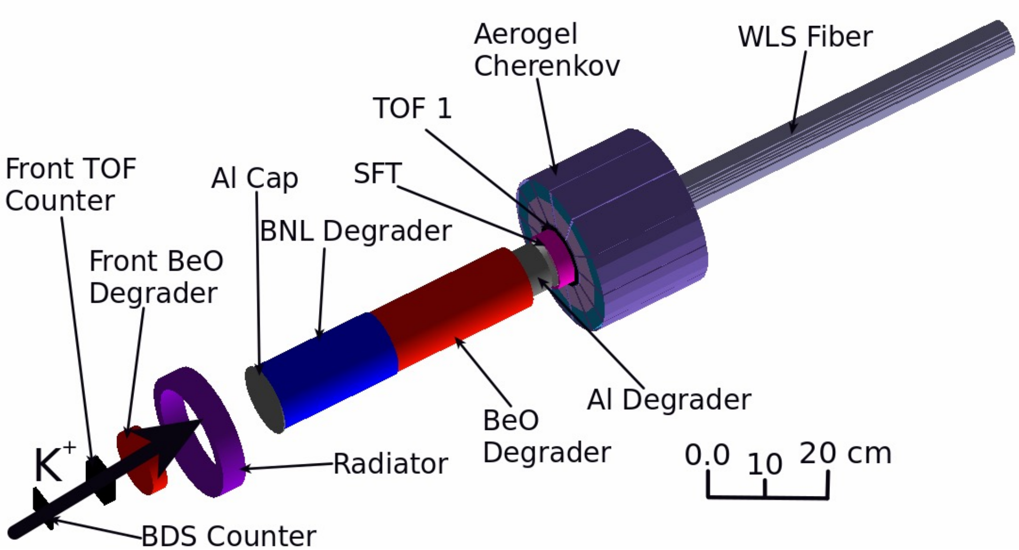
Zoomed inner detector (schematically)

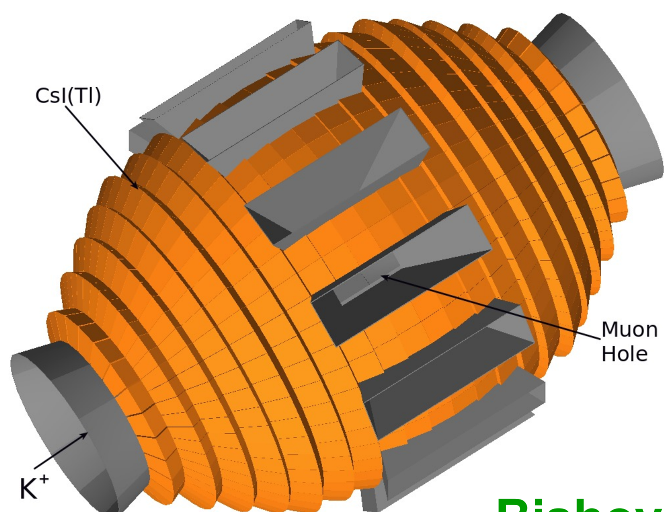


Geant4 description of TREK/E36







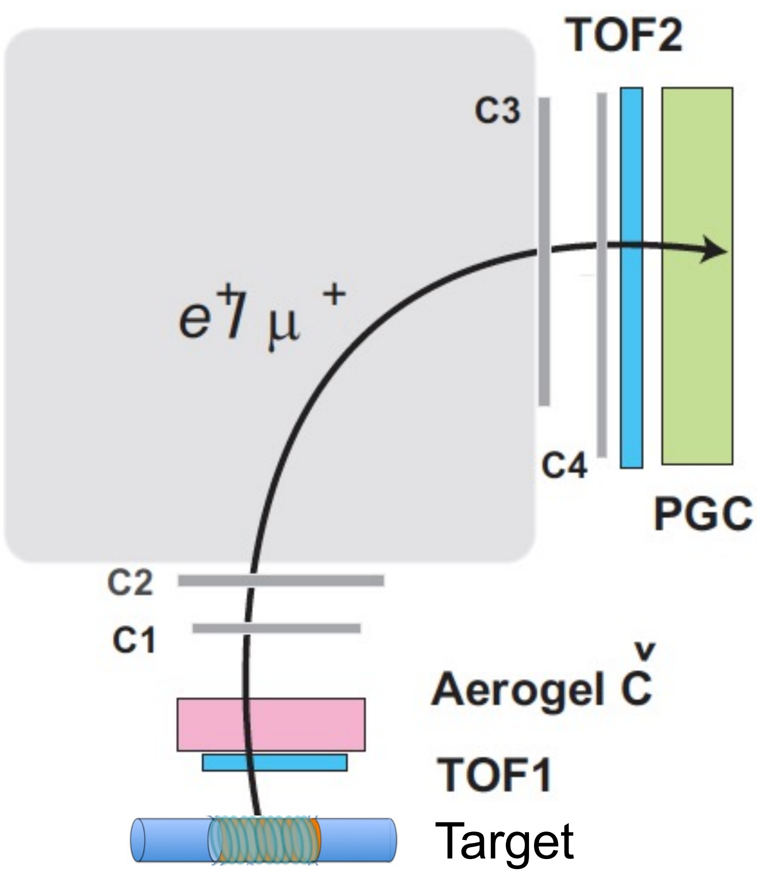


CsI(Tl)

Bishoy Dongwi

μ^+/e^+ identification (designed)

PID with:
- TOF
- Aerogel Č
- Lead glass

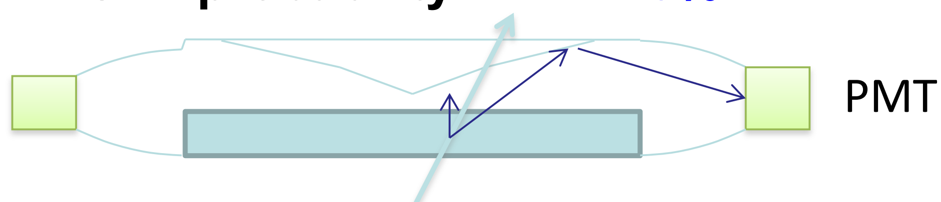


TOF

Flight length	250 cm
Time resolution	<100 ps
Mis-ID probability	7×10^{-4}

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%



Lead glass (PGC)

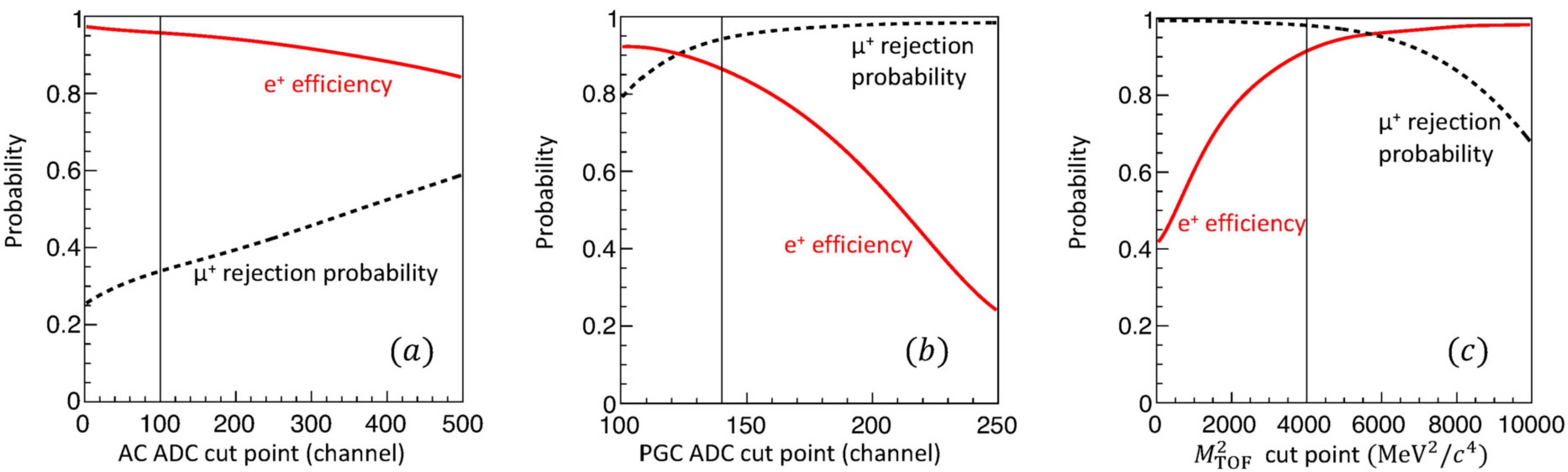
Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

μ^+/e^+ identification (typical performance)

- **Redundant PID to maximize e^+ efficiency and minimize μ^+ mis-ID**
- **PID with:**

Aerogel (AC) Leadglass (PGC) Time of flight (TOF)



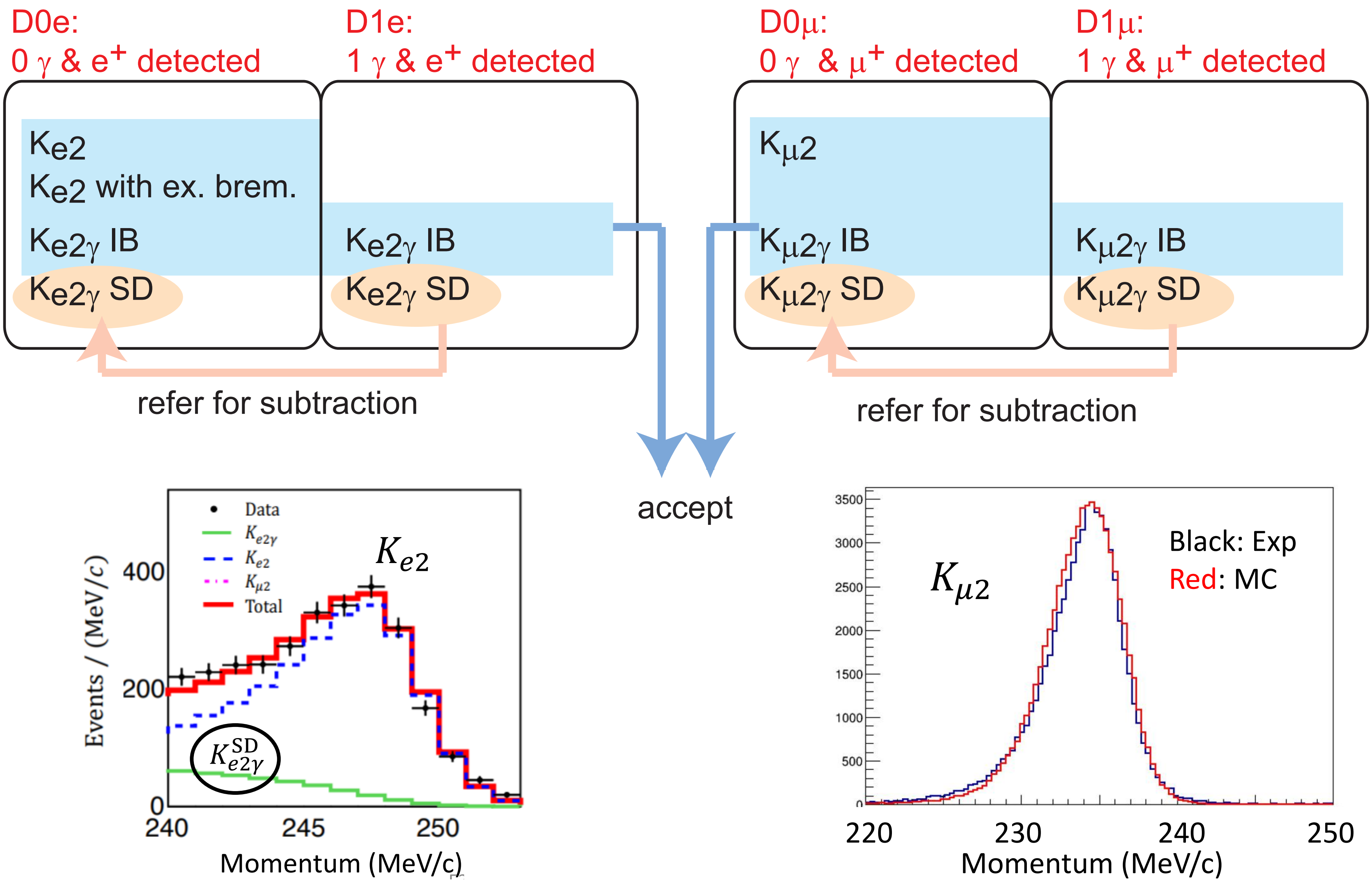
— e^+ efficiency ---- μ^+ rejection

H. Ito et al.,
PLB 826, 136913 (2022)

PID performance limitation requires subtraction of residual muon background

Toward $R_K = Br(K_{e2(\gamma)}) / Br(K_{\mu2(\gamma)})$

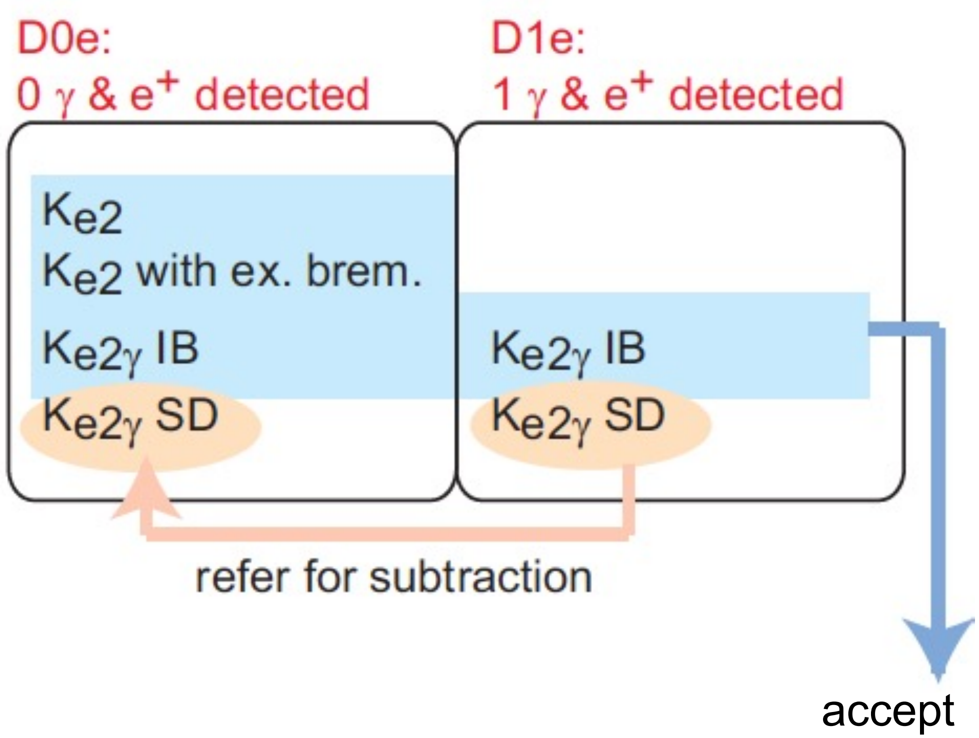
- **Subtraction of structure dependent $K_{e2\gamma}$ (SD) required**

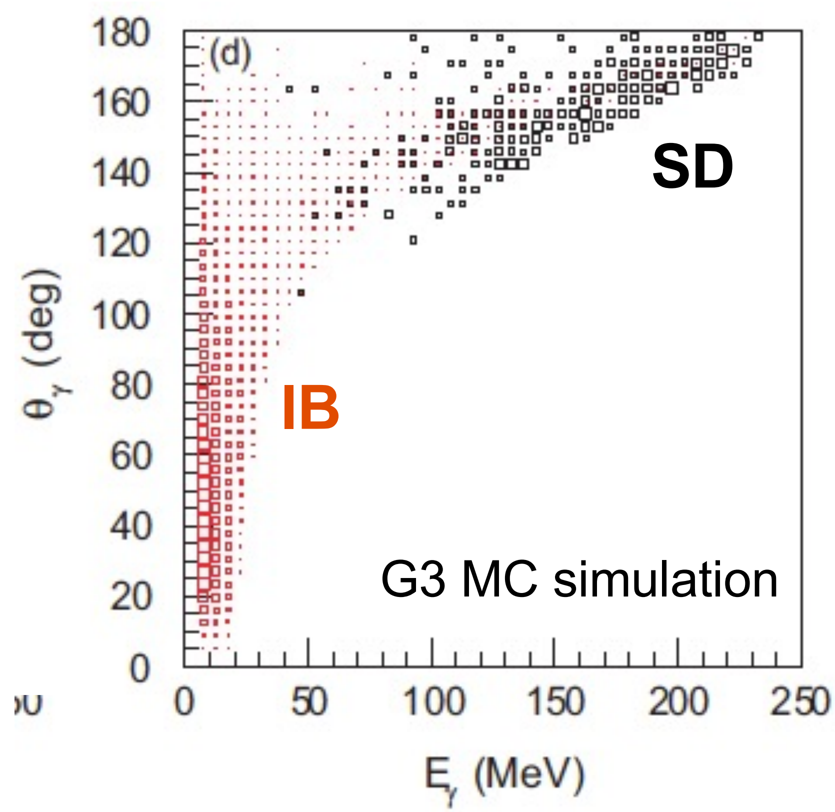


Extraction of $K_{e2\gamma}$(SD) and $K_{e2(\gamma)}$

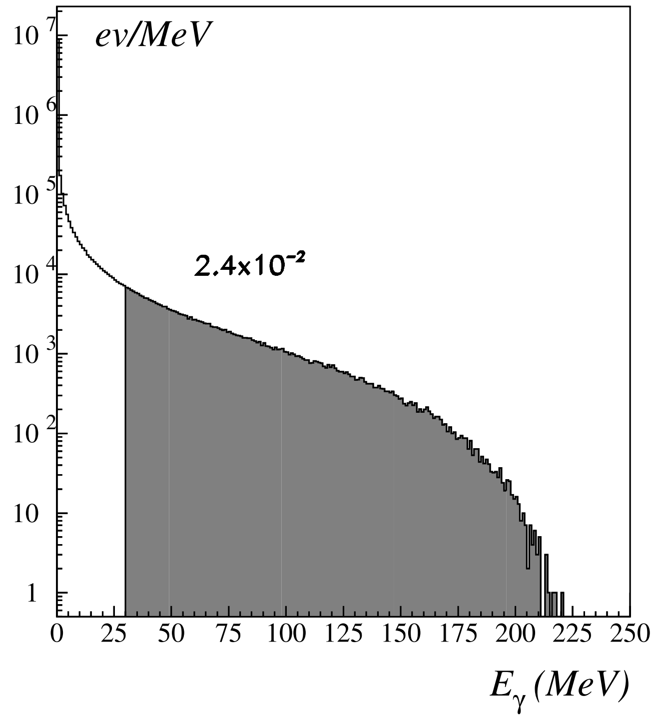
- Subtraction of structure dependent $K_{e2\gamma}$ (SD) required
- Internal bremsstrahlung (IB) to be included in K_{e2}: "$K_{e2(\gamma)}$"
- E36 and KLOE can measure the SD events
- $K_{e2\gamma}$ (SD) is important input for NA62 analysis ($\delta R_K/R_K=0.4\%$)

K. Horie, S. Shimizu





MC prescription by Gatti



C. Gatti, Eur. Phys. J. C 45, 417 (2006)

Example spectrum

Fig. 1. Energy spectrum for $K^0 \to \pi e \nu \gamma$ MC decays. 2.4% of the events have $E_\gamma > 30\,\mathrm{MeV}$

- **Analytic expressions for IB**

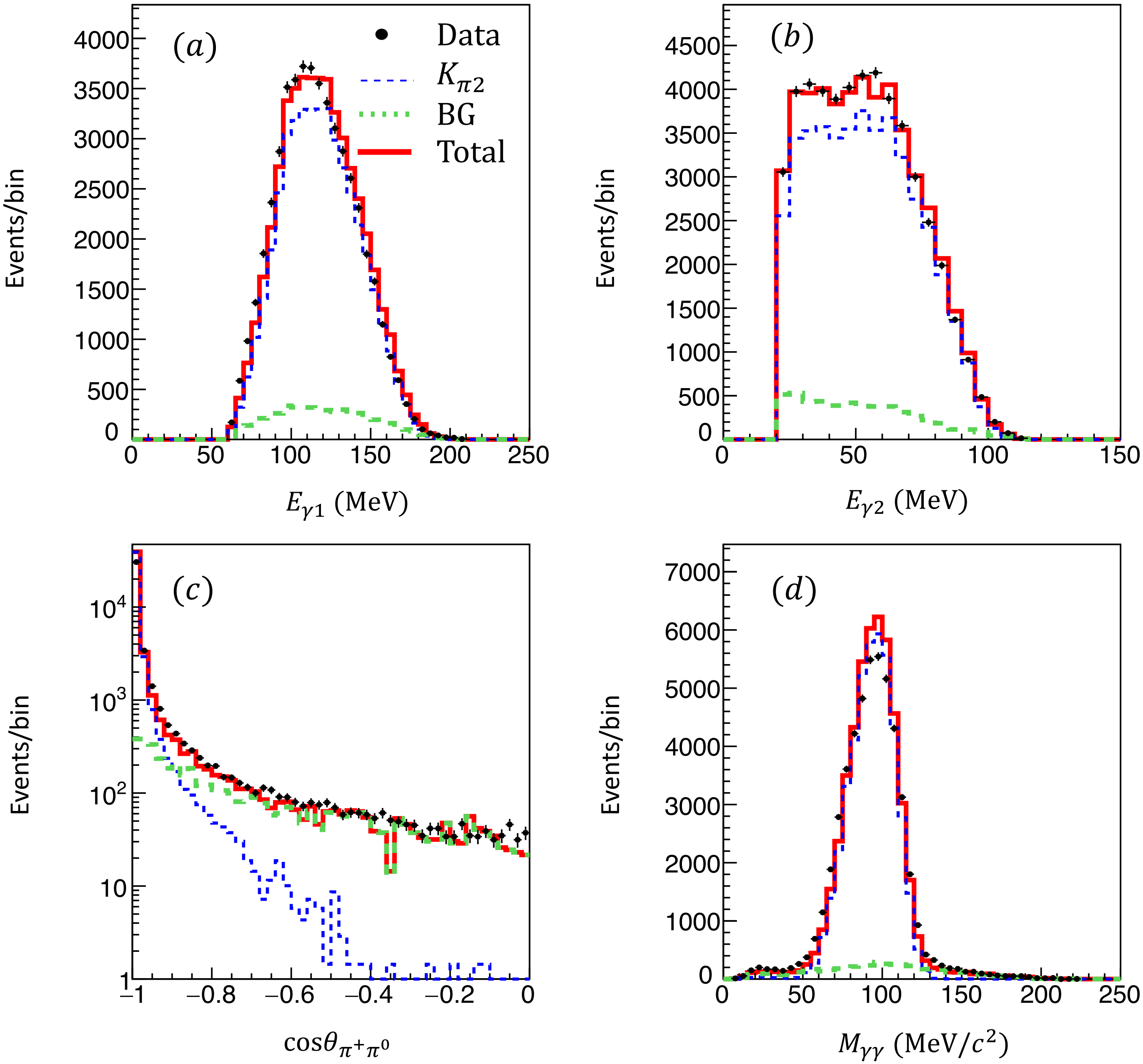
$$\frac{\mathrm{d}\Gamma_{\mathrm{incl}}}{\mathrm{d}E_\gamma} = \Gamma_0 b \frac{E_\gamma^{b-1}}{M^b} = \frac{\mathrm{d}\Gamma_{\mathrm{Brem}}}{\mathrm{d}E_\gamma}\left(\frac{E_\gamma}{M}\right)^b$$

$$b = -\frac{1}{8\pi^2}\sum_{m,n}\eta_m\eta_n e_m e_n \beta_{mn}^{-1}\ln\frac{1+\beta_{mn}}{1-\beta_{mn}}$$

$$\frac{\mathrm{d}\Gamma_{\mathrm{Brem}}}{\mathrm{d}E_\gamma} = \Gamma_0 \frac{b}{E_\gamma}$$

- **Works also for differential decay widths**
- **Simple implementation in MC generators**

CsI(Tl) calibration and accidental bg.



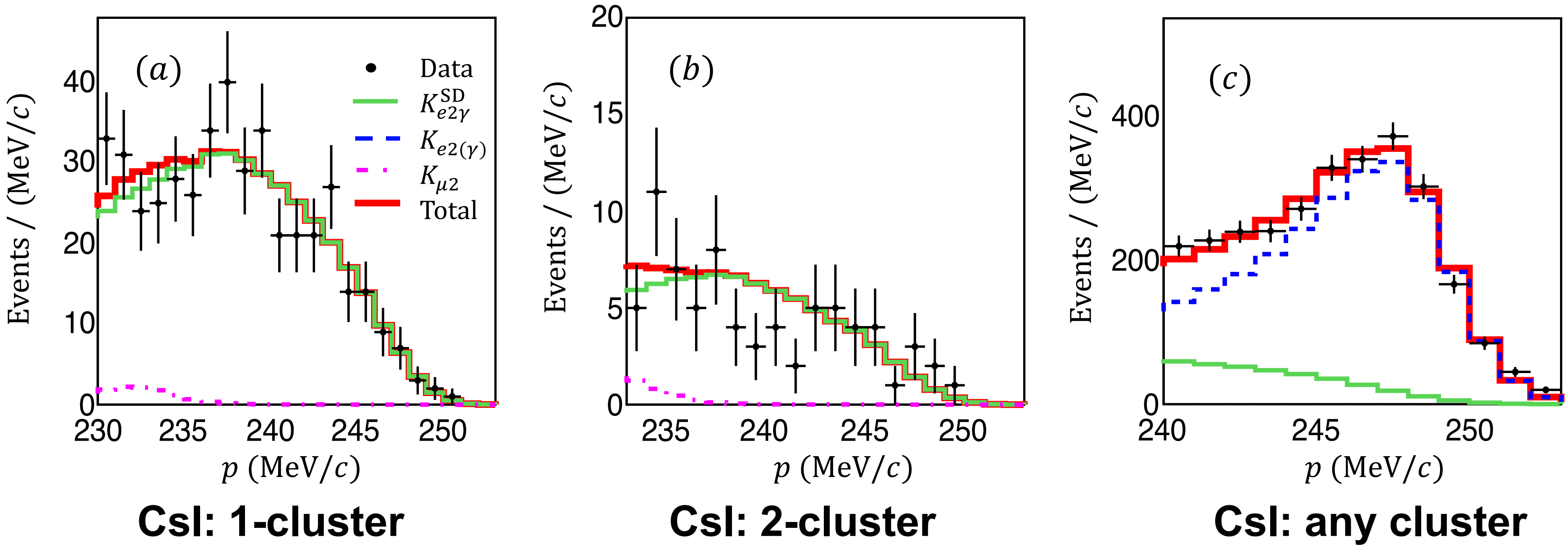
- $K_{\pi 2}$ ($K^+ \rightarrow \pi^+\pi^0$) recon. 2-cluster events
- **Accidental bg: $K_{\mu 2}$ + 1-cluster (~19%) exp. acc. spect.**
- **Mixing exp. acc. with simulated 1-cluster $K_{\pi 2}$ for acc. background in 2-cluster evts.**

Extraction of $K_{e2\gamma}$(SD) and $K_{e2(\gamma)}$

- **Positron momentum spectrum**
- **PID applied with AC, PGC, TOF**
- **Decomposition of $K_{e2(\gamma)}$, $K_{e2\gamma}^{SD}$, $K_{\mu 2}$, K_{e3} *yields***
- **Internal bremsstrahlung (IB) effect included in $K_{e2(\gamma)}$**

H. Ito et al., PLB 826, 136913 (2022)

C. Gatti, EPJC 45, 417 (2006)



E36 (CsI) result for $K_{e2\gamma}$ (SD):

$BR(K_{e2\gamma}^{SD})/BR(K_{e2(\gamma)}) = 1.12 \pm 0.07$ stat. $\pm$ 0.04 sys.

Comparison of $K_{e2\gamma}$(SD) w/ KLOE & Theory

E36: BR($K^{SD}_{e2\gamma}$)/BR($K_{e2(\gamma)}$) = 1.12 ± 0.07 stat. ± 0.04 sys.

H. Ito *et al.*, PLB 826, 136913 (2022)

Comparison with KLOE: convert E36 ratio, reduce phase space

$$\frac{Br(K^{\mathrm{SD}^+}_{e2\gamma})}{Br(K_{\mu 2})} = \frac{Br(K^{\mathrm{SD}^+}_{e2\gamma})}{Br(K_{e2(\gamma)})} \times \frac{Br(K_{e2(\gamma)})}{Br(K_{\mu 2})} = \frac{Br(K^{\mathrm{SD}^+}_{e2\gamma})}{Br(K_{e2(\gamma)})} \times R_K^{\mathrm{SM}}$$

$$R_\gamma = \frac{Br(K^{\mathrm{SD}^+}_{e2\gamma},\ p > 200\ \mathrm{MeV}/c,\ E_\gamma > 10\ \mathrm{MeV})}{Br(K_{\mu 2})}$$

E36: $R_\gamma = (1.85 \pm 0.11_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}}) \times 10^{-5}$

KLOE: $R_\gamma = (1.483 \pm 0.066_{\mathrm{stat}} \pm 0.013_{\mathrm{syst}}) \times 10^{-5}$

F. Ambrosino *et al.*, Eur. Phys. J. C64, 627 (2009)

ChPT:
$R_\gamma = 1.477 \times 10^{-5}$

J. Bijnens, G. Ecker, J. Gasser, Nucl. Phys. B 396, 81 (1993)

Lattice-QCD: $R_\gamma = (1.74 \pm 0.21) \times 10^{-5}$

R. Frezzotti, *et al.*, Phys. Rev. D 103, 053005 (2021)

E36: Agree with Lattice (~1σ), disagree with ChPT (~3σ)

New extraction of $K_{e2\gamma(\gamma)}$(SD)

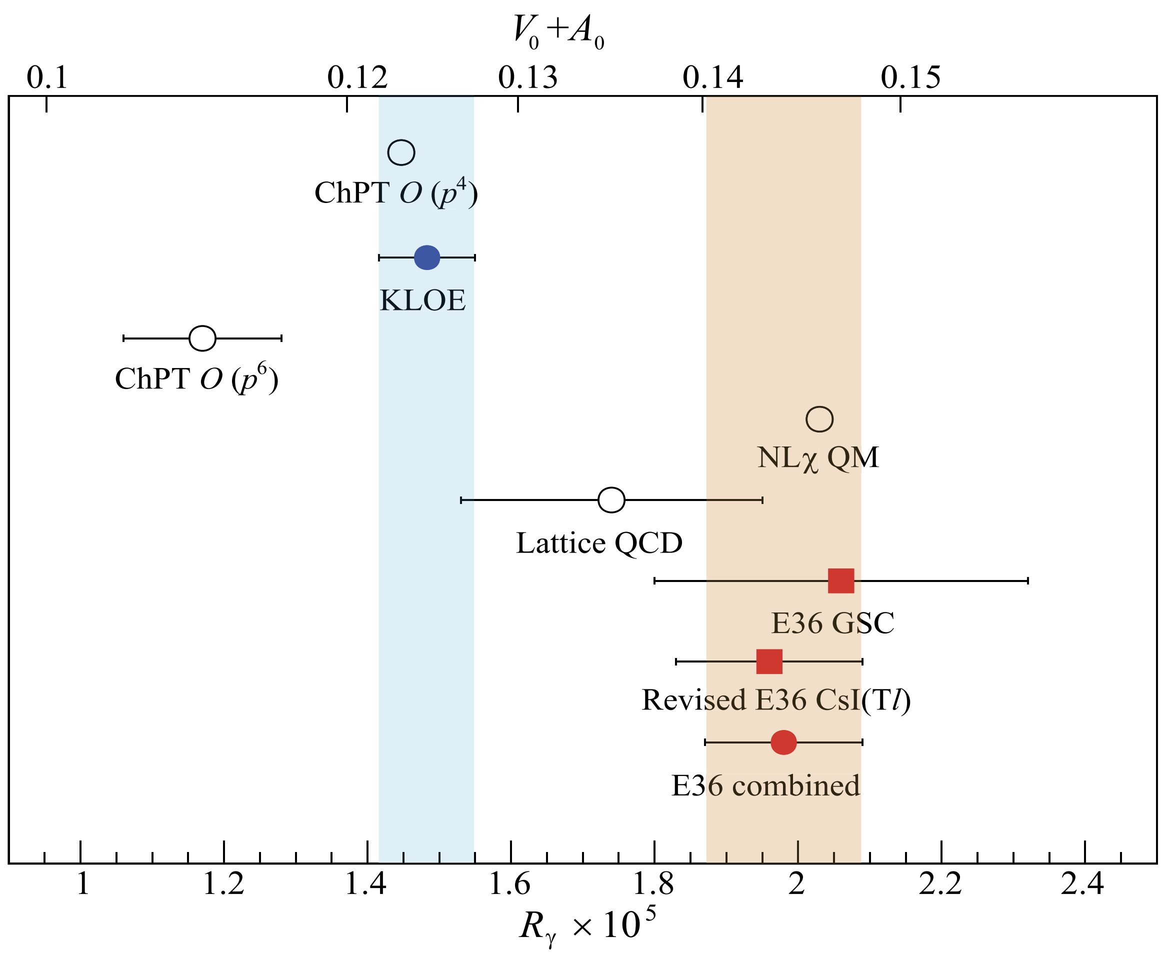
- **Caveat:** IB correction was only applied to $K_{e2(\gamma)}$, not to $K_{e2\gamma}$ (SD) Narrow e^+ momentum interval requires accounting for acceptance loss due to hard photon IB tail
- Similarly, acceptance of $K_{e2\gamma(\gamma)}$ (SD) affected by hard photon radiation, too
- **Implementation:** Following prescription by Gatti, using radiative MC generators for both $K_{e2(\gamma)}$ and $K_{e2\gamma(\gamma)}$ (SD)
  C. Gatti, Eur. Phys. J. C 45, 417 (2006)

- **E36:** Additional E36 data from Gap Scintillation Counters (GSC)
  → New E36 result for CsI(Tl) + GSC:

Previously: $BR(K_{e2\gamma})/BR(K_{e2(\gamma)})$ = 1.12 ± 0.07 stat. ± 0.04 sys.
H. Ito *et al.*, Phys. Lett. B 826, 136913 (2022)

$BR(K^{SD}_{e2\gamma(\gamma)})/BR(K_{e2(\gamma)})$ = 1.25 ± 0.14 stat. ± 0.08 sys. – GSC
$BR(K^{SD}_{e2\gamma(\gamma)})/BR(K_{e2(\gamma)})$ = 1.19 ± 0.07 stat. ± 0.04 sys. – CsI(Tl) [+6%]
Error-weighted mean: 1.20 ± 0.07 → $R_\gamma = (1.98 \pm 0.11) \times 10^{-5}$
Agree with Lattice (~1σ), disagree with ChPT (~4σ)
A. Kobayashi *et al.*, Phys. Lett. B 843, 138020 (2023) - *10 August, online June 14, 2023*

New extraction of $K_{e2\gamma(\gamma)}$(SD)



BR($K^{SD}_{e2\gamma(\gamma)}$)/BR($K_{e2(\gamma)}$) = 1.25 ± 0.14 stat. ± 0.08 sys. – GSC

BR($K^{SD}_{e2\gamma(\gamma)}$)/BR($K_{e2(\gamma)}$) = 1.19 ± 0.07 stat. ± 0.04 sys. – CsI(Tl) [+6%]

Error-weighted mean: 1.20 ± 0.07 → R_γ = (1.98±0.11) x 10^{-5}

Agree with Lattice (~1σ), disagree with ChPT (~4σ)

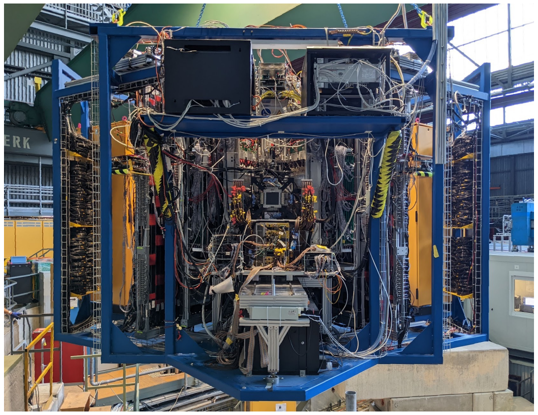
A. Kobayashi *et al.*, Phys. Lett. B 843, 138020 (2023) - *10 August, online June 14, 2023*

Summary

- **Lepton universality is challenged (BaBar, Belle, LHCb; g_μ-2; PRP)**
  However: Most recent LHCb result on μ-e universality agrees with SM
- **Muon g-2 and proton radius puzzle are so far largest hints for μ-e LUV**
- **MUSE: plays key role for testing of μ-e universality and solving PRP**

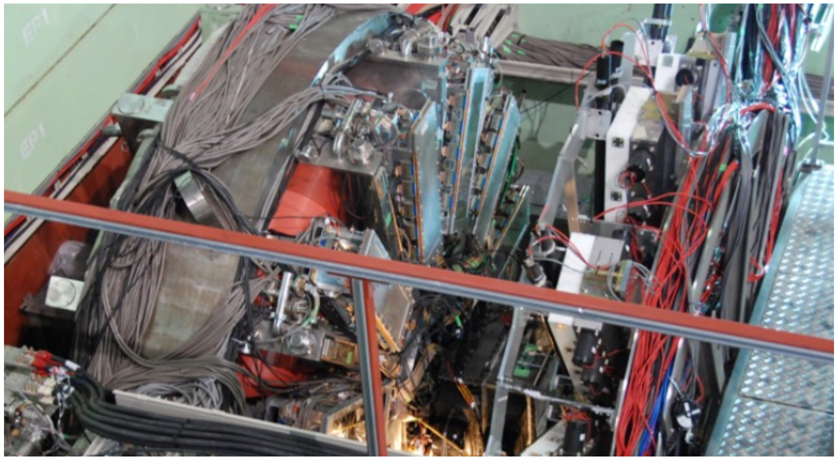
PAUL SCHERRER INSTITUT PSI

MUSE



- **TREK/E36:**
  Measurement of $R_K = BR(K_{e2(\gamma)})/BR(K_{\mu 2(\gamma)})$ – test of μ-e universality
  Extraction of R_K underway
  Measured structure-dep. $BR(K_{e2\gamma}(SD))$

J-PARC



Backup

Systematics

Table 2
Summary of the systematic uncertainties for the $Br(K_{e2\gamma}^{SD^+})/Br(K_{e2(\gamma)})$ ratio determination.

Source	Systematic uncertainty
Hole size of CsI(Tl) calorimeter	0.017
CsI(Tl) misalignment	< 0.001
Imperfect reproducibility of photon angular distribution	< 0.001
Accidental backgrounds in CsI(Tl)	0.004
Photon energy threshold of CsI(Tl)	0.007
Photon energy calibration of CsI(Tl)	< 0.001
Photon timing window	0.009
CsI(Tl) detection efficiency	0.012
AC detection(PID) efficiency	0.007
PGC detection(PID) efficiency	0.007
TOF detection(PID) efficiency	0.019
$K_{\mu 2}$ background subtraction	0.015
$K_{e2\gamma}^{SD^+}$ form factor	0.011
K^+ stopping distribution	0.003
Material thickness in the central parts	< 0.001
Positron momentum resolution	0.002
Magnetic field	0.002
In-flight kaon decay	0.002
Total	0.036