Lepton Universality Test with MUSE at PSI

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for the MUSE Collaboration

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Lepton universality

- **Lepton universality**
- **The Proton Radius Puzzle: A >7σ discrepancy**
- **The MUSE experiment**
  - **Sensitivity**
  - **Overview**
  - **Status**

Lepton non-universality is presently the most compelling signal for New Physics beyond SM

Limits of lepton universality (LU)

- 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 (update from March 2021)

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

3.1σ dev.

- Muon anomalous mag. moment (Apr 2021) $a_\mu = 116\,592\,061(41)\times 10^{-11}$

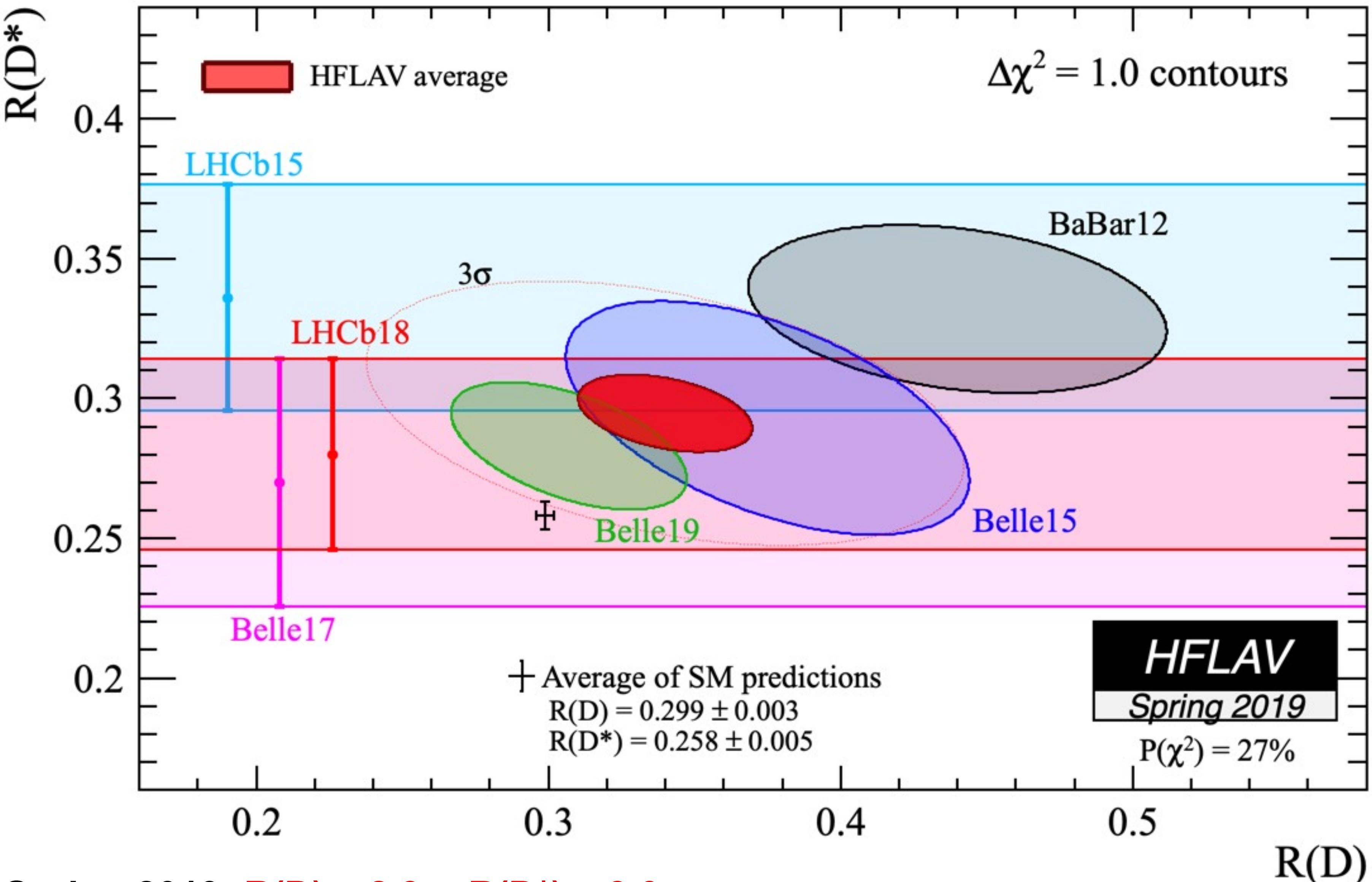
4.2σ dev.

- Proton charge radius puzzle (since 2010)

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

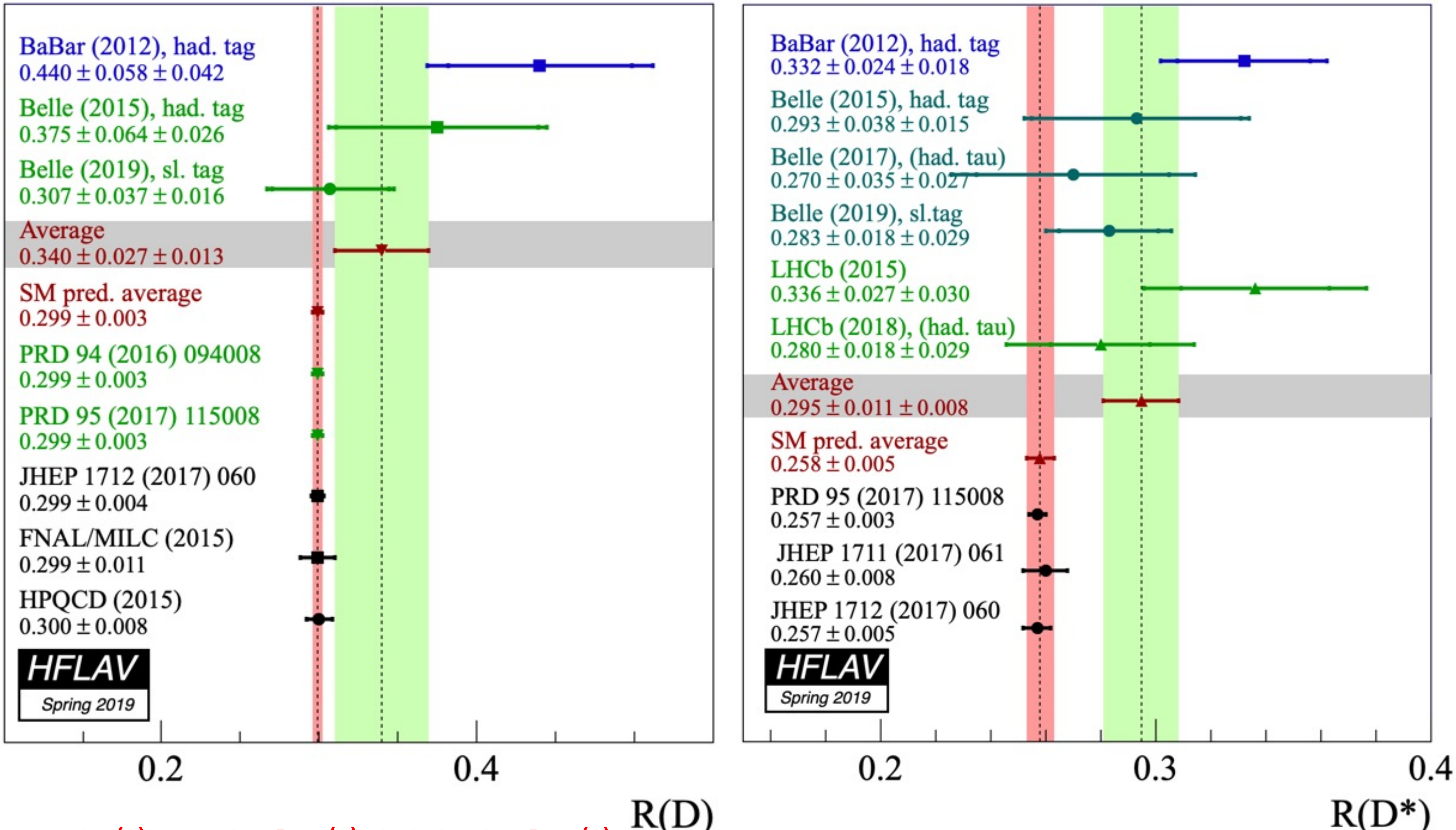
5.6σ dev.

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



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

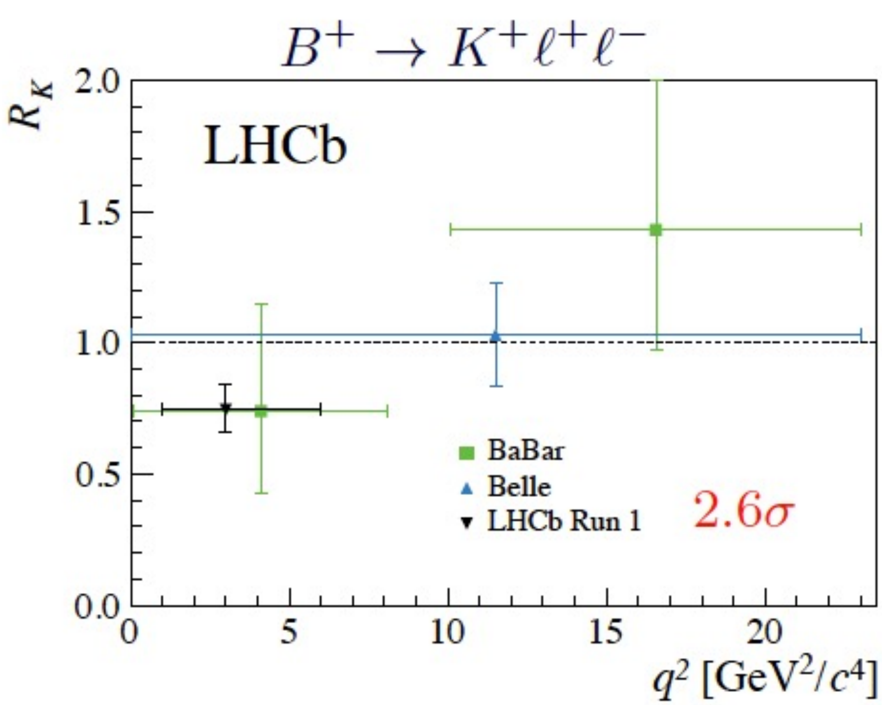
Lepton non-universality in B-decays (τ-μ)

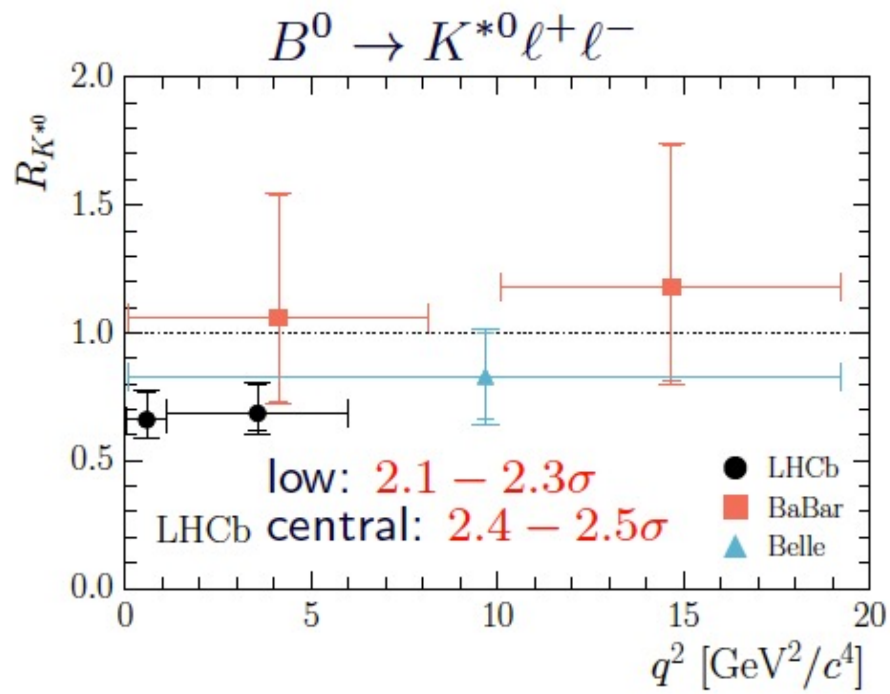


- **$R(D^{(*)}) = \Gamma(B \to D^{(*)}\tau^+\nu) / \Gamma(B \to D^{(*)}\mu^+\nu)$**
- **Spring 2019: R(D) ~ 2.3σ, R(D*) ~ 3.0σ Combined at 3.62σ**

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]

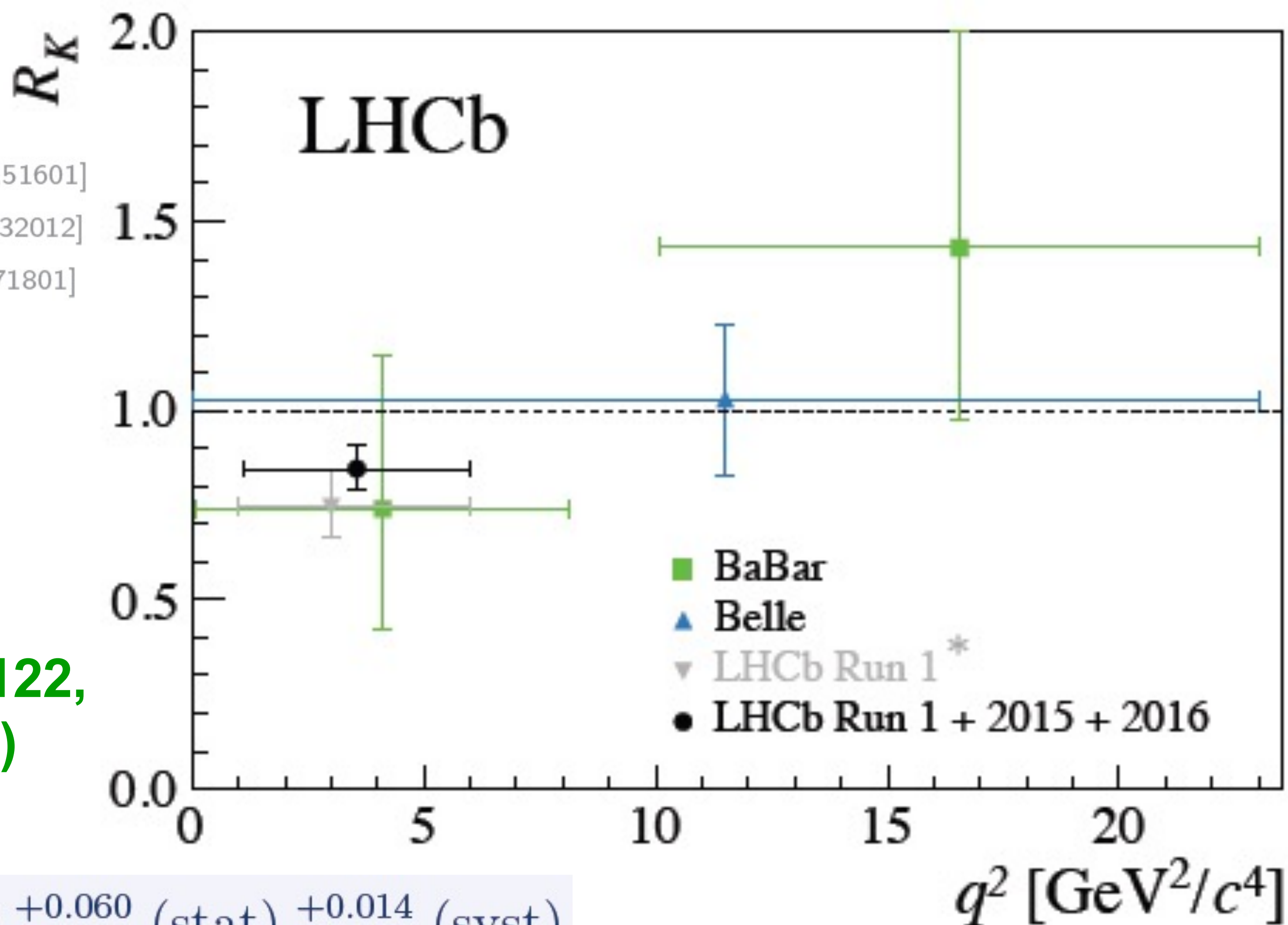
Lepton non-universality in B-decays (μ-e)

- LHCb: $R(K^+) = \Gamma(B^+ \to K^+ \mu^+\mu^-) / \Gamma(B^+ \to K^+ e^+e^-)$
- Spring 2019: $R(K^+)$ different from SM at 2.5σ level

[LHCb, PRL 113 (2014) 151601]

[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]



R. Aaji, PRL 122, 191801 (2019)

$$R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.014}_{-0.016}\,(\text{syst})$$

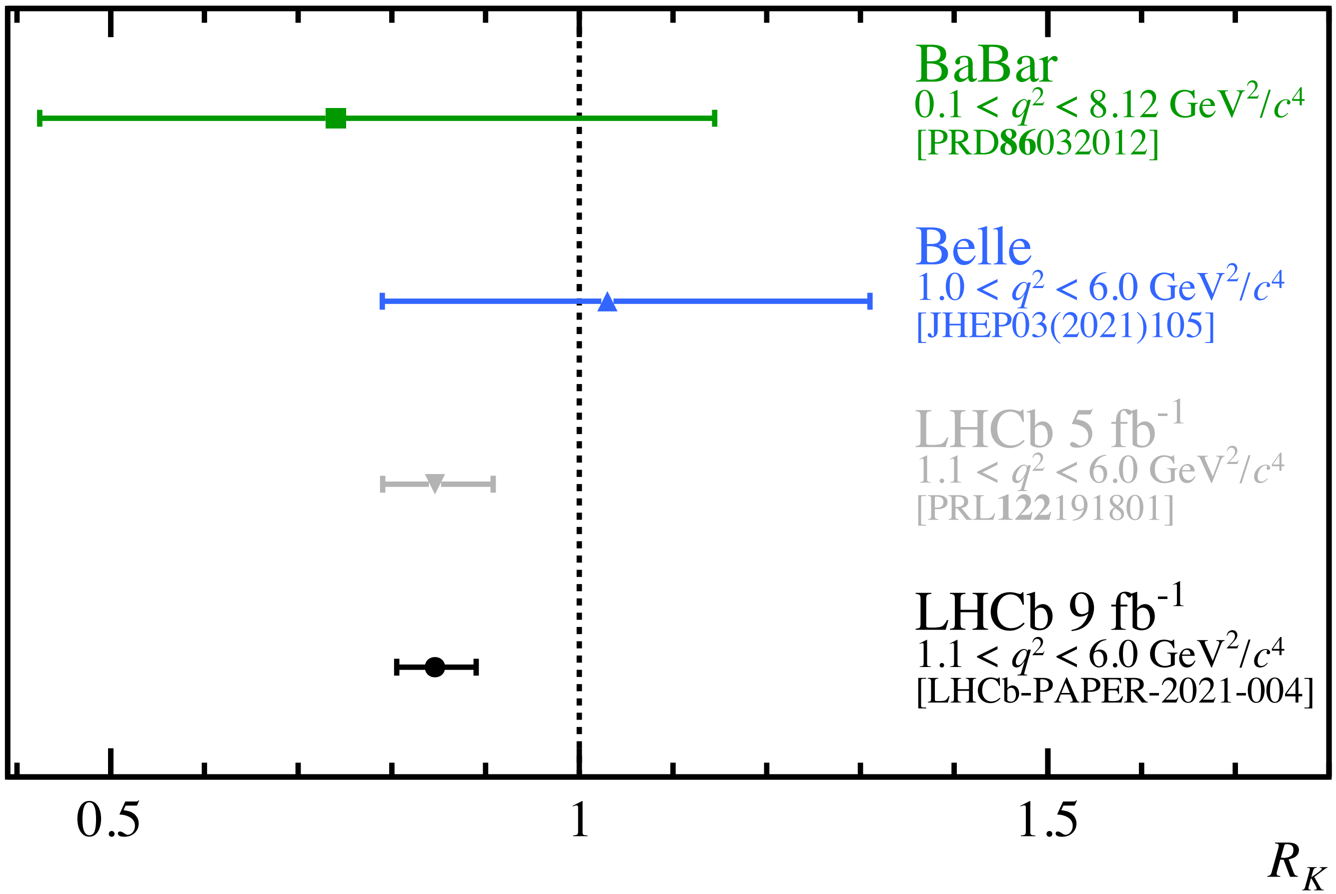
Lepton non-universality in B-decays (μ-e)

- 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]

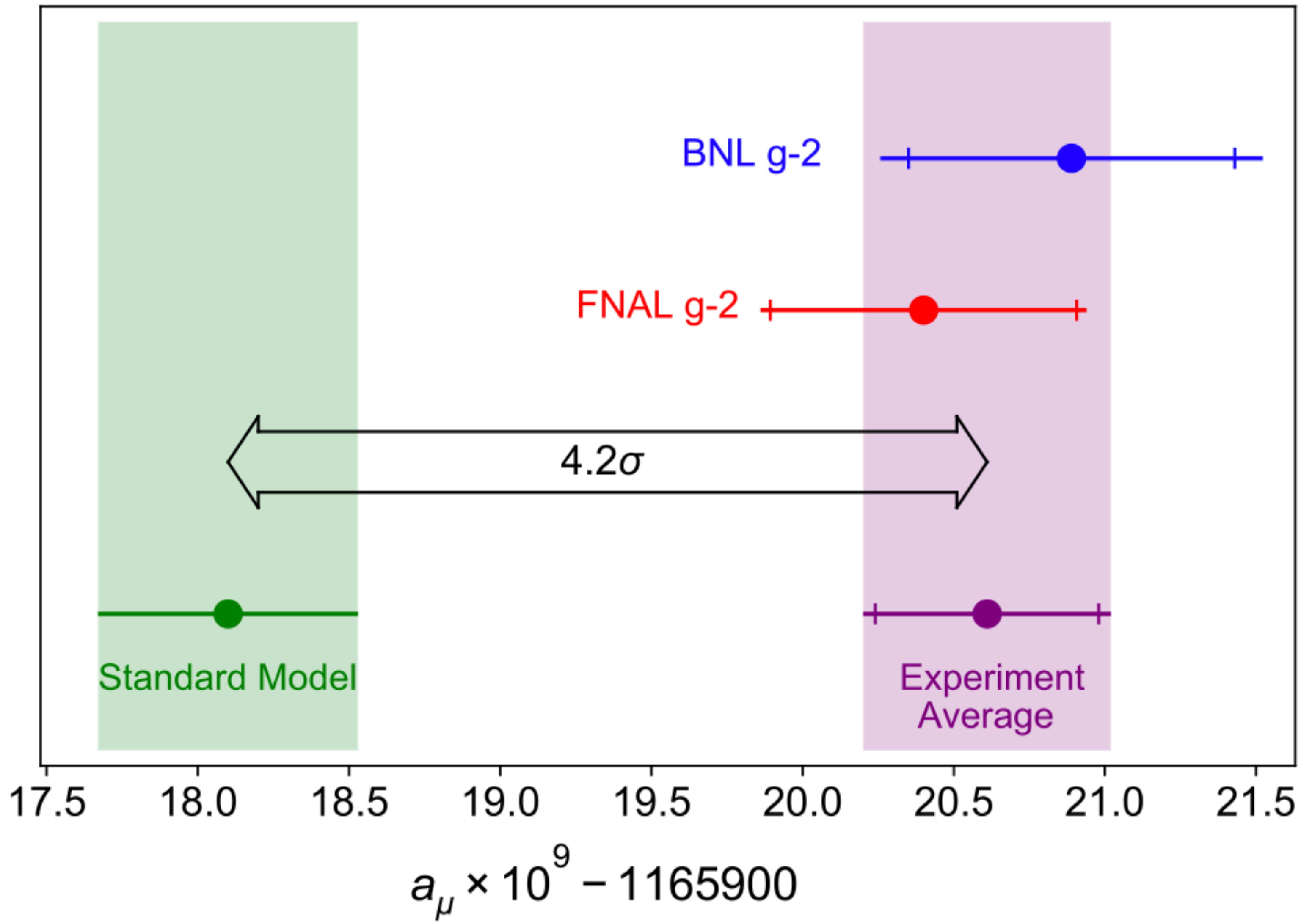
R. Aaji, PRL 122, 191801 (2019)

Full Run1 + Run2
arxiv:2103.11769



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

Lepton non-universality: Muon g-2



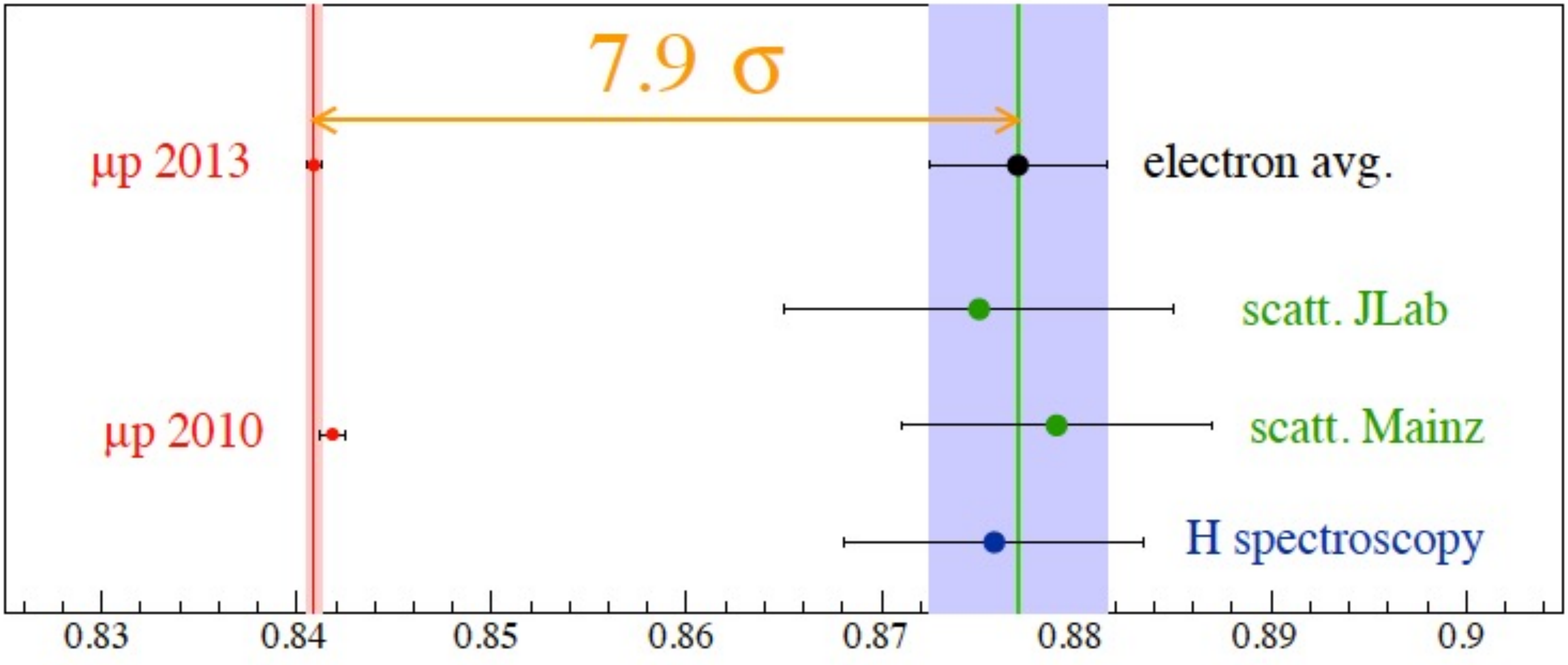
The Muon g-2 Collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, arXiv: 2104.03281

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)

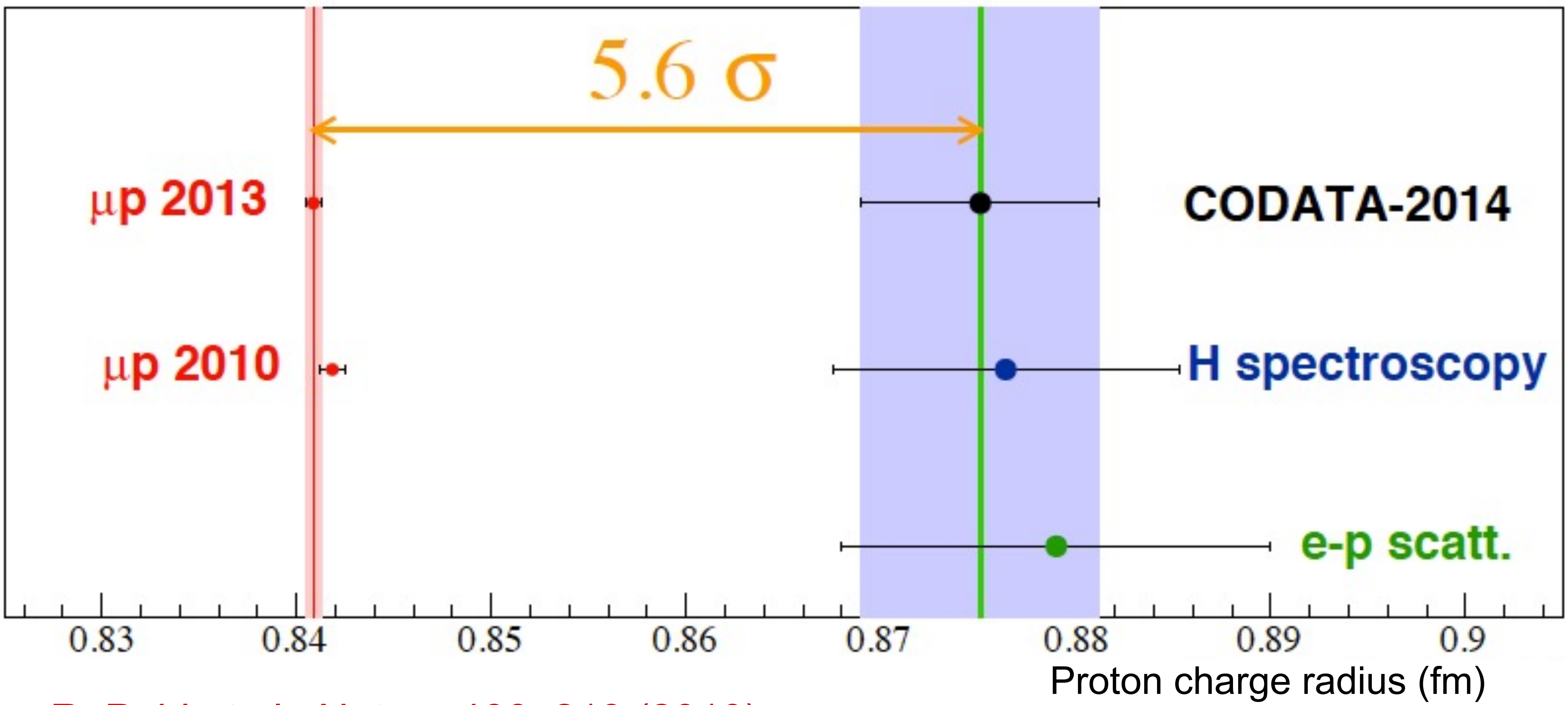
A. Antognini et al., Science 339, 417 (2013)

The proton radius puzzle in 2016

The proton rms charge radius measured with

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

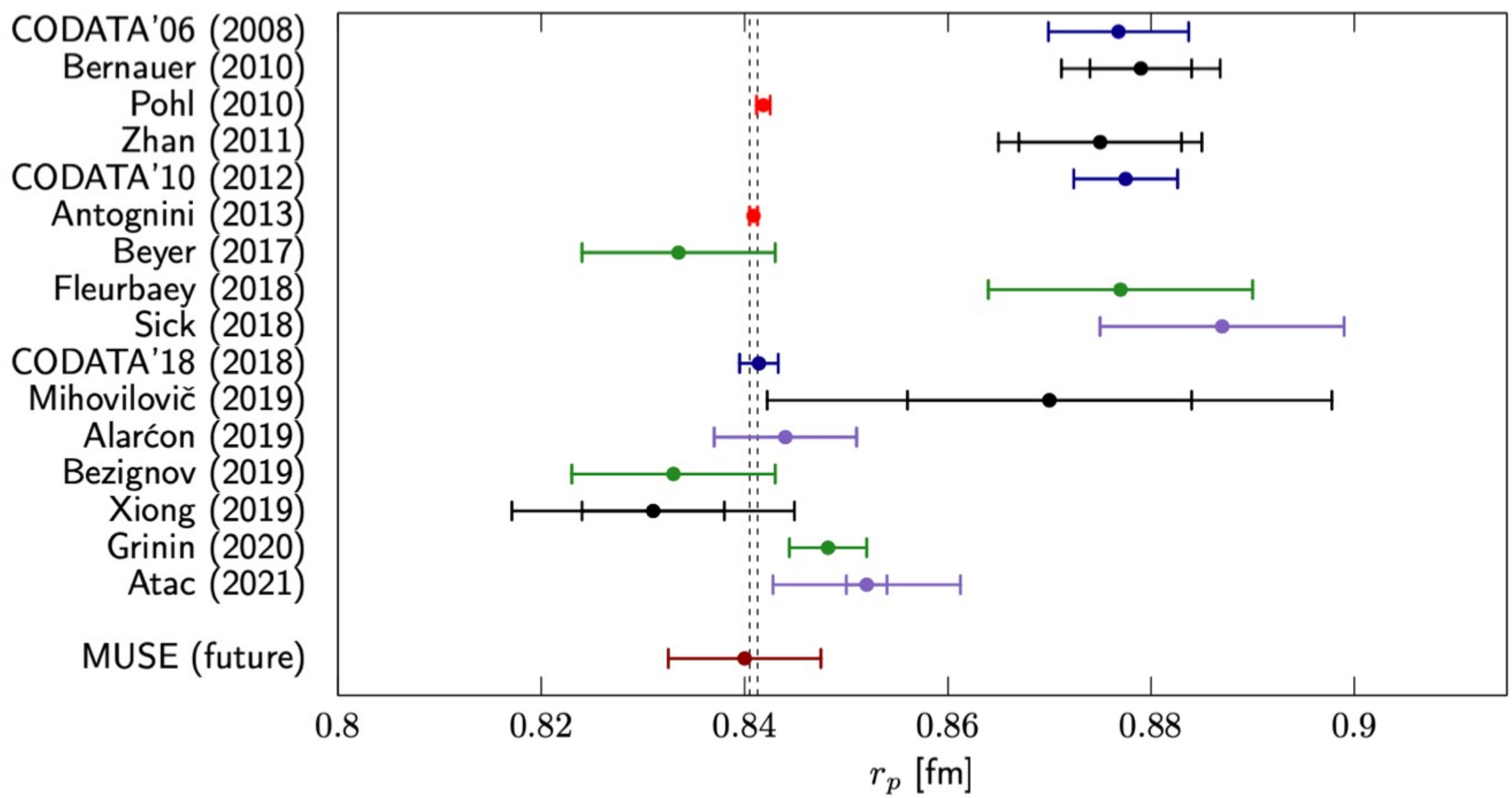
muons: (0.8409 ± 0.0004) fm



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

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

The proton radius puzzle in 2021



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

Possible resolutions to the puzzle

- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement

- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors

- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability (*effect* $\propto m_l^4$)

- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics e.g. from kaon decays (TREK@J-PARC)

MUSE will test

MUon Scattering Experiment (MUSE) at PSI

PAUL SCHERRER INSTITUT PSI

Appollo and the nine muses

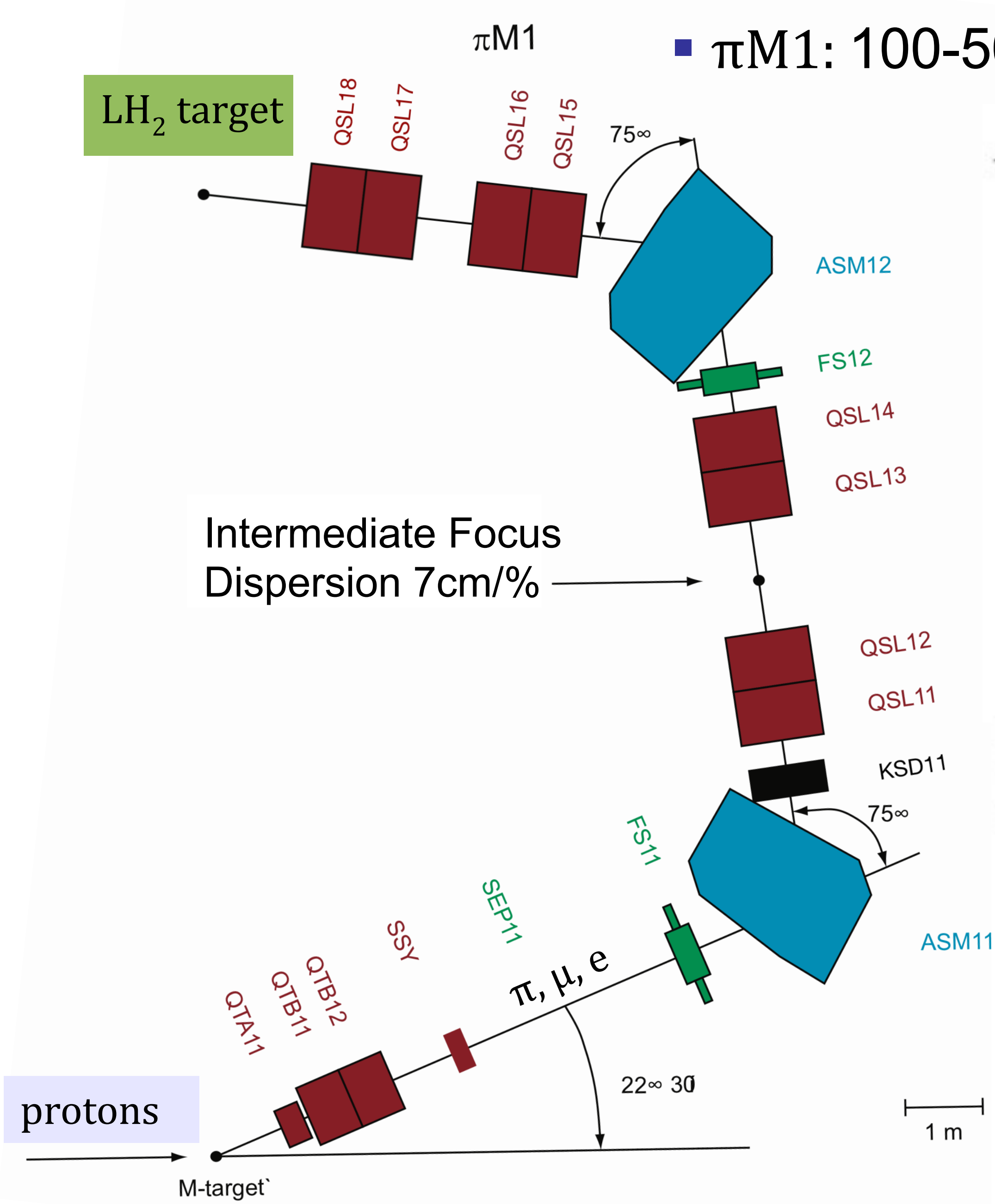
MUSE: MUon Scattering Experiment at PSI

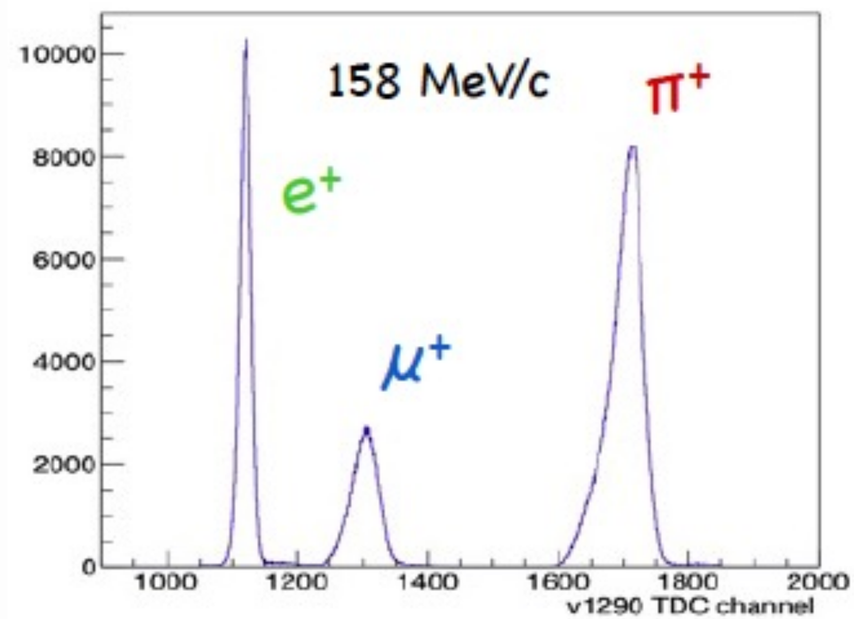
Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

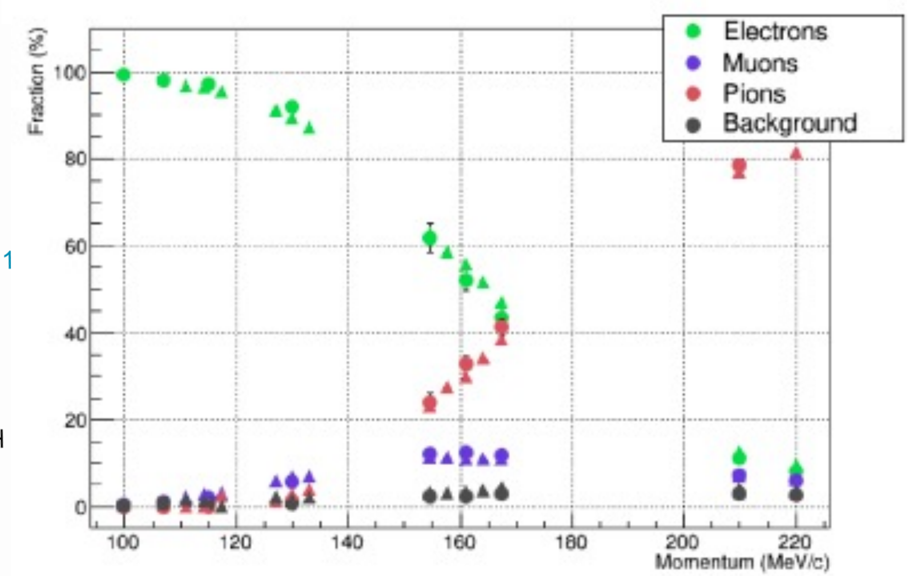
- **Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid H_2 target**
  - → Separation by time of flight
  - → Measure absolute cross sections for ep and μp
  - → Measure e+/μ+, e-/μ- ratios to cancel certain systematics
  - → If radii differ by 4%, then form factor slope by 8%, x-section slope by 16%
- **Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-**
- **Multiple beam momenta 115-210 MeV/c for broad low-Q^2 range to be covered**

πM1 / MUSE beamline

- πM1: 100-500 MeV/c RF+TOF sep. π, μ, e







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

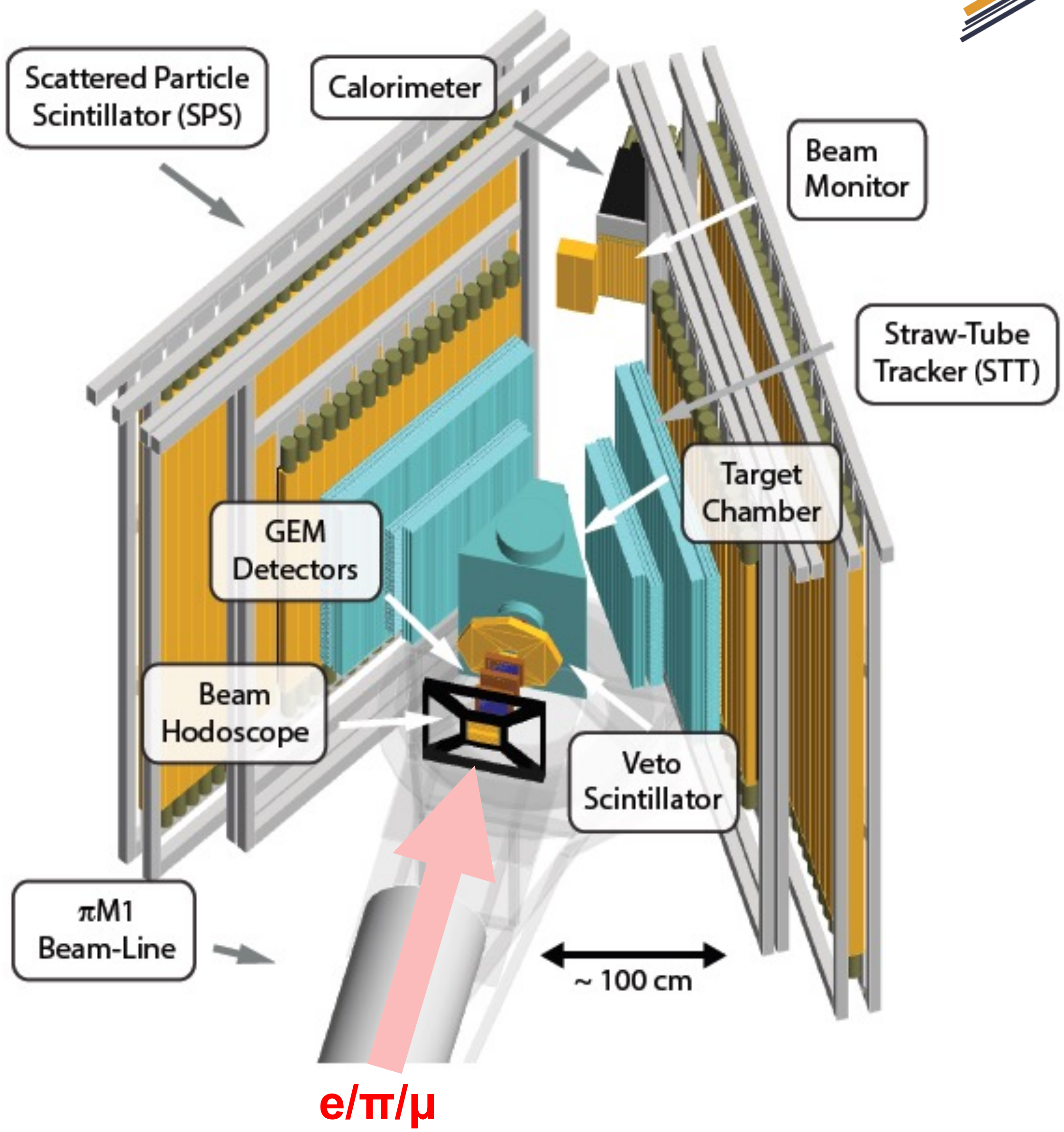
$\theta = 20^o$ to 100^o

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

$\varepsilon = 0.256 - 0.94$

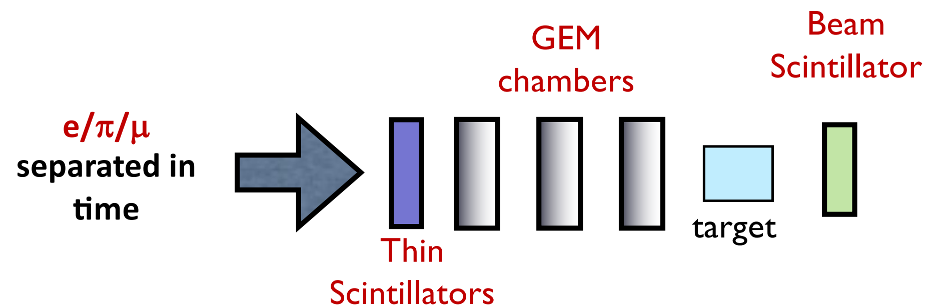
Challenges

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



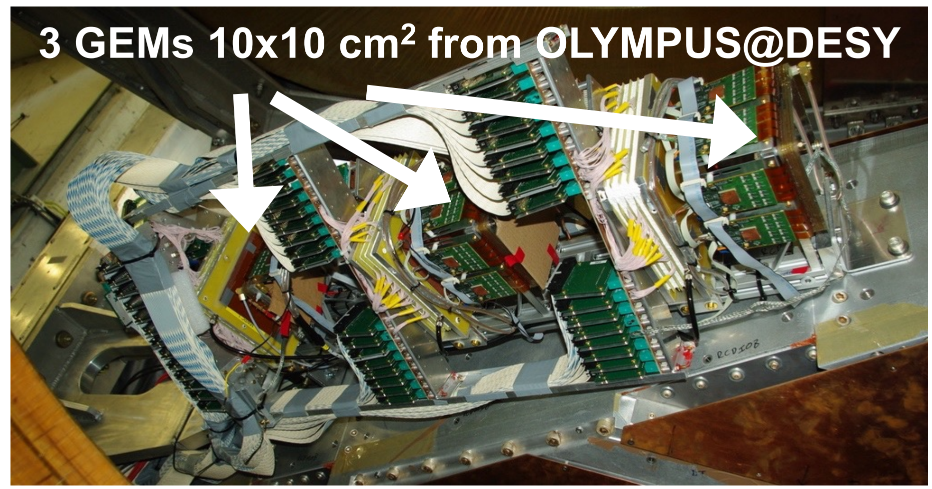
Beamline instrumentation

Beamline Elements:



GEM telescope
(Hampton University)

→ Incident track angle to
~0.5 mr intrinsic; <5 mr mult.sc.
→ Third GEM to reject ghost tracks
→ Existing chambers from
OLYMPUS



SiPM + 2 mm thin scintillators

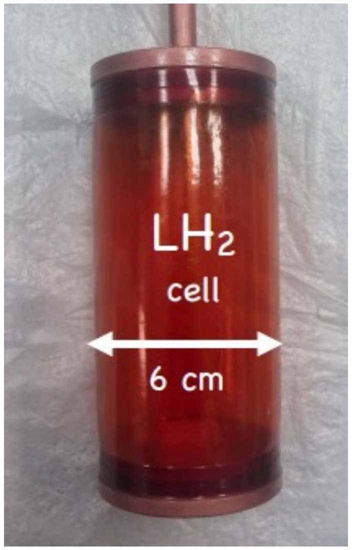
Thin scintillators with SiPM+CFD readout (PSI/Rutgers/TAU)

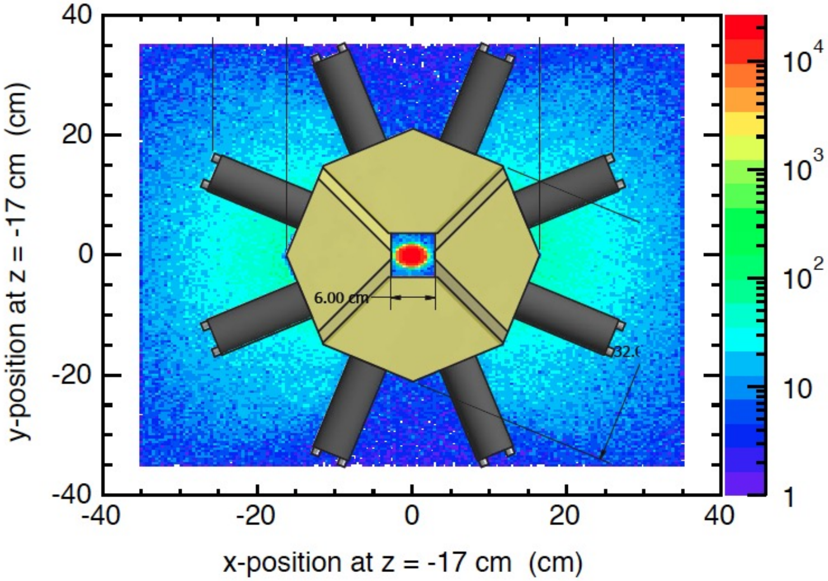
→ Fast timing (~60ps):
RF time and scattered particle TOF
→ Flux, PID, Trigger, TOF, momentum
→ Reject false tracks in GEMs

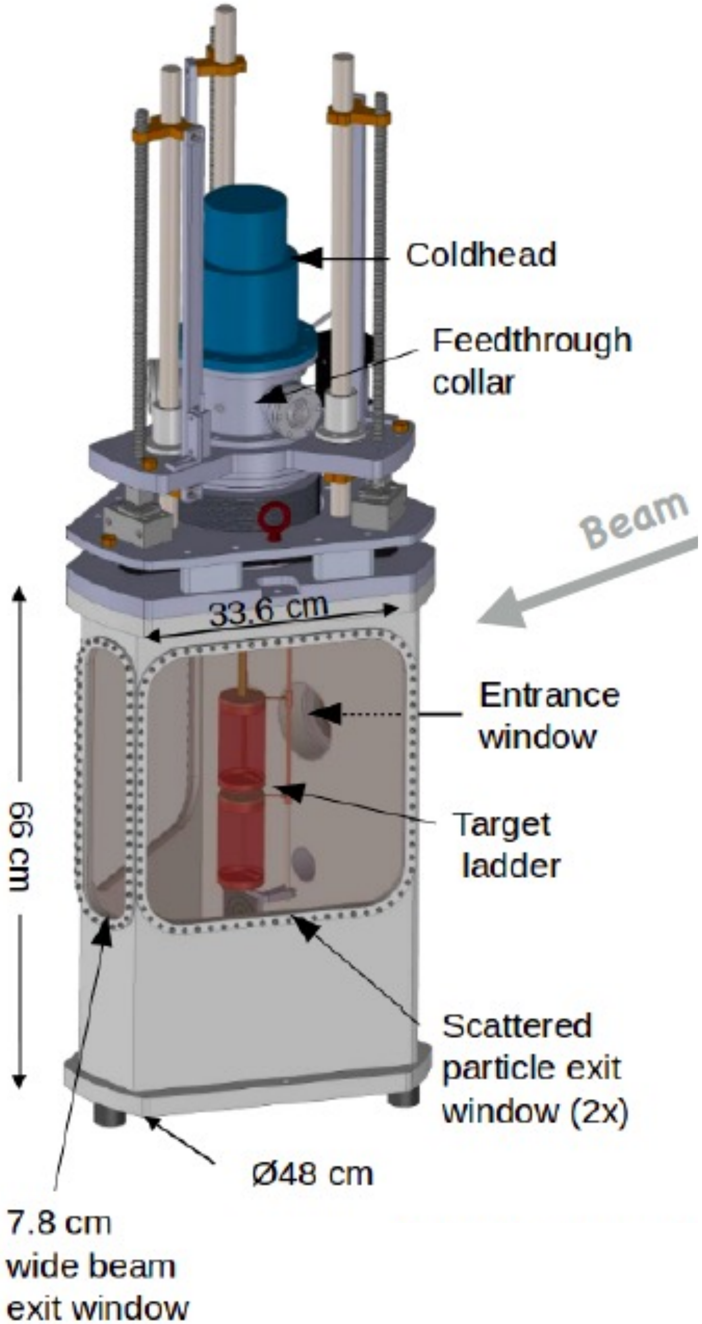
Target and veto

Low-power liquid hydrogen target
(UMich, GWU, Creare, PSI)

Target cell prototype







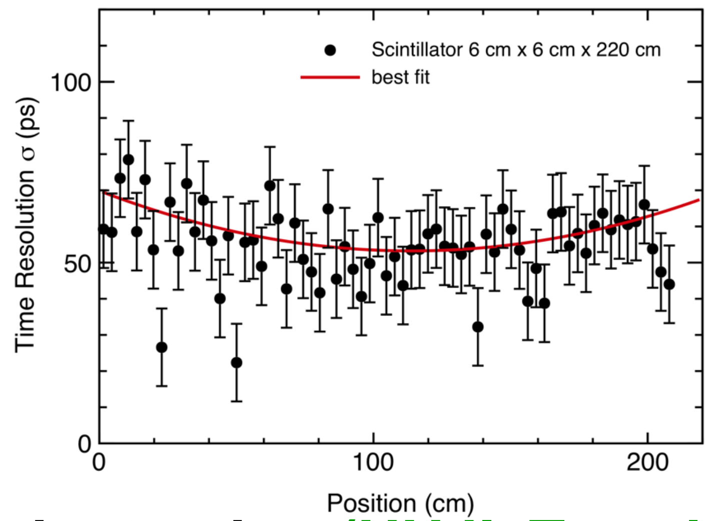
Veto scintillators (USC):

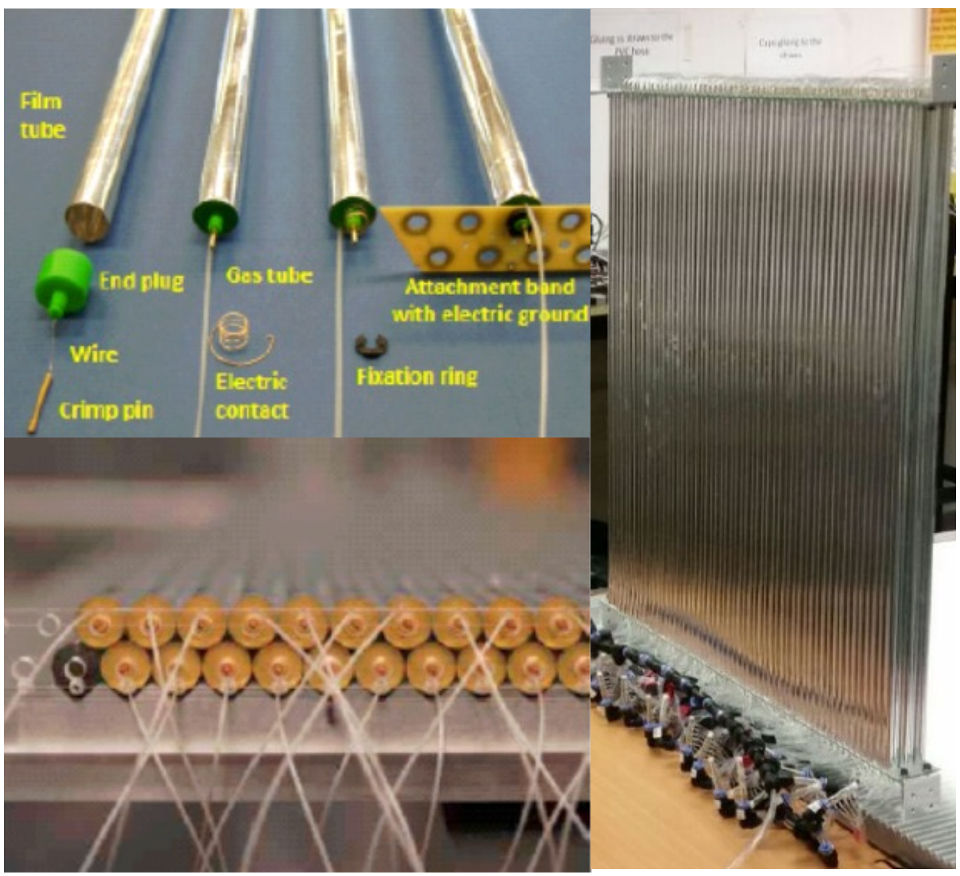
Annullar veto ring defines accepted beam aperture, smaller than transverse target cell diameter (6 cm)

Main detector instrumentation

Scattered particle scintillators (USC)

- 2 planes of scintillators (CLAS12 design)
- 94 bars (2 sides + beam)
- High precision (~50 ps) timing
- PID and trigger, background rejection



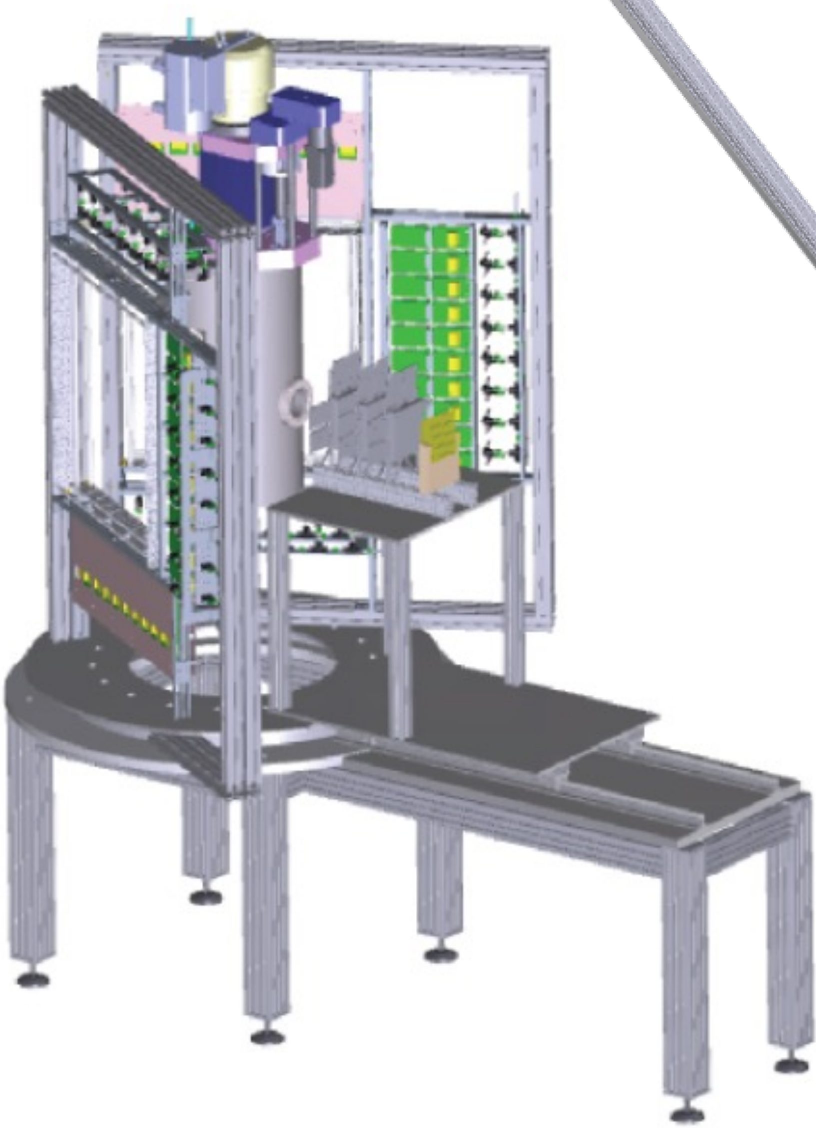


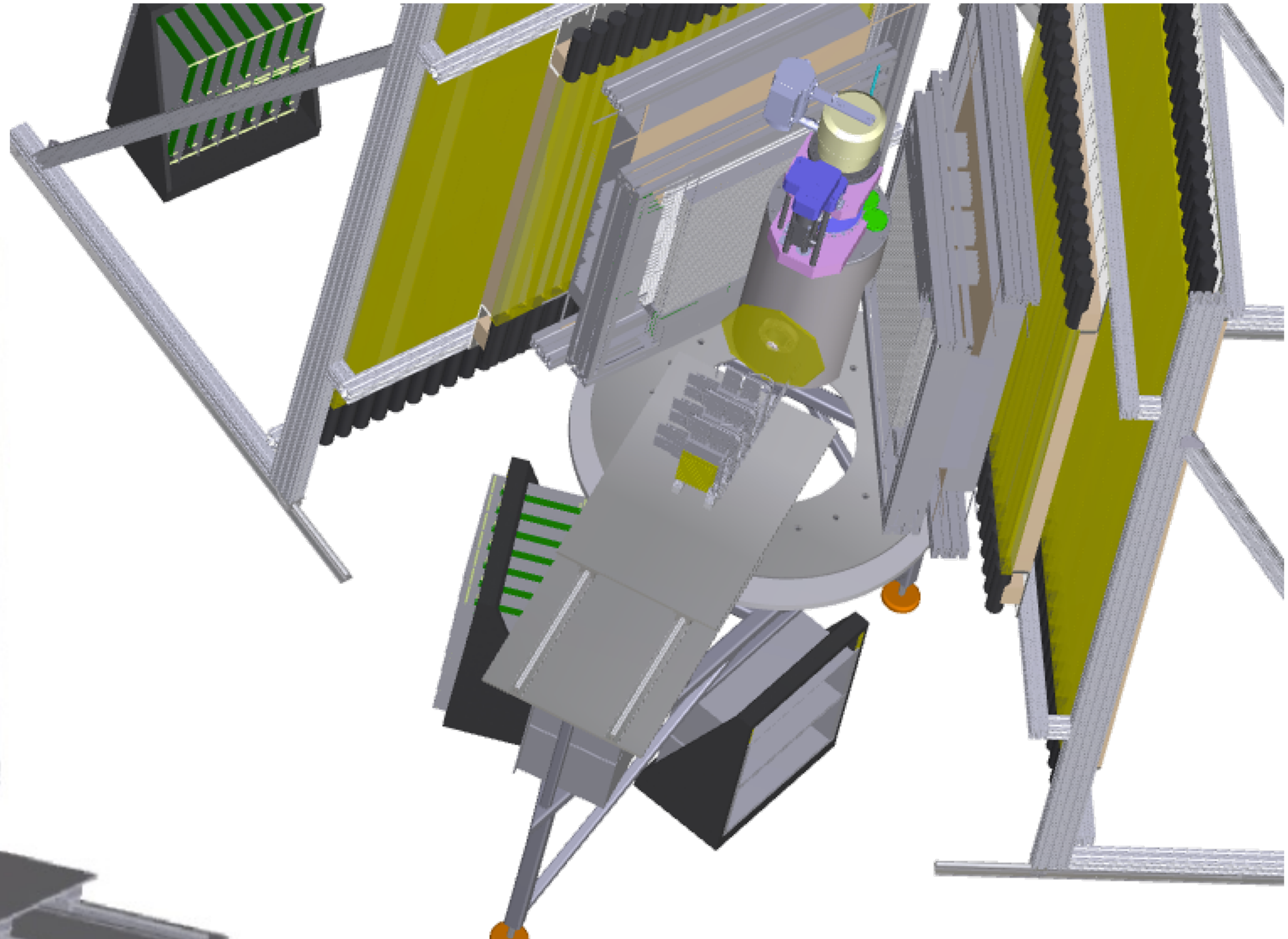
Straw tube tracker (HUJI, Temple)

- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design – 140 μm resol.
- Thin walls (25μm), overpressured (2 bar)
- Directly coupled to fast readout boards

Mechanical assembly

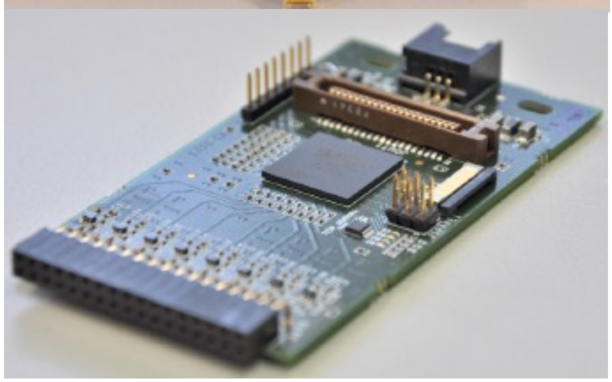
T. O'Connor **(ANL)**





Rotating table
Retractable beam tracker
Dedicated alignment procedures

DAQ and trigger



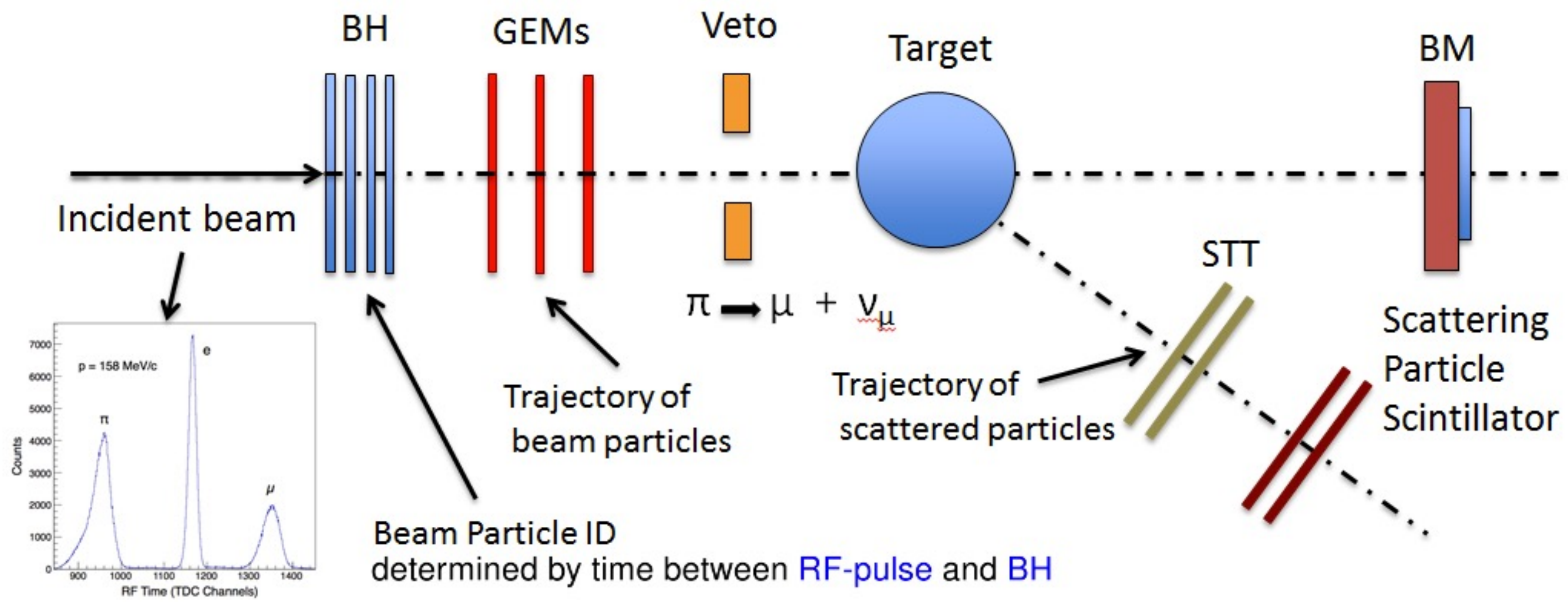
DAQ system (GWU and Montgomery Coll.)

- FPGAs as frontend discriminator/amplifier, custom designed TDCs (PADIWA/TRB3)
- High channel density (192ch/board)
- VME QDCs (MESYTEC)

Trigger (Rutgers)

- FPGA design for beam PID (TRB3)
- Beam hodoscope + beam RF → beam PID
- Count particles and reject pions
- e or μ beam part. + scattered part. + no veto

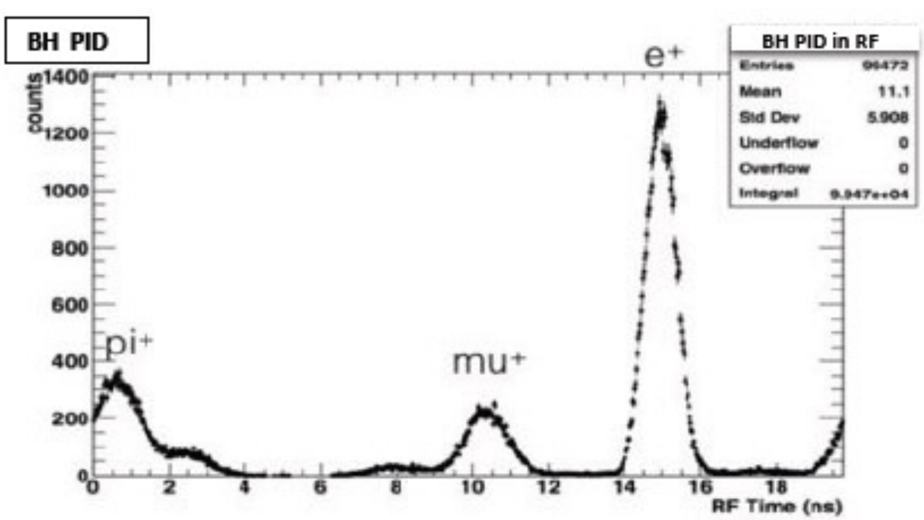
Trigger with pion rejection

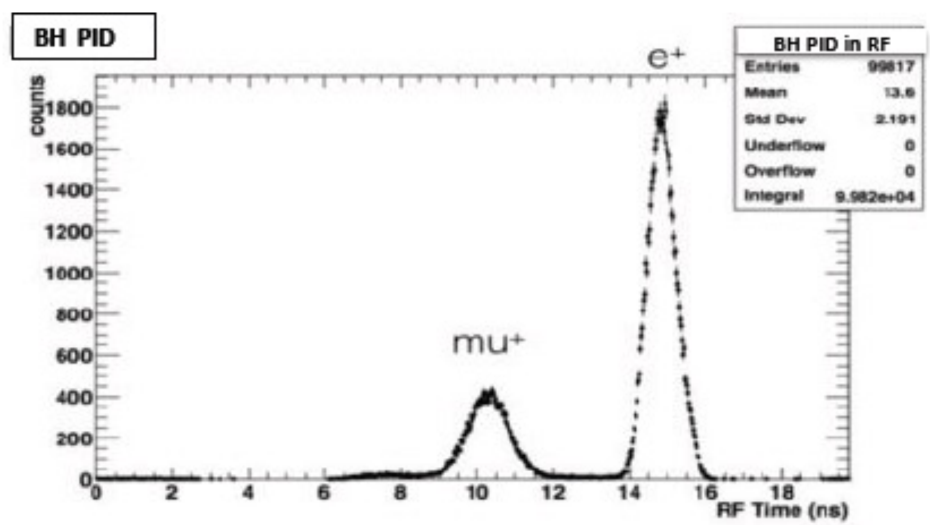


Trigger Logic: TRB3 FPGA-based:

accept $e^{\pm}$, $\mu^{\pm}$, reject $\pi^{\pm}$

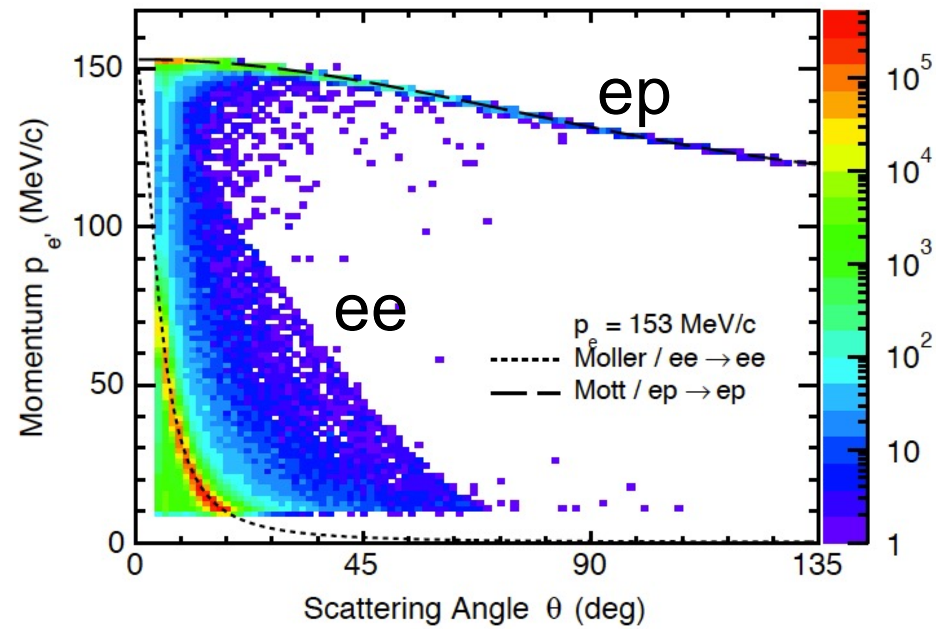
(e OR μ) AND (no π) AND (scatter) AND (no veto)

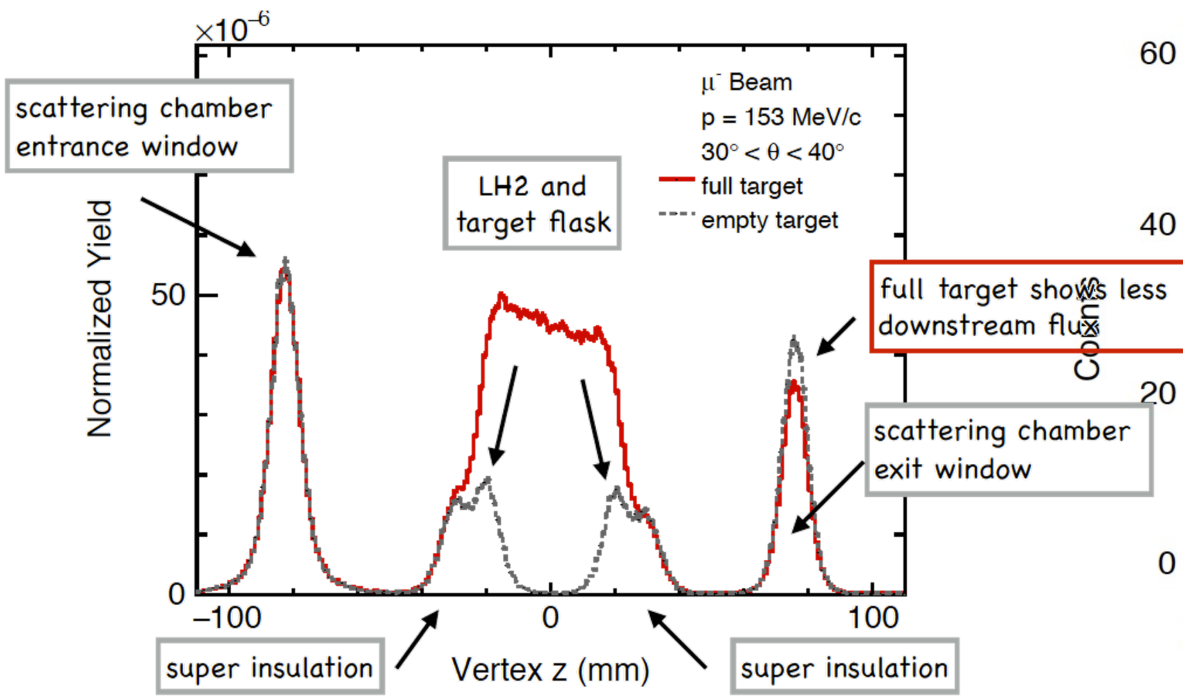


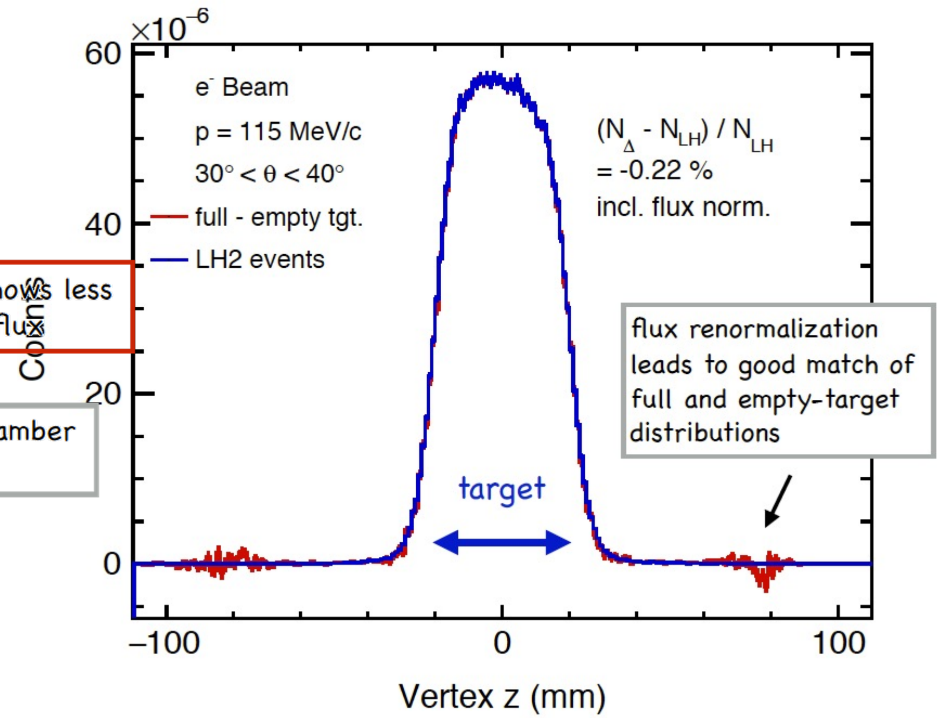


Simulations (S. Strauch, USC)

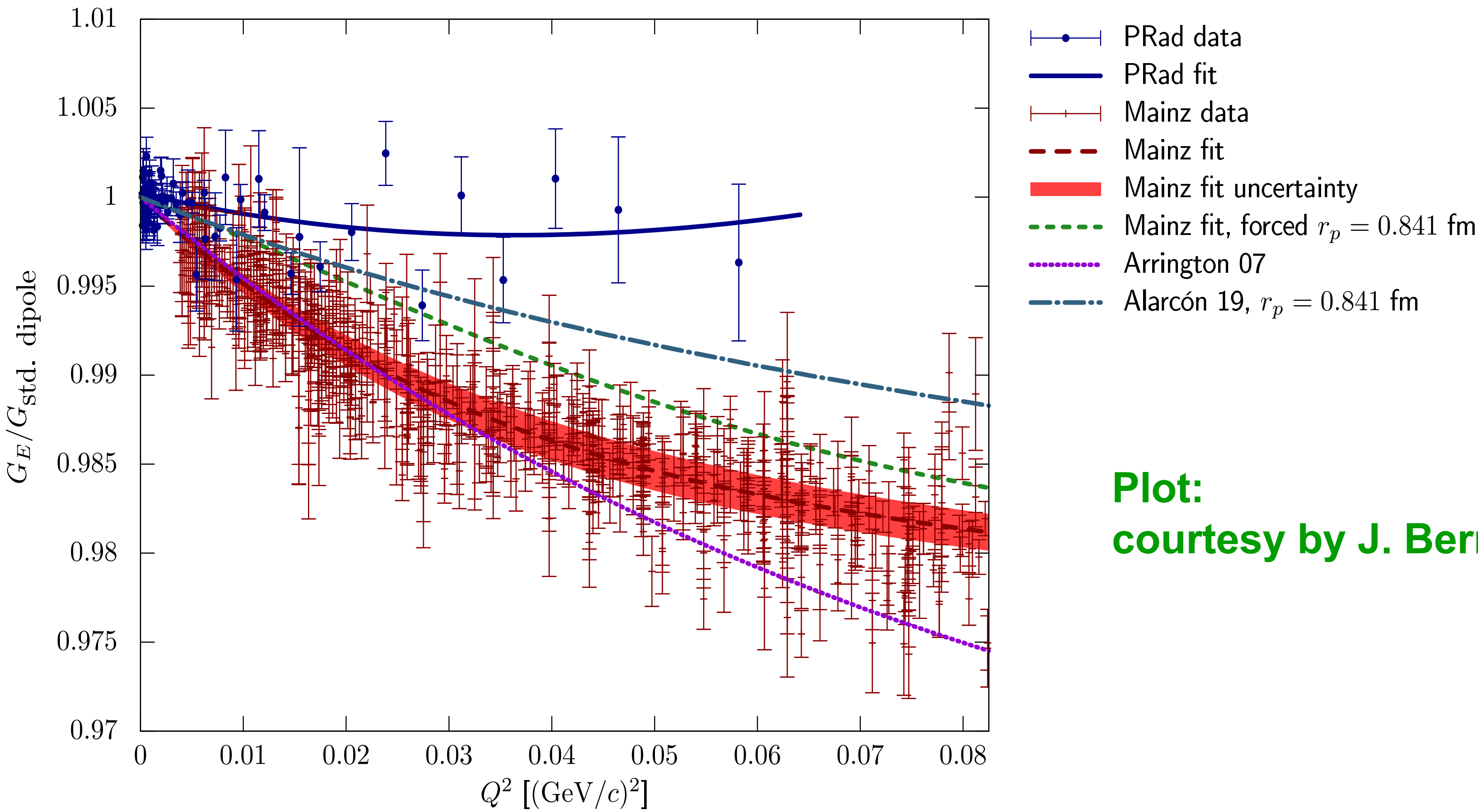
- Particle vertex and scattering-angle reconstruction meet MUSE requirements
- Background from target walls and windows can be cleanly eliminated or subtracted





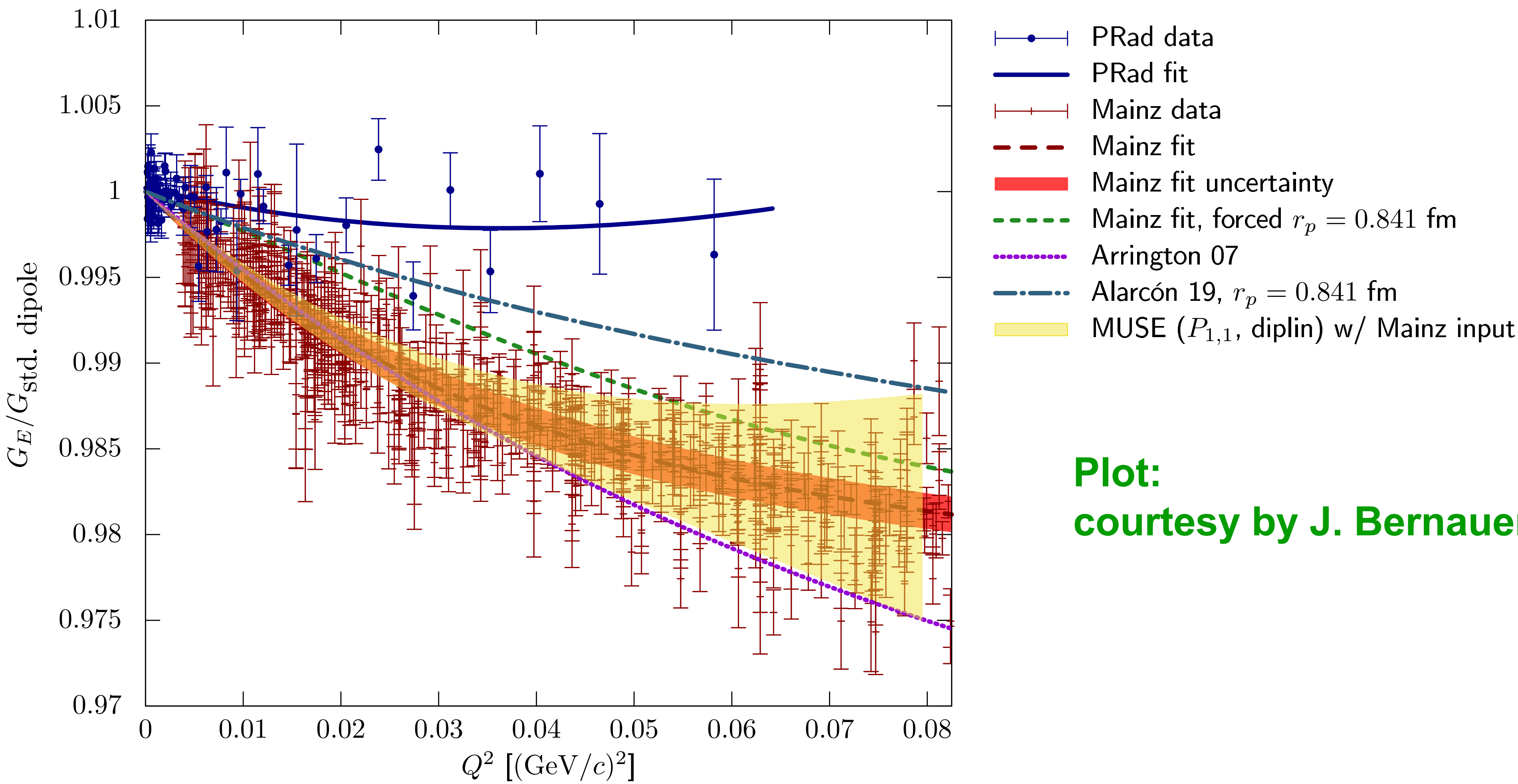


MUSE projected sensitivity: G_E



Plot:
courtesy by J. Bernauer

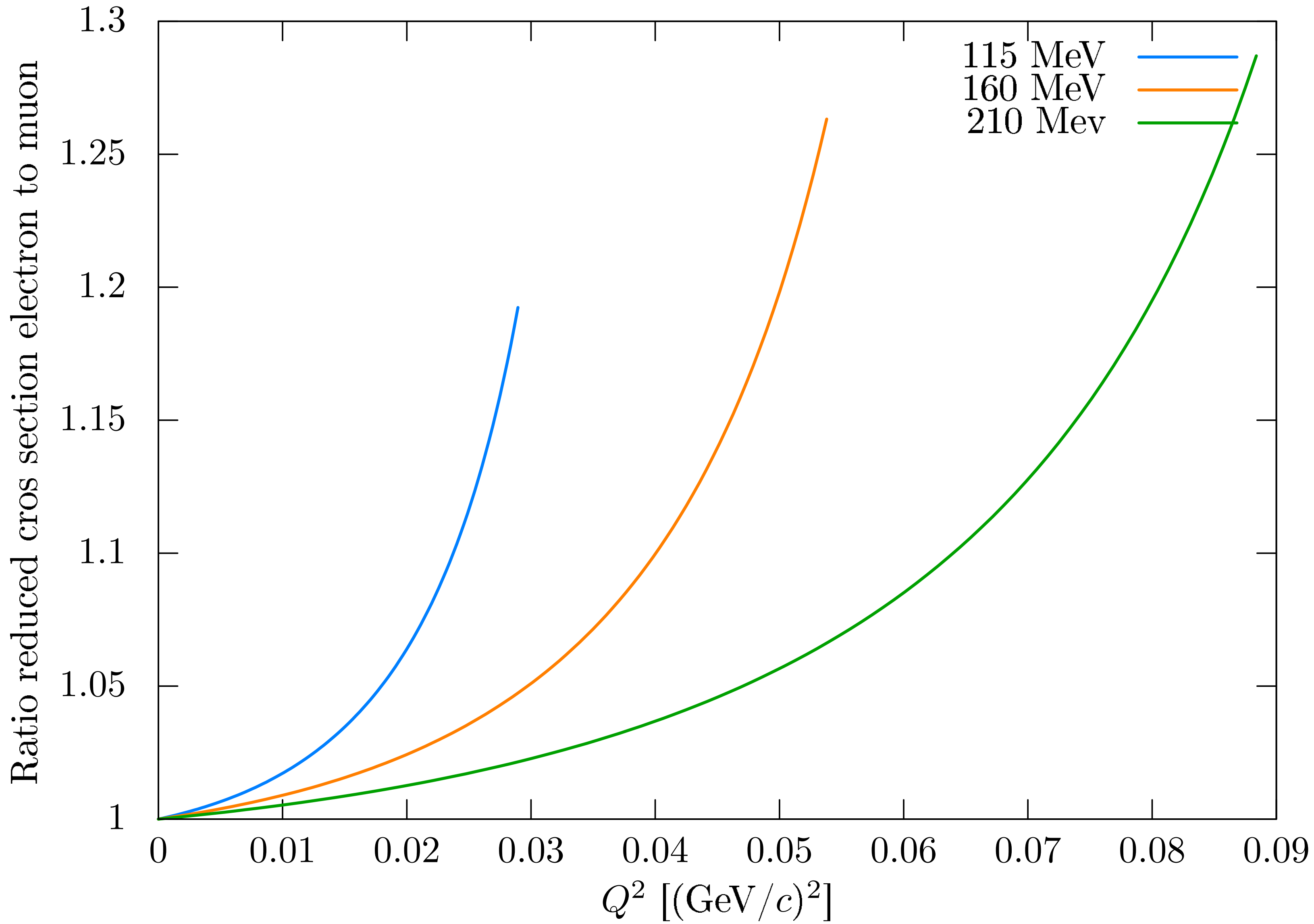
MUSE projected sensitivity: G_E



Plot: courtesy by J. Bernauer

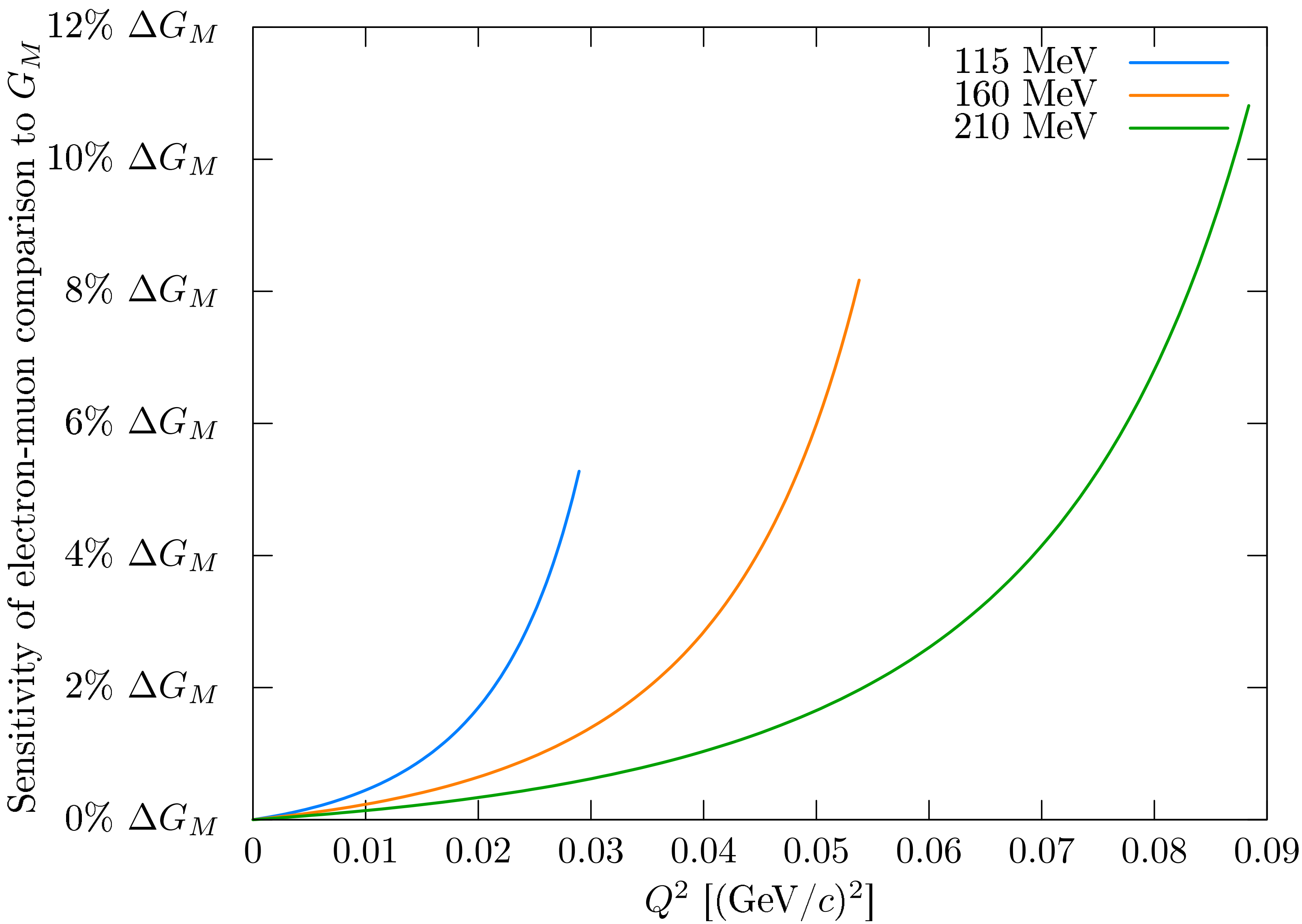
- Error band projected for MUSE data, using G_E and G_M from Mainz

MUSE expected e/μ reduced xsec ratio



- Cross section
- At fixed Q^2, magnetic contribution to reduced xsec e and μ different

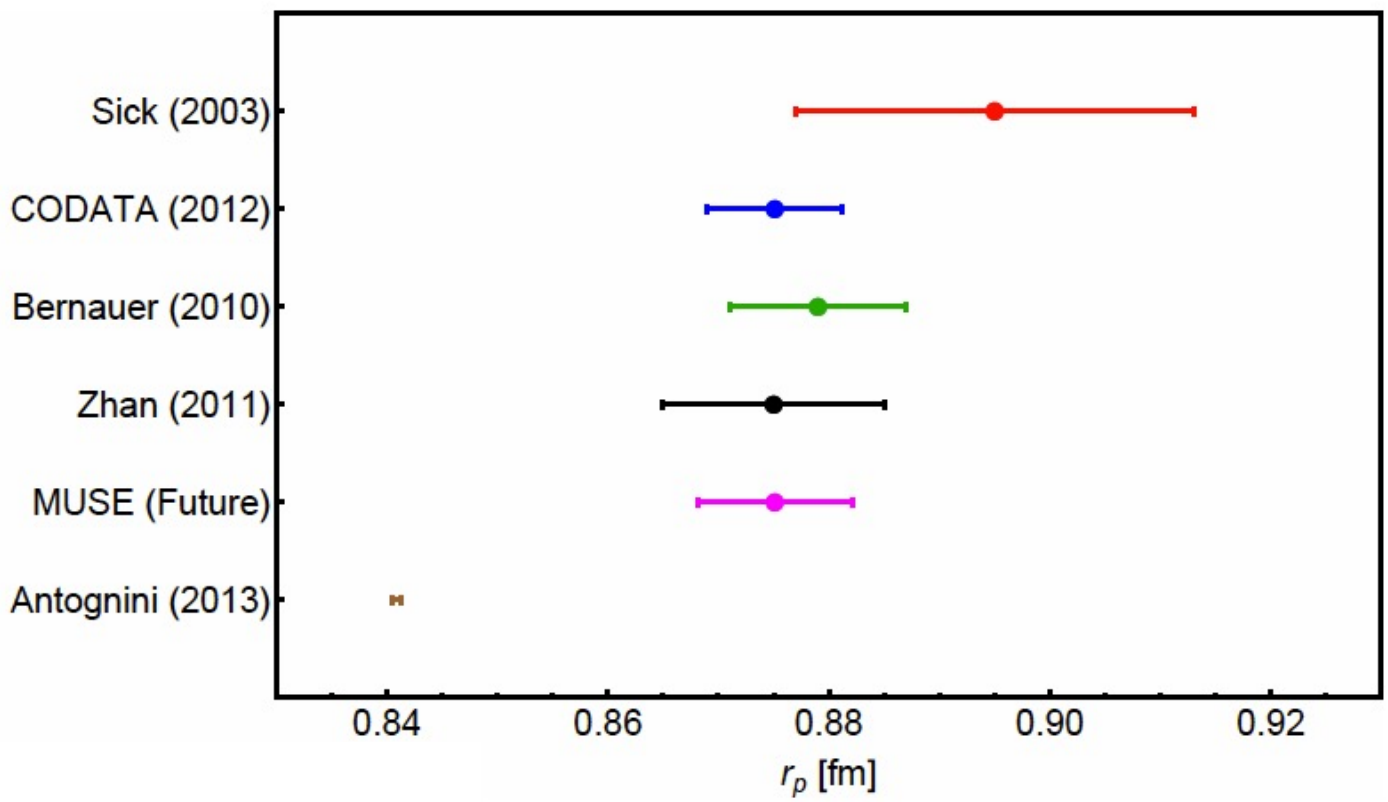
MUSE projected e/μ sensitivity: lead syst.



- Systematic in the e/μ ratio due to uncertainty in G_M
- <*O(1)%* uncertainty if G_M is known to <*O(10)%* at low Q^2

Projected sensitivity for MUSE

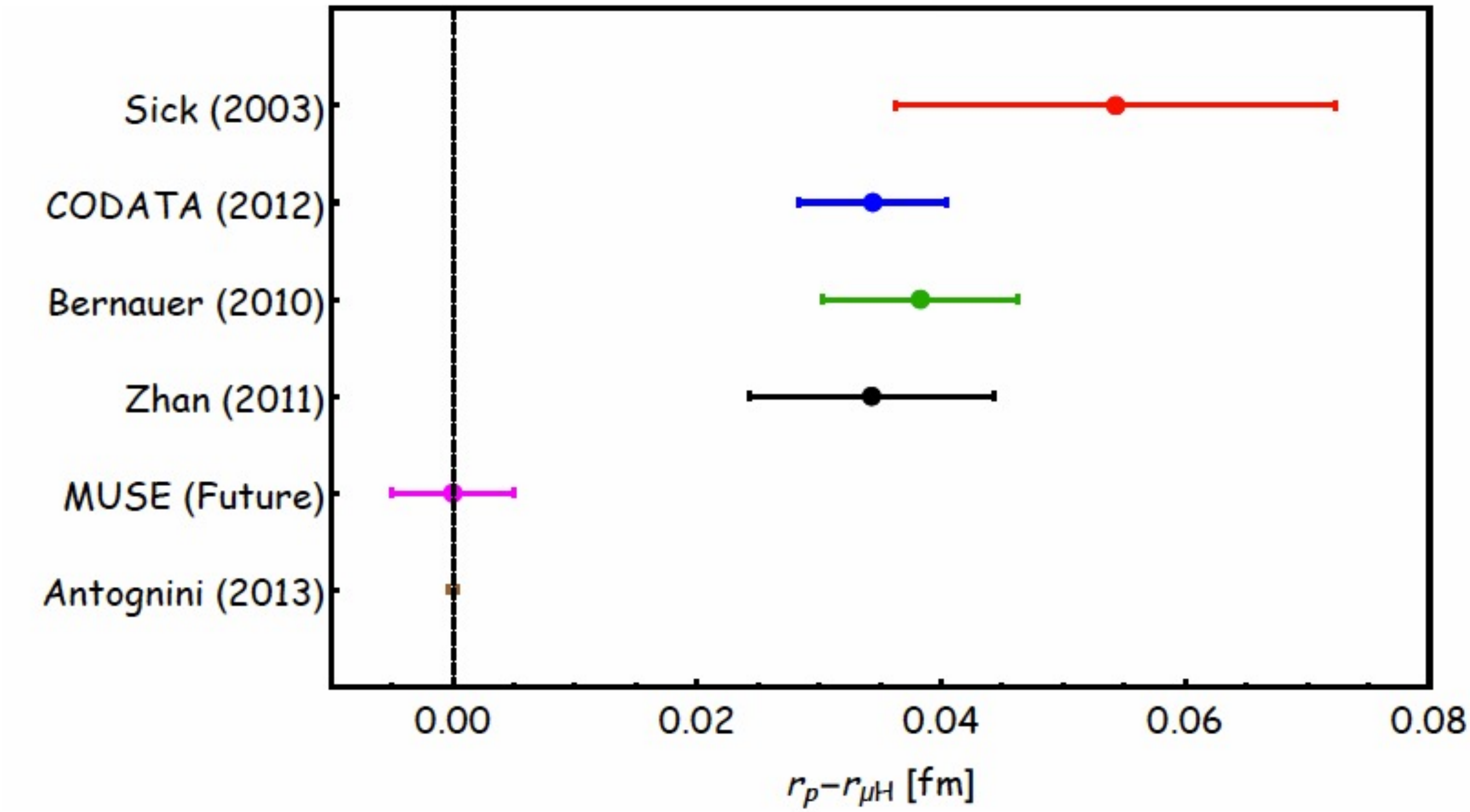
- **Cross sections** to <1% stat. for backward μ, <<1% for e and forward μ
  Absolute 2%, point-to-point relative uncertainties **few x10^{-3}**
- **Individual radius extractions** from $e^{\pm}$, $\mu^{\pm}$ each to **0.010 fm**
- Compare $e^{\pm}p$ and $\mu^{\pm}p$ for TPE. Charge-average to eliminate 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)



Projected sensitivity for MUSE

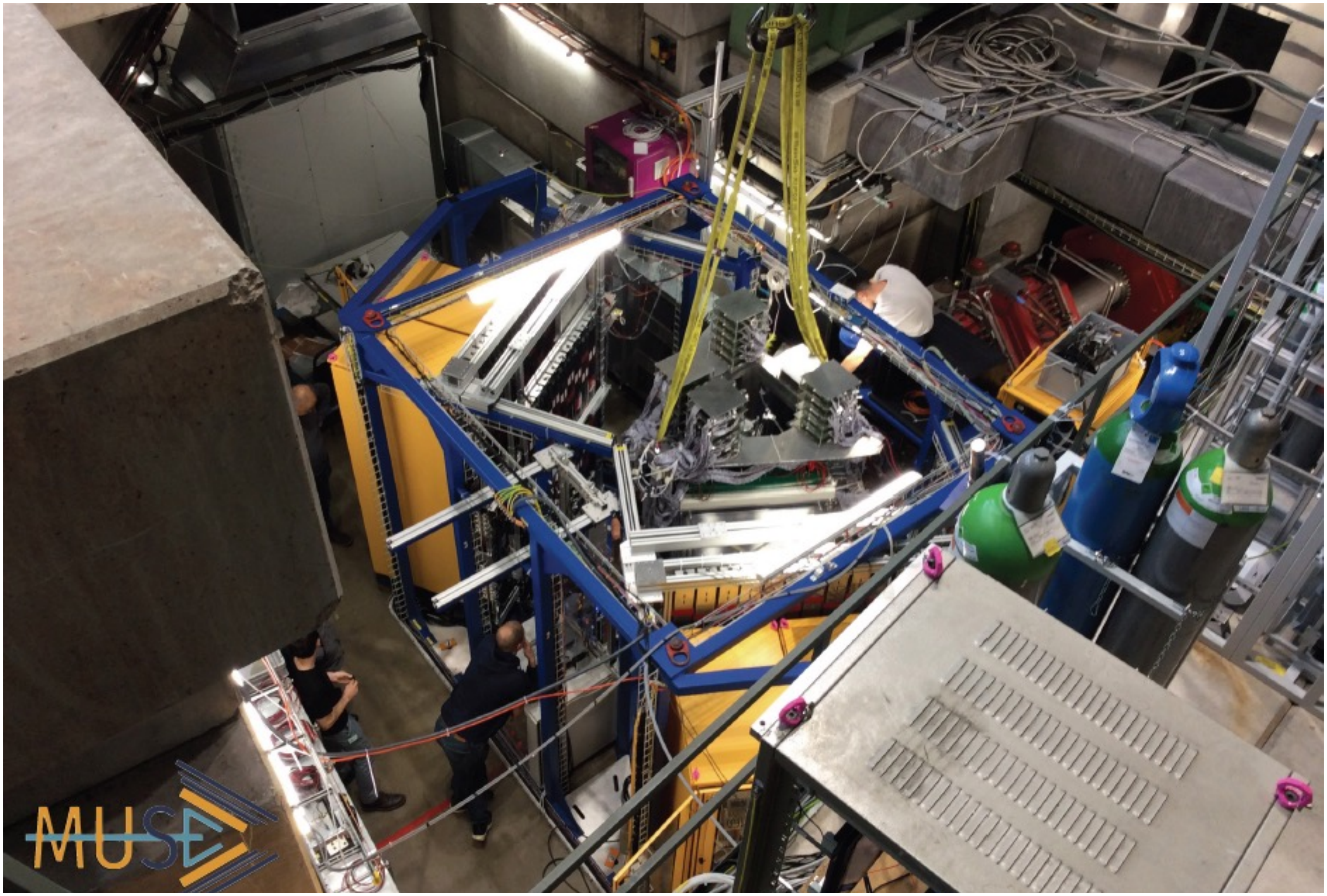
- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiment: Cancel in e+/e-, μ+/μ-, and μ/e comparisons
- R_e-R_μ = 0.034±0.006 fm (5.6σ), **MUSE: δ(R_e-R_μ) = 0.0045 fm (7.6σ)**

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



2018-2021 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 2021: Start production data for 12 beam months over ~2 years



MUSE activities and status

- Proton radius puzzle not solved in 2022 – 12 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 experiment 2016-2021

- Data taking for 12 months in 2022-2023

MUon Scattering Experiment – MUSE

72 MUSE collaborators from 25 institutions in 5 countries:

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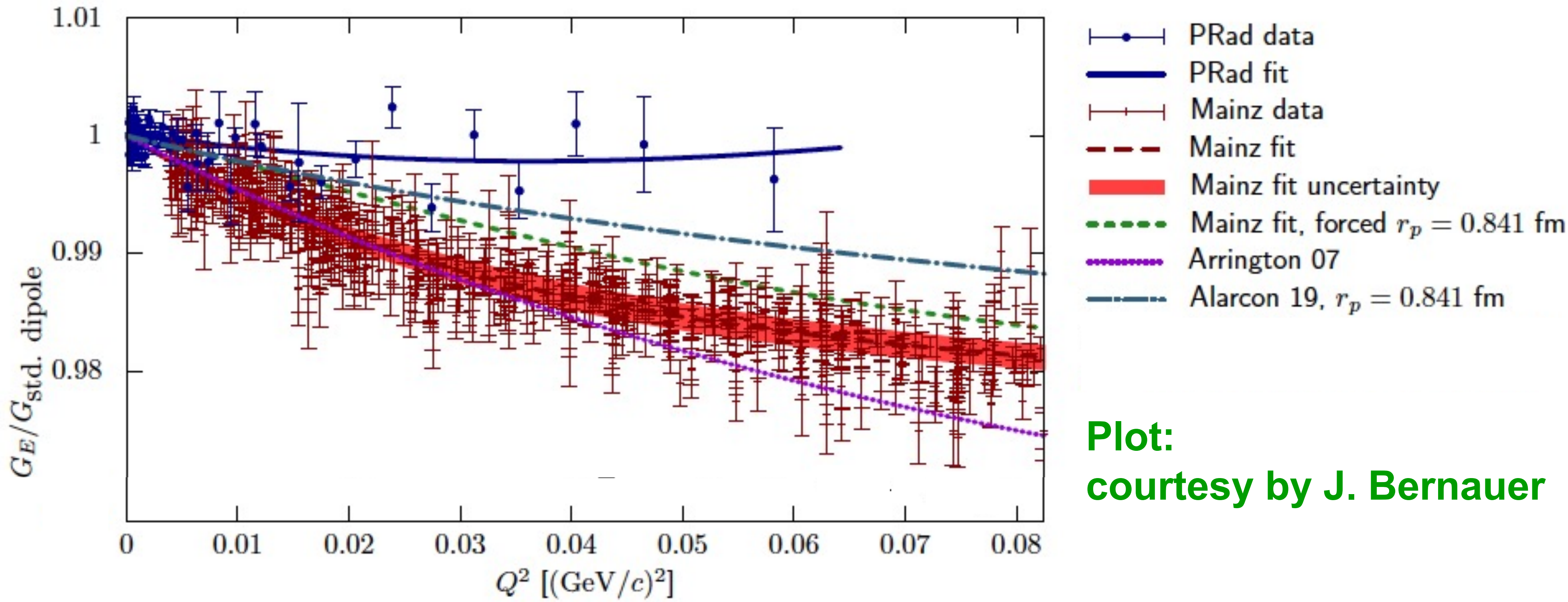
MUSE publications

- **E.O. Cohen *et al.*,**
  ***Development of a scintillating-fiber beam detector for the MUSE experiment*, NIM A**
  https://doi.org/10.1016/j.nima.2016.01.044
- **P. Roy *et al.*, *A Liquid Hydrogen Target for the MUSE Experiment at PSI*, NIM A**
  https://doi.org/10.1016/j.nima.2020.164801
- **T. Rostomyan *et al.*, *Timing Detectors with SiPM read-out for the MUSE Experiment at PSI*, NIM A**
  https://doi.org/10.1016/j.nima.2019.162874
- **E.Cline, J. Bernauer, E.J. Downie, R. Gilman, *MUSE: The MUon Scattering Experiment,* Review of Particle Physics at PSI**
  https://doi.org/10.21468/SciPostPhysProc.5
- **E. Cline *et al.*, *Characterization of Muon and Electron Beams in the Paul Scherrer Institute PiM1 Channel for the MUSE Experiment***
  PRC 105, 055201 (2022); arXiv: 2109.09508
  https://doi.org/10.1103/PhysRevC.105.055201

Thank you!

Puzzle solved?

- **Cross sections and form factors of PRad are different – why?**



Plot: courtesy by J. Bernauer

- **Accuracy of radiative corrections?**
- **What did previous experiments do wrong?**
- **Which result is to be preferred, and why?**

- **Need independent checks and validations (→ ISR, ULQ2, MUSE)**