

# **Low-energy lepton-proton scattering of $\mu^-$ , $\mu^+$ , $e^-$ and $e^+$ with the MUSE experiment at PSI**

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for the MUSE Collaboration

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# Outline

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- The Proton Radius Puzzle: A  $>7\sigma$  discrepancy
- Lepton universality
- Two-photon exchange
- The MUSE experiment
  - Sensitivity
  - Overview
  - Status

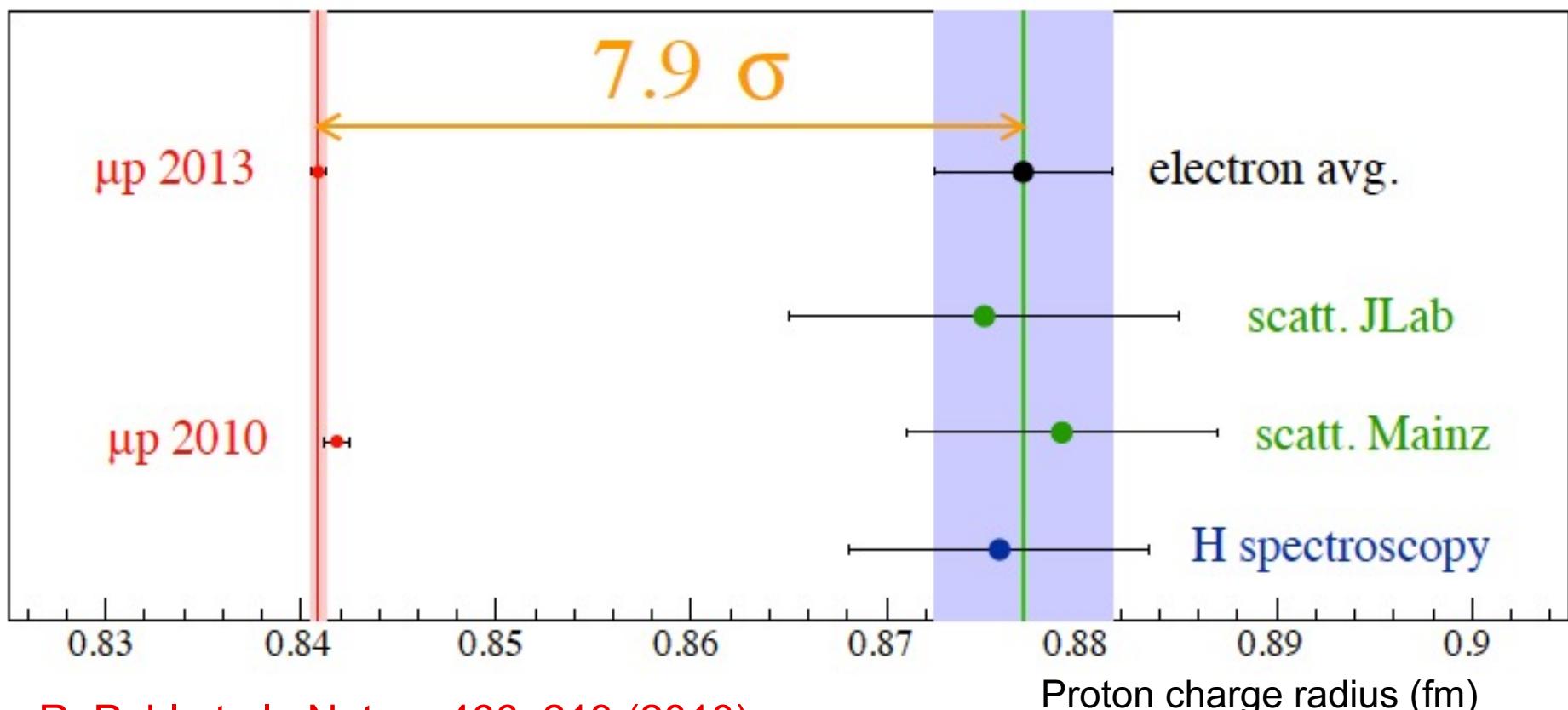


# The proton radius puzzle in 2010/2013

The proton rms charge radius measured with

electrons:  $0.8770 \pm 0.0045$  fm (CODATA2010+Zhan et al.)

muons:  $0.8409 \pm 0.0004$  fm



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

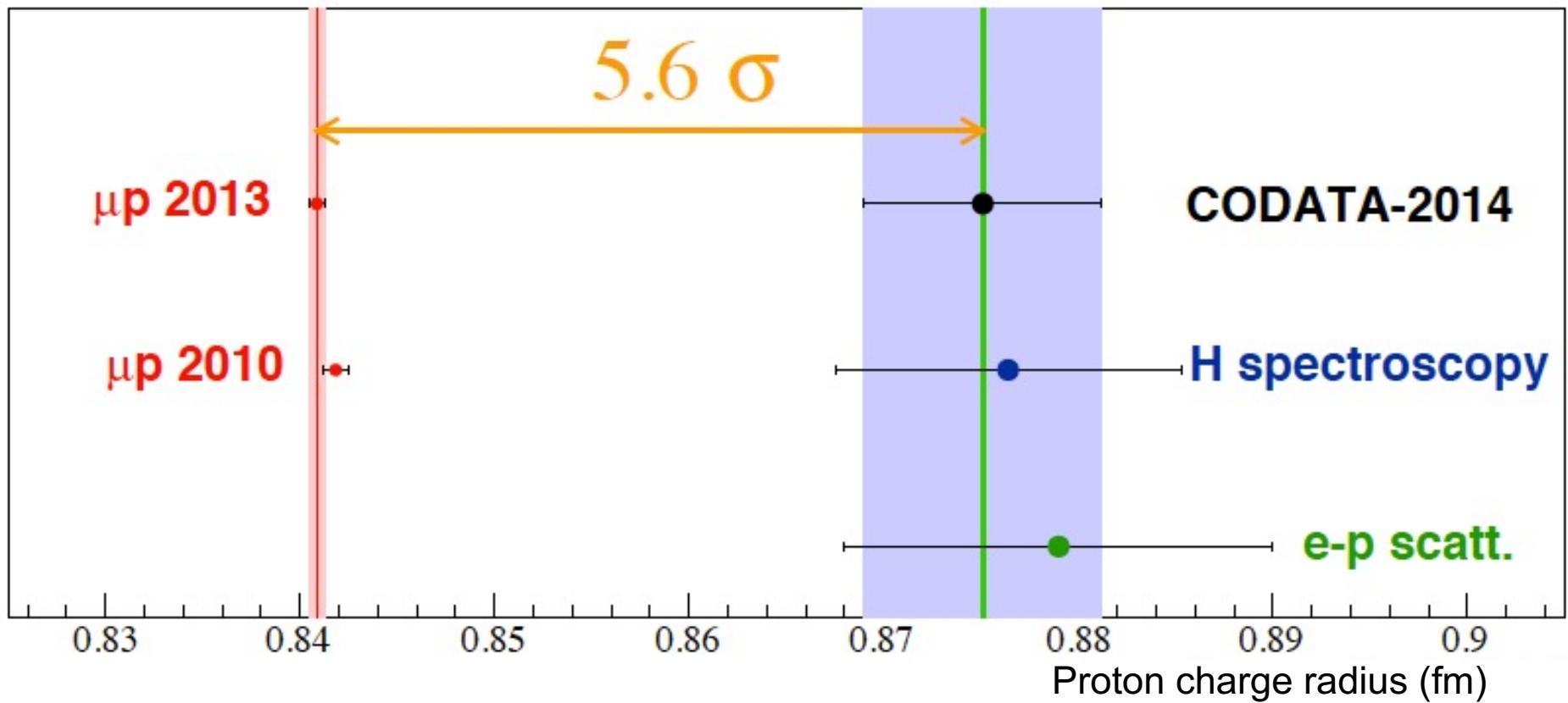
A. Antognini et al., Science 339, 417 (2013)

# The proton radius puzzle in 2016

The proton rms charge radius measured with

electrons:  $(0.8751 \pm 0.0061) \text{ fm}$  (**CODATA2014**)

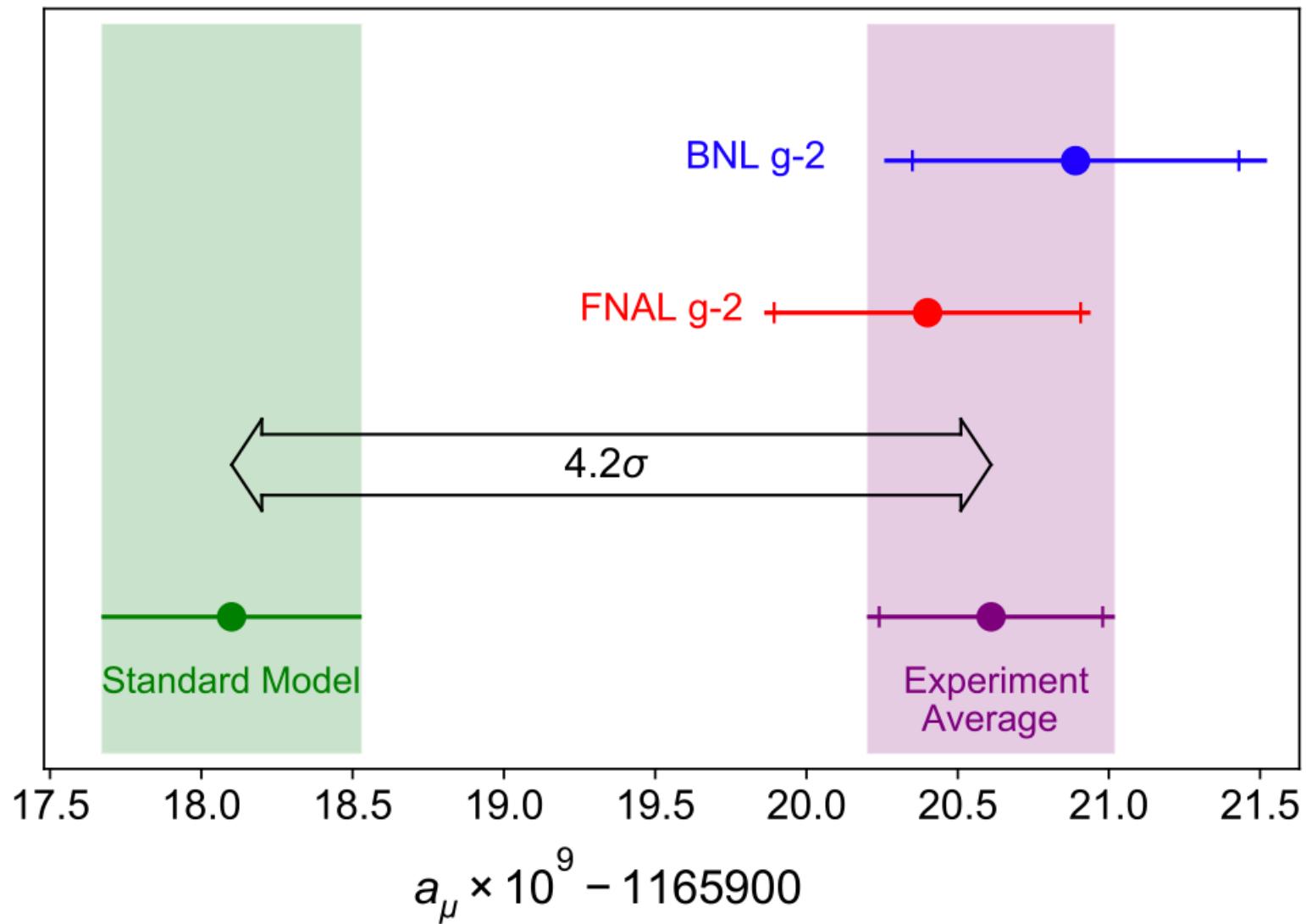
muons:  $(0.8409 \pm 0.0004) \text{ fm}$



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

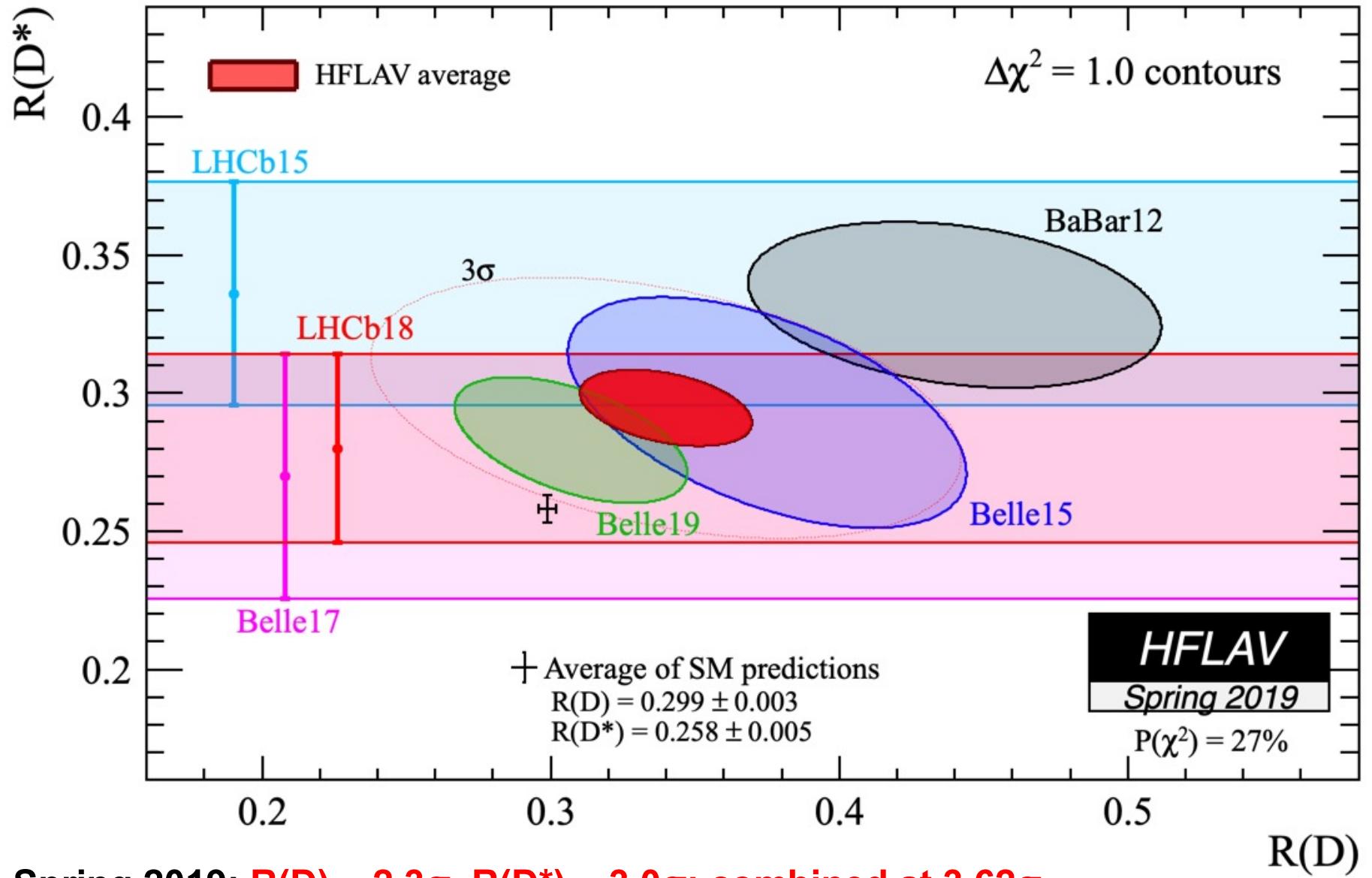
A. Antognini et al., Science 339, 417 (2013)

# Lepton non-universality: Muon g-2

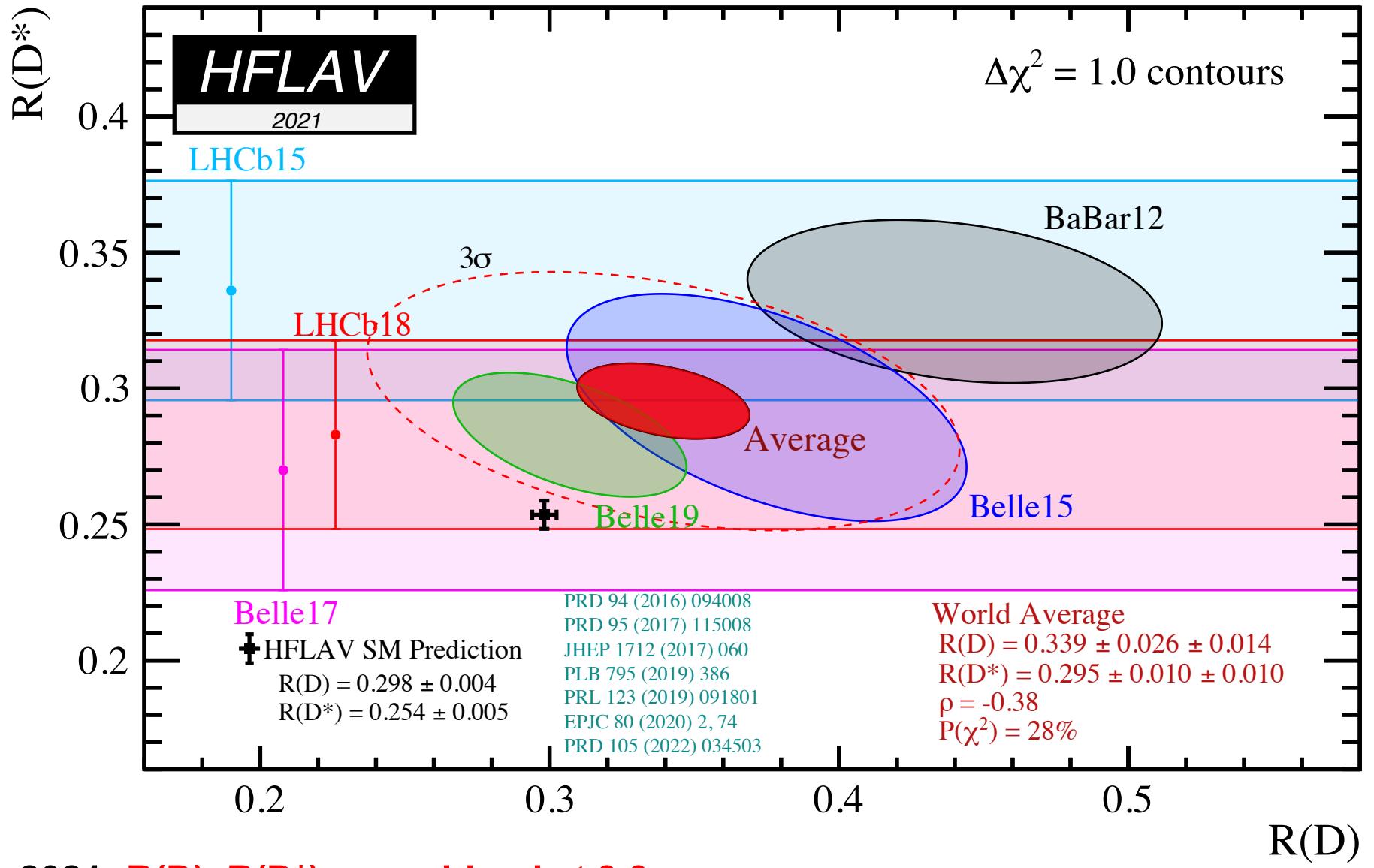


The Muon g-2 Collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, arXiv: 2104.03281

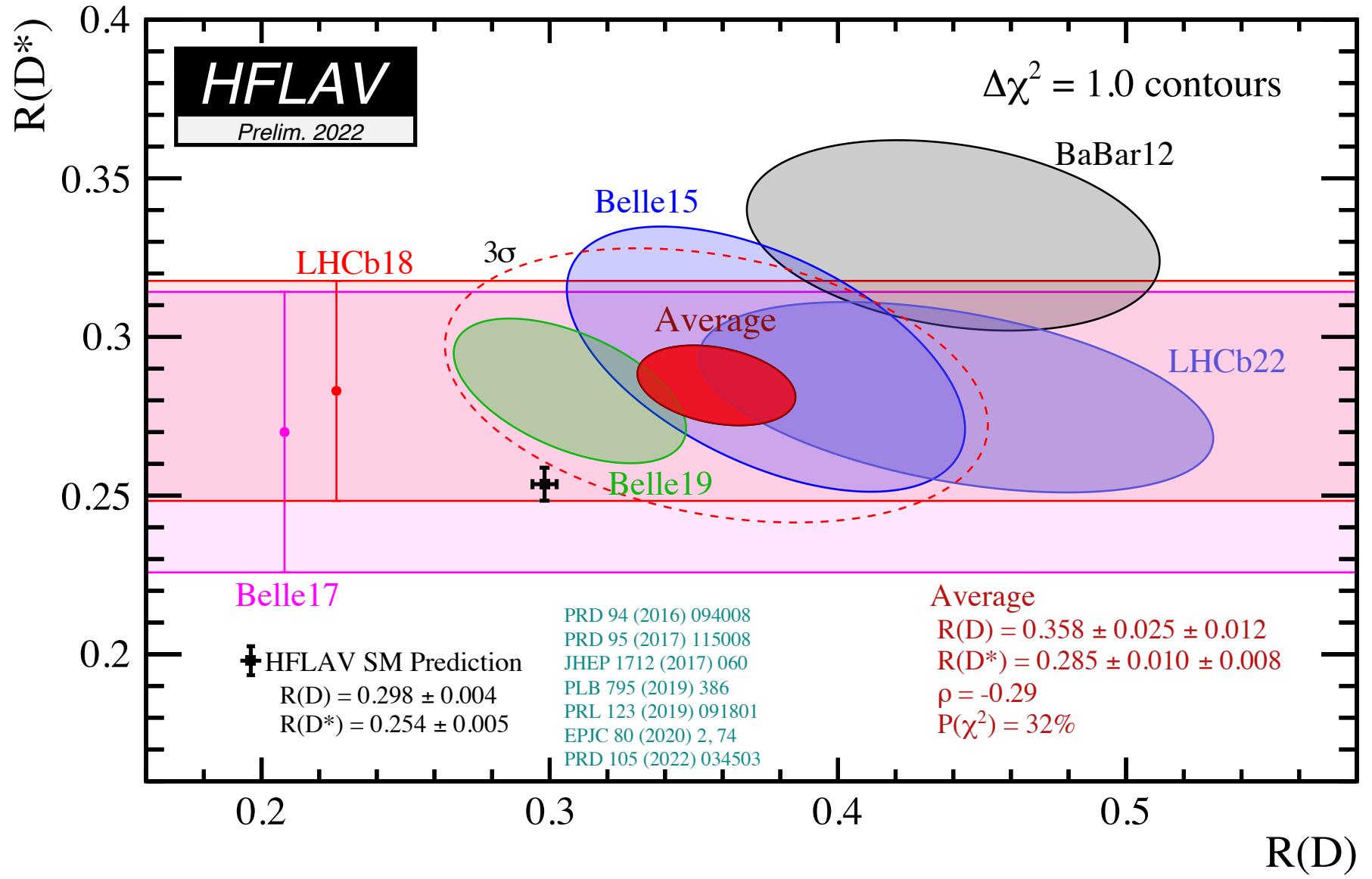
# Lepton non-universality in B-decays ( $\tau$ - $\mu$ )



# Lepton non-universality in B-decays ( $\tau$ - $\mu$ )



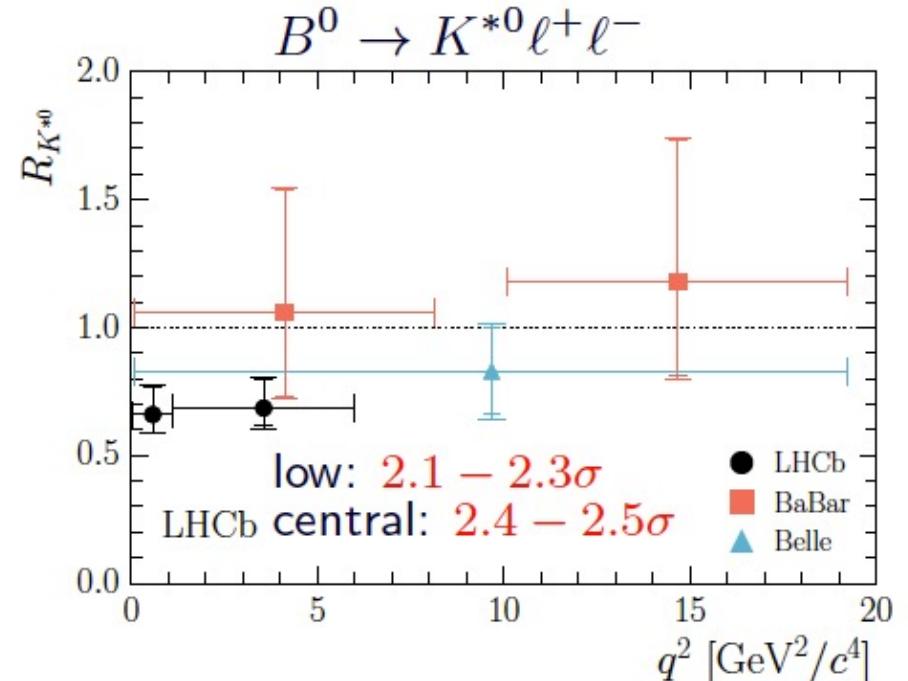
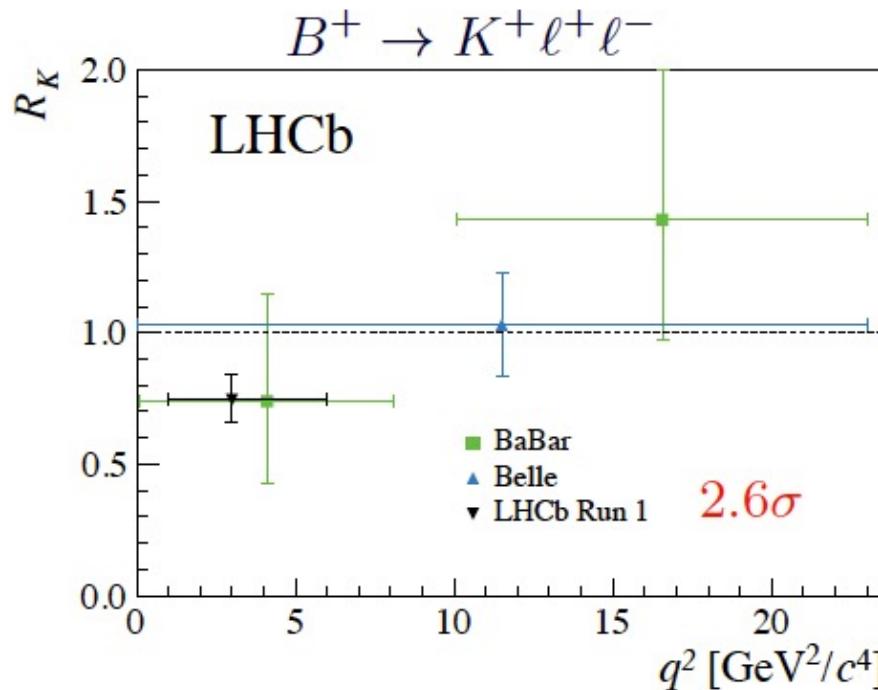
# Lepton non-universality in B-decays ( $\tau$ - $\mu$ )



- Oct. 2022:  $R(D)$ ,  $R(D^*) \sim$  combined at  $3.2\sigma$

# Lepton non-universality in B-decays ( $\mu$ -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  $2.5\sigma$  level



[LHCb, PRL 113 (2014) 151601]

[LHCb, JHEP 08 (2017) 055]

[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]

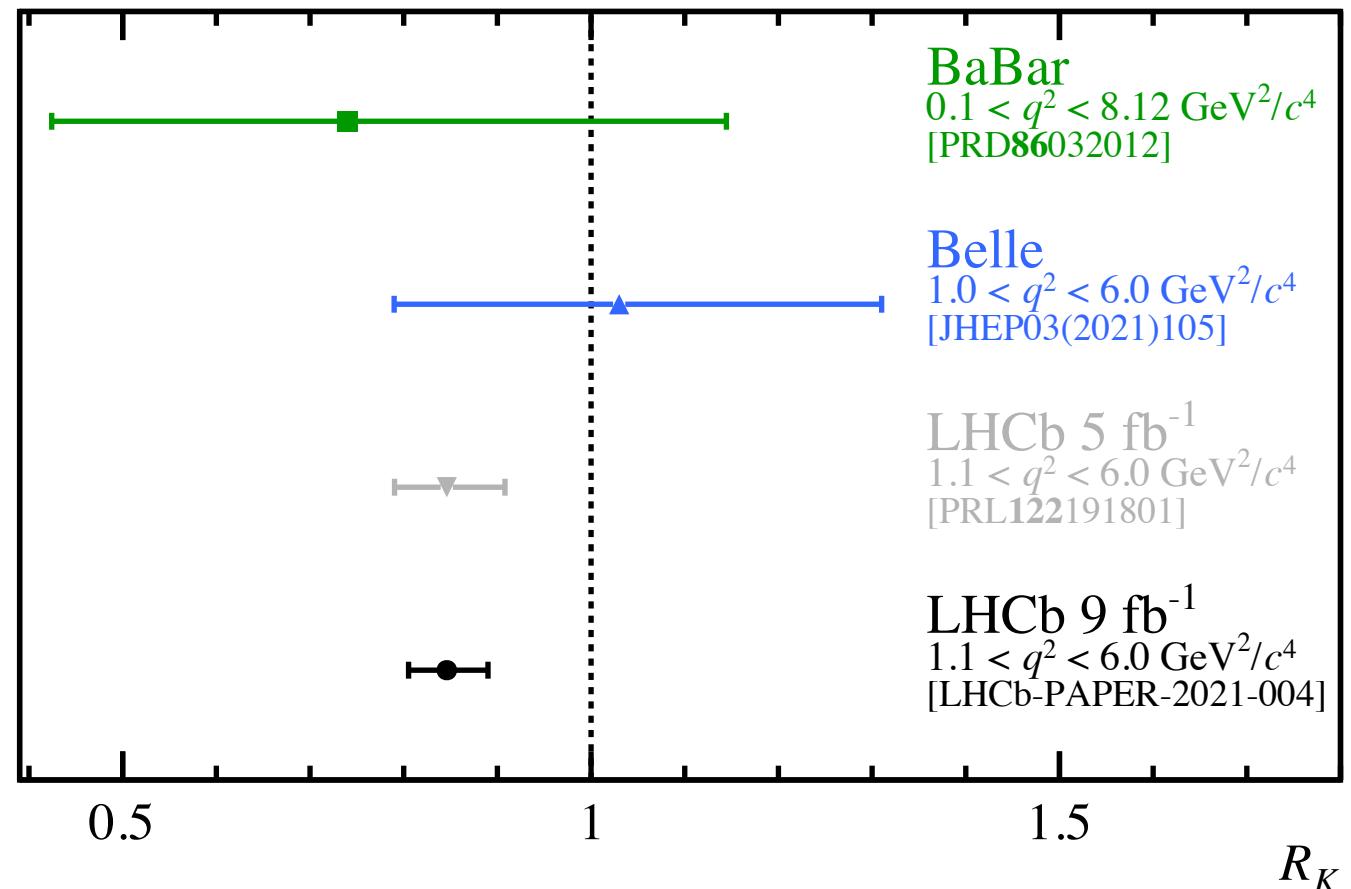
# Lepton non-universality in B-decays ( $\mu$ -e)

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

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

R. Aaji, PRL 122,  
 191801 (2019)

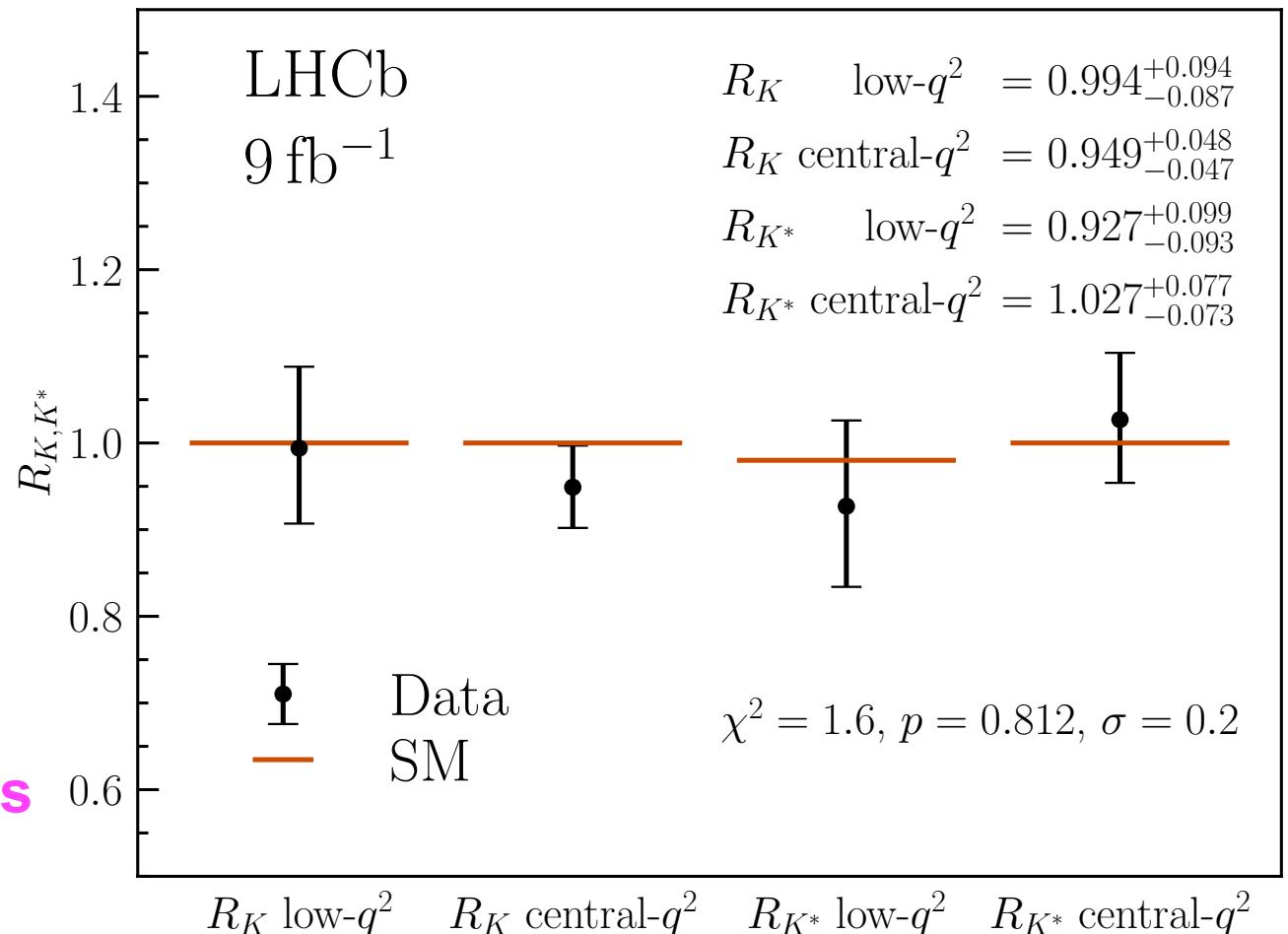
**Full Run1 + Run2**  
 arxiv:2103.11769



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

# Lepton non-universality in B-decays ( $\mu$ -e)

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

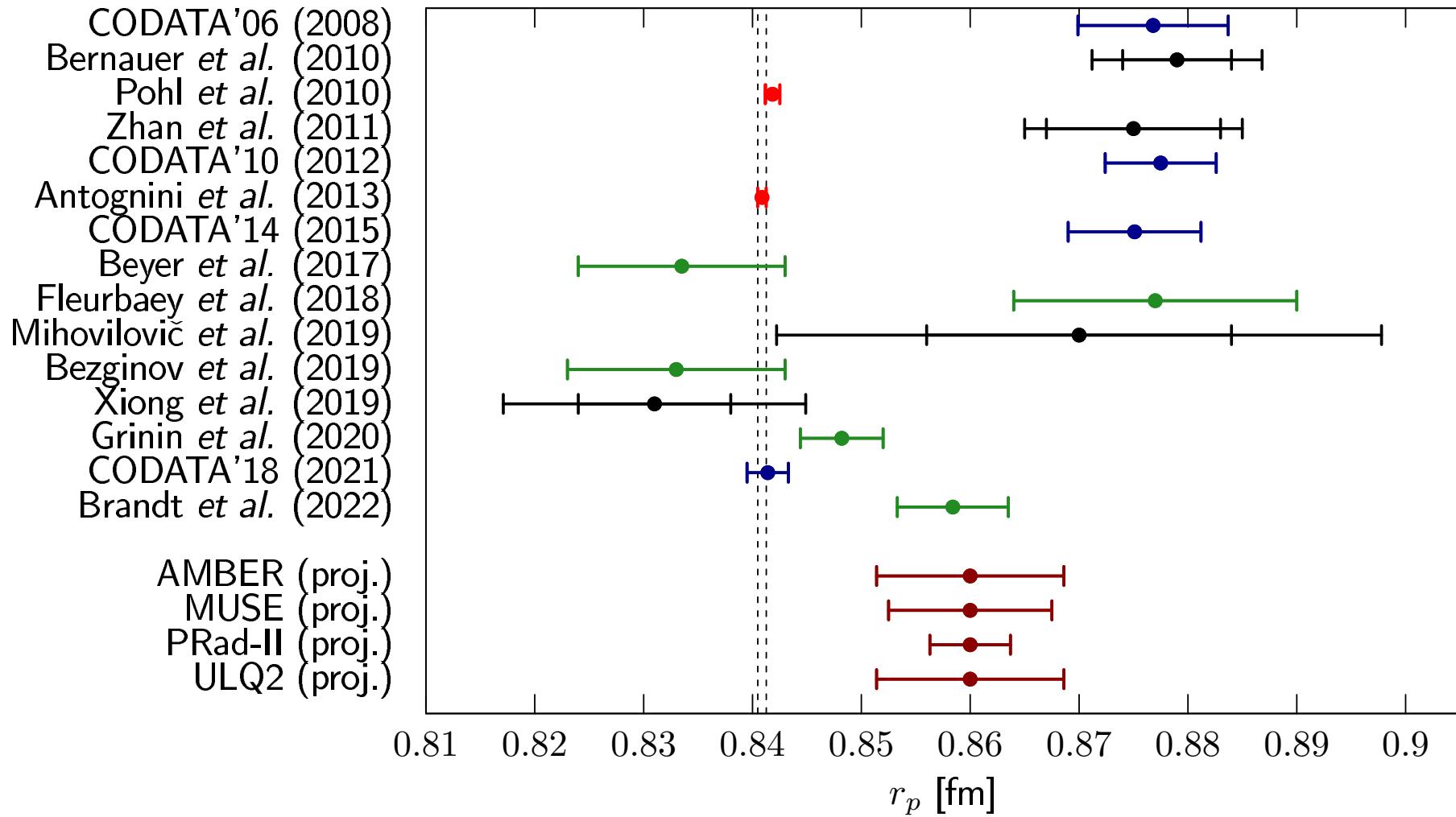


Full Run1 + Run2

arXiv:2212.09153

Supersedes previous  
results!

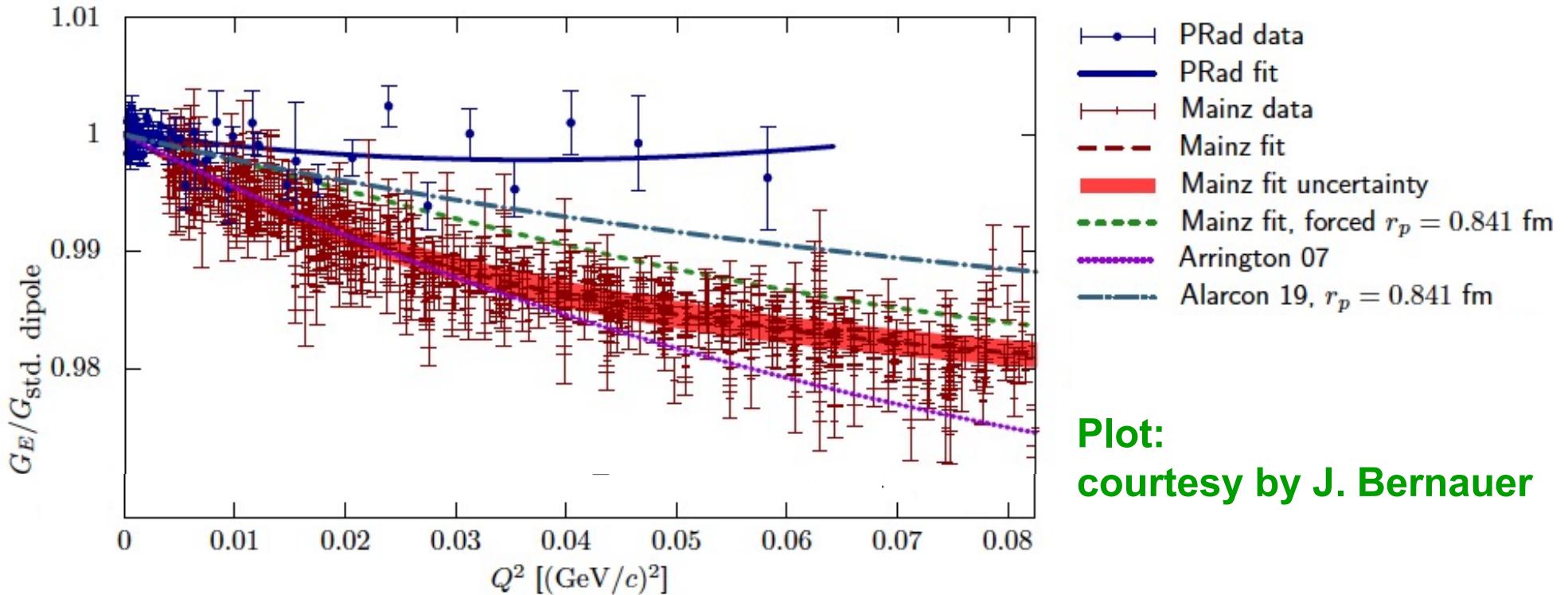
# The proton radius puzzle in 2023



Plot: courtesy by J. Bernauer

# Puzzle solved?

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



**Plot:**  
courtesy by J. Bernauer

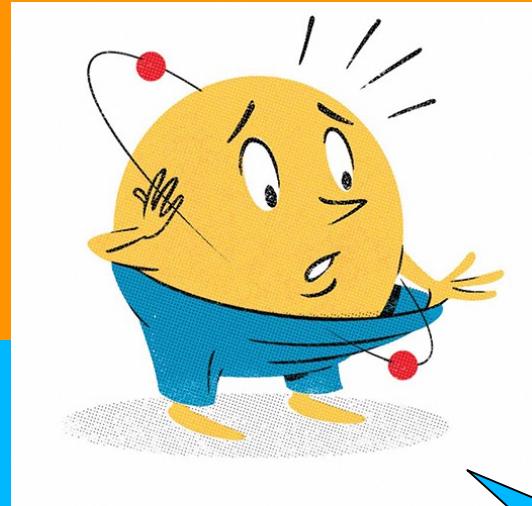
- Accuracy of radiative corrections?
- What did previous experiments do wrong?
- Which result is to be preferred, and why?
- Need independent checks and validations ( $\rightarrow$  ISR, ULQ2, MUSE)

# Motivation for $\mu p$ scattering

Electronic hydrogen

$0.8758 \pm 0.0077$

Spectroscopy



Muonic hydrogen

$0.84184 \pm 0.00067$

$0.84087 \pm 0.00039$

Electron scattering

$0.8770 \pm 0.0060$

Scattering

Muon scattering

???

# Possible resolutions to the puzzle

- **The  $\mu p$  (spectroscopy) result is wrong**

Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement

- **The  $e p$  (spectroscopy) results are wrong**

Accuracy of individual Lamb shift measurements?

Rydberg constant could be off by 5 sigma

- **The  $e p$  (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  $\mu$  and  $e$

Hadronic effects different for  $\mu p$  and  $e p$ :

e.g. proton polarizability ( $effect \propto m_l^{-4}$ )

- **Physics beyond Standard Model differentiating  $\mu$  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

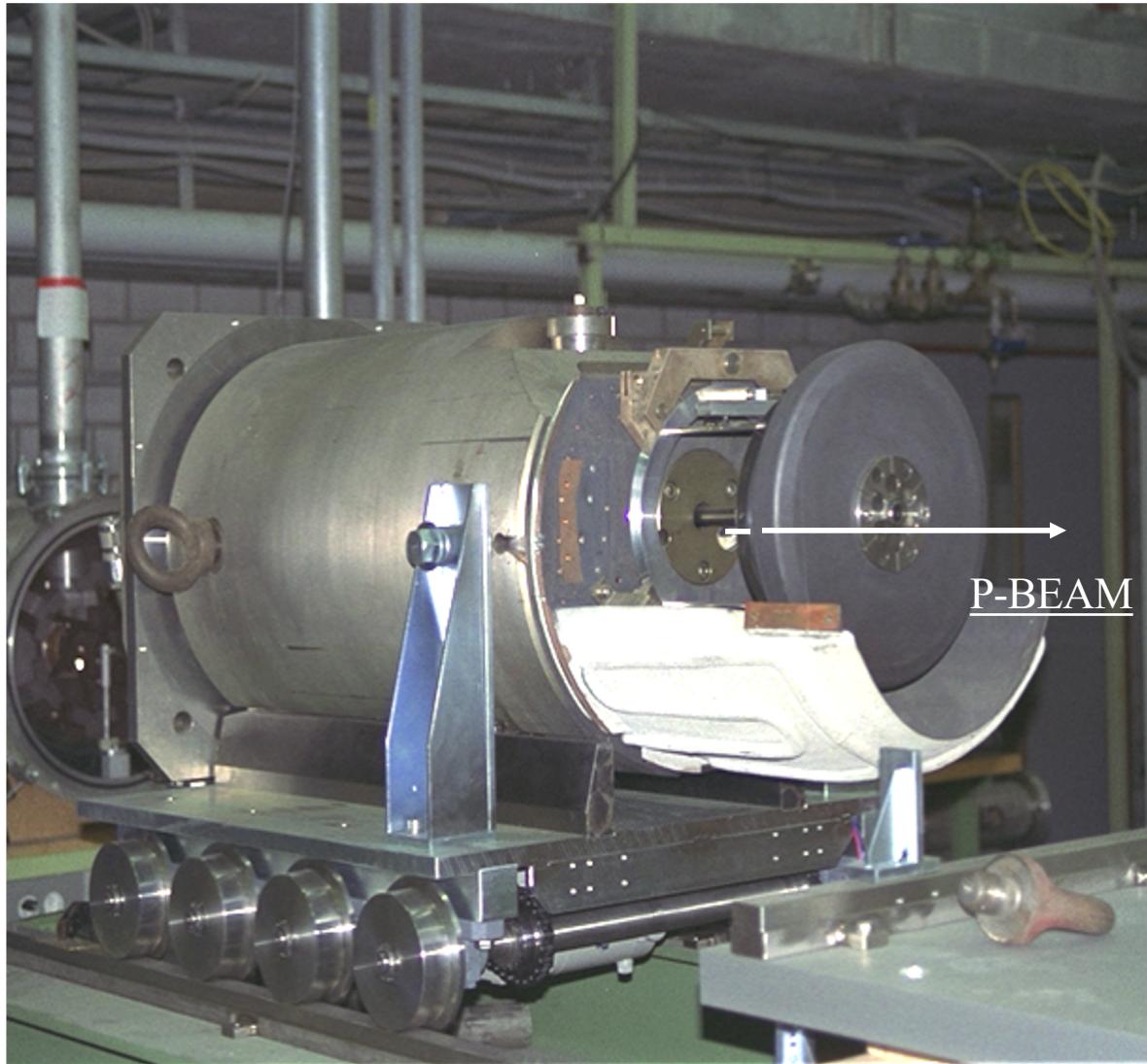
# MUSE: MUon Scattering Experiment at PSI



Use the world's most powerful low-energy separated  $e/\pi/\mu$  beam for a direct test if  $\mu p$  and  $e p$  scattering are different:

- Simultaneous, separated beam of  $(e^+/\pi^+/\mu^+)$  or  $(e^-/\pi^-/\mu^-)$  on liquid  $H_2$  target
  - Separation by time of flight
  - Measure absolute cross sections for  $e p$  and  $\mu p$
  - Measure  $e^+/\mu^+$ ,  $e^-/\mu^-$  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  $e^+/e^-$ ,  $\mu^+/\mu^-$
- Multiple beam momenta 115-210 MeV/c for broad low- $Q^2$  range to be covered

# M-target: secondary beam production



## Target M:

Mean diameter: 320 mm

Target thickness: 5.2 mm

Target width: 20 mm

Graphite density: 1.8 g/cm<sup>3</sup>

Beam loss: 1.6 %

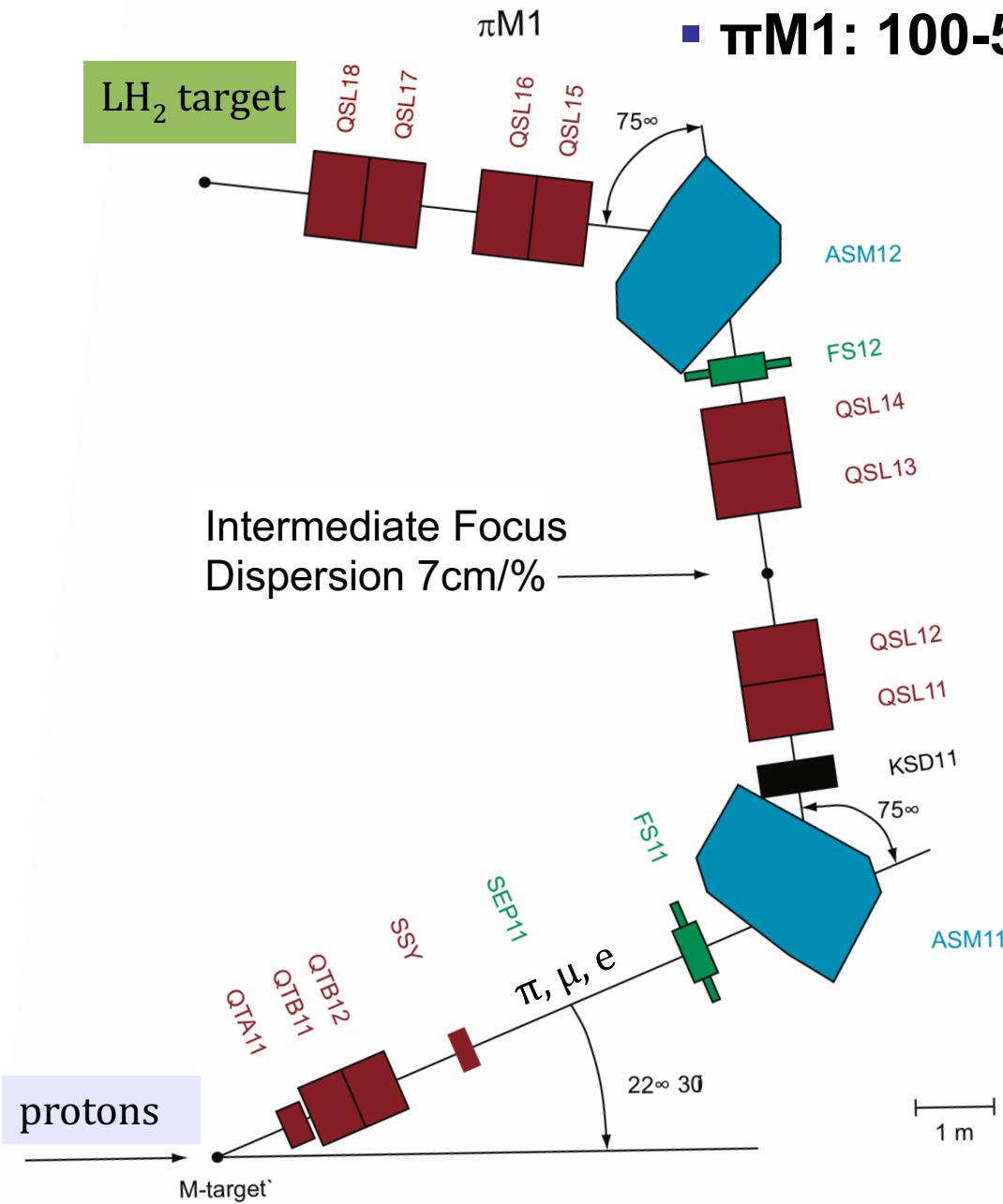
Power deposition: 2.4 kW/mA

Operating Temperature: 1100 K

Irradiation damage rate: 0.12 dpa/Ah

Rotational Speed: 1 Turn/s

# $\pi$ M1 / MUSE beamline



- $\pi$ M1: 100-500 MeV/c RF+TOF sep.  $\pi$ ,  $\mu$ ,  $e$

Secondary beams of  $\pi$ ,  $\mu$ ,  $e$  produced at M-target with 2 mA protons (590 MeV), 1-10 MHz flux collected with quads, jaws, and double-C

## Point-like source

- $\pi^\pm$  produced directly
- $e^\pm$  from  $\pi^0$  decay + conv.

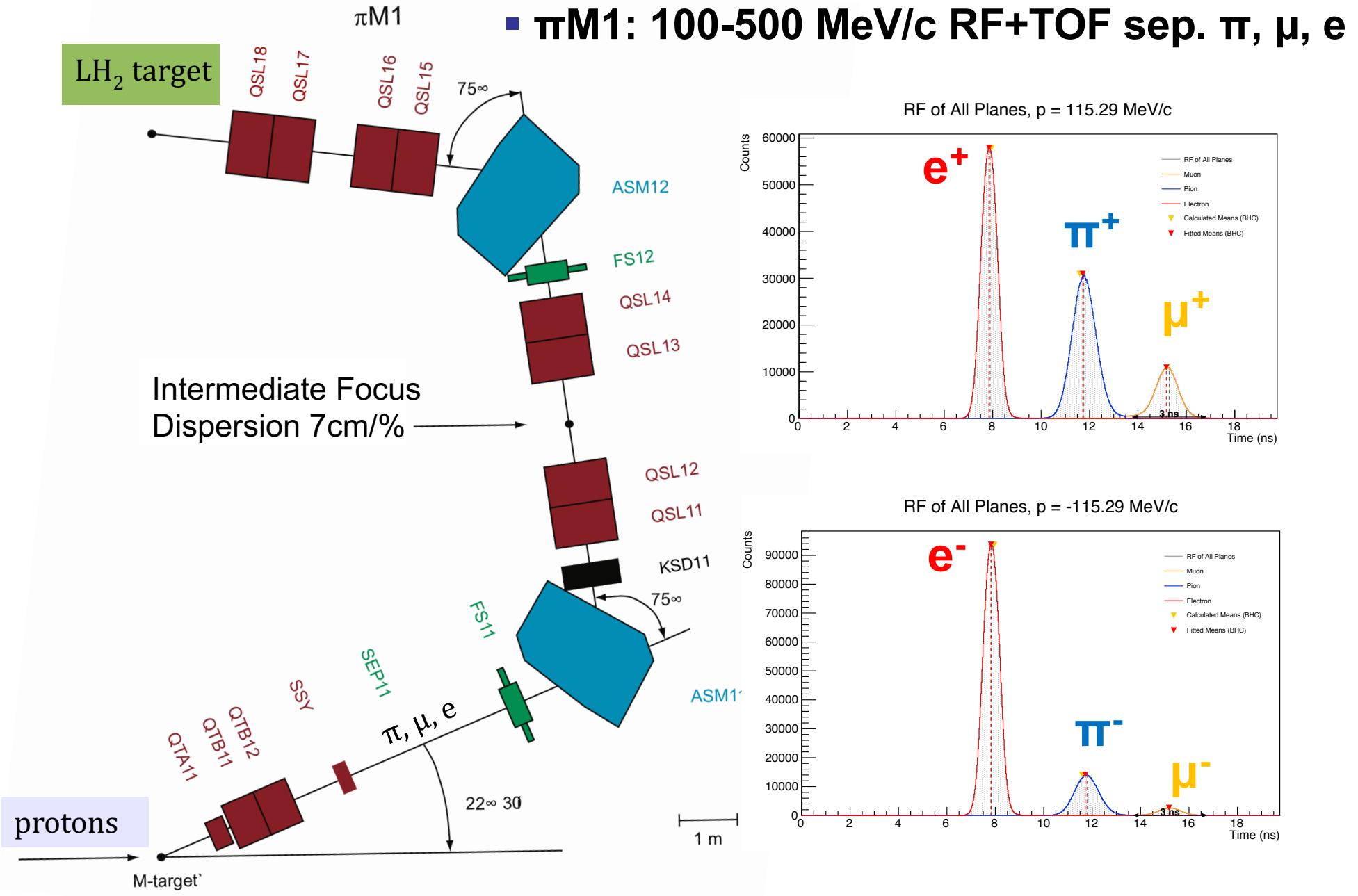
## Extended source

- $\mu^\pm$  from  $\pi^\pm$  decay in flight  $O(cm)$  transv.,  $O(m)$  longit.

Beam properties well understood with TRANSPORT, TURTLE, and G4Beamline

E. Cline et al., PRC105, 055201 (2022)

# $\pi$ M1 / MUSE beamline



# MUSE experiment layout

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

**Measure  $e^\pm p$  and  $\mu^\pm p$  elastic scattering**

$p = 115, 153, 210 \text{ MeV}/c$

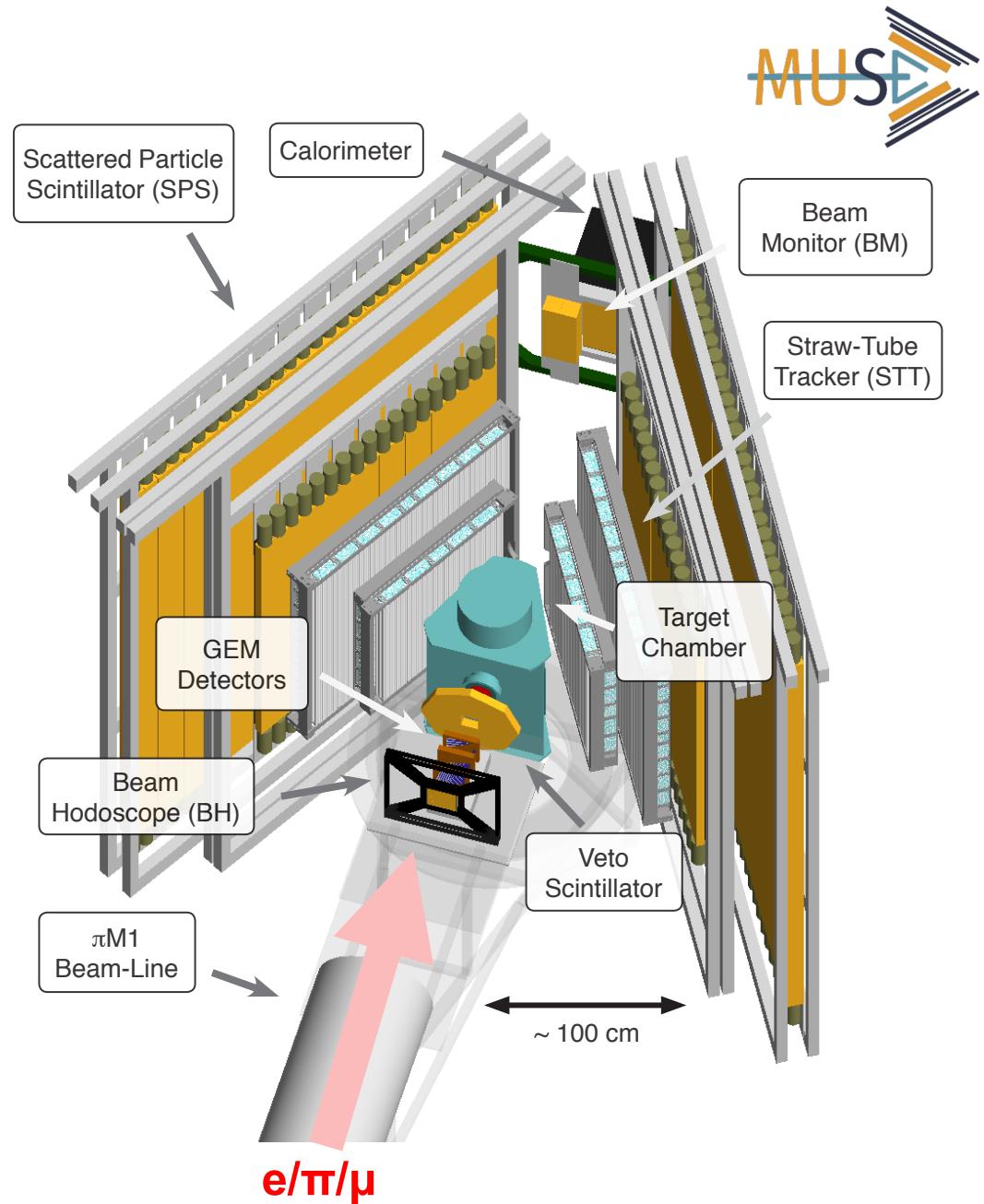
$\theta = 20^\circ \text{ to } 100^\circ$

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

$\varepsilon = 0.256 - 0.94$

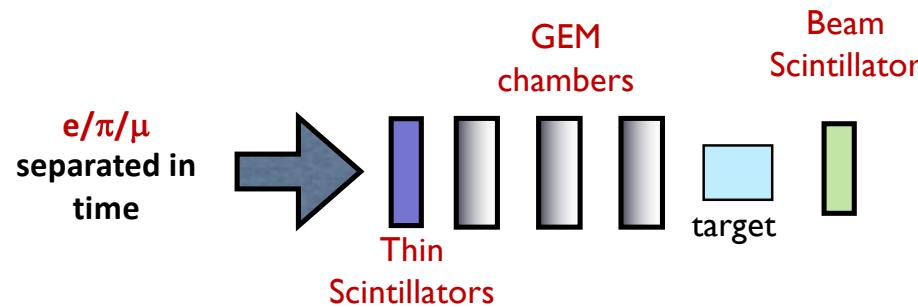
## Challenges

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



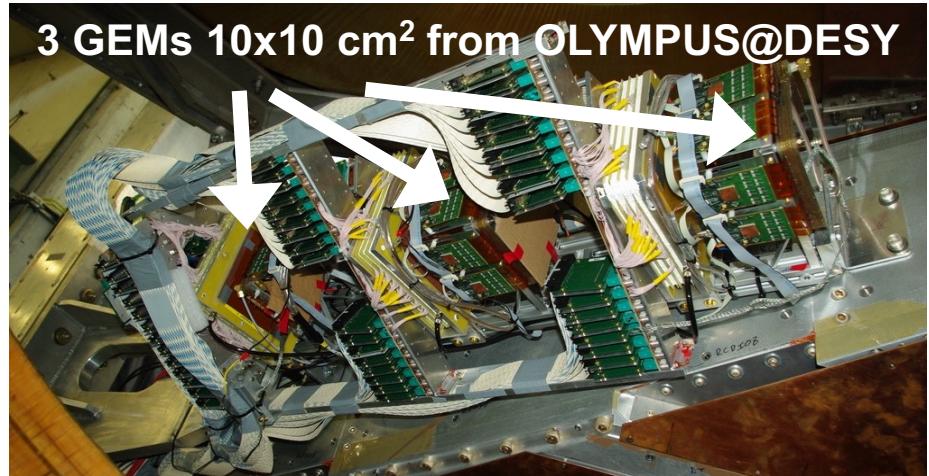
# Beamline instrumentation

## 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

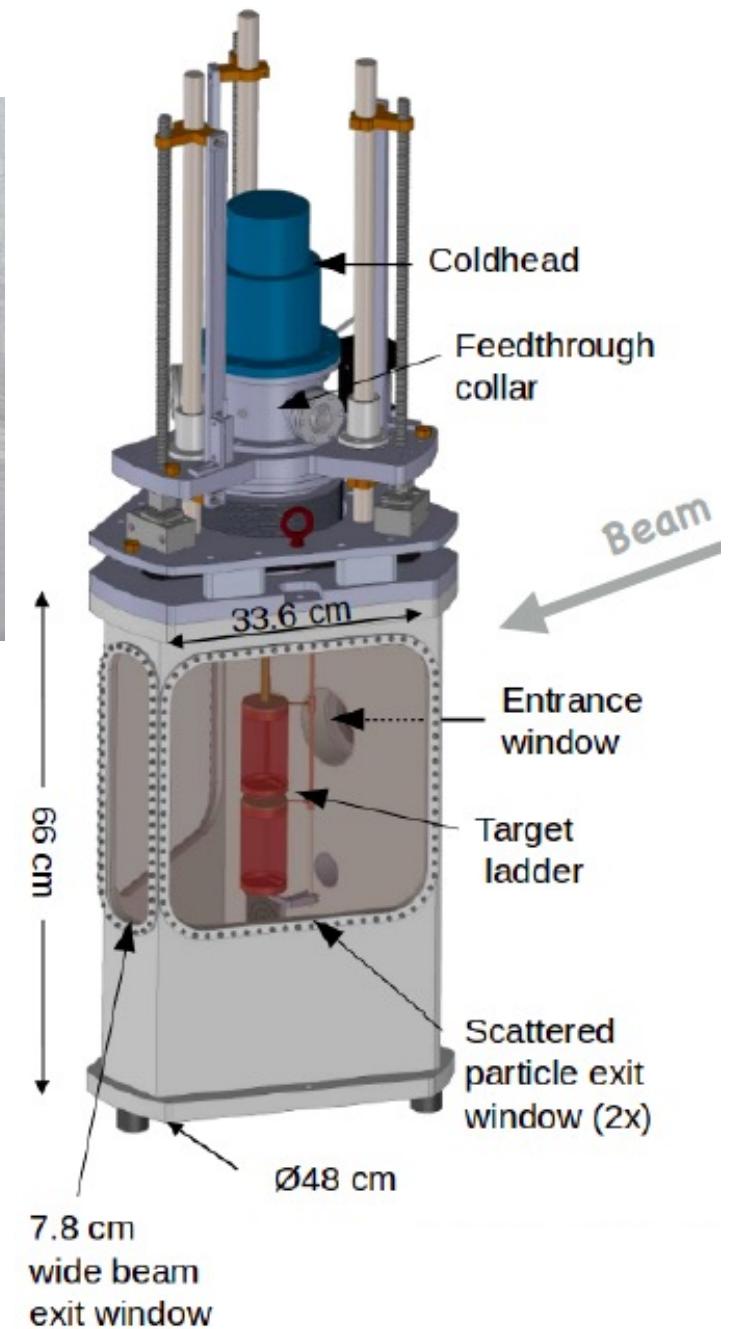
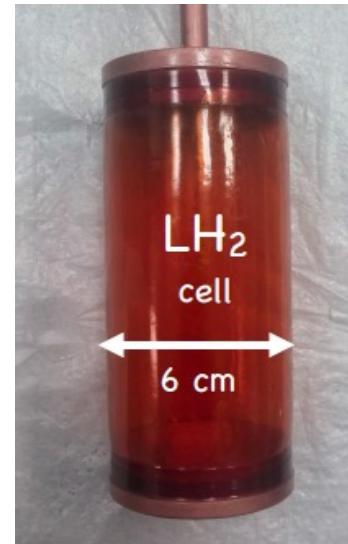
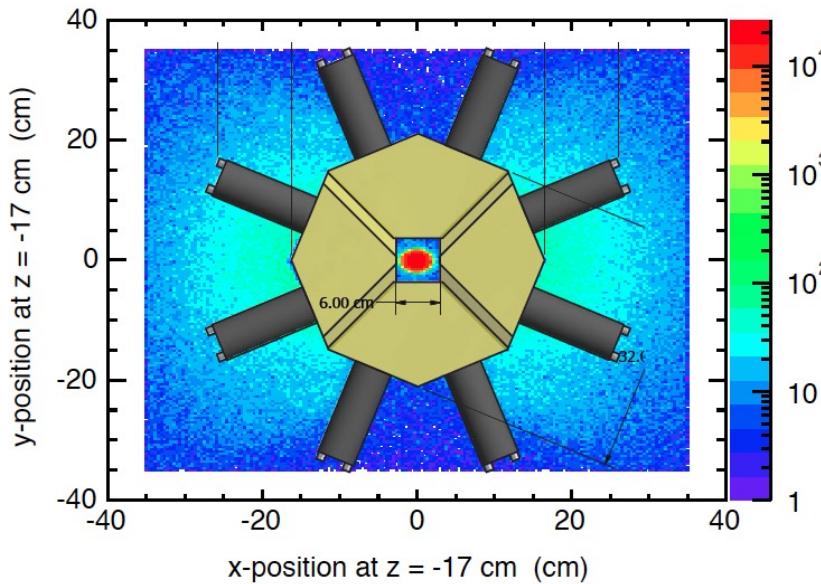
### Thin scintillators with SiPM+CFD readout (PSI/Rutgers/TAU)

- 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



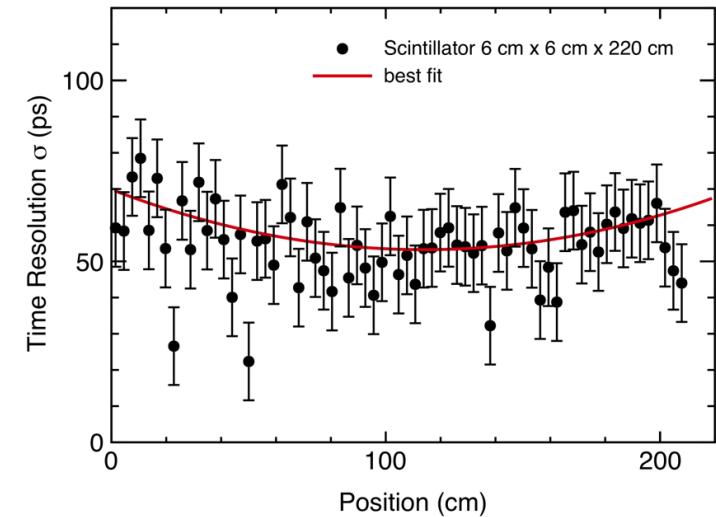
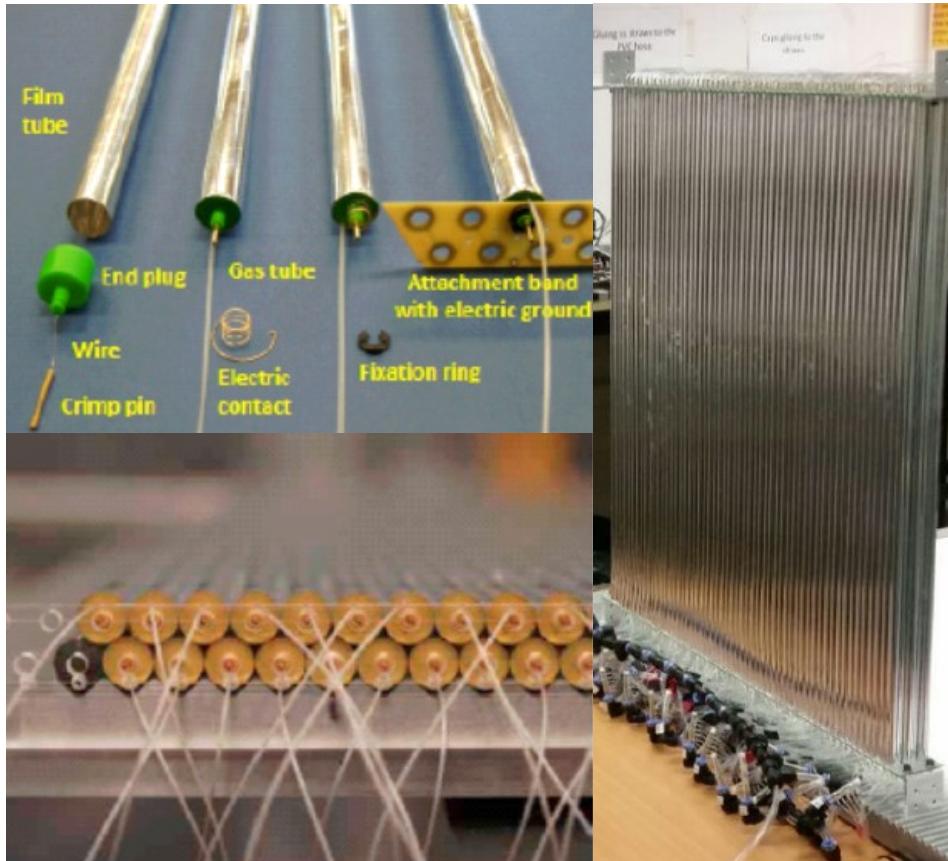
## Veto scintillators (USC):

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 ( $\sim 50$  ps) timing
- PID and trigger, background rejection

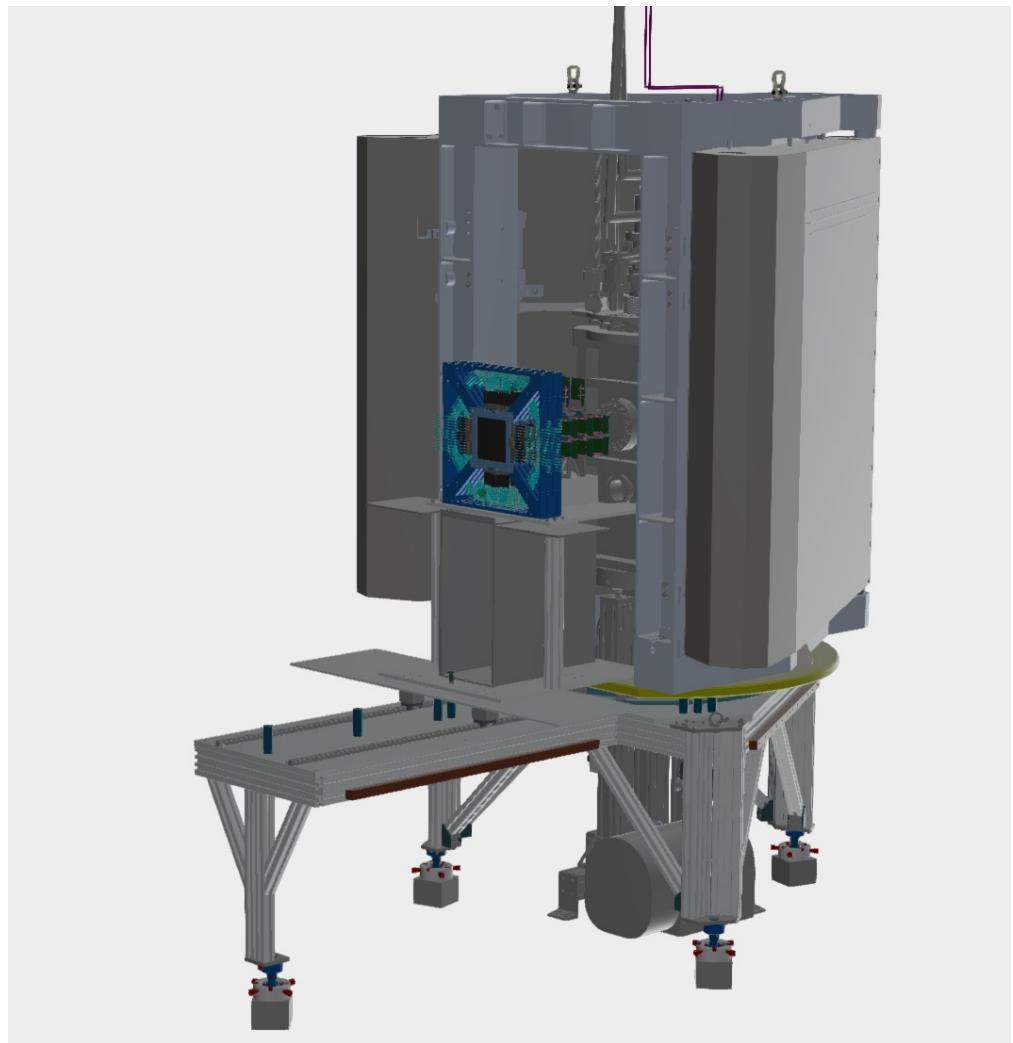
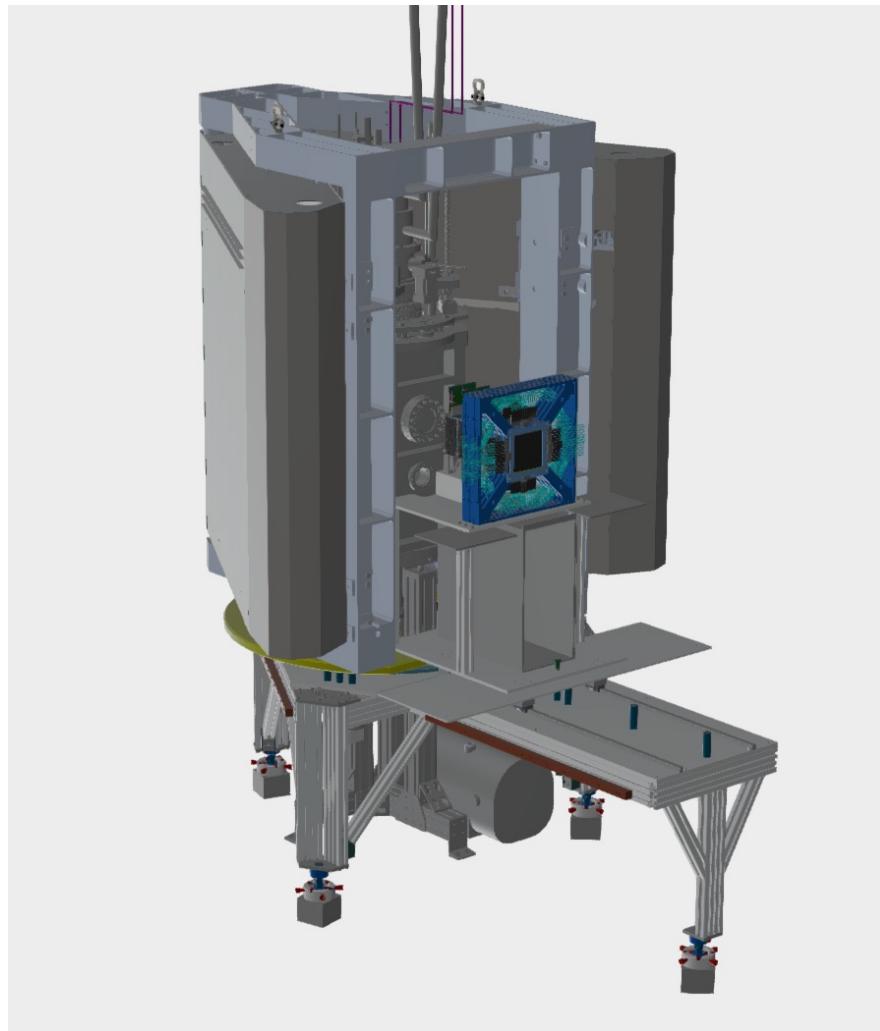


## Straw tube tracker (HUJI, Temple)

- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design –  $140 \mu\text{m}$  resol.
- Thin walls ( $25\mu\text{m}$ ), 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

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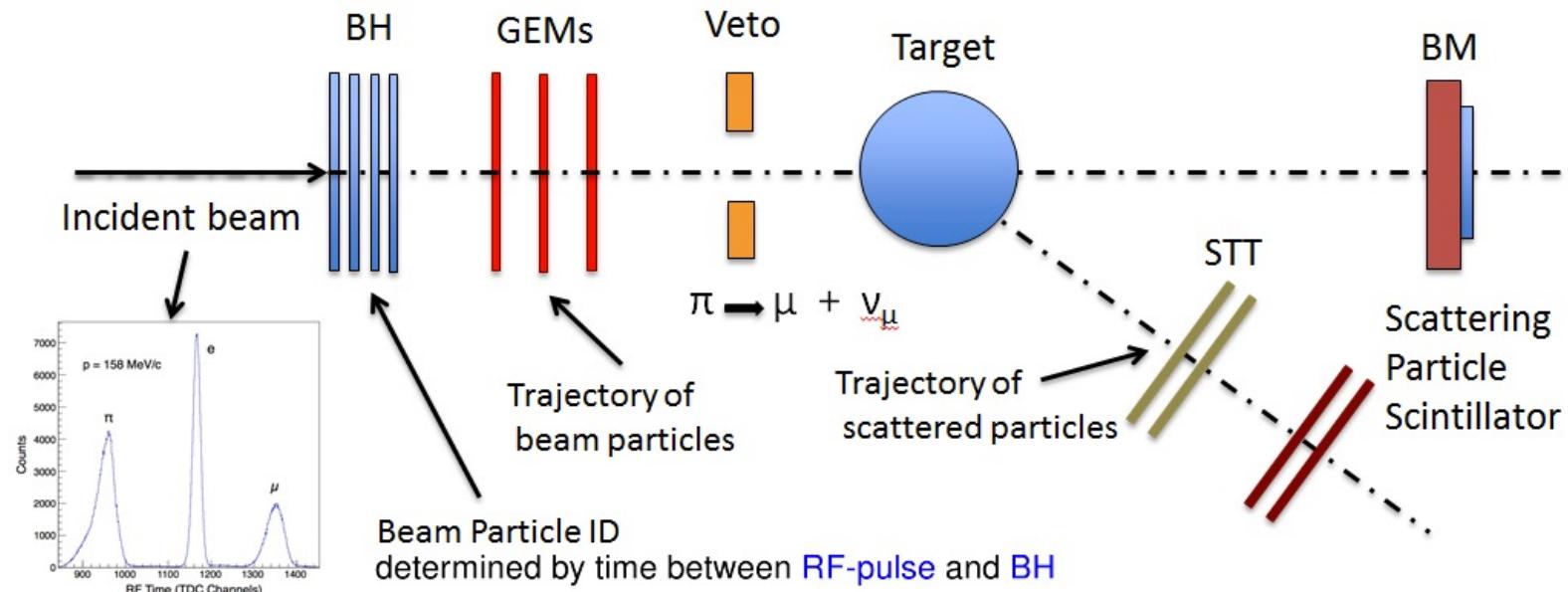
## DAQ system (**GWU and Montgomery Coll.**)

- 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  $\mu$  beam part. + scattered part. + no veto

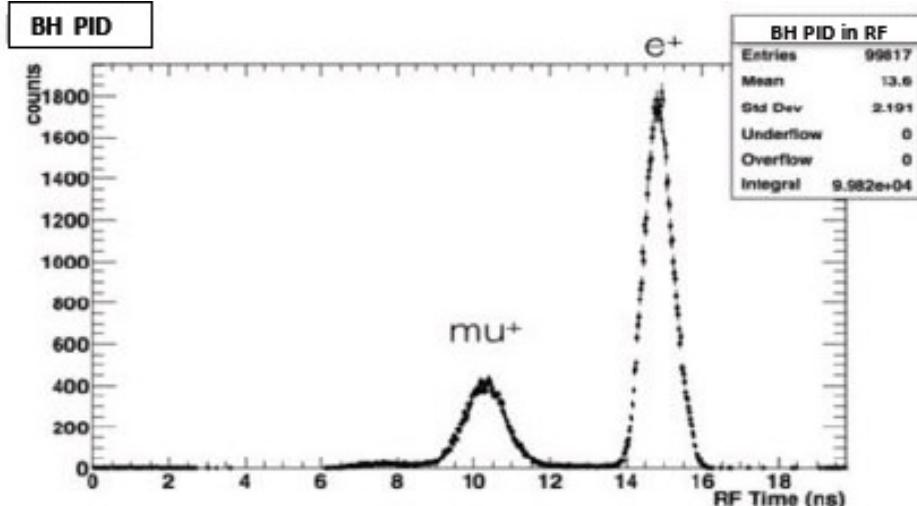
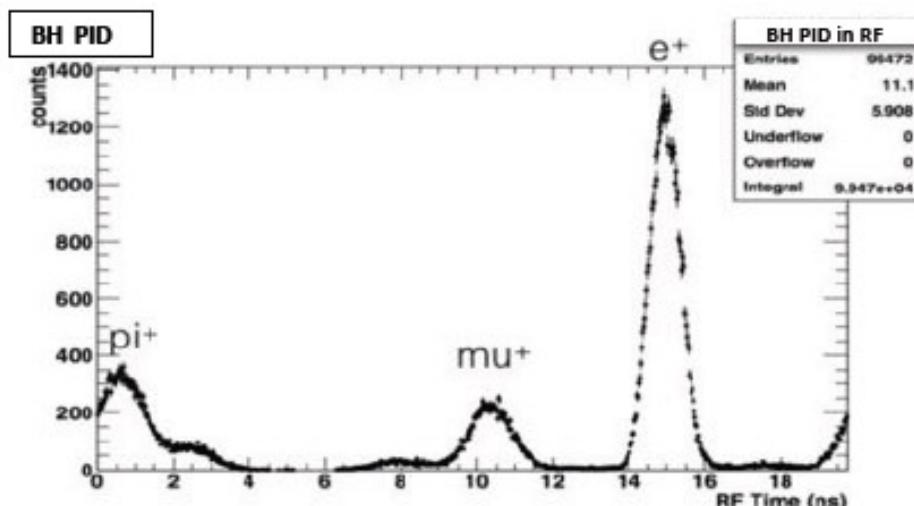
# Trigger with pion rejection



**Trigger Logic:** TRB3 FPGA-based:

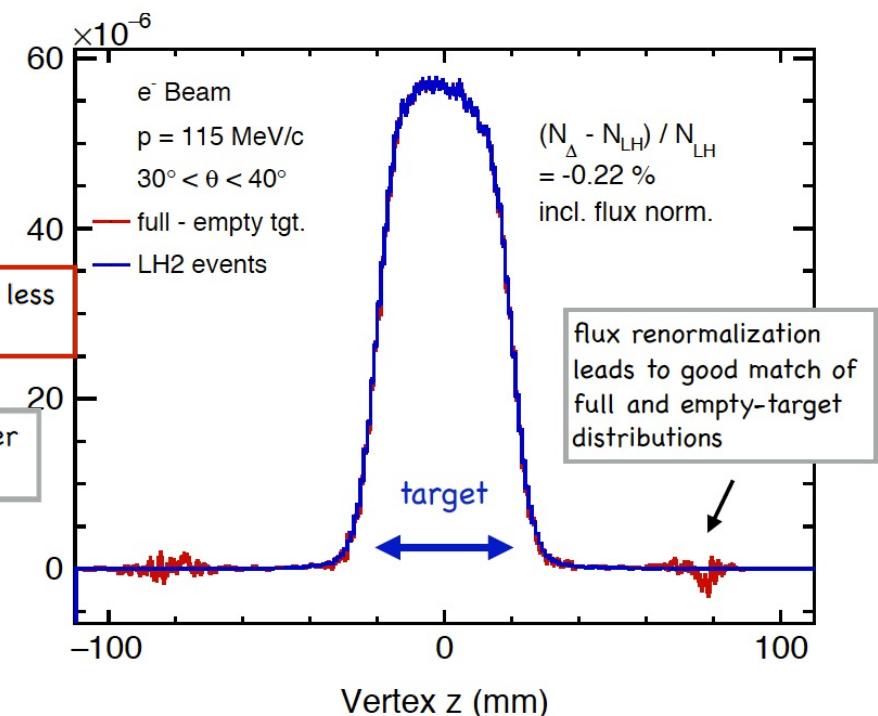
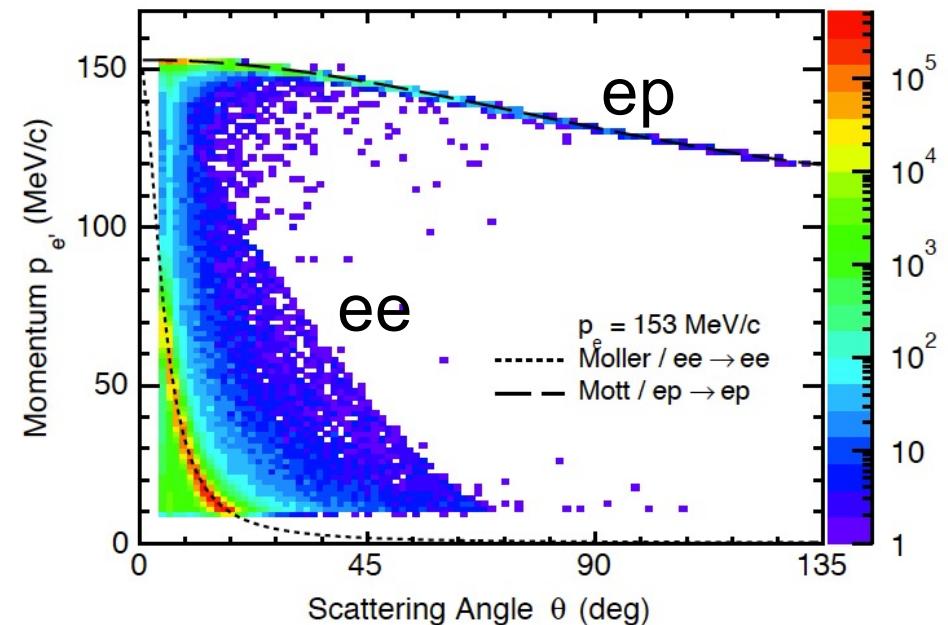
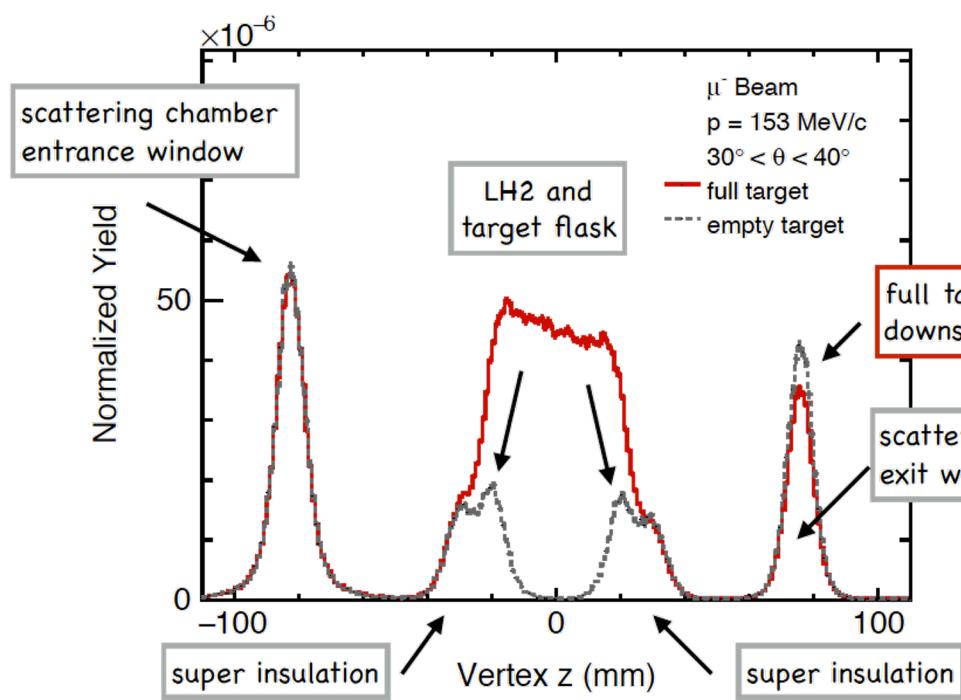
accept  $e^\pm, \mu^\pm$ , reject  $\pi^\pm$

( $e$  OR  $\mu$ ) AND (no  $\pi$ ) AND (scatter) AND (no veto)



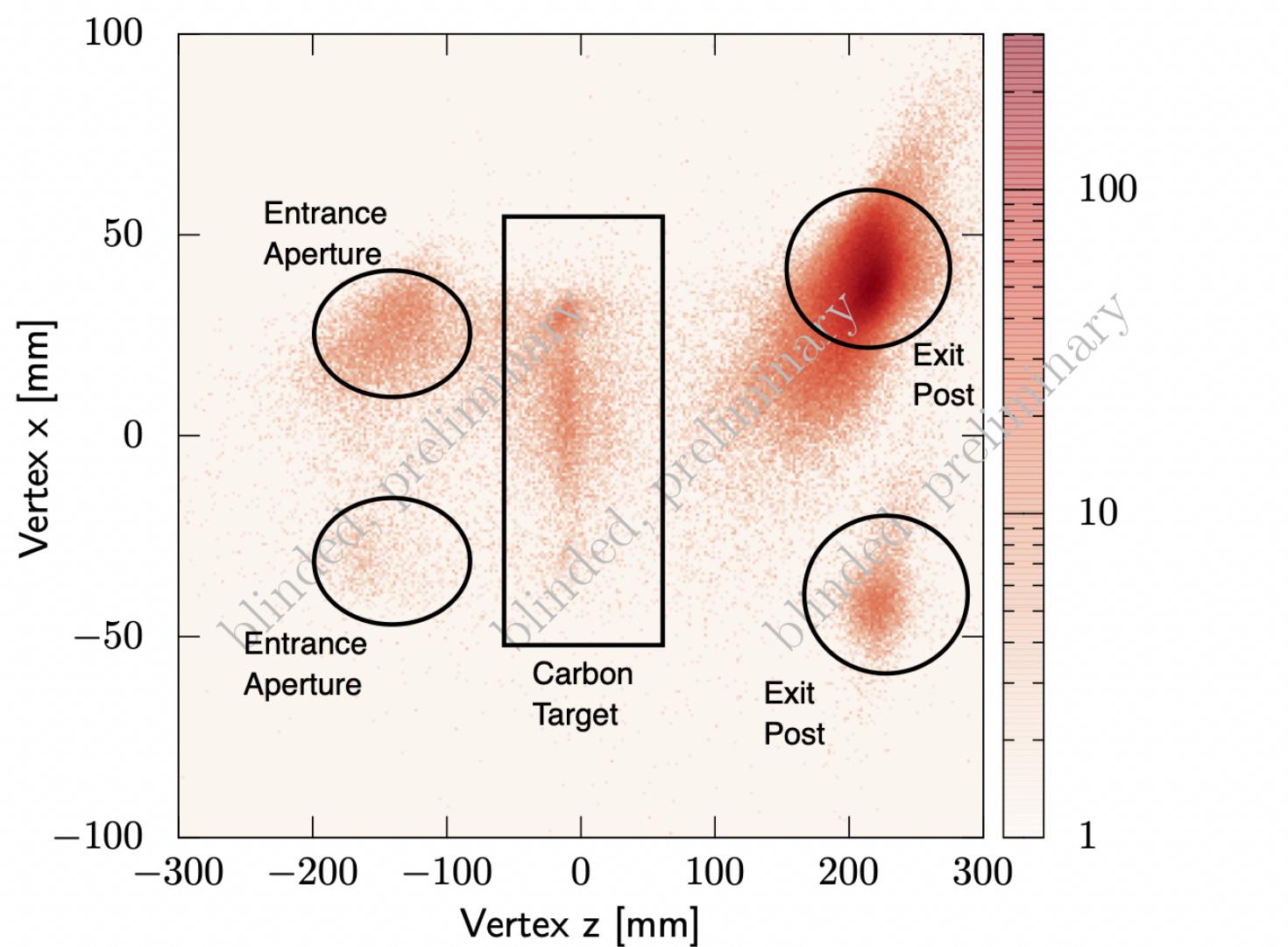
# Simulations (S. Strauch, USC)

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



# MUSE performance: $e^\pm$ scattering from C

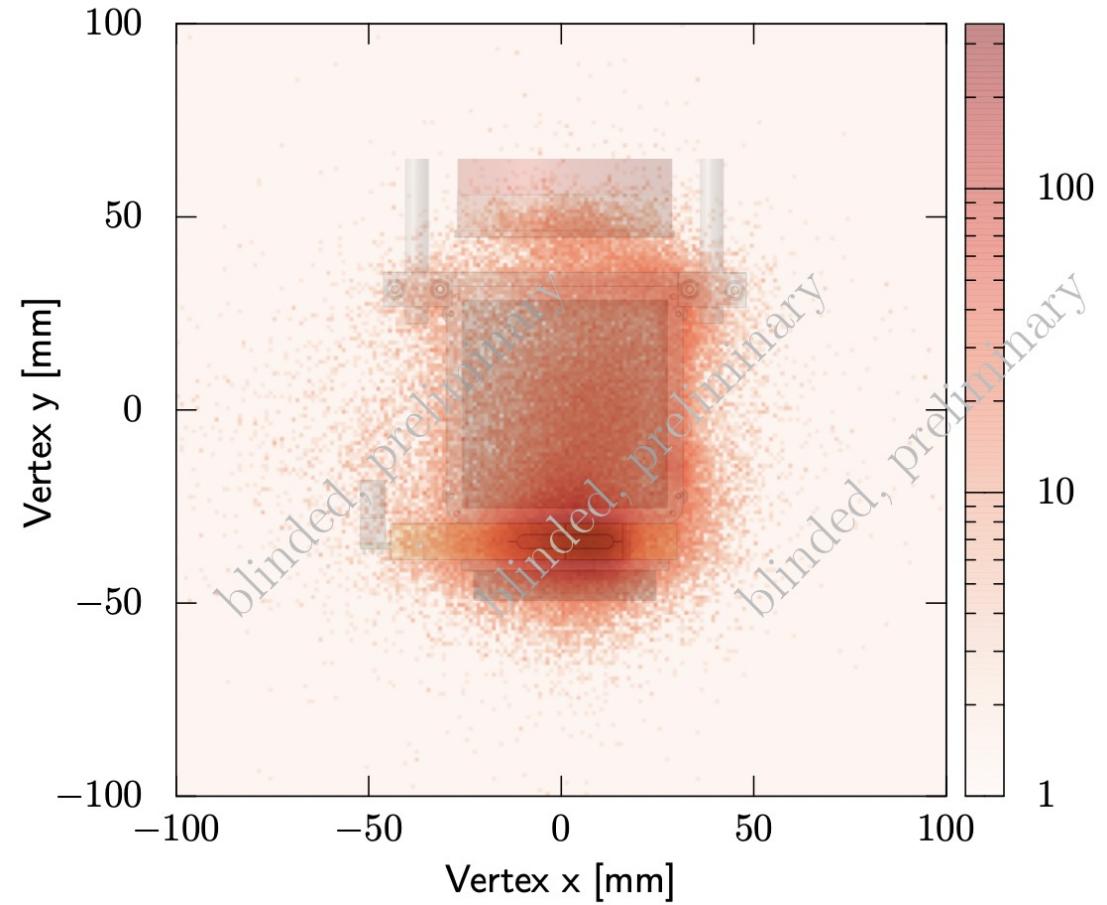
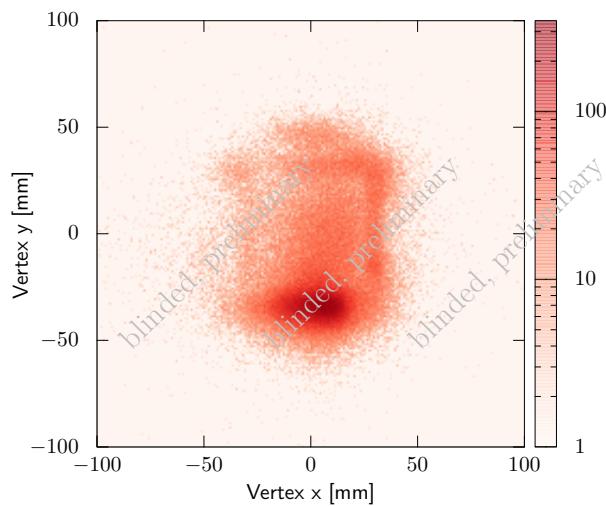
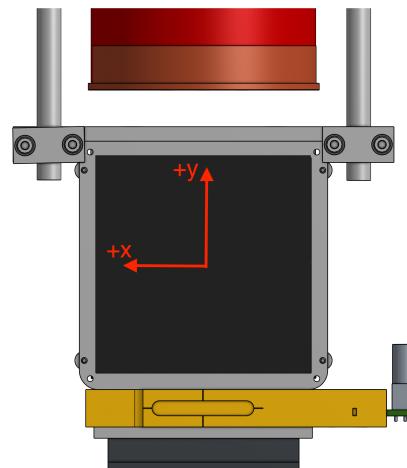
$e^-C$  and  $e^+C$  scattering at 115 MeV/c , 14M events (7 runs)



Cut on  $|y| < 25$  mm. Carbon target x y z vertex reconstruction

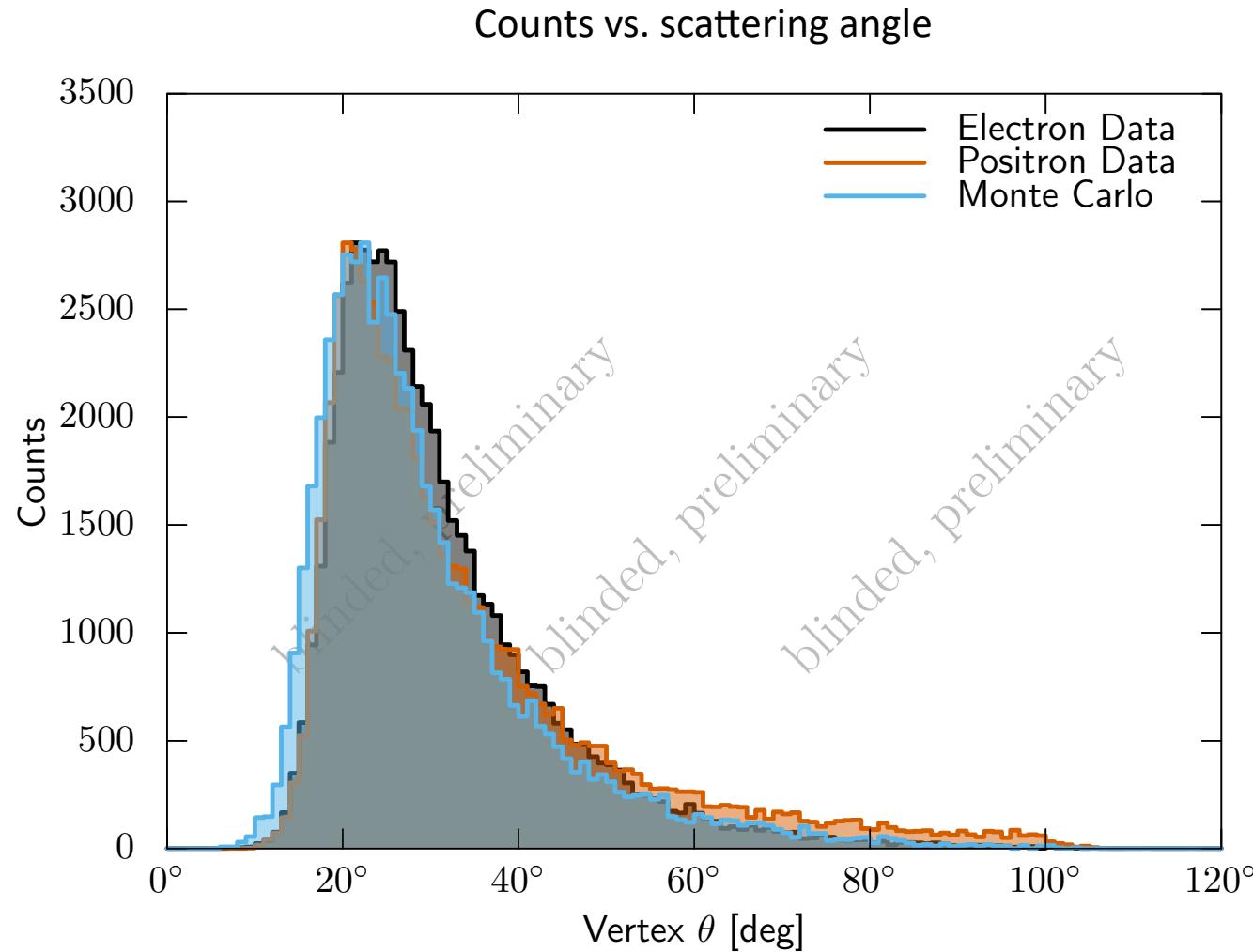
# MUSE performance: $e^\pm$ scattering from C

30



Cut on  $|z| < 80$  mm. Carbon target y vs. x vertex reconstruction (+x toward beam-left)

# MUSE performance: $e^\pm$ scattering from C



Cut on  $|x| < 25$  mm,  $|y| < 25$  mm, and  $|z| < 80$  mm

Blinded data!

Monte Carlo in progress

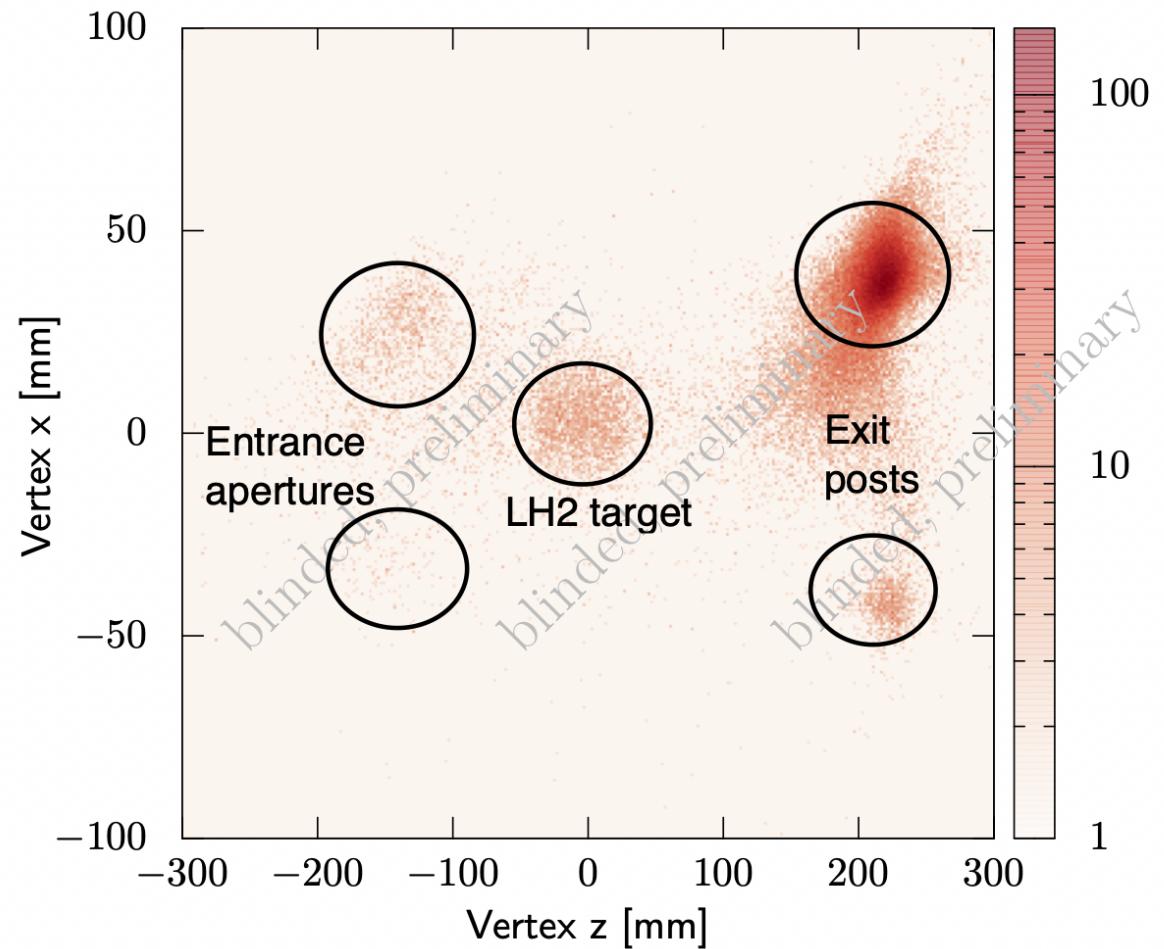
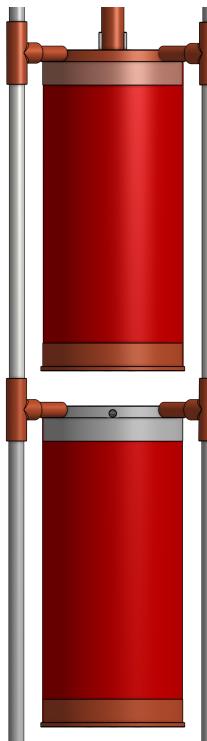
# MUSE performance: $e^+$ scattering from LH<sub>2</sub>

$e^+$  scattering from LH<sub>2</sub> at +160 MeV/c

Top:  
filled with LH<sub>2</sub>

Bottom:  
empty cell

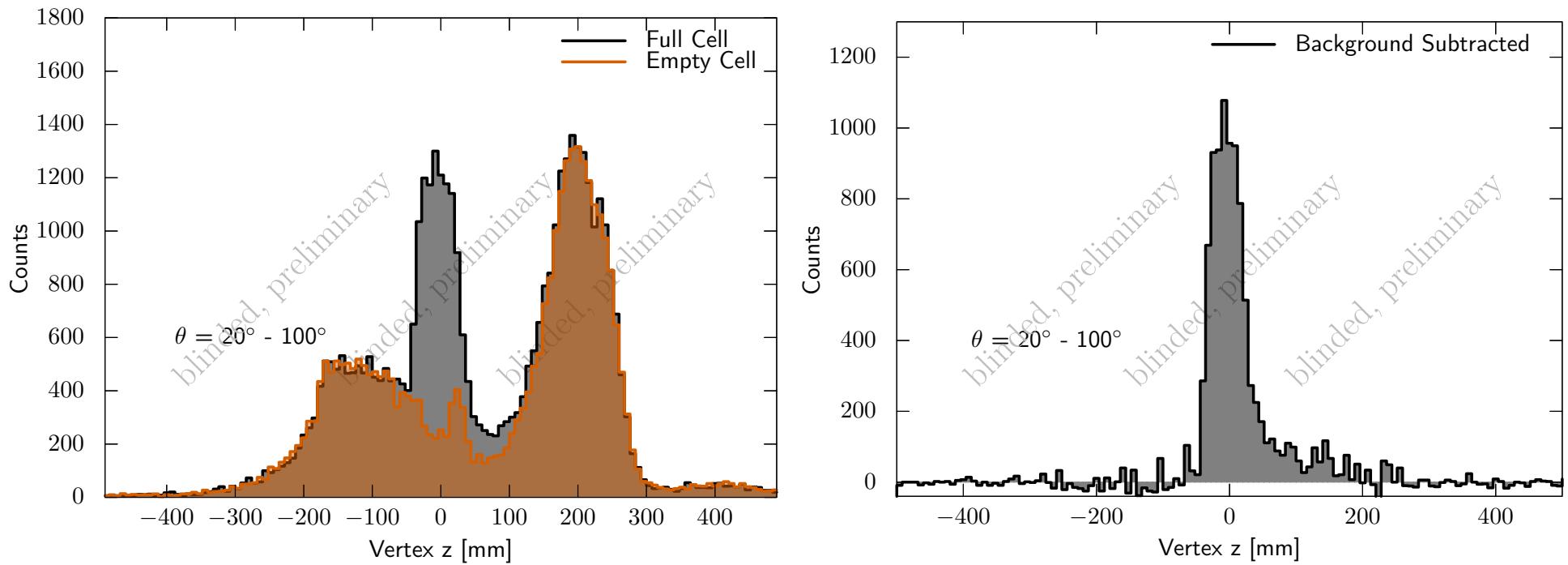
6 cm diameter  
13.7 cm tall



Cut on  $|y| < 50$  mm

# MUSE performance: scattering from LH2

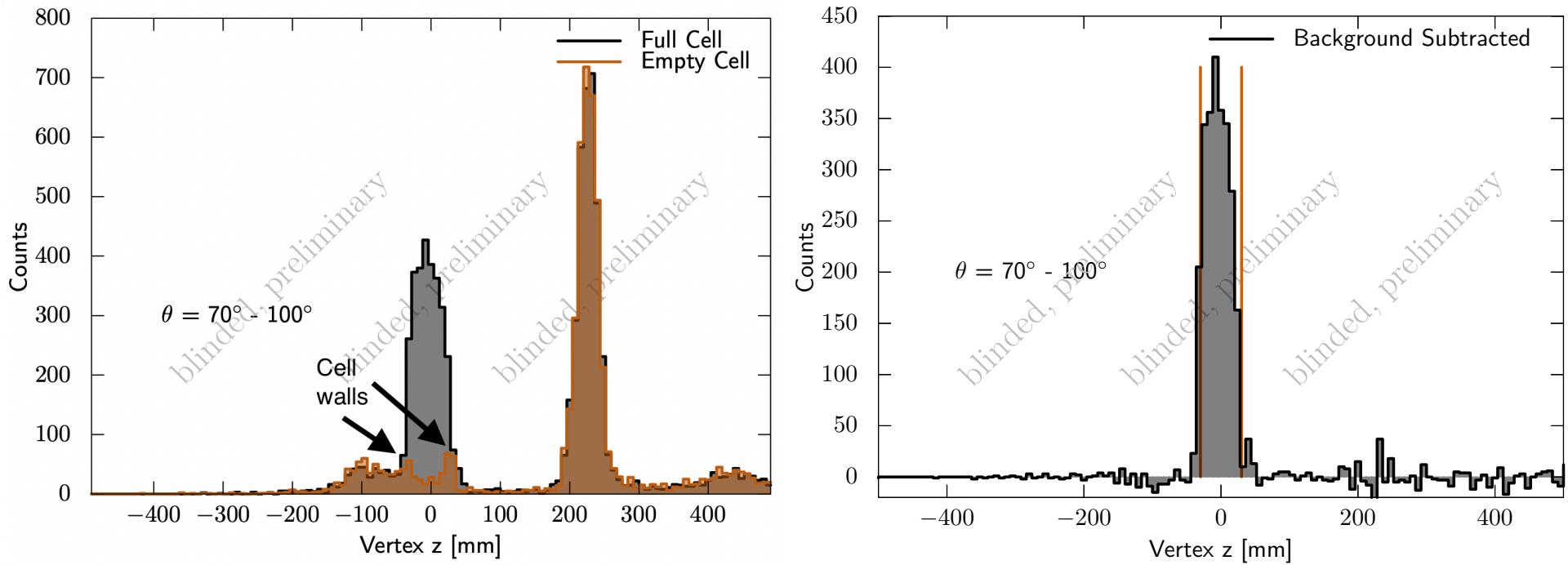
+160 MeV/c, full vs. empty target, reconstructed vertices



Cut on  $|x| < 25$  mm,  $|y| < 25$  mm,  $20 < \theta < 100$   
 Localized backgrounds, more pronounced at forward angles

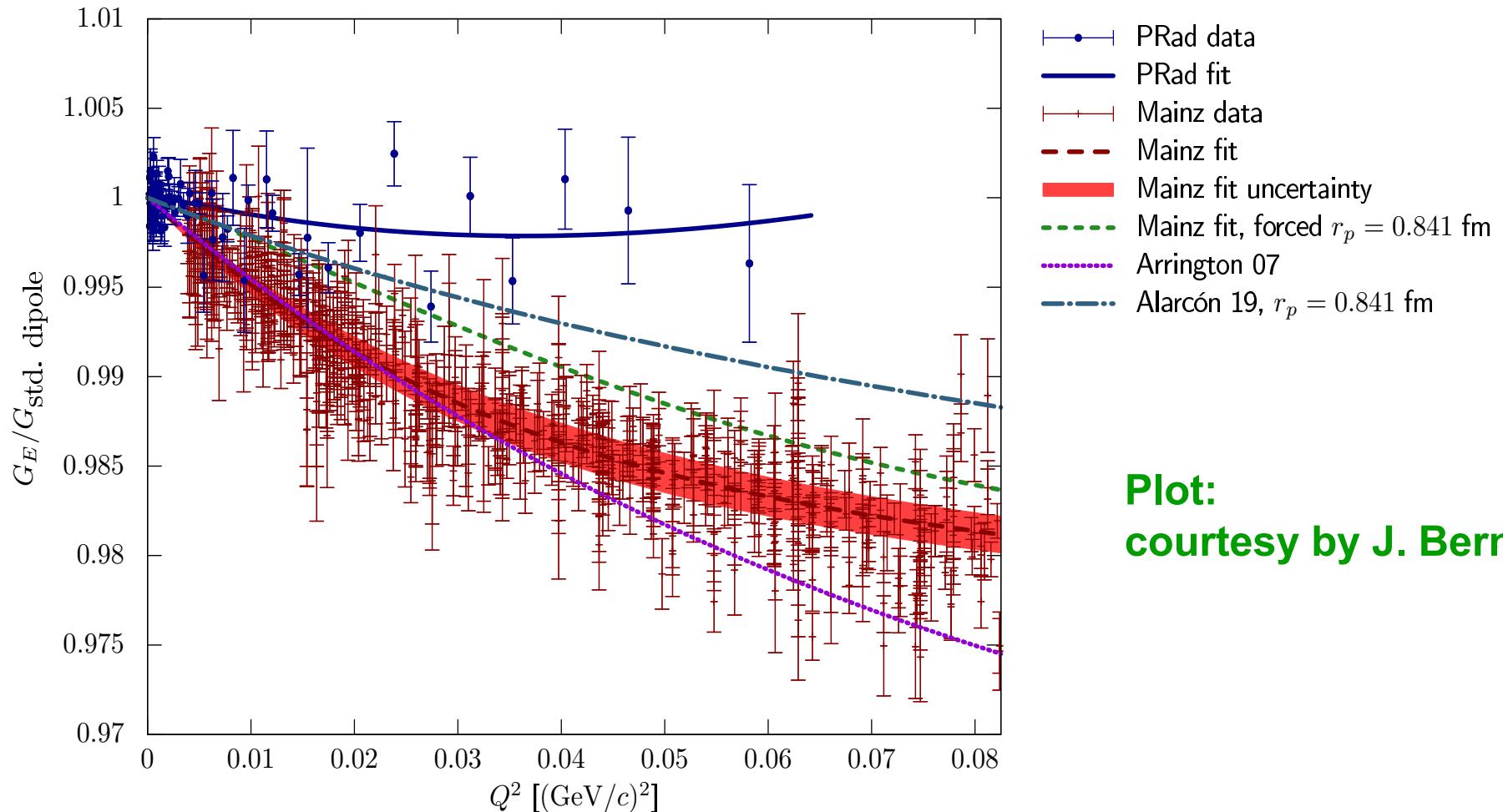
# MUSE performance: scattering from LH2

+160 MeV/c, full vs. empty target, reconstructed vertices



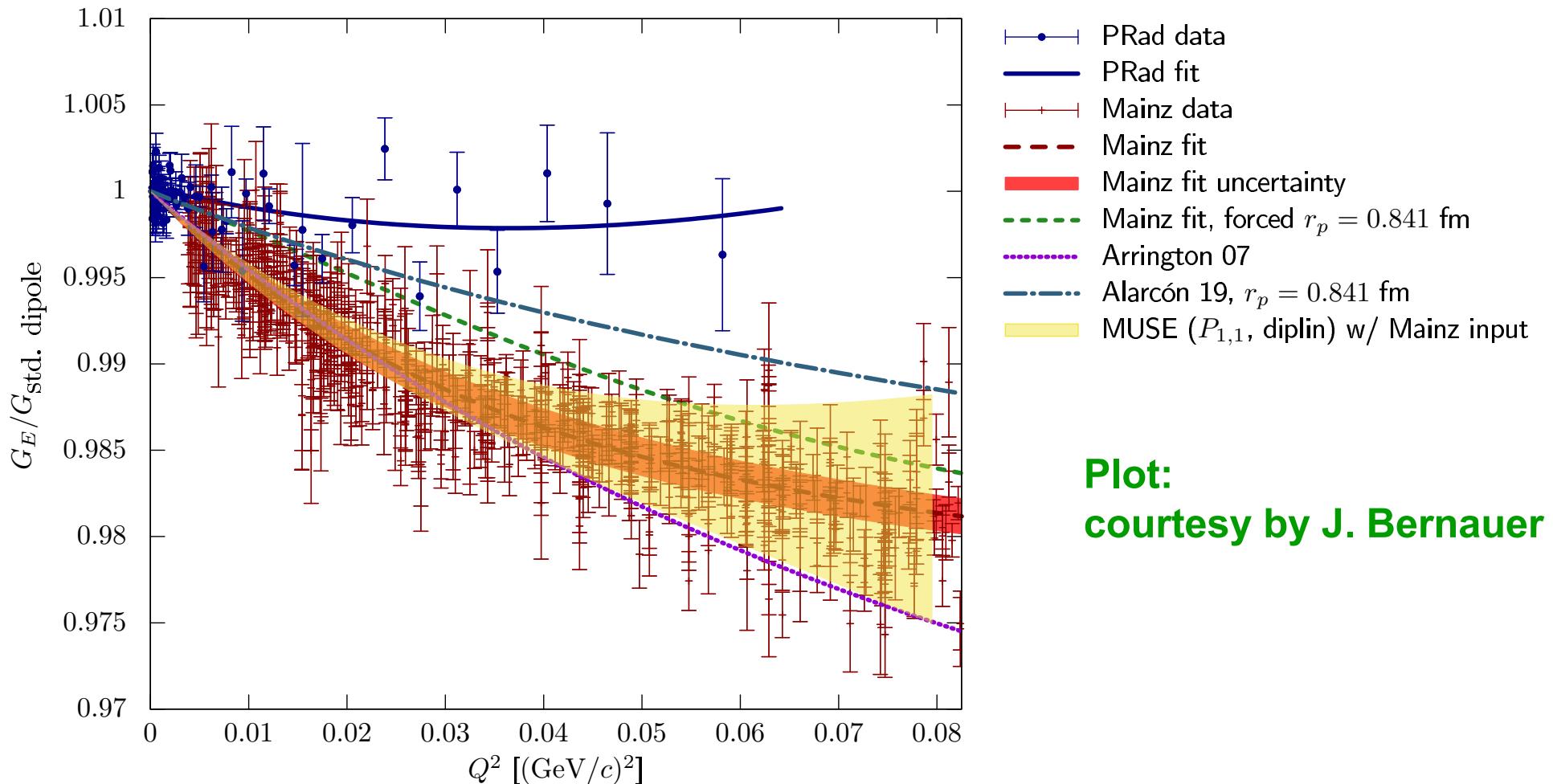
Cut on  $|x| < 25$  mm,  $|y| < 25$  mm,  $70 < \theta < 100$   
 Localized backgrounds, more pronounced at forward angles

# MUSE projected sensitivity: $G_E$



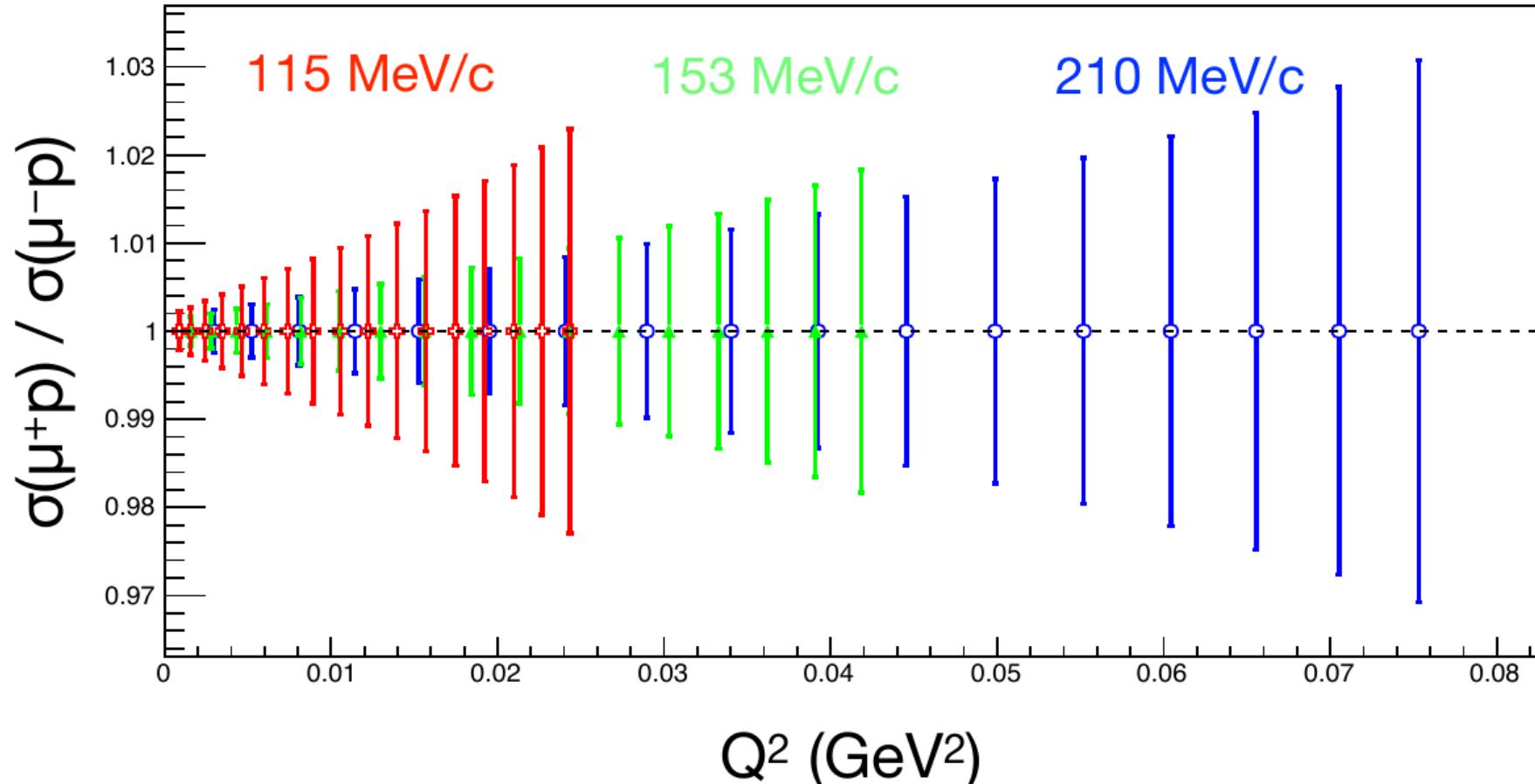
**Plot:**  
**courtesy by J. Bernauer**

# MUSE projected sensitivity: $G_E$



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

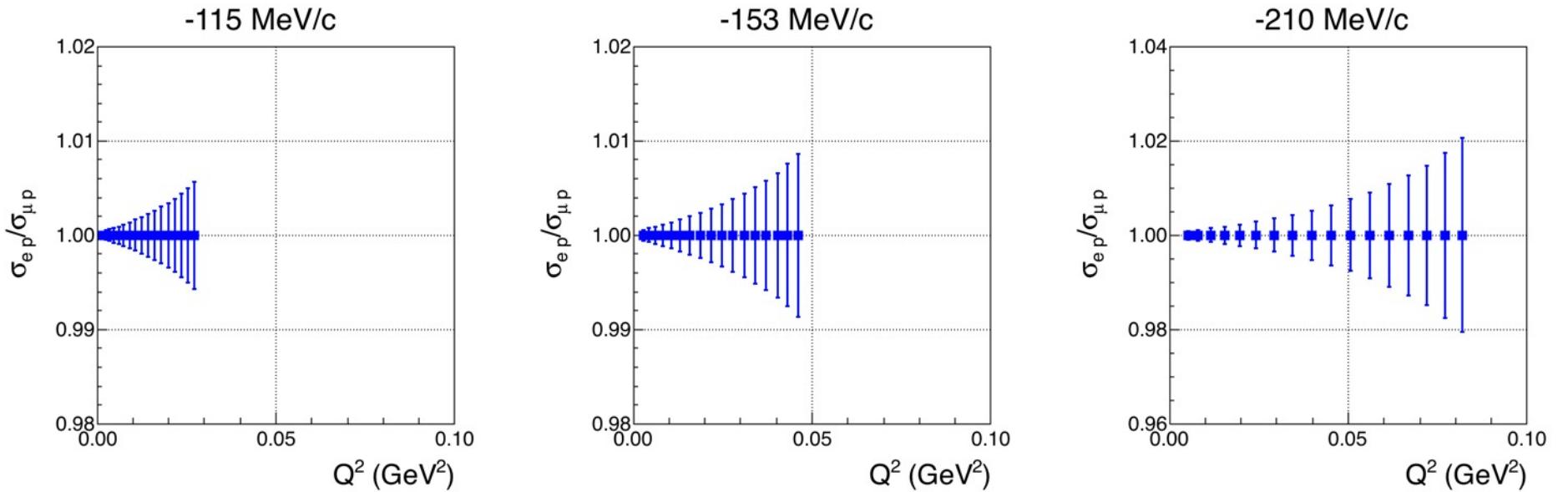
# MUSE expected TPE ratio (muons)



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

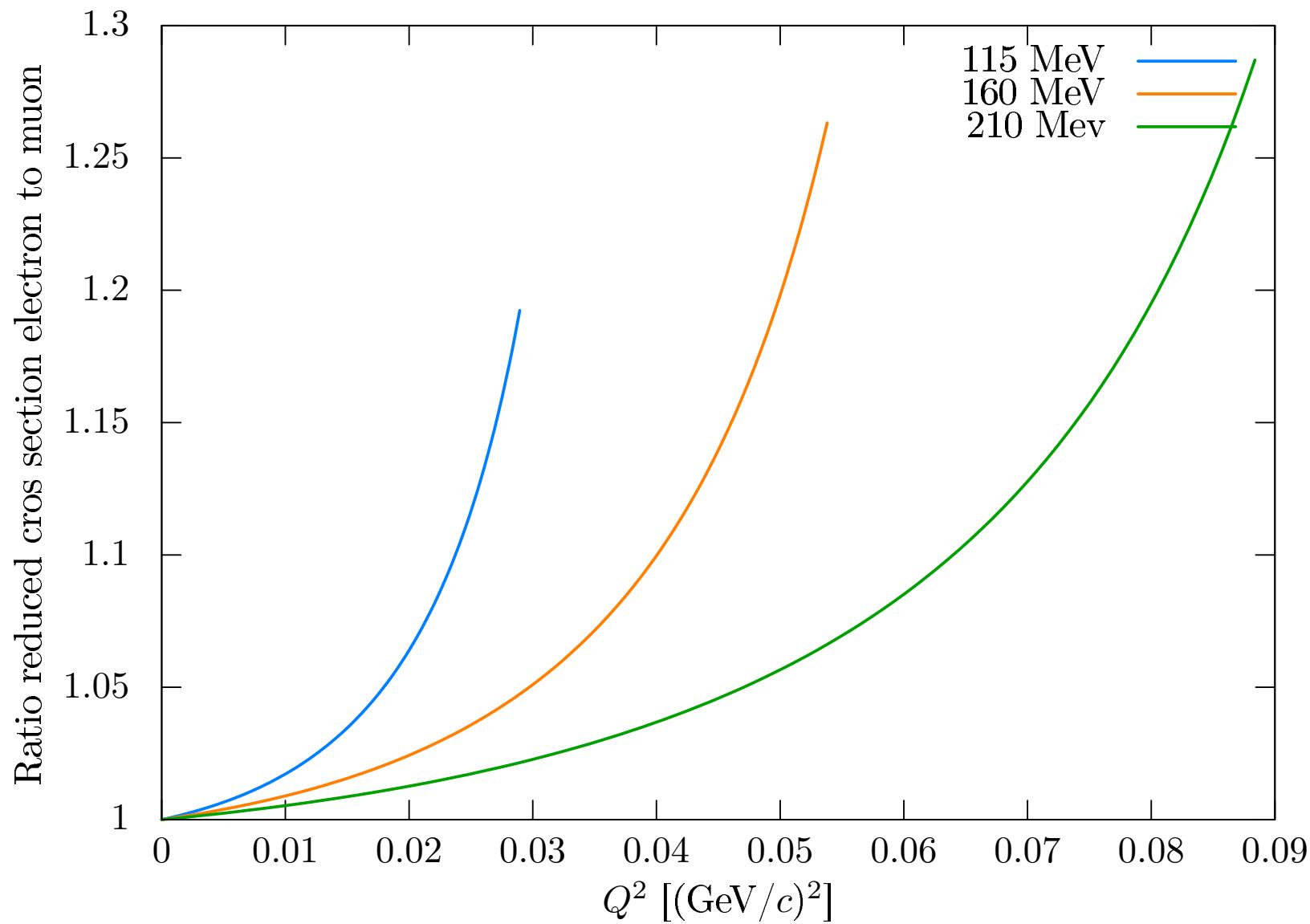
# MUSE expected LU ratio

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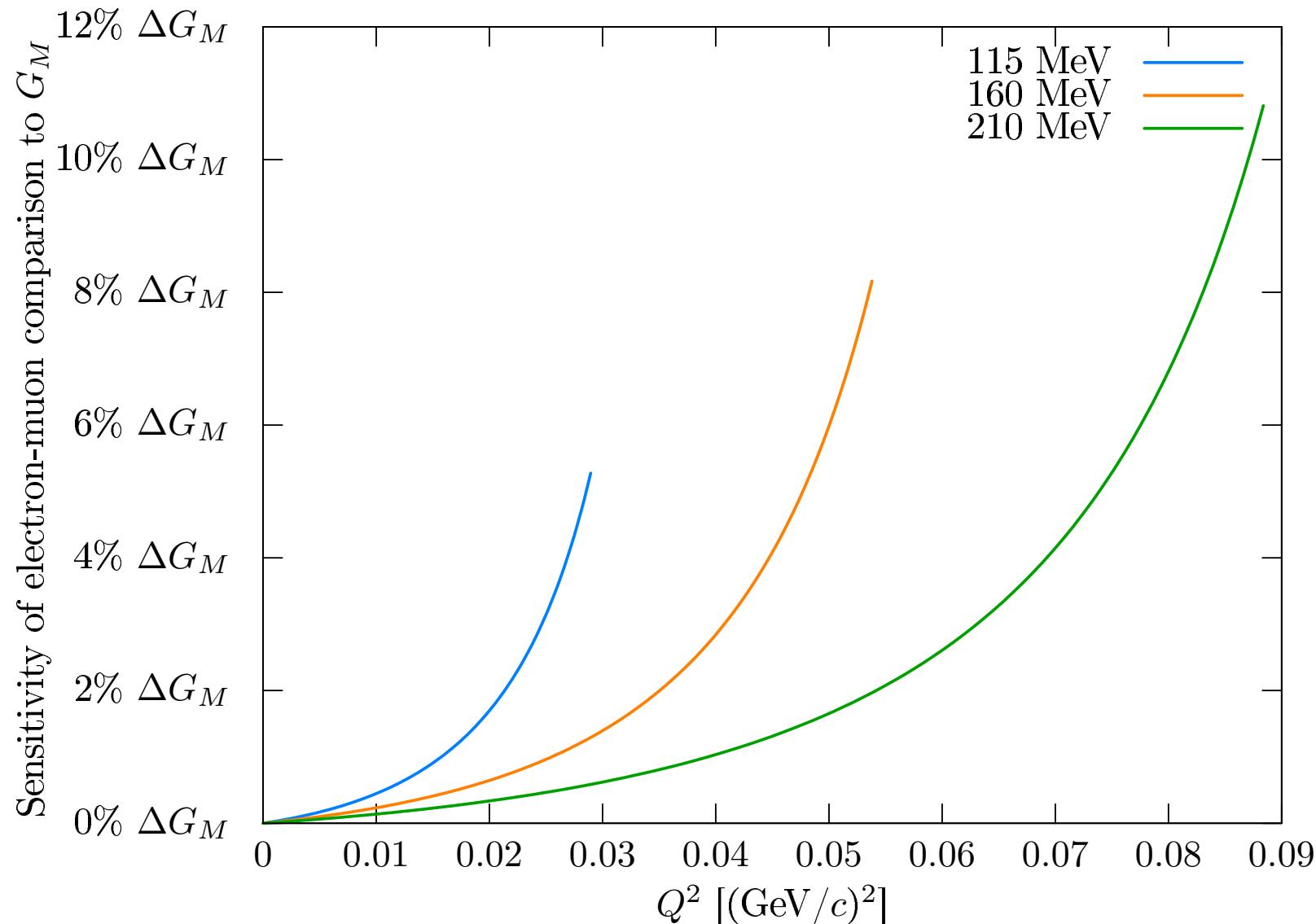
- Comparison of ep and  $\mu p$  cross section statistical uncertainty, systematic better than 0.5%
- *The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]*

# MUSE expected e/ $\mu$ reduced xsec ratio



- Cross section ratio
- At fixed  $Q^2$ , magn. contribution to e and  $\mu$  reduced xsec different

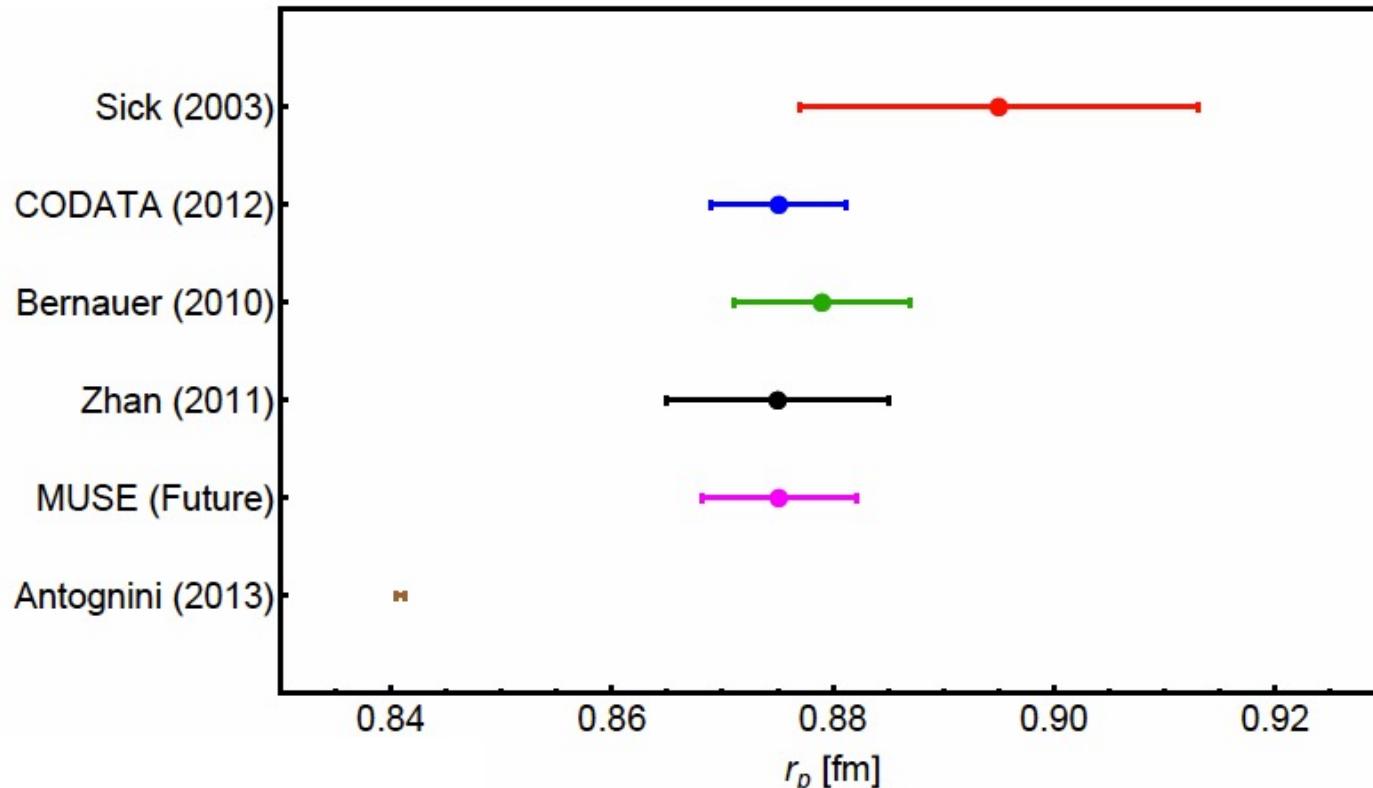
# MUSE projected e/ $\mu$ sensitivity: lead syst.



- Systematic in the e/ $\mu$  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

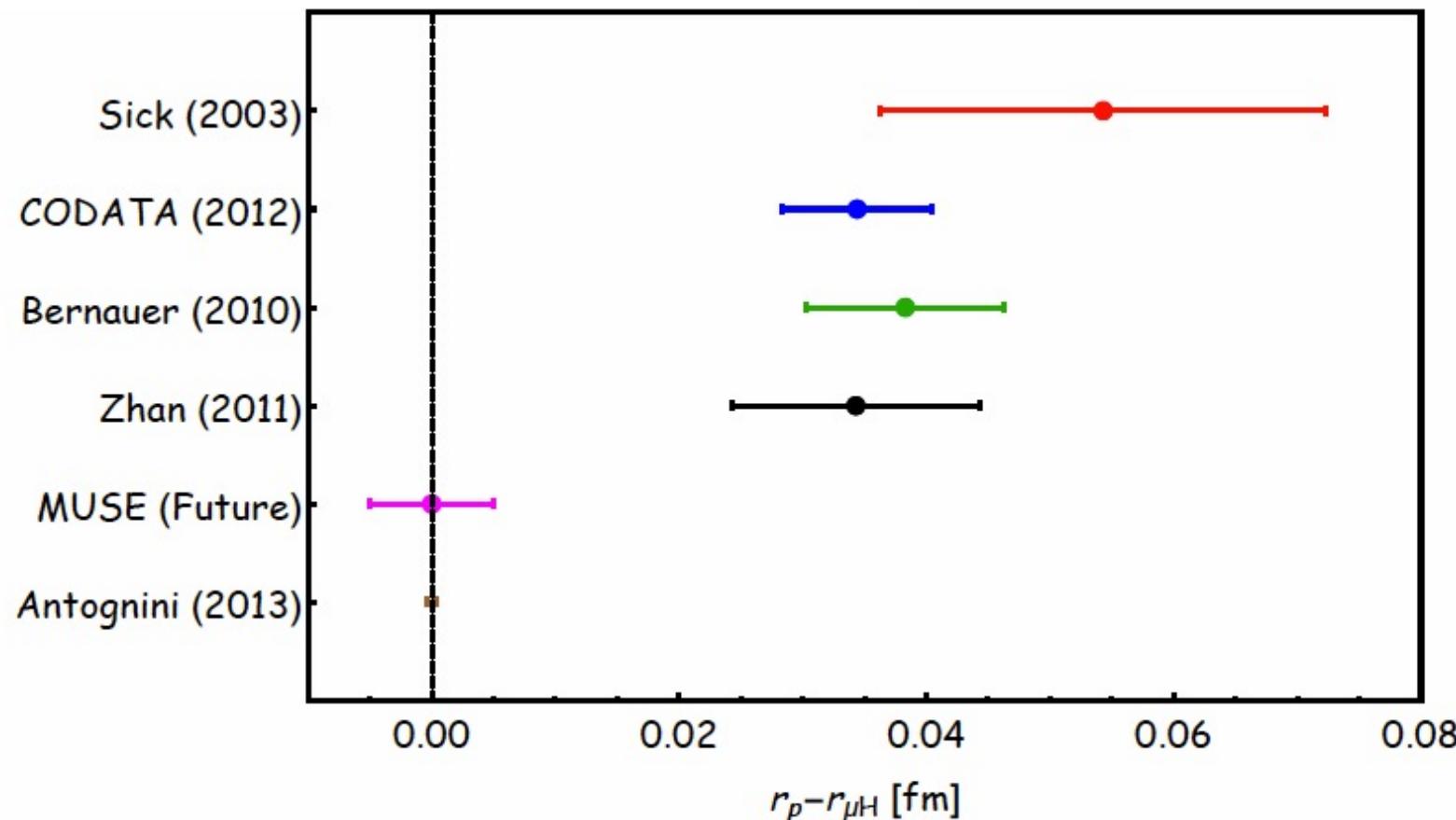
- **Cross sections** to <1% stat. for backward  $\mu$ , <<1% for e and forward  $\mu$   
Absolute 2%, point-to-point relative uncertainties **few  $\times 10^{-3}$**
- **Individual radius extractions** from  $e^\pm, \mu^\pm$  each to **0.010 fm**
- Compare  $e^\pm p$  and  $\mu^\pm p$  for TPE. Charge-average to eliminate TPE.
- From  $e/\mu$  xsec ratios: extract **e- $\mu$  radius difference** with minimal truncation error to **0.0045 fm or  $\sim 8\sigma$**  (1st-order fits)
- If no difference, extract **combined radius to 0.007 fm** (2nd-order fit)



# Projected sensitivity for MUSE

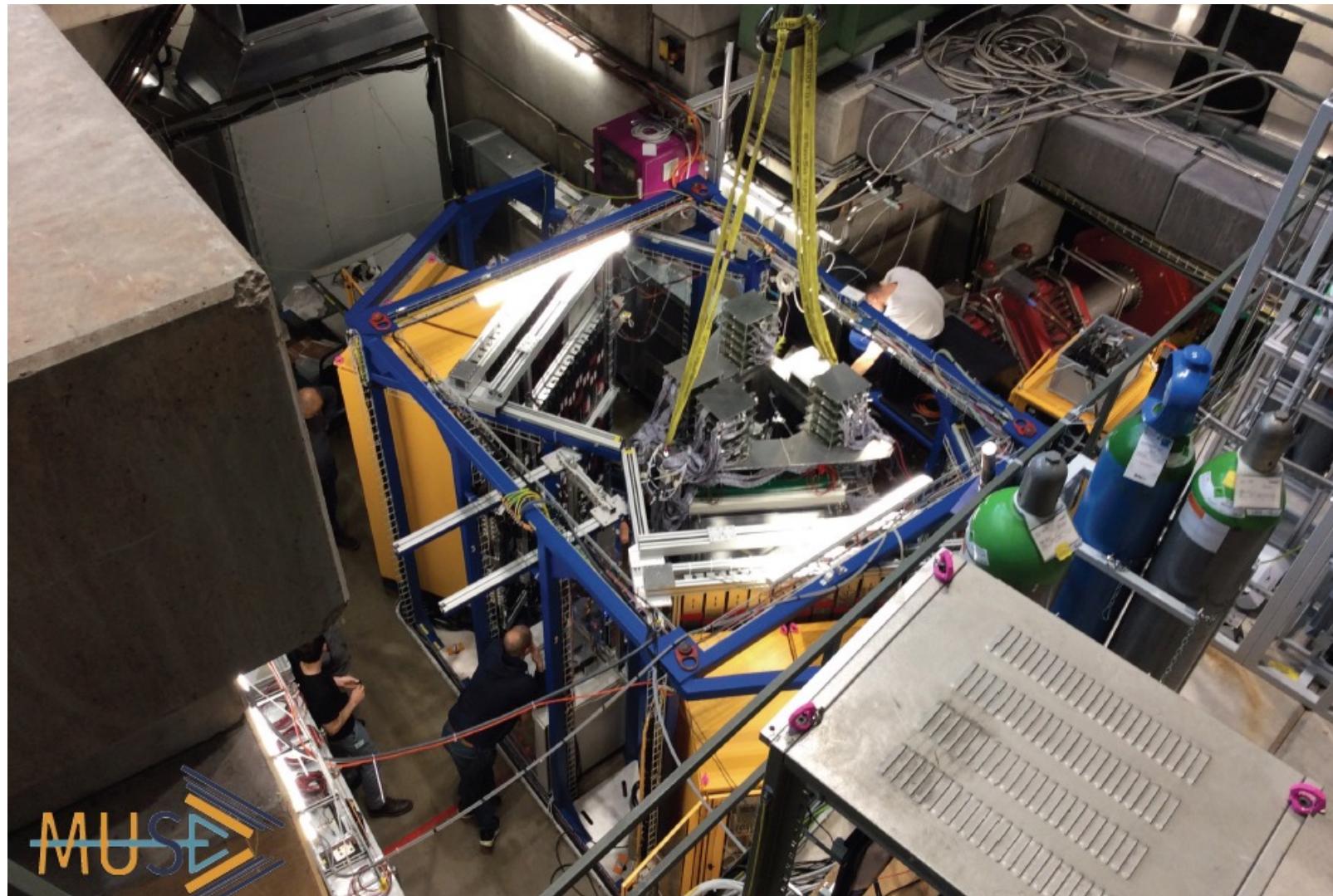
- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiment: Cancel in  $e^+/e^-$ ,  $\mu^+/\mu^-$ , and  $\mu/e$  comparisons
- $R_e - R_\mu = 0.034 \pm 0.006$  fm ( $5.6\sigma$ ), **MUSE:  $\delta(R_e - R_\mu) = 0.0045$  fm ( $7.6\sigma$ )**

**MUSE suited to verify  $5.6\sigma$  effect (CODATA2014) with  $7.6\sigma$  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



# MUSE timeline and status

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- 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 – 4 months in 2023 approved

# 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. Golossov, 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. Piaseczky, 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

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*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)*

# MUSE publications

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- 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>

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**Thank you!**