The MUSE Proton Radius Measurement

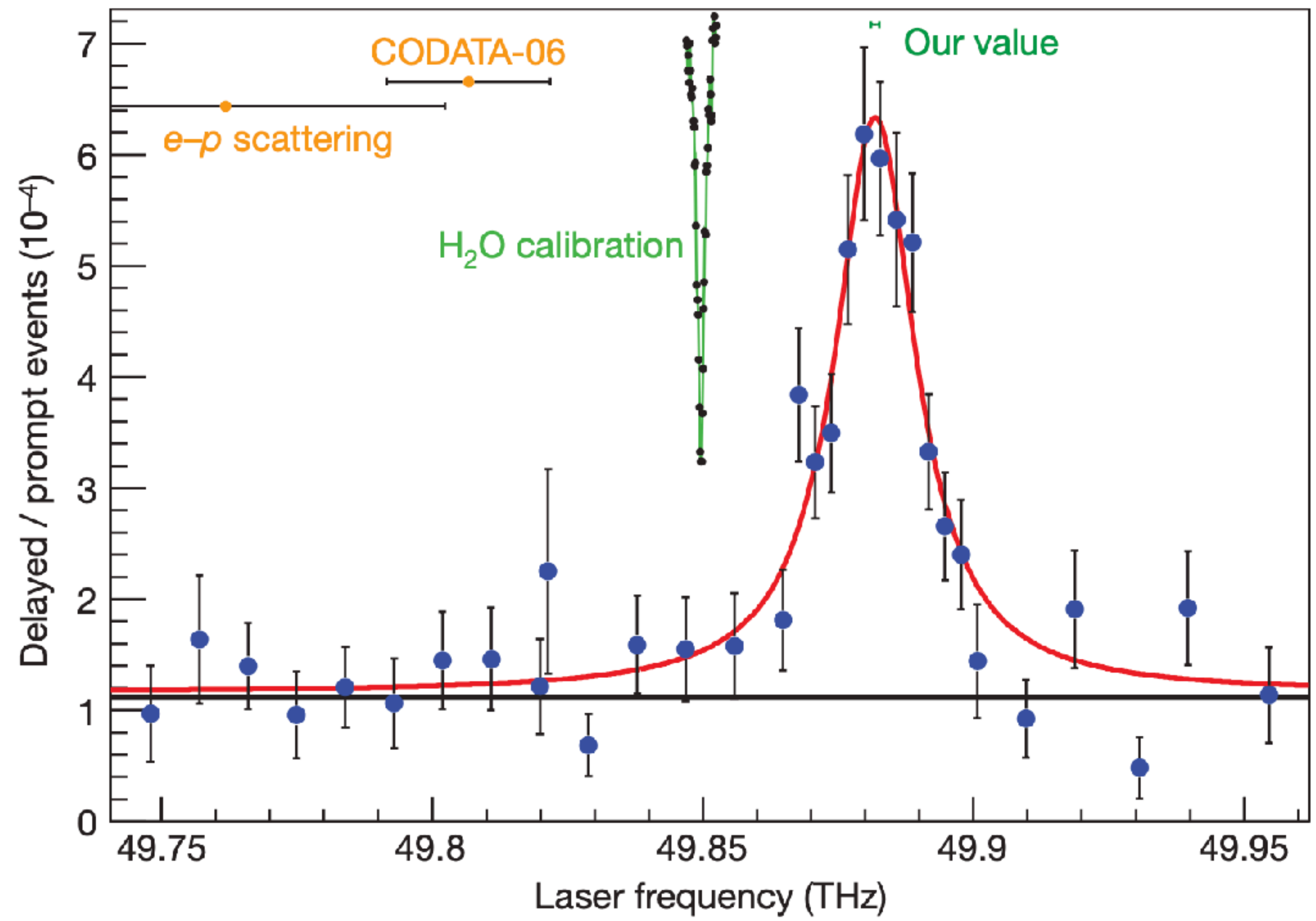
Ron Gilman, Rutgers

- Motivation
- Experiment and Status
- Summary / Outlook

This work supported in part by the US National Science Foundation, grant 1913653.

The Proton Radius Puzzle Appears

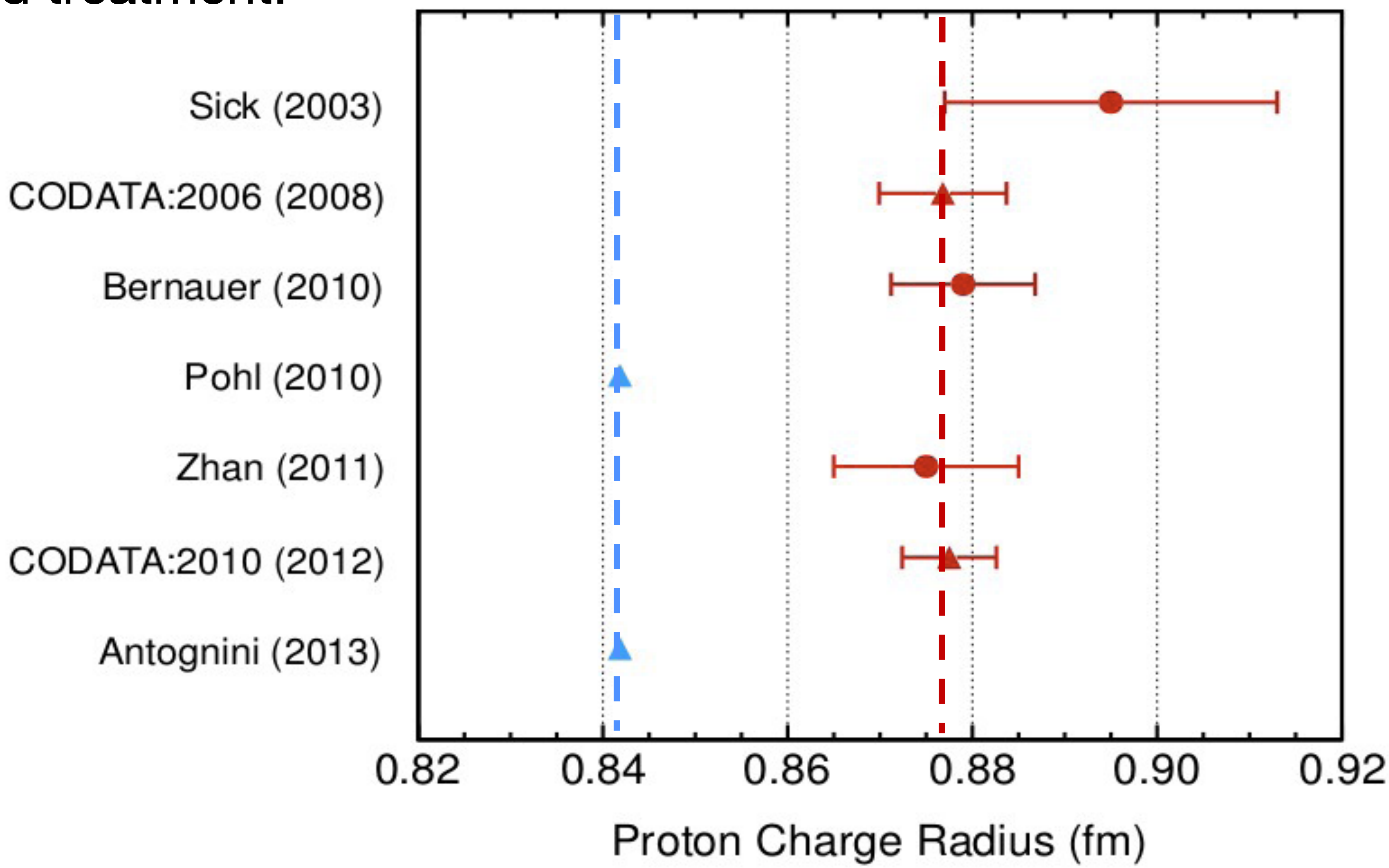
from: R. Pohl et al.
Nature 466, 213, 2010



- Atomic energy levels depend on the proton structure - μp 200^3 times more sensitive than ep.
- Stop a muon beam to generate muonic hydrogen, excite levels with laser, detect through de-excitation X-ray, deduce proton size from laser frequency

Proton Radius as of 2013

Many analyses like below — differences between ep and μp systems ranged from ~ 5.5σ - 8σ depending on data selection and treatment.



PRP Solutions

Two classes of explanations:

- Interesting new physics
  - New physics: forces / particles beyond the standard model
  - New aspects of conventional physics theory: proton structure, radiative corrections, …
- “Bad” experiment

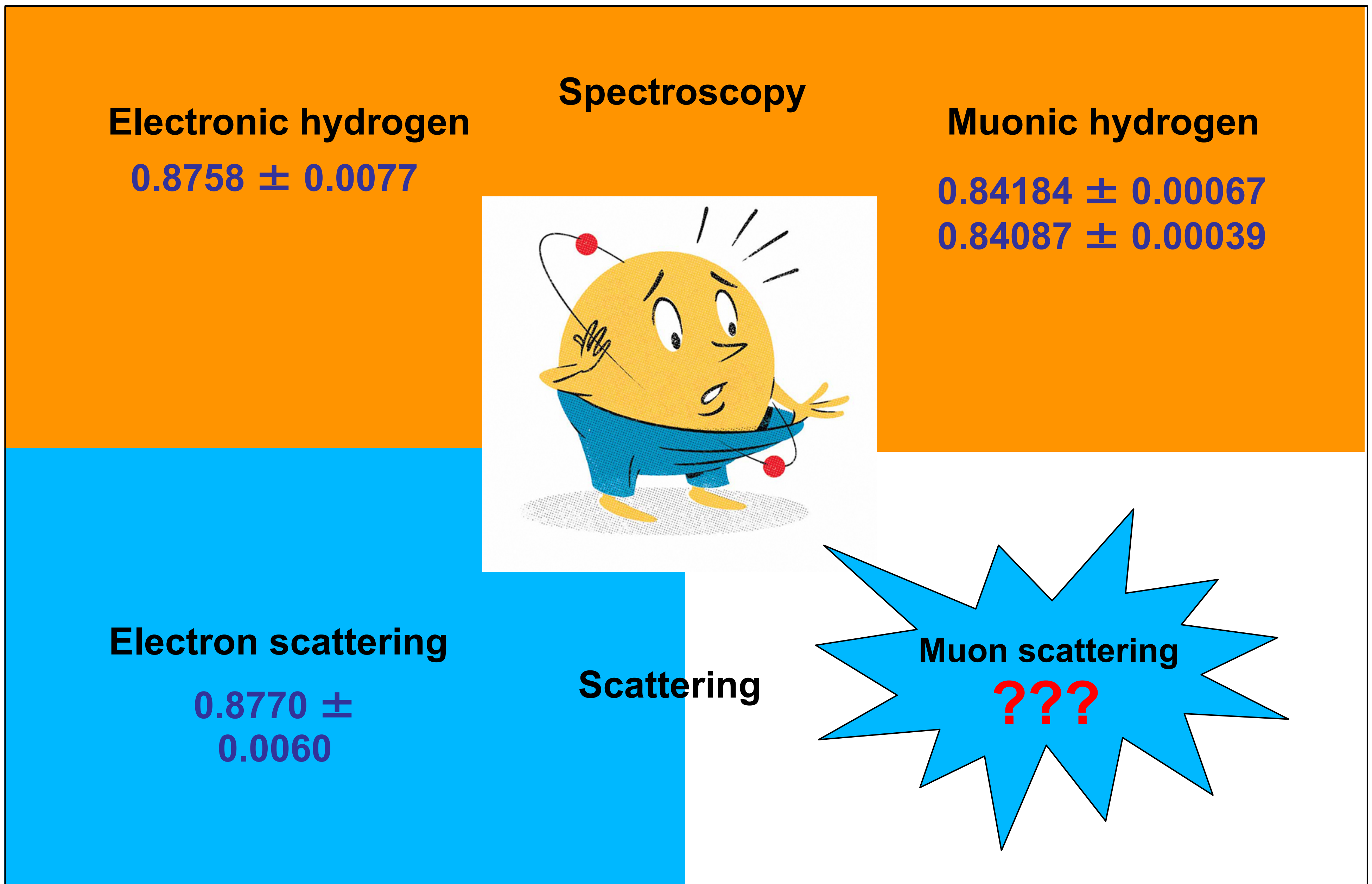
The missing data

Two classes of explanations:

- Interesting new physics
- “Bad” experiment

How to resolve the puzzle?

Test explanations with a new series of measurements…



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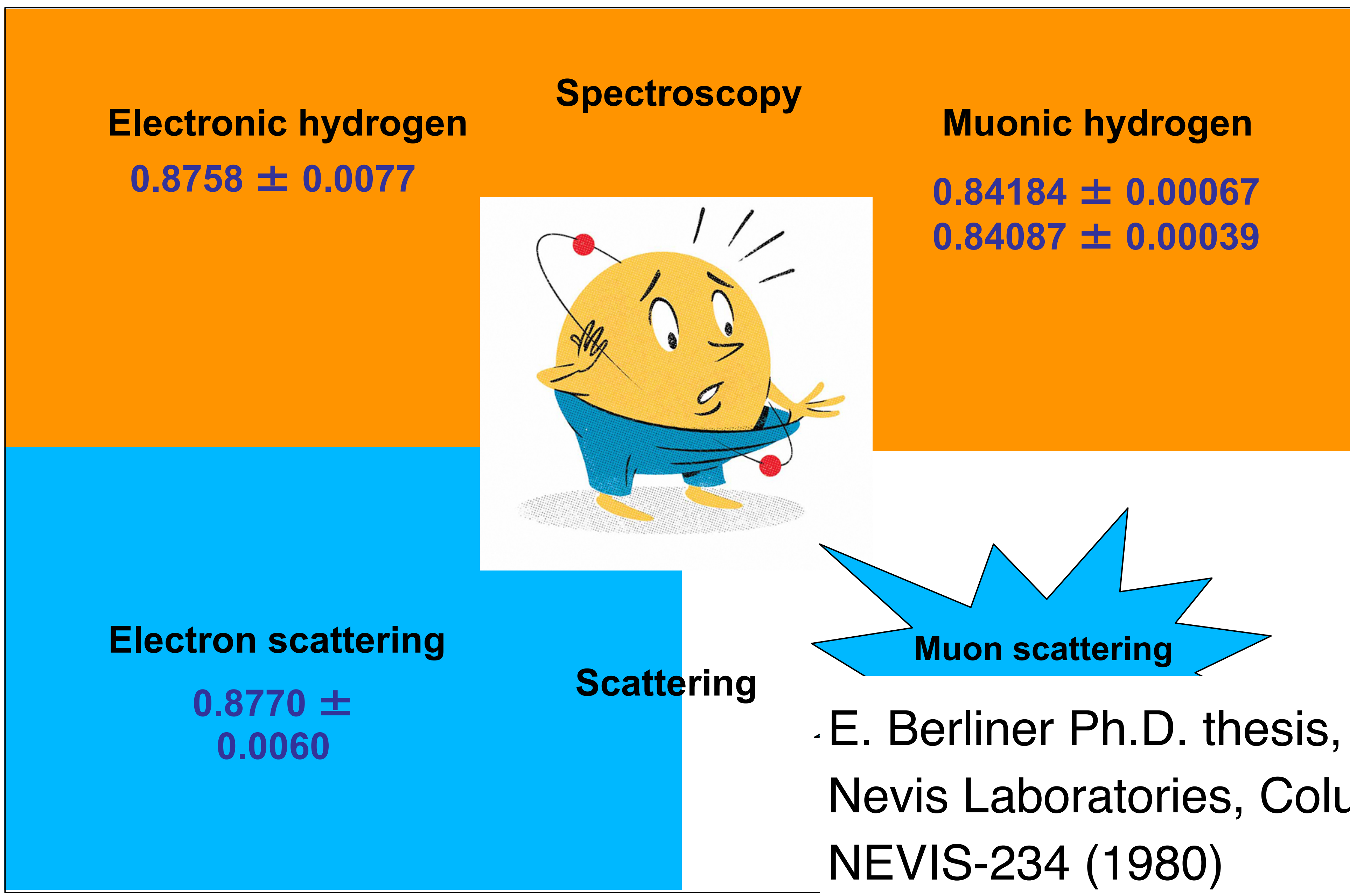
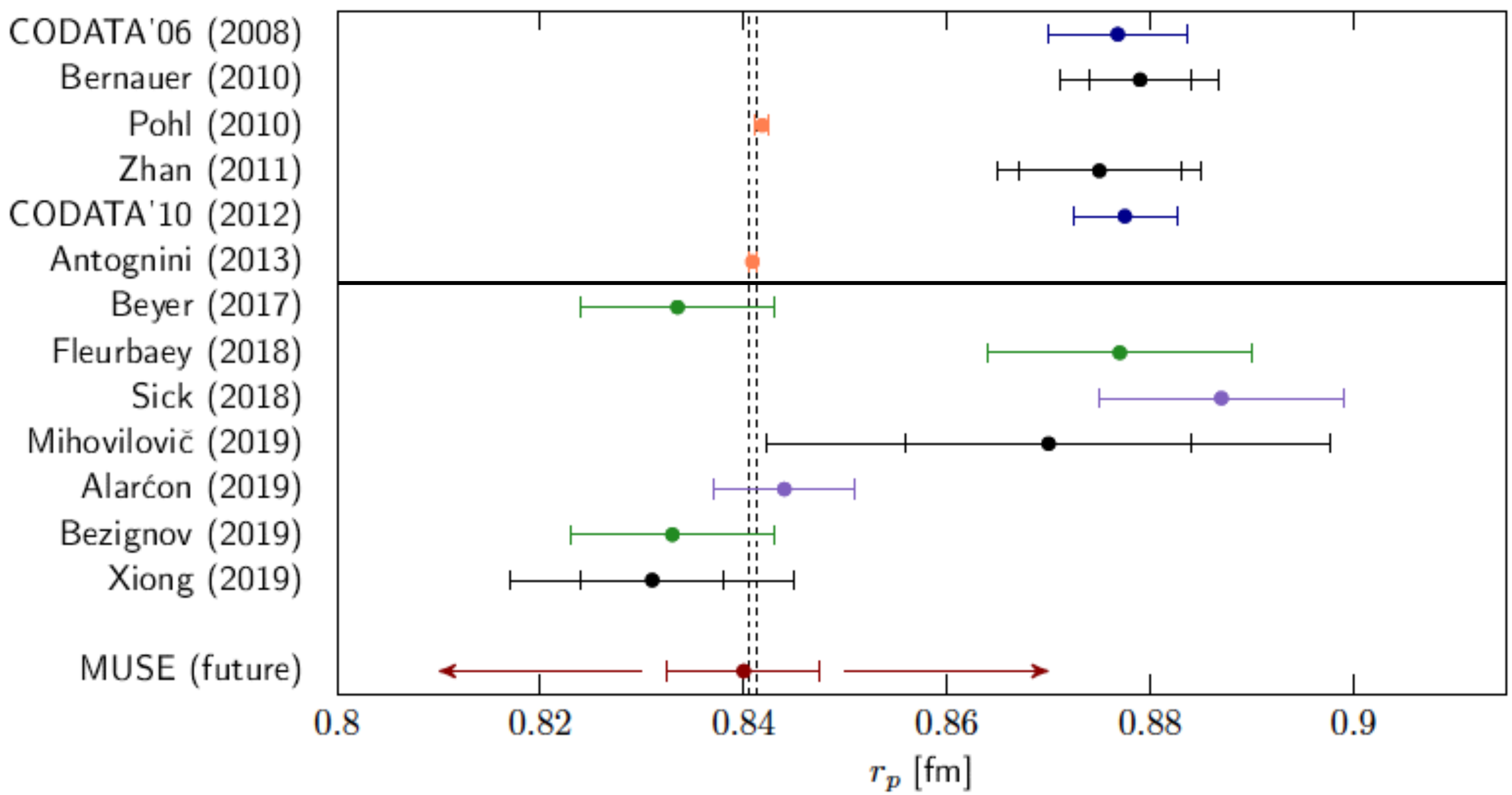


E. Berliner Ph.D. thesis, unpublished.
Nevis Laboratories, Columbia
NEVIS-234 (1980)
r = 1.13 ± 0.21 fm

New experiments

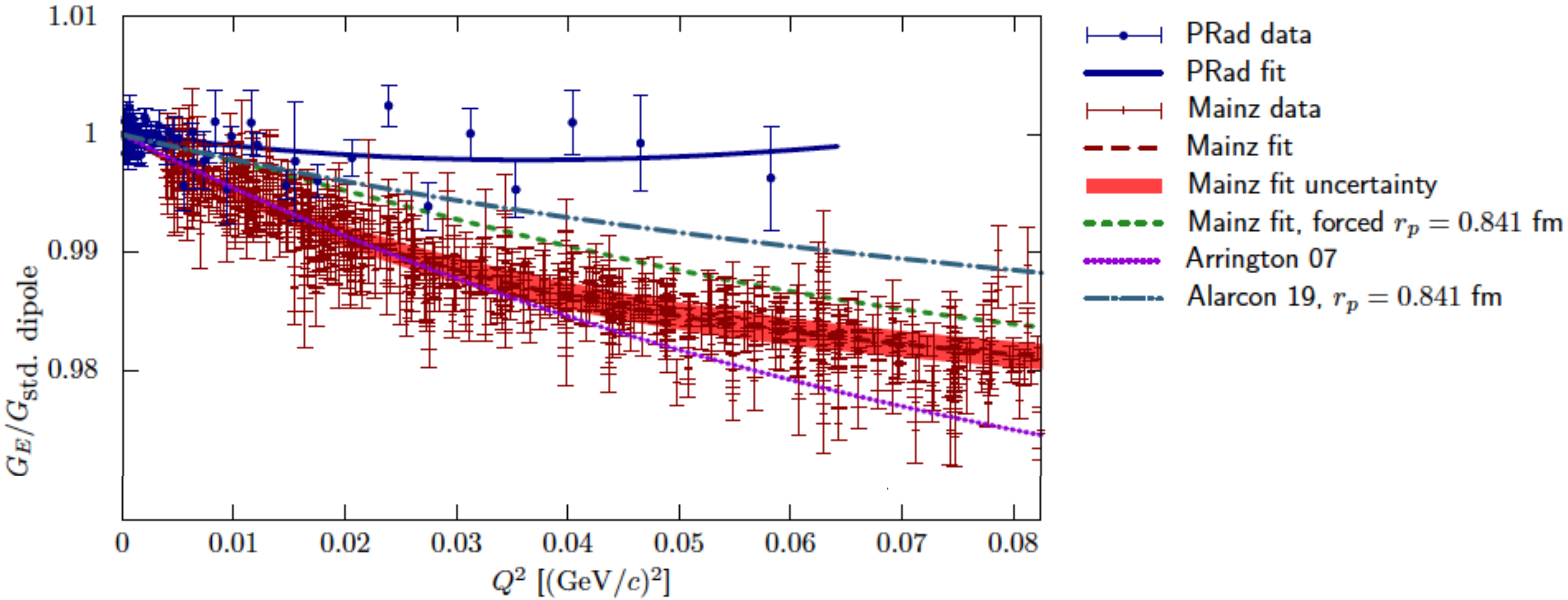
Recent results in atomic physics and scattering suggest the puzzle arose from poor experiments / radius extractions



Plot from Jan Bernauer

But …

But the overlap of data in the scattering experiments and the issues in previous spectroscopy experiments are not as clear as one would like.



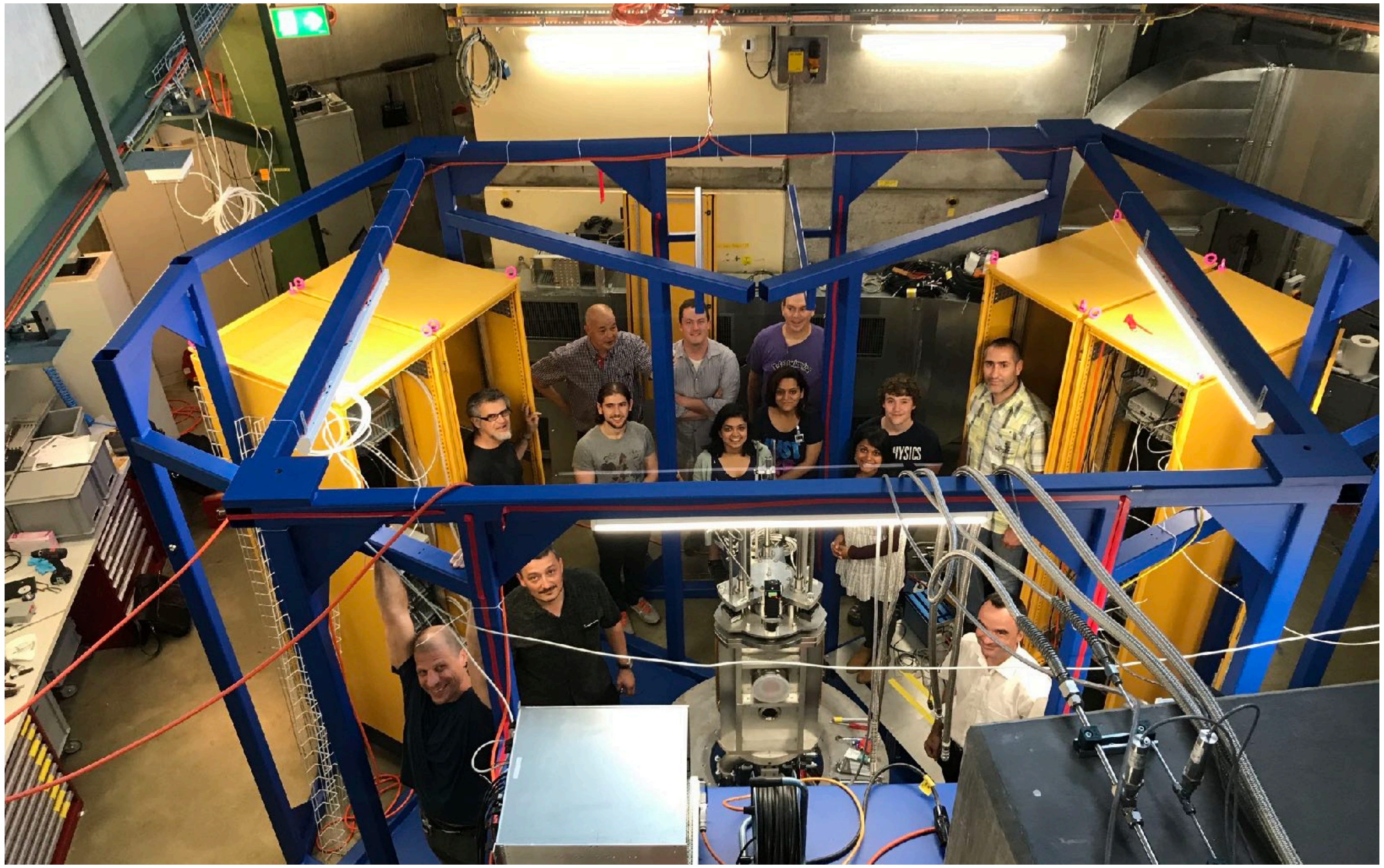
Plot from Jan Bernauer

Issue with experiment?

With radiative corrections?

MUSE at the Paul Scherrer Institute

We use the πM1 channel of the HIPA facility of PSI



mid 2018

MUSE at the Paul Scherrer Institute

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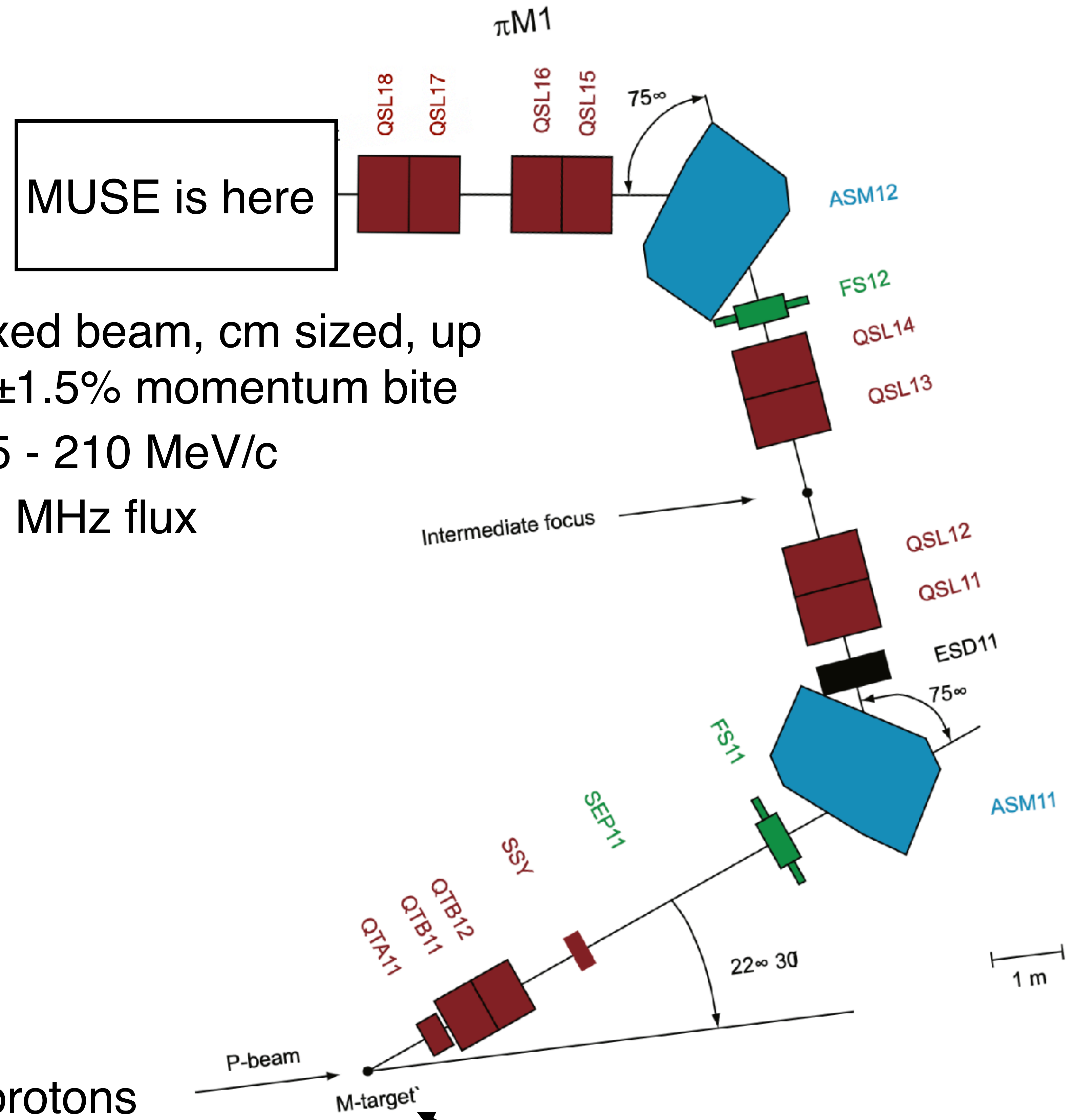


Mixed beam, cm sized, up to ±1.5% momentum bite

115 - 210 MeV/c

3.5 MHz flux

2 mA, 590 MeV protons

π, μ, e produced here

MUSE idea

"MUon (proton) Scattering Experiment - MUSE"

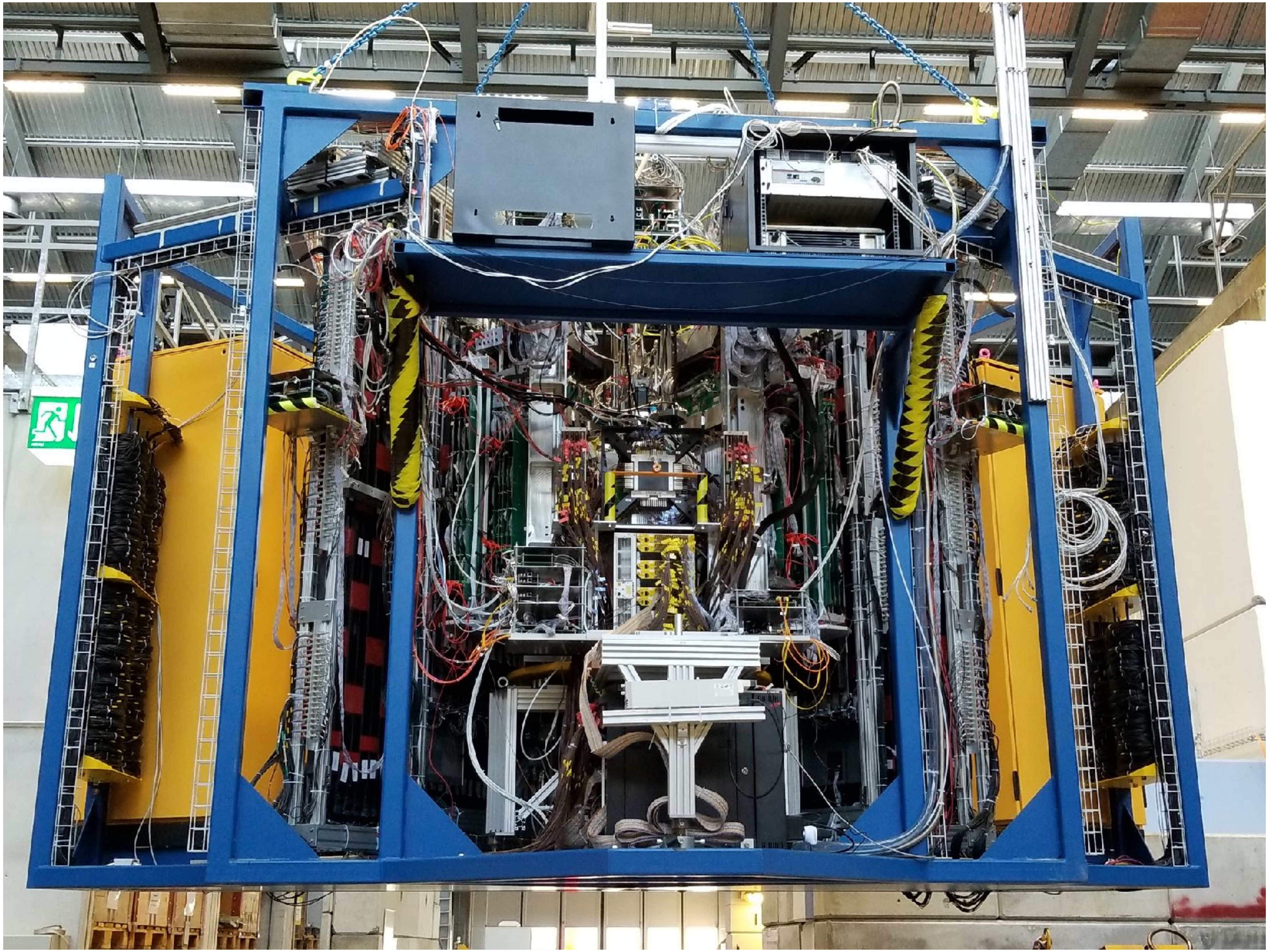
A low-luminosity, large-acceptance, non-magnetic-spectrometer scattering experiment

Broader than a proton radius with muons:

- Muon and electron scattering from protons for $d\sigma/d\Omega$, G_E and r, <u>at the same time</u>
  - Direct data-to-data comparisons remove fitting issues, provides lepton universality / radiative correction test
- Both beam polarities — measurement of two-photon exchange and radiative corrections
- The same μ and e measurements on carbon
- Pion scattering, <u>at the same time</u>, a necessary "evil", but also a QCD effective field theory test
- Inverse pion electro-production? …

MUSE

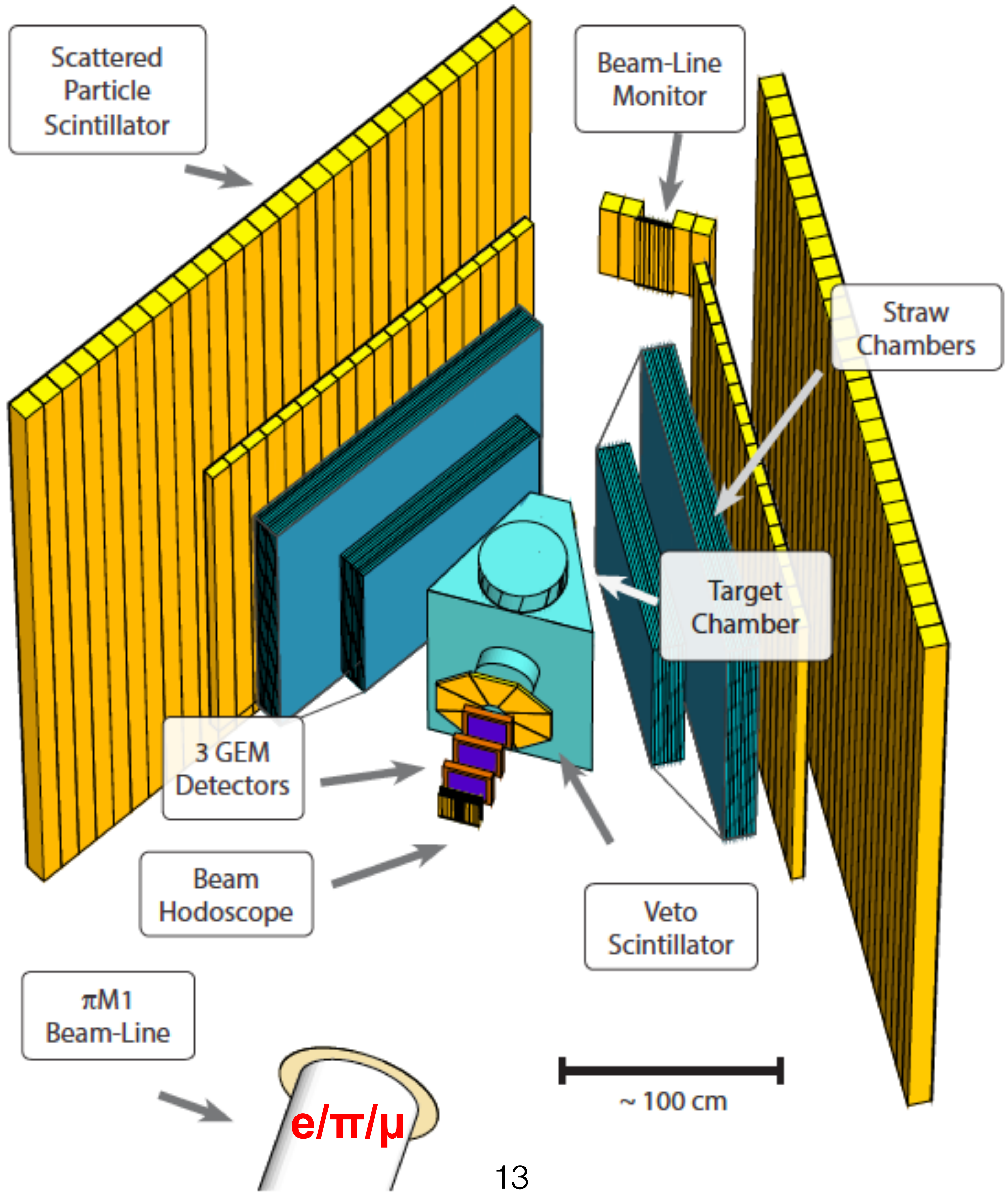
~$3.5M from NSF (2016-2020)
+ DOE, PSI, BSF, and others)



fall 2019

MUSE

Geant simulation view of detectors, support structures removed



SiPM Scintillators

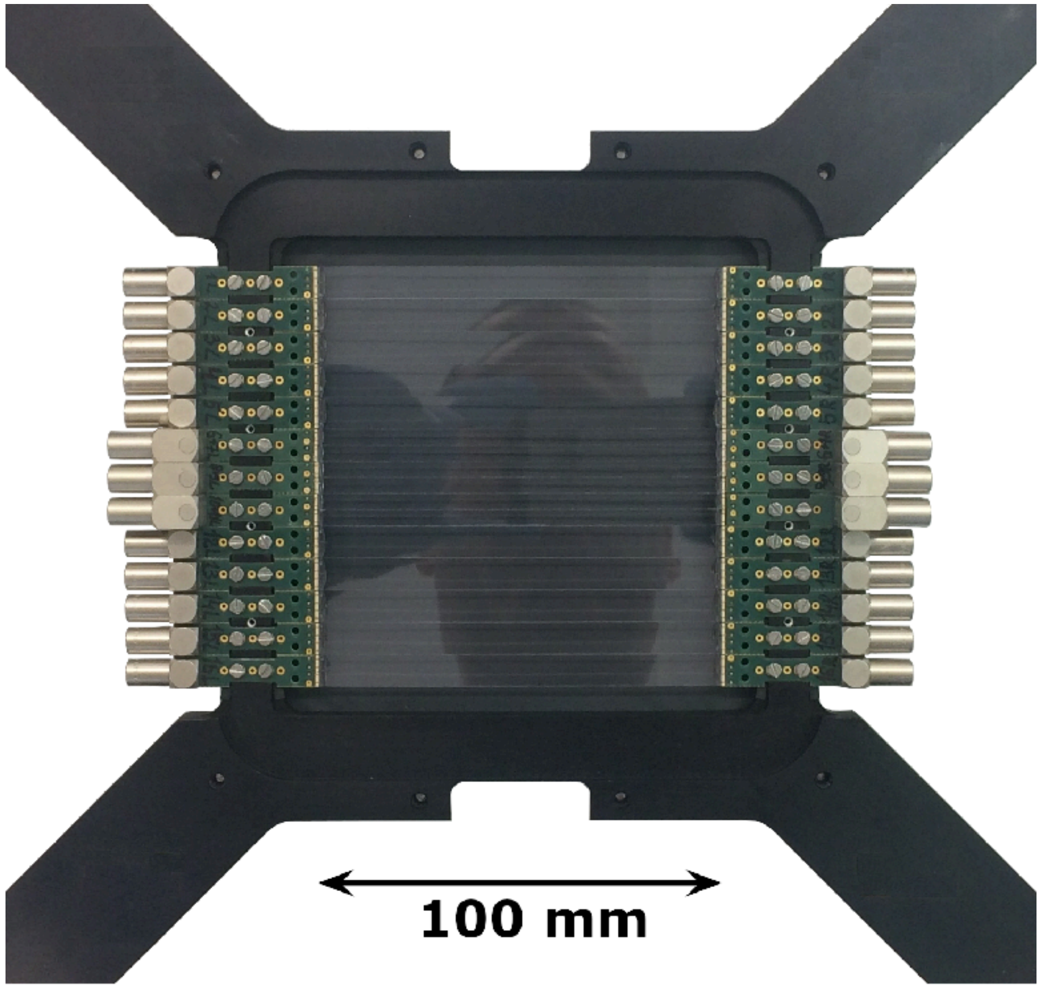
2-mm thick BC404 scintillator

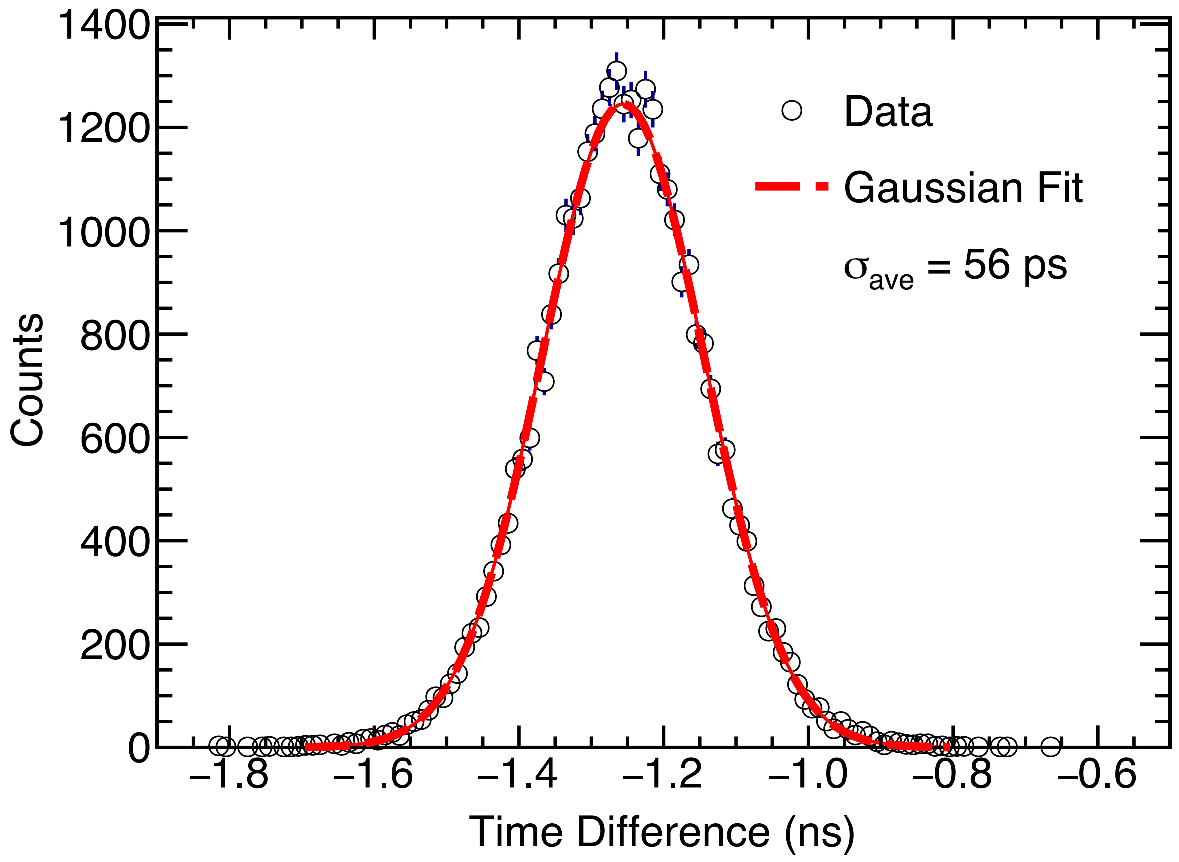
Hamamatsu SiPM readout (S13360-3075PE)

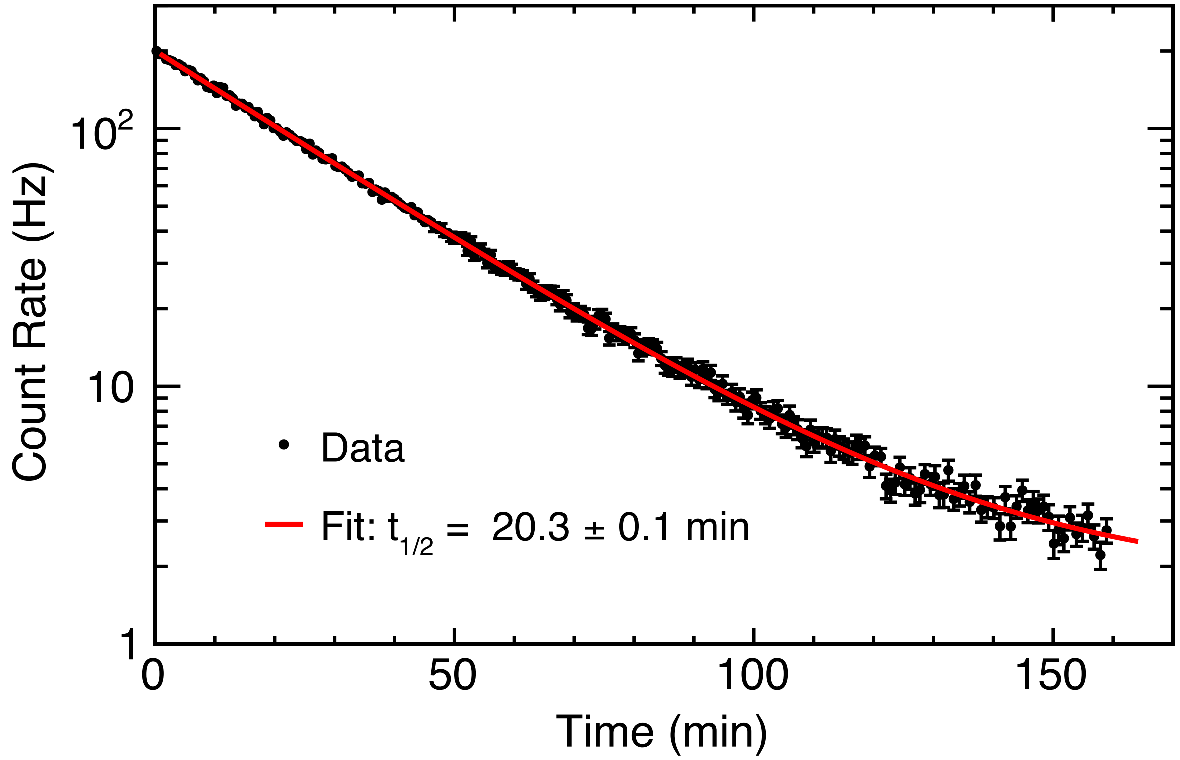
CFDs

Order of magnitude better time resolution than usual.

Performs well, but issues remain at the 10s of ps level.







SiPM Scintillators

Published: T. Rostomyan et al., https://doi.org/10.1016/j.nima.2020.164801

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 986, 11 January 2021, 164801

Timing detectors with SiPM read-out for the MUSE experiment at PSI

T. Rostomyan [a, b], E. Cline [a, c], I. Lavrukhin [d, e], H. Atac [f], A. Atencio [f], J.C. Bernauer [c, g], W.J. Briscoe [d], D. Cohen [h], E.O. Cohen [i], C. Collicott [d], K. Deiters [b], S. Dogra [a], E. Downie [d], W. Erni [j], I.P. Fernando [k], A. Flannery [n], T. Gautam [k], D. Ghosal [j] … N. Wuerfel [e]

Show more

https://doi.org/10.1016/j.nima.2020.164801

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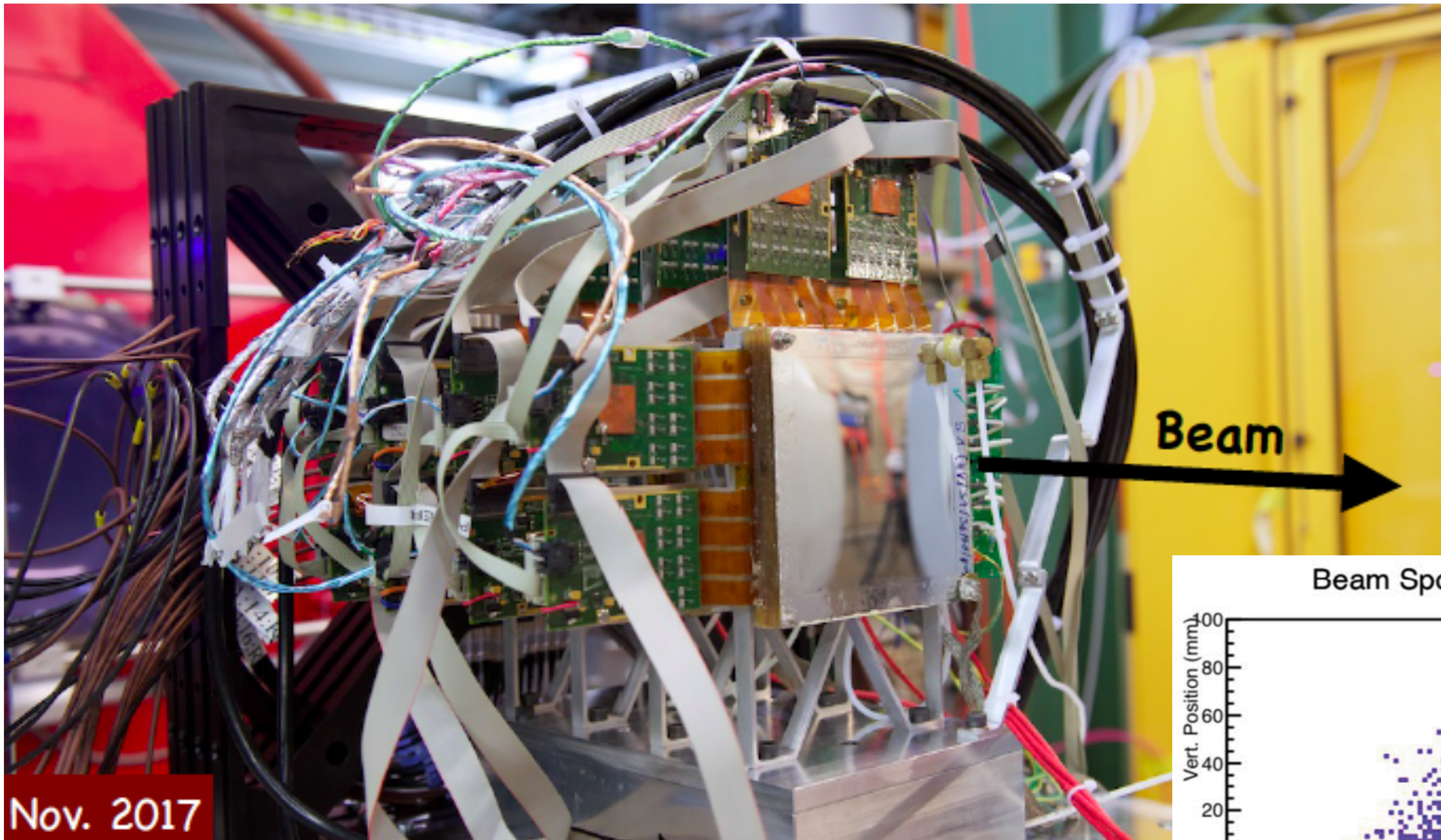
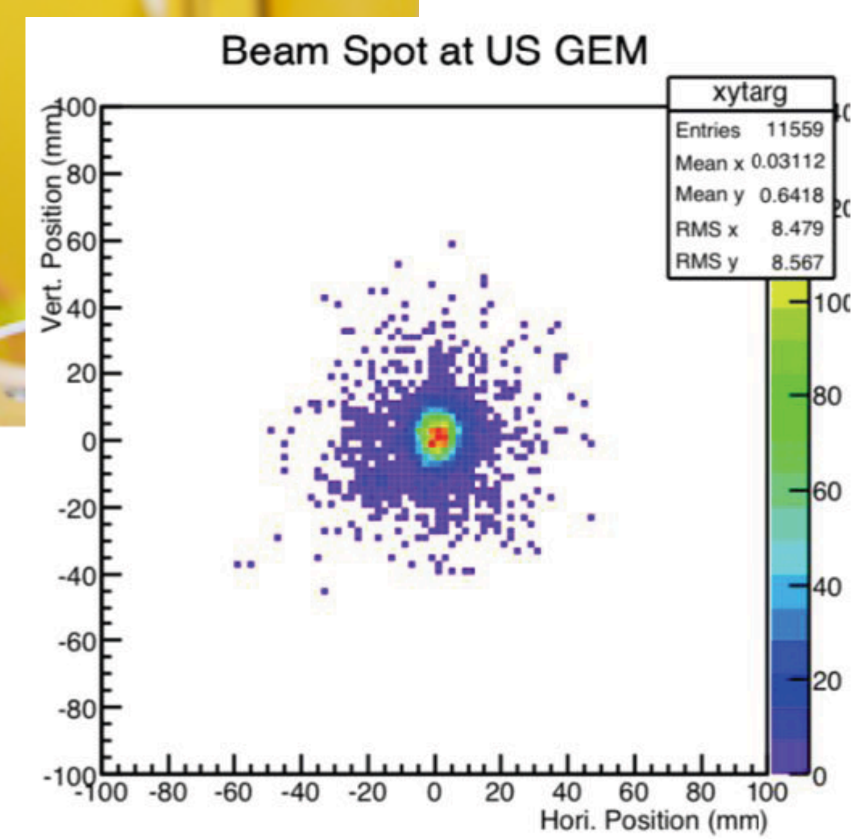
GEMs

From OLYMPUS, with readout and analysis upgrades





VETO Scintillator

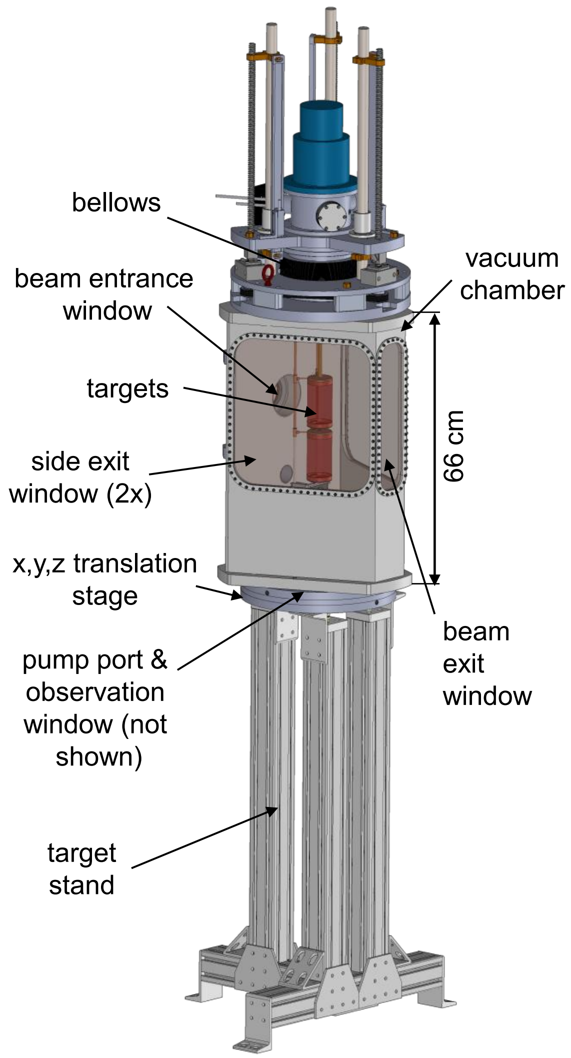
Immediately after GEMs (prior to installation)

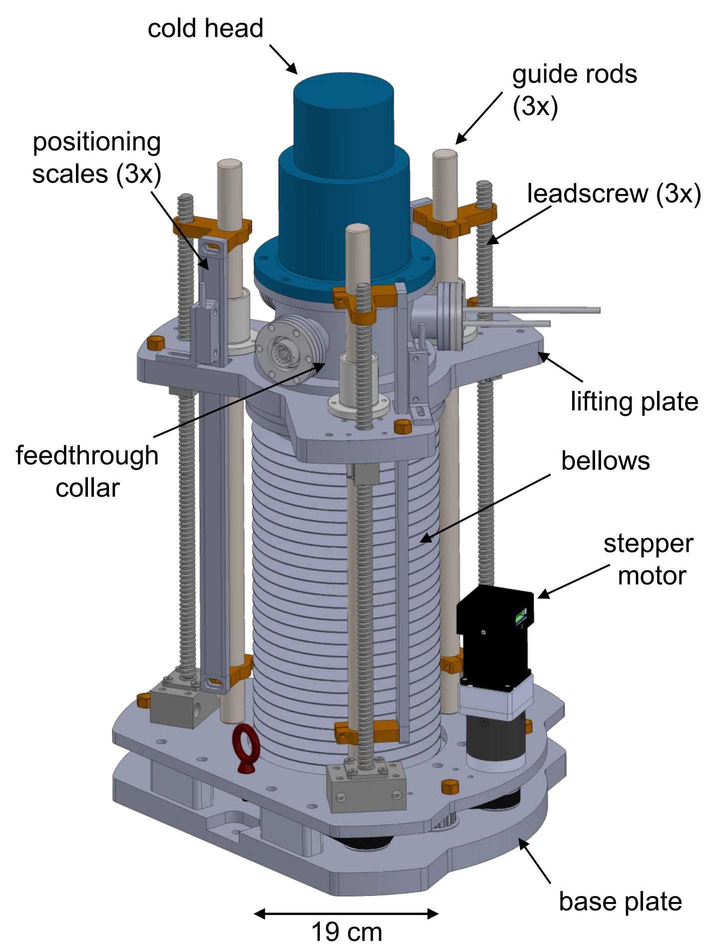
fall 2018

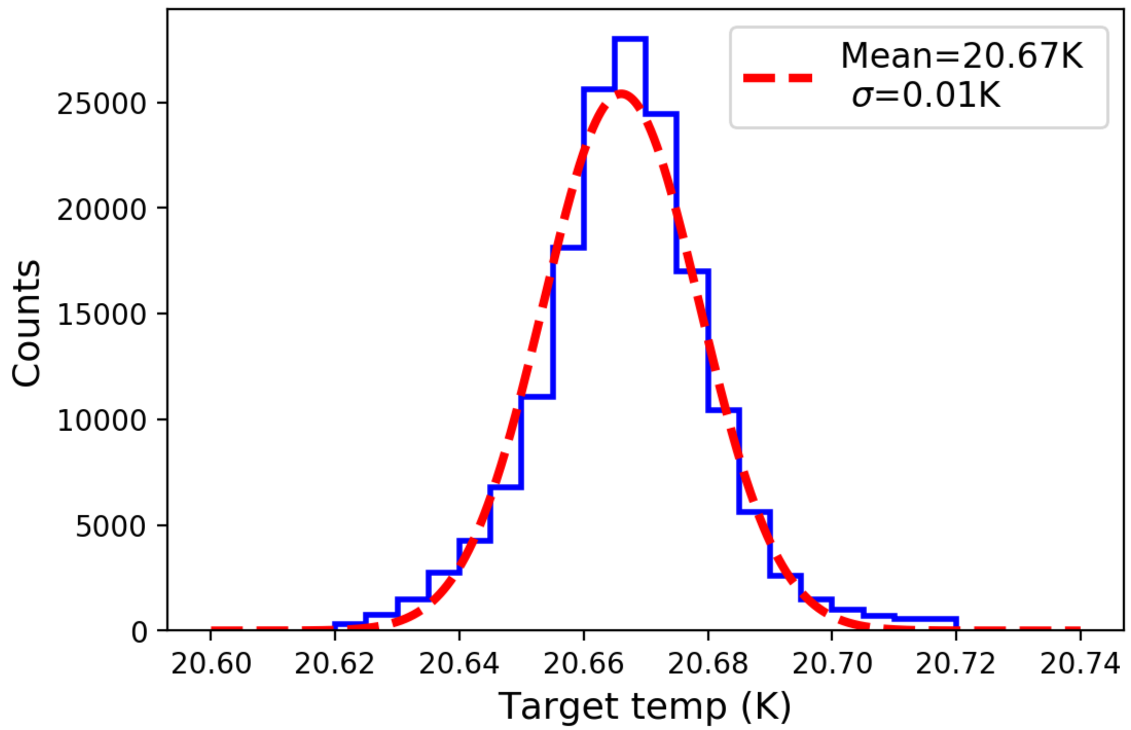
LH_2 Target

Operational since late 2018.

Published: P. Roy et al., https://doi.org/10.1016/j.nima.2019.162874

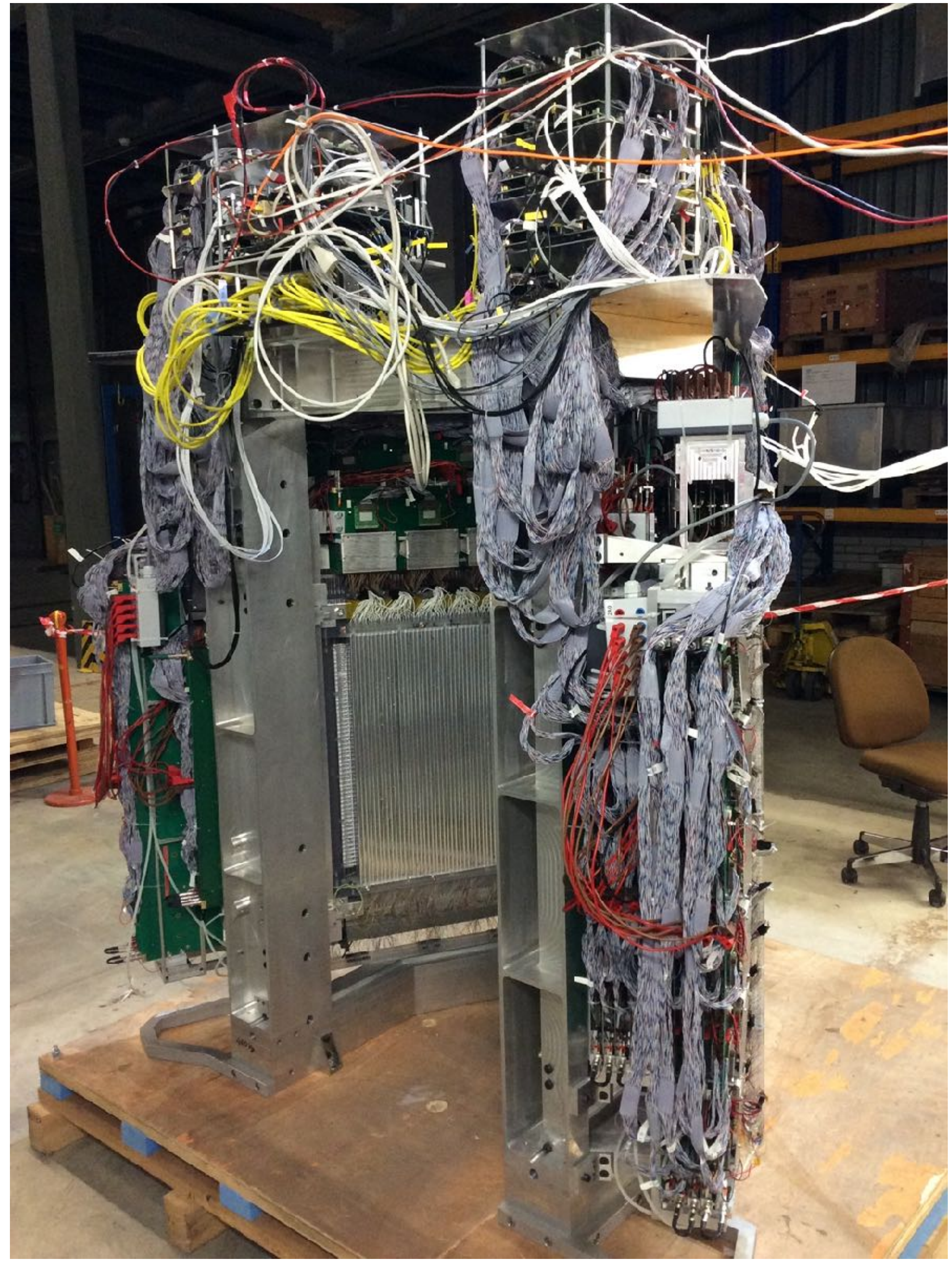






Straw Tube Tracker

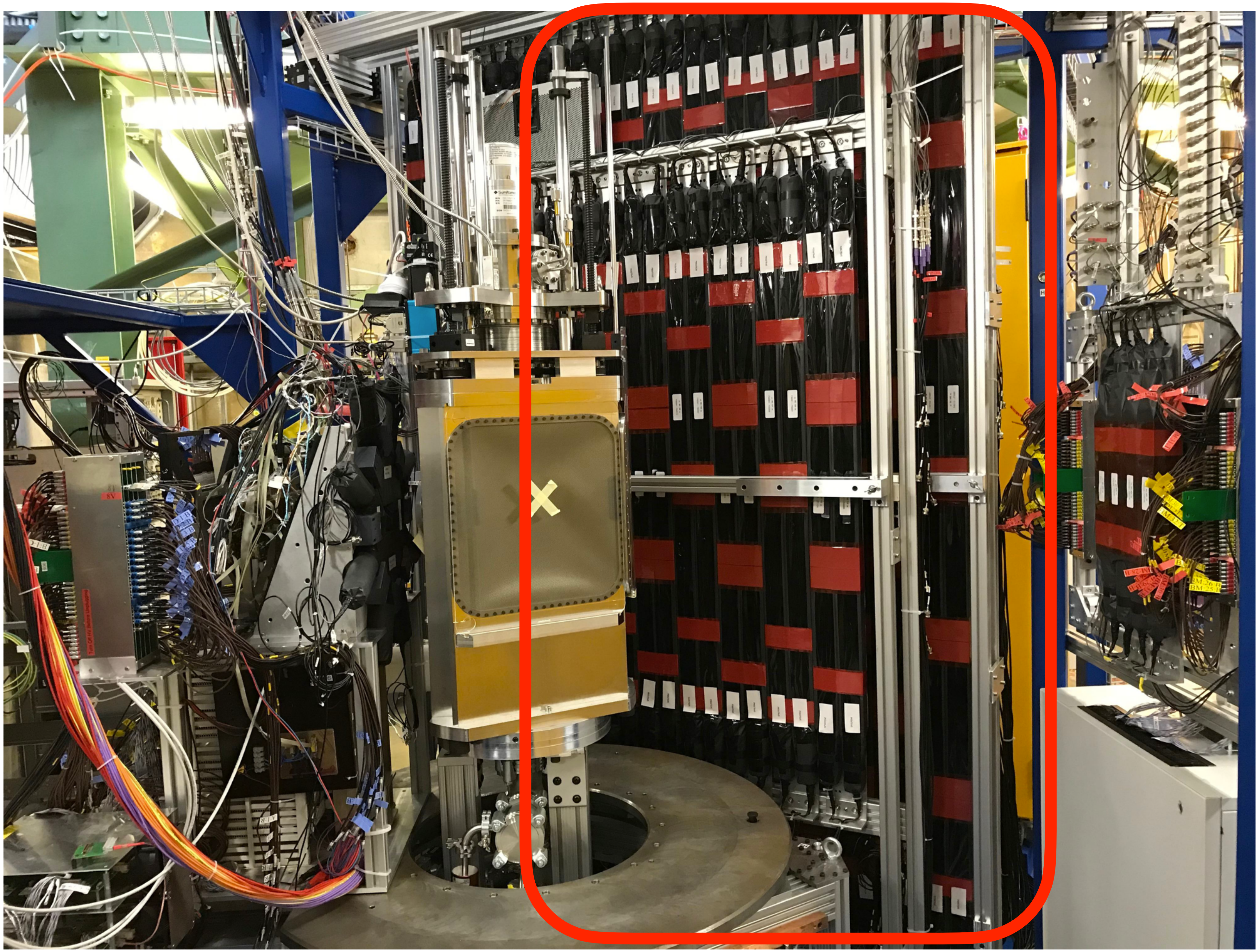
- Straw tube tracker, following PANDA straw design
- 1 atm over-pressured Ar-CO_2
- 10 x, 10 y planes on each side
- Readout with PASTTREC cards and TRB3 TDCs
- Connectors and gas system being redone during 2020, as well as one of the 8 chambers, to enhance reliability.



Jan 2020

Conventional scintillators

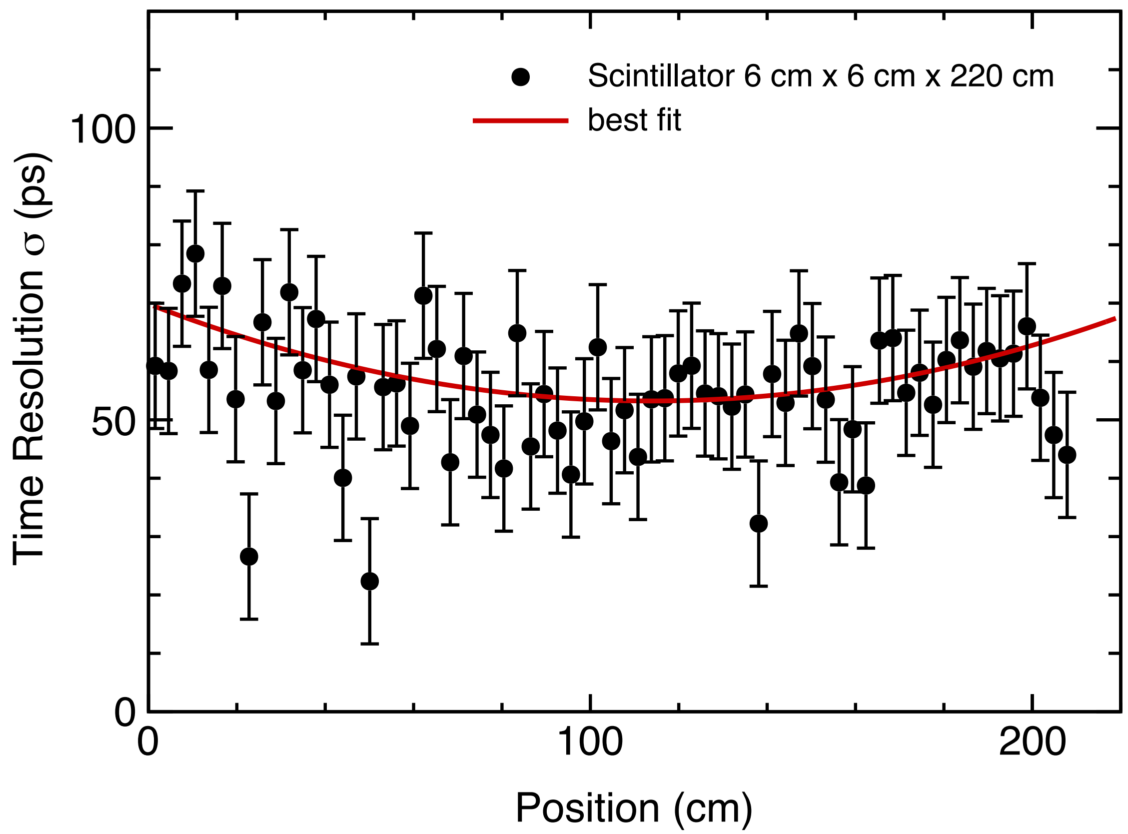
Conventional thick scintillators, Hamamatsu PMTs, 45-60 ps resolution

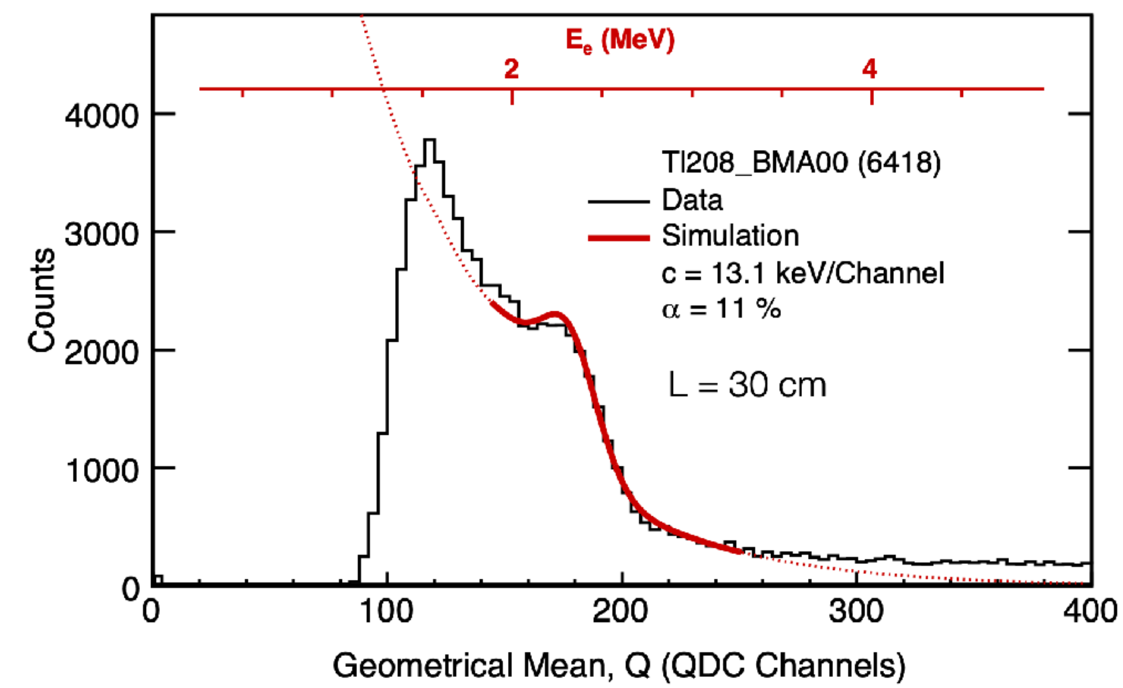


summer 2019, STT not yet installed

Conventional scintillators

Conventional thick scintillators, Hamamatsu PMTs, 45-60 ps resolution

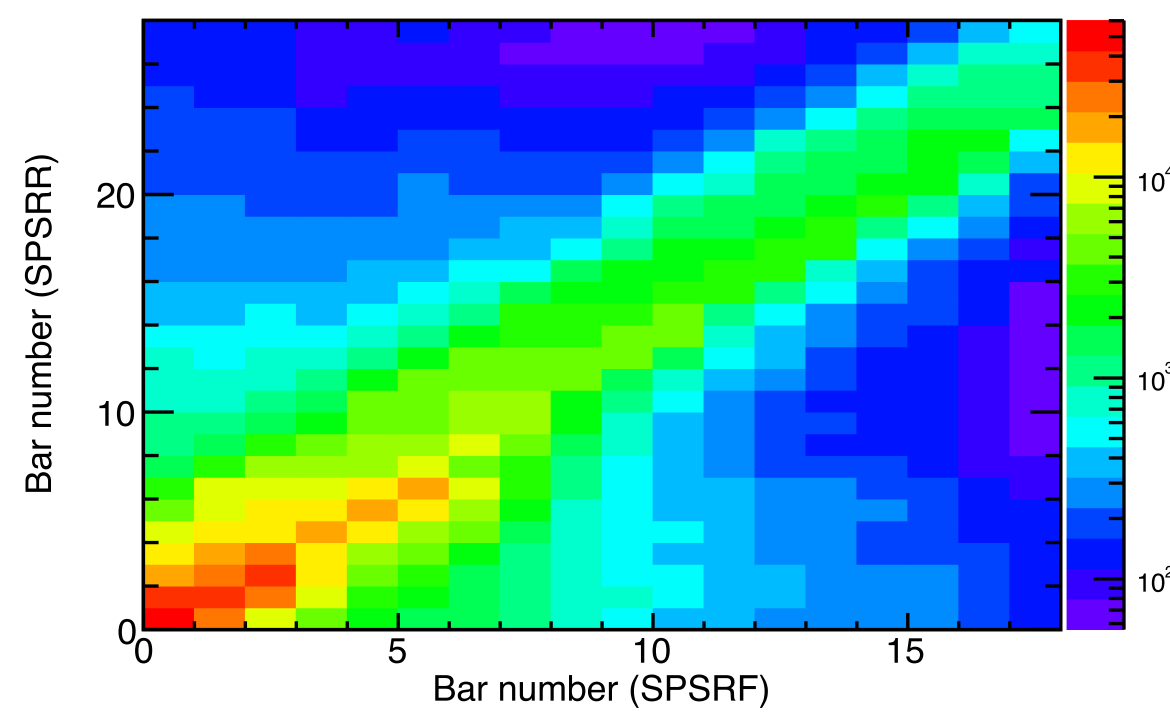




Top left: measured time resolution along bar

Top right: energy calibration of bar using room background - thalium Compton edge

Lower right: front vs rear wall bars in scattering data



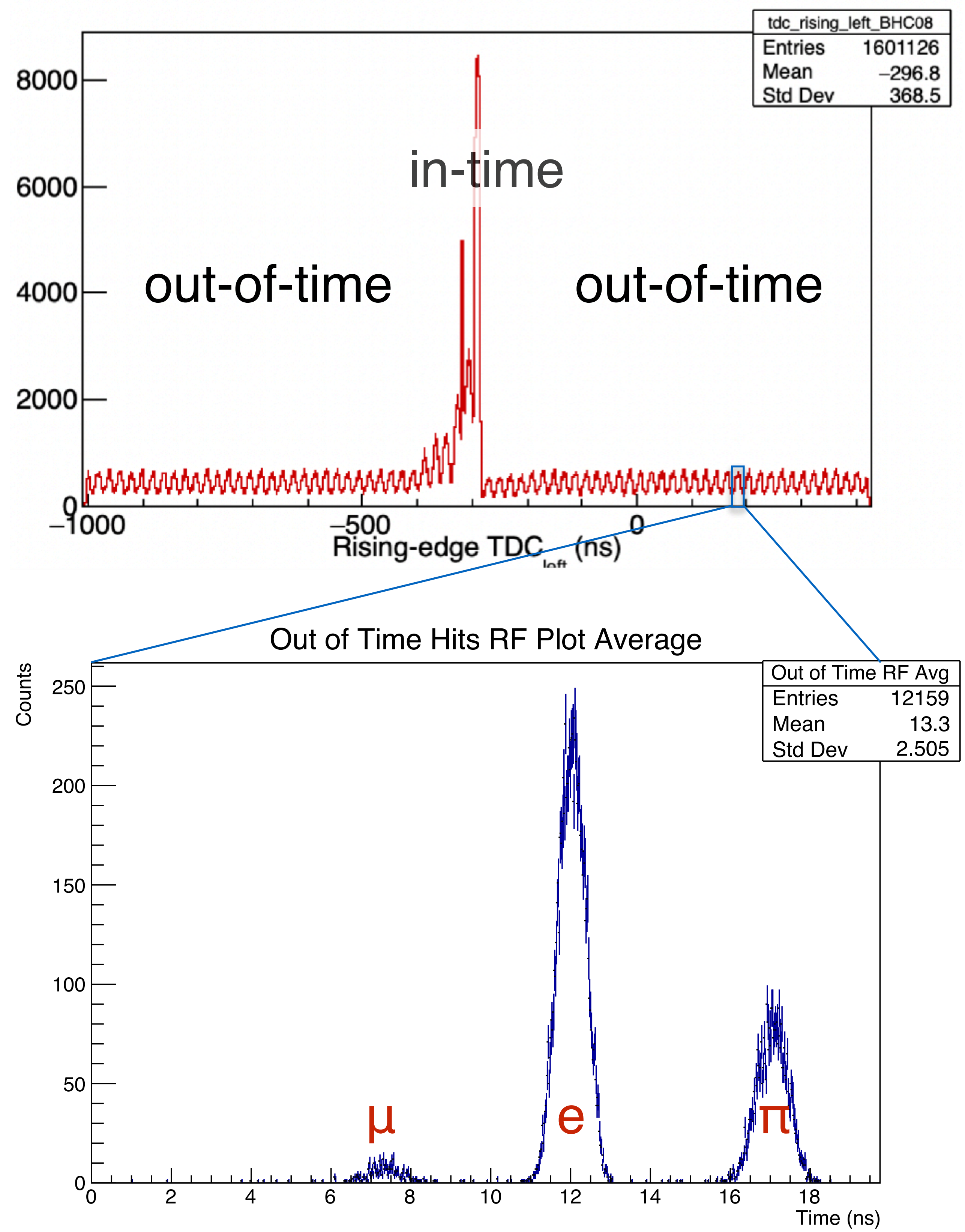
Trigger

Time of hits in BH compared to reference (trigger) time.

The 19.75 ns beam RF period can be seen.

There is not a sharp trigger peak, as the logic signals are aligned to FPGA clocks, rather than being aligned to the detector signals.

Good RF spectra are seen for both the in- and out-of-time signals.



Trigger

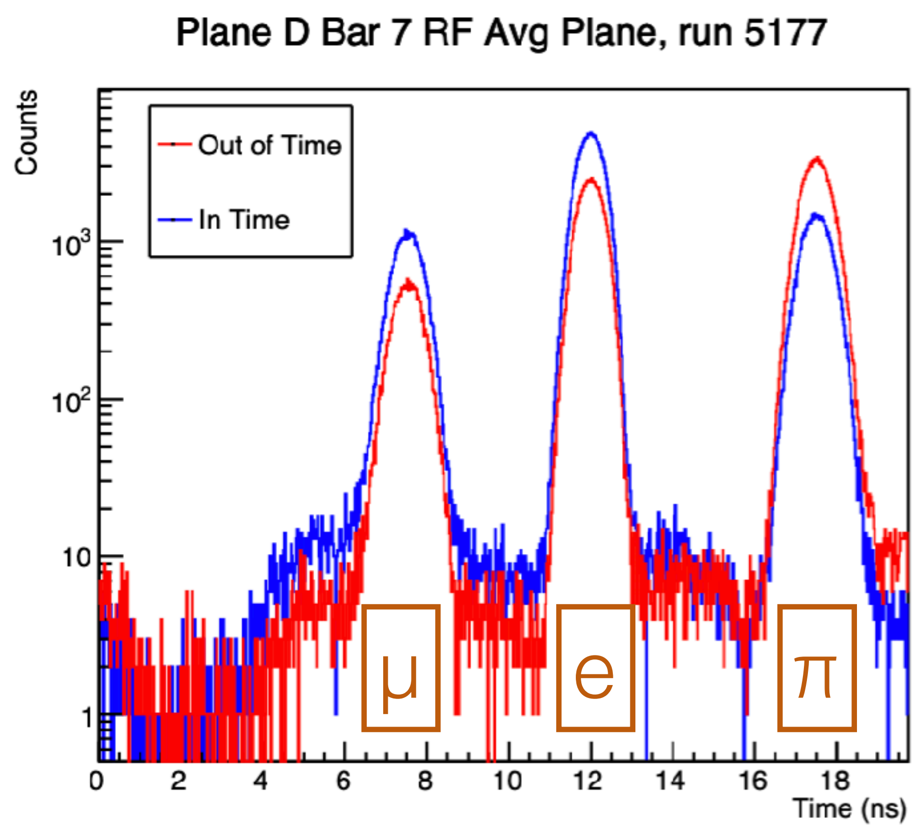
Primary proton beam generates e's, μ's, and π's every "20" ns.

About 3.5 MHz of them travel ~ 23 m (80 - 100 ns) to reach our detectors.

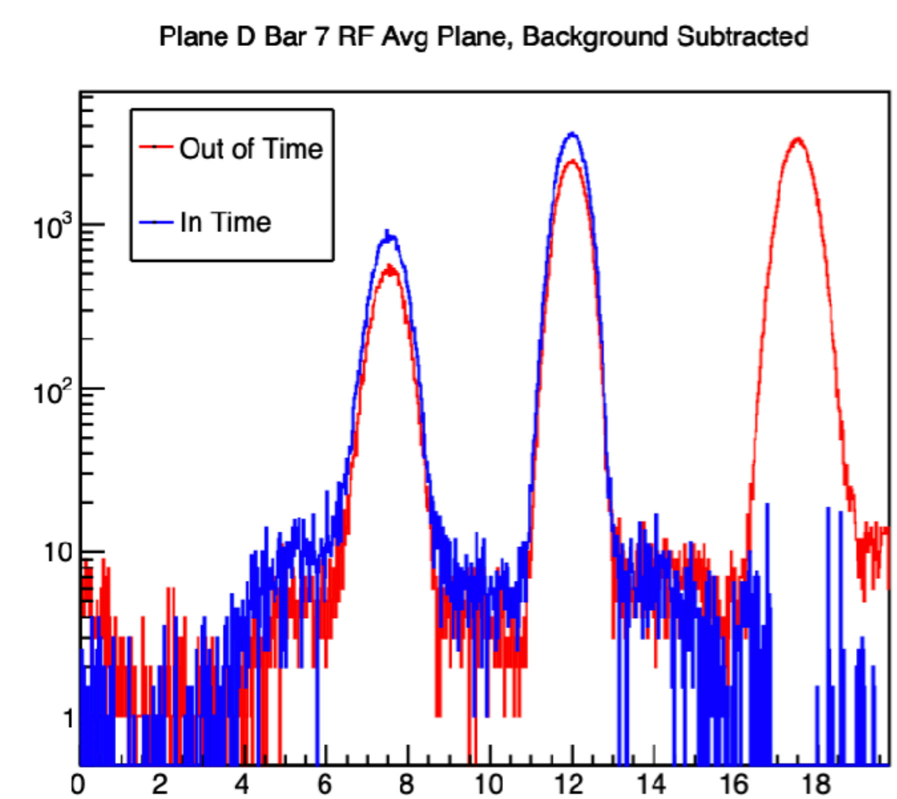
We need to identify the e's and mu's, since pi's scatter more frequently.

The FPGA trigger does this, within ~ 80 ns, for every beam particle, for triggering.

Plots show e + μ trigger implemented, without π implemented as a veto.



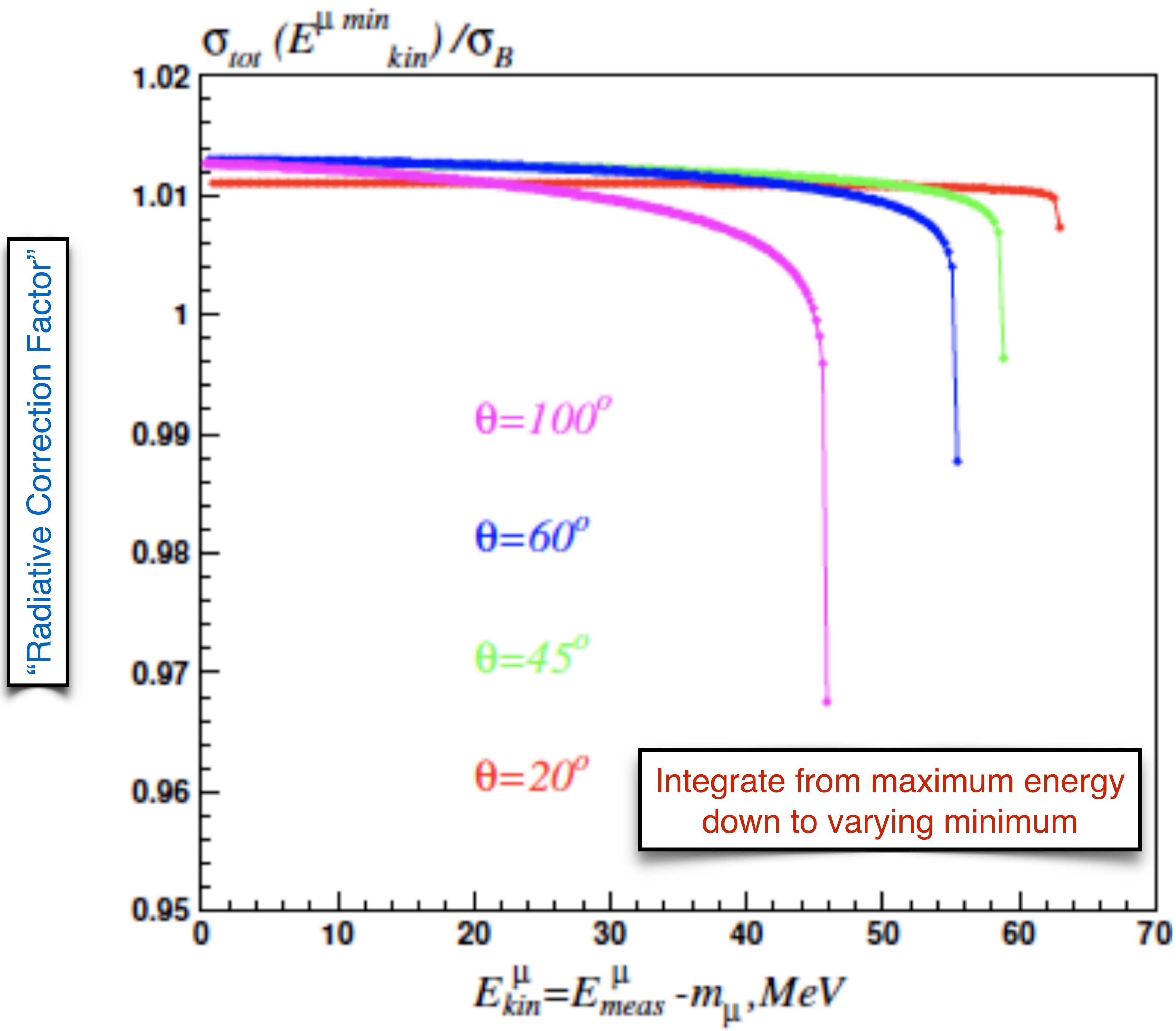
In-time vs Out-of-time



Background-subtracted In-time vs Out-of-time

Radiative Corrections

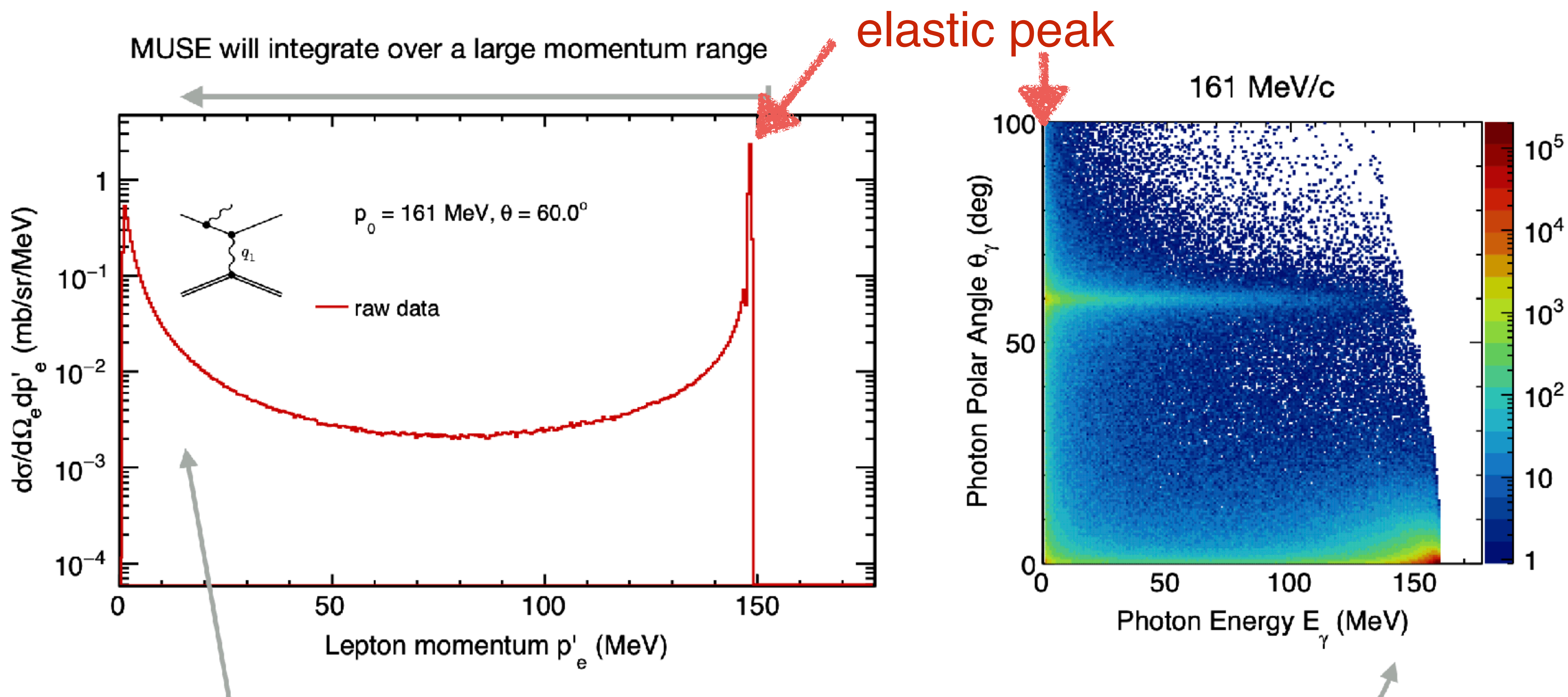
RC are small for μ's are ~ 1.2% ± 0.2%, over a wide range of angles and minimum detected muon momentum. Calculations from A Afanasev (GWU).



Radiative Corrections

RC are significant for e's. Slide from S Strauch and L Li (USC).
Greatest sensitivity is to pre-radiation. Uses ESEPP.

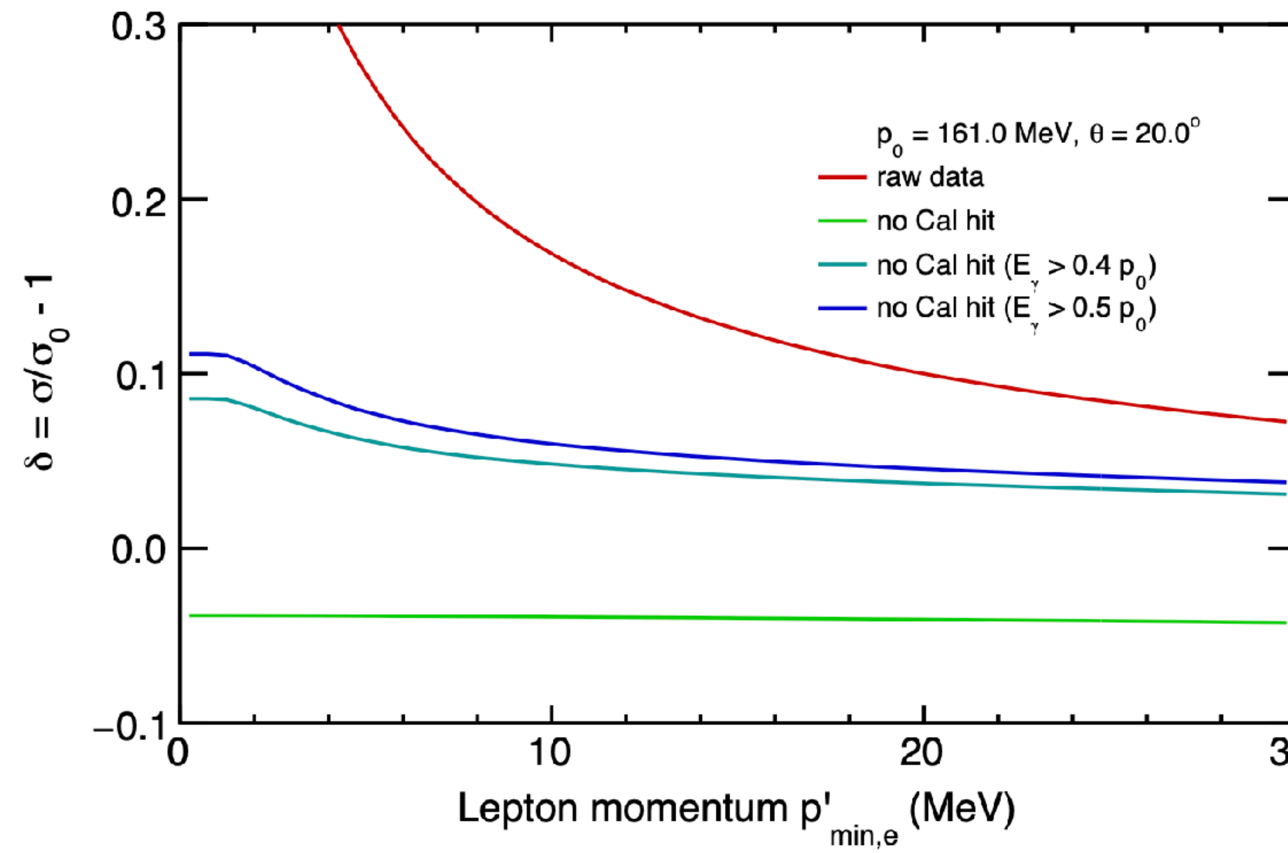
$ep \to e'p\gamma$ Cross section in MUSE kinematics



If the incident lepton loses energy due to emission of a hard photon then the probability for this lepton to be scattered by the proton increases.

Calorimeter

Assembled a forward-angle calorimeter from borrowed Mainz lead glass, to remove events with high-energy photons in beam direction.

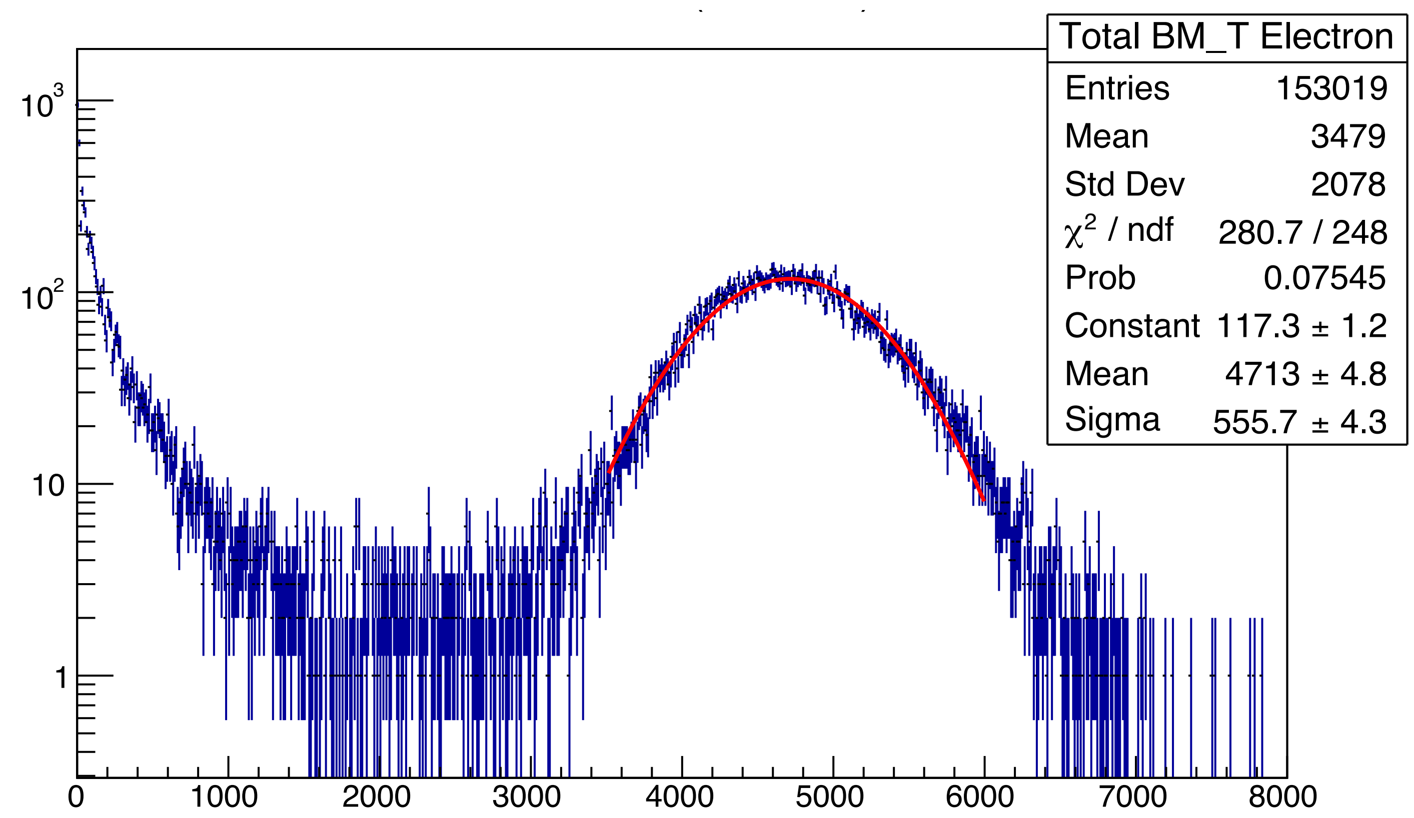


Cut on E_γ flattens the radiative correction curve, reducing sensitivity to cut on p'.

Calorimeter

Tested calorimeter with e's (and μ's, and π's).

210 MeV/c



rms / E ~ 12%, 13%, 16% at 210, 160, 115 MeV/c.

Radiative Corrections

L LI, S Strauch (USC): MUSE Geant4 with ESEPP generator (Gramolin et al.)

Systematic uncertainties about as expected for e’s, very small for μ’s.

Preliminary results

$\sigma_\delta(e^-)$	115 MeV			210 MeV		
	20°	60°	100°	20°	60°	100°
p'_{min}	0.05%	0.29%	0.56%	0.03%	0.23%	0.63%
p_0	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%
θ	0.13%	0.07%	0.05%	0.10%	0.14%	0.01%
E_γ	0.55%	0.57%	0.58%	0.35%	0.40%	0.38%
Total	**0.57%**	**0.65%**	**0.81%**	**0.37%**	**0.48%**	**0.74%**

Preliminary results

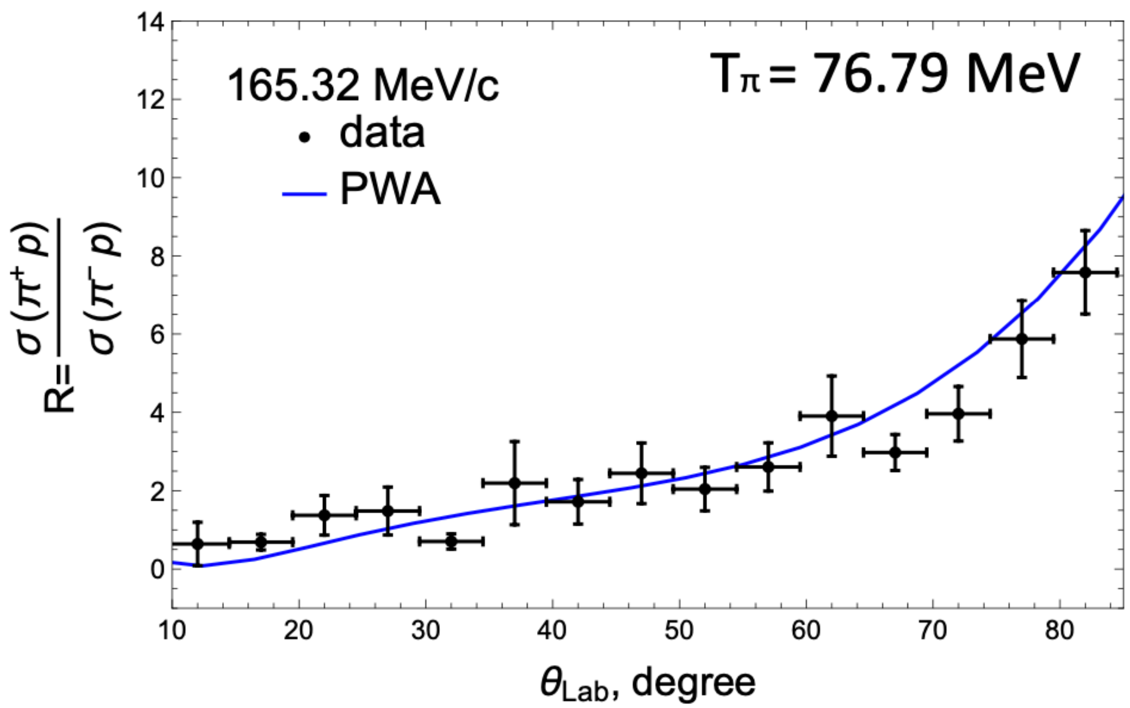
$\sigma_\delta(\mu^-)$	115 MeV			210 MeV		
	20°	60°	100°	20°	60°	100°
p'_{min}	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
p_0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
θ	0.06%	0.02%	0.04%	0.04%	0.03%	0.04%
E_γ	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	**0.06%**	**0.02%**	**0.04%**	**0.04%**	**0.03%**	**0.04%**

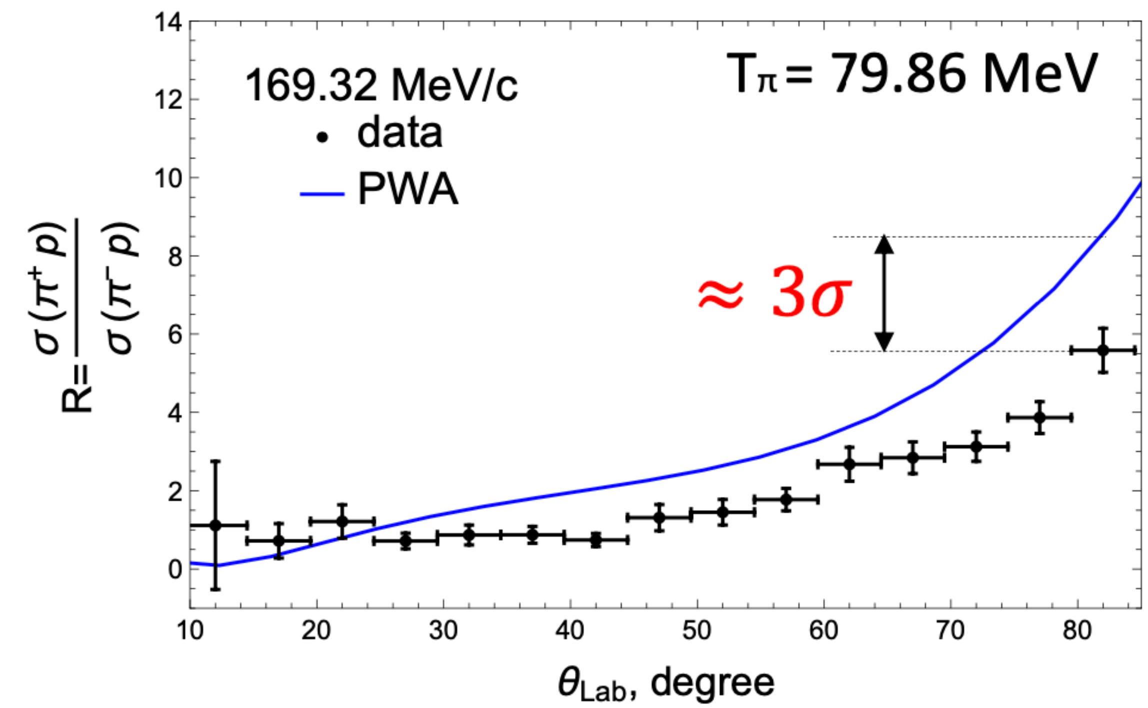
~ 0.4 - 0.8%

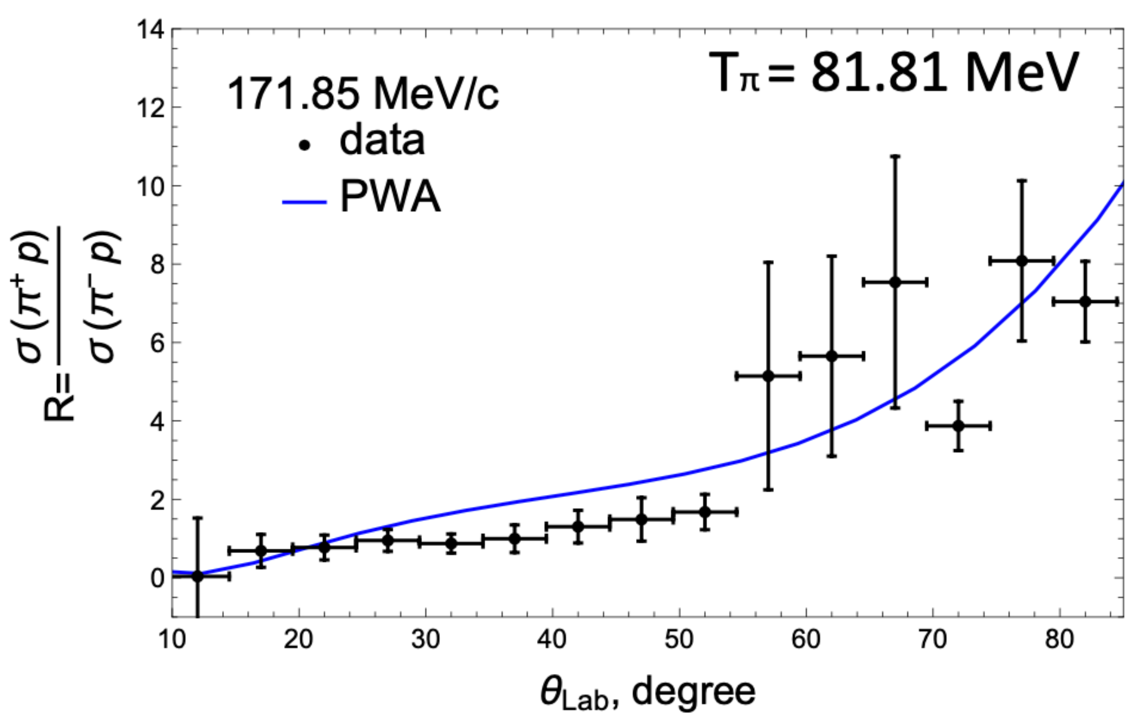
~ 0.02 - 0.06%

Pion scattering data

I. Lavrukhin Ph.D. thesis. 2019 data. Taken from his 2020 DNP talk.



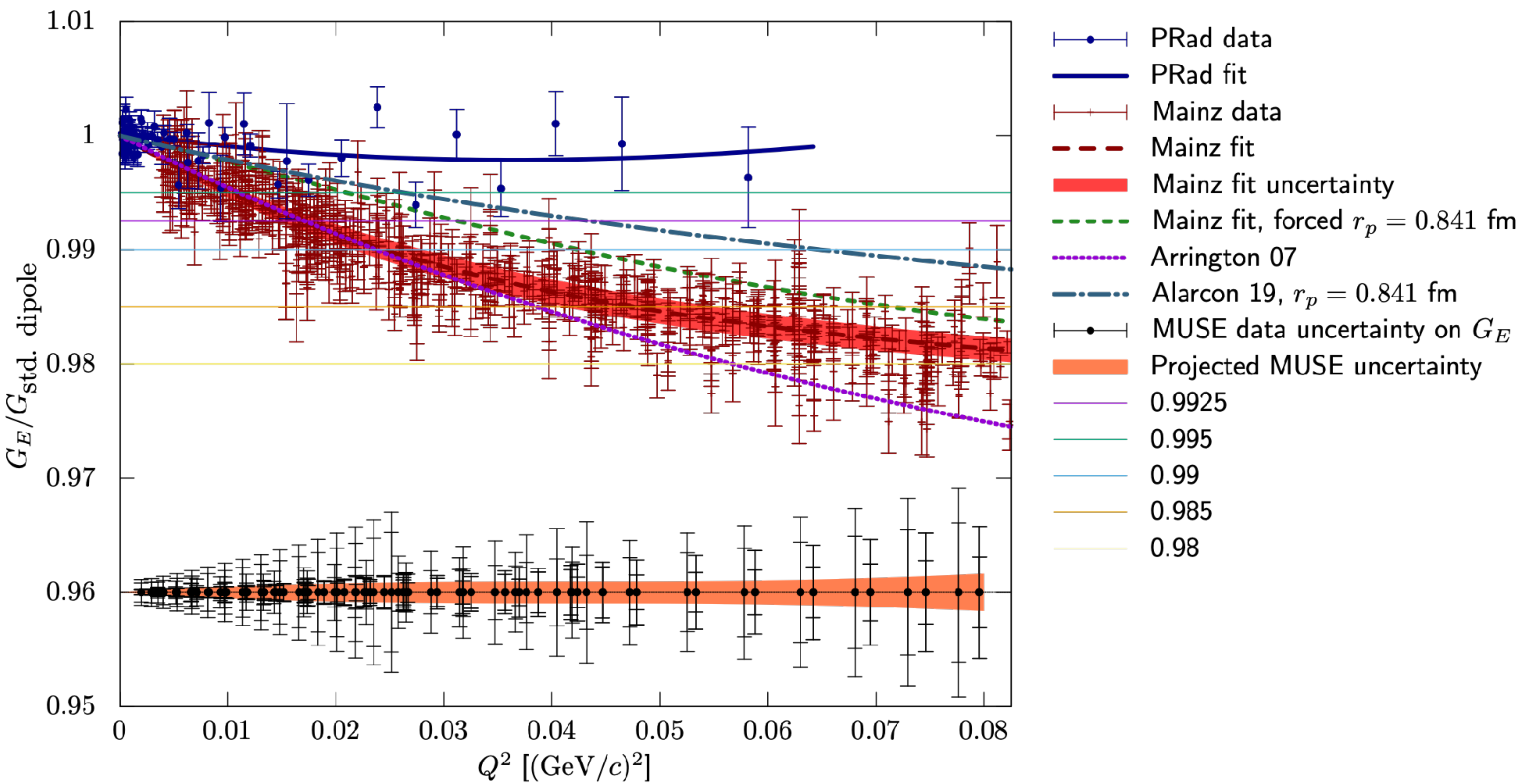




- Good agreement with PWA calculations bellow and above S11 resonance energy (T_π = 79.50 MeV)
- PWA doesn't describe data well abound predicted S11 resonance energy.
- PWA calculations are provided by Prof. Strakovsky (igor@gwu.edu).

MUSE Anticipated e, μ data

Anticipated MUSE uncertainties vs PRAD, Mainz

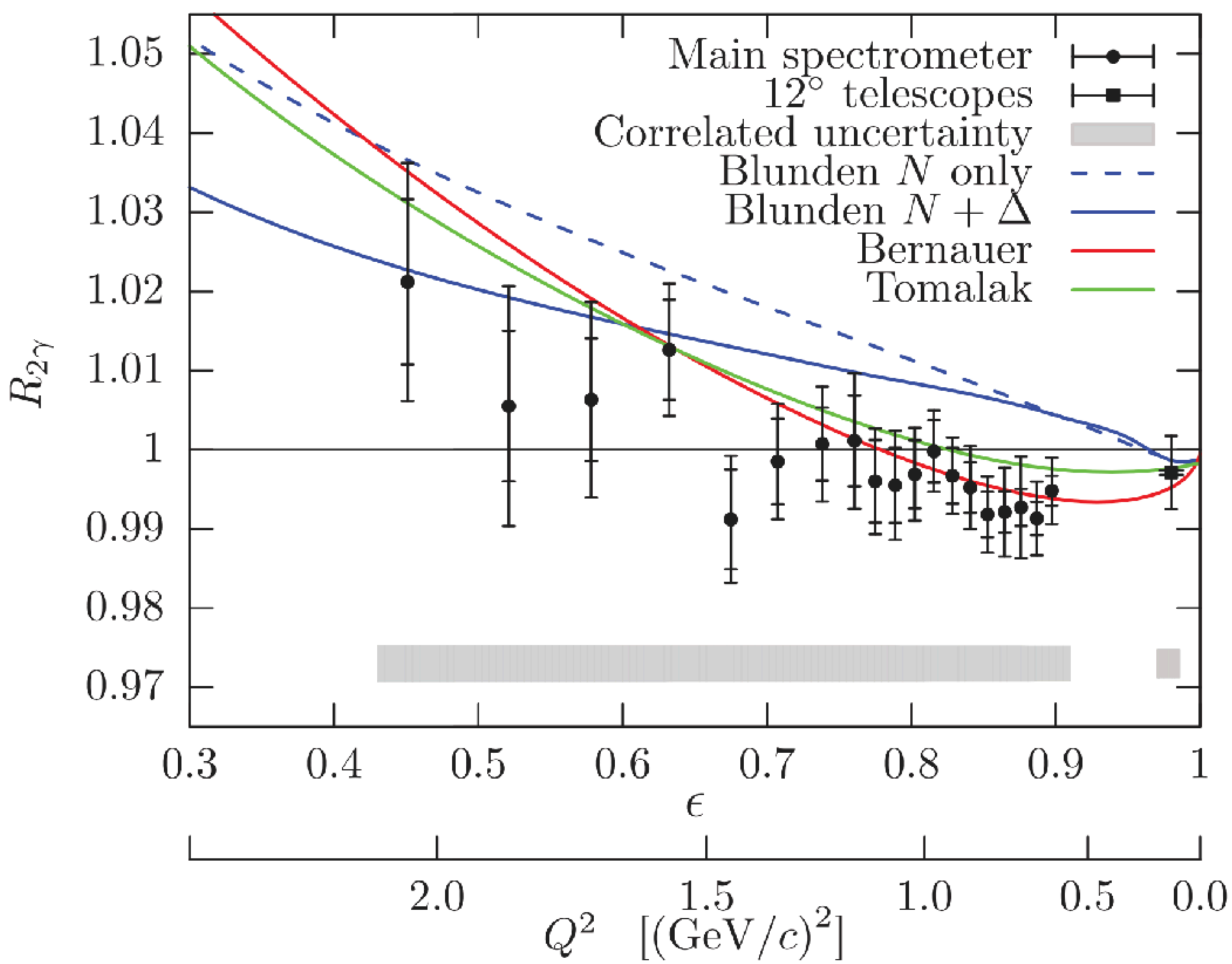


Plot from Jan Bernauer

Expected radius uncertainty ~ 0.006 (0.0045) fm for μ, e, depending on fit function.

Two-Photon Exchange

Current world's bet data for TPE exchange:
OLYMPUS, Henderson et al., PRL 118, 092501 (2017)



Blunden: theory

Tomalak, Bernauer: fits

MUSE: 2 x as many data points, ~ 2 x better uncertainties for e's. Similar uncertainties μ's.

Slightly wider ε range, but all small Q^2.

Status Summary

Full system assembled in 2019, but some detailed adjustments / upgrades / studies in progress.

Planned to complete these and take meaningful scattering data this year.

COVID happened.

Most of the upgrades completed, but will only be able to do tests of these, over the next few weeks.

Expect to reassemble full system in spring 2021, test, and move to production data taking.

Plan for 12 months of production running. 2021 - 2022 - 2023?

Radius will take all data, but other results might come out sooner. Need to maintain blinded analysis for radius.

Thank you

Two Photon Exchange Corrections