Proton Radius Measurements with Electron and Muon Scattering

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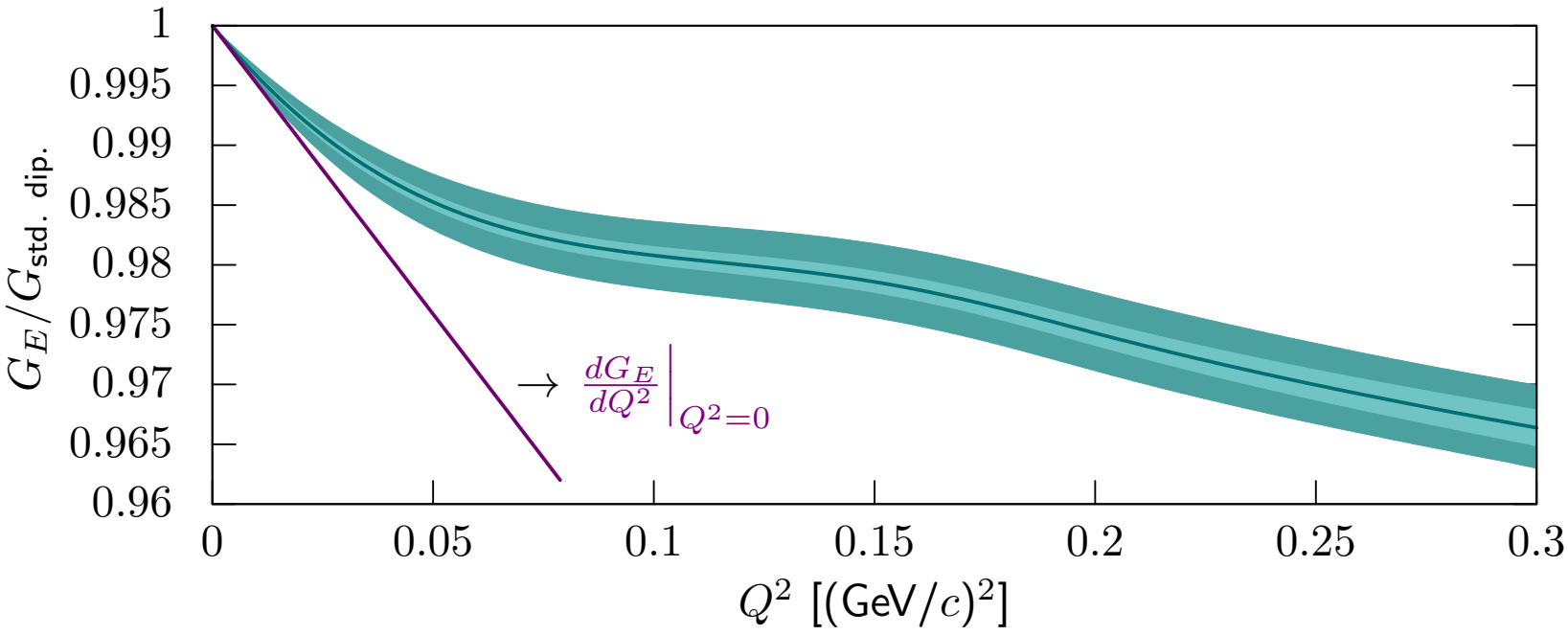
IWHSS 2018 - Bonn - March 2018

The proton radius puzzle

How to measure the proton radius

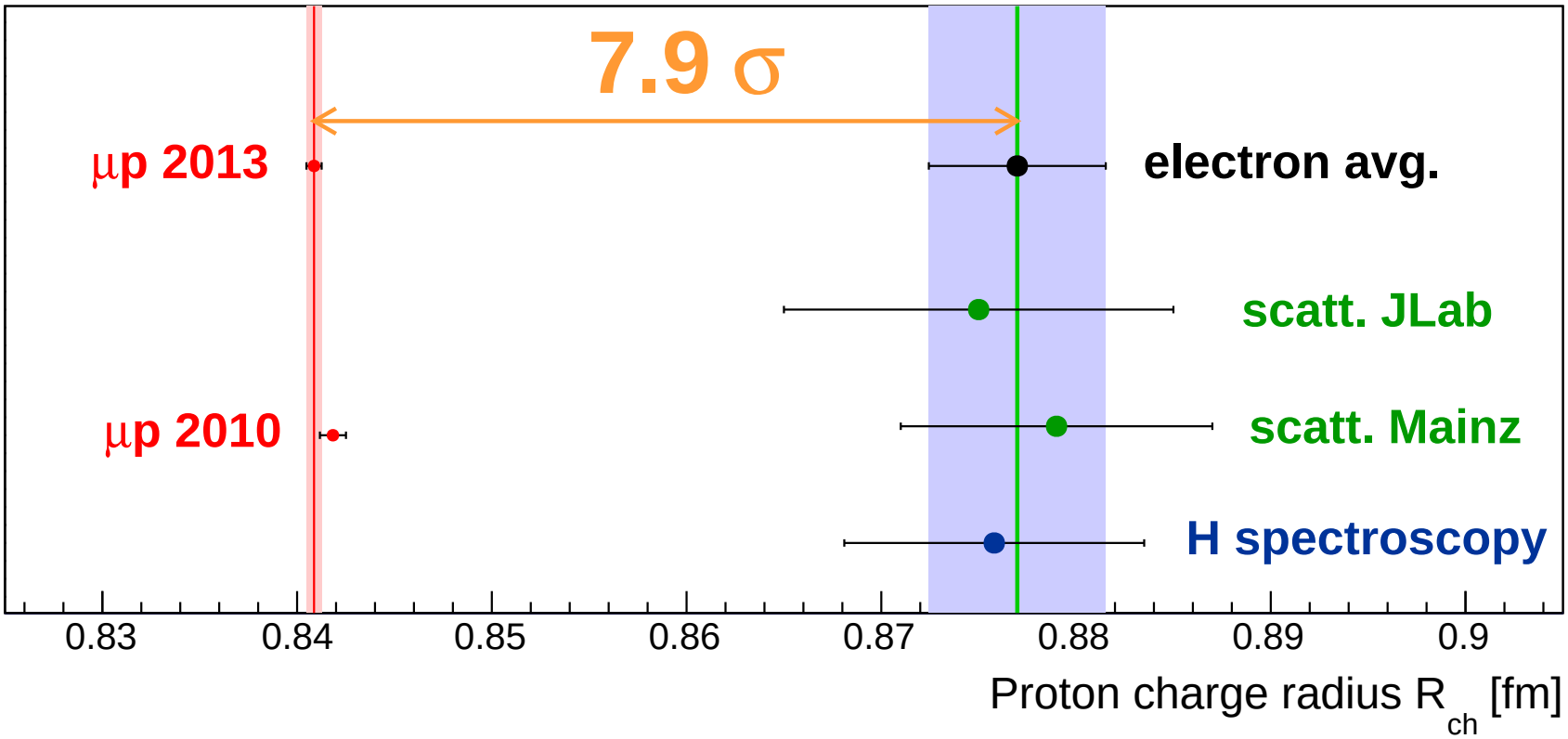
$$\left\langle r_E^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$



Alternatively: Lamb shift: finite proton size changes hydrogen energy levels

Extract from (muonic) hydrogen spectroscopy. (See next talk)

The proton radius puzzle



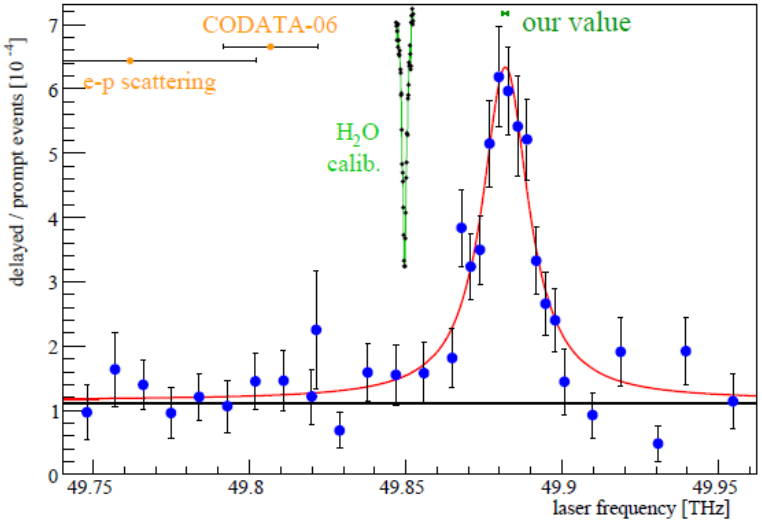
The proton radius puzzle

From the 2017 Review of Particle Physics

Until the difference between the $e\,p$ and $\mu\,p$ values is understood, it does not make sense to average the values together. For the present, we give both values. *It is up to the workers in this field to solve this puzzle.*

Solutions?

- μp experiment wrong?



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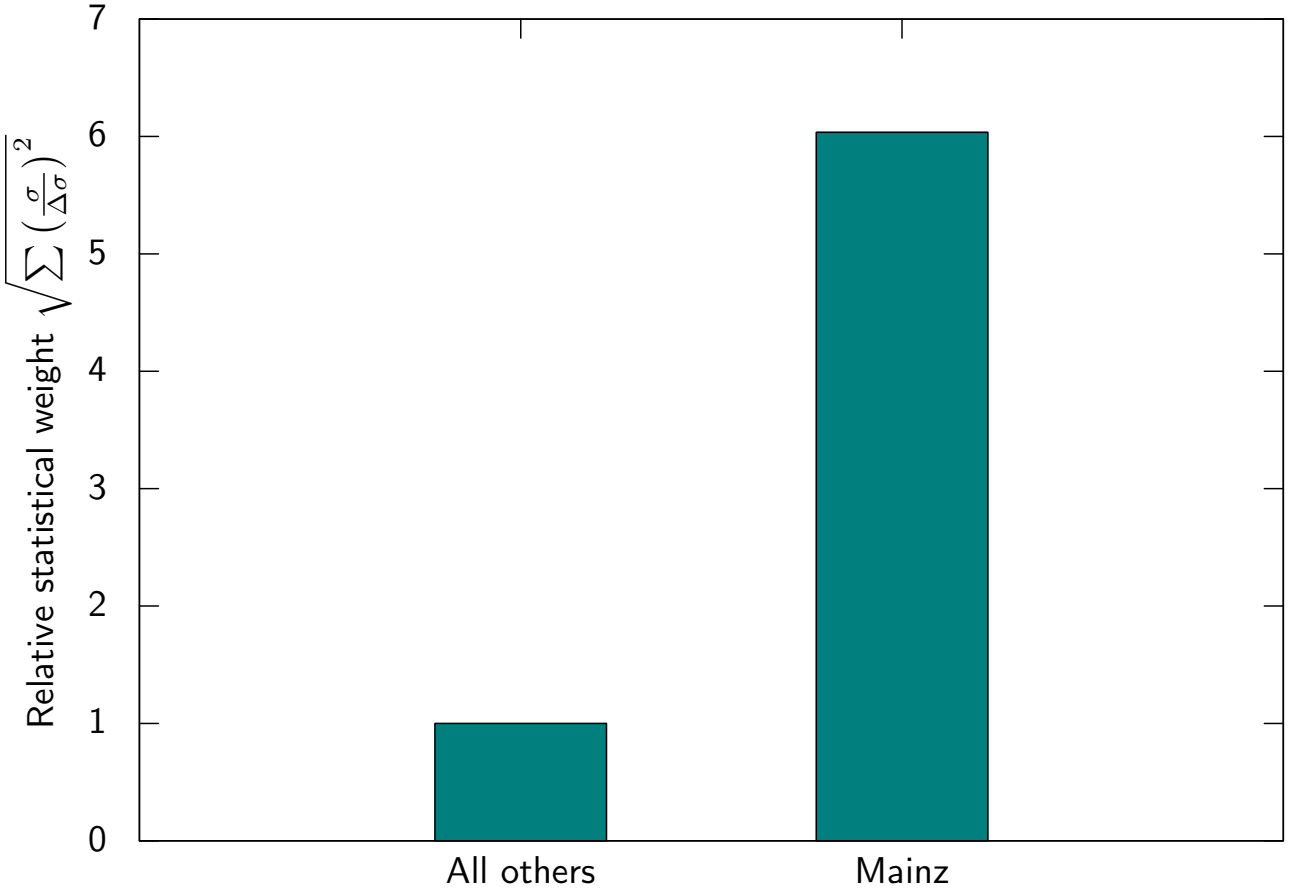
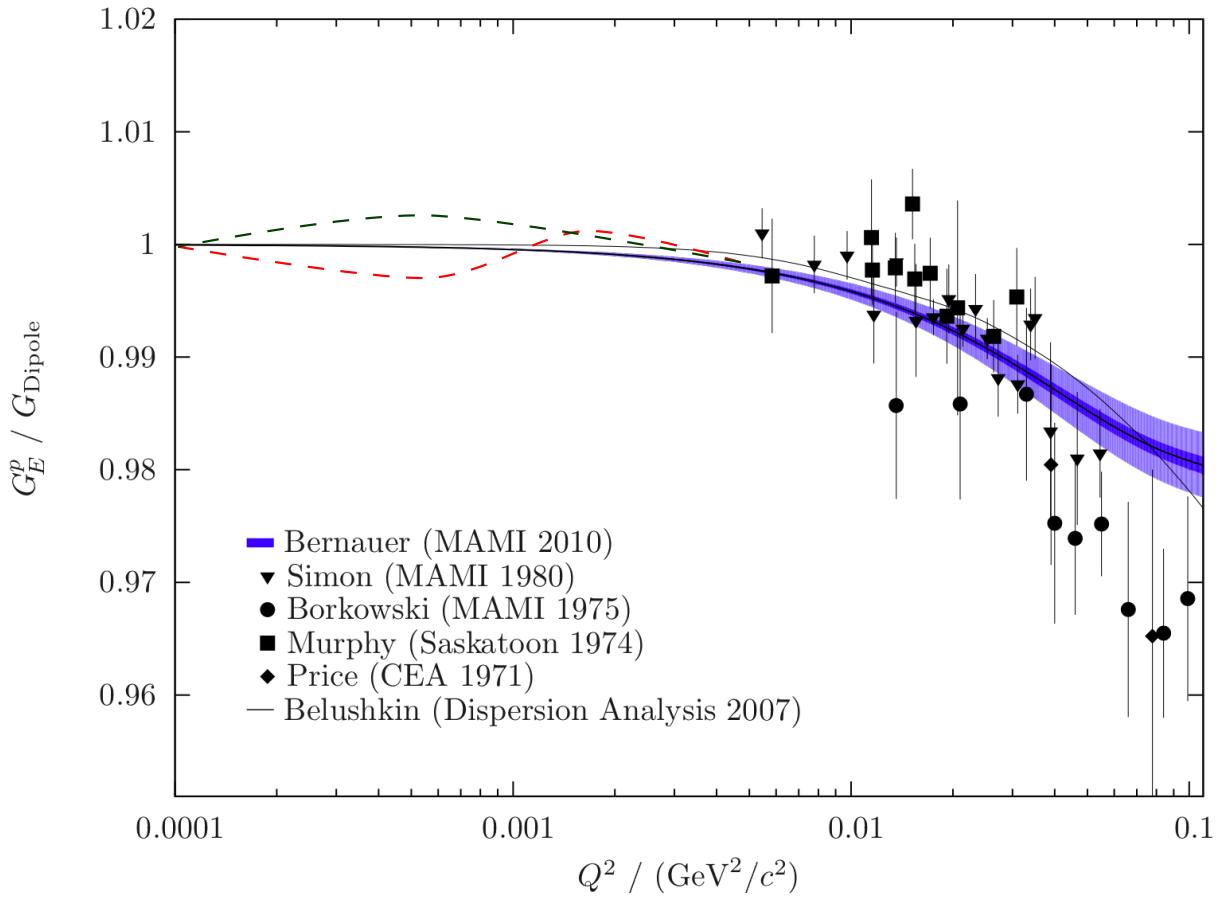
WE NEED MORE DATA

Volume of Mainz data set



Mainz data will dominate any fit. Need similar data set to validate!

Extrapolation problematic? Structures at low Q^2?

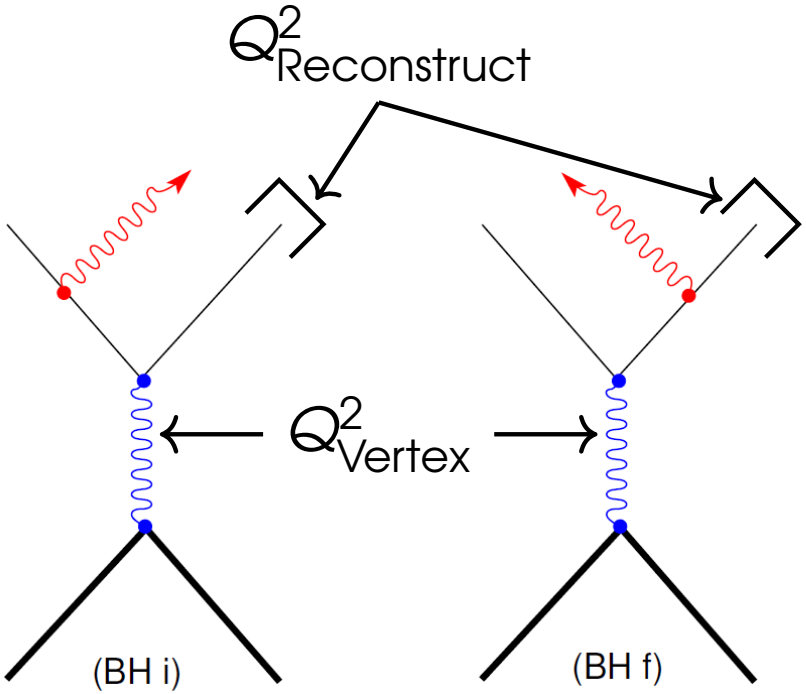


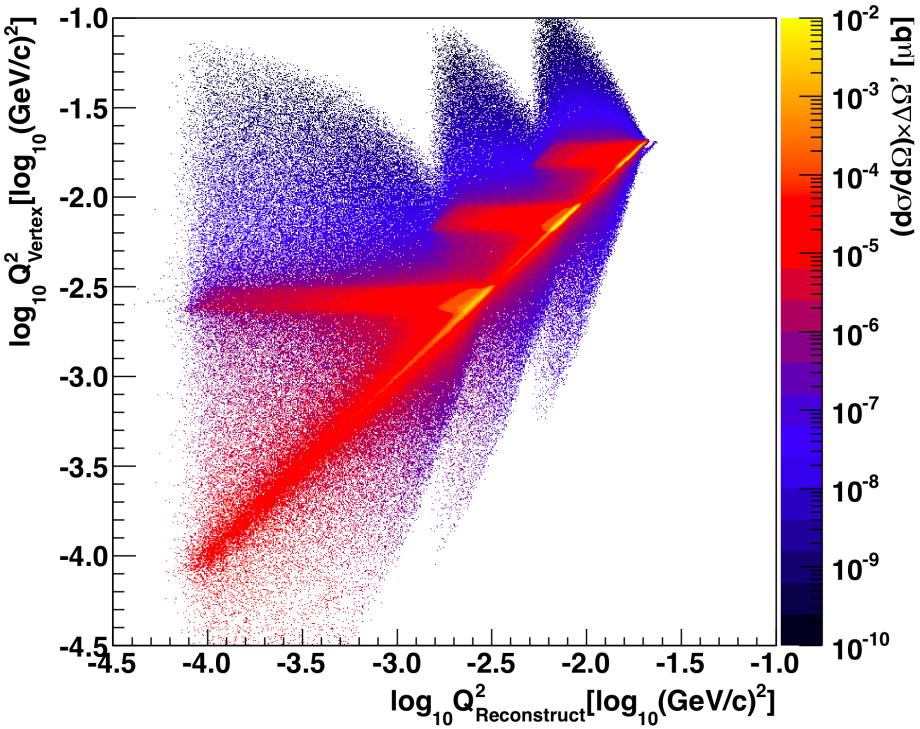
Three ways to get to lower Q^2

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

- Smaller scattering angle $\longrightarrow$ PRad
- Lower beam energy $\longrightarrow$ MESA
- Initial State Radiation

ISR method

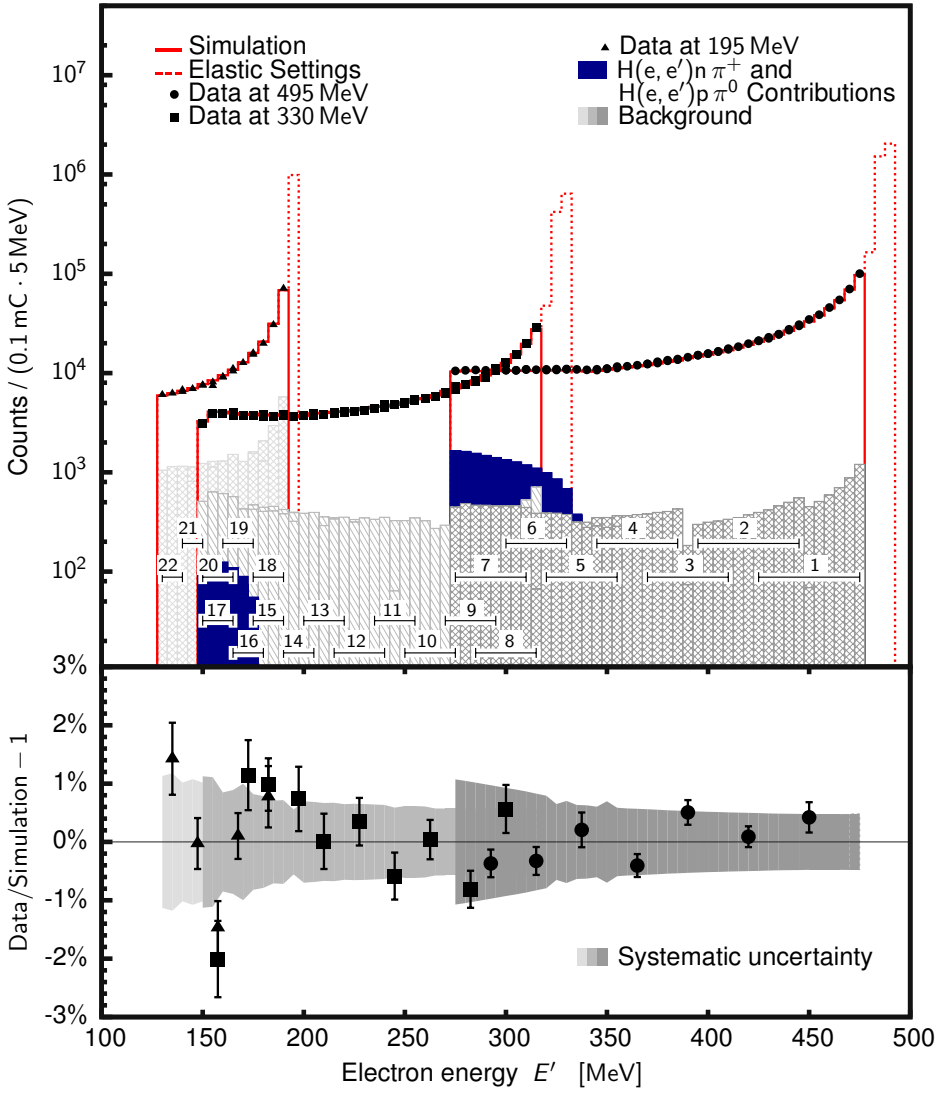




- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

ISR at MAMI

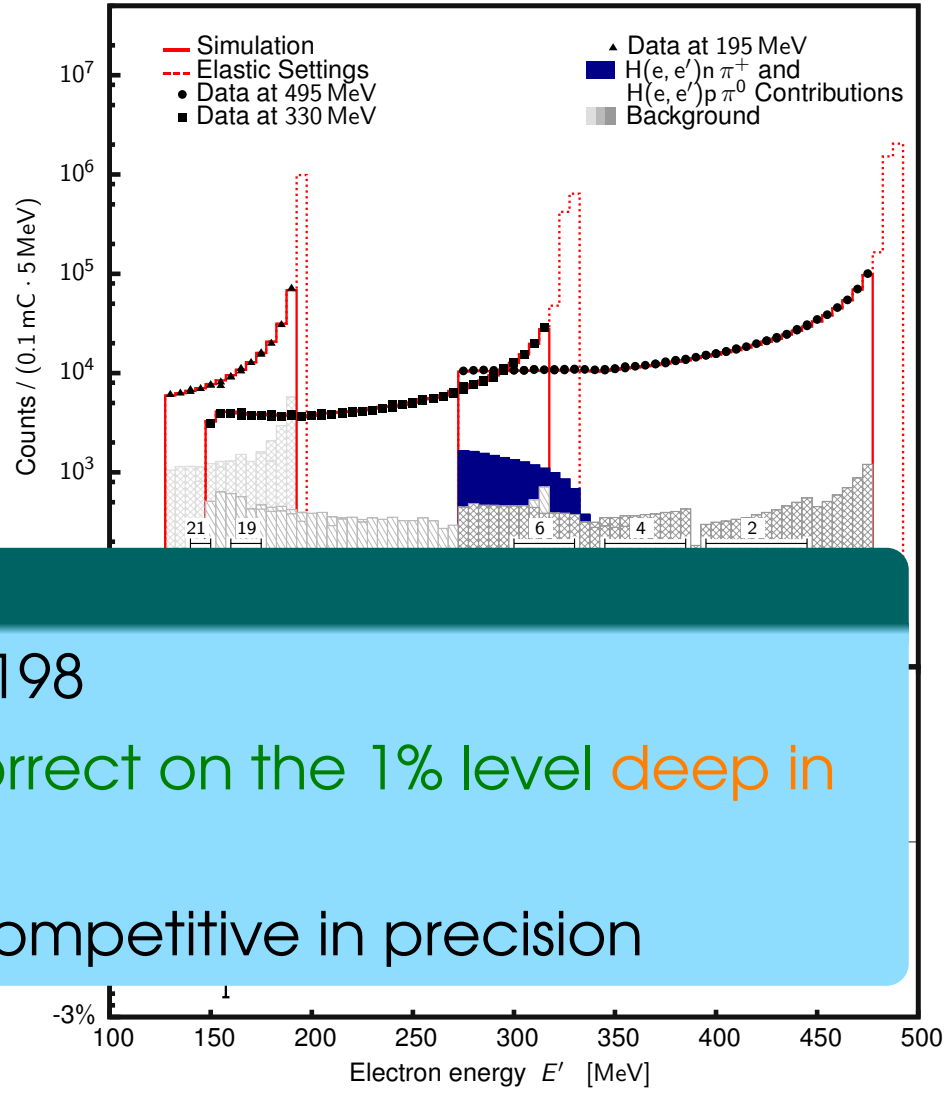
- ISR $\longrightarrow$ small E $\longrightarrow$ small Q^2
- Extract F.F. from radiative tail
- Or: test radiative tail description



See: arXiv:1612.06707

ISR at MAMI

- ISR $\longrightarrow$ small E $\longrightarrow$ small Q^2
- Extract FF from



See: arXiv:1612.06707

Status

- Published: PLB 771:194-198
- Radiative correction correct on the 1% level deep in the tail!
- Radius extraction not competitive in precision

Target dominant source of uncertainty

- For Mainz data, systematic errors dominate

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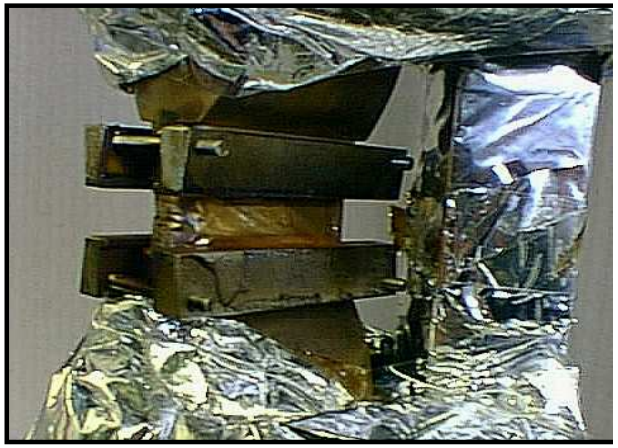
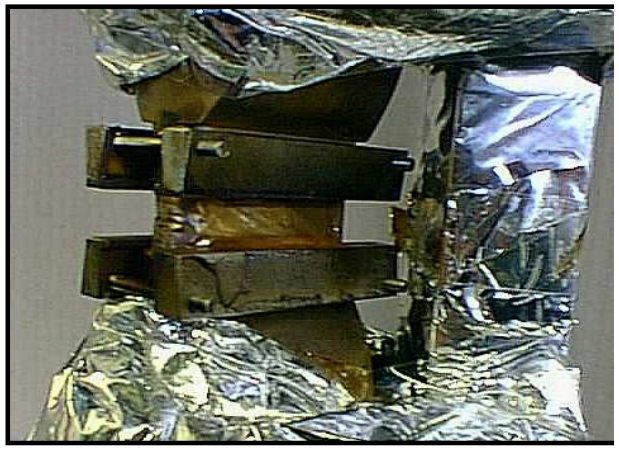
  - Background from target walls
  - Acceptance correction for extended target



Target dominant source of uncertainty

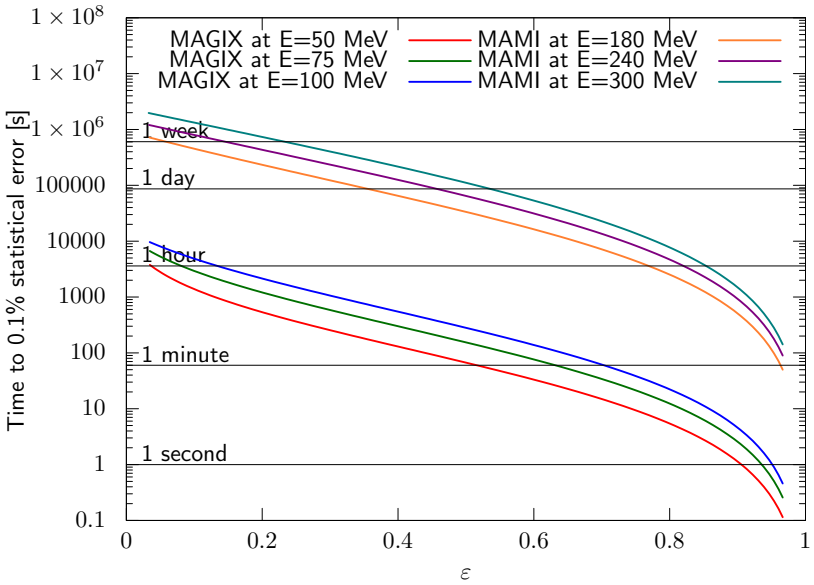
- For Mainz data, systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target
- Eliminate with jet target
  - point-like
  - no walls
  - but less density
- Rinse, repeat with D,^{3}He,^{4}He, ...

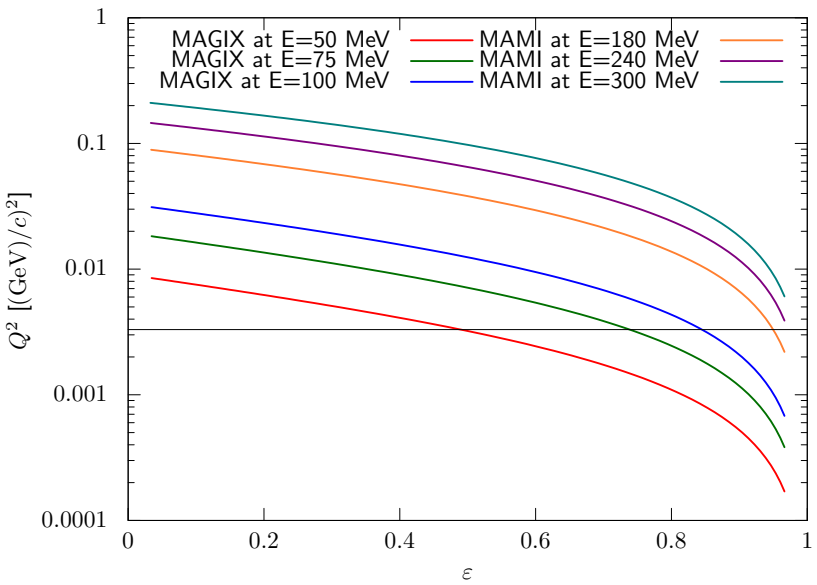


$\Downarrow$

Mainz future plans

- Repeat ISR with new target
- Use new target also for classic approach





First data in April!

Extrapolation to $Q^2 = 0$

Have to extrapolate form factor to $Q^2 = 0$.
Mainz lowest $Q^2 = 0.0033\,(\mathrm{GeV}/\mathrm{c})^2$.
We use a 10th order polynomial to fit data up to $1\,(\mathrm{GeV}/\mathrm{c})^2$. This gets people scared.

Can we fit just a linear term?

Can a linear fit work?

$$\frac{d\sigma}{d\Omega} \propto 1 - \underbrace{A}_{\mathcal{O}(6)} \cdot Q^2 + \underbrace{B}_{\mathcal{O}(30)} \cdot Q^4 + \ldots$$

(Q in units of GeV/c)

We want to measure the radius ($\sim\sqrt{A}$) to within 0.5%, without knowing B. So:

$$B/A \cdot Q^2 \ll 0.01 \longrightarrow Q^2 \ll 0.002\,(\mathrm{GeV}/c)^2$$

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But: Need to measure A to 1%, so measure $\frac{d\sigma}{d\Omega}$ to $6 \cdot 0.002 \cdot 0.01 = 0.012\%$. Good luck.

Why do low Q^2 then?

- Test / fix normalization
  Similar arguments apply, but helpful when dataset contains also higher Q^2.
- Test for new physics / ultra long range structure
  Signal can easily, but doesn't have to be undetectable small and still change the radius!
- Measure r_M
  Low Q^2 at $\epsilon = 1$ means lowish Q^2 at $\epsilon = 0$

The missing piece

r_E (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060	????

Measure radius with muon-proton scattering!

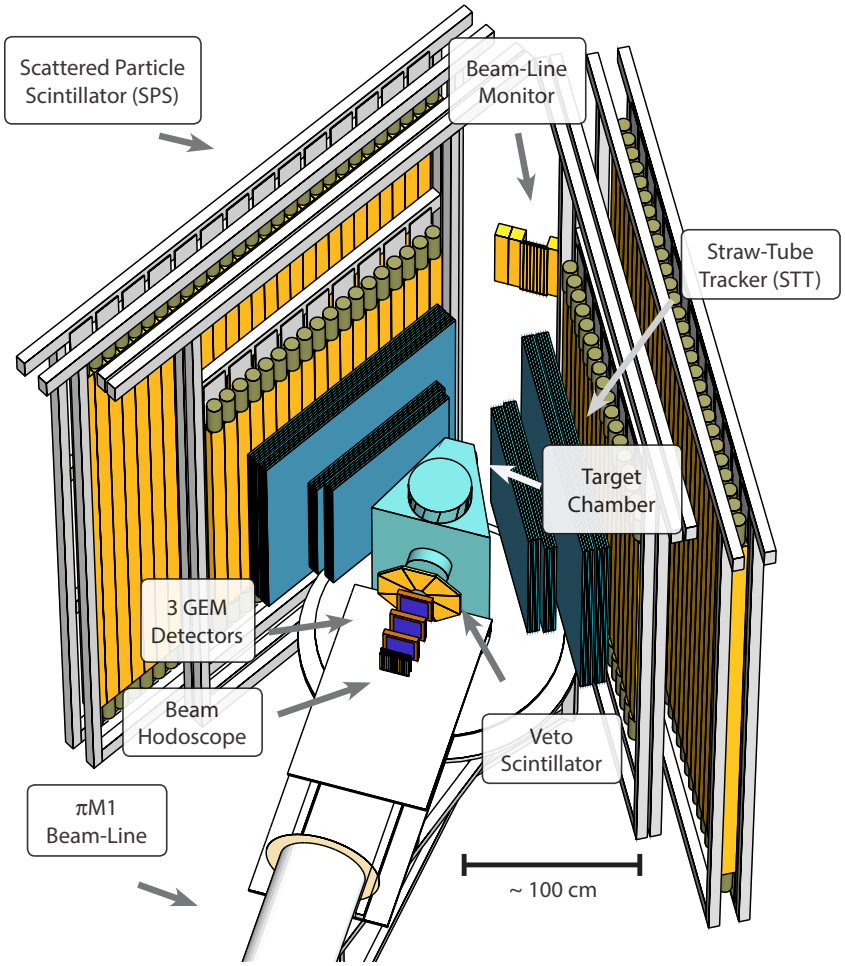
MUSE - Muon Scattering Experiment at PSI

World's most powerful low-energy $e/\pi/\mu$-beam:

Direct comparison of ep and μp!

- Beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on liquid H_2 target
  - Species separated by ToF, charge by magnet
- Absolute cross sections for ep and μp
- Ratio to cancel systematics
- Charge reversal: test TPE
- Momenta 115-210 MeV/c $\Rightarrow$ Rosenbluth G_E,G_M

Experiment layout

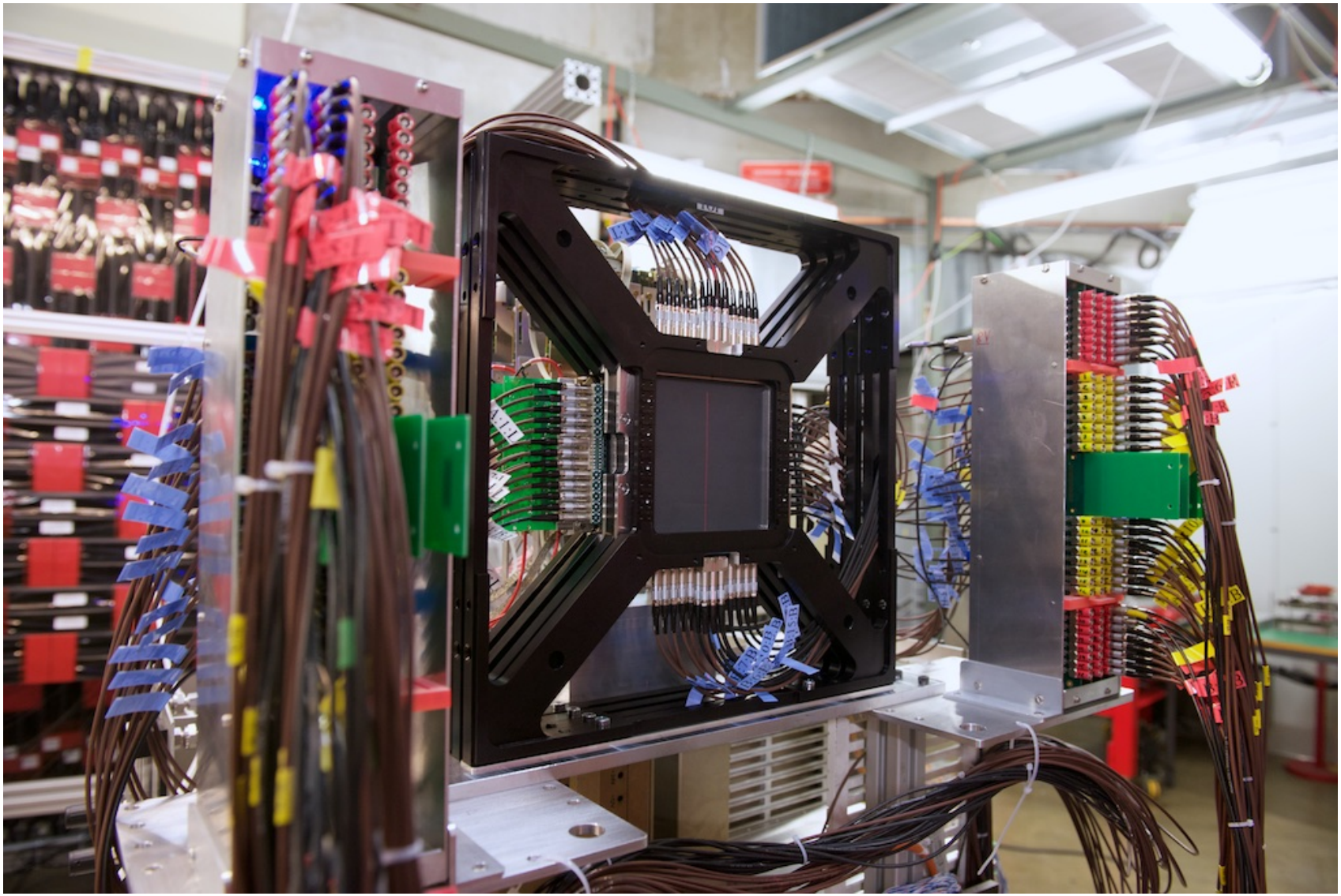


R. Gilman et al., arXiv:1303.2160 (nucl-ex)

- Secondary beam $\Longrightarrow$ track beam particles
- Low flux (5 MHz)$\Longrightarrow$ large acceptance
- Mixed beam $\Longrightarrow$ PID in trigger

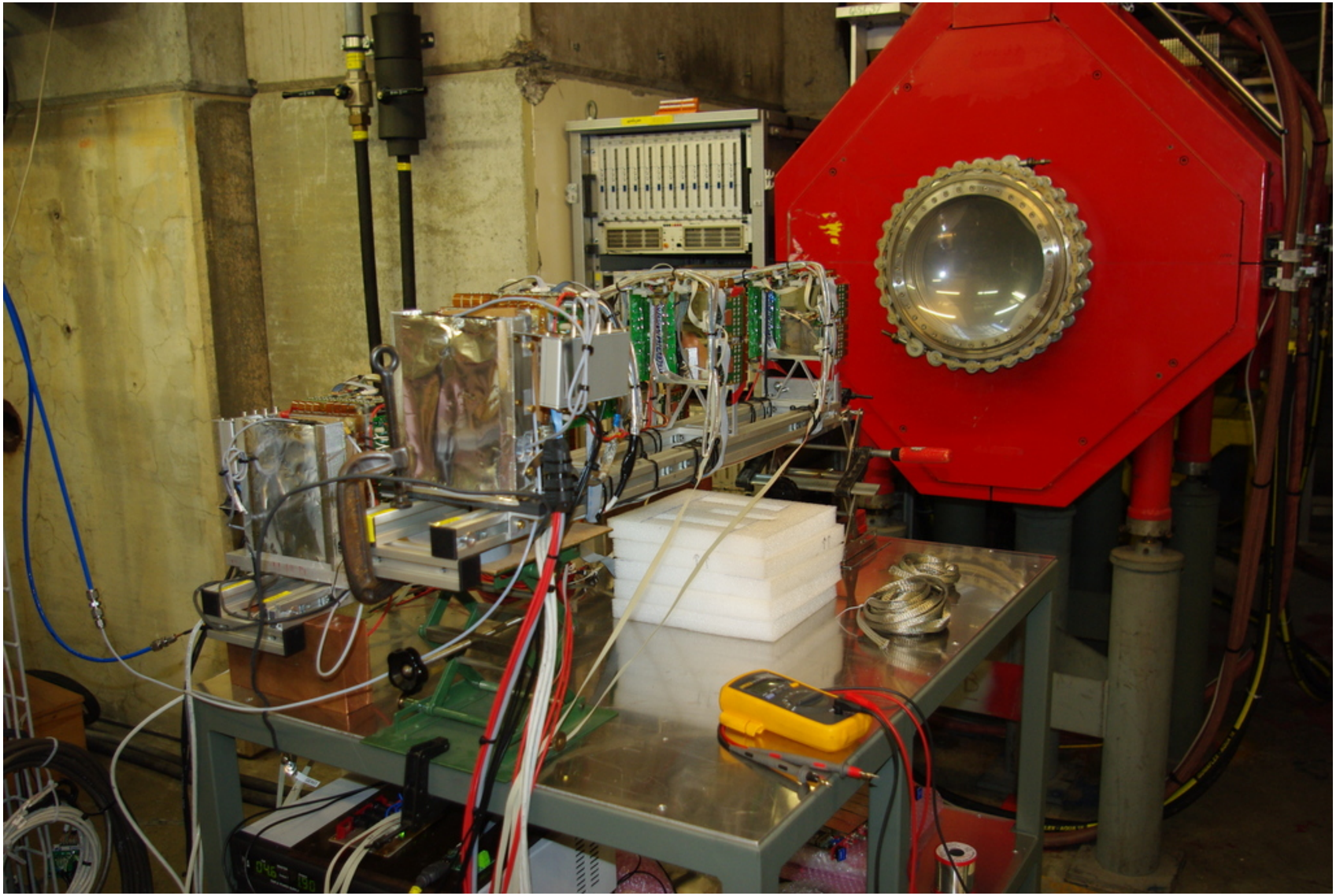
Beam hodoscope (TAU, Rutgers, PSI)

Time resolution 70ps at 99.8% efficiency!



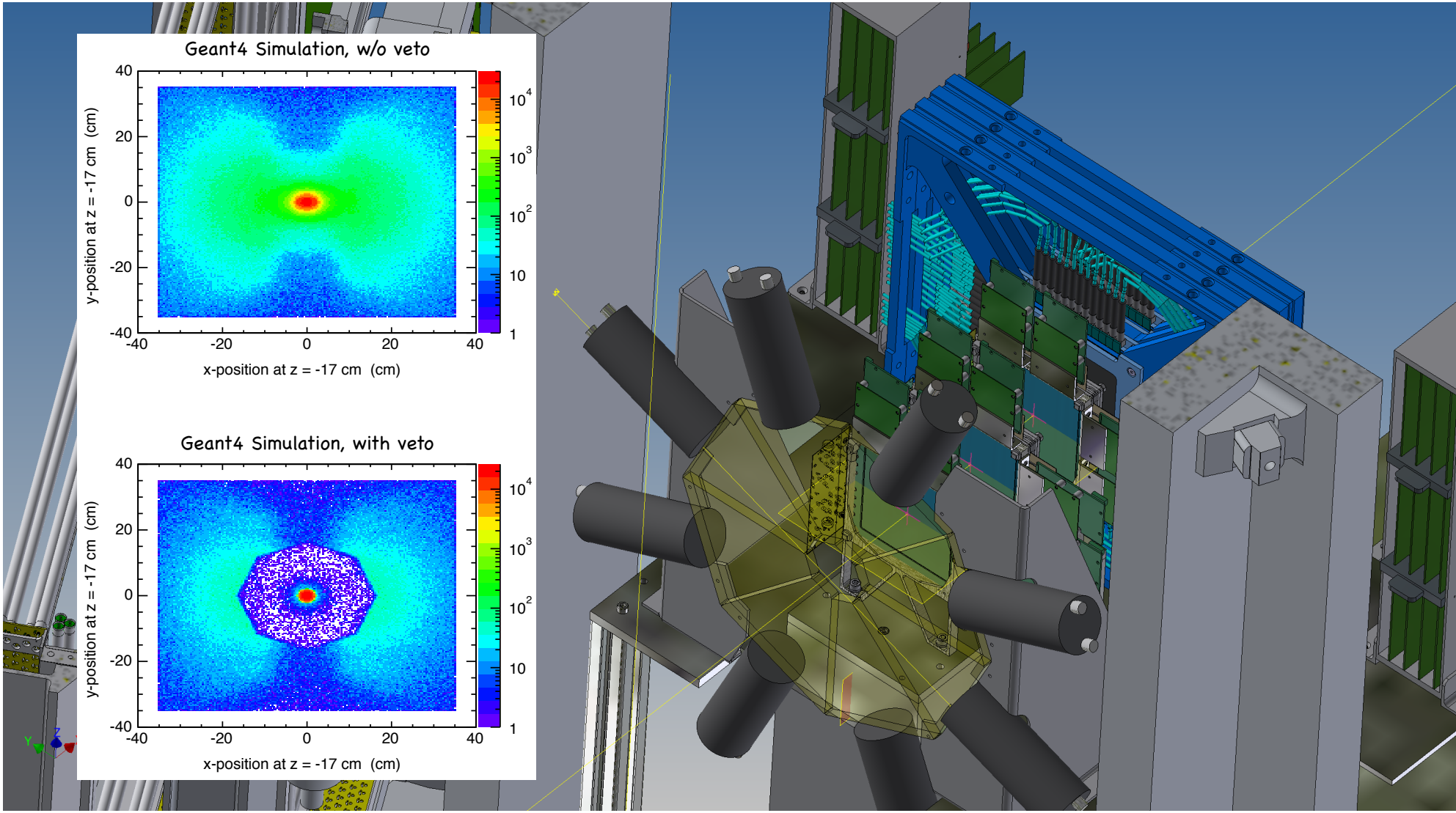
GEM telescope (HU)

Measure incoming trajectory particle by particle



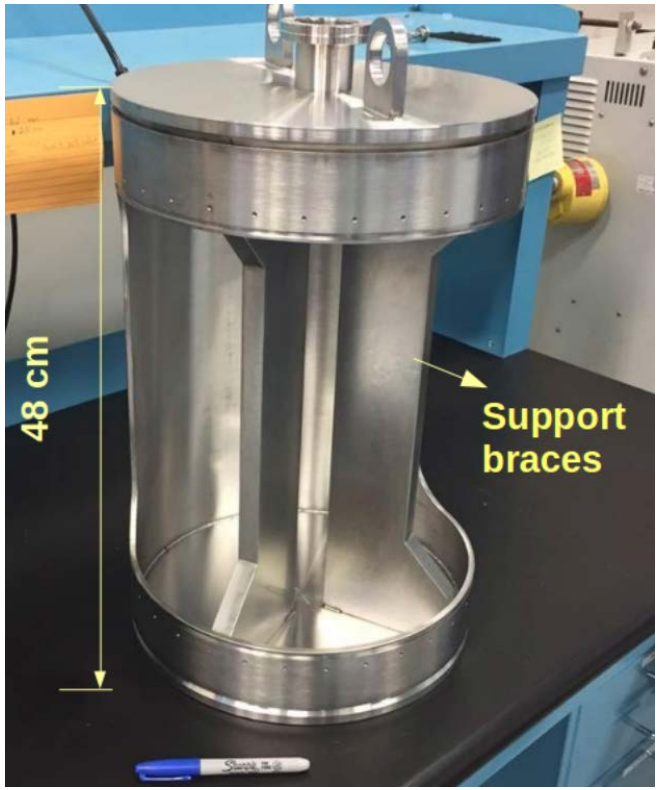
Beam veto detector (USC)

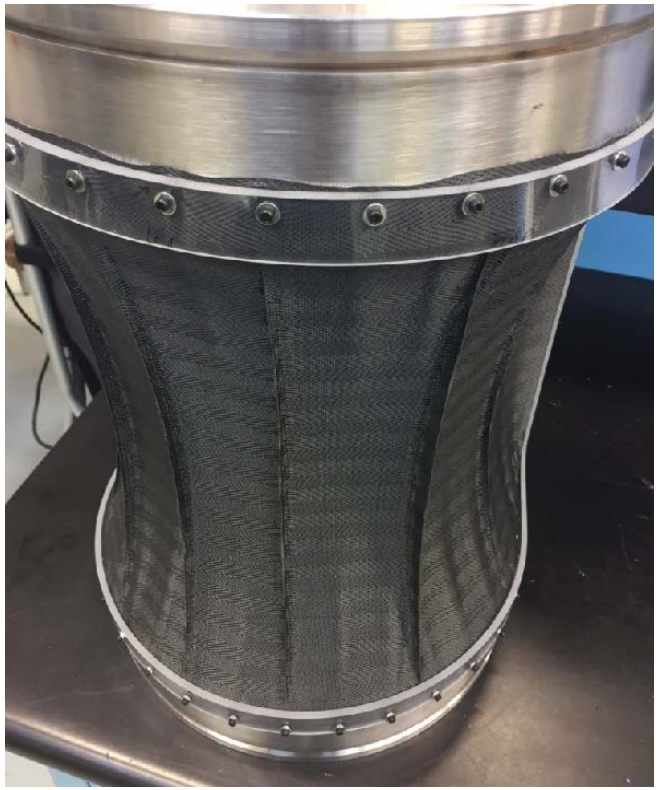
Significantly reduces trigger rate from background events



Target chamber

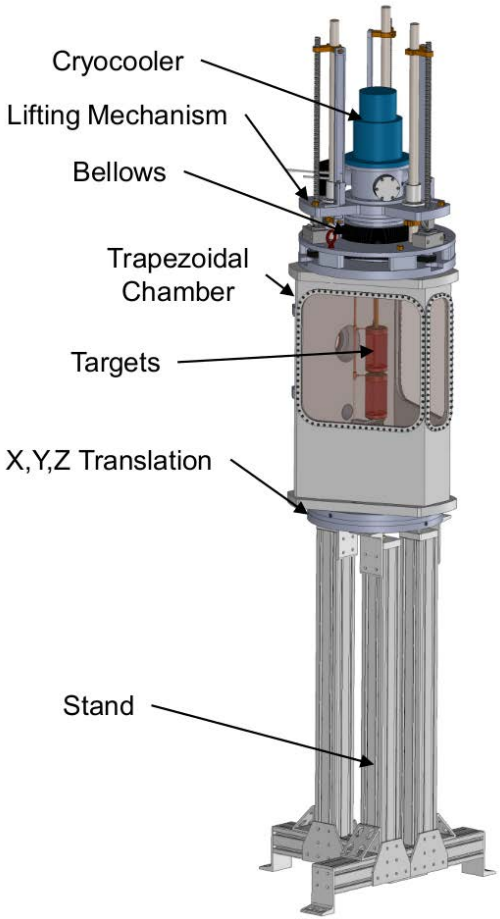
Cylindrical target chamber not possible. Folds.





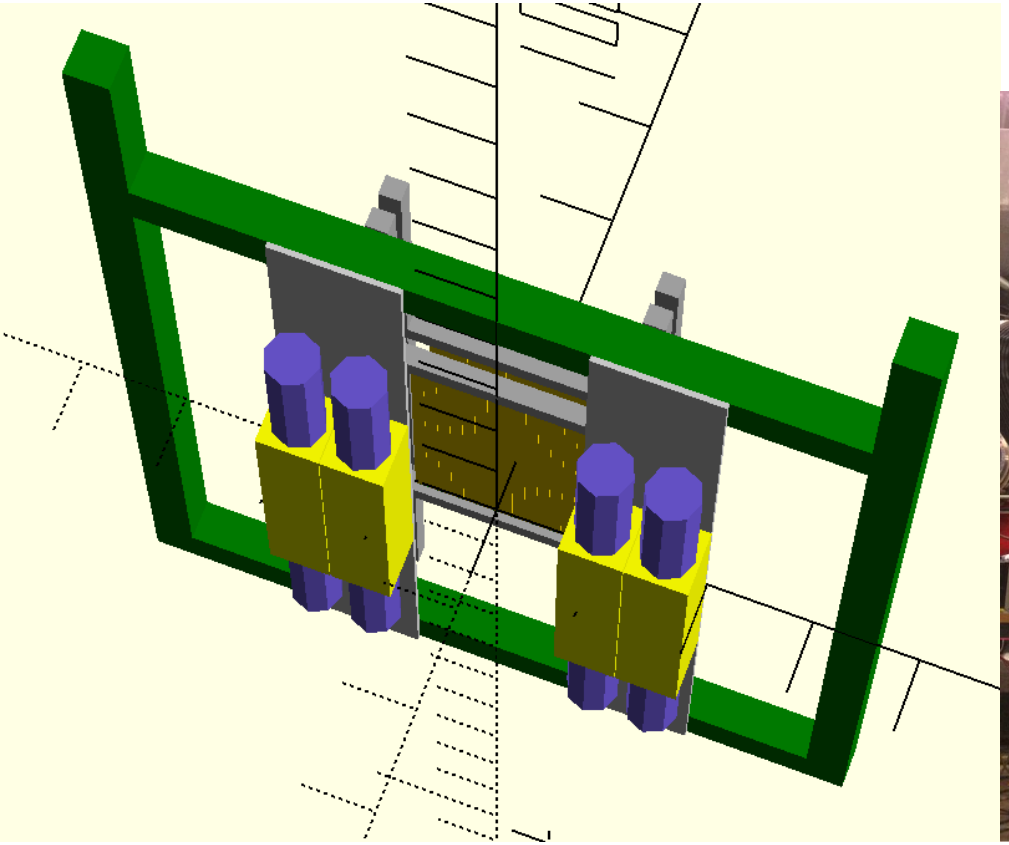
Target

New target design with rectangular windows.

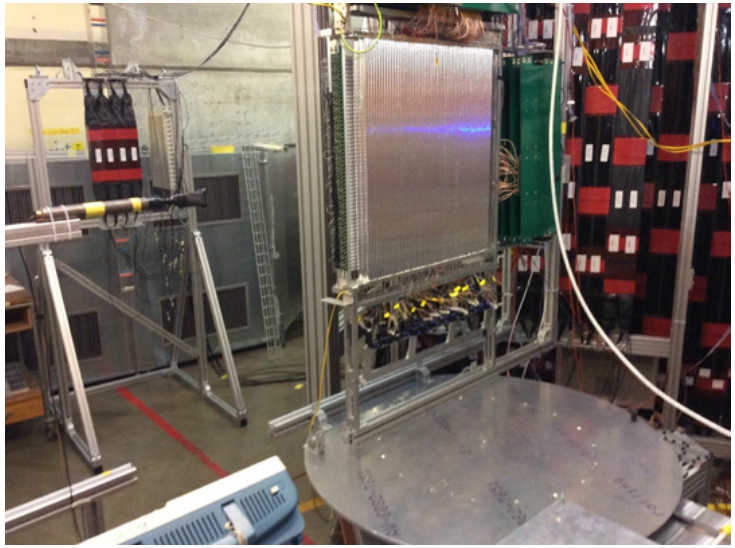


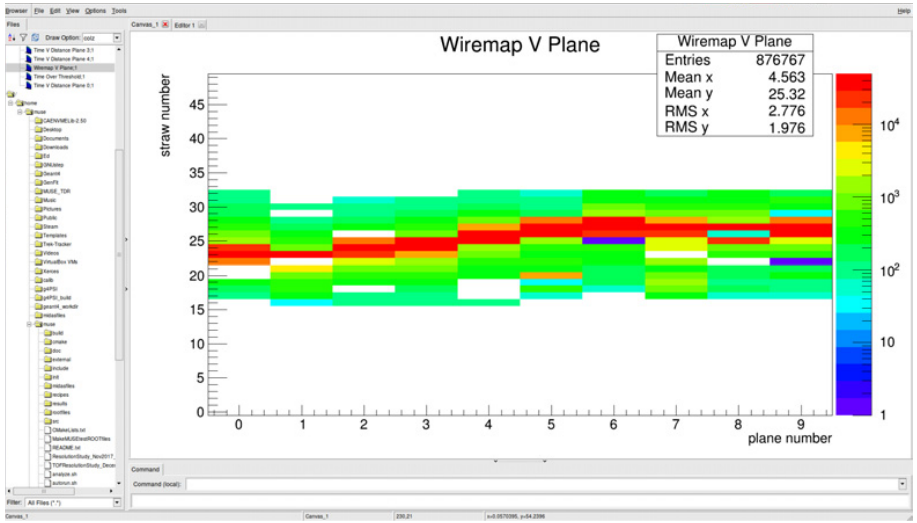
Beam monitor (TAU, Rutgers, USC)

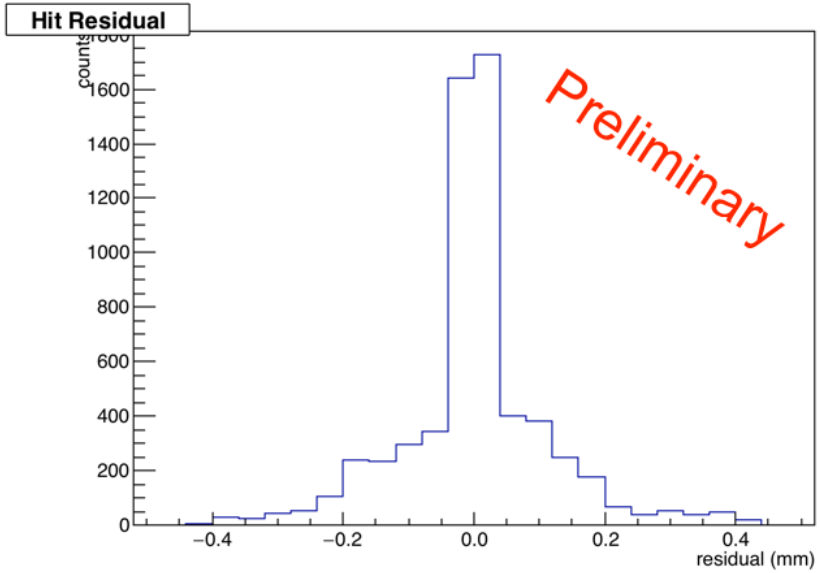
Determination of particle flux downstream of target, Moller/Bhabha veto, ToF

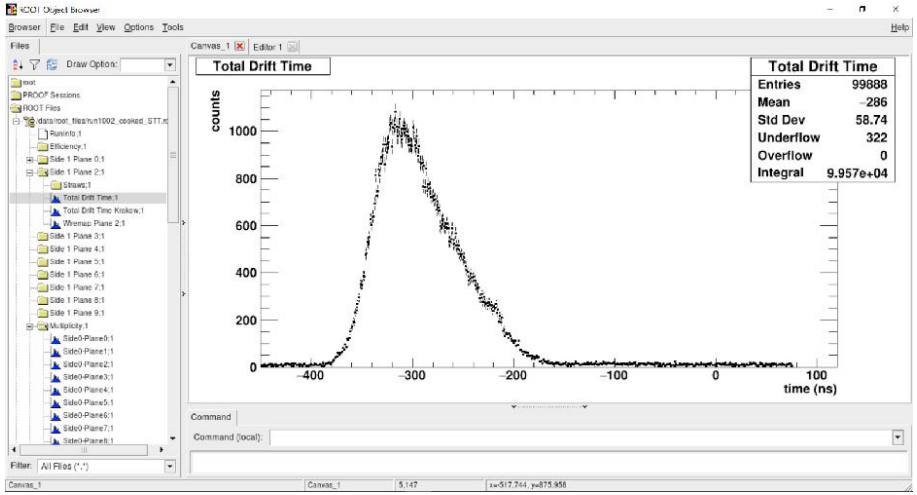


Strawtube tracker STT (HUJI): beam test

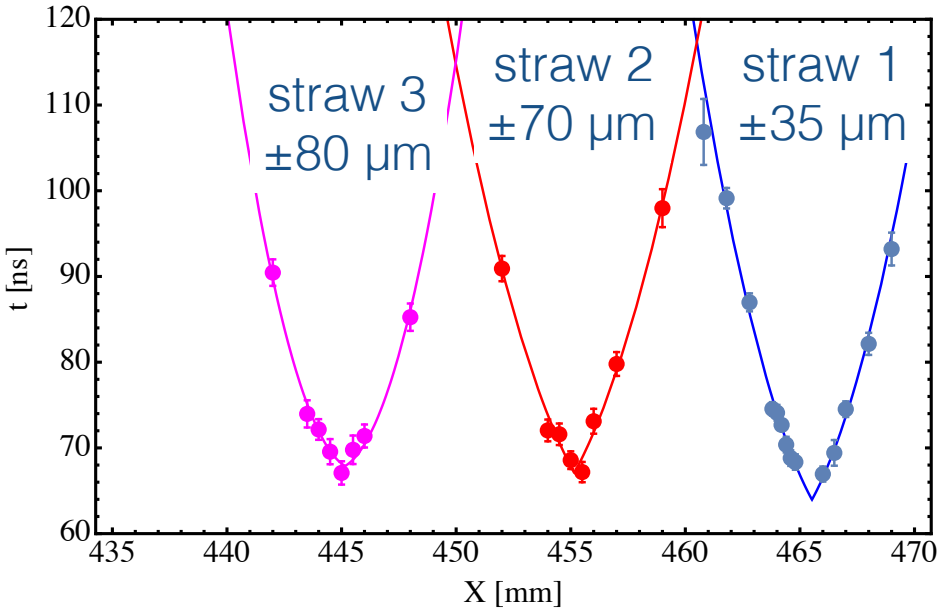




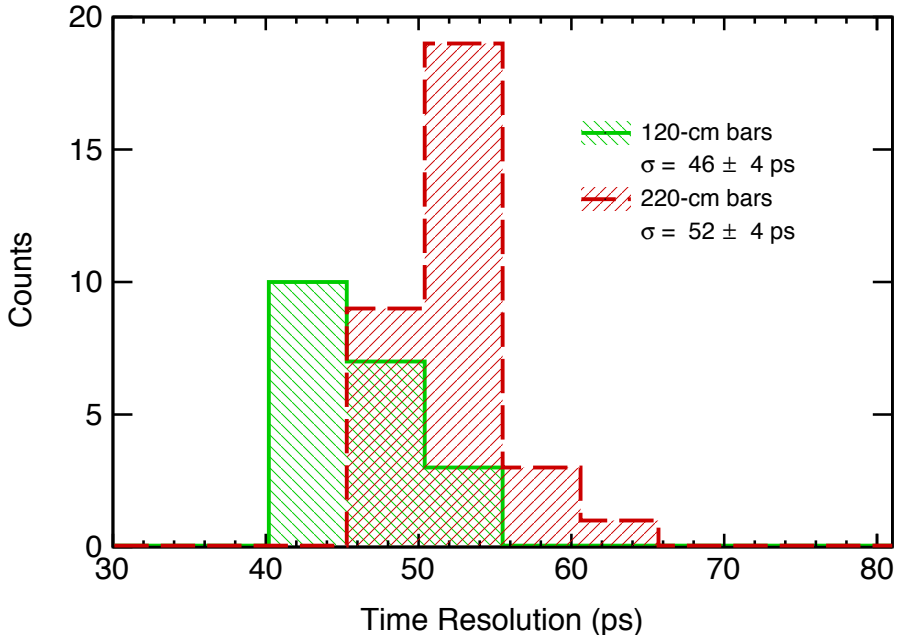




Strawtube tracker: wire calibration



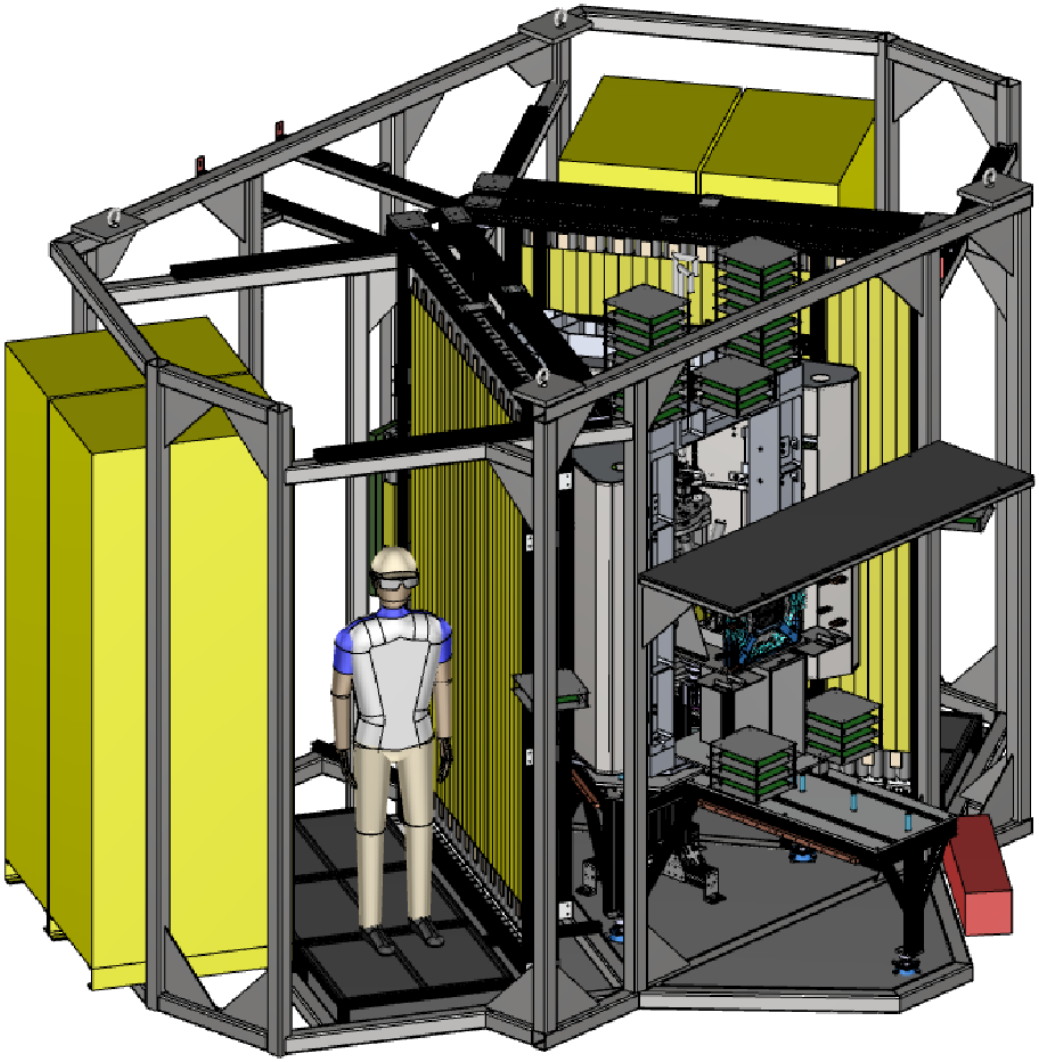
Scattered-particle scintillators SPS (USC)



Better time resolution than design requirement!

Partial setup during last beamtime

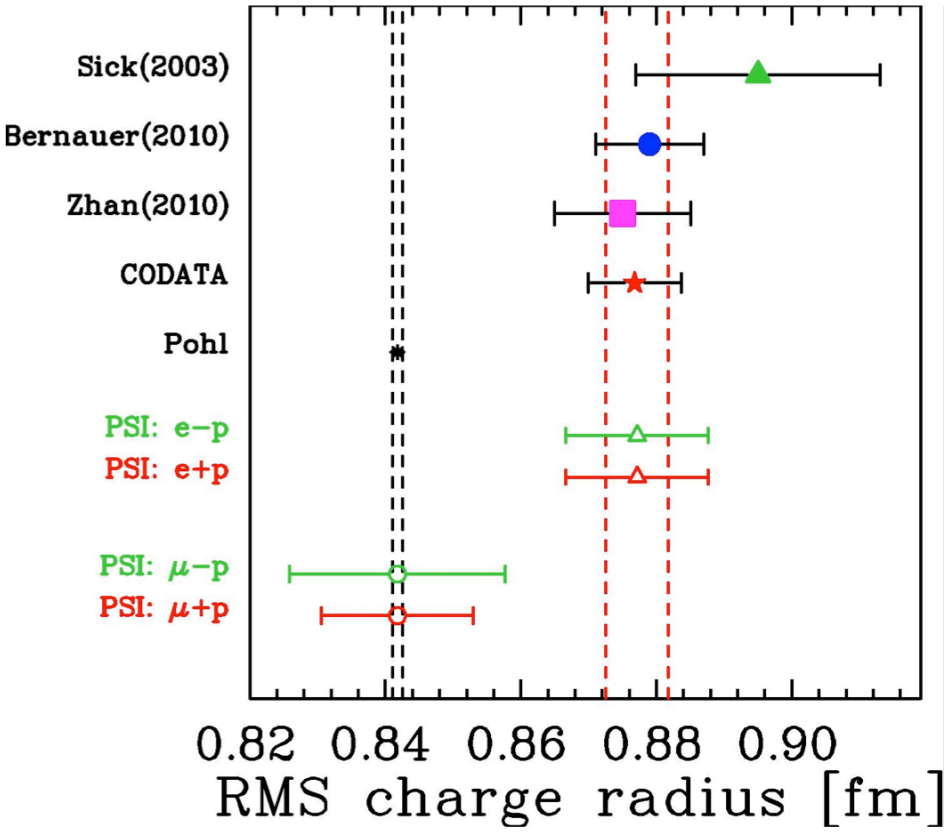
Frame for final installation (Argonne, PSI)



PSI is multi-user facility. Cannot guarantee exclusive use.
Frame makes whole experiment crane-able.

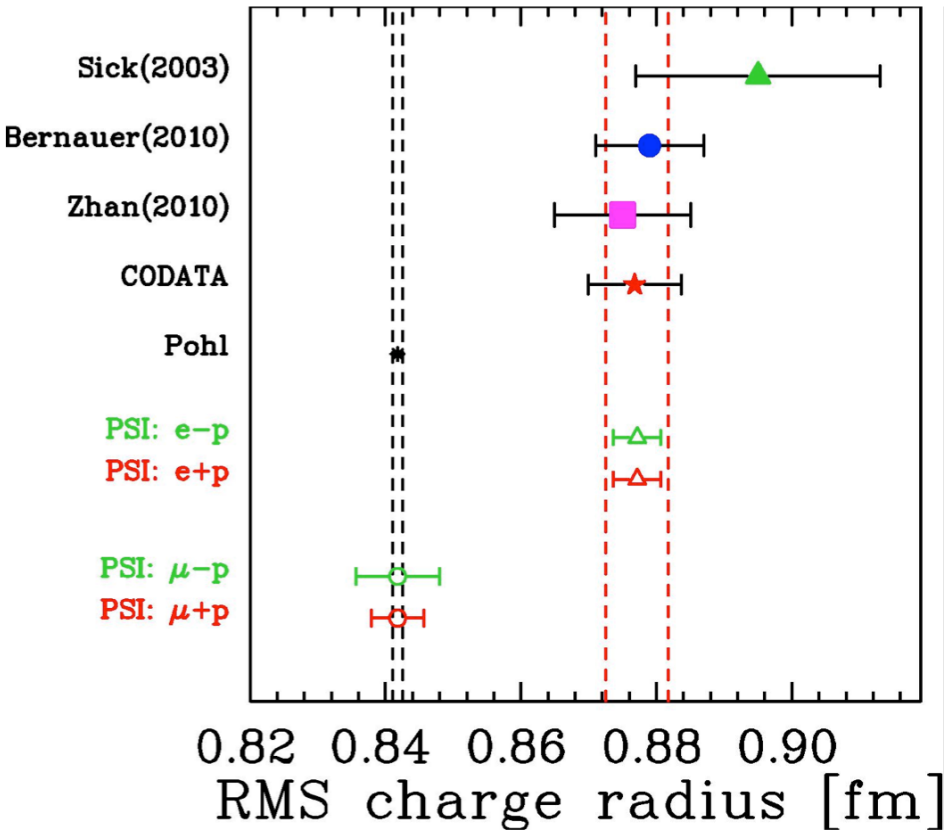
Predicted performance

- Absolute radius extraction uncertainties similar to current exp's.



Predicted performance

- Absolute radius extraction uncertainties similar to current exp's.
- Difference: Common uncertainties cancel!
- $\longrightarrow$ factor two more sensitivity



MUSE can verify 7σ effect with similar significance!

Summary

- Proton puzzle needs new data, also from scattering
- A lot of data incoming in the next years
- Mainz ISR shows radiative tail is well described
- MUSE, with electron and muon scattering, will test
  - existing radius value
  - lepton universality
  - two photon exchange / proton polarizability

The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but "That's funny . . . "

— *Isaac Asimov*