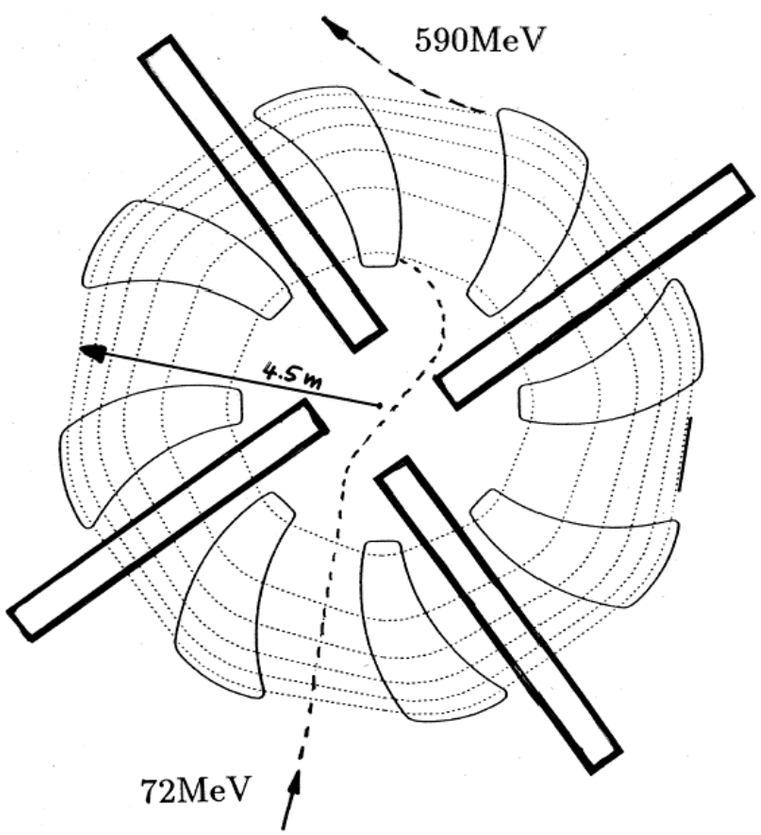
Alexander Golossanov

George Washingon University
& PSI

MUon-proton Scattering Experiment at PSI



workshop on Physics of fundamental Symmetries and Interactions - PSI2019

Paul Scherrer Institute, Switzerland
October 22 2019

μ-p Scattering – The missing Piece

Spectroscopy

Electronic hydrogen

2010 0.8758(77)

. . .

Muonic hydrogen

2010 0.84184(67)

2013 0.84087(39)

. . .

Discrepancies not explained

2018: (released May 20, 2019): 0.8414(19)

2014: 0.8751(61)

2010: 0.8775(51)

CODATA

Electron scattering

2010 0.8790(80)

2017 0.8770(60)

. . .

Scattering

Muon scattering

???

with similar precision

μ-p Scattering ?


Ronald Gilman


Michael Kohl


Gerry Miller


Zein-Eddine Meziani

Good idea !

How about μ and e scattering
… in the same experiment
μ+ e- μ- and e+ ?

cross sections

radii

form factors

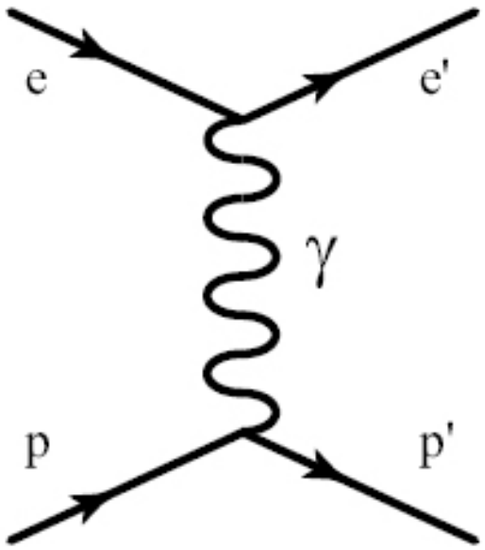
two photon exchange

charged lepton universality

Measure cross sections, form factors, and radius

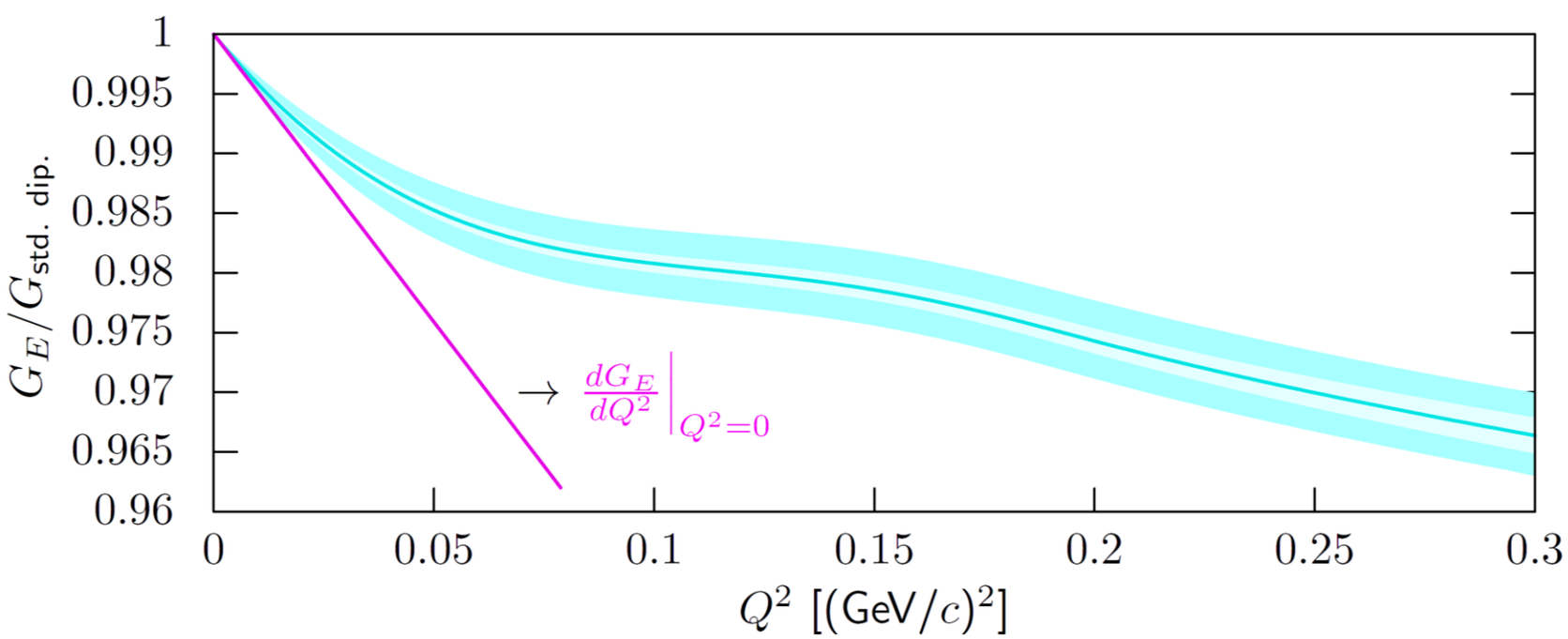
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left[G_E^2 + \frac{\tau}{\epsilon} G_M^2\right] \frac{1}{(1+\tau)}$$

$$\epsilon = [1 + 2(1+\tau)\tan^2 \tfrac{\theta_e}{2}]^{-1} \qquad \tau = \frac{Q^2}{4M^2}$$



$$\tau \propto Q^2 \qquad Q^2 \to 0 \implies \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_M \propto G_E^2$$

$$r_p \equiv \left(-6 \left.\frac{dG_E(Q^2)}{dQ^2}\right|_{Q^2=0}\right)^{1/2}$$



This definition is consistent with radius extracted from spectroscopy data

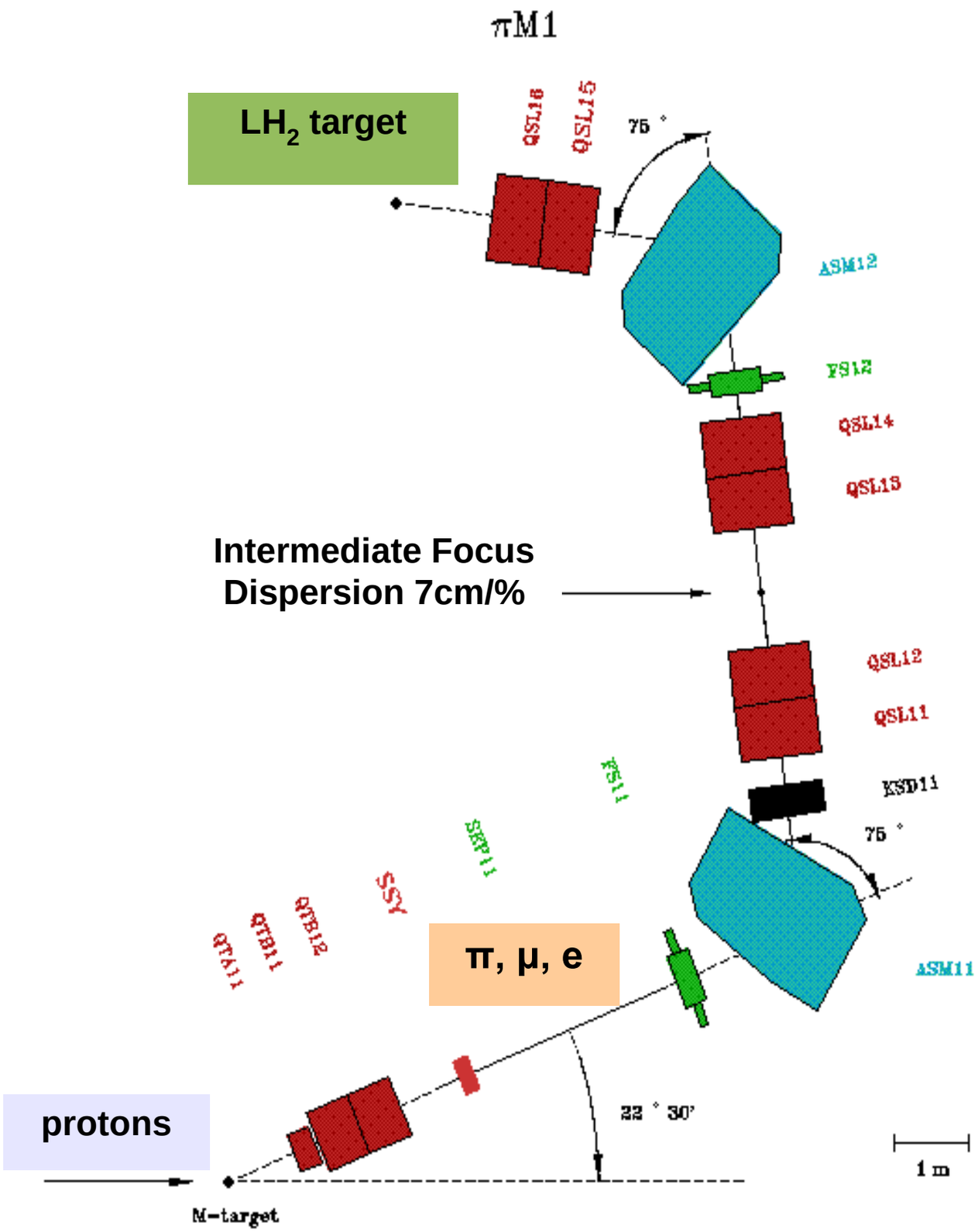
Gerald A. Miller, Phys. Rev. C 99 (2019) 035202.

Where to find beam with muons and electrons

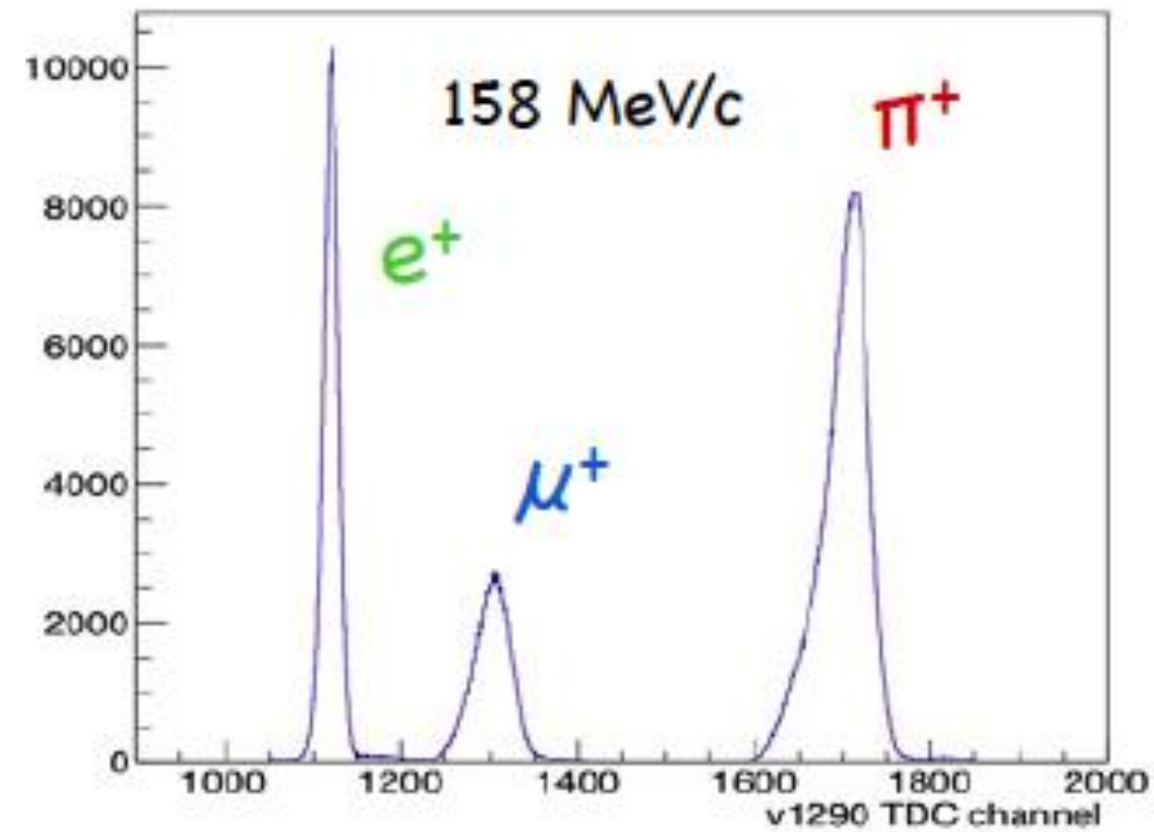
- Sep 2011: original idea
- 2012 - 2014: MUSE proposal, R&D funding from NSF & DOE, PSI physics approval
- Sep 15th 2016: full construction funding from NSF
- 2017: start building MUSE, beam tests, reviews
- 2018-2019: assembly, commissioning, beam tests, start taking production data

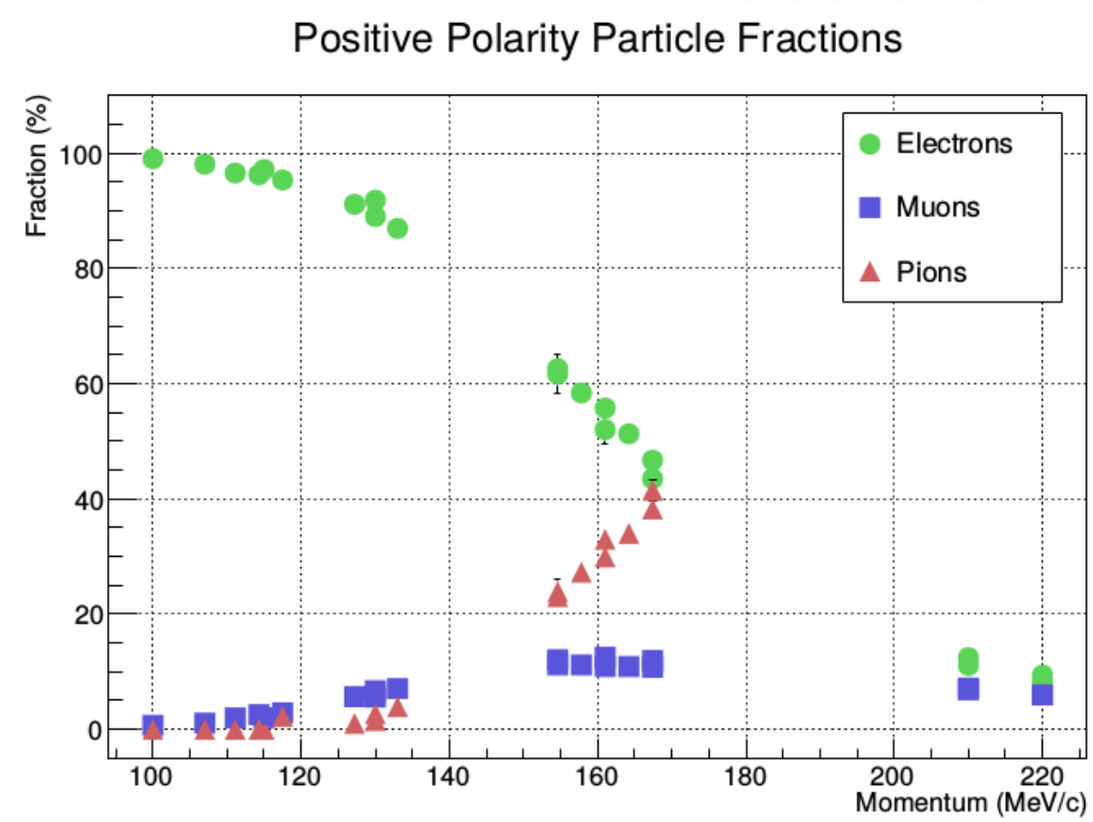
Paul Scherrer Institute

πM1 / MUSE beamline



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





MUSE setup

Non-magnetic spectrometer

Secondary beam

Liquid hydrogen target

Beam p = 115, 153, 210 MeV/c

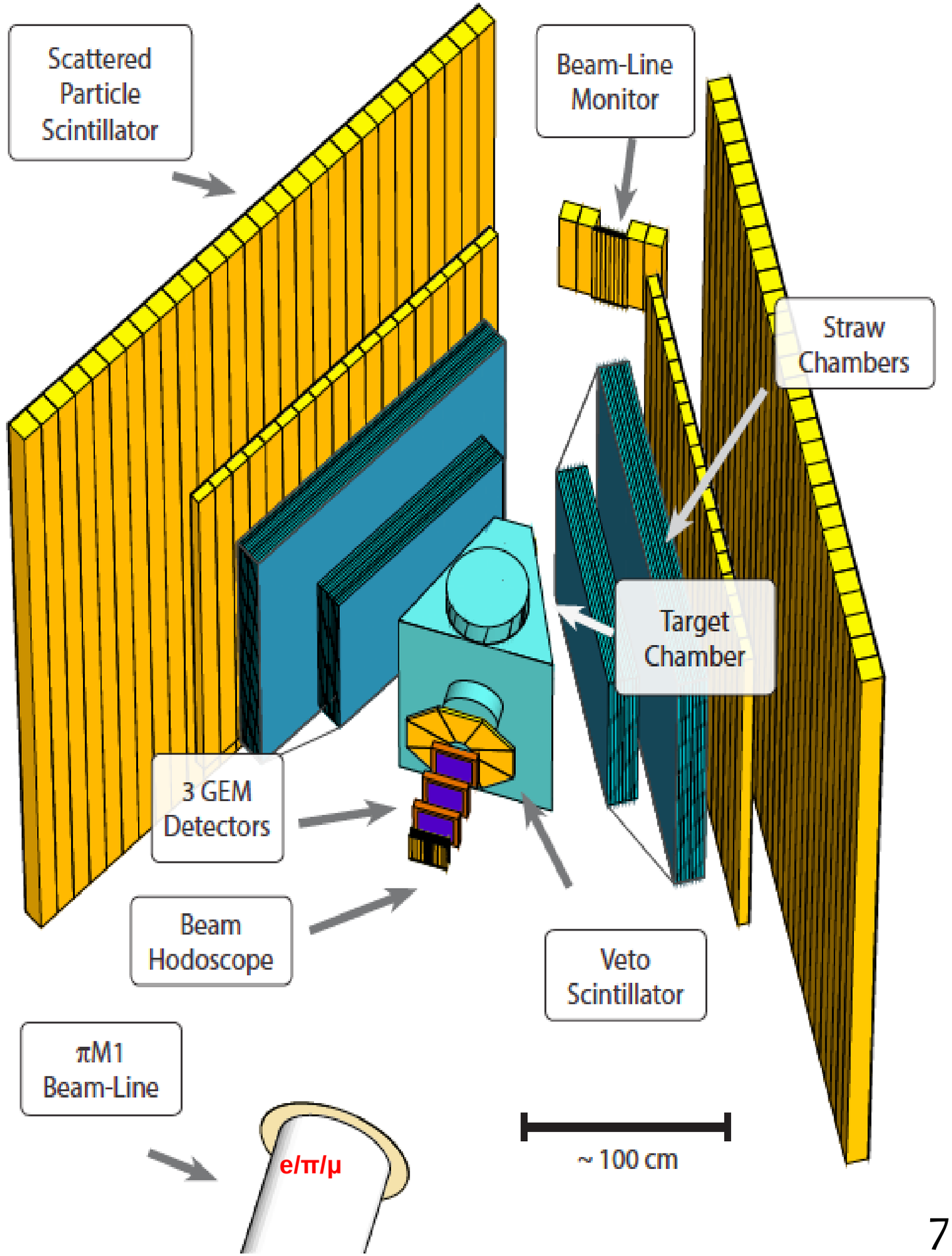
$\theta = 20° - 100°$

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

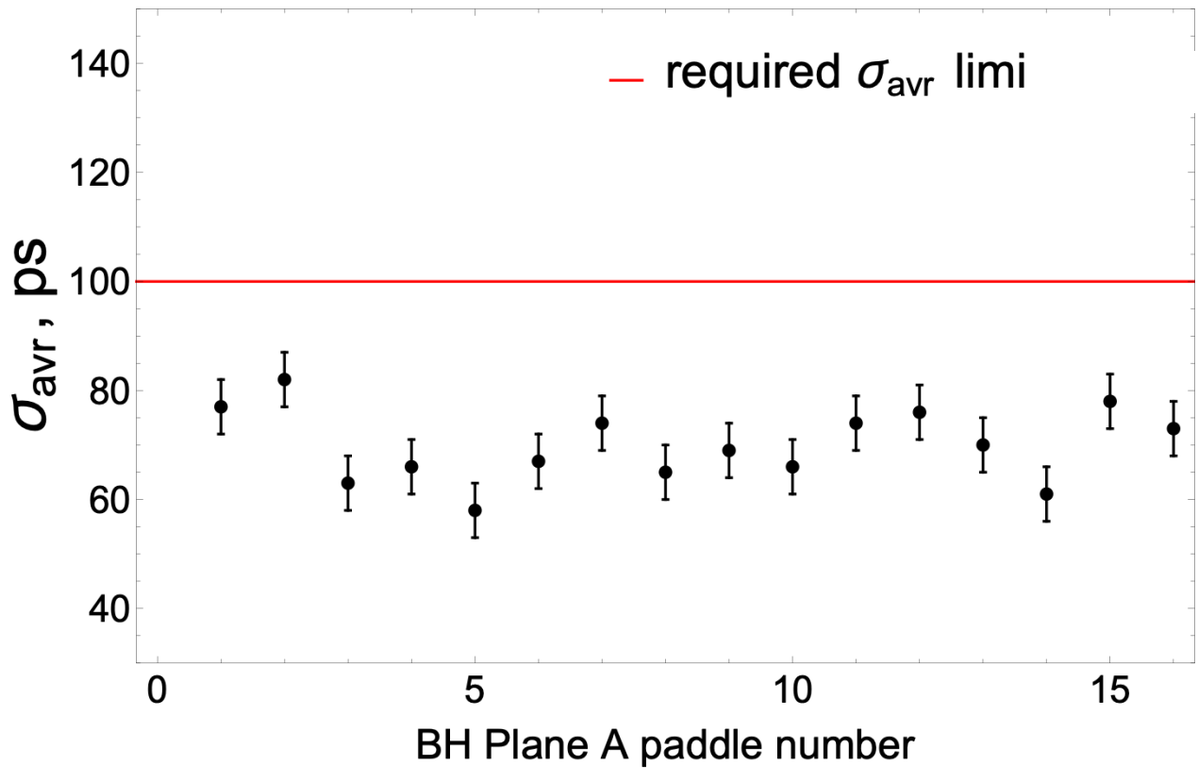
$\varepsilon = 0.256 - 0.94$

Particle ID and trajectory determined event by event

Momentum distribution determined by calibration

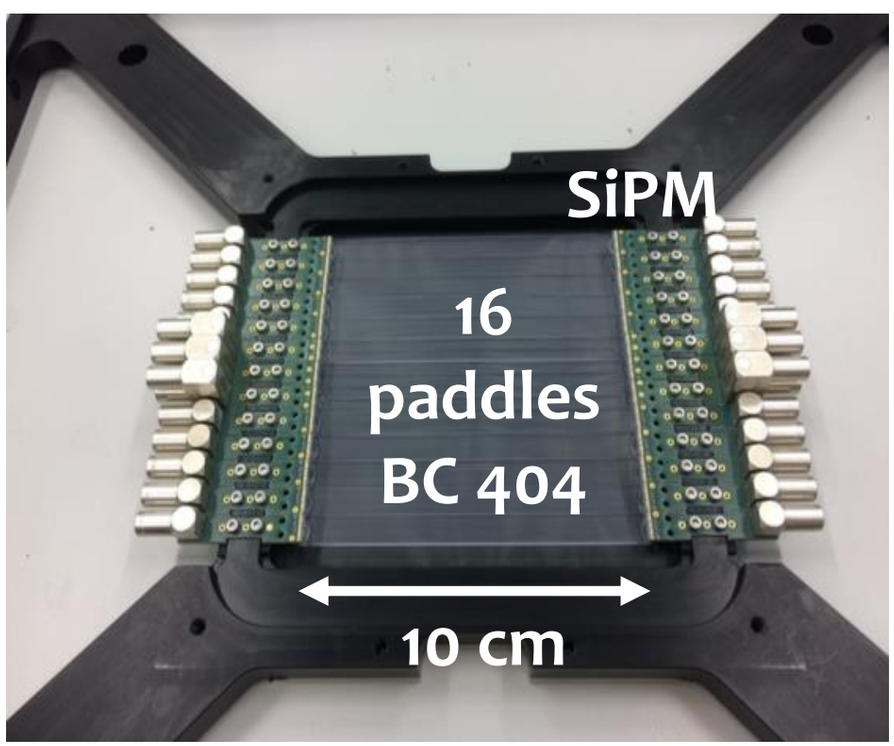


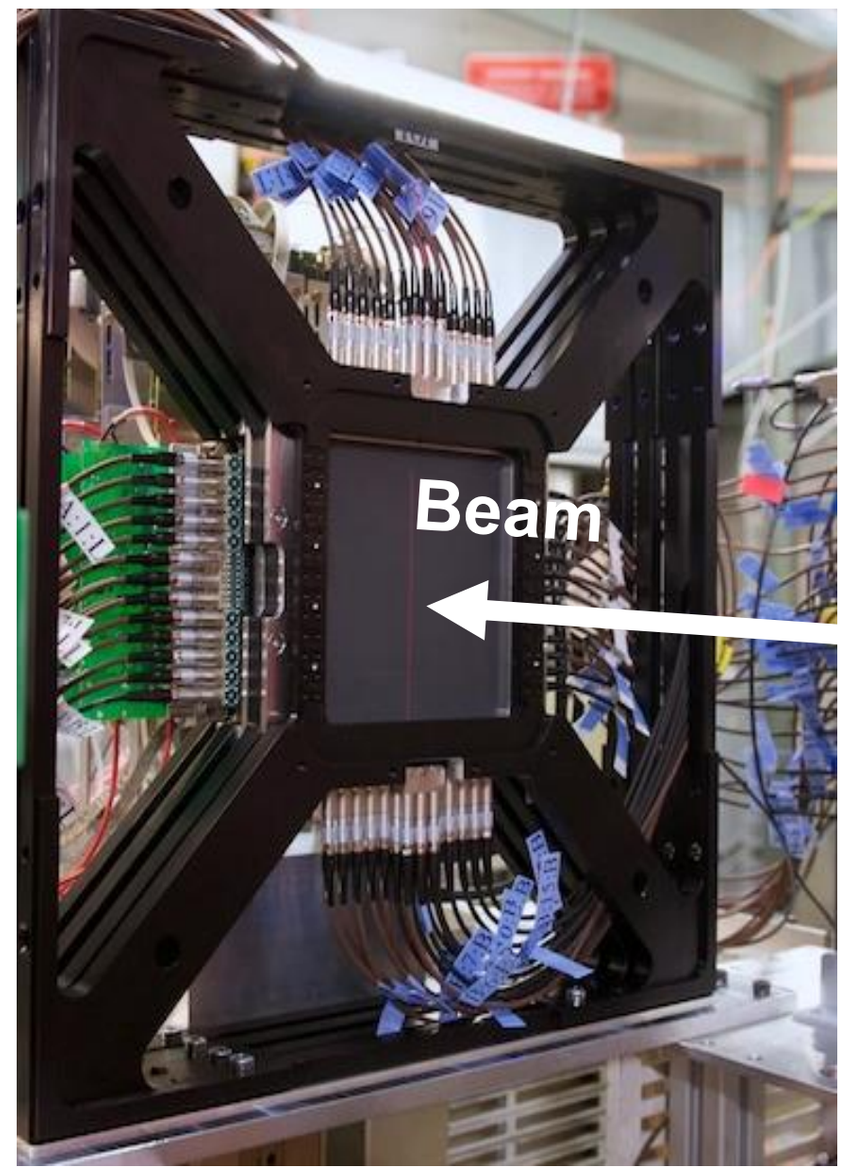
Beam Hodoscope



Counts and times incoming beam particles

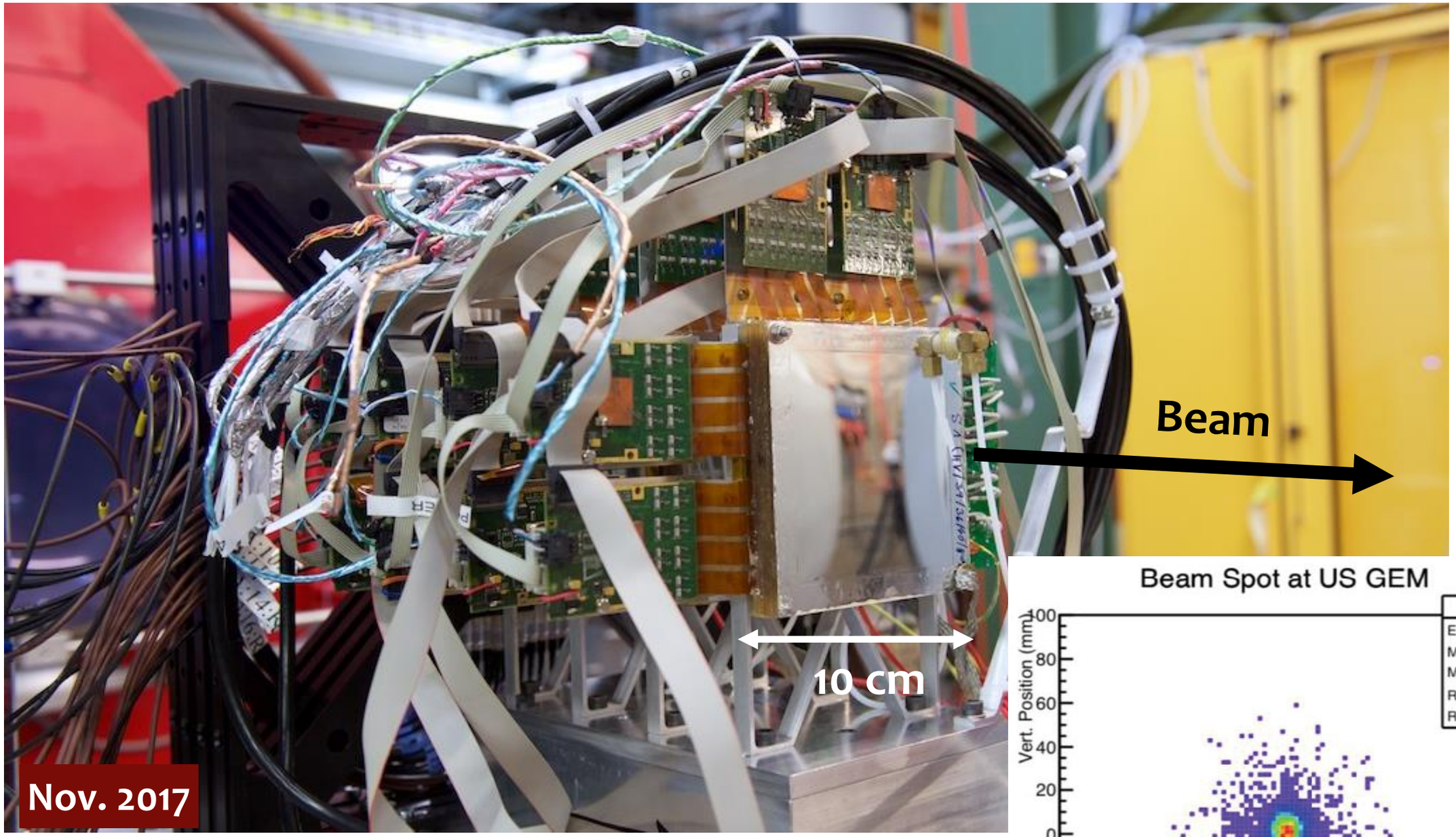
Achieved 80 ps time resolution and 99.8% efficiency.

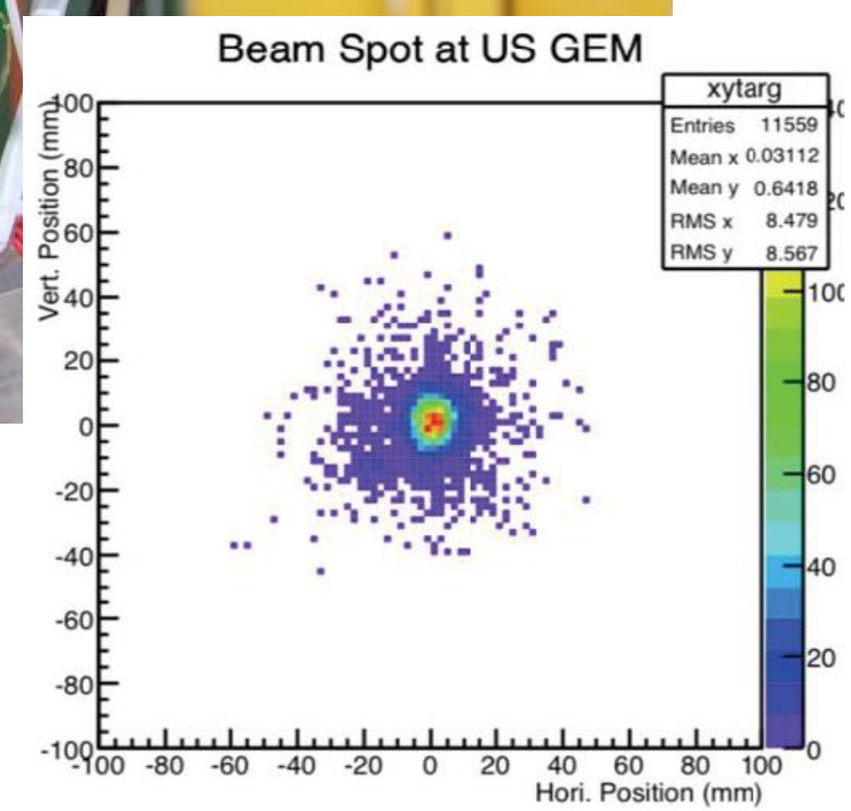




Observed slight activation from ^{11}C production, when beam turns off

GEM Telescope



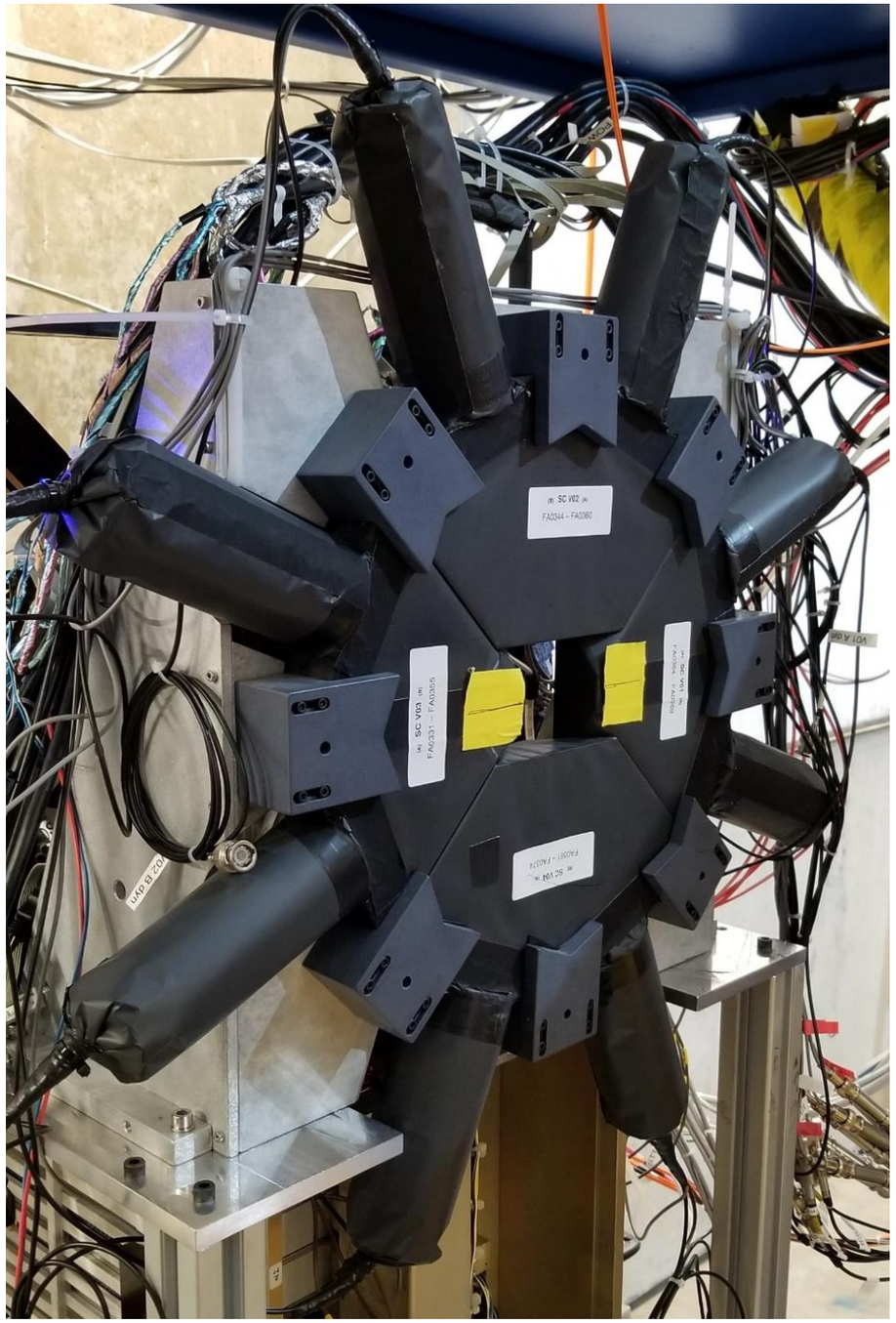


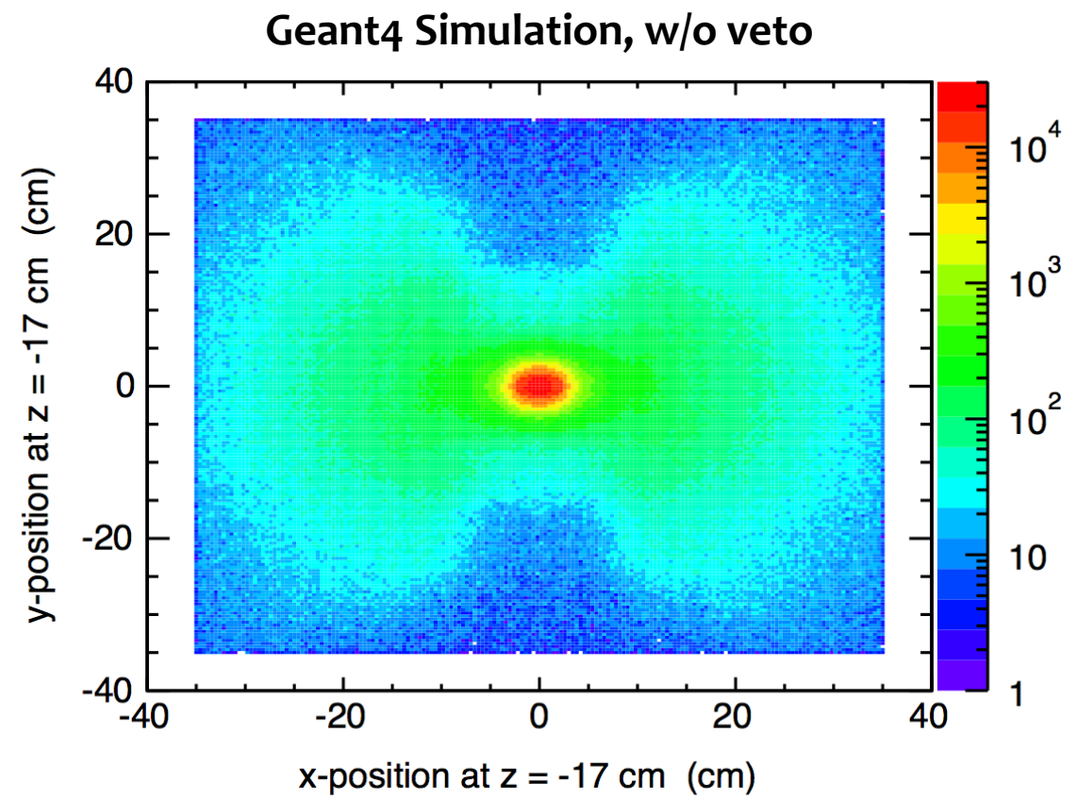
Measures incoming trajectories

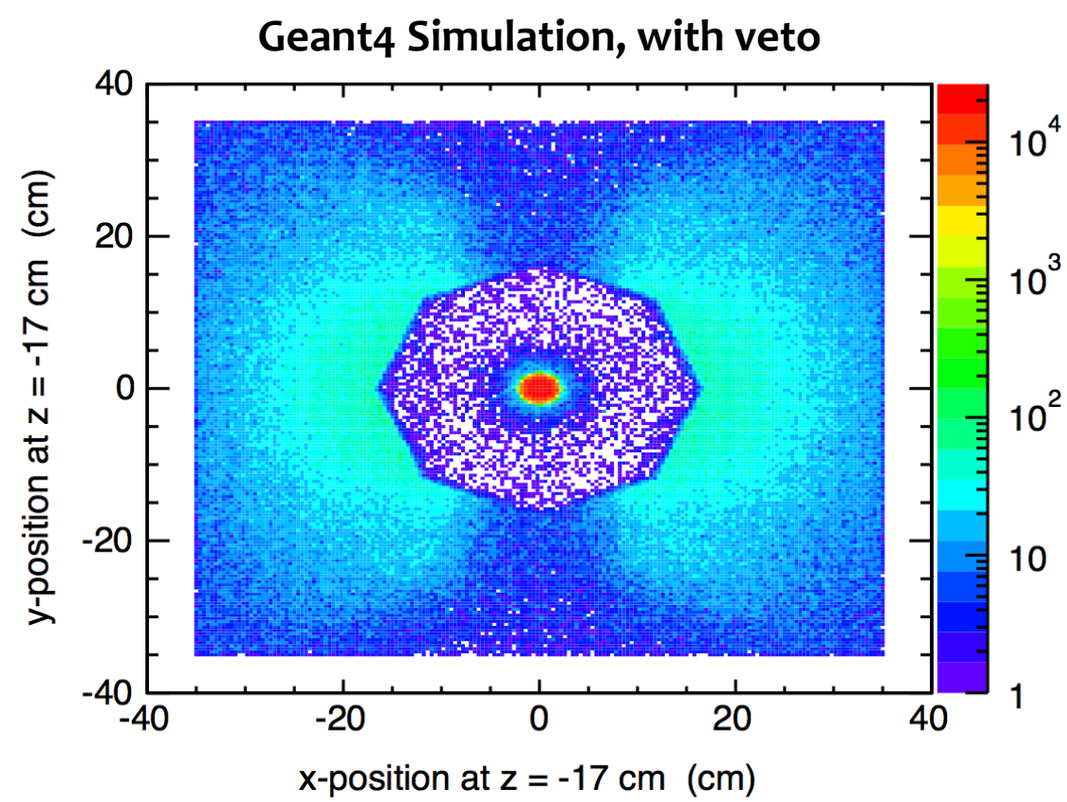
Achieved position resolution of 70 μm

Beam Veto

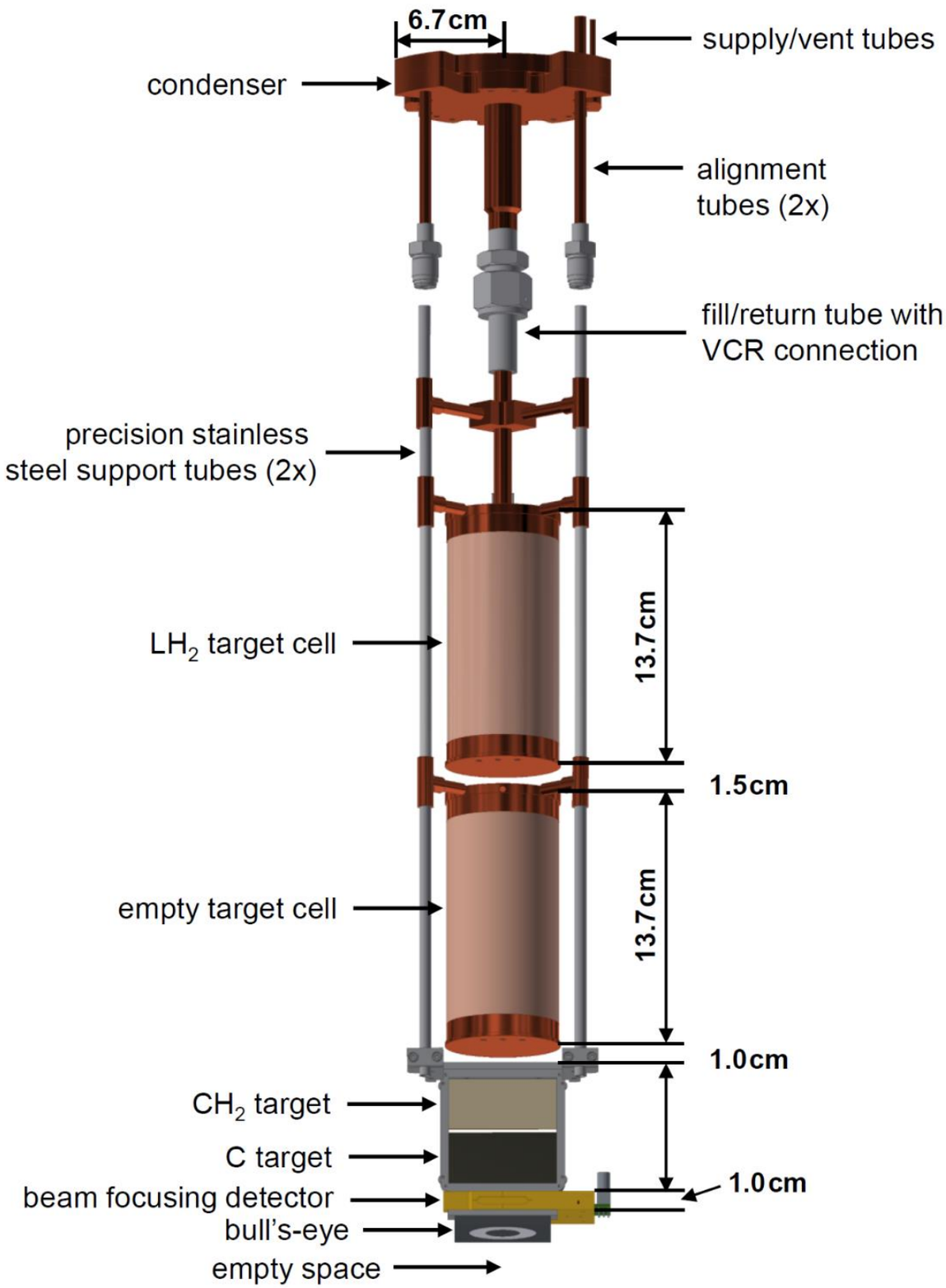
reduces trigger rate from background events



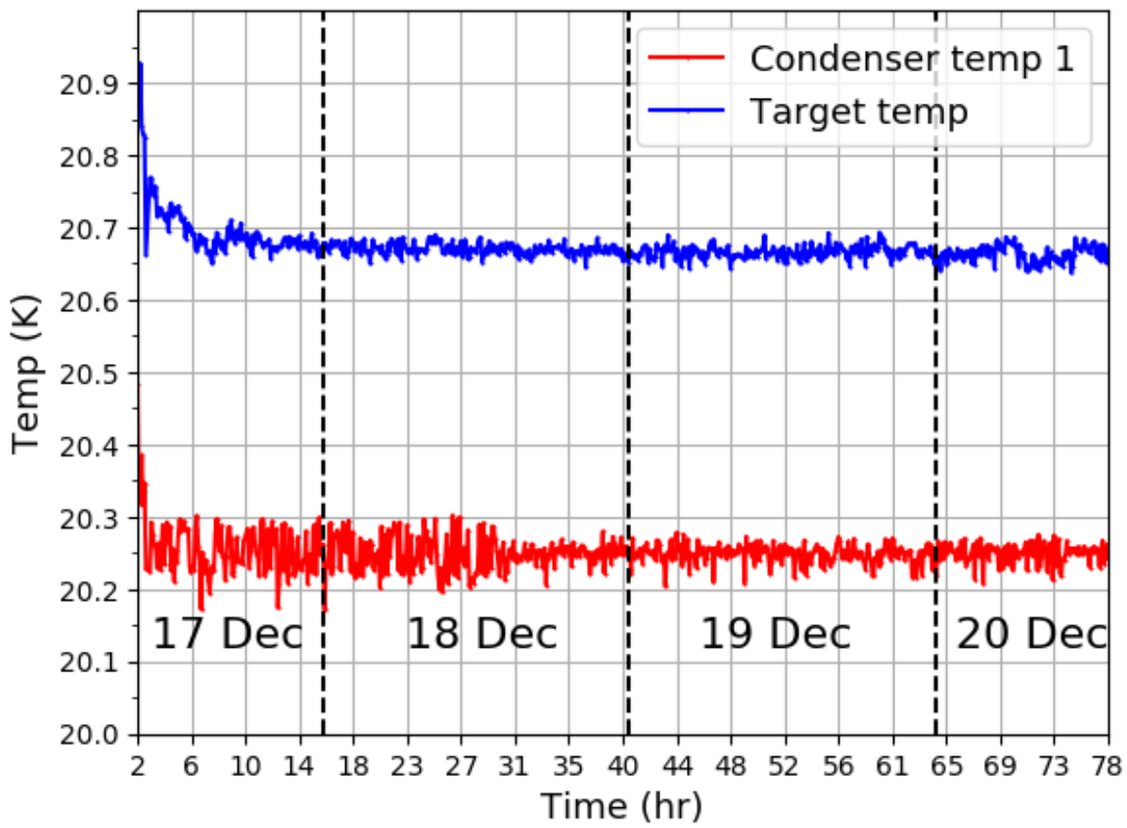




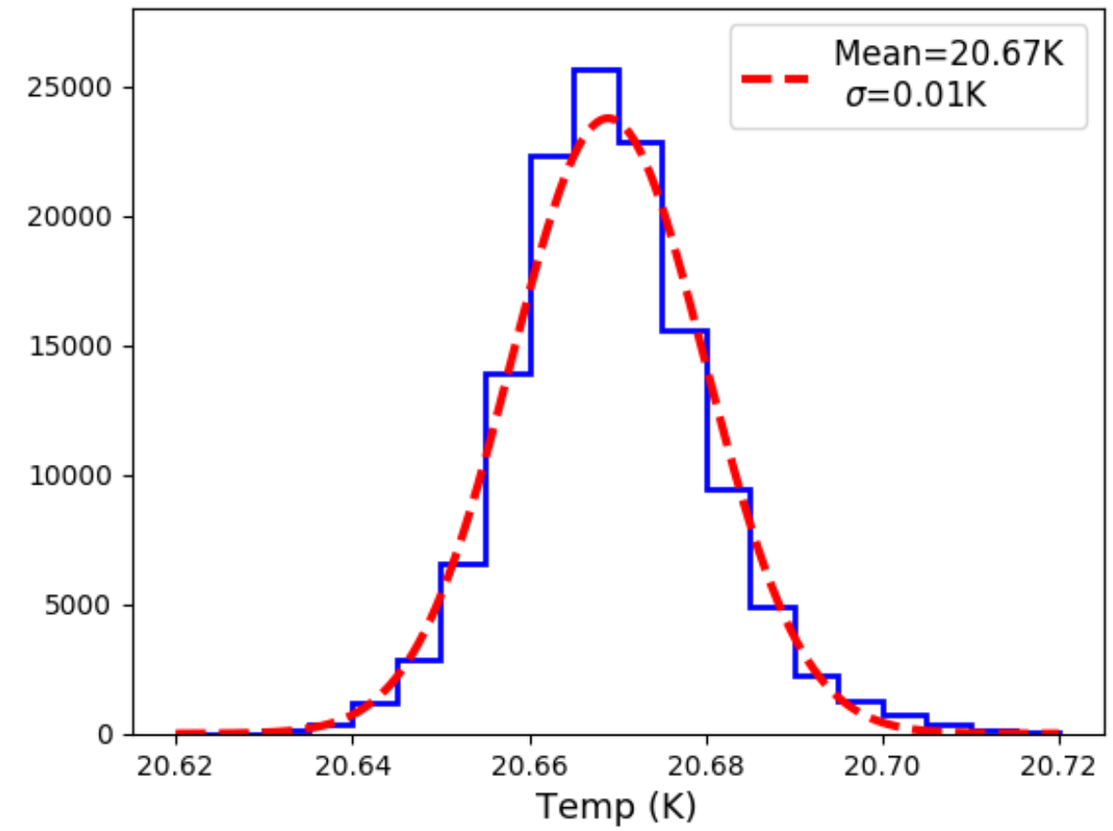
Liquid Hydrogen Target



Stable cryo-target operation



72 hr period



Temperature 20.67 ± 0.01 K

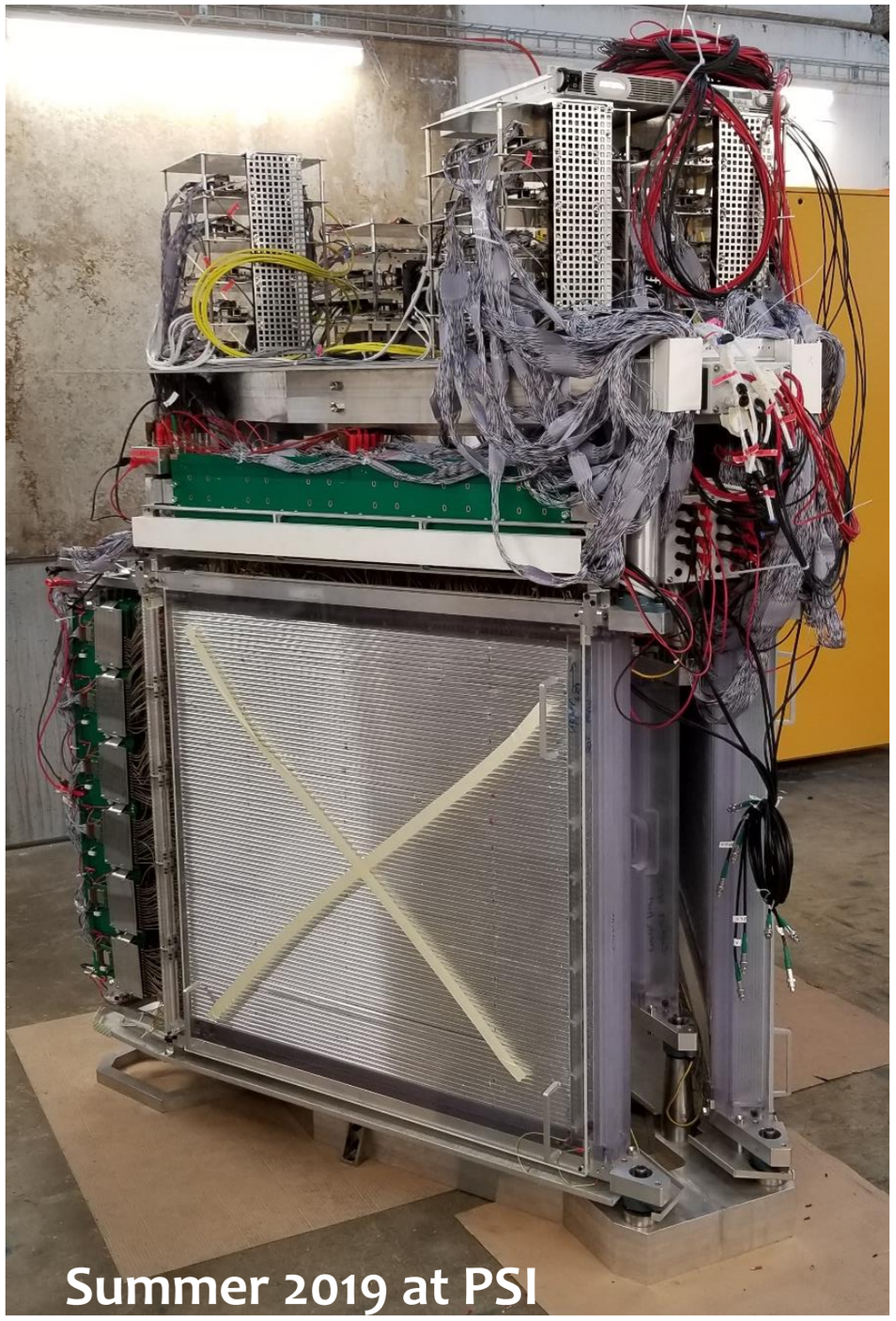
- **pressure of ~1.1 bar**

beam does not affect temperature

Density 70 mg/cm³ (stable to 0.02%)

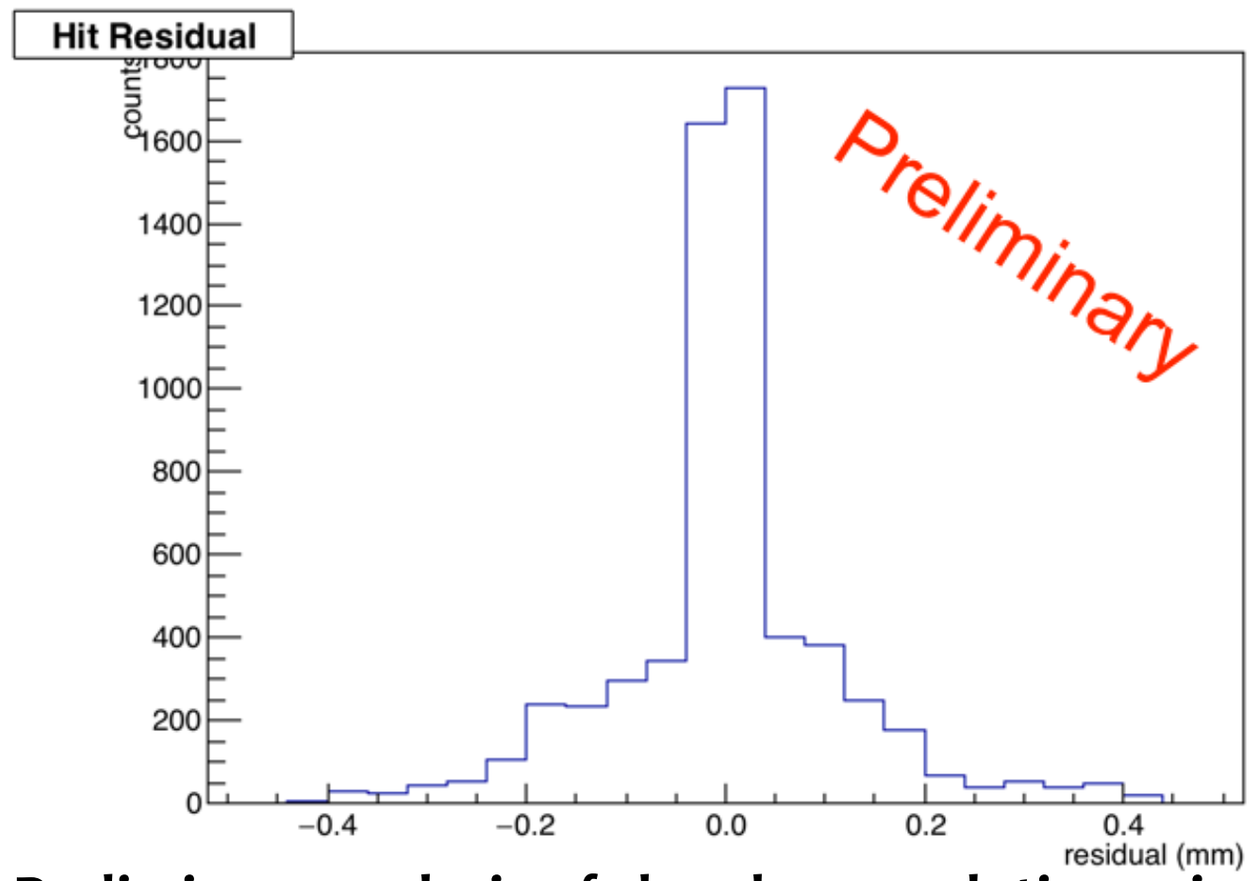
- **once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached**

Straw-Tube Tracker



tracks particles scattered from target with high resolution and high efficiency

consists of four chambers with 5 vertical and 5 horizontal planes each (2864 straws total)



Preliminary analysis of chamber resolution using a small calibration dataset shows position resolution of approximately 120 μm

Beam Monitor

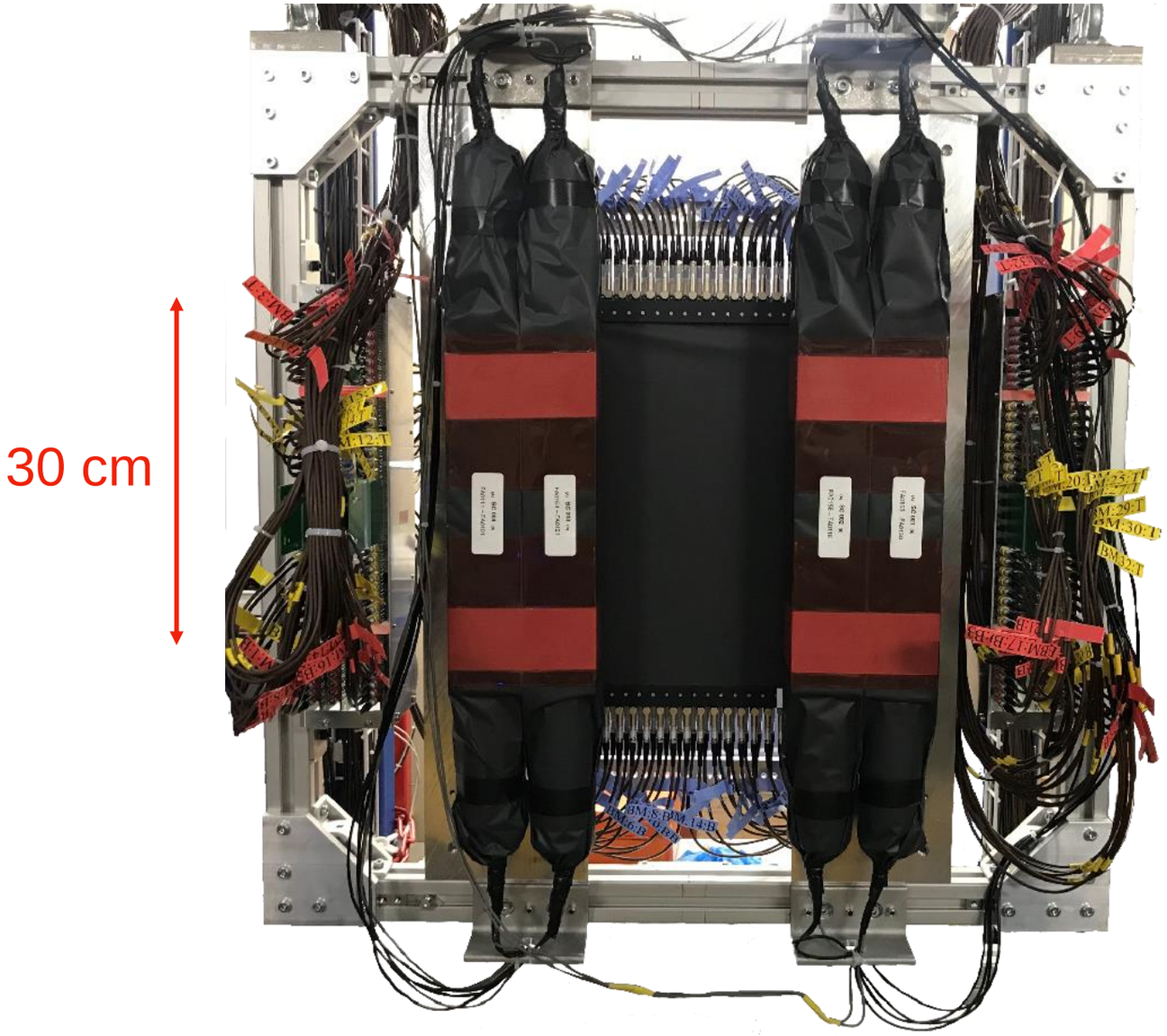
counts and times outgoing beam particles

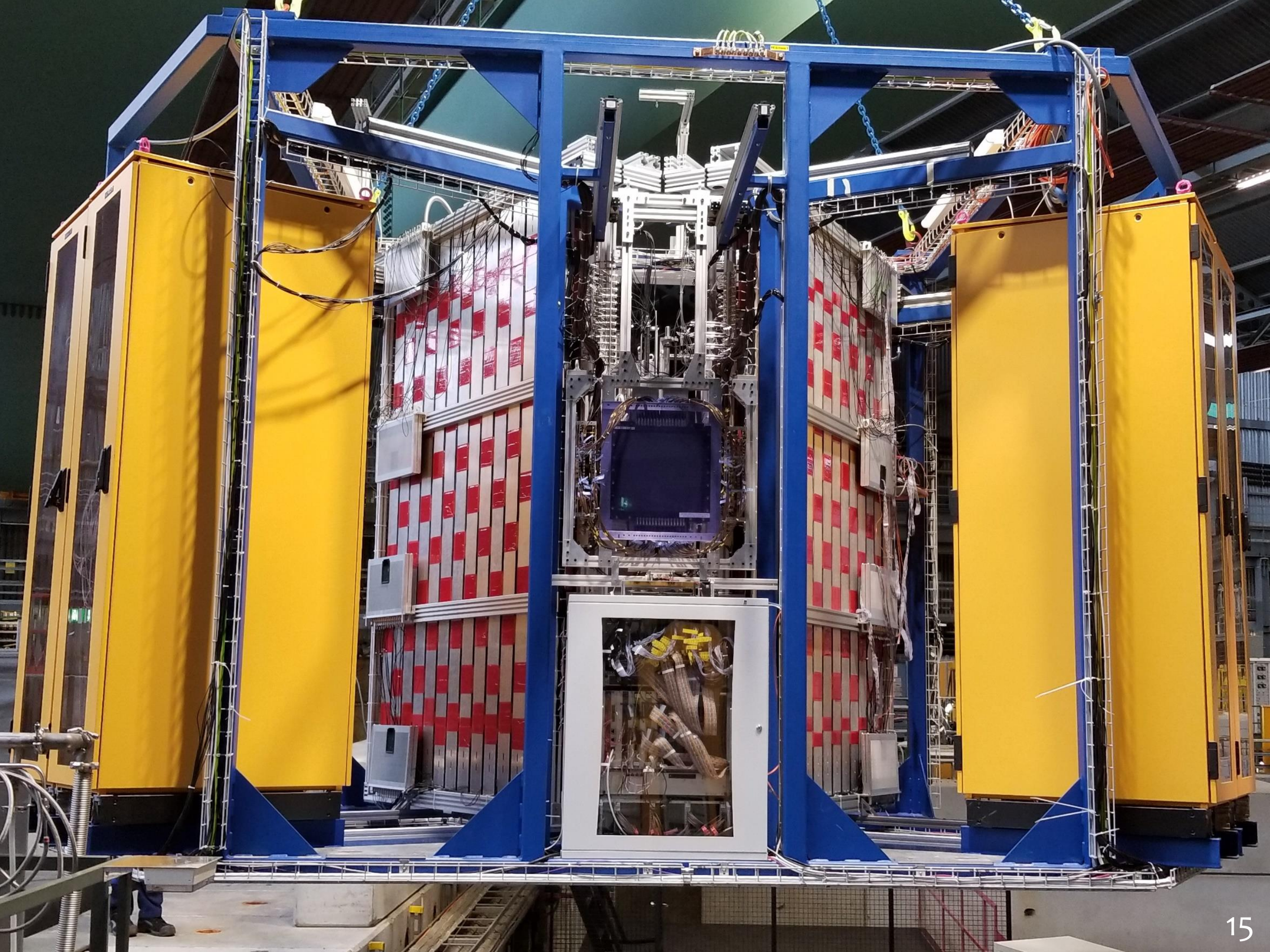
monitors beam stability

determines particle type independent of RF-time

determines muon and pion momenta based on TOF

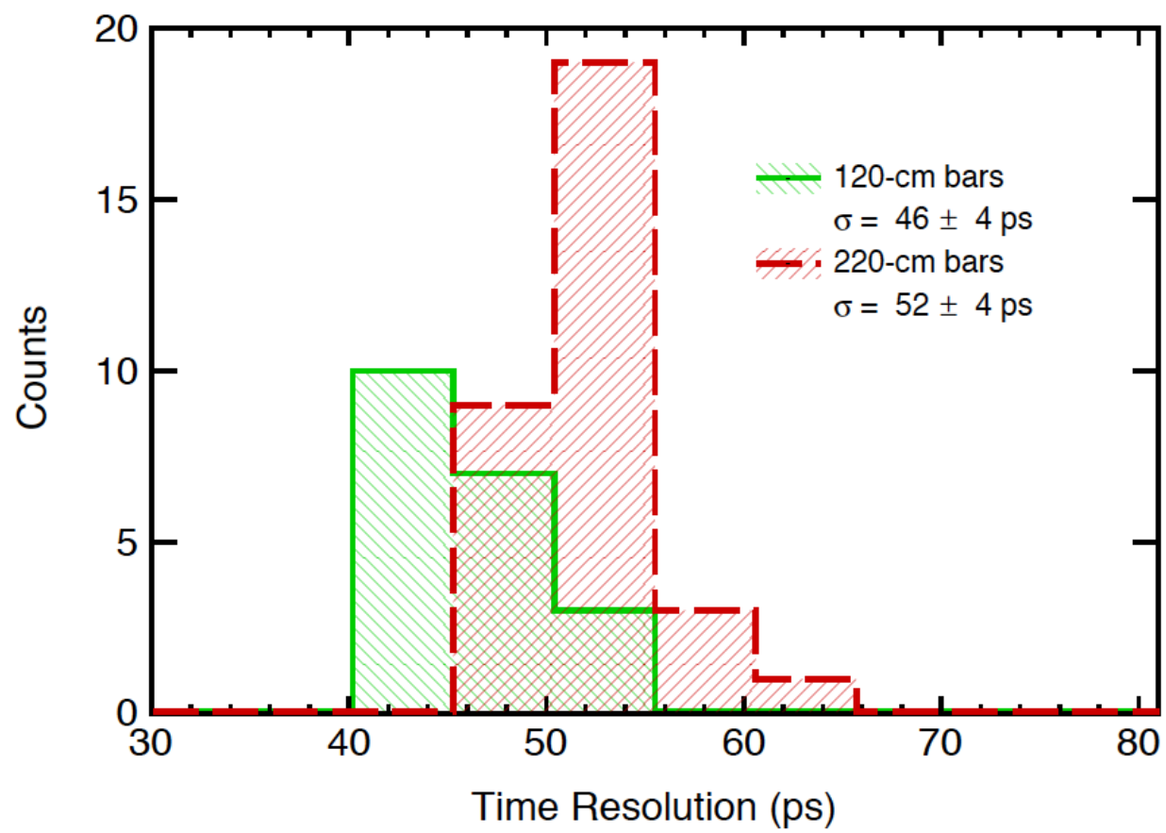
vetos Møller / Bhabha scattering background

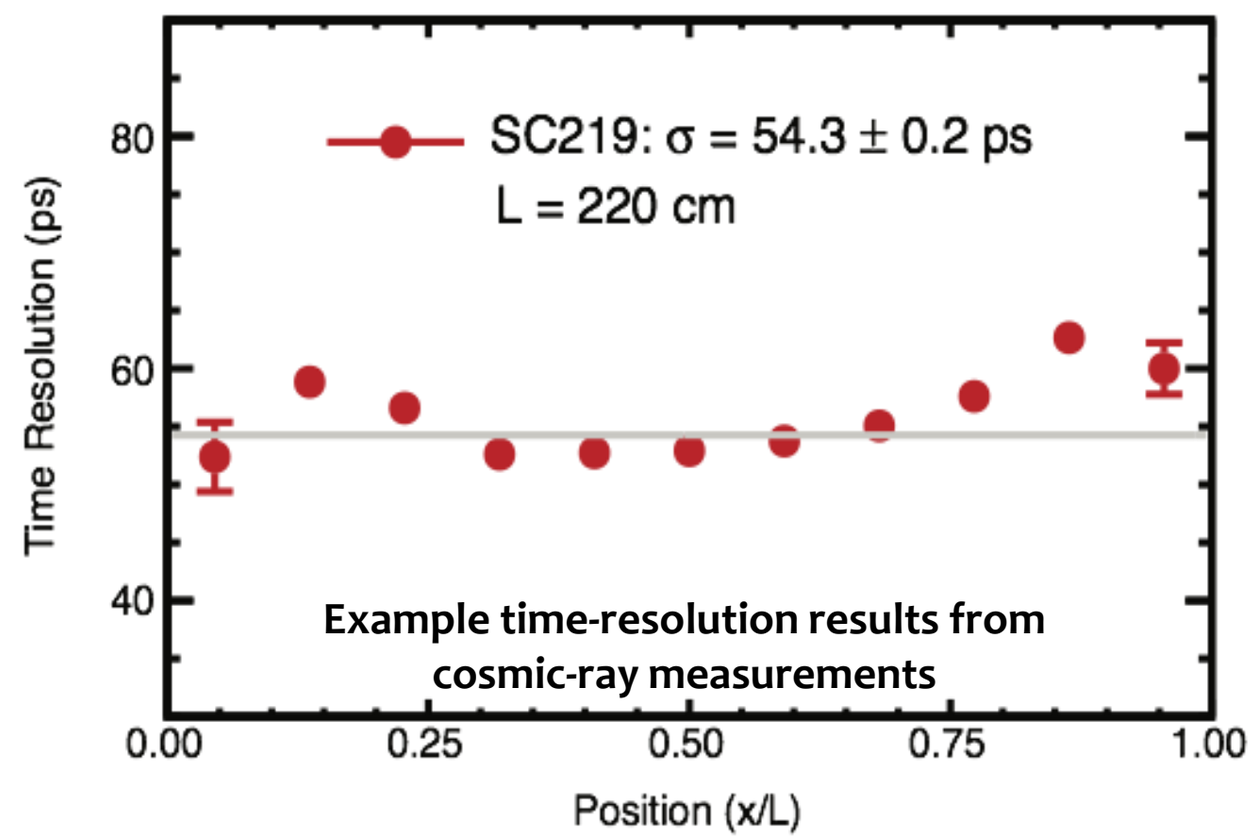




Scattered-particle scintillators

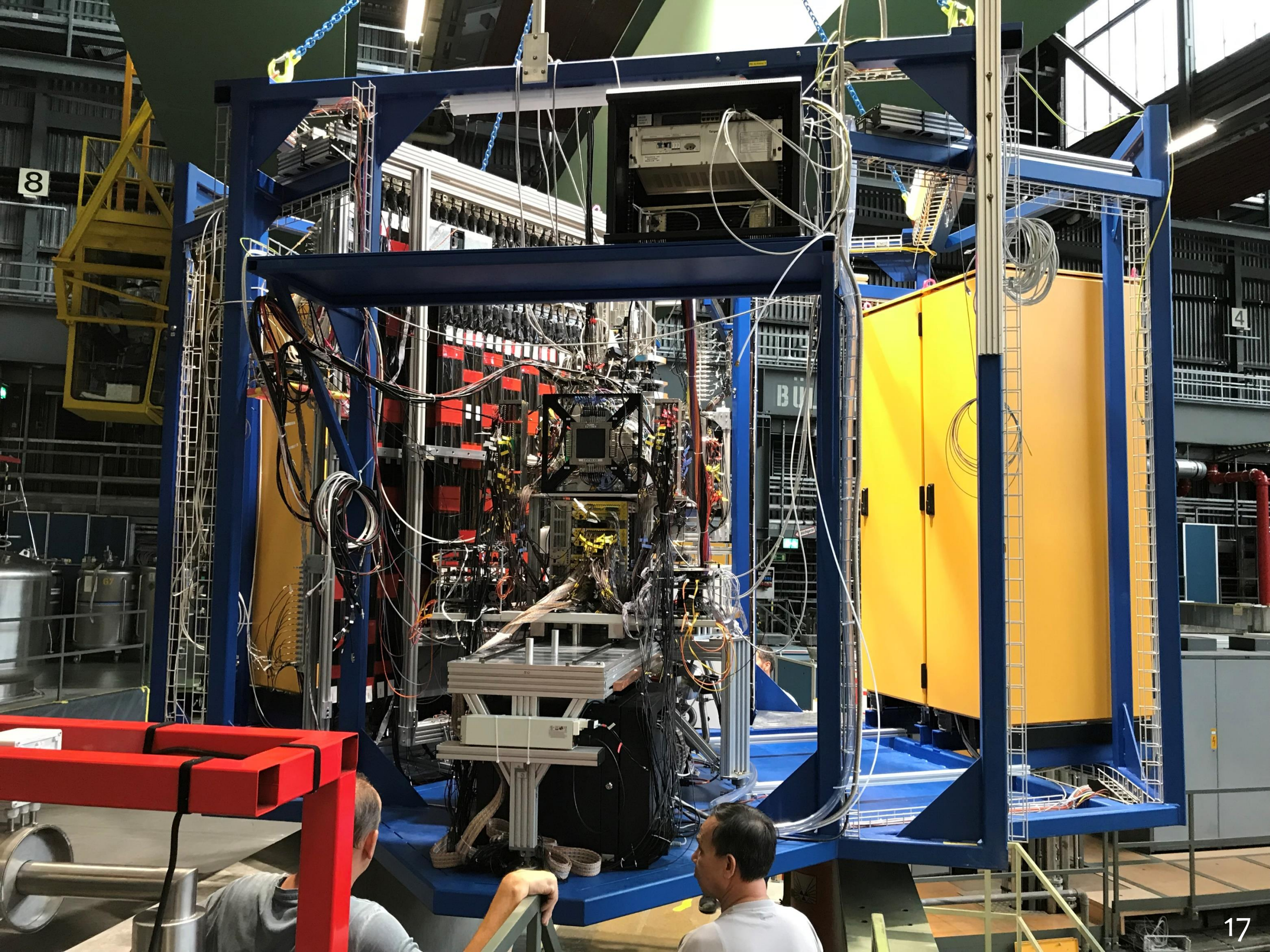
SPS provides event trigger and particle ID
Front wall: 18 bars (6 cm x 3 cm x 120 cm)
Rear wall: 28 bars (6 cm x 6 cm x 220 cm)





Scattered-particle scintillators exceed required time resolution:

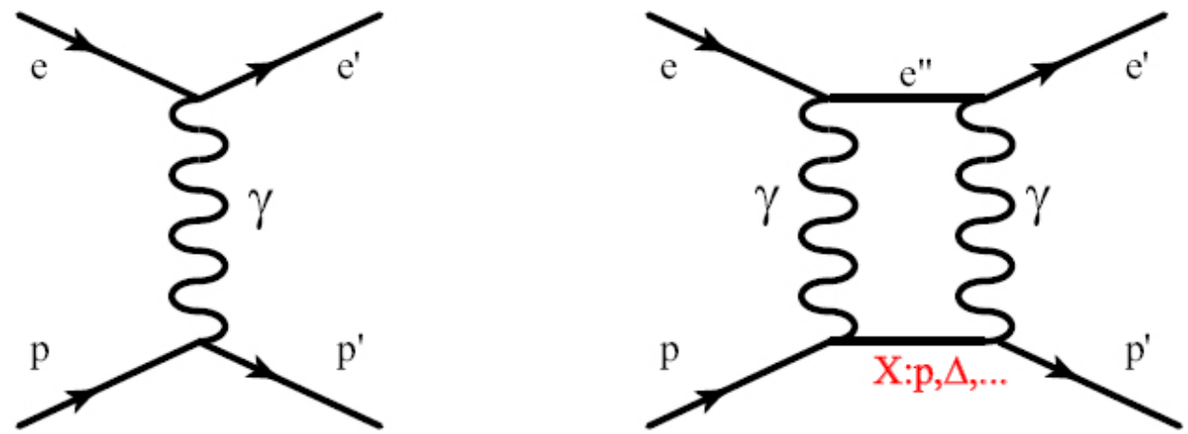
σ(Front) < 50 ps, σ(Rear) < 60 ps



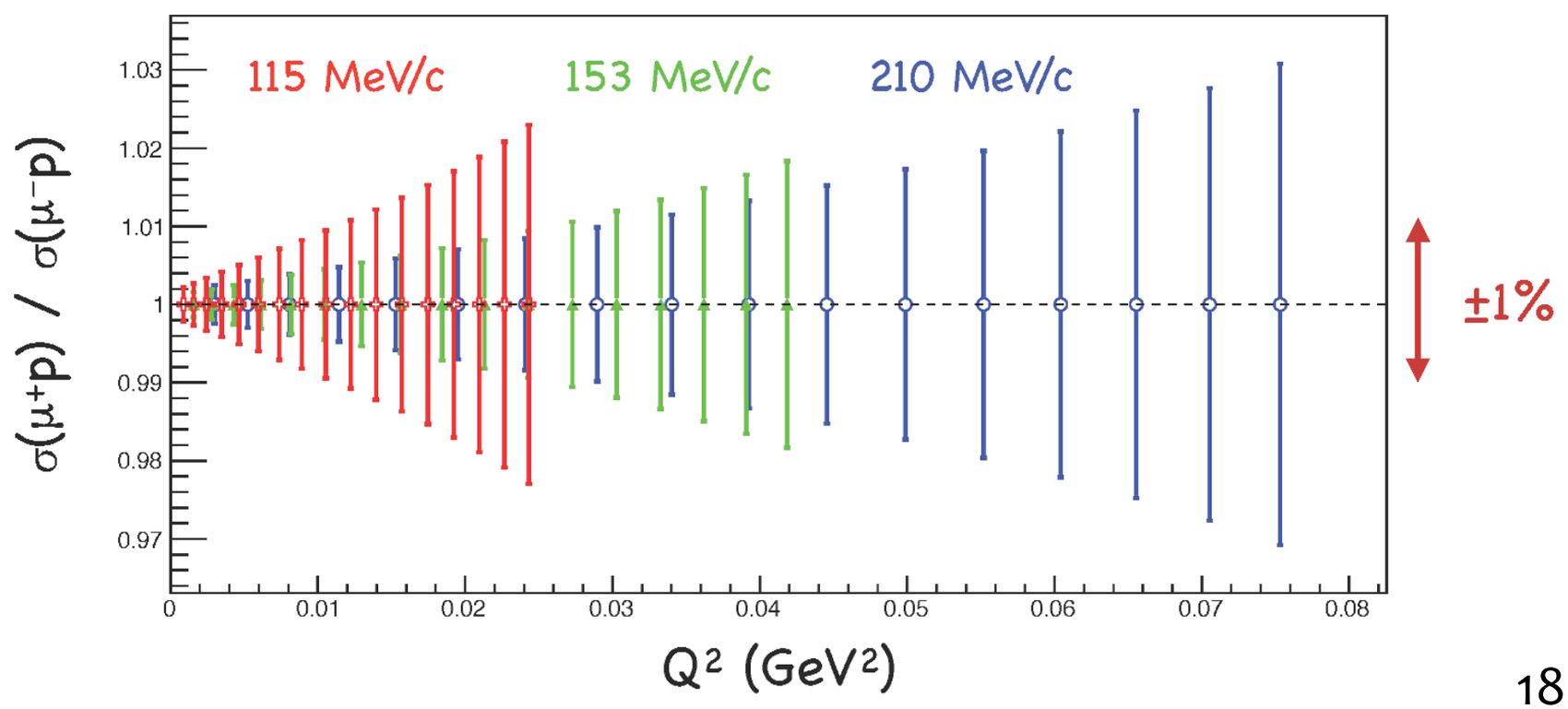
Two-photon exchange at low Q^2

- High precision test of TPE for electron and muons at low Q^2
- TPE largest theoretical uncertainty in low-energy proton structure
- expect sign change for e^+ and e^-

  (same applies to muons)



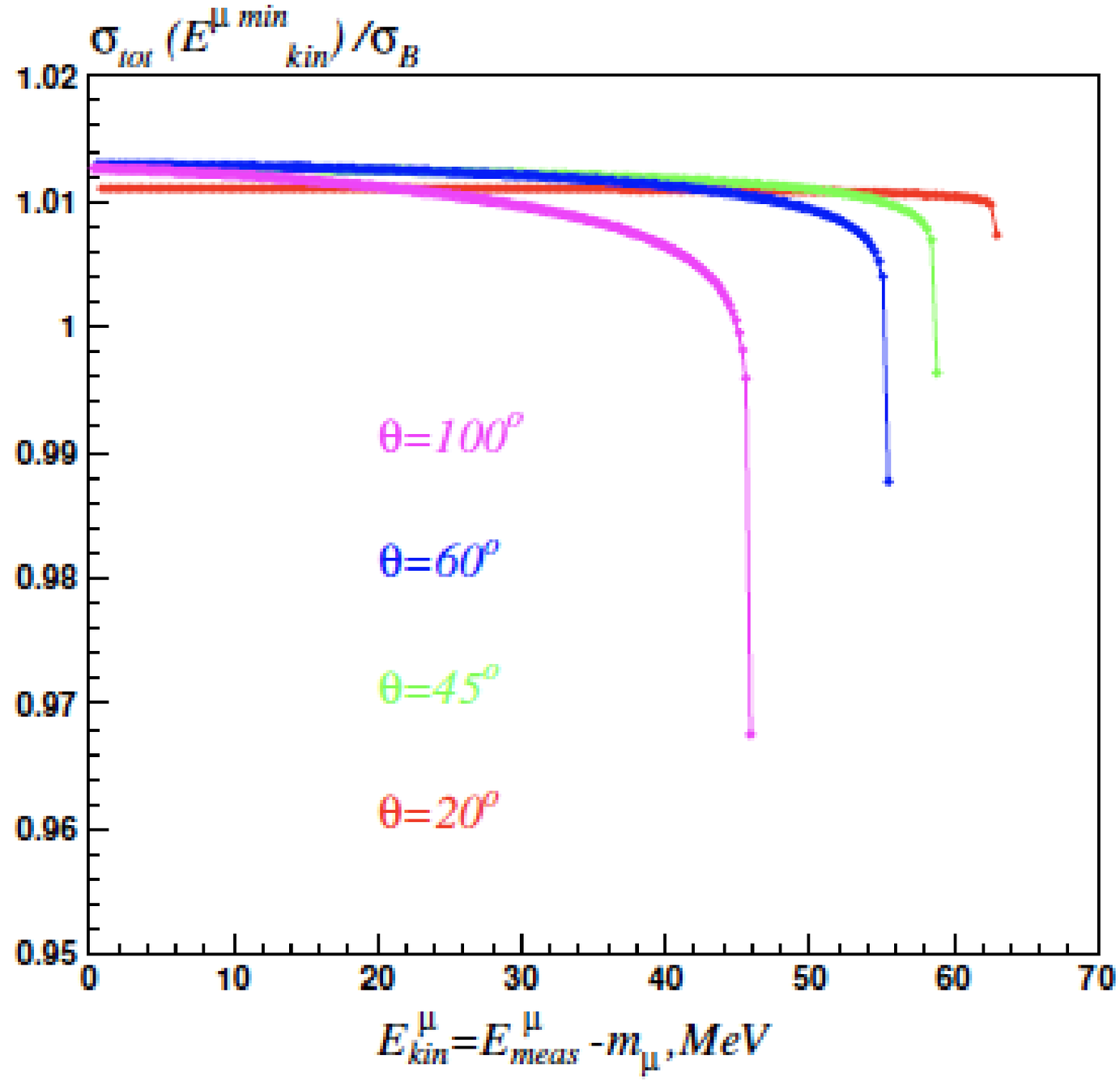
- projected relative uncertainty in μ^+p to μ^-p elastic cross sections
- systematics: 0.2%



Radiative corrections for muons

Recent calculation by
Afansev et al.
to be published soon

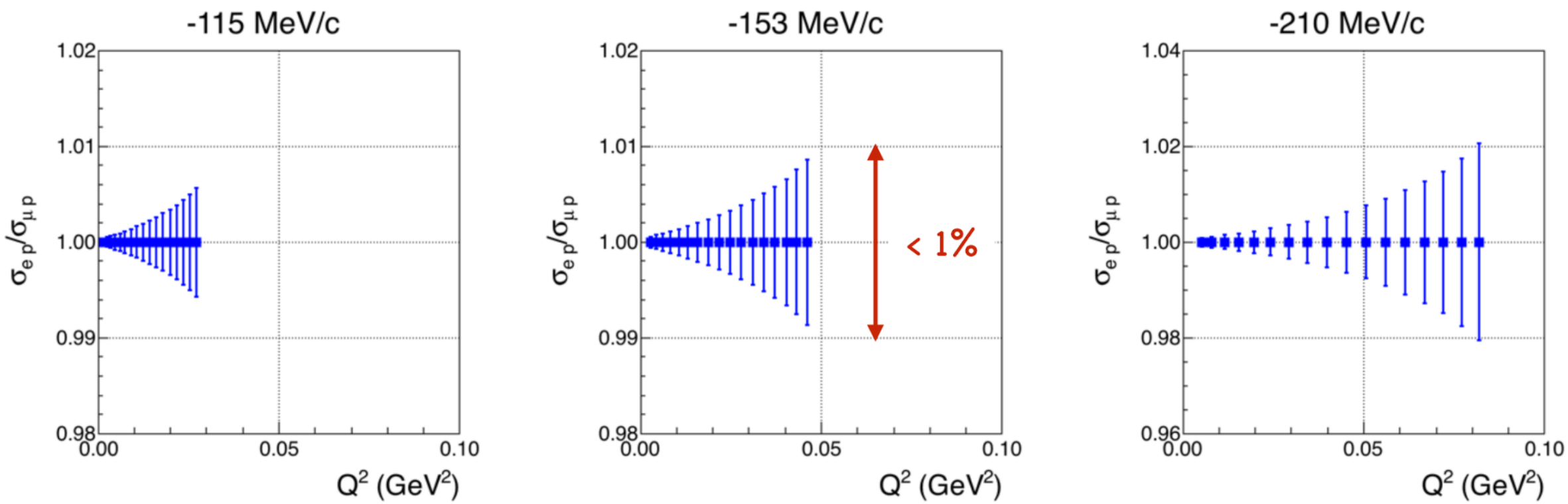
Integrate from
maximum energy
down to varying minimum



Not very sensitive to them

Compare e-p and μ-p elastic cross sections

- projected relative statistical uncertainties in the ratio of e-p to μ-p elastic cross sections
- systematics: 0.5%



- relative statistical uncertainties in the form factors are half as large

Projected sensitivity for MUSE

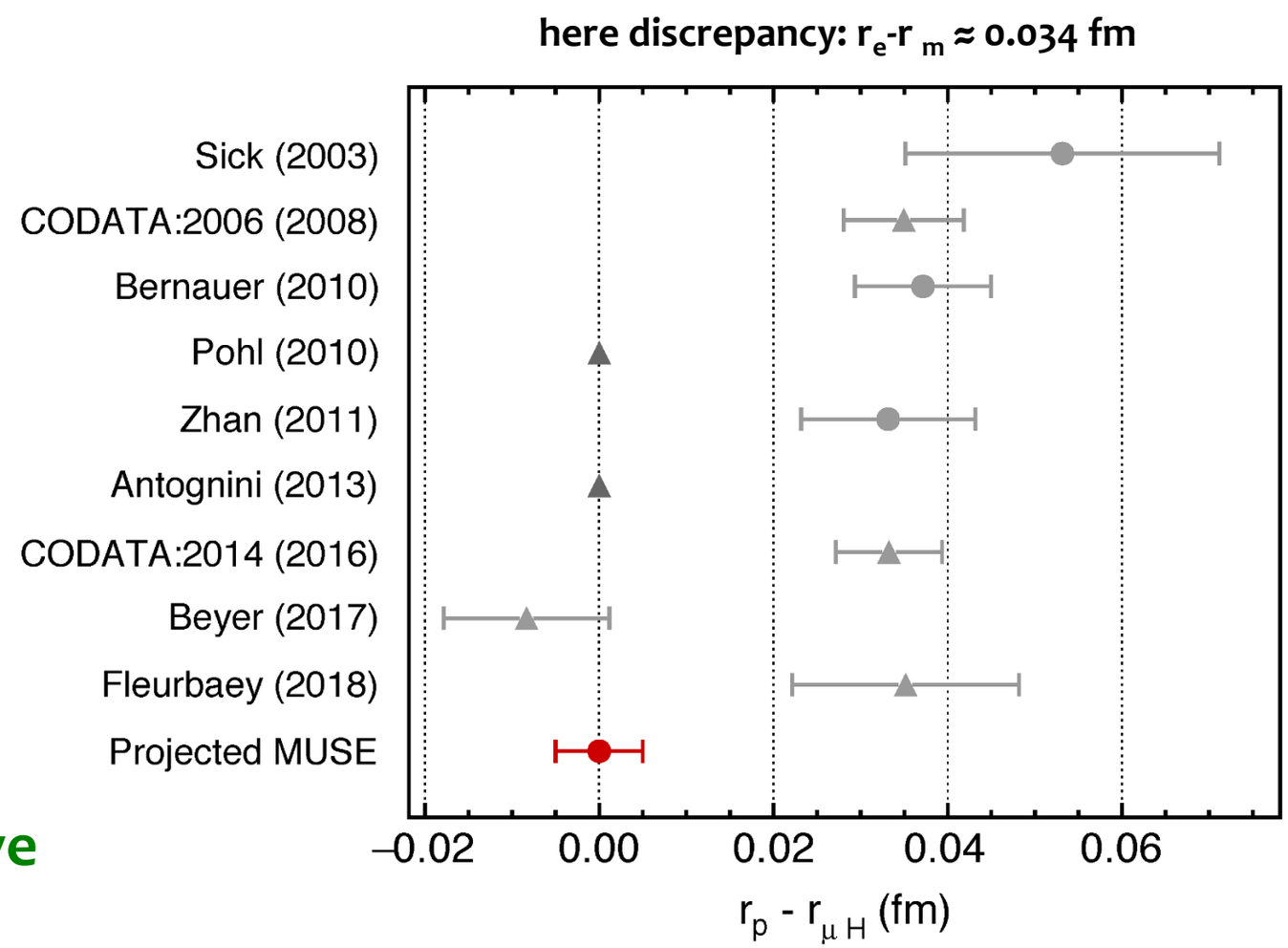
- **absolute radius extraction uncertainty similar to current experiments**

  $\sigma(r_e), \sigma(r_m) \approx 0.009$ fm

- **radius difference: common uncertainties cancel**
  - **comparison of μ to e, or μ^+ to μ^- insensitive to many syst. errors**

  $\sigma(r_e - r_m) \approx 0.005$ fm

  → almost factor two more sensitive than absolute radius extraction



Many worked on MUSE including dozens of PSI staff

70 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, A. Flannery, **D. Ghosal**, R. Gilman, A. Golossanov, R. Gothe, D. Higinbotham, **J. Hirschman**, **D. Hornidge**, Y. Ilieva, **K. Mesick**, **Z. Meziani**, L. Li, **P. M. Murthy**, N. Kalantarians, M. Kohl, **O. Koshchii**, **G. Korcyl**, **K. Korcyl**, **B. Krusche**, **I. Lavrukhin**, J. Lichtenstadt, W. Lin, A. Liyanage, W. Lorenzon, K.E. Mesick, J. Nazeer, **T. O'Connor**, **P. Or**, **T. Patel**, E. Piasetzsky, R. Ransome, R. Raymond, D. Reggiani, H. Raid, 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

PSI

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, Ieizmann Institute, Old Dominion University*

first precision measurement of proton charge radius with simultaneous low-momentum muon, electron and positron scattering

MUSE

NSF with additional support from BSF United States – Israel Binational Science Foundation

PAUL SCHERRER INSTITUT PSI

U.S. DEPARTMENT OF ENERGY Office of Science

STATUS

- construction completed
- engaged in commissioning

PLAN

- complete commissioning
- take data for total of 12 months in 2019 - 2021

EXPECT

- shapes of e- e+ μ- μ+ form factors
- test of existing values for proton radius
- test of two-photon exchange and lepton universality