Status of the MUon Scattering Experiment (MUSE) at PSI

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On behalf of the MUSE collaboration

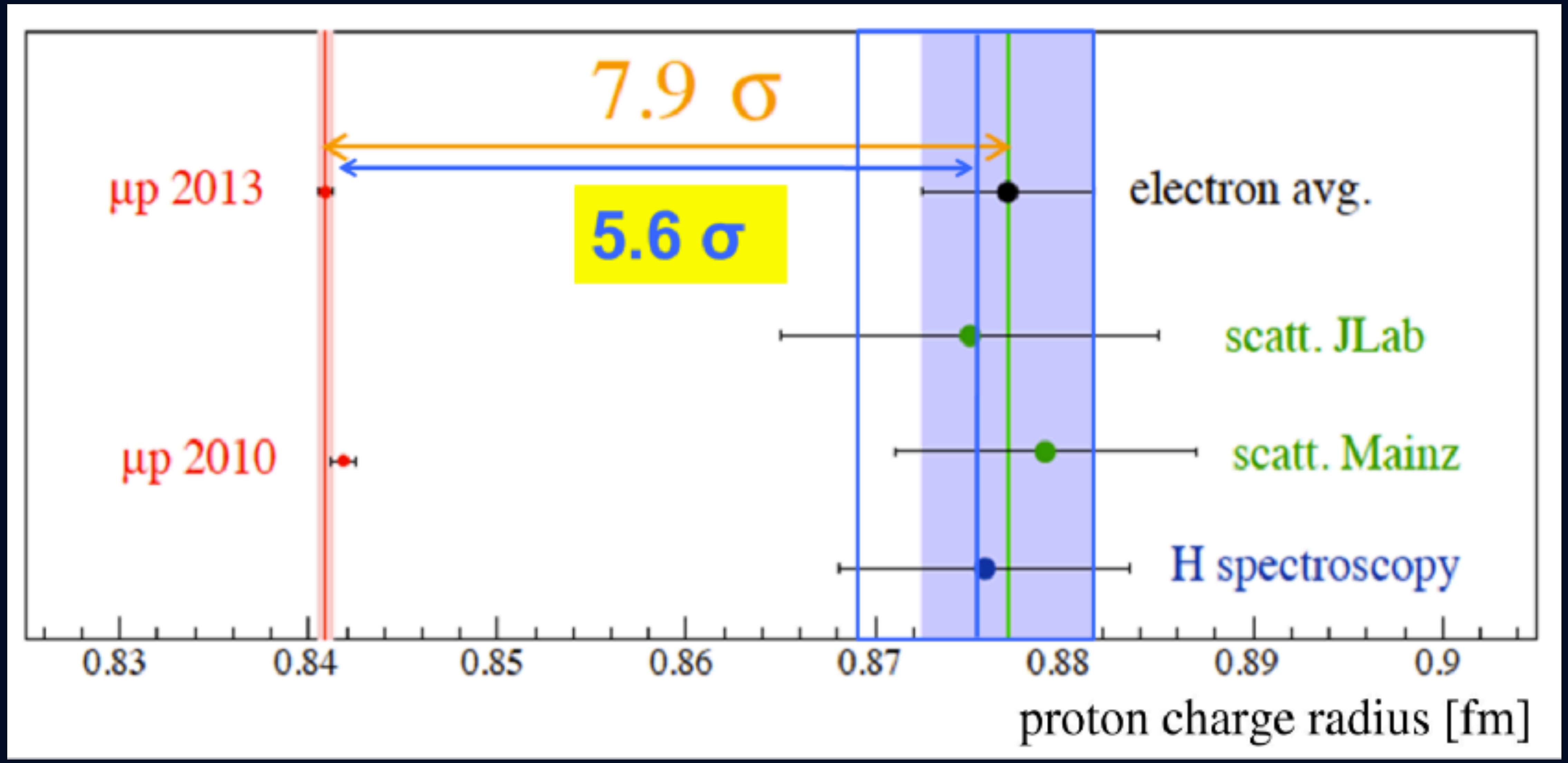
June 6, 2024

OUTLINE

- Introduction
    - Motivation: the proton radius puzzle
- MUSE experimental set up
- Analysis: event reconstruction
- Projected sensitivities and conclusions

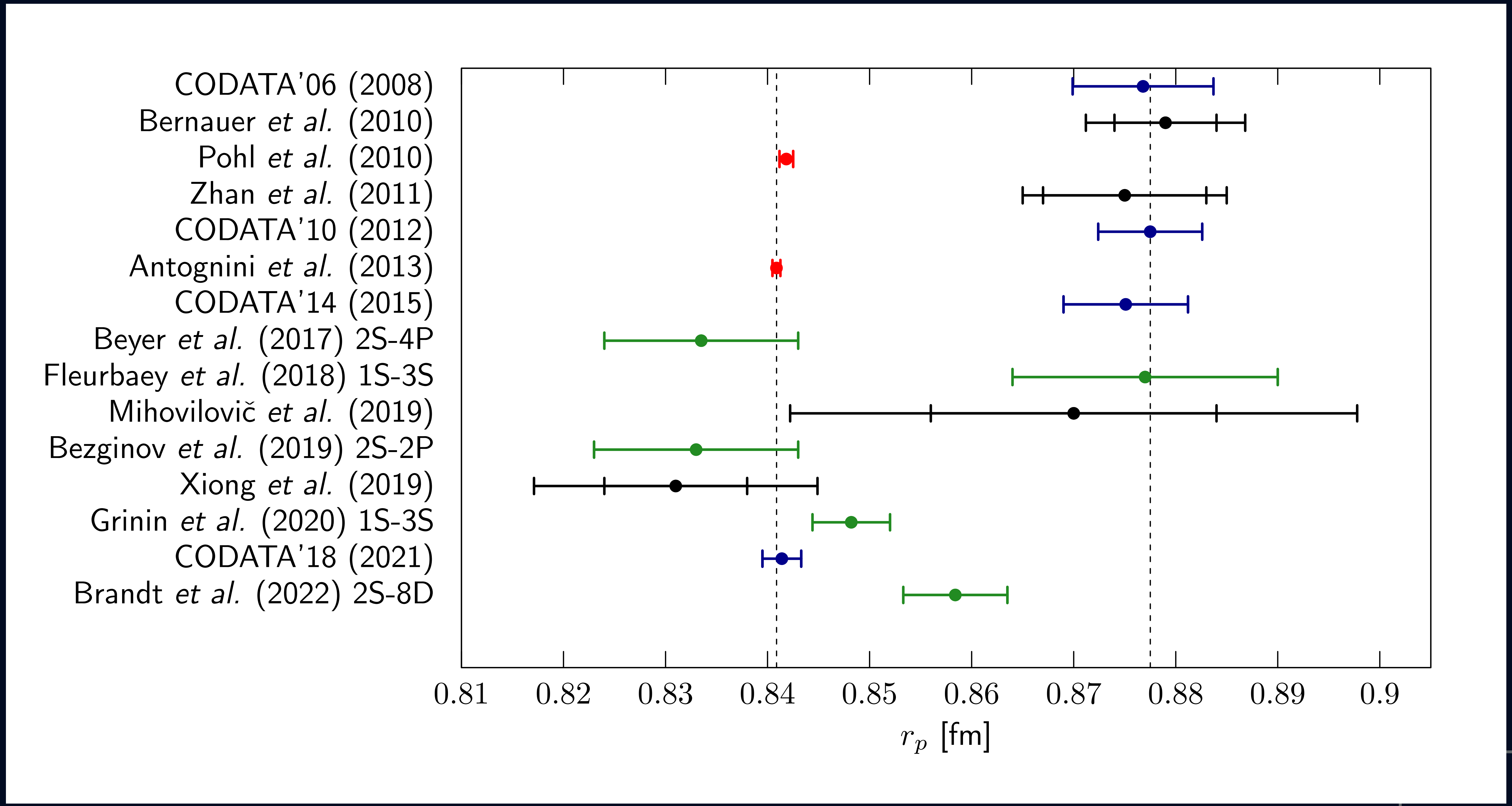
THE PROTON RADIUS PUZZLE

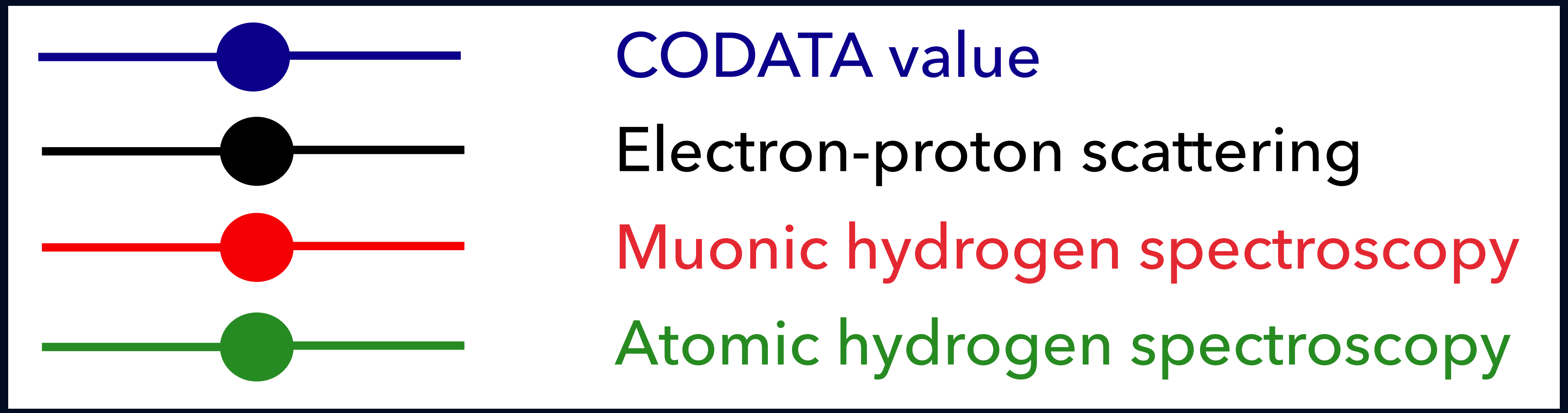
- 1st proton radius measurement from muonic hydrogen spectroscopy published in 2010
  - 10x more precise than previous measurements
- Significantly smaller and not in agreement with previous measurements
- r_p = 0.84184(67) fm
- Confirmation of muonic hydrogen measurement in 2013



r_p	Electron	Muon
Spectroscopy	0.8758 (77) fm	0.8409 (4) fm
Scattering	0.8790 (70) fm	N/A

THE PUZZLE IN 2024: MORE RADIUS MEASUREMENTS





- New experiments proposed, as well as data from past experiments reanalyzed
- More information needed to resolve the puzzle and understand its origin

r_p	Electron	Muon
Spectroscopy	Inconsistent	0.8409 (4) fm
Scattering	Inconsistent	N/A

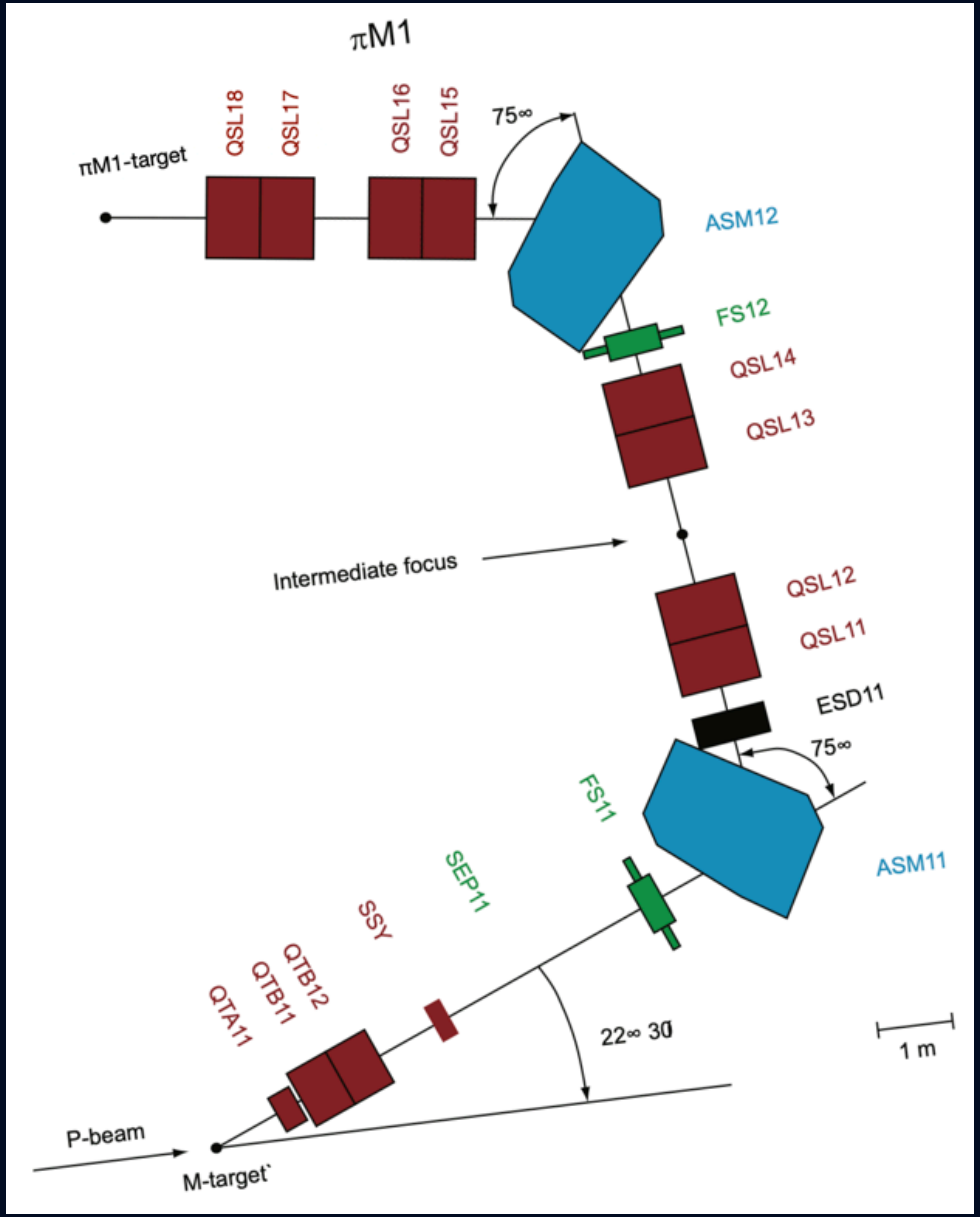
CAPABILITIES OF MUSE

Radiative correction effects →	Effects much smaller in muons → compare with electrons
Two photon exchange →	Both polarities make two photon contribution accessible
Beyond the standard model - violation of lepton universality →	Simultaneous look at electrons and muons → direct comparison of cross sections

THE MUON SCATTERING EXPERIMENT (MUSE)

- MUSE aims to
  - Simultaneously measure ep and μp elastic scattering cross sections
  - Directly compare ep and μp scattering at sub-percent level precision

MUSE: BEAMLINE



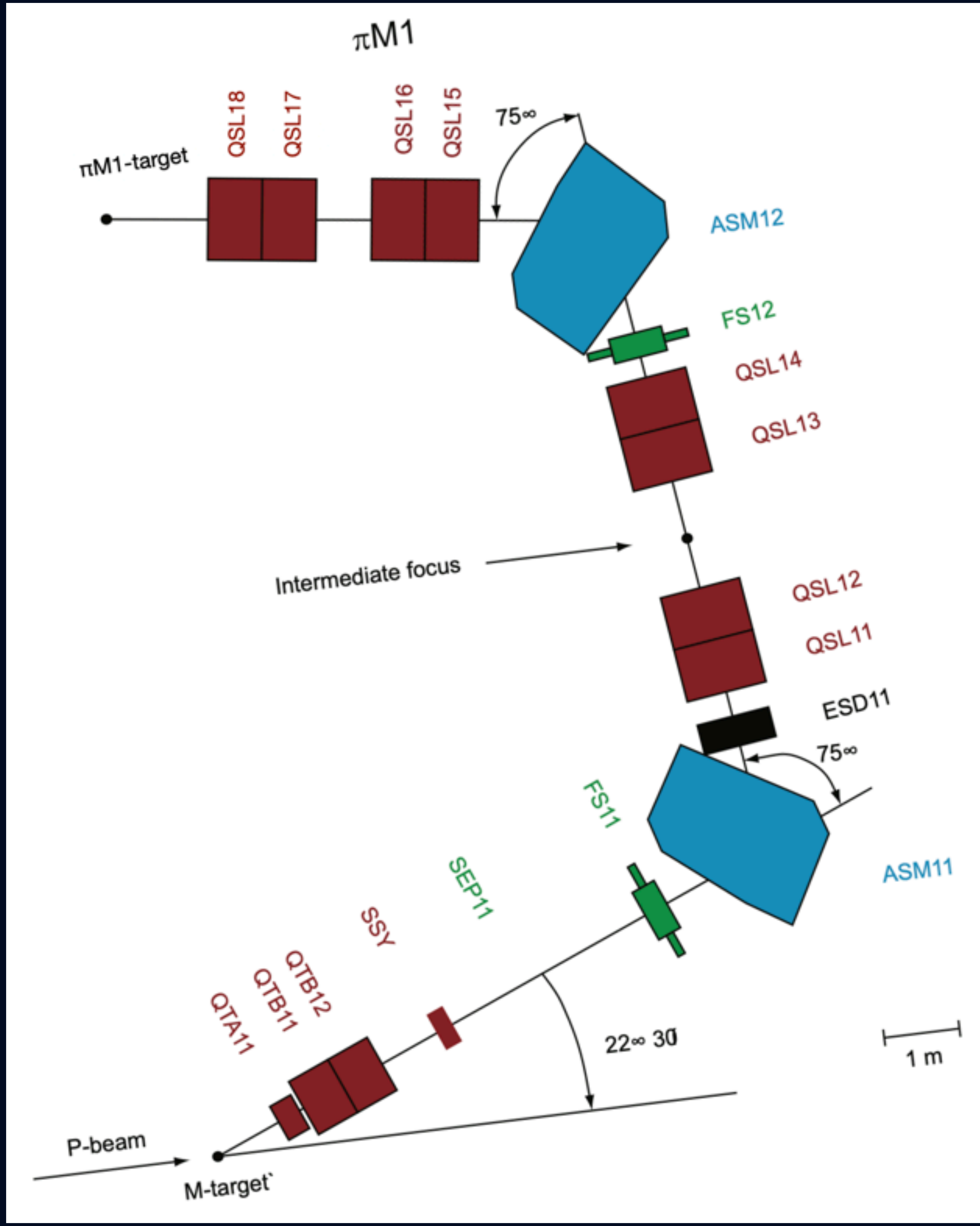
Cline, E. *et al.* (2017). arXiv1709.09753

- PiM1 beam line at PSI
  - Secondary beam line from 590 MeV proton beam
  - Produces electrons, pions, and muons in secondary beam

Quantity	Coverage
Beam Momenta (MeV/c)	115, 160, 210
Scattering Angle Range (degrees)	20 - 100
Q^2 range for electrons (GeV^2)	0.0016 - 0.0820
Q^2 range for muons (GeV^2)	0.0016 - 0.0799

Gilman, R. et al. (2017). arXiv1709.09753

MUSE: BEAMLINE



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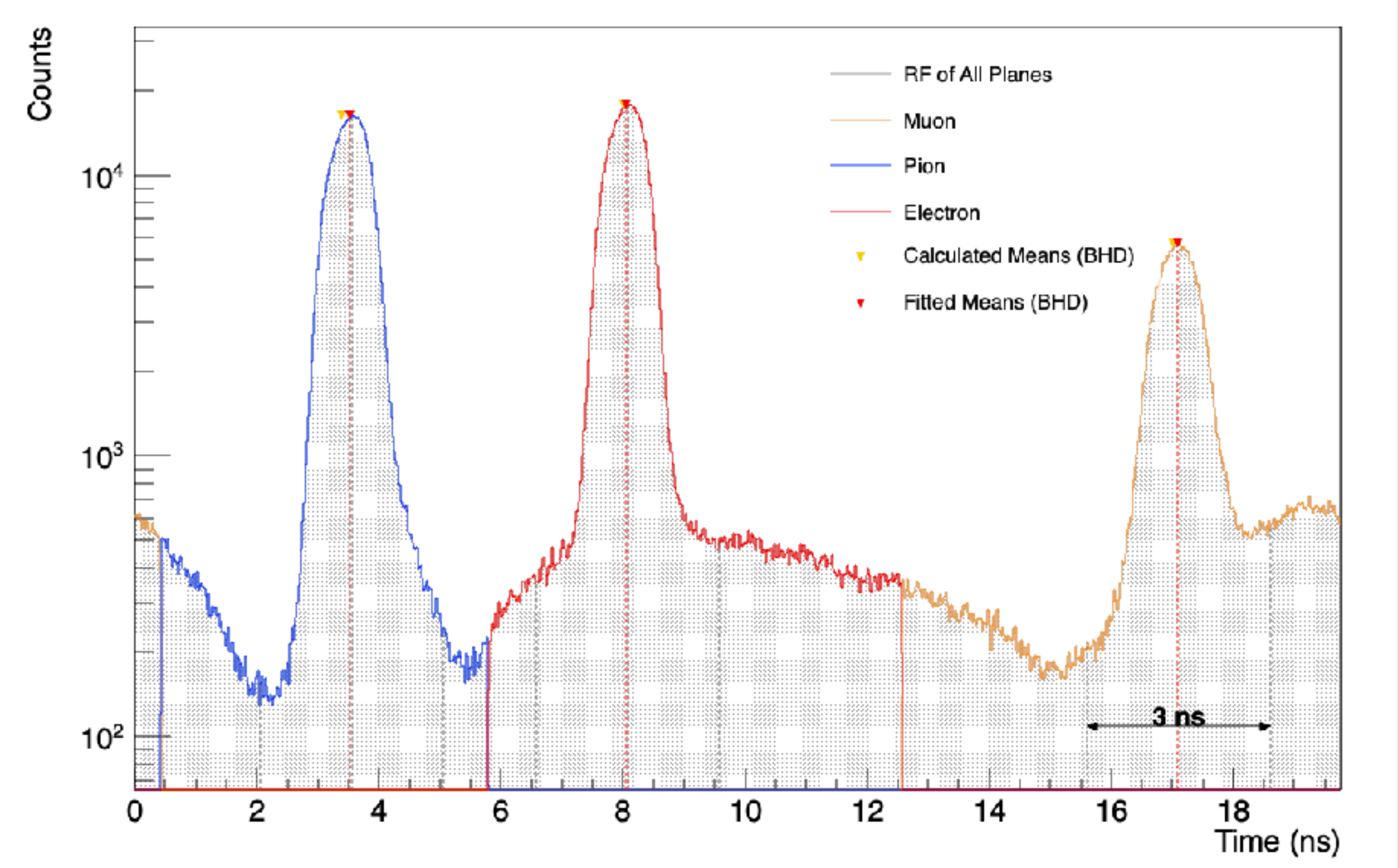
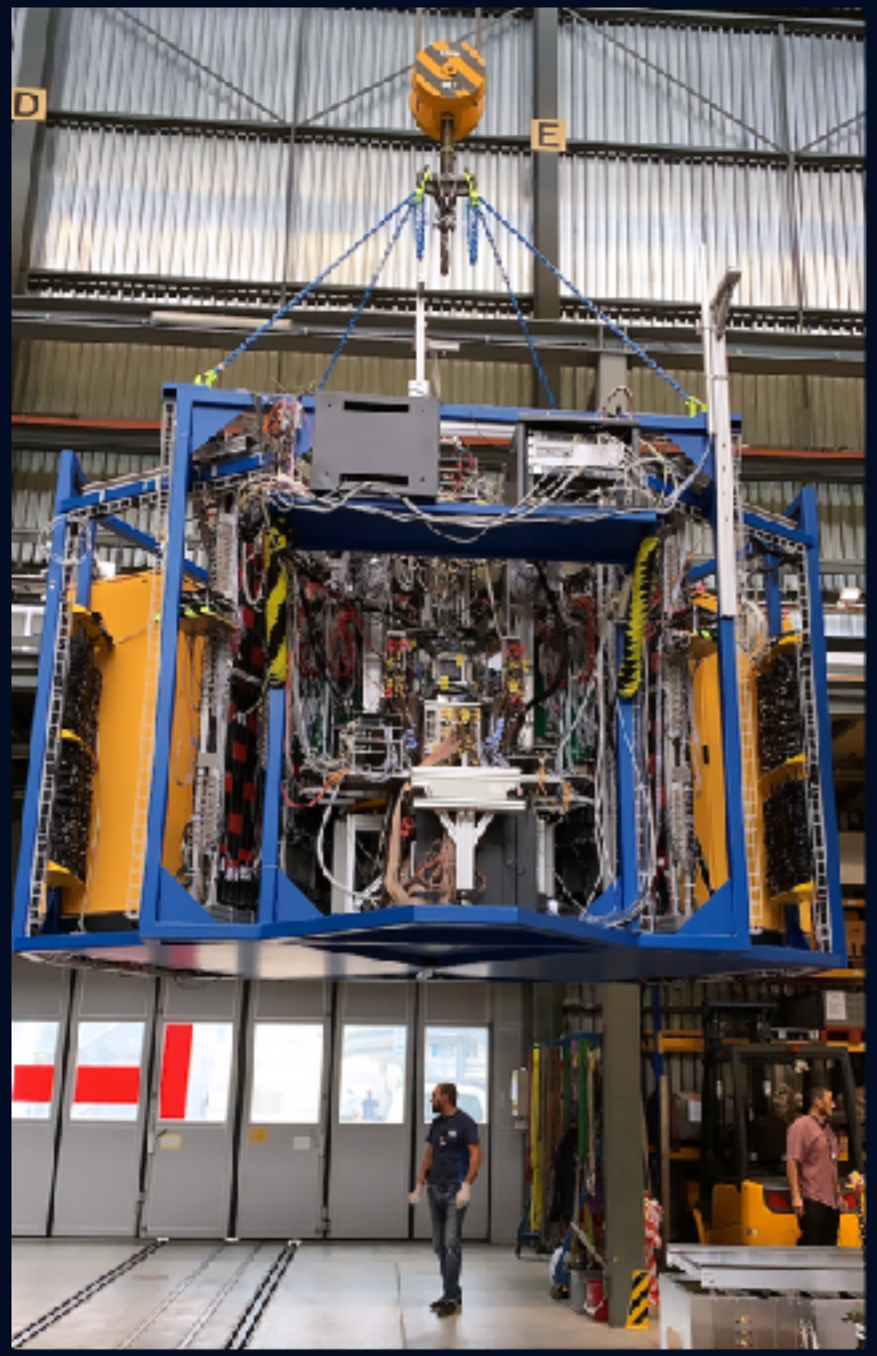
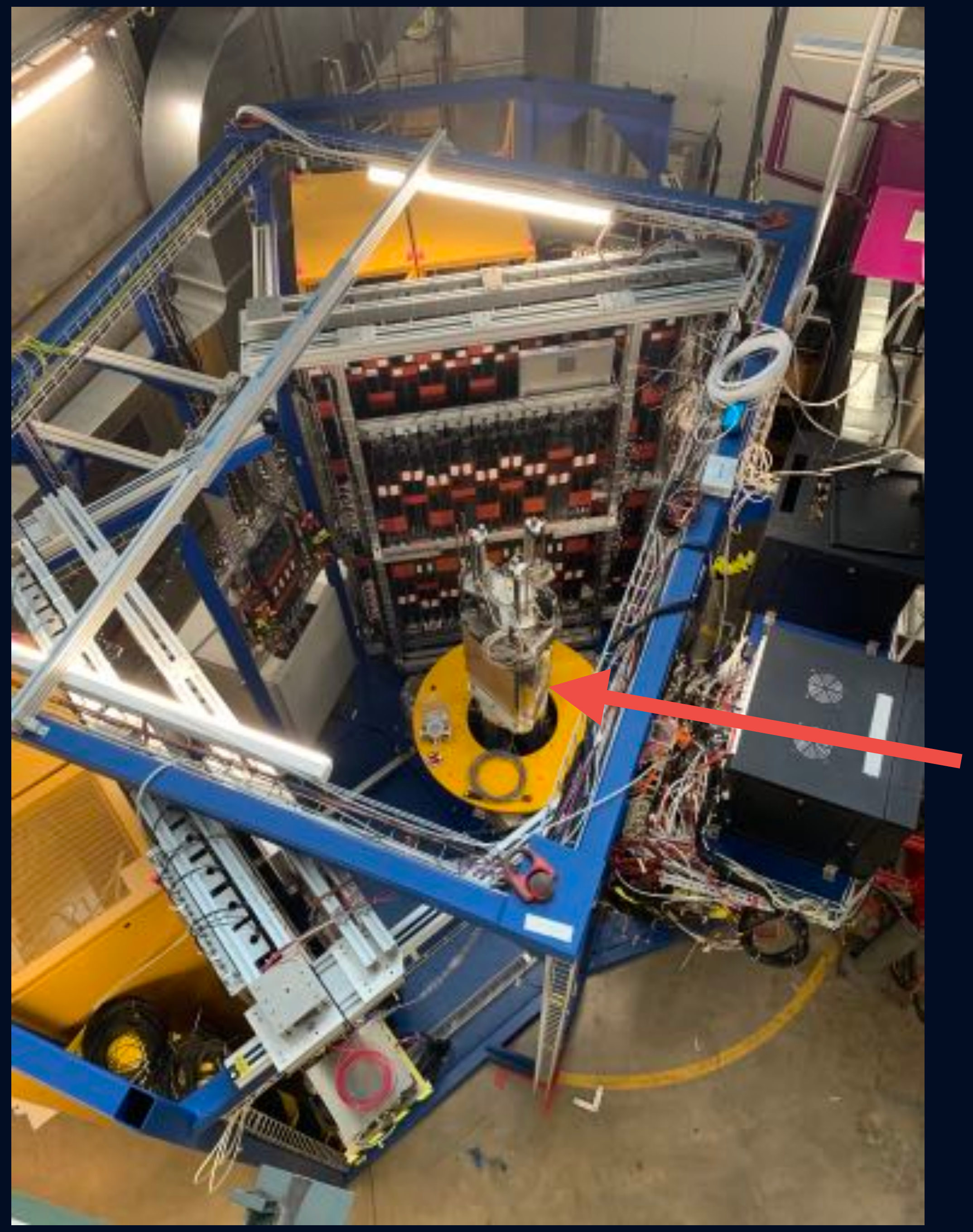
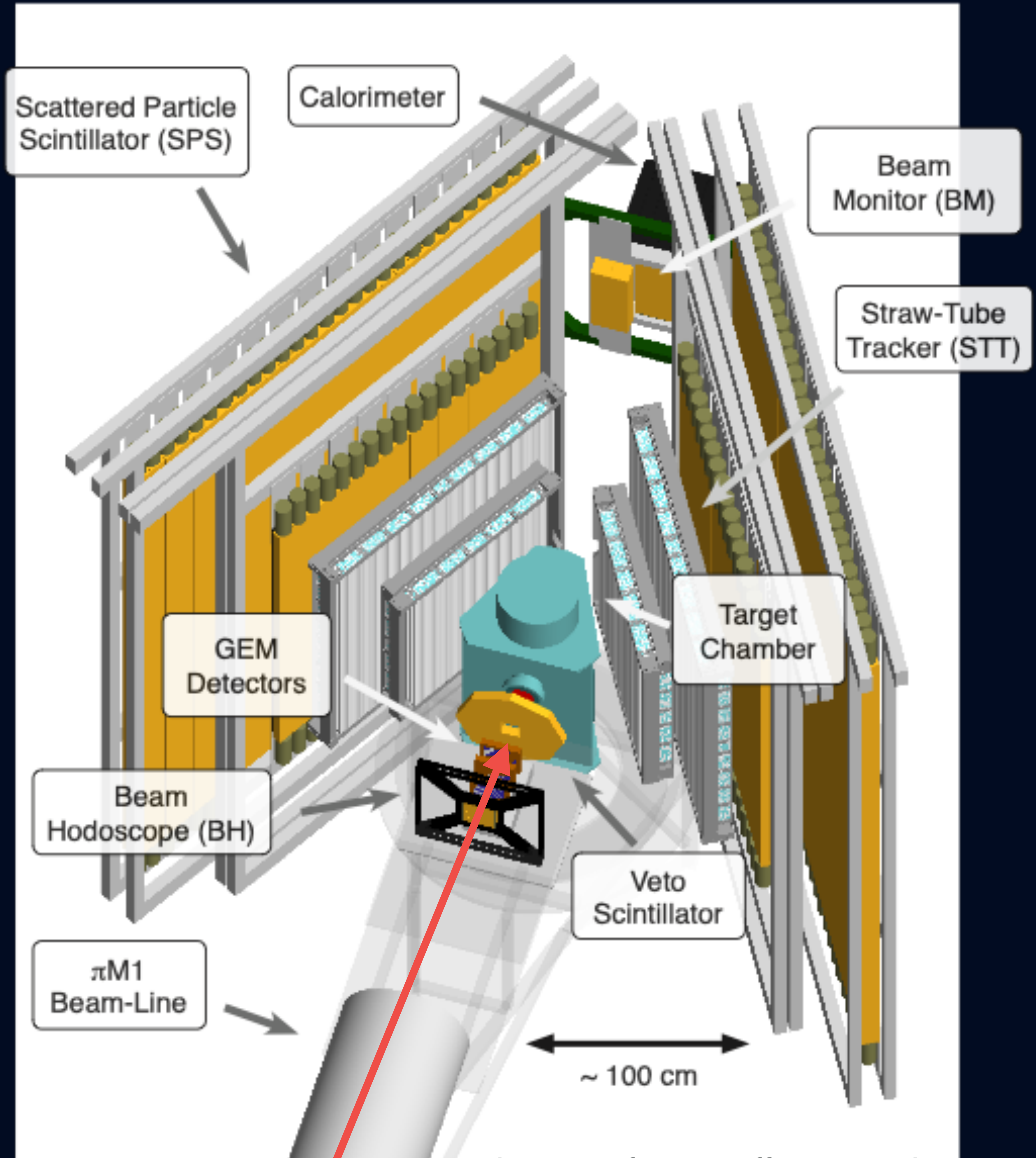


MUSE: EXPERIMENTAL SETUP

- Need beam line particle identification (PID) and tracking
- Large acceptance angle: 20°-100°
- No magnetic spectrometer



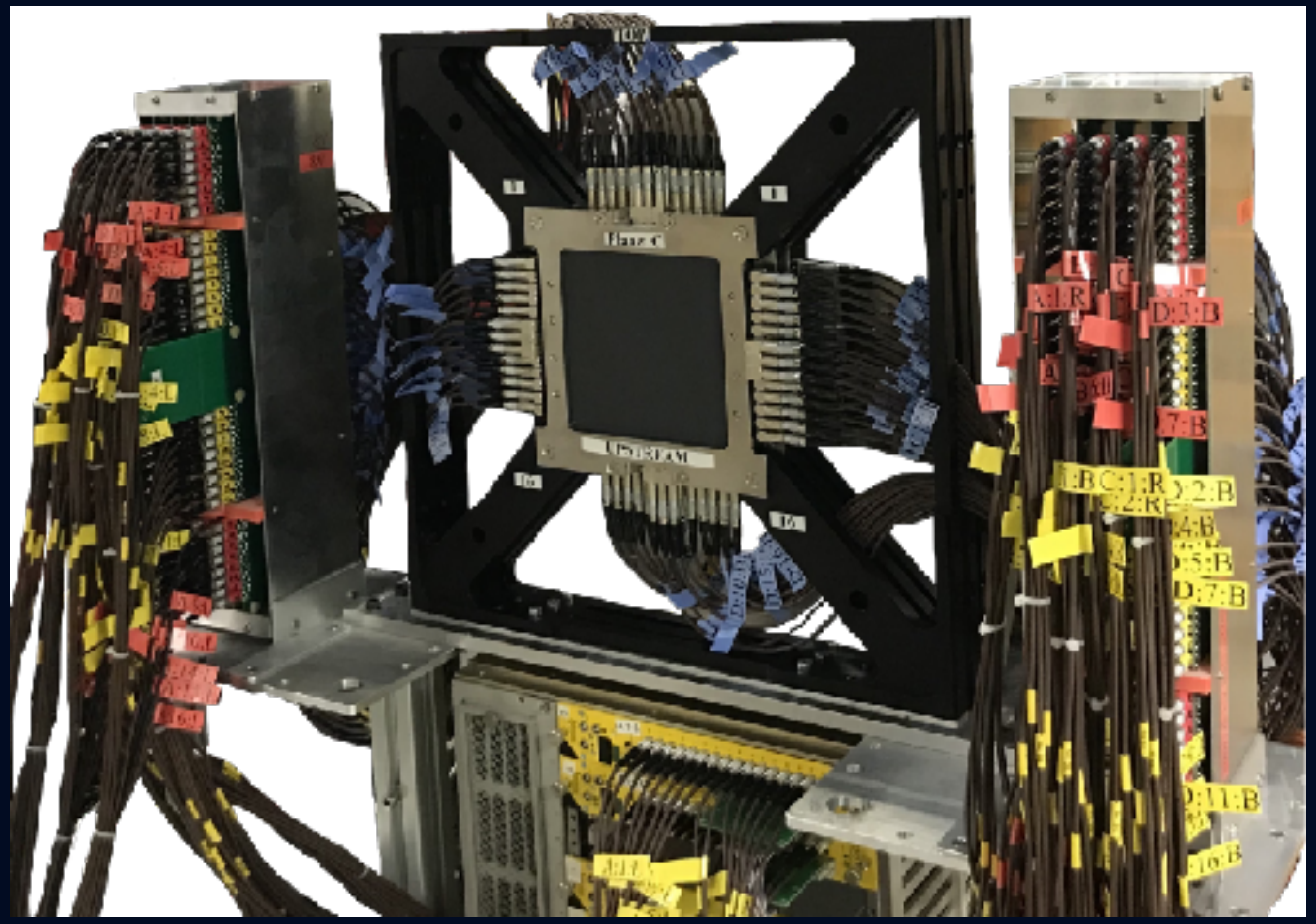




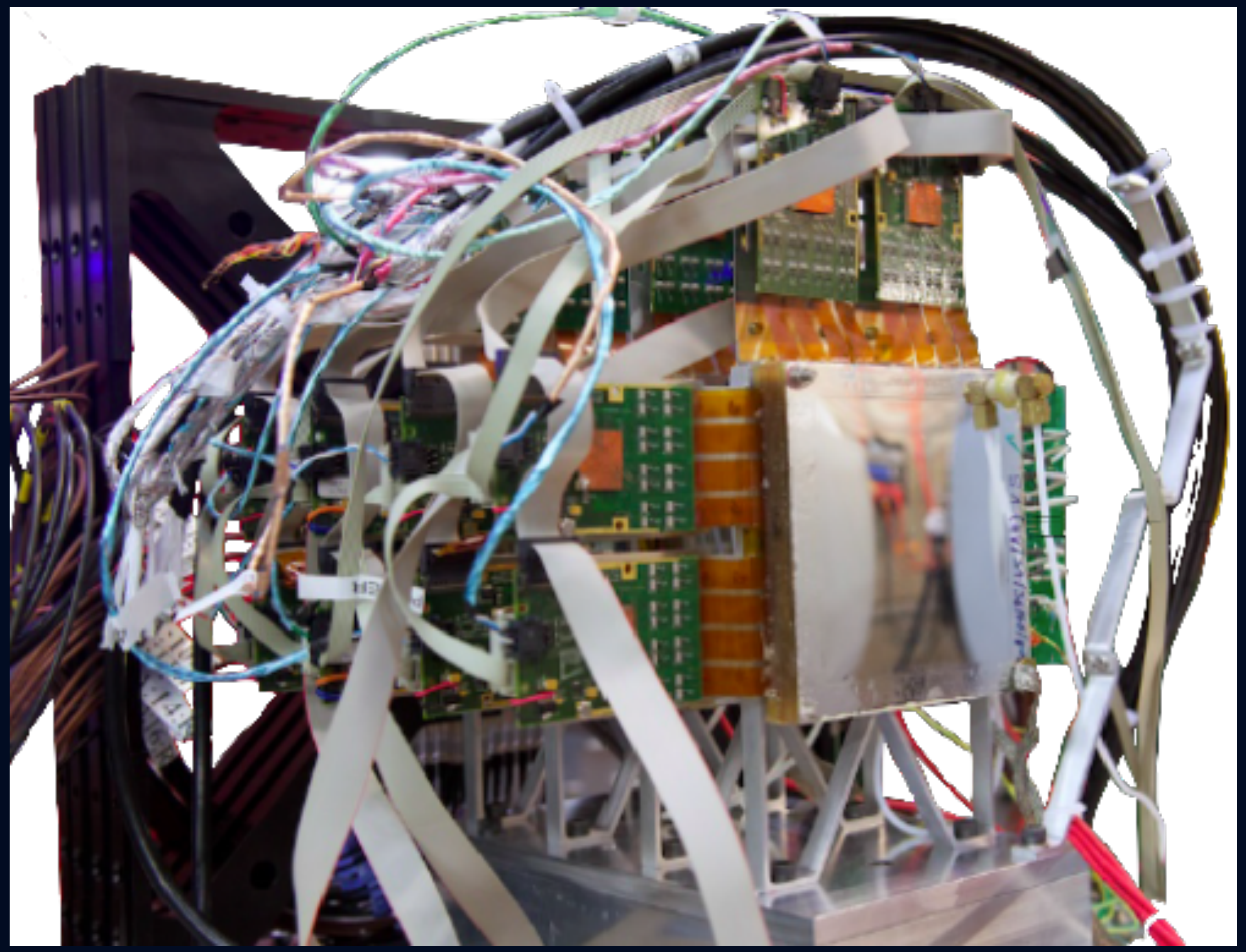
Schematic from Steffen Strauch

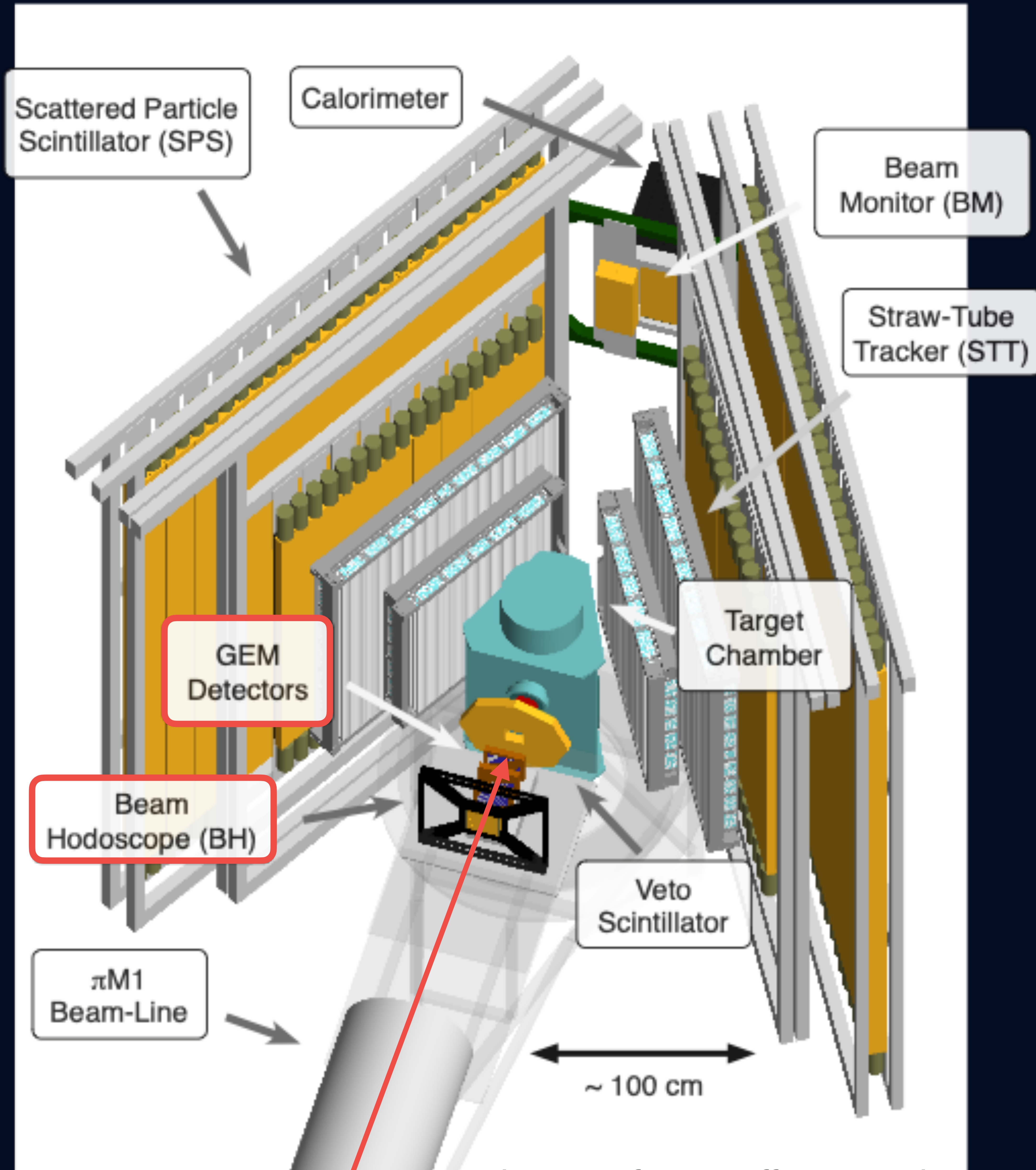
DETECTORS FOR MUSE: INCOMING PARTICLES

- Beam Hodoscope
  - Precise timing
  - Incident particle ID



- GEMs
  - Incident particle tracking

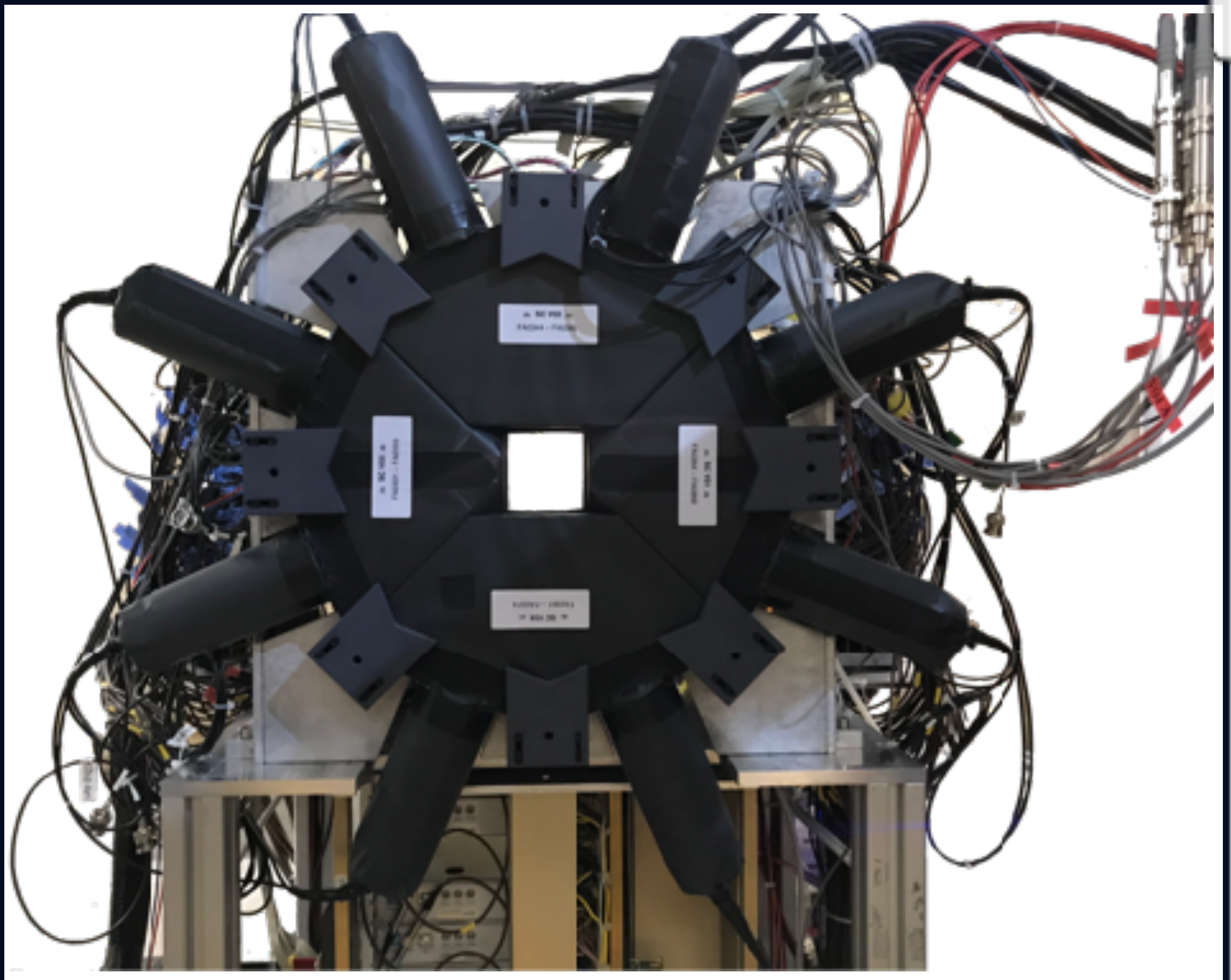


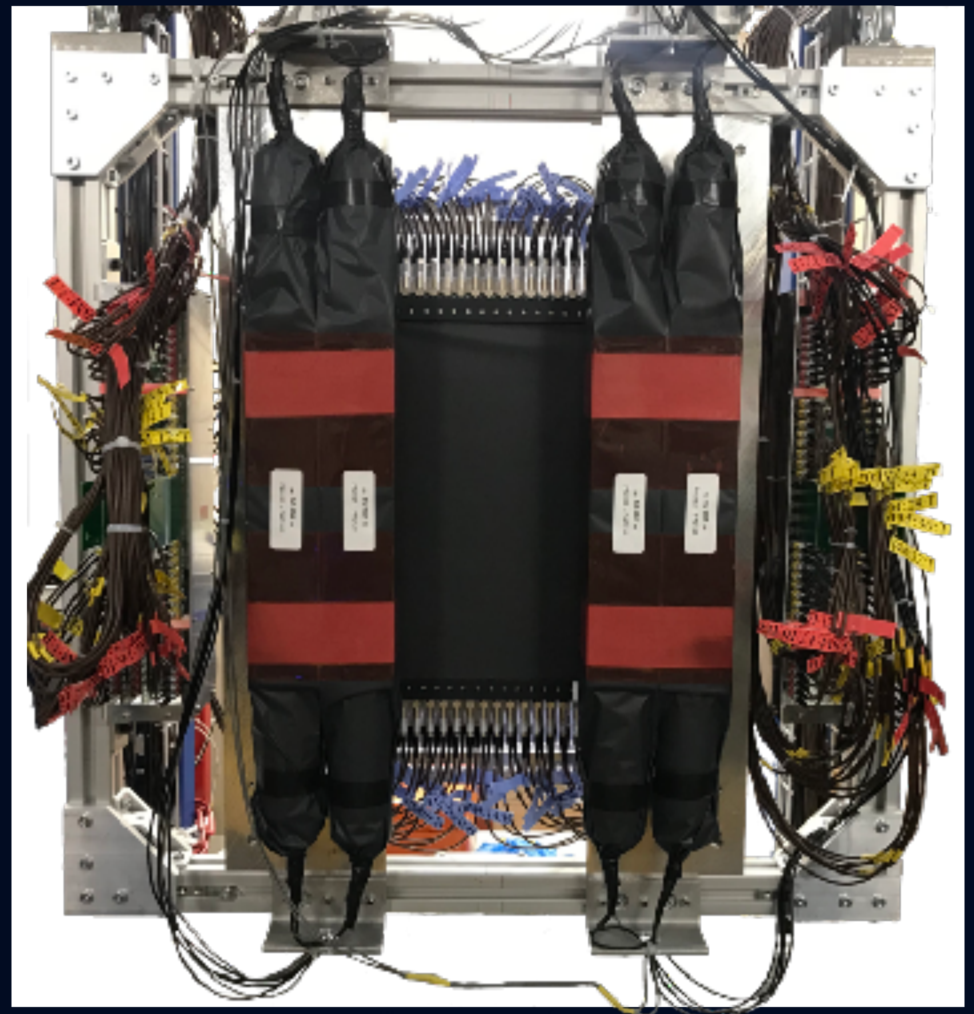


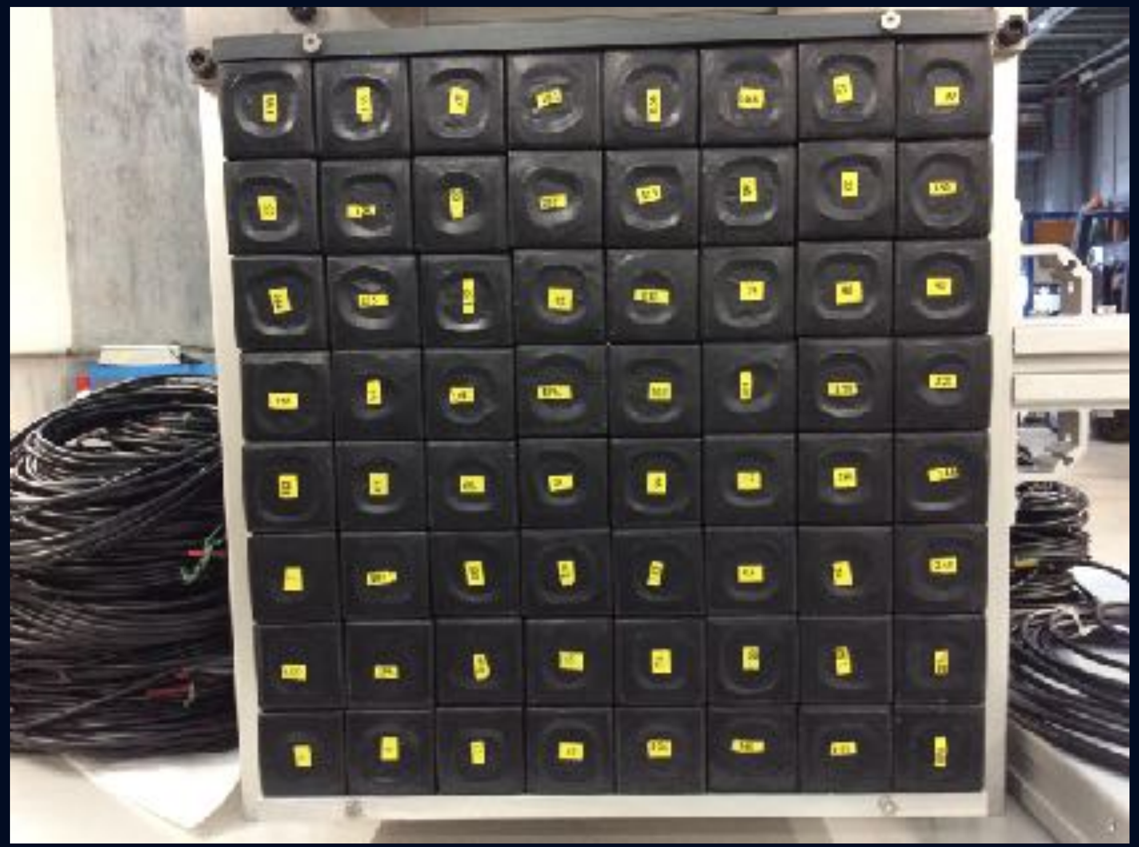
Schematic from Steffen Strauch

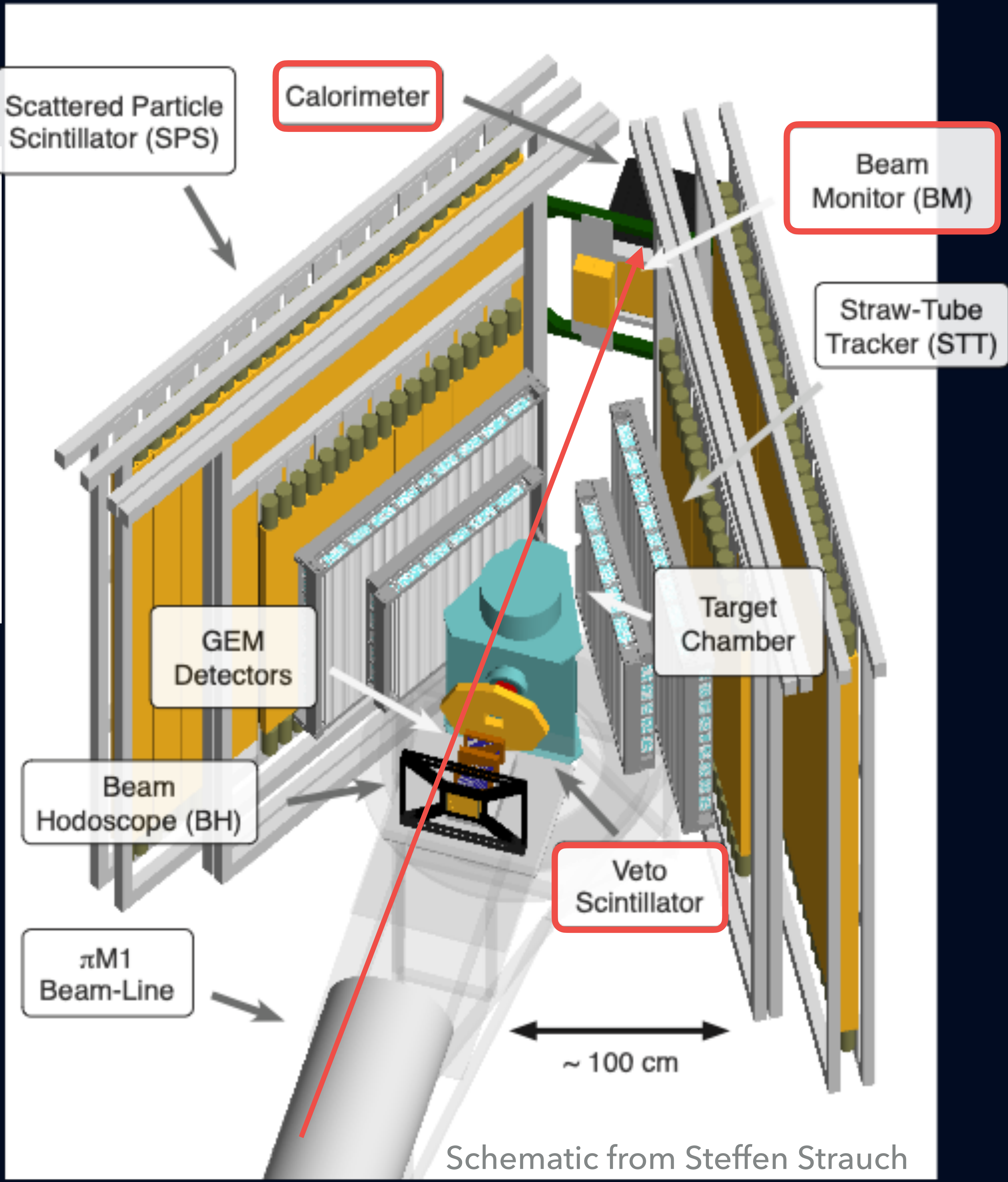
DETECTORS FOR MUSE: VETOING PARTICLES

- Veto
  - Particle decay events
- Beam Monitor
  - Moller and Bhabha scattering
- Calorimeter
  - Hard photon emission





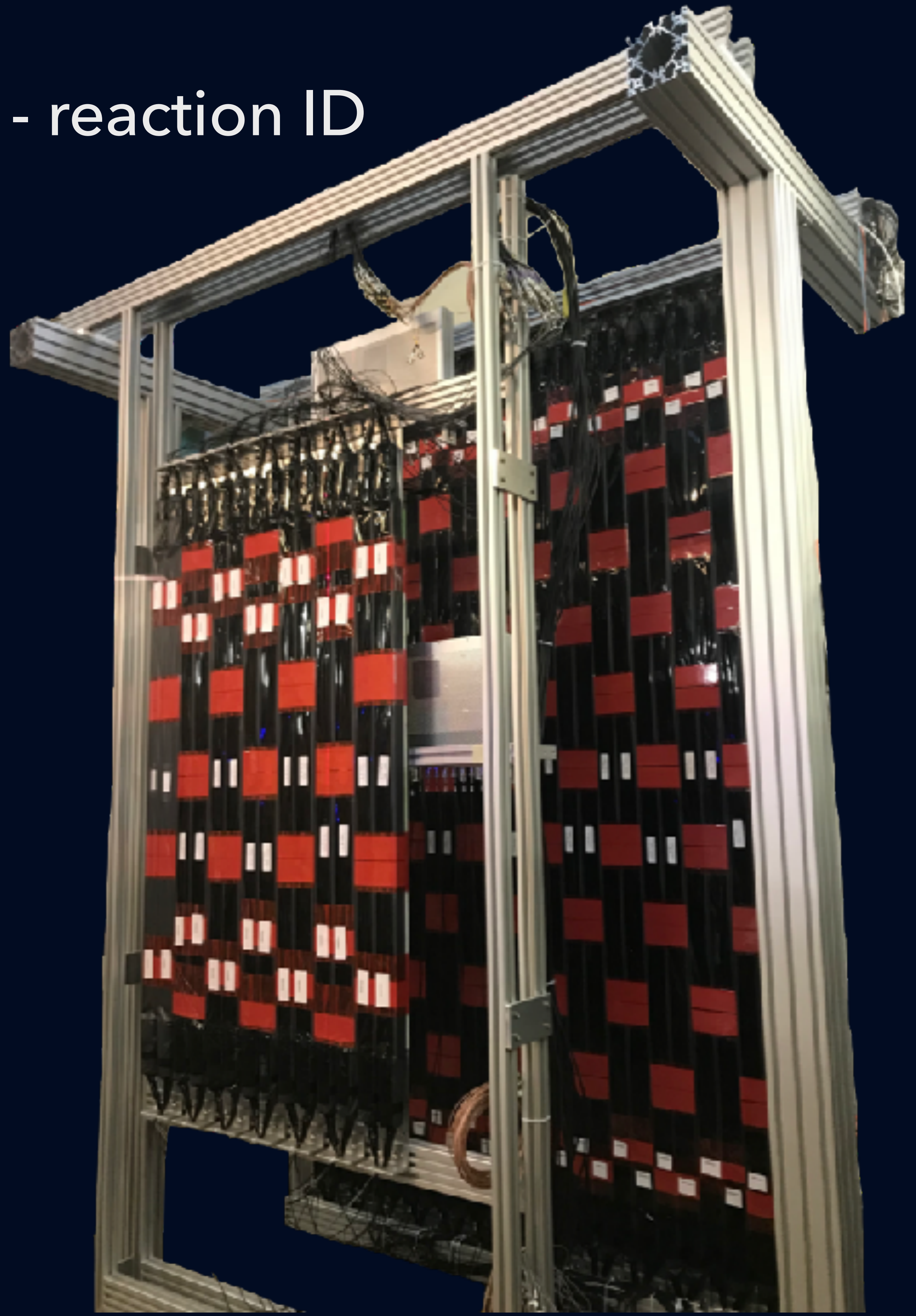


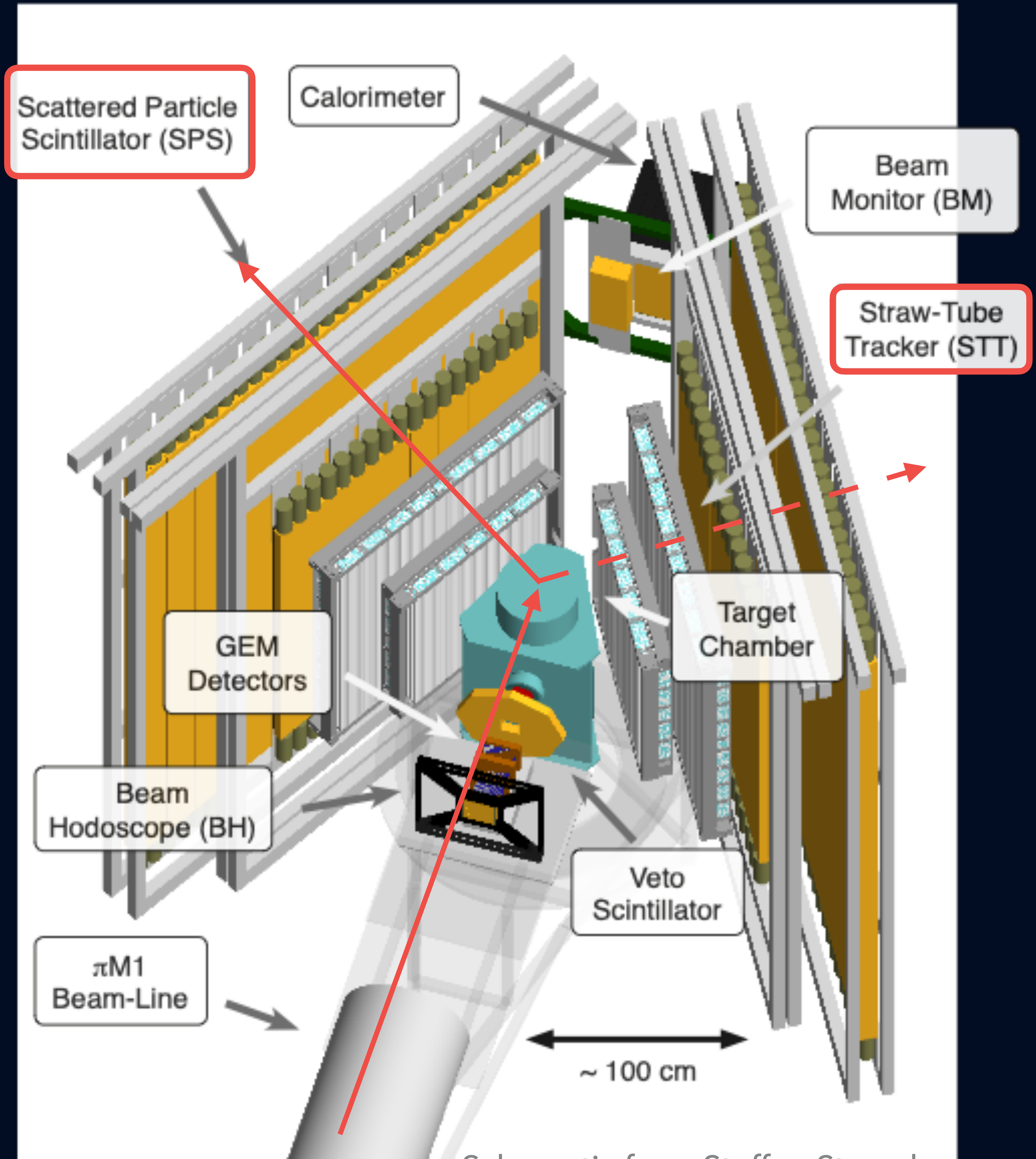


Schematic from Steffen Strauch

DETECTORS FOR MUSE: SCATTERED PARTICLES

- Straw Tube Tracker
  - Tracking for scattered particles
- Scattered Particle Scintillator
  - Timing for scattered particles - reaction ID

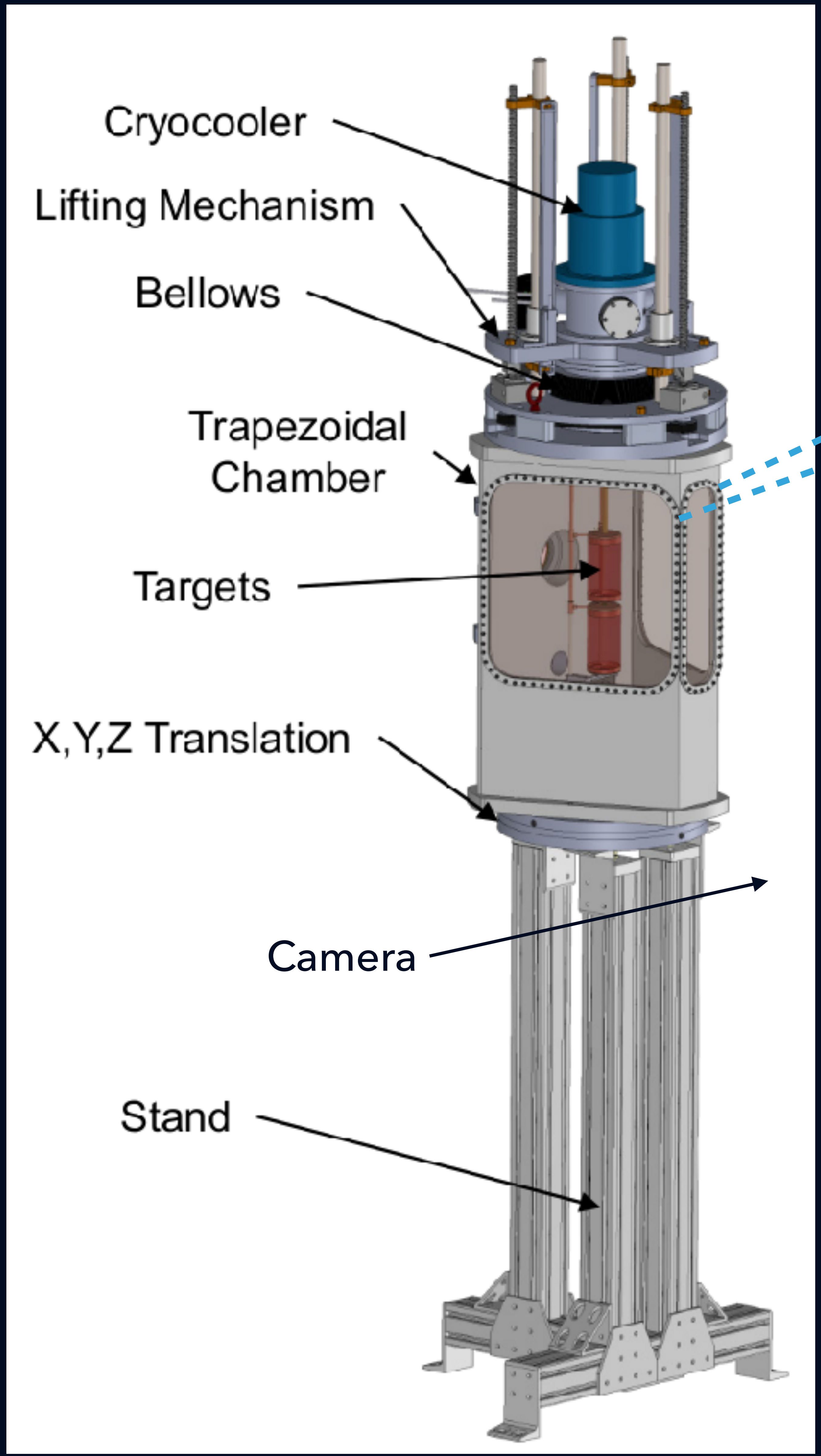




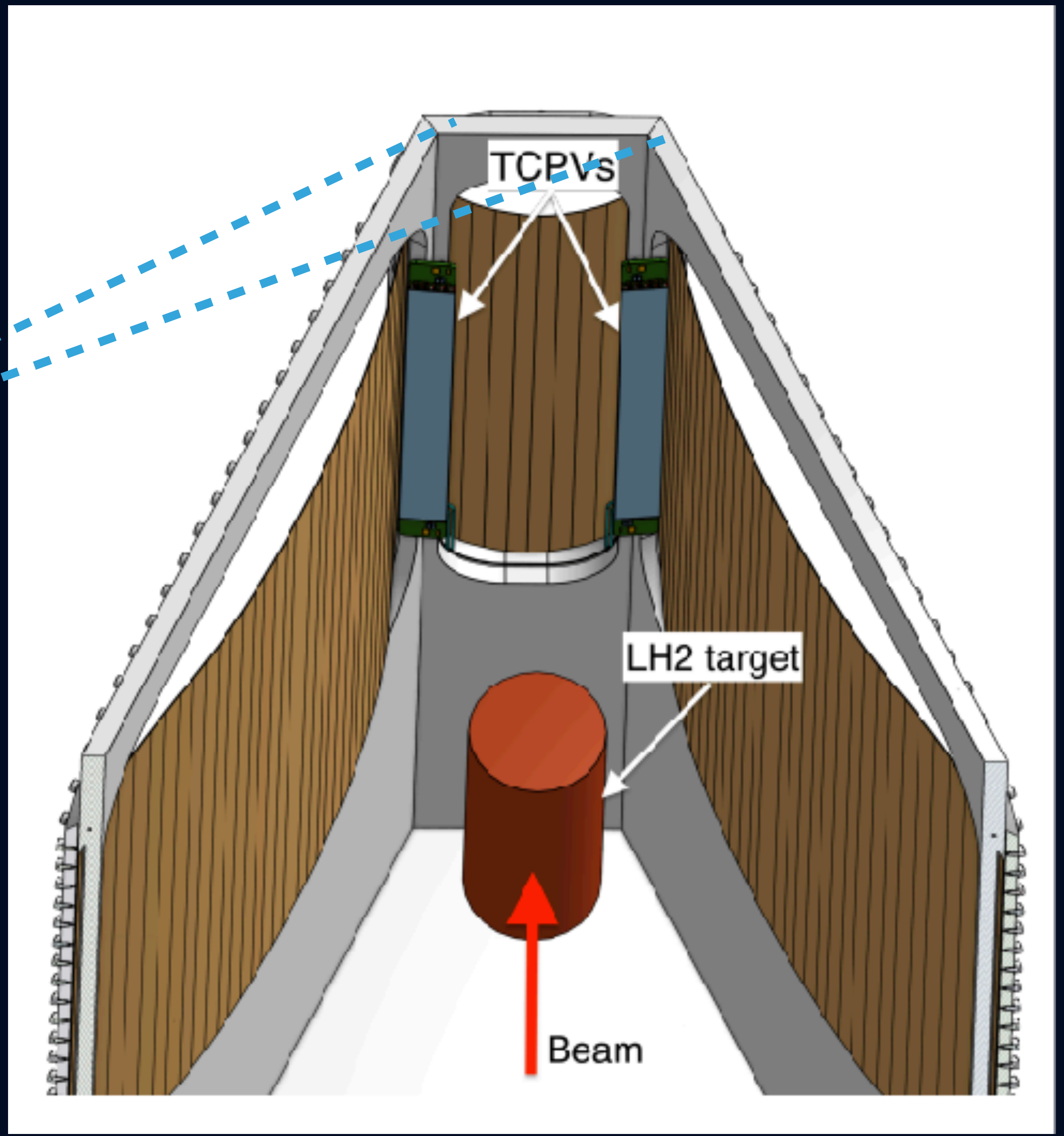
Schematic from Steffen Strauch

LIQUID HYDROGEN TARGET SYSTEM

- Components
  - Target ladder with 5 different target positions
  - Lifting mechanism
  - Cryocooler and condenser
  - Vacuum chamber
  - Target Chamber Post Vetos (TCPVs)
  - Slow control system monitors temperature, position, and pressure of the system



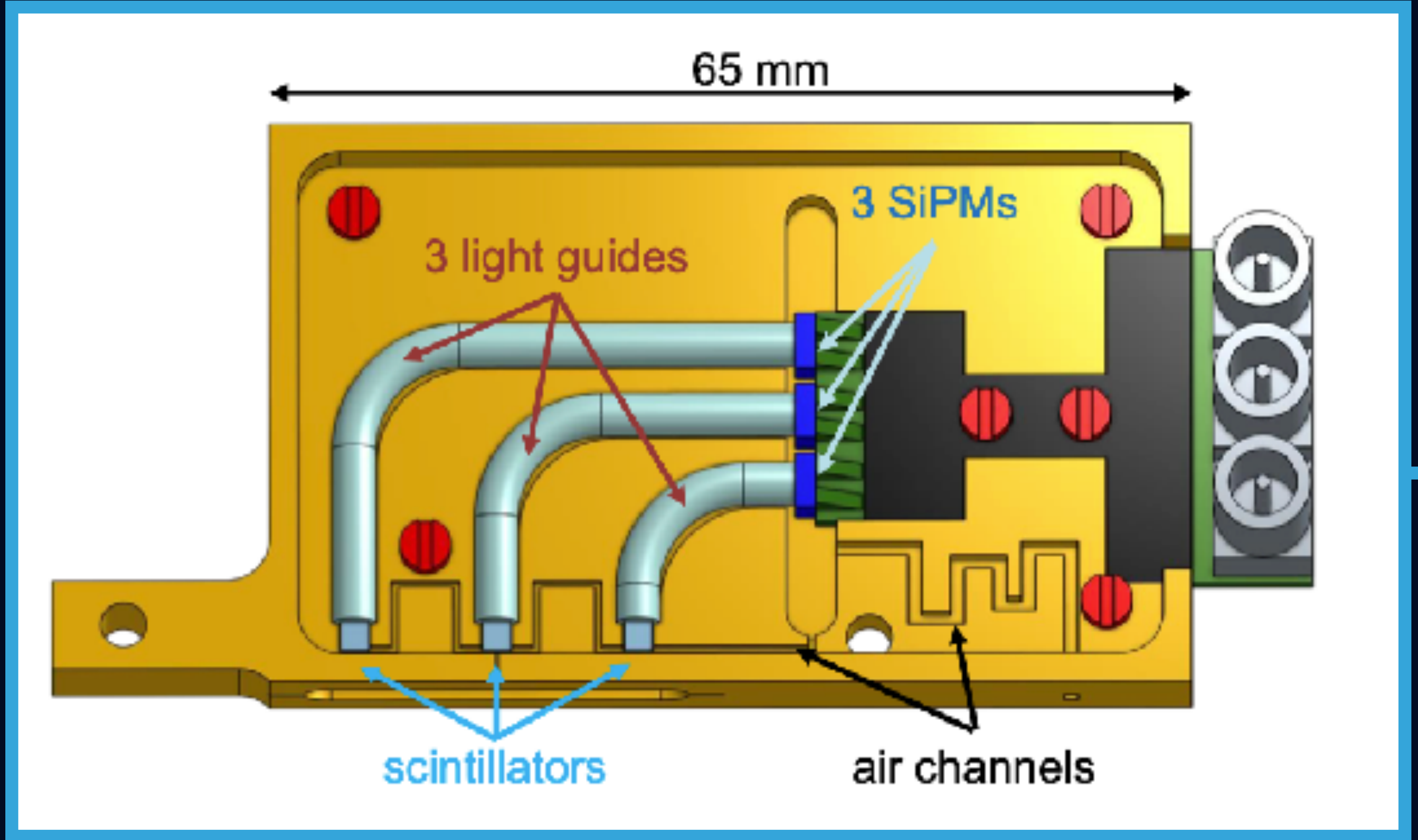
P. Roy, *et al.* (2019). A Liquid Hydrogen Target for the MUSE Experiment at PSI, NIMA

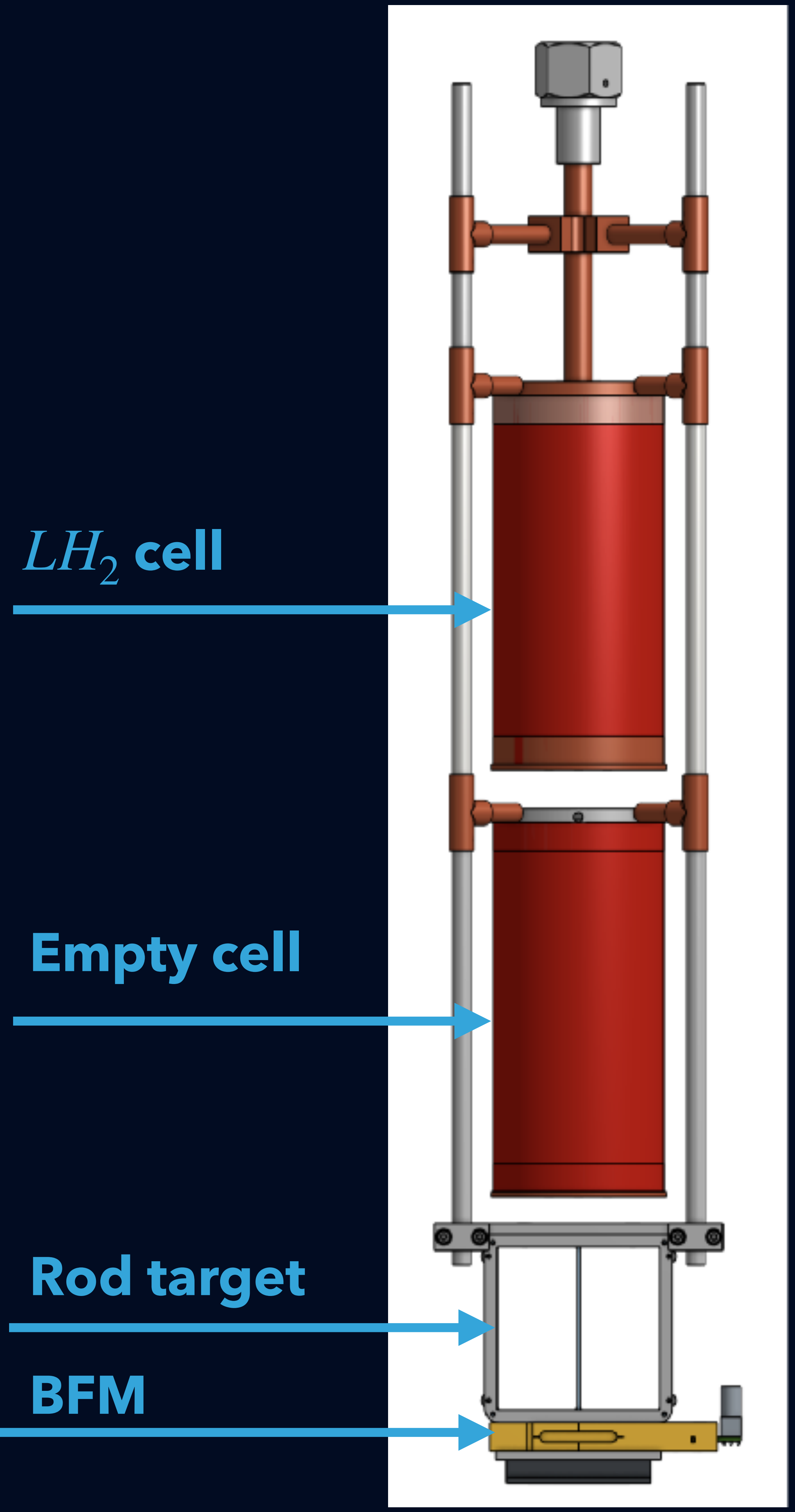


T. Rostomayan, *et al.* (*preprint submitted*). Suppression of the Background originating from the MUSE Target Vacuum Chambers Beam Exist Window Posts, NIMA

TARGET LADDER

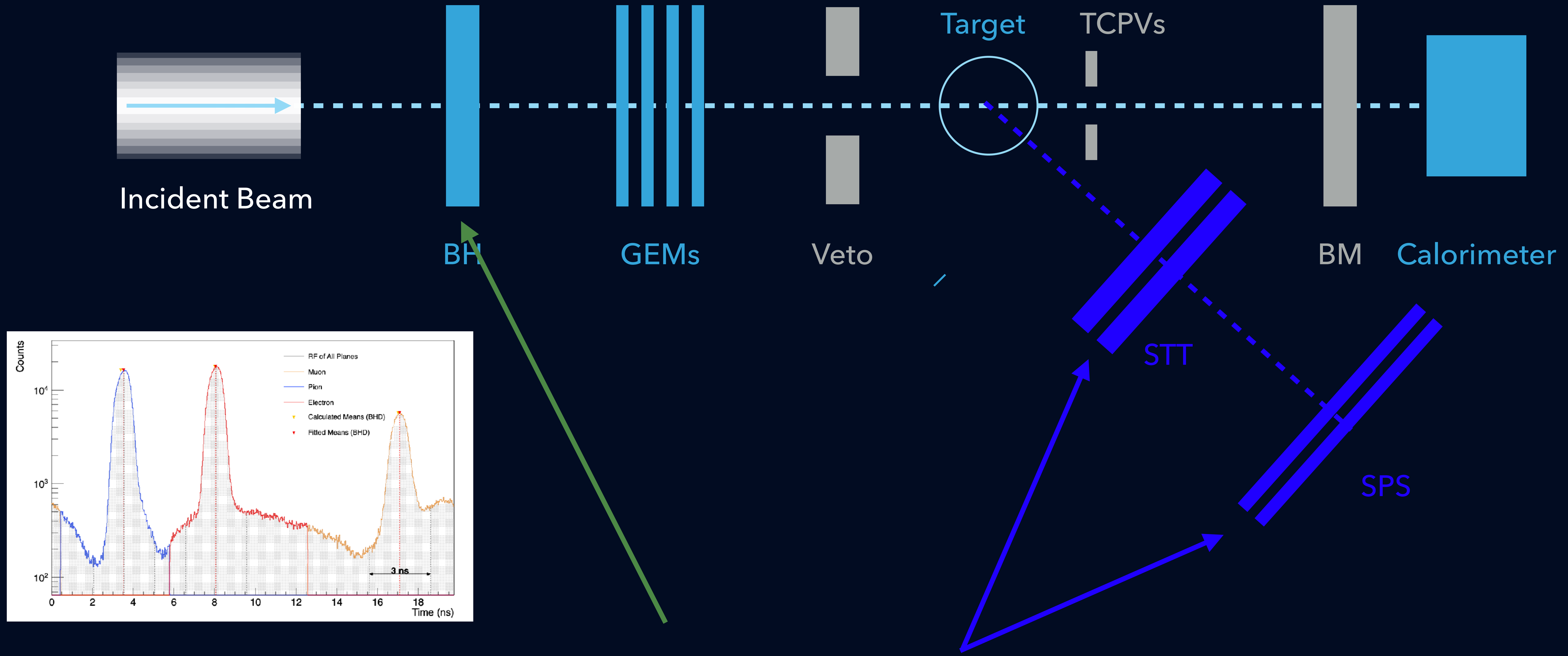
- Vertical ladder attached to condenser system
- 5 positions on ladder
- Beam focusing monitor used for beam characterization
- Bulls-eye added to bottom of ladder for precise monitoring with camera system





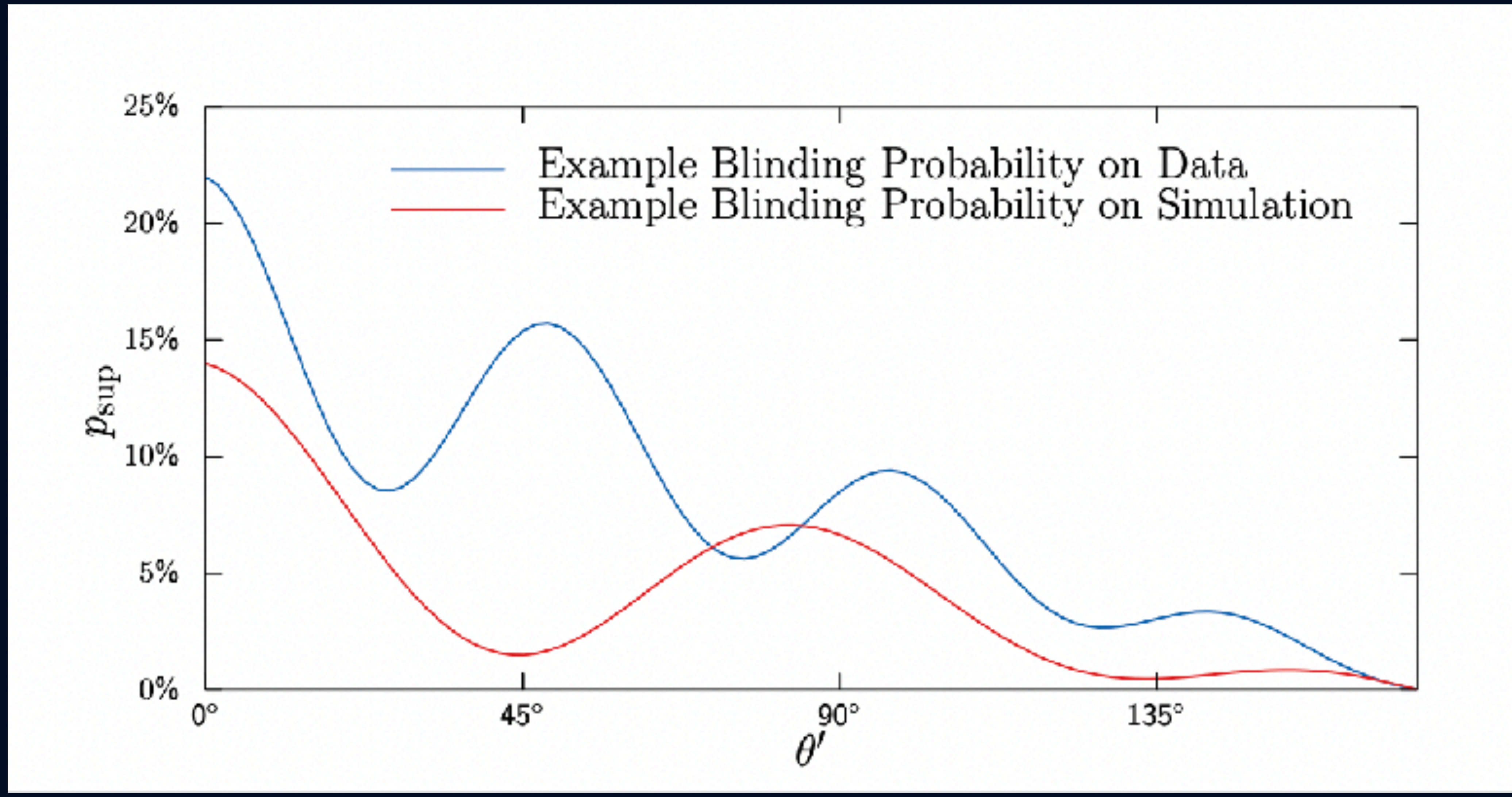
P. Roy, *et al.* (2019). A Liquid Hydrogen Target for the MUSE Experiment at PSI, NIMA

TRIGGERING ON SCATTERED EVENTS



(e OR μ) AND (scatter) AND (NOT veto)

BLINDING FOR MUSE

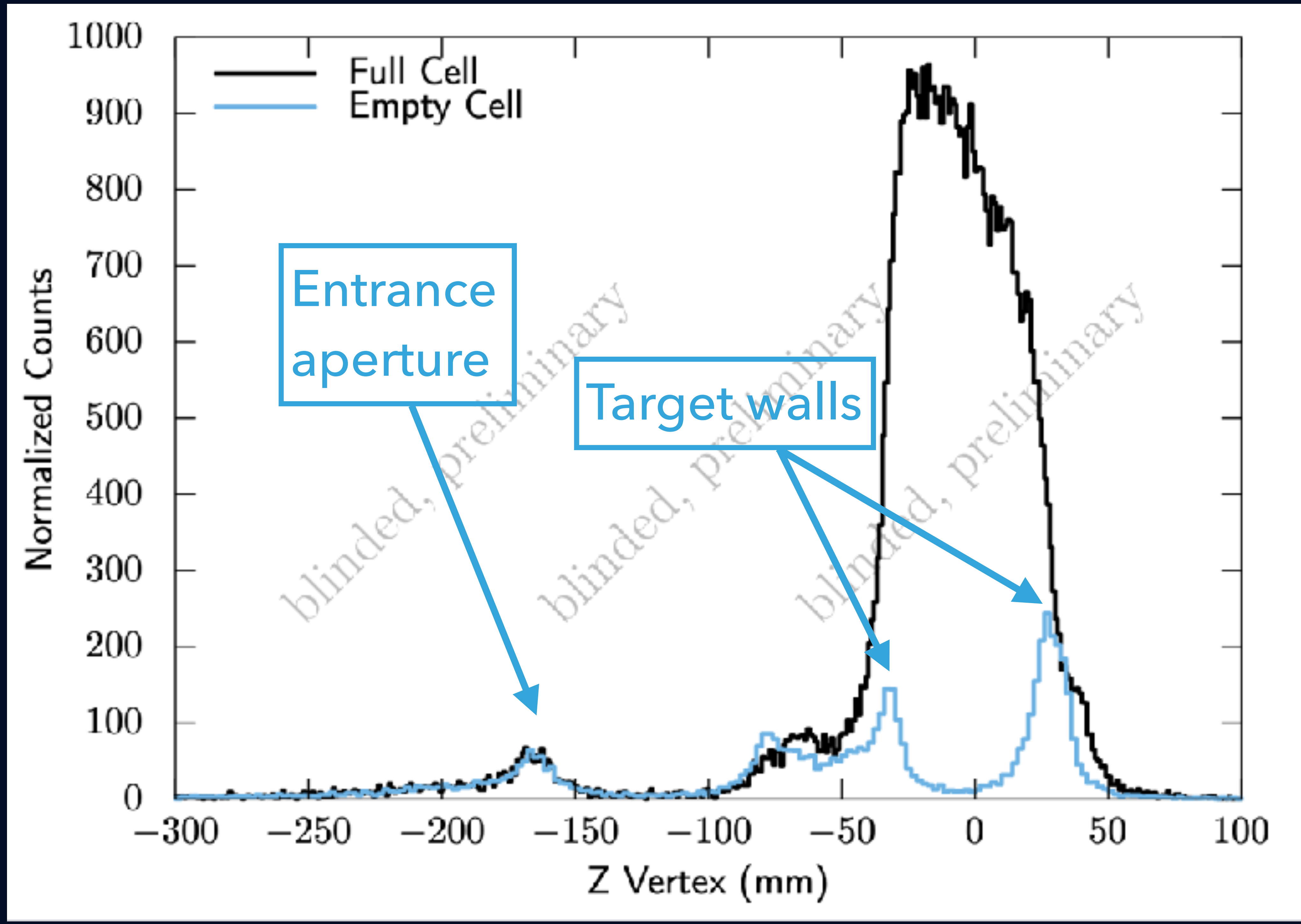


Bernauer, J.C. *et al.* (2023) arXiv:2310.11469v1

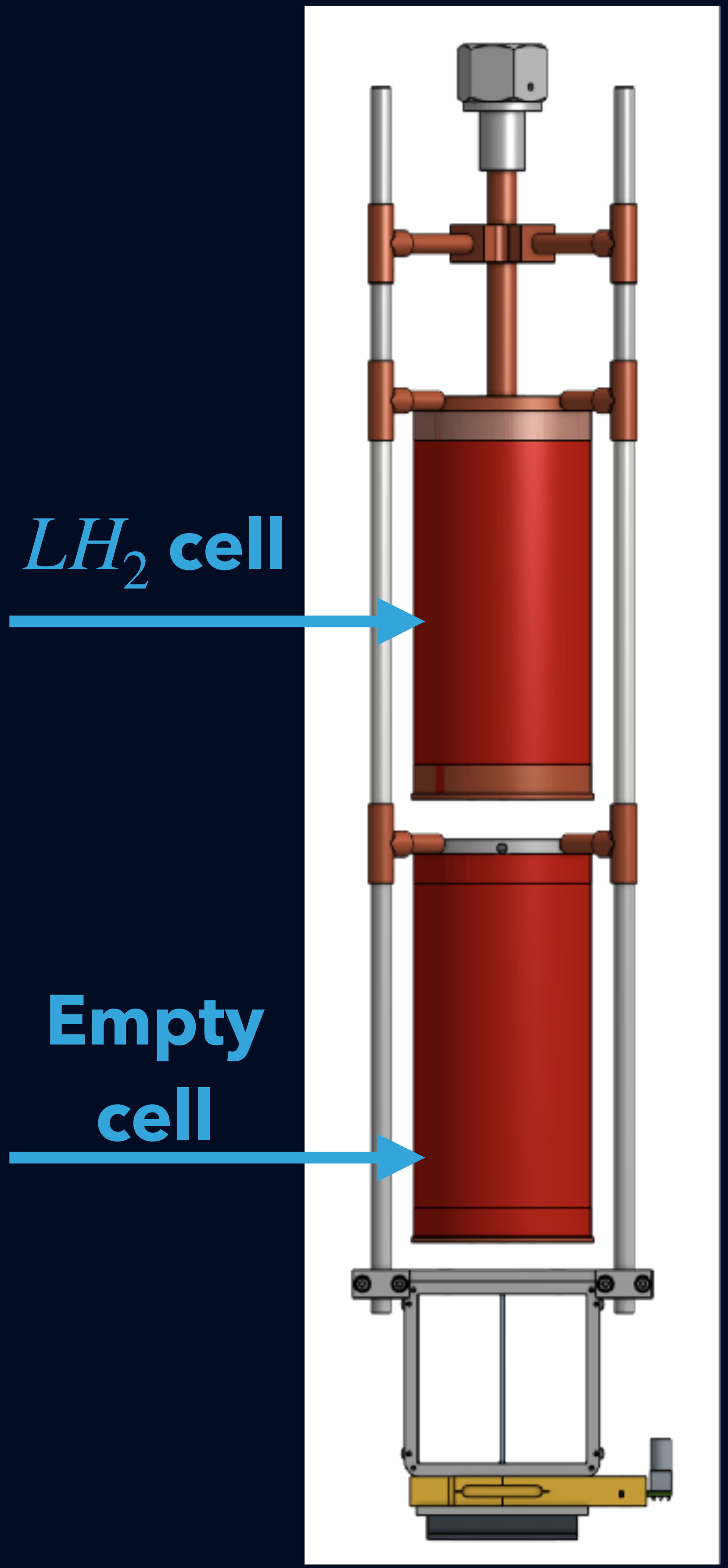
- Blinding implemented at the tracking level
  - Each scattered track has an independent blinding value
  - Blinding scheme introduces structure to cross section
- Blinding probability:

$$p_{sup} = \frac{0.2}{3}(A_i + 0.3\cos B_i\theta')(3.0 - \theta')$$

VERTEX RECONSTRUCTION



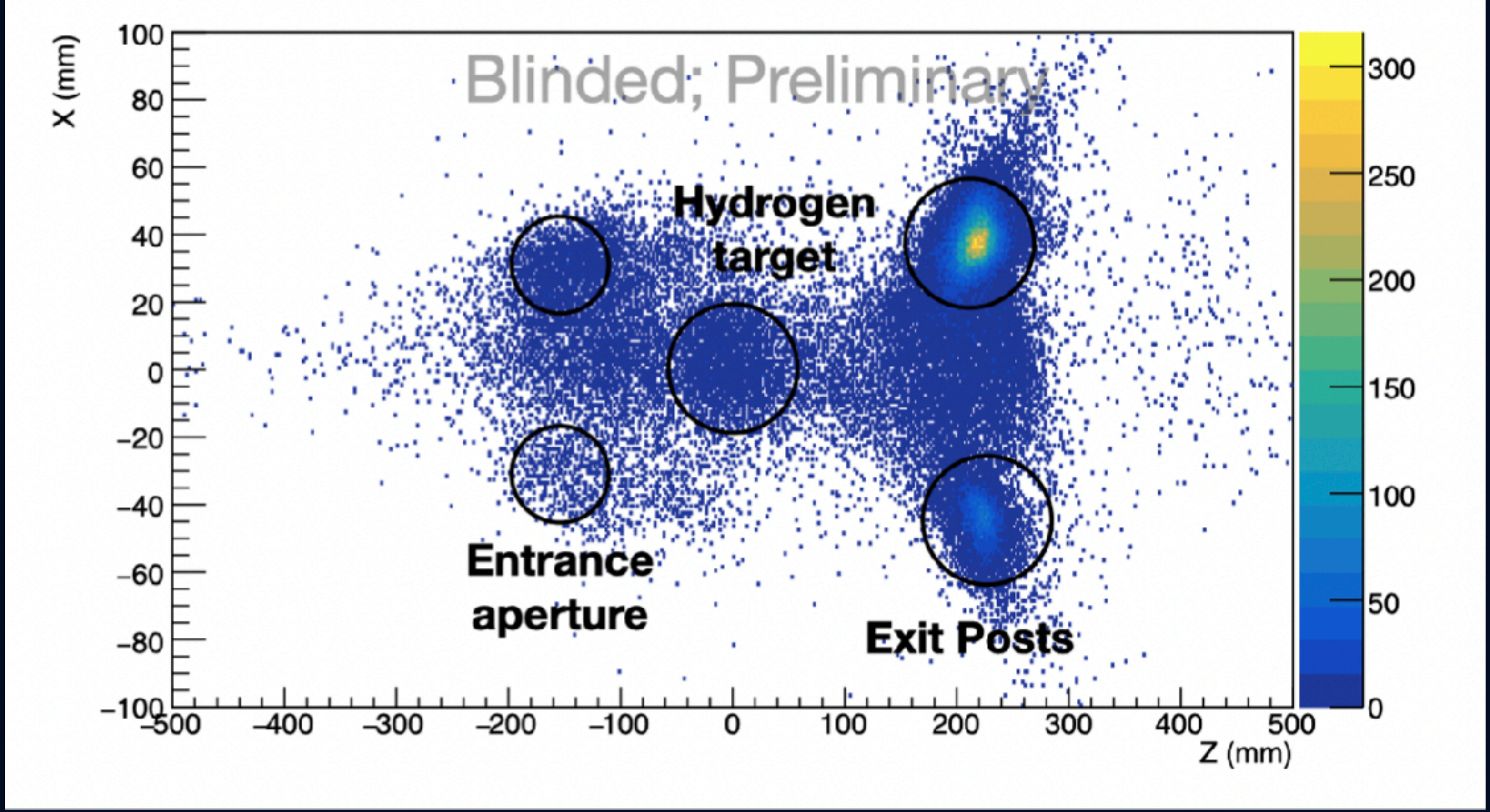
Plot from Ethan Cline

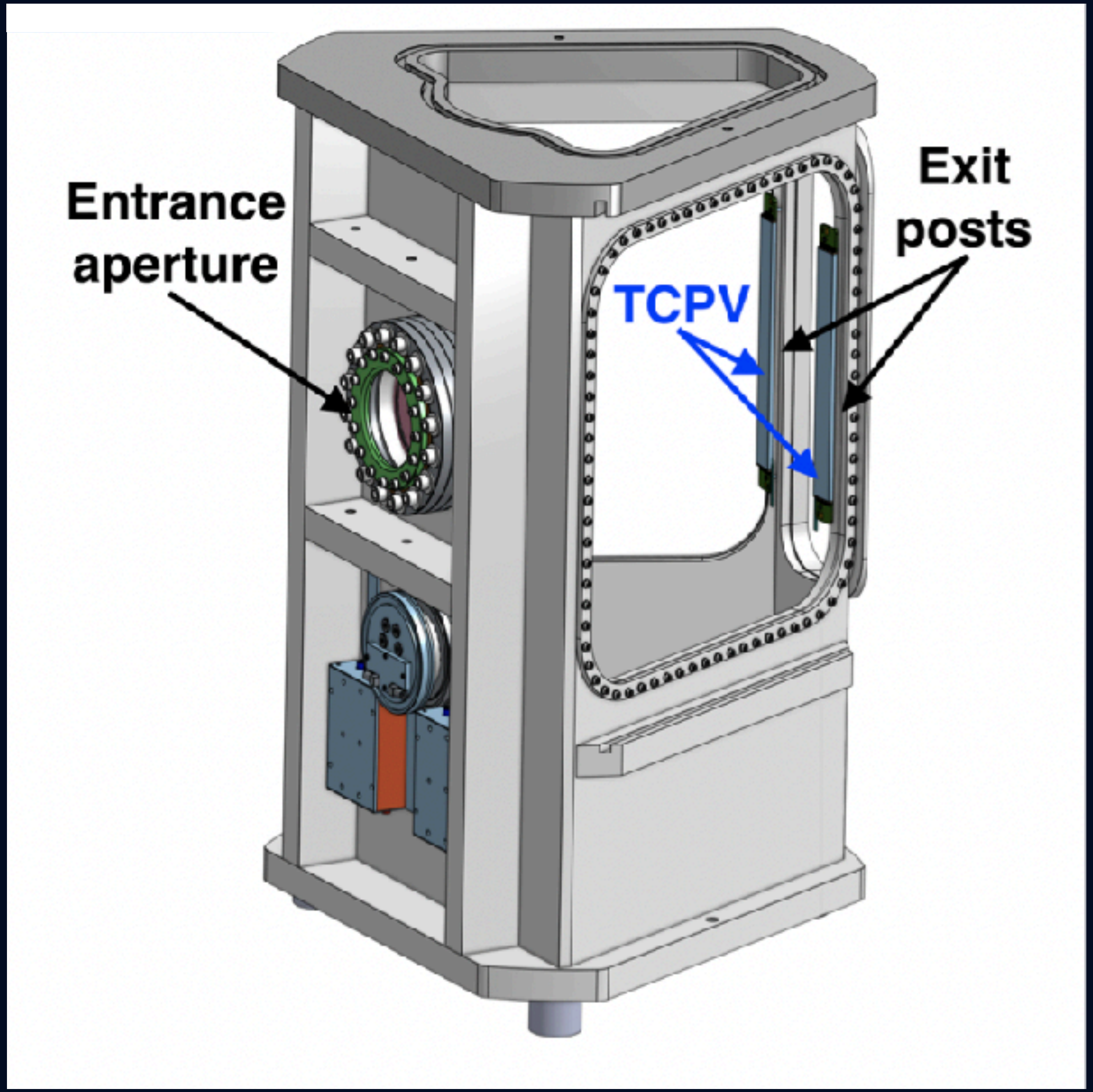


- Vertex calculated from incoming and scattered particle tracks
  - Must have coordinates within the target region
  - These coordinates used to calculate the incoming distance and scattered distance
- Background subtraction:
  $N_{H_2} = N_{full} - N_{empty}$

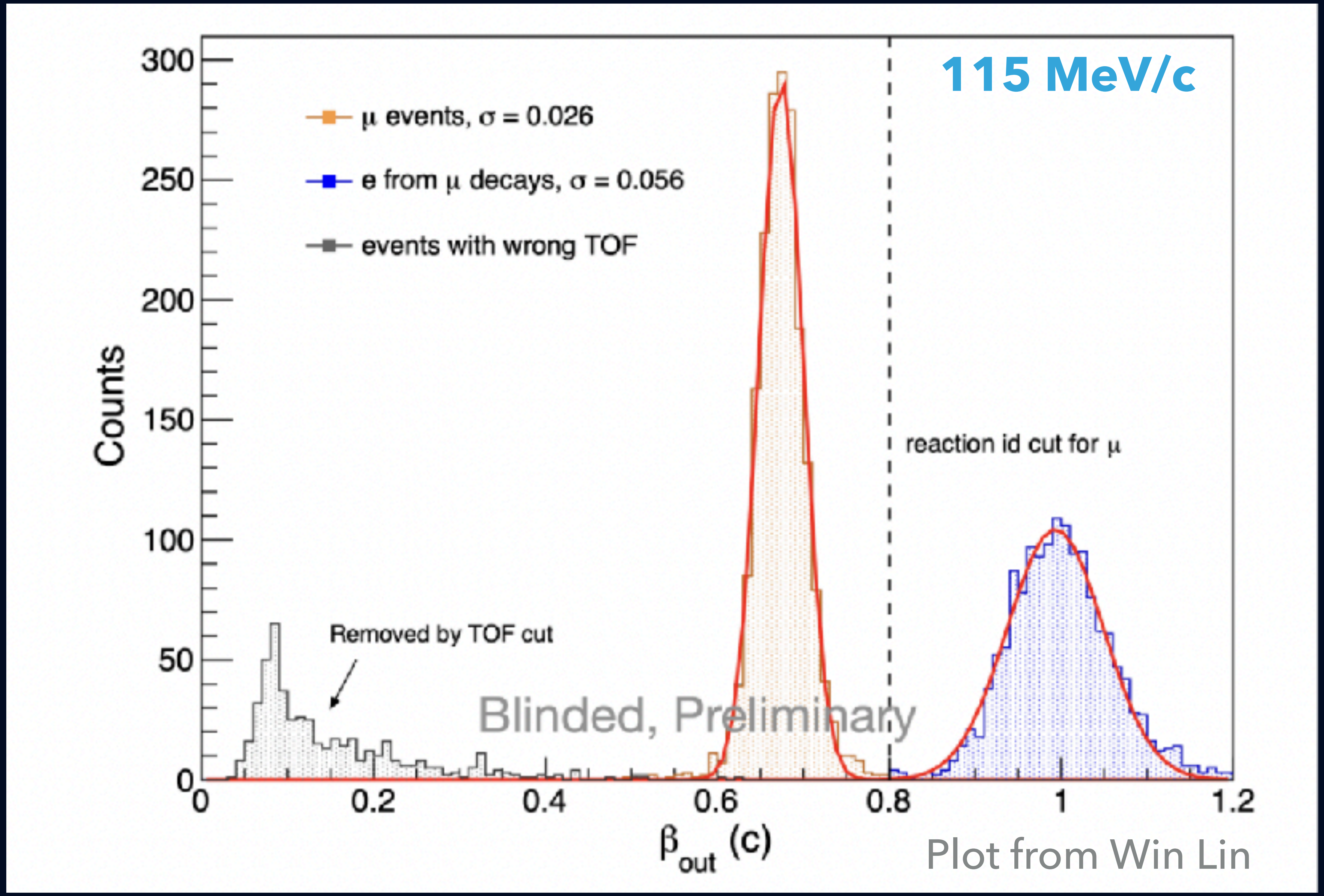
VERTEX RECONSTRUCTION

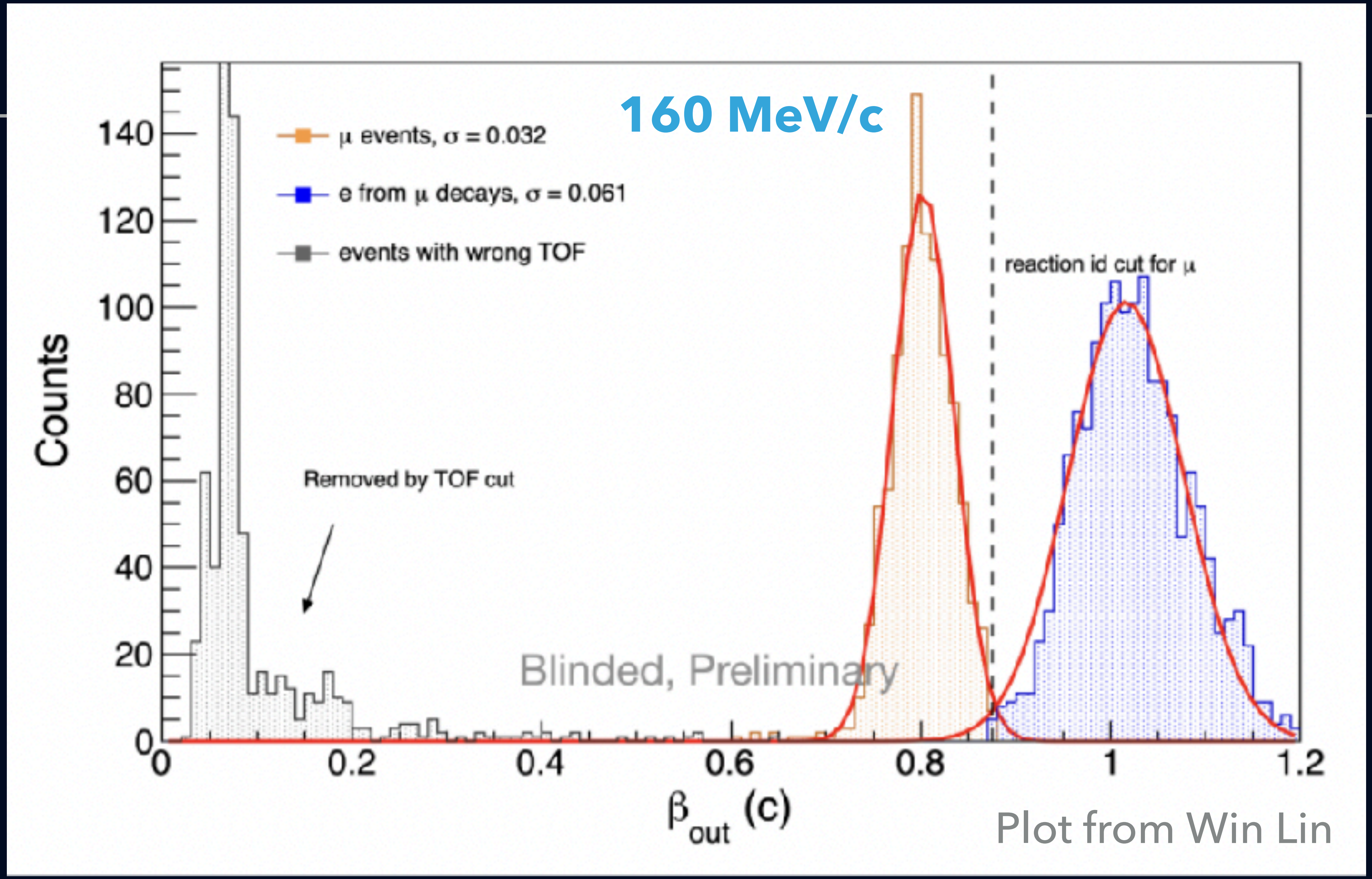
- Vertex reconstruction for hydrogen target at -115 MeV/c

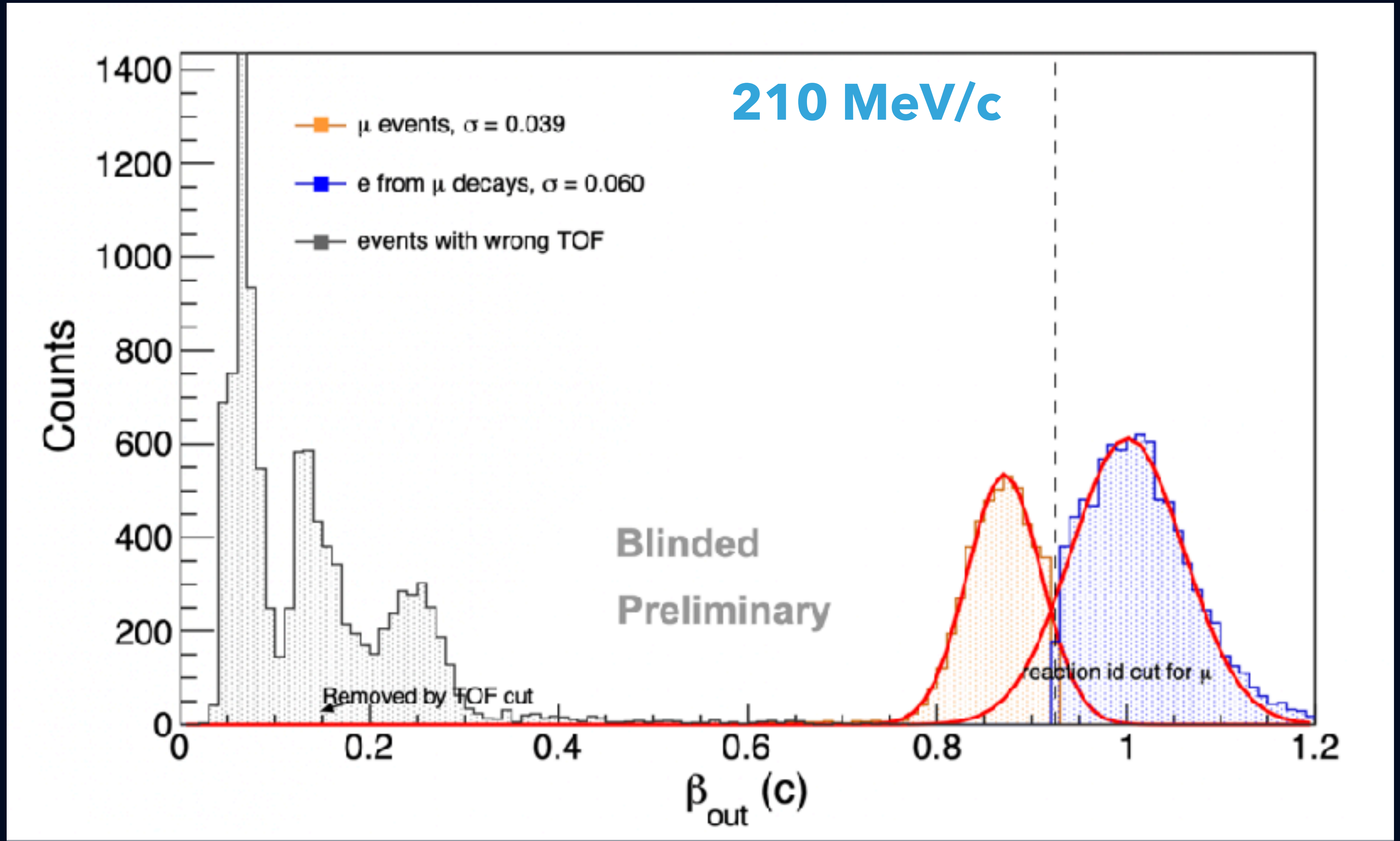




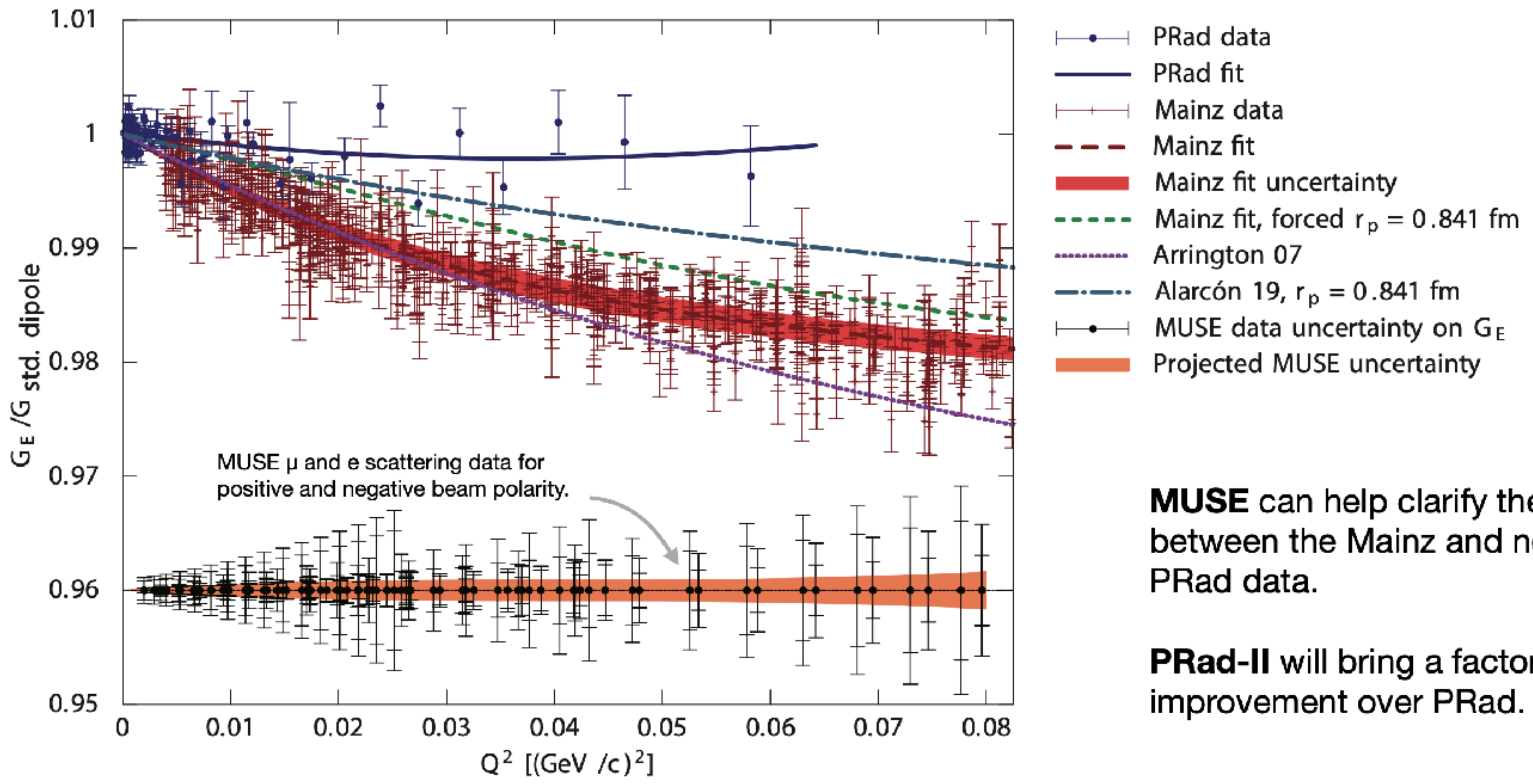
REACTION IDENTIFICATION: MUON DECAYS IN FLIGHT







PROJECTED SENSITIVITIES FOR MUSE



MUSE can help clarify the tension between the Mainz and new PRad data.

PRad-II will bring a factor of 4 improvement over PRad.

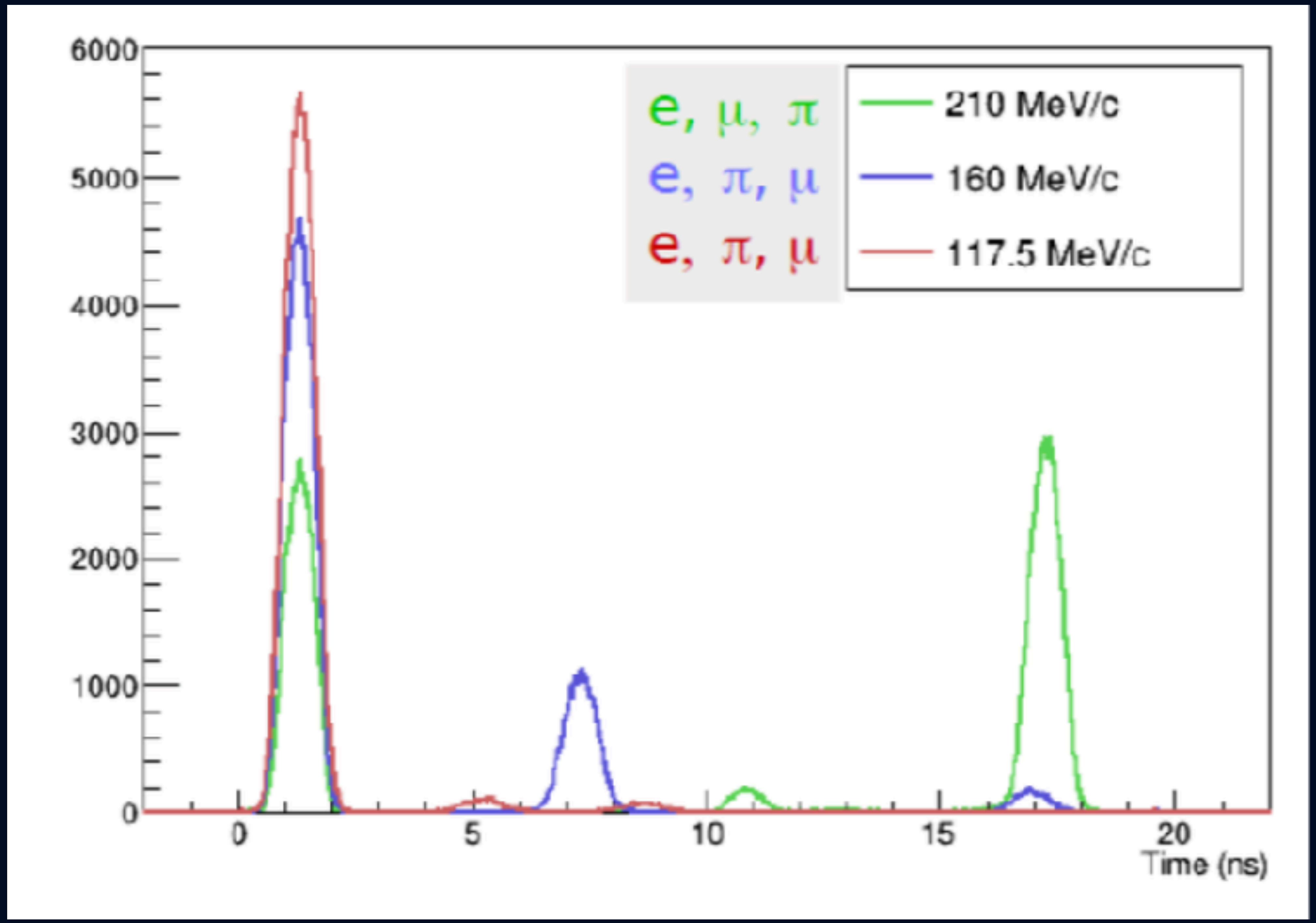
E. Cline, et al., SciPost Phys. Proc. 5, 023 (2021)

SUMMARY

- MUSE currently taking data
  - ~5 months of data taking
  - Will continue taking data through 2025
- In the process of extracting blinded, preliminary cross sections
- Will unblind and publish results after the data is analyzed fully

BACK UP SLIDES

MUSE: KINEMATICS



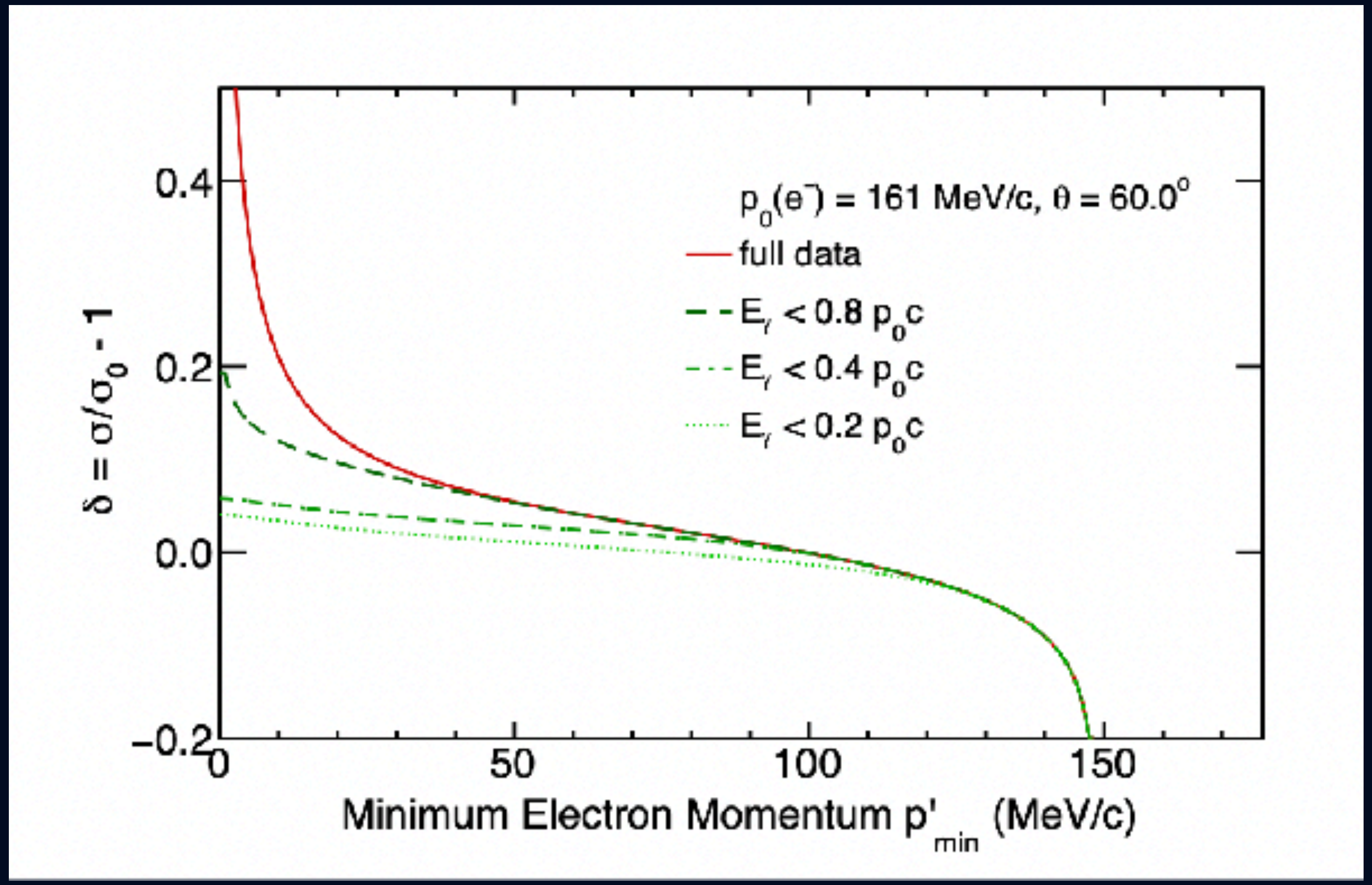
Gilman, R. et al. (2017). arXiv1709.09753

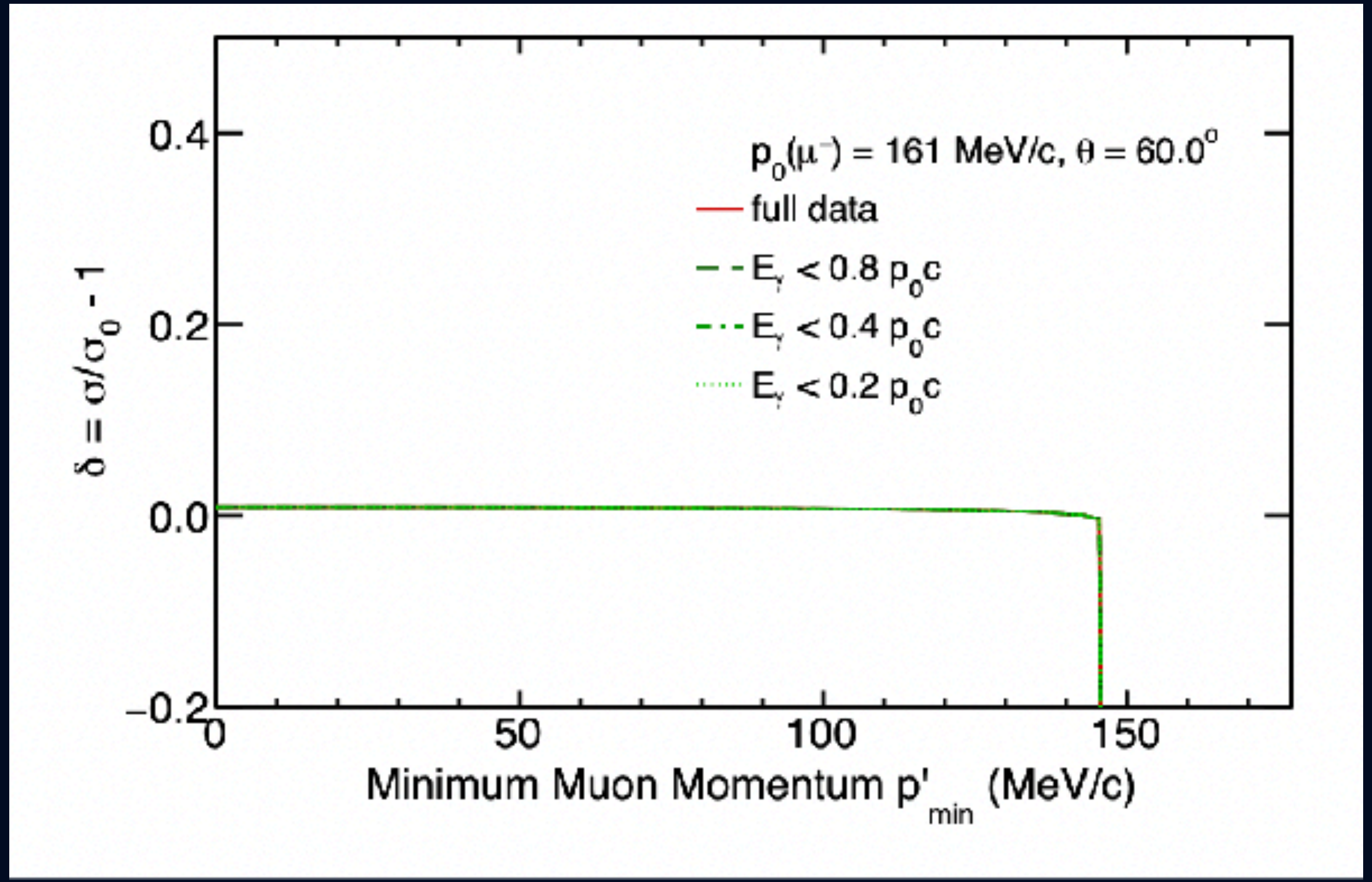
- Scattering events for both muons and electrons
  - Allows for testing lepton universality
- Measuring both charge polarities
  - Access to two photon exchange effects

P, MeV/c	Polarity	e (%)	μ (%)	π (%)
115	+	96.7	2.1	0.9
153	+	63.0	12.0	25.0
210	+	12.1	8.0	79.9
115	-	98.5	0.9	0.6
153	-	89.9	3.2	6.8
210	-	47.0	4.0	49.0

RADIATIVE CORRECTIONS

- Radiative event generator not yet implemented in simulation
  - Total effects can be up to a 25% correction
- Studies done to determine size of effects for different parameters
  - Most of radiative tail can be removed by vetoing on hard ISR in the calorimeter
  - Limit radiative corrections on cross section to 7% at most
    - Uncertainty less than 0.5%





L. Li et al., Eur. Phys. J. A 60:8 (2024)