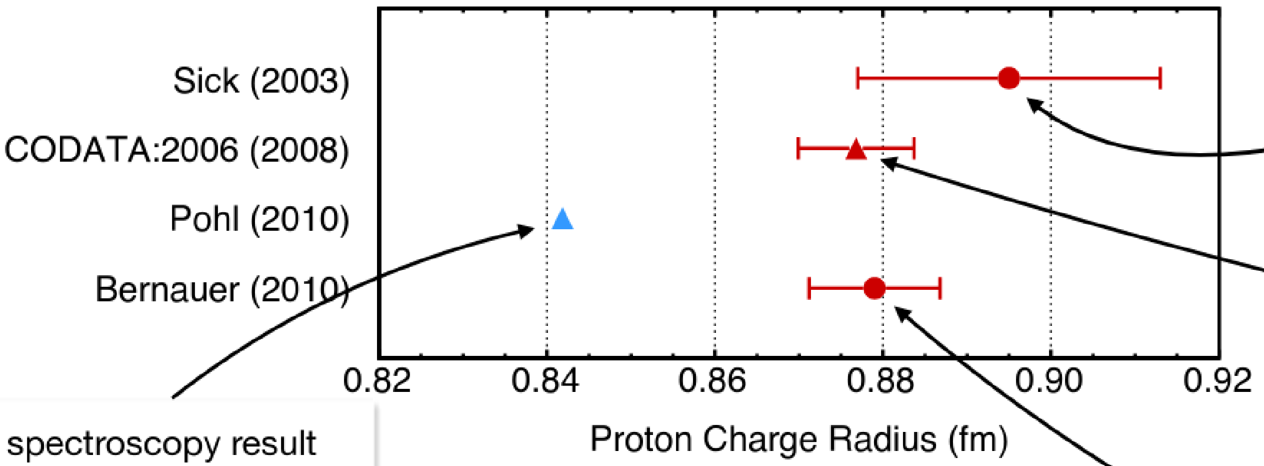
Status of the MUSE experiment

Dr. Tigran Armand Rostomyan :: Scientist :: Paul Scherrer Institute
Yerevan, Armenia, 02.Oct.2024

THE PROTON RADIUS PUZZLE (2010)



Analysis of world electron-scattering data

Analysis of hydrogen spectroscopy data Committee on Data for Science and Technology (CODATA)

r_p = 0.8768(69) fm

Muonic-hydrogen spectroscopy result

Ten times more precise, but 4% smaller than previously accepted value

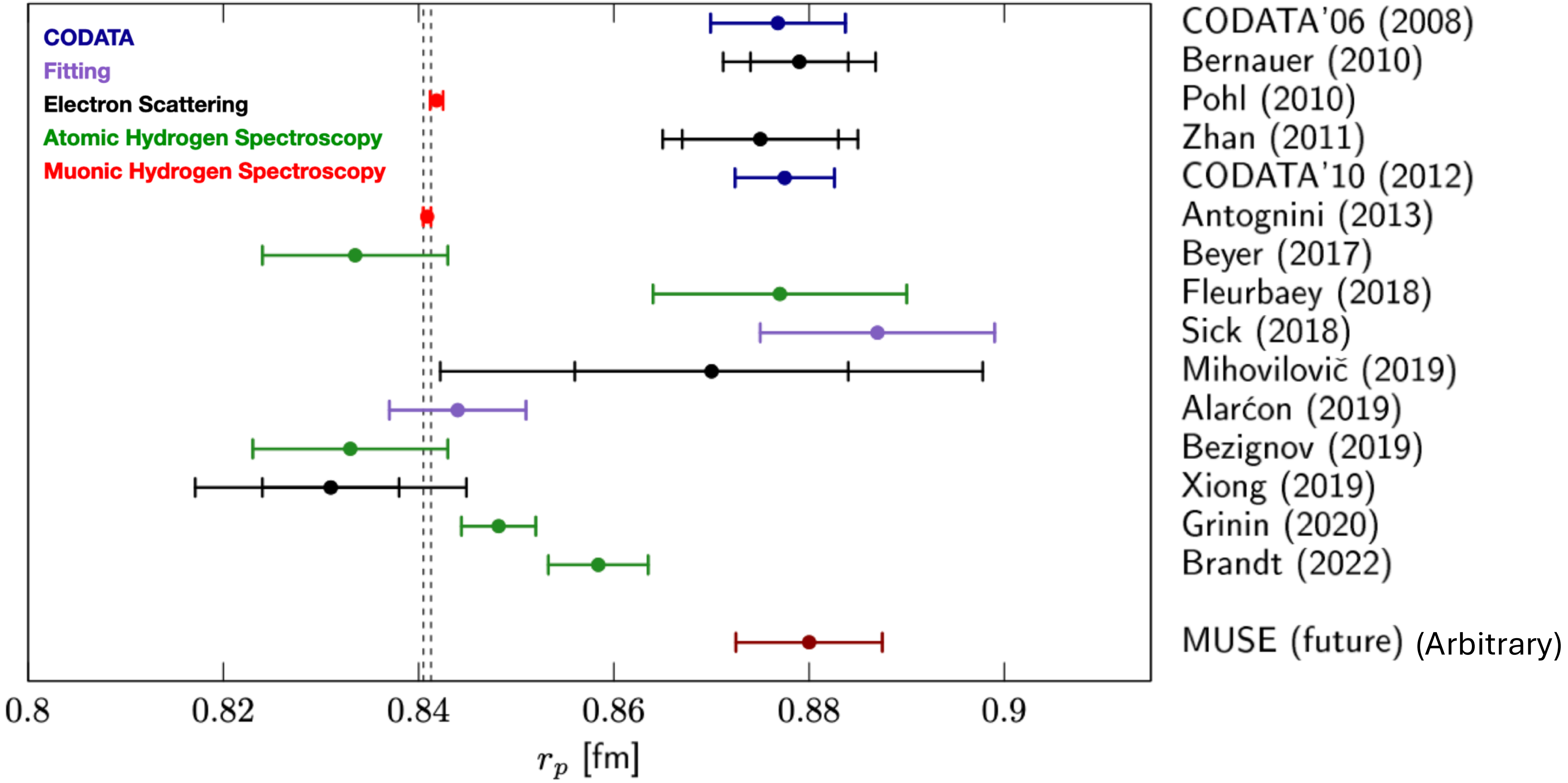
r_p = 0.84184(67) fm

Analysis of MAMI electron-scattering experiment

In 2010, the discrepancy between muonic and electronic measurements of the proton charge radius was a 5σ effect and grew to a 7σ effect in 2013.

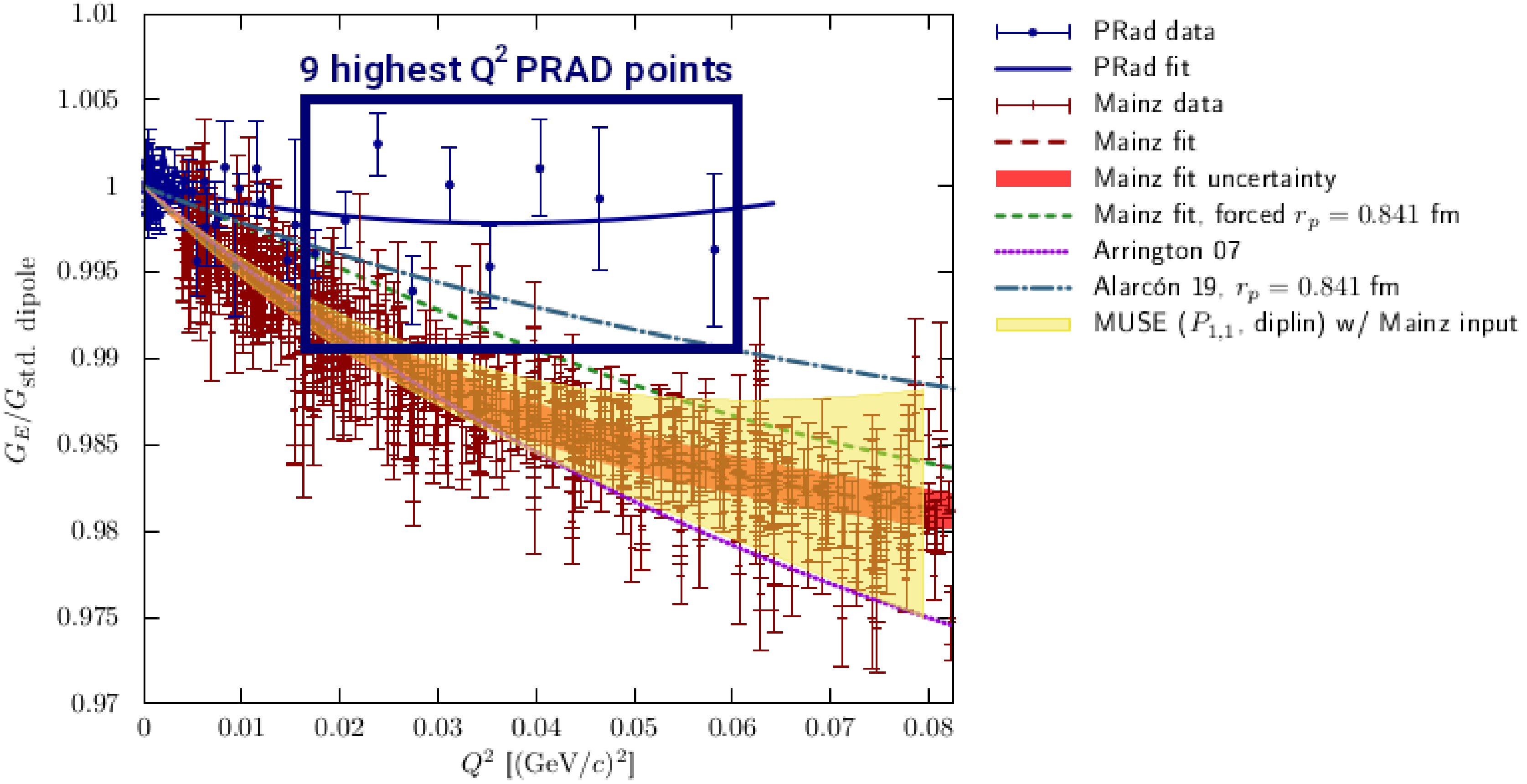
I. Sick, PLB 576, 62 (2003); P.J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008); J.C Bernauer et al., PRL 105, 242001 (2010); R. Pohl et al., Nature 466, 213 (2010)

Recent situation



Newer electronic measurements tend to show a smaller radius
Today some tension between experiments persists…

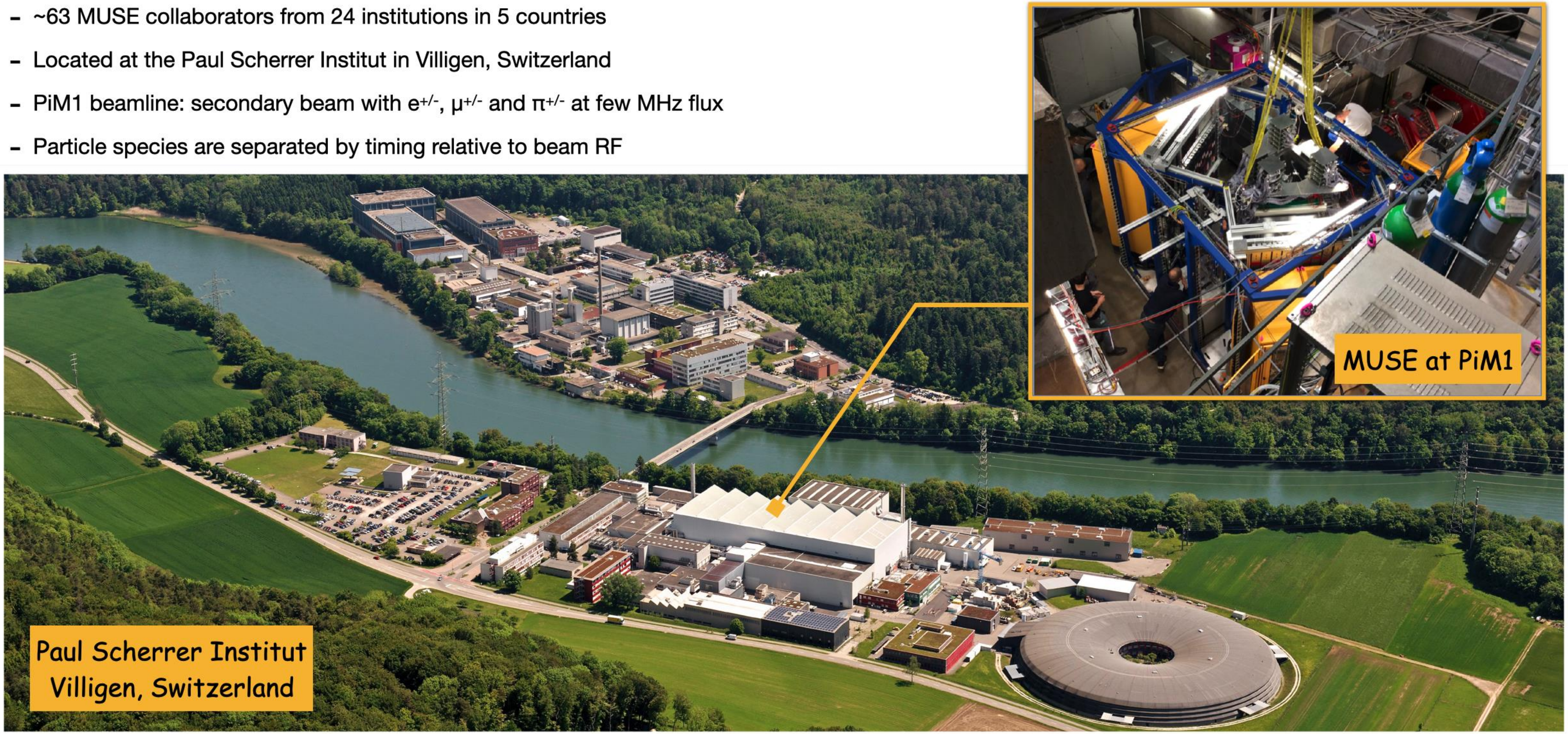
Disagreement of different Data



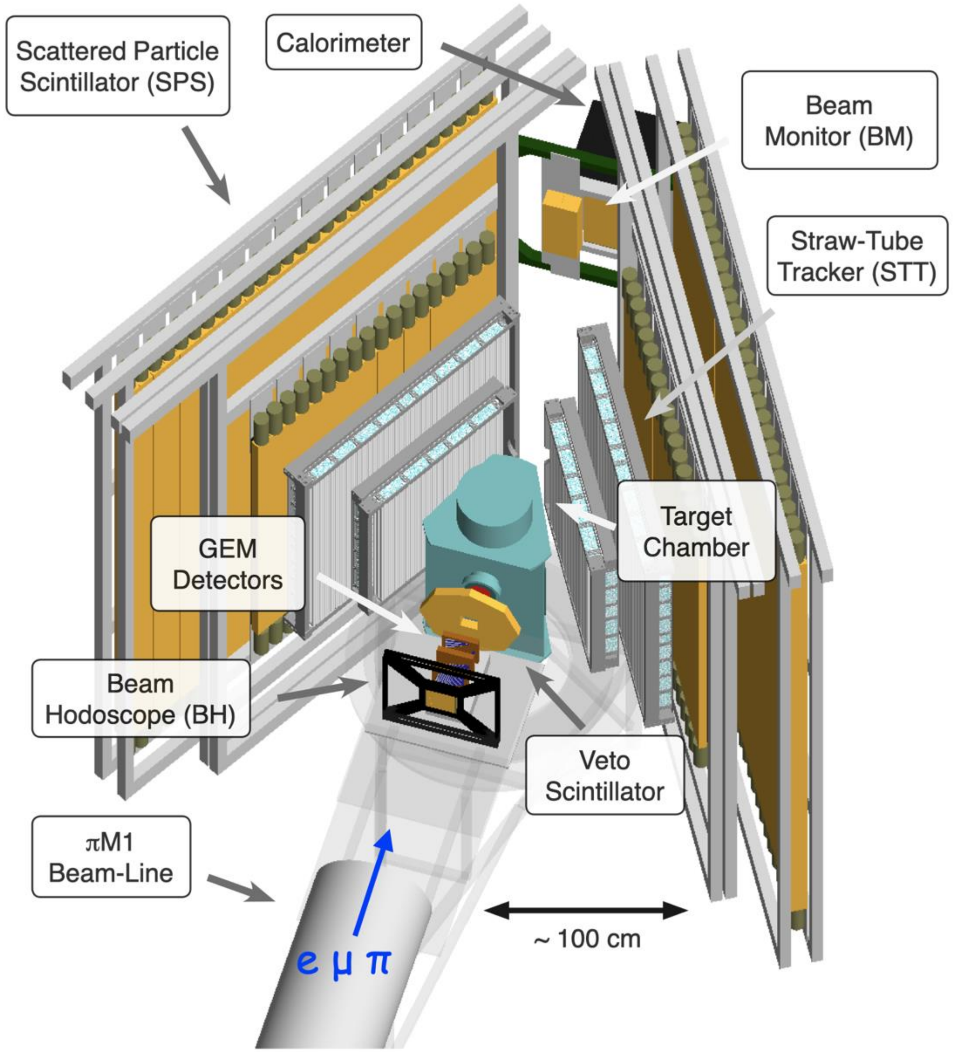
1,5% disagreement between **PRad** highest Q^2 and **Mainz** form factor values leads to **3,0%** discrepancy in cross-sections. According to *Domínguez, Alarcón and Weiss* dispersion + effective field theory calculations (**radius** is treated as a **free parameter**): this discrepancy leads to ~**0,04 fm** difference in extraction of the radius.

The MUon proton Scattering Experiment (MUSE)

- ~63 MUSE collaborators from 24 institutions in 5 countries
- Located at the Paul Scherrer Institut in Villigen, Switzerland
- PiM1 beamline: secondary beam with $e^{+/-}$, $\mu^{+/-}$ and $\pi^{+/-}$ at few MHz flux
- Particle species are separated by timing relative to beam RF



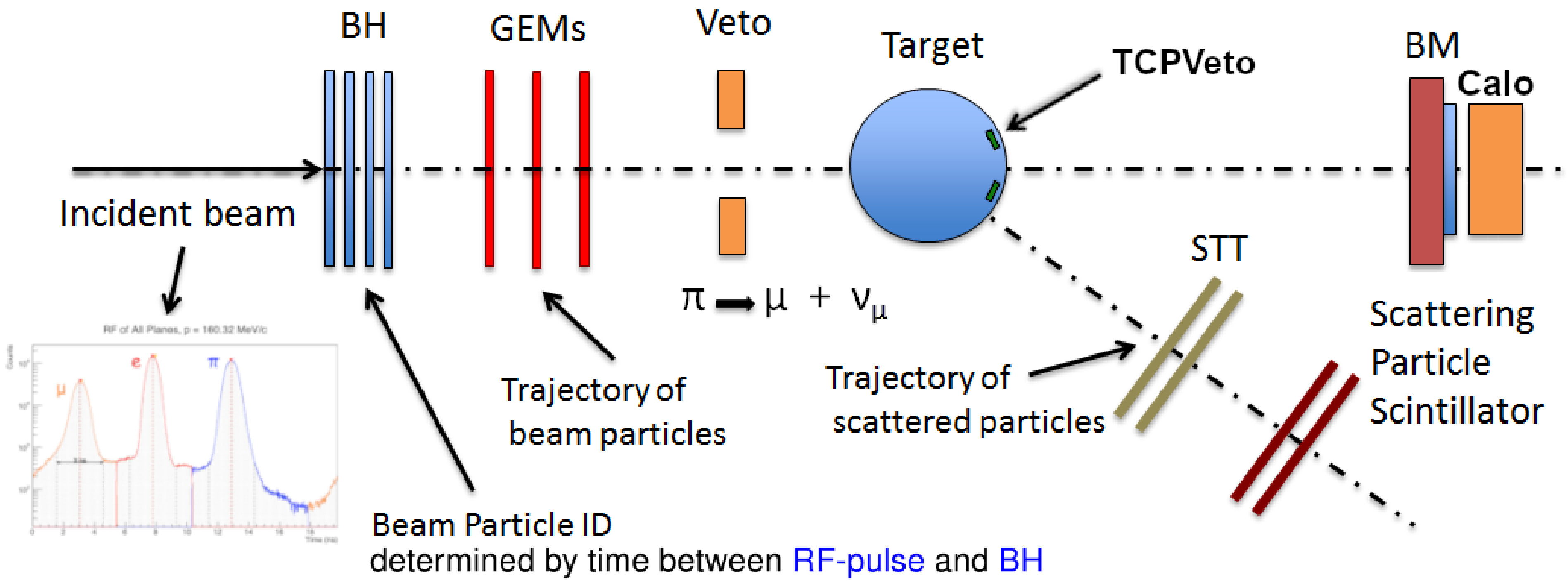
Muon Scattering Experiment (MUSE)



Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle	20 - 100 degrees
Q^2 range for e	0.0016 - 0.0820 GeV^2/c^4
Q^2 range for μ	0.0016 - 0.0799 GeV^2/c^4

- MUSE will directly compare ***ep*** and ***μp*** scatterings at sub-percent level precision at 3 different beam momenta in **πM1** area at PSI
- Low Q^2 kinematics for sensitivity to the **proton charge radius**
- Independent and combined determination of the charge form factor and Proton Charge Radius in ***e*$^{\pm}$*p*** and ***μ*$^{\pm}$*p*** elastic scatterings ⟶ tests lepton universality
- With ***μ*$^{+}$**, ***μ*$^{-}$** and **e^{+}**, ***e*$^{-}$** ⟶ study Two-Photon Exchange (**TPE**) mechanisms

MUSE Trigger



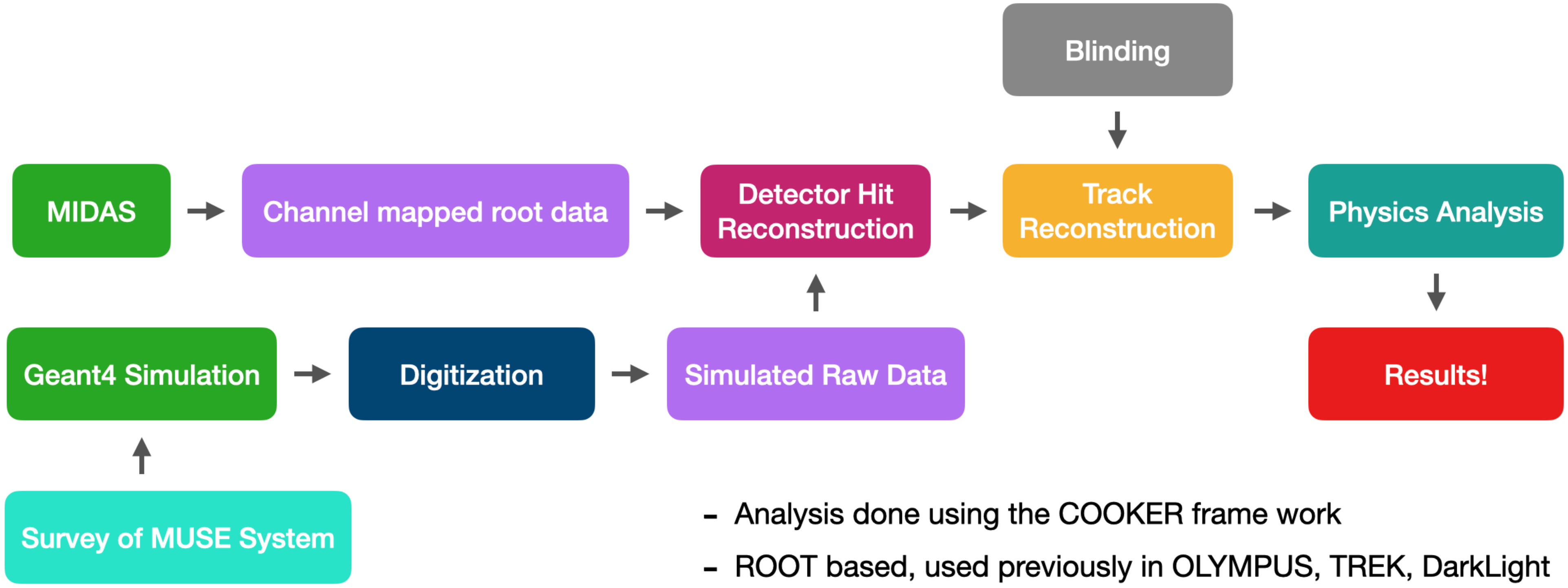
Trigger Logic: TRB3 FPGA-based:

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

(e OR μ) AND (no π) AND (scatter) AND (no veto)

PID is the Hardest Part

MUSE Analysis Diagram



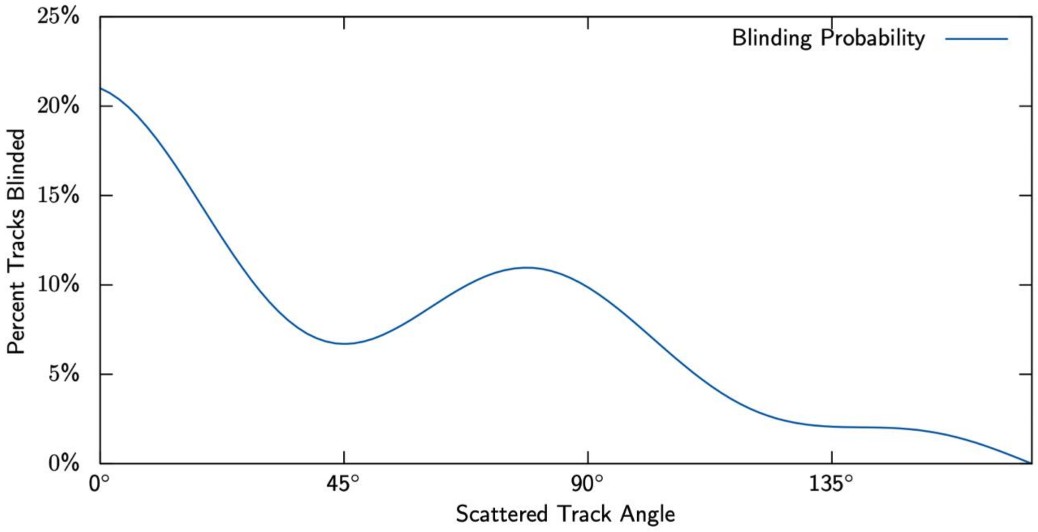
- Analysis done using the COOKER frame work
- ROOT based, used previously in OLYMPUS, TREK, DarkLight
- Decompose analyses into individual modules
  - Low-level: Typically one per detector
  - Mid-level: Tracking, TOF, blinding etc.
  - High-level: Physics analysis

Data Blinding

- Fraction of scattered tracks at each angle are stored and hidden for blinding data
- Whether or not a track is blinded is calculated by:

$$P = s \times \frac{3-\theta}{3}, \text{ where } s = 0.2(A + 0.3cos(B \times \theta)), \text{ and } A = 0.25 \rightarrow 1, B = 0.25 \rightarrow 1$$

- If $P \geq R$, where R is a uniformly distributed random number between 0 and 1, then the track is blinded
- Can blind up to 25% of tracks at any given angle

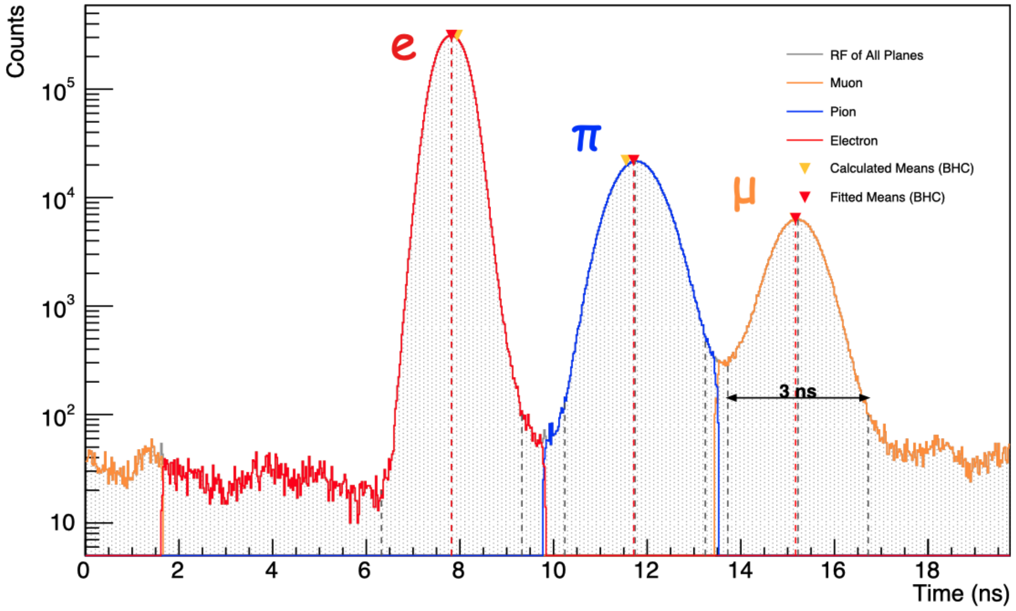


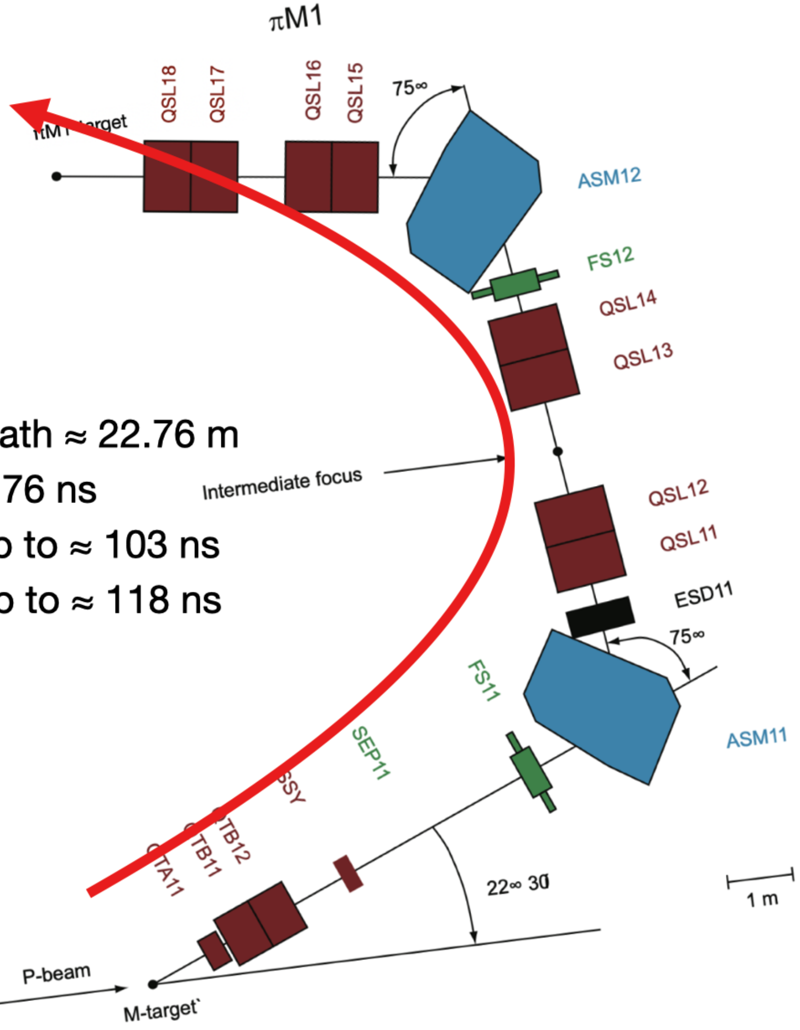
Chance of blinding a track for A = 0.75 and B = 4.2 as a function of STT angle.

Incoming Particle Identification

- RF time: time of particles in BH planes relative to accelerator 50.6 MHz RF signal

RF of All Planes, p = -115.29 MeV/c





Flight path ≈ 22.76 m

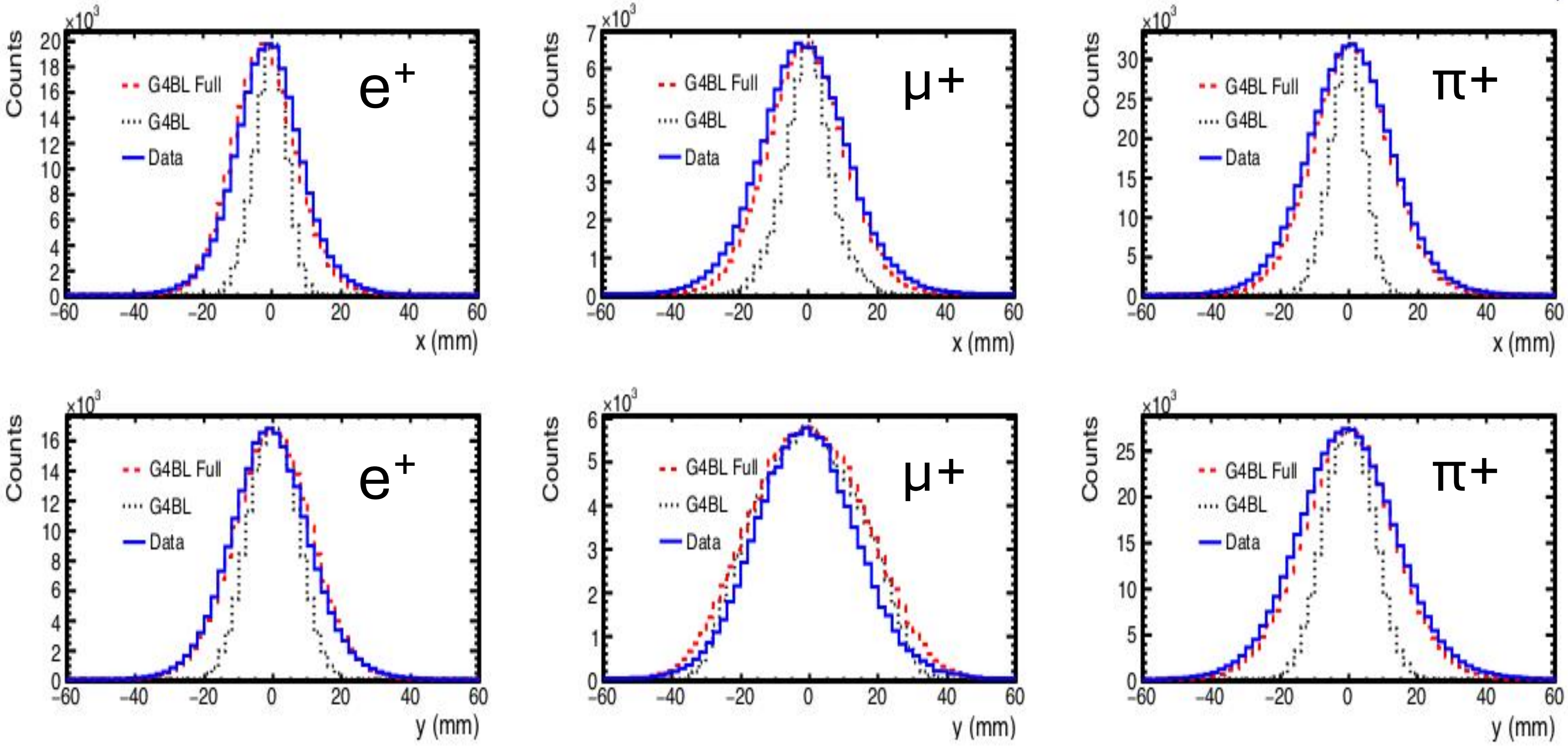
$TOF_e \approx 76$ ns

TOF_μ up to ≈ 103 ns

TOF_π up to ≈ 118 ns

Proton beam RF 50.6 MHz → pulses every 19.75 ns

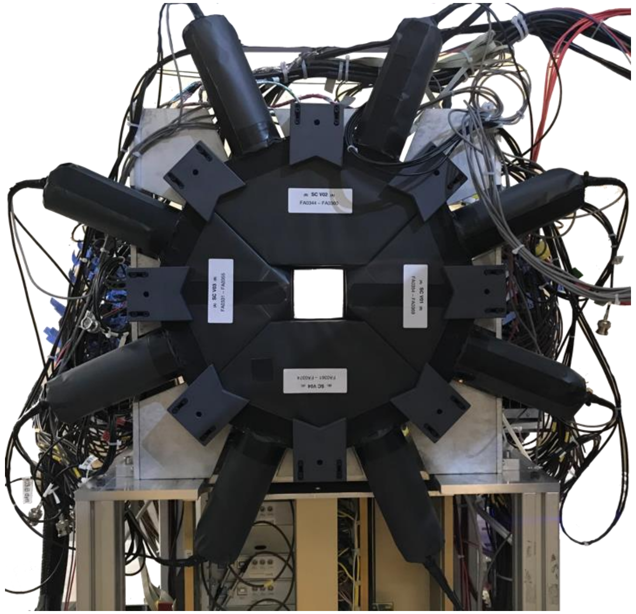
e^+, μ^+, π^+ distributions at +160 MeV/c in πM1



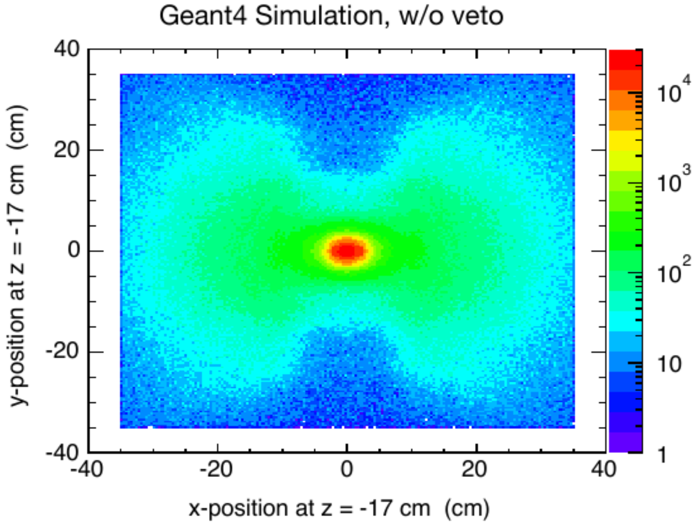
Comparison of data with simulation for different type particle distributions in πM1

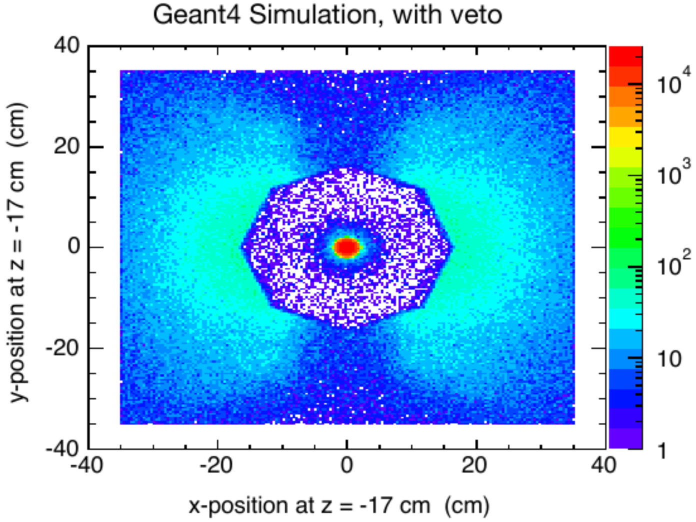
- E. Cline et al. (MUSE collaboration). PRC 105, 055201 (2022)

VETO detector

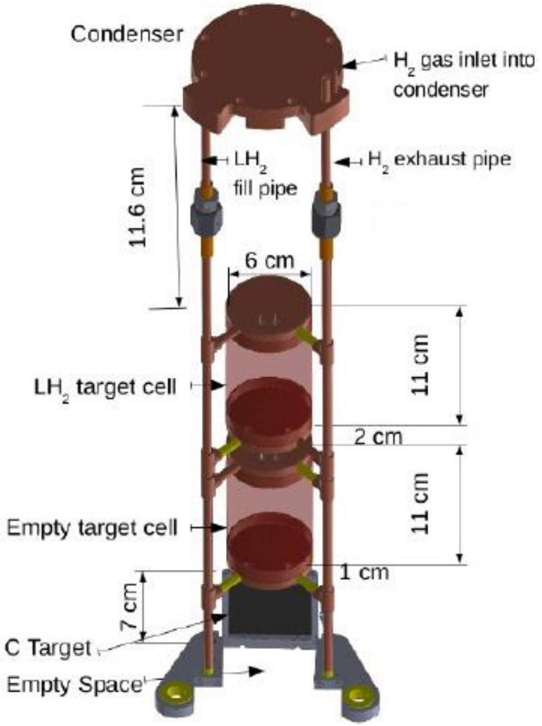


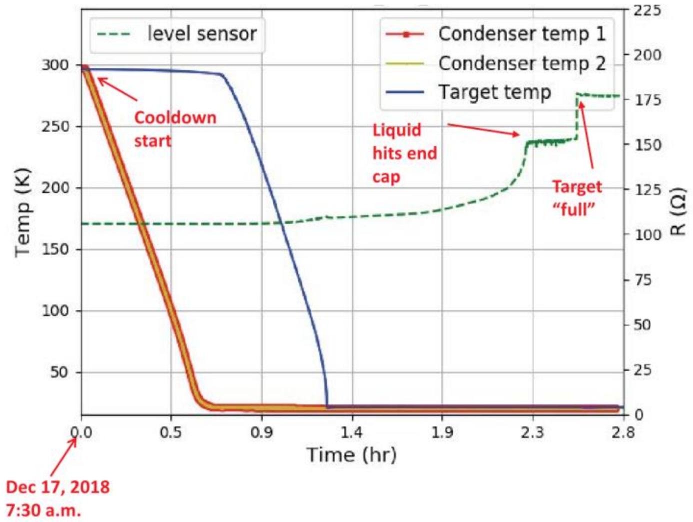
- Annular 4-element, with double PMT read-out, **VETO** detector, surrounding target entrance window
- Eliminates **upstream scattering** and **beam decays** from the data-stream, reduces trigger rate from background events by ~ 30%
- $\sigma_T \leq$ 200 ps (**1 ns**); ε > 99.0%

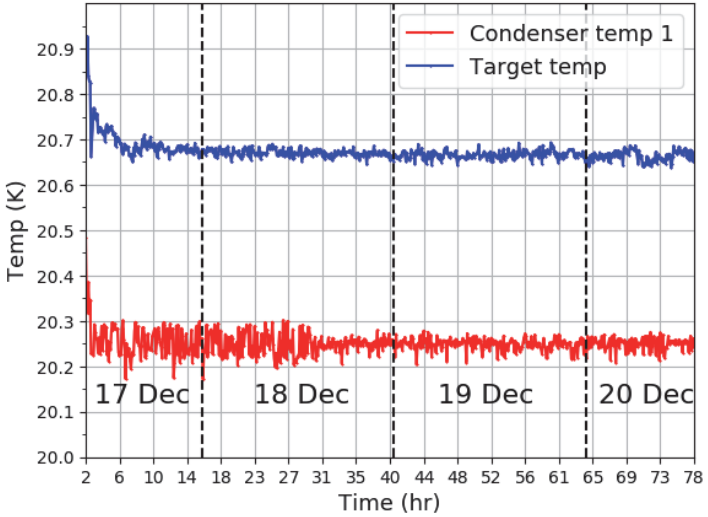




MUSE Liquid Hydrogen Target

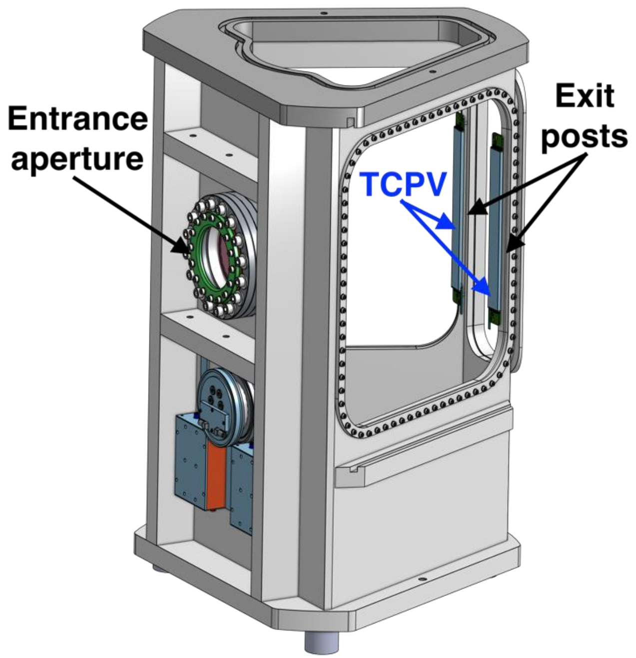


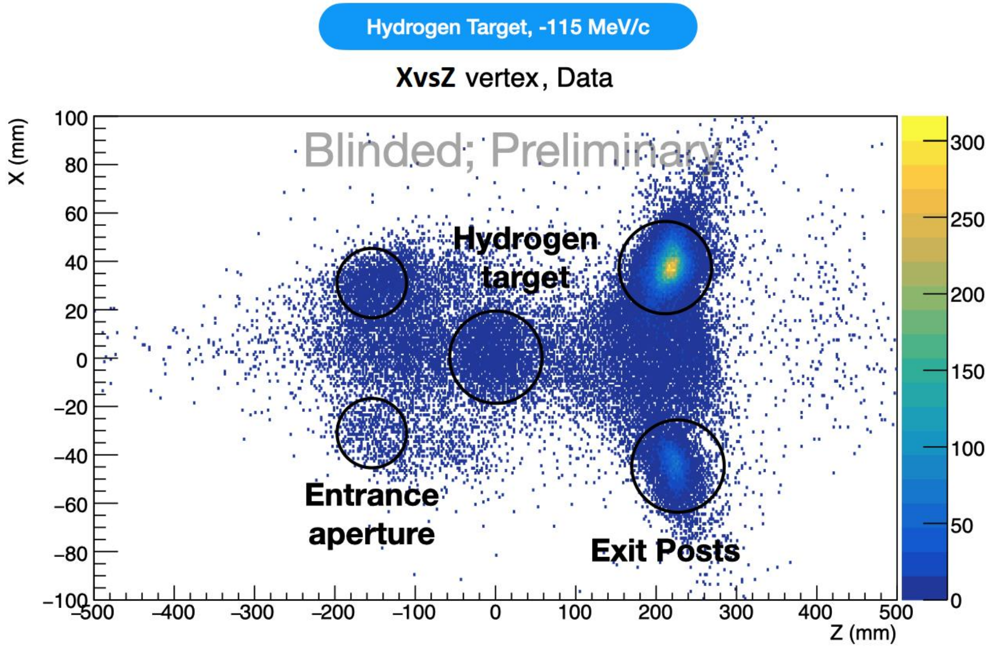


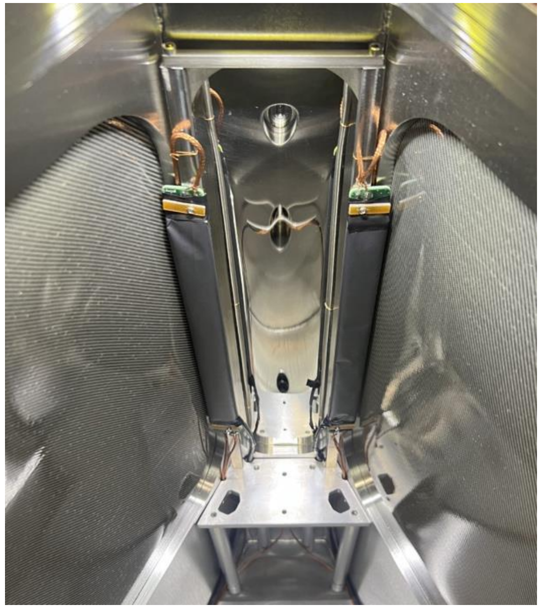


- **280** ml **LH2** target
- Target **T = 20.67 K**, stable at $\boldsymbol{\sigma_T}$ **= 0.01 K** level
- **Density = 0.070 g/cm**^{3}, stable at **0.02%** level

Target Chamber Post Veto (TCPV), Vertex Reconstruction





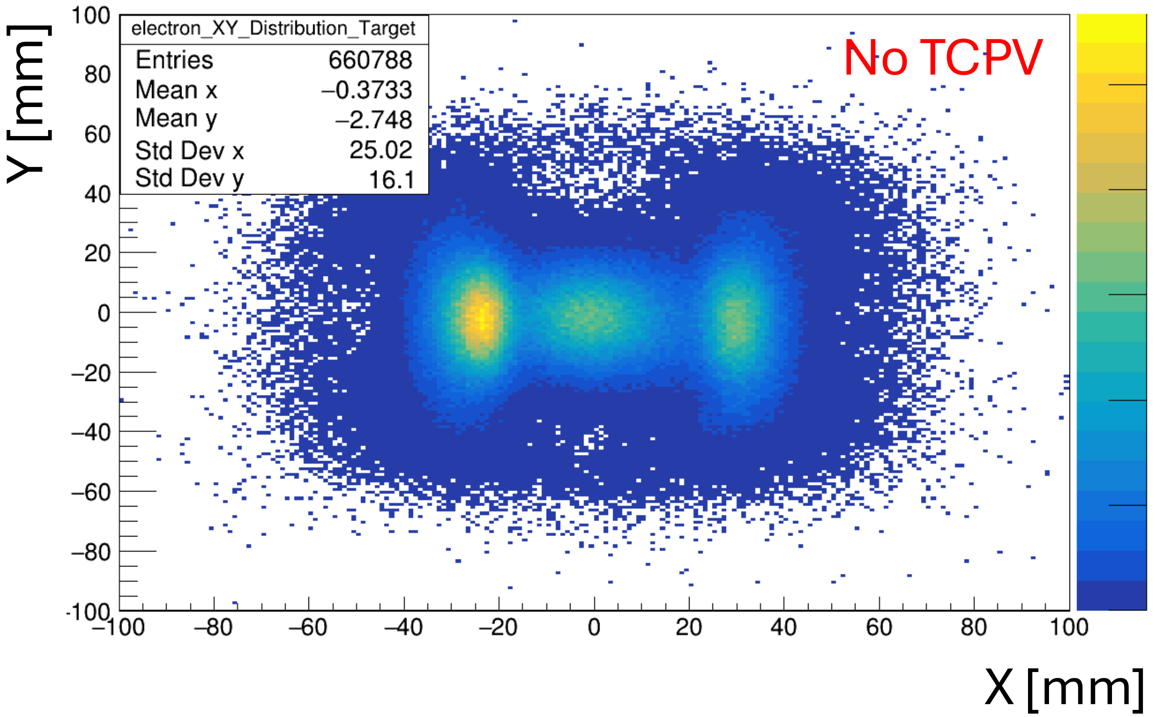


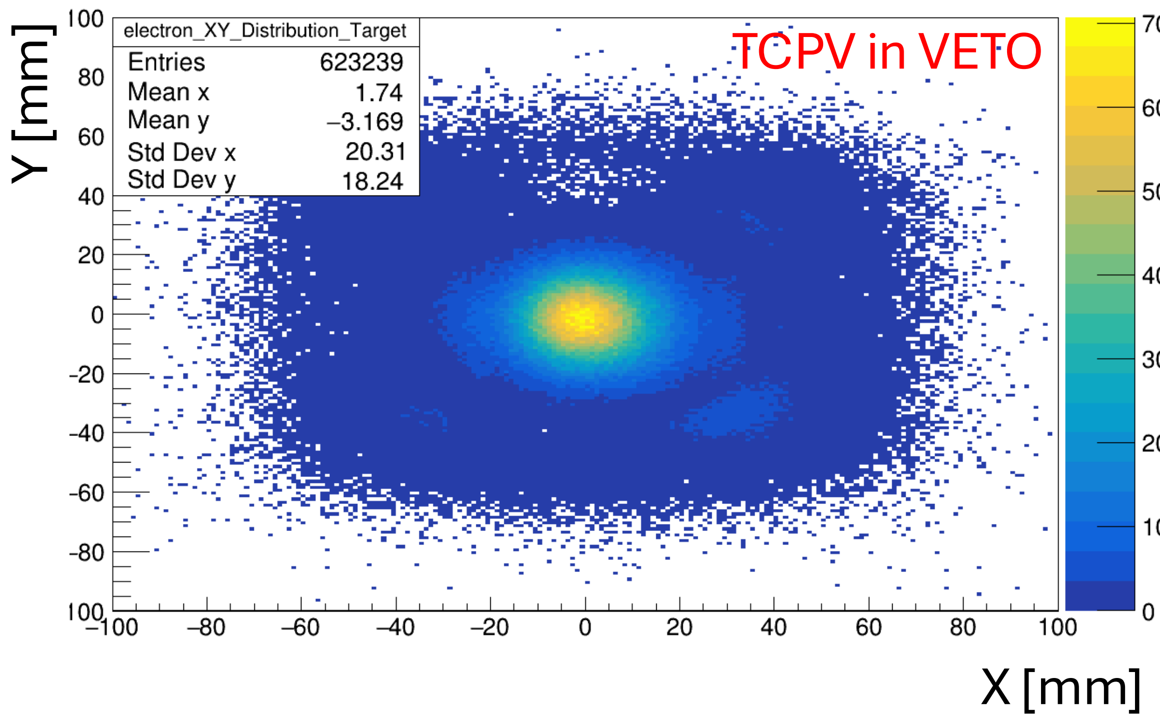
LH2 target reconstruction for p = -115 MeV/c

- Large fraction of triggers are background from the target chamber exit posts:

  Slows down data taking ⟶ increases uncertainties
- TCPV (scintillator with SiPM readout) detector designed and constructed to online veto background events originating from the target chamber exit posts

GEM Tracks at the MUSE Target



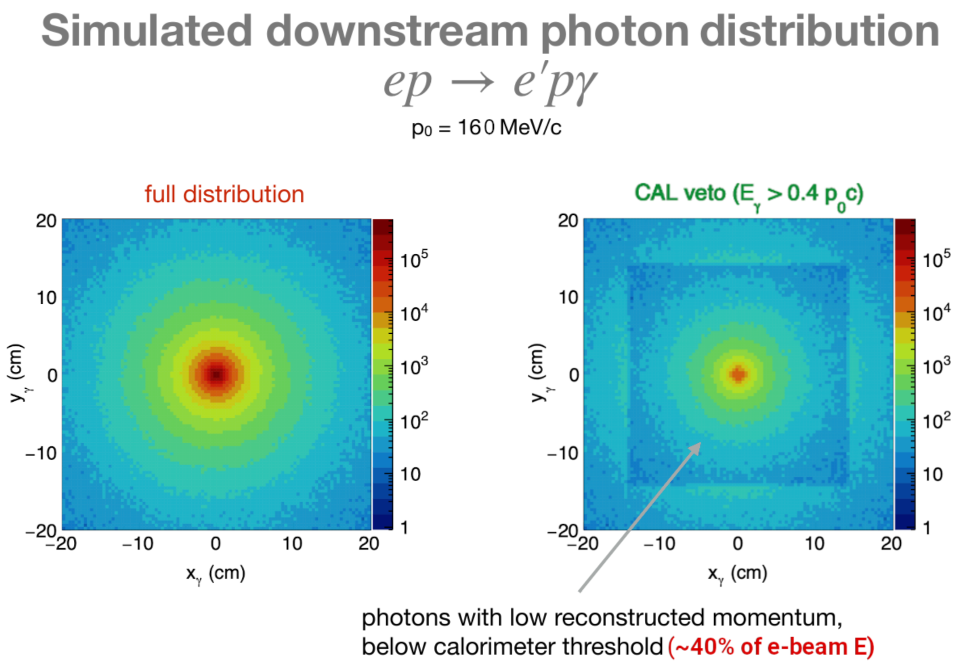


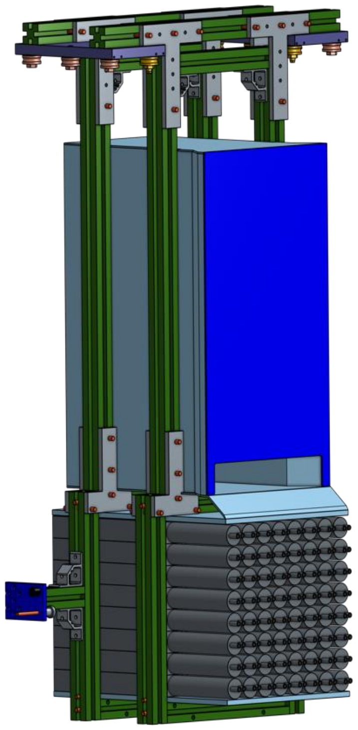
- No configuration changes other than TCPV
- Consistent beam rate at -160 MeV/c
- No TCPV vs TCPV in VETO ⟶ 48 % trigger rate reduction

TCPV state	MIDAS rate (Hz)	Beam rate (kHz)
No TCPV	2170	1620
TCPV in VETO	1130	1620

Forward-Angle Calorimeter for MUSE (PSI)

- Calorimeter removes flying forward, high-energy γ from initial-state radiation
- 64× (4 × 4 × 30) cm^3 Lead-Glass crystals

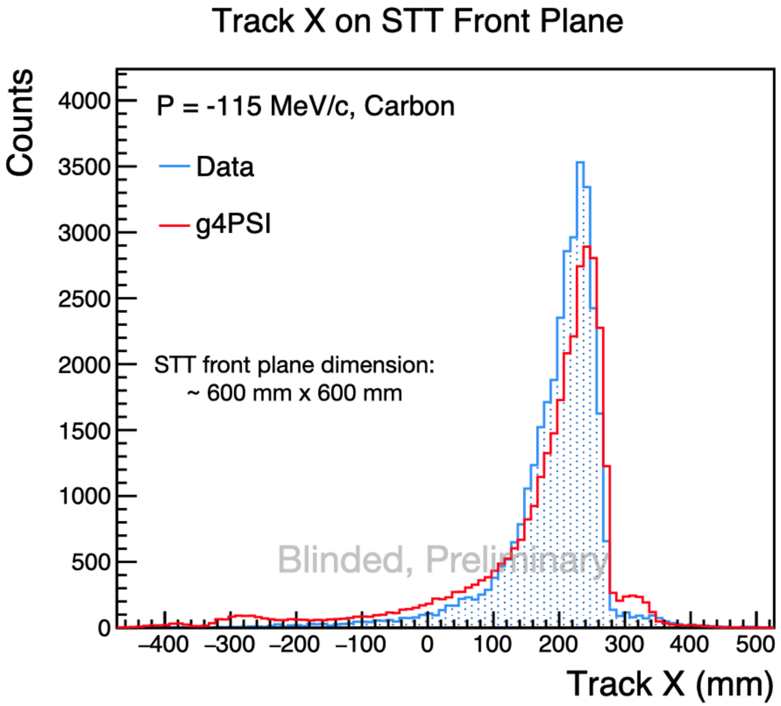


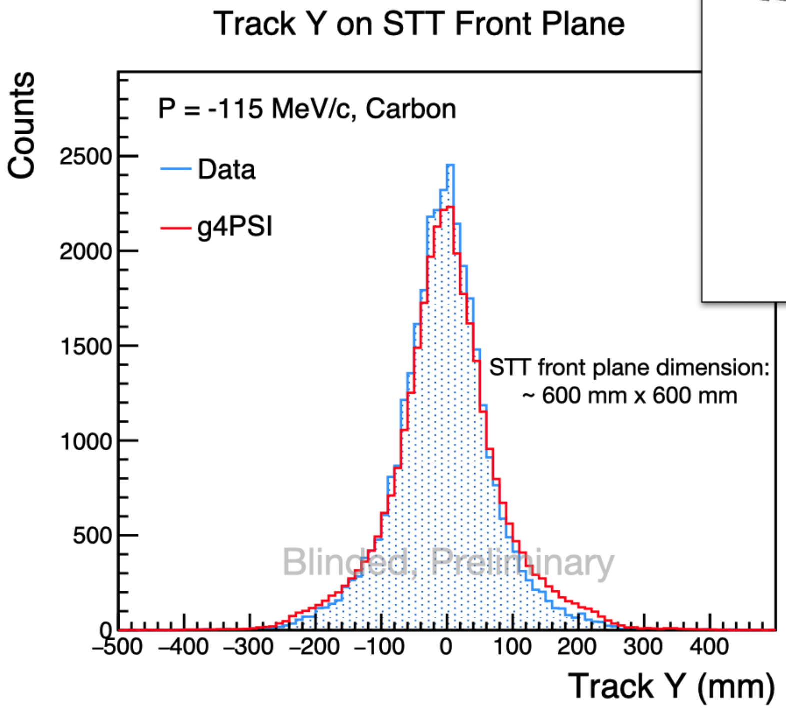


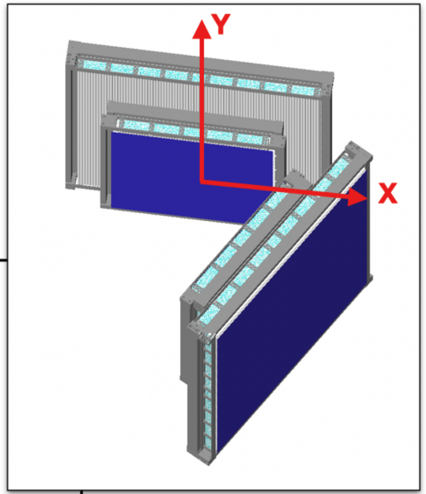
- S. Strauch et al. (MUSE collaboration) https://arxiv.org/pdf/2307.06417.pdf
- W. Lin and T. Rostomyan et al. (MUSE collaboration). Paper in preparation

STT Tracking

- STT has **2. chambers, 5 planes** each in **X and Y**: in total **2850** Straws
- Tracking using "GenFit"; Require hits in at least **3 X**-planes and at least **3 Y**-planes on the same side
- Good agreement between data and simulation for the track position on STT
- Beam is expected to center at about **Y = 0** and **positive X**





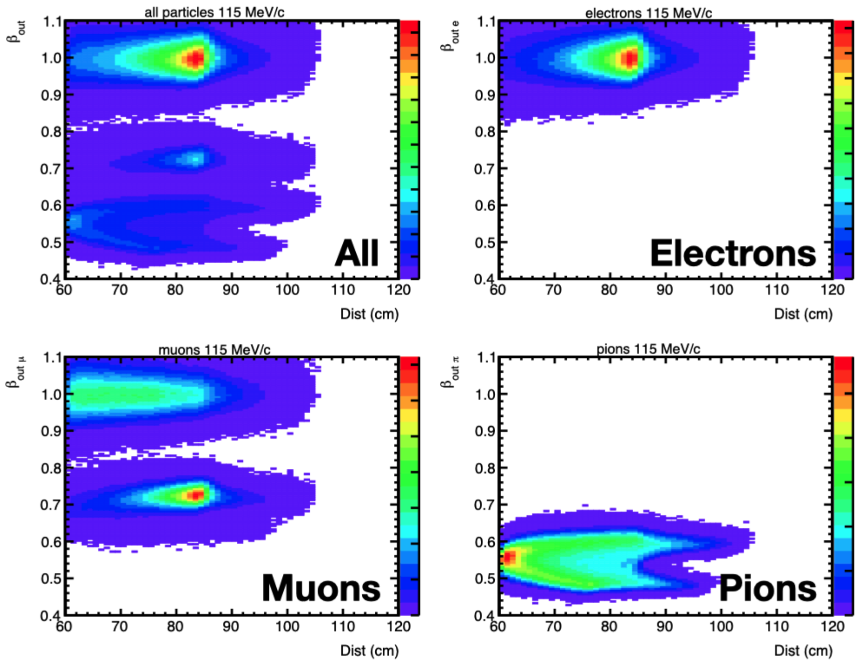


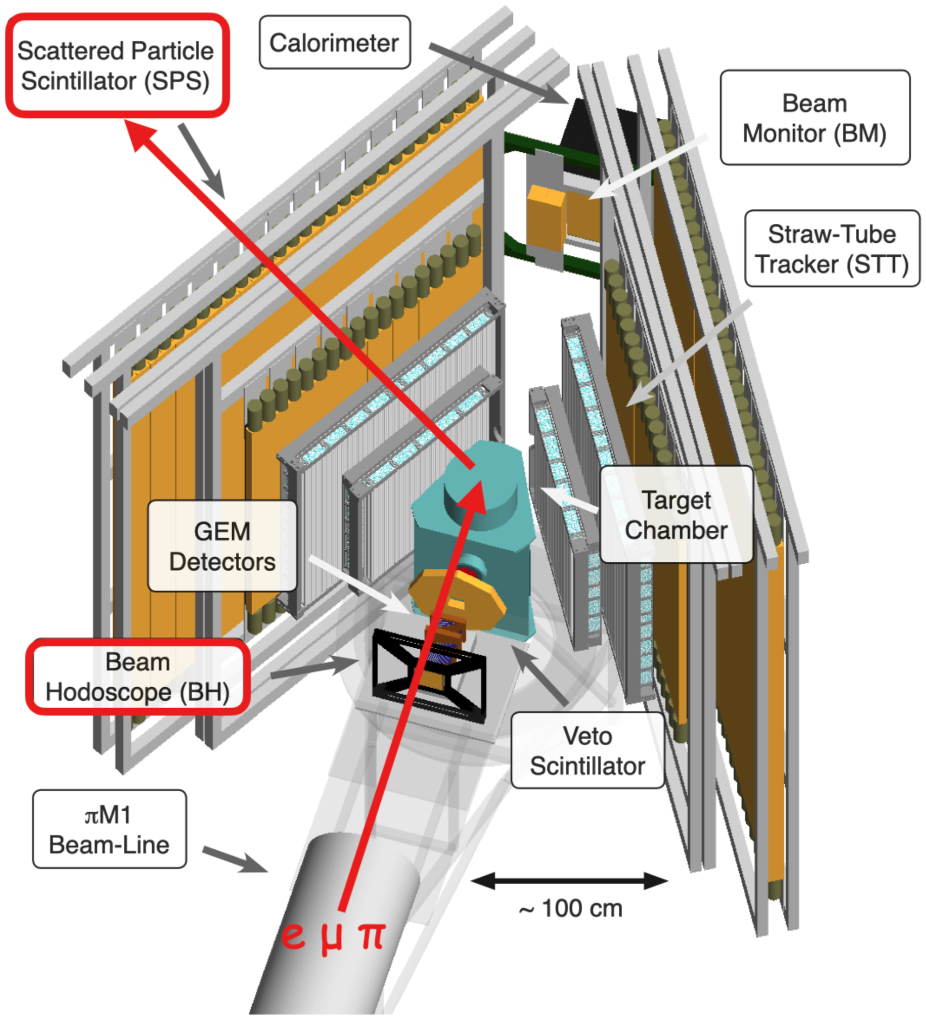
* In STT local coordinates

Reaction Identification

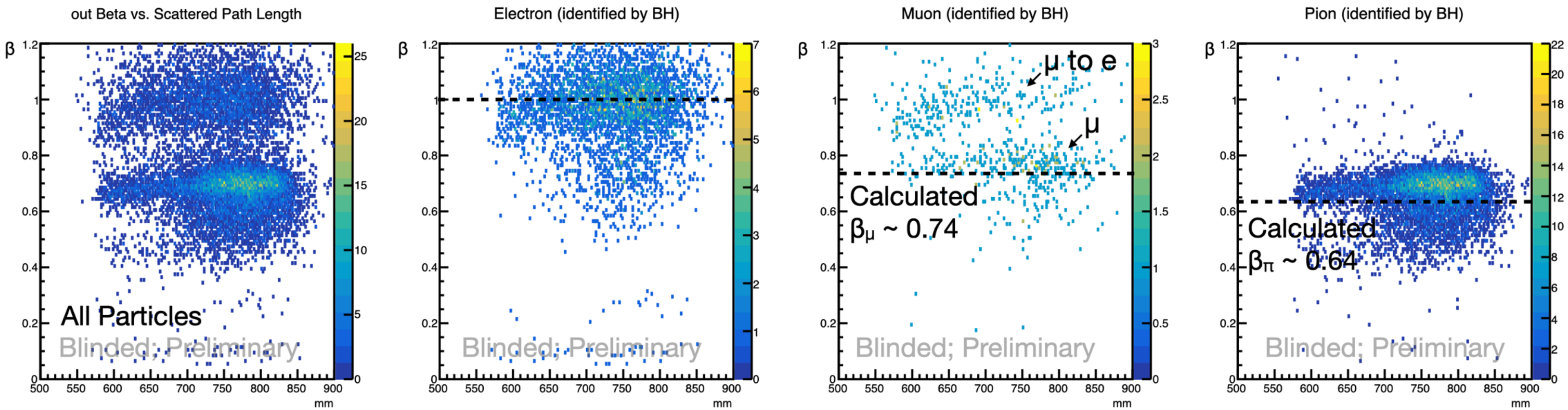
- Reaction is identified from the TOF (SPS - BH) and the path length between BH and SPS
- From the track reconstruction, we can get the path length
- Knowing the incoming particle momentum and the TOF, we can find $\beta_{incoming}$ and $\beta_{outgoing}$

Simulation of outgoing Beta vs Scattered Path Length



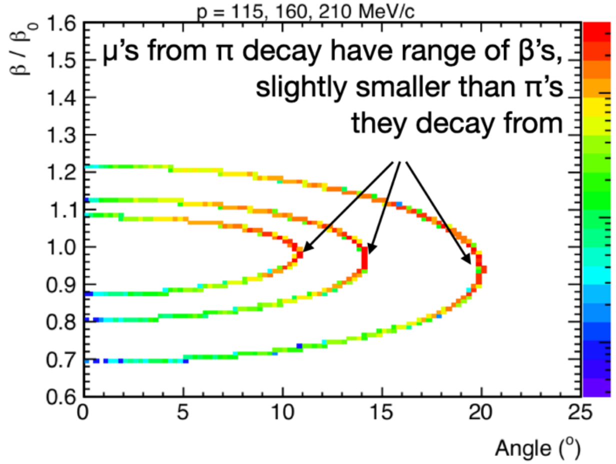


Reaction Identification



Carbon Target, -115 MeV/c

Momentum of μ from π—> μ + νμ

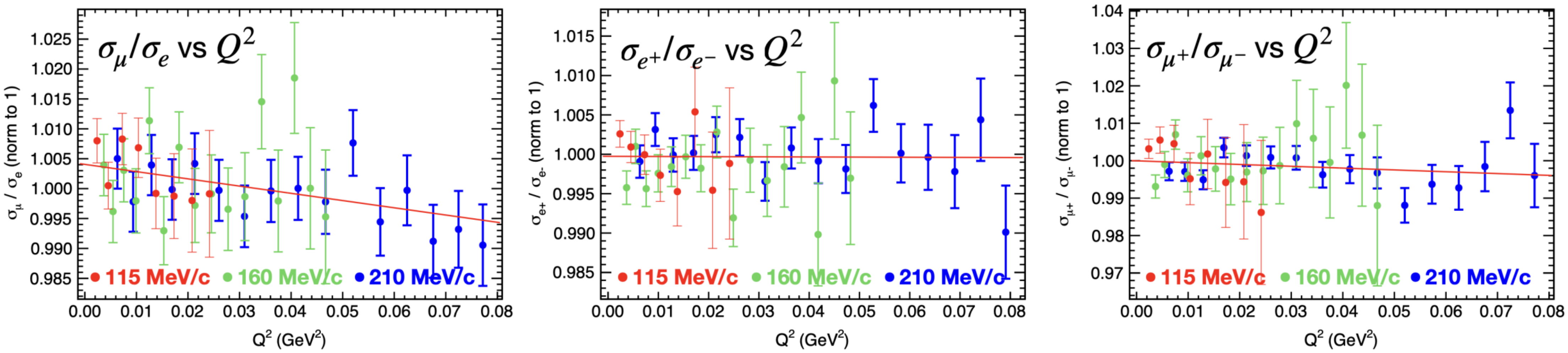


β_π and Most probable $\beta_{decay\ \mu}$

p	115 MeV/c	160 MeV/c	210 MeV/c
π	0,64	0,75	0,83
decay μ	0,60	0,72	0,82

- β_e is normalised to 1, β_μ is faster than calculated value and β_π is even faster
- Might be due to the time walk; dE\dx(π) > dE/dx(μ) > dE/dx(e)
- With better walk correction, we will be able to achieve 100 ps / 5 ns ~ 2% for β

MUSE Pseudo-Data for Cross Section Ratios

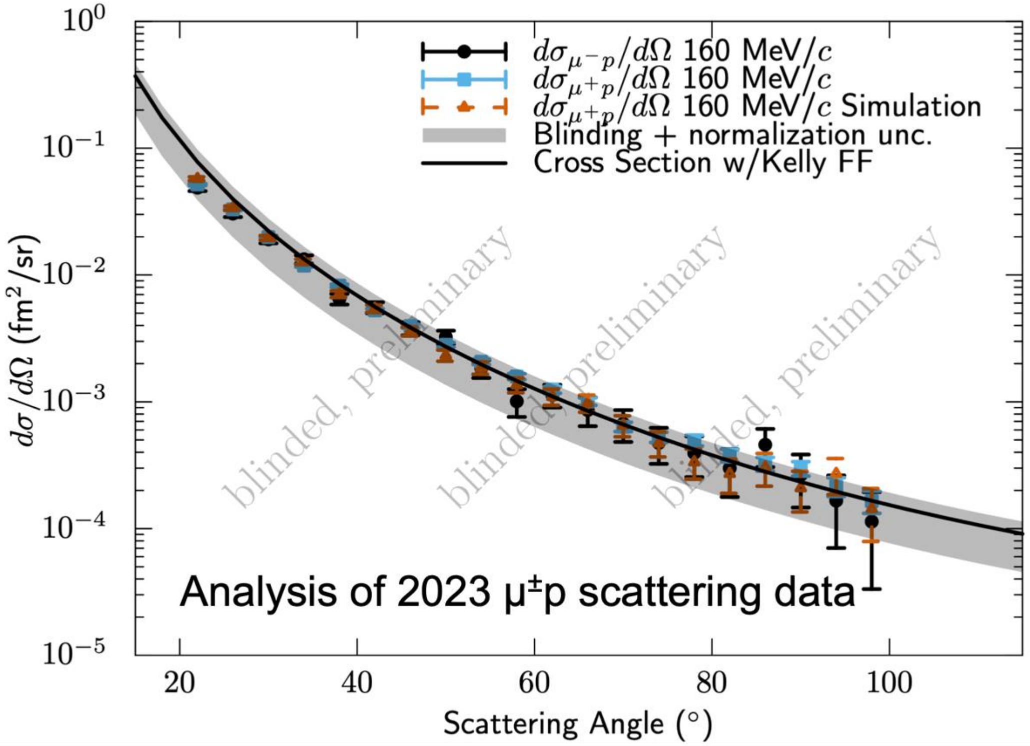


- Projected uncertainties of one full year of scattering data taking
- Estimated how we divided the time, with more time at the highest momentum
- Statistics is based on 2022 data set
- Estimated systematics from the readout rate before TCPV implementation is included
- Take away message: on avarage we will be able to reach smaller than 1% uncertainties
- More work to be done

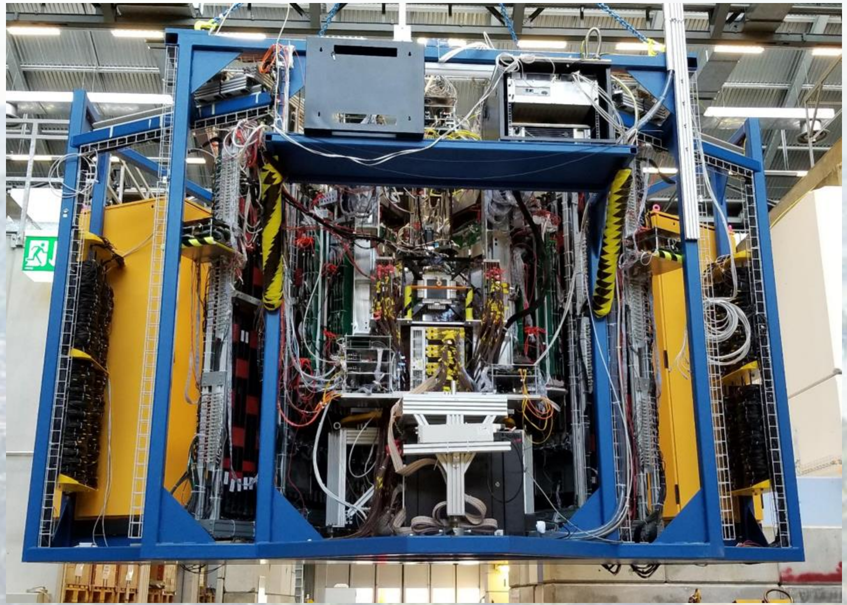
Summary and Outlook

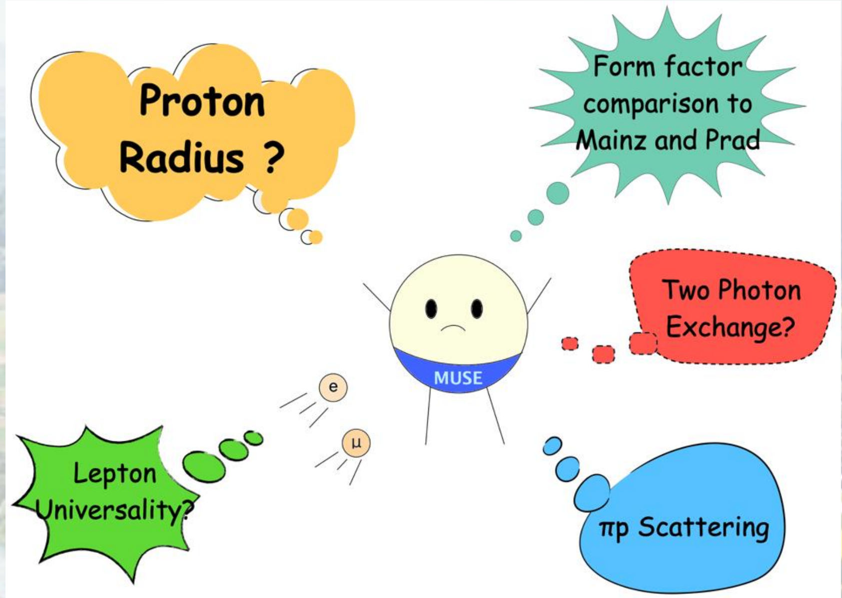
Proton form factor, charge radius, two-photon exchange, and lepton universality measurements at Paul Scherrer Institute (PSI) with elastic scattering of 115 – 210 MeV/c $e^{\pm}$ and $\mu^{\pm}$ from hydrogen

- **2021:** Obtained **first** high statistics scattering data set at ±115 MeV/c.
- **2022**: Completed 5 months of data taking.
  - Took data in all experimental kinematics on LH_2
- **2023**: Completed 5 months of awarded beam time
- **2024**: completed first half of the 5 months of awarded beam time
  - Collected approximately 50-60 % of expected total statistics
  - Expect to reach 75 % by the end of the year
  - Refining the analysis procedure
- **2025**: Similar 5 months of beam time is expected to complete the data taking



Thank You for Your Attention





MUSE will be the **first muon scattering measurement** with the required precision to address the **Proton Radius Puzzle!**

MUSE publications:

- P. Roy *et al.*, **NIM A 949 (2020) 162874**
- T. Rostomyan *et al.*, **NIM A 986 (2021) 164801**
- E. Cline *et al.*, **SciPost Phys. Proc. 5, 023 (2021)**
- E. Cline *et al.*, **Physical Review C 105, 055201 (2022)**
- L. Li *et al.*, **EPJ A (2024) 60:8**
- J. C. Bernauer *et al.*, **In preparation for PRC**
- **Calorimeter**, **STT** and **TCPV** papers: **In preparation**

START OF BACKUP SLIDES

P_e

E. Cline *et al.*, **Physical Review C 105 (2022) 055201**

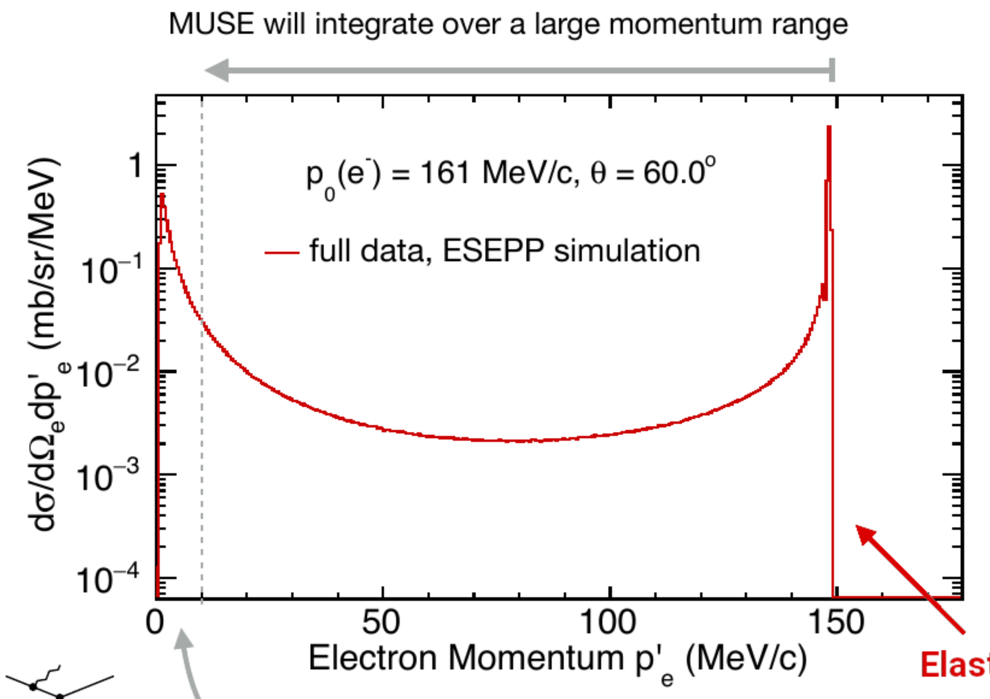
Characterization of μ and *e* beams in the PSI PiM1 channel:

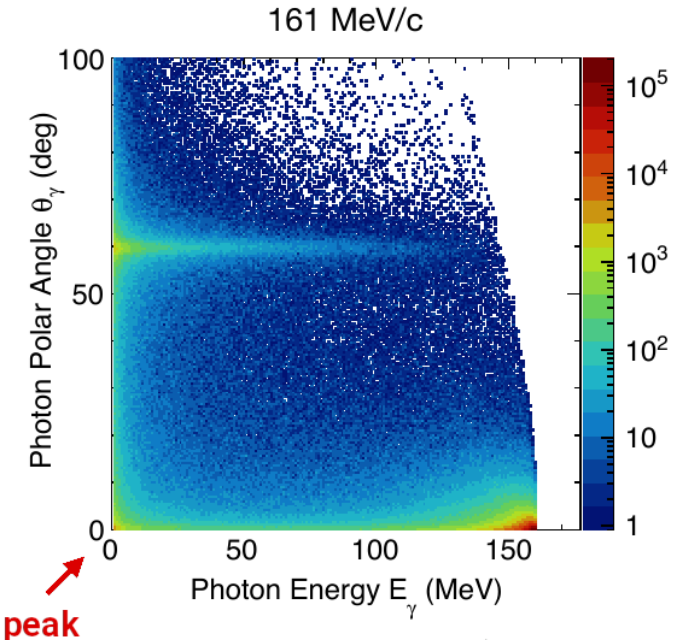
- Average momentum of particles passing through the channel agrees with the central set momentum to within **0.03%**
- The positions of the different particle species were observed to be consistent at roughly **2 mm** level, indicating their momenta are consistent to within approximately **0.02%**
- RF time measurements of particles propagating through the channel showed approximately **0.1%** agreement with the set momentum
- Muon and electron beams have quite similar properties to the pion beam and to each other: knowing p_π or p_μ means we know p_e quit precisely

Radiative Corrections

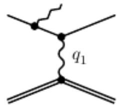
Radiative Corrections are significant for ***e***'s.
Greatest sensitivity is to **pre-radiation**. **Photon** flies **forward**

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



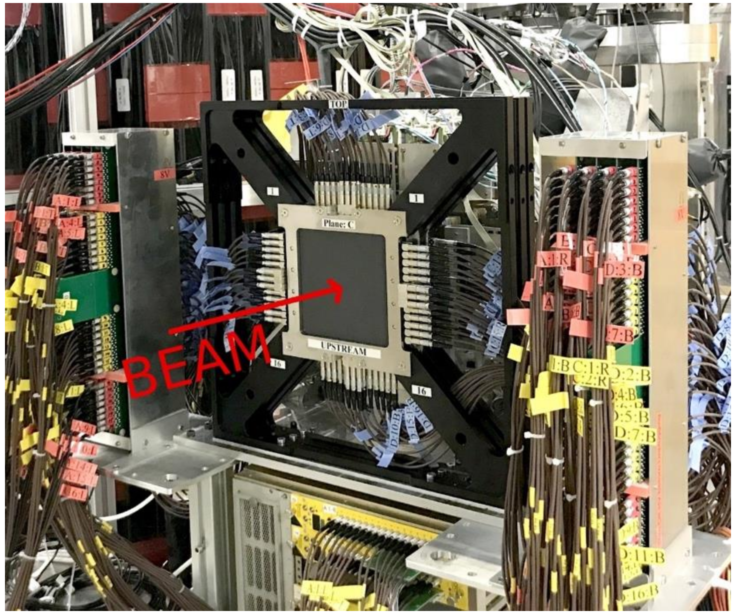


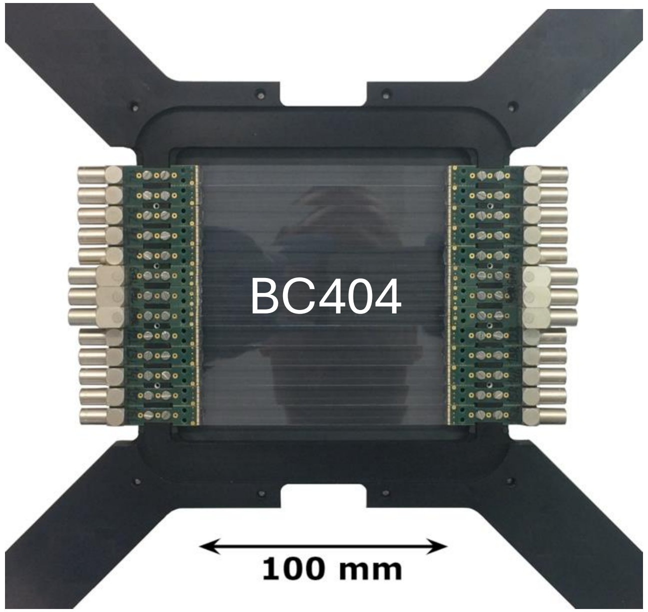
Elastic peak



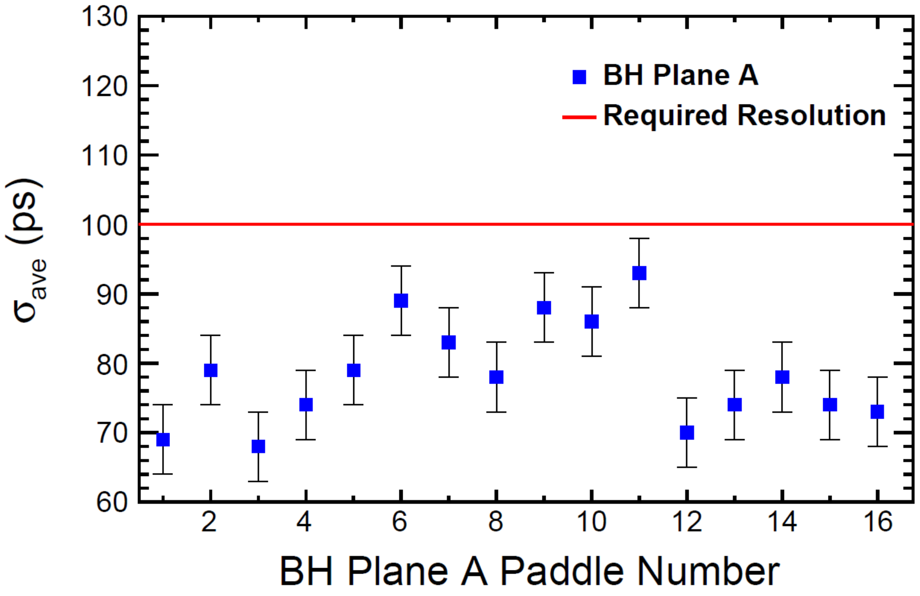
If the incident lepton loses energy due to the emission of a hard photon, then the probability for this lepton to be scattered by the proton increases.

Beam Hodoscope (BH) for MUSE

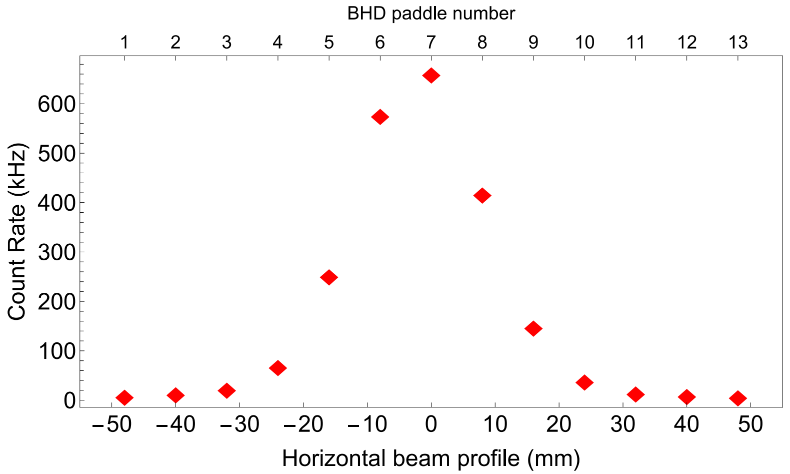


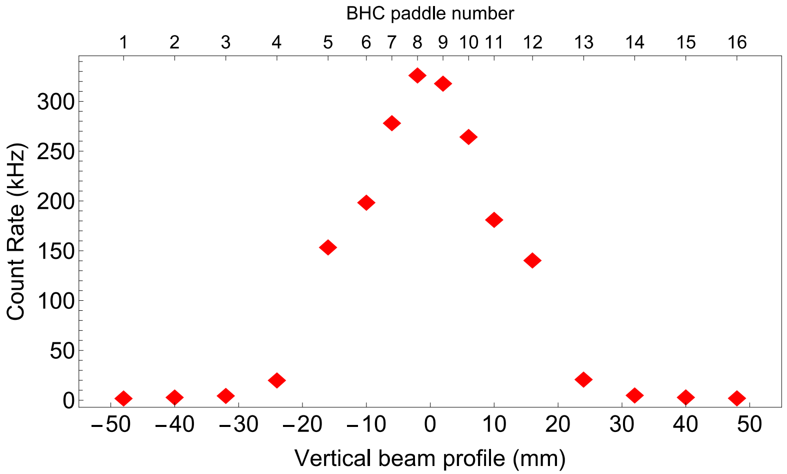


- BH is most upstream MUSE beam-line detector
- BH is used for beam-particle identification and TOF
- 5 planes built in total
- All time resolutions ⟶ below 100 ps
- Best achieved time resolution ⟶ 55 ps



πM1 Beam Profile



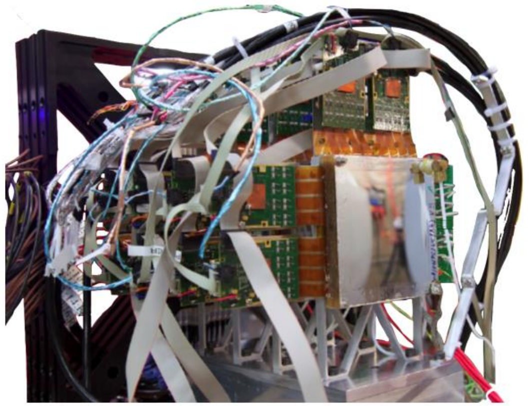


Beam X and Y profiles at πM1 obtained with BH live analysis

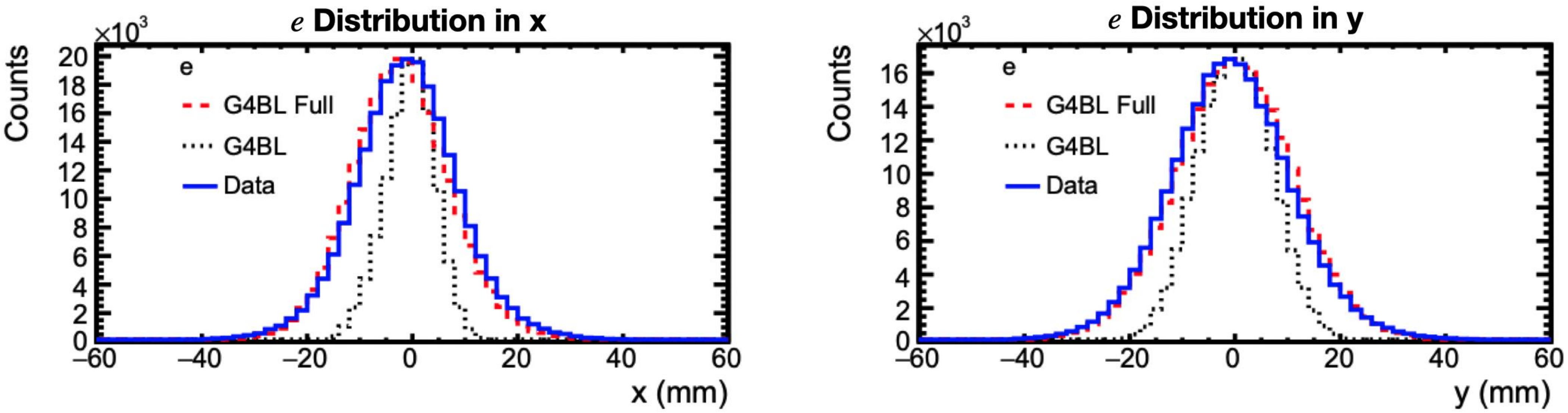
- BHD is 13 paddle plane, with 8 mm wide vertical paddles
- BHC is 16 paddle plane, with 4 and 8 mm wide horizontal paddles

GEM as incident particle tracker

- Incoming beam is tracked by the GEM detectors
- Tracking using “GenFit”; Require hits in at least 2 out of 4 GEM planes
- Particle distribution of the πM1 beam is well understood

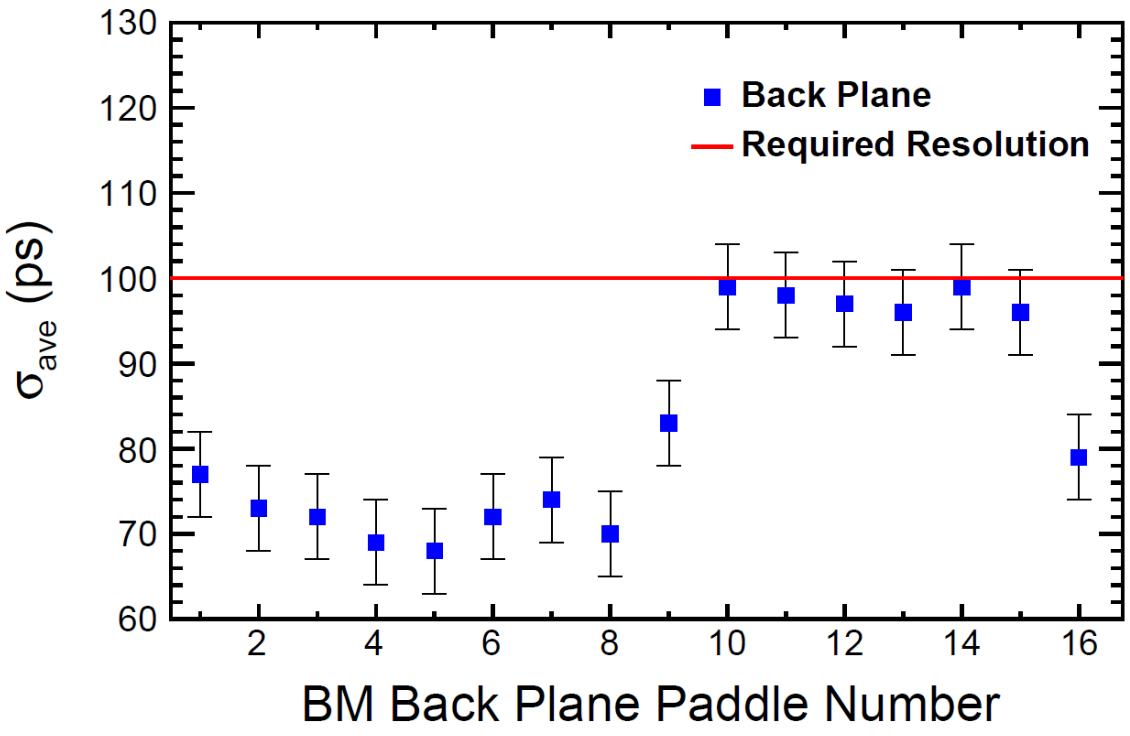


Comparison of G4beamline simulations and data at the MUSE target



E. Cline *et. al.*, Phys. Rev. C 105, 055201

Beam Monitor (BM) for MUSE



- BM is installed in the beam-line downstream of the MUSE target
- Is used for TOF from BH to BM for Muon and Pion beam momenta
- Is used for flux determination of un-scattered beam particles downstream the target
- Indicates background events like Møller or Bhabha scattering

Scattered Particle Scintillator (SPS)

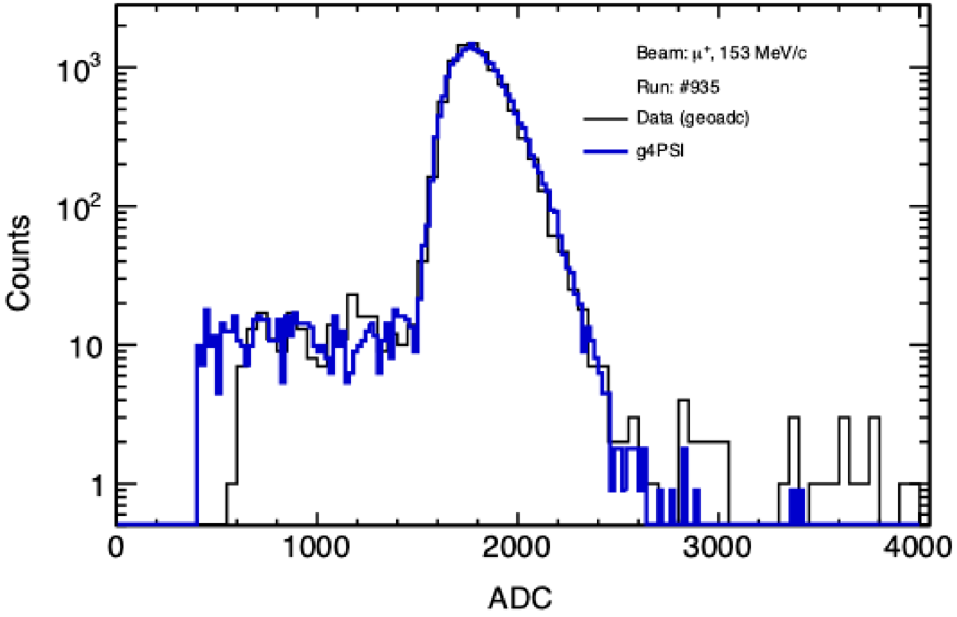
- 2 walls on each side of beam. 92 bars, double-ended readout
- Determines **Energy** and **Time** of the scattered off the target particles
- **Muon Decays** in flight can be removed with **TOF** (BH→SPS)

Front wall: 18 bars

(6cm x 3cm x 120cm

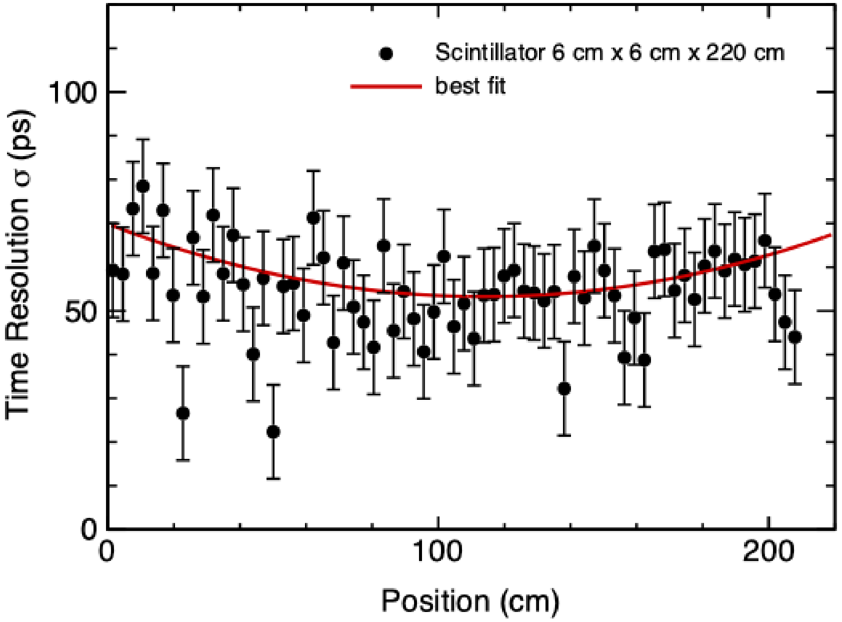
Rear wall: 28 bars

(6cm x 6cm x 220cm)



Peak: particles going through the bar.

Low energy tail: particles going out of the side of the bar



220 cm BC404 bars: $\sigma_{av.} = 52ps \pm 4ps$

120 cm BC404 bars: $\sigma_{av.} = 46ps \pm 4ps$