

# Pion-Proton Scattering in the MUSE Experiment

Kyle Salamone

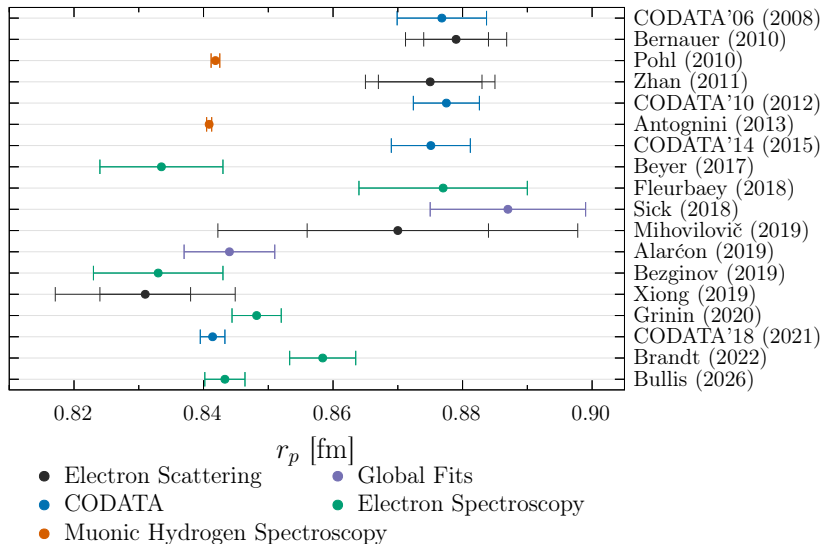
Center for Frontiers in Nuclear Science, Stony Brook University

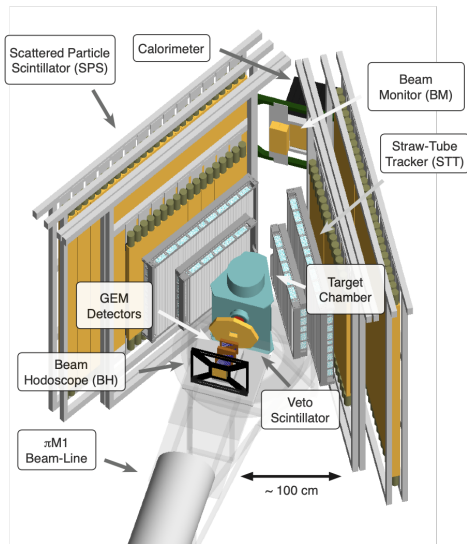
October 20, 2026



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# The Proton Radius Puzzle





## Kinematic Parameters

- **Beam momenta**  
115, 160, 210 MeV/c
- **Beam species**  
 $e^{\pm}, \mu^{\pm}, \pi^{\pm}$
- **$\theta$  coverage**  
 $20^{\circ} - 100^{\circ}$
- **$\phi$  coverage**  
 $\sim 30\%$  of  $2\pi$
- **$Q_{\pi}^2$  range**  
 $[0.0016, 0.0786] \text{ (GeV/c)}^2$

- Probe  $\chi$ PT – low energy EFT for QCD/strong force with  $(\pi^-, \pi^0, \pi^+)$  as Goldstone bosons
- Various papers<sup>1,2</sup>:  $\chi$ PT valid for  $p_{\text{lab}} \lesssim 200 \text{ MeV}/c$

| $\pi$ Lab Momentum (MeV/c) | $T_\pi$ (MeV) | $\sqrt{s}$ (GeV) |
|----------------------------|---------------|------------------|
| 115                        | 41.28         | 1.11             |
| 160                        | 72.75         | 1.14             |
| 210                        | 112.58        | 1.17             |

- MUSE momenta lie in range of interest for  $\chi$ PT  $\rightarrow$  can provide more data to test understanding of theory

<sup>1</sup> N. Fettes, U.-G. Meißner, and S. Steininger, Nucl. Phys. A 640, 199 (1998)

<sup>2</sup> B.-L. Huang, Phys. Rev. D 102, 116001 (2020)

## Traditional Approach

Separate corrections for:

- Detector acceptance/efficiency
- Radiative effects
- Decay-in-flight
- DAQ efficiency, etc.

## Simulation-Driven Extraction

- Efficiencies, acceptance, and decays built into the simulation
- Cross section model from an event generator
- Tunable model parameters

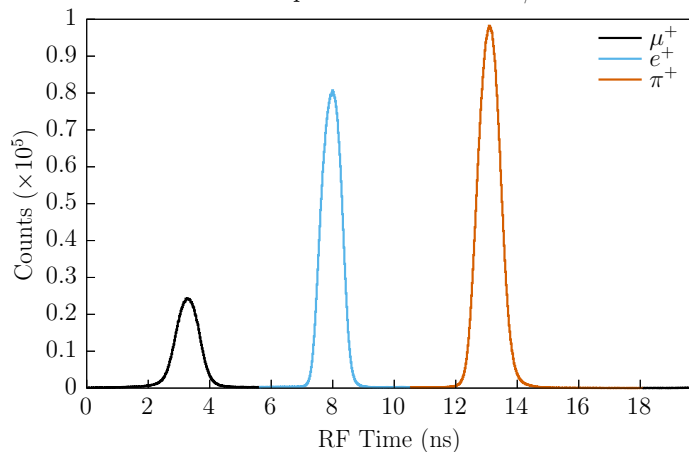
## MUSE Approach

Use a detailed `GEANT4` simulation (`g4PSI`) with a realistic detector response, and **tune it until it matches the data**.

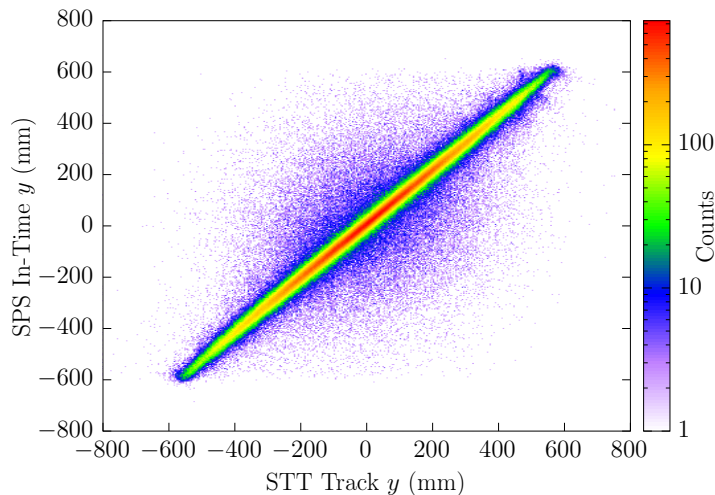
**Match simulation to data**

$$\left( \frac{d\sigma}{d\Omega} \right)_{\text{exp}} = \frac{N_{\text{exp}}/\mathcal{L}_{\text{exp}}}{N_{\text{sim}}/\mathcal{L}_{\text{sim}}} \left( \frac{d\sigma}{d\Omega} \right)_{\text{sim}}$$

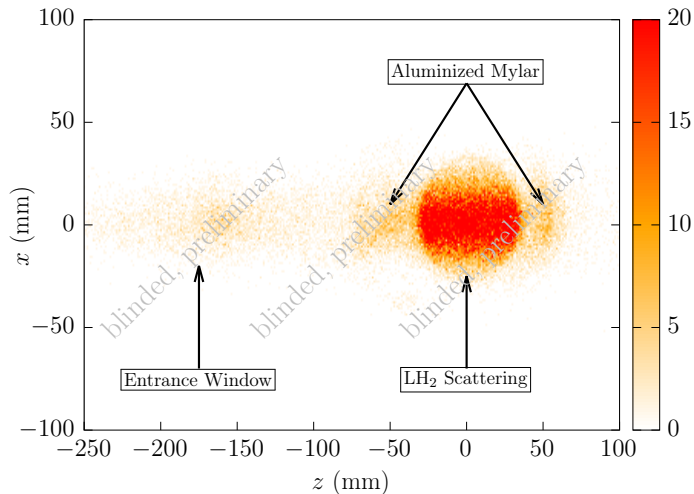
RF Spectrum: 160 MeV/c



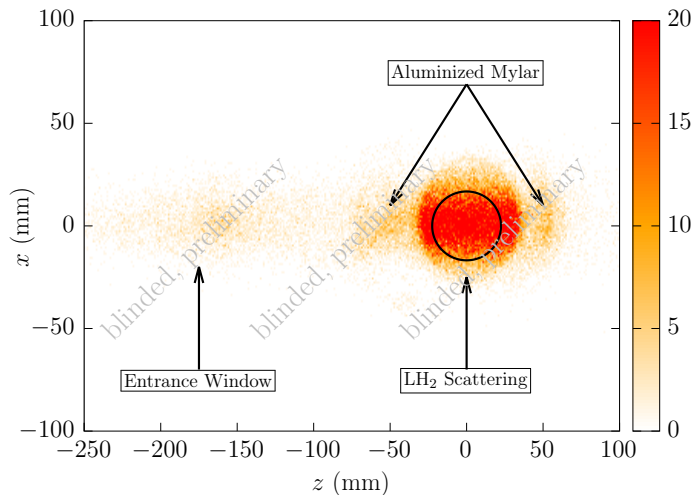
- 1 **RF must indicate  $\pi$  event**
- 2 Tracks correlate to in-time scintillator hits
- 3 Vertex in target volume, DOCA cut
- 4 In-time by scintillator timing
- 5 Reject decay-in-flight from reconstructed  $\theta$



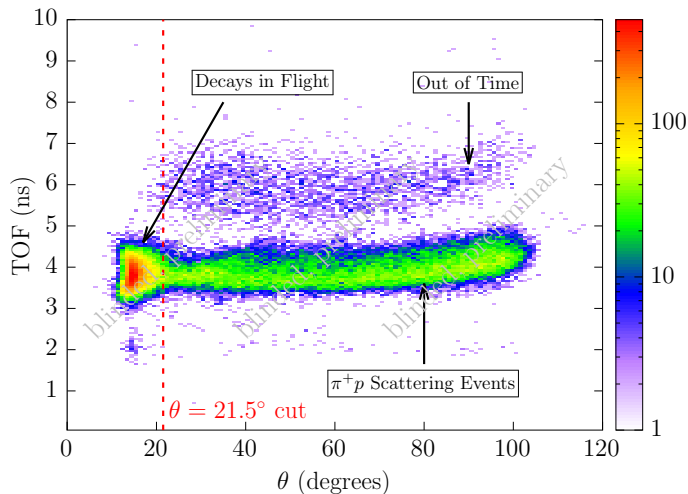
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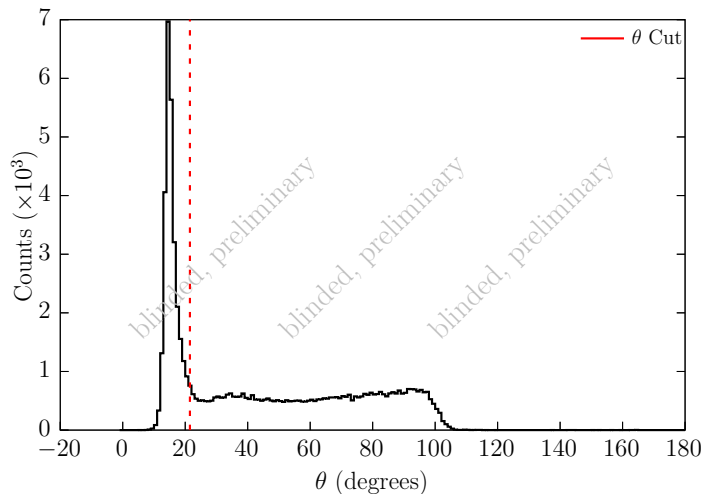
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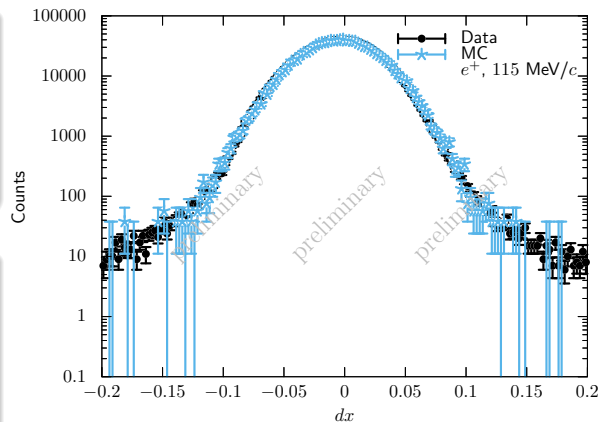
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## Physics Lists/Event Generator

- **Leptons:** radiative effects, rare-event simulation
- **Pions:** hadronic elastic scattering physics (PiPES, later)

## Realism

- Realistic beam parametrization
- Decay-in-flight physics for  $\pi$  and  $\mu$
- *Digitization:* detector smearing, noise, resolution effects



Detailed detector + physics model in GEANT4 → simulation matched to experimental data

- In simulation, know which generated angles reconstruct in which reconstructed bins  $G_{ij}$  with generator bin  $i$ , reconstructed bin  $j$
- Each minimization step: reweight generator truth bins by

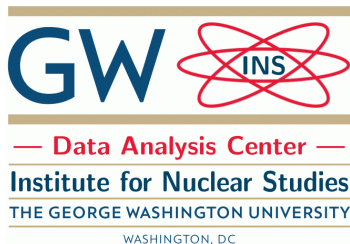
$$w_i(\vec{p}_{\text{new}}) = \frac{(d\sigma/d\Omega)(\theta_i|\vec{p}_{\text{new}})}{(d\sigma/d\Omega)(\theta_i|\vec{p}_{\text{sim}})}$$

- Apply to reconstructed bins:

$$N_{\text{sim}}^j(\vec{p}_{\text{new}}) = \frac{\mathcal{L}_{\text{exp}}}{\mathcal{L}_{\text{sim}}} \sum_i G_{ij} w_i(\vec{p}_{\text{new}})$$

- Free parameters  $\vec{p}_{\text{new}}$ ; minimize Poisson deviance between  $N_{\text{exp}}^j$  and  $N_{\text{sim}}^j$
- Need functional, tunable model for  $\pi p$  cross sections inside simulation...

- Developed to simulate  $\pi p$  elastic scattering at low  $Q^2$
- Rejection sampling in lab or CM frame along user-defined  $\theta_{\min}$ ,  $\theta_{\max}$  range
- Makes use of SAID PWA phase shifts from WI08 solution<sup>1</sup>
- **Work in progress**



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<sup>1</sup>INS Data Analysis Center, The George Washington University, [gwdac.phys.gwu.edu](http://gwdac.phys.gwu.edu)

- Decompose the cross section into a sum of partial waves
  - Follows formalism of Tromborg *et al.*<sup>1</sup> and Koch & Pietarinen<sup>2</sup>
  - MUSE kinematics:  $\eta \approx 1$ , only consider  $s$ - and  $p$ -wave contributions

$$\left( \frac{d\sigma}{d\Omega} \right)_{\pi p} = |f(\theta)|^2 + |g(\theta)|^2$$

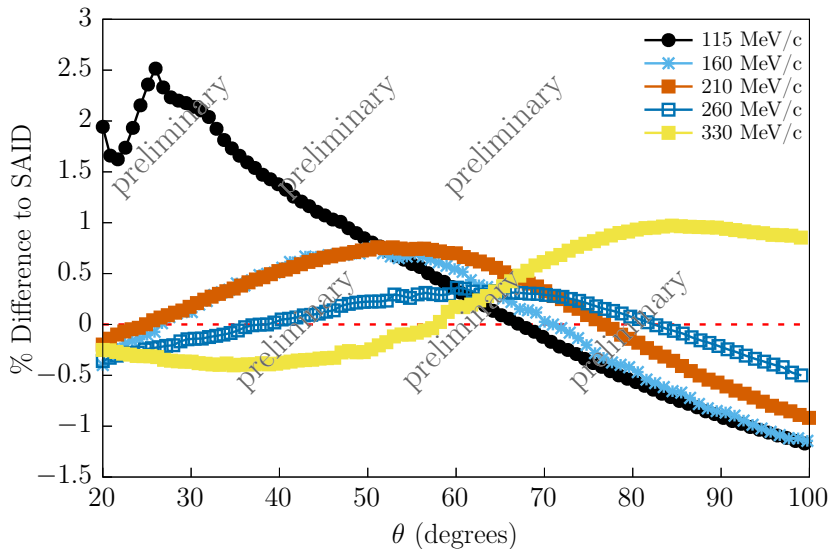
$$f(\theta) = \underbrace{f_C(\theta)}_{\text{Coulomb}} + \underbrace{\frac{1}{k_{CM}} \sum_{l=0}^{\infty} [(l+1) f_{l+} + l f_{l-}] P_l(\cos \theta)}_{\text{Hadronic}}$$

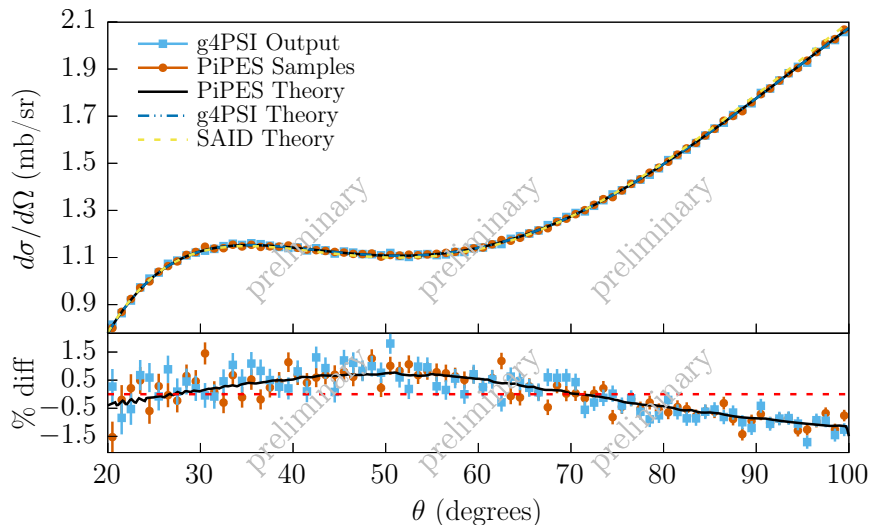
$$g(\theta) = \underbrace{g_C(\theta)}_{\text{Coulomb}} + \underbrace{\frac{1}{k_{CM}} \sum_{l=0}^{\infty} (f_{l+} - f_{l-}) P'_l(\cos \theta)}_{\text{Hadronic}}$$

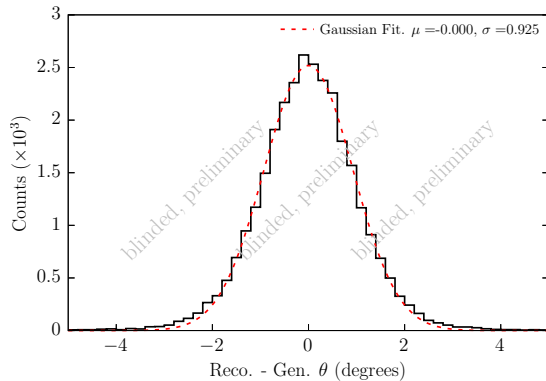
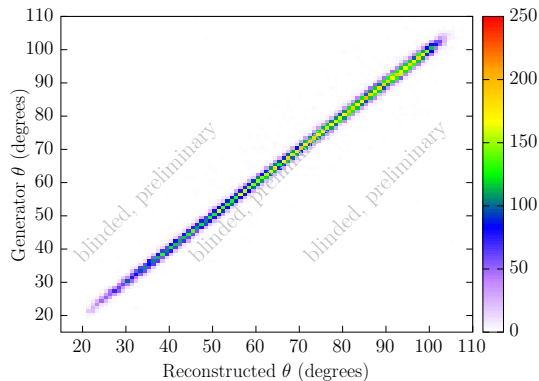
$$f_{l\pm} = \underbrace{e^{2i\Sigma_{l\pm}}}_{\text{Coulomb}} \underbrace{\frac{\eta_{l\pm} e^{2i\delta_{l\pm}} - 1}{2i}}_{\text{Hadronic}}$$

<sup>1</sup>B. Tromborg, S. Waldenstrøm, and I. Øverbø, Phys. Rev. D 15, 725 (1977)

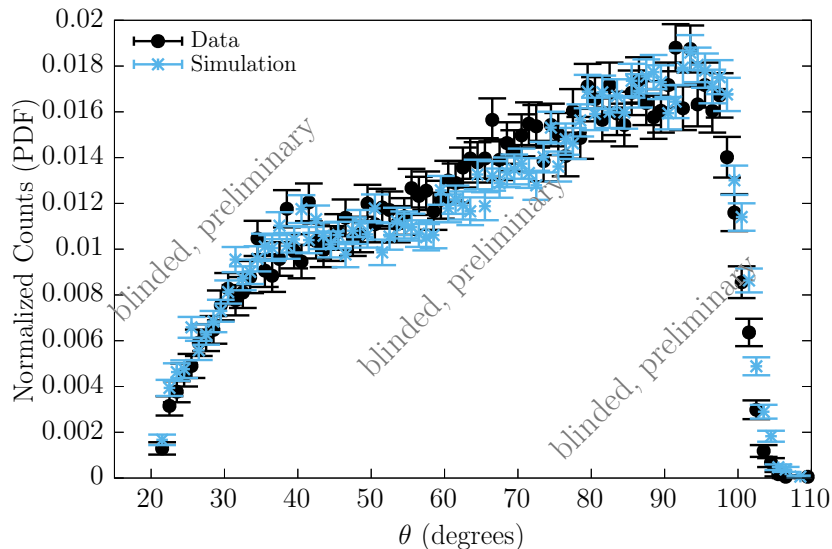
<sup>2</sup>R. Koch and E. Pietarinen, Nucl. Phys. A 336, 331 (1980)



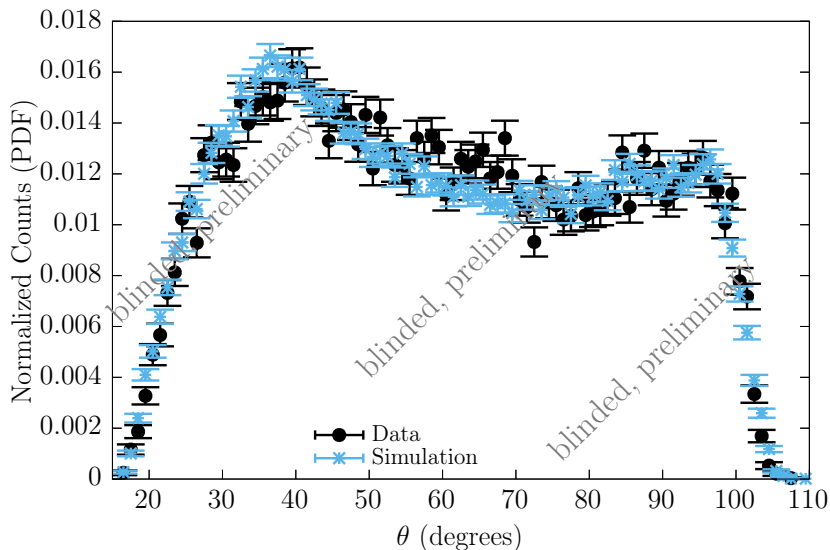




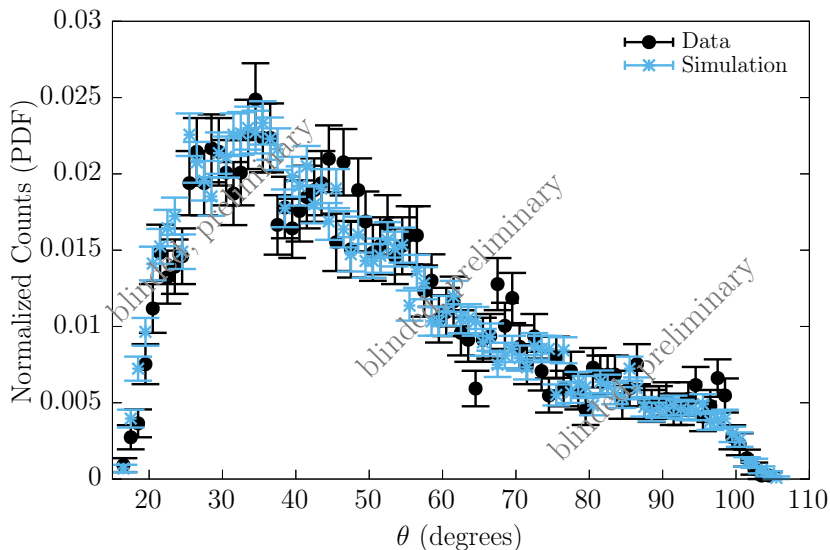
$G_{ij}$  in minimization procedure.



Shape reflects cross section, detector acceptance ...



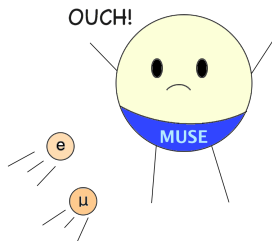
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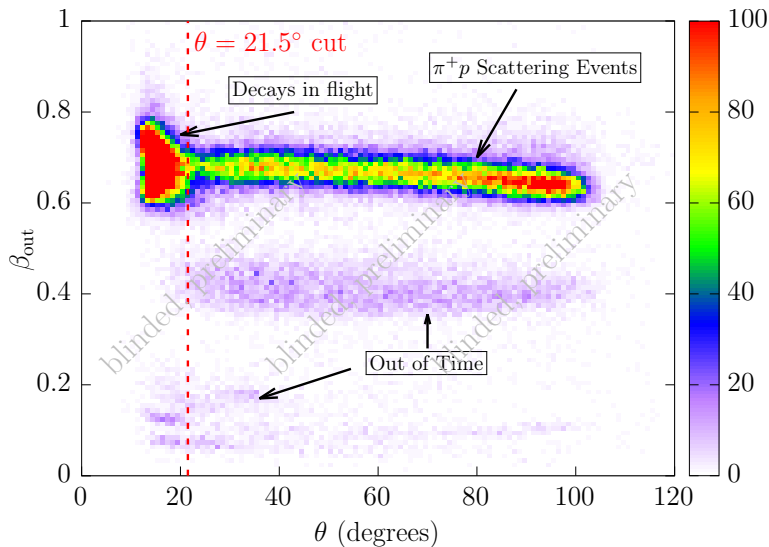


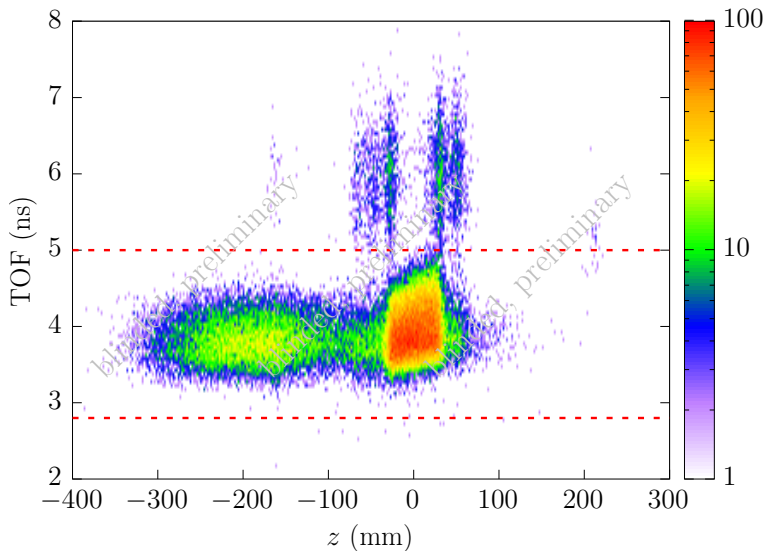
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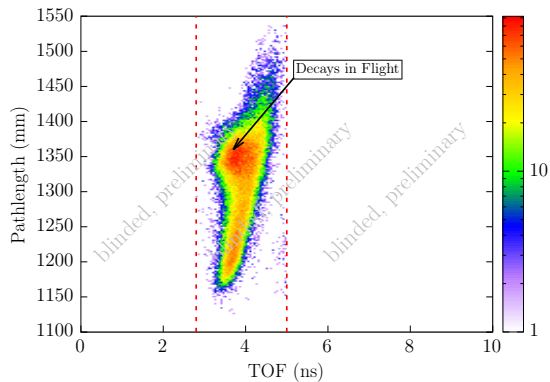
- For MUSE to unblind: must be satisfied with detector calibrations, realistic simulation digitization and results upon other factors
- Unblinding will be done in stages:  $\pi^\pm$  will be done first in a few stages, then later the lepton data
- Blinded analysis of  $\pi p$  scattering data: expected *May 2027*
- Expected unblinding timeline of  $\pi^\pm$  MUSE data: *2028*

- MUSE has a wealth of  $\pi p$  scattering data that can be used for extraction of partial wave phase shifts
- PiPES event generator has been developed to simulate  $\pi p$  scattering events based on SAID PWA results
- PiPES/MUSE simulation framework will be used in reweighting-based fitting procedure to extract MUSE  $\pi p$  cross sections
- Expecting blinded analysis of MUSE  $\pi p$  scattering data: *by May 2027*
- Expected unblinding timeline: *2028*

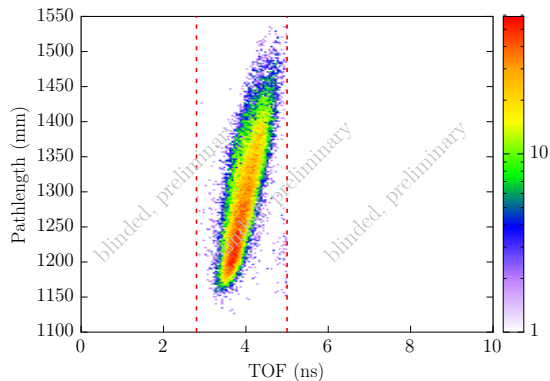








All in-time events.



In-time events with  $\theta$ -based decay cut applied.