A Blind Analysis for PRad-II Experiment using the PRad Data

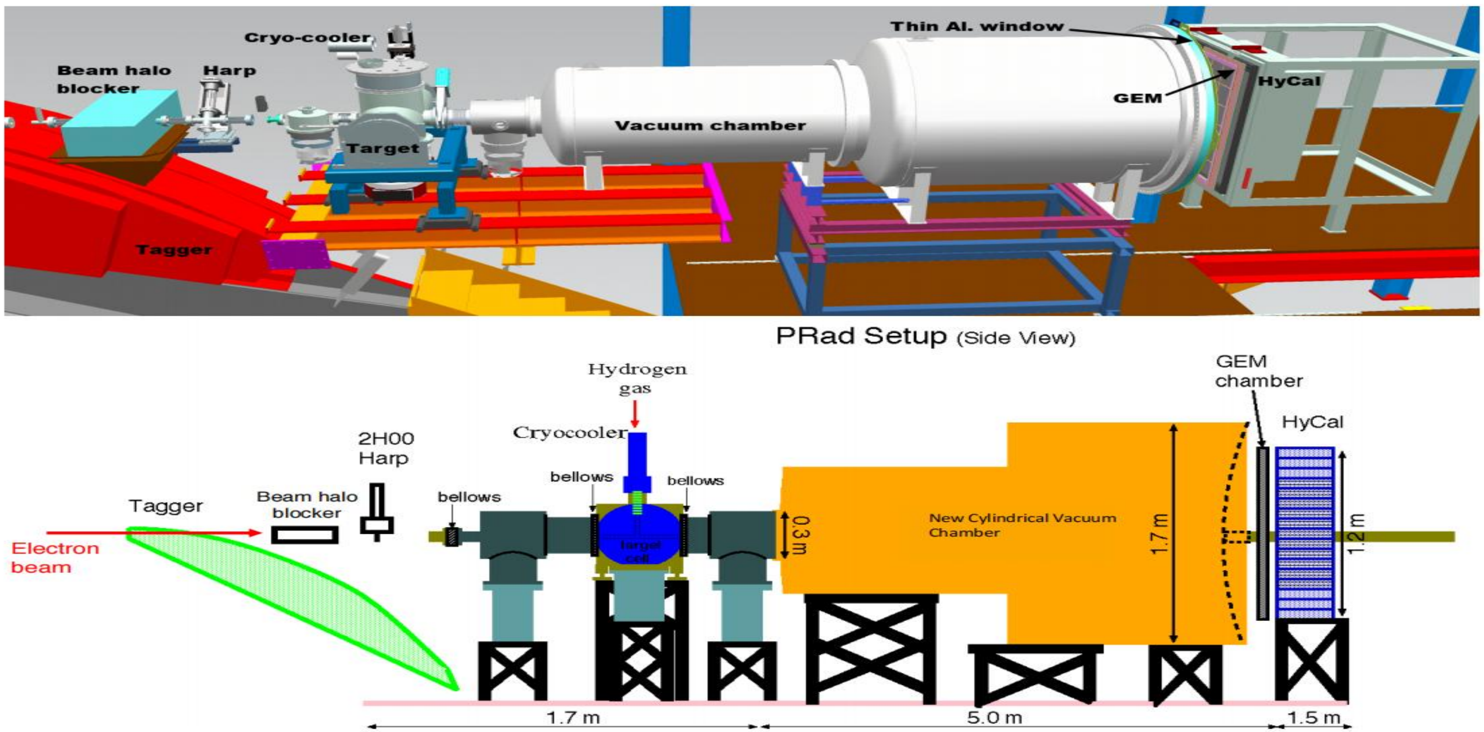
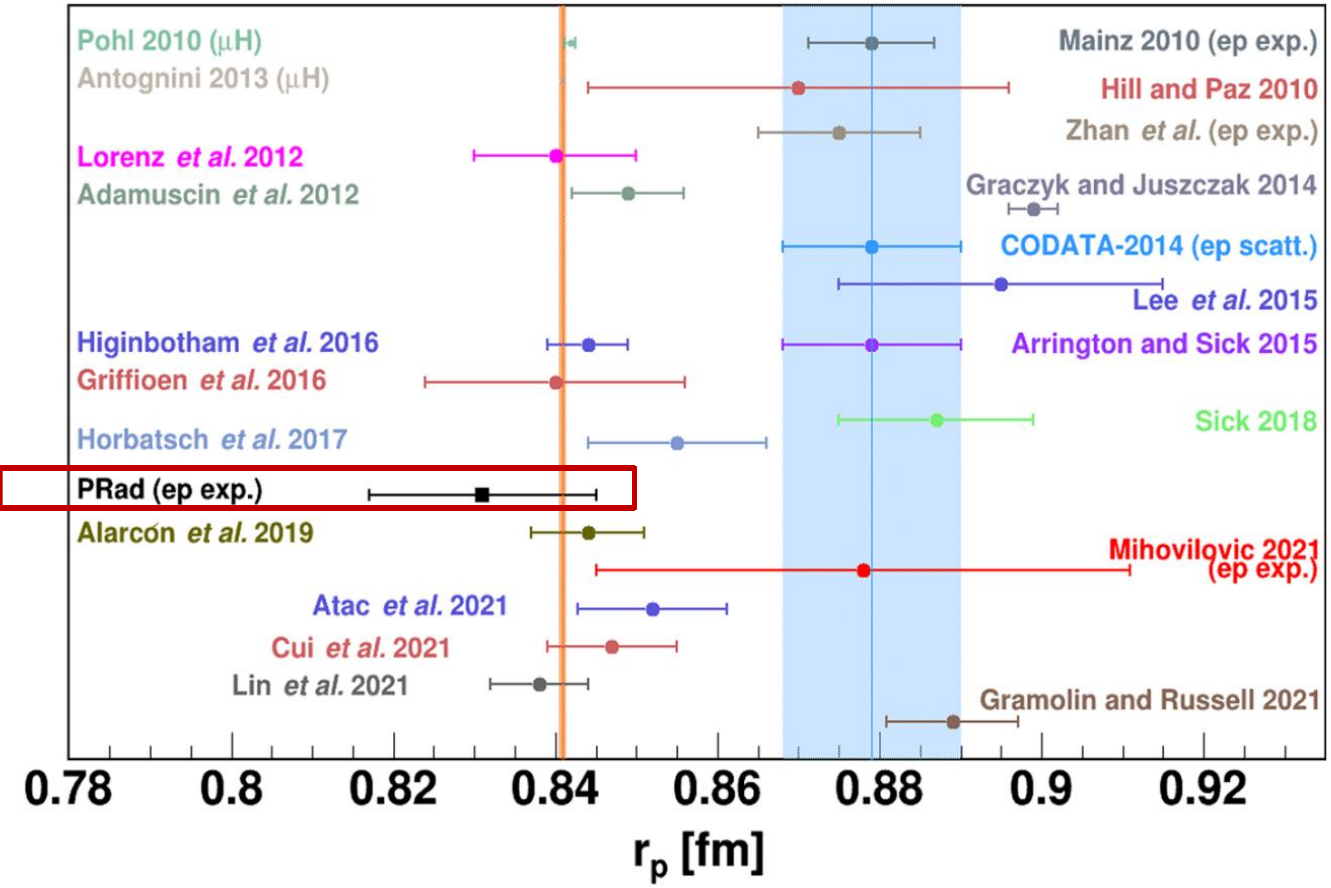


Figure 1: Schematic diagram of PRad Setup

Duke University

YINING LIU 09/12/2025

Result of the PRad Experiment



Xiong *et al.*, *Nature* 575, 147–150 (2019).

PRad:

- Two independent analyses (Weizhi Xiong from Duke, Xinzhan Bai from UVA)
- **No blind analysis**

$$r_p = 0.831 \pm 0.007_{\text{stat.}} \pm 0.012_{\text{syst.}} \text{ fm}$$

Why do we need a blind analysis?

We presented on how to carry out a blind analysis for PRad-II during the PRad-II C1 review

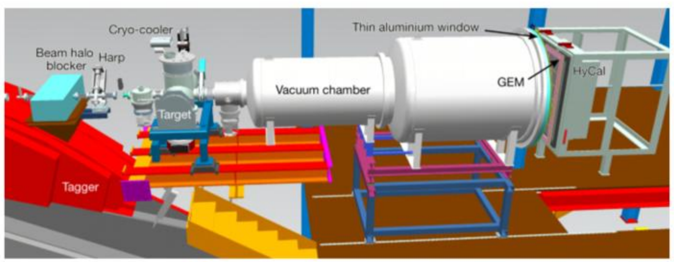
Studies of Radiative Corrections for the PRad-II Experiment

Haiyan Gao
Duke University
For the PRad Collaboration

PRoton Radius

PRad-II C1 Review

March 12, 2021



PRad-II C1 review, March 12, 2021 PRoton Radius 1

Outline

Outline	Plan for blind analysis for PRad-II	RC studies for PRad	RC studies for PRad-II	Summary

- Plan for blind analysis to extract the proton radius (r_p) for PRad-II
- Radiative correction (RC) studies for PRad
  - PRad's estimation of the RC systematic uncertainty of r_p
  - Independent study of the RC systematic uncertainty of r_p
- RC studies for PRad-II
  - Integrated Møller method
  - Plans for the next-to-next leading order (NNLO) calculations
  - Improvement from PRad to PRad-II
  - Partial testing of calculations of radiative effects
- Summary

PRad-II C1 review, March 12, 2021 PRoton Radius 2

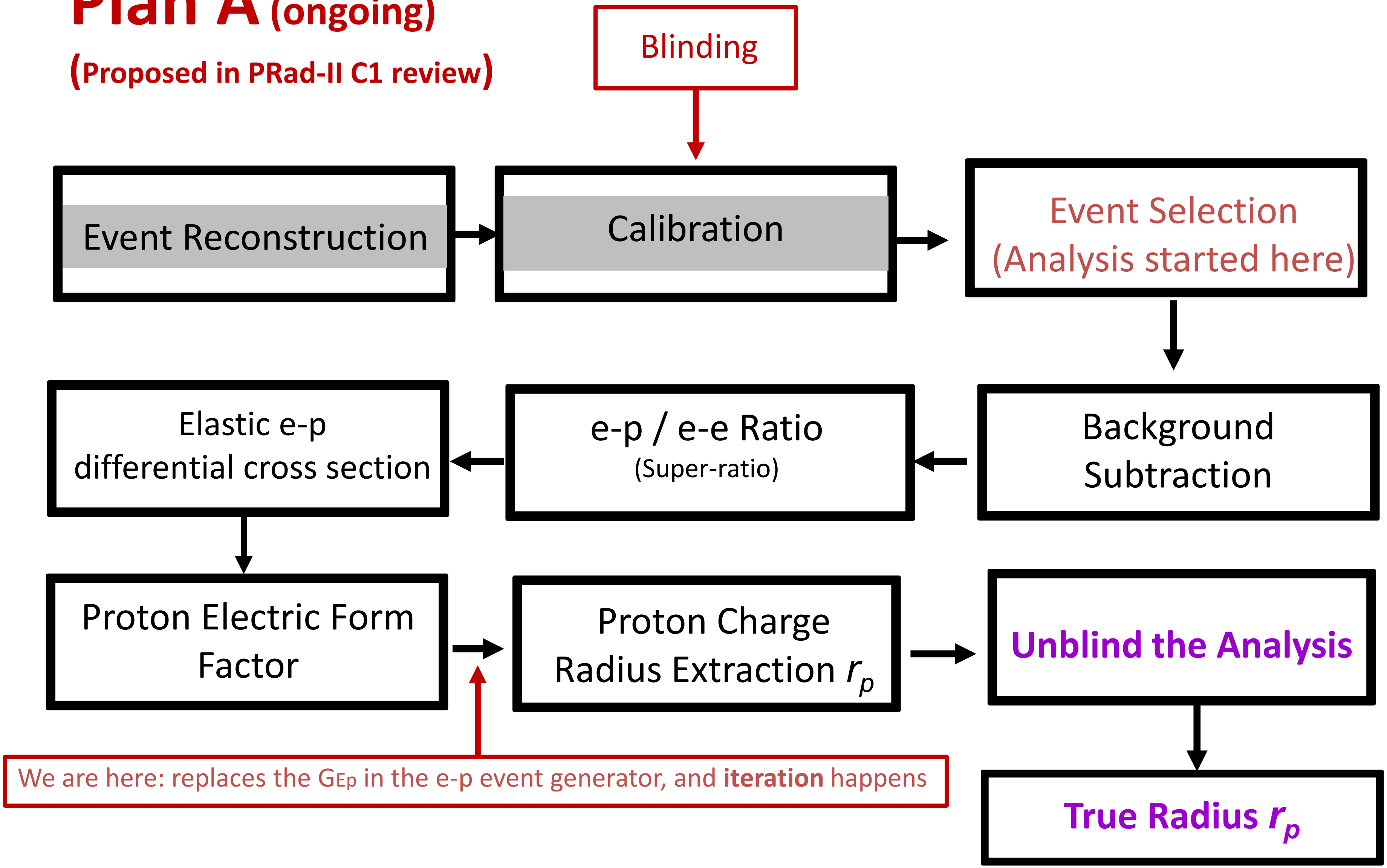
- Goal of this study:

Test the proposed approaches and apply the blind analysis for PRad-II to enhance objectivity.

Goal: Blind analysis for extraction of r_p for PRad-II

Plan A (ongoing)

(Proposed in PRad-II C1 review)



Iteration Process Flow Chart

Generate events with *e-p* event generator

Propagate generated particles in Geant4 simulation, and perform digitization and reconstruction

Extract *e-p* elastic scattering cross section, and electric form factor

Fit the extracted form factor and replace that in the generator

Using blind data to form the Super-ratio First

$$\frac{\tilde{N}^{\mathrm{e,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{e,r}}_{ee}(\theta_j)}{\tilde{N}^{\mathrm{s,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{s,r}}_{ee}(\theta_j)}$$

Experimental cross section

$$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{e,b}}_{ep}(\theta_i) = \frac{\tilde{N}^{\mathrm{e,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{e,r}}_{ee}(\theta_j)}{\tilde{N}^{\mathrm{s,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{s,r}}_{ee}(\theta_j)} \cdot \left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{s,b}}_{ep}(\theta_i).$$

Reduced cross-section and GEp

$$\sigma_{\mathrm{reduced}} = \frac{E(1+\tau)\left(\frac{d\sigma}{d\Omega}\right)_{ep}}{E'\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} = (G^p_E)^2 + \frac{\tau}{\epsilon}(G^p_M)^2.$$

Best fitter for PRad and PRad-II:

$$f_{Rational(1,1)}(Q^2) = p_0\frac{1+p_1^aQ^2}{1+p_1^bQ^2}$$

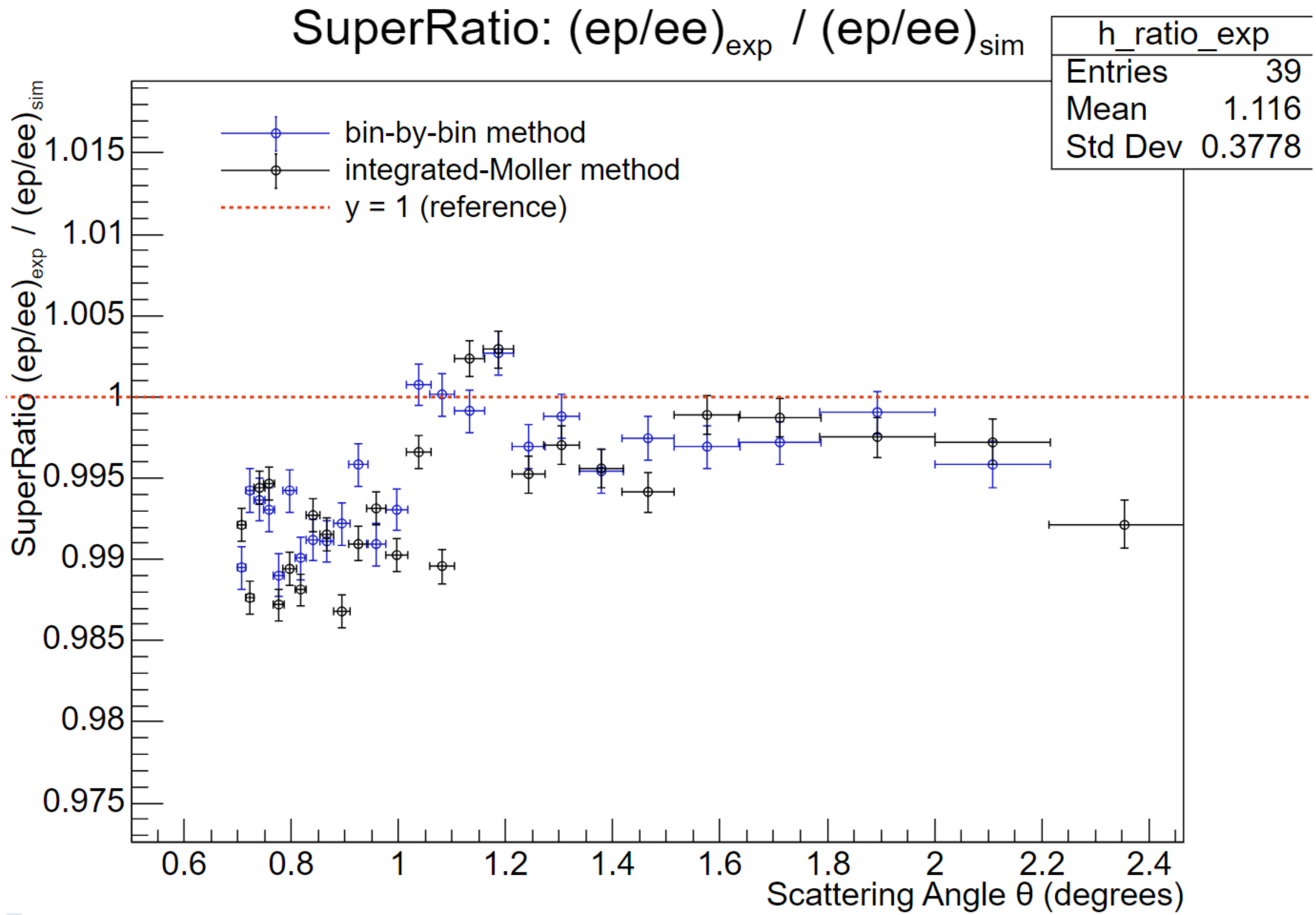
$$r_{\mathrm{fit}} = \sqrt{6(\mathrm{p}_1^{\mathrm{a}} - \mathrm{p}_1^{\mathrm{b}})}$$

Used the Rational(1,1) form for the Electric Form Factor

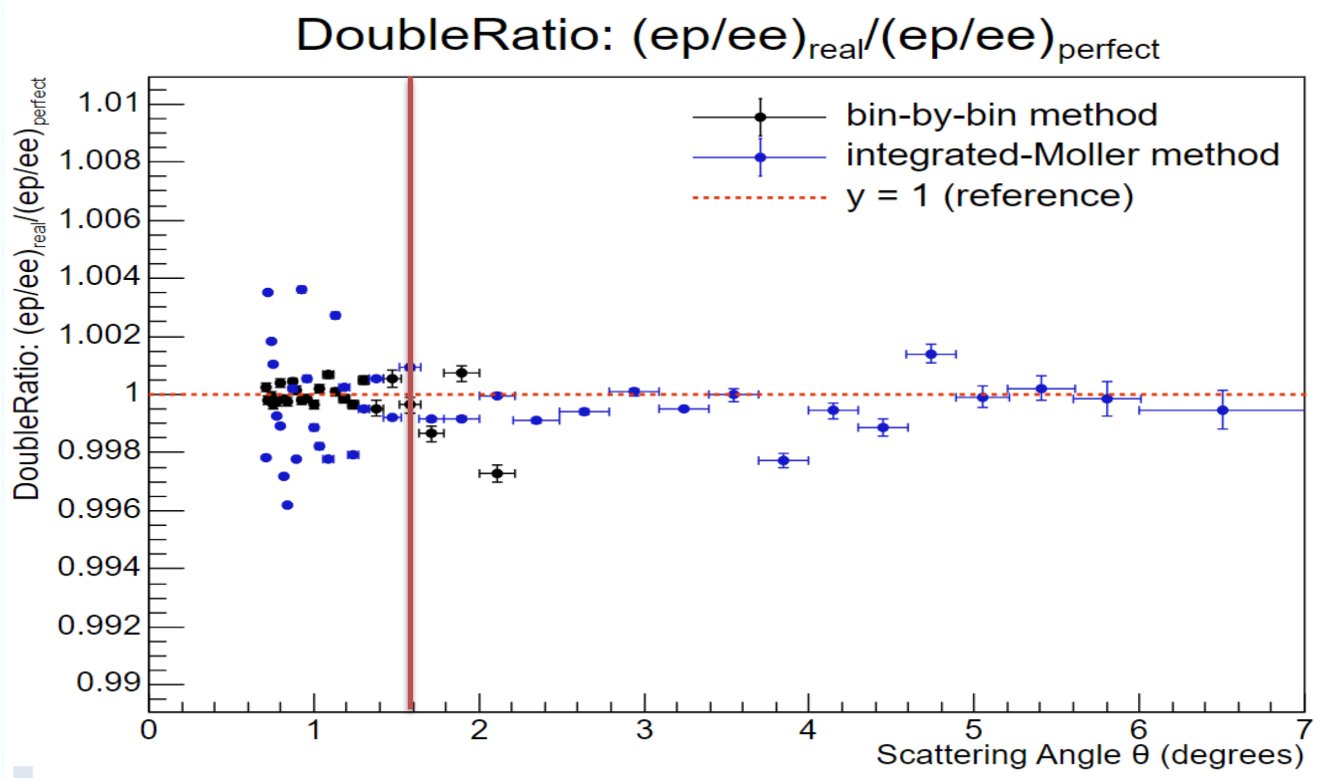
E_beam=2.143 GeV

$$\frac{\tilde{N}^{e,r}_{ep}(\theta_i)/\tilde{N}^{e,r}_{ee}(\theta_j)}{\tilde{N}^{s,r}_{ep}(\theta_i)/\tilde{N}^{s,r}_{ee}(\theta_j)}$$

Superratio: bin-by-bin and integrated Moller methods



Double-ratio: The GEM efficiency corrected $e-p$ to $e-e$ ratio from the simulation with more realistic GEM detectors that include all the dead areas, over the same ratio from the simulation with perfect GEM detectors.



Conclusion:

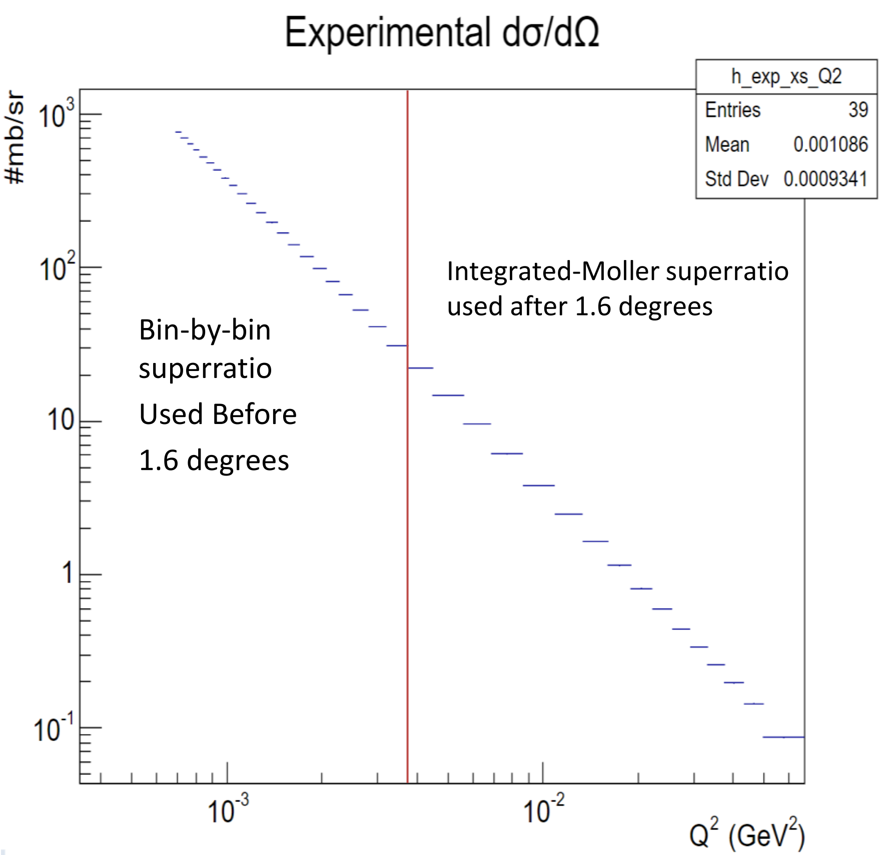
Below 1.6 degrees, we should use the bin-by-bin method to cancel the energy-independent part of the GEM efficiency.

For the larger angles, we must use the integrated-Möller method.

E_beam=2.143 GeV

$$(\frac{d\sigma}{d\Omega})^{\mathrm{e,b}}_{ep}(\theta_i) = \frac{\tilde{N}^{\mathrm{e,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{e,r}}_{ee}(\theta_j)}{\tilde{N}^{\mathrm{s,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{s,r}}_{ee}(\theta_j)} \cdot (\frac{d\sigma}{d\Omega})^{\mathrm{s,b}}_{ep}(\theta_i).$$

- Blind Analysis Cross Section



Weizhi's Cross Section in His Thesis

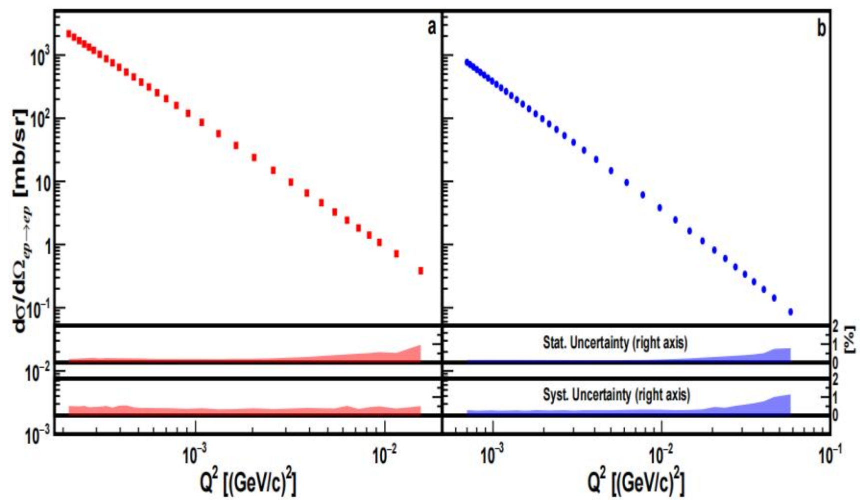
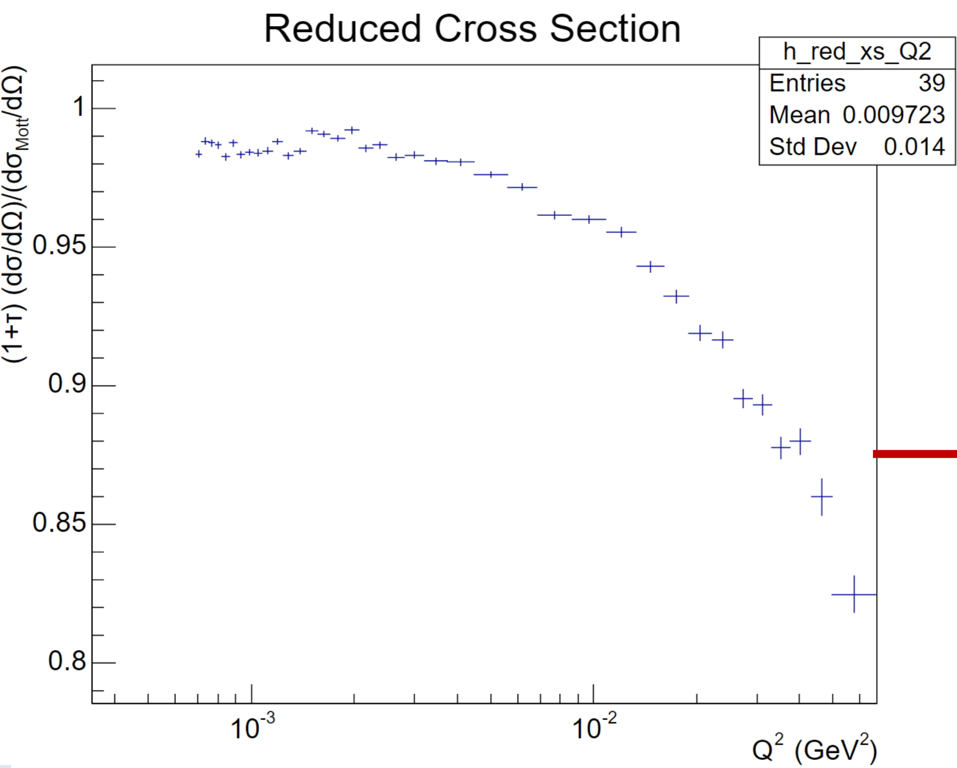


Figure 4.44: The Born level differential cross sections for the $e-p$ elastic scattering from (a) the 1.1 GeV and (b) the 2.2 GeV data sets. Statistical and systematic uncertainties are shown as separate bands and are scaled to the right axes of each plot.

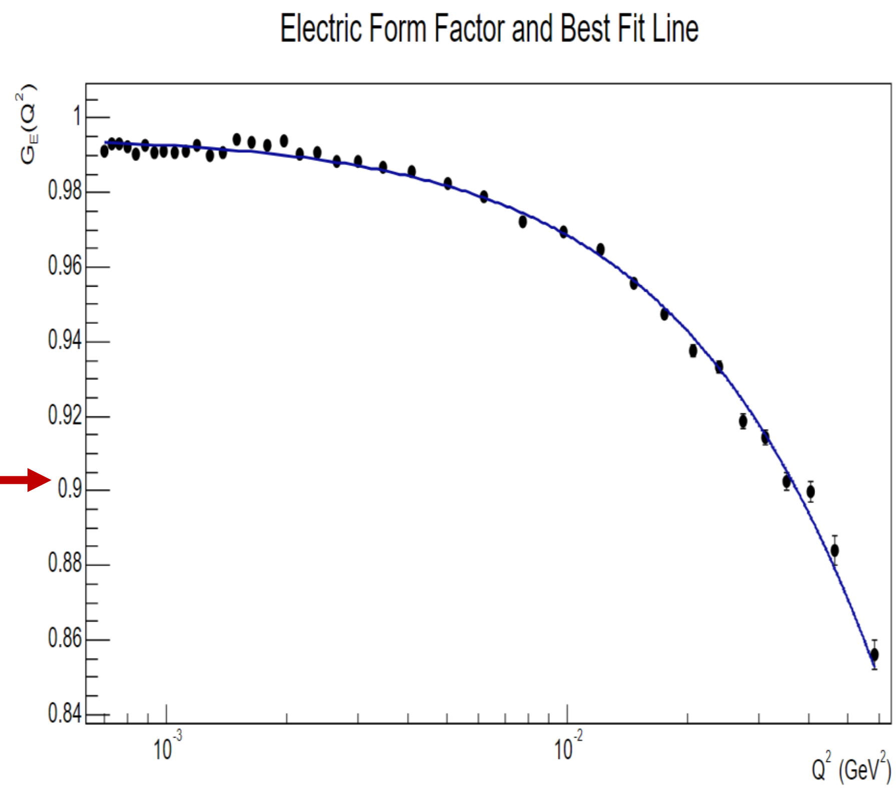
The Q^2 range for the data set is from 7.0 $\times$ 10^{-4} to 5.9 $\times$ 10^{-2} $(\mathrm{GeV}/c)^2$, covered by 38 data points.

E_beam=2.143 GeV

Blind Analysis Reduced Cross-section



Extracted Electric Form factor



$$\sigma_{\text{reduced}} = \frac{E(1+\tau)\left(\frac{d\sigma}{d\Omega}\right)_{ep}}{E'\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} = (G_E^p)^2 + \frac{\tau}{\epsilon}(G_M^p)^2.$$

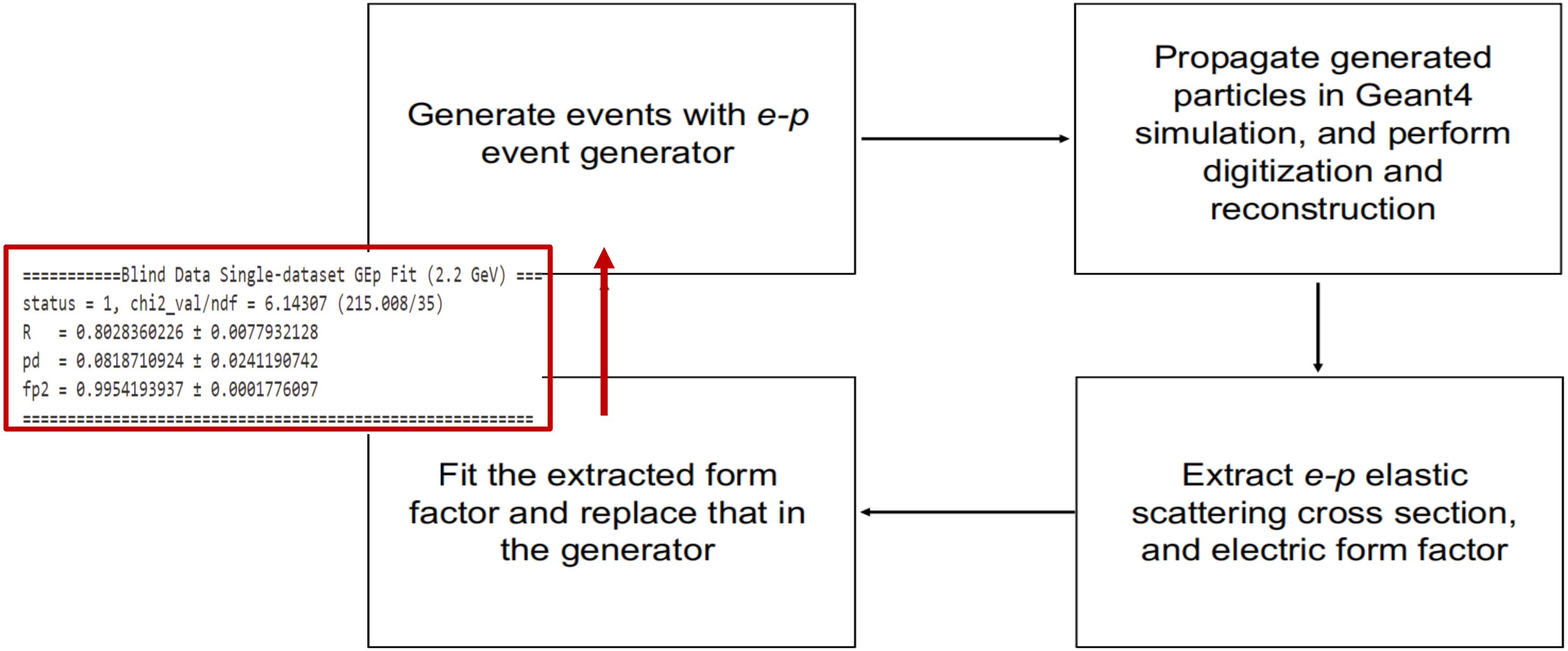
Assuming Kelly Magnetic Form factor, we can directly extract the GEp

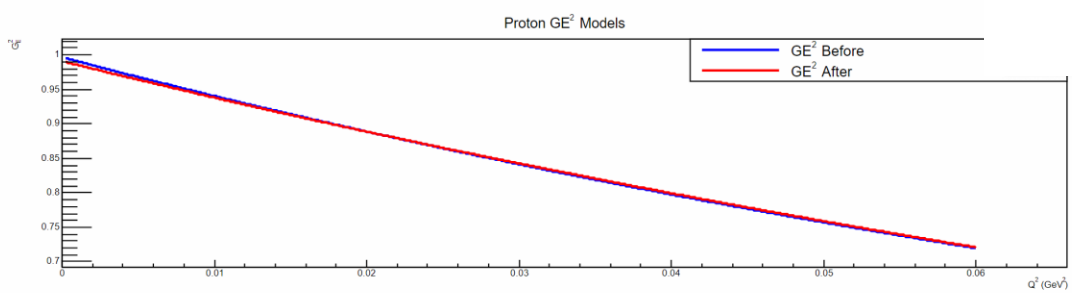
Best fitter for PRad and PRad-II:

$$f_{Rational(1,1)}(Q^2) = p_0 \frac{1 + p_1^a Q^2}{1 + p_1^b Q^2}$$

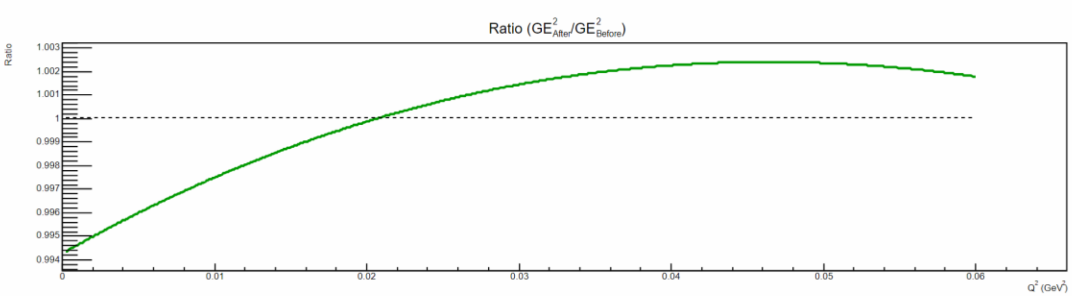
$$r_{\text{fit}} = \sqrt{6(p_1^a - p_1^b)}$$

Used the Rational(1,1) form for the Electric Form factor





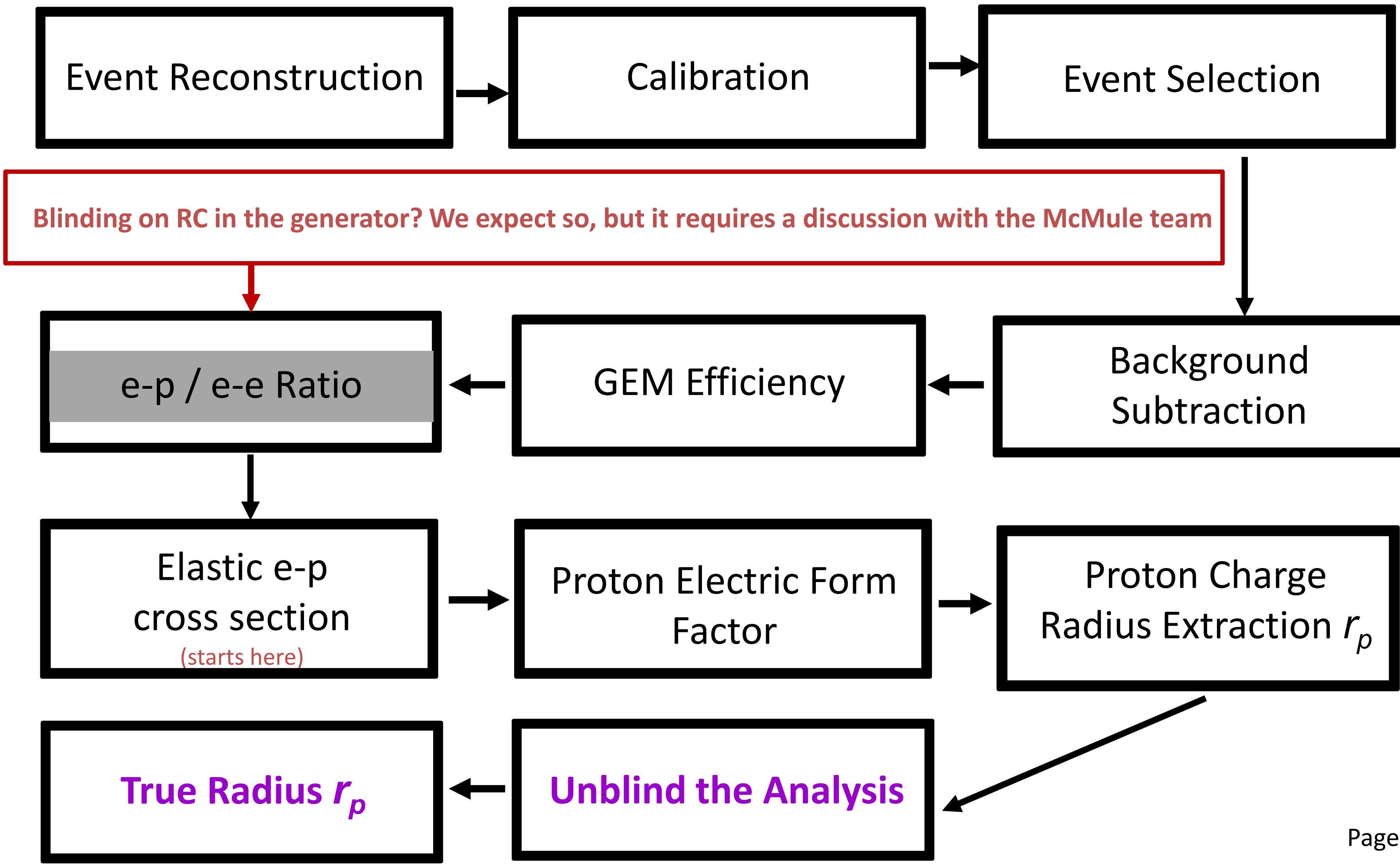
Extracted GEp Squared from the blind data and compared it with Weizhi's latest electric form factor GEp Squared (blue Line)



Ratio:
Extracted GEp Squared from the blind data over Weizhi's latest electric form factor GEp Squared (Green Line)

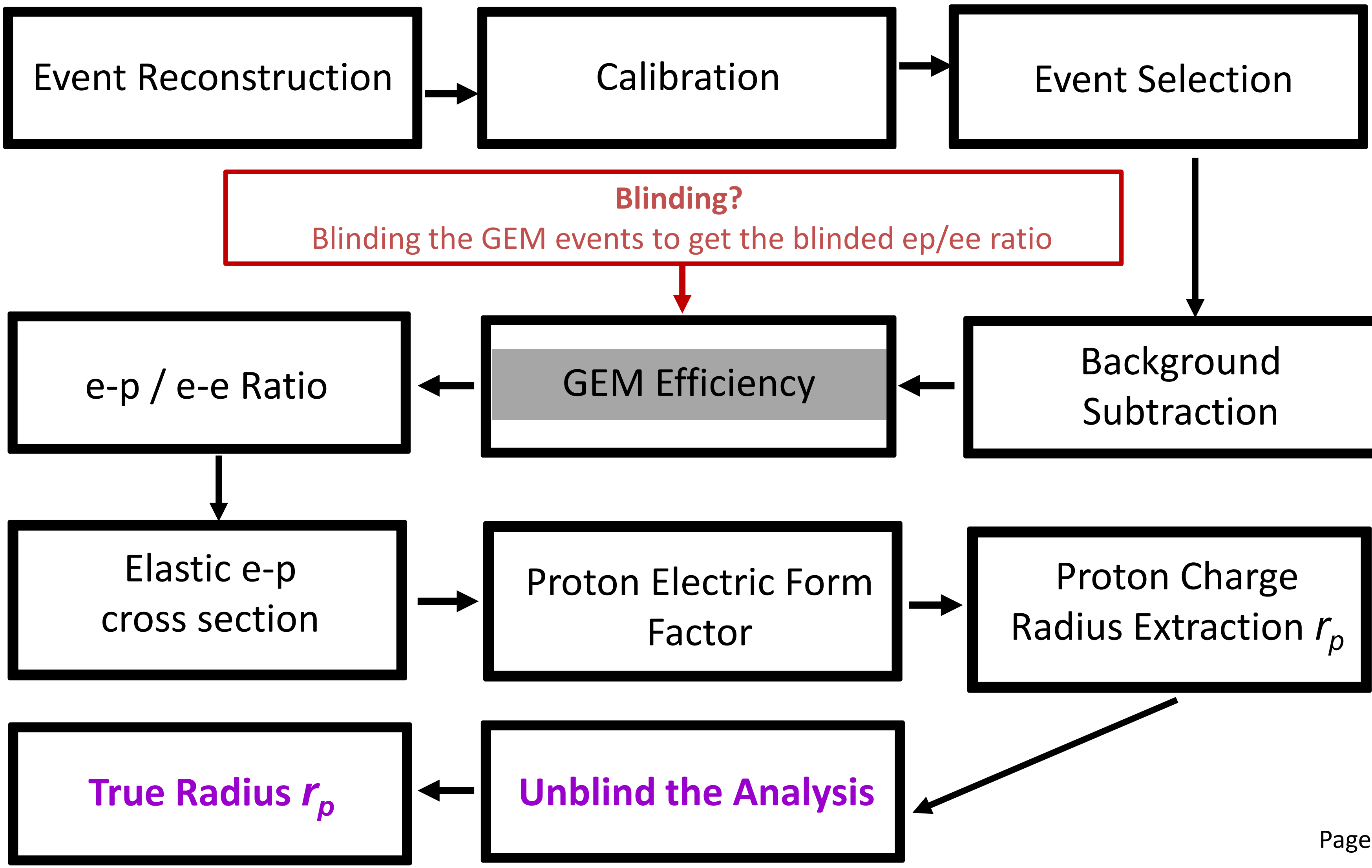
Goal: Blind analysis for extraction of r_p for PRad-II

Plan B (Proposed in PRad-II C1 review)



Goal: Blind analysis for extraction of r_p for PRad-II

Plan C: Blind at the GEM LEVEL



Conclusion

- Blind analysis helps reducing bias when performing the analysis.
- Apply and test the blinding mechanism (Ongoing Plan A or "Blinding on RC Effects" or "Blinding at GEM Level") to PRad Data and then proceed with such approaches to PRad-II.

This study is in collaboration with Weizhi Xiong, Jingyi Zhou, Chao Peng, Bo Yu, Zhiwen Zhao, Yi Yu, and Haiyan Gao and partly supported by the Dept of Physics of Duke and Nuclear Physics, the Office of Science of the DOE under Contract No. DE-FG02-03ER41231

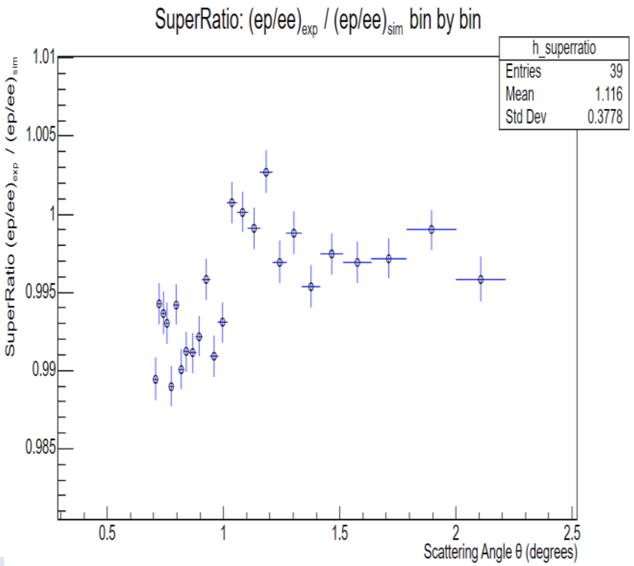
Thank you!

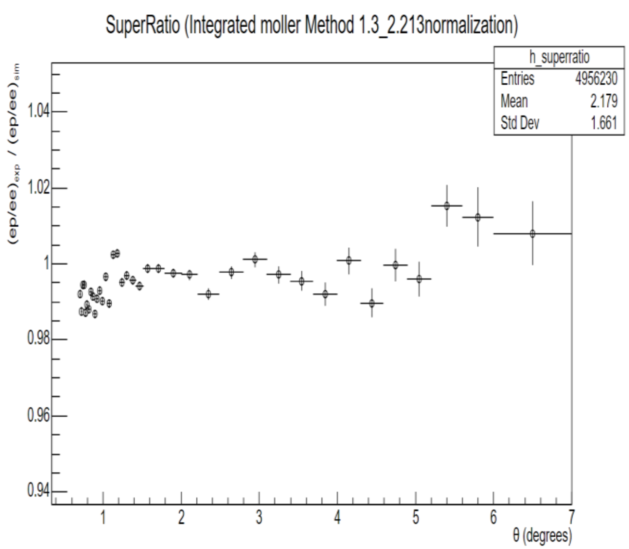
Back-Up Slides

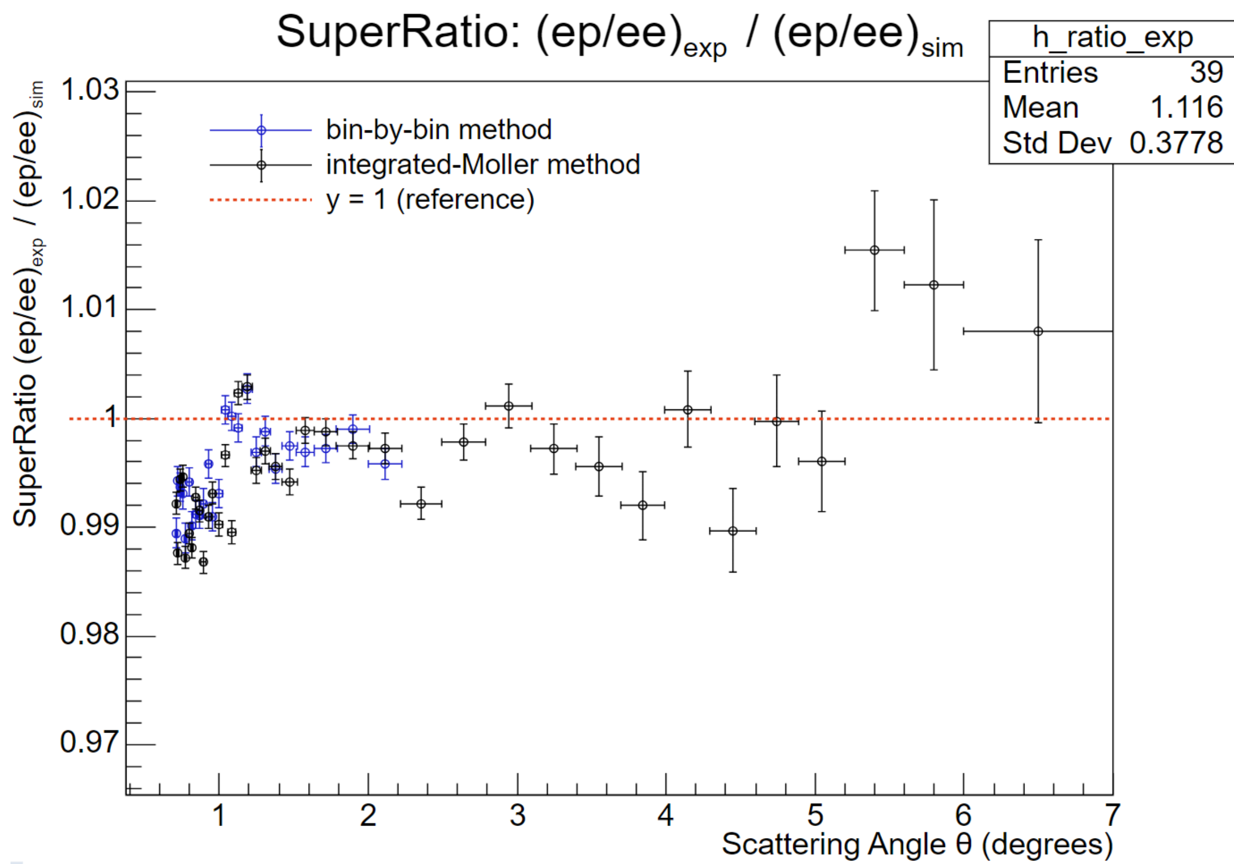
from November collaboration meeting

$$\frac{\tilde{N}^{\mathrm{e,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{e,r}}_{ee}(\theta_j)}{\tilde{N}^{\mathrm{s,r}}_{ep}(\theta_i)/\tilde{N}^{\mathrm{s,r}}_{ee}(\theta_j)}$$

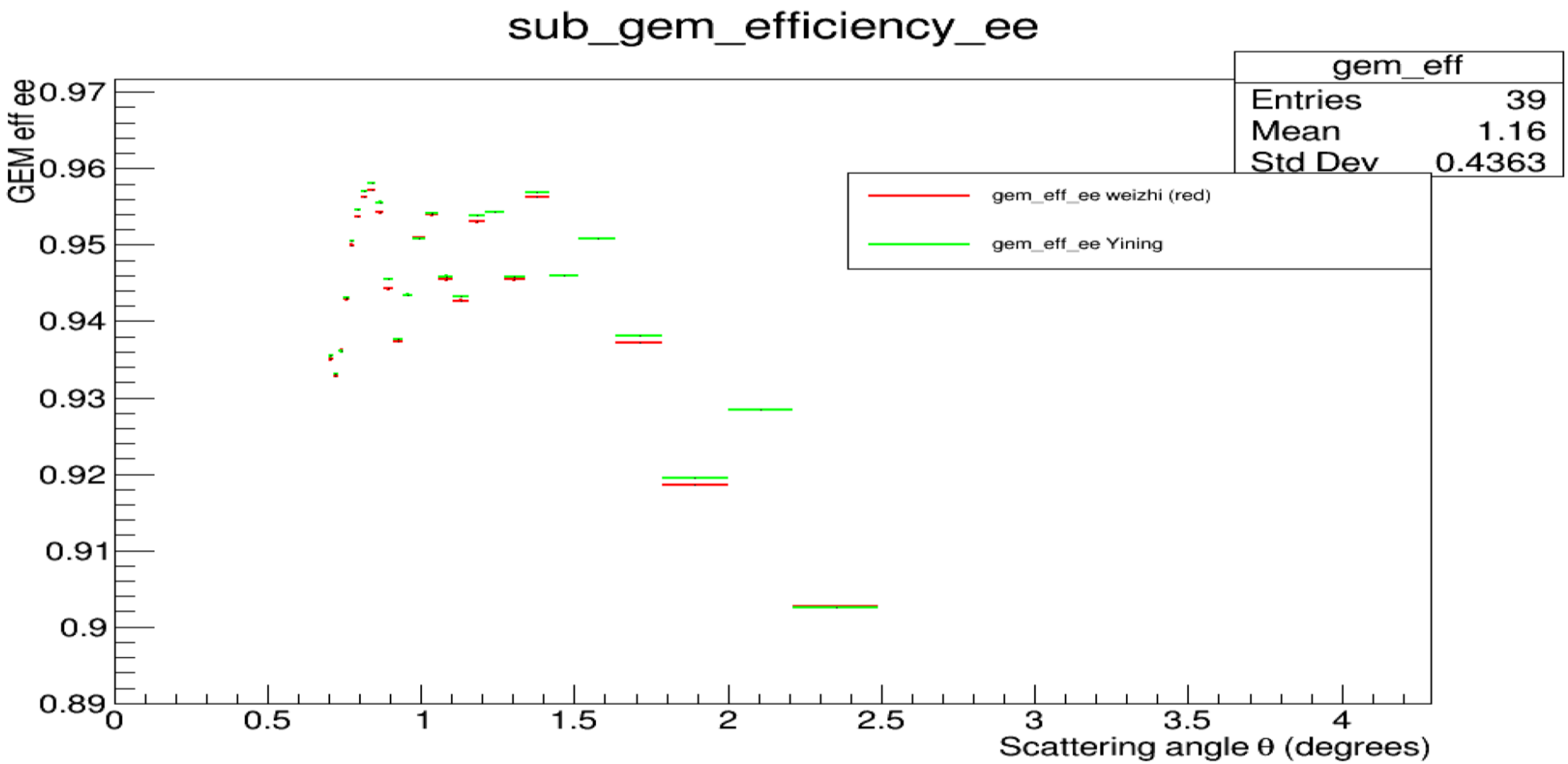
Superratio: bin-by-bin and integrated Moller methods







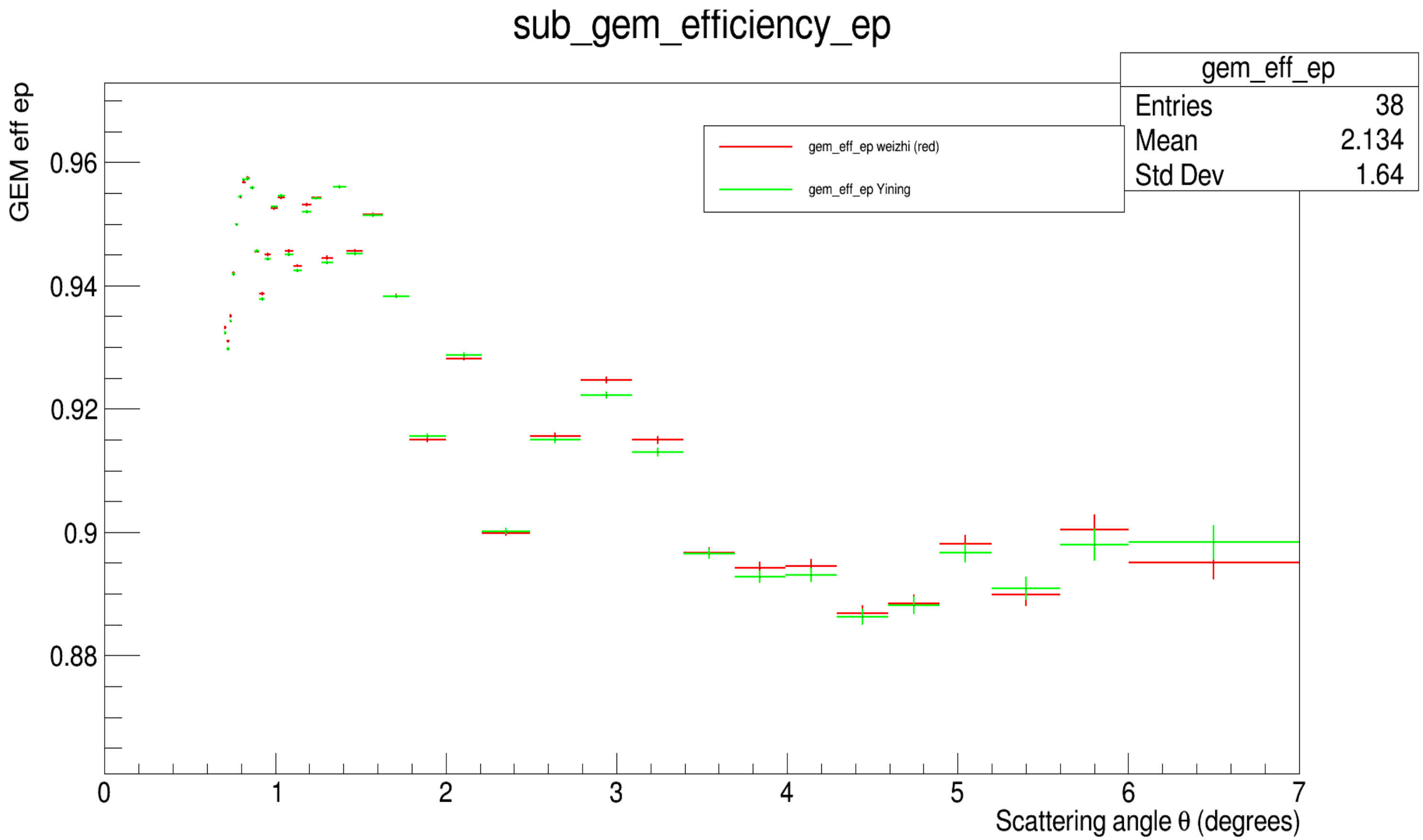
GEM Efficiency Study (e-e case)



RMS Value for difference between 2 sets(%)	e-e: ~0.0498

Statistics: 100% Beam Energy: 2.143(GeV)

GEM Efficiency Study (e-p case)

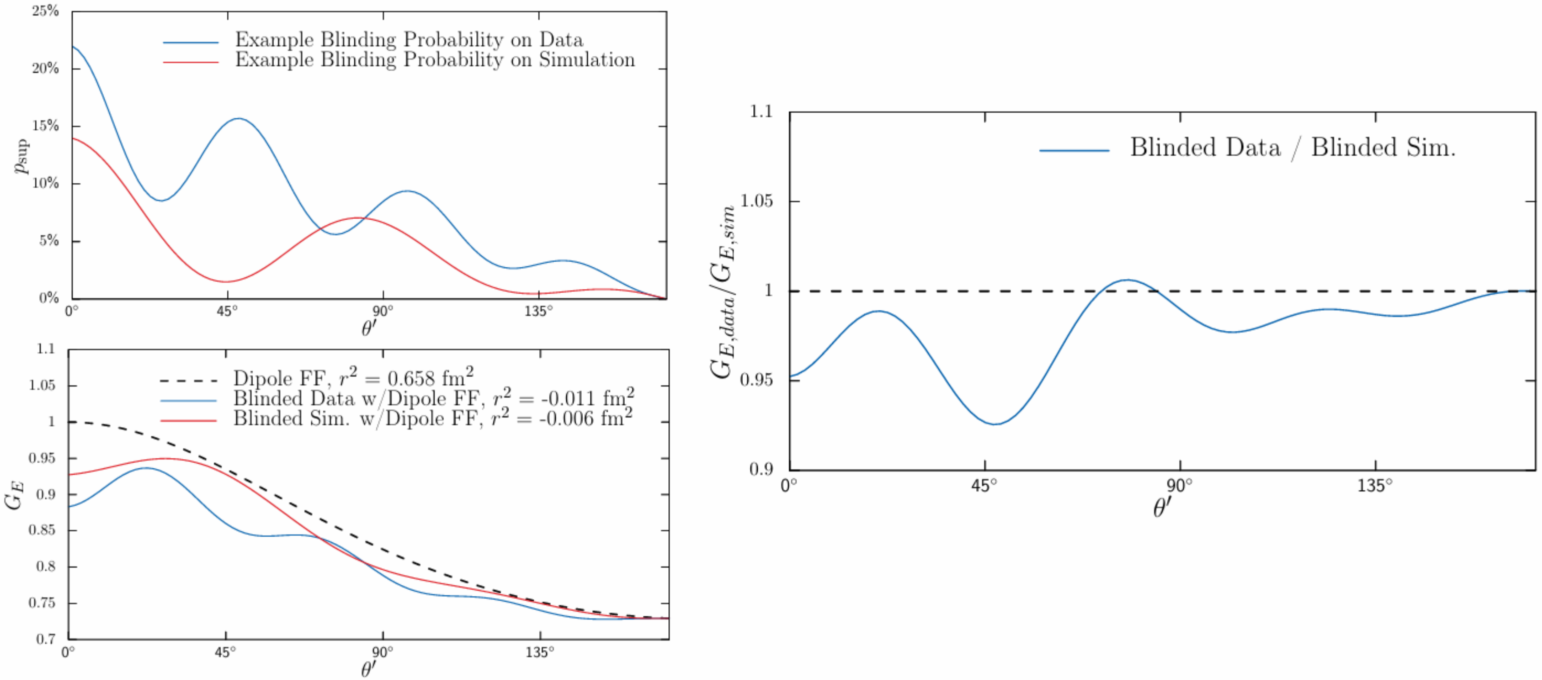


RMS Value for difference between 2 sets(%)	e-p: ~0.106

Statistics: 100% Beam Energy: 2.143(GeV)

Case Study and Example:
MUSE Experiment

$$p_{\text{sup}} = \frac{0.2}{3}\left(A_i + 0.3\cos B_i\theta'\right)\left(3-\theta'\right) \qquad A_i \in [0.25, 1] \qquad B_i \in [3, 10]$$



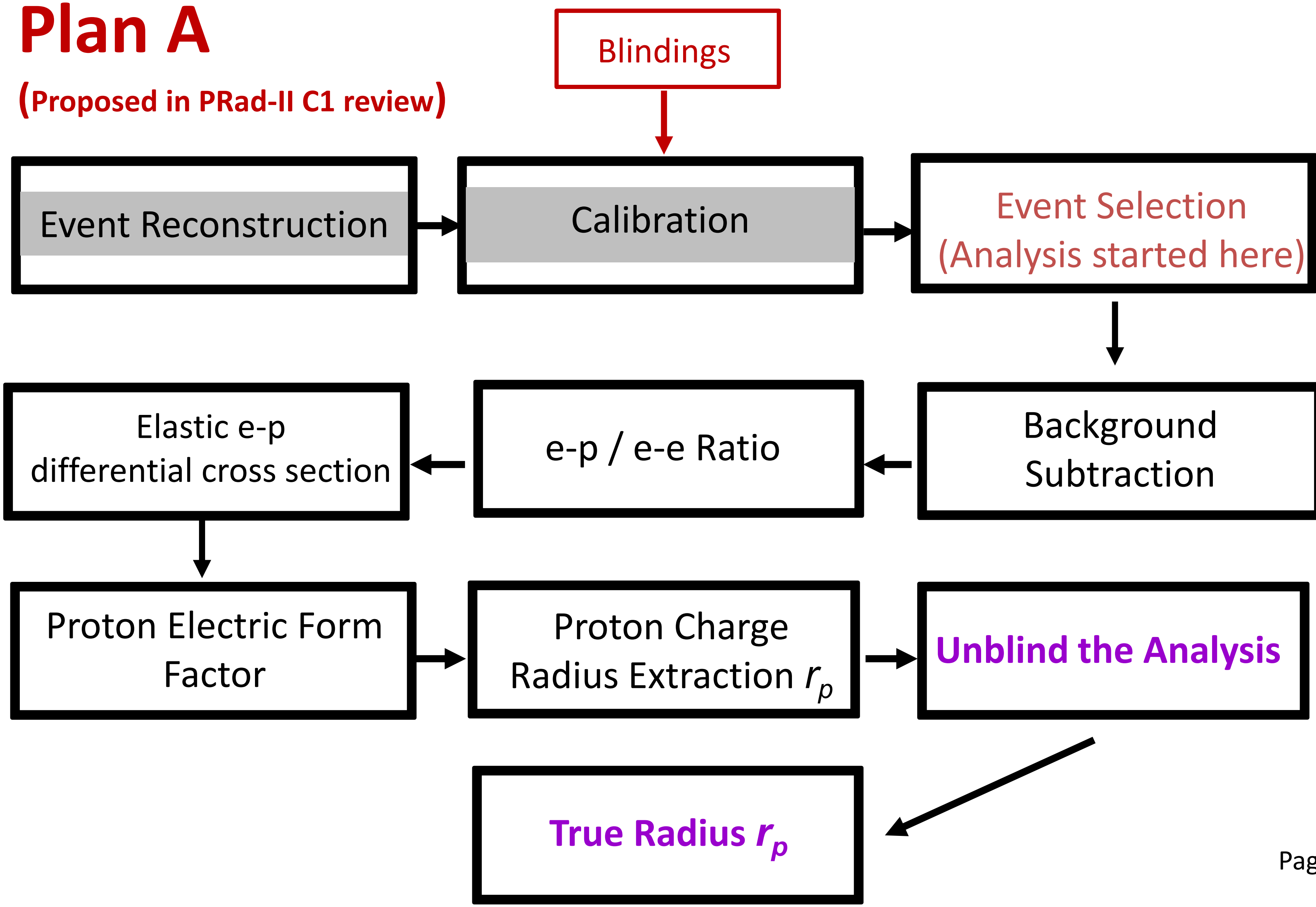
J.C. Bernauer *et al.*,
***Blinding for precision scattering experiments: The MUSE approach as a case study,* Phys. Rev. C, under review; arXiv:2310.11469v1 [physics.data-an]**

citation:
https://indico.lns.tohoku.ac.jp/event/255/contributions/2094/attachments/788/1103/Talk_MUSE_LEES2024_MichaelKohl.pdf

Goal: Blind analysis for extraction of r_p for PRad-II

Plan A

(Proposed in PRad-II C1 review)



Event Selections

1. Matching hits between GEMs and HyCal.

   Remove Dead Modules on HyCal.

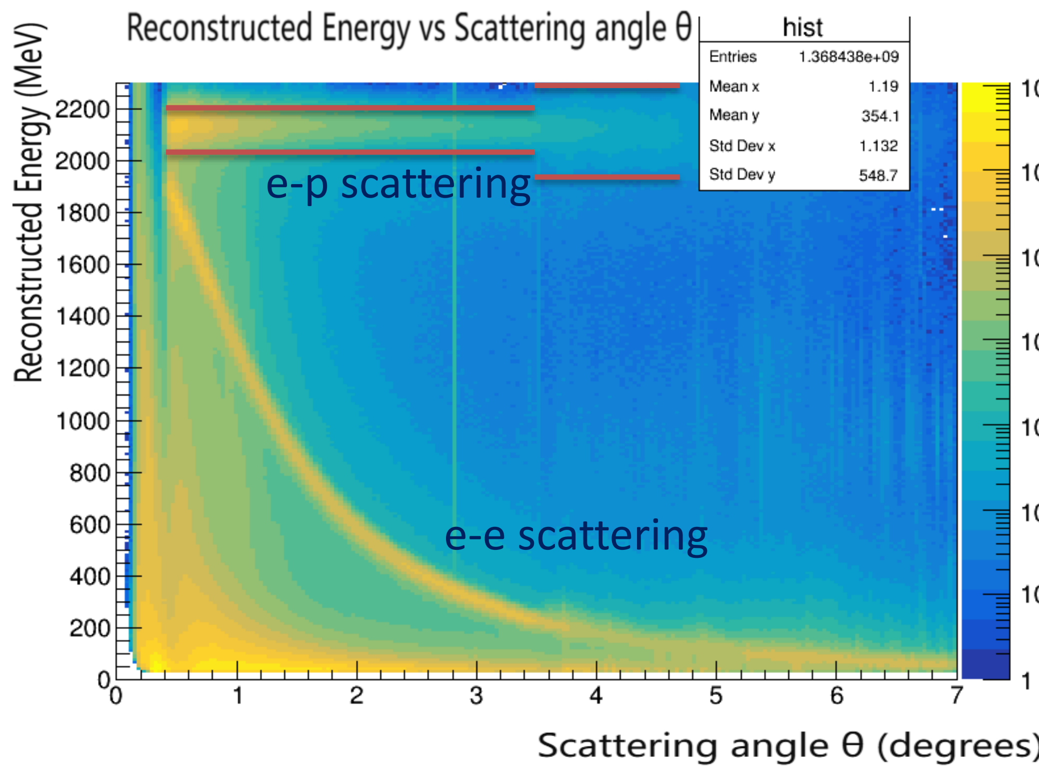
   edges of HyCal modules cut.

2. For selecting both e-p and e-e events, Apply angle-dependent expected energy cuts based on kinematics.

$$|E_{\text{rec}} - E_{\text{exp}}| < N\sigma_{\text{det}}$$

(Cut sizes depend on detector's resolution)

$E_{beam} = 2.143\,\text{GeV}$



Event Selections

3. In addition to 2, we apply additional cuts to find the double-arm e-e events:

- Co-planarity: $|\phi_{e1} - \phi_{e2} - \pi| < 10°$,

- Reconstructed Vertex z:

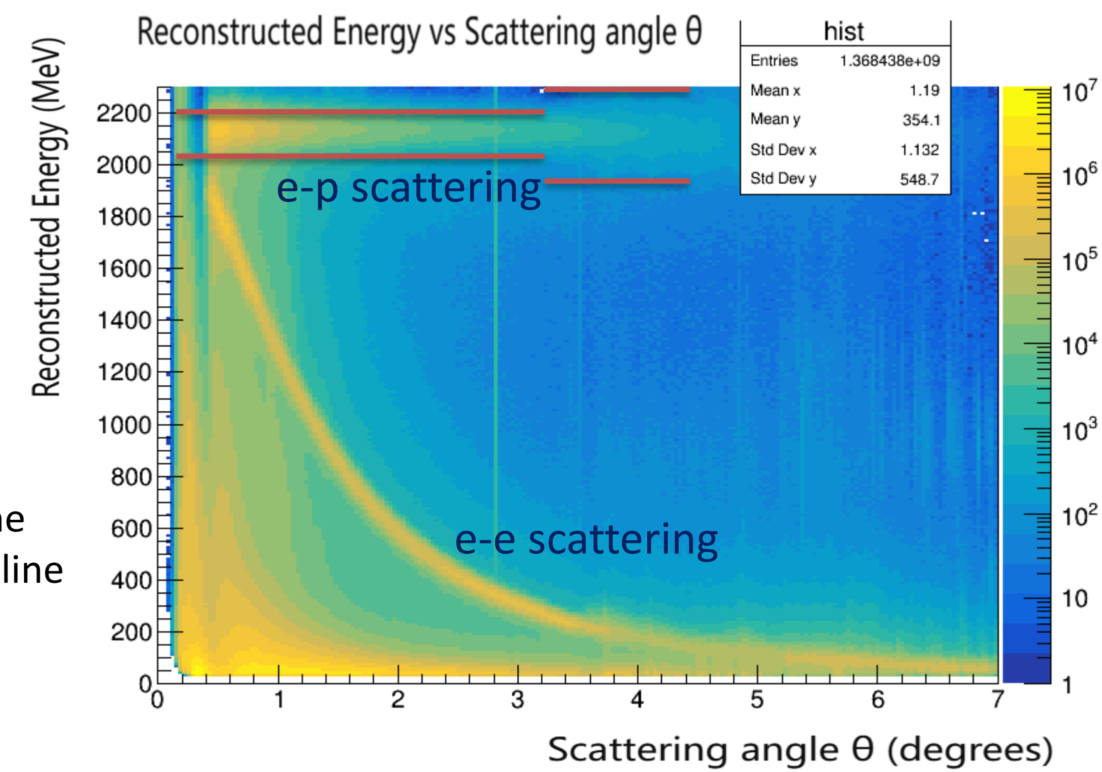
$$z = \sqrt{\frac{(m + E_\ell)R_1 R_2}{2m}},$$

($R_{1,2}$ is the transverse distance between the hit position on the detector and the beam-line of the scattered electron.)

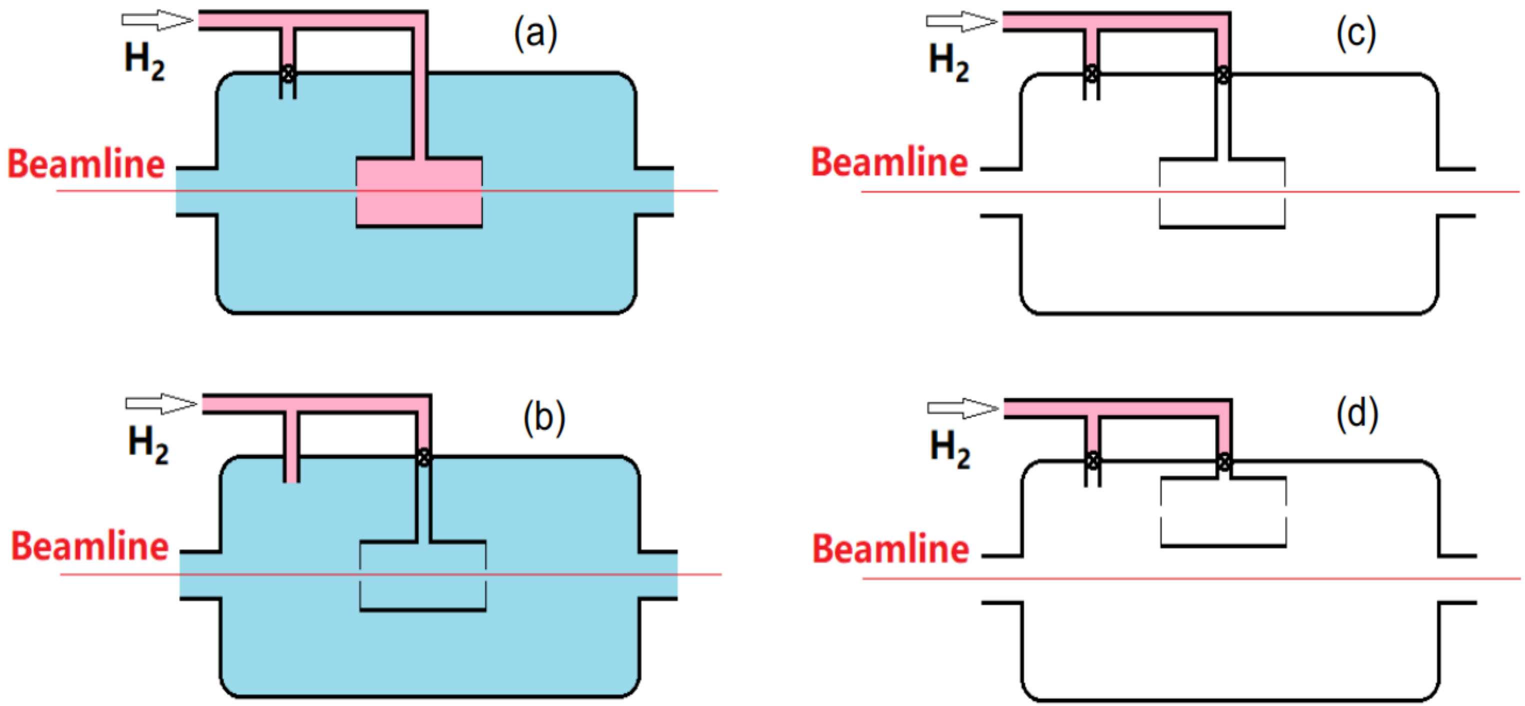
- Elasticity :

$$|E_{\text{total}} - E_b - m| = |E_{e1} + E_{e2} - E_b - m| < N\sigma_{\text{det}}$$

$E_{beam} = 2.143\,\text{GeV}$



Background Subtraction



a) Full Target run: H_2 gas was filled directly into the target cell

b)Empty Target run: H_2 gas was flled directly into the chamber

Goal: Blind analysis for extraction of r_p for PRad-II

Plan A

(Proposed in PRad-II C1 review)

Blinding

Event Reconstruction → Calibration → Event Selection (Analysis started here)

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}^{\mathrm{e,b}}(\theta_i) = \frac{\tilde{N}_{ep}^{\mathrm{e,r}}(\theta_i)/\tilde{N}_{ee}^{\mathrm{e,r}}(\theta_j)}{\tilde{N}_{ep}^{\mathrm{s,r}}(\theta_i)/\tilde{N}_{ee}^{\mathrm{s,r}}(\theta_j)} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ep}^{\mathrm{s,b}}(\theta_i).$$

We are here: got the super-ratio and beginning the iteration in simulation

Background Subtraction → e-p / e-e Ratio **(Need GEM Efficiency Correction)** → Elastic e-p differential cross section

Proton Electric Form Factor → Proton Charge Radius Extraction r_p → **Unblind the Analysis**

True Radius r_p