Reaching the PRad-II Precision

PRad-II/X17 Collaboration Meeting

Weizhi Xiong

11/11/2024

Outline

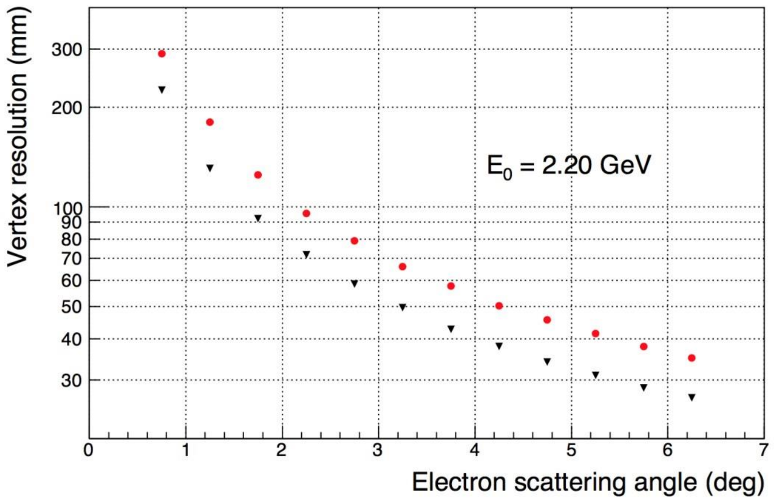
- Review of the systematics from PRad
- The key to reach PRad-II desired precision
- Other things we wish we had done during PRad data-taking (things we should consider doing during PRad-II data-taking)

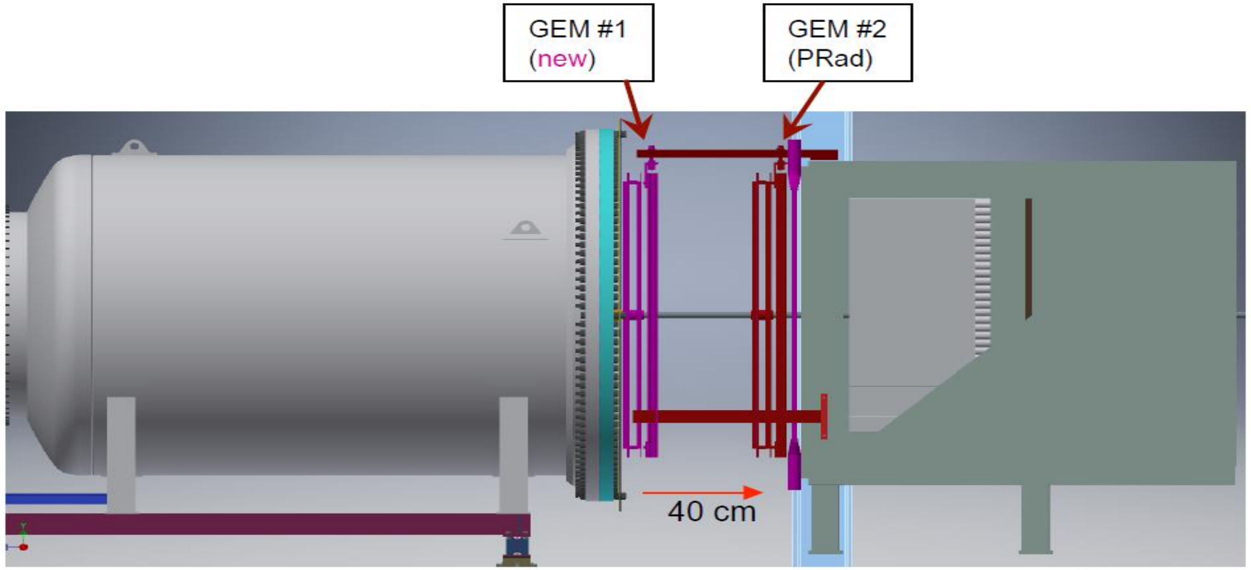
Systematic Uncertainty Table

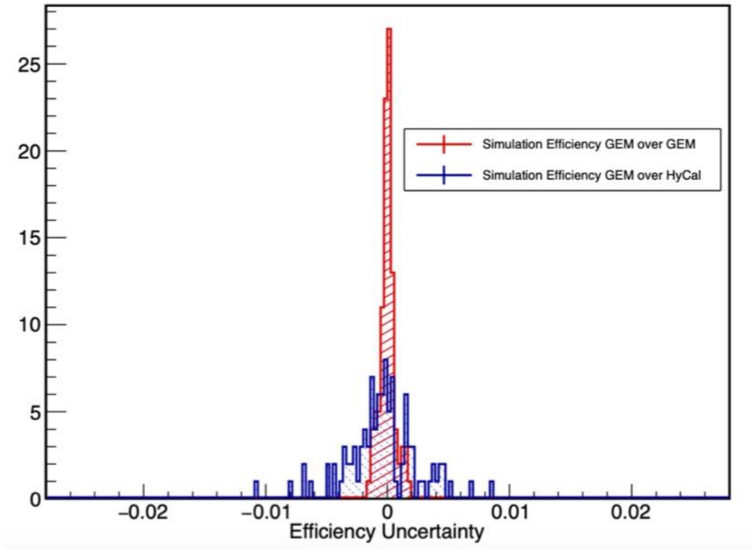
Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0017
Event selection	0.0070	0.0030
Radiative correction	0.0069	0.0004
Detector efficiency	0.0042	0.0030
Beam background	0.0039	0.0011
HyCal response	0.0029	0.0001
Acceptance	0.0026	0.0001
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p parameterization	0.0006	0.0001
Total syst. uncertainty	0.0115	0.0045
Total uncertainty	0.0137	0.0048

Key to Reach PRad-II Precision – GEM related

- Majority of improvement comes from adding a second GEM
  1. Vertex z can be reconstructed to reject upstream background (mostly collimator, 1.8m upstream)
  2. Allow far better accuracy in GEM efficiency determination

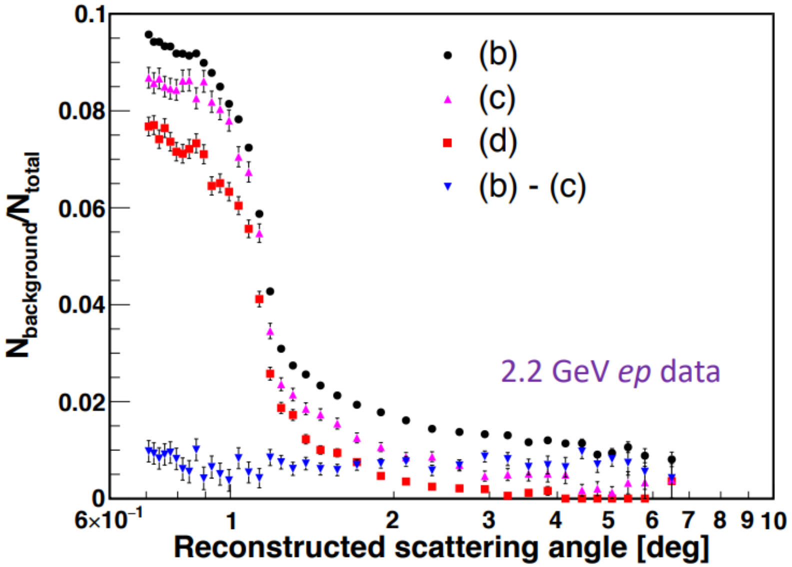


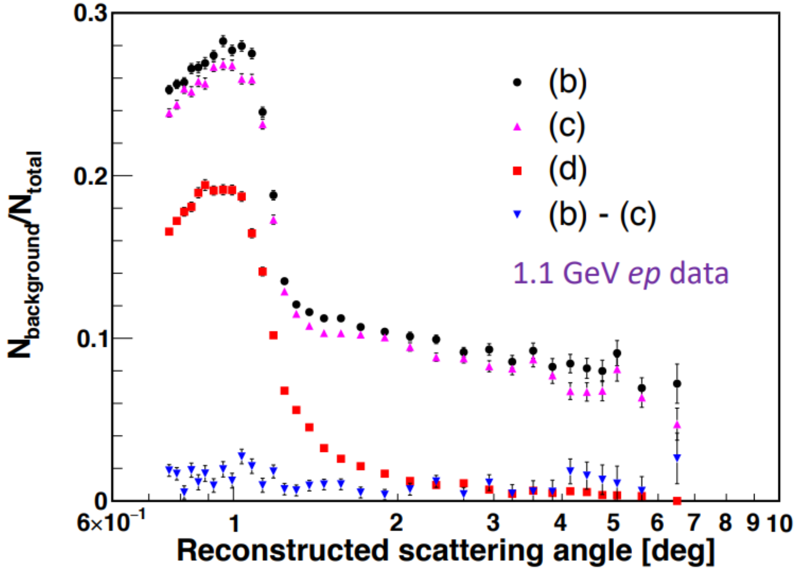


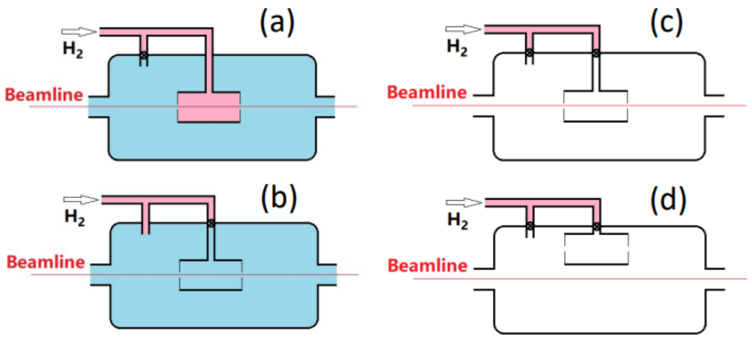


Key to Reach PRad-II Precision – GEM related

- Using vertex z reconstructed by GEM to reject backgrounds from collimator and upstream gas
  - Roughly 10% (30%) of events at forward angle come from collimator for the 2.2 (1.1) GeV
  - Expect significant reduction for beam background related systematics







Key to Reach PRad-II Precision – GEM related

Bin-by-bin method: taking the ep/ee ratio within the **same angular bin**

Good: Detector acc. and eff. cancal at leading order

Bad: Easily introduce Q2-dependent syst. from Moller

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\rm geom}^{e^-e^-}}{\varepsilon_{\rm geom}^{ep}} \cdot \frac{\varepsilon_{\rm det}^{e^-e^-}}{\varepsilon_{\rm det}^{ep}}\right] \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

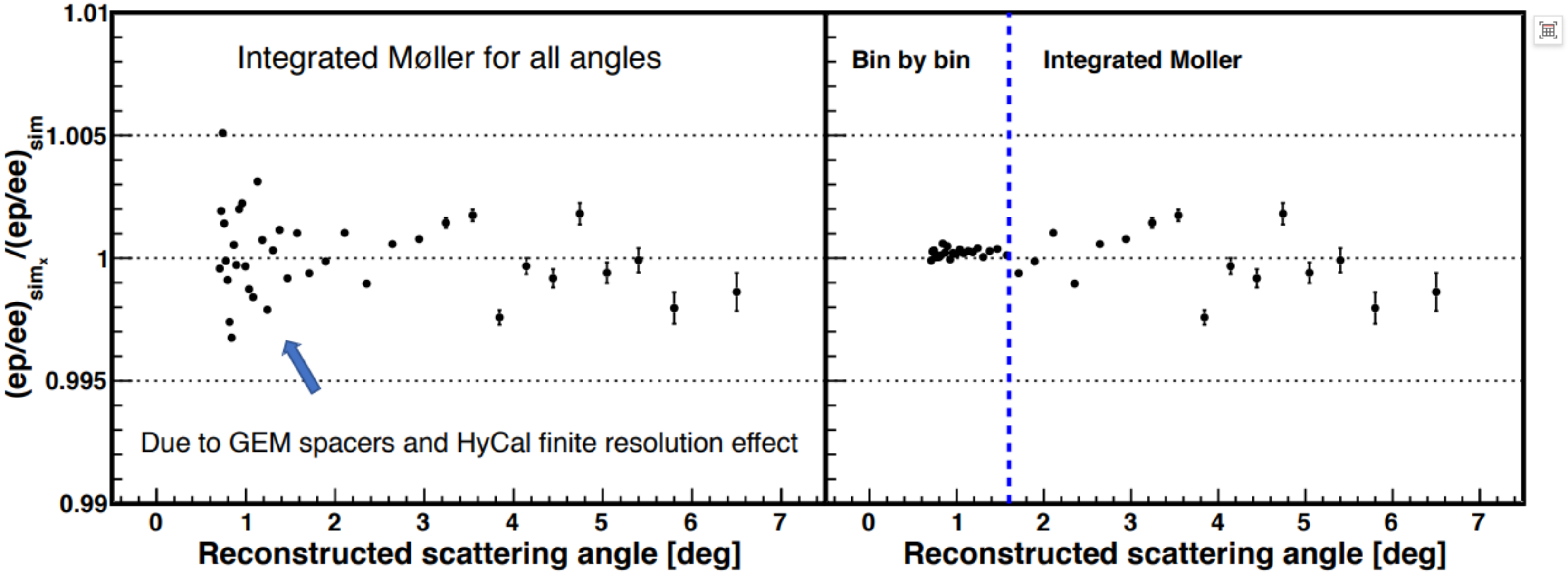
Integrated Moller method: select ee in an angular range, and use it to normalize **all ep**

Good: Not limited by Moller acceptance, Moller uncertainty only affect normalization

Bad: Need accurate GEM efficiency measurement

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep,\ \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^-,\ \text{on PWO})}\right] \frac{\varepsilon_{\rm geom}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\rm geom}^{ep}(\theta_i \pm \Delta\theta)} \frac{\varepsilon_{\rm det}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\rm det}^{ep}(\theta_i \pm \Delta\theta)} \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

- GEM efficiency uncertainty become very large for angles below 1.3 deg
- Mostly due to spacers, HyCal pos. resolution not good enough to resolve



Key to Reach PRad-II Precision – GEM related

Bin-by-bin method: taking the ep/ee ratio within the same angular bin

Good: Detector acc. and eff. cancal at leading order

Bad: Easily introduce Q2-dependent syst. from Moller

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\rm geom}^{e^-e^-}}{\varepsilon_{\rm geom}^{ep}} \cdot \frac{\varepsilon_{\rm det}^{e^-e^-}}{\varepsilon_{\rm det}^{ep}}\right] \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

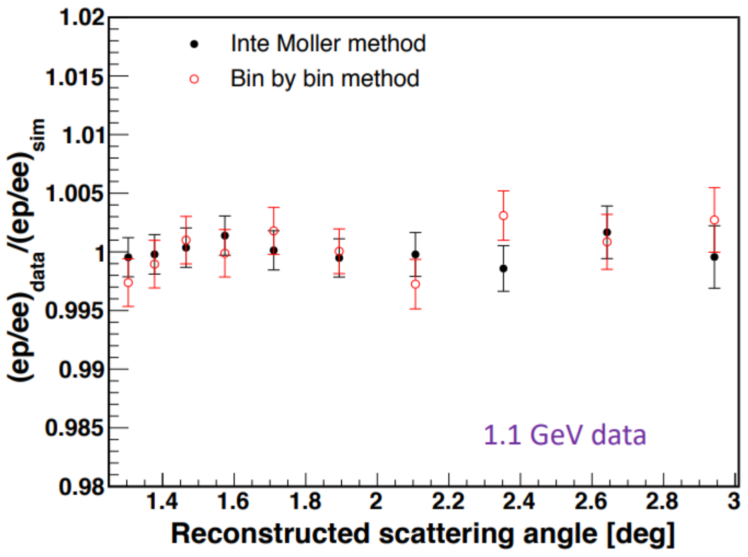
Integrated Moller method: select ee in an angular range, and use it to normalize all ep

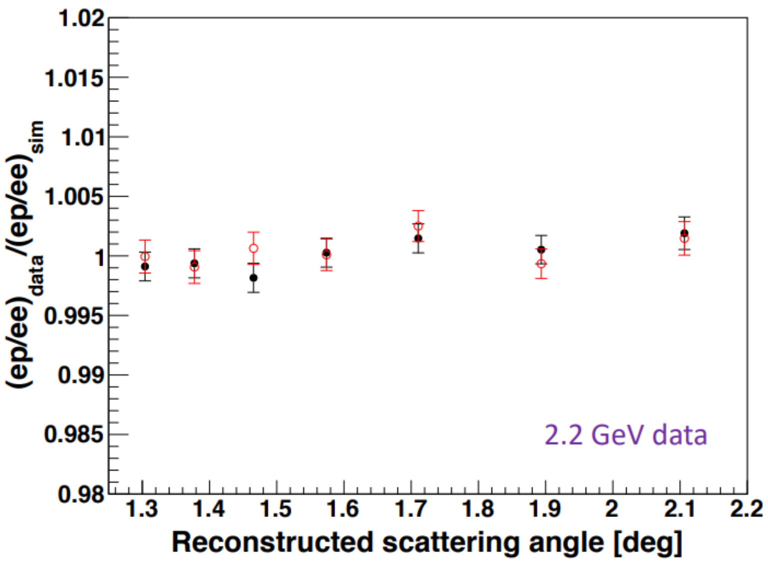
Good: Not limited by Moller acceptance, Moller uncertainty only affect normalization

Bad: Need accurate GEM efficiency measurement

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep,\ \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^-,\ \text{on PWO})}\right] \frac{\varepsilon_{\rm geom}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\rm geom}^{ep}(\theta_i \pm \Delta\theta)} \frac{\varepsilon_{\rm det}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\rm det}^{ep}(\theta_i \pm \Delta\theta)} \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

- The two methods affected by very different systematics
- A powerful way to check whether all systematics are under control
- Precise GEM efficiency allow this comparison to be done for all angles covered by double-arm moller

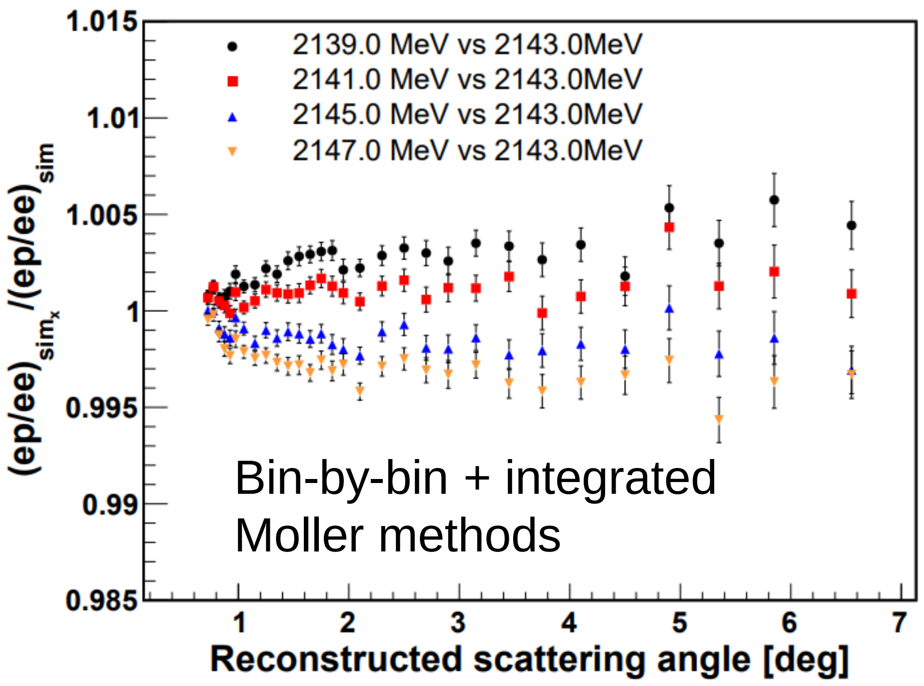


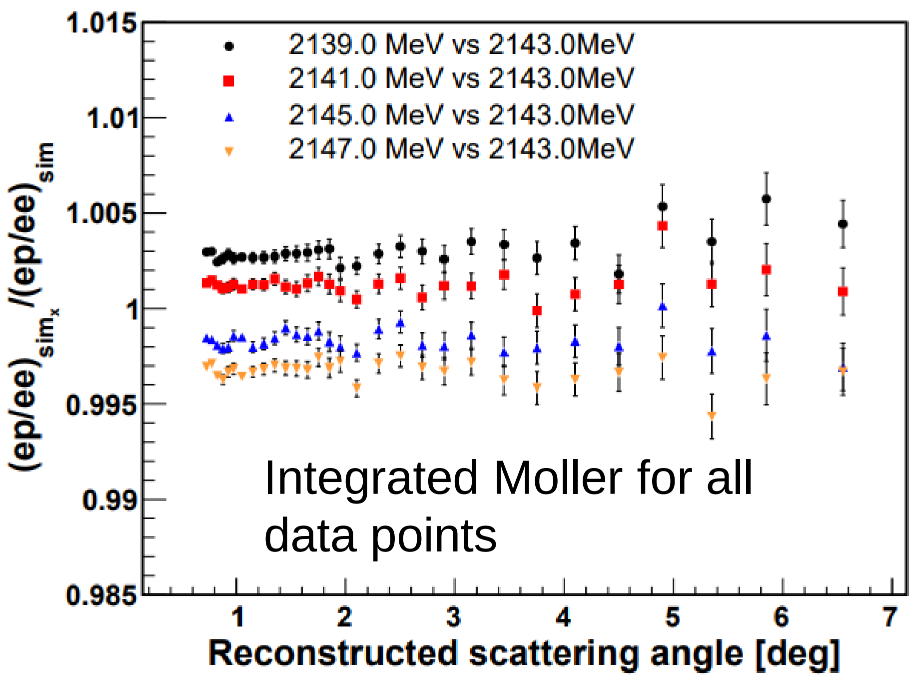


Key to Reach PRad-II Precision – GEM related

- For integrated Moller method, all systematic uncertainties from Moller only affect normalization of data points, **don't introduce Q2-dependet systematics:**
  - ➢ **Do not affect the radius**

Example of beam energy systematic

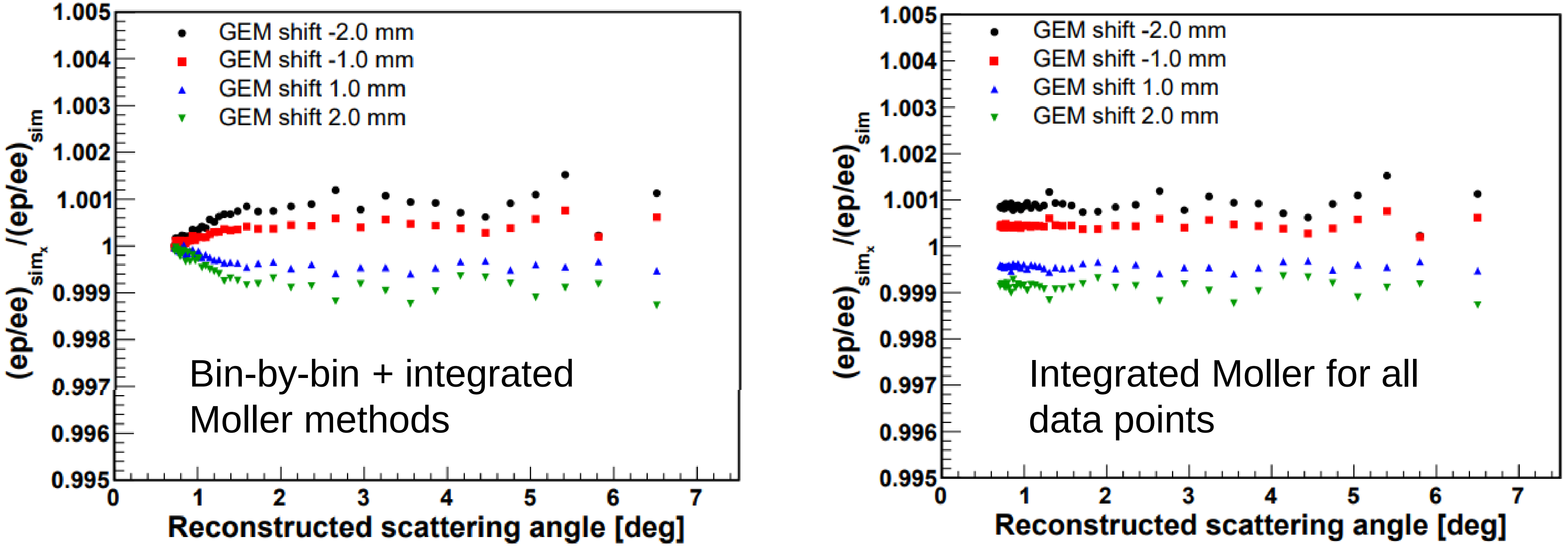




Key to Reach PRad-II Precision – GEM related

- For integrated Moller method, all systematic uncertainties from Moller only affect normalization of data points, **don’t introduce Q2-dependet systematics:**
  - ➢ **Do not affect the radius**

Example of GEM position systematics



Key to Reach PRad-II Precision – GEM related

- Improvements from adding a second GEM are highlighted with colored boxes
- Red ones due to using integrated Moller method (Moller only affect normalization), blue for Vz reconstruction

Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0017
Event selection	0.0070	0.0030
Radiative correction	0.0069	0.0004
Detector efficiency	0.0042	0.0030
Beam background	0.0039	0.0011
HyCal response	0.0029	0.0001
Acceptance	0.0026	0.0001
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p parameterization	0.0006	0.0001
Total syst. uncertainty	0.0115	0.0045
Total uncertainty	0.0137	0.0048

Key to Reach PRad-II Precision – GEM related

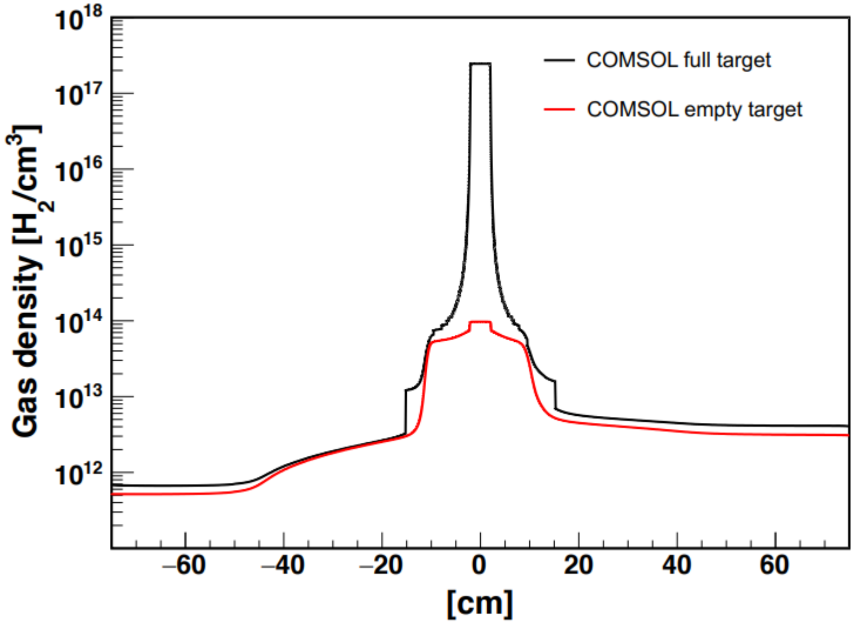
- Improvements from adding a second GEM are highlighted with colored boxes
- Red ones due to using integrated Moller method (Moller only affect normalization), blue for Vz reconstruction

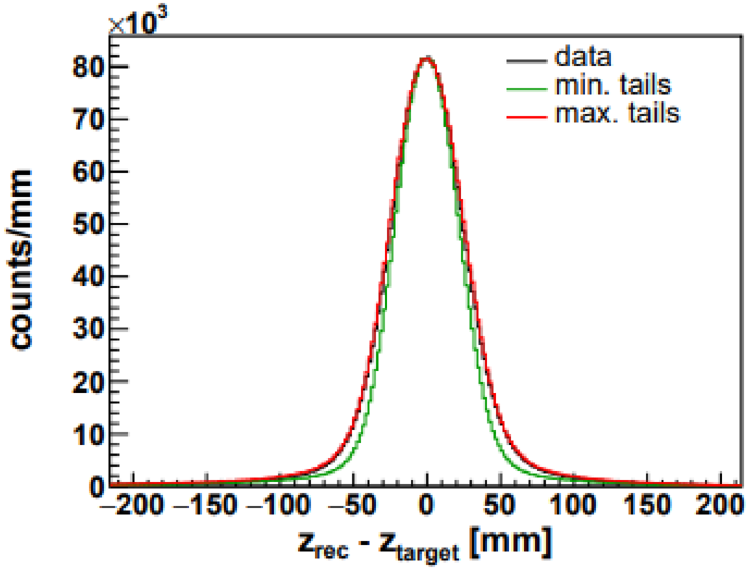
Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0017
Event selection	0.0070	0.0030
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p parameterization	0.0006	0.0001
Total syst. uncertainty	0.0115	0.0045
Total uncertainty	0.0137	0.0048

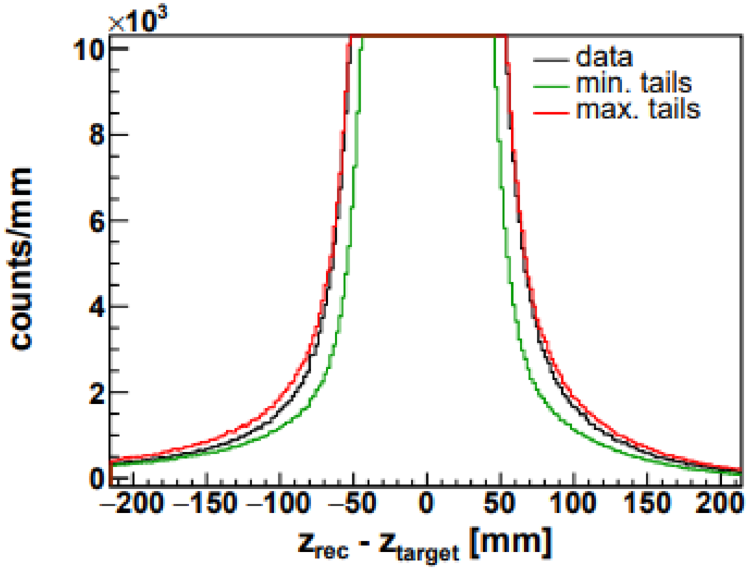
We need to have the GEM efficiency uncertainty suppressed to a level of 0.1% or better (see Xinzhan's talk for more details)

Key to Reach PRad-II Precision – Residual Gas

- For PRad, we have done a COMSOL simulation for the gas profile (Yang Zhang)
- Might not be very precise, fail to fully reproduce the tails in Moller Vz distribution, need some better simulation packages
- Good to have a way to “measure” this during experiment







Key to Reach PRad-II Precision – Other Items

- Radiative correction:
  - The dominating part is from the Moller
  - RC for ep contributes about 0.0020 fm uncertainty to rp
  - Need to include ep NNLO correction to further suppress it down to 0.004 fm
  - The McMule collaboration has done NNLO corrections for Moller, MUSE and ULQ2, so better continue connecting with them

- Non-linearity:
  - If using only $PbWO_4$, non-linearity effect “should be” small
  - It is still good to take some special measurements for procedure to validate it is under control
  - Any thought would be welcomed

Things we should consider doing during PRad-II data-taking

1. Take cosmic data during the beam-down period, with both HyCal and GEM on
    - Very little cosmic data were taken during the PRad experiment
    - Can be used to study linearity and systematic of GEM efficiency due to cosmic background

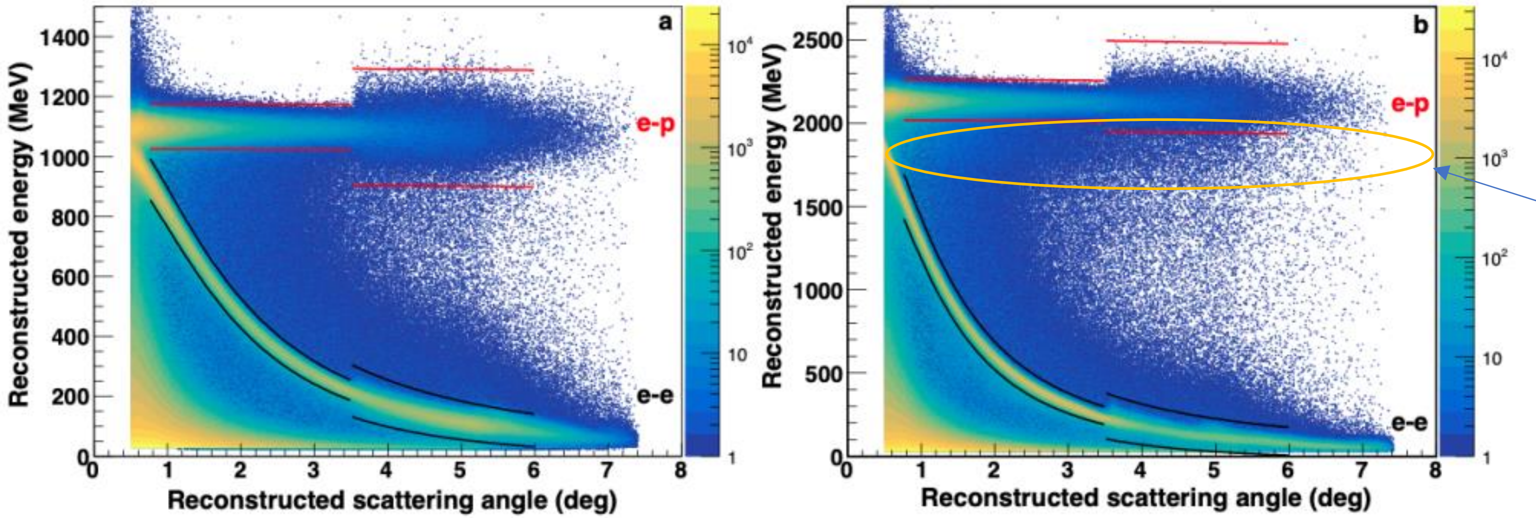
2. Have the full monitoring software developed and fully tested before the experiment

3. Both GEMs and HyCal were damaged during/before the experiment, some protection mechanism?

Things we should consider doing during PRad-II data-taking

4. Taking some non-linearity data

- For PRad, the non-linearity of production runs was studied using ep and ee, but for large angle modules, the energy between them is fairly large
- No calibration point around the △-resonance to make sure it is reconstructed correctly
- If changing HyCal high-voltage is needed for runs with different Ebeam, might consider:
  - i.e. before changing from 2.1 GeV to 3.5 GeV, change the HV setting to 3.5 GeV first, but let the beam stay at 2.1 GeV to take some 2.1 GeV ep data



△-resonance region

Things we should consider doing during PRad-II data-taking

5. Carbon foil run needs to be done right this time
    - Previous carbon foil run has various issues, pre-scale factor, background…

6. Special run to measure residual gas background and collimator background from upstream?
    - Special runs that change gas pressure along the beamline, remove collimators…?

7. Special run to help with GEM efficiency measurement?

Where Workforce Would be Needed

1. Connecting with McMule folks and have a complete generator for PRad-II

2. Online event monitor for the GEMs

3. Gas profile simulation

4. Continue with the GEM efficiency study to ensure we get the desired precision

Summary

- To achieve PRad-II desired precision, the focus is on the GEM efficiency, need to suppress the uncertainty to be below 0.1%

- More sophisticated RC including NNLO and better gas profile simulation would also be needed

- In addition, we need to start thinking about special runs that can help control various systematics, in particular
  - To validate residual gas simulation
  - To validate non-linearity of HyCal
  - To improve GEM efficiency calculation