The PRad Experiment – Manpower and Data Analysis

The PRad Experiment Readiness Review
March 25, 2016

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Duke University and Duke Kunshan University

Duke UNIVERSITY

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

PRad Collaboration Institutional List

- ***17 collaborating universities and institutions***

Jefferson Laboratory
NC A&T State University
Duke University
Idaho State University
Mississippi State University
Norfolk State University
Argonne National Laboratory
University of North Carolina at Wilmington
University of Kentucky
Hampton University
College of William & Mary
University of Virginia
Tsinghua University, China
Old Dominion University
ITEP, Moscow, Russia
Budker Institute of Nuclear Physics , Novosibirsk, Russia
MIT

Collaboration Manpower: (a list with significant manpower)

Institution	Senior Researcher	Postdoc	Graduate student	Others (for shifts)
Duke Univ.	H. Gao (40%)	1 FTE* (50%)	1.5 FTE	2 postdocs for shifts 4 grad students for shifts
Mississippi State Univ.	D. Dutta (50%)	1 postdoc (50%) located at JLab	1 FTE	2 faculty for shifts, 0.5 postdoc 3 grad students for shifts
Idaho State Univ.	M. Khandaker (50%)			
NC A&T SU	A. Gasparian (75%)	1 postdoc (100%)	0.5 FTE (1 M.S. degree)	1 Visiting Scientist (5 months)
UVa	N. Liyanage (20%)	1 postdoc (75%)	1 FTE	1 postdoc and 1 grad student
Argonne				1 faculty for shifts (25%) 2 postdocs for shifts (50%)
MIT	S. Kowalski	1 postdoc (50%)		1 faculty for shifts (25%)
Hampton U.				2 postdocs for shifts (25%) 2 grad students for shifts
ITEP Moscow				1 visiting scientist (50%)
TOTAL	**2.5 FTE**	**3.25 FTE**	**4.0 FTE**	**8 postdocs (~ 40%)** **I faculty (50%)** **10 grad students (50%)** **1 visiting Scientist (50%)**

PRad Collaboration Shift Taking Team

30 people in the previous table: 24 shift taking users in the collaboration and 6 people as RC and expert problem solvers

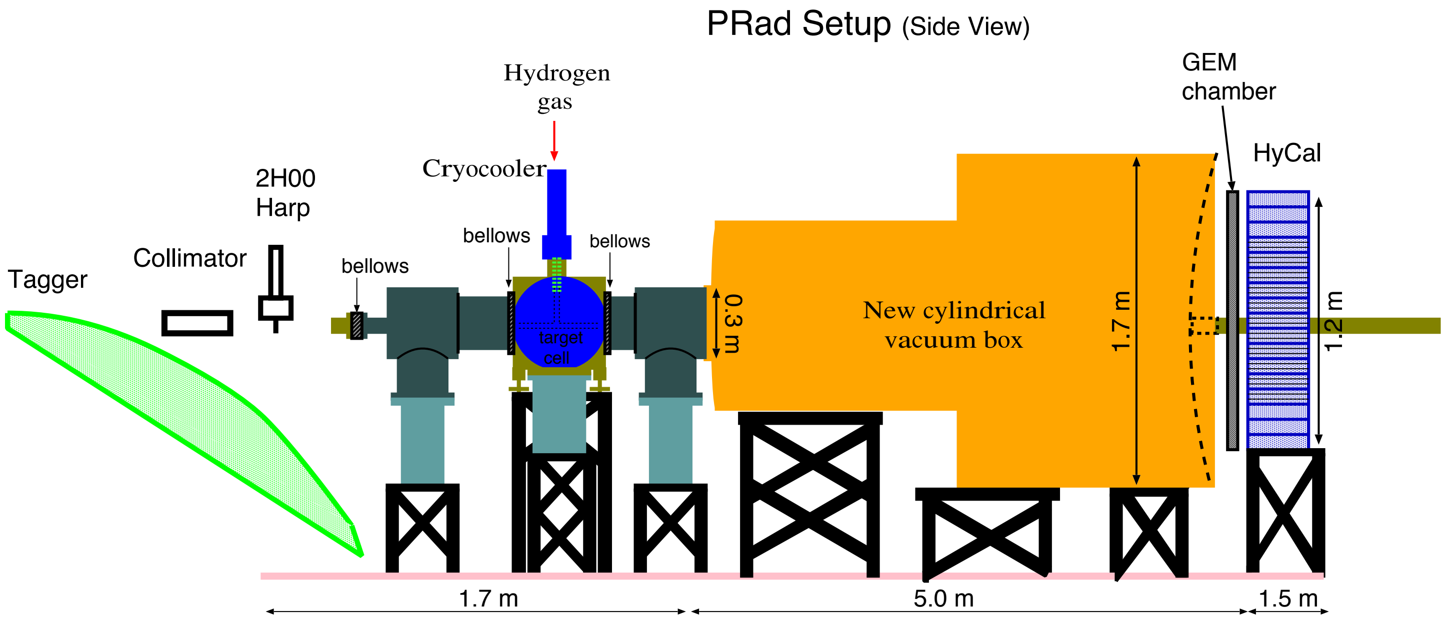
Assuming 2 people per shift, 4 calendar weeks, 7 shifts/person – adequate for continuous running

PRad Collaboration Analysis Team (students and PDs)

Jefferson Laboratory
NC A&T State University (1 postdoc, 1 M.S. graduate student)
Duke University (2 Ph.D. students, 1 postdoc)
Mississippi State University (2 Ph.D. students, 0.5 postdoc)
University of Virginia (1 Ph.D. student, postdoc)

Goals:
(i) Preliminary results April APS meeting 2017
(ii) Final results: DNP meeting Fall 2017

PRad Experimental Setup in Hall B at JLab



- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of $2\text{x}10^{-4}$ – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

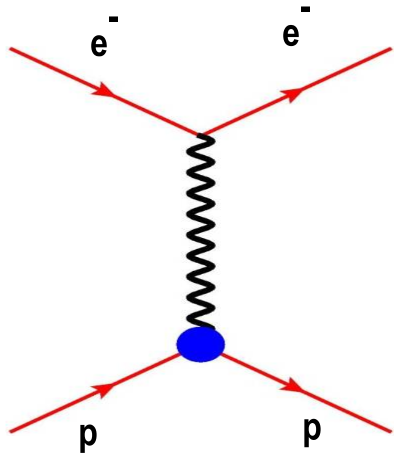
Spokespersons: A. Gasparian, D. Dutta, H. Gao, M. Khandaker

The Proton Charge Radius

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



- Structure less ``proton”:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2\left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

- At very low Q^2, cross section dominated by G_{Ep}:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} G_E^{p\,2}(Q^2)$$

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

- r.m.s. charge radius given by the slope:

$$\langle r^2\rangle = -6 \left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

- **Simultaneous detection of elastic and Moller electrons**

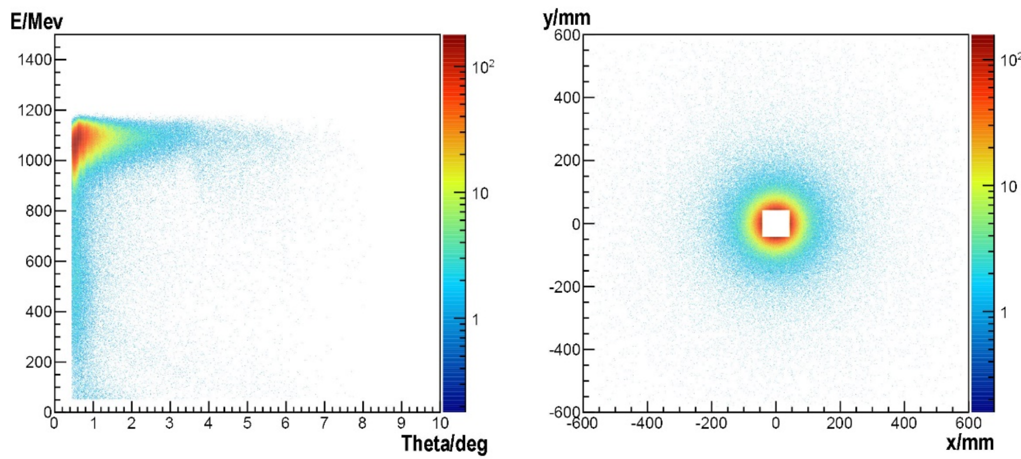
Data Analysis Procedure

- Cluster reconstruction
- e-p and Møller separation
- Empty target subtraction
- Radiative corrections
- Events ratio correction
- Form factor extraction
- Extraction of the proton charge radius

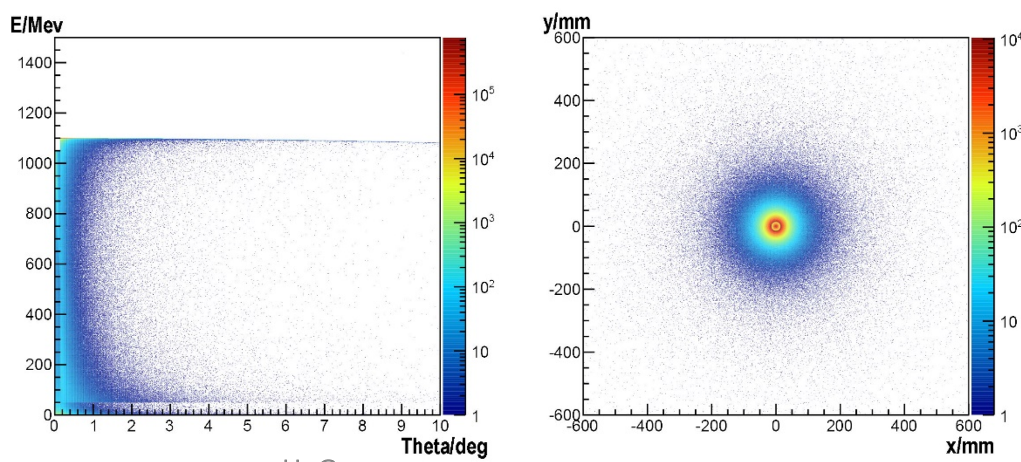
Cluster reconstruction

- Reconstruction of clusters
  - Only e-p events with radiative corrections are shown here

Reconstructed events



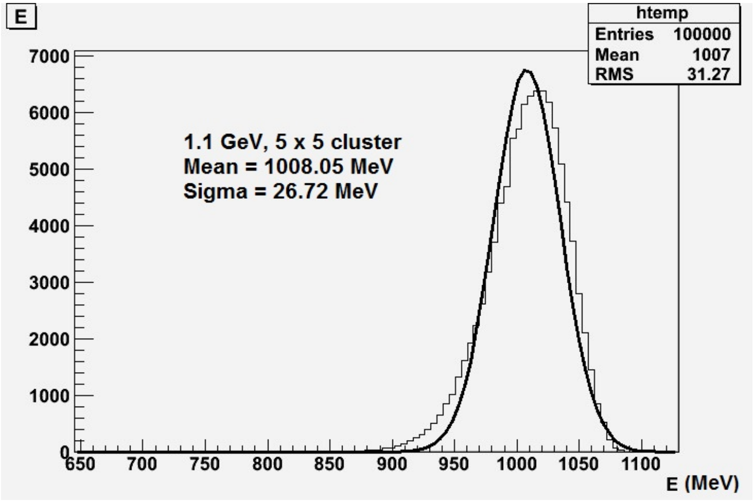
Events from RC e-p generator



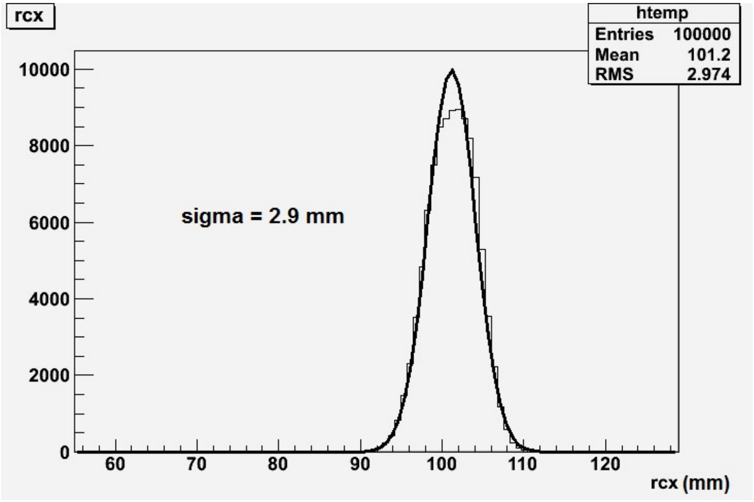
Cluster reconstruction

- Center of gravity method is studied by simulation
  - 5 × 5 cluster, 1.1 GeV at x = 100 mm
  - Crystal module result is shown, lead glass module will have about 2 times of the resolution

Reconstructed energy

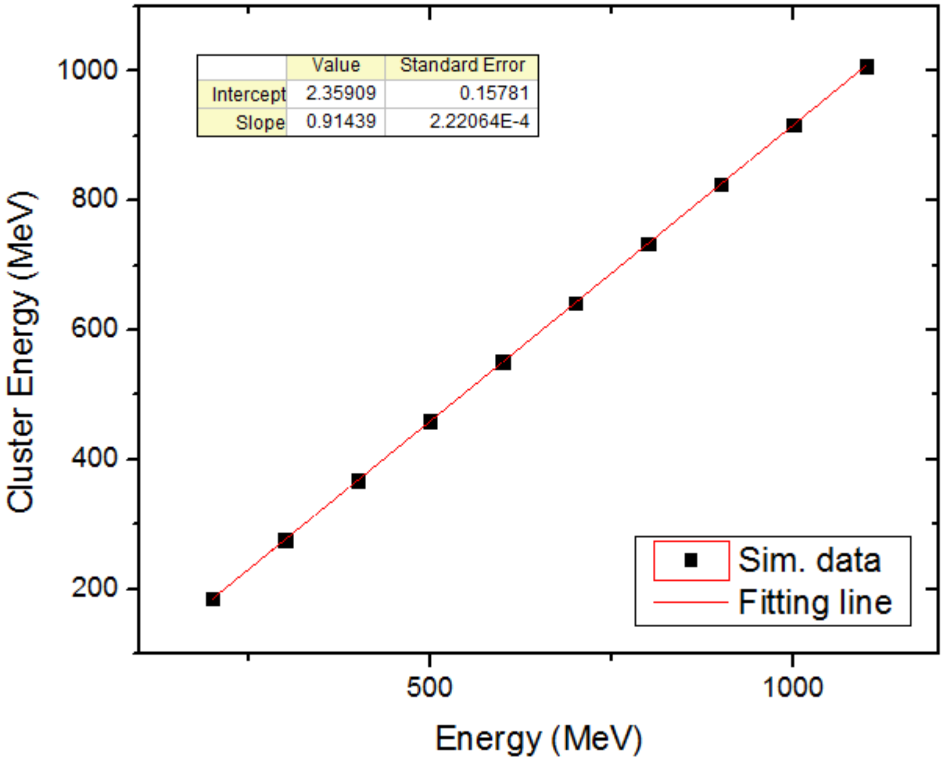


Reconstructed position



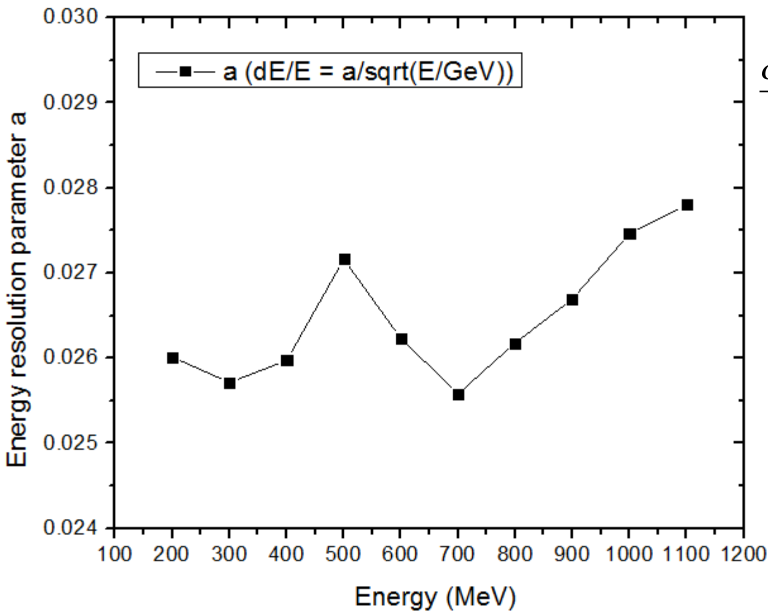
Cluster reconstruction

- Energy calibration $E = (E_{cluster} - 2.359\ \text{MeV})/0.91439$

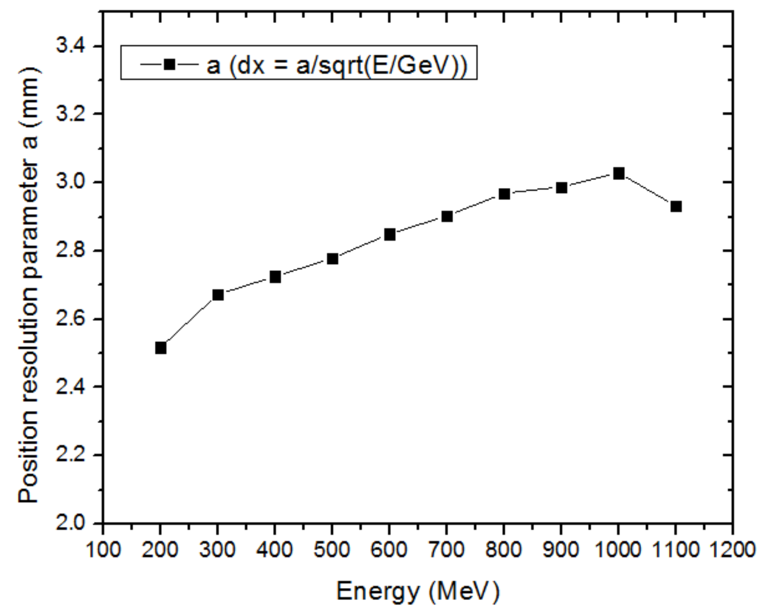


Cluster reconstruction

- Resolution from simulation is consistent with HyCal behavior in PrimEx experiment
  - $\frac{\sigma E}{E} = \frac{2.6\%}{\sqrt{E/GeV}}, \ \sigma_x = \frac{2.5mm}{\sqrt{E/GeV}}$



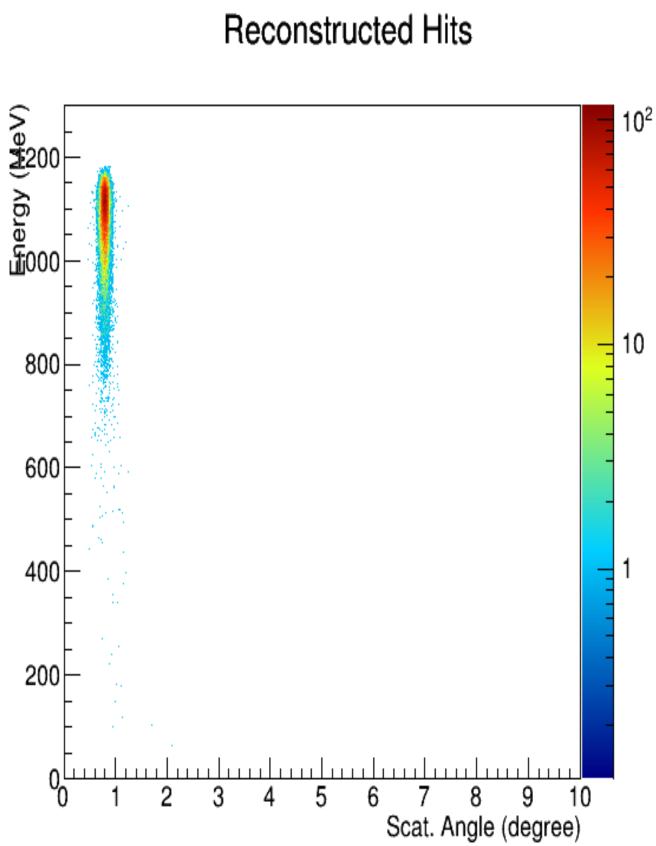
$\frac{\sigma E}{E}$

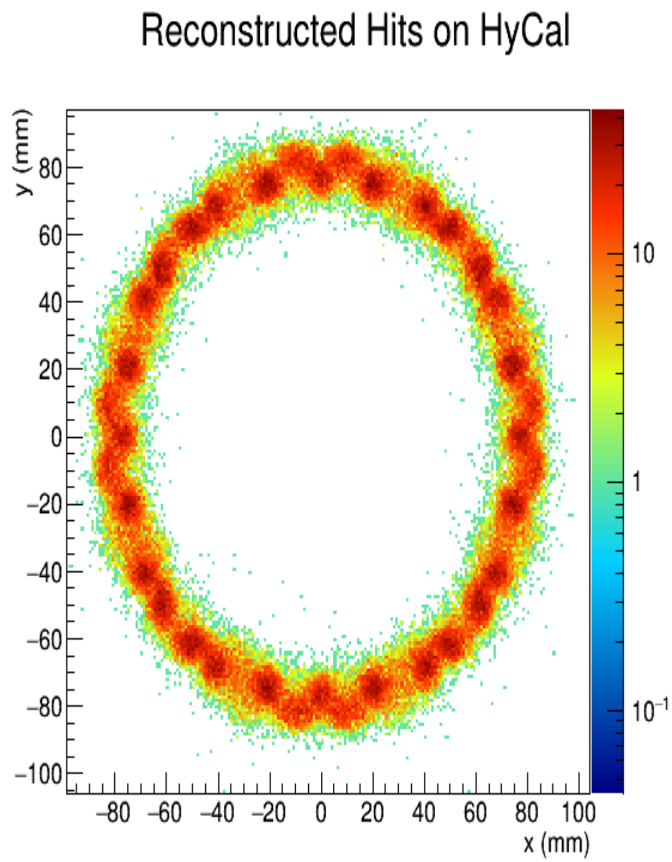


Cluster reconstruction

- GEM hits reconstruction

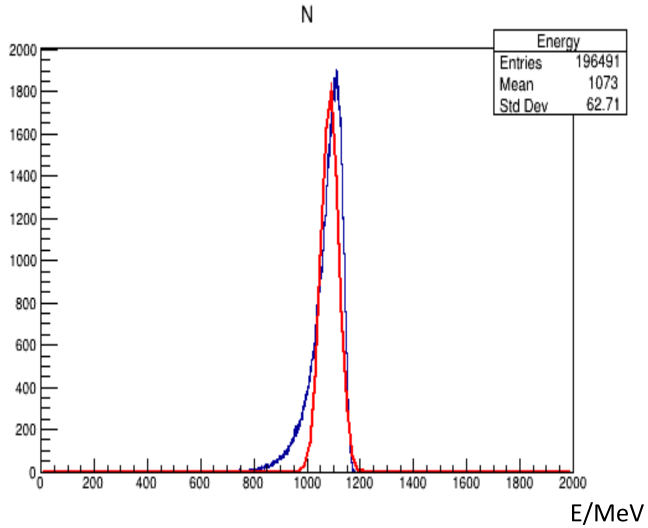
- With GEM, the reconstruction for HyCal can be further improved in the following way:
  - Reconstructed position of cluster -> find hits on GEM
  - Hits on GEM -> provide accurate information about the position of hits -> improve reconstruction on HyCal



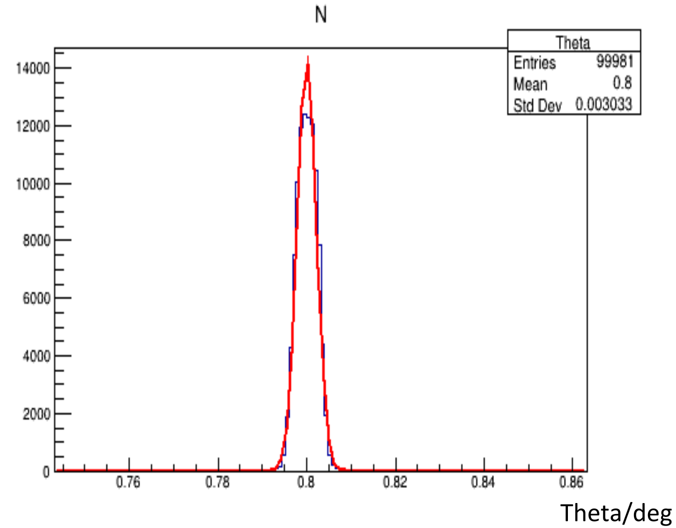


The reconstruction of 0.8 degree ring with only HyCal detector

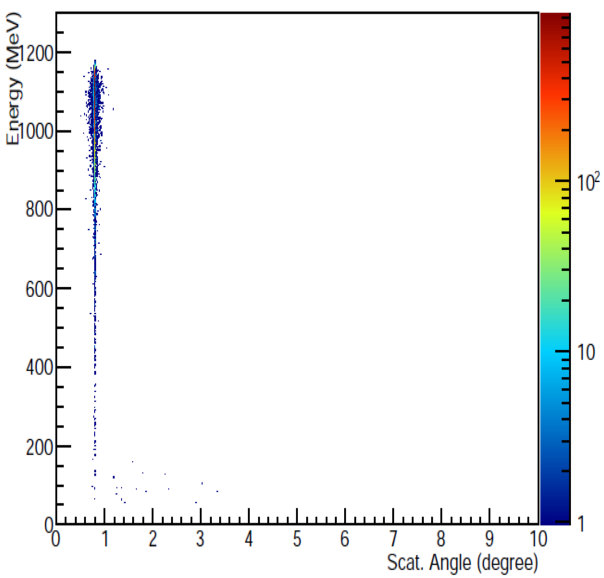
HyCal and GEM detectors (frame + foils)



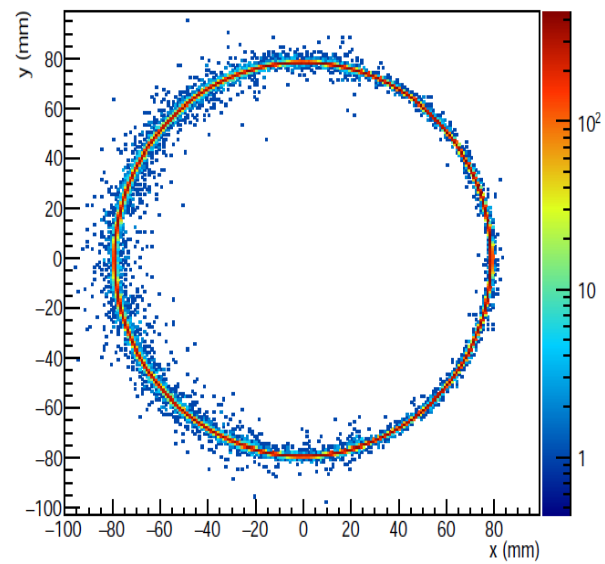
HyCal + GEM, energy resolution ~ 26 MeV



HyCal + GEM, angular resolution 0.0025 degree



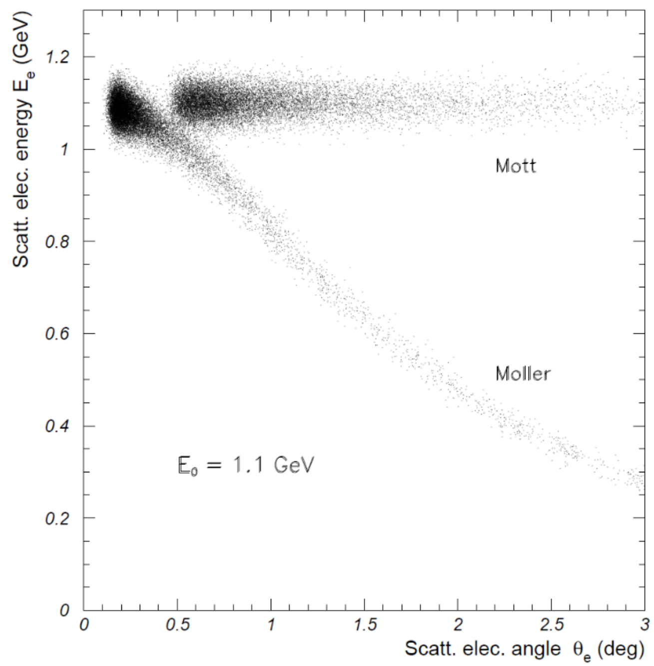
Energy vs. angle, reconstructed hits

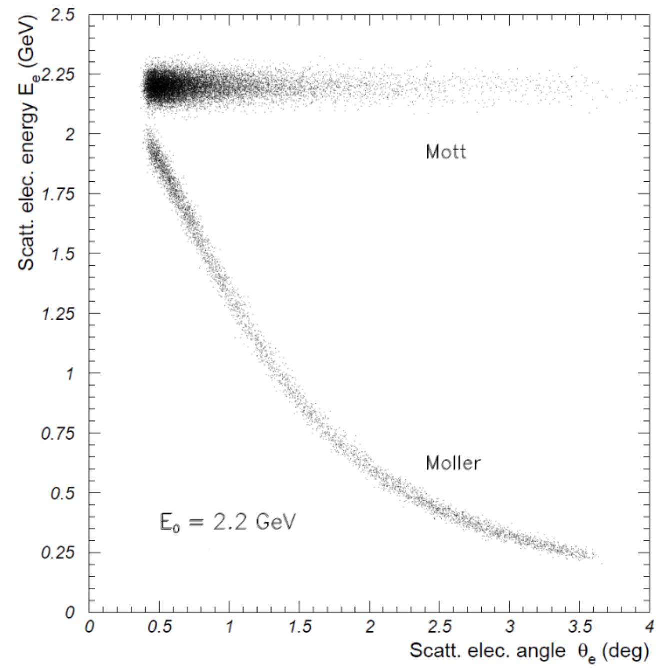


Reconstructed theta ring (0.8 degree)

Events separation

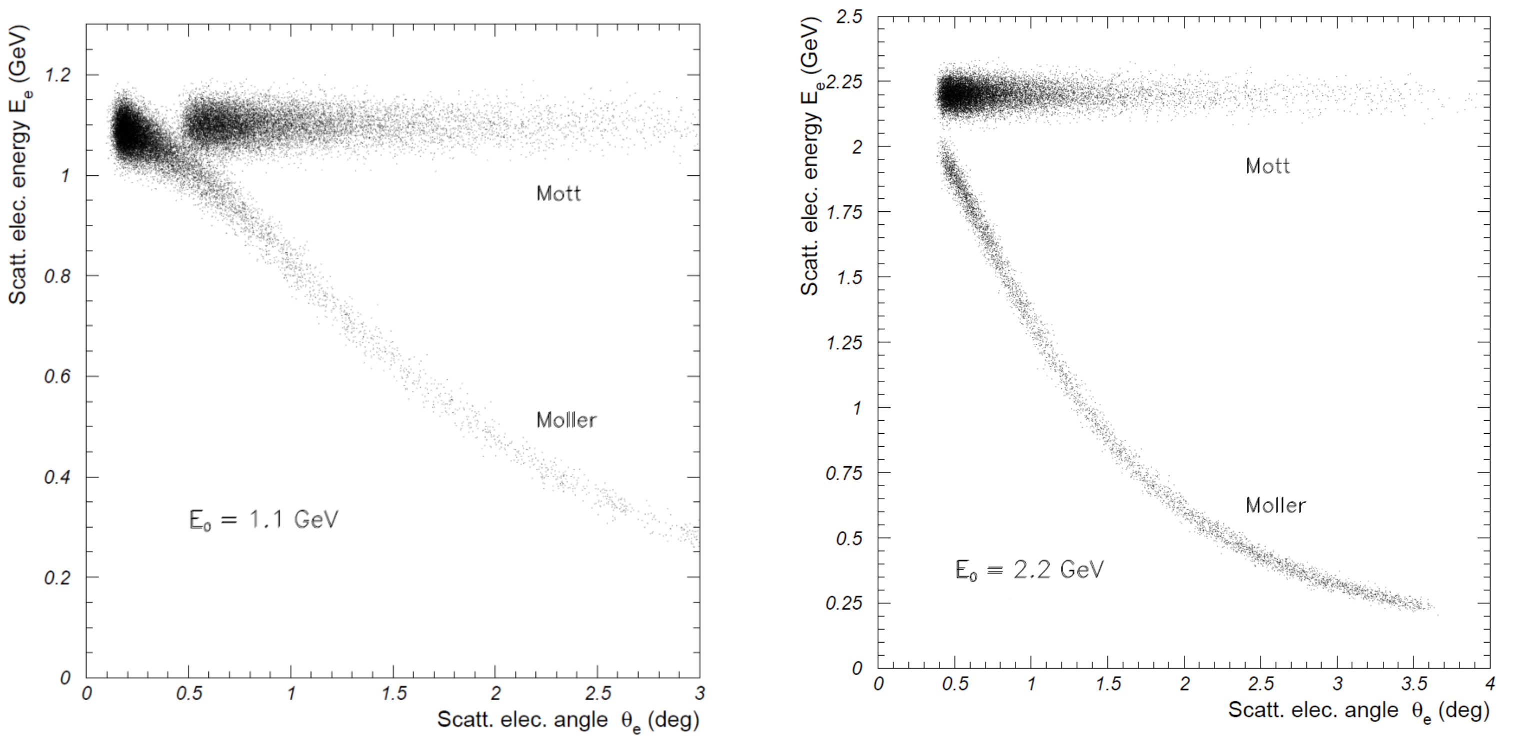
- In our kinematics, the Møller and ep events can be separated by a 2D cut





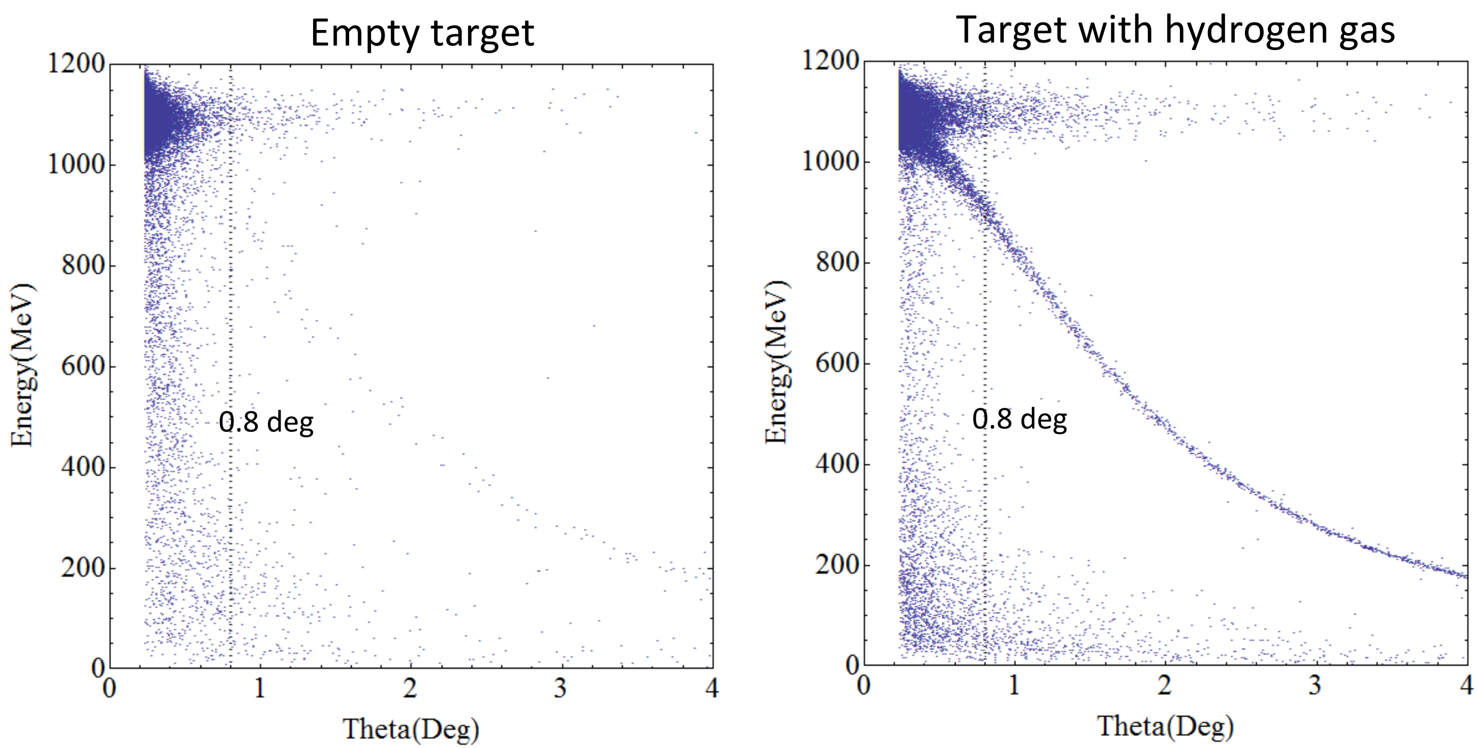
Events separation

- In our kinematics, the Møller and ep elastic events can be separated by a 2D cut
  - Due to radiation effects, the two types of events cannot be perfectly separated, but this effect will be corrected during radiative corrections.



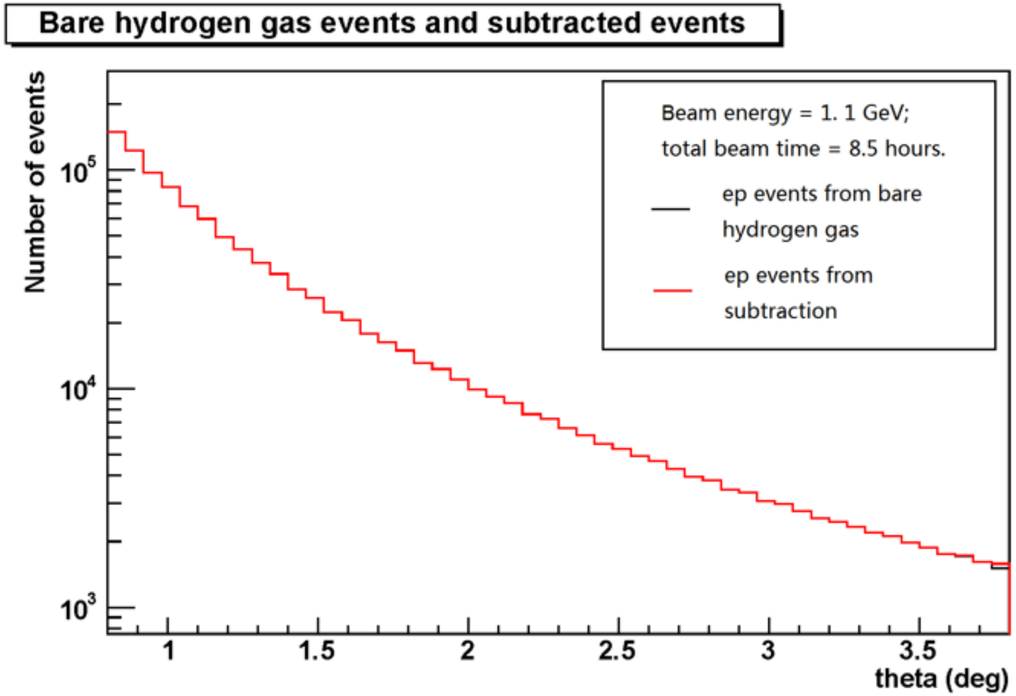
Empty target subtraction

- An empty target run will be performed, and the events will be subtracted from production run.
- The subtraction minimizes the background from target cell structure and residual gas.



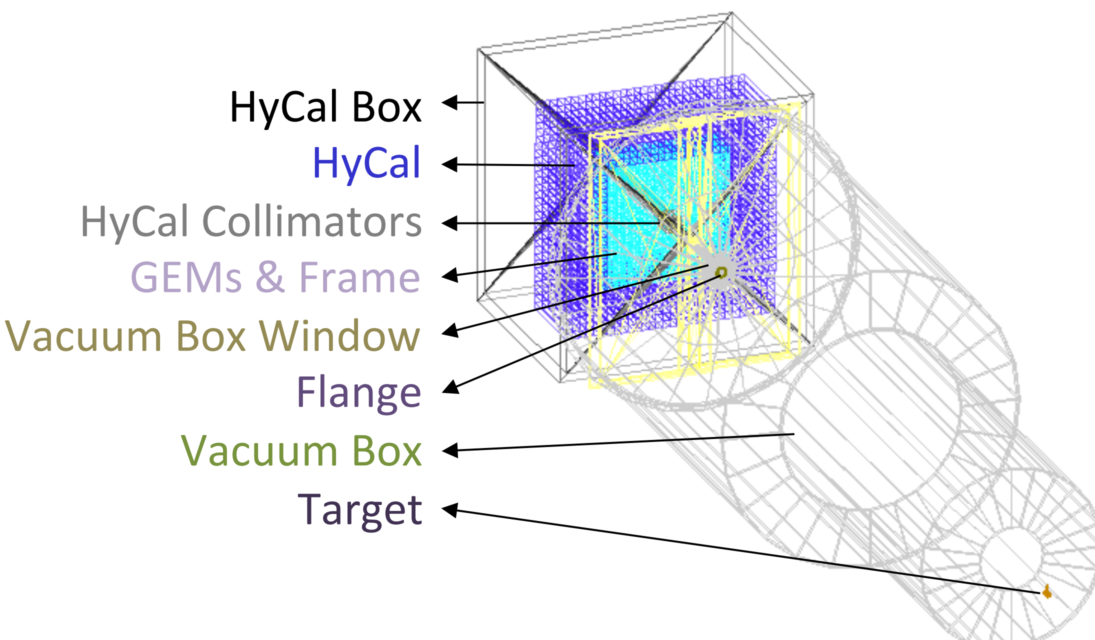
Empty target subtraction

- Comparison between subtracted events and bare hydrogen target events:
  - 3 days of beam time, 20% beam time is for empty target run
  - uncertainty 0.06% ~ 0.5% for 12 angular bins from 0.8 degree to 3.8 degree



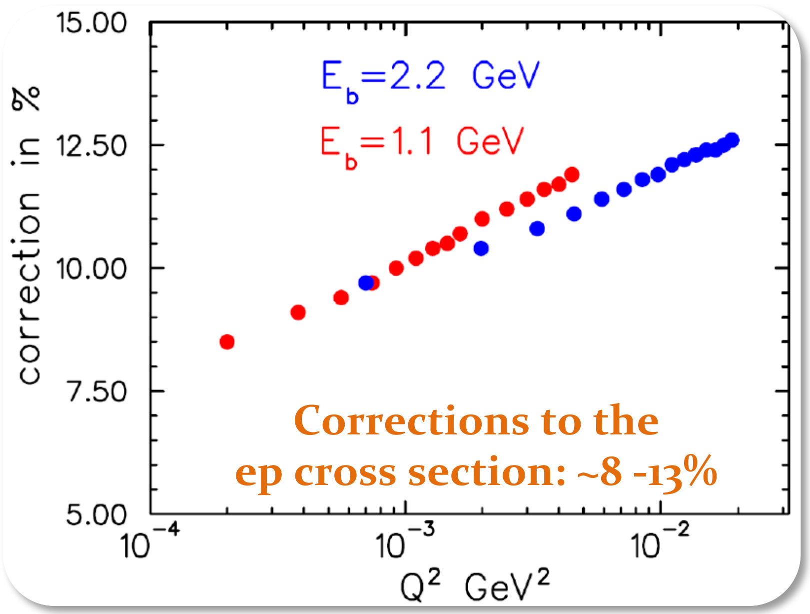
Radiative corrections

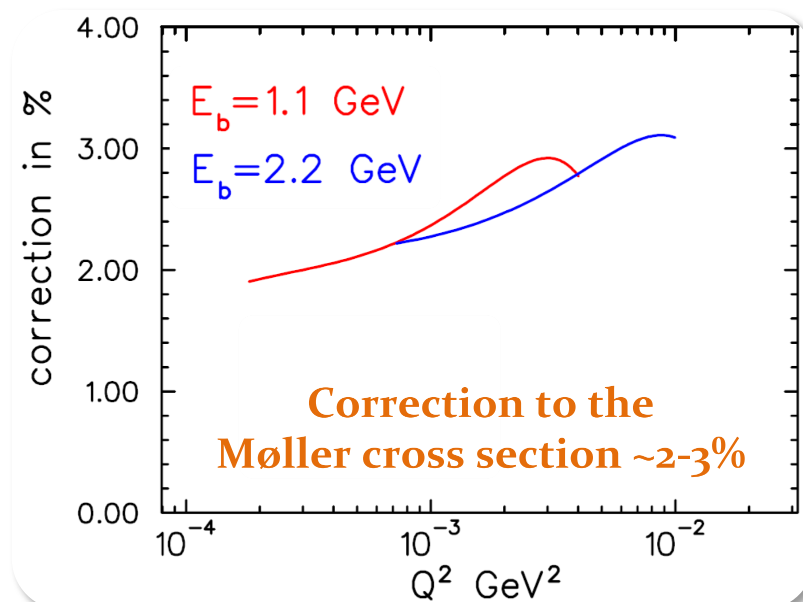
- External corrections
  - GEANT4 simulation, current geometry in code is shown below



Radiative corrections

- Internal corrections
  - Event generators including radiation effects of e-p and e-e scattering were developed
  - For very low Q^2, go beyond the ultra-relativistic approximation (URA, $m^2 << Q^2$)

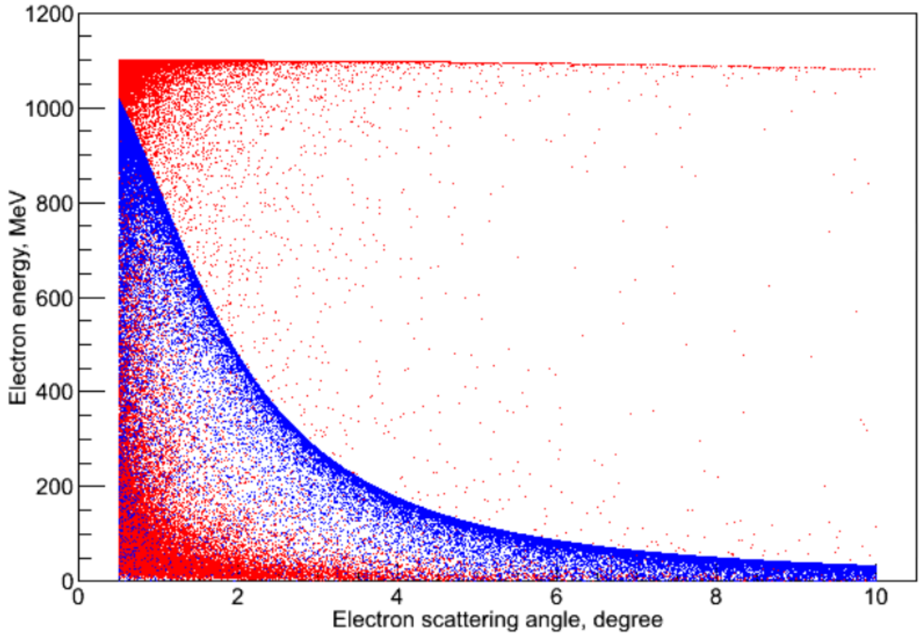




I. Akushevich, H. Gao, A. Ilyichev, and M. Meziane, Eur. Phys. J. A 51, 1 (2015)

Radiative corrections

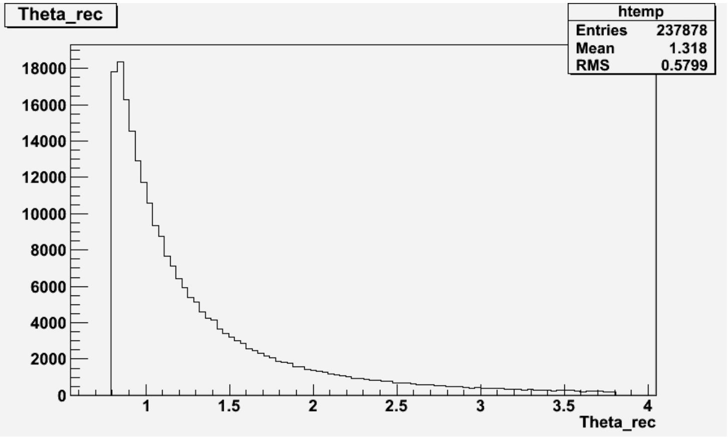
- Different event generator to check the corrections
  - Developed by A. Gramolin
  - Lowest order QED radiative corrections
  - First order bremsstrahlung without soft-photon or ultra-relativistic approximations



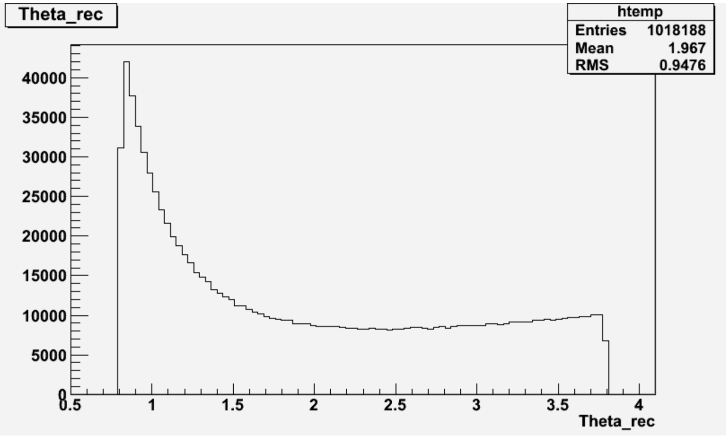
Events ratio correction

- e-p elastic cross sections are normalized to Møller cross sections
- Events distributions are different, so the acceptance ratio for each angluar bin will be affected by the resolution

e-p Born level

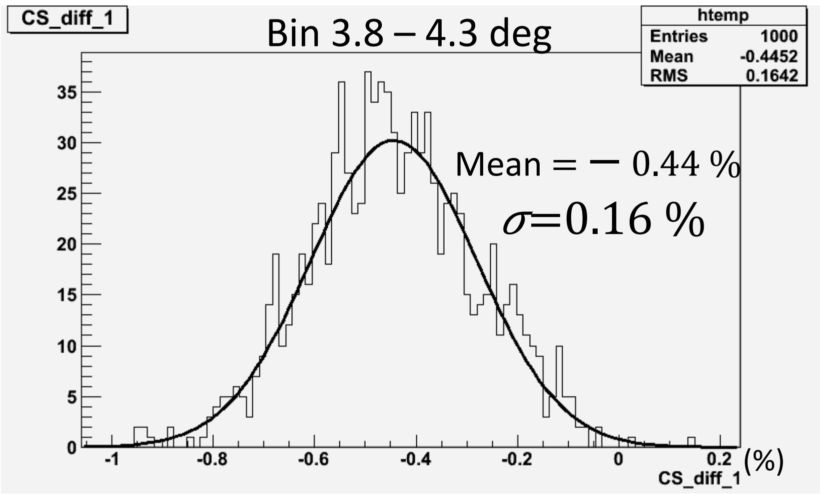


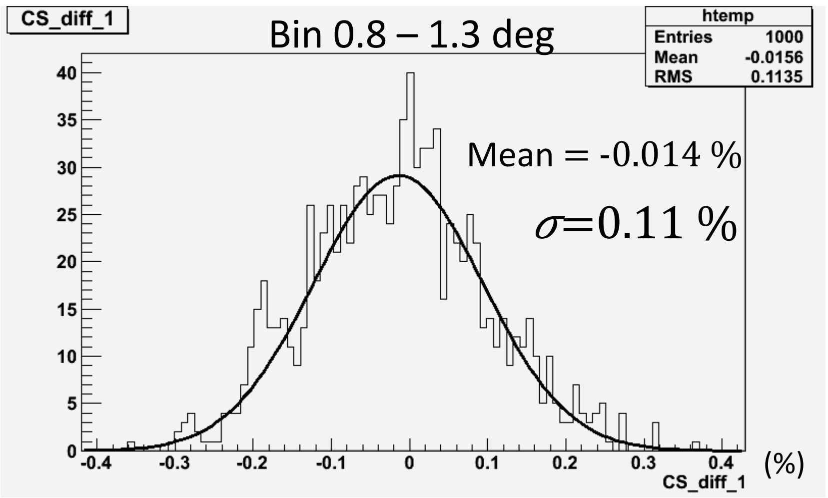
Møller Born level



Events ratio correction

- Mean value shift of the ratio can be corrected, uncertainty will propagate into determination of cross-sections
  - Results for a few bins are shown as example
  - Estimation of the uncertainty: 0.1 % ~ 0.3 %





Form factor extraction

- Rosenbluth formula

$$\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{\sigma_{Mott}}{\epsilon}\frac{\tau}{1+\tau}\right) = \frac{\epsilon}{\tau} G_E^{p\,2} + G_M^{p\,2}$$

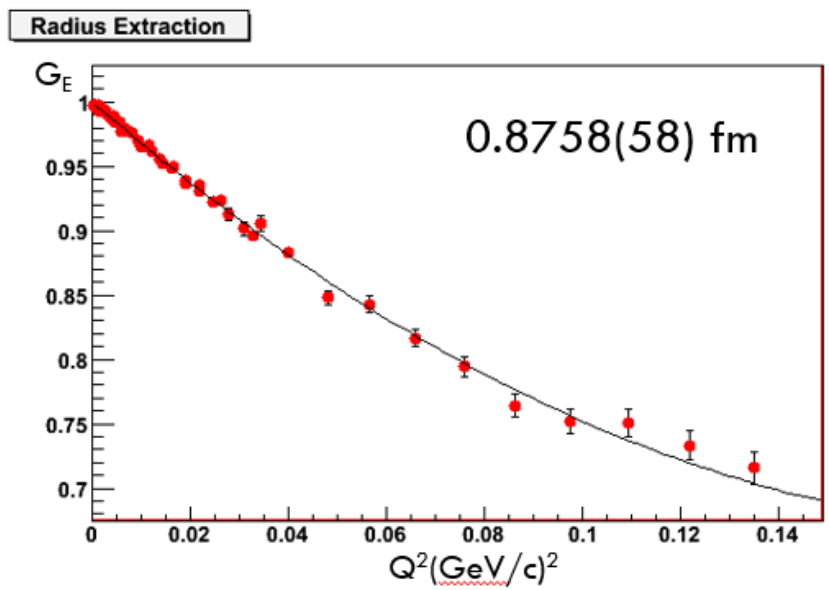
- At 1.1 GeV, G_M contribution is 0.015% ~ 0.06%, can be neglected
- High Q^2 part at 2.2 GeV, G_E is still dominating, G_M contribution can be simply determined by existing data with a reasonable uncertainty

Extraction of proton radius

- Rms proton charge radius, slope of G_E at Q^2 close to 0

$$\frac{\langle r^2 \rangle}{6} = - \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

- The slope is extracted through fitting
  - Linear fit, polynomial fit, dipole fit and continuous fraction fit were tested with simulation data (dipole fit is shown)



PRad Projected Result with world data