Analysis and the Preliminary Results of the PRad Experiment at JLab

Chao Gu

Duke University

On behalf of the PRad Collaboration

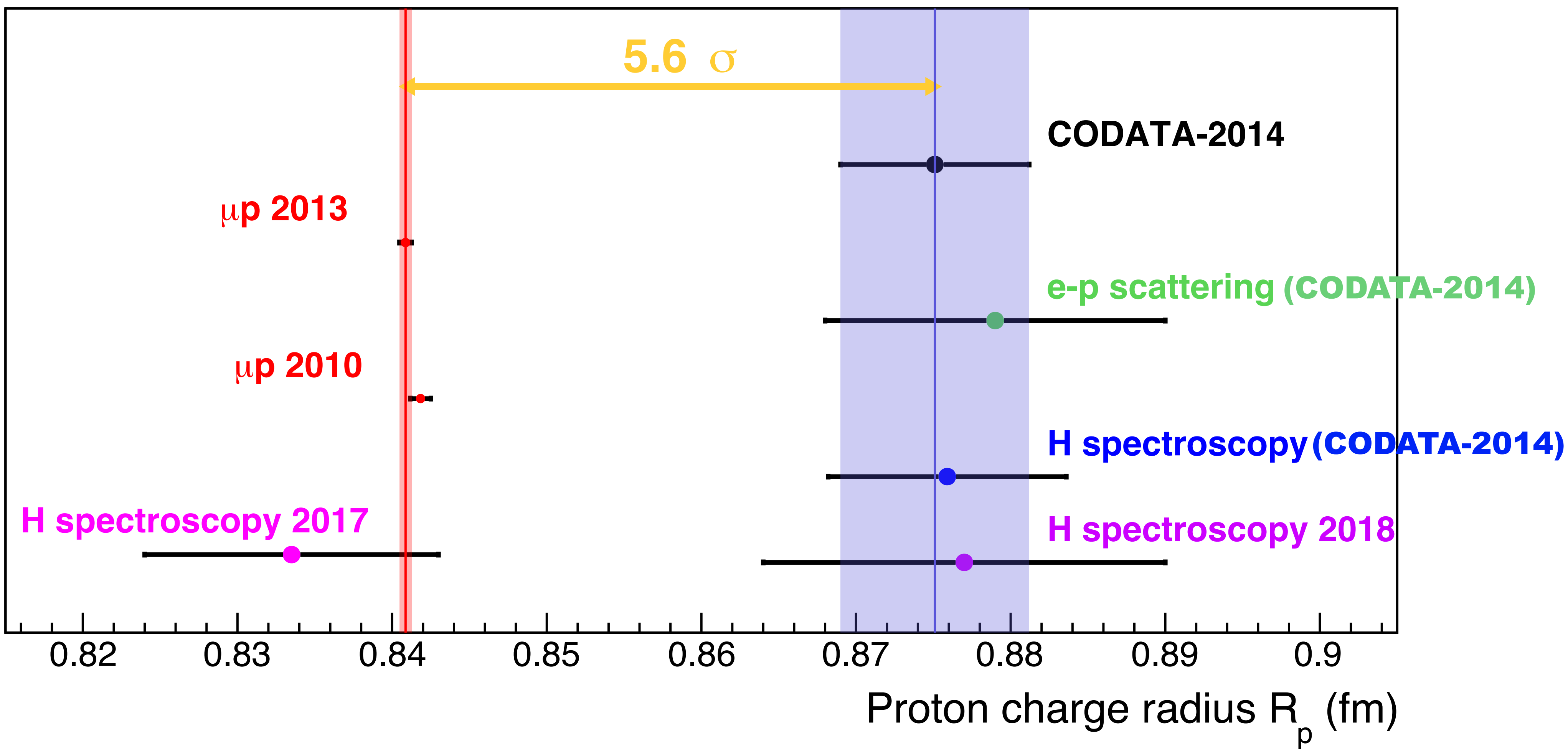
NuFACT, Aug 2018

Outline

- Proton Charge Radius Puzzle and PRad Experiment
- Experimental Apparatus
- Analysis Status and Preliminary Results

The Proton Charge Radius Puzzle

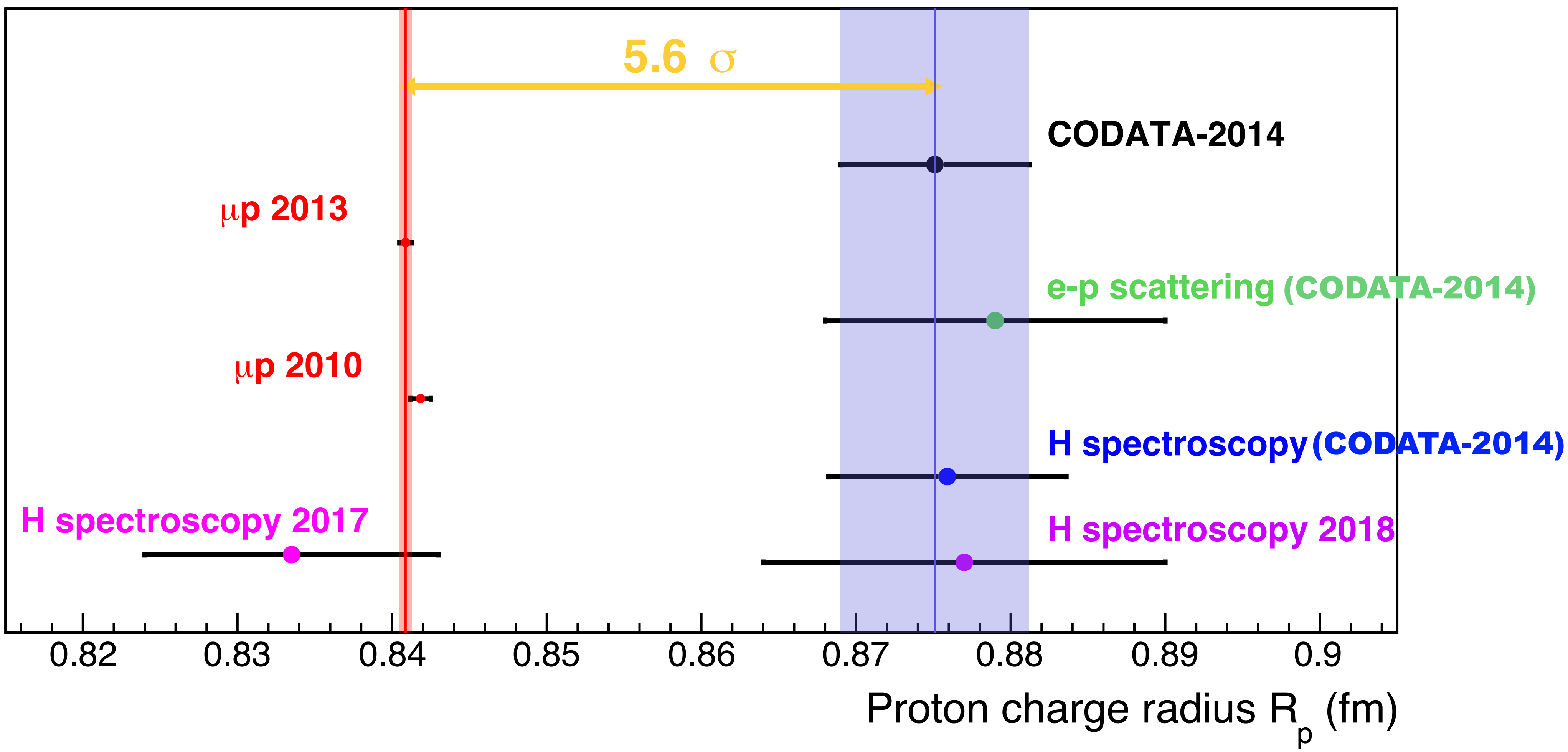
- Proton radius is one of the most fundamental quantities in physics:
  - Critically important for atomic physics in precision spectroscopy of atom
  - Precision test of nuclear/particle models
  - Connects atomic and subatomic physics



Electron scattering:	0.879 ± 0.011 fm (CODATA 2014)
Muonic spectroscopy:	0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017):	0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017)6359)
H spectroscopy (2018):	0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018)183001)

The Proton Charge Radius Puzzle

- Different methods to measure the proton charge radius:
  - Hydrogen spectroscopy (ordinary hydrogen, muonic hydrogen)
  - Lepton-proton elastic scattering (ep, μp)
- The proton charge radius puzzle



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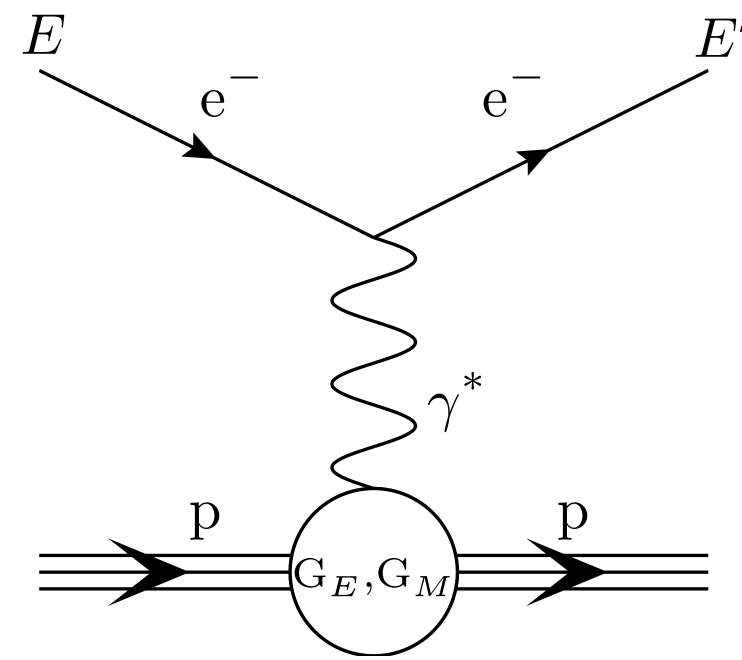
ep Scattering

- Elastic ep scattering, in the limit of Born approximation (one photon exchange):



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

$$Q^2 = 4EE' \sin^2(\theta/2) \qquad \tau = Q^2/4M_p^2$$

$$\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$$

- G_E and G_M are from factors for electric (E) and magnetic (M) charge distributions
  - G_E and G_M can be extracted using Rosenbluth separation
  - In PRad Experiment, cross sections are dominated by G_E since Q^2 is very small

- Tylor expansion of G_E at low Q^2:

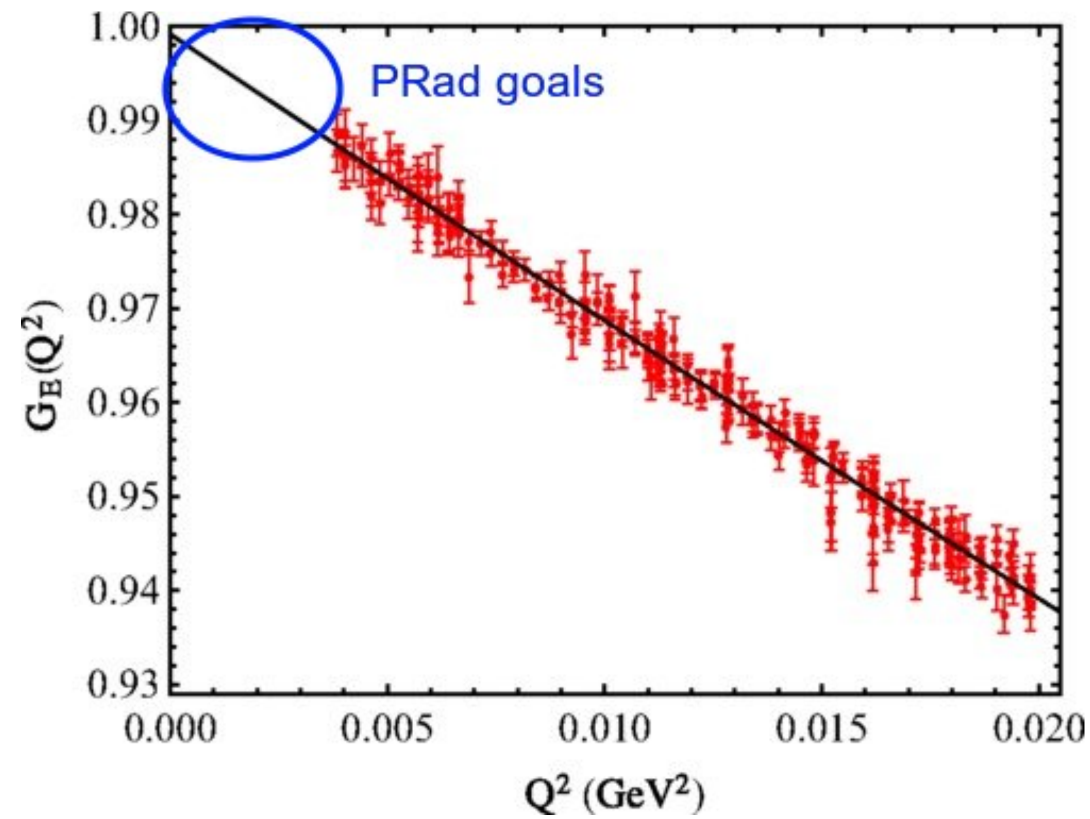
$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2 \rangle + \frac{Q^4}{120}\langle r^4 \rangle + \cdots$$

- Derivative at low Q^2 limit:

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

PRad Goal

- Measuring proton charge radius using ep elastic scattering:
  - Unprecedented low Q^2 region (~2×10^{-4} GeV^2)
  - Covers two orders of magnitude in low Q^2 (~2×10^{-4} to 6×10^{-2} GeV^2) with the same detector setting
  - Normalize to the simultaneously measured Moller scattering process
    - best known control of systematics
- Extract the radius with precision from sub-percent cross section measurement



Mainz Low Q^2 data set

Phys. Rev. C 93(2016)065207

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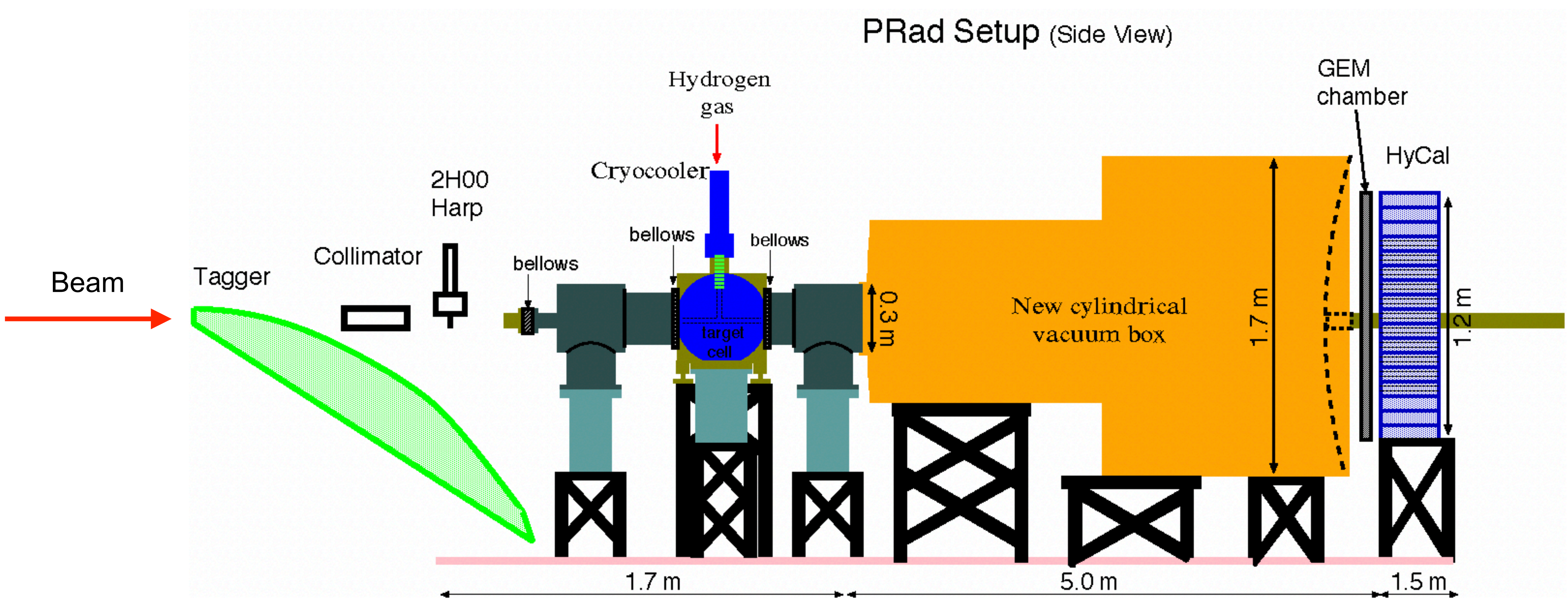
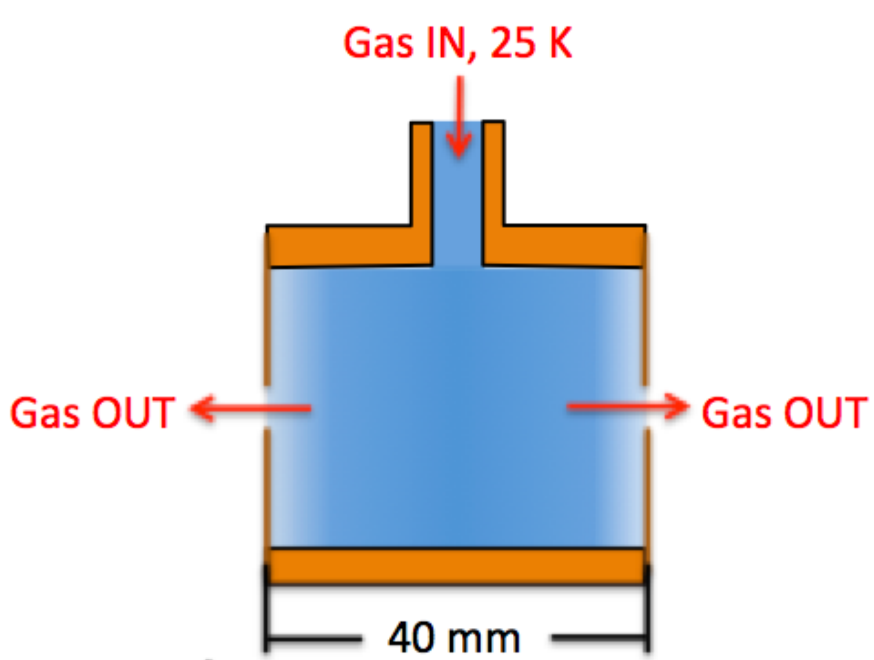
PRad Setup

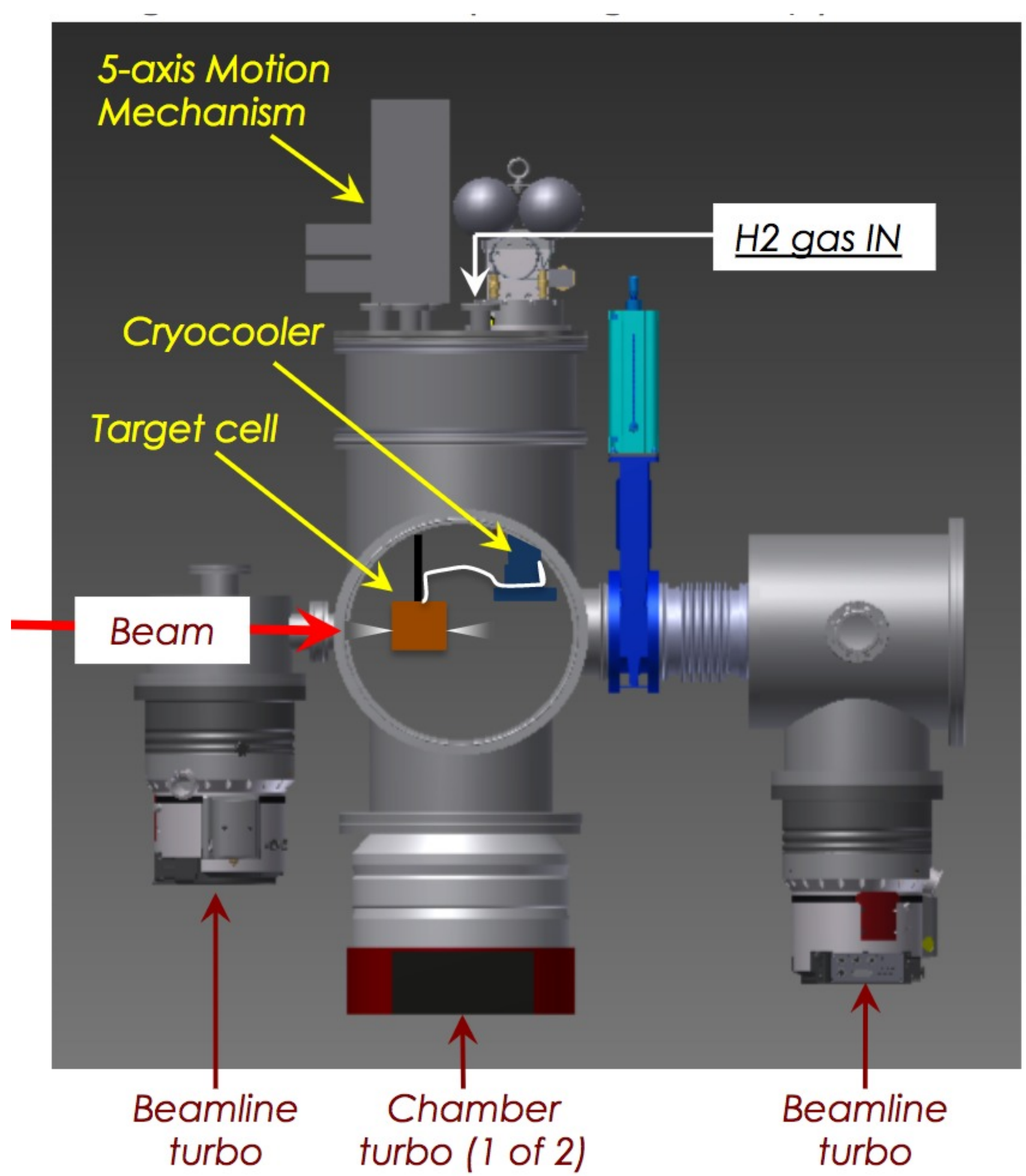
- Electron beam at 1.1 GeV and 2.2 GeV
- Windowless H_2 gas flow target
- Vacuum Chamber
- GEM detectors
- Hybrid EM Calorimeter (HyCal)



Windowless H_2 Gas Flow Target

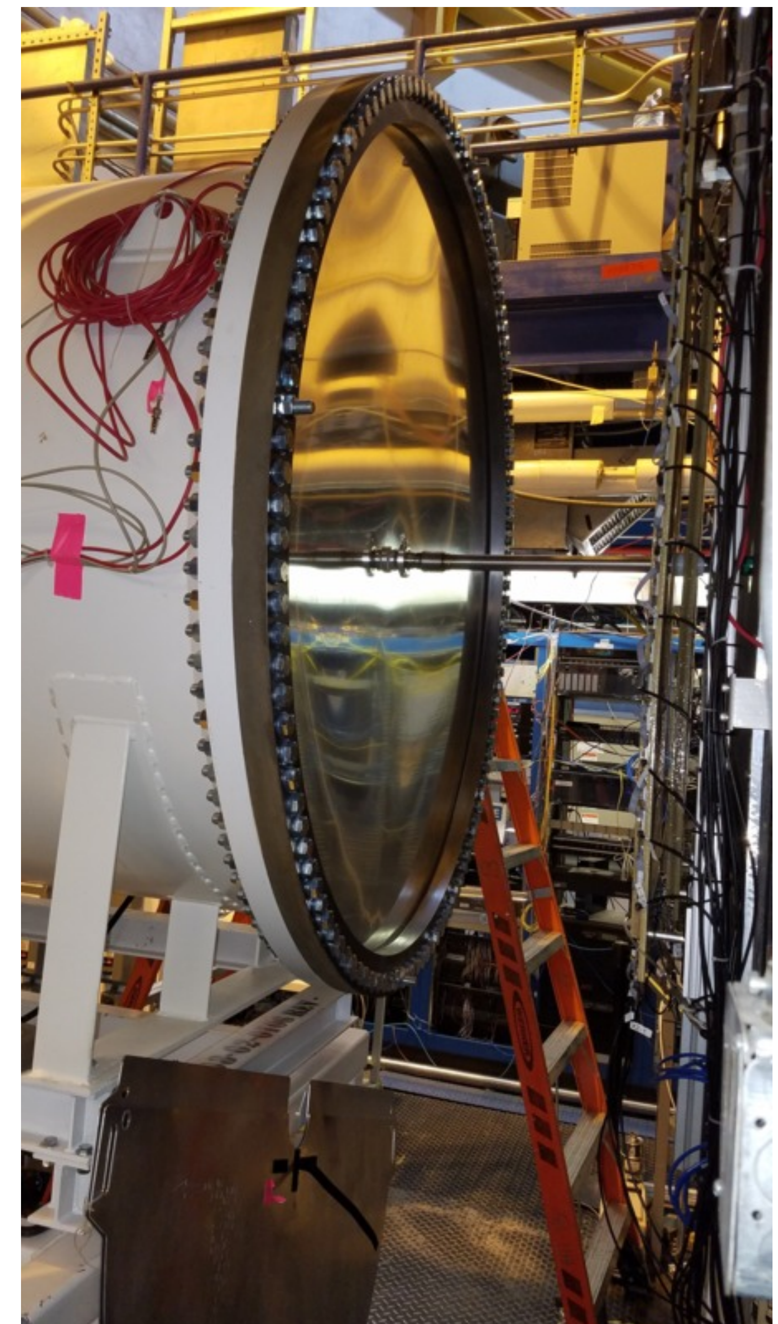
- A windowless gas target of cryogenically cooled hydrogen:
  - 4 cm long copper target cell
  - 7.5 μm Kapton windows with 2 mm beam orifices, allows beam to pass through
  - H_2 gas at 471 mTorr
  - Target density: ~2x10^{18} H atoms/cm^2





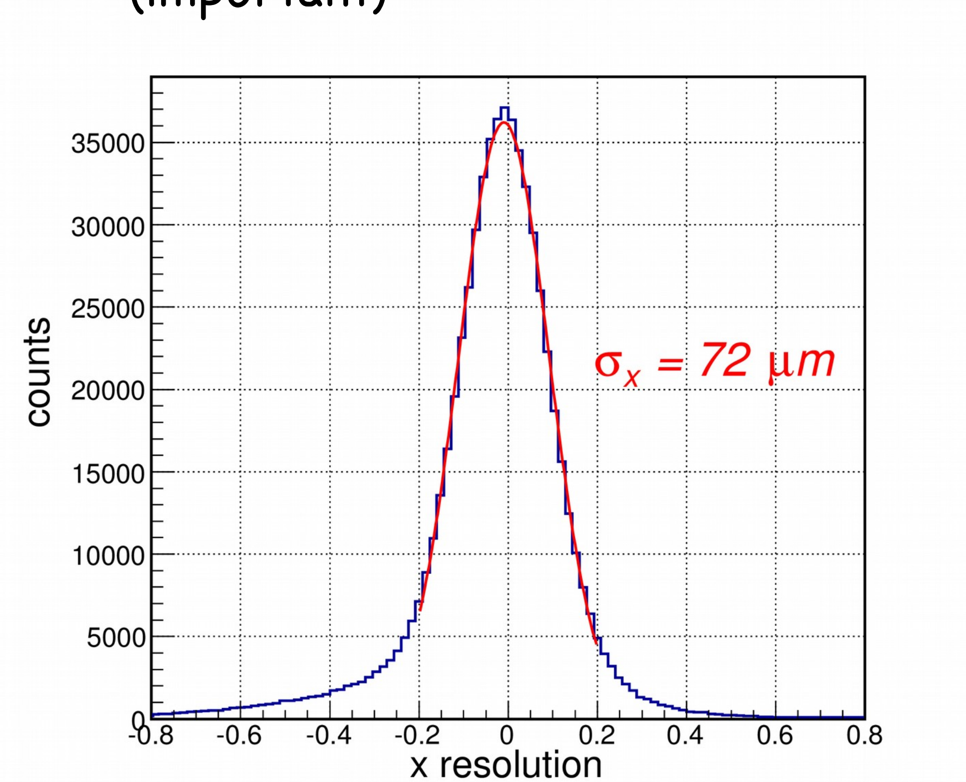
Vacuum Chamber

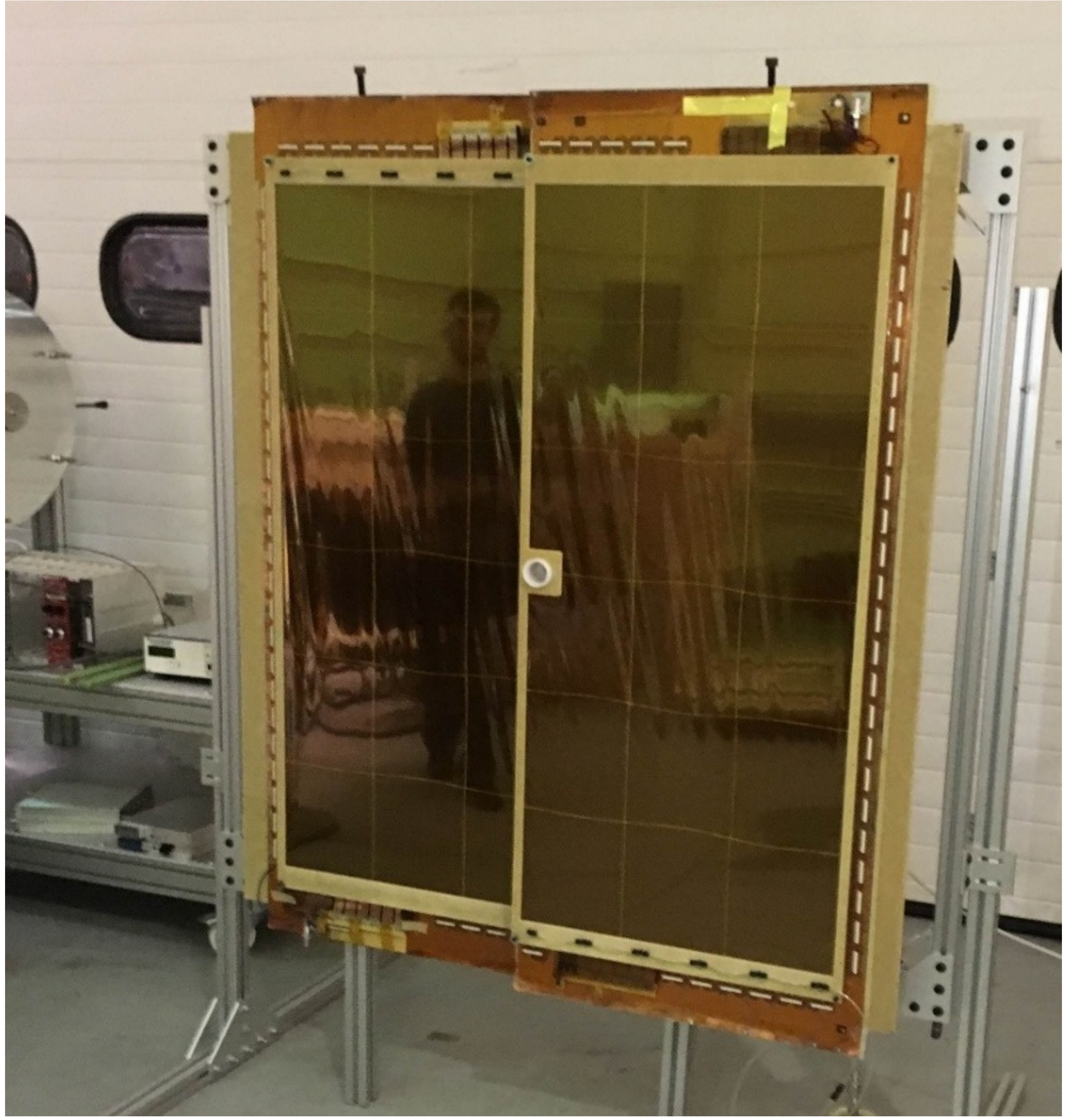
- 5 m long two stage vacuum chamber, further suppress the background



GEM Detectors

- Two large area GEM detectors (55 cm x 123 cm)
    - Small overlap region between two planes with a hole for the beam passage
- Excellent position resolution (72μm)
- A factor of >20 improvements in coordinate resolutions
    - Large improvements in Q^2 resolution (important)

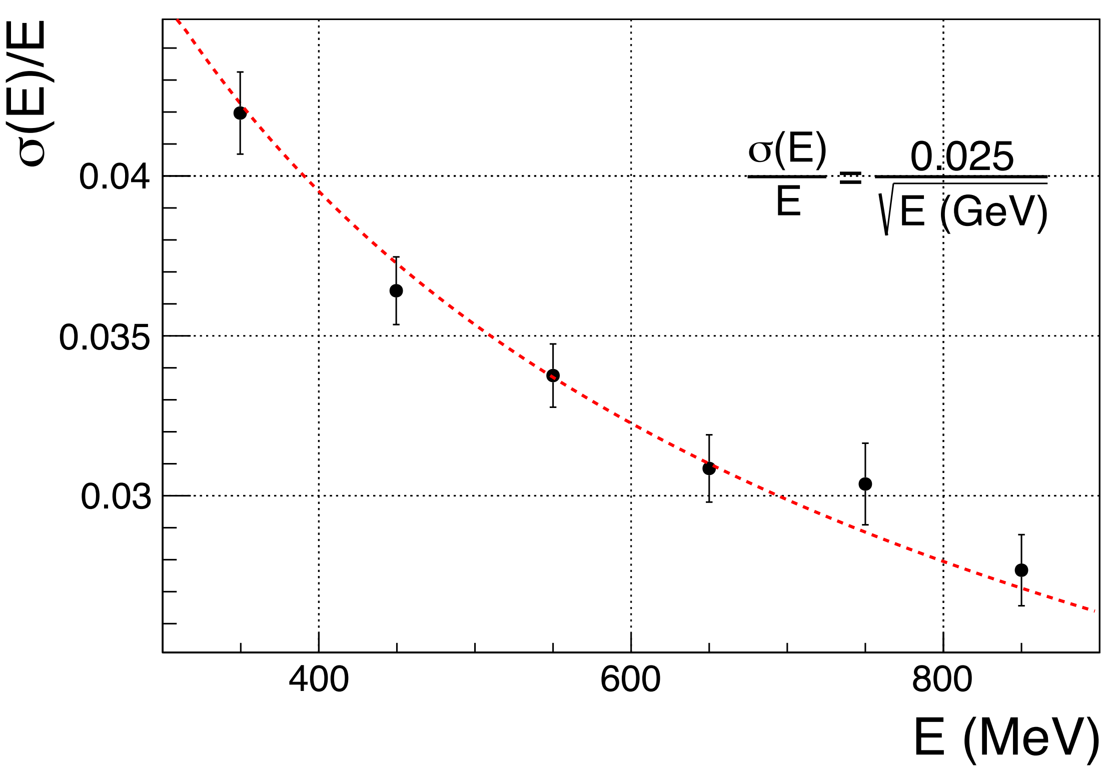


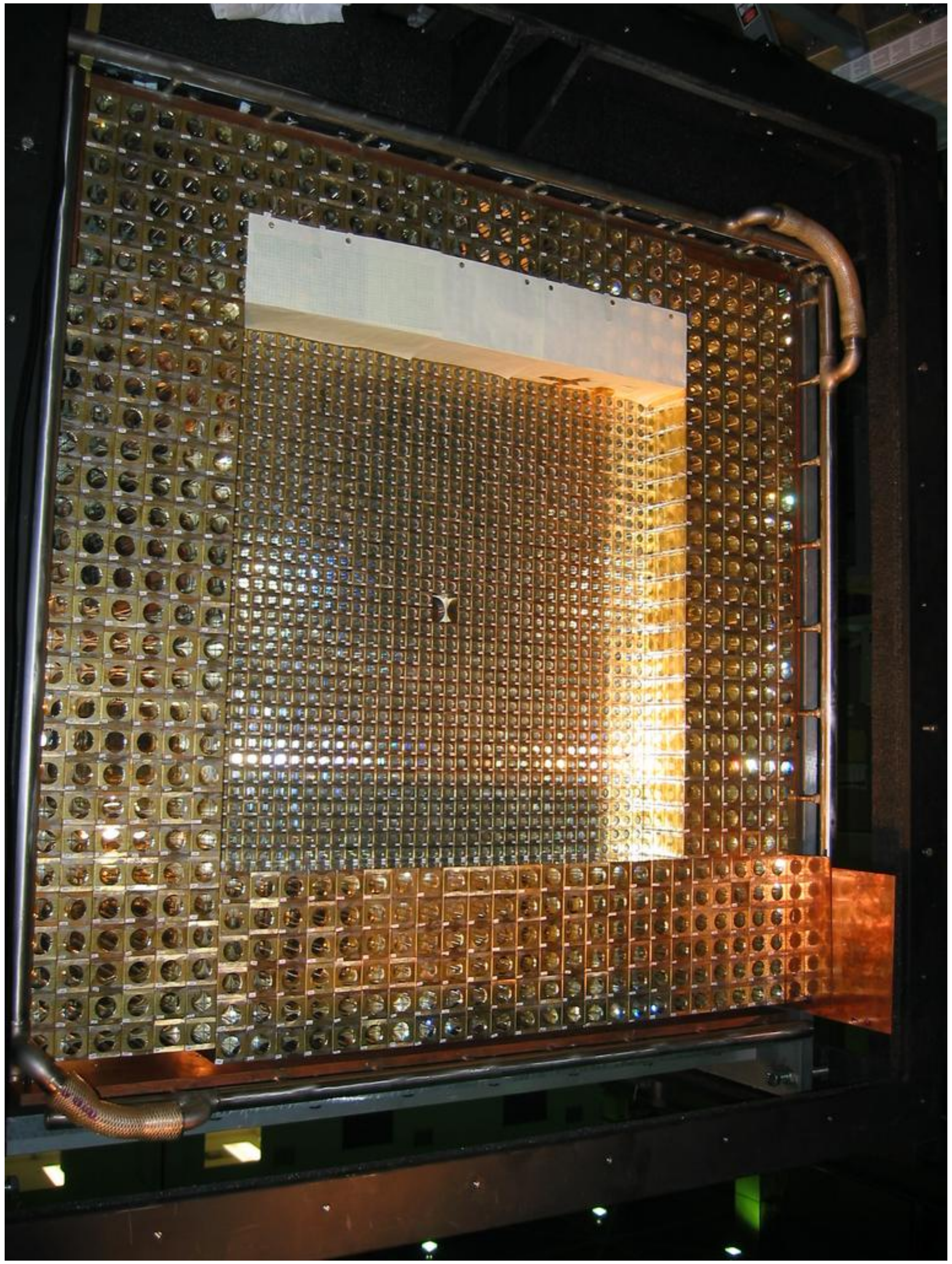


Plots courtesy of X. Bai

EM Calorimeter

- Hybrid EM Calorimeter (HyCal)
  - Inner 1156 $PbWO_4$ shower detectors
  - Outer 576 Pb-glass shower detectors
- 5.8 m from the target
- Scattering angle coverage: ~0.6 to 7.5 deg
- High resolution and efficiency
  - 2.5% at 1 GeV for $PbWO_4$ part
  - 6.1% at 1 GeV for Pb-glass part





Plots courtesy of M. Levillain

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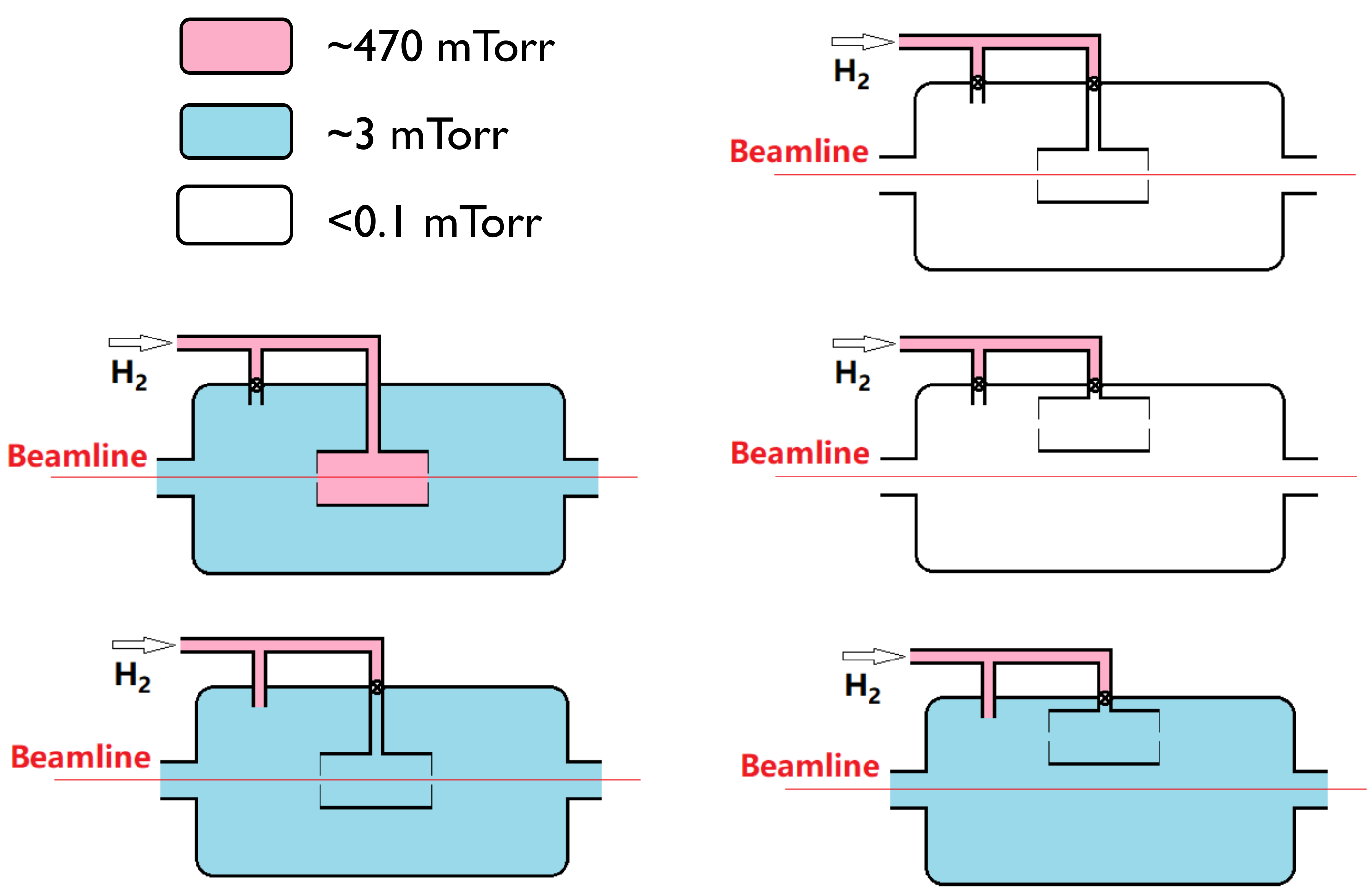
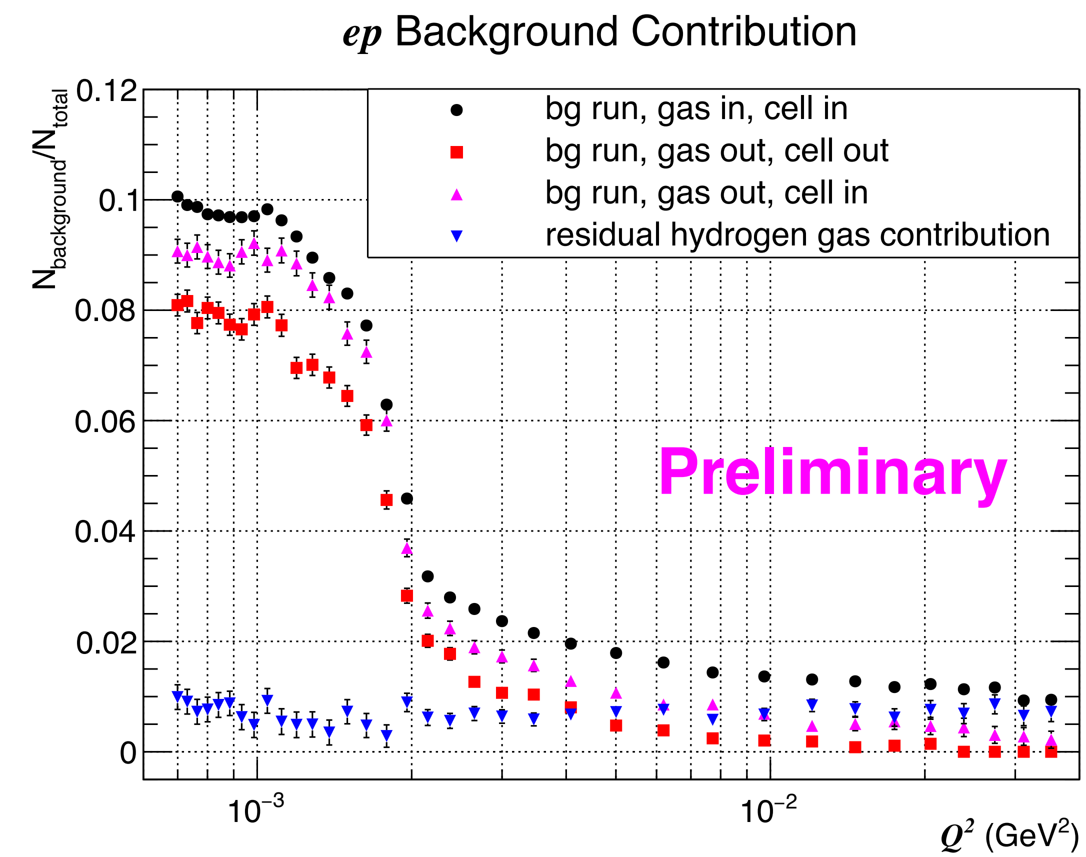
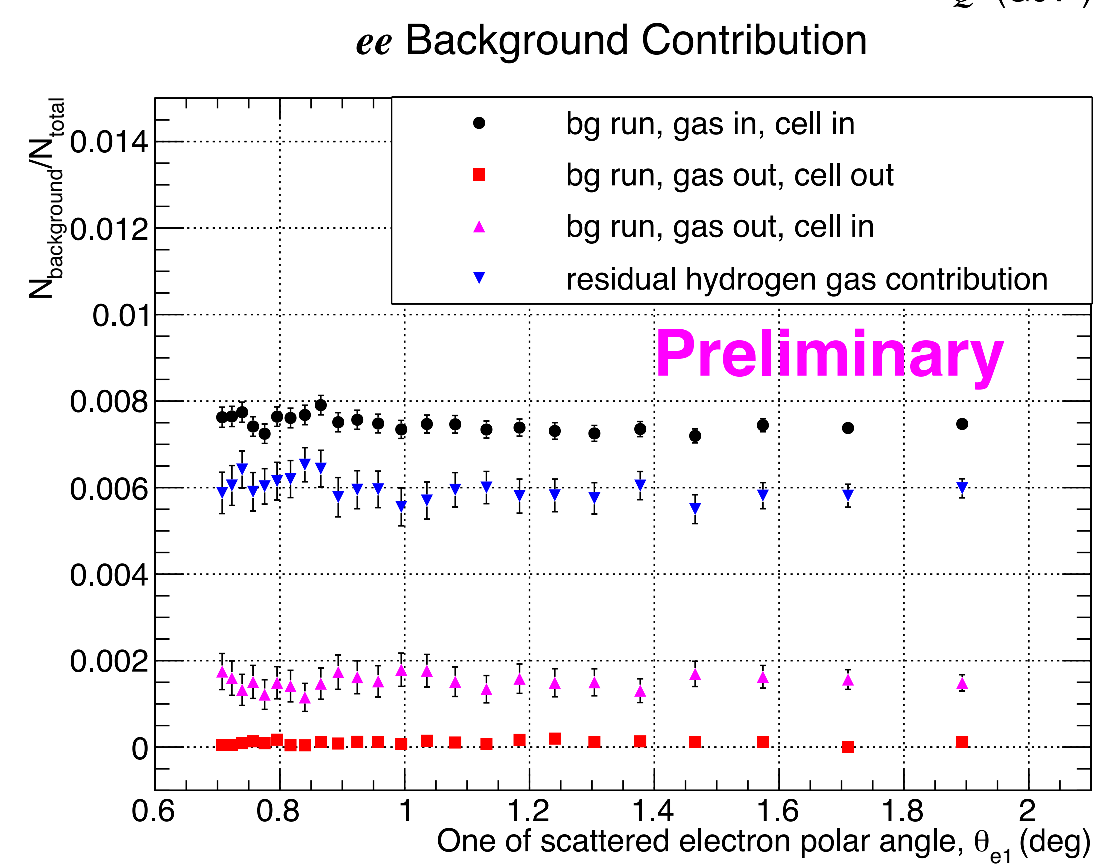
Background Subtraction

- Runs with different target conditions taken for background subtraction and studies for the systematic uncertainty
- ep background rate ~10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- ee background rate ~0.8% at all angles



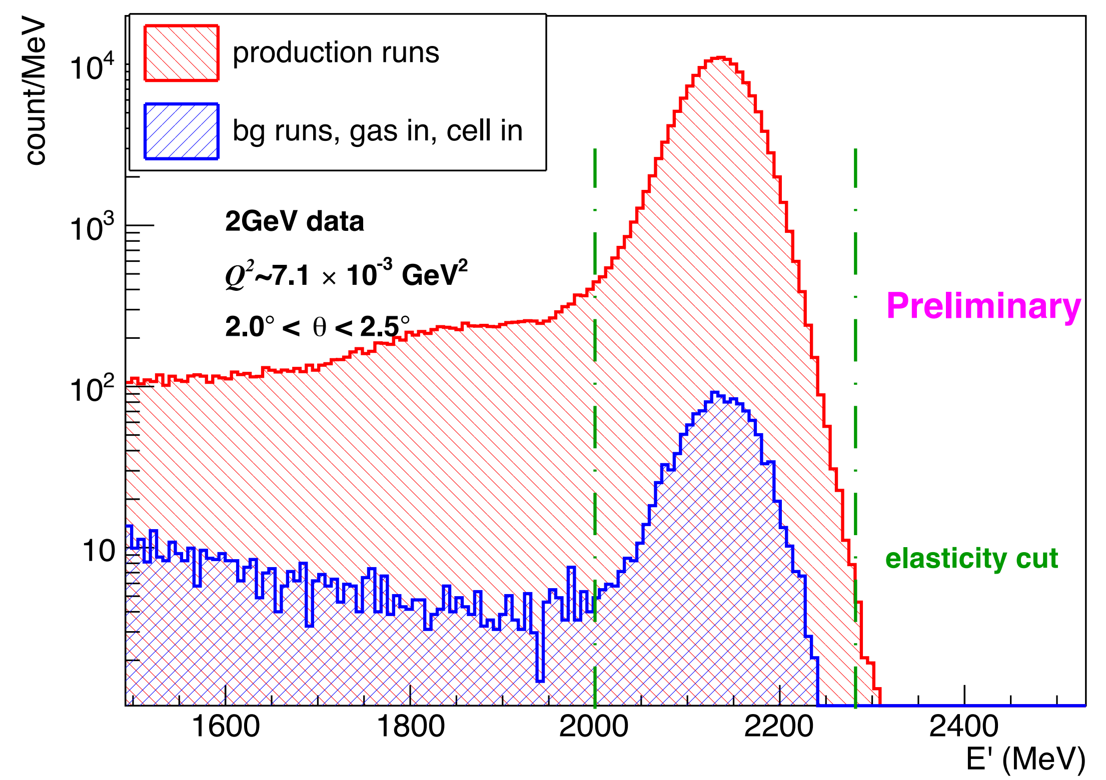


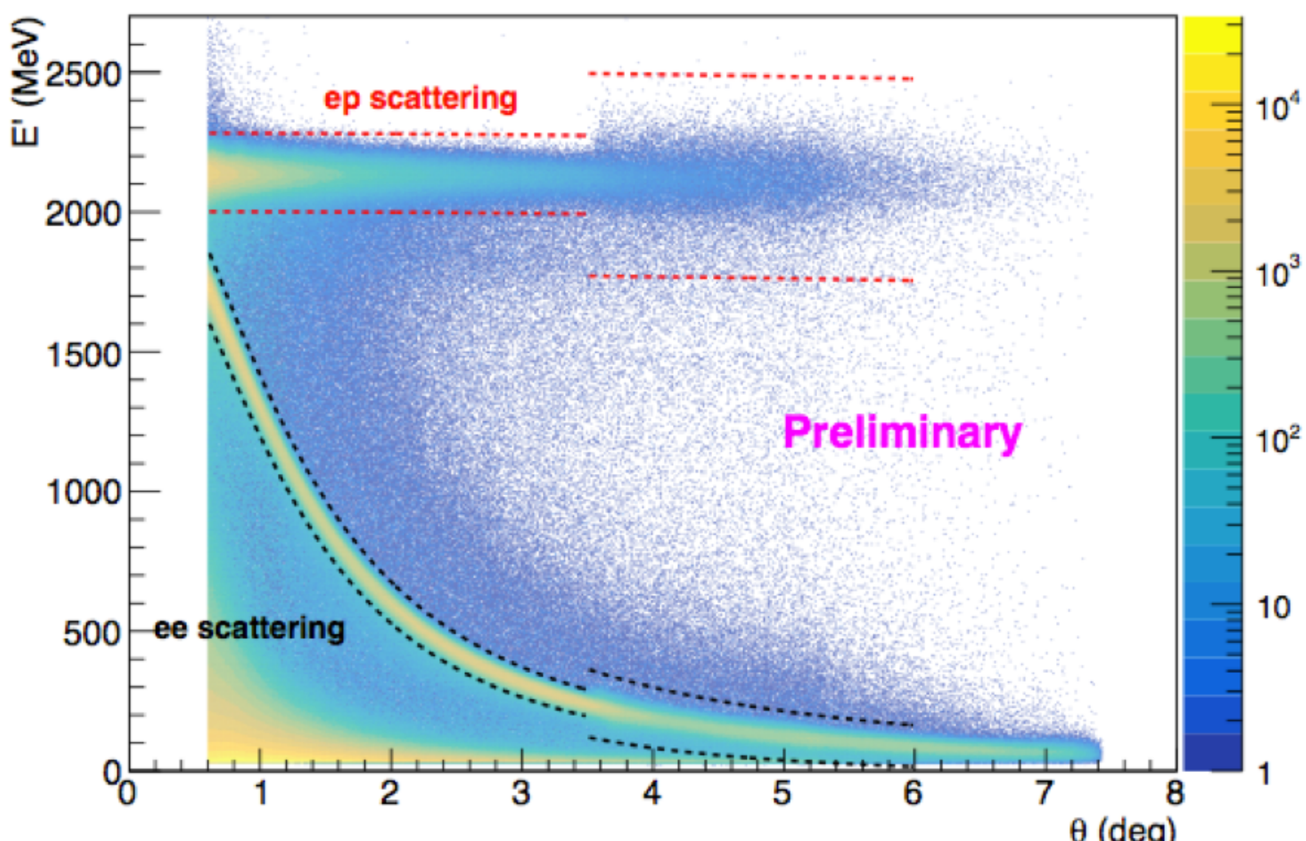


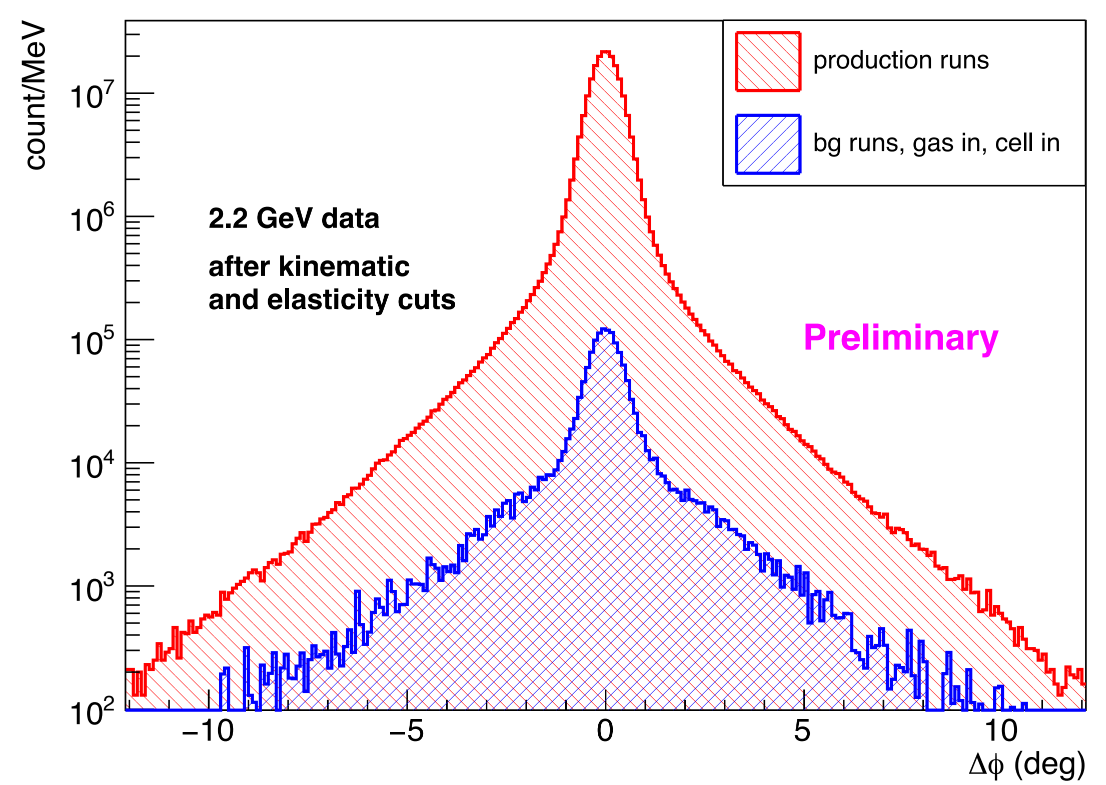
Plots courtesy of W. Xiong

Event Selection

- For all events, require hit matching between GEMs and HyCal
- For ep and ee events, apply angle dependent energy cut based on kinematics
  - Cut size depend on local detector resolution
- For ee events, if requiring double-arm events, apply additional cuts:
  - Elasticity, Co-planarity, Vertex z,...







Plots courtesy of W. Xiong

Extraction of ep Elastic Cross Section

- To reduce the systematics uncertainty, the ep elastic cross section is normalized to the Moller cross section:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{ep} = \left[\frac{N_{\mathrm{exp}}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\mathrm{exp}}(ee \to ee)} \cdot \frac{\varepsilon^{ee}_{\mathrm{geom}}}{\varepsilon^{ep}_{\mathrm{geom}}} \cdot \frac{\varepsilon^{ee}_{\mathrm{det}}}{\varepsilon^{ep}_{\mathrm{det}}}\right] \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{ee}$$

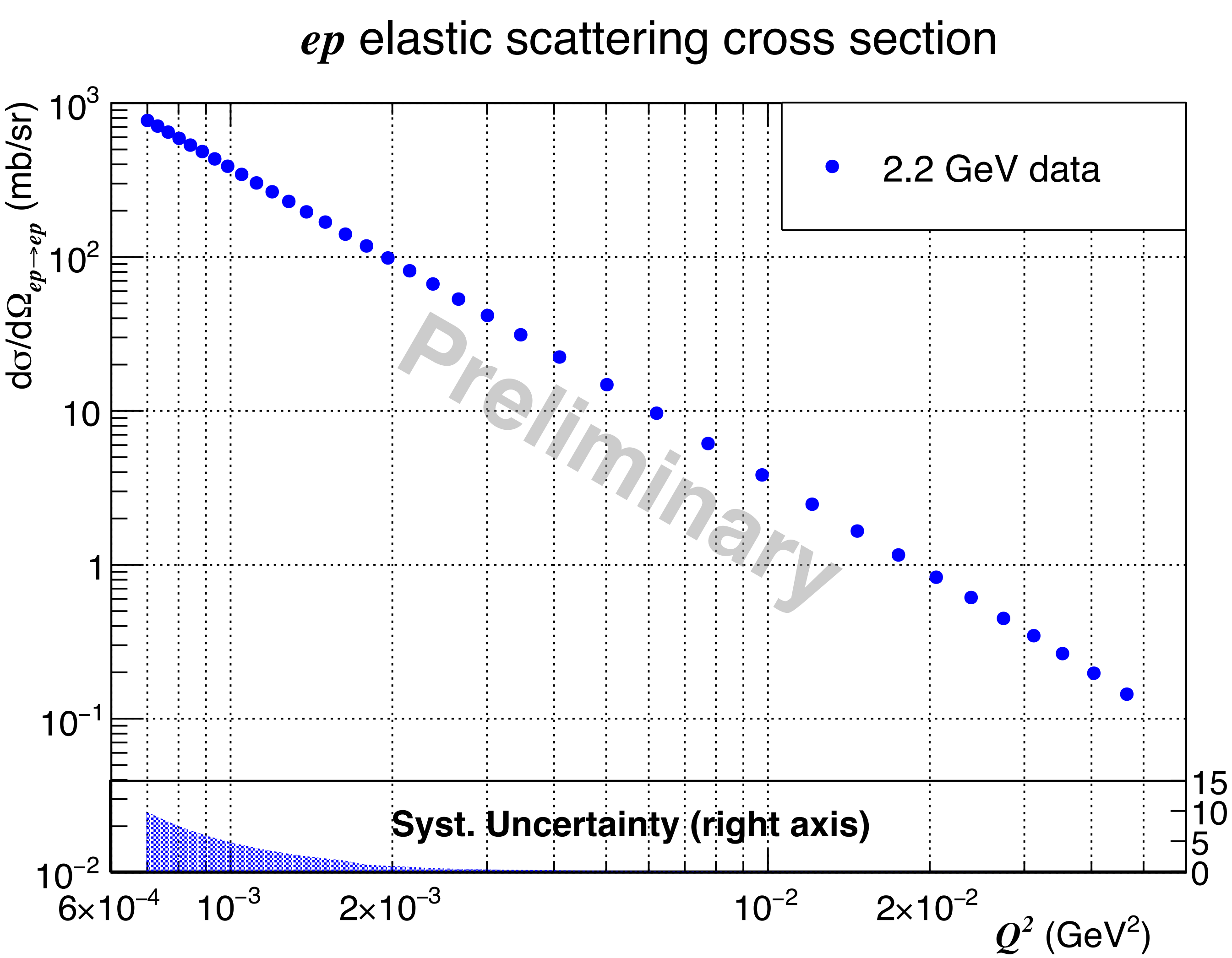
- Event generators for unpolarized elastic ep and Moller scatterings have been developed based on complete calculations of radiative corrections beyond the ultra relativistic approximation
  - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
- A Geant4 simulation package is used to study the radiative effects:

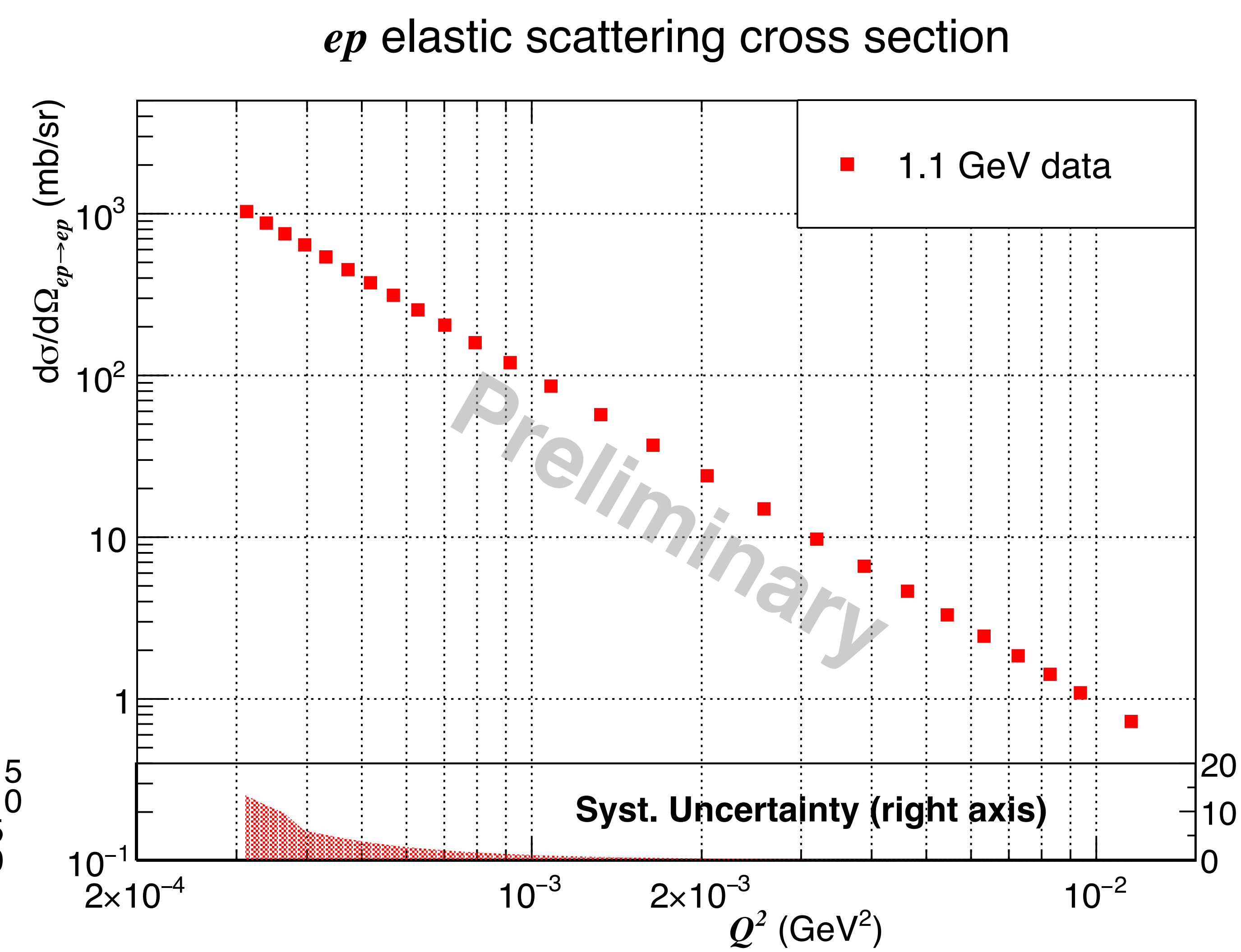
$$\sigma^{\mathrm{born}}_{ep} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\mathrm{exp}} \cdot \left(\frac{\sigma_{ee}}{\sigma_{ep}}\right)^{\mathrm{sim}} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\mathrm{born}} \cdot \sigma^{\mathrm{born}}_{ee}$$

- Iterative procedure applied for radiative correction

Differential Cross Sections (Preliminary)

- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Statistical uncertainties at current stage: ~0.18% for 2GeV, ~0.3% for 1GeV per point
- Systematic uncertainties at current stage: 0.8%~2.0% for 2GeV, 0.9%~2.0% for 1GeV (shown as shadow area)





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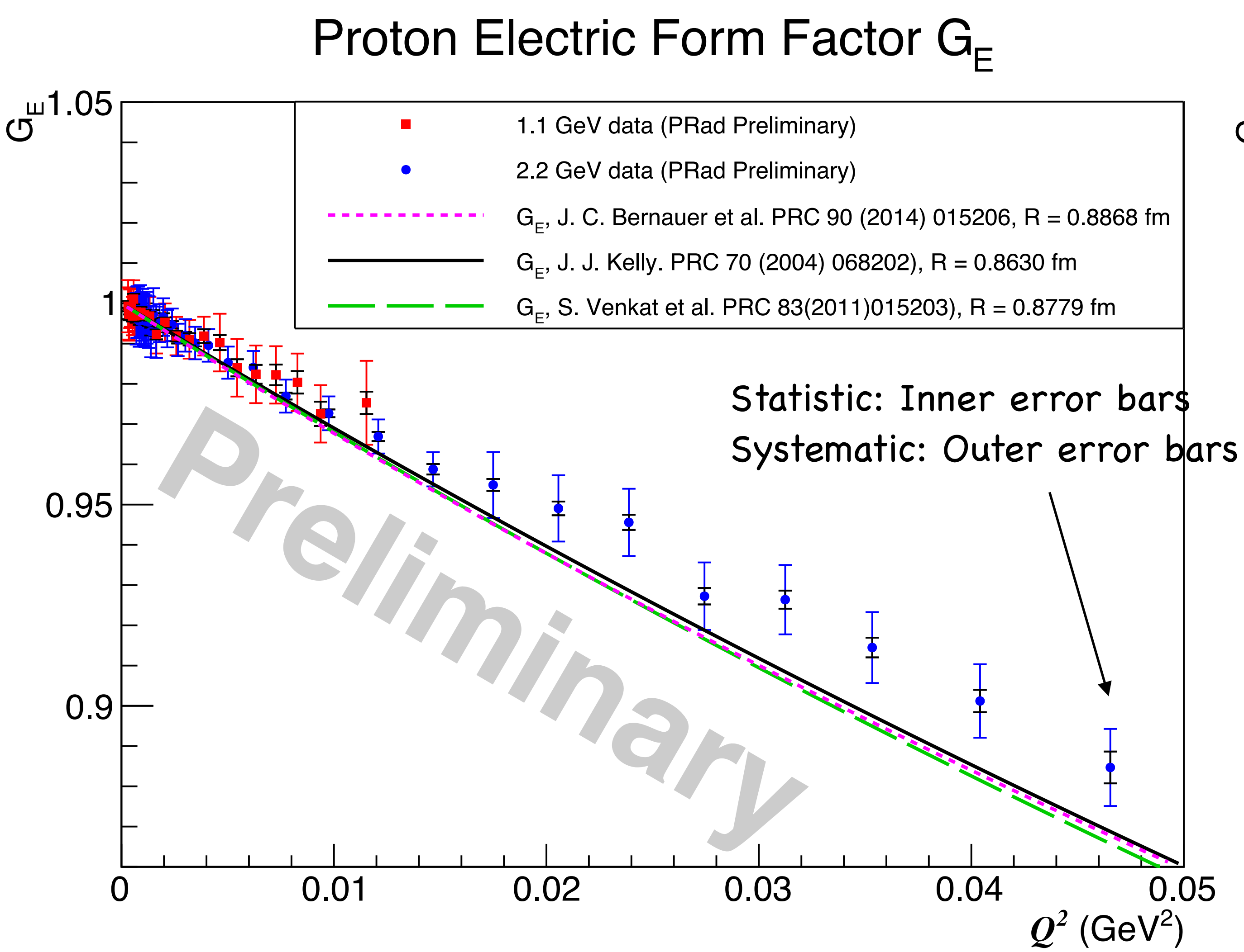
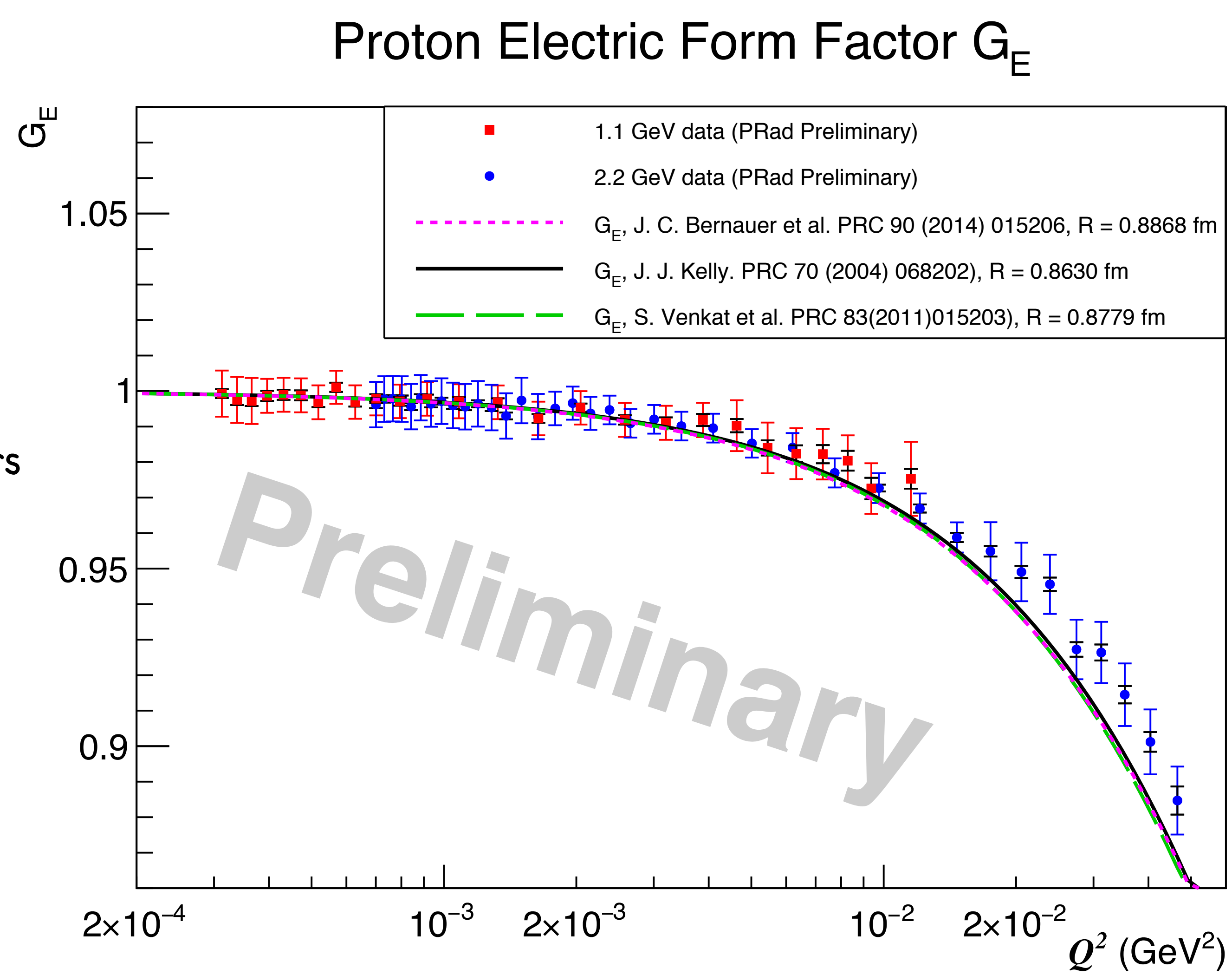
Form Factor G_E (Preliminary)

- Proton electric form factor G_E v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Statistic and systematic uncertainties shown as error bars
- Preliminary G_E slope seems to favor smaller radius





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Radius Fitting Study

- Data always measured at finite Q^2. Need to extrapolate to $Q^2 = 0$ to obtain charge radius.
- Study the "robustness" of the fit functions: "robust" meaning that fit function should give correct proton radius for data (or pseudo data) manufactured using a generating function.
(X. Yan, D. W. Higinbotham et al., arXiv 1803.01629)
- Lots of different generating functions and lots of fit functions has been tested
  - Three-parameter fit function: $f(Q^2) = p_0(1 + p_1 Q^2)/(1 + p_2 Q^2)$

TABLE VIII. The fitting results using the rational-function fitter ($N = 1$, $M = 1$), when different generators are used. Notation as in Table I.

Generator	R(input) (fm)	R(mean) (fm)	δR (fm)	RMS (fm)
Dipole	0.8500	0.8503	0.0003	0.0097
Monopole	0.8500	0.8499	−0.0001	0.0099
Gaussian	0.8500	0.8509	0.0009	0.0094
Kelly-2004	0.8630	0.8631	0.0001	0.0096
Arrington-2004	0.8682	0.8686	0.0004	0.0094
Arrington-2007	0.8965	0.8965	0.0000	0.0094
Venkat-2011	0.8779	0.8777	−0.0002	0.0096
Bernauer-2014	0.8868	0.8844	−0.0024	0.0097
Alarcón-2017	0.8500	0.8499	−0.0001	0.0096
Alarcón-2017 (codata)	0.8750	0.8758	0.0008	0.0093
Alarcón-2017 (μ)	0.8400	0.8407	0.0007	0.0096
Ye-2018	0.8790	0.8750	−0.0040	0.0097
Ye-2018 (re-fix)	0.8500	0.8514	0.0014	0.0096

- Uncertainty in the fit is not too large
- No Bias, which means radii missed on high side as often as on low side

Conclusion

- The PRad experiment was uniquely designed to address the "Proton Radius Puzzle"
    - Discrepancy between electron scattering and muon spectroscopy results
    - Unprecedented low Q^2 data set ($\sim 2\times10^{-4}$ GeV^2) has been collected in ep elastic scattering experiment
    - Data with two orders of magnitude in low Q^2 range ($\sim 2\times10^{-4}$ to 6×10^{-2} GeV^2) in one experimental setting
- Preliminary cross section and G_E extracted, covering Q^2 from 3×10^{-4} to 5×10^{-2} GeV^2
- Preliminary G_E slope seems to favor smaller radius
- Preliminary extraction of the proton radius is expected to be done by this year

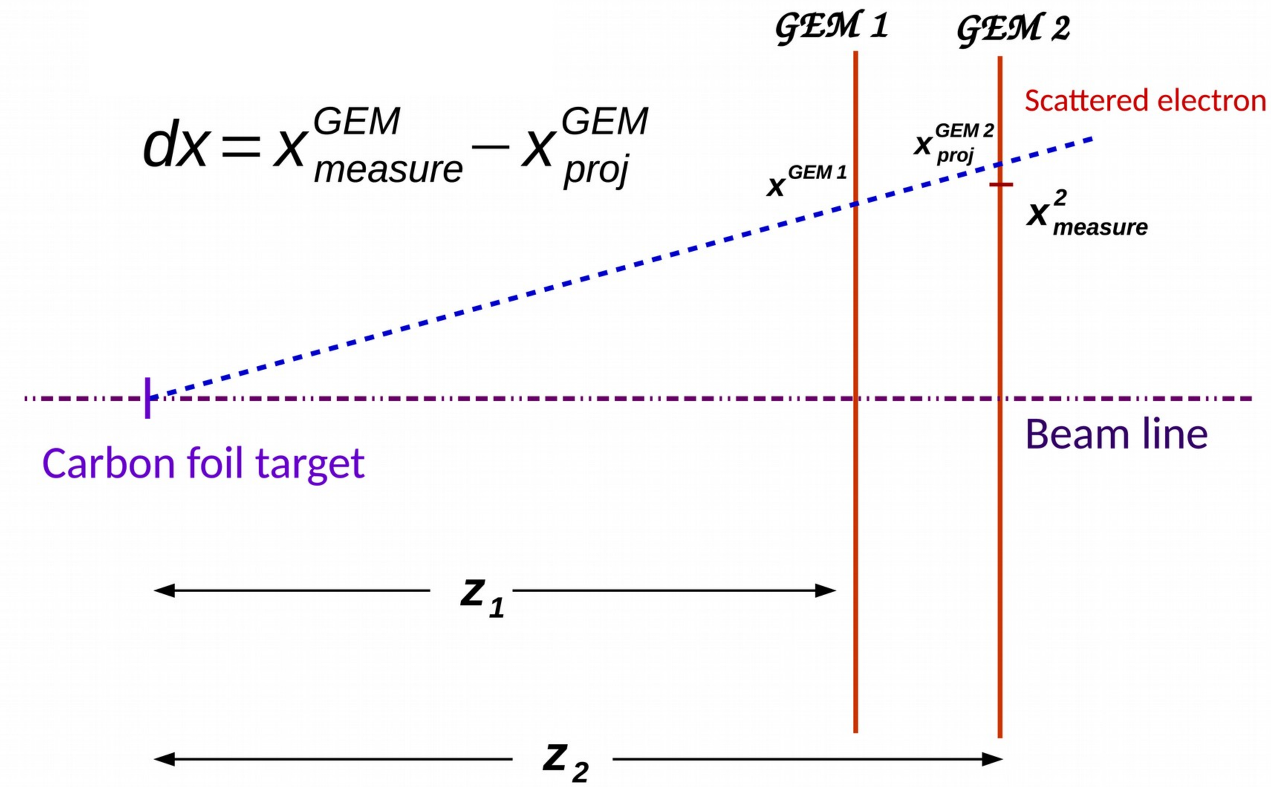
PRad is supported in part by NSF MRI award #PHY-1229153
and US DOE grant DE-FG02-03ER41231.

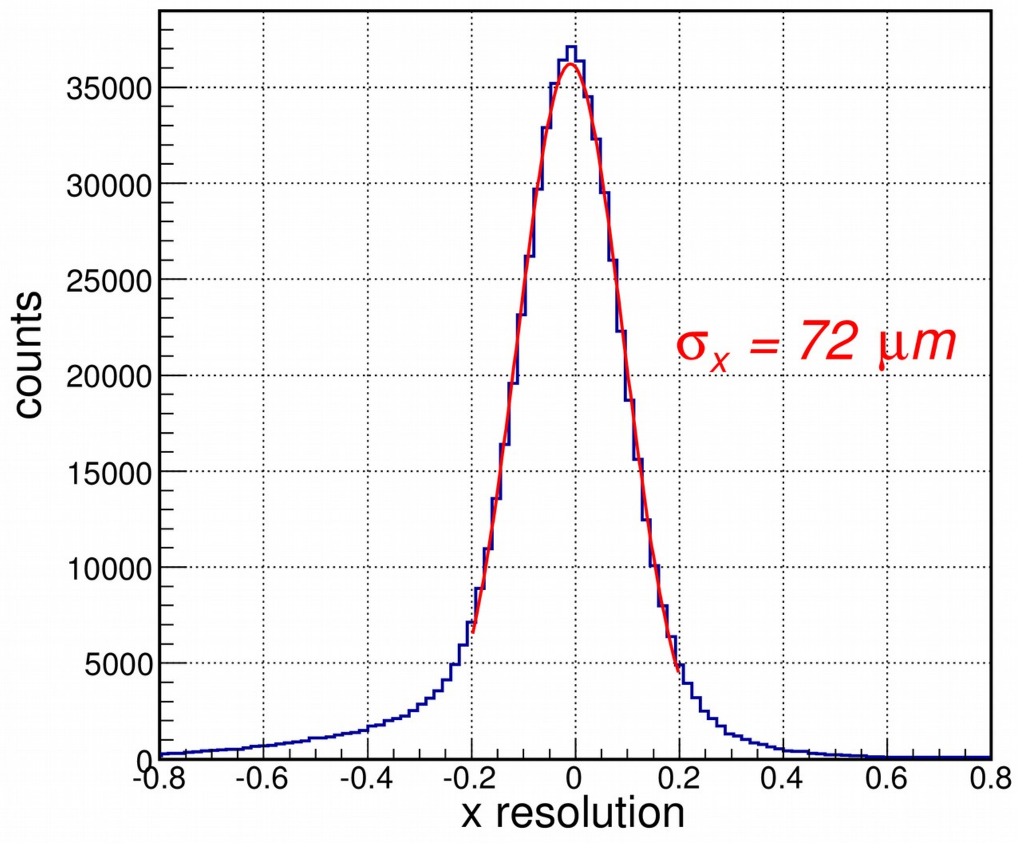
Thanks

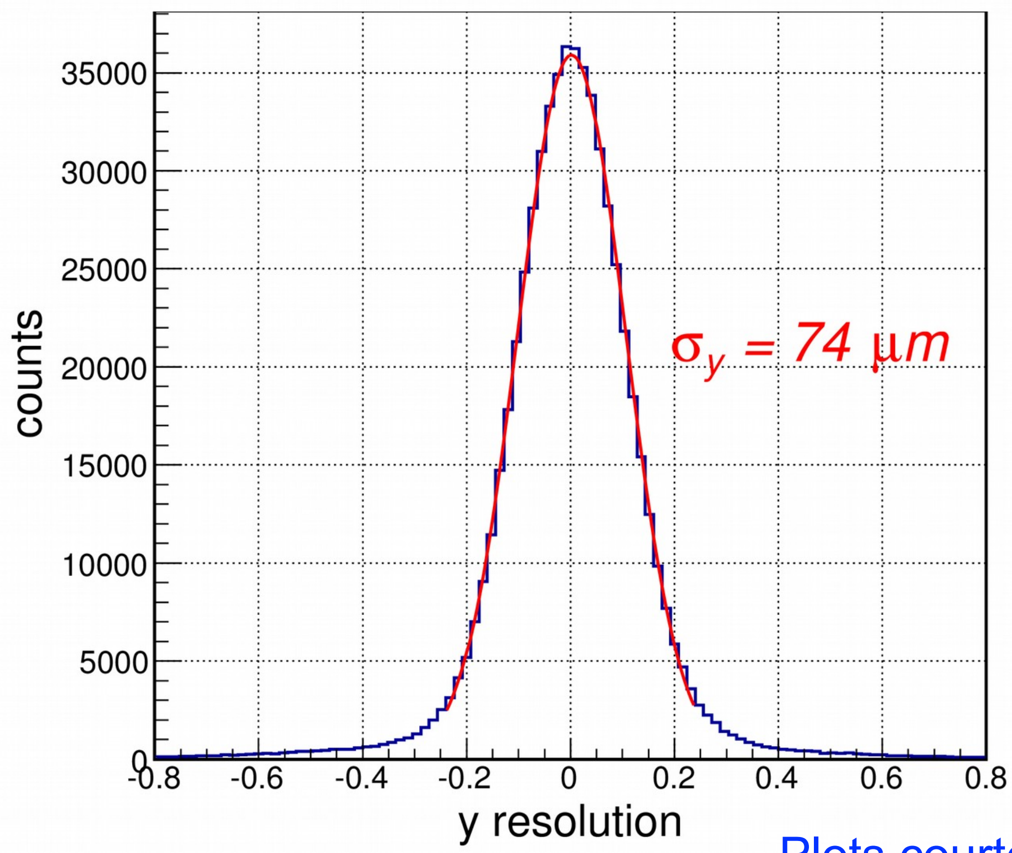
Backups

GEM Resolution

- Extraction of GEM spatial resolution using GEM central overlapping region
- Good spatial resolution achieved: ~70 um, close to the expected value



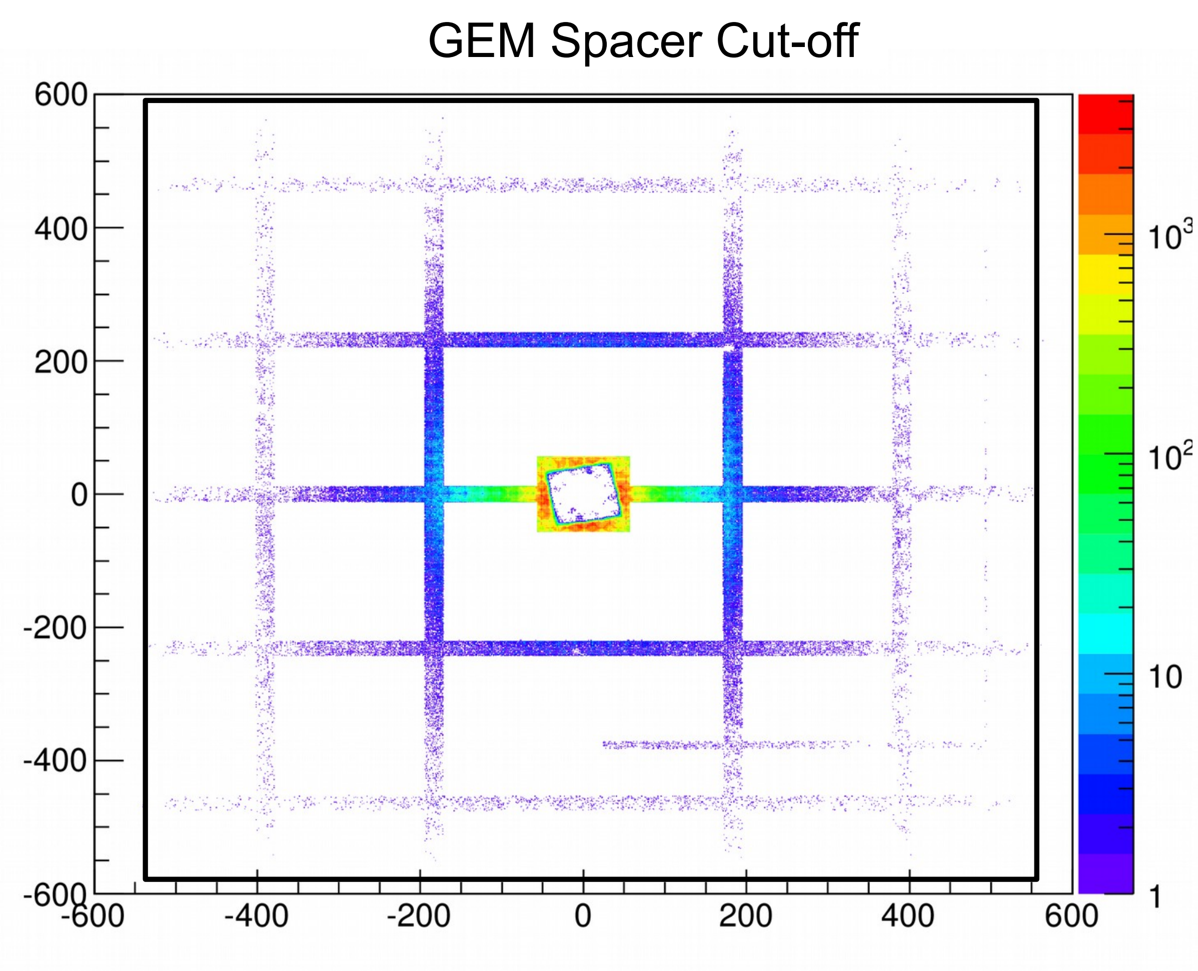


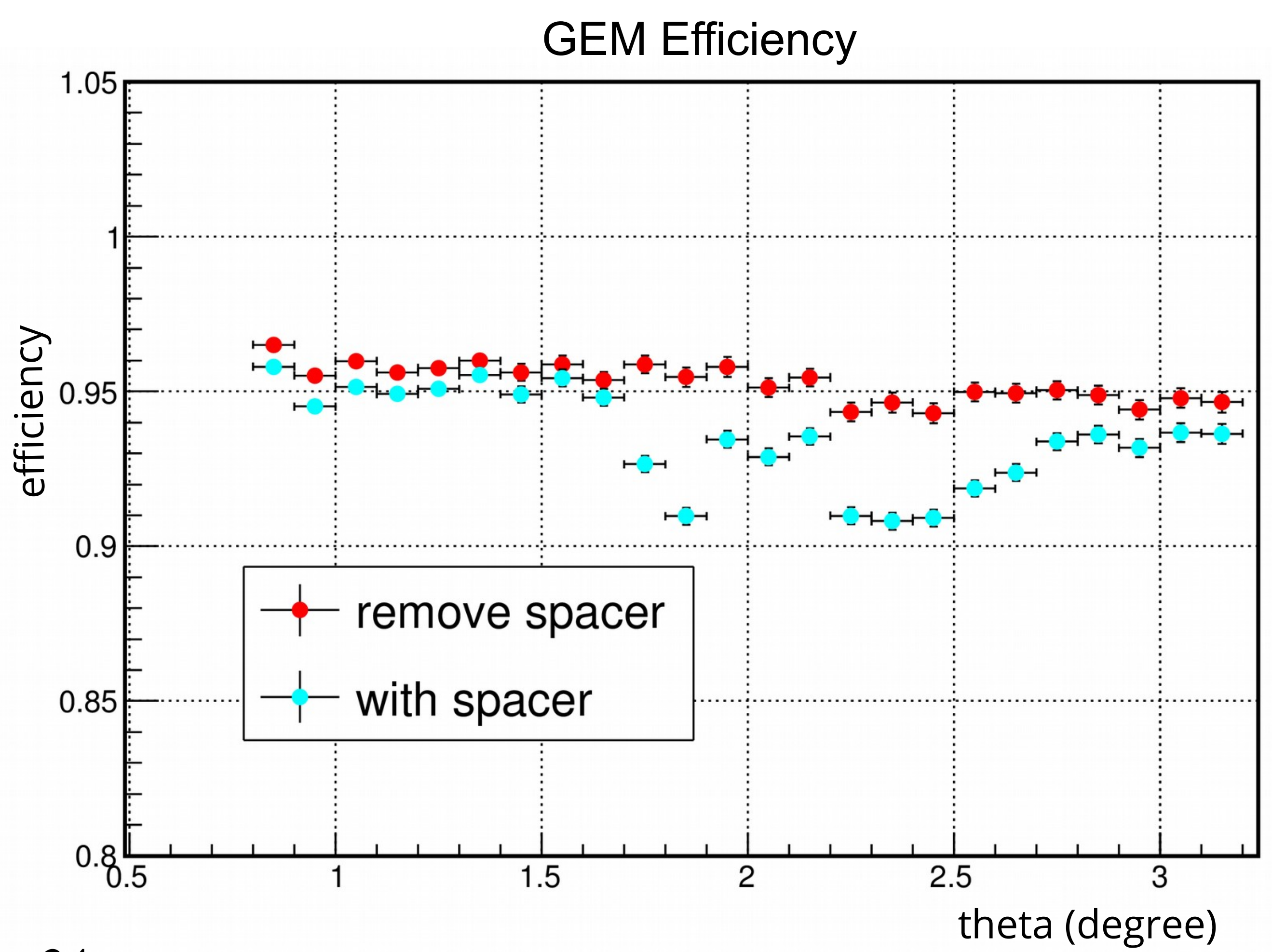


Plots courtesy of X. Bai

GEM Detection Efficiency

- GEM detection efficiency calibrated using physics runs
  - GEM spacer introduces deficient area
  - Evenly distributed efficiency after spacer cut-off
- Stable GEM efficiency over time
  - Average efficiency fluctuation: ~0.5% level

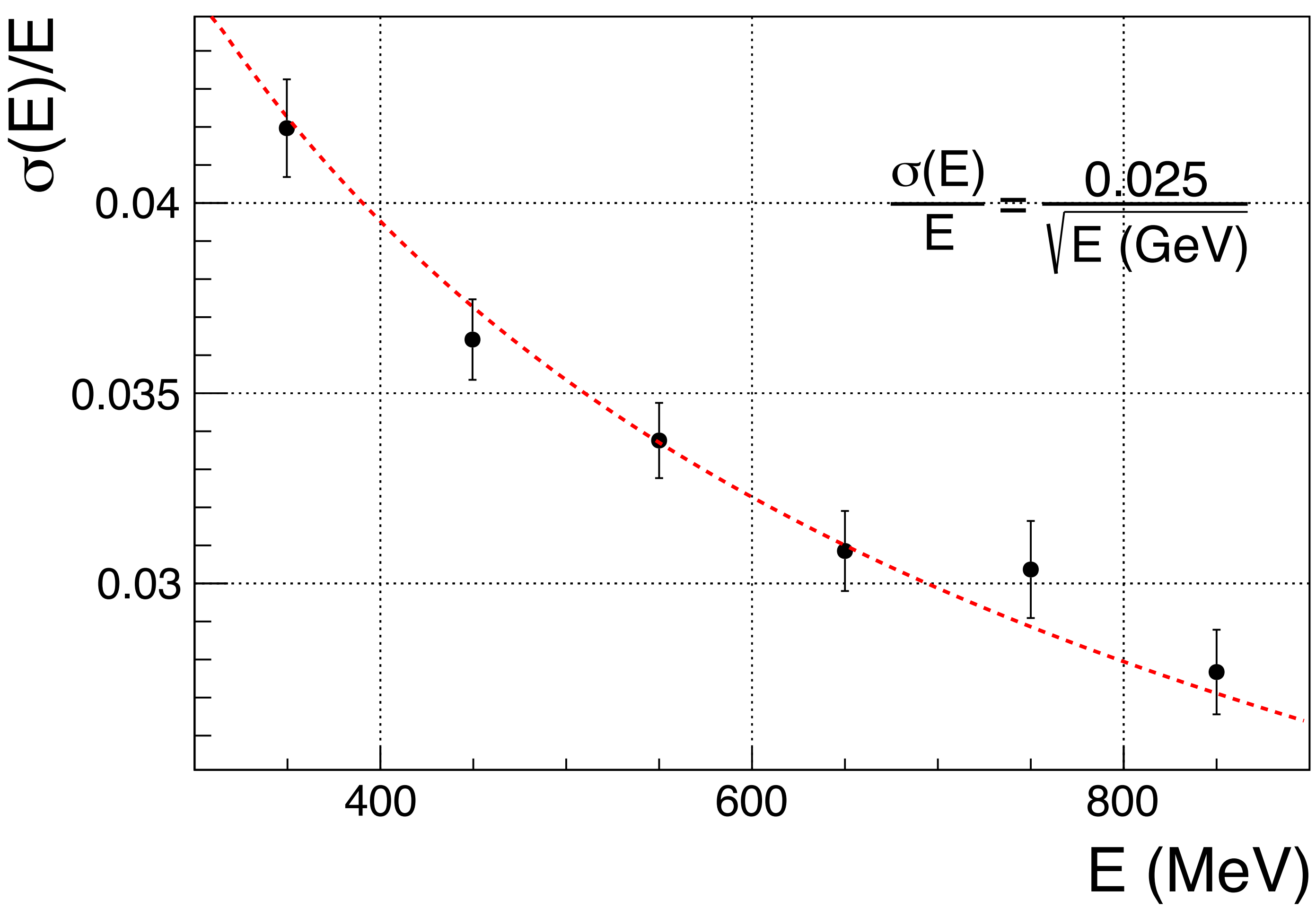




Plots courtesy of X. Bai

HyCal Calibration

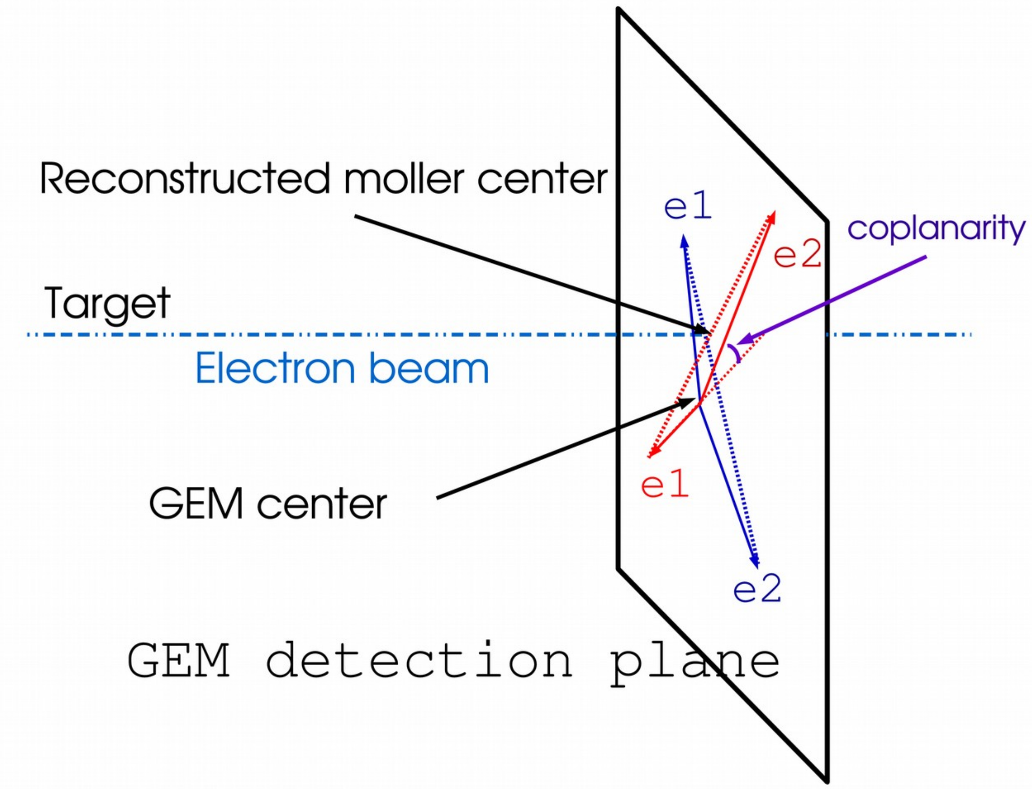
- Gains controlled by Light Monitoring System (LMS)
- Two different calibrations:
  - Before data taking: Scan with 250-1050 MeV tagged photon beam moved in front of each module to study of resolution, efficiency and non-linearity
  - During data taking: With Moller and ep elastic events
- Achieved expected energy resolution:
  - 2.5% at 1 GeV for $PbWO_4$ part
  - 6.1% at 1 GeV for Pb-glass part
- Plot shows the energy resolution for PbWO4 part with statistical uncertainties and systematic coming from non-uniformity

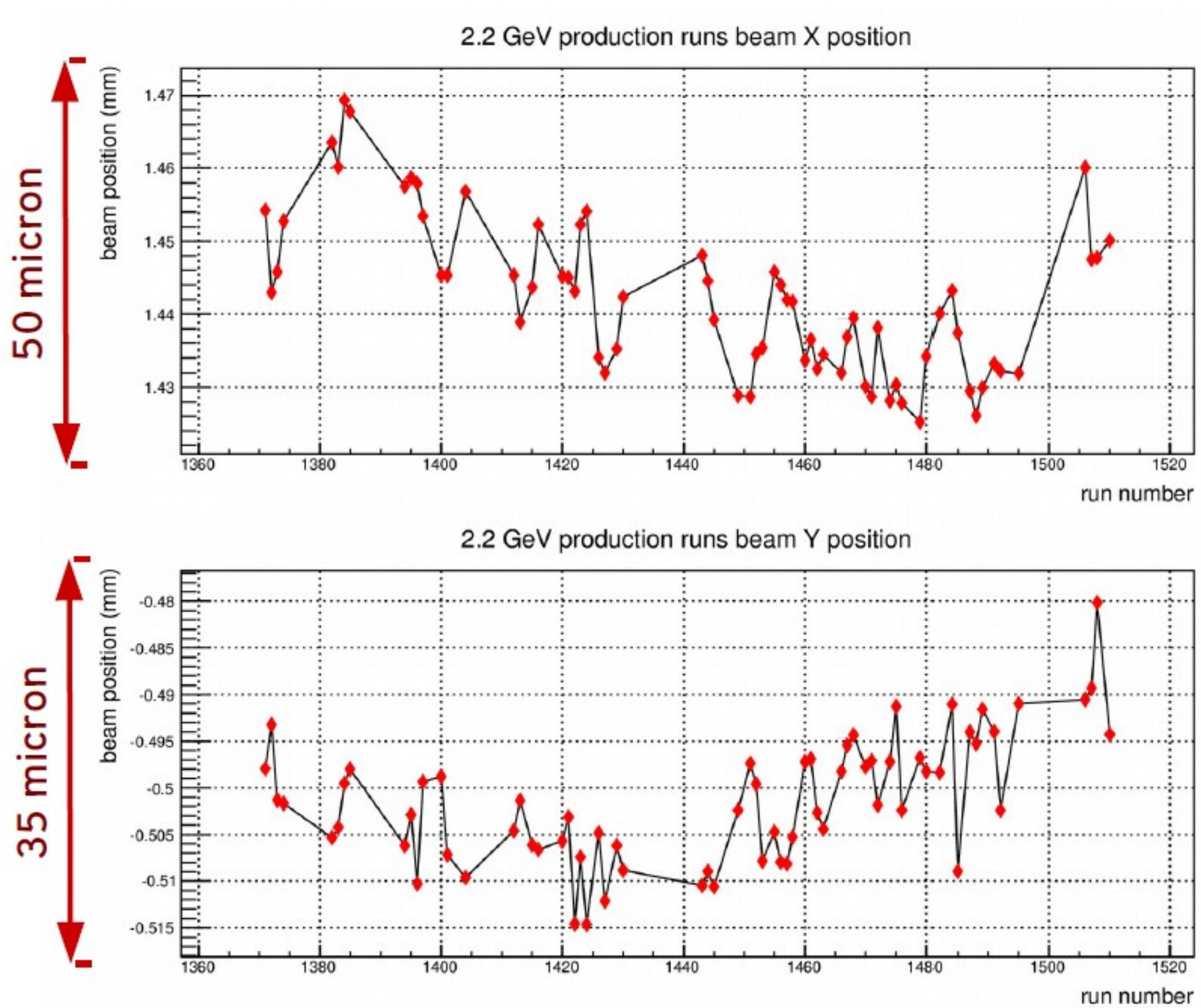


Plots courtesy of M. Levillain

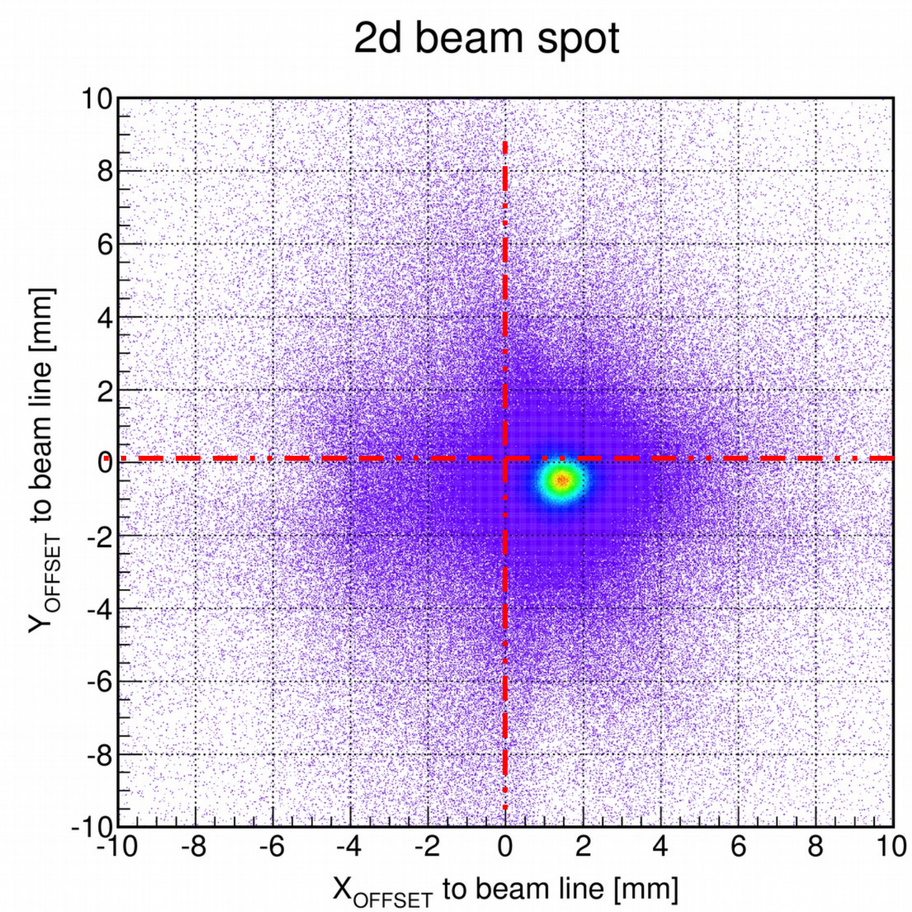
Beam positions monitored by GEM detectors

- Beam position important to the experiment.
- Using moller events to find beam position.
- Allows us to continuously monitor beam position upto *0.05mm* level.





Beam position monitored by GEM detectors in different runs



Extracting the ep / ee ratio

- At least four different ways to form the ratio, luminosity is always canceled by the ratio:
  - ep / single arm Moller (ee1): for ep in each theta (Q^2) bin, normalize it to the Moller yield selected using single arm Moller technique
    - Best at cancellation of energy independent detector acceptance and efficiency
    - Worst in ee signal to background ratio
  - ep / double arm Moller (ee2): for ep in each theta (Q^2)bin, normalize it to the Moller yield selected using double arm Moller technique
    - Partial cancellation for energy independent detector acceptance and efficiency
    - Best at ee signal to background ratio
  - ep / integrated double arm Moller (inte Moller)
    - No cancellation for energy independent detector acceptance and efficiency
    - The only way to include ep bins in region that is not "effectively" covered by Moller
- GEM detectors are always required for the above three types of ratio
  - ep / (HyCal double arm + GEM single arm Moller) (s_ee1): using HyCal to select double arm events first. When using GEM, apply the ep / single arm Moller method
    - Excellent ee signal to background ratio
    - Complete cancellation for the energy independent acceptance and efficiency from GEM