# Measuring the $\pi^0$ Transition Form Factor in the Space-like Region

***In preparation for running at JLab Hall B***

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Precision tests of fundamental Physics with light mesons, ECT, June 2023

# Outline

- Physics motivation for the measurement
- Experimental setup at Jefferson Lab Hall B
- Resolution and acceptance
- Signal and background yields
- Outlook for running the experiment

# Muon anomalous magnetic moment $(g-2)_\mu$

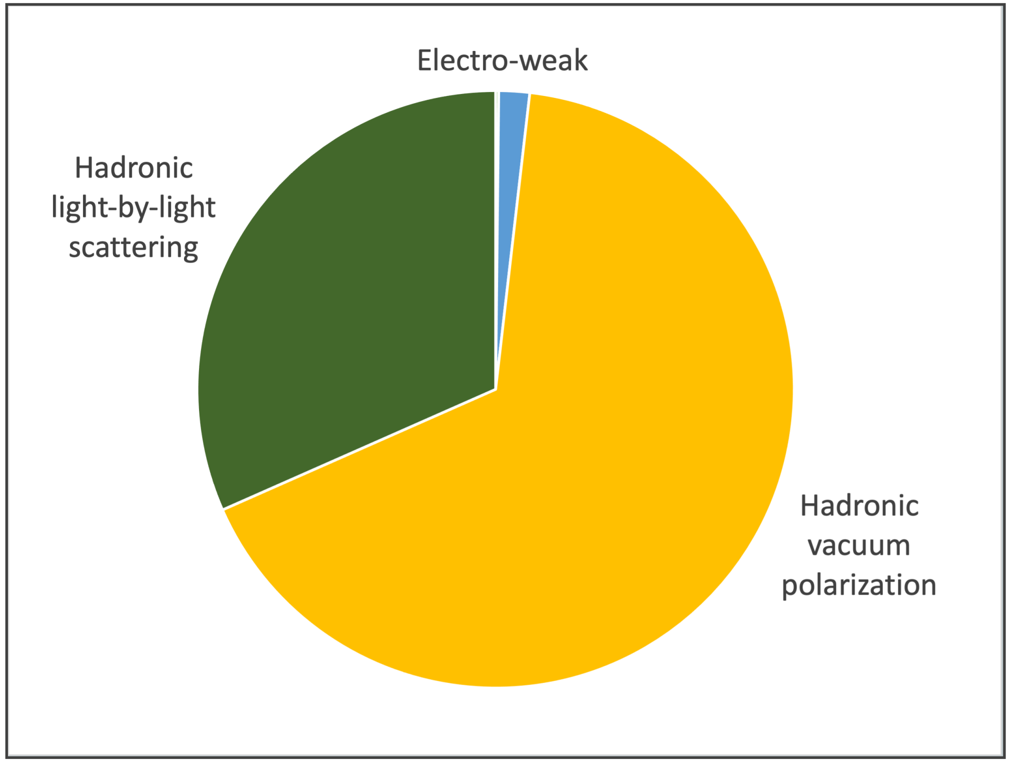
- There is a 4.2σ disagreement between experiment and standard model prediction for the muon anomalous magnetic moment $a_\mu^{SM} = (g-2)_\mu/2$

- The largest uncertainty in $a_\mu^{SM}$ is from Hadronic Vacuum Polarization (HVP), which is constrained from the ratio $\dfrac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$

- As BES III and other colliders accumulate data on $e^+e^- \to X$, the error in HVP will decrease

- **By far, the most model dependent contribution to $a_\mu^{SM}$ is from Hadronic Light-by-Light scattering (HLbL)**

*Estimated errors in $a_\mu^{SM}$*



# Reducing experimental uncertainties in $a_\mu^{HLbL}$

- Unlike HVP, HLbL can not be reduced to simple "data-driven" forms, and must be evaluated with a combination of experimental data and hadronic models.

- By far, the largest contribution to HLbL is from the pseudo-scalar meson transition form factors: $\pi^0$, $\eta$, $\eta'$

- Due to it's low mass, the $\pi^0$-pole accounts for $\approx 2/3$ of the pseudo-scalar contribution to HLbL.

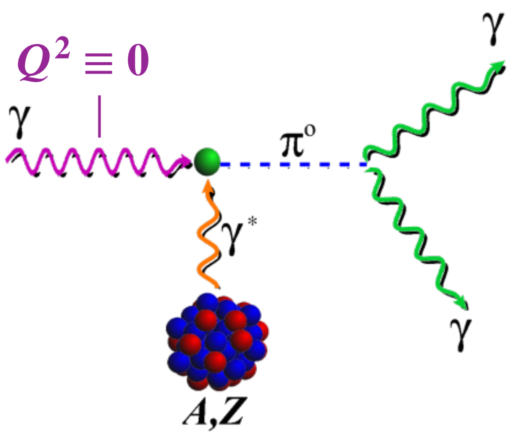
# Measuring the $\pi^0$ transition form factor in the space-like region

Primakoff neutral pion electroproduction can be used to measure the $\pi^0$ TFF measurement at low $Q^2$ values, constraining,

a. the TFF $O(Q^2)$ slope,
b. the TFF $O(Q^4)$ curvature,
c. the $\pi^0$radiative width $\Gamma(\pi^0 \to \gamma\gamma)$

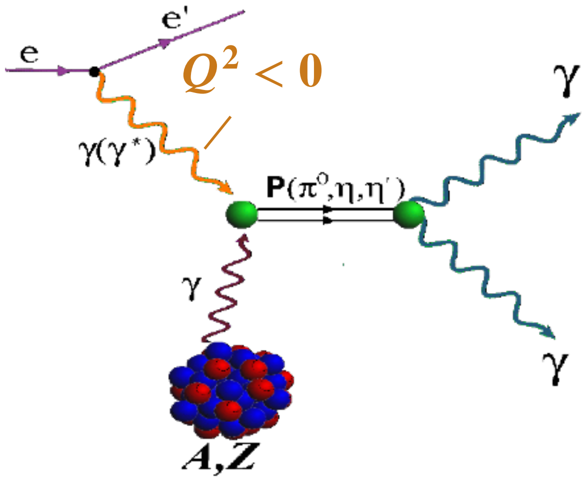
# $\pi^0$ photoproduction vs electroproduction

**Photoproduction (PrimEx-I, and II)**



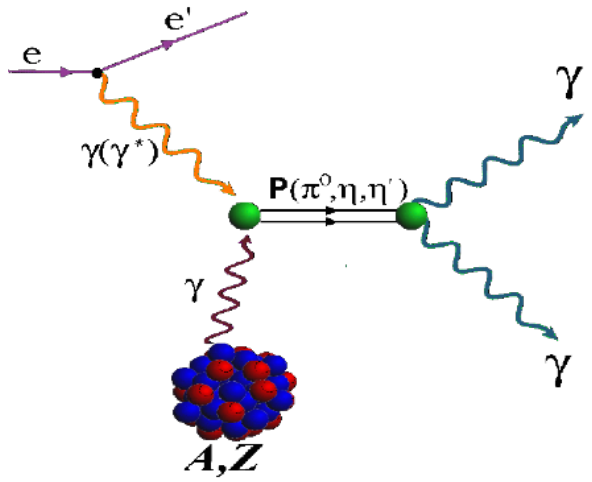

$\Gamma(\pi^0 \to \gamma\gamma)$
or $\sigma(Q^2 = 0)$,
1.5% uncertainty

**Electroproduction (proposed measurement)**




$\Gamma(\pi^0 \to \gamma\gamma)$ *and*
$\frac{d\sigma}{dQ^2}(-Q^2 = 0.003...0.3 GeV^2)$,
comparable uncertainty

# $\pi^0$ Primakoff with virtual photon beam




$$\frac{d^3\sigma_P}{dE_2 d\Omega_2 d\Omega_\pi} = \frac{Z^2\eta^2}{\pi}\sigma_M \frac{k_\pi^4}{t^2}\frac{\beta_\pi^{-1}}{E_\pi}|F_N(t)|^2 \left|\frac{F_{\gamma^*\gamma^*\to\pi^0}(-Q^2,t)}{F_{\gamma^*\gamma^*\to\pi^0}(0,0)}\right|^2 sin^2(\frac{\theta_e}{2})sin^2(\theta_\pi) \times \left[4E_1E_2 sin^2\phi_\pi + |\vec{q}|^2/cos^2(\frac{\theta_e}{2})\right]$$

TFF

TFF — radiative width — slope — curvature

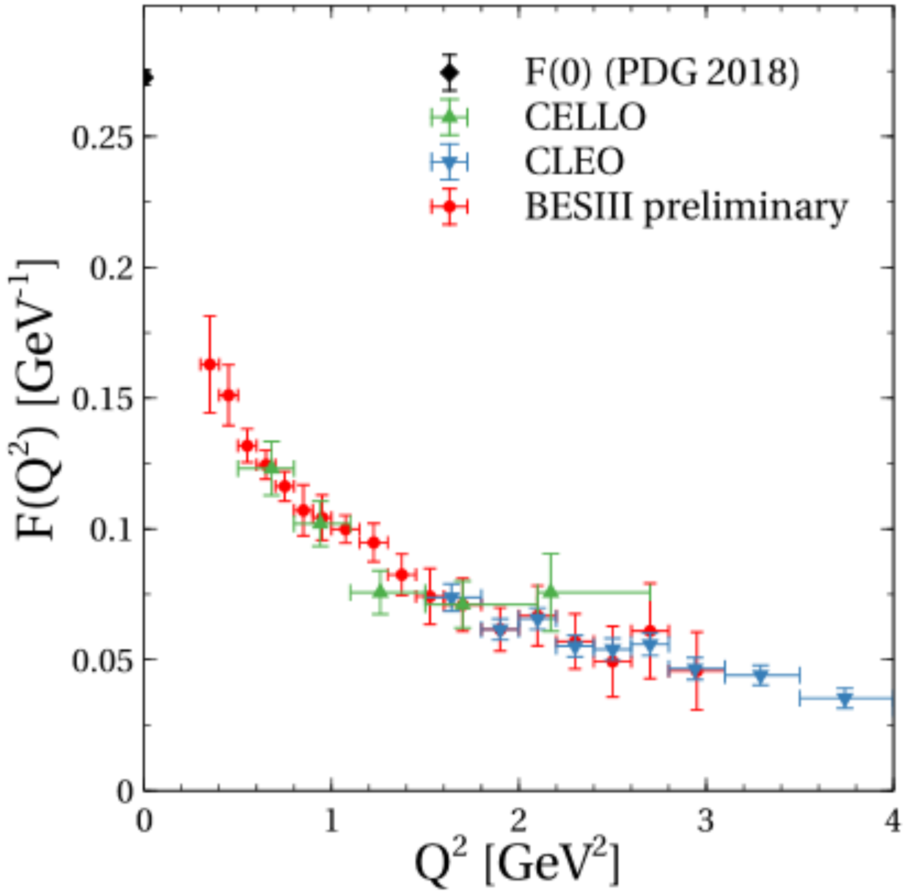
$$F_{\gamma^*\gamma^*\to\pi^0}(-Q_1^2,-Q_2^2) = \sqrt{\frac{4\Gamma_{\pi^0\to\gamma\gamma}}{\pi\alpha^2 m_\pi^3}}\left[1-\frac{a_\pi}{m_\pi^2}\left(Q_1^2+Q_2^2\right)+\frac{b_\pi}{m_\pi^4}\left(Q_1^4+Q_2^4\right)+\frac{c_\pi}{m_\pi^4}Q_1^2Q_2^2+\ldots\right]$$

Mean square electromagnetic radius of the $\pi^0 = <r^2>_{EM} = 6\frac{a_\pi}{m_\pi^2}$

# Previous $\pi^0$ TFF Measurements in the space-like region

| Experiment | Method | $Q^2$ range, [$GeV^2$] |
|---|---|---|
| CELLO | | 0.7-2.2 |
| CLEO | | 1.6 - 8 |
| BES III | | 0.3 -3.1 |
| Belle | | ~ 4 - 40 |
| BABAR | | ~ 4 – 40 |
| NA 62 | Dalitz decay | |
| A2 | | |

The lowest $Q^2$ $\pi^0$ TFF data collected in the space-like region to date



# The Jefferson Lab $\pi^0$ TFF measurement

- The $\pi^0$TFF measurement was approved by Jefferson Lab PAC-50 for running in Hall-B (E12-22-006)
- Experimental conditions: 10.5 GeV beam energy, 10 nA beam current , 250 micron thick silicon-28 target, using the PRad experimental setup, and running time of 67 days
- Experiment has sensitivity to the $\pi^0$ TFF over the $Q^2$ range 0.003 to 0.3GeV$^2$ , allowing for a clean determination of the TFF parameters and excellent sensitivity to $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

# JLab $\pi^0$ TFF collaboration

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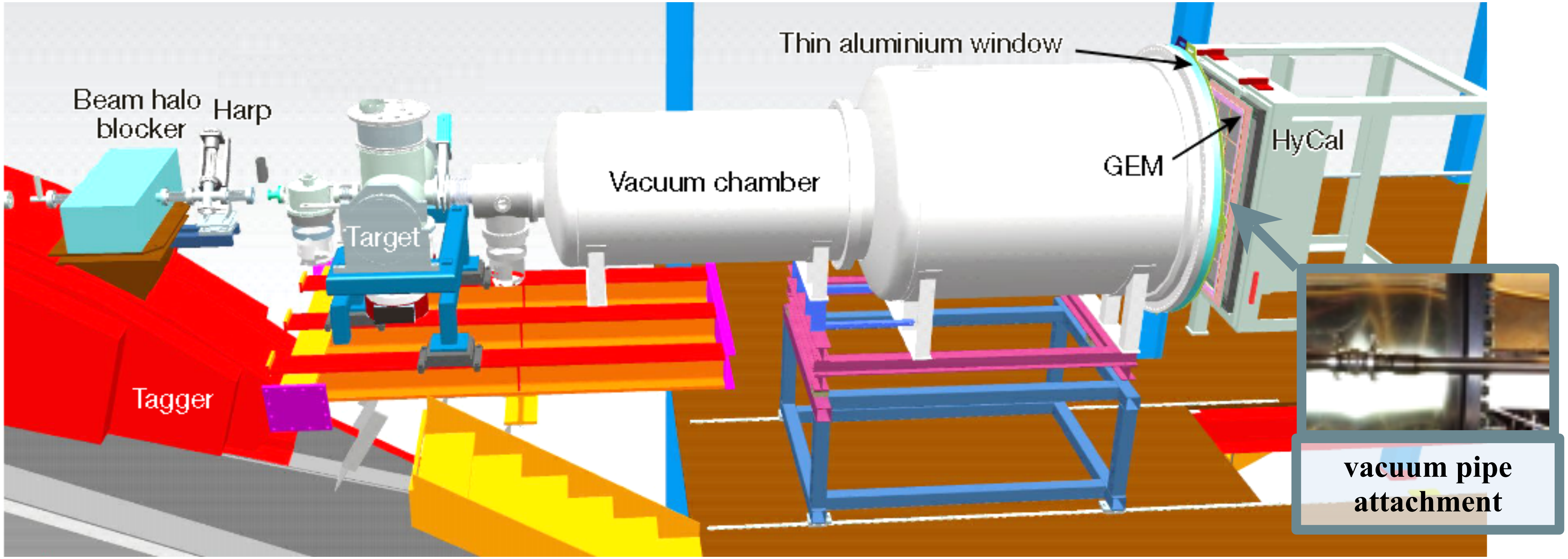
**New experimental and theoretical collaborators are very welcome!**

# Plan to use the PRad experimental setup

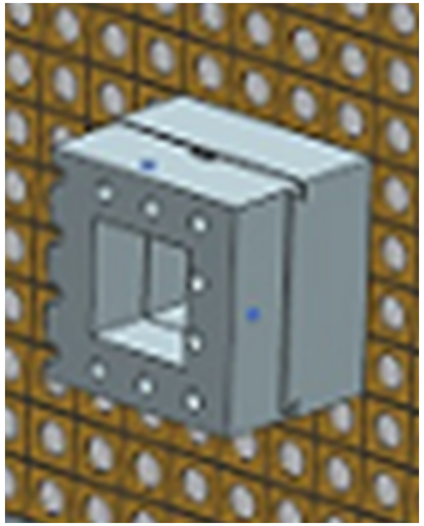



**The existing ultra low background PRad setup with high resolution EM calorimeter, vacuum chamber, and GEM detector fits our experimental requirements very well**

# Modifications to the existing PRad setup

- New target and target chamber: solid silicon target 250 μm thick replaces the PRad hydrogen gas cell

- New tungsten absorber covering the two inner HYCAL layers, instead of one as in PrimEx, and PRad, with twice the thickness



- Add a second GEM detector in front of the calorimeter for identifying charged tracks

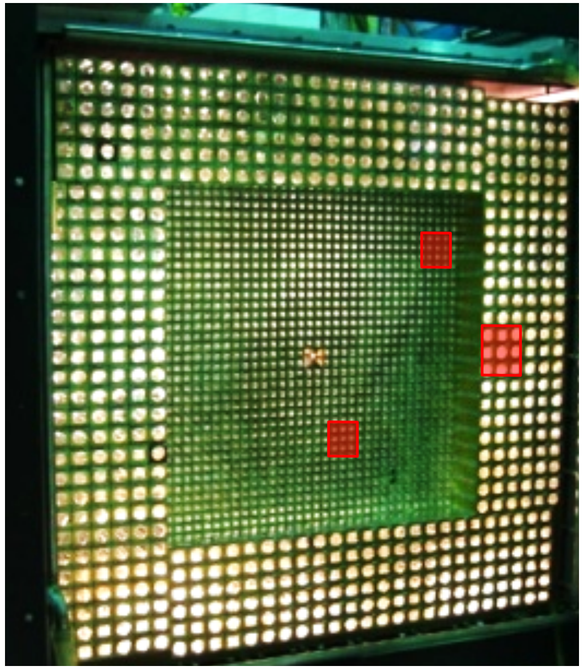
- Event triggering based on detection of 3 clusters of energy in the calorimeter

# High resolution calorimeter

- The final state particles will be detected with the high resolution HYbrid electromagnetic CALorimeter (HYCAL): the lead-tungstate insert has energy and spatial resolutions of $\frac{2.7\%}{\sqrt{E[GeV]}}$ and $\frac{2.5mm}{\sqrt{E[GeV]}}$

- Two GEM detectors will be used to improve electron hit coordinate resolution to *~0.07mm* value or better. They will also reduce charged background in $\pi^0$ candidate selection.

High resolution hybrid electromagnetic calorimeter HYCAL



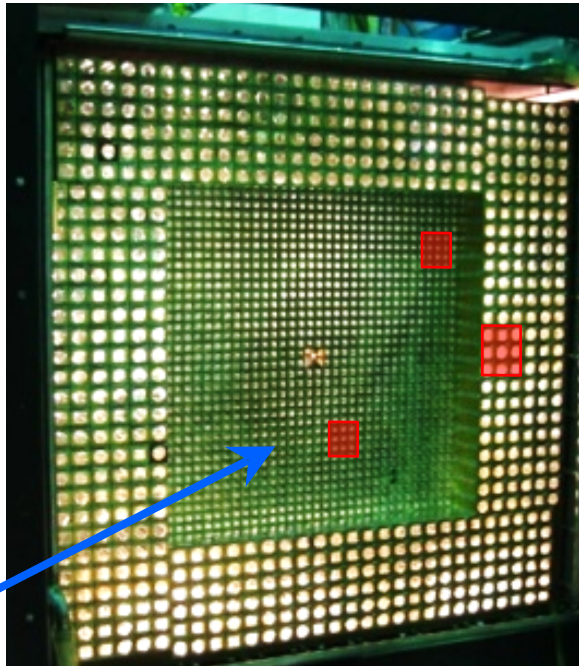
# Event trigger

- The total energy sum trigger used in the PrimEx and PRad experiments gives a rate of ~250 kHz for a 4 GeV threshold, which is too high for the DAQ

- Use "intelligent" 3-cluster trigger, requiring three clusters of energy in groups of 3x3 modules in HYCAL, with minimum energy of 0.3 GeV in each cluster, and total energy deposition of 4 GeV. Estimated trigger rate ~20 kHz.

- Upgrade the 1,728 lead-glass and lead tungstate blocks in HYCAL with JLab FADC-250 electronics, which supports a programmable trigger of this type.

**High resolution hybrid electromagnetic calorimeter HYCAL**

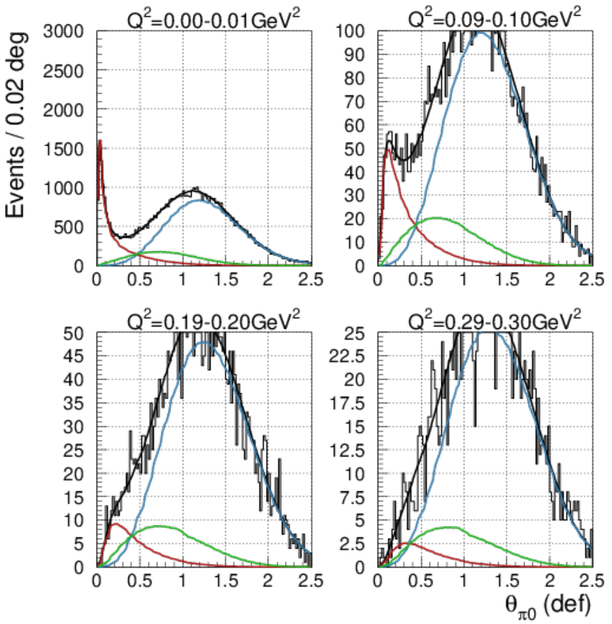


"typical" $\pi^0$ TFF event showing hits from $e^-\gamma\gamma$

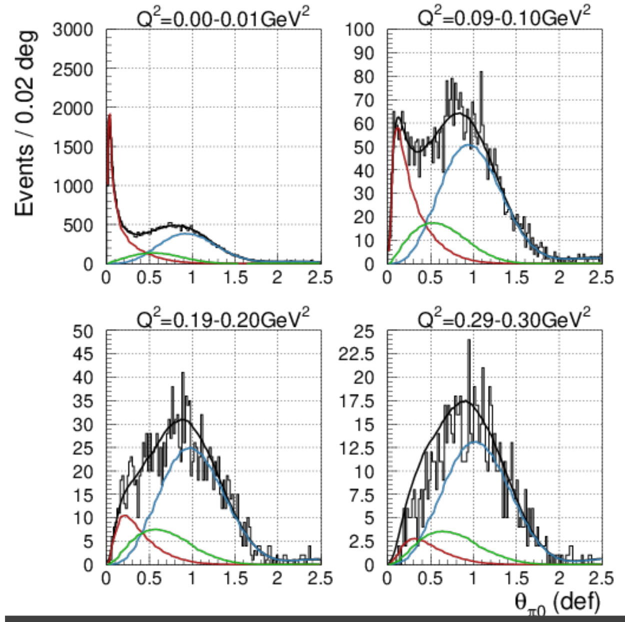
# Choice of target: $^{28}Si$

- $J^{\pi} = 0^{+}$ targets tested tested in simulation: $^{12}C$, $^{28}Si$, $^{40}Ar$, $^{98}Mo$, $^{108}Pd$, $^{196}Pt$, and $^{208}Pb$

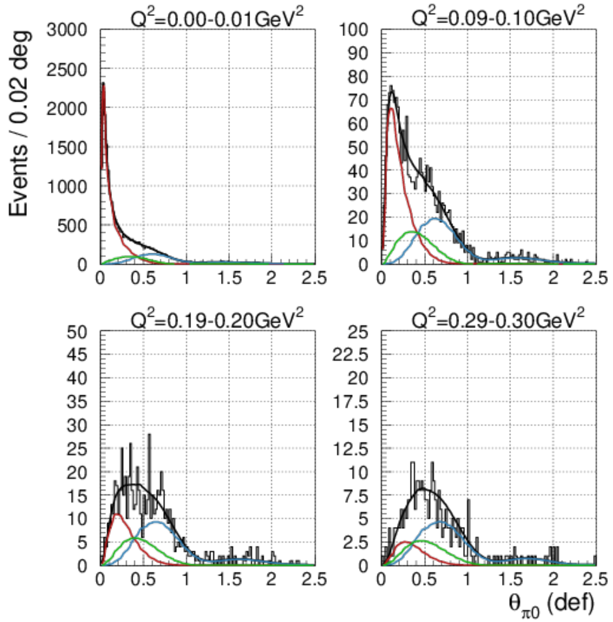
**$^{12}C$**




**$^{28}Si$**



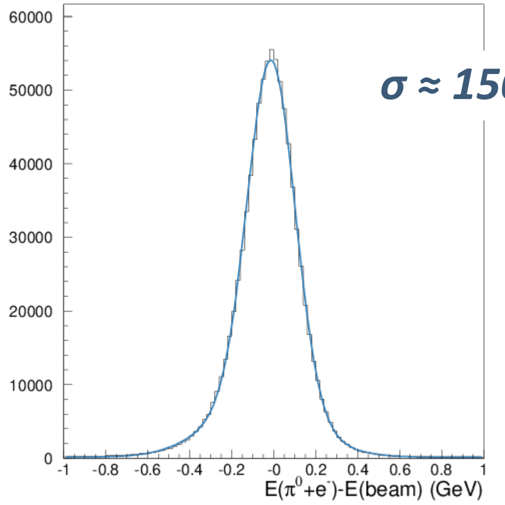

**$^{108}Pd$**




**the best production mechanism resolution**

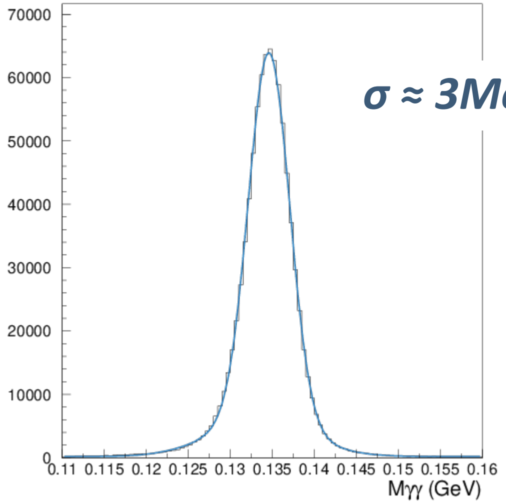
# Detector resolutions

*Energy conservation*



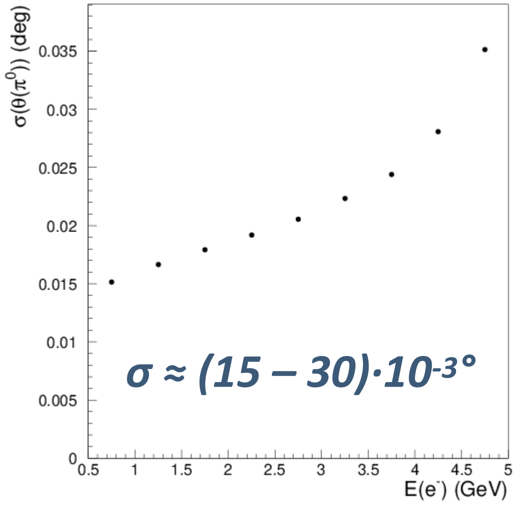

σ ≈ 150MeV

*Pion mass*



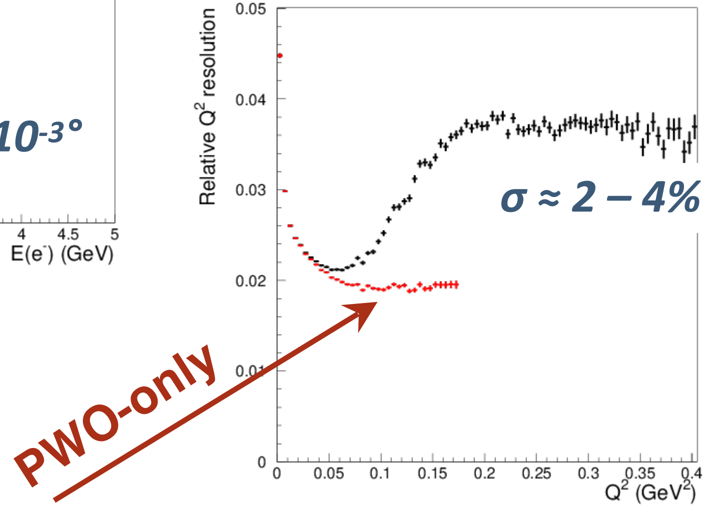

σ ≈ 3MeV

*Pion angle in the Q-vector frame vs scattered electron energy*



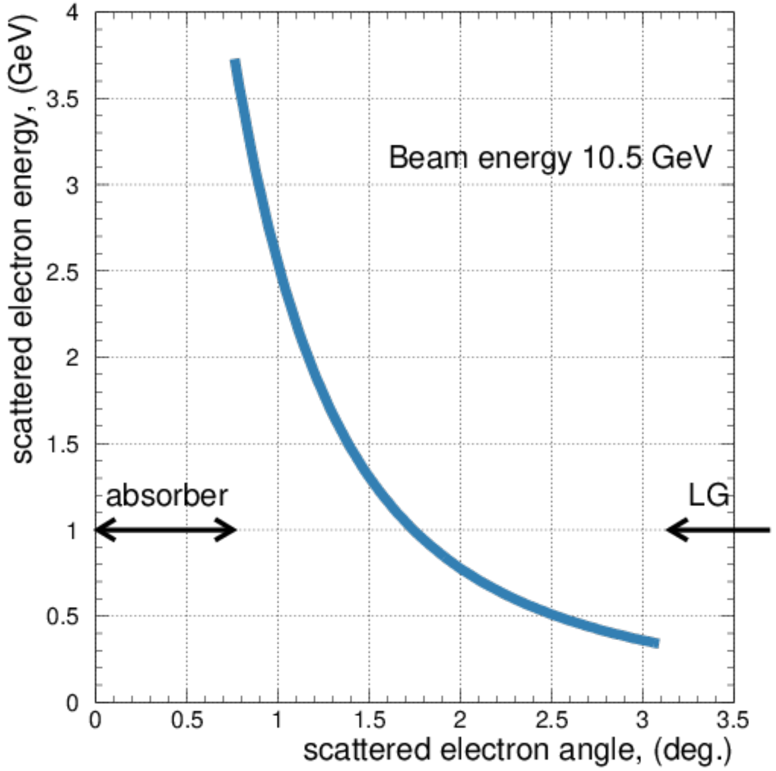

$\sigma \approx (15 - 30) \cdot 10^{-3\circ}$

*Relative $Q^2$ resolution vs $Q^2$*




σ ≈ 2 – 4%

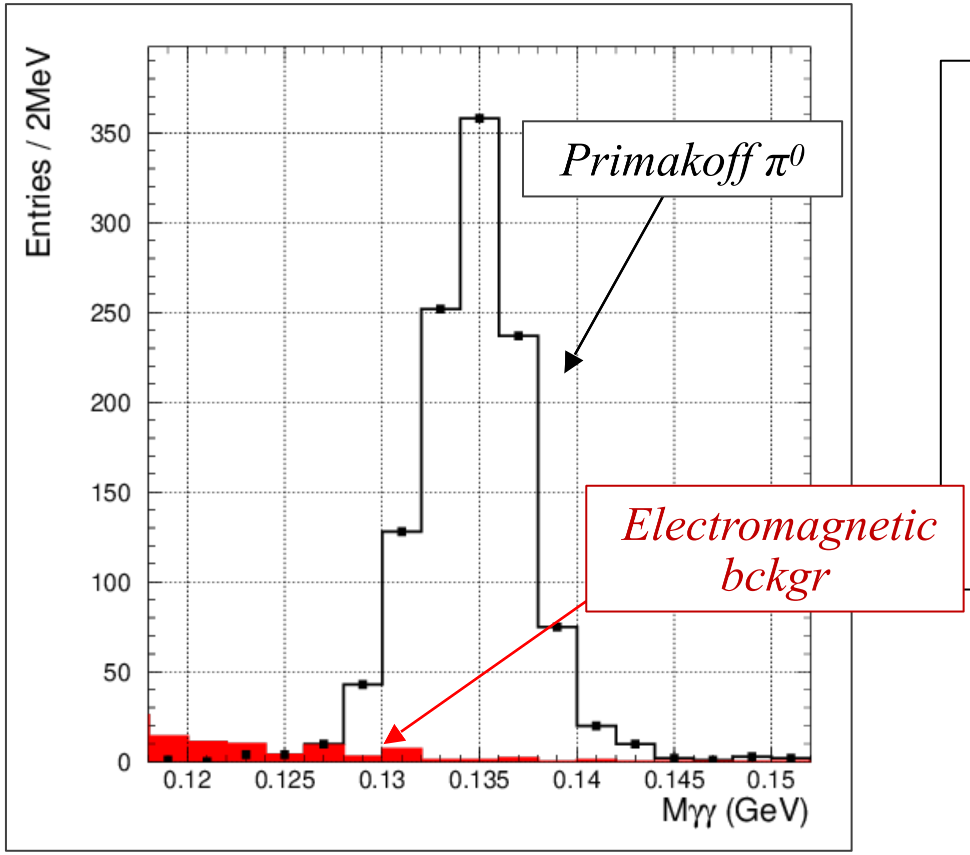
# Luminosity control and calibration through "single-arm" Moller scattering




- **Møller scattering, i.e. electron-electron scattering will be used for additional luminosity control and calibration.**
- **The setup has an excellent acceptance for the "single-arm" (one electron detected) Møller scattering.**
- **A simple prescaled "Møller" trigger will be added to the data stream.**

# $\gamma\gamma$ invariant mass spectrum with GEM detector rejection of charged tracks

*1 day of running*

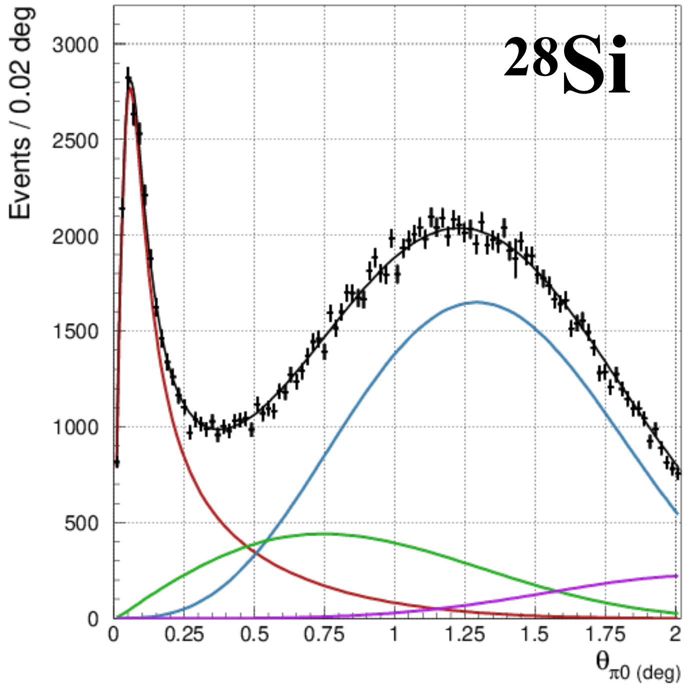



- **Direct electromagnetic background effectively suppressed by GEM detectors, timing and energy conservation.**
- **The main contribution from hadronic background is $\pi^0$ and ω photoproduction from bremsstrahlung in target. We estimate this contribution to be at 0.5% level compared to Primakoff electroproduction.**

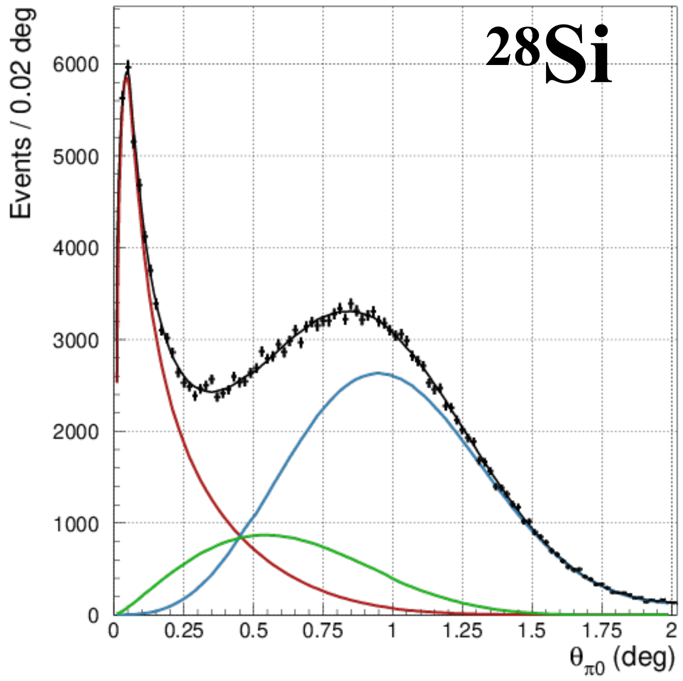
# Expected Yield vs $\pi^0$ production angle

*Photoproduction at 5 GeV (PrimEx)*

*Electroproduction at 10.5 GeV (current proposal)*




- Primakoff
- Strong Coherent
- Interference



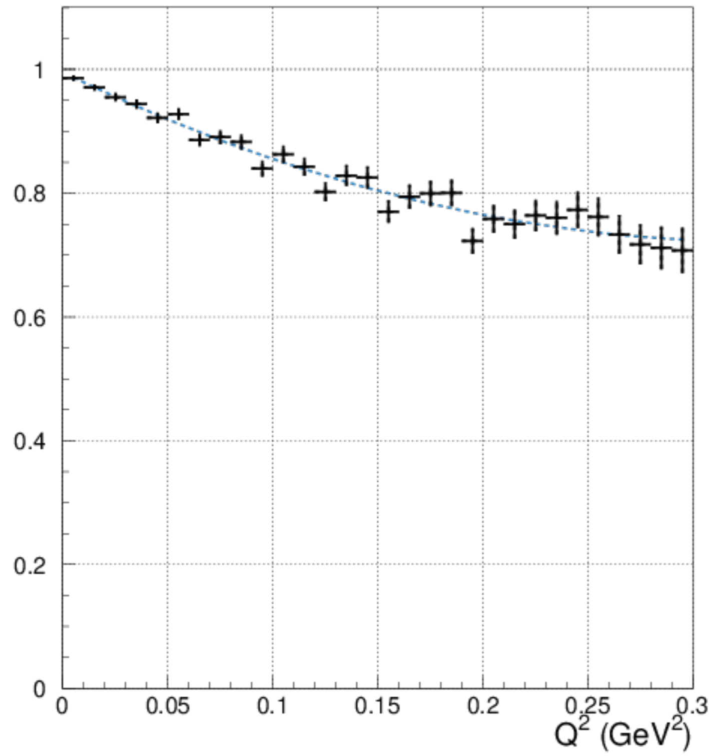

- PrimEx-II: ~<u>33K Primakoff</u> events on silicon and 9K events on carbon targets
- Proposed experiment: ~<u>70K Primakoff</u> events on silicon target

# Expected statistical uncertainties

**Expected statistical uncertainties and comparison with experimental data**

- TFF $O(Q^2)$ slope term ~6%
  vs. 15% for NA62 and 33% for A2
- TFF $O(Q^4)$ curvature term ~17%
  no measurement
- radiative width $\Gamma(\pi^0 \to \gamma\gamma) \approx 0.7\,\%$
  vs. 0.8% for PrimEx II

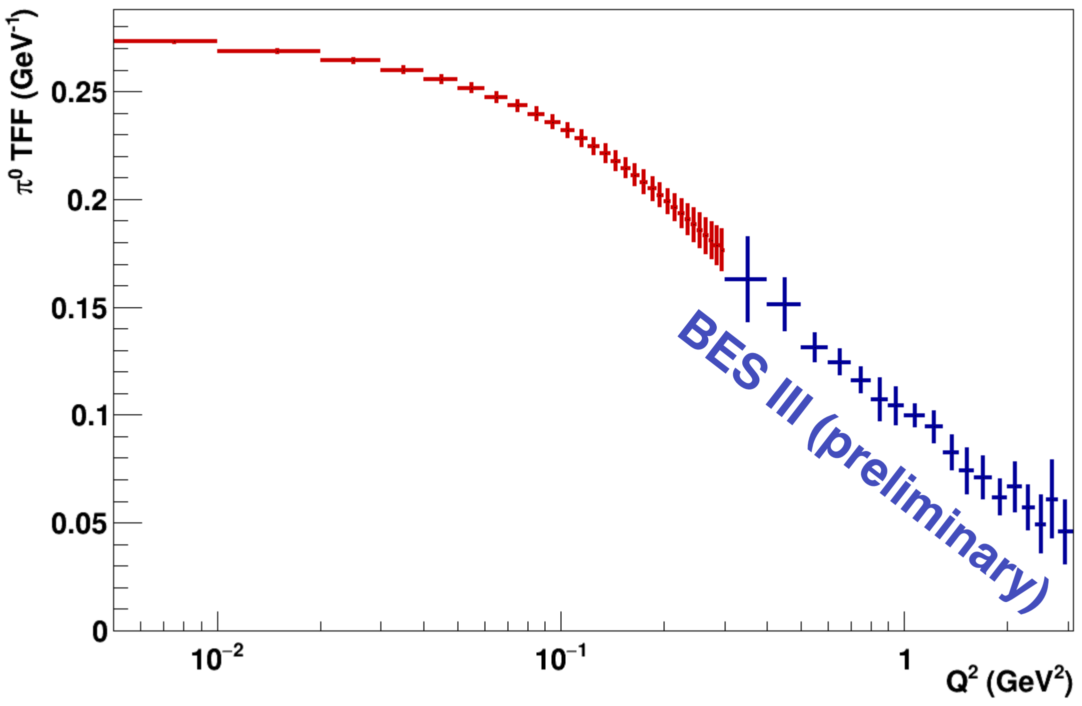
*Expected $\pi^0$ TFF points vs $Q^2$*



$\Gamma(\pi^0 \to \gamma\gamma)_{PrimEx}$ $\Gamma(\pi^0 \to \gamma\gamma)_{TFF}$

| Item | photoproduction (Si target, PrimEx-II) | electroproduction (this proposal) | TFF slope | TFF quadrature term |
|---|---|---|---|---|
| Yield extraction | 0.93% | 0.7% (vac. box) | 0.7% | 0.7% |
| Beam flux | 0.8% | 0.8% | none | none |
| Production model | 0.45% | 0.45% | 0.45% | 0.45% |
| Acceptance | 0.6% | 0.7% | 0.7% | 0.7% |
| Target | 0.35% | 0.4% | none | none |
| Event selection | 0.2% | 0.4% | 0.4% | 0.4% |
| Trigger | 0.1% | 0.1% | 0.1% | 0.1% |
| Rad. corrections | <0.1% | <0.1% | <0.1% | <0.1% |
| High order terms | none | 0.1% | 2% | 10% |
| Syst. | 1.4% | 1.4% | 2.4% | 10% |
| Stat. | 0.8% | 0.7% | 6% | 17% |
| Total | 1.6% | 1.6% | 6.5% | 20% |

# Expected data points and $a_\mu^{\pi^0-pole}$




Evaluation of $a_\mu^{\pi-pole}$ shows that the statistics and $Q^2$ range of the JLab experiment will enable measurement of ~2/3 of the $\pi^0$-pole contribution to HLbL, with an estimated uncertainty of ~5%

# Outlook for running $\pi^0$ TFF at JLab

- $\pi^0$ TFF will need upgrades in three areas: (1) beamline, (2) 2nd GEM detector, and (3) HYCAL readout electronics

  while at the same time…

- a significant program is planned for running HYCAL in JLab Hall B:
  a. PRad-2 proton charge radius measurement. Approved with A rating
  b. DRad deuteron charge radius measurement. Resubmitted to PAC
  c. X17 search experiment. Approved with A rating

- Jefferson Lab management is working to find resources to build these experiments, and is planning for an extended run period of one year or longer to sequentially run them.

# Summary

- The largest model-dependence in *(g-2)*$_{SM}$ is associated with HLbL, and the largest single contribution to HLbL is the $\pi^0$-pole term. We conclude that precision low-Q$^2$ data on the $\pi^0$TFF are needed to calibrate and test lattice QCD and dispersion model calculations of HLbL
- The JLab $\pi^0$ TFFexperiment will be make a precision measurement of the $\pi^0$ TFF in the low Q$^2$ space-like region Q$^2$ = .003 to 0.3 GeV$^2$, and provide a measurement of $\Gamma(\pi^0 \to \gamma\gamma)$ comparable in statistical precision to the PrimEx-II result

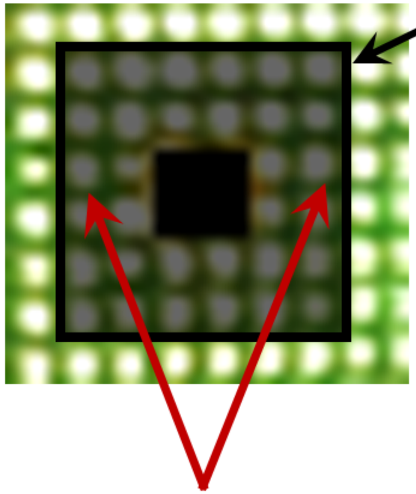
Many thanks to the JLab $\pi^0$ TFF collaboration, esp. Ilya Larin,
to the organizers of this conference,
and to the audience for your attention!

# Spare slides

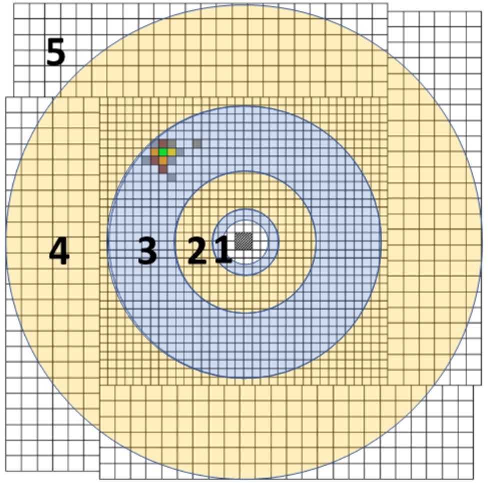
For event simulation we use the VMD+V transition form factor

# Moller background rates in the calorimeter

*"symmetric" Moller event in the central region:*

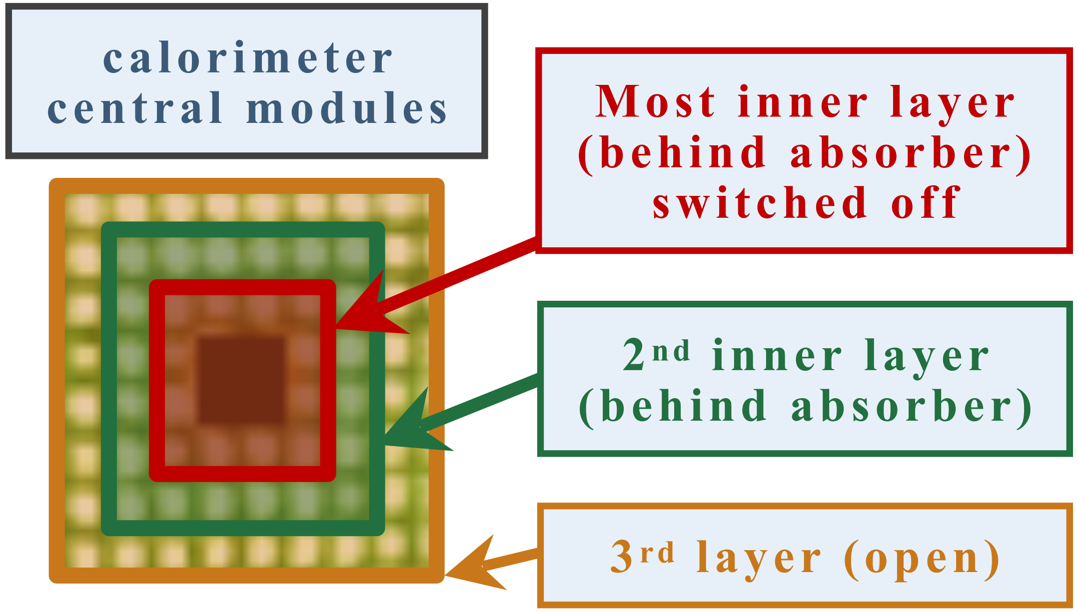



| Zone | Møller angle in the CM frame [rad] | Møller angle in the lab frame [deg] | Calorimeter hit to beam-line distance [cm] | Electron energy range [GeV] | Integrated Møller rate [kHz] | Maximum Møller event per module rate [kHz] |
|---|---|---|---|---|---|---|
| 1* | 1.47 1.93 | 0.49 0.79 | 5 8 | 5.77 3.33 | 15 | 1.2 |
| 2 | 1.93 2.5 | 0.79 1.7 | 8 17.2 | 3.33 1.05 | 190 | 1.5 |
| 3 | 2.5 2.8 | 1.7 3.25 | 17.2 33 | 1.05 0.3 | 630 | 1.3 |
| 4 | 2.8 2.95 | 3.25 5.9 | 33 60 | 0.3 0.095 | 1940 | 3.5 |
| 5 | 2.95 3.00 | 5.9 8.2 | 60 84 | 0.095 0.045 | 400 | 2.2 |



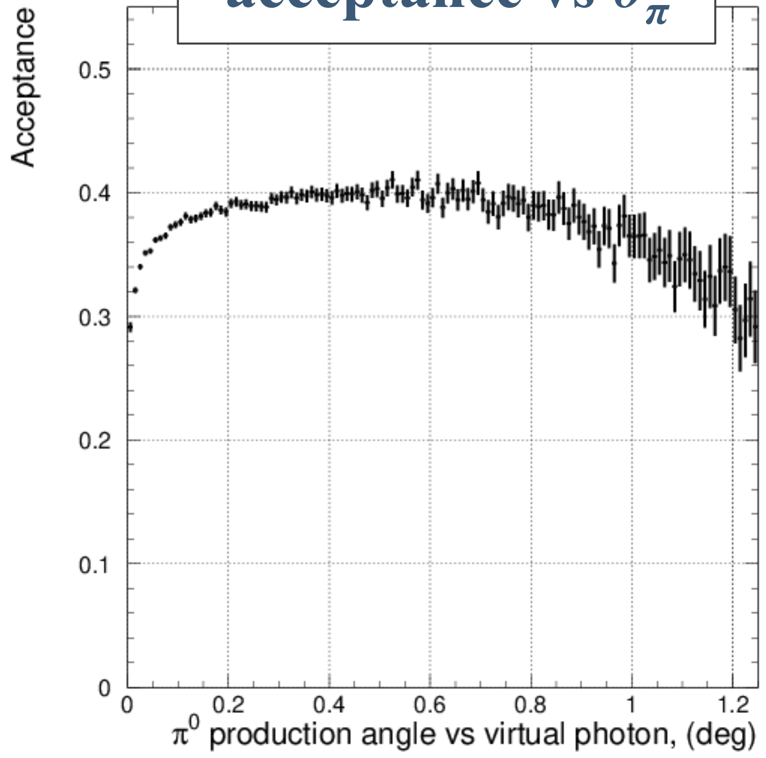
# Radiation dose to the calorimeter

- We estimate radiation dose to the calorimeter modules as 8 - 10 rad/hr for the most inner layer, and 4 - 6 rad/hr for the 2nd and 3rd layers. For other layers the dose decreases fast with the distance from the beamline. That may cause ~2 - 5% degradation in transparency and light yield and time reversable
- The calorimeter module rates in the most inner layer expected to be ~2 MHz, and within 200 kHz in the 2nd and 3rd layers. The most inner layer needs to be switched off
- The absorber size is increased by a factor of 1.5 in width and twice in thickness in comparison with the used in PrimEx and PRaD

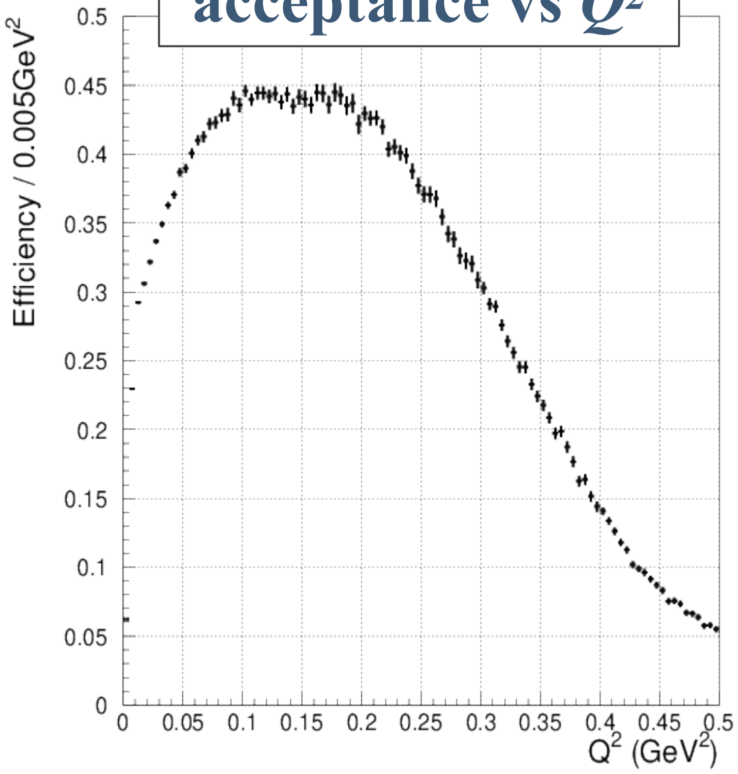


# Acceptance

acceptance vs $\theta_\pi$




acceptance vs $Q^2$




**Typical setup acceptance for virtual Primakoff production ~0.3**