Update on the π^0 Transition Form Factor Measurement in the Space-like Region

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All members of the PRad and X17 collaborations are invited to join the π^0 TFF experiment

PRad collaboration meeting, Sept. 12, 2025

JLab π^0 TFF collaboration

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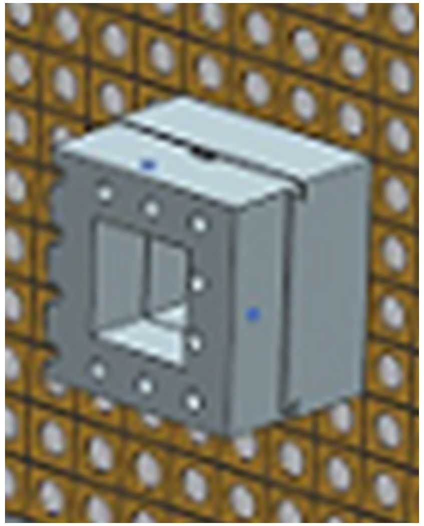
Overview of the Jefferson Lab π^0 TFF measurement

- The π^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

Modifications to the X17 setup

- Target: silicon target 250 μm thick

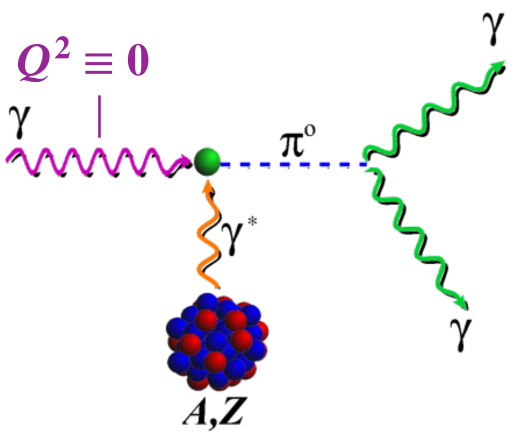
- New tungsten absorber covering the two inner HYCAL layers, instead of one as in PrimEx and with twice the thickness, and the inner-most HYCAL layer turned off



- Event triggering based on detection of 3 clusters of energy in groups of 3x3 modules in the calorimetor, with minimum energy of 0.3 GeV in each cluster, and total energy deposition of 4 GeV. Estimated trigger rate ~20 kHz.

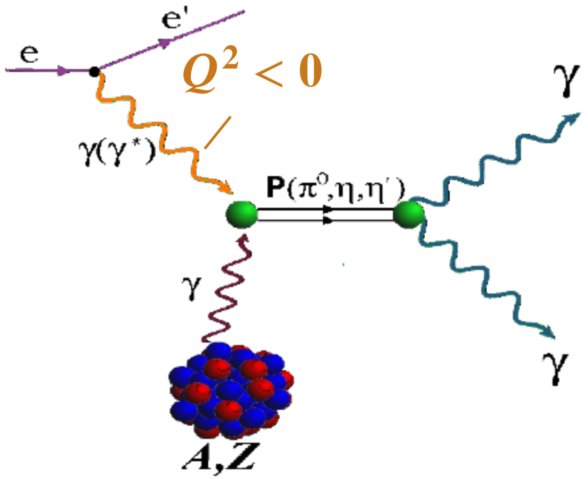
Primakoff π⁰ photoproduction vs electroproduction

Photoproduction (PrimEx-I, and II)



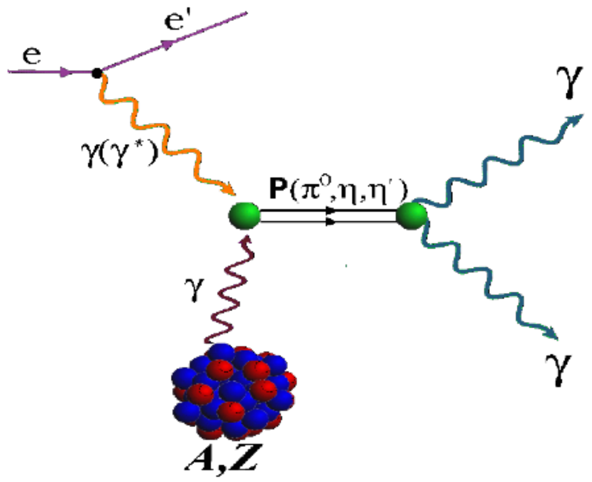
$\Gamma(\pi^0 \to \gamma\gamma)$
or $\sigma(Q^2 = 0)$,
1.5% uncertainty

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

π^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

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

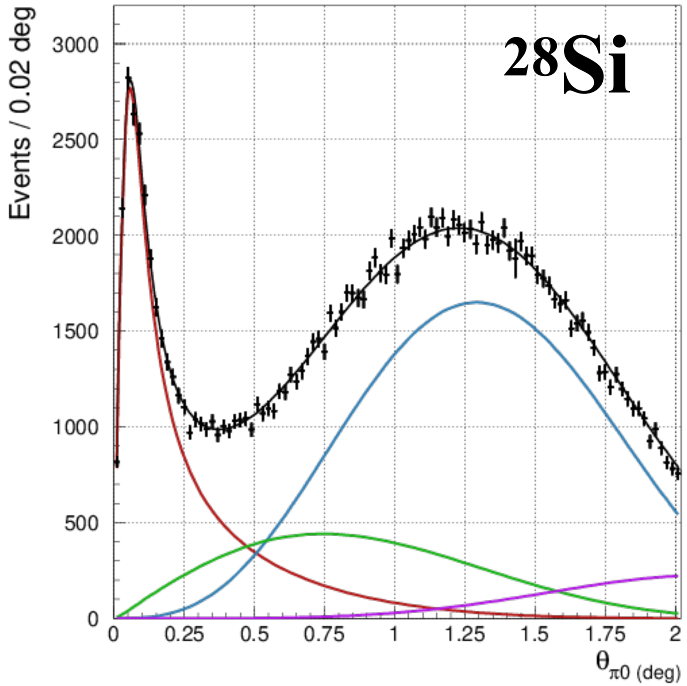
Neutral pion mean square electromagnetic radius $< r^2 >_{\pi^0} = 6\frac{a_\pi}{m_\pi^2}$

Expected Yield vs π^0 production angle

Photoproduction at 5 GeV (PrimEx)

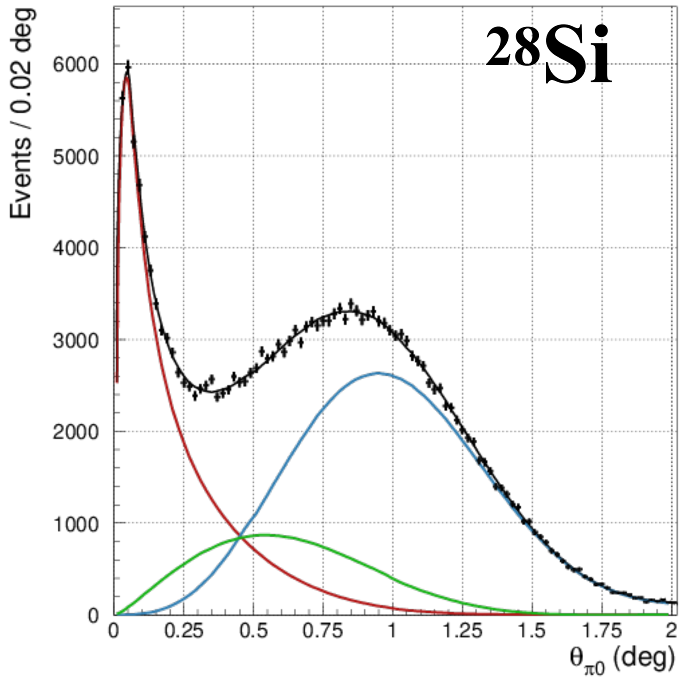
Electroproduction at 10.5 GeV (current proposal)

- Primakoff
- Strong Coherent
- Interference



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

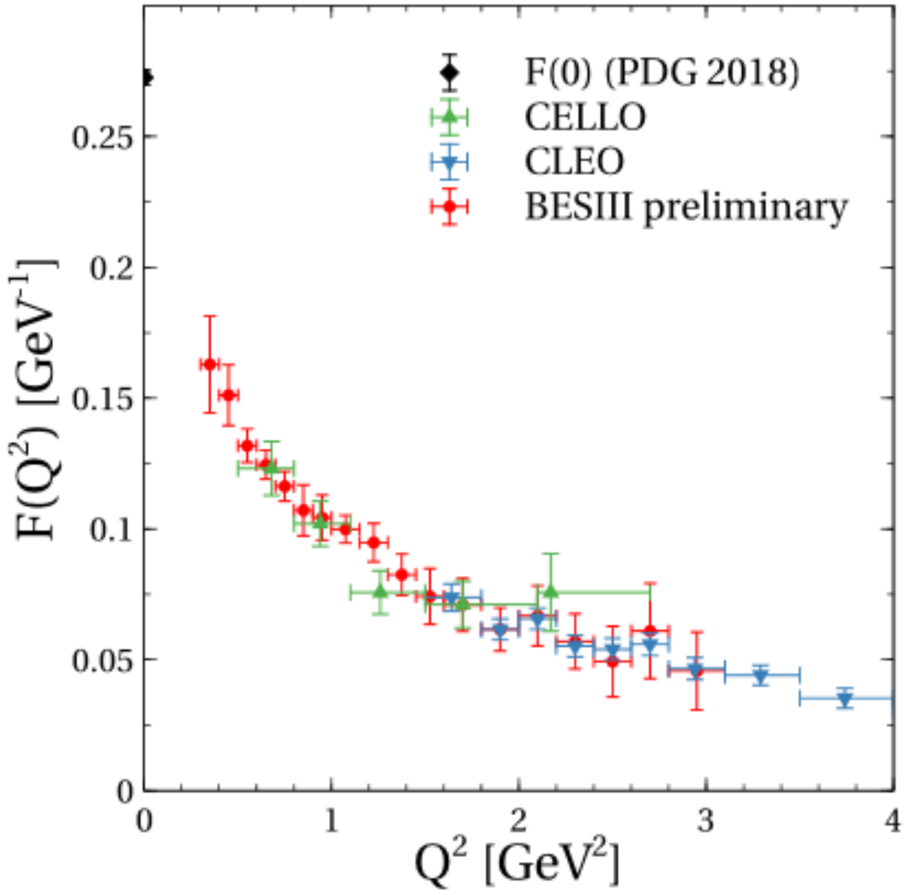
- Proposed experiment: ~<u>70K Primakoff </u>events on silicon target



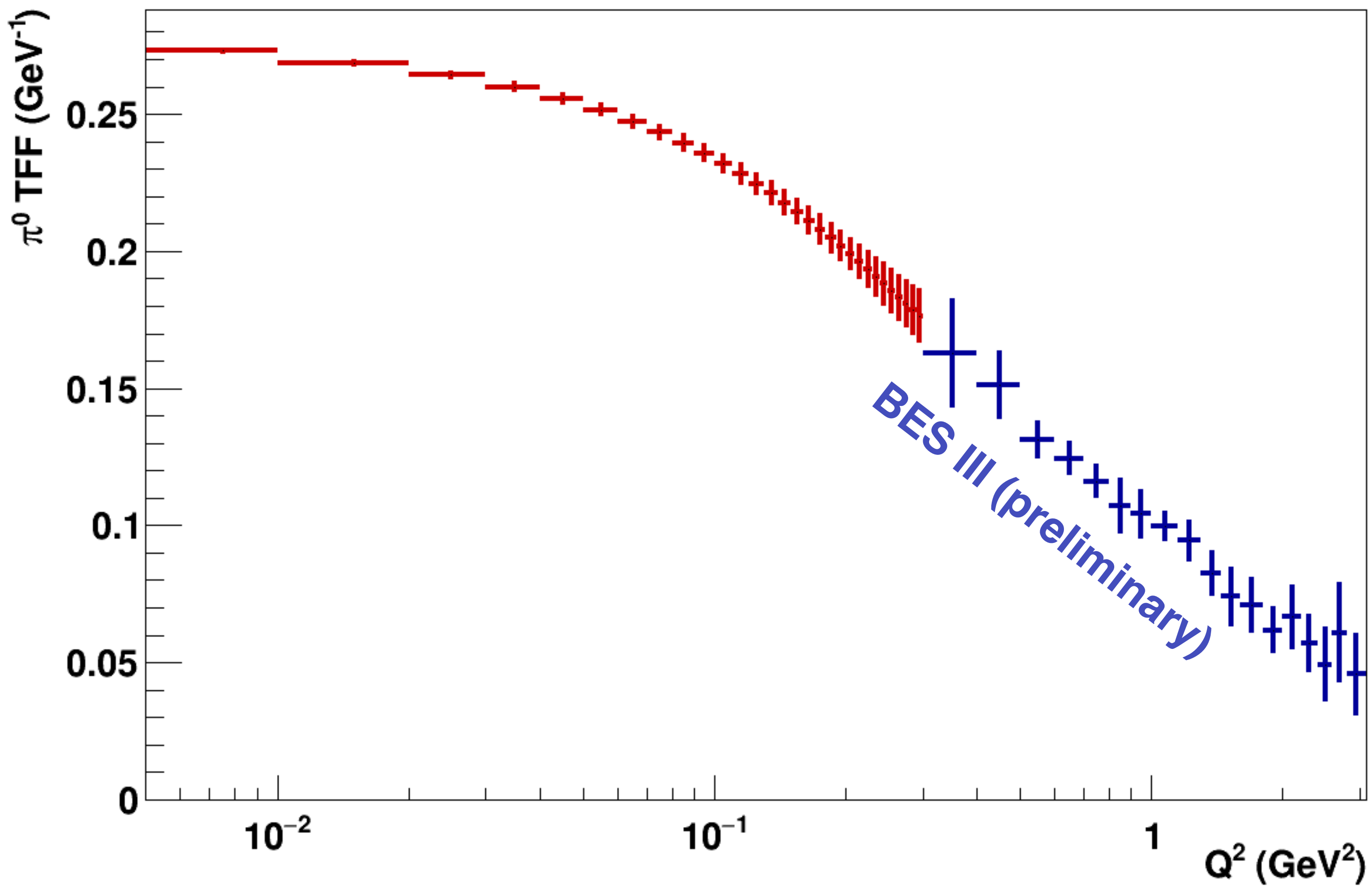
Previous π^0 TFF Measurements in the space-like region

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 π^0 TFF data collected in the space-like region to date



Projected data points



If the PbG in HYCAL is not available for use, then we would be limited to a maximum of Q^2 of approximately 0.1 to 0.15 GeV^2, still with good statistics

Projected results for the experiment

- π^0 radiative width $\Gamma(\pi^0 \to \gamma\gamma)$, with projected error of $0.7(1.4)\,\%$ stat(sys). This is comparable to the PrimEx I + II combined result, where there's a $\approx 2\sigma$ discrepancy between experiment and predictions.

- π^0 electromagnetic transition radius with projected error of $3\,\%$. The uncertainty in the PDG average is $6\,\%$, which I believe is underestimated.

- Provide data to constrain calculations of the hadronic light-by-light (HLbL) scattering correction to the muon anomalous magnetic moment, a_μ^{HLbL}

Reducing experimental uncertainties in a_μ^{HLbL}

- HLbL can not be reduced data-driven forms, and must be evaluated with a combination of experimental data, hadronic models, and LQCD

- By far the largest contribution to HLbL is from the pseudo-scalar meson transition form factors: π^0, η, η'

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

- The TFF measurement will constrain approximately 65% of the π^0-pole contribution to a_μ^{HLbL} with an accuracy of $\approx 6\,\%$

Update on the muon anomalous magnetic moment $(g-2)_\mu$

- The Muon g-2 collaboration published their latest and final result this past summer, and **the new measurement for a_μ agrees with previous measurements.**

- Early this year the Muon g-2 Theory Initiative released White Paper 2025, WP-25, with significant updates to their prediction for a_μ^{SM}. The WP's evaluate three classes of theoretical corrections to muon g-2, which ranked from smallest to largest are,

  1. Electro-weak
  2. Hadronic light-by-light scattering (HLbL)
  3. Hadronic vacuum polarization (HVP)

- The biggest change from WP20 to WP25 is the use of lattice-QCD (LQCD) calculations for calculating HVP, and **not data-driven dispersion techniques** which use as input the ratio,

$$\frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

where WP25 found tensions among the experimental data sets

Present status for muon $(g-2)_\mu$

- The Fermi Lab experiment has concluded, and the final published result is consistent with the previous value
- **There is no tension between experiment and theory when using LQCD calculations for HVP**
- The source of the discrepancy between LQCD and data-driven dispersion calculations for HVP is being investigated

Final thoughts

All members of the PRad and X17 collaborations are invited to join the π^0 TFF experiment

Contact person: Ilya Larin

It would be very efficient for JLab and the collaboration to schedule the running of TFF soon after X17 completes data taking.

Spare slides

Expected statistical uncertainties

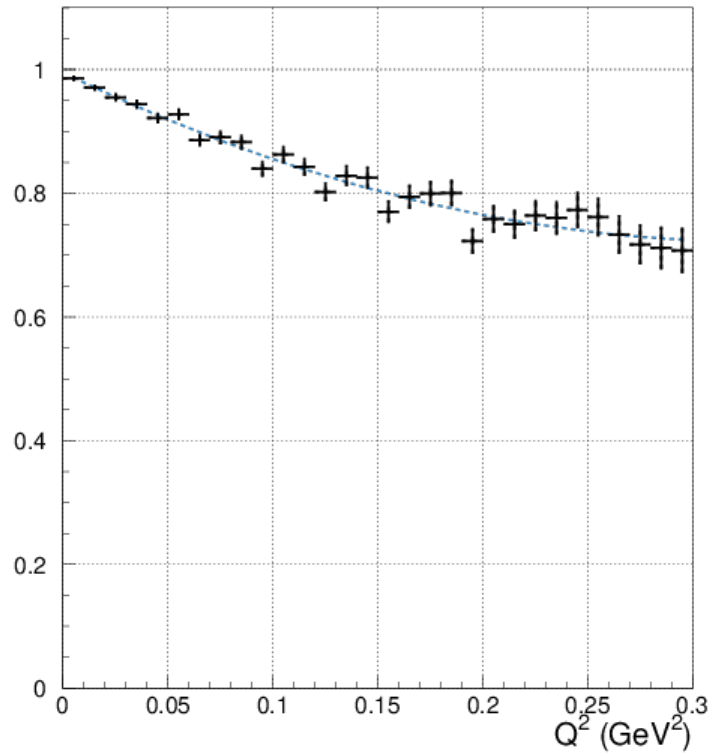
Expected statistical uncertainties and comparison with experimental data

- TFF $O(Q^2)$ slope term ~6%
  vs. 15% for NA62 and 33% for A2

- TFF $O(Q^4)$ curvature term ~17%
  no measurement

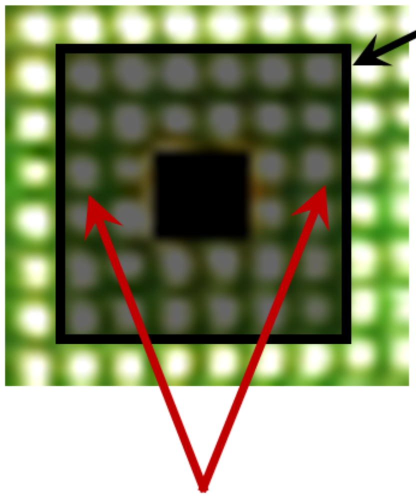
- radiative width $\Gamma(\pi^0 \to \gamma\gamma) \approx 0.7\,\%$
  vs. 0.8% for PrimEx II

Expected π^0 TFF points vs Q^2

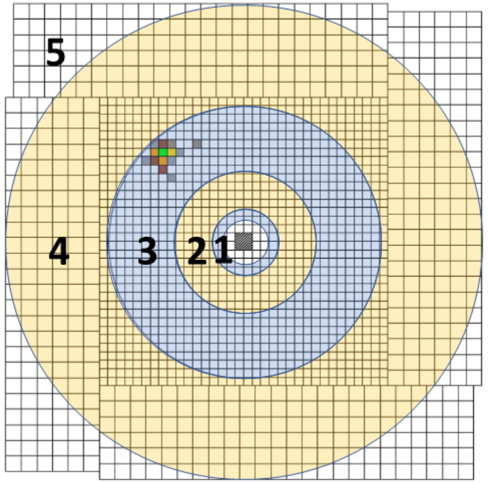


Moller background rates in the calorimeter

“symmetric” Moller event in the central region:



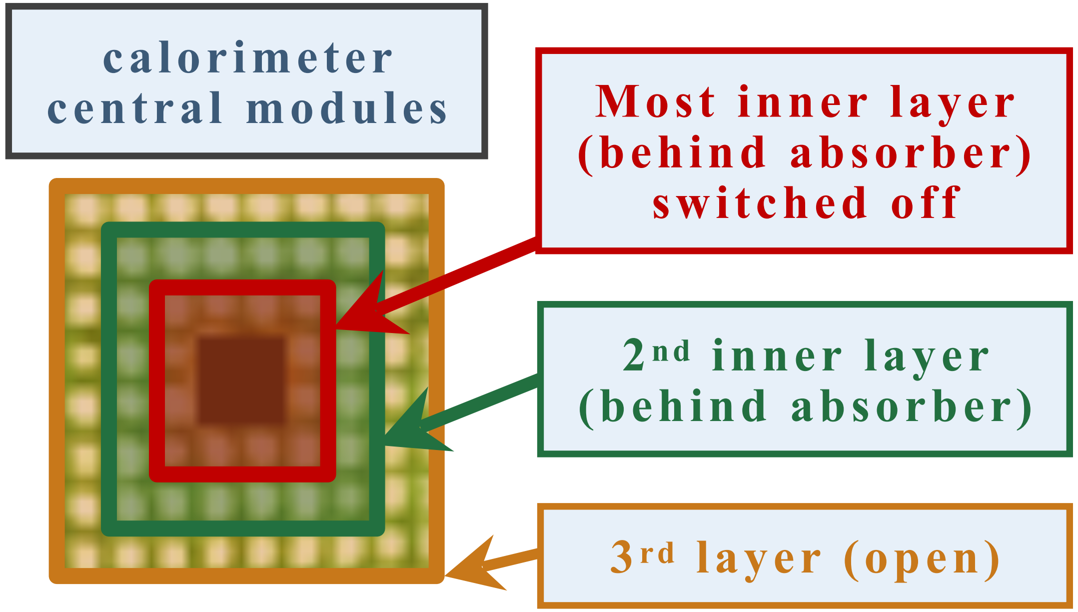
Zone	Møller angle in the CM frame [rad]	Møller angle in the lab frame [deg]	Calorimeter hit to beam-line distance [cm]	Electron energy range [GeV]	Integrated Møller rate [kHz]	Maximum Møller event per module rate [kHz]
1*	1.47 1.93	0.49 0.79	5 8	5.77 3.33	15	1.2
2	1.93 2.5	0.79 1.7	8 17.2	3.33 1.05	190	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



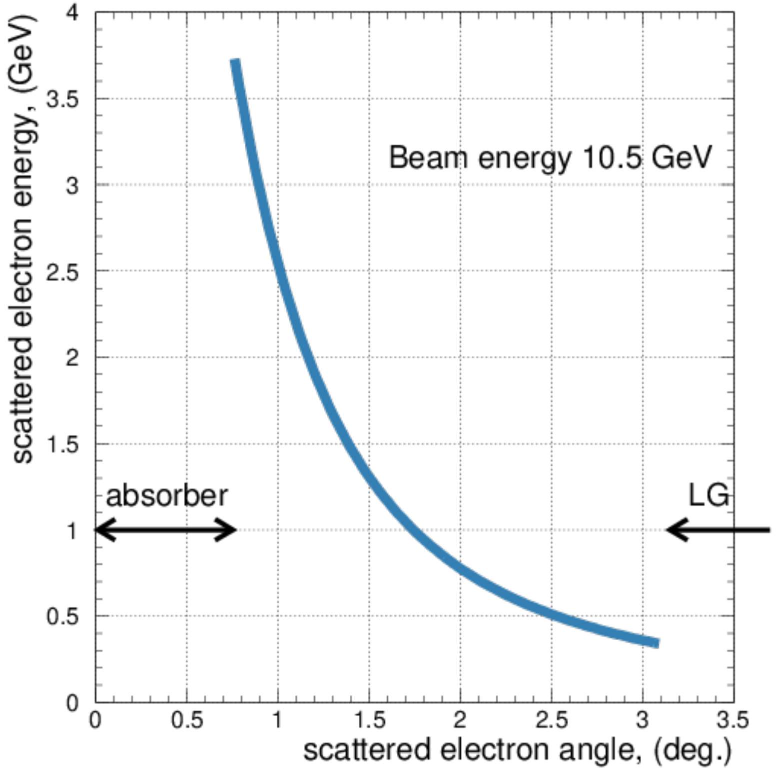
Radiation dose to the calorimeter

- 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



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.