PR12-22-003: Precision Measurement of the Neutral Pion Transition Form Factor

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for the pi0 TFF collaboration

JLab PAC 50, July 2022

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Outline

- Physics motivation and previous measurements
- The experimental setup and trigger
- Resolutions and acceptance
- Signal and background yields
- Uncertainties
- Summary

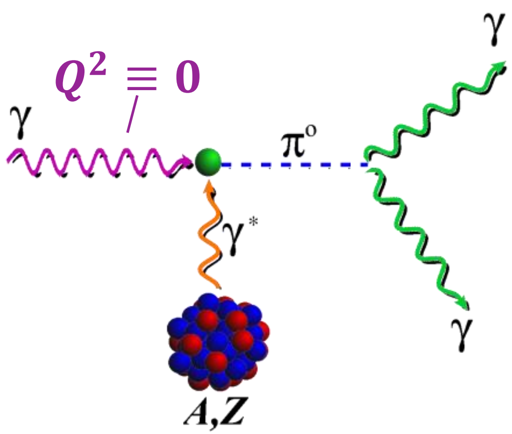
Pi0 TFF measurement: motivation and facts

- There is high interest in measurement of the neutral pion transition form factor (TFF) as a mean to constrain hadronic corrections to the muon magnetic moment, as it currently has 4.2 standard deviations from the SM.
- Primakoff neutral pion electroproduction can be used for the TFF measurement at low Q^2 values.
- Measurement of the TFF at low Q^2 values can fix:
  - The TFF $O(Q^2)$ slope,
  - The TFF $O(Q^4)$ curvature term,
  - Determine the π^0 radiative width $\Gamma(\pi^0 \to \gamma\gamma)$.

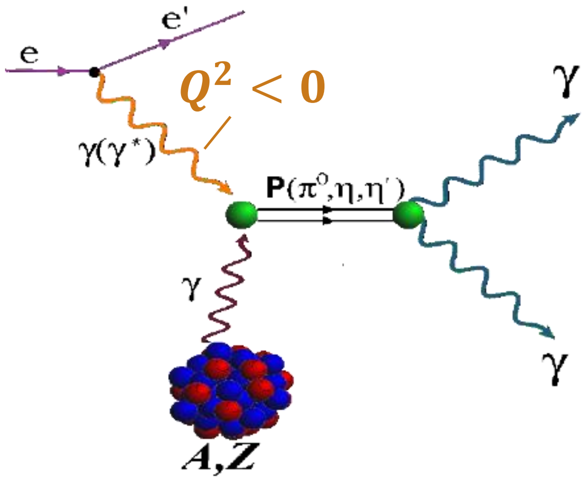
π^0 photoproduction vs electroproduction

Photoproduction
(PrimEx-I, and II)

Electroproduction
(proposed measurement)

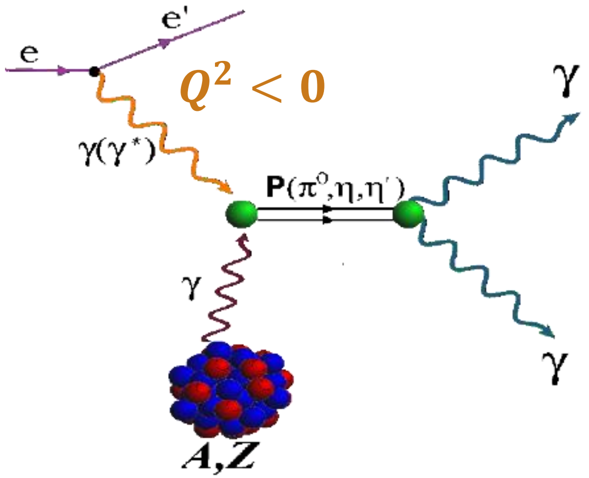


$\Gamma(\pi^0 \to \gamma\gamma)$
or $\sigma(Q^2 = 0)$,
1.5% uncertainty



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

π^0 Primakoff on virtual photon beam



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

TFF

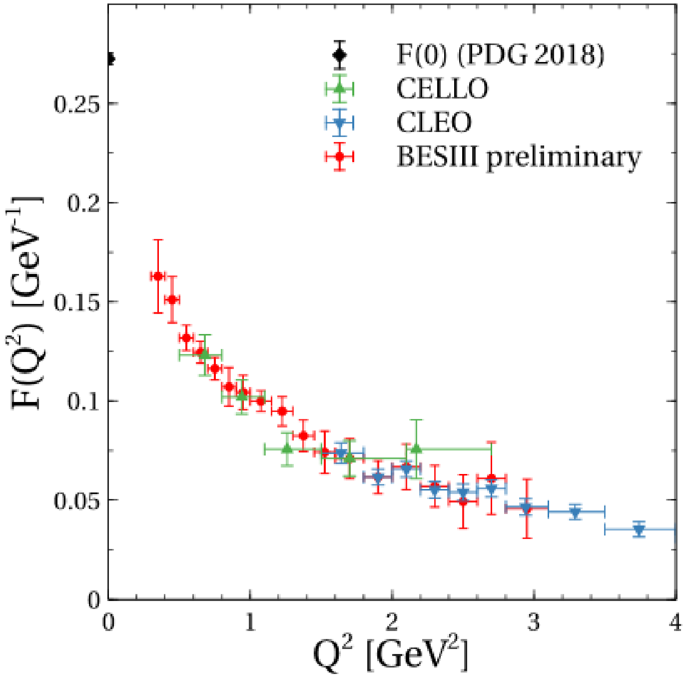
TFF — slope — quadratic term

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

Previous pi0 TFF Measurements

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

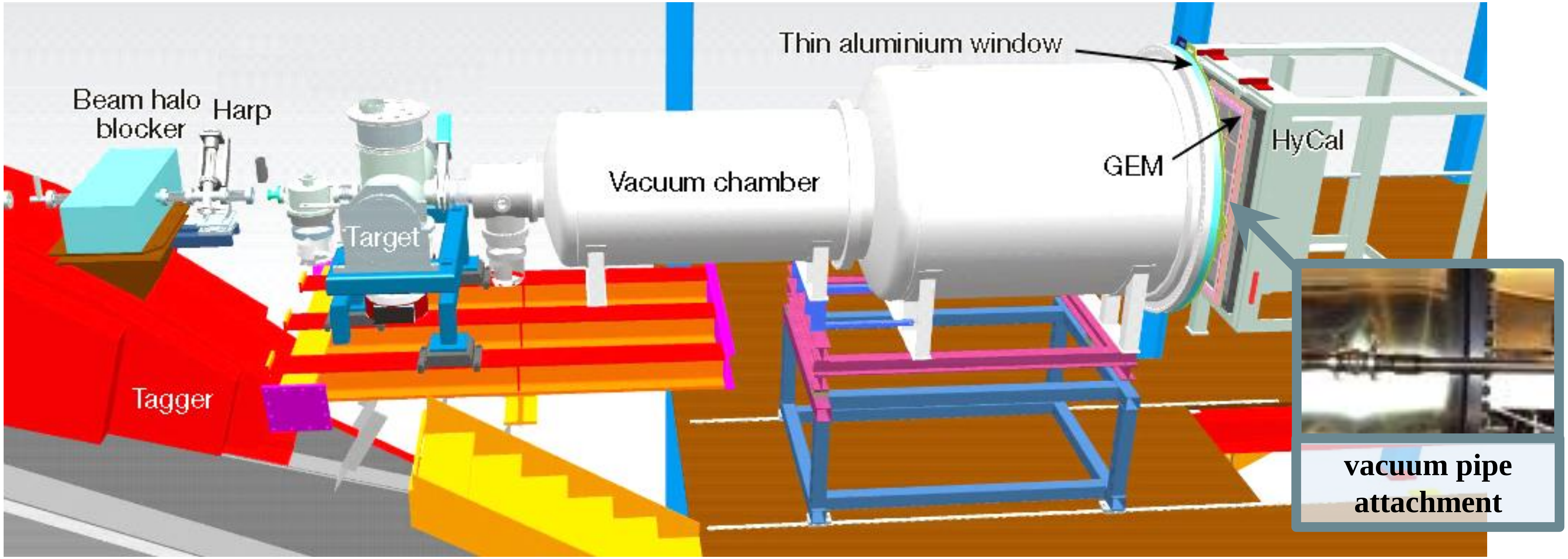
Experiment	Method	Q^2 range, [GeV^2]
CELLO	$e^+ e^- \to e^+ e^- \pi^0$	0.7-2.2
CLEO		1.6 - 8
BES III		0.3 -3.1
Belle		~ 4 - 40
BABAR		~ 4 – 40
NA 62	Dalitz decay	
A2		



The Proposed Measurement

- The proposed experiment will have sensitivity to the neutral pion TFF over the 0.003 - 0.3GeV^2 Q^2 range allowing a clean determination of the TFF parameters and having excellent sensitivity to the neutral pion radiative decay width.
- The large uncertainty in the SM prediction for the muon magnetic moment, HLbL scattering, critically depends on the knowledge of TFF in the low Q^2 region.
- We propose measurement with 10 nA electron beam, 250 micron thick silicon-28 target and the upgraded PRad experiment setup. The required physics running time is 60 days, and 67 days total.

Experimental Setup



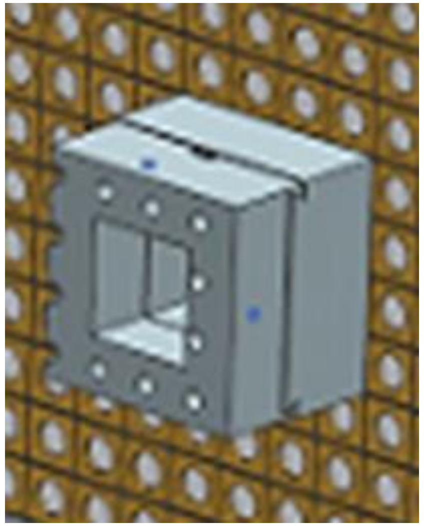
The existing ultra low background PRad setup with high resolution e-m calorimeter, vacuum chamber, and GEM detector perfectly fits our needs.

Minor modifications required:

- additional GEM detector (background suppression)
- new solid silicon target

Modifications to the existing PRad setup

Calorimeter center shielding increase



New tungsten absorber now covering two inner HyCal layers instead of one and twice thicker to protect from scattered electron beam

New target

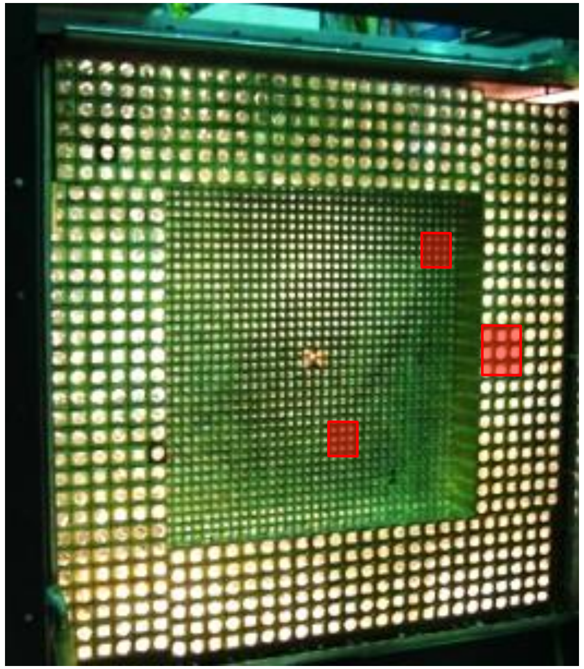
New solid silicon target 250µm thick replaces PRad hydrogen target

New sophisticated trigger working with flash-ADCs

New Trigger

- The previously used in PrimEx and PRad total energy trigger rate is estimated to be ~250 kHz for 4 GeV threshold, which is too high for the DAQ.
- Sophisticated 3-"clusters" trigger is proposed: it requires at least three 3x3 modules clusters with minimum energy of 0.3 GeV And 4 GeV total energy deposition. The rate for such trigger is estimated to be ~20 kHz.
- The calorimeter electronics needs to be upgraded with flash-ADCs.

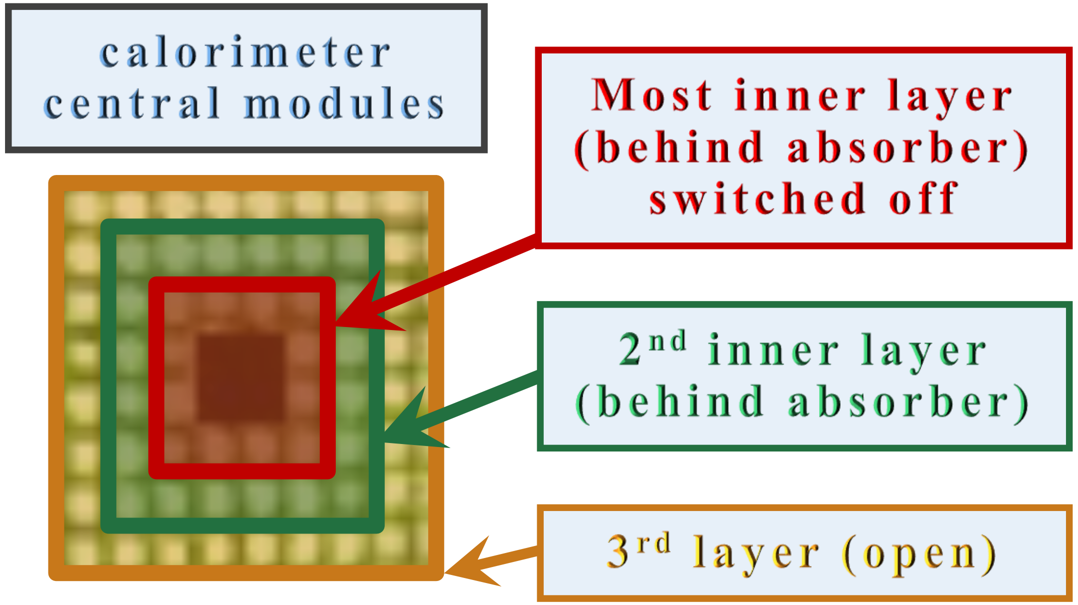
High resolution hybrid electromagnetic calorimeter HyCal



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



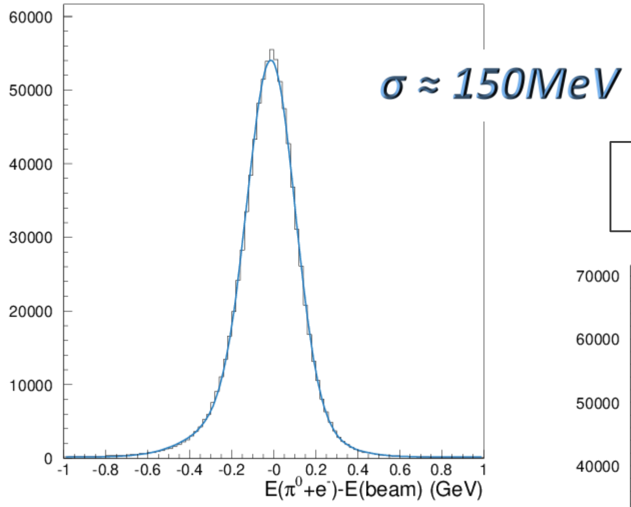
Setup resolution

- **The final state particles will be detected with a high resolution hybrid electromagnetic calorimeter with the central lead tungstate part energy resolution $\frac{2.7\%}{\sqrt{E[GeV]}}$ and $\frac{2.5mm}{\sqrt{E[GeV]}}$ spatial resolution.**

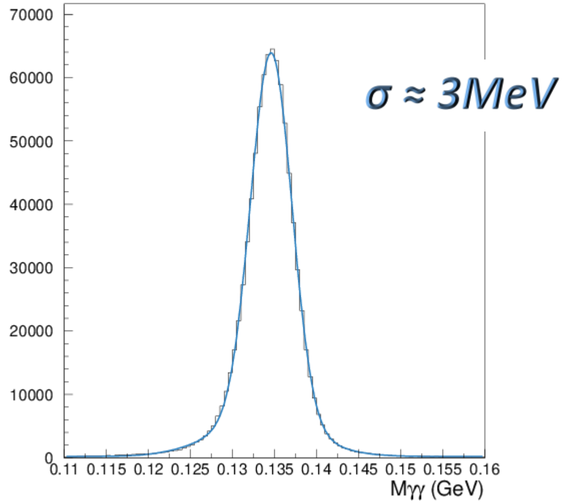
- **Two GEM detectors will be used to improve electron hit coordinate resolution to *~0.07mm* value or better. They will also reduce charged background in π^0 candidate selection.**

Setup resolutions

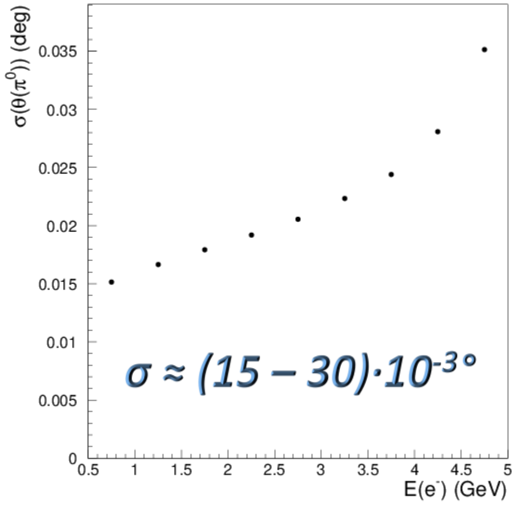
Energy conservation



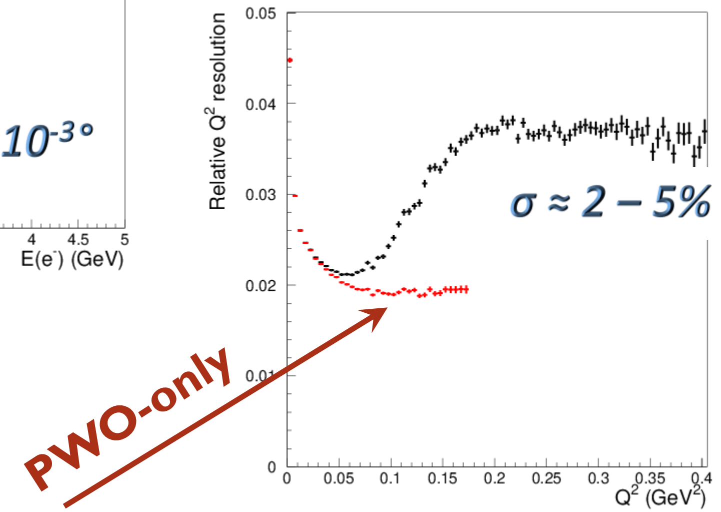
Pion mass



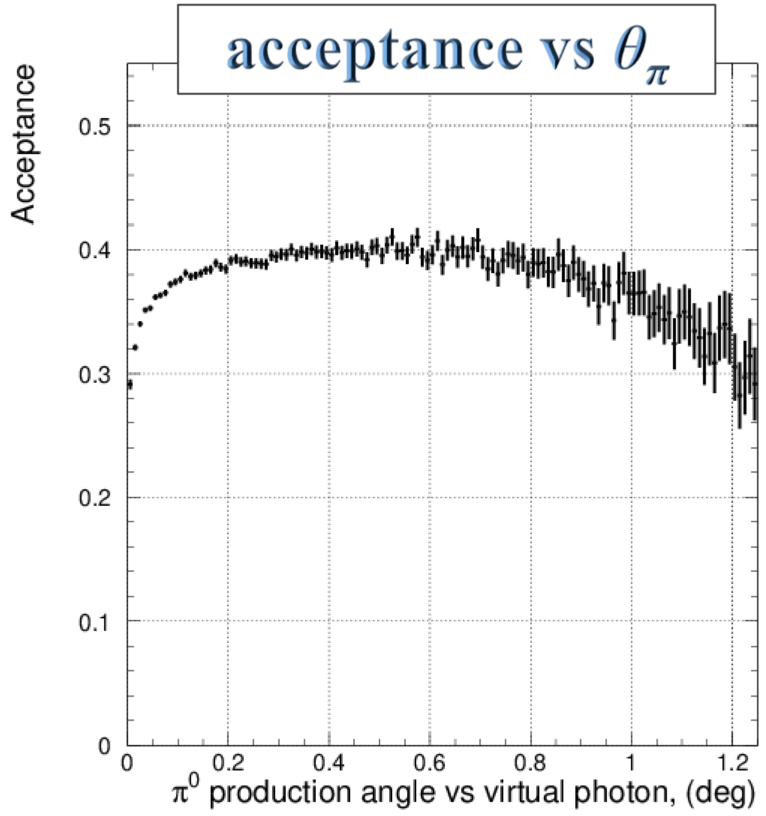
Pion angle in the Q-vector frame vs scattered electron energy

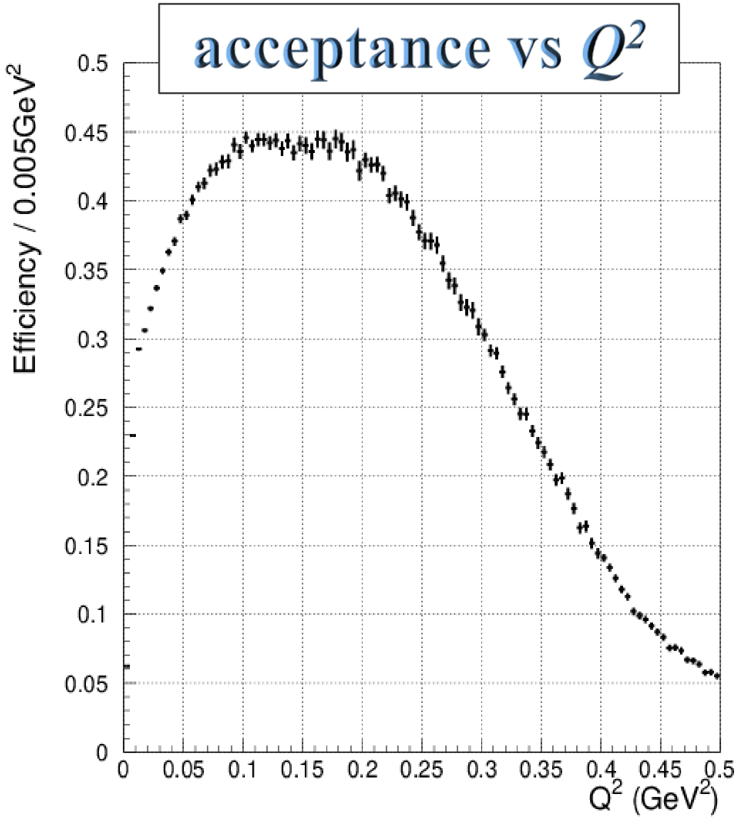


Relative Q^2 resolution vs Q^2



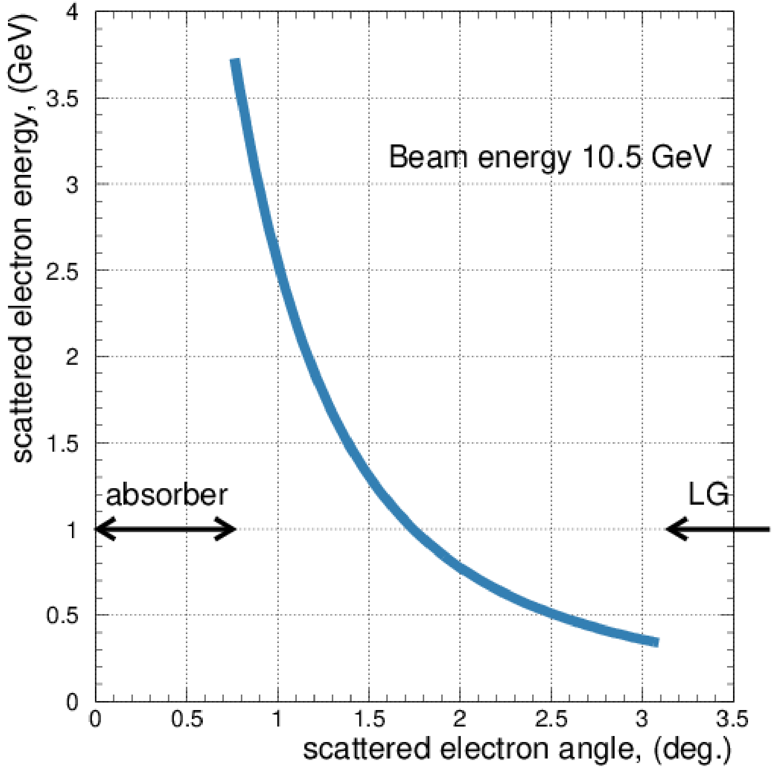
Setup Acceptance





Typical setup acceptance for virtual Primakoff production ~0. 3

Møller process cross section measurement ("single-arm" Moller)



- Well-known Møller scattering will be used for the additional luminosity control and calibration.

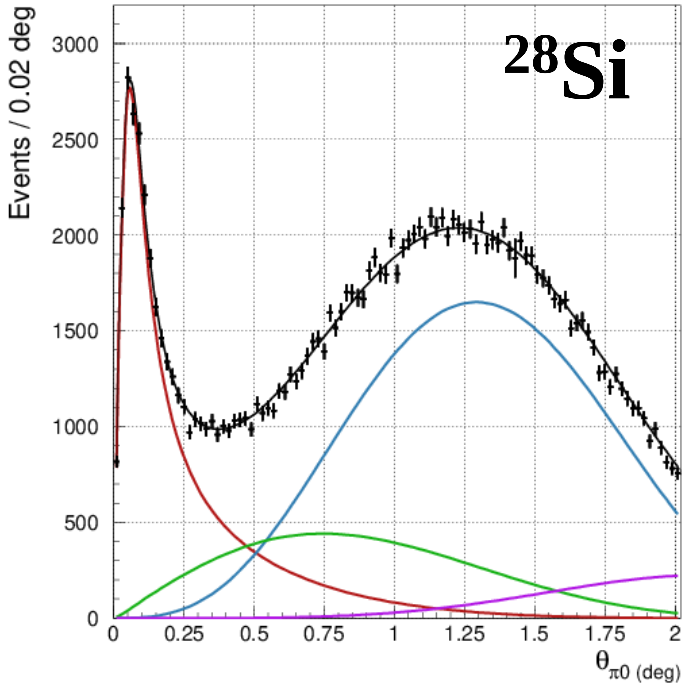
- The setup has an excellent acceptance for the "single-arm" (one electron detection) Møller scattering.

- A simple prescaled "Møller" trigger will be added to the data stream.

Expected Signal Yield vs π^0 production angle

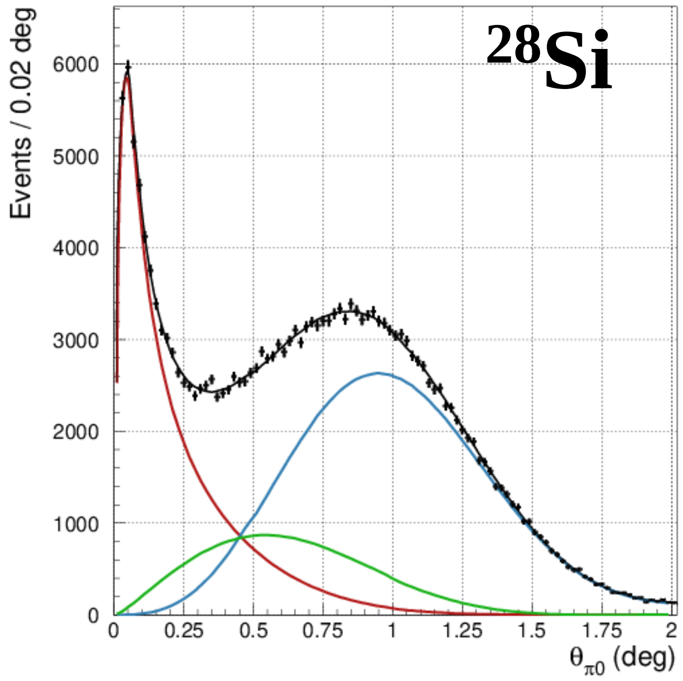
Photoproduction at 5 GeV (PrimEx)

Electroproduction at 10.5 GeV (current proposal)



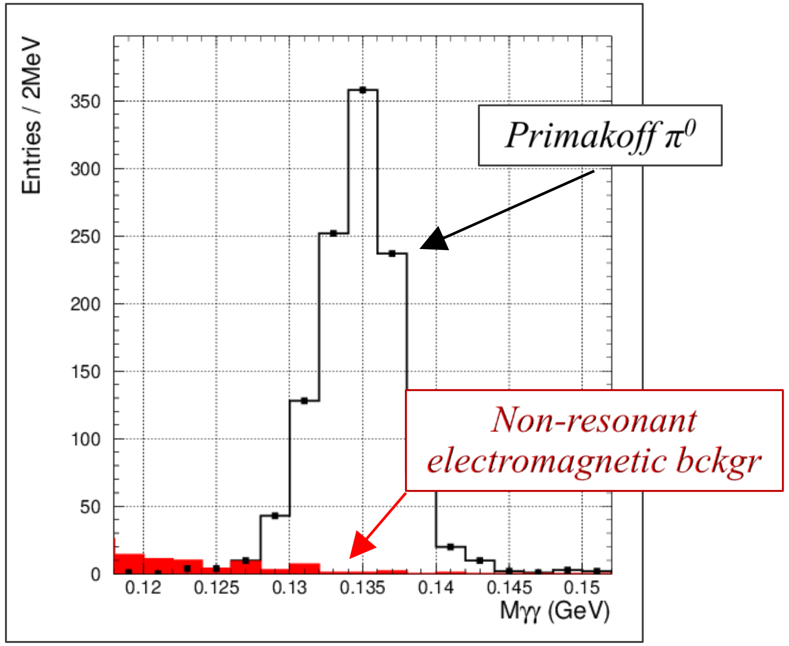
- Primakoff
- Strong Coherent
- Interference

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



Background conditions: γγ invariant mass spectrum with GEM detector rejection of charged tracks

1 day of running

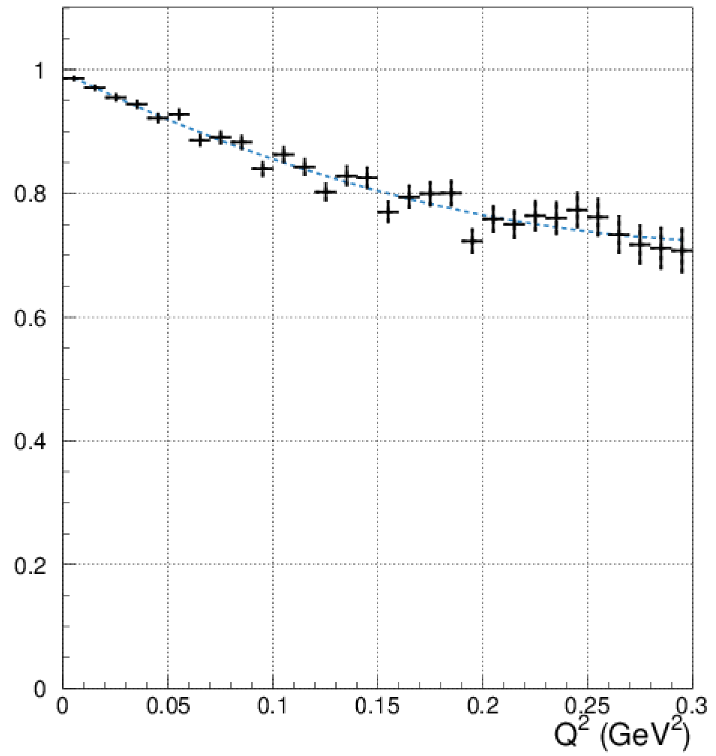


- Direct electromagnetic background effectively suppressed by GEM detectors, timing and energy conservation.
- The main contribution from hadronic background is π^0 and ω photoproduction from bremsstrahlung in target. We estimate this contribution to be at 0.5% level compared to Primakoff electroproduction.

Expected statistical uncertainty

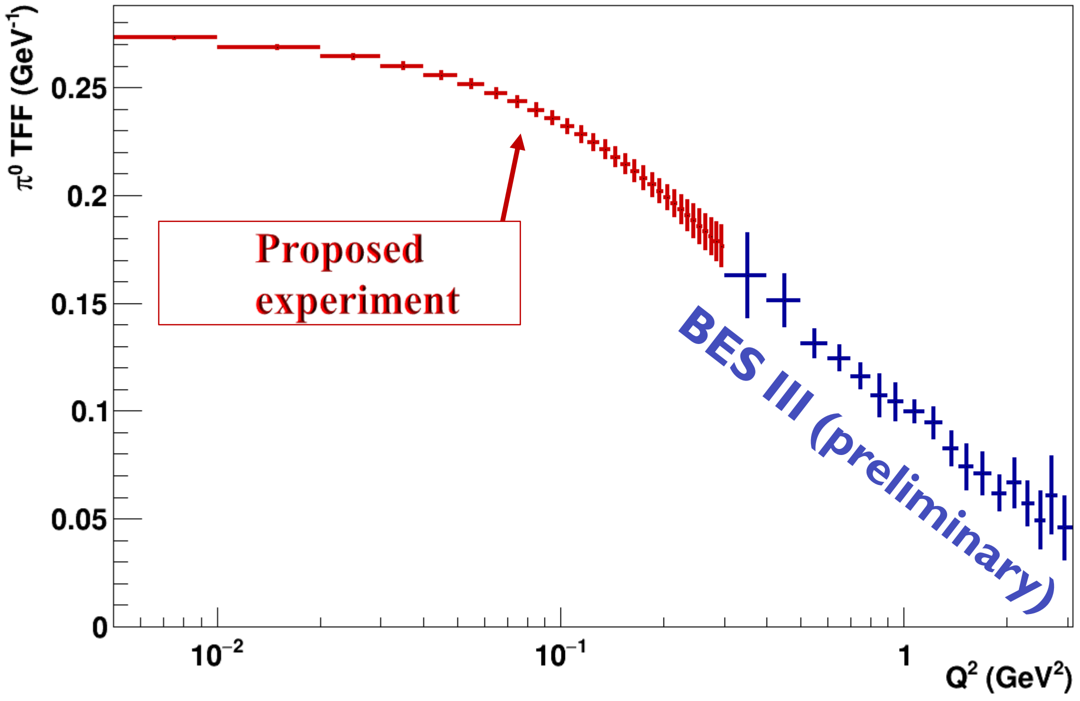
Expected π^0 TFF points vs Q^2

- The expected statistical uncertainty for
  - the TFF $O(Q^2)$ slope parameter ~6%,
  - the TFF $O(Q^4)$ quadratic term ~17%,
  - for radiative width $\Gamma(\pi^0 \to \gamma\gamma) \sim 0.72\%$ (compare with PrimEx stat. uncertainty for $\Gamma(\pi^0 \to \gamma\gamma) \sim 0.67\%$.



The expected TFF data points

The proposed experiment entirely complements the previous measurements in covering the low Q^2 range with good acceptance and resolution.



Measurement uncertainty components

Item	$\Gamma(\pi^0 \to \gamma\gamma)$ photoproduction (Si target, PrimEx-II)	$\Gamma(\pi^0 \to \gamma\gamma)$ electroproduction (this proposal)	π^0 TFF slope	π^0 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%

Beam Time Request

Experimental phase	Energy/Current	**Time [days]**
Production, silicon target	10.5GeV / 10 nA	60
Production, empty target	10.5GeV / 10 nA	2
Setup checkout, tests, gain equalization, energy change	10.5GeV / 10 nA; 4.5GeV / 1 nA	5
Total		67

Summary

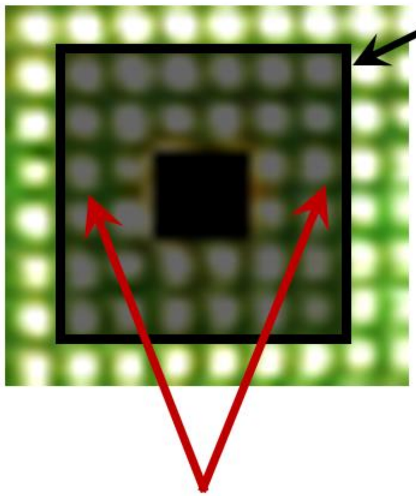
- Our group has experience with successfully working with the PrimEx setup, and precise extraction of the neutral pion production cross section. The proposed setup has been significantly improved since the PrimEx experiments. It will be a great advantage for this experiment.
- The proposed measurement will be the first precision measurement of π^0 TFF at the low Q^2 range in the space-like region.
- It will significantly improve known TFF parameters and provide independent measurement of π^0 radiative width.
- The largest systematic error in $(g\text{-}2)_{SM}$ is associated with HLBL, and the largest single contribution to HLBL is the pion-pole term. We conclude that precision low Q^2 data on the neutral pion TFF are absolutely needed to calibrate and test lattice QCD and dispersion model calculations of HLBL.

Acknowledgement: the project preparation is supported by the US DOE under contract DE-FG02-88ER40415

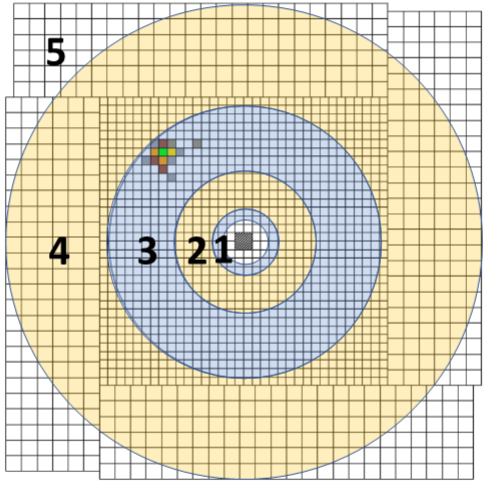
Spare slides

Moller background rates in the calorimeter

“symmetric” Moller event in the central region:



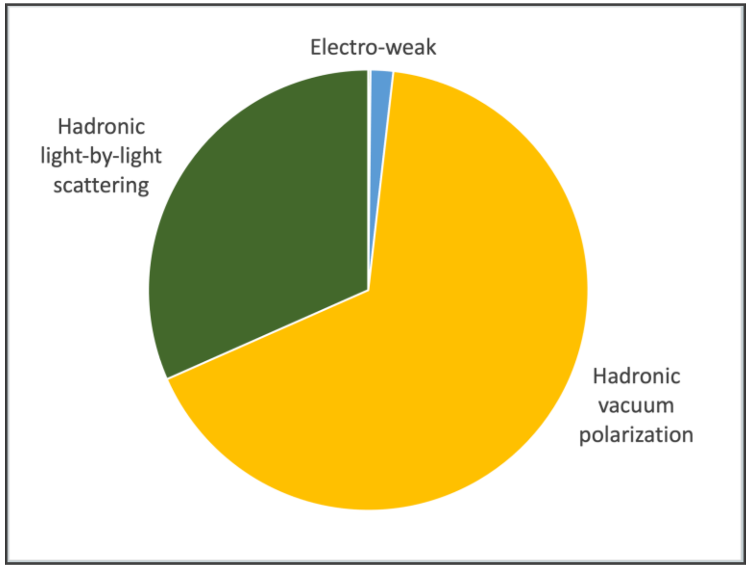
Zone	Møller angle in the CM frame [rad]	Møller angle in the lab frame [deg]	Calorimeter hit to beam-line distance [cm]	Electron energy range [GeV]	Integrated Møller rate [kHz]	Maximum Møller event per module rate [kHz]
1*	1.47 1.93	0.49 0.79	5 8	5.77 3.33	15	1.2
2	1.93 2.5	0.79 1.7	8 17.2	3.33 1.05	190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



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

- Currently a 4.2σ disagreement between measurement and calculation of the muon anomalous magnetic moment $a_\mu^{SM} = (g-2)_\mu/2$.
- Comprehensive theoretical and experimental efforts are underway to reduce the SM uncertainty in a_μ^{SM}
- The largest uncertainty in a_μ^{SM} is from Hadronic Vacuum Polarization (HVP), fixed from the ratio $\frac{\sigma(e^+e^-\to hadrons)}{\sigma(e^+e^-\to\mu^+\mu^-)}$. However, as BES III and other colliders accumulate data on $e^+e^- \to X$, the error in HVP will decrease.
- The most model dependent contribution to a_μ^{SM} is from Hadronic Light-by-Light scattering (HLbL).

Estimated errors in a_μ^{SM}



Impact of the proposed measurement on $(g-2)_\mu$

- 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.

- The largest contribution by far to HLbL is from pseudo-scalar (π^0, η, η') transition form factors

- Due to light mass, the π^0 -pole accounts for ~67% of the pseudo-scalar pole contribution to HLbL.

- With the projected statistics and Q^2 range, the proposed Hall-B experiment will enable the measurememt of ~65% of the π^0 -pole contribution to HLbL, with an estimated uncertainty of ~5%.

- The data will also provide an important cross check on the theoretical modeling used to estimate HLbL.

TAC questions (1)

Q: The proposed luminosity for the production data-taking is more than two orders of magnitude higher than during the PRad experiment and three times higher than proposed in C12-21-003. In the latter, the 3-cluster trigger rate was estimated to be 25 kHz at 3.3 GeV beam energy.

A: The proposed experiment will use a 10.5 GeV beam in conjunction with a wider tungsten absorber around the beam hole. This will help to block most of the Moller scattering events from our trigger (as described in the proposal), while PRad and C12-21-003 would be affected by such Moller events significantly. The main contributors to our trigger are elastic and quasi-elastic beam electrons scattering off the target at large angles in coincidence with other accidental hits in the calorimeter. The simulated rates agree with analytical cross section calculations.

Q: On page 15, there is a mention of a new beam halo blocker upstream of the Hall-B tagger magnet without any details. Depending on the requirements for the blocker, the existing wire harp and the pair of the Hall-B raster magnets currently mounted in that location may have to be removed or relocated. The wire harp is a crucial device for beam tuning. The current arrangement decouples the beamline vacuum from the tagger scattering chamber. Therefore, there is no need to replace the Hall-B tagger vacuum chamber window, as mentioned on page 15.

A: We do not intend to remove the wire harp. The Hall-B raster magnets (used only for polarized targets) will have to be removed to make way for the second halo blocker, which will be retractable similar to the HPS beam halo blocker. It will be retracted from the beamline if it is found to have a negative effect on the background. The exact location of this beam halo blocker will be worked out later by collaborating with the C12-21-003 group.

TAC questions (2)

Q: The experiment will detect the scattered electron and the decay photons using the PRad HyCal. It is proposed to replace the old readout electronics of the calorimeter with fADC125. Hall-B does not have fADC125 and never used it. The existing JLAB fADC125 modules do not support trigger setup. A new version of fADC125 is in the works but far from a final being ready for production. The fADC125, VXS crates, or trigger modules are all new equipment that must be purchased or borrowed. Note that the two other experiments, E12-20-004 and C12-21-003, will use the same calorimeter and are proposing to have the readout and triggering based on fADC250.

A: The mentioned fADC-125 modules are sufficient for the proposed experiment. Using fADC-250 modules would give better performance, and therefore are perfectly fine to use, which is mentioned on the page 15 of the Proposal: "*While an upgrade to fADC-250s is beneficial to TFF, using fADC-125s does satisfy our experimental requirements*". Since E12-20-004 and C12-21-003 will use fADC-250, we will use the same as well.

Q: The proposed ~2 ns time window on page 18 for triggering to reduce out-of-time background seems very unrealistic. There are two similar calorimeters in Hall-B, HPS, and the CLAS12 forward tagger that run cluster-based trigger systems using fADC250. A typical time window for the trigger is 16 fADC clocks or 64 ns. For fADC125, the window will be even larger.

A: The mentioned 2 ns time window on page 18 refers to the HyCal timing resolution. All background calculations conservatively include timing accidentals within a 40 ns trigger window. The CLAS12 and HPS experiments successfully use a 16 ns trigger window, which satisfies the proposed experiment needs perfectly and will be implemented.

TAC questions (3)

Q: How HyCal will be calibrated? One should note that for 12 GeV operations of CLAS12, we removed the photon tagger focal plane counters. Re-installation is possible, but the photon energy knowledge will not have the same accuracy as it was during the first PrimEx experiment. Also, over time vacuum in the tagger scattering chamber degraded due to the deterioration of the chamber window. This affects the photon beam energy resolution.

A: HyCal will be calibrated on the transporter via a snake scan following the same procedure that was well established during the previous PrimEx-I & II, and PRad experiments. Combining the proposed experiment together with E12-20-004 and C12-21-003 back to back if approved would save time as the TFF experiment can use the calibration constants from the other experiment, if it runs just before. The purpose of the calibration is to check the status and linearity of each module and to equalize the energy gain and timing offset of all counters. Only about 25% of the tagger counters are required, which are T1-T5, T28-T33, T56-T61 and corresponding E-counters. The obtained energy calibration constants will be used for the triggering and ~5% precision is enough for this purpose. The precise calibration constants for the physics analysis will be obtained from calibration on neutral pions and Moller events using the production data. We plan to address the issues of the vacuum window for the tagger scattering chamber by working with the E12-20-004, C12-21-003, and PR12-22-003 groups.

Q:. Details for the second GEM detector plane? Are these the same GEM planes proposed in E12-20-004 or C12-21-003. We strongly advise that the proponents of these three proposals work together to develop one set of tracking detectors for the proposed E12-20-004, C12-21-003, and PR12-22-003.

A: The same GEM chambers as for the approved PRad-II experiment (E12-20-004) will be used. This experiment can run back to back with PRad-II or another proposed experiment and use the same set of tracking detectors.