High Precision Neutral Pion Transition Form Factor Measurement with the CEBAF 24 GeV Energy Upgrade

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for the PrimEx Collaboration

Outline

- PrimEx program with 24 GeV upgrade
- π^0 transition form factor on nuclei
- π^0 transition form factor on atomic electron
- Proposed experimental setup
- Kinematics and geometrical acceptances
- Summary

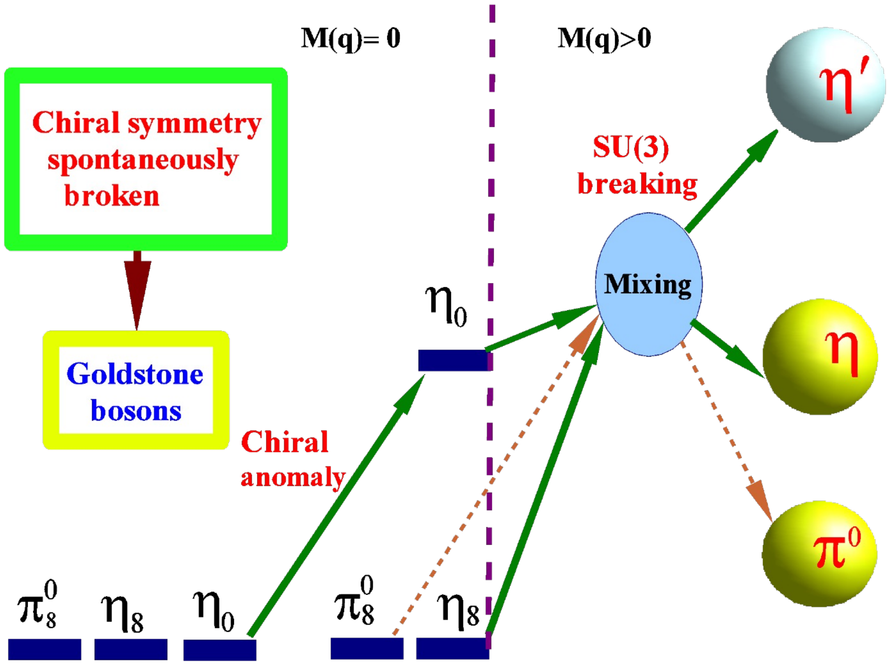
Physics Motivation: Symmetries in QCD

- Classical QCD Lagrangian in Chiral limit is invariant under:

$$\boxed{SU_L(3)\times SU_R(3)\times U_A(1)\times U_B(1)}$$

- Chiral $SU_L(3)xSU_R(3)$ spontaneously broken:
  - 8 Goldstone bosons (π,K,η)
- $U_A(1)$ is explicitly broken:

  (axial or chiral anomaly)
  - $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  - mass of η_0
- quarks are massive and different, SU(3) is broken:
  - Goldstone bosons are massive
  - mixing of π^0 η η'



The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

The PrimEx Project with 12 GeV at JLab

- **Experimental program:**

1) Precision measurements of two-photon decay widths (real photon exchange):

   a) $\Gamma(\pi^0 \to \gamma\gamma)$

   b) $\Gamma(\eta \to \gamma\gamma)$

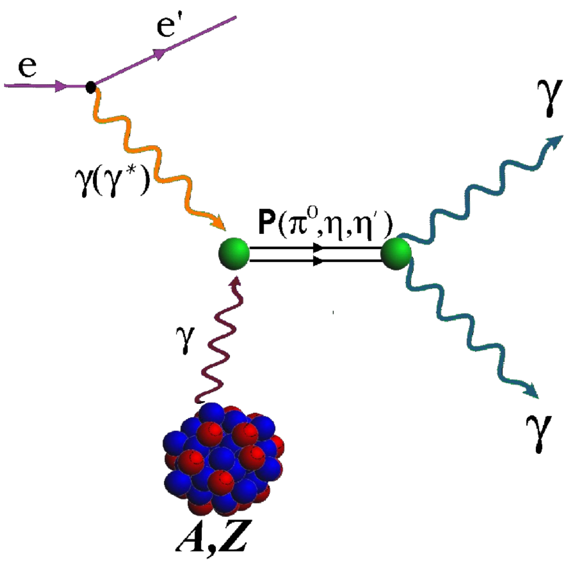
   c) $\Gamma(\eta' \to \gamma\gamma)$

2) Transition Form Factors at very low Q^2 range, 0.001-0.5 GeV^2/c^2 (virtual photon exchange):

   a) $F(\gamma\gamma^* \to \pi^0)$

   b) $F(\gamma\gamma^* \to \eta)$

   c) $F(\gamma\gamma^* \to \eta')$



- **Physics reach:**

a) precision tests of chiral symmetry and anomalies

b) determination of light quark mass ratio

c) mixing angles

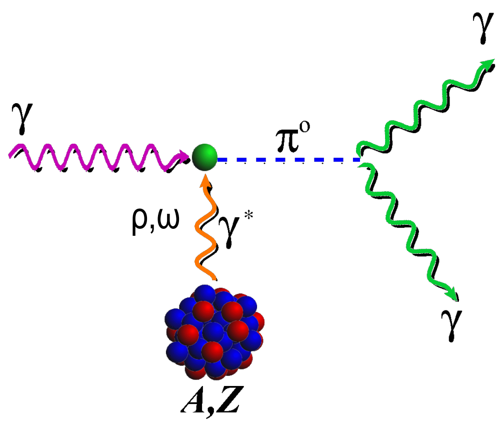
d) π^0, η and η' interaction electromagnetic radii

e) Is η' an approximate Goldstone boson?

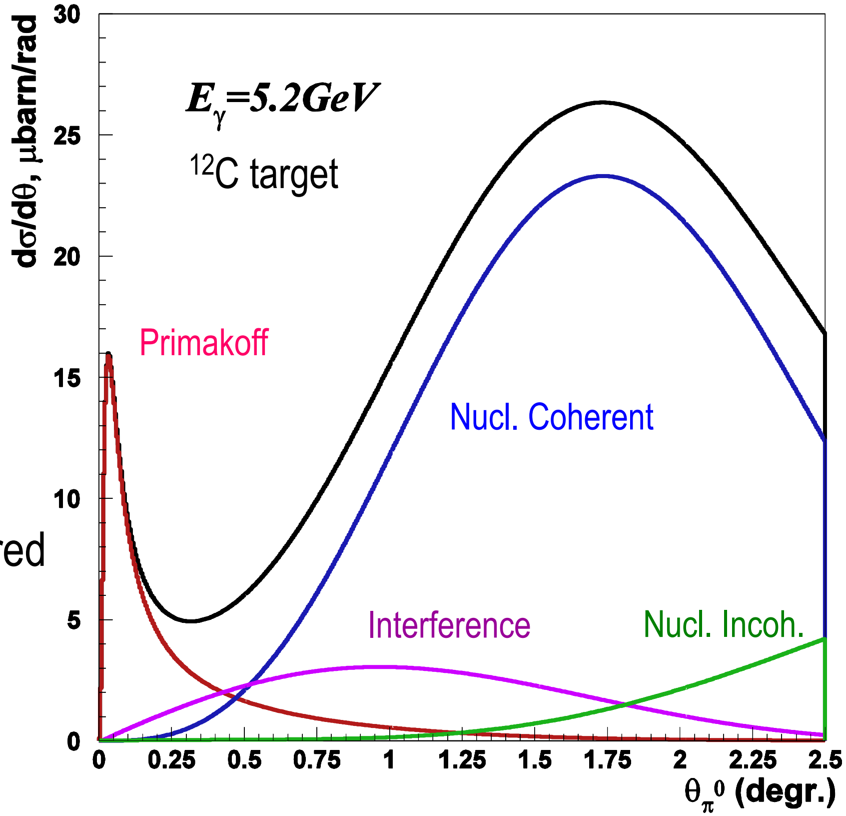
f) Critical contributions to HLbL calculations for $(g\text{-}2)_\mu$

- **Included in the JLab @12 GeV upgrade CDR**

Primakoff Method (on Nuclear Target)



$$\frac{d^3\sigma_{Pr}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\pi$$



- Primakoff coherent cross section measurement required

$$\left\langle \theta_{Pr} \right\rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \theta_{NC} \propto \frac{2}{E \bullet A^{1/3}}$$

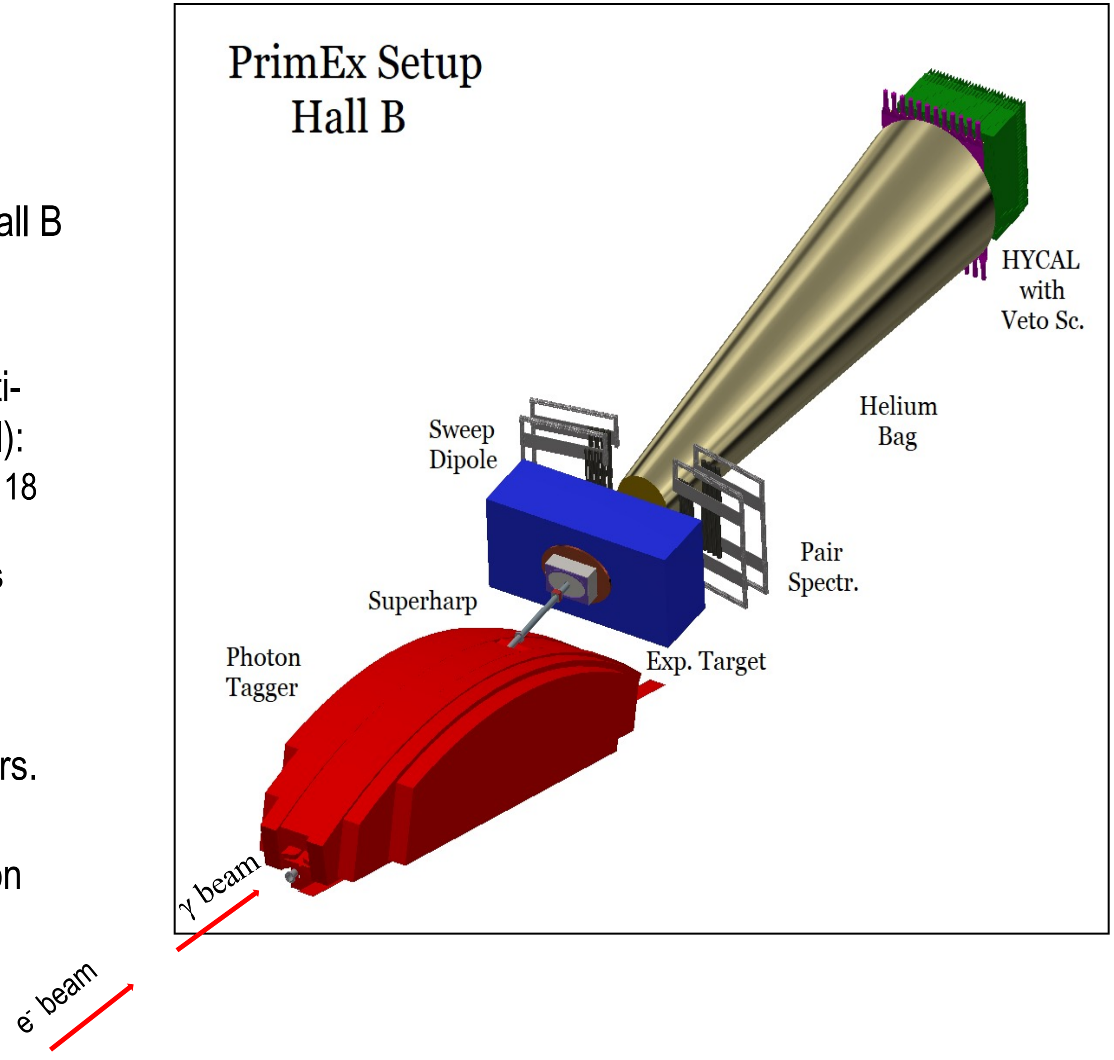
- $(d\sigma/d\Omega)_{\text{Prim. at peak}} \sim E^4$

- Challenge of the method:
  - measure the cross section at forward angles with high precision
  - extract the Primakoff amplitude from diff. cross sections vs. angle

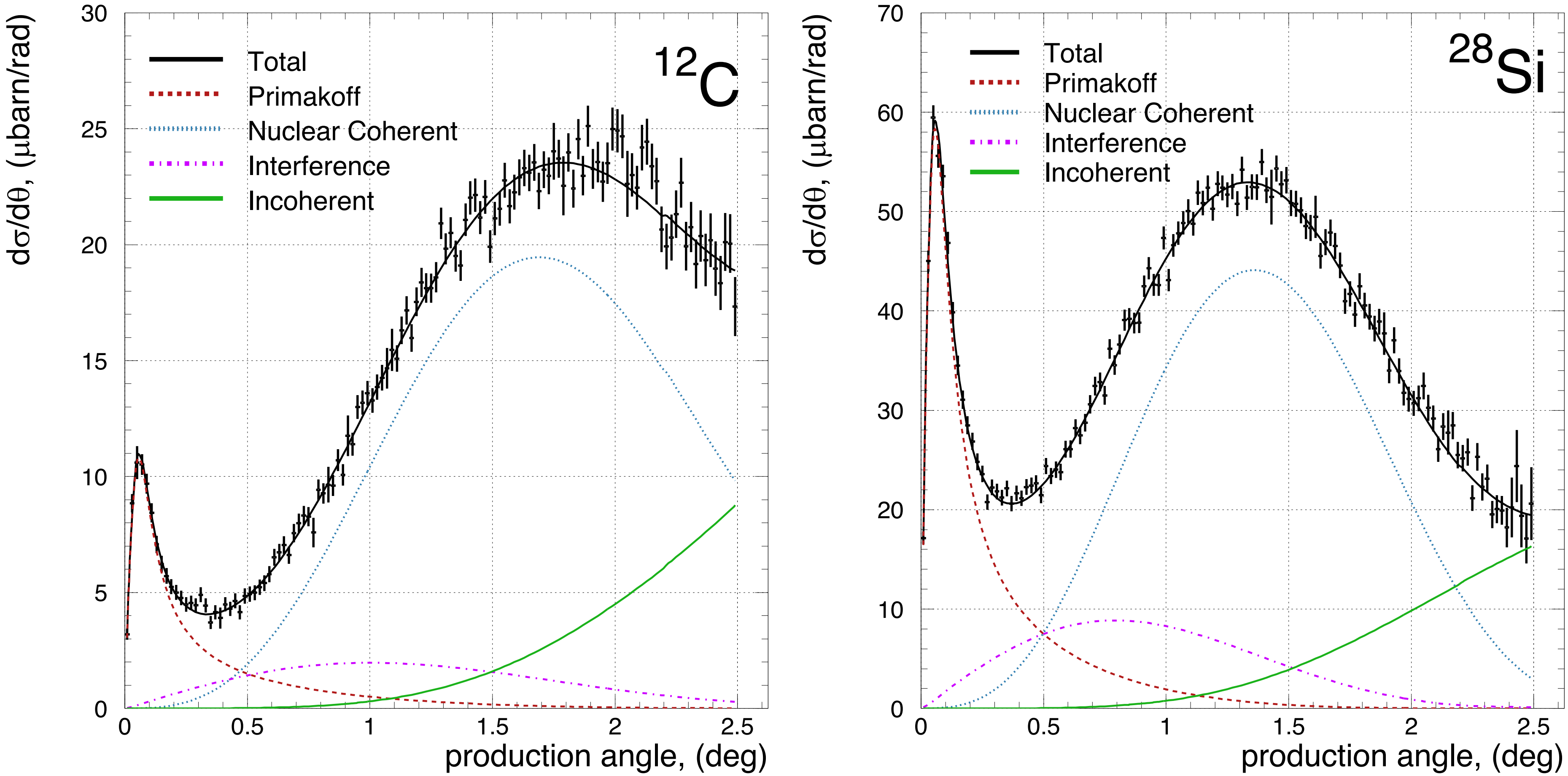
An Example: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Decay width Measurement
PrimEx Experiments in Hall B at JLab

- PrimEx-I performed in Hall B in 2004

  using:
  - ✓ high resolution, high intensity Hall B photon tagging facility.
  - ✓ new high resolution hybrid multi-channel EM calorimeter (HyCal):
    - ✧ 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors
    - ✧ 576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)
    - ✧ Total area: 118 x 118 cm^2
  - ✓ set of 12 scintillator veto counters.
  - ✓ new pair spectrometer for photon flux control at high intensities.



PrimEx-II: Extracted Differential Cross Sections



- To extract $\Gamma(\pi^0 \to \gamma\gamma)$:
  - ✓ angular and energy resolutions smeared the theoretical distributions to fit the experimental cross sections.

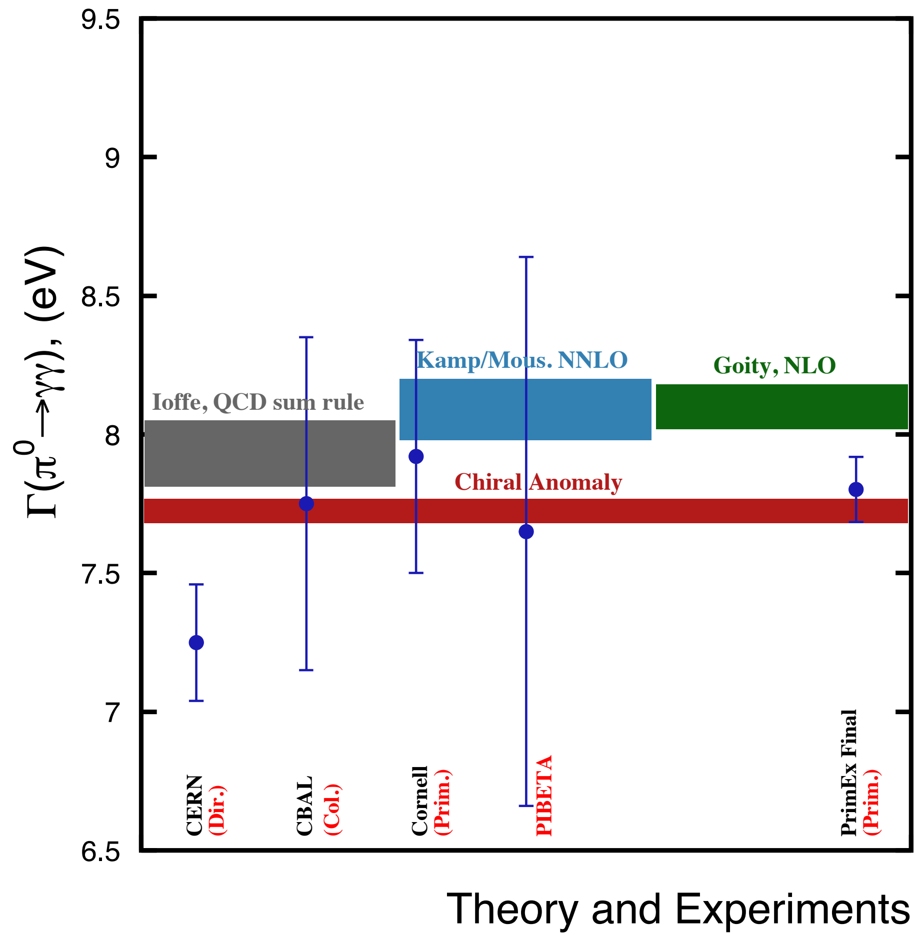
$\Gamma(\pi^0\to\gamma\gamma)$: Final Result from PrimEx

- Weighted average from two experiments, PrimEx-I and PrimEx-II is:

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.802 ±0.052(stat) ± 0.105(syst.) eV

with the total uncertainty of: ± 1.5%

- the nuclear background contribute significantly to the total uncertainty.

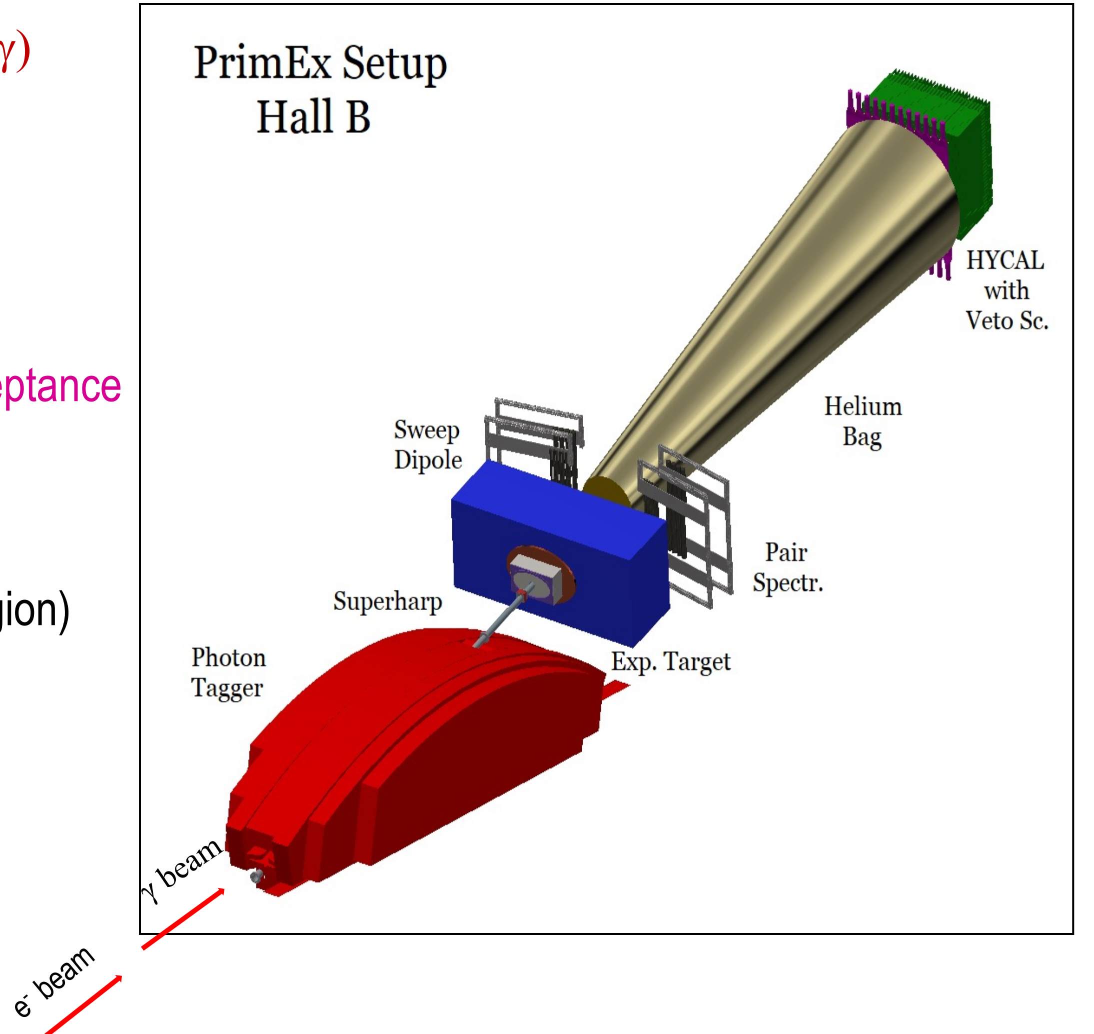


Decay Width Measurements of π^0, η and η' Mesons with the 24 GeV Energy Upgrade

- Critical for the $\Gamma(\eta\rightarrow\gamma\gamma)$ and $\Gamma(\eta'\rightarrow\gamma\gamma)$ measurements with few percent accuracies

- Requires a high energy photon tagger:
  - ✓ Is that the Hall D tagger?
- Requires high resolution and large acceptance electromagnetic calorimeter:
  - ✓ HyCal with all $PbWO_4$ crystals
- Requires a "clean" beamline (vacuum from target up to detection region)
- Requires a "cleaning" dipole magnet

- Use nuclear targets, similar to PrimEx
  - ✓ Background from the nuclear processes will still be dominated

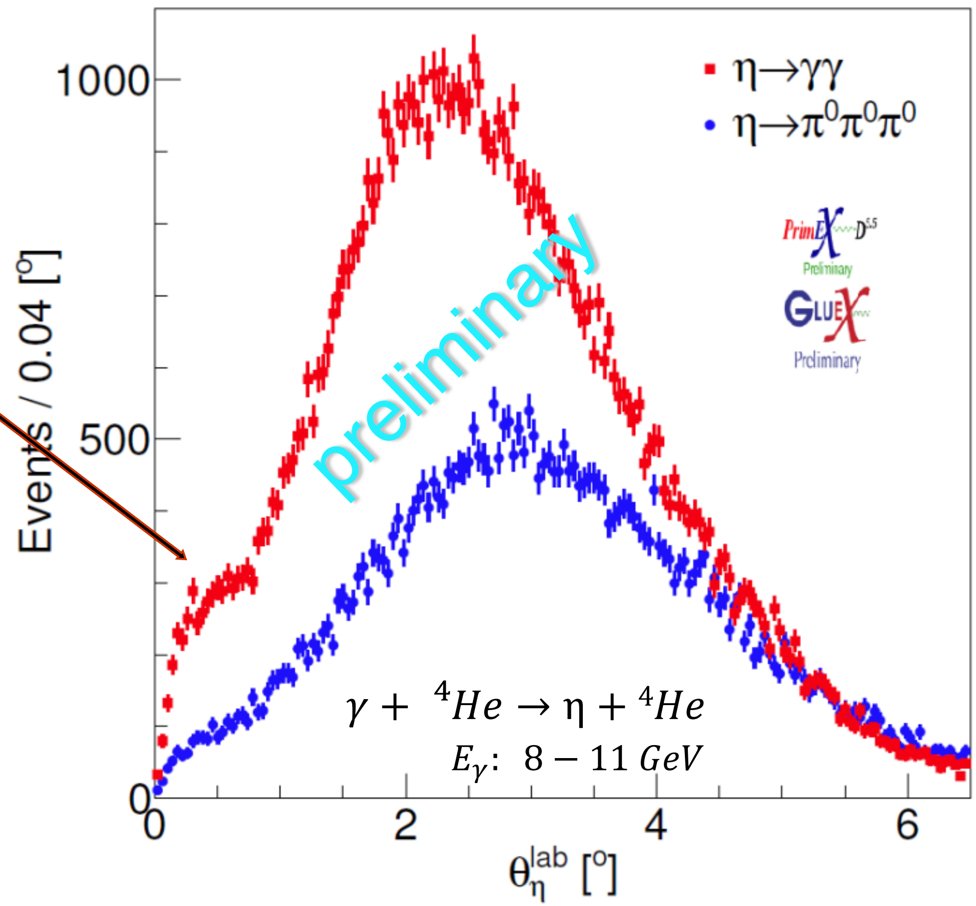


$\Gamma(\eta\rightarrow\gamma\gamma)$ and $\Gamma(\eta'\rightarrow\gamma\gamma)$ Measurements with the 24 GeV Energy Upgrade

- Significant gain in Primakoff yield for $\Gamma(\eta\rightarrow\gamma\gamma)$:

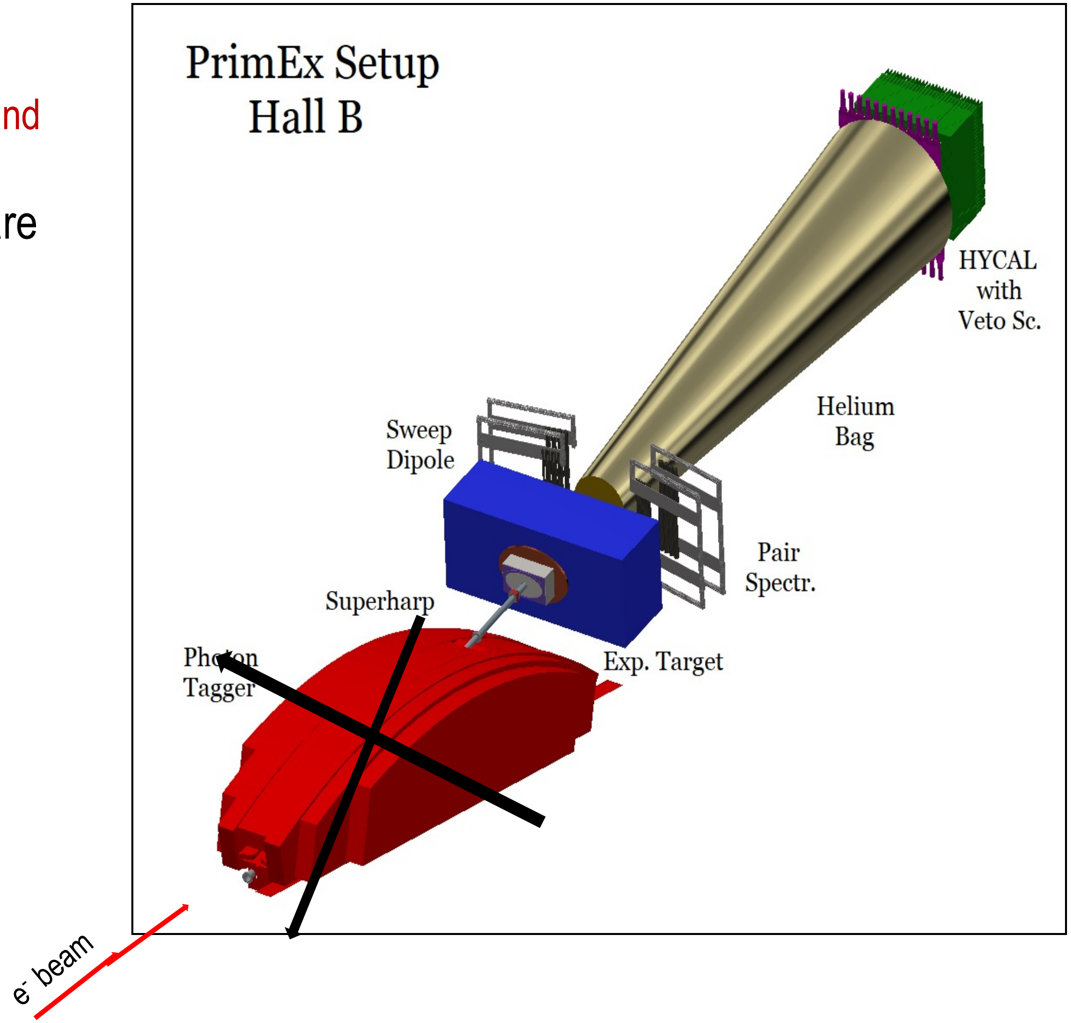
$$(N_{E24}/N_{E12}) \sim \left(\frac{24}{12}\right)^4 \approx 16$$

- $\Gamma(\eta'\rightarrow\gamma\gamma)$ measurement can be done with the 24 GeV CEBAF beam energy upgrade only



Transition Form Factor Measurements on Nuclear Targets with the 24 GeV Energy Upgrade

- "cleaning" dipole magnet cannot be used
  - ✓ relatively large electromagnetic background
- Sub percent resolutions in cross section are needed :
  - ✓ not easy experiments
- Will use nuclear targets, similar to PrimEx
  - ✓ background from the nuclear processes is still present



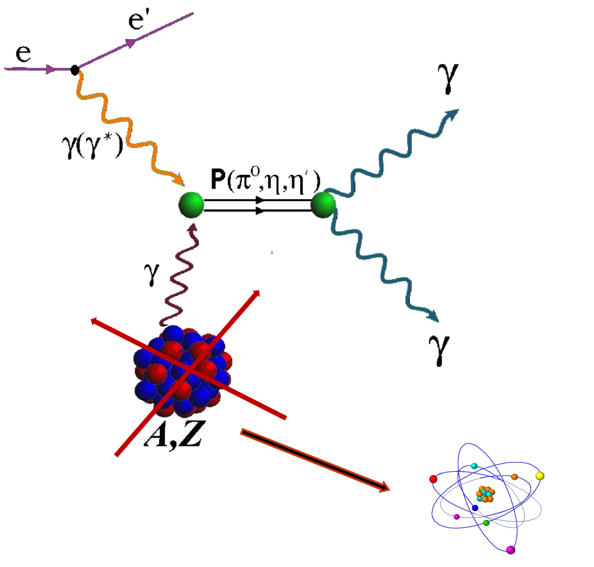
$F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment on Electron Target

- Change the nuclear target to atomic electron
  $e^- + e^- \to e' + e^- + \boldsymbol{\pi^0}$
  $\pi^0 \to \gamma\gamma$
- The problem, requires threshold energy for γ^*

  $E_{\gamma^*} = ((m_{\pi 0} + m_{e-})^2 - m_{\gamma^*}{}^2 - m_{e-}{}^2)/(2\, m_{e-})$

  for $Q^2 \approx 0.001$ GeV^2: $E_{\gamma^*} \approx 18$ GeV

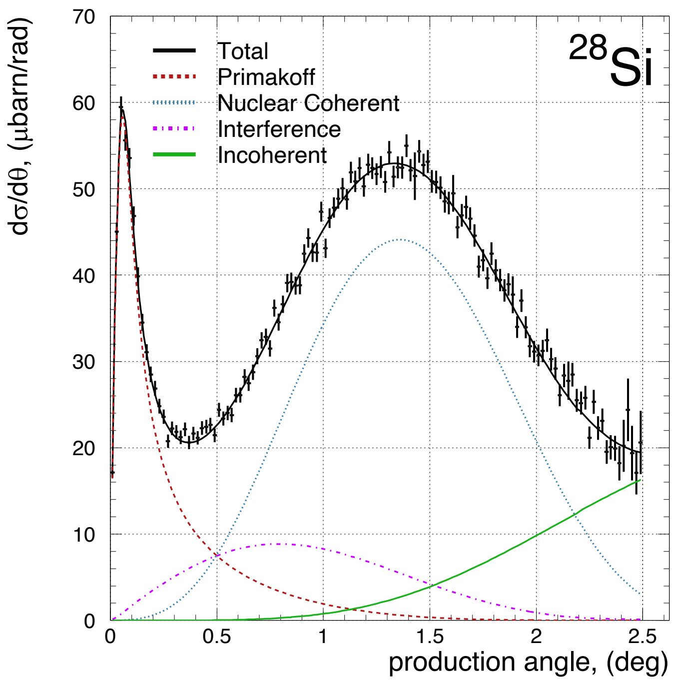
- Experimental method:
  detect all 4 final state particles:
  - ✓ scattered electrons
  - ✓ recoil electrons
  - ✓ two photons from pion decay
- Providing full control of the experiment:
  - ✓ reaction identification;
  - ✓ total energy conservation;
  - ✓ total 3-momentum conservation.

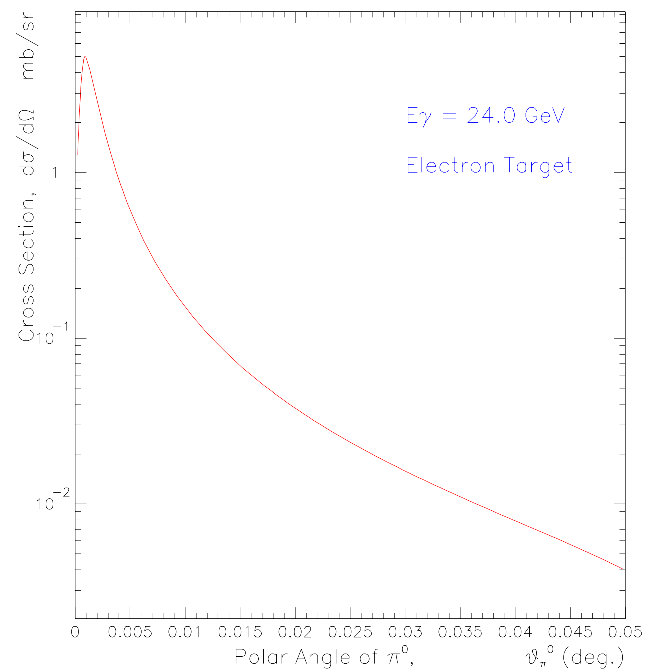


$F(\gamma\gamma* \to \pi^0)$ Transition Form Factor Experiment
Differential Cross Section on Electron Target

- Change the nuclear target to atomic electron
  $e^- + e^- \to e' + e^- + \pi^0$
  $\pi^0 \to \gamma\gamma$
- No nuclear processes on electron contributing to the background

Main challenges for nuclear targets:
- nuclear background
- nuclear effects in form factor
- no recoil detection

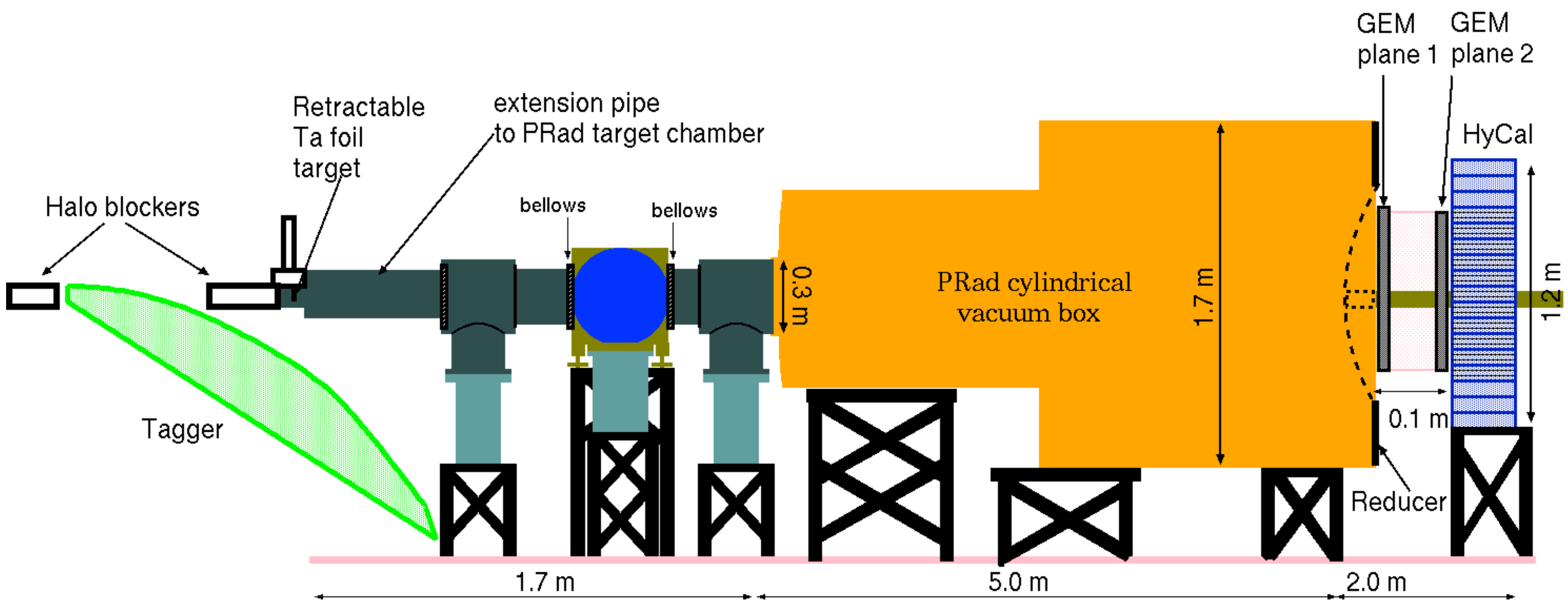




The Proposed Experimental Setup: (PRad – II experimental setup)

- Target to detector distance: Z $\approx$ 10 m
- Detection of the forward scattered electrons in HyCal/GeM (low Q^2 range: 10^{-3} – 10^{-1} GeV^2)
- $\pi^0 \rightarrow \gamma\gamma$ detection with the HyCal calorimeter
- Detection of the Recoil electron:
  - ✓ with the HyCal calorimeter (at $Q^2 \approx 10^{-3} - 10^{-2}$ GeV^2 range);
  - ✓ or/and with the scintillator ring close to target from the PRad-II experiment (for $Q^2 \approx 10^{-1}$ GeV^2)

Experimental Setup (Side View)

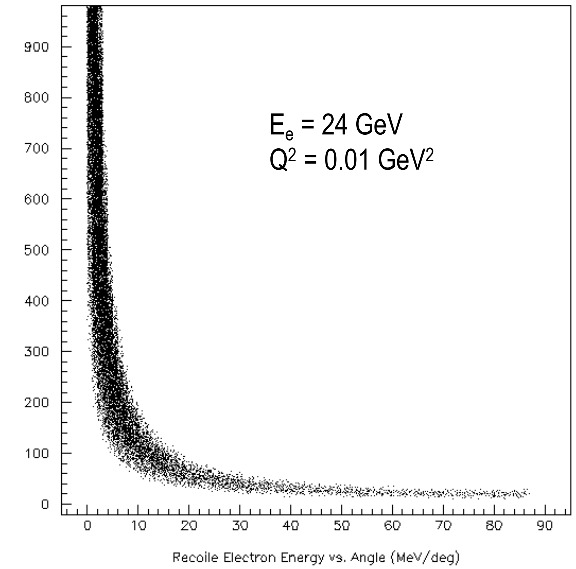


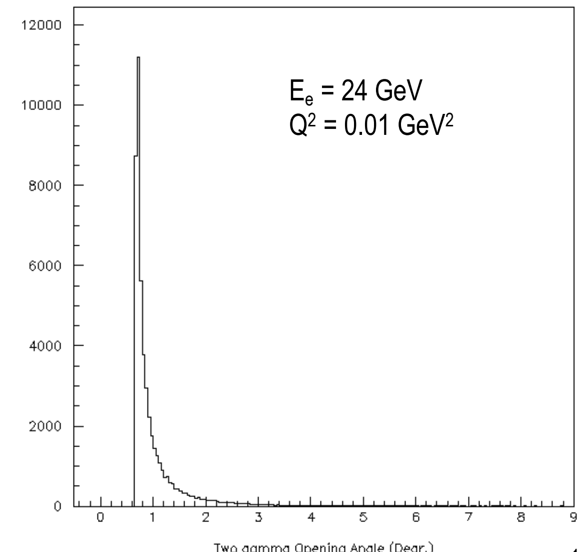
$F(\gamma\gamma * \rightarrow \pi^0)$ Transition Form Factor Experiment

(Reaction Kinematics at E_e = 24 GeV)

$$e^- + e^- \rightarrow e' + e^- + \boldsymbol{\pi^0}$$
$$\pi^0 \rightarrow \gamma\gamma$$

- Scattered electron in HyCal (provides low Q^2 range: $\approx 10^{-3} - 10^{-1}$ GeV^2):
  $\vartheta \approx 0.3^0 - 3^0$,
  $E_{e'} \approx 0.3 - 3.5$ GeV
- The γ^* and π^0 are produced on extremely forward directions with energies >20 GeV
- Recoil electrons angle: (forward – 90^0)
- $\pi^0 \rightarrow \gamma\gamma$ decay is very forward due to high energy





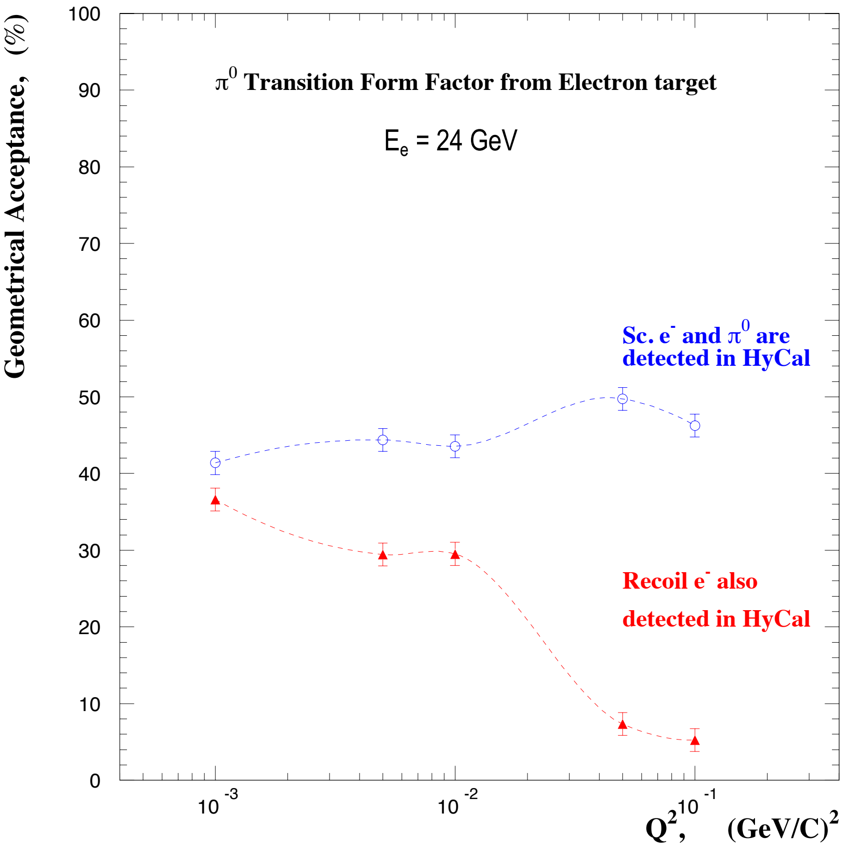
$F(\gamma\gamma * \rightarrow \pi^0)$ Transition Form Factor Experiment
(Geometrical Acceptance at E_e = 24 GeV)

- Only GEM/HyCal are used for all 4 final state particles (including the Recoil Electrons)

- Scattered electron in HyCal:
  $\vartheta_{e'} \approx 0.3^0 - 3^0$,
  $E_{e'} \approx 0.3 - 3.5$ GeV

  E_γ > 0.5 GeV from $\pi^0 \rightarrow \gamma\gamma$ decay

. Recoil Electron
  $\vartheta_{recoil\ e} = 0.3^0 - 3^{0.}$ Recoil Electron
  $E_{recoil\ e}$ > 0.03 GeV



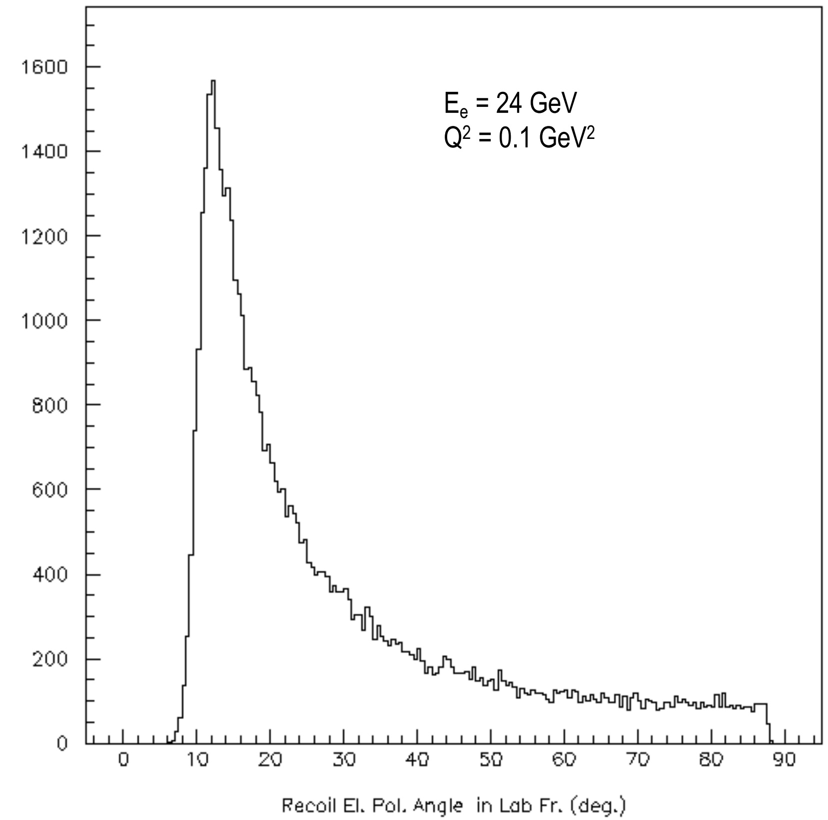
$F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment

(Reaction Kinematics at E_e = 24 GeV and Relatively High Q^2 Range ($\sim 10^{-1}$ GeV^2))

- HyCal angular angular coverage at Z=10 m:

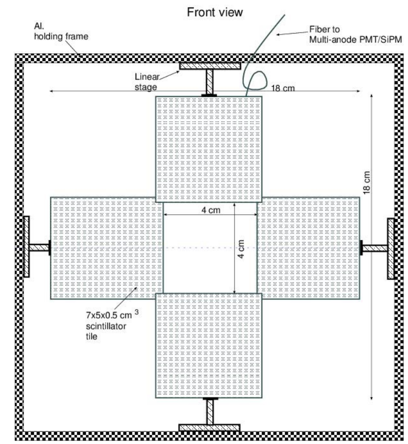
  $\vartheta \approx 0.3^0 - 3^0$

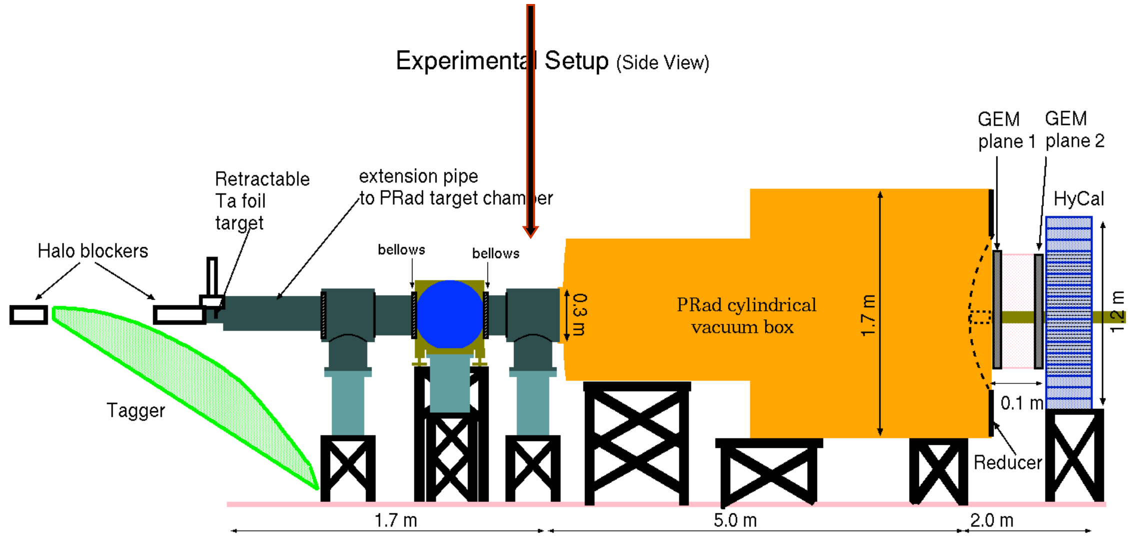
- For the Q2 $\sim 10^{-1}$ GeV^2 range recoil electrons are out of the HyCal acceptance



The Proposed Experimental Setup: New ScintillatorRing

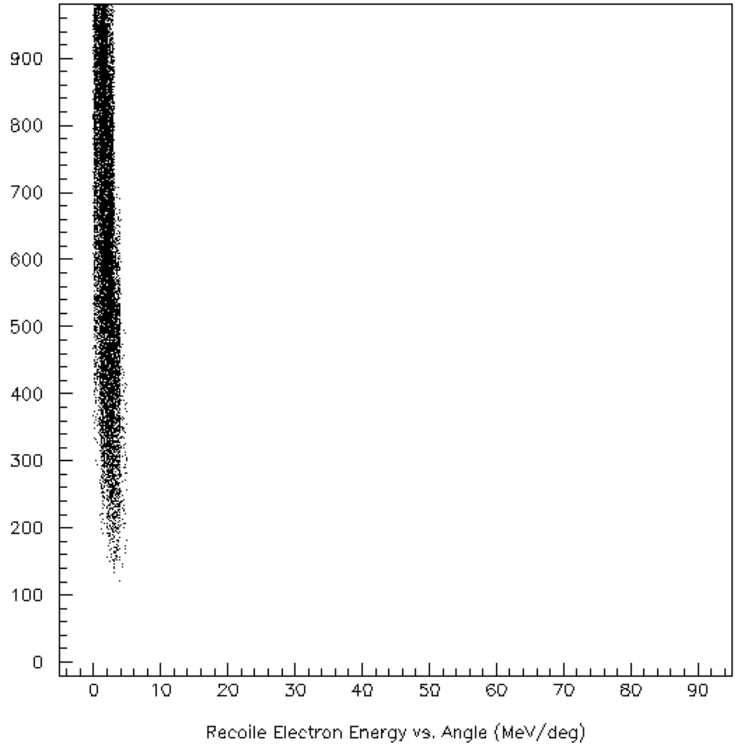
- Add a scintillator ring like the PRad-II experiment

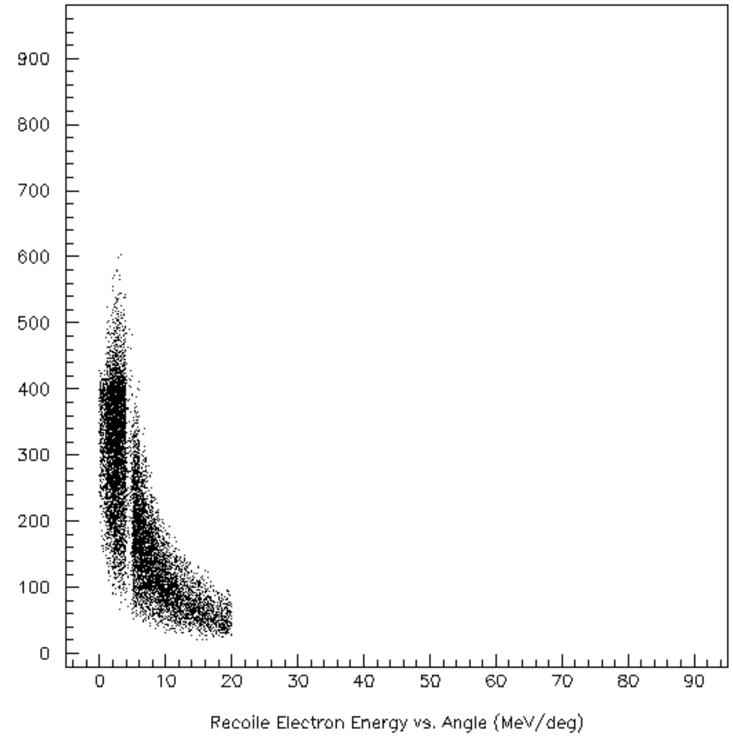




Transition Form Factor Measurements on Electron Target
(combination of HyCal/GEM and Scintillator Ring

E_e = 24 GeV
Q^2 = 0.01 GeV^2





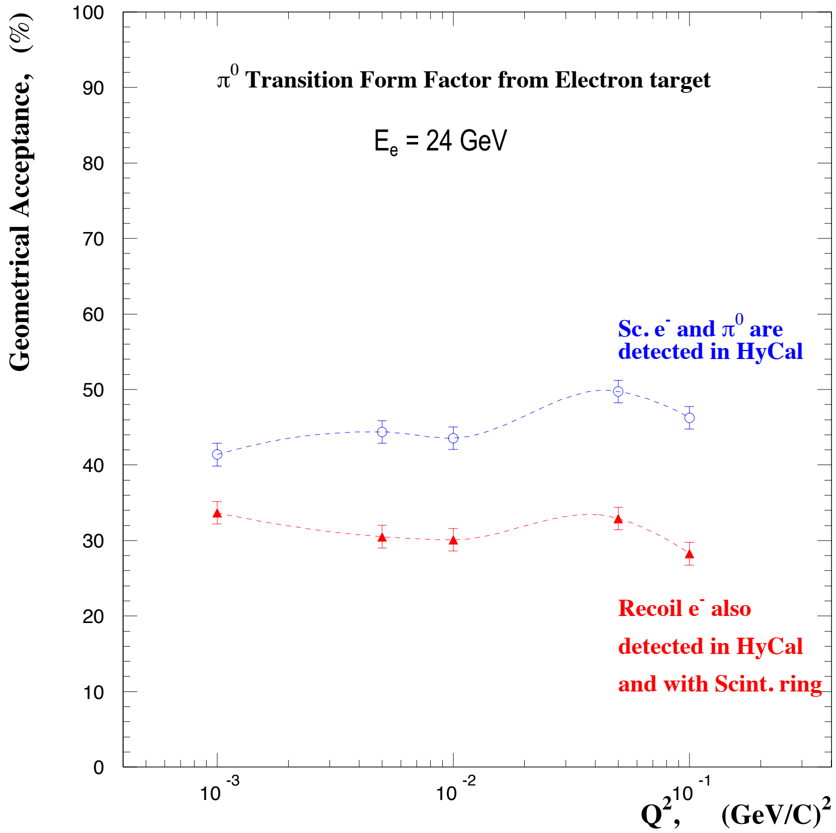
All in HyCal/GEM

Part of the Recoil electrons in the Scintilator Ring

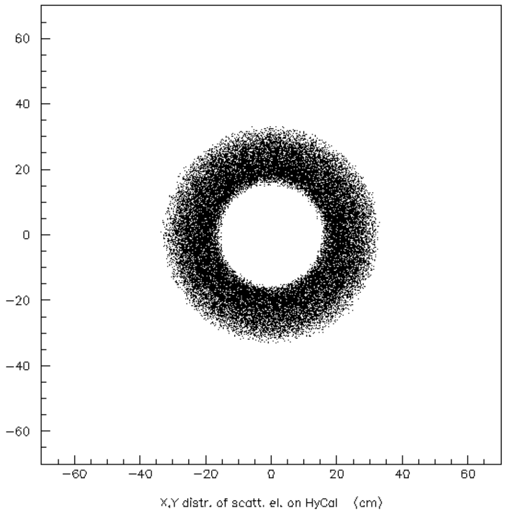
$F(\gamma\gamma* \rightarrow \pi^0)$ Transition Form Factor Experiment

(Geometrical Acceptance at E_e = 24 GeV)

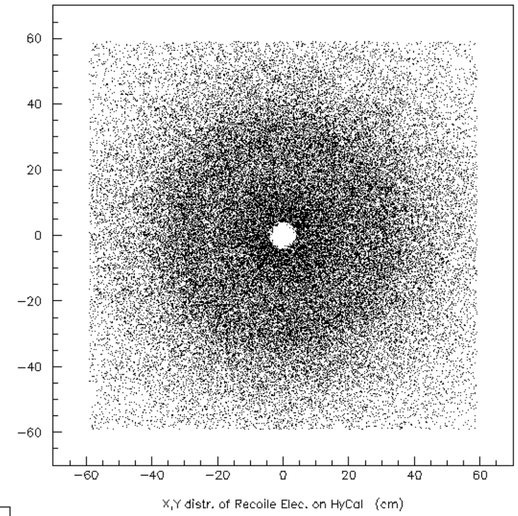
- Detection of all 4 final state particles in HyCal (including the Recoil electron)

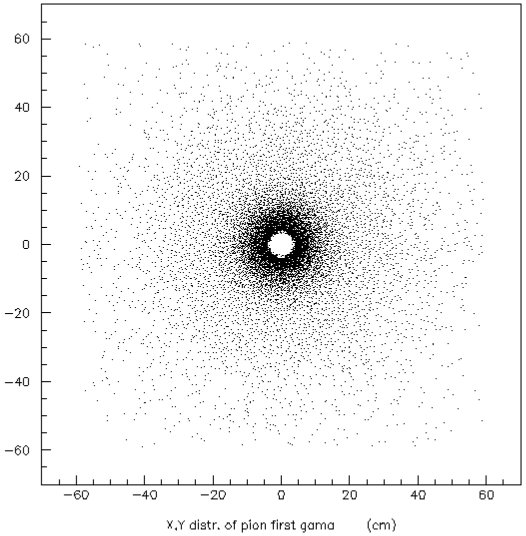


Transition Form Factor Measurements on Electron Target
(X-Y distribution of events on HyCal)



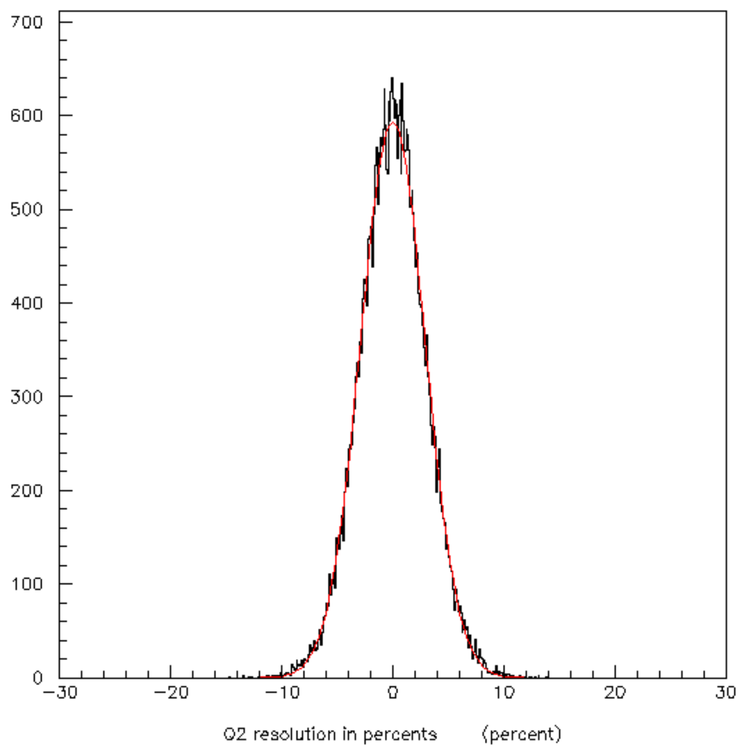
E_e = 24 GeV
Q^2 = 0.01 GeV^2

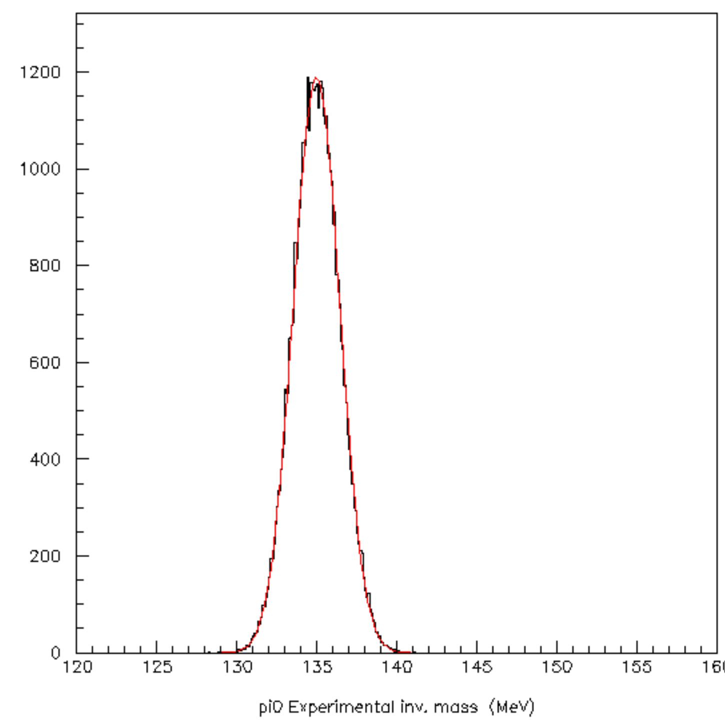




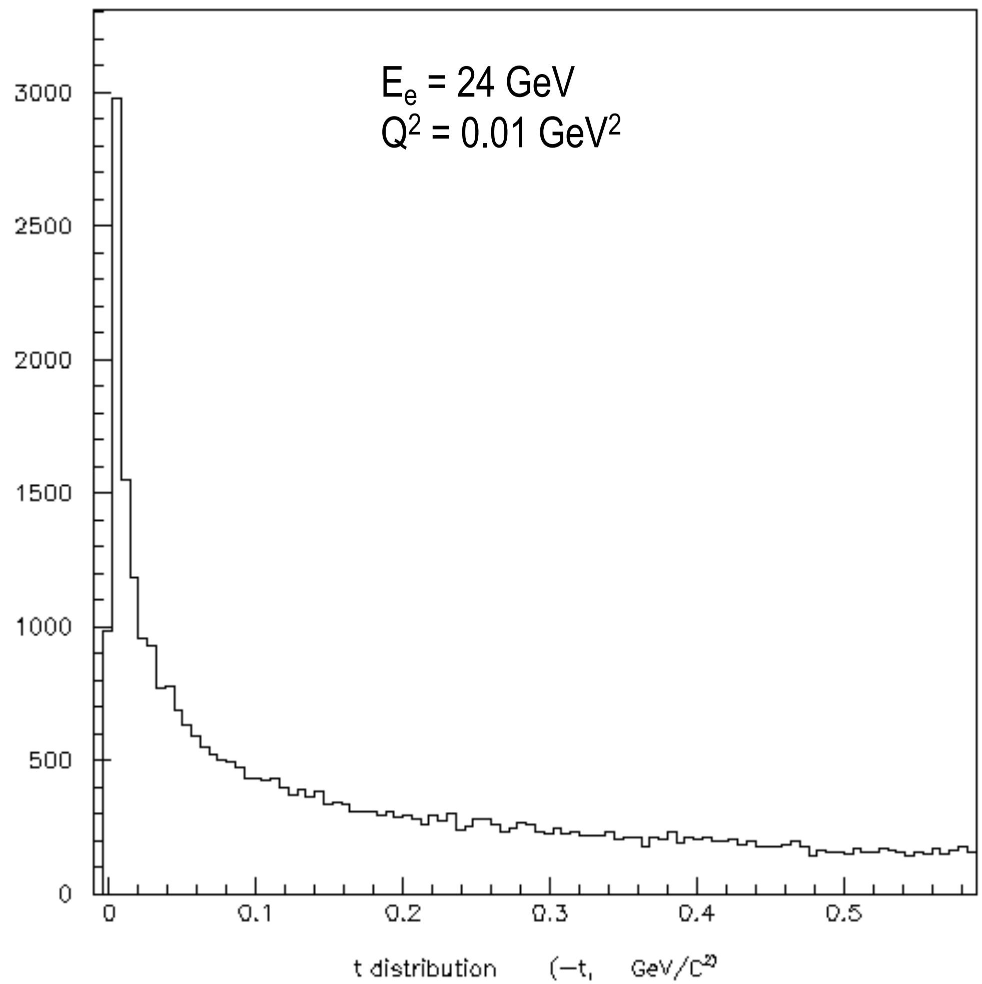
Transition Form Factor Measurements on Electron Target (Experimental Resolutions)

E_e = 24 GeV
Q^2 = 0.01 GeV^2





Transition Form Factor Measurements on Electron Target (kinematical distributions)



Summary

- The CEBAF 24 GeV energy upgrade will significantly enhance the PrimEx experimental program at JLab.

- It will make critical imputes to symmetries, most importantly, their partial breaking effects in QCD directly observable at GeV energy range.

- The sub-percent measurement of the $\Gamma(\pi^0 \to \gamma\gamma)$ transition form factor at low Q^2 range on the atomic electron will provide a critical input to the current $(g\text{-}2)_\mu$ anomaly in physics.

- Currently, work is in progress for the optimization and final development of the $\Gamma(\pi^0 \to \gamma\gamma)$ experiment on atomic electron.

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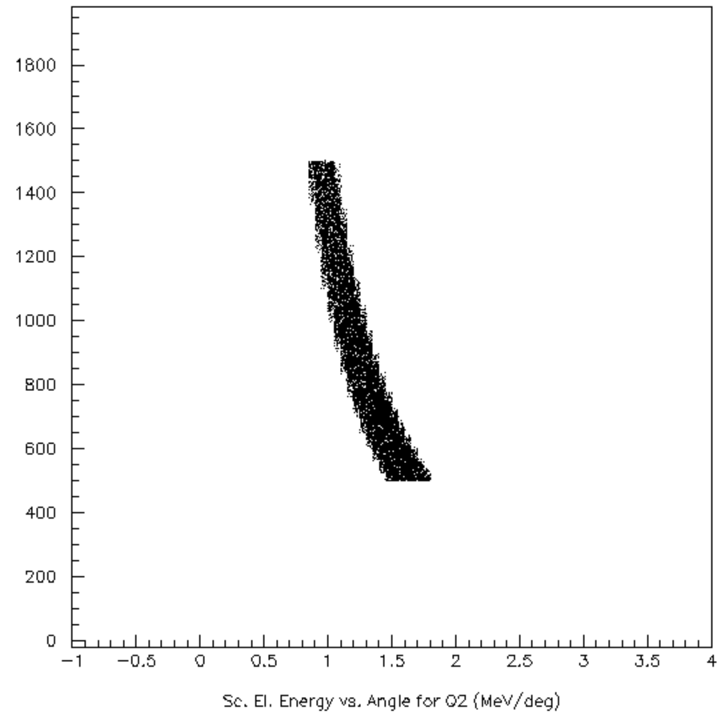
My work is supported in part by research award NSF PHY-PHY-1812421

Transition Form Factor Measurements on Electron Target

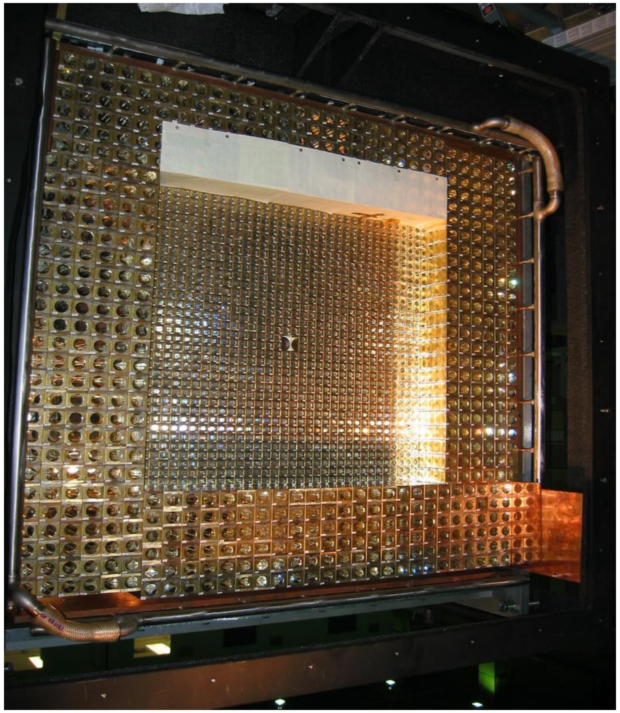


Hybrid EM Calorimeter (HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 cm^2)

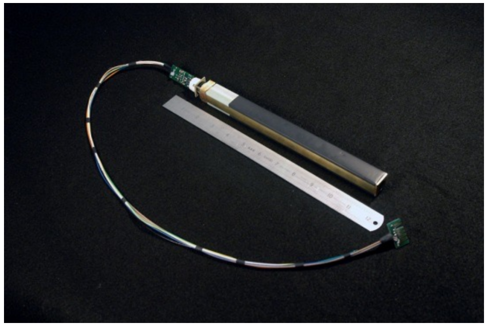
$PbWO_4$ crystals → resolution
Pb-glass → budget

- ✓ 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors (1152 $PbWO_4$ detectors)
- ✓ 576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)
- ✓ 2 x 2 $PbWO_4$ modules removed in middle for beam passage
- ✓ ≈7.5 m from target



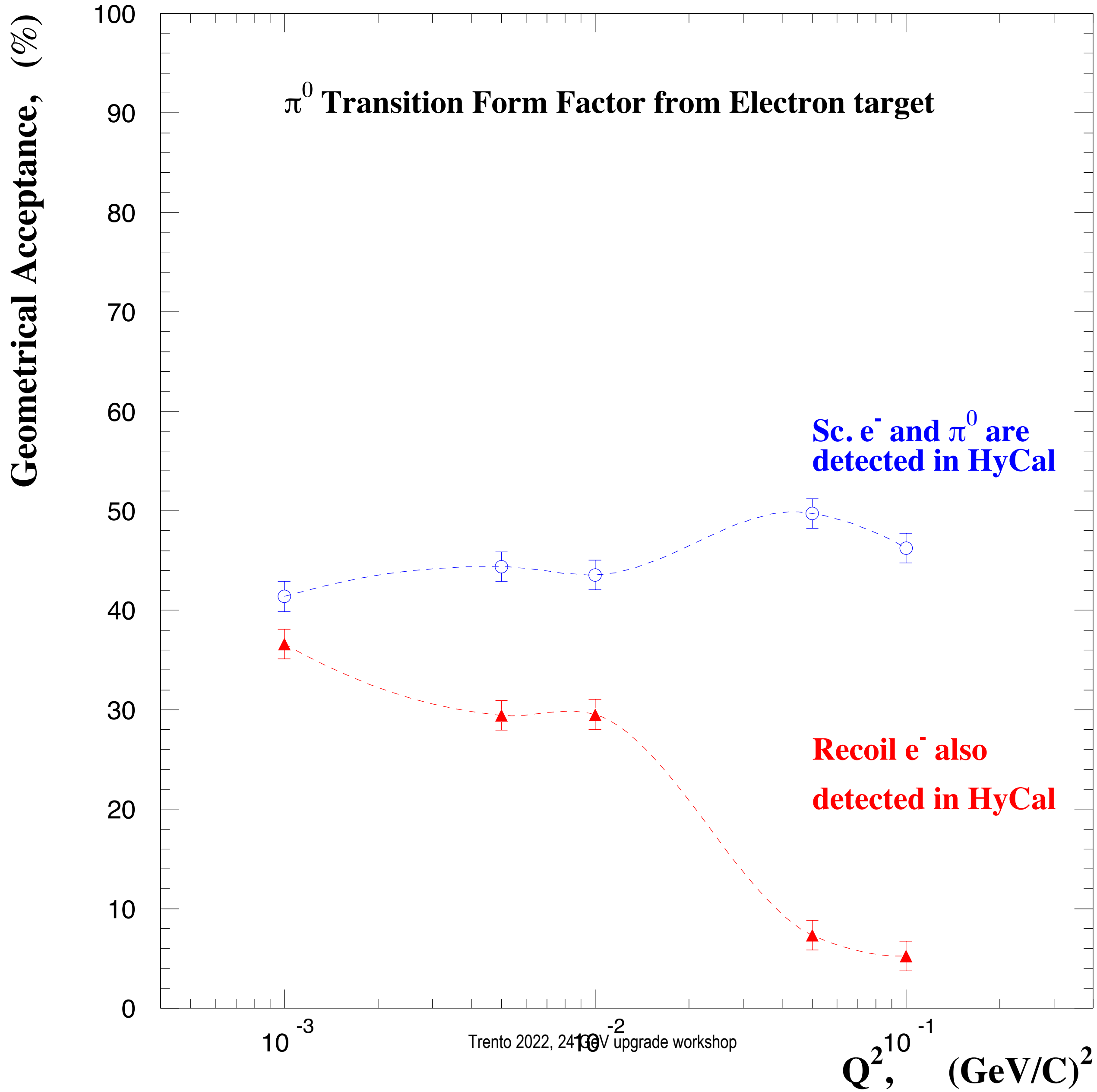
front view, before Light Monitoring System assembly

- Good energy and position resolutions:
  - ✓ $\sigma_E / E = 2.6\% / \sqrt{E}$
  - ✓ $\sigma_{xy} / E = 2.7\ mm / \sqrt{E}$
- Good photon detection efficiency (≈100%)
- Served in 3 precision experiments!



Single $PbWO_4$ detector

Transition Form Factor Measurements on Electron Target



PrimEx Approach for a New Generation Primakoff Experiment

- Use tagged photon beam:
  - ✓ better knowledge of photon flux
  - ✓ energy and timing of incident photons

- Parallel measurement of purely QED processes to control/verify the cross section on 1% level:
  - ✓ Compton scattering from target electrons $(\gamma + e^- \rightarrow \gamma + e^-)$
  - ✓ e^+e^- Pair production from target $(\gamma + {}^{12}C \rightarrow e^+ + e^- + {}^{12}C)$

- Use high resolution electromagnetic calorimeter:
  - ✓ better π^0 invariant mass resolution
  - ✓ better π^0 production angle resolution
  - ✓ less background in "event selection"

- Use particle ID detectors for charged background separation:
  - ✓ reduction of background at event selection stage

- Monitor photon flux at high intensities (with Pair Spectrometer):
  - ✓ photon flux measurement on 1% level