# PrimEx Project with the CEBAF 22 GeV Energy Upgrade

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for the PrimEx Collaboration

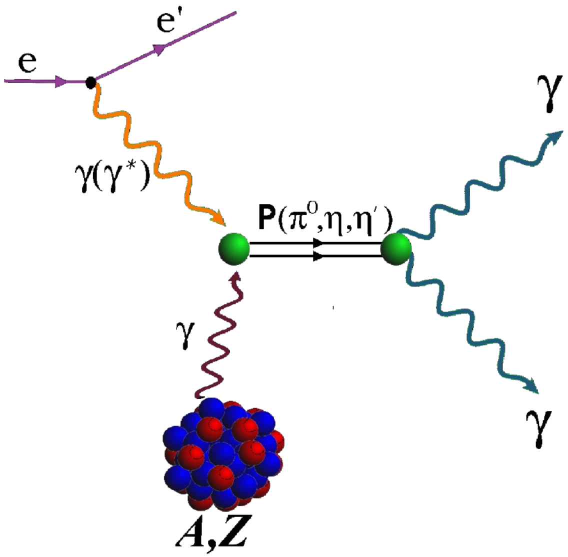
## Outline

- PrimEx program at JLab
- Decay widths at 22 GeV (nuclear and electron targets)
- $\pi^0$ transition form factor on atomic electron
- Proposed experimental setup
- Kinematics and geometrical acceptances
- Summary

# The PrimEx Project 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) $F(\gamma\gamma^* \to \eta')$

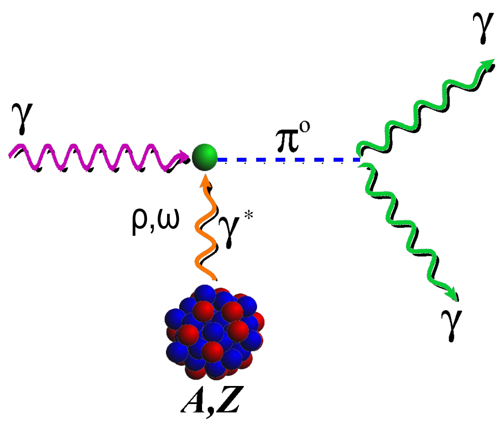



- **Physics reach:**

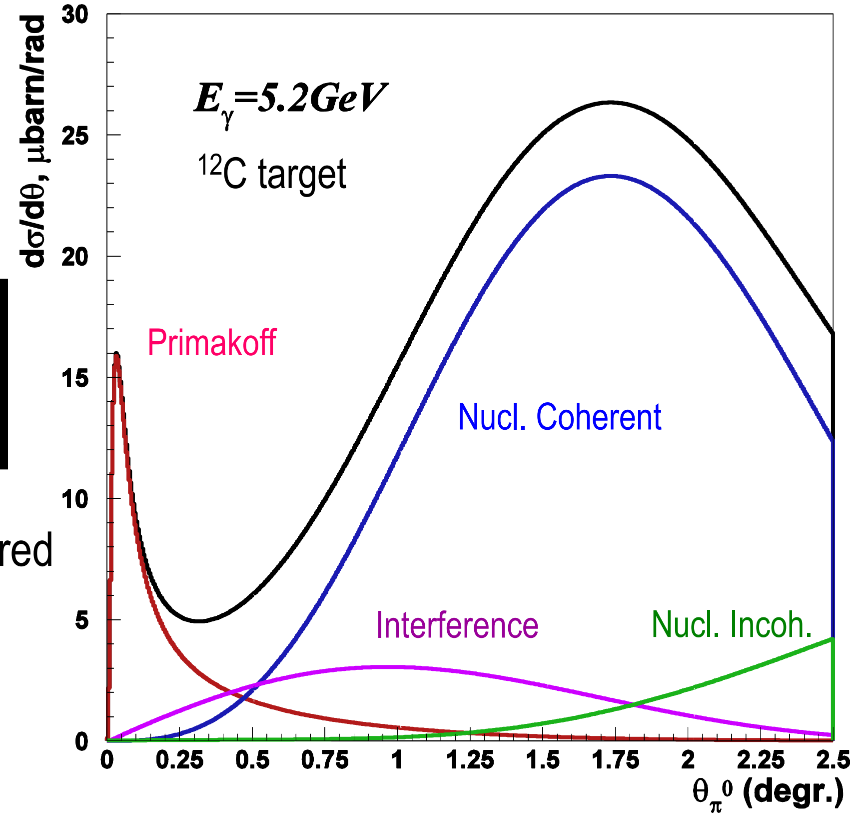
a) precision tests of chiral symmetry and anomalies
b) determination of light quark mass ratio
c) mixing angles
d) $\pi^0$, $\eta$ and $\eta'$ interaction electromagnetic radii
e) Is $\eta'$ an approximate Goldstone boson?
f) Critical contributions to HLbL calculations for $(g\text{-}2)_\mu$

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

# Primakoff Method (on Nuclear Target)




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




- Primakoff coherent cross section measurement required

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

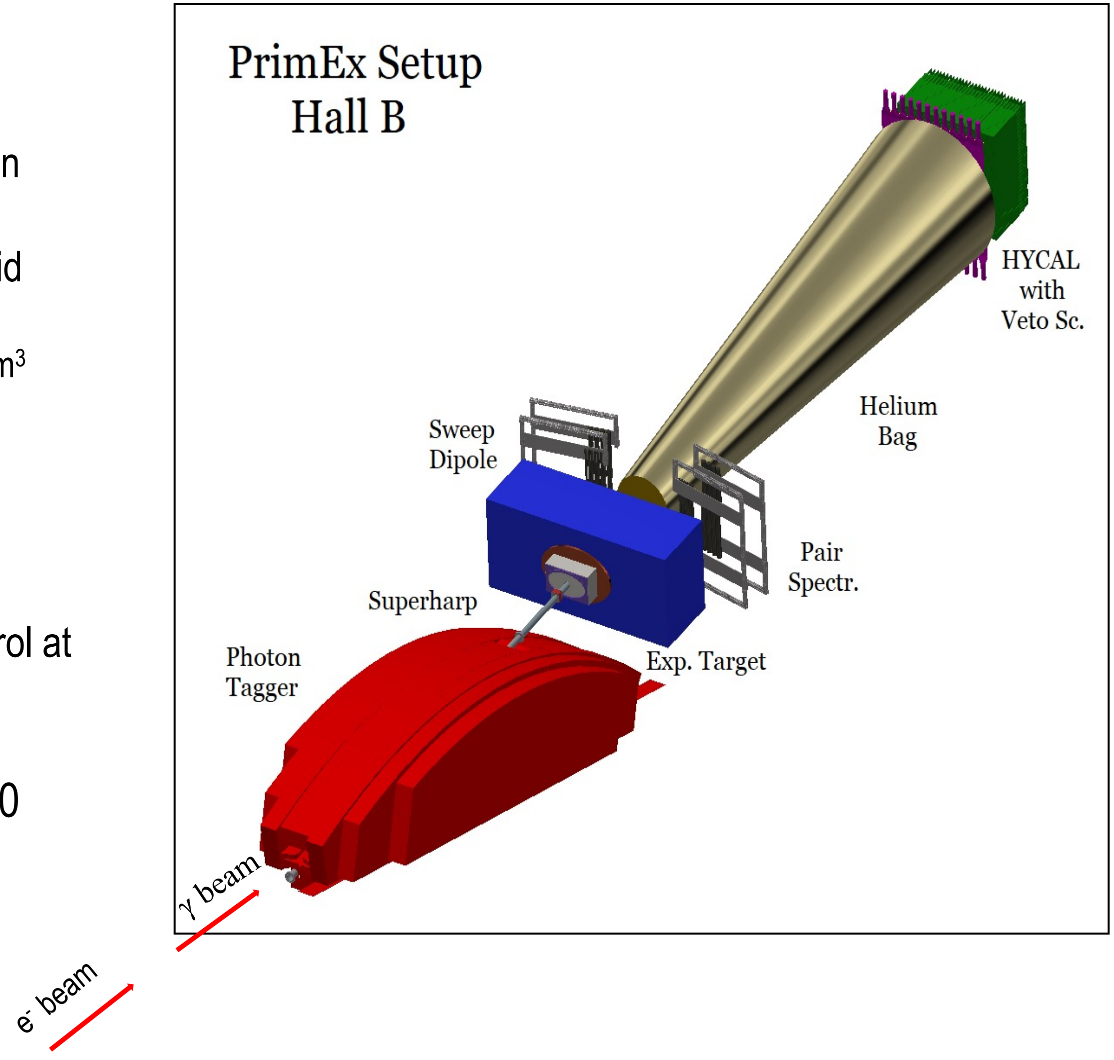
- $(d\sigma/d\Omega)_{\text{Prim. at peak}} \sim E^4$

- Challenges of the method:
  - measure the cross section at very forward angles with high precision
  - extract the Primakoff process from competing nuclear processes

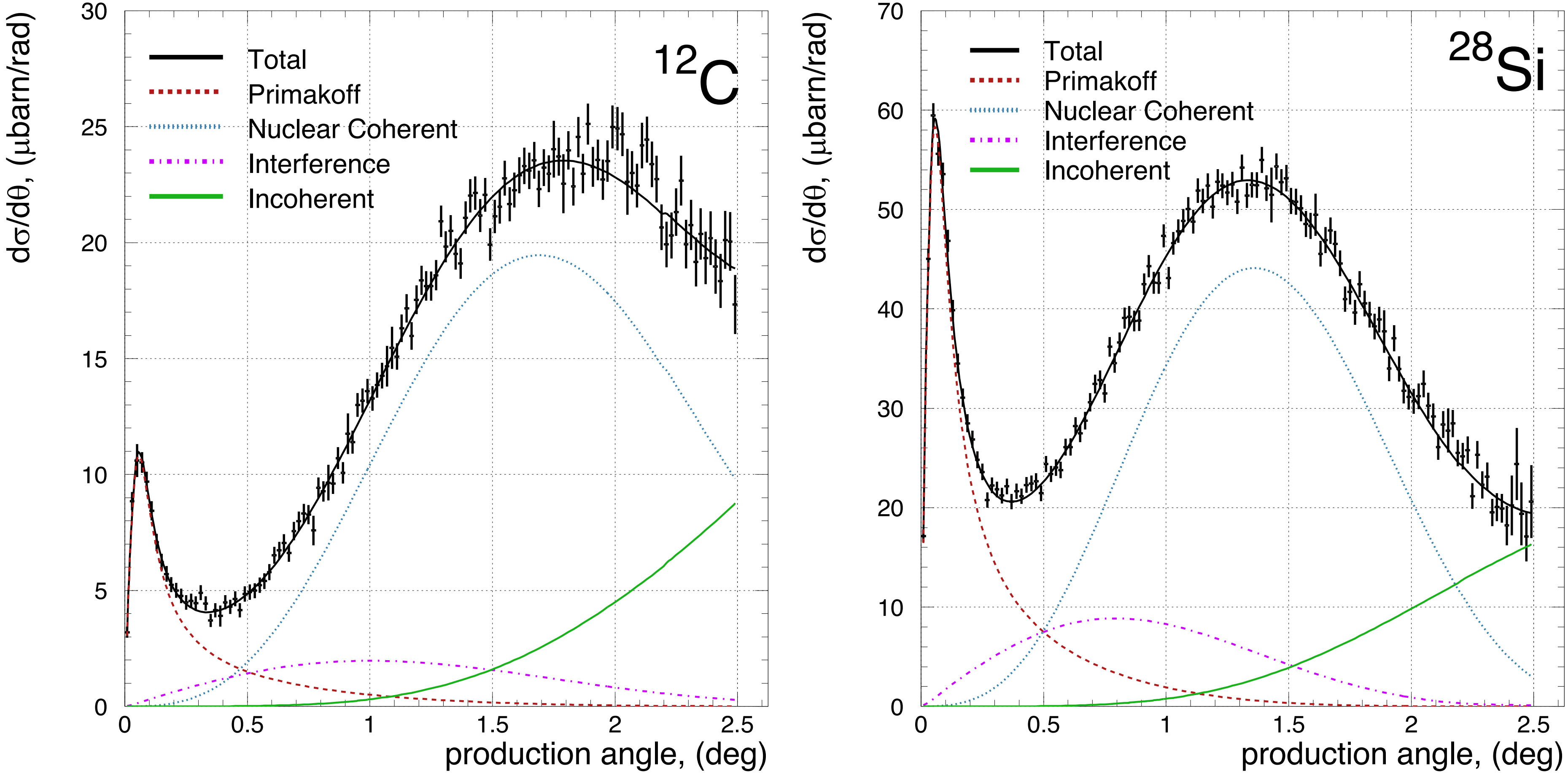
# An Example: $\Gamma(\pi^0 \to \gamma\gamma)$ Decay width Measurement
## (PrimEx Experiments in Hall B at JLab)

- PrimEx-I performed in Hall B in 2004 using:
  - ✓ high resolution, high intensity Hall B photon tagging facility.
  - ✓ new high resolution large acceptance hybrid 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.

- Upgraded PrimEx-II performed in 2010



# PrimEx-II: Extracted Differential Cross Sections




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

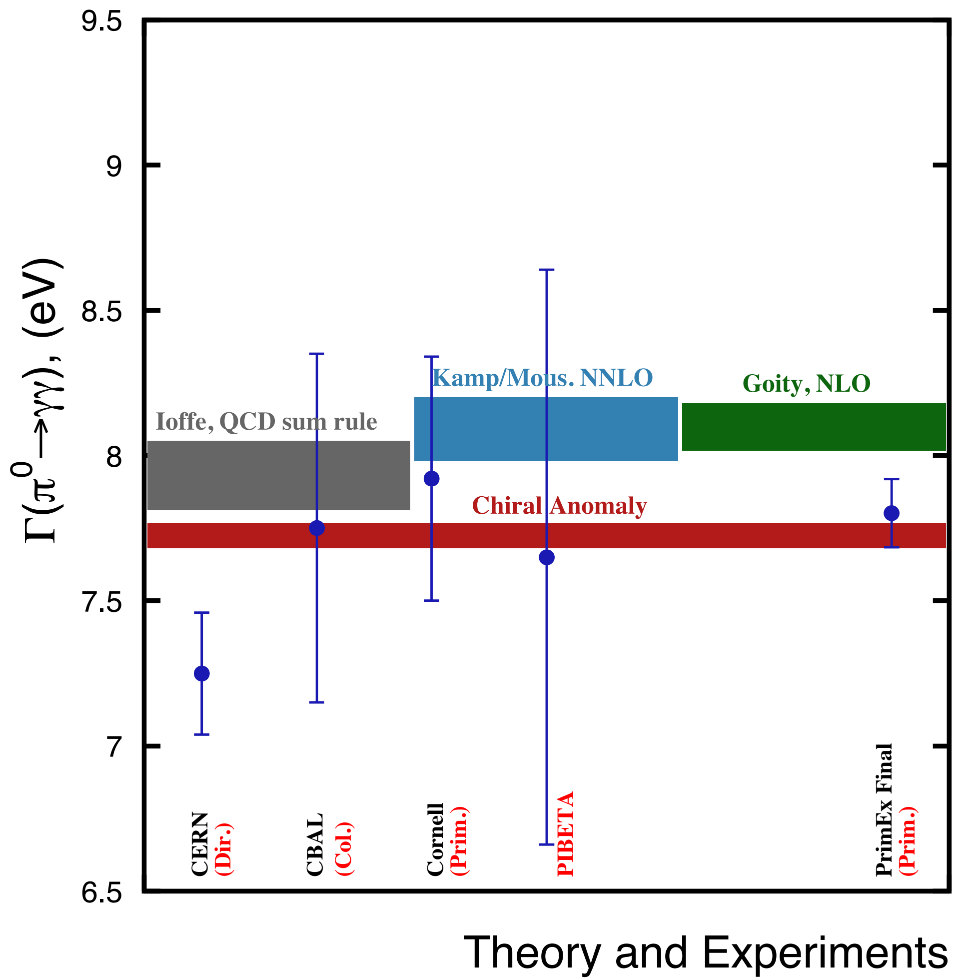
# $\Gamma(\pi^0 \to \gamma\gamma)$: Final Result from PrimEx

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

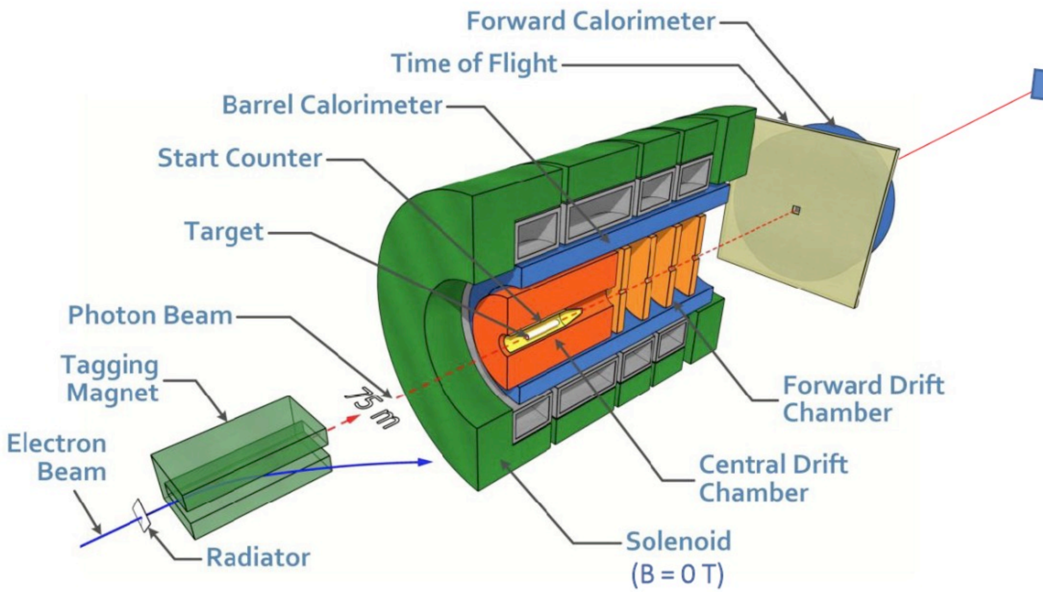
$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.802 ±0.052(stat) ± 0.105(syst.) eV

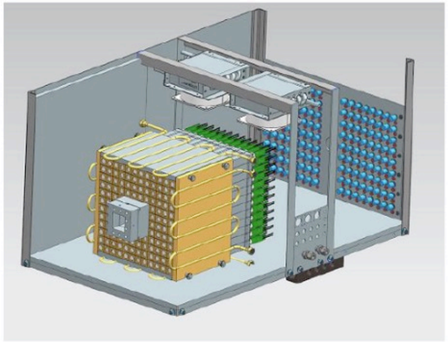
with total uncertainty: ± 1.5%

- contribution of the nuclear background: ± 1.0%

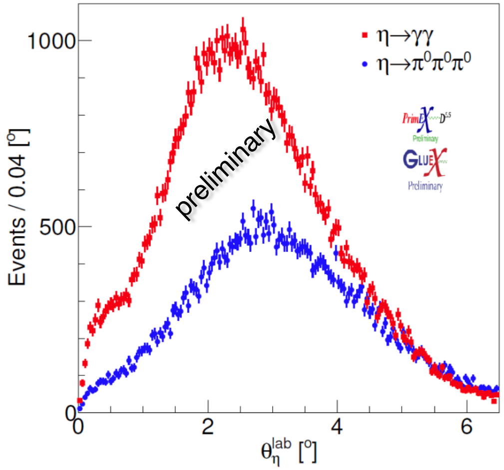


# $\Gamma(\eta \to \gamma\gamma)$ Decay Width Experiment in Hall D



- ✓ Tagged photon beam (~8.0-11.7 GeV)
- ✓ PS and TAC for photon flux control
- ✓ Liquid $^4$He target (~4% R.L.)
- ✓ The $\eta$ decay photons detected by FCAL
- ✓ Compton scattering (FCAL and CCAL) to control
- ✓ overall systematics
- ✓ Data taking completed in December 2022.
- ✓ Expected total uncertainty: 5 – 10%



# $\Gamma(\pi^0\to\gamma\gamma)$ Measurement with the 22 GeV Upgrade (on Atomic Electron)

- Primakoff effect on atomic electron

$$\gamma + e \to \pi^0 + e$$

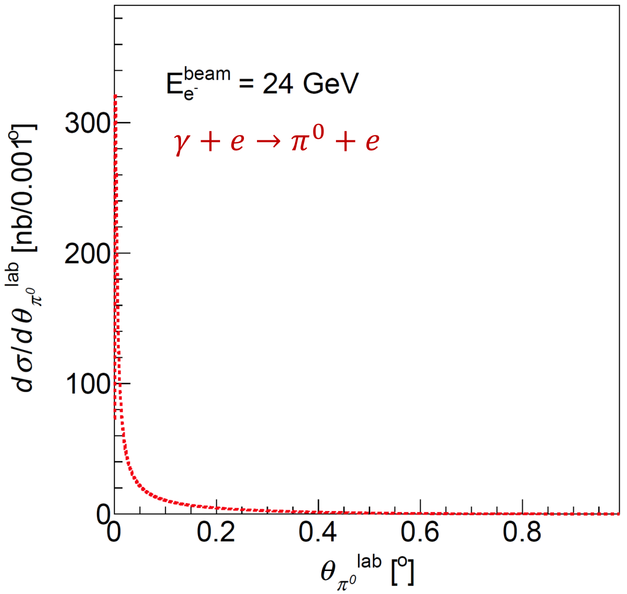
$$\frac{d\sigma_{\mathrm{Pr}}}{d\Omega} = \Gamma_{\gamma\gamma}\frac{8\alpha}{m_\pi^3}\frac{\beta^3 E^4}{Q^4}\sin^2\theta_\pi$$

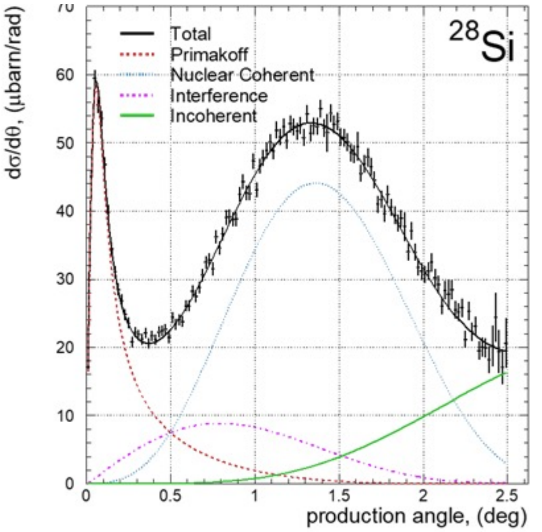
- Advantages of using atomic electron target
  - ✓ no nuclear (hadronic) processes
  - ✓ no nuclear absorption processes
  - ✓ target is point-like, no form factors
  - ✓ detection of recoil electron is feasible
  - ✓ sub-percent uncertainty in $\Gamma(\pi^0\to\gamma\gamma)$ with 22 GeV is realistic

- Requires threshold energy:

$$E_\gamma = ((m_{\pi 0} + m_{e-})^2 - m_{e-}^2)/(2\, m_{e-}) \approx 18\ \text{GeV}$$

- Can be performed with 22 GeV energy upgrade



# $\Gamma(\eta\to\gamma\gamma)$ and $\Gamma(\eta'\to\gamma\gamma)$ Experiments with 22 GeV Upgrade (on Nuclear Targets)

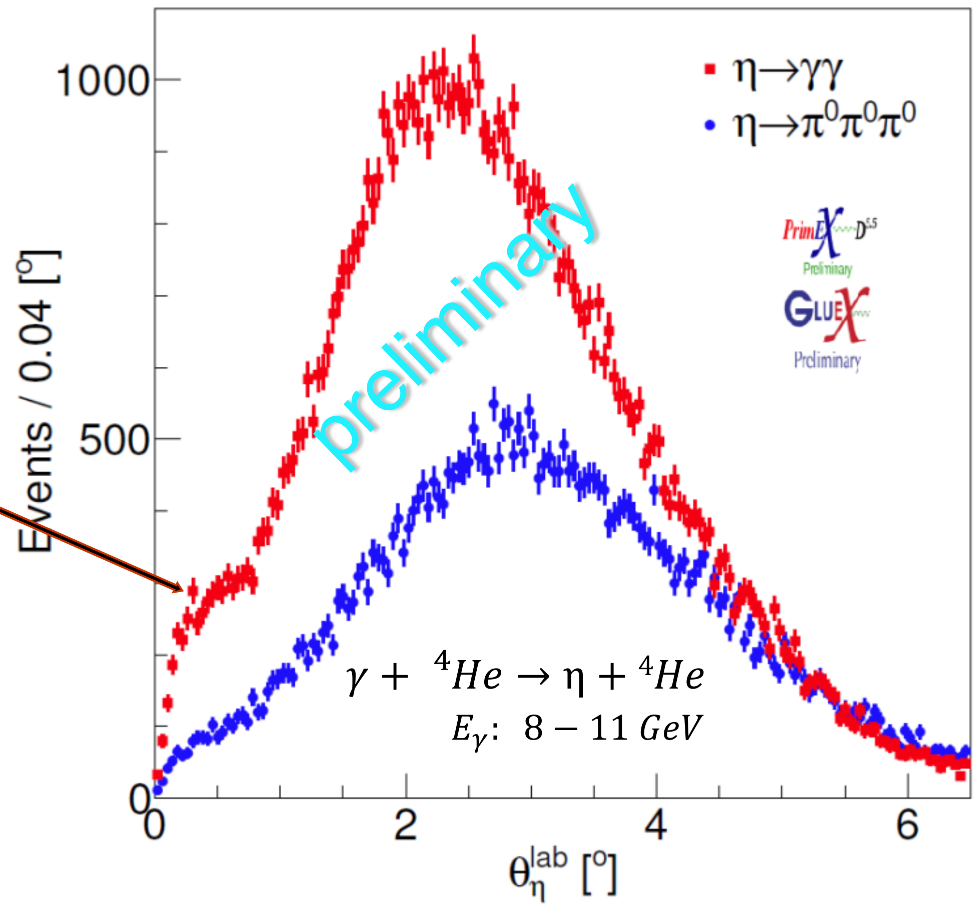
- Using standard PrimEx method on nuclear target

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

$$(N_{E22}/N_{E12}) \sim \left(\frac{24}{12}\right)^4 \approx 16$$

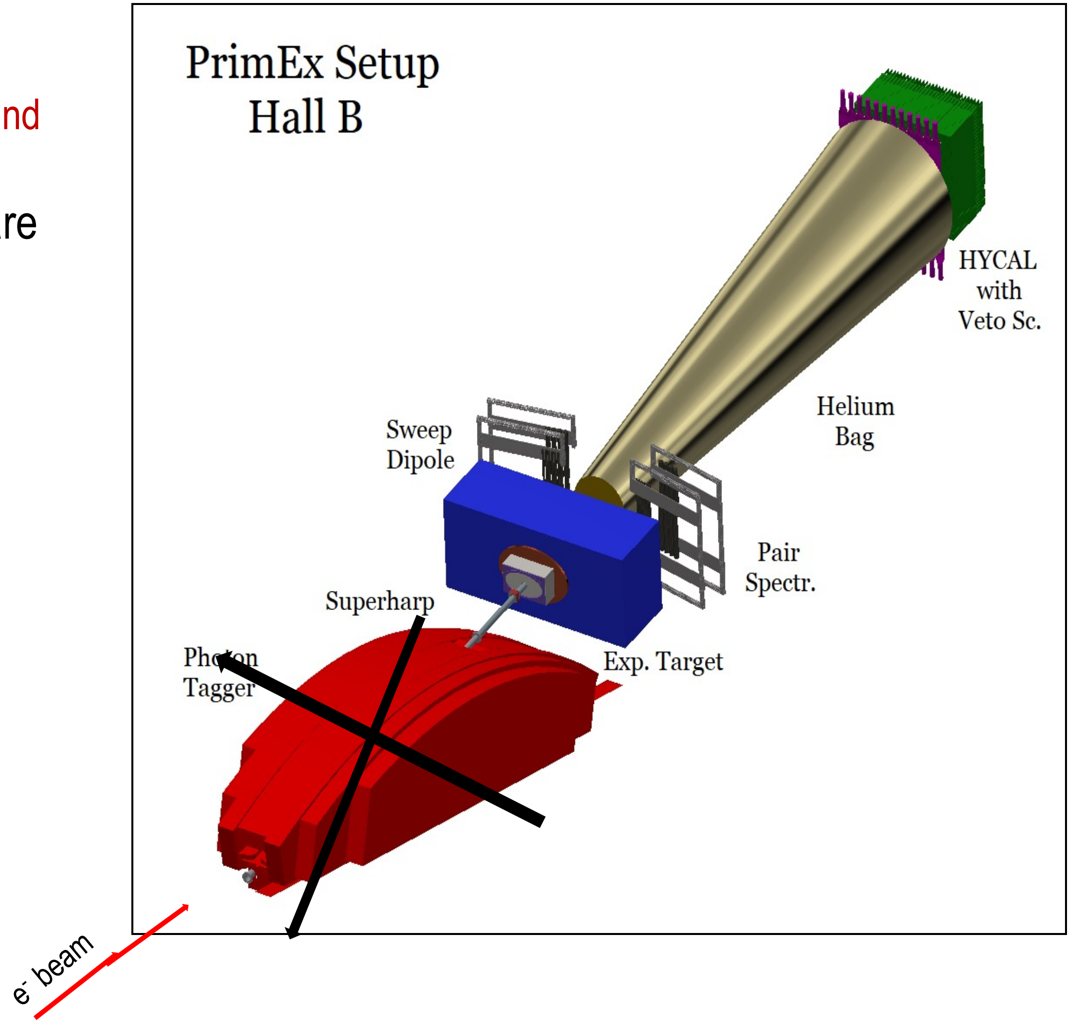
2 - 3% uncertainty in $\Gamma(\eta\to\gamma\gamma)$ can be reached.

- $\Gamma(\eta'\to\gamma\gamma)$ measurement can be done with the 22 GeV energy upgrade only



# Transition Form Factor Measurements on Nuclear Targets with the 22 GeV Energy Upgrade

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

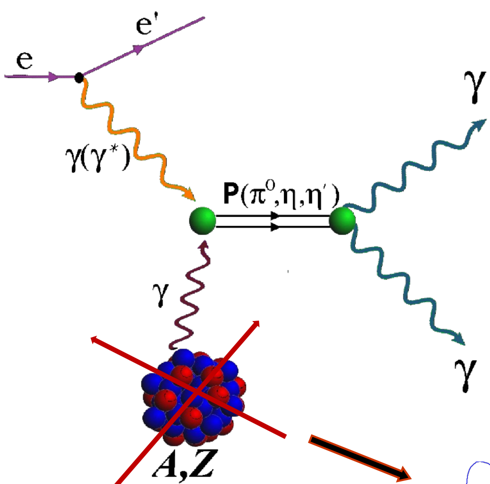


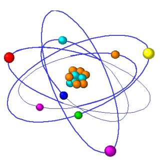
# $F(\gamma\gamma* \rightarrow \pi^0)$ Transition Form Factor Experiment
## (on Atomic Electron with 22 GeV Upgrade)

- Use atomic electron as a target
  $e^- + e^- \rightarrow e' + e^- + \boldsymbol{\pi^0}$
  $\pi^0 \rightarrow \gamma\gamma$
- Requires threshold energy for $\gamma$*

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

  for $Q^2 \approx 0.001$ GeV$^2$: $E_{\gamma*} \approx 18.1$ GeV



e⁻ from atom

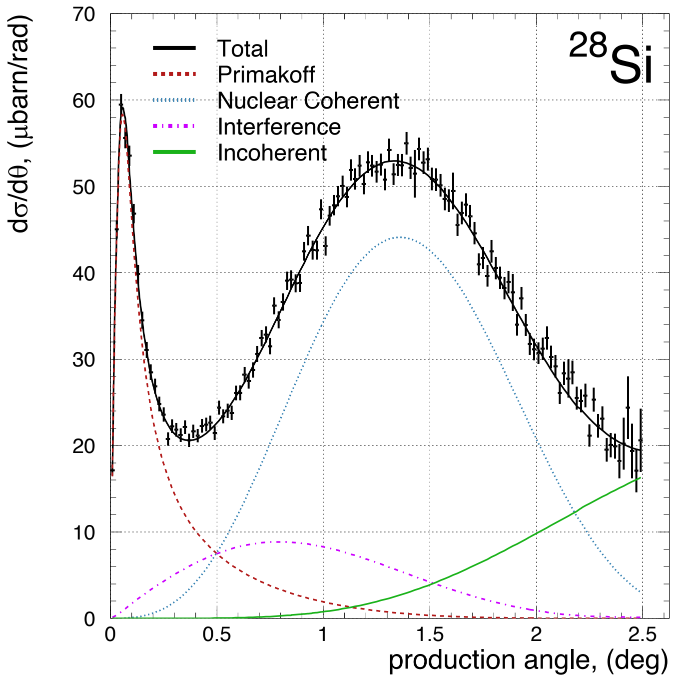
- Experimental method: detect all 4 final state particles:
  - ✓ scattered electrons
  - ✓ recoil electrons
  - ✓ two photons from $\boldsymbol{\pi^0}$ decay
- Will provide full kinematical control:
  - ✓ reaction identification;
  - ✓ total energy conservation;
  - ✓ total 3-momentum conservation.

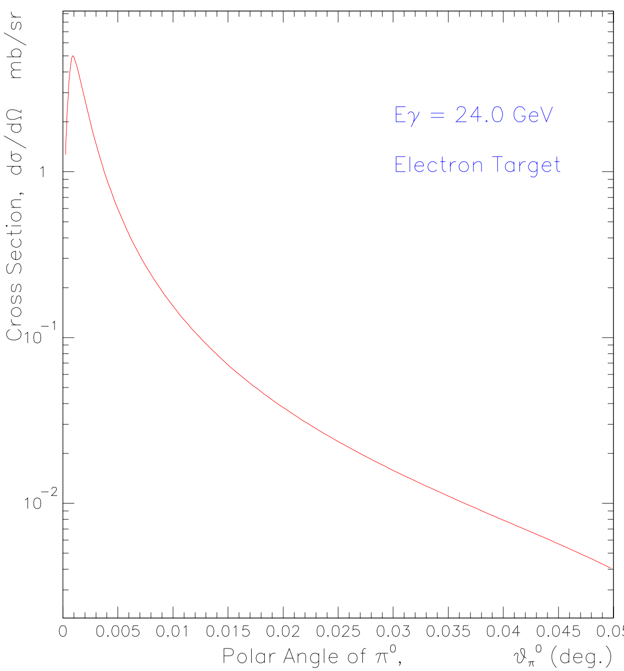
# $F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment
# (on Atomic Electron with 22 GeV Upgrade)

- Primakoff production on atomic electron:

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

- Advantages of using atomic electron target
  - ✓ no nuclear (hadronic) processes
  - ✓ no nuclear absorption processes
  - ✓ target is point-like, no form factors
  - ✓ detection of recoil electron is feasible
  - ✓ sub-percent uncertainty in $F(\gamma\gamma^* \to \pi^0)$ is realistic

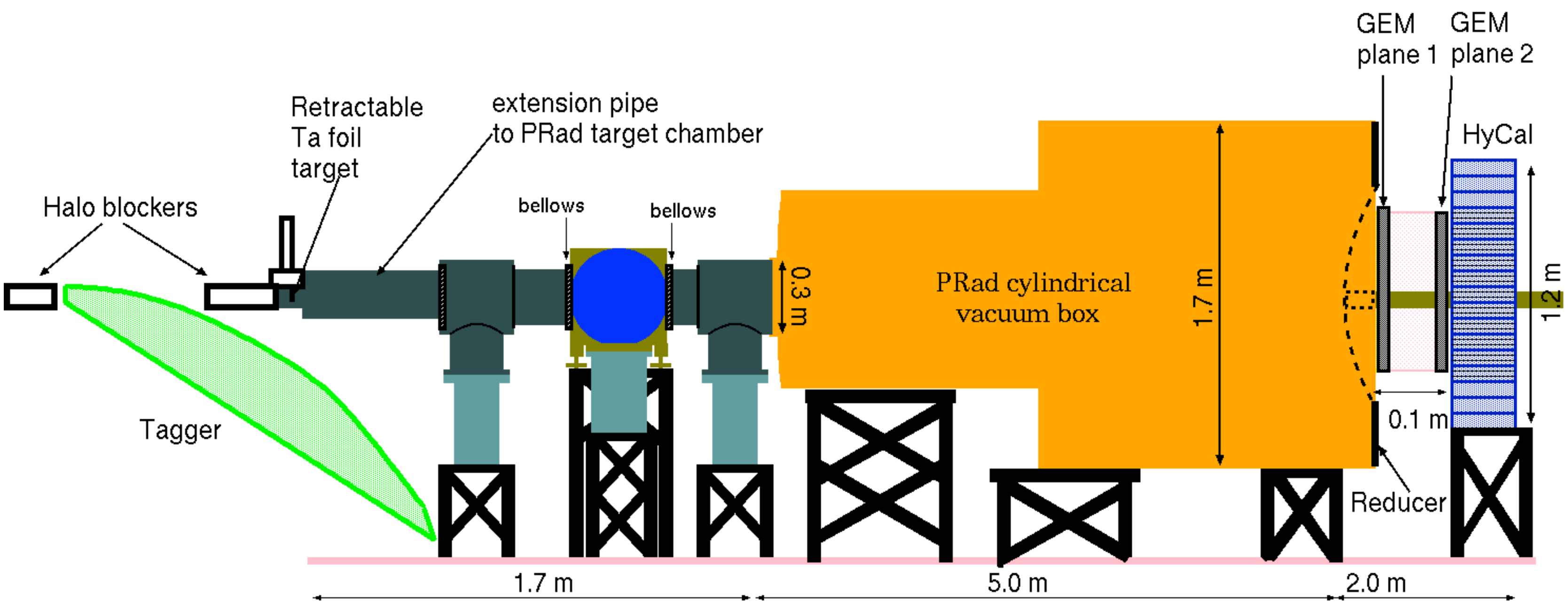


# Proposed Experimental Setup
## (Use PRad experimental setup)

- 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)



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

## (Reaction Kinematics at $E_e$ = 22 GeV)

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

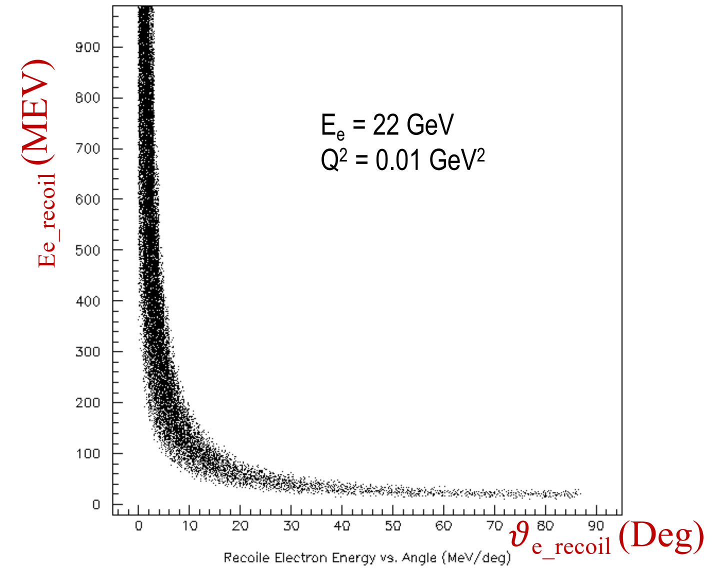
$$\pi^0 \to \gamma\gamma$$

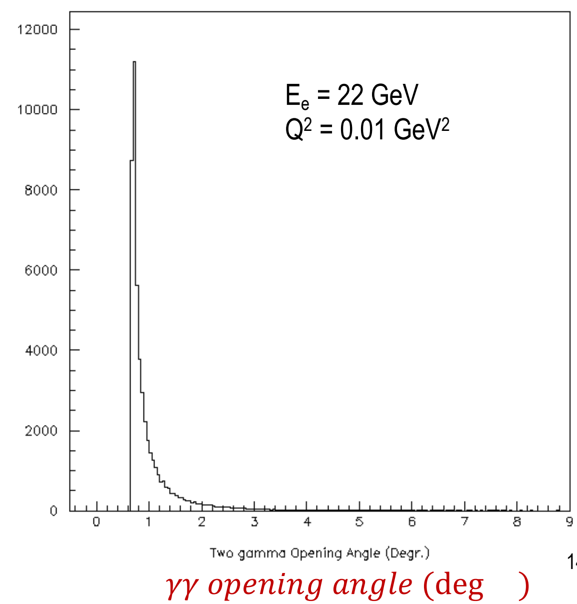
- Scattered electron in HyCal
(provides low $Q^2$ range: $\approx 10^{-3} - 10^{-1}$ GeV$^2$):
$\vartheta \approx 0.3^0 - 3^0$,
$E_{e'} \approx 0.3 - 3.5$ GeV

- The $\gamma^*$ and $\pi^0$ are produced on extremely forward directions with energies $\approx$20 GeV

- Recoil electron angles: (forward – $90^0$)

- $\pi^0 \to \gamma\gamma$ decay is very forward due to high energies



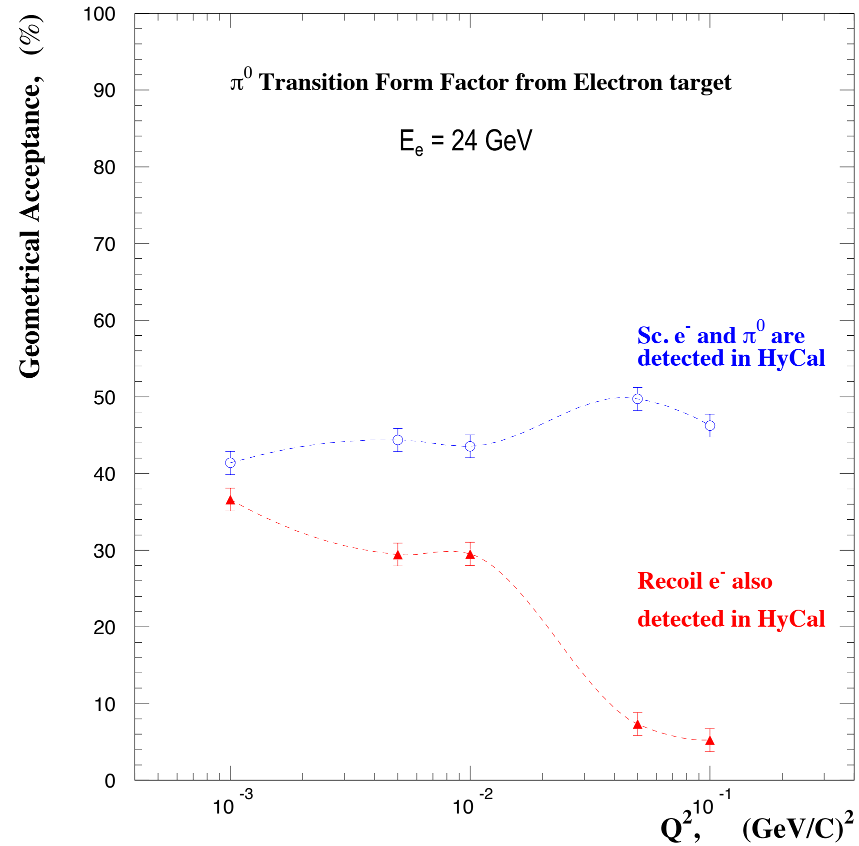
# $F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment
## (Geometrical Acceptance at $E_e$ = 22 GeV)

- 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

  $E_\gamma > 0.5$ GeV from $\pi^0 \to \gamma\gamma$ decay

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



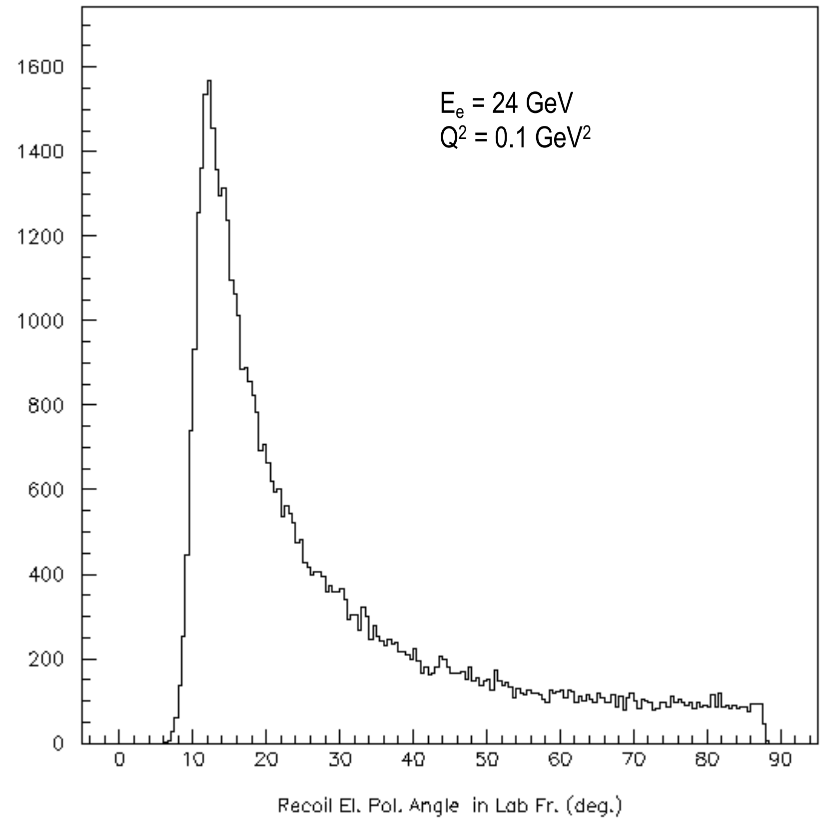
# $F(\gamma\gamma * \to \pi^0)$ Transition Form Factor Experiment

## (Reaction Kinematics at $E_e$ = 22 GeV and Relatively High $Q^2$ Range ($\sim 10^{-1}$ $GeV^2$))

- HyCal angular coverage at Z=10 m:

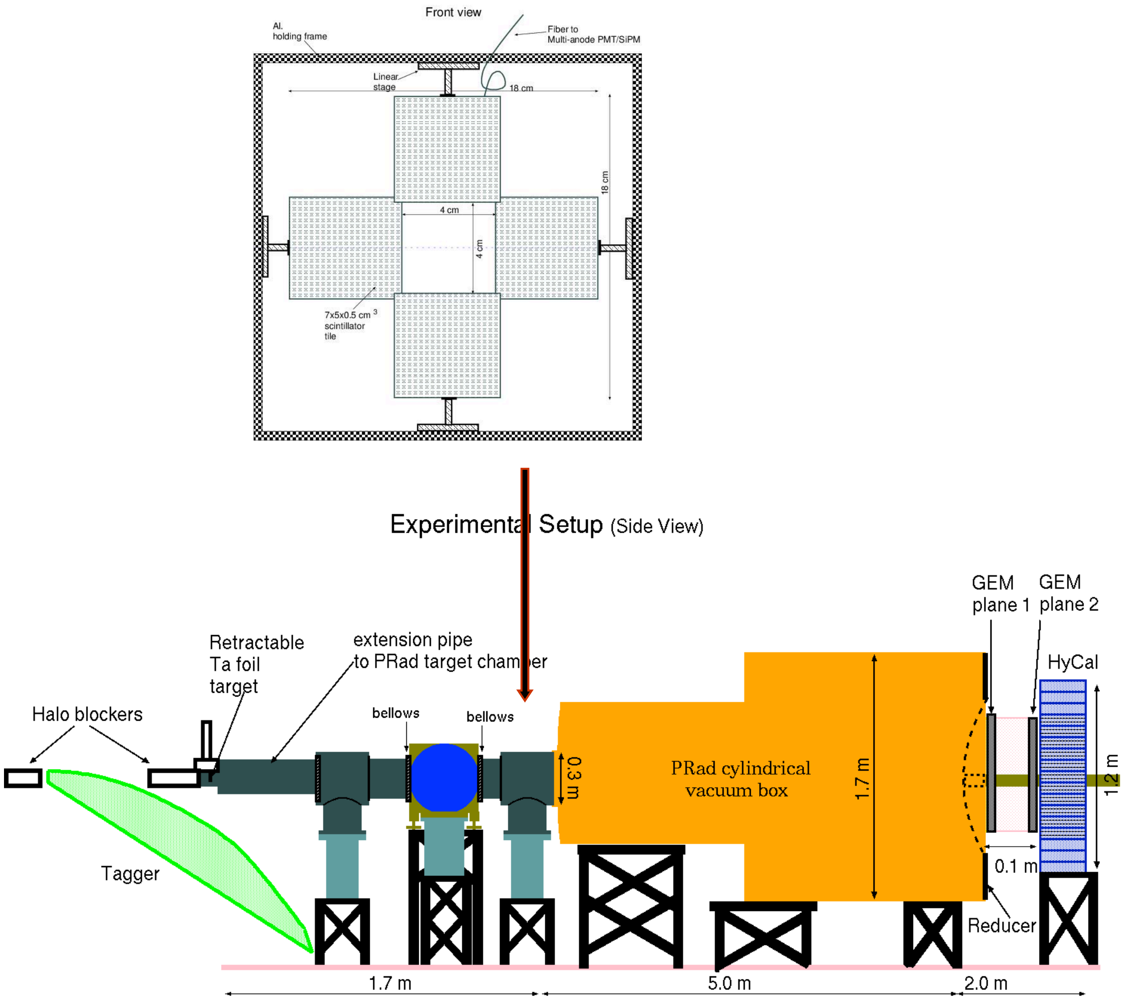
  $\vartheta \approx 0.3^0 - 3^0$

- For the $Q^2 \sim 0.1$ $GeV^2$ range recoil electrons are out of the HyCal acceptance



# The Proposed Experimental Setup: New Scintillator Ring (similar to PRad-II experiment)

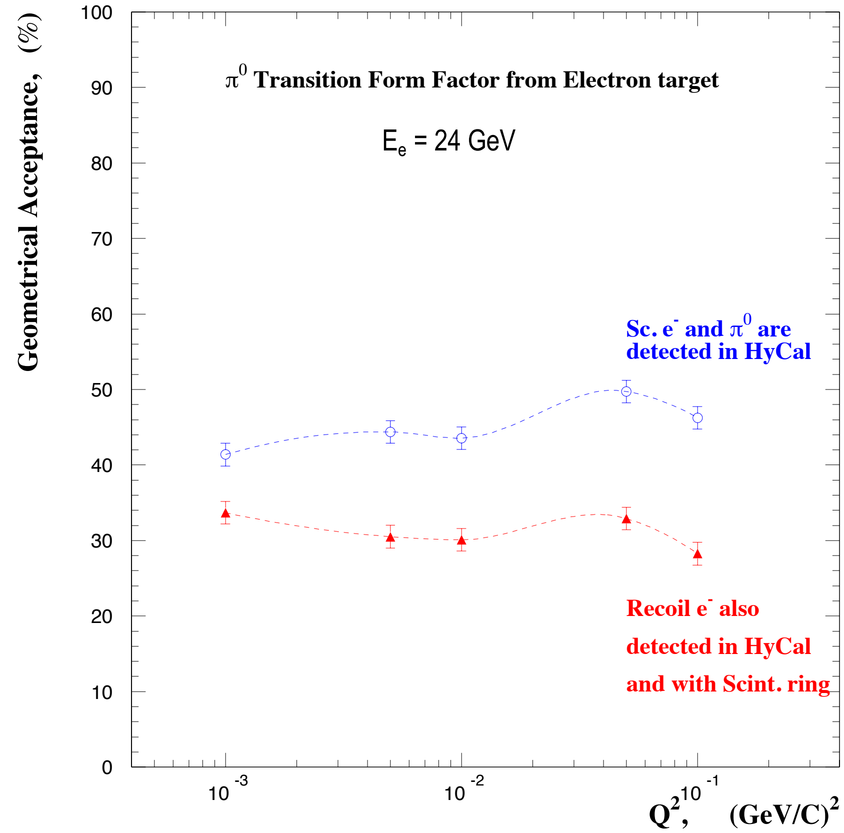
- Add a scintillator ring like the PRad-II experiment



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

## (Geometrical Acceptance at $E_e$ = 22 GeV)

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



# Summary

- The CEBAF 22 GeV energy upgrade will significantly enhance the PrimEx experimental program at JLab.
- The sub-percent measurement of the $\Gamma(\pi^0\rightarrow\gamma\gamma)$ 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.
- It will provide a unique opportunity to measure the $\pi^0\rightarrow\gamma\gamma$ decay width with a sub-percent accuracy, providing a critical information for fundamental symmetries in QCD.
- It will provide a critical opportunity for the $\eta' \rightarrow\gamma\gamma$ decay width measurement for the first time providing a critical information for fundamental symmetries in QCD.
- All these experiments are easily feasible and do not require a "large scale funding".

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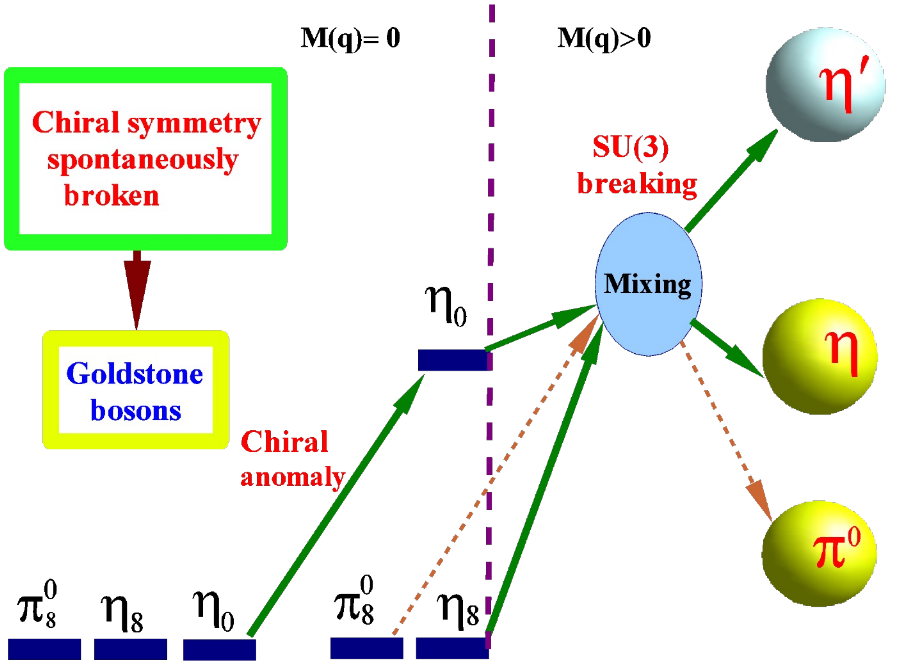
# Physics Motivation: Symmetries in QCD

- Classical QCD Lagrangian in Chiral limit is invariant under:

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

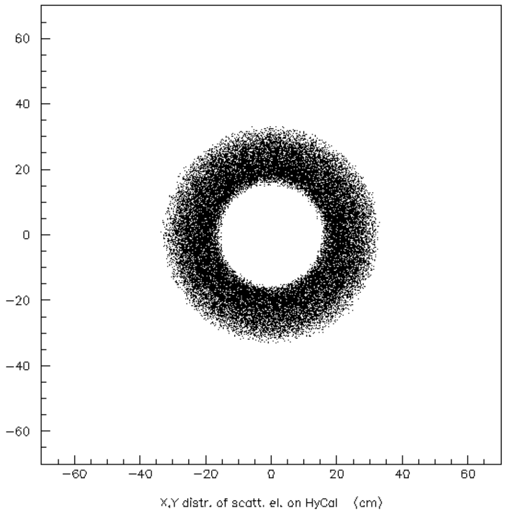
- Chiral $SU_L(3)xSU_R(3)$ spontaneously broken:
  - 8 Goldstone bosons (π,K,η)
- $U_A(1)$ is explicitly broken:

(axial or chiral anomaly)
  - $\Gamma(\pi^0\rightarrow\gamma\gamma)$, $\Gamma(\eta\rightarrow\gamma\gamma)$, $\Gamma(\eta'\rightarrow\gamma\gamma)$
  - mass of $\eta_0$
- quarks are massive and different, SU(3) is broken:
  - Goldstone bosons are massive
  - mixing of $\pi^0$ $\eta$ $\eta'$

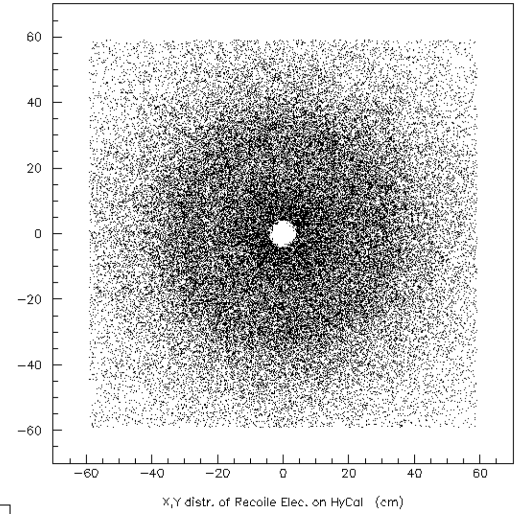


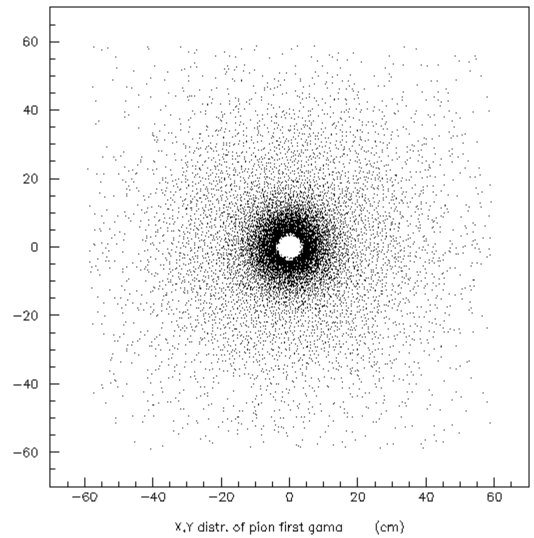

The $\pi^0$, $\eta$, $\eta'$ system provides a rich laboratory to study the symmetry structure of QCD at low energies.

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




$E_e$ = 22 GeV
$Q^2$ = 0.01 GeV$^2$

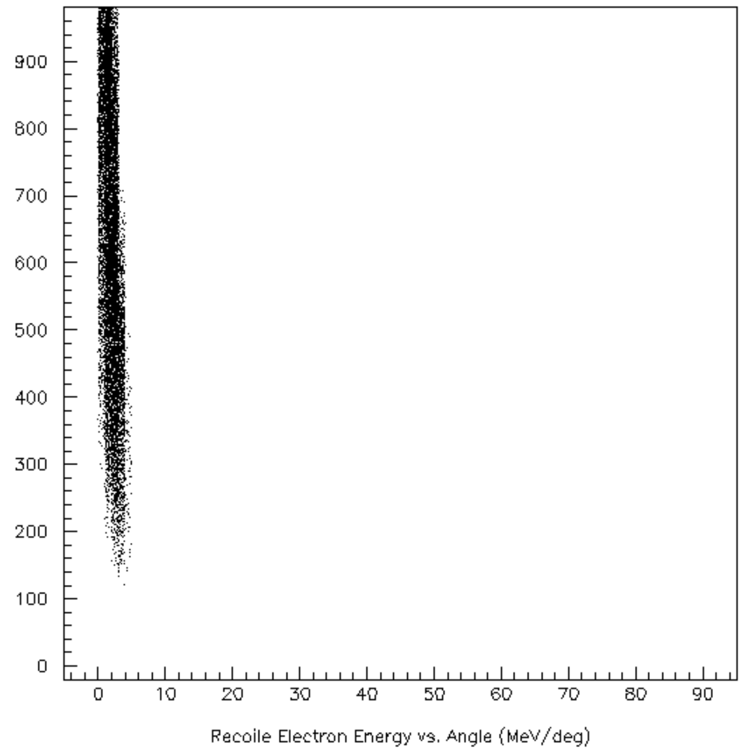


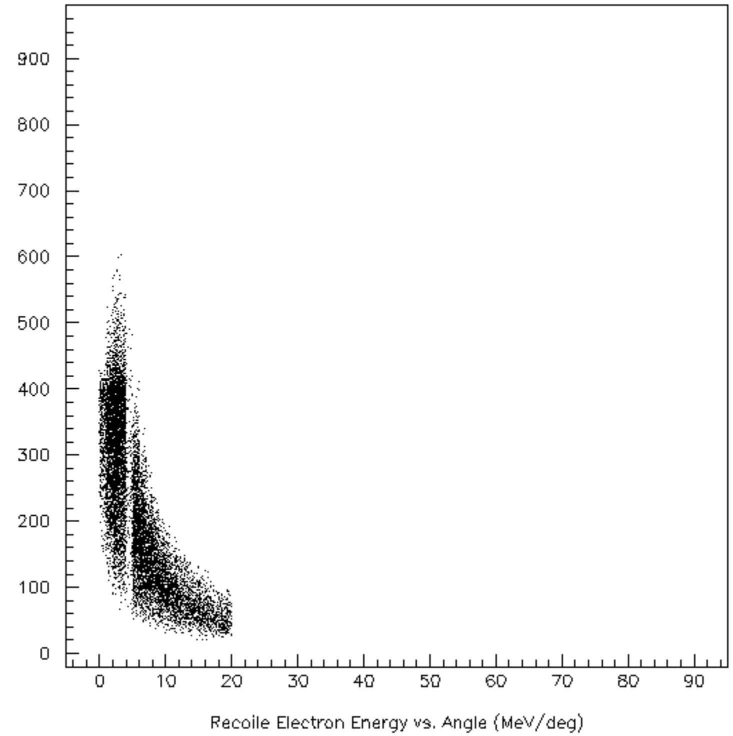
# Transition Form Factor Measurements on Atomic Electron

## (combination of HyCal/GEM and Scintillator Ring)

$E_e$ = 22 GeV
$Q^2$ = 0.01 GeV$^2$

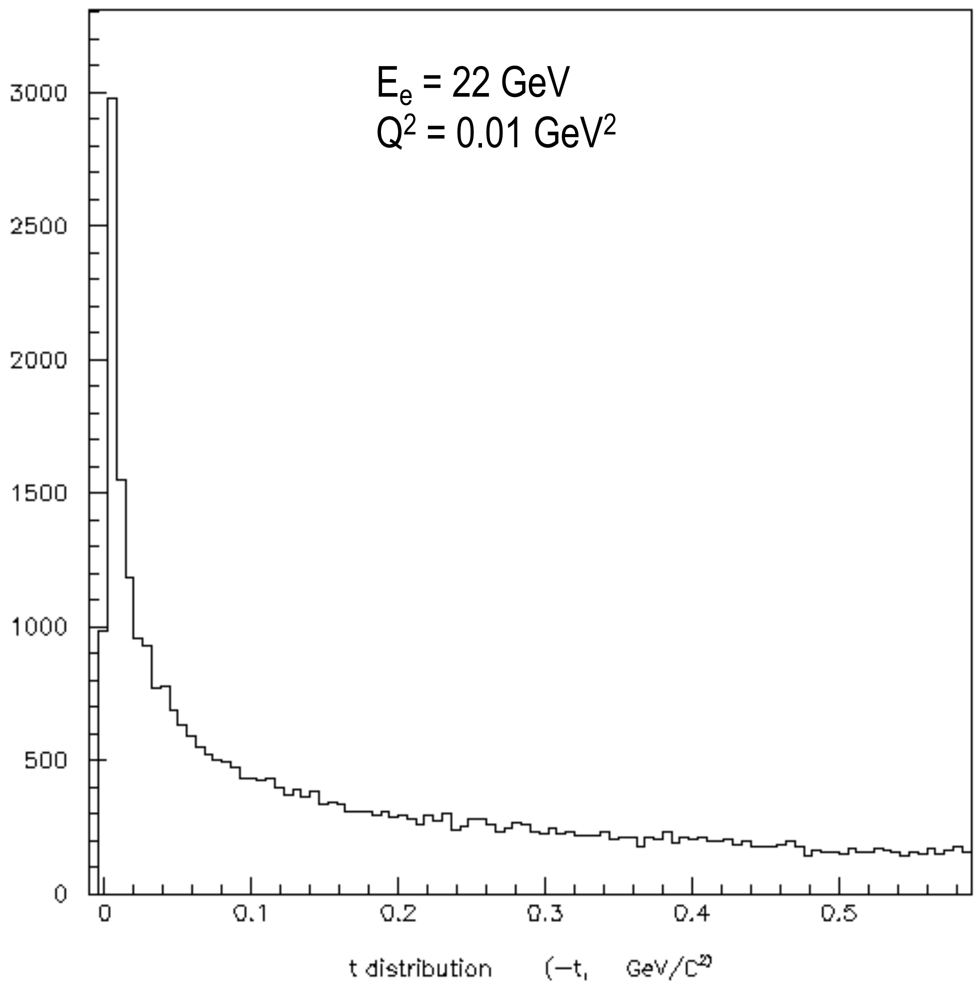



All in HyCal/GEM



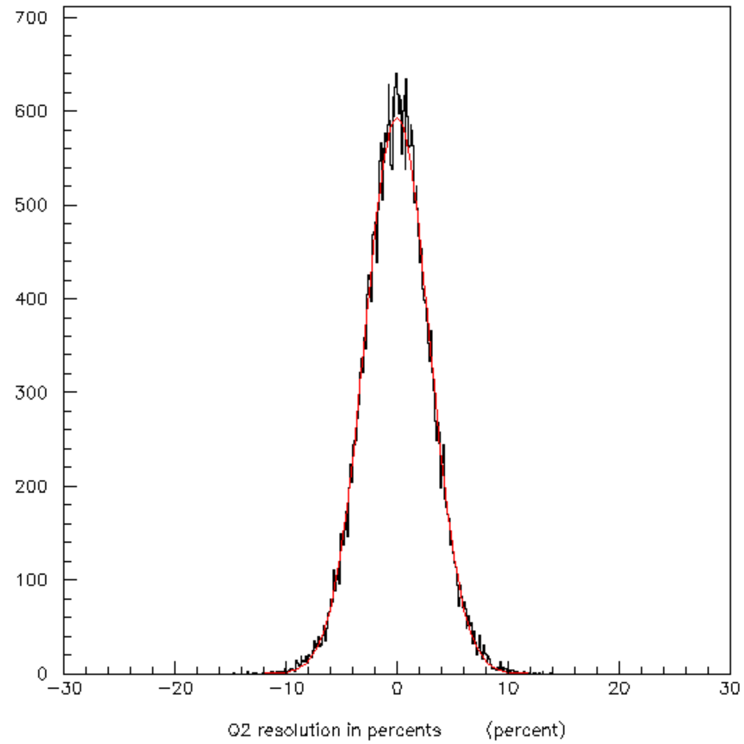

Part of the Recoil electrons in the Scintilator Ring

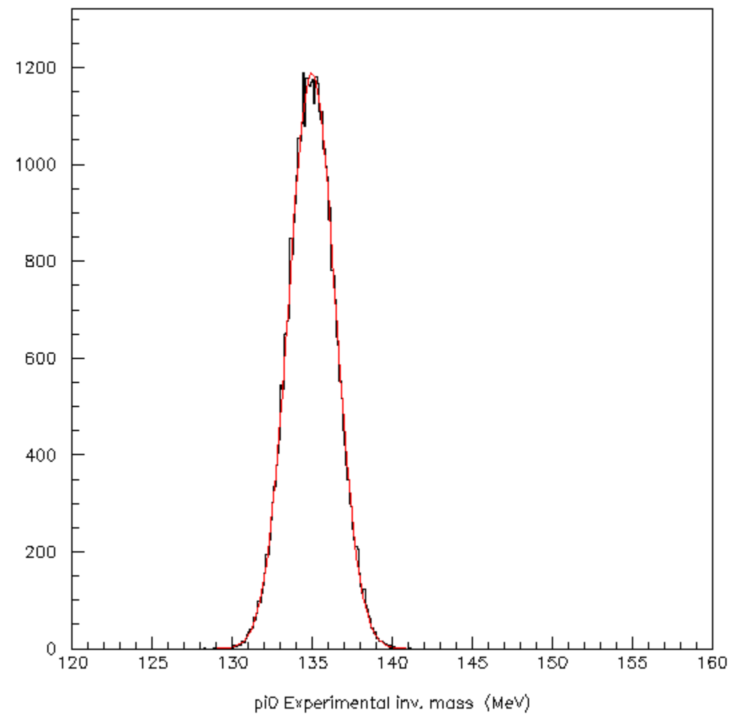
# Transition Form Factor Measurements on Electron Target
## (kinematical distributions)



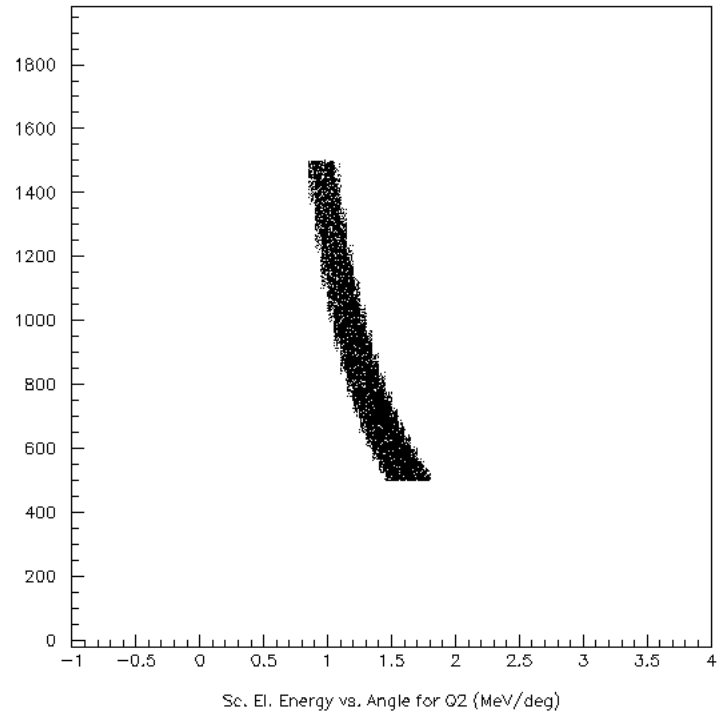
# Transition Form Factor Measurements on Electron Target
# (Experimental Resolutions)

$E_e$ = 22 GeV
$Q^2$ = 0.01 $GeV^2$



# Transition Form Factor Measurements on Electron Target

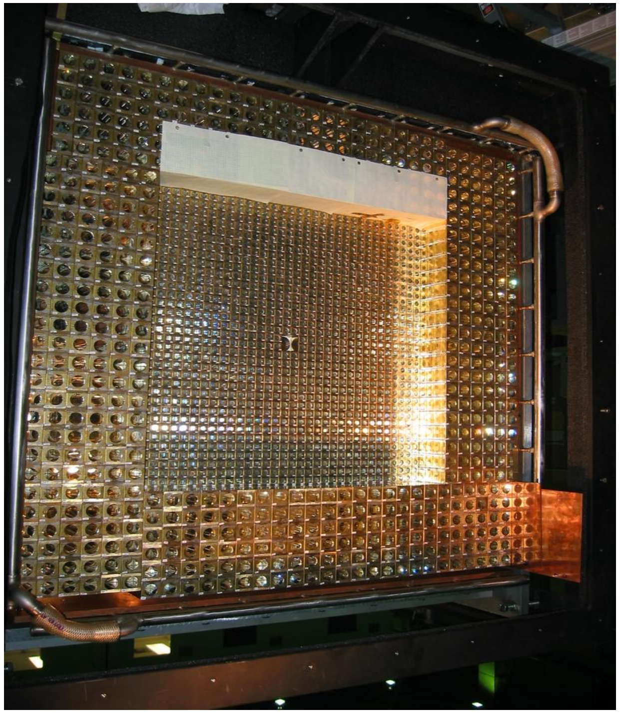


# Hybrid EM Calorimeter (HyCal)

- 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

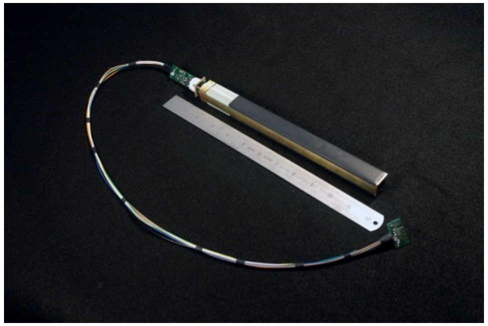
- Good energy and position resolutions:

  ✓ $\sigma_E / E = 2.6\% / \sqrt{E}$

  ✓ $\sigma_{xy} / E = 2.7\ \text{mm} / \sqrt{E}$

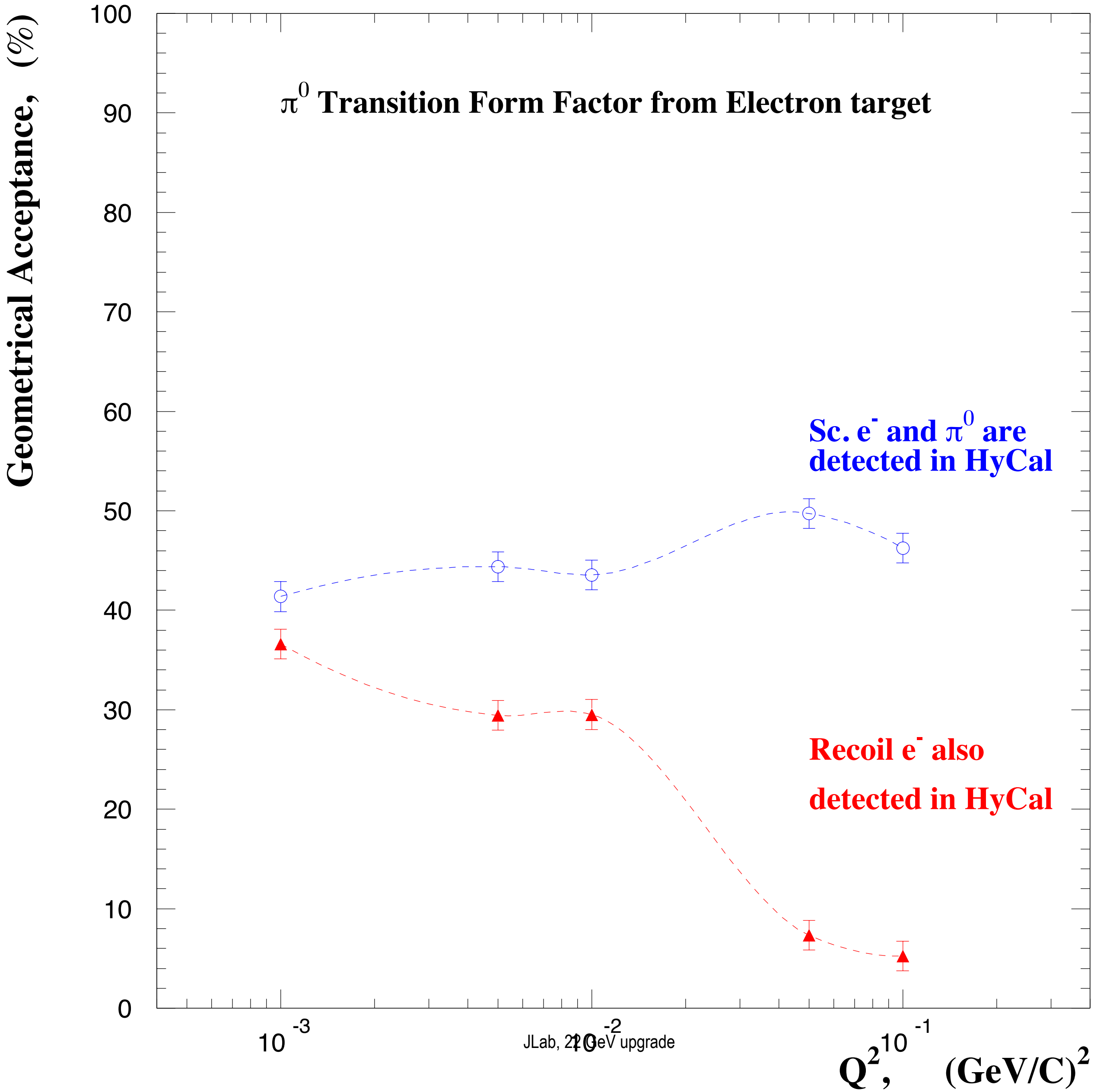
- Good photon detection efficiency (≈100%)

- 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 $\pi^0$ invariant mass resolution
  - ✓ better $\pi^0$ 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