Precision Measurements of the Electromagnetic Properties of Pseudoscalar Mesons at 11 GeV via the Primakoff Effect

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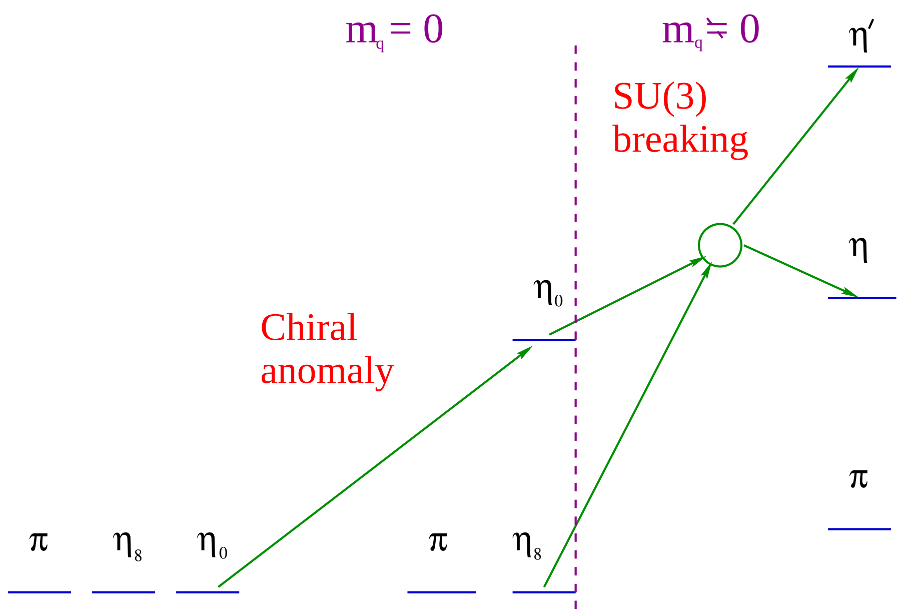
PrimEx Collaboration

Contents

Physics Motivation



Symmetry is a fundamental building block for the low energy QCD.

a. **Chrial $SU_L(3) \times SU_R(3)$ spontaneously breaking:**
$\Longrightarrow$ **Goldstone pseudoscalar mesons** (π, K, η_8)
b. **Chiral anomalies:**
$\Longrightarrow$ η_0 **mass**
$\Longrightarrow$ $P \to \gamma\gamma$ **(P:** π^0, η, η')
c. **quark flavor SU(3) breaking:**
$\Longrightarrow$ **the mixing of** η **and** η'

A study of π^0, η, η' meson system provides a powerful tool to test QCD at the confinement scale.

1. $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$ measurement:

Chiral anomaly predicts:

$$A(\pi^o \to \gamma\gamma) = \frac{\alpha}{8\pi f_\pi}\epsilon^{\mu\nu\rho\sigma}\epsilon_\mu\epsilon'_\nu k_\rho k'_\sigma$$

$$\longrightarrow \Gamma(\pi^o \to \gamma\gamma) = \frac{m_{\pi^0}^3}{64\pi}(\frac{\alpha N_c}{3\pi f_\pi})^2$$

$$A(\eta_8 \to \gamma\gamma) = \frac{\alpha}{8\sqrt{3}\pi \bar{f}_{\eta_8}}\epsilon^{\mu\nu\rho\sigma}\epsilon_\mu\epsilon'_\nu k_\rho k'_\sigma$$

$$A(\eta_0 \to \gamma\gamma) = \frac{\alpha}{\sqrt{24}\pi \bar{f}_{\eta_0}}\epsilon^{\mu\nu\rho\sigma}\epsilon_\mu\epsilon'_\nu k_\rho k'\sigma$$

- **η_0–η_8 mixing**

$$\eta = \cos\theta\eta_8 - \sin\theta\eta_0,$$
$$\eta' = \cos\theta\eta_8 + \cos\theta\eta_0$$

$$\begin{aligned}
\Gamma(\eta \to \gamma\gamma) &= \frac{\alpha_{\rm em}^2}{64\pi^3}\frac{M_\eta^3}{3f_\pi^2}\left[\frac{f_\pi}{\bar{f}_{\eta_8}}\cos\theta - \sqrt{8}\frac{f_\pi}{\bar{f}_{\eta_0}}\sin\theta\right]^2 , \\
\Gamma(\eta' \to \gamma\gamma) &= \frac{\alpha_{\rm em}^2}{64\pi^3}\frac{M_{\eta'}^3}{3f_\pi^2}\left[\frac{f_\pi}{\bar{f}_{\eta_8}}\sin\theta + \sqrt{8}\frac{f_\pi}{\bar{f}_{\eta_0}}\cos\theta\right]^2
\end{aligned}$$

the mixing angle θ will be extracted.

- **Mixing independent ratio**

$$R = \left[\frac{\Gamma(\eta\to\gamma\gamma)}{M_\eta^3} + \frac{\Gamma(\eta'\to\gamma\gamma)}{M_{\eta'}^3}\right]\frac{M_\pi^3}{\Gamma(\pi^0\to\gamma\gamma)} = \frac{1}{3}\left(\frac{f_\pi^2}{\bar{f}_{\eta 8}^2} + 8\,\frac{f_\pi^2}{\bar{f}_{\eta 0}^2}\right) \;,$$

$\bar{f}_{\eta 0}$ ***will be extracted.***

- **Improve experimental** $\Gamma(\eta\to 3\pi)$

(a) χ**PT predicts** $\Gamma_{\eta\to 3\pi}$
(b) $m_d - m_u$

the amplitude of $\eta\to 3\pi$ **is:**

$$A(\eta\to 3\pi) \propto m_d - m_u$$

- **Improve life time determination of** η **and** η'

2. Transition Form Factor $F_{\gamma\gamma^* P}$ of π^0, η, η' at low Q^2 (0.001–$0.5\ GeV^2$)

- Slope measurement:

  $\Longrightarrow$ ***Size of mesons'*** **electromagnetic interaction radii**

  $$F(Q^2) \sim 1 - \frac{1}{6} < r^2 > Q^2$$

  $\Longrightarrow$ ***Determine a constant ($\mathcal{O}(p^6)$) in the effective Chiral Lagrangian***

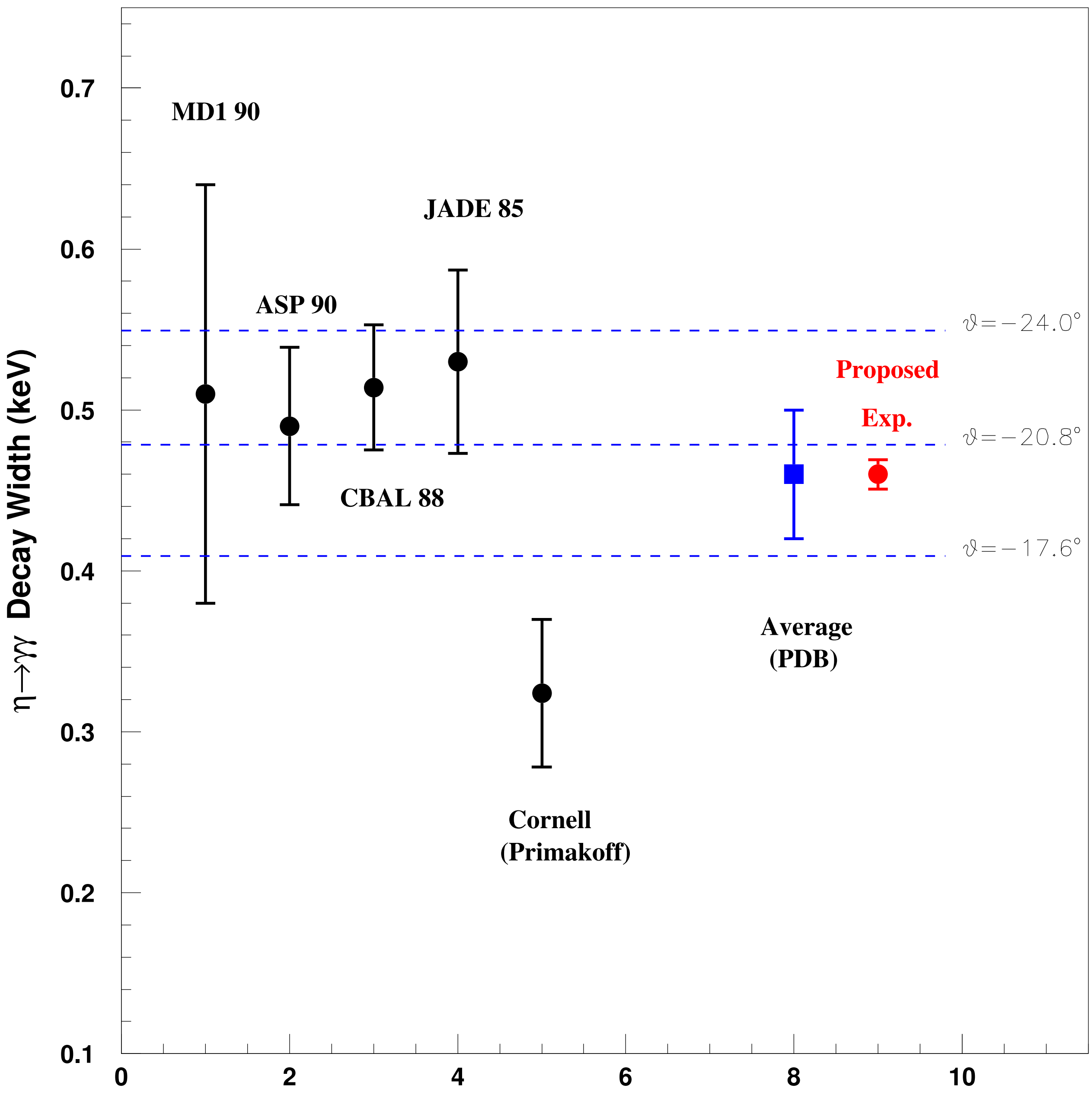
- χPT at $N_c \to \infty$ predicts a relationship between the slopes

- Test QCD based models

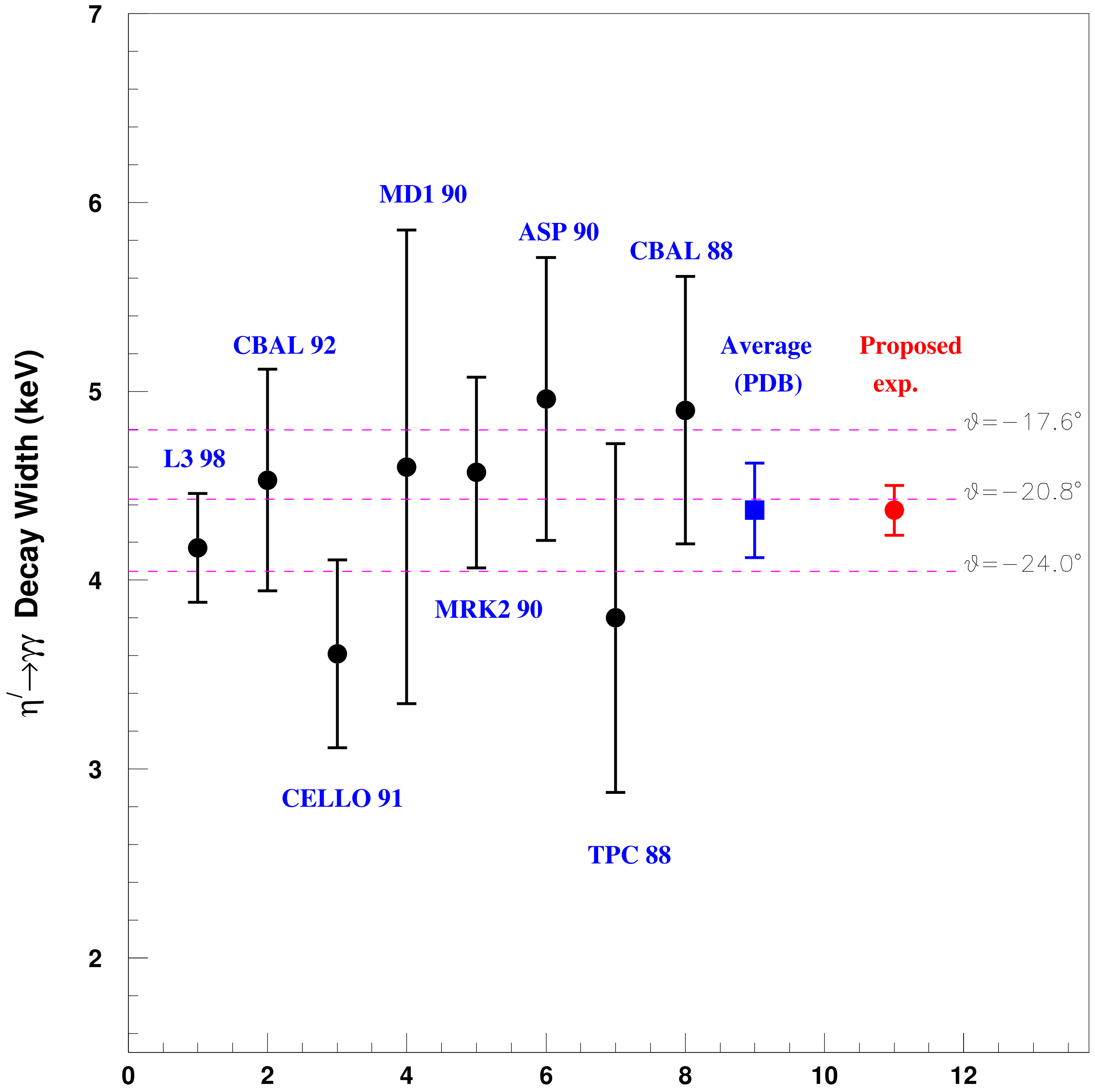
- Gluonic components of η and η'

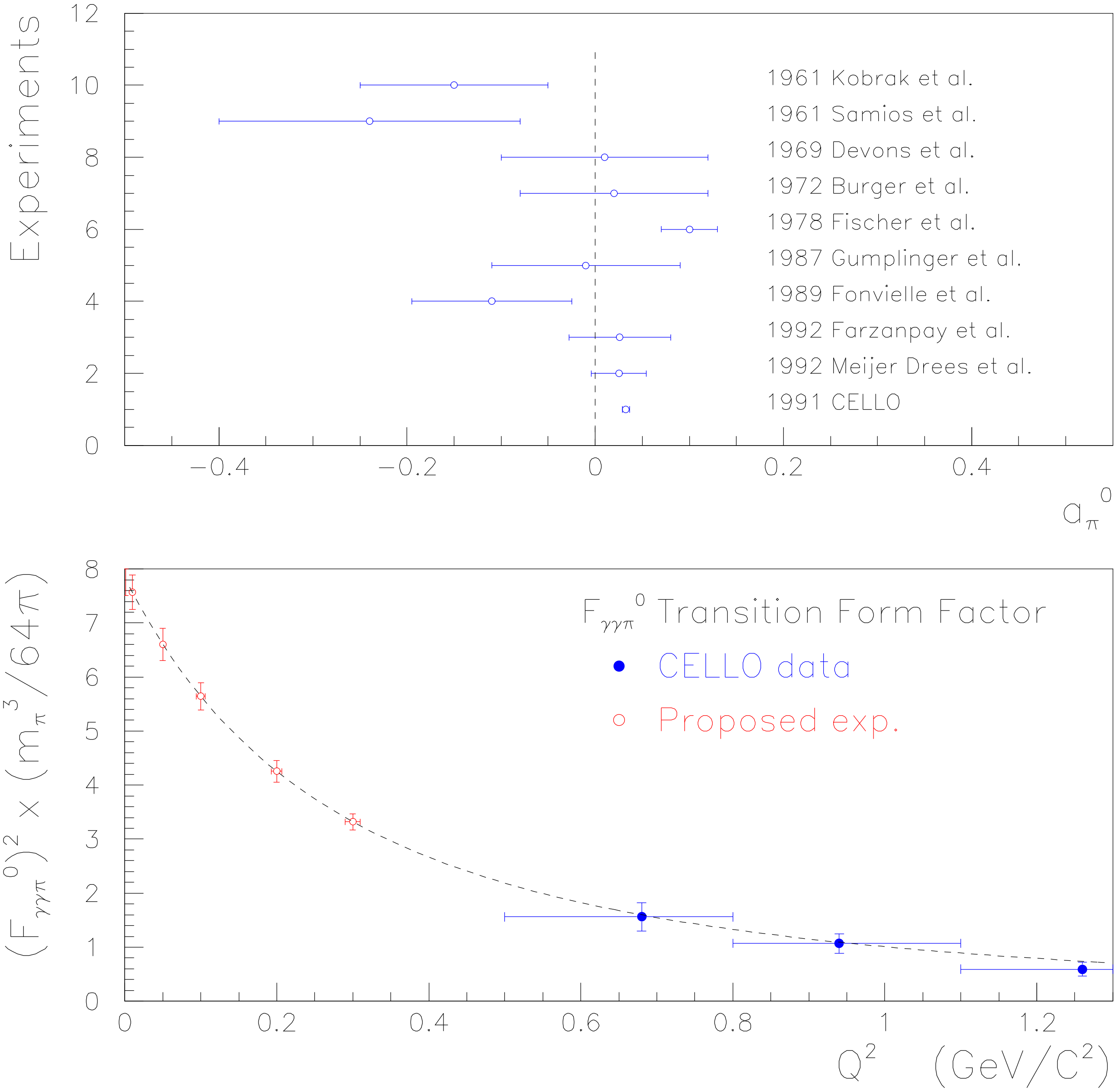
- Future lattice calculations

Experimental status

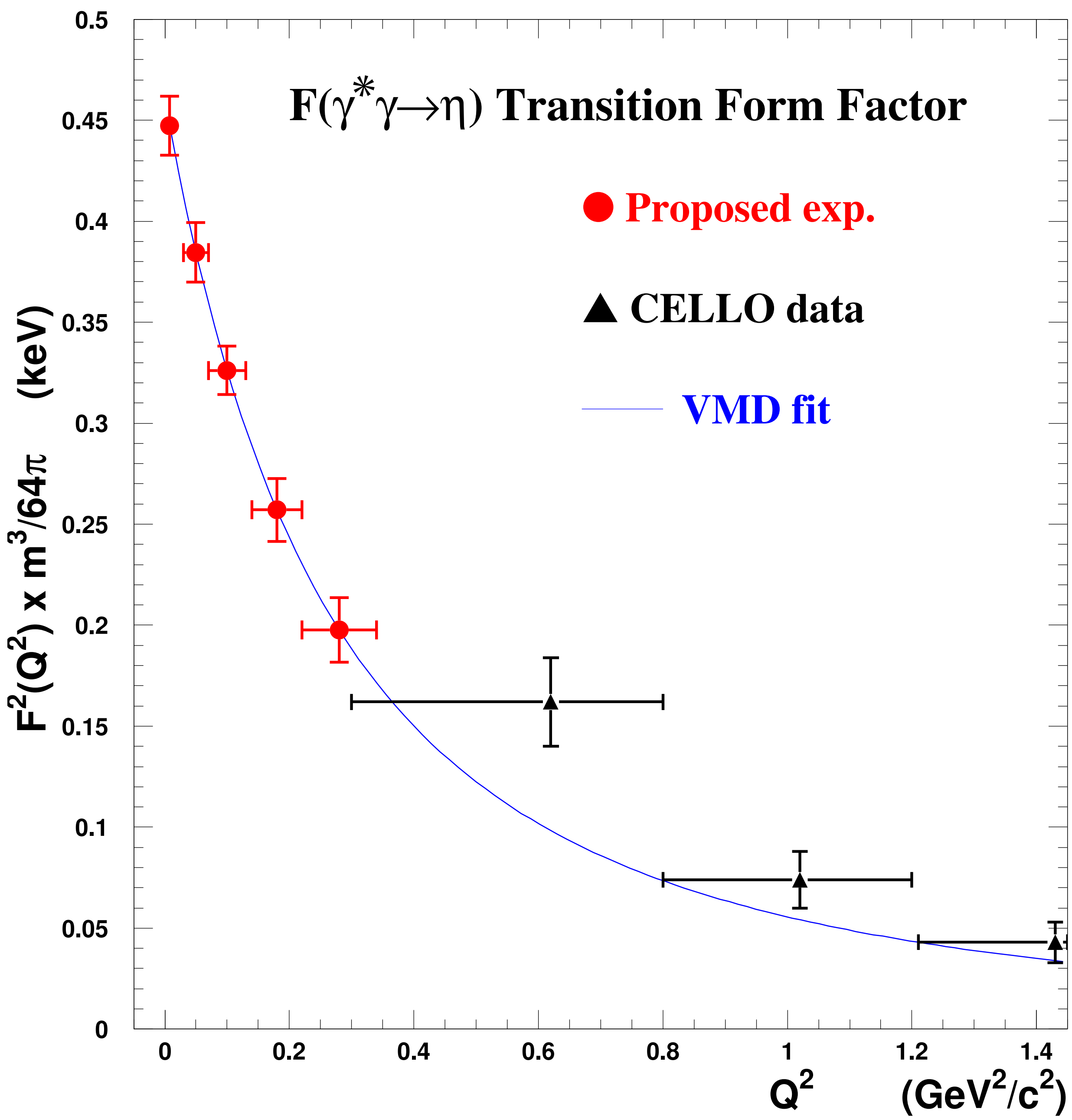


PAC18 @ 12 GeV, July 2000





Experiments
1961 Kobrak et al.
1961 Samios et al.
1969 Devons et al.
1972 Burger et al.
1978 Fischer et al.
1987 Gumplinger et al.
1989 Fonvielle et al.
1992 Farzanpay et al.
1992 Meijer Drees et al.
1991 CELLO
a_{π^0}
$F_{\gamma\gamma\pi^0}$ Transition Form Factor
CELLO data
Proposed exp.
$(F_{\gamma\gamma\pi^0})^2 \times (m_\pi^3/64\pi)$
Q^2 (GeV/C^2)



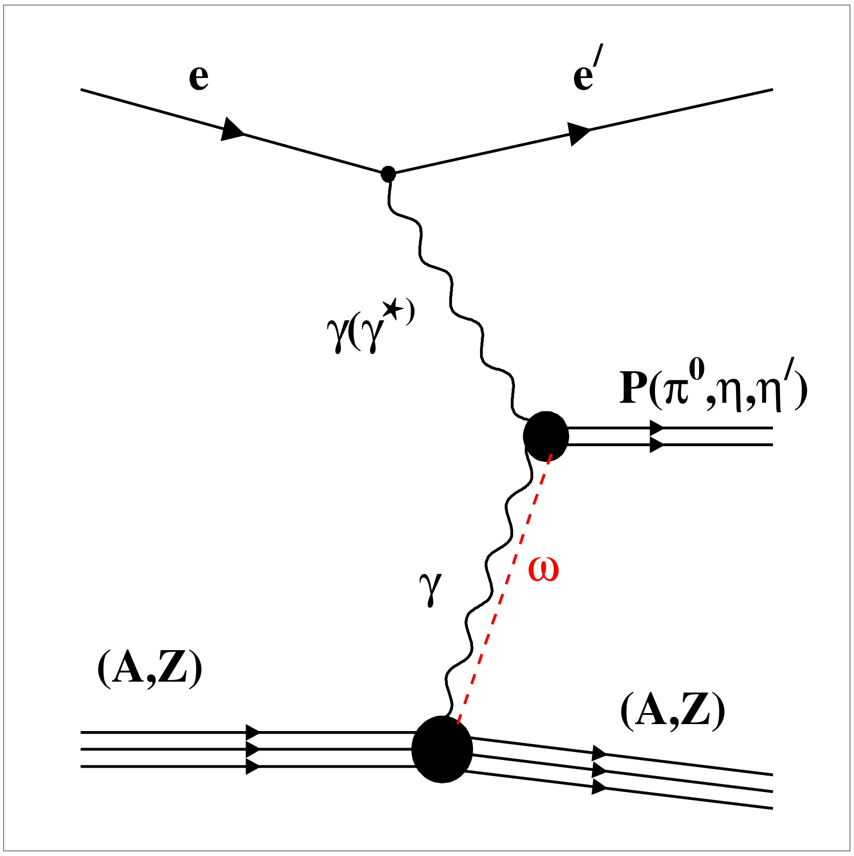
F(γ*γ→η) Transition Form Factor
Proposed exp.
CELLO data
VMD fit
F²(Q²) x m³/64π (keV)
Q² (GeV²/c²)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4

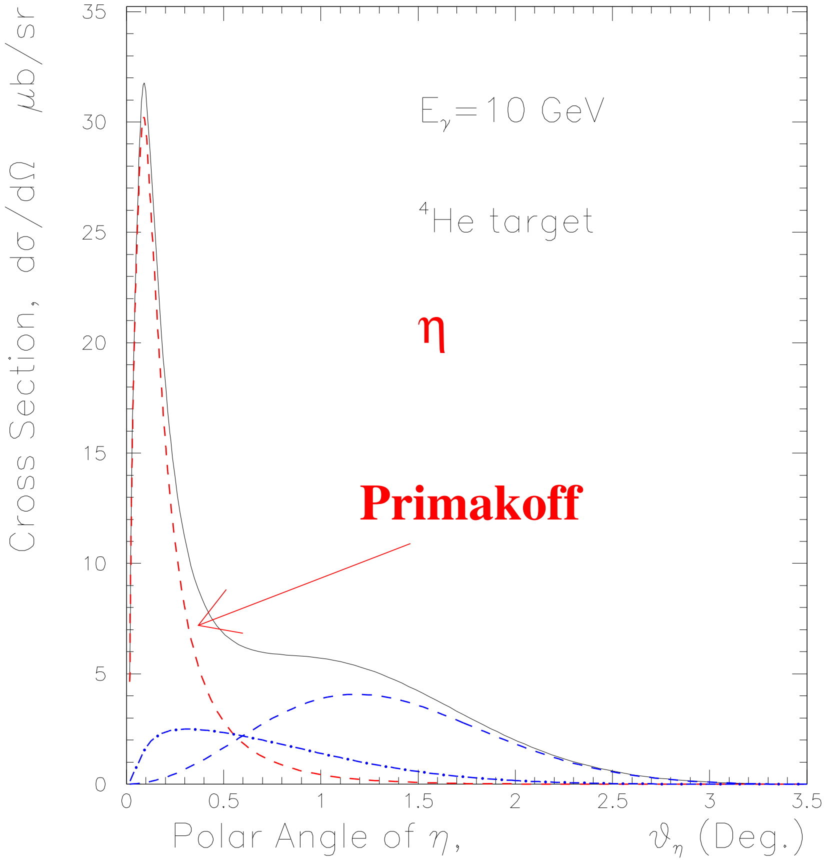
What and how to measure?

We propose to measure:

- $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
- **Transition Form Factor** $F_{\gamma\gamma^* P}$ **of** π^0, η, η' **at low** Q^2 **(0.001–0.5** GeV^2**)**

through *Primakoff effect.*





Cross section:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{Pr} + \frac{d\sigma}{d\Omega}|_{NC} + 2\sqrt{\frac{d\sigma}{d\Omega}|_{Pr} \cdot \frac{d\sigma}{d\Omega}|_{NC}} \cdot \cos\phi + \frac{d\sigma}{d\Omega}|_{I}$$

Primakoff cross section:

real photon production

$$\frac{d\sigma}{d\Omega}|_{Pr} = \mathbf{\Gamma}_{\gamma\gamma}\frac{8\alpha Z^2}{m^3}\frac{\beta^3 E^4}{Q^4}|F_{em}(Q^2)|^2 \sin^2\theta$$

virtual photon production

$$\frac{d^3\sigma}{d\epsilon_2 d\Omega_2 d\Omega_P} = \frac{Z^2\eta^2}{\pi}\sigma_M\frac{Q^4}{K^4}\frac{\beta_P^{-1}}{\omega_P}|F_{em}(K^2)|^2|F_{\gamma^*\gamma P}(q_\mu^2)|^2 sin^2(\frac{\theta_e}{2})sin^2(\theta_P)$$
$$\times[4\epsilon_1\epsilon_2 sin^2\phi_P + |\vec{q}|^2/cos^2(\frac{\theta_e}{2})]$$

Why do we need 11 GeV beam?

1. increase Primakoff cross section:

$$\sigma_{Pr} \propto E^4$$

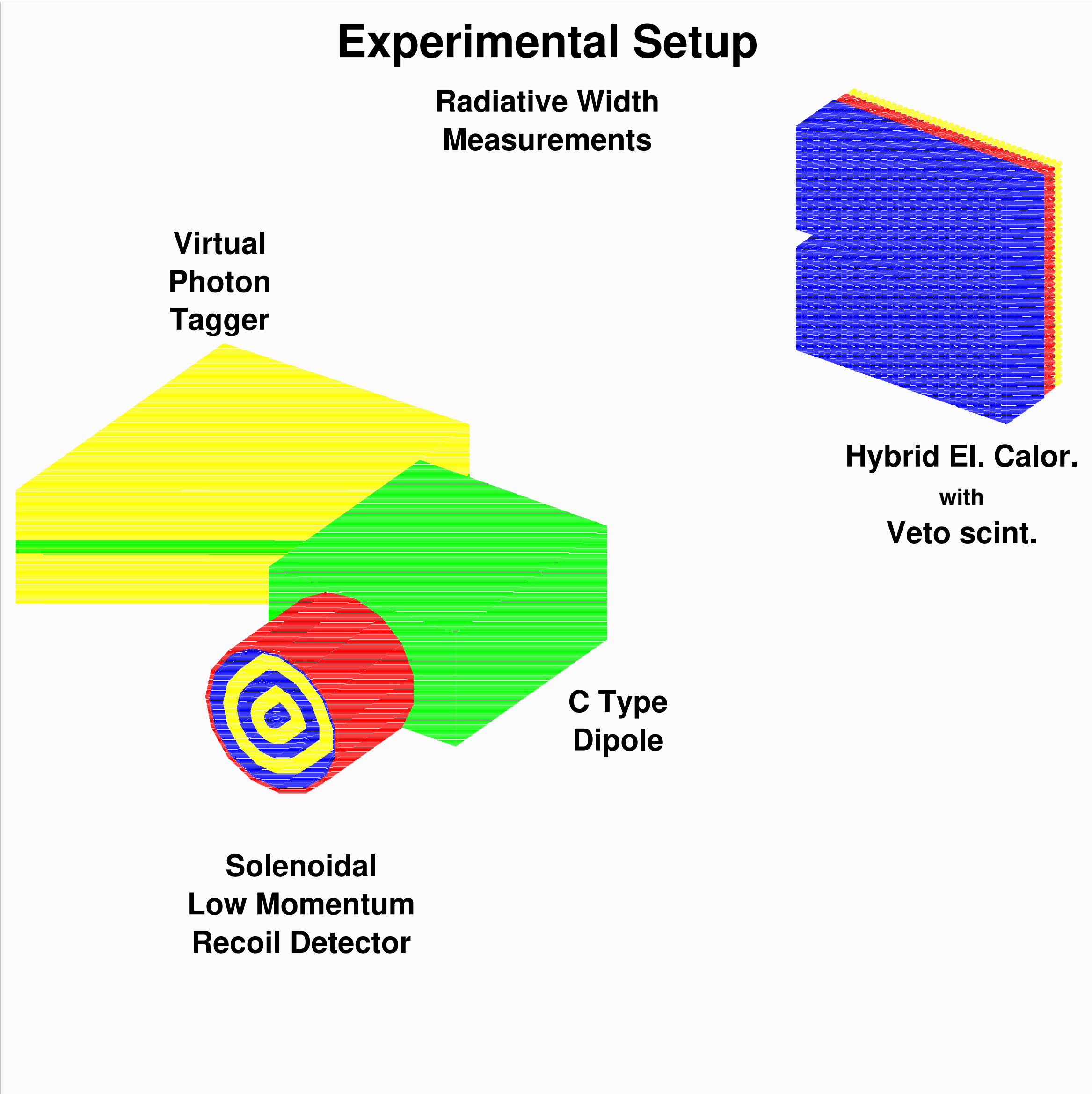
2. better separation of Primokoff reaction from other processes:

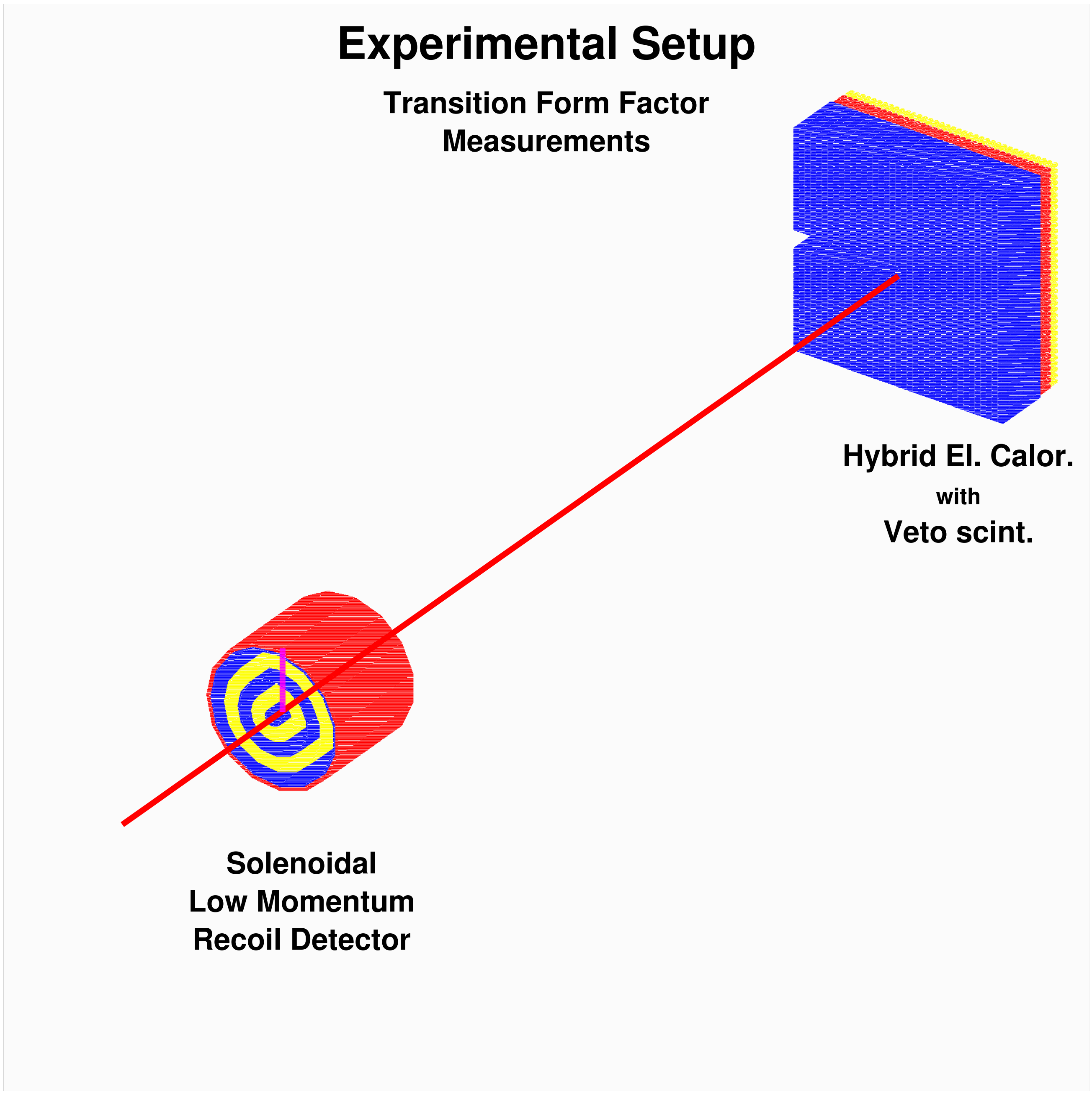
$$\theta_{Pr} \sim \frac{m^2}{2E^2}, \qquad \theta_{NC} \sim \frac{2}{E \cdot A^{1/3}}$$

3. momentum transfer become less

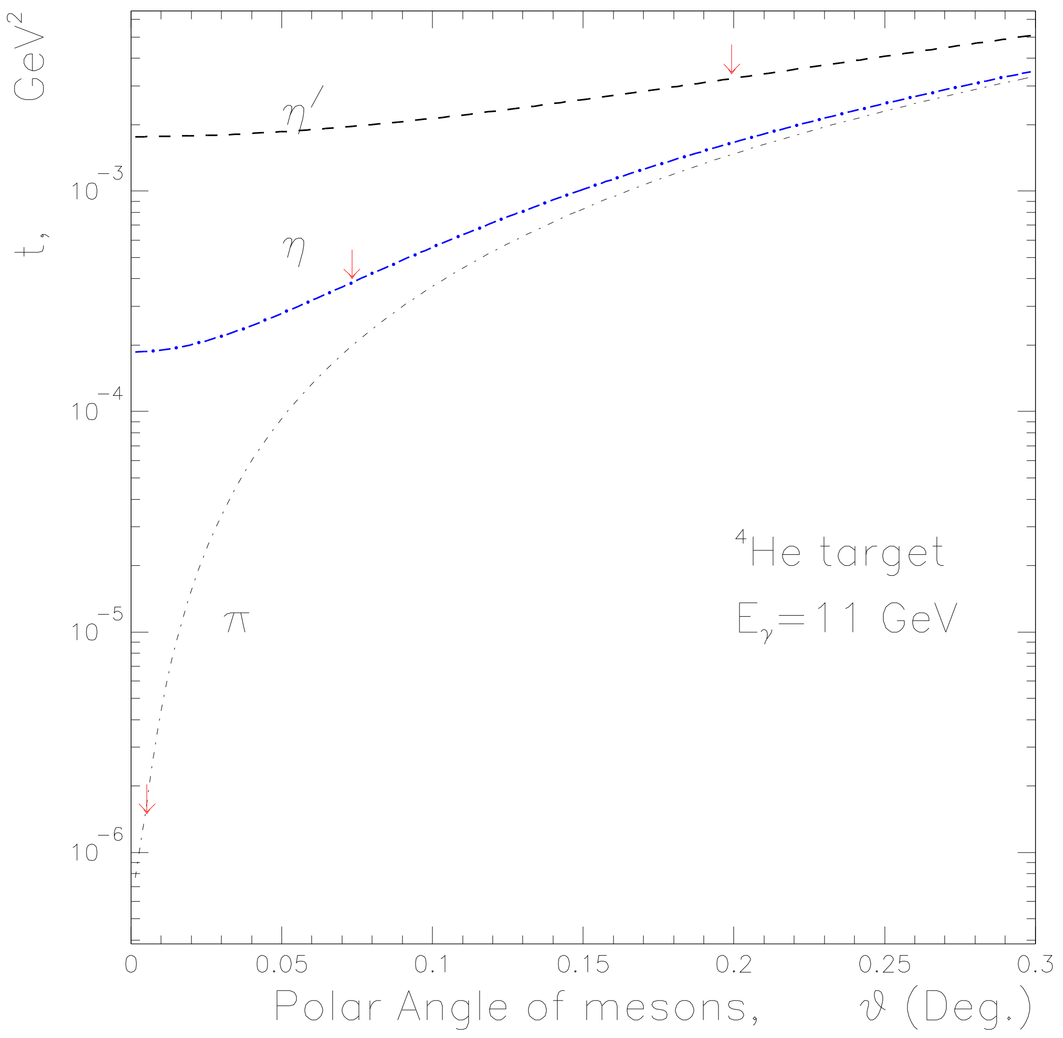
4. unique CEBAF beam quality:
   - small beam spot size and divergence
   - beam energy stability
   - high intensity.

Experimental Setup




Experimental Setup
Transition Form Factor
Measurements
Hybrid El. Calor.
with
Veto scint.
Solenoidal
Low Momentum
Recoil Detector

Coherent Reaction



It is necessary to check the coherency in η and η' cases.
Recoil detection **is required.**

Recoil detection

- separate the coherent process from the incoherent background

- directly tag the mesons

Solenoid recoil detector based on LPMPC:

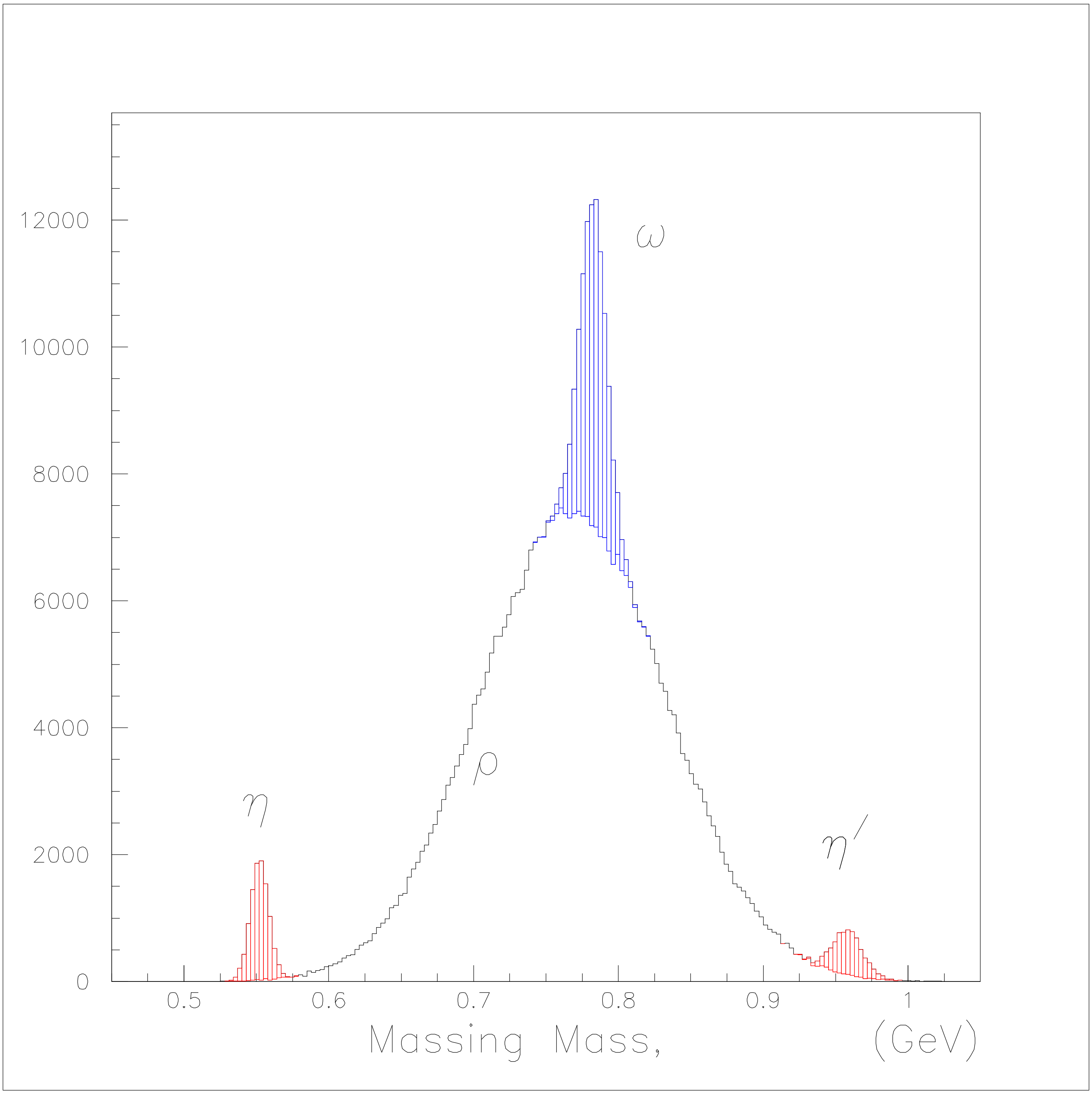
- Extremely thin material for detecting low energy recoils ($\sim 10^{-5}$ **R.L.** for C_7H_{16} & ^4He,at 1 torr)

- High efficiency for low energy recoil nuclei

- Insensitivity to electromagnetic background

- Good time and position resolutions

PAC18 @ 12 GeV, July 2000

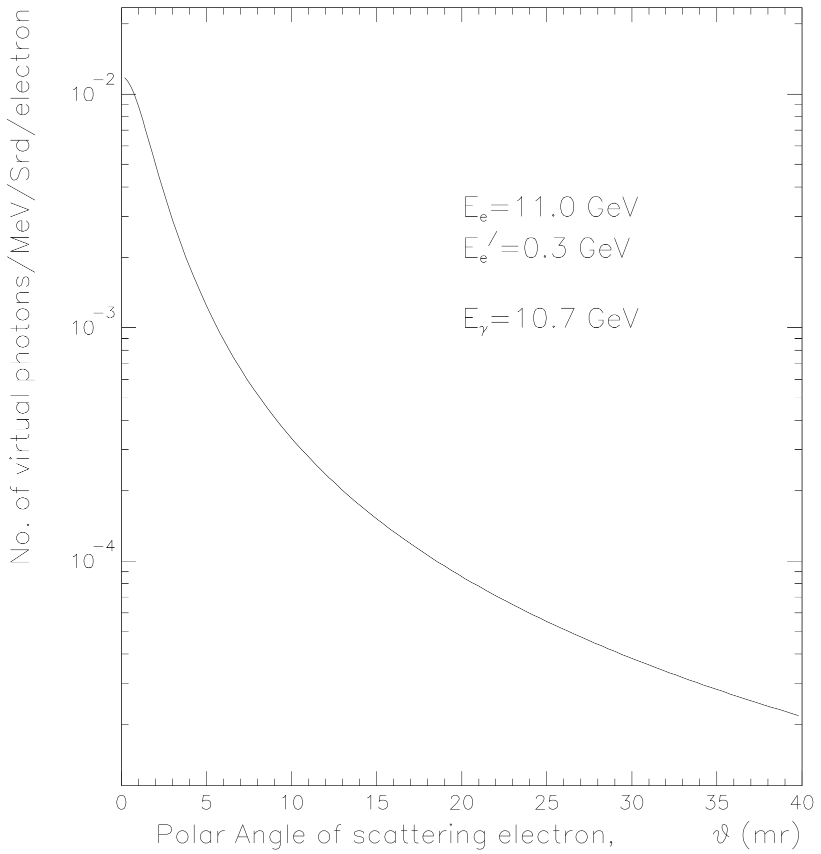


Virtual photon tagging at 0 degree

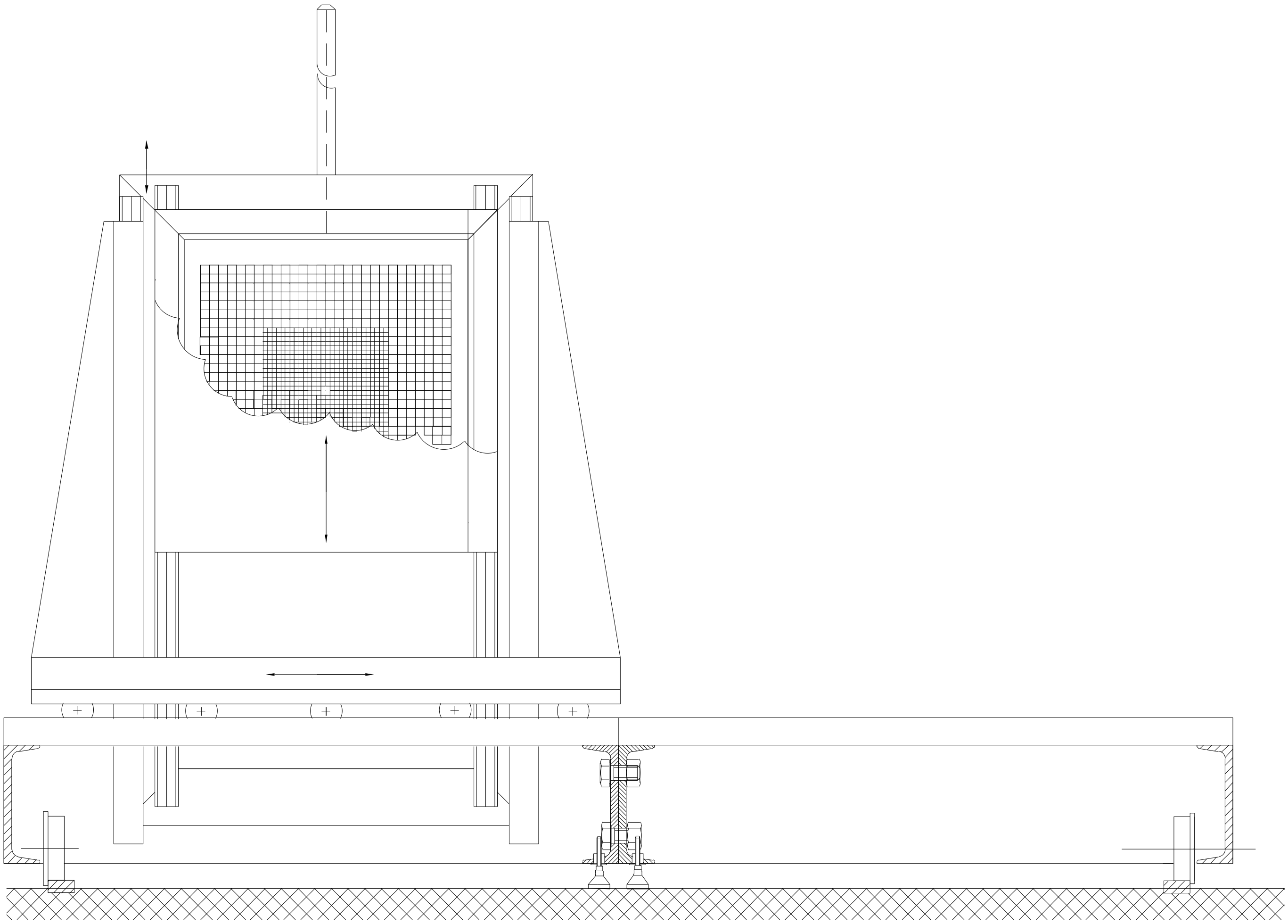
The ratio of the counting rates for zero degree electron scattering and tagged photons is given by:

$$\frac{R_{(0^0 e,e'x)}}{R_{(tagged-\gamma,x)}} = \frac{t^V + t/2}{t} \sim \frac{0.02+10^{-5}}{10^{-5}} \sim 10^3$$

For very thin target, virtual photon tagging has big advantage.



Shower Detector



- detect the scattering electrons in the transition form factor measurements

- detect the electromagnetic particles from the meson decays.

Rate Estimation

1. Primakoff Production rate:

$$N_{\eta(\eta')} = N_{^{12}C} \cdot N_\gamma \cdot \sigma \cdot \varepsilon$$

5uA electron beam, $K = 11.$GeV, $\Delta k = 0.4$ GeV

For η,

$$\begin{aligned} N_\eta &\sim 2. \cdot 10^{19} \times 5. \cdot 4. \cdot 10^9 \times 0.05 \cdot 10^{-30} \times 1. \\ &\sim 2. \times 10^{-2} \eta/sec \\ &\sim 1.7 \times 10^3 \eta/day \end{aligned}$$

For η',

$$\begin{aligned} N_{\eta'} &\sim 2 \cdot 10^{19} \times 5. \cdot 4. \cdot 10^9 \times 0.03 \cdot 10^{-30} \times 1. \\ &\sim 1.2 \cdot 10^{-2} \eta'/sec \\ &\sim 1. \times 10^3 \eta'/day \end{aligned}$$

2. Electron tagging rate:

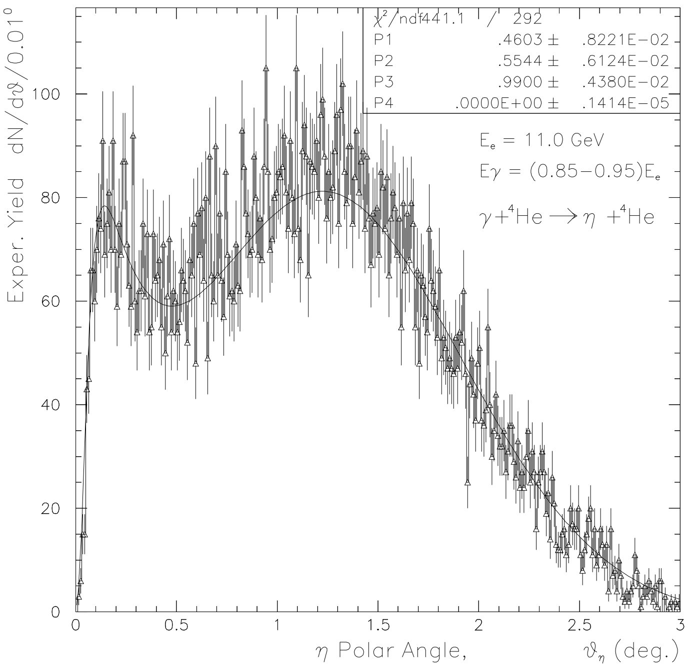
$$\begin{aligned} N_{e'} &= I_e \cdot t \cdot \frac{\Delta k}{k} \\ &\sim 5. \cdot 6.25 \times 10^{12} \times 6 \times 10^{-6} \times 0.4/11 \\ &\sim 7. \times 10^6 e'/sec \end{aligned}$$

3. Recoil detection rate:

assume 10% of $\sigma_{tot}(\gamma,^{12}C) \rightarrow recoil$,

$$\begin{aligned} N_{rec} &= N_C \cdot N_\gamma^{tot} \cdot \sigma_{tot}(\gamma,^{12}C) \\ &\sim 2. \cdot 10^{19} \times 5. \cdot 5. \cdot 10^9 \times 50 \times 1.0 \cdot 10^{-27}/10 \\ &\sim 3. \times 10^3/sec \end{aligned}$$

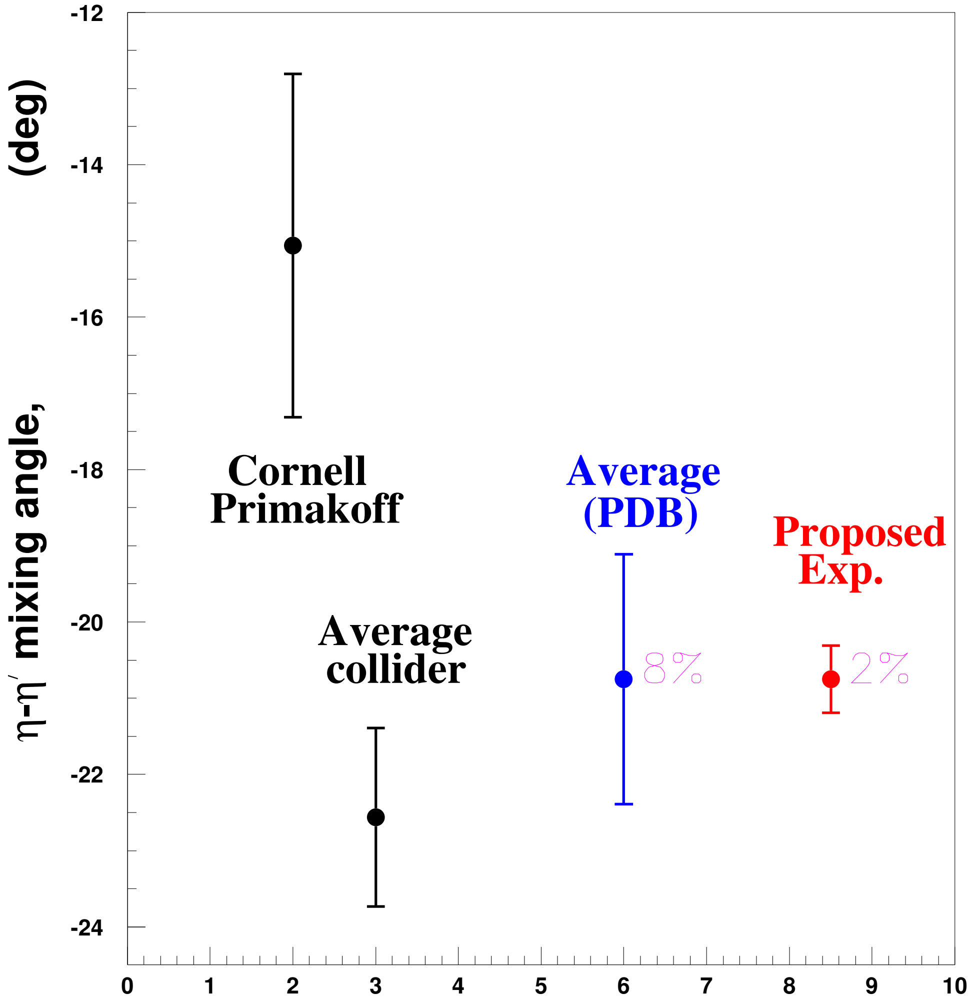
Error Estimation



Statistical	< 1.% (30 days)
photon flux	1.%
target thickness	1.%
acceptance, misalignment	0.4%
background subtract	0.3%
beam energy	0.2%
distorted form factor	0.3%
branching ratio	0.8% (PDB)
Total	2.0%

Table 1: Estimation of the experimental uncertainties for $\Gamma(\eta \to \gamma\gamma)$ measurement.

Improvement on η–η' mixing angle



Summary

1. **High precision measurements ($\sim$ 2–3%):**

- $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
- **Transition form factor of π^0, η, η' at low Q^2 (0.001–0.5 GeV^2)**

2. **Fundamental input to physics:**

- **Test Chiral anomaly predictions**
- **η–η' mixing angle**
- **Decay constant $\bar{f}_{\eta_0}$**
- **Slopes of $F_{\gamma\gamma^* P}$ (P: π^0, η, η') :**
  $\Longrightarrow$ electromagnetic interaction radii of π^0, η, η'
  $\Longrightarrow$ a constant ($\mathcal{O}(p^6)$) in Chiral Lagrangian
- **Improve $\Gamma_{\eta \to 3\pi}$ decay width**
- **Test QCD based models**

Why do we use light target

- Competitive processes

$$\frac{d\sigma_{Pr}}{d\Omega} \propto Z^2, \ \frac{d\sigma_{NC}}{d\Omega} \propto A^2, \ \frac{d\sigma_{IC}}{d\Omega} \propto A$$

- Figure of merit

- Better separation from the background

$$\theta_{Pr} \propto \frac{m^2}{2E^2}, \qquad \theta_{NC} \propto \frac{2}{E{\cdot}R} \propto \frac{2}{E{\cdot}A^{1/3}}$$

- Meson absorption

The final state interaction becomes stronger when A increases.

- Coherency