Photoproduction of Pseudoscalar Mesons at Forward Angles on Medium and Heavy Nuclei

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Outline

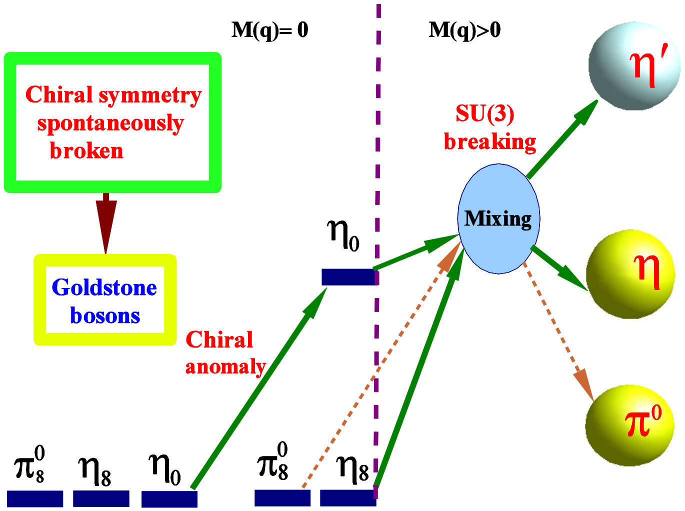
- Motivation: radiative decay widths ($\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, $\eta' \to \gamma\gamma$)
- Prior theoretical treatments of mesons in nuclei
- Our recent developments
- Some extracted experimental results
- Summary

Symmetries in QCD and Light Pseudoscalar Mesons

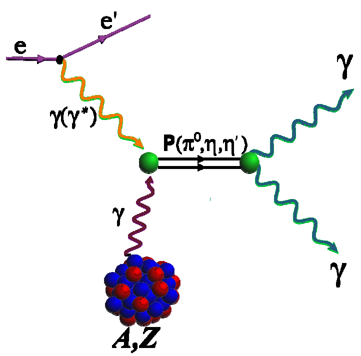
- Classical QCD Lagrangian in Chiral limit is invariant under:

$$SU_L(3)\times SU_R(3)\times U_A(1)\times U_B(1)$$

- Chiral $SU_L(3)xSU_R(3)$ spontaneously broken:
  - 8 Goldstone bosons:
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  Mass of η_0
- Massive quarks, SU(3) broken:
  Goldstone bosons are massive
  Mixing of π^0 η η'



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

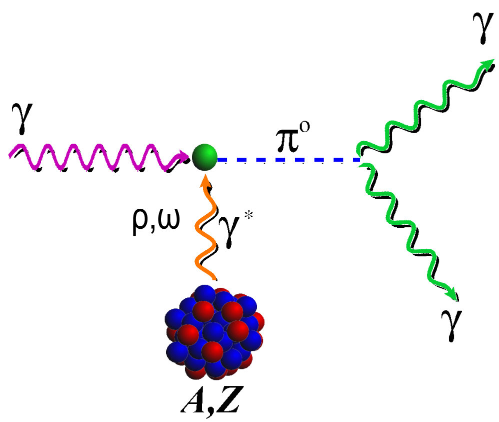


PrimEx experimental program at JLab:

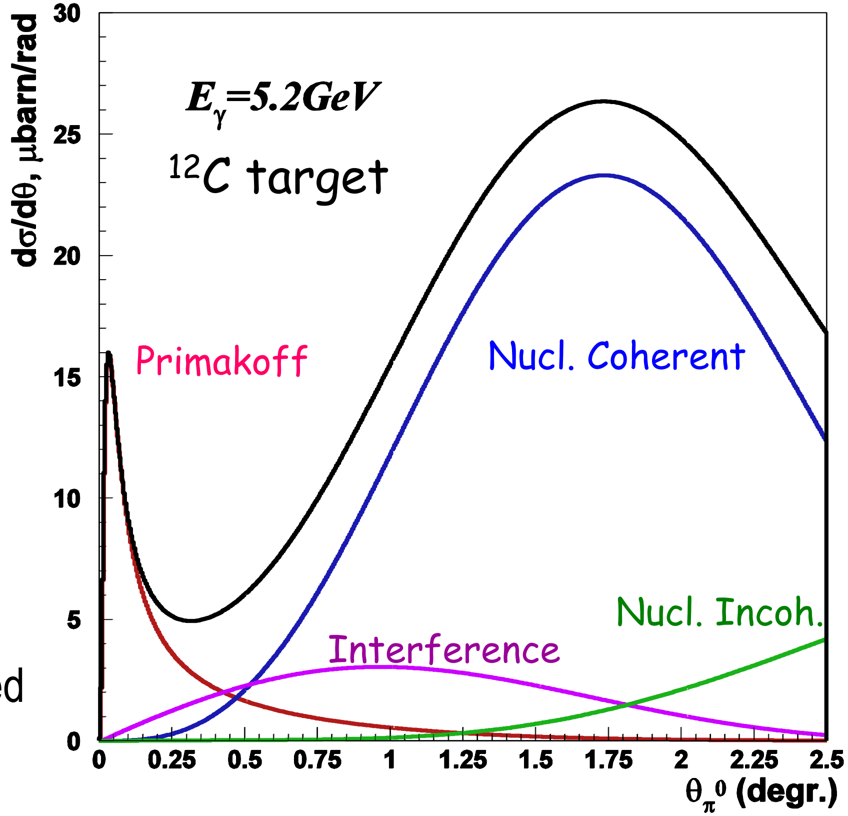
$\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$ decay widths

$F(\gamma\gamma^*\to\pi^0)$, $F(\gamma\gamma^*\to\eta)$, $F(\gamma\gamma^*\to\eta')$ transition form factors

An Example: Forward Photoproduction of π^0 on Nuclei



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

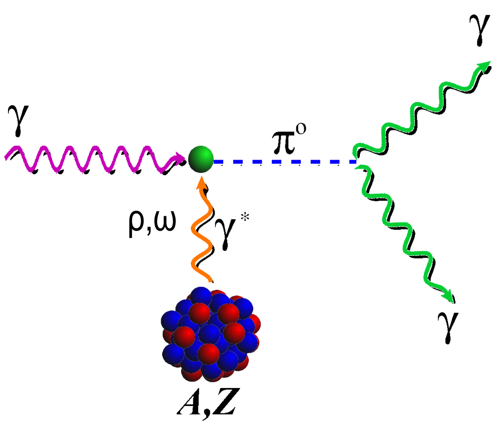


- Primakoff coherent cross section measurement required

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

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

Forward Photoproduction of Light Pseudoscalar Mesons (π^0 η η') on Nuclei



- Forward Photoproduction of pseudoscalar mesons on Nucleus:

$$\gamma + A \to Ps + A; \qquad Ps = \pi^0, \eta, \eta'$$

  - coherent processes
  - Incoherent processes

- Coherent processes:
  - coulomb interaction (T_C)
  - strong interaction (T_S)

- Full amplitude for the coherent production:

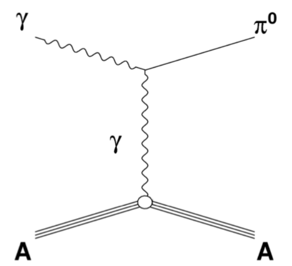
$$T = T_C + e^{i\varphi} T_S$$

φ – relative phase between T_C and T_S amplitudes

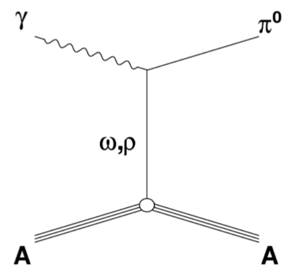
- Differential cross section for the process including the incoherent part:

$$\frac{d\sigma}{d\Omega} = \frac{k^2}{\pi}\frac{d\sigma}{dt} = \ | T_C + e^{i\varphi} T_S |^2 + \frac{d\sigma_{inc}}{d\Omega}$$

- Interference term



The pion photoproduction in the nuclear Coulomb field.



The pion photoproduction in the strong field of a nucleus.

General Theoretical Treatments of the Process

- The amplitudes for nucleus are related to the elementary amplitudes on nucleon:

(nuclear amplitude) ~ (nucleon amplitude) x (form factor)

✓ the form factors need to be modified for the final state interactions of the outgoing mesons with nucleus

- The "Shadowing" effect:

  interaction of incident photons with nuclear matter

- Incoherent processes:

  excitation or a break up of the target nuclei (not discussed in this talk)

General Theoretical Treatments of the Process (Cont'd)

- The first comprehensive treatment of the pion Final State interactions (FSI) in nuclei was done by:
  G. Morpurgo, Nuovo Cimento 31, 569 (1964)
  - ➢ absorption of pions in the strong nuclear field of nucleus;
  - ➢ Distorted Wave Approximation (DWA) is used;
  - ➢ uniform nuclear density distribution, ρ(r)

  - ✓ Corrections to the strong and el-magnetic form factors in nuclei is given (absorption part only);

  However:
  - ✓ effect of the pion re-scattering to forward angles was not taken into account
  - ✓ very important for the precision cross sections at forward angles.

- The effect of pion re-scattering was first discussed in:
  G. Faldt, Nucl. Phys. B43, 591 (1972)
  - ➢ in the framework of the Glauber theory of multiple scattering;

  - ✓ The general expression for the amplitudes are correctly given;

  However,
  - ✓ Analytically integrable formula is derived for the equal absorption in a nucleus of the incident and produced particles only ($\pi N \to \pi N$, $\gamma N \to \gamma N$, *etc.*)

Recent Developments: the Electromagnetic Amplitude (T_C)

- The PrimEx collaboration at JLab for the past decade extended the theoretical treatments of forward production of pseudoscalar mesons on nuclei:

S. Gevorkyan, A. Gasparian, L. Gan, I. Larin, M. Khandaker — **Phys. Rev. C80, 055201 (2009)**
S. Gevorkyan, A. Gasparian, L. Gan, I. Larin — **Phys. Part. Nucl. Lett. 9, 3, (2012)**
S. Gevorkyan, A. Gasparian, L. Gan — **PrimEx Note 45, URL: www.jlab.org/primex**

Based on:

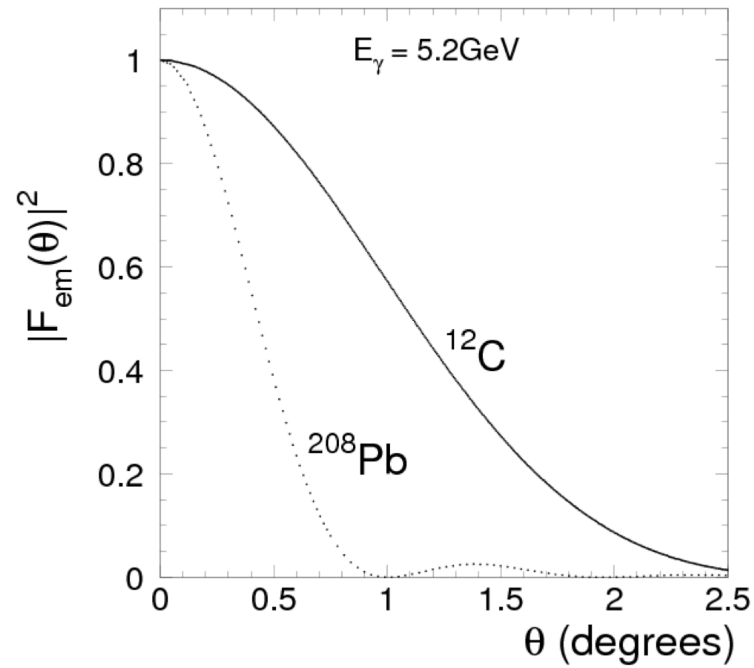
- Glauber theory of multiple scattering;
- Independent particle model for nucleons.

1) The Coulomb amplitude have been derived:

$$T_C = Z\sqrt{8\alpha\Gamma}\left(\frac{\beta}{m_\pi}\right)^{3/2}\frac{k^2\sin\theta}{q^2+\Delta^2}F_{em}(q,\Delta)$$

with the electromagnetic form factor

$$F_{em}(q,\Delta) = \frac{q^2+\Delta^2}{q}\int J_1(qb)\frac{bd^2bdz}{(b^2+z^2)^{3/2}}e^{i\Delta z} \times \exp\left(-\frac{\sigma'}{2}\int_z^\infty \rho(b,z')dz'\right)\int_0^{\sqrt{b^2+z^2}} x^2\rho(x)dx$$



The Strong Amplitude (T_S)

- Following G. Faldt, Nucl. Phys. B43, 591 (1972) the strong amplitude can be expressed by:

$$T_S(q,\Delta) = \frac{ik}{2\pi}\int e^{i(\vec{q}\cdot\vec{b}+\Delta z)}\Gamma_p(\vec{b}-\vec{s})\rho(\vec{s},z) \times \left[1-\int\Gamma_s(\vec{b}-\vec{s}')\rho(\vec{s}',z')d^2s'dz'\right]^{A-1} d^2bd^2sdz$$

or in the factorized form:

$$T_S(q) = (\vec{h}\cdot\vec{q})\phi(0)F_{st}(q,\Delta)$$

$$F_{st}(q,\Delta) = -\frac{2\pi}{q}\int J_1(qb)\frac{\partial\rho(b,z)}{\partial b}bdbdze^{i\Delta z}\exp\left(-\frac{\sigma'}{2}\int_z^\infty\rho(b,z')dz'\right)$$

the strong form factor can be expressed as a sum of two terms:

$$F_{st}(q,\Delta) = \int e^{i\vec{q}\cdot\vec{b}}\rho(b,z)d^2bdze^{i\Delta z}\exp\left(-\frac{\sigma'}{2}\int_z^\infty\rho(b,z')dz'\right) - \frac{\pi\sigma'}{q}\int J_1(qb)\rho(b,z_1)\frac{\partial\rho(b,z_2)}{\partial b}bdbdz_1dz_2e^{i\Delta z_1}\exp\left(-\frac{\sigma'}{2}\int_{z_1}^\infty\rho(b,z')dz'\right)$$

✓ However, it is valid for the equal absorption of the incident and produced mesons in nucleus.

The second term is responsible for the enhancement at 0-degree scattering due to multiple scattering of the nonzero degree produced pions

Photon Shadowing in Nuclei

- The photon shadowing effect in nuclei is a result of the two-step process:
  - ✓ initial photon produces a vector meson in nucleus (VMD) ($\gamma \to V$);
  - ✓ then the vector meson produces a pseudoscalar meson on another nucleon ($V + N \to P_s + N$)
- the main contribution comes from the ρ meson

- Based on the multiple scattering techniques the contribution from intermediate ρ-channel to the strong form factor can be expressed as (S. Gevorkyan, et al. **Phys. Rev. C80, 055201 (2009)):**

$$F_I(q) = -\frac{\pi\sigma'}{q}\int J_1(qb)\rho(b,z_1)\frac{\partial\rho(b,z_2)}{\partial b}\theta(z_2-z_1)bdbdz_1dz_2 \times e^{i\Delta_\rho(z_1-z_2)+i\Delta z_2}\exp\left(-\frac{\sigma'}{2}\int_{z_1}^{\infty}\rho(b,z')dz\right)$$

- The strong amplitude (TS) with the shadowing effect can be expressed by:

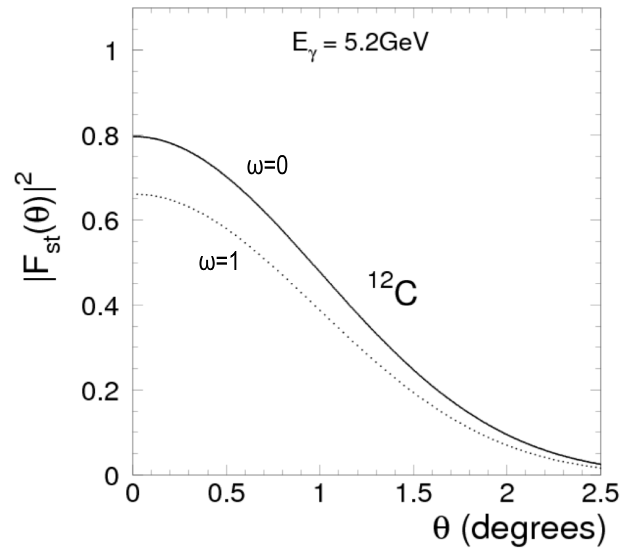
$$T_S(q) = (\vec{h}\cdot\vec{q})\phi(0)(F_{st} - wF_I)$$

$$w = \frac{f(\gamma N \to \rho N) f(\rho N \to \pi N)}{f(\rho N \to \rho N) f(\gamma N \to \pi N)}$$

- with the shadowing parameter: ω = [0 ÷ 1]
  (0- no shadowing, 1- complete shadowing)

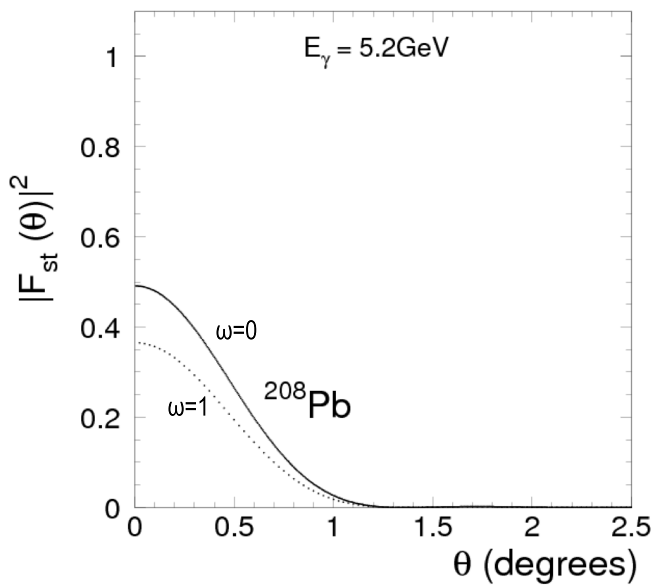
Photon Shadowing and the Strong Form Factor

- at relatively high energies the longitudinal momentum transfer is vanishing ($\Delta = \Delta_\rho = 0$), and assuming $\omega = 1$ (naive VDM) the shadowing term and second term in Faldt's formula are canceling each other.
 (S. Gevorkyan, et al. **Phys. Rev. C80, 055201 (2009))**

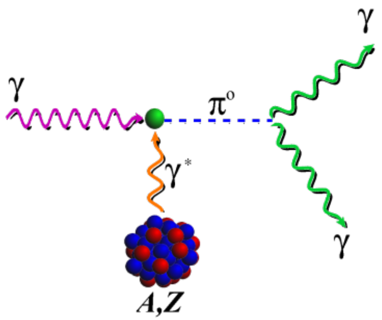


✓ Then, the strong amplitude is determined by the first term only in the Faldt's formula, and integration can be done analytically:

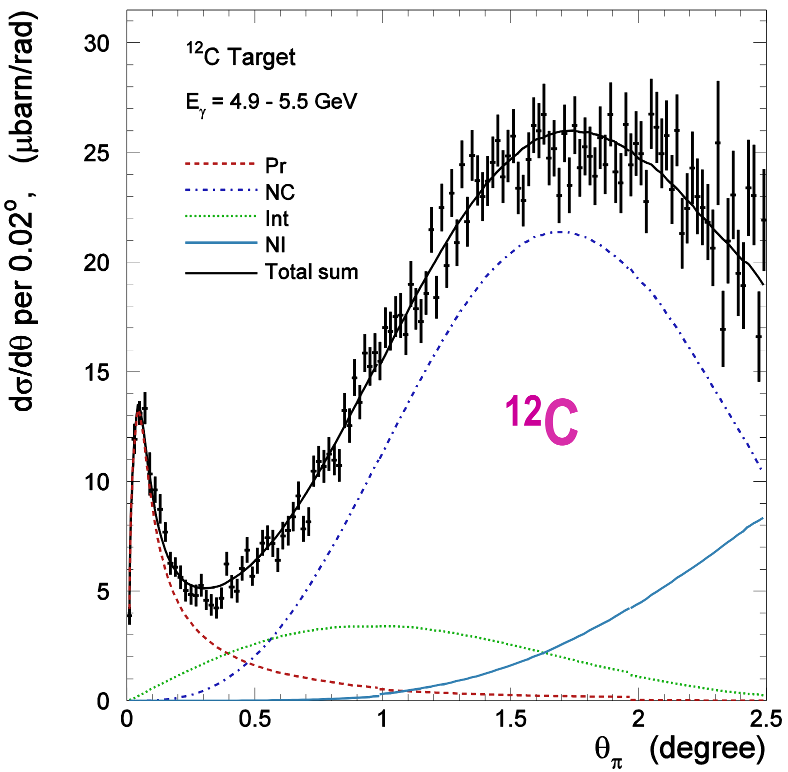
$$F_{st}(q) = \frac{2}{\sigma'} \int d^2 b e^{i\vec{q}\cdot\vec{b}} \left[1 - \exp\left(-\frac{\sigma'}{2} \int \rho(b, z')dz\right)\right]$$

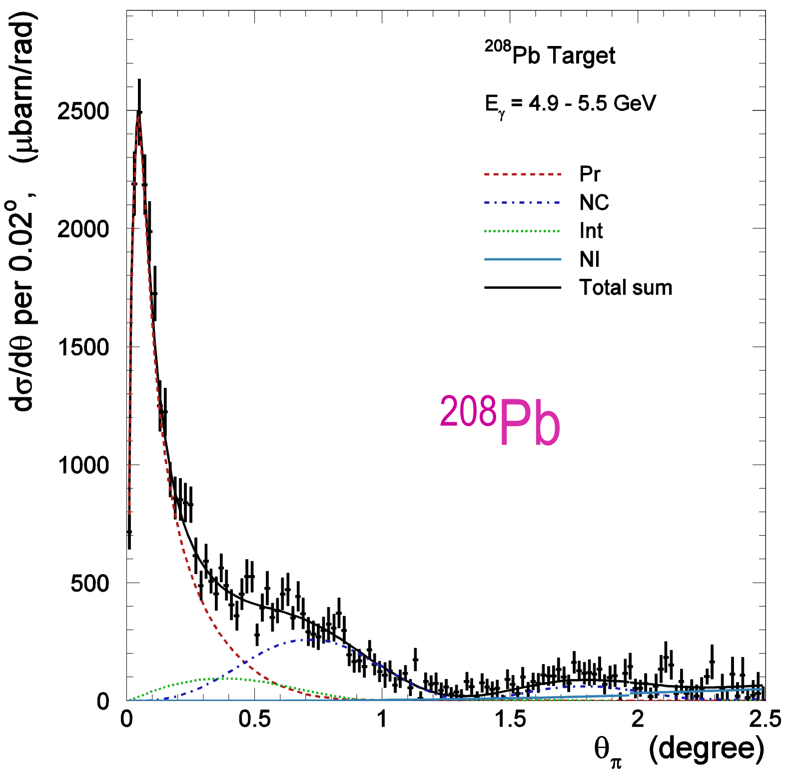


Results from the PrimEx-I Experiment



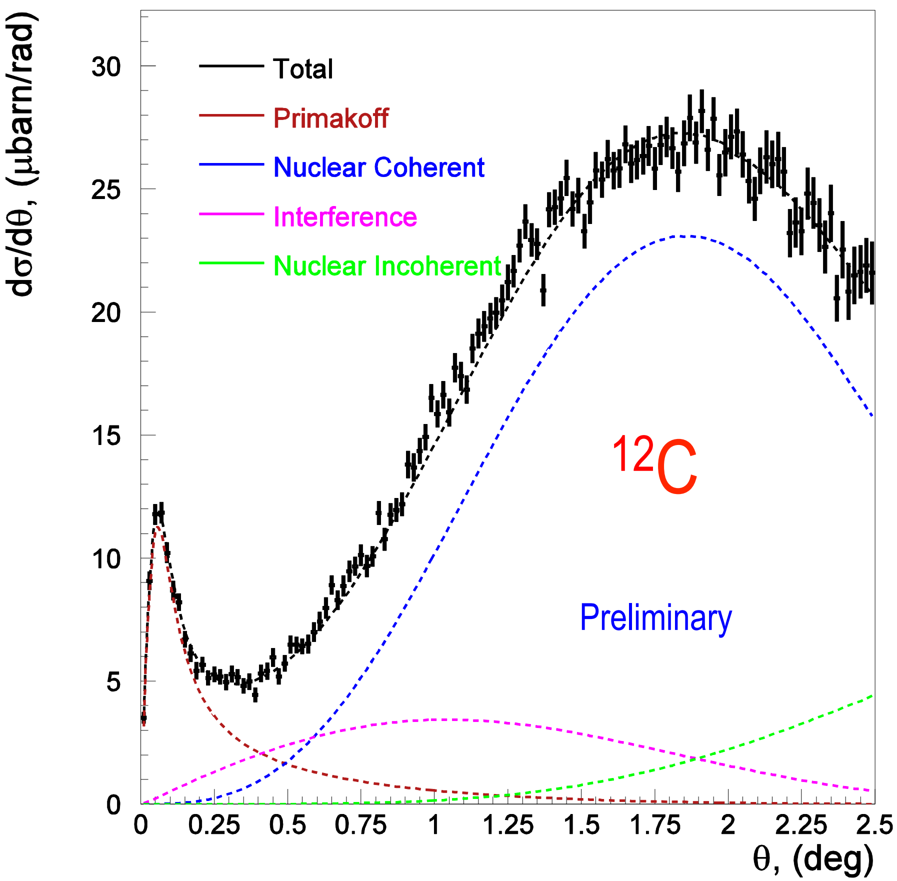
- Nuclear targets: ^{12}C and ^{208}Pb
- 6 GeV Hall B tagged beam
- experiment performed in 2004

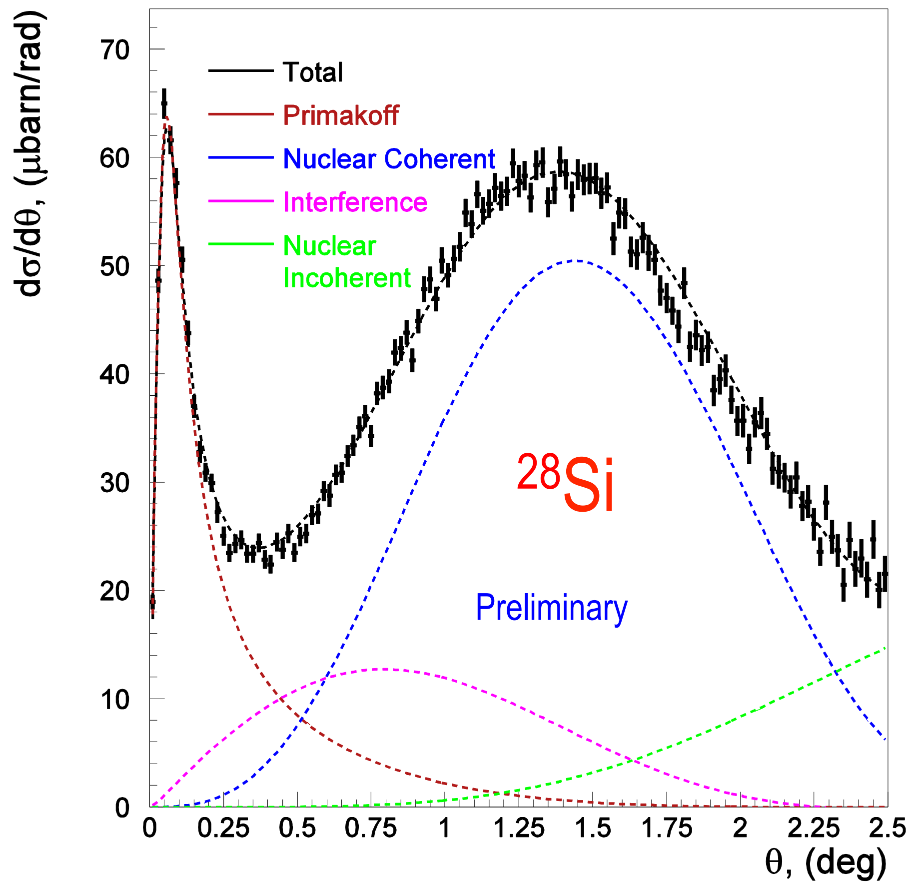




Extracted Differential Cross Sections and Fit Results from PrimEx-II (first analysis group)

(Eγ = 5.0 GeV)





Extracted Differential Cross Sections and Fit Results from PrimEx-II (second analysis group)

✓ The second analysis group (Duke/A&T/ITEP) finished the preliminary results for the ^{28}Si target:

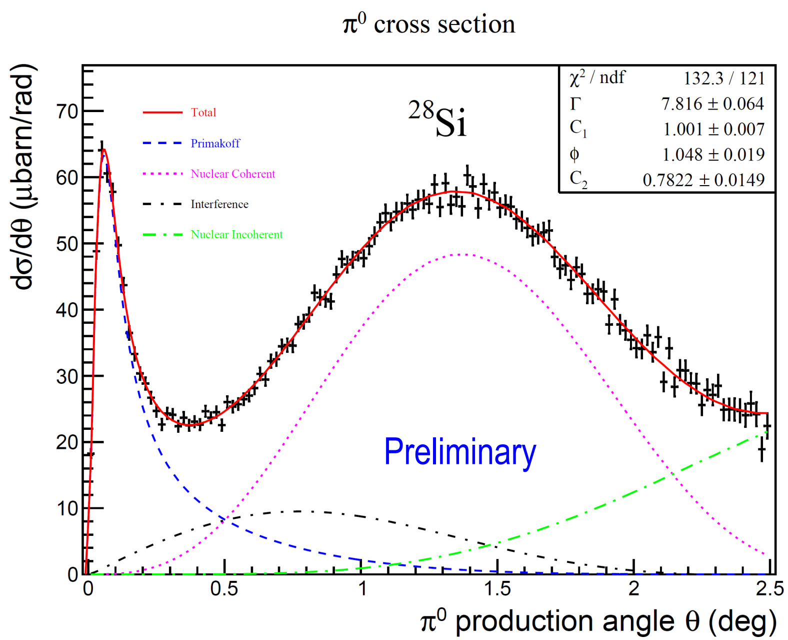
a) differential cross section has been extracted (left plot);

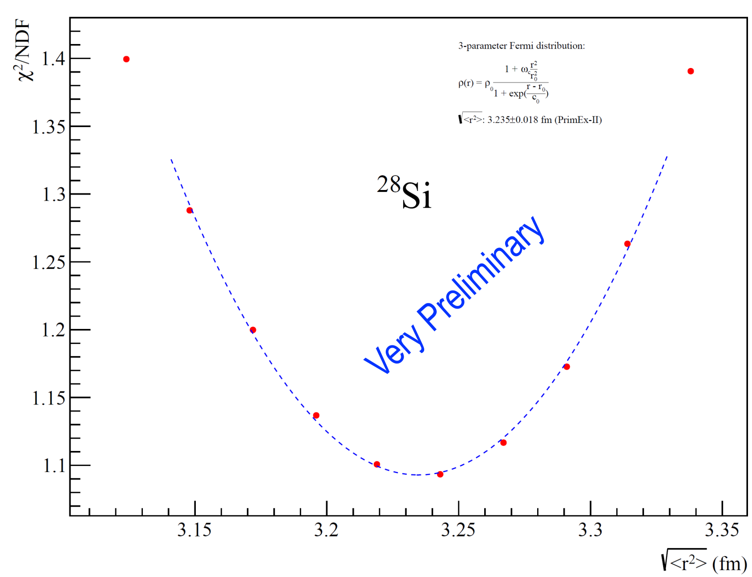
b) the π^0 decay width is extracted (left plot):

7.82 ± 0.06 (stat.) ± 0.13 (sys.) eV, with 1.6% total uncertainty (preliminary)

c) the ^{28}Si radius has been extracted from the measured nuclear coherent process (right plot):

$\sqrt{<r^2>}$ = 3.24 ± 0.02 fm (preliminary)





Summary

- Percent level measurements of the forward photoproduction of pseudoscalar mesons are recently available for the high precision extraction of their radiative decay widths.
- Theoretical treatments are required on the same percent level to support the extraction of physical quantities.
- We have extended the theoretical treatments of these processes available in literature:
  - ✓ Glauber theory of multiple scattering
  - ✓ Independent particle model for nucleons
- Charge and matter distributions are separately included for the light nuclei.
- The photon shadowing effect is correctly treated for the first time.
- The final state interactions and the exclusion principle are included for the incoherent processes (not discussed in this talk).

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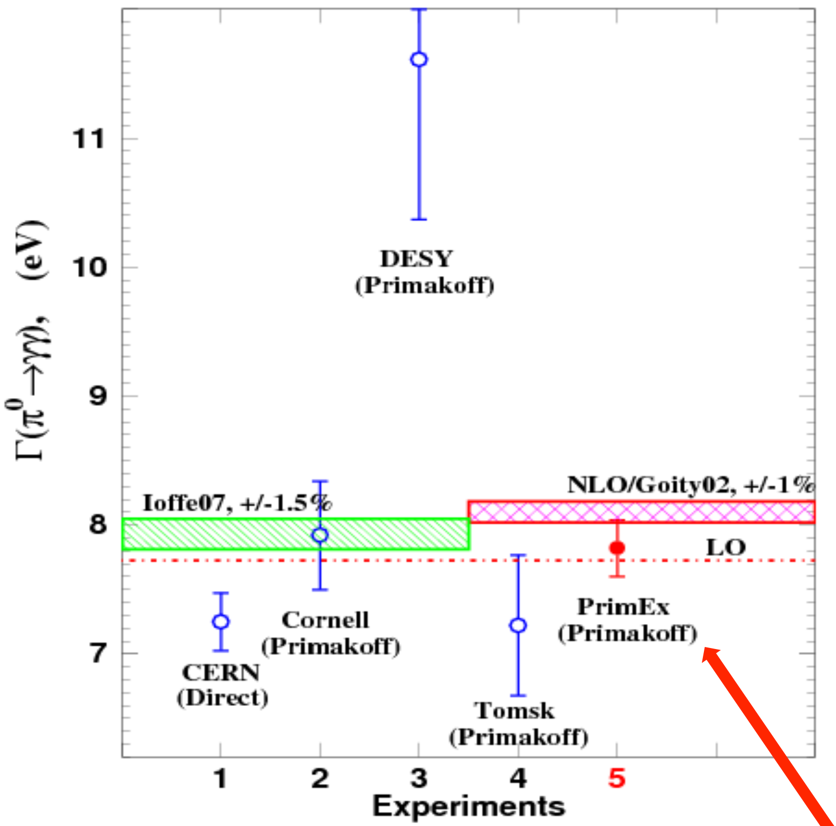
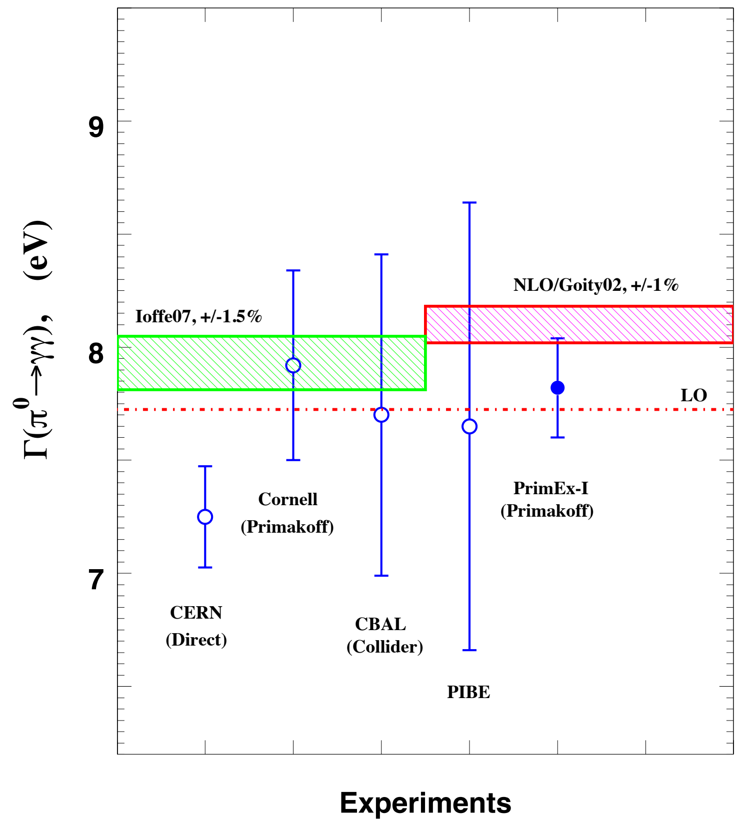
$\Gamma(\pi^0 \to \gamma\gamma)$, PDG Status Before and After the PrimEx-I Experiment



$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty



- ✓ PDG average on $\Gamma(\pi^0 \to \gamma\gamma)$ improved by factor of 2

Results from the PrimEx-II Experiment
(Preliminary)

- Results from the first group (ITEP Moscow/China) are presented (Preliminary).

$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.74 ± 0.06(stat.) ± 0.12(syst.) eV
1.7% total uncertainty

- Results from the second group (Duke University) are expected soon.