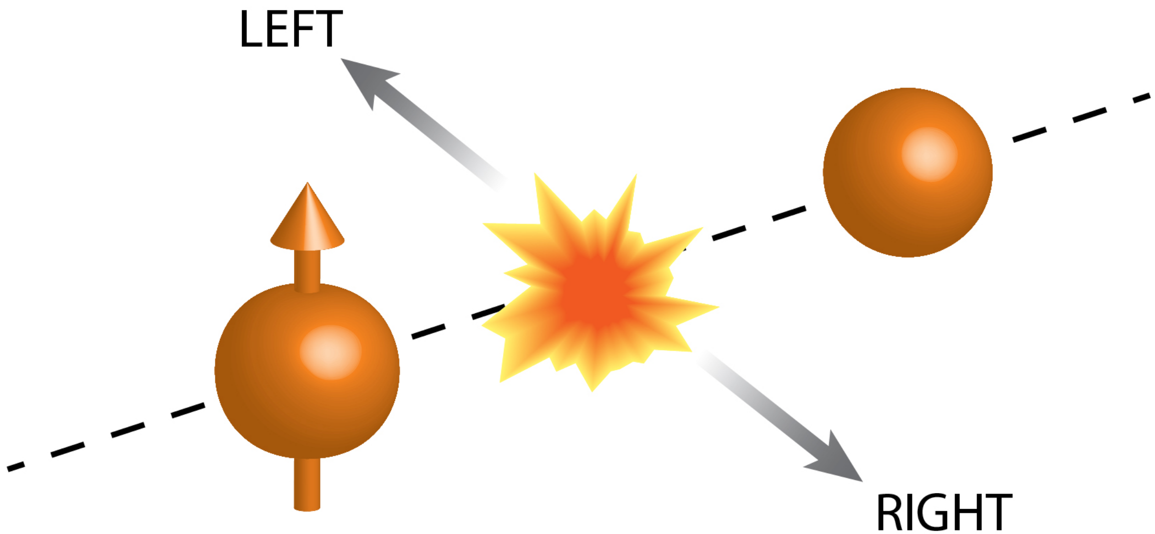
Very Forward Neutron Asymmetry in Transversely Polarized p+A collision

Itaru Nakagawa
on behalf of PHENIX Collaboration

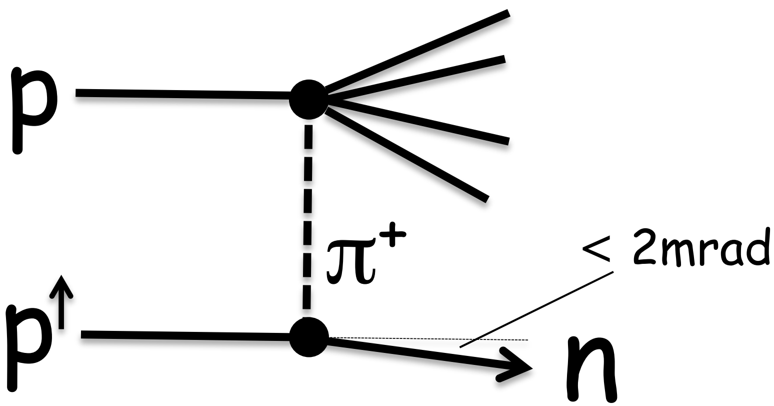


Forward π^0 and very forward neutron

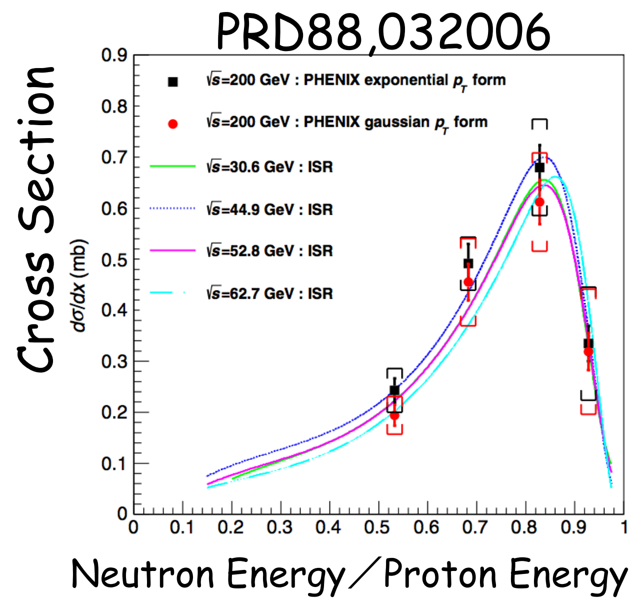
TRANSVERSE SINGLE SPIN ASYMMETRY

Production Mechanism of Forward Neutron

Cross Section

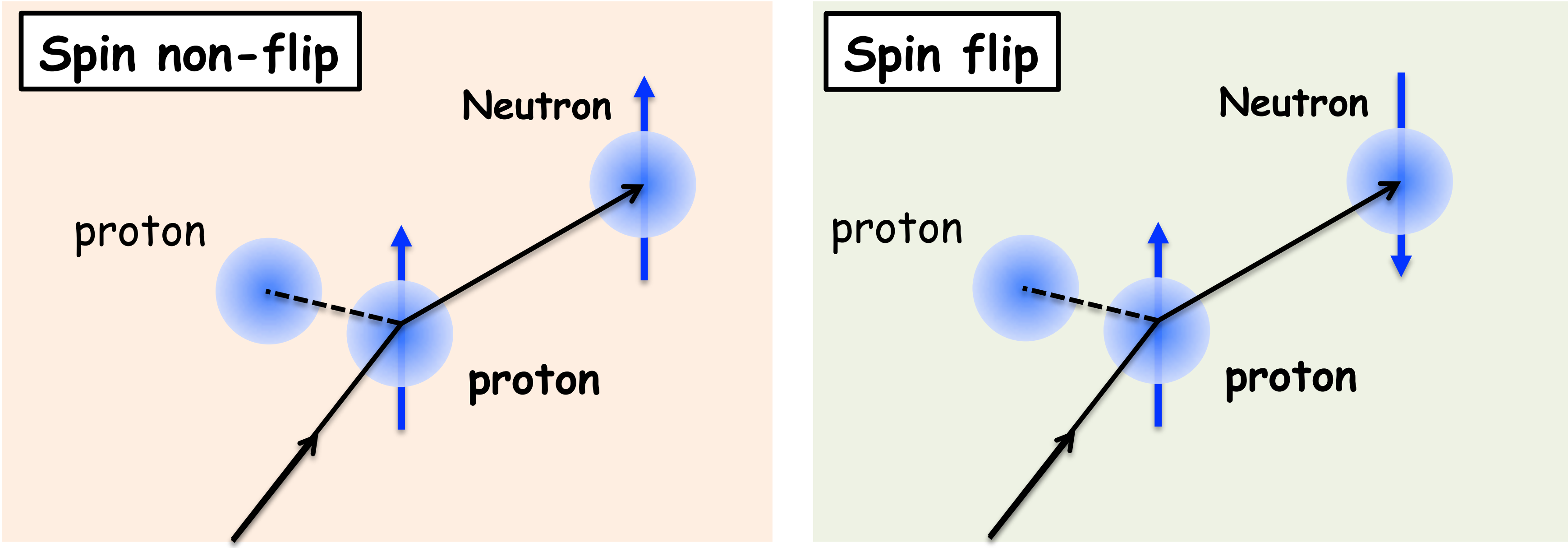


Momentum Transfer ~ 100MeV



Well Explained by
One-Pion Exchange

$p^{\uparrow}$+p Forward Neutron A_N

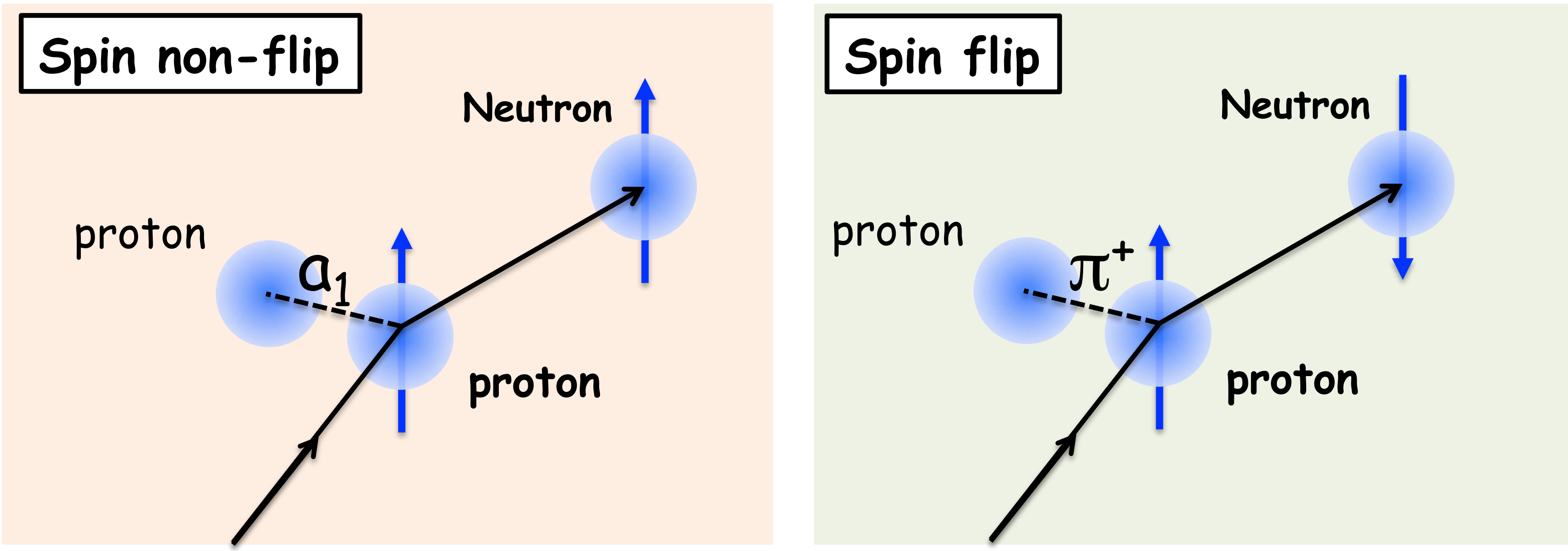


$$A_N \approx \frac{\left(\phi^*_{non-flip}\phi_{flip}\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

Unpolarized Cross Section

δ : phase shift

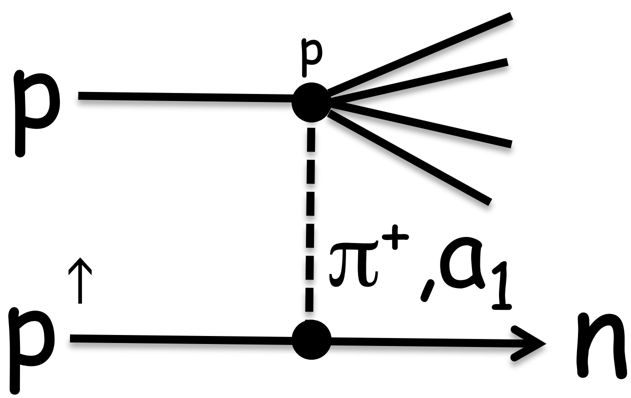
p$^{\uparrow}$+p Forward Neutron A_N



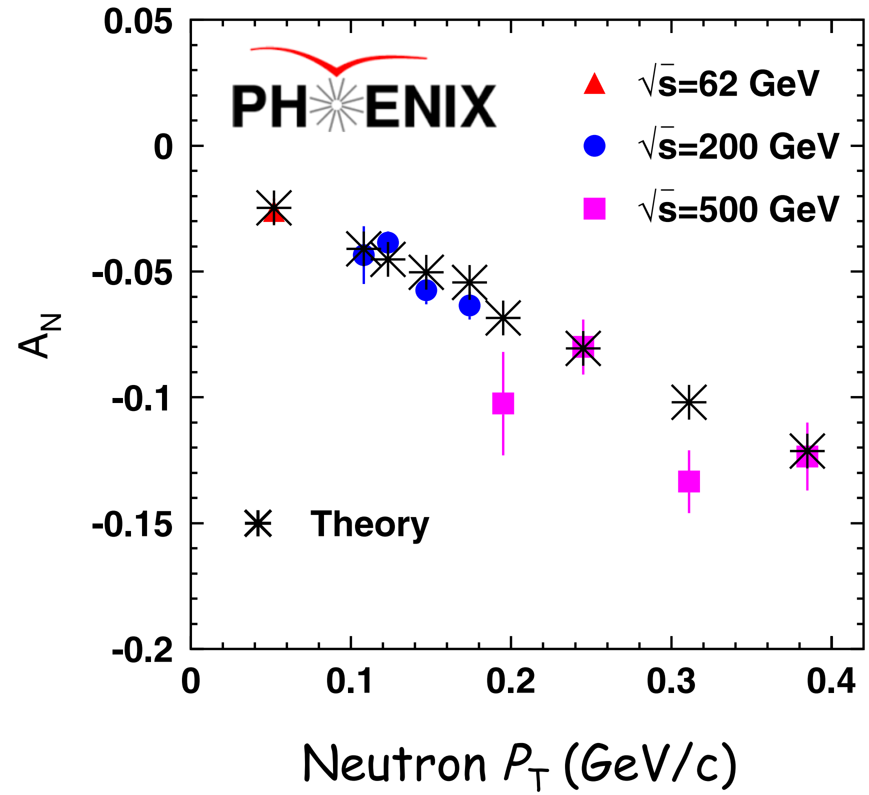
$$A_N \approx \frac{\left(\phi^*_{non-flip}\,\phi_{flip}\,\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

δ : phase shift

$p^{\uparrow}$+p Forward Neutron A_N



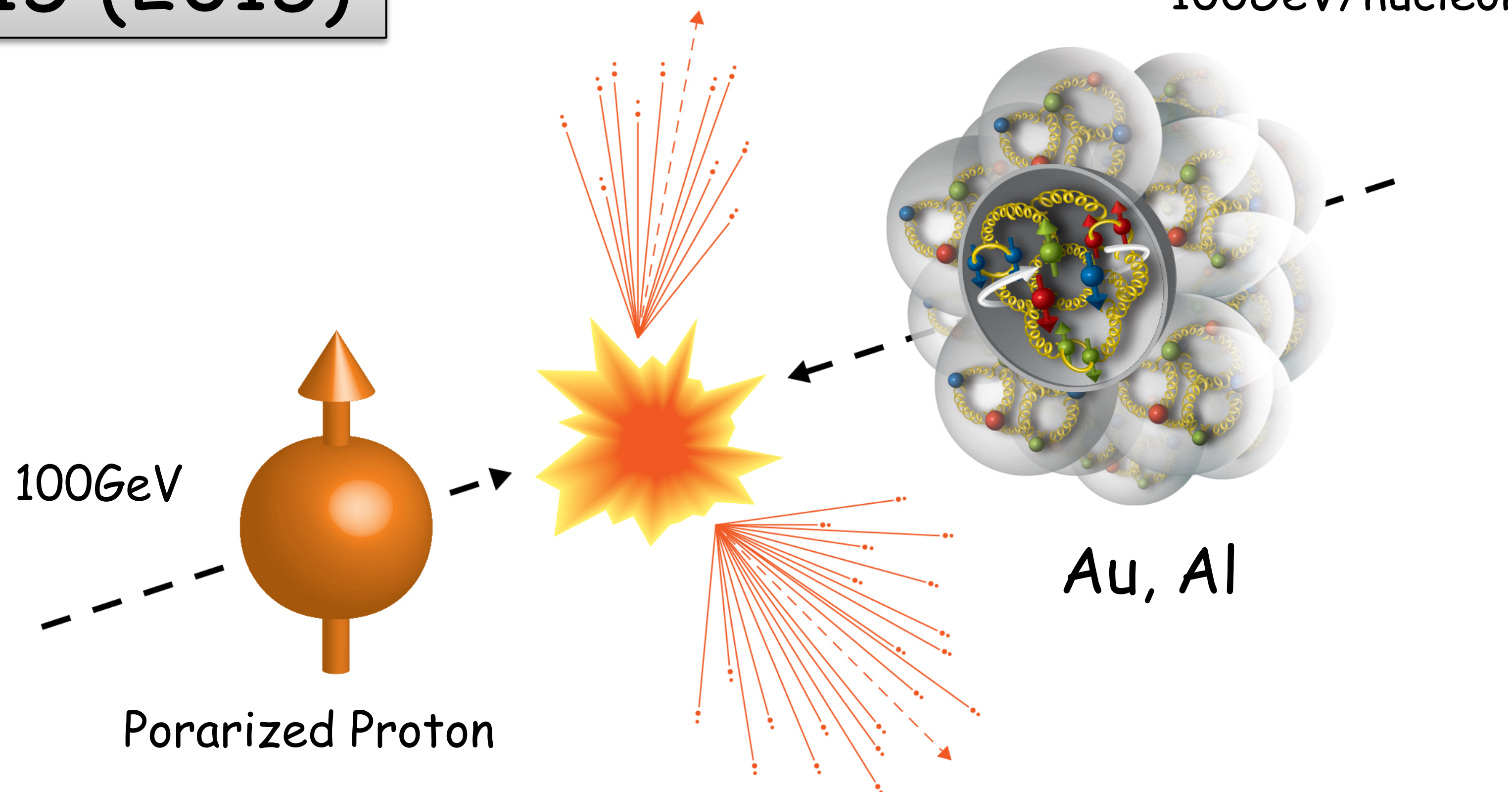
PRD84,114012(2011)



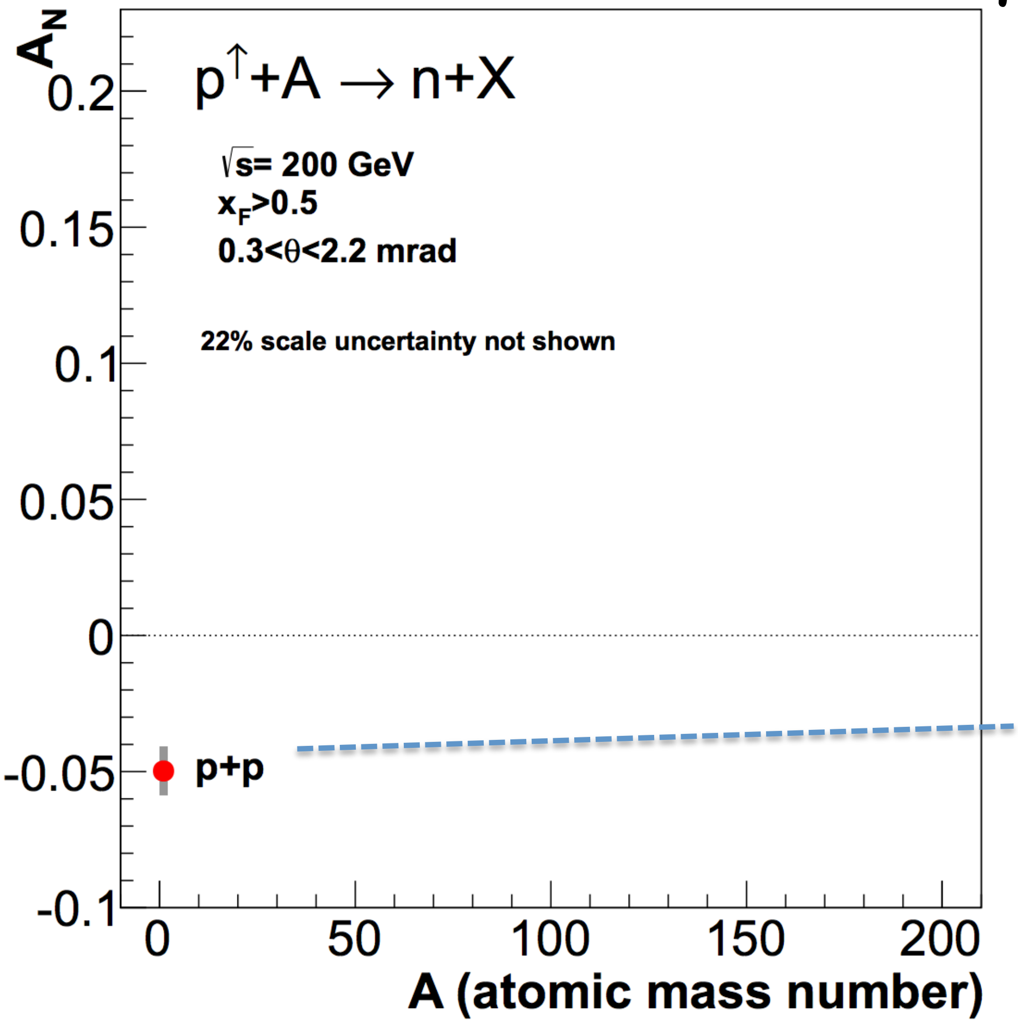
Data are well reproduced by the interference between π and a_1 Reggeon

The First Time Ever
High Energy $p^{\uparrow} + A$ Collisions

Run15 (2015)

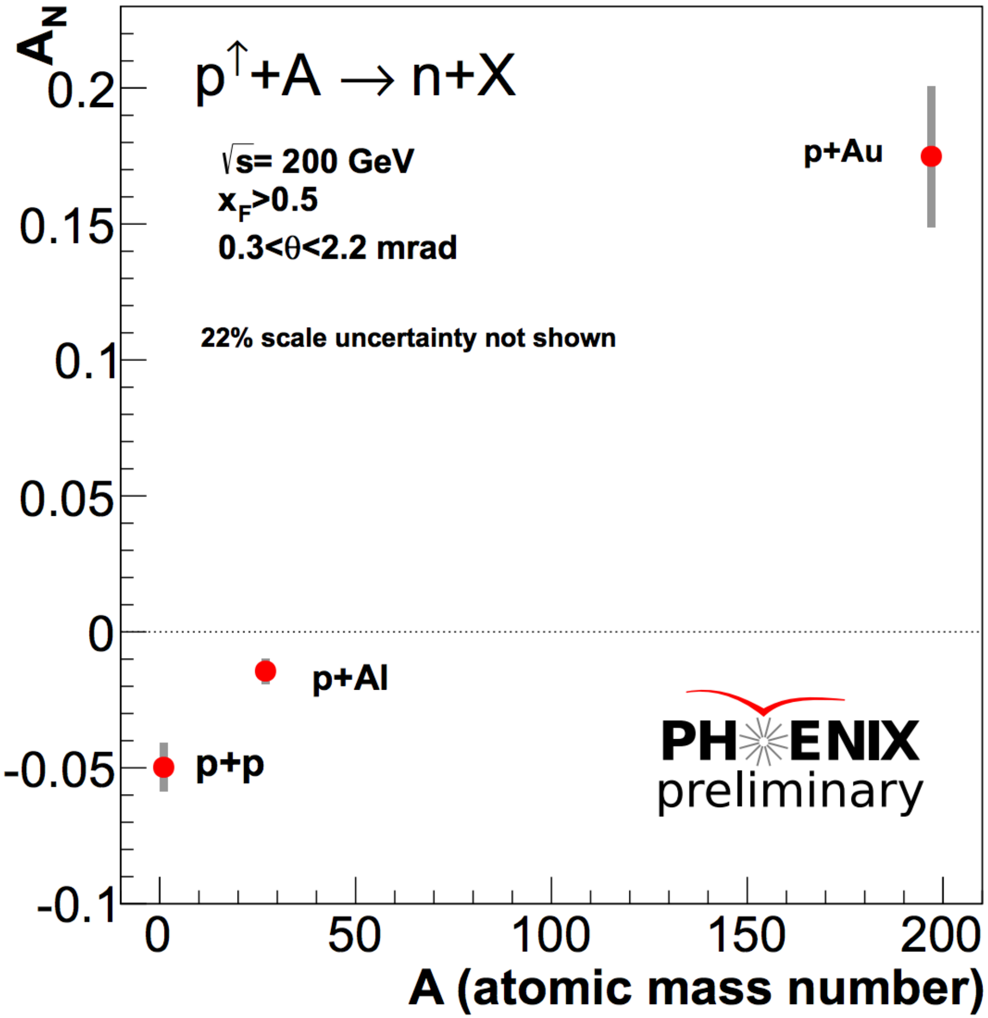


A-Dependent A_N (inclusive)



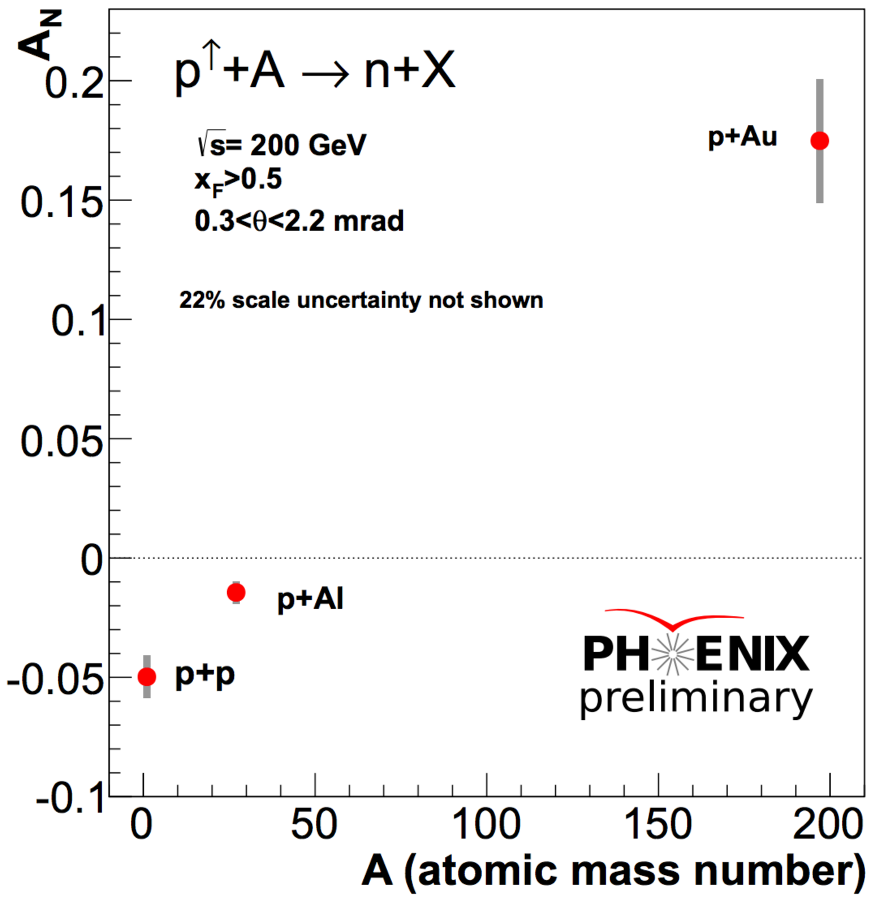
Present Frame Work

A-Dependent A_N (inclusive)



Analysis by
Minjung Kim (SNU/RIKEN)

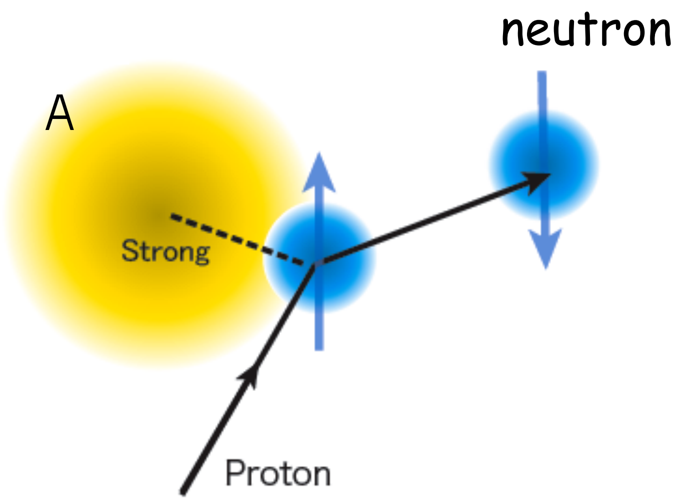
What is going on ?

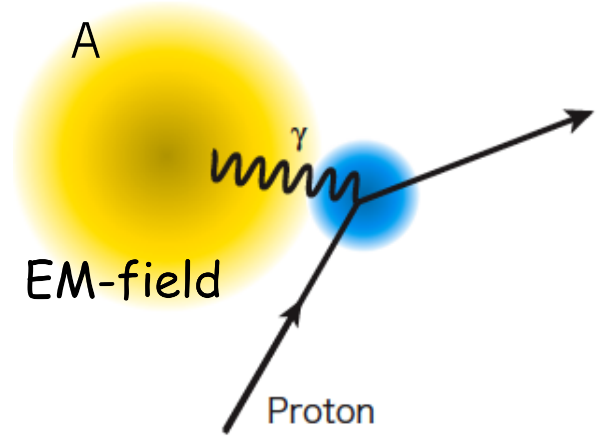


	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

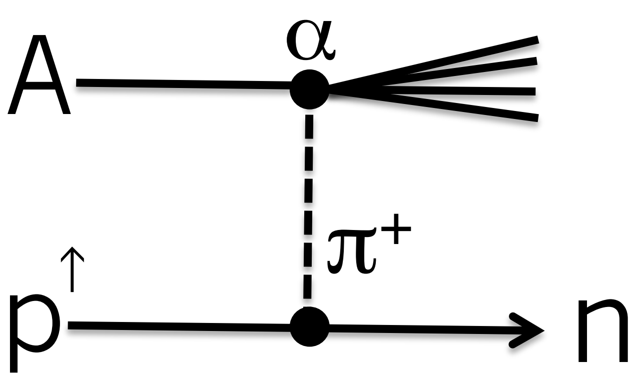
- Isospin Symmetry
- Surface Structure of Nucleus
- QED Process
- Gluon Saturation
- Else…

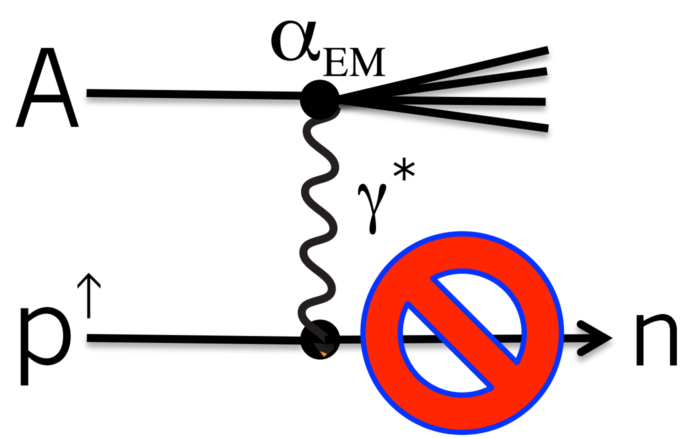
Primakoff Effect
Electro-Magnetic



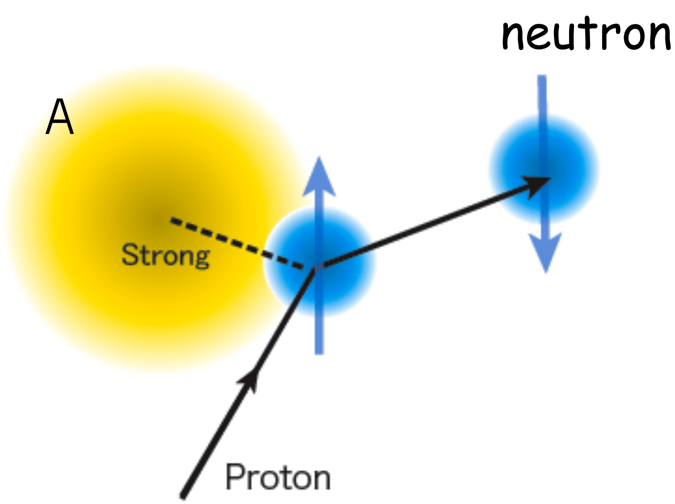


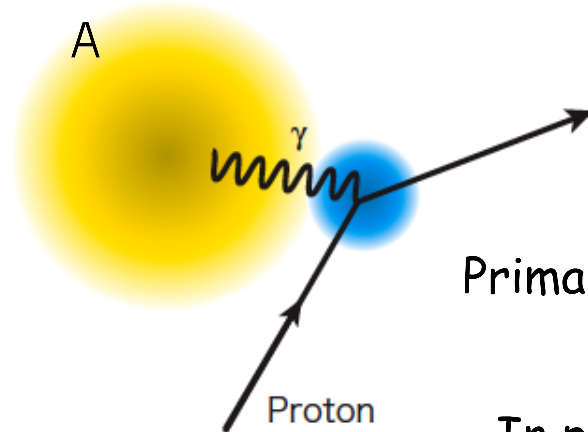
$t \to 0$





Primakoff Effect (Electro-Magnetic)



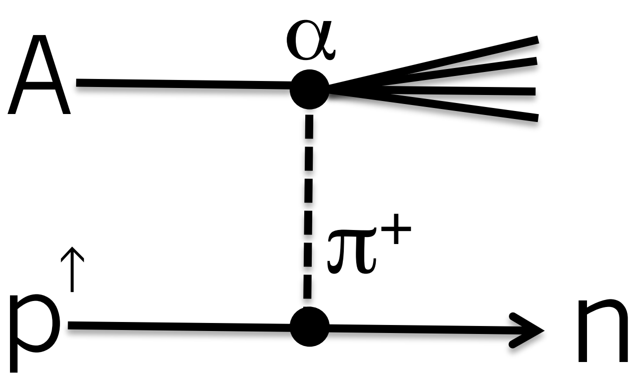


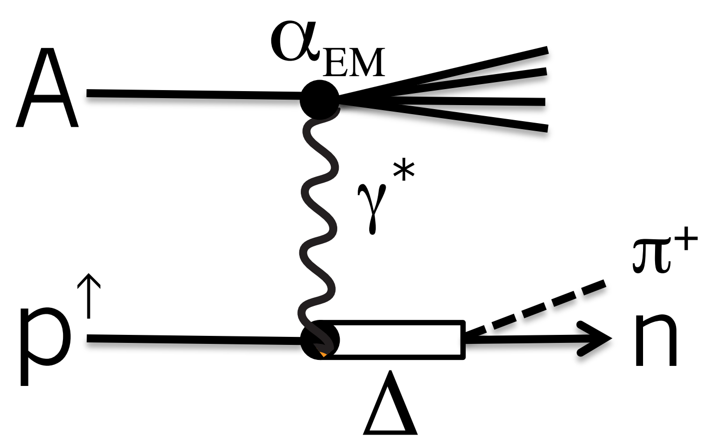
Primakoff

In pAu case

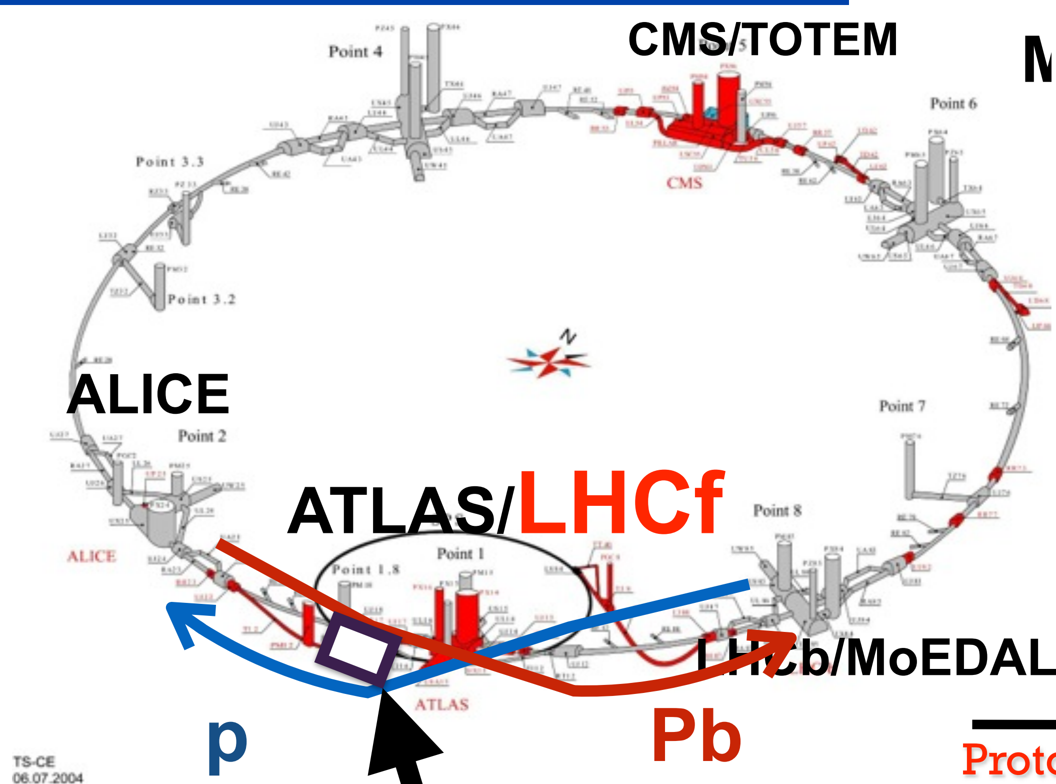
$t \to 0$

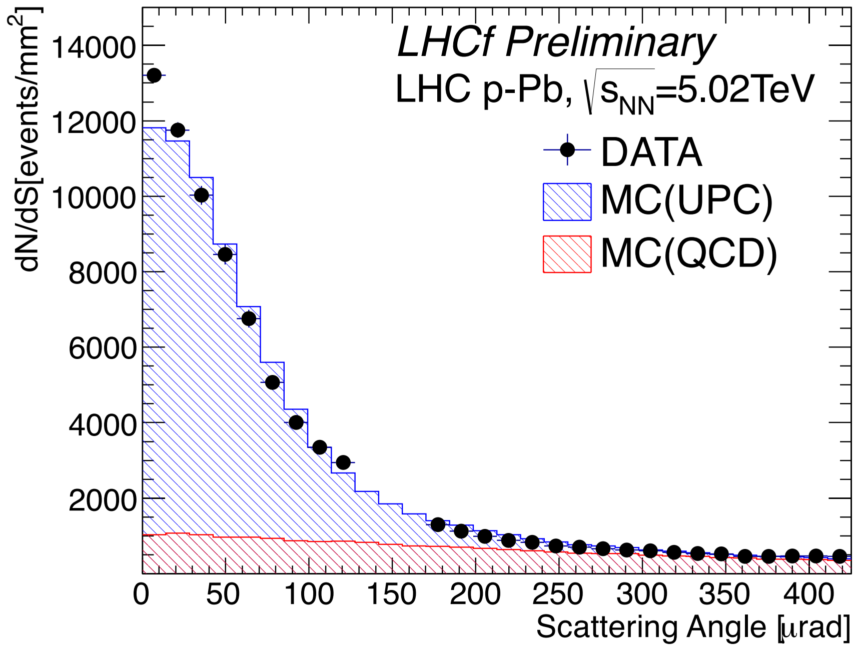
$Z \bullet \alpha_{EM} \sim 79/137$

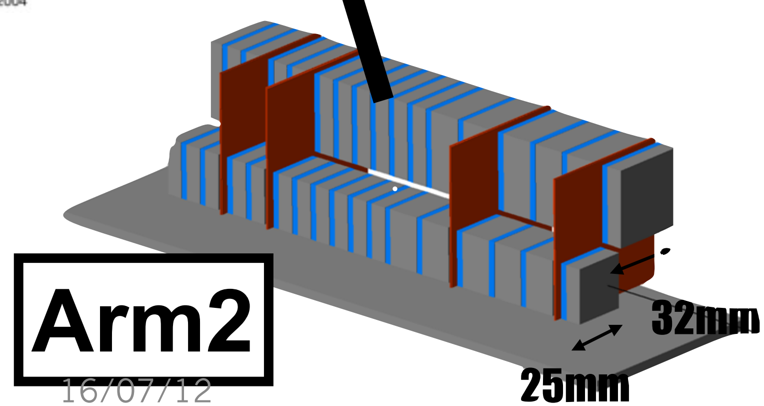


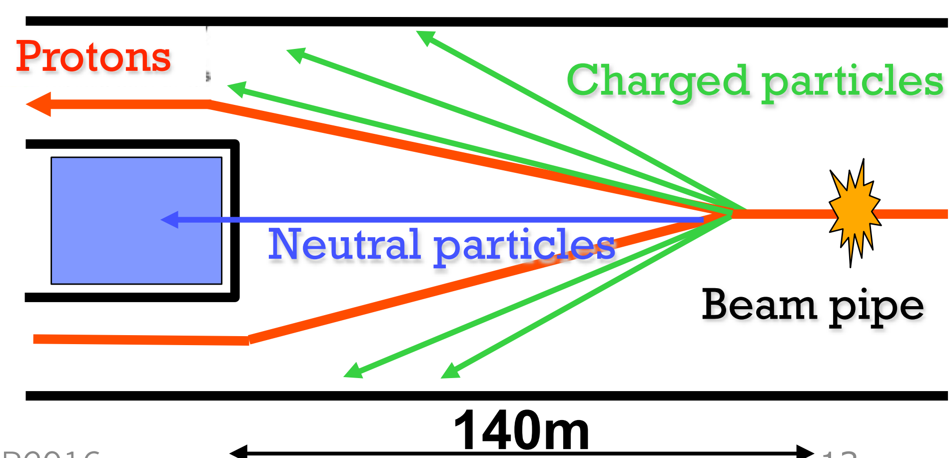


The LHCf experiment









UPC Monte Carlo

Eur. Phys. J. C (2015) 75:614
DOI 10.1140/epjc/s10052-015-3848-0

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Special Article - Tools for Experiment and Theory

Forward hadron production in ultra-peripheral proton–heavy-ion collisions at the LHC and RHIC

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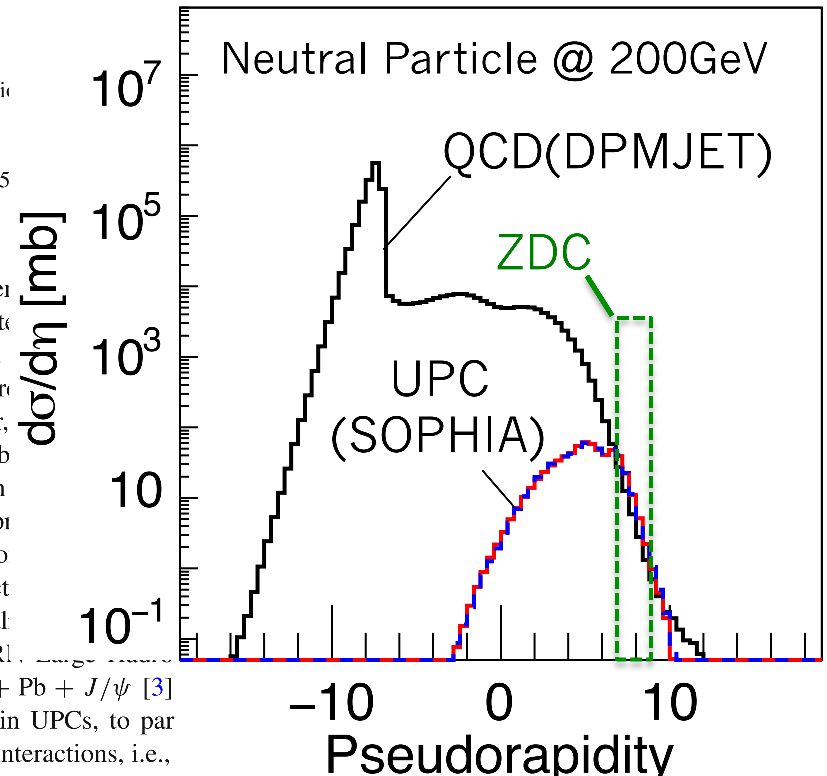
Received: 26 April 2015 / Accepted: 15 December 2015 / Published online: 26 December 2015

Abstract We present a hadron production study in the forward rapidity region in ultra-peripheral proton–lead ($p+$Pb) collisions at the LHC and proton–gold ($p+$ Au) collisions at RHIC. The present paper is based on the Monte Carlo simulations of the interactions of a virtual photon emitted by a fast moving nucleus with a proton beam. The simulation consists of two stages: the STARLIGHT event generator simulates the virtual photon flux, which is then coupled to the SOPHIA, DPMJET, and PYTHIA event generators for the simulation of particle production. According to these Monte Carlo simulations, we find large cross sections for ultra-peripheral collisions particle production, especially in the very forward region. We show the rapidity distributions for charged and neutral particles, and the momentum distributions for neutral pions and neutrons at high rapidities. These processes lead to substantial background contributions to the investigations of collective nuclear effects and spin physics. Finally we pro-

virtual photons e
may anyway int
usually referred
Ref. [1,2] for a r
UPCs, so far,
the gluon distrib
photoproduction
collisions can p
density in proto
momentum fract
measurements al
tion at the CER
$p+$ Pb $\rightarrow$ $p+$ Pb $+ J/\psi$ [3]
has been paid, in UPCs, to par
photon–proton interactions, i.e.,
less such particle production should be considered as well
in the investigation of collective nuclear effects. Because a



Predicts comparable yields between QCD and UPC processes

Full Description of A_N

$$A_N \propto 2\,\mathrm{Im}\left\{\phi^{*}_{non-flip}\phi_{flip}\right\}$$

$$\phi_{flip} = \phi^{had}_{flip} + \phi^{EM}_{flip}$$

$$\phi_{non-flip} = \phi^{had}_{non-flip} + \phi^{EM}_{non-flip}$$

$d_{1\sim4}$: relative phase of amplitudes

$$A_N \propto 2\,\mathrm{Im}\left(\phi^{had}_{non-flip} + \phi^{EM}_{non-flip}\right)\left(\phi^{had*}_{flip} + \phi^{EM*}_{flip}\right)$$

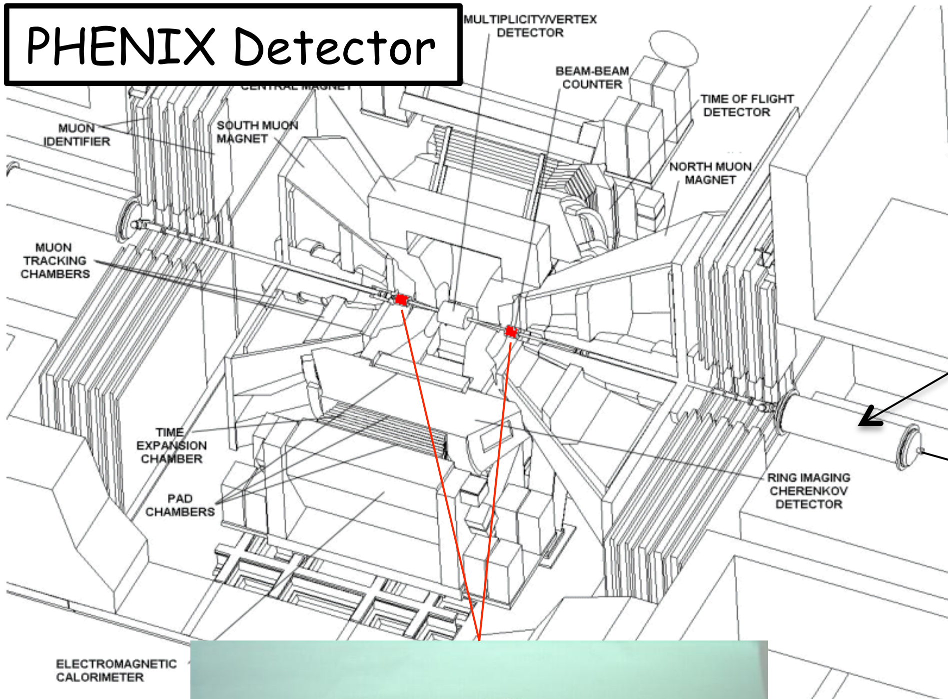
$$= 2\left(\phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4\right)$$

$\rightarrow 0$ (For pp)

large ← $-t$ → small

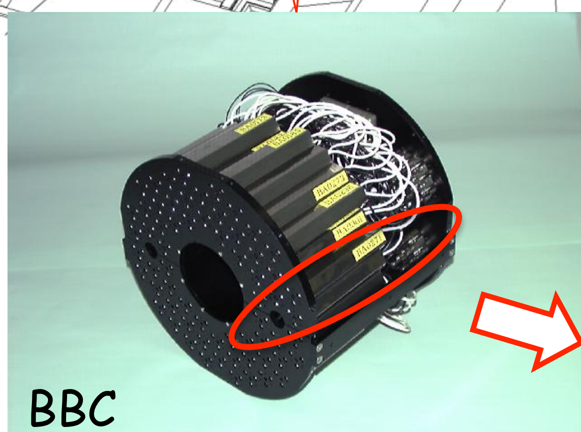
Beam-Beam Counter

PHENIX Detector



Dipole Bending Magnet

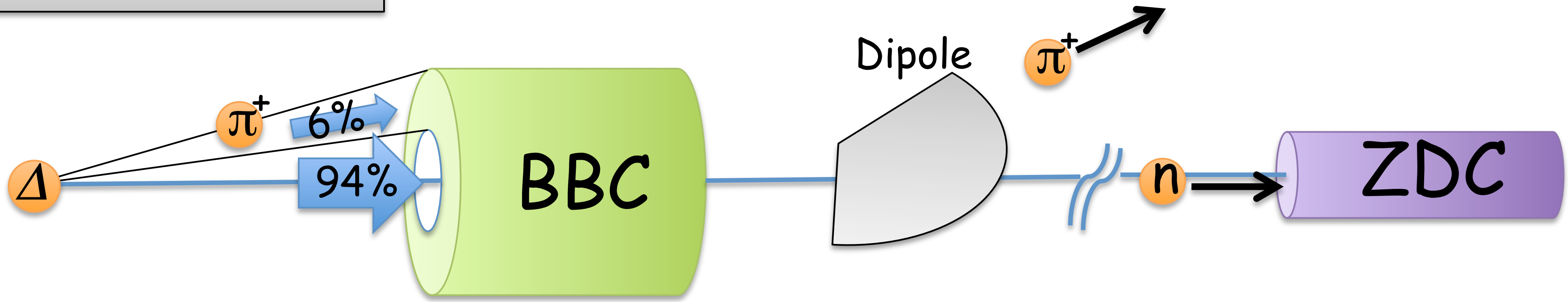
ZDC



Quartz Cherenkov radiator

Can we identify Primakoff events?

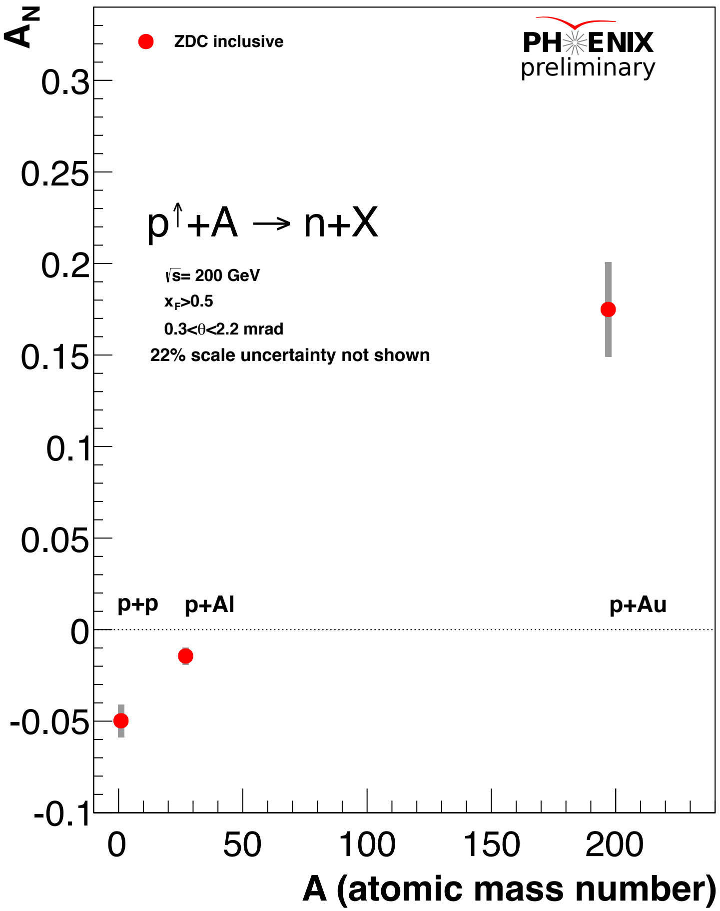
Semi-Inclusive



Primakoff MC : SOPHIA
G. Mitsuka, Eur. Phys. J.C. (2015) 75:614

BBC	tag	veto
Primakoff	Small	Large

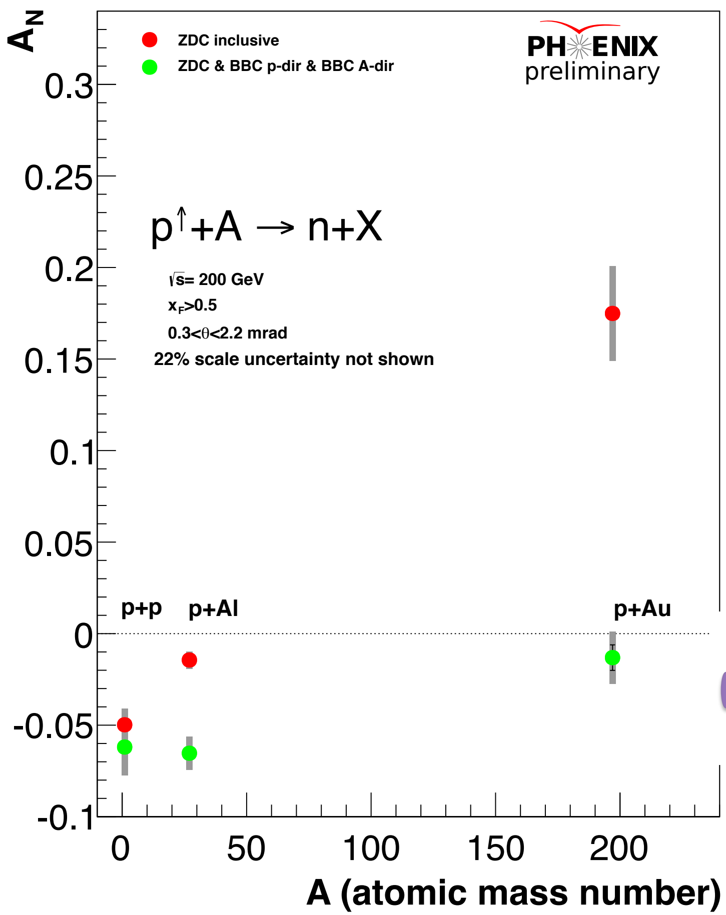
BBC Tagging and Vetoing

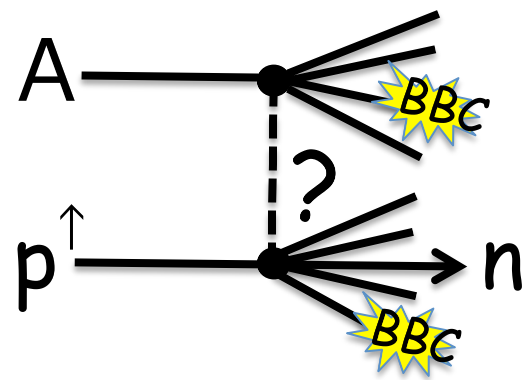


Inclusive

$$A_N \sim \boxed{had * had + had * EM + EM * had + EM * EM}$$

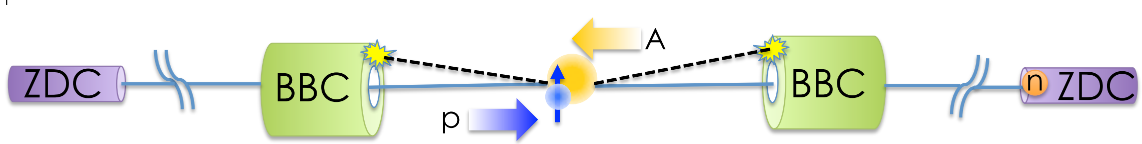
BBC Tagging and Vetoing





Non-diffractive

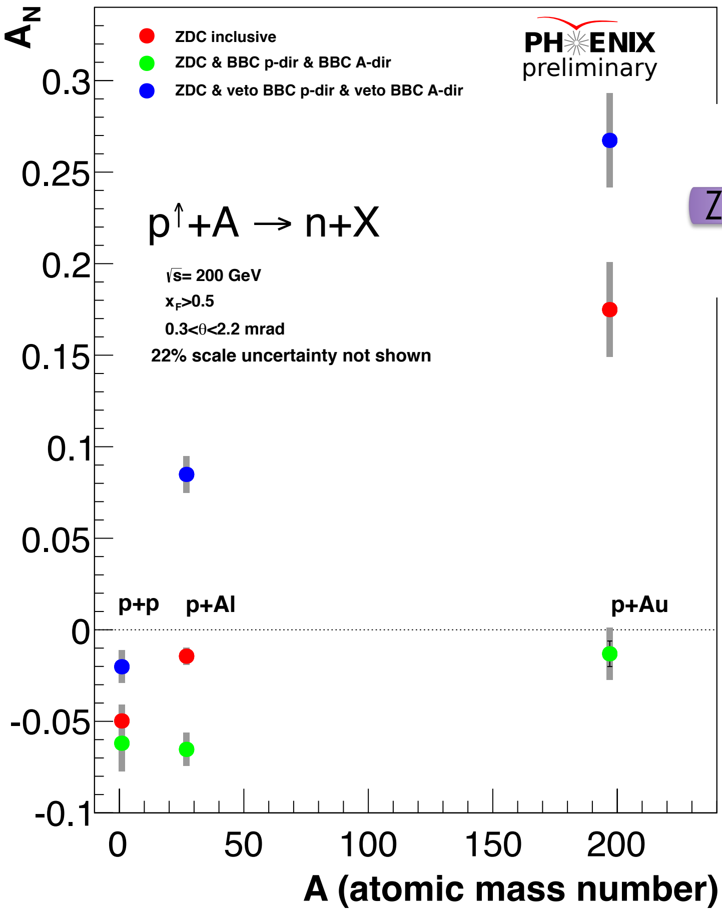
BBC Tagging



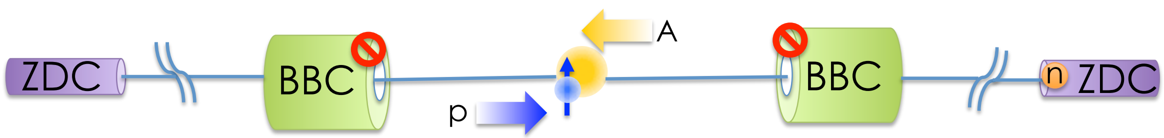
EM surpressed

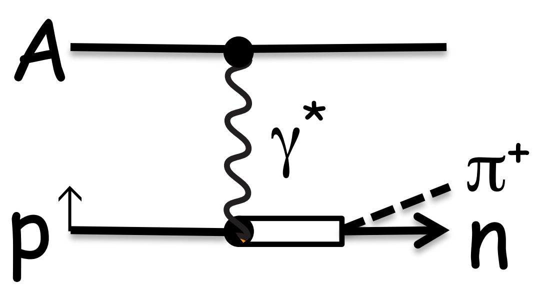
$$A_N \sim \boxed{had * had} + \underbrace{had * EM + EM * had + EM * EM}$$

BBC Tagging and Vetoing



BBC Vetoing





Diffractive

EM enhanced

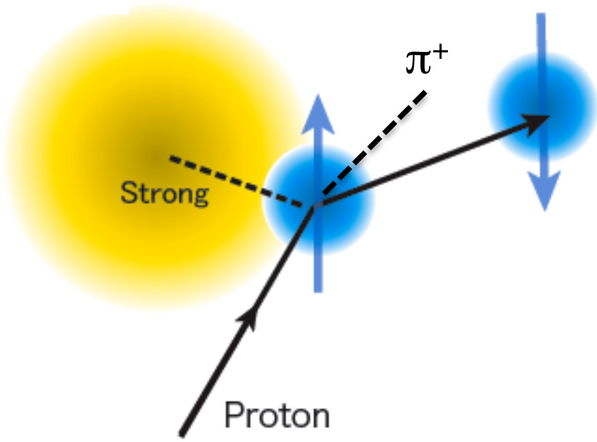
$$A_N \sim had * had + had * EM + EM * had + EM * EM$$

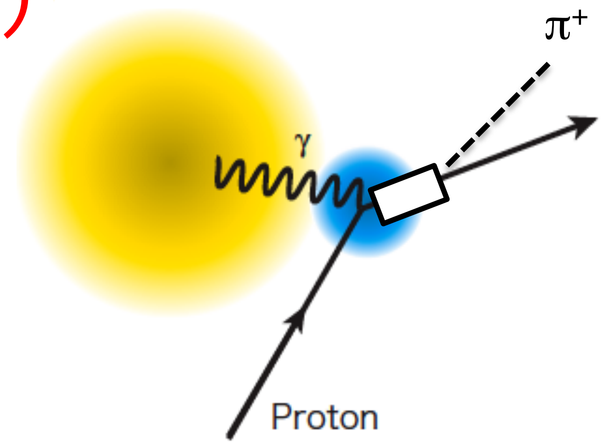
Fractions

	p+p	p+Al	p+Au
Inclusive	36 %	34 %	13 %
BBC veto	24 %	31 %	67 %
BBC tag	36 %	34 %	13 %

Coulomb-Nuclear Interference

(CNI)





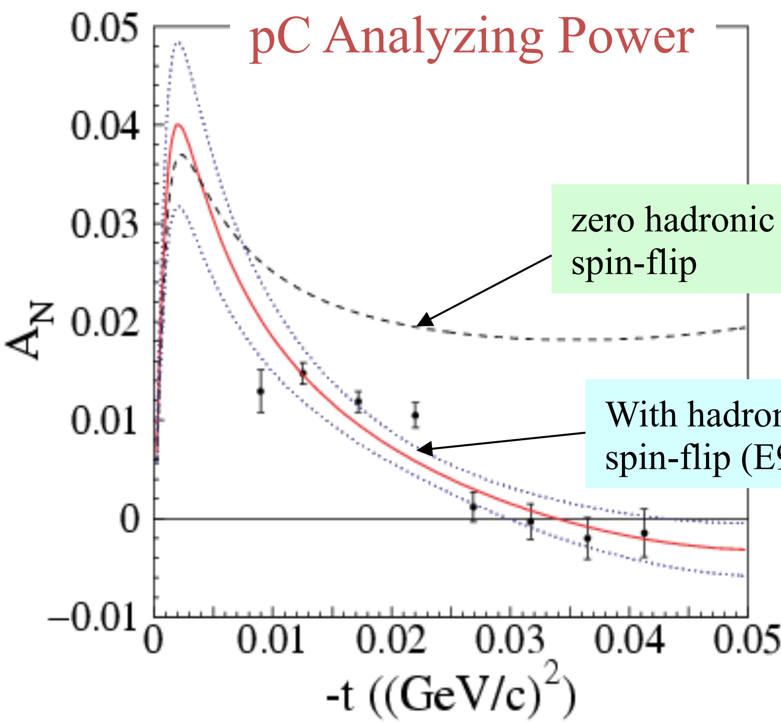
$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Elastic A_N at Coulomb Nuclear Interference

$$A_N \sim 2\,\mathrm{Im}\left\{\phi^{EM*}_{non-flip}\,\phi^{had}_{flip}\sin\delta_2 + \phi^{had*}_{non-flip}\,\phi^{EM}_{flip}\sin\delta_3\right\}$$

$\propto \alpha s/t$ | Pomeron | $\propto \sqrt{\sigma^{had}_{pC}}$ | $\propto (\mu_p - 1)$

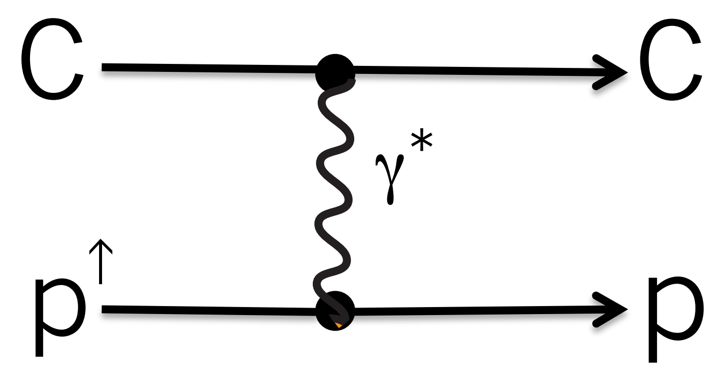
(High energy & small t limit)



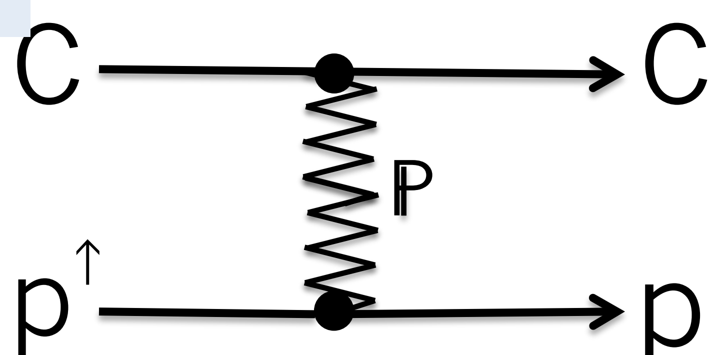
Phys.Rev.Lett.,89,052302(2002)

E_{beam} = 21.7GeV

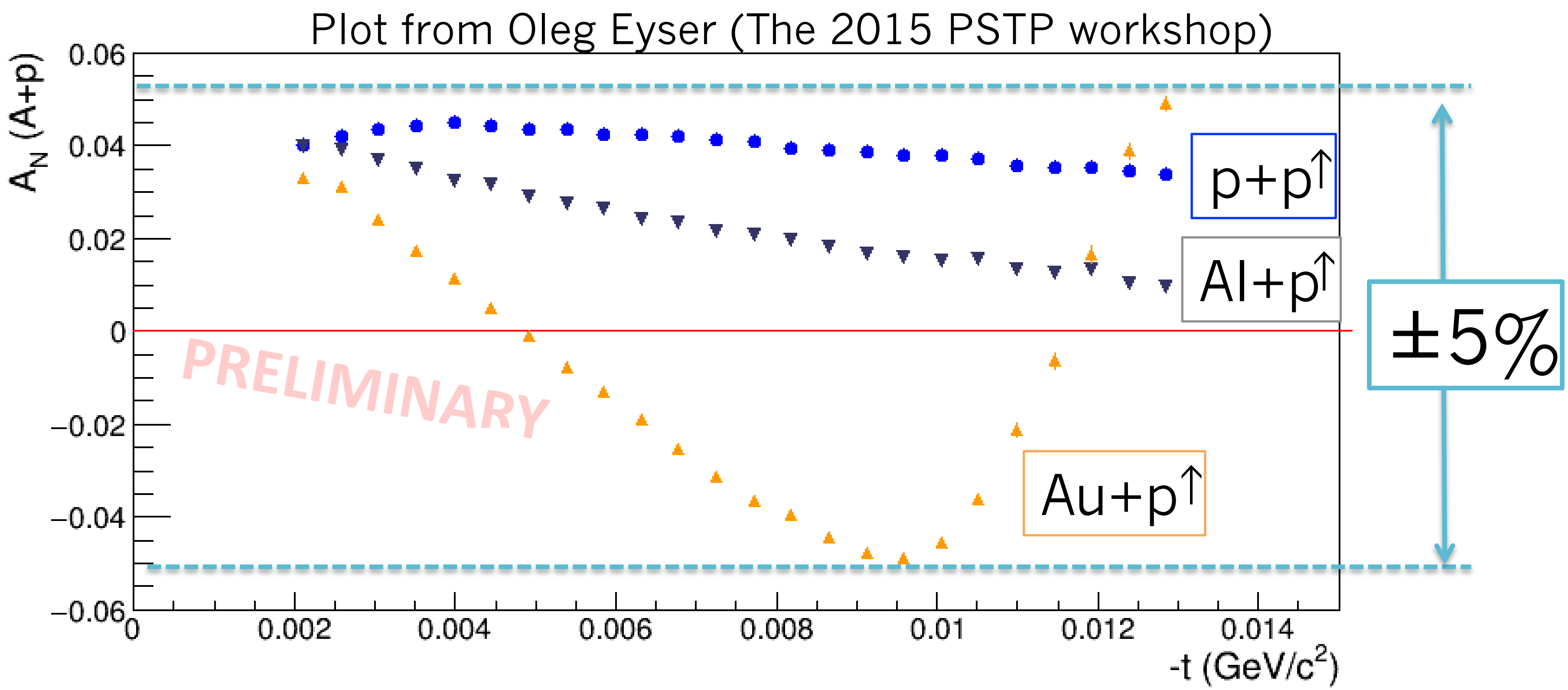
EM



had



Run15 Au,Al beam + p↑ target

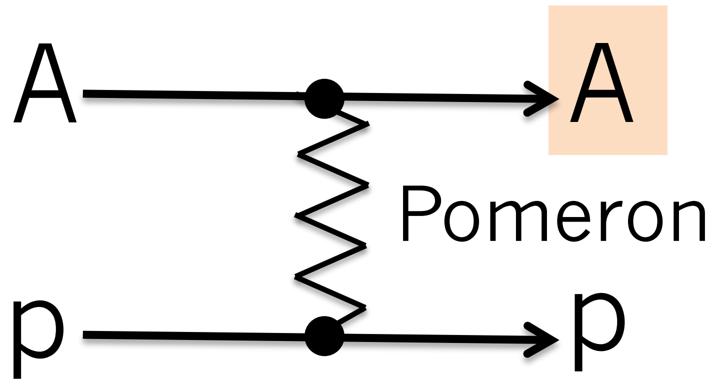


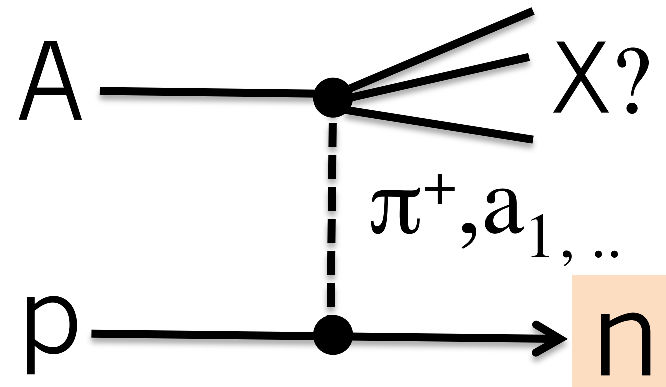
- Strong A-Dependence
- Flips sign of A_N in Au+p↑
- 0.002 < -t < 0.014 $(\mathrm{Gev/c})^2$

Forward Neutron
0.02 < -t < 0.5 $(\mathrm{Gev/c})^2$

Underlying Mechanism Comparison

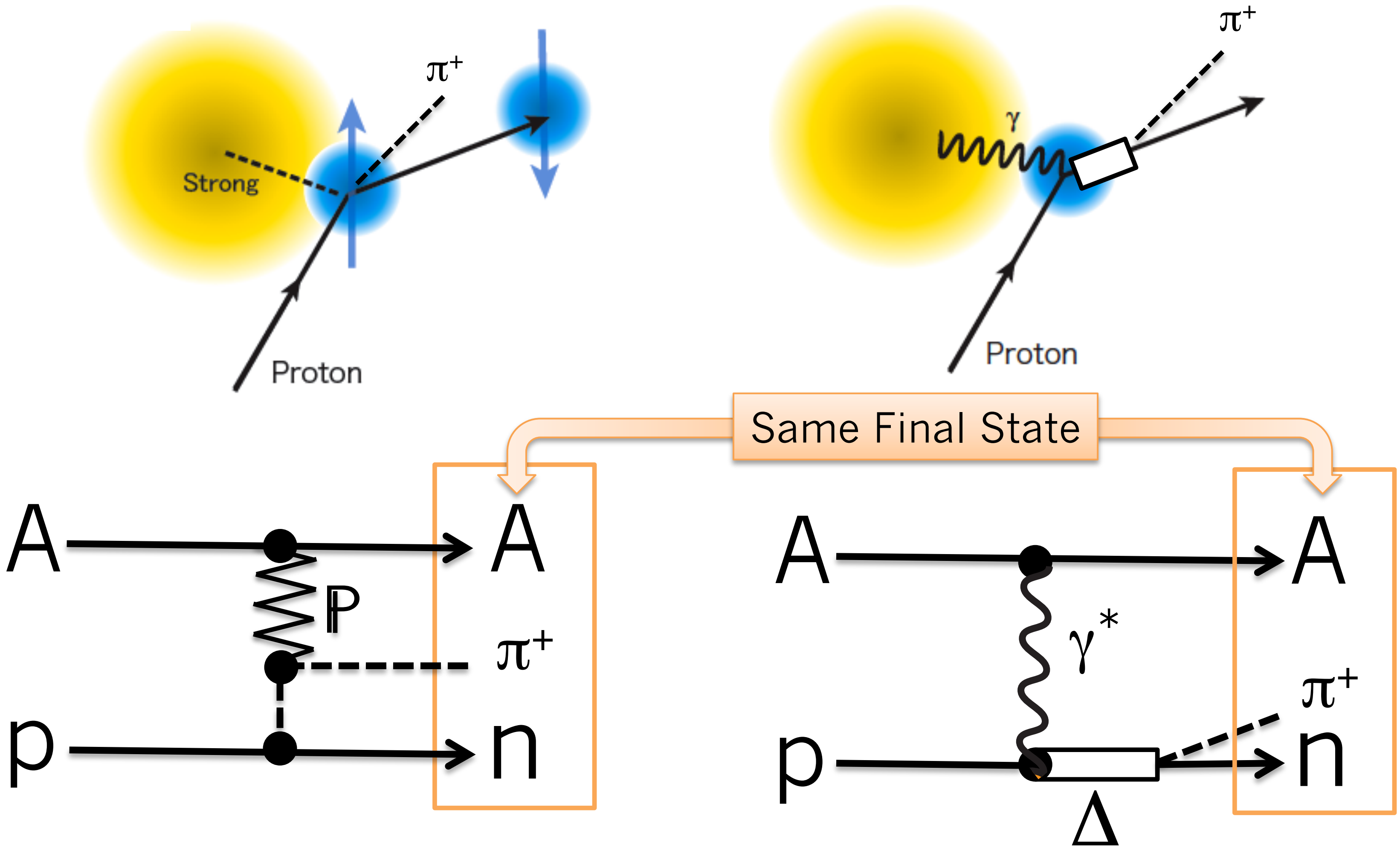
Polarimeter	Forward n





Elastic	Inelastic
$\sqrt{s}$ = 14 GeV	$\sqrt{s}$ = 200 GeV
0.002 < -t < 0.014	0.02 < -t < 0.5
$\Delta I = 0$	$\Delta I = 1$

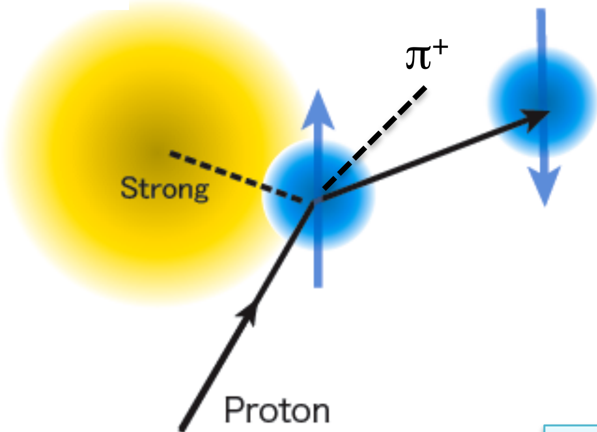
Coulomb-Nuclear Interference in Forward Neutron Production

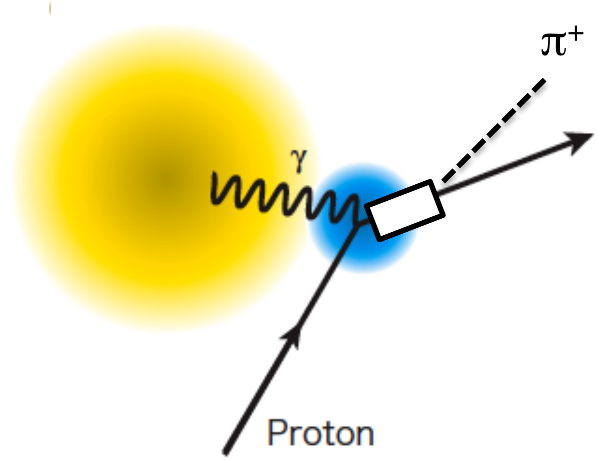


$$A_N \sim had * had + had * EM + EM * had + EM * EM$$

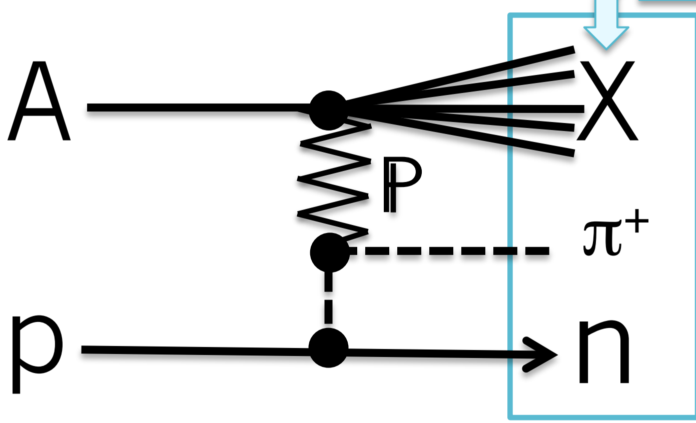
Diffractive Process Required?

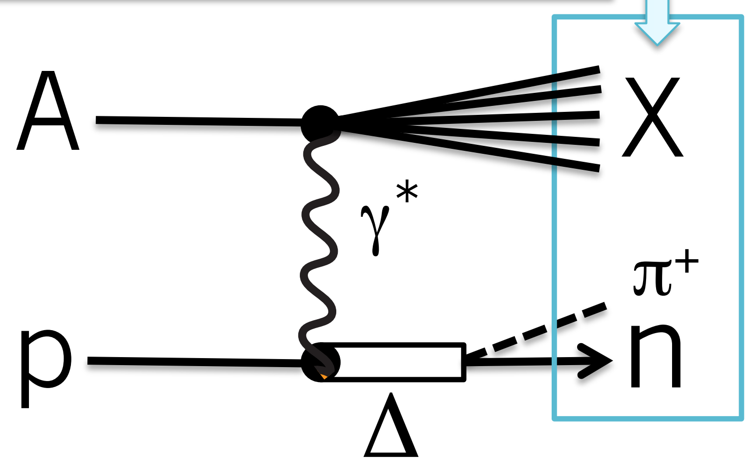
Non-Diffractive Events





Little chance to be same final state





$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Suppressed?

Summary

- Observed large asymmetry in very forward neutron A_N in p+A collision.
- Strong A-dependence in neutron + BBC vetoed events and flips the sign of A_N between p+p and p +Al.
- Indication of EM from related experiments
  - LHCf observed Primakoff Peak in p+Pb->n+X
  - Primakoff MC indicates EM is relatively enhanced in BBC veto events where large positive A_N is observed.
  - Elastic p+p, p+C at high energy also shows $A_N<5\%$ due to interference between EM and strong force.

Primakoff Effect

Itaru Nakagawa
RIKEN/RBRC

Primakoff Paper

Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. PRIMAKOFF†
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

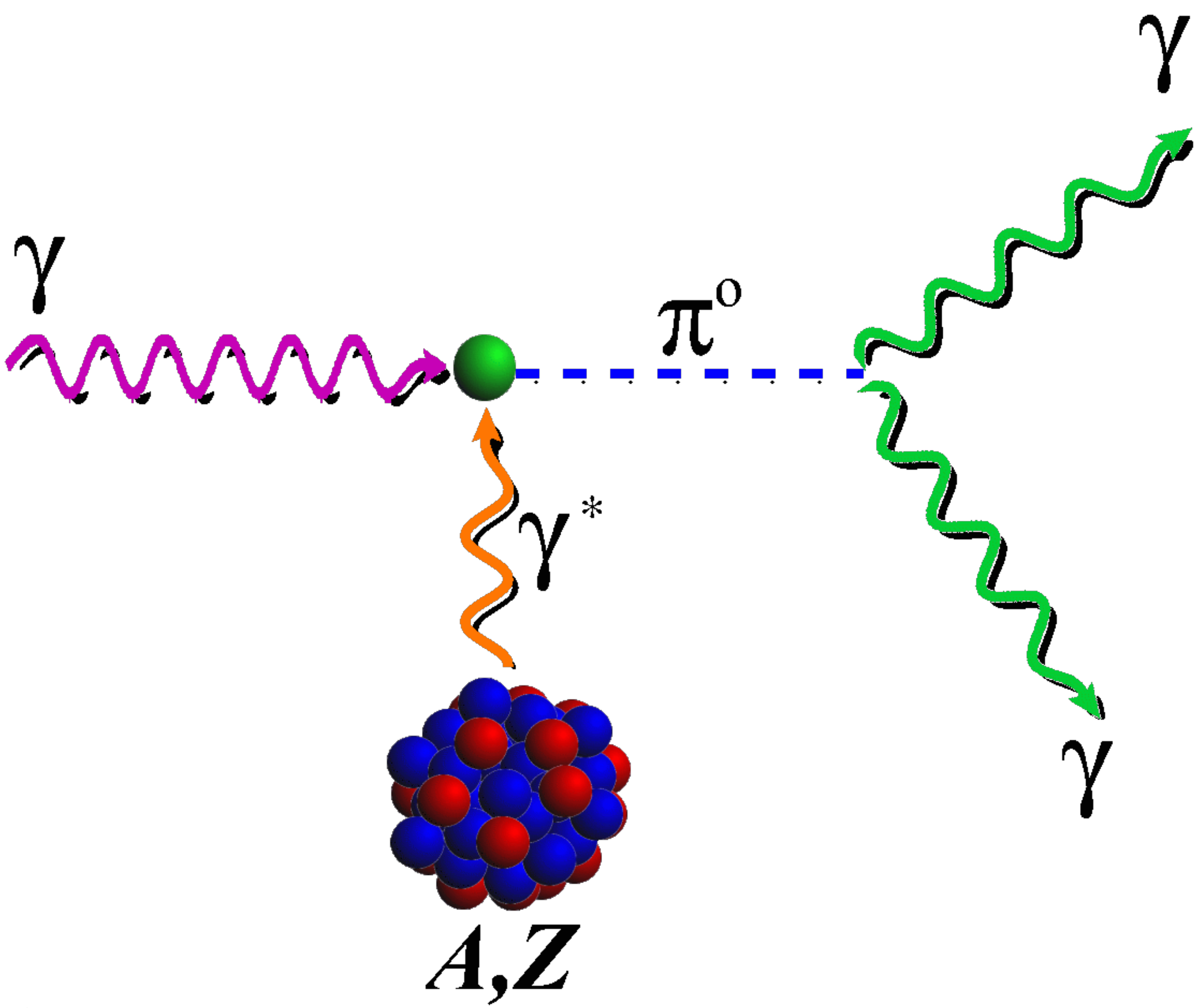
IT has now been well established experimentally that neutral π-mesons (π^0) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero π^0 spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the π^0 wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

Here φ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of π^0),

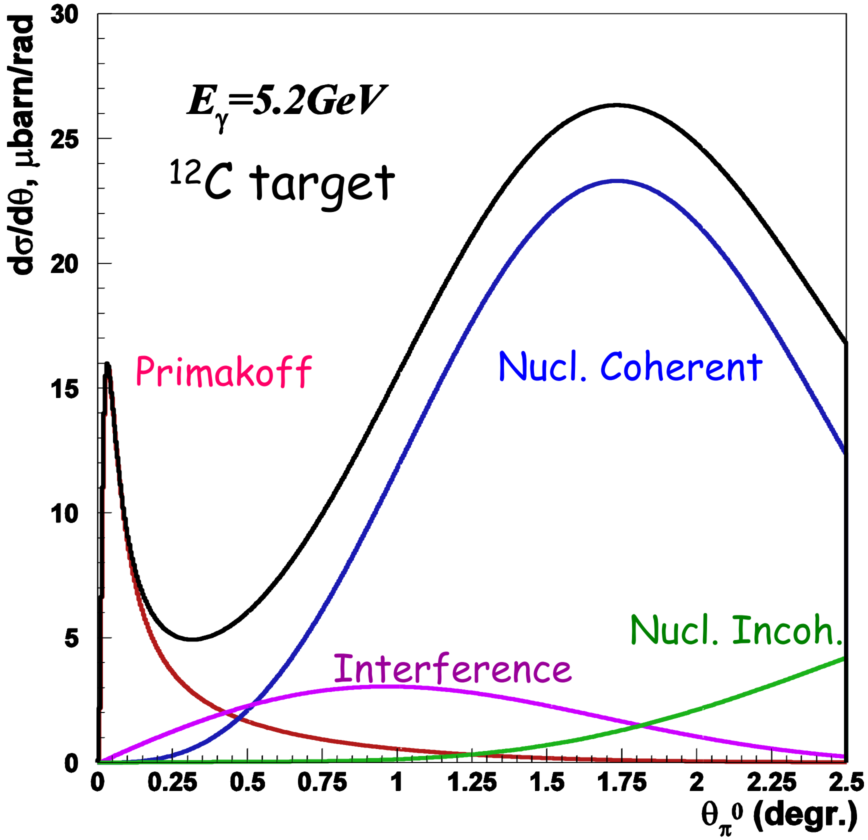
Henry Primakoff, Phys. Rev. 81, 899 (1951).

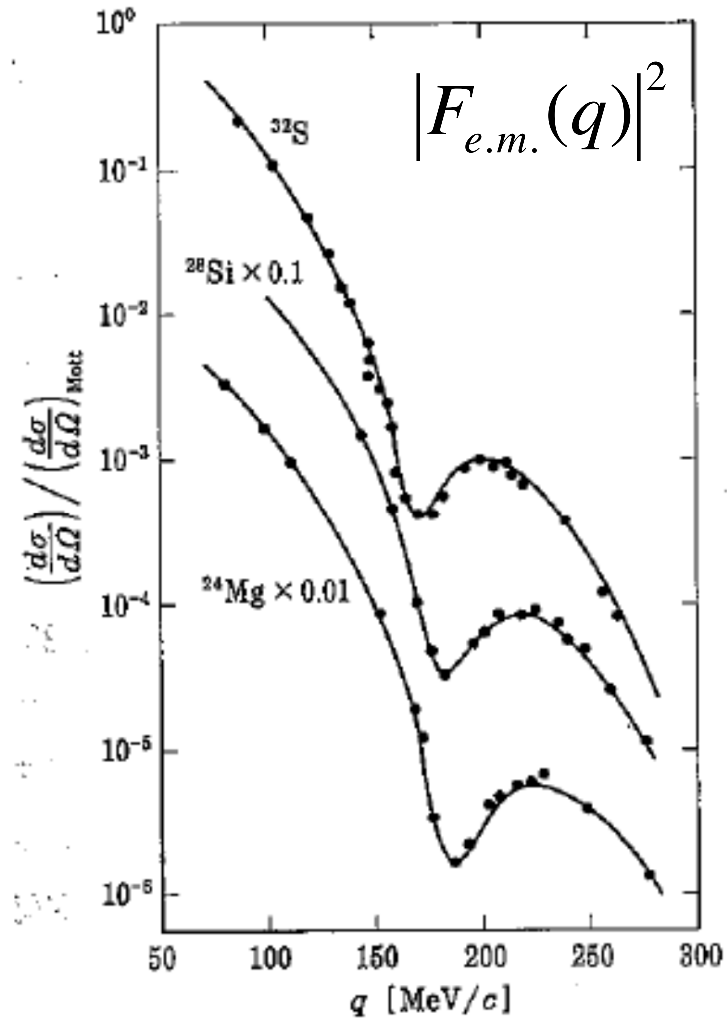
Primakoff Experiment (Hall-B, Jlab)



PRL 106, 162303 (2011)

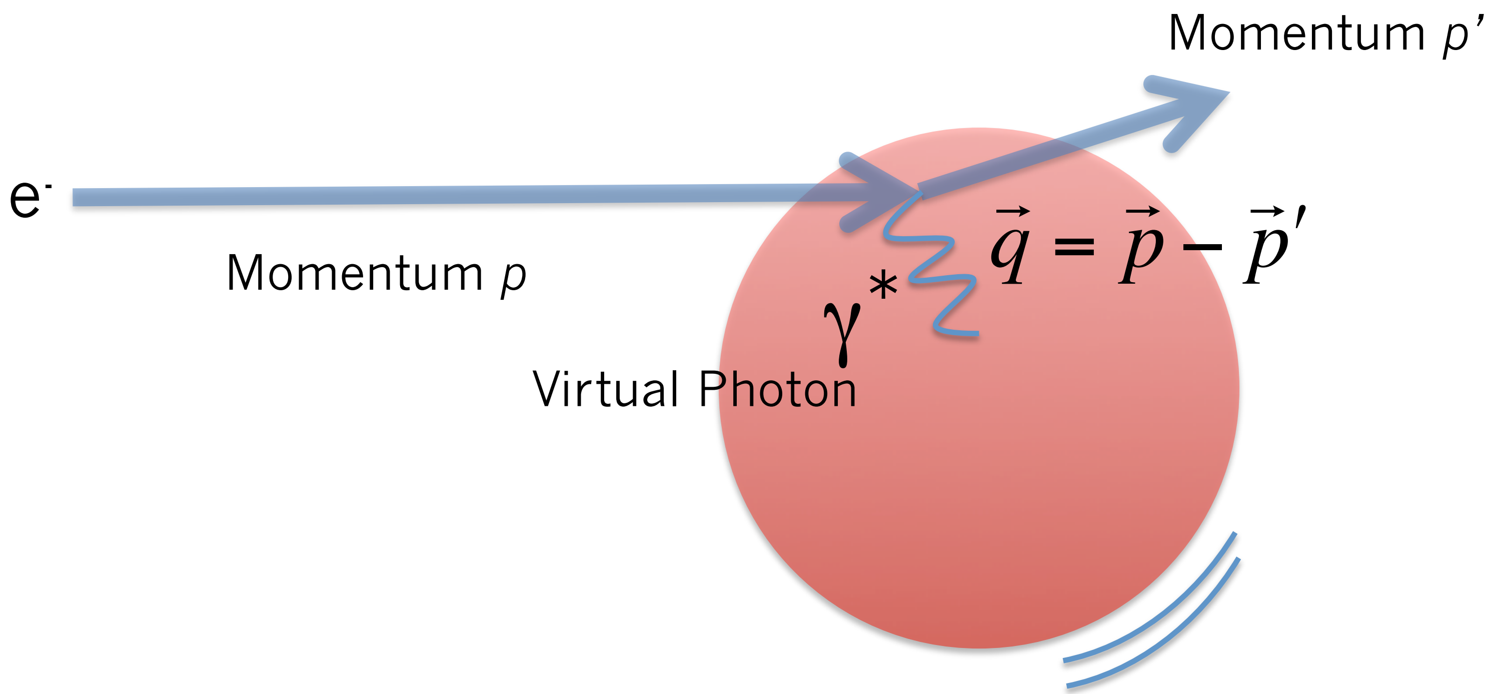
π^0 angular distribution





$$\frac{d\sigma_{\text{Primakoff}}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} \left|F_{e.m.}(Q)\right|^2 sin^2(\theta)$$

Nuclear Electromagnetic Form Factor



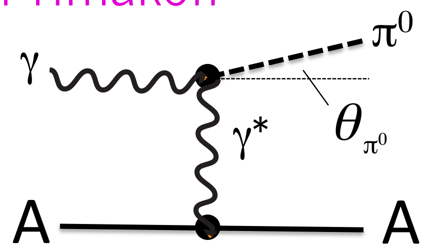
$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \bullet \left|F(q^2)\right|^2$$

q: Momentum Transfer

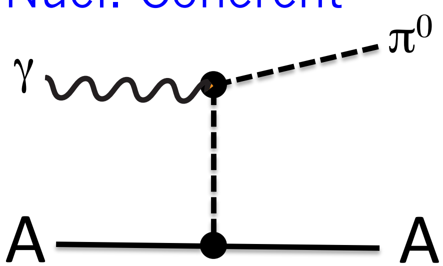
Electromagnetic form factor

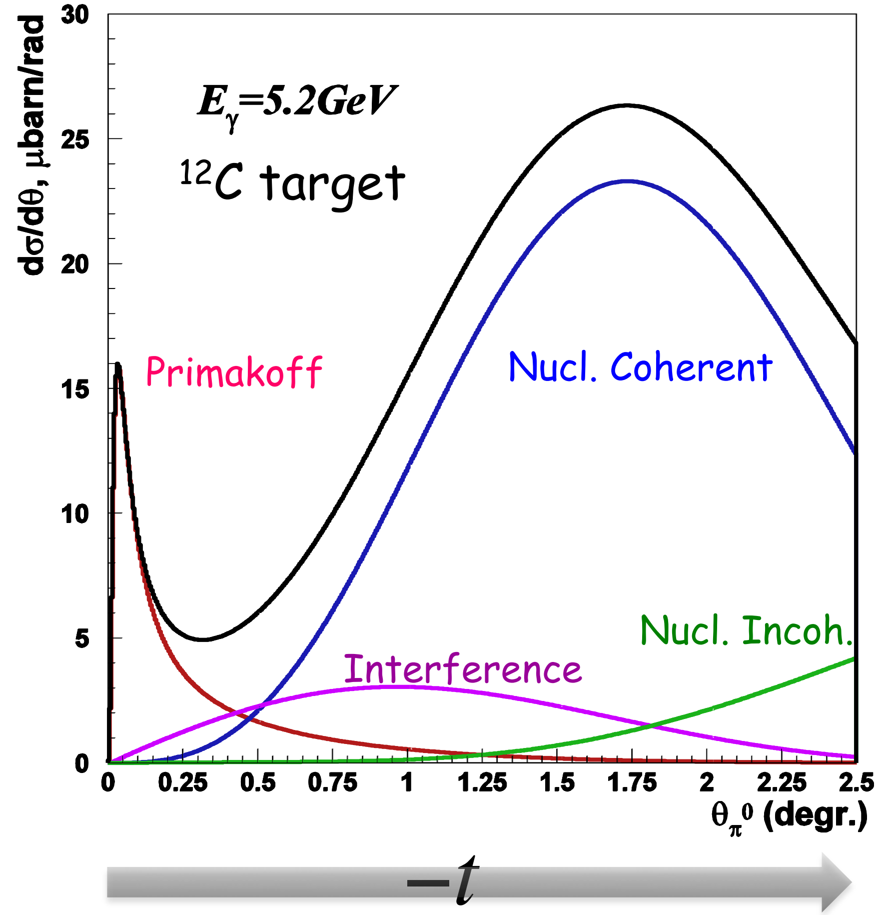
π^0 angular distribution

Primakoff

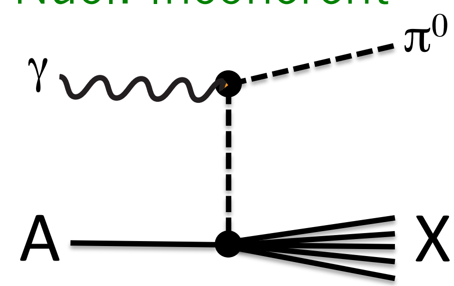


Nucl. Coherent



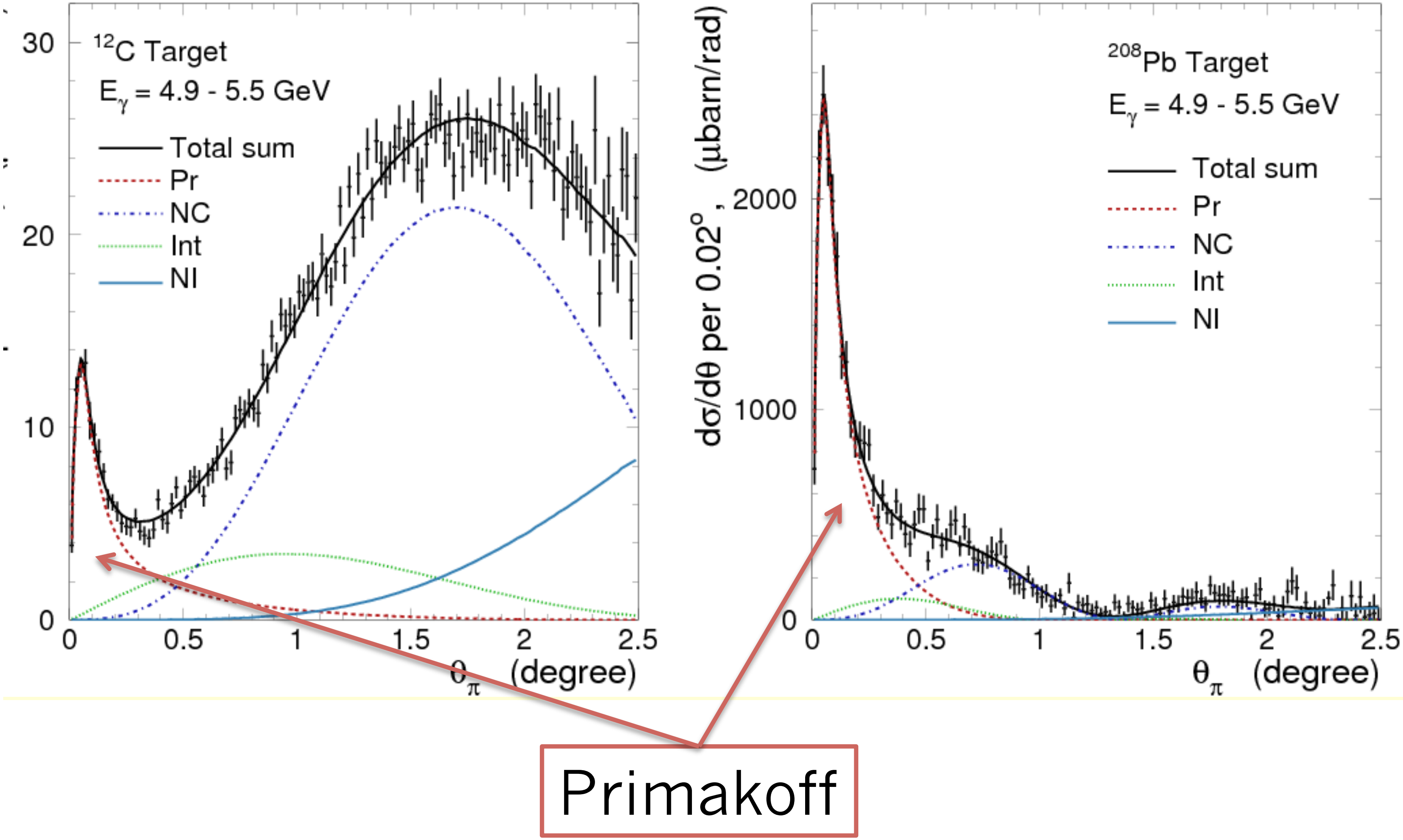


Nucl. Incoherent



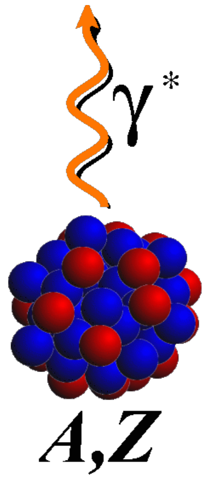
$$\frac{d\sigma_{\text{Primakoff}}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} \left|F_{e.m.}(Q)\right|^2 sin^2(\theta)$$

A(Z)-Dependence



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

Primakoff Summary



- Photon pick up from the Coulomb field of nucleus
- Out-going products through Primakoff effect has strongly forward boosted.
- Primakoff effect is suppressed rapidly as a function of emission angle or momentum transfers.
- Primakoff effect gets stronger as a function of Z.

Measurement of the Analyzing Power in the Primakoff Process with a High-Energy Polarized Proton Beam

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The origin of Asymmetry

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cording to Eq. (1), the asymmetry seen in photoproduction due to the interference between Δ and N^* is expected in coherent Coulomb π^0 production by polarized protons, using the same region of the π^0-p invariant mass. Therefore this process may be used to measure the polarization of the proton at high energies.[6] Until now, there has been no measurement of the asymmetry in the nuclear coherent process.

The cross section for the Coulomb coherent process (1) has a sharp peak at $t' \sim 10^{-5}$ $(\mathrm{GeV}/c)^2$ and decreases rapidly as t'/t^2. The "width" of the Coulomb peak is determined by the detector resolution. Diffractive dissociation due to the strong interaction is also present, but it has a much slower t' dependence.

We have measured the analyzing power (azimuthal asymmetry) of nuclear Coulomb coherent production from a Pb target by using the newly constructed 185-GeV/c Fermilab polarized proton beam.[7] The beam polarization is 45% and this is further described in Ref. 7. To reduce certain systematic errors, the spin direction of the incident proton was flipped every 10 min using a spin-rotator system.[7]

monitored to a 1% accuracy with a xenon-flash-tube system. A 30-GeV positron beam was used to calibrate the calorimeter. The measured energy resolution is 3% (rms) at 30 GeV and the position resolution is 2 mm (rms). The measured π^0 energies in this experiment ranged from 25 to 75 GeV.

A set of thin plastic scintillation counters (TP1) is placed downstream of the magnet and provides the trigger for the scattered protons. The set consists of four counters arranged to distinguish protons scattered to the left, right, up, and down. The calorimeter also has left, right, up, and down sections, and signals from each section are summed for the trigger. In the coherent process where t' is almost zero, the π^0 and scattered protons are coplanar. Thus the trigger logic is such that the energy deposit is larger than 25 GeV in the left half of the calorimeter, less than 5 GeV in the right half, and a proton hits the right segment of TP1. There are four such combinations to cover the whole range of azimuthal angles. To reject the events which have any extra particle besides a proton and π^0, veto counters are included in the trigger logic.

Experiment

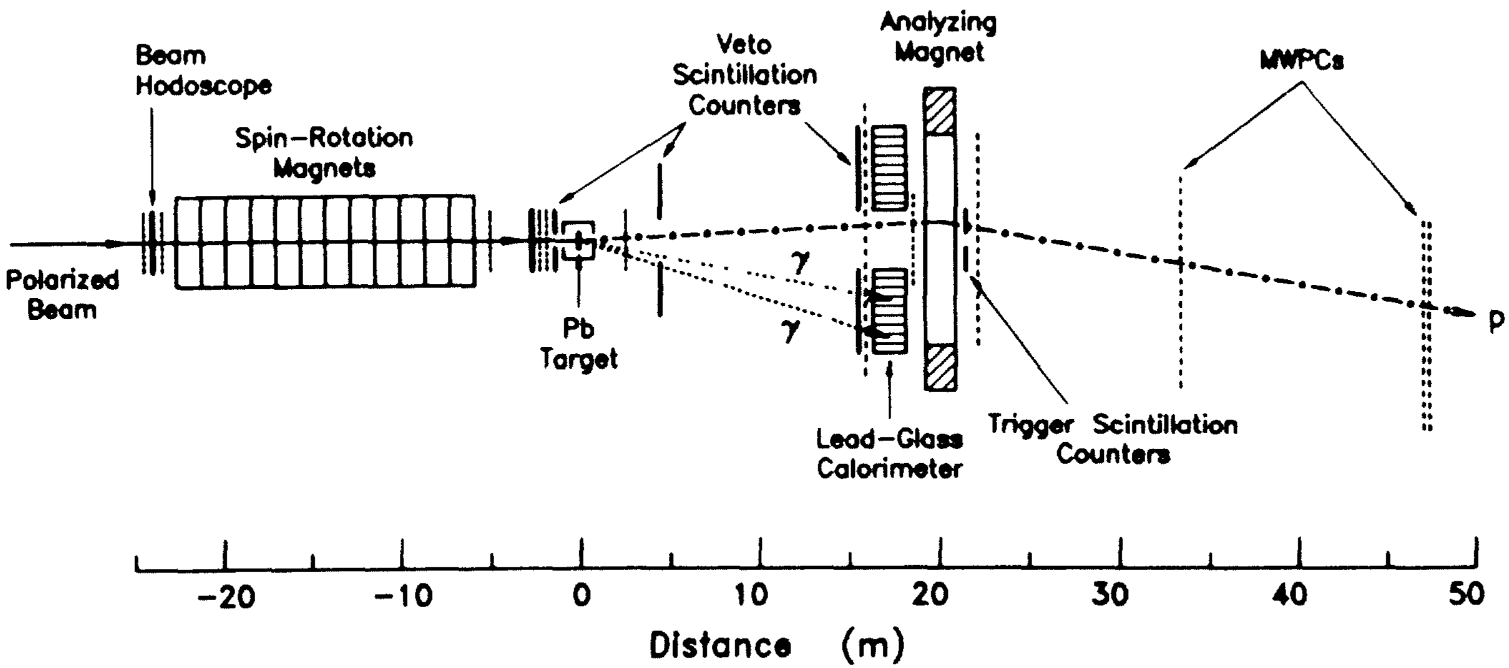


FIG. 1. Schematic view of the experimental setup. The dimensions transverse to the beam are not scale.

$$p+Z \rightarrow \Delta/N^* + Z \rightarrow \pi^0 + p + Z.$$

Invariant Mass Distribution

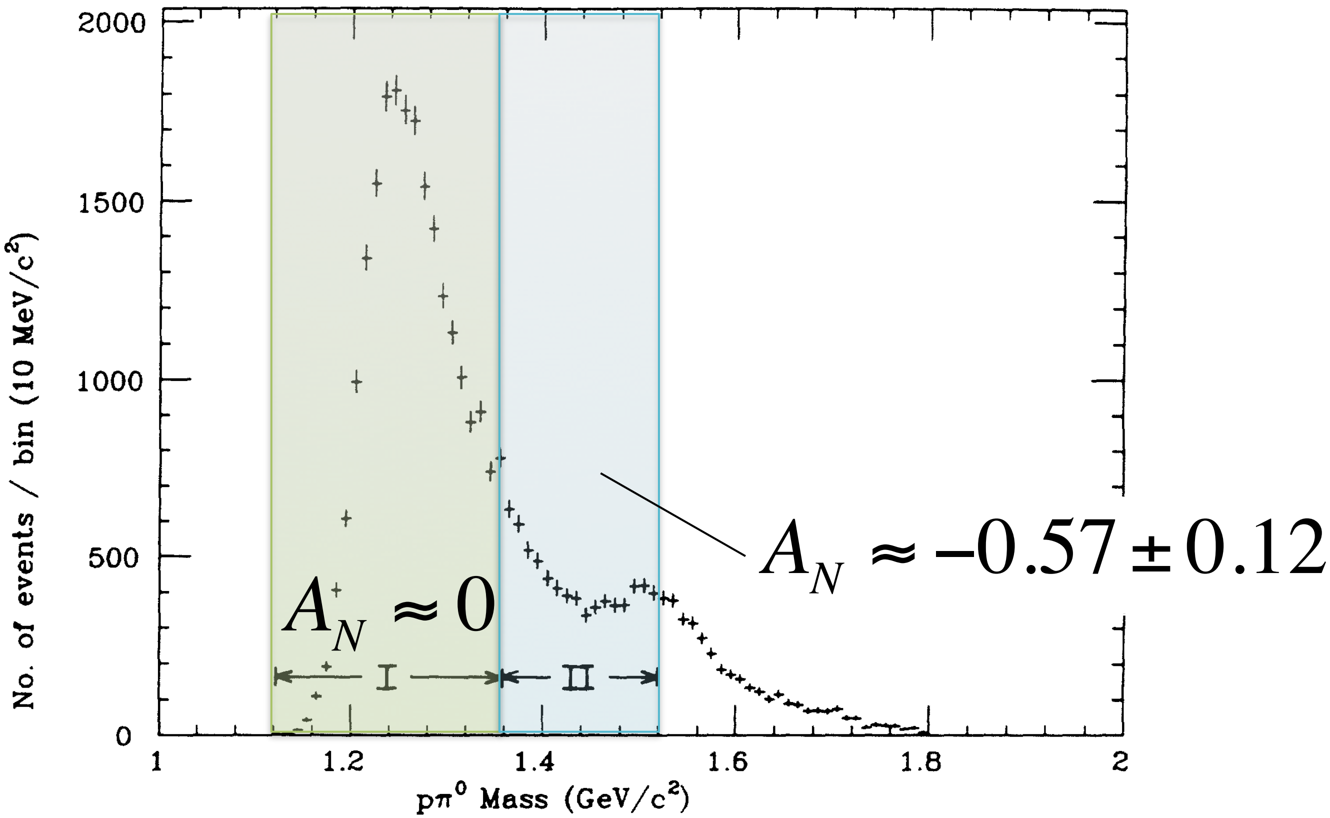


FIG. 2. The invariant-mass spectrum of the π^0-p system in $p + \mathrm{Pb} \to \pi^0 + p + \mathrm{Pb}$ for $|t'| < 1 \times 10^{-3}$ $(\mathrm{GeV}/c)^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.

$-t$ Distribution

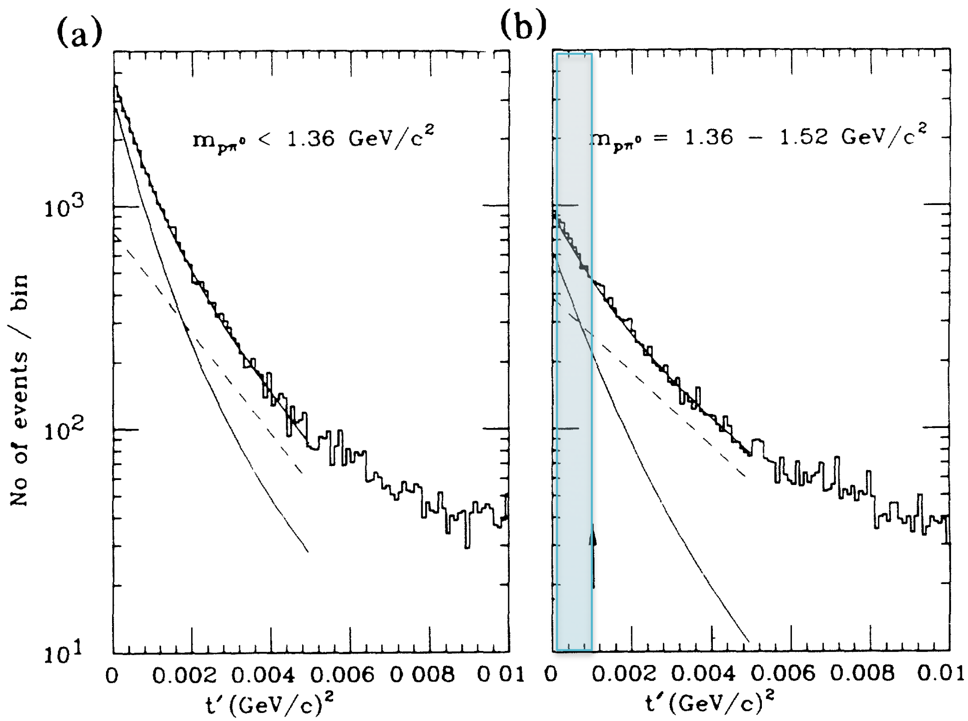
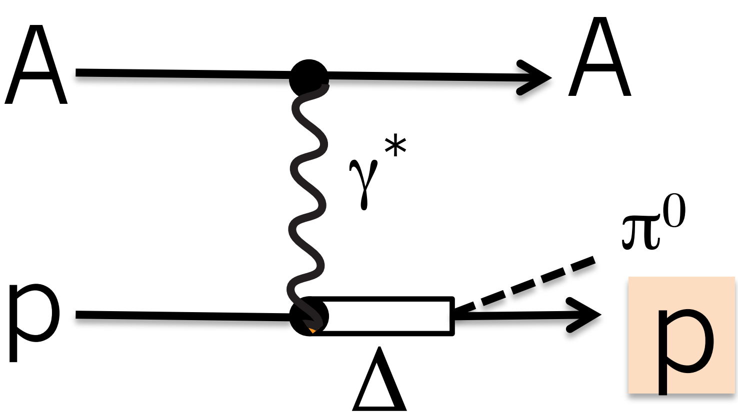


FIG. 3. The t' distribution of the $p + \mathrm{Pb} \rightarrow p + \pi^0 + \mathrm{Pb}$, at (a) $M_{p\pi^0} < 1.36$ GeV/c^2 and (b) $M_{p\pi^0} = 1.36$–1.52 GeV/c^2. The curves are obtained by fitting the data. The dashed and dotted lines show the diffractive process and the amount of background events, respectively, and the solid curve represents the Coulomb process. The arrow indicates the position of the t' cut.

$-t$ \ M	**< 1.36 [GeV]**	**1.36 – 1.62 [GeV]**
< 0.001 (GeV/c)²	❌	⭕
> 0.001 (GeV/c)²	❌	❌

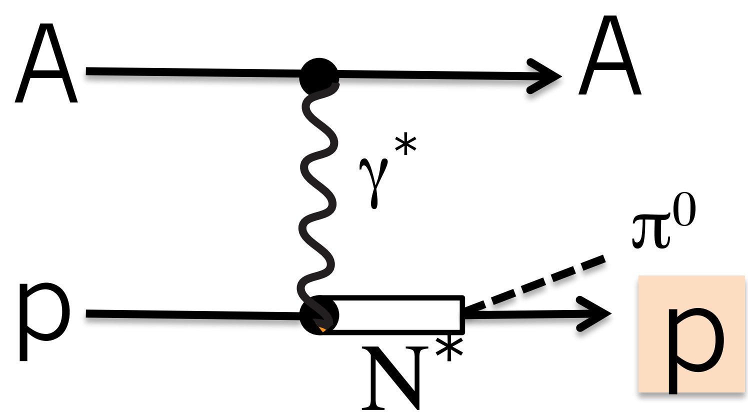
Origin of the Asymmetry

Spin flip



×

Spin non-flip



Δ^*(1232) P33

↳ $N\pi$ (>99%)

N^*(1440 and higher) P11

↳ $N\pi$ (60~70%)

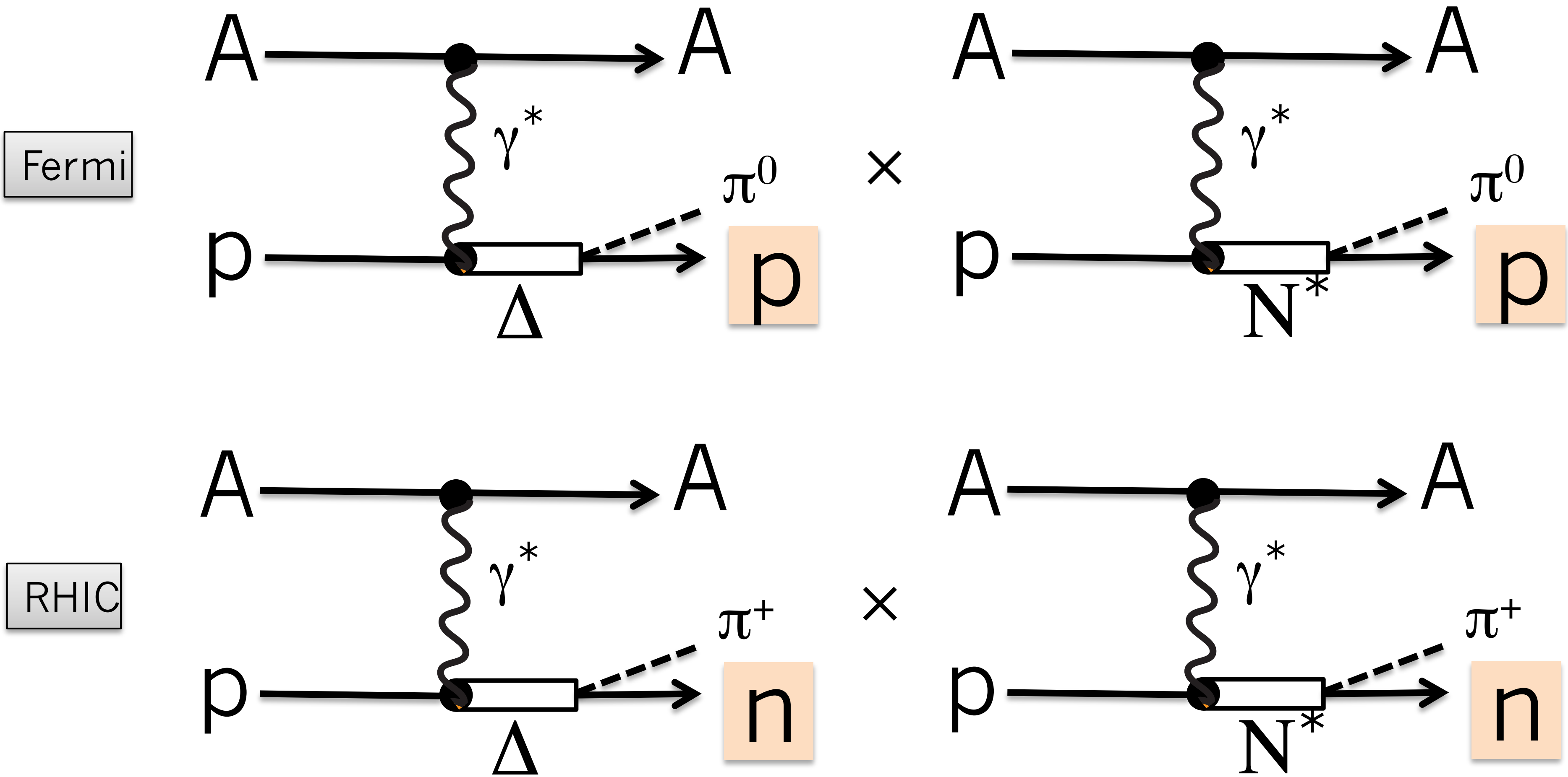
$N\pi\pi$ (30~40%)

$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \boxed{\phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4}$$

Fermi Experiment Summary

- Large asymmetry observed in Fermi forward pi0 production in pol(p)+Pb.
- Large asymmetry is observed by selecting Primakoff kinematics (Small –t).
- The asymmetry is known in photo pion production as a consequence of interference between Delta and N*.

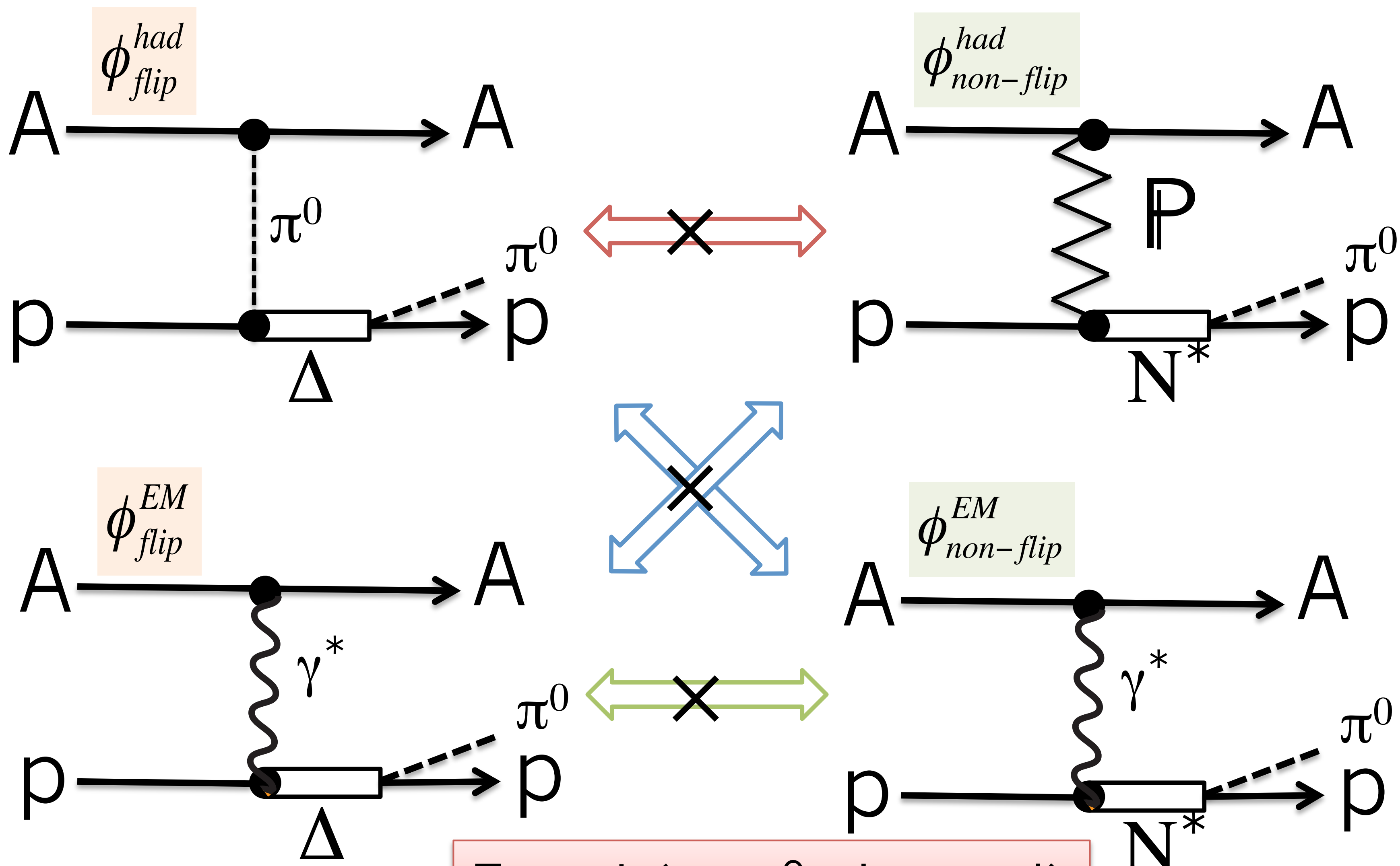
Origin of the Asymmetry



$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4$$

$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4$$

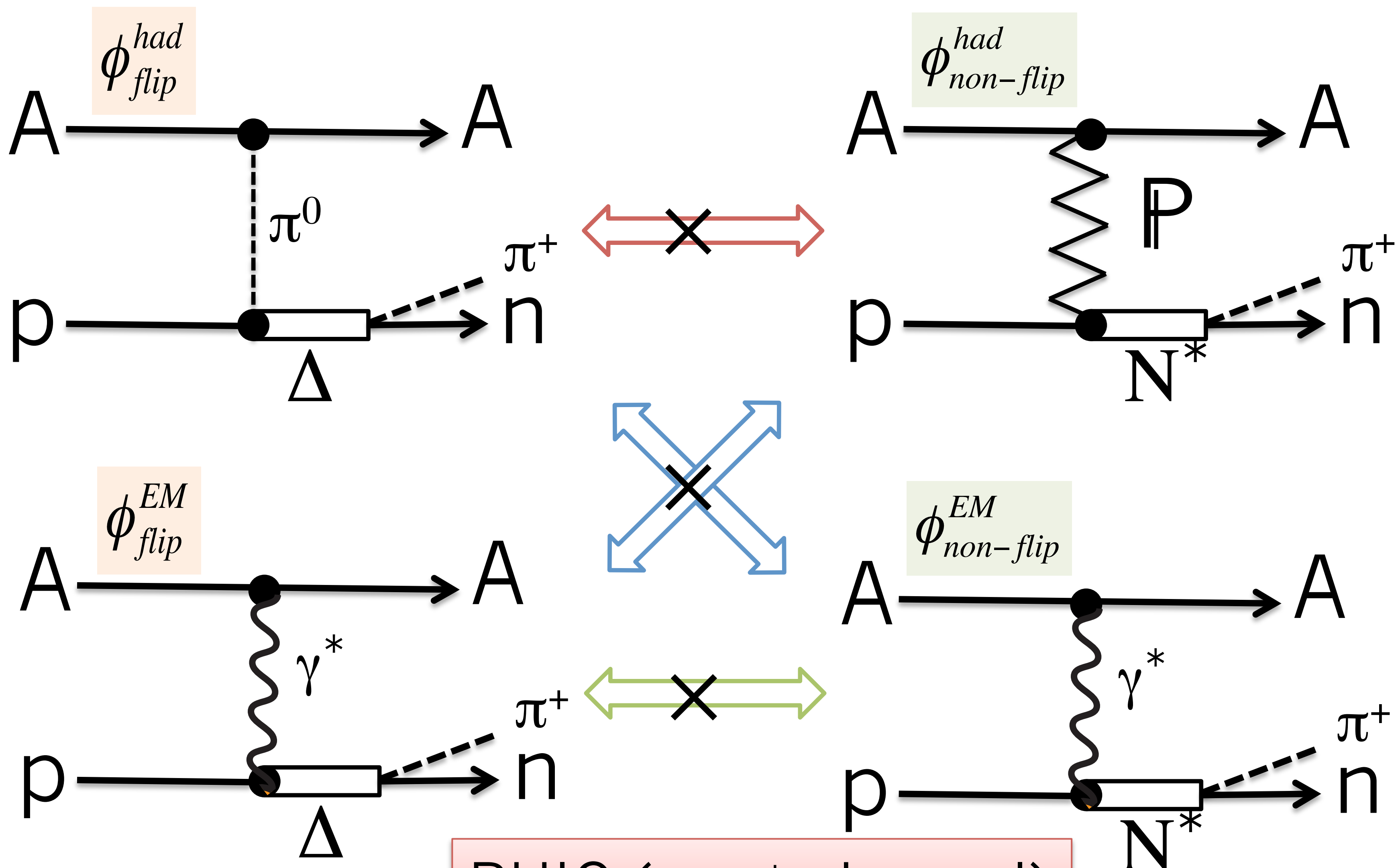
hadronic　　CNI　　Primakoff



Fermi (p+π^0 channel)

$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4$$

hadronic | CNI | Primakoff

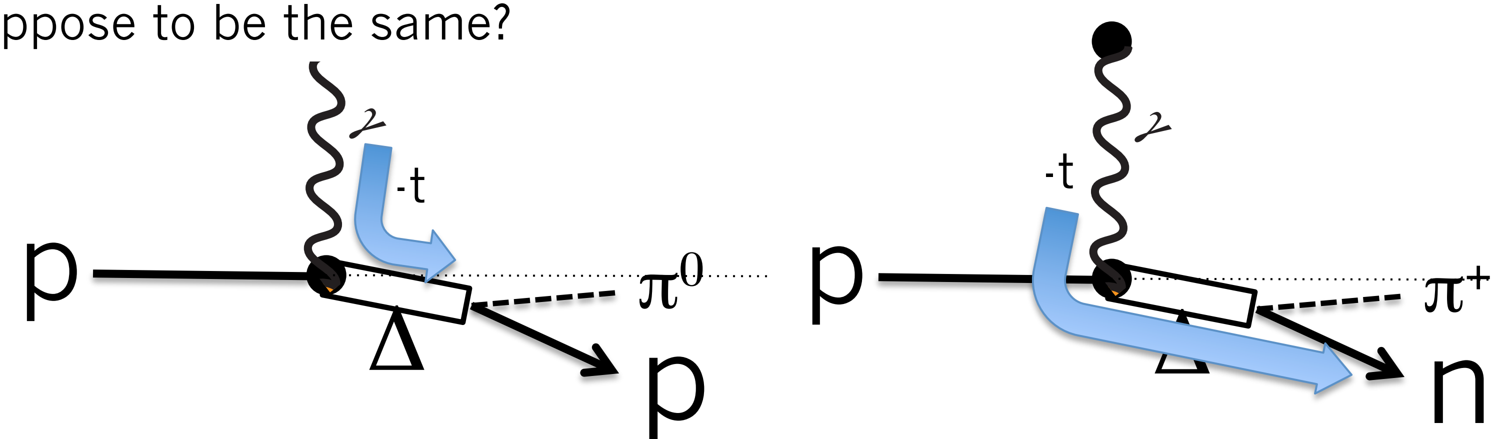


RHIC (n+π^+ channel)

Comparison between two

	Fermi	BNL
Beam Energy [GeV]	185	100
$\sqrt{s}$ [GeV]	19.5	200
Target	Pb	Au
Observables	$p + \pi^0$	n (+ charged)
t'	< 0.001	0.02 < -t < 0.5
M	$1.36 < M(\pi^0 p) < 1.52$	?
A_N	$-0.57 \pm (0.12)_{sta} + 0.21 - 0.18$	+ 0.27 ± 0.003 (BBC veto)

If the asymmetry is induced at D or N* excitation, does the sign suppose to be the same?



Comparison between two

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Target	Pb	Au
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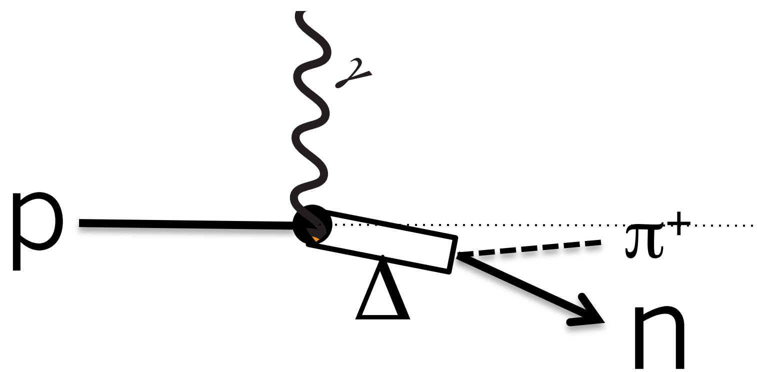
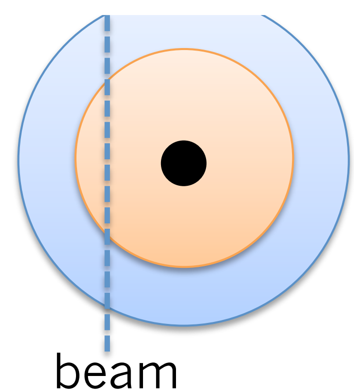
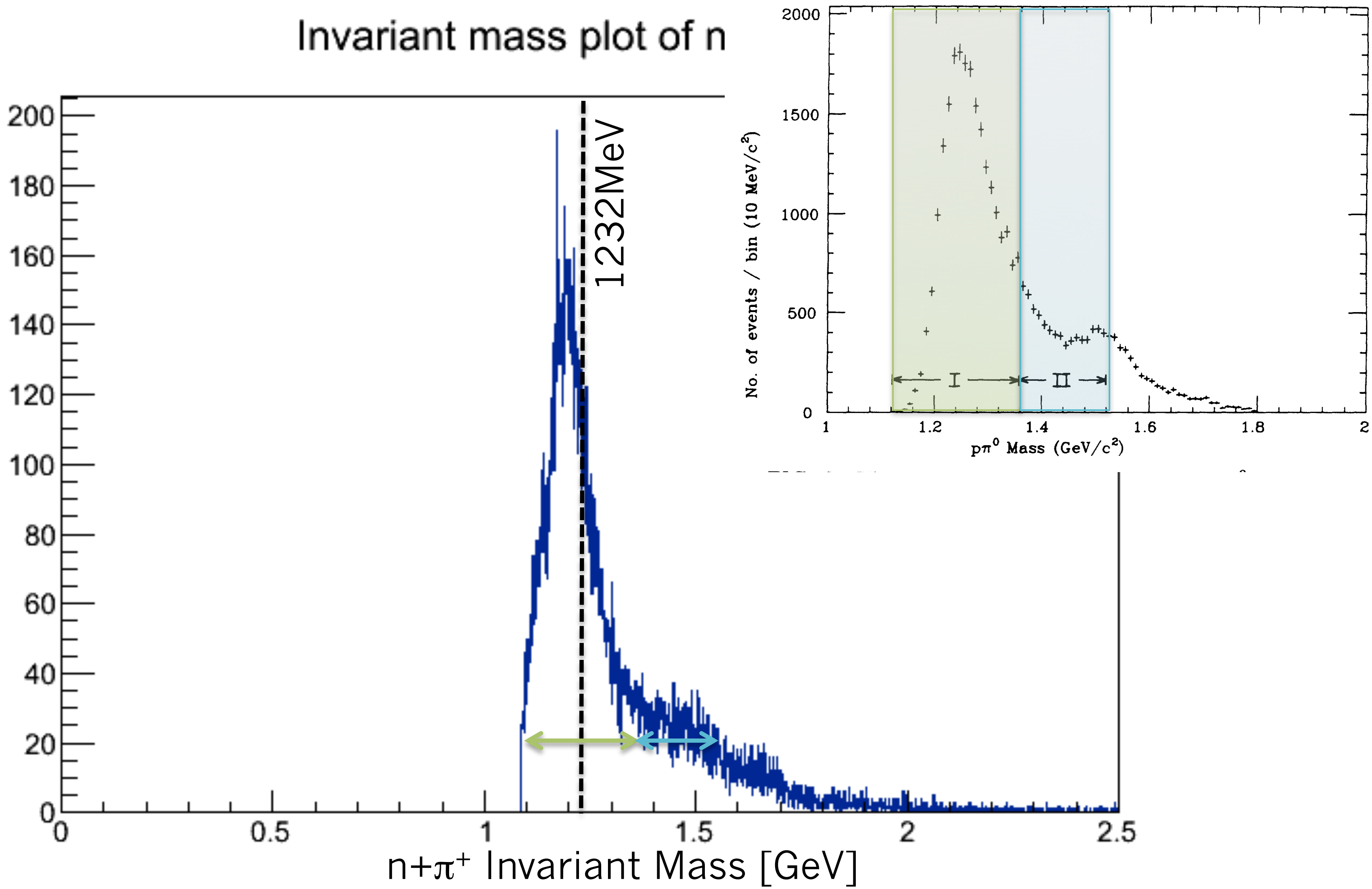
t'	< 0.001	$0.02 < -t < 0.5$
M	$1.36 < M(\pi^0 p) < 1.52$	?
A_N	$-0.57 \pm (0.12)_{sta} + 0.21 - 0.18$	$+$ 0.27 $\pm$ 0.003 (BBC veto)

If the asymmetry is induced at D or N* excitation, does the sign suppose to be the same?



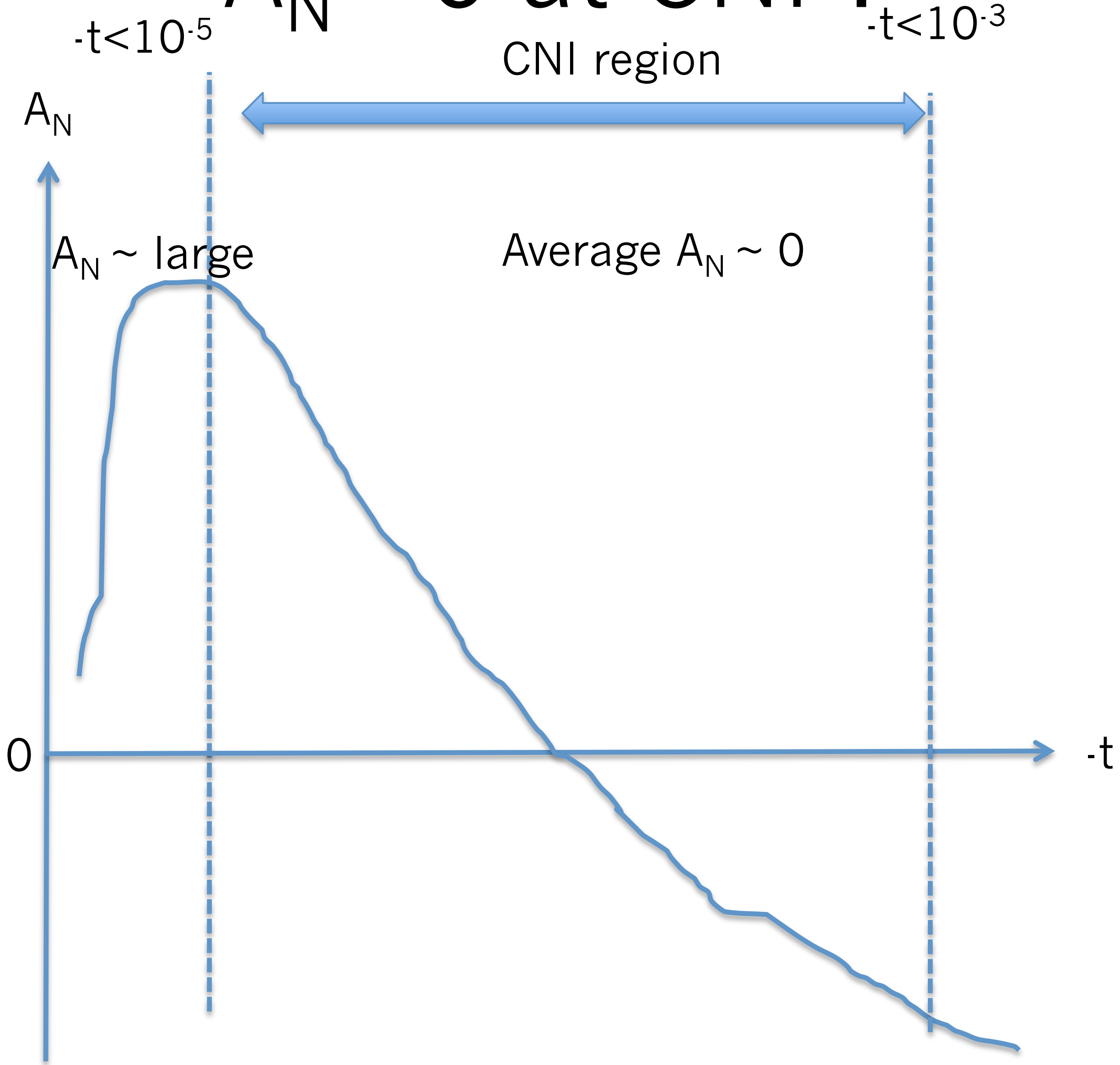


UPC MC



Plot made by Minho Kim

$A_N \sim 0$ at CNI ?



What we can learn from Fermi Exp.?

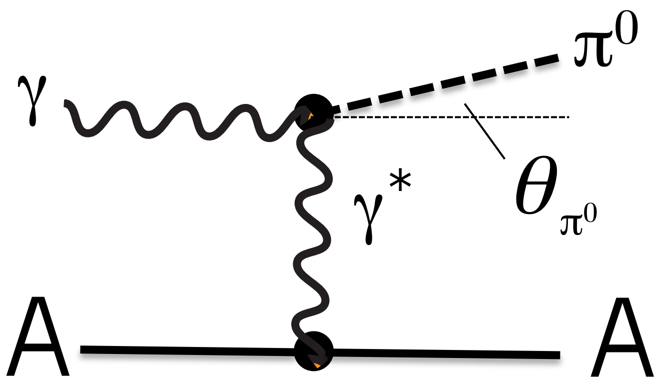
- If we consider the difference between PHENIX neutron and p+pi0 as just a difference in the decay channels from Delta and N*, then both mechanisms are similar.
- PHENIX –t is expected to be larger than Fermi, so CNI may be important in PHENIX.
  - Although Fermi claims A_N is zero at CNI, it may be just because of accident?
  - Not straight forward to perform kinematic decomposition in PHENIX data.
- Sign of A_N are opposite between two experiments. Are we measuring the same A_N?

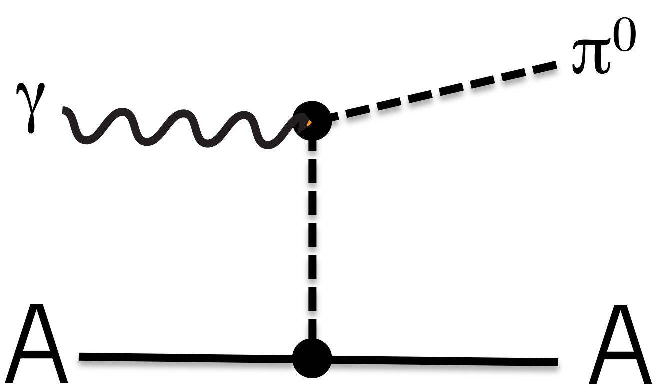
BACKUPS

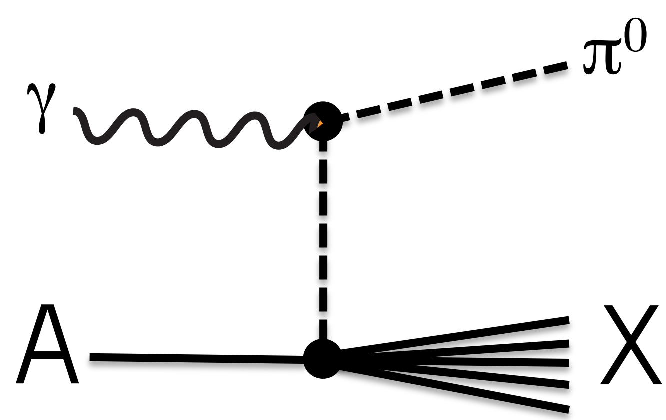
Comparison between two

	Fermi	PHENIX	STAR17
Beam Energy [GeV]	185	100	255
√s [GeV]	19.5	200	22
Target	Pb	Au	Al/Sn/Au
Observables	$p + \pi^0$	n (+ charged)	n (+ charged) π^0 ?
t'	< 0.001	0.02 < -t < 0.5	
M	$1.36 < M(\pi^0 p) < 1.52$	?	?
A_N	$-0.57 \pm (0.12)_{sta} + 0.21 - 0.18$	$+ 0.27 \pm 0.003$ (BBC veto)	

Primakoff Diagrams







Neuclear/Nucleon Photo-Excitation