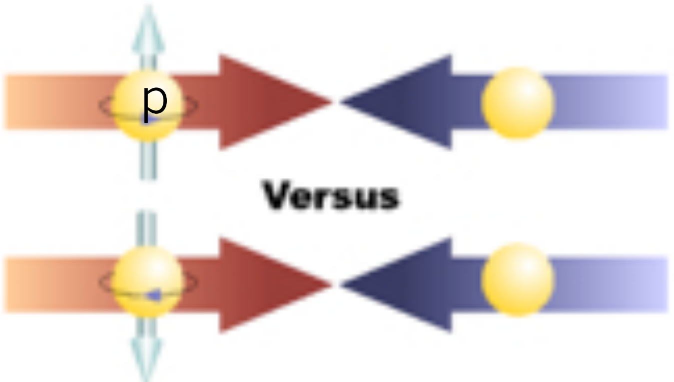
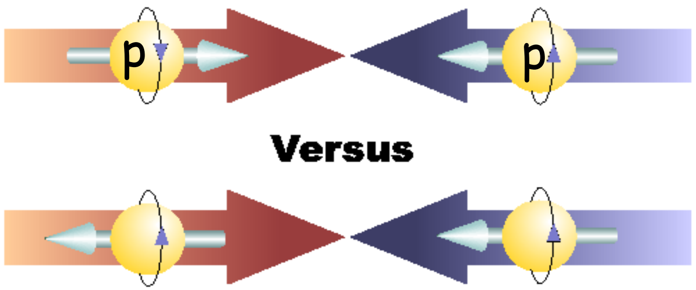
Gluon polarization measurements and the possible role of diffractive process in the transverse single spin asymmetry measurements in RHIC-PHENIX

Itaru NAKAGAWA
on behalf of RHIC Spin Collaboration
RIKEN/RBRC

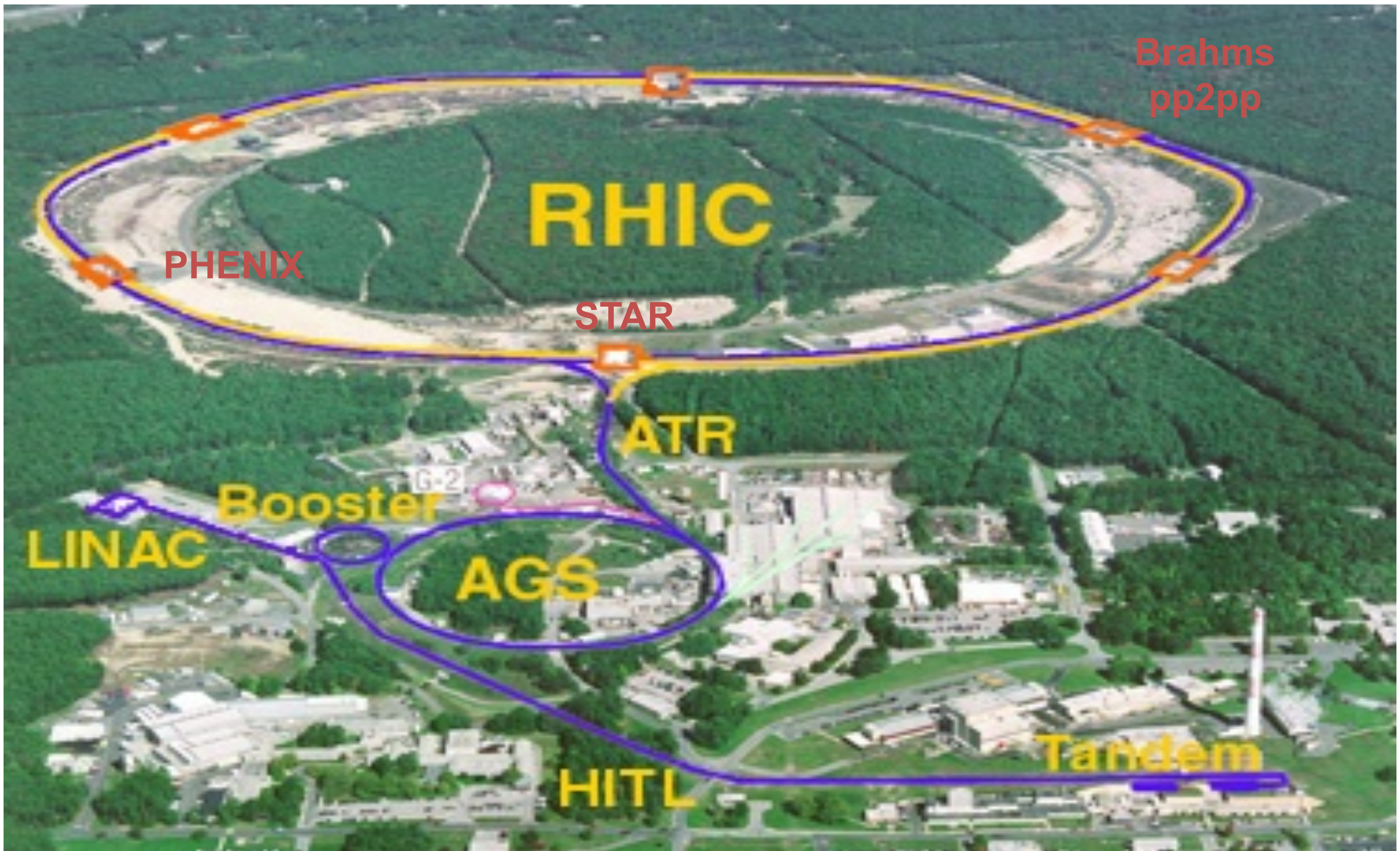
Outline

- RHIC
  - PHENIX @ Polarized Proton @ RHIC
- Transverse
  - very forward neutron
- Longitudinal
  - Gluon Spin

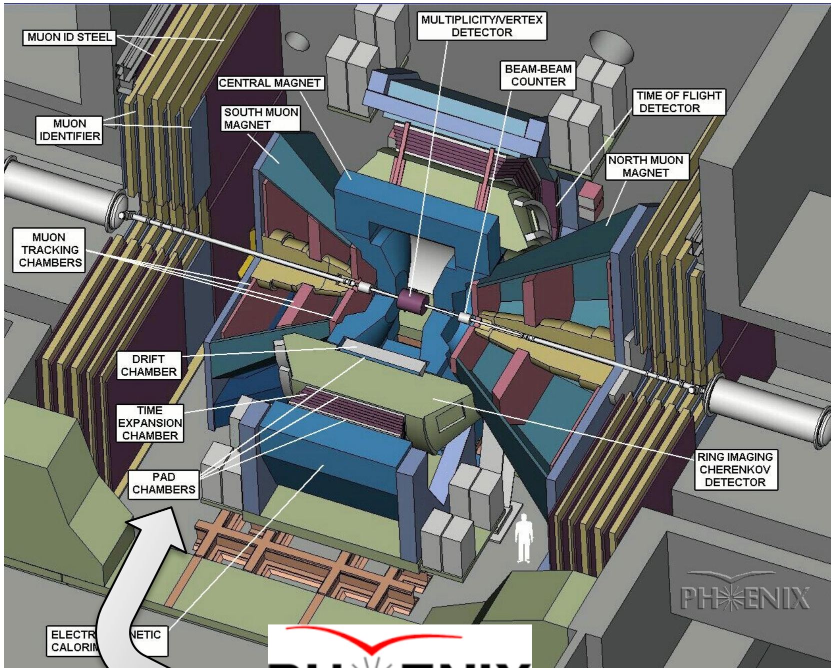


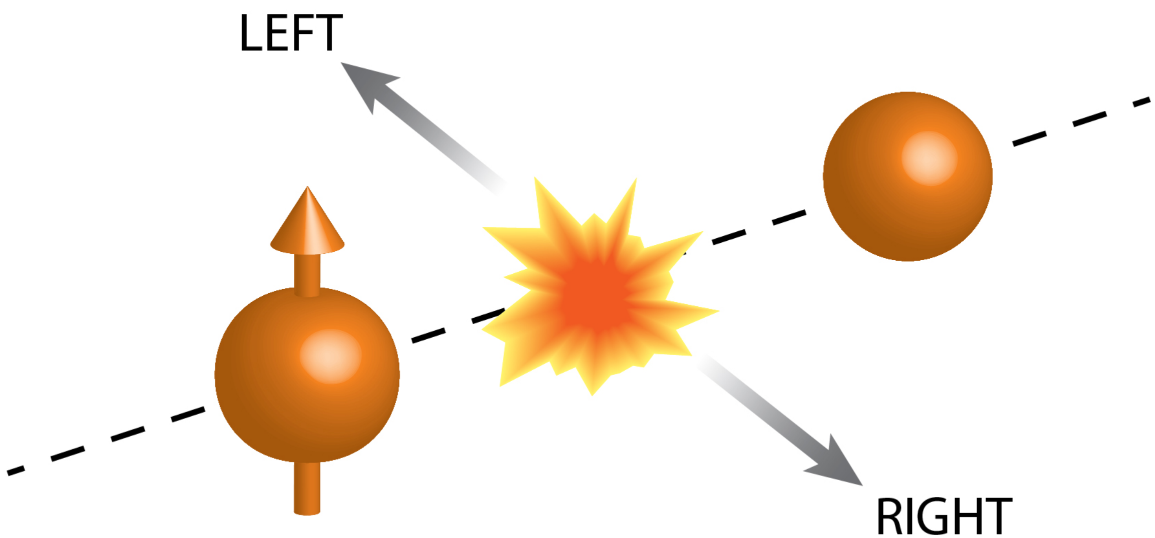


The Relativistic Heavy Ion Collider accelerator complex at Brookhaven National Laboratory



Collision Energy : 62 ~ 510 GeV
Polarization : 50 – 60 %
Luminosity : 10 pb^{-1}/week

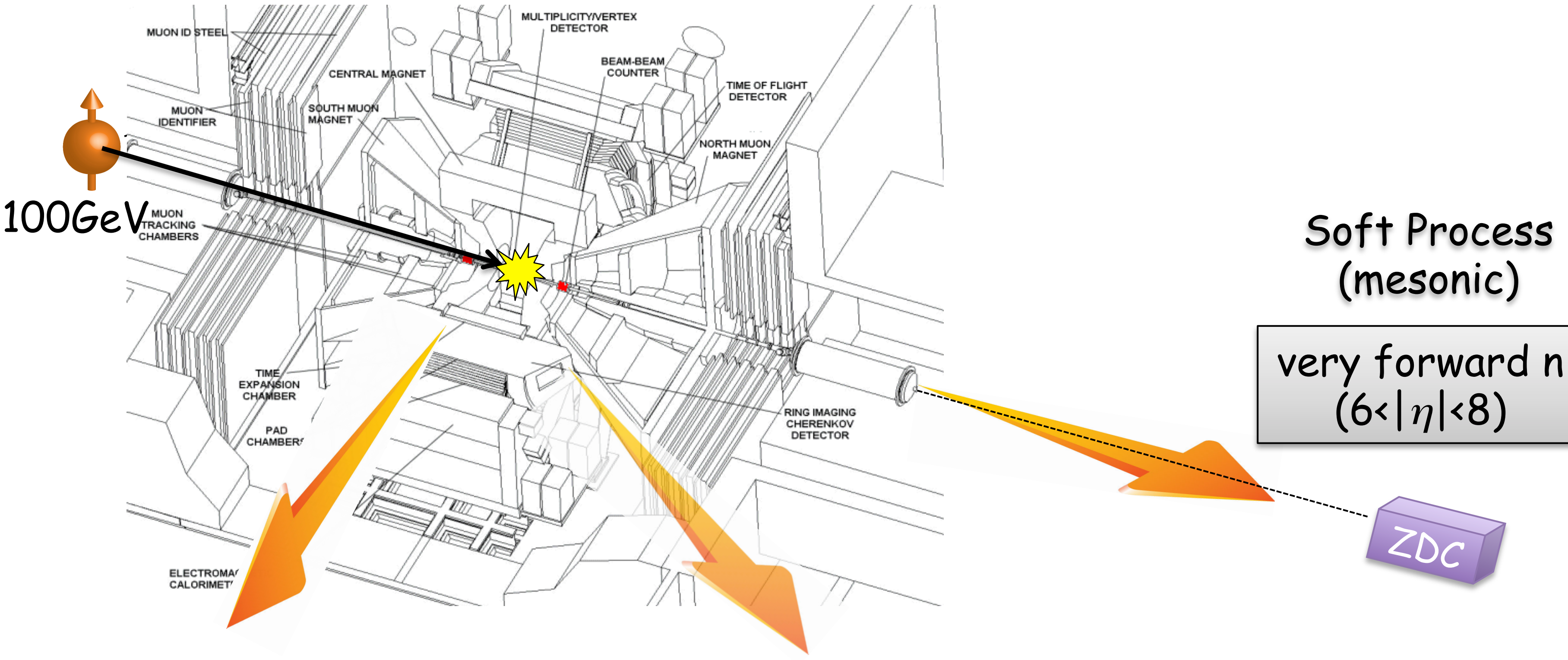




Forward π^0 and very forward neutron

TRANSVERSE SINGLE SPIN ASYMMETRY

Transverse Asymmetry Observables



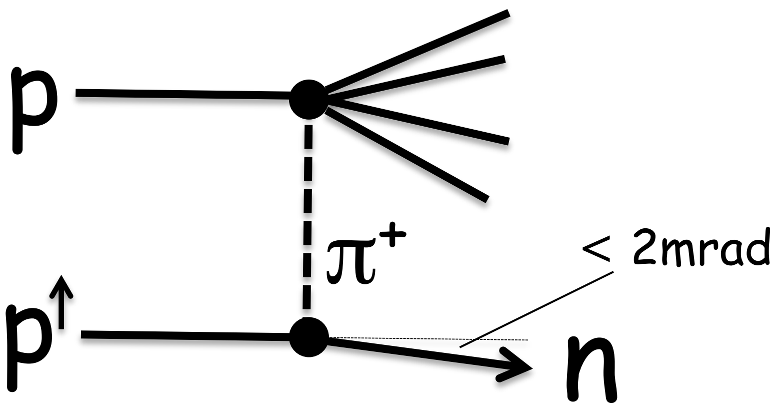
Soft Process
(mesonic)

very forward n
($6<|\eta|<8$)

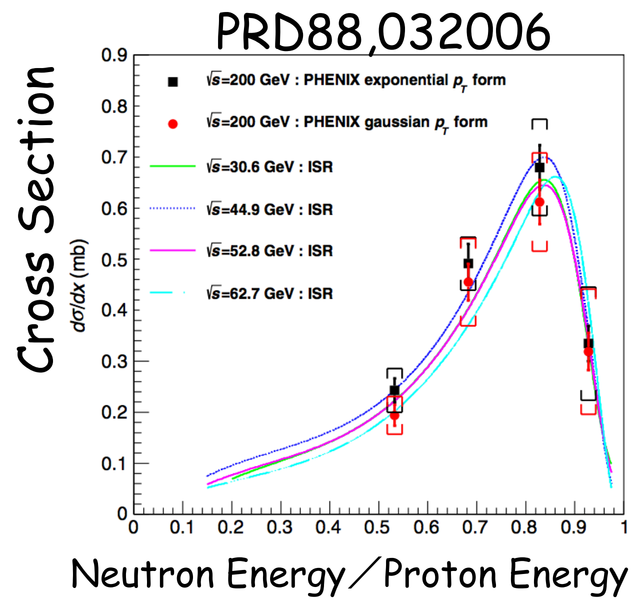
Hard Process
(partonic)

Production Mechanism of Forward Neutron

Cross Section

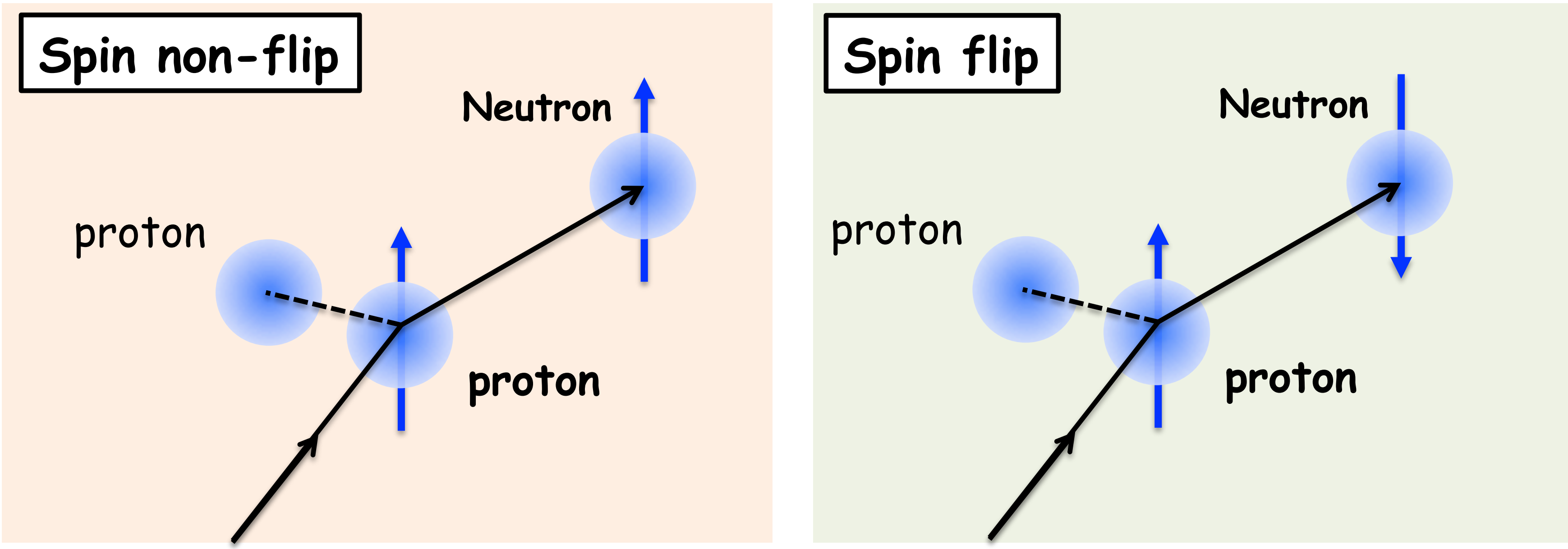


Momentum Transfer ~ 100MeV



Well Explained by
One-Pion Exchange

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

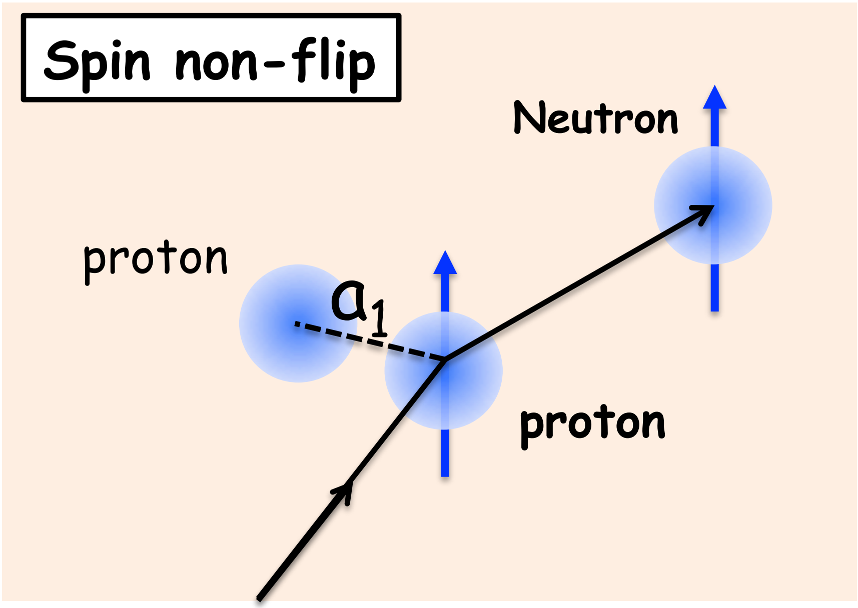


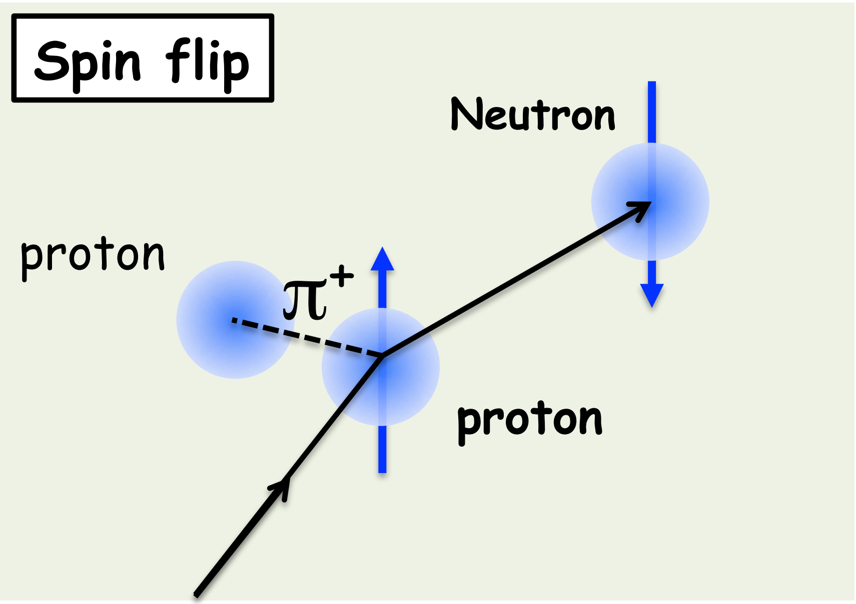
$$A_N \approx \frac{\left(\phi^{*}_{non-flip}\phi_{flip}\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

Unpolarized Cross Section

δ : phase shift

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

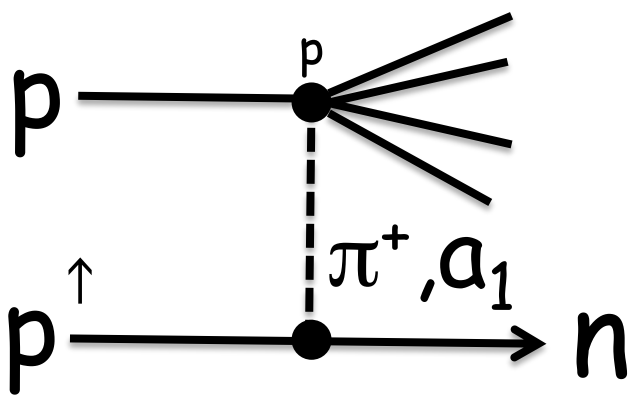




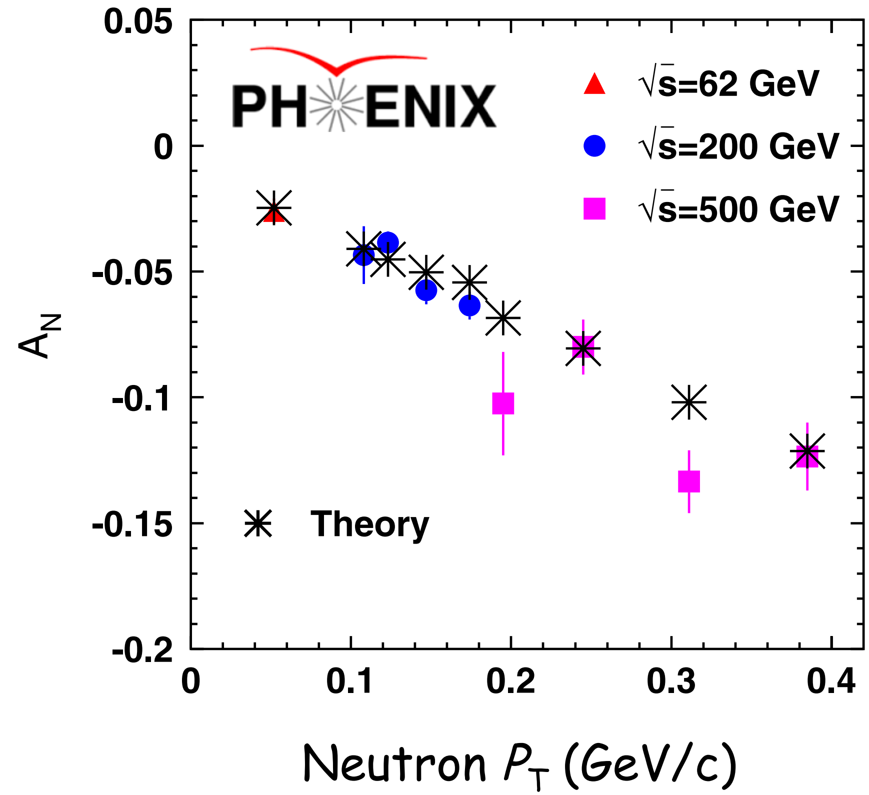
$$A_N \approx \frac{\left(\phi^{*}_{non-flip}\,\phi_{flip}\,\sin\delta\right)}{\left|\phi_{non-flip}\right|^{2}+\left|\phi_{flip}\right|^{2}}$$

δ : phase shift

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



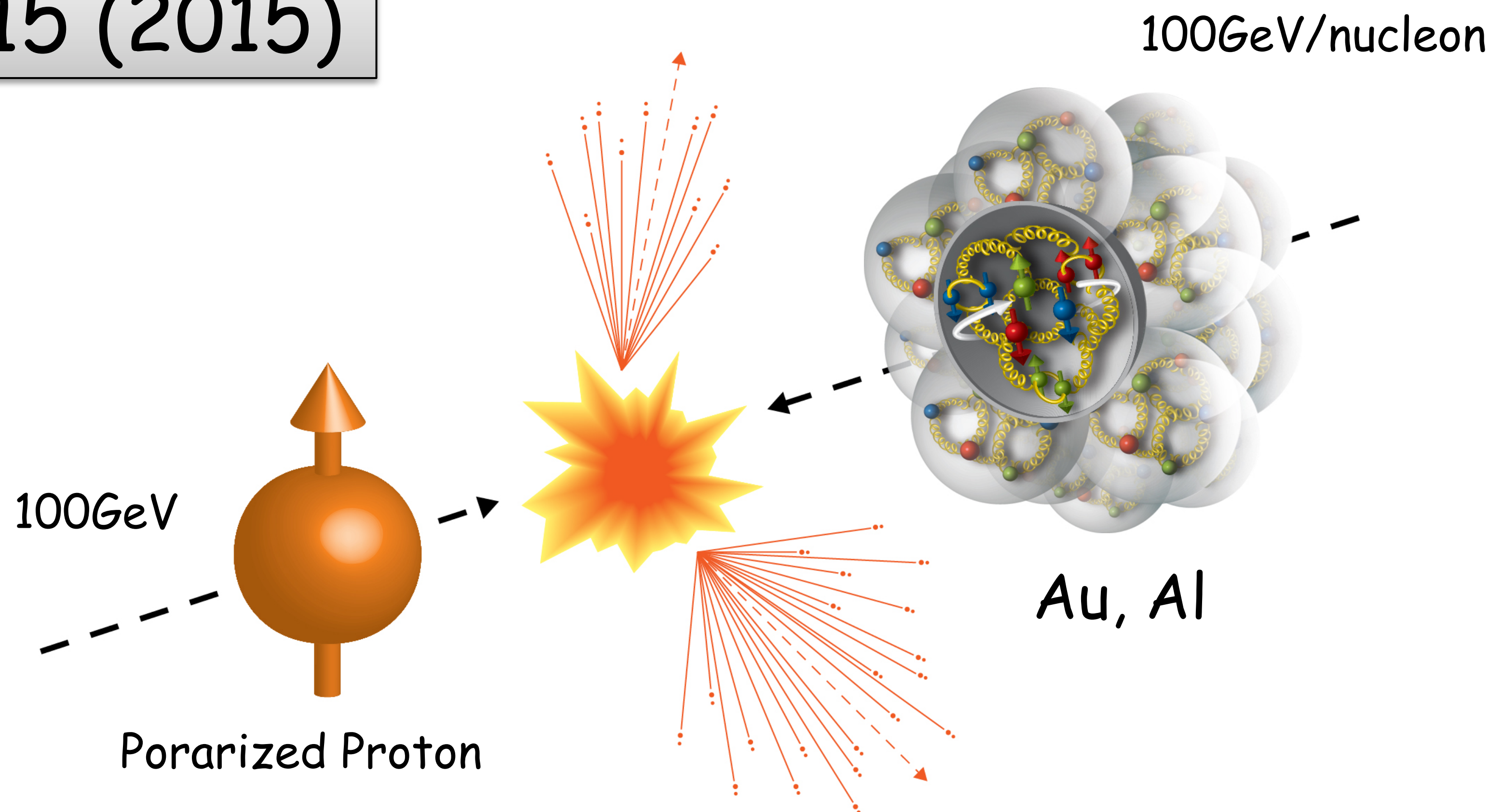
PRD84,114012(2011)



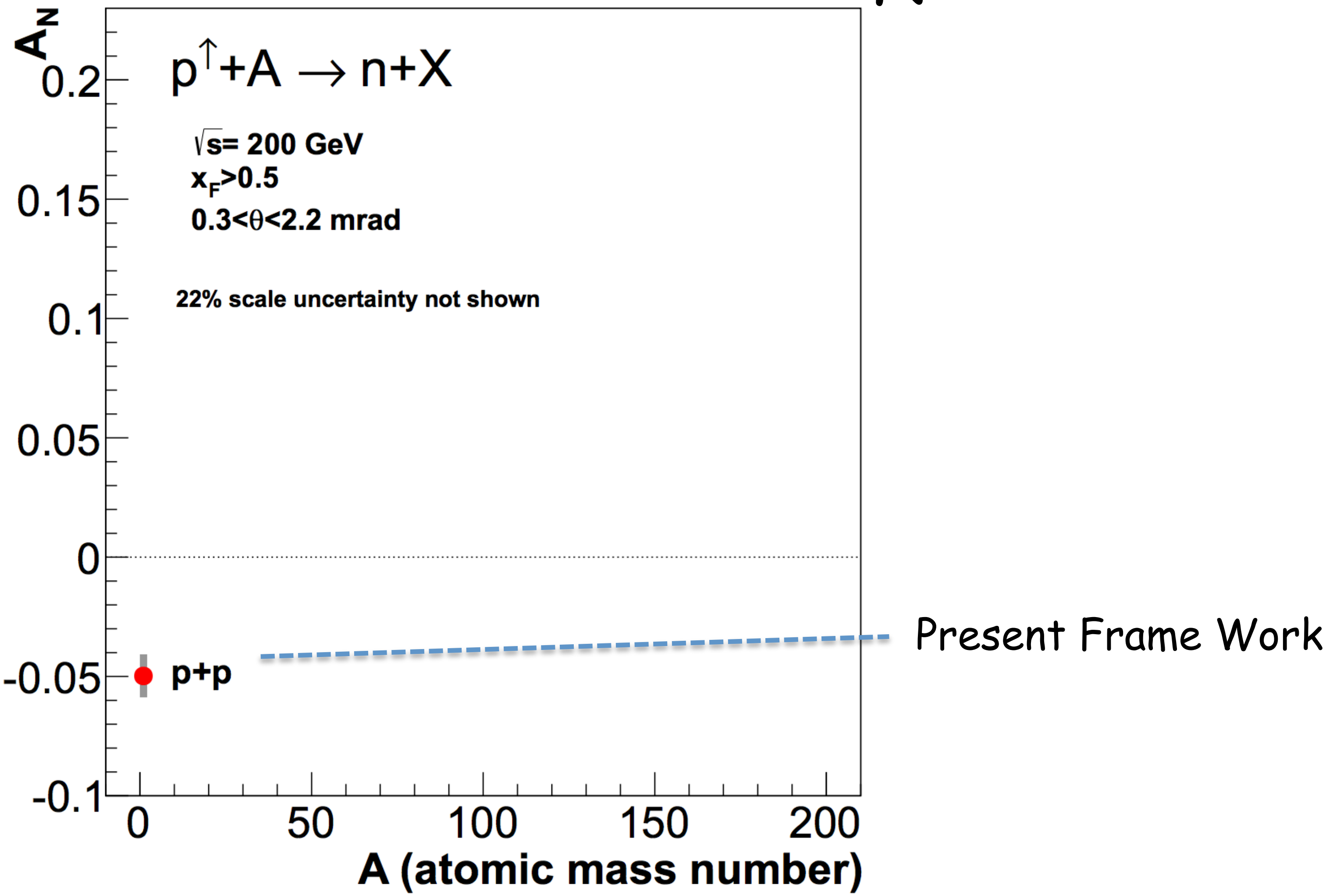
Data are well reproduced by the interference between π and a_1 Reggeon

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

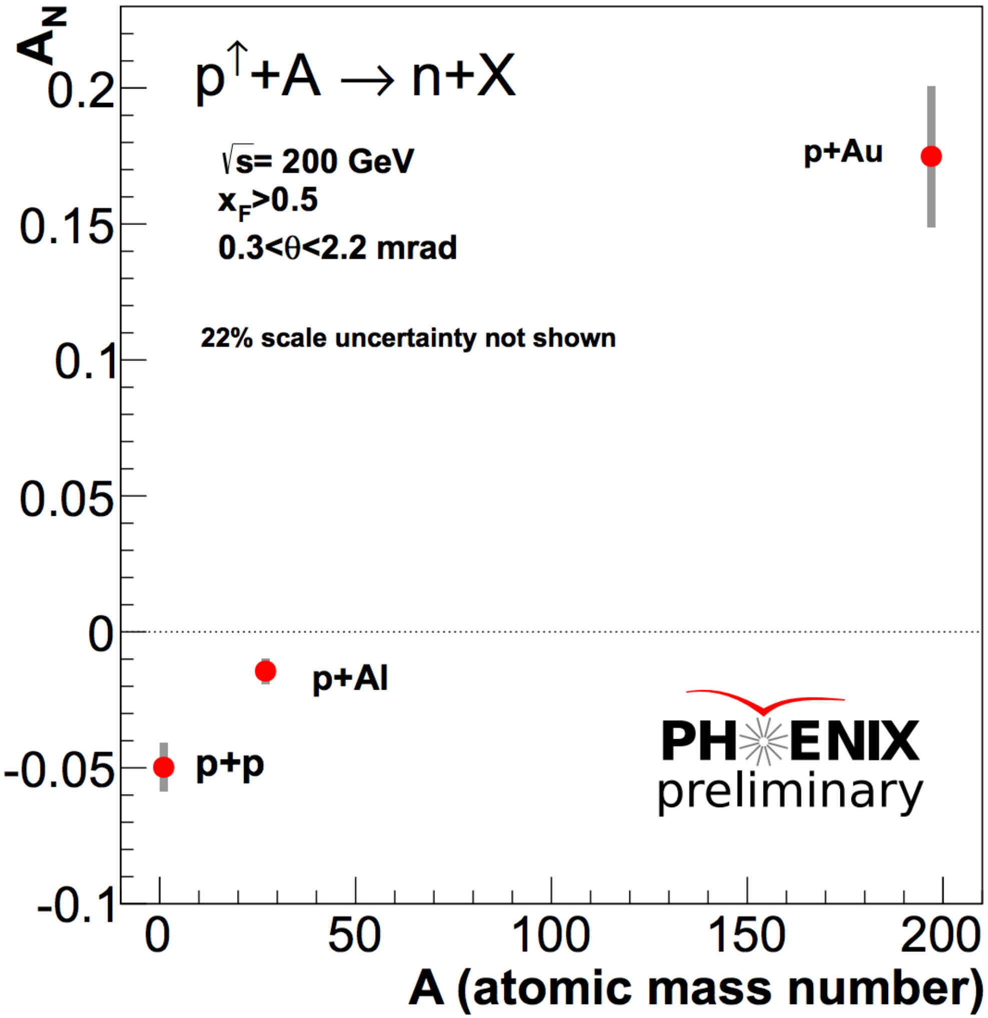
Run15 (2015)

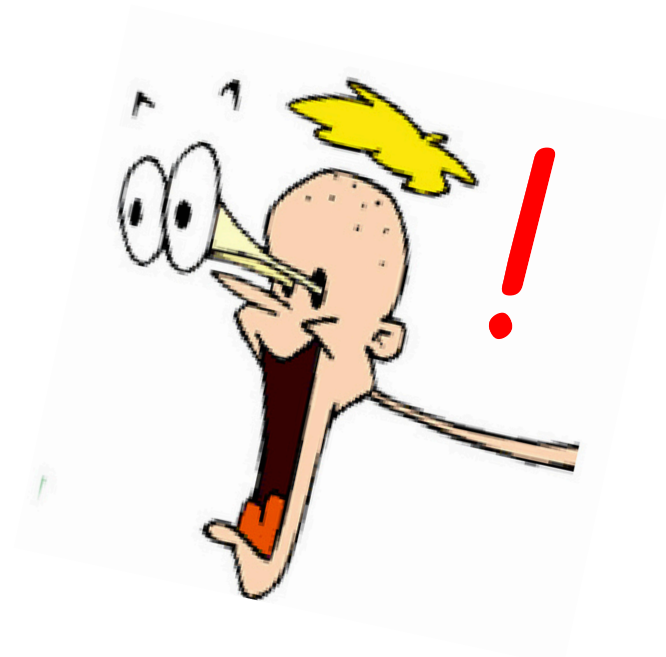


A-Dependent A_N (inclusive)



A-Dependent A_N (inclusive)

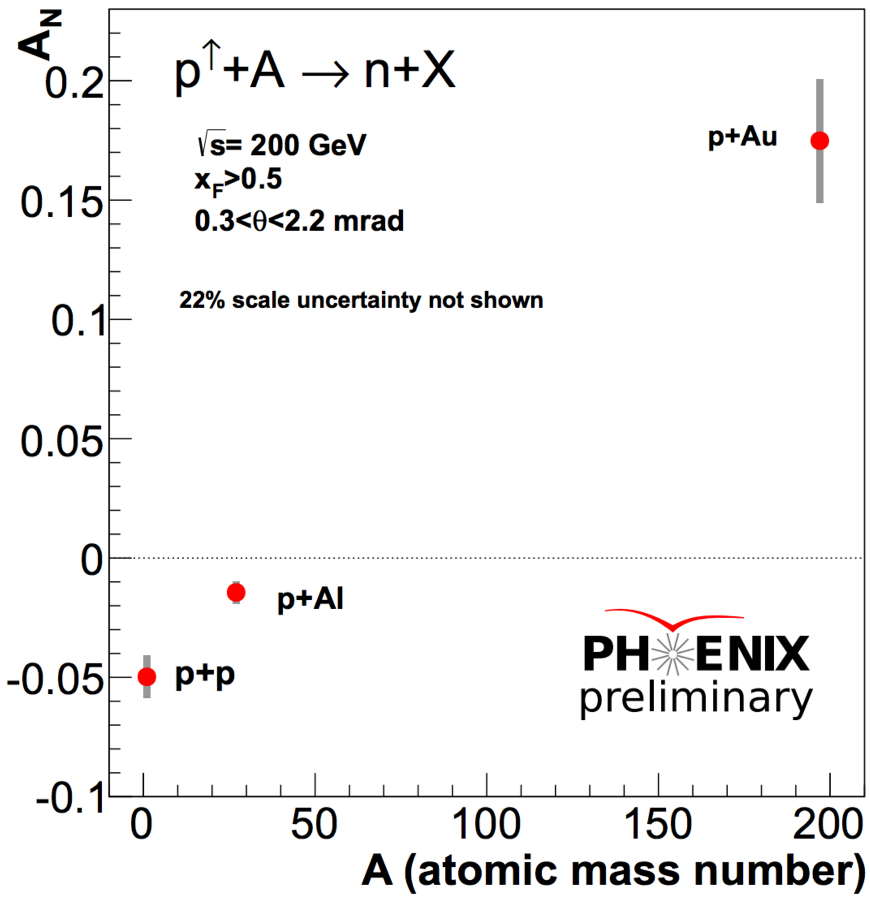




Absolutely Unexpected!

Analysis by
Minjung Kim (SNU/RIKEN)

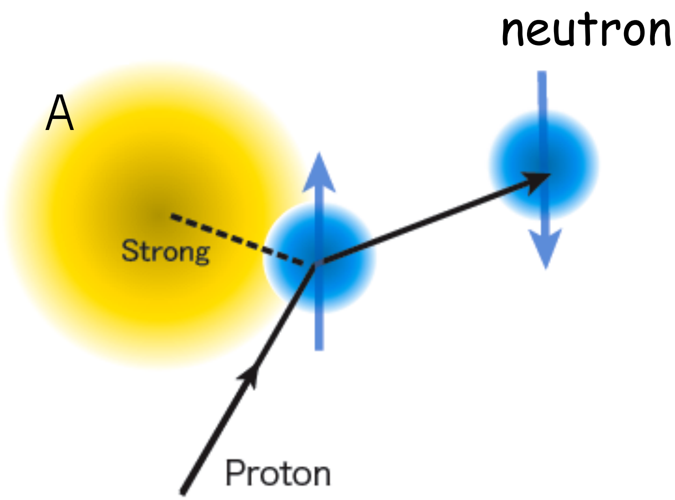
What is going on ?

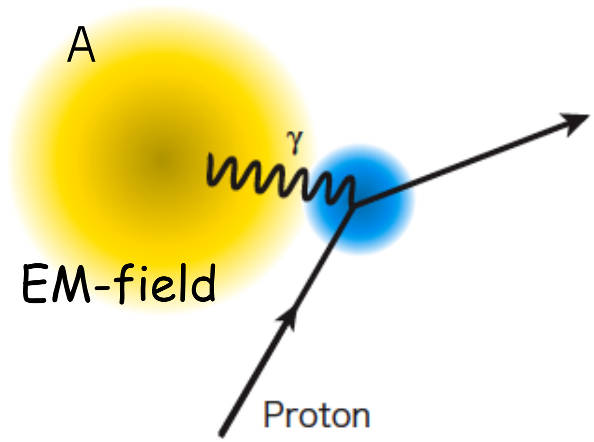


	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

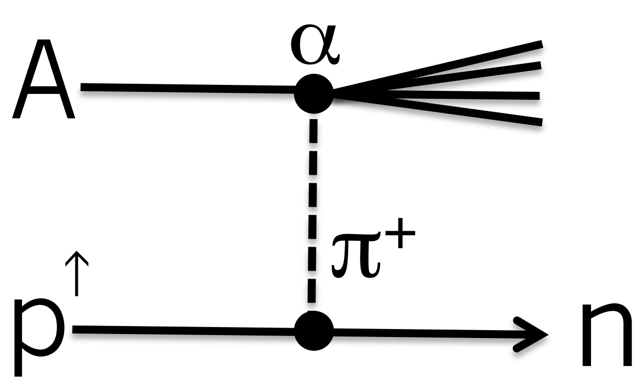
- Isospin Symmetry
- Surface Structure of Nucleus
- QED Process
- Gluon Saturation
- Else…

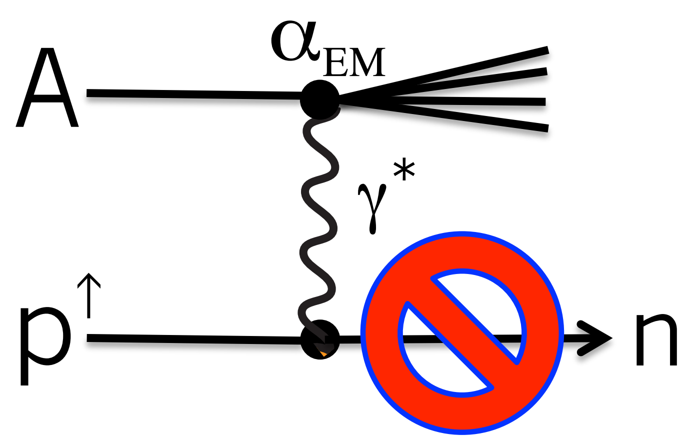
Ultra Peripheral Effect (UPC)
Electro-Magnetic



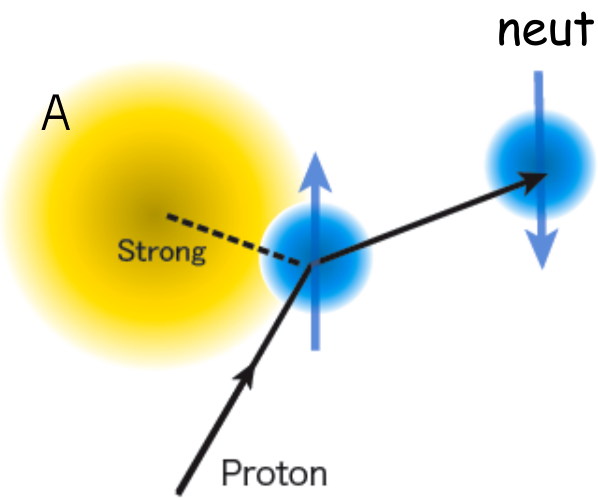


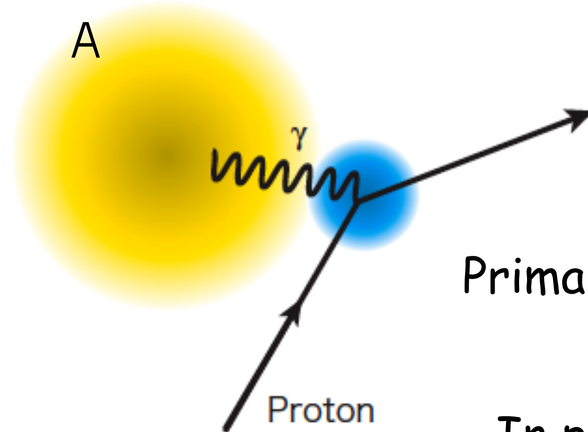
$t \to 0$





Ultra Peripheral Effect (UPC) Electro-Magnetic



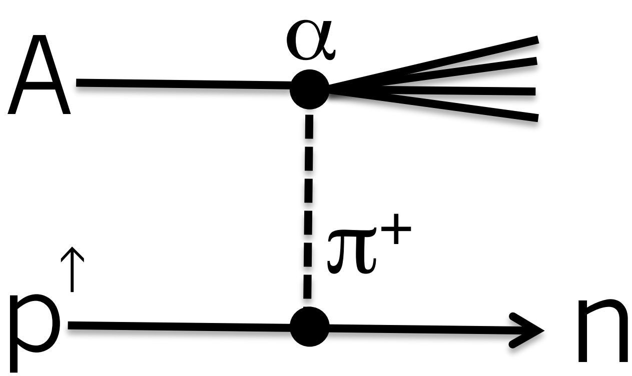


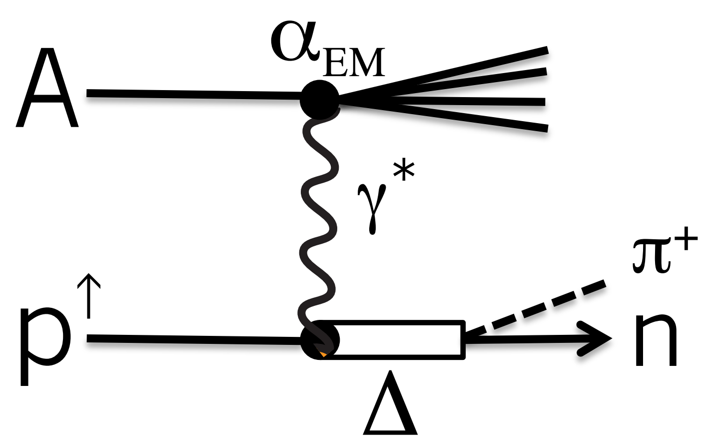
Primakoff

In pAu case

$t \to 0$

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





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

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

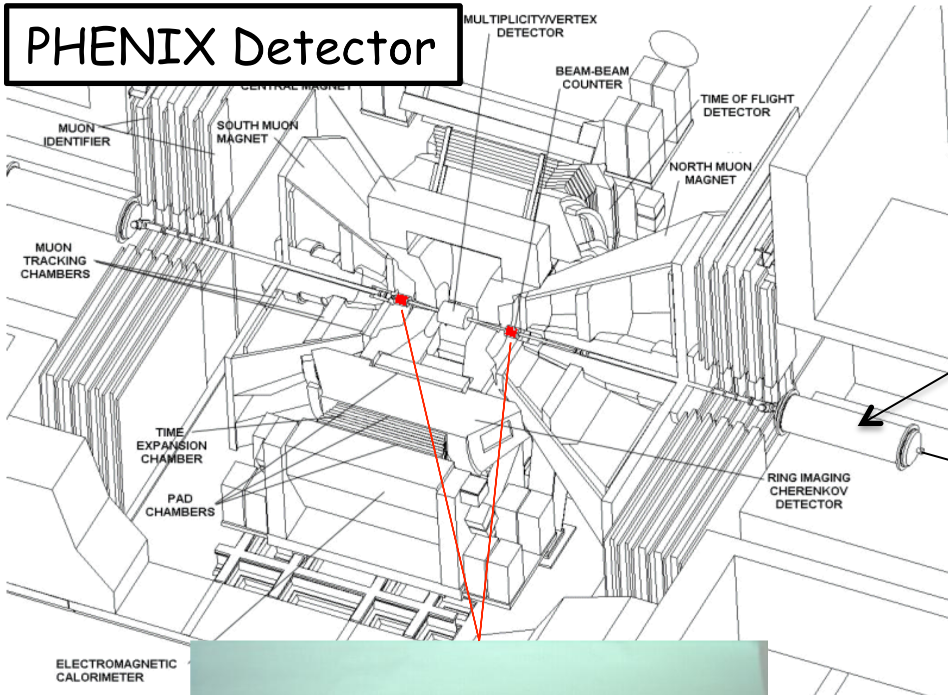
$$= 2\left(\phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \underbrace{\phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4}\right)$$

$\rightarrow 0$ (For pp)

large ← $-t$ → small

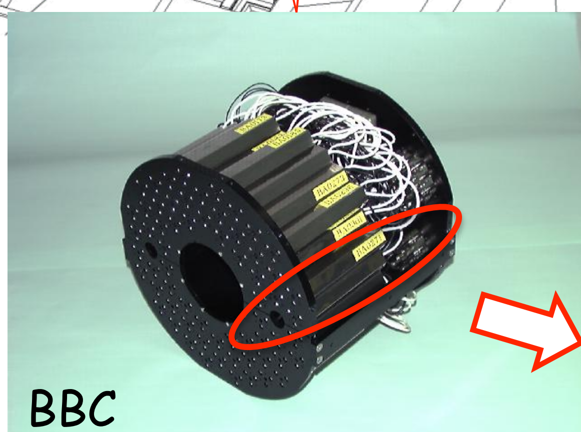
Beam-Beam Counter

PHENIX Detector



Dipole Bending Magnet

ZDC

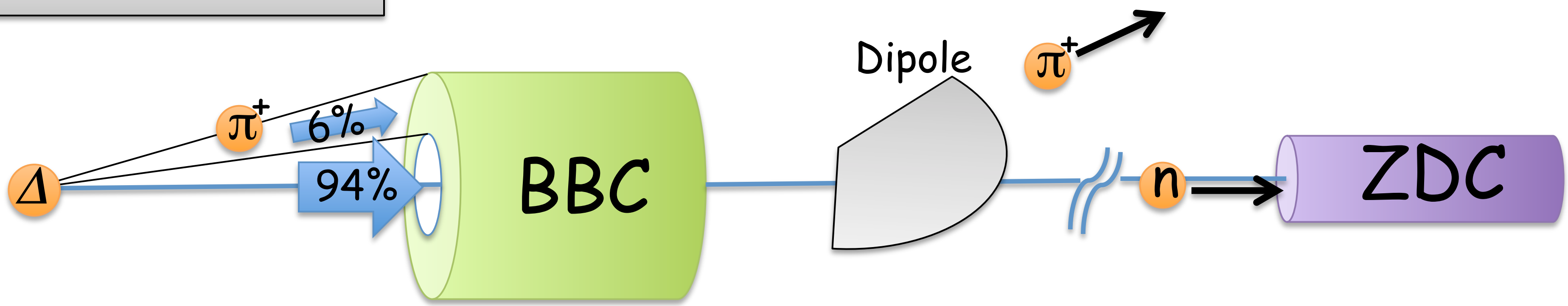


BBC

Quartz Cherenkov radiator

Can we identify UPC events?

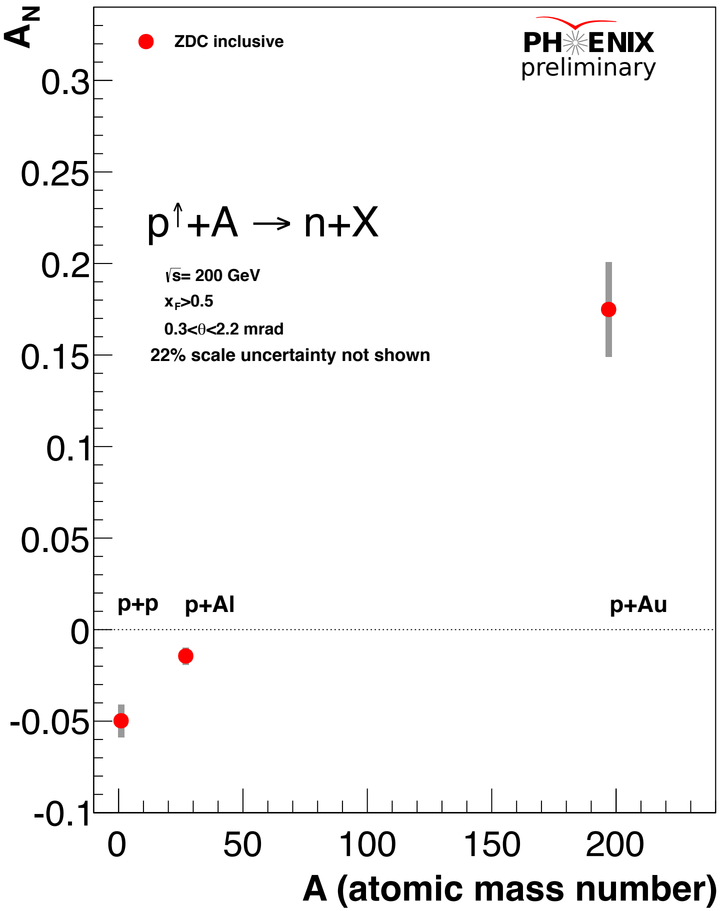
Semi-Inclusive



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

BBC	tag	veto
Primakoff	Small	Large

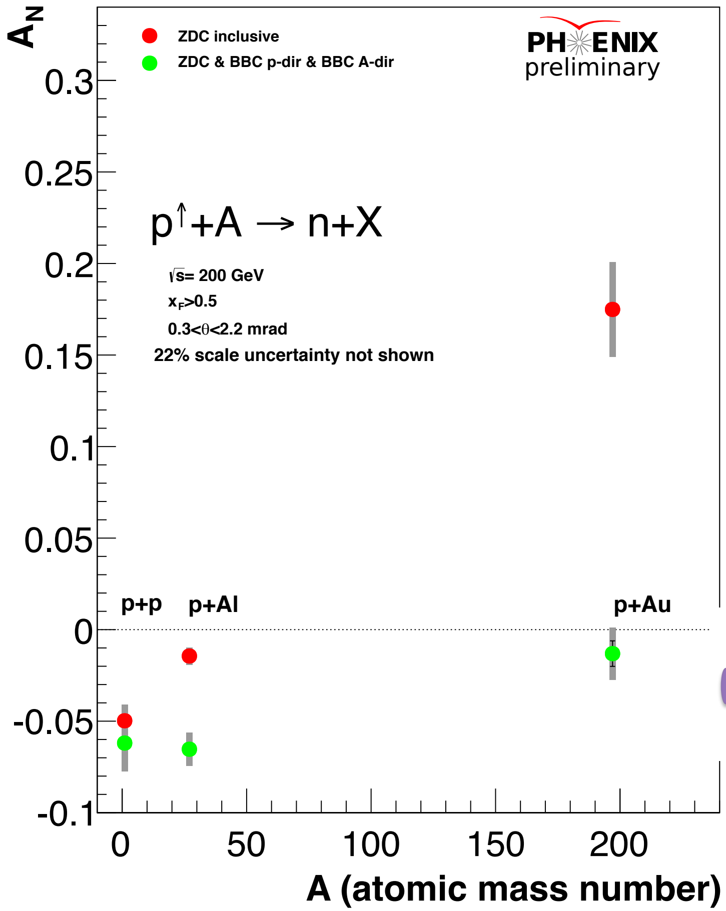
BBC Tagging and Vetoing

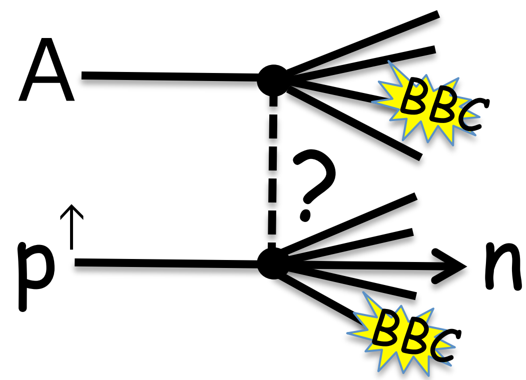


Inclusive

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

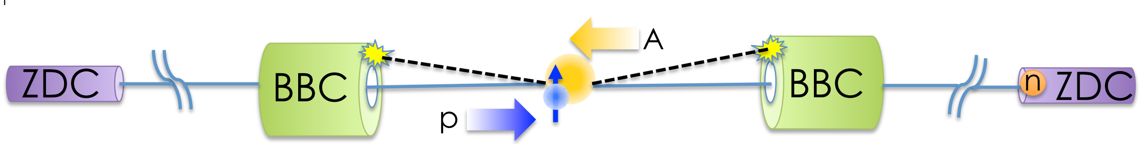
BBC Tagging and Vetoing





Non-diffractive

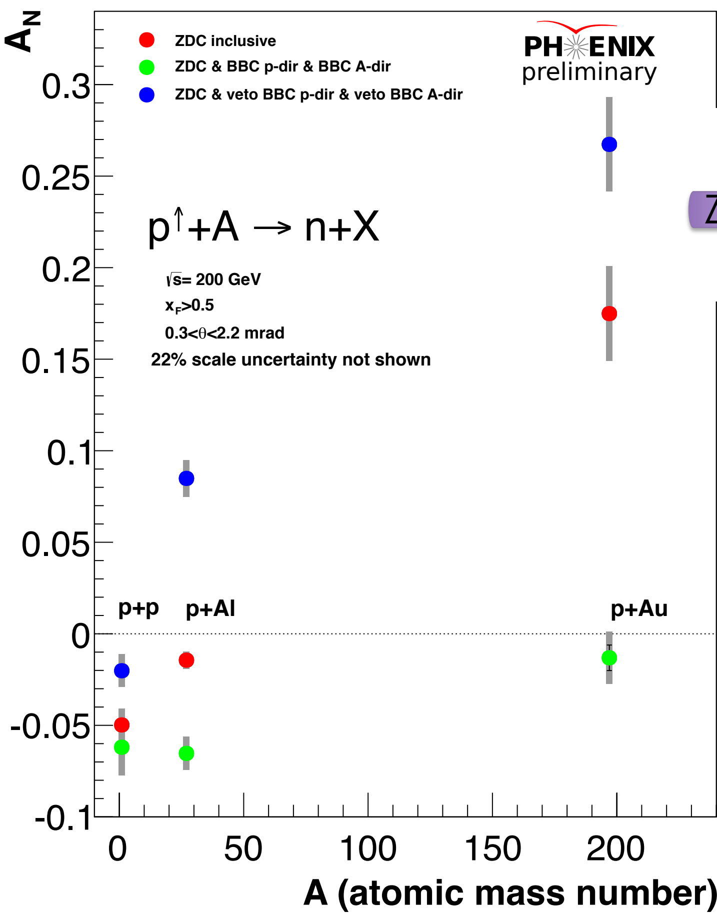
BBC Tagging



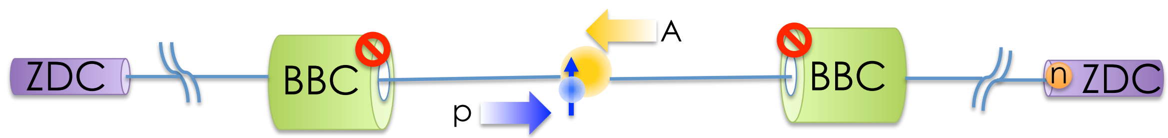
EM surpressed

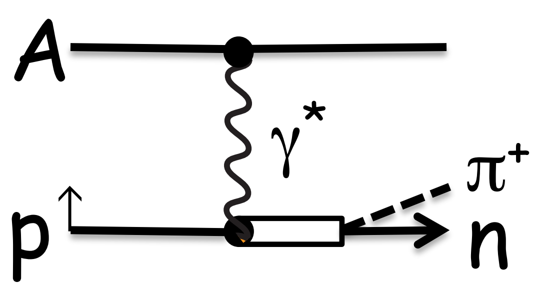
$$A_N \sim \boxed{had * had} + \underbrace{had * EM + EM * had + EM * EM}$$

BBC Tagging and Vetoing



BBC Vetoing



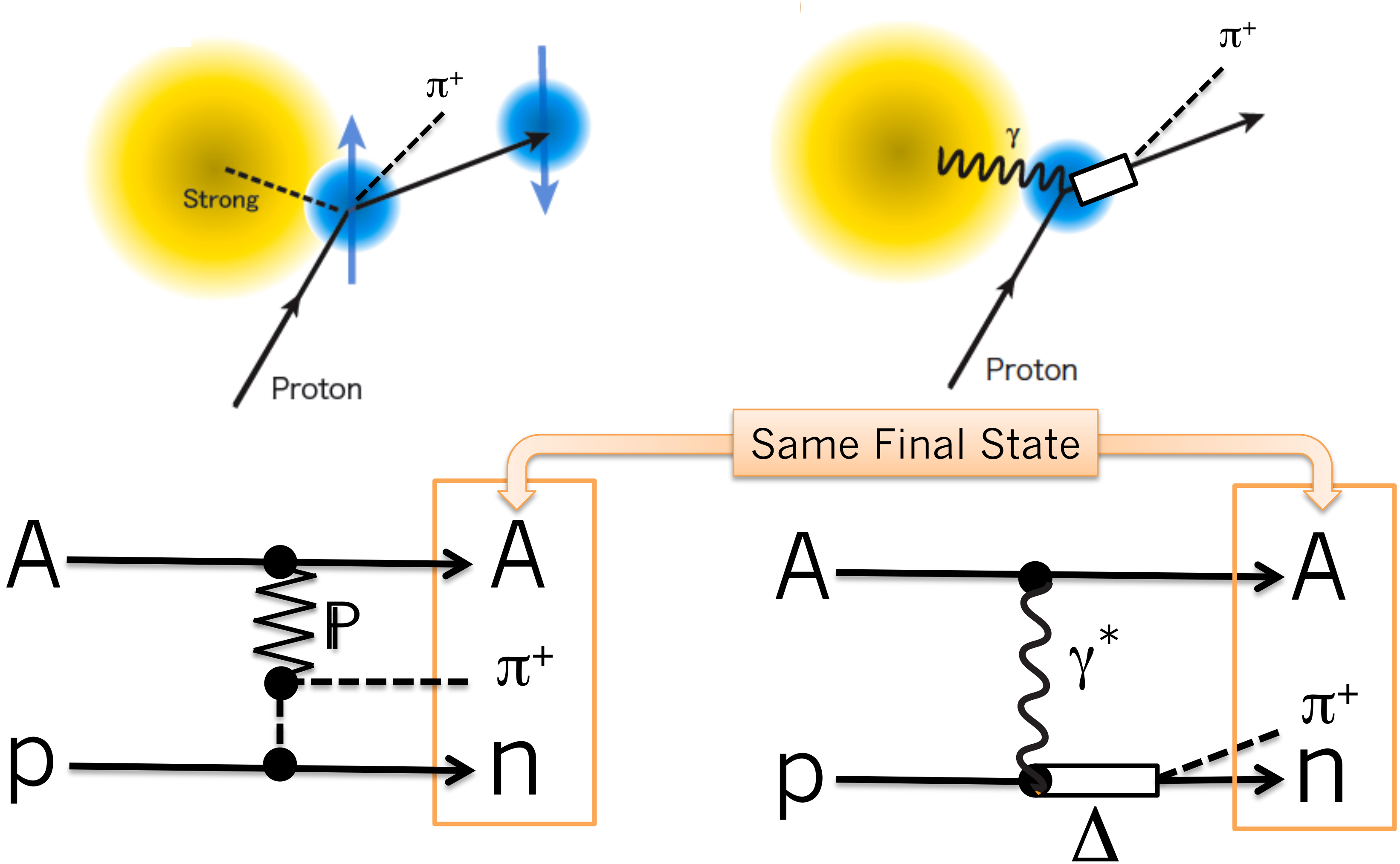


Diffractive

EM enhanced

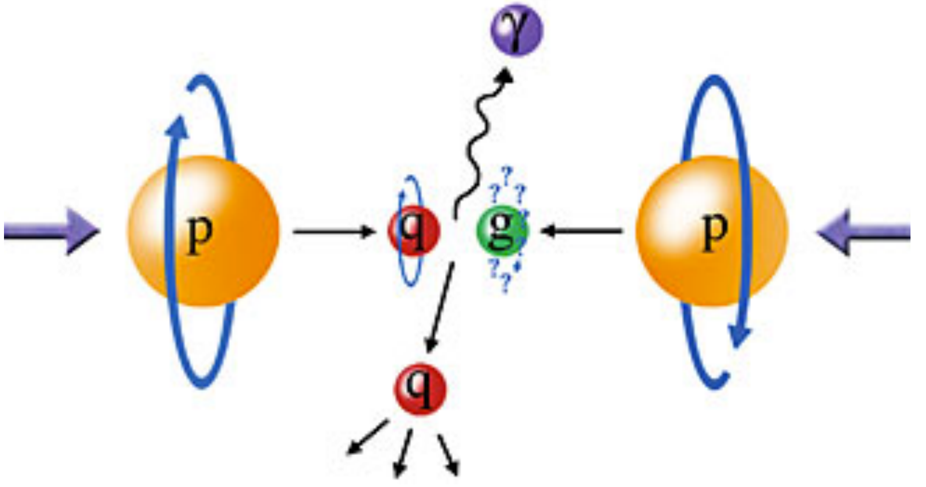
$$A_N \sim had * had + had * EM + EM * had + EM * EM$$

Coulomb-Nuclear Interference in Forward Neutron Production



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

Diffractive Process Required?

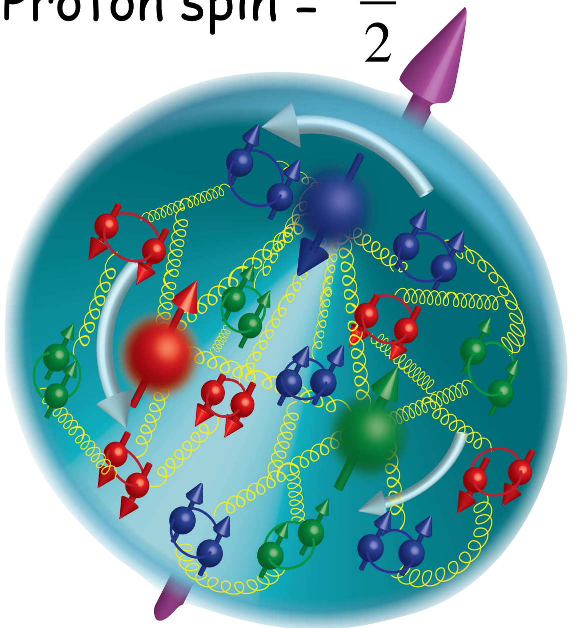


$\Delta G, \Delta \overline{q}$ Polarization

LONGITUDINAL PROGRAM

Proton Spin Decomposition

Proton spin = $\frac{1}{2}$



Longitudinal Spin Sum Rule

$$S_z = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

$\Delta\Sigma \downarrow$ ~30% $\Delta G \downarrow$? $L_z \downarrow$??

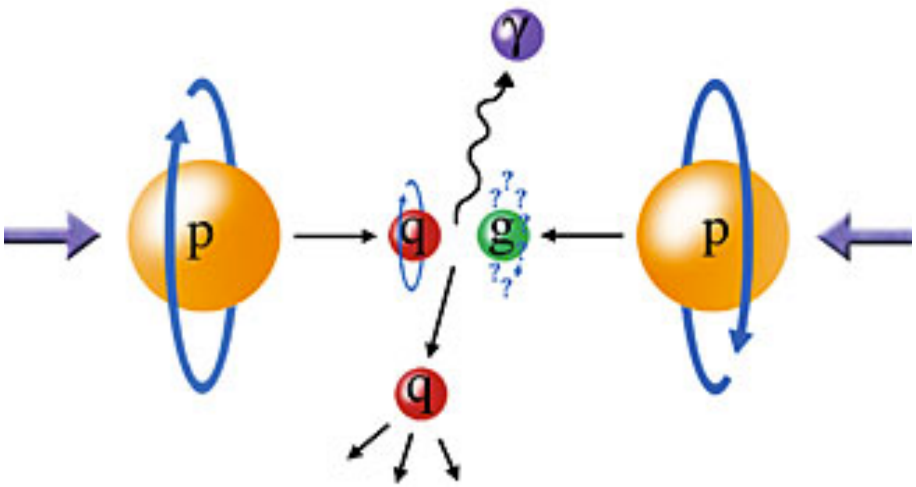
Quark Spin $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})\, dx$

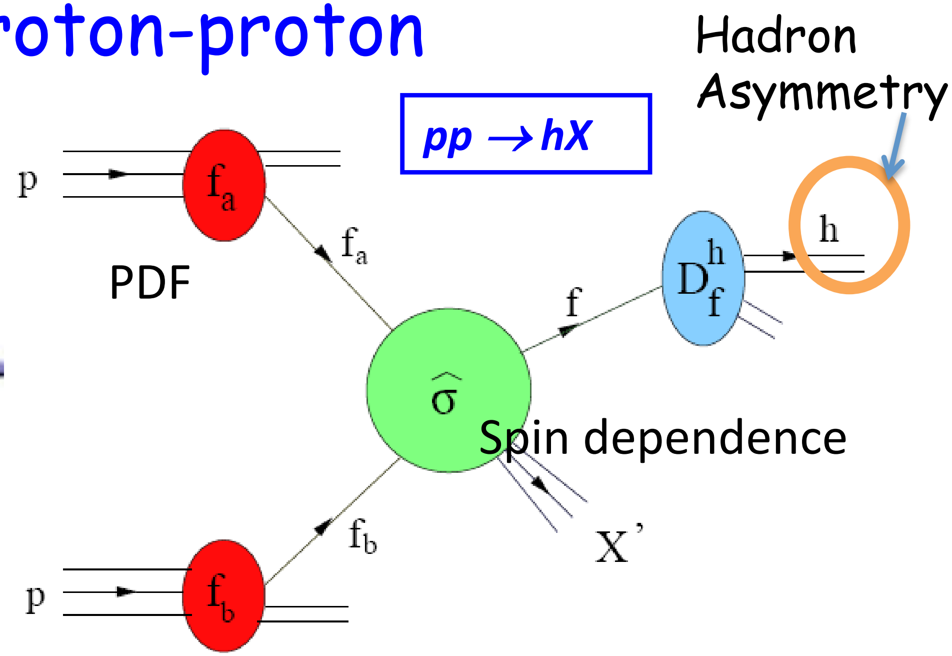
Sea quark ($\Delta\bar{u} + \Delta\bar{d}$)

Gluon Spin $\Delta G(x) = \int \Delta g(x)\, dx$

Longitudinal Spin Structure

Longitudinally Polarized proton-proton



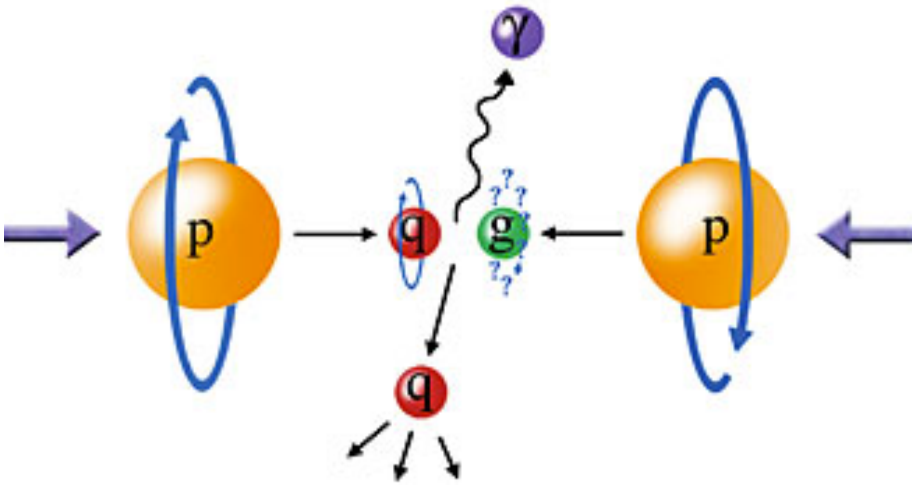


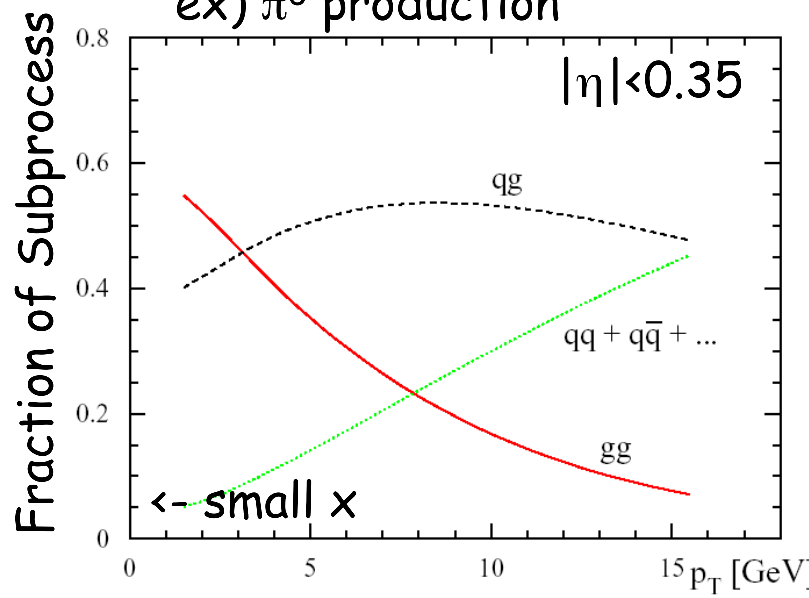
Fragmentation Function

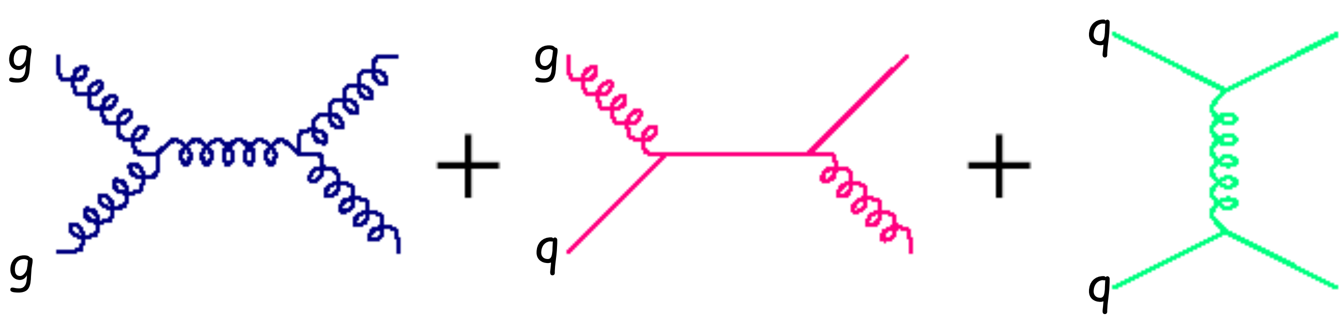
Double Helicity Asymmetry A_{LL}

$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow fX} \cdot \hat{a}_{LL}^{f_a f_b \rightarrow fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow fX} \otimes D_f^h}$$

Subprocess of pp



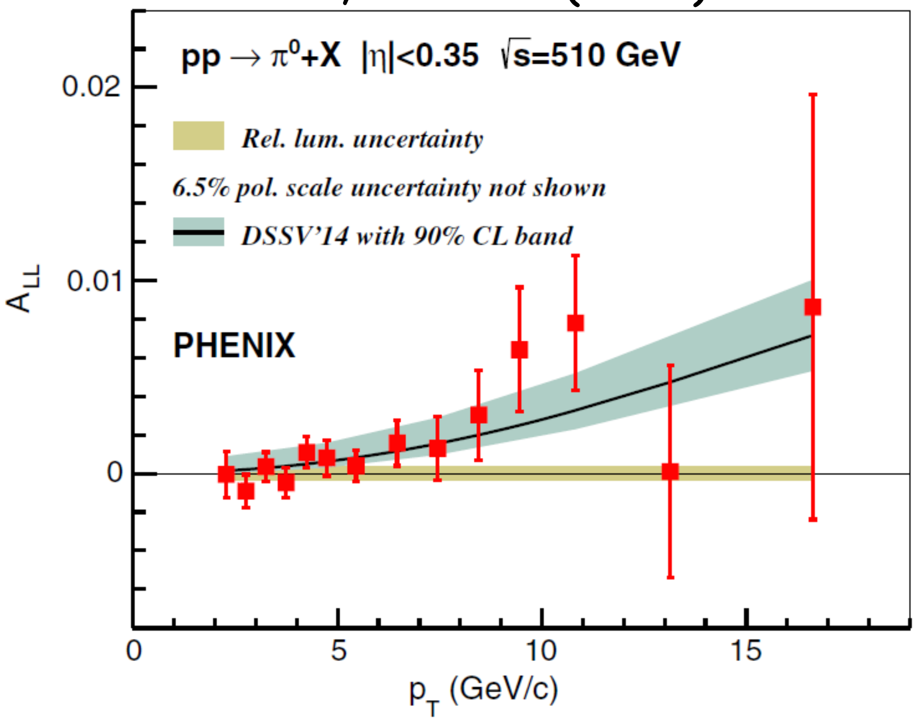




$$A_{LL} \propto [\omega_{gg}]\Delta g \Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q \Delta q]$$

Latest A_{LL} Results

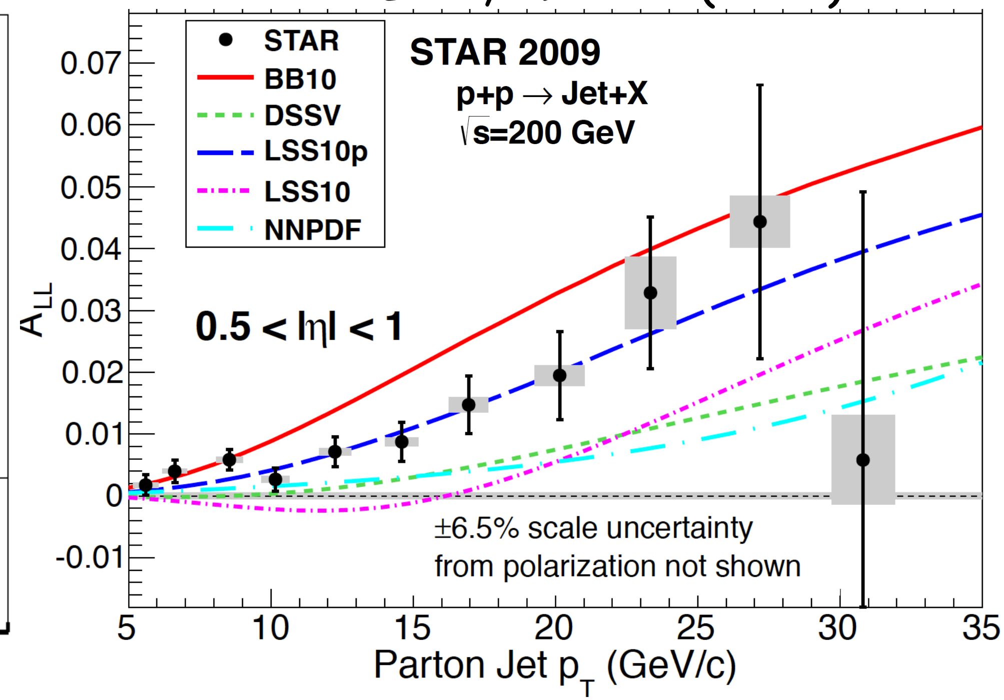
PRD **93**, 011501R (2016)



PHENIX

$$pp \rightarrow \pi^0 + X$$

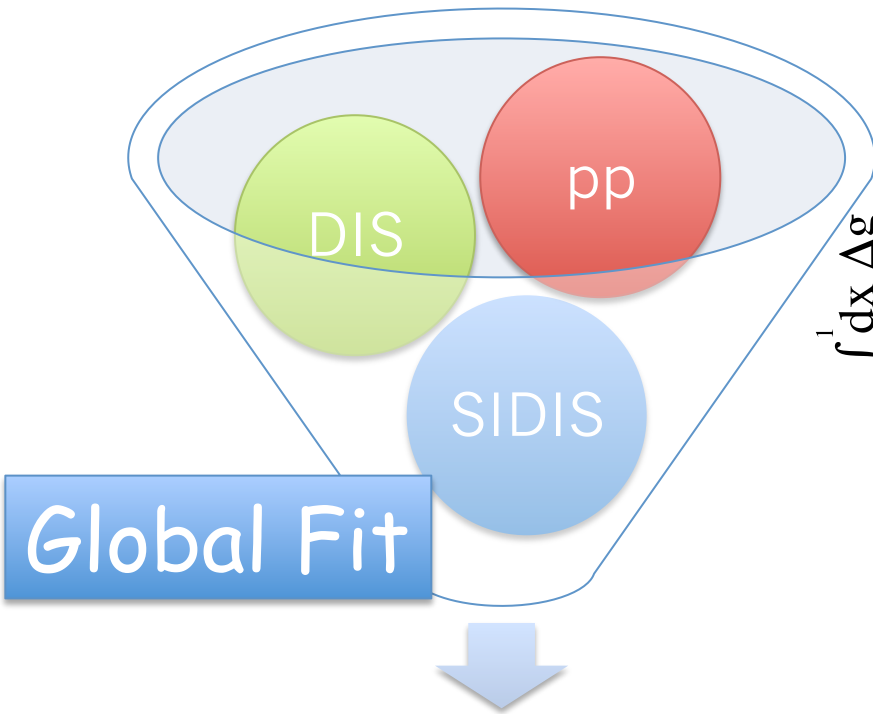
PRL115, 092002 (2015)



STAR

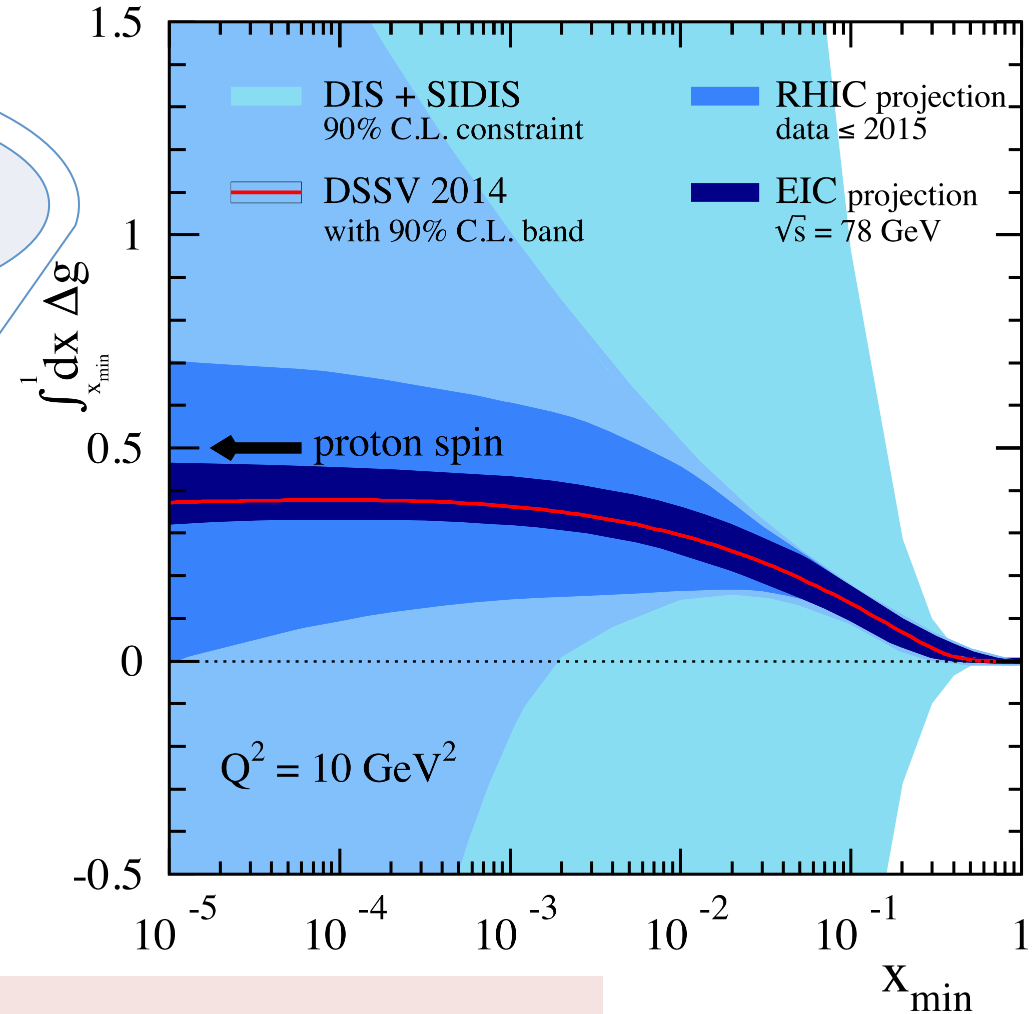
$$pp \rightarrow jet + X$$

$\Delta g(x)$ extraction : Global Fit



$\Delta q(x)$, $\Delta\bar{q}(x)$, $\Delta g(x)$

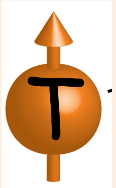
arXiv:1602.03922



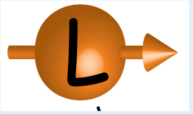
$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.2 \pm^{0.06}_{0.07}$$

Summary

- RHIC spin program has been providing new insights to spin structure of proton
- Absolutely unexpected strong A-dependence in very forward neutron TSSA of p+A.
- EM process likely to be taken into account.

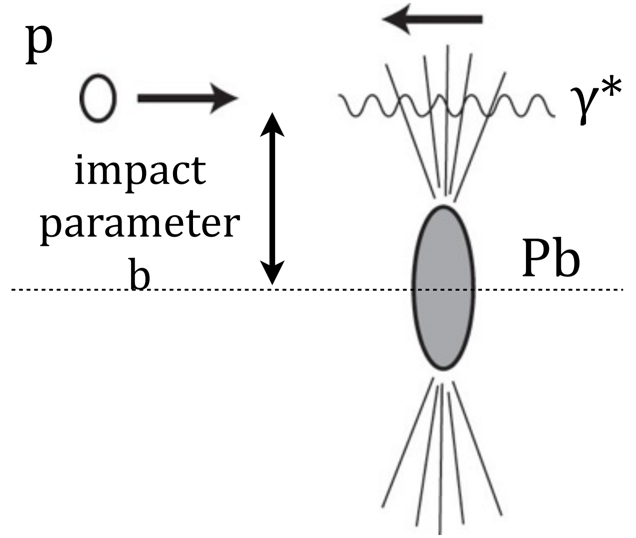


- Latest data shows non-zero gluon spin fraction



BACKUP SLIDES

Event Generation of UPCs



Event Generation of UPCs

=

Flux of quasi photons

×

Cross section of p-γ

×

Event Generation of p-γ

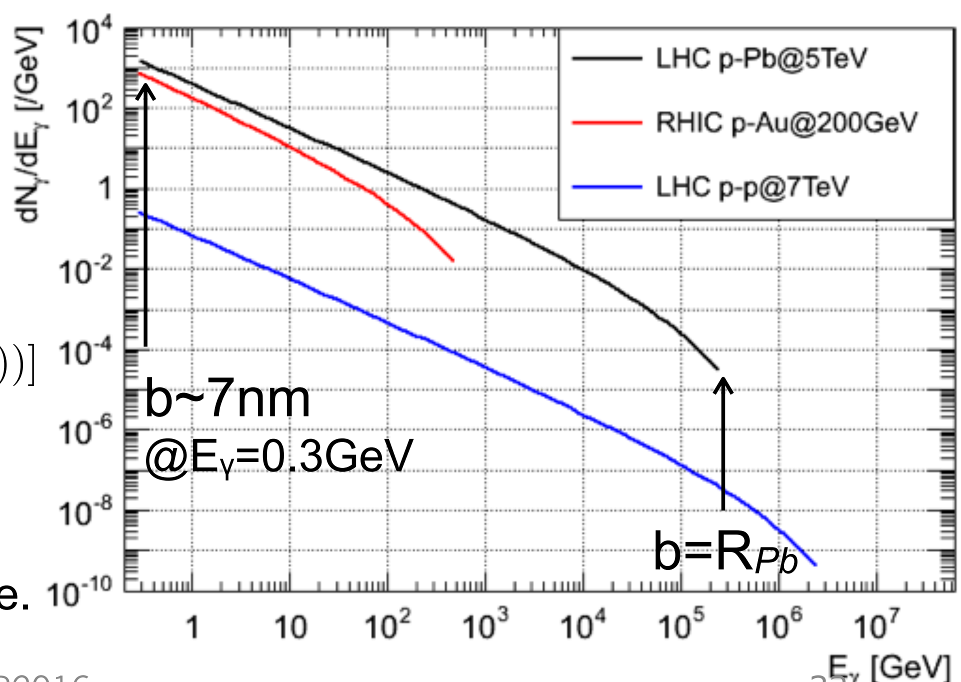
Flux of quasi photons

Weizsacker-Williams method

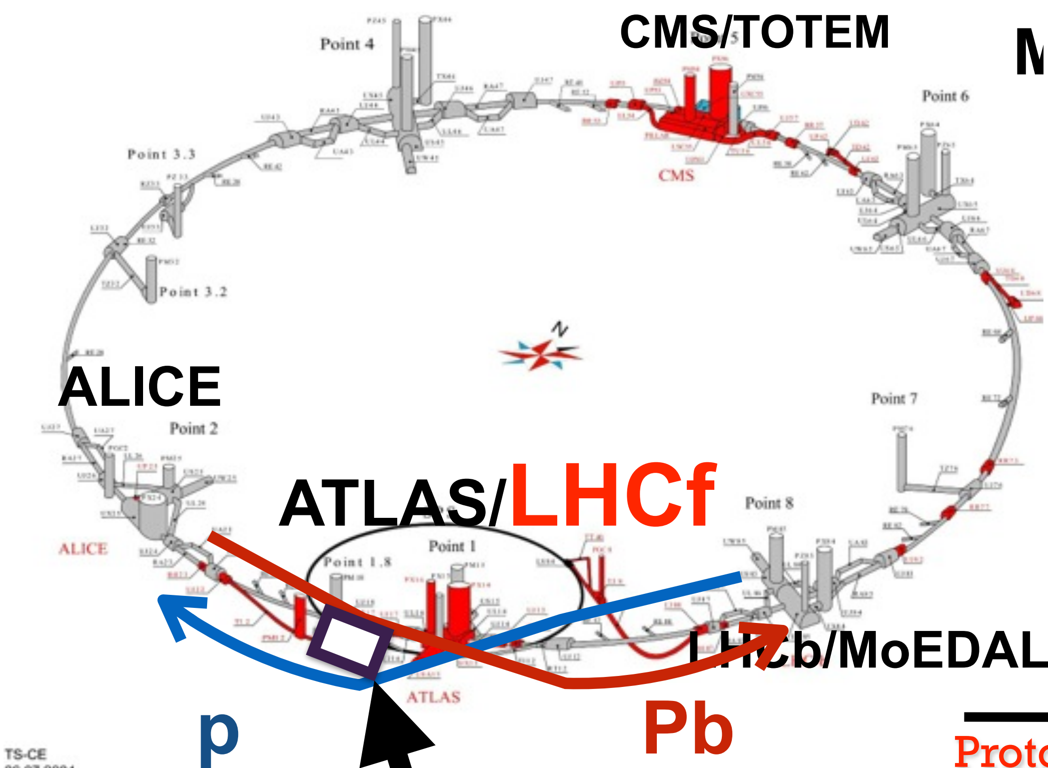
$$\frac{dN_{\gamma *}}{dE_{\gamma *}} = \frac{2Z^2\alpha}{\pi E_{\gamma *}}[xK_0(x)K_1(x) + \frac{x^2}{2}(K_0^2(x) - K_1^2(x))]$$

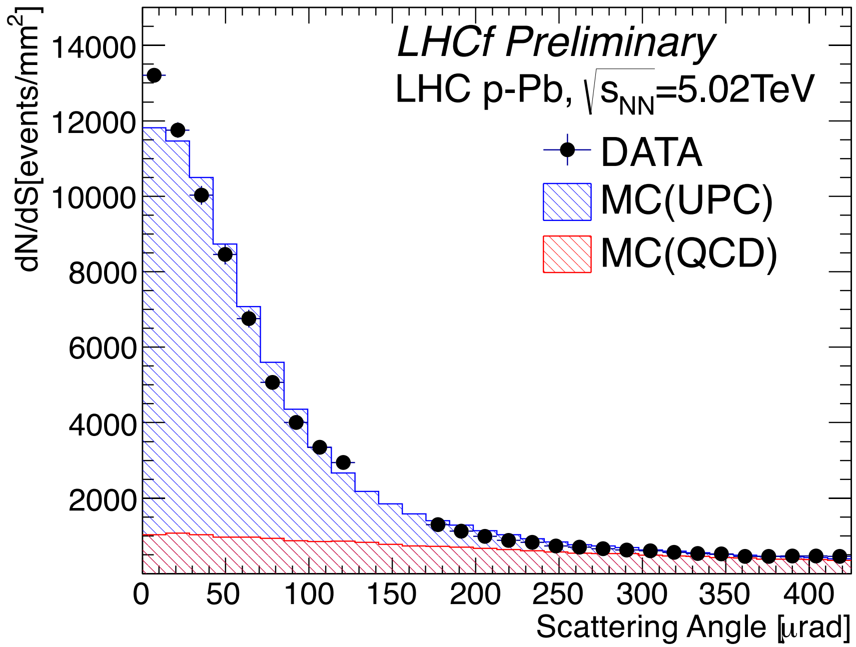
$$\simeq \frac{2Z^2\alpha}{\pi E_{\gamma *}}(log\frac{1.123}{x} - 1) \quad (if\ E_{\gamma *} << E_{max})$$

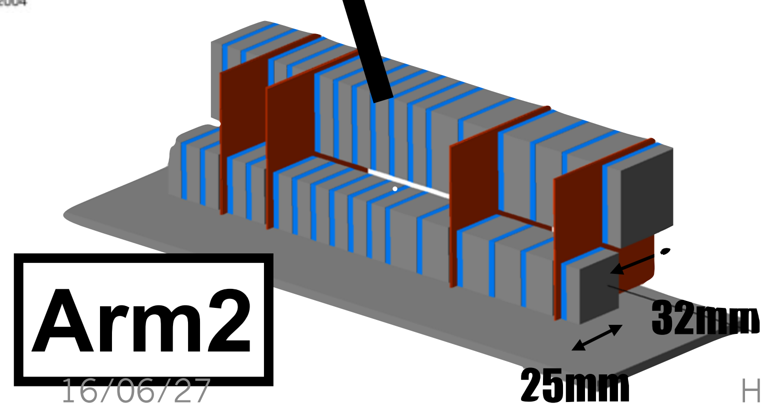
$E_{\gamma *}$: energy of photons at the proton rest frame.

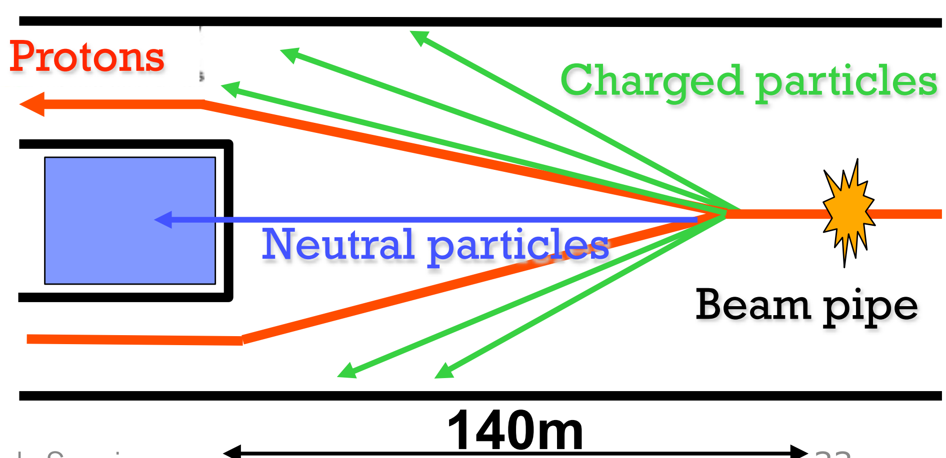


The LHCf experiment









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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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-

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Ref. [1,2] for a r
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$p+\text{Pb} \rightarrow p+\text{Pb}+J/\psi$ [3]
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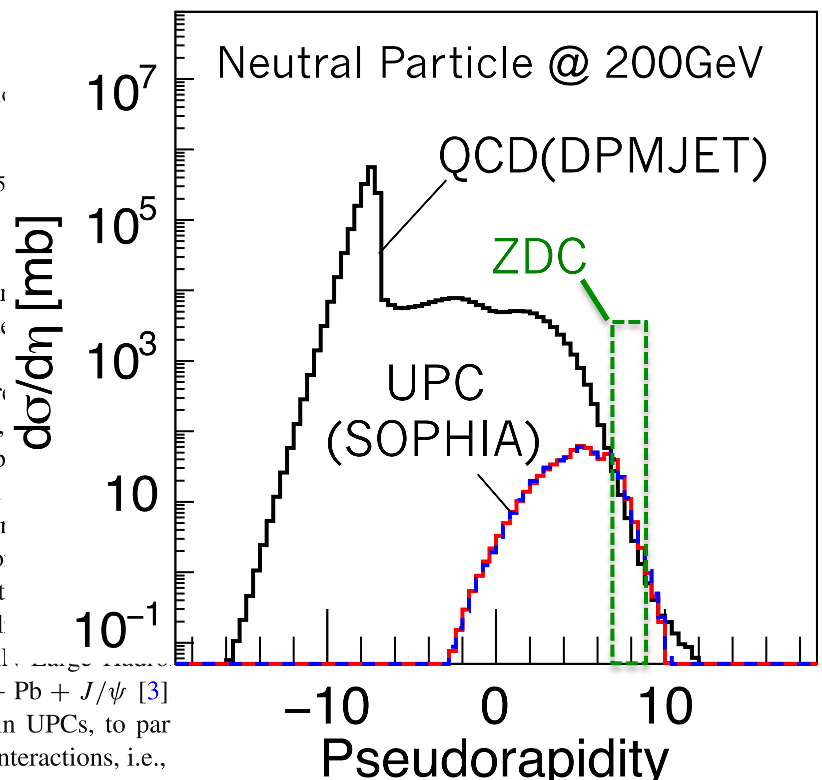
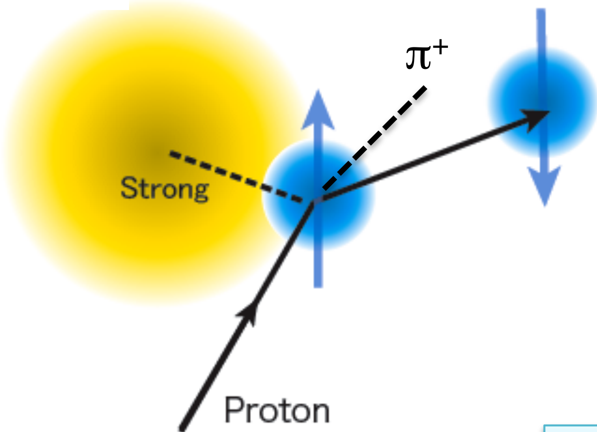
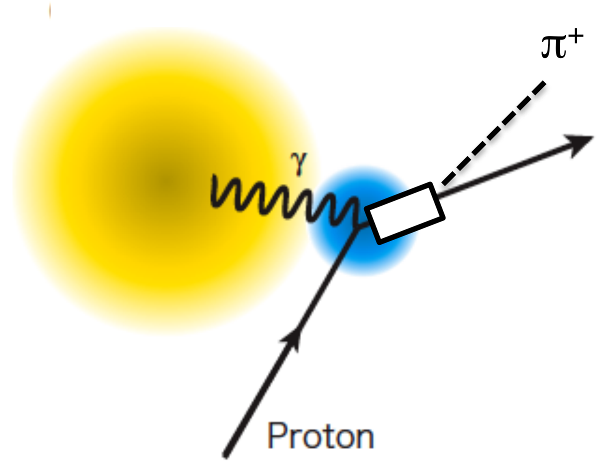


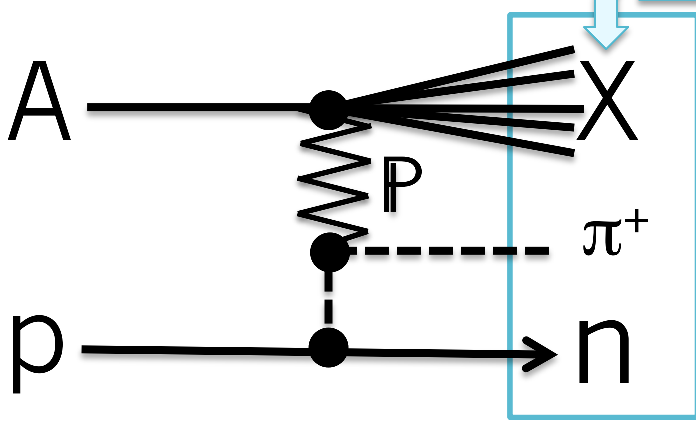
Predicts comparable yields between QCD and UPC processes

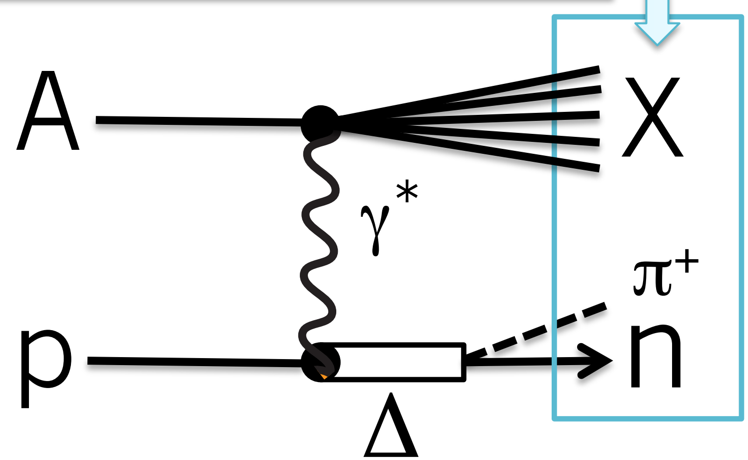
Non-Diffractive Events





Little chance to be same final state

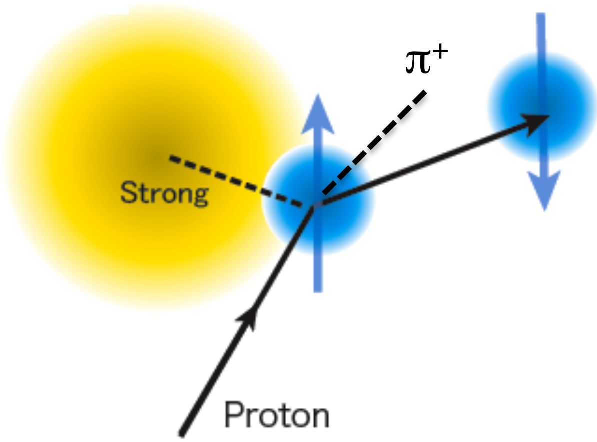


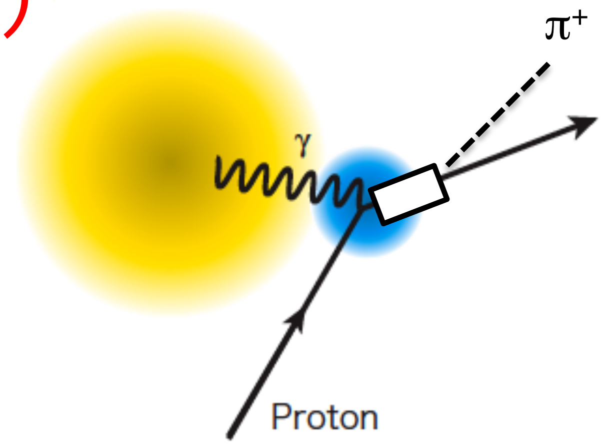


$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Suppressed?

Coulomb-Nuclear Interference
(CNI)





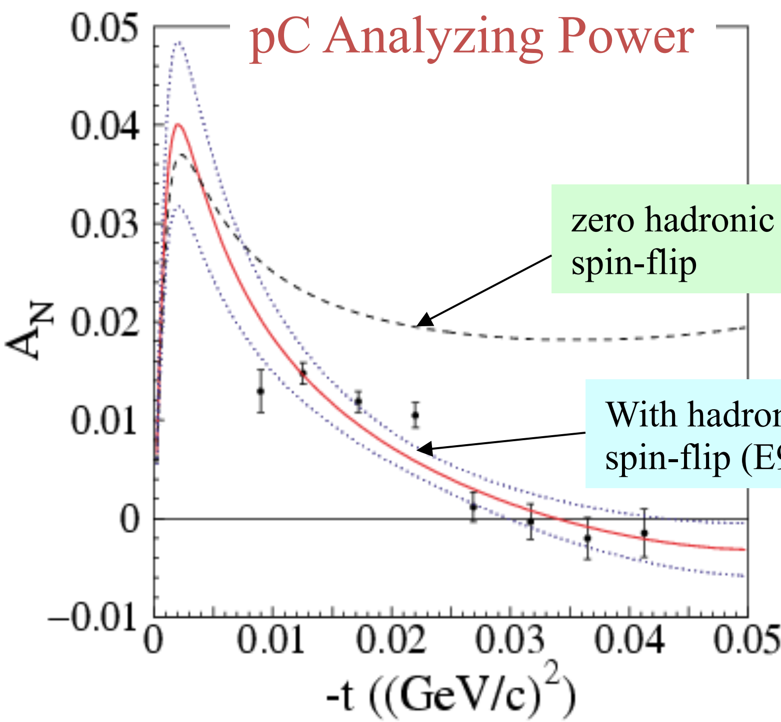
$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Elastic A_N at Coulomb Nuclear Interference

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

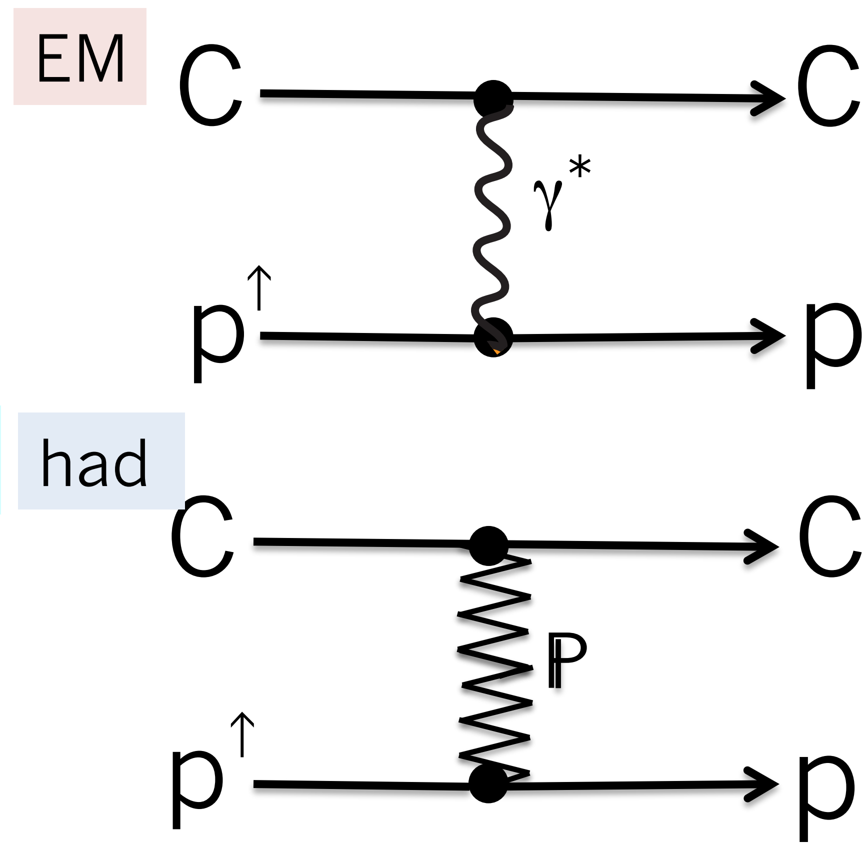
$\propto \alpha s/t$ — Pomeron — $\propto \sqrt{\sigma^{had}_{pC}}$ — $\propto (\mu_p - 1)$

(High energy & small t limit)

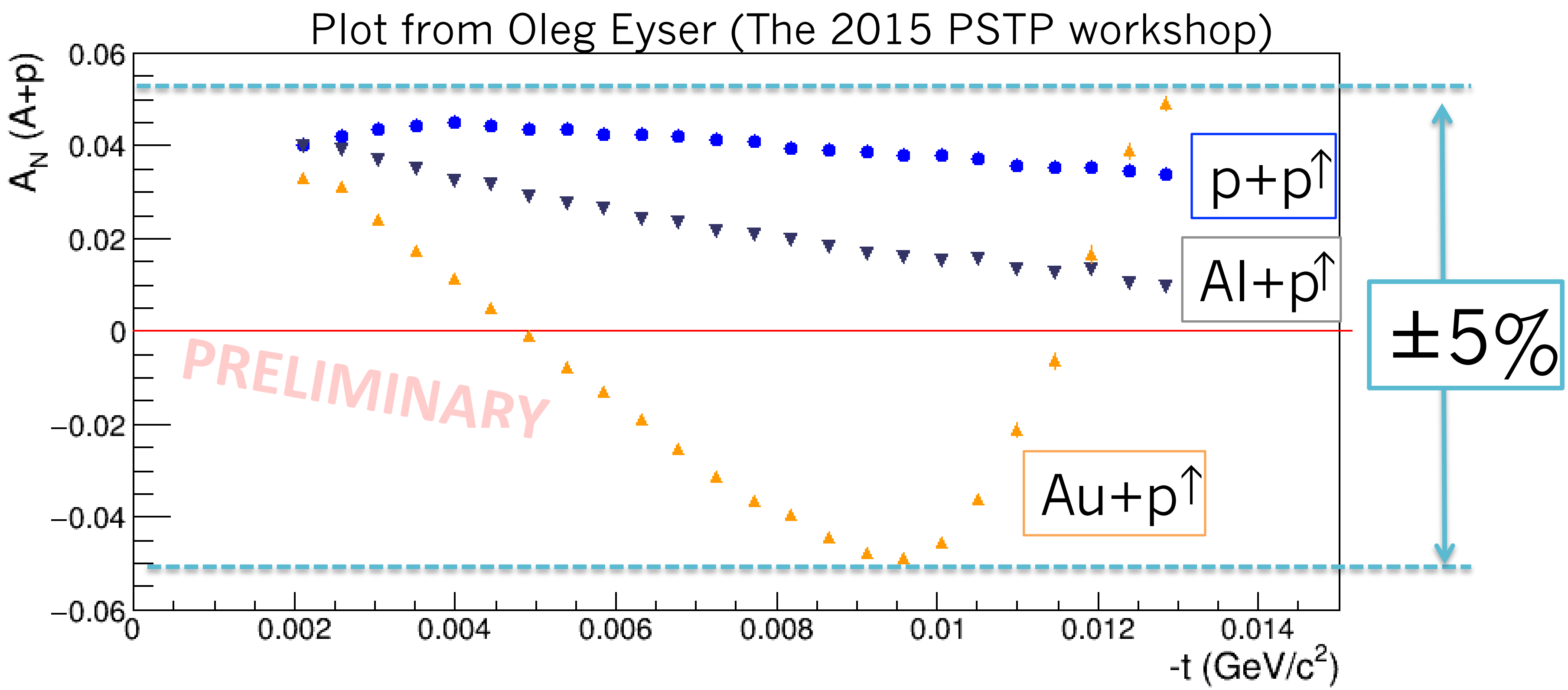


Phys.Rev.Lett.,89,052302(2002)

E_{beam} = 21.7GeV



Run15 Au,Al beam + p↑ target

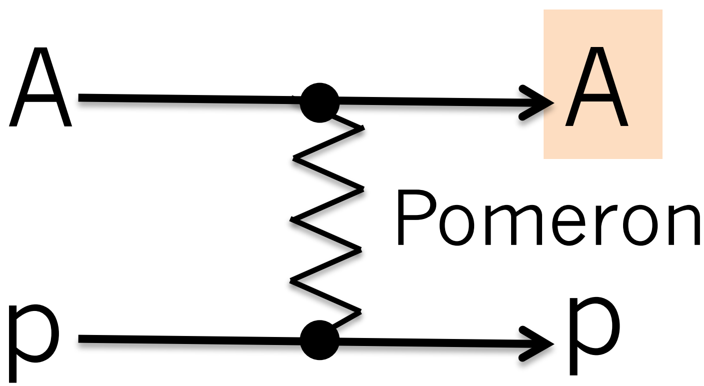


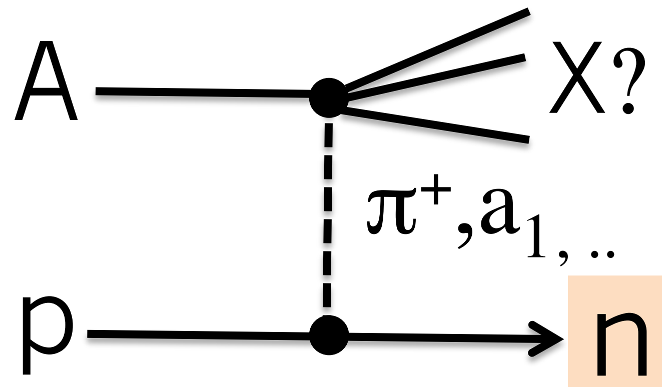
- Strong A-Dependence
- Flips sign of A_N in Au+p↑
- 0.002 < -t < 0.014 $(\mathrm{Gev/c})^2$

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
$\Delta I = 0$	$\Delta I = 1$

Interim Summary (CNI)

- CNI is not necessarily new.
- Elastic in much smaller $-t$ than present neutron results observed similar behavior, but the asymmetry is in the order of 5% or less.
- There are possible diagram to hadron and EM interfere for neutron production as well.

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

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The origin of Asymmetry

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.

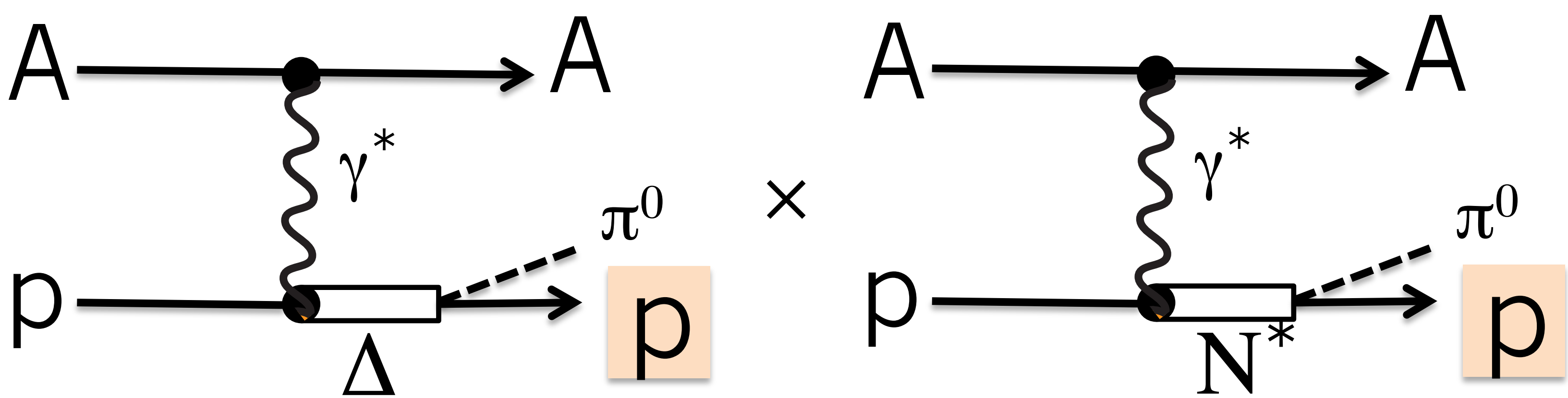
The cross section for the Coulomb coherent process (1) has a sharp peak at $t' \sim 10^{-5}$ $(\mathrm{GeV}/c)^2$ and decreases rapidly as t'/t^2. The "width" of the Coulomb peak is determined by the detector resolution. Diffractive dissociation due to the strong interaction is also present, but it has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

Origin of the Asymmetry



$\Delta^*(1232)$ P33

↳ $N\pi$ (>99%)

$N^*(1440)$ P11

↳ $N\pi$ (60~70%)

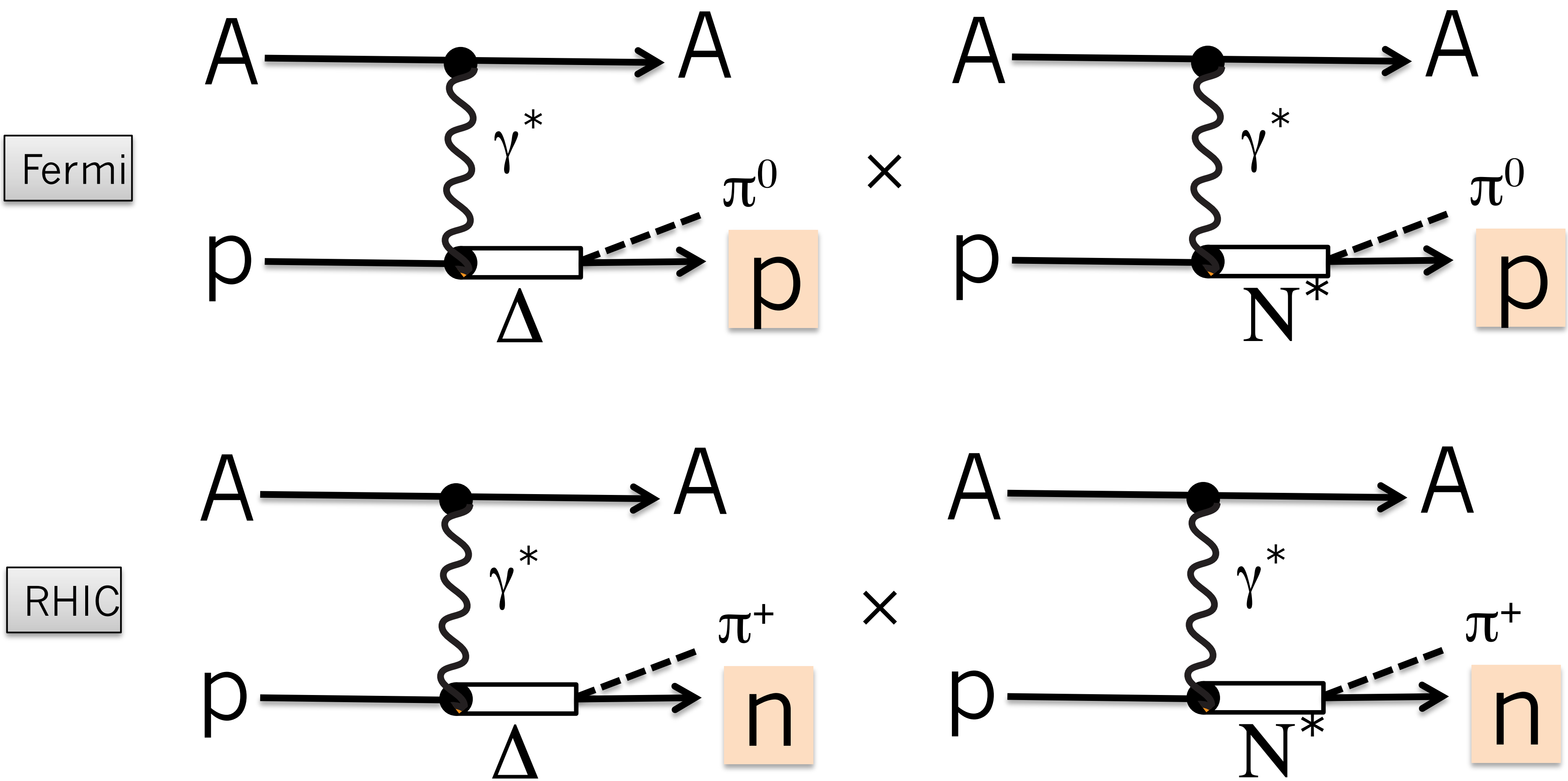
$N\pi\pi$ (30~40%)

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

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 + π^0	n (+ charged)	n (+ charged) π^0 ?
t'	< 0.001	0.02 < -t < 0.5	
M	1.36 < M(π^0p)<1.52	?	?
A_N	- 0.57 ± $(0.12)_{sta}$+ 0.21 - 0.18	+ 0.27 ± 0.003 (BBC veto)	

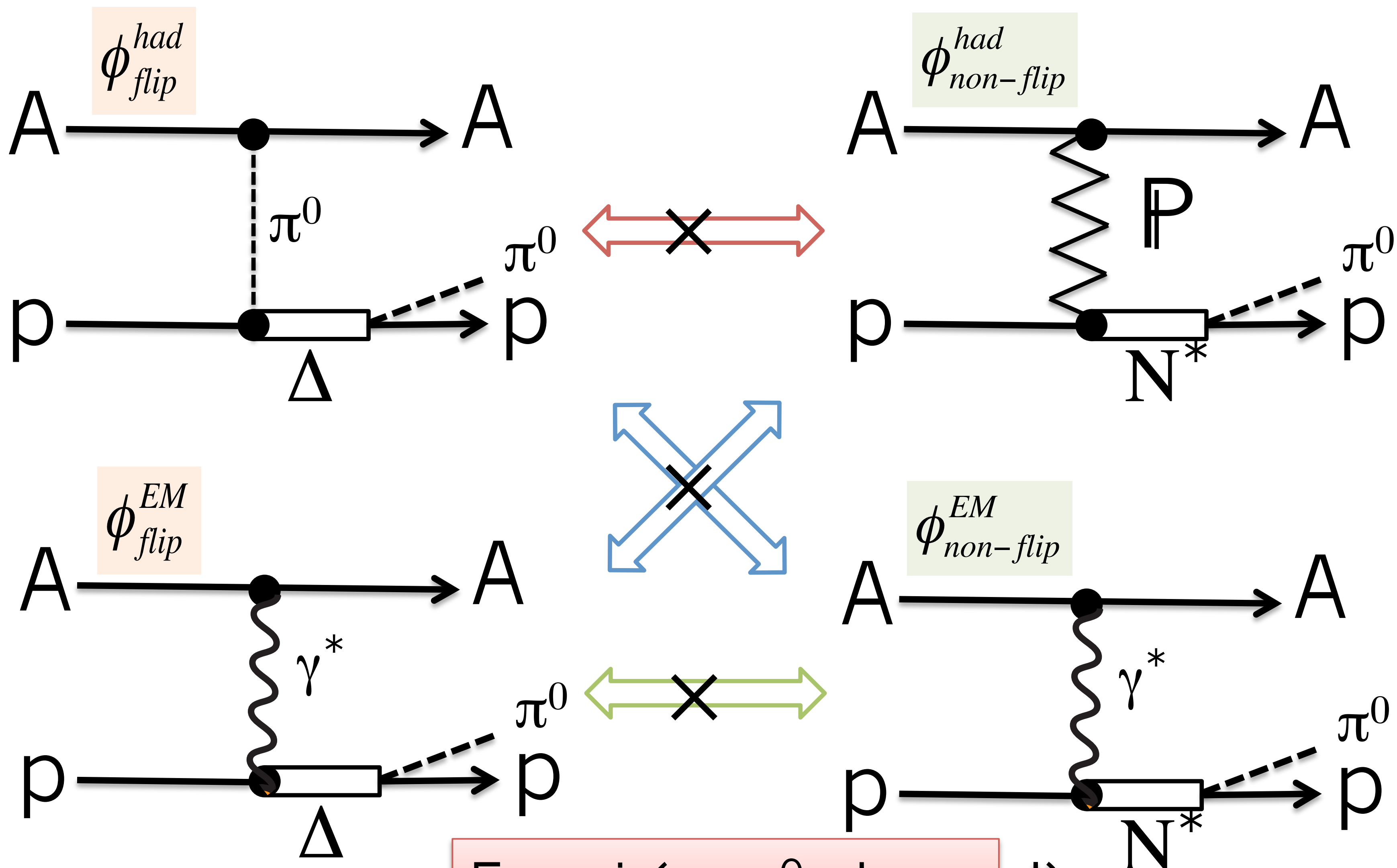
Origin of the Asymmetry



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

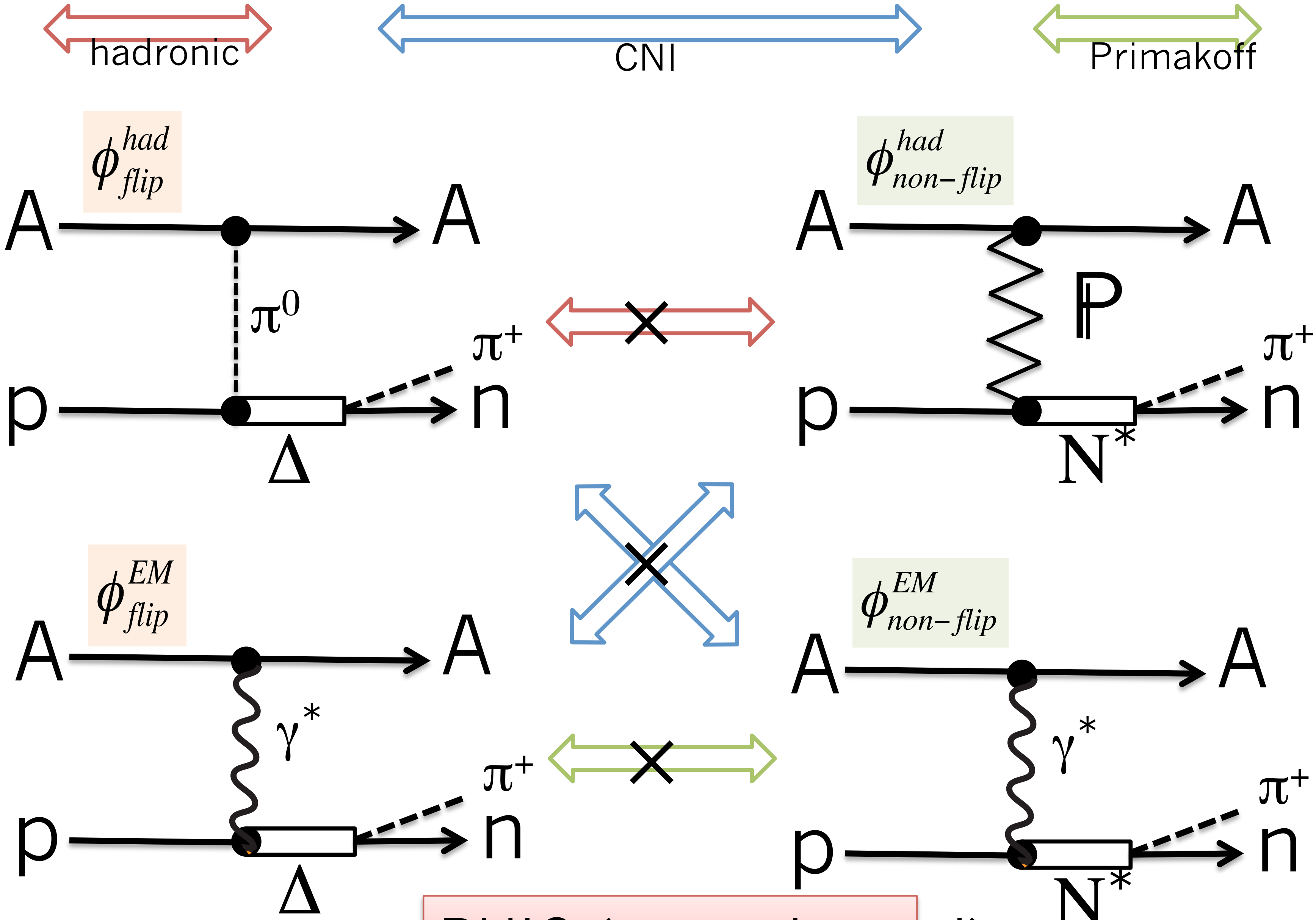
$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4$$

hadronic CNI Primakoff



Fermi (p+π^0 channel)

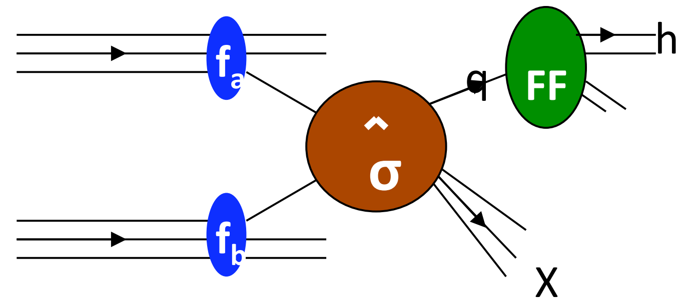
$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4$$



RHIC ($n+\pi^+$ channel)

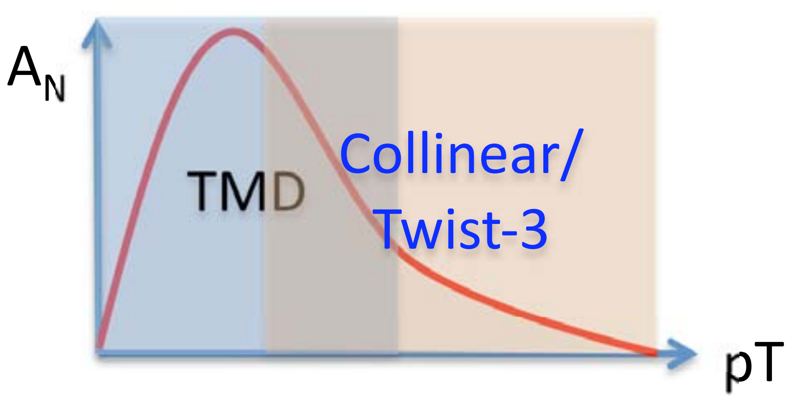
Theory: K_T vs Collinear Factorization

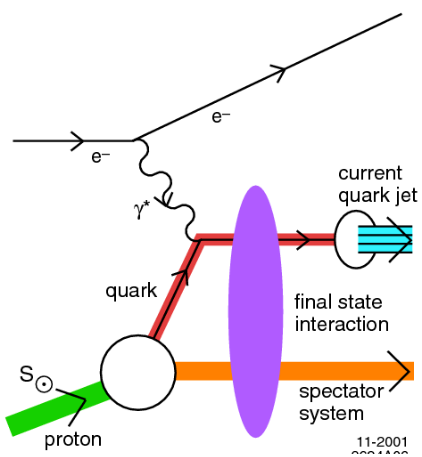
- Tran. Mom. Dep. Funs
  - Sivers Fun
  - Collins Fun

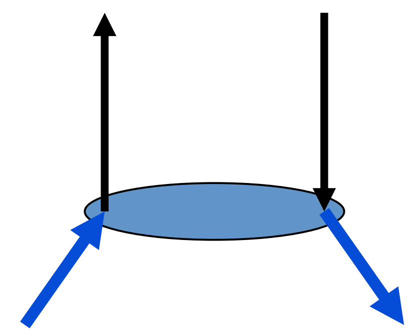


$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \rightarrow h + X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot q_j(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \rightarrow q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

- Twist-3 collinear
  - Quark-gluon correl.
  - Gluon-gluon correl.

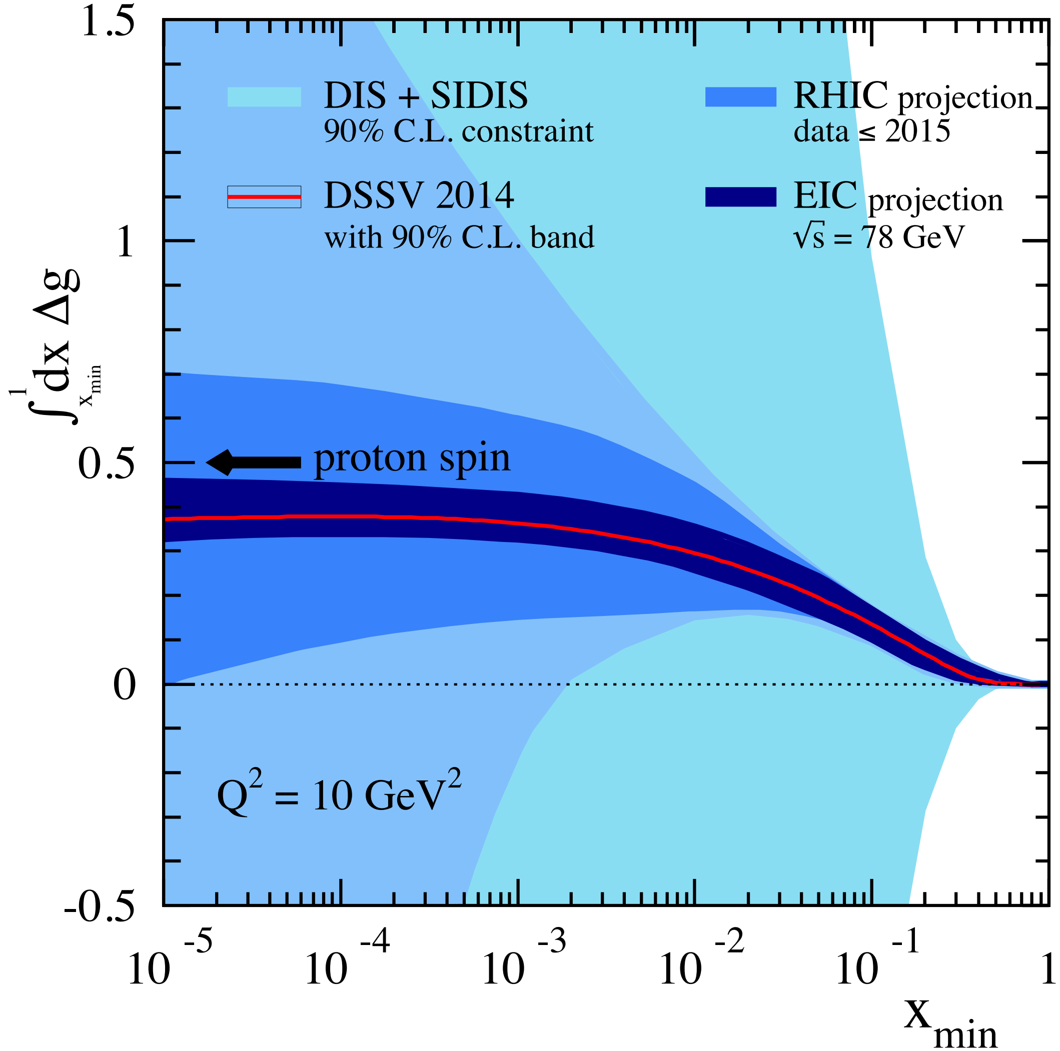






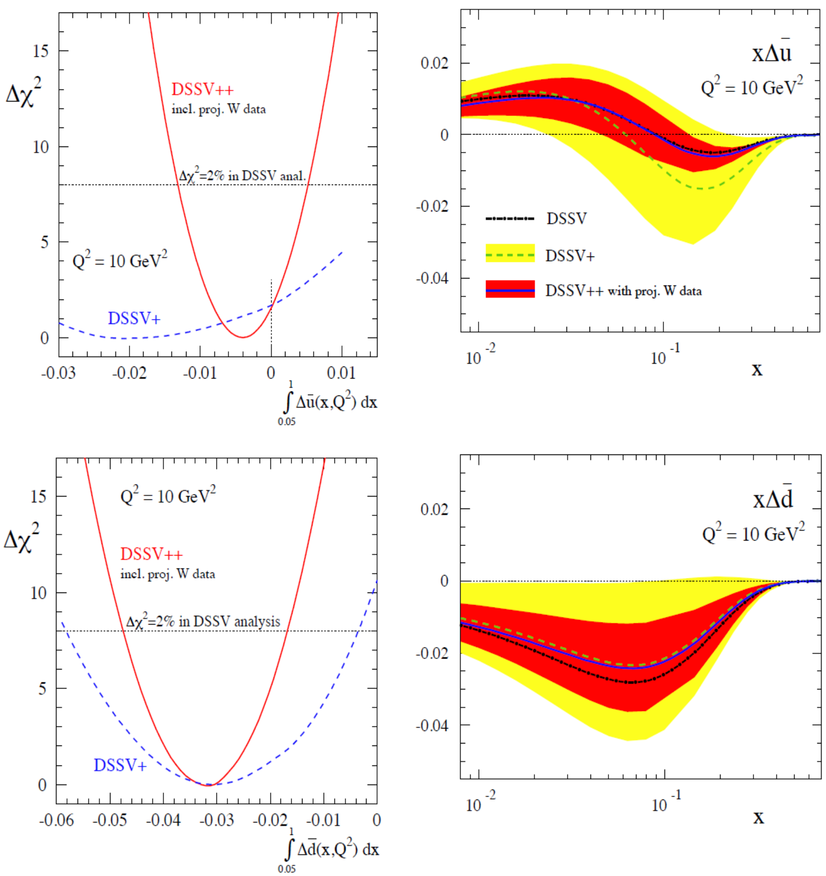
Future

arXiv:1602.03922

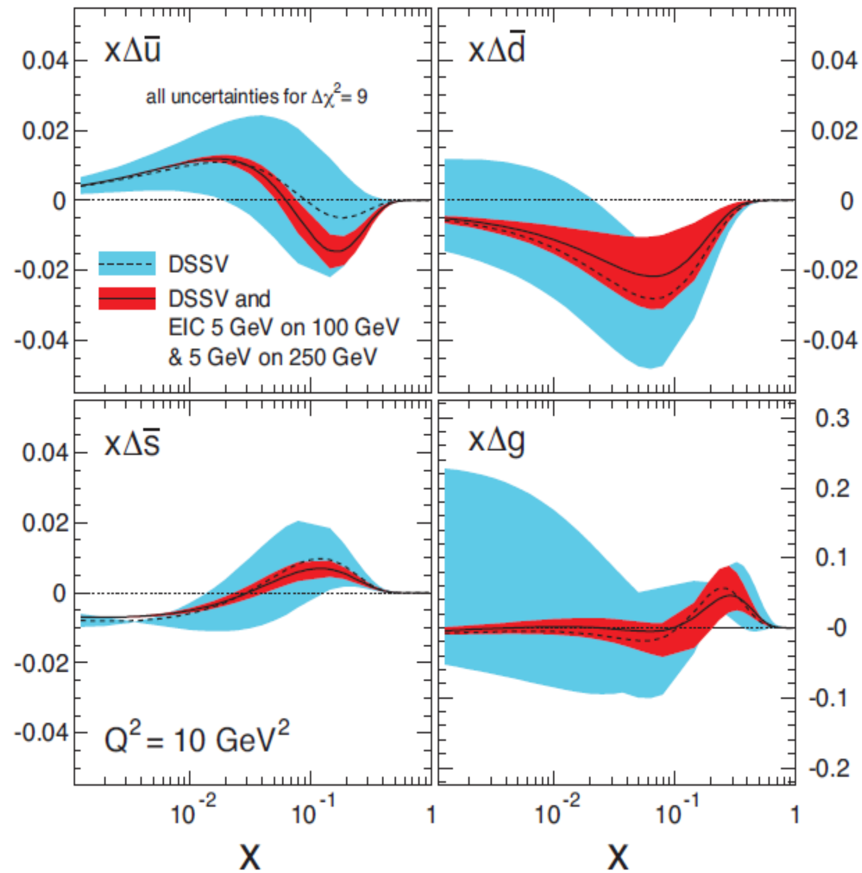


Present and Future

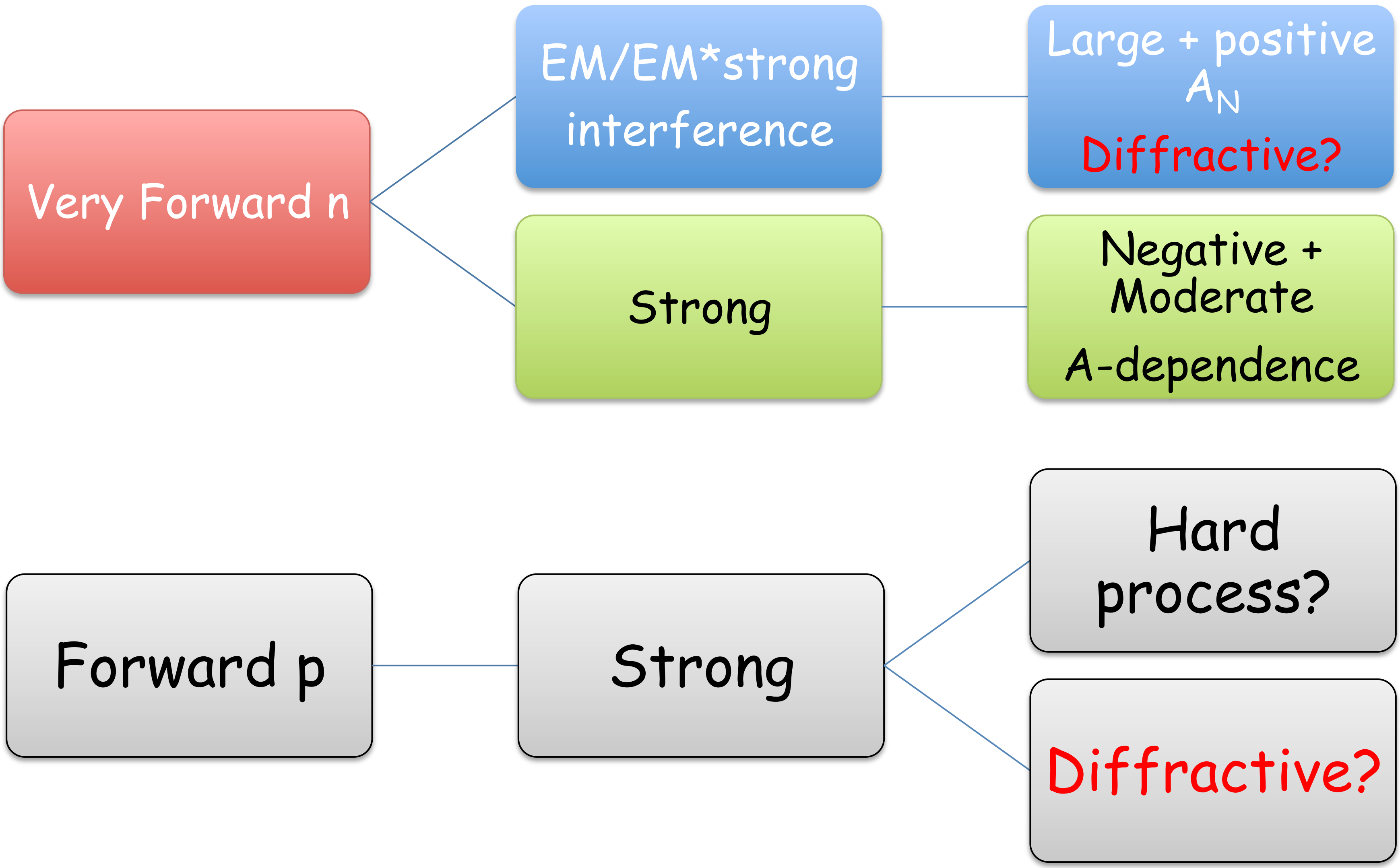
arXiv: 1501.01220



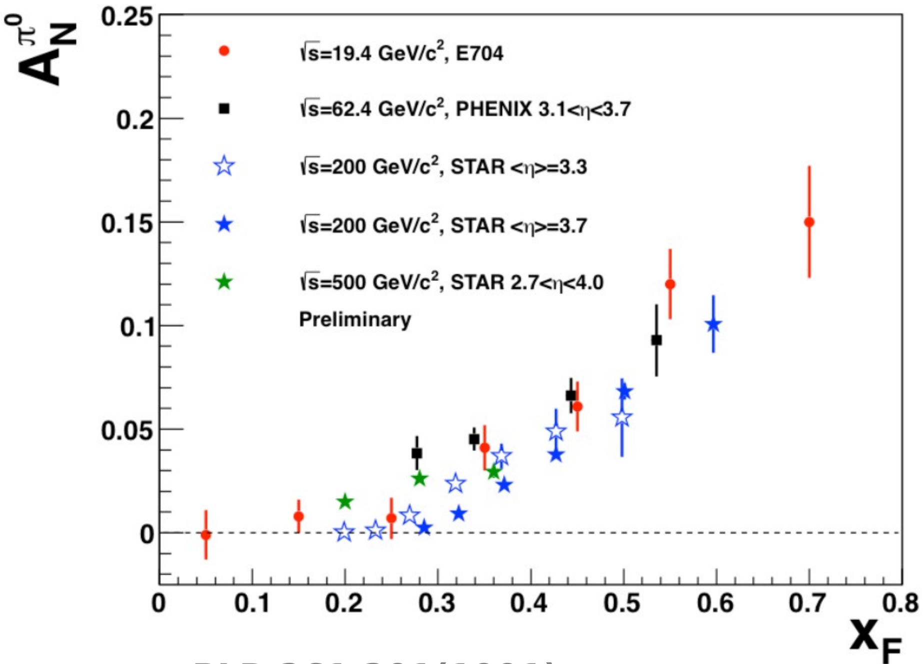
arXiv: 1212.1701



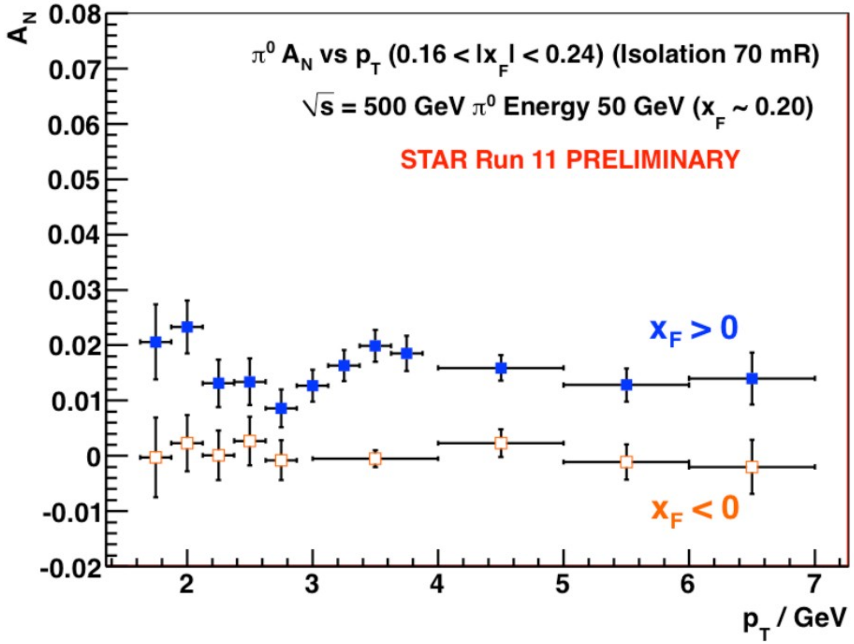
Transverse Summary



x_F and p_T Dependence



PLB,261,201(1991)
PRL,101,222001(2008)
PRD,90,012006(2014)

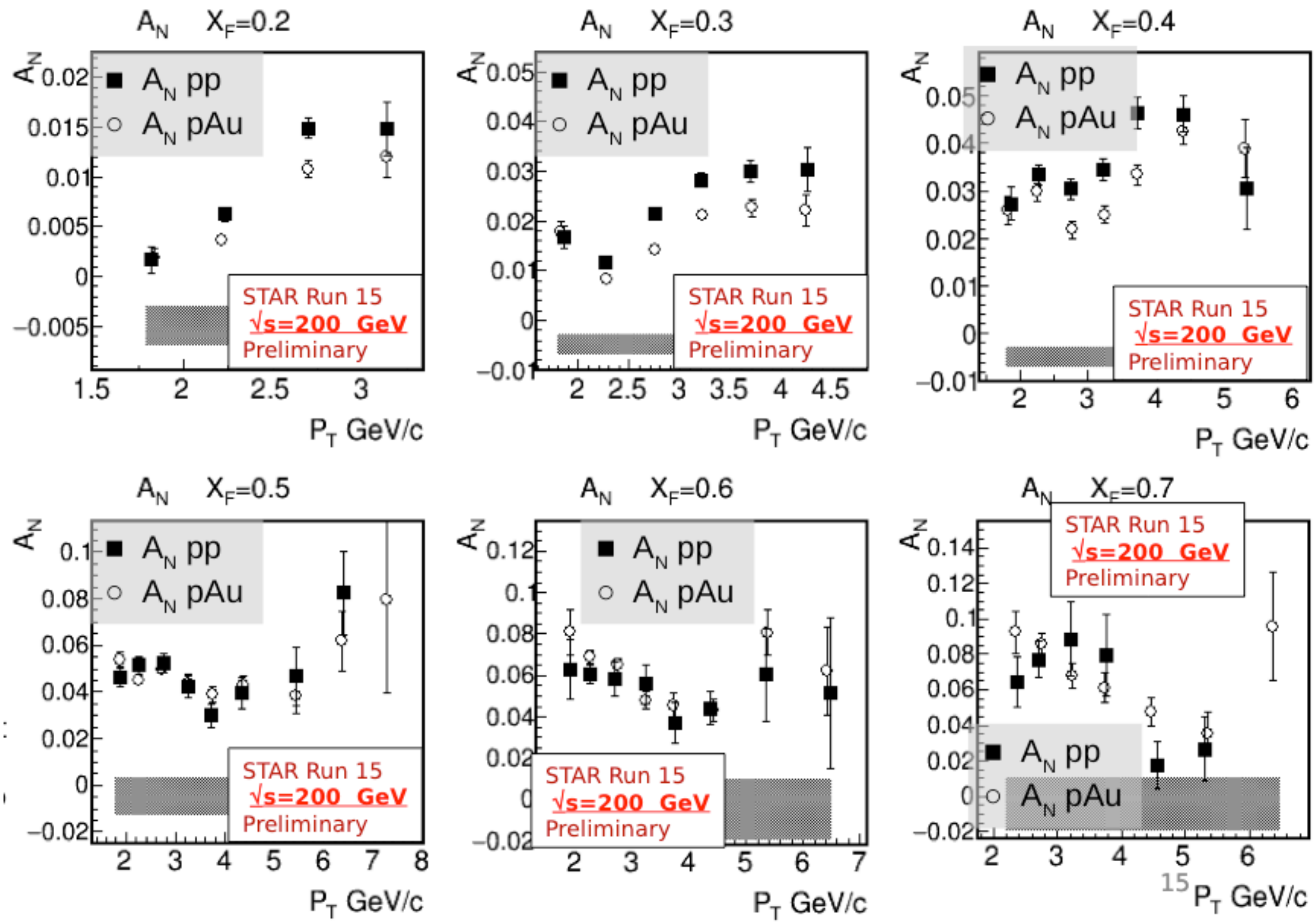


Steve Heppelmann – CIPANP 2012

$s^{1/2}$=200 GeV and 500 GeV show same rise of A_N vs. x_F as lower $s^{1/2}$ measurements

- Collins, Sivers, Twist-3 suggest A_N~$1/p_T$
- Flat P_T-dependence observed and raises the question as to what causes it

Forward π^0 A_N in p+Au



Did not observe A-dependence unlike very forward neutron A_N in PHENIX