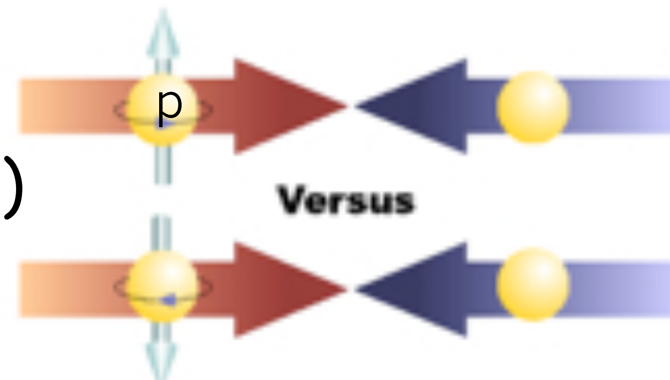
Review on recent results from RHIC polarized collider; unexpected forward neutron asymmetry

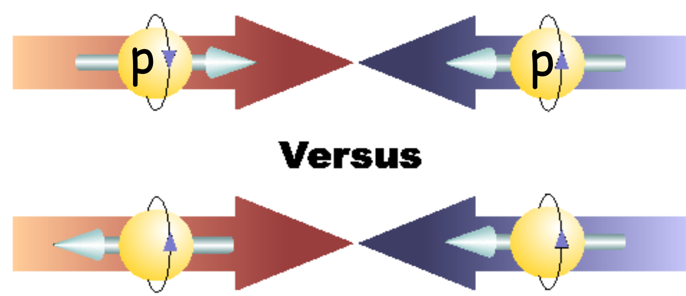
Itaru NAKAGAWA
on behalf of RHIC Spin Collaboration
RIKEN/RBRC

Outline

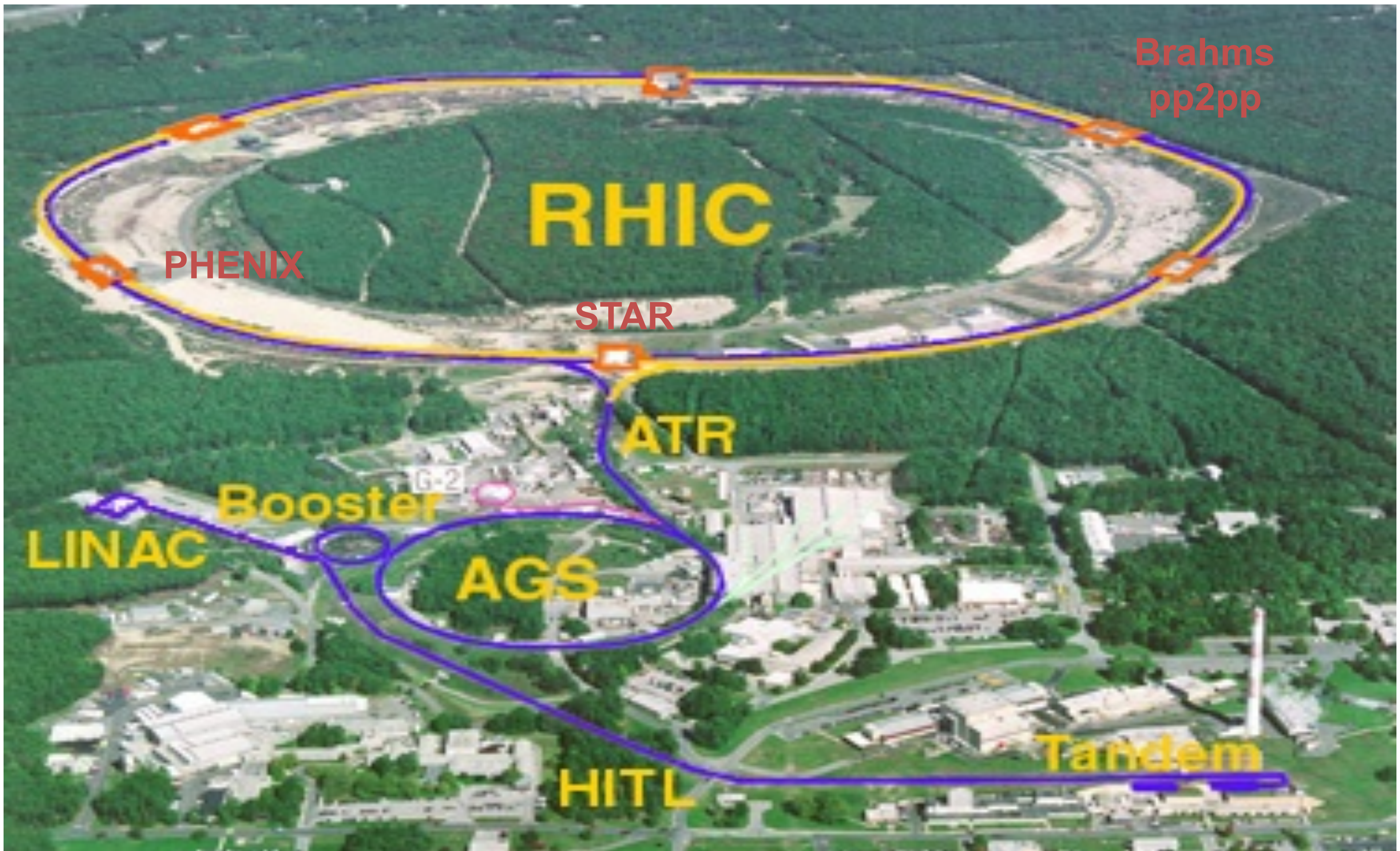
- RHIC
  - Polarized Proton
  - STAR & PHENIX
- Transverse
  - Soft Process (very forward n)
  - Hard Process (forward π)

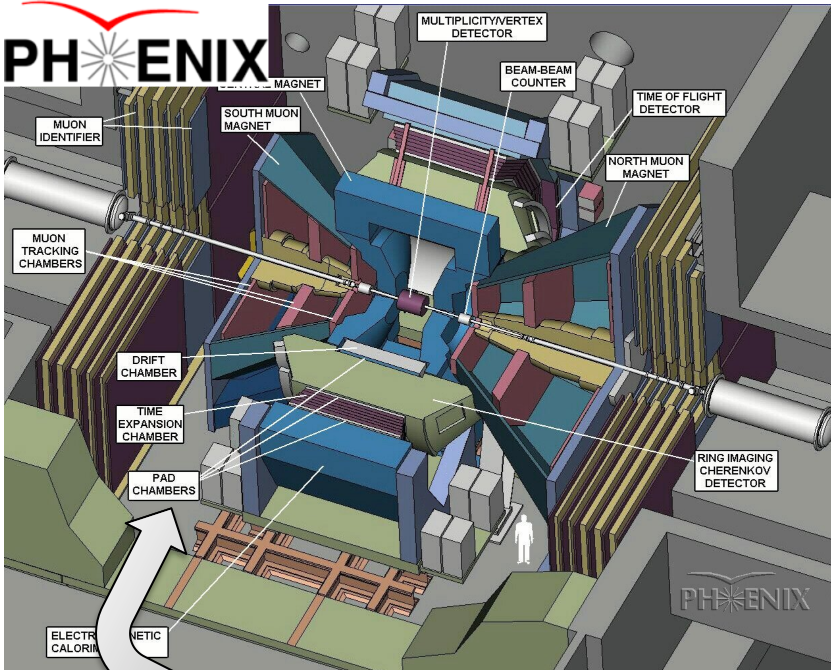


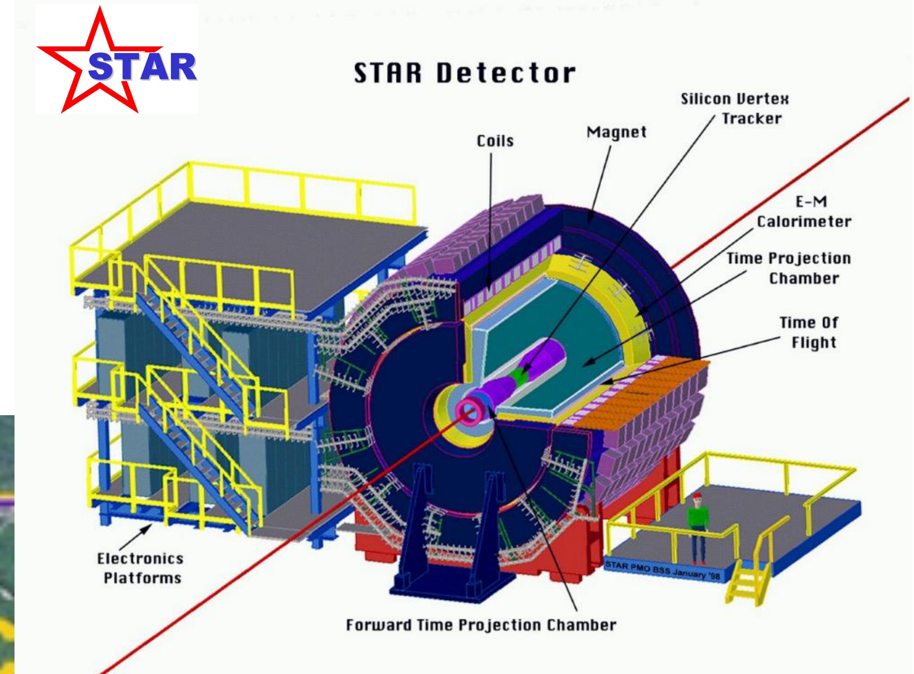
- Longitudinal
  - Gluon Spin
  - Sea Quark Spin

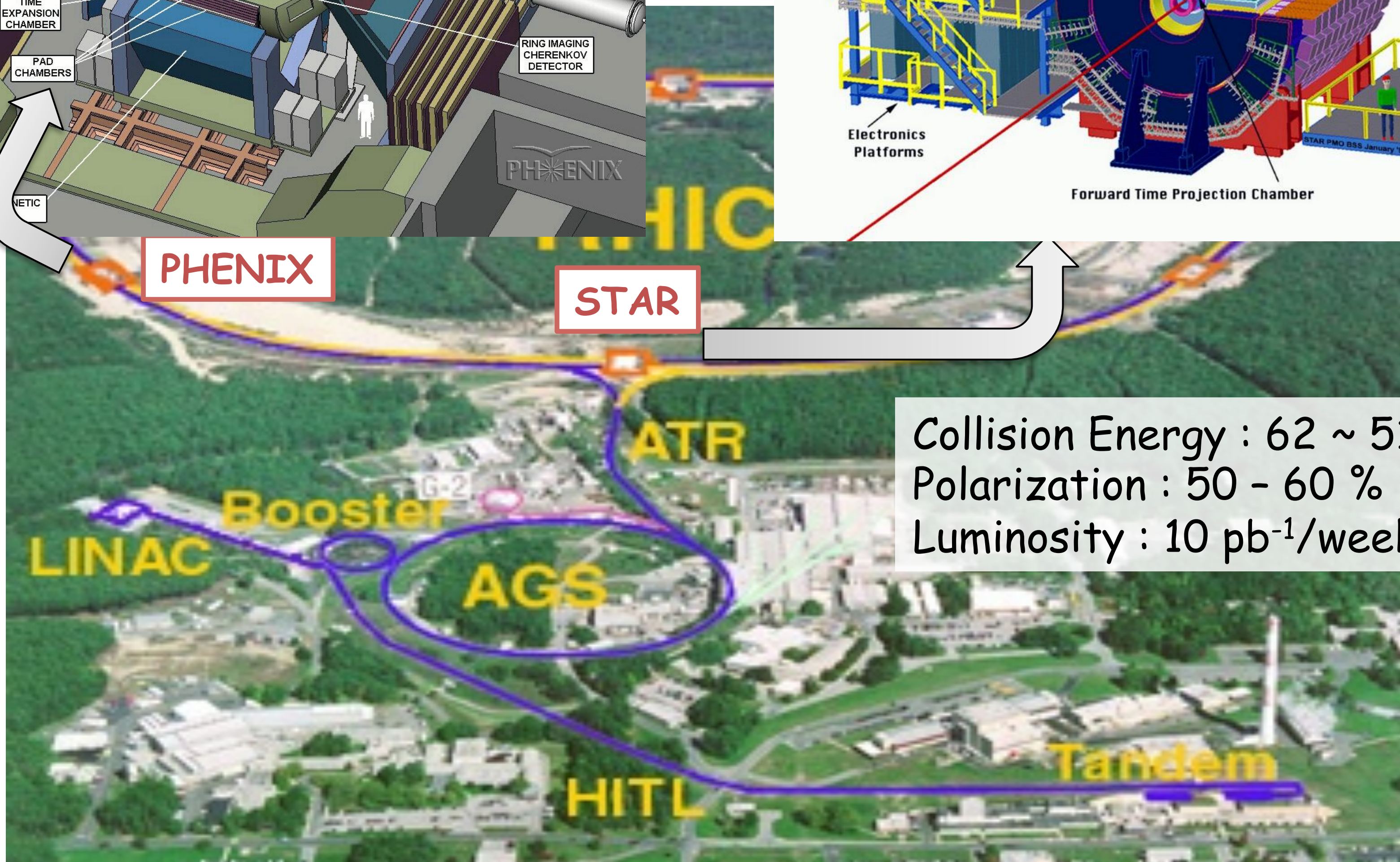


The Relativistic Heavy Ion Collider accelerator complex at Brookhaven National Laboratory

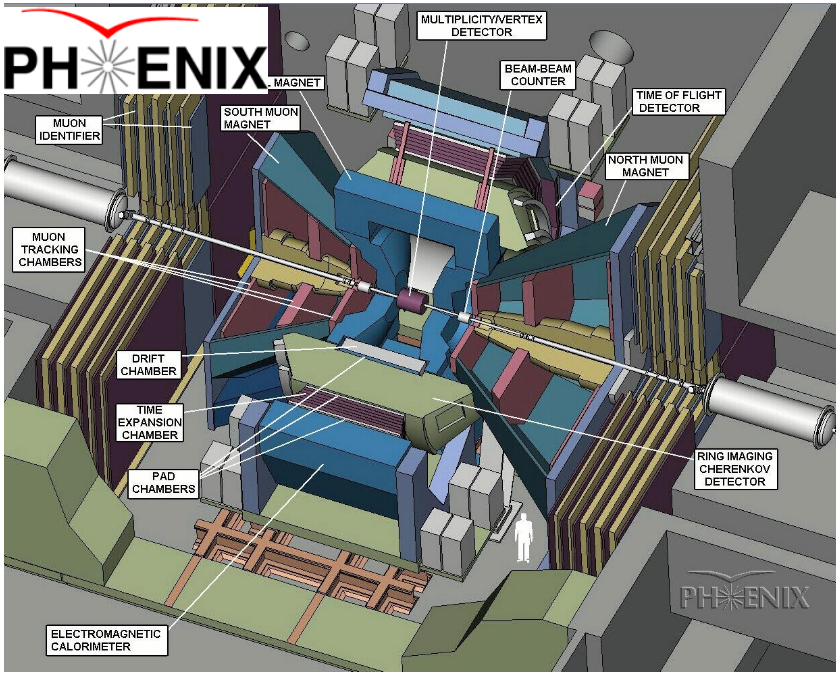


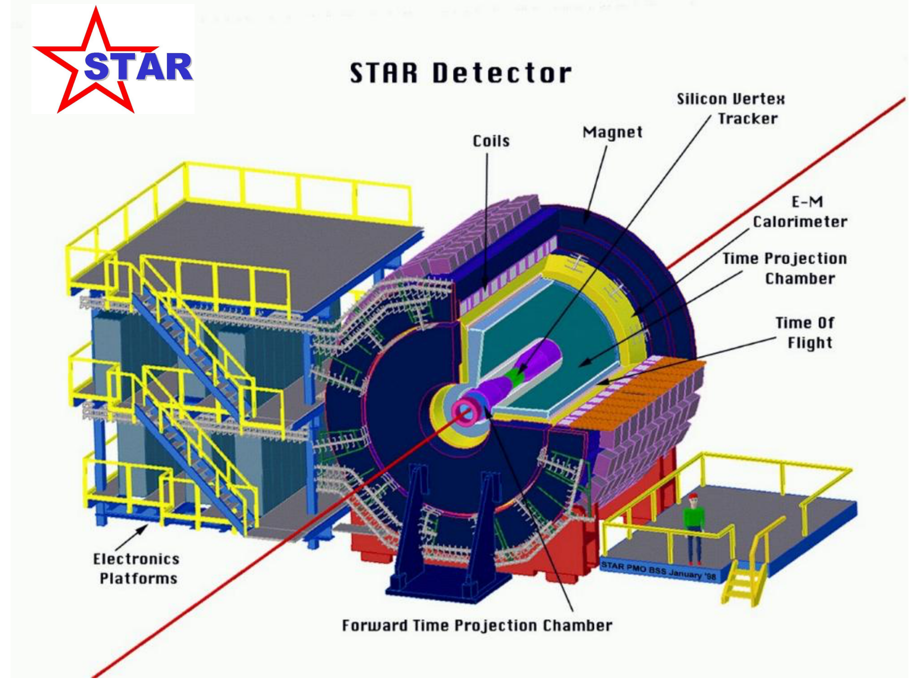




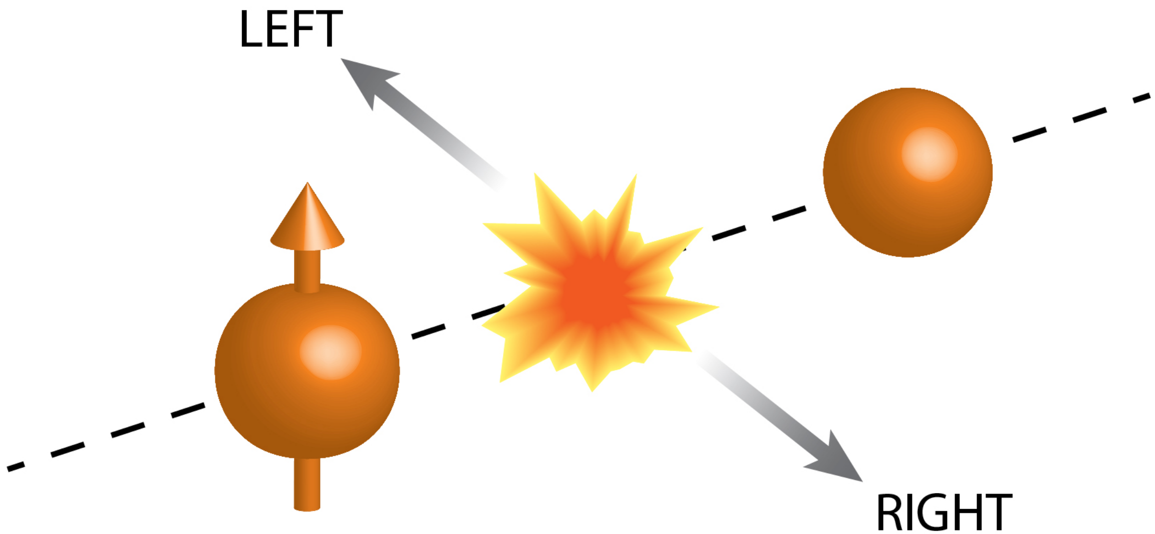


Collision Energy : 62 ~ 510 GeV
Polarization : 50 – 60 %
Luminosity : 10 pb^{-1}/week





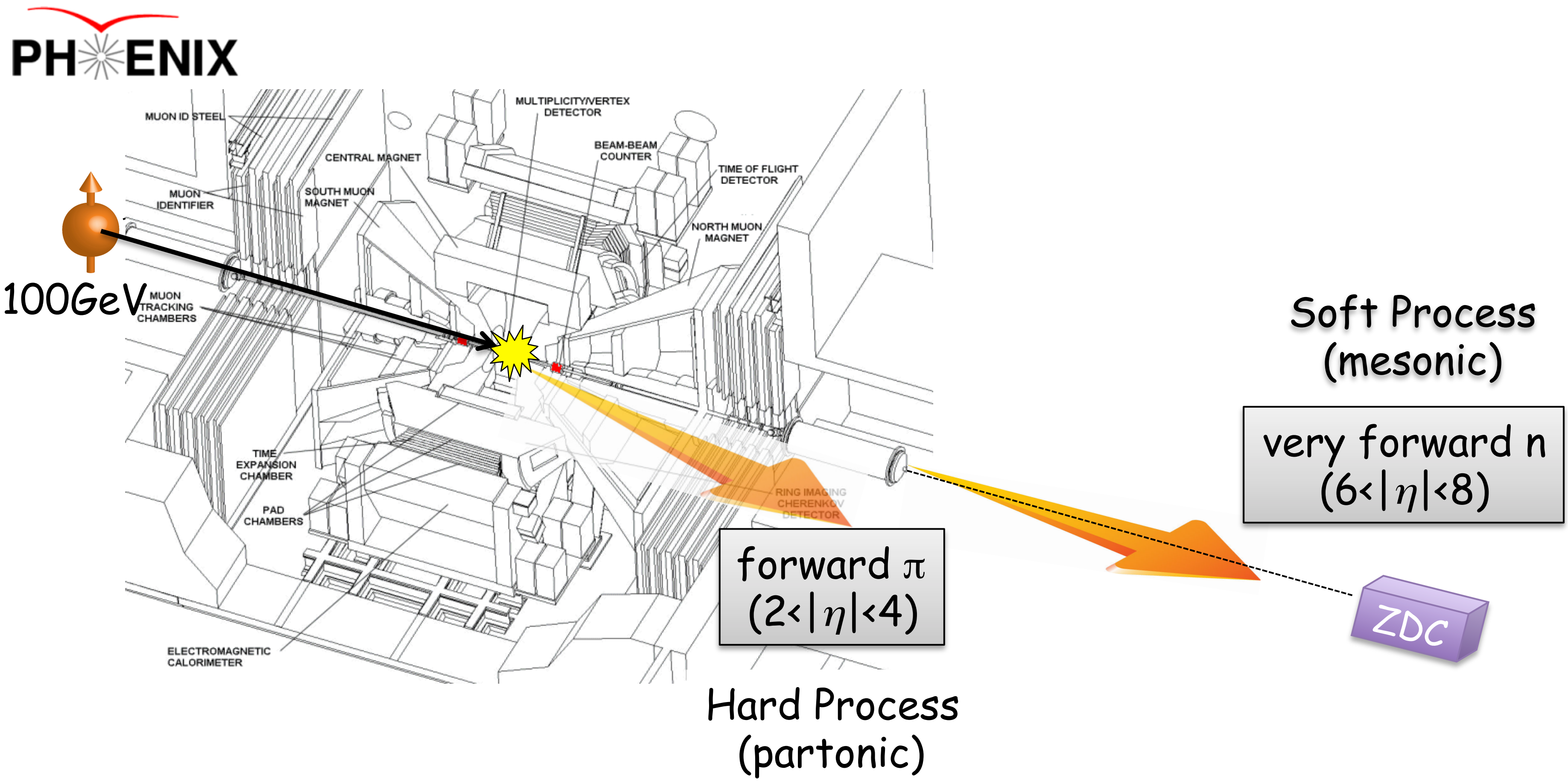
	PHENIX	STAR
Advantage	High resolution and rates	Large acceptance and low mass
Central arm	$\lvert\eta\rvert<0.35$, $\Delta\phi\sim\pi$	$\lvert\eta\rvert<1$, $\Delta\phi\sim2\pi$
Target observables	γ, π^0 and η	Jet and correlation
Forward arm	$1.2<\lvert\eta\rvert<2.4$	$2<\lvert\eta\rvert<4$
Target observables	μ	π^0 and η



Forward π^0 and very forward neutron

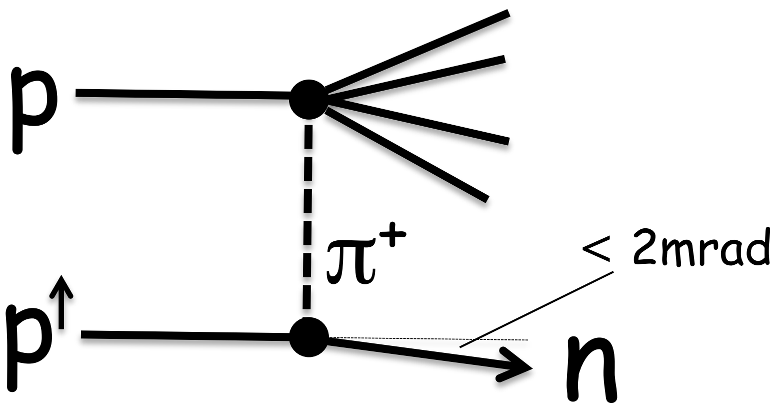
TRANSVERSE SINGLE SPIN ASYMMETRY

Transverse Asymmetry Observables



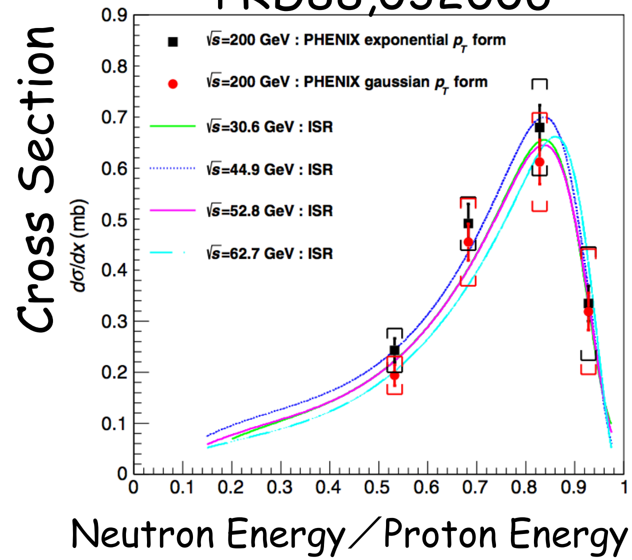
Production Mechanism of Forward Neutron

Cross Section



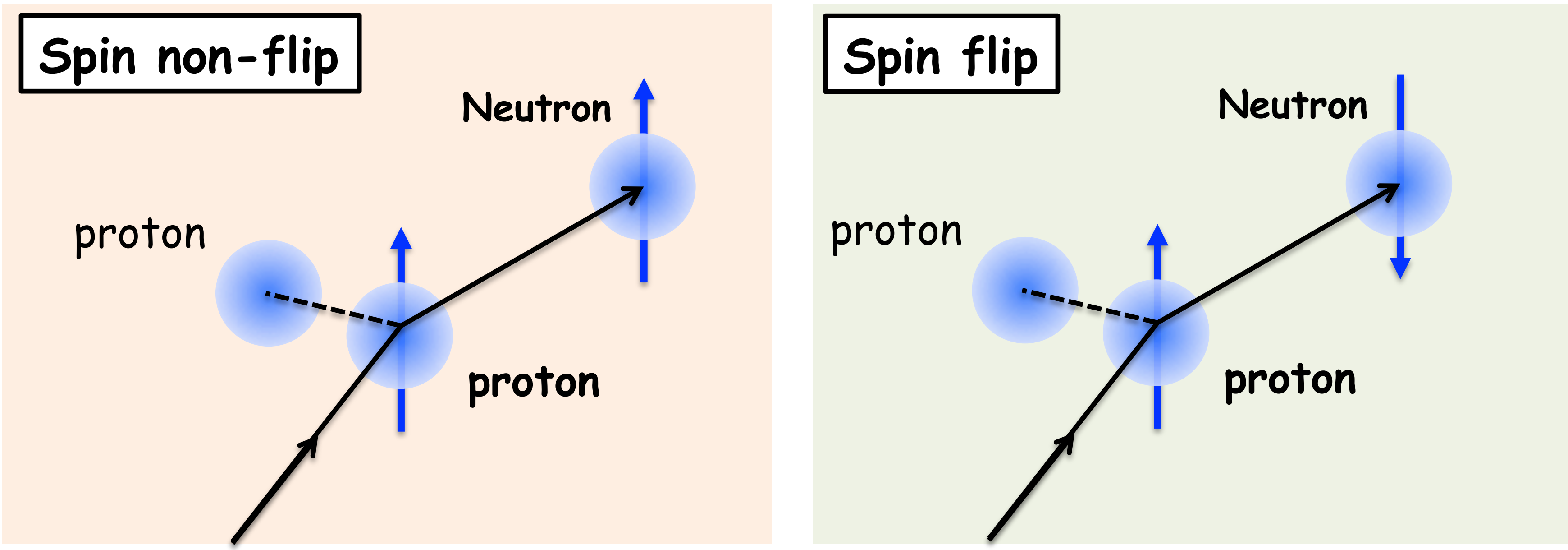
Momentum Transfer ~ 100MeV

PRD88,032006



Well Explained by
One-Pion Exchange

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

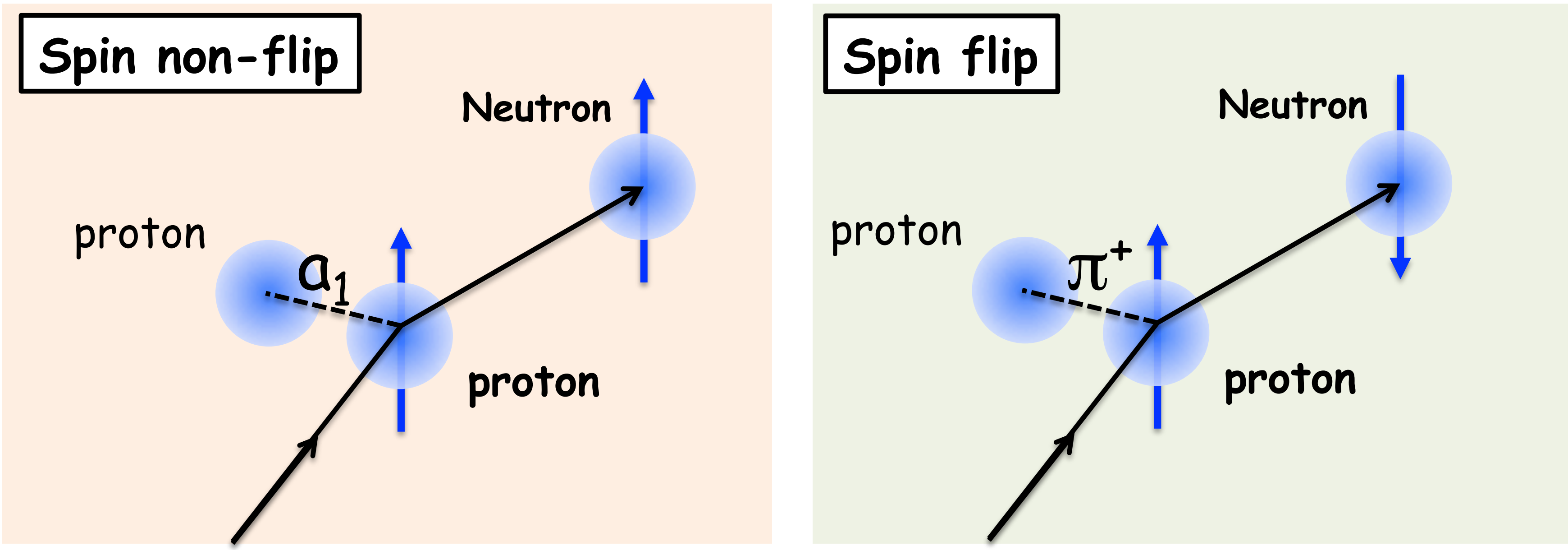


$$A_N \approx \frac{\left(\phi^*_{non-flip}\phi_{flip}\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

δ : phase shift

Unpolarized Cross Section

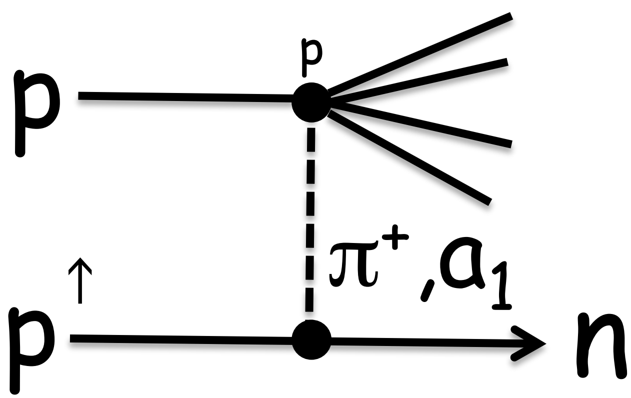
$p^{\uparrow}$+p Forward Neutron A_N



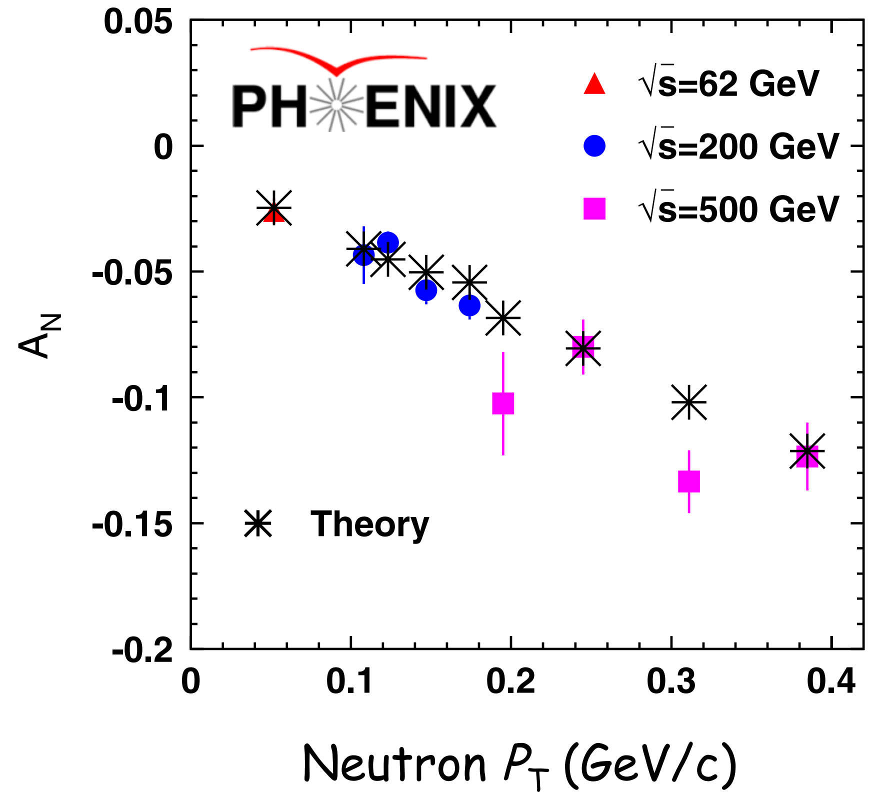
$$A_N \approx \frac{\left(\phi^*_{non-flip}\,\phi_{flip}\,\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

δ : phase shift

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



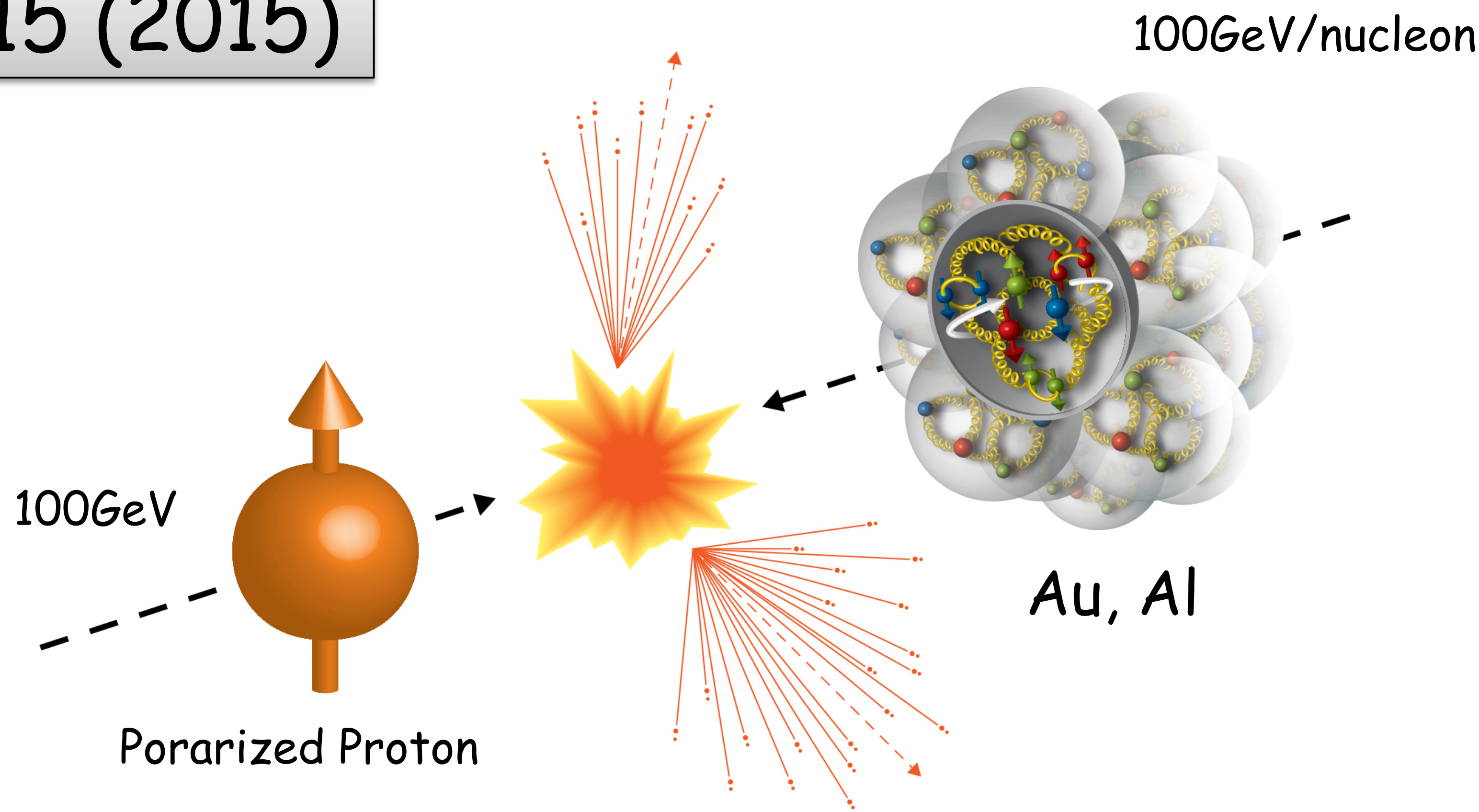
PRD84,114012(2011)



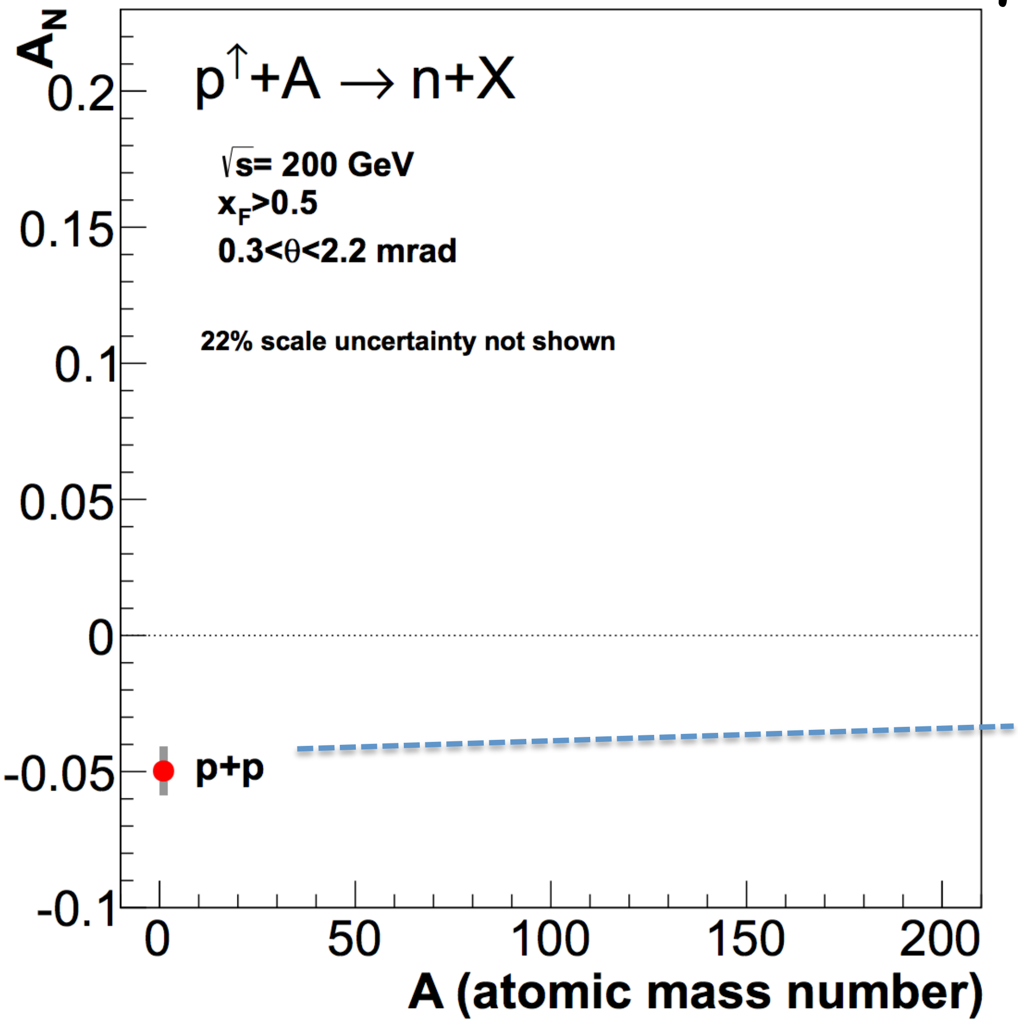
Data are well reproduced by the interference between π and a_1 Reggeon

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

Run15 (2015)

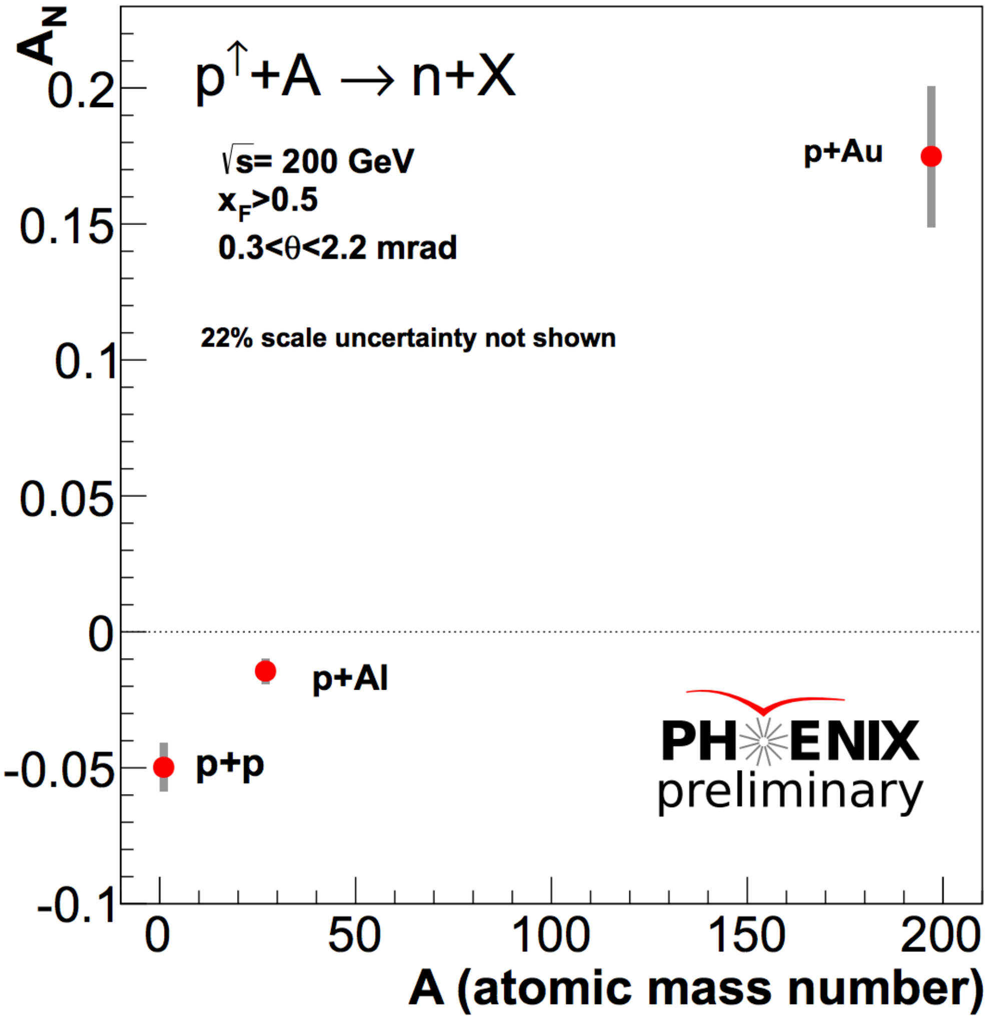


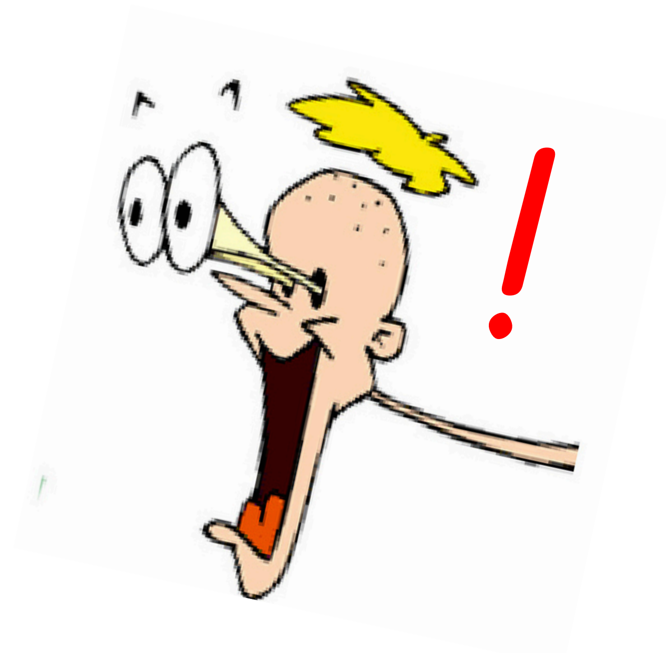
A-Dependent A_N (inclusive)



Present Frame Work

A-Dependent A_N (inclusive)

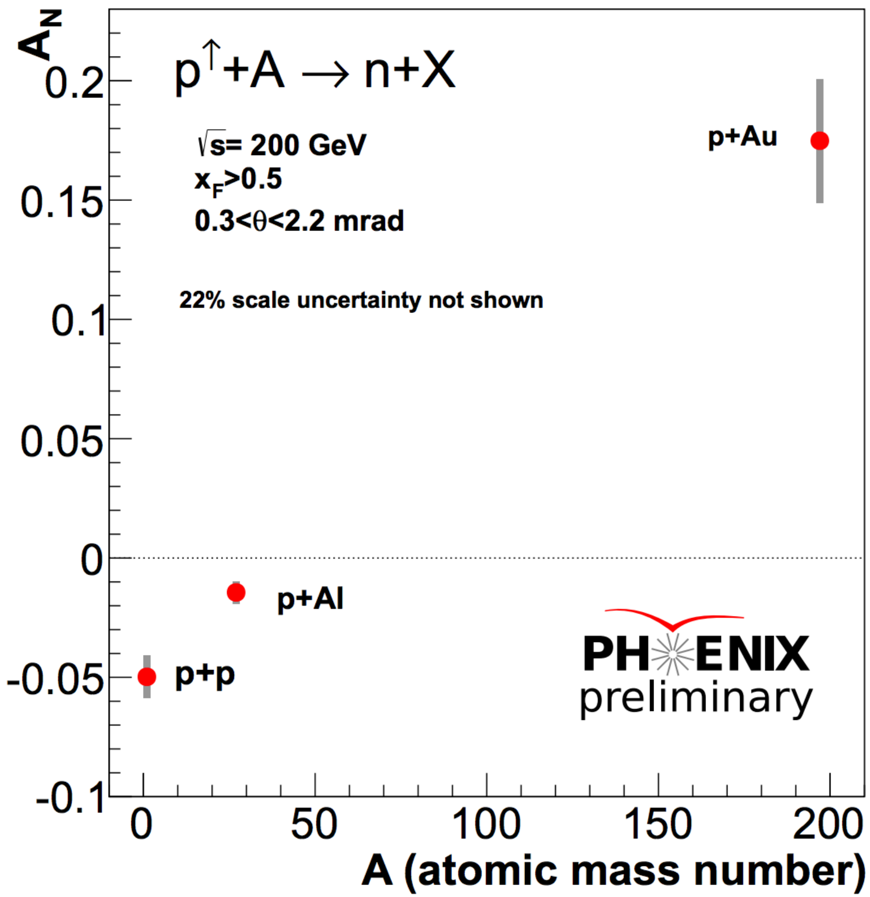




Absolutely Unexpected!

Analysis by
Minjung Kim (SNU/RIKEN)

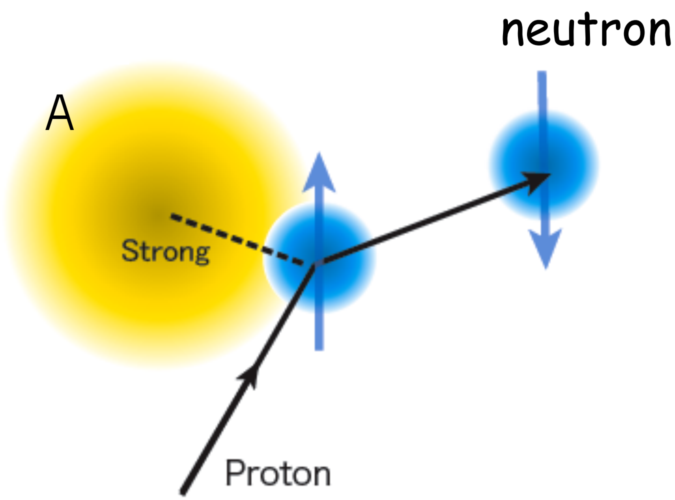
What is going on ?

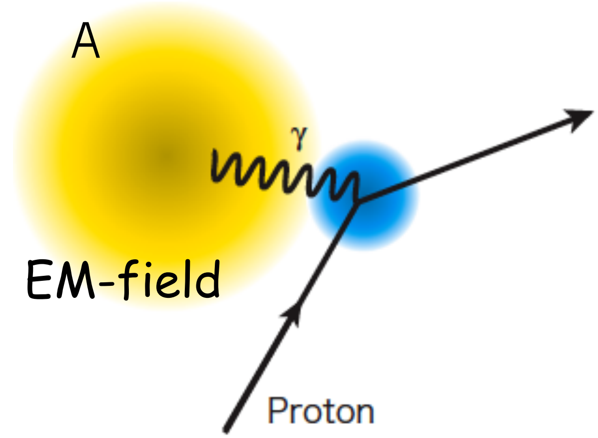


	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

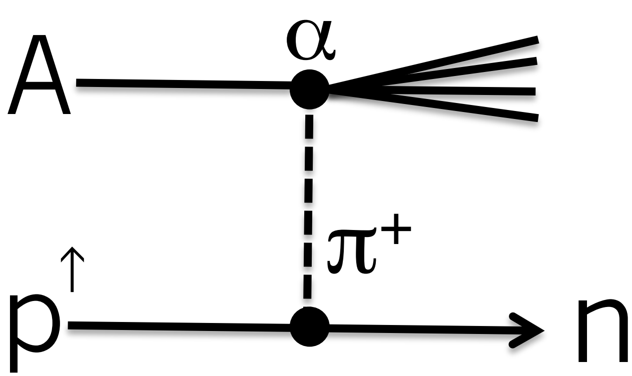
- Isospin Symmetry
- Surface Structure of Nucleus
- QED Process
- Gluon Saturation
- Else…

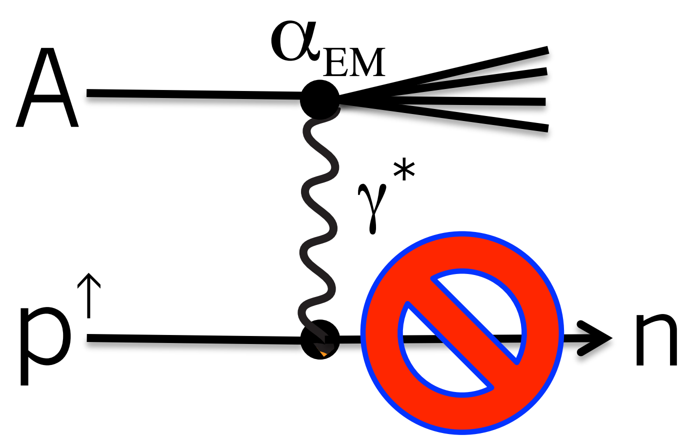
Primakoff Effect
Electro-Magnetic



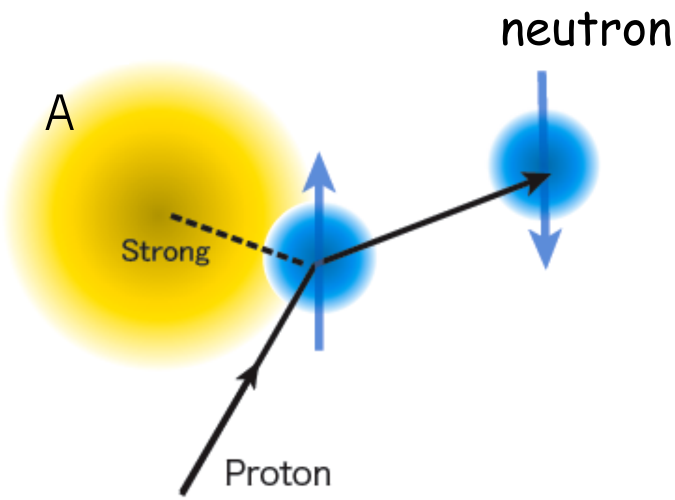


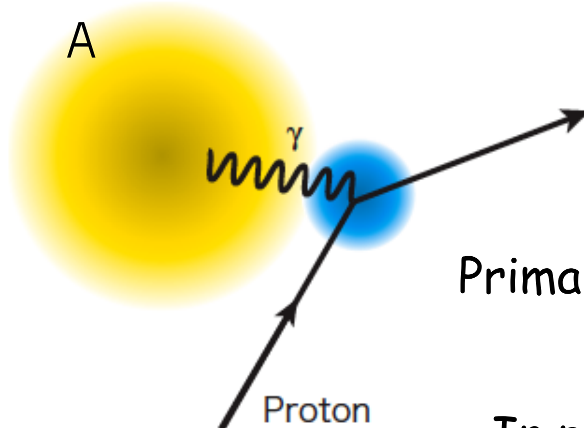
$t \rightarrow 0$





Primakoff Effect (Electro-Magnetic)



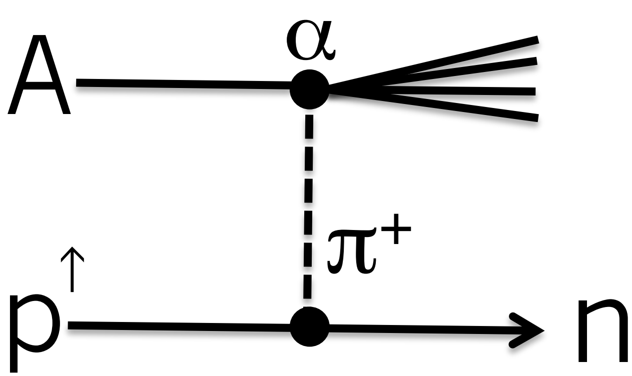


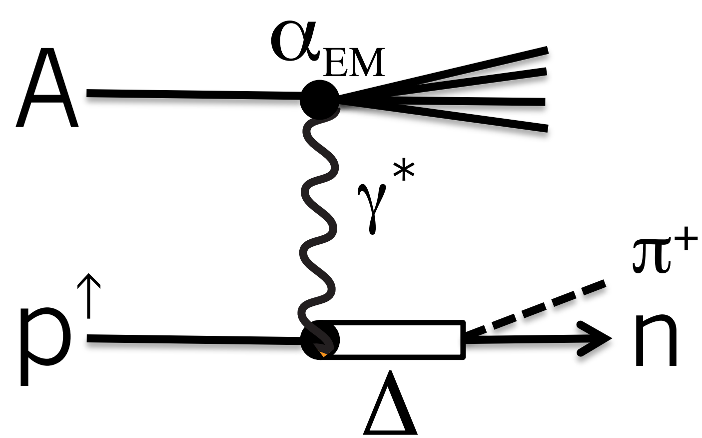
Primakoff

In pAu case

$t \to 0$

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





Full Description of A_N

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

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

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

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

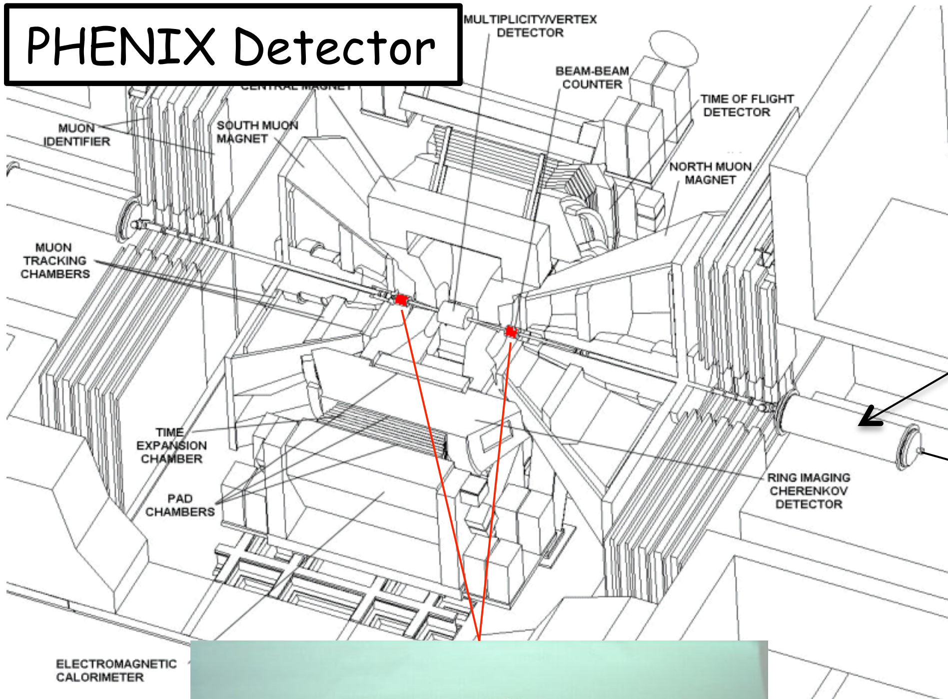
$$A_N \propto 2\,\mathrm{Im}\left(\phi^{had}_{non-flip} + \phi^{EM}_{non-flip}\right)\left(\phi^{had*}_{flip} + \phi^{EM*}_{flip}\right)$$

$$= 2\left(\phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \underbrace{\phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4}_{\to 0 \text{ (For pp)}}\right)$$

large ← $-t$ → small

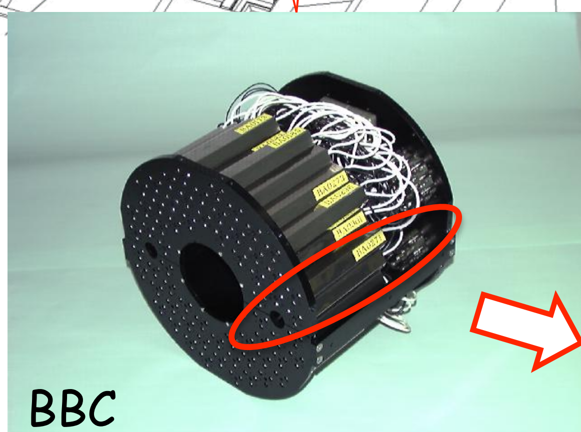
Beam-Beam Counter

PHENIX Detector



Dipole Bending Magnet

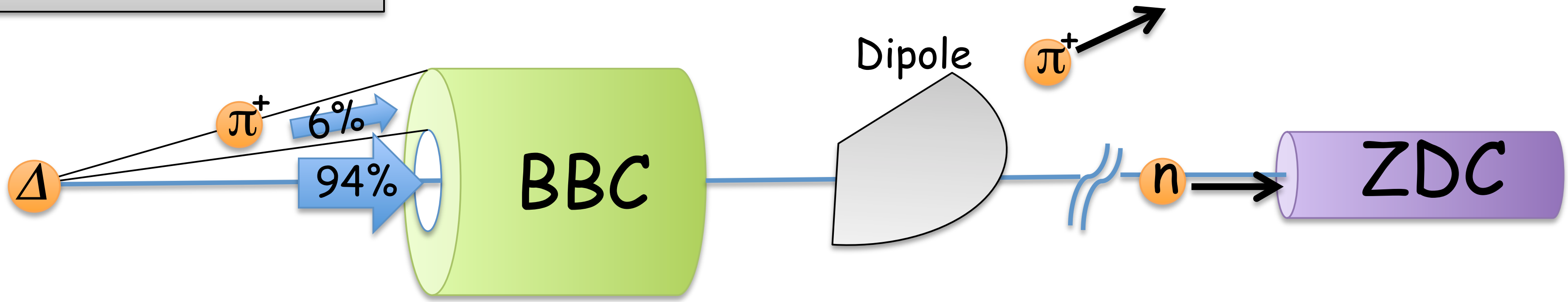
ZDC



Quartz Cherenkov radiator

Can we identify Primakoff events?

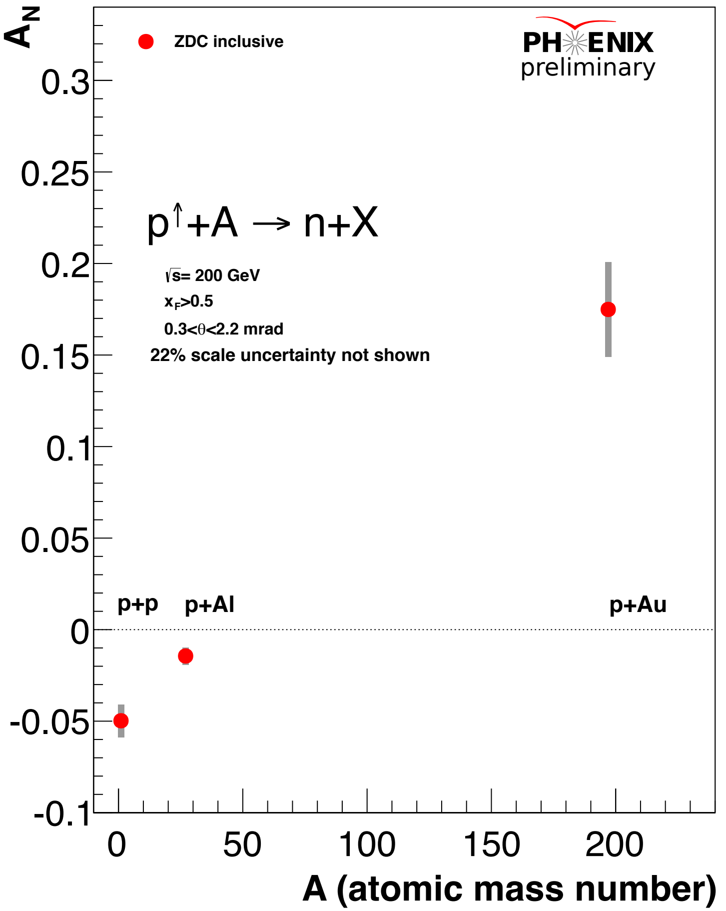
Semi-Inclusive



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

BBC	tag	veto
Primakoff	Small	Large

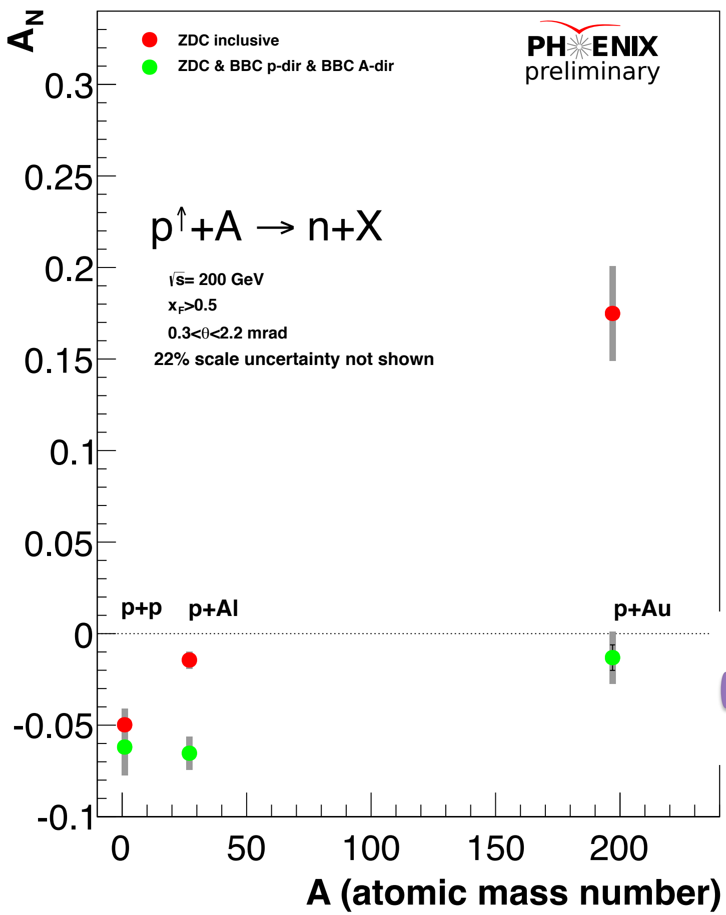
BBC Tagging and Vetoing

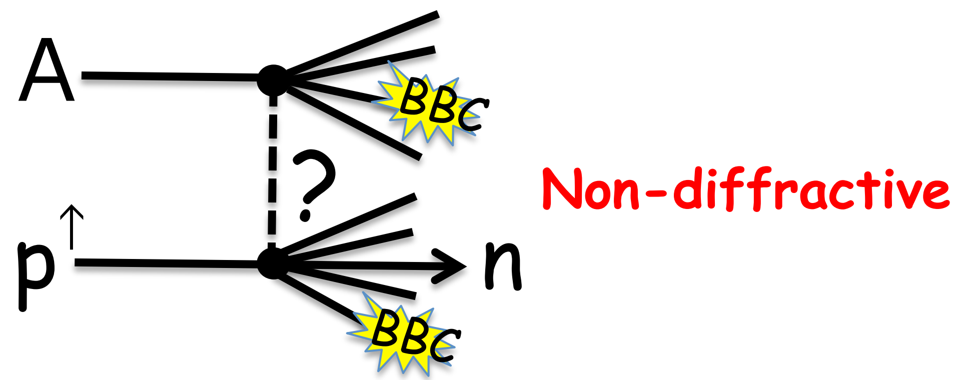


Inclusive

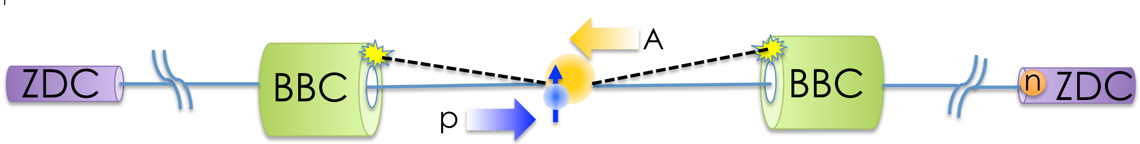
$$A_N \sim \boxed{had * had + had * EM + EM * had + EM * EM}$$

BBC Tagging and Vetoing



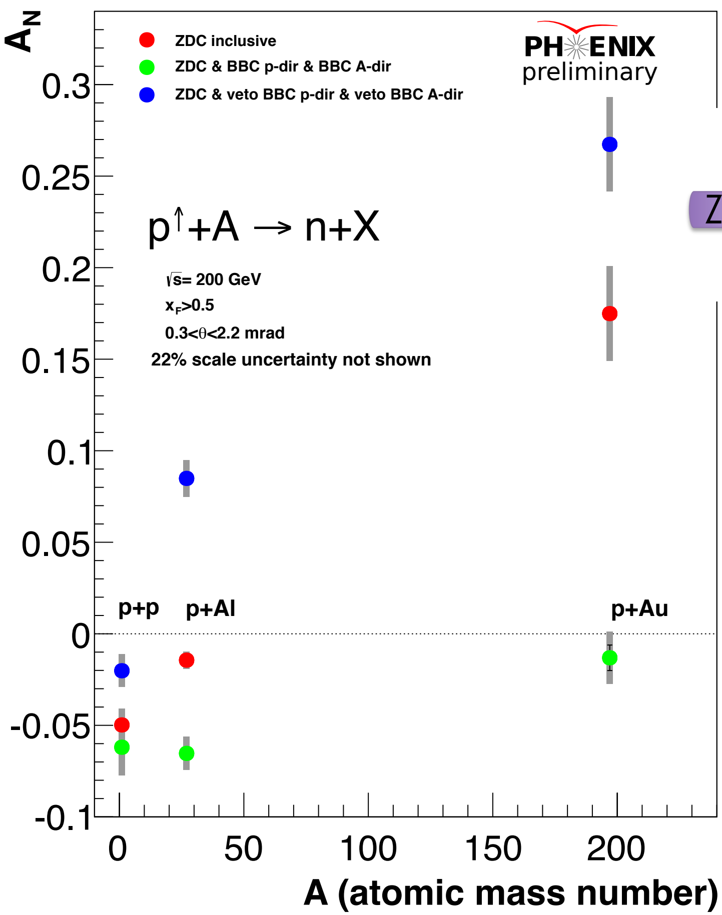


BBC Tagging

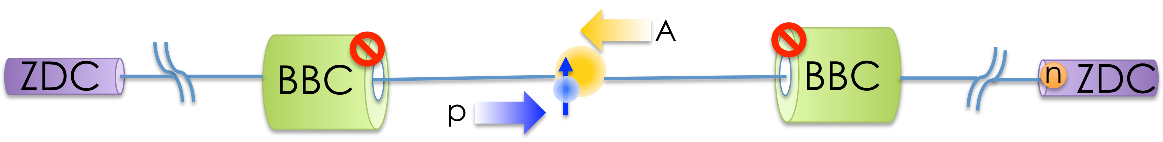


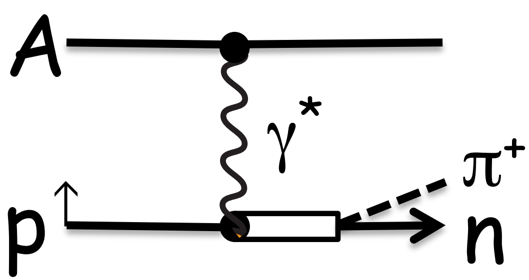
$$A_N \sim \boxed{had * had} + \overbrace{had * EM + EM * had + EM * EM}^{\text{EM surpressed}}$$

BBC Tagging and Vetoing



BBC Vetoing

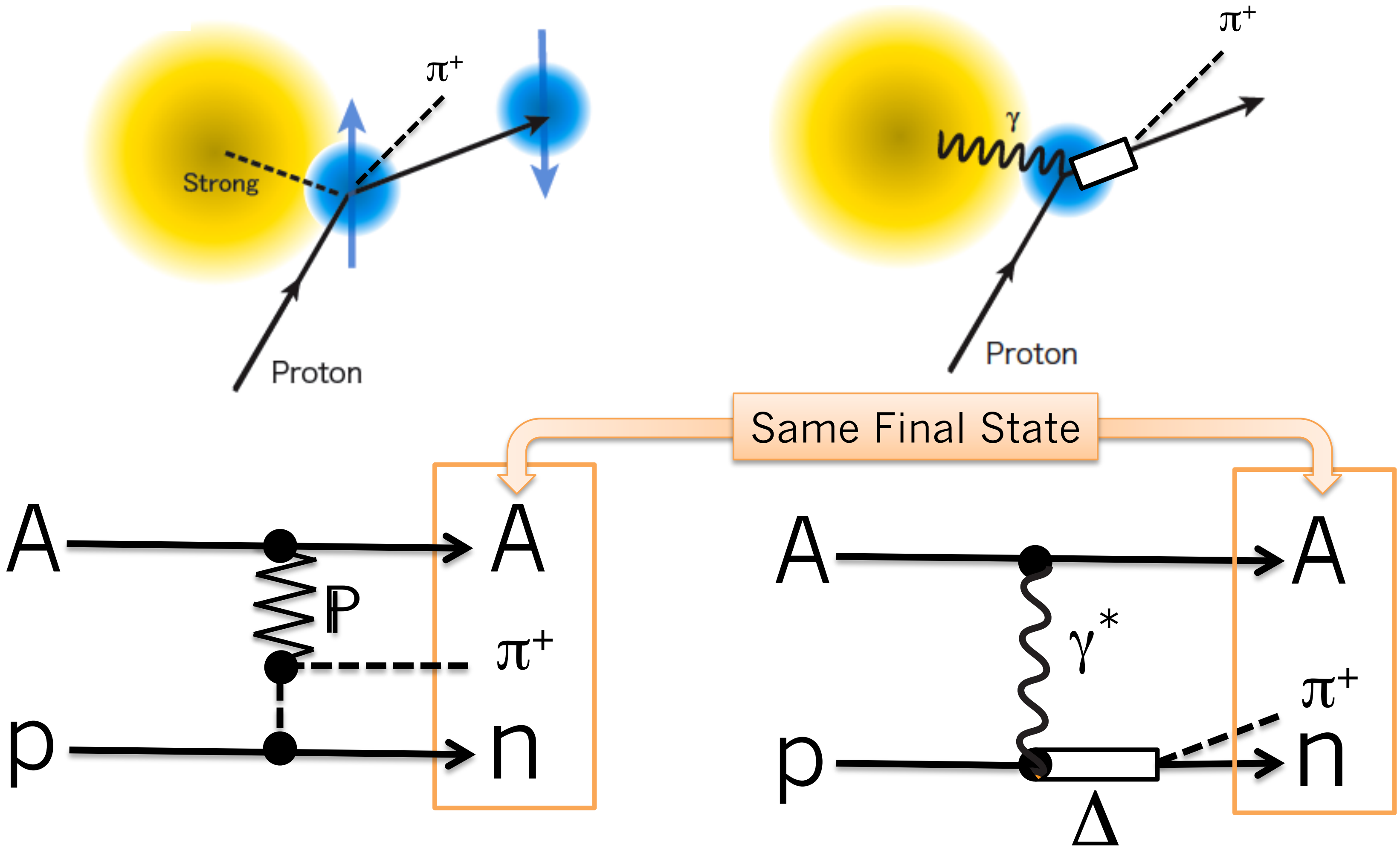




Diffractive

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

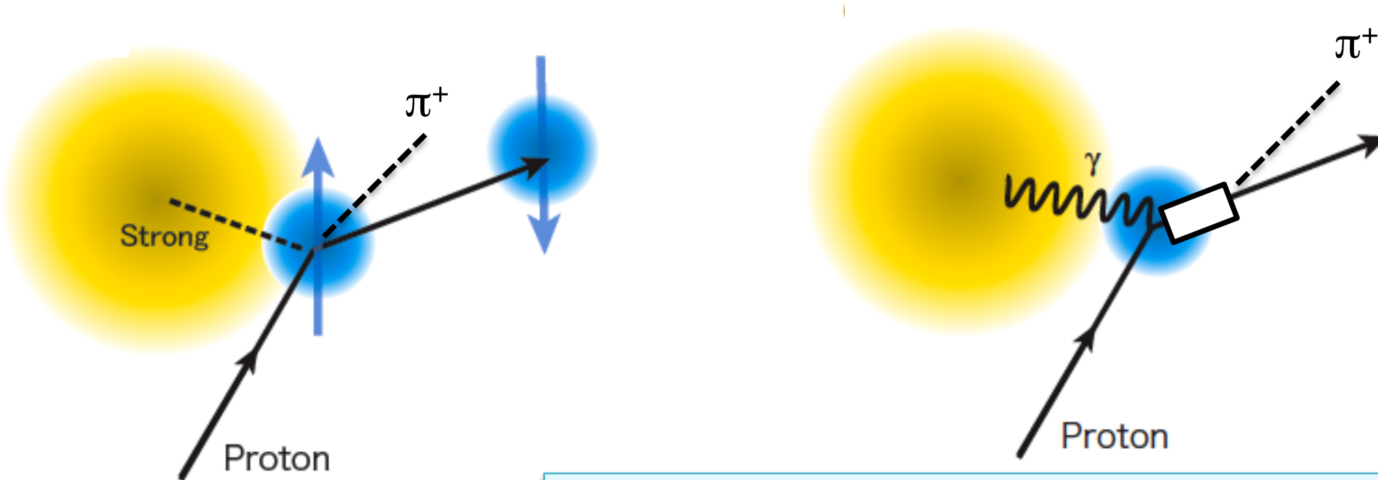
Coulomb-Nuclear Interference in Forward Neutron Production

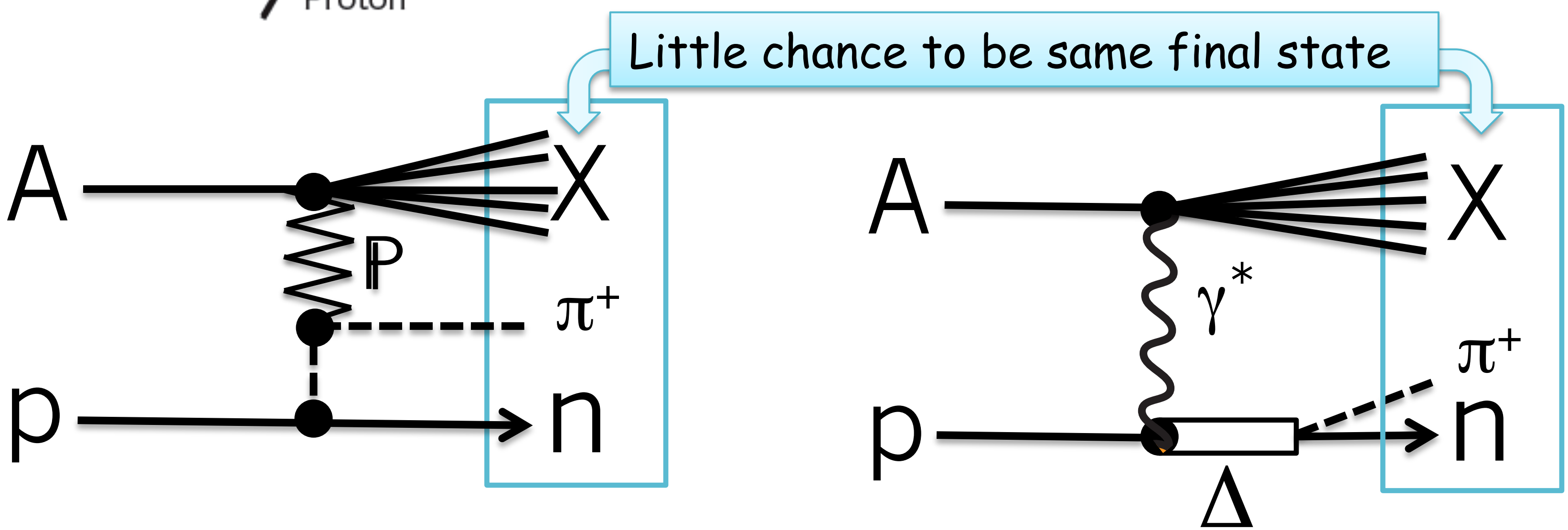


$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Diffractive Process Required?

Non-Diffractive Events

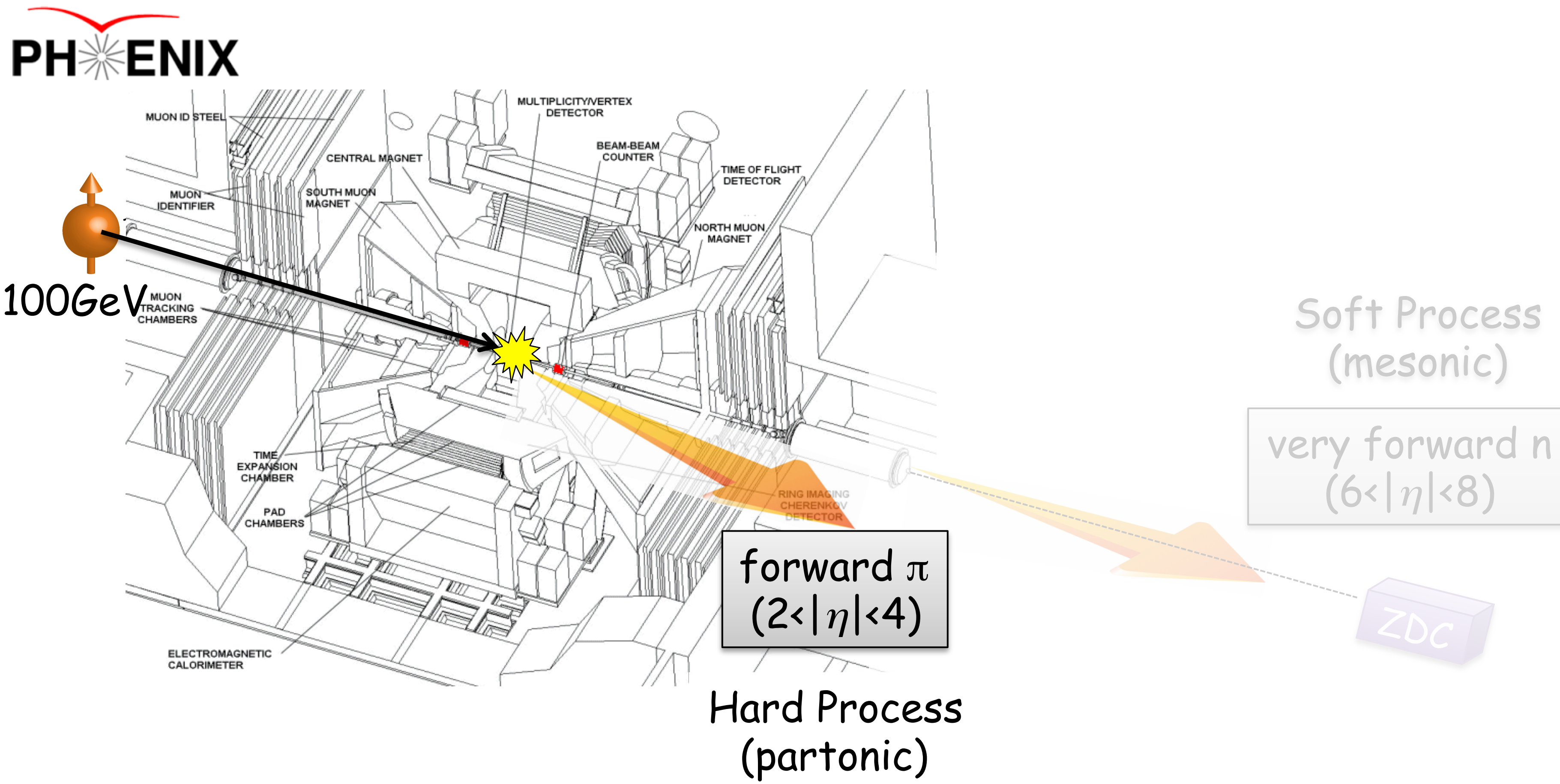




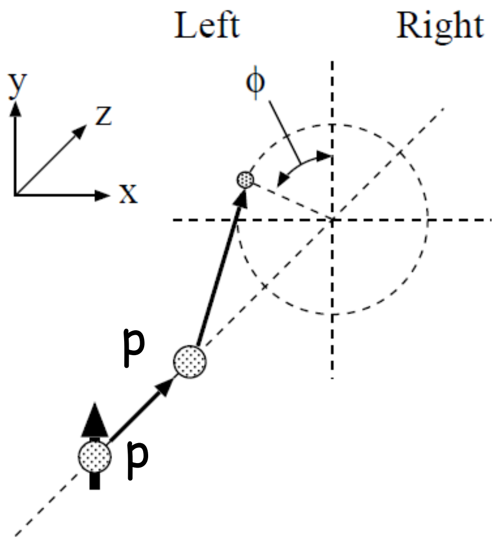
$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Suppressed?

Transverse Asymmetry Observables



Single Transverse Spin Asymmetries



$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

Theory Expectation:
Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689-1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

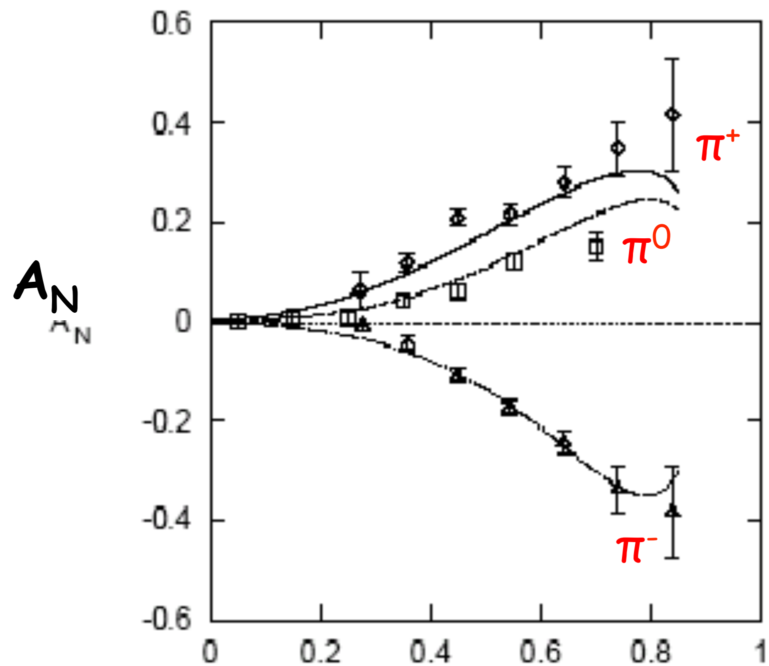
A_N O(10^{-4}) Theory

Experiment:
(E704, Fermi National Laboratory, 1991)

$$pp^\uparrow \rightarrow \pi + X$$
$$\sqrt{s} = 20\,\text{GeV}$$

A_N O(10^{-1}) Measured

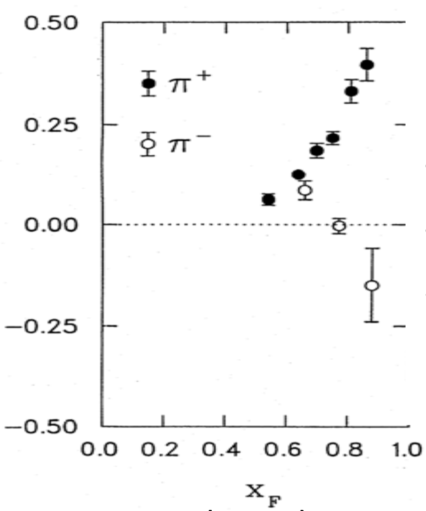
E704: Left-right asymmetries



$$x_F = \frac{2p_L}{\sqrt{s}}$$

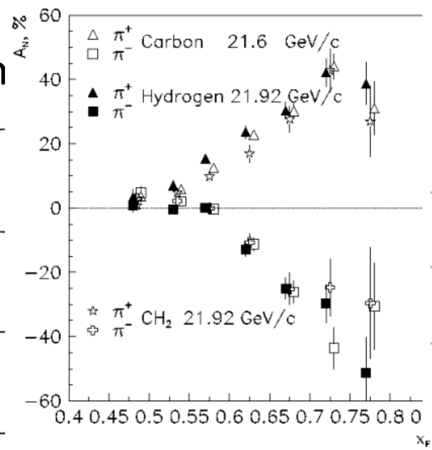
Energy Dependence of A_N

ZGS 12 GeV bean



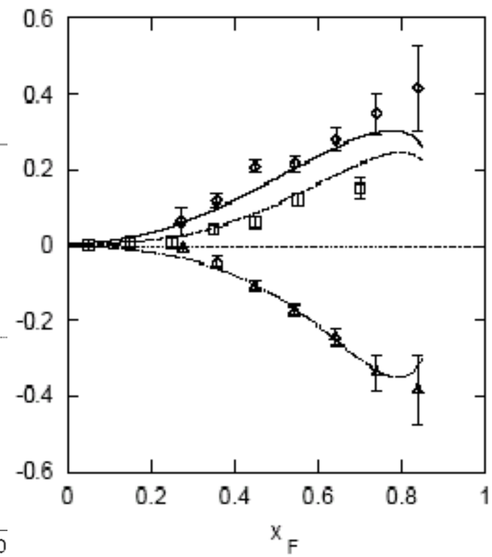
PRL36, 929 (1976)

AGS 22 GeV beam



PRD65, 092008 (2002)

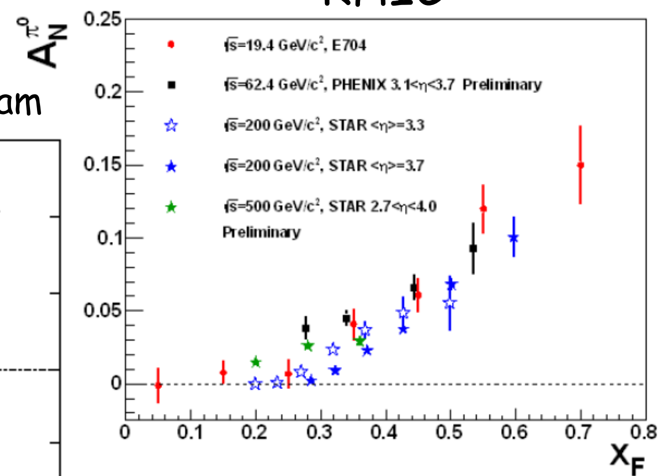
E704 200GeV beam



PLB261, 201 (1991)

PLB264, 462 (1991)

RHIC

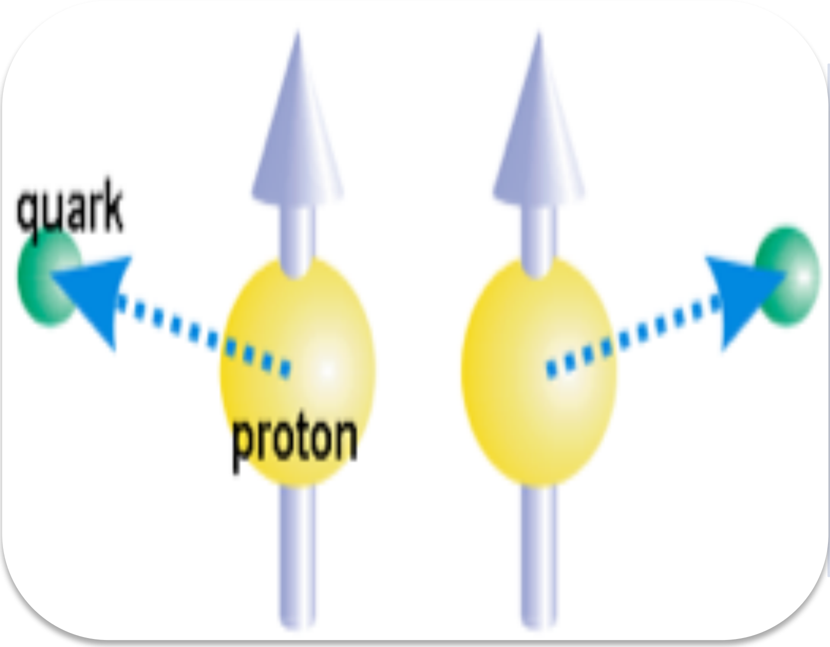


Asymmetry still persists even in high energy!

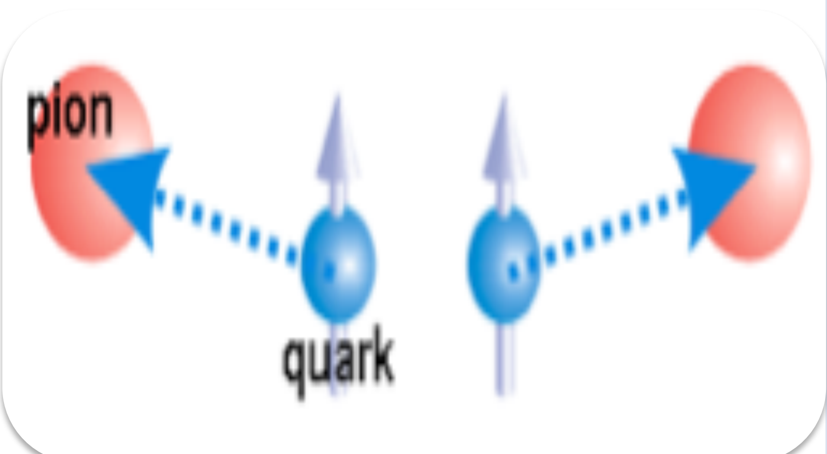
Non-perturbative

Perturbative

What Could be the Cause?

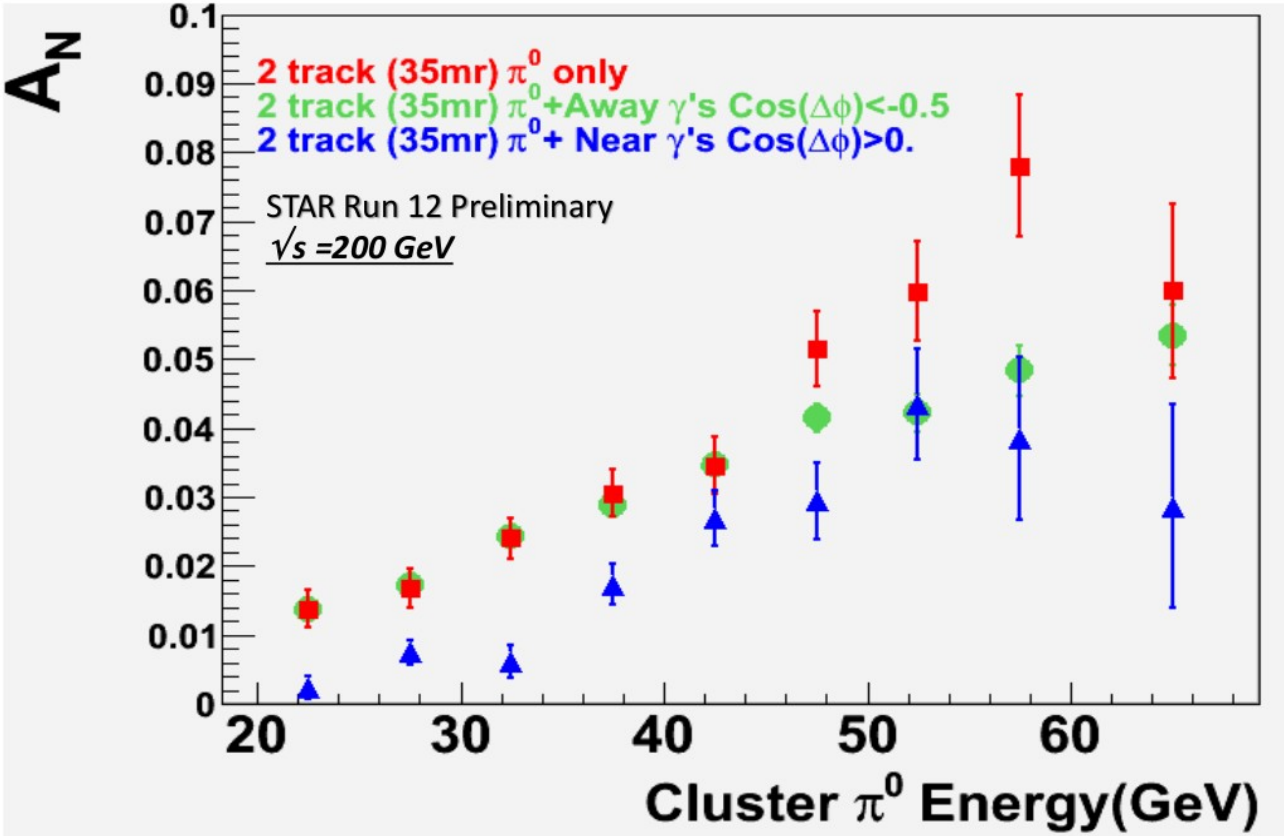


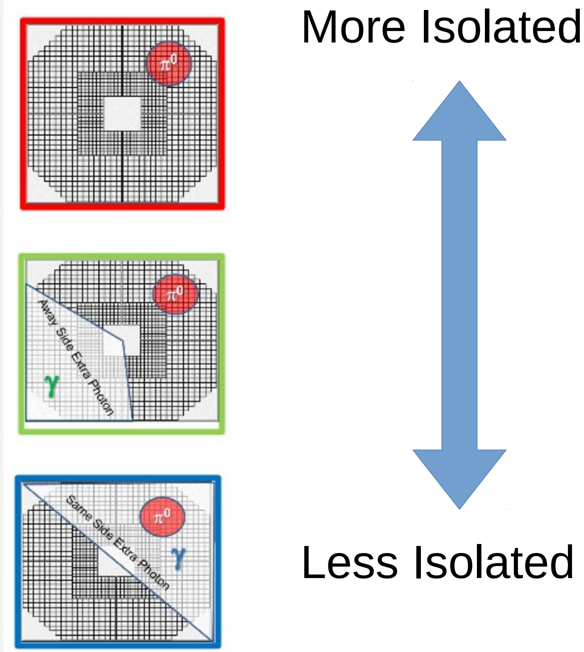
- **Sivers Effect +higher twist**
  - transverse-momentum dependence of partons inside the transversely-polarized nucleon



- **Collins Effect +higher twist**
  - correlation between transversely-polarized nucleon and transversely polarized partons inside
  - Collins fragmentation function

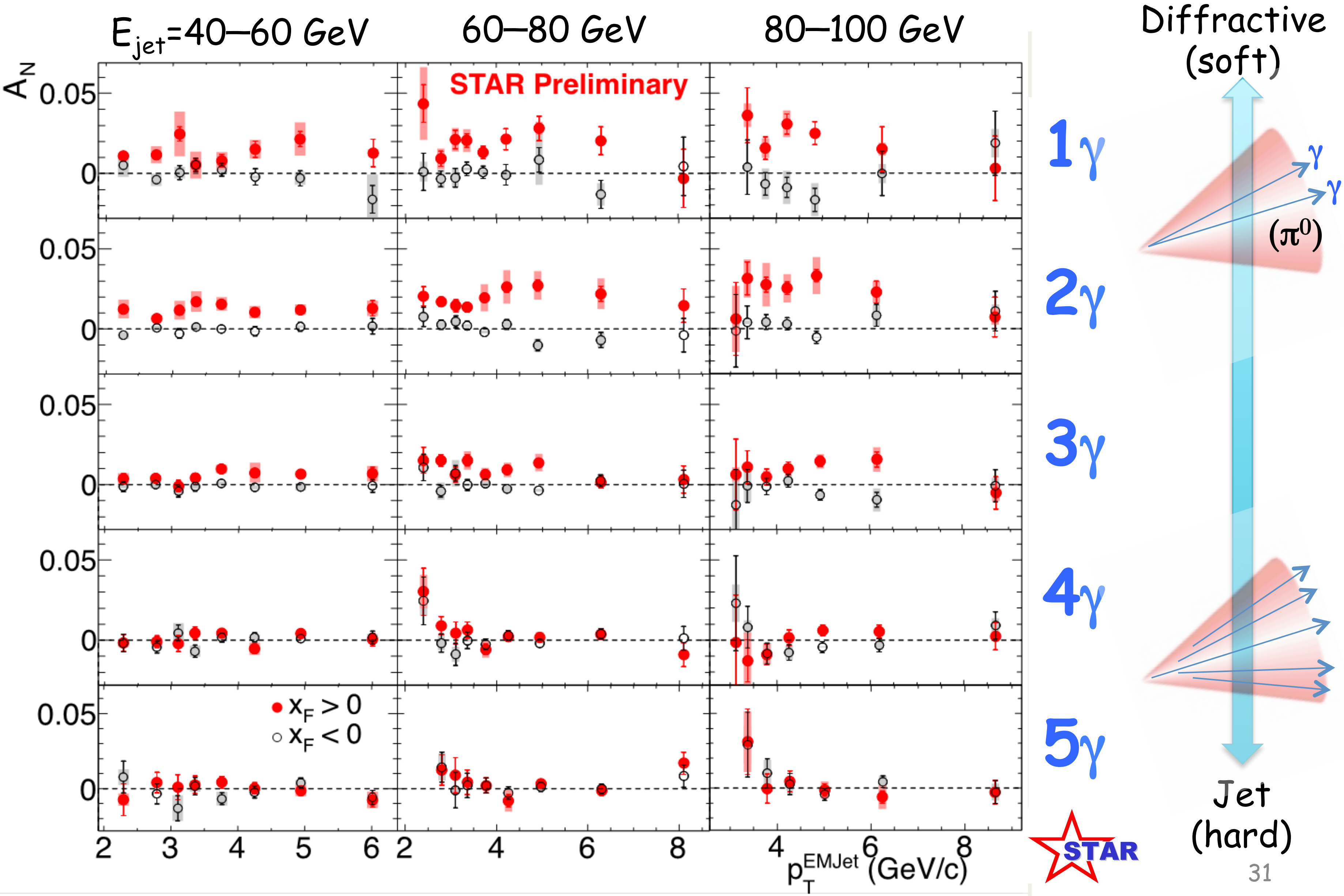
Activities around π^0



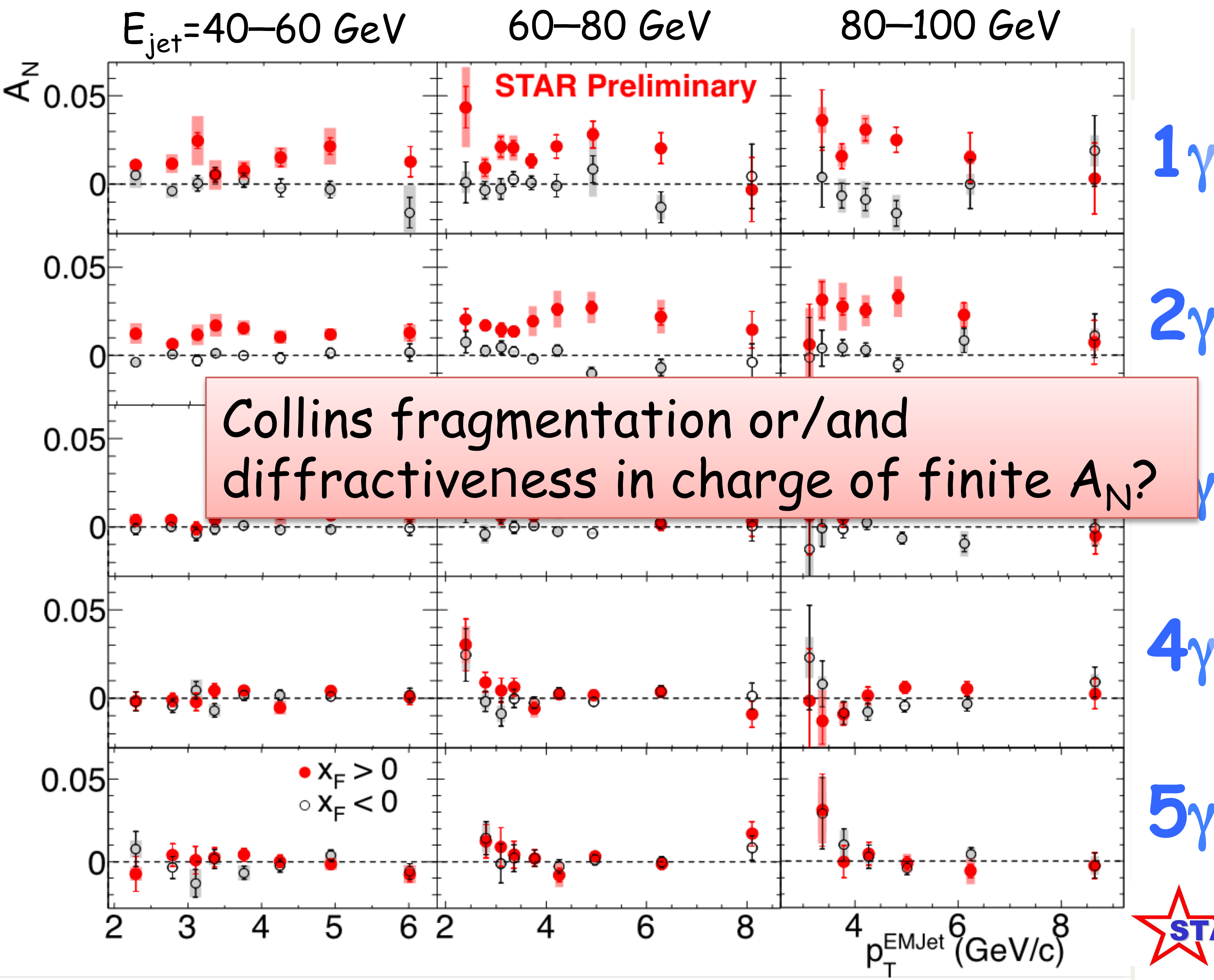


The more isolated π^0, the larger the A_N.
Smaller A_N for jet-like events?

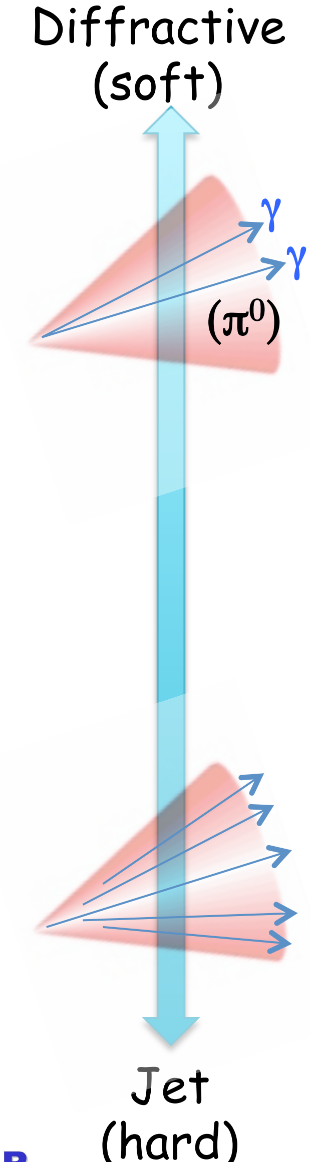
Event Topology: Forward TSSAs



Event Topology: Forward TSSAs



Collins fragmentation or/and diffractiveness in charge of finite A_N?

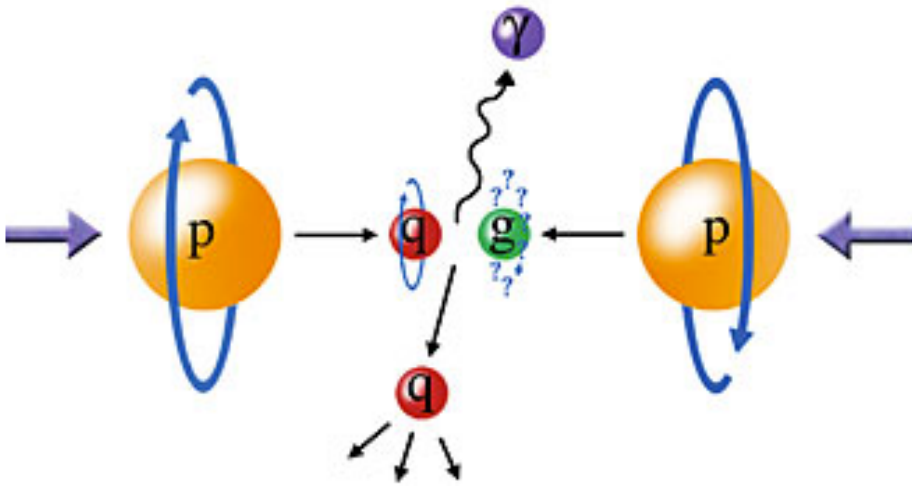


Transverse Summary

- Very drastic and unexpected A-dependence was observed in very forward neutron A_N.
- According to MC study, EM process likely to be in charge of the large positive asymmetry in large A.
- A-dependence in strong interaction is likely to be moderate as existing model predicts.

- Forward π has been studied in pQCD framework, but recent data indicate possibility of soft process may be (partially) playing a role.

So far, "diffractiveness" can be the common key word of both asymmetries.

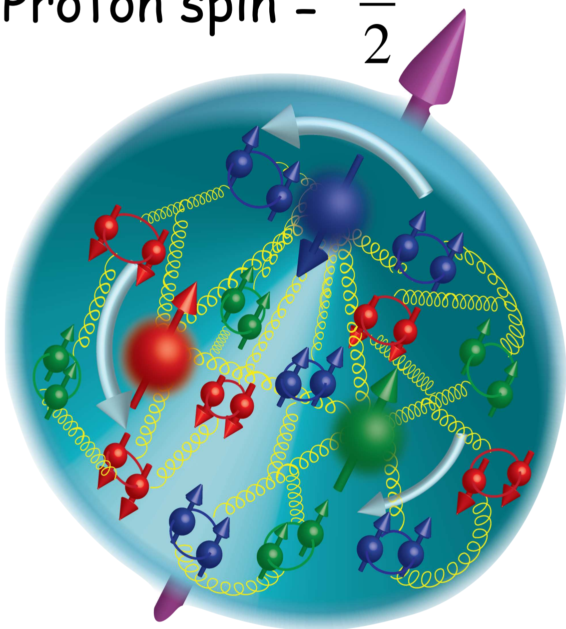


$\Delta G, \Delta \overline{q}$ Polarization

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% $\Delta G \downarrow$? $L_z \downarrow$??

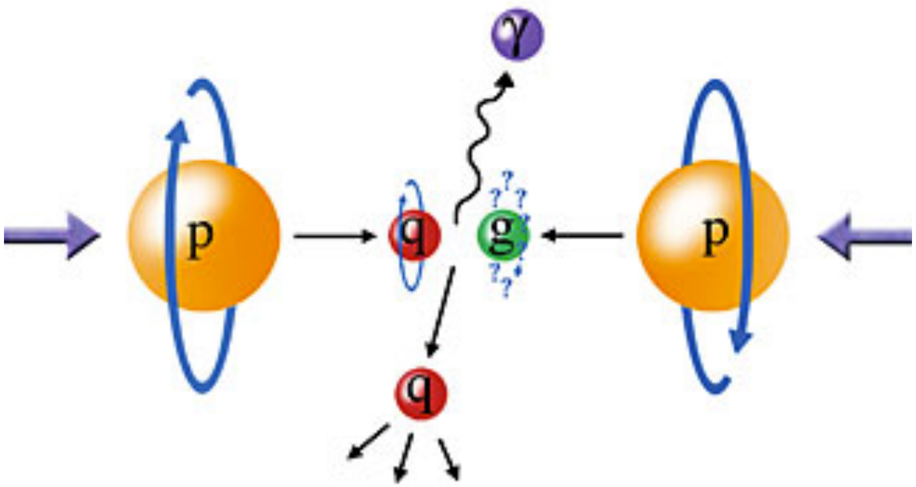
Quark Spin $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \boxed{\Delta\bar{u} + \Delta\bar{d}} + \Delta\bar{s})\, dx$

Sea quark

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

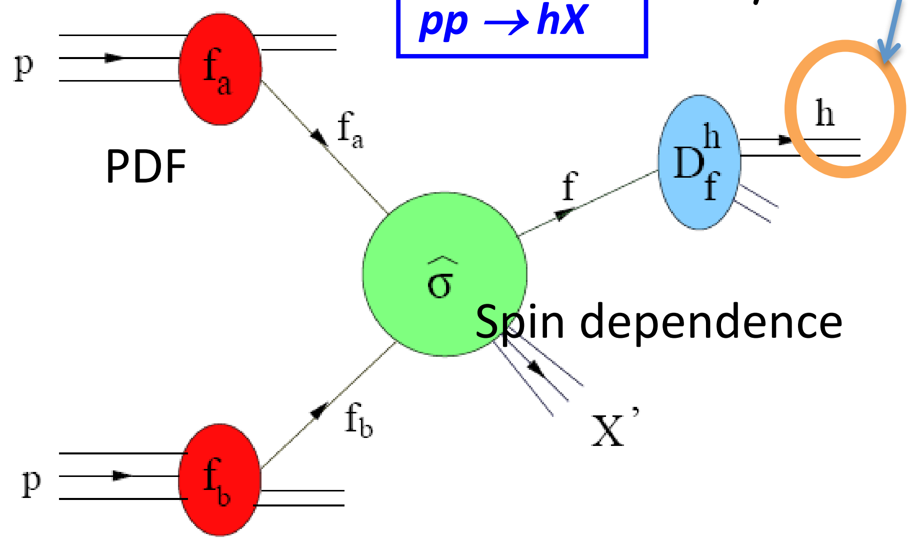
Longitudinal Spin Structure

Longitudinally Polarized proton-proton



$pp \to hX$

Hadron Asymmetry

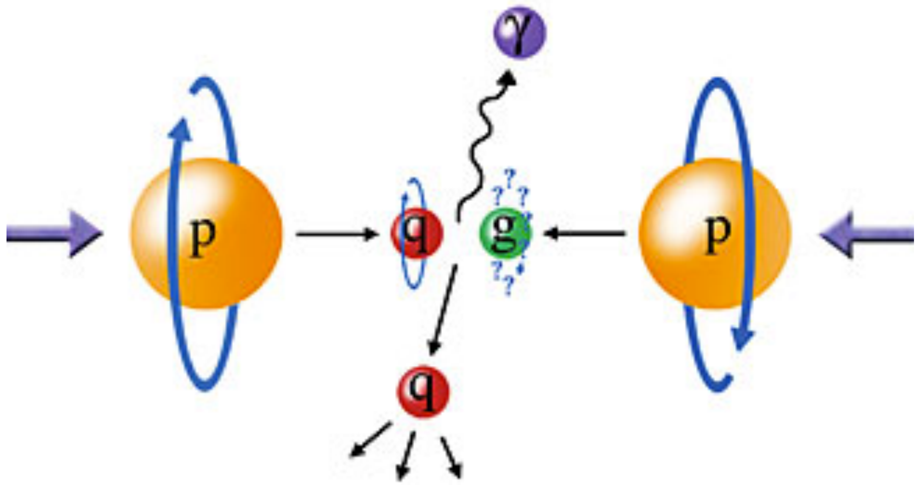


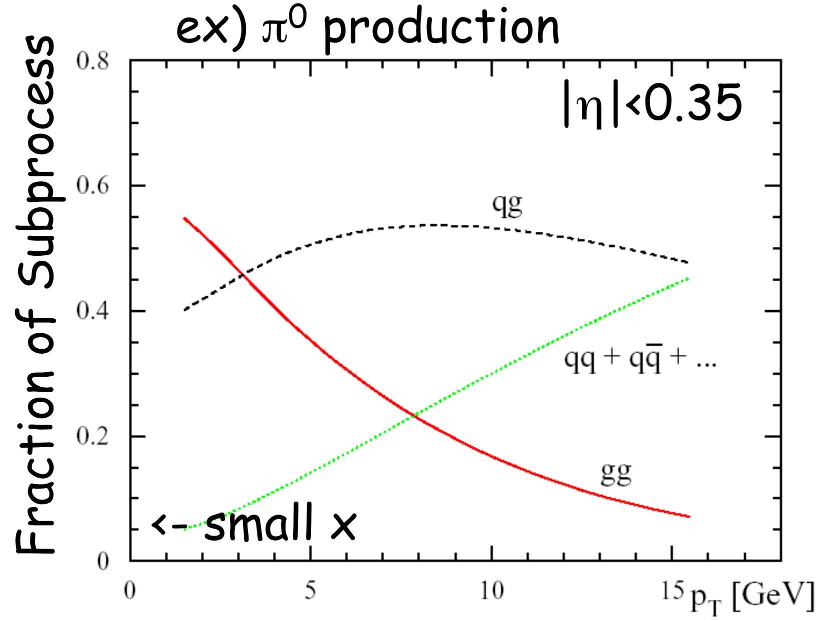
Fragmentation Function

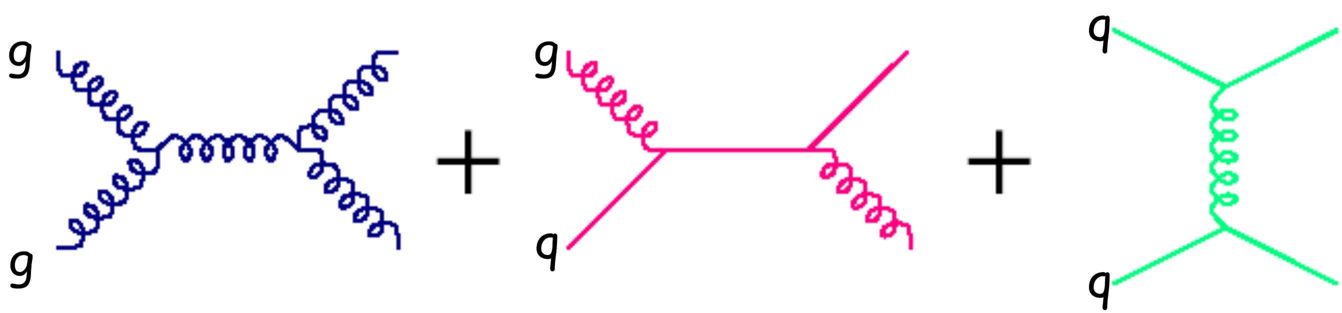
Double Helicity Asymmetry A_{LL}

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

Subprocess of pp



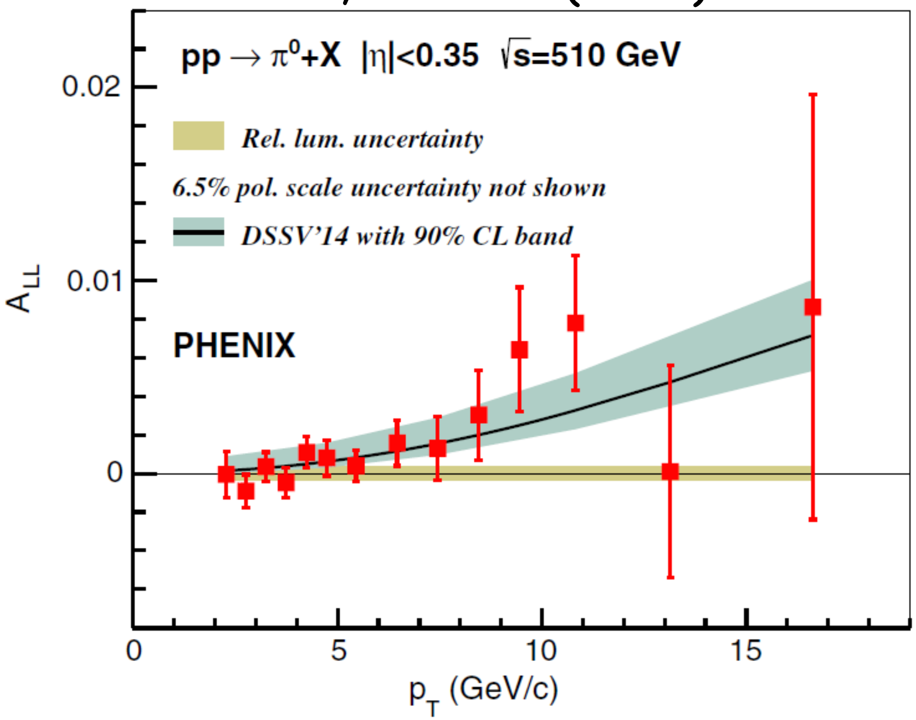




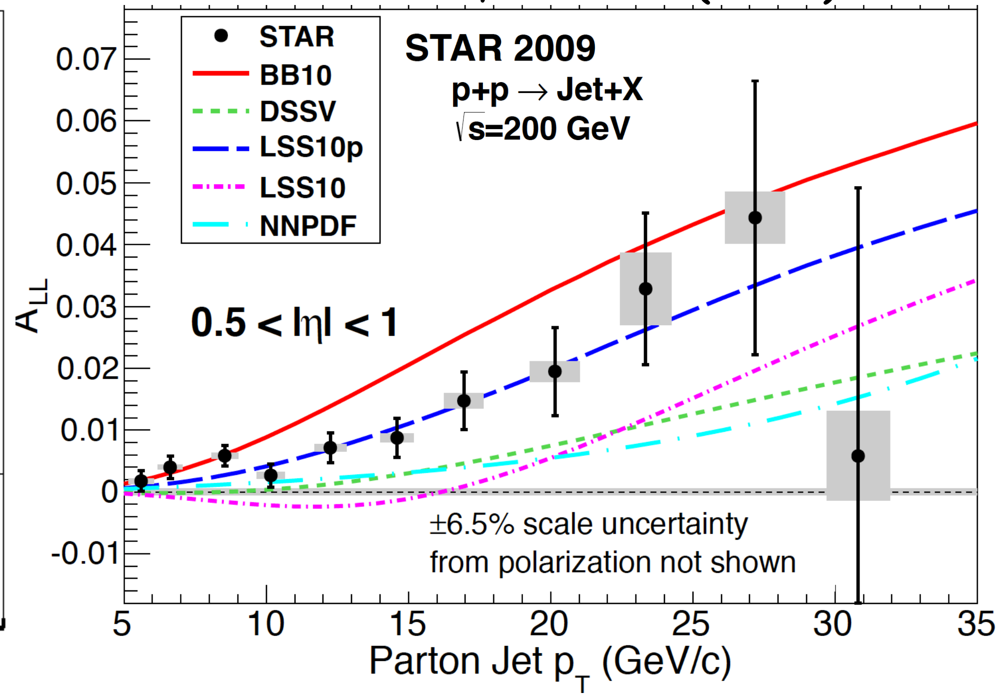
$$A_{LL} \propto [\omega_{gg}]\Delta g \Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q \Delta q]$$

Latest A_{LL} Results

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



PRL115, 092002 (2015)



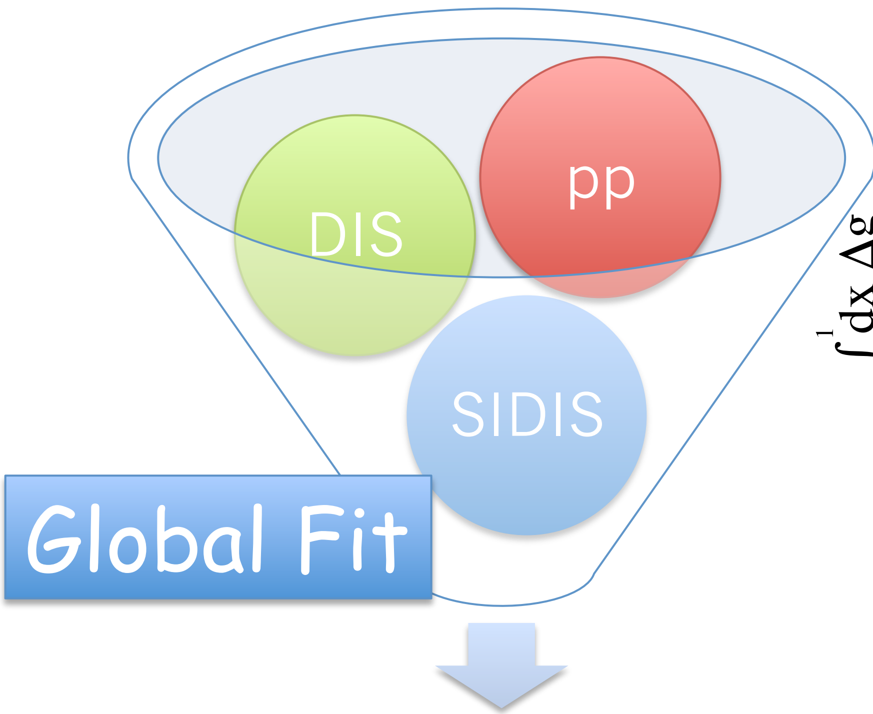
PHENIX

STAR

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

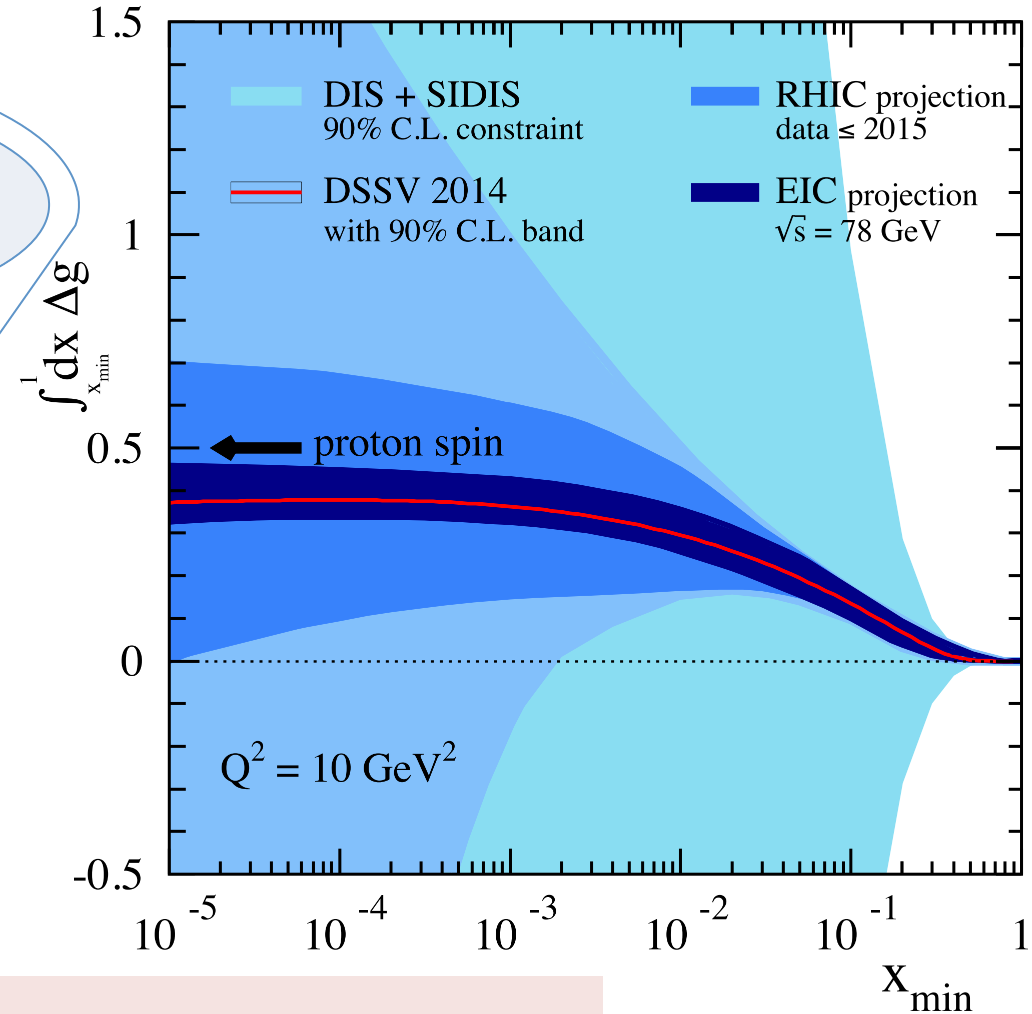
$$pp \to jet + X$$

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



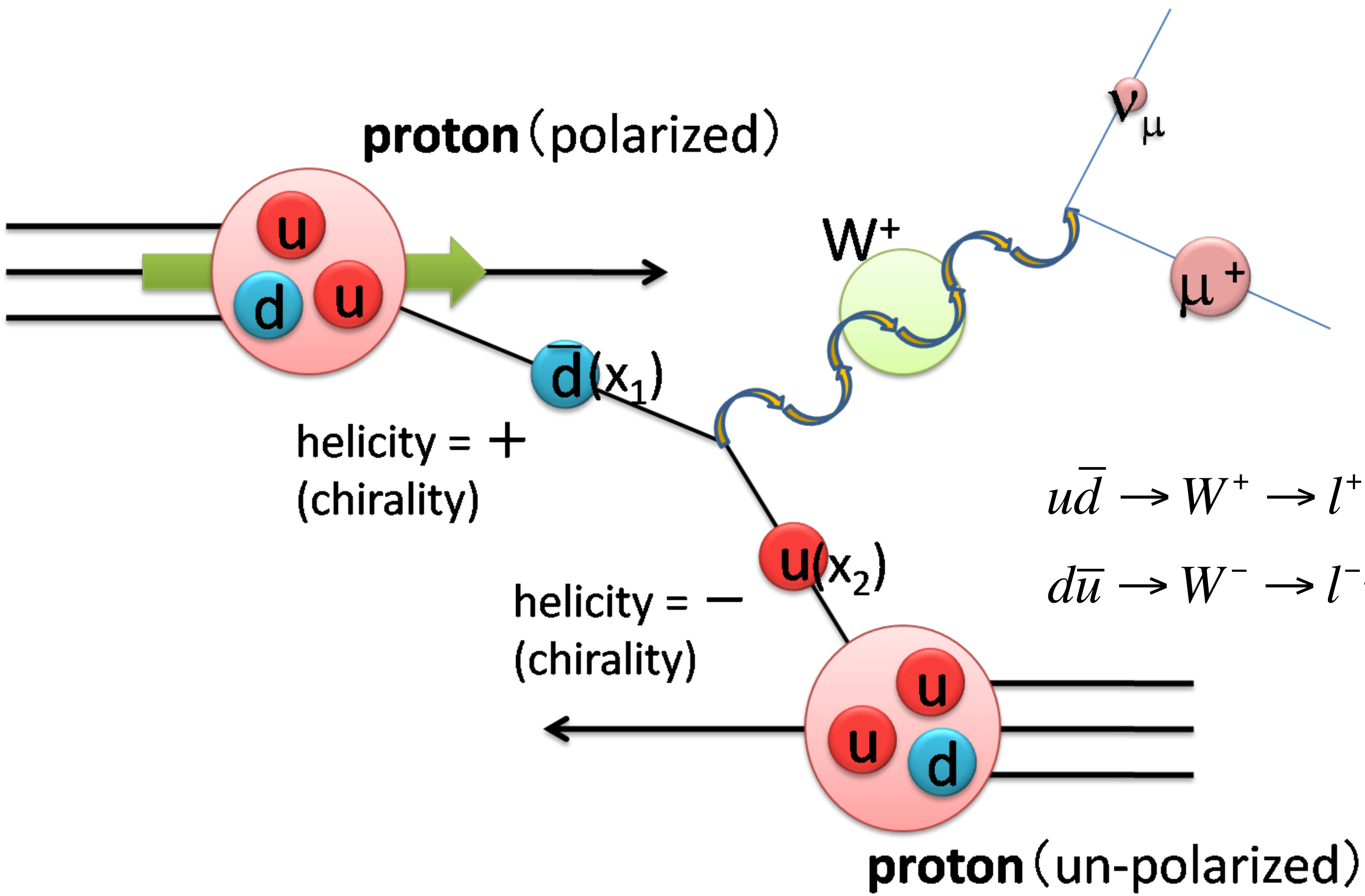
$\Delta q(x)$, $\Delta\bar{q}(x)$, $\Delta g(x)$

arXiv:1602.03922



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

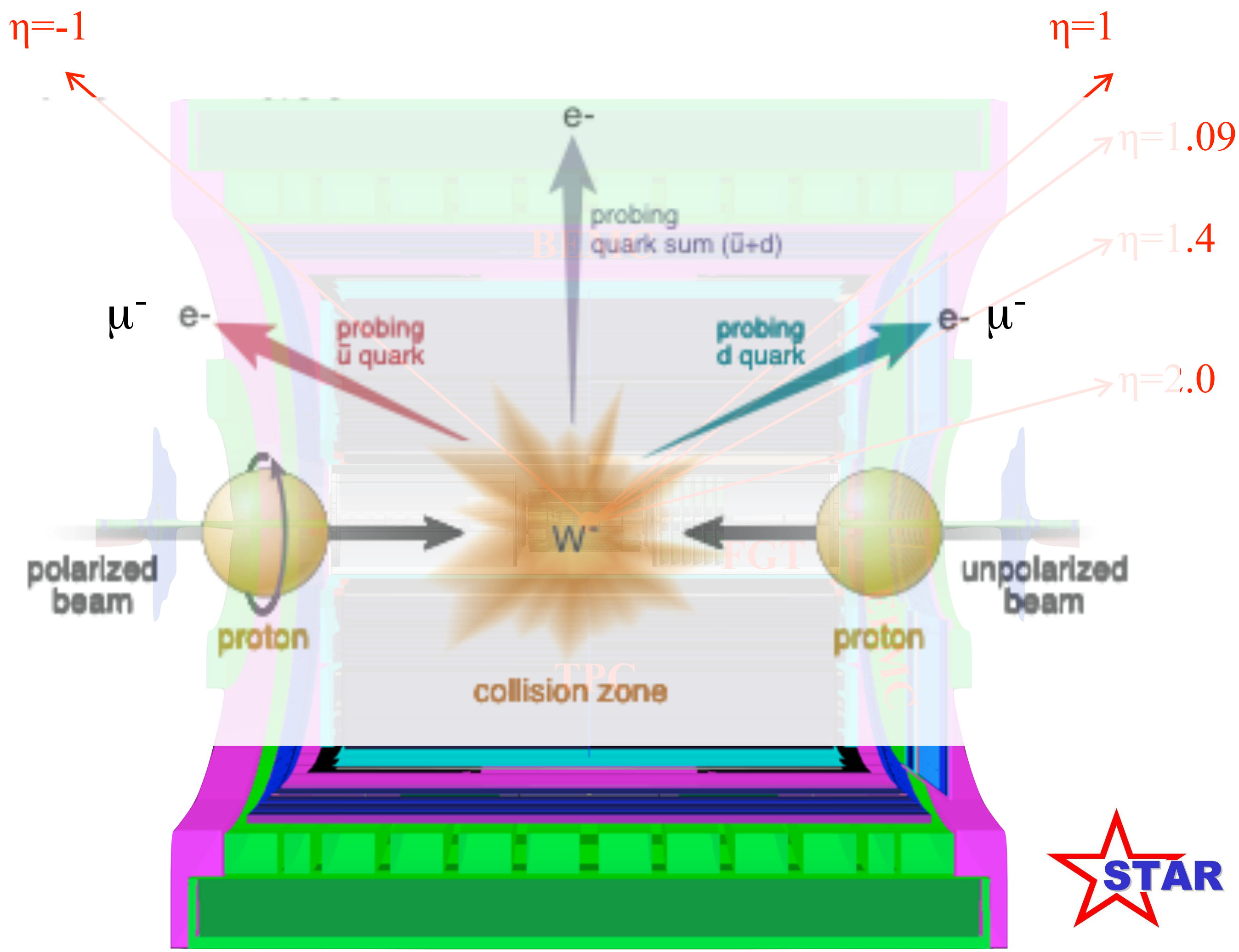
Sea Quark Polarization



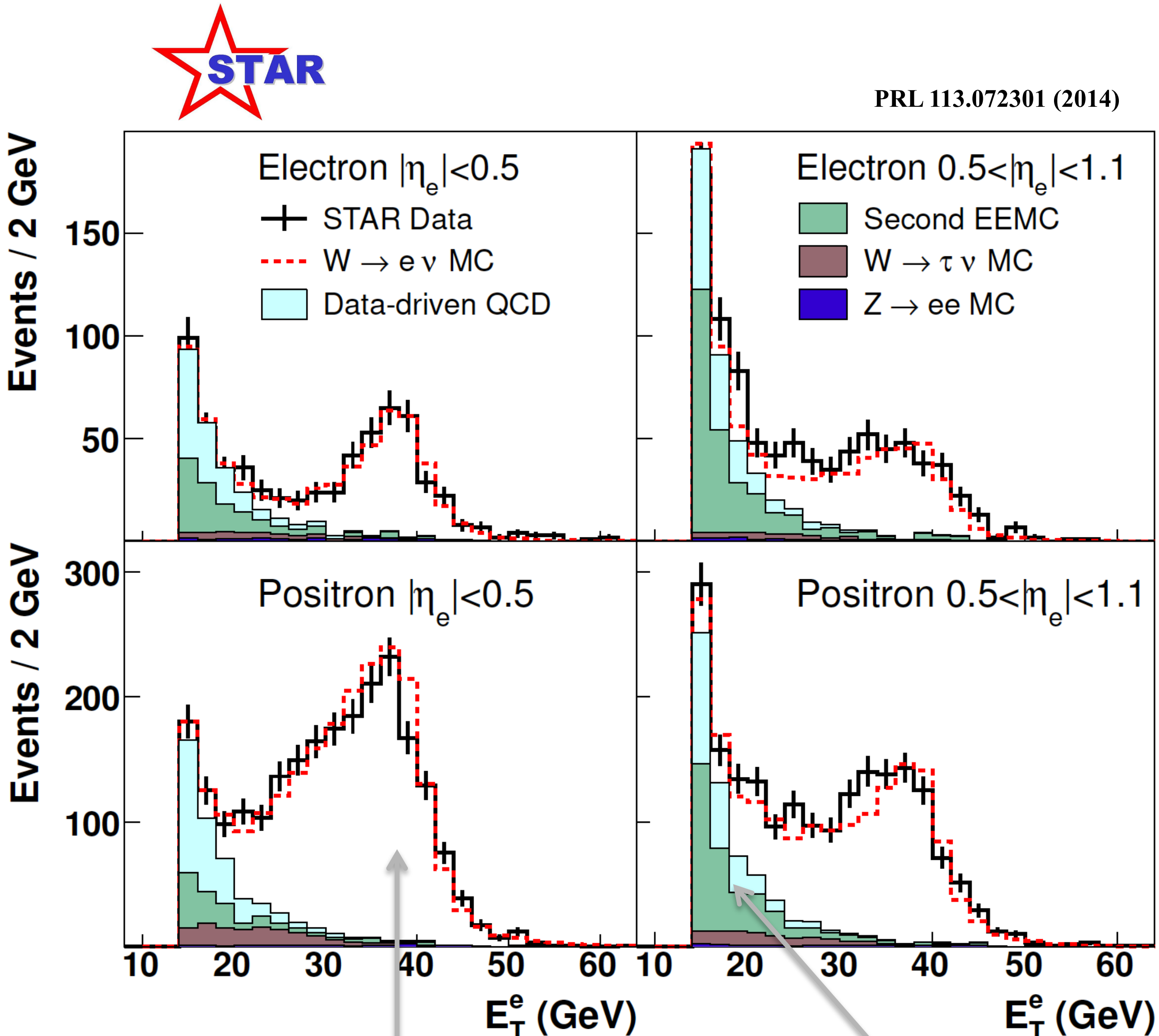
$$u\bar{d} \rightarrow W^+ \rightarrow l^+\nu$$

$$d\bar{u} \rightarrow W^- \rightarrow l^-\nu$$

Single Lepton Measurement



Energy Spectra



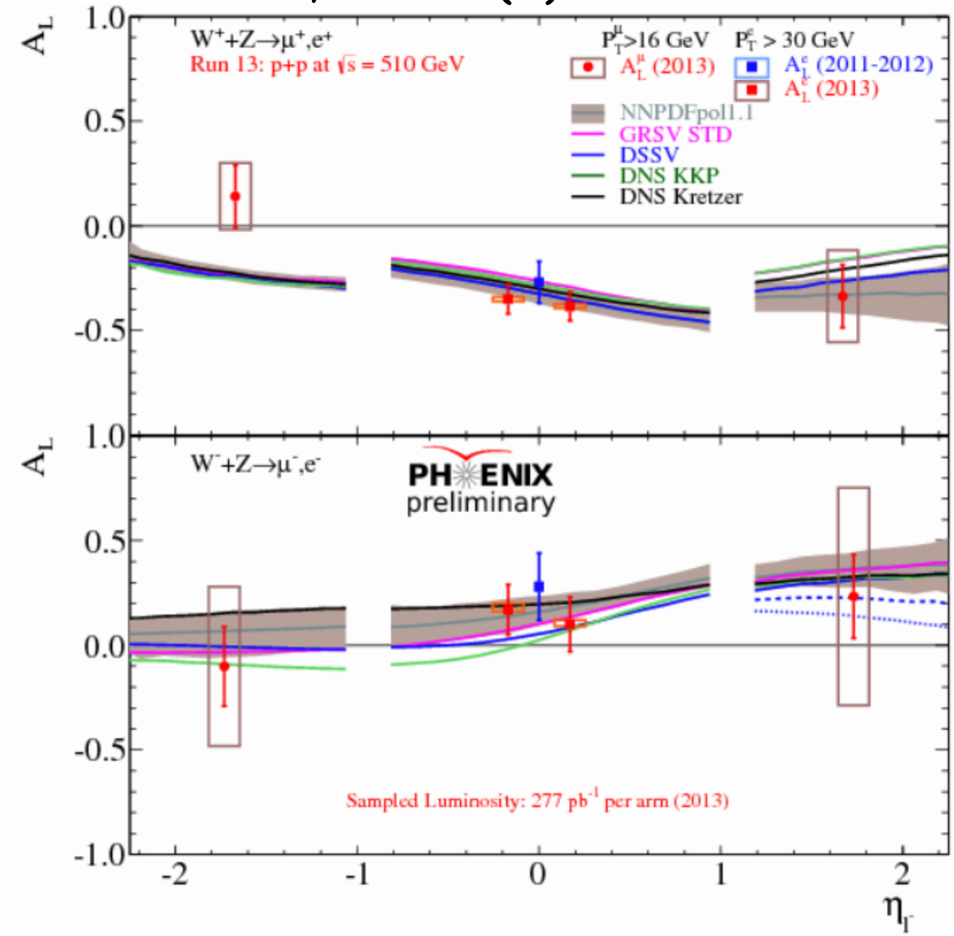
$$W^+ \rightarrow e^+ + \nu$$

(M_W = 80GeV)

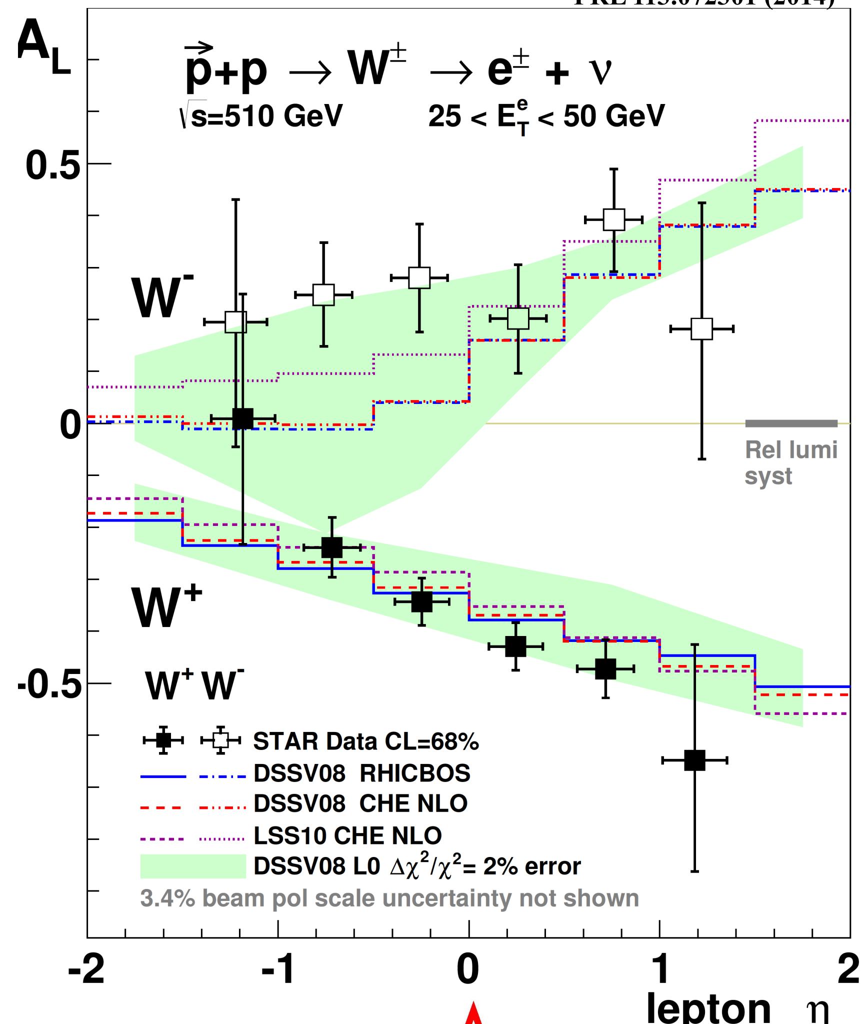
Backgrounds

Single Lepton Asymmetry A_L

PRD93, 051103(R) 2016



PRL 113.072301 (2014)

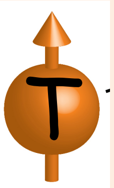


PHENIX

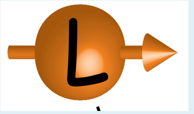
STAR

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.
- More sophisticated measurements on forward π TSSA to disentangle competing effects (ISI or FSI).

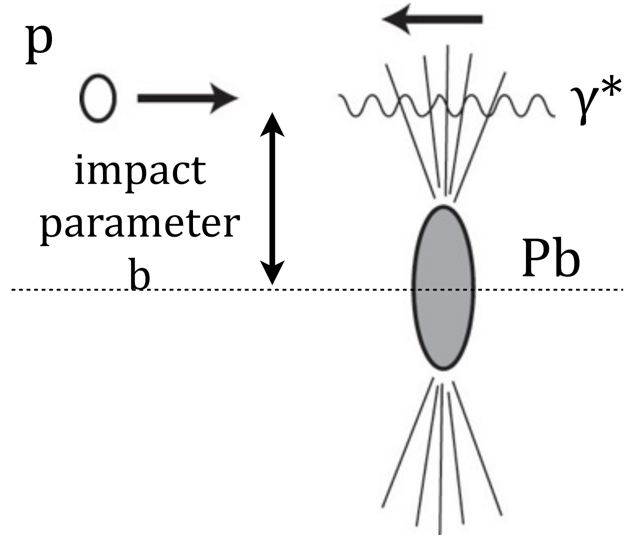


- Diffractiveness may connects between forward π and very forward n.
- Latest data shows non-zero gluon spin fraction
- Ongoing W analyses will improve precision of sea-quark polarized parton distribution



BACKUP SLIDES

Event Generation of UPCs



Event Generation of UPCs

=

Flux of quasi photons

×

Cross section of p-γ

×

Event Generation of p-γ

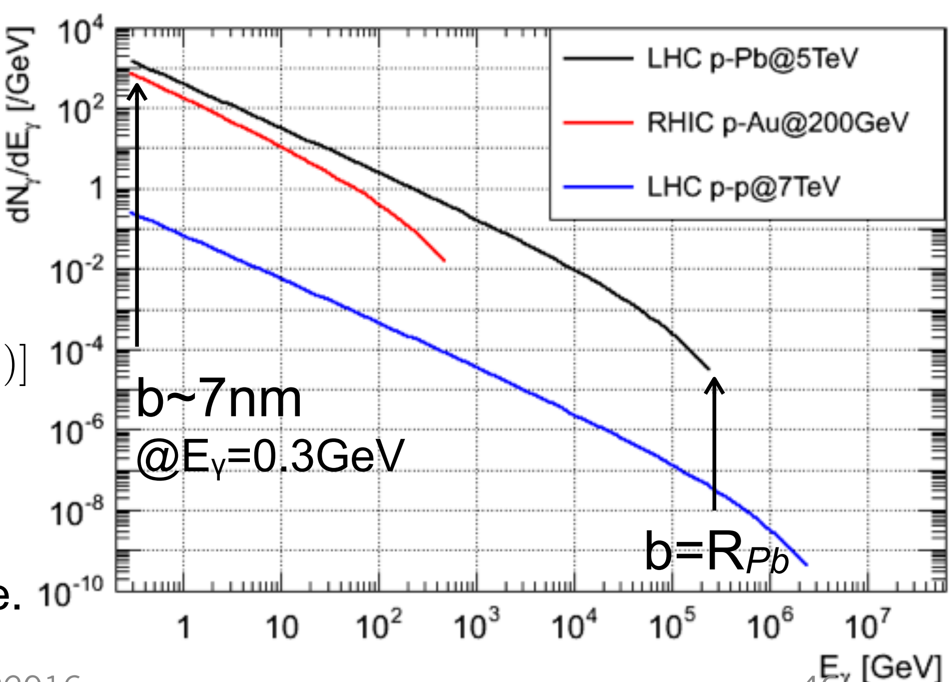
Flux of quasi photons

Weizsacker-Williams method

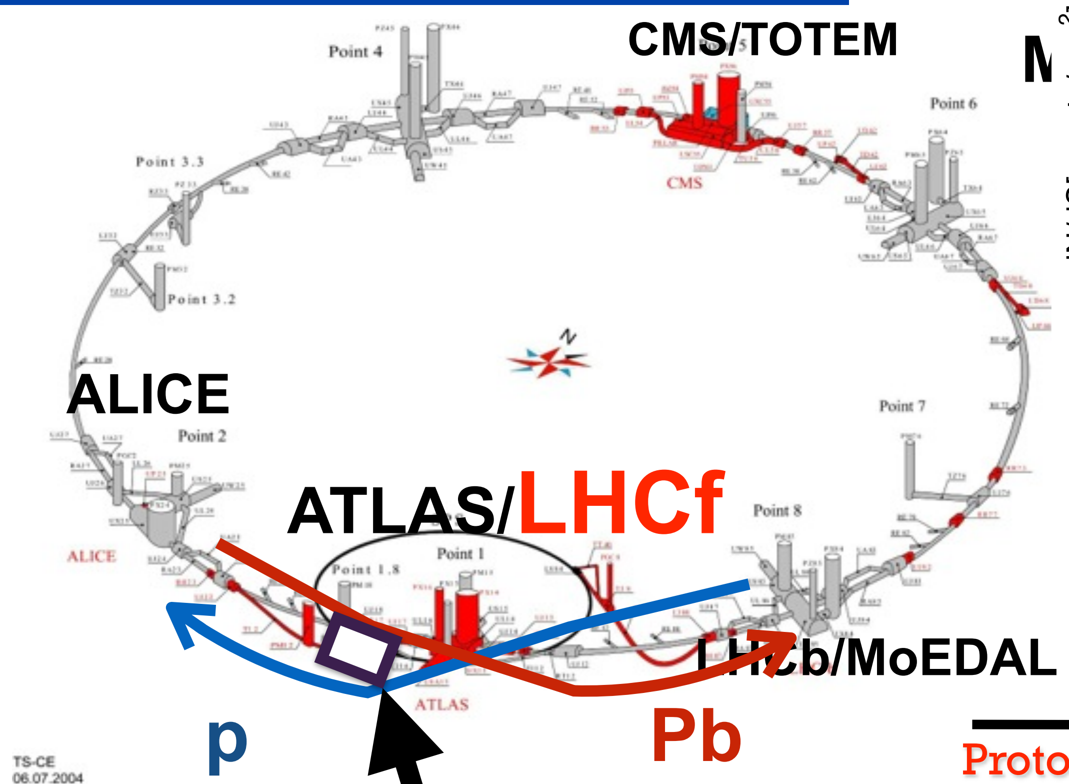
$$\frac{dN_{\gamma*}}{dE_{\gamma*}} = \frac{2Z^2\alpha}{\pi E_{\gamma*}}[xK_0(x)K_1(x) + \frac{x^2}{2}(K_0^2(x) - K_1^2(x))]$$

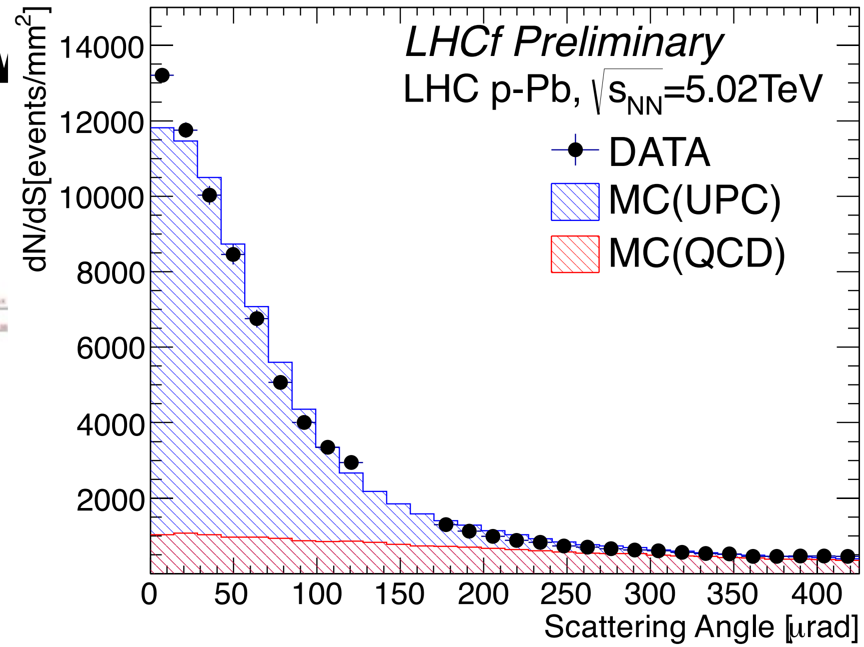
$$\simeq \frac{2Z^2\alpha}{\pi E_{\gamma*}}(log\frac{1.123}{x} - 1) \qquad (if\ E_{\gamma*} << E_{max})$$

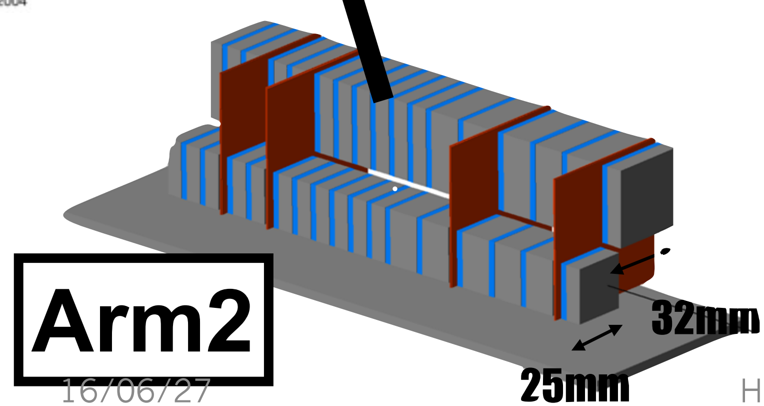
$E_{\gamma*}$: energy of photons at the proton rest frame.

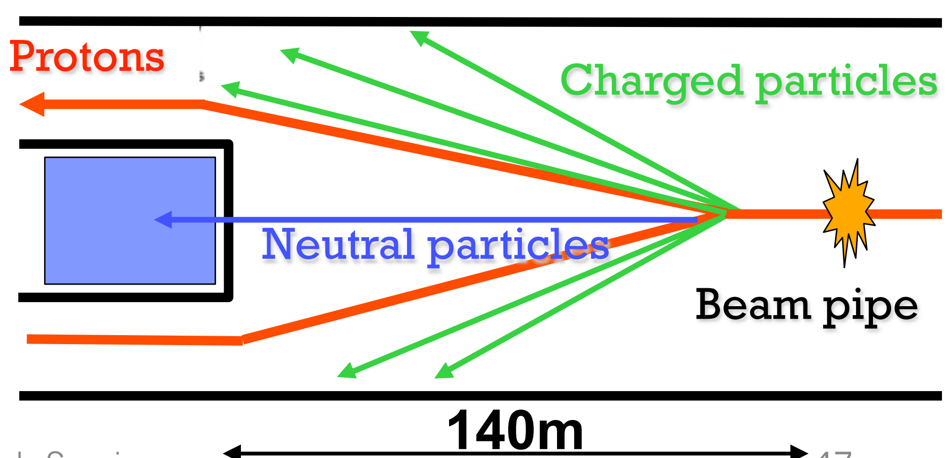


The LHCf experiment









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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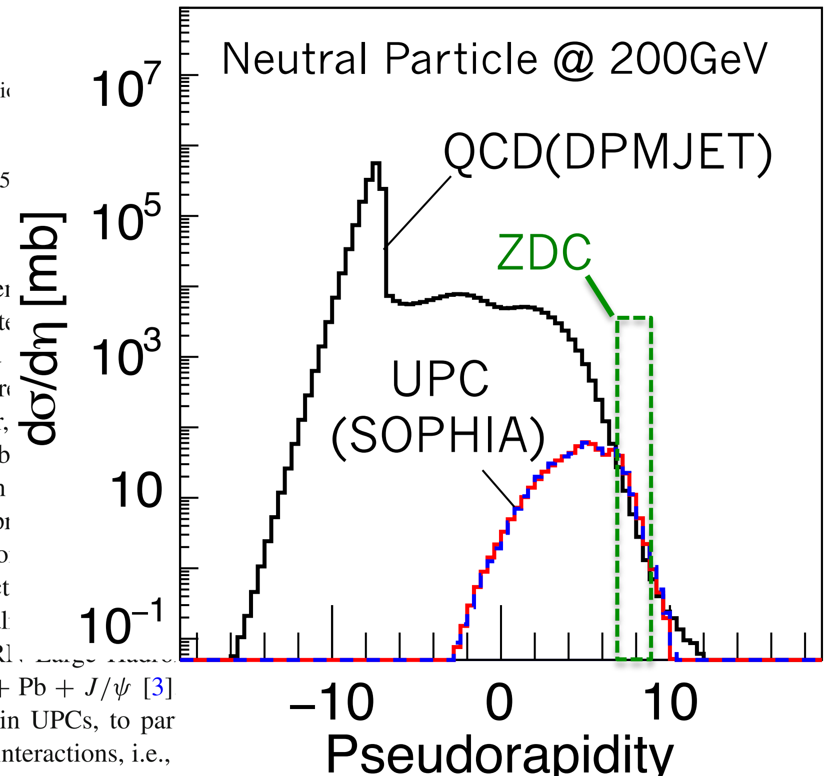
Abstract We present a hadron production study in the forward rapidity region in ultra-peripheral proton–lead ($p+$Pb) collisions at the LHC and proton–gold ($p+$Au) collisions at RHIC. The present paper is based on the Monte Carlo simulations of the interactions of a virtual photon emitted by a fast 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

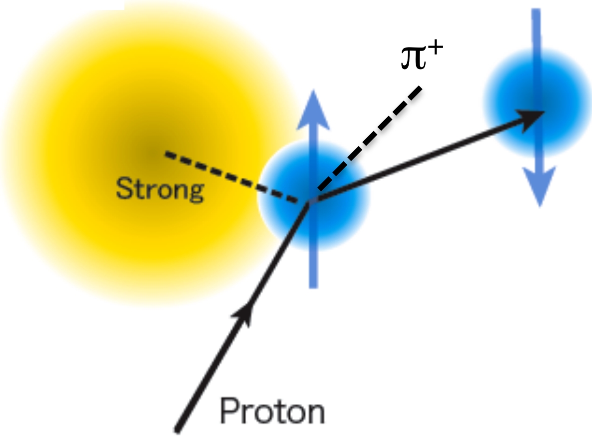
virtual photons e
may anyway int
usually referred
Ref. [1,2] for a r
UPCs, so far,
the gluon distrib
photoproduction
collisions can p
density in prot
momentum fract
measurements al
tion at the CER
$p+\mathrm{Pb} \to p+\mathrm{Pb}+J/\psi$ [3]
has been paid, in UPCs, to par
photon–proton interactions, i.e.,
less such particle production sh

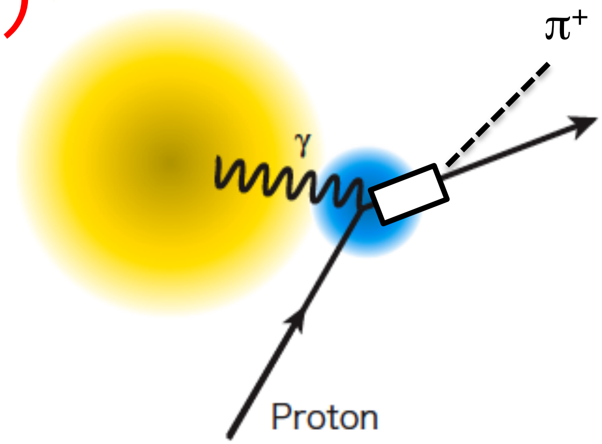


Predicts comparable yields between QCD and UPC processes

Coulomb-Nuclear Interference

(CNI)



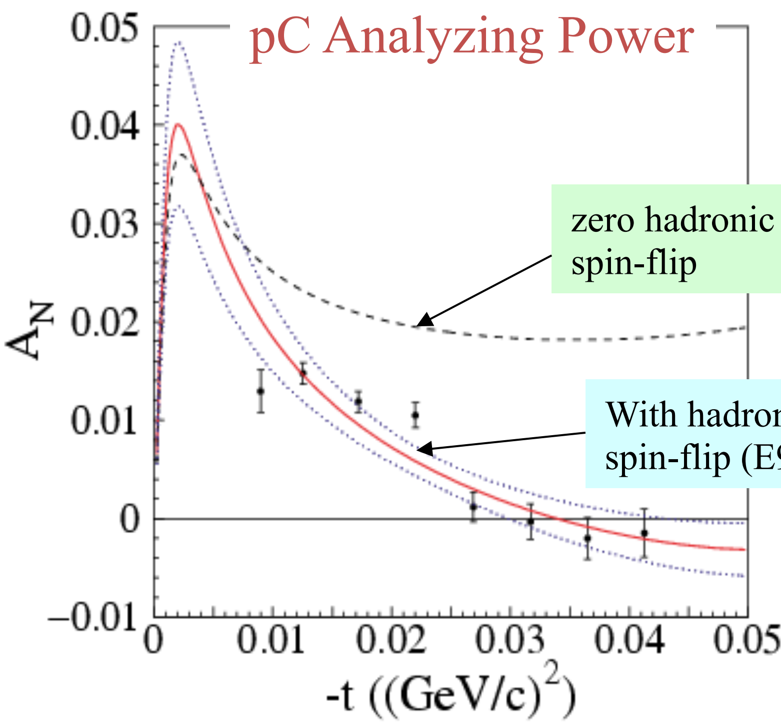


$$A_N \sim had * had + \boxed{had * EM + EM * had} + EM * EM$$

Elastic A_N at Coulomb Nuclear Interference

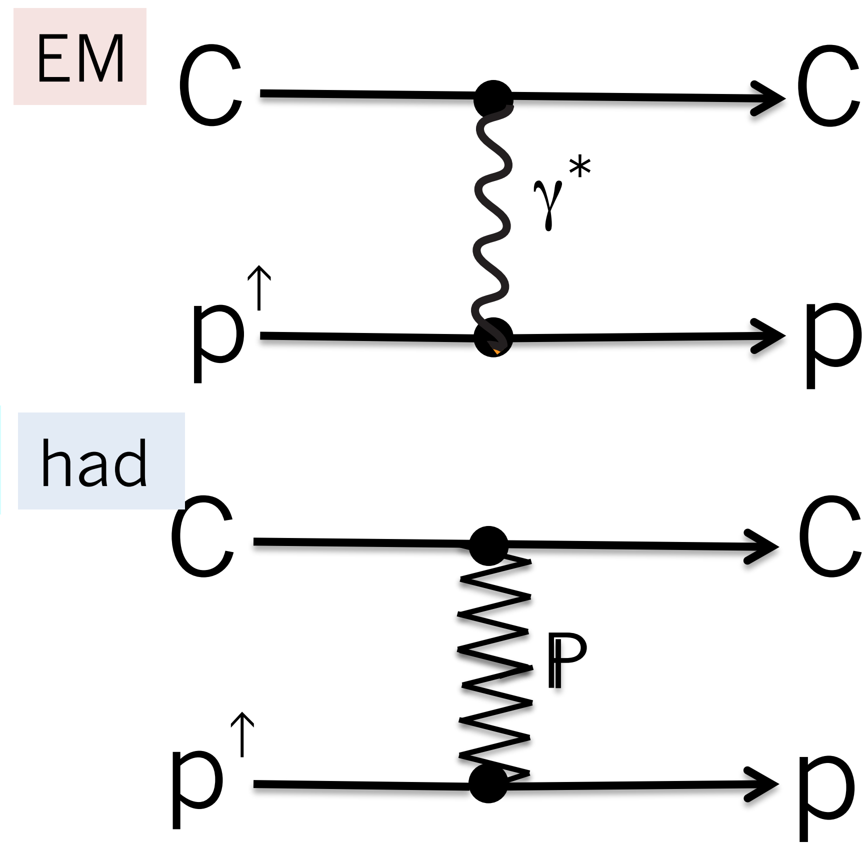
$$A_N \sim 2\,\mathrm{Im}\left\{ \underbrace{\phi^{EM*}_{non-flip}}_{\propto \alpha s/t} \underbrace{\phi^{had}_{flip}}_{\text{Pomeron}} \sin\delta_2 + \underbrace{\phi^{had*}_{non-flip}}_{\propto \sqrt{\sigma^{had}_{pC}}} \underbrace{\phi^{EM}_{flip}}_{\propto (\mu_p - 1)} \sin\delta_3 \right\}$$

(High energy & small t limit)

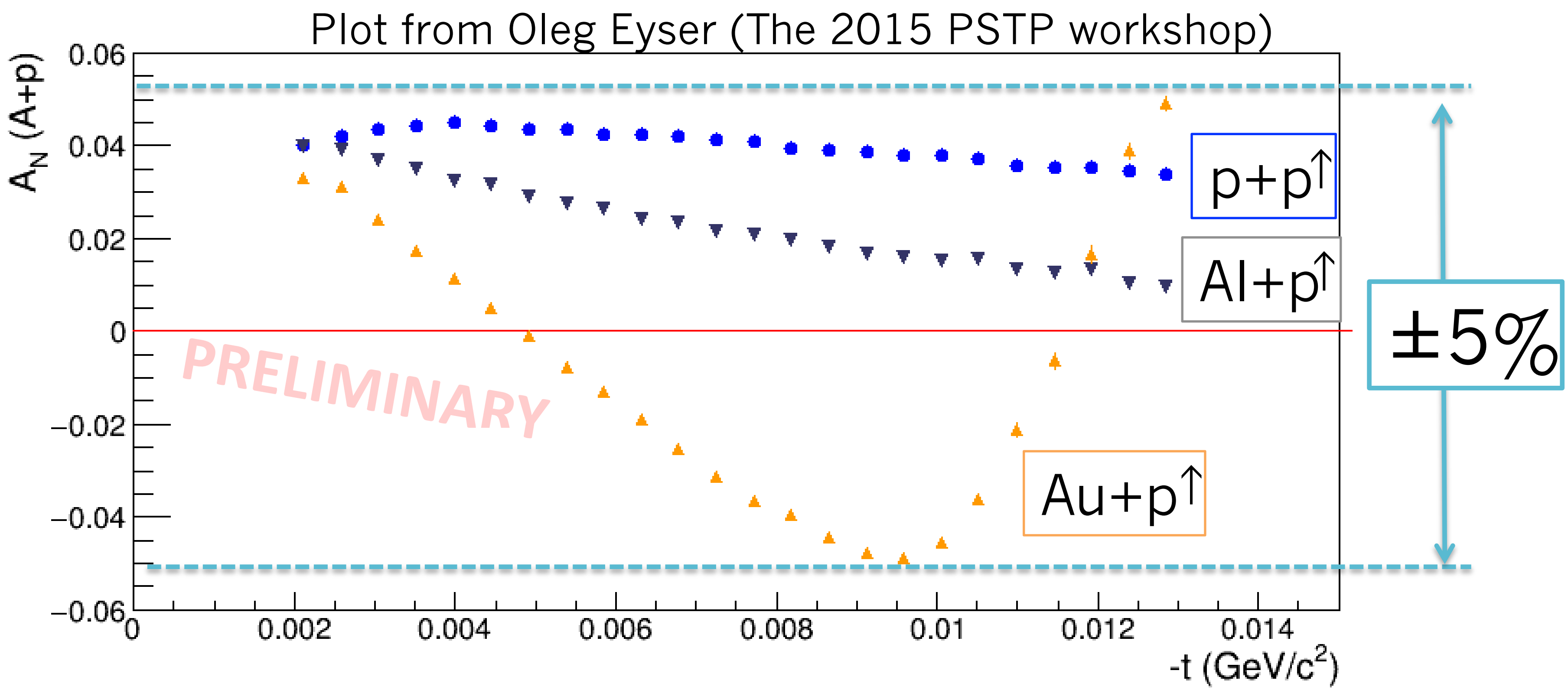


Phys.Rev.Lett.,89,052302(2002)

E_{beam} = 21.7GeV



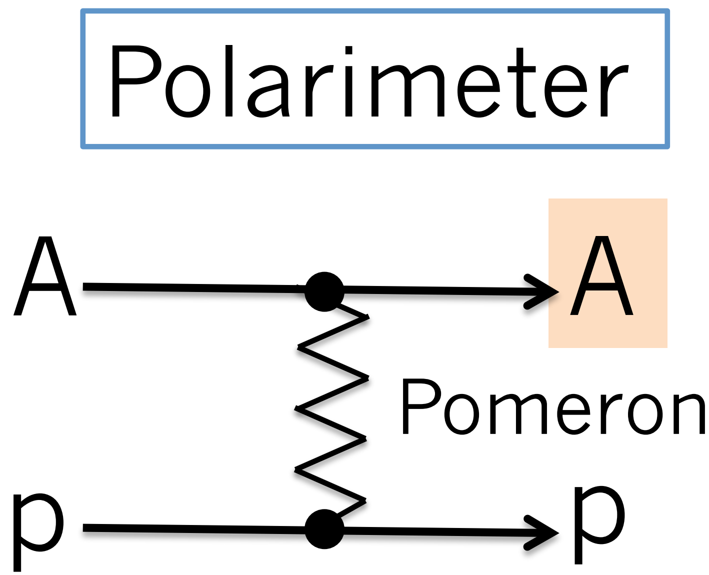
Run15 Au,Al beam + $p^{\uparrow}$ target

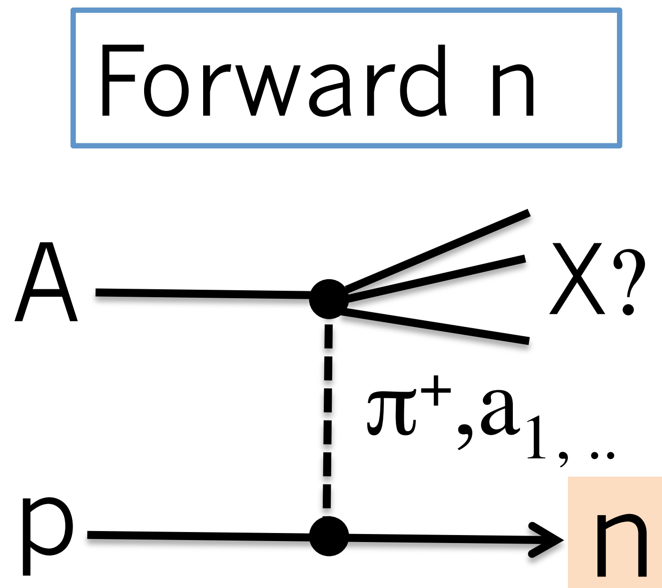


- Strong A-Dependence
- Flips sign of A_N in Au+$p^{\uparrow}$
- 0.002 < -t < 0.014 (Gev/c)^2

Forward Neutron
0.02 < -t < 0.5 (Gev/c)^2

Underlying Mechanism Comparison





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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(Received 26 September 1989)

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.

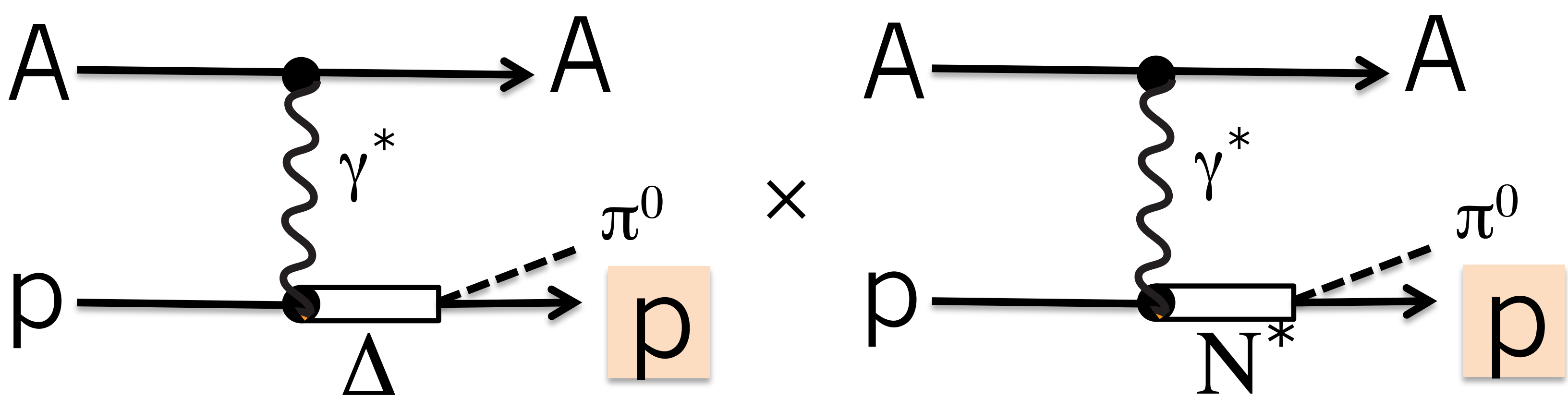
The cross section for the Coulomb coherent process (1) has a sharp peak at $t' \sim 10^{-5}$ $(\text{GeV}/c)^2$ and decreases rapidly as t'/t^2. The "width" of the Coulomb peak is determined by the detector resolution. Diffractive dissociation due to the strong interaction is also present, but it has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

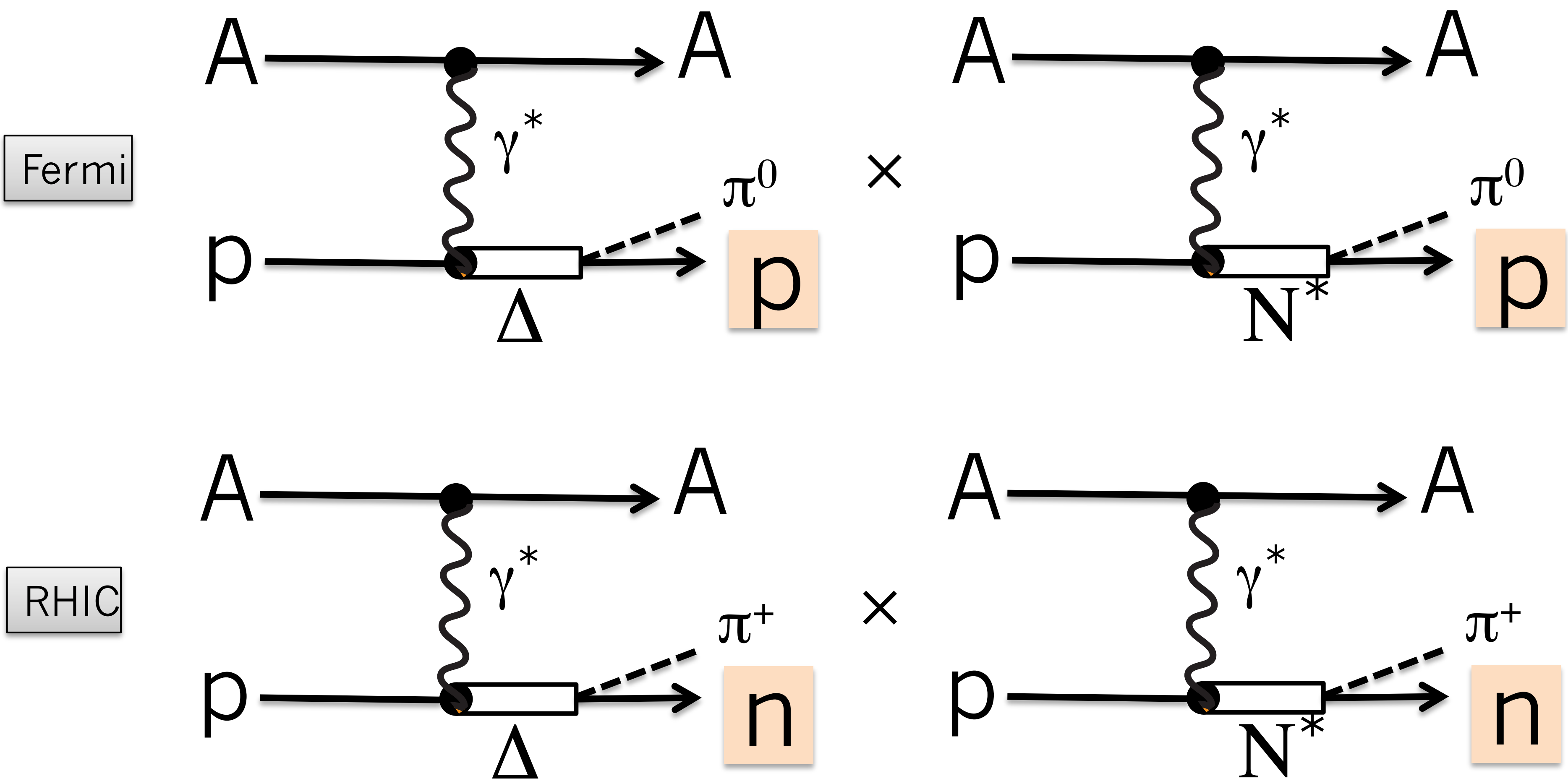
$N\pi\pi$ (30~40%)

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

Comparison between two

	Fermi	PHENIX	STAR17
Beam Energy [GeV]	185	100	255
$\sqrt{s}$ [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 ± 0.003 (BBC veto)	

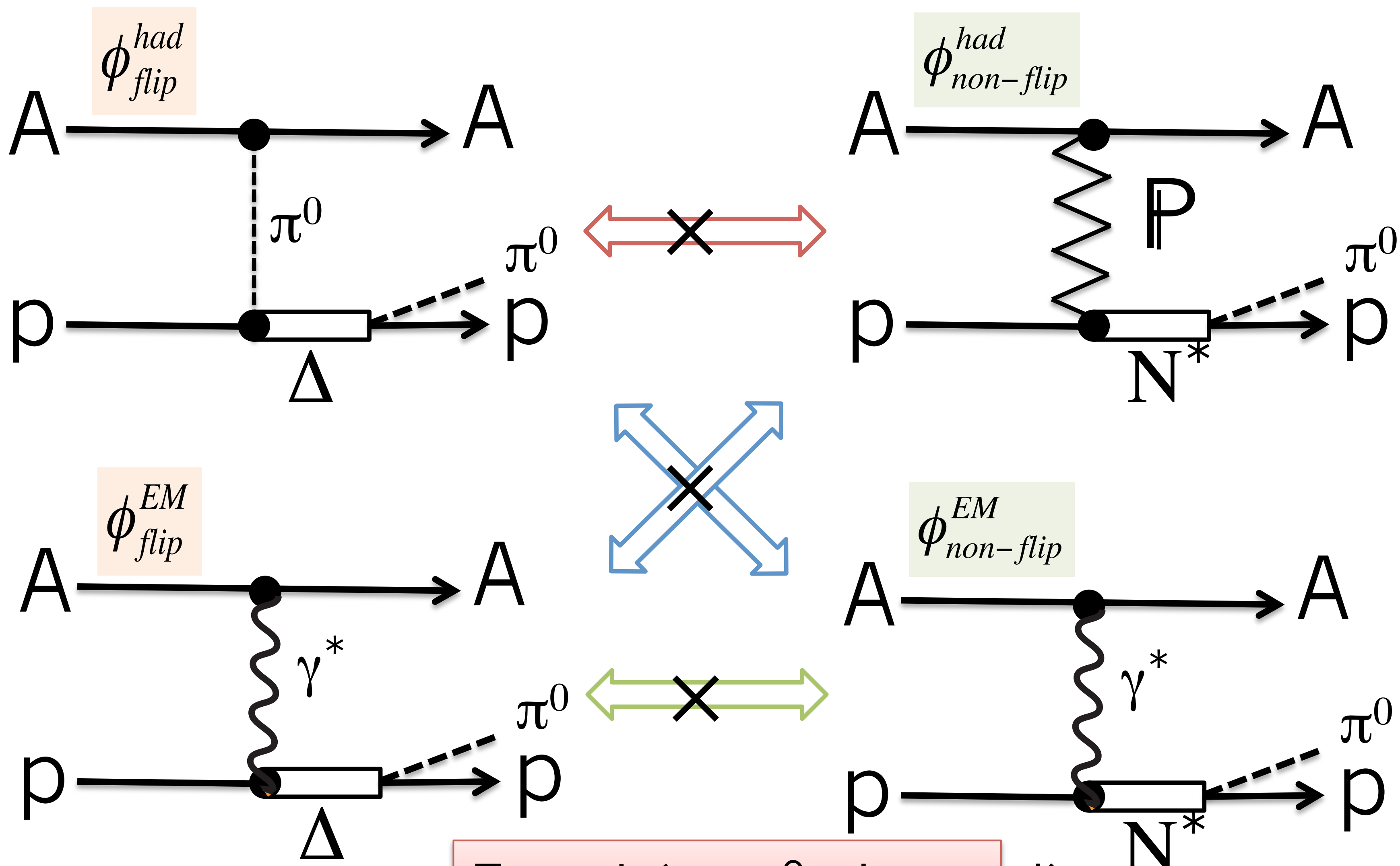
Origin of the Asymmetry



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

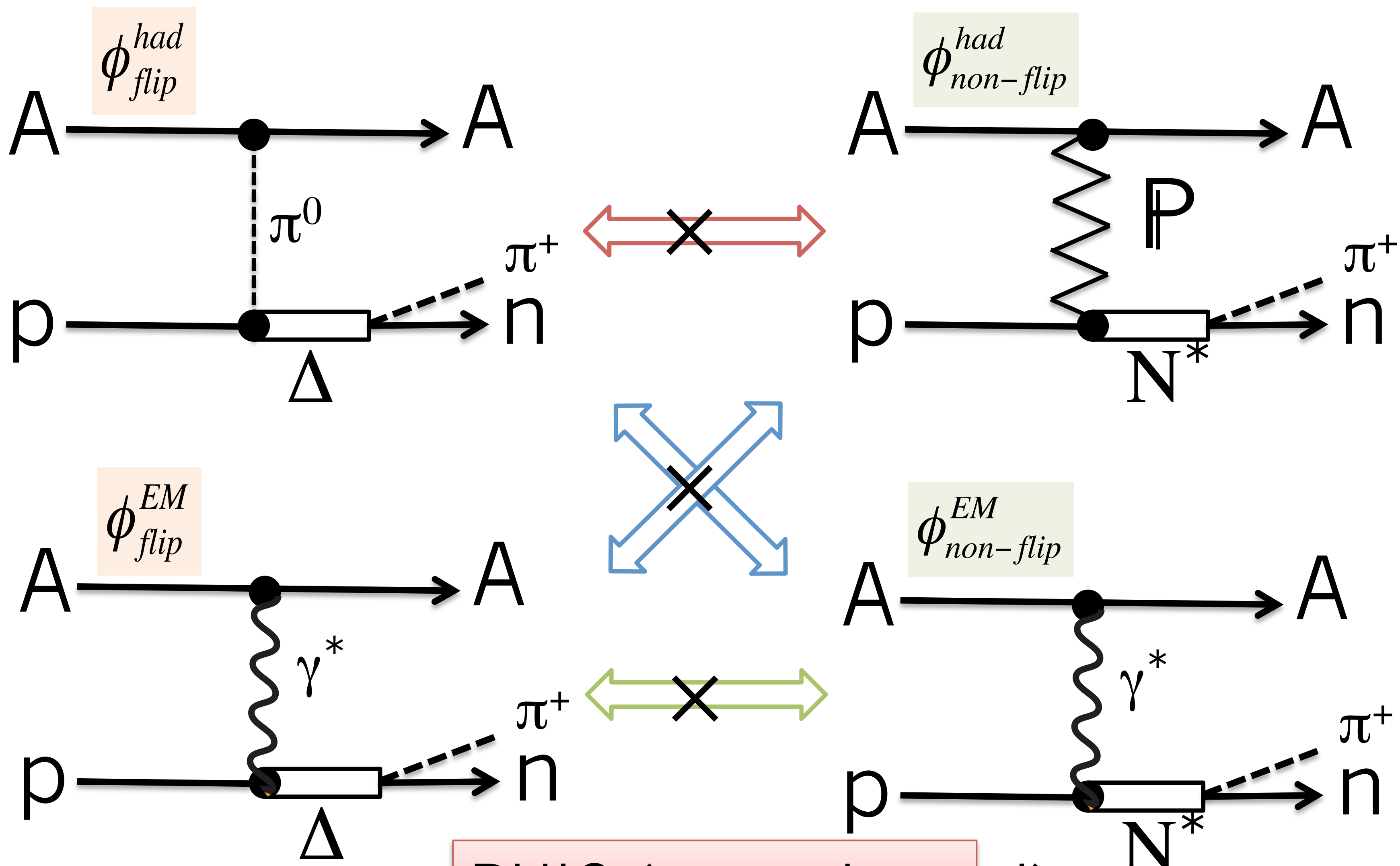
$$A_N \propto \phi^{had}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM}_{non-flip}\phi^{EM}_{flip}\sin\delta_4$$

hadronic CNI Primakoff



Fermi (p+π^0 channel)

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

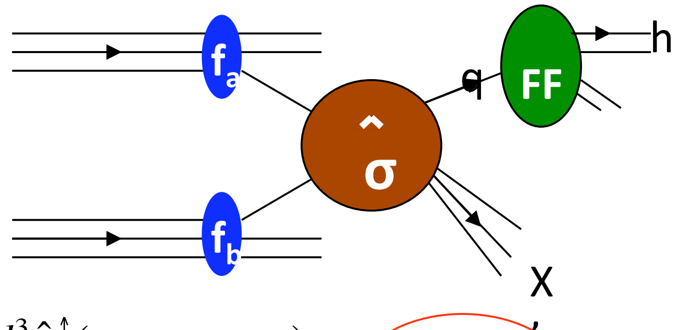


RHIC (n+π^+ channel)

Theory: K_T vs Collinear Factorization

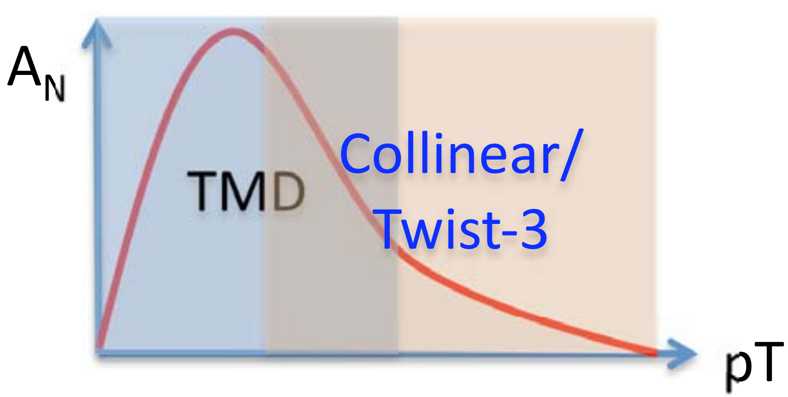
PHENIX

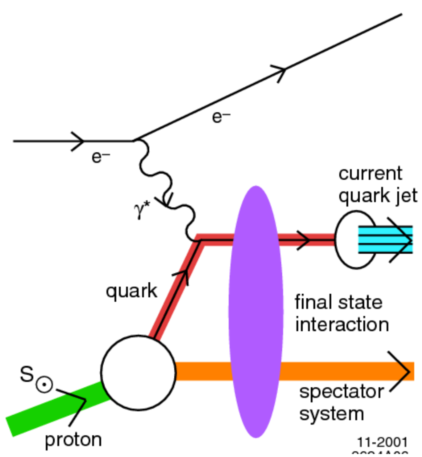
- Tran. Mom. Dep. Funs
  - Sivers Fun
  - Collins Fun

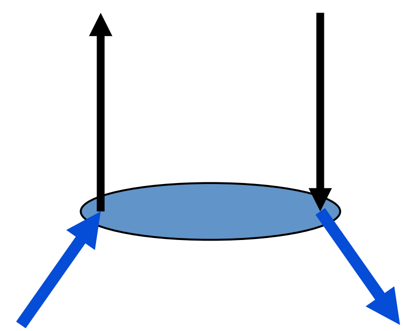


$$\frac{d^3\sigma^\uparrow\left(pp^\uparrow \to h+X\right)}{dx_1 dx_2 dz} \propto q_i^\uparrow(x_1,k_{q,T})\cdot q_j(x_2)\times\frac{d^3\hat{\sigma}^\uparrow(q_i q_j \to q_k q_l)}{dx_1 dx_2}\times FF_{q_{k,l}}(z,p_{h,T})$$

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

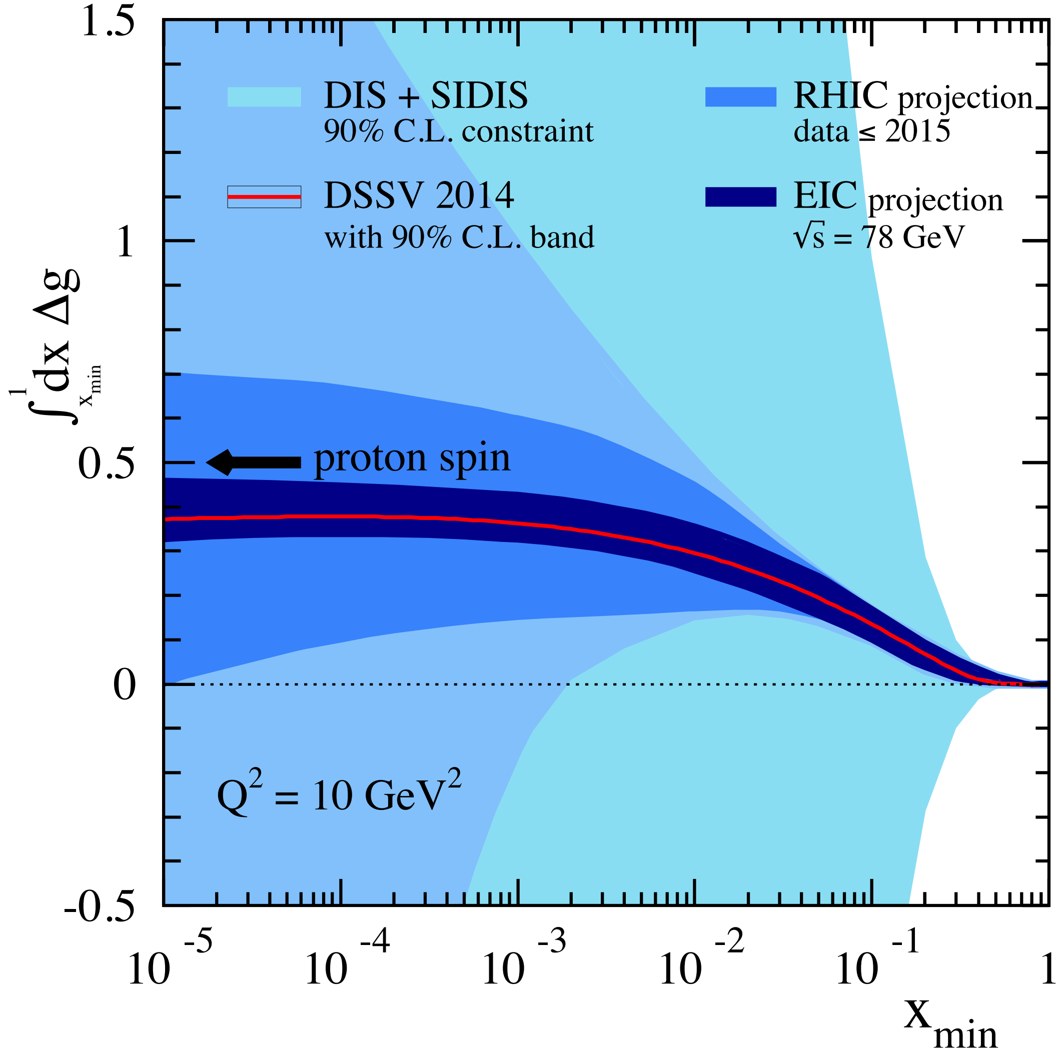






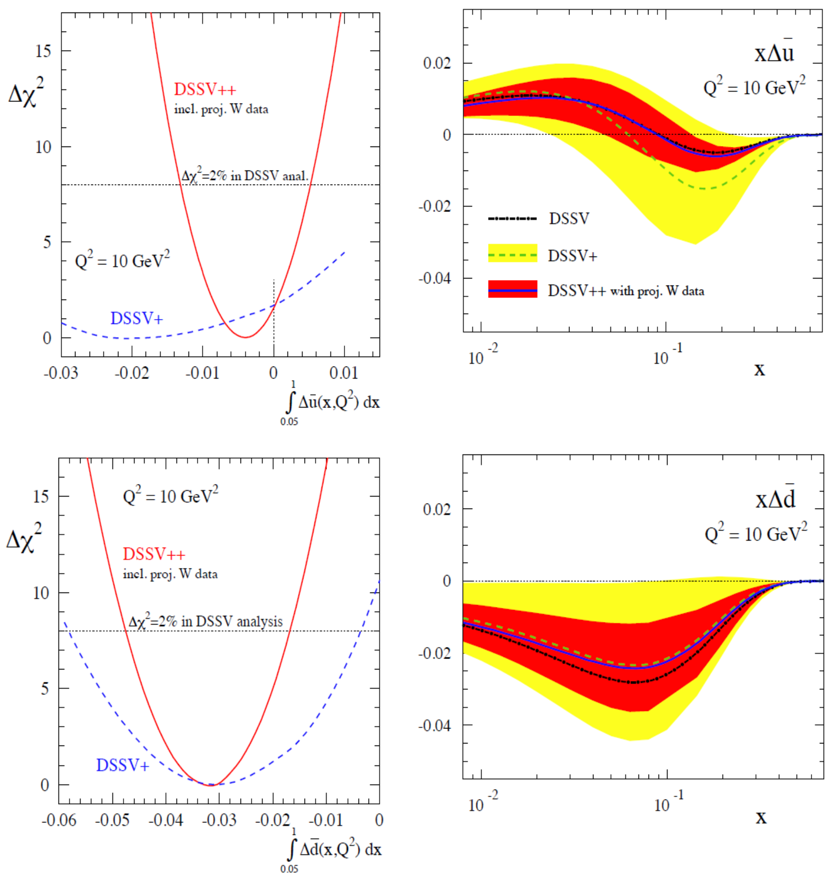
Future

arXiv:1602.03922

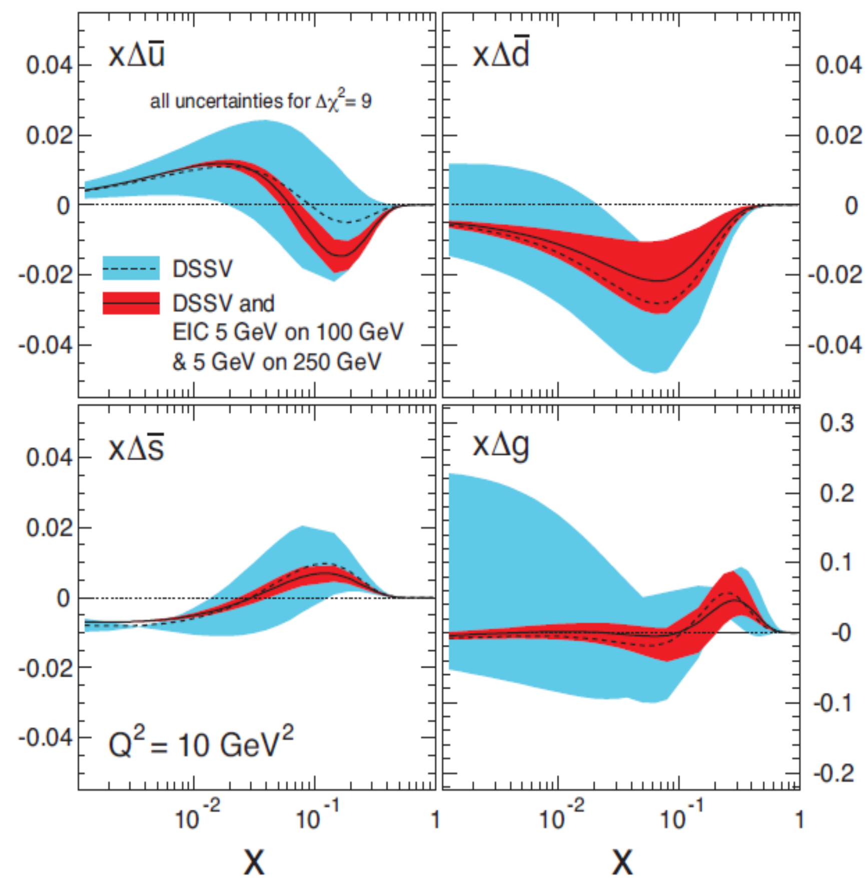


Present and Future

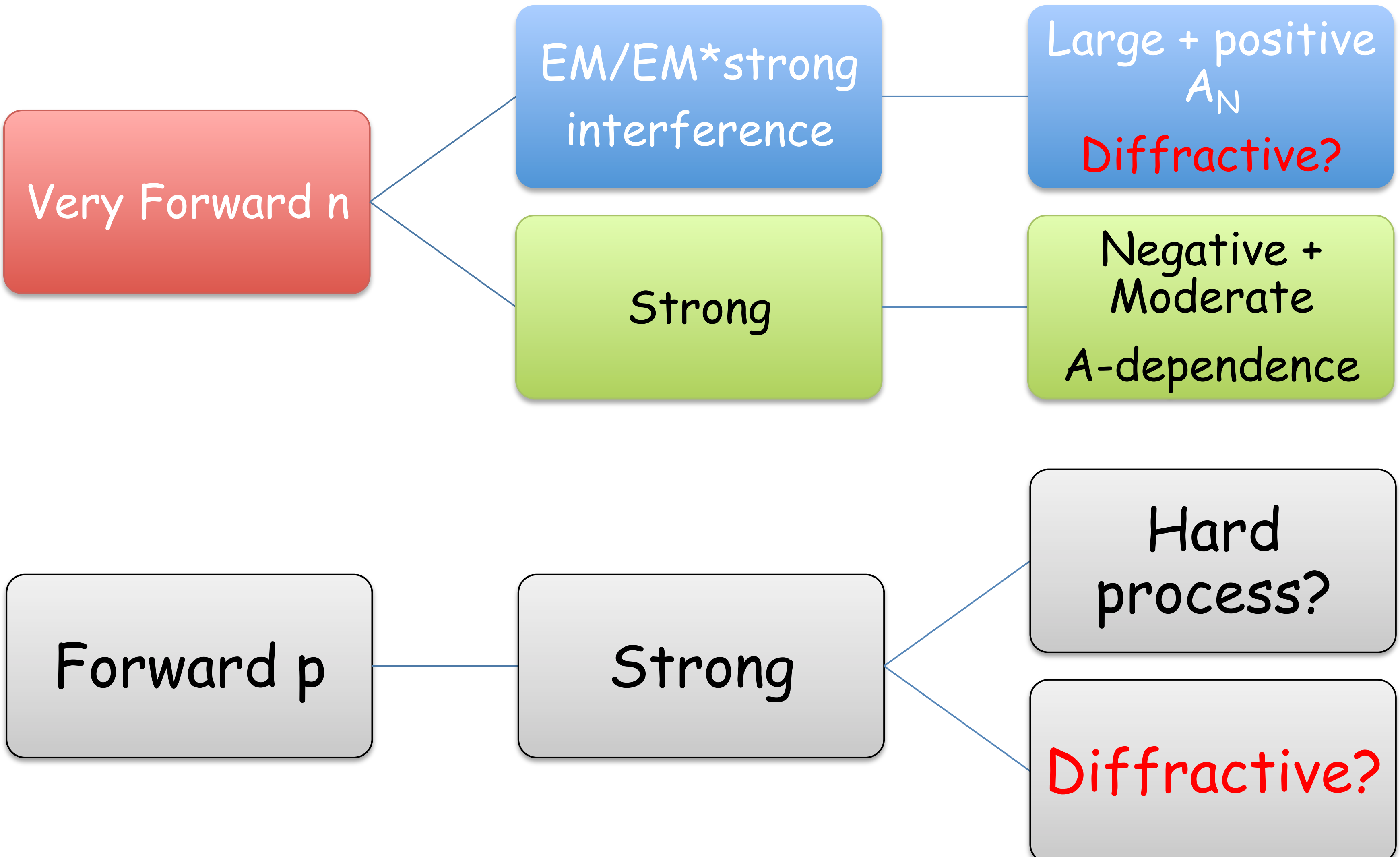
arXiv: 1501.01220



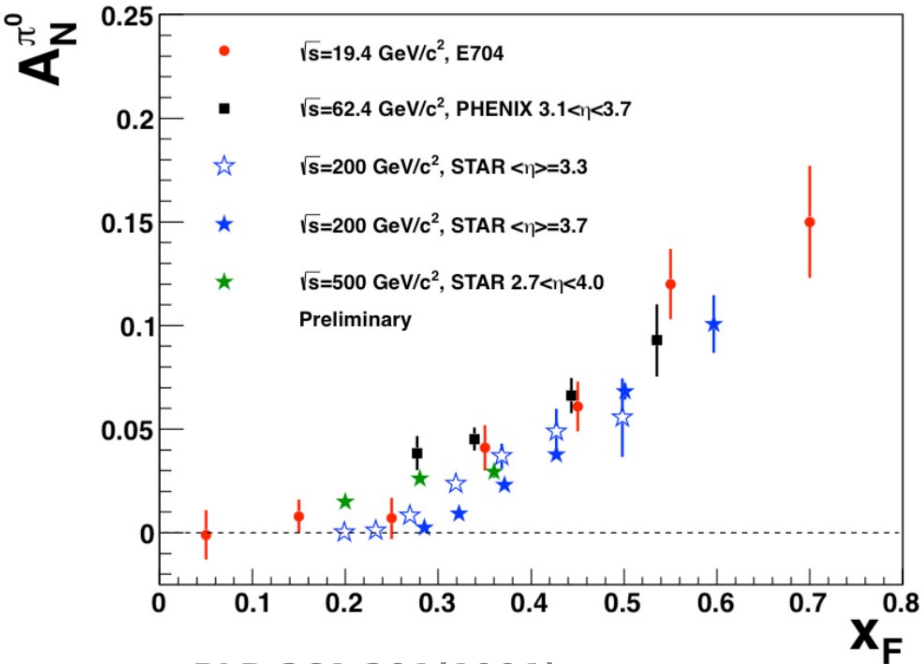
arXiv: 1212.1701



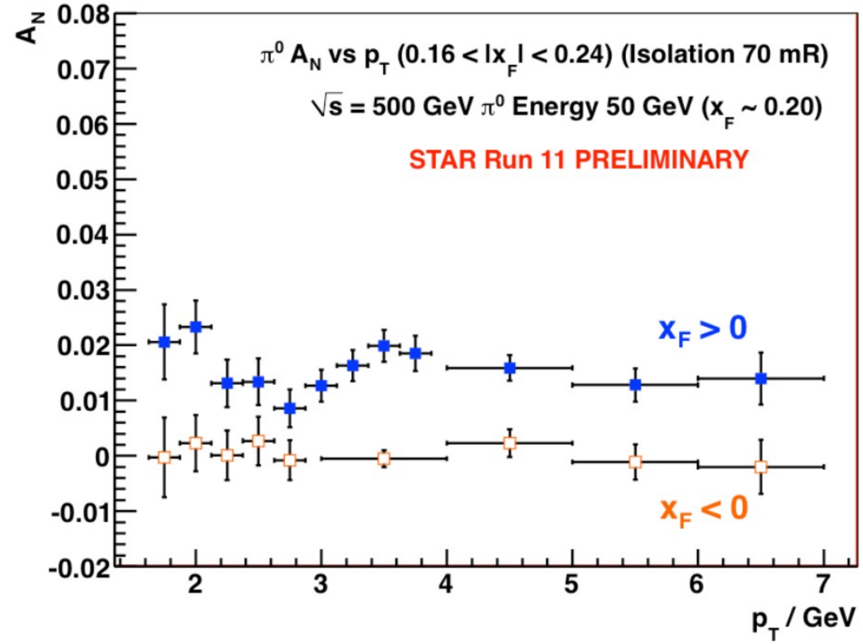
Transverse Summary



x_F and p_T Dependence



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

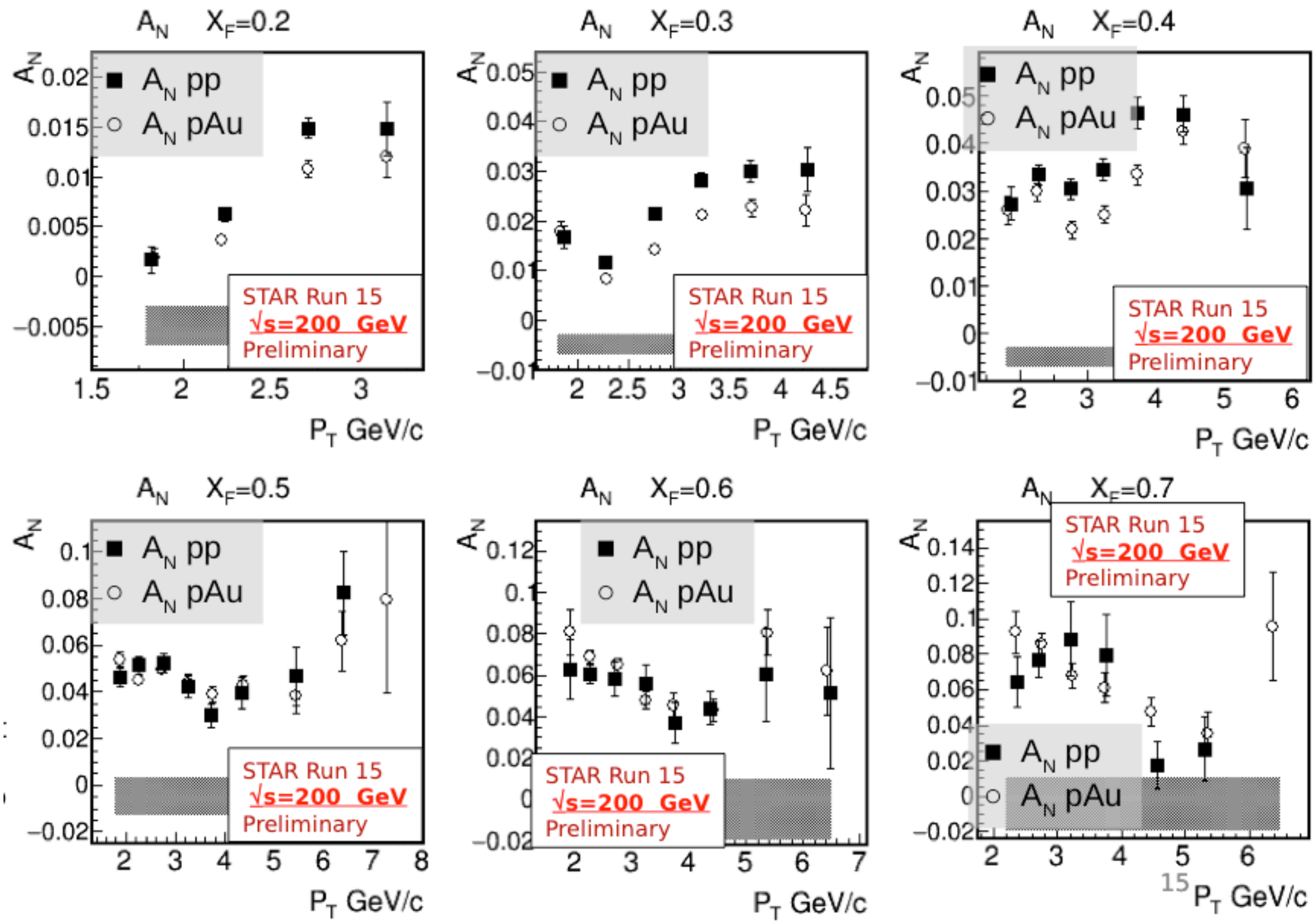


Steve Heppelmann – CIPANP 2012

$s^{1/2}$=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 $A_N \sim 1/p_T$
- 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