PHENIX Transverse Spin Measurements

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for the
PHENIX Collaboration

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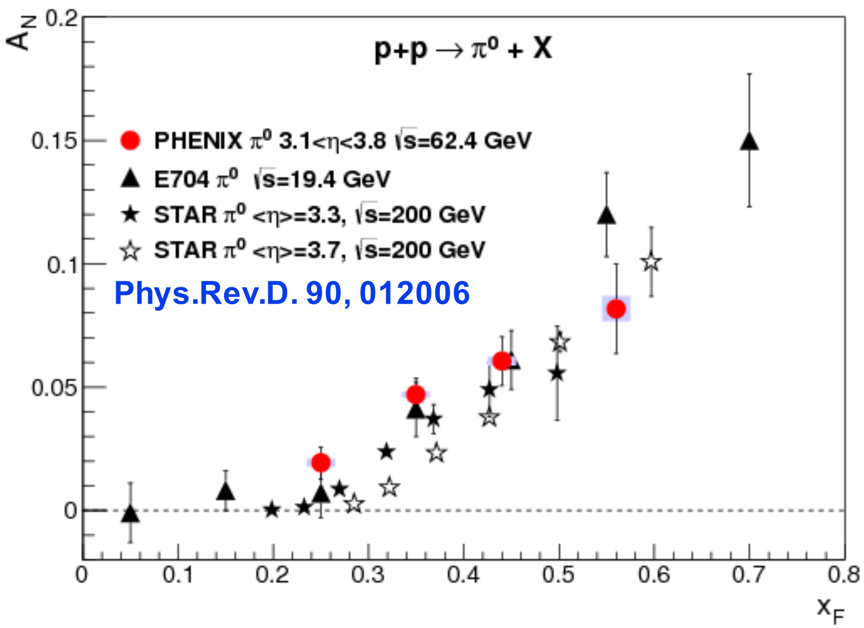
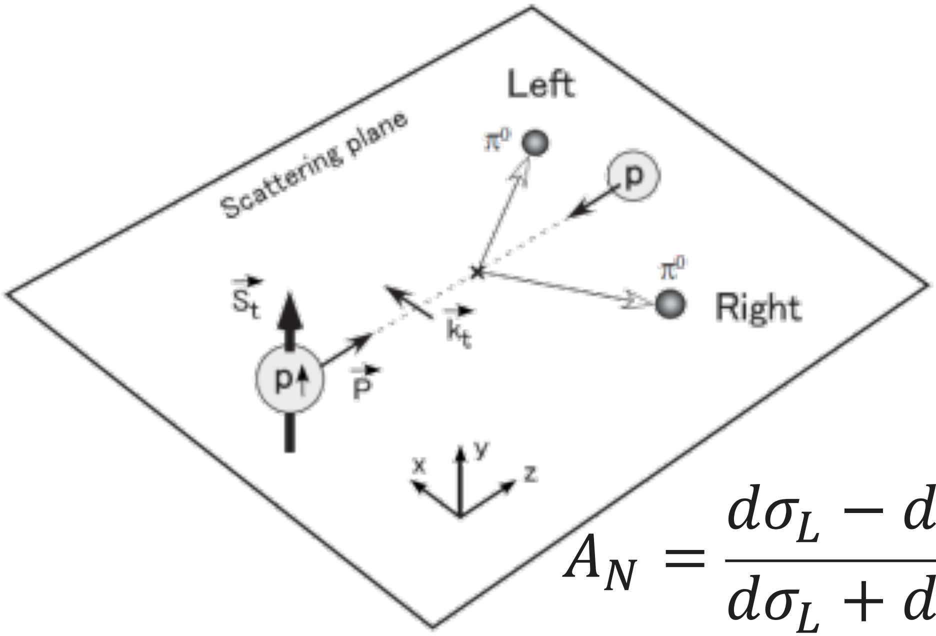
PHENIX

UC RIVERSIDE
UNIVERSITY OF CALIFORNIA

Transverse Spin Asymmetries

- The persistence of large transverse asymmetries at RHIC energies, where collinear pQCD describes the cross-sections well, was a surprise.
- The transverse structure of the nucleon is largely unknown
- Very forward neutron asymmetries, which is in soft region, are also not well understood.





$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

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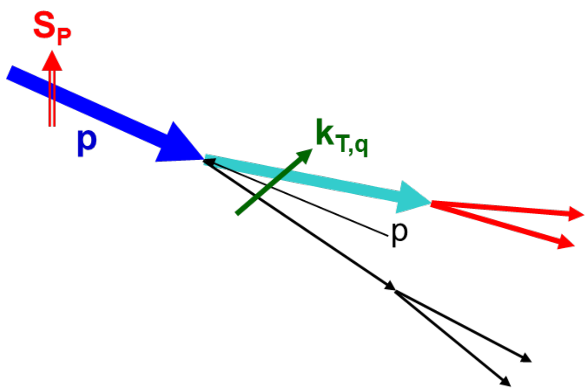
Transverse Spin Asymmetry Sources

(I) Initial State Effects: “Sivers”

Correlation between proton-spin and intrinsic transverse quark momentum

$$\underbrace{\bar{f}_{1T}^{\,q}(x,k^2)}_{\text{Sivers distribution (initial state)}}\ D_q^h(z)$$



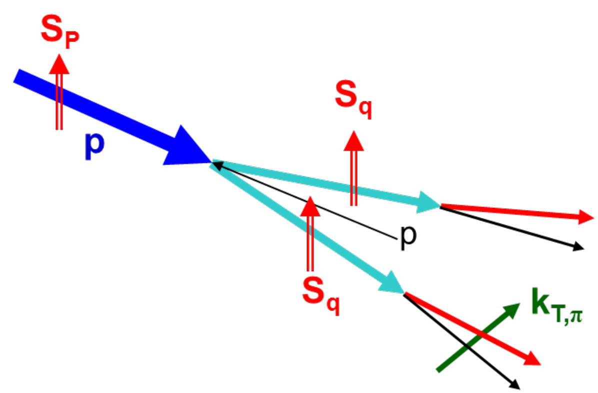
D. Sivers, Phys. Rev. D **41**, 83 (1990)

Twist-3 quark-gluon/gluon-gluon correlators in polarized hadron.

(II) Final State Effects: “Collins”

Correlation between proton & quark spin + spin dependant fragmentation function

$$\underbrace{q(x)}_{\text{Quark transverse spin distribution}}\ H_1\underbrace{(z_2,\bar{k}^2)}_{\text{Collins FF (final state)}}$$

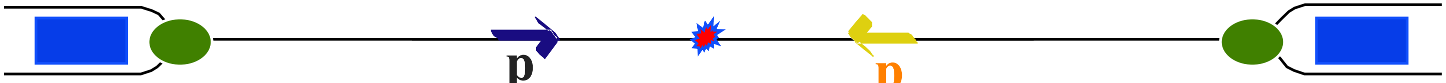


J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

Twist-3 quark-gluon fragmentation function.

Very forward A_N (p_T<0.1GeV/c)

Very forward neutron production in pp collision



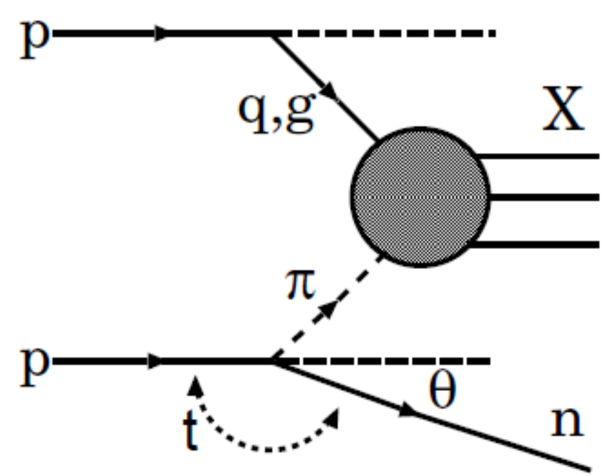
pQCD not applicable (p_T < 0.1 GeV/c)

Mechanism, Regge theory?

- » Pion exchange?
- » Pomeron exchange & decay?
- » Other reggeons?

Asymmetries

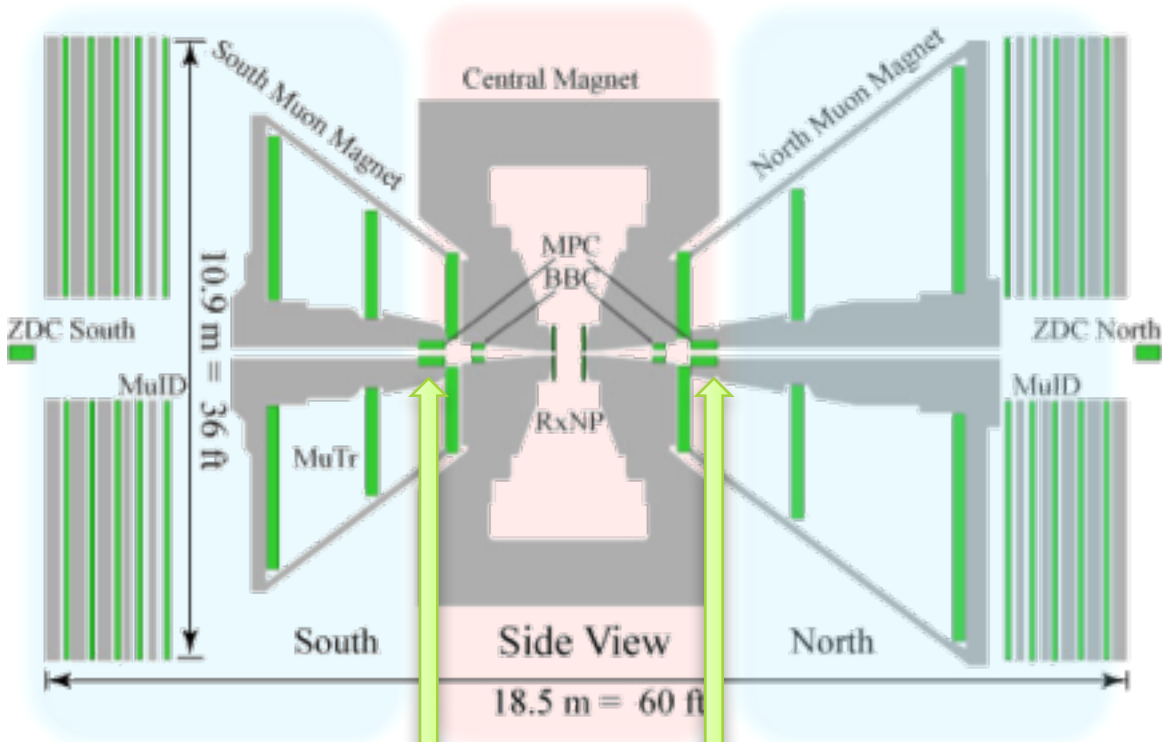
- » Initial surprise, used for polarimetry at RHIC
- » Can arise from interference between a spin flip and non-flip with different phases, e.g. π-a_1
- » A dependence?



The PHENIX Detector

Central Arms
$|\eta| < 0.35$
- charged hadrons
- π^0, η
- direct photon
- J/Ψ
- heavy flavor

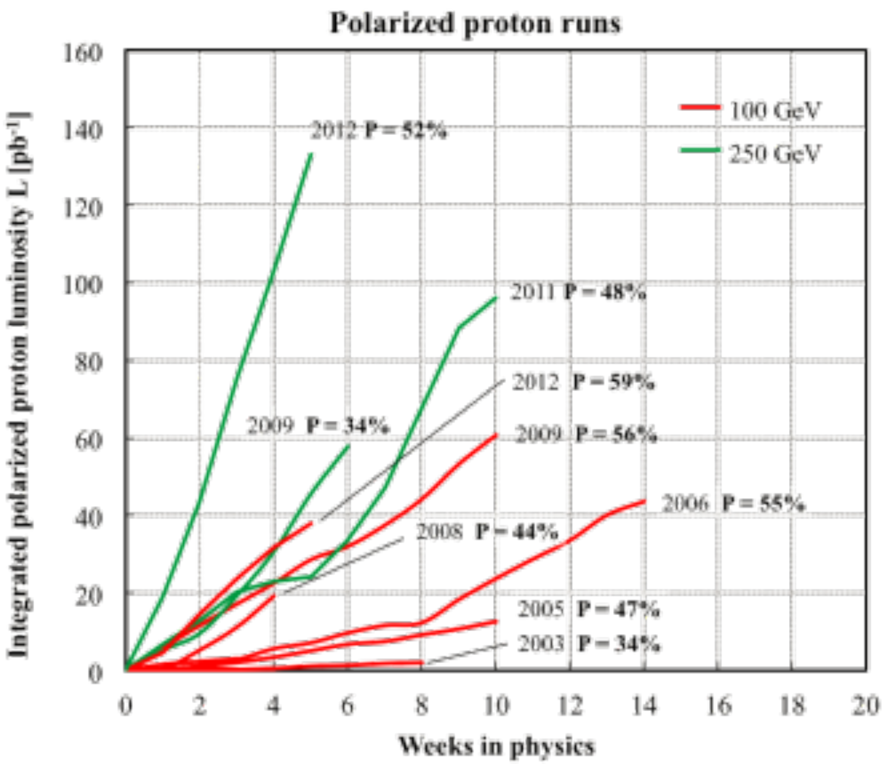
ZDCs: very forward neutrons, $\eta > 5.9$



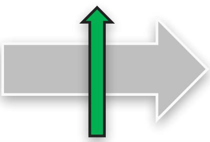
Muon Arms
$1.2 < |\eta| < 2.4$
- J/Ψ
- charged hadrons
- heavy flavor

MPC $3.1 < |\eta| < 3.9$
- π^0, η

Polarized Protons at RHIC-PHENIX



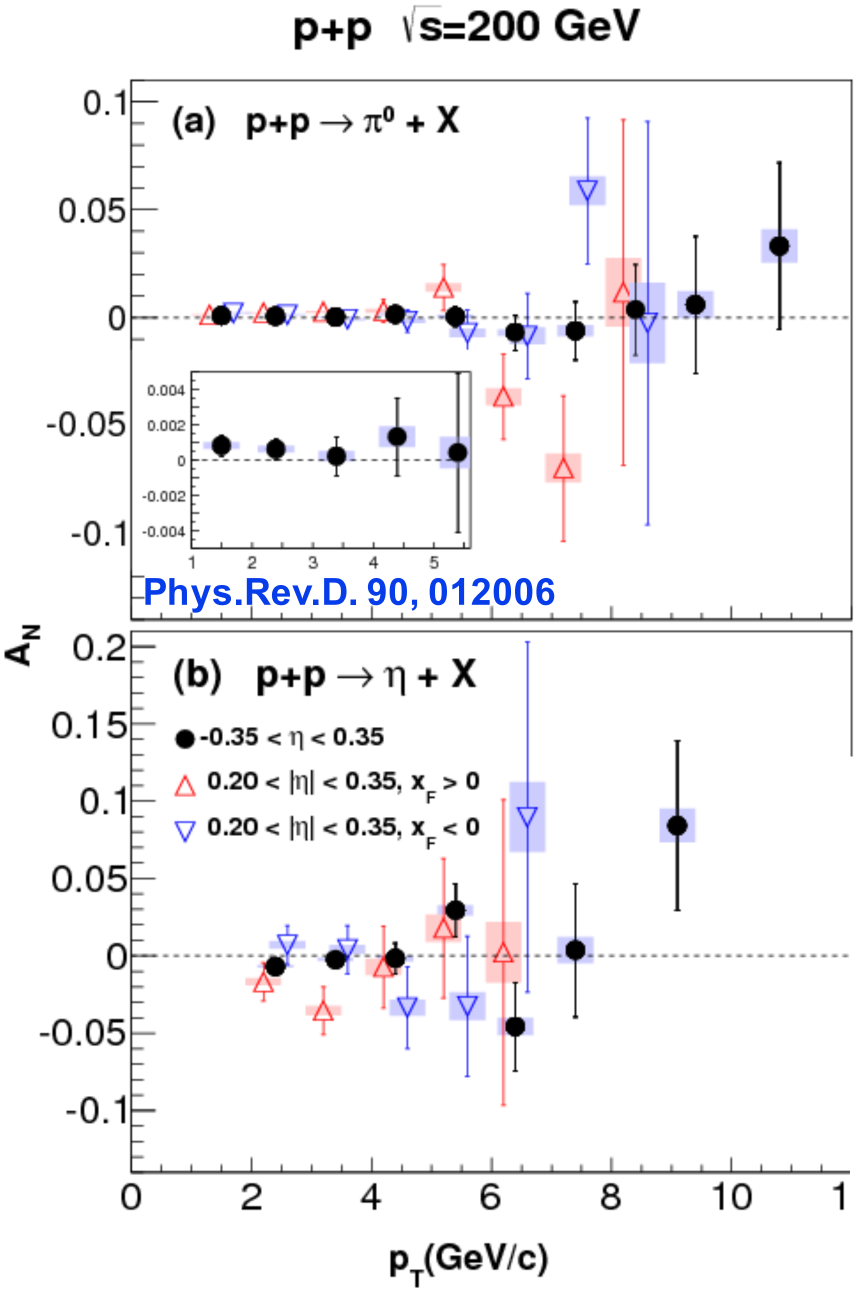
Transverse



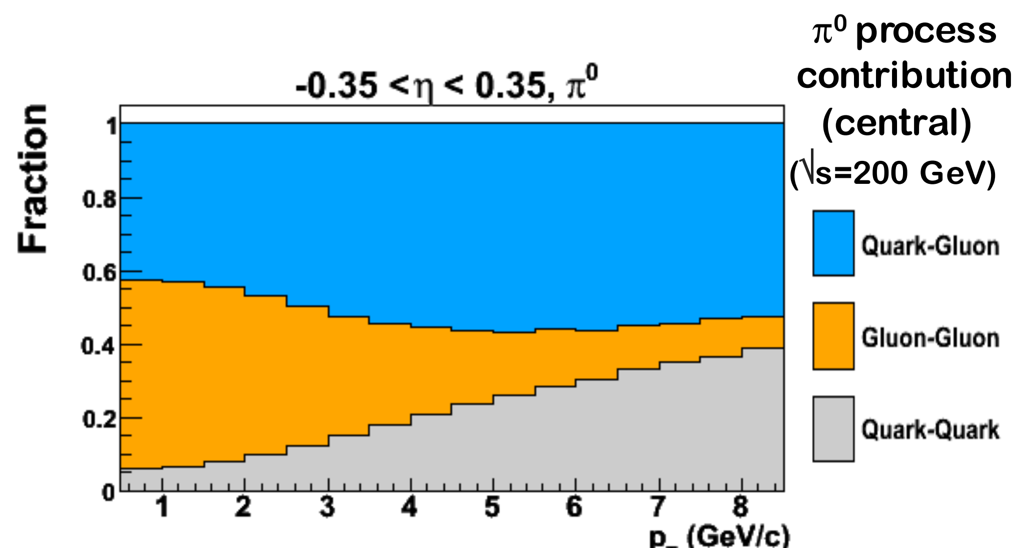
Year	Species	$\sqrt{s}$ (GeV)	L (pb^{-1})	P
2006	pp	62.4	0.02	48%
2006	pp	200	2.7	51%
2008	pp	200	5.2	46%
2012	pp	200	9.2	58%
2015	pp	200	50	60%
2015	pAu	200	1.27	60%
2015	pAl	200	3.97	54%

- **PHENIX A_N measurements:**
  - Central ($|\eta|<0.35$) π^0, η
  - Forward ($1.2<\eta<2.4$) μ, J/ψ ($3.1<\eta<3.9$) π^0, η
  - Very forward ($\eta>5.9$, $1.2<\theta<2.4$ mrad) neutrons

A_N: mid-rapidity π^0 and η



- π^0 asymmetries consistent with zero observed over a wide p_T range
- Exceed precision of previous publication (Phys. Rev. D 74, 094011) by a factor of 20 and extends p_T range.
- Constrains gluon Sivers
- η asymmetries are also consistent with zero.



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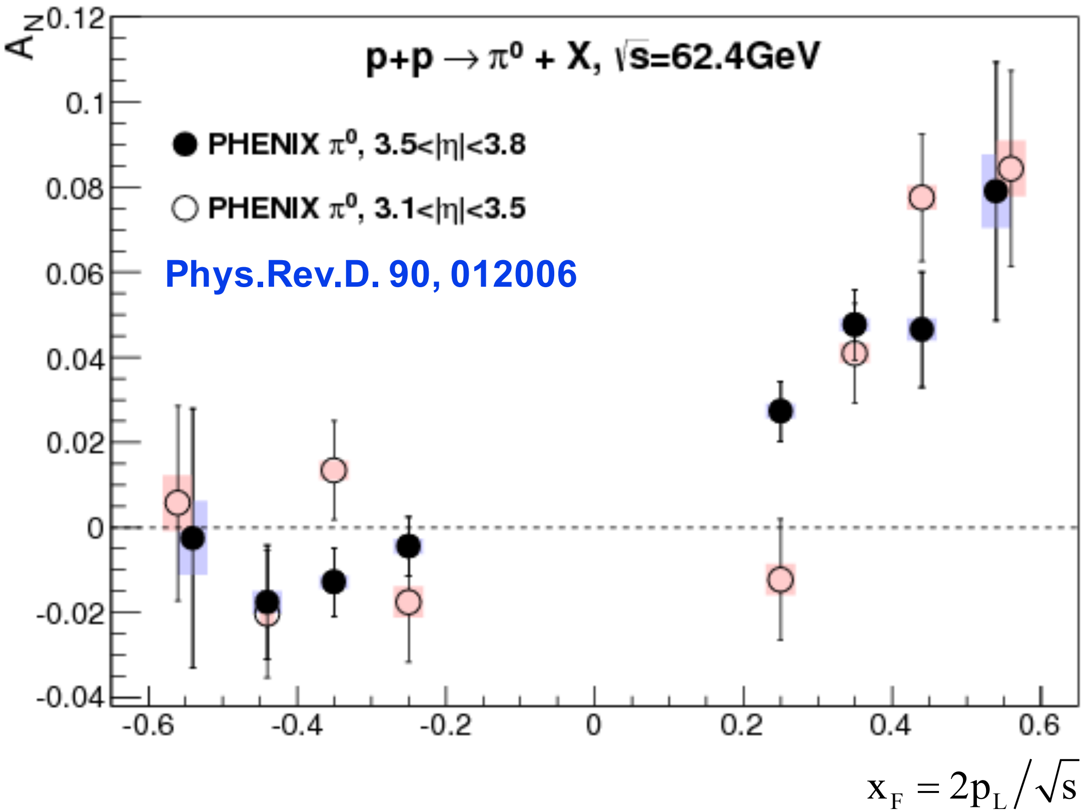
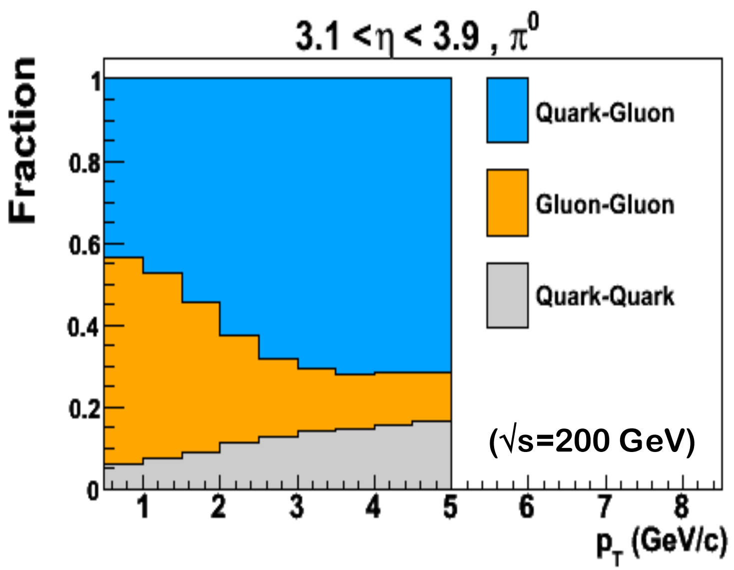
Forward π^0 A_N (62.4 GeV)

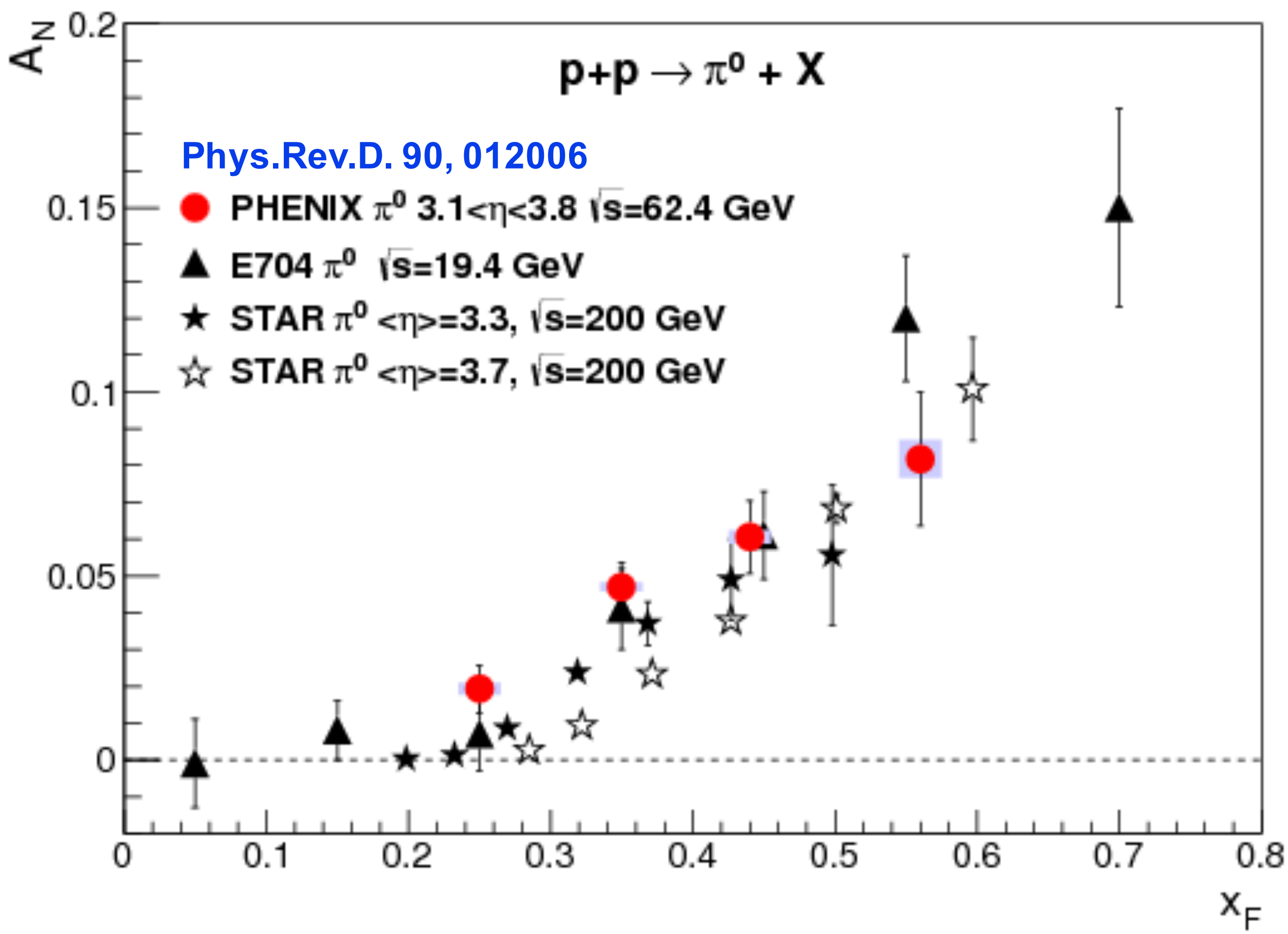


π^0 process contribution in PHENIX forward arms



- Significant asymmetries for x_F>0 (~ linear for x_F > 0.2)
- A_N consistent with zero for x_F<0
- Quark-gluon is the dominant partonic component.

Forward π^0 A_N √s dependence

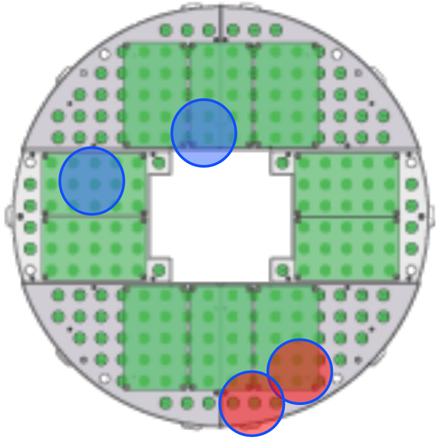


- **Sizable forward non-zero asymmetries**
- **No dependence on √s apparent from 19.6 GeV to 200GeV**
- **Note: slight differences in pseudorapidity and/or p_T**

Forward A_N for EM Clusters

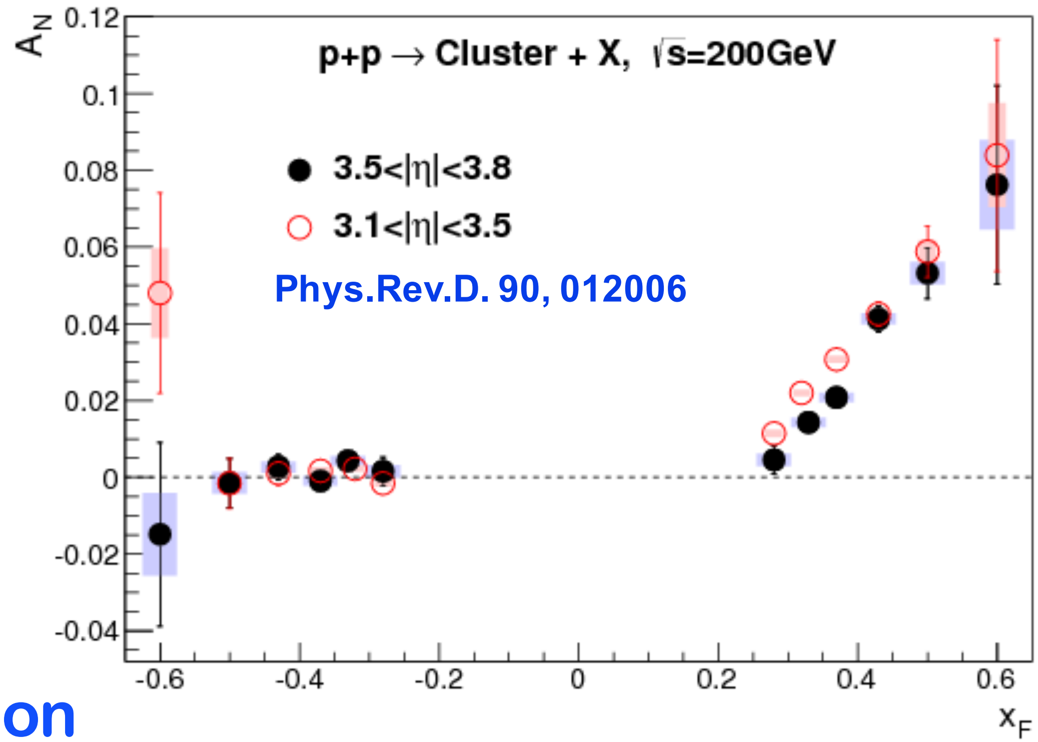
MPC

tower size 2.25^2 cm^2
220 cm from vertex

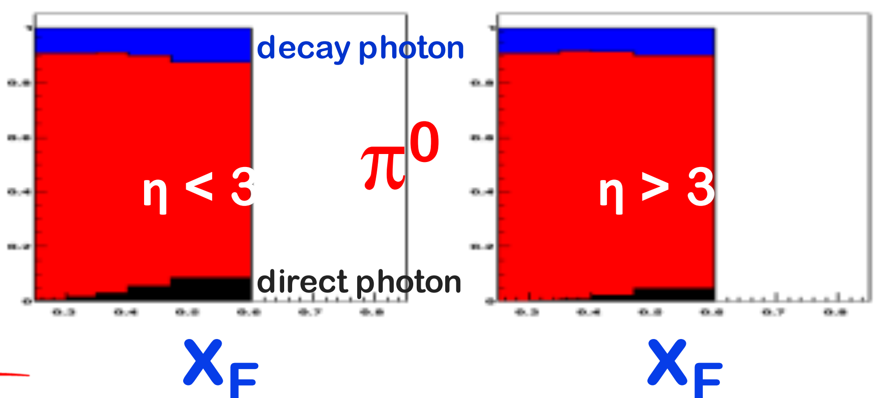


Decay photon impact positions for low and high energy π^0's.

$\sqrt{s}$ = 200 GeV

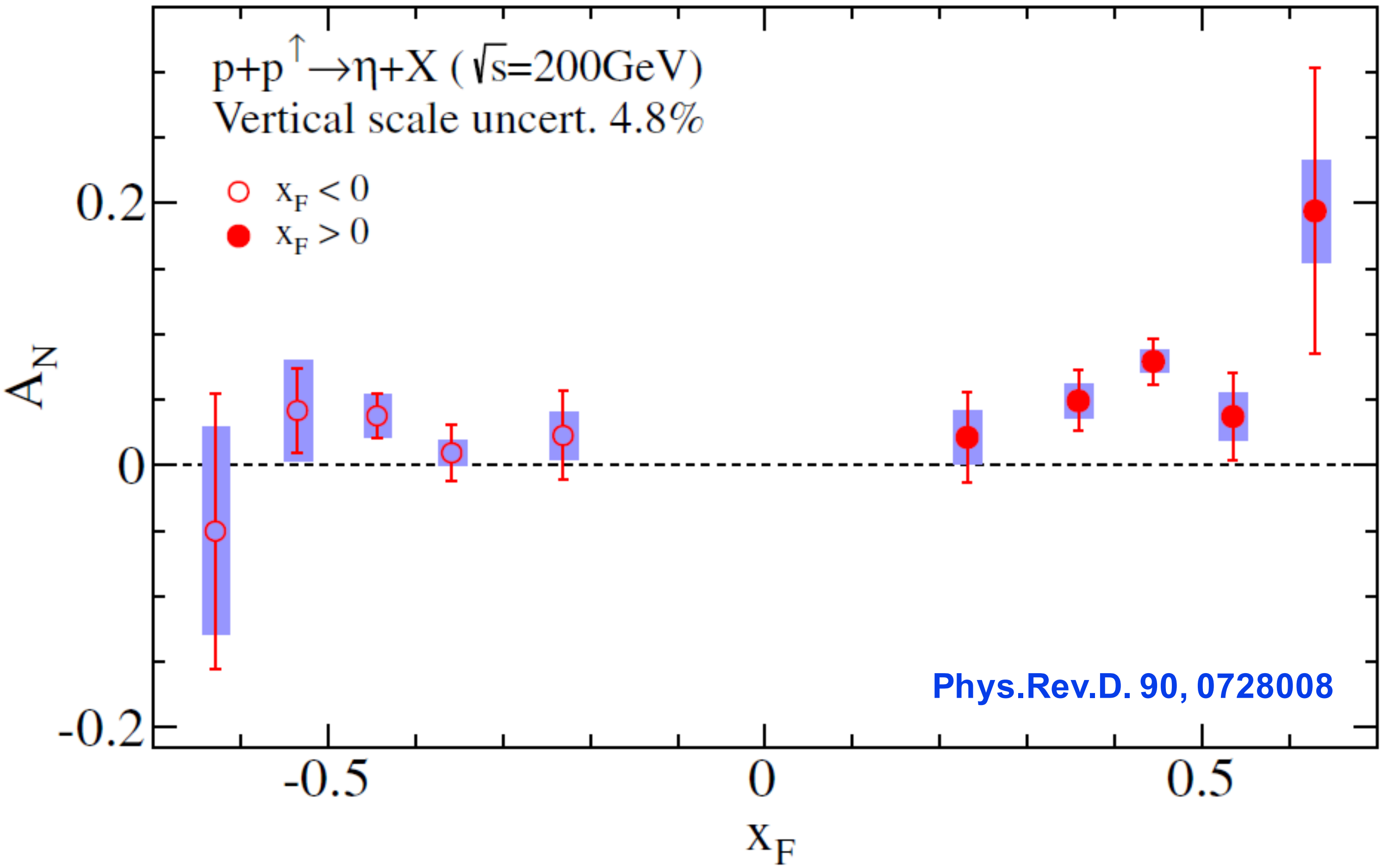


EM Cluster contribution



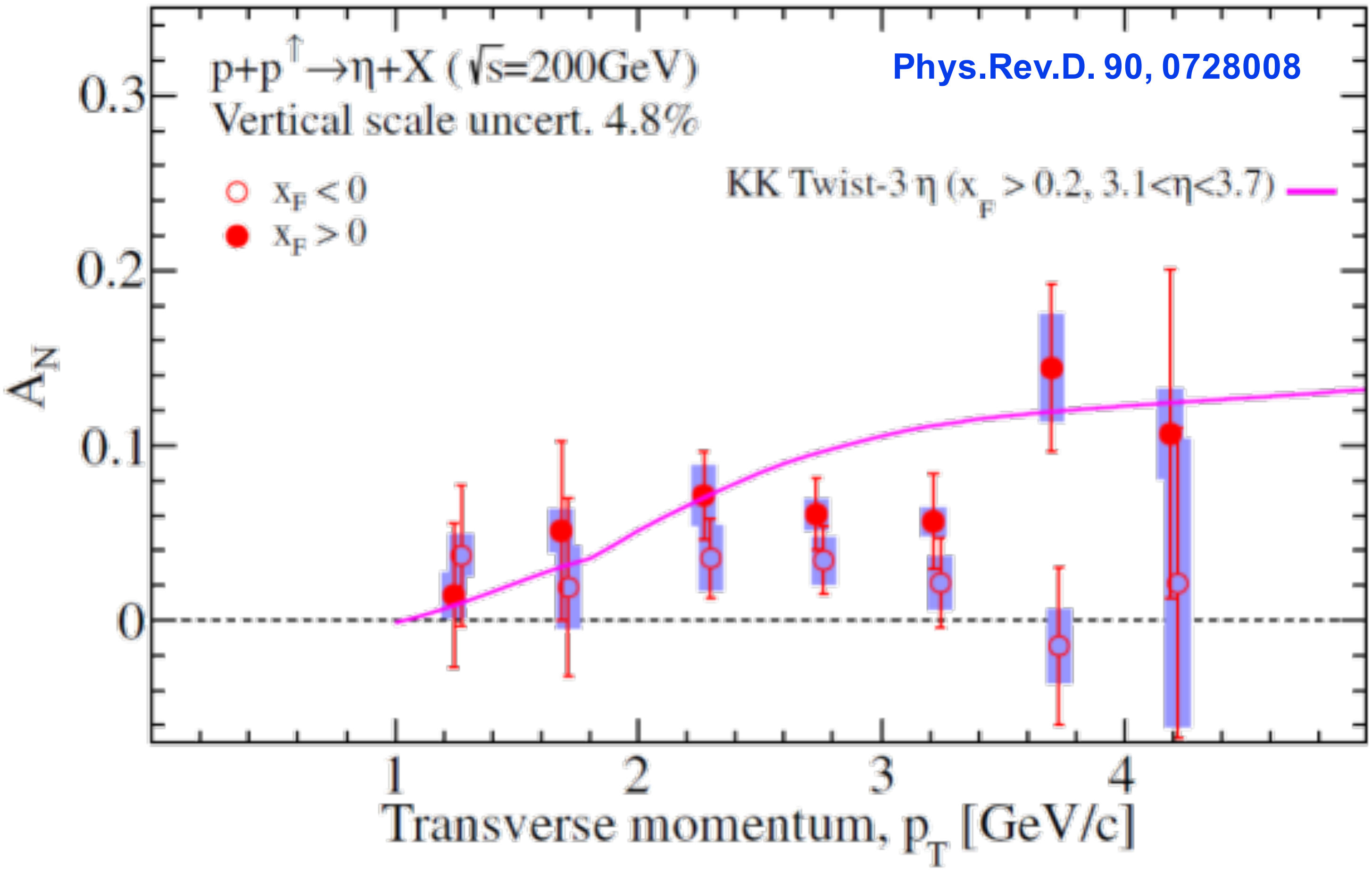
Magnitude of forward asymmetries similar to E704 (19.4 GeV/c^2) and STAR at (200GeV/c^2)

Forward $A_N(\eta)$ x_F dependence



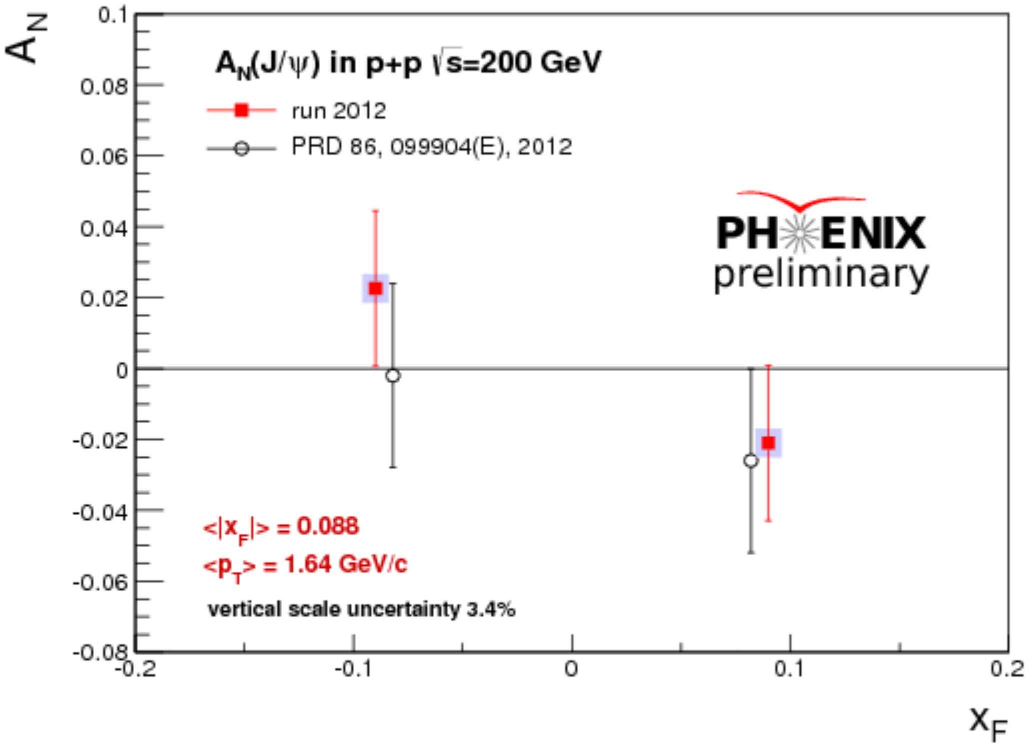
- Rising A_N ranging from 2% to 20% for positive (forward) x_F
- Consistent with flat & zero (1.7σ) at negative (backward) x_F

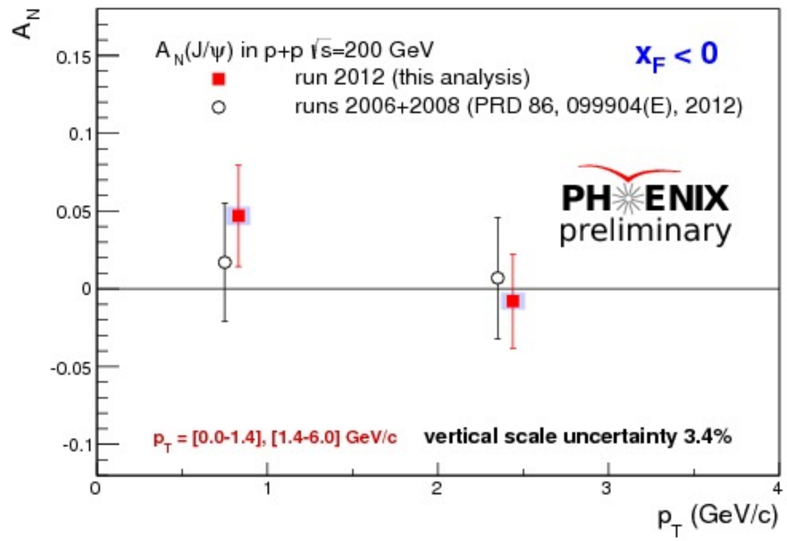
Forward $A_N(\eta)$ p_T dependence

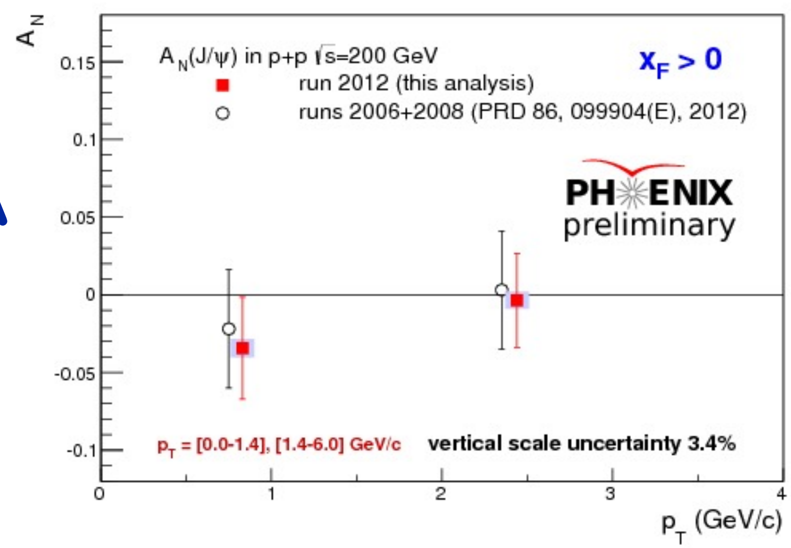


- $x_F >$ 0.2: Non-zero asymmetry is seen $\langle A_N \rangle = 0.061 \pm 0.012$.
- $x_F <$ -0.2: Consistent with zero within 1.7σ

A_N Forward J/ψ at 200GeV (Run 12)







- Only color single generates SSA ⇒sensitive to production mechanism.
- A_N is consistent with zero.
- Precession limited by statistics ⇒ Run 15 (>5x statistics) + p↑A.

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A_N Forward single muon (200 GeV)

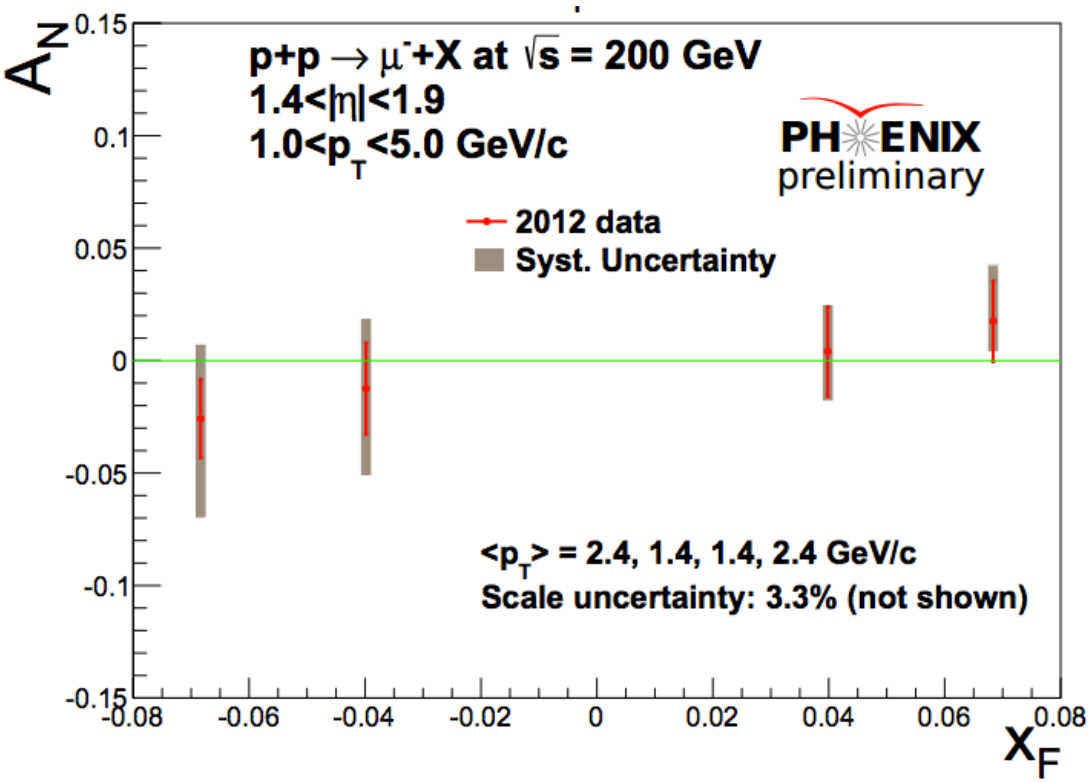
Single muon A_N from D meson decay

» Production dominated by gg fusion

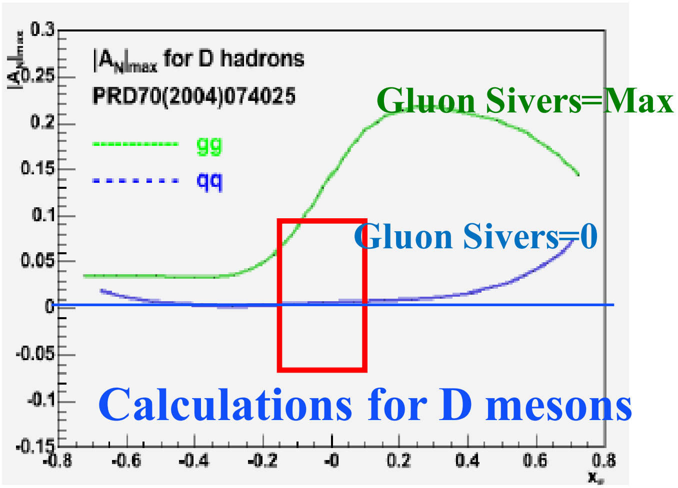
» Probes gluon related correlation functions (initial state)

– Koike and Yoshida, Phys Rev. D84 (2011) 014026.

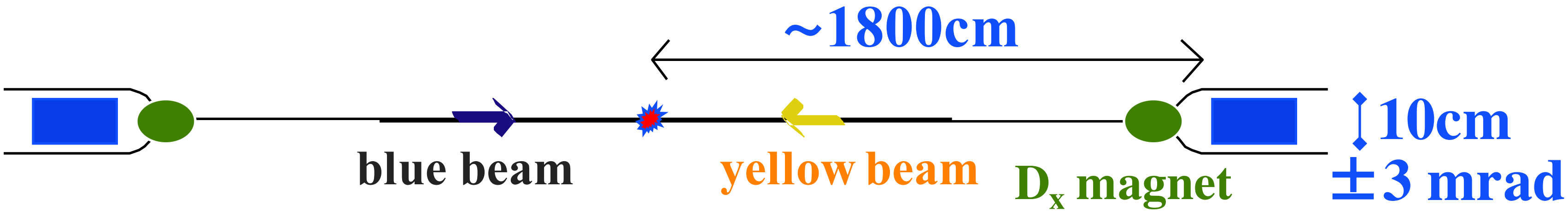
» Sensitive to gluon Sivers distribution



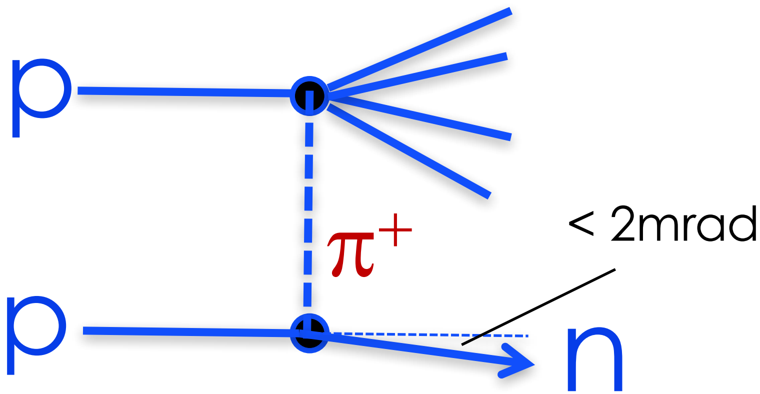
- A_N consistent with zero
- Both charges are studied for Run12 *p*+*p* 200 GeV, result will be released soon
- Run15 *p*+A 200 GeV analysis is ongoing



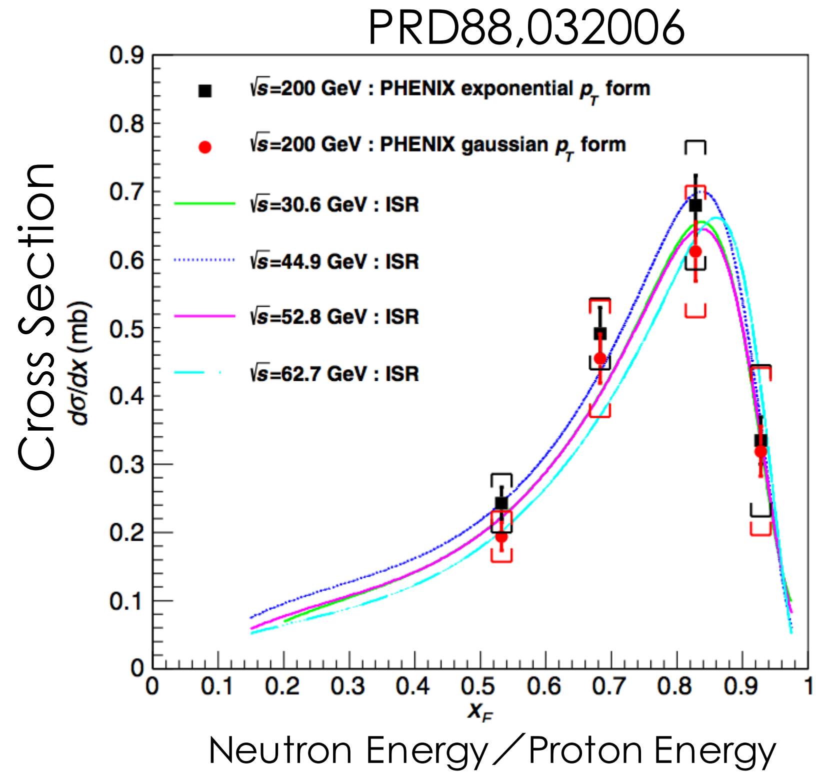
Very Forward Neutron Production pp



Cross Section

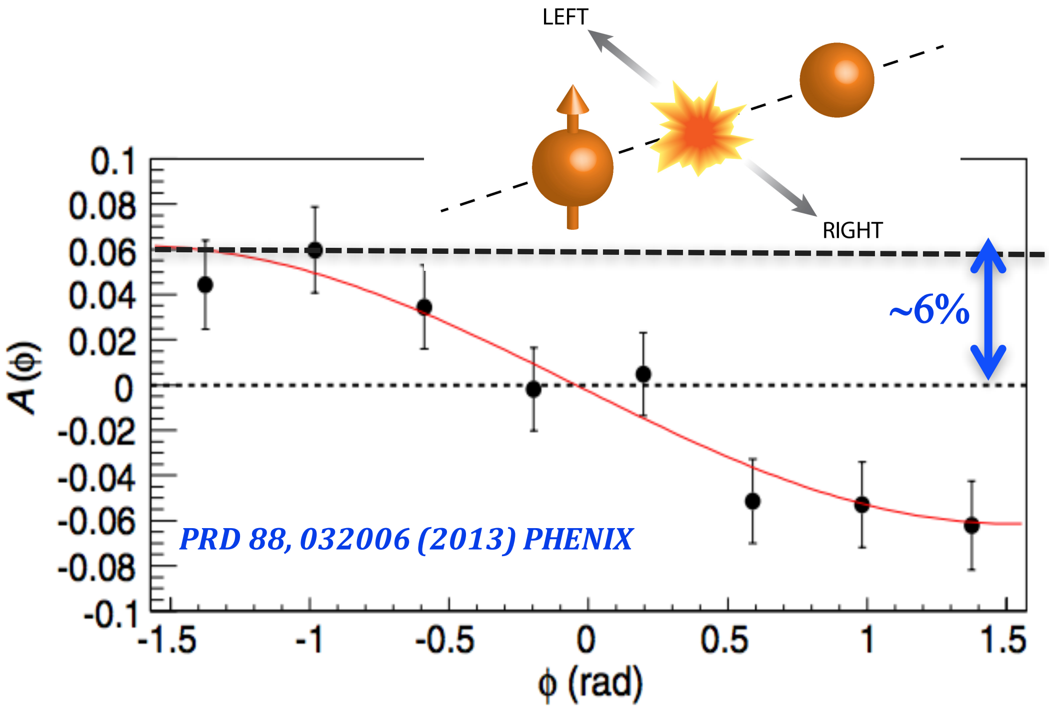


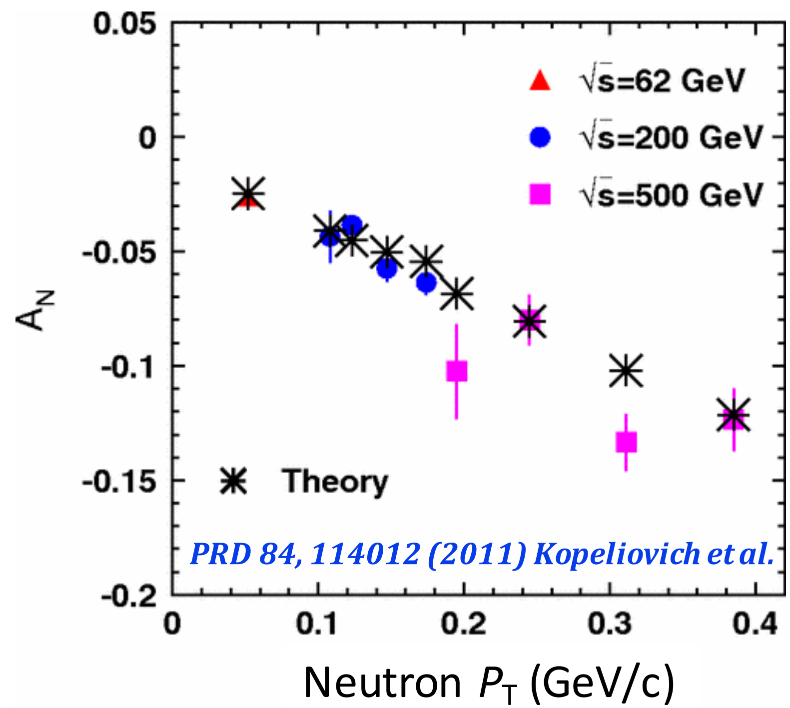
Momentum Transfer ~ 100MeV



Neutron cross-section is well described by One-Pion Exchange in Regge theory.

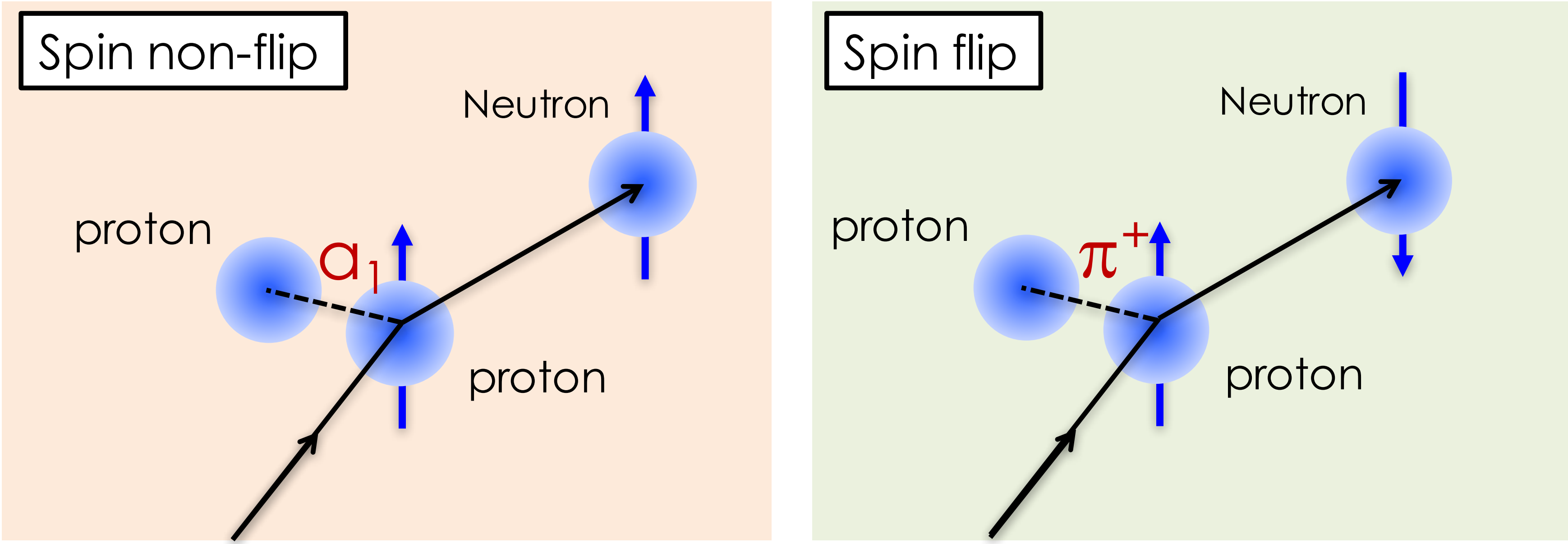
A_N(neutron) very forward p↑p





- Large asymmetry were not expected before the measurements
  - Large forward neutron A_N measured @ PHENIX with dedicated neutron detectors (2006)
  - pQCD is not applicable for p_T<0.22GeV at 200 GeV
- Interference between a spin-flip amplitude due to the pion exchange and spin nonflip amplitudes from other Reggeon exchanges can account for asymmetry.

Origin of non-zero very forward $A_N(n)$



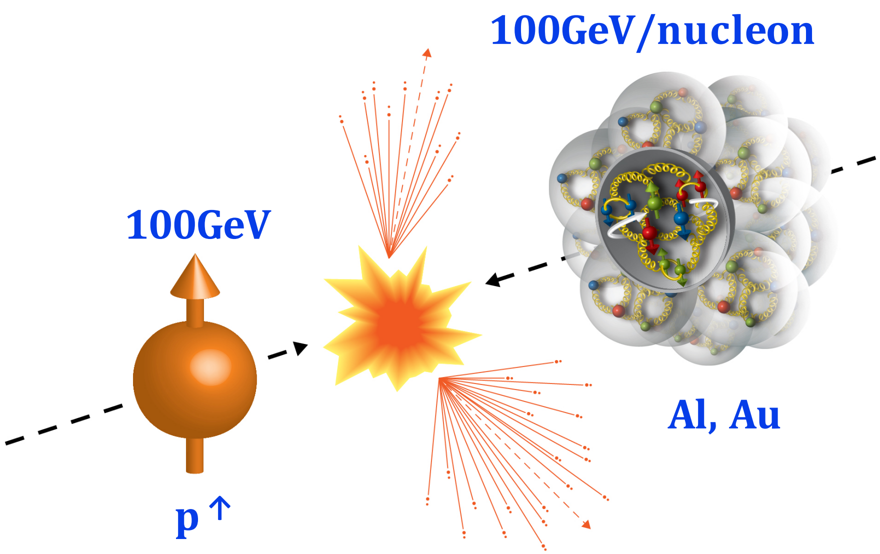
$$A_N \approx \frac{2\,\mathrm{Im}\left(\phi^*_{non-flip}\phi_{flip}\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

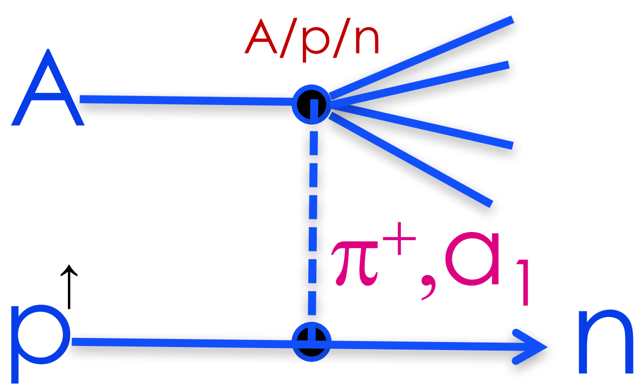
a_1 (1260) Reggeon
Spin Parity = 1^+

δ : phase shift

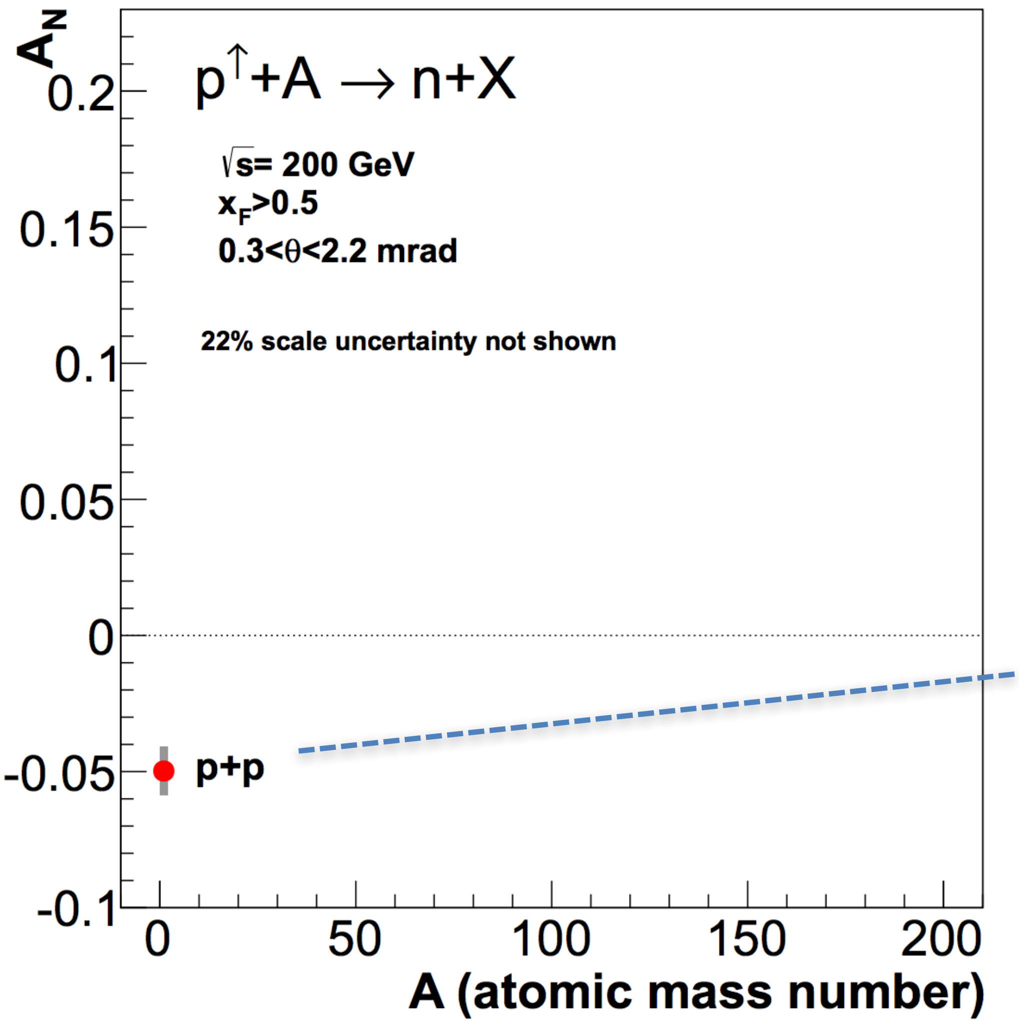
p↑A very forward Neutron A_N

- **Run 15 first p↑A run**
  - Atomic mass dependence of $A_N(n)$?
  - Can measurements be explained by π-a_1 interference in the existing Reggeon framework?
- **Expectations:**
  - Weak dependence on A



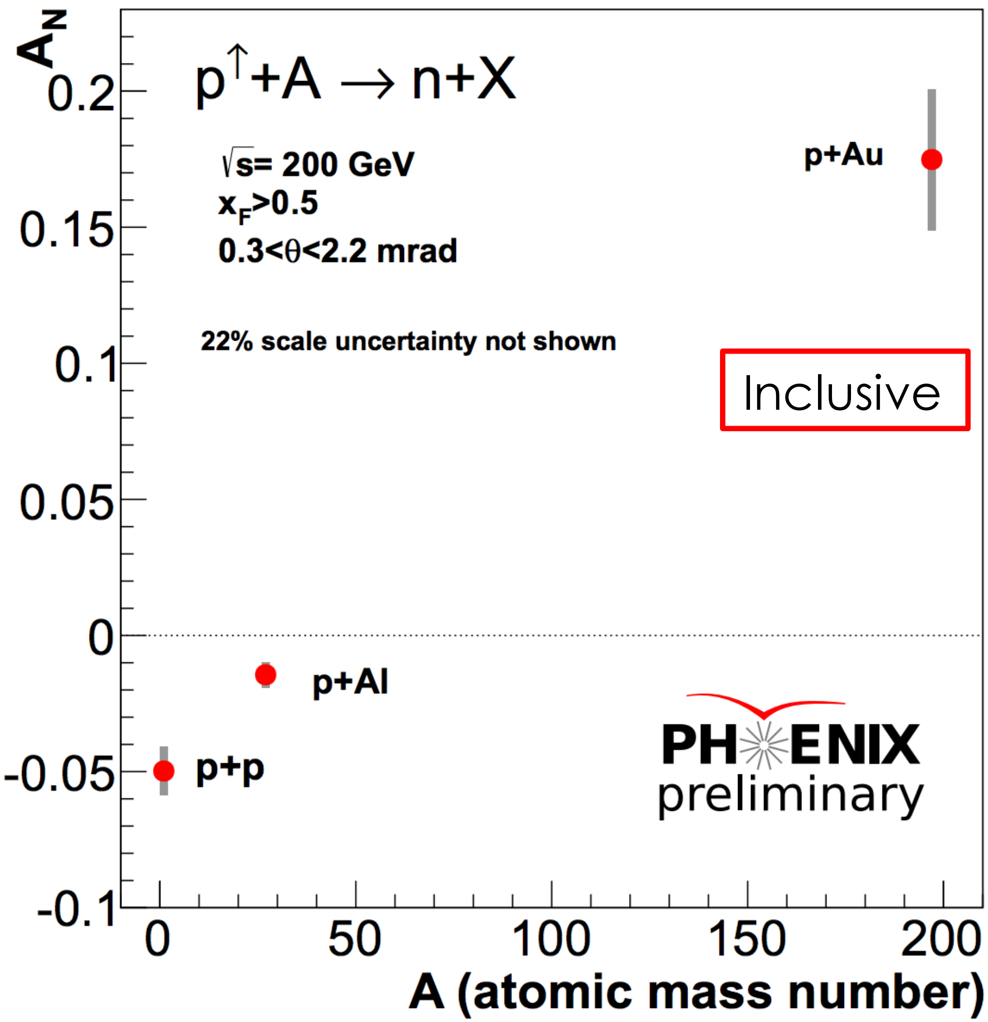


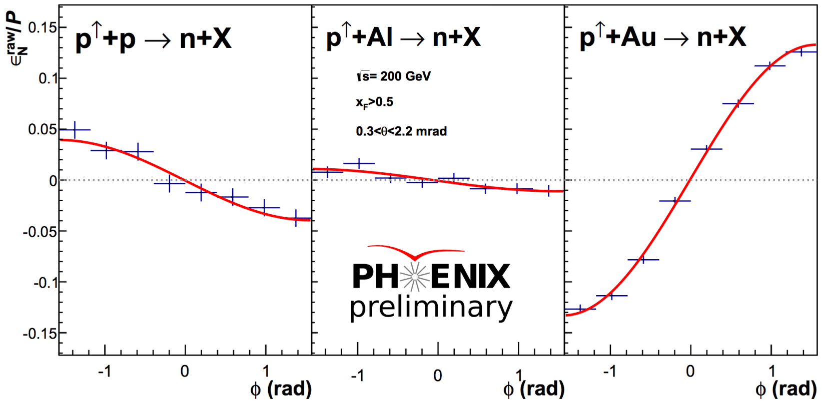
A_N (n) A-dependence (inclusive)



Vanishing (present framework)?

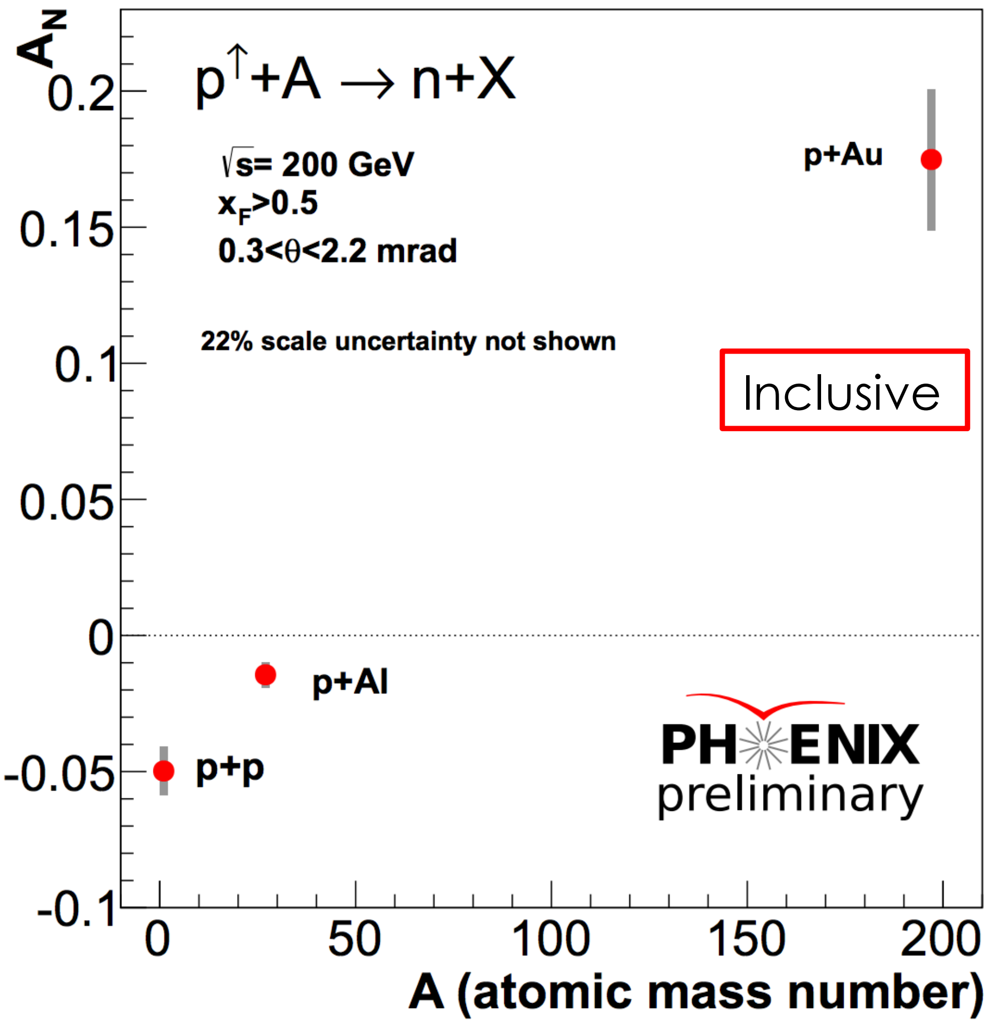
A_N (n) A-dependence (inclusive)

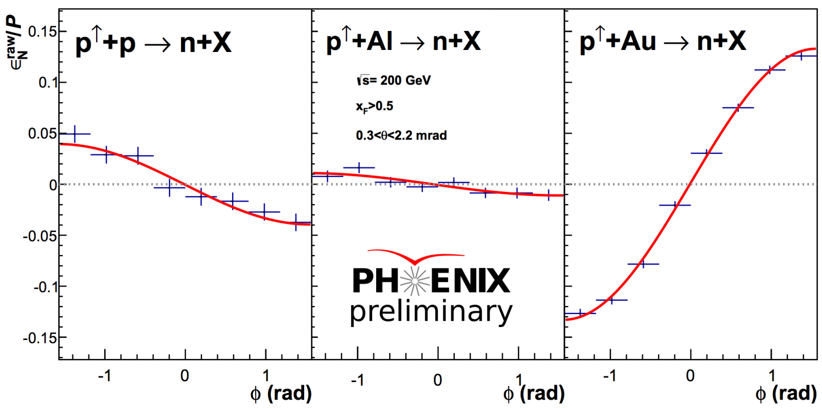




- **Data!**
  - Strong A dependence
  - Even sign changes
- **Simple *π*-a_1 interference predicts small dependence**
- **Mechanism? Why?**

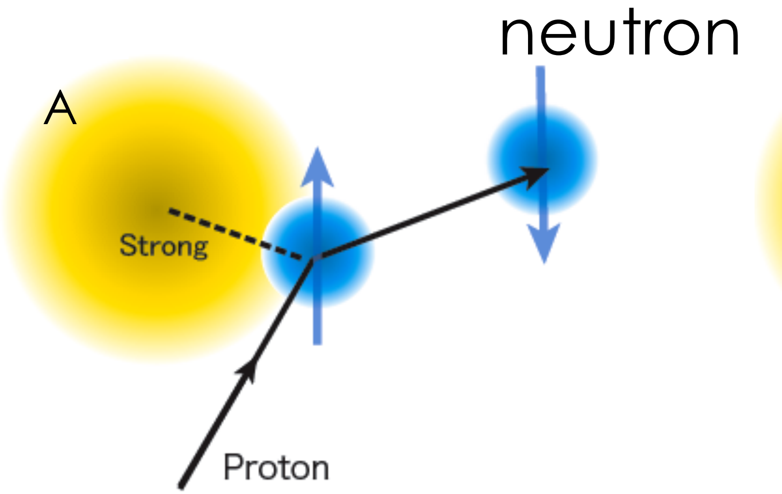
A_N (n) A-dependence (inclusive)

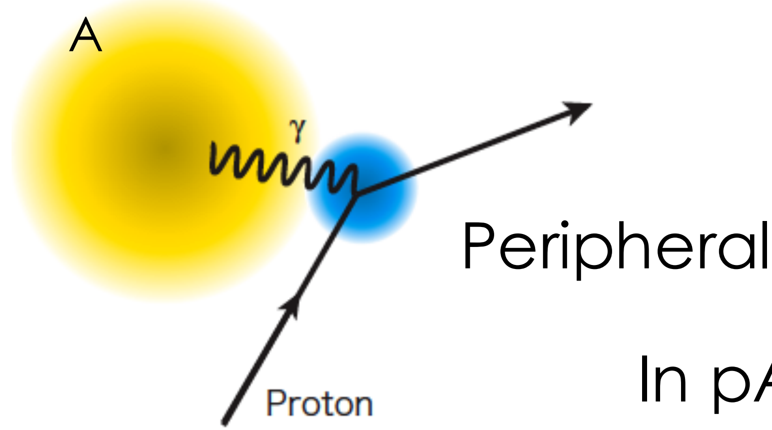




	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

EM Ultra Peripheral Collision (UPC)

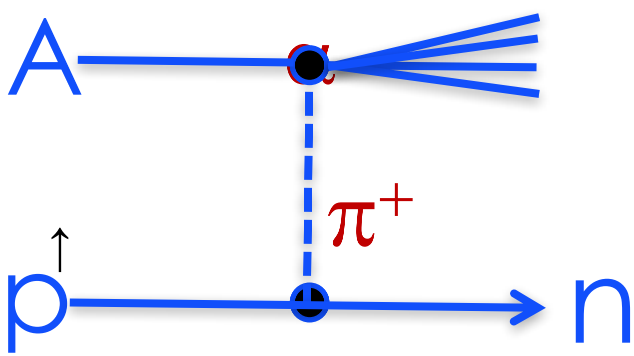


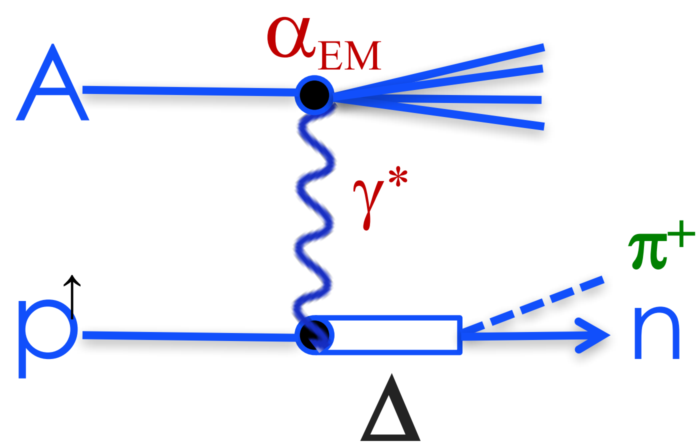


In pAu case

$t \rightarrow 0$

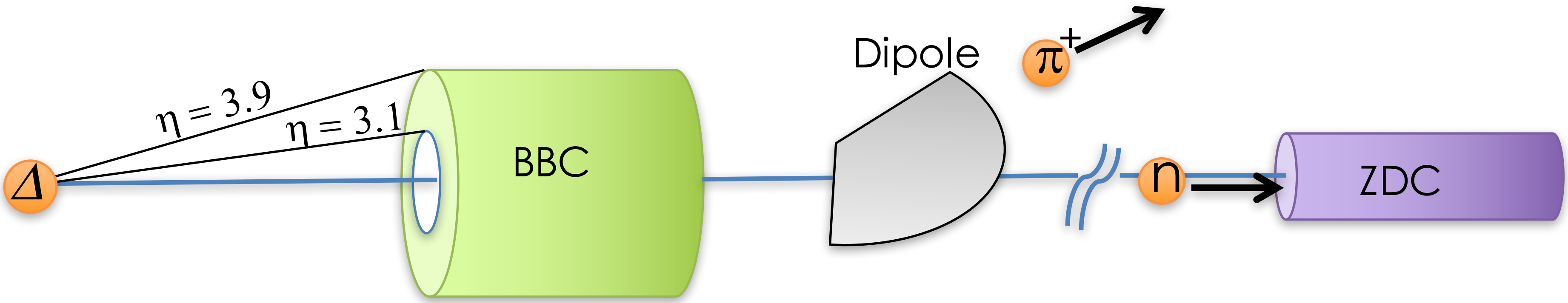
$Z^2 \bullet \alpha_{EM} \sim 79^2/137 \sim 45$





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

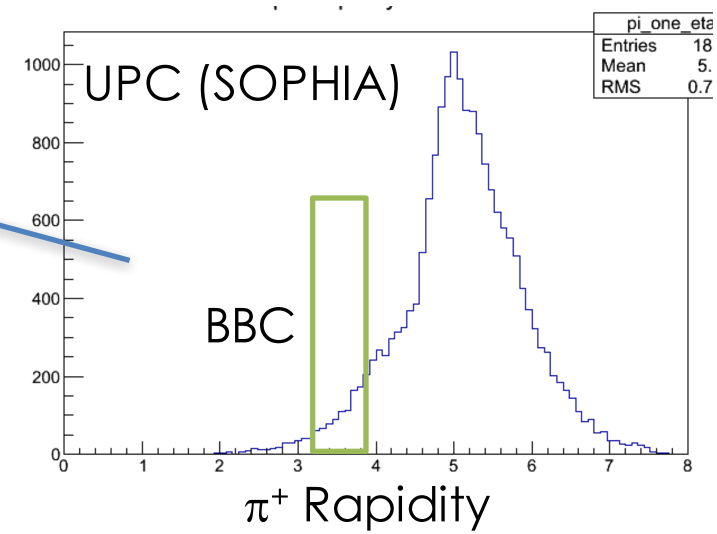
Identify UPC



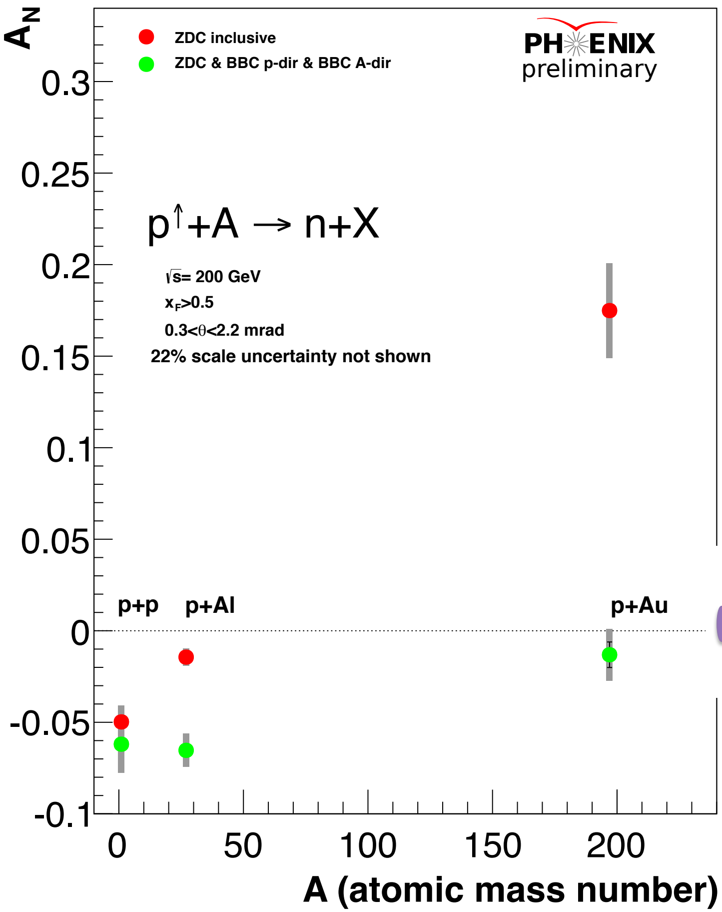
Most of decayed pions go through BBC hole and will be swept away by the dipole magnet (DX).

Very little coincidence measurements of final state from resonance.

η_π distribution of $n+\pi^+$ events

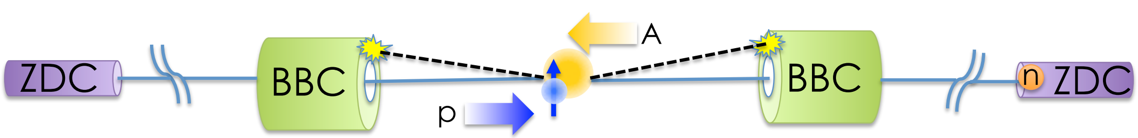


BBC Tagging and Vetoing



- Large A_N vanished in p+Au
- No sign flip in A_N
- A_N for p+p and p+Al are comparable

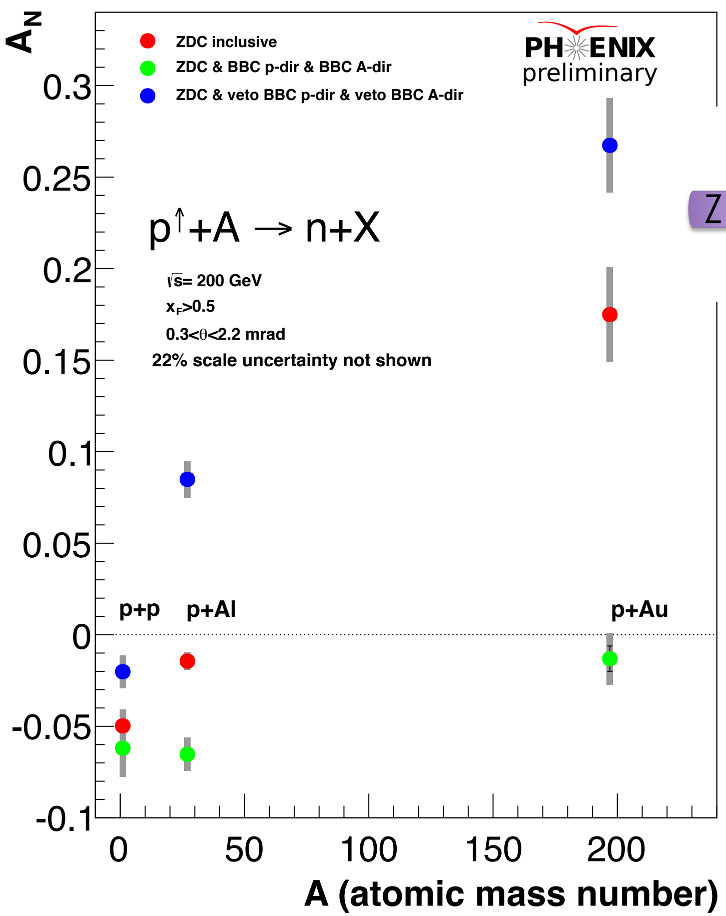
BBC Tagging



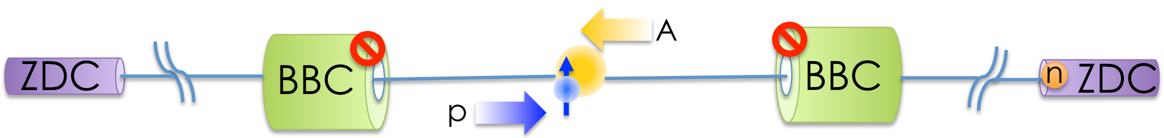
EM suppressed

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

BBC Tagging and Vetoing



BBC Vetoing

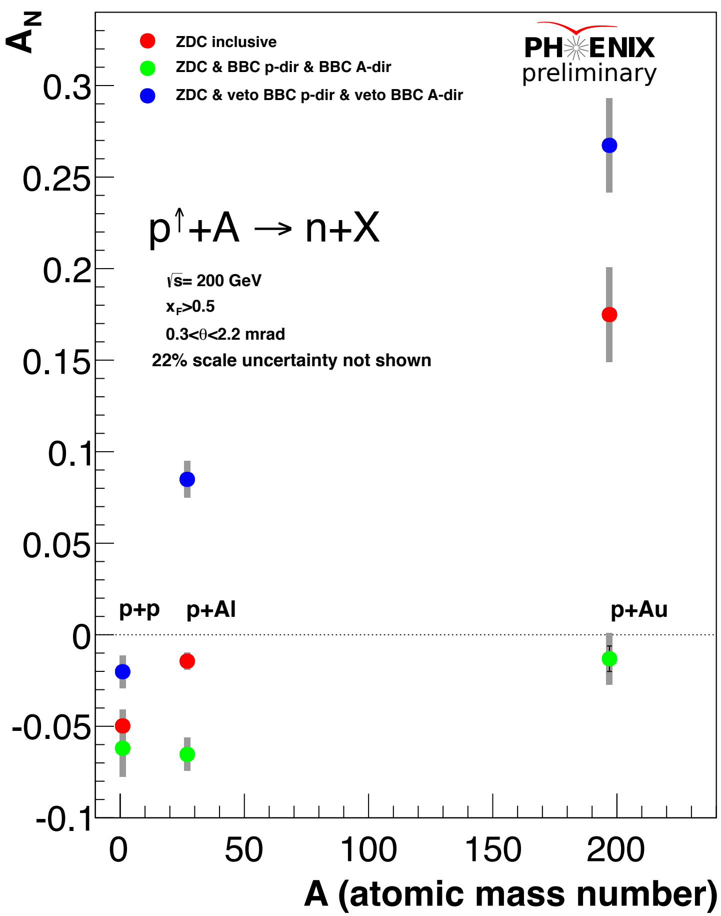


- Even larger A_N ~ 0.28 in p+Au
- Sign flip occurs between p+p and p+Al
- A_N for p+p gets even smaller ~ 0.02

EM enhanced

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

BBC Tagging and Vetoing



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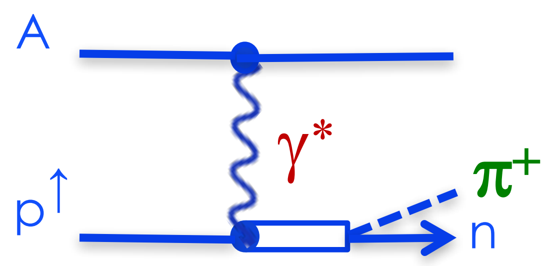
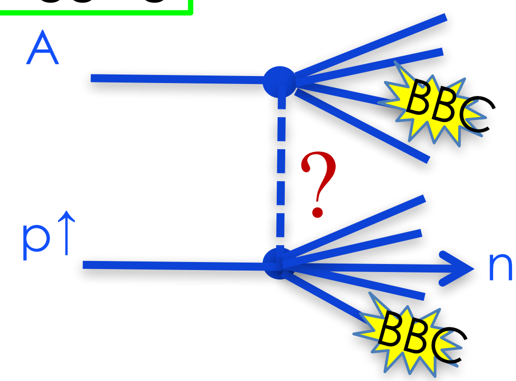


$A_N > 0$

… but why?

BBC Tagging



$A_N < 0$

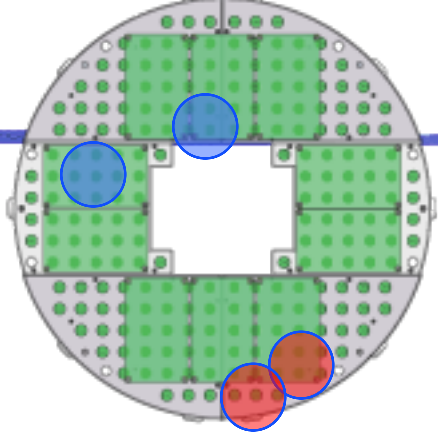
$$A_N \sim had * had + had * EM + EM * had + EM * EM$$

Summary

- **Central rapidity measurements**
  - A_N for π^0 and $\eta \Rightarrow$ constrain gluon Sivers
- **Forward rapidity measurements**
  - A_N for π^0 , EM Clusters, and η including p_T , x_F dependence
    - Comparison with data at different $\sqrt{s}$ and charged pions
  - FVTX enhances forward heavy-flavor program (μ, J/ψ)
- **Forward very neutron asymmetries – First $p^{\uparrow}A$ result**
  - Large $A_N(n)$ observed.
  - Strong dependence on A observed.
    - A_N magnitude increases by factor of ~3 from *p+p* to *p+*A.
    - changes sign from $p^{\uparrow}+p$ to $p^{\uparrow}+Au$,
  - $A_N(n)$ sensitive to correlations with BBC correlations, may indicate UPC effects
  - The A_N result is not currently explained theoretically.

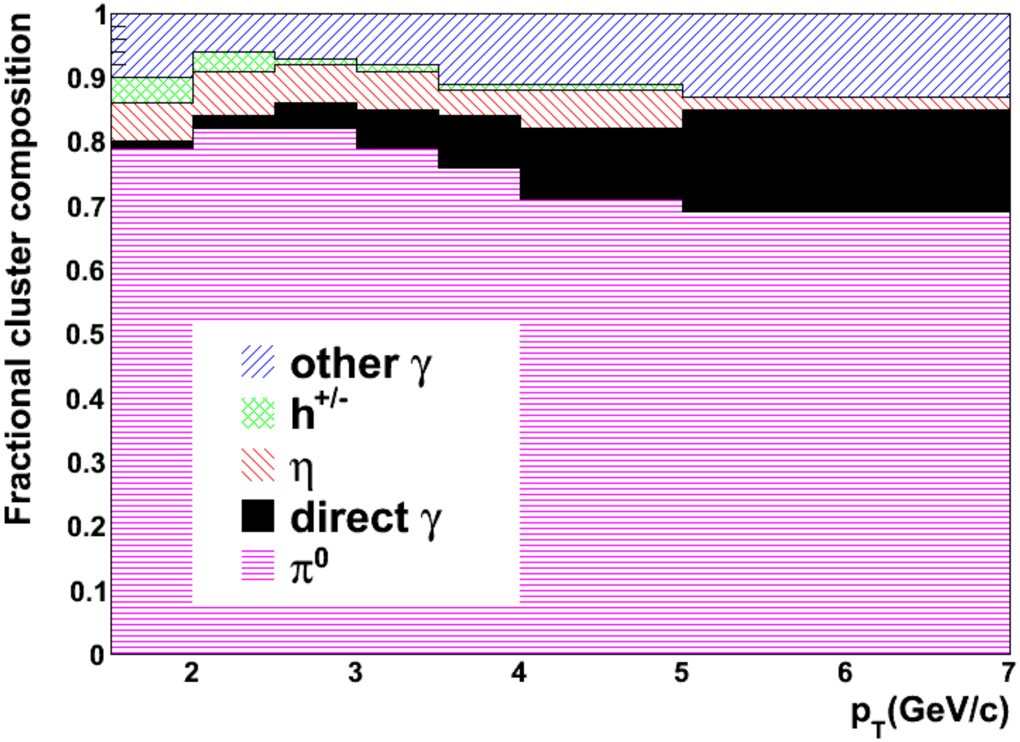
Extra slides…

MPC detectors

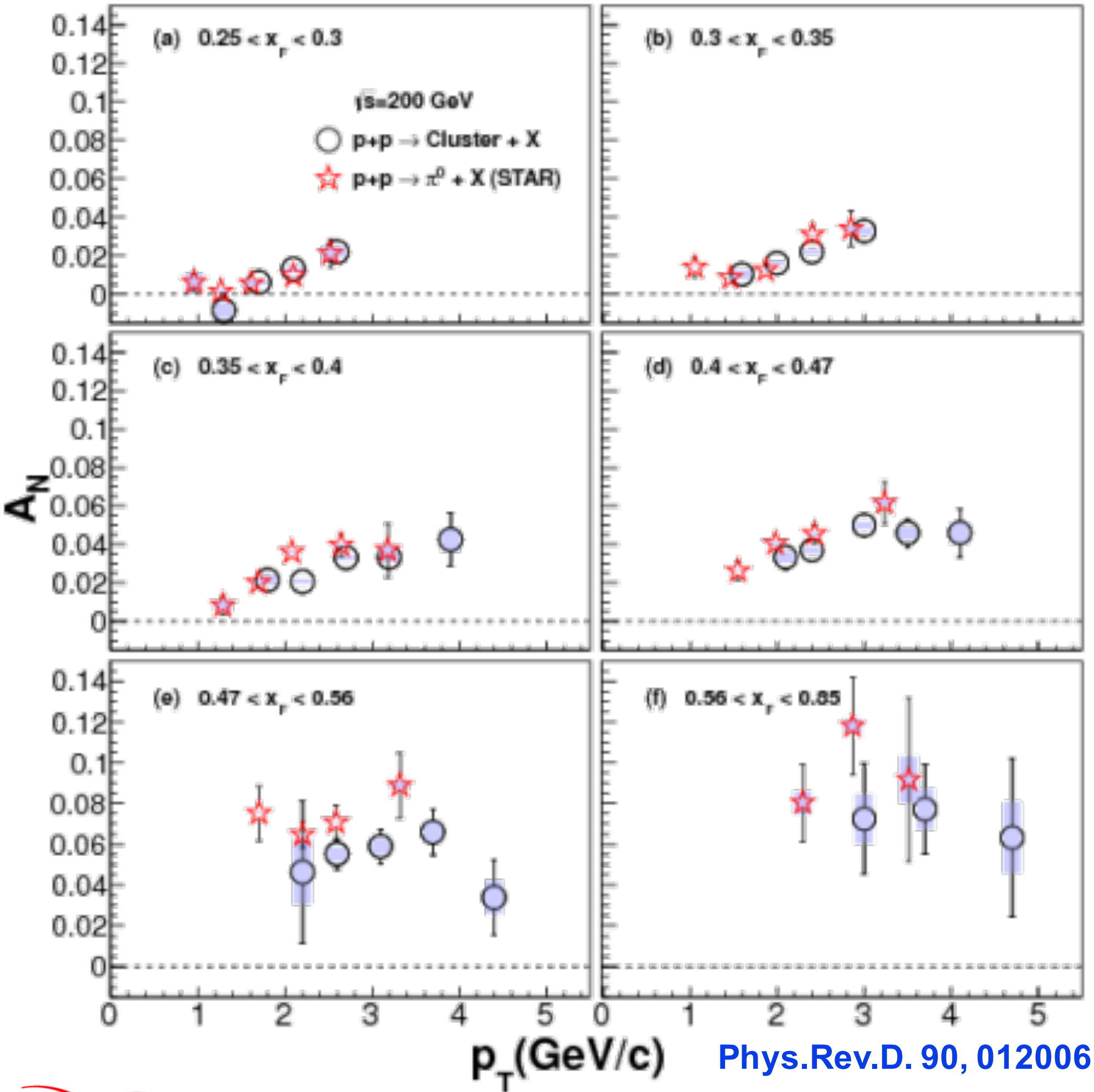


tower size 2.25^2 cm^2
220 cm from vertex

- **Lead-tungstate EMCal ($3.1<|\eta|<3.8$)**
  - » Enables measurements of forward π^0 and η mesons
- **Photon merging effects significant for E>20 GeV (p_T>2 GeV/c)**
  - » For $\sqrt{s}$=62 GeV, 20 GeV $\rightarrow$ 0.65 $x_F \Rightarrow$ two photon π^0 analysis
  - » For $\sqrt{s}$=200 GeV, 20 GeV $\rightarrow$ 0.20 $x_F \Rightarrow$"Single clusters"
- **Single Clusters**
  - » π^0's are dominant source.
  - » With increasing p_T, there is a sizable increase in contributions from direct and other photons.



Comparison of clusters with STAR π^0



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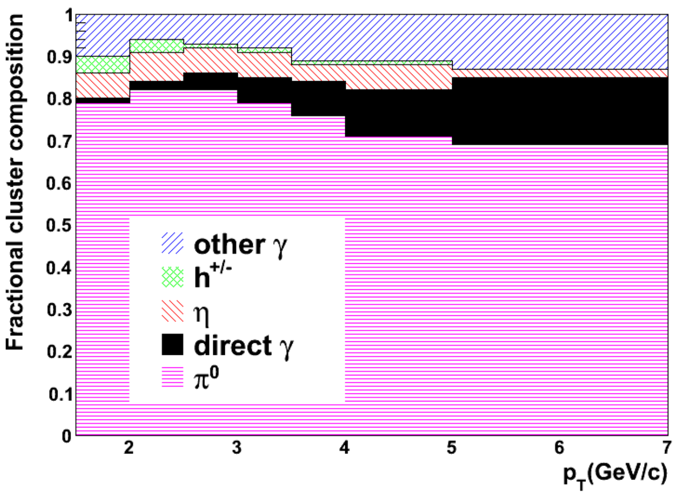
- Good agreement for $x_F < 0.4$.
- For $x_F > 0.4$, statistically limited, but there is a possible difference between clusters and π^0's, leaving room a direct photon contribution.

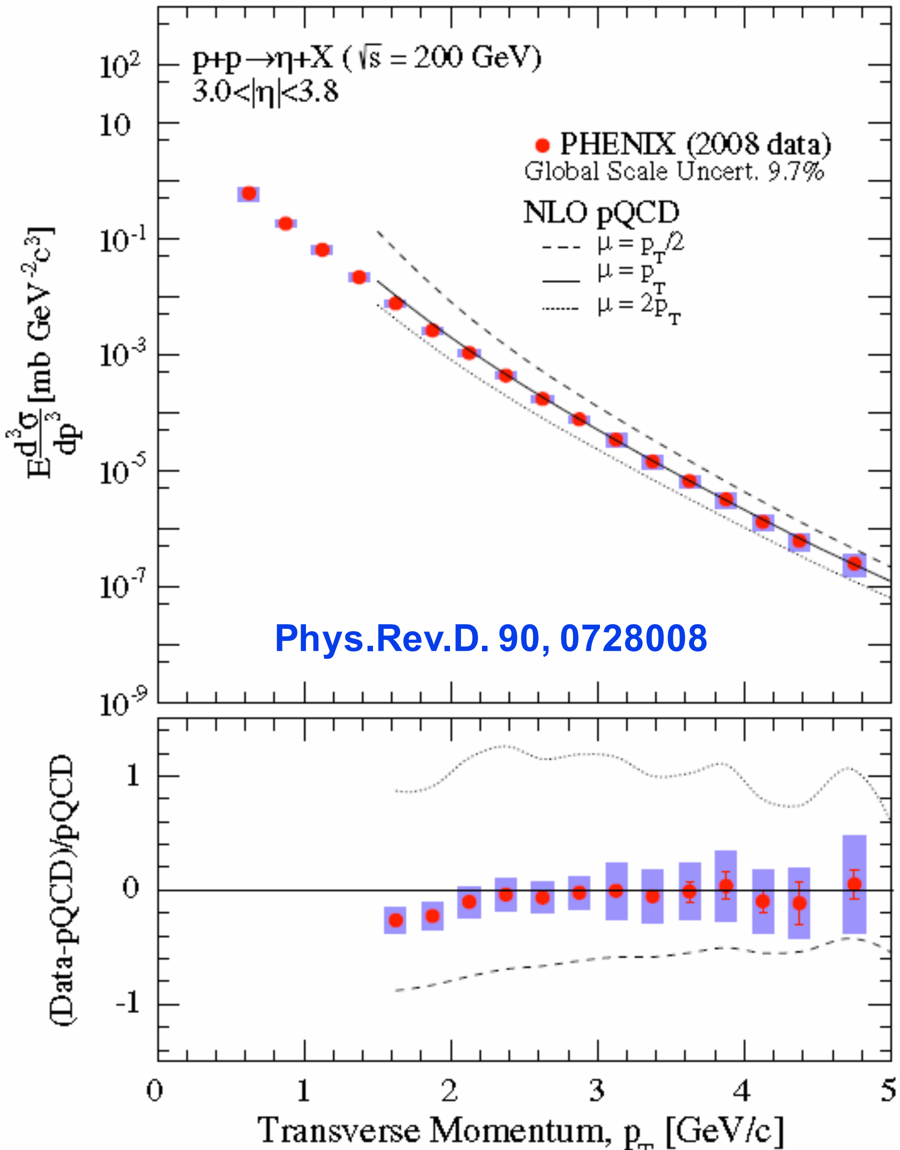


Forward η cross-section

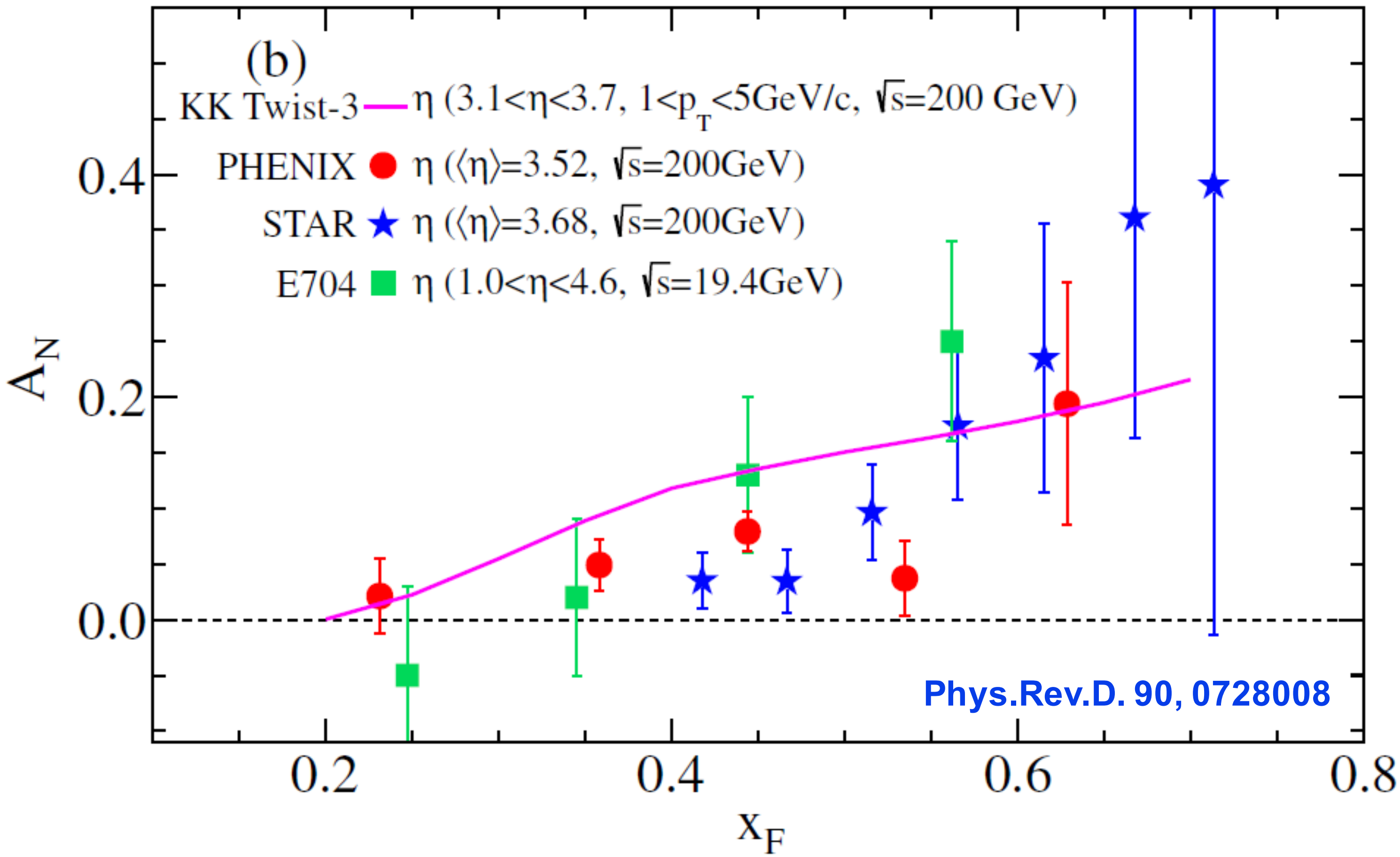
- Consistent with pQCD calculations at a scale of $\mu=p_T$ consistent with data.
- Can be used to improve constraints on η fragmentation functions.
- pQCD calculations by M. Stratmann (pp->hx + η FF)

  PhysRev.D.67, 054005(2003), Phys.Rev.D83, 034002 (2011)

- Comparison of π, η, and K may provide info about initial vs final spin-momentum correlations as well as possible isospin, strangeness, and mass effects



Comparison with η meson results



For X_F>0.55 STAR A_N(η) may be larger, but consistent within uncertainty.

Comparison with twist-3 calculations

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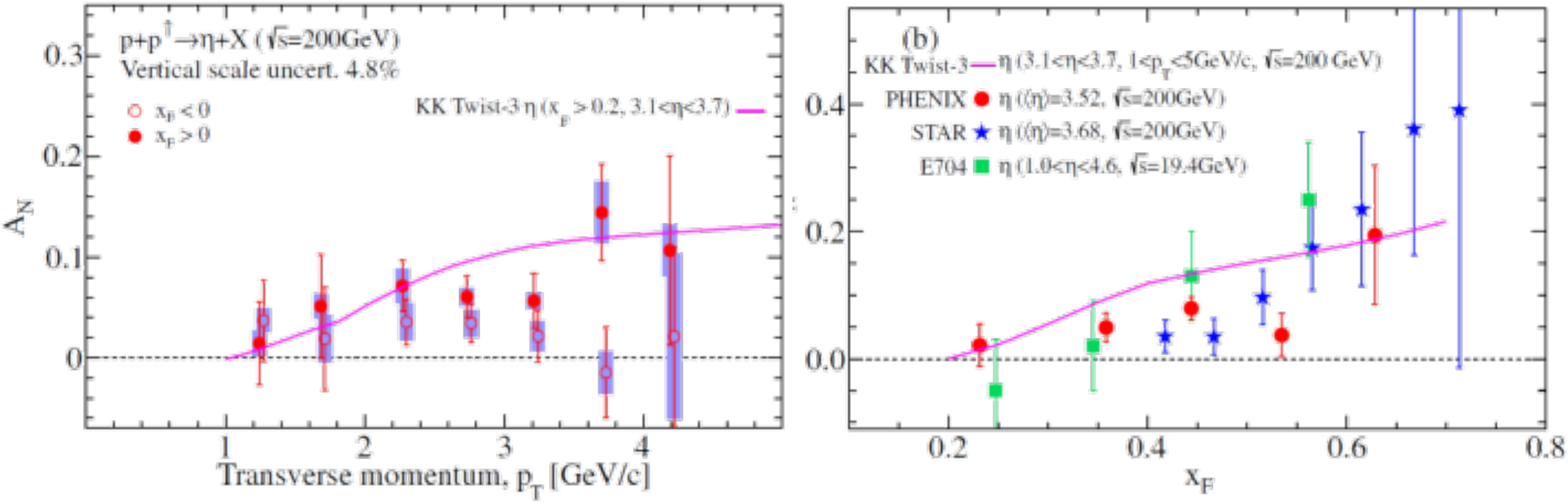
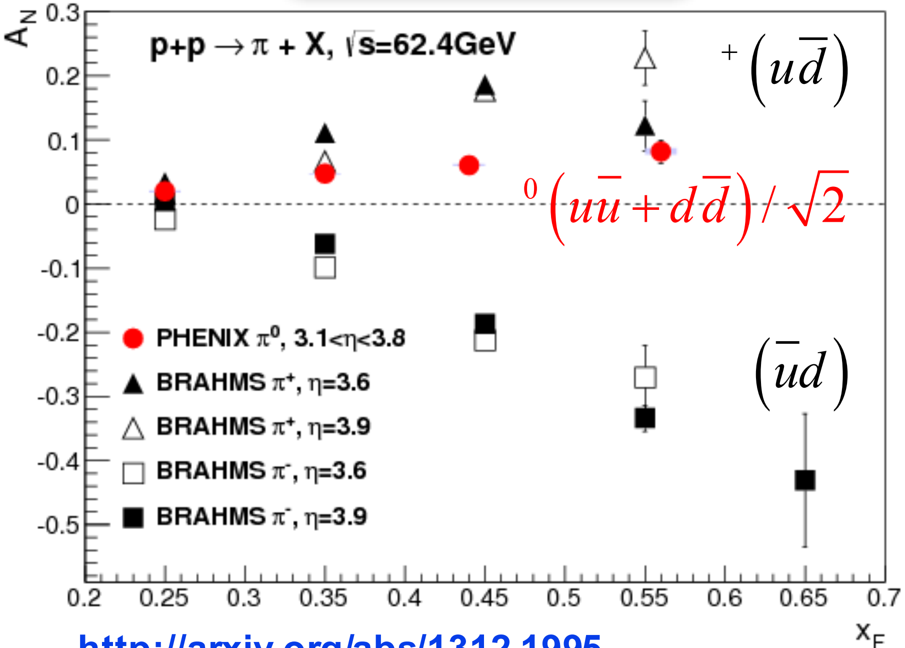


- Measurement consistent with this particular calculation at low and high p_T and x_F, but consistency with mid x_F and p_T not clear.
- Theoretical uncertainties uncertain. Development of theoretical framework underway (e.g. Pitonyak and Y. Koike, ArXiv: 1404,1033)
- With higher statistics data, a double differential measurement of A_N if x_F and p_T could provide a more stringent test of models.

Isospin Comparison of pion A_N

$\sqrt{s}$ = 62.4 GeV



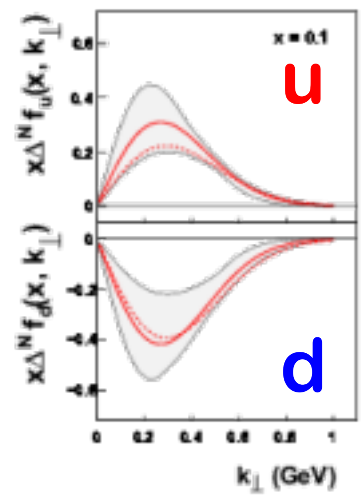
http://arxiv.org/abs/1312.1995

Quark origins of pions (PYTHIA):

- $u \to \pi^+ / d \to \pi^+$: 100 / 0
- $u \to \pi^0 / d \to \pi^0$: 75 / 25
- $u \to \pi^- / d \to \pi^-$: 50 / 50

Data cannot be explained by initial state effects of quarks (Sivers) alone (assuming u and d quark Sivers functions extracted from SIDIS)

Sivers



A_N as a function of p_T

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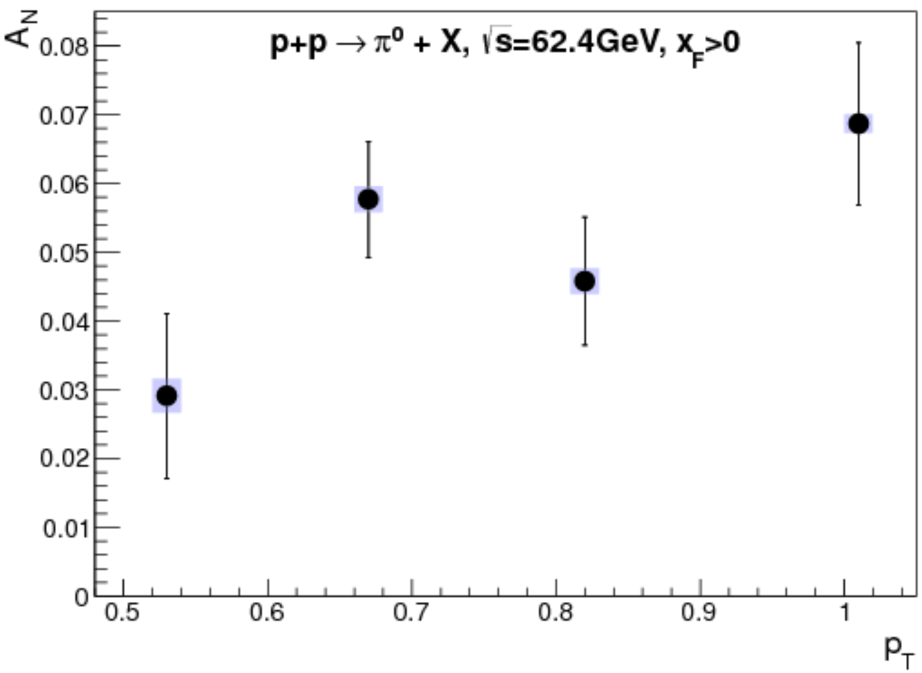
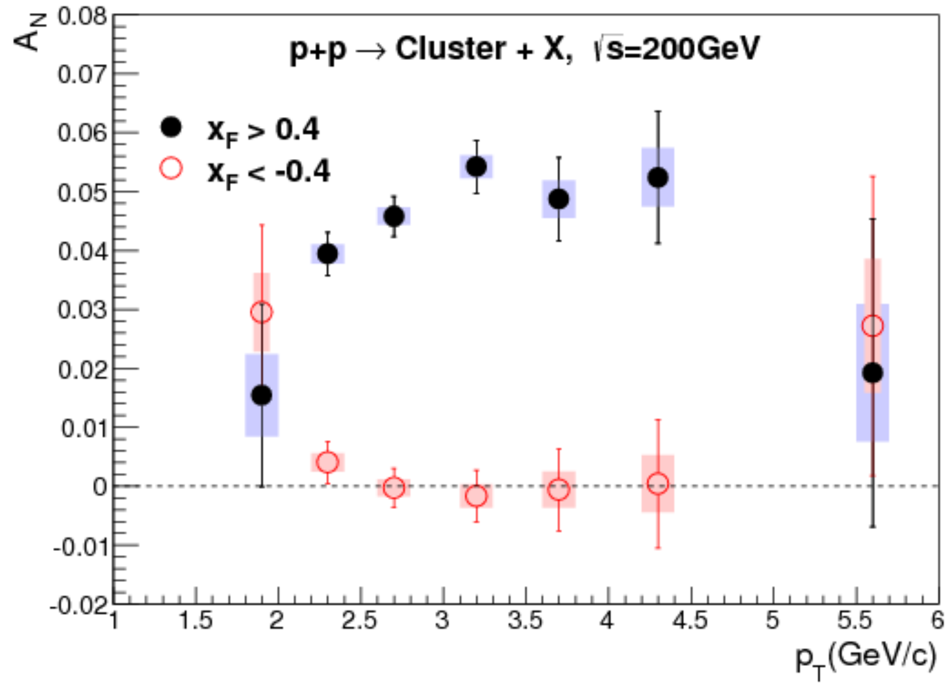




A significant decrease of the asymmetry as expected from higher twist calculations is not conclusive.

Full description of AN

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

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

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

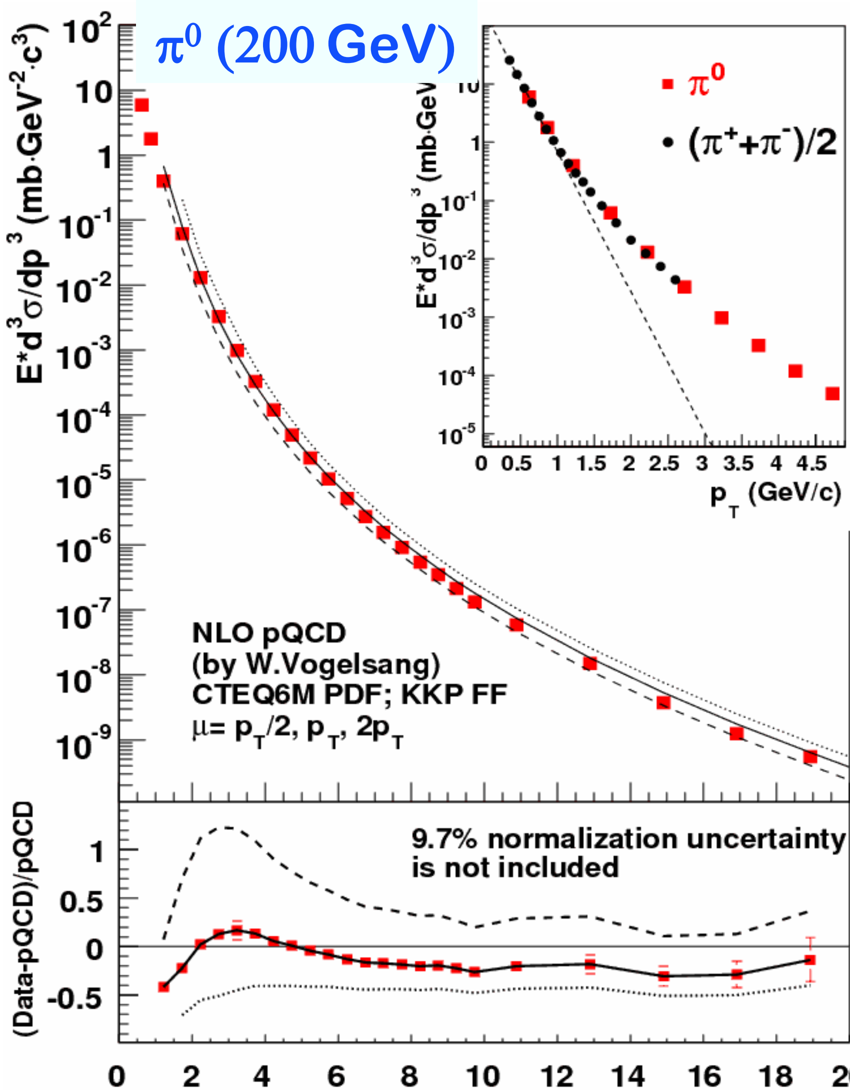
$\Delta_{1\sim4}$: relative phase of amplitudes

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

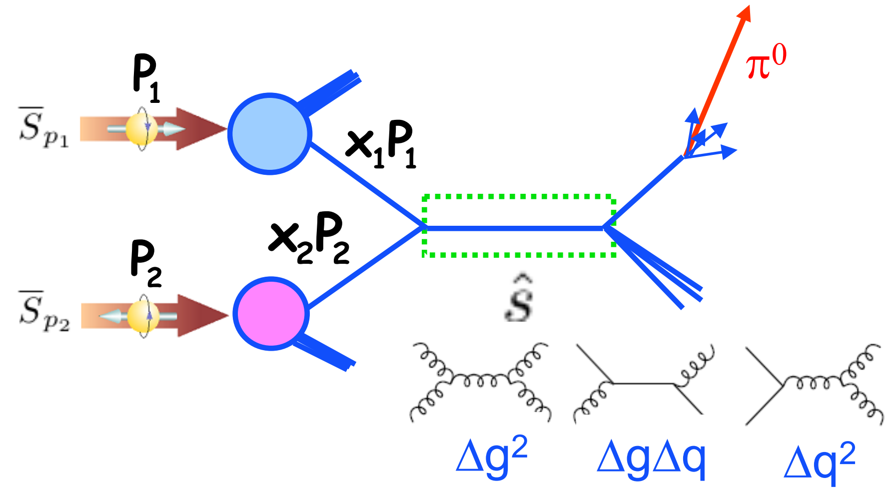
$$= 2\,\mathrm{Im}\left(\phi^{had*}_{non-flip}\phi^{had}_{flip}\sin\delta_1 + \phi^{EM*}_{non-flip}\phi^{had}_{flip}\sin\delta_2 + \phi^{had*}_{non-flip}\phi^{EM}_{flip}\sin\delta_3 + \phi^{EM*}_{non-flip}\phi^{EM}_{flip}\sin\delta_4\right)$$

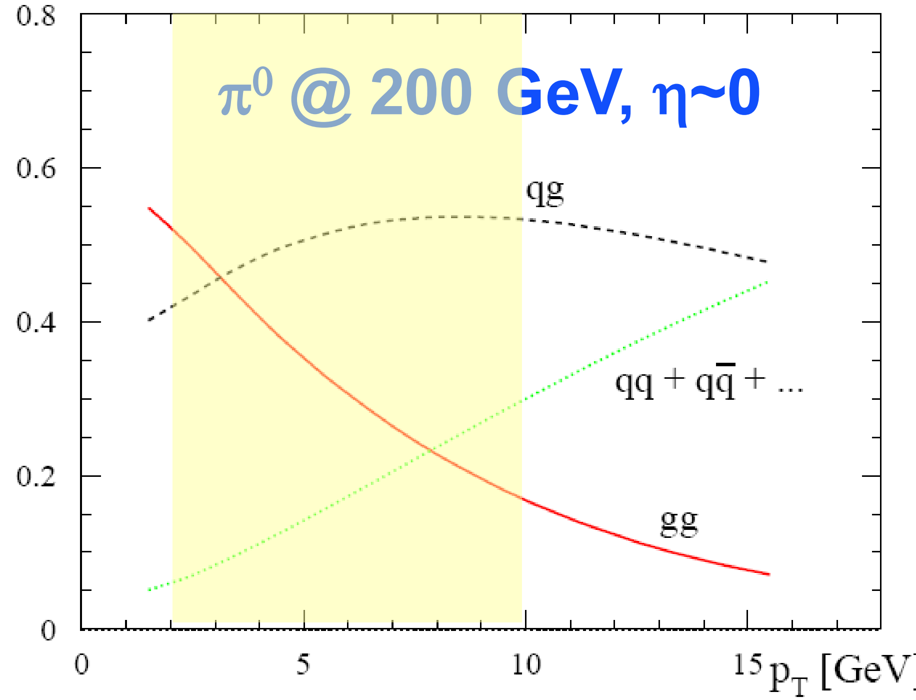
$\rightarrow 0$ (For pp)

Cross sections



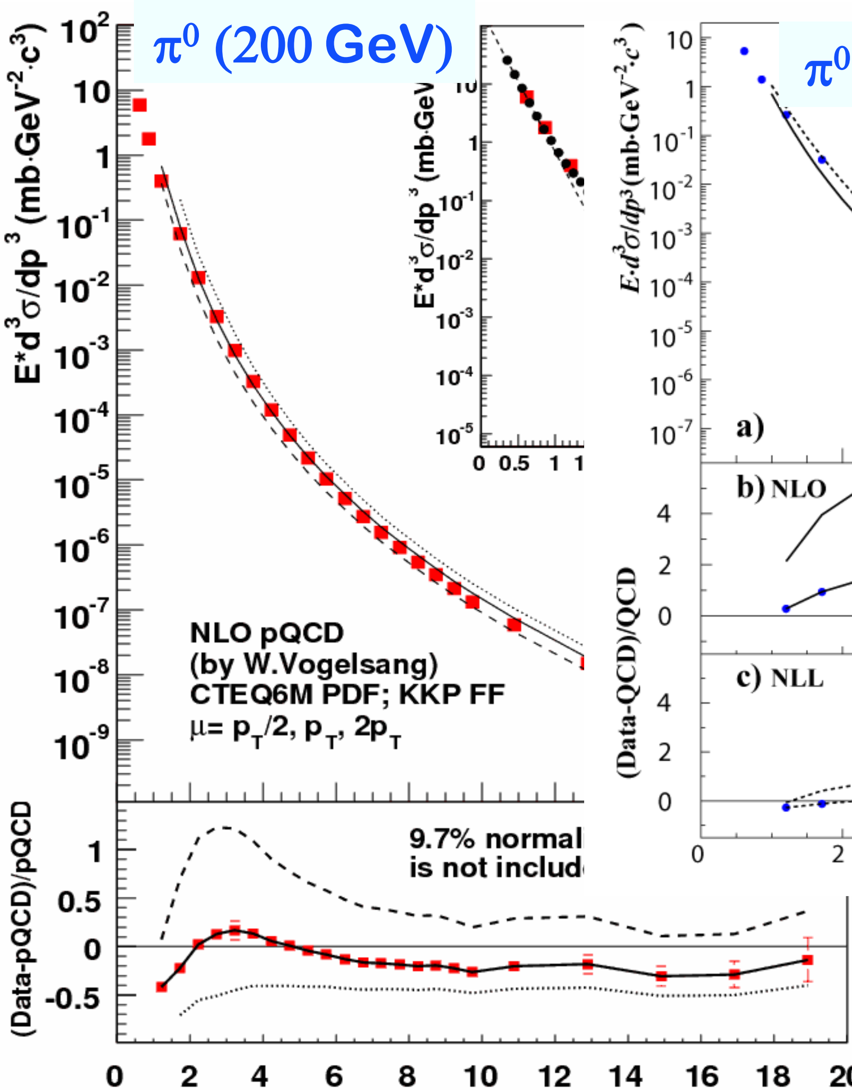
PRD76:051106,2007



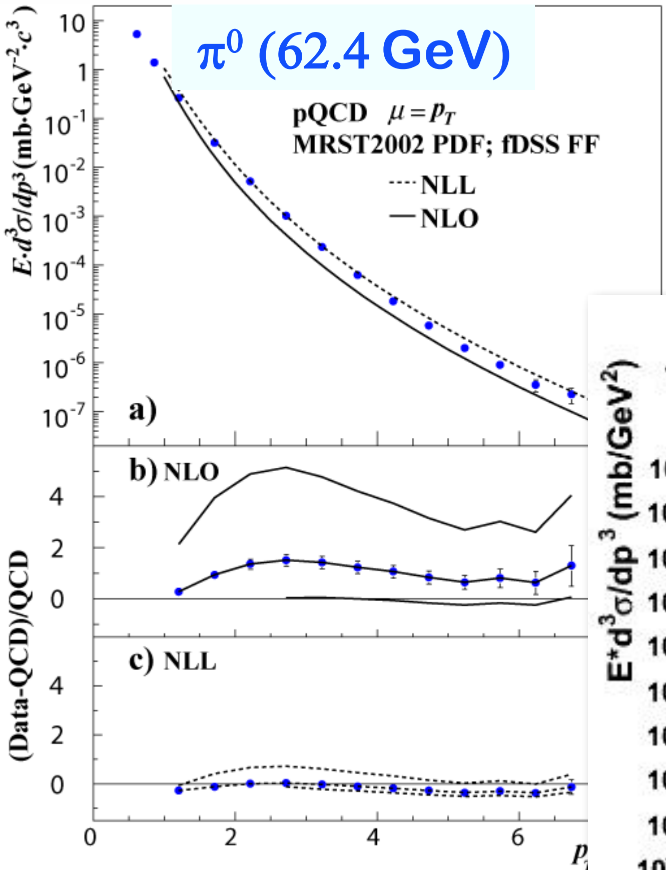


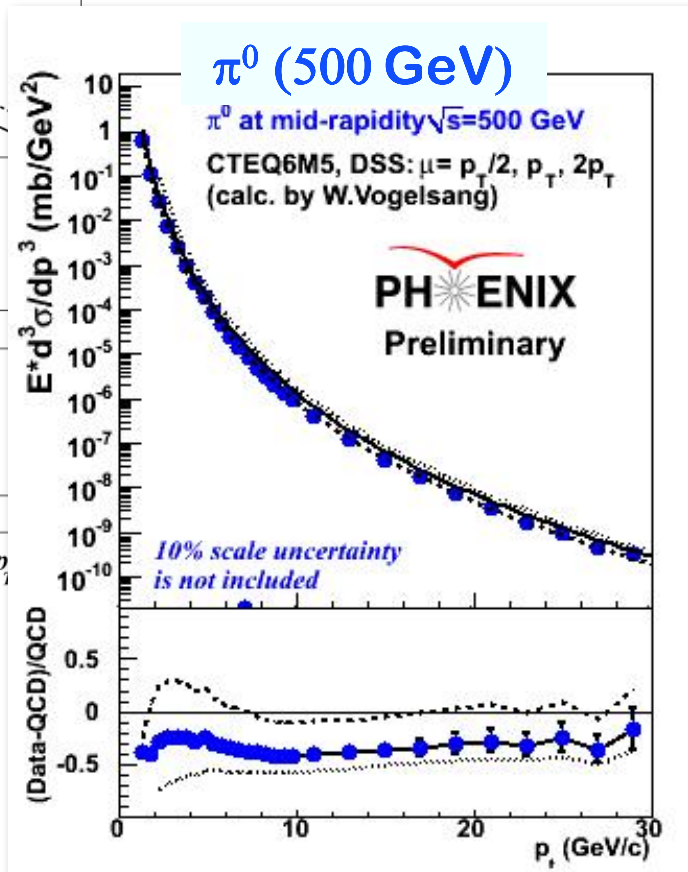
NLO pQCD calculations are consistent with cross-section measurements

Cross sections



PRD76:051106,2007

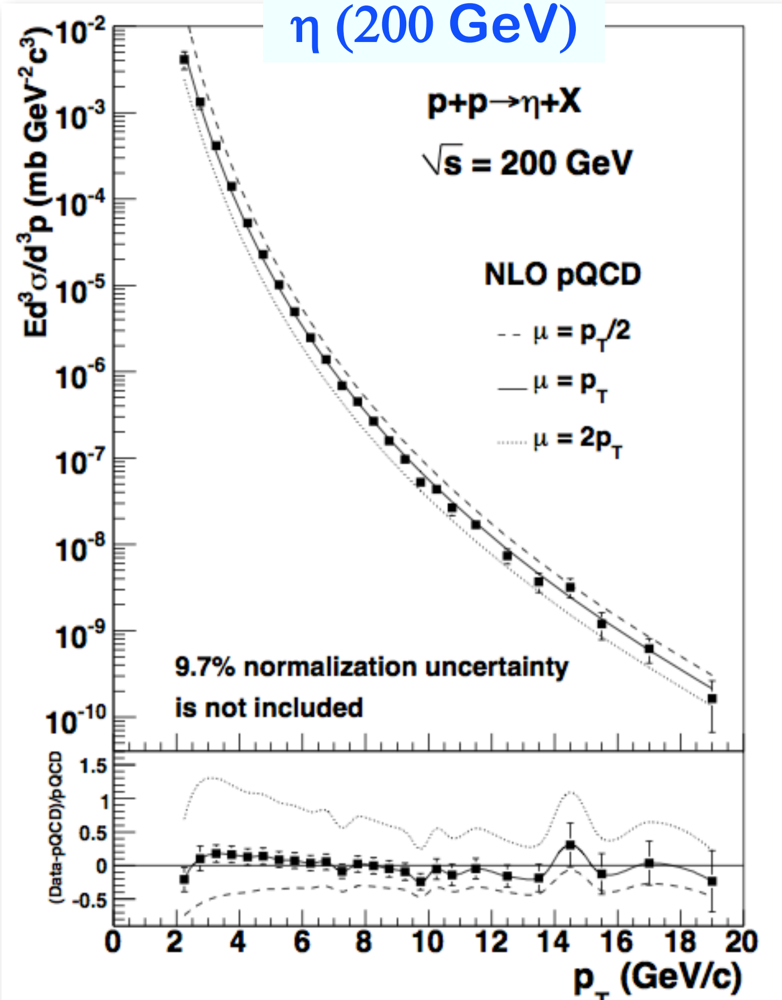




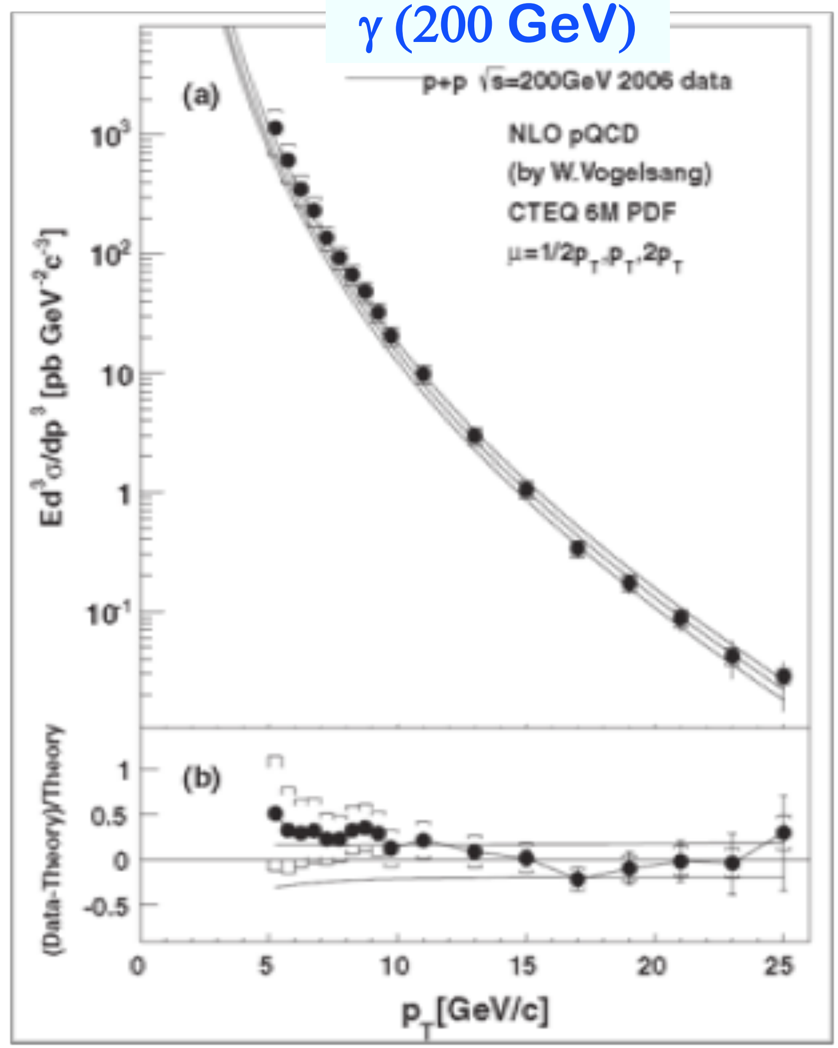
NLO pQCD calculations are consistent with cross-section measurements

Cross sections

η (200 GeV)



γ (200 GeV)



PRD83:032001,2011

PRD86:072008,2012

NLO pQCD calculations are consistent with cross-section measurements