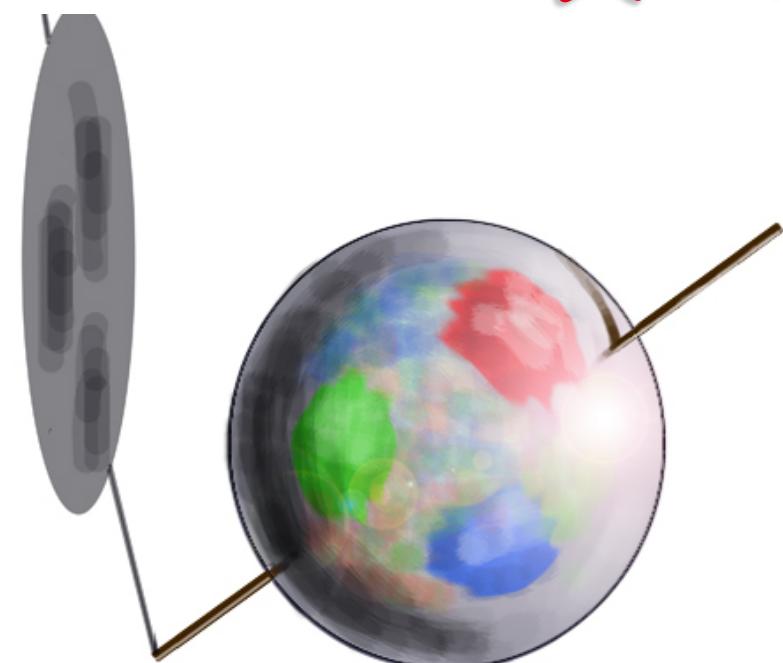


Experimental study of proton spin at PHENIX



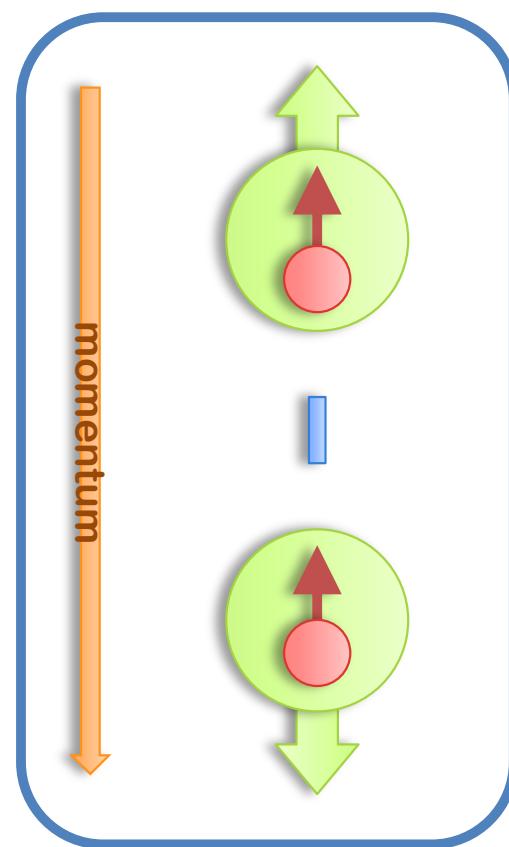
Kenneth N. Barish
PACIFIC SPIN 2019
AUGUST, 2019



The Proton Spin Structure ($p+p$)

Polarization experiments

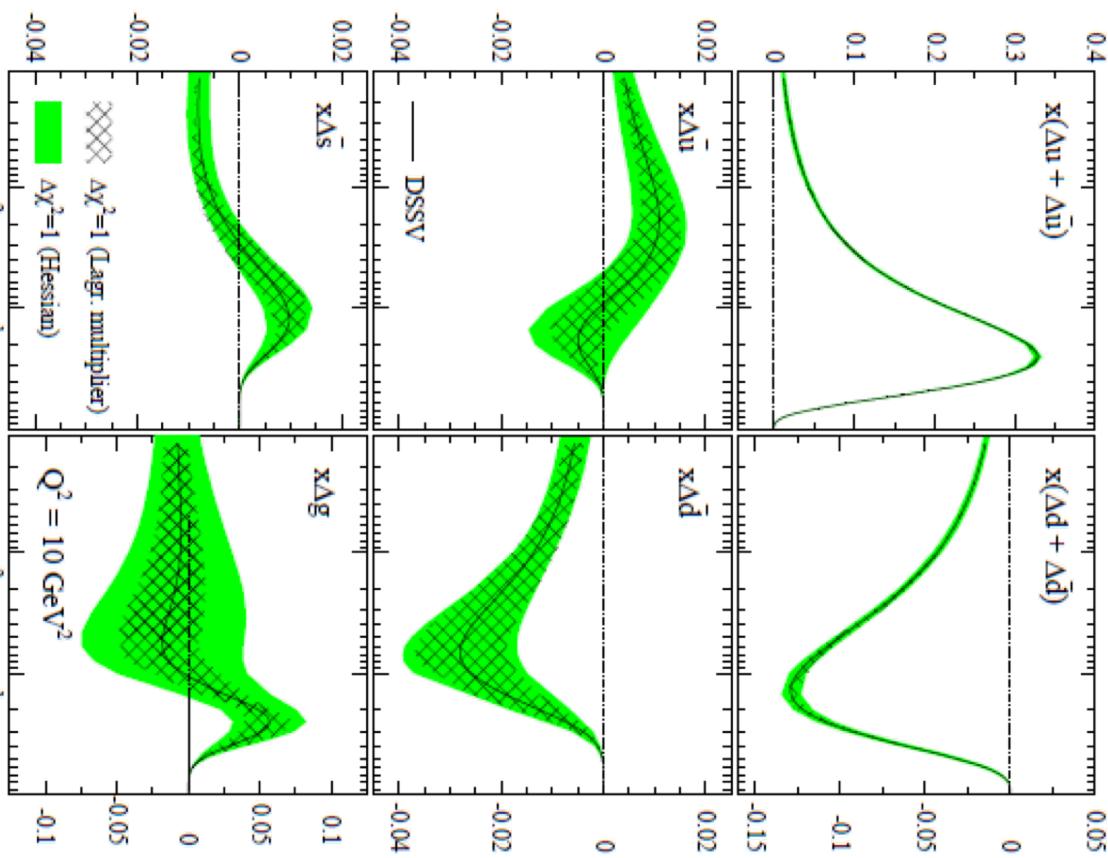
- » **Helicity**
- Valence quarks
- Gluon polarization (I)
- Sea quarks (II)



$$\frac{1}{2} = \frac{1}{2} \Delta \sum_{\text{valence + sea}} + \Delta \mathbf{G} + \mathbf{L}_{\text{quark spin}}$$

gluon spin

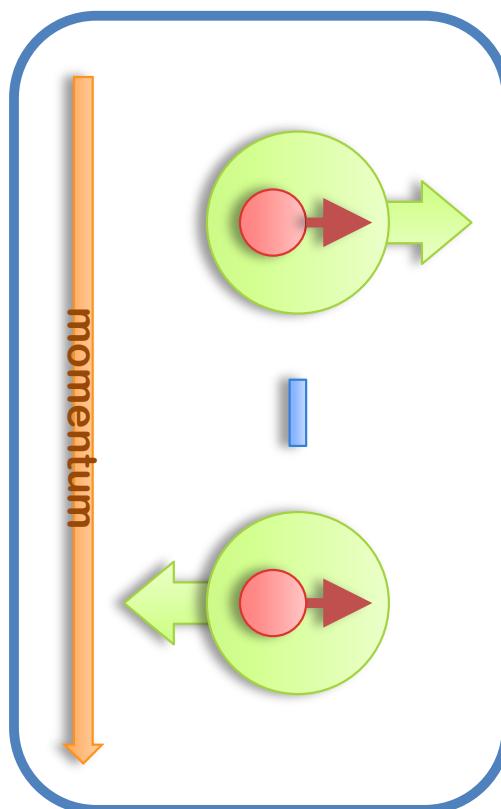
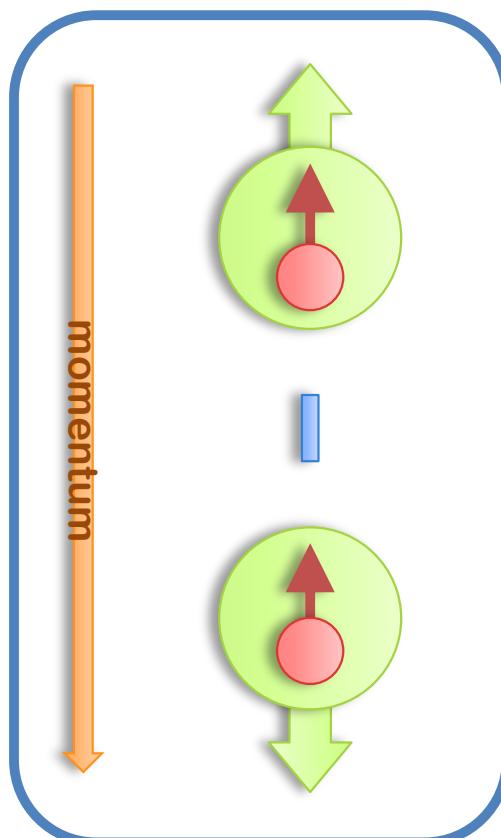
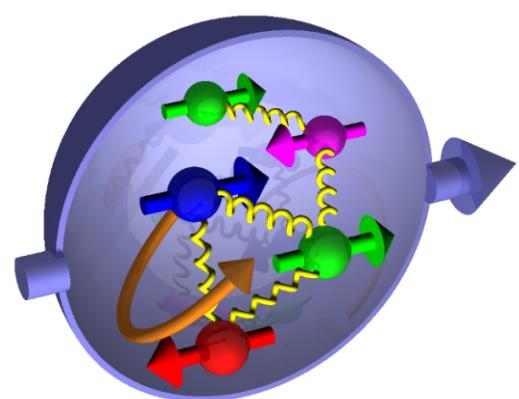
quark & gluon orbital motion



The Proton Spin Structure ($p+p$)

Polarization experiments

- » **Helicity**
 - Valence quarks
 - Gluon polarization (I)
 - Sea quarks (II)
- » **Transversity**
 - Transverse spin (III)



$$\frac{1}{2} = \frac{1}{2} \Delta \sum_{\text{valence + sea quark spin}} + \Delta \mathbf{G}_{\text{quark & gluon orbital motion}} + \mathbf{L}_{\text{gluon spin}}$$

What is the connection to orbital angular momentum?

The PHENIX Detector for Spin Physics

Philosophy:

- ✓ High rate capability and granularity at cost of acceptance
- ✓ Good mass resolution & particle ID
- ✓ Trigger for rare events

$\pi^0/\gamma/\eta$ detection (central and forward)

Electromagnetic Calorimeter, MPC

π^+/π^- (central)

Drift Chamber

Ring Imaging Cherenkov Counter

J/ ψ (central and forward)

Muon Id/Muon Tracker

Resistive Plate Chambers (RPC)

Relative Luminosity

Beam Beam Counter (BBC)

Zero Degree Calorimeter (ZDC)

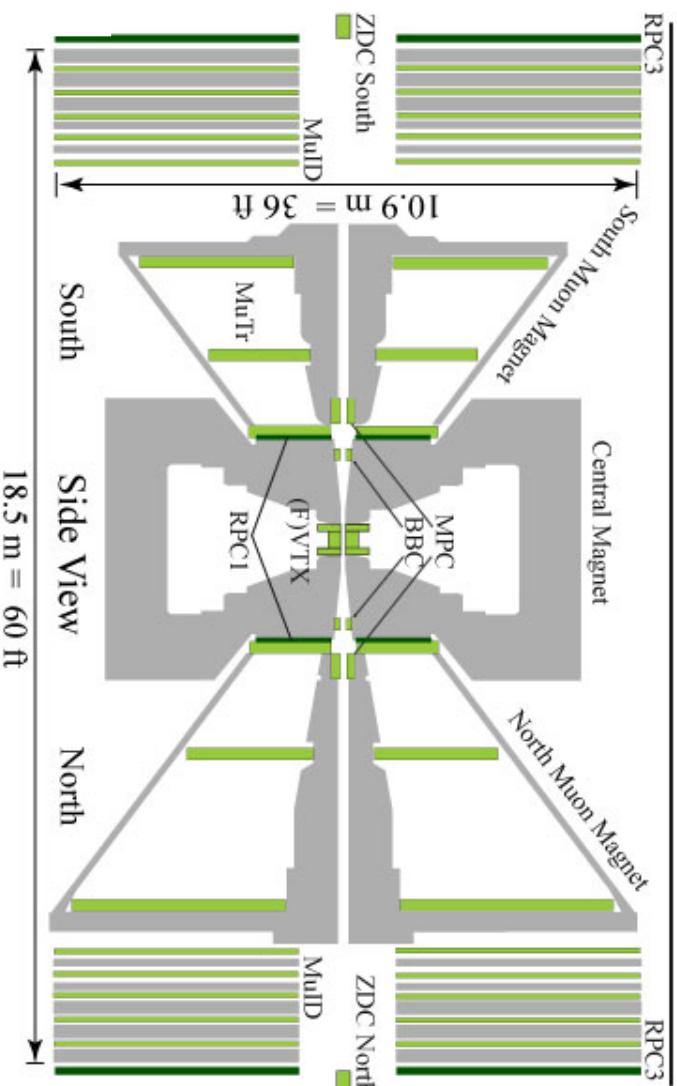
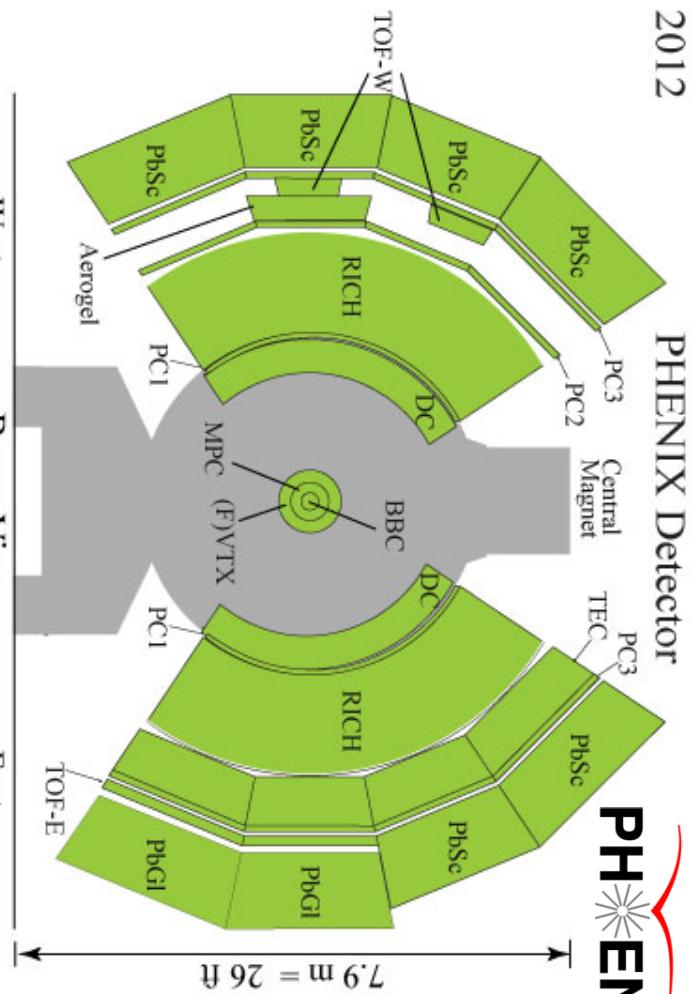
Local Polarimetry - ZDC

Filters for “rare” events

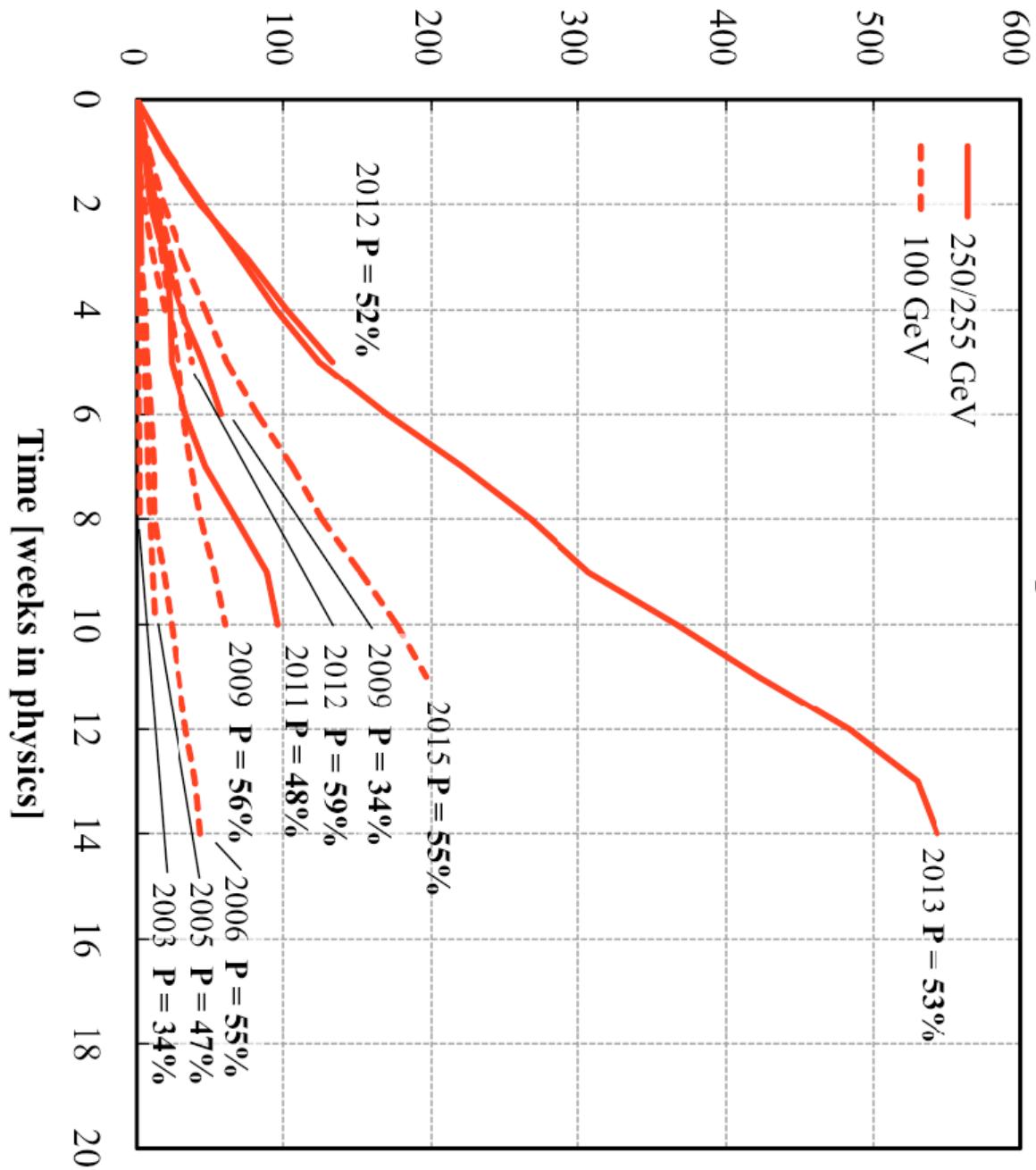
2012

PHENIX Detector

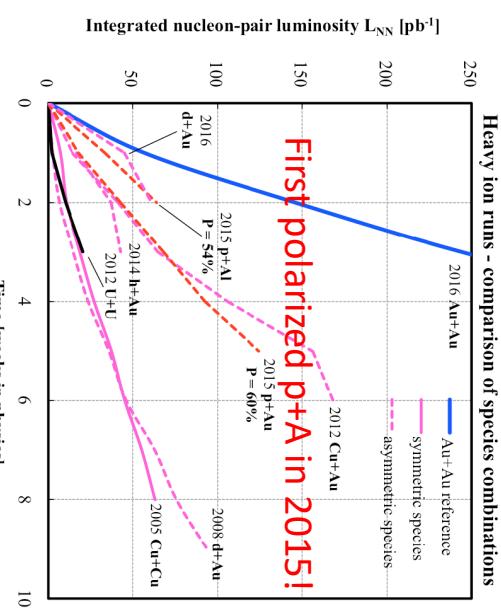
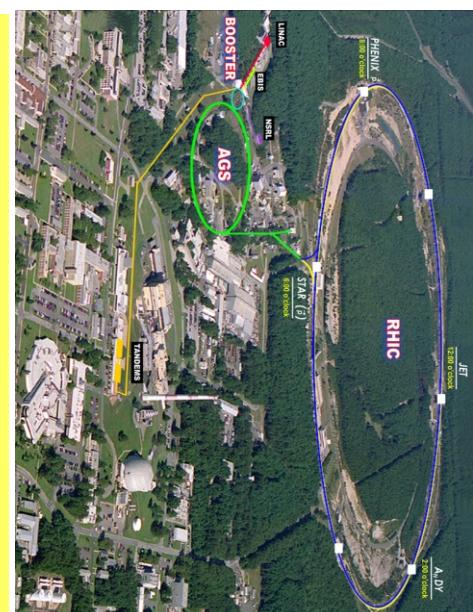
PHENIX



RHIC Polarized Proton Runs



**World's first and
only high energy
spin-polarized
proton collider**



I. Gluon Polarization

Robust measurement covering wide x_g region through multiple channels:

The figure shows five Feynman diagrams illustrating different channels for gluon-gluon and gluon-quark interactions:

- $gg \rightarrow gg$: Two gluons interact via a virtual photon exchange.
- $gq \rightarrow gq$: A gluon and a quark interact via a virtual photon exchange.
- $qq \rightarrow qq$: Two quarks interact via a virtual photon exchange.
- $gq \rightarrow g\gamma$: A gluon and a quark interact via a virtual photon exchange, producing a gluon and a photon.
- $gg \rightarrow Q\bar{Q}$: Two gluons interact via a virtual photon exchange, producing a quark-antiquark pair ($Q\bar{Q}$).

Below each diagram is a corresponding mathematical expression involving the ratio of the change in coupling constant (ΔG) to the coupling constant (G):

$$\propto \frac{\Delta G}{G} \frac{\Delta G}{G}$$
$$\propto \frac{\Delta q}{q} \frac{\Delta G}{G}$$
$$\propto \frac{\Delta q}{q} \frac{\Delta q}{G}$$
$$\propto \frac{\Delta q}{q} \frac{\Delta G}{G}$$
$$\propto \frac{\Delta G}{G} \frac{\Delta G}{G}$$

Each experimental channel (π^0 , γ , etc) covers different ranges in x_g , have different systematics, and in principle, uniquely contribute to a Global fit.

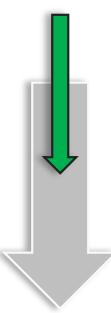
I. Gluon Polarization

Robust measurement covering wide x_g region through multiple channels:

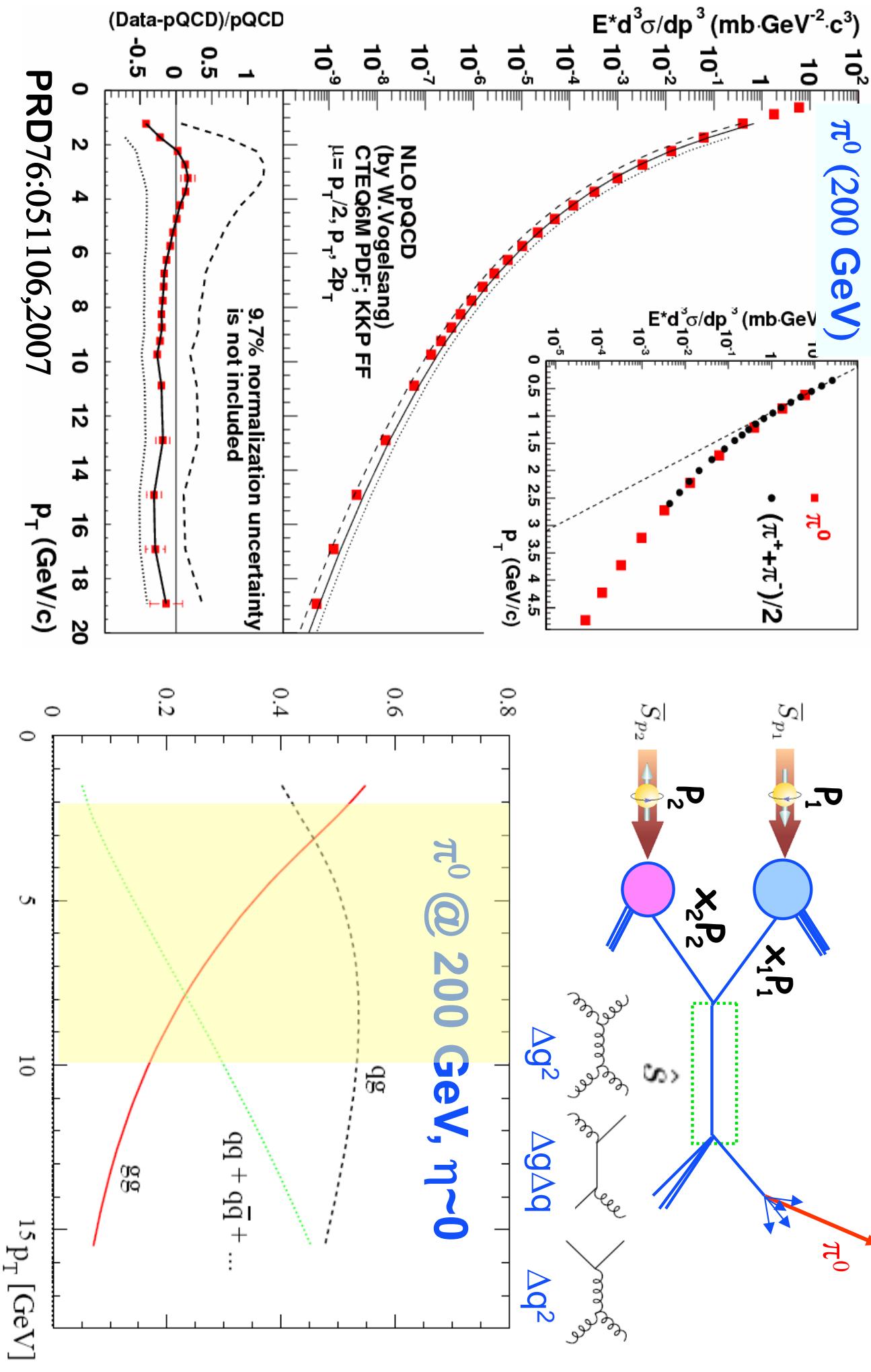
Year	\sqrt{s} (GeV)	Int. L (pb $^{-1}$)	$\langle P \rangle$ (%)	FoM1 ($L \cdot \langle P \rangle^2$)	FoM2 ($L \cdot \langle P \rangle^4$)
09	200	15.6	56 / 57	4.98	1.59
	500	14	33 / 36	1.66	0.20
11	500	27.6	48 / 48	6.36	1.47
12	510	49.6	50.3 / 53.5	13.35	3.59
13	510	242.1	50.5 / 55.4	67.73	18.95

Entire sample,

Recent Longitudinal Data

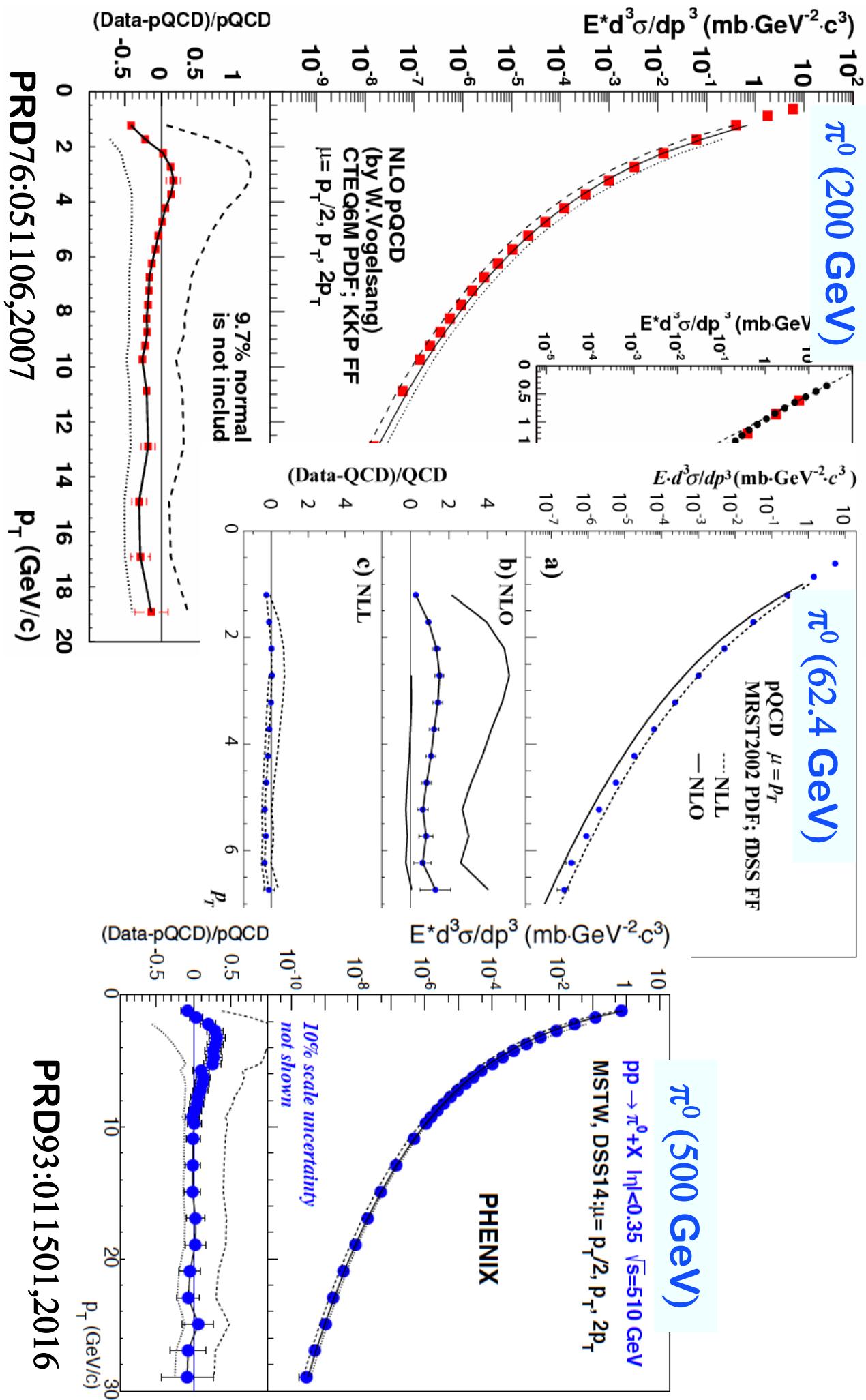


Cross sections



NLO pQCD calculations are consistent with cross-section measurements

Cross sections



NLO pQCD calculations are consistent with cross-section measurements

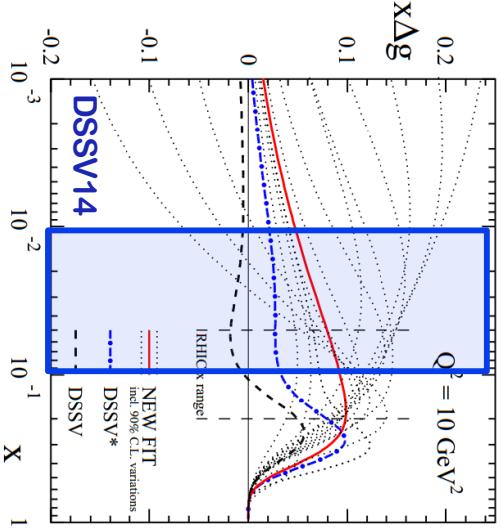
PRD76:051106, 2007

PRD93:011501, 2016

Neutral pion asymmetry

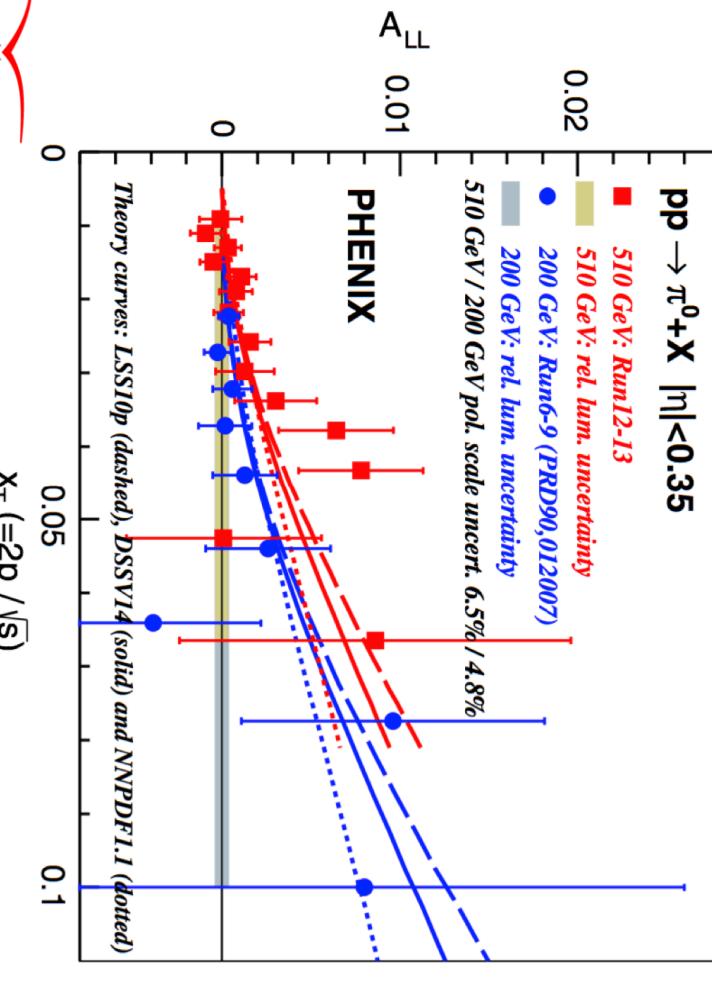
10.1103/PhysRevLett.113.012001

- Final PHENIX π^0 double spin asymmetry published in 2016 (including Run13)
- Favor positive gluon polarization
- Sensitive down to $x \sim 10^{-2}$
- Additional constrain in global fit beyond DSSV14



PhysRevD.93.011501 (2016)

PhysRevD.93.011501 (2016)



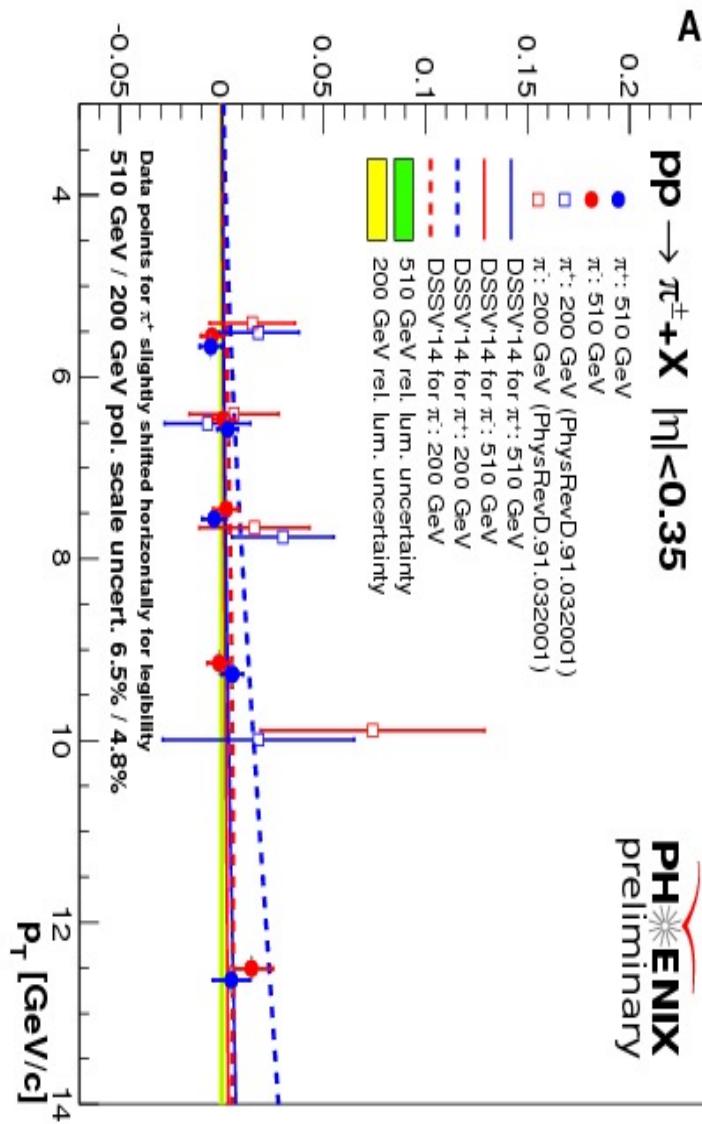
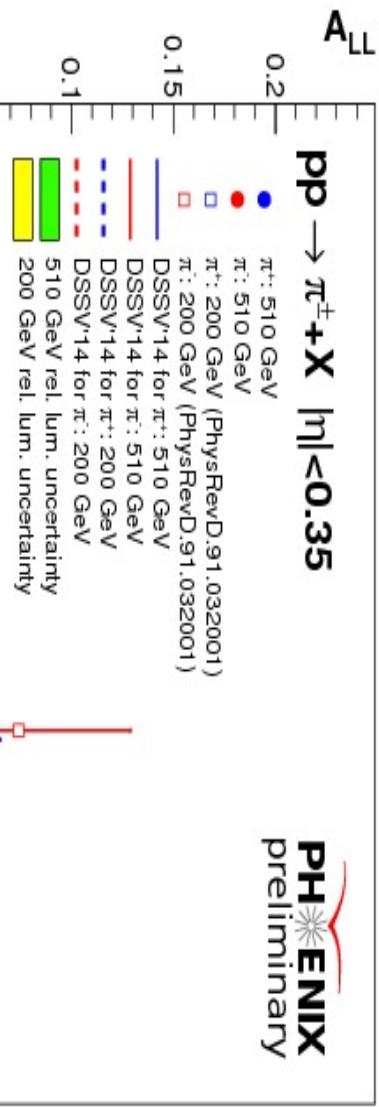
PHENIX

PHENIX

K. Barish

Charged pion, eta, and electron asymmetries

PhysRevD.91.012007 (2014)



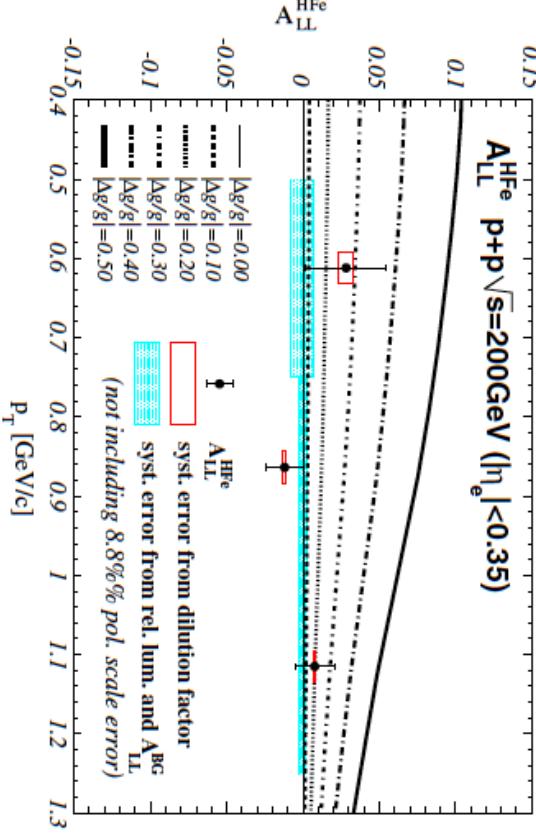
➤ Charged pions sensitive to sign change via pion A_{LL} ordering

- Reduced statistics compared to π^0 due to triggering.

➤ η provides a good test for

strangeness fragmentation functions

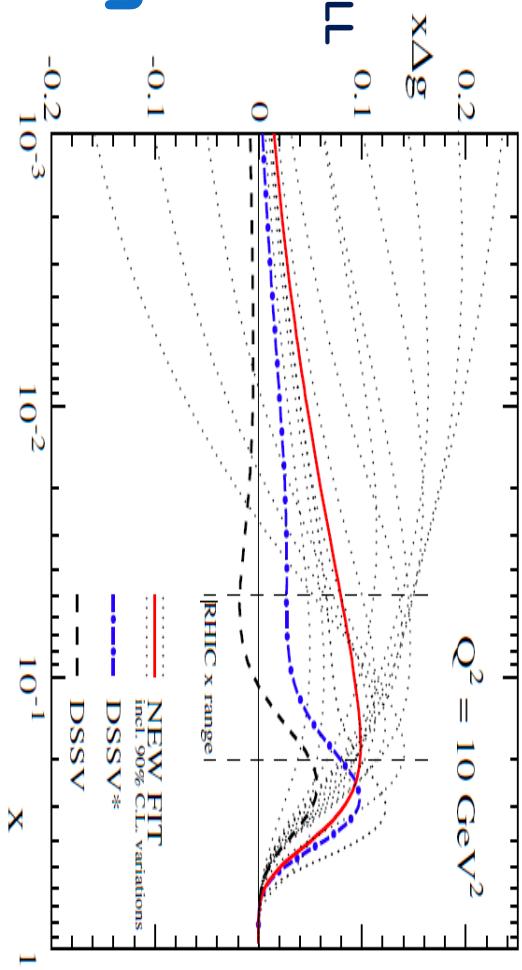
- Electrons: sensitive to large scale given by heavy flavor quark masses.



Impact on $\Delta g(x)$

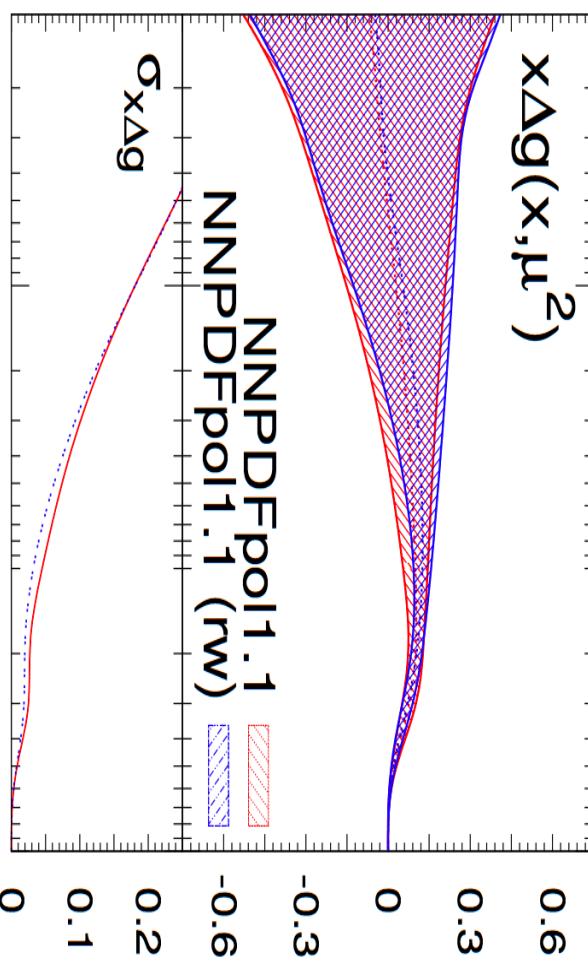
DSSV14: PhysRevLett.113.012001

- Published Include in Global fittings
 - 2006 200GeV and 62.4GeV $\pi^0 A_{LL}$
 - 2009 200GeV $\pi^0 A_{LL}$
 - 2012,2013 510GeV $\pi^0 A_{LL}$
- Published, Not yet include in Global fittings
 - 2013 510GeV Central $\pi^\pm A_{LL}$
 - 2013 510GeV Forward $J/\psi A_{LL}$
- Ongoing
 - 2013 510GeV Central direct photon A_{LL}
 - 2013 Jet A_{LL} at central rapidity
 - 2009, 2011 di- $\pi^0 A_{LL}$
 - 2011, 2013 500, 510GeV Forward $\pi^0 A_{LL}$



E. Nocera arXiv:1702.05077

$x\Delta g(x, \mu^2)$



II. Sea Quark Helicity

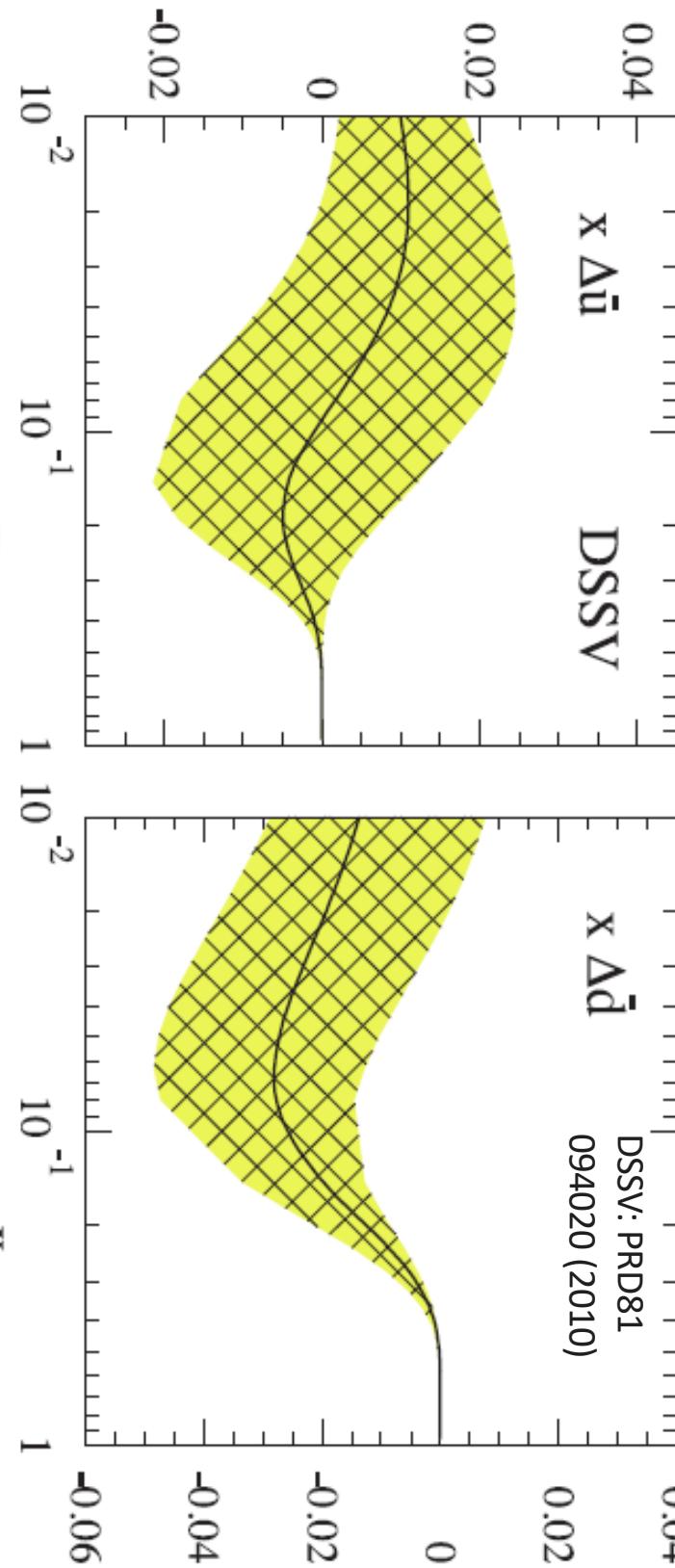
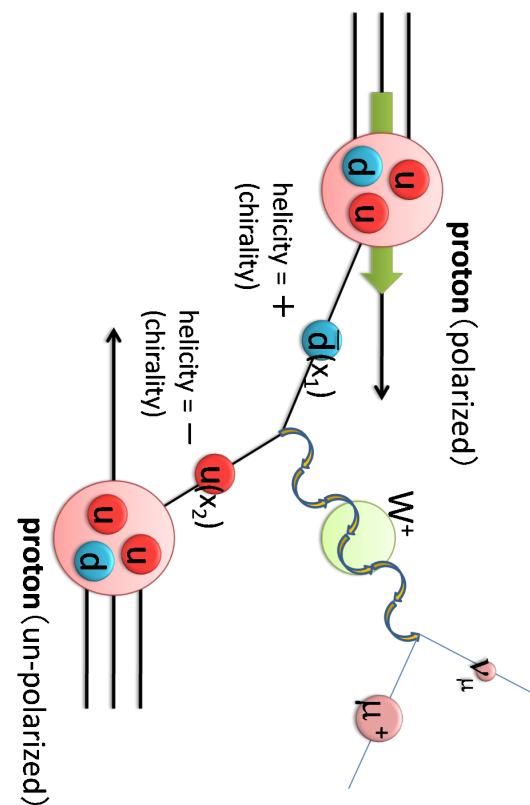
Features:

➤ High energy scale, Parity violating,
Flavor conserving, Low rate

PHENIX Measurements:

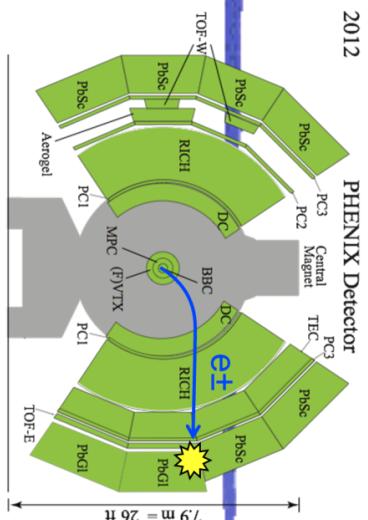
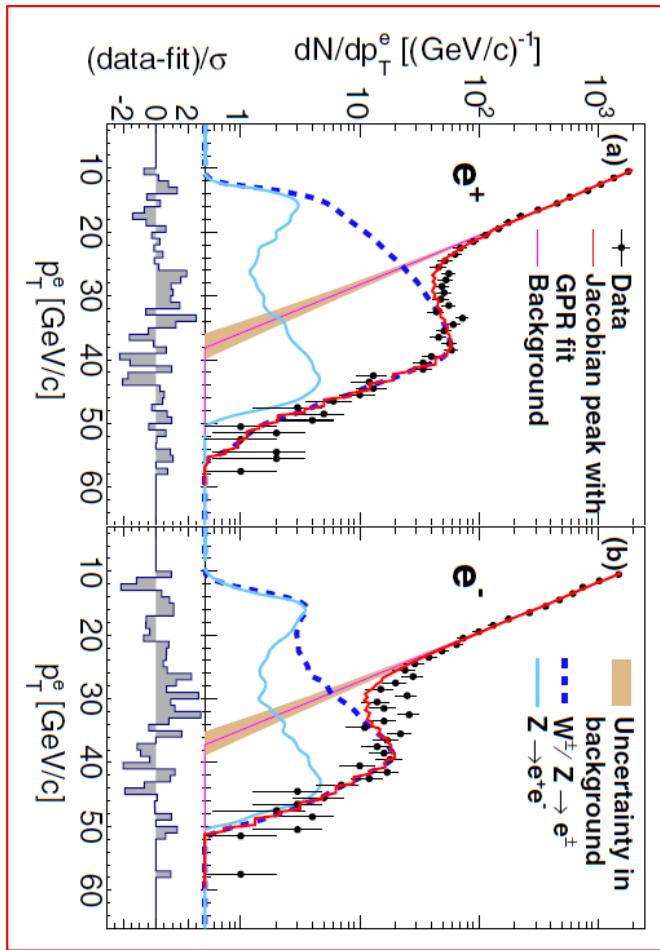
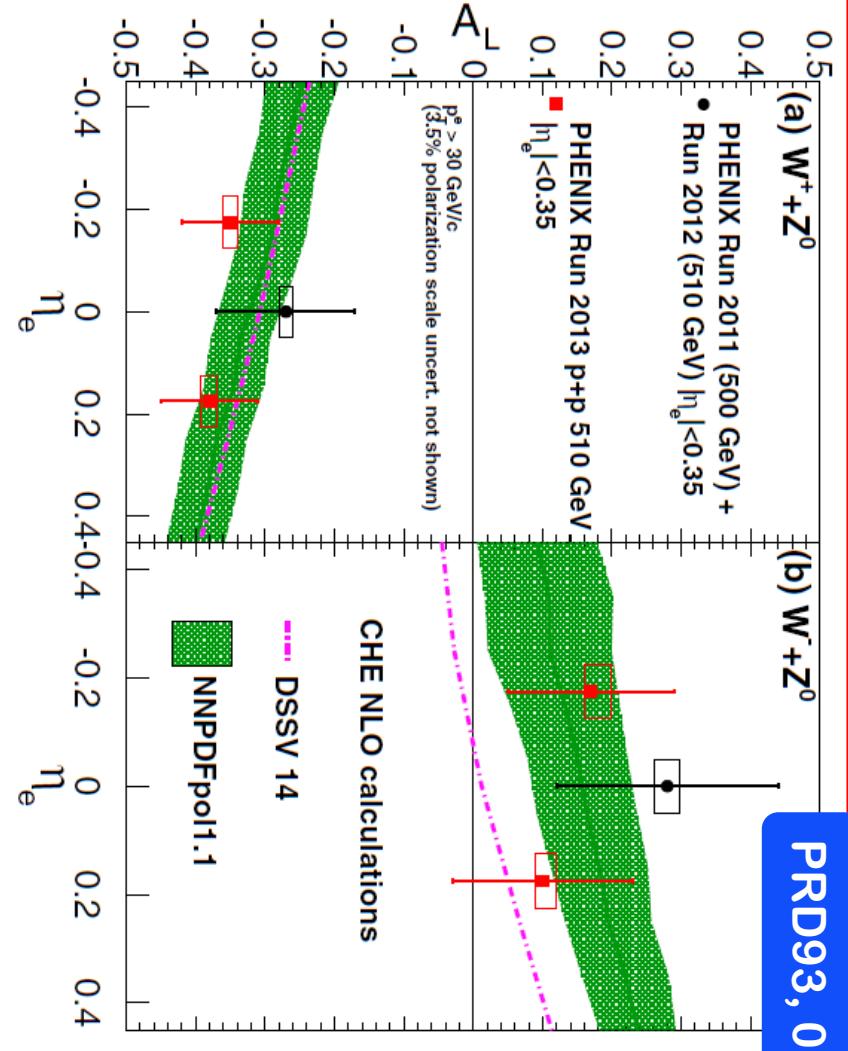
- Midrapidity ($|y| < 0.35$): $W^\pm \rightarrow e^\pm$
- Forward rapidity ($1.2 < |y| < 2.2$ /
2.4): $W^\pm \rightarrow \mu^\pm$

Sea quark polarization have sizable uncertainties (pre-RHIC).



$W \rightarrow e$ in Central Arms

PRD93, 051103 (2016)



$W^\pm \rightarrow e^\pm A_L$ with integrated Run11-13 data

- » Leptonic W decays clearly visible via Jacobian peak
- » Probed Bjorken x of ~ 0.16 (M_W/\sqrt{s})
- » e^- significantly above latest global fit.
- » Sizable asymmetries found, consistent between experiments

W \rightarrow e in Central Arms

0.5
0.4
0.3
0.2
0.1
0.0

0.8
0.6
0.4
0.2
0.0

(b) e $^{-}$

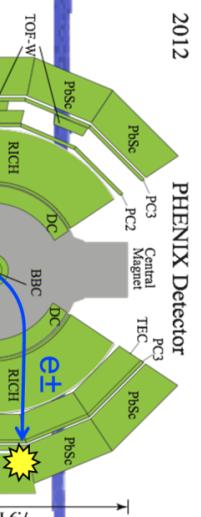
• PHENIX Run 2C
Run 2012 (510)
• | η_e |<0.35, $p_T^e > 30$ GeV/c

0.5
0.4
0.3
0.2
0.1
0.0

• PHENIX Run 2C
Run 2012 (510)
• | η_e |<0.35, $p_T^e > 30$ GeV/c

PRD93, 051103 (2016)

7.9 m = 26 ft



0.5
0.4
0.3
0.2
0.1
0.0

0.8(a) e $^{+}$
• PHENIX 2011-2013 W $^{\pm}$ +Z 0
• | η_e |<0.35, $p_T^e > 30$ GeV/c

0.5
0.4
0.3
0.2
0.1
0.0

• PHENIX 2011-2013 W $^{\pm}$ +Z 0
• | η_e |<0.35, $p_T^e > 30$ GeV/c

CHE NLO calculations

0.5
0.4
0.3
0.2
0.1
0.0

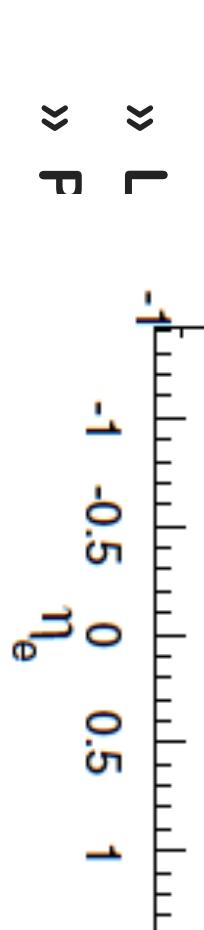
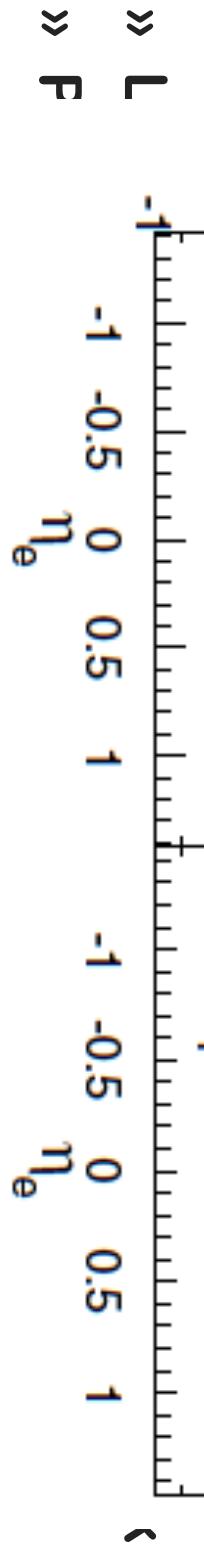
• PHENIX 2011-2013 W $^{\pm}$ +Z 0
• | η_e |<0.35, $p_T^e > 30$ GeV/c

DSSV 14 W $^{\pm}$ +Z 0
 $p_T^e > 25$ GeV/c

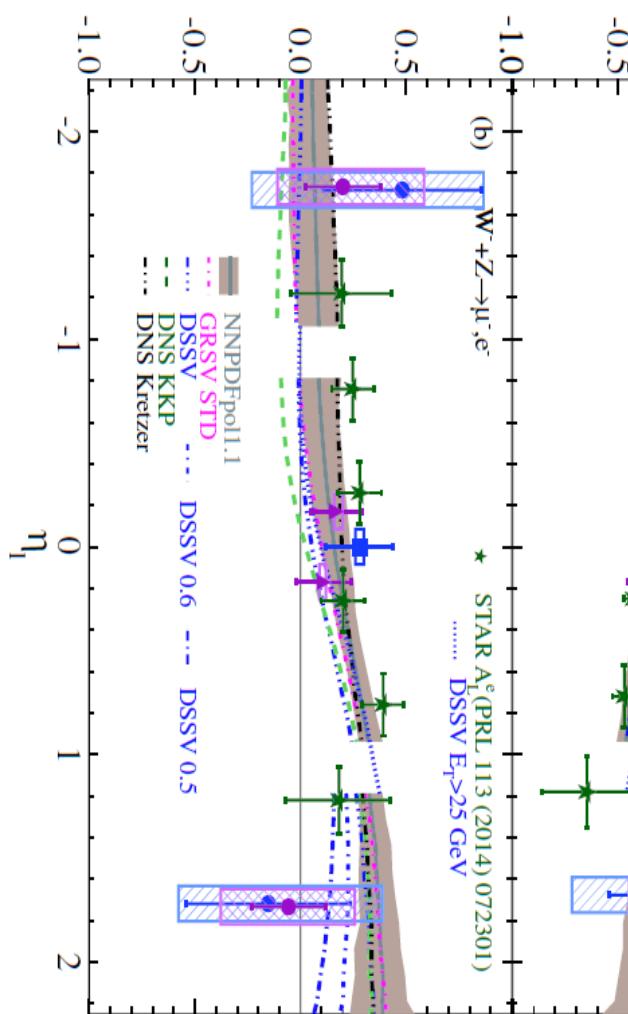
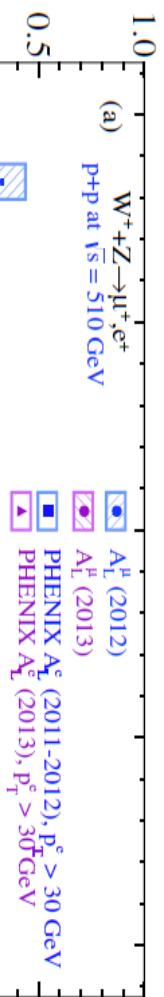
0 30 40 50 60
 p_T^e [GeV/c]

(a) W $^{+}$ +Z 0

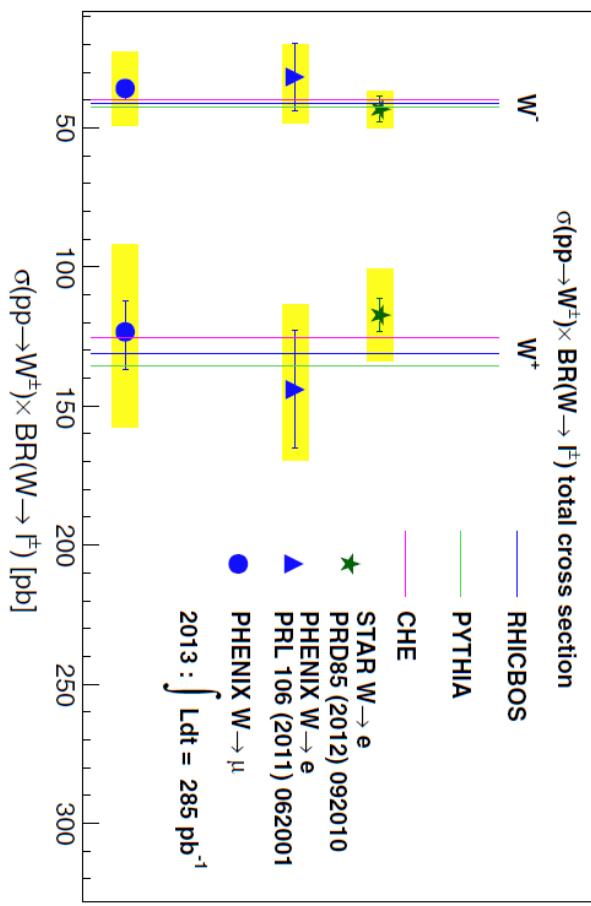
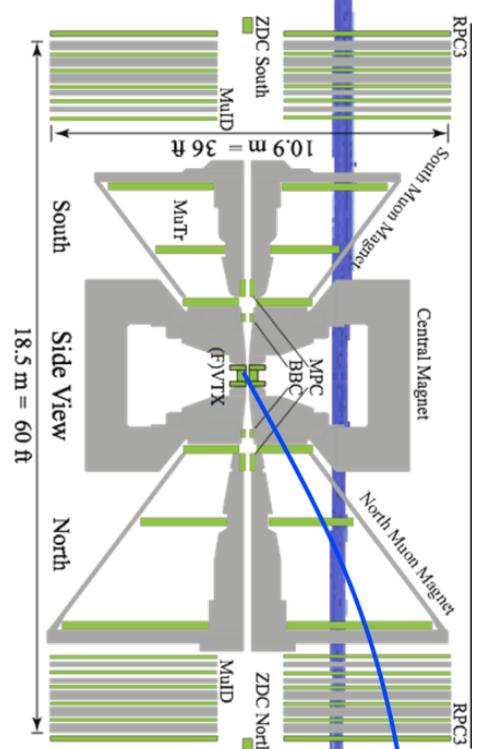
• PHENIX Run 2C
Run 2012 (510)
• | η_e |<0.35, $p_T^e > 30$ GeV/c



$W \rightarrow \mu$ in muon arms



PRD98, 032007 (2018)



$W^\pm \rightarrow \mu^\pm A_L$ with Run13 data

- » $\sqrt{s} = 510$ GeV, Int. $L = 277$ pb⁻¹
- » Signal extraction via W likelihood + unbinned max. likelihood fit
- W cross section agrees within large uncertainty
- » Theory parameterizations consistent with data except for some tension at backward W^+ and forward W^-

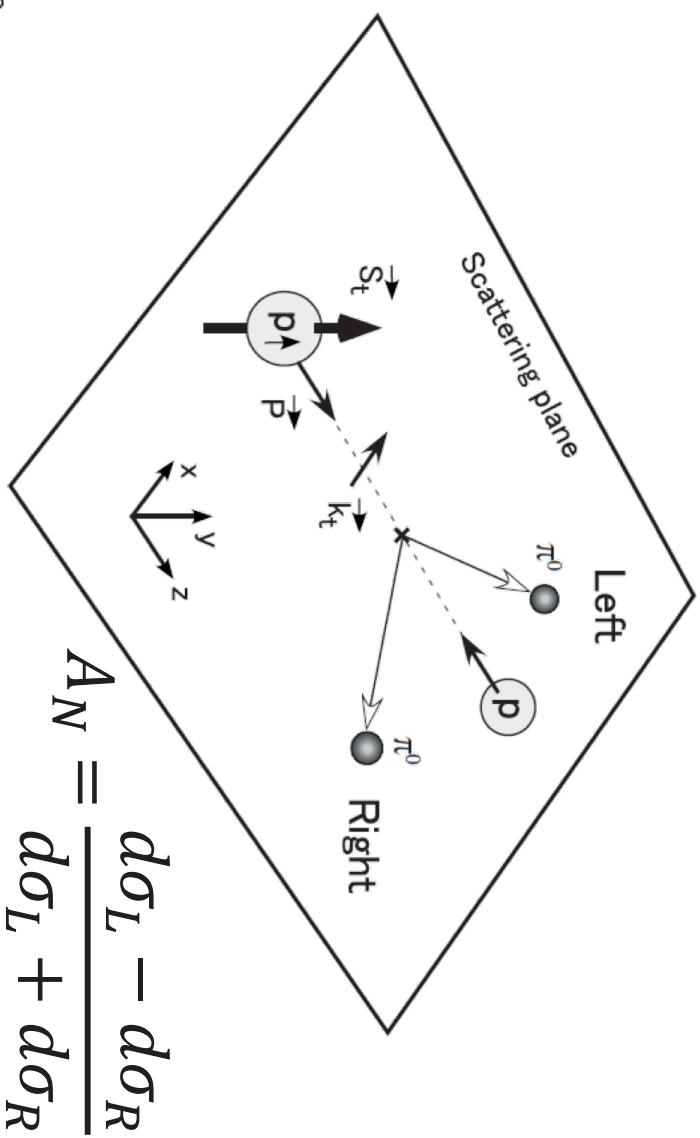
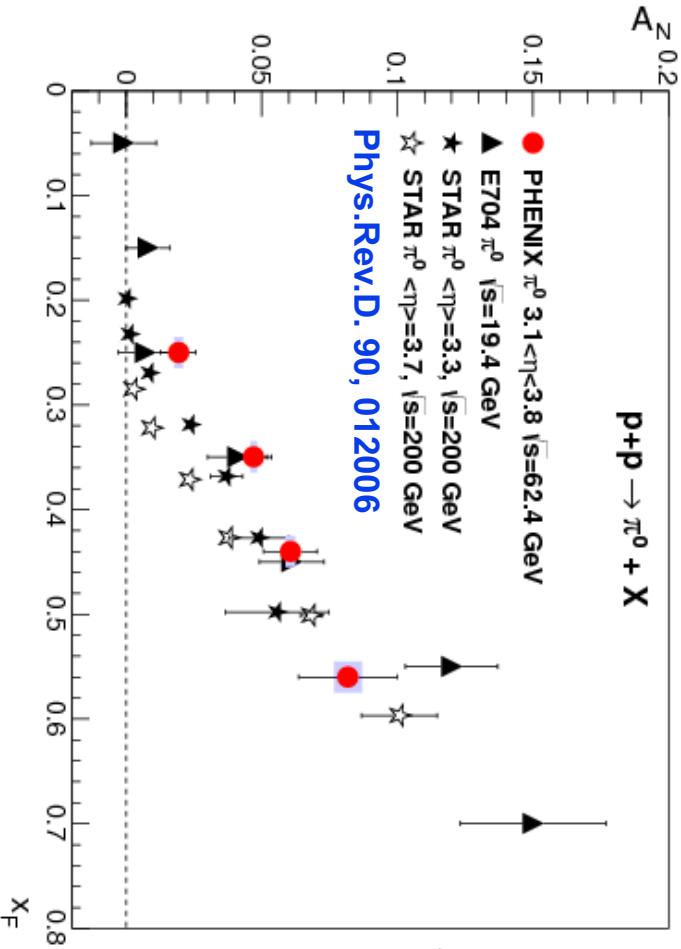
III. Transverse Spin (A_N)

- The persistence of large transverse asymmetries at RHIC energies, where collinear pQCD describes the cross-sections well, was a surprise.

$$A_N \approx \frac{m_q \alpha_s}{p_T}$$

- The transverse structure of the nucleon is largely unknown

- Very forward neutron asymmetries, which is in soft region, are also not well understood.

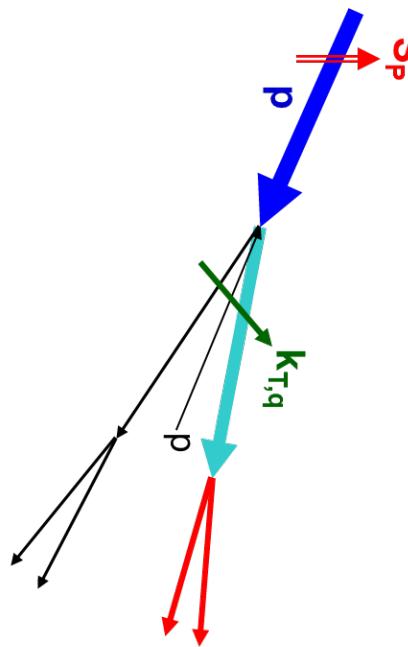


Transverse Spin Asymmetry Sources

(I) Initial State Effects: “Sivers”

Correlation between proton-spin and intrinsic transverse quark momentum

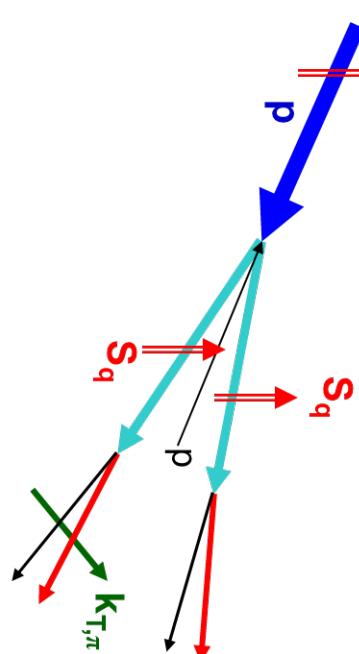
$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_\perp^2)}_{\text{Sivers distribution (initial state)}} \cdot D_q^h(z)$$



(III) Final State Effects: “Collins”

Correlation between proton & quark spin + spin dependant fragmentation function

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



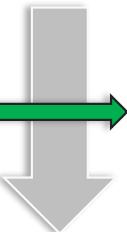
D. Sivers, Phys. Rev. D 41, 83 (1990)

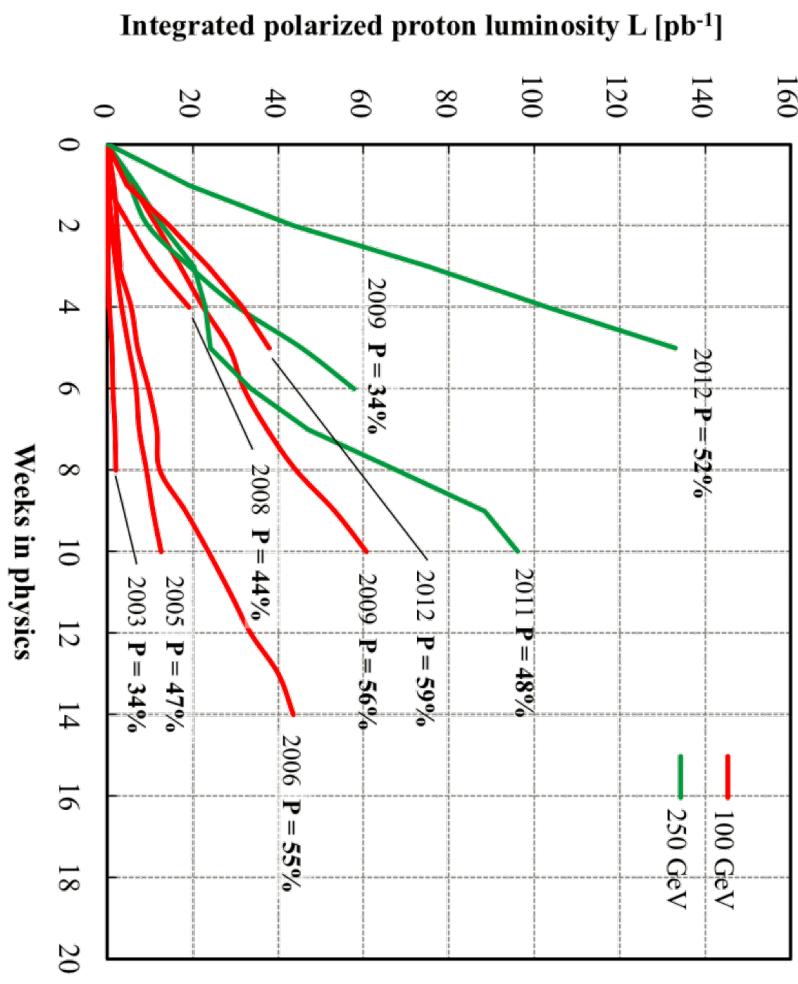
Twist-3 quark-gluon/gluon-gluon correlators in polarized hadron.

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

Twist-3 quark-gluon fragmentation function.

Polarized Protons at RHIC-PHENIX

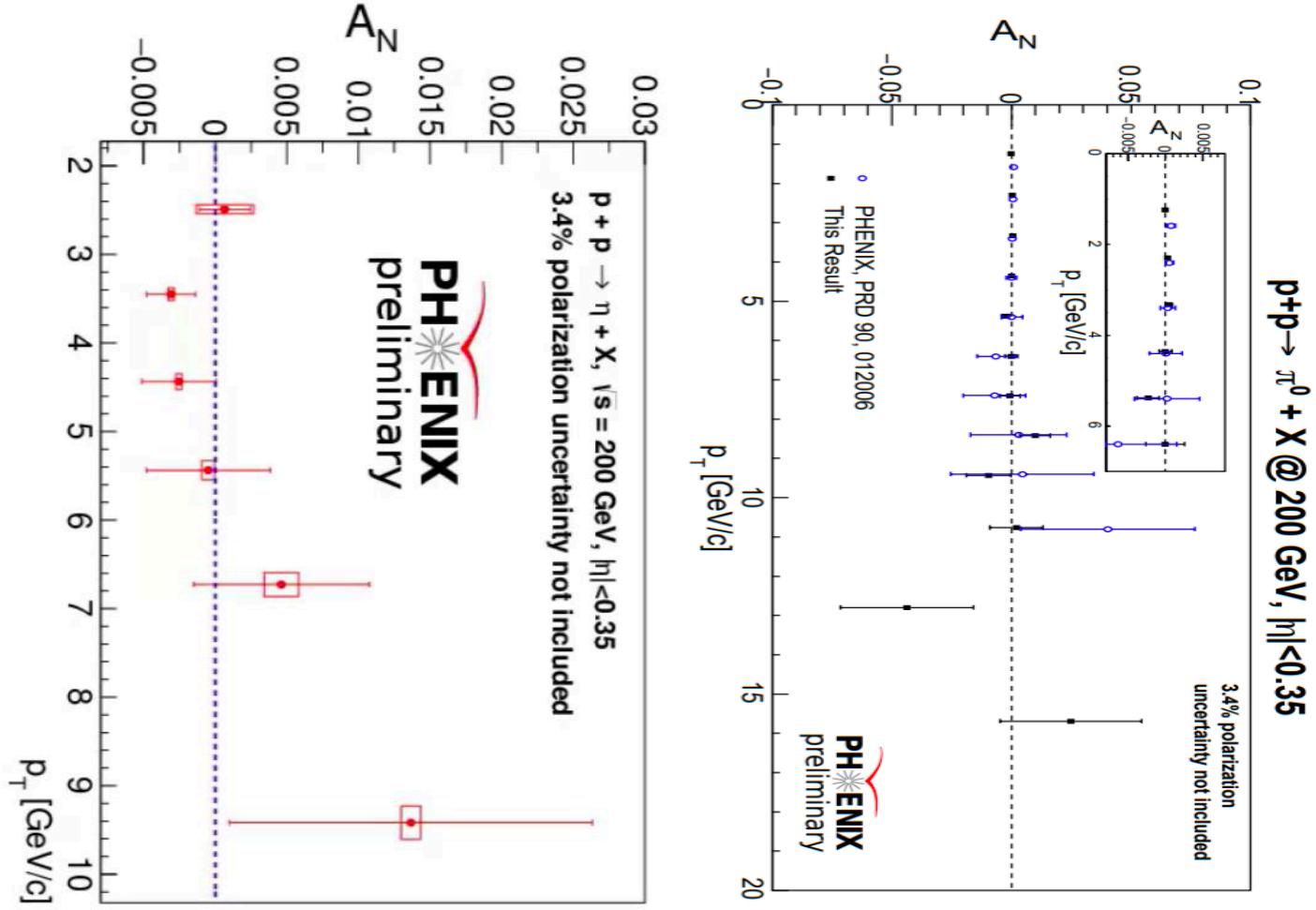
Transverse 



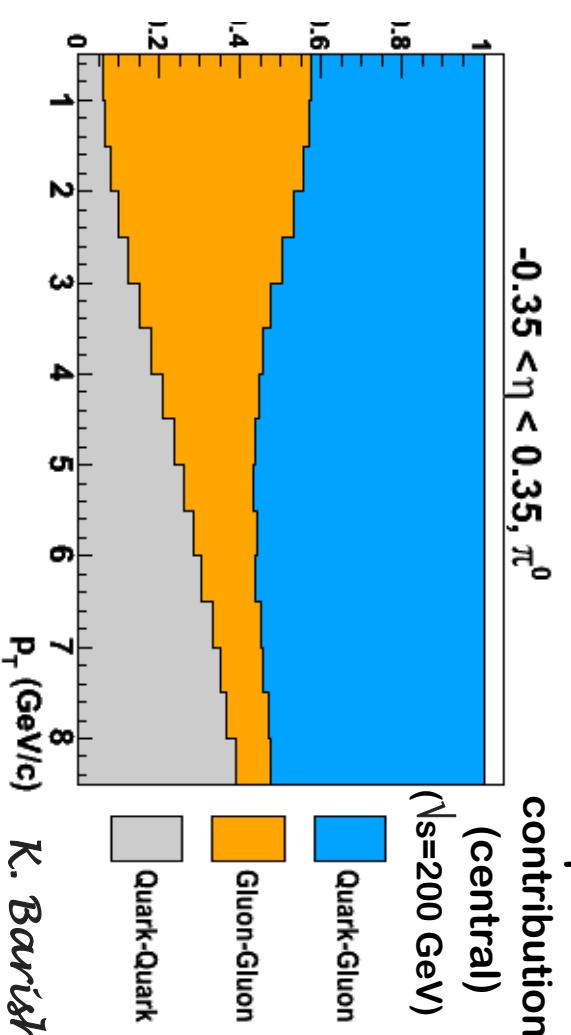
Year	Species	\sqrt{s} (GeV)	L (pb^{-1})	P
2006	p \bar{p}	62.4	0.02	48%
2006	p \bar{p}	200	2.7	51%
2008	p \bar{p}	200	5.2	46%
2012	p \bar{p}	200	9.2	58%
2015	p \bar{p}	200	50	60%
2015	pAu	200	1.27	60%
2015	pAl	200	3.97	54%

- **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 (200 GeV)

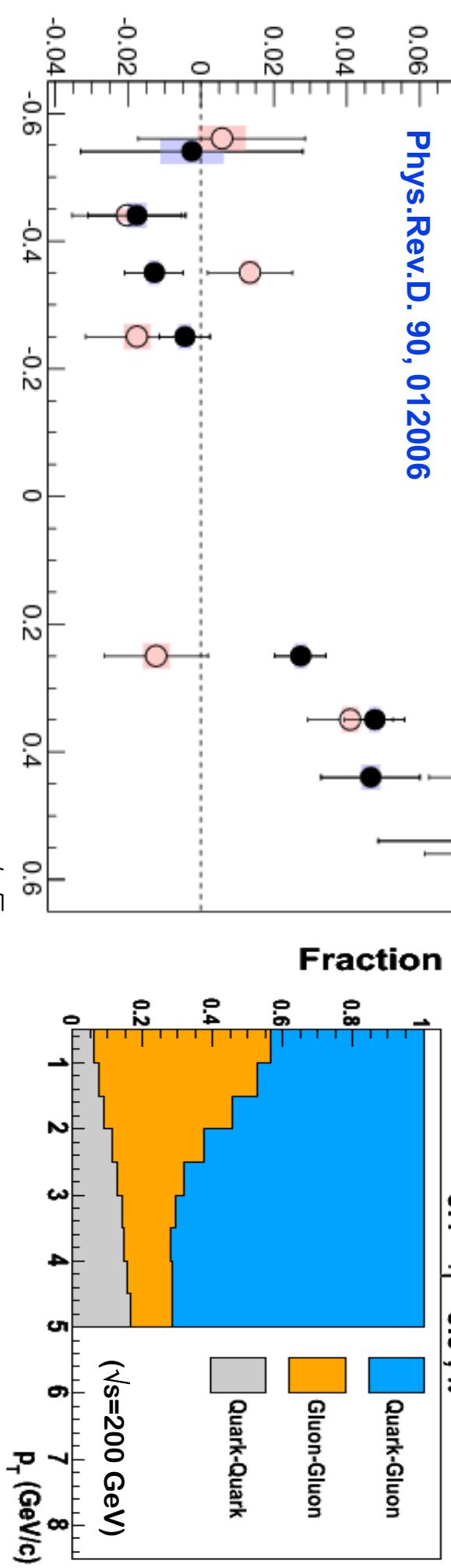
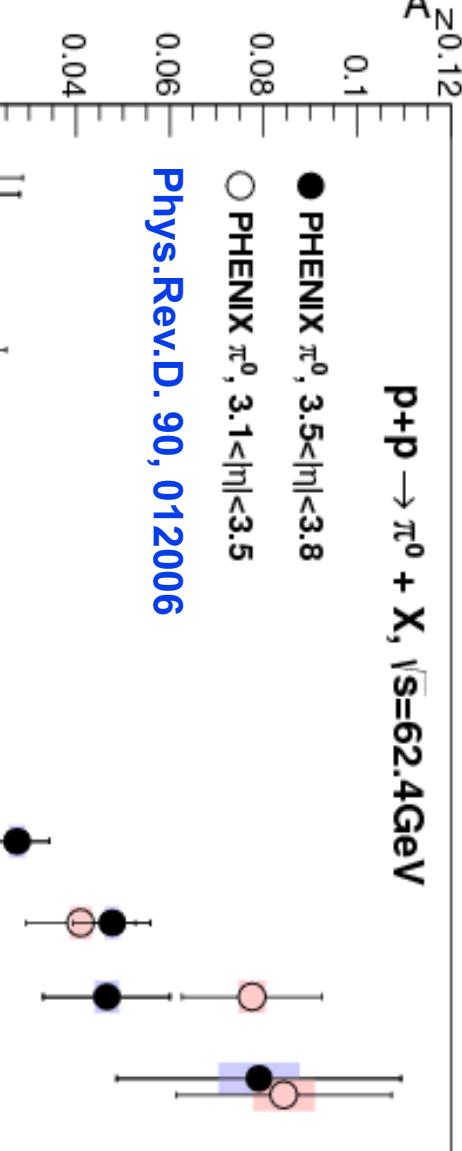


- ▷ π^0 asymmetries consistent with zero (to within 10^{-4} at low p_T) observed over a wide p_T range.
- ▷ Constrains gluon Sivers function (*JHEP 09, 119 (2015)*)
- ▷ η asymmetries are also consistent with zero (to within 0.005 at low p_T)
- ▷ π^0/η may provide insight on effects due to strangeness, isospin, or mass



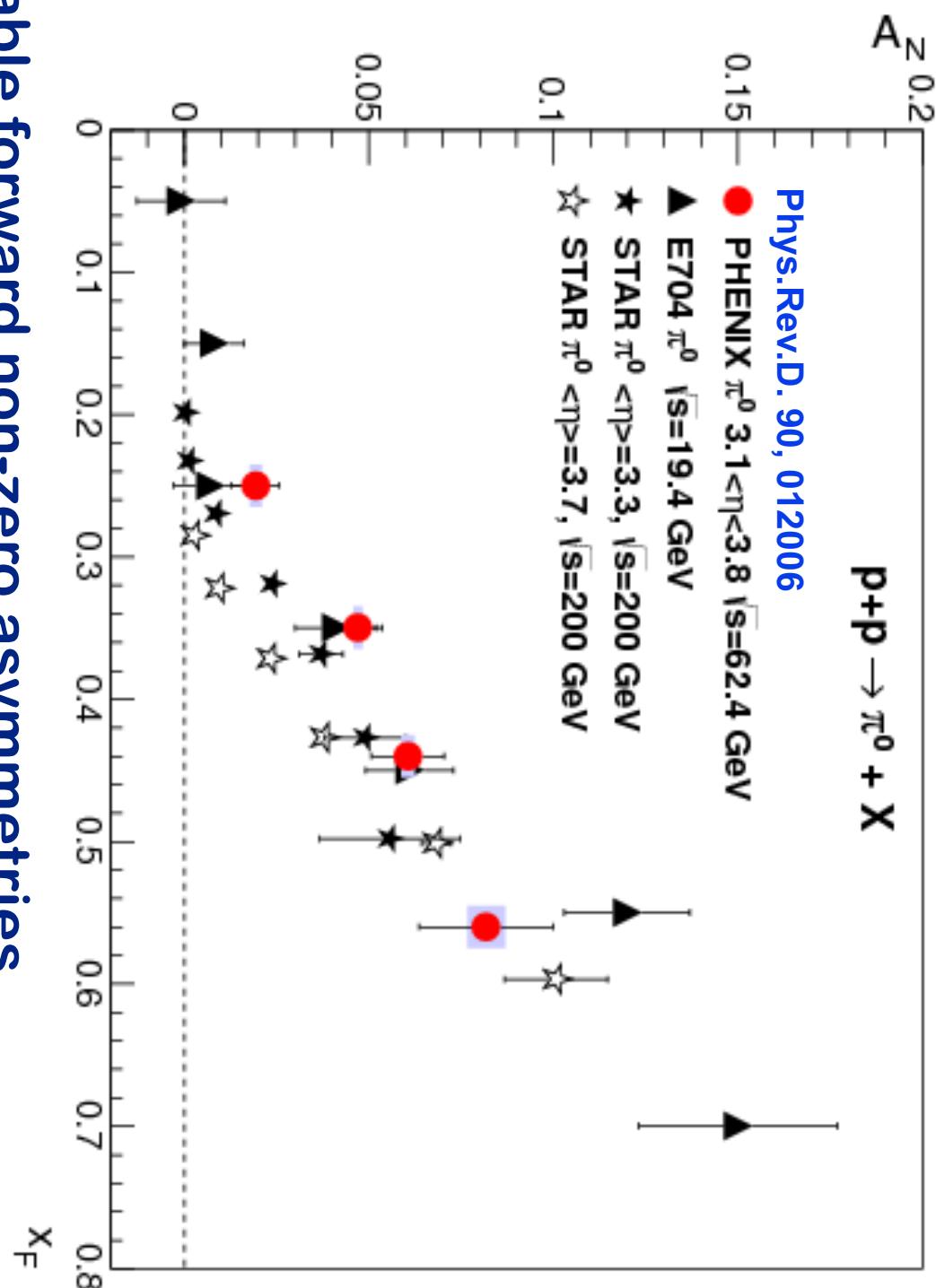
Forward $\pi^0 A_N$ (62.4 GeV)

π^0 process contribution
in PHENIX forward arms



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

Forward $\pi^0 A_N$ \sqrt{s} dependence



- Sizable forward non-zero asymmetries
- No dependence on \sqrt{s} apparent from 19.6 GeV to 200GeV
- Note: slight differences in pseudorapidity and/or ρ_T
- Updated Run 12 data coming soon.

A_N Forward single muon

Single muon A_N from D meson decay

- » Production dominated by gg fusion

- » Probes tri gluon correlation functions

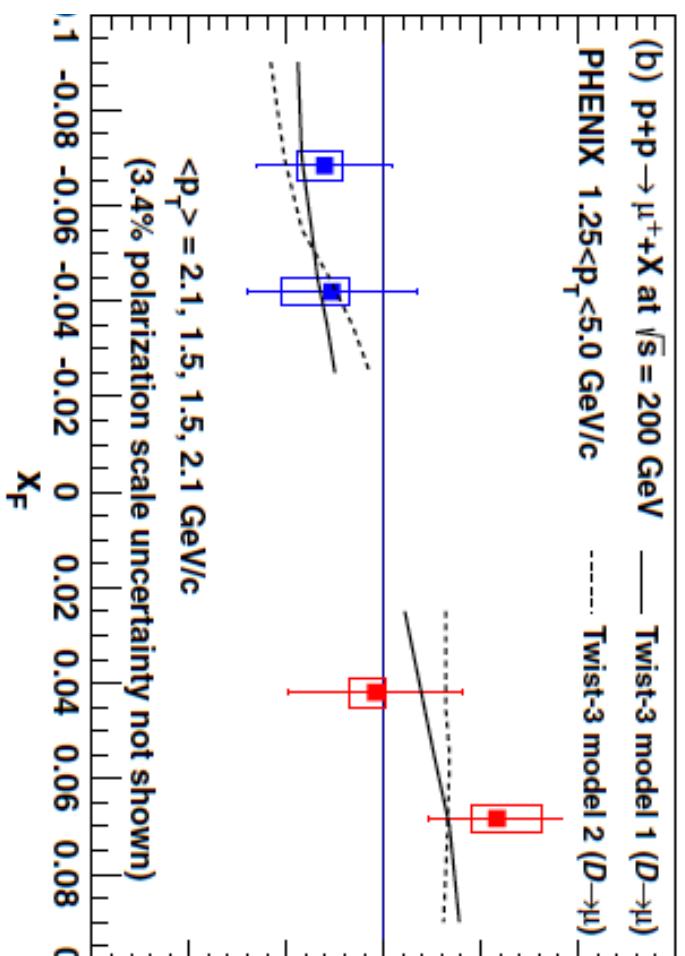
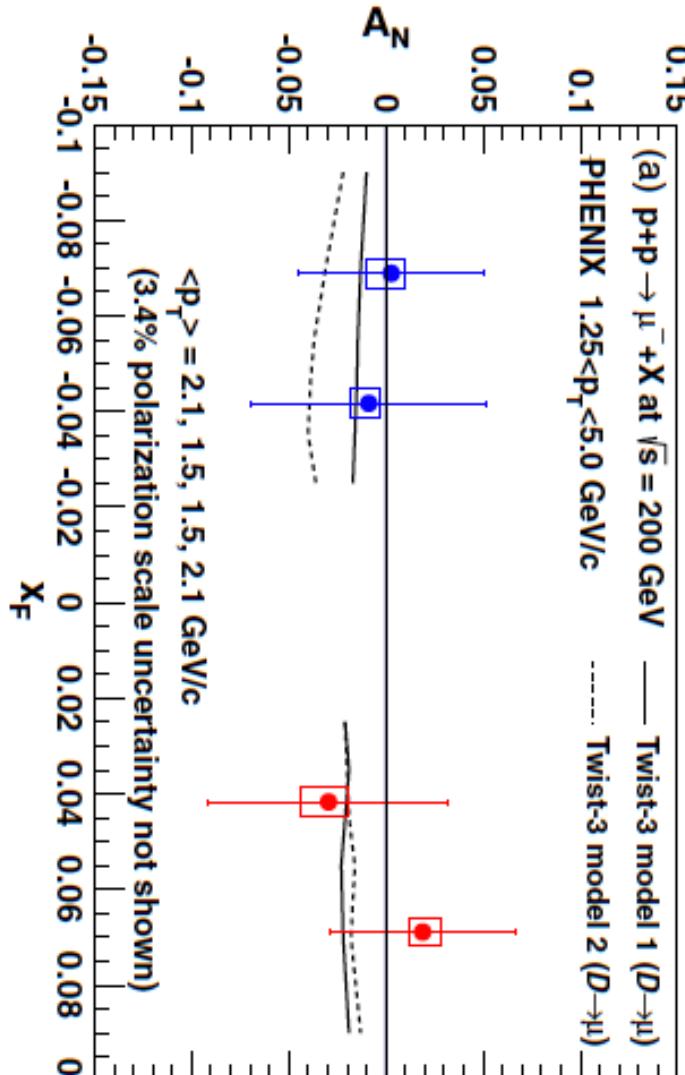
(initial state)

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

- » Related to gluon Sivers distribution

➤ A_N consistent with zero within uncertainties, but also with twist 3 models.

Phys.Rev.D. 95, 112001 (2017)



Nuclear Dependence on Transverse Spin (A_N)

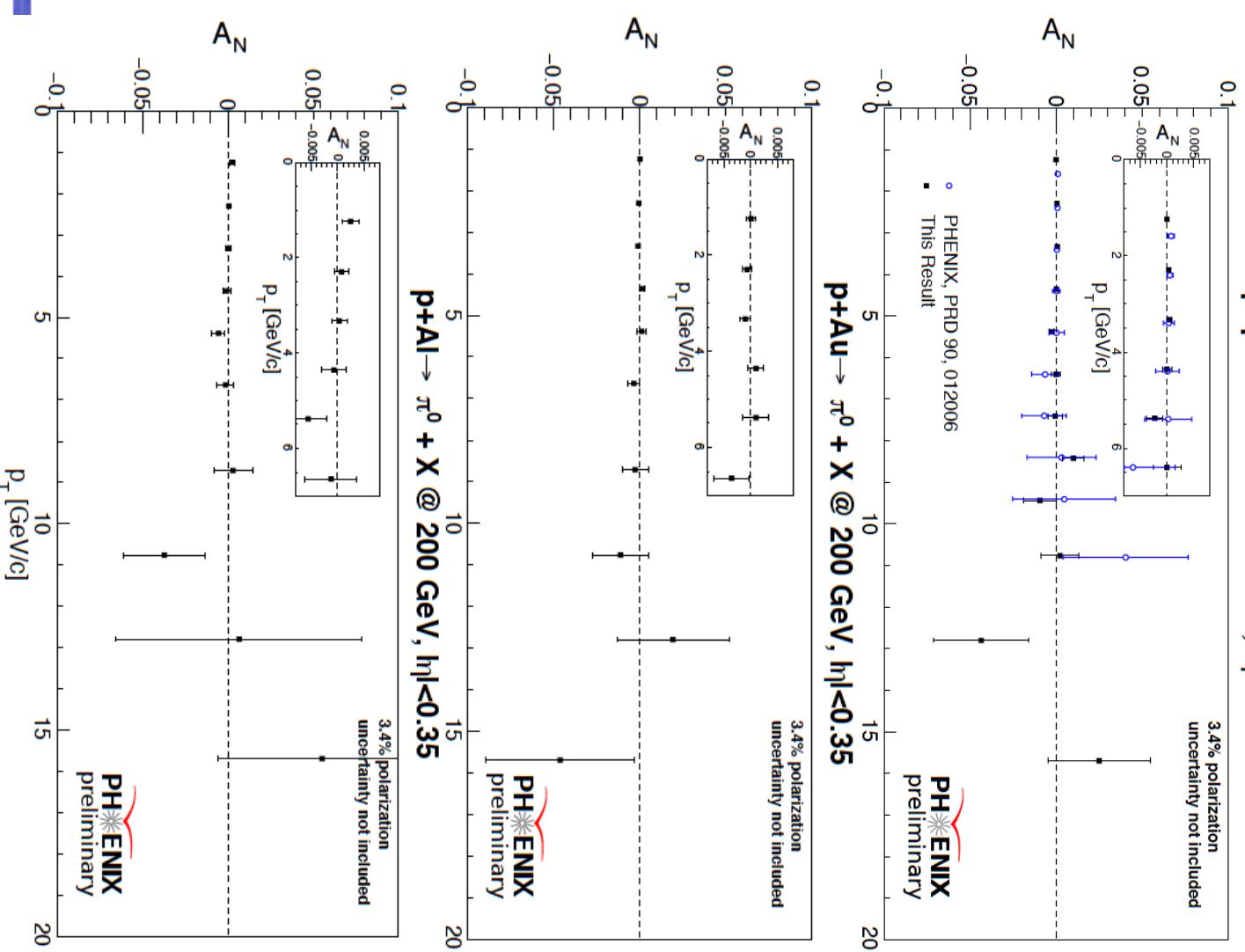
A_N: mid-rapidity π^0 A dependence

- Central rapidity A_N(π^0) sensitive to Gluon Sivers Twist-3 counter-part

- A_N p+p results

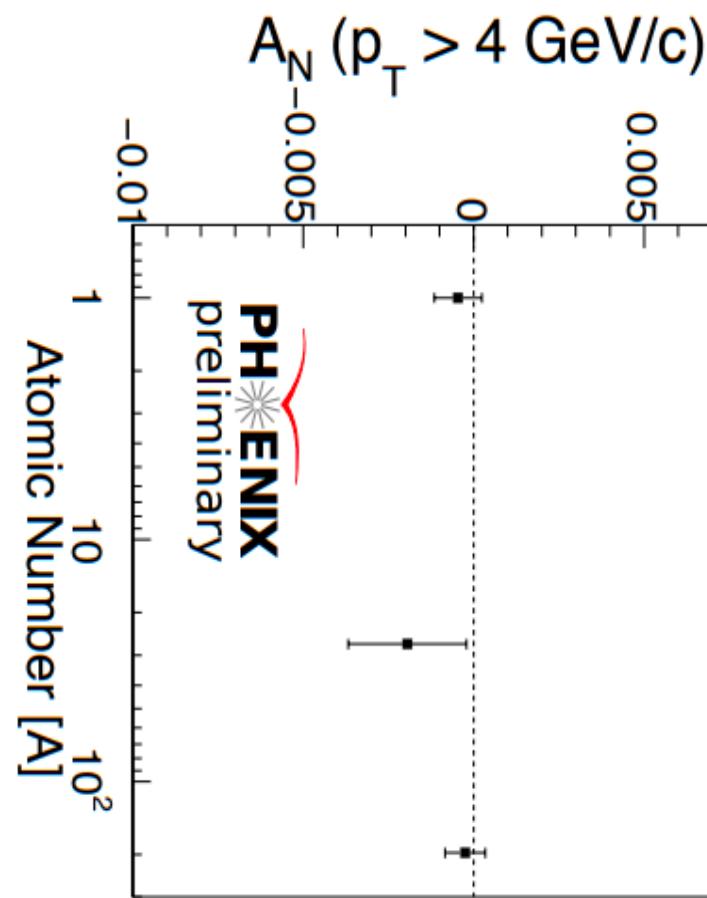
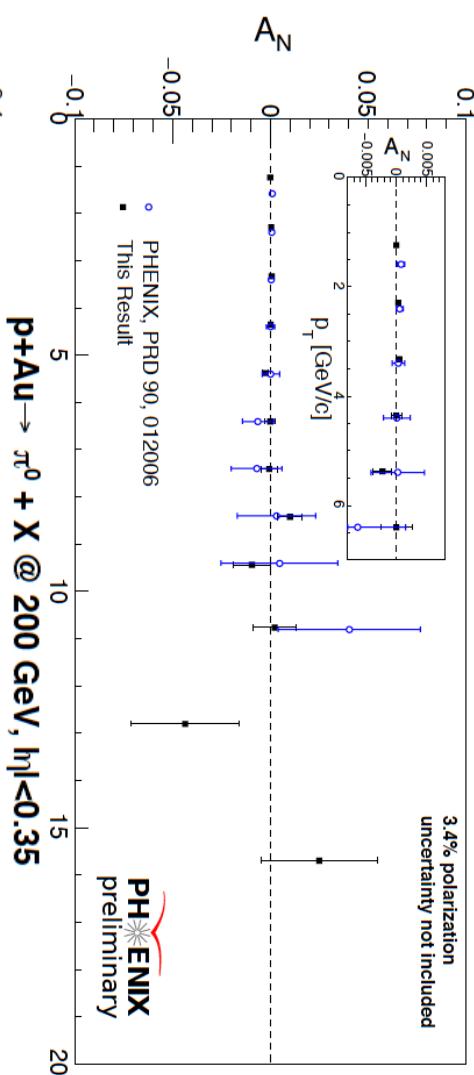
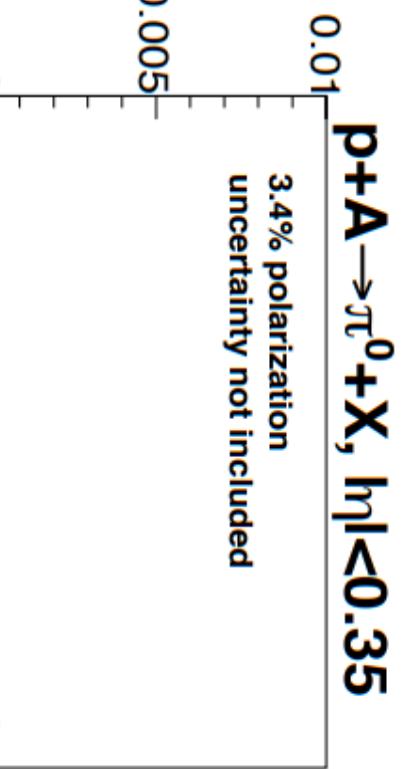
consistent with zero

- Factor 3 increase precision from Phys.Rev.D. 90, 012006
- Higher p_T reach
- No surprises in A dependence
- Asymmetry is consistent with zero within the uncertainties



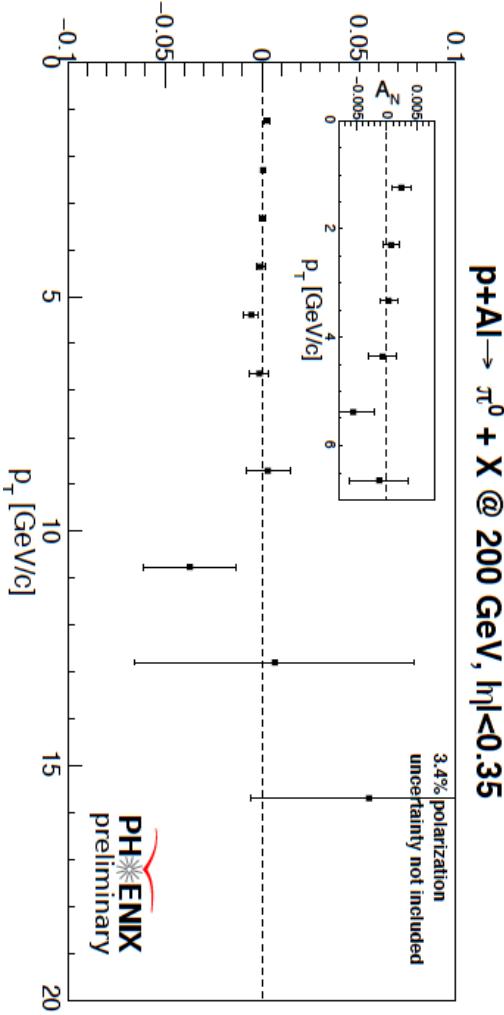
A_N: mid-rapidity π^0 A dependence

$p+p \rightarrow \pi^0 + X @ 200 \text{ GeV}, |\eta| < 0.35$



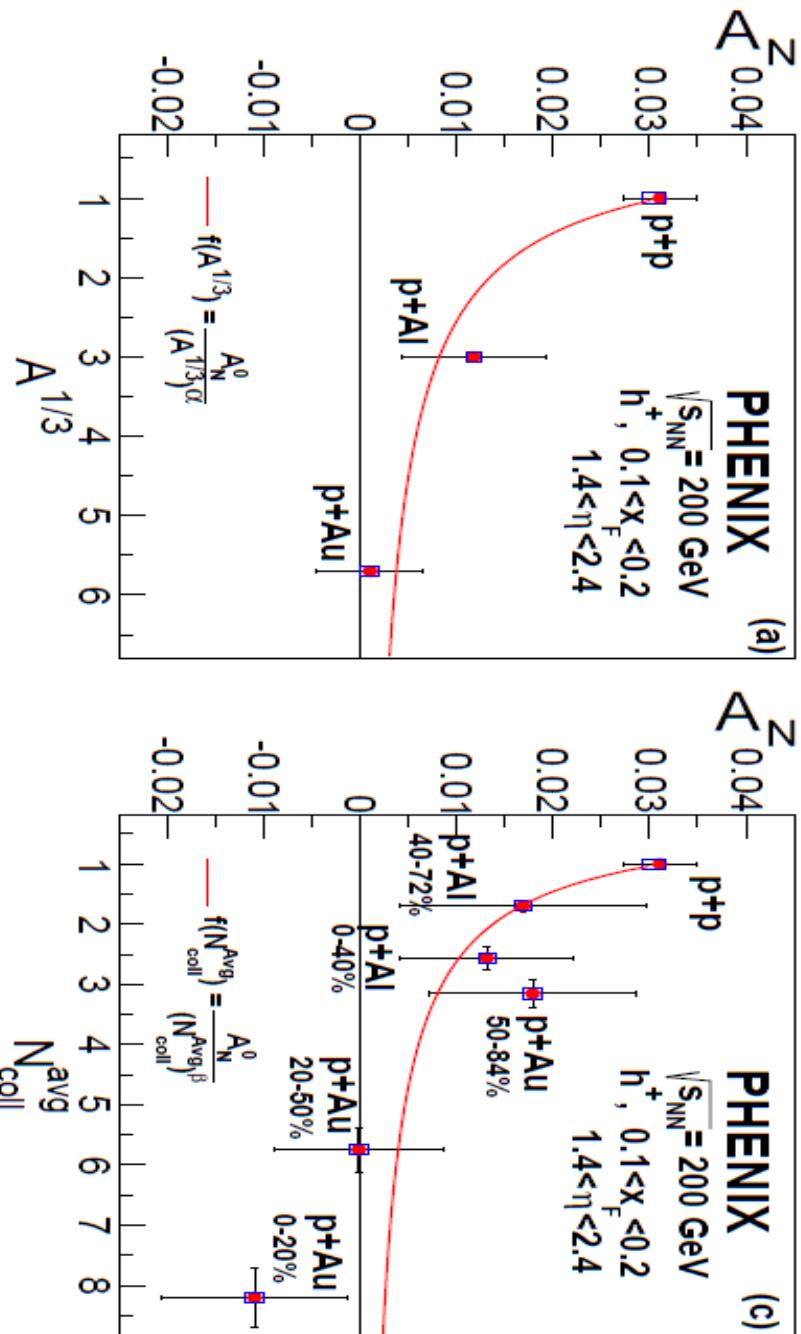
➤ No surprises in A dependence

- Asymmetry is consistent with zero within the uncertainties

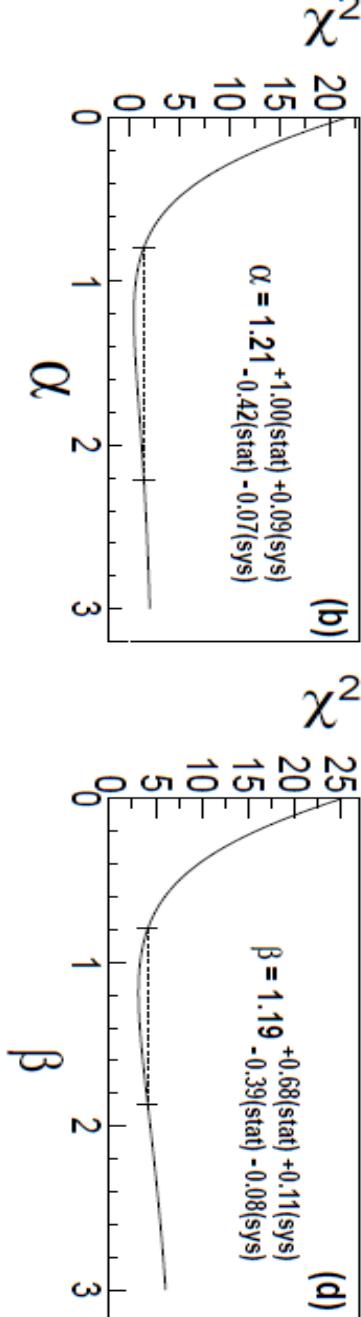


AN Forward Charged Hadrons (200GeV)

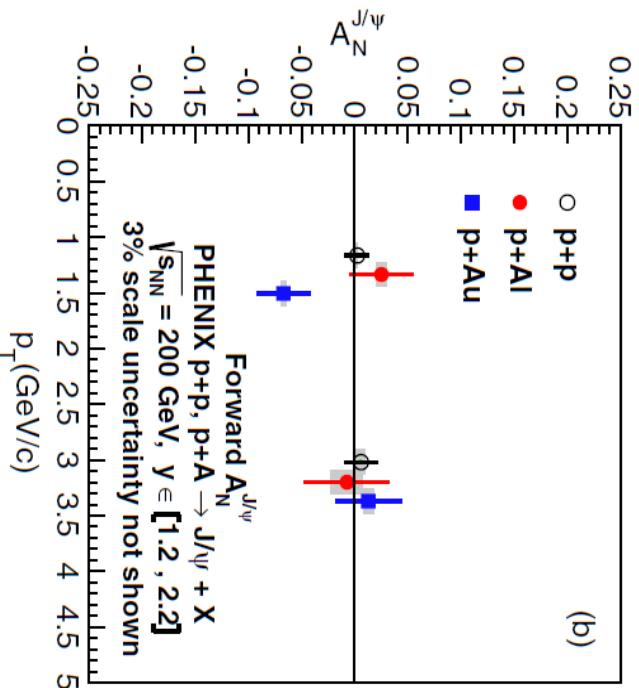
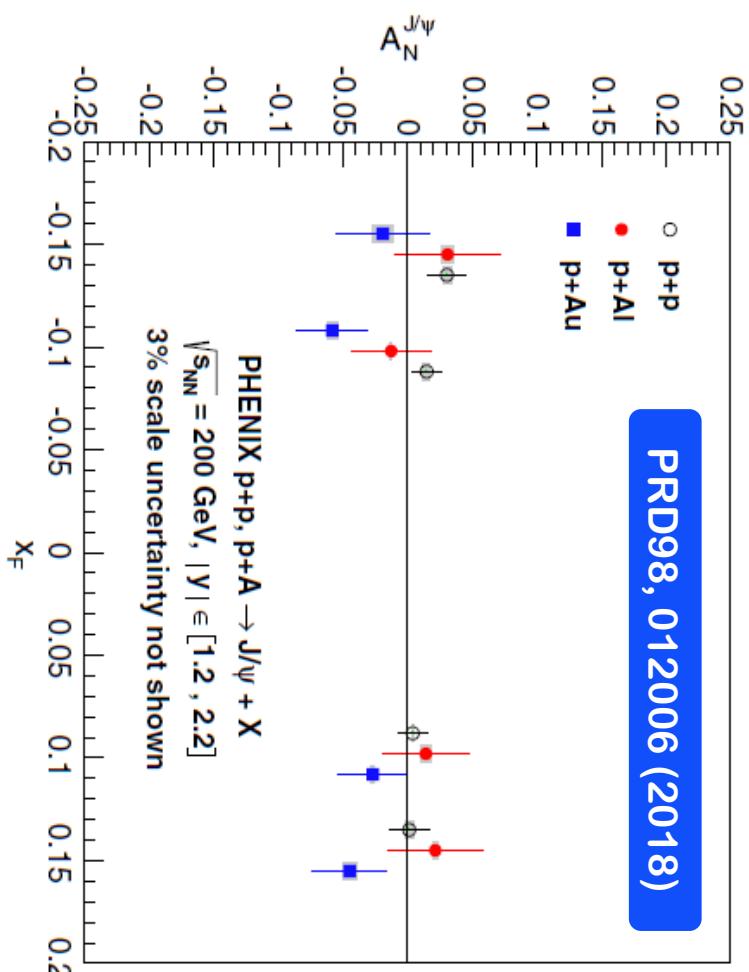
arXiv:1903.07422 (2019), accepted for publication in PRL



- Clear decrease of asymmetry as a function of A
- Fit as a function of $A^{1/3}$
- Suggests that the suppression of A_N is related to the density of nuclear matter traversed by the proton



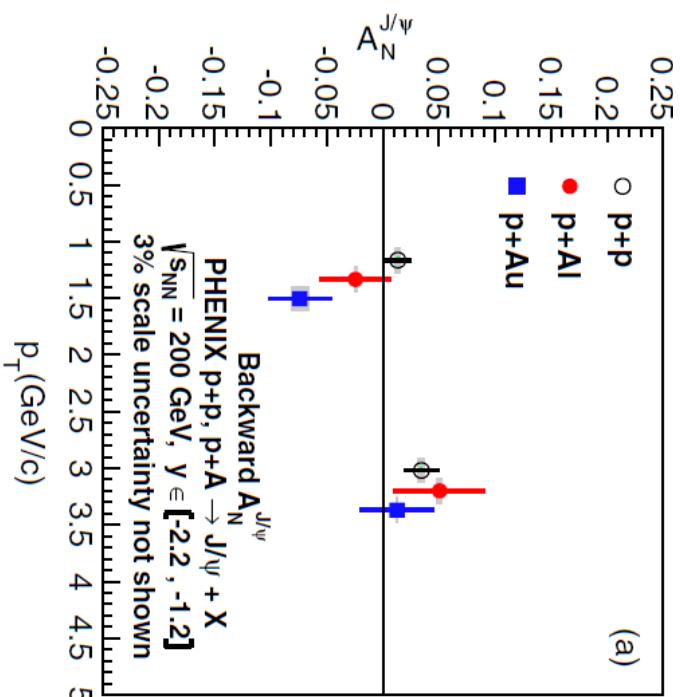
AN Forward J/ ψ (200GeV)



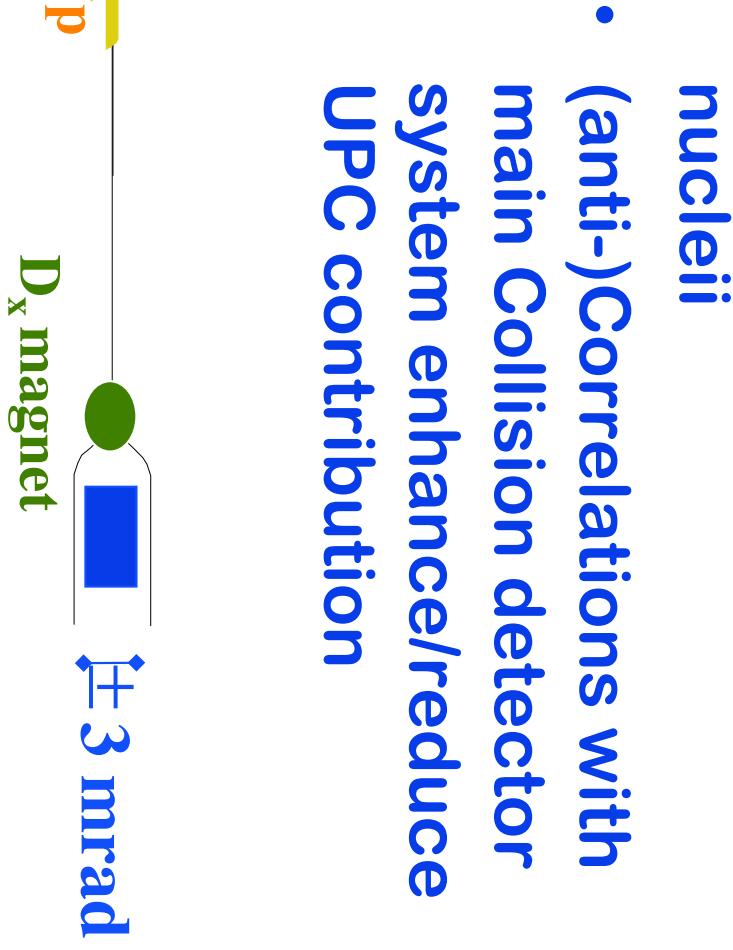
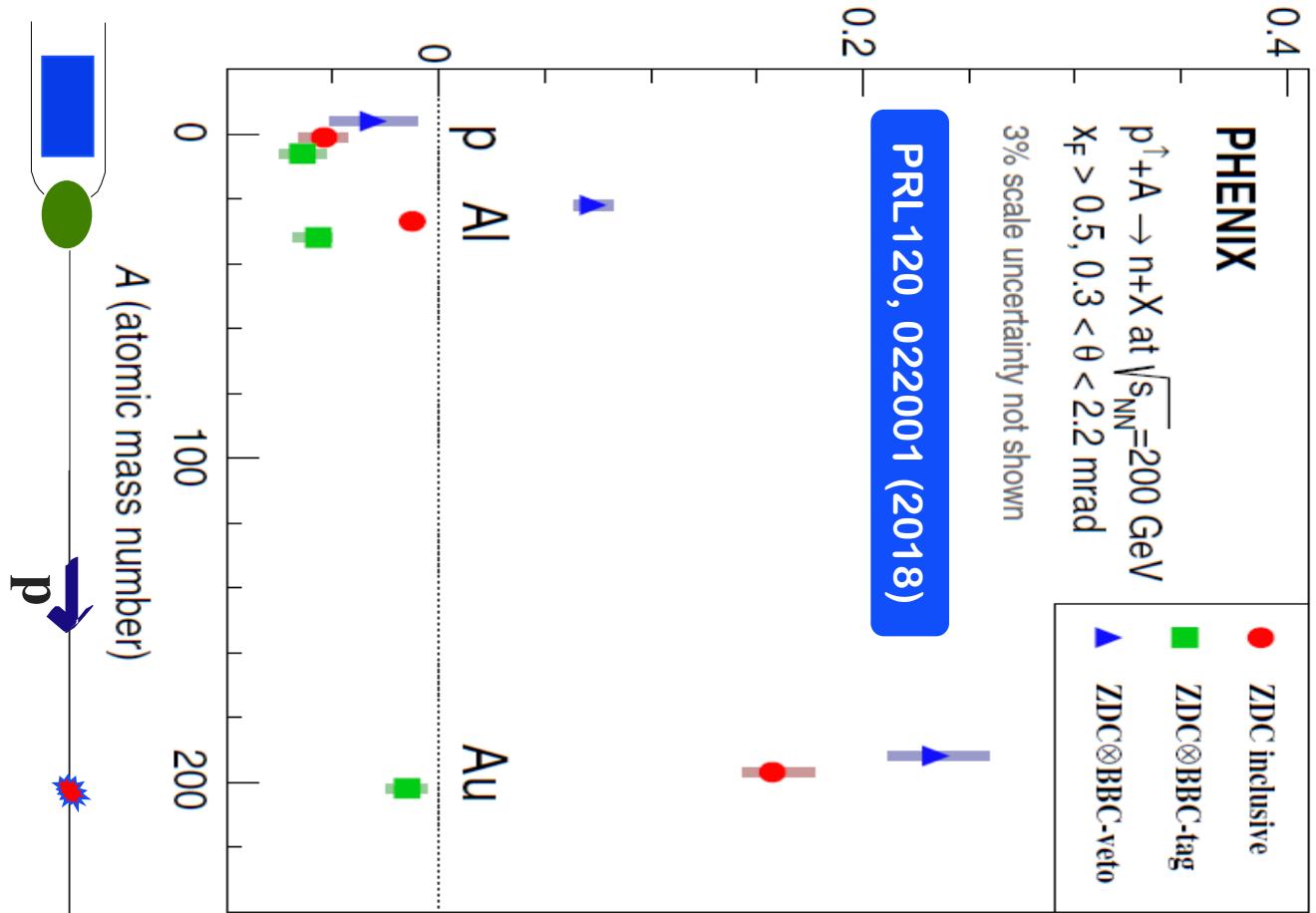
➤ **$p + p$ and $p + Al$ are consistent with zero, but $p + Au$ favors negative A_N (2 σ significance)**

— Nonzero effect only visible at the lowest available P_T

➤ **One of the possible contributions could come from electromagnetic interactions.**



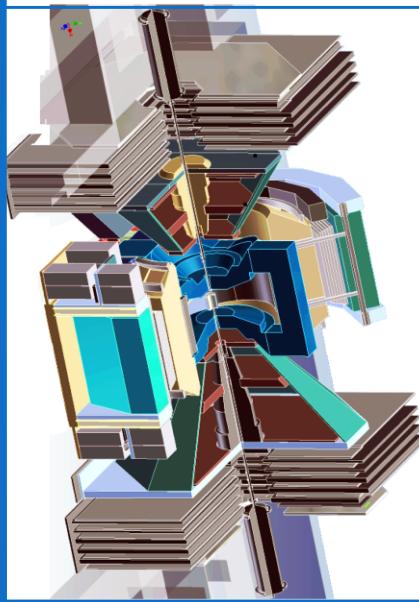
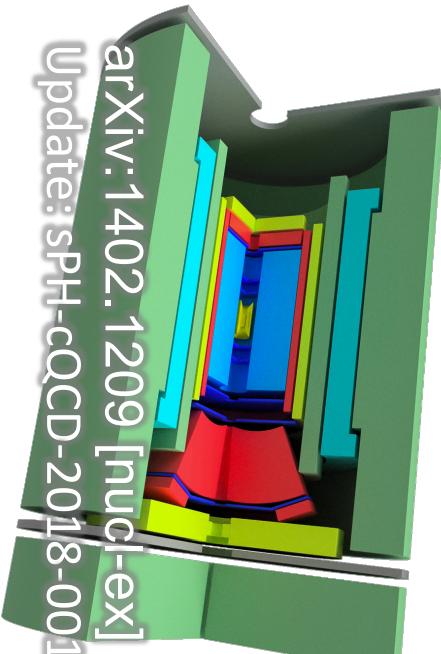
Very Forward Neutron A_N ($p_T < 0.1 \text{ GeV}/c$)



- Unexpectedly large A dependence in neutron asymmetries
- Sign change seen
- Possibility of ultra-peripheral collisions(UPC) effect, enhanced by Z^2 for nuclei
- (anti-)Correlations with main Collision detector system enhance/reduce UPC contribution

IV. Evolution of PHENIX

Interaction Region

Original PHENIX	SPHENIX (+fsPHENIX?)	An EIC detector
 <ul style="list-style-type: none"> 16y+ operation 100+M\$ investment Broad spectrum of physics (QGP, Hadron Physics, DM) 189+ published physics papers with 25K citations 1.4M channel streaming 	 <ul style="list-style-type: none"> Comprehensive central upgrade based on BaBar magnet Rich jet and HF physics program → nature of QGP fsPHENIX : forward tracking, HCAL and muon ID → Spin, CNM 	 <ul style="list-style-type: none"> SPHENIX upgrade path leads to a capable EIC detector Large coverage of tracking, calorimetry, and PID Full streaming DAQ based on SPHENIX
~2000	2017 -> 2022, SPHENIX CD-1/3A Approval	≥ 2025
RHIC: A+A, spin-polarized p+p, spin-polarized p+A	arXiv:1501.06197 [nucl-ex]	arXiv:1402.1209 [nucl-ex] Update: sPHENIX-cQCD-2018-001
Time		

Summary

➤ Gluon polarization

- DSSV14 $\int_{\textcolor{red}{0.05}}^1 dx \Delta G(x) = 0.20^{+0.06}_{-0.07}$ at 90 % C.L. (RHIC Run 6-9)
- Gluon spin contribution confirmed at higher collision energies.
- New measurements pushing to lower x

➤ Flavor decomposed quark distribution via W

- Polarized light sea seems to be asymmetric and disfavors pion cloud models

➤ Transverse spin measurements

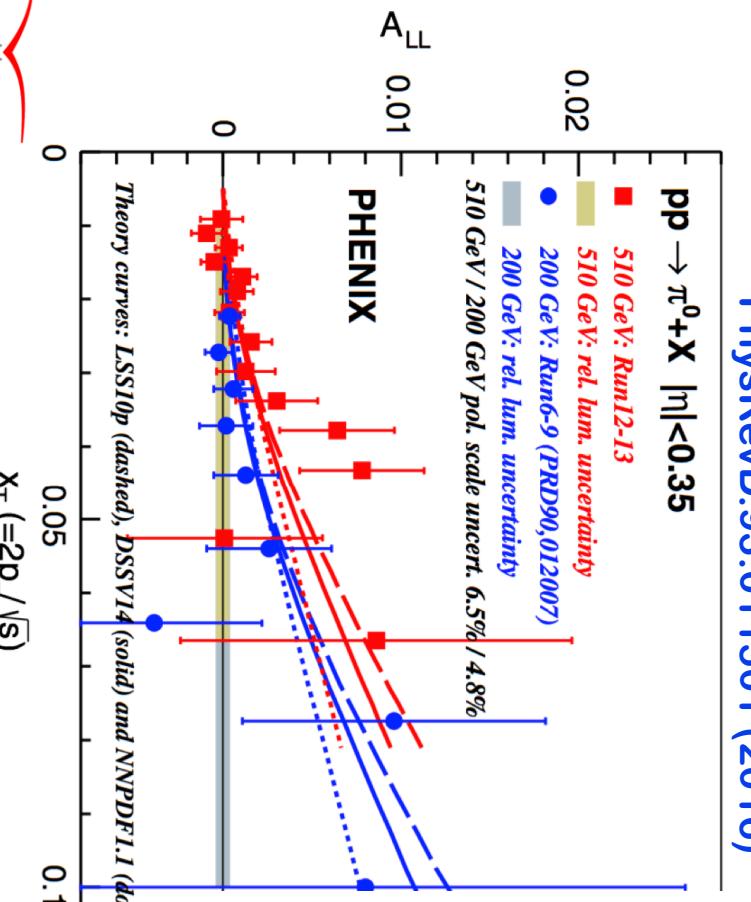
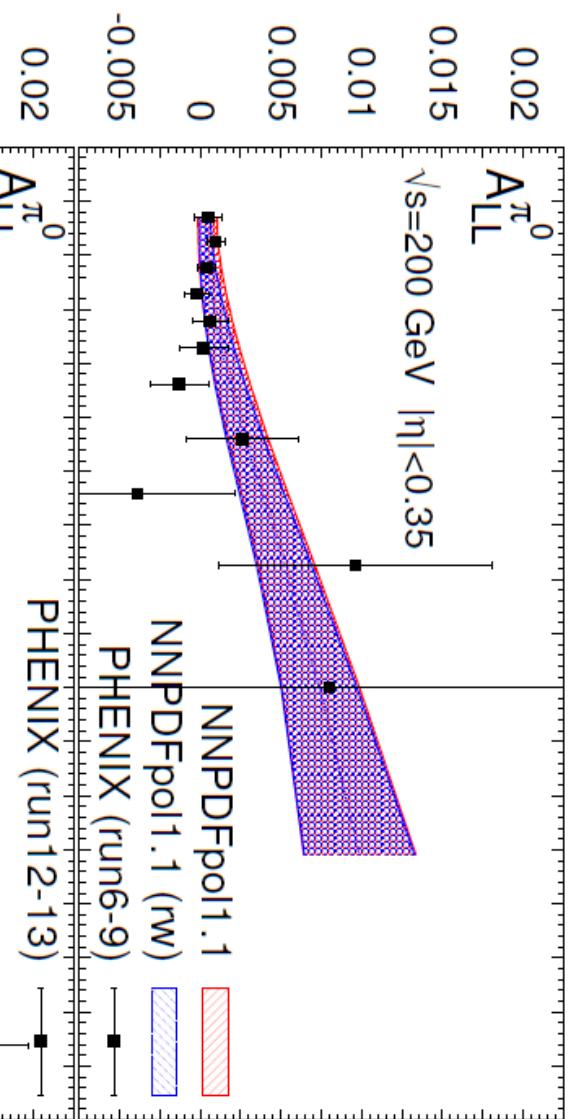
- TSSA measurements related to Collins and Sivers through twist 3 quark and gluon correlators.
- New information towards understanding transverse asymmetries in hadron collisions, but also new puzzles (such as A dependence)

Extra slides...

Neutral pion asymmetry

arXiv:1702.05077

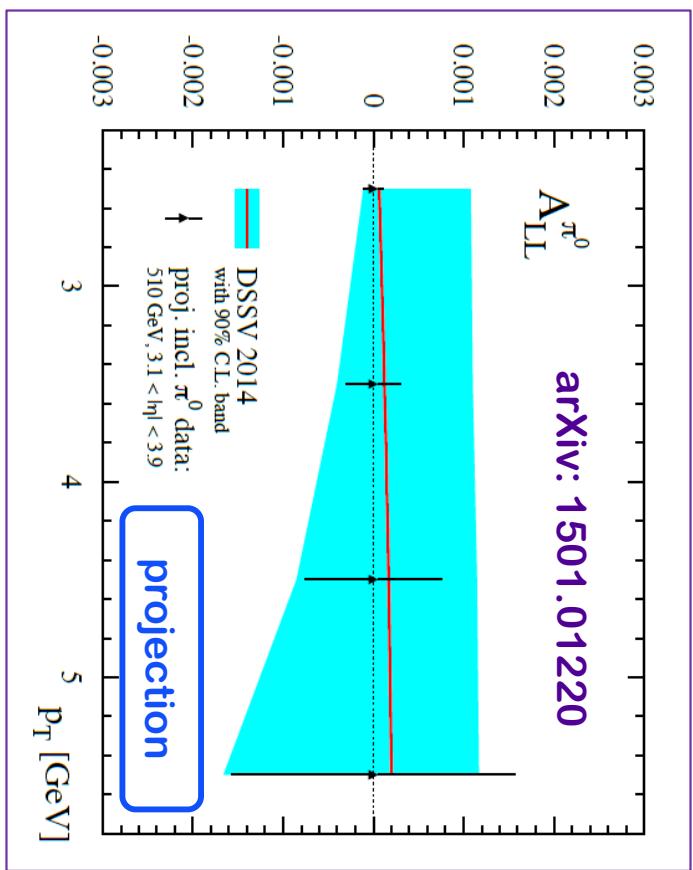
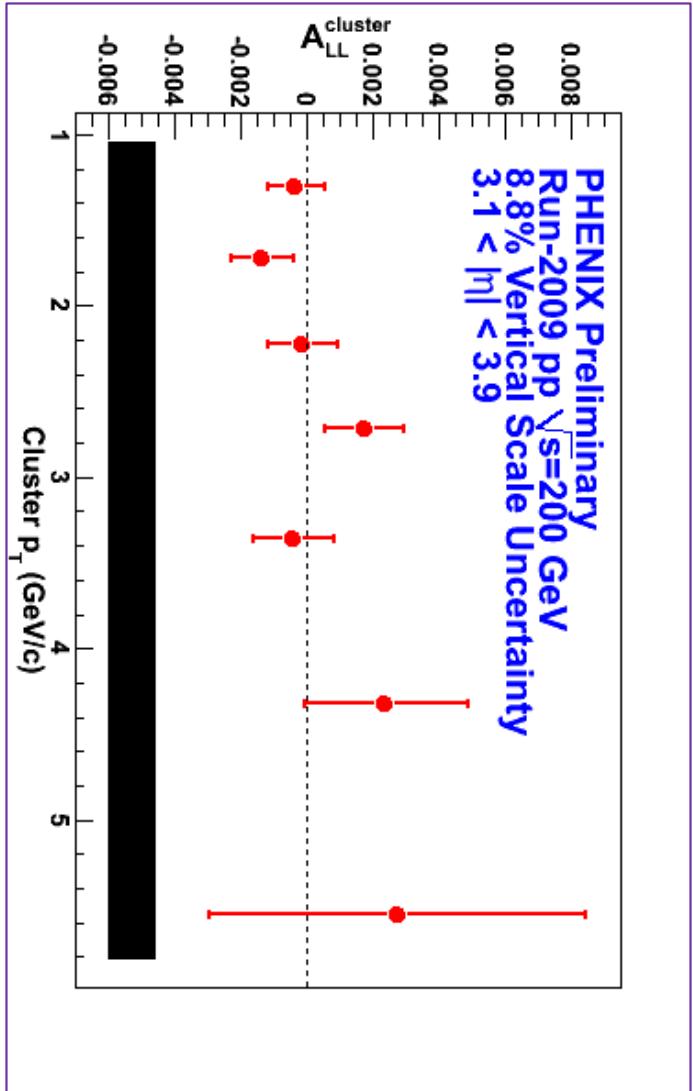
- Final PHENIX π^0 doublets published in 2016 (inclus)
- Favor positive gluon pole
- Sensitive down to $x \sim 10^{-5}$
- Additional constrain in g
- DSSV14



Forward EM clusters ($3.1 < |\eta| < 3.8$)

EM clusters A_{LL}^{cluster} at very forward rapidity

- » Run9 200 GeV preliminary (left) / Run11 500 GeV preparing publication / Run13 510 GeV analysis is underway (right)
- » π^0 rich ($> 70\%$) EM clusters
- » Reaches Brorken x down to ~ 0.001

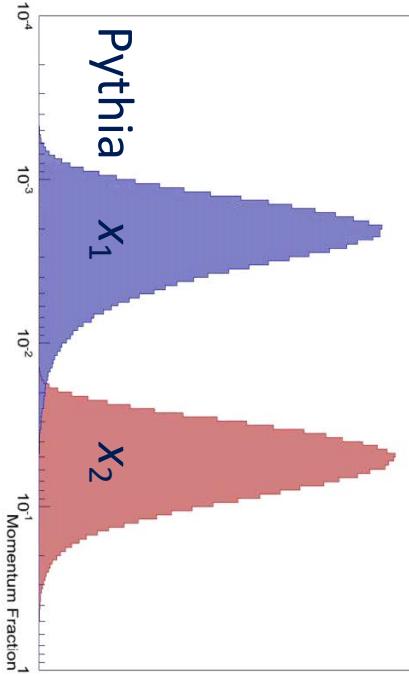
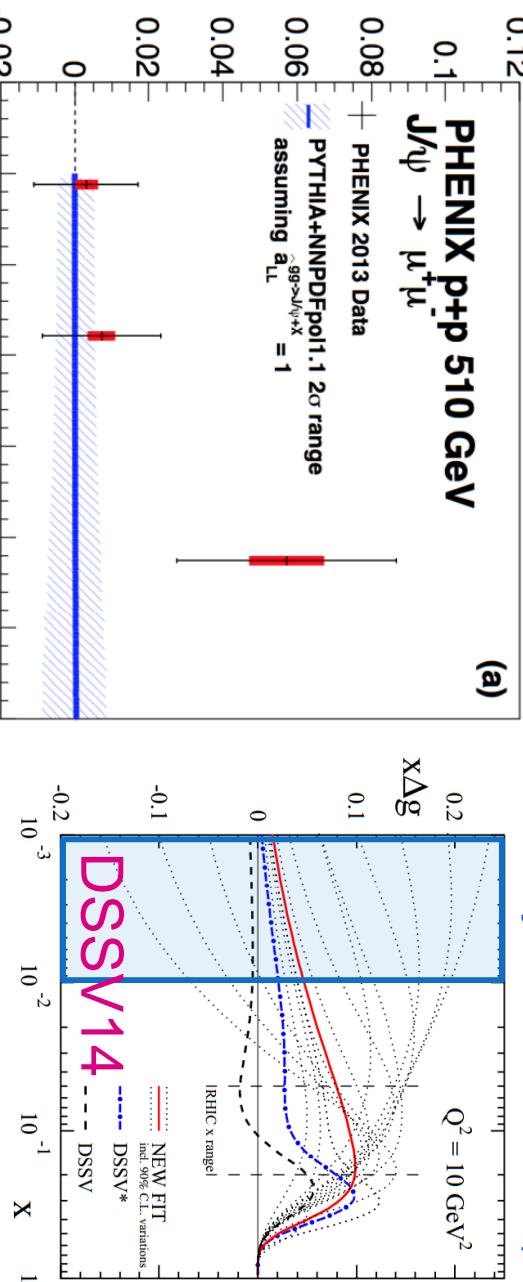


Forward J/ ψ asymmetries

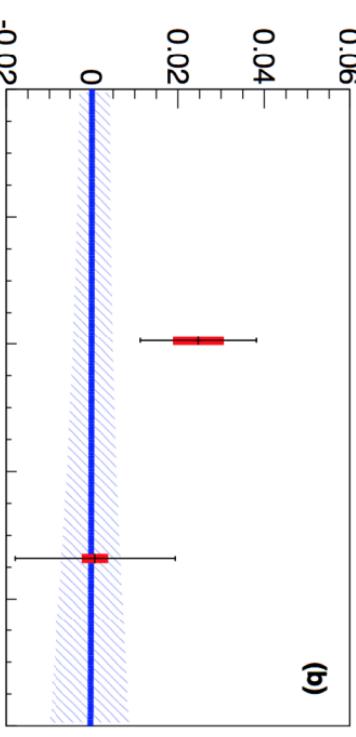
10.1103/PhysRevD.94.112008 (2016)



10.1103/PhysRevLett.113.012001 (2014)

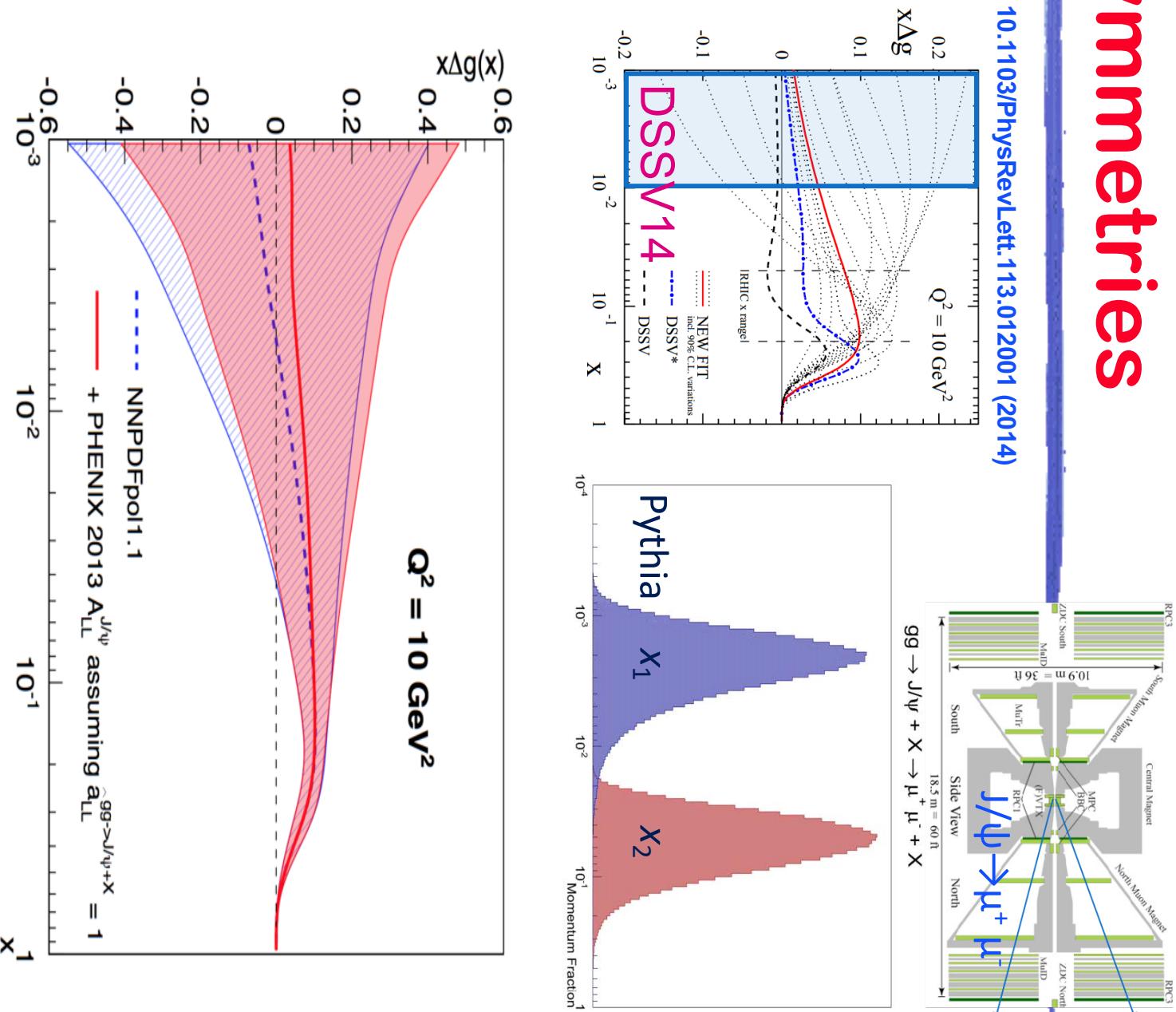
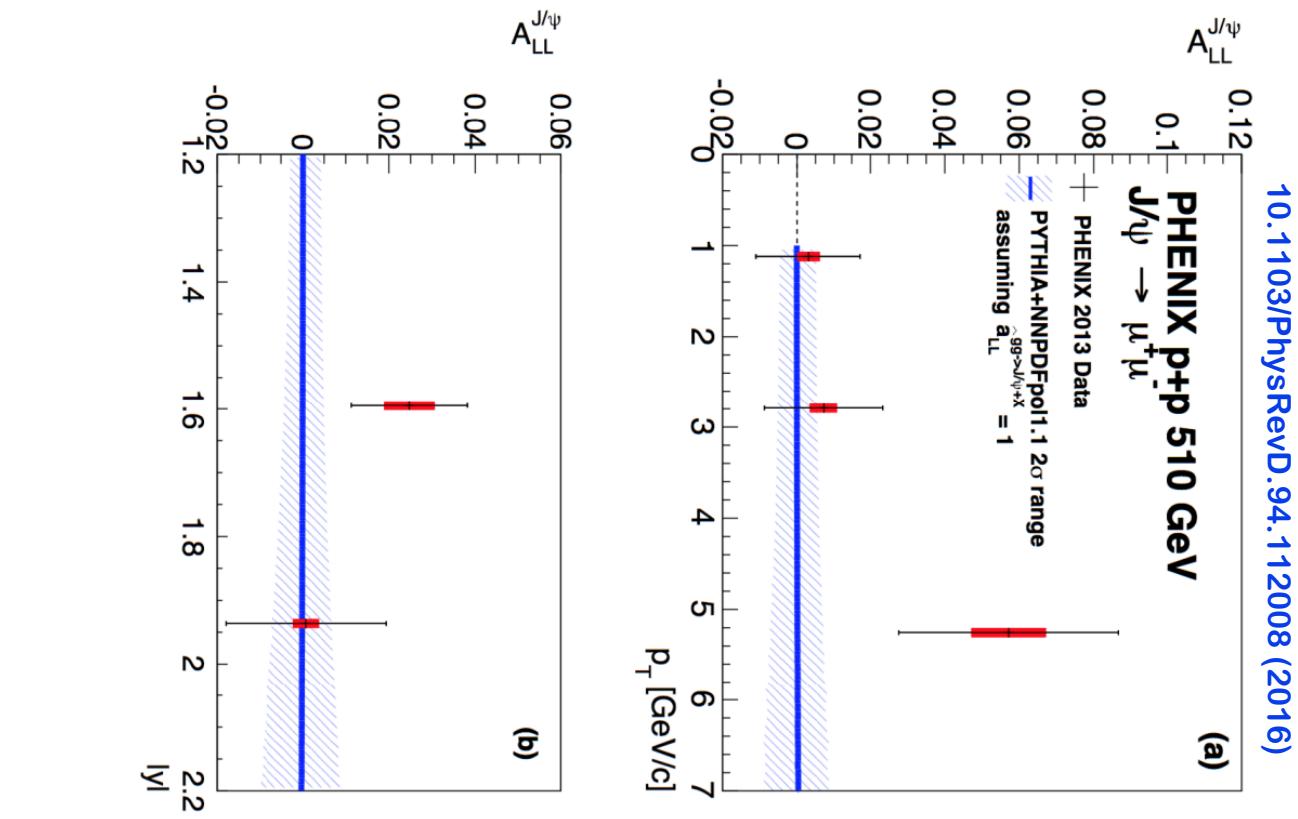


(b)



- Sensitive to gluon polarization down to $x \sim 10^{-3}$
- Production dominated by gg fusion
- Interpretation difficult due to uncertainty in J/ ψ production mechanism

Forward J/ ψ asymmetries



Impact on $\Delta g(x)$

➤ Published include in Global fittings

- 2006 200GeV and 62.4GeV $\pi^0 A_{LL}$
- 2009 200GeV $\pi^0 A_{LL}$
- 2012,2013 510GeV $\pi^0 A_{LL}$

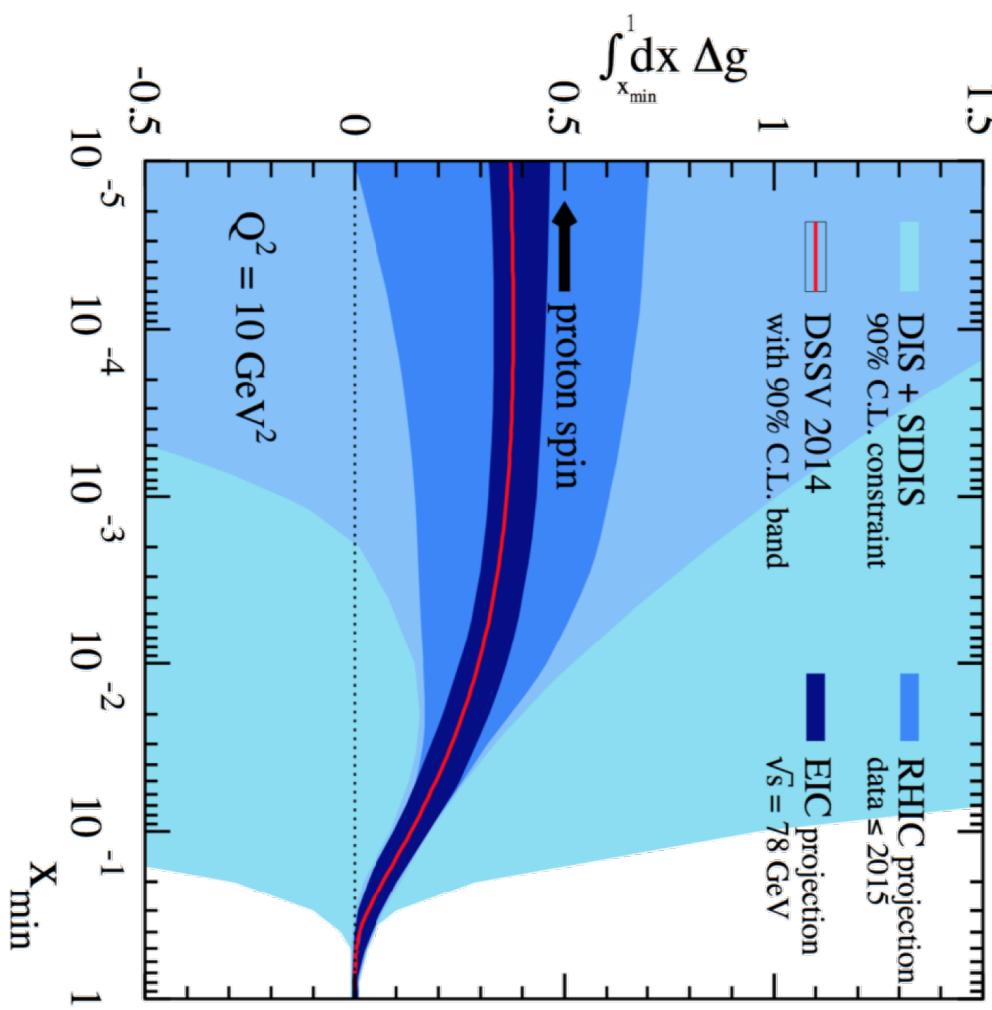
➤ Published, Not yet include in Global fittings

- 2013 510GeV Central $\pi^\pm A_{LL}$
- 2013 510GeV Forward $J/\psi A_{LL}$

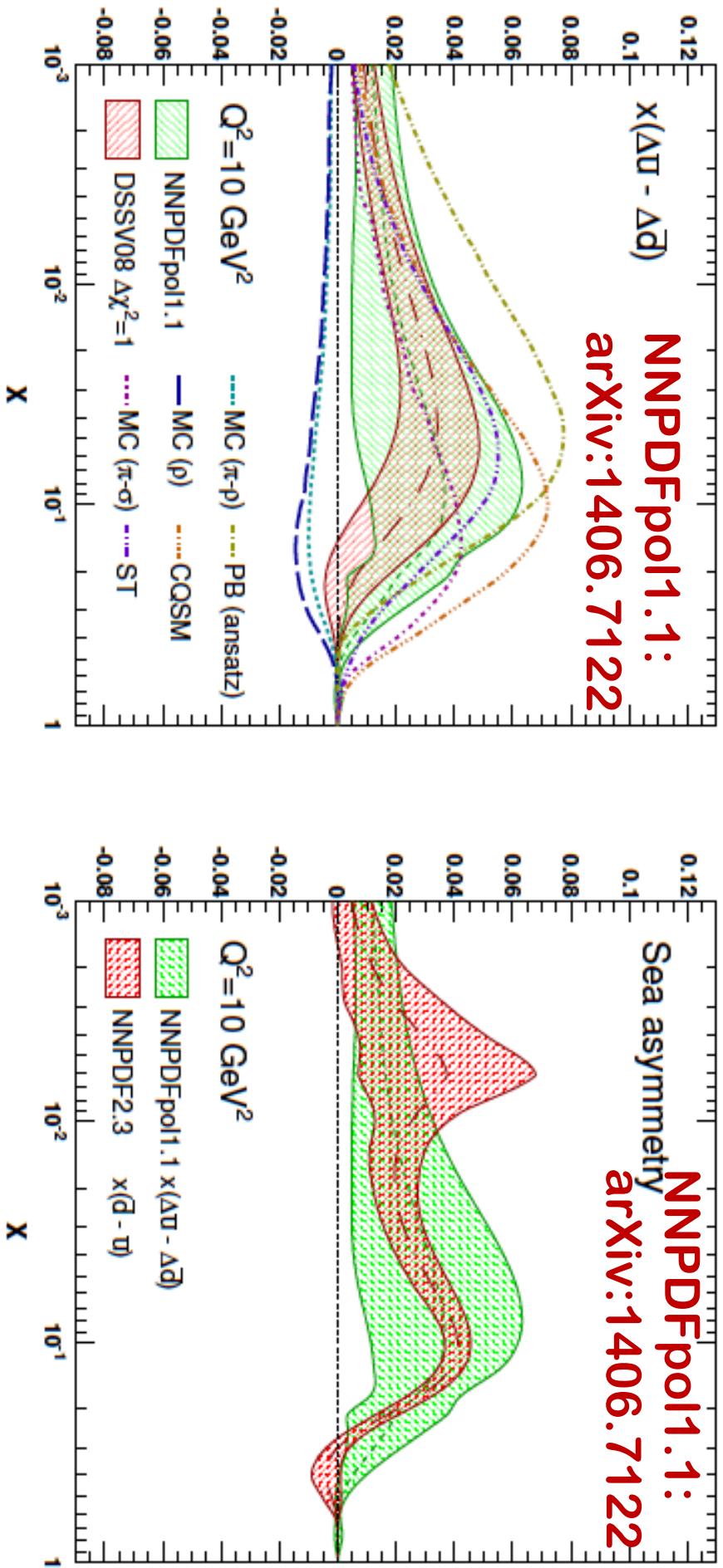
➤ Ongoing

- 2013 510GeV Central direct photon A_{LL}
- 2013 Jet A_{LL} at central rapidity
- 2009, 2011 di- $\pi^0 A_{LL}$
- 2011, 2013 500, 510GeV Forward $\pi^0 A_{LL}$

DSSV14: 10.1103/PhysRevLett.113.012001



Polarized light sea-quark constraints

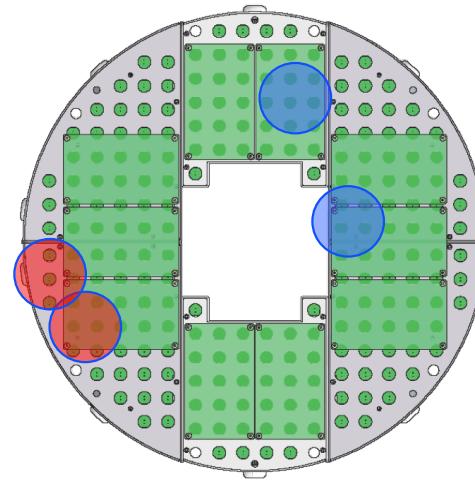


- STAR 2012 data at boundary of DSSV uncertainty bands
- Reweighted NNPDFpol1.1 shows substantial polarized light sea asymmetry
- Opposite sign to most cloud models
- All PHENIX data (central and forward) published

Forward A_N for EM Clusters

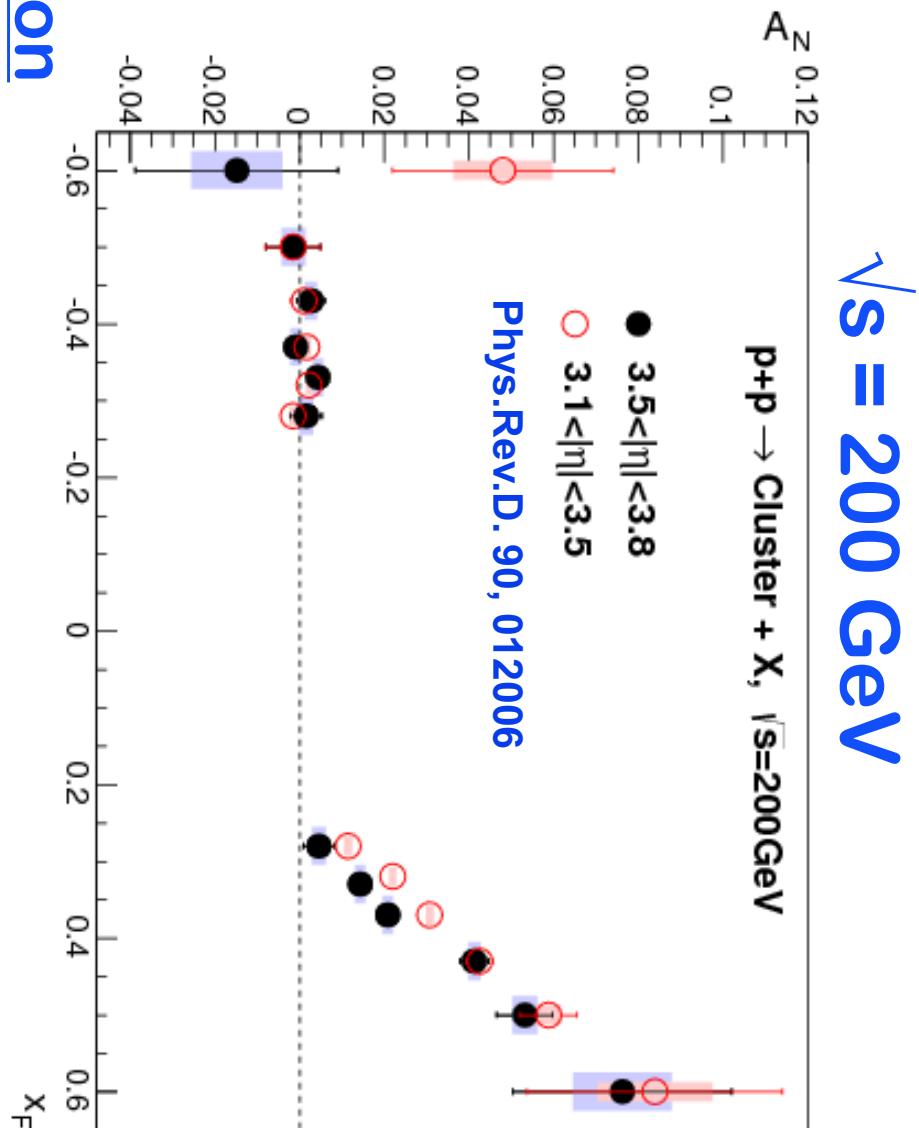
MPC

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

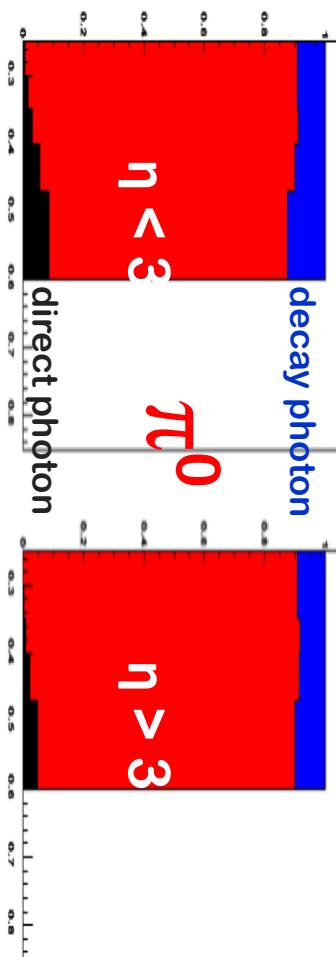


Decay photon impact positions
 for low and high energy π^0 's.

EM Cluster contribution



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

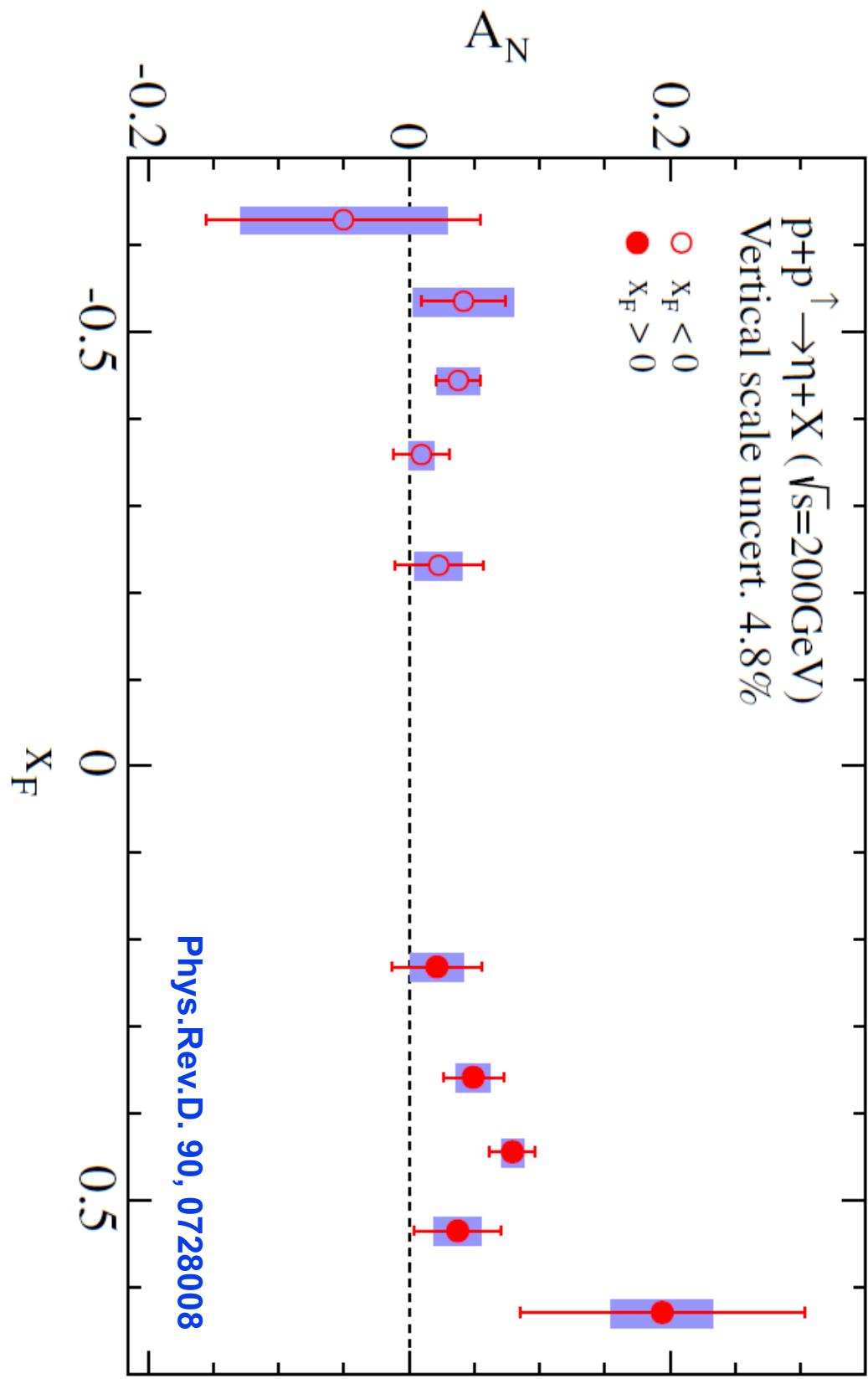


X_F

K. Barish

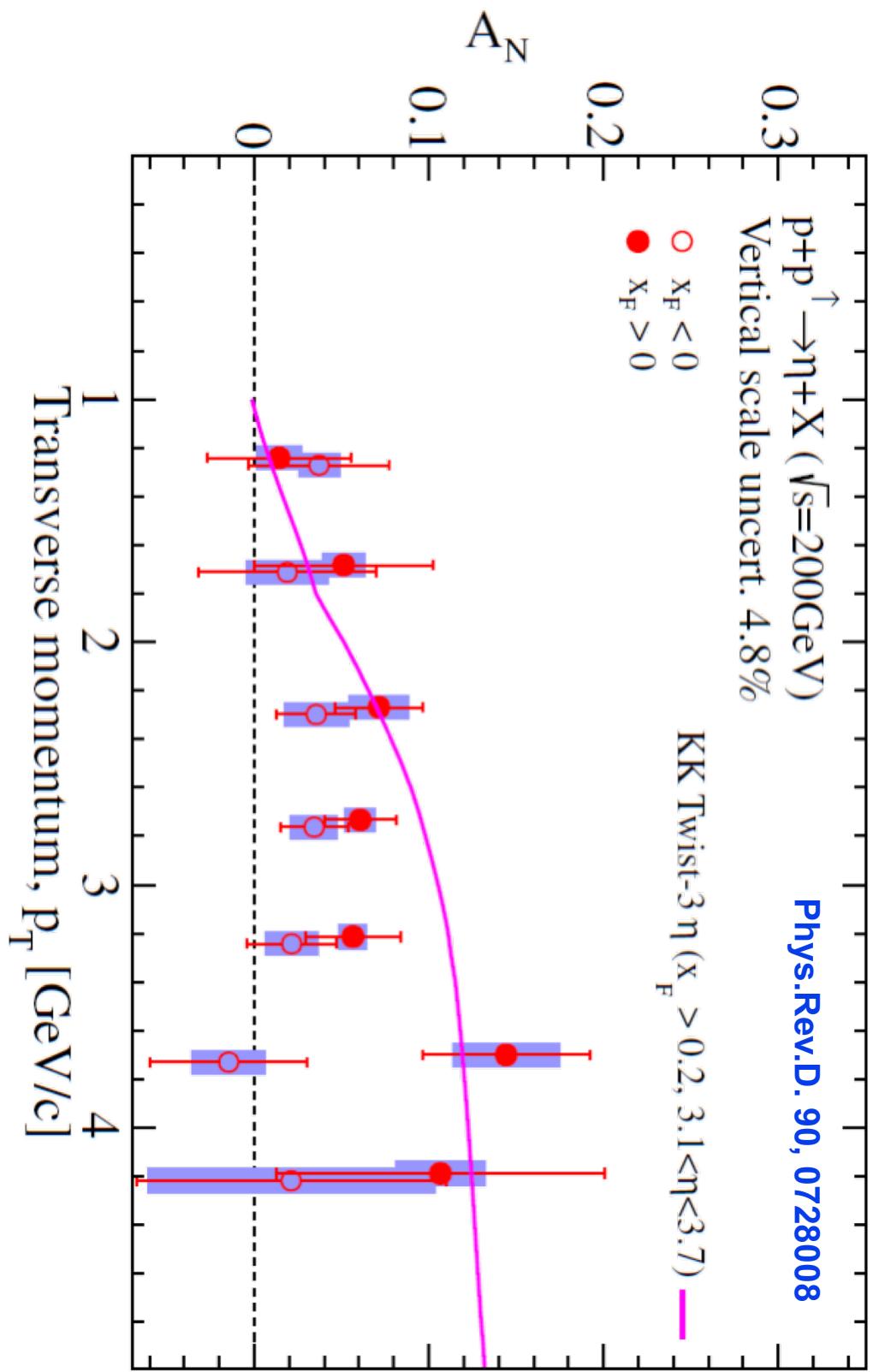
PHENIX

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

Di-hadron and γ - γ correlations

Phys.Rev. D95 (2017) 072002

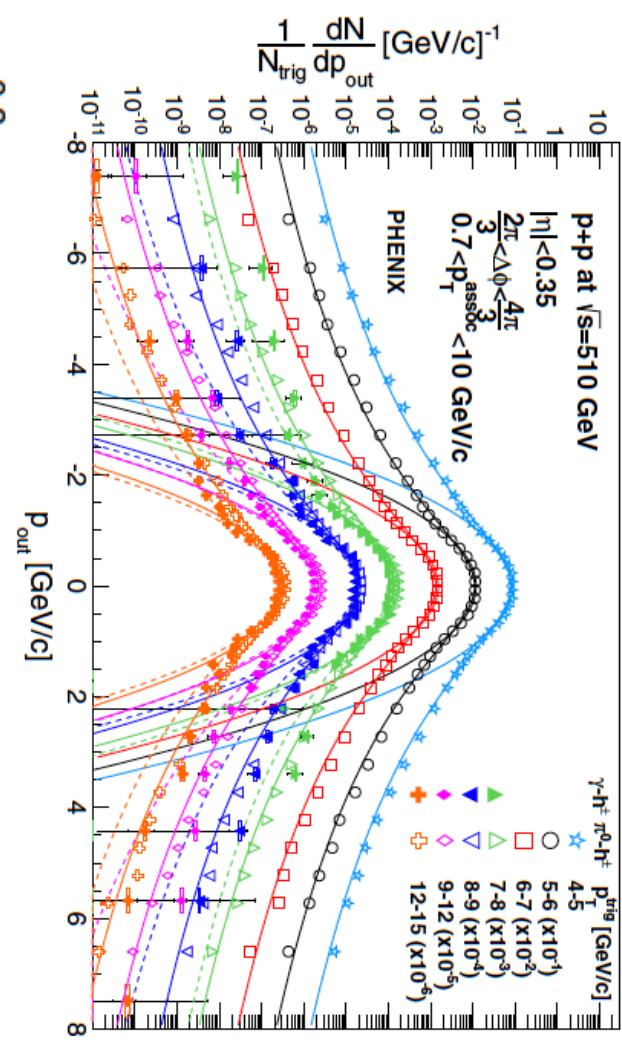
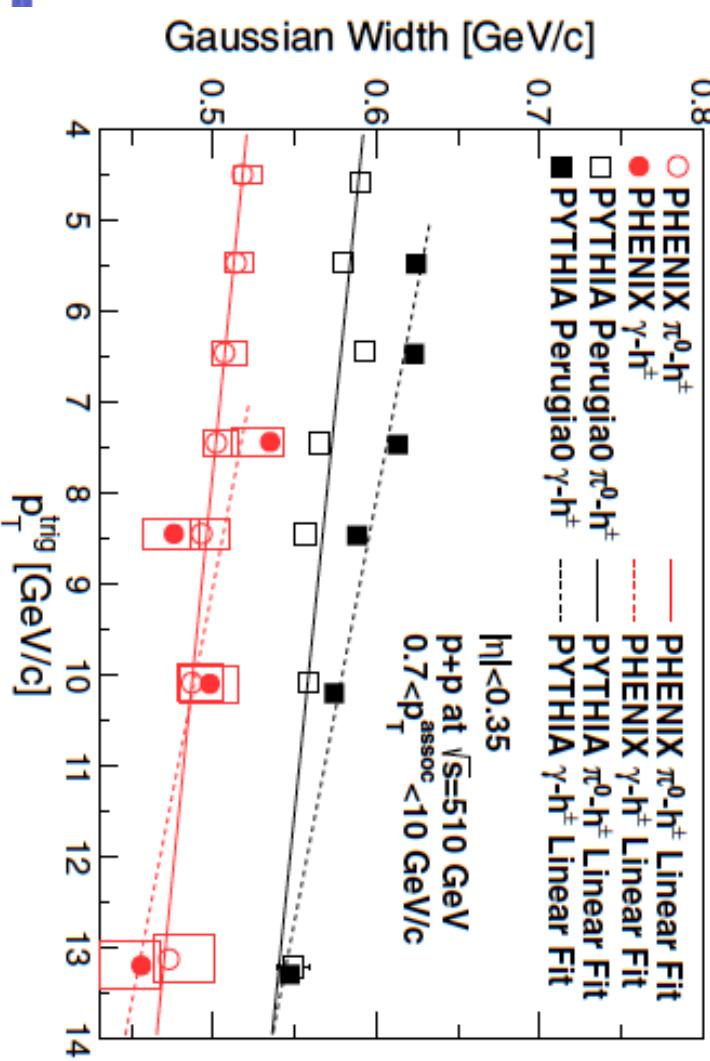
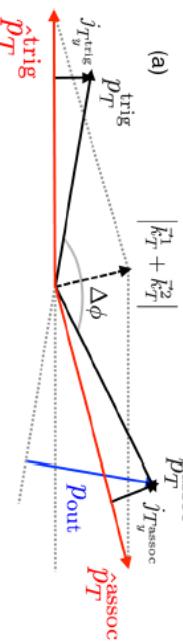
- Look at angular correlation between nearly back-to-back particles

Widths of Gaussian components decrease with trigger particle

momentum \Rightarrow evolution

not driven by the CSS soft factor (in contrast with DY and SIDIS).

- Pythia qualitatively describes this effect



Di-hadron and γ - γ correlations

Phys.Rev. D95 (2017) 072002

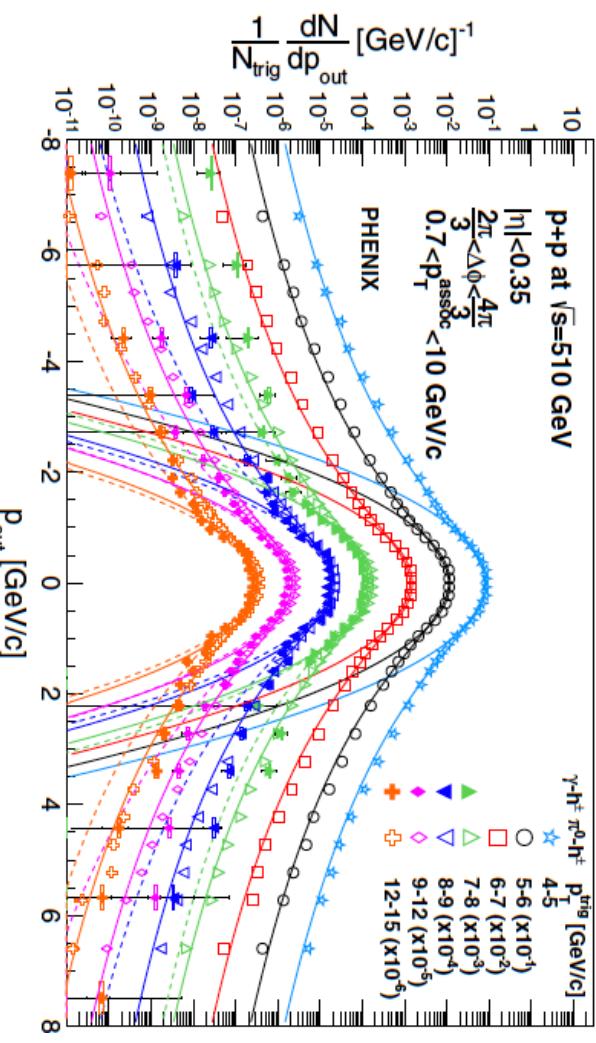
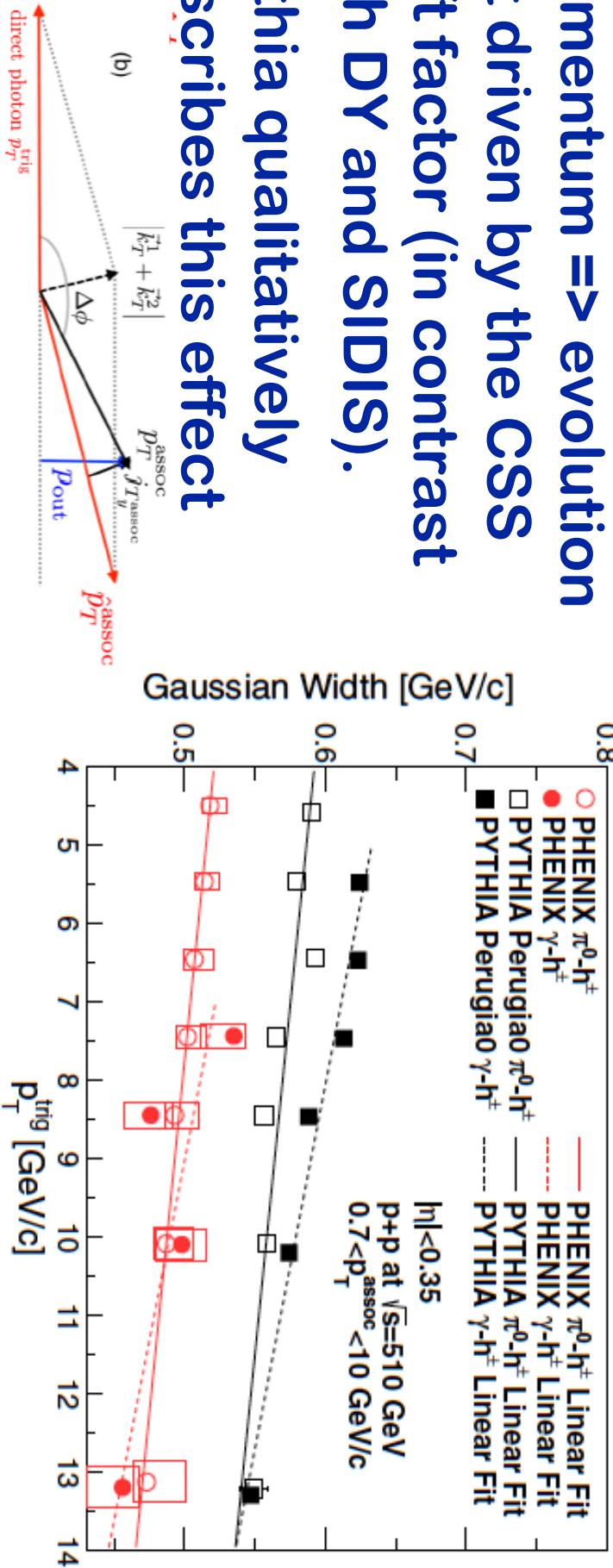
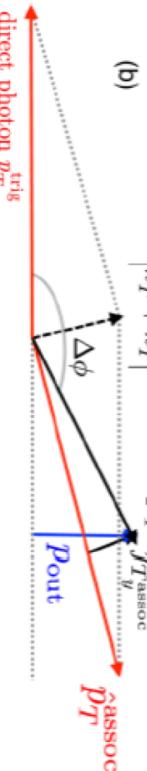
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Pythia qualitatively describes this effect



Very forward A_N ($p_T < 0.1 \text{ GeV}/c$)

Very forward neutron production in pp collision



pQCD not applicable ($p_T < 0.1 \text{ GeV}/c$)

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?**

