PIC2023
Physics in Collision
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Recent spin physics results from PHENIX

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for the PHENIX Collaboration

Proton spin structure

How the spin of the proton is carried by its constituents inside?

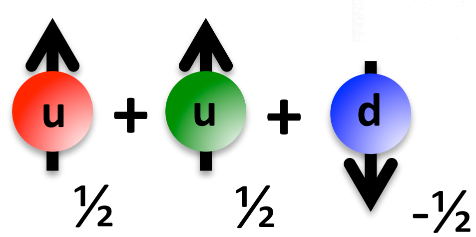
Proton Spin Decomposition

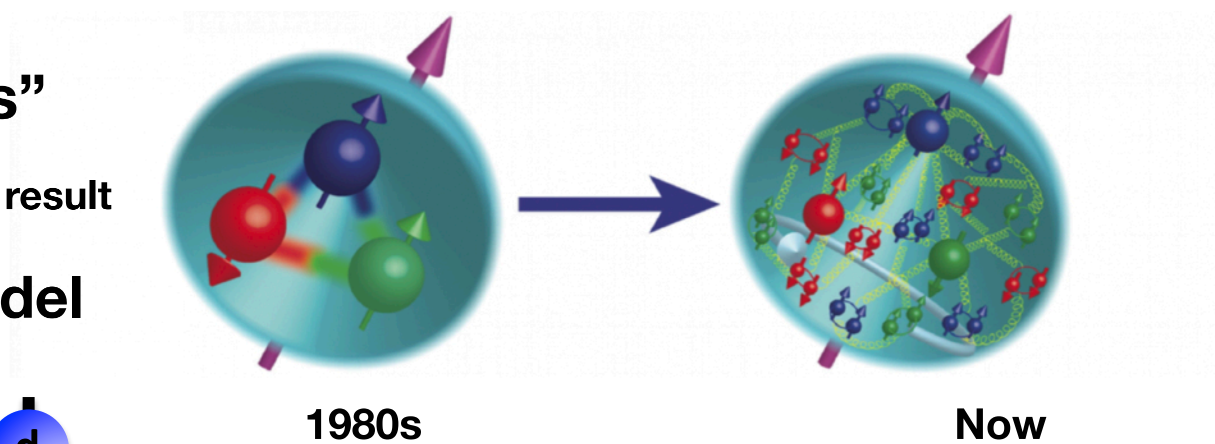
“Proton spin crisis”

Naive interpretation of the EMC result

Naïve quark model

$\frac{1}{2} \stackrel{?}{=}$





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

(Quark + antiquark) helicity contribution

$$\frac{1}{2}\int dx(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

~30%. Well constrained by polarized DIS

Gluon helicity contribution

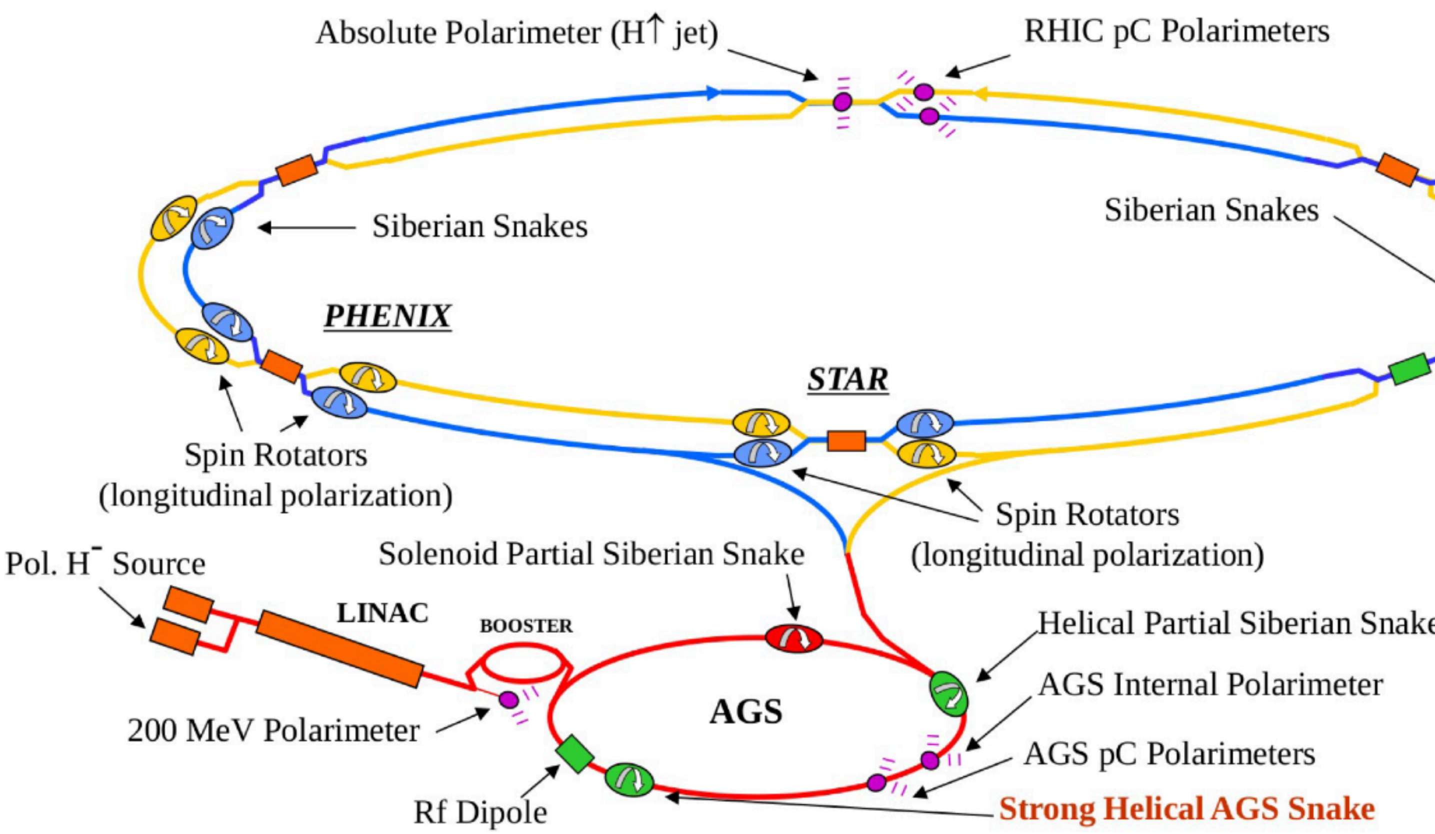
$$\Delta G = \int dx \Delta g(x)$$

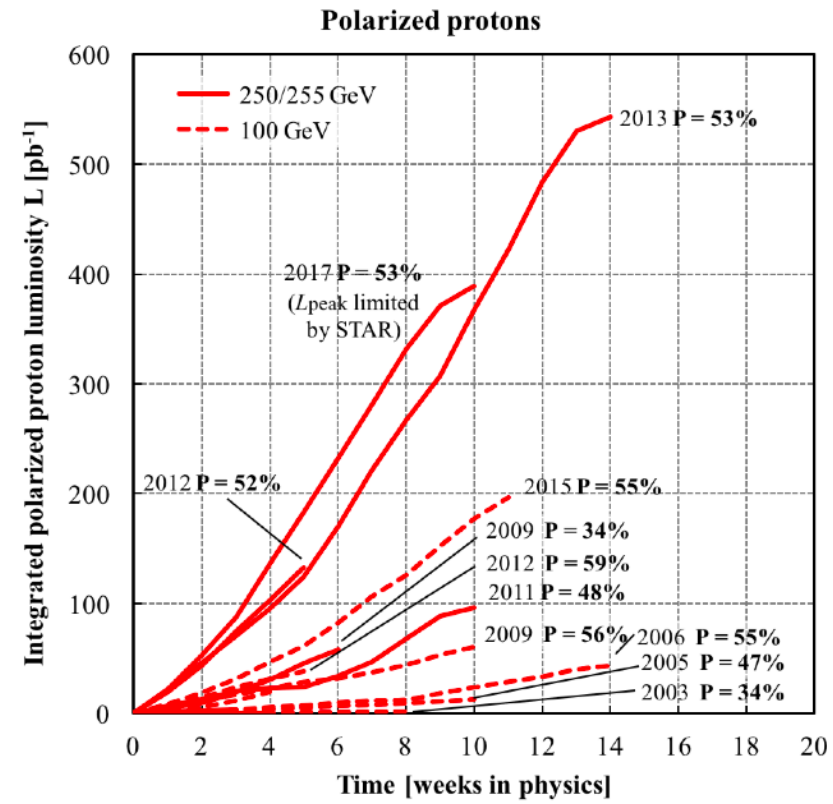
Start to understand better with RHIC pp data

Quark and gluon orbital angular momentum

Very little known
Need to know 3D structure!

RHIC as polarized proton collider



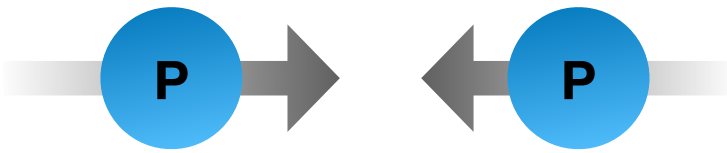


- **How do gluons contribute to the proton spin?**
- **What is the landscape of the polarized sea in the nucleon?**
- **What do transverse spin phenomena teach us about proton structure?**

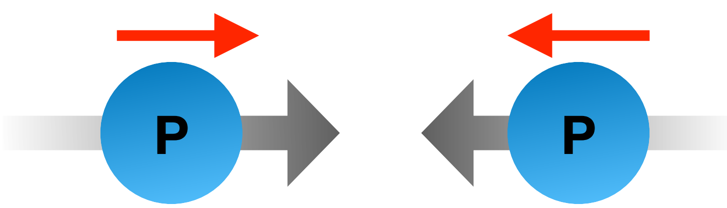
PHENIX spin dataset

Run#	system	energy (GeV)	Polarization direction
Run6	p+p	62.4	transverse, longtudinal
		200	transverse, longtudinal
Run8	p+p	200	transverse
Run9	p+p	200, 500	longitudinal
Run11	p+p	510	longitudinal
Run12	p+p	200	transverse
		510	longitudinal
Run13	p+p	510	longitudinal
Run15	p+p, p+Al, p+Au	200	transverse

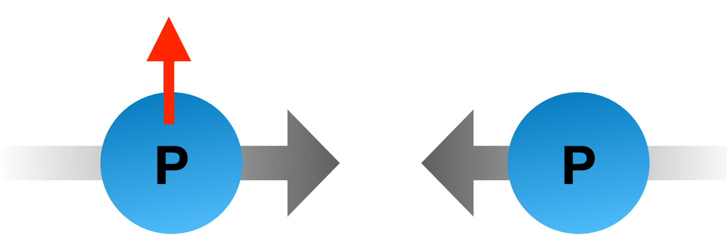
(Un)Polarized p+A Collisions



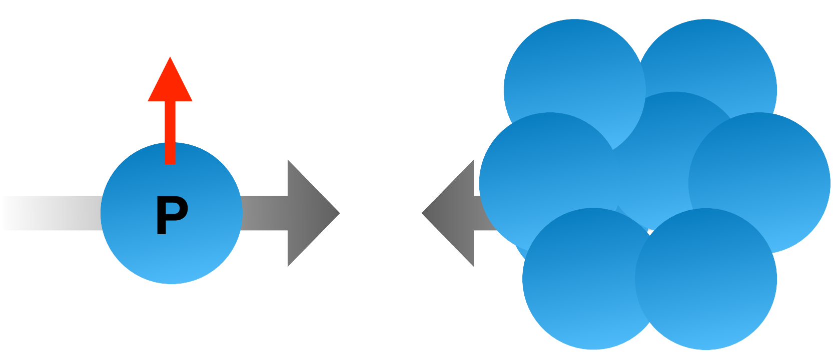
Unpolarized anti-quark sea via W production. Provide baseline for heavy ion collisions



Gluon polarization inside the proton
Polarized sea via W production

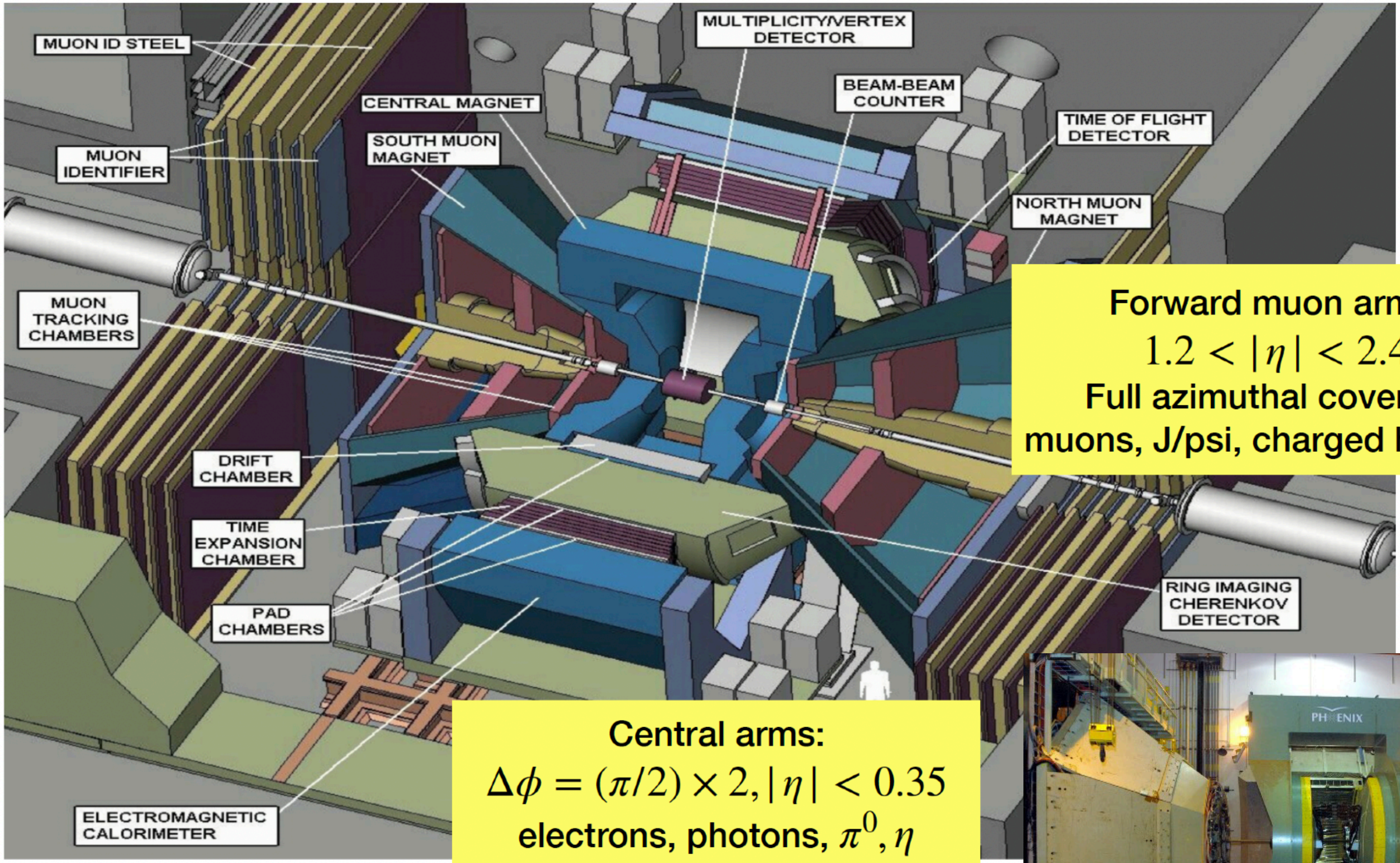


Origin of large transverse spin asymmetry
Transverse motion of partons inside the proton



p+A Collisions provides unique opportunities to study nuclear effects to quarks and gluons distributions, and their interaction and correlations

PHENIX Detector



Forward muon arms:
$1.2 < |\eta| < 2.4$
Full azimuthal coverage
muons, J/psi, charged hadrons

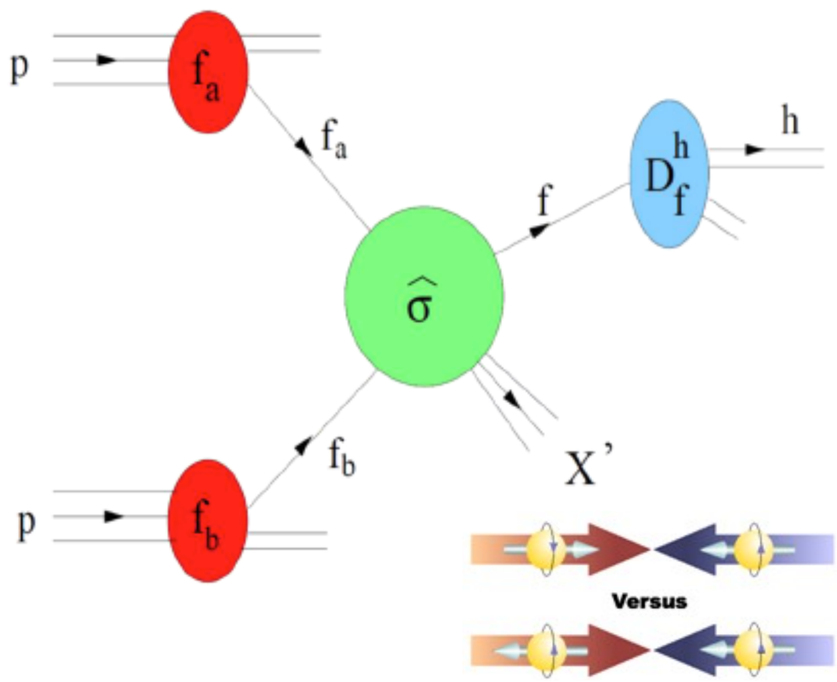
Central arms:
$\Delta\phi = (\pi/2) \times 2, |\eta| < 0.35$
electrons, photons, π^0, η
charged hadrons

Longitudinal spin results

Gluon helicity measurements

Sea quark helicity measurement via W production

Accessing gluons in p+p at RHIC



Polarized PDFs

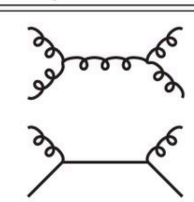
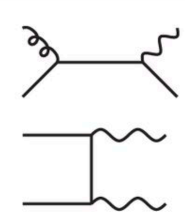
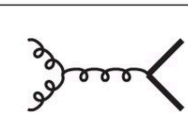
Parton-level hard scattering cross section calculable in pQCD

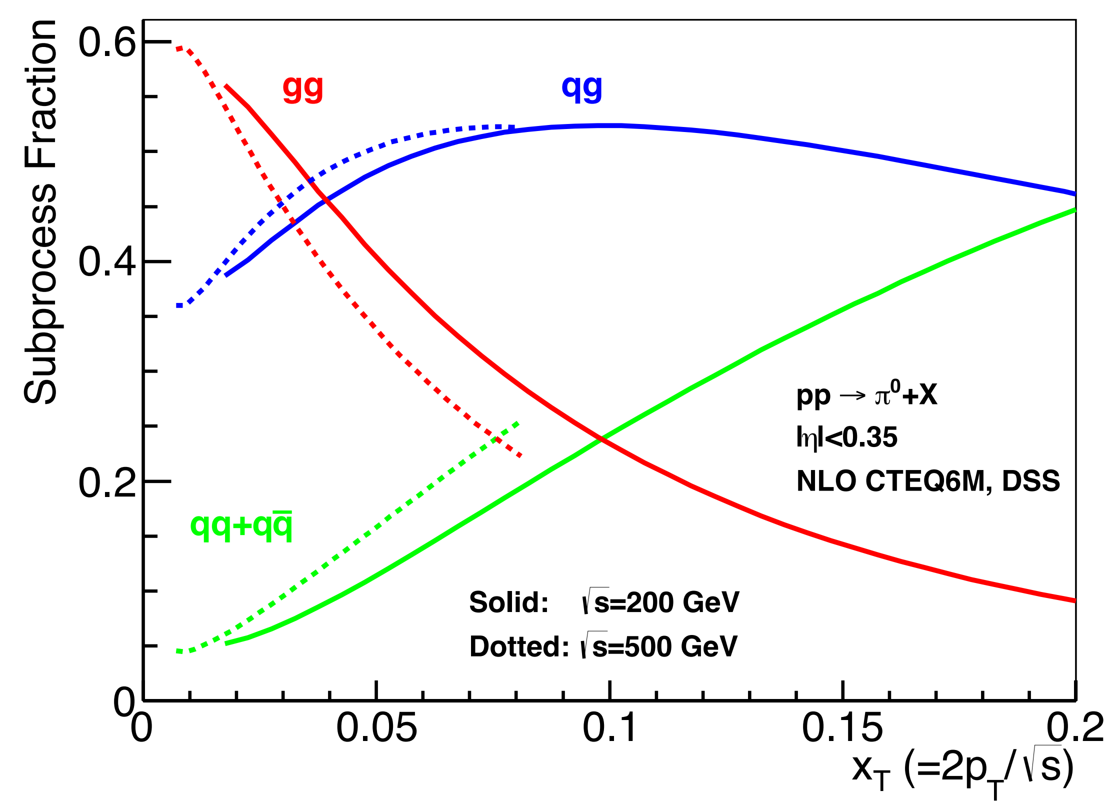
$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{\pi^0}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{\pi^0}}$$

What's measured

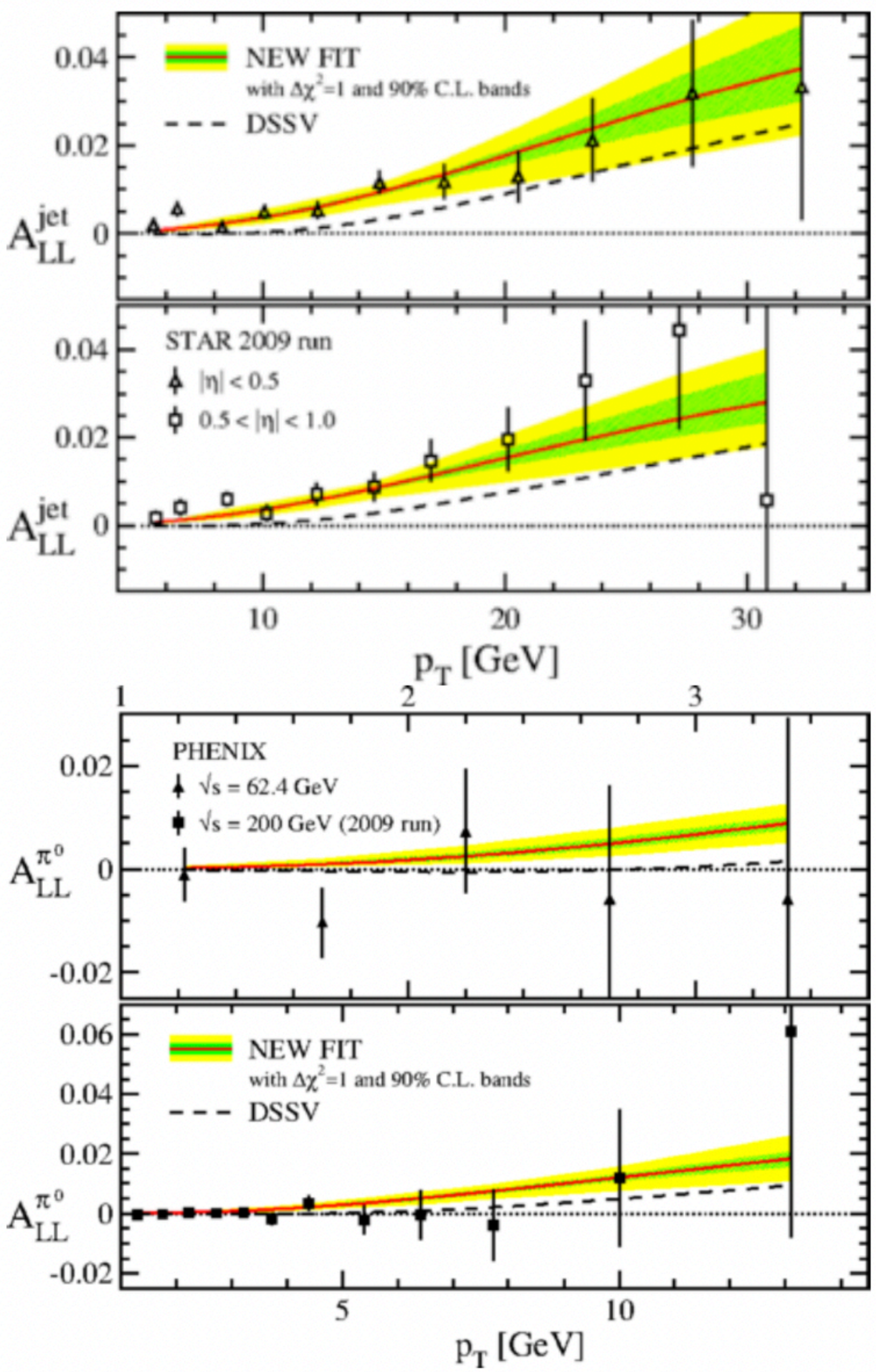
Unpolarized PDFs

Fragmentation functions from e+e- scattering

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

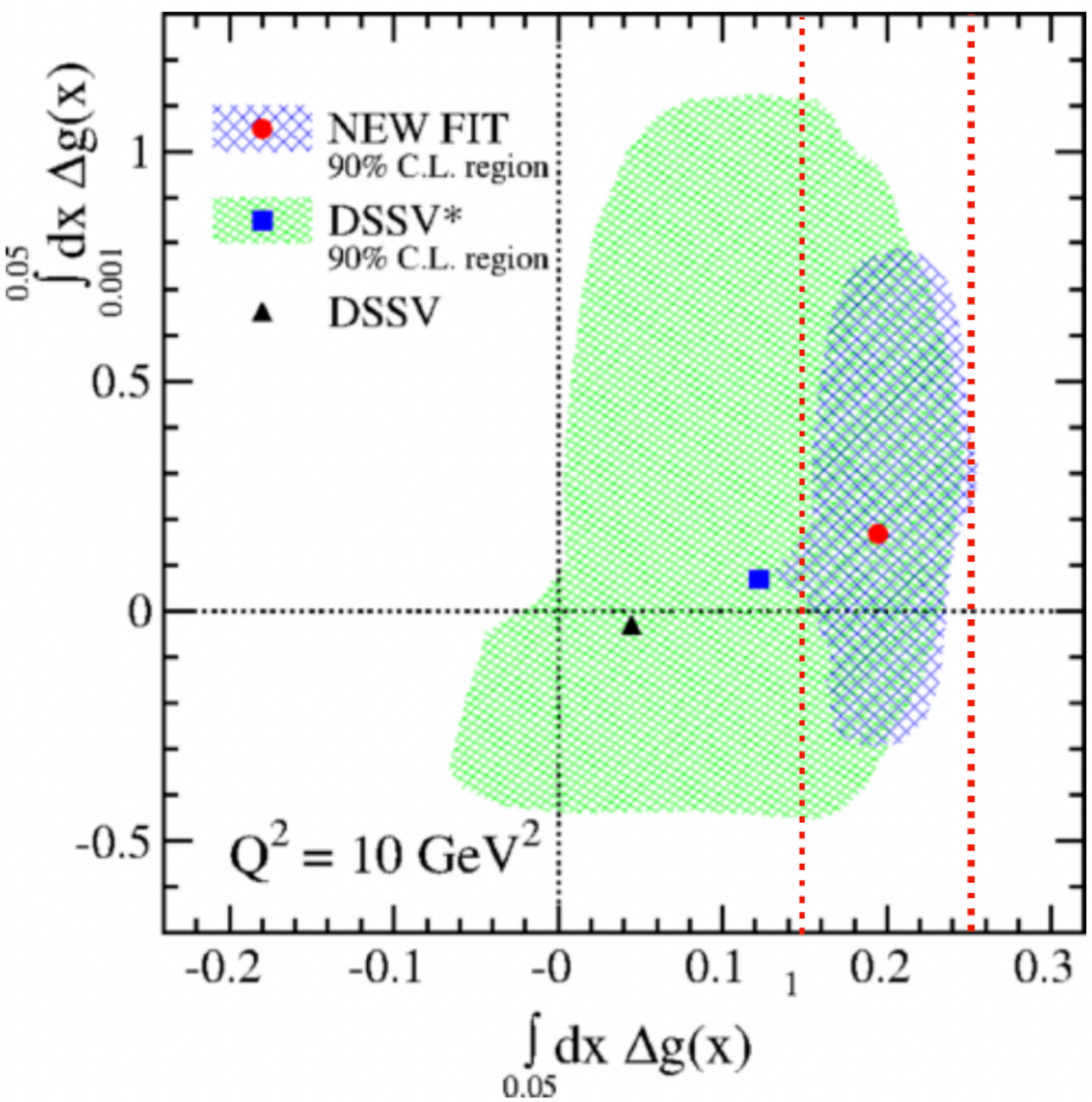


First evidence of non-zero gluon spin



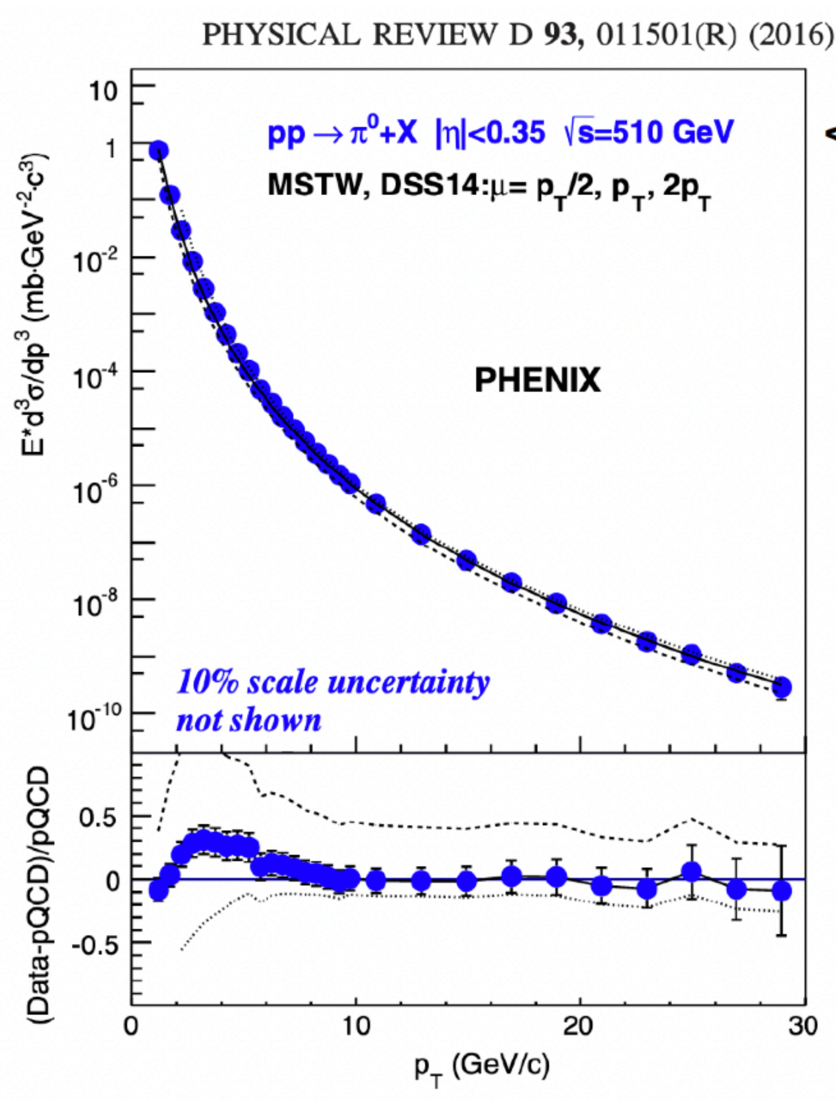
Phys. Rev. Lett. 113 (2014) 012001

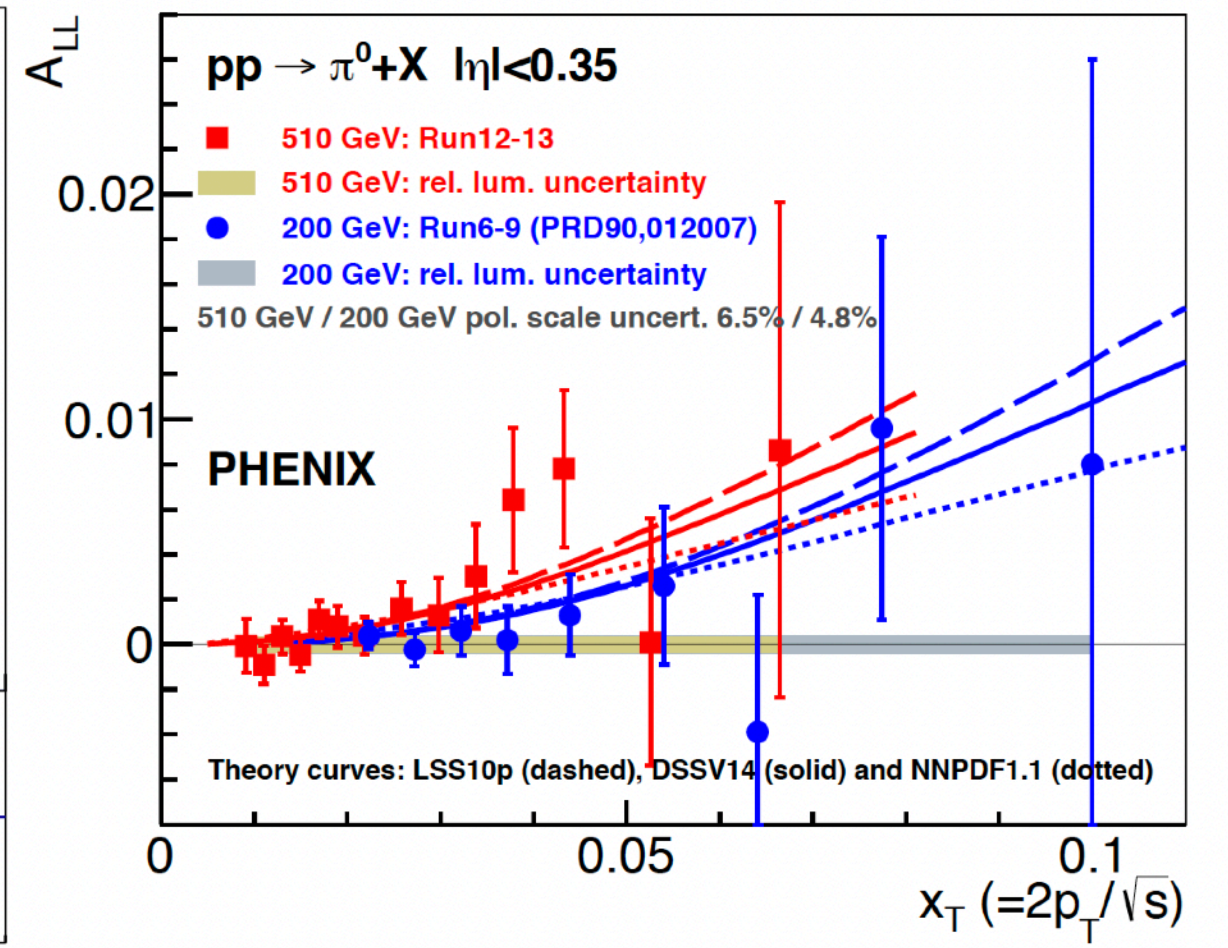
$$\int_{0.05}^{1} dx\Delta g(x) = 0.2^{+0.06}_{-0.07}(Q^2 = 10\text{GeV}^2)$$

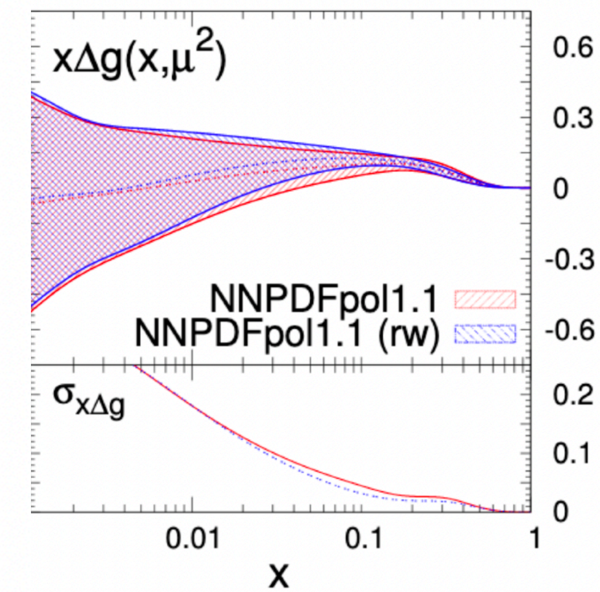


DSSV14: Phys. Rev. Lett. 113 (2014) 012001
(included 2009 200 GeV data only)

PHENIX Δg measurements: π^0





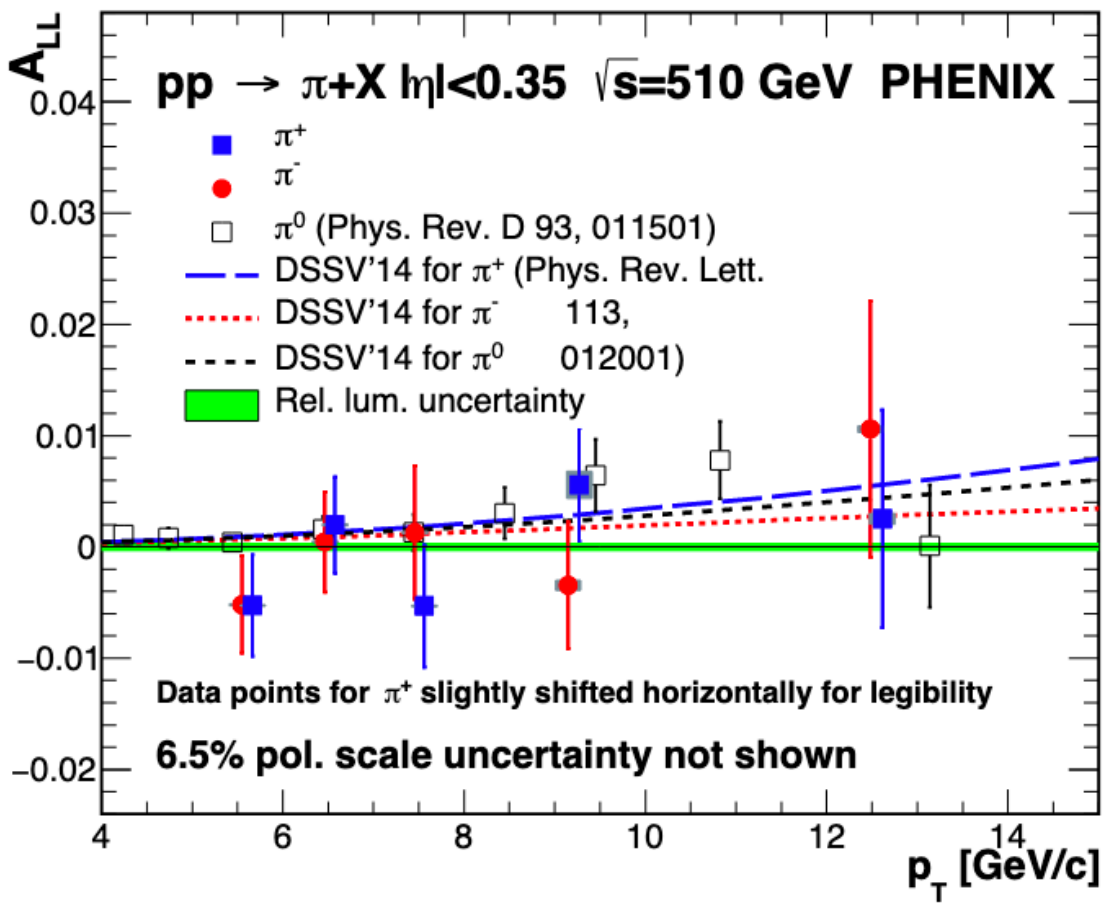


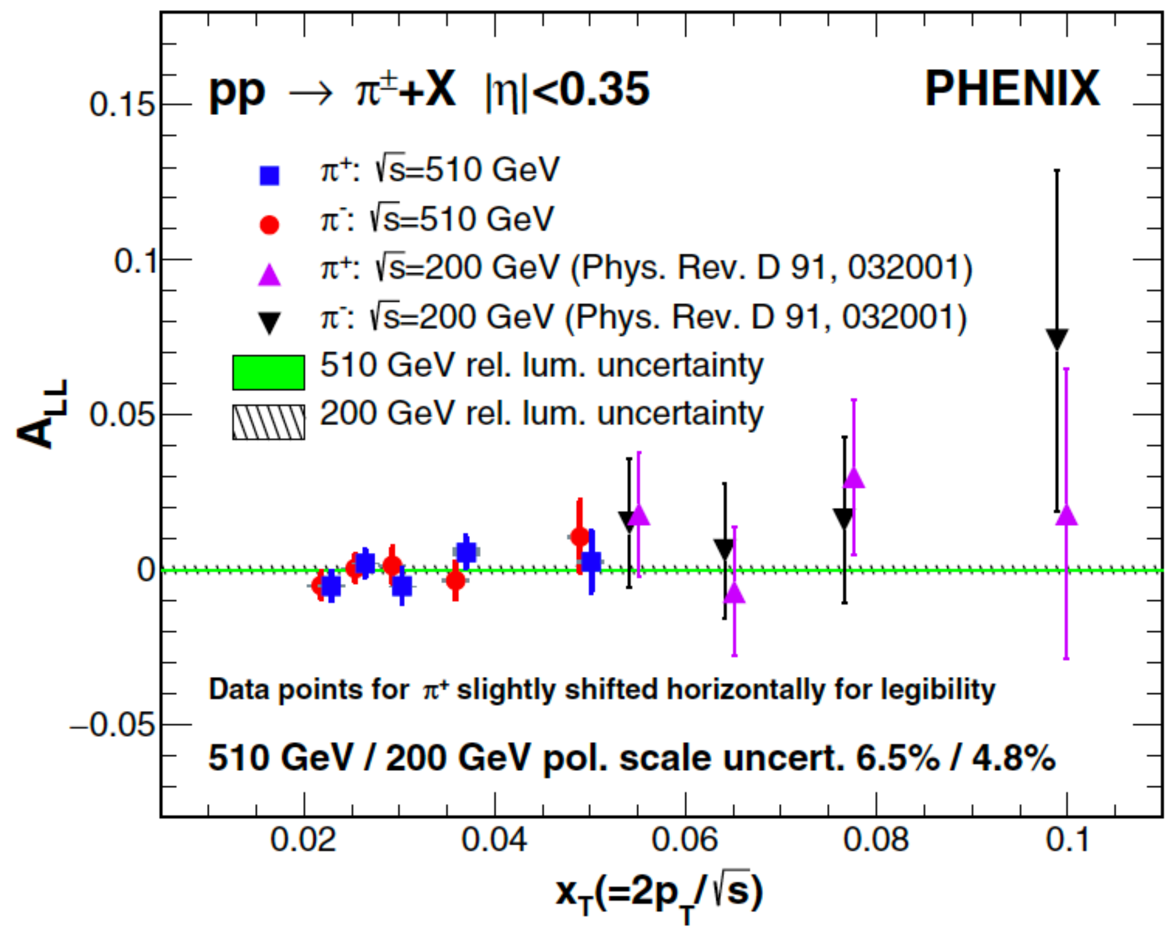
NNPDF reweighing including STAR 200 GeV di-jet and PHENIX pi0 data (arXiv:1702.05077)

- NLO pQCD calculations in excellent agreement with PHENIX cross section data
- Access lower x by higher energy (x down to ~10-2)
- Confirms non-zero gluon spin contribution at 510 GeV
- Recent global fits agree well with the data

Charged pion A_{LL}

Phys. Rev. D 102, 032001 (2020)

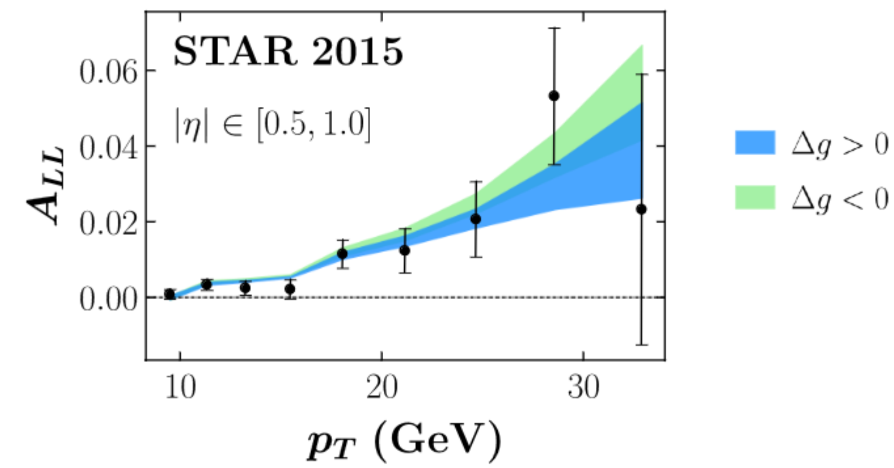




- First charged pion asymmetry measurements at 510 GeV, consistent with the positive gluon polarization from DSSV fits within statistical uncertainty
- Charged pions potential indicator for sign of Δg via pion A_{LL} ordering
- Future sPHENIX will be able to measure it much precisely

Direct photon measurements

- Mixed gg and qg contributions: Recent analysis by JAM collaboration showed that existing data cannot rule out negative Δg scenario [JAM, Phys. Rev. D 105, 074022 (2022)]



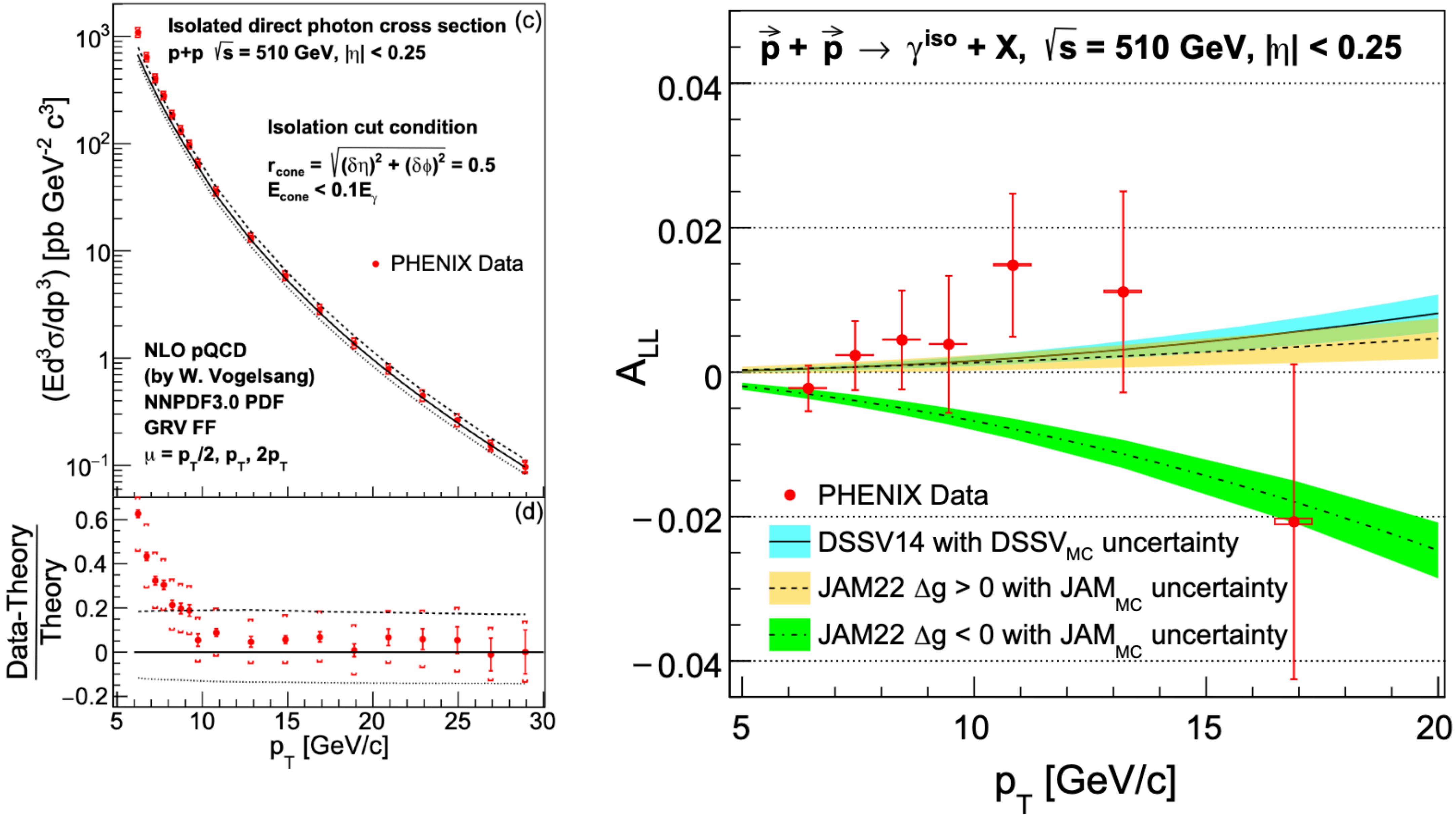
- Theoretically clean measurement: only sensitive to initial partonic hard process and doesn't involve strong interaction
- Direct photons are produced dominantly by qg Compton scattering - linearly sensitive to gluon helicity distribution

$$A_{LL}^{pp\to\gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{\Delta g(x_g)}{g(x_g)} \cdot a_{LL}^{qg\to\gamma q}$$

- Proposed as a *golden channel* to study the gluon spin (RHIC Spin Proposal, 1992)
- Effectively reduced BGs by π^0decay tagging and isolation cut

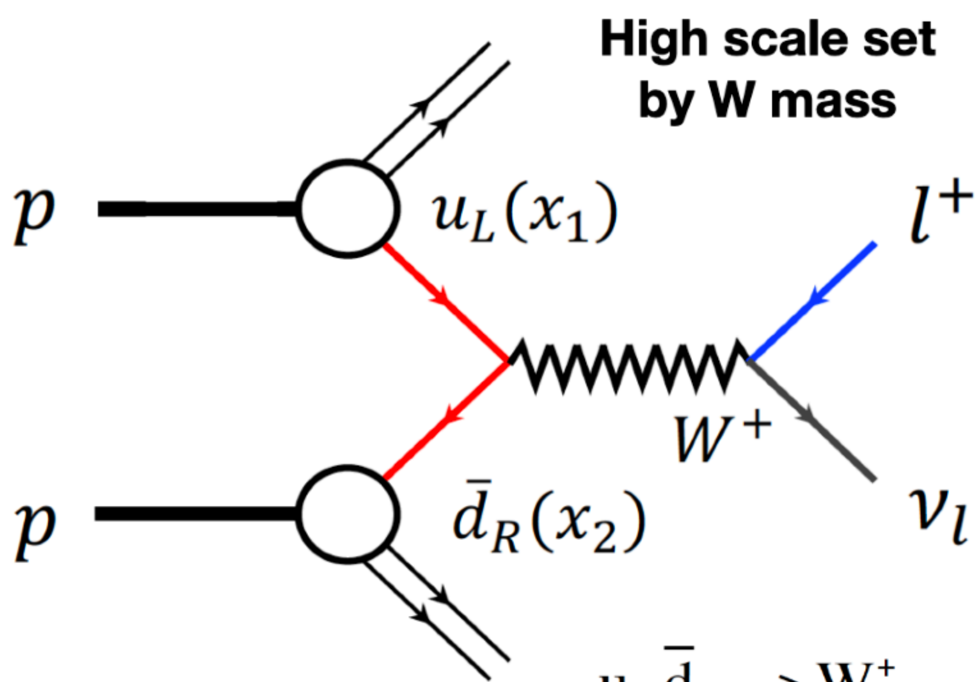
Direct photon A_{LL}

[Phys. Rev. Lett. 130, 251901 (2023)]



- First published measurement of direct photon A_{LL}
- Compared with two scenarios for gluon spin
- Data consistent with the positive gluon spin contributions and disfavor the negative Δg scenario

Separating quark flavor: W production



$$u_L \bar{d}_R \rightarrow W^+$$
$$d_L \bar{u}_R \rightarrow W^-$$

- Parity violating spin asymmetries directly access to flavor separated polarized quark distributions

$$A_L^{W^+} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

- Combined with weak decay kinematics
  - Quark flavor mixed at mid-rapidity
  - Sensitive to antiquark at forward/backward rapidity

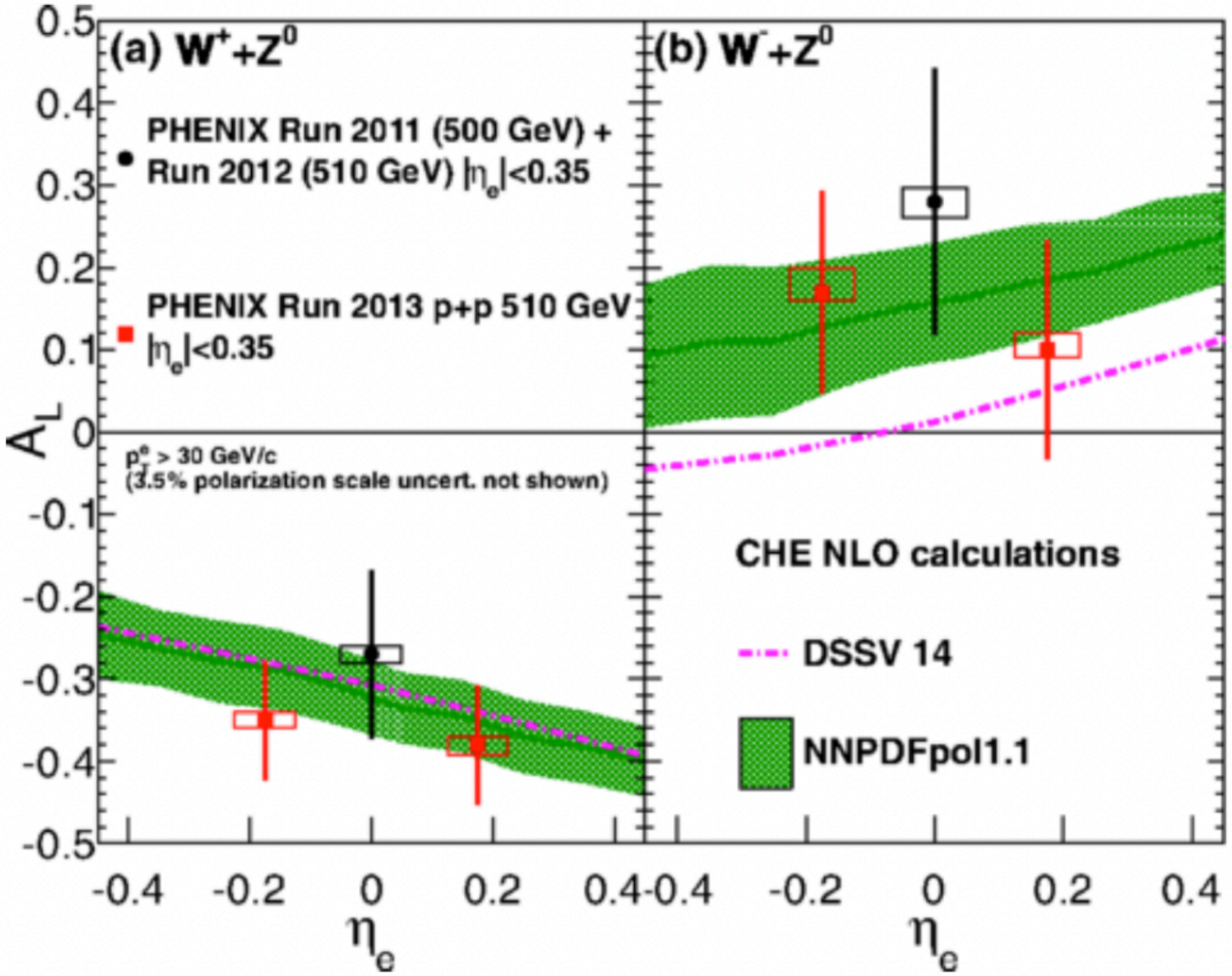
$$A_L^{W^+\to\ell^+} \approx \frac{\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}{\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}$$

$$A_L^{W^-\to\ell^-} \approx \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

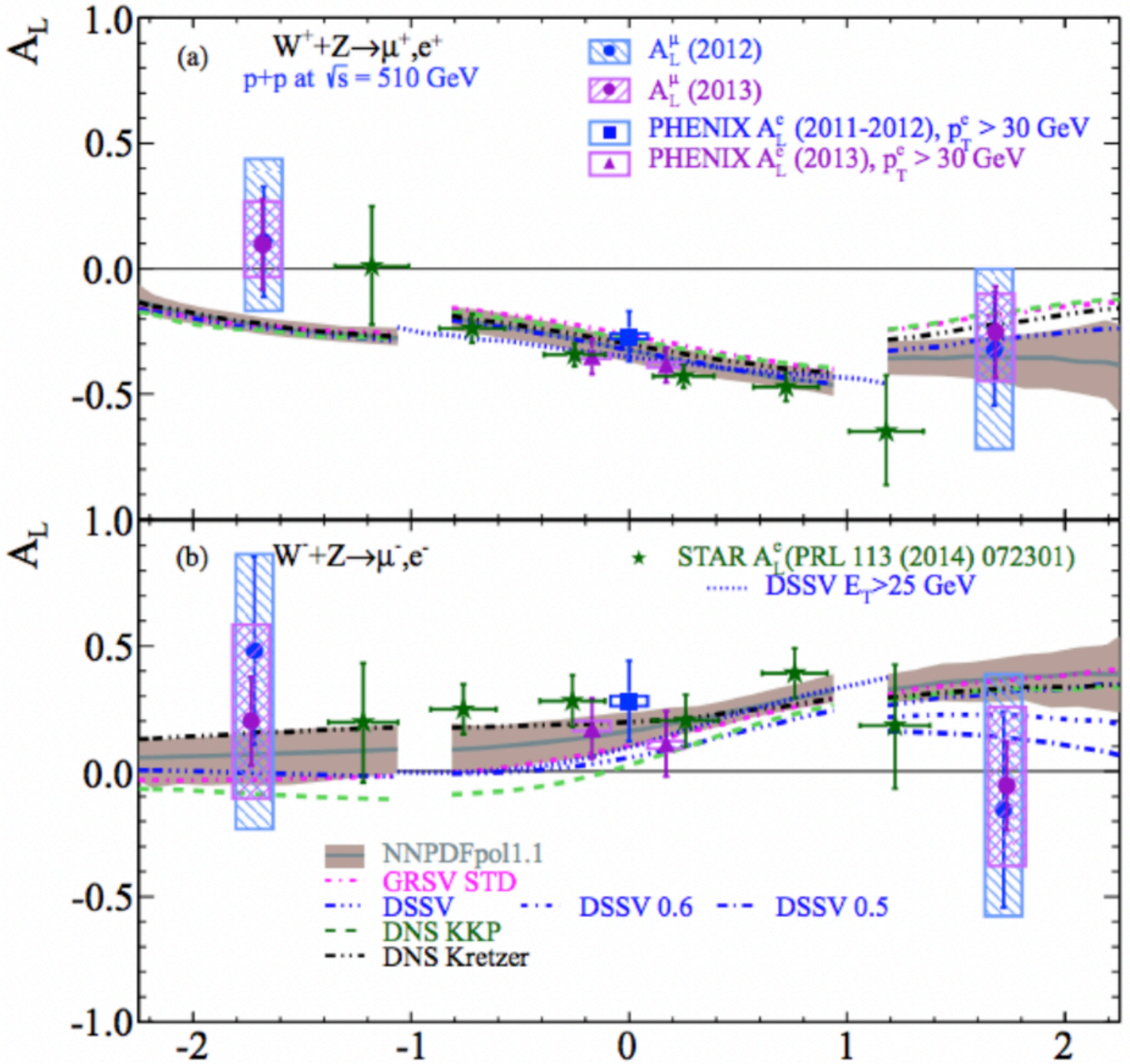
S. Park

Parity violating spin asymmetries of W

Phys.Rev. D93 (2016), 051103



Phys. Rev. D 98 (2018), 032007

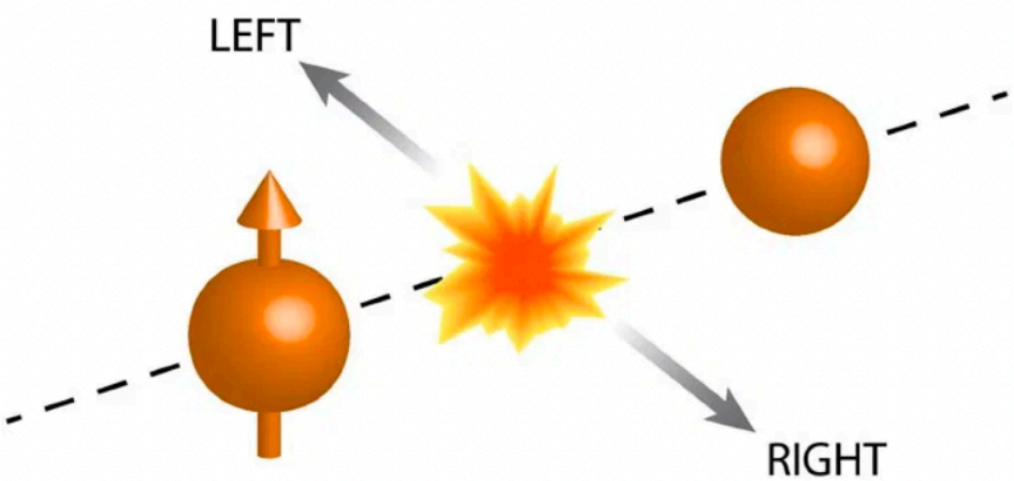


- Data above DSSV14 global fit for e$^-$, indicating larger $\Delta\bar{u}$ contribution in the covered x region (~0.16)
- First measurement of muon decay channel, consistent with theory calculations within uncertainties

Transverse spin results

Transverse single spin asymmetry (TSSA)
Twist-3 multiparton correlation functions
TSSA in nuclear environment

Transverse spin phenomena: Spin-momentum correlation

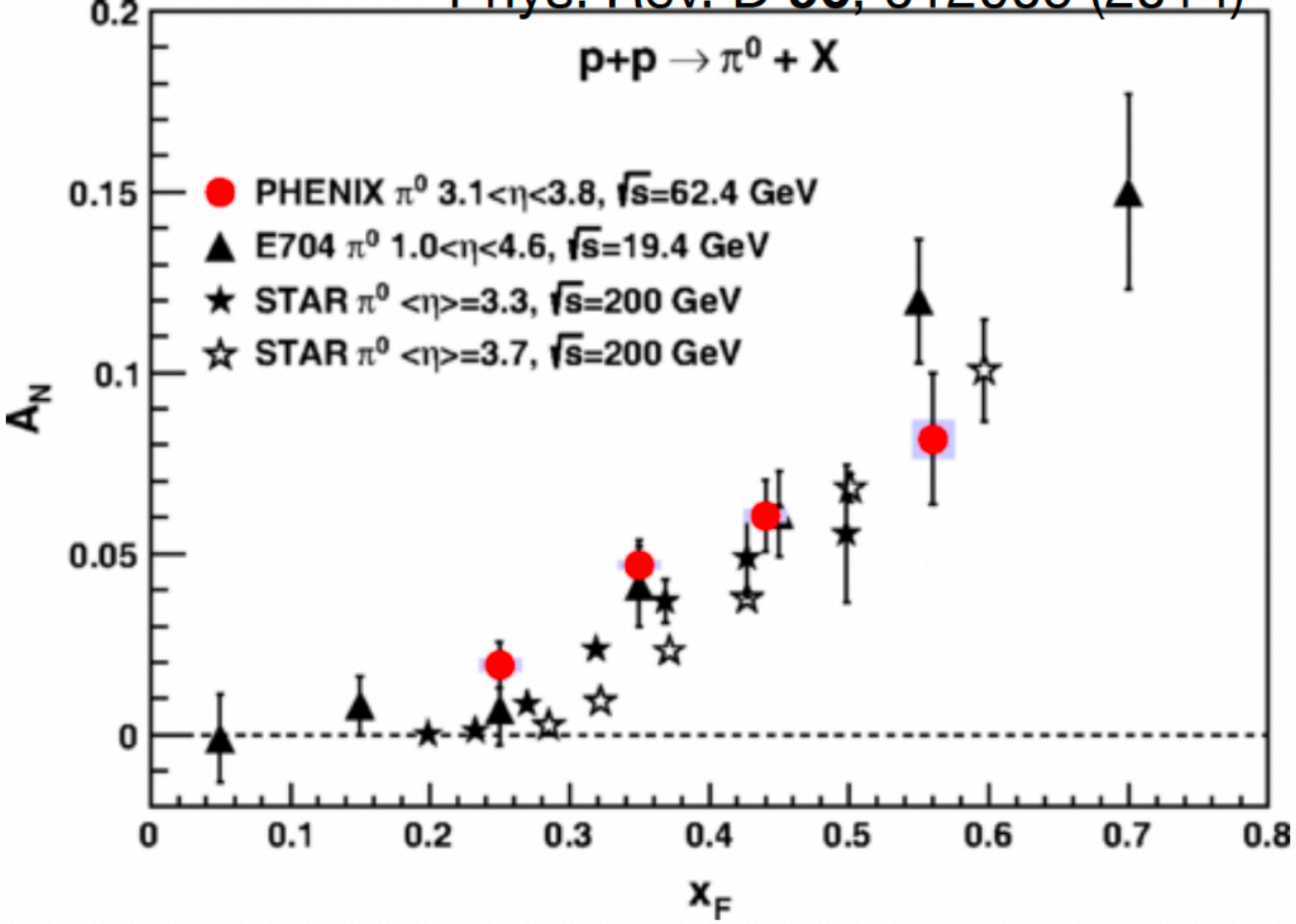


Transverse single spin asymmetry (TSSA)

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Naïve pQCD predicted very small asymmetry (PRL 41 1689 (1978))
- Surprisingly large TSSAs observed A_N ~ 40% (FNAL E704)
- Asymmetries survive at higher energy, nearly independent of collision energies

Phys. Rev. D **90**, 012006 (2014)

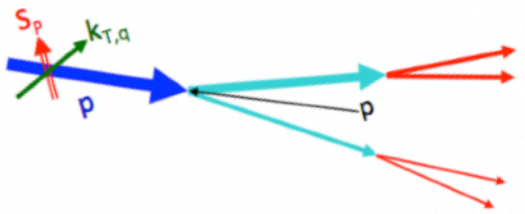


Towards the understanding the origin of TSSAs

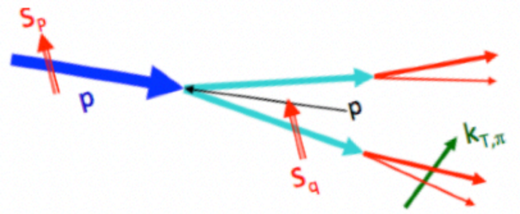
- Transverse-momentum-dependent (TMD) distributions and fragmentations

  Need one hard (Q^2) and soft (pT) scale to be applicable

  Initial state correlation: Sivers effect; proton spin and parton momentum correlation



  Final state correlation: Collins effect; fragmenting parton spin and hadron transverse momentum correlation



- Multi-parton correlation in collinear framework

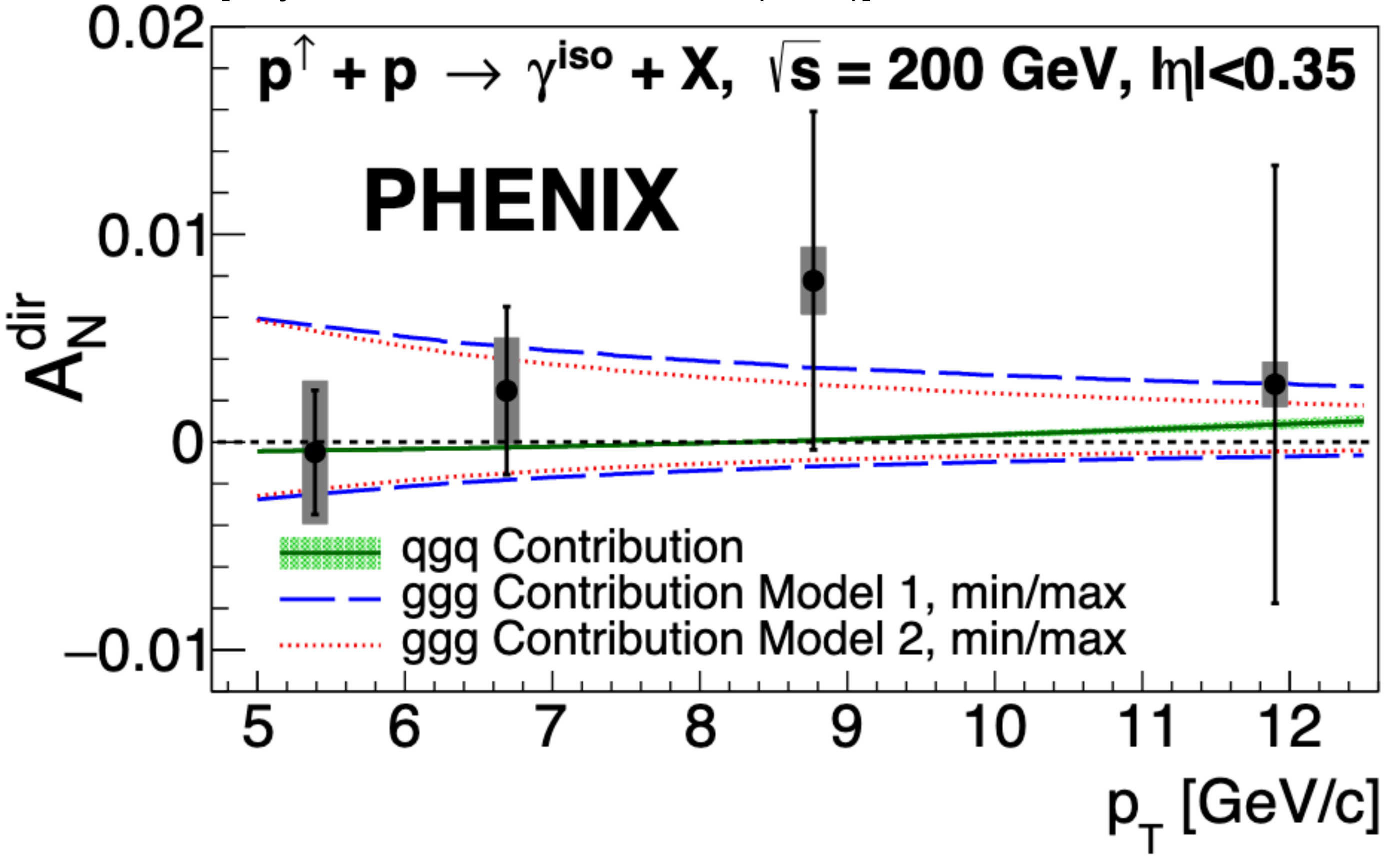
  Need one hard scale (pT), relevant to such as inclusive hadron productions in p+p

  SSA appears as twist-3 observable

  Multi-parton correlations in the initial state or in the fragmentation process

A_N: direct photons

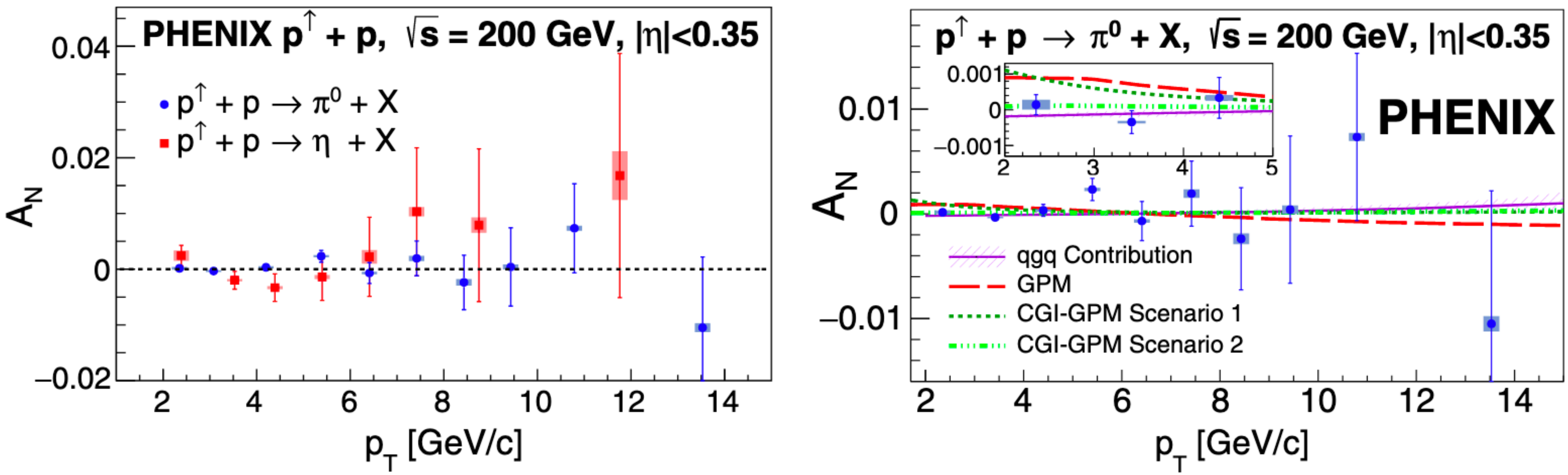
[Phys. Rev. Lett. 127, 162001 (2021)]



- Direct photon channel is sensitive to initial state effects
- Indirect access to Sivers function
- First measurement of direct photon A_N at RHIC,
- The result presents statistical precision to constraint the trigluon correlation functions

A_N: π^0 and η

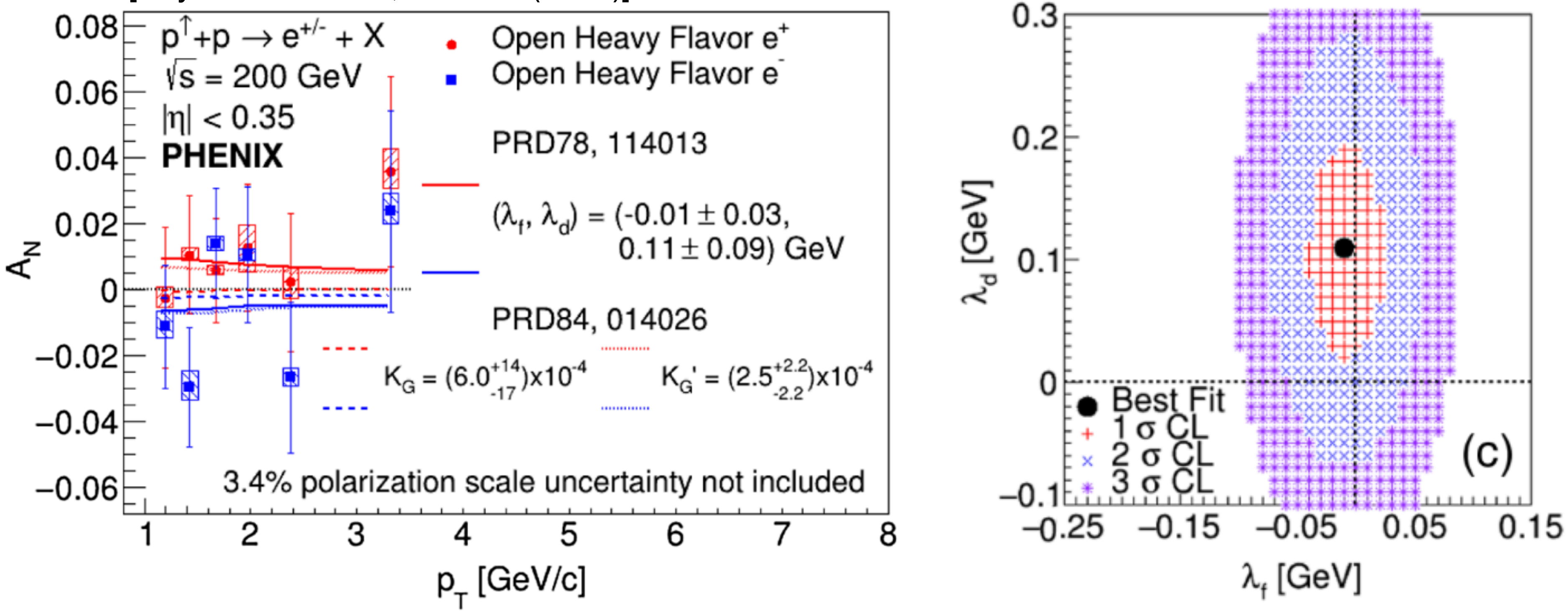
[Phys. Rev. D 103, 052009 (2021)]



- sensitive to both initial and final state effects
- Mid-rapidity measurements are sensitive to gluons
- Asymmetries consistent with zero
- New data significantly improved precision compared to previous PHENIX results

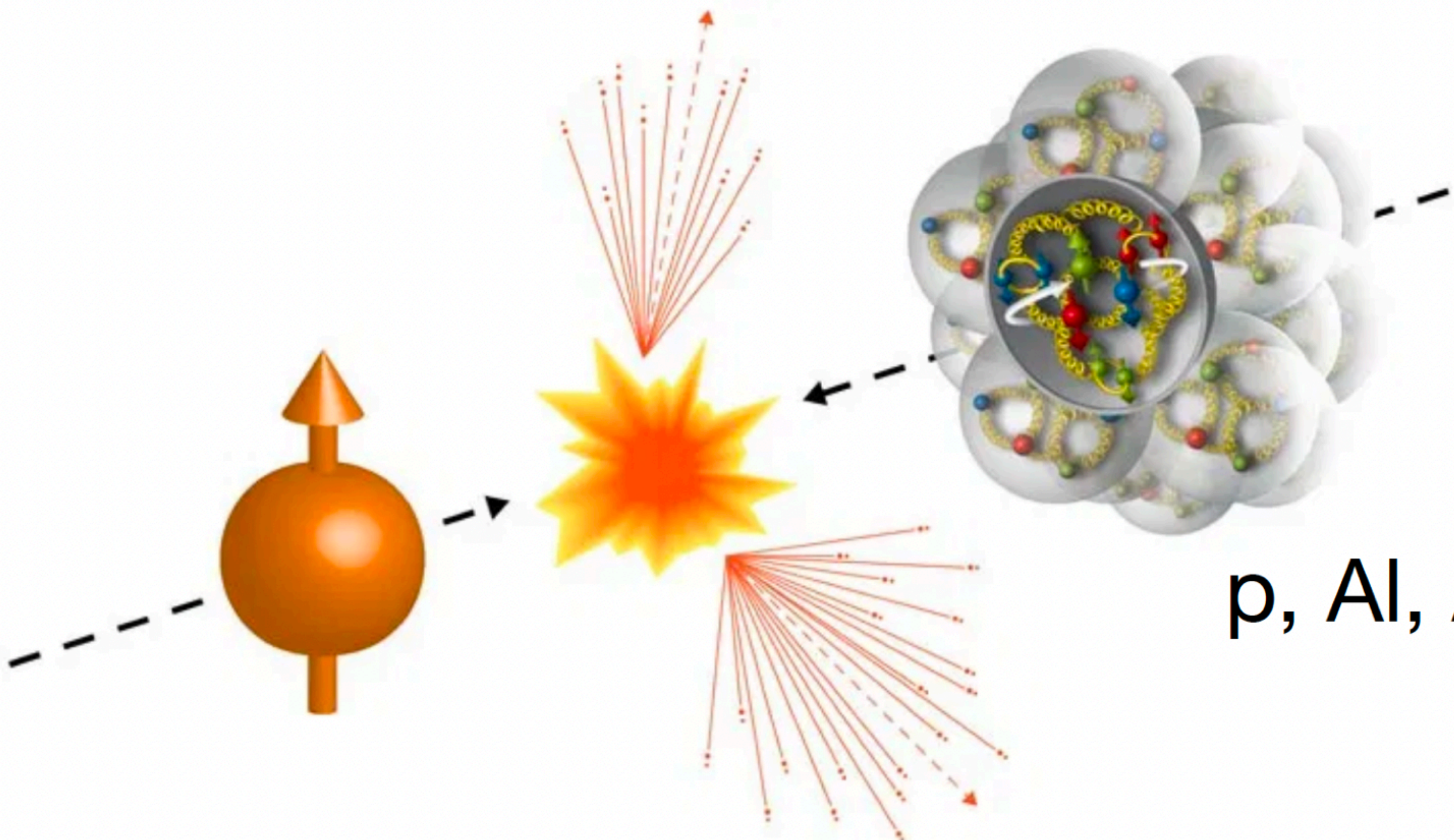
A_N: Heavy flavor electrons

[Phys. Rev. D 107, 052012 (2023)]



- At RHIC energies, mostly produced by gg fusion, ideal to study gluons
- Open charm production is dominant contribution
- Sensitive to trigluon correlators in the collinear framework
- Asymmetries consistent with zero within the uncertainties for the given pT range
- Performed statistical analysis to extract best fit parameters of λ_f and λ_d. Results compared with theoretical calculations for $D^0 \to e^{\pm}$ (PRD78, 114013):
  - Constrain the normalization parameters of ggg correlates w.r.t unpolarized gluon PDF

TSSAs in nuclear environment

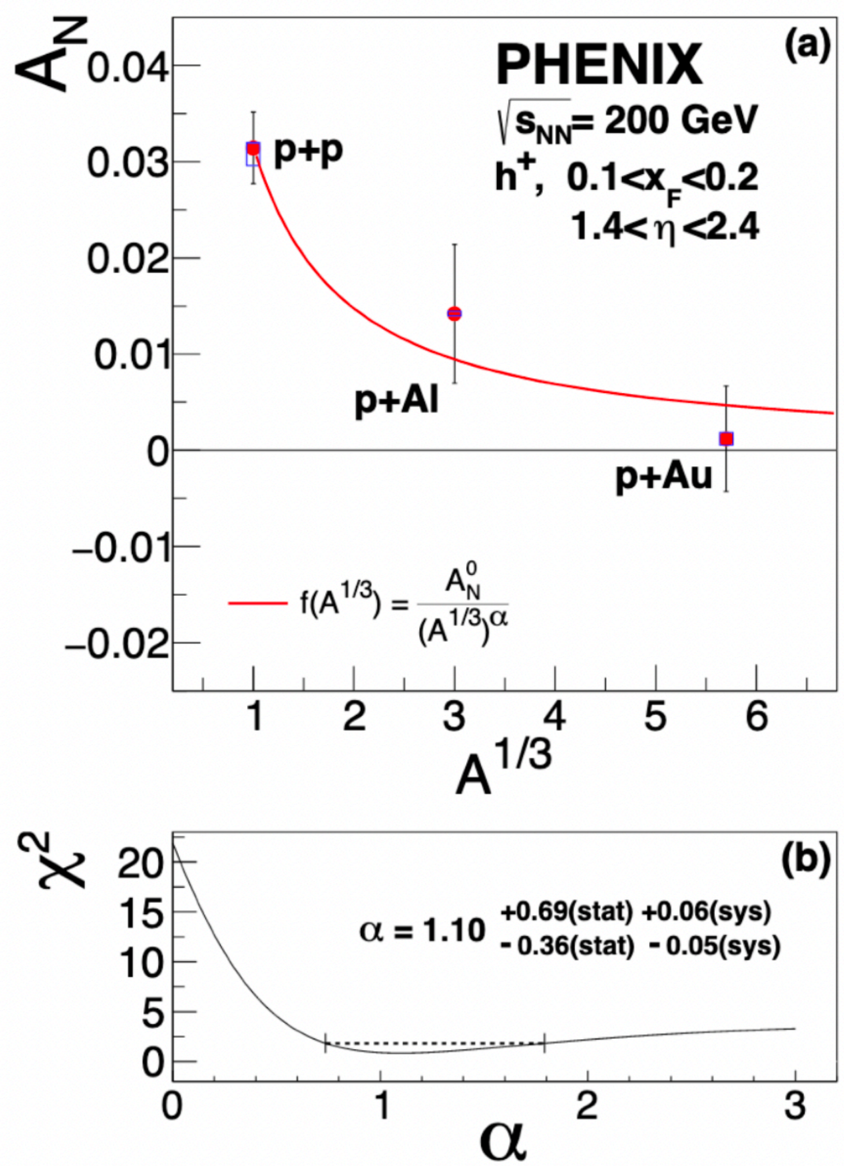


p, Al, Au

- First time polarized p+A collisions in 2015
- Study nuclear effects in A_N

Forward charged hadron A_N in p+A

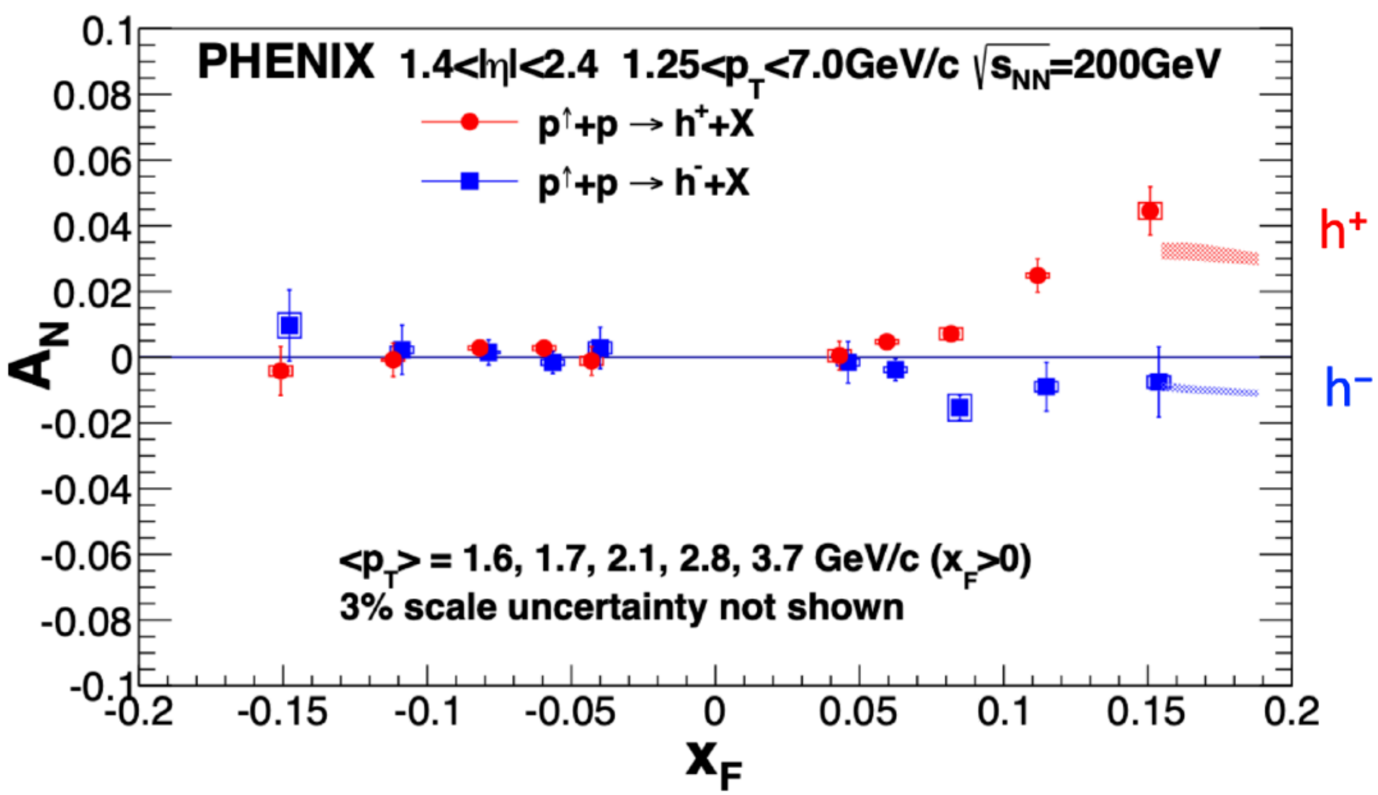
Phys. Rev. Lett. 123, 122001 (2019)

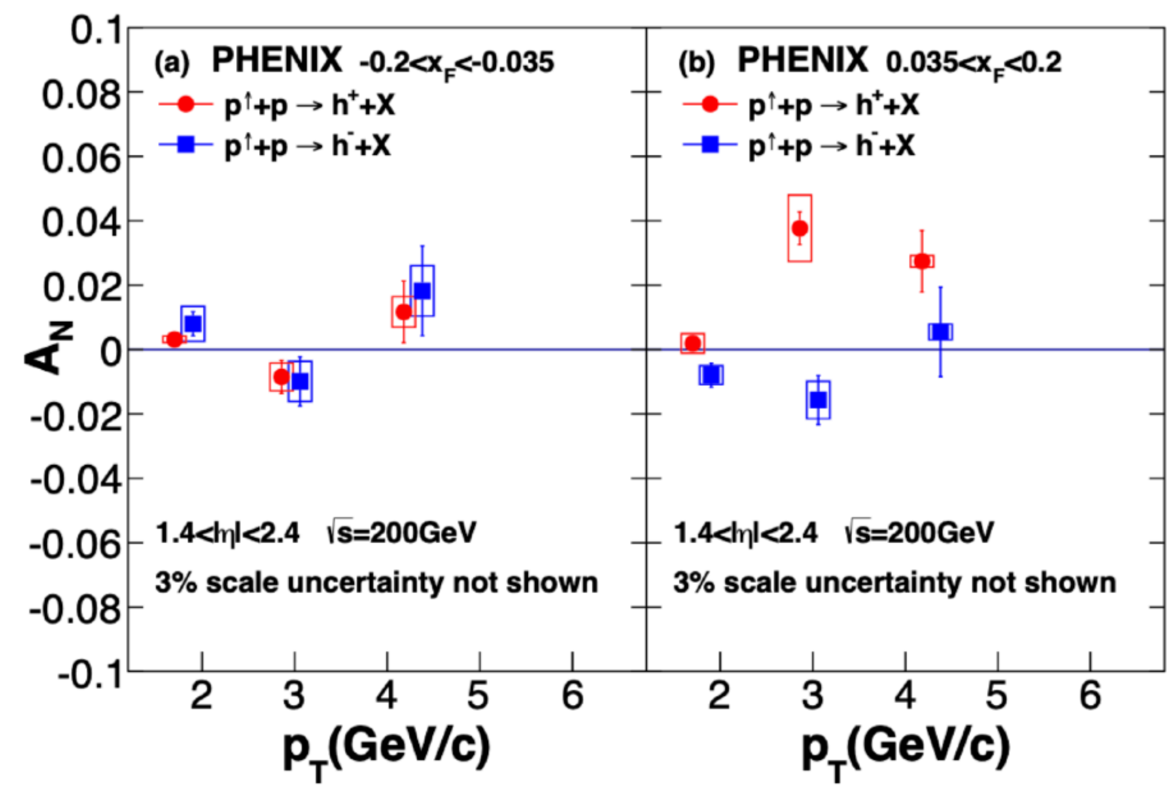


- Inclusive positively charged hadrons AN
- Particle composition $\pi^+/K^+/p$: 45%/47%/5%
- Suppression of A_N in p+Au observed
  - Suppression in p+A is sensitive to saturation scale
  - $A^{1/3}$ suppression in models with gluon saturation effects:

    PRD84 (2011) 034019, PRD95 (2017) 014008
  - <pT> of this measurement > saturation scale in Au

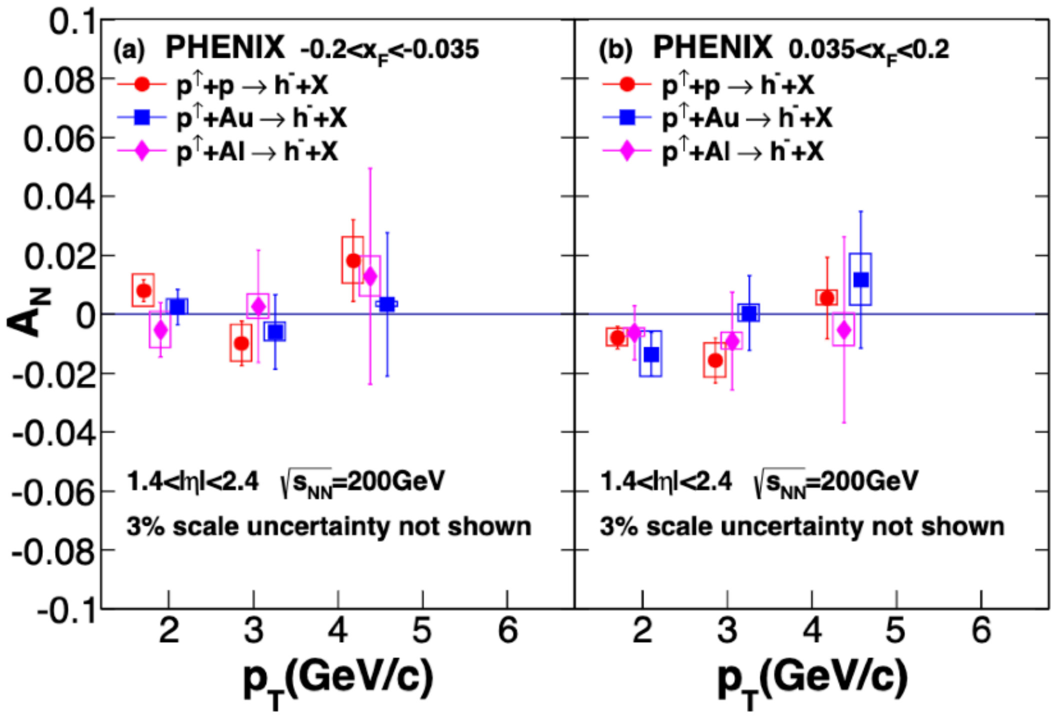
Forward charged hadron A_N in p+A: pT and xF dependence

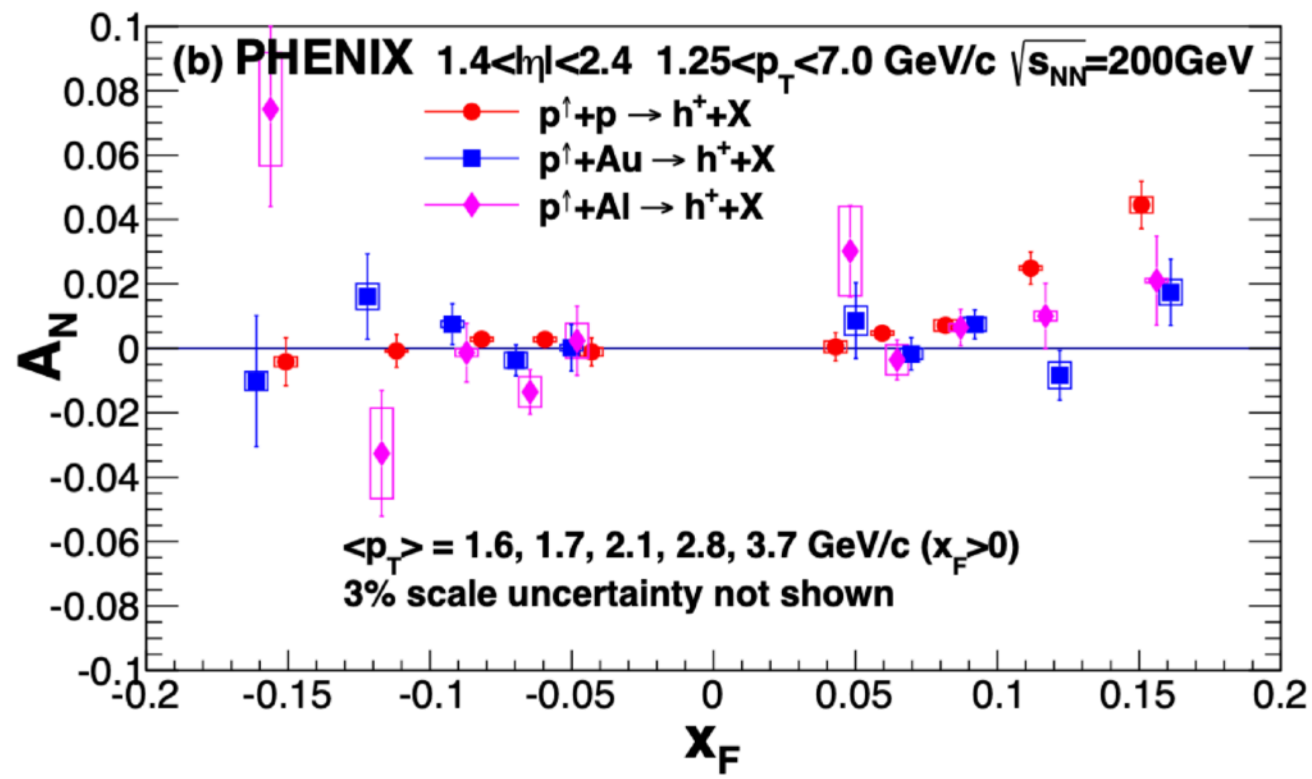


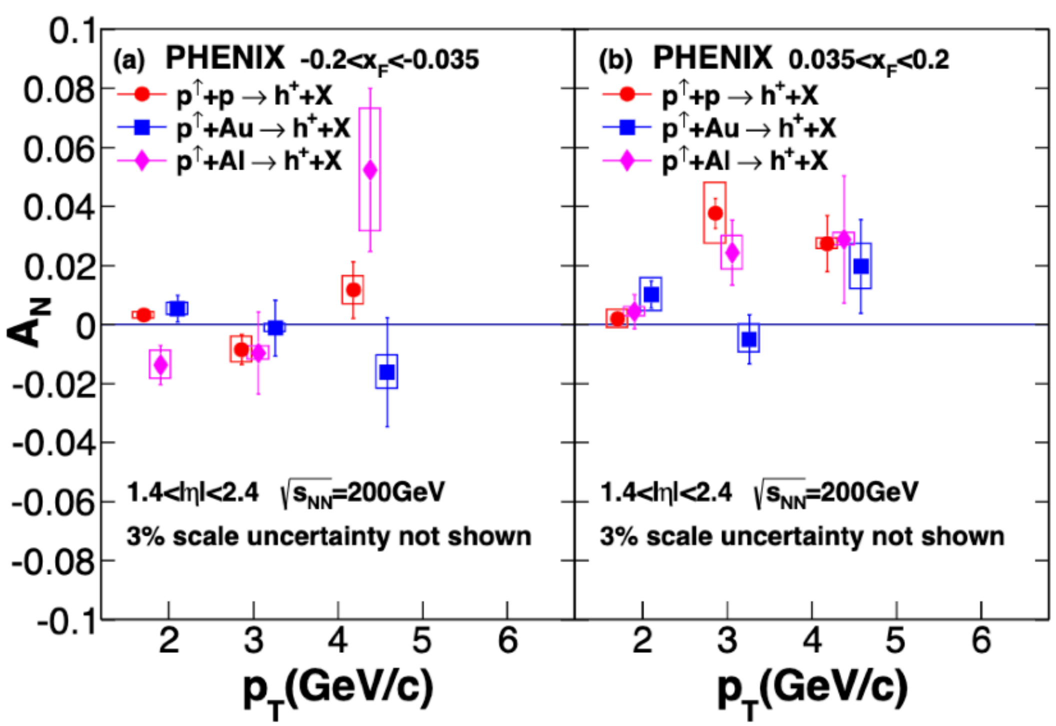


- p+p results: asymmetries increase for positively charged hadrons at xF > 0.

Forward charged hadron A_N in p+A: pT and xF dependence



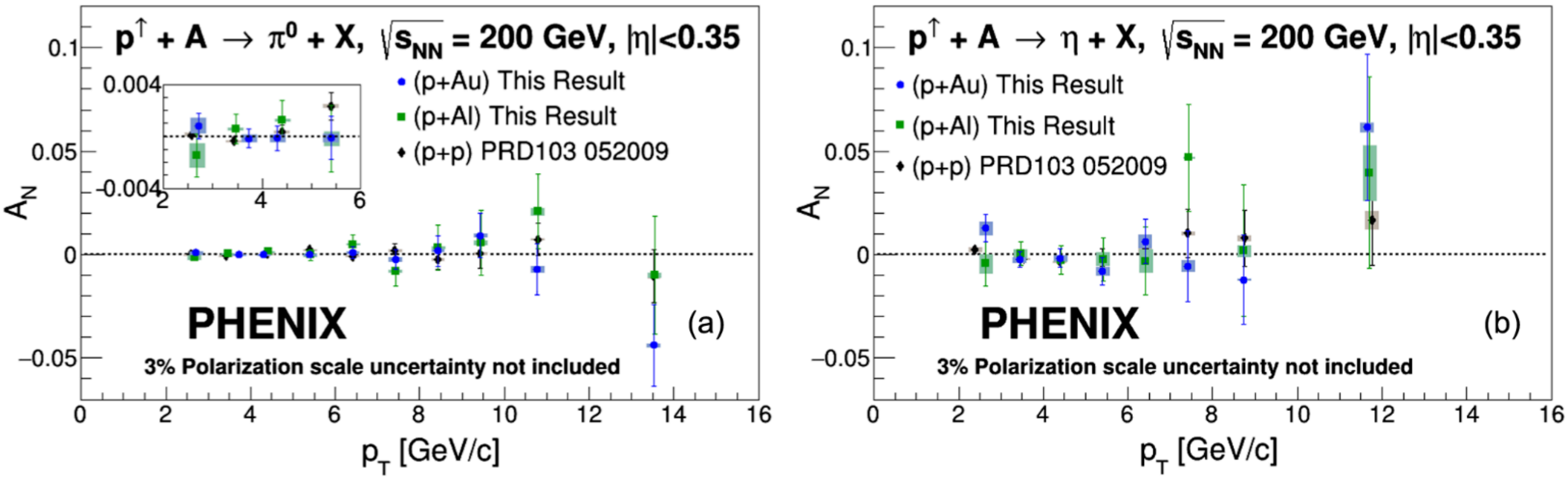




- For xF<0, asymmetries are consistent with zero for all collision systems.
- Suppression of A_N in p+A at 0.1 < xF < 0.2 compared to p+p
- The results provide detailed information and opportunities to study the origin of A_N and how nuclear environment affects the observables

A_N: Midraidity π^0 and η

[Phys. Rev. D 107, 112004 (2023)]



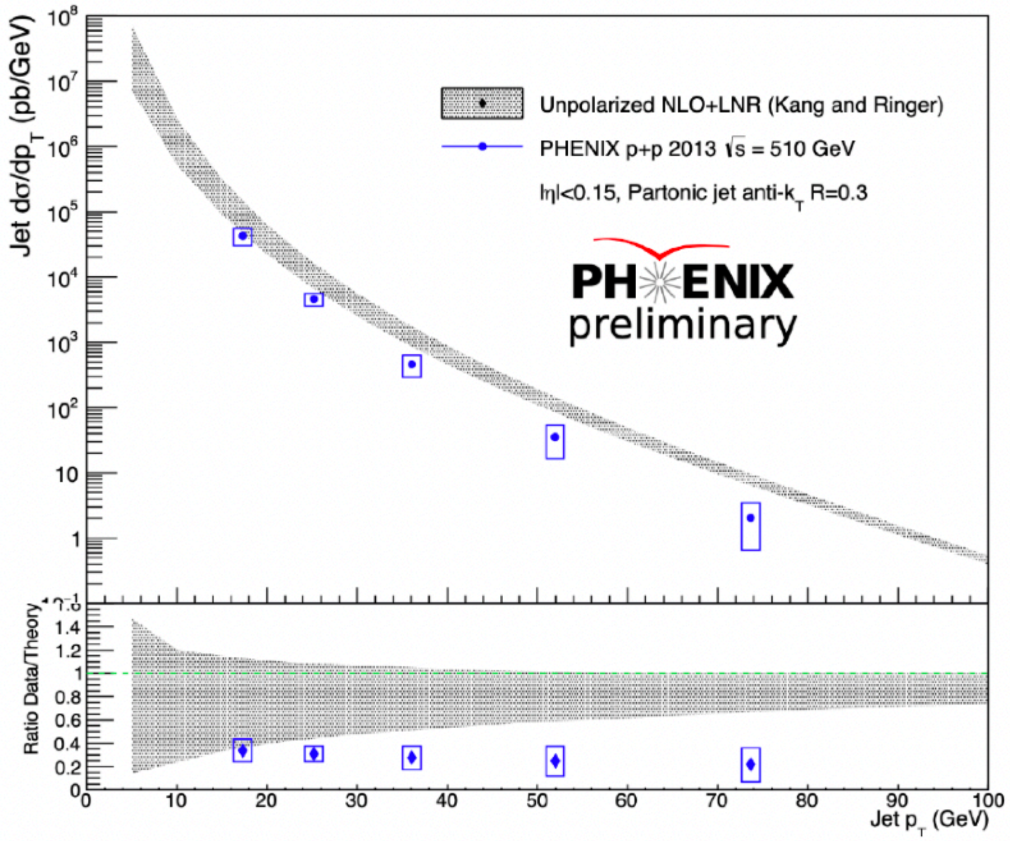
- First midrapidity π^0 and η asymmetry measurements in p+A
- Asymmetries in p+Al and p+A consistent with zero and with p+p measurements
- No indication of nuclear modification of the asymmetries observed

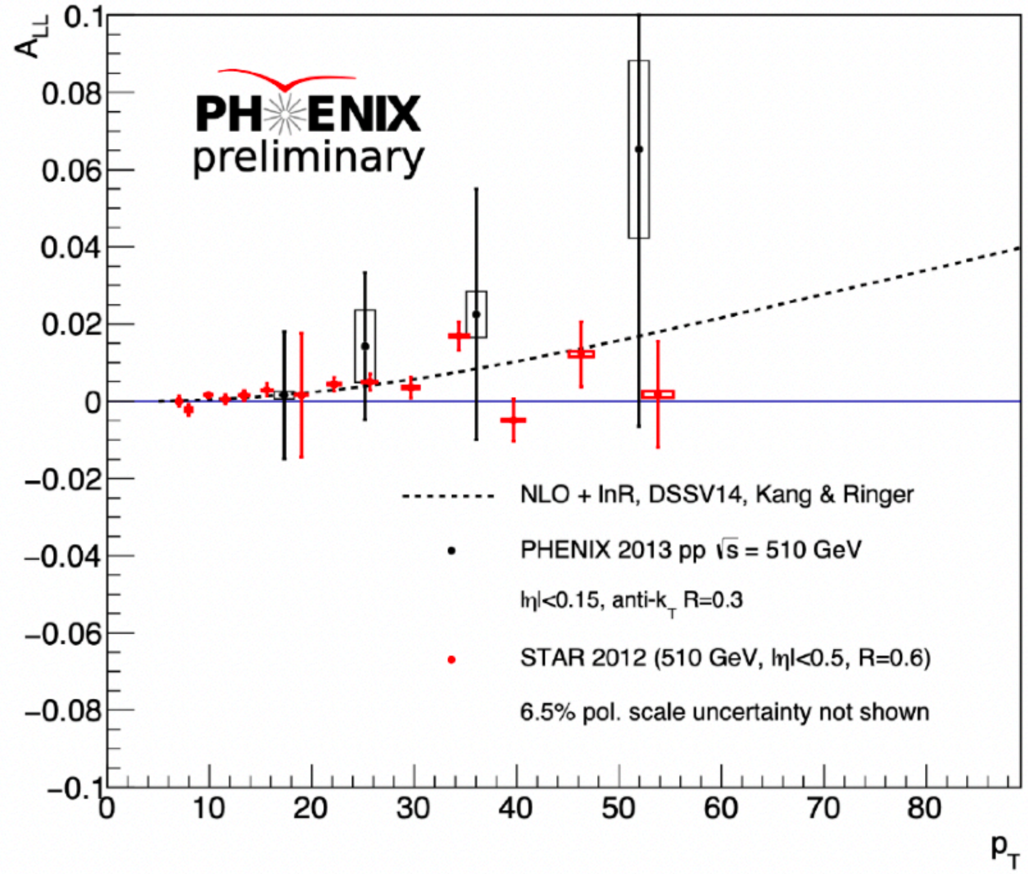
Summary

- **PHENIX spin program has been playing an important role for our understanding of QCD with unique dataset**
  - Confirmed nonzero gluon polarization in the proton
  - W program to disentangle quark and antiquark helicity distributions
  - Various observables to understand transverse spin asymmetries
  - p+A data provides new surprises and insights
- **More results expected from ongoing analyses:**
  - Very forward π^0 and mid-rapidity eta A_{LL}
  - Forward heavy flavor muon A_N with significantly improved statistics
  - pT dependence of very forward neutron A_N at various collision energies

Backup

Jet Cross Section and A_{LL} @ 510 GeV

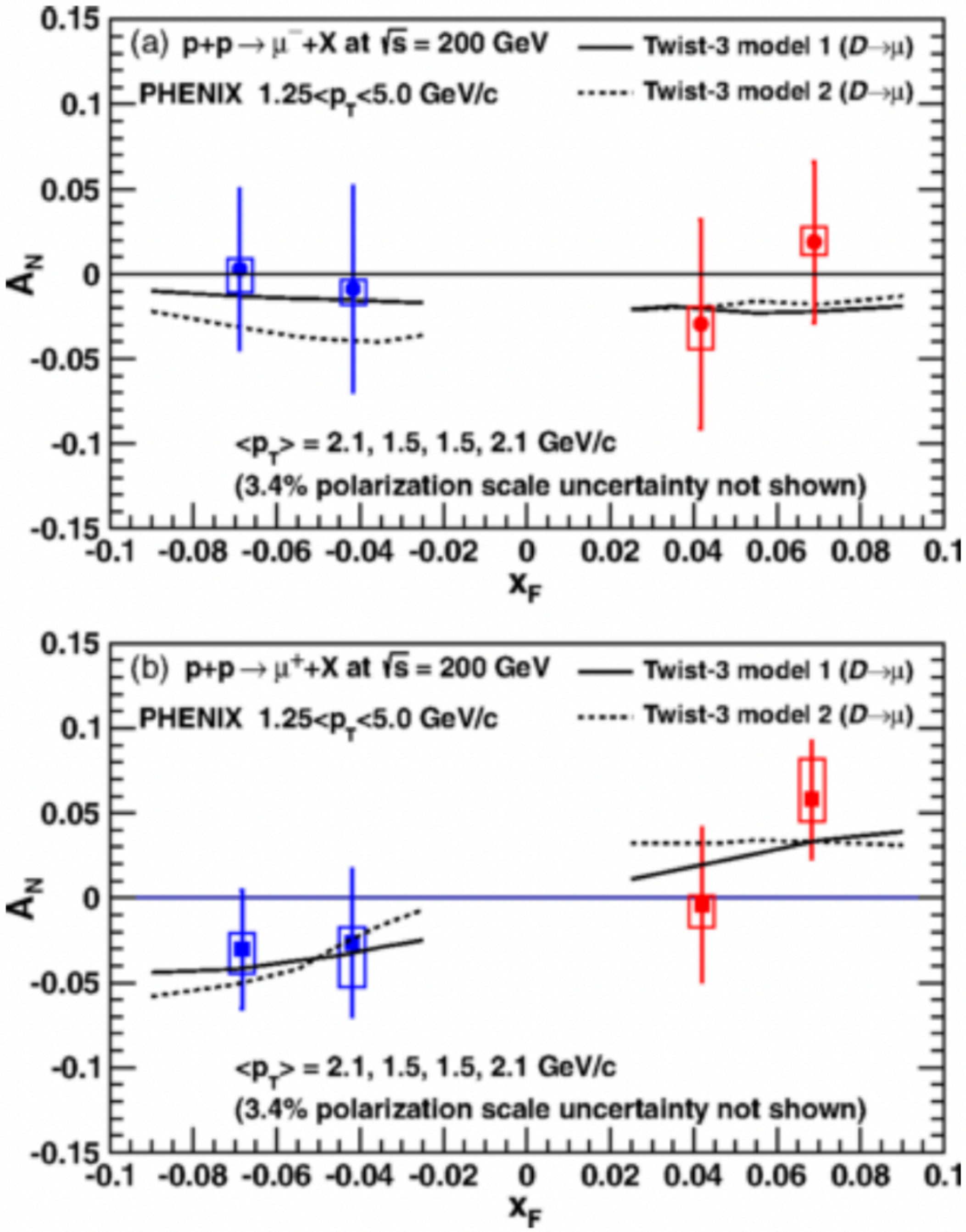




- Jet reconstructed with anti-k_T R=0.3
- NLO+LNR calculation overestimates the cross section (similar findings from LHC for small R using anti-k_T method)
- First jet A_{LL} result from PHENIX, asymmetry consistent with zero and STAR measurements

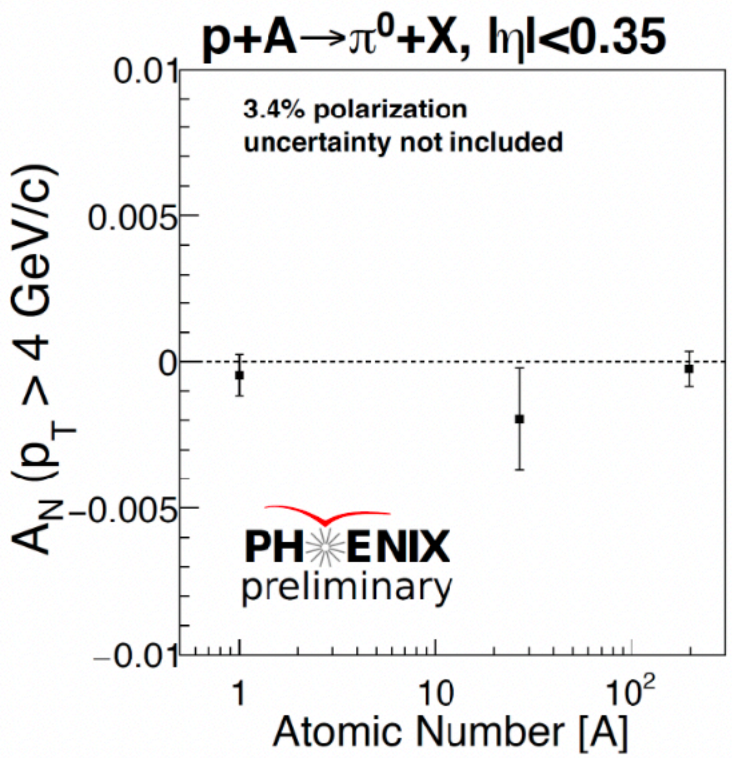
A_N: Open heavy flavor

Phys. Rev. D 95, 112001

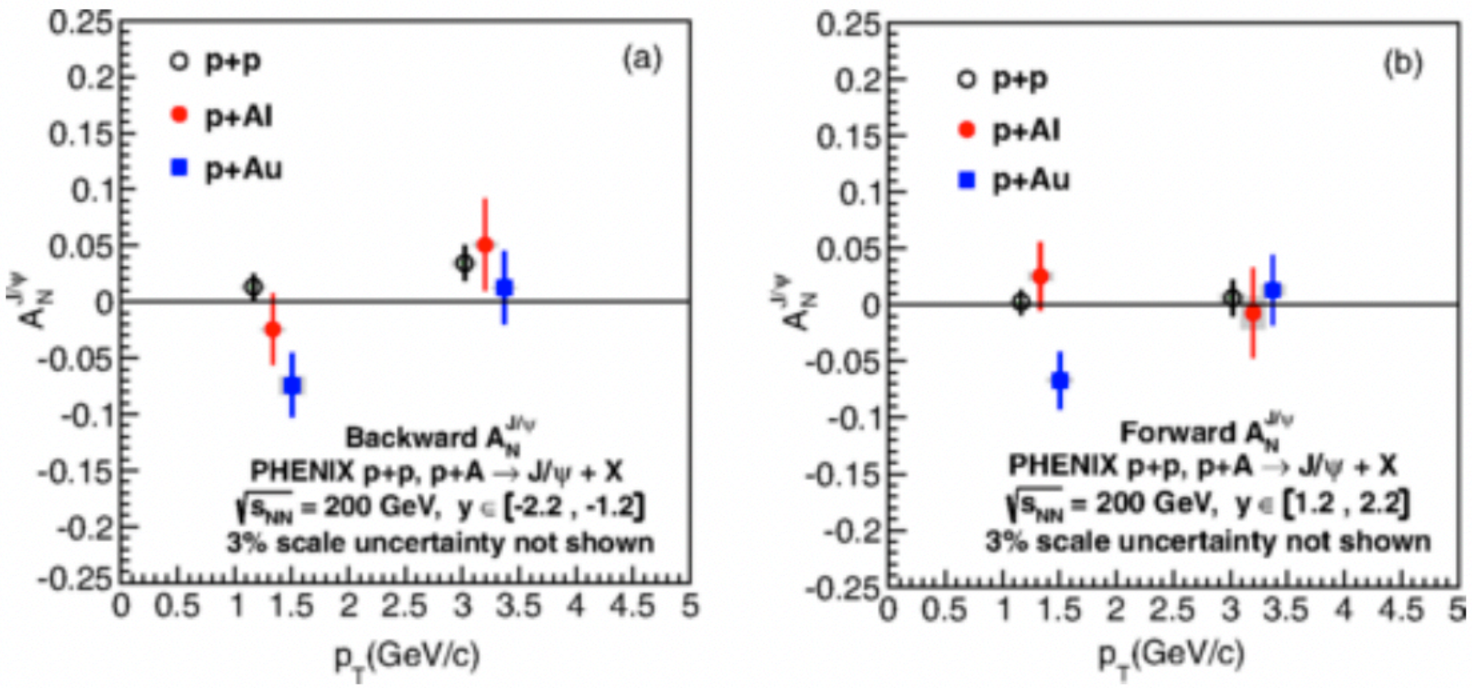


- At RHIC energies, mostly produced by gg fusion, ideal to investigate gluon distributions
- Sensitive to gluon Sivers-type effect, three-gluon correlations in the collinear factorization framework
- No clear indication of non-zero asymmetries within the uncertainty
- Theory calculations agree with data
- New high statistics data analysis ongoing

J/psi A_N in p+A



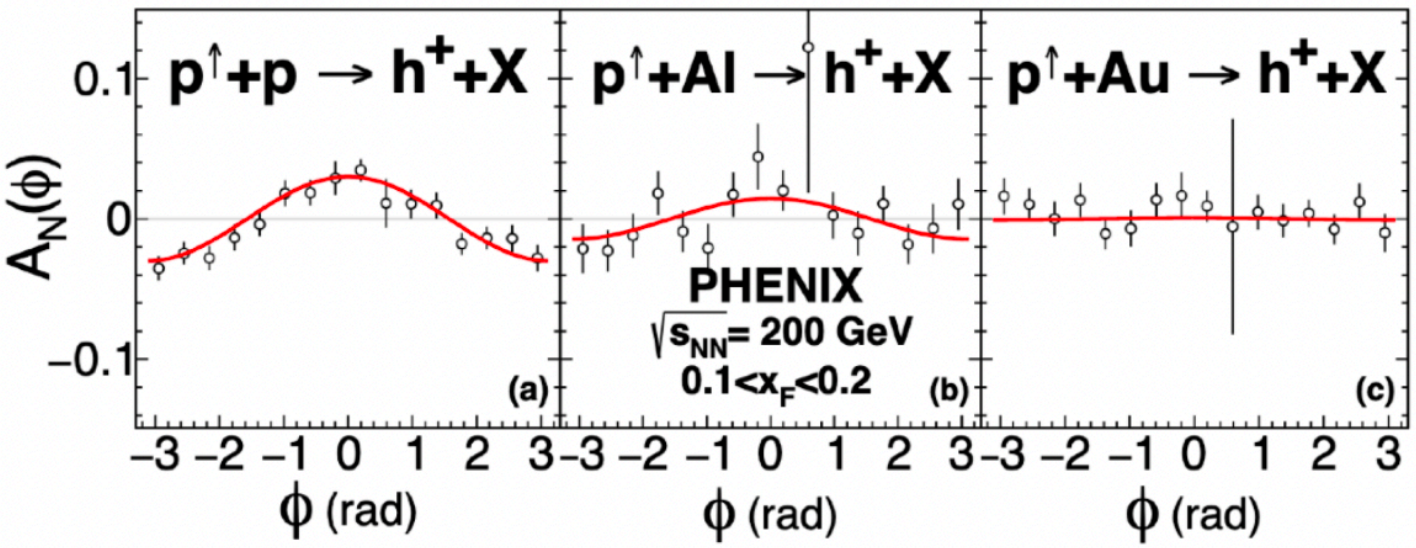
Phys. Rev. D 98, 012006



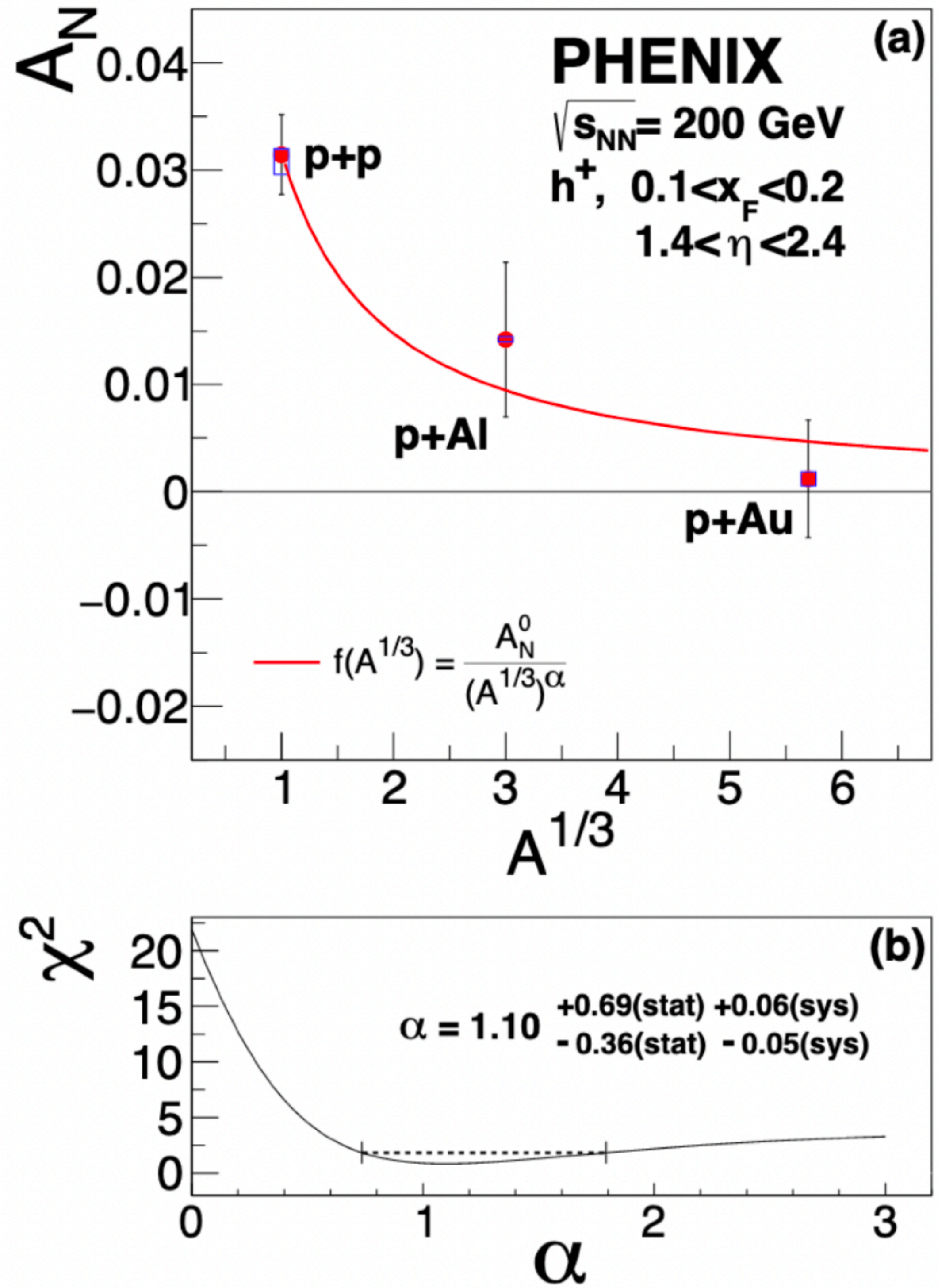
- Mid-rapidity pi0 measurement: no A-dependence observed
- Forward J/psi measurements:

  p+p results consistent with previous measurements
  2-sigma level asymmetry observed in p+Au in both forward and backward rapidity
  Large unexpected effects at low pT

Charged hadron AN



Phys. Rev. Lett. 123, 122001 (2019)



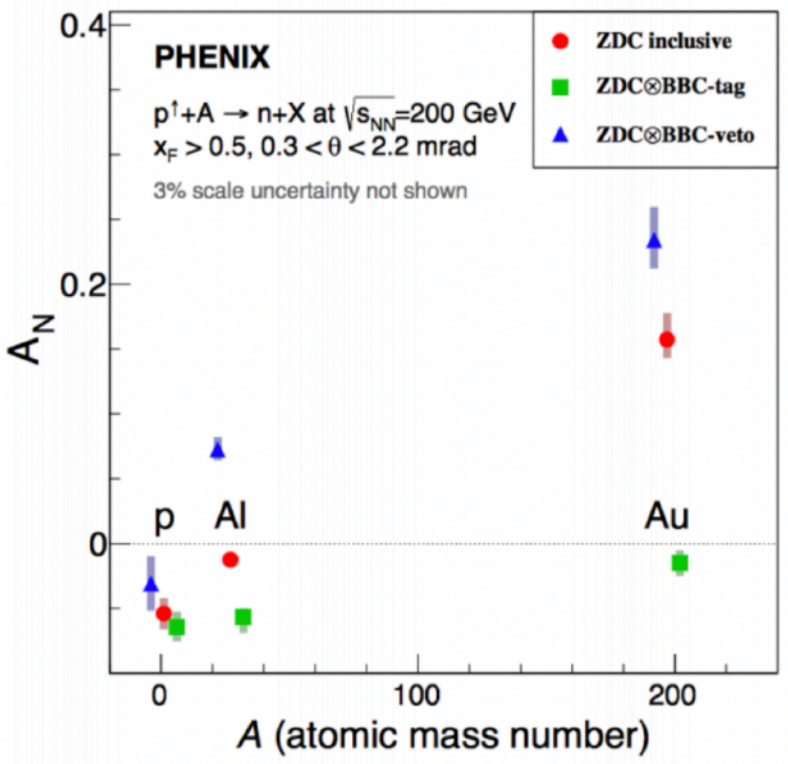
$$f(A^{1/3}) = \frac{A_N^0}{(A^{1/3})^\alpha}$$

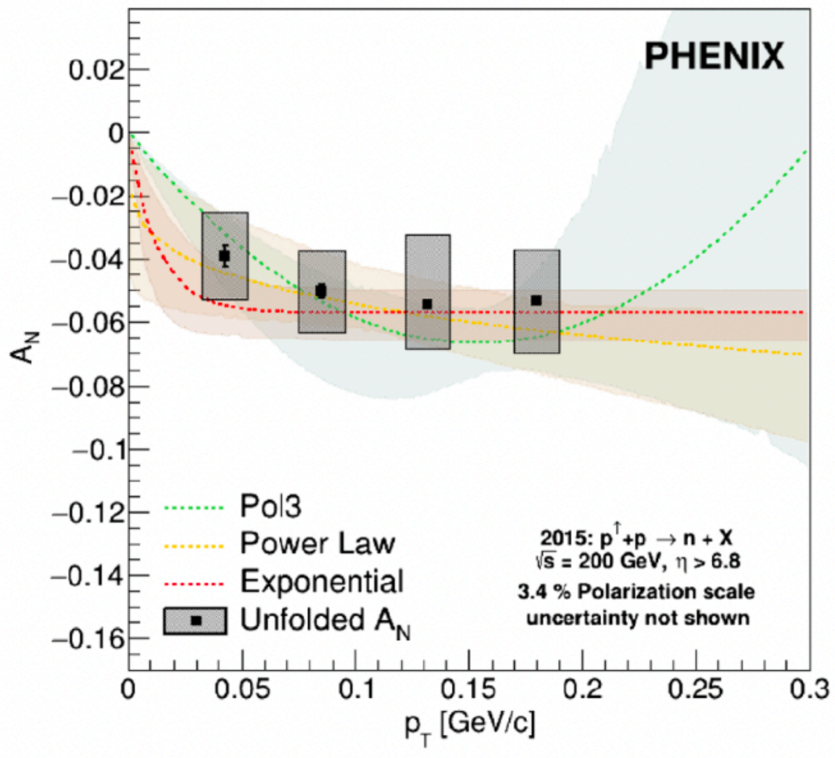
- Inclusive positively charged hadrons AN
- Particle composition $\pi^+/K^+/p$: 45%/47%/5%
- Suppression of A_N in p+Au observed
  - Suppression in p+A is sensitive to saturation scale
  - $A^{1/3}$ suppression in models with gluon saturation effects:

    PRD84 (2011) 034019, PRD95 (2017) 014008
  - <pT> of this measurement > saturation scale in Au

Forward neutron A_N

- Strong nuclear dependence of forward neutron AN (PRL 120, 022001)
- Explicit pT dependence of the asymmetries: Phys. Rev. D 103, 032007 (2021)





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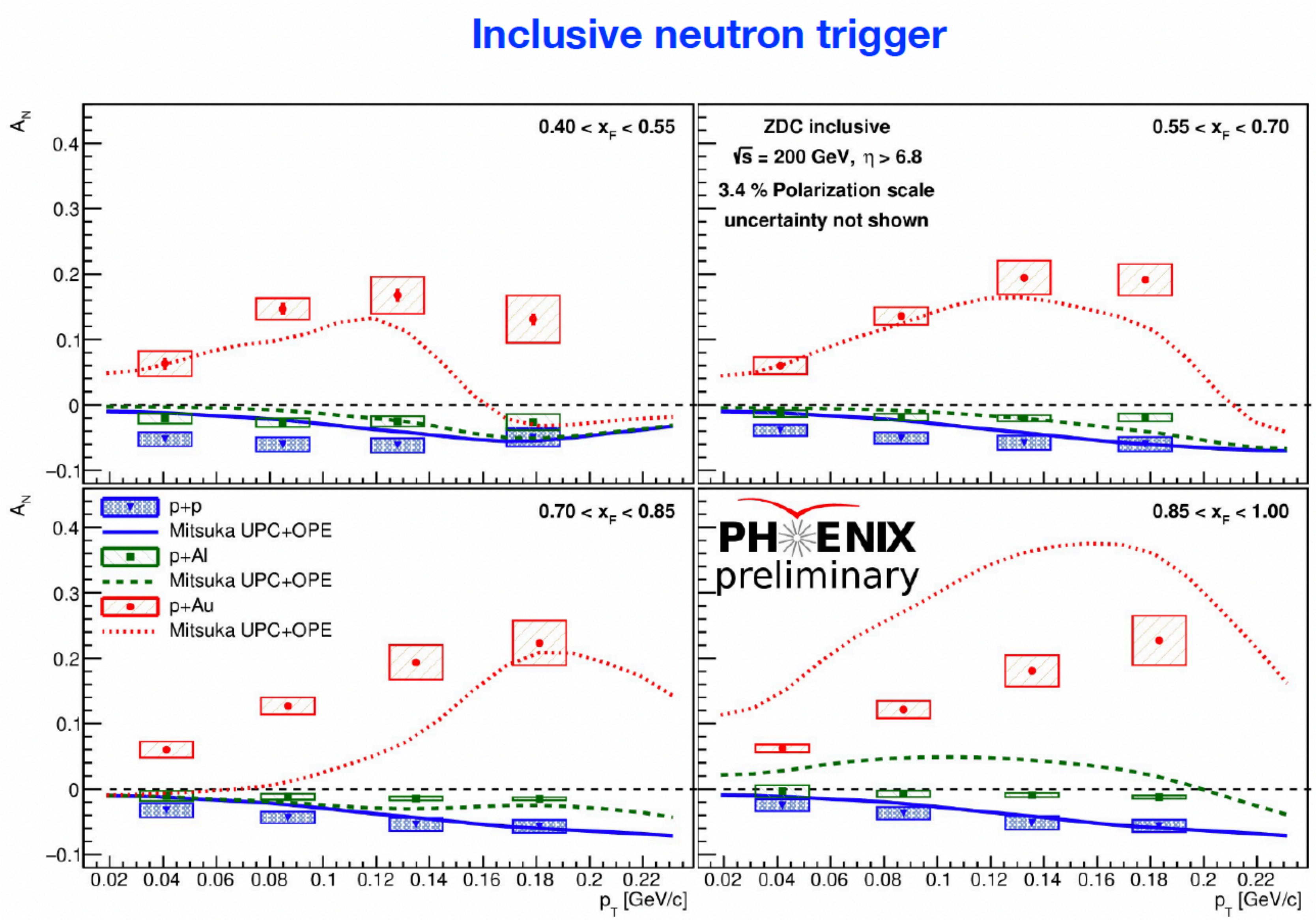
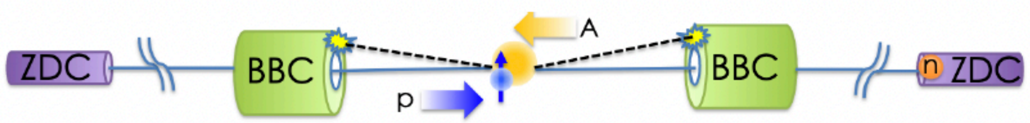
    - Enhance / suppress UPC contribution



Forward neutron A_N



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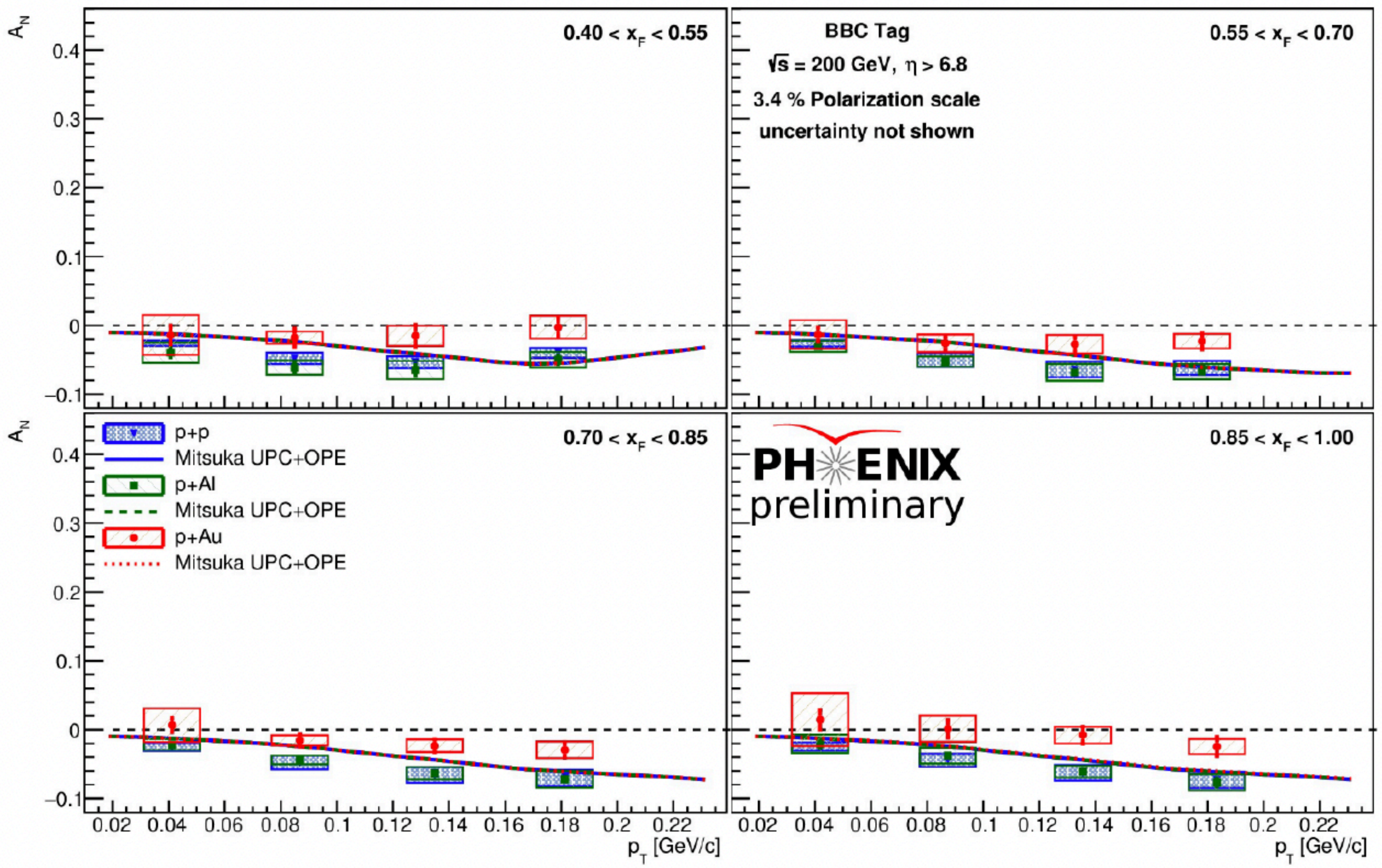

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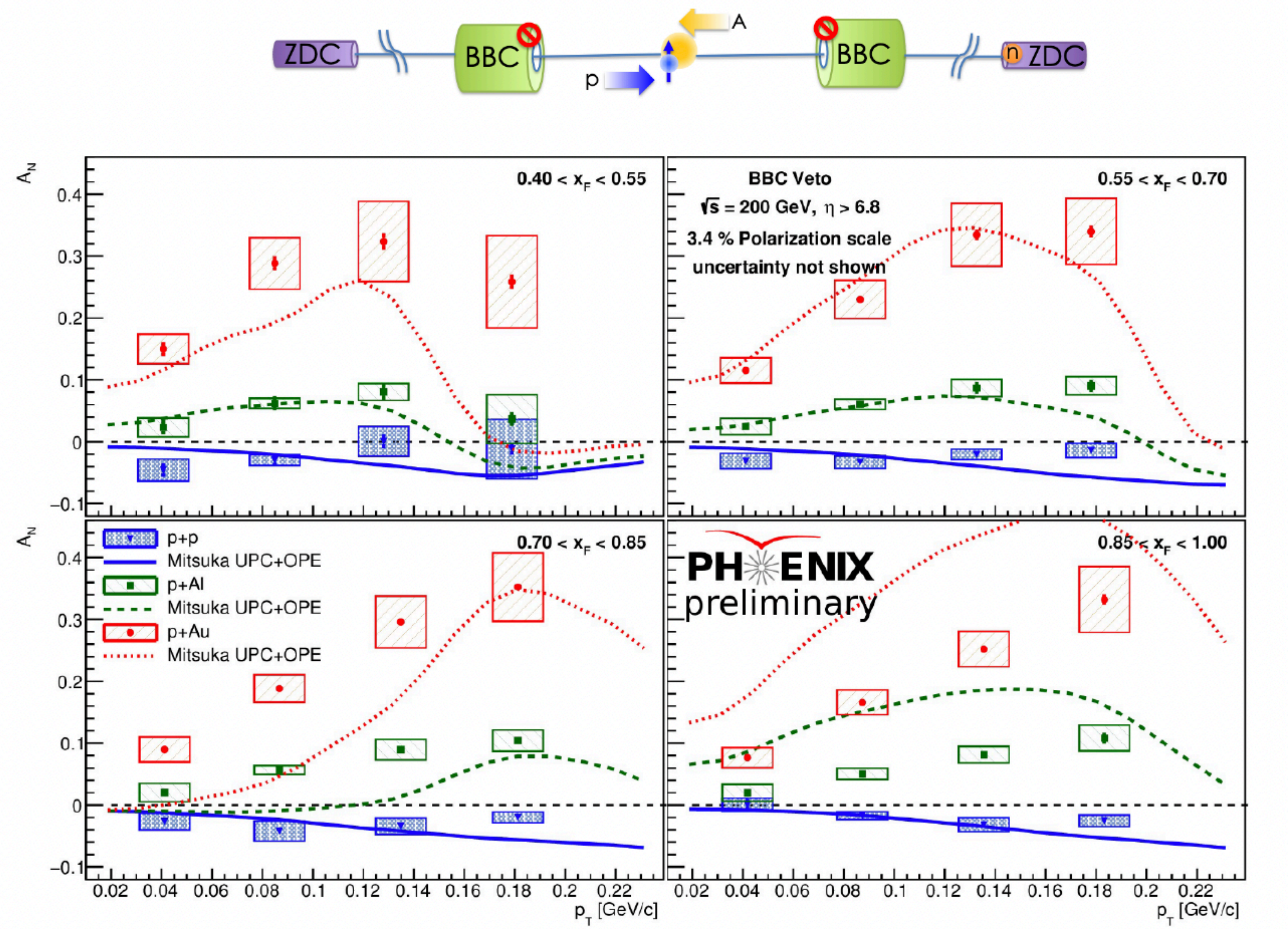
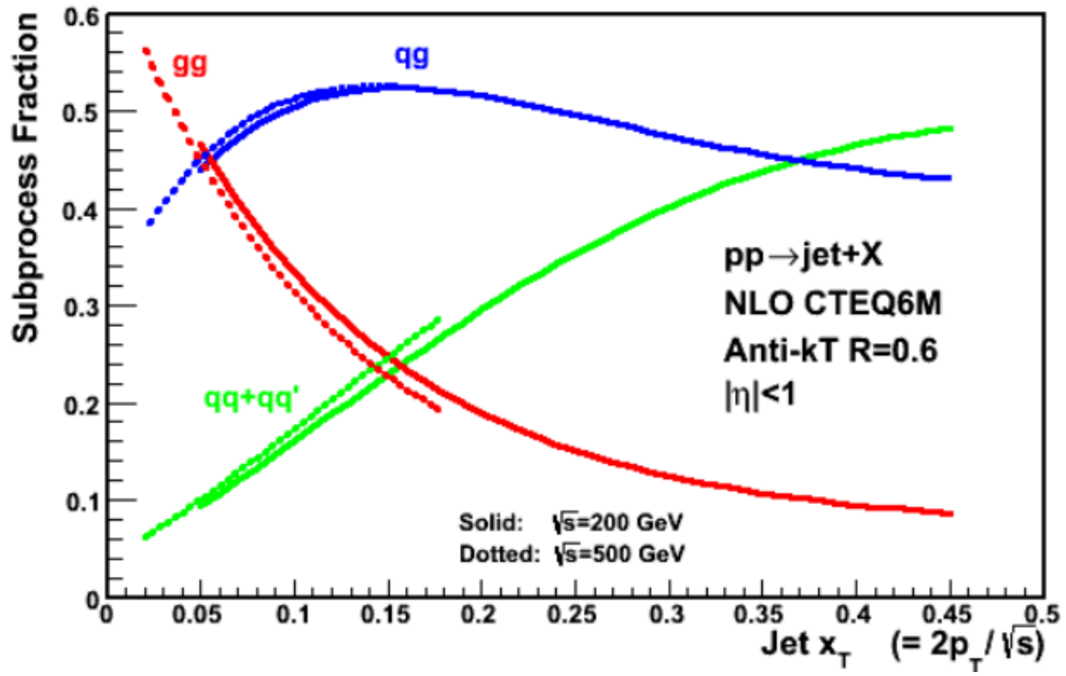
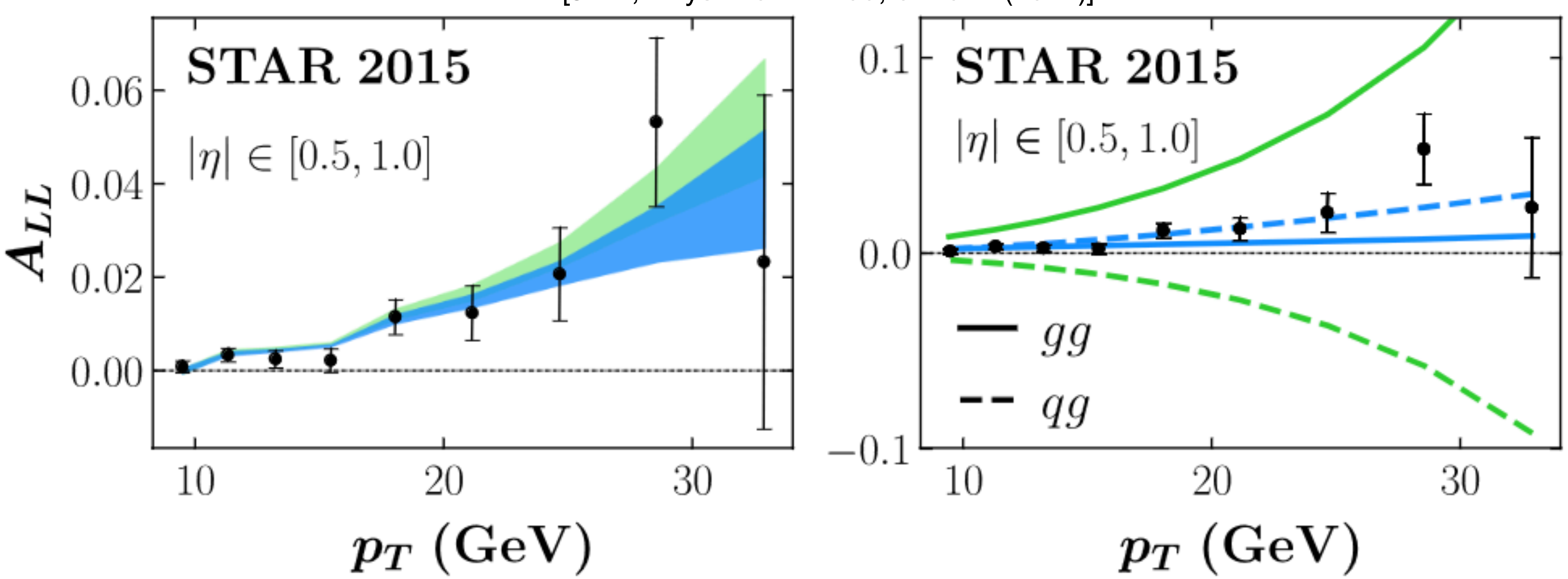


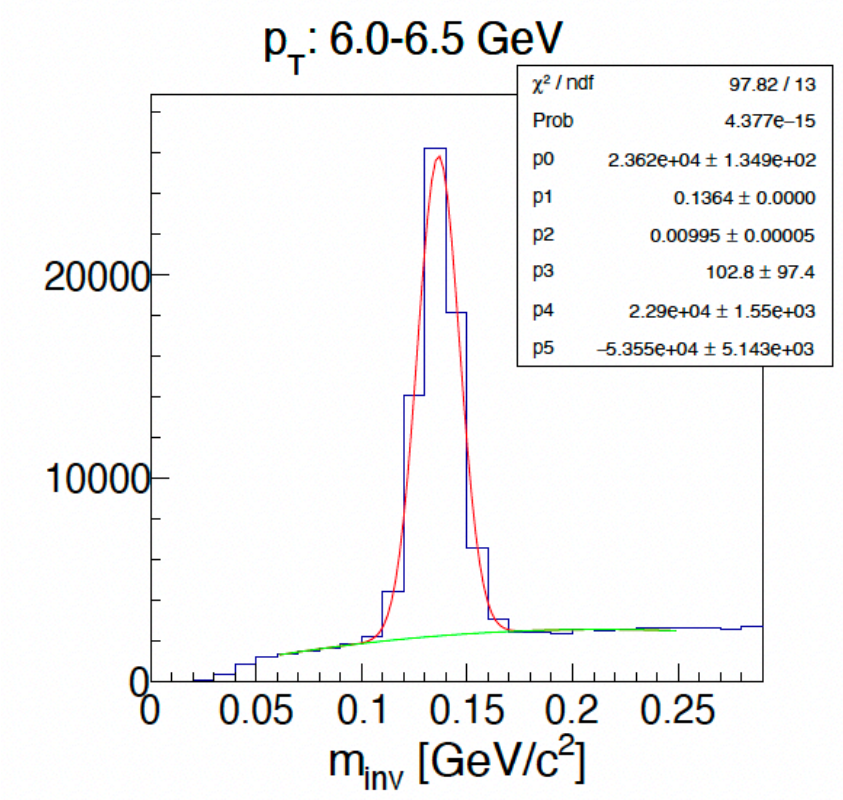


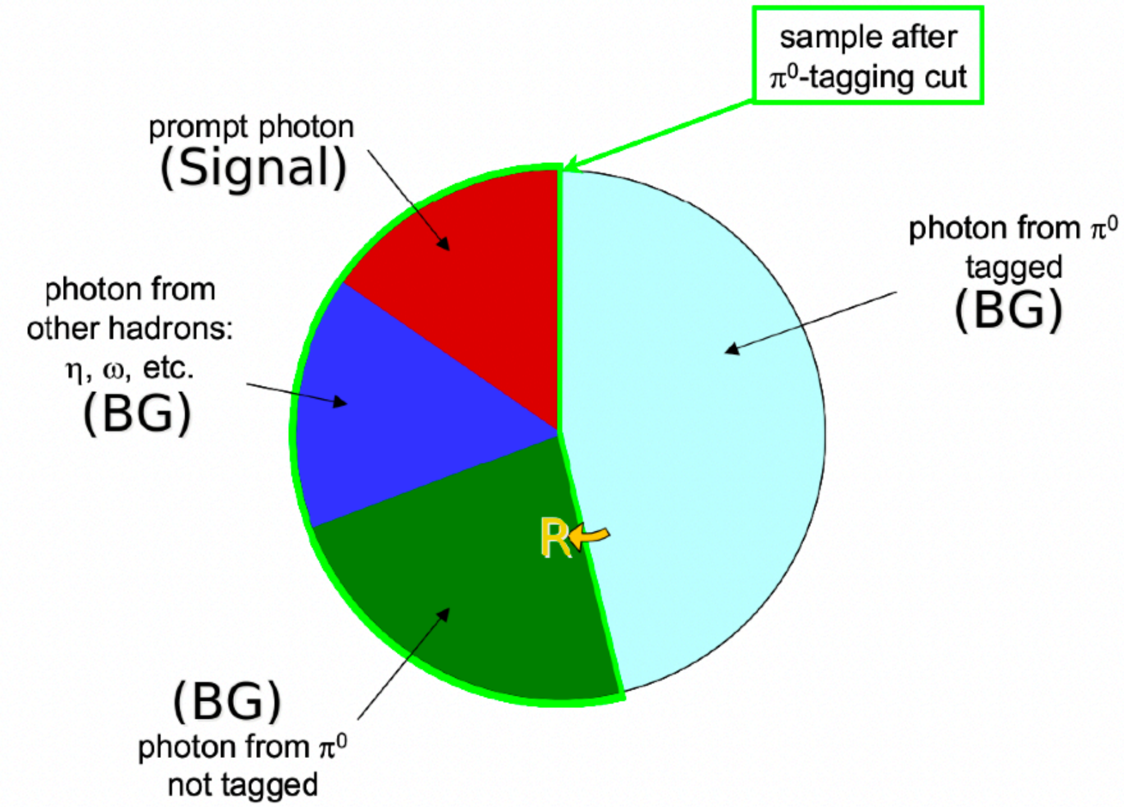
[JAM, Phys. Rev. D 105, 074022 (2022)]



Analysis overview

- Photons detected by EMCal
- Effectively reduced BGs by π^0decay tagging





Yield of direct photon:

- $N_{dir} = N_{total} - (1 + A)(1 + R)N_{\pi^0}$
  - R: π^0 one photon missing ratio.
  - A: Other hadrons' to π^0's photon ratio.

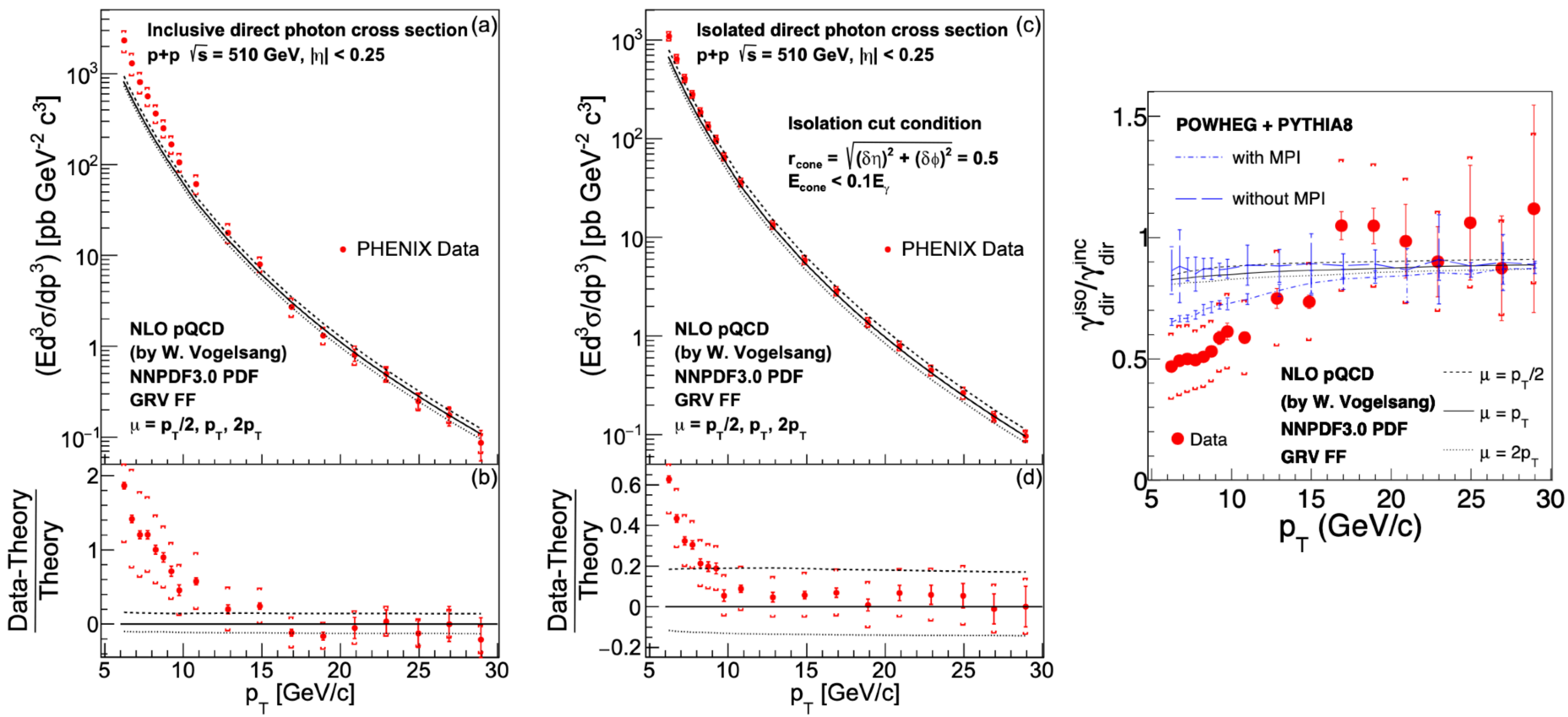
- Isolation cut: reduced the BG contributions from parton fragmentation and hadron decays

$$r_{cone} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5\ rad$$

$$E_{cone} < E_\gamma \cdot 10\,\%$$

Direct photon cross section

Phys. Rev. Lett. 130, 251901 (2023)



- NLO pQCD calculation underestimates the inclusive cross section data at low pT
- Multiparton interaction (MPI) and parton shower are important to better understand the data
- With isolation criteria, the calculation consistent with the data.