# TRANSVERSE SINGLE-SPIN ASYMMETRIES OF MIDRAPIDITY DIRECT PHOTONS AND NEUTRAL MESONS AT PHENIX

Nicole Lewis

University of Michigan

Deep Inelastic Scattering 2021

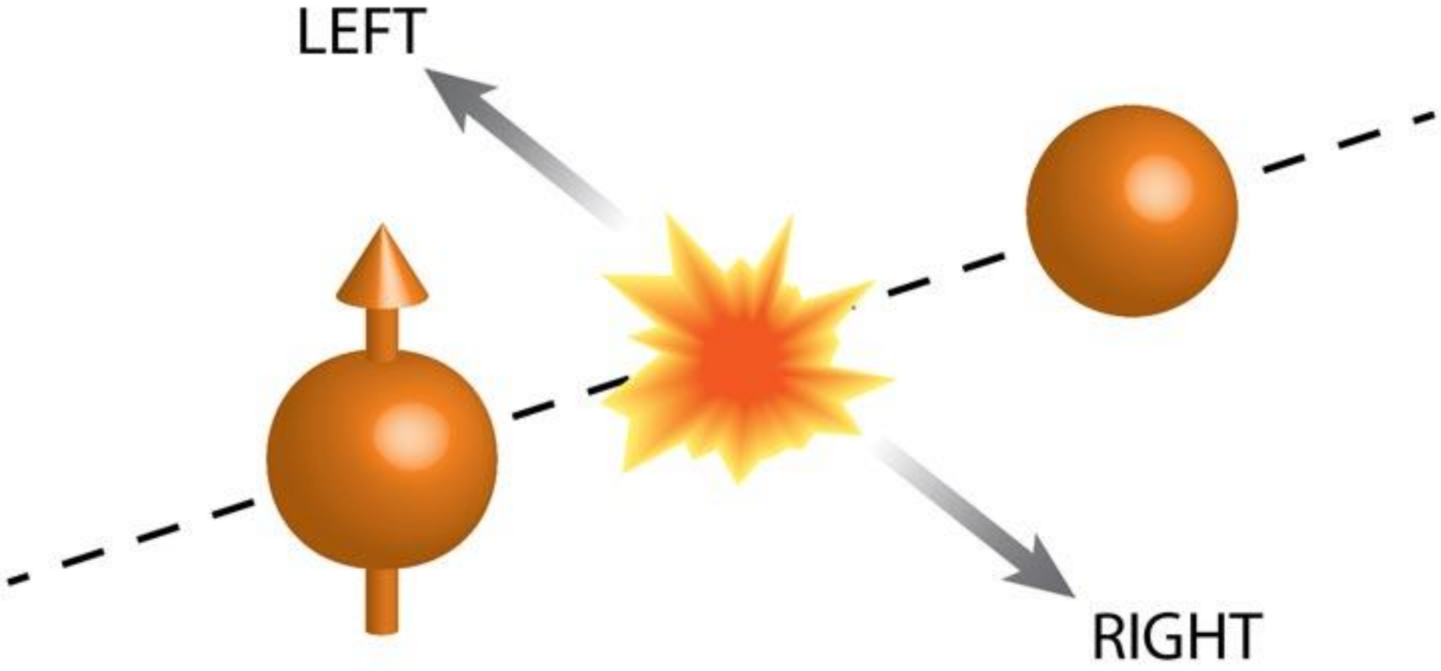
U.S. DEPARTMENT OF ENERGY

Office of Science

PHENIX

UNIVERSITY OF MICHIGAN

# Transverse Single-Spin Asymmetries




https://phys.org/news/2015-02-polarized-protons-uncover-secrets.html

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

G. L. Kane, J. Pumplin, and W. Repko *PRL* **41**, 1689 (1978): TSSA due to ***perturbative*** QCD effects:

$$A_N \propto \frac{m_q \alpha_s}{p_T} \approx 0.001$$

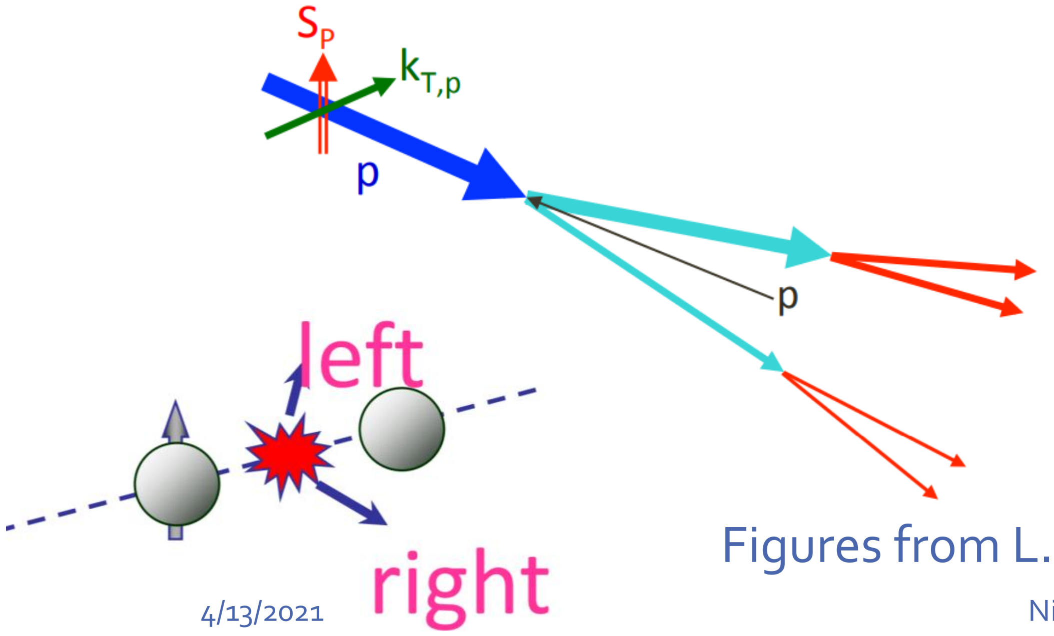
# TMD Functions for inclusive $A_N$ in $p^{\uparrow} + p$ collisions

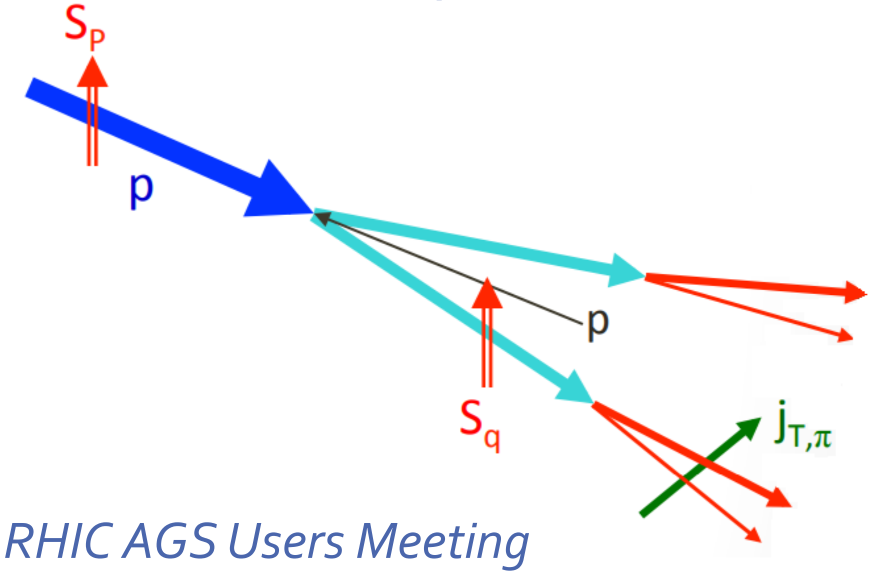
<u>Sivers Effect</u> - Initial State Effect

Sivers Function - Correlation between proton spin and parton $k_T$

<u>Collins Effect</u> - Final State effect

Convolution of Collins Fragmentation Function and Transversity – correlation between quark transverse spin and proton transverse spin.



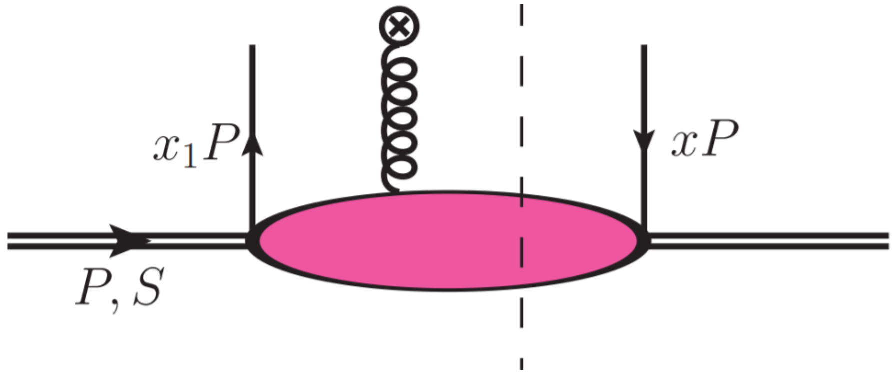




Figures from L. Nogach 2006 *RHIC AGS Users Meeting*

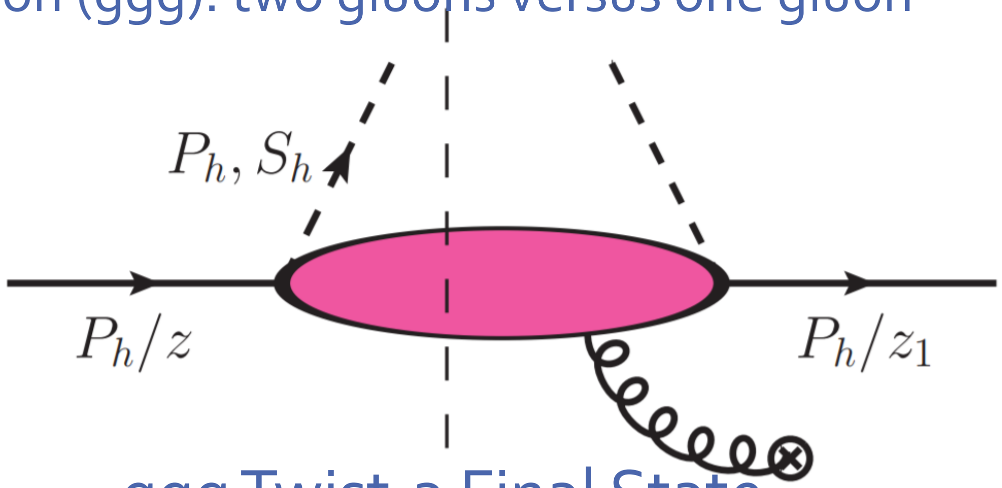
# Collinear Twist-3 Functions

Multiparton correlations: quantum mechanical interference between scattering off of one parton at a given $x$ versus a parton of the same flavor and at the same $x$ plus a gluon

- Quark-Gluon-Quark (qgq) Correlation Function: scattering off of a quark and a gluon versus a single quark of the same flavor and same $x$
- Trigluon (Three-gluon) Correlation Function (ggg): two gluons versus one gluon




qgq Twist-3 Initial State

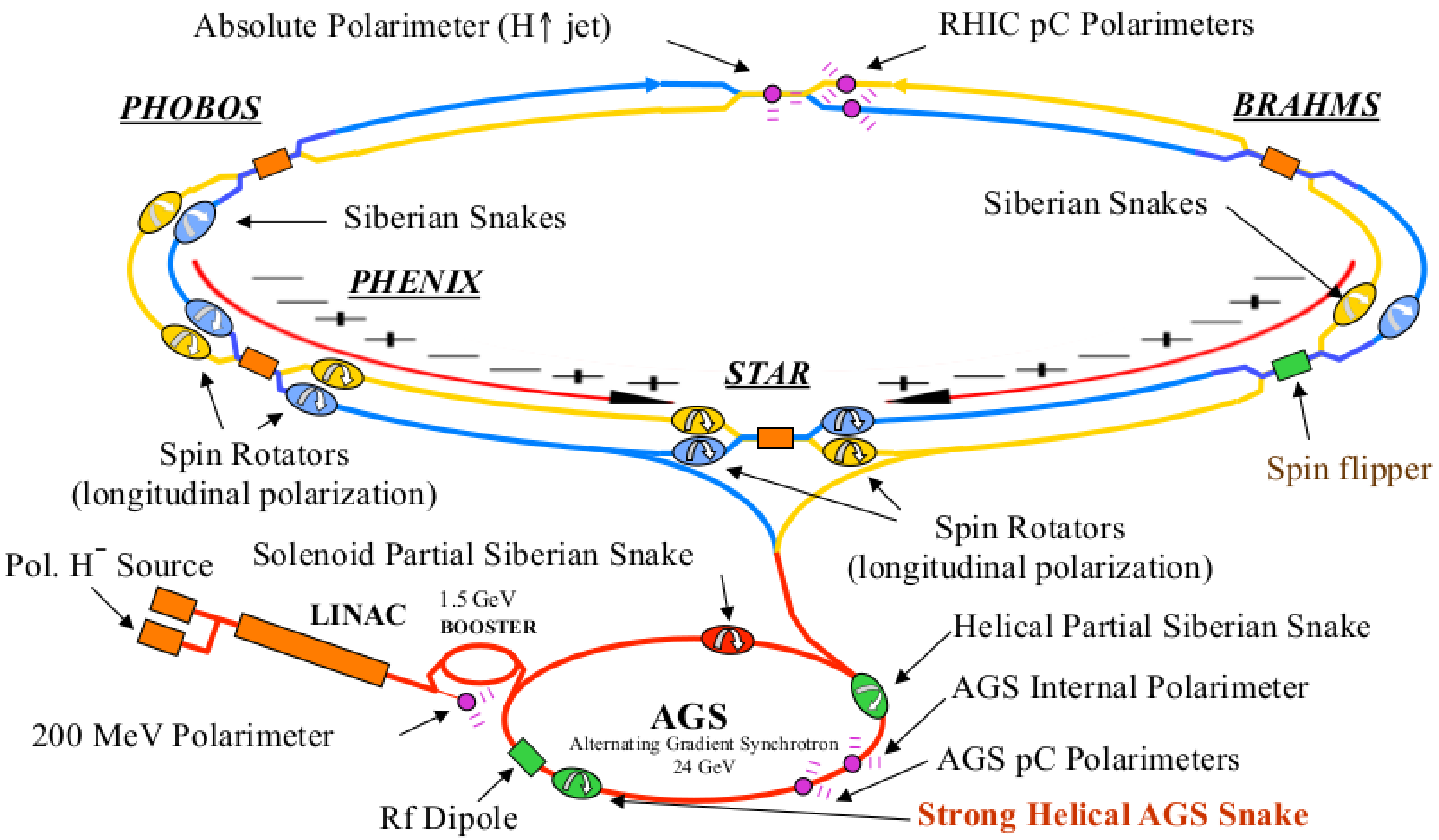



qgq Twist-3 Final State

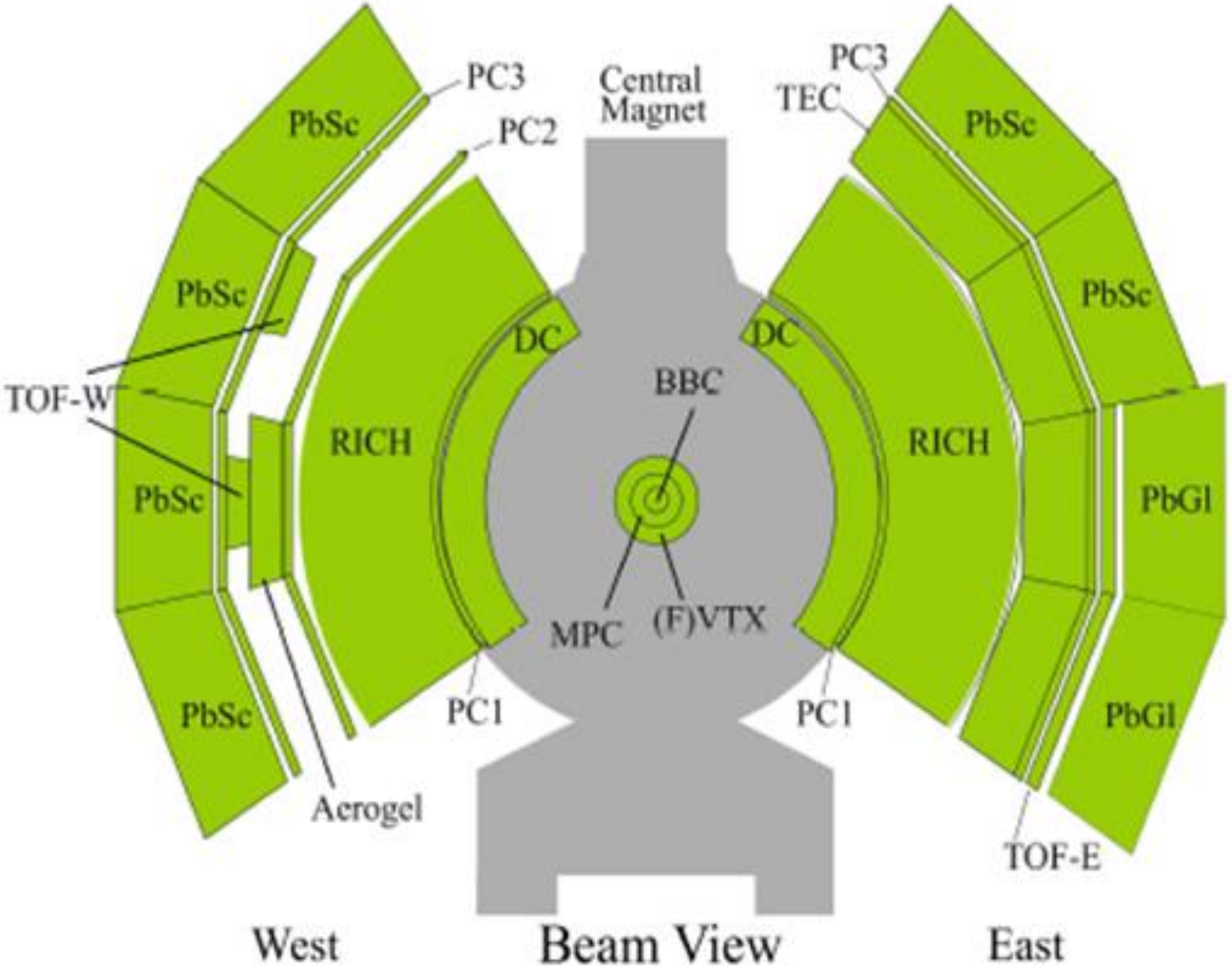
Daniel Pitonyak *International Journal of Modern Physics A* **31**, No. 32, 1630049 (2016)

# Relativistic Heavy Ion Collider (RHIC)

## Only collider in the world able to run polarized proton beams



# PHENIX Detector

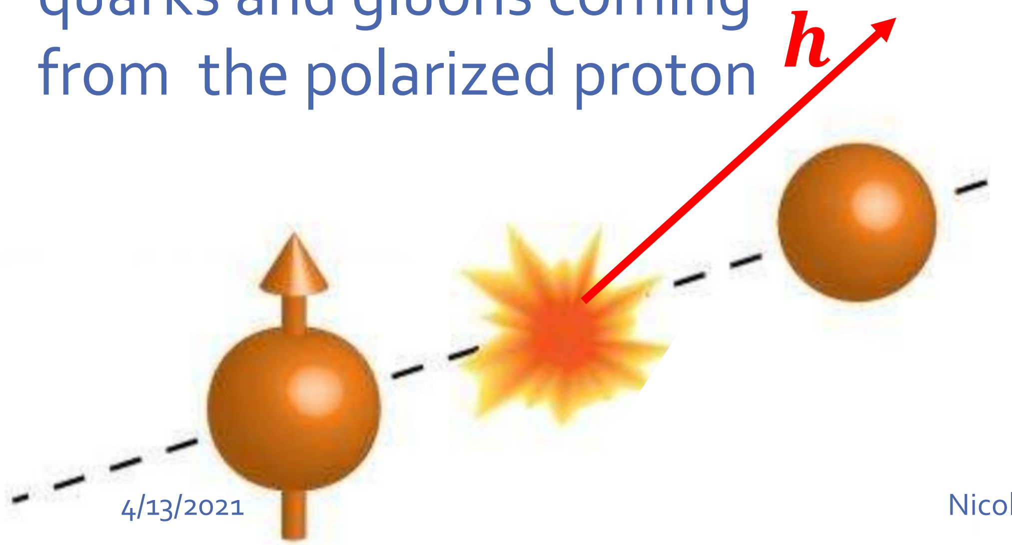


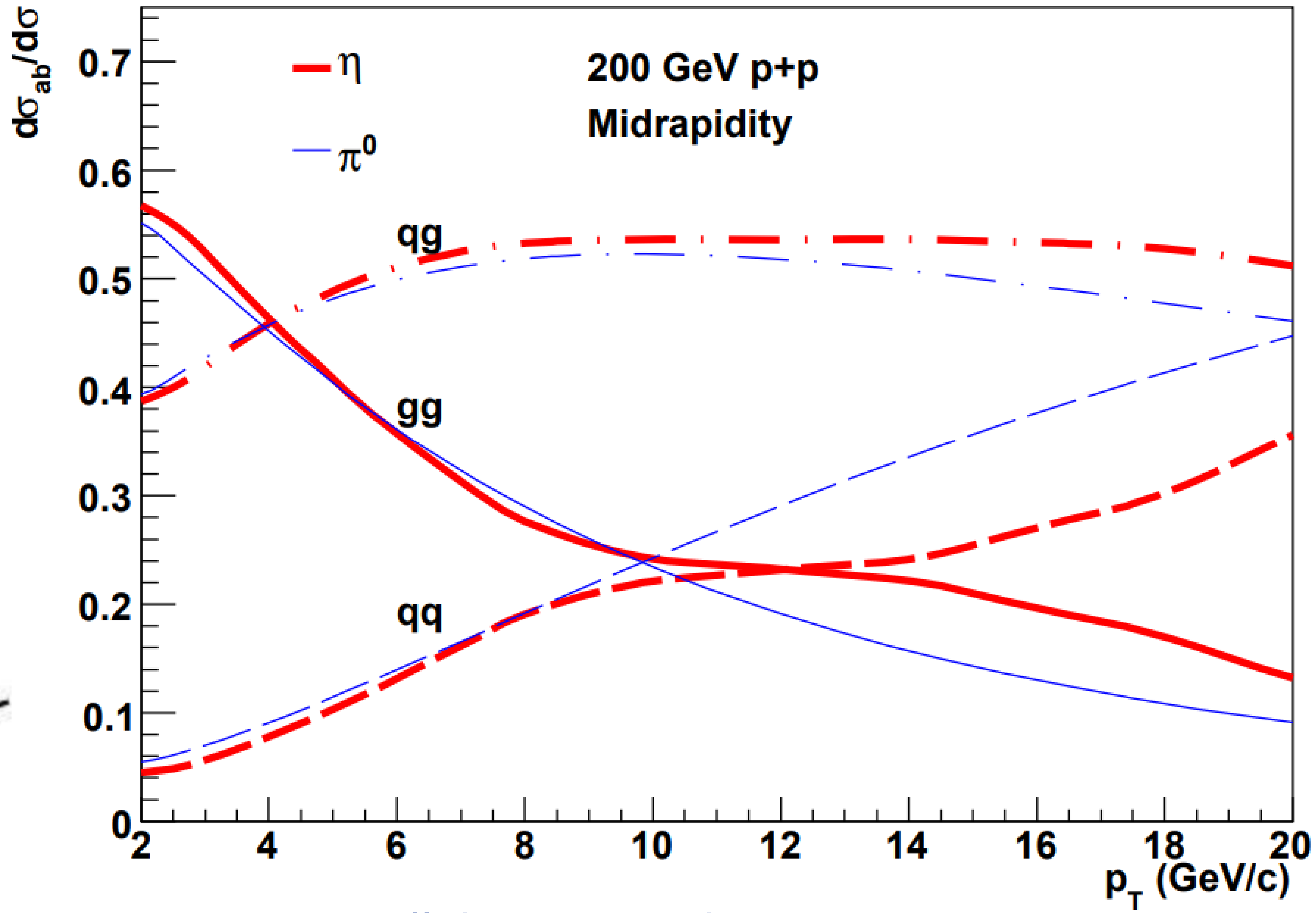

- PHENIX Central Arms
  - $\Delta\phi \sim \pi$
  - $|\eta| < 0.35$
- Electromagnetic Calorimeter used for $\gamma$, $\pi^0 \rightarrow \gamma\gamma$, and $\eta \rightarrow \gamma\gamma$ detection
  - Lead scintillator (PbSc) sectors: $\Delta\phi \times \Delta\eta \approx 0.011 \times 0.011$
  - Lead Glass (PbGl) sectors: $\Delta\phi \times \Delta\eta \approx 0.008 \times 0.008$

# Partonic Contributions for $\pi^0$ and $\eta$ production in $p+p$

**Forward Rapidity:** Mostly quarks coming from the polarized proton

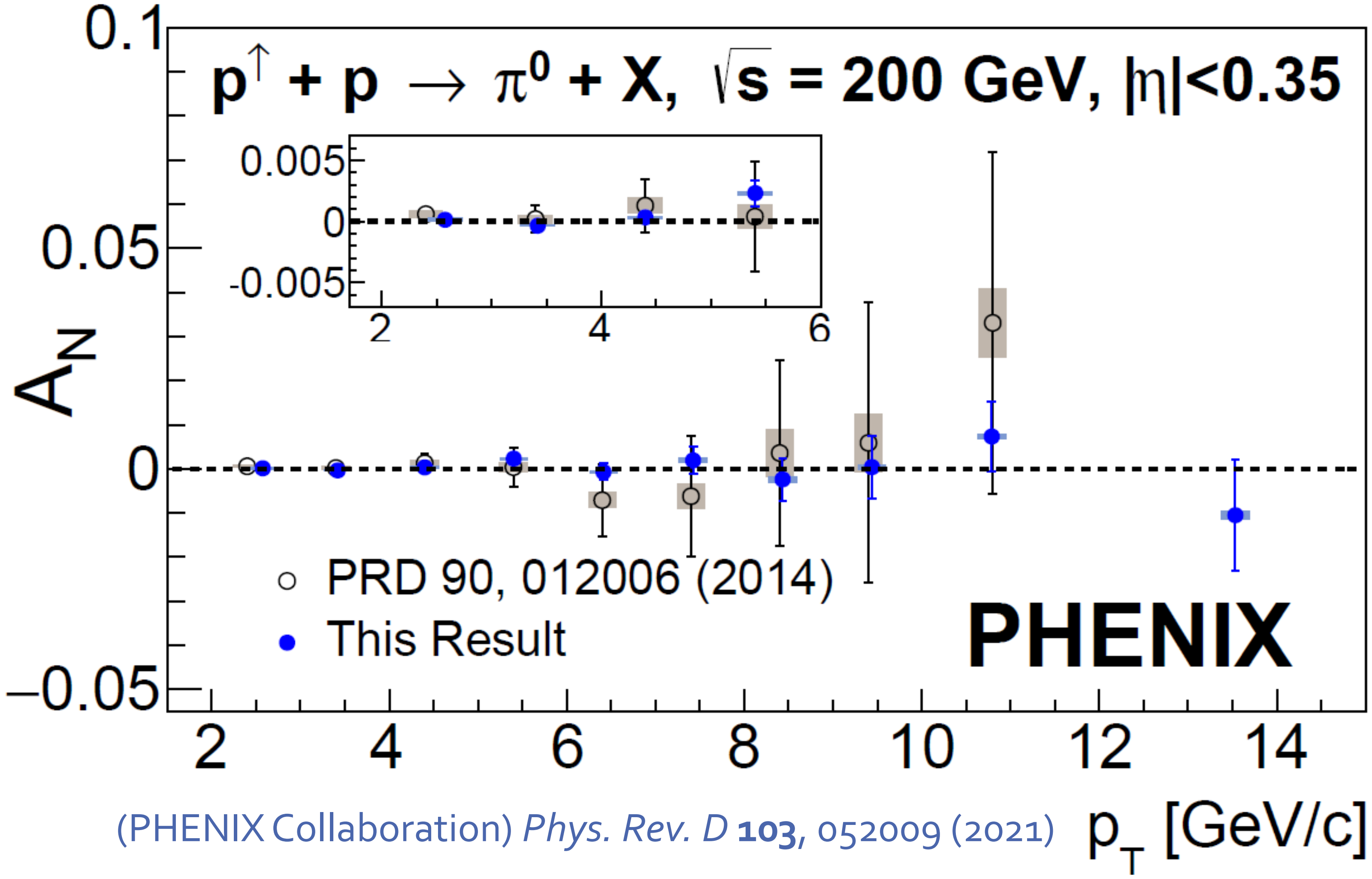
**Mid Rapidity:** Combination of quarks and gluons coming from the polarized proton




(PHENIX Collaboration) *Phys. Rev. D* **83**, 032001 (2011)

# $A_N^{\pi^0}$ at midrapidity

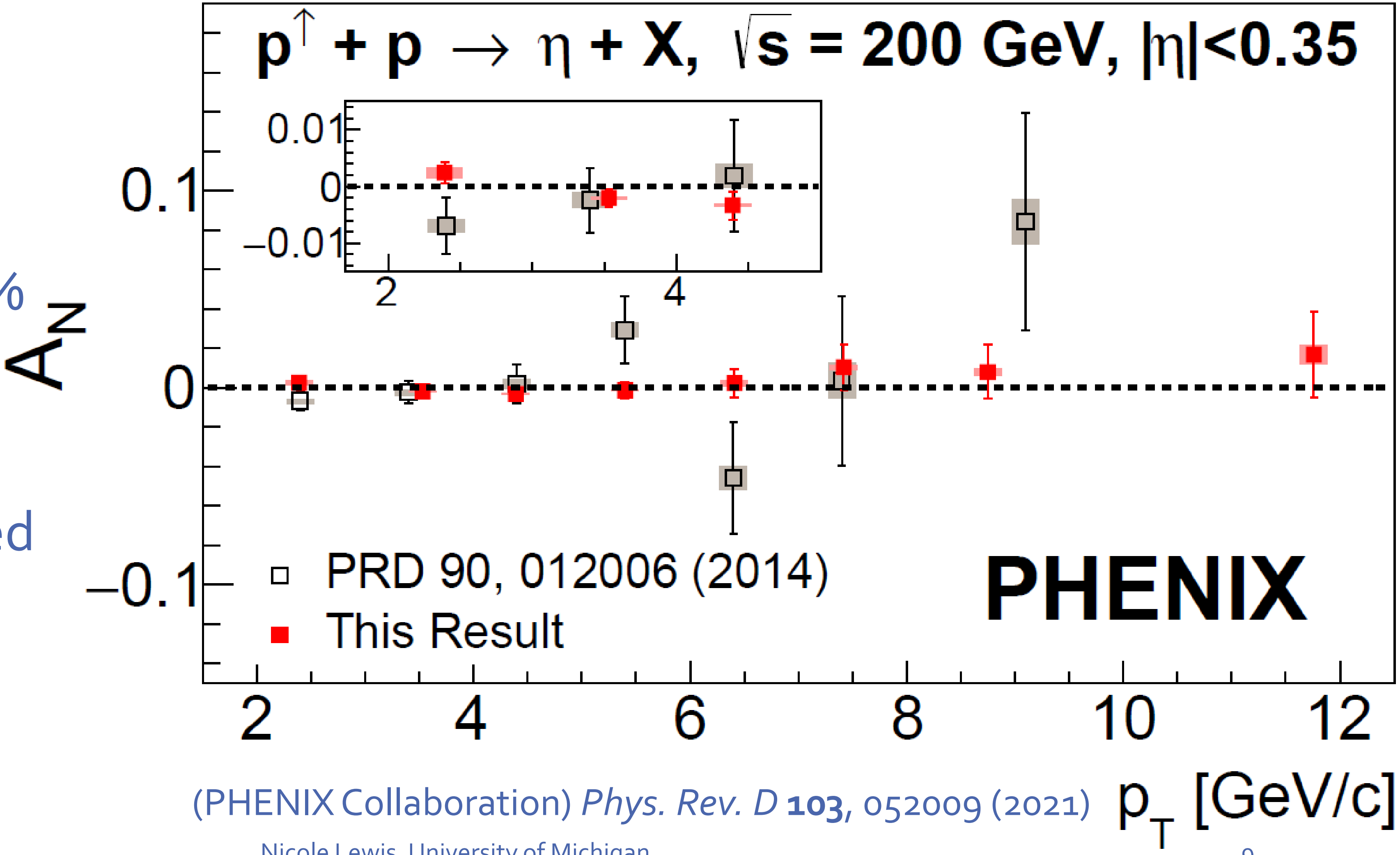



(PHENIX Collaboration) *Phys. Rev. D* **103**, 052009 (2021)

- Consistent with zero to within $10^{-4}$ at low $p_T$
- Final polarized proton data taken by PHENIX
- Factor of 3 increase in precision for statistical uncertainty compared to the previous result and higher reach in $p_T$

# $A_N^\eta$ at midrapidity

- $A_N^\eta$ is sensitive to strangeness in twist-3 functions
- Consistent with zero to within 0.5% at low $p_T$
- Also a factor of 3 increase in precision compared to the previous PHENIX result
- Higher $p_T$ range

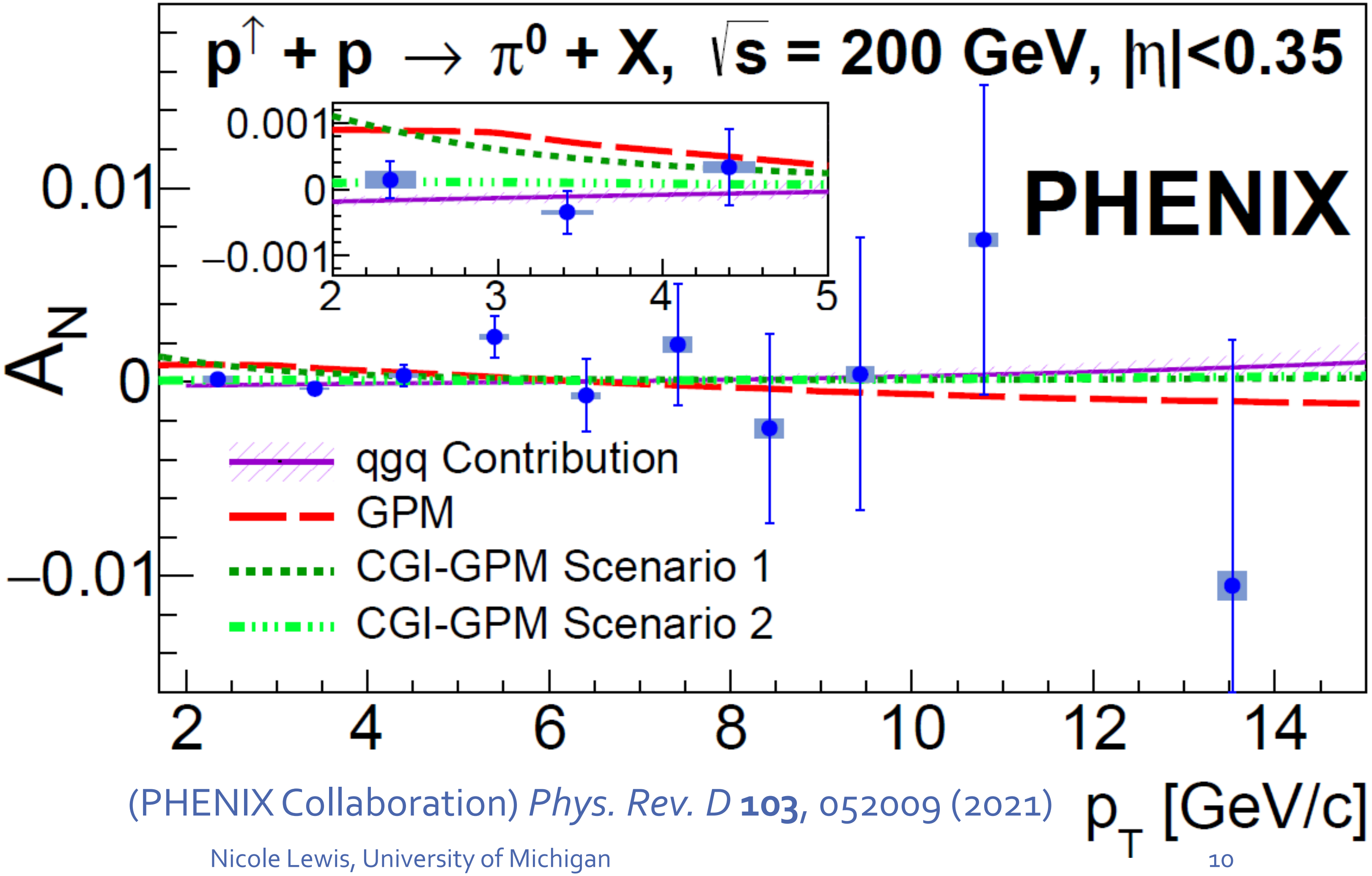



(PHENIX Collaboration) *Phys. Rev. D* **103**, 052009 (2021)

# Theoretical Predictions for Midrapidity $A_N^{\pi^0}$

Midrapidity → sensitive to gluons

- constrain twist-3 trigluon function
  *PRD* **89**, 034029 (2014)
- constrain gluon Sivers function - in the Generalized Parton Model (GPM)
  *PRD* **99**, 036013 (2019)

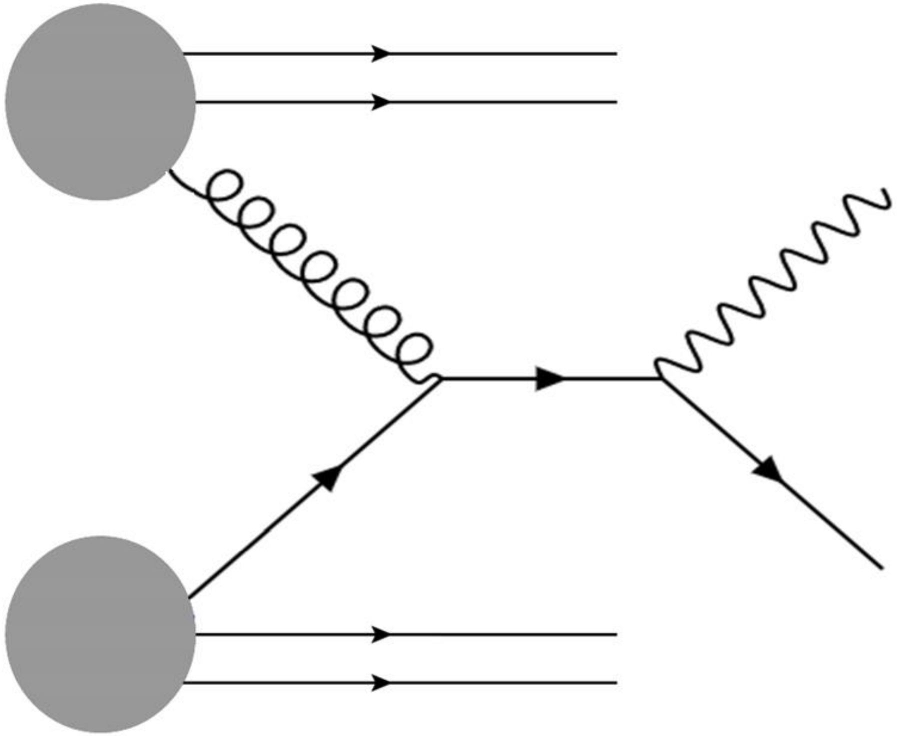


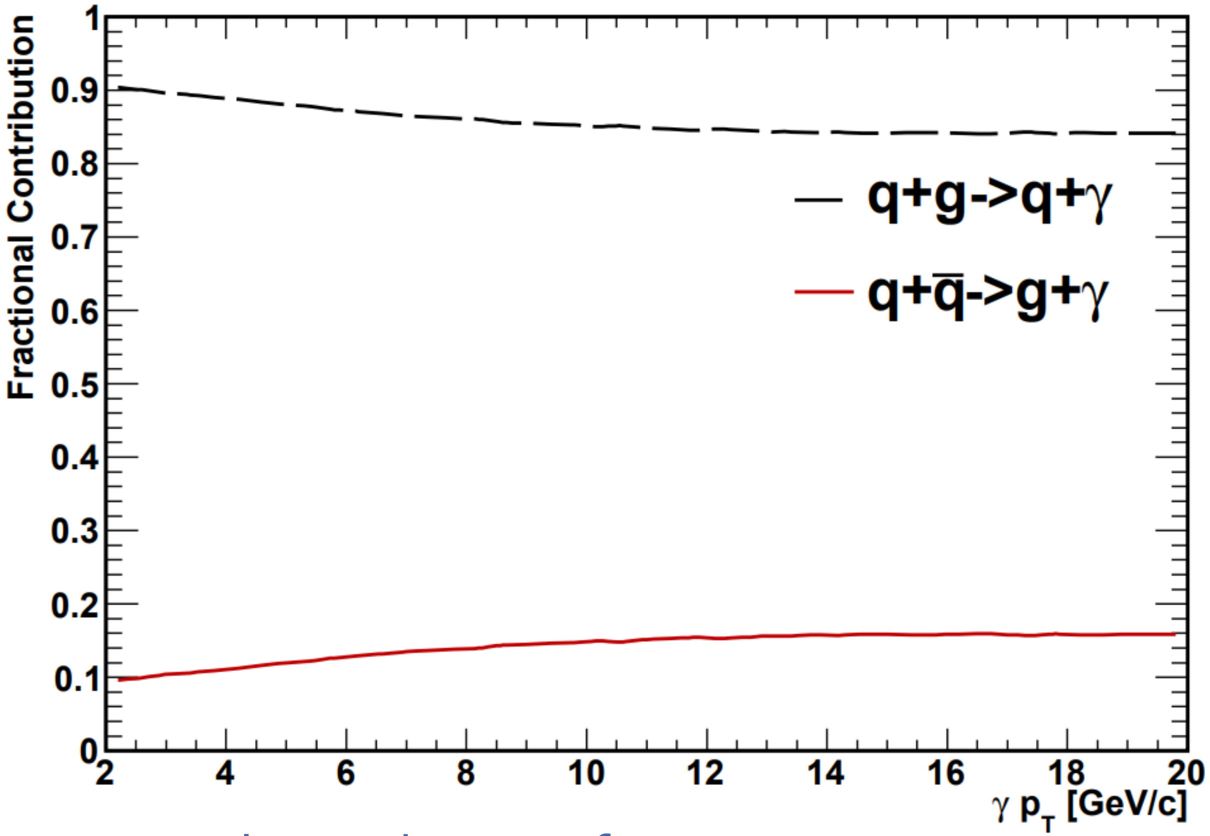

(PHENIX Collaboration) *Phys. Rev. D* **103**, 052009 (2021)

# Direct Photons in $p + p$

Only sensitive to initial state effects, no effects from fragmentation

Strong sensitivity to gluon PDFs






Fractional contribution of parton scattering to inclusive direct photon production at leading order for $p + p$ collisions at $\sqrt{s} = 200\ GeV$ for midrapidity (PHENIX Collaboration), Phys. Rev. D **82,** 072001 (2010)

# Direct Photon Selection

As we have already seen, there are many photons in an event that do not come directly from the collision, e.g. $\pi^0 \rightarrow \gamma\gamma$ branching ratio is ~99%

**Tagging cut -** subtract out photons that are tagged as coming from $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ decays

**Isolation Cut –** used to eliminate decay photons and next-to-leading fragmentation photons

$$E_\gamma * 10\% > E_{cone}$$

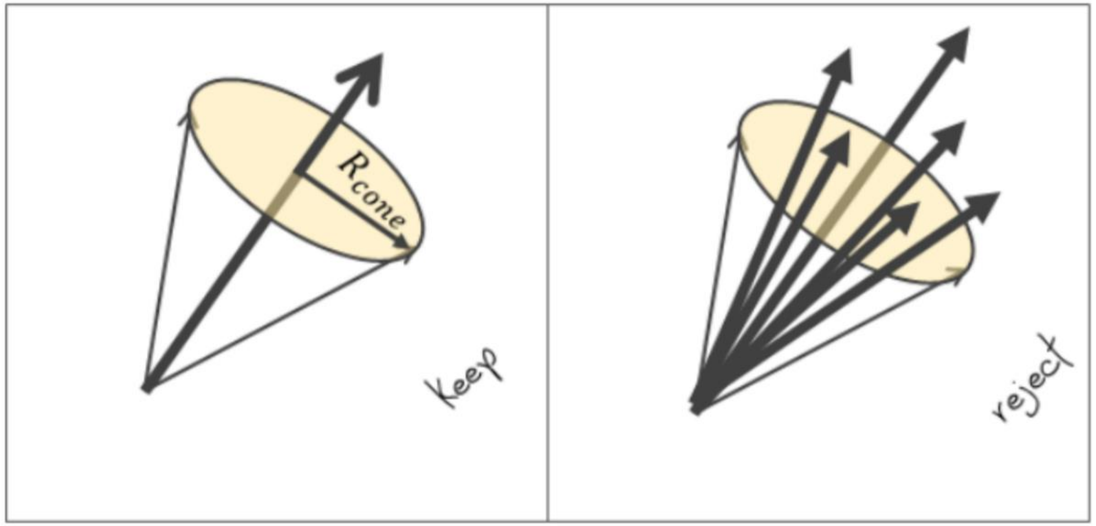
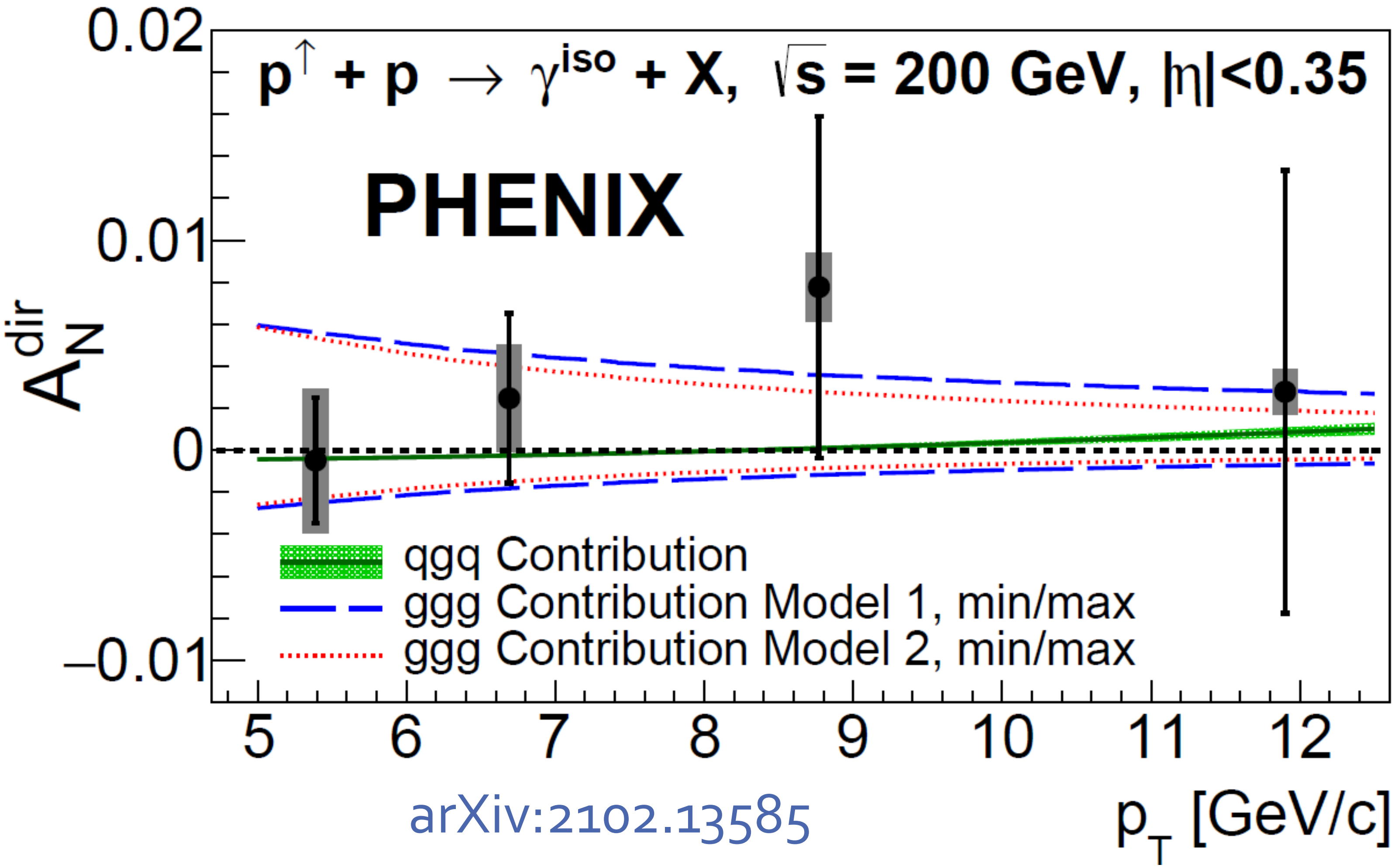



Figure from Joe Osborn's Thesis Defense

# Direct photon result




arXiv:2102.13585

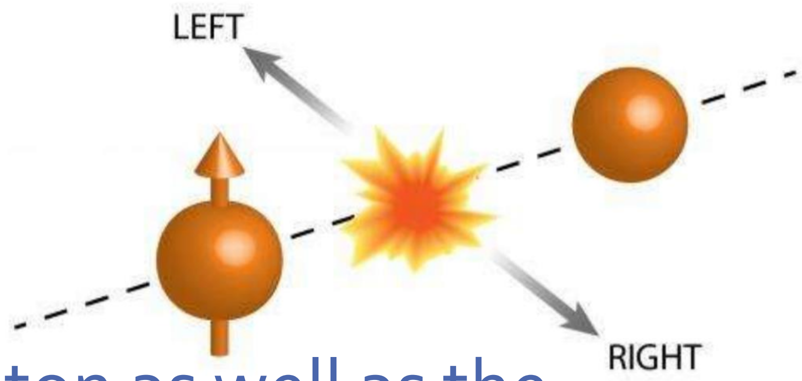
Measured for the first time at RHIC → Consistent with zero to within ~2%

This result will help constrain the trigluon function

*qgq* contribution – PRD 91, 014013 (2015)

*ggg* contribution – PRD 85, 034030 (2012)

# Conclusion




- TSSAs probe the parton dynamics in the proton as well as the process of hadronization
  - Twist-3 only require a single hard energy scale to be measured directly
- $\pi^0$ and $\eta$ $A_N$ at midrapidity $\sqrt{s} = 200$ GeV shown
  - Consistent with zero, factor of 3 higher precision than the previous PHENIX results
  - Sensitive to initial- and final-state effects for both gluons and quarks.
  - $A_N^\eta$ sensitive to strangeness in twist-3 functions
- Direct Photon $A_N$ measured for the first time at RHIC
  - Also consistent with zero
  - Sensitive to gluon initial state effects

# Back Up

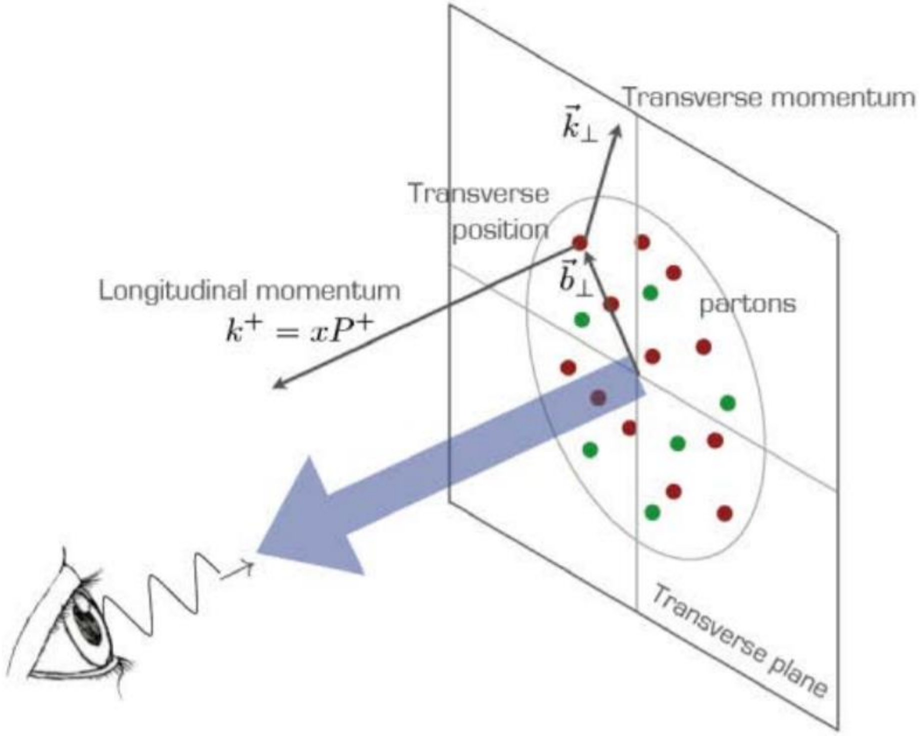
# Transverse Momentum Dependent Nonperturbative Functions

**Collinear:** Integrate over the internal dynamics of the proton or hadronization

**Transverse Momentum Dependent (TMD):** functions explicitly depend on the nonperturbative transverse momentum $k_T$

- In order for TMD factorization to apply $k_T^2 \ll Q^2$.
- 2-scale process: for the TMD regime to be applied a measurement needs sensitivity to both $k_T$ and $Q$

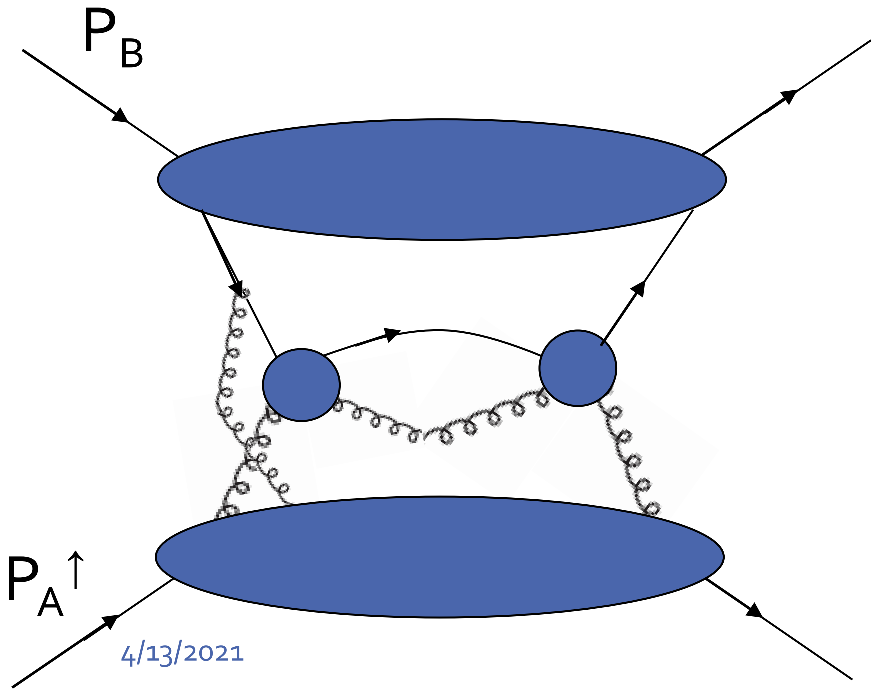
from Alessandro Bacchetta



# Higher Twist Functions

Formal definition of twist: “mass dimension minus spin” of the operator in a matrix element within the Operator Product Expansion

**Twist 2:** traditional PDFs and FFs only consider interactions of one parton in the proton and one parton that is hadronizing at a time




**Twist 3:** Quantum mechanical interference between scattering off of one parton versus scattering off of two partons at the same $x$

Can be used to describe spin-momentum correlations in the proton and in hadronization

# Connecting TMD to Collinear Twist-3 Functions

Twist-3 collinear functions are related to $k_T$ moments of twist-2 TMD PDFs and fragmentation functions D. Boer, P. J. Mulders, and F. Pijlman, *Nucl. Phys. B* **667**, 201 (2003)

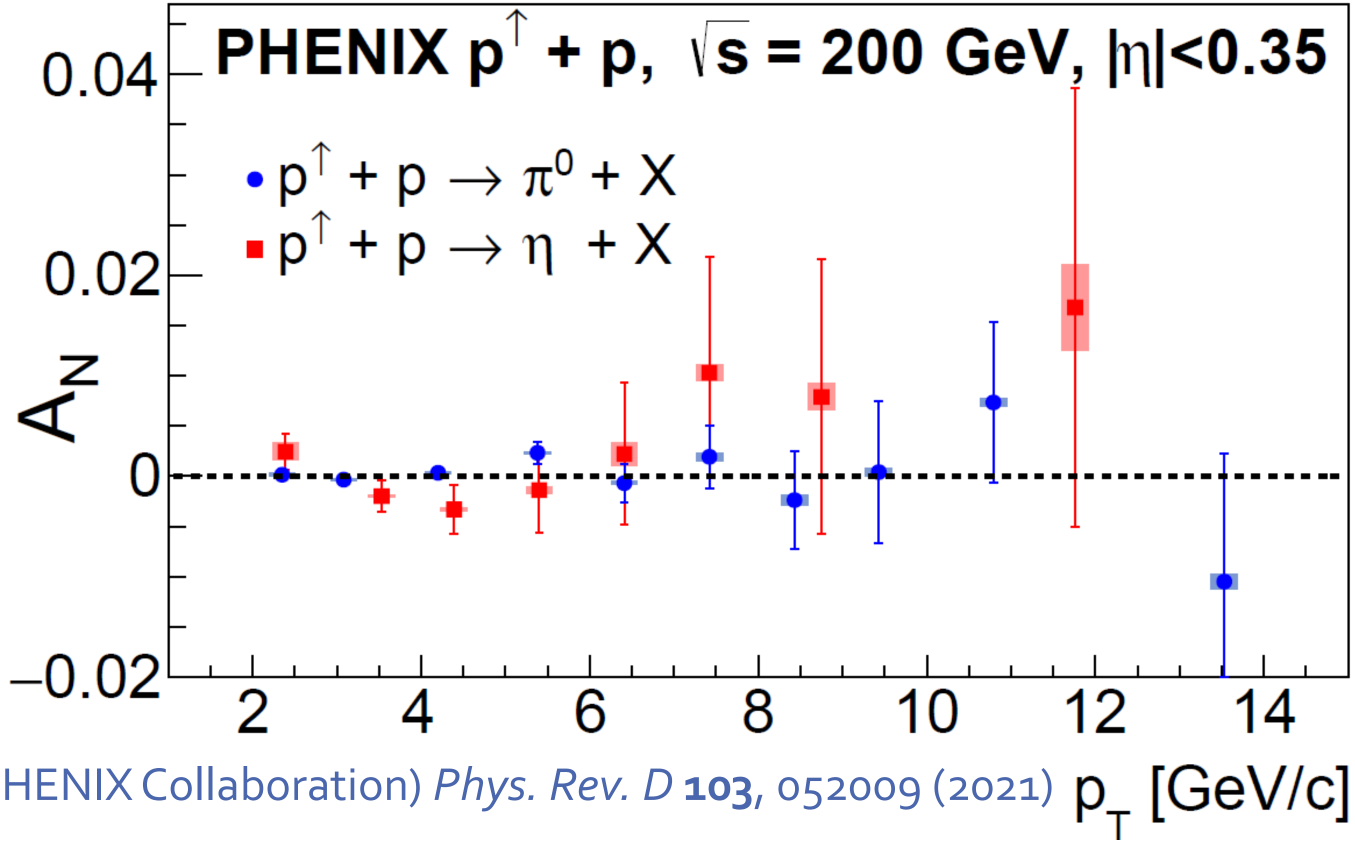
For example, the quark Sivers function can be related to the Qiu-Sterman – twist-3 qgq correlator for partons coming from the polarized proton

$$-\int d^2k_T \, \frac{|k_T|^2}{M} f_{1T}^{\perp q}(x, k_T^2)\Big|_{SIDIS} = G_F(x, x)$$

But TMD factorization is only valid for $k_T^2 \ll Q^2$ and this expression integrates over all $k_T$

Also equating truncated terms of two *different* types of perturbative expansion

# Comparing $\pi^0$ to $\eta$ results




(PHENIX Collaboration) *Phys. Rev. D* **103**, 052009 (2021)

Differences in $\pi^0$ and $\eta$ $A_N$ could be due to the effects of isospin or strangeness in hadronization:

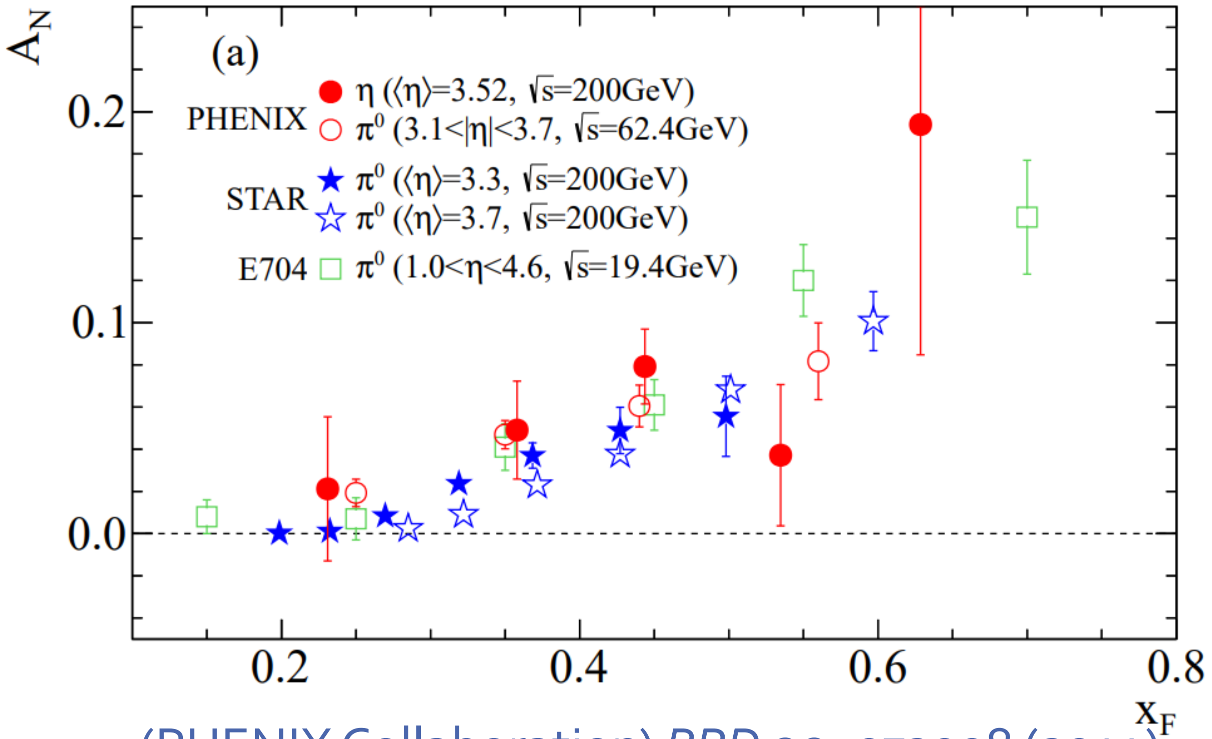
$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$\eta \approx \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

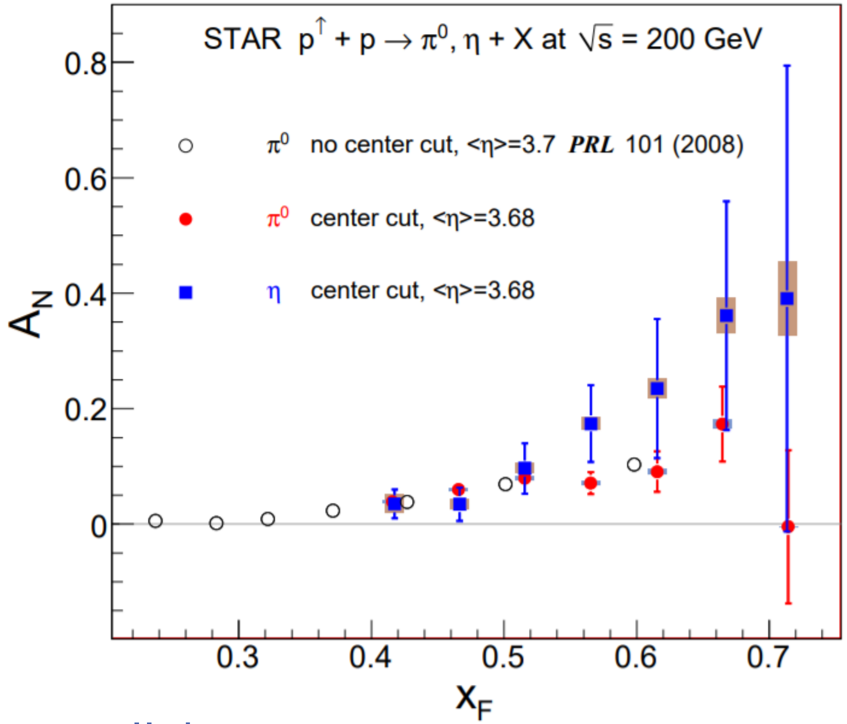
Or even because of the effects of hadron mass in hadronization:

$m_{\pi^0} \approx 135$ MeV/c² $\qquad m_\eta \approx 548$ MeV/c²

# Comparing $A_N^{\eta}$ to $A_N^{\pi^0}$ at forward rapidity




(PHENIX Collaboration) *PRD* **90,** 072008 (2014)




(STAR Collaboration) *PRD* **86**, 051101(R) (2012)

Forward rapidity → Large contribution of quarks coming from the polarized proton

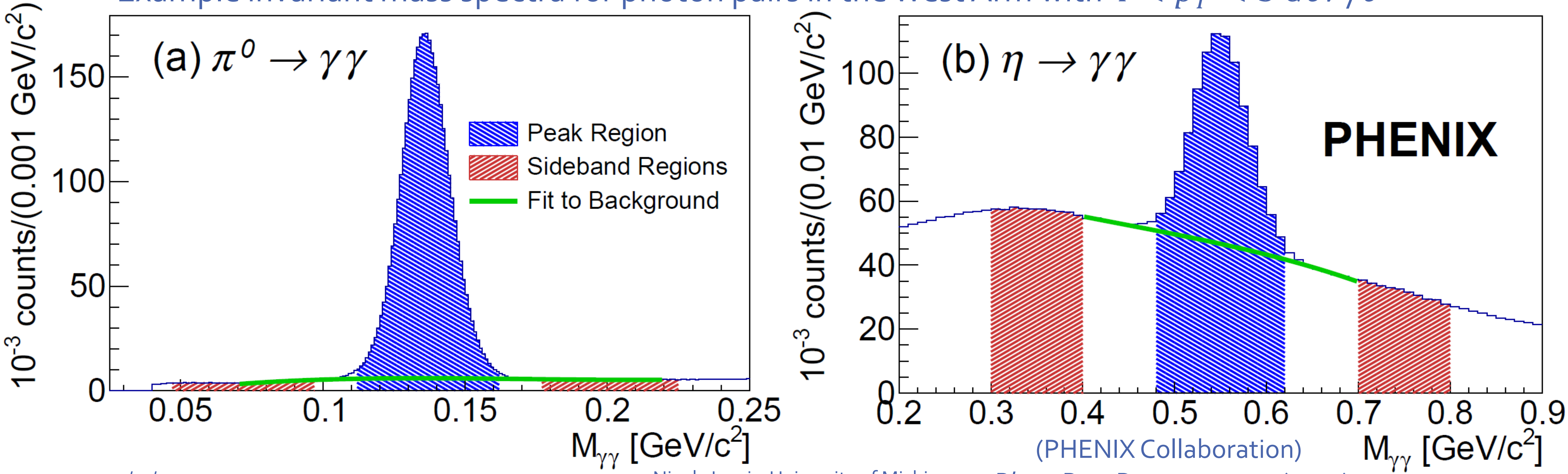
Results hint that $A_N^{\eta}$ is larger than $A_N^{\pi^0}$ at forward rapidity. Further studies required.

# Asymmetry Background Subtraction

$$A_N = \frac{A_N^{peak} - r\, A_N^{bg}}{1 - r}$$

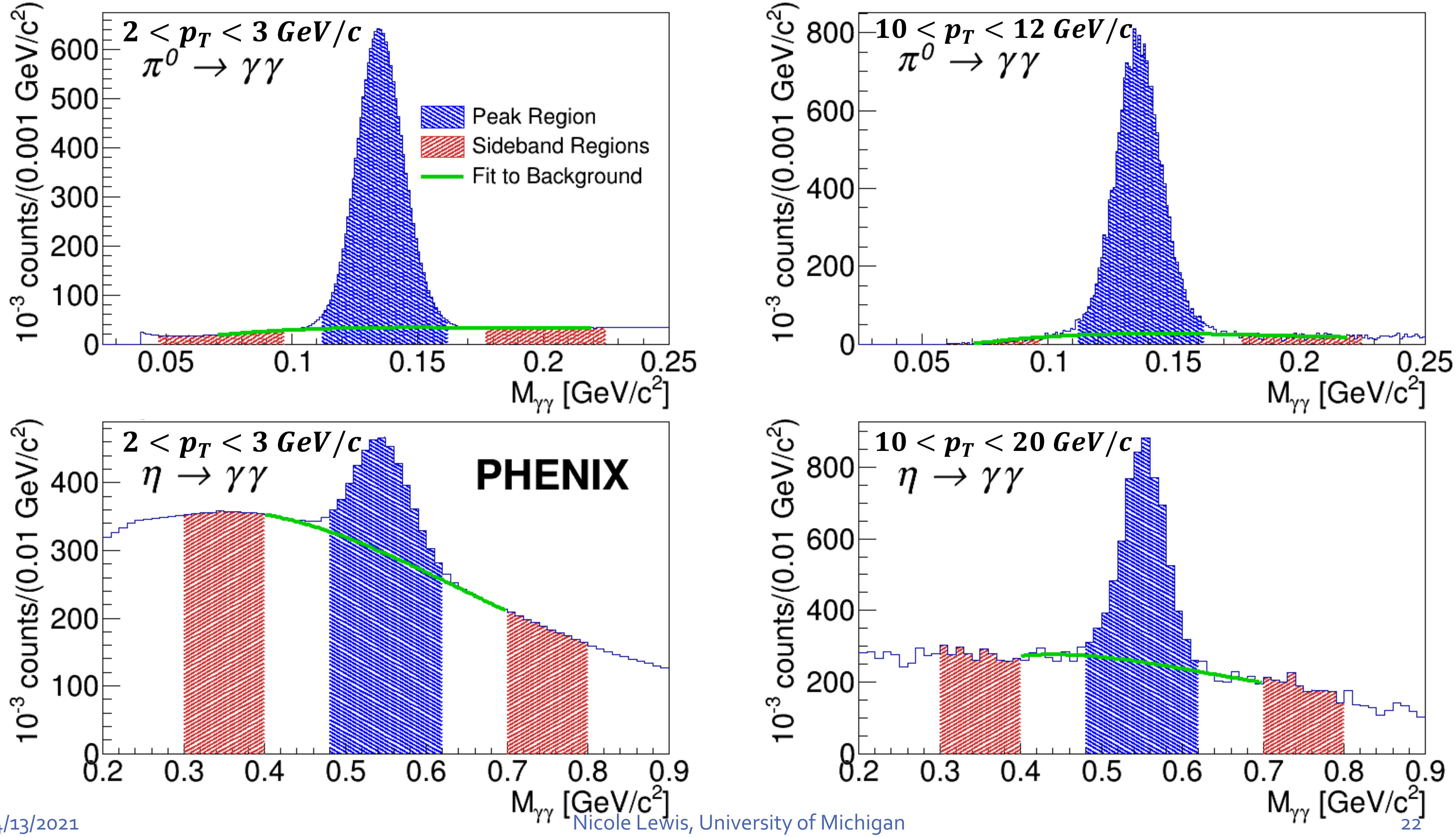
Where $r = \frac{N_{bg}}{N_{sig}+N_{bg}}$ measured from a fit in the invariant mass peak region

Example invariant mass spectra for photon pairs in the West Arm with $4 < p_T < 5\ GeV/c$




(PHENIX Collaboration) *Phys. Rev. D* **103**, 052009 (2021)

# Invariant Mass Spectrum at Different $p_T$ in the West Arm



# Direct Photon Background

Sometimes only one of the photons from a $h \to \gamma\gamma$ decay is measured and the second photon is missed

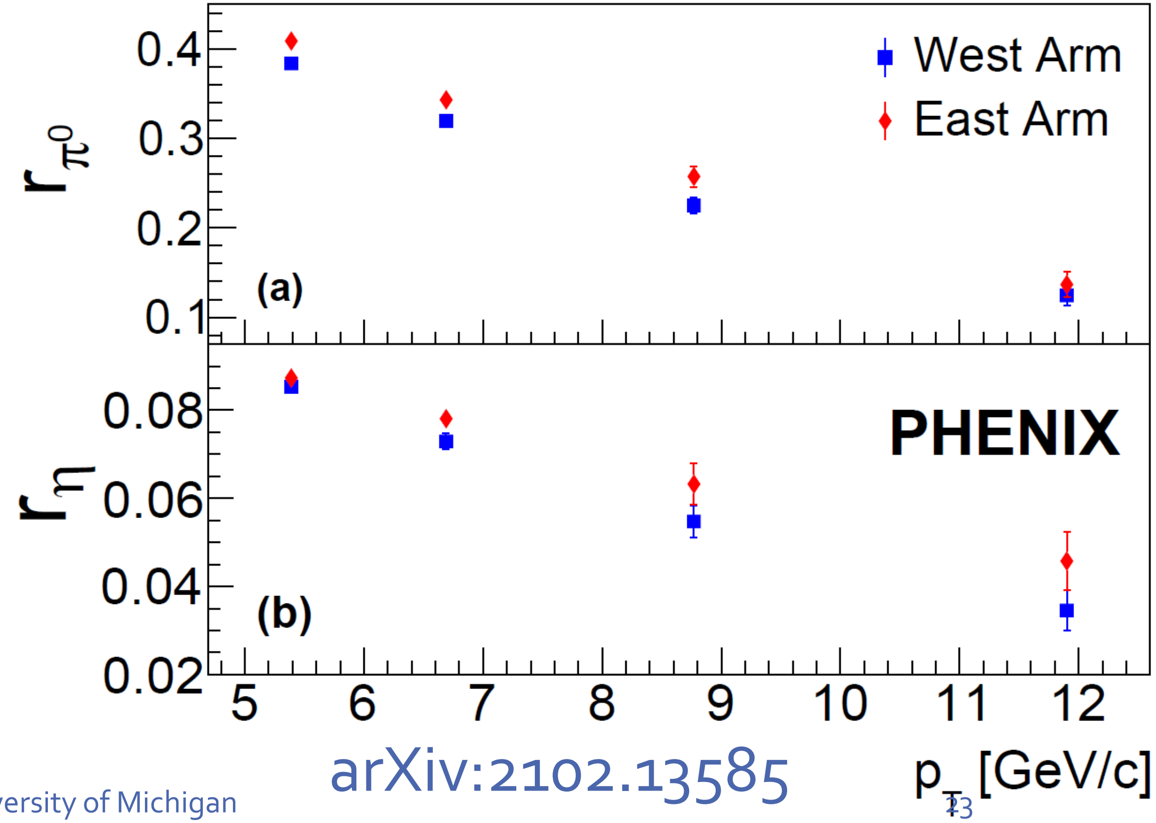
- $\eta$ decays tend to be more asymmetric because they are ~4 times heavier than $\pi^0$s

Estimate number missed using ones that were tagged

**From Data:** Ratio of number isolated decay photons to direct photon sample

$$r_{miss} = \frac{N_{bg}}{N_{sig} + N_{bg}} = R\,\frac{N_{tag}^{iso,h}}{N^{iso}}$$

**From Simulation:** Converts between tagged decay photons to missed decay photons




arXiv:2102.13585

# Direct Photon Background - $\pi^0$ Merging

Photon merging - sometimes the two photons from a $\pi^0 \rightarrow \gamma\gamma$ decay are so close together that the EMCal cannot resolve them as separate photons

Similar to the background fraction due to missing the one of the decay photons

Found to be negligible after a cluster shower shape cut

**From Data:** Ratio of number isolated decay photons to direct photon sample

$$r_{merge} = \frac{N_{bg}}{N_{sig} + N_{bg}} = \frac{N_{merge}}{N_{tag}} \frac{N_{tag}^{iso,h}}{N^{iso}}$$

**From Simulation:** Converts between tagged decay photons to merged $\pi^0$ photons