Physics of STAR Forward π° Transverse Single Spin Asymmetries (AN) with pA and pp Beams.

BNL 5/4/2021 Steve Heppelmann (Penn State)

This experiment and Polarized RHIC began 30 years ago, in 1990.

RHIC spin started at Penn State University in 1990

My personal goal was single spin asymmetries in pA

("We") did not push **pA** as a major justification for polarized RHIC because

- The physics was controversial. Many avoided thinking about **Transverse Single Spin Asymmetries.**
- it was not clear RHIC could do polarized **pA**!!
- In 2013, a small group began planning for a 2015 polarized **pA** run.

TOPICS

Plenary Talks on:
- Technical Accelerator Issues
- Spin Physics Background

Workshop Sessions on Polarization Effects in:
- Strong Interactions—Jets, Direct Photons, Parton Distributions, Heavy Quark Production
- Electroweak Interactions—W and Z Production, Parity Violation Effects, Drell-Yan, Beyond Standard Model
- Polarized P-Nucleus Collisions

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Polarized Collider Workshop

The Pennsylvania State University — November 15-17, 1990

Run 15 (2015)

With recent advances in the technology of polarized proton acceleration, the polarization option for future hadron colliders (RHIC, SSC, LHC) is within reach. The purpose of this workshop is to review these technical issues and study the theoretical value of polarized collider experiments in the near term at the RHIC collider and later at SSC or LHC.

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Comparison of transverse single-spin asymmetries for forward π^0 production in polarized pp, $p\,\mathrm{Al}$ and $p\,\mathrm{Au}$ collisions at nucleon pair c.m. energy $\sqrt{s_{NN}} = 200$ GeV

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. D **103**, 072005 – Published 16 April 2021

- The **Forward Transverse Single Spin Asymmetries arise, not because of the spin dependence of parton-parton scattering**, but because of aspects of the QCD environment in which hard scattering partons interact.

- **For non-zero A_N**, initial or final state interactions **partons must acquire a non-zero internal transverse momentum (k_T)** from initial, final state or higher twist (spectator parton) interactions. Above that **(k_T) scale, A_N should fall with hard scattering p_T.**

- The dependence of A_N on forward kinematics for the produced π° is measured for $p+p \rightarrow \pi^\circ + X$. **From these new data: The asymmetry increases with transverse momentum up to a surprising p_T scale around 5 GeV/c.**

- A mysterious observation: **A_N is much larger for isolated π° events** than for more "jet-like" events.

- The role of a spectator nucleus, containing the unpolarized proton, could arise from several exotic mechanisms. Among possible mechanisms, is a modification of the soft gluon distribution, as might be associated with "Color Glass Condensate". **PHENIX recently published a measurement** for charged hadron production in nuclei that may be **consistent with predicted large suppression of A_N** from gluon saturation effects. **The STAR measurement, with neutral pions, observes a much smaller nuclear suppression of A_N than the PHENIX result.**

Kinematics of forward pion production via q-g scattering.

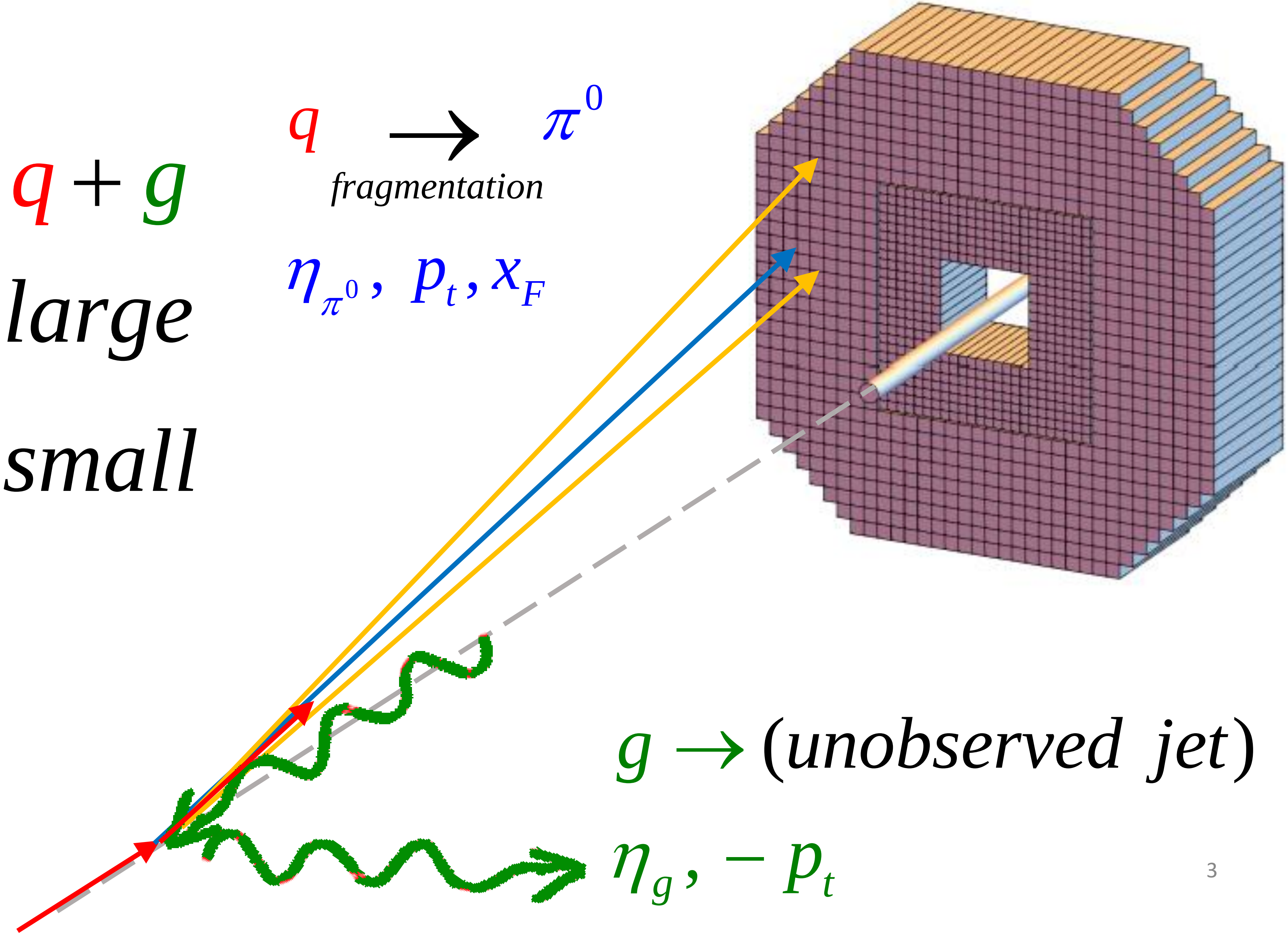
$$q + g \rightarrow q + g$$

$$x_{quark} \rightarrow large$$

$$x_{gluon} \rightarrow small$$

$$q \xrightarrow[fragmentation]{} \pi^0$$

$$\eta_{\pi^0},\ p_t,\ x_F$$

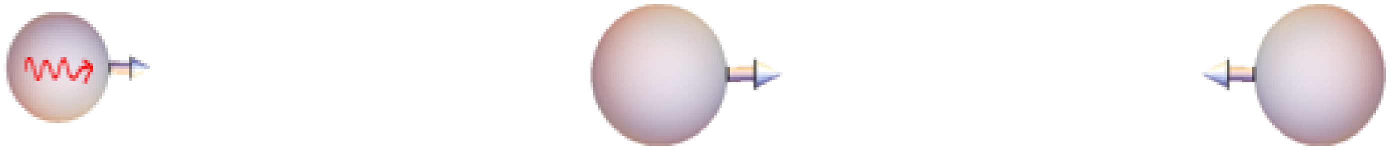


$$g \rightarrow (unobserved\ jet)$$

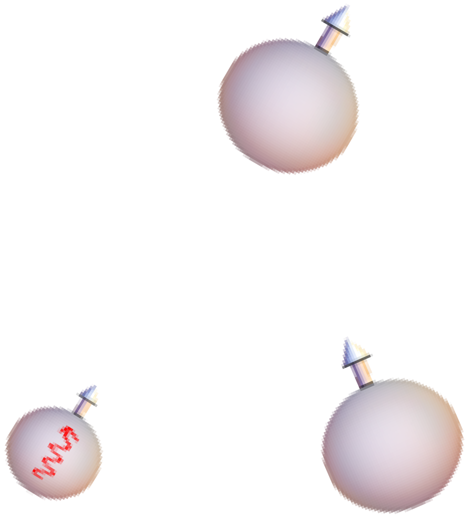
$$\eta_g,\ -p_t$$

How Helicity Conservation Explains Spin Dependent Cross Sections (animation)

In the quark rest frame, **a polarized quark** absorbs a **helicity polarized photon (gluon)** flipping the quark spin.
Only 1 quark spin state can absorb or emit polarized gauge boson.



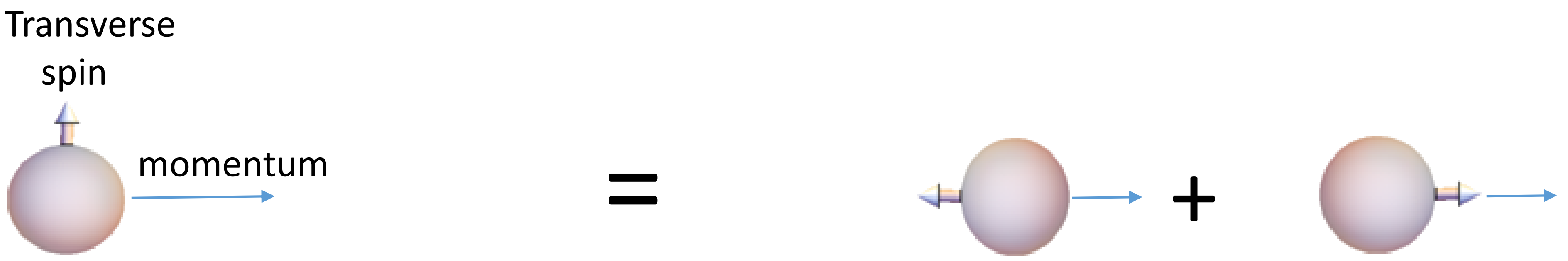
Same process, different frame.
Helicity polarized quark
absorbs helicity polarized photon (gluon).
Intermediate state quark at rest!!



A helicity polarized quark
absorbs only one of two helicity polarized photon or gluon state.
In a frame where quark is always relativistic!!
Conservation of helicity in photon or gluon quark interaction **explains A_{LL}.**

Helicity conservation of quark is always applicable, but for frames involving quarks that come to rest during the interaction (like fixed target collisions).
The consequences of helicity conservation are surprising!!

A quark transverse spin state is superposition of helicity states.



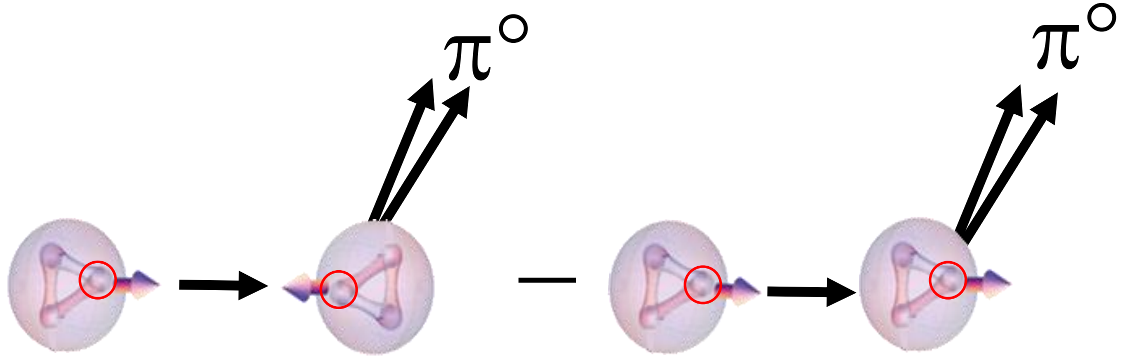
While scattering of a longitudinally polarized quark cross sections can prefer a particular spin state (A_{LL}) ....

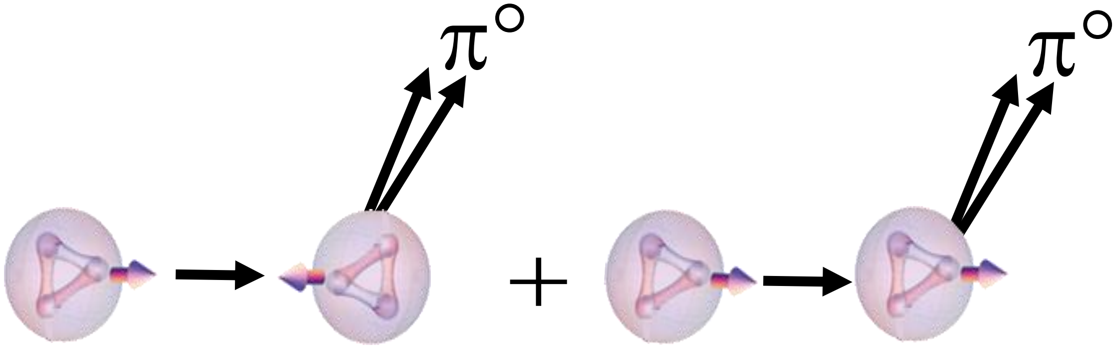
the transverse spin state of the quark is the superposition of the two helicity states (equal magnitude). This means that while helicity conservation explains A_{LL}, it forbids A_N in the parton-parton scattering process.

A_N comes from initial state and final state interactions.

Conventional PQCD models for **longitudinal spin asymmetry**, A_{LL}, in pp scattering derives from calculable longitudinal spin dependence of constituent partons. Helicity conservation of high-energy partons implies parton level longitudinal asymmetries.

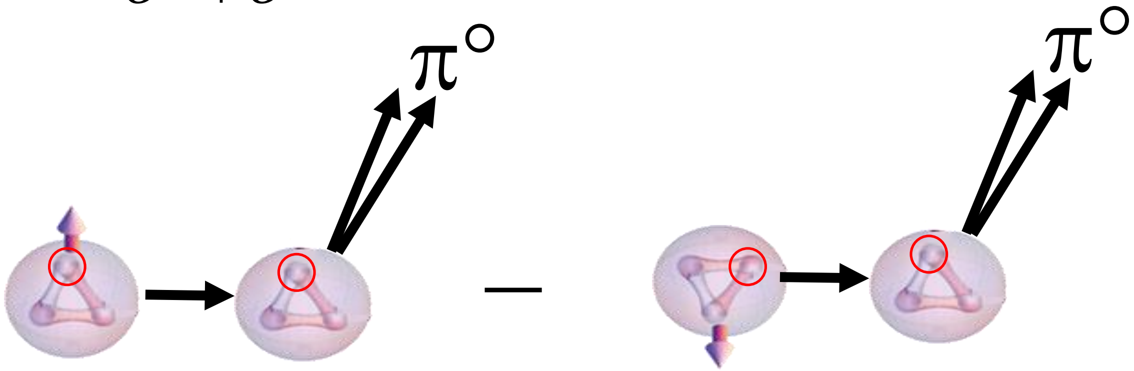
$$A_{LL} \equiv \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} =$$

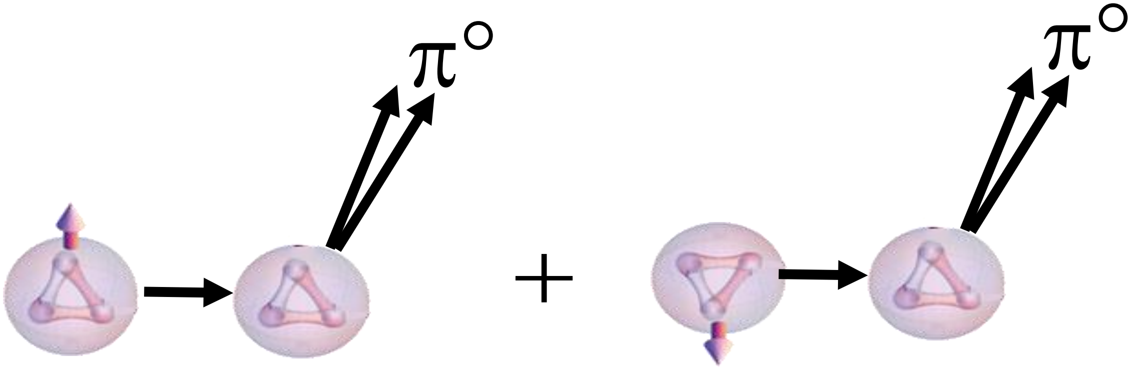




With conventional PQCD models for **transverse spin asymmetry**, A_N, in pp scattering can be expressed in a longitudinal bases. Helicity conservation of high-energy partons, an essential aspect of PQCD, implies vanishing parton level transverse asymmetries.

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





A_N can not come from the parton cross section itself.

But if pion transverse momentum p_T^π contains a component $\pm k_T$ (which is correlated with spin ↑ or ↓), from initial or final state interactions (or fragmentation), transverse asymmetry A_N is possible.

$$p_T^\pi = |\vec{p}_T + \vec{k}_T|$$

If the unpolarized parton cross section falls with parton transverse momentum with a power law dependence.

$$\frac{d\sigma}{dp_T} \propto p_T^{-N}$$

$$A_N(x_F, p_T) = \frac{\sigma^\uparrow(x_F, p_T, 0) - \sigma^\uparrow(x_F, p_T, \pi)}{\sigma^\uparrow(x_F, p_T, 0) + \sigma^\uparrow(x_F, p_T, \pi)}$$

$$\simeq \frac{(p_T^\pi - k_T)^{-N} - (p_T^\pi + k_T)^{-N}}{(p_T^\pi - k_T)^{-N} + (p_T^\pi + k_T)^{-N}}$$

$$\simeq N \frac{k_T}{p_T^\pi}$$

- Initial state and final state parton interactions can generate such $\pm k_T$
- Changes in the shape (power N) of the parton hard cross section can alter the asymmetry. (ie. gluon saturation effects).

A_N should fall with p_T above some nominal p_T scale.

Why might A_N be different in pp vs pAu?

- The fundamental parton process has A_N nearly equal to zero.
  For $q+g \to q+g$ A_N is nearly equal to zero.

- Non-zero A_N must involve initial and final state interaction.
  This implies a possible dependence on nuclear environment pp, pAl, pAu.

- The models for A_N require initial or final state to **add transverse momentum k_T to the larger p_T.** The observable A_N are amplified by the **steepness of the p_T dependence** of the parton-parton cross section.

- For forward scattering, where scattering involves a low x gluon, **saturation effects** may change the shape of the p_T dependence of the cross section.

- This means that a saturation model, like **Color Glass Condensate**, may imply less severe cross sections and thus smaller A_N. This has become an important question.

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Single-spin production asymmetries from the hard scattering of pointlike constituents

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(Received 28 April 1989)

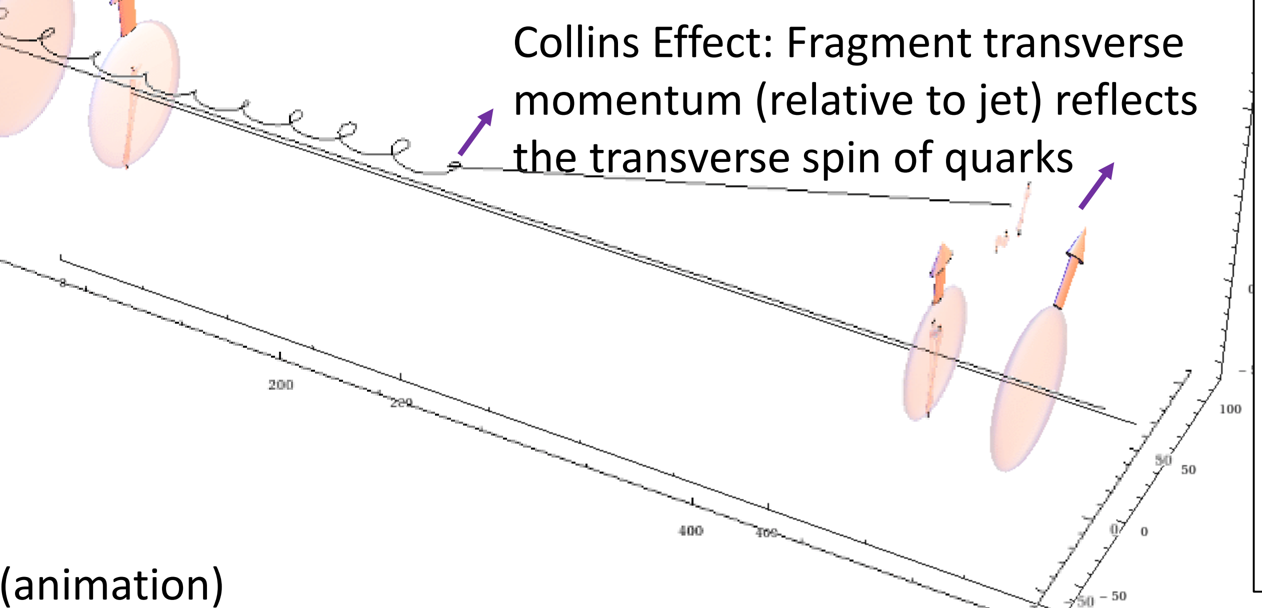
When one takes into account the transverse momenta of the constituents in a polarized proton, there exists a kinematic, "trigger-bias," effect in the formulation of the QCD-based hard-scattering model which can lead to single-spin production asymmetries. It seems convenient to represent the coherent spin-orbit forces in a polarized proton by defining an asymmetry in the transverse-momentum distribution of the fundamental constituents. It may then be possible to organize the hard-scattering model so that the kinematic consideration of hard 2→2 scattering provide the leading contribution at large transverse momentum to asymmetries of the type $A_N d\sigma(hp_\uparrow \to \text{jet}+x)$, $A_N d\sigma(hp_\uparrow \to$ "π"$x)$, where $p_\uparrow$ denotes a transversely polarized proton and "π" represents any spinless meson composed of light quarks. This approach provides testable relationships between different asymmetries.

Sivers Effect

Generate k_T

Sivers Effect: Initial state parton has transverse momentum. Experiments may select "trigger bias" events with a bias in the transverse momentum.

Collins Effect: Fragment transverse momentum (relative to jet) reflects the transverse spin of quarks



(animation)

NUCLEAR PHYSICS B

Nuclear Physics B 420 (1994) 565–582

Measuring transversity densities in singly polarized hadron–hadron and lepton–hadron collisions

John C. Collins [a], Steve F. Heppelmann [a], Glenn A. Ladinsky [b]
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Received 21 April 1993; revised manuscript received [illegible] January 1994; accepted 26 January 1994

Collins Effect

Abstract

We show how the transverse polarization of a quark initiating a jet can be probed by the azimuthal distribution of two hadrons (of large z) in the jet. This permits a twist-2 asymmetry in hard processes when only one of the initial particles is polarized transversely. Applications to hadron–hadron and lepton–hadron scattering are discussed.

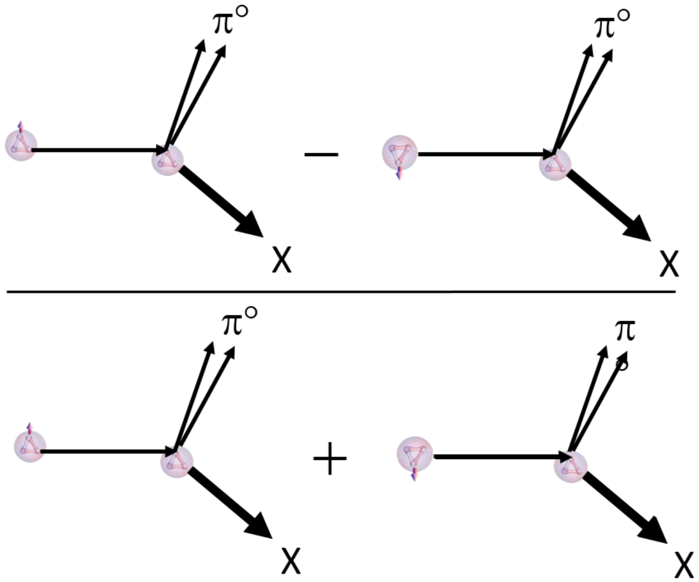
In recent years, there have been many **calculations** based on **Collins, Sivers or twist-3 collinear** methods, with a goal to reproduce the basic nature of A_N dependence on kinematics {Kouvaris et al(2006), Anselmino et al (2013, Kanazawa et all 2014, Anselmino et al 2015, Gamberg et al 2018}.

- There has been success at describing the dependence of A_N on x_F but less success on p_T dependence.
- These new STAR data shows an increasing A_N with p_T up to $x_F < 0.5$ and $2 < p_T < 5$ GeV/c.
- The Kanazawa calculation, based on twist-3 collinear methods, finds a parameterization, consistent with DIS measurements, that does resulted in a nearly flat, or only a very slowly falling p_T dependence above about 3 GeV/c.

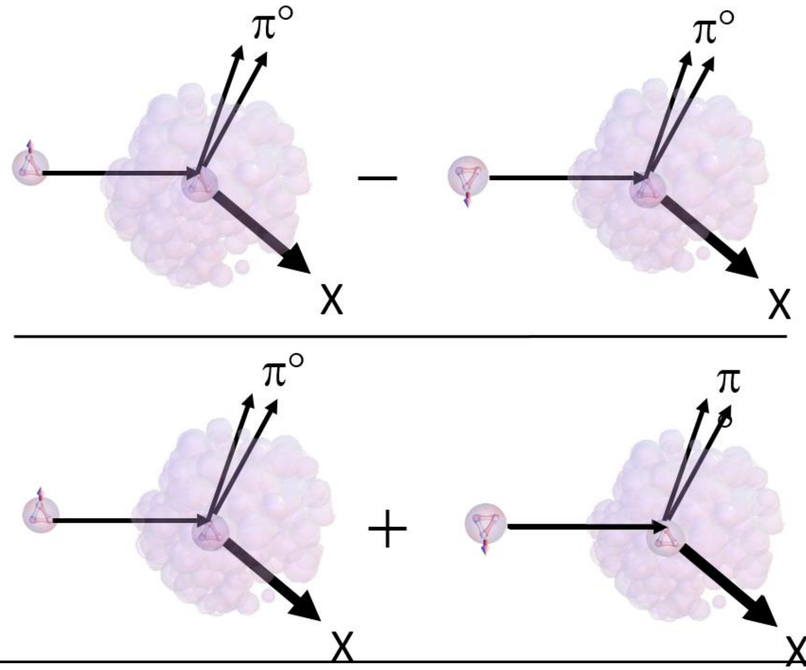
The required large value of internal k_T implied by these data is counter-intuitive.

Transverse Asymmetries (A_N) are insensitive to spin dependence of parton-parton cross sections.
They are sensitive to the "**environment**", including initial or final state interactions of hard scattering partons.

$$A_N(pp) \equiv \frac{\sigma_{pp}^{\uparrow} - \sigma_{pp}^{\downarrow}}{\sigma_{pp}^{\uparrow} + \sigma_{pp}^{\downarrow}} =$$



$$A_N(pA) \equiv \frac{\sigma_{pA}^{\uparrow} - \sigma_{pA}^{\downarrow}}{\sigma_{pA}^{\uparrow} + \sigma_{pA}^{\downarrow}} =$$



Event Selection for π^0 events:

1. **<u>Analyze FMS for all photon</u>** candidates.
   Here a photon (γ) is an EM shower that has been fit successfully to photon hypothesis

2. Two photon events include two **photon candidate** (**γ's)**,

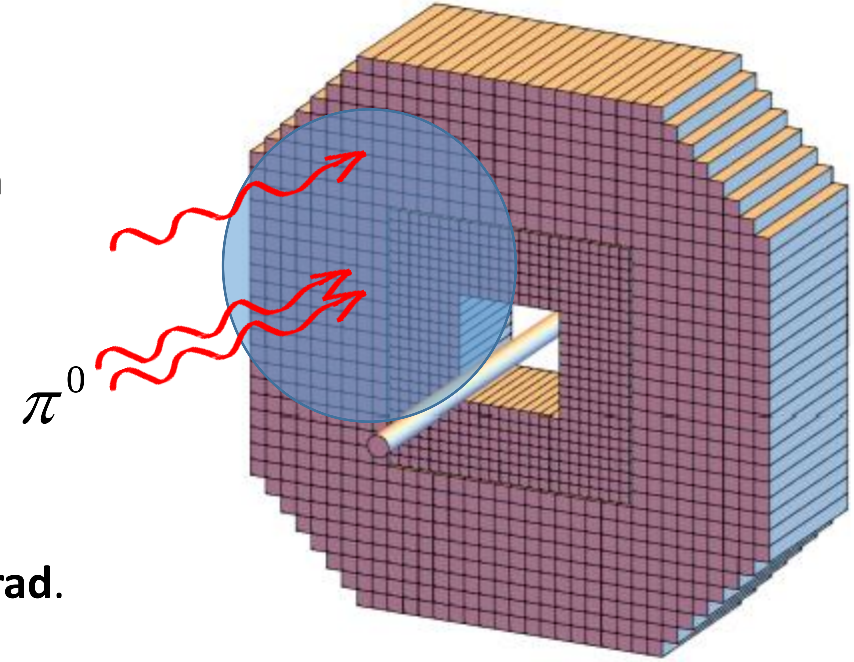
   a. Select photon candidates with a minimum energy of 1 GeV

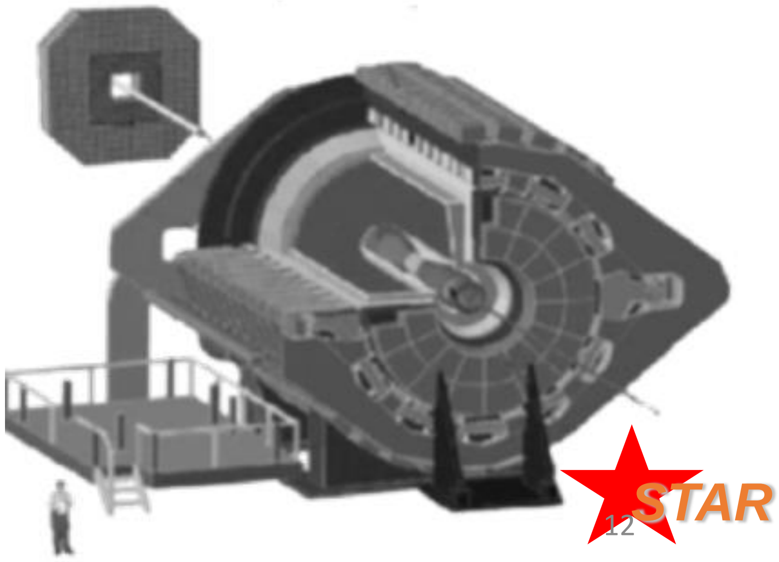
   b. At least two photons (γ) are found within a fixed cone size **Δθ =0.08 rad**. There may also be additional FMS **γ's** outside isolation cone.

   c. Separate events into two categories
      i) Isolated: Exactly 2 photons in cone.
      ii) Non-Isolated: More than 2 photons in cone. (jet-like)

   d. Select pion candidates that have leading (largest pt) pair of photons in cluster.

   e. Pair hit energy distribution is fit to 2 positions and 2 energies. At higher energy the separation approaches the cell dimension and mass fits broadens to larger mass.



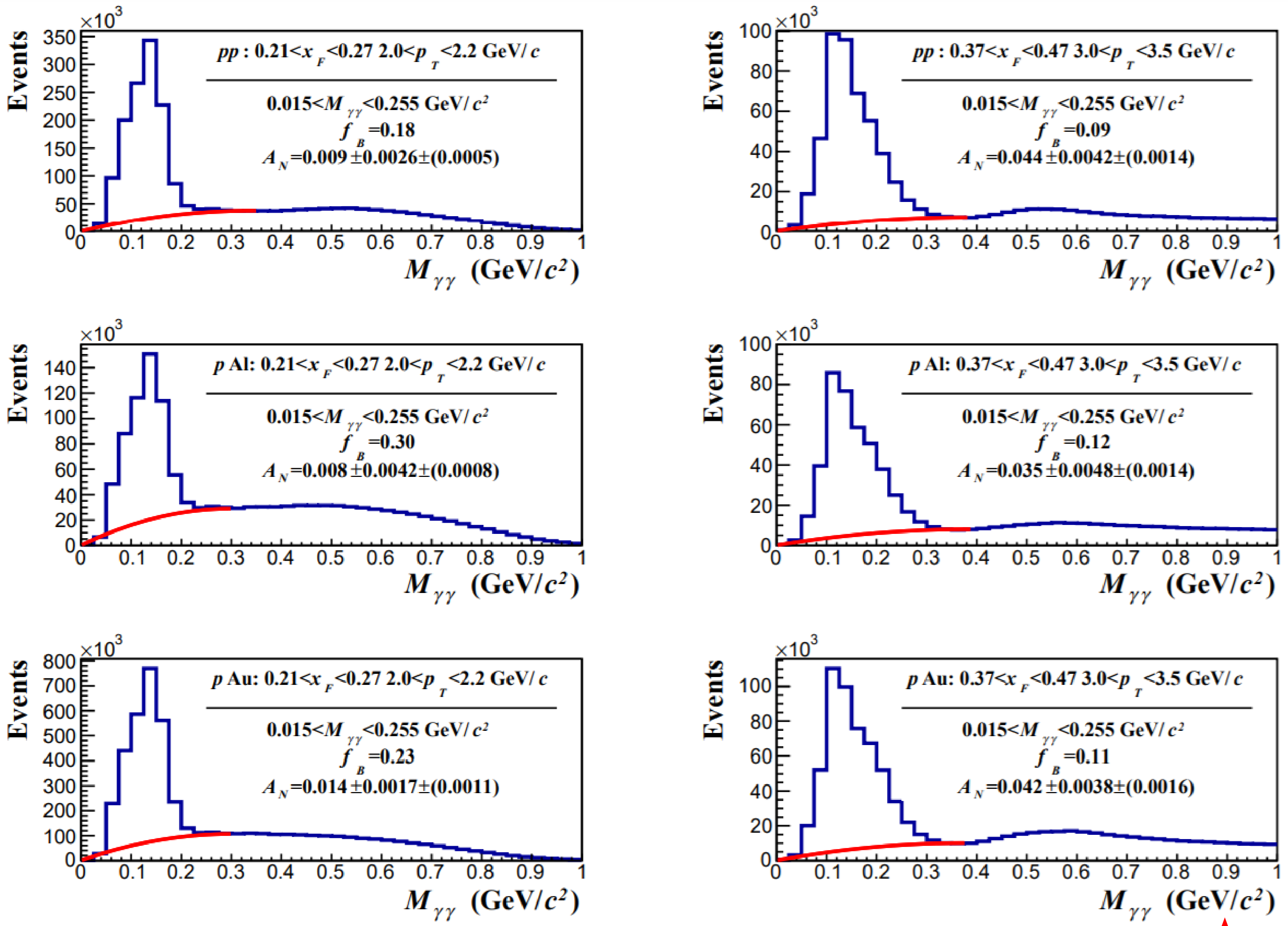


Mass distributions

For two specific kinematic regions.

For 3 collision systems
pp, pAl,   pAu .

Simple background fits
under pion peak.



Uncorrected transverse spin asymmetries for the same 6 regions. The azimuthal distributions of the uncorrected asymmetries,

$$a_0(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$

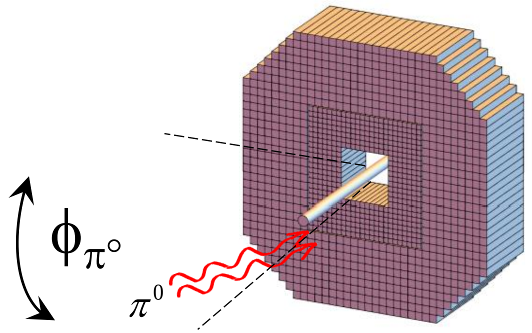
This is shown for events in the mass range

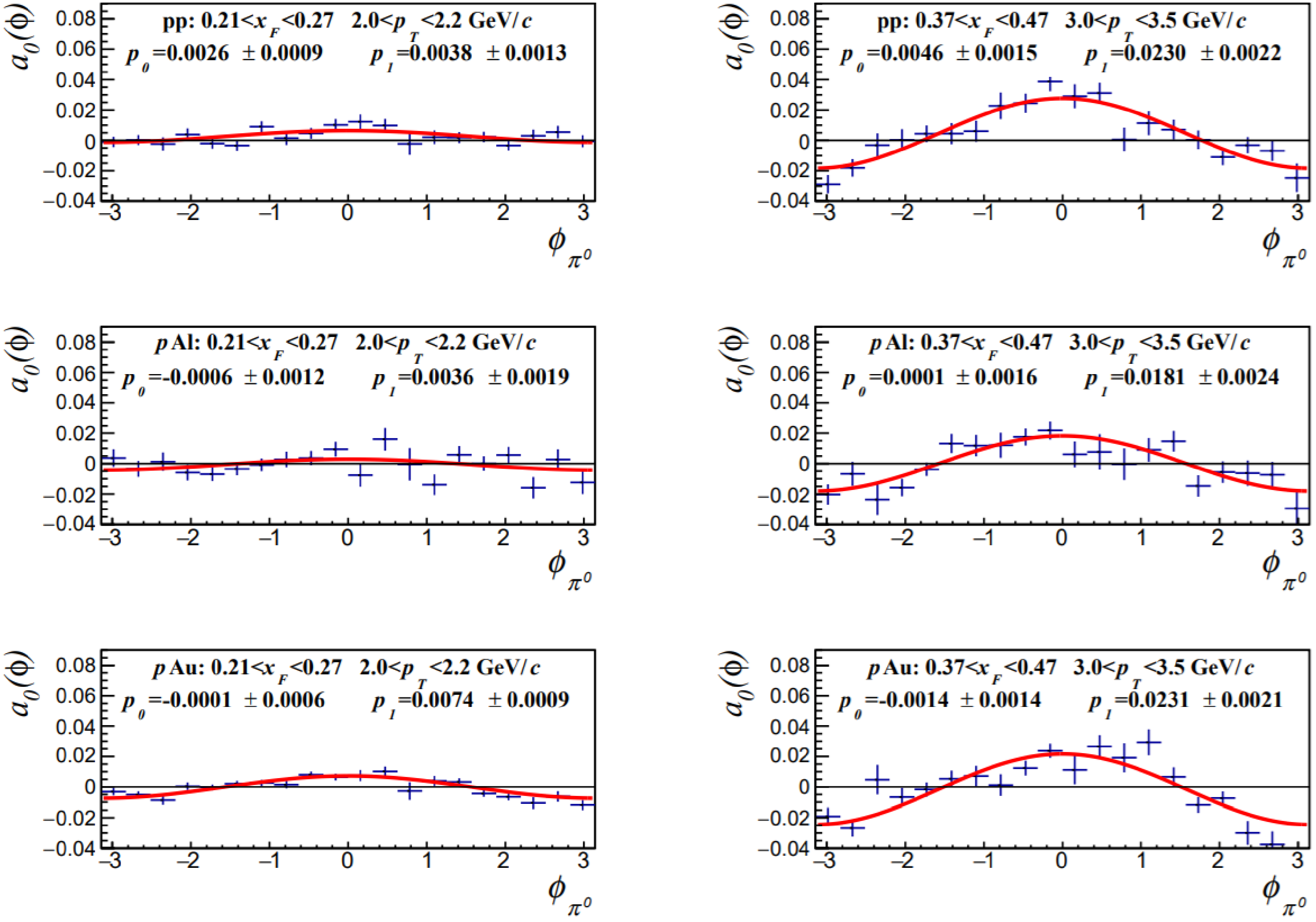
$$0.015 < M_{\gamma\gamma} < 0.255 \quad \text{GeV/c} .$$

Fits to the functional form

$$a_0(\phi) = p_0 + p_1 \cos\phi$$

with parameters p_0 and p_1.





STAR

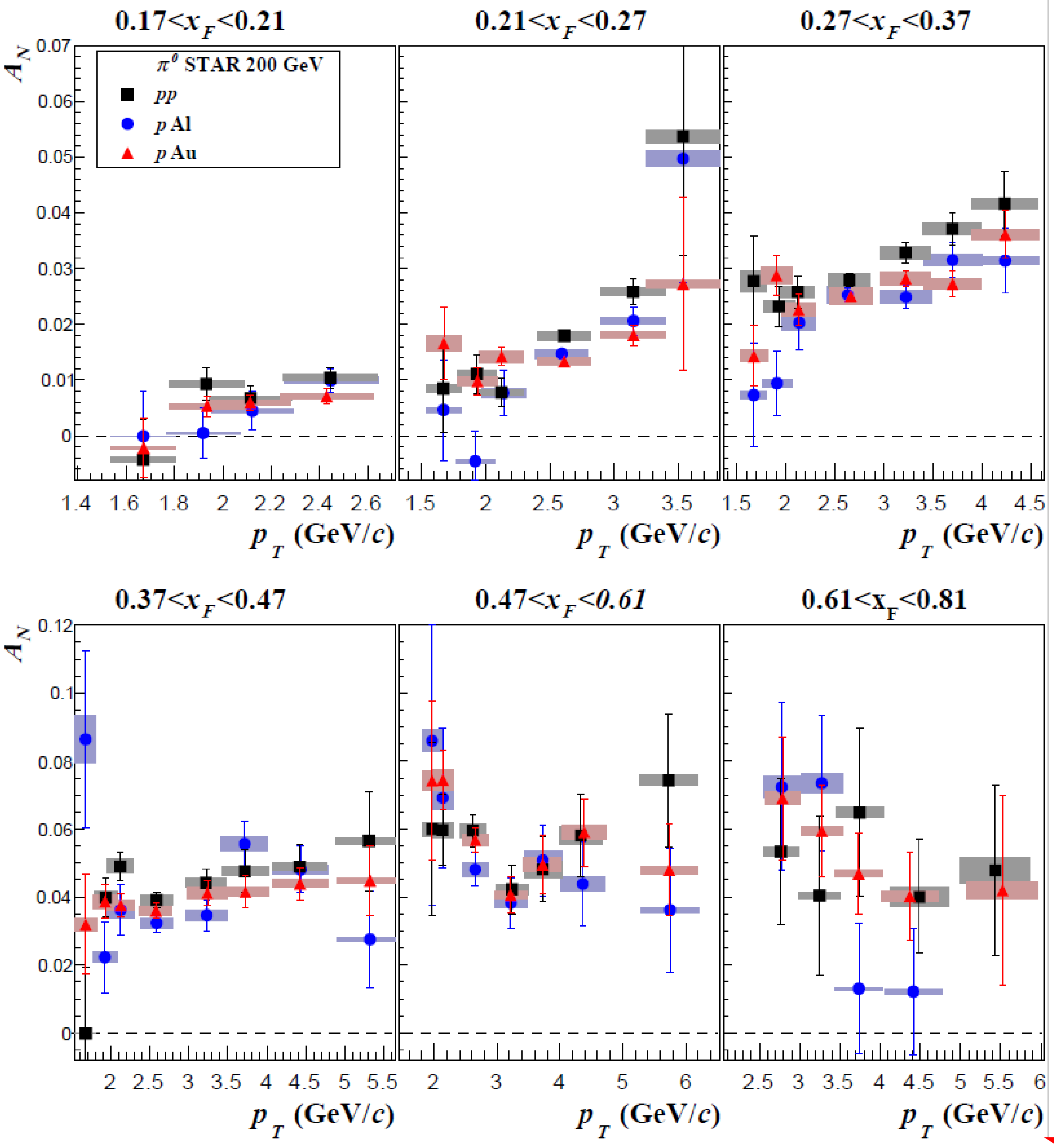
$$a_0 \; + \text{"}\left(\begin{array}{c} \textit{polarization} \\ \\ \textit{background corrections} \end{array} \right)\text{"} \rightarrow A_N$$

1) For pp, pAl , pAu: A_N are all similar.

2) For x_F<0.47: A_N increasing function of p_T , up through p_T~5 GeV/c. (***Surprising***).

Above some $p_T >$ **k$_T$ scale**, we expected A_N to fall with p_T:

$$A_N(x_F, p_T) = \frac{\sigma^{\uparrow}(x_F, p_T, 0) - \sigma^{\uparrow}(x_F, p_T, \pi)}{\sigma^{\uparrow}(x_F, p_T, 0) + \sigma^{\uparrow}(x_F, p_T, \pi)}$$
$$\simeq \frac{(p_T^{\pi} - k_T)^{-N} - (p_T^{\pi} + k_T)^{-N}}{(p_T^{\pi} - k_T)^{-N} + (p_T^{\pi} + k_T)^{-N}}$$
$$\simeq N \frac{k_T}{p_T^{\pi}}$$



Calculations by theorists.

The X_F dependence of A_N is correctly characterized in many theoretical calculations. The rise with p_T is more difficult to explain.

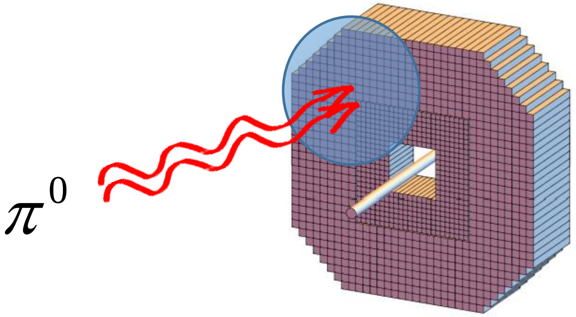
A twist-3 calculation , involving fits to many parameters, resulted in calculations that were in agreement with single inclusive deep inelastic scattering asymmetries and with the x_F dependence of π^0 A_N in pp collisions.

This calculation also resulted in a nearly flat, or **very slowly falling, p_T dependence above about 3 GeV/c for the π^0 A_N in pp scattering.**

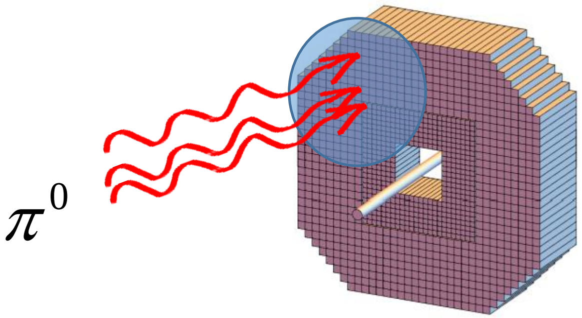
Towards an explanation of transverse single-spin asymmetries in proton-proton collisions: the role of fragmentation in collinear factorization

Koichi Kanazawa,[1,2] Yuji Koike,[3] Andreas Metz,[2] and Daniel Pitonyak[4]

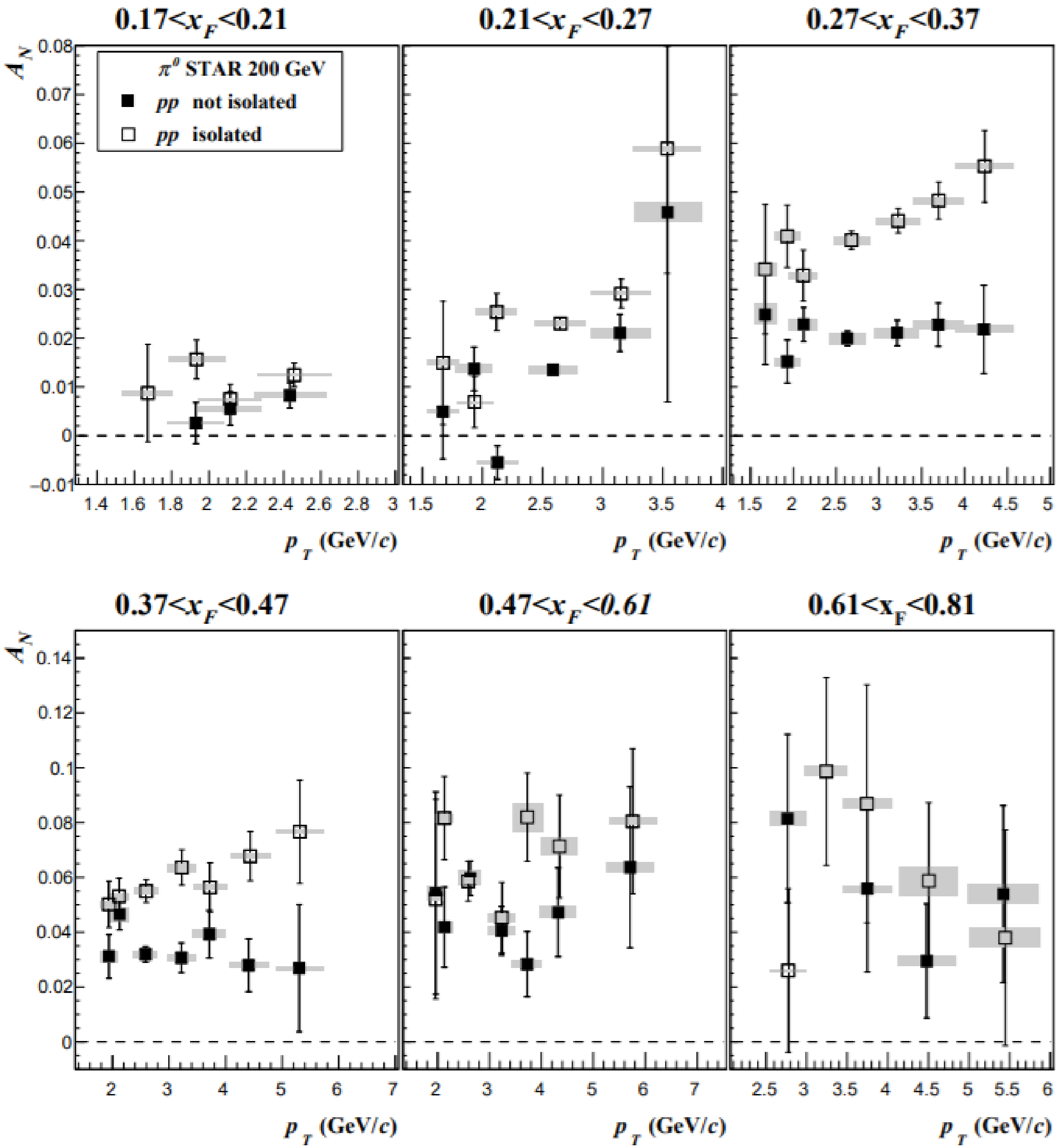
Towards an explanation of transverse single spin asymmetries in proton-proton collisions: the role of fragmentation in collinear factorization. Phys. Rev. D89, 111501 (2014).



Isolated (1/3 of events)

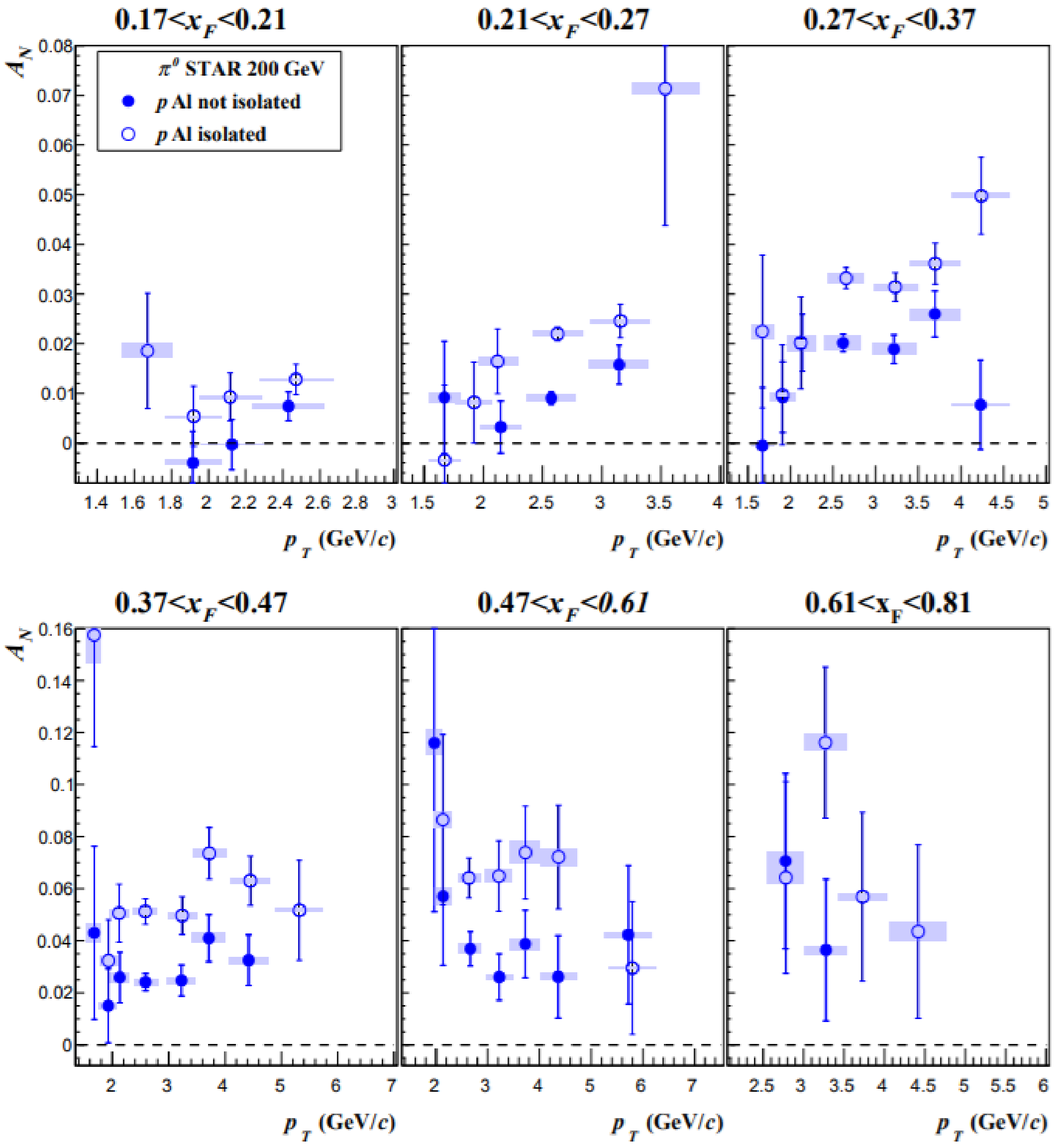


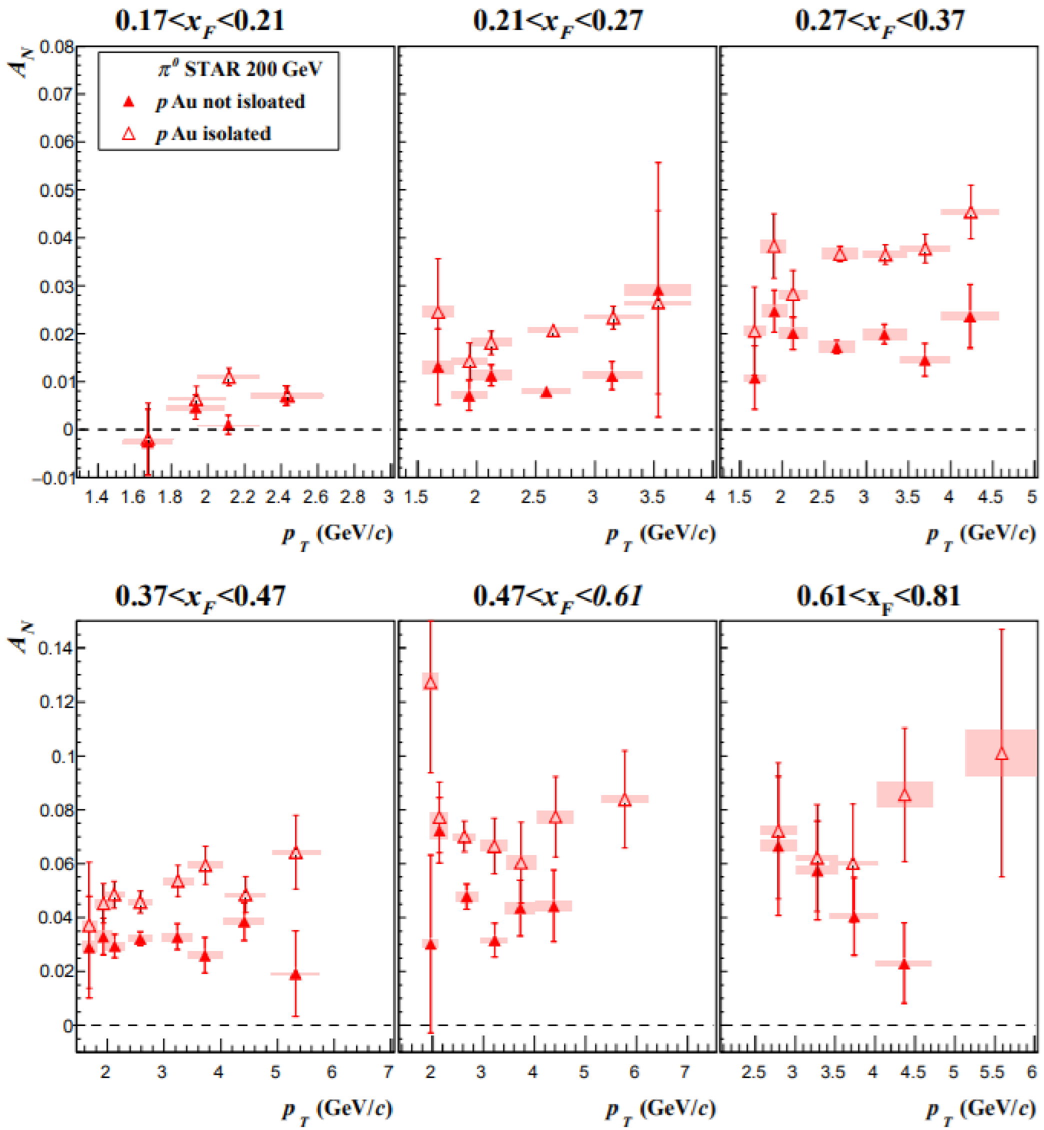
not-isolated (2/3 of events)



A_N for isolated events about twice as large as non-isolated events.

A_N **for isolated $\pi°$events** also **about twice as large** as non-isolated events for pAl and pAu collisions.

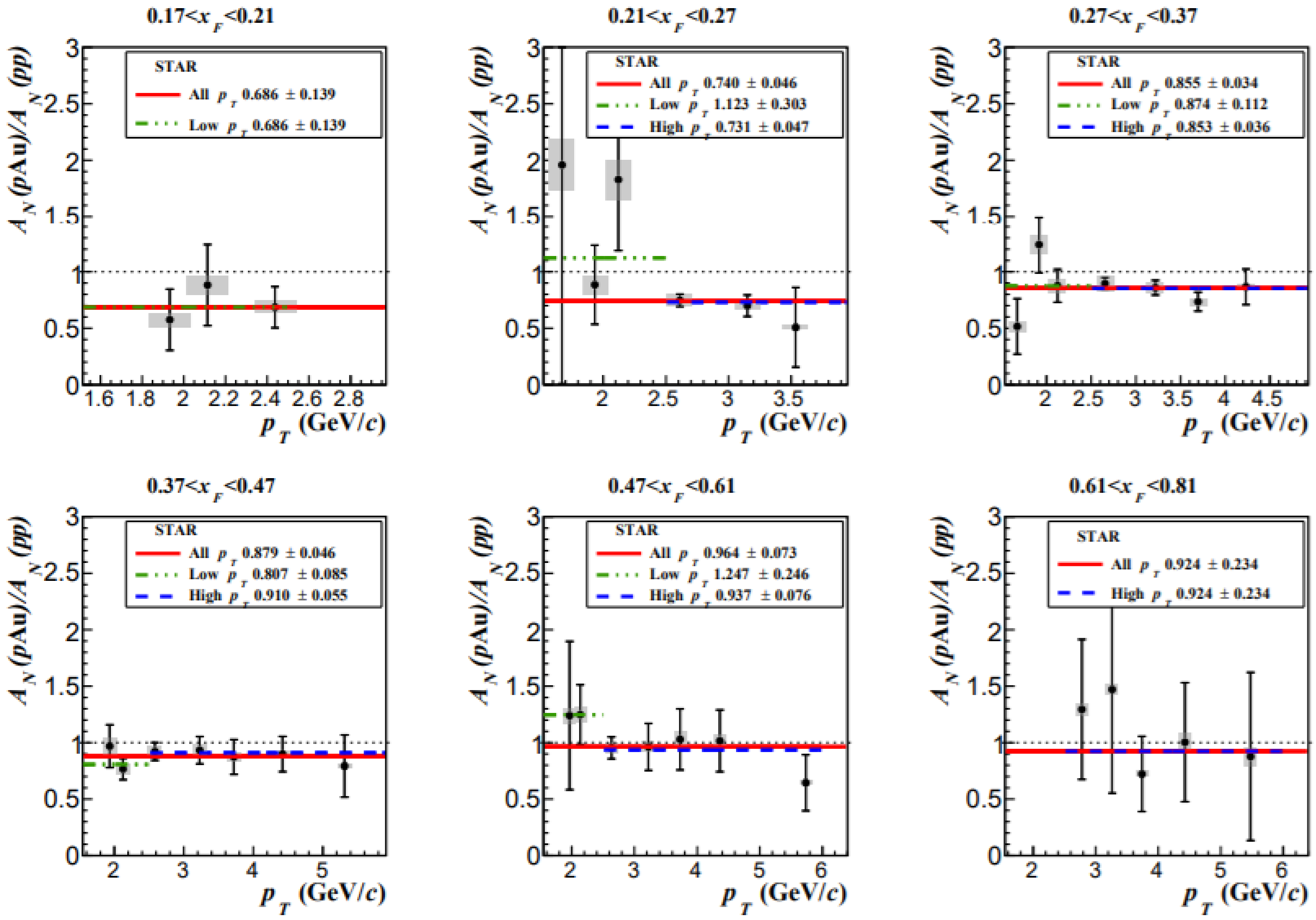




STAR

$$p^{\uparrow}A \rightarrow \pi^{0} X$$

$$ratio: \frac{A_N(pA_{Au})}{A_N(pp)}$$



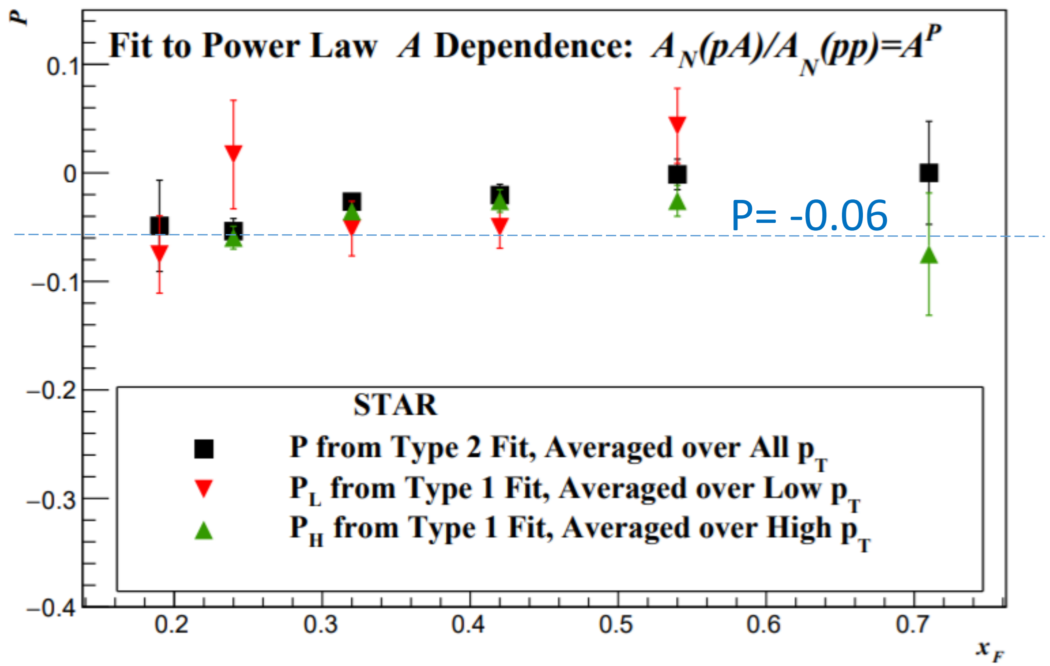
For $p^{\uparrow}A \rightarrow \pi^0 X$

Dependence of A_N on Nuclear A.

Fit to exponent P with

$$A_N(pA) = A_N(pp)A^P$$

Average measured value of exponent P= -0.06.



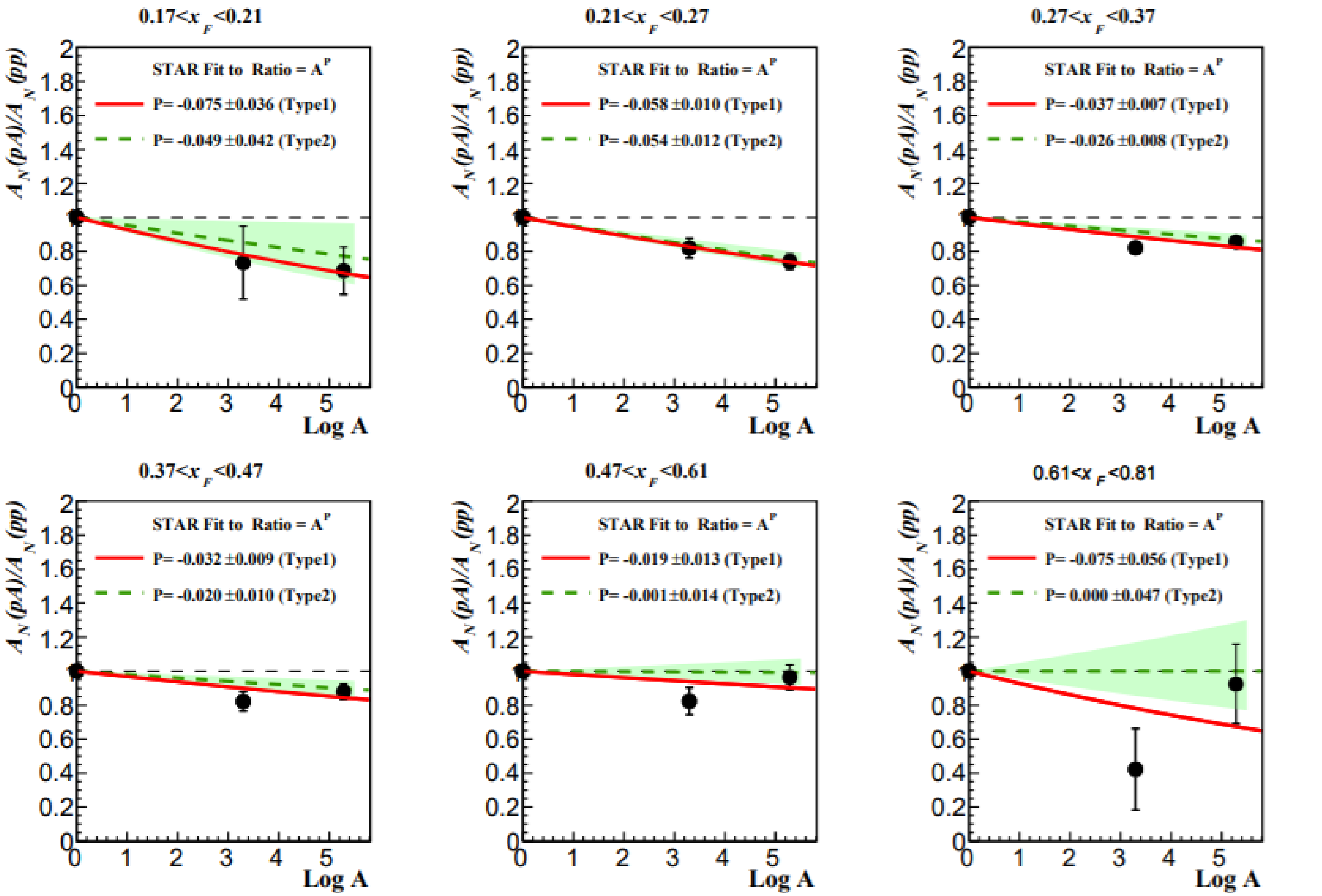


FIG. 8. The ratio of A_N for pA scattering to that for pp scattering is shown for six x_F regions, averaging over the full range of p_T dependence. The fitted form for these ratios as a function of A is obtained using Type 1 and Type 2 analyses as described in the text. The dependence of A_N as a function of log A is displayed with a filled error band, obtained from the Type 2 analysis, shown as the dashed line.

$$q + g \to q + g$$
$$x_{quark} \to large$$
$$x_{gluon} \to small$$

Inclusive quark-gluon process kinematics (pion observed)

Direct Observables:

η^{π} (pion pseudo-rapidity) $\to$ y_q (quark rapidity)

p_T (pion Pt)) $\to$ p_t (quark Pt)

x_F (pion longitudinal momentum fraction Feynman X)

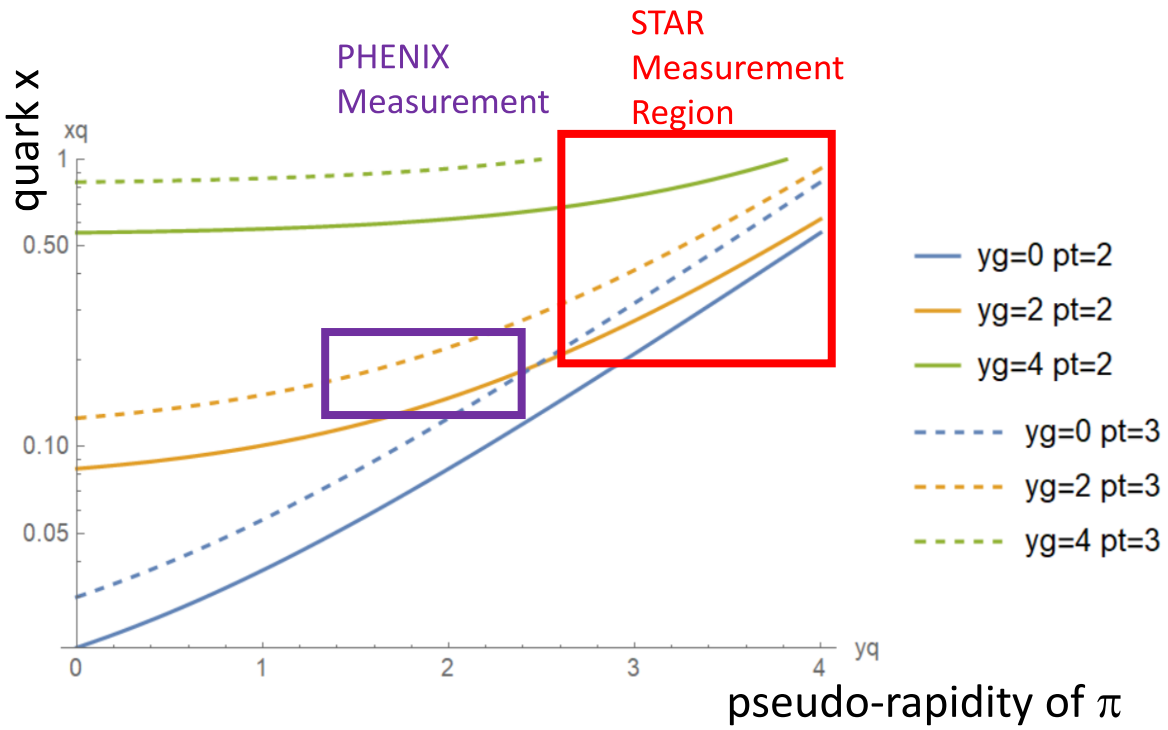
Unobserved: $\eta^{recoil} \to$ yg (gluon recoil rapidity)

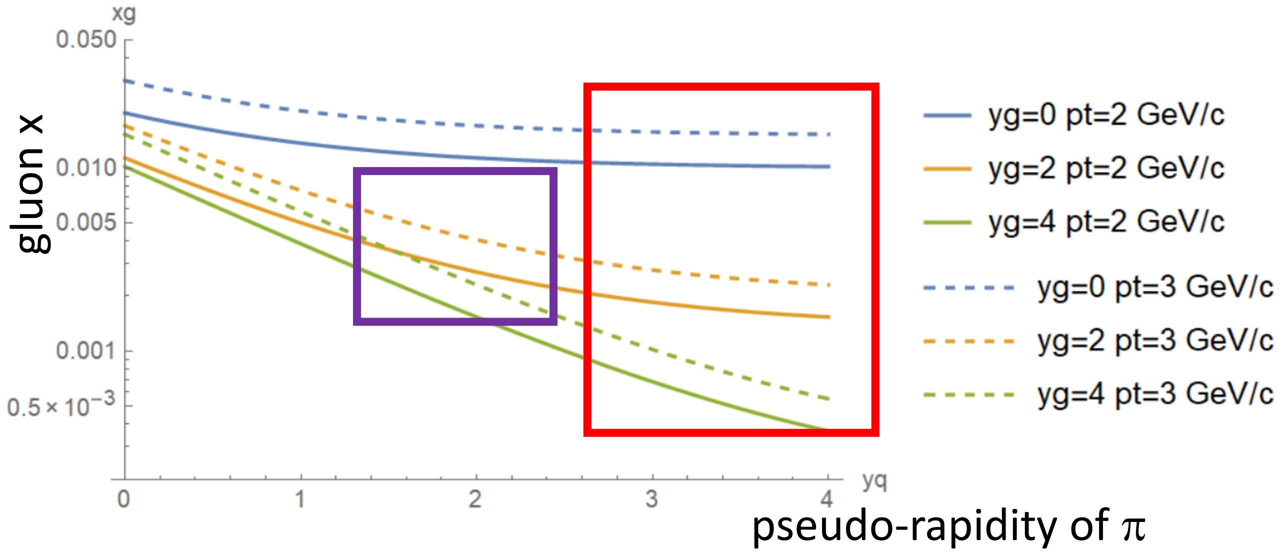
Underlying variables:

x_q (quark momentum fraction)

x_g (gluon momentum fraction)

p_t (quark transverse momentum)





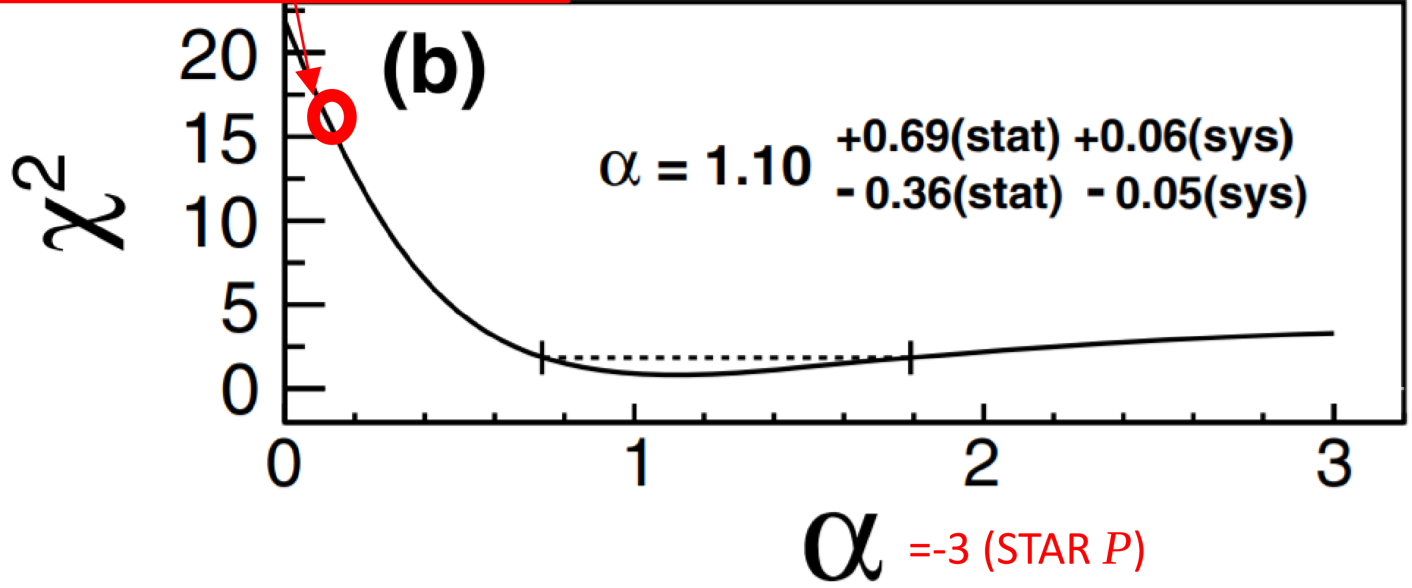
PHENIX published a measurement of A_N for **+charged hadrons,** comparing within a single kinematic region for each of pp, pAl and pAu.

$$0.1 < x_F < .2$$

$$1.8 < p_T < 7.0\,GeV/c$$

STAR points for π°s at $x_F > 0.17$

Equivalent STAR point
Not likely consistent with
PHENIX point.



=-3 (STAR P)

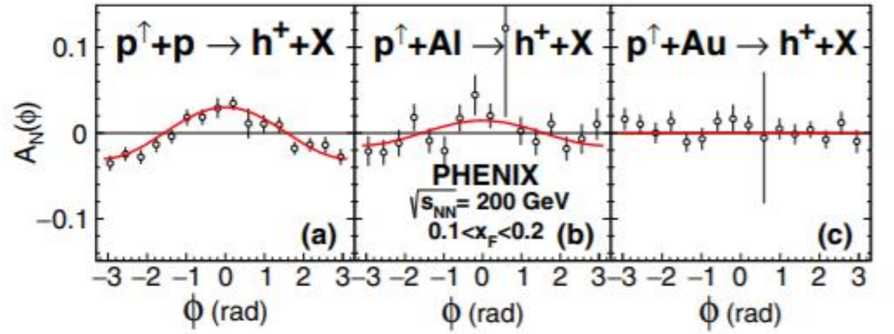


FIG. 1. Azimuthal modulation of positively charged hadrons for $1.4 < \eta < 2.4$, $0.1 < x_F < 0.2$, and $1.8 < p_T < 7.0$ GeV$/c$ in (a) $p^\uparrow + p$, (b) $p^\uparrow +$ Al, and (c) $p^\uparrow +$ Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

C. Aidala et al, Nuclear Dependence of the Transverse Single-Spin Asymmetry in the Production of Charged Hadrons at Forward Rapidity in Polarized $p+p$, p+Al, and p+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. Lett.* 123, 122001 (2019).

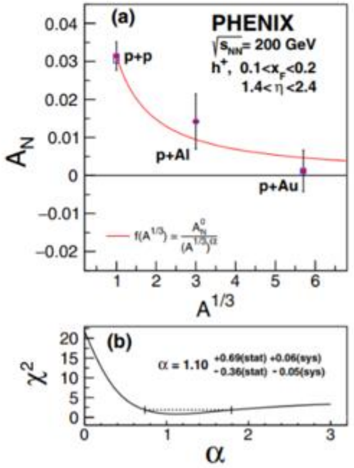


FIG. 2. Upper panels are A_N of positively charged hadrons for $0.1 < x_F < 0.2$, $1.8 < p_T < 7.0$ GeV$/c$, and $1.4 < \eta < 2.4$ in $p^\uparrow + p$, $p^\uparrow +$ Al, and $p^\uparrow +$ Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of (a) $A^{1/3}$ and (c) $N_{\mathrm{coll}}^{\mathrm{avg}}$. The fit functions, $A_N^0/(A^{1/3})^\alpha$ and $A_N^0/(N_{\mathrm{coll}}^{\mathrm{avg}})^\beta$ are shown as solid [red] curves. Vertical bars (boxes) represent statistical (systematic) uncertainties. A 3% scale uncertainty due to polarization uncertainty is not shown. Lower panels show χ^2 distributions as a function of power parameters (b) α and (d) β, taking into account the statistical uncertainty only. Dashed lines represent the range of α and β for $\Delta\chi^2 < 1$.

$$STAR: \frac{A_N(pA)}{A_N(pp)} = A^P$$

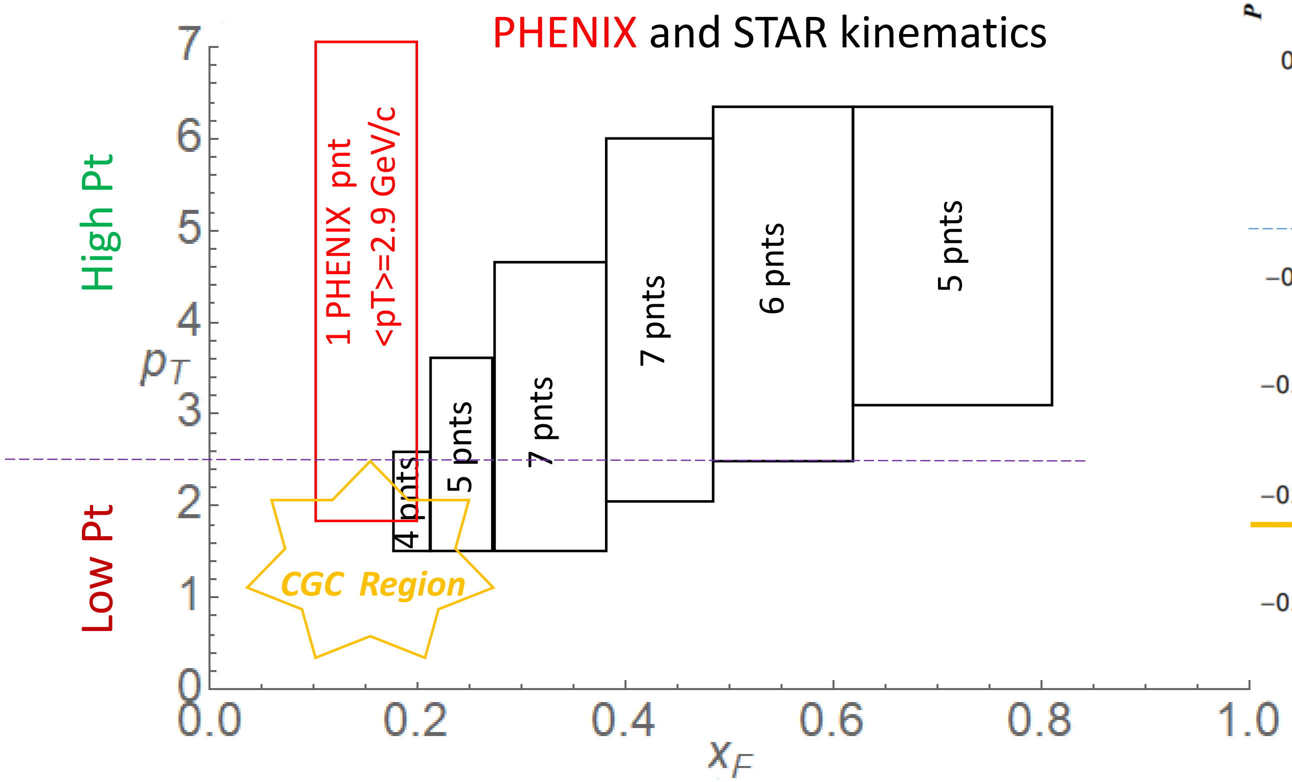
$$PHENIX: \quad A_N(pA) = A_N(pp)\left(A^{-1/3}\right)^\alpha$$

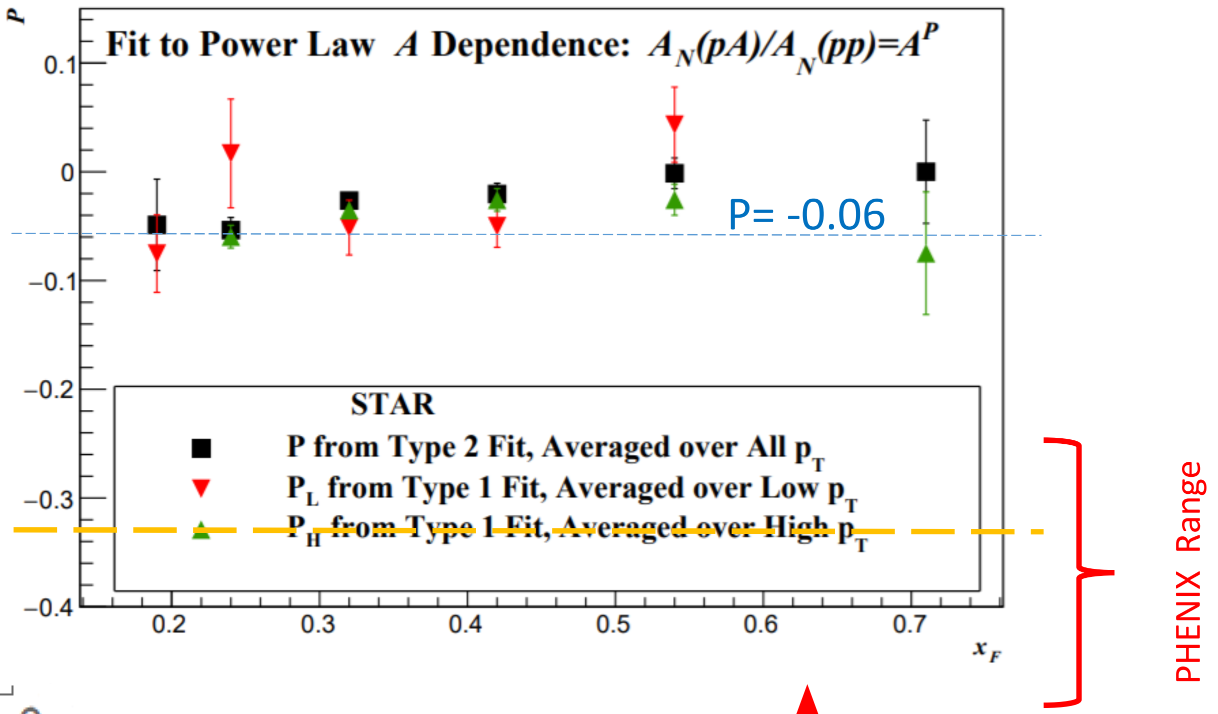
$$P = -0.06 \rightarrow \alpha = -3P = 0.18$$

There has been interest in the possible impact from saturation effects, including Color Glass Condensate, on A_N. In the forward region, of where the parton collision can involve a soft gluon of very low momentum fraction (x), the prediction could be:

$$A_N(A) \propto A^P = A^{-1/3}$$

This CGS (P=-1/3) predictions appears to apply only to the very low corner of the kinematic range (x_F vs p_T) covered by STAR.

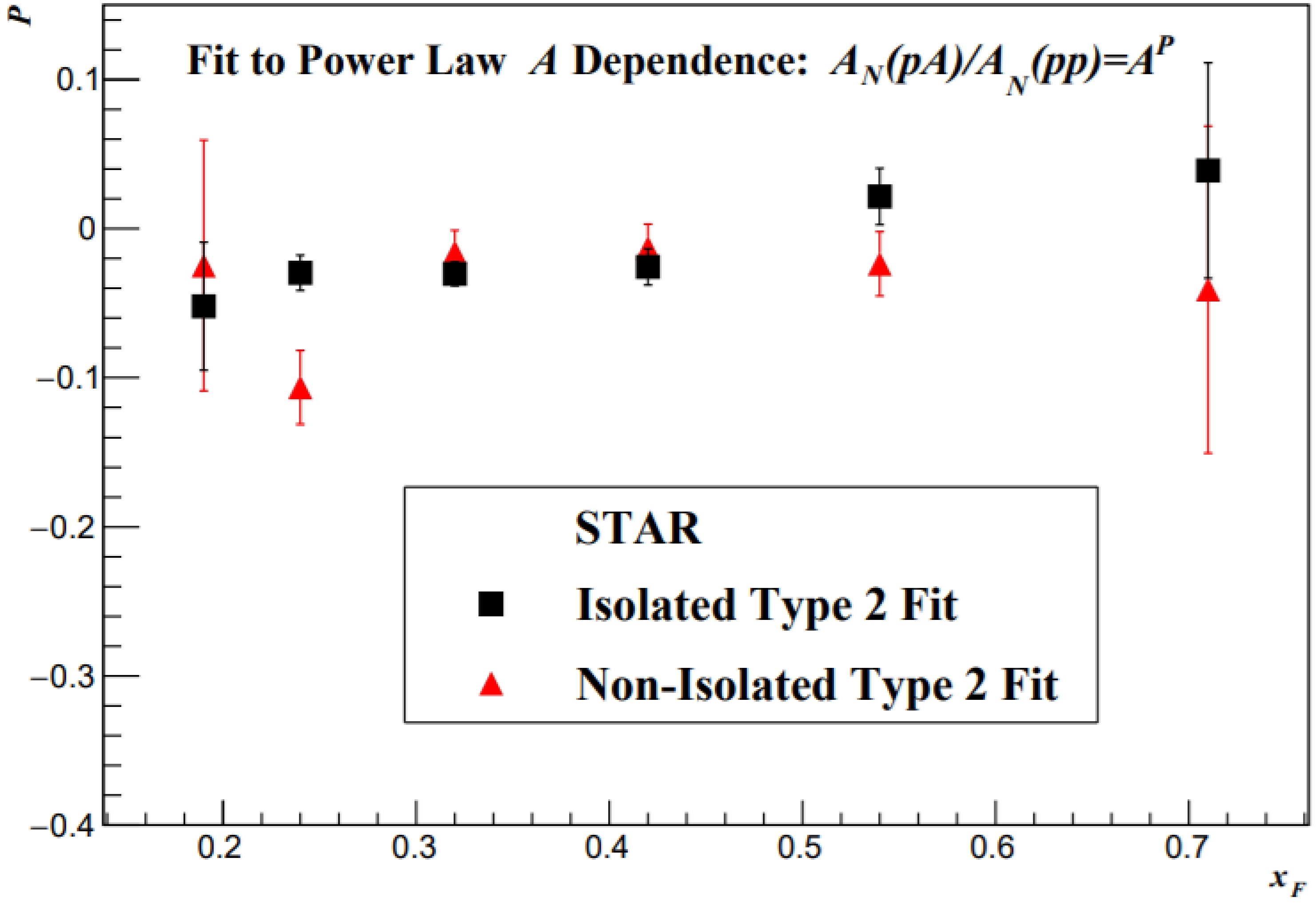




$$A_N(pA) = A_N(pp)A^P$$

Does the exponent, P, depend on the isolation of the final state pion.

Apparently Not.



What is the message: That isolated events have larger A_N.

Does this suggest that the conventional model of pion production is not the sub-process with the large A_N?

Conventional sub process

$$q + g \to q + g$$

$$quark \to fragment\ to\ pion$$

We have long known that "exclusive scattering" results in very large spin asymmetries.

Could we be scattering from a pion within the proton, without emphasis on the parton sub-process at all?

More thought is needed.

Conclusions

- **STAR has measured the dependence of A_N on forward kinematics for the produced $\pi°$ is measured for p+p $\rightarrow \pi°$+X.**

- In contrast to intuition, for x_F<0.47, **A_N rises with increasing p_T through p_T~5 GeV/c.**

- The **asymmetry A_N is larger** (by about a factor of two) **for events that have isolated $\pi°$s** in the FMS than for events showing evidence of jet fragments.

- For collisions of polarized protons with nuclei, p+A $\rightarrow \pi°$+X, **the dependence of A_N on nuclear size (A) is measured to be small.**

- The nuclear dependence of A_N for these $\pi°$s may **be difficult to reconcile with the recent PHENIX measurement** for charged hadrons in a slightly different kinematic region.

- **The agreement of PHENIX data with <u>gluon saturation models</u> *is not verified*** by these STAR data. (The kinematics for PHENIX, and even for STAR, may not be ideal for applicability of the saturation of Color Glass Condensate predictions).

Combine A_N data for All systems.