

INDICATION ON PROCESS DEPENDENCE OF THE SIVERS EFFECT

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April 24, 2013

“Experiments with spin have killed more theories than any other single physical parameter”

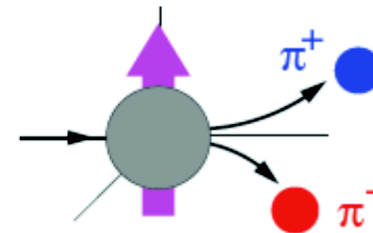
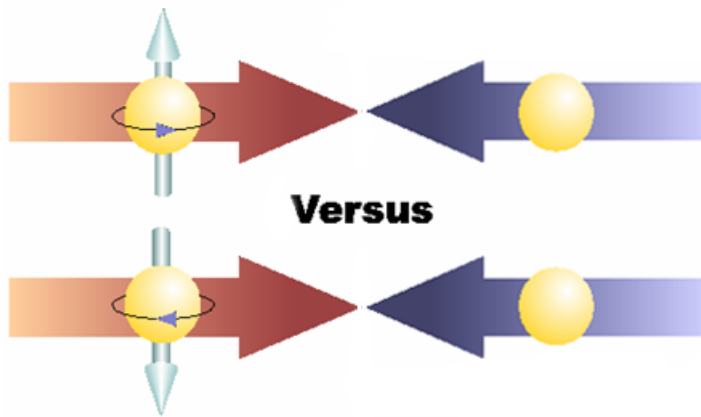
Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

“Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection”

J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

Spin and QCD

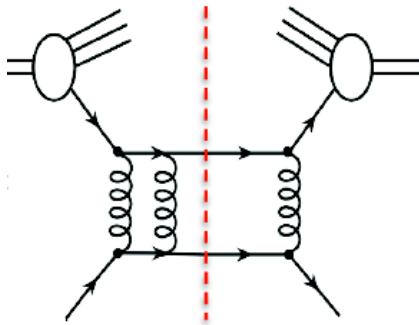
Consider A_N in hadron hadron collision:



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

QCD had a very simple prediction:

Helicity flip is proportional to the small mass of the quark, thus

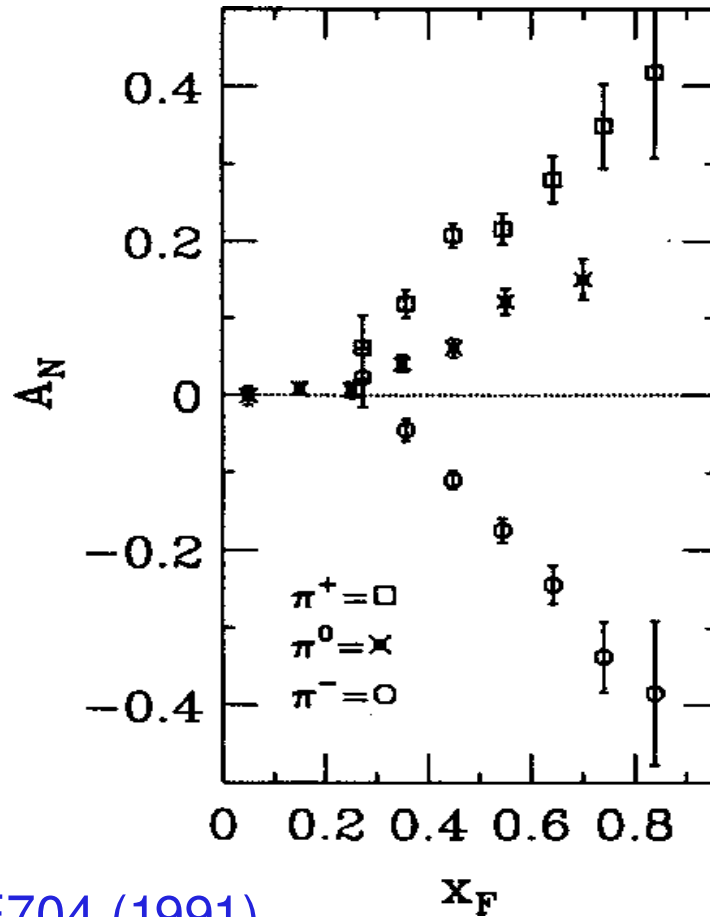


$$\propto \alpha_s \frac{m_q}{p_T}$$

$$A_N \simeq 0.001$$

Kane, Pumplin and Repko (1978)

Experiment proved this prediction wrong

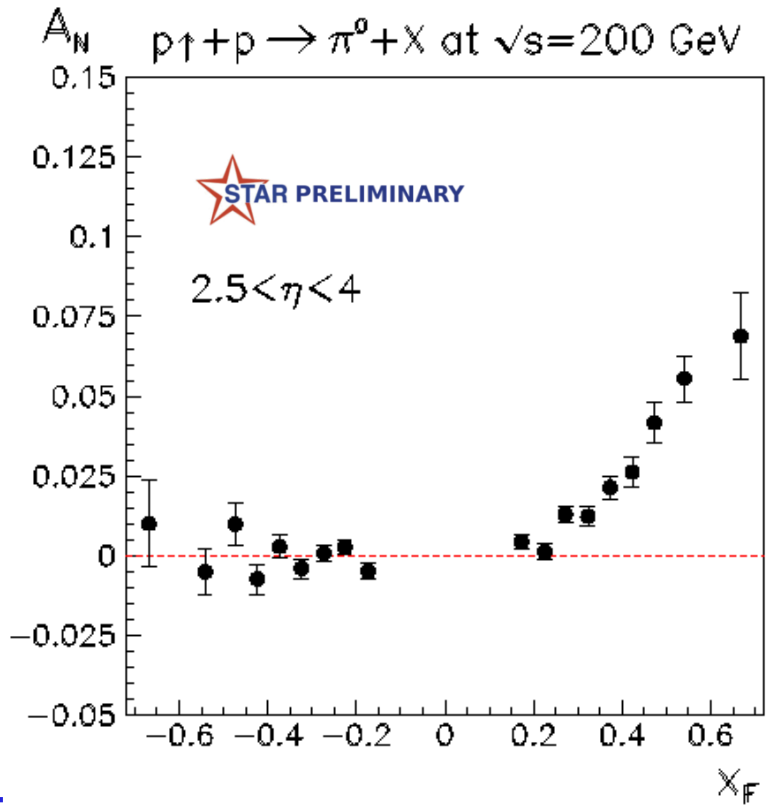
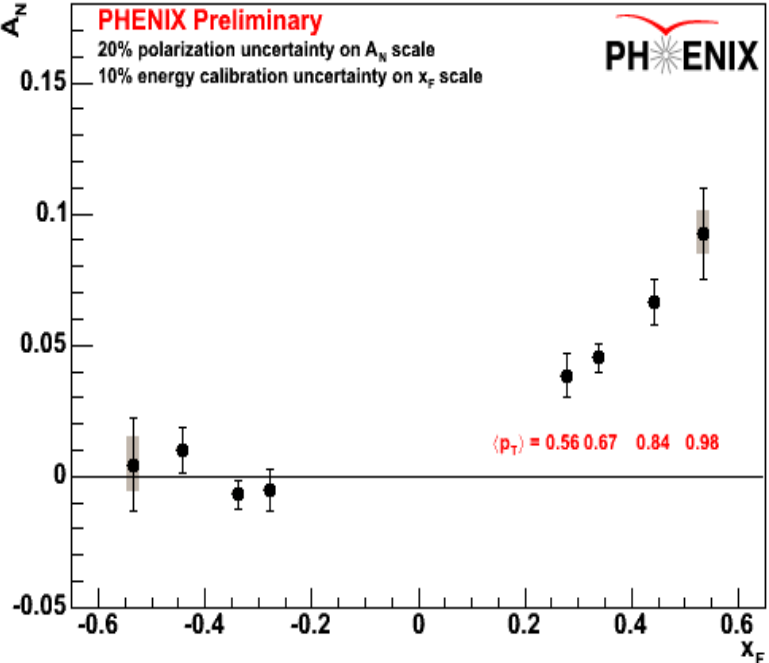


$$A_N \simeq 40\%$$

E704 (1991)

Asymmetry survives with energy

$$\sqrt{s} = 62 \text{ GeV}$$



RHIC: STAR, BRAHMS and PHENIX

Failure of QCD?



Not at all: better understanding of QCD



Better understanding of QCD

$$\sigma(Q, \vec{s}) \propto \left| \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \text{Diagram 3} \\ \dots \end{array} \right|^2$$

The diagrams show a series of Feynman diagrams for a hard scattering process. The first diagram shows a hard vertex (represented by a blob) with an incoming parton carrying momentum k and an outgoing parton carrying momentum $t \sim 1/Q$. The second diagram shows a gluon exchange between the hard vertex and a parton. The third diagram shows a more complex multi-parton correlation involving a gluon exchange between two partons. The diagrams are summed and then squared to give the cross section.

Multy parton correlations contribute to the cross section.

These correlations are called [Efremov-Teryaev-Qiu-Sterman](#) matrix elements, They appear at twist-3 level in cross section.

$$\begin{aligned} \sigma &= \sigma^{LT} + \frac{Q_s}{Q} \sigma^{HT} + \dots \\ &= H^{LT} \otimes f_2 \otimes f_2 + \frac{Q_s}{Q} H^{HT} \otimes f_3 \otimes f_2 + \dots \end{aligned}$$

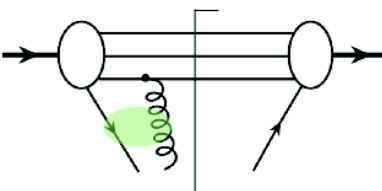
Better understanding of QCD

If only one large scale is present in the process, then

$$\begin{aligned} A_N &\propto \sigma(p_T, S_\perp) - \sigma(p_T, -S_\perp) \\ &\propto T^{(3)}(x, x, S_\perp) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x, S_\perp) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) + \dots \end{aligned}$$

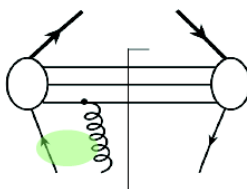
Leading power cancels

Twist-3 parton correlation functions

$$T^{(3)}(x, x, S_\perp) \propto$$


Qiu-Sterman 1991

Twist-3 parton fragmentation functions

$$D^{(3)}(z, z) \propto$$


Kang, Yuan, Zhou 2010

No probability interpretation!

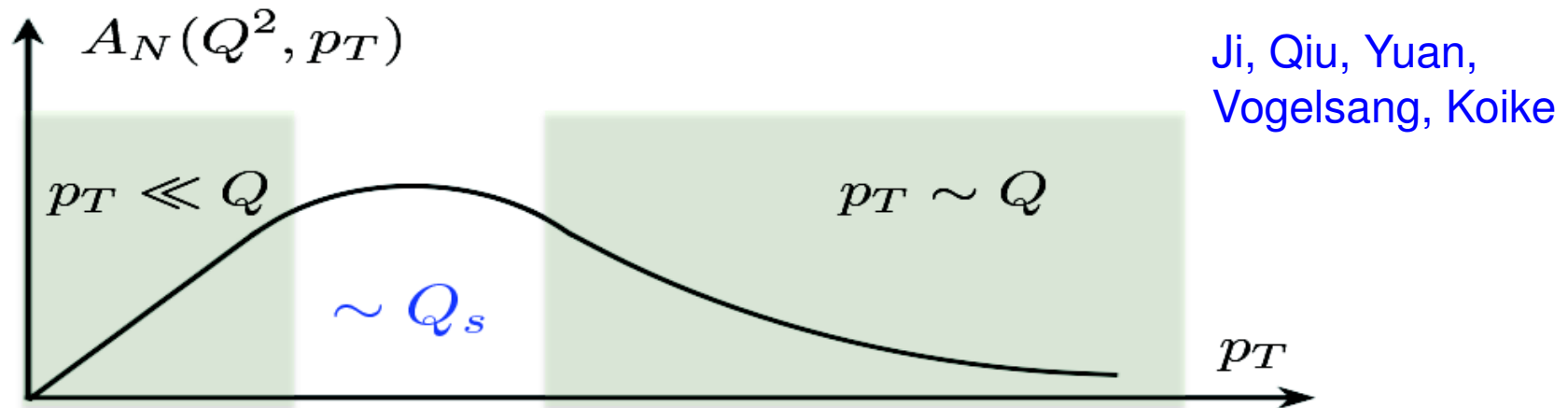
Collinear vs TMD factorization

We can consider two different kinematical regions

$$Q_1, Q_2, \dots \gg \Lambda_{QCD} \quad \text{Collinear}$$

$$Q_1 \gg Q_2 > \Lambda_{QCD} \quad \text{TMD}$$

- Twist-3 – integration over parton momenta
- TMD – direct information on partonic transverse motion

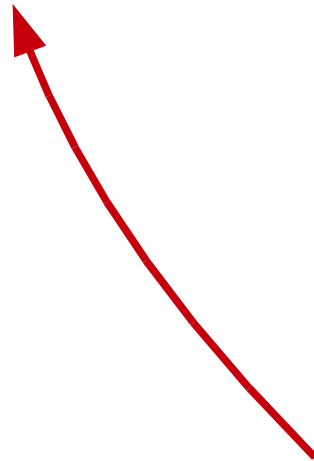


Consistent in the overlap region!

TMDs and twist-3 are related

At operator level:

$$T_F(x, x) = - \int d^2 \vec{k}_\perp \frac{k_\perp^2}{M} (f_{1T}^\perp(x, k_\perp))_{SIDIS}$$



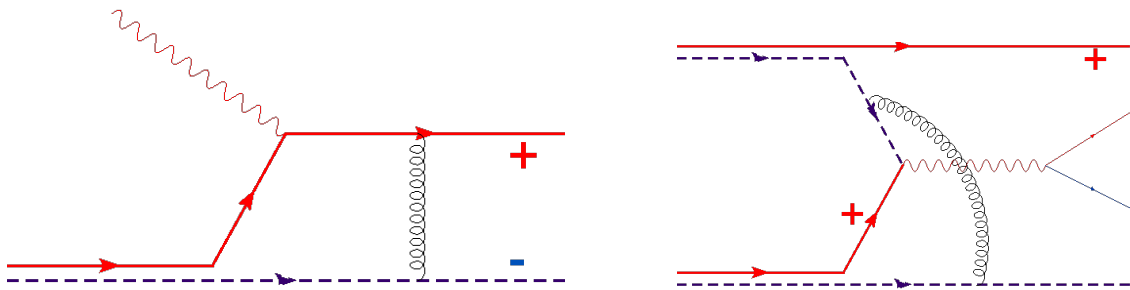
Universal in all processes!

Boer, Mulders, Pijlman,
Ji, Qiu, Vogelsang, Yuan,
Koike, Vogelsang, Yuan
Zhou, Yuan, Liang
Bacchetta, Boer, Diehl, Mulders

Physics of gauge links

Colored objects are surrounded by gluons, profound consequence of gauge invariance.

Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)



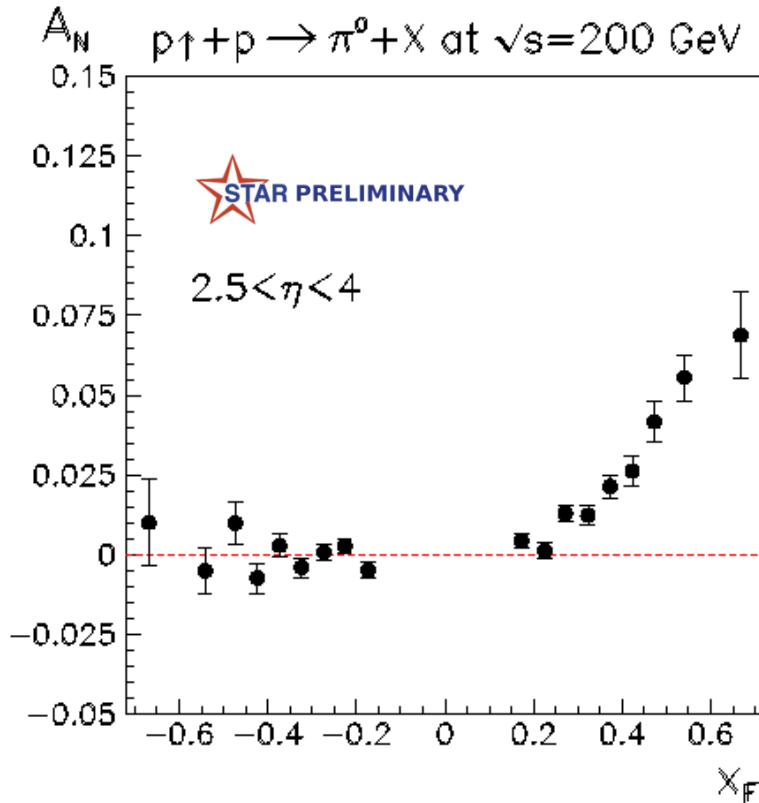
Brodsky, Hwang,
Schmidt
Belitsky, Ji, Yuan
Collins
Boer, Mulders, Pijlman,
etc

$$f_{1T}^{\perp \text{SIDIS}} = -f_{1T}^{\perp \text{DY}}$$

One of the main goals is to verify this relation.
It goes beyond “just” check of TMD factorization.
Motivates Drell-Yan experiments

AnDY, COMPASS, JPARC, PAX etc

Barone et al., Anselmino et al., Yuan, Vogelsang, Schlegel et al., Kang, Qiu, Metz, Zhou



Asymmetry contains contributions from distribution (Sivers) and fragmentation (Collins)

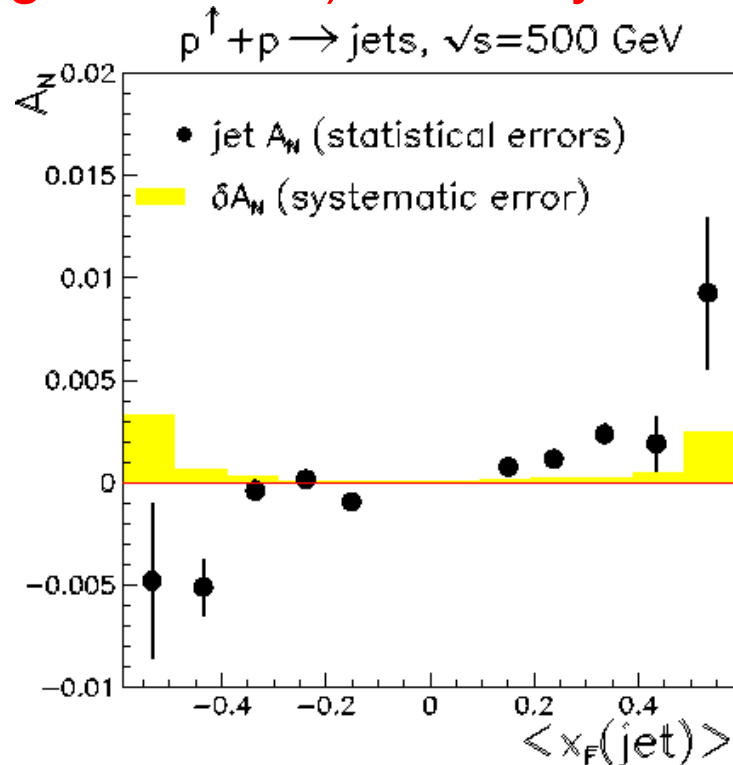
Comparison is difficult:
Sign puzzle

Kang, Qiu, Vogelsang, Yuan (2011)

AnDY data on jet AN

Can we measure AN that contains only one of the effects?

Yes! – Jet AN (no fragmentation) has only Siverts like contributions!



$$P^\uparrow P \rightarrow \text{Jet} X$$

AnDY Collaboration (2013)
arXiv:1304.1454

Jet AN contains:

Process dependence \rightarrow test of the process dependence

Relation twist-3 and TMD \rightarrow test of twist-3 and TMD relation

We calculate jet AN in twist-3:

$$E_J \frac{d\Delta\sigma(s_\perp)}{d^3 P_J} = \epsilon_{\alpha\beta} s_\perp^\alpha P_{J\perp}^\beta \frac{\alpha_s^2}{s} \sum_{a,b} \int \frac{dx}{x} \frac{dx'}{x'} f_{b/B}(x') \\ \times \left[T_{a,F}(x, x) - x \frac{d}{dx} T_{a,F}(x, x) \right] \\ \times \frac{1}{\hat{u}} H_{ab \rightarrow c}^{\text{Sivers}}(\hat{s}, \hat{t}, \hat{u}) \delta(\hat{s} + \hat{t} + \hat{u}),$$



Process dependence is here

Gamberg, Kang, AP (2013)

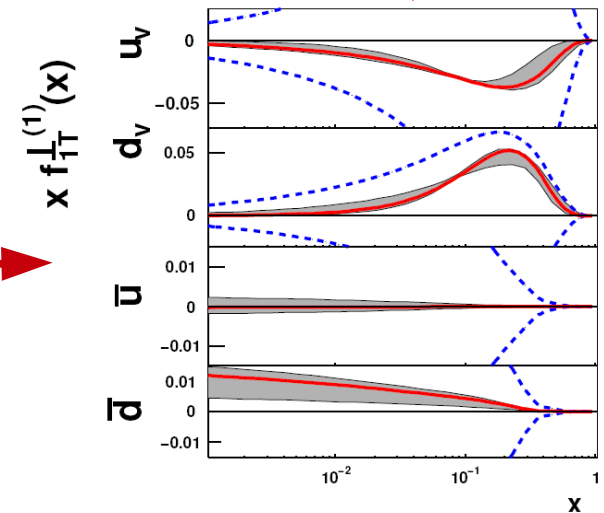
Jet AN

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Twist-3 TMD relation

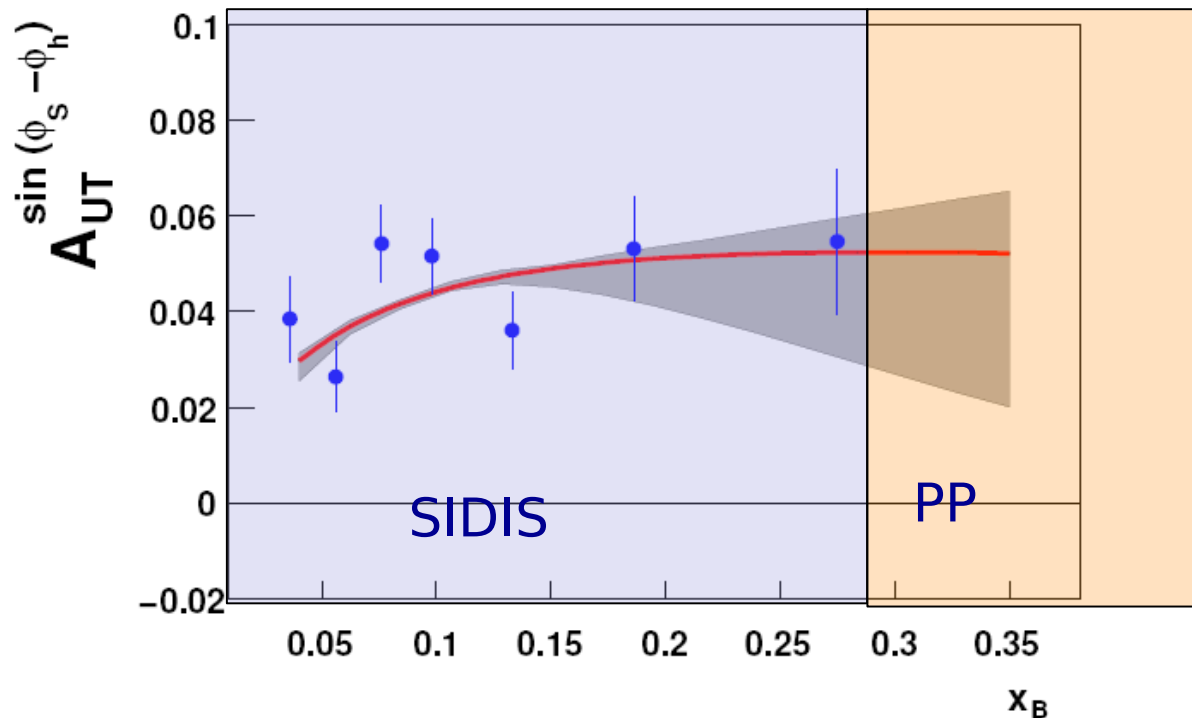
Use Sivers that describes SIDIS:



Gamberg, Kang, AP (2013)

Jet AN

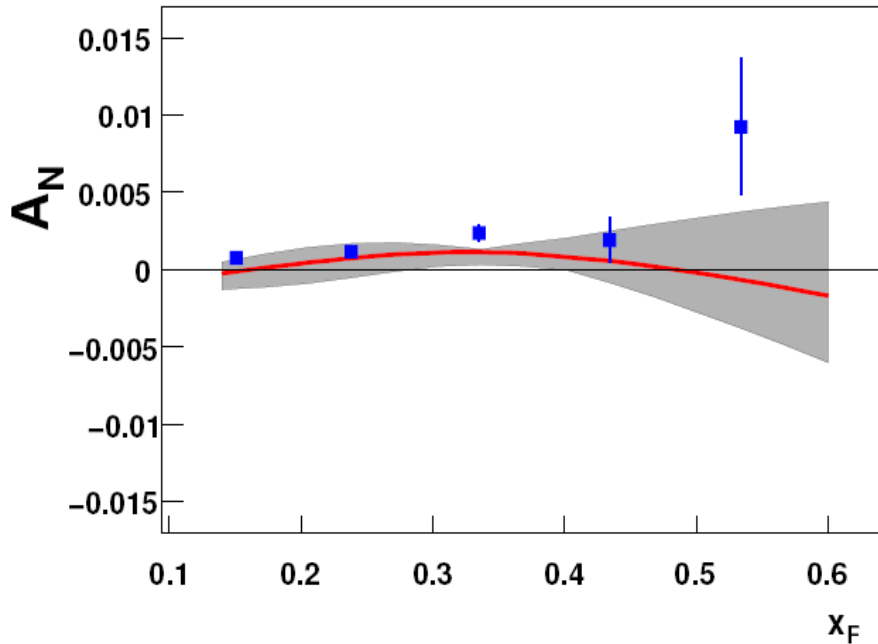
Jet AN corresponds to high x region which is not yet accessible in SIDIS \rightarrow refit SIDIS data in order to explore high x region



Gamberg, Kang, AP (2013)

Compatible with Anselmino et al (2009)

Compare with AnDY data:

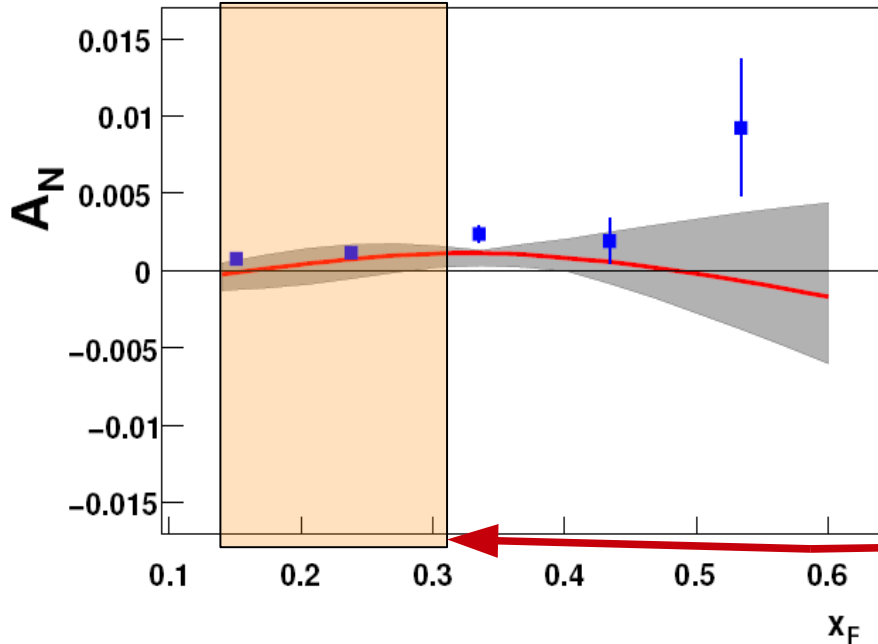


$$\langle y \rangle = 3.25, \quad \sqrt{s} = 500(GeV)$$

Gamberg, Kang, AP (2013)

Jet AN

Compare with AnDY data:



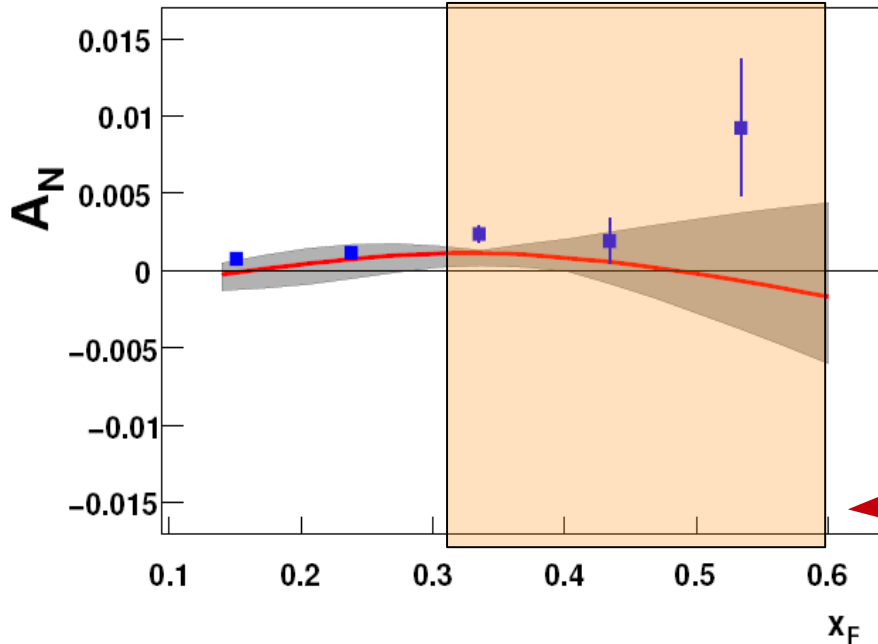
This region corresponds to SIDIS kinematical region: agreement is very encouraging

$$\langle y \rangle = 3.25, \quad \sqrt{s} = 500(\text{GeV})$$

Gamberg, Kang, AP (2013)

Jet AN

Compare with AnDY data:



This region relies on large- x region, future JLab 12 measurement is important

$$\langle y \rangle = 3.25, \sqrt{s} = 500(\text{GeV})$$

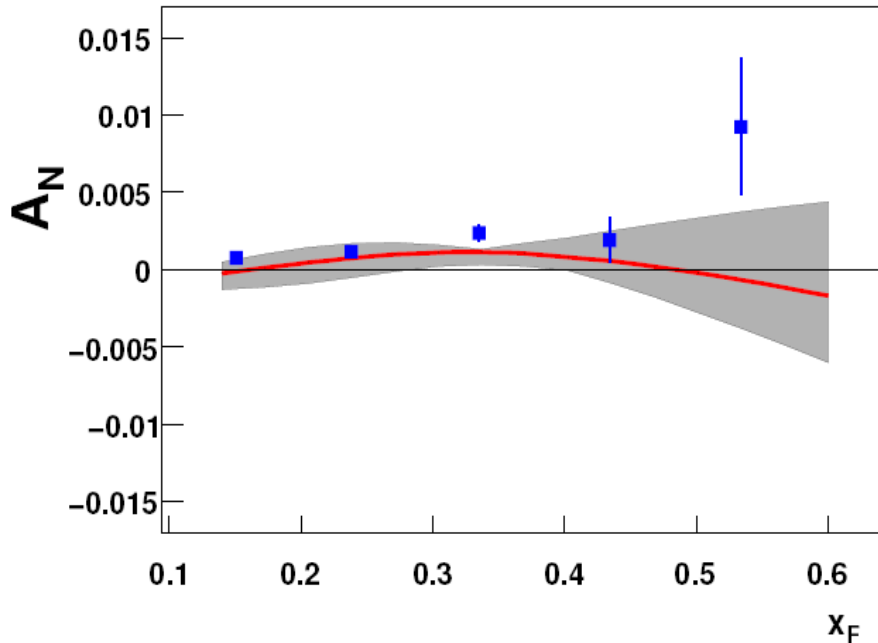
Gamberg, Kang, AP (2013)

Jet AN

Compare with AnDY data:

✓ The sign is correct

✓ The size is correct

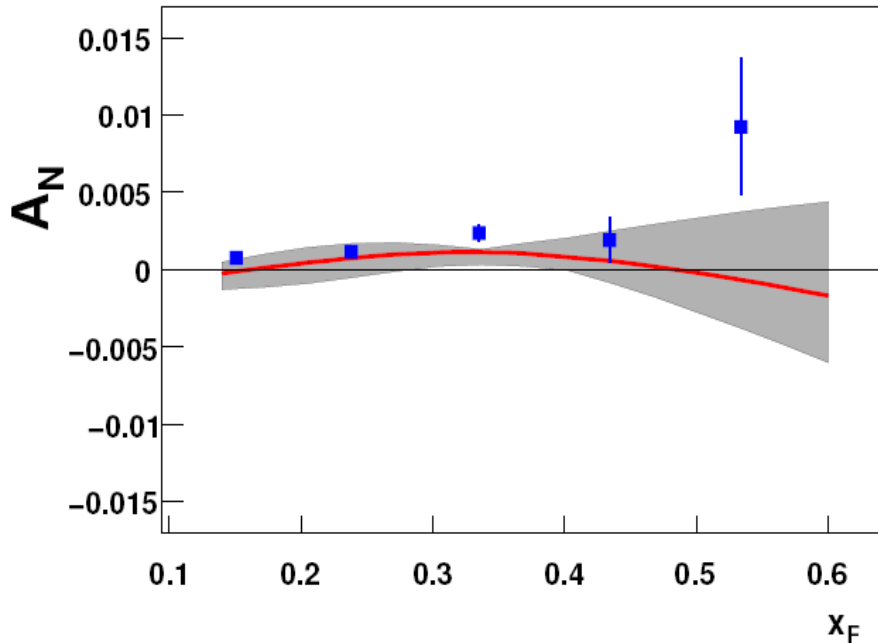


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Gamberg, Kang, AP (2013)

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Gamberg, Kang, AP (2013)

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Result is indication

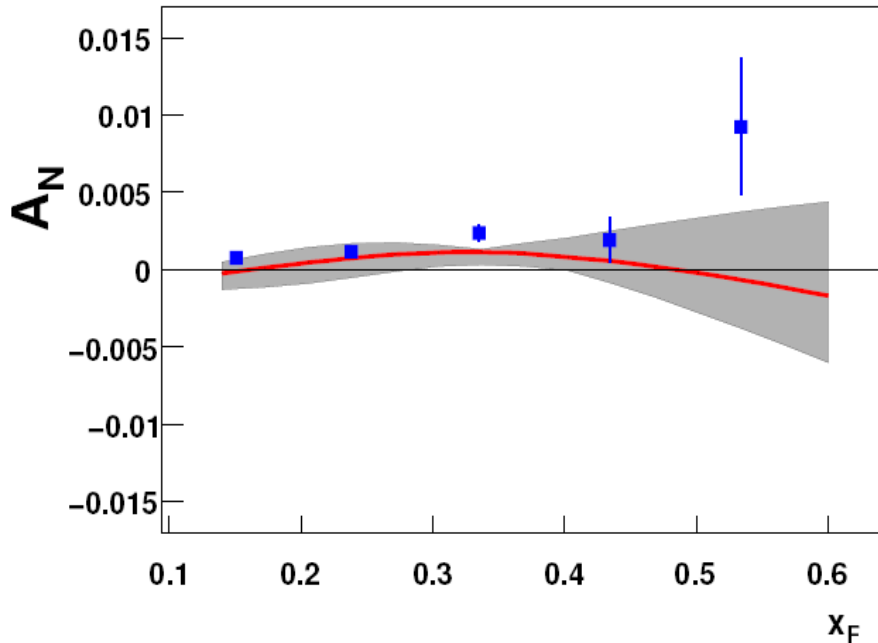
✓ TMD and twist-3
are compatible

✓ Sivers effect is process
dependent

Fundamental tests of QCD!

Jet AN

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Gamberg, Kang, AP (2013)

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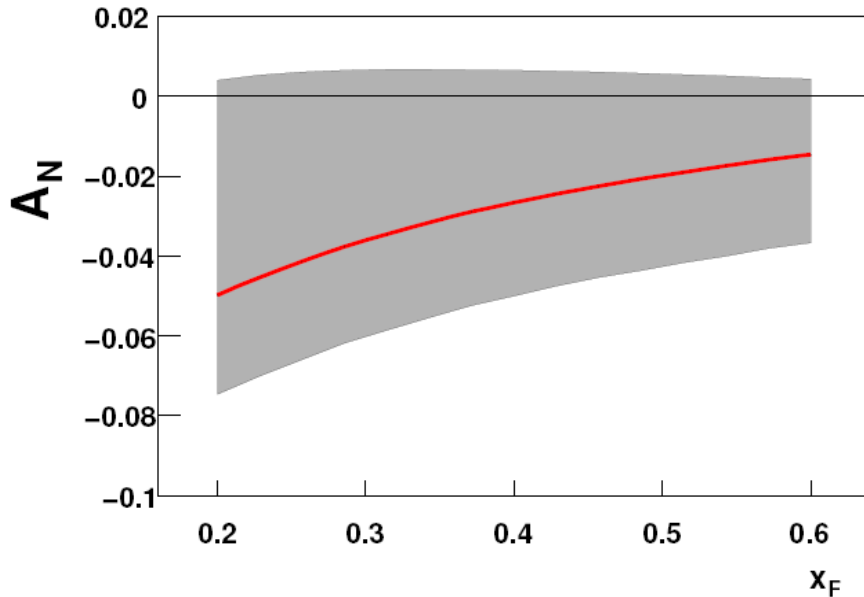
✓ TMD and twist-3
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✓ Sivers effect is process
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Yet future measurements are necessary
to confirm it: [see talk by Stefano Melis](#)

Future

Direct photon production $P^\uparrow P \rightarrow \gamma X$



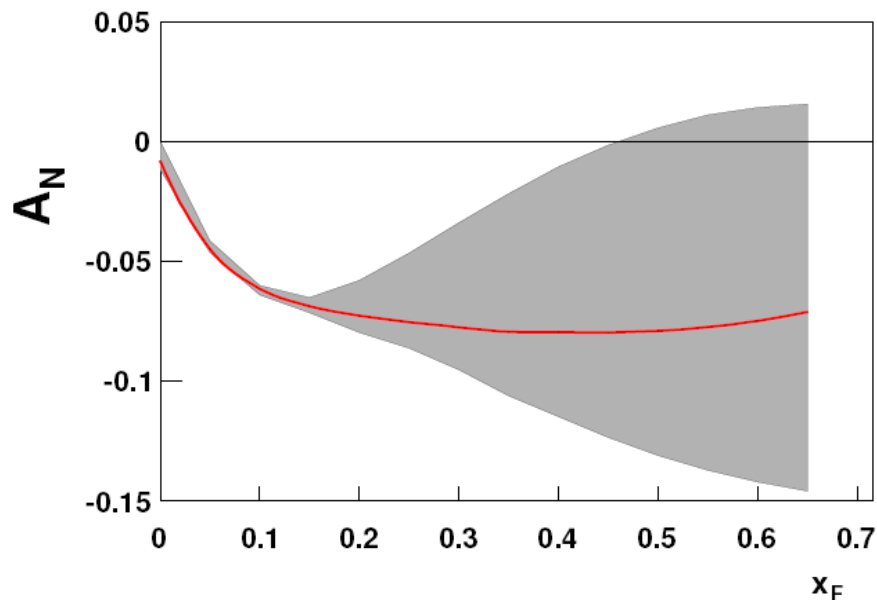
- Bigger asymmetry
- This measurement allows to test consistency of TMD and twist-3 factorizations

$$\langle y \rangle = 3.5, \sqrt{s} = 200(\text{GeV})$$

Gamberg, Kang, AP (2013)

Drell-Yan

$$P^\uparrow P \rightarrow \ell^+ \ell^- X$$



- This measurement proves directly process dependence of Sivers effect

$$4 < Q < 8(\text{GeV}) \quad \sqrt{s} = 500(\text{GeV})$$

Gamberg, Kang, AP (2013)

Conclusions

Recent AnDY data on Jet AN indicate

- Correctness of TMD and twist-3 relation
- The process dependence of the Sivers function

Future measurements to perform

- Direct photon
- Drell-Yan



QCD Evolution Workshop

QCD Evolution 2013

Jefferson Lab, May 6-10, 2013

<http://www.jlab.org/conferences/qcd2013/>

QCD Frontier 2013

QCD Frontier 2013

Exploring QCD with next generation facilities

Jefferson Lab, October 21-22, 2013

<http://jlab.org/conferences/qcd-frontier-2013/>