The RHIC Cold QCD Plan for 2017 to 2023
A Portal to the EIC

arXiv:1602.03922

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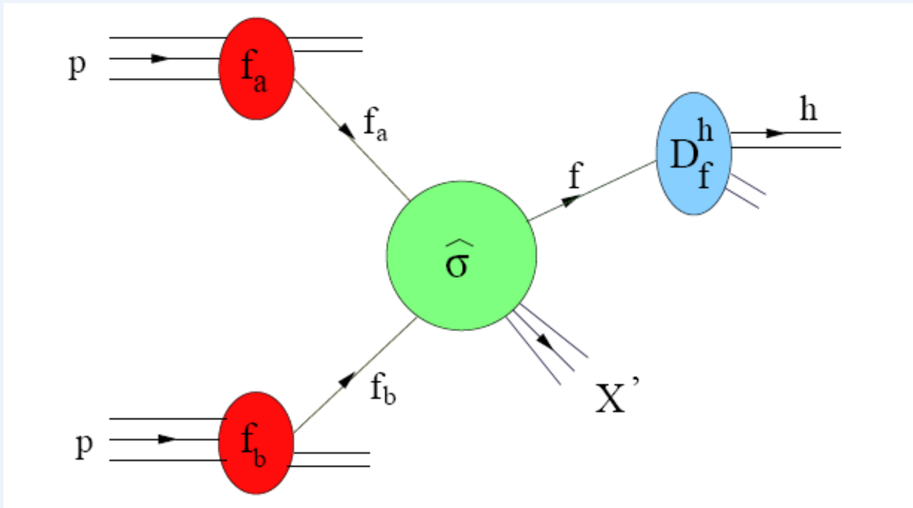
For RHIC Spin Collaboration

The 33rd Winter Workshop on Nuclear Dynamics

January 8-14, 2017

Snowbird, Utah

Factorization – a Cornerstone of QCD



Predictive power (for hard probes):

$$\sigma(pp \rightarrow hX) \sim f_a(x_1) \otimes f_b(x_2) \otimes \hat{\sigma}^{f_a f_b \rightarrow f}(\hat{s}) \otimes D_f^h(z)$$

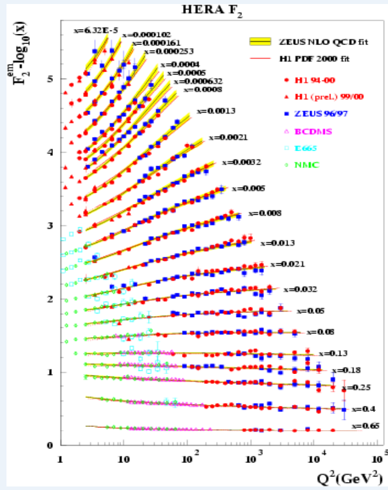
Parton Distribution Func.
from experiment
<u>**Universal**</u>

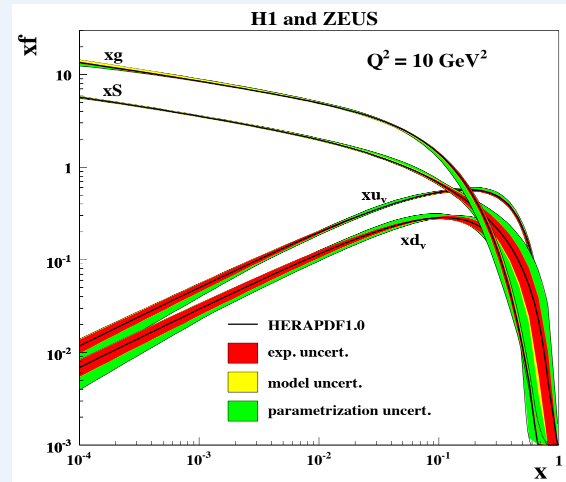
Partonic x-section
from pQCD
Process dependent

Fragmentation Func.
from experiment
<u>**Universal**</u>

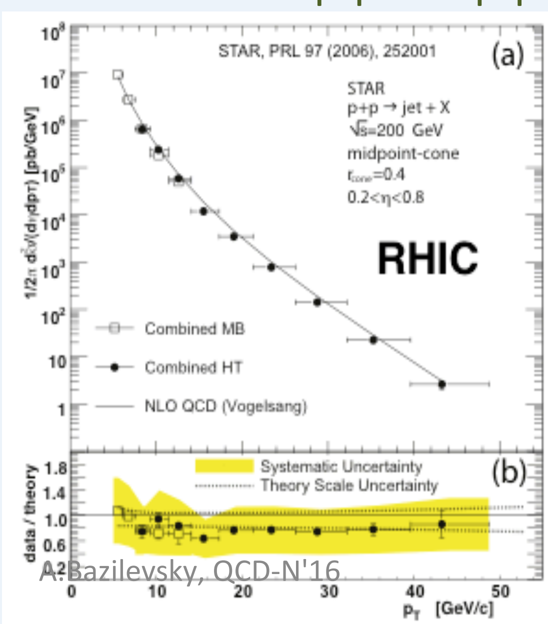
PDF (and FF) Universality

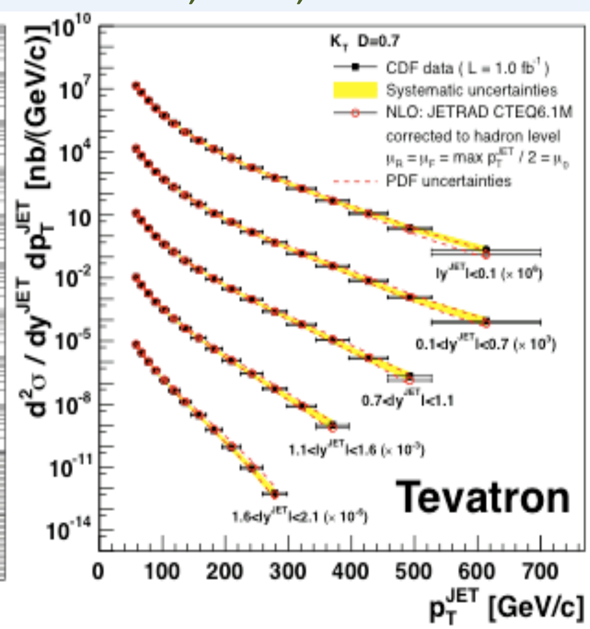
Measure PDFs in ep at 0.3 TeV (HERA):

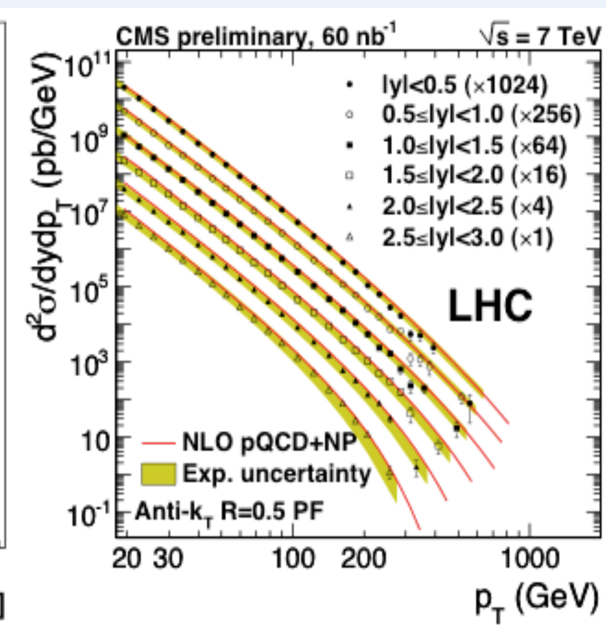




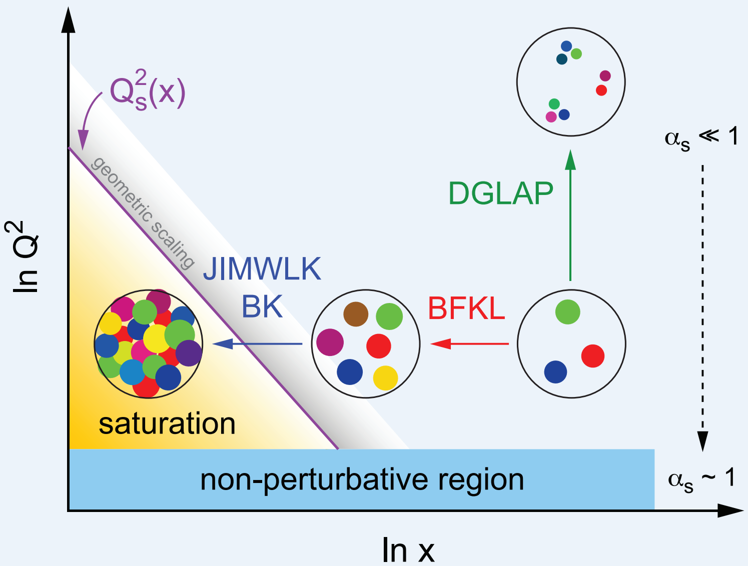
Predict p-p and p-pbar at 0.2, 1.96, and 7 TeV





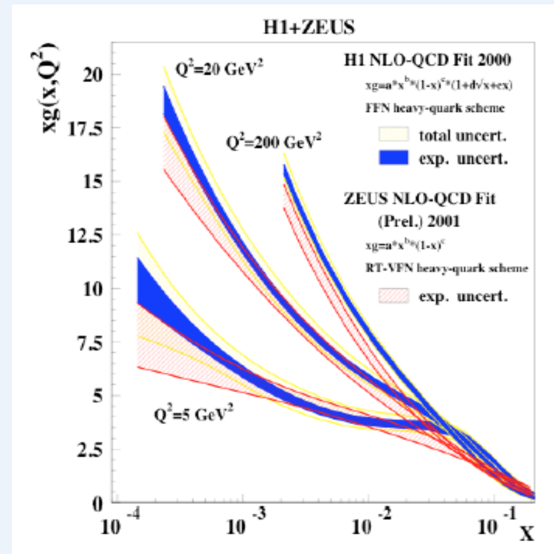


Evolution in QCD



DGLAP

f(x) -> f(x,Q)



Evolution is different (more complicated) for:

TMD: f(x) -> f(x,k_T)

Twist-3: f(x) -> T(x,x)

➔ Important for Spin effects studies

Completing the RHIC mission

US DOE Charge

- Compelling physics questions the future polarized p+p and p+A program at RHIC can address
- Unique "must-do" measurements, which require running beyond the currently planned RHIC runs
- Key measurements which are critical for the planning of the EIC physics program or are necessary as sources of critical information for the interpretation of the expected EIC data.
- Possible detector upgrades that are required to perform the proposed measurements

Year	Species @ √s (GeV)	Goals
2017	pp@510 GeV	Transverse Spin in QCD
2018	^{96}Ru - ^{96}Zr	Chiral Magnetic Effect in HI
2019/20	AuAu, low energy scan	Search for QGP critical point
2022	AuAu@200 GeV	Precision QGP measurements
2023	pp@200 GeV pA@200GeV	Transverse Spin in QCD A-dependence of nPDF and nFF

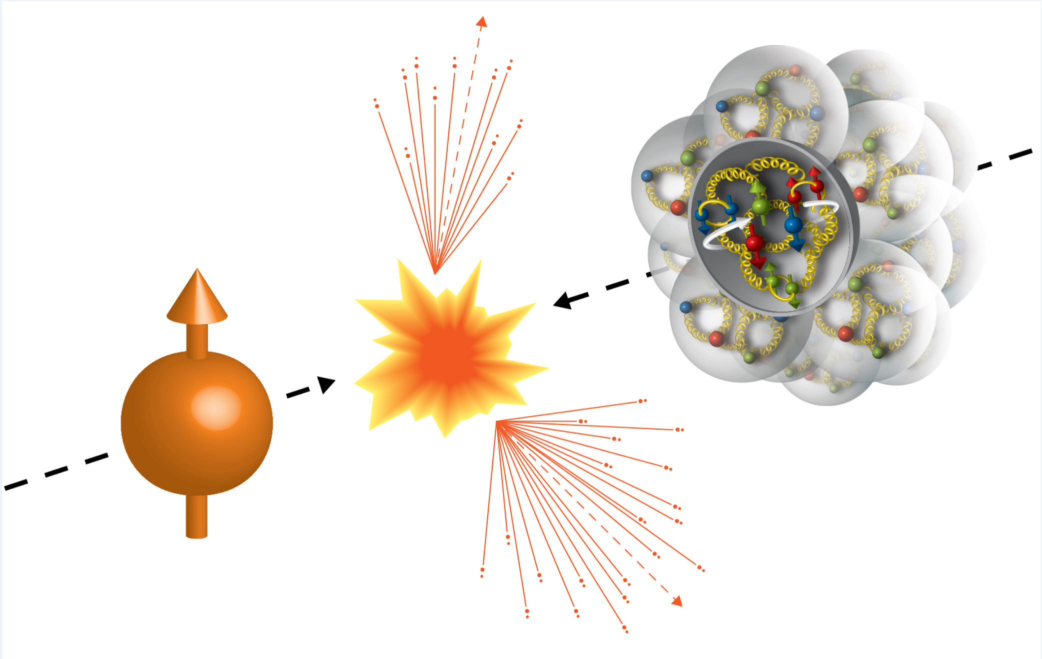
The Goals of the Plan

- Establish the validity and limits of **factorization** and **universality**
  - Essential to separate **intrinsic properties of hadrons** from **interaction-dependent dynamics**
  - Requires pushing the envelope beyond just those measurements that have been proven theoretically

    E.g. challenge theory prediction on **evolution** for Twist-3 and TMD PDF and FF
  - Requires precision measurements to enable meaningful comparisons between RHIC data and future EIC data

- Perform **key measurements** with a **broader range of probes** and **wider kinematic coverage** than will be possible at the EIC alone
  - Significantly enhance the impact and interpretation of the future EIC data

pA



RHIC's unique opportunities

→ A-scan (Au, Cu, Al, He, d …)

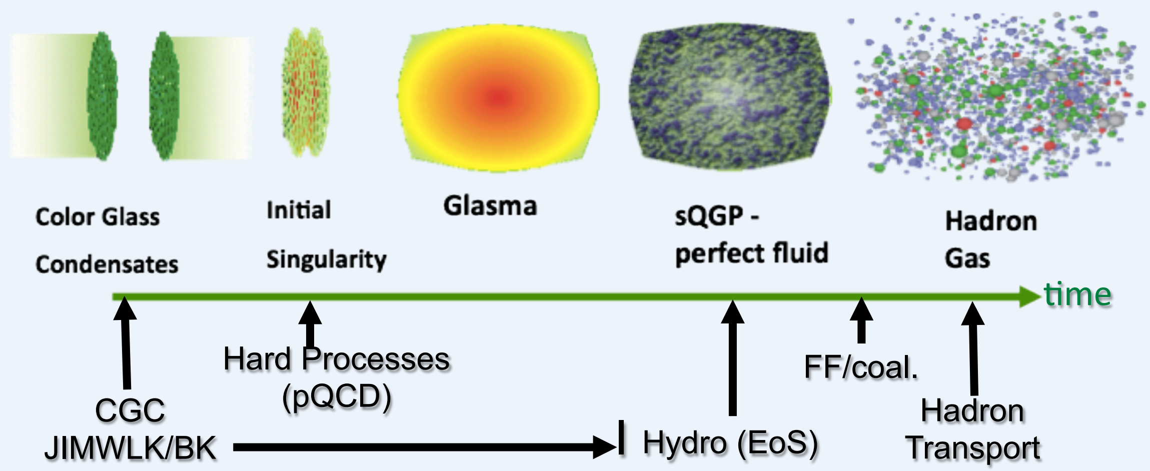
Nuclear dependence of PDFs, test for saturation models

→ Polarized proton beam

→ Energy scan

To separate different underlying mechanisms

pA -> Cold Nuclear Matter

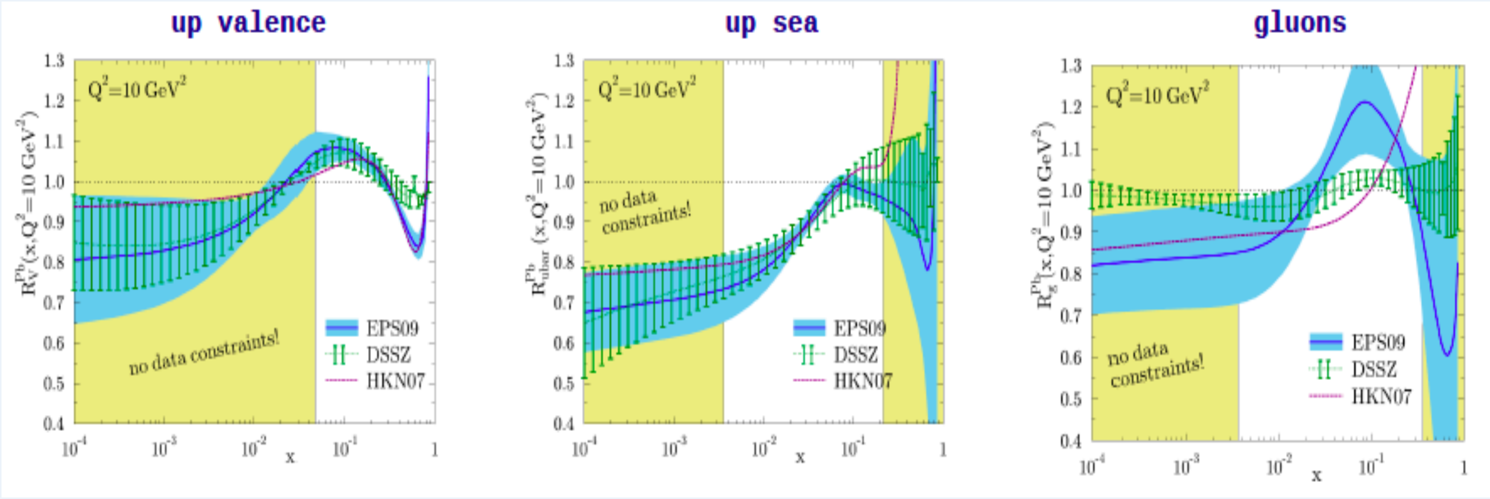


Understanding of Cold Nuclear Matter effects is necessary to understand fundamental properties of Hot Nuclear Matter (Glasma, sQGP)

Need to separate initial and final state effects

- Parton dynamics (Non-linear evolution? Saturated gluon fields?)
- Parton energy loss in CNM (connection to TMD?)
- Hadronization mechanisms

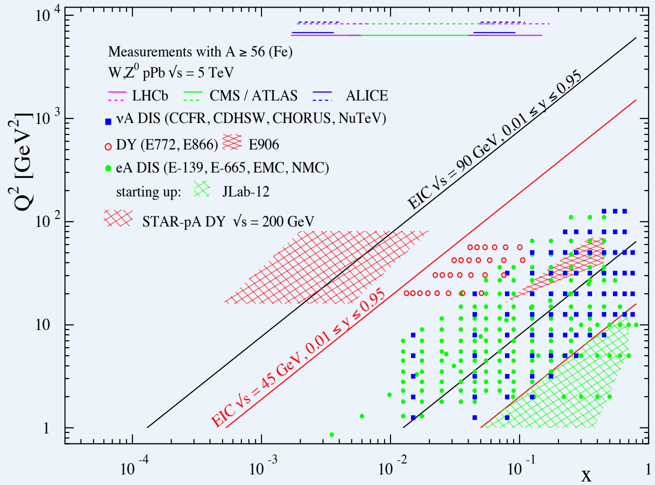
nPDF: Current State



DGLAP: predicts Q^2 but not A-dependence and x-dependence

Saturation models: predict A-dependence and x-dependence but not Q^2

Need: wide range in x at various Q^2; A-scan

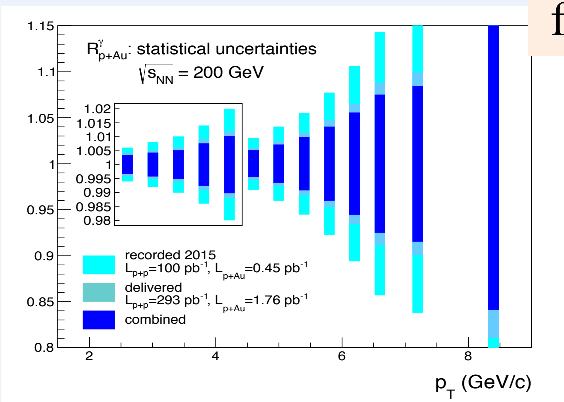


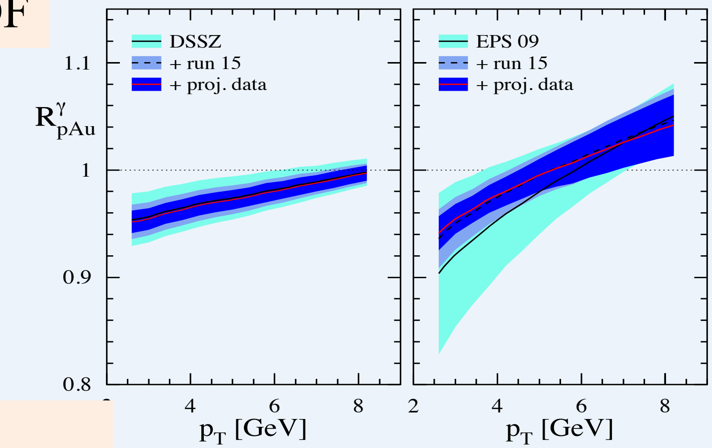
Observables:

- R_{pA} for dir. γ and DY (forward for low x)
- Correlations (di-h, di-jet, γ-h, γ-jet)

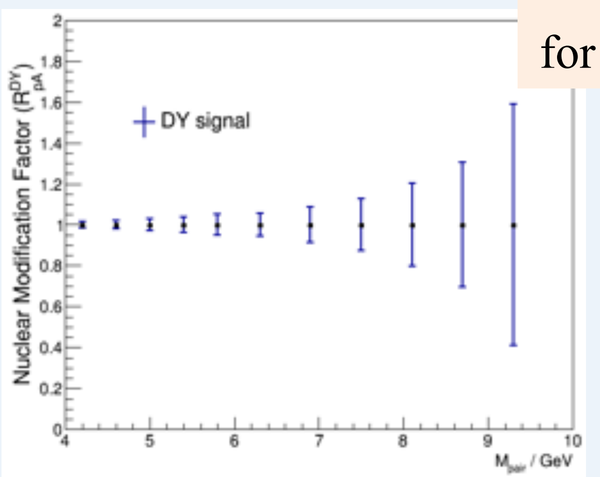
pA: nPDF

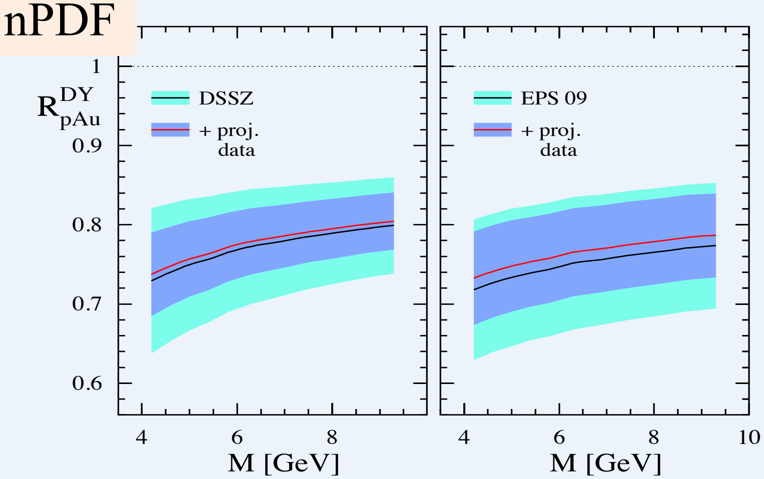
Direct γ
for gluon nPDF





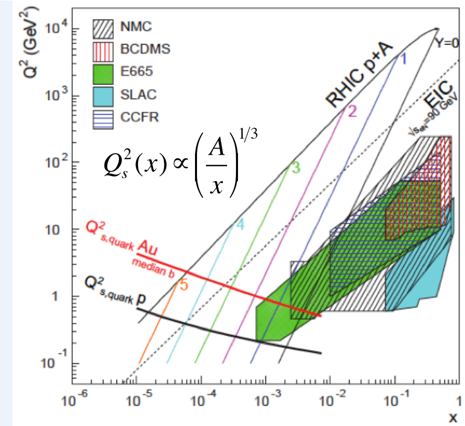
DY
for sea quark nPDF



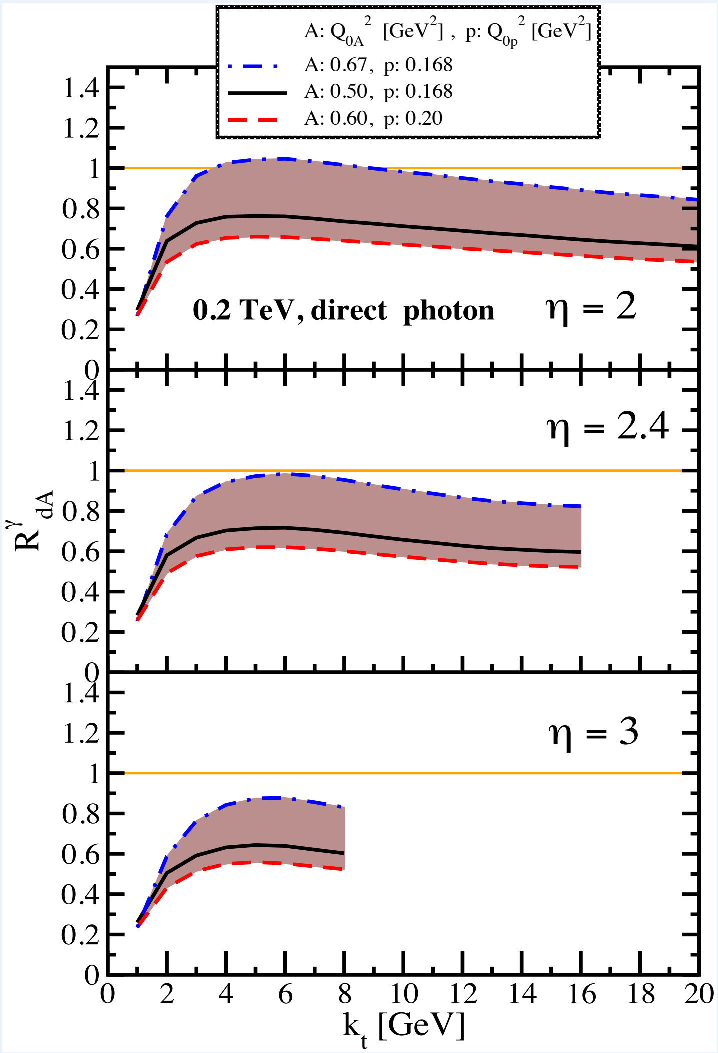


Significant constraint of nPDF with alternative observable and kinematics to EIC

pA: Saturation



CGC prediction for direct photon R_{pA}

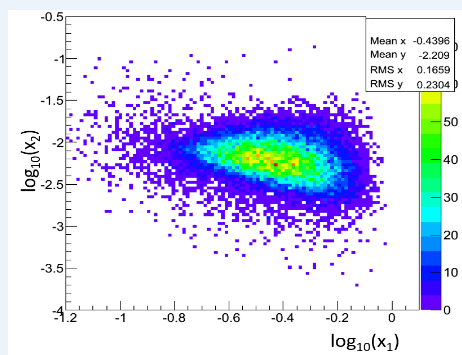


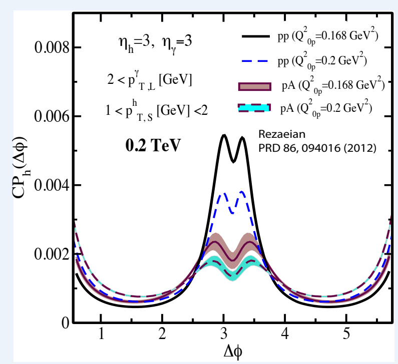
Forward-forward correlations

Selects large-x parton (quark) in p and low-x parton (gluon) in A

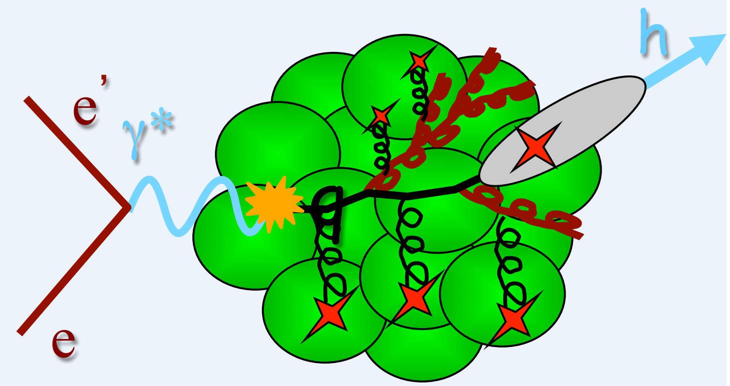
Di-hadron includes both initial and final state contributions

γ-jet and γ-h: no final state contribution; 1M events expected in 2023 from pAu and pAl

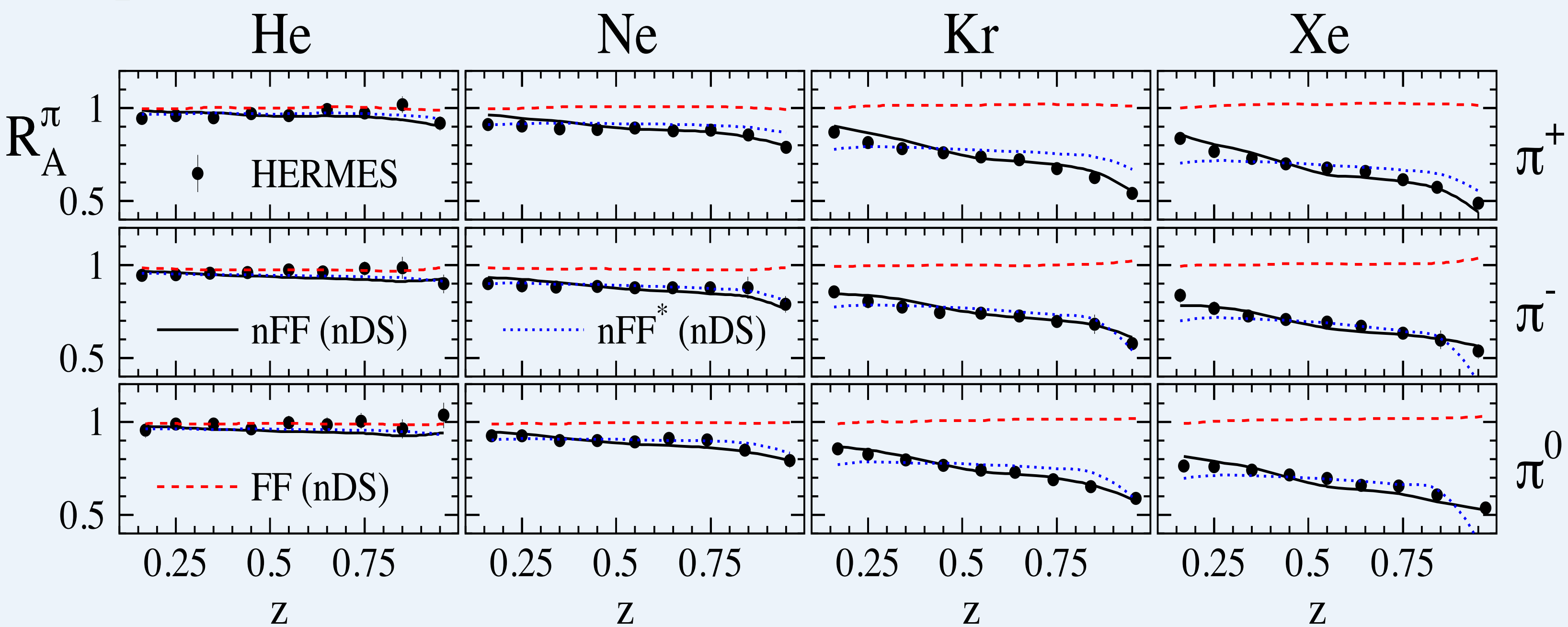




nFF



eA/ep



Production rate of hadrons in eA differs from ep

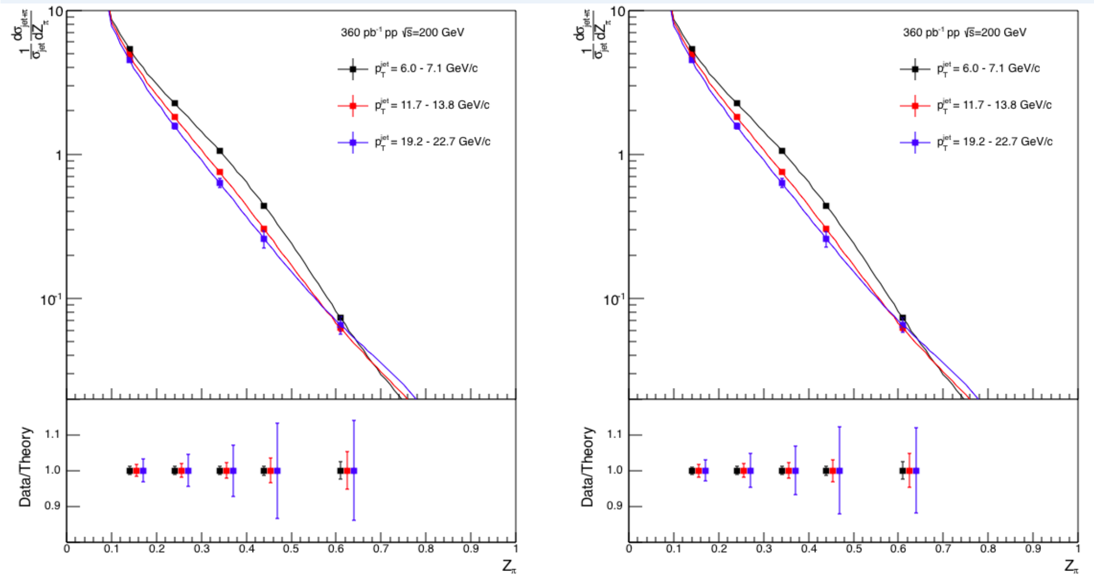
Can not be explained by nPDF

Do these effects survive at high √s?

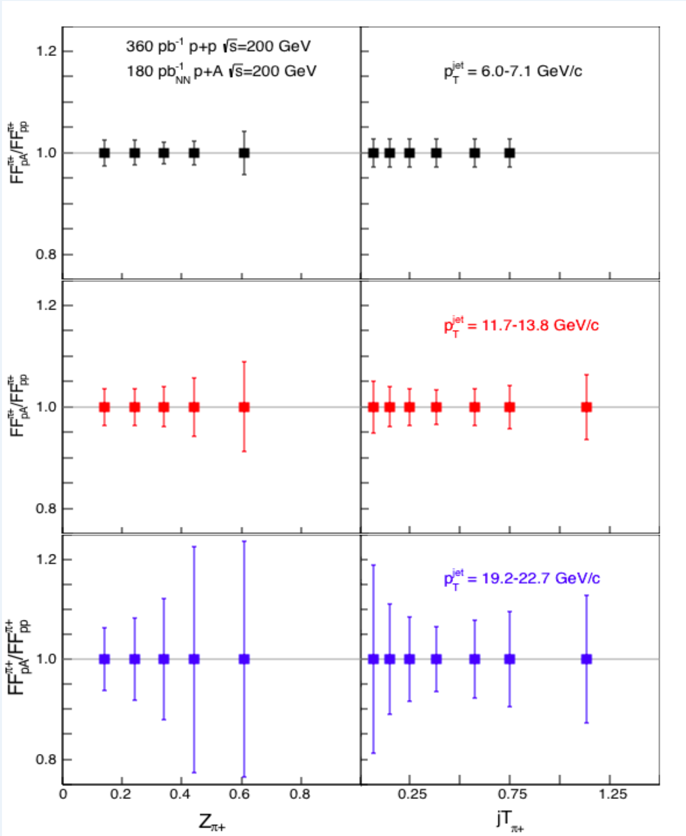
Are these effects universal?

=> RHIC pp

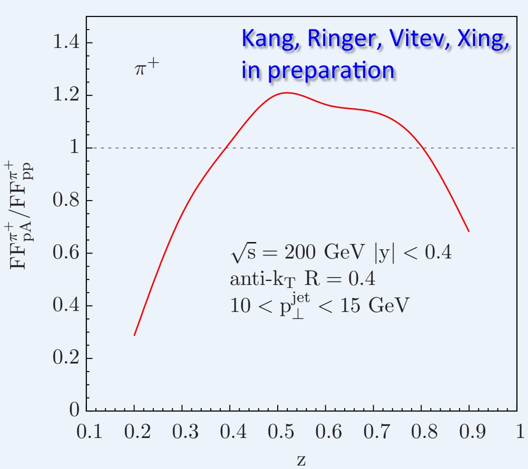
pA: nFF



Measure $d\sigma/dz_h$ within jet



Compare to pp



Polarized pp (pA)

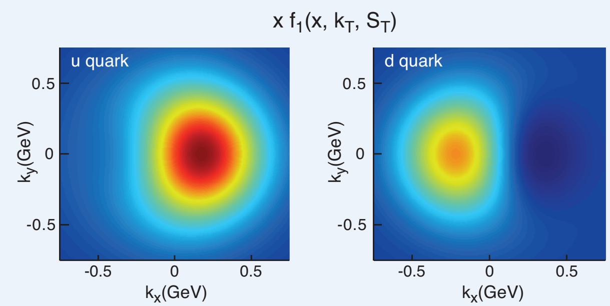
Focus on TMDs

Transverse Momentum Distributions (TMD)

Initially driven by spin studies, now getting broader application

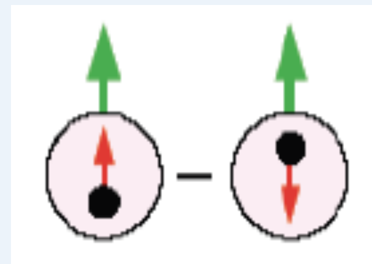
Expand nucleon and nuclei imaging from 1D to (2+1)D

Correlation between proton trans. spin and parton kT (Sivers function) is sensitive to orbital angular momentum



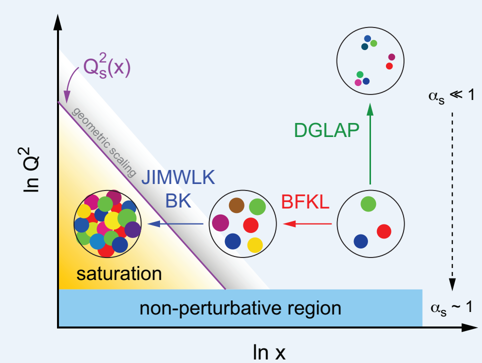
Correlation between trans. spin of fragmented quark and hadron pT (Collins FF) gives access to tensor charge (valence quark transversity $\delta q = \int_0^1 (\delta q(x) - \delta \bar{q}(x))dx$)

- Fundamental value, calculable on the lattice
- Sensitivity to beyond standard model (BSM)



Un-integrated gluon density g(x,Q2,kT) is critical for physics at small x

- Connection to CGC
- Applications to LHC, e.g. Higgs production



Trans. Spin: To measure at RHIC

Initial State:

Sivers/Twist3 mechanism

- A_N for jets, direct photons
- A_N for heavy flavor ➔ gluon
- A_N for W, Z, DY

Sensitive to correlations
proton spin – parton **transverse motion**

Not universal between SIDIS & pp

Final State:

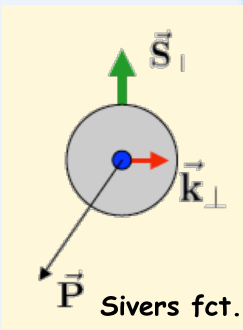
Collins mechanism

- Hadron azimuthal asymmetry in jet
- Hadron pair azimuthal asymmetry
  (Interference fragmentation function)

Sensitive to
transversity x spin-dependent FF

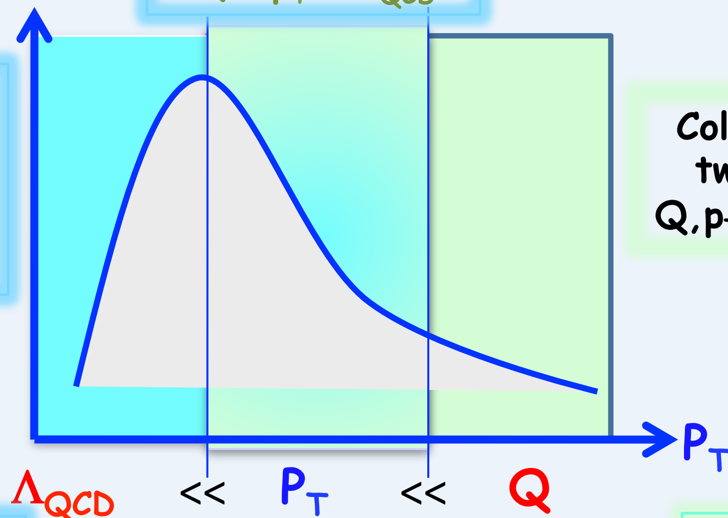
Universal between SIDIS & pp & e+e-

Initial State: TMD vs Twist3

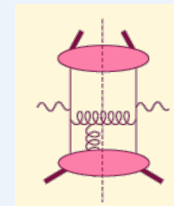


Transverse momentum dependent
$Q >> p_T >= \Lambda_{QCD}$

Intermediate p_T
$Q >> p_T >> \Lambda_{QCD}$



Collinear/ twist-3
$Q, p_T >> \Lambda_{QCD}$



Efremov, Teryaev; Qiu, Sterman

Requires 2 scales:

Hard Q^2 and soft p_t

SIDIS, DY, W/Z

Access to full kT dynamics

Ji, Qiu, Vogelsang, Yuan, PRL. **97**, 082002 (2006).

Single hard scale p_T

Applicable to pp observables $A_N(\pi^0/\gamma/jet)$

Access the average <kT>

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

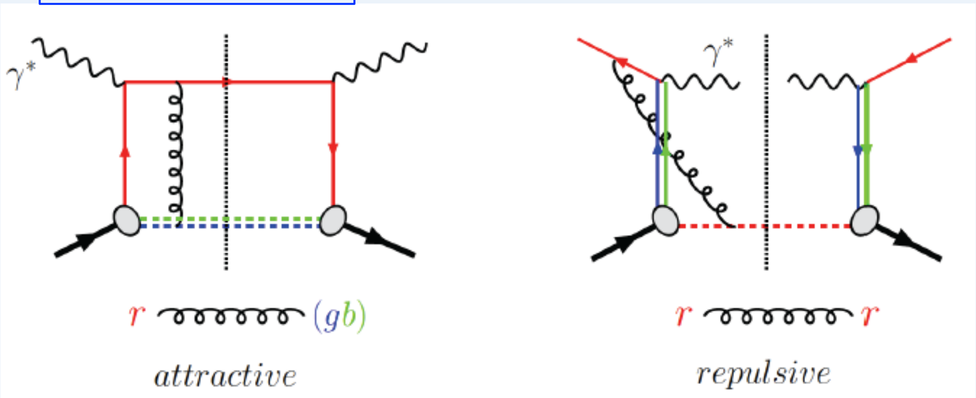
Color Interaction in QCD

Controlled non-universality of Sivers function

QCD:

DIS
Attractive FSI

Drell-Yan, W or Z
Repulsive ISI



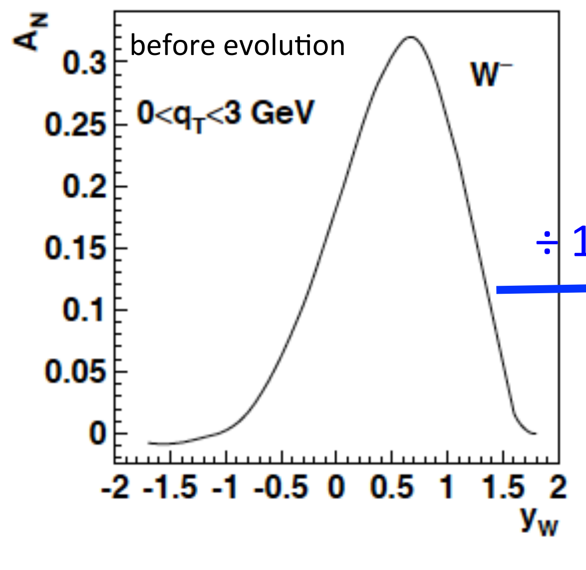
$\text{Sivers}_{DIS} = -(\text{Sivers}_{DY}$ or Sivers_{W} or $\text{Sivers}_{Z})$

A_N(dir. γ) has related sign change in Twist-3

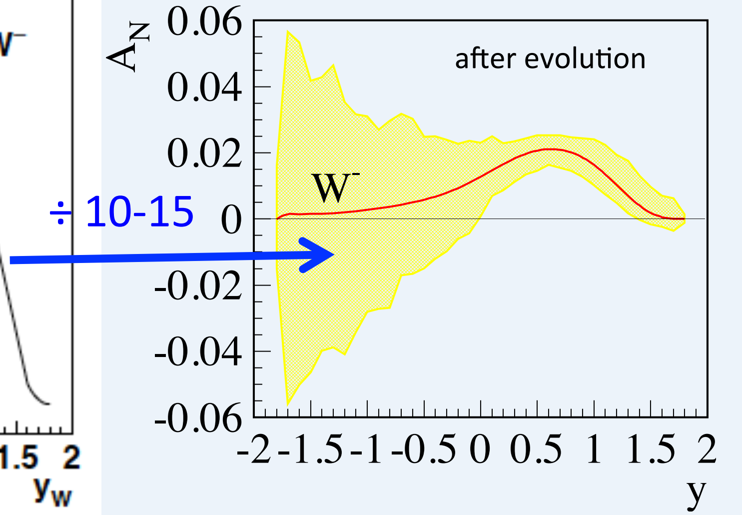
Critical test of TMD factorization
All observables can be explored at RHIC

Trans. Spin: Initial state

Z.-B. Kang & J.-W. Qui arXiv:0903.3629



Z. Kang: original paper arXiv:1401.5078

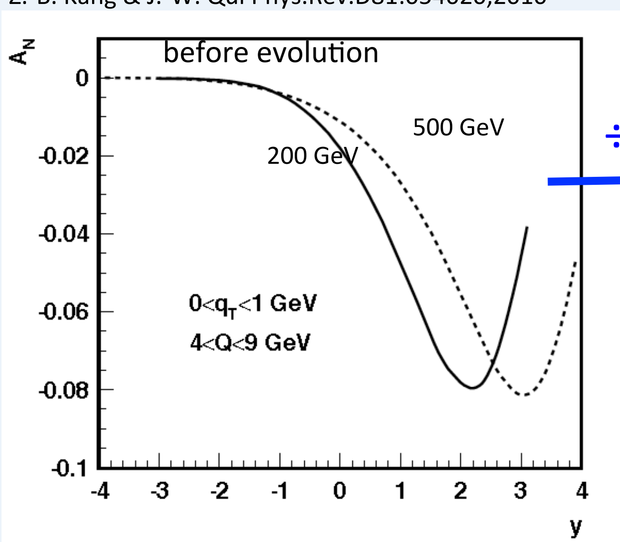


Sivers function non-universality and evolution

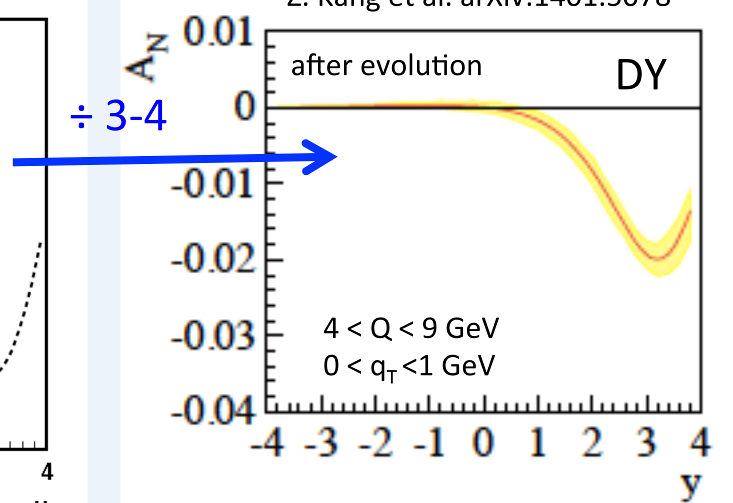
Too strong evolution effect ?
– No consensus yet

Need experimental data!

Z.-B. Kang & J.-W. Qui Phys.Rev.D81:054020,2010

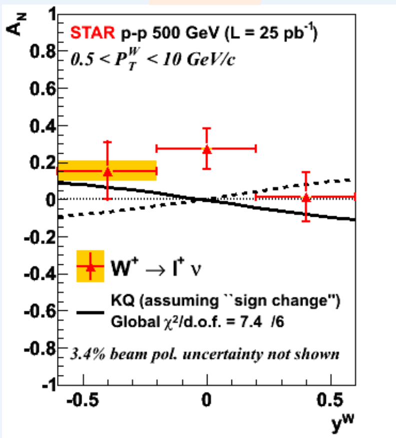


Z. Kang et al. arXiv:1401.5078

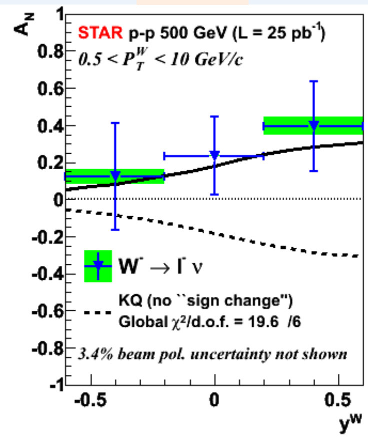


Trans. Spin: Initial State

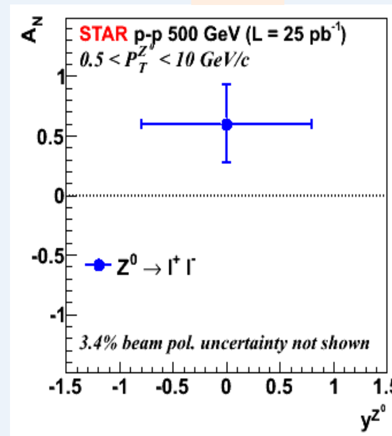
W+



W−



Z0

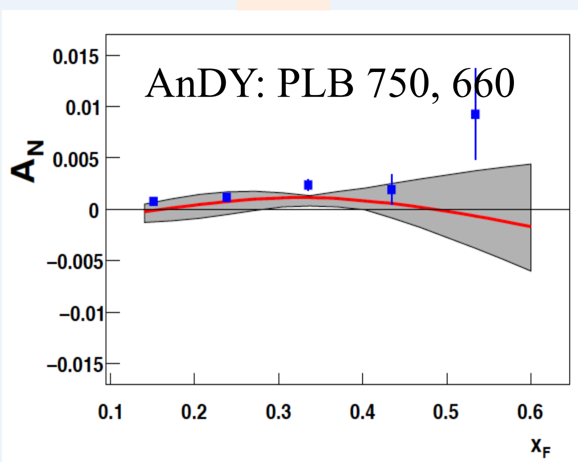


Run-2009
(PRL 116, 132301)

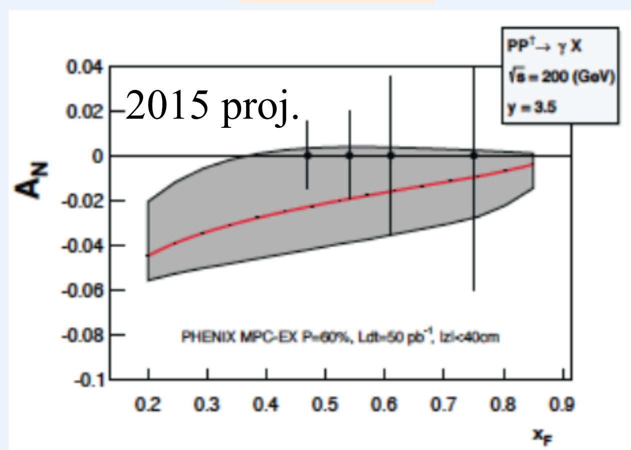
First hint
for Sivers function
sign change!

Evolution is small?

Jet



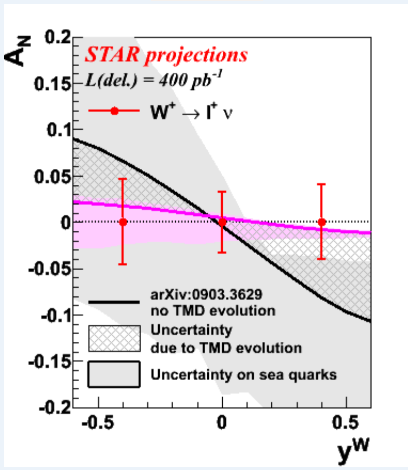
Photons



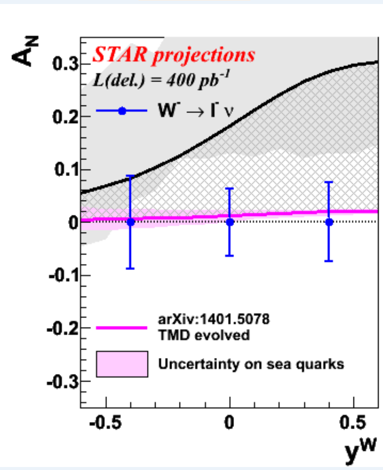
Trans. Spin: Initial State

Run 2017
$p\uparrow p @ 510 GeV$

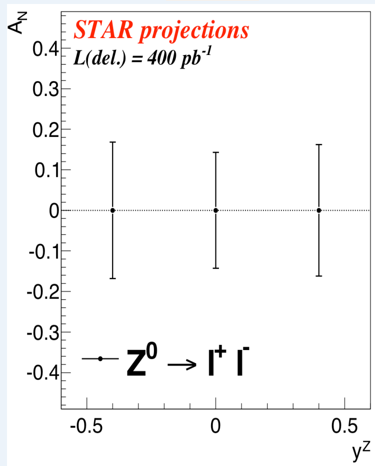
W+



W−



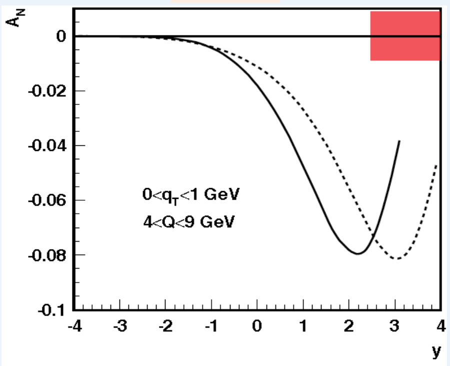
Z0



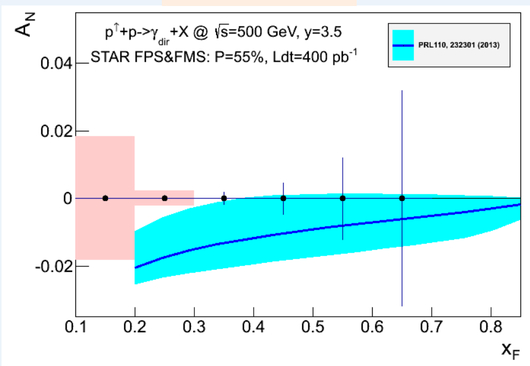
Proj. for Run-2017

(a factor ~4 reduced uncertainties compared to Run9)

DY



Photons

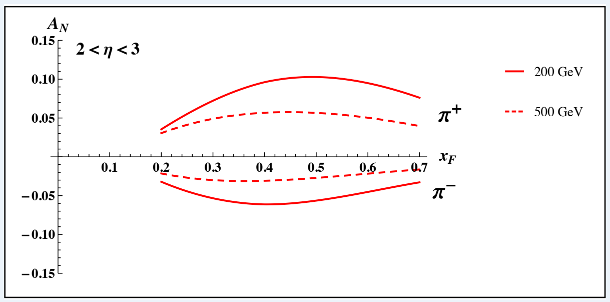


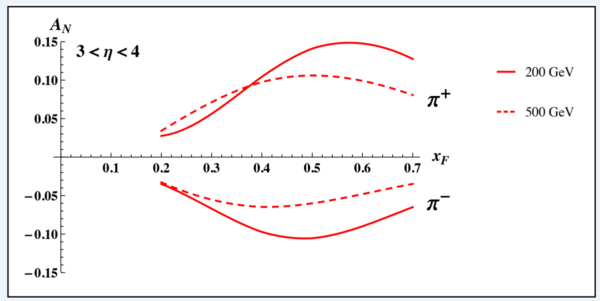
Trans. Spin: Initial state

Run 2023+
$p\uparrow p@200,510\,GeV$

×2 reduced uncertainties for earlier measurements: W, Z, DY, γ

With forward upgrade: Calorimetry + Tracking



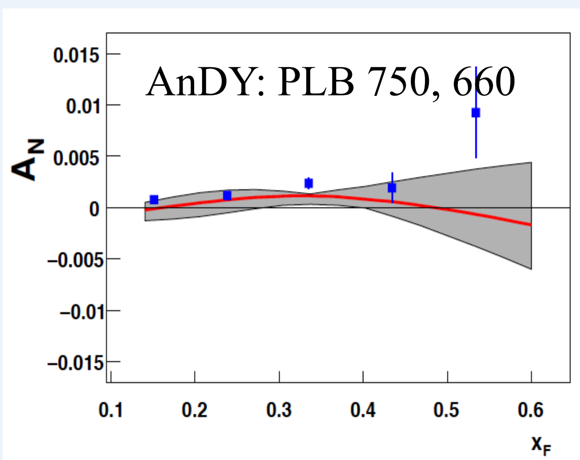


Charged hadron A_N at highest √s

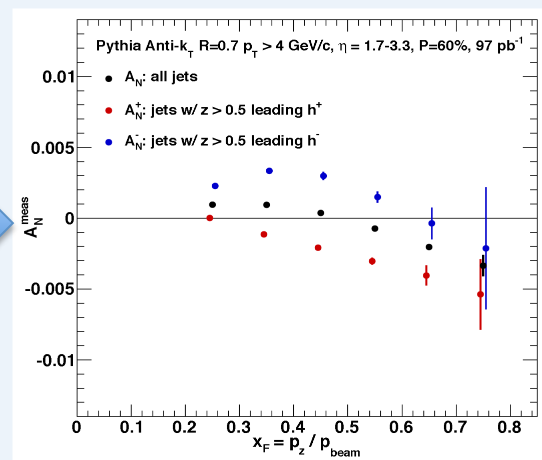
Twist-3 correl. func. flavor dependence and evolution

Twist-3 FF contribution

Jet



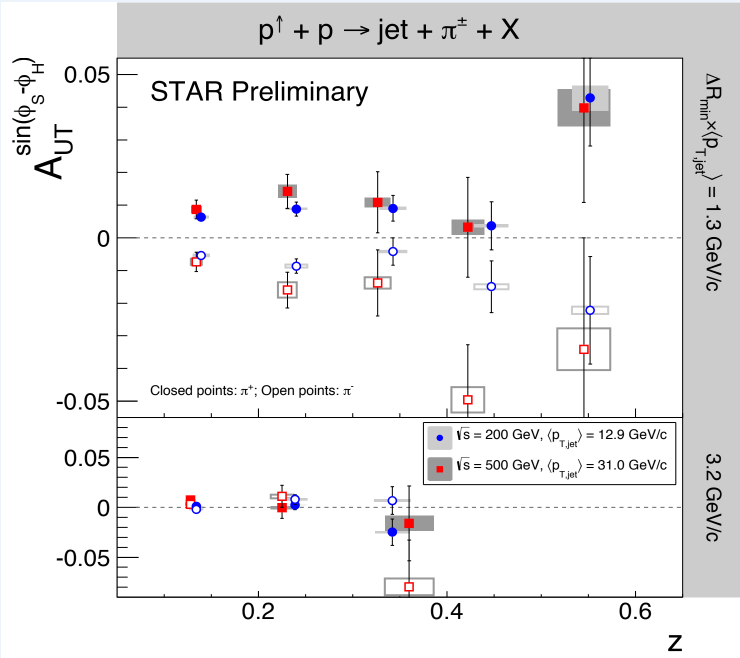
u/d enhanced jet

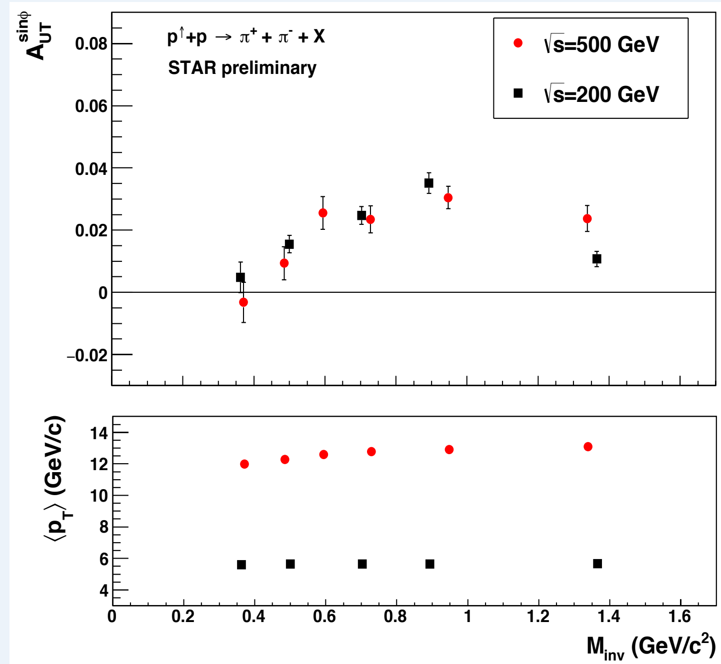


Twist-3 correl. func. flavor dependence:

u (d) jet enhanced by h+(-) tagging at z>0.5

Trans. Spin: Final State Mechanism





First Collins asymmetry in pp !

=> Access to transversity!

Asymmetry similar at 200 vs 500 GeV

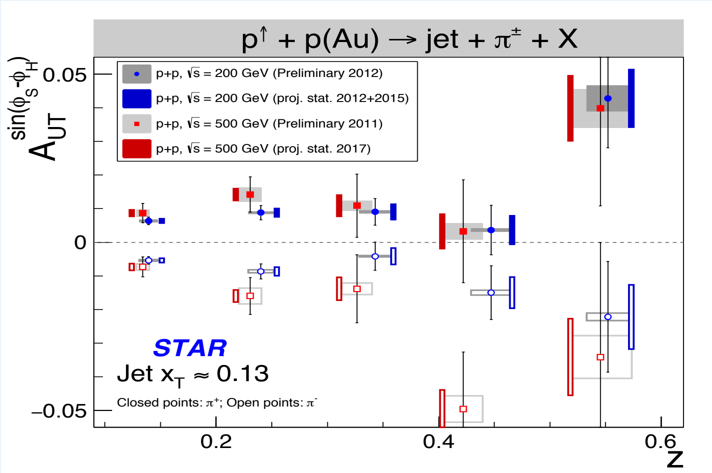
=>TMD evolution is small?

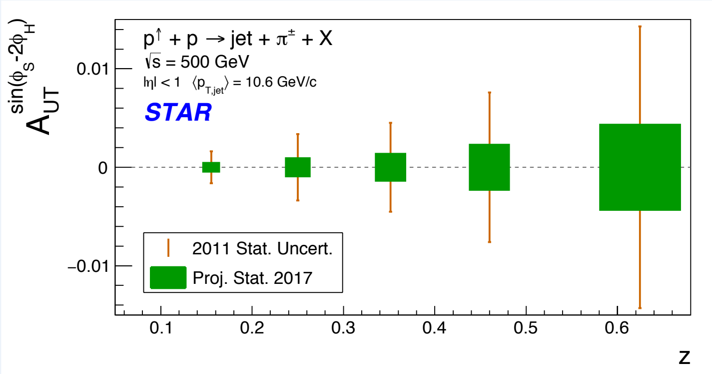
First IFF (Interference Fragmentation) asymmetry in pp !

=>Another way to access transversity !

Trans. Spin: Final state

Run 2017
$p\uparrow p@510GeV$





<u>Considerably improve earlier measurements:</u>

Transversity through Collins vs IFF
⇒ Universality and factorization breaking

√s=200 vs 500 GeV
⇒ Evolution

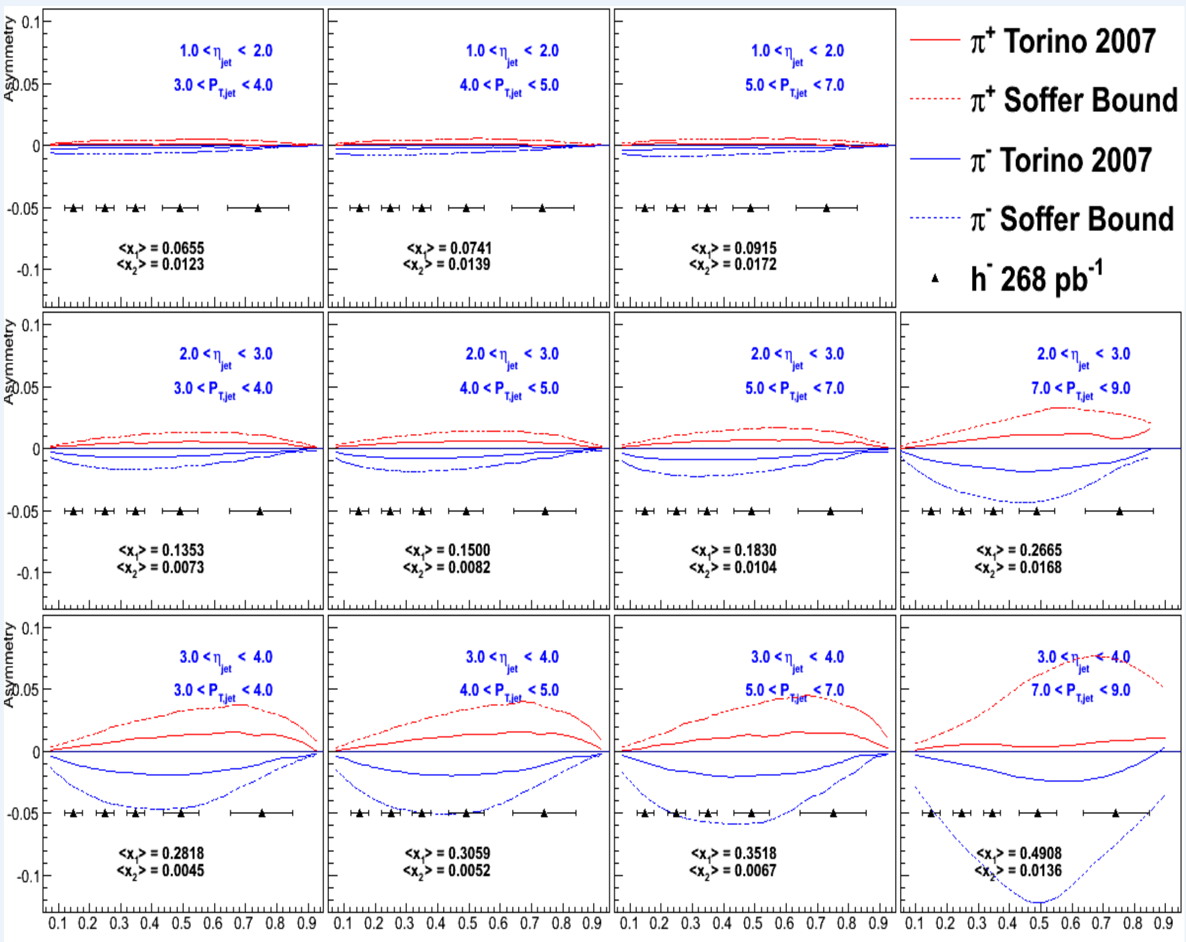
Linearly polarized gluon PDF through $\sin(\phi_s\text{-}2\phi_h)$ modulation

Trans. Spin: Final state

Run >2023?
$p\uparrow p@510GeV$

×2 reduced uncertainties for earlier measurements

h± Collins asymmetry within jet



Need forward upgrade:

To understand the contribution of final state effect to hadron SSA

Need x>0.3 (for tensor charge)

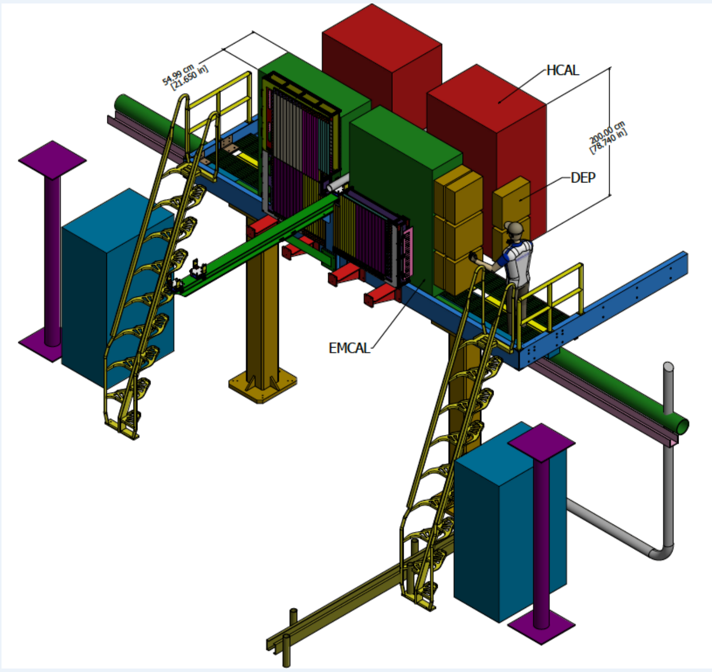
Need lower x (to study gluons)

Proposal Summary

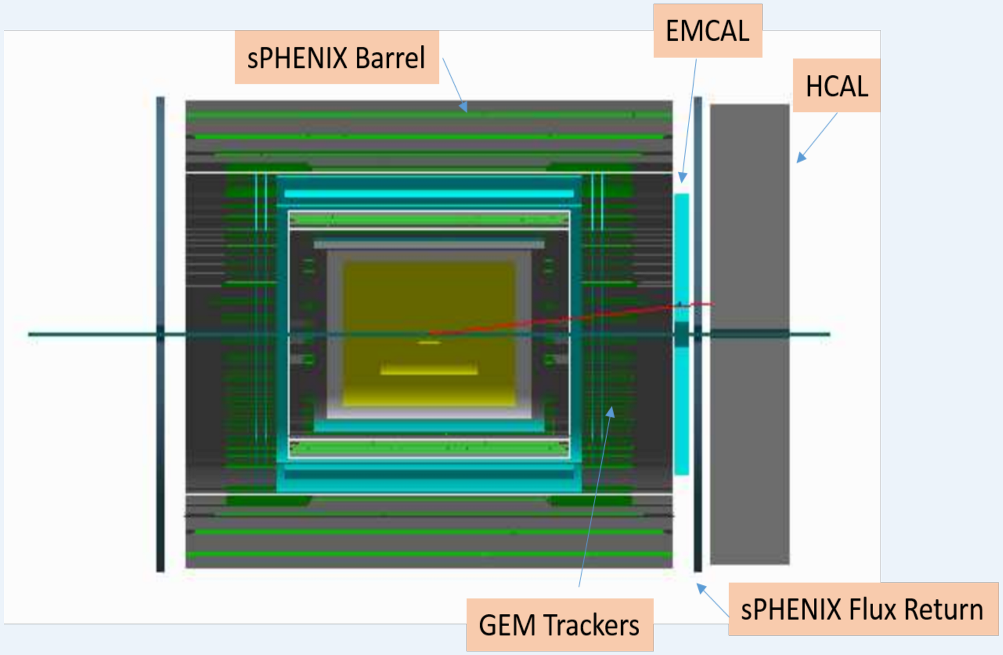
	Year	$\sqrt{s}$ (GeV)	Goals	Observables	Upgrade	
Scheduled RHIC Running	2017 $p\uparrow p$	510	Sivers non-universality TMD and Twist-3 evolution Transversity, Collins FF, lin. pol. gluons, gluon Sivers GPD Eg	A_N for γ, W, Z, DY A_{UT}~$\sin(\phi_s-\phi_h)$, $\sin(\phi_s-2\phi_h)$ within jet, A_{UT}~$\sin(\phi_s)$ for jets A_{UT} for J/ψ in UPC	DY: Postshower to FMS@STAR None None	
	2023 $p\uparrow p(A)$	200	Source of A_N at high xF, Twist-3 flavor dependence Diffraction	A_N for h± and flavor enhanced jets A_N for diffraction	Forward None	
Proposed Running	202X $p\uparrow p$	510	TMD at low and high x Validity and limits of factorization and universality in ep vs pp	A_{UT} for h± in jet in forward- and mid-rapidity	Forward None	
	202X $\vec{p}p$	510	Δg at small x	A_{LL} for jets, π0, di-jets, h/γ-jet	Forward	If EIC not realized or delayed

Forward upgrade for 2020+

STAR



fsPHENIX



Add forward instrumentation up to η=4:
EMCal+Hcal+Tracking

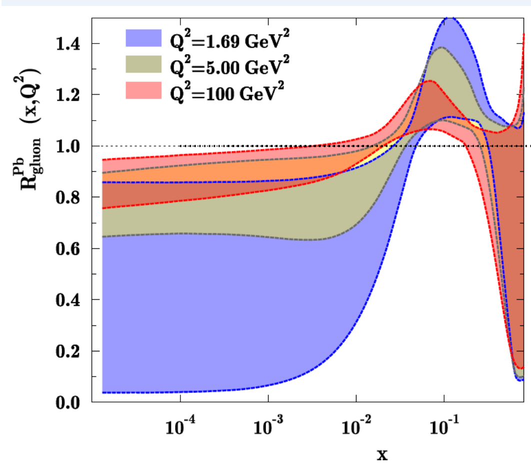
(Instead of) Summary

Factorization & Universality	=> both p+p(A) and e+p(A)
Evolution	=> different √s
Higher and lower x Also the source of large A_N in pp	=> forward instrumentation
Precision	=> more L
Unique measurements: probes and kin. ranges; e.g. W, DY, Twist-3	=> p+p(A)

Backup

nPDF from LHC

N. Armesto, *et al.*, arXiv:1512.01528



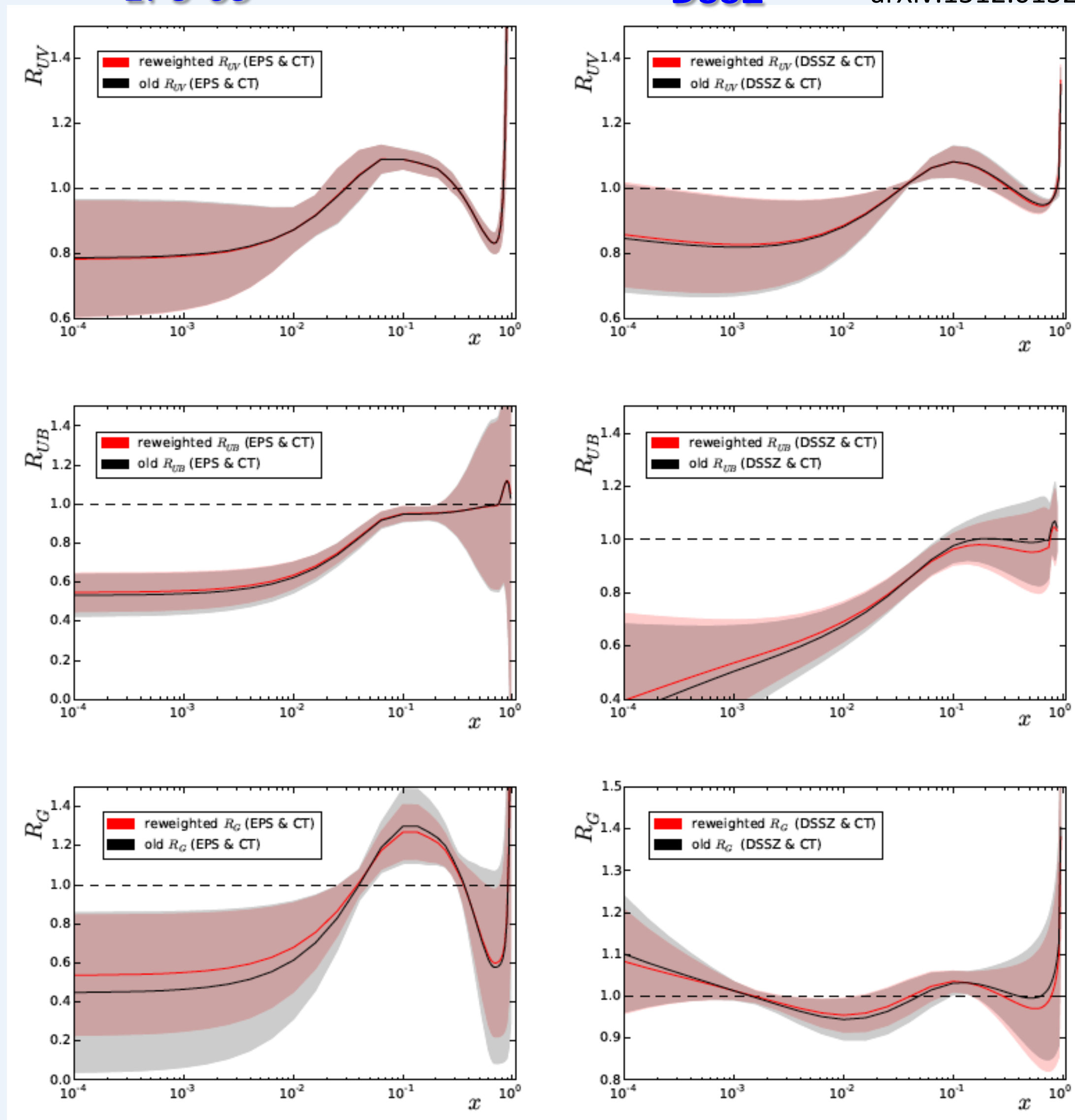
EPS-09

DSSZ

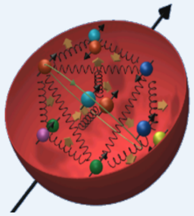
Valence Quark

Sea Quark

gluons

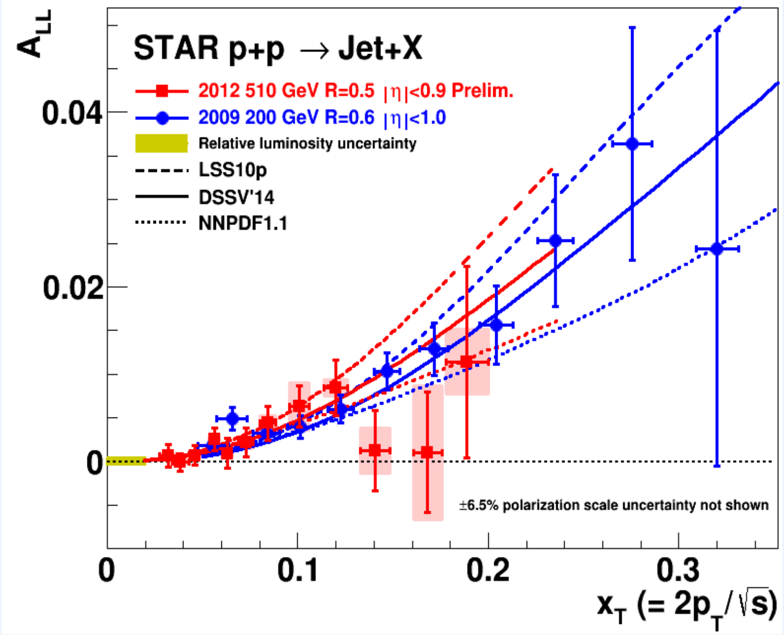


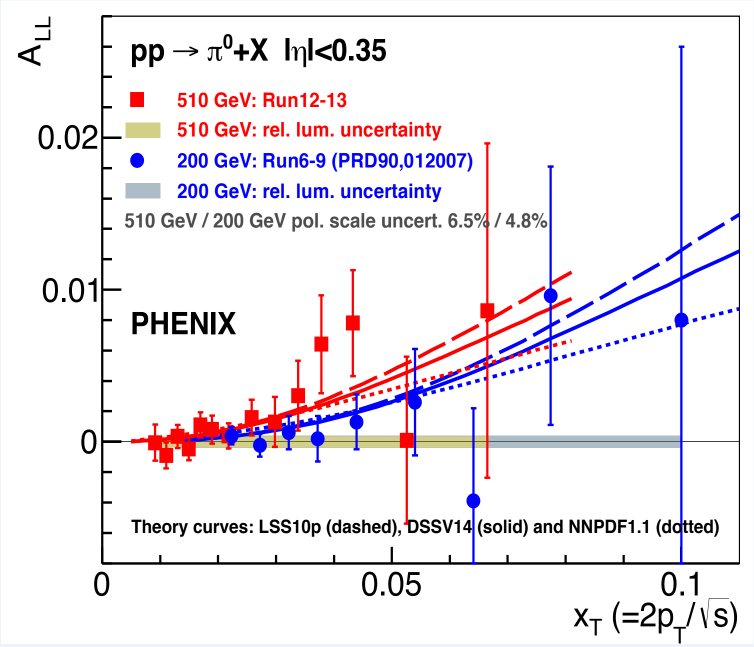
ΔG: π0 and jet A_{LL}



Are gluons polarized?

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta\bar{q}) + \Delta G + L_z$$

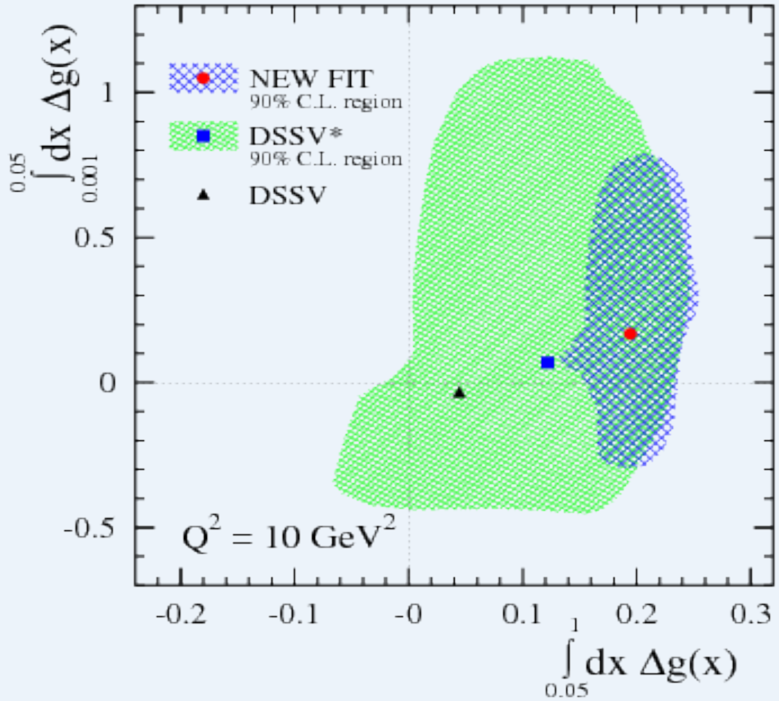




Observation of non-zero A_{LL}
associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

DSSV:
D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang



DSSV: Phys Rev Lett, 101, 072001 (2008)
Data from up to 2006

New DSSV: Phys Rev Lett, 113, 012001 (2014)
Data from up to 2009

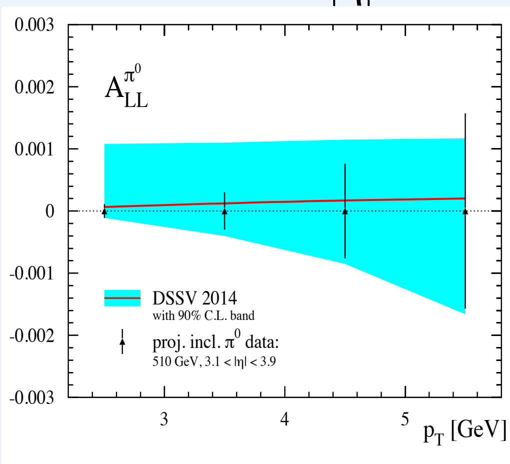
$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07}$$

Significant non-zero Δg(x) in the kin. region probed by RHIC
Similar result from another global fit NNPDF
Still huge uncertainty in unmeasured region (x<0.05)
=> Measurements at higher √s and forward rapidity

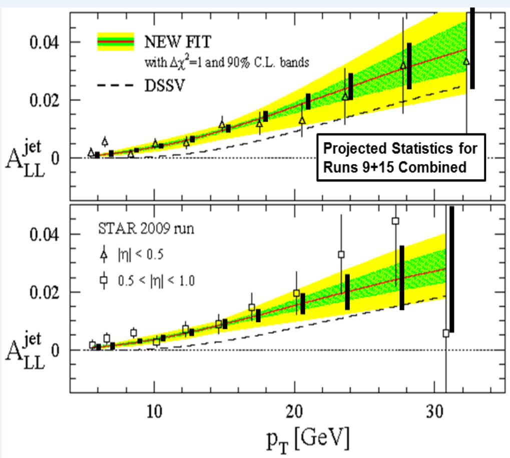
ΔG: Near Term Projections

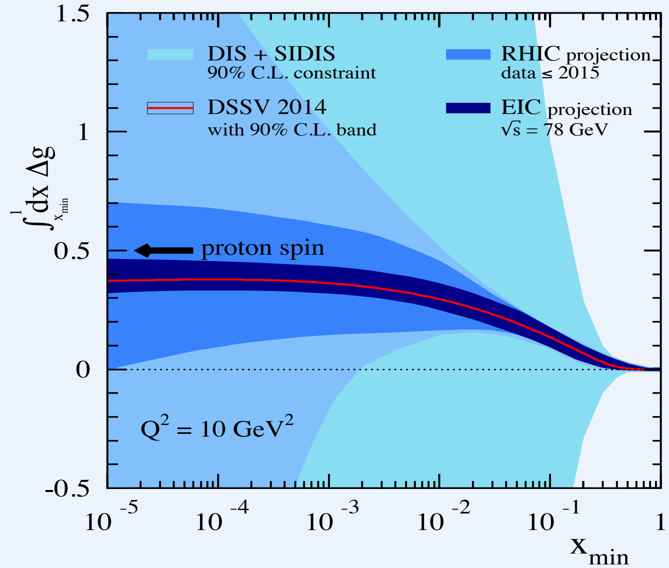
From already available data from 2011-15

π0: 3.1<|η|<3.9



Jets: |η|<1





Other channels also being measured (but with weaker stat. power)

γ, η, π±, h±, heavy flavor through e and μ, jet-jet, h-h, γ-jet, γ-h

Great improvement expected

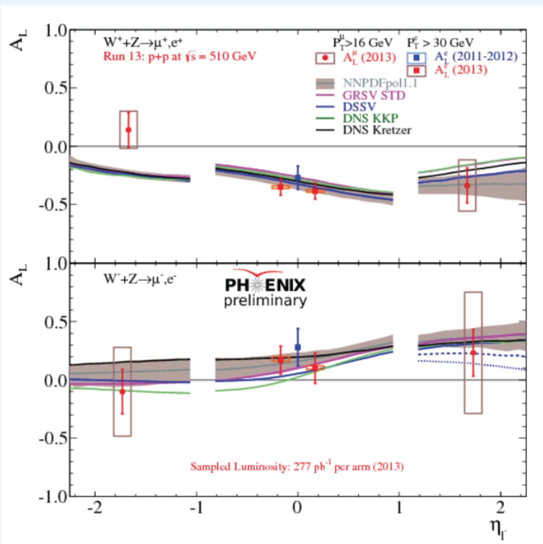
… Still not enough precision for ΔG full integral

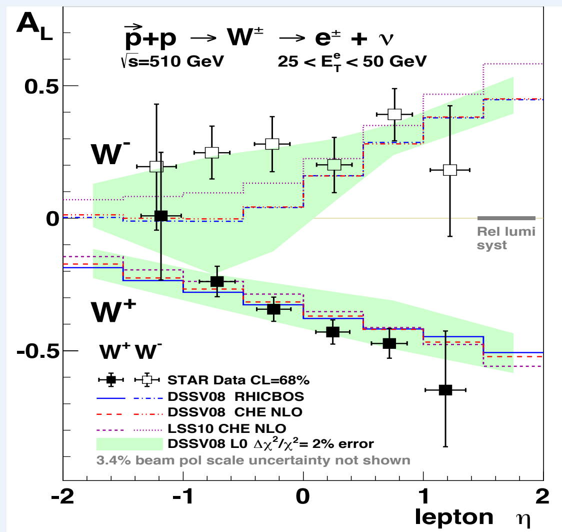
$$d_L \bar{u}_R \rightarrow W^-$$
$$u_L \bar{d}_R \rightarrow W^+$$

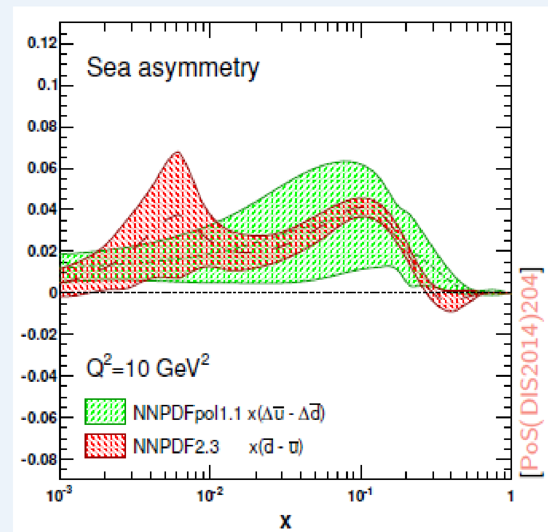
Δq-bar: W± → l±

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_Z$$

Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at x>0.05, with no fragmentation involved (as in SIDIS)



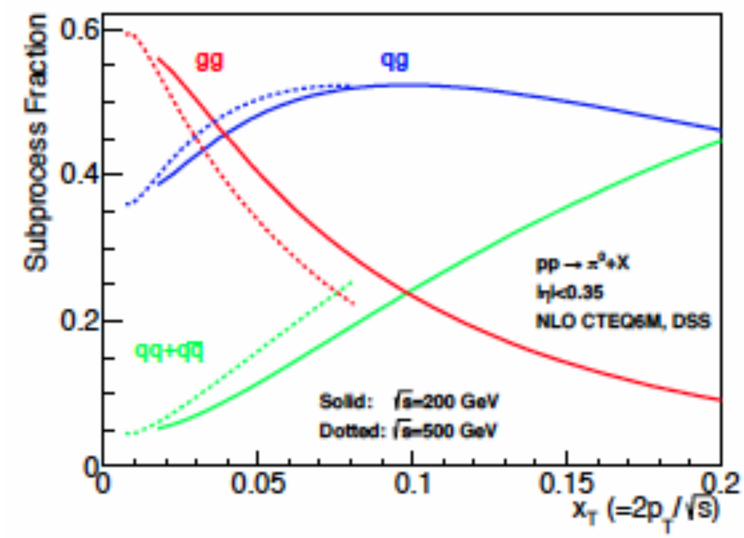


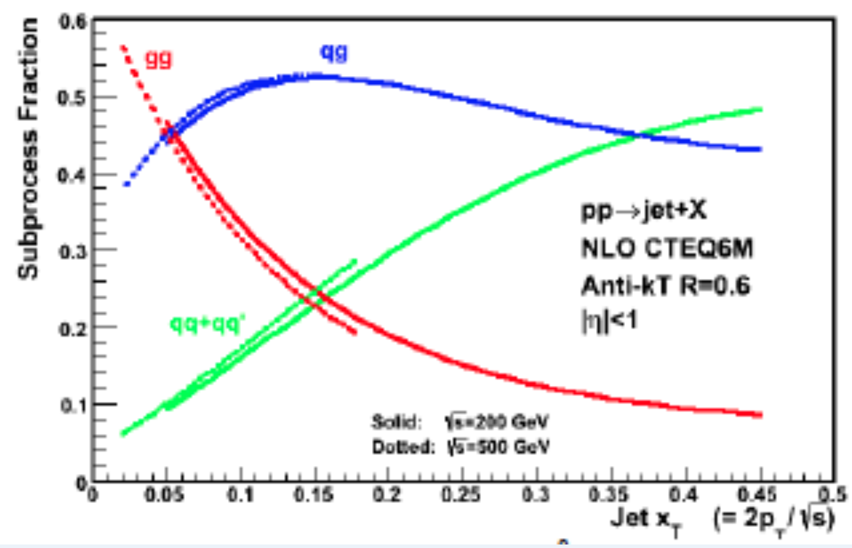


Δu-bar tends to be more positive

=> Symmetry breaking in polarized sea?

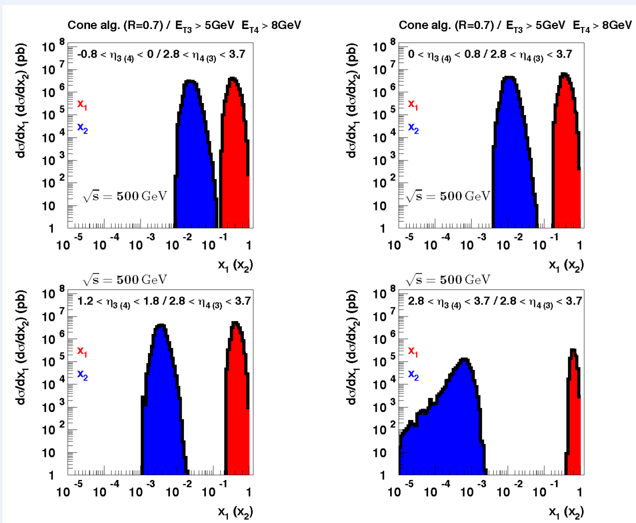
Twice reduced uncertainties when all data analyzed


Subprocess Fraction
gg
qg
qq+qq̄
pp → π⁰+X
|η|<0.35
NLO CTEQ6M, DSS
Solid: √s=200 GeV
Dotted: √s=500 GeV
x_T (=2p_T/√s)


Subprocess Fraction
gg
qg
qq+qq'
pp→jet+X
NLO CTEQ6M
Anti-kT R=0.6
|η|<1
Solid: √s=200 GeV
Dotted: √s=500 GeV
Jet x_T (= 2p_T / √s)

Long. Spin: ΔG

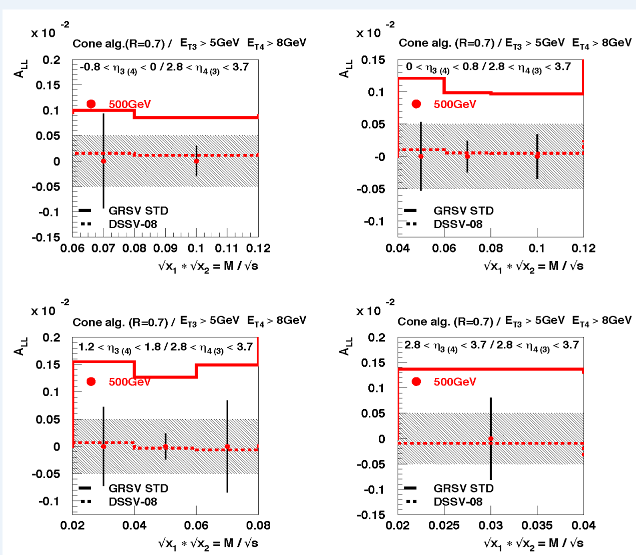
Run >2023?
$\vec{p}p@510GeV$



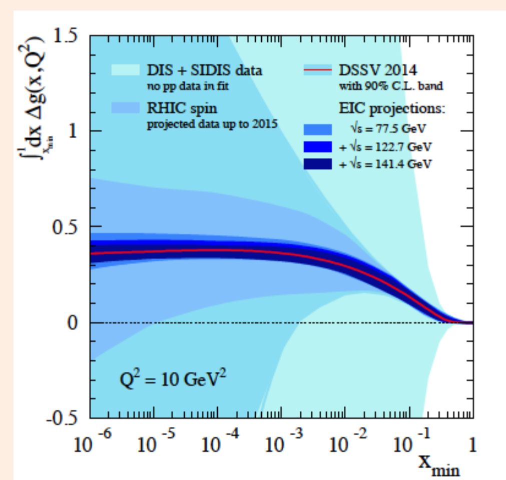
×1.5 more statistics for "traditional" channels (incl. π0 and jets)

Photons and π± will get sensitivity to non-zero ΔG
Though with smaller stat. power than incl. π0 and jets

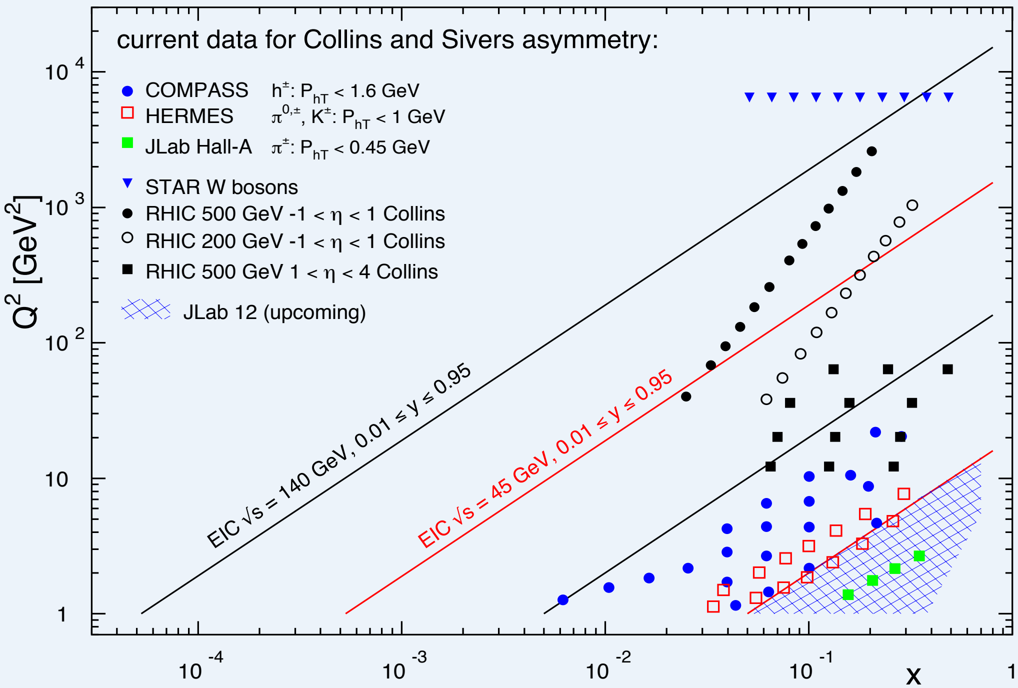
With forward upgrade (to η~4):
Di-jets – cleaner access to lower x down to 10^{-3}.



EIC can do it down to $x{\sim}10^{-5}$ with considerably higher precision

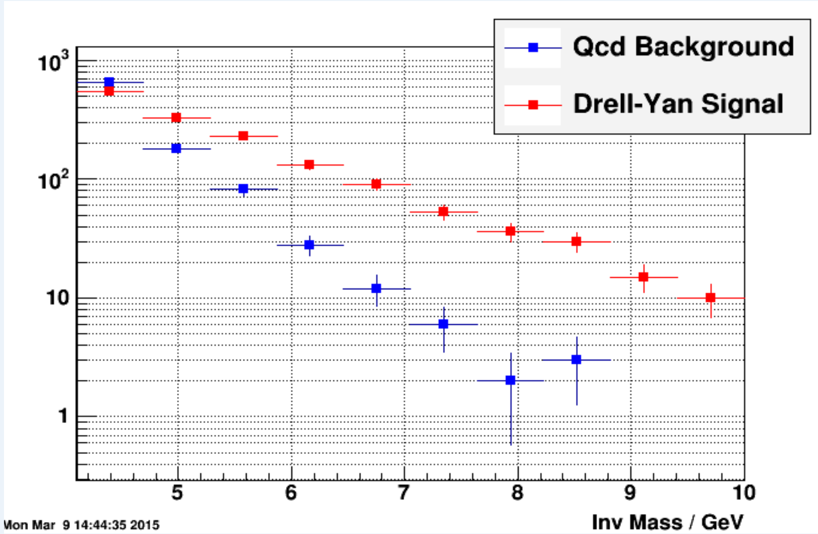


Sivers



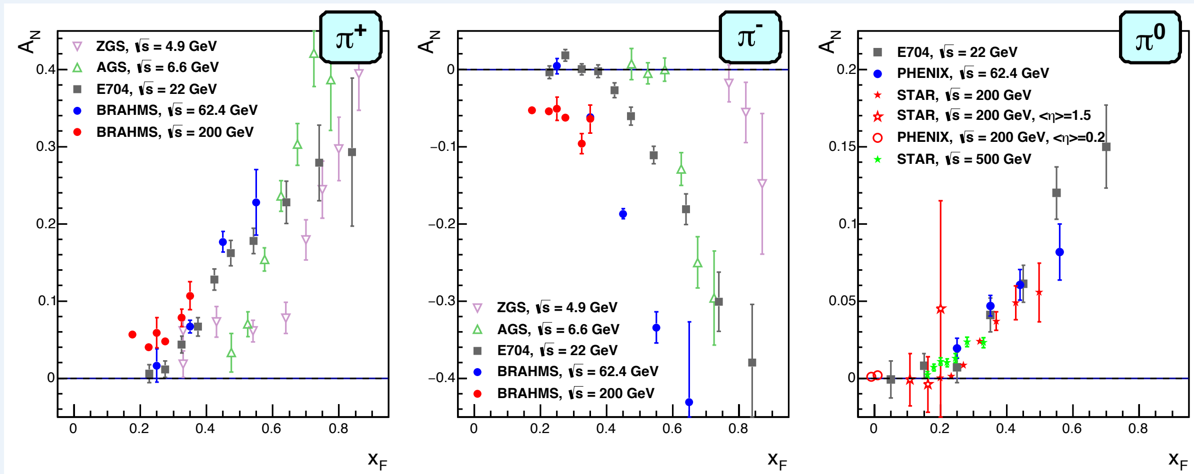
current data for Collins and Sivers asymmetry:
COMPASS h±: P_hT < 1.6 GeV
HERMES π0,±, K±: P_hT < 1 GeV
JLab Hall-A π±: P_hT < 0.45 GeV
STAR W bosons
RHIC 500 GeV -1 < η < 1 Collins
RHIC 200 GeV -1 < η < 1 Collins
RHIC 500 GeV 1 < η < 4 Collins
JLab 12 (upcoming)
EIC √s = 140 GeV, 0.01 ≤ y ≤ 0.95
EIC √s = 45 GeV, 0.01 ≤ y ≤ 0.95
Q2 [GeV2]
x

DY

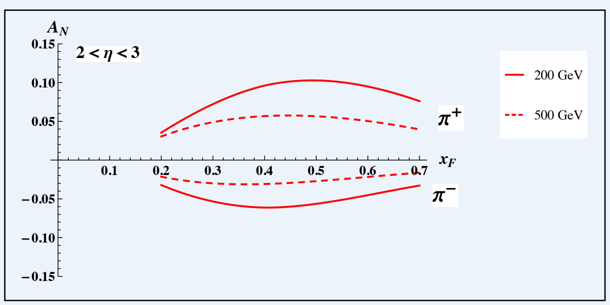


Qcd Background
Drell-Yan Signal
10^3
10^2
10
1
5
6
7
8
9
10
Mon Mar 9 14:44:35 2015
Inv Mass / GeV

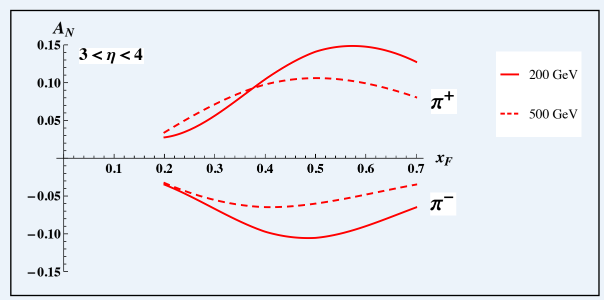
A_N



π+
ZGS, √s = 4.9 GeV
AGS, √s = 6.6 GeV
E704, √s = 22 GeV
BRAHMS, √s = 62.4 GeV
BRAHMS, √s = 200 GeV
π-
ZGS, √s = 4.9 GeV
AGS, √s = 6.6 GeV
E704, √s = 22 GeV
BRAHMS, √s = 62.4 GeV
BRAHMS, √s = 200 GeV
π0
E704, √s = 22 GeV
PHENIX, √s = 62.4 GeV
STAR, √s = 200 GeV
STAR, √s = 200 GeV, <η>=1.5
PHENIX, √s = 200 GeV, <η>=0.2
STAR, √s = 500 GeV
A_N
x_F

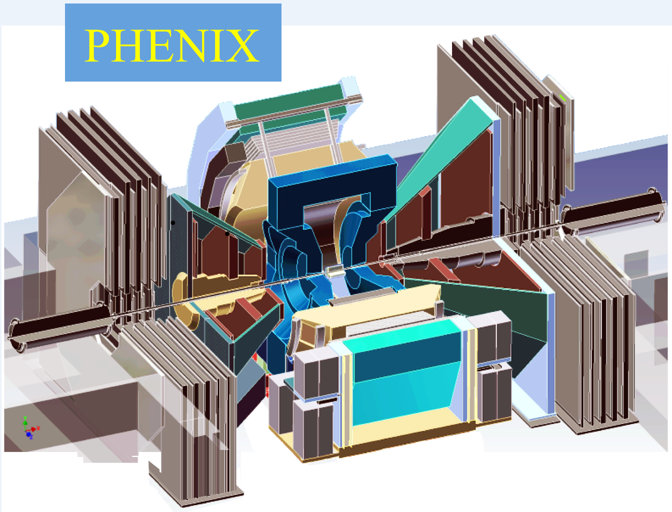


A_N
2 < η < 3
200 GeV
500 GeV
π+
π−
x_F

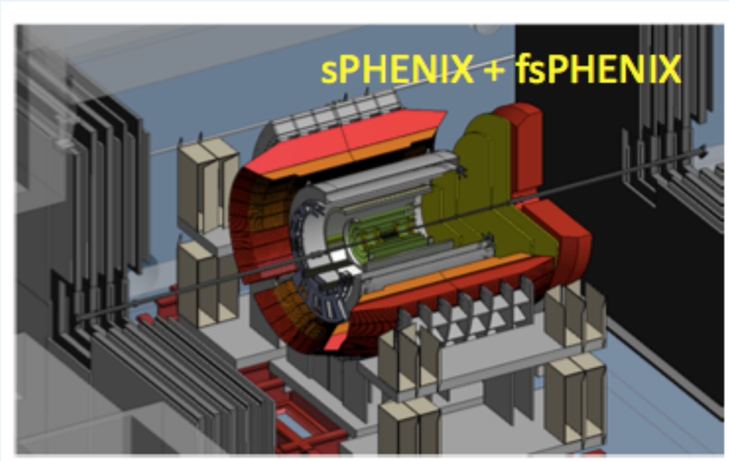


A_N
3 < η < 4
200 GeV
500 GeV
π+
π−
x_F

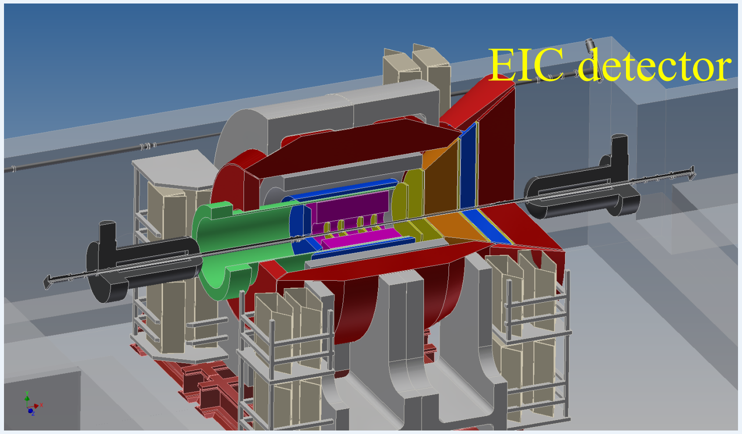
PHENIX: longer term plans



~2021-22



By ~2025



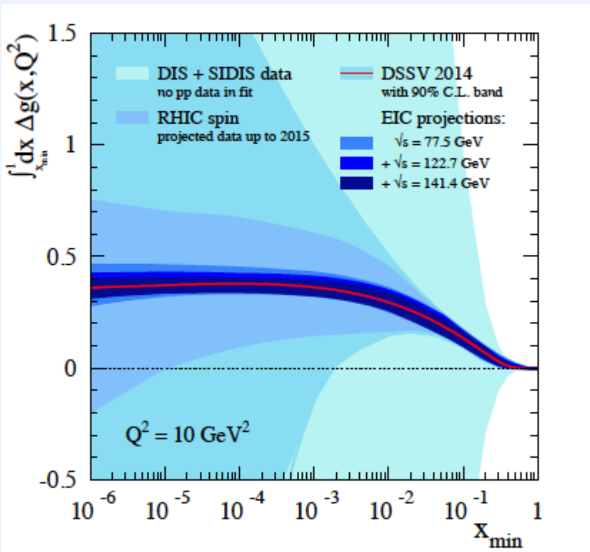
Evolve sPHENIX (pp and HI detector) to EIC Detector (ep and eA detector)

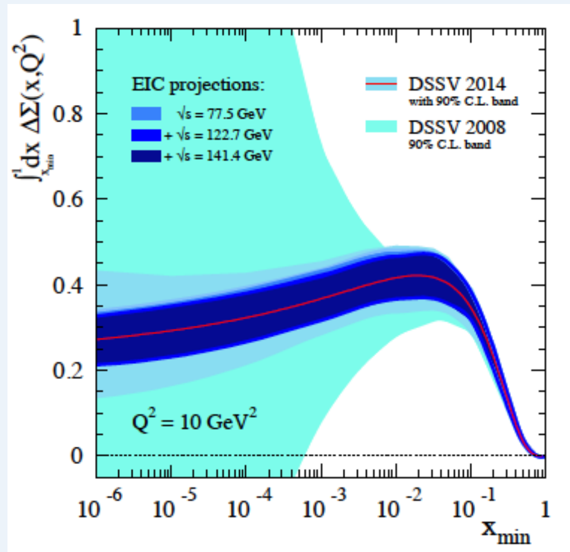
- To utilize e and p (A) beams at eRHIC with *e*-energy up to 15 GeV and *p*(*A*)-energy up to 250 GeV (100 GeV/n)
- *e*, *p*, *He*3 polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~1fb^{-1} /month)

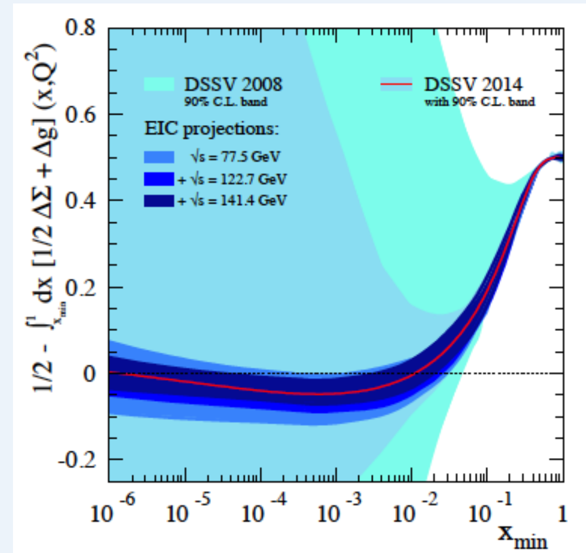
Nucleon Helicity Structure: from RHIC to EIC

$$\frac{1}{2} = \frac{1}{2}\sum_{q}\left[\Delta q + \Delta \bar{q}\right] + \Delta g + L$$

arXiv: 1509.06489



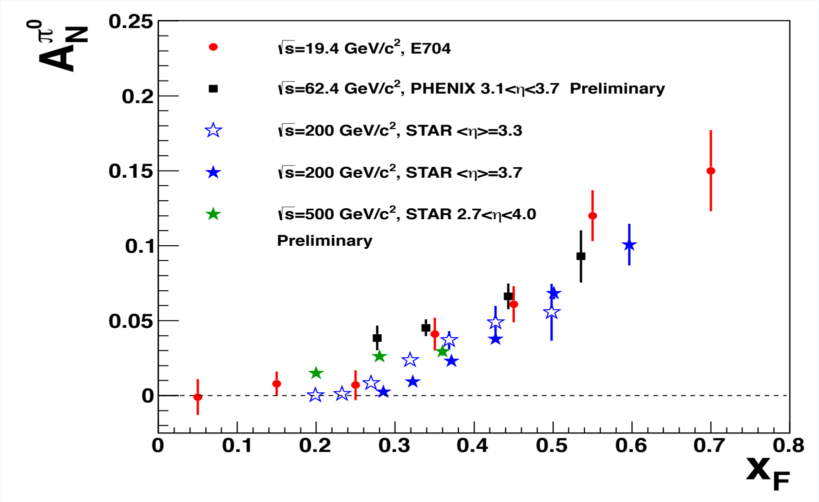




1/2 - Gluon - Quarks = Orbital angular momentum

Spin puzzle will be solved

RHIC Transverse Spin



Naïve collinear pQCD predicts

$A_N \sim \alpha_s m_q / p_T \sim 0$

Asymmetries survive at highest √s

Non-perturbative regime!

Asymmetries of the ~same size at all √s

Asymmetries scale with x_F

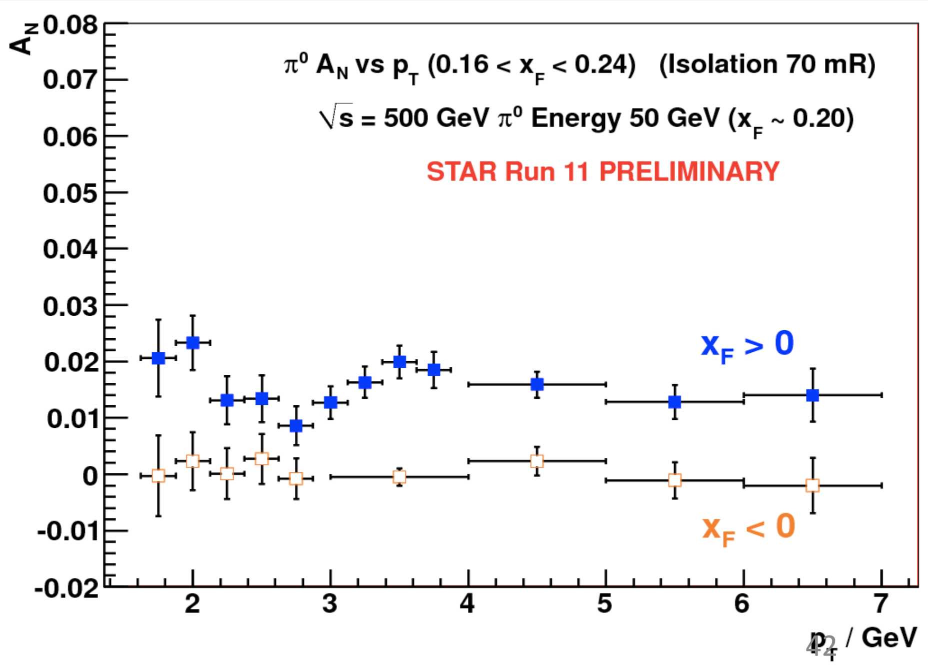
Collinear (higher twist) pQCD predicts

$A_N \sim 1/p_T$ … at what p_T ?

No fall off is observed out to $p_T \sim 7$ GeV/c

Main focus:

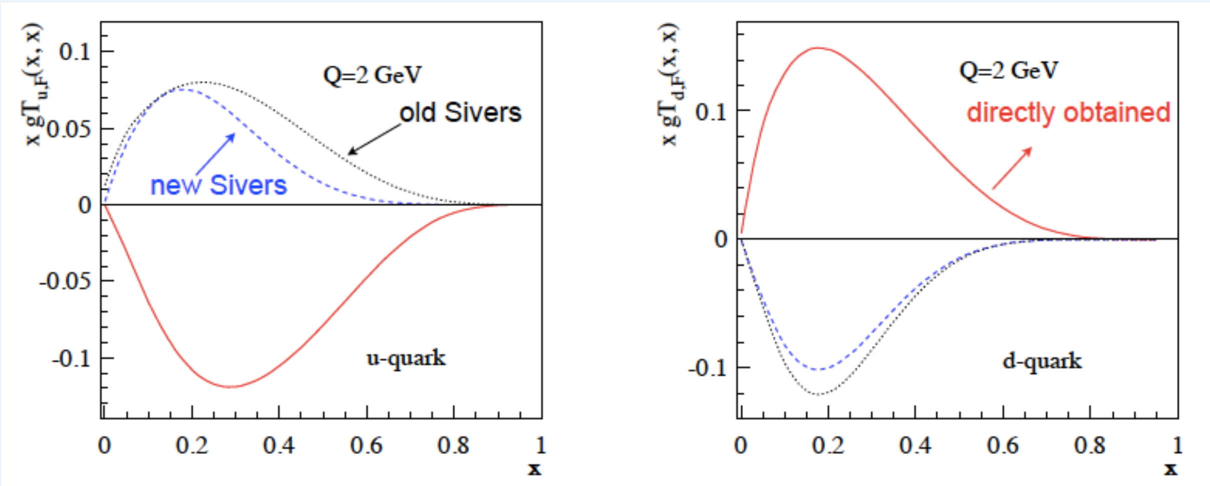
Disentangle different contributors



TMD vs Twist3: Sign Mismatch?

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

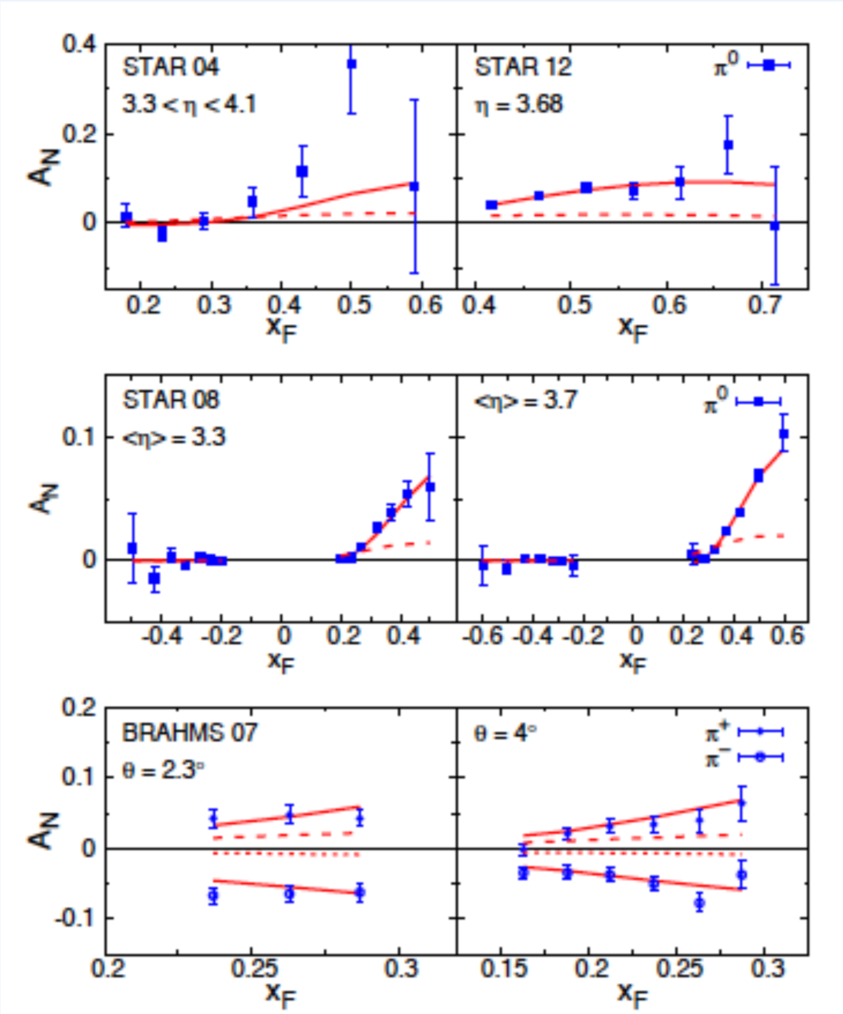
Kang, Qiu, Vogelsang, Yuan
PRD 83 (2011), 094011



pp→π X (Twist-3)
SIDIS (TMD)

Sign mismatch!
Sivers contribution is small in pp→π X ?
=> Collins dominate?

Collins dominate?

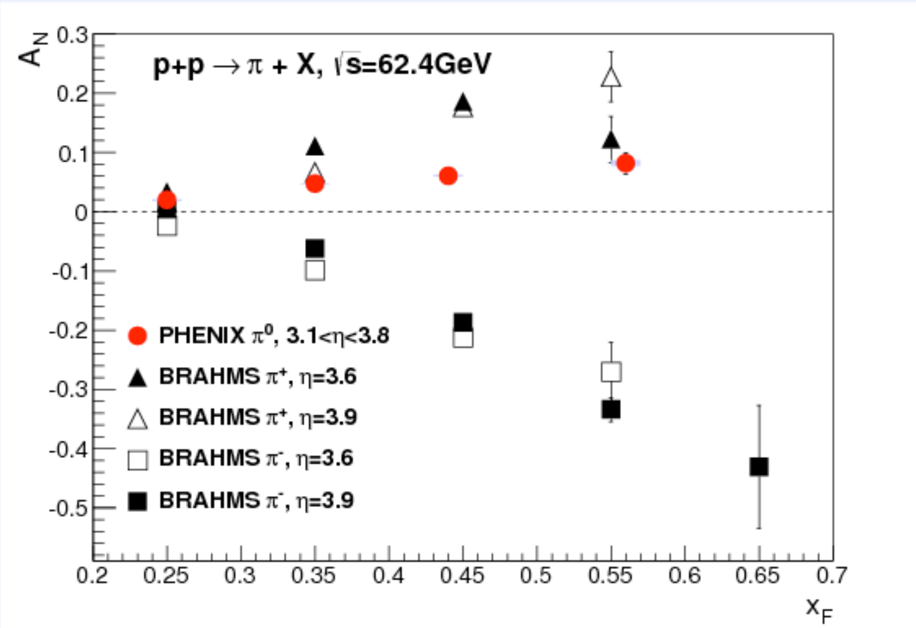


A_N from twist-3 fragmentation functions (Kanzawa, Koike, Metz, Pitoniak, arXiv:1404.1033)

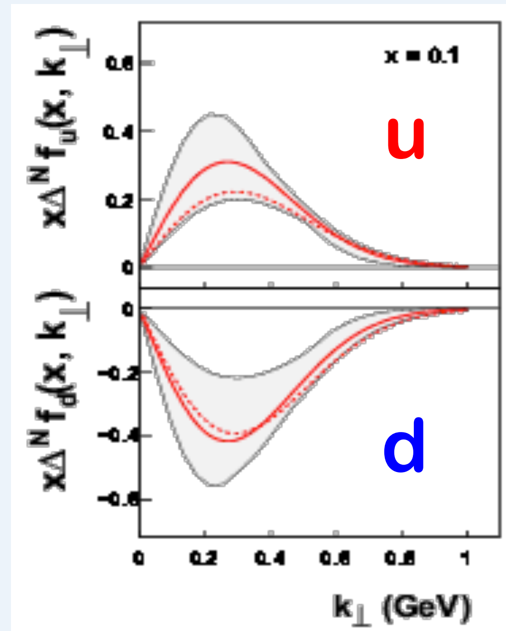
Describes data well !

A_N: pp→π X

PRD90 (2014), 012006



Anselmino et al., Eur. Phys. J. A39, 89 (2009)



PYTHIA:

π+ mainly produced from u

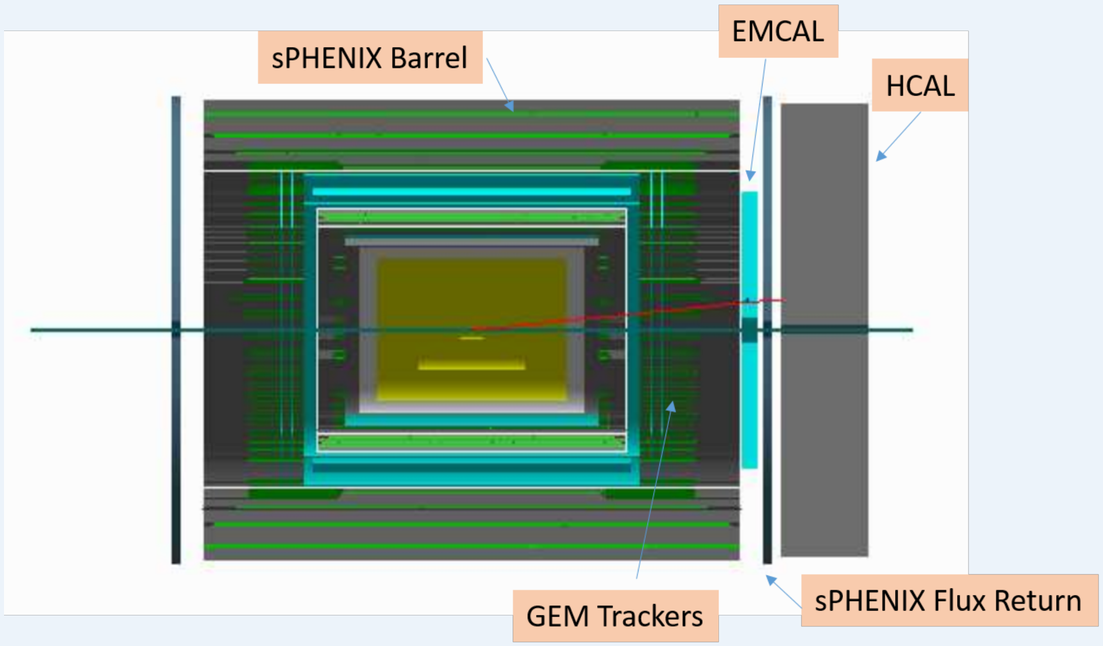
π- equally produced from d and u

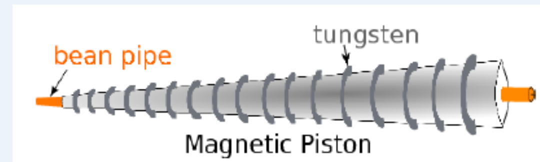
=> $|A_N(\pi+)| >> |A_N(\pi-)|$

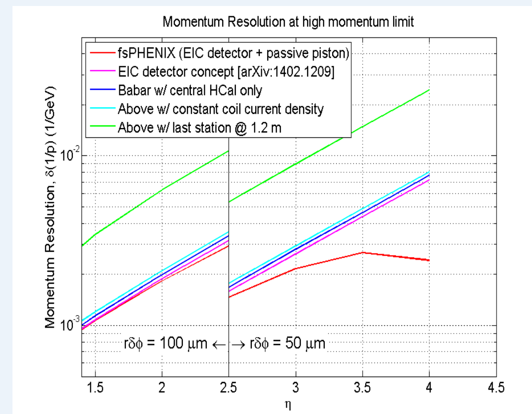
Sivers contribution is small in pp→π X ?

f+sPHENIX

Forward upgrade to barrel sPHENIX detector







η=1.1 – 4: π0, γ, e, μ, h±, jets

EMCal + MPC (from PHENIX): $\sigma_E/E \sim 8\%/\sqrt{E}$
HCal (PbSc): $\sigma_E/E \sim 100\%/\sqrt{E}$
Magnetic piston field shaper
Tracking (GEM): $\sigma_p/p < 0.3\%*p$
MuID (from PHENIX)
Roman Pots

The majority of the cost – as a down payment to potential EIC detector ("ePHENIX")