XVII Workshop on High Energy Spin Physics

DSPIN - 17

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Recent STAR Spin Results & Spin Measurements at RHIC

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for the STAR Collaboration

Outline:

- Introduction
- RHIC as collider of polarized protons
- STAR detector
- Theory background: PDFs, FFs
- Recent STAR spin results:
  jet, di-jet, $W^{\pm}$, Z, π^0, (π^+,π^-), $(\pi^{\pm}$,jet) asymmetries
- STAR forward upgrade and future plans
- Summary

Motivation

Spin as well as mass, charge (electric, baryonic, lepton), flavor
is one of the fundamental properties of particles.

Origin of spin is one of the mysteries of Nature.

Origin of spin is connected with the structure
and symmetries of space-time at small scales.

Spin is a sophisticated probe of hadron and nuclear matter and fields.

QCD is the non-abelian gauge theory of quarks and gluons:
asymptotic freedom and confinement are properties of the theory.

Main questions:

What is origin of spin ?

What is the spin structure of proton
in terms of interacting quarks and gluons
at different scales ?

Relativistic Heavy Ion Collider

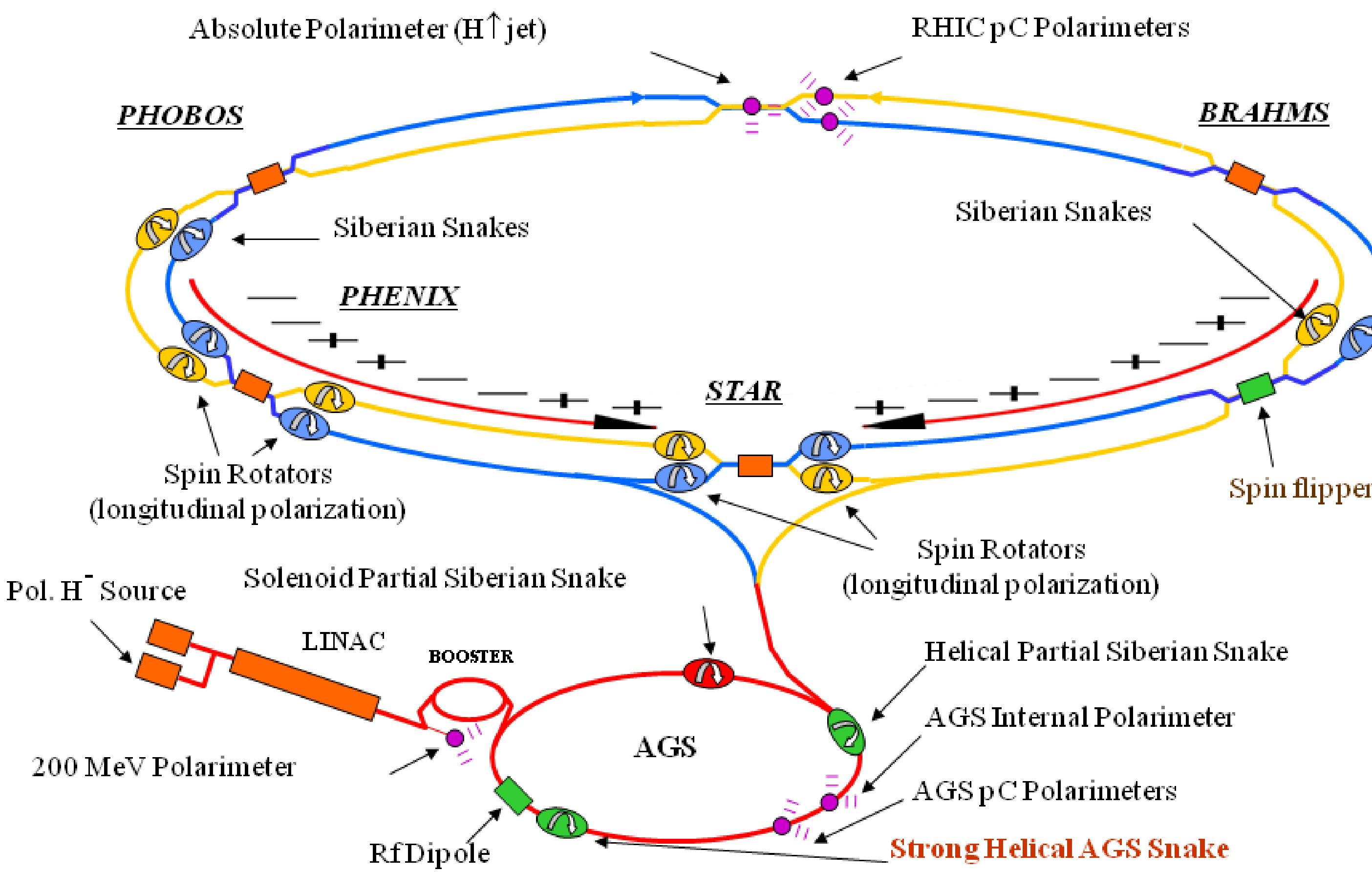
Commissioning 1999

- 3.83 km circumference
- Two separated rings:
  120 bunches/ring
  106 ns bunch crossing time

Nucleus-nucleus collisions (AuAu, CuCu, dAu, CuAu, UU, … $\sqrt{s_{NN}}$ =7.7-200 GeV)
RHIC is uniquely suited to map the QCD phase diagram at finite baryon density.

Polarized proton-proton collisions $\sqrt{s}$ =62.4, 200, 500, 510 GeV
RHIC is uniquely suited to map the proton spin structure.

First polarized p-p collider in the world



- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

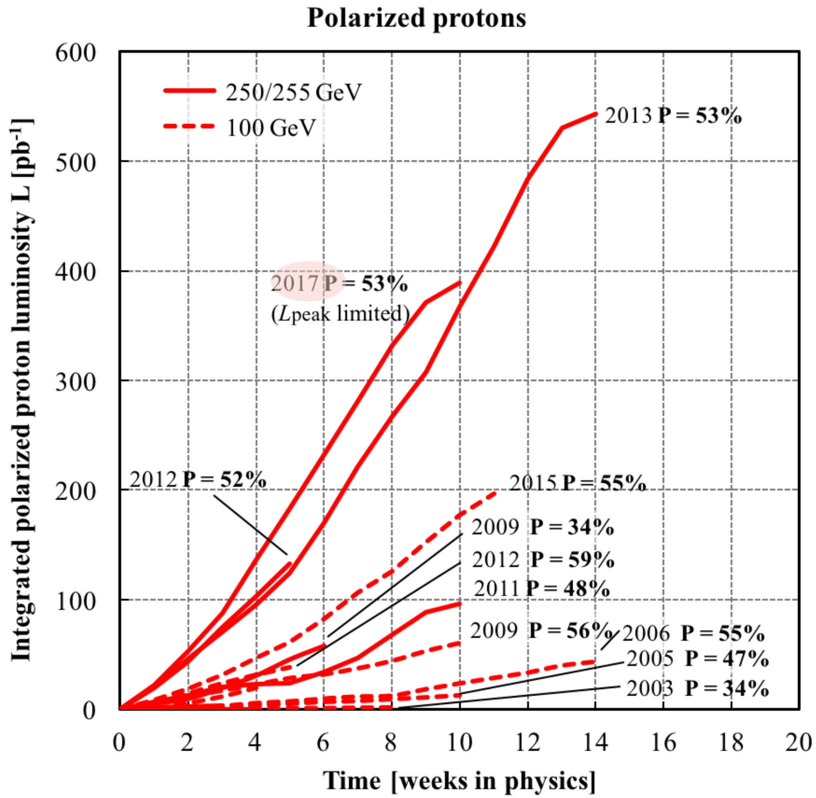
Experimental aspects - RHIC

RHIC has completed
very successful polarized
p+p runs at √s =200,500,510 GeV.

Over the past several years luminosity
at RHIC has steadily increased.

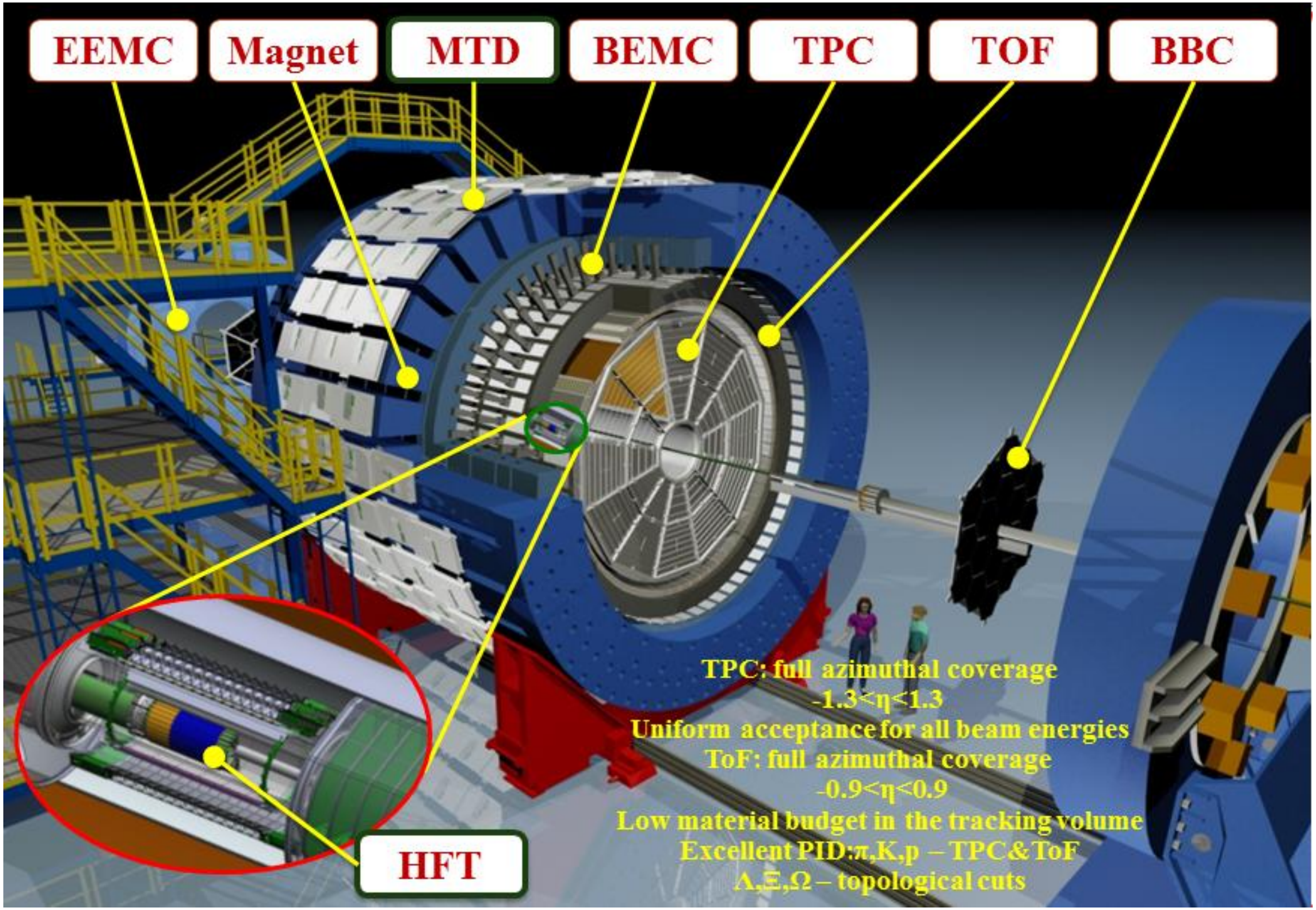
Run 2017

Average store polarization:
Blue ring - (54.6±0.2)%
Yellow ring - (55.7±0.2)%
Average store luminosity
$1.27 \cdot 10^{32}$ $cm^{-2}s^{-1}$



V. H. Ranjbar et al.,
"RHIC polarized proton operation for 2017",
Proc. IPAC'17, Copenhagen, Denmark (2017).

The Solenoidal Tracker At RHIC (STAR)

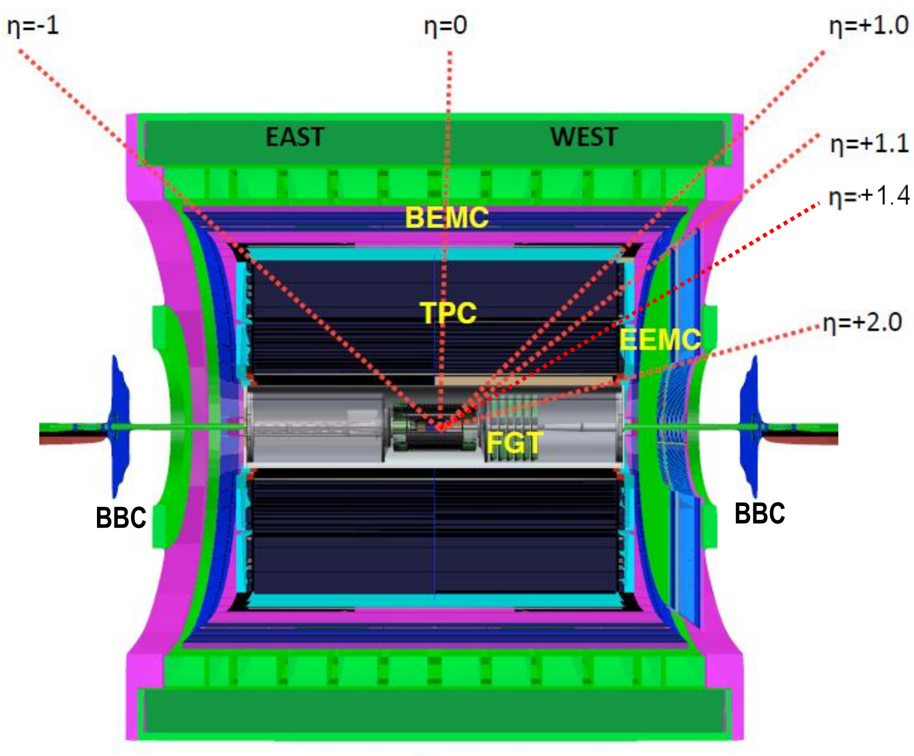


Magnet
- 0.5 T Solenoid

Triggering & Luminosity Monitor
- Beam-Beam Counters
  $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

Tracking
- Large-volume TPC
  $|\eta| < 1.3$
- Forward GEM Tracker
  $1<\eta<2$

Calorimetry with 2π coverage:
- Barrel EMC (Pb/Scintilator)
  $|\eta| < 1.0$
- Endcap EMC (Pb/Scintillator)
  $1.1 < \eta < 2.0$
- Forward Meson Spectrometer (not shown)
  $2.5 < \eta < 4.0$



$\eta = -\ln[tg(\theta/2)]$

Nucleon structure in terms of PDFs: DIS, SIDIS,..

Parton Distribution Function

f(x) probability density to find a parton with flavor *f* and momentum fraction *x* in nucleon

$$f(x) = f^{\rightarrow}(x) + f^{\leftarrow}(x)$$

Helicity Distribution

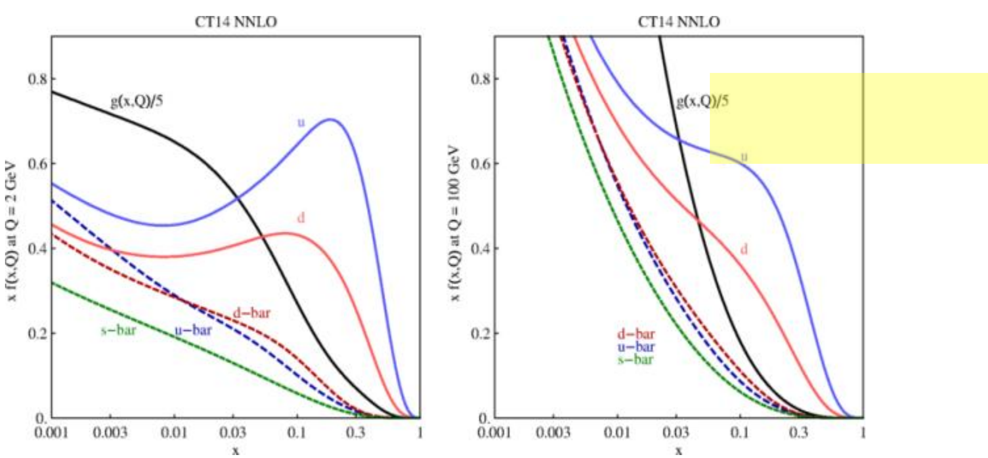
Δf(x) probability density to find a longitudinally polarized parton with flavor *f* and momentum fraction *x* in longitudinally polarized nucleon

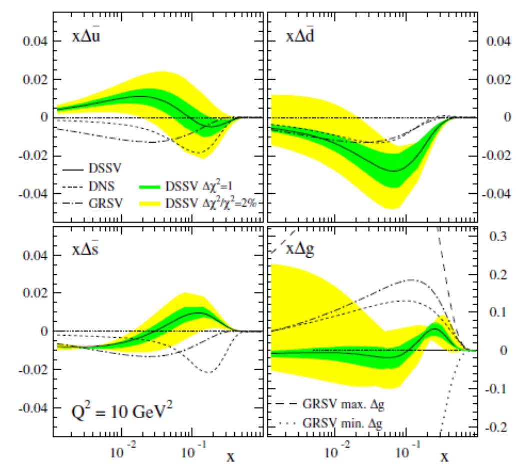
$$\Delta f(x) = f^{\rightarrow}(x) - f^{\leftarrow}(x)$$

Transversity Distribution

δf(x) probability density to find a transversely polarized parton with flavor *f* and momentum fraction *x* in transversaly polarized nucleon

$$\delta f(x) = f^{\uparrow}(x) - f^{\downarrow}(x)$$





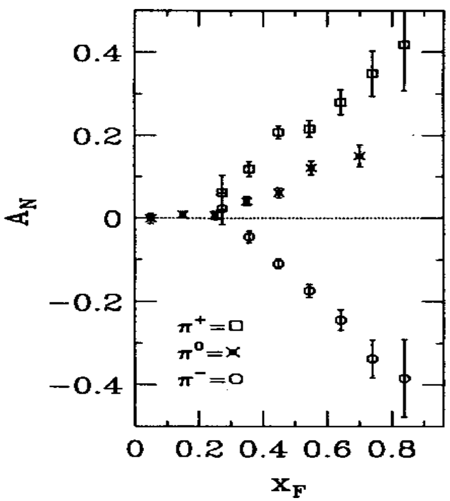
Global QCD analysis of DIS and SIDIS data for understanding proton spin structure in terms of $f(x,Q^2)$, $\Delta f(x,Q^2)$, $\delta f(x,Q^2)$

Mechanisms for large transverse single-spin asymmetry A_N

$$p^{\uparrow} + p \rightarrow \pi^{\pm,0} + X$$

$\sqrt{s}$=19.4 GeV, p_T = 0.2-2.0 GeV/c

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



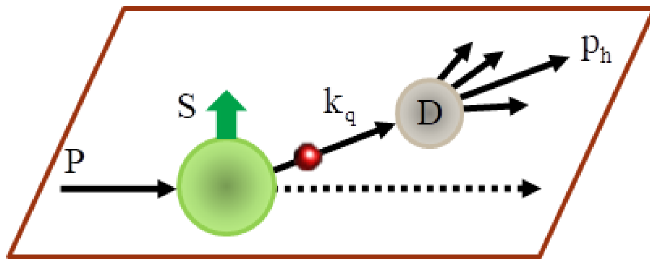
E704 Collaboration
PLB261 (1991) 201
PLB264 (1991) 462

STAR
Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660040
Phys.Rev.D 89, 012001 (2014)

(1) Transverse Momentum Distributions

PDFs & FFs

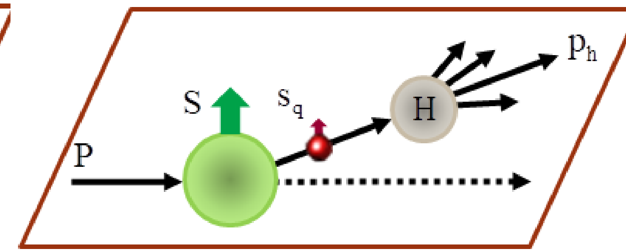
Sivers effect (PDF) 1990



Correlation of proton spin and parton transverse momentum

$$P \cdot (S \times k_q)$$

Collins effect (FF) 1993



Correlation of parton spin and transverse momentum of produced hadron

$$P \cdot (s_q \times p_h)$$

(2) Collinear twist-3 quark-gluon-quark correlations in the initial state proton or in the fragmentation process

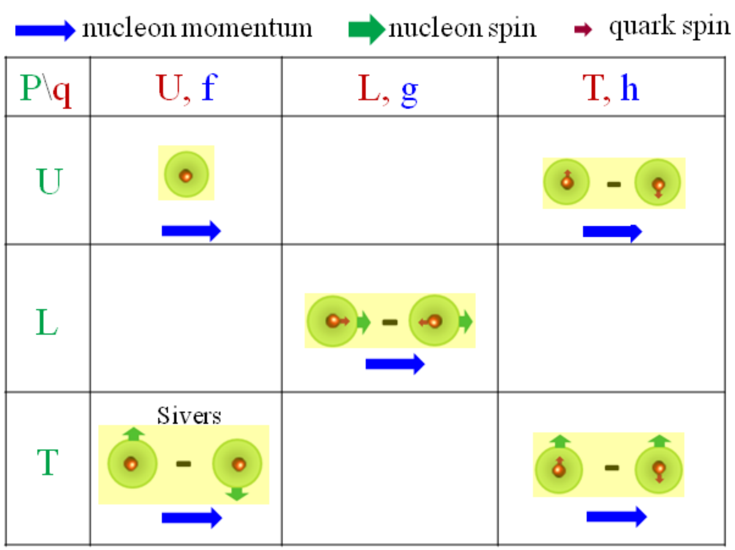
To disentangle the Sivers and the Collins effects and test their universality properties

- To isolate the Sivers effect: W, Z and Drell-Yan production.
- To isolate the Collins effect: Di-hadron IFF asymmetries and Collins azimuthal asymmetry.

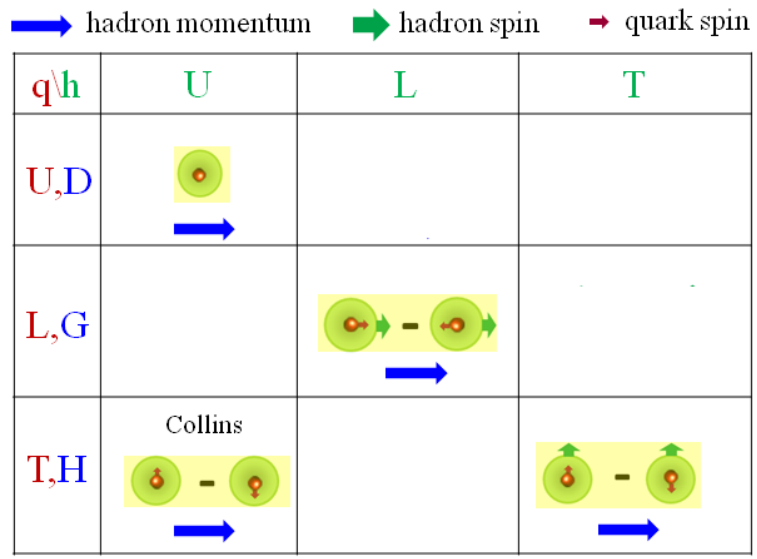
Spin-dependent PDFs and FFs

Correlations of proton momentum (P), proton spin (S), quark momentum (k_q), quark spin (s_q), orbital momentum of quark (L_q) and gluon (L_g) in initial and final states reflect a variety of PDFs and FFs.

PDFs



FFs



Sivers (1990) $P\cdot(S\times k_q)$

Boer & Mulders (1998) $P\cdot(s_q\times k_q)$

Collins (1993) $P\cdot(s_q\times p_h)$

- PDFs probe the internal structure of the proton
- FFs probe the structure of fragmentation process

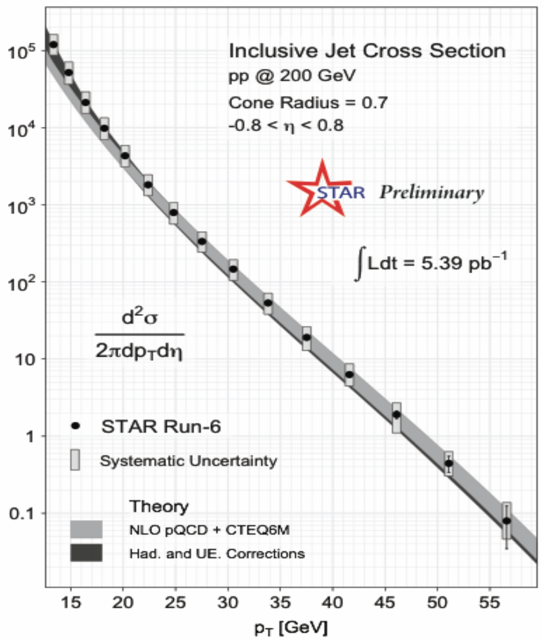
A.Accardi, arXiv:1602.02035

A.Metz, A.Vossen, Prog.Part.Nucl.Phys. 91 (2016) 136–202

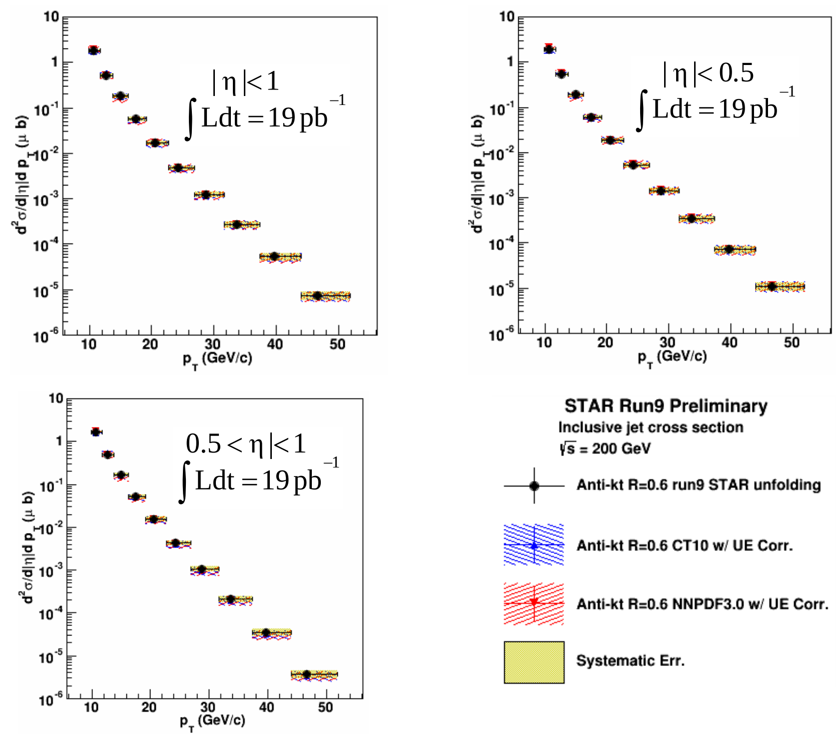
Inclusive jet cross section at √s=200 GeV

$$p + p \rightarrow \text{jet} + X$$

BNL: STAR
M.Calderon,
Extrem QCD, San Carlos,
Mexico, July 18-20, 2011



Different pseudo-rapidity regions



STAR data (√s=200 GeV) close the gap of jet production in pp mode ISR (√s=62 GeV) and LHC (√s=7-14 TeV)

- Hadronization and UE corrections evaluated using PYTHIA applied to NLO calculations for data comparison.
- Comparison to NLO calculations for CT10, NNPDF3.0 and MRST-W2008 with a preference for CT10.

STAR , arXiv:1506.06314

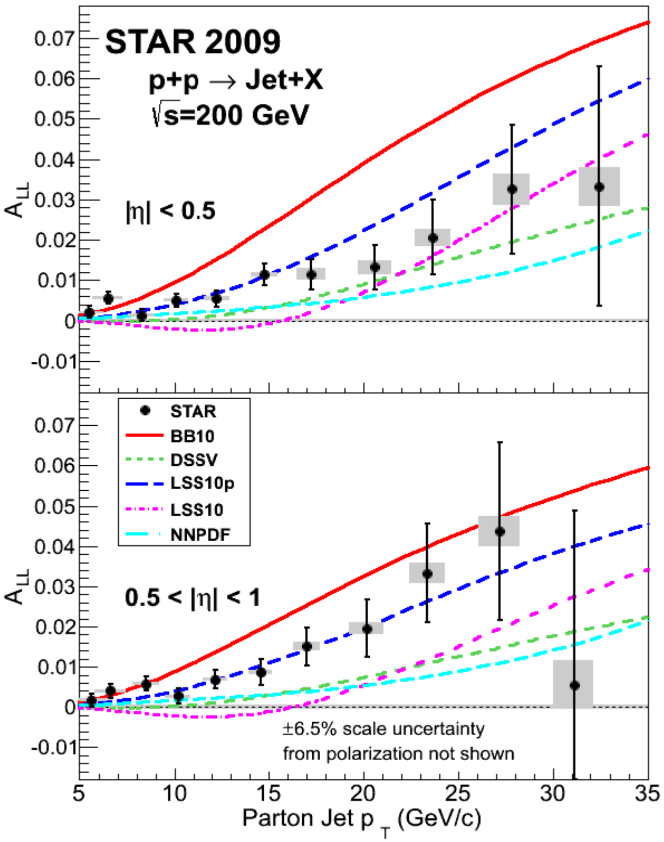
Longitudinal double-spin asymmetry A_{LL} of jet production

$$p + p \rightarrow \text{jet} + X$$

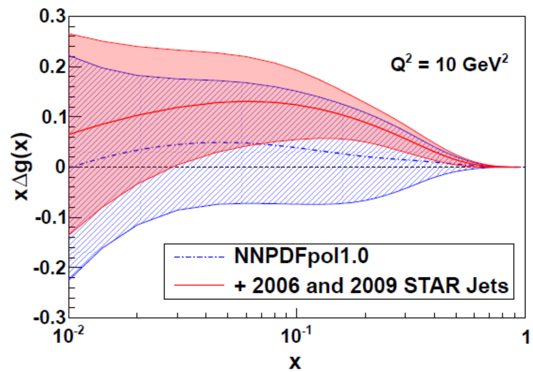
$$A_{LL}^{jet} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$

σ_{++} (σ_{+-}) is the diff. cross section when polarized beam protons has the same (opposite) helicity.

STAR Collaboration
Phys. Rev. Lett. 115, (2015) 092002.



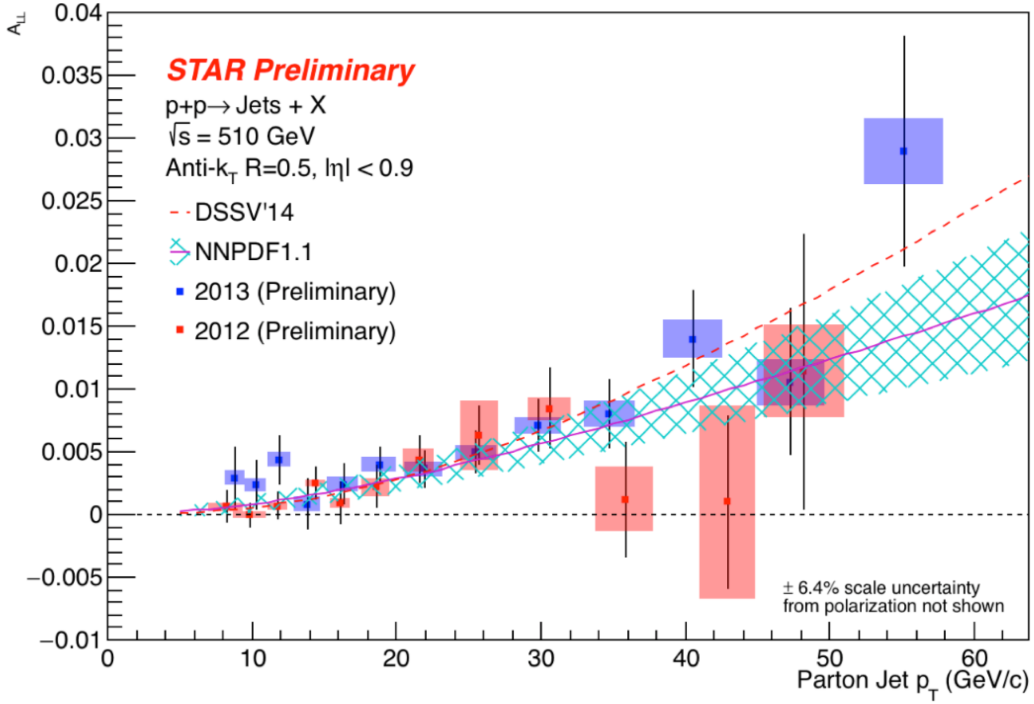
- The measurement of the inclusive jet longitudinal double-spin asymmetry A_{LL} in polarized pp collisions at $\sqrt{s}$=200 GeV
- The results of NLO QCD fits for NNPDF are dramatically changed for ΔG over $0.05<x<0.5$ at $Q^2=10$ (GeV/c)^2 from 0.06±0.18 to 0.21±0.10 by including or after reweighting the fit using the STAR jet data.
- When included in updated global analyses, they provide evidence at the 3σ level for positive gluon polarization in the region x > 0.05.



The inclusion of the STAR jet data results in a substantial reduction in the uncertainty for the gluon polarization in the region x > 0.05 and indicates a preference for the gluon helicity contribution to be positive in the RHIC kinematic range.

R. D. Ball et al. NNPDF Collaboration
Nucl. Phys. B 887, 276 (2014).

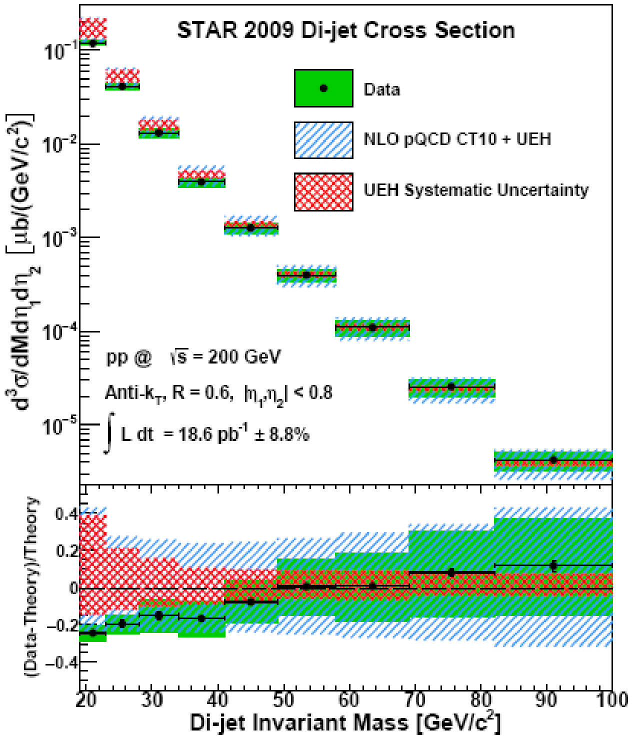
Asymmetry A_{LL} of jet production in p-p at $\sqrt{s}$=510 GeV

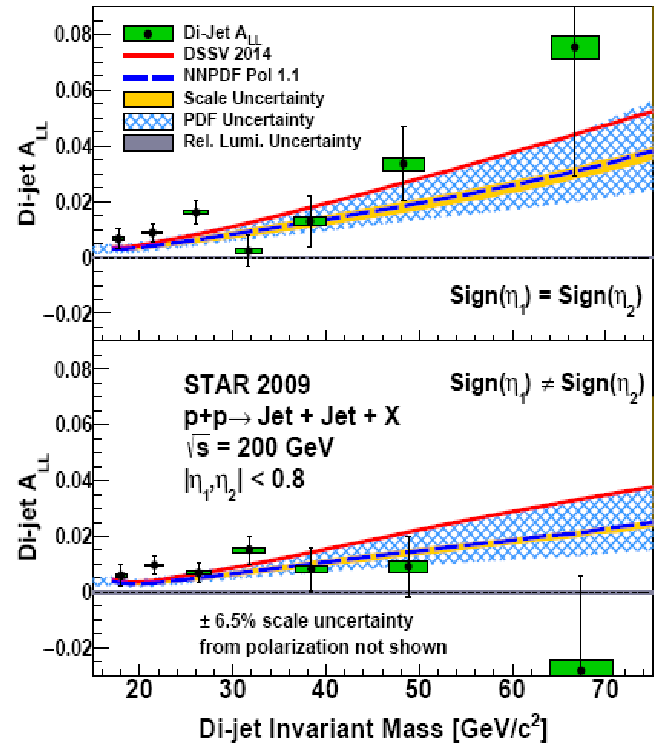


- RHIC had very successful pp runs with 510 GeV during 2012 and 2013
  -- higher center-of-mass energy probes lower x partons
- A_{LL} at 510 GeV is well described by global fits that previously gave a good description of the 2009 measurements at 200 GeV.

Di-jet production in p-p at √s=200 GeV

First measurement of di-jet spectra and di-jet asymmetry A_{LL}





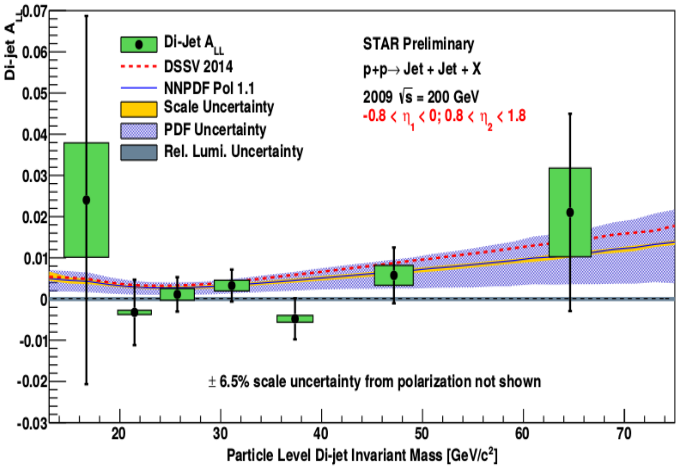
The cross section result is consistent with NLO pQCD plus hadronization and underlying event corrections and has the potential to constrain unpolarized PDFs.

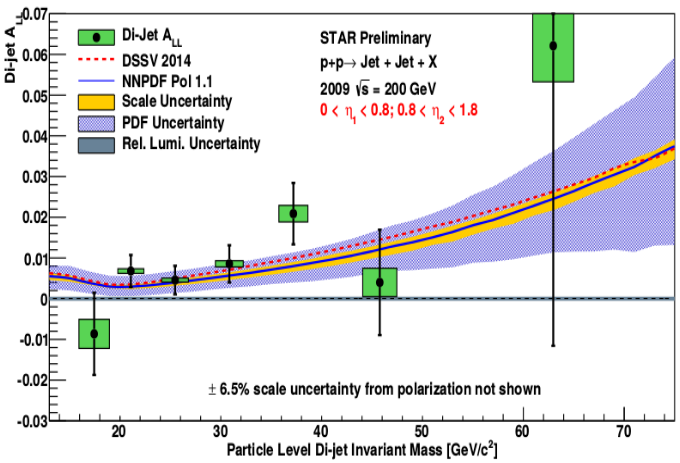
The A_{LL} results support the most recent DSSV and NNPDF NLO global analyses, which included 2009 RHIC data and found the first non-zero ΔG value for $x > 0.05$.

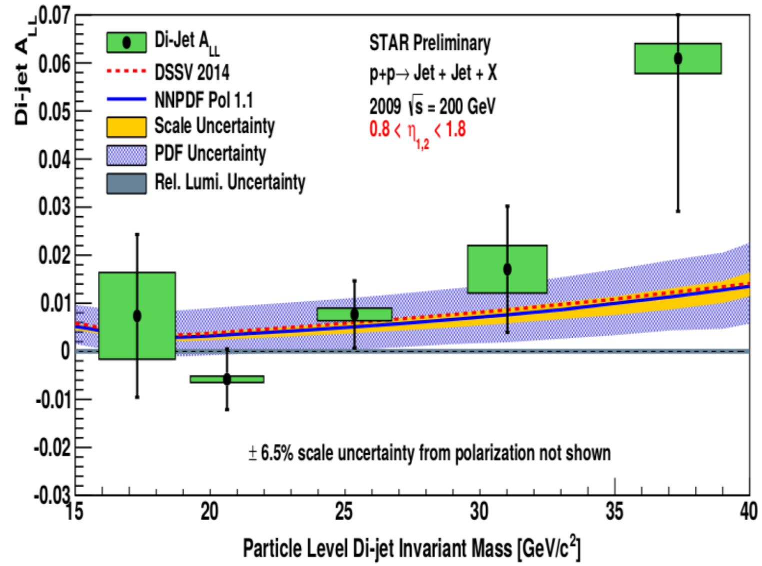
STAR, PRD 95, 071103 (R) (2017)

Di-jet asymmetry A_{LL} in p-p at $\sqrt{s}$=200 GeV

Forward-rapidity measurement (Run 2009)





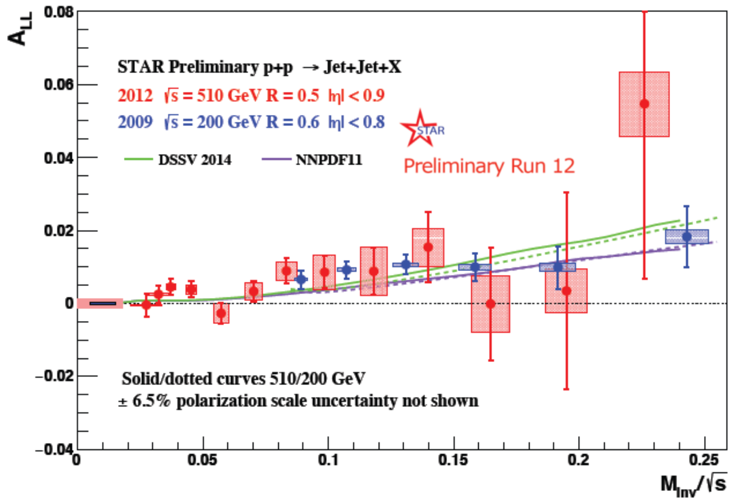


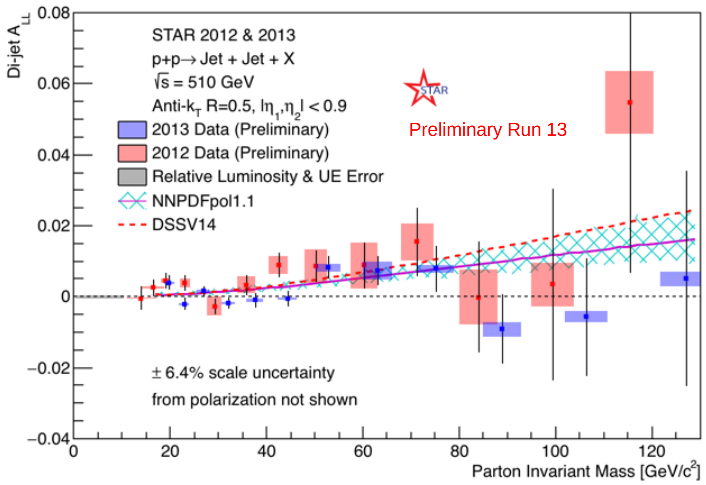
- Forward rapidity Di-Jet A_{LL} measurement based on three topological combinations in η:
  - Barrel East (-0.8<η<0) - EEMC (0.8<η<1.8)
  - Barrel West (0<η<0.8) - EEMC (0.8<η<1.8)
  - EEMC (0.8<η<1.8) - EEMC (0.8<η<1.8)
- Forward A_{LL} measurement consistent with global fit results constrained by Run 2009 A_{LL} data

Di-jet asymmetry A_{LL} in p-p at $\sqrt{s}$=510 GeV

STAR, Collaboration
PRD 95, 071103.(R) 2017

Mid-rapidity measurement (Runs 2012,2013)





A_{LL} measurements (Runs 2012,2013) consistent with DSSV2014 and NNPDF1.1 constrained by Run 2009 data and consistent with Run 2009 di-jet results

Di-jet measurements at forward rapidity and higher $\sqrt{s}$ provide more precise mapping of $\Delta g(x)$ at lower x:

-- x ~ 0.02 has been reached
-- x ~ 10^{-2} will be reached with additional recorded data
-- x ~ 10^{-3} will be reached with STAR forward upgrade

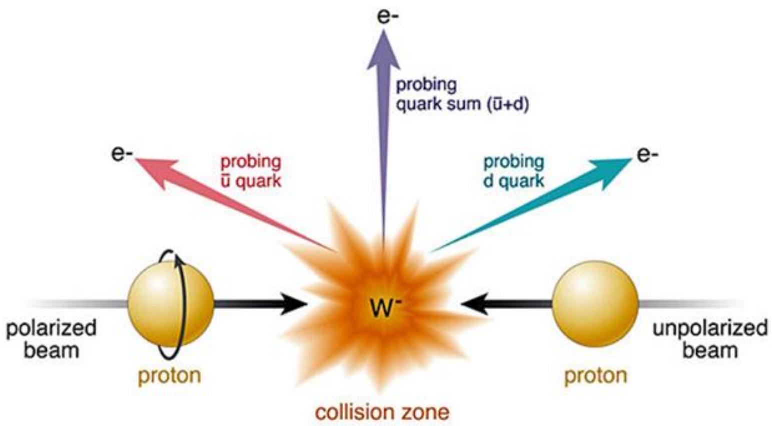
STAR preliminary,
C.Gagliardi , ICNFP 2017

Longitudinal single-spin asymmetry A_L $W^{\pm}$ production in p-p collisions

$$p + p \to W^{\pm} + X$$

$$A_L^W = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

σ_+ (σ_-) is the cross sections when the polarized proton beam has positive (negative) helicity



$$W^+ \to e^+ + \nu$$

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

$$W^- \to e^- + \bar{\nu}$$

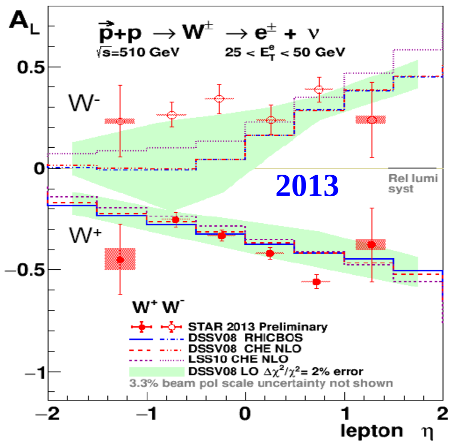
$$A_L^{W^-} \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \bar{u}(x_2)\Delta d(x_1)}{\bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_1)}$$

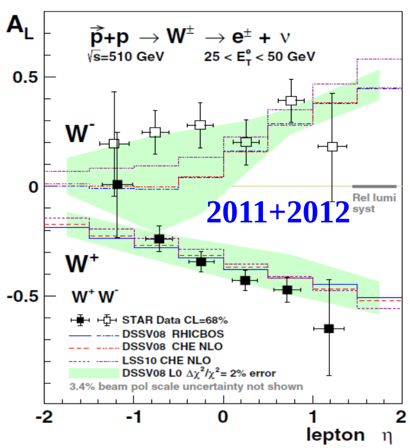
The measurements provides a direct probe of the helicity-dependent PDFs ($\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}$) through a parity-violating longitudinal single-spin asymmetry A_L

STAR is well equipped to measure A_L for $W^{\pm}$ production within a range of $|\eta| < 1$ (TPC, BEMC, EEMC).

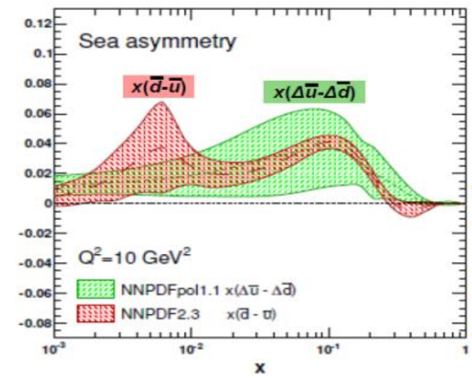
Longitudinal single-spin asymmetry A_L
$W^{\pm}$ production in p-p collisions at $\sqrt{s}$=510 GeV

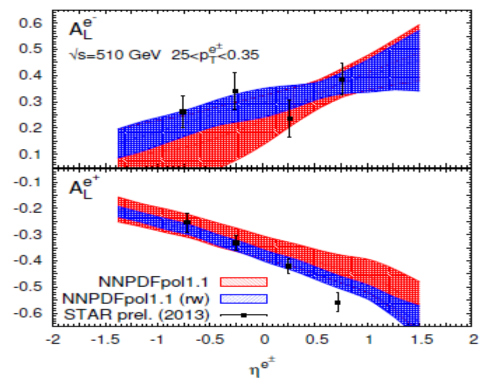
New preliminary A_L results from Run 2013





- The asymmetries for $W^{\pm}$ measured as a function of the decay lepton pseudorapidity provides a theoretically clean probe of the proton's polarized quark distributions at the scale of the $W^{\pm}$ mass.
- STAR 2013 results are consistent with 2011+2012 results and the most precise measurements of A_L so far.
- The results are compared to theoretical predictions, constrained by polarized DIS measurements, and show a preference for a sizable, positive up antiquark polarization in the range 0.05 < x < 0.2.
- Further constraints on sea quark helicity distributions.





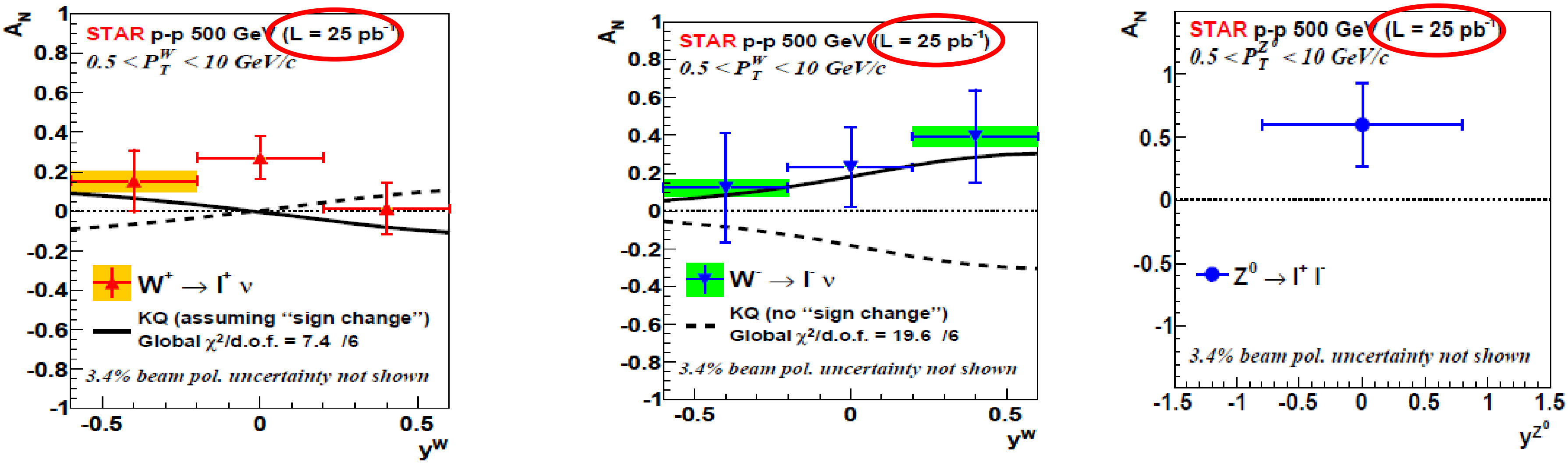
E.R.Nocera
arXiv:1702.05077

STAR preliminary, arXive:1702.02927
STAR, Phys.Rev.Lett.113,072301(2014)

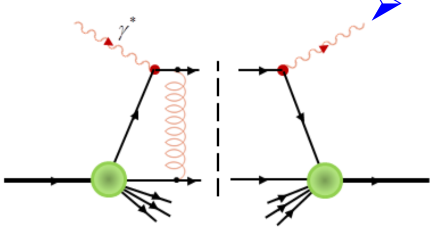
STAR Transverse single-spin asymmetry A_N at $\sqrt{s}$=500 GeV

STAR Collaboration
Phys.Rev.Lett.
116, 132301 (2016)

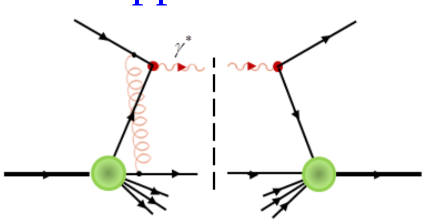
$$p^{\uparrow} + p \rightarrow W^{\pm}(Z) + X$$



- A_N is sensitive to the Sivers function
- Expect opposite sign for the Sivers function in SIDIS and pp



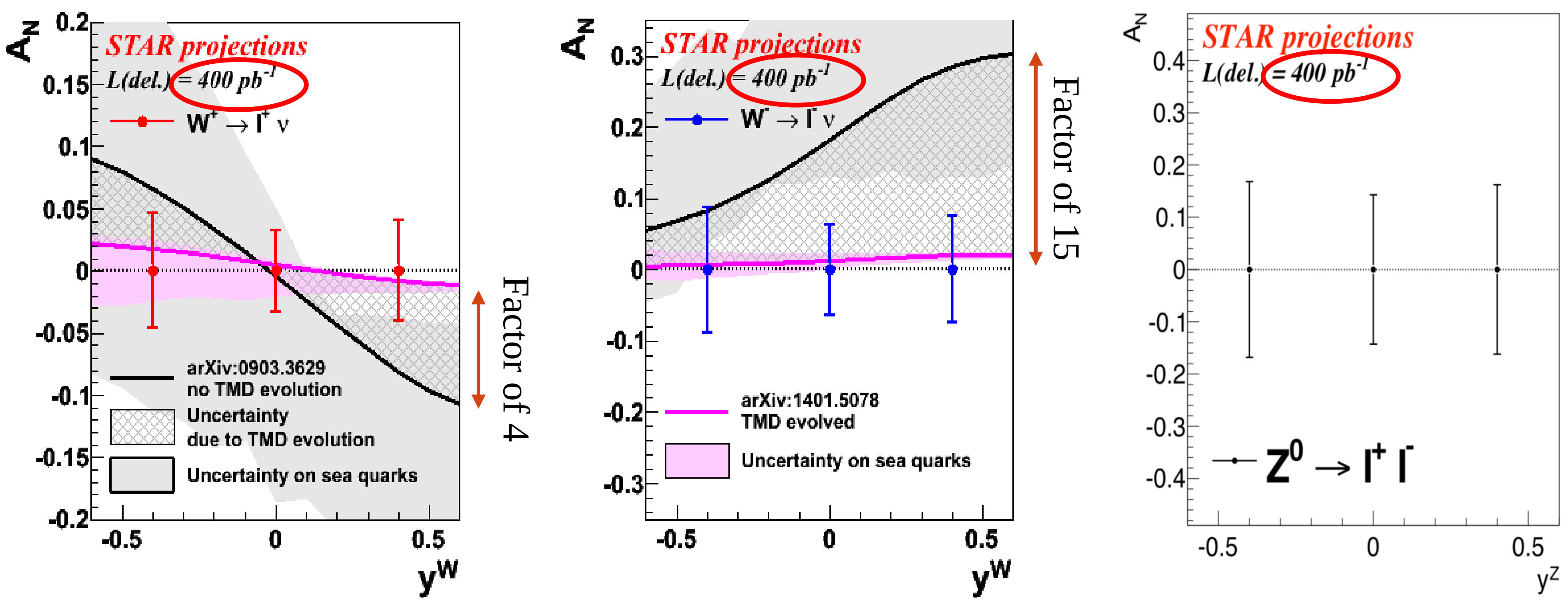
$$f_{q/h^{\uparrow}}^{\text{SIDIS}}(x, k_T, Q^2) = -f_{q/h^{\uparrow}}^{p+p\rightarrow DY/W^{\pm}/Z^0}(x, k_T, Q^2)$$



- Sivers-sign change scenario preferred over no-sign change scenario, if TMD evolution effects are small.

Run 2017 sensitivity projections for A_N

The 2017 program (higher luminosity) – test non-universality of Sivers effect through TMDs



- The sign change if evolution effects are small.
- Probe anti-quark Sivers function for the first time.
- Directly measure the evolution effects.

arXiv: 1602.03922

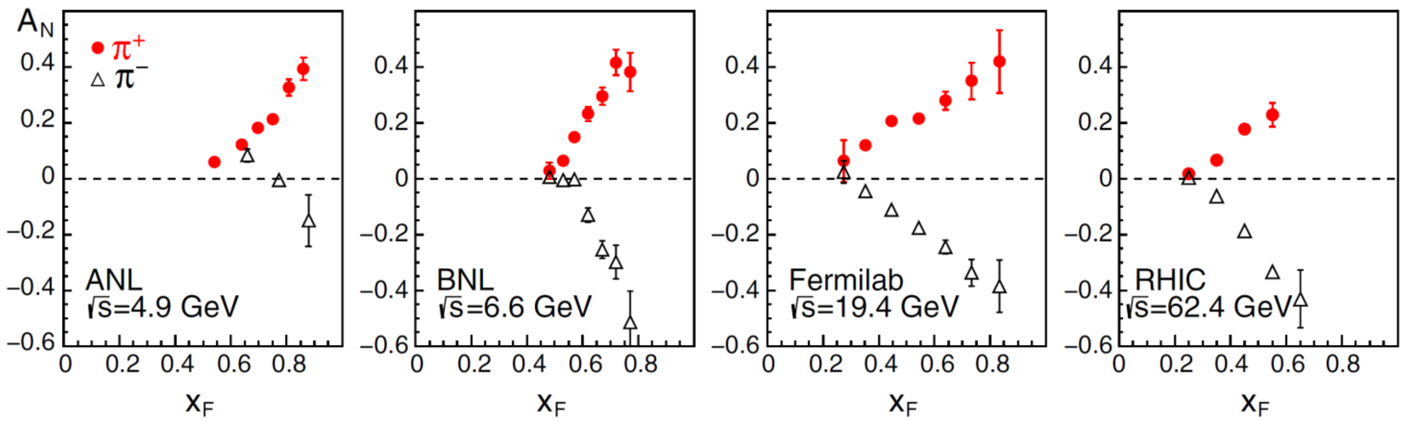
Run 2017: A_N for W, Z and Drell-Yan at $\sqrt{s}$=510 GeV

Transverse Single-Spin Asymmetry A_N

Anomalously large asymmetry A_N

$$p^{\uparrow} + p \rightarrow \pi^{\pm} + X$$

C.A.Aidala et al Rev.Mod. Phys. 85,655 (2013)



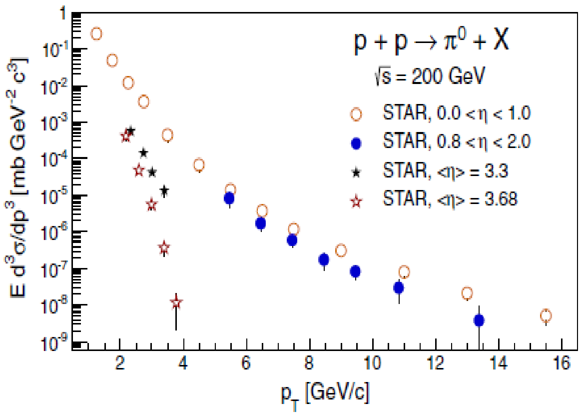
$$x_F = \frac{p_{z,\pi}}{p_{z,\max}}$$

Asymmetry reaches 40% for charged pions and exhibits similar x_F dependence over a wide range of $\sqrt{s}$

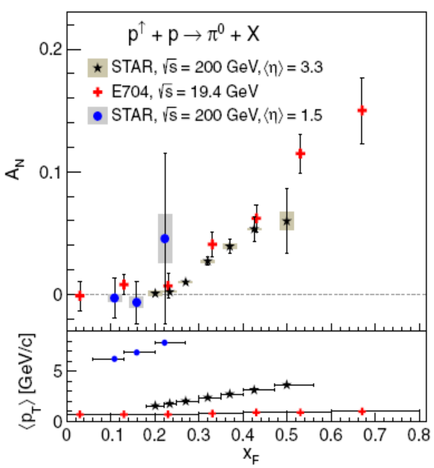
- SSAs are related to the structure of hadrons and their spin and orbital angular momentum content in terms of partons.
- They play a crucial role in the 3D mapping of the nucleons.

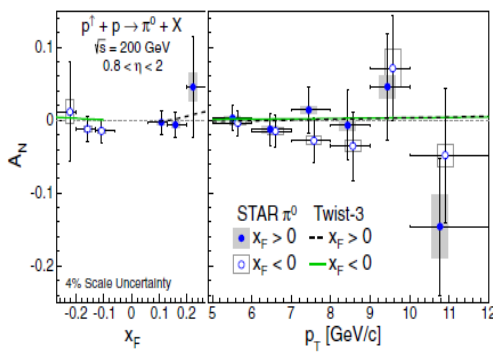
STAR Transverse single-spin asymmetry A_N at $\sqrt{s}$=200 GeV

STAR, Phys.Rev. D89, 012001 (2014)



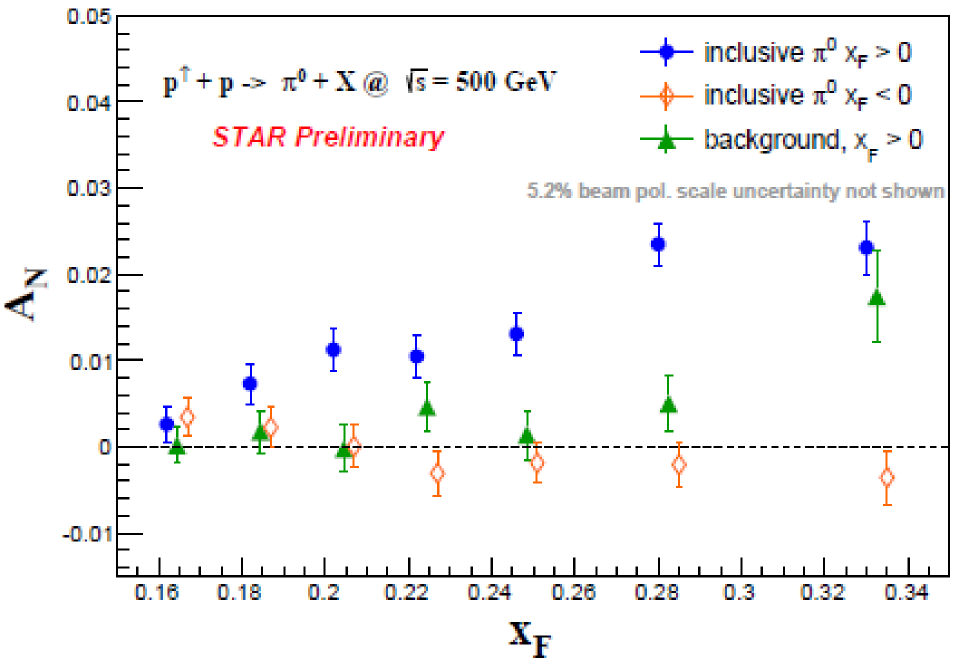
- The cross section for neutral pions produced in polarized p-p collisions over the range $0.8 < \eta < 2.0$ and $5 < p_T < 16$ GeV/c at $\sqrt{s}$=200 GeV was measured.
- The transverse asymmetry A_N is measured over a previously unexplored kinematic range in x_F and p_T
- Such measurements may aid our understanding of the onset and kinematic dependence of the large asymmetries observed at more forward pseudo-rapidity ($\eta \approx 3$) and their underlying mechanisms.
- A_N results are consistent with a twist-3 model prediction of a small asymmetry over the present kinematic range.





Transverse single-spin asymmetry A_N at $\sqrt{s}$=500 GeV

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



STAR Collaboration
Y.Pan
Int. J. Mod. Phys. Conf. Ser., **40**, 1660037 (2016).

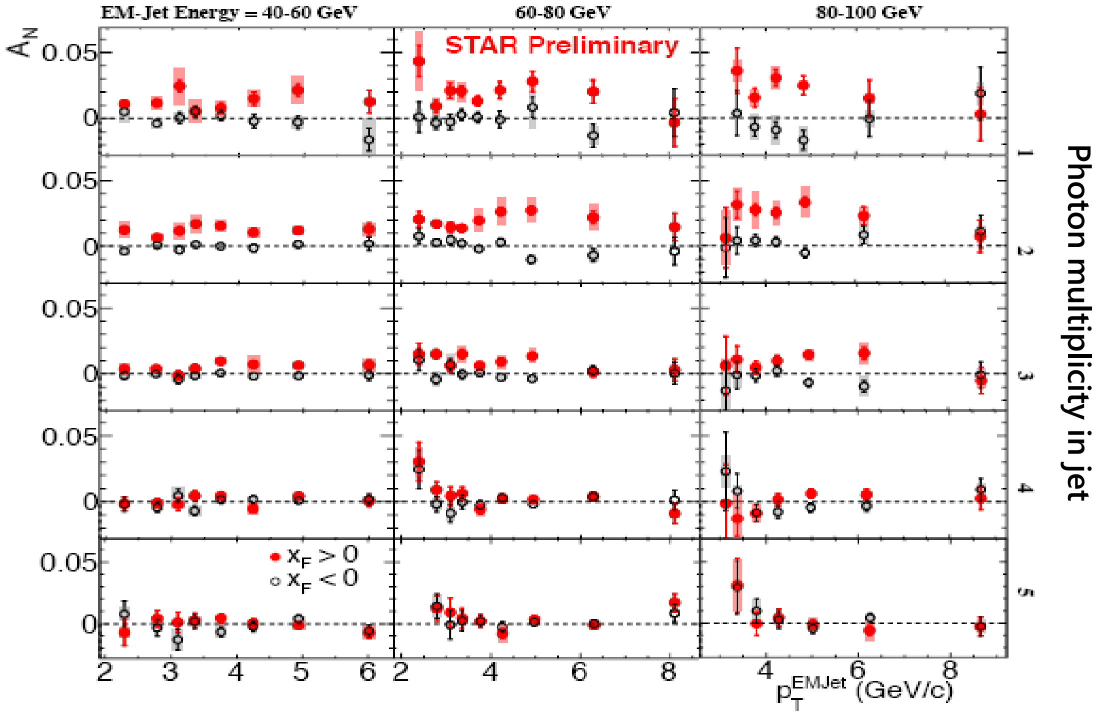
- Asymmetry A_N increases with x_F in the fragmentation range of polarized proton (x_F >0) .
- Asymmetry A_N is ~ zero in the fragmentation range of unpolarized proton (x_F <0) and for forward background.
- Slow dependence on collision energy: ~ 4% (FNAL, 20 GeV), ~ 2.5% (RHIC, 500 GeV).

E704, PLB261 (1991) 201

Transverse single-spin asymmetry A_N

A_N vs. p_T for "electromagnetic jets" at forward rapidities $(2.5<\eta<4.0)$

Jet-like events reconstructed from photons in the FMS



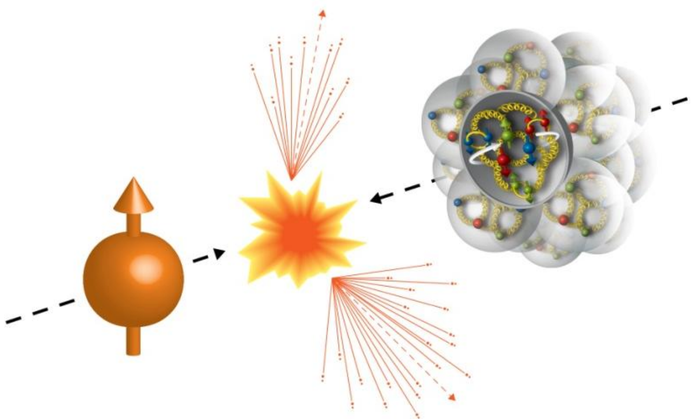
- The asymmetry decreases with increasing number of photons in the "electromagnetic jet".
- The asymmetries are basically flat as a function of jet p_T for all jet energies and photon multiplicities in the jet.
- This behavior is very different from naive expectations $(\sim 1/p_T)$ for an asymmetry driven by QCD subprocesses.

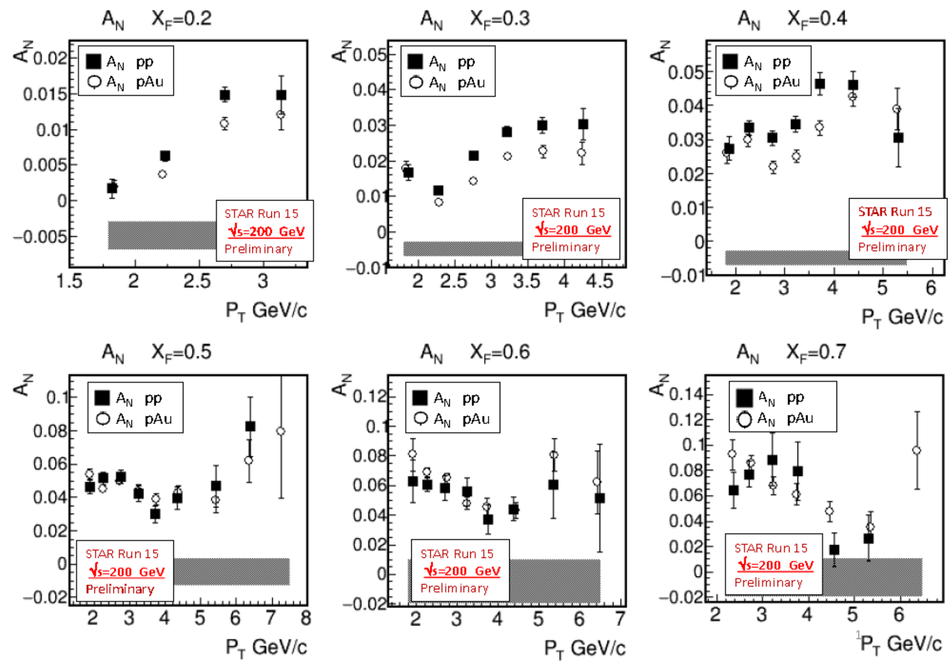
STAR Collaboration
M.M. Mondal,
PoS DIS2014(2014)216.

A_N from polarized p-Au

A_N: Single Spin Asymmetry
in Forward π^0 (low x) in p+p and p+Au

STAR FMS & 2.5<|η|<4.0
$p+p$ @ $\sqrt{s}$=200 GeV



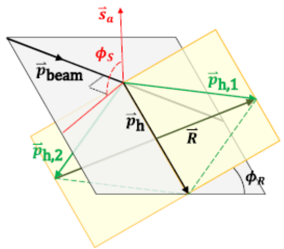


Shaded bands represent systematic uncertainty, dominated by dependence of A_N on observed BBC multiplicity

- Nuclear effects on fragmentation process
- Possible gluon saturation effects (CGC)

No suppression has been observed so far.

Transverse asymmetry A_{UT} of $\pi^+\pi^-$ pairs at $\sqrt{s}$=500 GeV



$\phi_{RS} = \phi_R - \phi_S$

$r = L^{\uparrow}/L^{\downarrow}$

$N^{\uparrow/\downarrow}$ the number of pion pairs

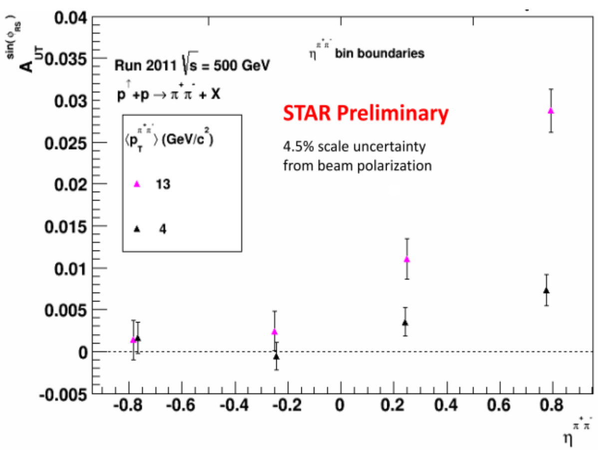
$$\frac{N^{\uparrow}(\phi_{RS}) - r\cdot N^{\downarrow}(\phi_{RS})}{N^{\uparrow}(\phi_{RS}) + r\cdot N^{\downarrow}(\phi_{RS})} = P_{beam} A_{UT} \sin(\phi_{RS})$$

Mid-rapidity range

$$p^{\uparrow} + p \rightarrow \pi^+\pi^- + X$$

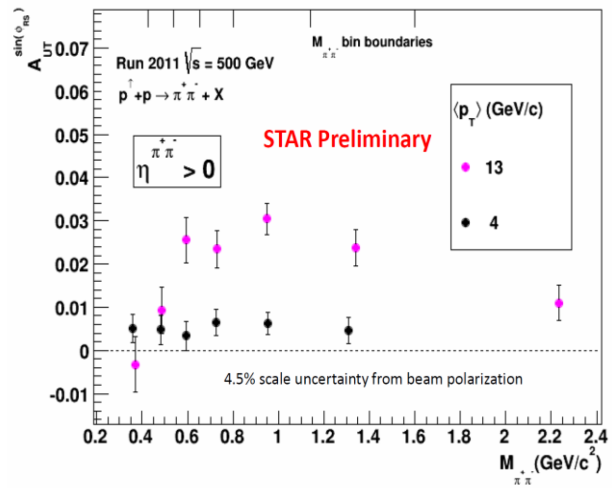
$$A_{UT} \propto h_1 \otimes H_1^{<}$$

Asymmetry vs. (η, p_T)



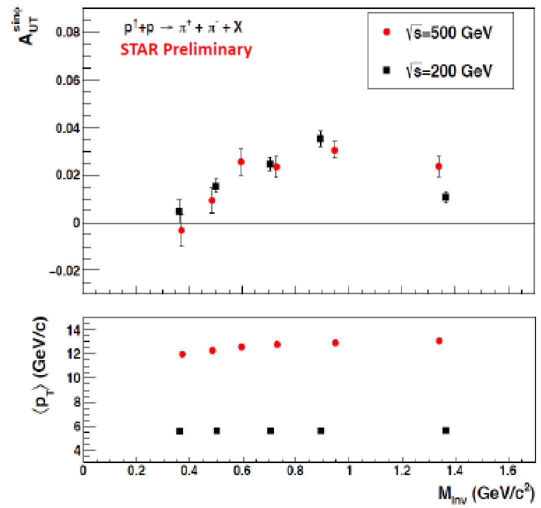
- A_{UT} as a function of η
- Significant asymmetry seen at high η and p_T

Asymmetry vs. ($M_{\pi\pi}$, p_T)



- A_{UT} as a function of M_{inv} plotted for 2 p_T bins
- Avg M_{inv} in each M_{inv} bin decreases with $<p_T>$
- Significant asymmetry seen at mid-M_{inv} and high p_T

Asymmetry vs. ($M_{\pi\pi}$, $<p_T>$)



- A_{UT} is scaled at $\sqrt{s}$=200 and 500 GeV with M_{inv}

- A_{UT} is sensitive to transversity - h_1 , and interference FF - $H_1^{<}$.
- The possibility to extract transversity without a full global analysis.

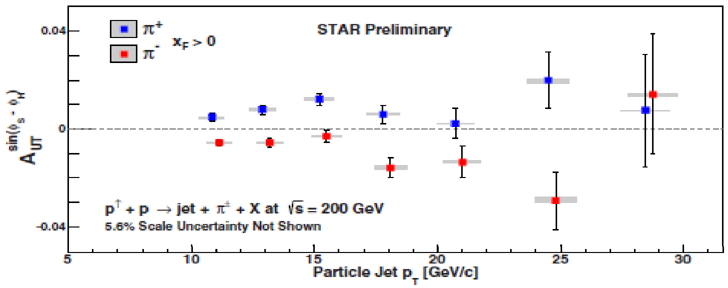
STAR publication is in preparation

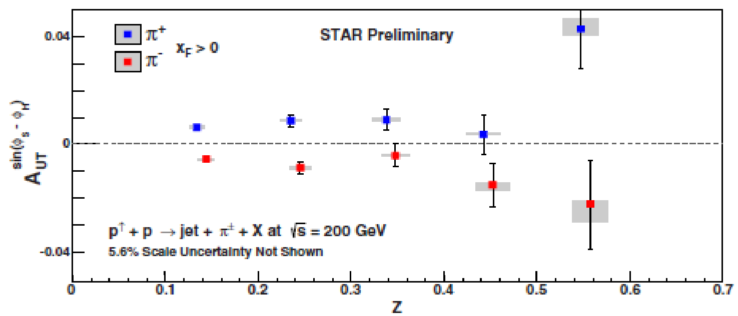
XIII Workshop on High Energy Spin Physics, DUBNA 2017

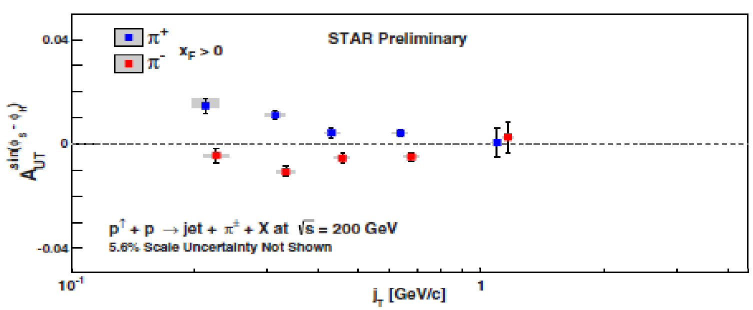
$$A_{UT} \qquad p^{\uparrow} + p \rightarrow \pi^{\pm} + jet + X$$

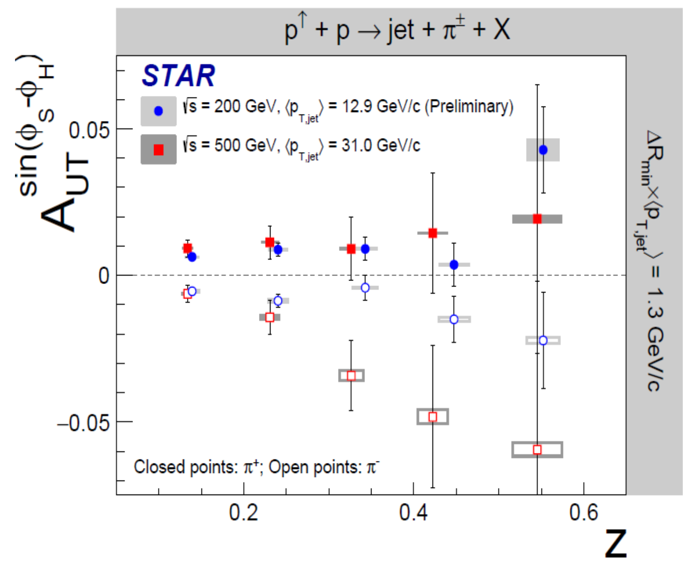
STAR
Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660040

Azimuthal distribution of charged pions inside jets are sensitive to the transversity distribution and the Collins fragmentation function.

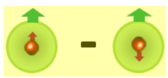








Transversity h_1



Collins FF ΔD

$z = p_{\pi}/p_{jet}$

$0 < \eta < 1$

$0.1 < x < 0.35$

Non-zero Collins asymmetry A_{UT} at $\sqrt{s} = 500$ and 200 data.
The visible dependence of A_{UT} on $\sqrt{s}$ for π^- .

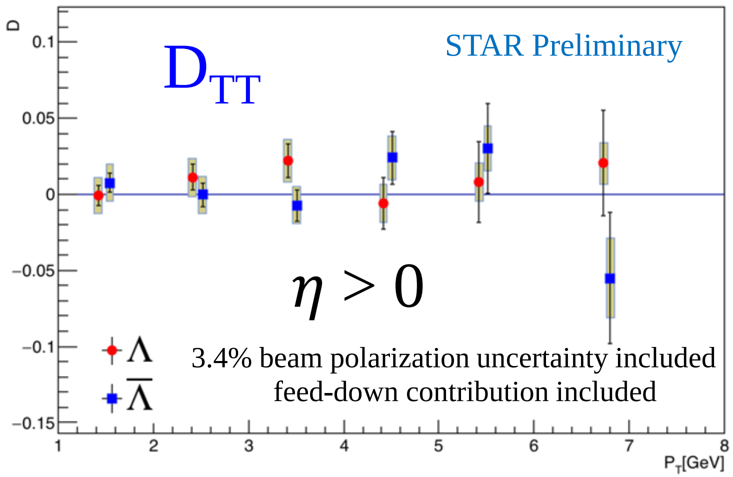
The opportunity to test the universality of both the Collins and transversity distributions and to study factorization breaking effects in hadronic collisions.

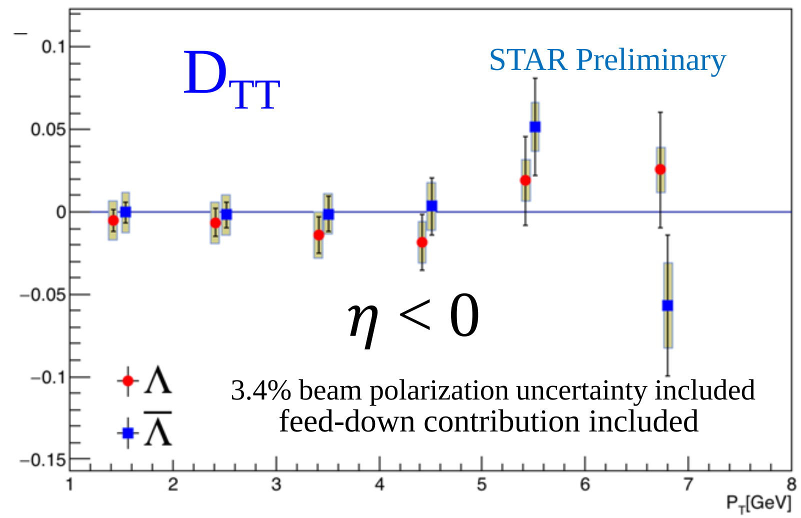
STAR, arXiv:1708.07080

Transverse spin transfer coefficient D_{TT}

Transverse spin transfer from polarized proton to $\Lambda(\bar{\Lambda})$ at $\sqrt{s}$=200 GeV provides insights into transversely polarized fragmentation and transversity distribution functions

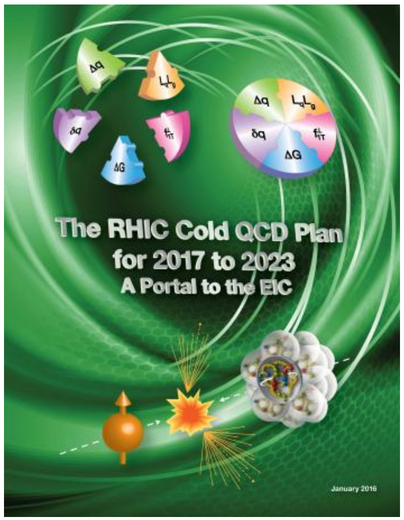
$$p^{\uparrow} + p \rightarrow \Lambda^{\uparrow} + X \qquad D_{TT} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}}$$





- Most precise measurement on $\Lambda(\bar{\Lambda})$ polarization in p+p collision at RHIC, which reach $p_T \sim 8$ GeV/c with statistical uncertainty of 0.04 .
- The dominant source of systematic uncertainty is from relative luminosity in low p_T.
- D_{TT} of Λ and $\bar{\Lambda}$ are consistent with each other and consistent with zero at the presently available precision.

Physics opportunities with transversally, longitudinally polarized p-p and with (un)polarized p-A collisions



	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR None None
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. None None
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. None Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. None Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. None
	202X	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

E.-C.Aschenauer at el., for the RHIC SPIN, PHENIX and STAR Collaborations, arXiv:1602.03922

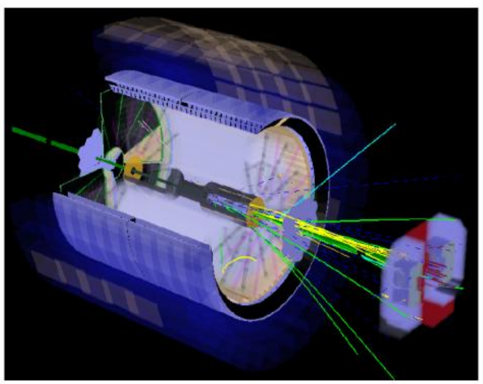
STAR Forward upgrade

The STAR forward upgrade is motivated mainly
by exploration of cold QCD physics
in the very high and low regions of Bjorken *x*.

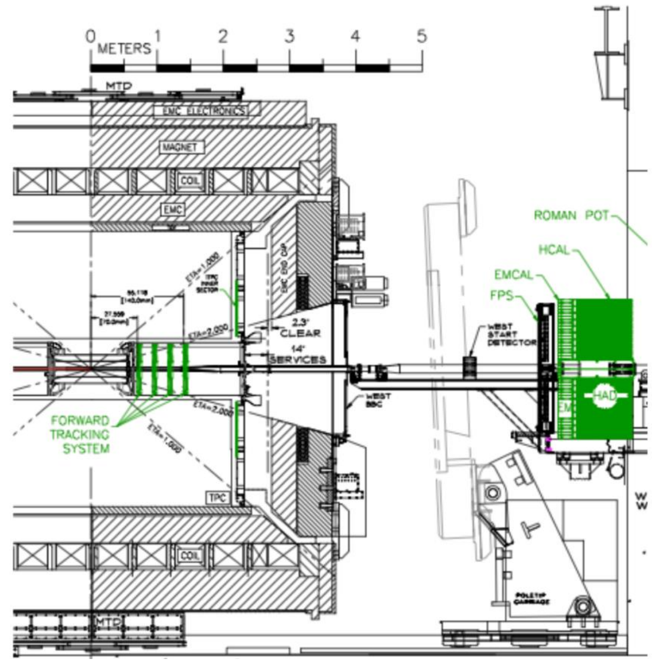
The forward upgrade will enable STAR
to investigate the full physics program outlined
in the RHIC Cold QCD Plan.

The STAR forward Calorimeter System and Forward Tracking System beyound BES-II Note 648
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

The STAR Forward Calorimeter System and Forward Tracking System



Proposal
May 2017



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

STAR Note 648

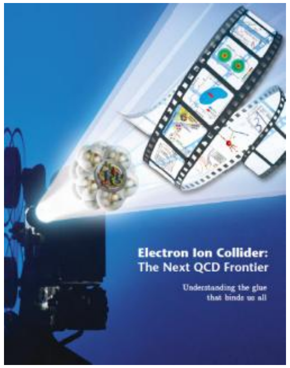
STAR Forward upgrade

- The forward upgrade program of STAR will enable us to study the longitudinal structure of the proton, the breaking of boost invariance in heavy-ion collisions, to explore the transport properties of the hot and dense matter formed in heavy-ion collisions near the region of perfect fluidity.

- The measurements at forward rapidity at RHIC will provide crucial tests for the effective theories of high-energy QCD and its evolution equation.

Such measurements will be complementary and necessary for a smooth transition toward the physics program in e+A collisions at a future Electron Ion Collider and fully explore the results from the EIC as well.

arXiv:1212.1701



Summary

- RHIC remains the only accelerator with polarized proton beams in the world.
- Large and uniform acceptance, excellent PID of the STAR experiment allows to perform measurements with unpolarized, longitudinally and transversally polarized protons up to $\sqrt{s}$= 510 GeV and obtain new data.
- The measurements of single and double-spin asymmetries of inclusive jets, di-jets, W and Z bosons, pions and pion pairs, the spin transfer coefficient of Λ in p+p provide verification of QCD in perturbative and non-perturbative region.
- The inclusion of STAR data into global PDF and FF analyses helps determine the gluon polarization contribution to proton spin, helicity of sea quarks and to understand the origin of transverse spin asymmetry.
- The forward upgrade at STAR would significantly improve the capabilities of the STAR experiment for measurements of observables such as asymmetries of pion, jet, Drell-Yan e^+e^- pairs produced at forward rapidity in p+p and p+A collisions.

Spin stays a key element in the exploration of fundamental physics at RHIC.

Thank You for Your Attention !

Back-up slides

Global Λ hyperon polarization in nuclear collisions

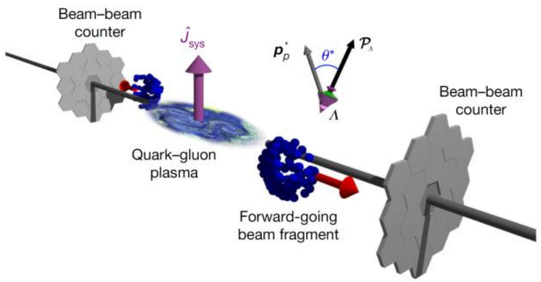
PRC 76, 024915 (2007); (E) PRC 95, 039906 (2017)

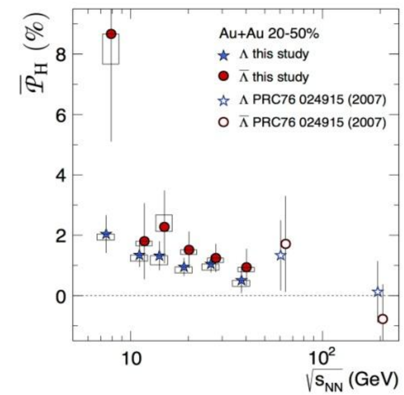
STAR has recently reported the first observation of global polarization of Λ hyperons in heavy ion collisions.
The discovery has been published in Nature 548, **62** (2017) as a cover story.

The polarization direction of the Lambdas is correlated at the level of several percent with the direction of the system angular momentum in non-central AuAu collisions at $\sqrt{s_{NN}}$=7.7-32 GeV.

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1+\alpha_H|\mathcal{P}_H|\cos\theta^*)$$

$$\overline{\mathcal{P}}_H \equiv \langle \mathcal{P}_H \cdot \hat{J}_{sys} \rangle$$





HI collisions at RHIC produce the most vortical fluid.

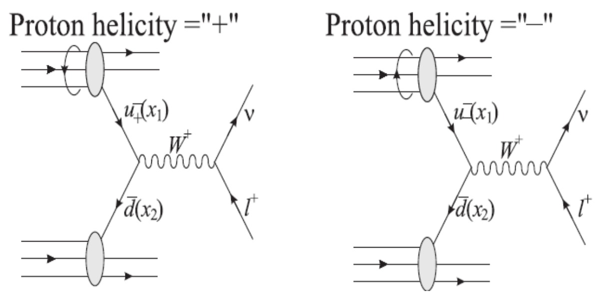
The rotational substructure of the fluid nuclear matter created at RHIC represents an entirely new direction in hot QCD research (Chiral Magnetic and Chiral Vortical Effects) and are planned to study for the future.

Probing sea quark polarization via $W^{\pm}$ production

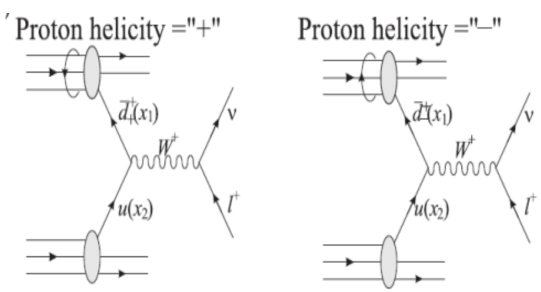
$$p + p \rightarrow W^{\pm} + X$$

$$A_L^W = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

σ_+ (σ_-) is the cross sections when the polarized proton beam has positive (negative) helicity



$$\Delta\sigma \propto \Delta u(x_1)\bar{d}(x_2)$$



$$\Delta\sigma \propto \Delta\bar{d}(x_1)u(x_2)$$

$\Delta u, \quad \Delta\bar{d}$

$$\begin{cases} A_L^{W^+} \propto -\dfrac{\Delta u(x_1)}{u(x_1)} & x_1 >> x_2 \\ A_L^{W^+} \propto \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)} & x_1 << x_2 \end{cases}$$

$\Delta d, \quad \Delta\bar{u}$

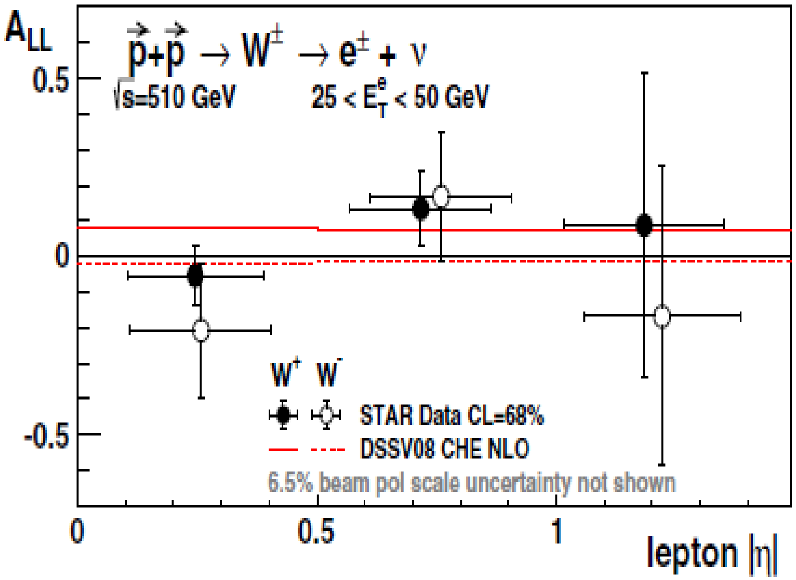
$$\begin{cases} A_L^{W^-} \propto -\dfrac{\Delta d(x_1)}{d(x_1)} & x_1 >> x_2 \\ A_L^{W^-} \propto \dfrac{\Delta\bar{u}(x_1)}{u(x_1)} & x_1 << x_2 \end{cases}$$

Longitudinal double-spin asymmetry A_{LL} $W^{\pm}$ production in p-p collisions

$$p + p \to W^{\pm} + X$$

$$A_{LL}^{W} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$

STAR, Phys.Rev.Lett. 113, 072301 (2014)



- The W double-spin asymmetry is sensitive to the product of quark and antiquark polarizations and has also been proposed to test positivity constraints using a combination of A_L and A_{LL} .
- The measured double-spin asymmetries are consistent with the theoretical predictions and in conjunction with A^W_L satisfy the positivity bounds within the current uncertainties.

The inclusion of this measurement in global QCD analyses of RHIC and DIS data should significantly improve the determination of the polarization of up and down antiquarks in the proton and provide new input on the flavor symmetry of the proton's antiquark distributions.

Transverse single-spin asymmetry A_N

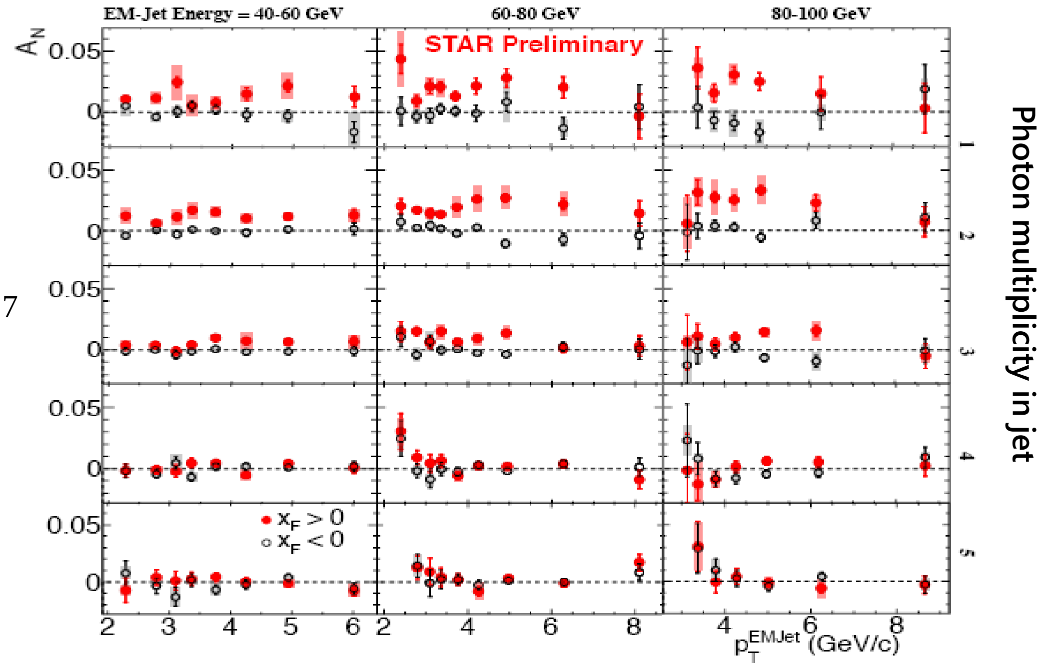
A_N vs. p_T for "electromagnetic jets" at forward rapidities $(2.5<\eta<4.0)$

Jet-like events reconstructed from photons in the FMS

$$\frac{N\uparrow(\phi)-N\downarrow(\phi)}{N\uparrow(\phi)+N\downarrow(\phi)} = p_0 + P \times A_N \cos(\phi)$$

P- beam polarization

p_0 – relative up/down lum.



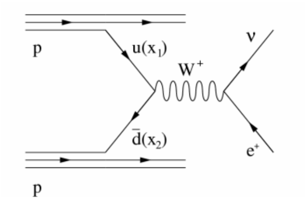
- The anti-k_T jet algorithm is used with R = 0.7 to find jets in the forward (FMS photons) and central (EMC+BEMC towers) rapidity regions, with $p_T^{EM-jets} > 2.0$ GeV/c and pseudo-rapidity $2.8 < \eta^{EM-Jet} < 4.0$ and $-1.0 < \eta^{EM-Jet} < 2.0$, respectively.
- Energy of the forward EM-jets: $40 < E^{EM-Jet} < 100$ GeV, $0.16 < x_F < 0.4$.
- Only one EM-jet from the forward and central regions is chosen with the highest-energy EM-Jet in the forward region and highest $p_T^{EM-jets}$ from mid-rapidity.

- The asymmetry decreases with increasing number of photons in the "electromagnetic jet".
- The asymmetries are basically flat as a function of jet p_T for all jet energies and photon multiplicities in the jet.
- This behaviour is very different from naive expectations $(\sim 1/p_T)$ for an asymmetry driven by QCD subprocesses.

STAR Collaboration
M.M. Mondal,
PoS DIS2014(2014)216.

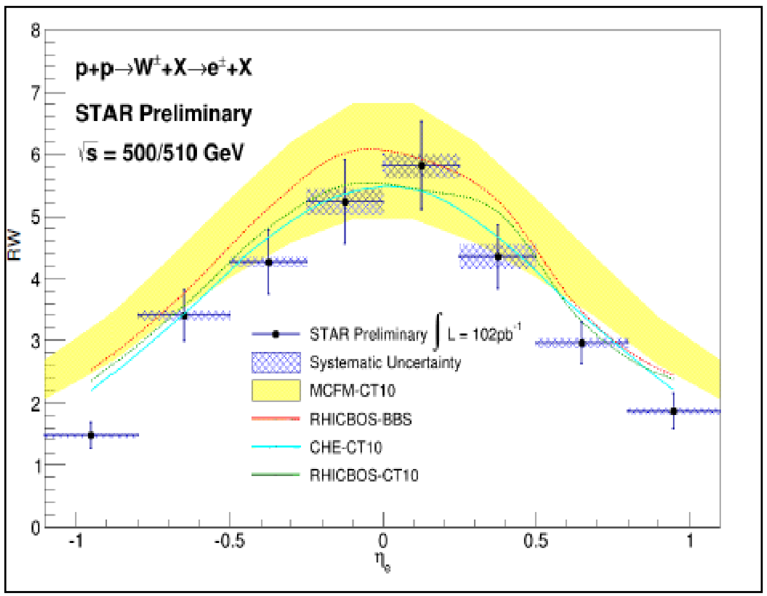
Cross section ratio W^+/W^- in pp at $\sqrt{s}$= 510 GeV

The ratio provides a direct measurement of the unpolarized flavor structure of sea

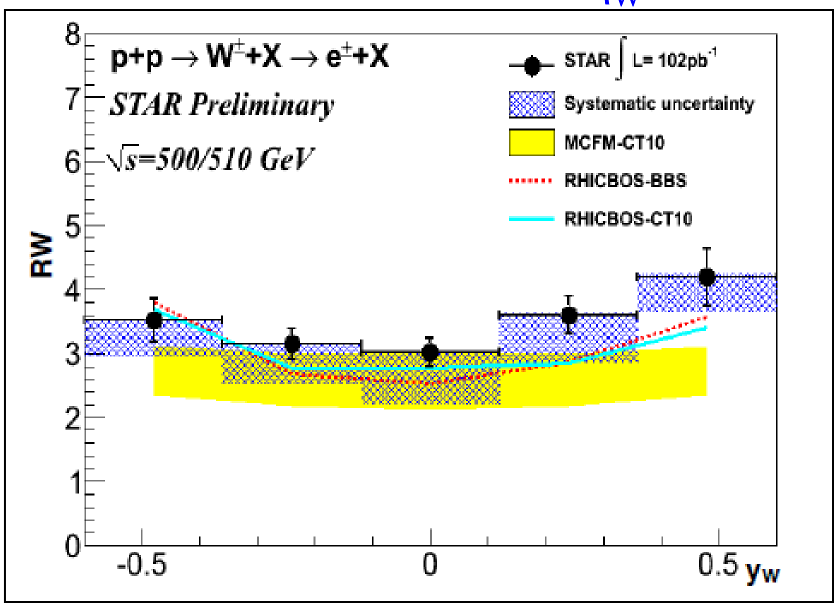


$$\frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

Ratio W^+/W^- vs. η_e



Ratio W^+/W^- vs. η_W



STAR constraint on $\bar{d}/\bar{u}$ at high x

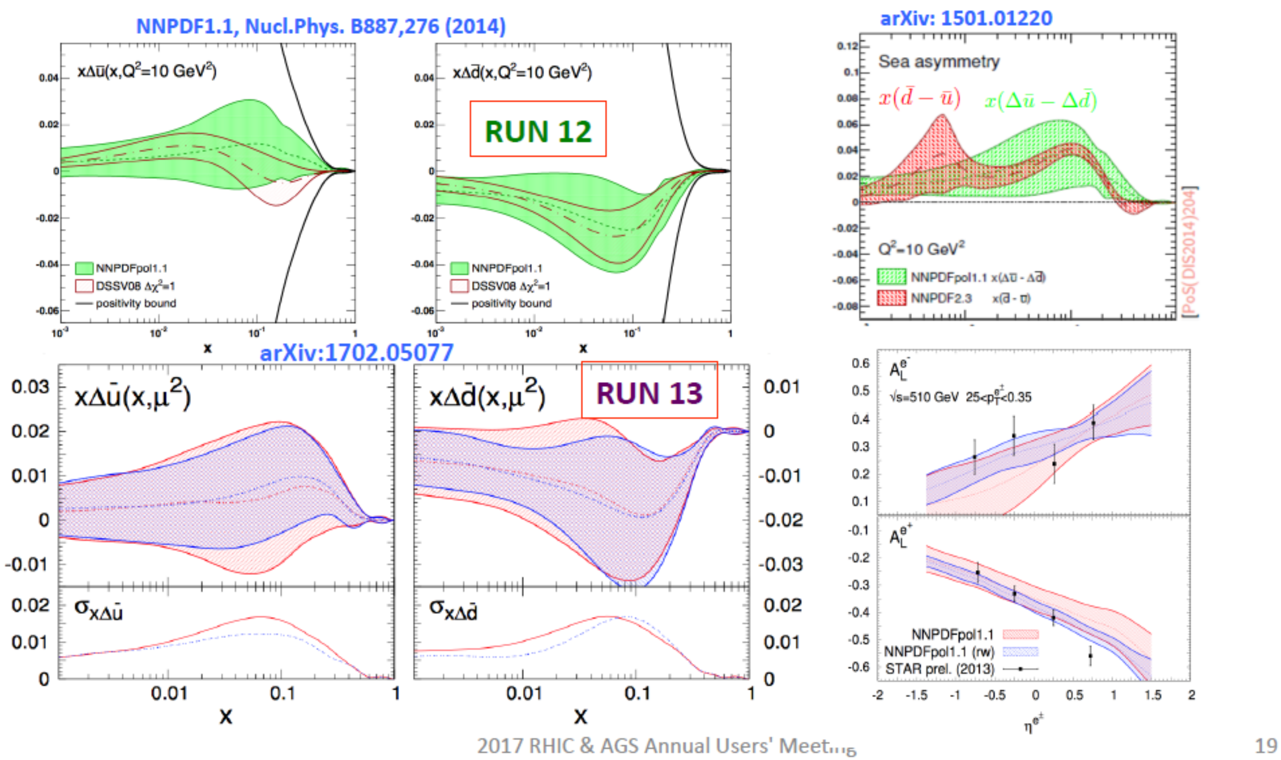
TPC+BEMC+EEMC
0.06<x<0.4, -2<η<2

STAR, arXive:1702.02927

STAR

Global Fits with STAR Results

Big impact seen in NNPDFpol1.1 global analysis after including STAR A_L data



New constraints on spin-dependent PDFs from STAR

STAR Collaboration
A.Kraishan , *RHIC & AGS Annual User's Meeting, 2017*

Single-Spin Asymmetries (SSA)

- There are multiple contributions to transverse single-spin asymmetries in the TMD framework
- STAR is sensitive to several modulations

Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers•PDF•FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity•Boer-Mulders•FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity•Boer-Mulders•FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$

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*Analogous modulations for gg scattering also exist Phys. Rev. D 83 034021 (2011)