The RHIC Spin Program

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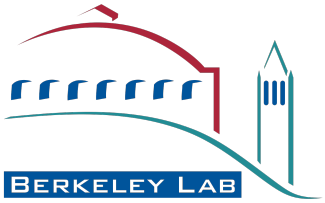


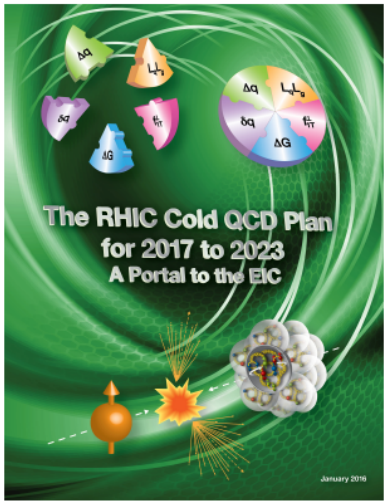
U.S. DEPARTMENT OF ENERGY

Outline

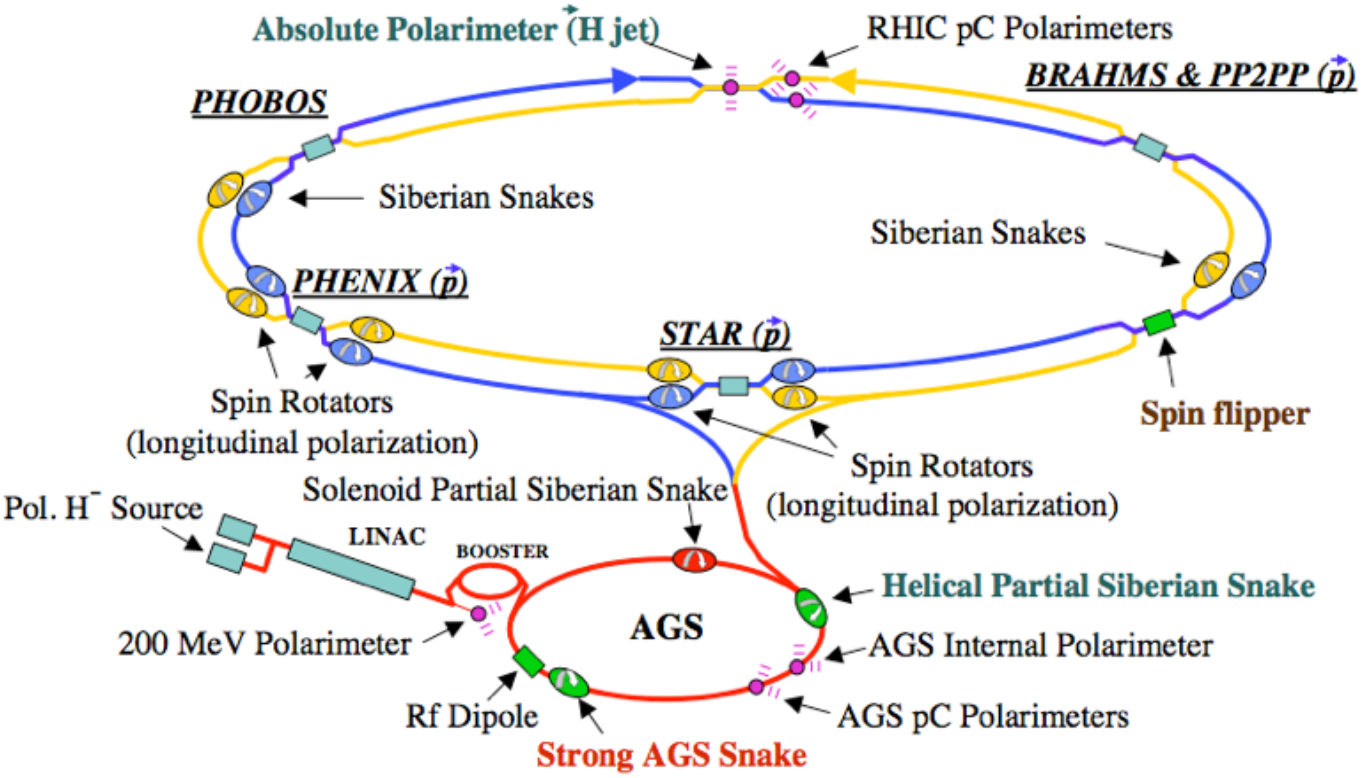
- RHIC, polarized proton-proton collider
  - STAR and PHENIX
- Unique physics opportunities at RHIC and selected recent results
  - Helicity structure of proton: gluons and quarks
  - Studies on transverse dimensions
- Outlook and Summary

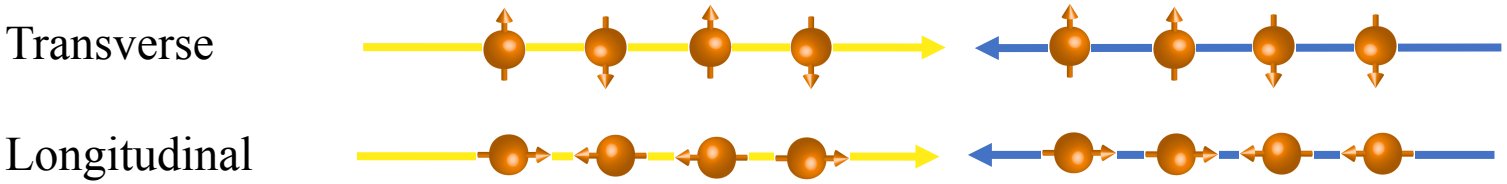
arXiv: 1501.01220

arXiv:1602.03922

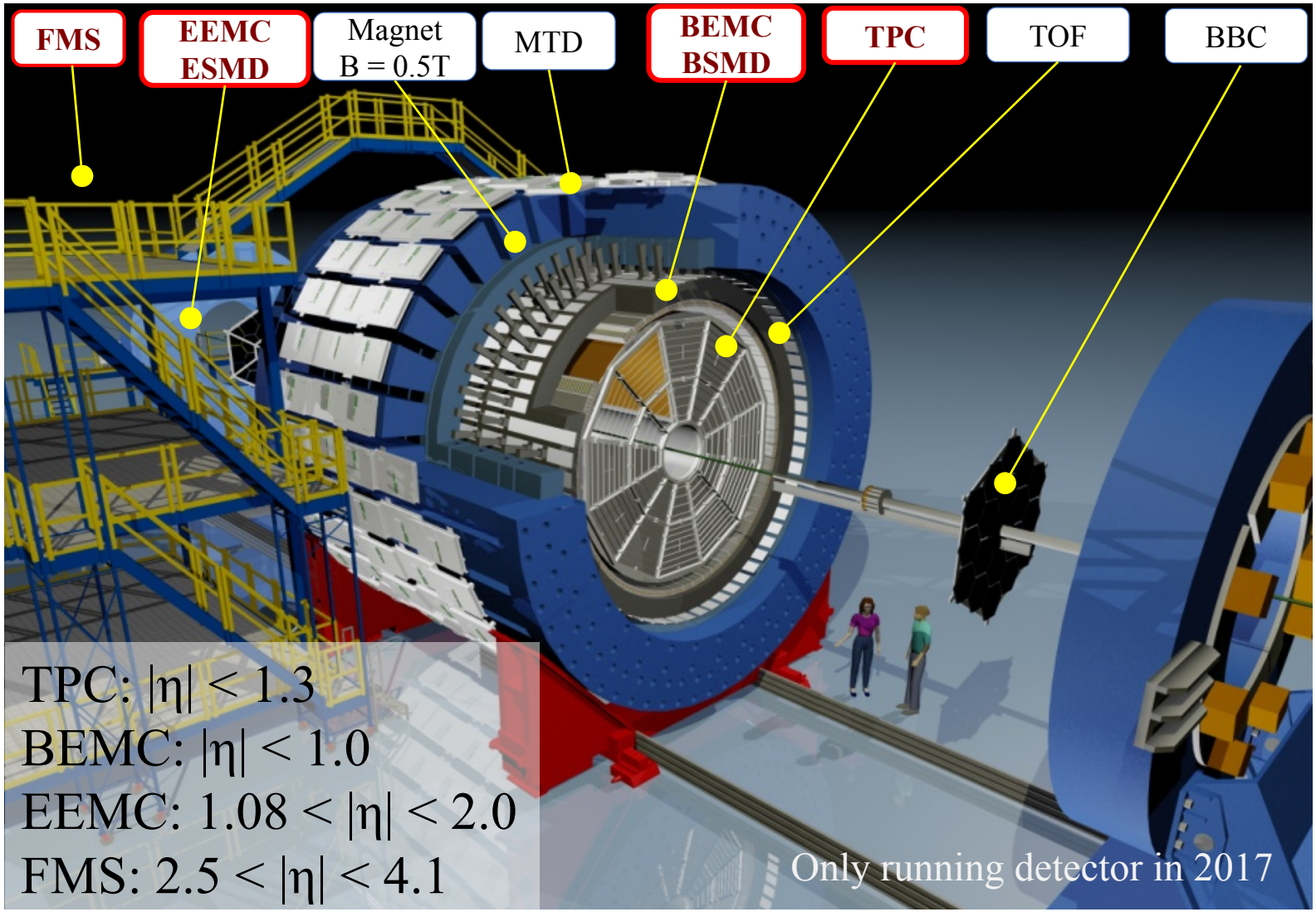


RHIC – Polarized Proton-Proton Collider

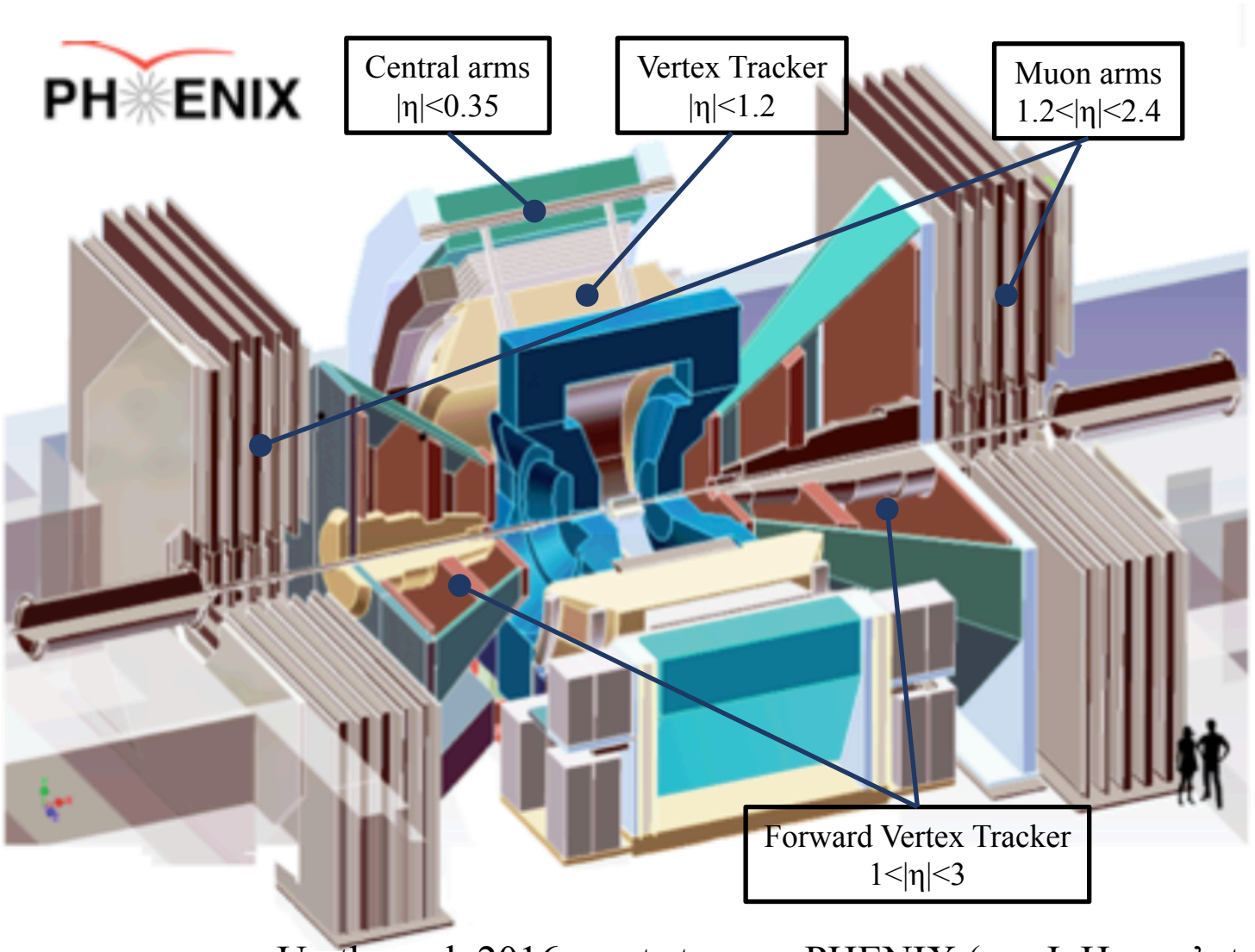




STAR Detector Overview



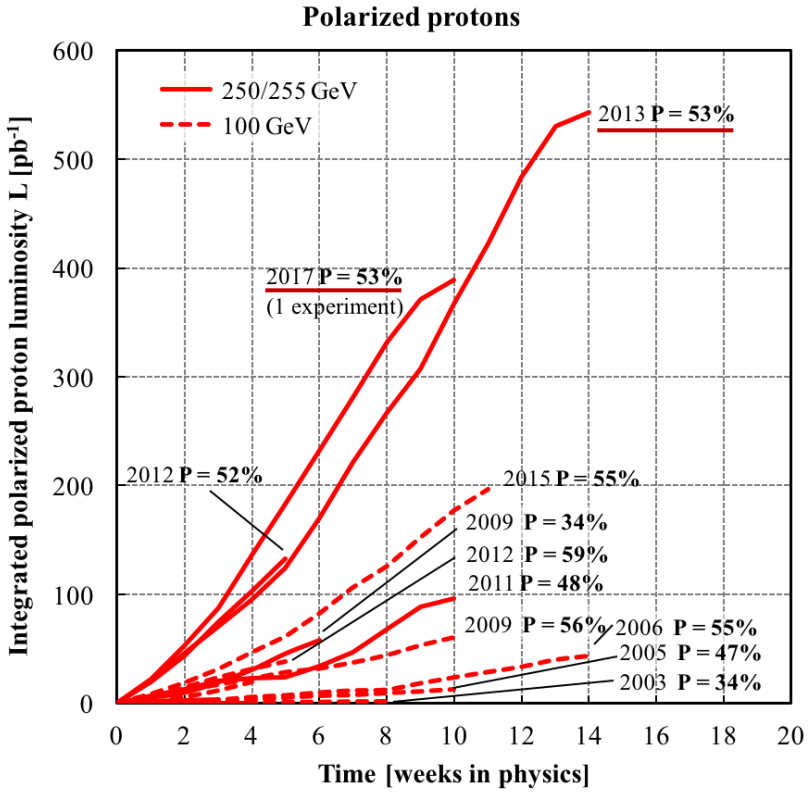
PHENIX Detector Overview



Up through 2016, next stage – sPHENIX (see J. Huang's talk)

Polarized p+p Data Accumulation at RHIC

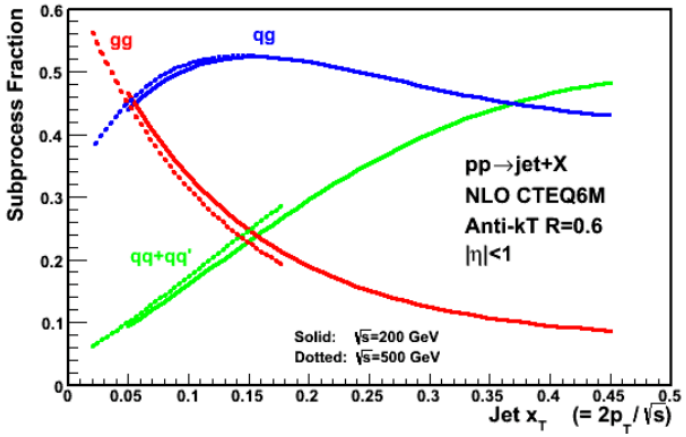
	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	50	60
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	50	60
	2017	510	356	55



Probe Gluon Polarization via Hadron/Jet

Double-spin asymmetry:

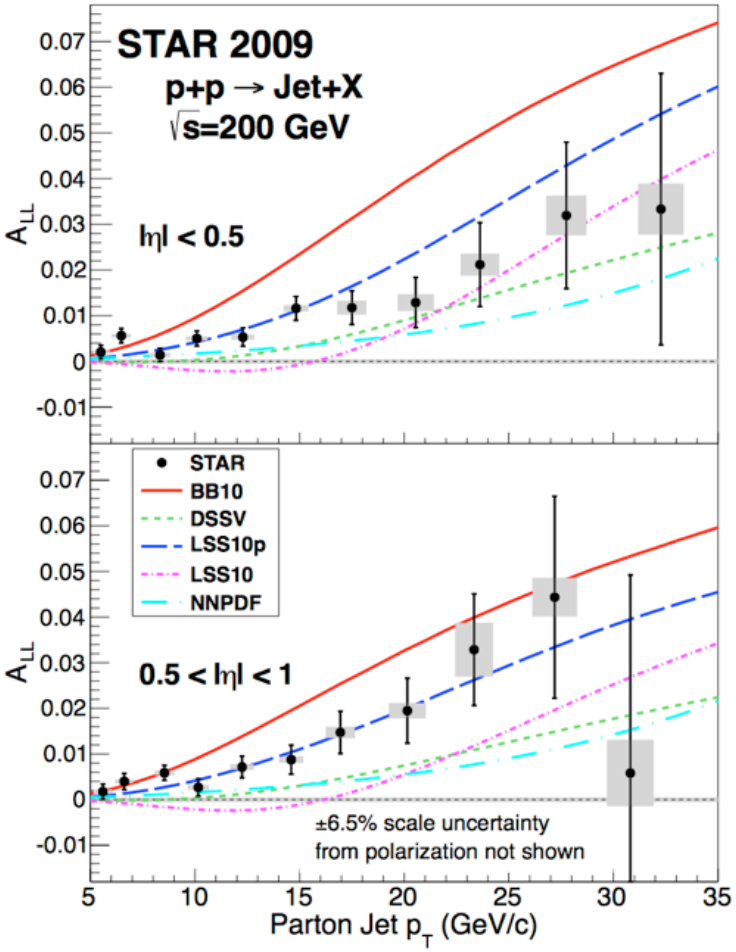
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$



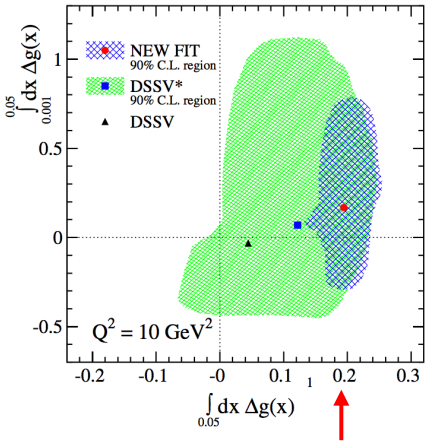
- Abundant yields of π^0 and jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\pi^0,\text{jets}} / \sqrt{s} \bullet e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

Inclusive Jet A_{LL}: first non-zero ΔG

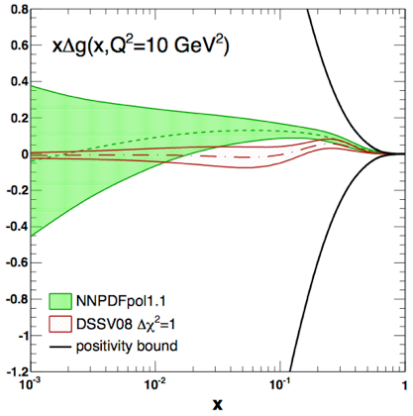
PRL115 (2015) 092002



PRL113 (2014) 012001



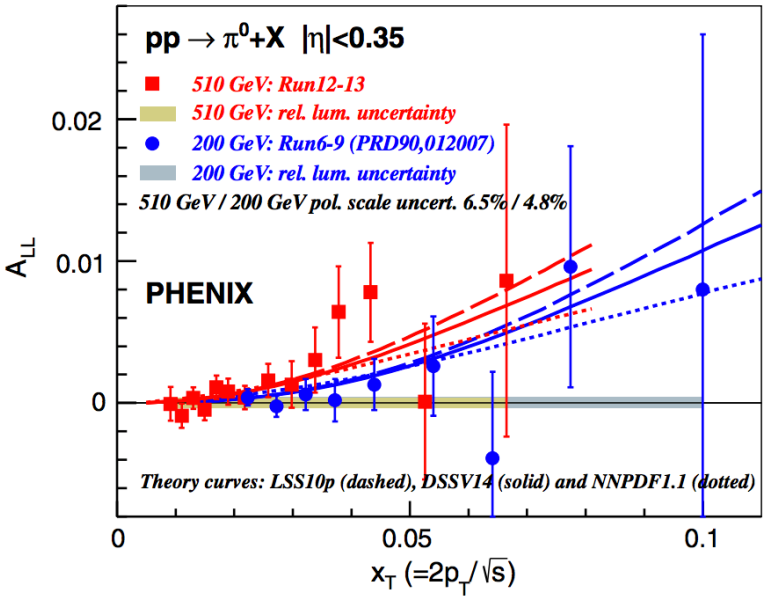
Nucl. Phys. B887 (2014) 276



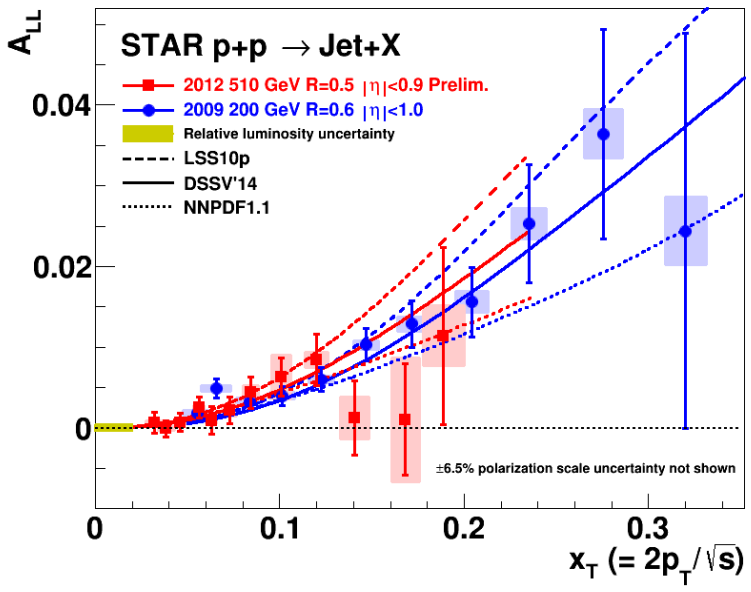
- First evidence of non-zero contributions from gluon spin at $Q^2 \sim 10$ GeV^2
- Drive the constraints on ΔG

Inclusive Hadron/Jet A_{LL} Results

PHENIX, PRD93(2016)011501



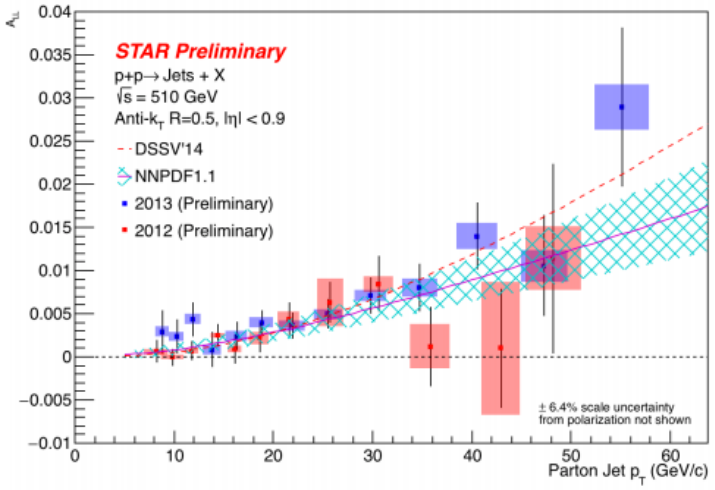
Z.Chang, SPIN2014

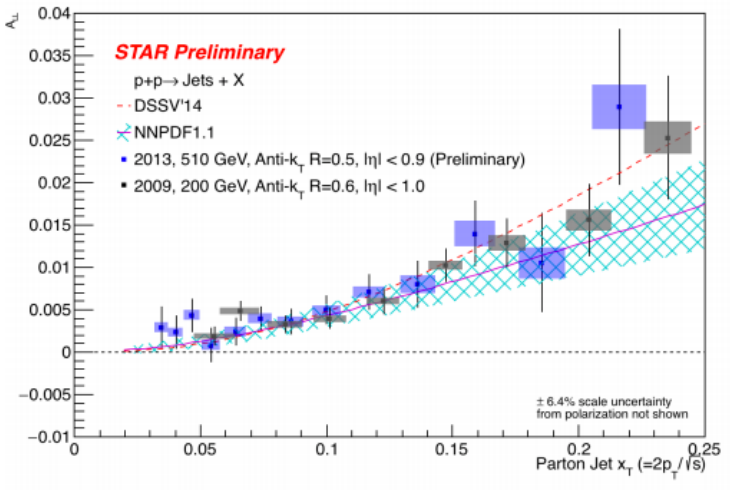


- PHENIX and STAR released higher statistics π^0 and jet results since then.
- Measurement at $\sqrt{s}$ = 510 GeV access to lower x values
- Consistent descriptions from π^0 and jet at different energy

New Preliminary Inclusive Jet A_{LL}

A.Quintero, RHIC&AGS Users' Meeting 2017

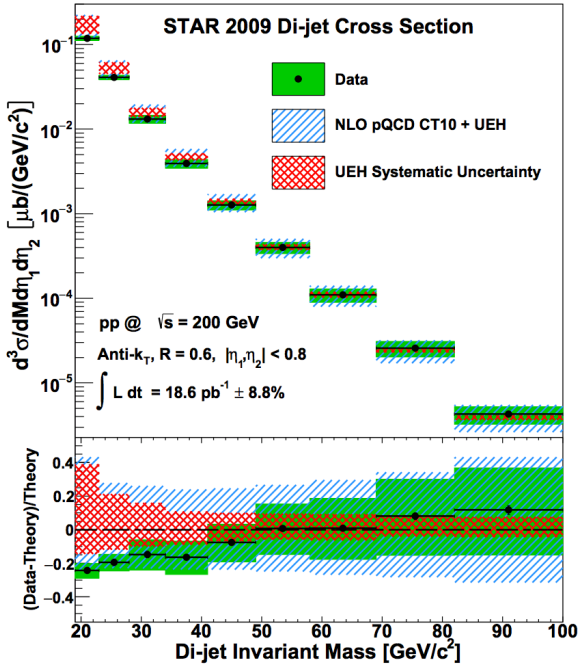


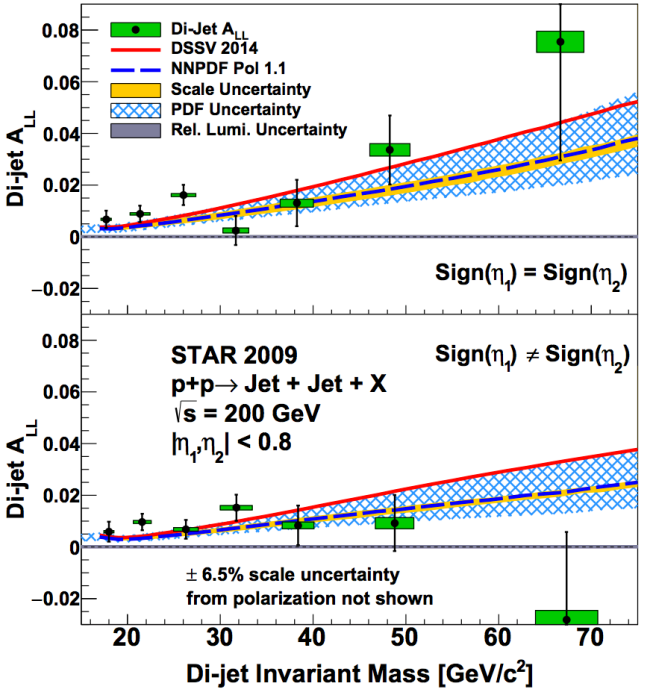


- New preliminary results from STAR 2013 data (256pb^{-1}) just released last month.
- Good agreement with 2009 (200 GeV) and 2012 (510 GeV) results with much better precision.

Measurement of Di-jet Production

STAR, PRD 95 (2017) 71103

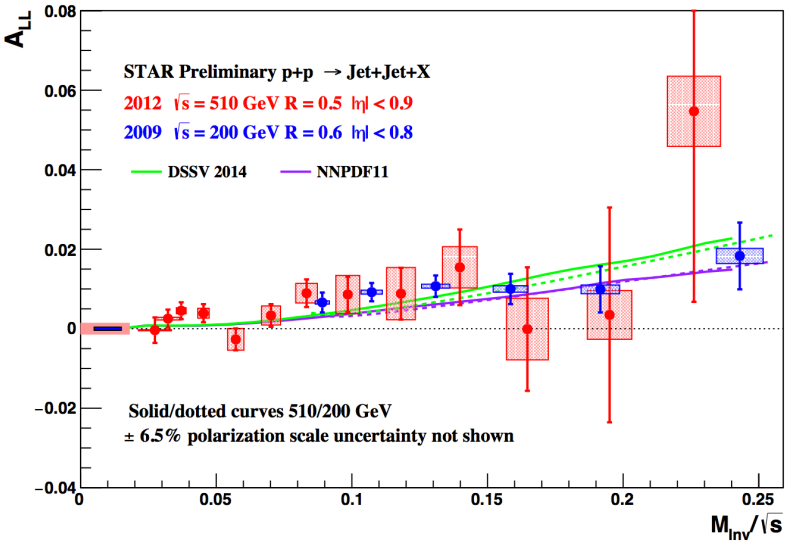




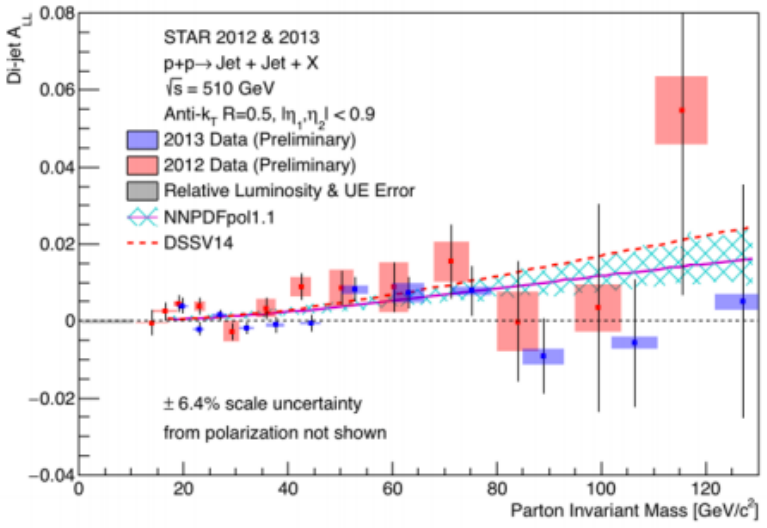
- Access initial partonic kinematics, $\frac{M}{\sqrt{s}} = \sqrt{x_1 x_2}$
- Initial di-jet A_{LL} data are consistent with DSSV and NNPDF expectations

Measurement of Di-jet Production

S. Ramachandran, DIS 2016



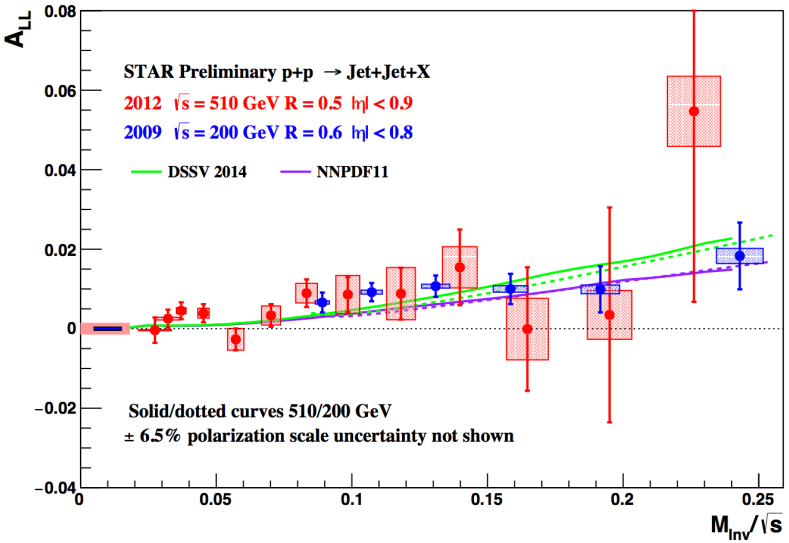
D.Olvitt.Jr, RHIC&AGS Users' Meeting 2017



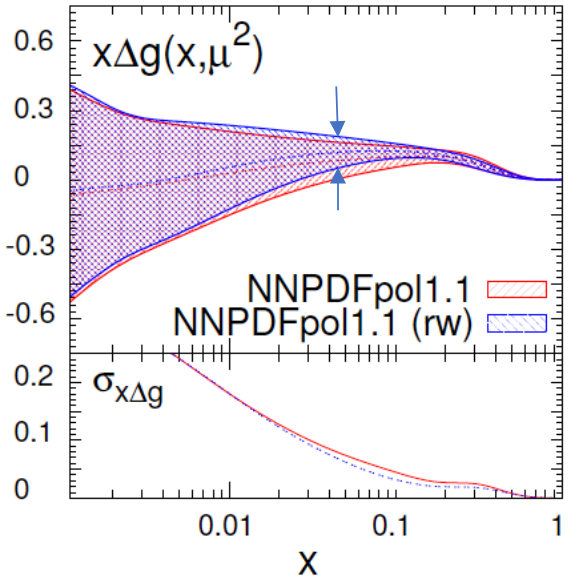
- Extending to √s = 510 GeV, new results from much larger data samples taken in 2012 and 2013 agree with the initial 2009 di-jet results, and with the DSSV and NNPDF expectations.

Measurement of Di-jet Production

S. Ramachandran, DIS 2016

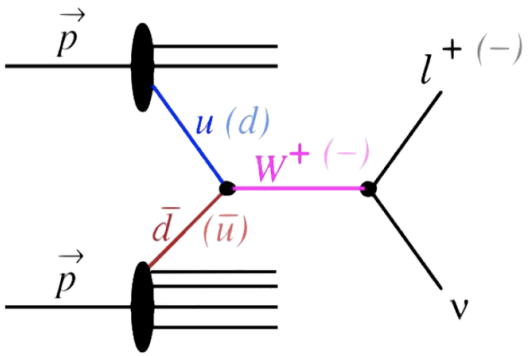


E. Nocera, SPIN2016



- Extending to √s = 510 GeV, new results from much larger data samples taken in 2012 and 2013 agree with the initial 2009 di-jet results, and with the DSSV and NNPDF expectations.
- NNPDF reweighting included STAR 2012 Di-jet results together PHENIX π^0 results, further constraining gluon polarization distribution.

Probe Sea Quark via W Boson



(LO)

- Great opportunity with W boson production in RHIC polarized proton-proton collisions at √s = 500 GeV
  - Elegant process: $u\bar{d} \to W^+ \to e^+\nu_e$ and $\bar{u}d \to W^- \to e^-\bar{\nu}_e$
  - No uncertainties from fragmentation
  - Perfect spin selection in V-A structure of weak interaction
  - Flavor-ID from final lepton charge-ID

Single-spin asymmetry:

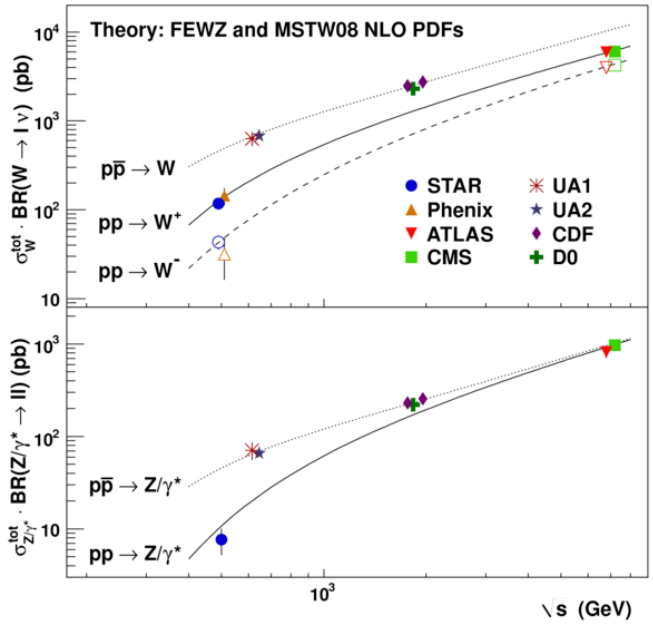
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

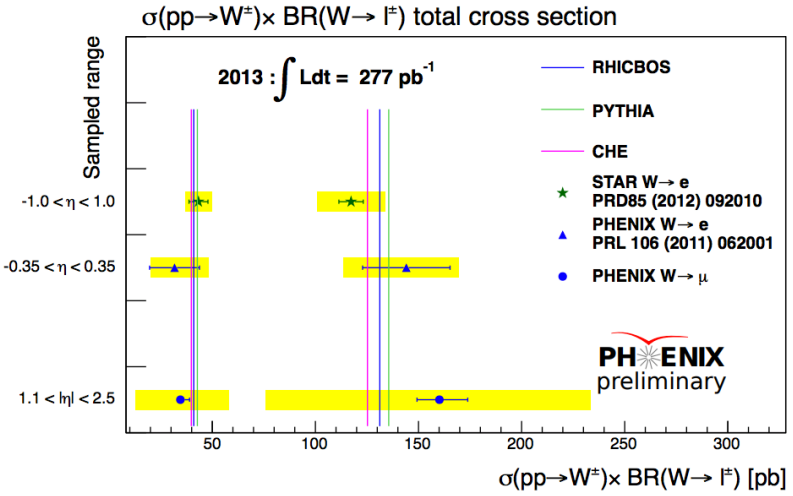
$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \approx \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, x_1 \gg x_2 \\ \dfrac{\Delta \boldsymbol{\bar{d}}(\boldsymbol{x_1})}{\boldsymbol{\bar{d}}(\boldsymbol{x_1})}, x_1 \ll x_2 \end{cases}$$

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \approx \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, x_1 \gg x_2 \\ \dfrac{\Delta \boldsymbol{\bar{u}}(\boldsymbol{x_1})}{\boldsymbol{\bar{u}}(\boldsymbol{x_1})}, x_1 \ll x_2 \end{cases}$$

W Cross Section

STAR, Phys. Rev. D 85 (2012) 92010

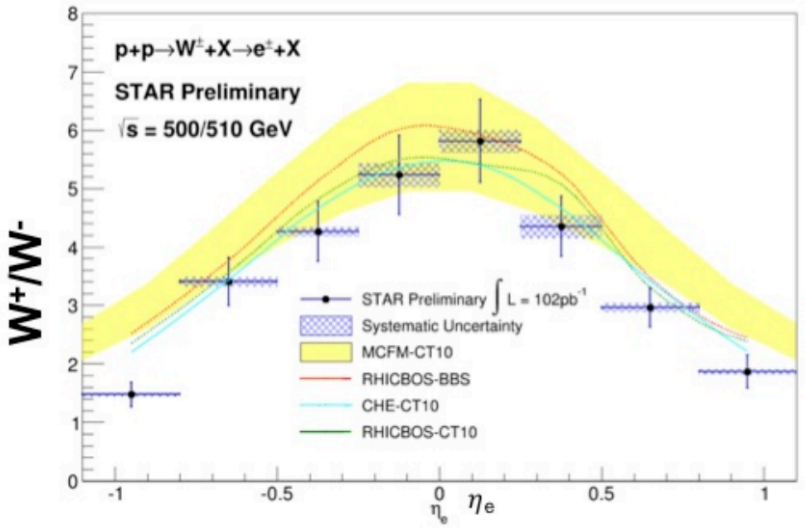


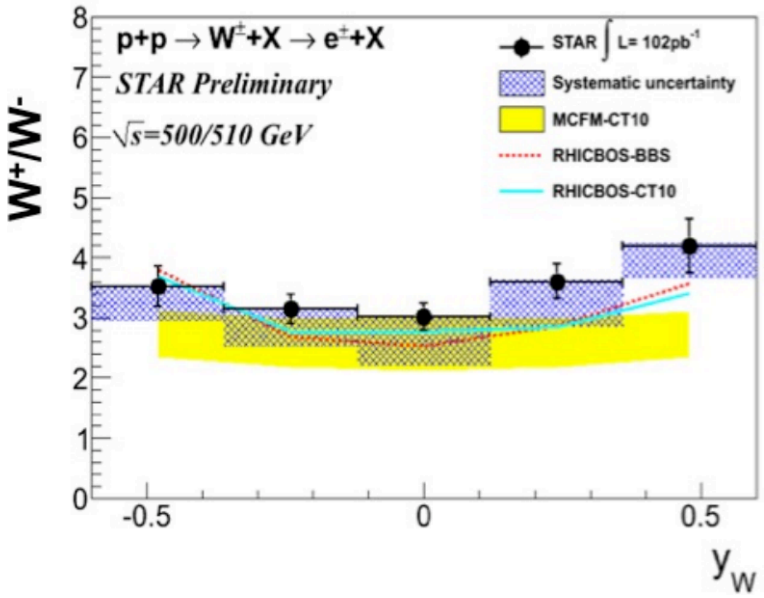


- PHENIX and STAR both successfully selected W leptonic decay signals.
- Cross section results consistent with theoretical predictions.

W Cross Section Ratio

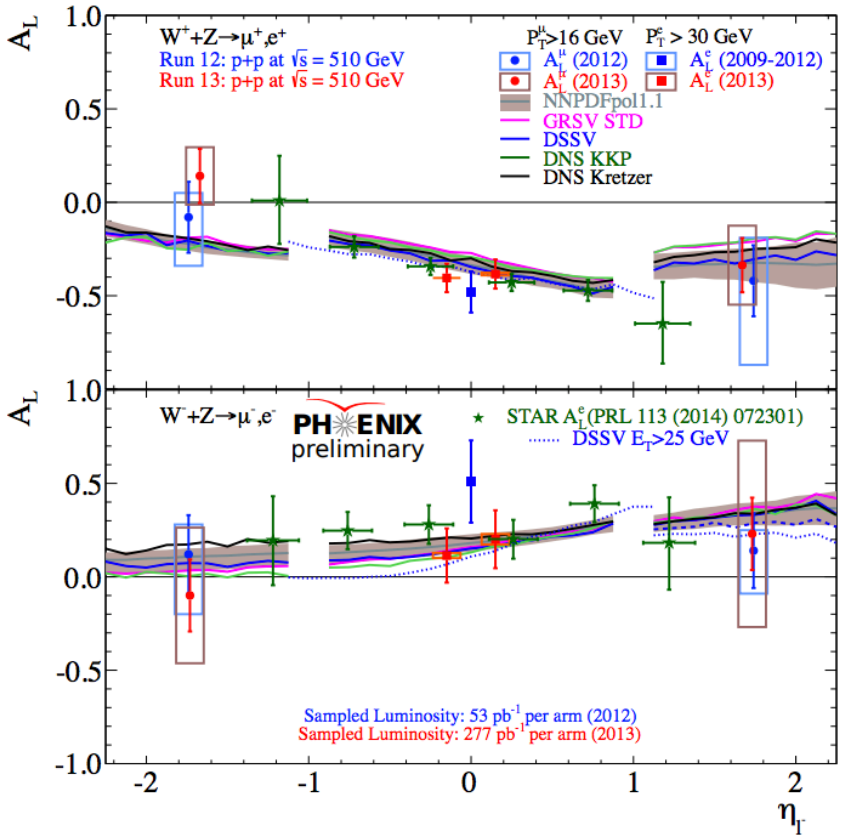
M. Posik, S. Fazio, et al. (STAR Collaboration), DIS 2015.





- Unpolarized sea symmetry: Complementary to NA51, E866, and SeaQuest
- Preliminary 2011+2012 results from data of 102 pb^{-1}
- 256 pb^{-1} and 360 pb^{-1} recorded during 2013 and 2017
- **W kinematics reconstructed from its recoil, key for W A_N measurement.**

W A_L Results



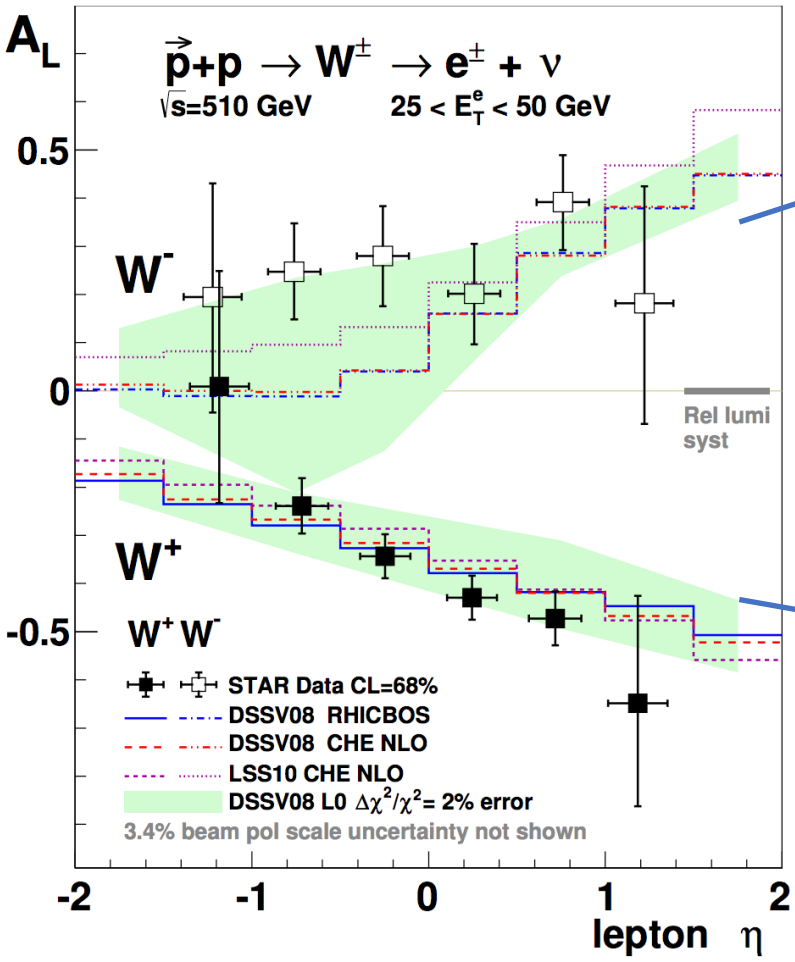
PHENIX PRD 93 (2016) 051103 (mid-rapidity)

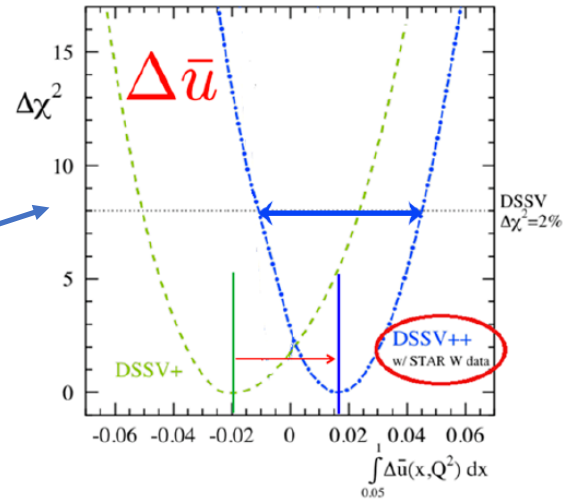
STAR, PRL113 (2014) 072301

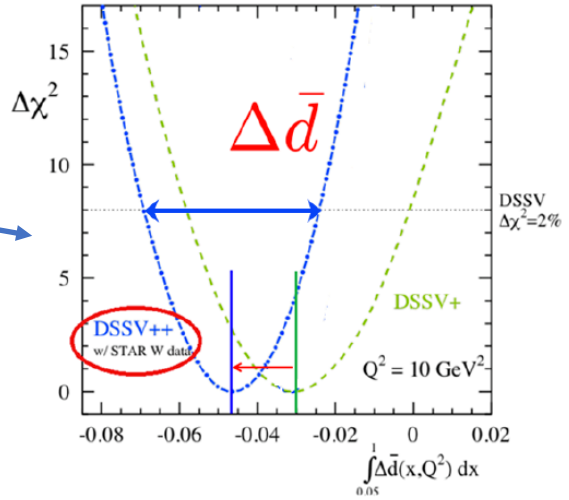
- PHENIX measured W A_L with central arms ($e^{\pm}$ channel) and forward muon arms ($u^{\pm}$ channel), consistent with theoretical predictions within uncertainties
- STAR published W A_L results as a function of lepton η.
- W^- A_L for negative η_e are at the upper band of the DIS-based expectations. This implies that $\Delta\bar{u}$ is larger than expected.

W A_L Results

STAR, PRL113(2014)072301



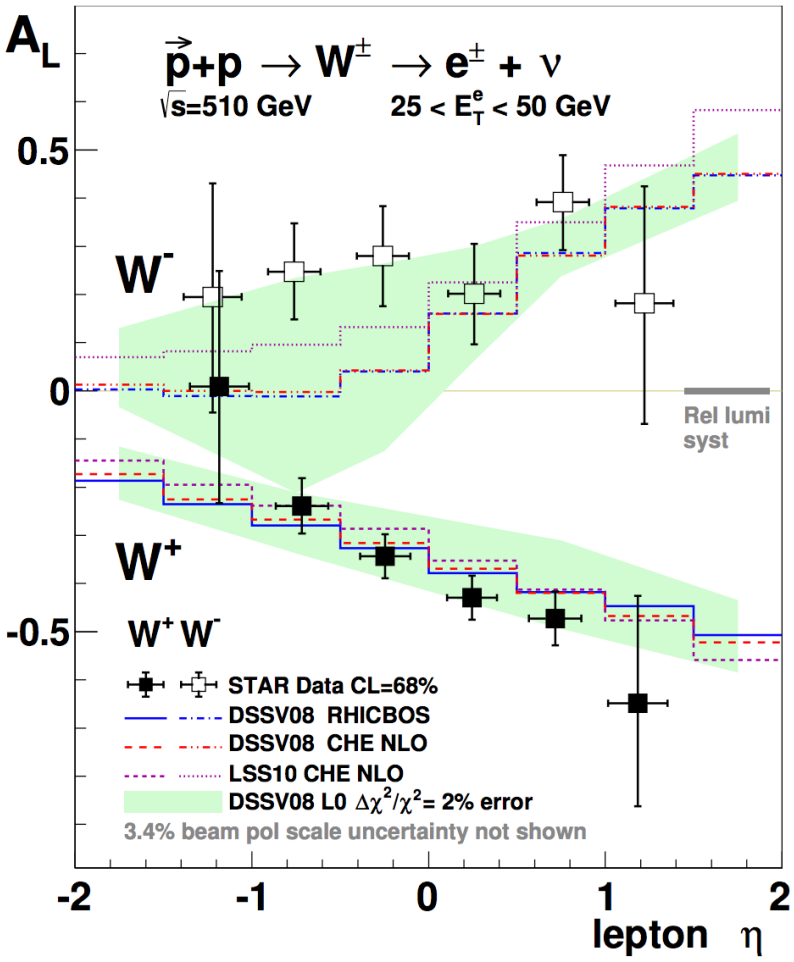




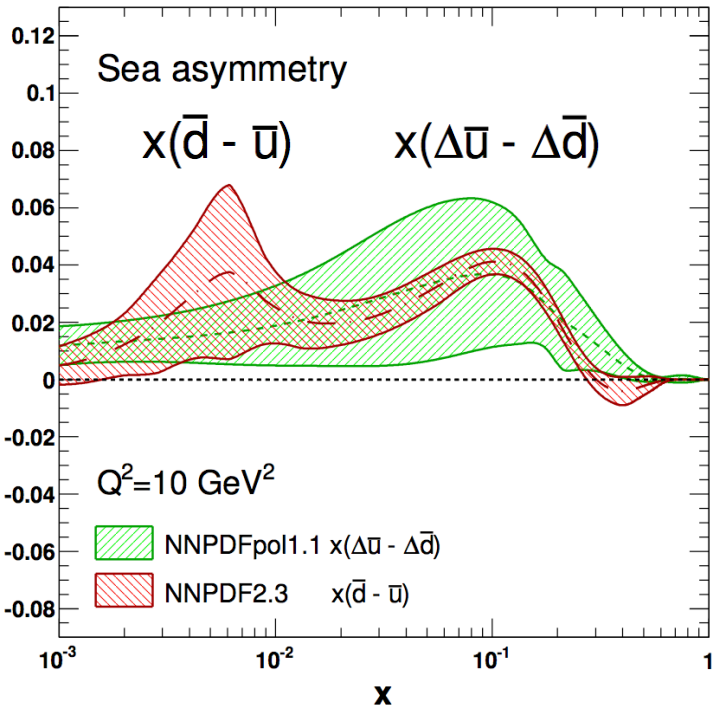
arXiv:1304.0079

W A_L Results

STAR, PRL113(2014)072301



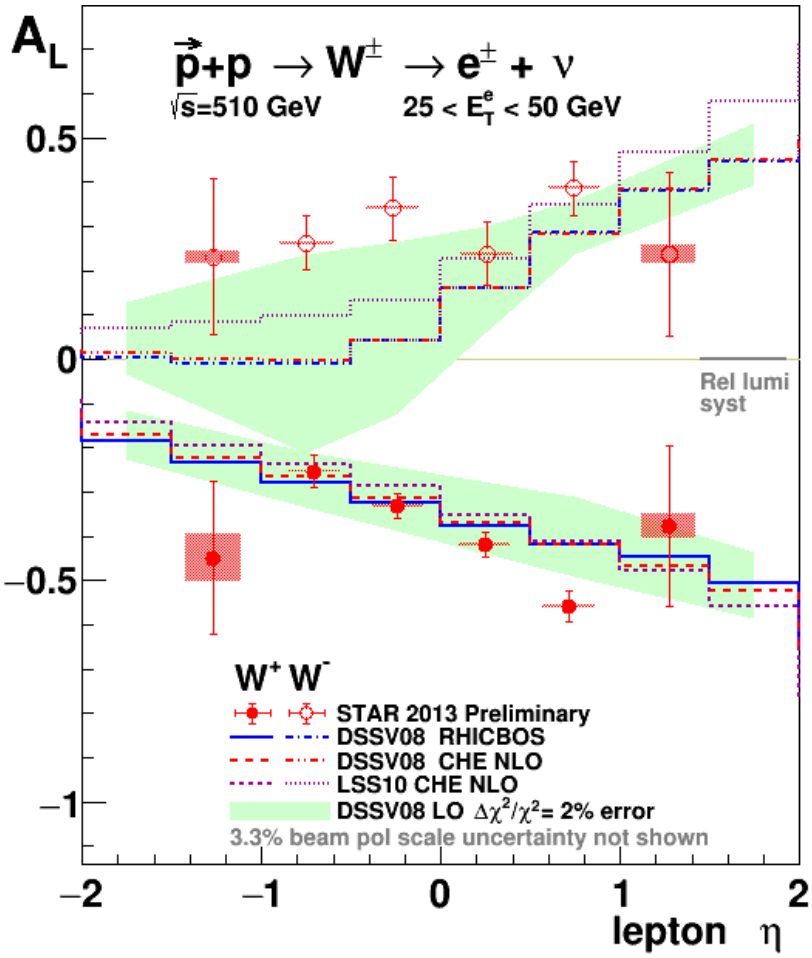
E. Nocera, PoS(DIS2014)204



$\Delta\bar{u} > \Delta\bar{d}$? Opposite to unpolarized sea.

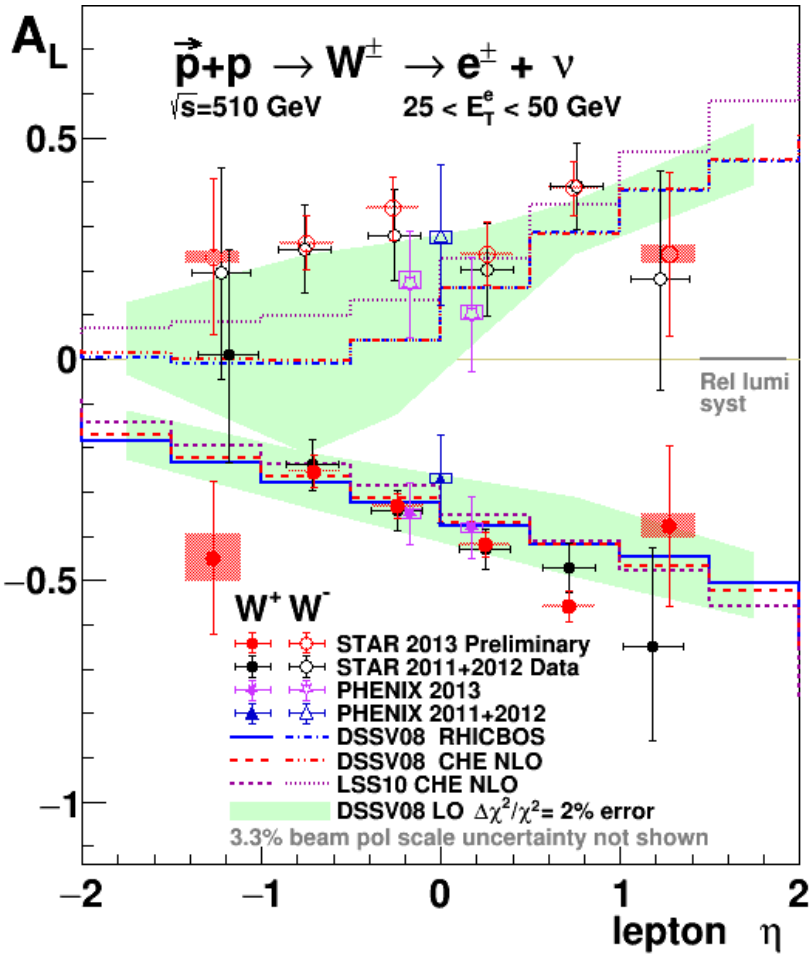
Motivation for more precise data.

W A_L New Preliminary Results



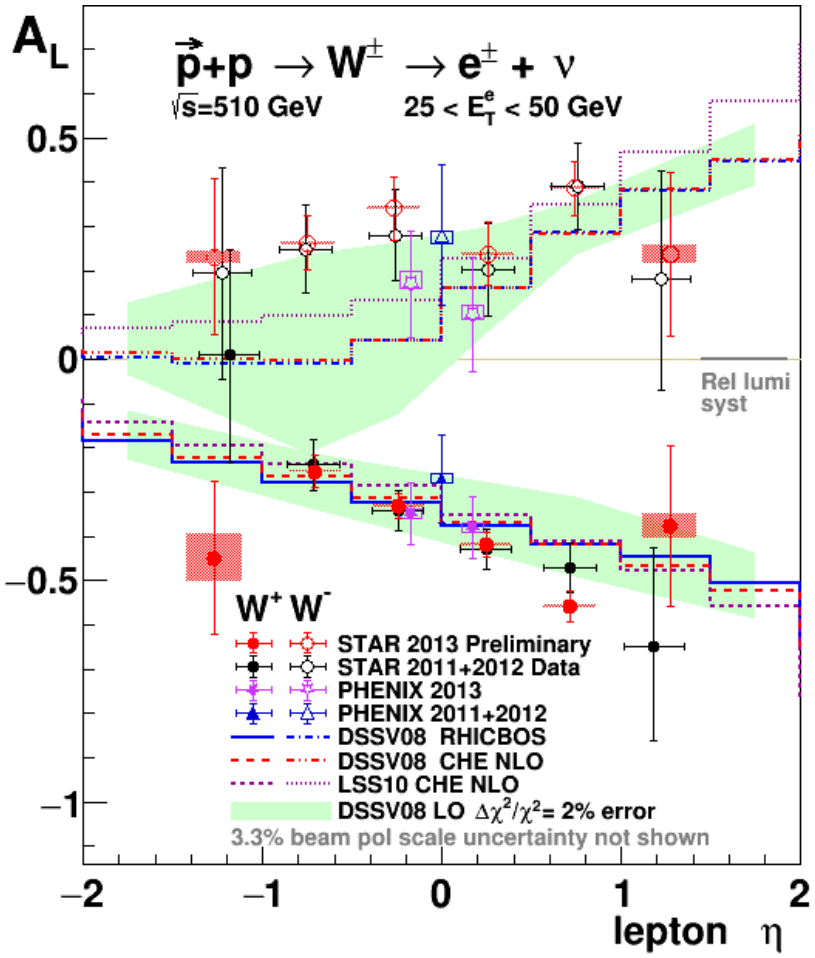
- Most precise measurements of W A_L, with STAR 2013 data (256 pb^{-1})

W A_L New Preliminary Results



- Most precise measurements of W A_L, with STAR 2013 data (256 pb^{-1}).
- Overall, consistent with the published STAR 2011+2012 results and PHENIX mid-rapidity W/Z A_L measurements
- The tendency that W^- A_L for negative η_e are at the upper band of the DIS-based expectations is confirmed with better precision.

W A_L New Preliminary Results



- Most precise measurements of W A_L, with STAR 2013 data (256 pb^{-1}).
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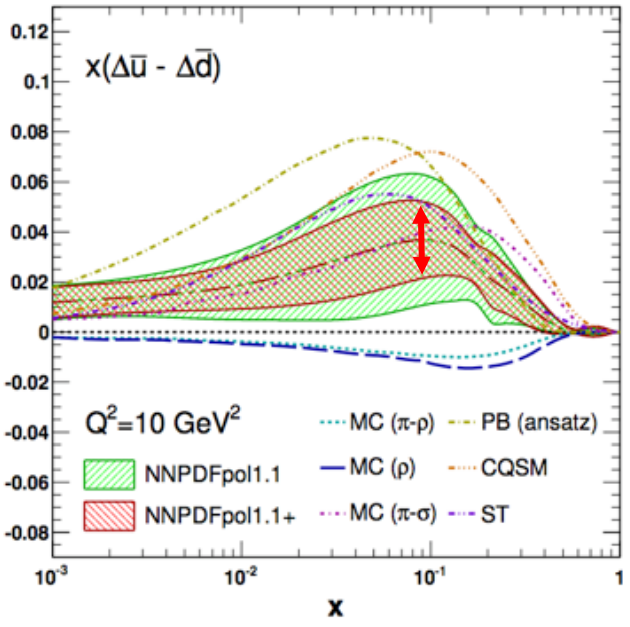
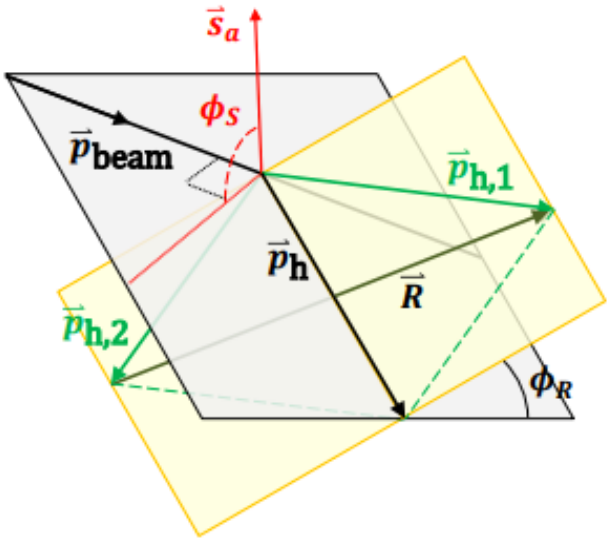
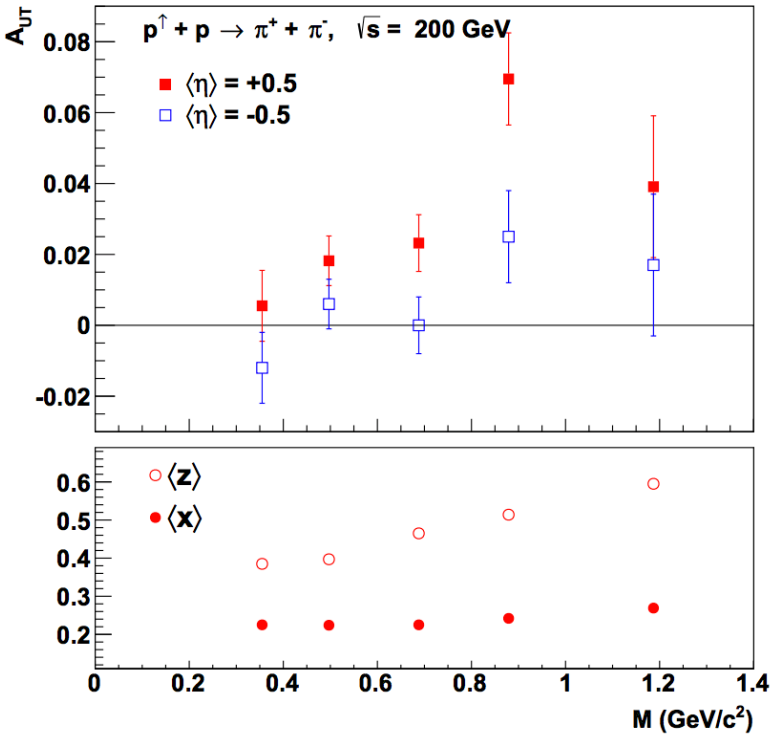
E. Nocera, SPIN2016



Probe Quark Transversity via Interference Fragmentation

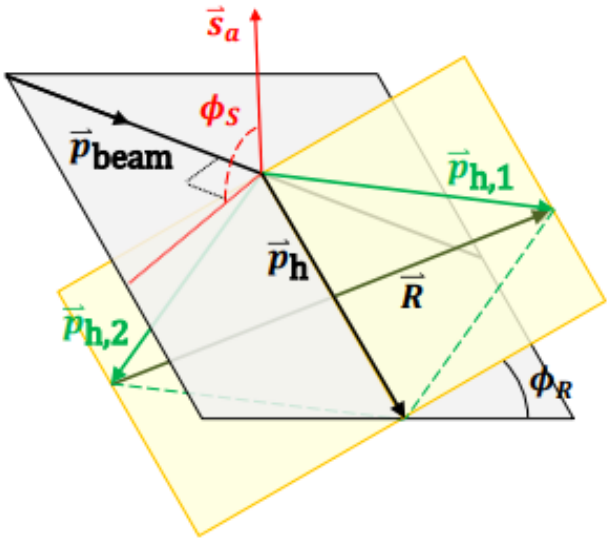


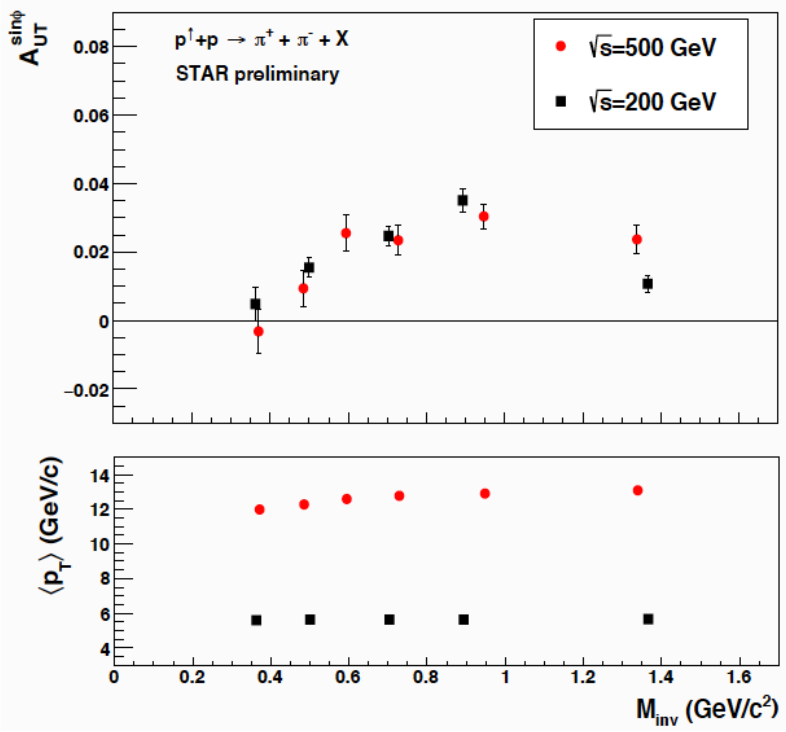
STAR, PRL115 (2015) 242501



- First non-zero transversity signal observed in $p^\uparrow$+p collisions
- Complementary kinematic regions to SIDIS; important test of factorization and universality

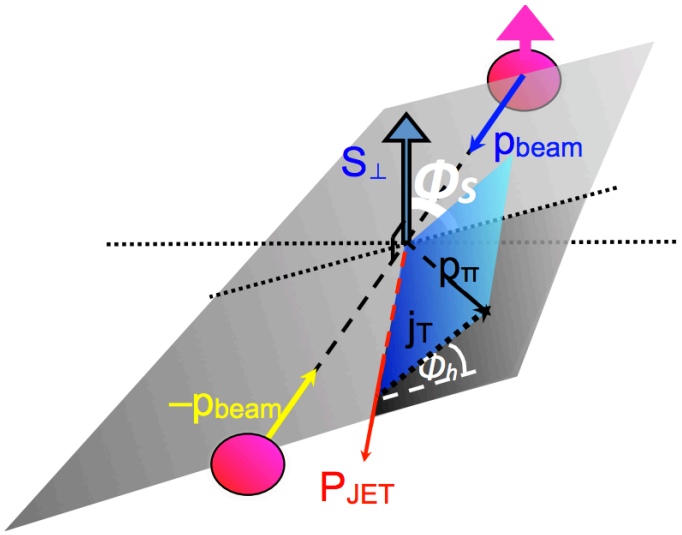
Probe Quark Transversity via Interference Fragmentation



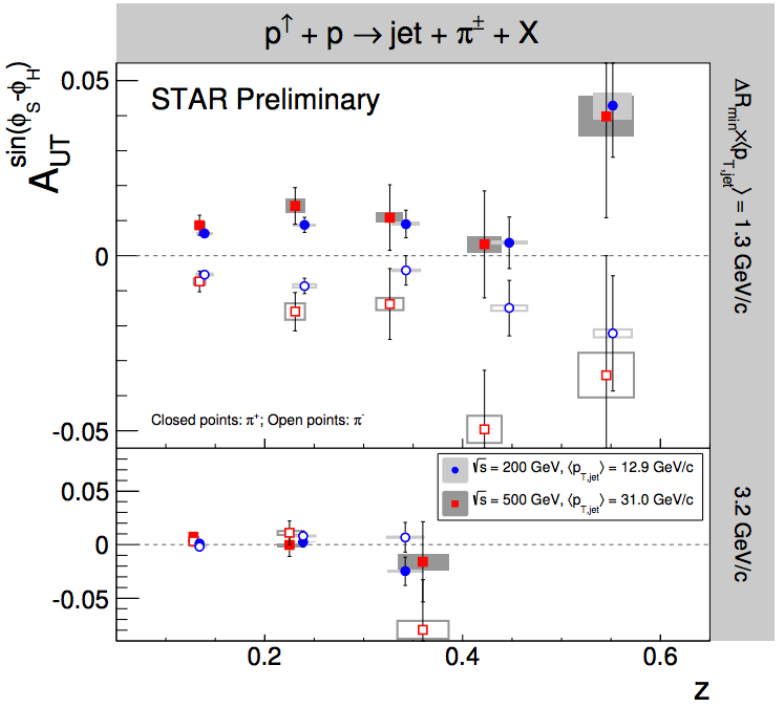


- First non-zero transversity signal observed in $p^{\uparrow}+p$ collisions.
- Similar results from $\sqrt{s}$ = 200 and 510 GeV. Small TMD evolution in IFF ?

Probe Quark Transversity via Collins Asymmetry

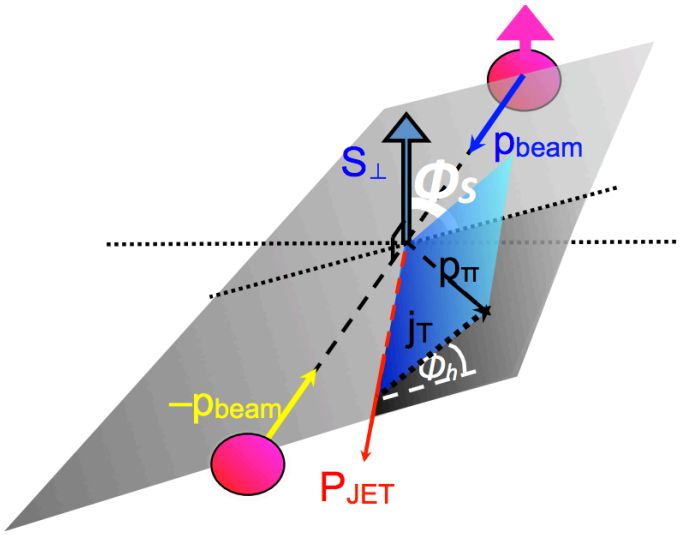


Collins modulation: $\sin(\varphi_S - \varphi_H)$



- First statistically significant non-zero Collins asymmetries measured in hadronic collisions
- Similar results from √s = 200 and 510 GeV. Small TMD evolution in FF ?

Probe Quark Transversity via Collins Asymmetry



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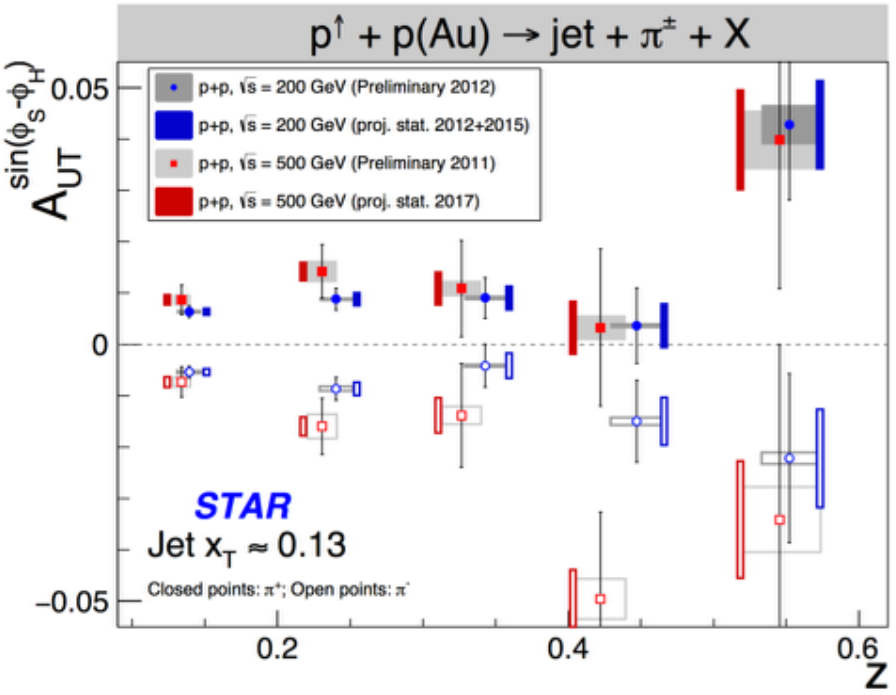

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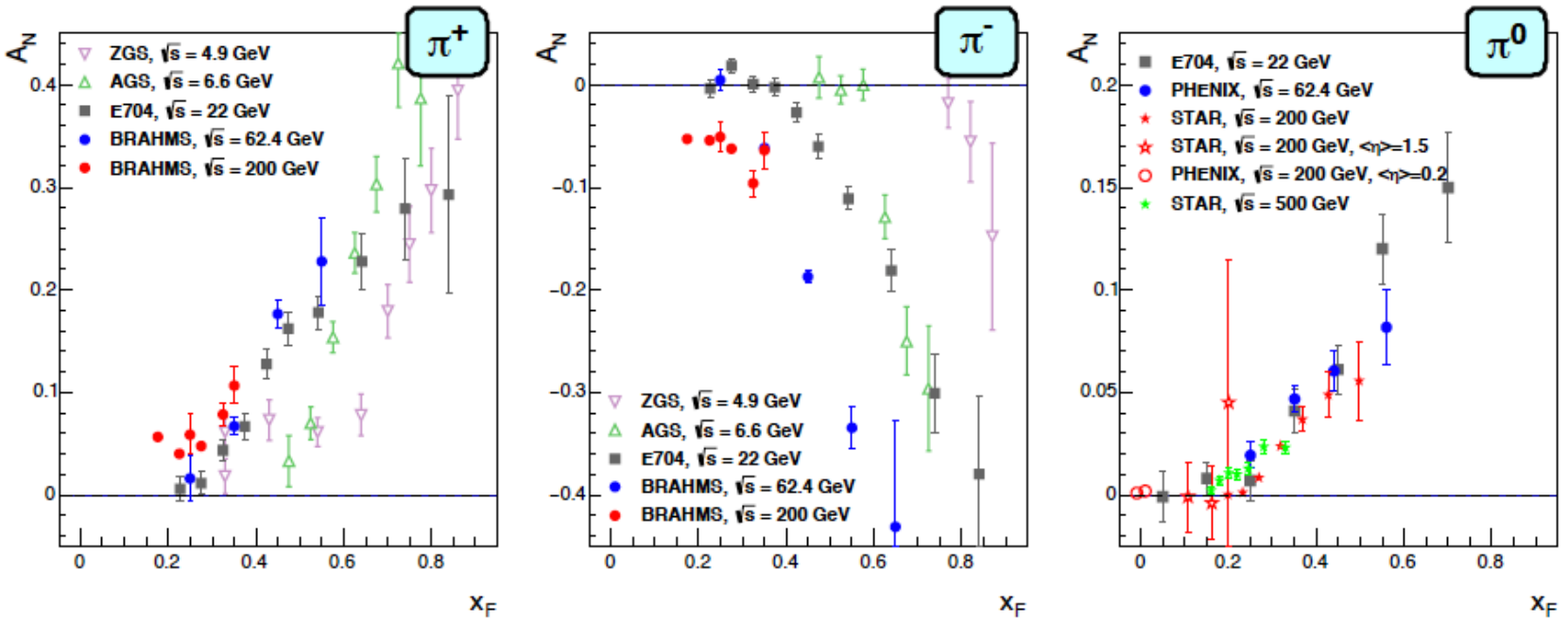
Forward A_N – remains mystery

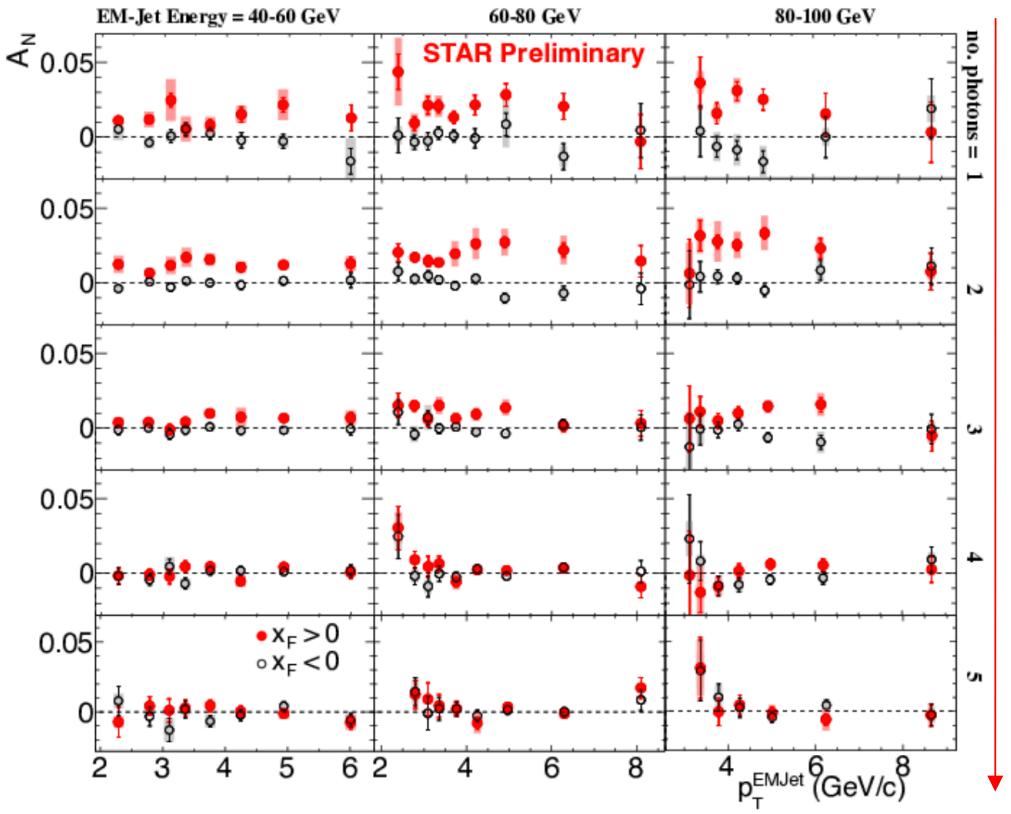
see also J. Huang's talk



- Surprisingly large transverse single-spin asymmetries
- Nearly independent of √s over a very wide range (√s: 4.9 GeV to 500 GeV).

Forward A_N – remains mystery

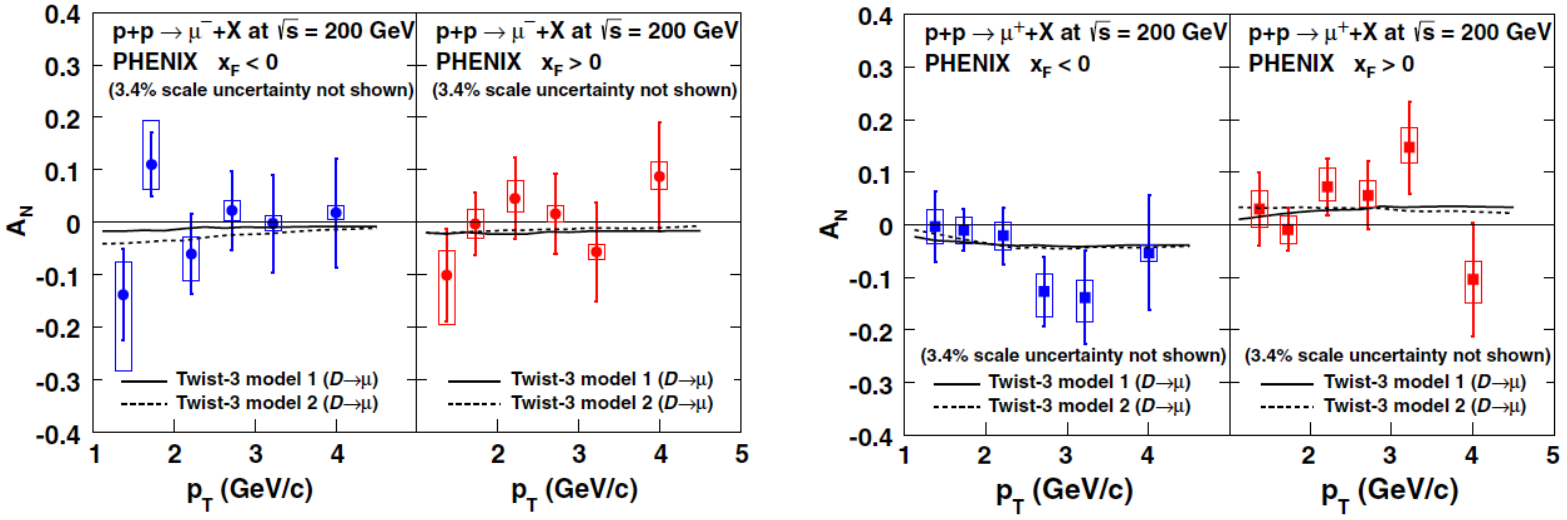
M.Mondal (STAR Collaboration), DIS2014



- Asymmetry decrease as "jettiness" (no. of photons)
- How much of the large A_N is due to diffractive events ?
- Looking forward to STAR Roman Pot results

Forward A_N: Heavy Flavor

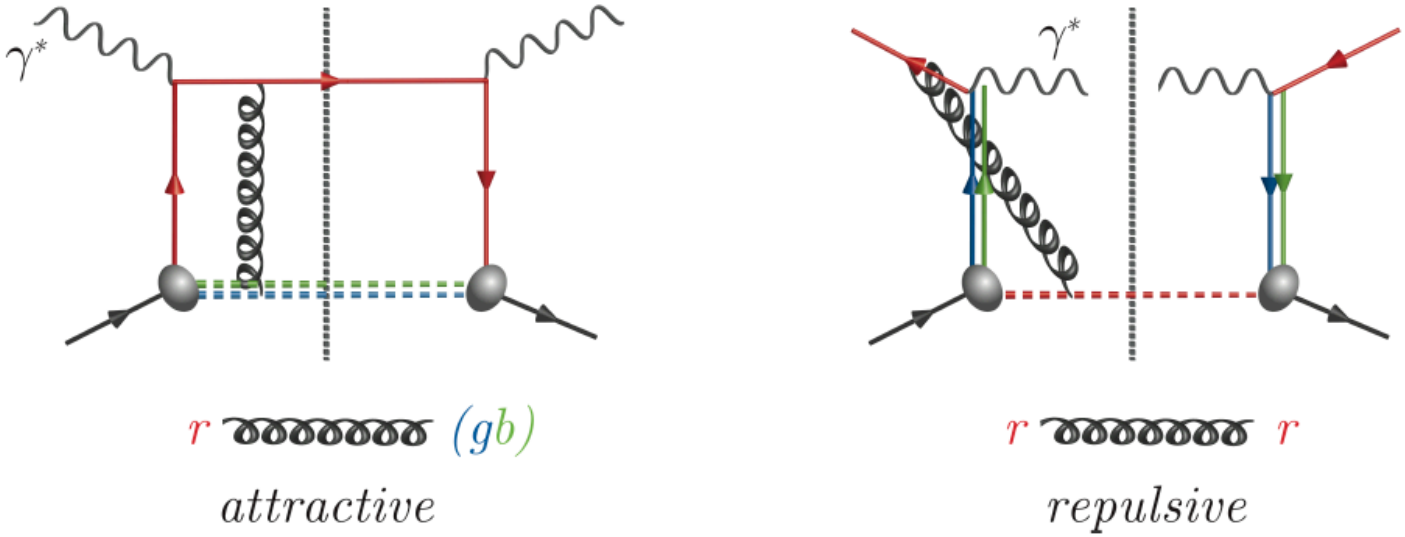
PHENIX, PRD95, 112001(2017)



- Dominated by gluon-gluon interactions, and sensitive to gluon Sivers' function
- Main contribution to single muons: D-meson decay
- Consistent with zero within uncertainties

Sivers' Sign-change

see also M. Grosse Perdekamp's talk



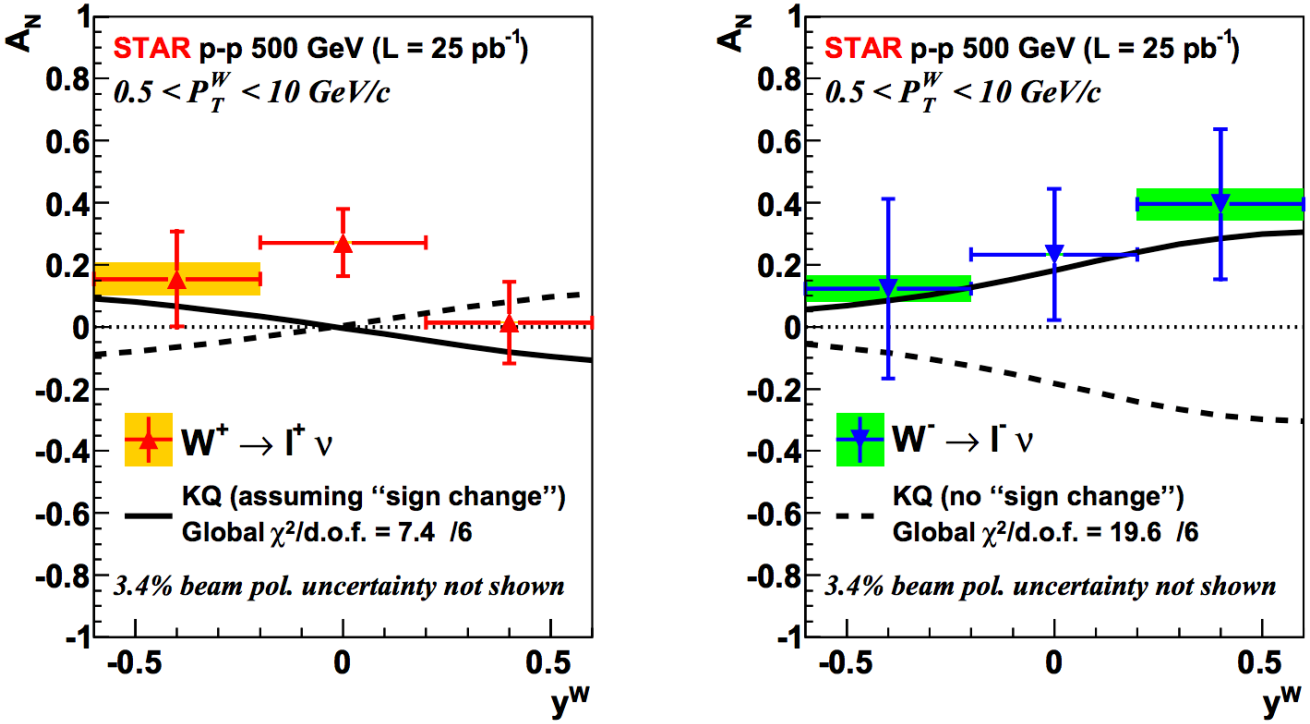
Sivers (DIS) = - Sivers (DY or W/Z)

- DIS: γq scattering attractive final-state interaction
- p+p: quark anti-quark annihilation repulsive initial-state interaction
- Experimental test is critical for our understanding of TMDs and TMD factorization

First W A_N results

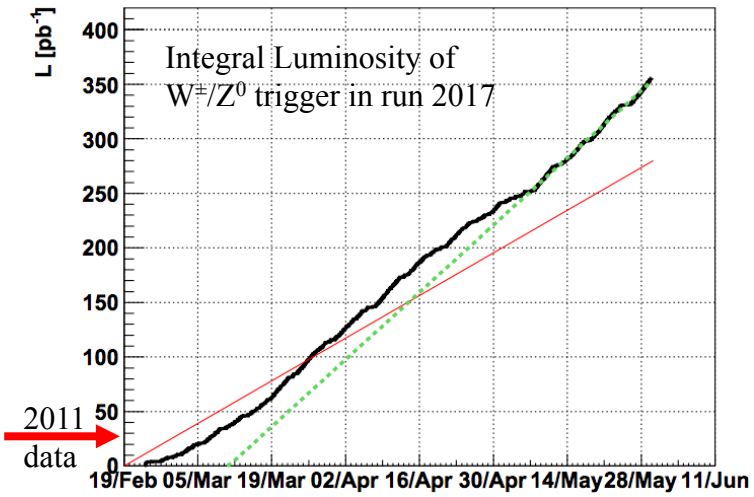
see also B. Mueller's talk

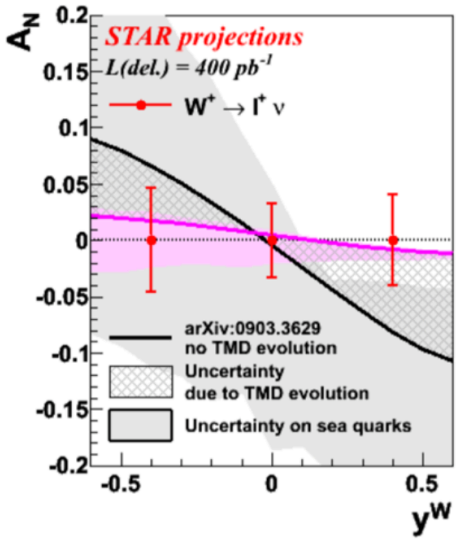
STAR, PRL116(2016)132301

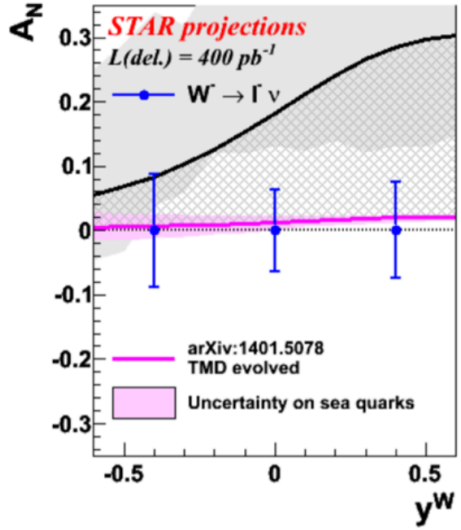


- Initial transverse W A_N results prefer to the Sivers' sign-change from an integrated luminosity of ~25 pb^{-1}

Potential of 2017: W A_N







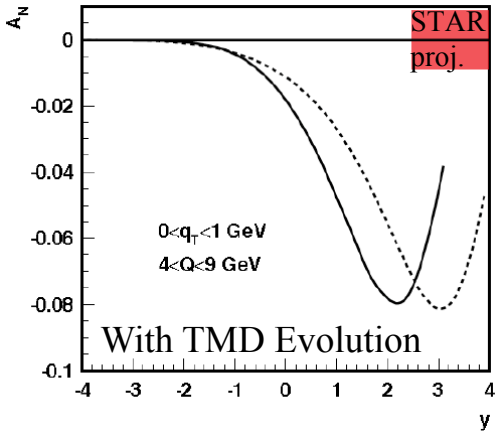
- Very successful Run-2017, STAR recorded **356** pb^{-1} with 55% polarization,
- Anticipate: Access TMD evolution,

  first constraints on sea quark Sivers' function,

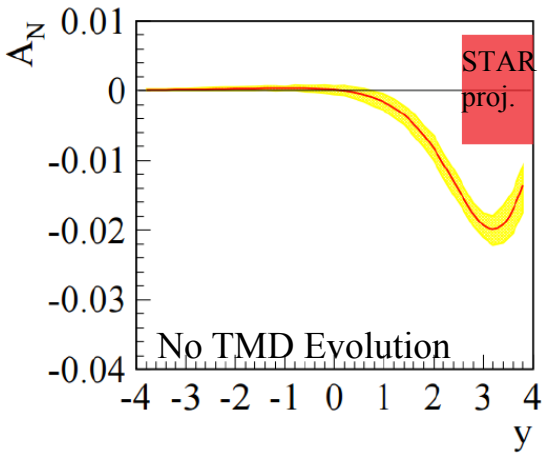
  precise data to test for the Sivers' sign change.

Potential of 2017: Drell-Yan and Direct-γ

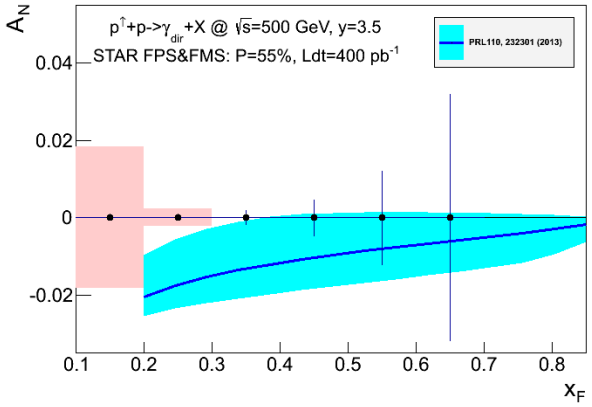
Z.Kang, J.Qiu, PRD81(2010)054020



M.Echevarria *et.al*, PRD89(2014)074013



L.Gamberg *et.al*, PRL110(2013)232301



- In 2017, STAR operated FMS pre-shower and post-shower detectors to select DY and direct-γ events.
- Anticipate DY A_N to $\pm$ 0.008 in with a delivered luminosity of 400 pb^{-1}
- Direct-γ A_N will provide important complementary constraints.

RHIC Cold QCD Plan – a Portal to the EIC

arXiv:1602.03922

see also J. Huang's talk

	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	A_N for γ, $W^{\pm}$, Z^0, DY	A_N^{DY}: Postshower to FMS@STAR
				Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3	$A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets	**None**
				First look at GPD Eg	A_{UT} for J/Ψ in UPC	**None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Yes Forward instrum.
				evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for γ A_N for diffractive events	**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	R_{pAu} direct photons and DY	R_{pAu}(DY):Yes Forward instrum.
				Nuclear dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	**None**
				Clear signatures for Saturation	Dihadrons, γ-jet, h-jet, diffraction	Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF,	R_{pAl}: direct photons and DY	R_{pAl}(DY): Yes Forward instrum.
				A-dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	**None**
				A-dependence for Saturation	Dihadrons, γ-jet, h-jet, diffraction	Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	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.
				quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions		**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.

RHIC Cold QCD Plan – a Portal to the EIC

arXiv:1602.03922

see also J. Huang's talk

	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, (nearly) pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	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.

Successful data taking with detector upgrades

During sPHENIX 2023 running

High-impact measurement if opportunity arises

Summary

- Jet and neutral pion longitudinal double-spin asymmetry measurements have provided first evidence for and unique constraints on non-zero gluon polarization.
- Longitudinal W measurements have provided first evidence of symmetry breaking in the polarized sea, $\Delta\bar{u} > \Delta\bar{d}$
- Non-zero transverse asymmetries have been observed at mid-rapidity and provide sensitivity to quark transversity.
- Initial transverse W measurements are consistent with Sivers' sign change.
- The Cold QCD Plan:
  - Look forward to data analysis of the just concluded Run 2017, **successful first stage!**
  - Proposes modest forward upgrades for a **second stage** of Sivers, Collins, and gluon polarization measurements in 2023+