

Overview of RHIC Longitudinal Spin Physics Program

Ming Liu

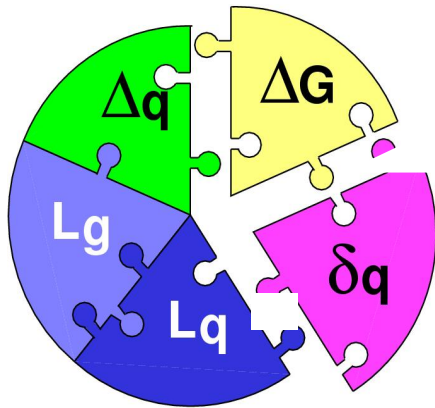
Los Alamos National Laboratory

CIPANP 2018, CA

Many thanks to the PHENIX and STAR collaborations for providing the latest results

Three Decades of the Proton Spin Puzzle

- Early expectation: large gluon polarization



$$\Delta\Sigma' = \Delta\Sigma - \frac{\alpha_s}{2\pi} \cdot \Delta G$$

$$\frac{\alpha_s}{2\pi} \cdot \Delta G = 0.3 \pm 0.1$$

Axial anomaly
Cheng & Li, PRL (1989)

EMC, 1980s

$$\frac{1}{2} = \frac{1}{2} \Delta q + L_q^z + \Delta G + L_g^z$$

$$\Delta q \sim 30\% \quad (\text{pol. SIDIS})$$

$$\Delta G \sim 20\% \quad (\text{RHIC} - \text{spin})$$

$$L \sim ? \quad (\text{RHIC, FNAL?})$$

	Quark Spin	Gluon Spin
SLAC -> 2000	E80 – E155	
CERN ongoing	EMC, SMC, COMPASS	
DESY ->2007	HERMES	
JLab ongoing	Hall A,B,C	
RHIC ongoing	(BRAHMS), (PHENIX), STAR	



SIDIS/DIS

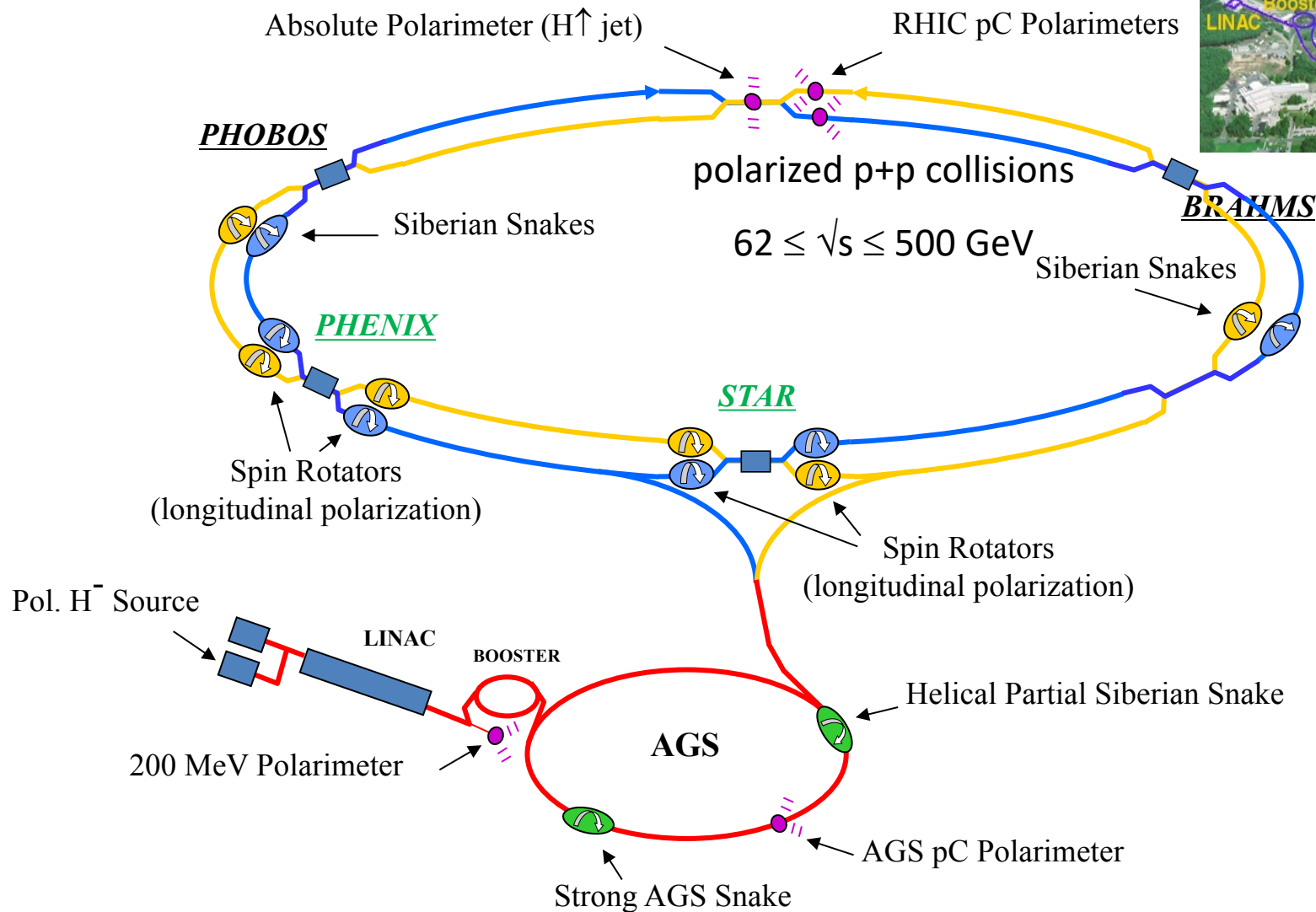


Polarized p+p

Outline

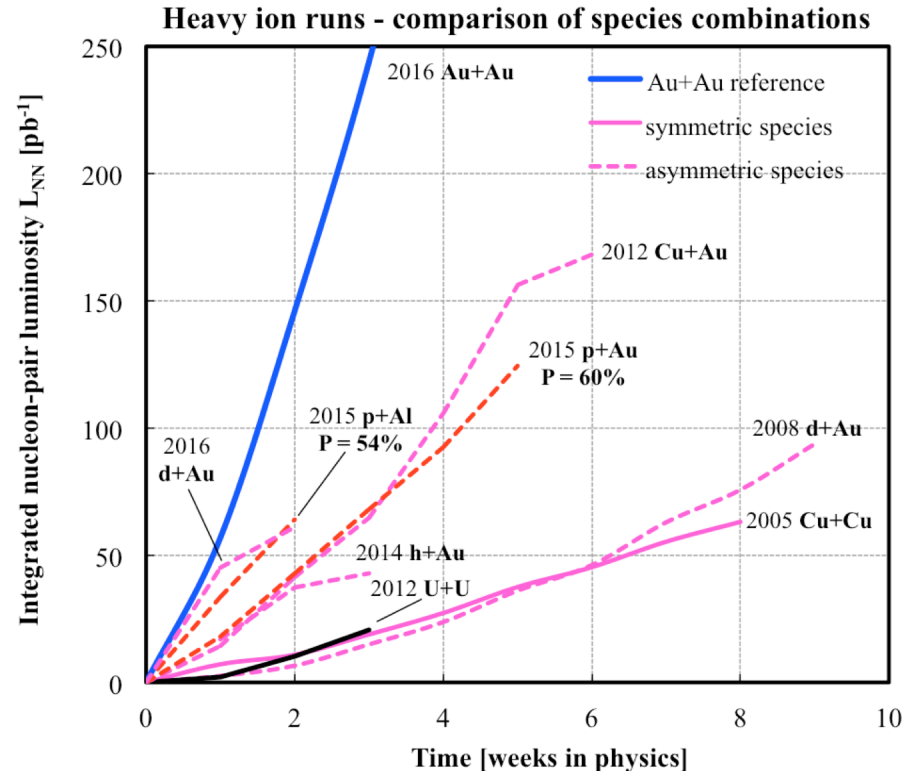
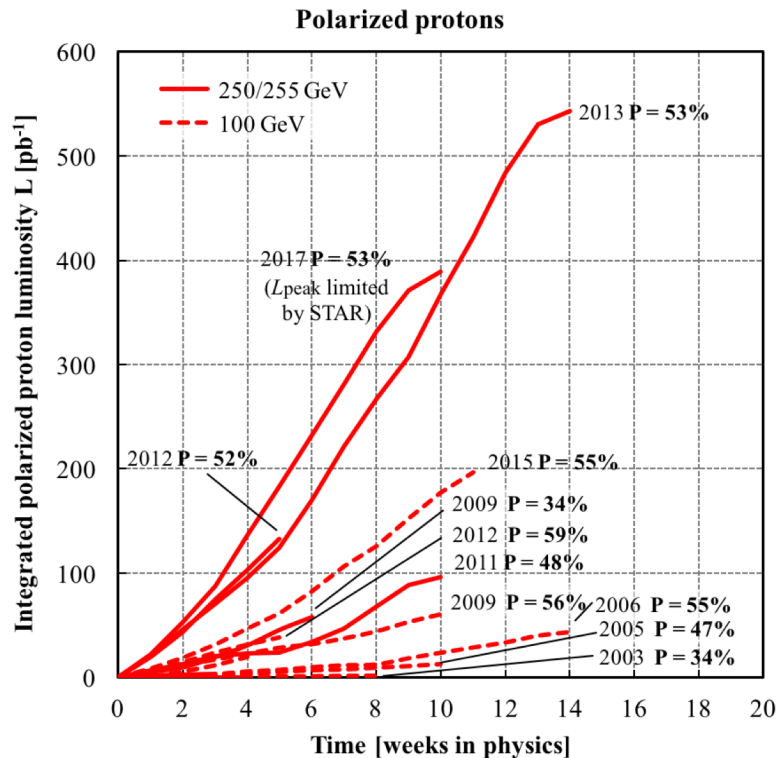
- Longitudinal spin physics program at RHIC
- Gluon polarization
- Flavor identified sea-quark polarization
- Outlook

Polarized Proton Collider at RHIC



History of RHIC Spin Runs

RHIC is capable of delivering the polarized p+p/A for precision spin physics



- A very challenging task to deliver polarized p+p, excellent performance from 2012+
- Longitudinally and transversely polarized p+p,
- Transversely polarized p+Au and p+Al, in 2015

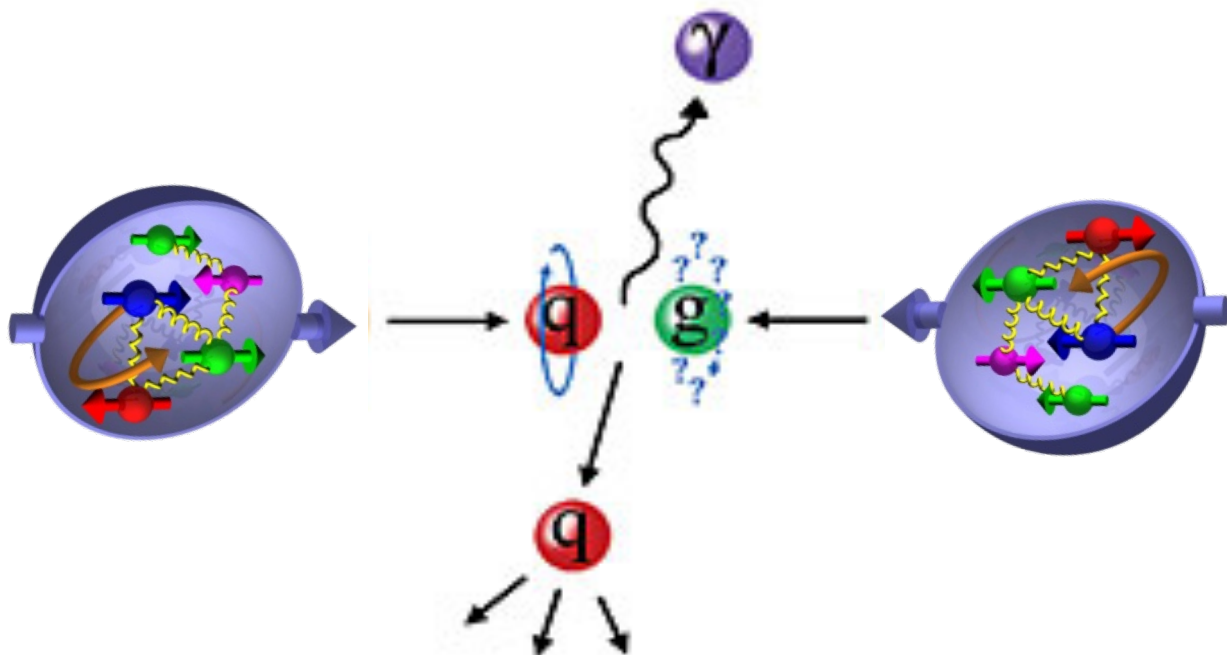
Physics with Longitudinally Polarized p+p Collisions



Versus



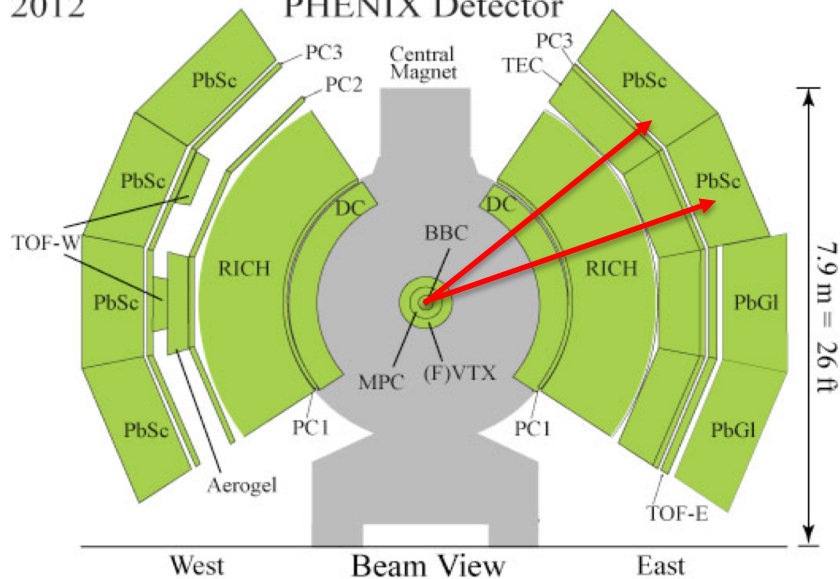
Versus



PHENIX Detector at RHIC

2012

PHENIX Detector



Central Arms $|\eta| < 0.35$

- Identified charged hadrons
- **Neutral Pions**
- Direct Photon
- Heavy Flavor

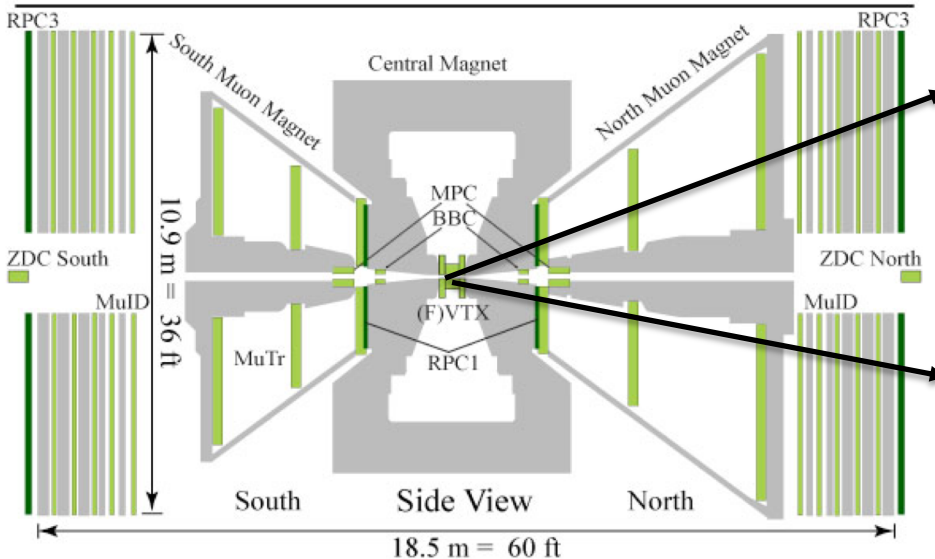
Muon Arms $1.2 < |\eta| < 2.4$

- J/Psi
- Heavy Flavor
- Charged hadrons

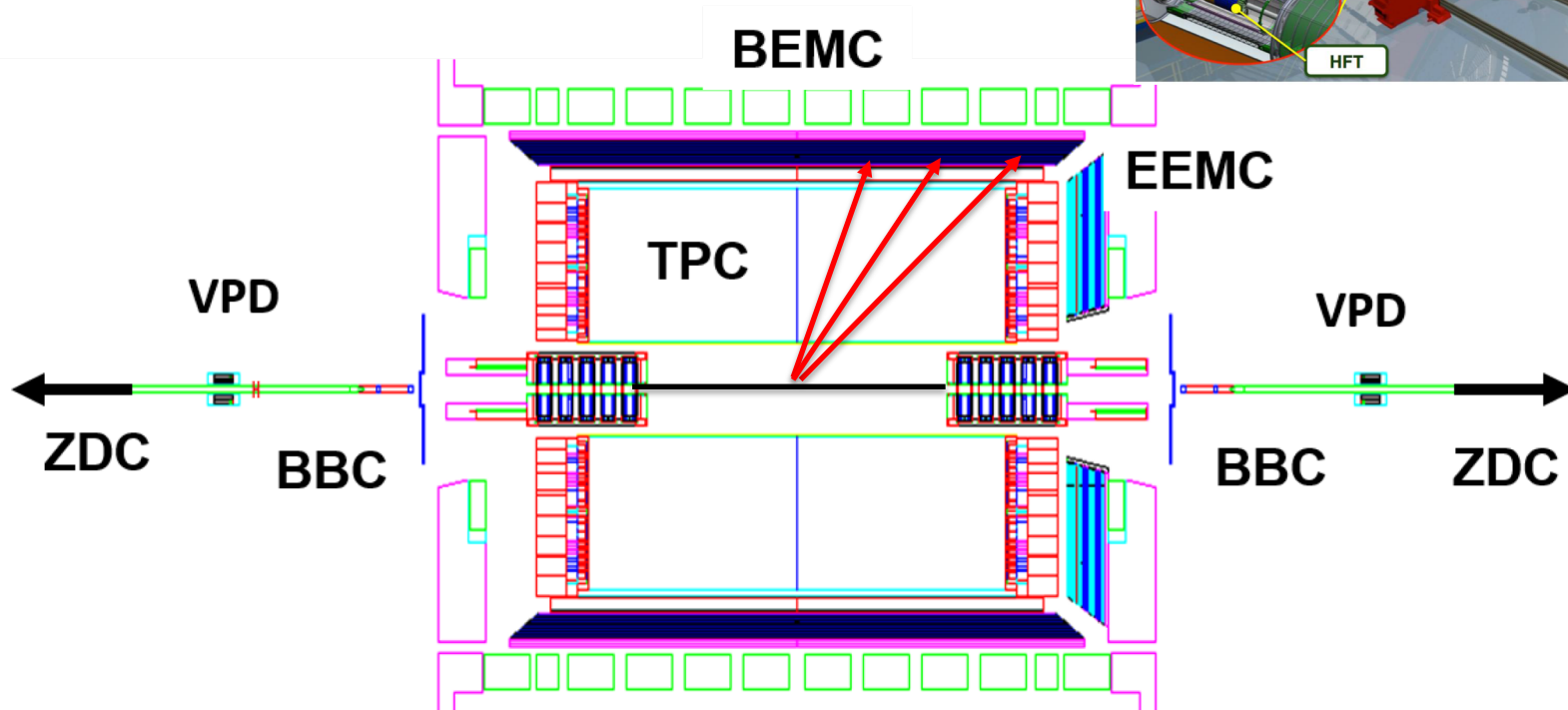
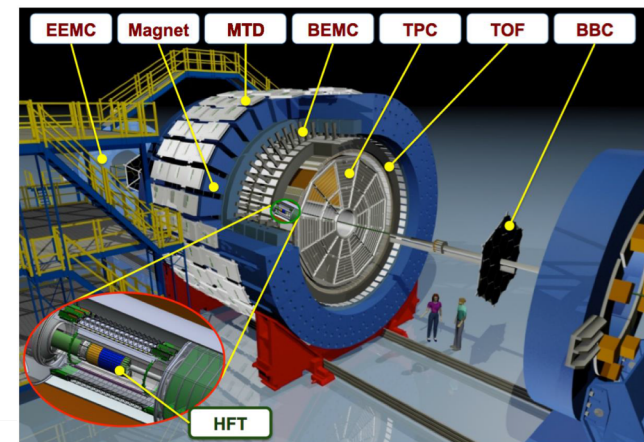
MPC $3.1 < |\eta| < 3.9$

- Neutral Pion's
- Eta's

BBC ZDC (Relative) luminosity



The STAR Experiment



Large acceptance:

Tracking: TPC+TOF, : $-1.3 < \eta < 1.3$

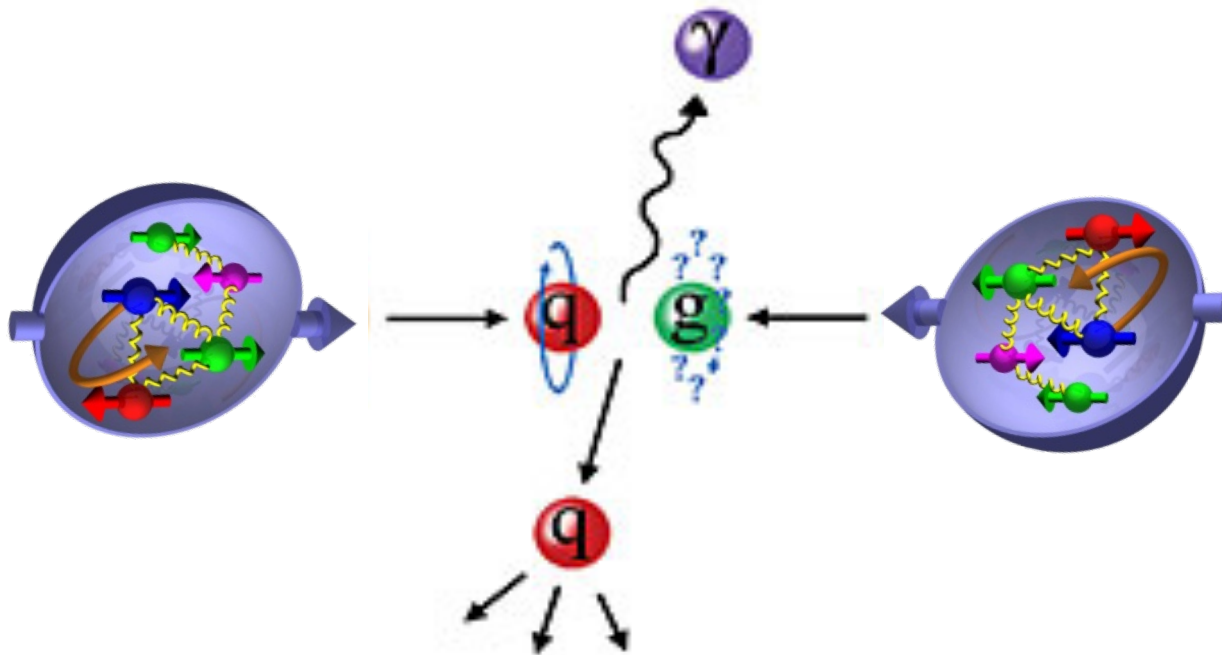
Central EMCal: $-1 < \eta < 2$

Forward EMCal: $2.5 < \eta < 4.2$

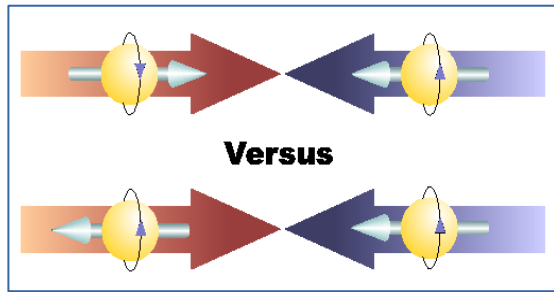
BBC, ZDC

- Jets
- π^0 and (identified) charged hadrons
- Electrons & Muons

Gluon Polarization

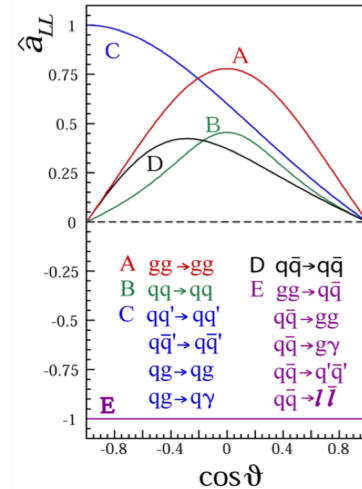


Gluon Polarization and π^0 (or jet) A_{LL}

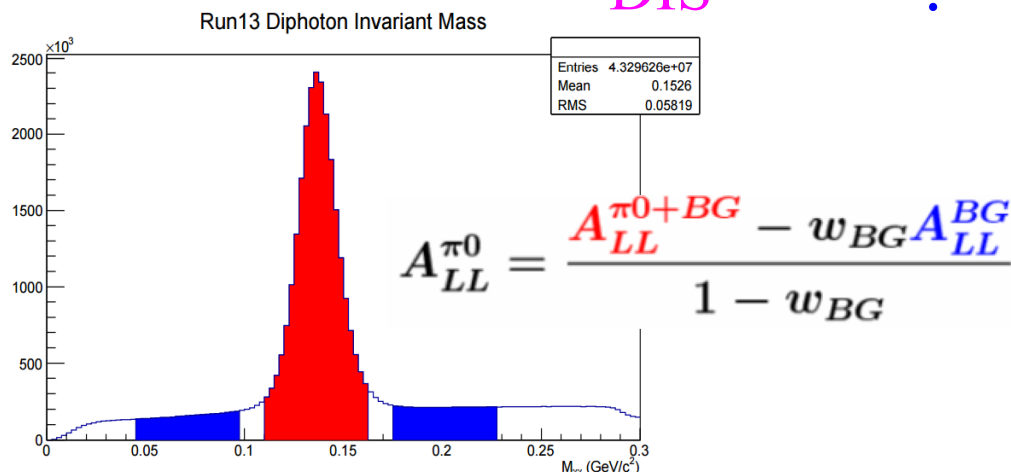


$$A_{LL} = (N^{++} - N^{+-}) / (N^{++} + N^{+-})$$

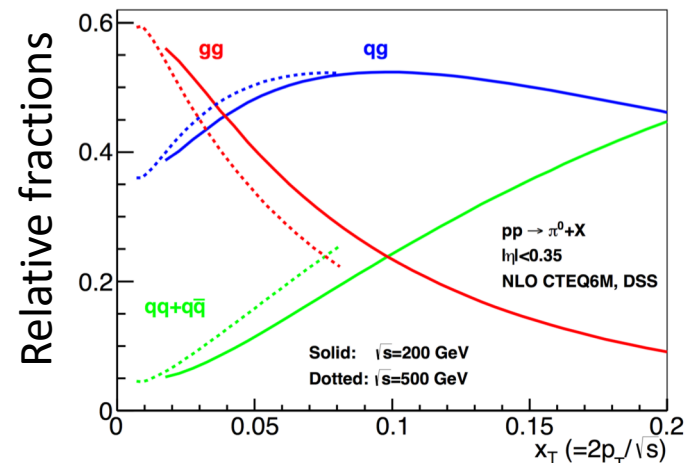
- Parton distribution functions
- Partonic hard scattering rates
- Fragmentation functions



$$\Delta\sigma(pp \rightarrow \pi^0 X) \approx \underbrace{\Delta q(x_1)}_{\text{DIS}} \otimes \underbrace{\Delta g(x_2)}_{?} \otimes \underbrace{\Delta\hat{\sigma}^{qg \rightarrow qg}(\hat{s})}_{\text{pQCD}} \otimes \underbrace{D_q^{\pi^0}(z)}_{\text{e+e-}} \dots$$

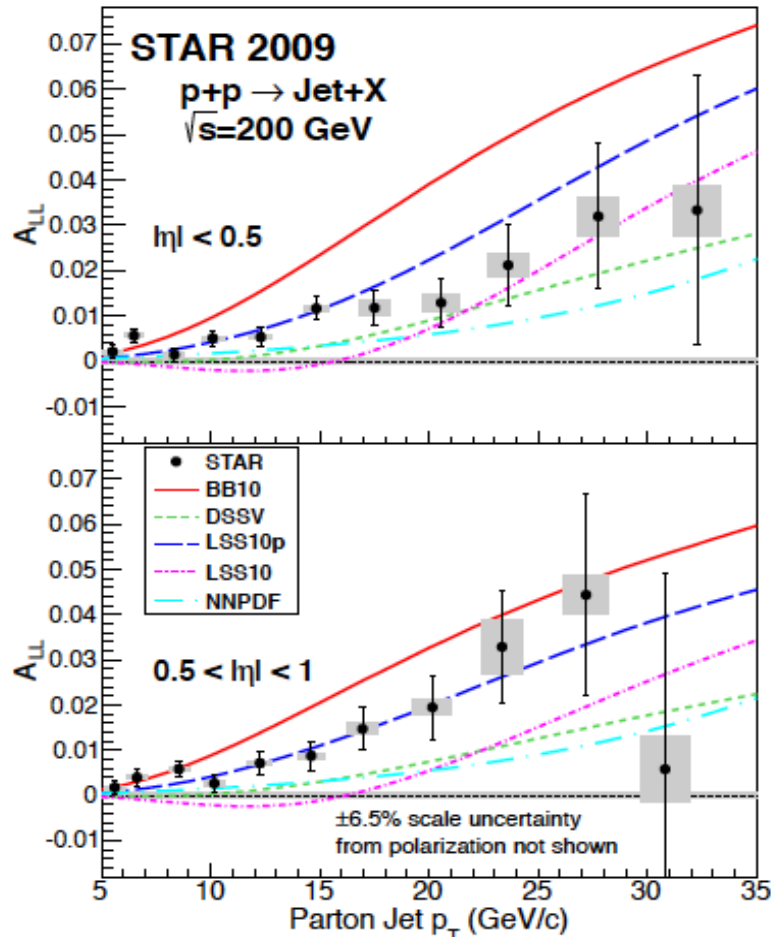


Di-photon mass: π^0 peak

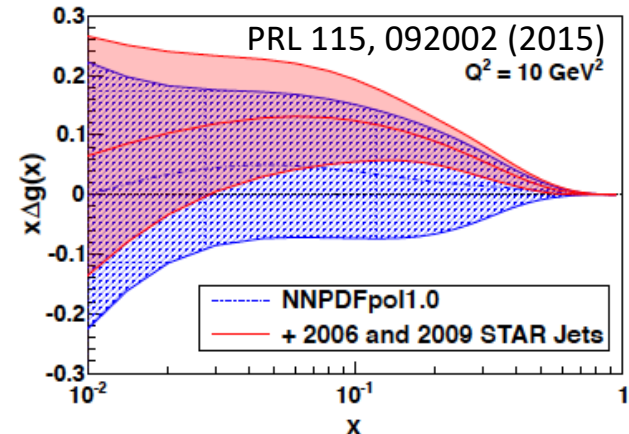
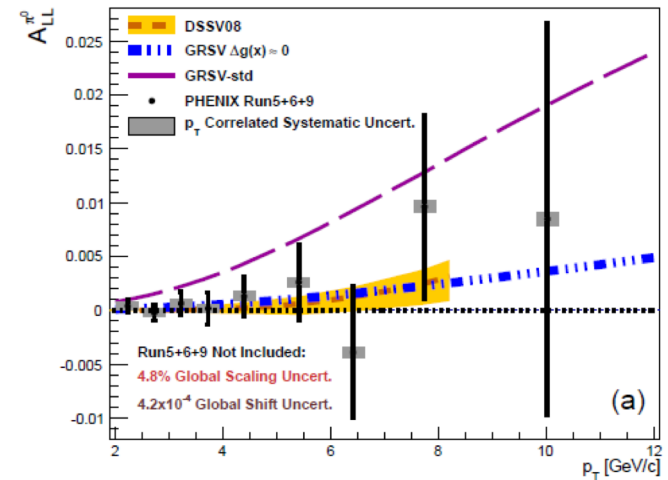


First Precision Measurements of Longitudinal Double-Spin Asymmetry A_{LL} from RHIC

STAR: PRL 115, 092002 (2015)

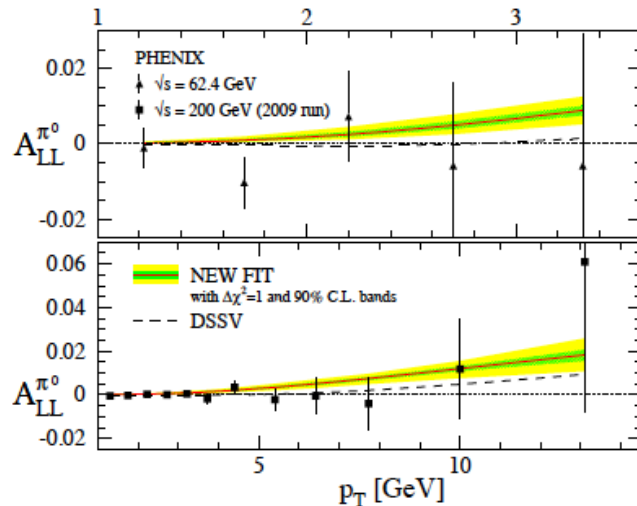
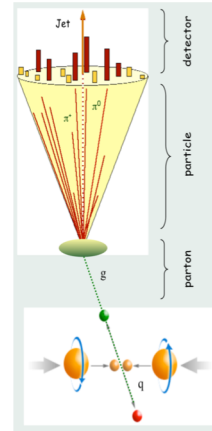
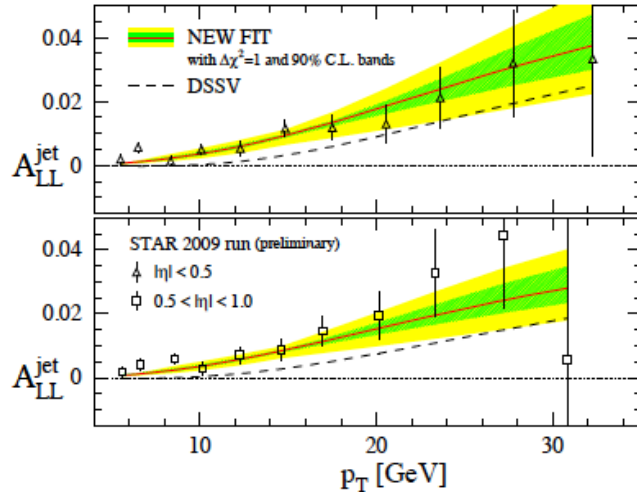


PHENIX: PRD 90, 012007 (2014)

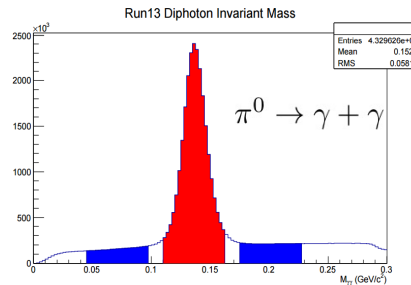


First Hint of Non-zero Gluon Polarization from RHIC

- PHENIX and STAR A_{LL} data



Run 2009
p+p@200GeV

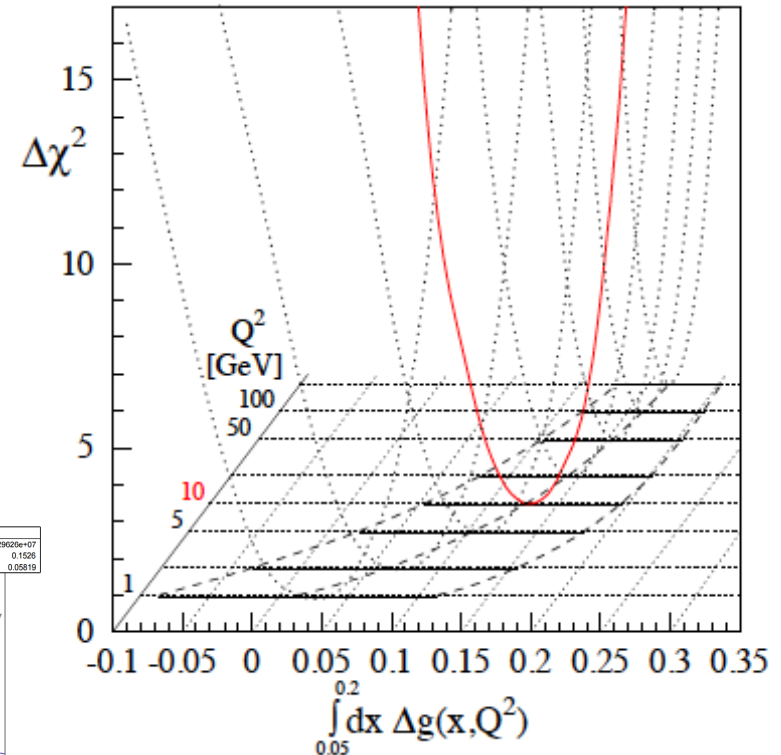


Ming X. Liu, CIPANP2018

$$\int_{0.05}^1 \Delta g(x, Q^2) dx = 0.2^{+0.06}_{-0.07}$$

@ $Q^2 = 10 \text{ GeV}^2$

PRL 113, 012001 (2014), DSSV



More Results Coming from RHIC

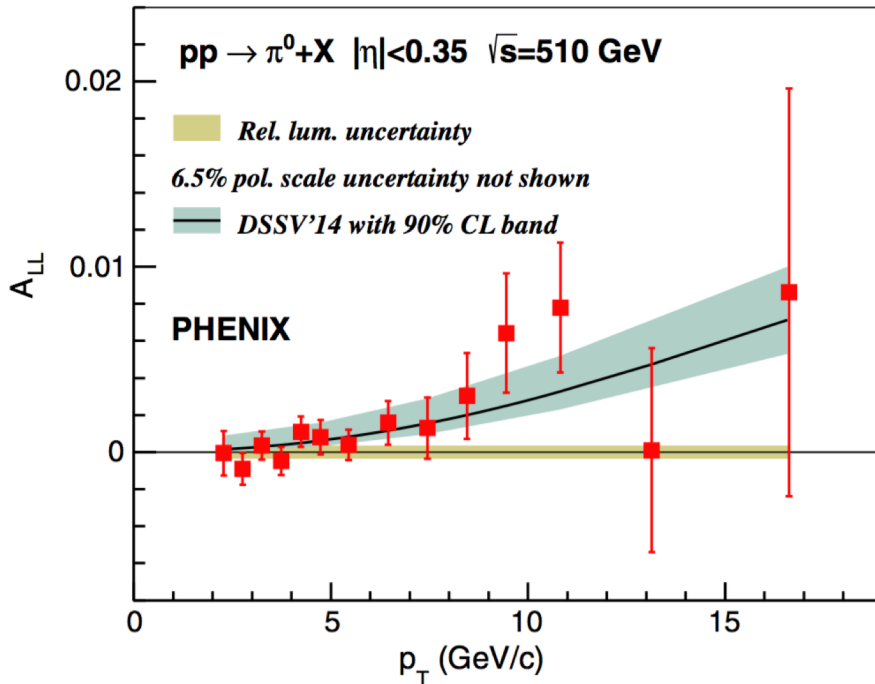
“RHIC Cold QCD Plan for 2017-2023”, arXiv:1602.03922

Year	\sqrt{s} (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	$\langle P \rangle$ in %
2006	62.4	-- pb ⁻¹ / 0.2 pb ⁻¹	0.08 pb ⁻¹ / 0.02 pb ⁻¹	48
	200	6.8 pb ⁻¹ / 8.5 pb ⁻¹	7.5 pb ⁻¹ / 2.7 pb ⁻¹	57
2008	200	-- pb ⁻¹ / 7.8 pb ⁻¹	-- pb ⁻¹ / 5.2 pb ⁻¹	45
2009	200	25 pb ⁻¹ / -- pb ⁻¹	16 pb ⁻¹ / -- pb ⁻¹	55
	500	10 pb ⁻¹ / -- pb ⁻¹	14 pb ⁻¹ / -- pb ⁻¹	39
2011	500	12 pb ⁻¹ / 25 pb ⁻¹	18 pb ⁻¹ / -- pb ⁻¹	48
2012	200	-- pb ⁻¹ / 22 pb ⁻¹	-- pb ⁻¹ / 9.7 pb ⁻¹	61/56
	510	82 pb ⁻¹ / -- pb ⁻¹	32 pb ⁻¹ / -- pb ⁻¹	50/53
2013	510	300 pb ⁻¹ / -- pb ⁻¹	155 pb ⁻¹ / -- pb ⁻¹	51/52
2015	200	52 pb ⁻¹ / 52 pb ⁻¹	-- pb ⁻¹ / 60 pb ⁻¹	53/57

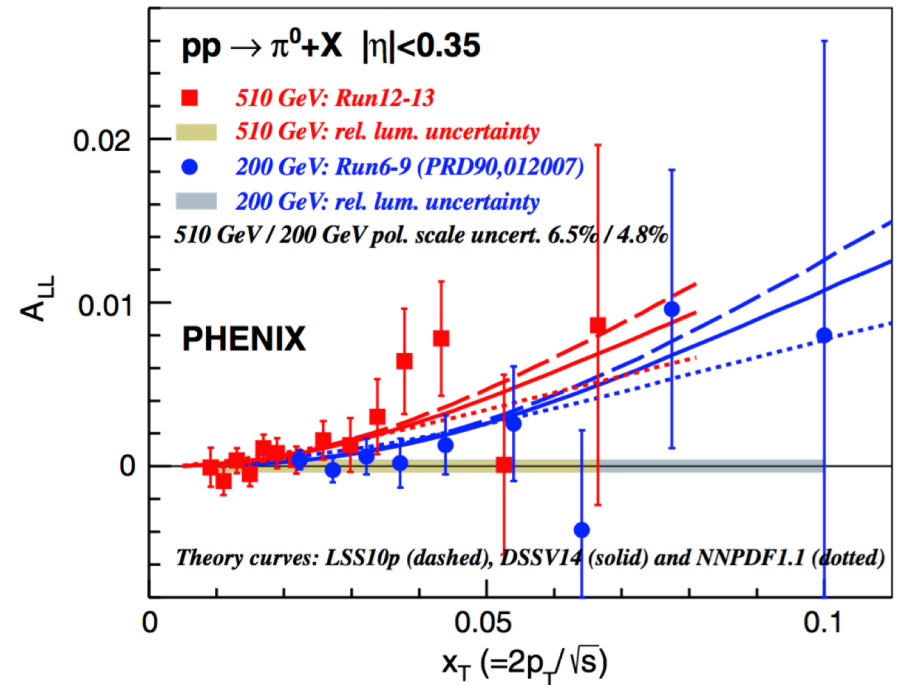
PHENIX: $\pi^0 A_{LL}$ at central rapidity ($|\eta| < 0.35$)

- Positive gluon polarization at moderate $x \sim 0.05 - 0.2$

PRD 93, 011501 (2016)



ALL vs x_T for pp 200GeV and 510GeV



PHENIX $h^{+/-}$ and HF $e^{+/-}$ A_{LL}

- Sensitive to polarized u and d quark as well as gluon distributions through charge sign

- Statistically limited due to lack of effective triggers

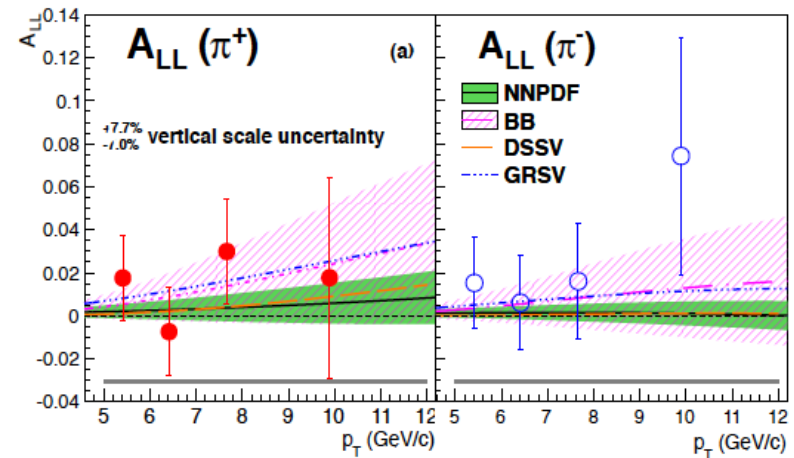
$$u + g \rightarrow h^+ + X$$

$$d + g \rightarrow h^- + X$$

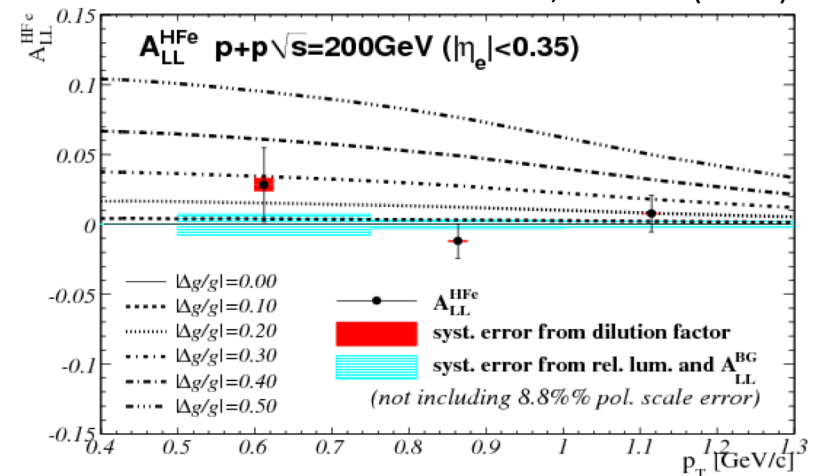
- Use HF decay electrons to probe gluon polarization
- Statistically limited

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{\alpha}^{gg \rightarrow D \rightarrow e} \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)}$$

PRD 91, 032001 (2015)



PRD 87, 012011 (2013)



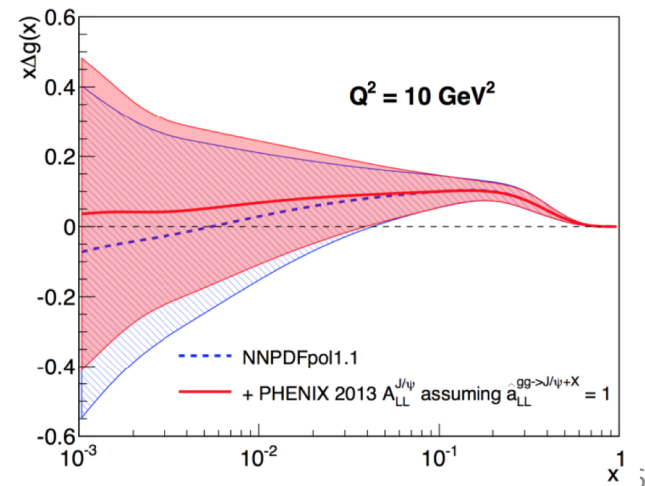
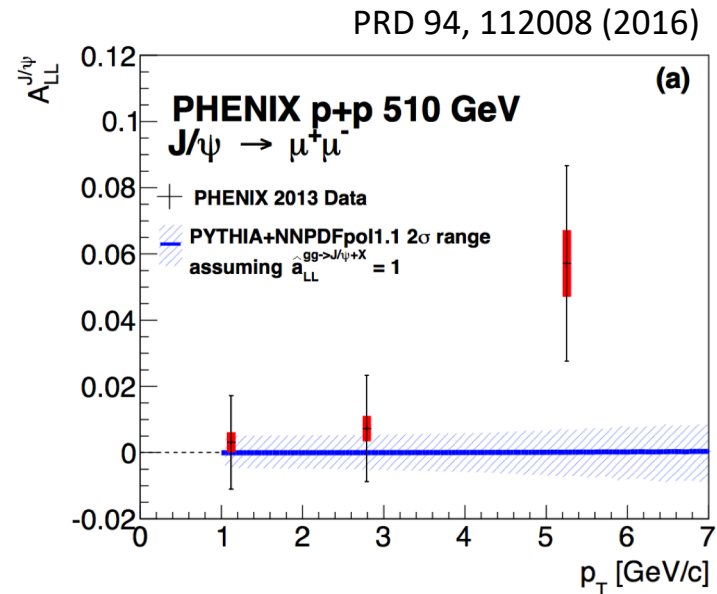
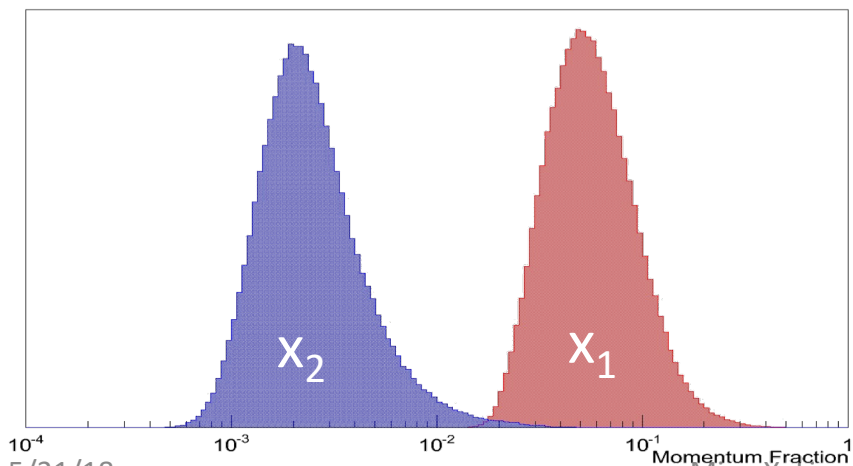
PHENIX: J/ψ A_{LL} at Forward Rapidity

- Access gluons in small-x region, $x_2 < 0.01$
- At RHIC energies J/ψ production is dominated by gluon-gluon fusion.
 - Statistically limited

The A_{LL} for J/ψ at LO:

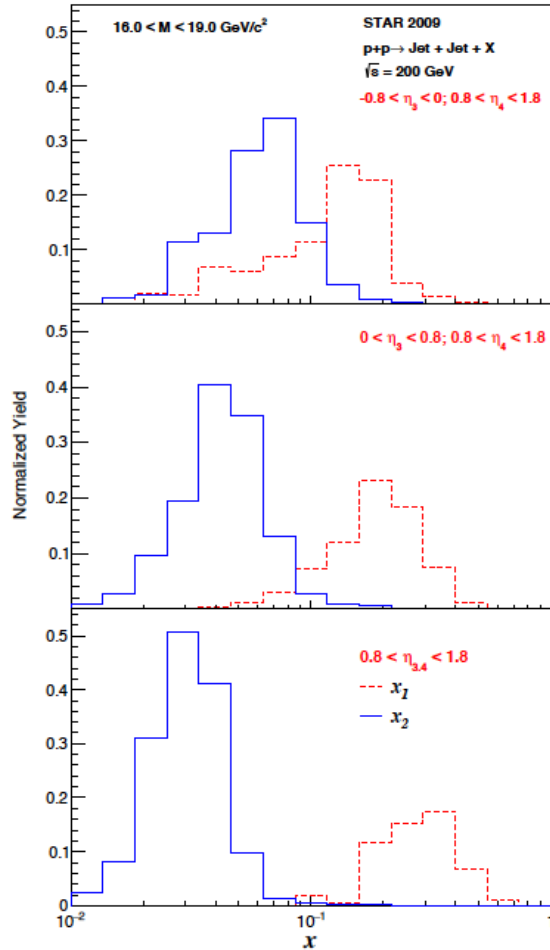
$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{a}^{gg \rightarrow J/\psi} \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)}$$

$$gg \rightarrow J/\psi + X \rightarrow \mu^+ \mu^- + X$$

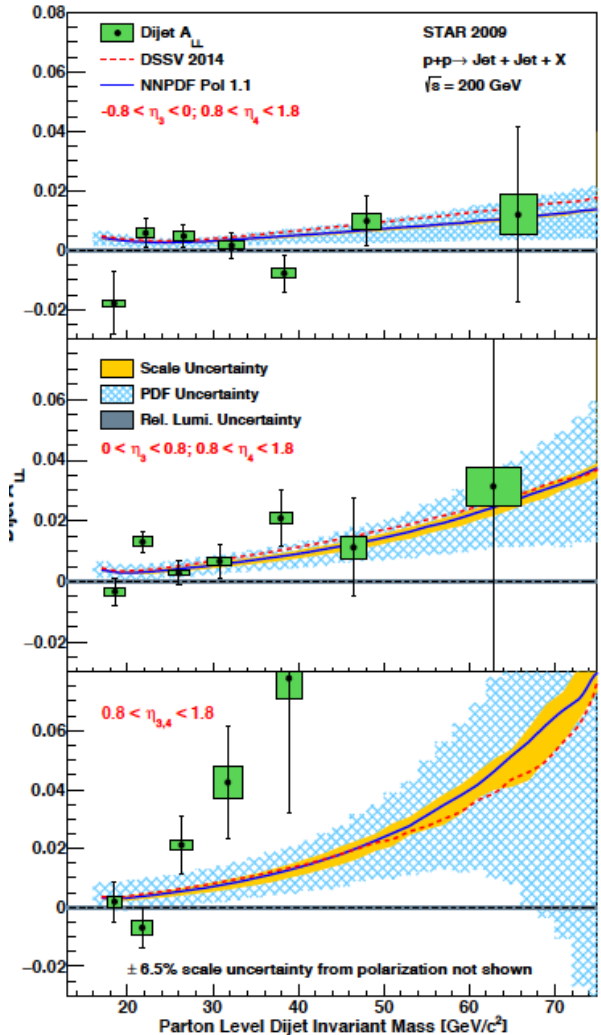
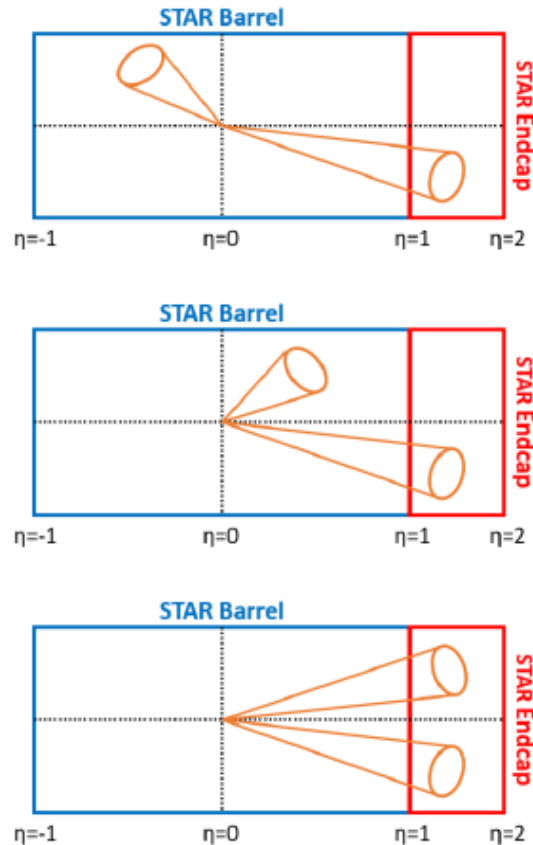


STAR: Di-Jet A_{LL} , pp 200GeV

arXiv:1805.09742



Probed parton x1 and x2 distributions

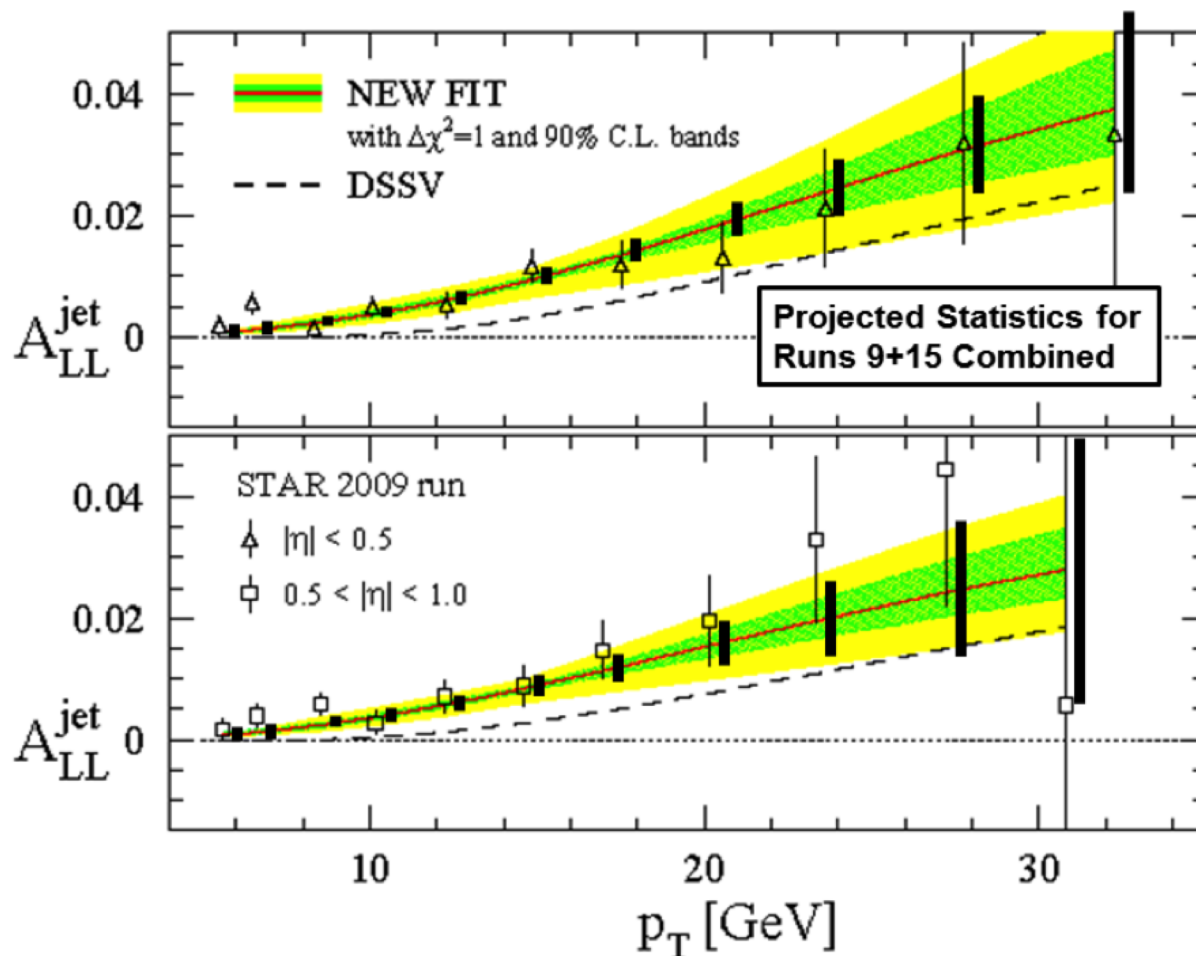


di-jet mass

In Progress: 200 GeV Inclusive Jet A_{LL}

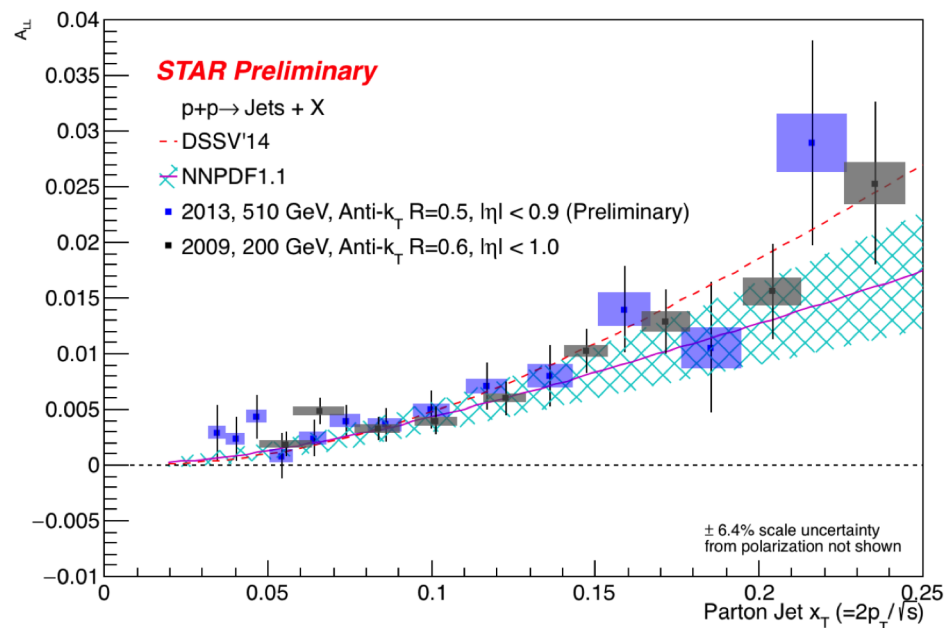
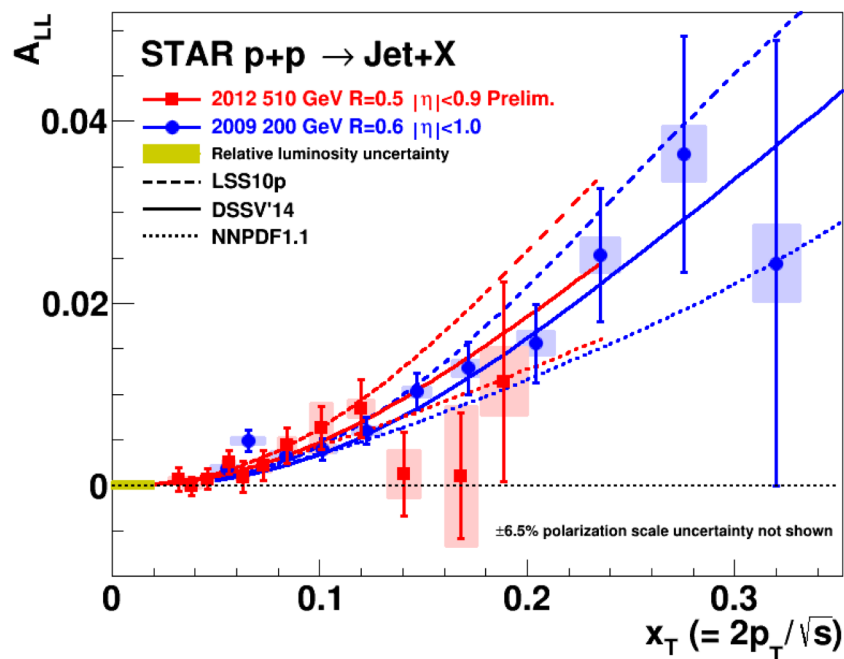
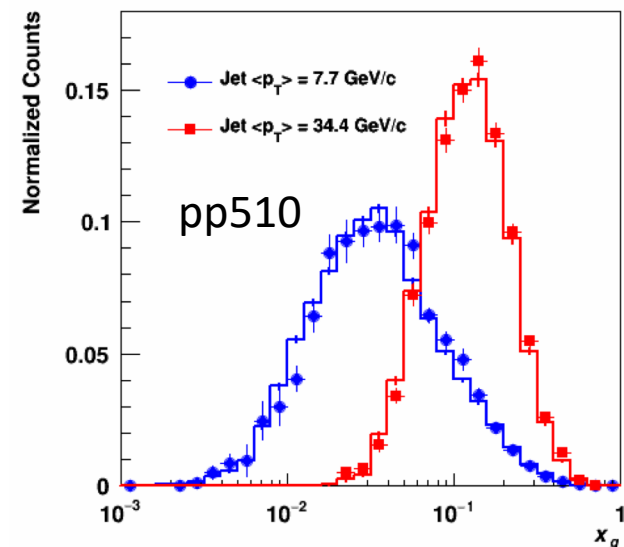
Projected combined Jet A_{LL} from STAR: run2009 + 2015

- 2x improvement over 2009 results



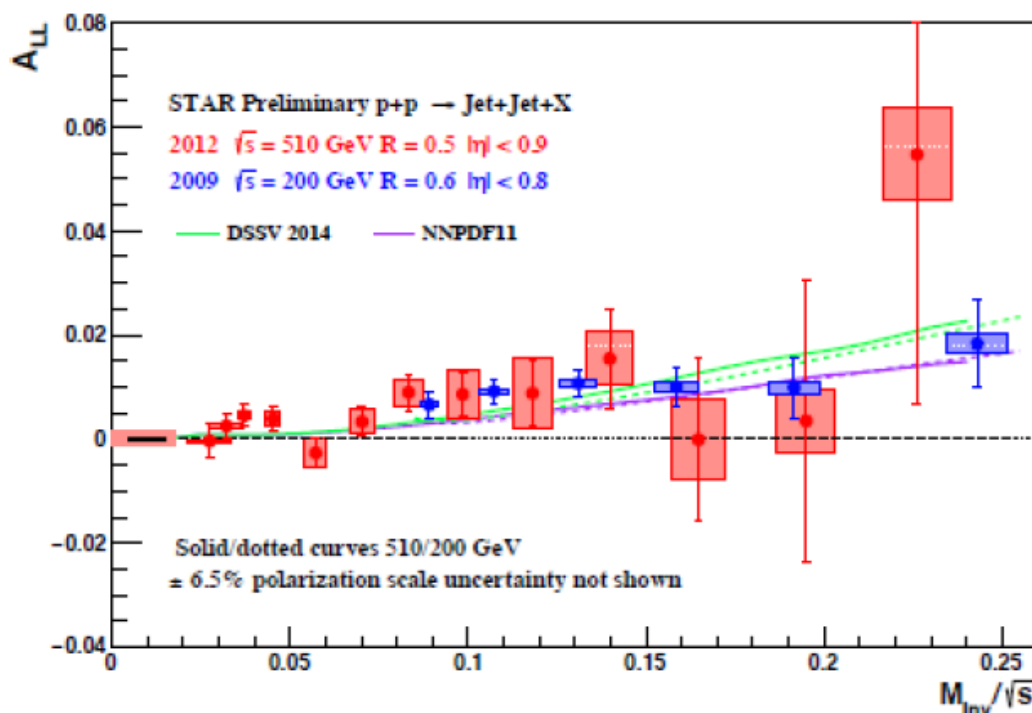
STAR: 510 GeV pp Jet A_{LL}

- Preliminary 2012/2013 pp510 A_{LL} results
 - Access smaller x_g than pp200
 - Agree with recent pol PDF predictions
 - Consistent with published pp200 data

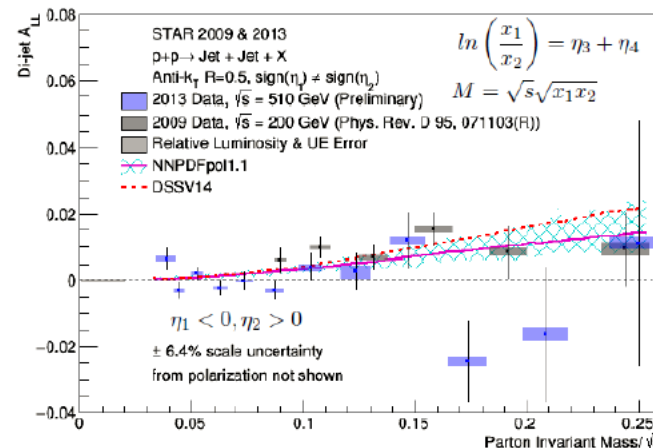
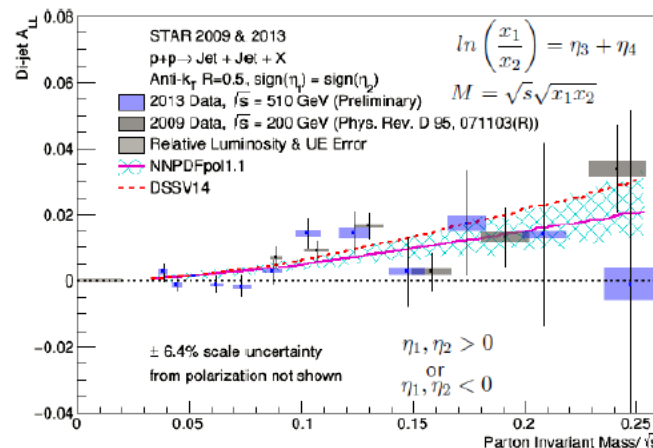


STAR: pp510 Di-jet A_{LL}

Run12 pp510 di-jet A_{LL} measured $|\eta| < 0.9$
- consistent with STAR pp200GeV results



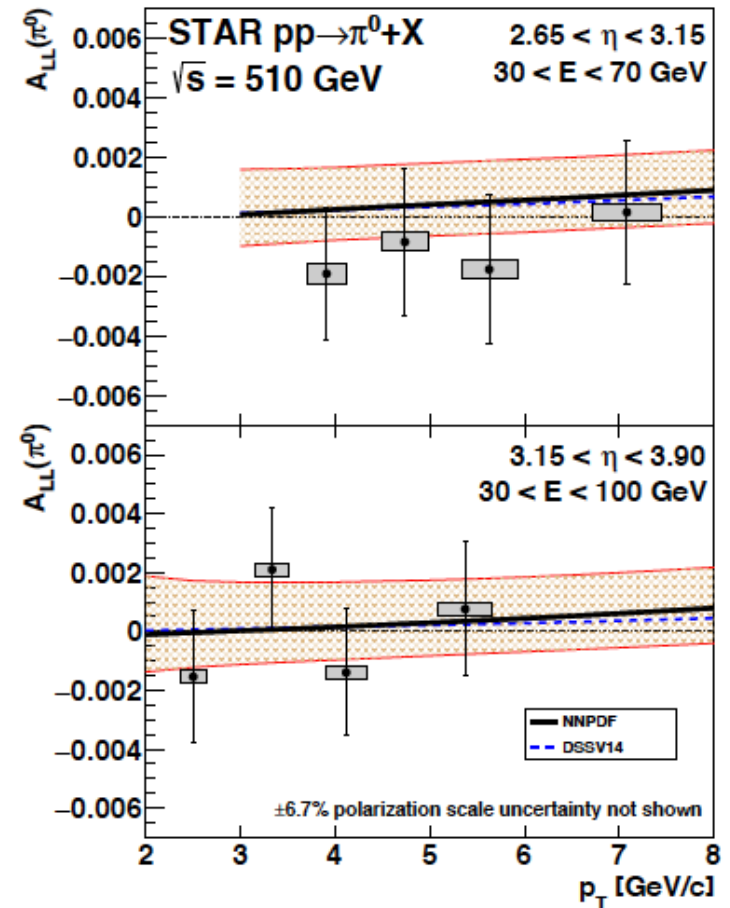
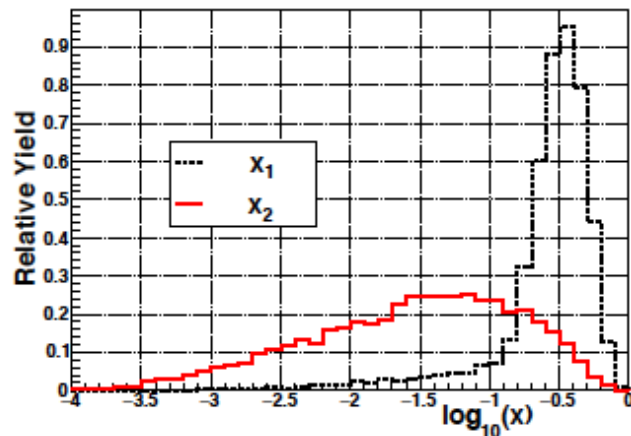
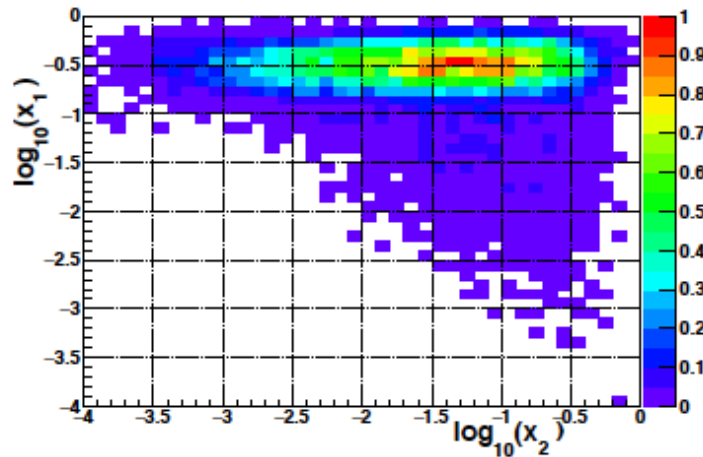
Run13 pp510 di-jet A_{LL}



STAR: Forward π^0 ALL in pp 510GeV

access small-x gluons

arXiv:1805.09745



Impact of RHIC data on Gluon Polarization

- Favors positive gluon polarization

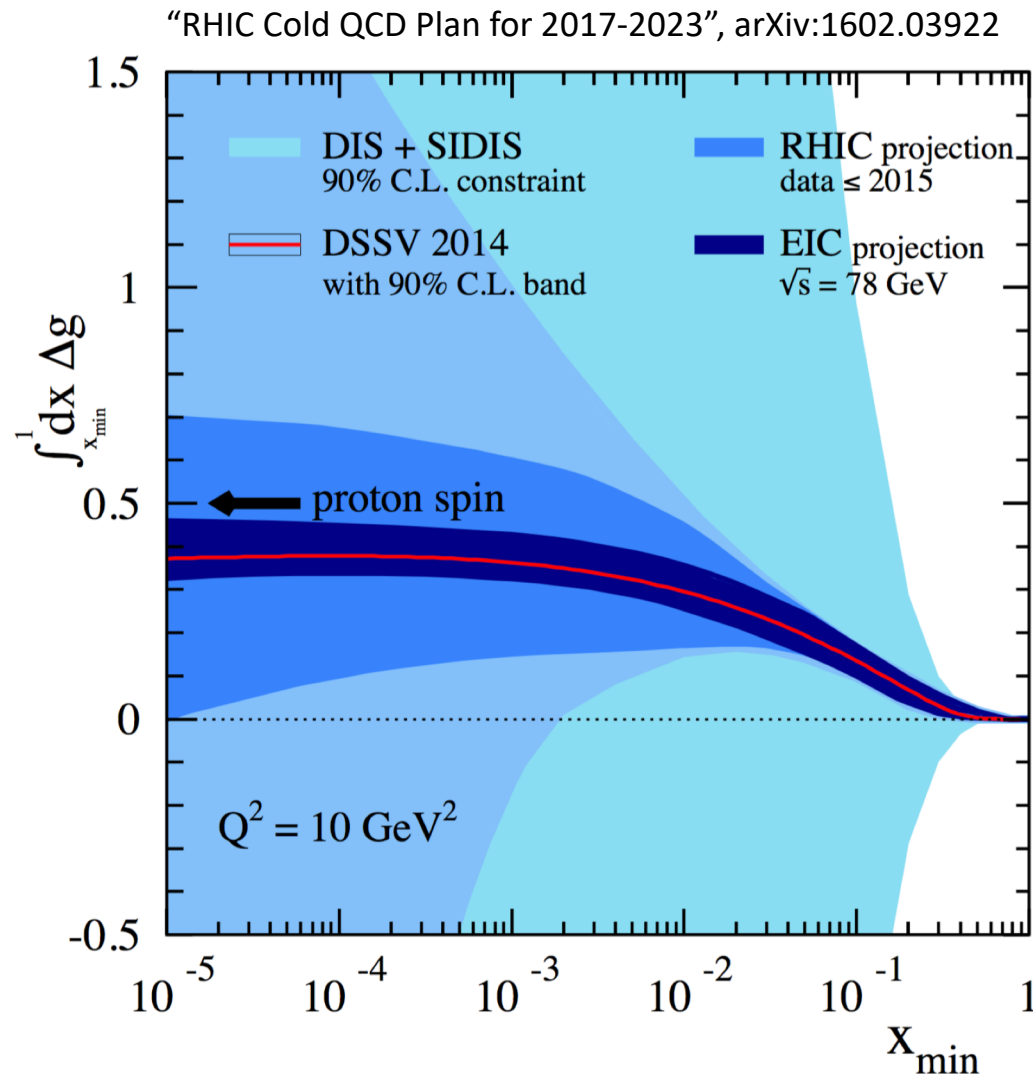
– PHENIX/STAR data:

- 62GeV $\pi^0 A_{LL}$
- 200GeV $\pi^0 A_{LL}$
- 510GeV $\pi^0 A_{LL}$
- 200/510GeV (di)jets A_{LL}

Statistically limited but could be improved in the future high luminosity program:

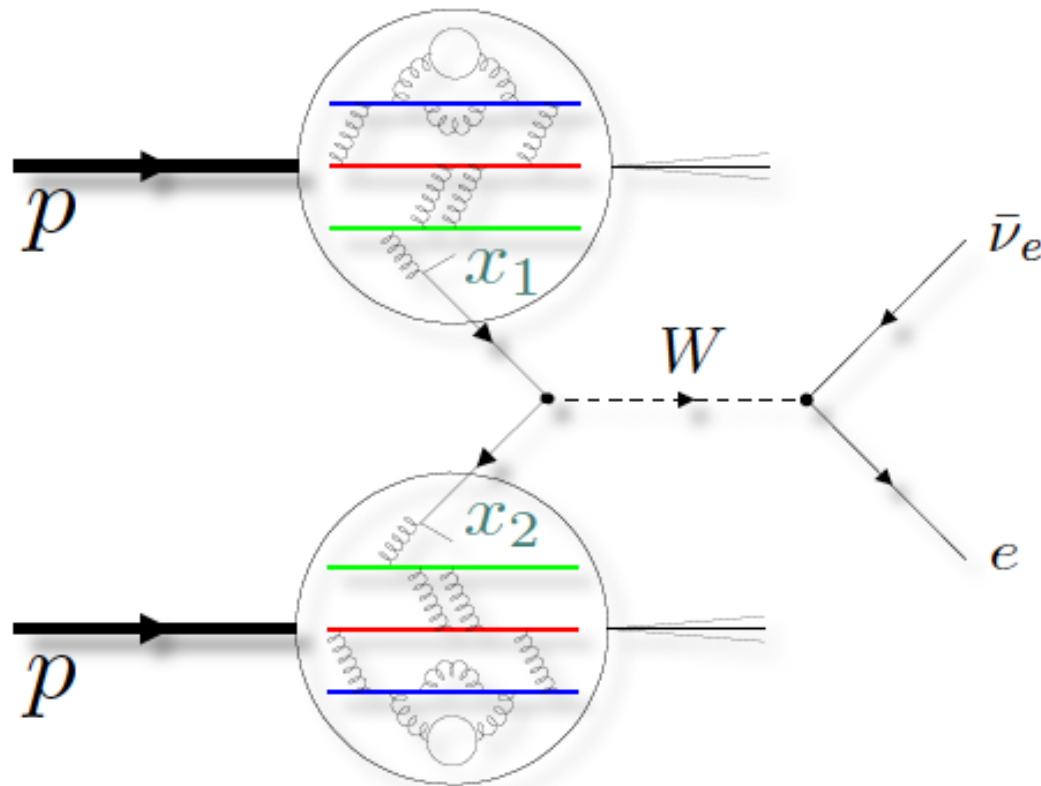
- 200/510GeV charged hadron A_{LL}
- 200/510GeV HF A_{LL}
- 200/510GeV $J/\psi A_{LL}$

- EIC future, 2025+



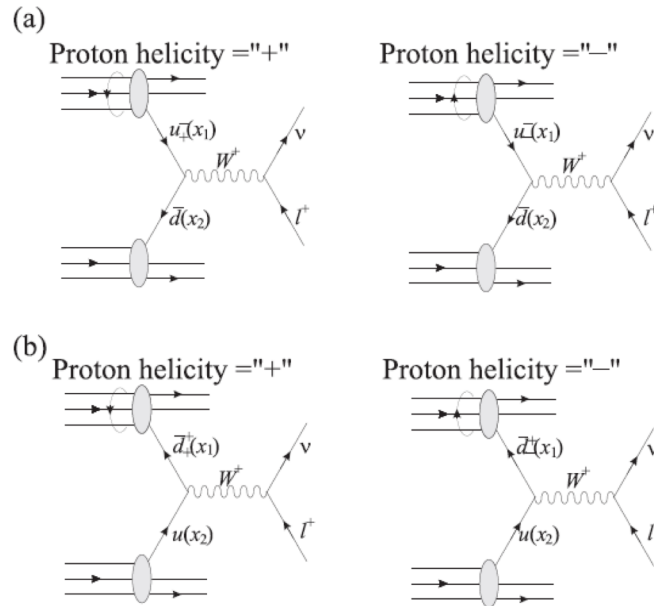
Electroweak Probe for Sea Quarks at High Energy at RHIC

$$q(x_1) + \bar{q}'(x_2) \rightarrow W^\pm \rightarrow e^\pm + \nu(\bar{\nu})$$



Access sea-quark with W⁺/₋

Bourrely & Soffer, NP B423 (1994) 329-348



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

$$A_L^{W^+} \sim \frac{\Delta \bar{d}}{\bar{d}} (\text{forward})$$

$$A_L^{W^+} \sim -\frac{\Delta u}{u} (\text{backward})$$

$$A_L^{W^-} \sim -\frac{\Delta d}{d} (\text{forward})$$

$$A_L^{W^-} \sim \frac{\Delta \bar{u}}{\bar{u}} (\text{backward})$$

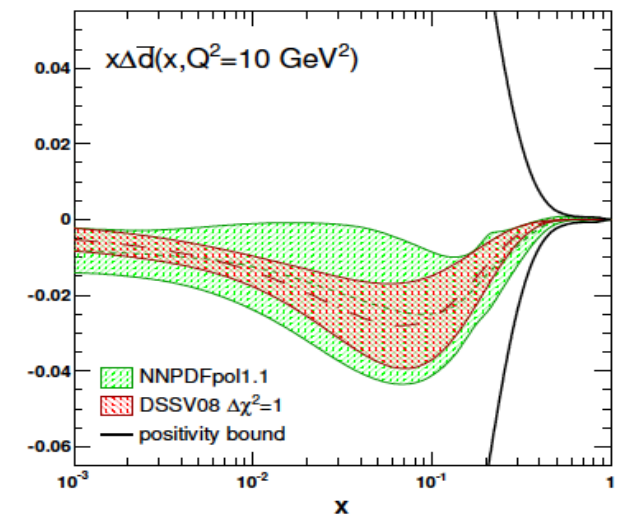
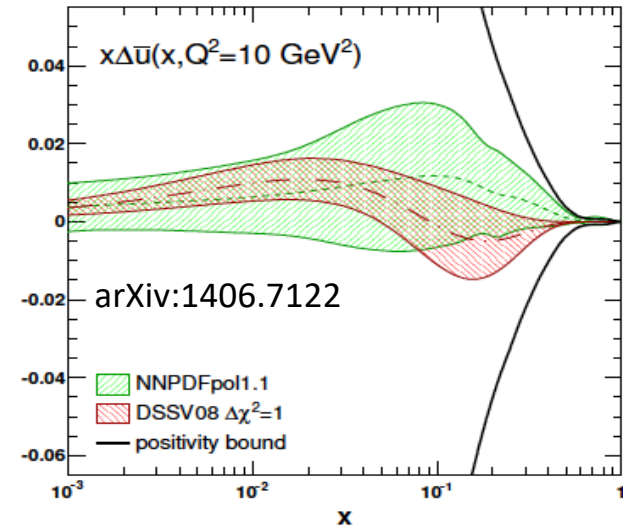
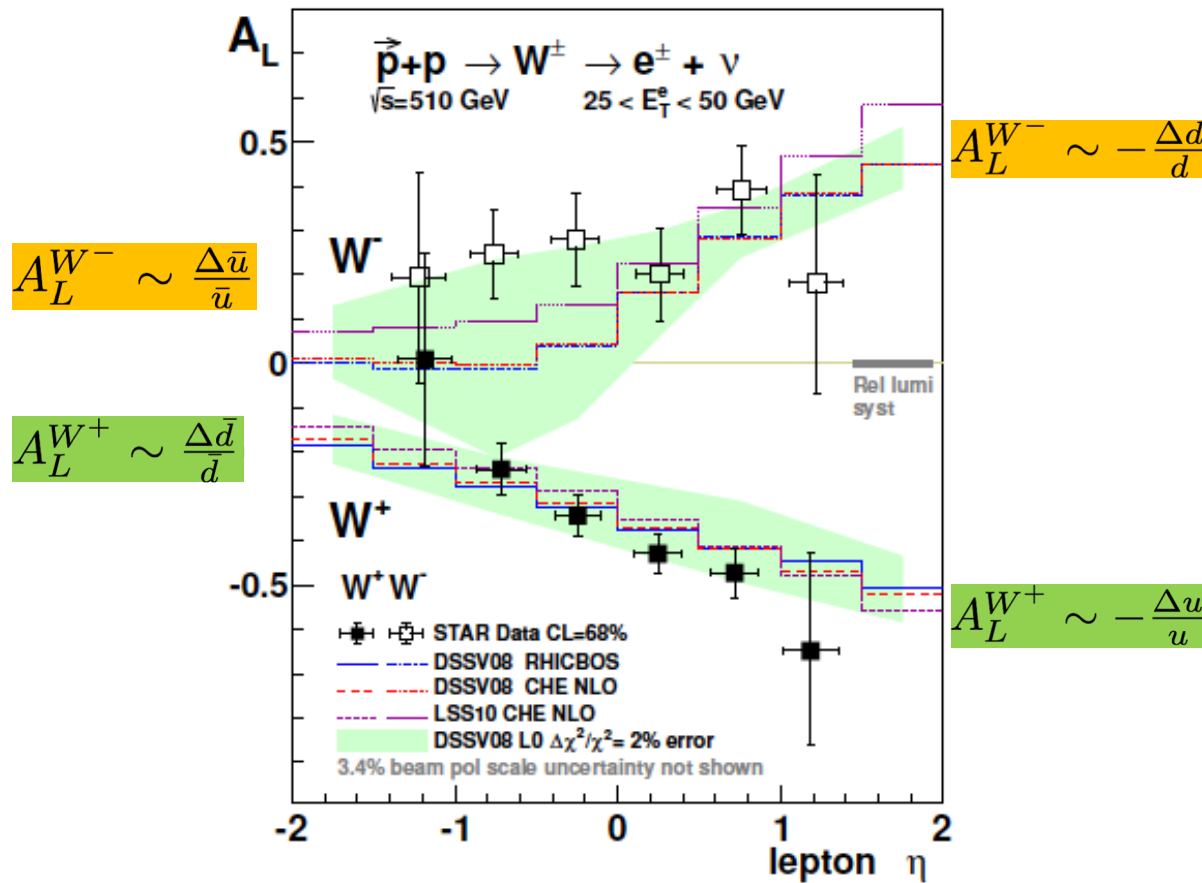
$$A_L^{W^+} \approx \frac{-\Delta u(x_1) \bar{d}(x_2) (1 - \cos \theta)^2 + \Delta \bar{d}(x_1) u(x_2) (1 + \cos \theta)^2}{u(x_1) \bar{d}(x_2) (1 - \cos \theta)^2 + \bar{d}(x_1) u(x_2) (1 + \cos \theta)^2}$$

$$A_L^{W^-} \approx \frac{-\Delta d(x_1) \bar{u}(x_2) (1 + \cos \theta)^2 + \Delta \bar{u}(x_1) d(x_2) (1 - \cos \theta)^2}{d(x_1) \bar{u}(x_2) (1 + \cos \theta)^2 + \bar{u}(x_1) d(x_2) (1 - \cos \theta)^2}$$

First Direct Measurements of Flavor Identified Sea Quark Polarization

RHIC has unique access to flavor identified sea-quarks via real $W^{+/-}$

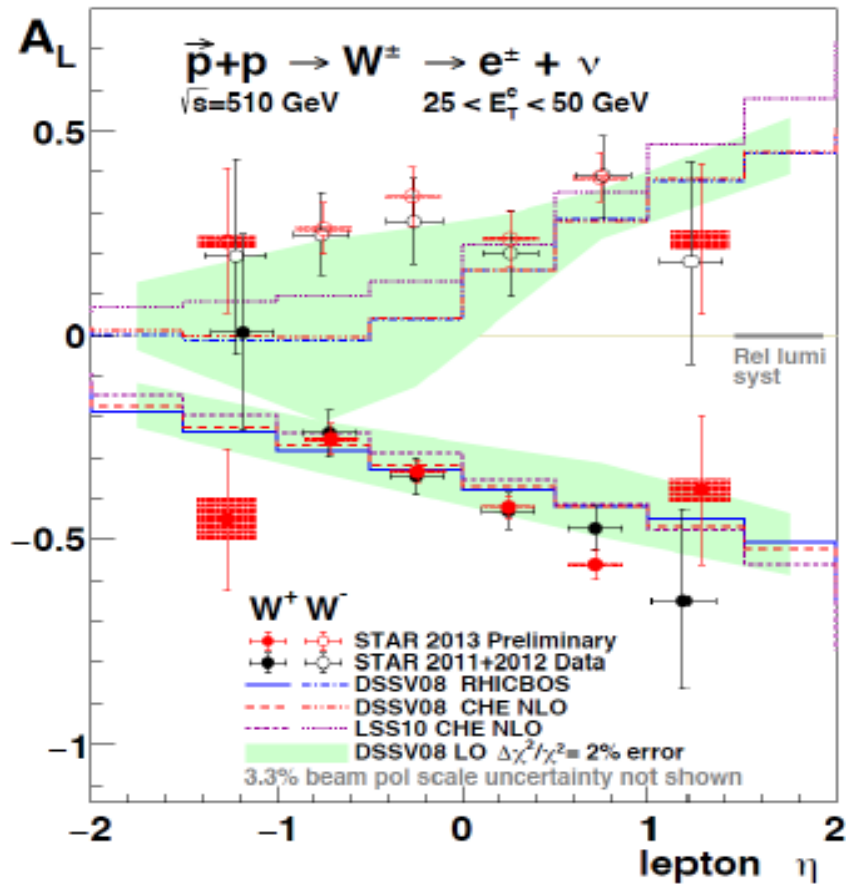
STAR: PRL 113, 072301 (2014)



Latest $W^{+/-}$ A_L from STAR and PHENIX

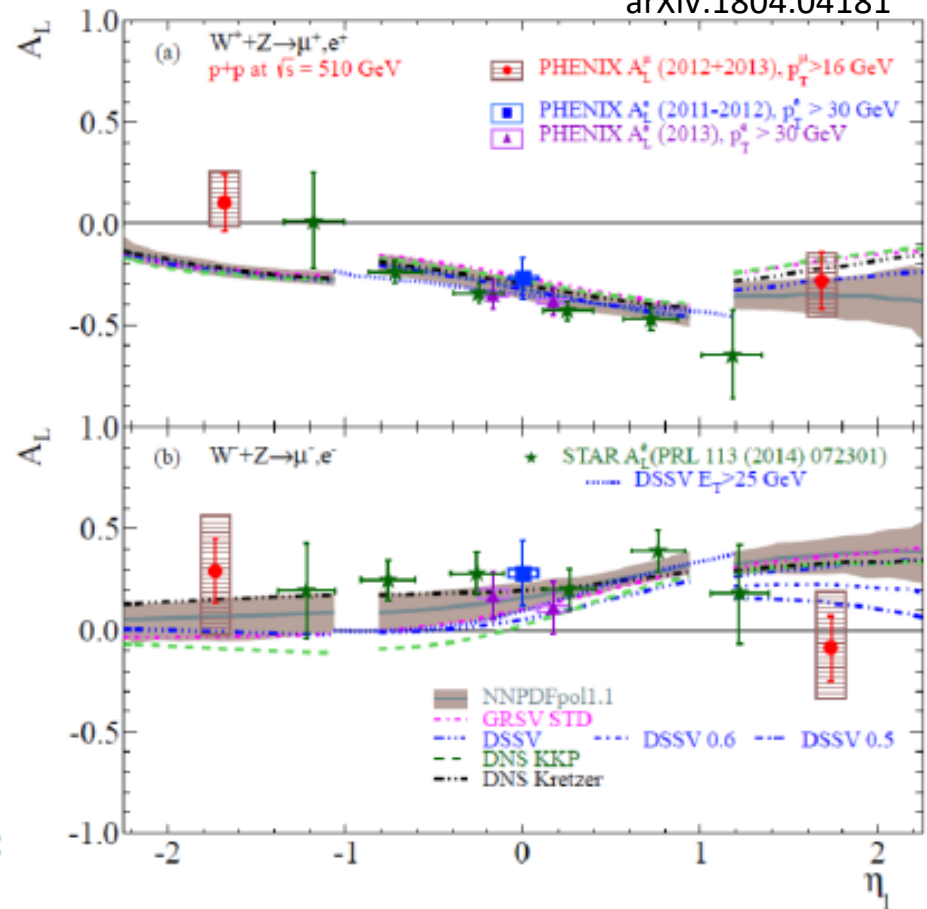
$$p + p \rightarrow W^\pm \rightarrow e^\pm$$

arXiv:1702.05077



$$p + p \rightarrow W^\pm \rightarrow \mu^\pm (e^\pm)$$

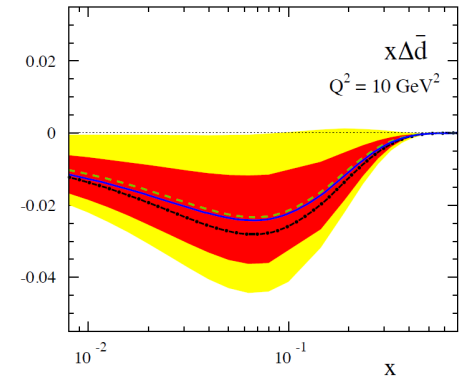
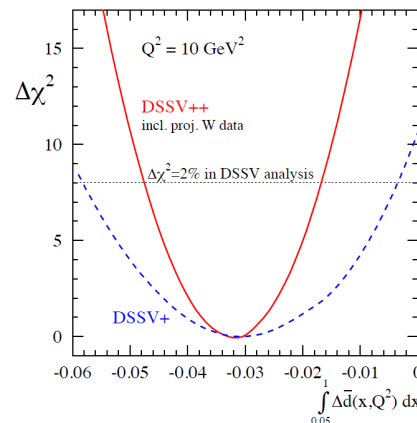
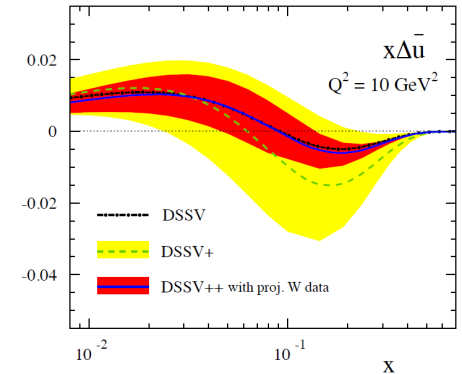
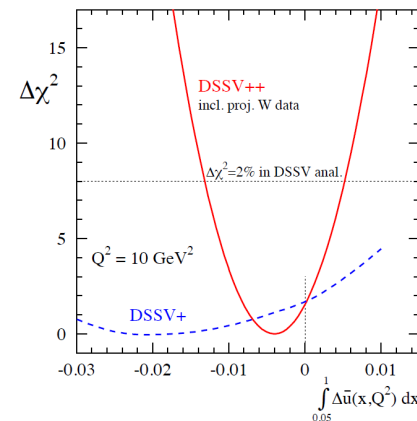
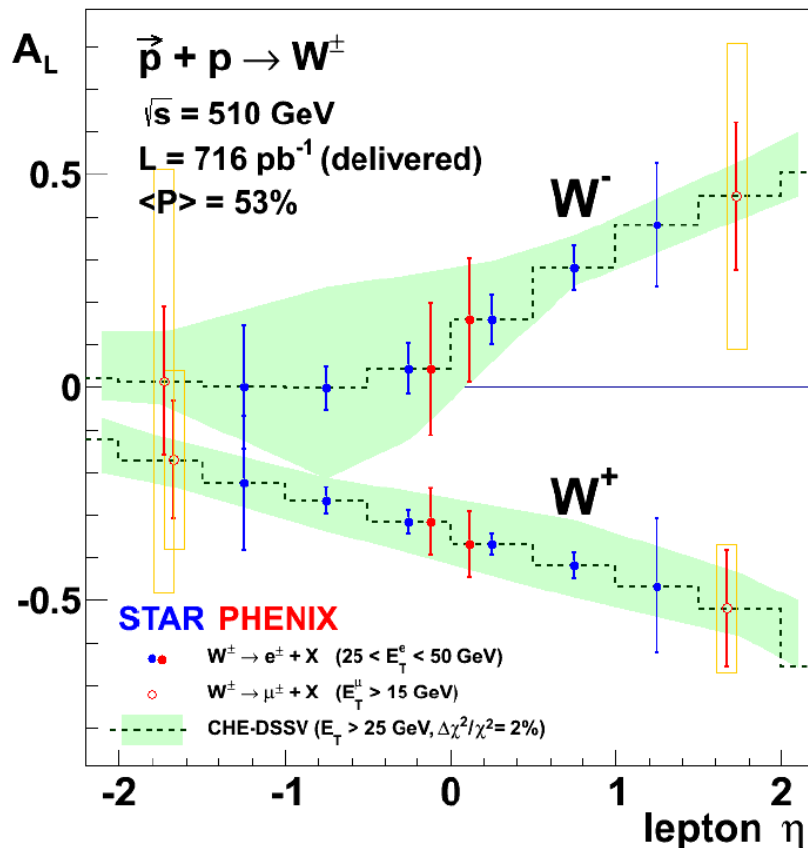
arXiv:1804.04181



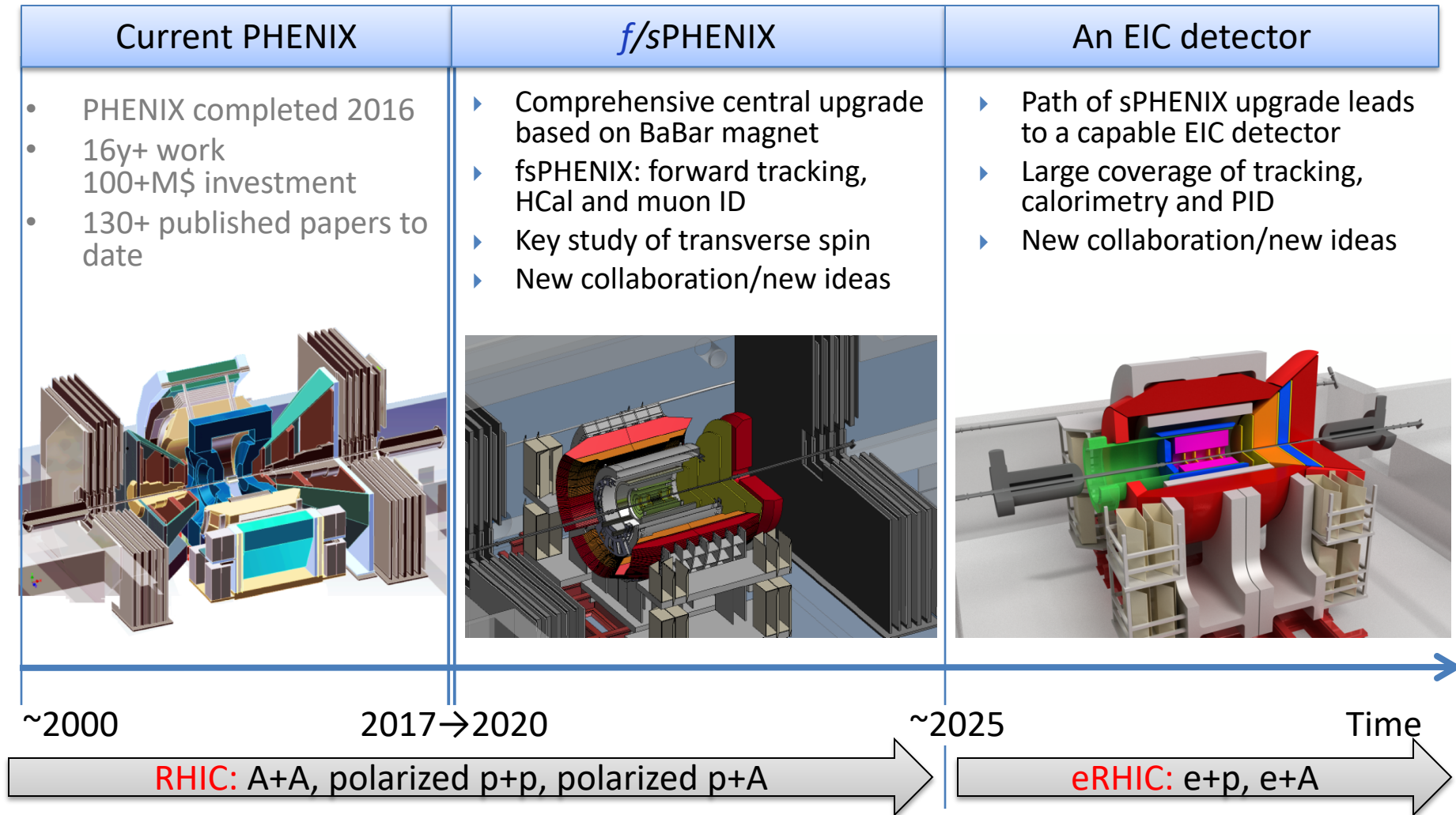
RHIC $W^\pm \rightarrow l^\pm$ data Impact on Sea Quark Polarization

- Expect significant improvement of flavor identified sea quark polarization

The RHIC Spin Program, arXiv: 1501.01220

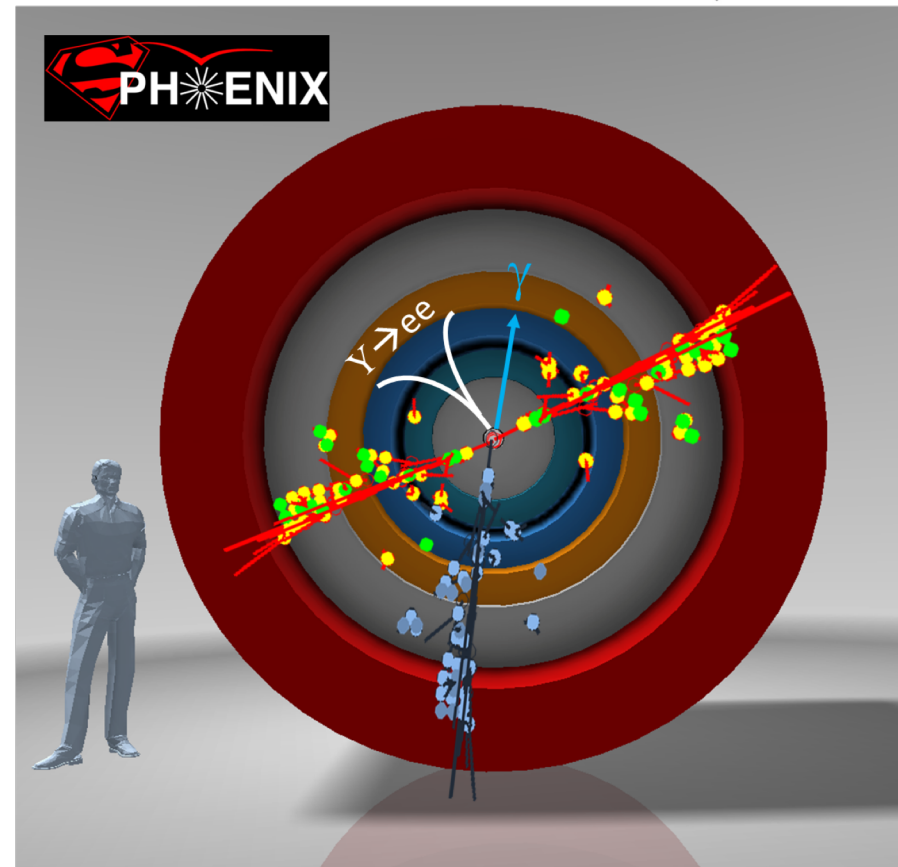
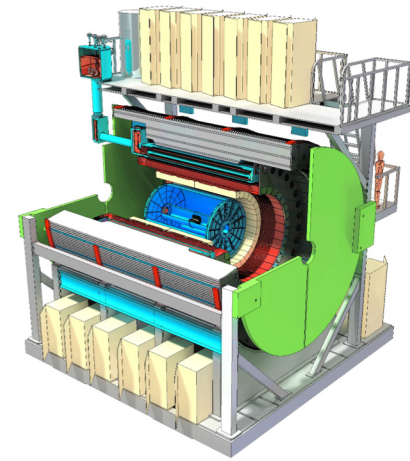


Future: PHENIX -> sPHENIX -> EIC@RHIC



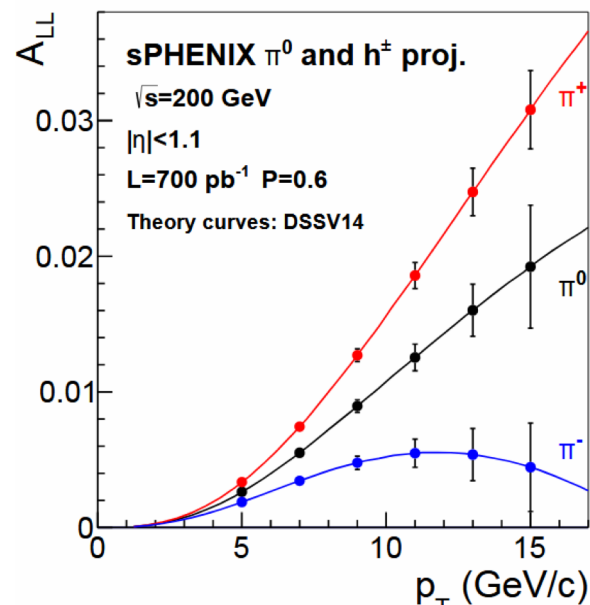
sPHENIX at RHIC

- Large acceptance, high rate next generation experiment at RHIC
 - QGP and Cold QCD physics with,
 - Jets
 - Heavy quarkonia
 - Open heavy flavor
 - Study p+p, p+A and Au+Au collisions at top energy 200GeV
 - Central barrel: $|\eta| < 1$, 2π coverage
 - EMCal & HCal
 - MVTX/INTT/TPC
 - Forward upgrade being developed
 - DAQ rate: 15kHz
- Project Status
 - Granted DOE CD-0, 10/2016
 - CD-1 reviewed, 5/2018
 - Construction: 2018-2022
 - Day-1 physics, 1/2023

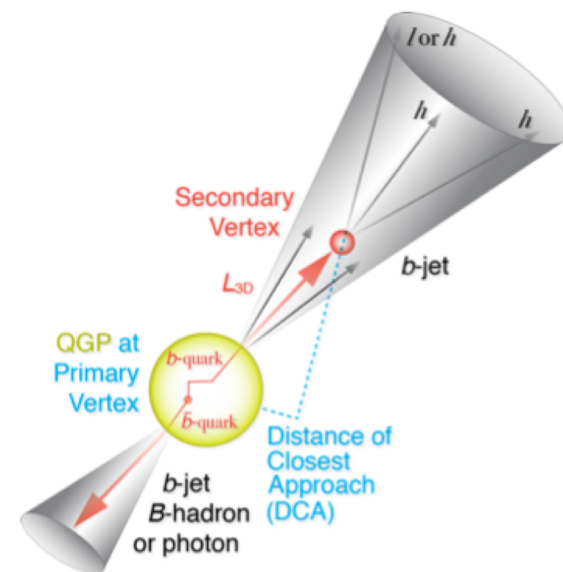


RHIC Multi-Year Plan: sPHENIX 2023-2027+ (Cold QCD plan under development now)

- Jets, hadrons and heavy flavor and more



RHIC 2015 pp200
Recorded lumi ~ 50 pb $^{-1}$



Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb $^{-1}$	8.7 nb $^{-1}$	34 nb $^{-1}$
Year-2	p+p	200	11.5	—	48 pb $^{-1}$	267 pb $^{-1}$
Year-2	p+Au	200	11.5	—	0.33 pb $^{-1}$	1.46 pb $^{-1}$
Year-3	Au+Au	200	23.5	14 nb $^{-1}$	26 nb $^{-1}$	88 nb $^{-1}$
Year-4	p+p	200	23.5	—	149 pb $^{-1}$	783 pb $^{-1}$
Year-5	Au+Au	200	23.5	14 nb $^{-1}$	48 nb $^{-1}$	92 nb $^{-1}$

Proposed STAR Forward Upgrade

Access small-x Gluons

To install a Forward Calorimeter System (FCS) in early 2020s:

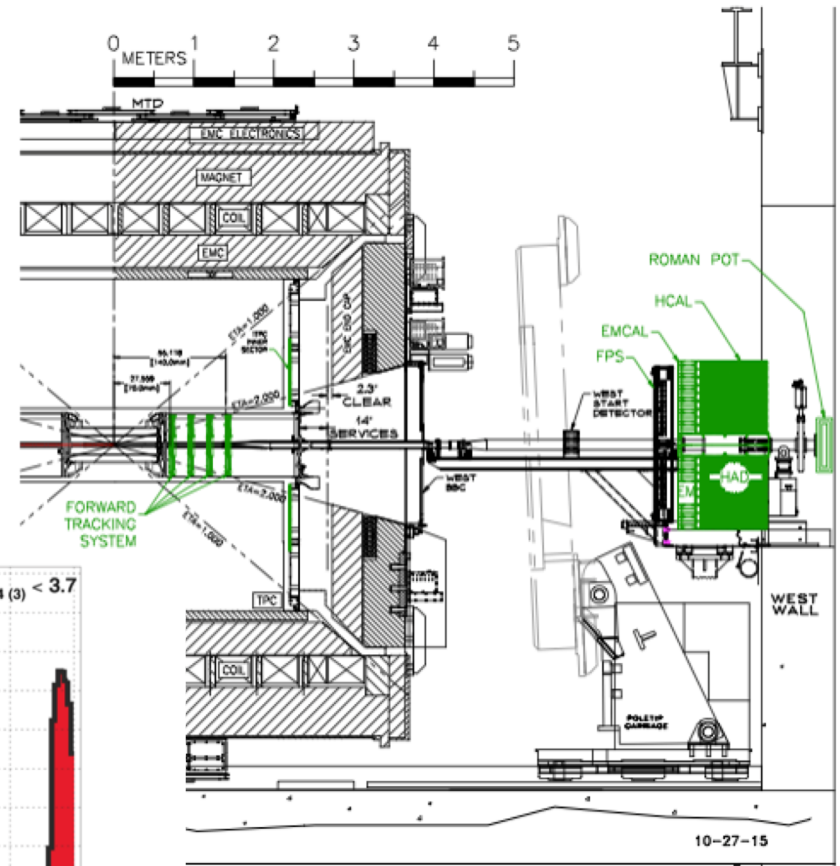
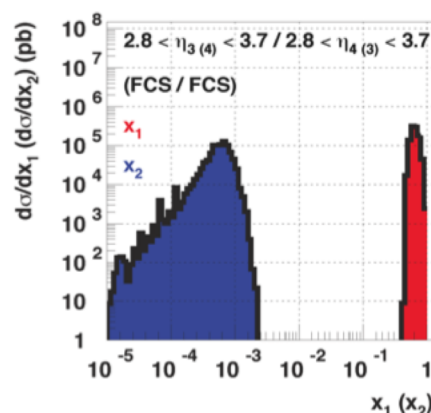
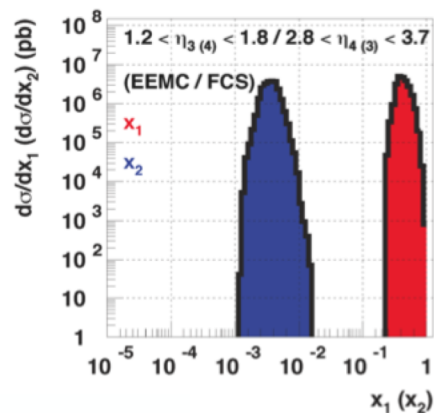
- EMCal
- Hcal
- Tracking, charge separation

	p+p / p+A
ECAL	$\approx 10\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$

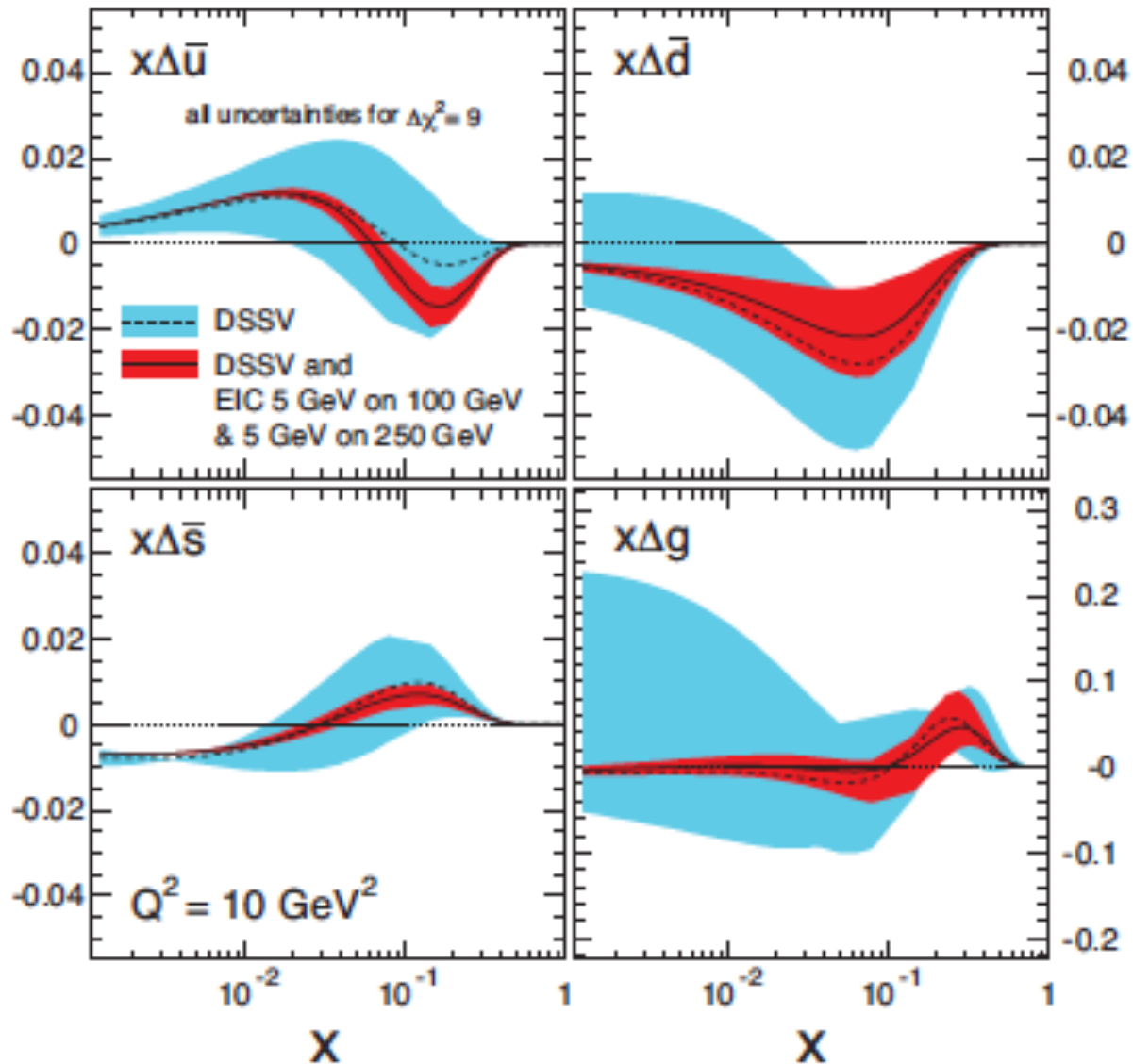
Di-jet in the forward region ($2.8 < \eta < 3.7$)

Access gluon polarization at low x:

- $X \sim 5 \times 10^{-3}$ (central + forward)
- $X \sim < 1 \times 10^{-3}$ (forward - forward)

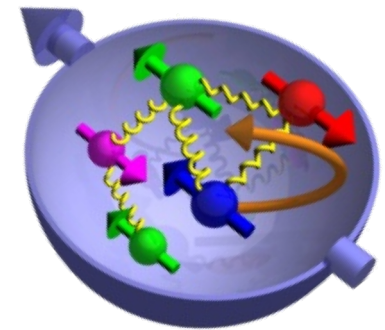
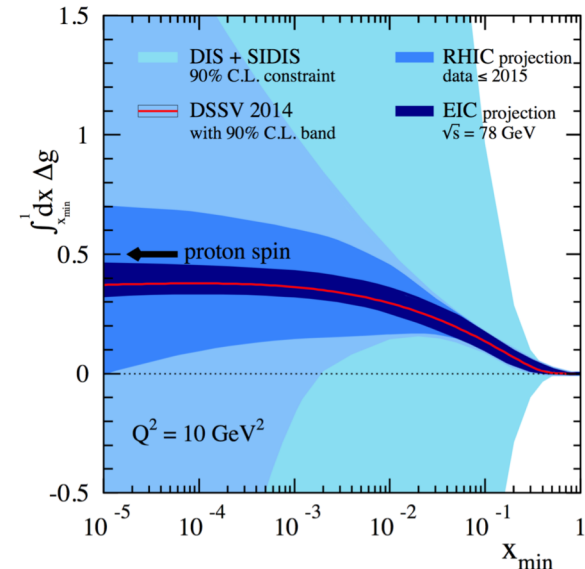


EIC Future @RHIC



Summary and Outlook

- First evidence of non-zero gluon polarization
 - PHENIX: π^0 A_{LL}
 - STAR: 200/510 GeV inclusive jets and di-jet A_{LL}
- First direct measurements of sea-quark polarization with $W^{+/-}$
 - PHENIX: $W \rightarrow e, \mu$
 - STAR: $W \rightarrow e$
- Cold QCD plan being developed
 - Exciting long-term polarized pp/pA 2020+
 - sPHENIX
 - STAR/Forward upgrade proposal
- EIC future 2025+

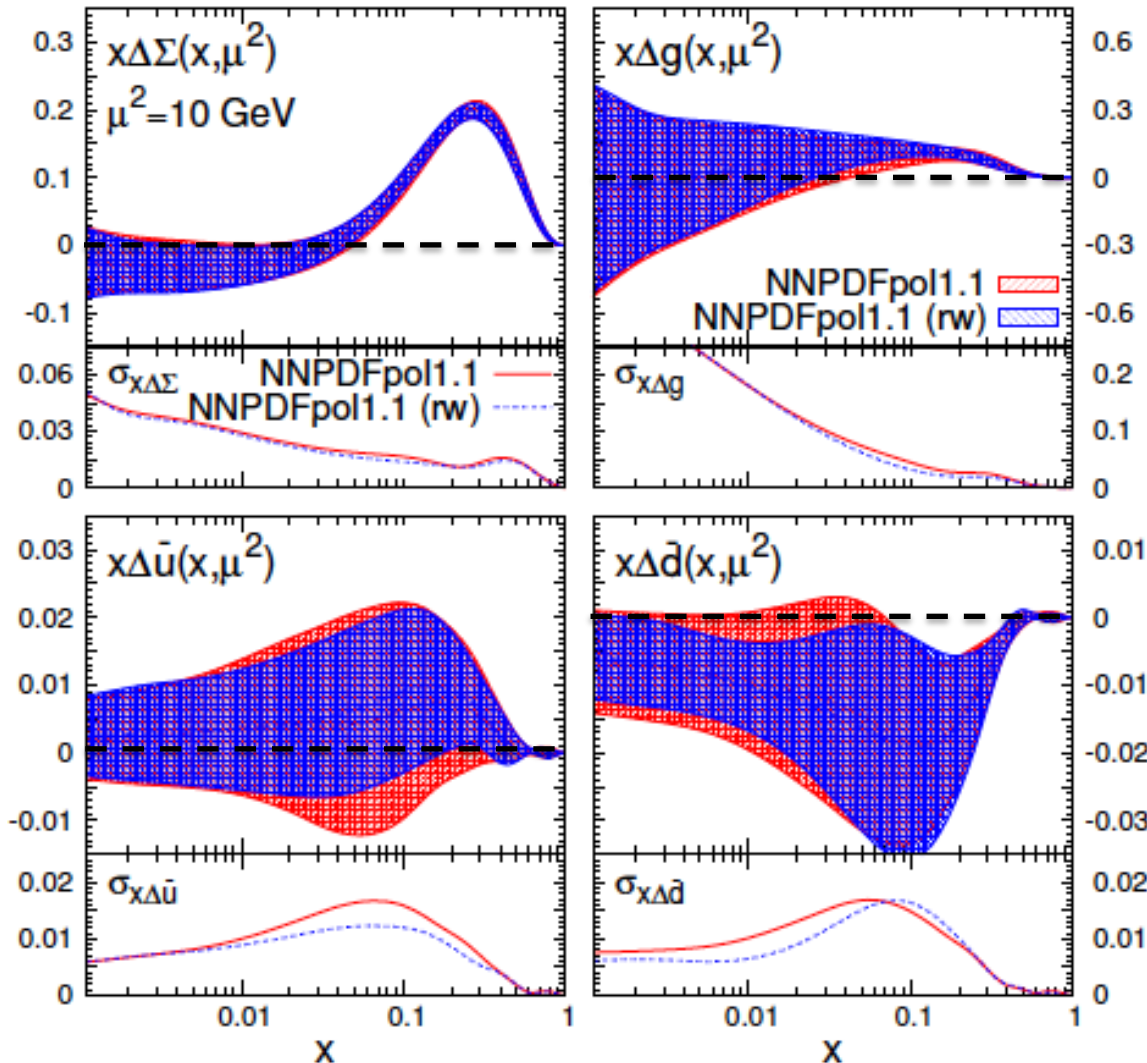


Backup slides

Latest Pol NNPDFPol Global Fit

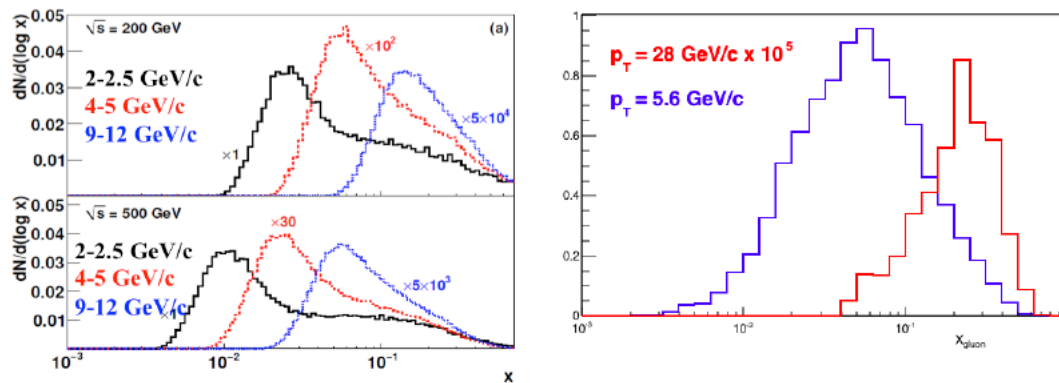
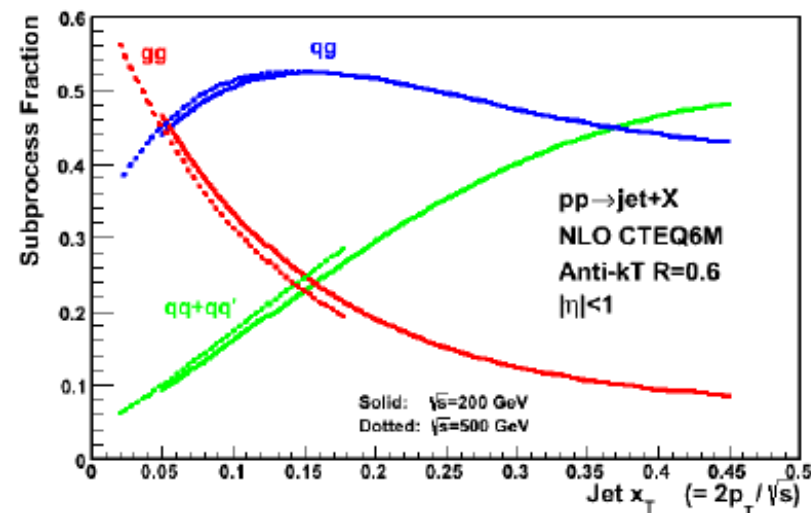
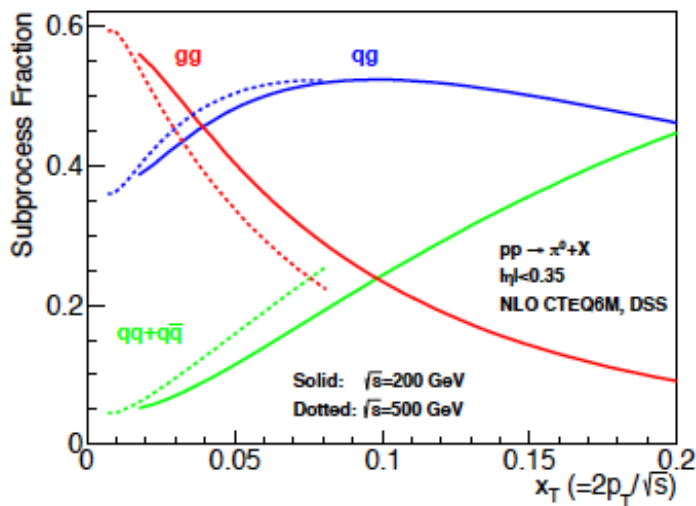
arXiv:1702.05077

-SI/DIS data
-RHIC data



Relative contributions

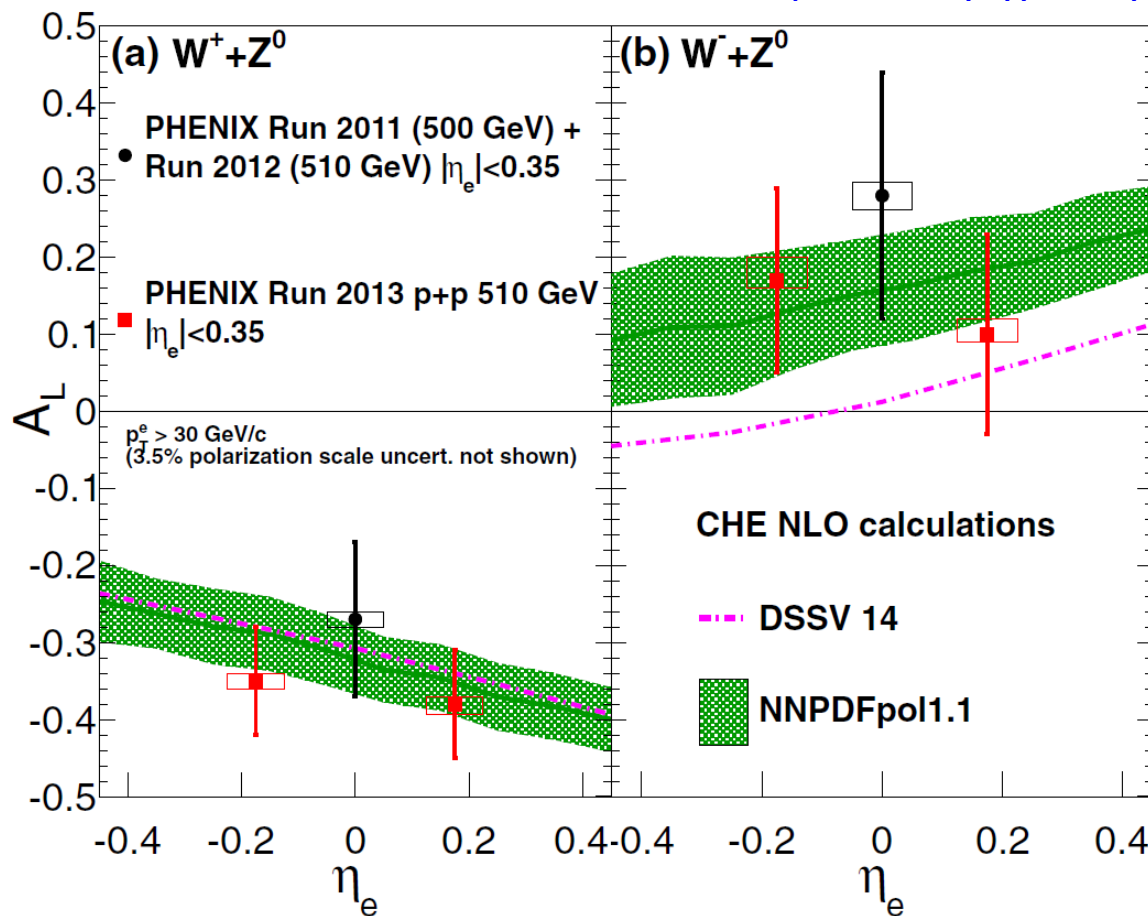
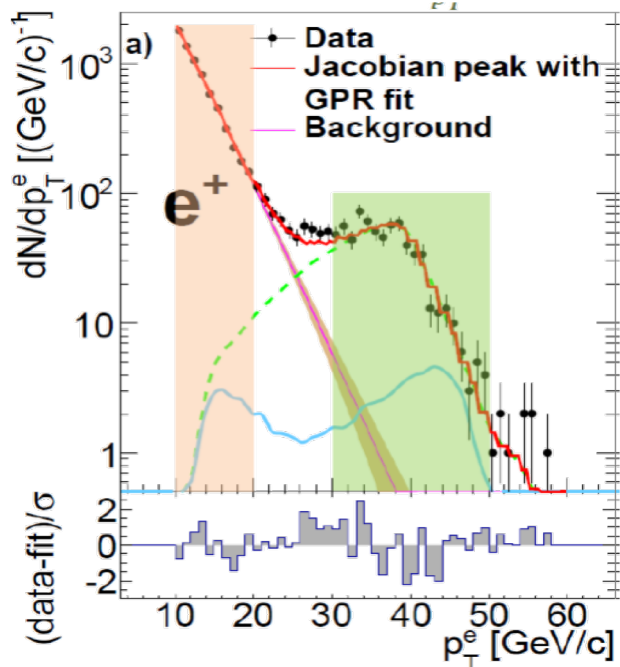
RHIC Spin Program, arXiv:1501.01220



PHENIX: pp510GeV $W^\pm \rightarrow e^\pm A_L$

PRD 93, 051103(R)(2016)

High p_T electrons from
 $W^{+/-}$ decays



STAR Forward Proposal

Year	\sqrt{s} (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
2021	$p^+p^- @ 510$	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
2021	$p^+p^- @ 510$	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ -jets at $\eta > 1$	Forward instrum. ECal+HCal
2023	$p^+p^- @ 200$	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	Forward instrum. ECal+HCal+Tracking
2023	$p^+ \text{Au} @ 200$	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ -jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
2023	$p^+ \text{Al} @ 200$	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl} : direct photons and DY Dihadrons, γ -jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking