Overview of RHIC Longitudinal Spin Physics Program

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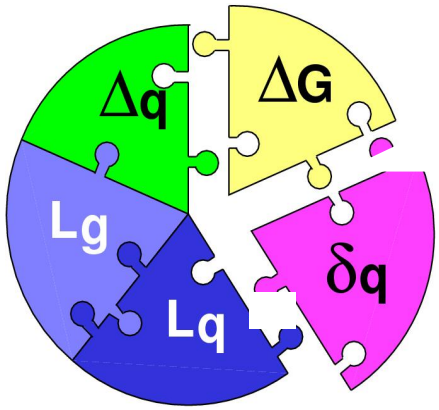
Many thanks to the PHENIX and STAR collaborations for providing the latest results

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

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

$$\Delta q \sim 30\% \quad (SIDIS/DIS)$$

$$\Delta G \sim 40\% \quad (RHIC)$$

$$L \sim ? \quad (RHIC, FNAL?)$$

	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	

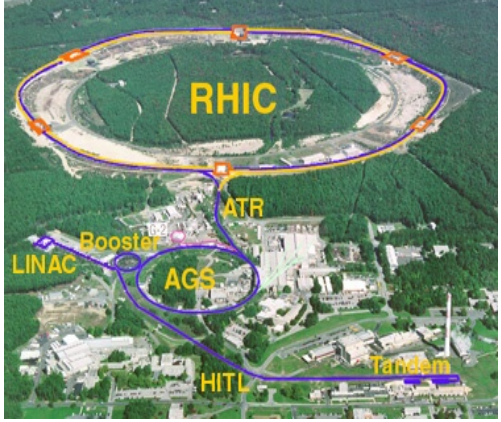
SIDIS/DIS

Polarized p+p

Outline

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

Polarized Proton Collider at RHIC



Absolute Polarimeter (H↑ jet)

RHIC pC Polarimeters

PHOBOS

polarized p+p collisions

$62 \leq \sqrt{s} \leq 500$ GeV

BRAHMS

Siberian Snakes

Siberian Snakes

PHENIX

STAR

Spin Rotators
(longitudinal polarization)

Spin Rotators
(longitudinal polarization)

Pol. H^- Source

LINAC

BOOSTER

AGS

Helical Partial Siberian Snake

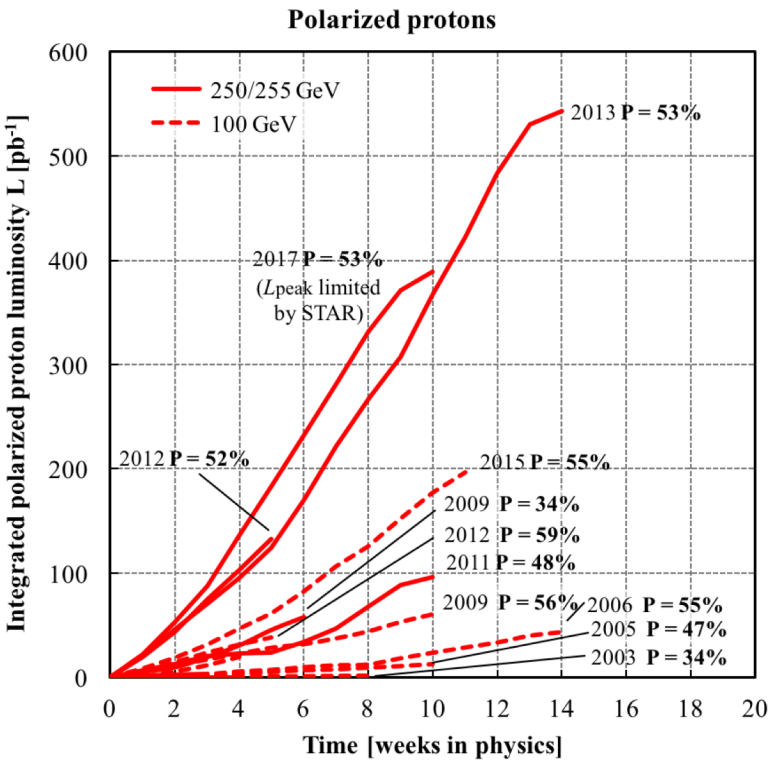
200 MeV Polarimeter

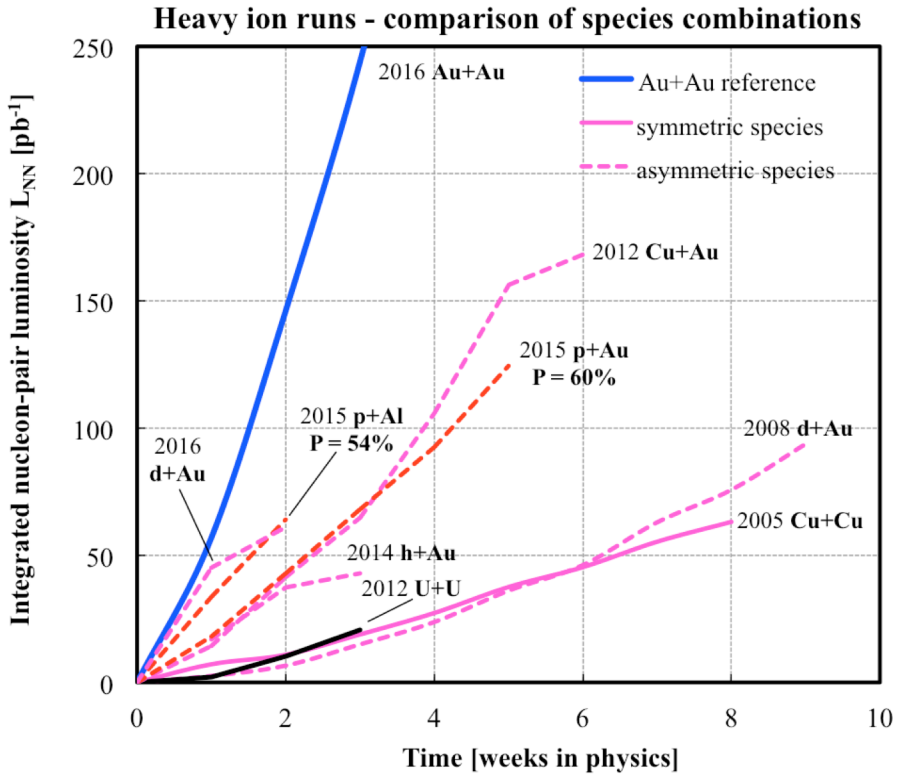
AGS pC Polarimeter

Strong AGS Snake

History of RHIC Spin Runs

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

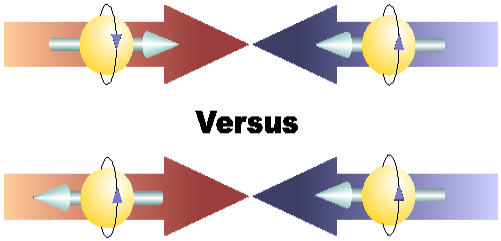




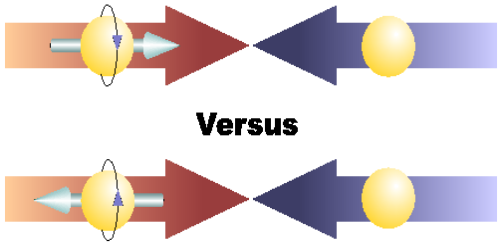
- A very challenging task to deliver polarized p+p, excellent performance from 2012+
- Longitudinally and transversely polarized p+p,
- Transversely polarized p+Au and p+Al, in 2015

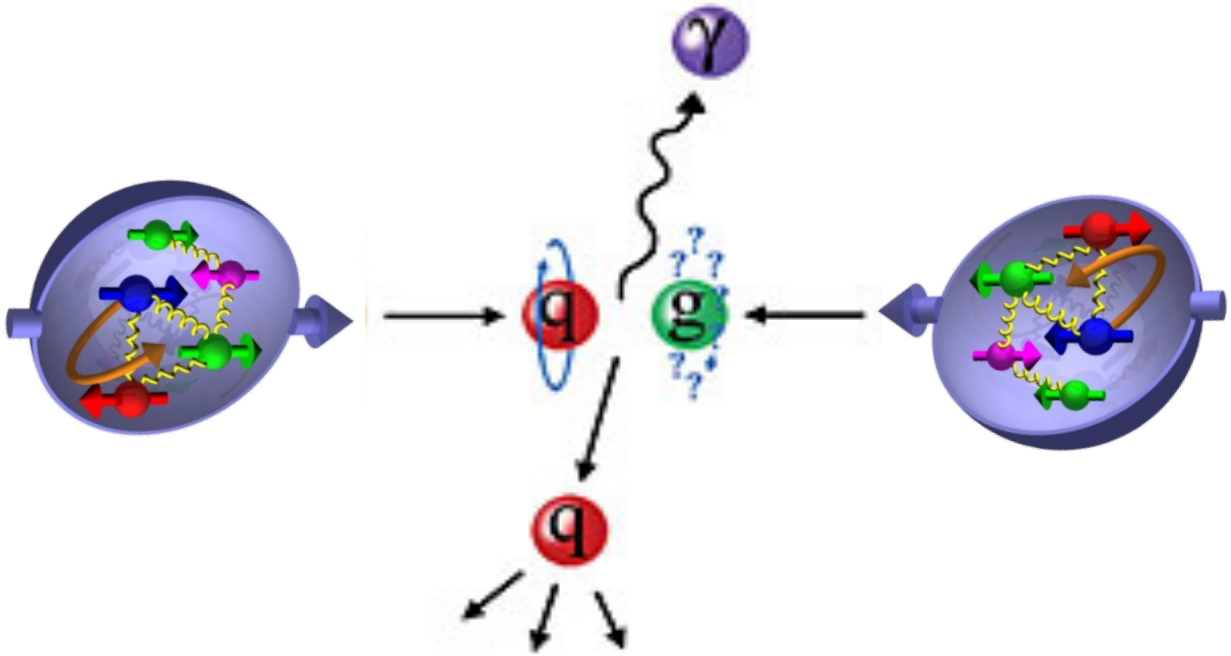
Physics with Longitudinally Polarized p+p Collisions

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

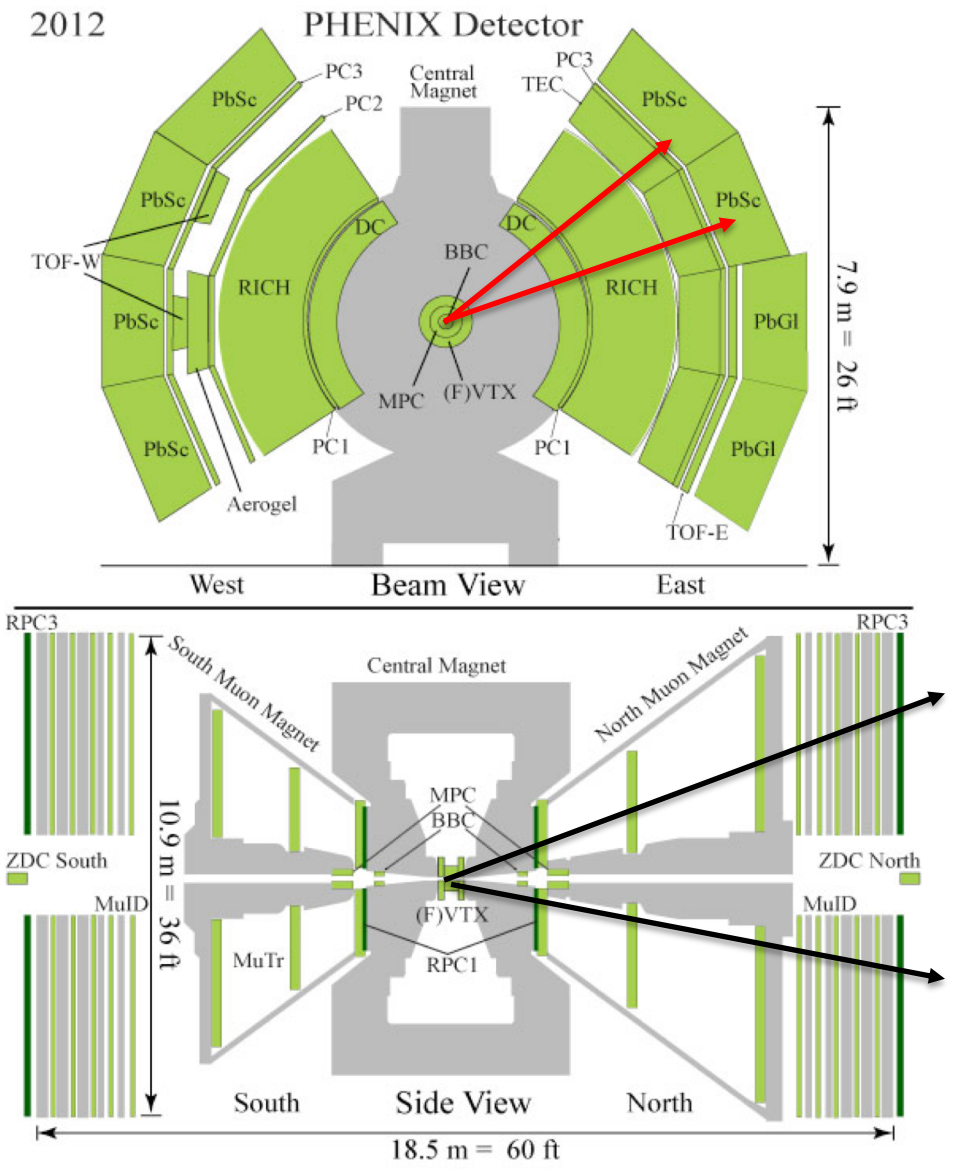


$A_L = (N^{+}-N^{-})/(N^{+}+N^{-})$





PHENIX Detector at RHIC



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

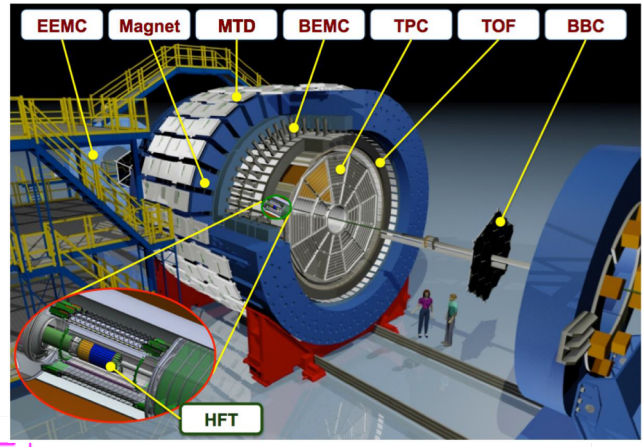
MPC $3.1 < |\eta| < 3.9$

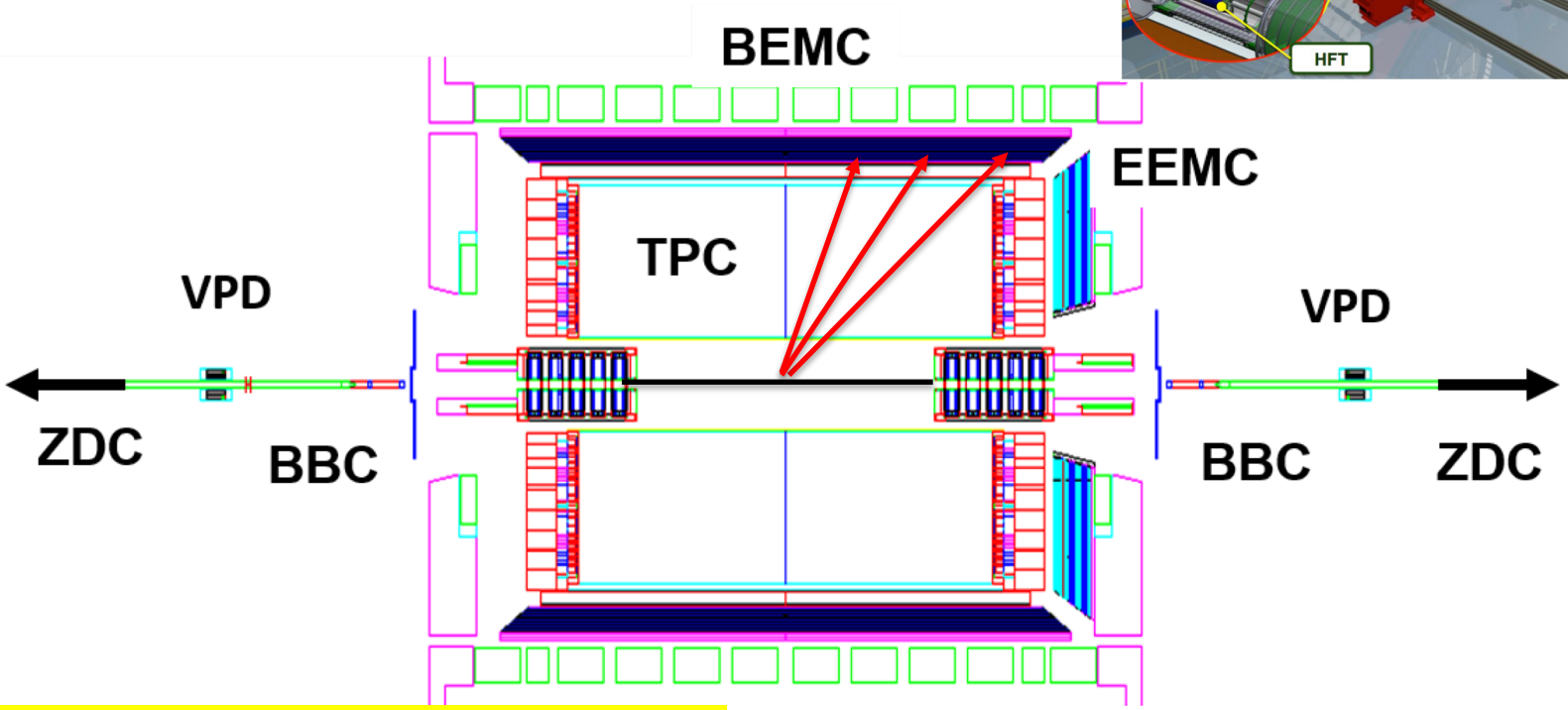
- Neutral Pion's
- Eta's

BBC **(Relative) luminosity**

ZDC

The STAR Experiment

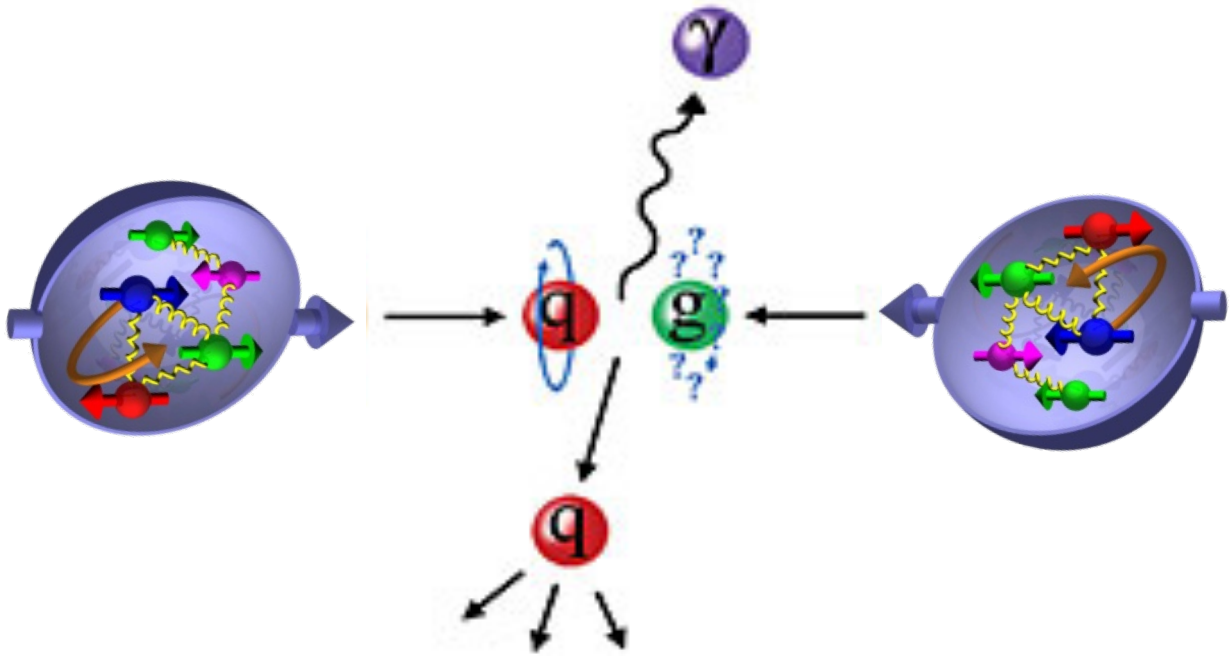




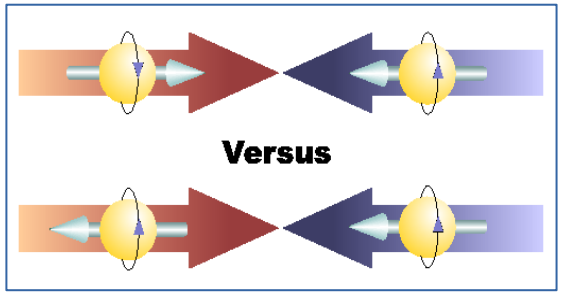
Large acceptance:
Tracking: TPC+TOF, : -1.3 < eta < 1.3
Central EMCal: -1 < eta < 2
Forward EMCal(FMS): 2.5 < eta < 4.2
BBC, ZDC

- **Jets**
- Pi0 and (identified)charged hadrons
- Electrons & Muons

Gluon Polarization

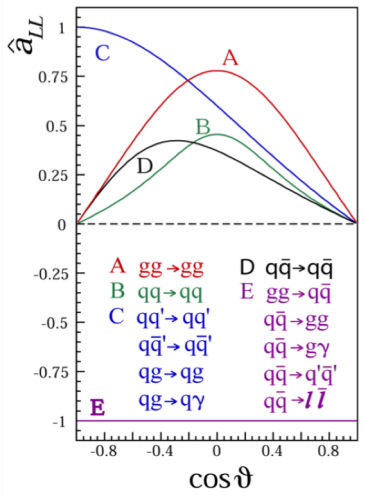


Gluon Polarization and π^0 (or jet)A_{LL}



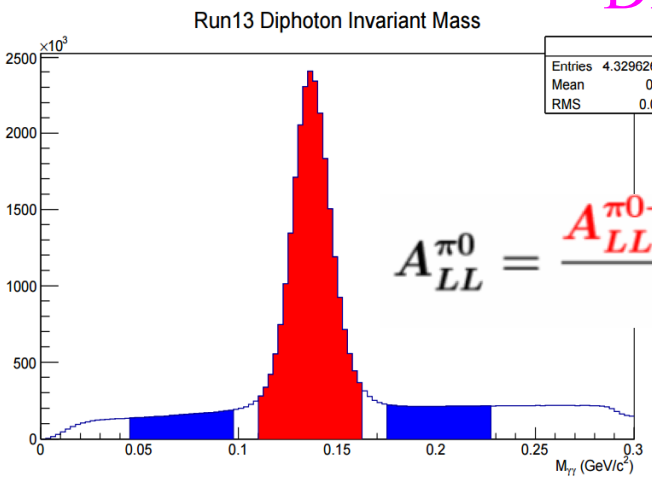
$A_{LL}=(N^{++}-N^{+-})/(N^{++}+N^{+-})$

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



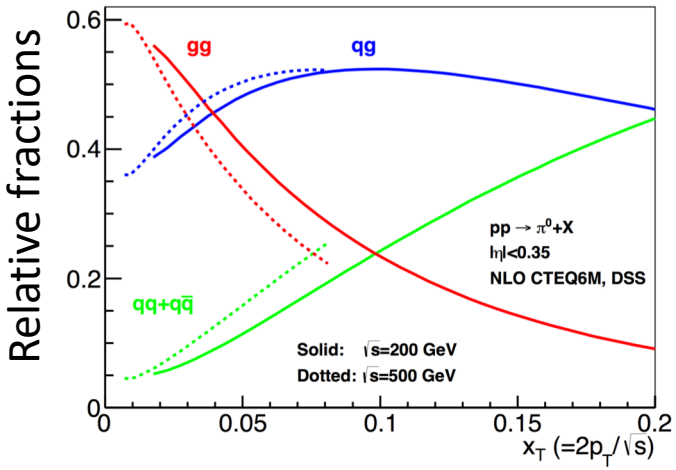
$$\Delta\sigma(pp\to\pi^0 X)\approx\Delta q(x_1)\otimes\Delta g(x_2)\otimes\Delta\hat{\sigma}^{qg\to qg}(\hat{s})\otimes D_q^{\pi^0}(z)\ldots$$

DIS ? pQCD e+e-



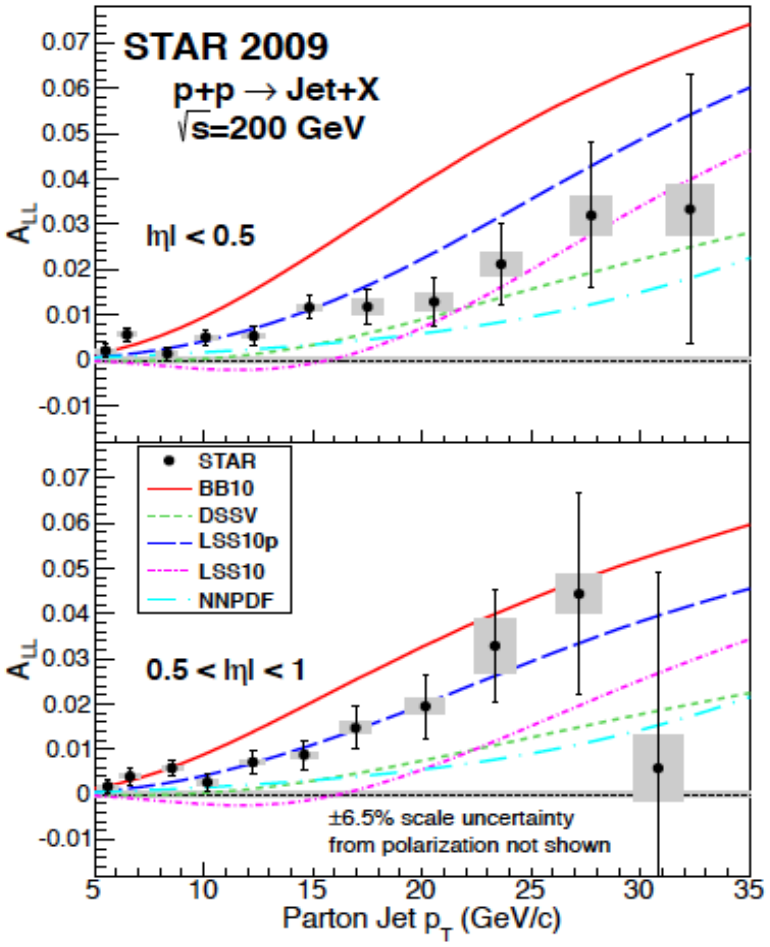
$$A_{LL}^{\pi 0}=\frac{A_{LL}^{\pi 0+BG}-w_{BG}A_{LL}^{BG}}{1-w_{BG}}$$

Di-photon mass: π^0 peak

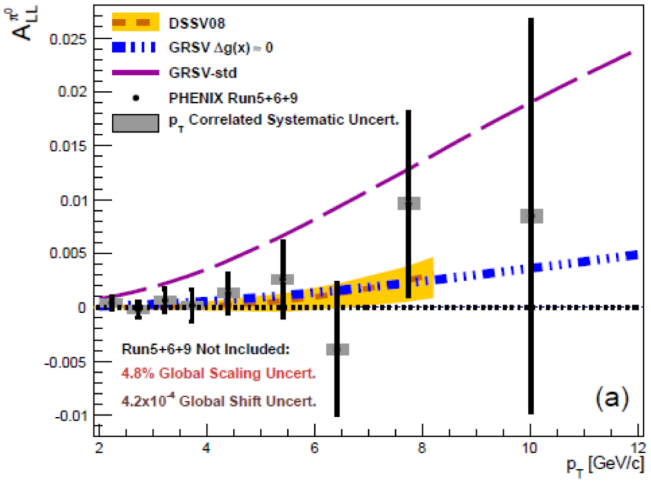


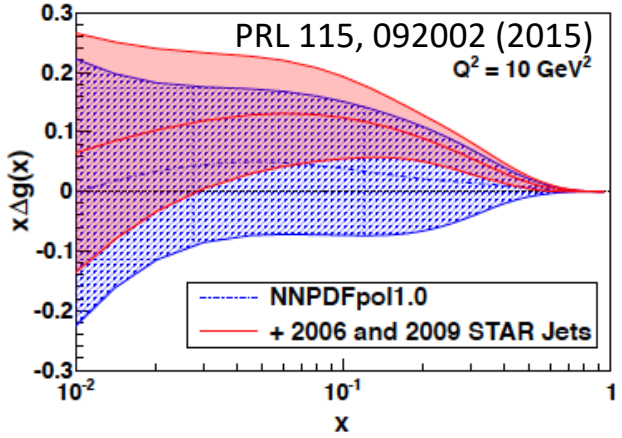
First Precision Measurements of Longitudinal Double-Spin Asymmetry A_{LL} from 2009 RHIC Run

STAR: PRL 115, 092002 (2015)



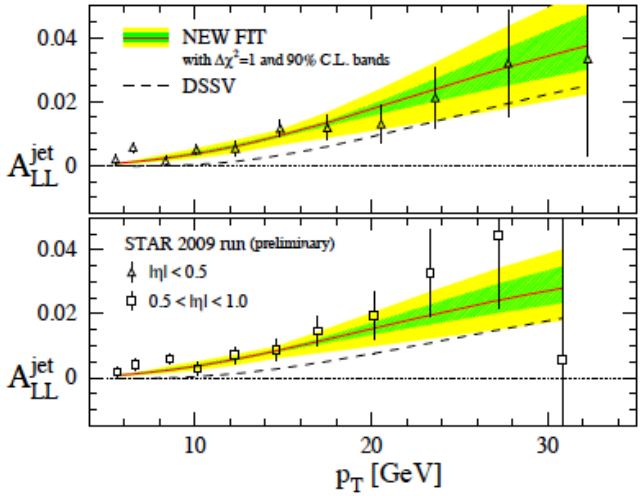
PHENIX: PRD 90, 012007 (2014)

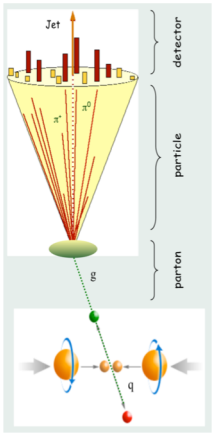


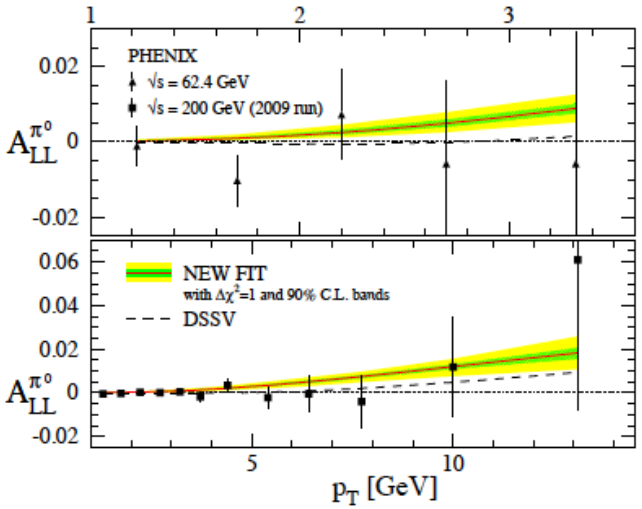


First Hint of Non-zero Gluon Polarization from RHIC

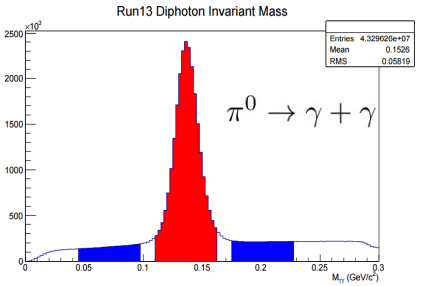
- PHENIX and STAR A_{LL} data







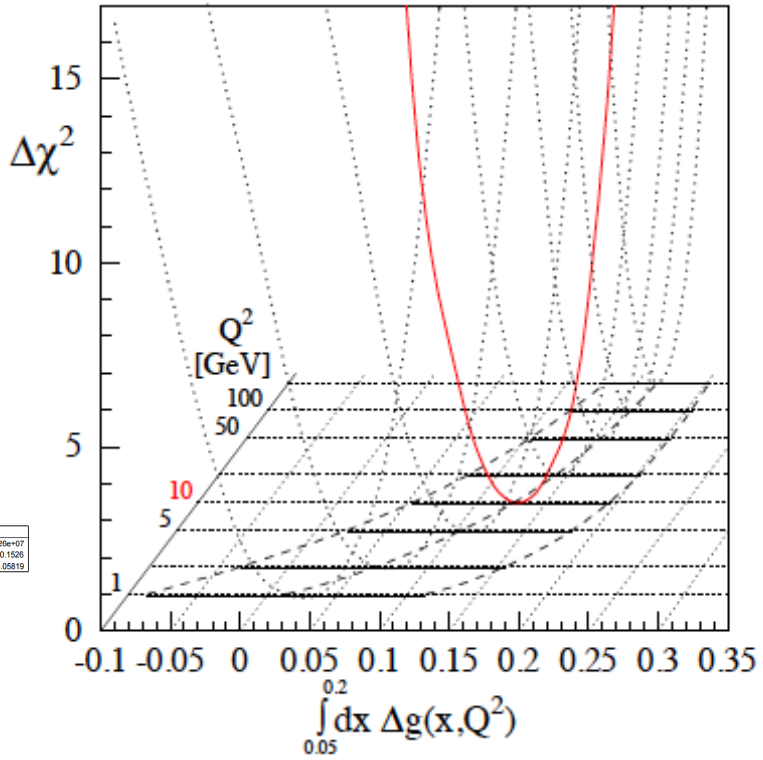
Run 2009
p+p@200GeV



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

@ Q^2 = 10 GeV^2

PRL 113, 012001 (2014), DSSV



More Recent Results from RHIC

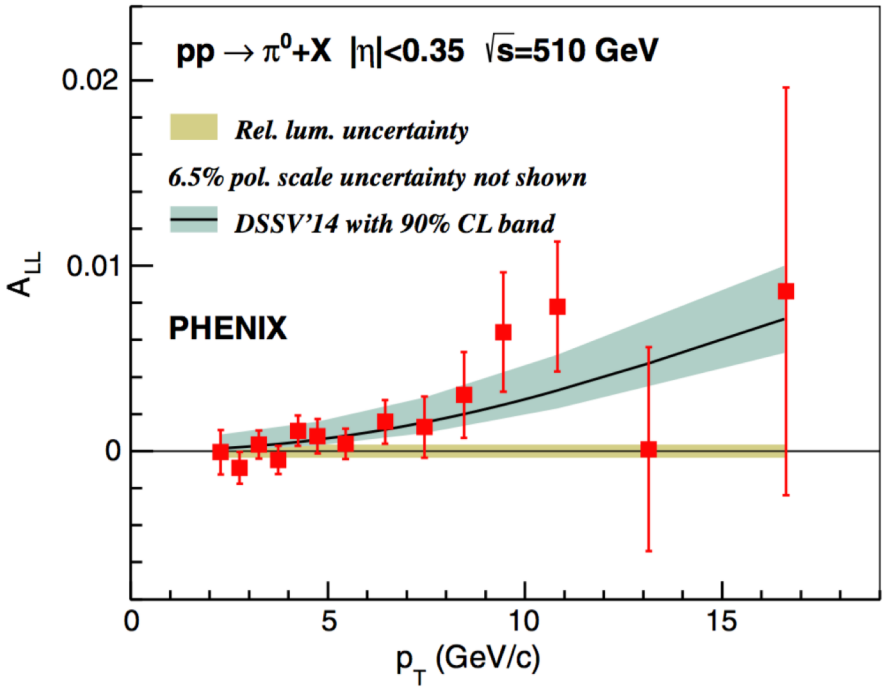
"RHIC Cold QCD Plan for 2017-2023", arXiv:1602.03922

Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> 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

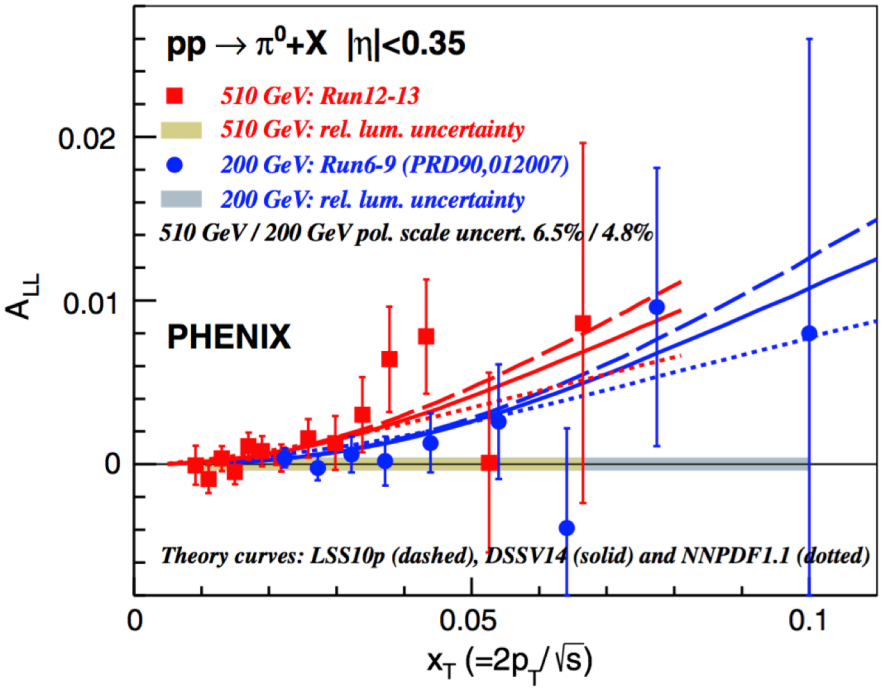
PHENIX: π^0 A_{LL} at central rapidity ($|\eta|$<0.35)

- Access gluon at moderate x ~ 0.01 - 0.2

PRD 93, 011501 (2016)



ALL vs xT for pp 200GeV and 510GeV



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

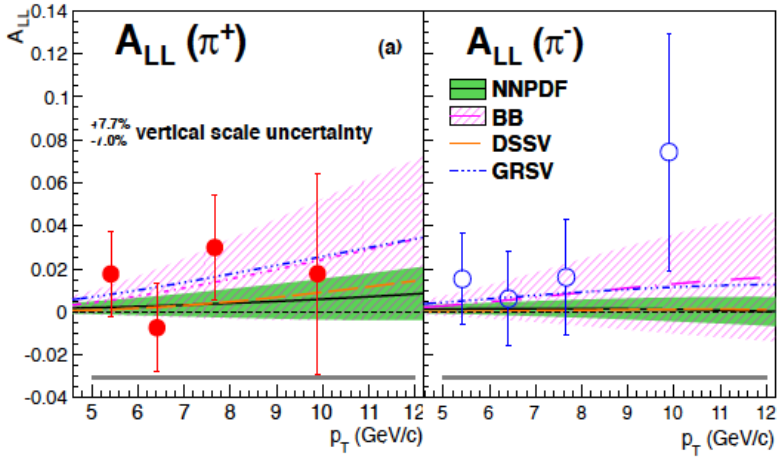
- Sensitive to polarized u and d quark as well as gluon distributions through charge sign
  - Statistically limited due to lack of effective triggers

$$u + g \rightarrow h^{+} + X$$
$$d + g \rightarrow h^{-} + X$$

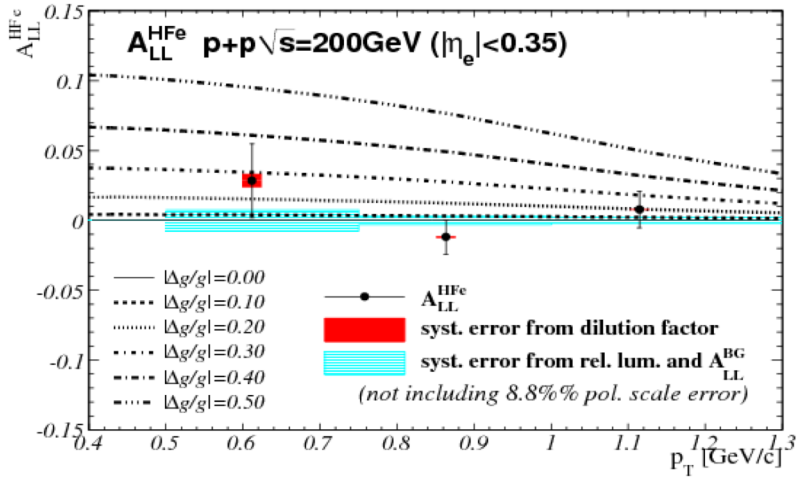
- Use HF decay electrons to probe gluon polarization
  - Statistically limited

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{a}^{gg\rightarrow D\rightarrow e} \frac{\Delta g(x1)}{g(x1)} \frac{\Delta g(x2)}{g(x2)}$$

PRD 91, 032001 (2015)



PRD 87, 012011 (2013)



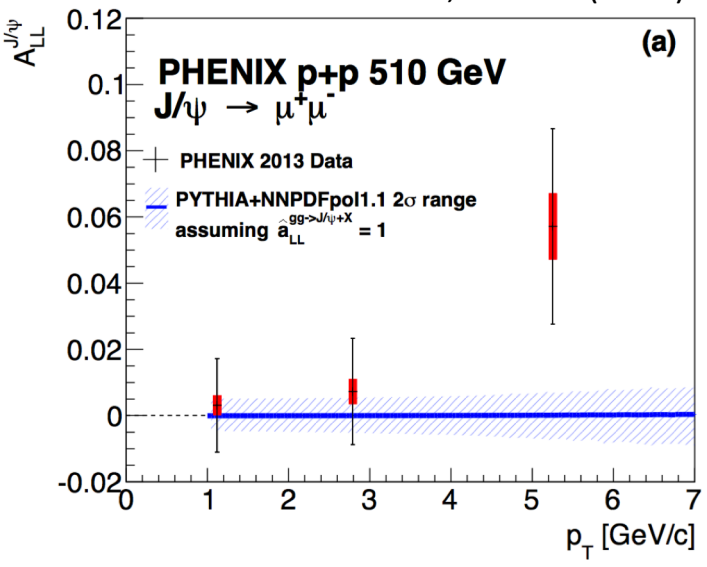
PHENIX: J/ψ A_{LL} at Forward Rapidity

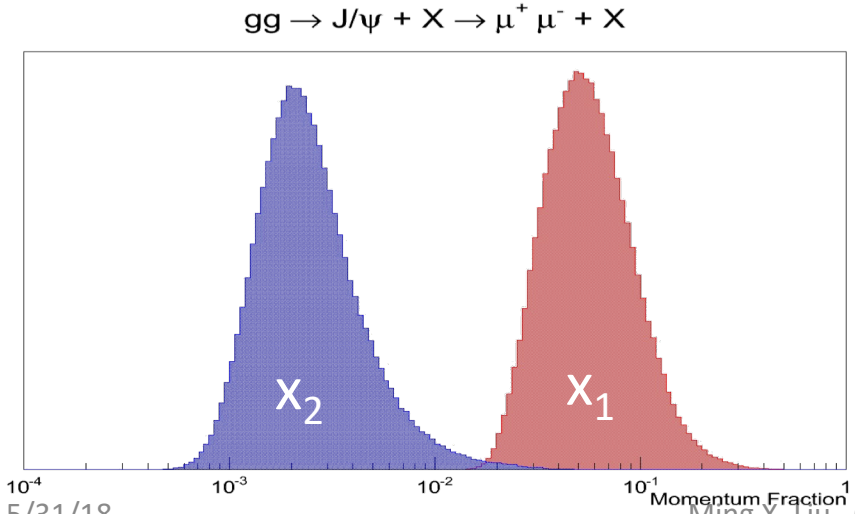
- Access gluons in small-x region, x_2<0.01
- At RHIC energies J/ψ production is dominated by gluon-gluon fusion.
  - Statistically limited

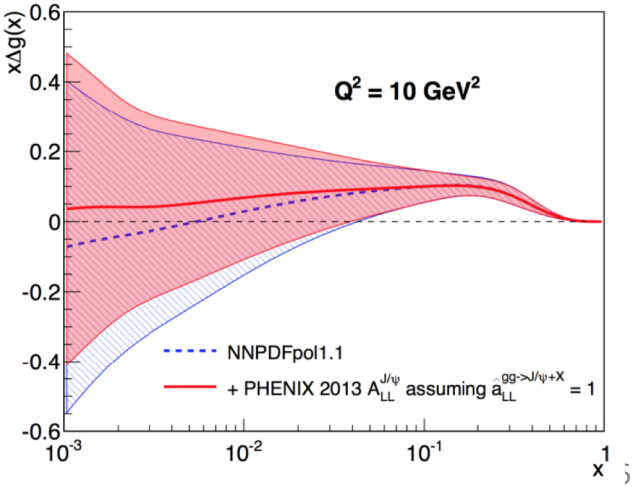
A_{LL} for J/ψ at LO:

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{a}^{gg\to J/\psi}\frac{\Delta g(x1)}{g(x1)}\frac{\Delta g(x2)}{g(x2)}$$

PRD 94, 112008 (2016)

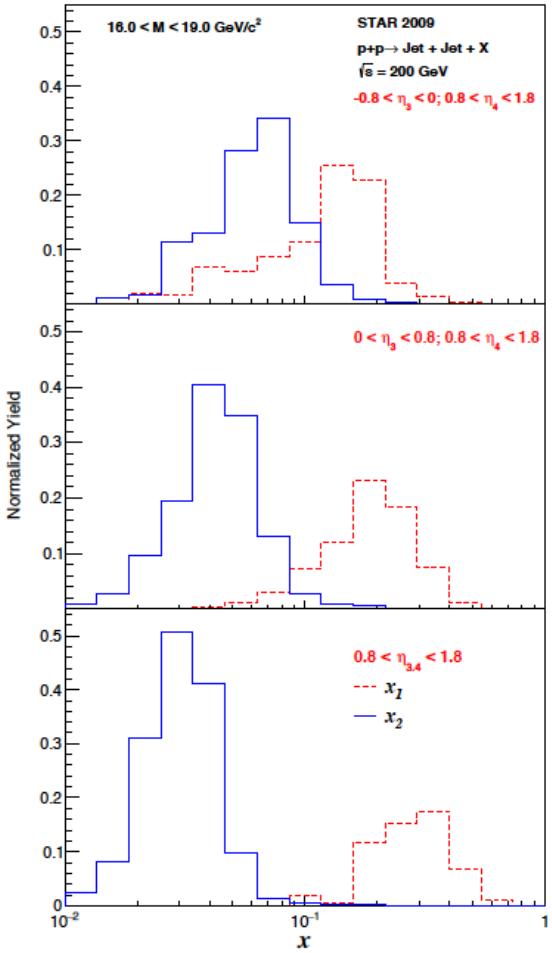


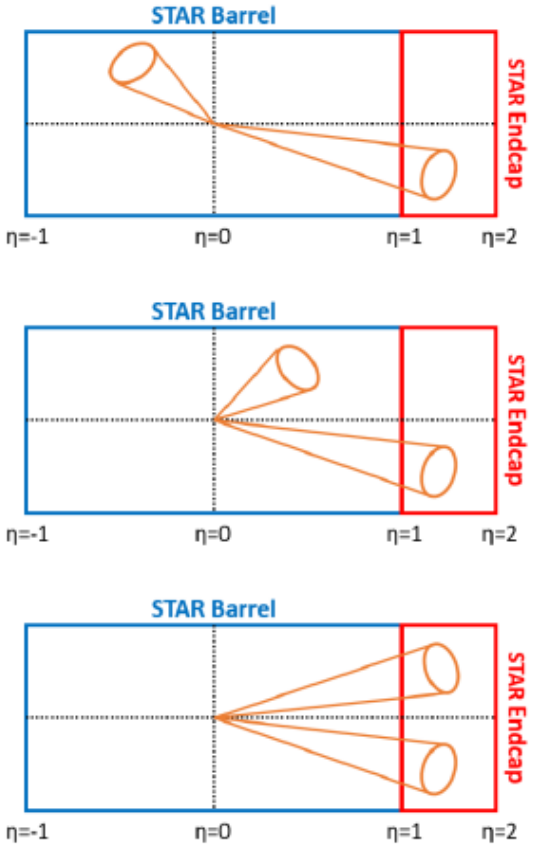


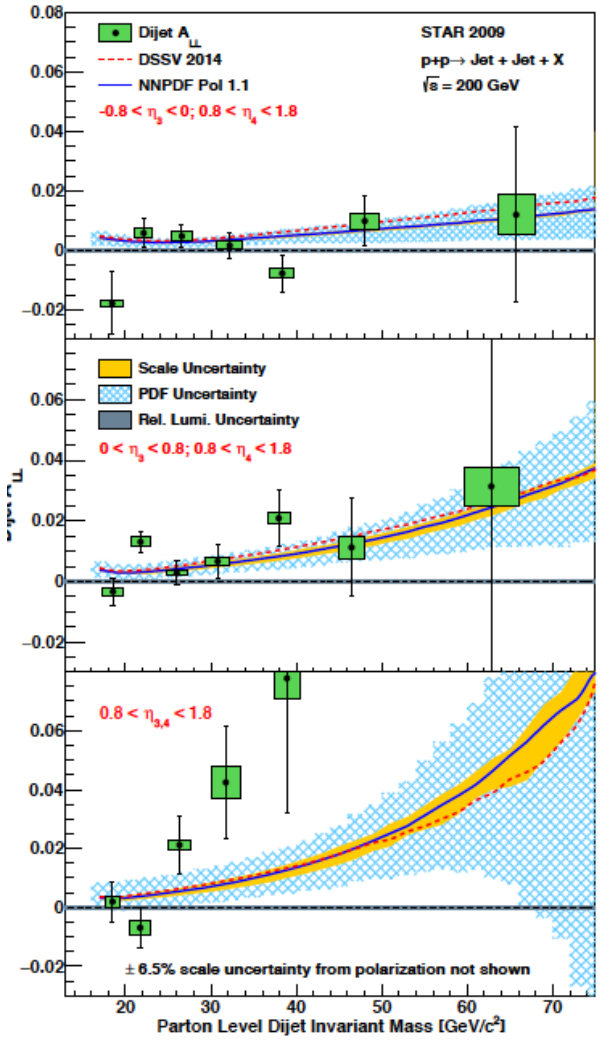


STAR: Di-Jet A_{LL}, pp 200GeV

arXiv:1805.09742





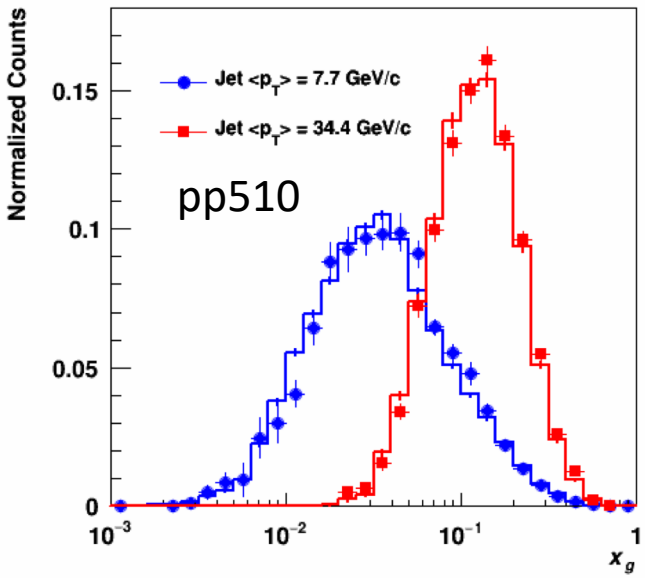


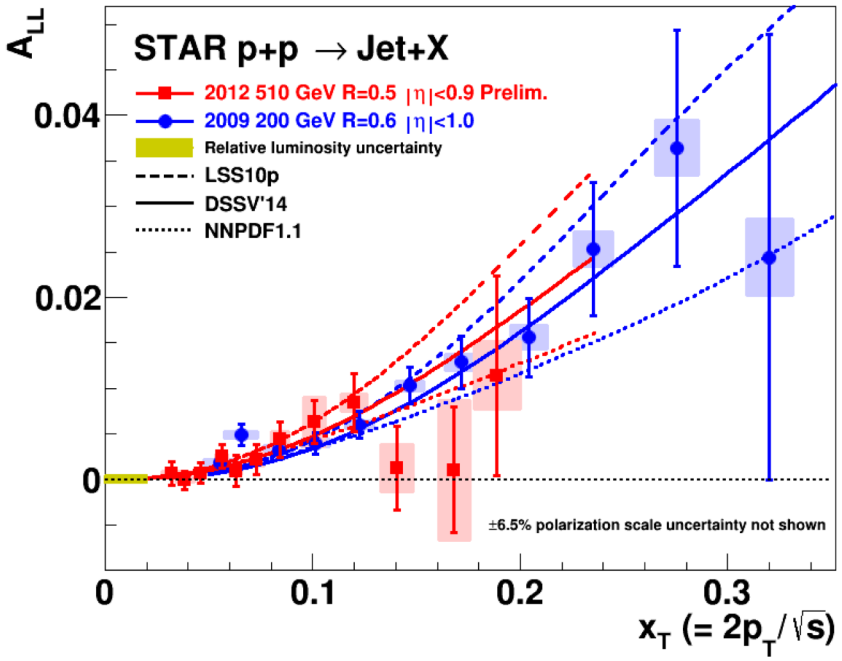
Probed parton x1 and x2 distributions

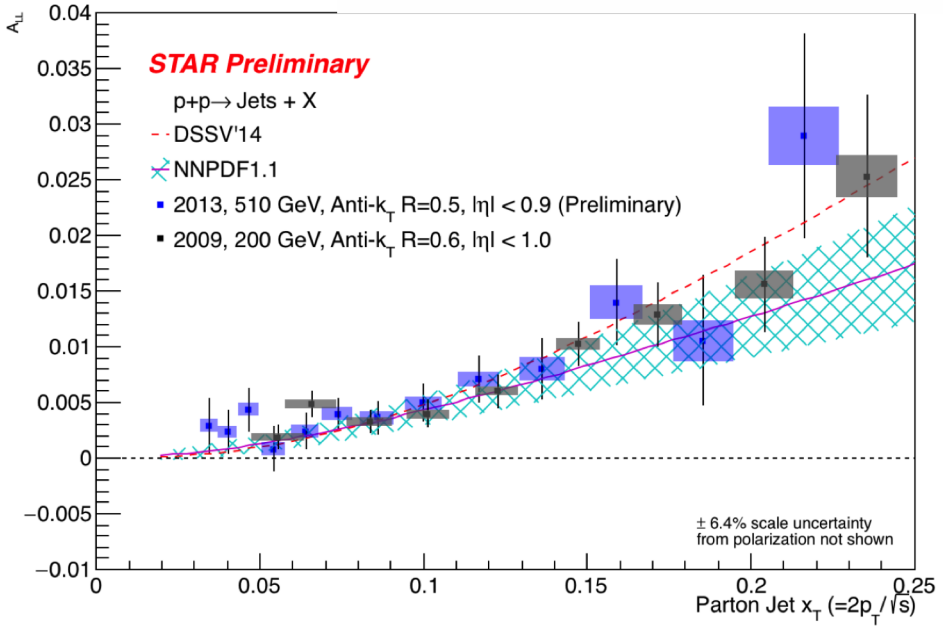
di-jet mass

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

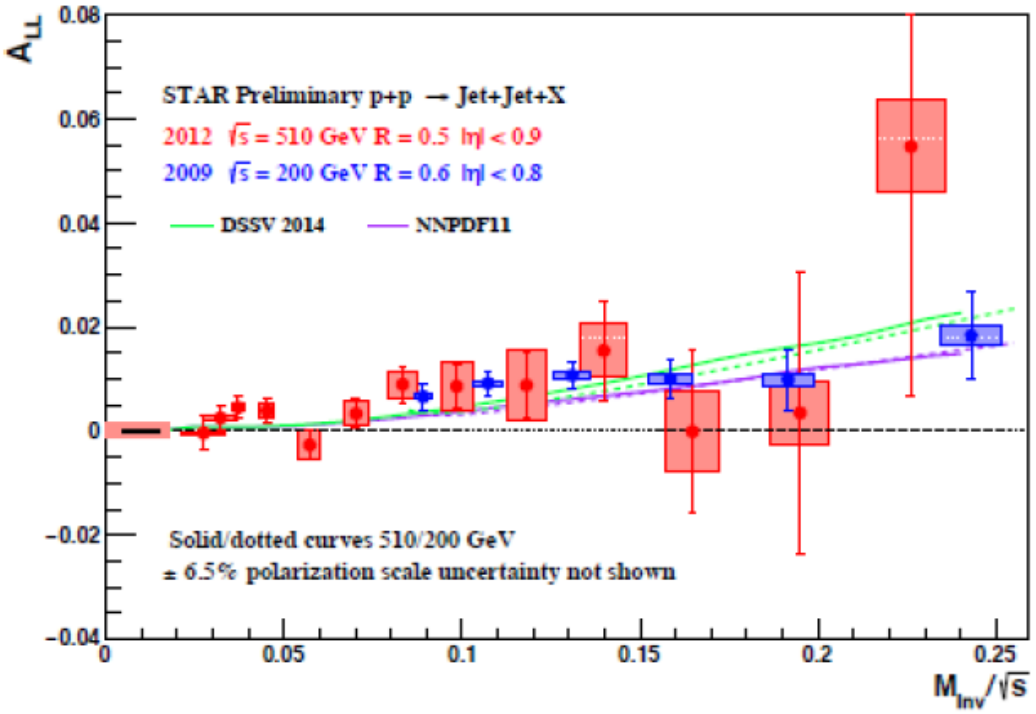




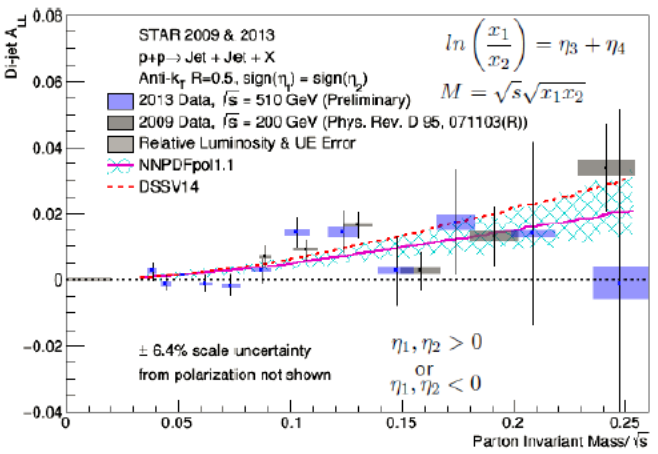


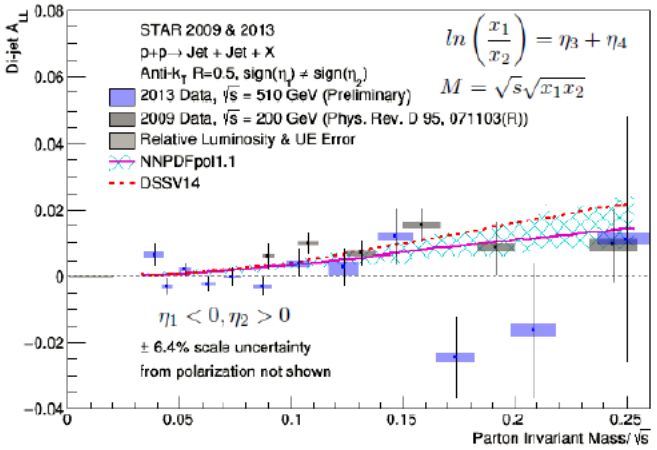
STAR: pp510 Di-jet A_{LL}

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



Run13 pp510 di-jet A_{LL}

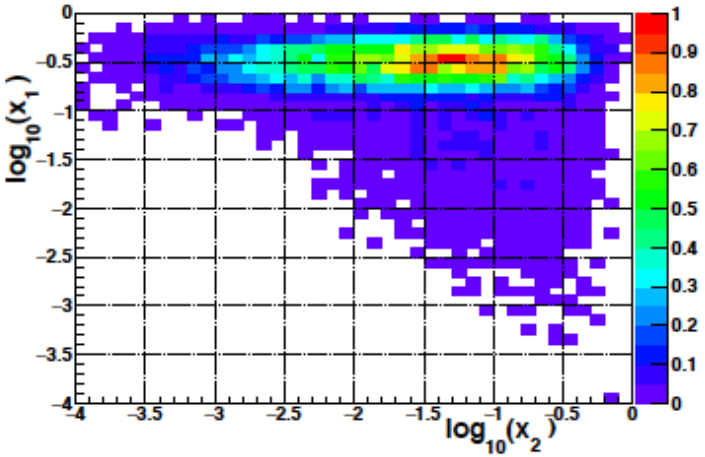


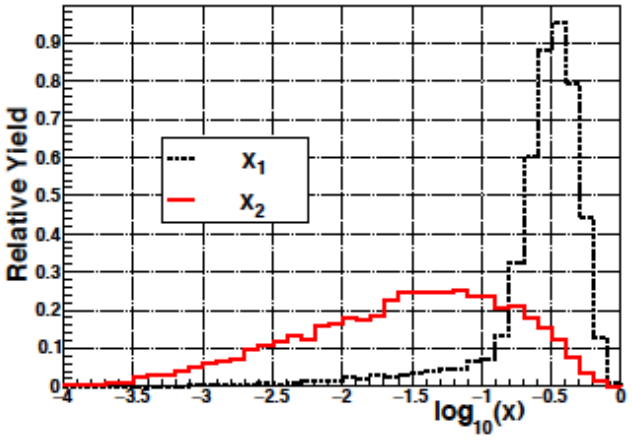


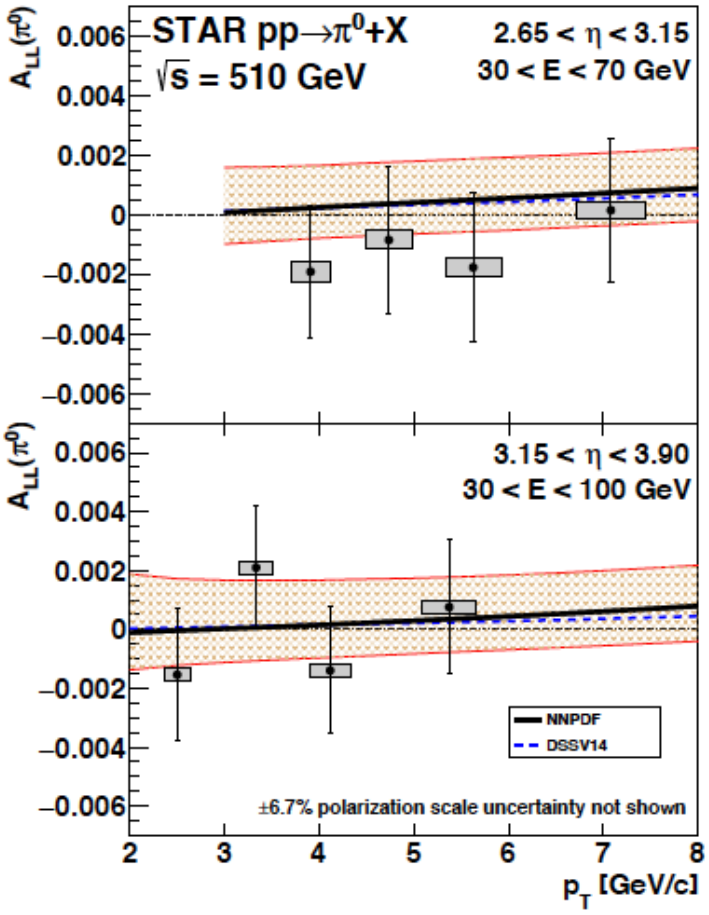
STAR: Forward pi0 ALL in pp 510GeV

access small-x gluons

arXiv:1805.09745



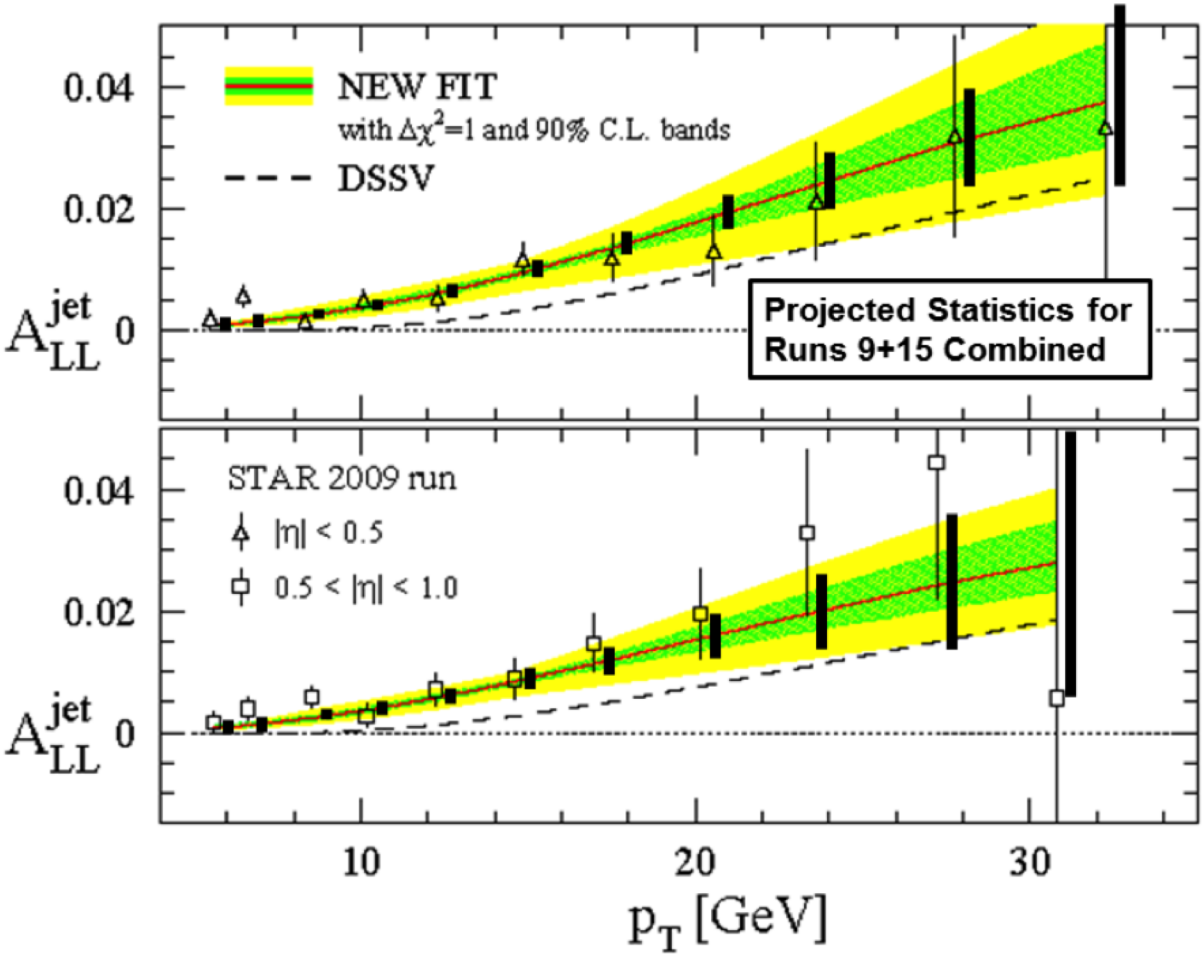




In Progress: 200 GeV Inclusive Jet A_{LL}

Projected combined Jet A_LL from STAR: run2009 + 2015

- Expect 2x improvement over 2009 results



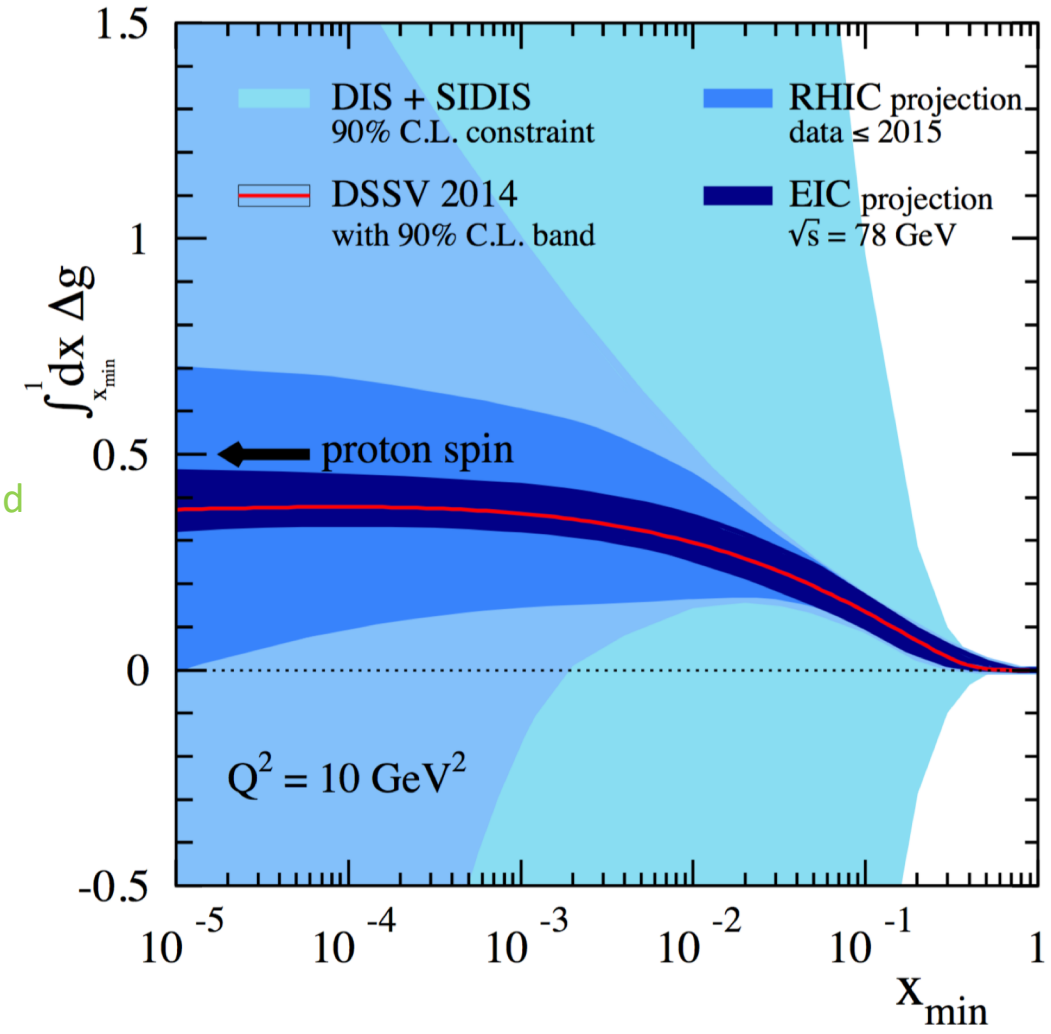
Projected Impact of RHIC data on Gluon Polarization

- Favors positive gluon polarization
  - PHENIX/STAR data:
    - 62GeV π^0 A_{LL}
    - 200GeV π^0 A_{LL}
    - 510GeV π^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/ψ A_{LL}

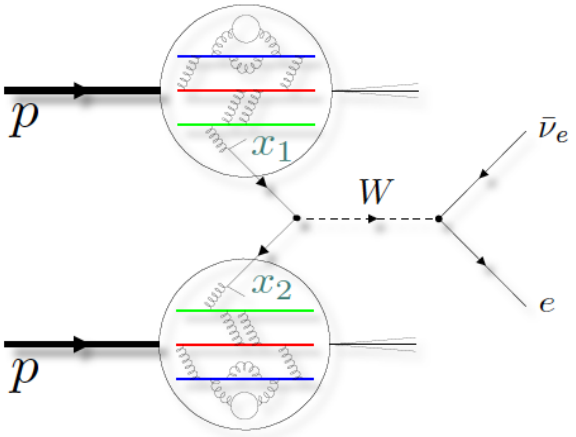
- EIC future, 2025+

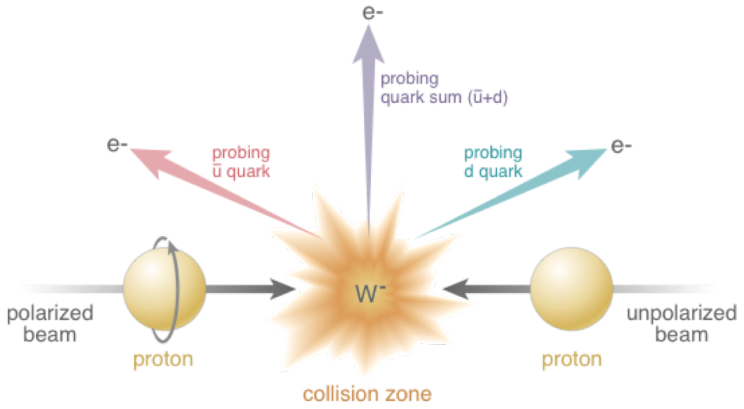
"RHIC Cold QCD Plan for 2017-2023", arXiv:1602.03922



Electroweak Probe for Sea Quarks at High Energy at RHIC

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





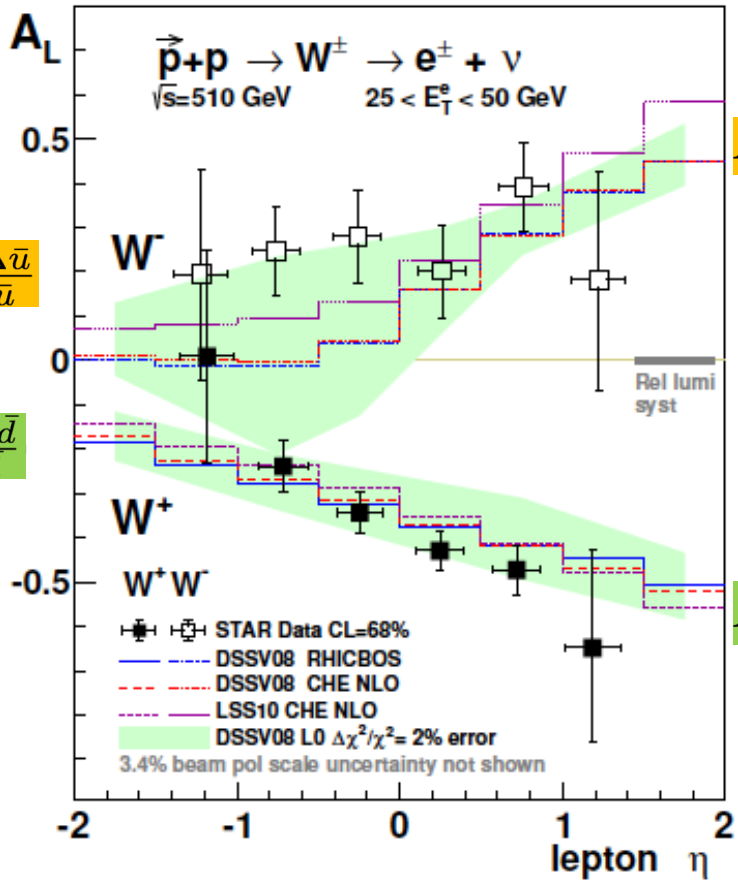
$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2}{u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \bar{d}(x_1)u(x_2)(1+\cos\theta)^2}$$

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

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)

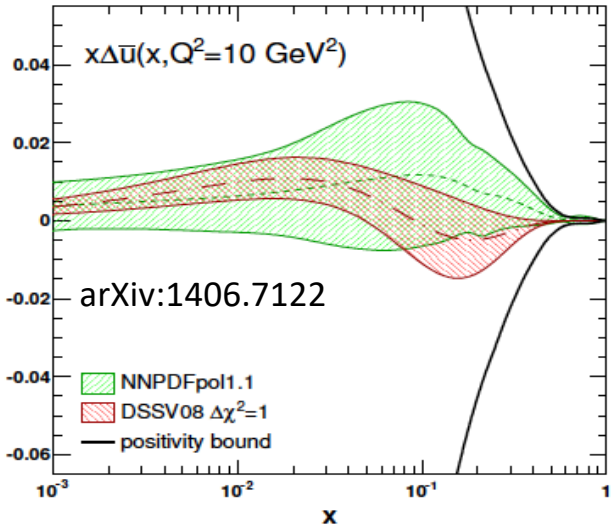


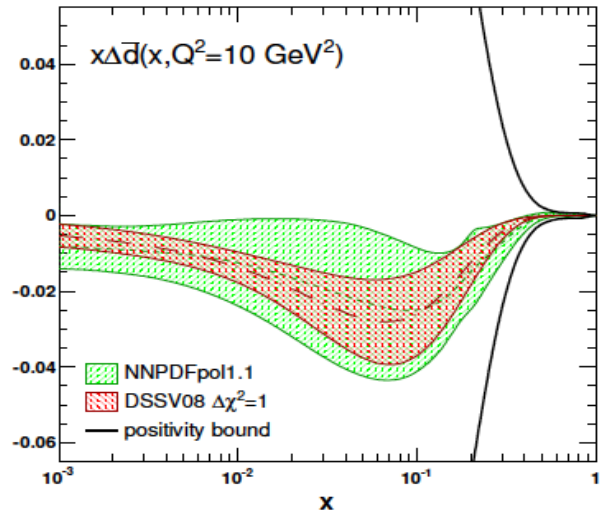
$A_L^{W^-} \sim \frac{\Delta\bar{u}}{\bar{u}}$

$A_L^{W^+} \sim \frac{\Delta\bar{d}}{\bar{d}}$

$A_L^{W^-} \sim -\frac{\Delta d}{d}$

$A_L^{W^+} \sim -\frac{\Delta u}{u}$

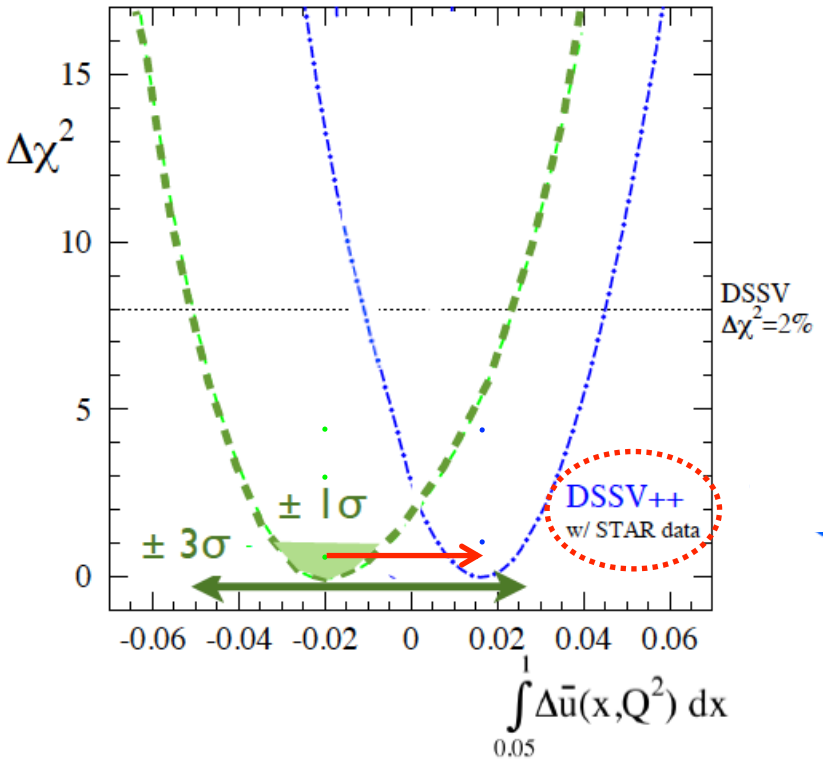


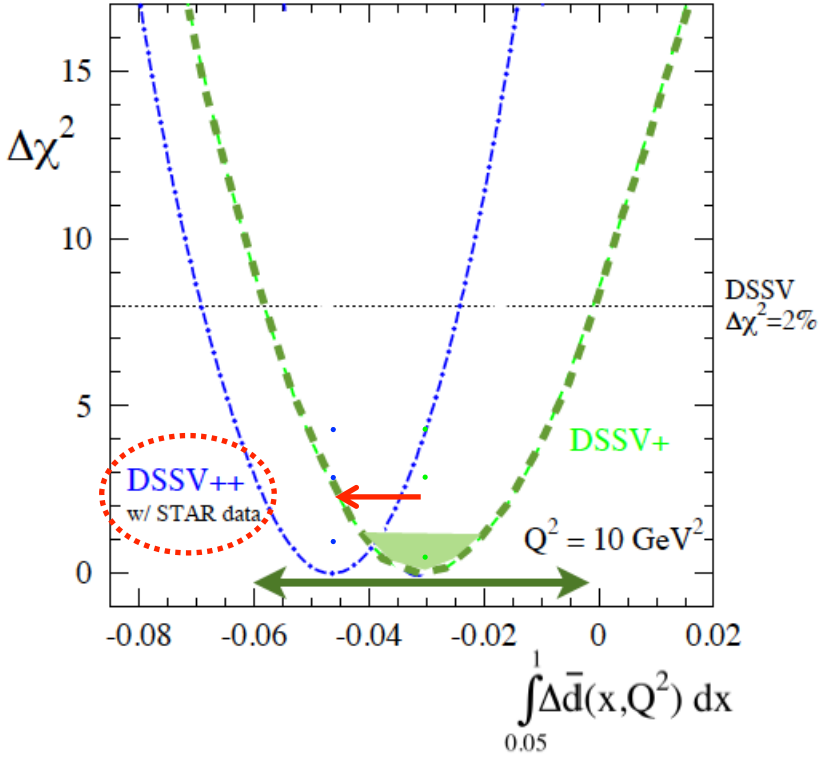


Sea Quark Polarization Global Fit (DSSV)

First significant constraint on sea-quark polarization

Overall contribution to the proton spin is small [x=0.05-1]

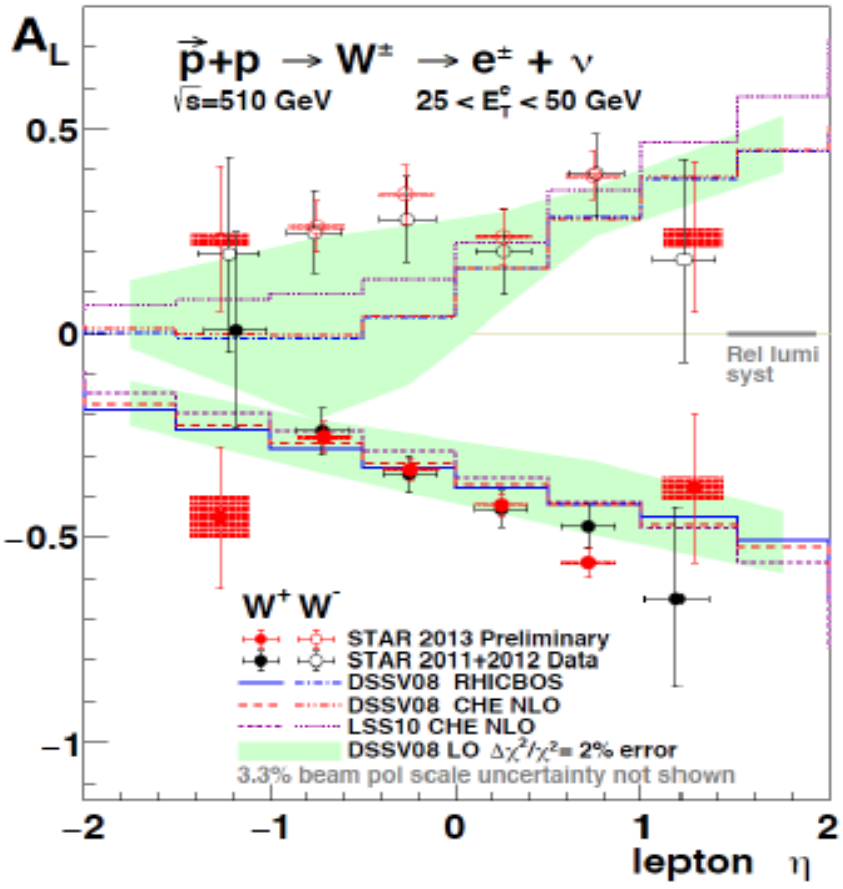




Latest $W^{+/-}$ A_L from STAR and PHENIX

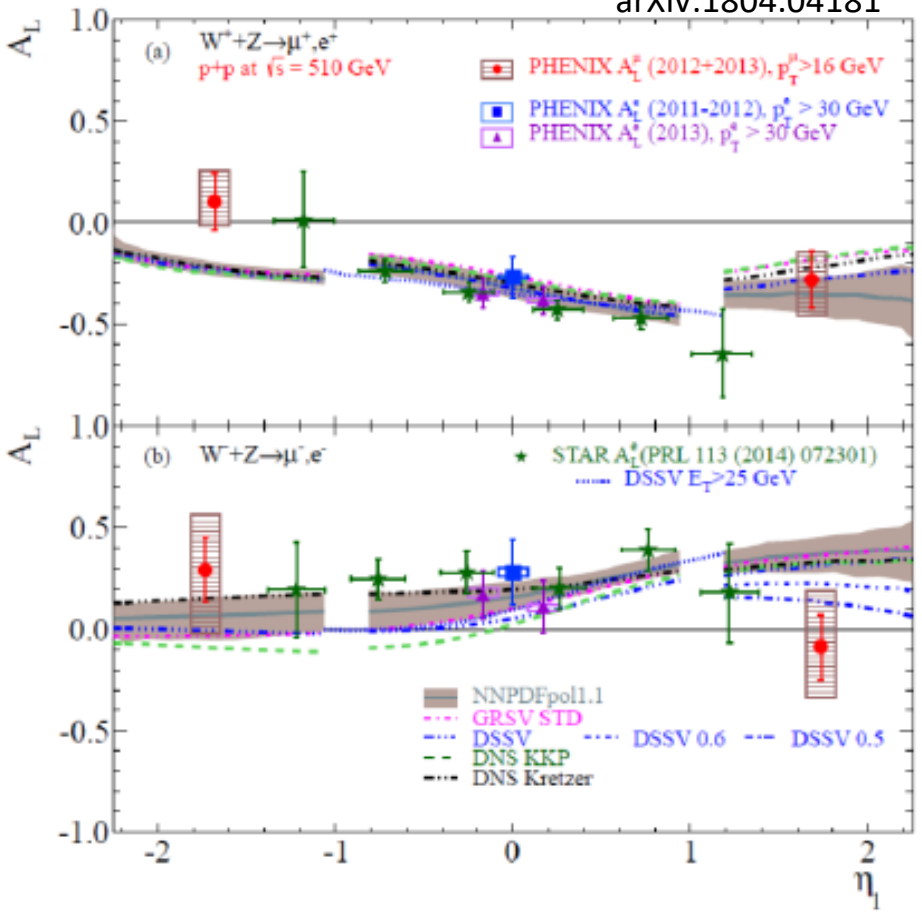
$p + p \rightarrow W^{\pm} \rightarrow e^{\pm}$

arXiv:1702.05077



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

arXiv:1804.04181

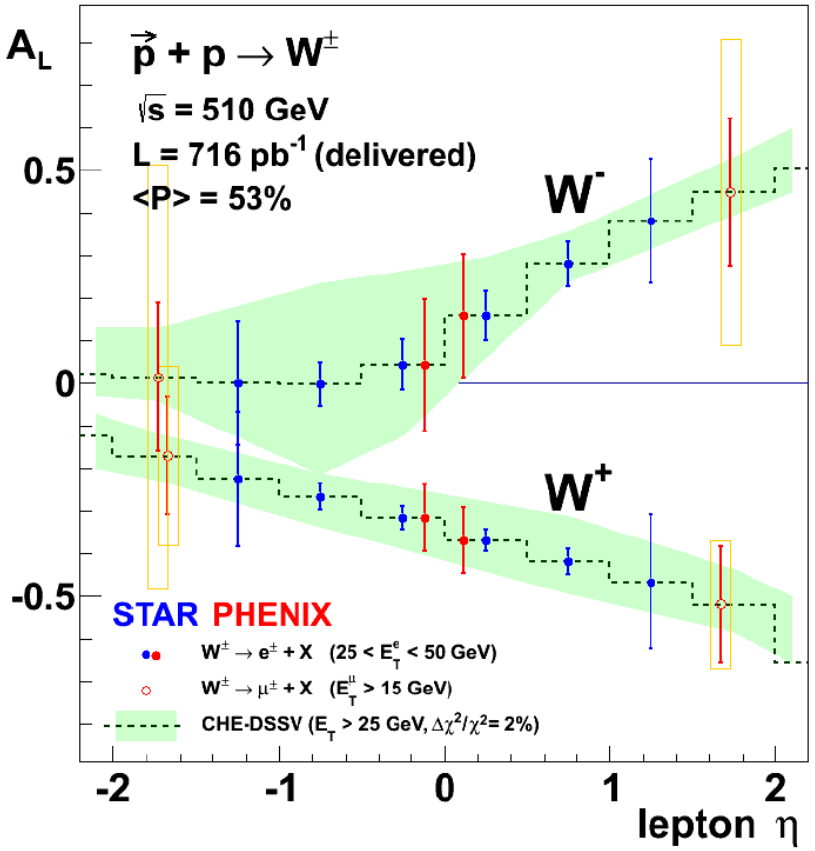


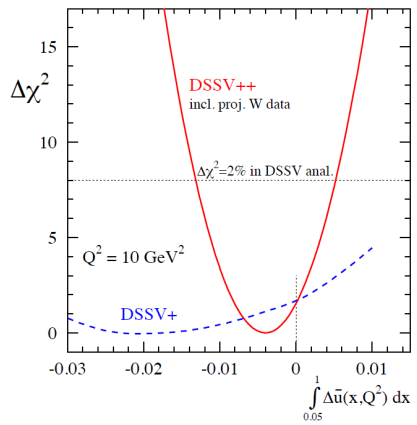
Most precise A_L from STAR 2013, will further constraint sea-quark polarization

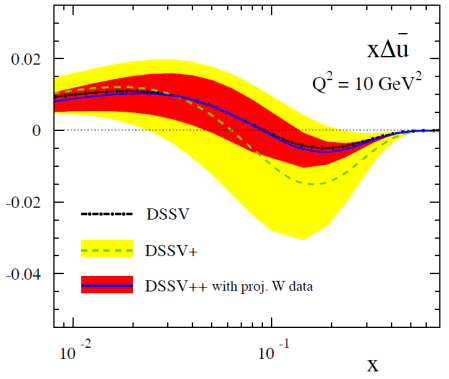
Projected RHIC $W^{\pm} \rightarrow l^{\pm}$ data Impact on Sea Quark Polarization Determination

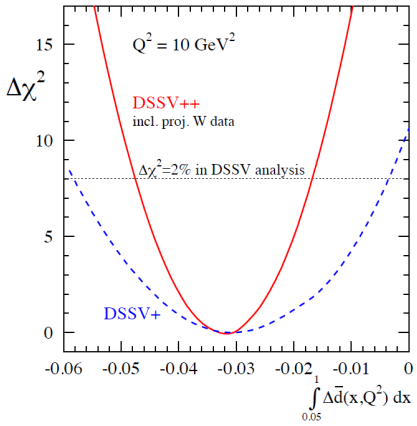
- Expect significant improvement of flavor identified sea quark distributions

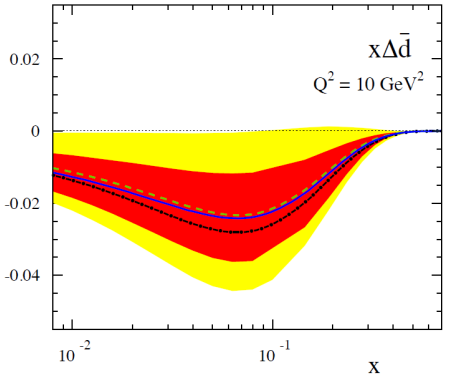
The RHIC Spin Program, arXiv: 1501.01220









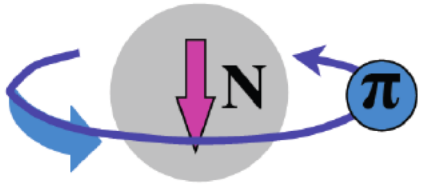


Unpolarized Sea Quark Distributions

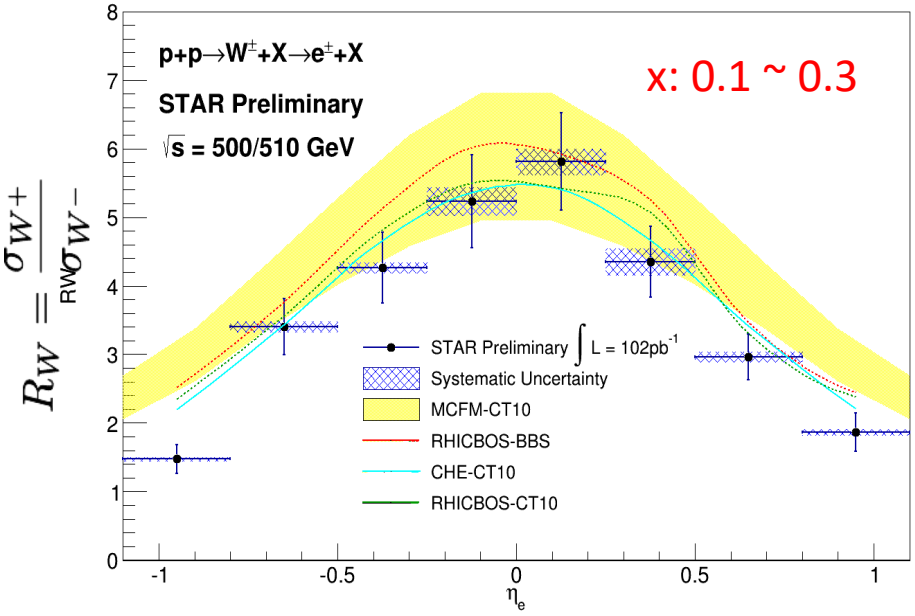
$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} =$$

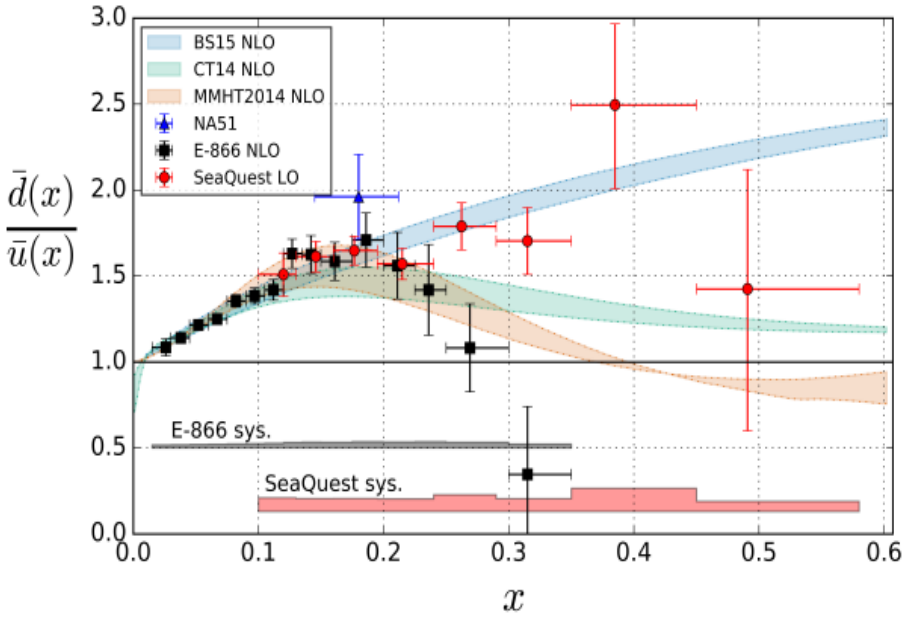
$$\frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

Sea quark flavor asymmetry and pion cloud model



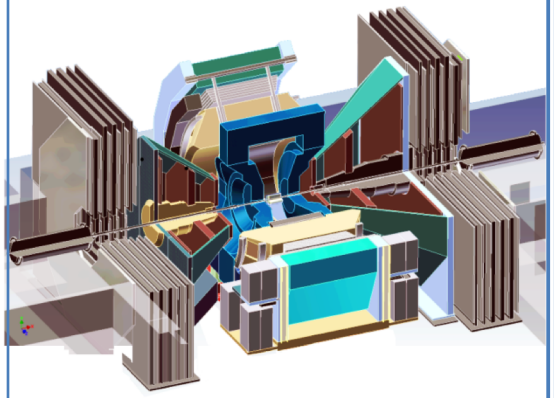
SeaQuest/E906 @Fermilab

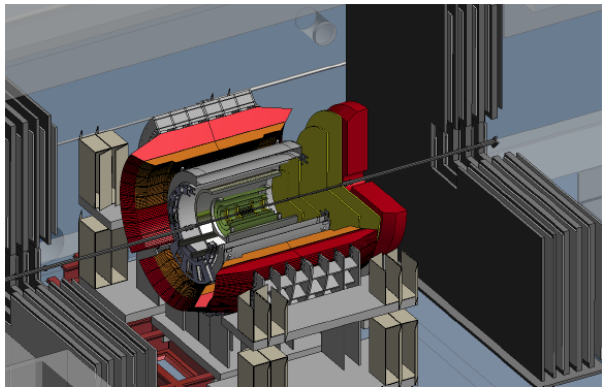


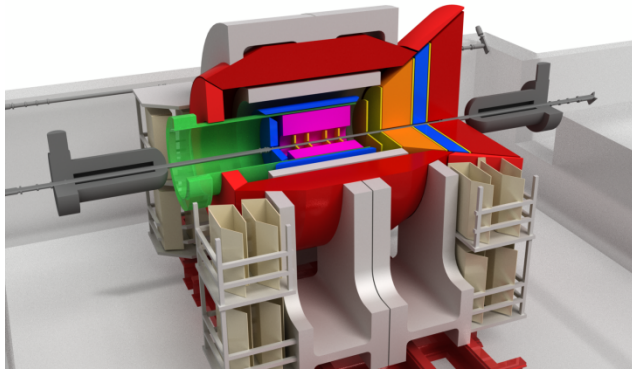


Future: PHENIX -> sPHENIX -> EIC@RHIC

Current PHENIX	*f*/sPHENIX	An EIC detector
• PHENIX completed 2016 • 16y+ work 100+M$ investment • 130+ published papers to date	▸ Comprehensive central upgrade based on BaBar magnet ▸ fsPHENIX: forward tracking, HCal and muon ID ▸ Key study of transverse spin ▸ New collaboration/new ideas	▸ Path of sPHENIX upgrade leads to a capable EIC detector ▸ Large coverage of tracking, calorimetry and PID ▸ New collaboration/new ideas





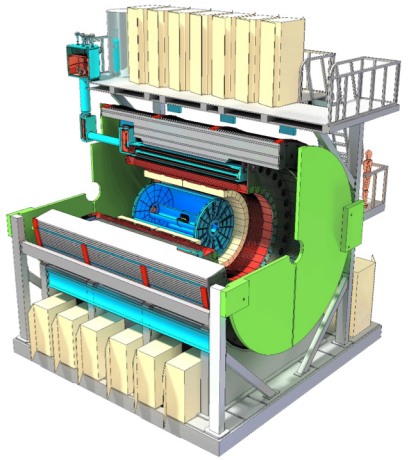


~2000 2017→2020 ~2025 Time

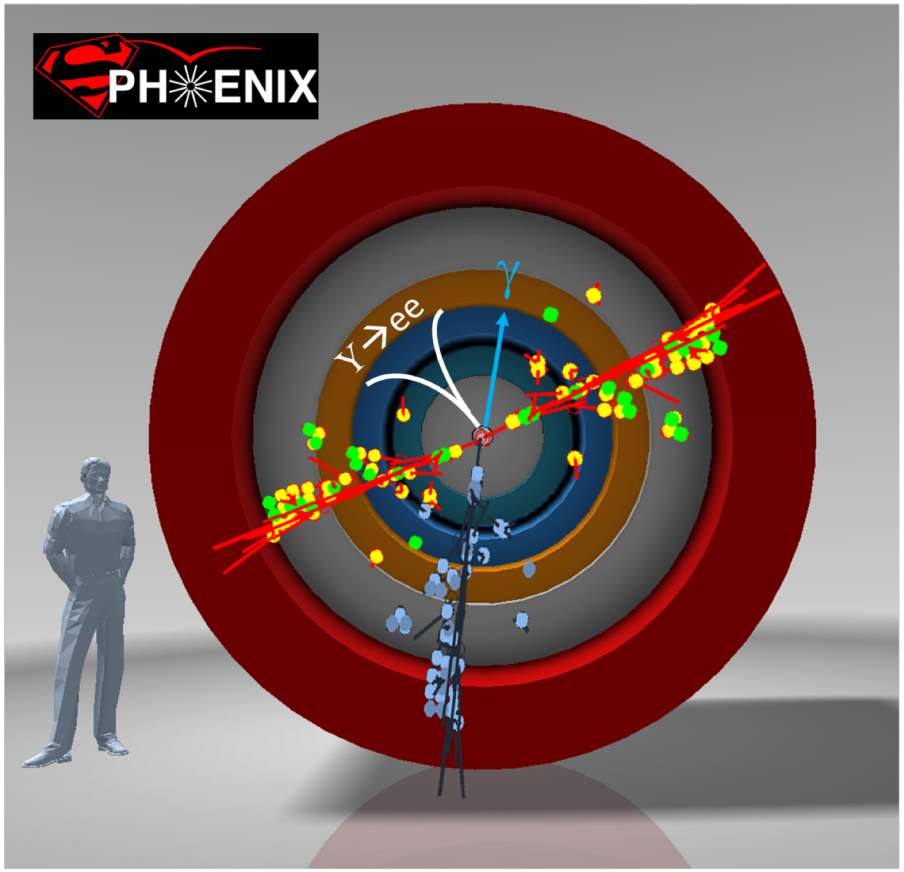
RHIC: A+A, polarized p+p, polarized p+A

eRHIC: e+p, e+A

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, 2pi coverage
      - EMCal & HCal
      - MVTX/INTT/TPC
    - Forward upgrade being developed
    - DAQ rate: 15kHz

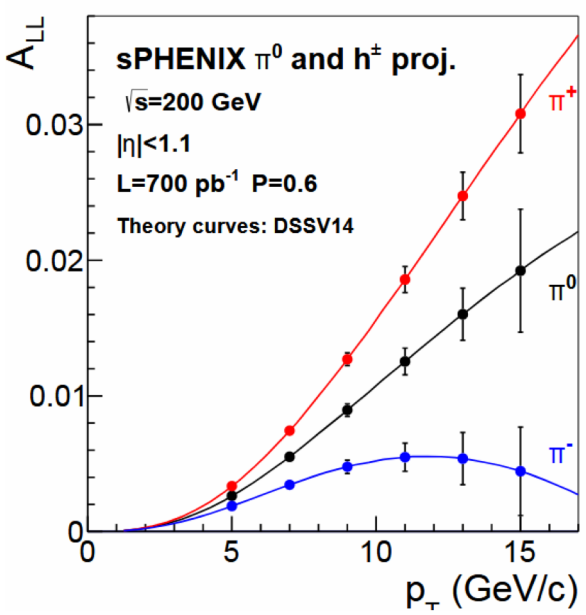


- Project Status
  - Granted DOE CD-0, 10/2016
  - CD-1 reviewed, 5/2018
  - Construction: 2018-2022
  - Day-1 physics, ~1/2023

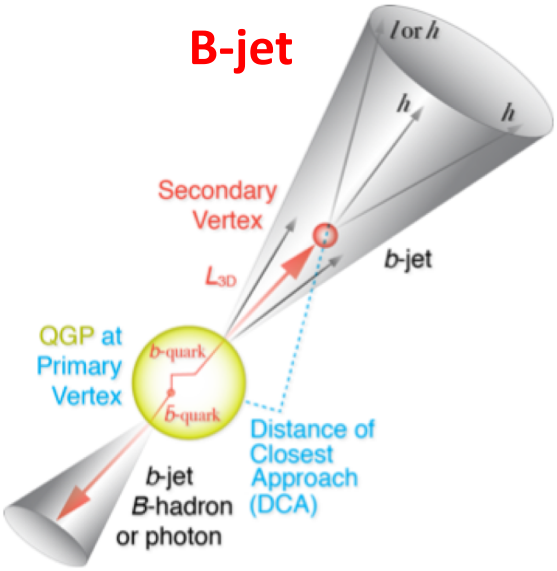
RHIC Multi-Year Plan: sPHENIX 2023-2027+

(Cold QCD plan under development now)

- Jets, hadrons and heavy flavor and more



RHIC 2015 pp200
Recorded lumi ~50pb^{-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

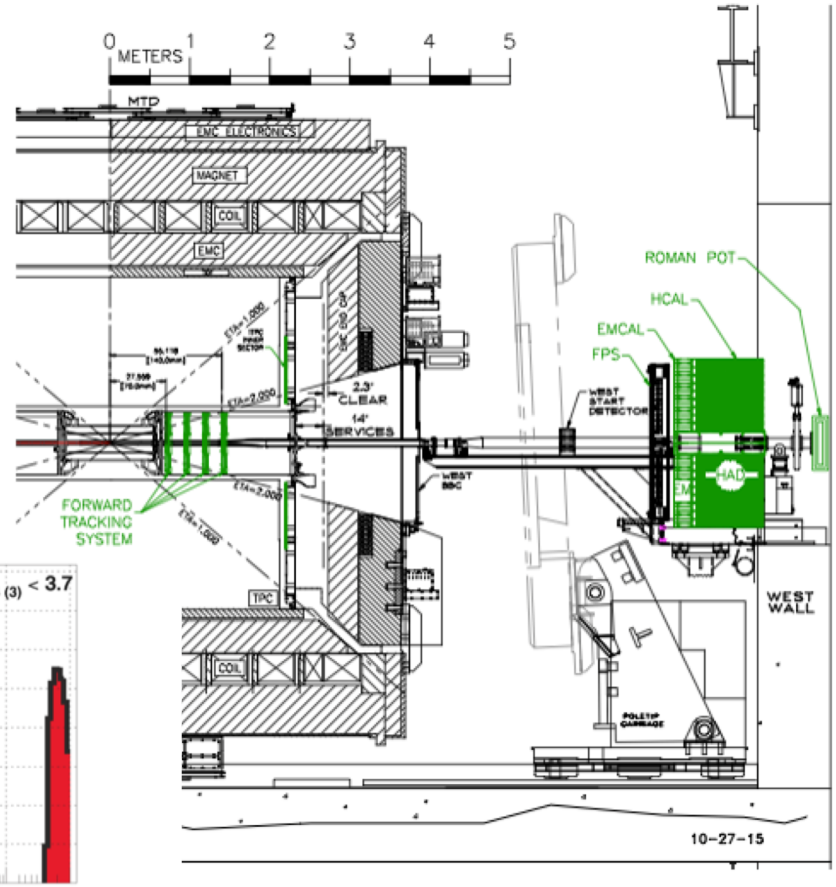
To install a Forward Calorimeter System (FCS) in early 2020s:

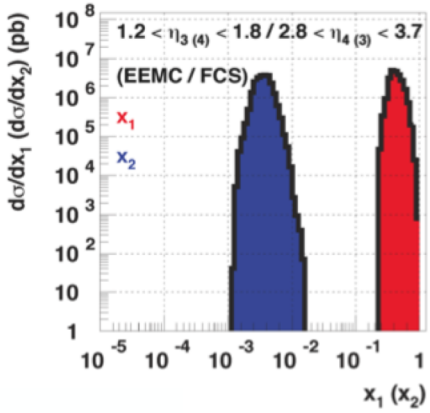
- EMCal
- Hcal
- Tracking, charge separation

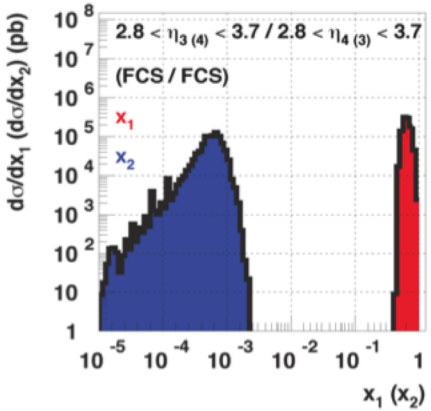
	p+p / p+A
ECAL	$\approx 10\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$

Di-jet in the forward region (2.8<eta<3.7)
Access gluon polarization at low x:

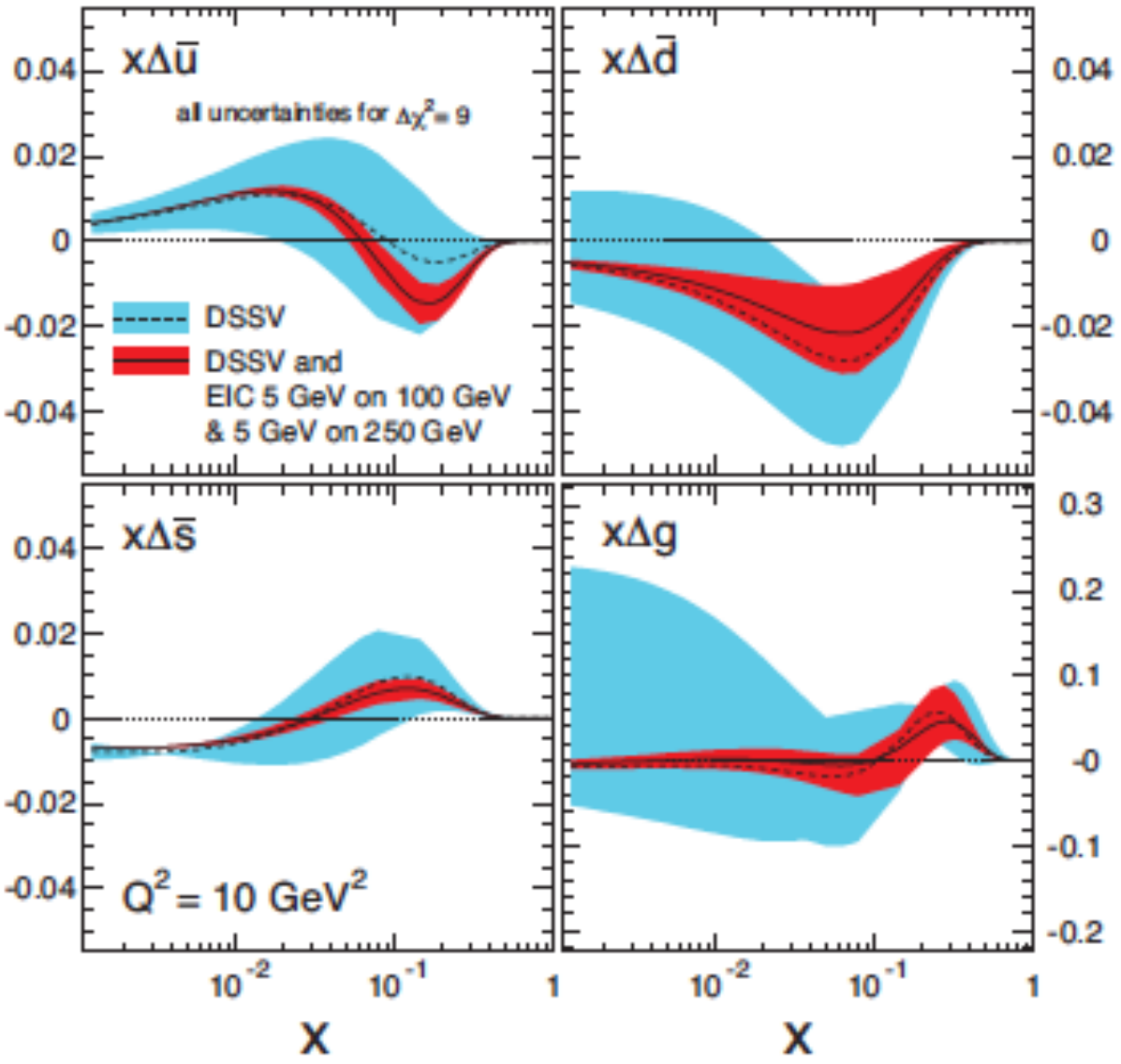
- X ~ 5x10^-3 (central + forward)
- X~ <1x 10^-3 (forward - forward)





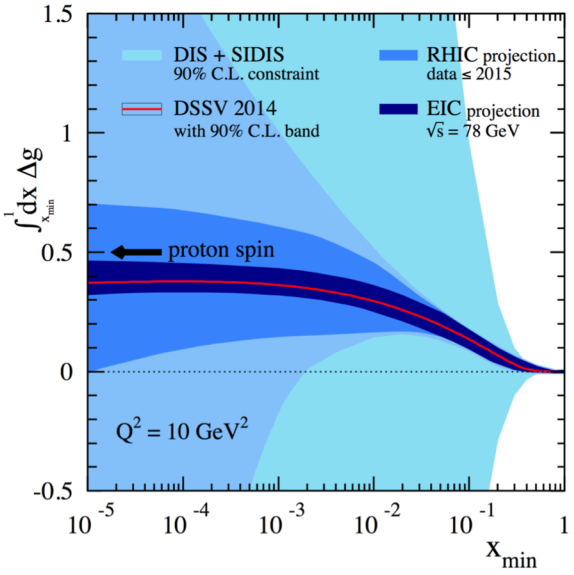


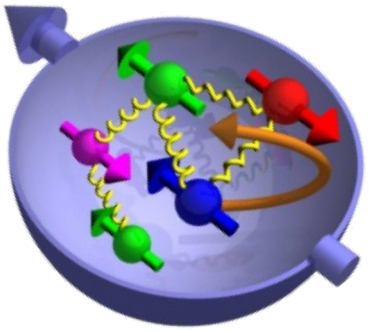
EIC Future @RHIC



Summary and Outlook

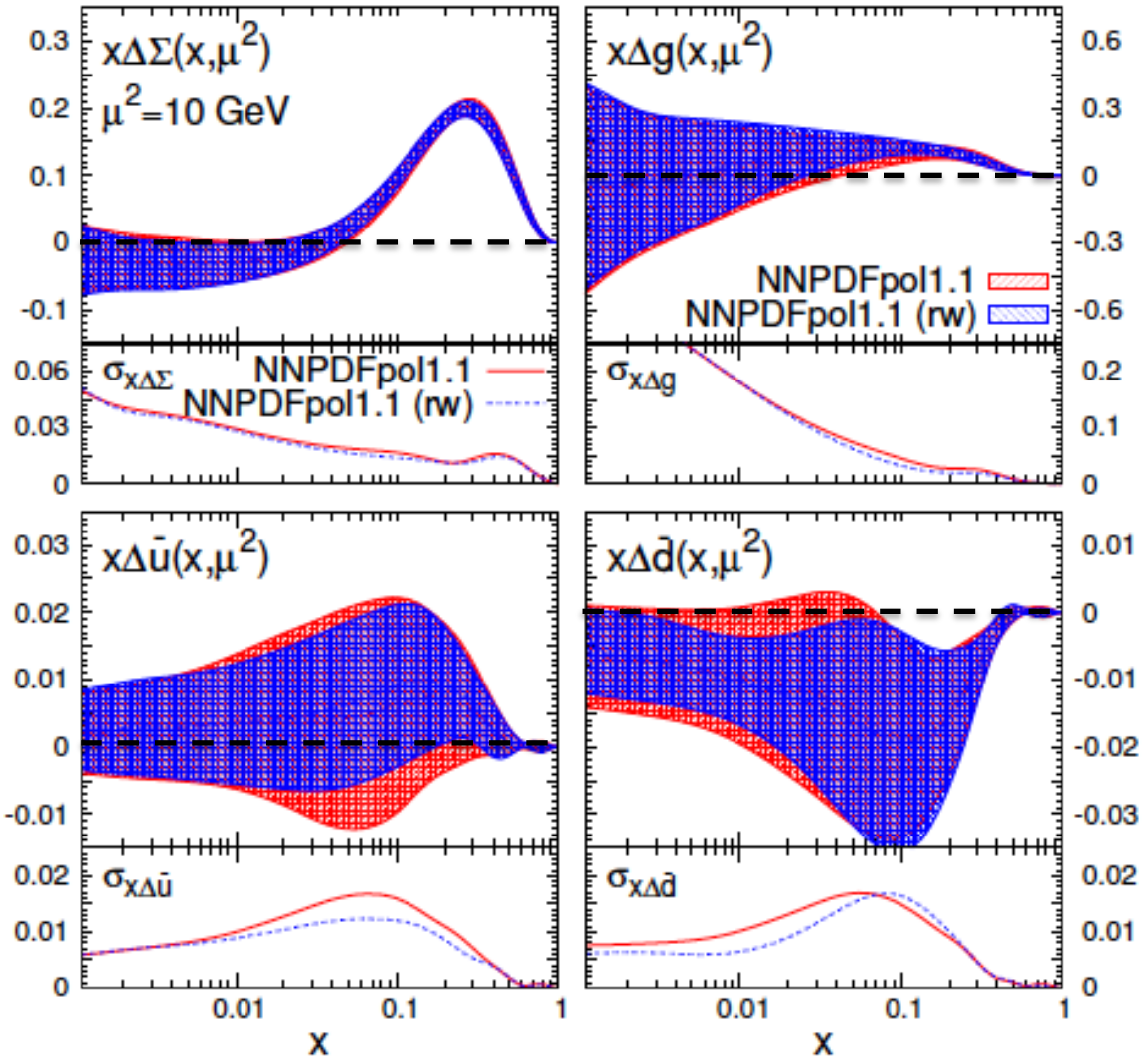
- First evidence of non-zero gluon polarization
  - PHENIX: pi0 A_{LL}
  - STAR: 200/510GeV inclusive jets and di-jet A_{LL}
- First direct measurements of sea-quark polarization with $W^{+/-}$
  - PHENIX: W->e, mu
  - START: W->e
- Cold QCD plan being developed
  - Exciting long-term polarized pp/pA 2020+
    - sPHENIX
    - STAR/Forward upgrade proposal
- EIC future 2025+





Backup slides

Latest Pol NNPDFPol Global Fit

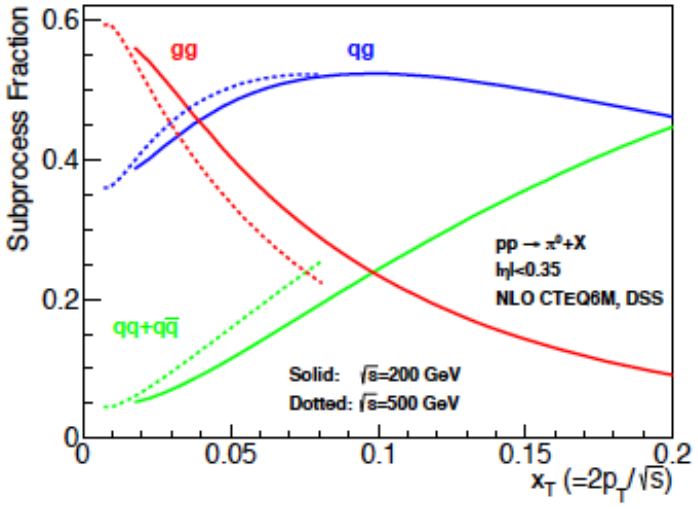


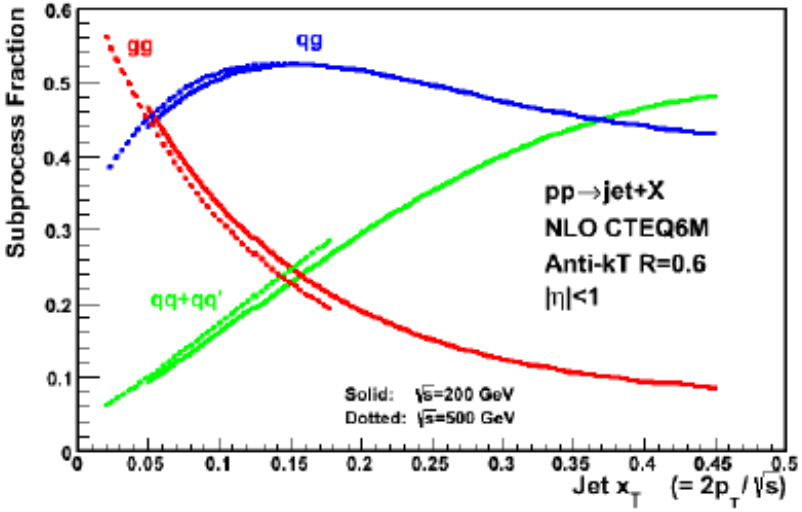
arXiv:1702.05077

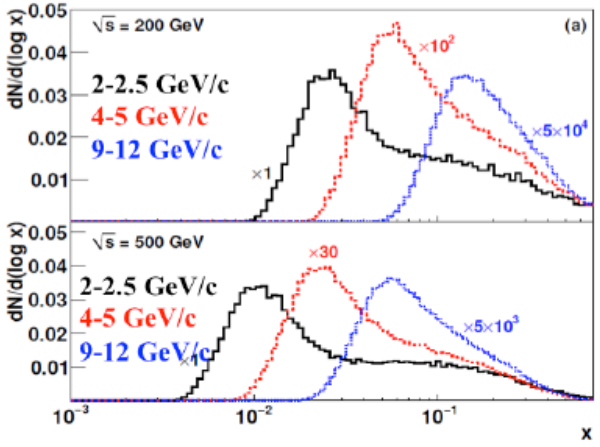
-SI/DIS data
-RHIC data

Relative contributions

RHIC Spin Program, arXiv:1501.01220







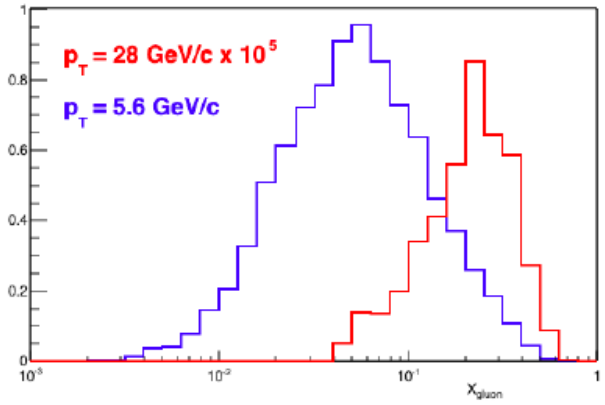
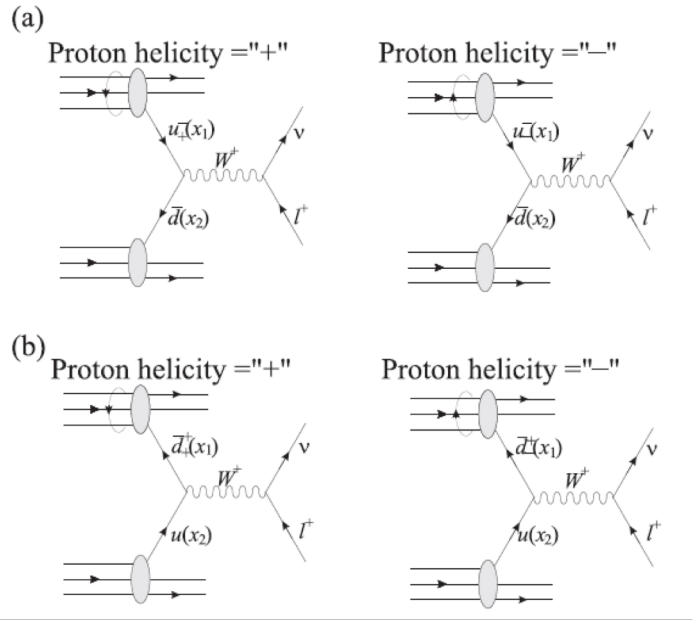


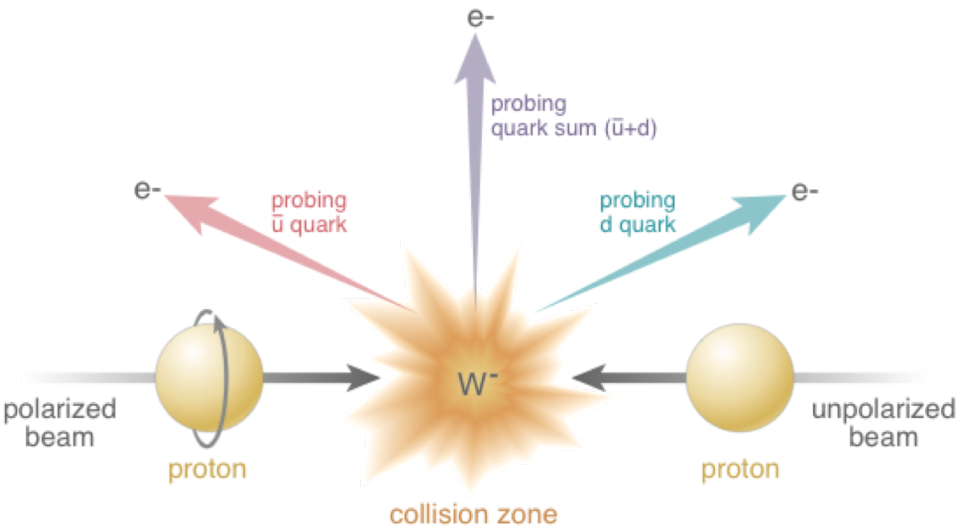
Figure 2-2 Left panel: distributions of gluon momentum fractions x sampled in three p_T bins obtained from a NLO pQCD simulation of π^0 production at $\sqrt{s}$=200 GeV and 500 GeV. The right panel shows the relative contributions of gluons with a given momentum fraction x to high p_T inclusive jet cross production in p+p collisions at mid rapidity for $\sqrt{s}$=200 GeV [2].

Access sea-quark with W+/-

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



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



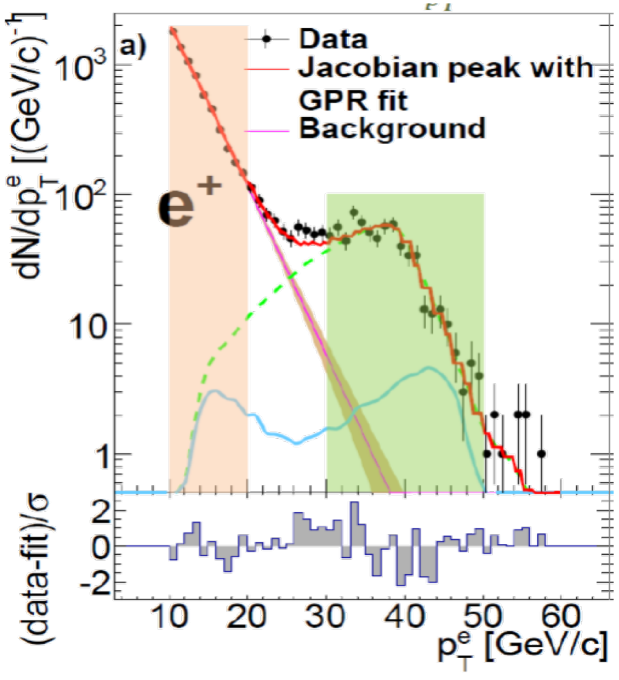
$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2}{u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \bar{d}(x_1)u(x_2)(1+\cos\theta)^2}$$

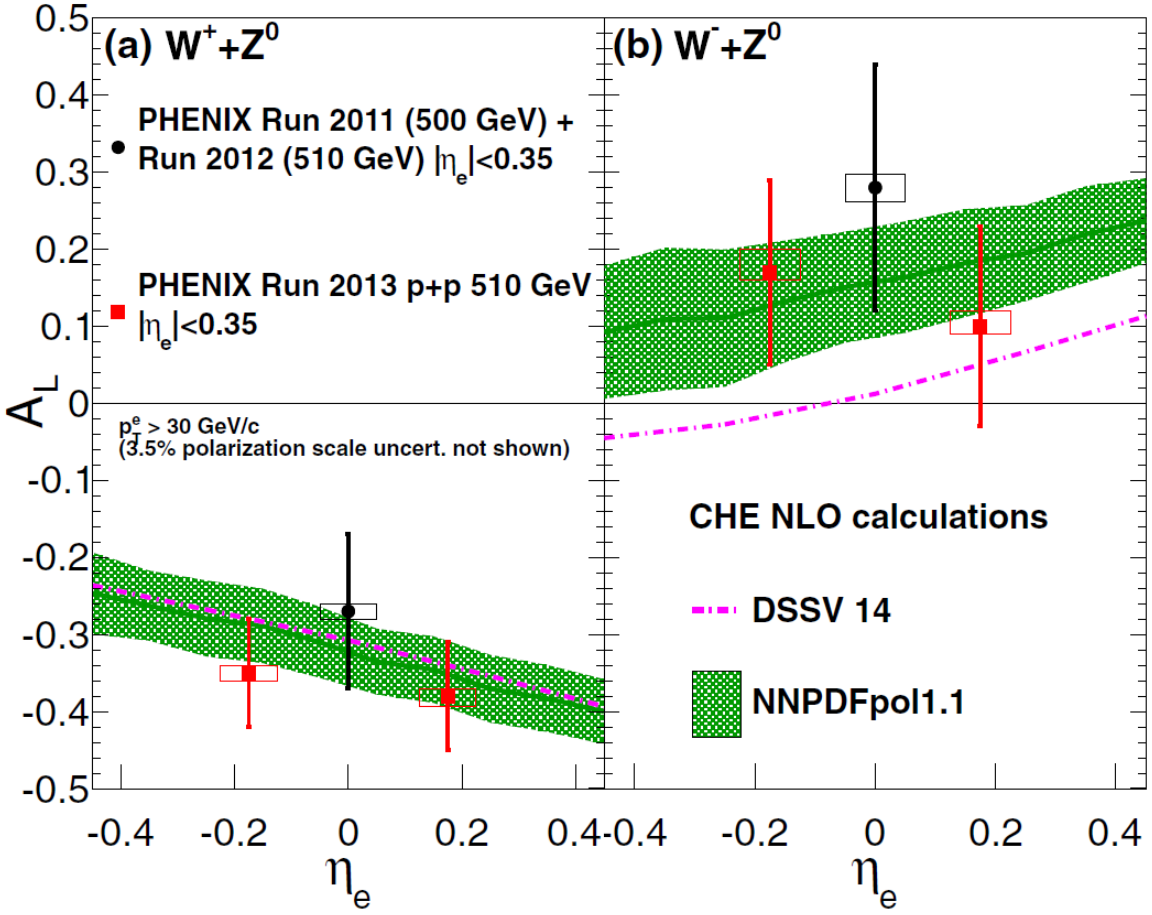
$$A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2}{d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \bar{u}(x_1)d(x_2)(1-\cos\theta)^2}$$

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

PRD 93, 051103(R)(2016)

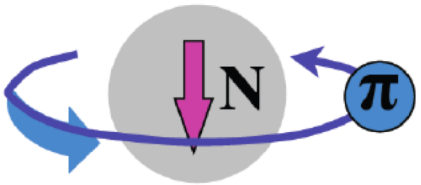
High pT electrons from $W^{+/-}$ decays





Unpolarized Sea Quark Distributions

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



C. Bourrely and J. Soffer (2013)