PHENIX Longitudinal Spin Highlights

Chong Kim

University of California at Riverside

QCD – N'16

Palacio San Joseren, Getxo, Spain

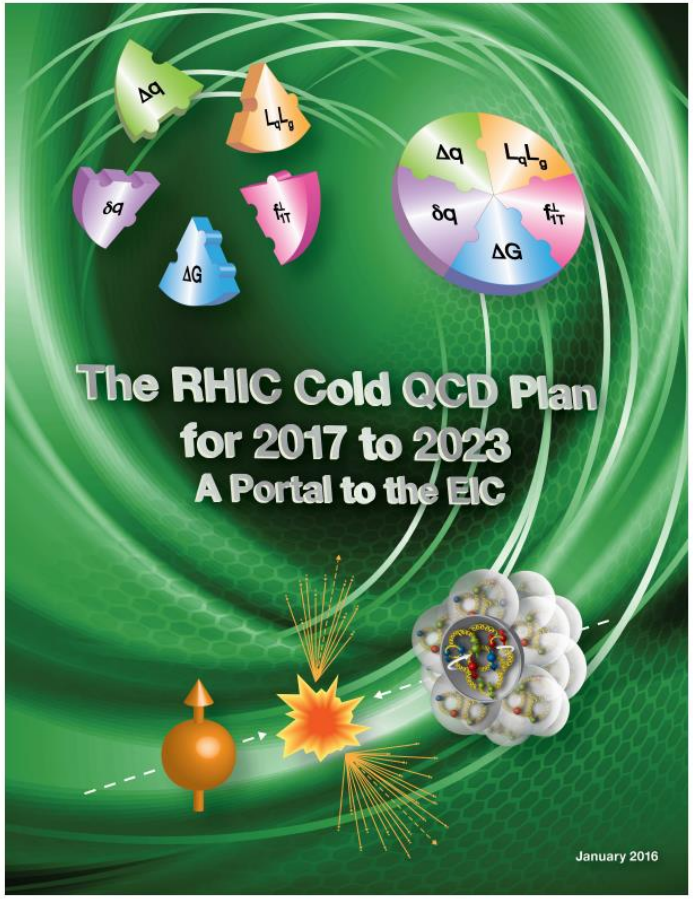
July 11, 2016

For the PHENIX collaboration

Outline

- **Introduction**
  - Physics motivations
  - RHIC
  - PHENIX
- **PHENIX longitudinal spin highlights**
  - Polarized gluon distributions (ΔG)
  - Polarized light sea quark distributions ($\Delta\bar{q}$)
- **Summary and Outlook**

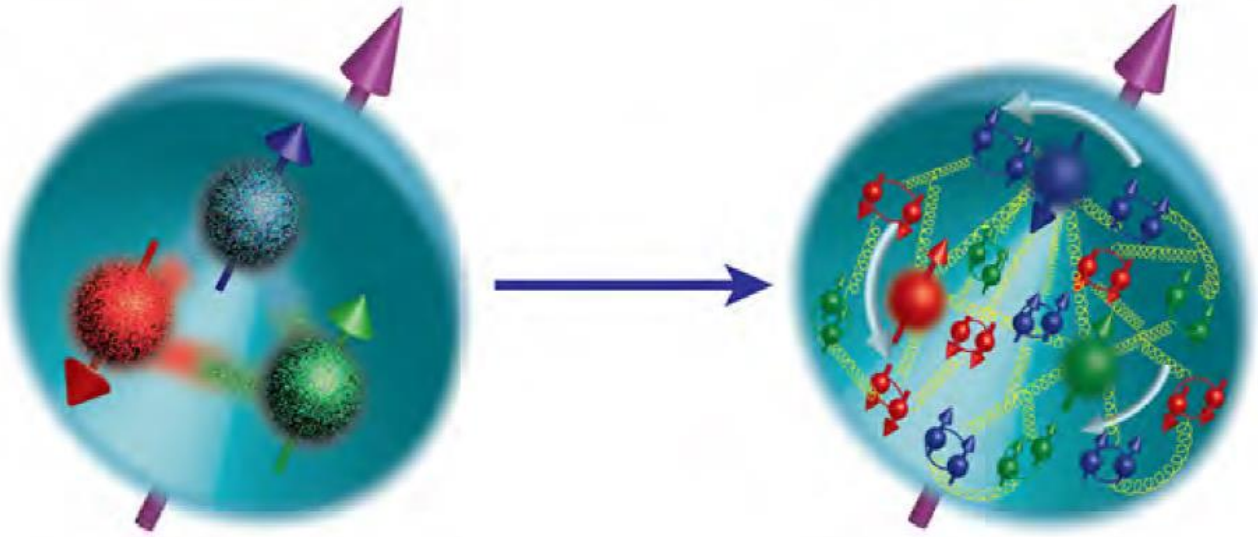
arXiv: 1501.01220



arXiv: 1602.03922

Introduction

Physics motivations

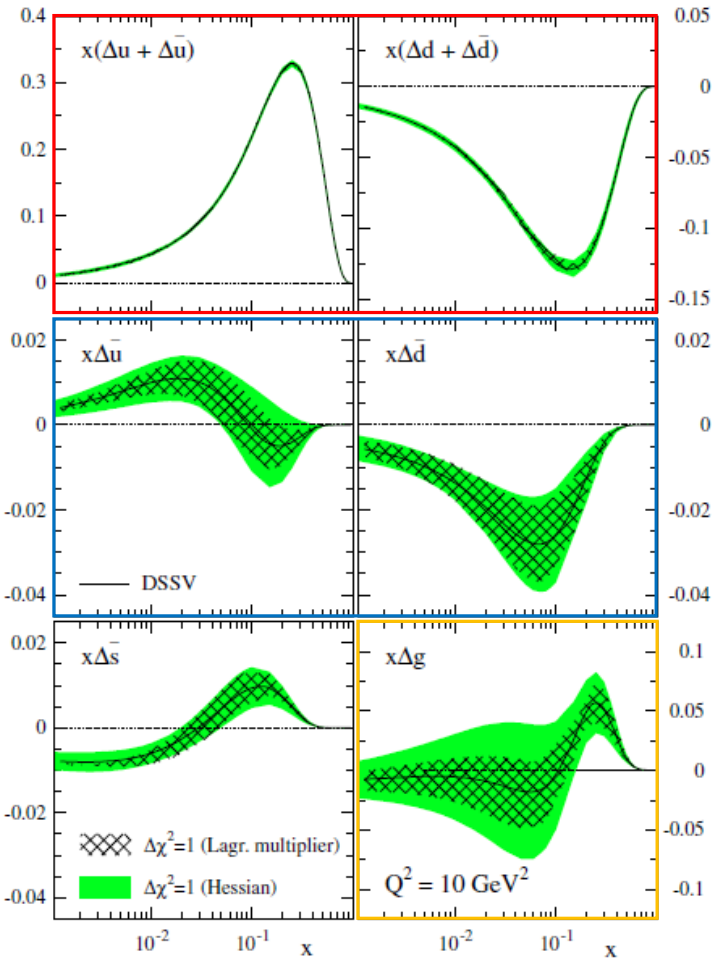


- **It's not a simple sum of big 3 chunks**
  - Jaffe-Manohar spin sum rule: $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
  - PHENIX (RHIC) aims: both longitudinal spin structure and transverse spin phenomena

This talk

Dr. Kenneth Barish, Friday 9:30

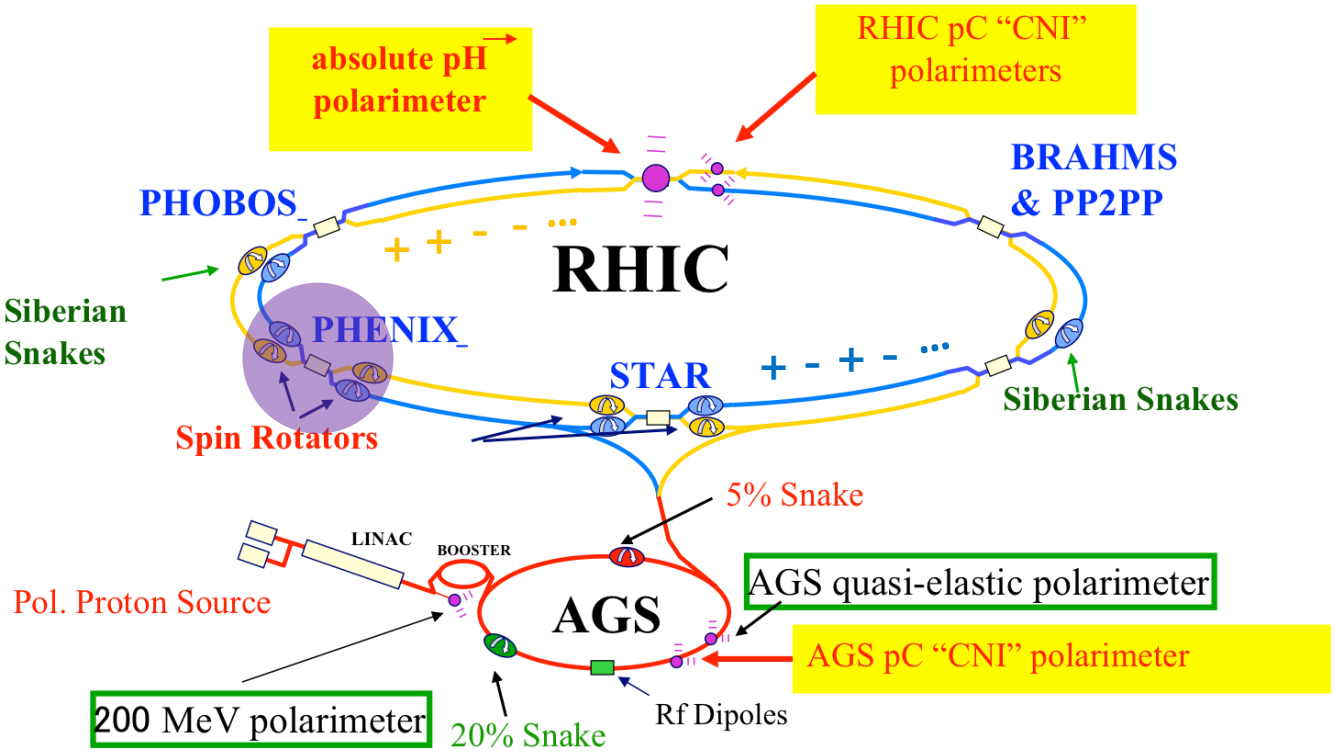
Introduction Physics motivations



PRD80. 034030 (2009)

- $S_p = \frac{1}{2} = \frac{1}{2}\,\mathbf{\Delta\Sigma} + \mathbf{\Delta G} + L_z$
  - How much we understand?
- ΔΣ?
  - $(\Delta q + \Delta\bar{q})$: well constrained down to **x ~ 10^{-3}**, thanks to DIS results
  - $\Delta\bar{q}$: poorly constrained with large uncertainty, mainly originated from fragmentation functions
    → RHIC: fragmentation free *W* decay leptons
- ΔG?
  - Largely unconstrained:
    barely accessible via DIS, limited access via SIDIS
  - → RHIC: gluon sensitive polarized p + p collisions, various probes

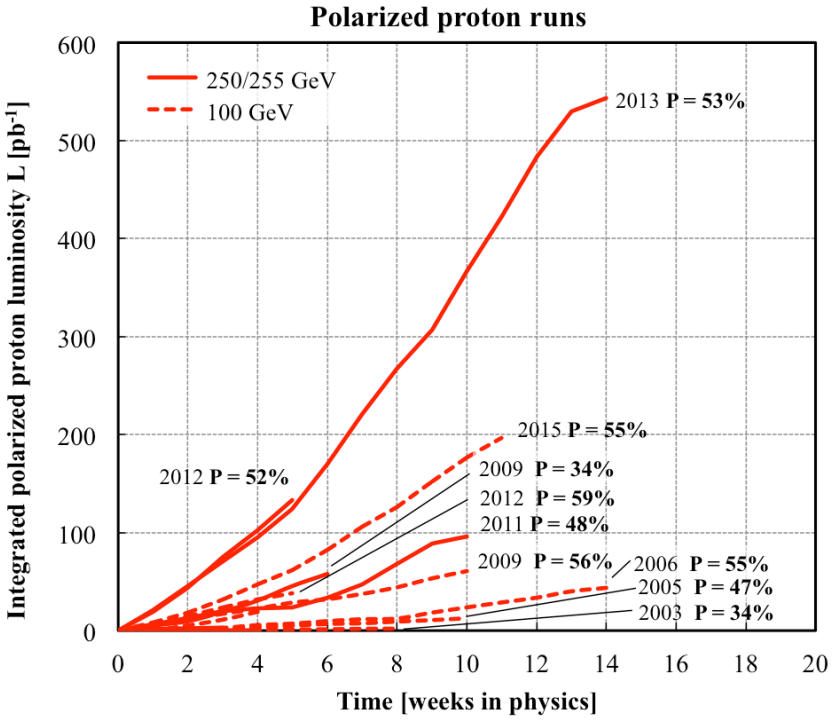
Introduction RHIC and PHENIX



- **RHIC @ Brookhaven Lab., NY**
  - Polarized p + p @ √s = 62.5 to 510 (GeV)
  - Maximum average polarization ($\langle P \rangle$) ≈ 60 (%)

Introduction

Recent longitudinal spin runs

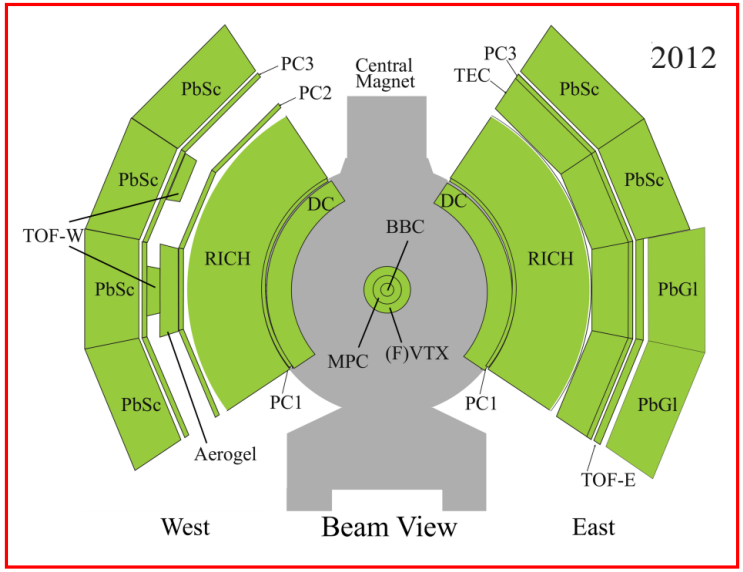


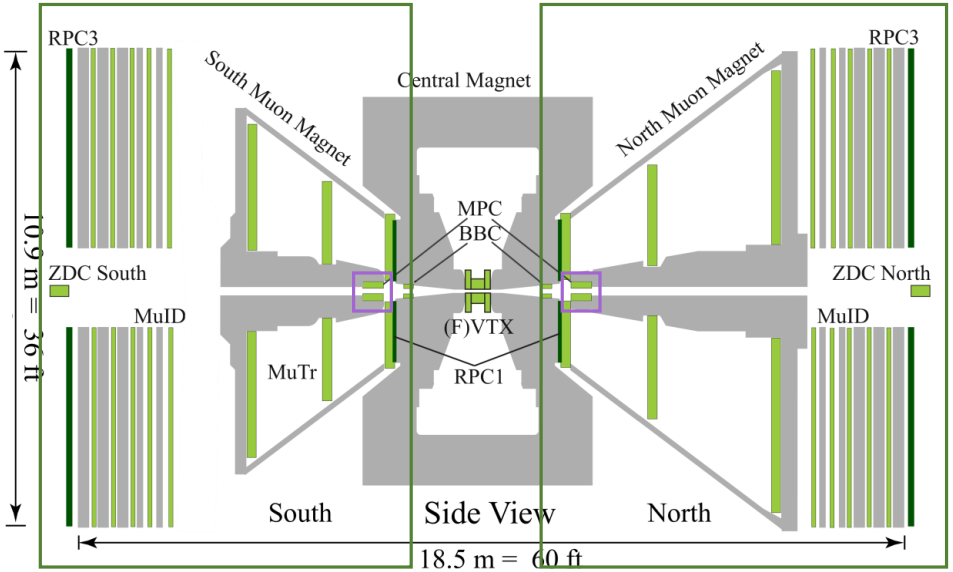
Year	√s (GeV)	Int. L (pb^{-1})	$\langle P \rangle$ (%)	FoM1 ($L \cdot \langle P \rangle^2$)	FoM2 ($L \cdot \langle P \rangle^4$)
09	200	15.6	56 / 57	4.98	1.59
	500	14	33 / 36	1.66	0.20
11	500	27.6	48 / 48	6.36	1.47
12	510	49.6	50.3 / 53.5	13.35	3.59
13	**510**	**242.1**	**50.5 / 55.4**	**67.73**	**18.95**

* Int. L: MinBias with wide (no) vertex at PHENIX

- **Figure of merit related to each topic**
  - FoM1 (Int. $L \cdot \langle P_B \rangle \cdot \langle P_Y \rangle$) : single spin asymmetry (A_L) ↔ $\Delta\bar{q}$
  - FoM2 (Int. $L \cdot \langle P_B \rangle^2 \cdot \langle P_Y \rangle^2$) : double spin asymmetry (A_{LL}) ↔ ΔG

Introduction PHENIX detectors (continue)



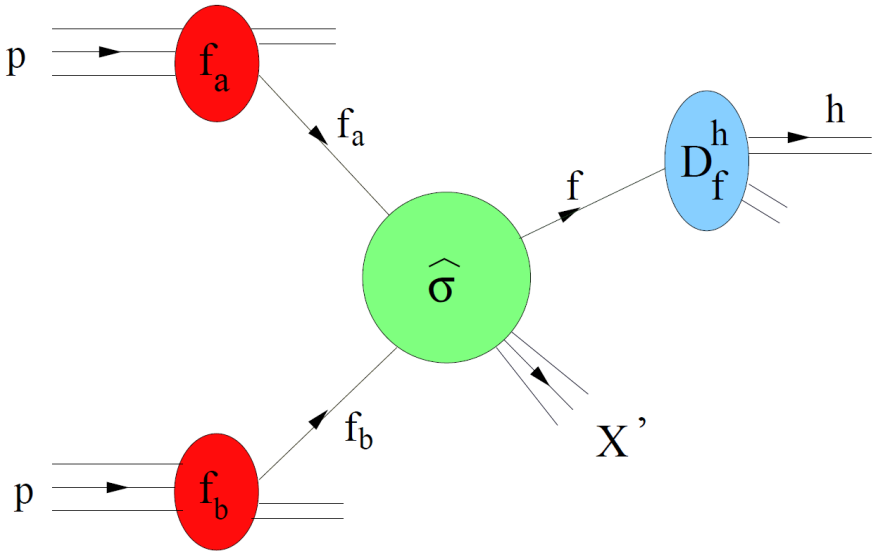


- **Central Arms** ($|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$)
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc
- **Muon Arms** ($1.2 < |\eta| < 2.2$ (S) or 2.4 (N), $\Delta\phi = 2\pi$)
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs
- **MPCs** ($3.1 < |\eta| < 3.8$, $\Delta\phi = 2\pi$)
  - EMCal ($PbWO_4$)

Polarized gluons (ΔG)

Observable: double longitudinal spin asymmetry (A_{LL})

ΔG Double longitudinal spin asymmetry (A_{LL})



$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

$$= \frac{\Sigma_{abf}\ (\Delta f_a \otimes \Delta f_b) \otimes \Delta\hat{\sigma}^{\,a+b\to h+X} \otimes D_f^h}{\Sigma_{abf}\ (f_a \otimes f_b) \otimes \hat{\sigma}^{\,a+b\to h+X} \otimes D_f^h}$$

- f (Δf) : unpol (pol) PDF
- $\hat{\sigma}$ ($\Delta\hat{\sigma}$) : unpol (pol) partonic cross section
- D_f^h : fragmentation function

technically,

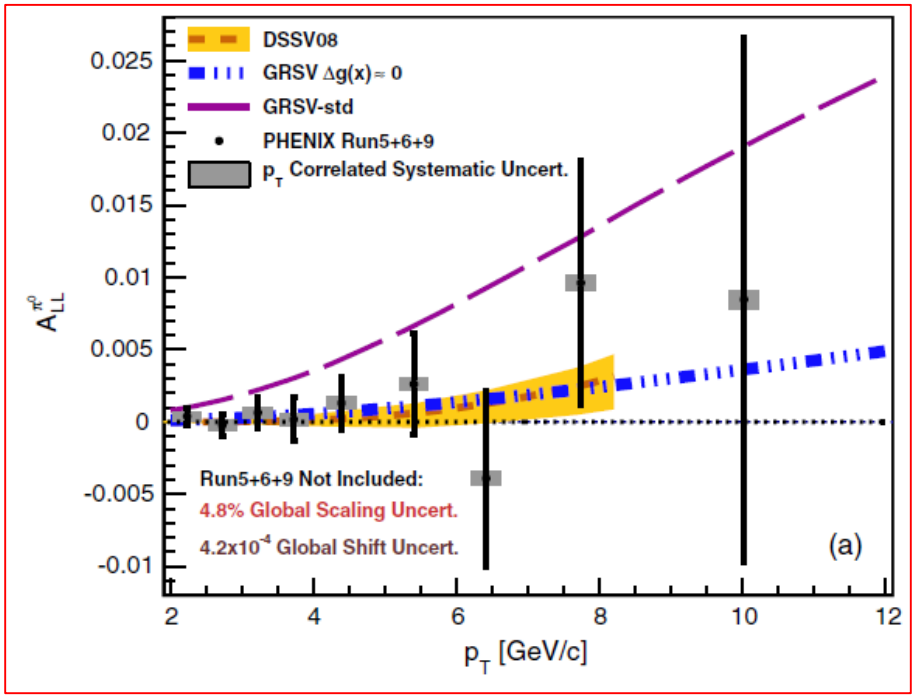
$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

- P : avg. polarization of each beam
- N++ (N+-) : yields in same (opposite) helicity
- R ($\frac{L++}{L+-}$) : relative luminosity

- **ΔG measurements at PHENIX**
  - Midrapidity (|η| < 0.35): direct γ, **π⁰**, π±, η, heavy flavor decay electrons
  - Forward (1.2 < |η| < 2.2 / 2.4, 3.1 < |η| < 3.8): **heavy flavor decay muons**, π⁰, η, **π⁰ rich EM clusters**

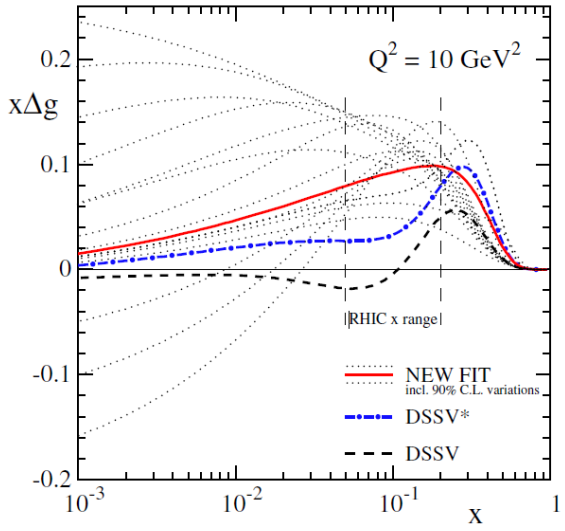
ΔG Current understanding: DSSV global analysis (2014)

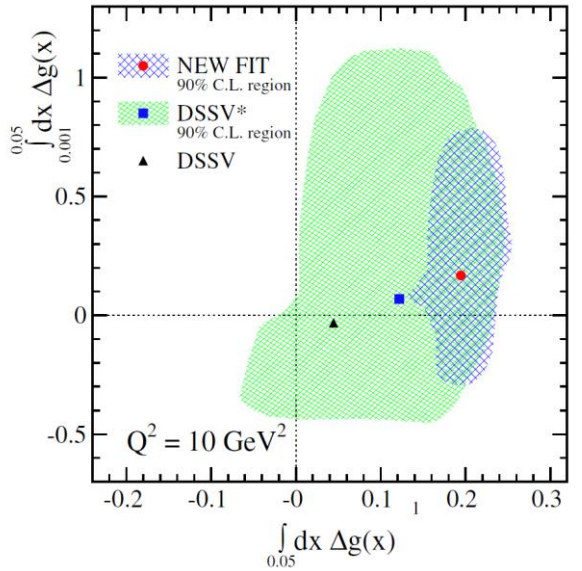
PRD90, 012007 (2014)



- **PHENIX Run9 200 GeV inclusive π^0 A_{LL} ($|\eta| < 0.35$)**
  - Reaches Bjorken x down to ~ **0.05**
  - For PHENIX data alone, it was hard to say clear non-zero gluon polarization exists

ΔG Current understanding: DSSV global analysis (2014)





PRL113, 012001 (2014)

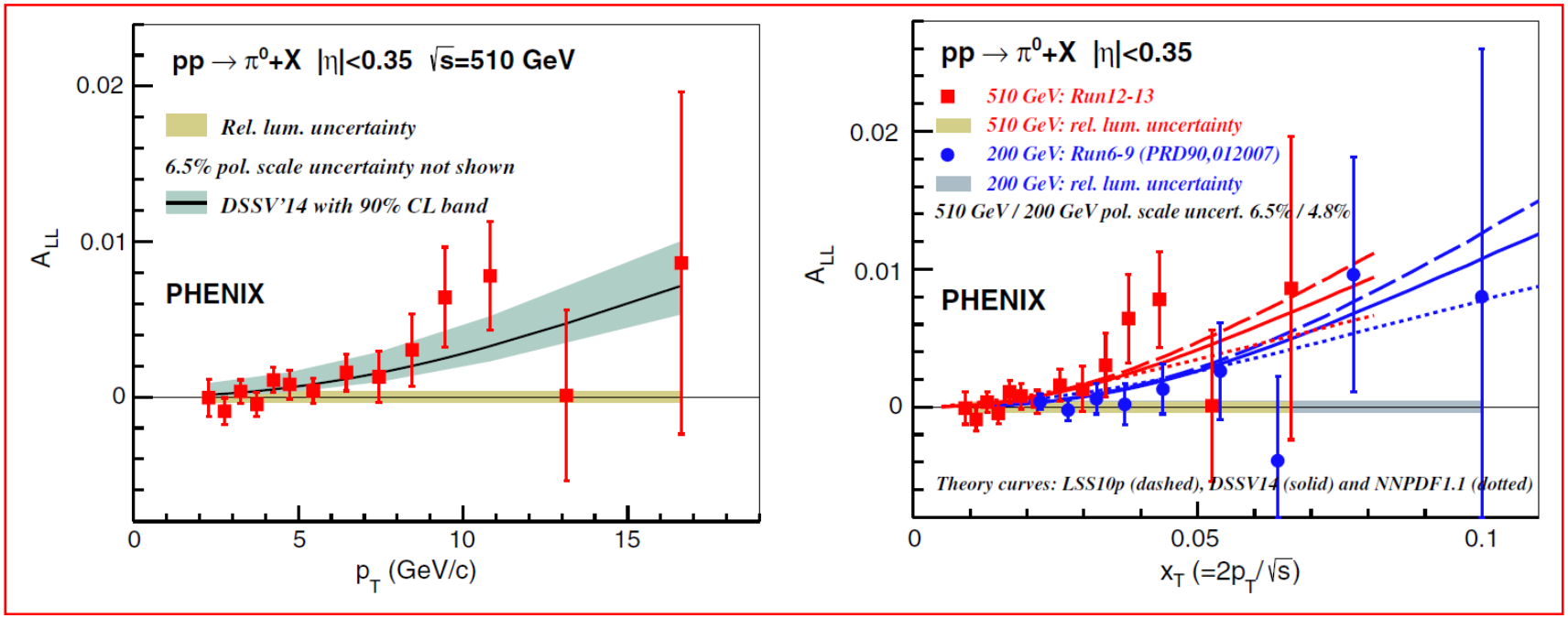
- **DSSV2014 (DSSV* and New fit):**
  - Both of them includes:

    RHIC data for original DSSV (before Run9) +

    New COMPASS SI(DIS) data sets

- $\int_{0.05}^{1} dx\ \Delta g\,(x)$
  - DSSV*: without RHIC Run 9 data
  - DSSV New fit: with RHIC Run 9 data
    - *a.* $0.20^{+\,0.06}_{-\,0.07}$ at 90 % C.L.
    - b. LSS10p, DSSV, and NNPDF1.1 agree
- $\int_{0.001}^{0.05} dx\ \Delta g\,(x)$
  - Large uncertainty due to limited data points
  - Upcoming forward data (later slides)

ΔG π^0 @ midrapidity ($|\eta| < 0.35$)

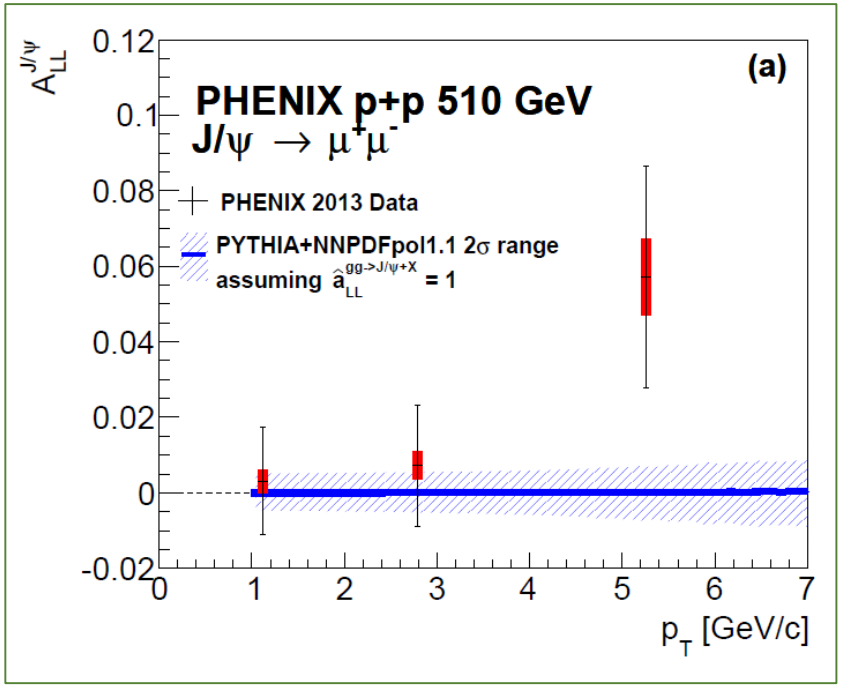


- **New inclusive π^0 A_{LL} with Run12-13 data**

PRD93, 011501 (2016)

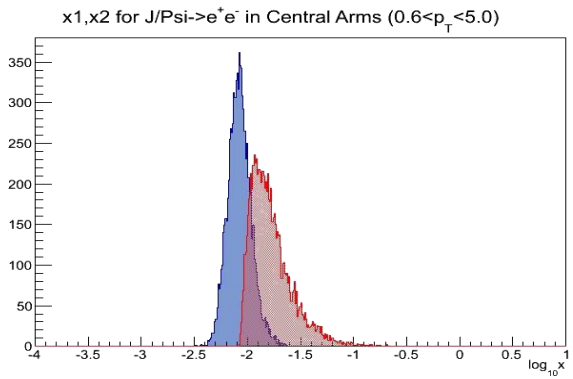
  - $\sqrt{s}$ = 510 GeV, Int. L = 20, 108 pb^{-1}
  - Confirms non-zero gluon polarization via hadron production
  - Extended Bjorken x coverage down to ~ **0.01**
  - Ongoing analysis: Run13 charged pions ($\pi^{\pm}$) and Run9 π^0 pair

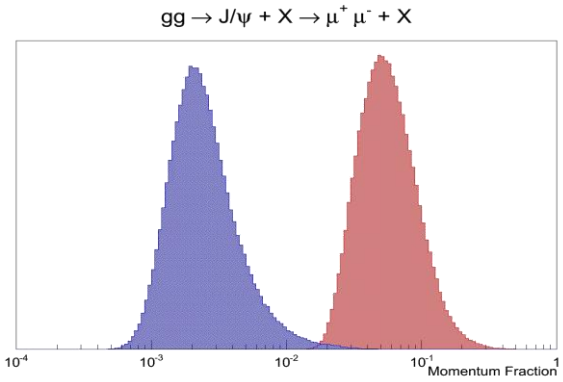
ΔG J/ψ @ forward rapidity (1.2 < |η| < 2.2 / 2.4)



arXiv: 1606.01815 — Submitted to PRD

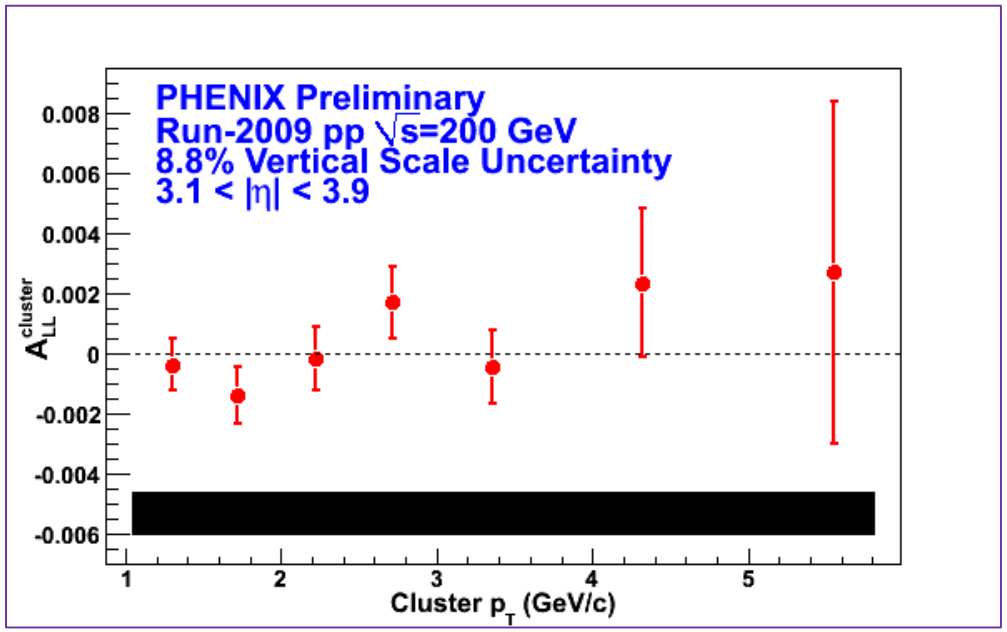
- **Forward J/ψ A_{LL} with Run13 data**
  - √s = 510 GeV, Int. *L* = 150 pb^{-1}
  - Predominant production via gg scattering
  - Uncertainty of production mechanism limits constraining power
  - Another indication of non-zero ΔG
  - Reaches Bjorken x down to **2 ~ 3 × 10^{-3}**

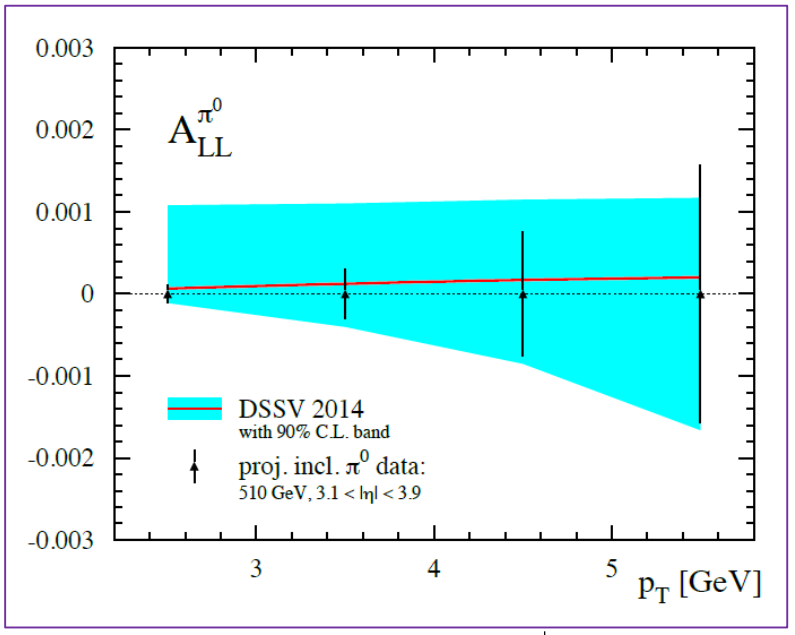




x_1 and x_2 distributions of J/ψ decay leptons (PYTHIA)

ΔG EM clusters @ very forward rapidity (3.1 < |η| < 3.8)





- **EM clusters A_{LL} at very forward rapidity**
  - Run9 200 GeV preliminary (left) / Run11 500 GeV preparing publication / Run13 510 GeV analysis is underway (right)
  - π^0 rich (> 70 %) EM clusters
  - Reaches Brorken x down to **~ <u>0.001</u>**

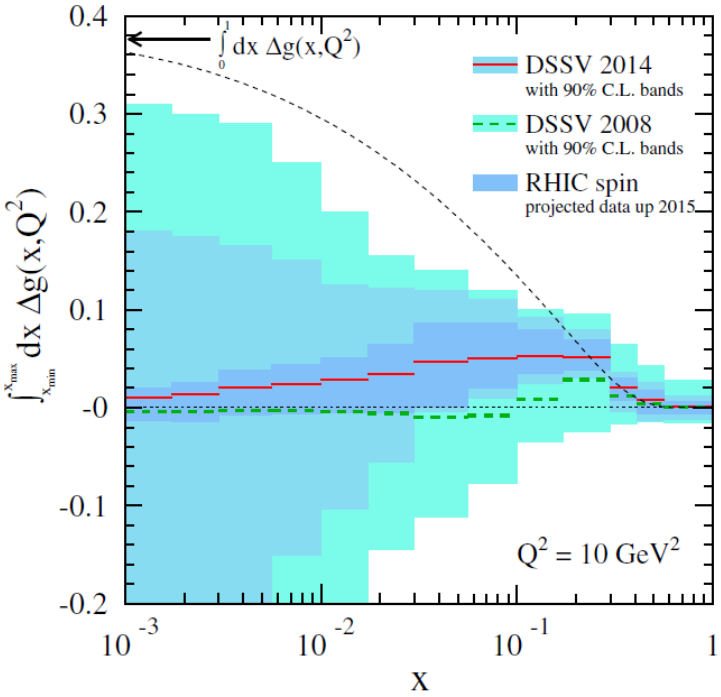
arXiv: 1501.01220

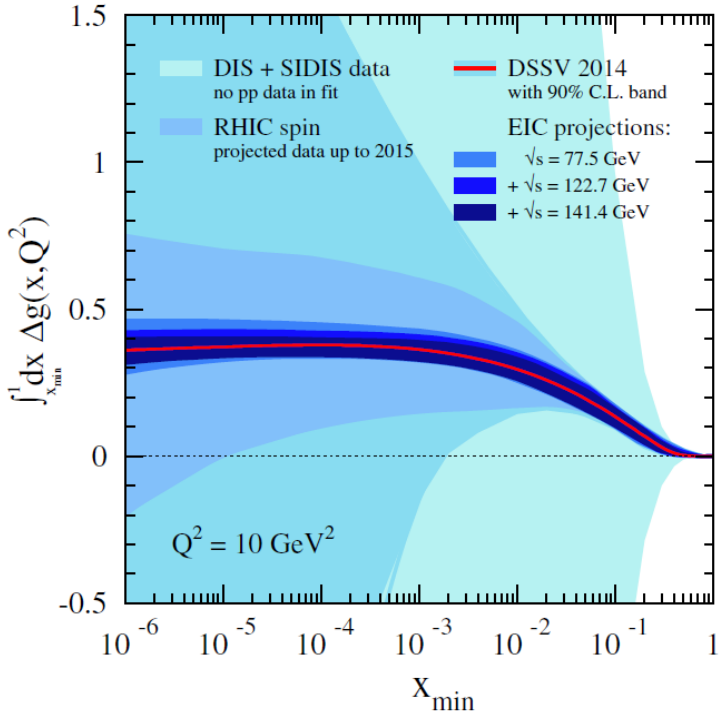
A projection

ΔG Next?

PRD92, 094030 (2015)

$E_e \times E_p$ (GeV)	$\sqrt{s}$ (GeV)	x_{min} for $y = 0.95$	x_{max} for $y = 0.01$
15×100	77.5	1.8×10^{-4}	1.7×10^{-2}
15×250	122.7	7.0×10^{-5}	6.7×10^{-3}
20×250	141.4	5.3×10^{-5}	5.0×10^{-3}





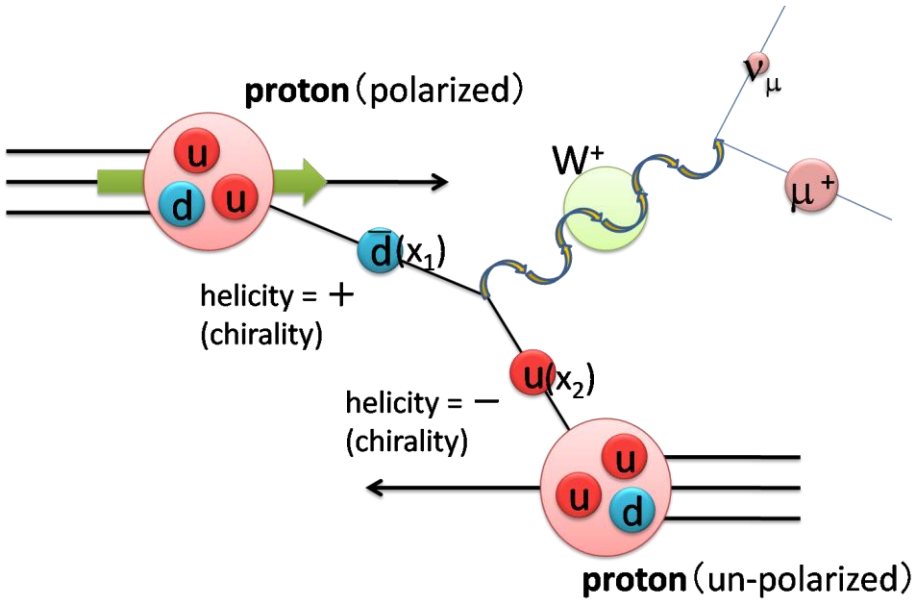
- **Improve even further with existing RHIC data, Move toward to the EIC**
  - Not all of data took into account in global analysis. For PHENIX,

    Run13 π^0, J/ψ (published) + forward EM clusters, $\pi^{\pm}$, π^0 pairs, and others (ongoing)

Polarized light sea quarks ($\Delta\bar{q}$)

Observable: single longitudinal spin asymmetry (A_L)

$\Delta\bar{q}$ Single longitudinal spin asymmetry (A_L) via *W* decay leptons



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

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

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

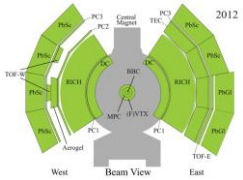
technically,

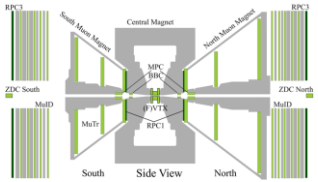
$$A_L^{W} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

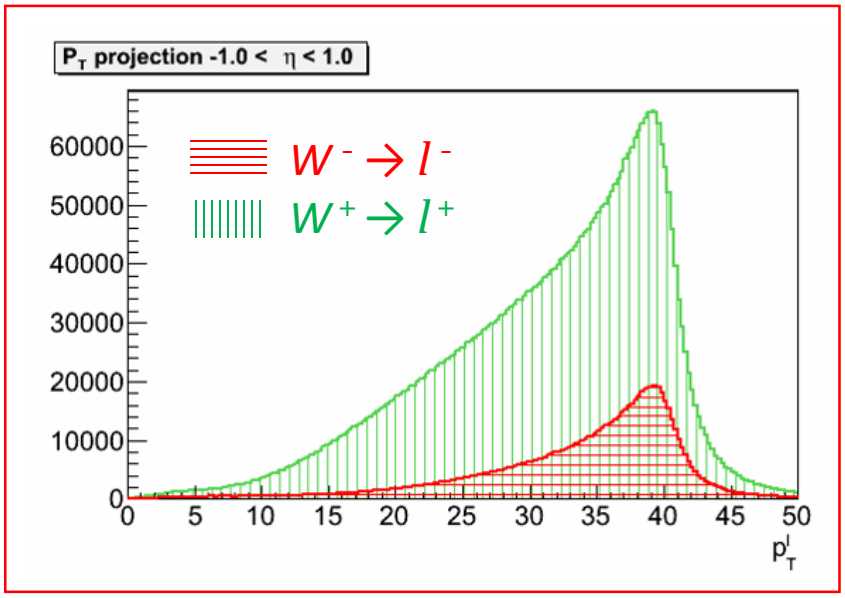
- *P* : avg. polarization of each beam
- *N*+ (*N*-) : yields in same (opposite) helicity
- *R* ($\frac{L++}{L+-}$) : relative luminosity

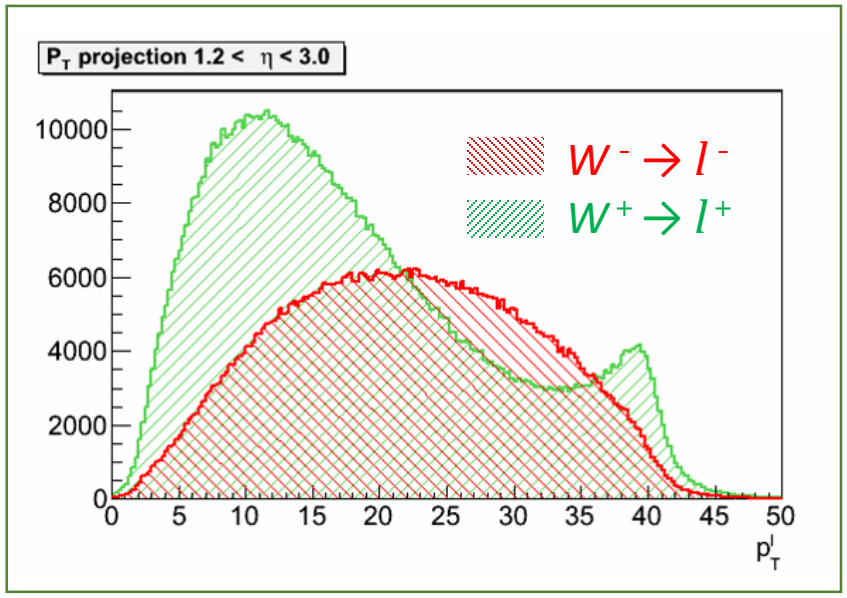
- **$\Delta\bar{q}$ measurements at PHENIX**
  - Midrapidity ($|\eta| < 0.35$): $W^{\pm} \rightarrow e^{\pm}$
  - Forward rapidity ($1.2 < |\eta| < 2.2 / 2.4$): $W^{\pm} \rightarrow \mu^{\pm}$

$\Delta\bar{q}$ $W \rightarrow l^{\pm}$ @ PHENIX









- **$W^{\pm} \rightarrow e^{\pm}$** at $|\eta| < 0.35$
  - Distinct Jacobian peak

    Triggered by energy

    Momentum by energy

    Charge by tracking in B-field

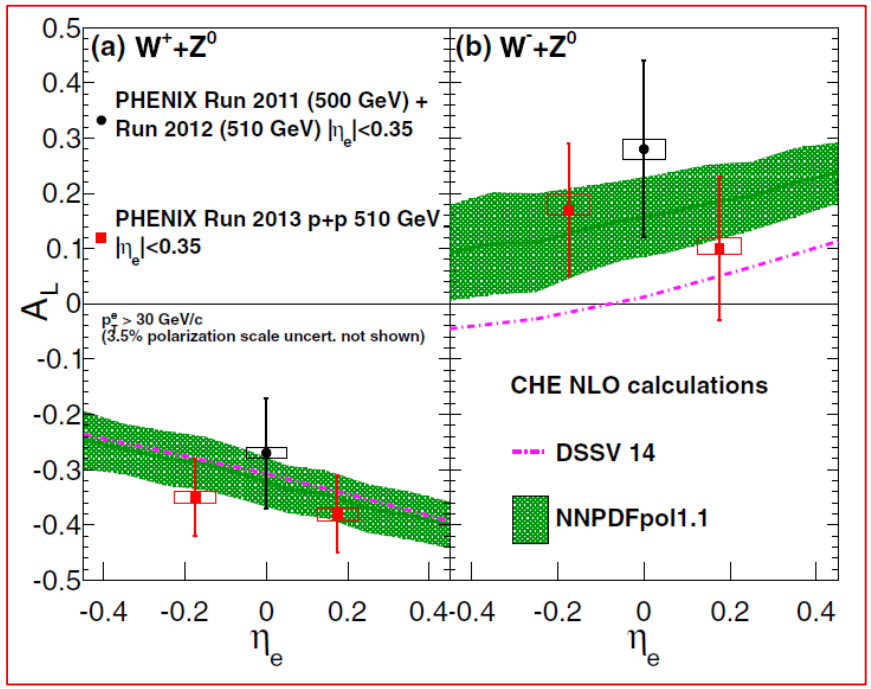
- **$W^{\pm} \rightarrow \mu^{\pm}$ at** $1.2 < |\eta| < 2.2 / 2.4$
  - Suppressed/No Jacobian peak

    Triggered by momentum

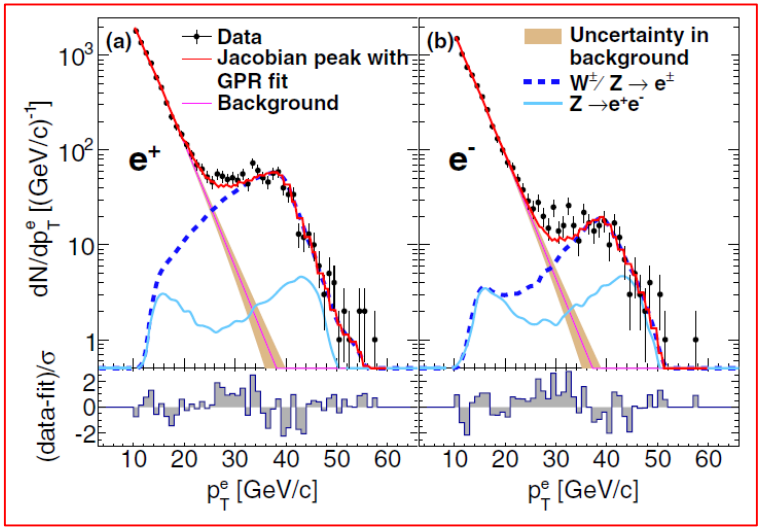
    Momentum by tracking in B-field

    Charge by tracking in B-field

$\Delta\bar{q}$ $W^{\pm} \rightarrow e^{\pm}$ @ midrapidity ($|\eta| < 0.35$)

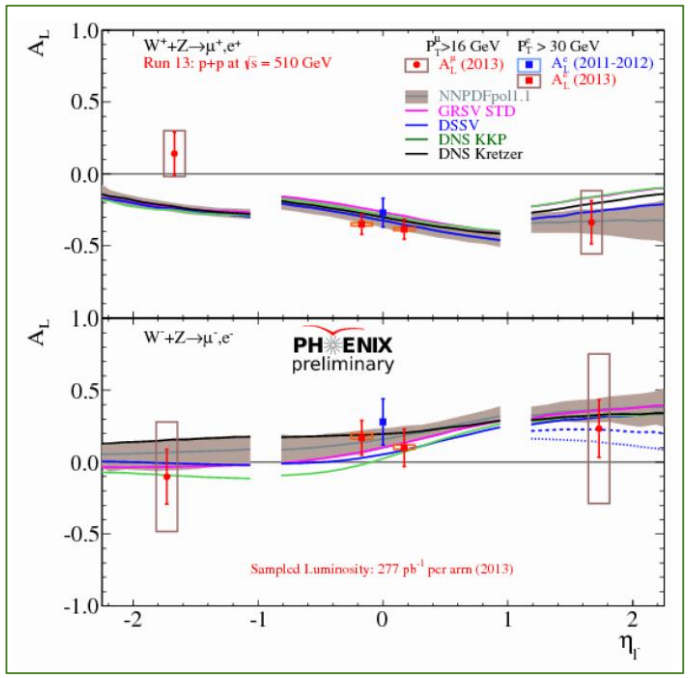


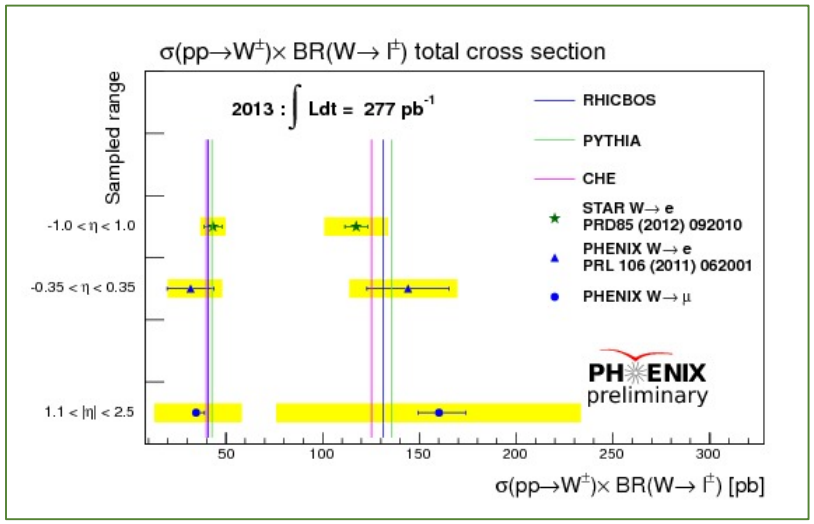
PRD93, 051103 (2016)



- **$W^{\pm} \rightarrow e^{\pm}$ A_L with integrated Run11-13 data**
  - $\sqrt{s}$ = 500 (11) / 510 (12, 13) GeV, Int. L = 240 pb^{-1}
  - Signal extraction via charge isolation + backgrounds estimation by Gaussian Process Regression
  - Probed Bjorken x of ~ **0.16** (M_W / $\sqrt{s}$)

$\Delta\bar{q}$ $W^{\pm} \rightarrow \mu^{\pm}$ @ forward rapidity ($1.2 < |\eta| < 2.2 / 2.4$)



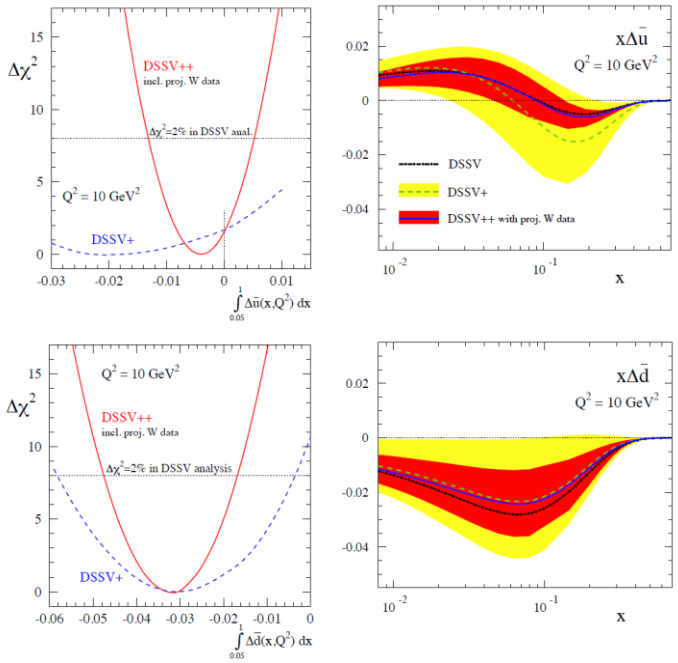


- **$W^{\pm} \rightarrow \mu^{\pm}$ A_L with Run13 data**
  - $\sqrt{s}$ = 510 GeV, Int. L = 277 pb^{-1}
  - Signal extraction via W likelihood + unbinned max. likelihood fit

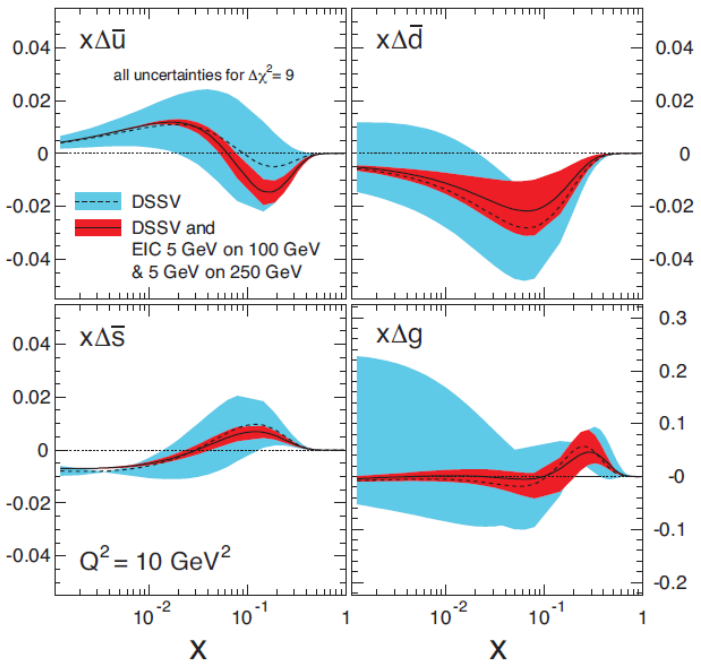
    → W cross section agrees within large uncertainty
  - Analysis is underway to improve S/BG and relevant uncertainties

$\Delta\bar{q}$ Next?

arXiv: 1501.01220



arXiv: 1212.1701



- **Improve even further with existing RHIC data, Move toward to the EIC**
  - Significant constraint in $\Delta\bar{q}$ is expected once **all** existing RHIC data included in the global analysis
  - Even further constraint can be possible with future EIC data

Summary and Outlook

- **PHENIX longitudinal spin**
  - ΔG:
    a. Confirms non-zero gluon polarization via hadron (π^0, J/ψ) production, with extended x coverage (down to **0.01** for π^0, **2 ~ 3 × 10^{-3}** for J/ψ)
    b. DSSV14 $\int_{\mathbf{0.05}}^{1} dx\, \Delta G(x)$, with Run6-9 RHIC data: $0.20\ ^{+0.06}_{-0.07}$ at 90 % C.L.
       → Even further improvement can be possible with Run11-13 data
       → Data points in even smaller x (~ 0.001) can be obtained via forward π^0 rich EM clusters
       → Other probes (ex. $\pi^{\pm}$) also can be used
  - $\Delta\bar{q}$:
    a. Fragmentation free *W*/Z → leptons in Run11-13
    b. Significant constraint in flavor separated sea-quark contribution is expected
- **Future longitudinal spin**
  - Further improvement is available with data on tape until Run15
  - EIC in 202X: back to the DIS, but with much higher *L* and √s

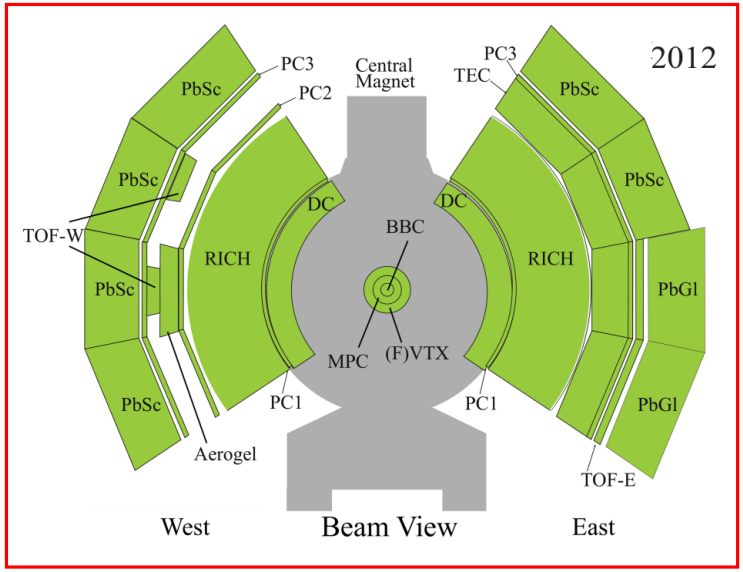
Backup

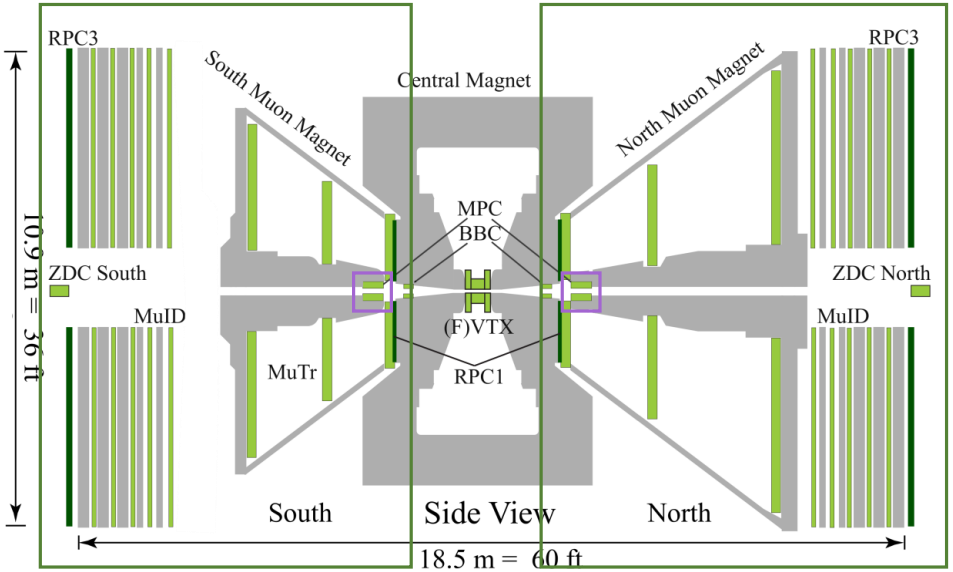
Experiments related to spin structure study

Facility	ΔG	$\Delta\bar{q}$
SLAC (→ 2000)	E80 – E155	
CERN (finished/ ongoing)	EMC, SMC, NMC, and COMPASS	
DESY (→ 2007)	HERMES	
JLab (ongoing)	Hall A, B, and C	
FermiLab (ongoing)		MicroBooNE, E1039 (soon)
RHIC (ongoing)	BRHAMS, PHENIX, and STAR	

- **DIS + SIDIS**
- **Polarized p + p**

Backup PHENIX detectors by physics observables



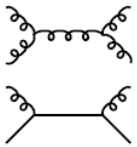
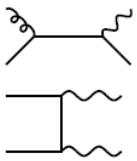
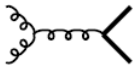
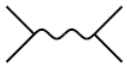
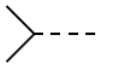


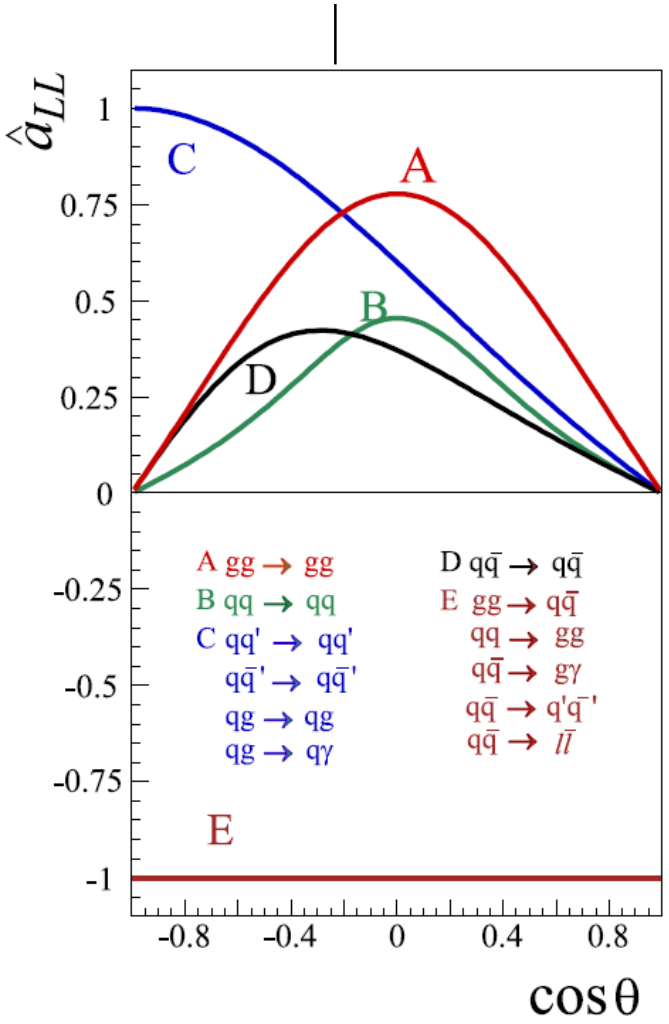
- **Central Arms** ($|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$)
  - $\pi^0 \rightarrow \gamma\gamma$
  - $\pi^{\pm}$
  - Direct γ
  - $W^{\pm} \rightarrow e^{\pm}$ …
- **Muon Arms** ($1.2 < \eta < 2.2$ (S) or 2.4 (N), $\Delta\phi = 2\pi$)
  - $J/\psi \rightarrow \mu^+ \mu^-$
  - Heavy flavor decay single μ
  - $W^{\pm} \rightarrow \mu^{\pm}$ …
- **MPCs** ($3.1 < |\eta| < 3.8$, $\Delta\phi = 2\pi$)
  - $\pi^0 \rightarrow \gamma\gamma$, EM clusters ($\pi^0$, η, direct γ, etc)

Backup

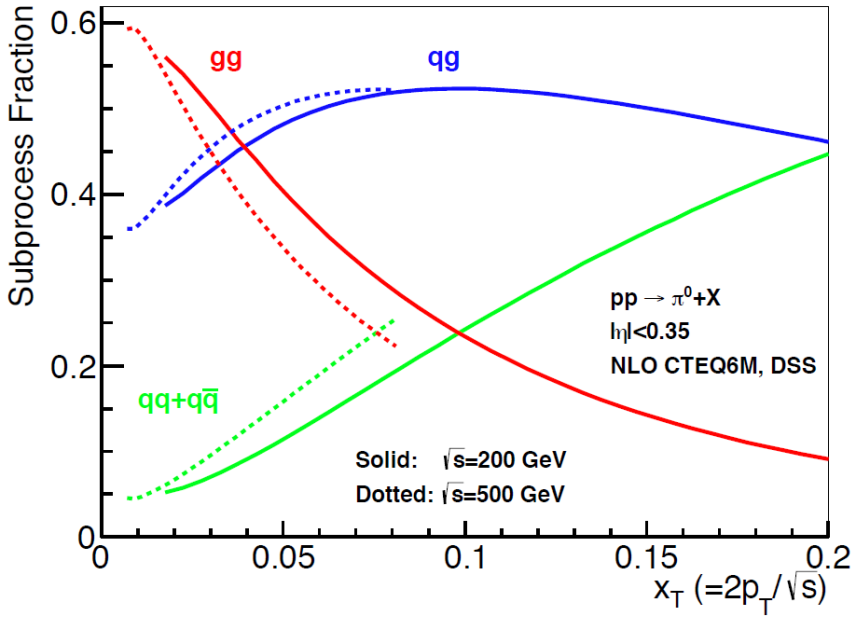
LO dominant partonic processes

LO helicity dependent double spin asymmetries for partonic reactions at RHIC

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$ [78]	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm, q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	



Backup Gluon polarization and π^0 A_{LL}

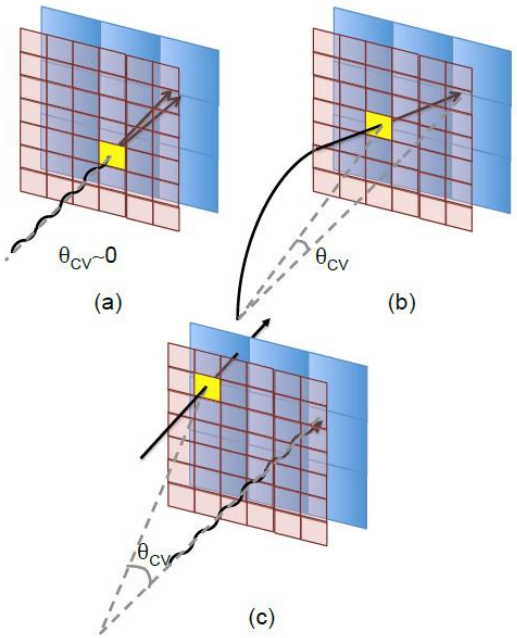


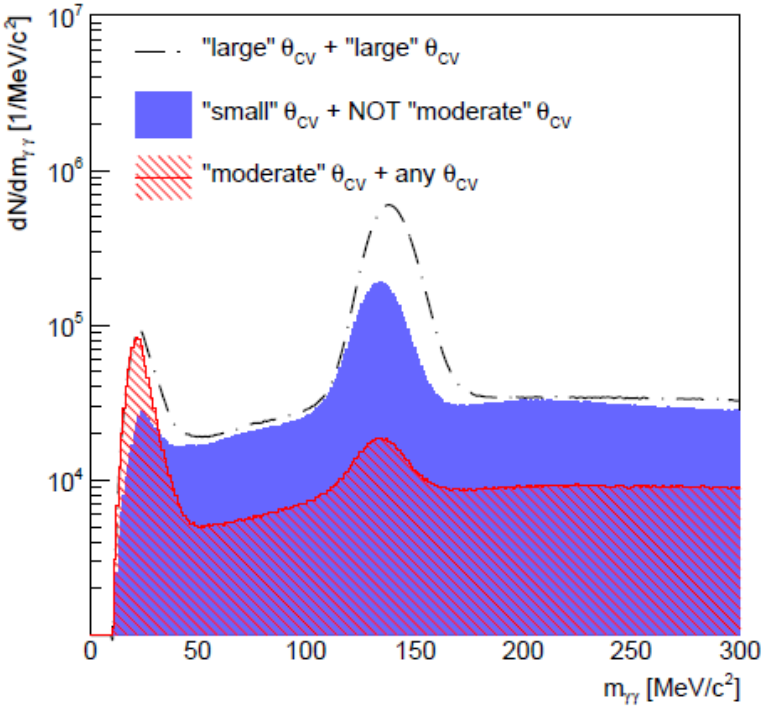
arXiv: 1501.01220

- $\Delta\sigma\,(pp \rightarrow \pi^0\,X) \approx \Delta q\,(x_1) \otimes \Delta g\,(x_2) \otimes \Delta\hat{\sigma}^{gq \rightarrow gq}\,(\hat{s}) \otimes D_q^{\pi^0}(z)$
  - $\Delta q\,(x_1)$: quark PDF (parton distribution functions), via DIS
  - $\Delta g\,(x_2)$: gluon PDF, ?
  - $\Delta\hat{\sigma}^{gq \rightarrow gq}\,(\hat{s})$: partonic hard scattering cross section, via pQCD calculation
  - $D_q^{\pi^0}(z)$: fragmentation functions, via $e^+ e^-$ collision

Backup π^0 analysis

PRD90, 012007

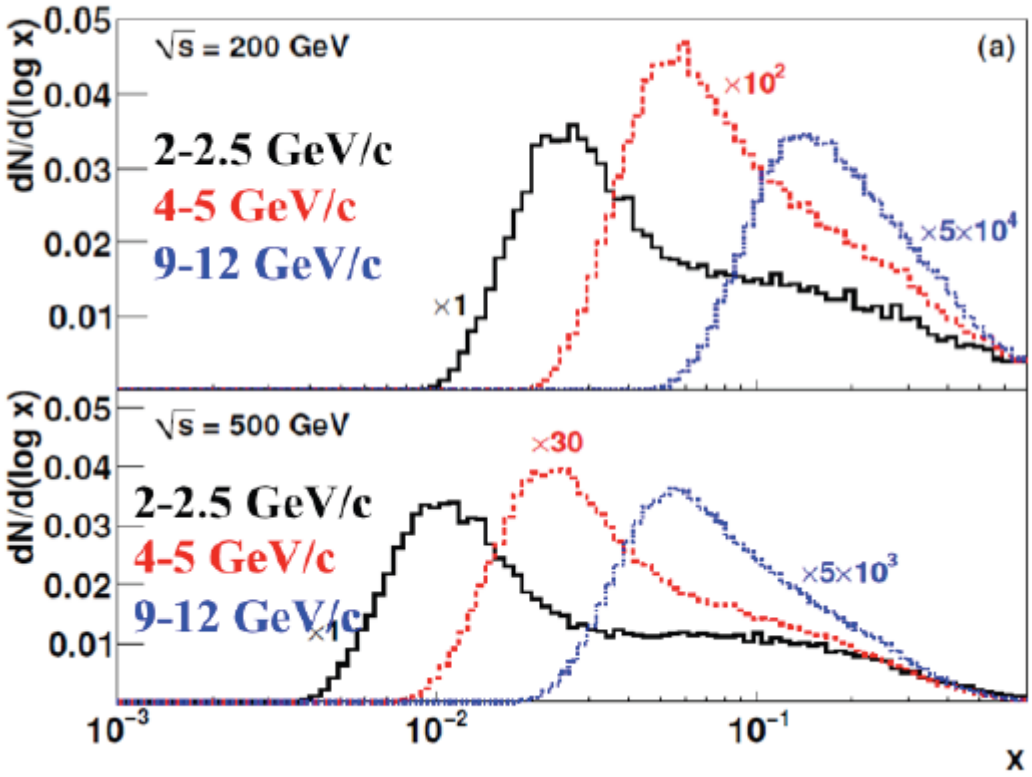




- **Inclusive π^0 analysis**
  - Charge veto (θ_{CV}) + Time of flight + Relative Luminosity correction + Background asymmetry correction (by background sampling)

Backup

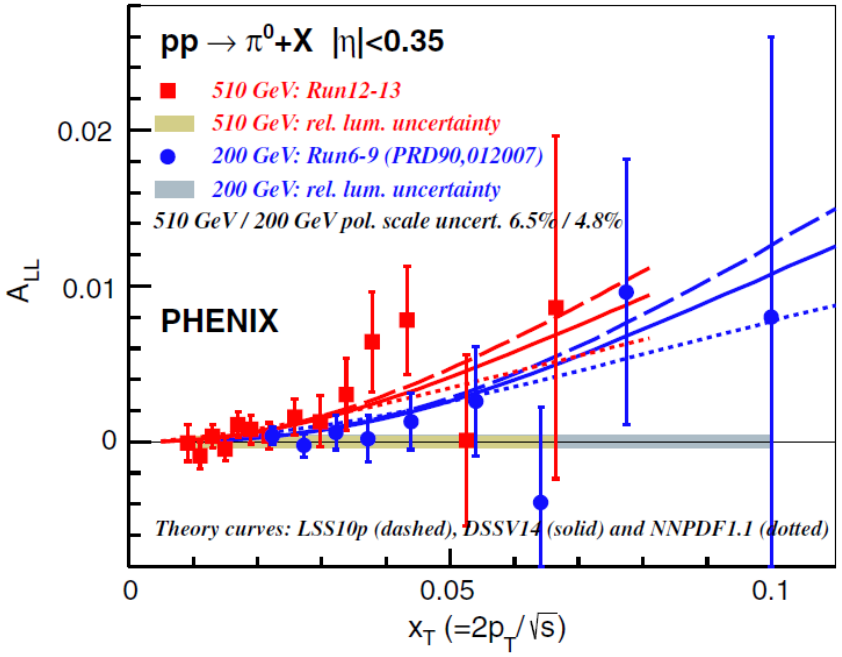
Bjorken x distributions of gluons in $gg \rightarrow \pi^0 \rightarrow \gamma\gamma$



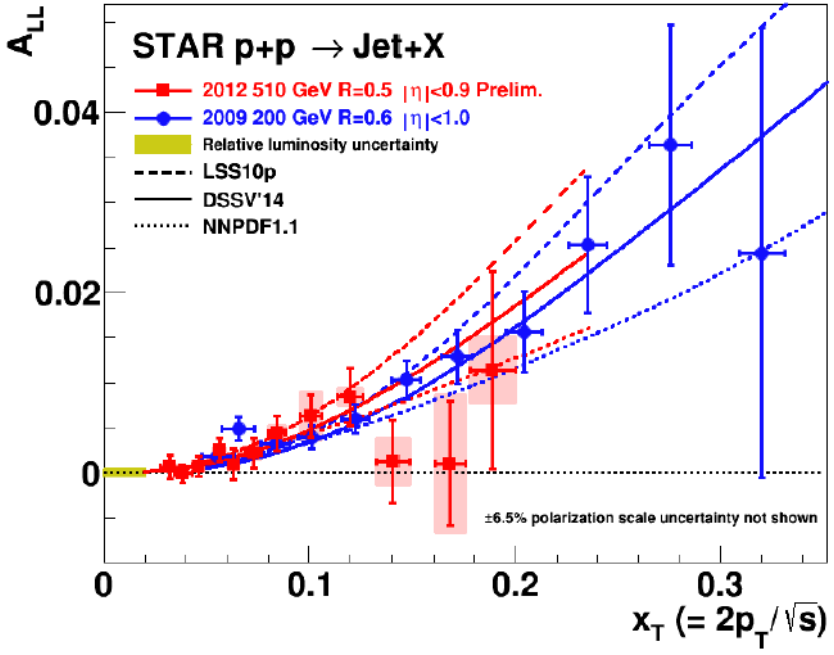
arXiv: 1501.01220

- **NLO pQCD π^0 simulations**

Backup ΔG A_{LL} comparison between PHENIX and STAR

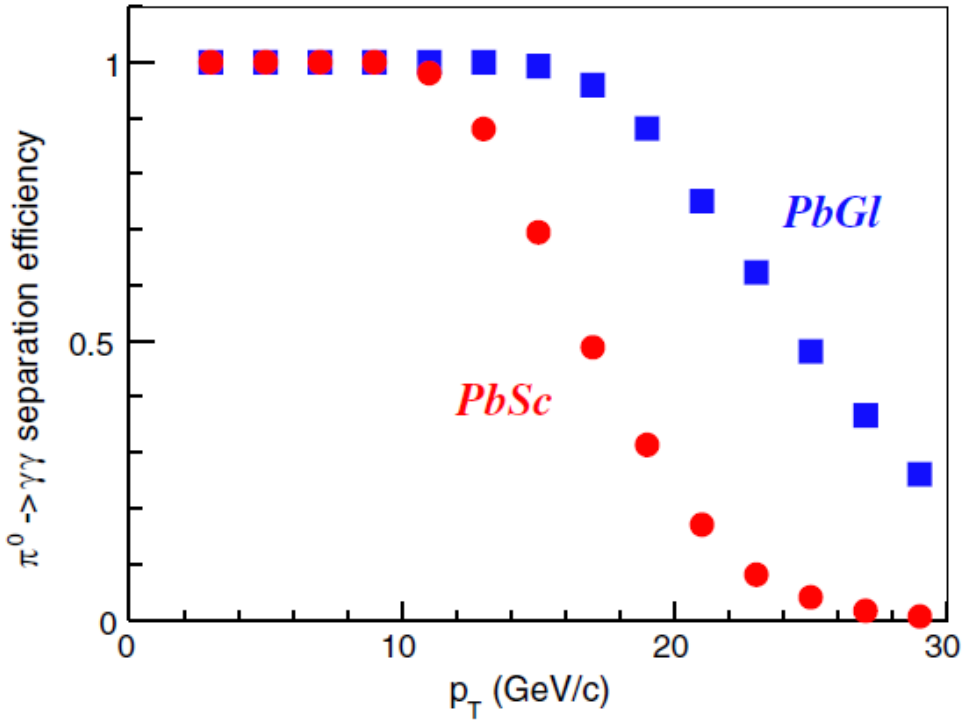


PRD93, 011501 (2016)



arXiv: 1602.03922

Backup PHENIX PbSc / PbGl efficiencies vs p_T

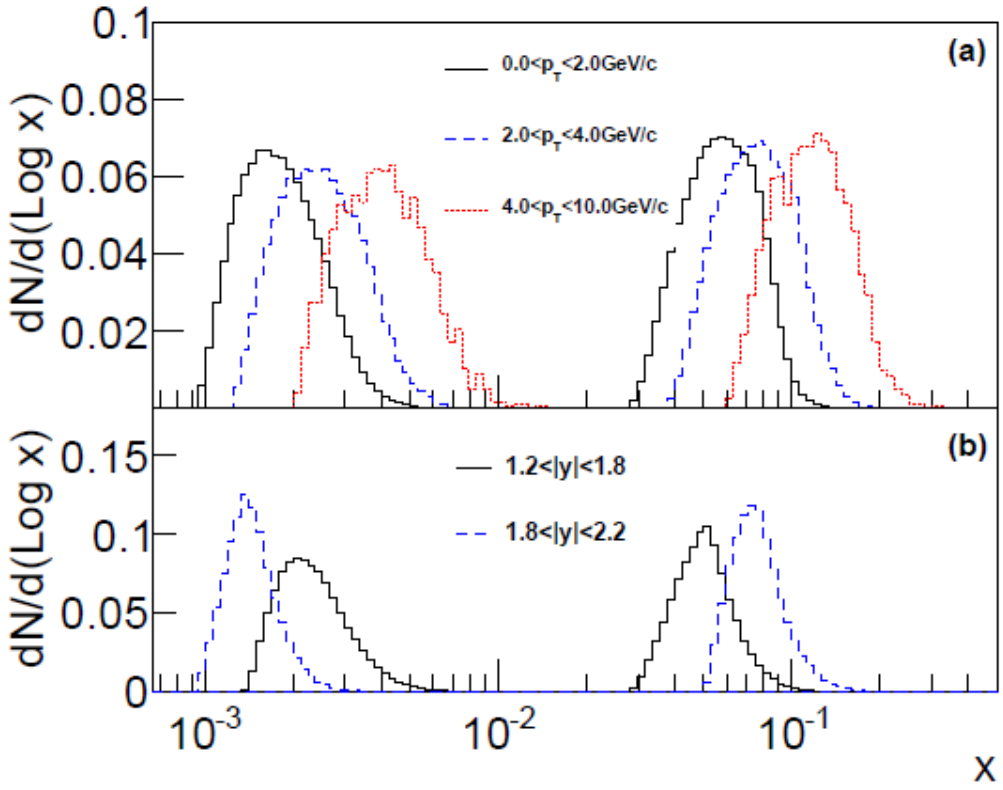


PRD93, 011501 (2016)

- **PYTHIA simulation**
  - Asymmetry between two photons energy < 0.8

Backup

Bjorken x distributions of gluons in $gg \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X$

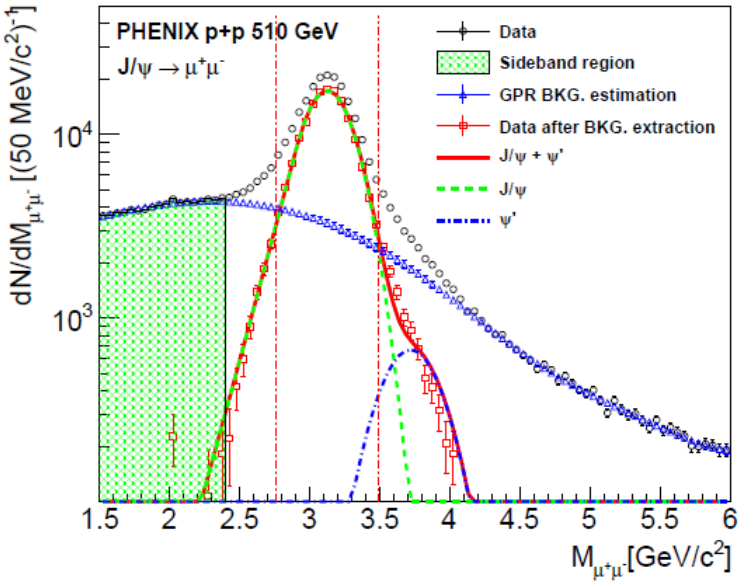


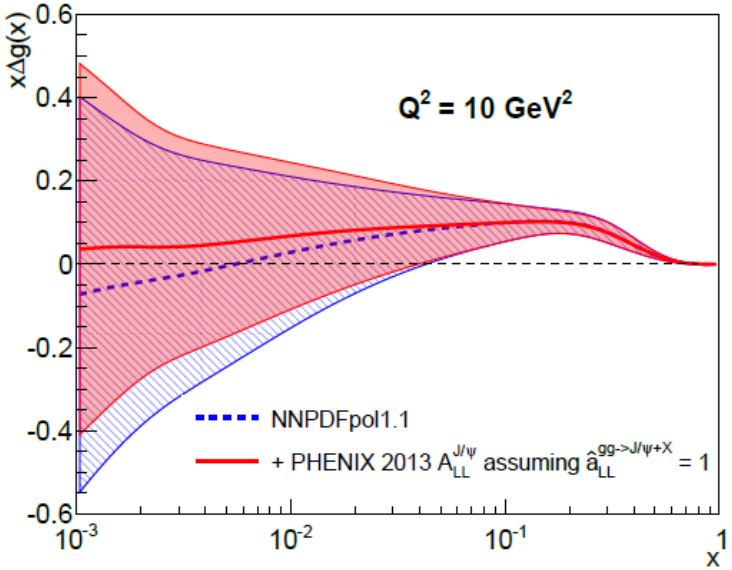
arXiv: 1606.01815

- **PYTHIA simulation**
  - J/ψ generated in $1.2 < |\eta| < 2.2$ and decay muons within $1.2 < |\eta| < 2.2 / 2.4$

Backup Forward A_{LL} via $J/\psi + X \rightarrow \mu^+\mu^-$

arXiv: 1606.01815

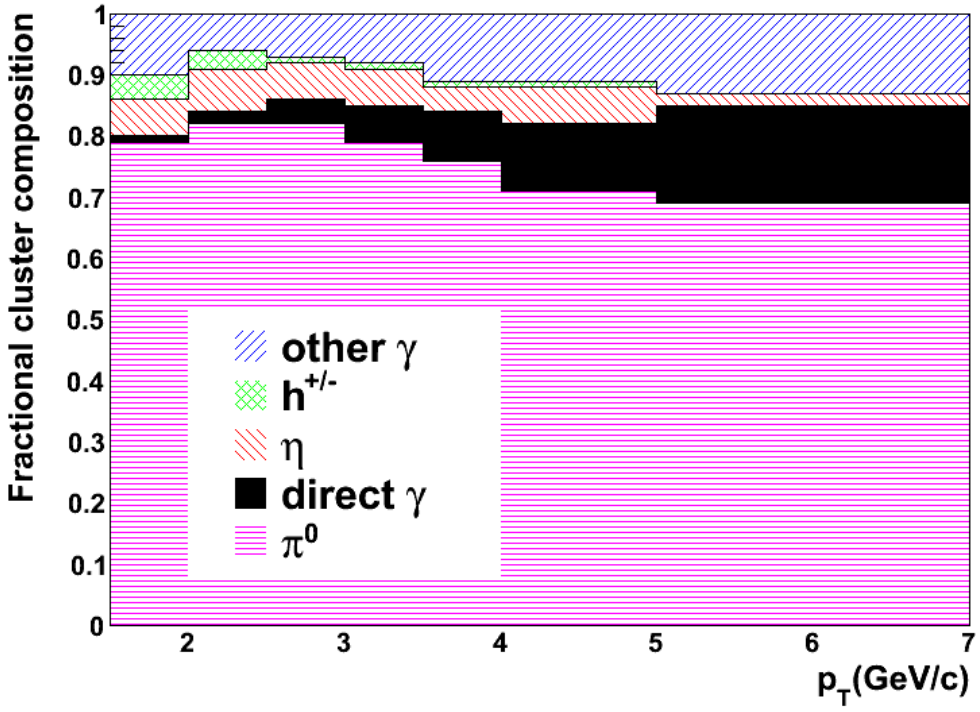




- **Signal extraction (left) and Comparison with NNPDFPol1.1 (right)**
  - For the comparison, 100 replicas of NNPDFPol1.1 was used
  - Red line + band indicates reweighted NNPDFPol1.1 by J/ψ results

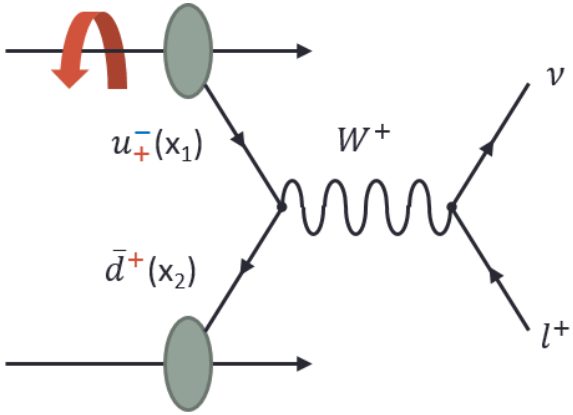
Backup π^0 abundance in forward EM clusters

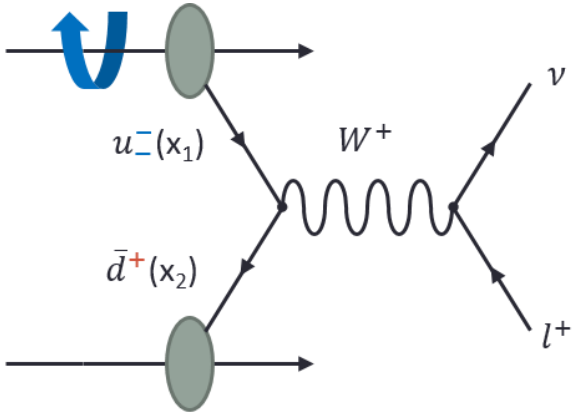
arXiv: 1312.1995v1



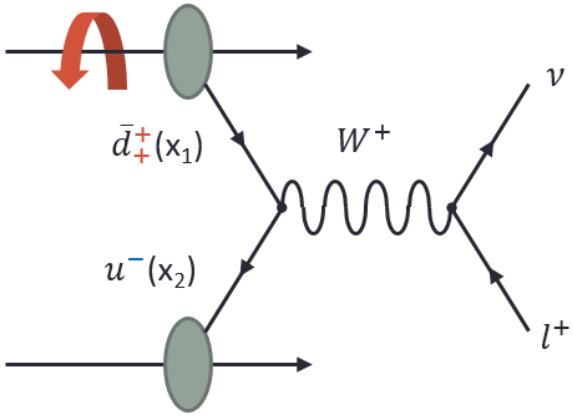
- **PYTHIA for √s = 200 GeV with full detector (MPC) simulation**
  - Kinematic cuts applied

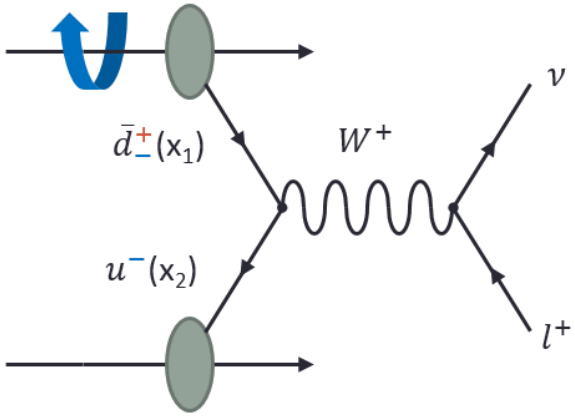
Backup *W* partonic processes





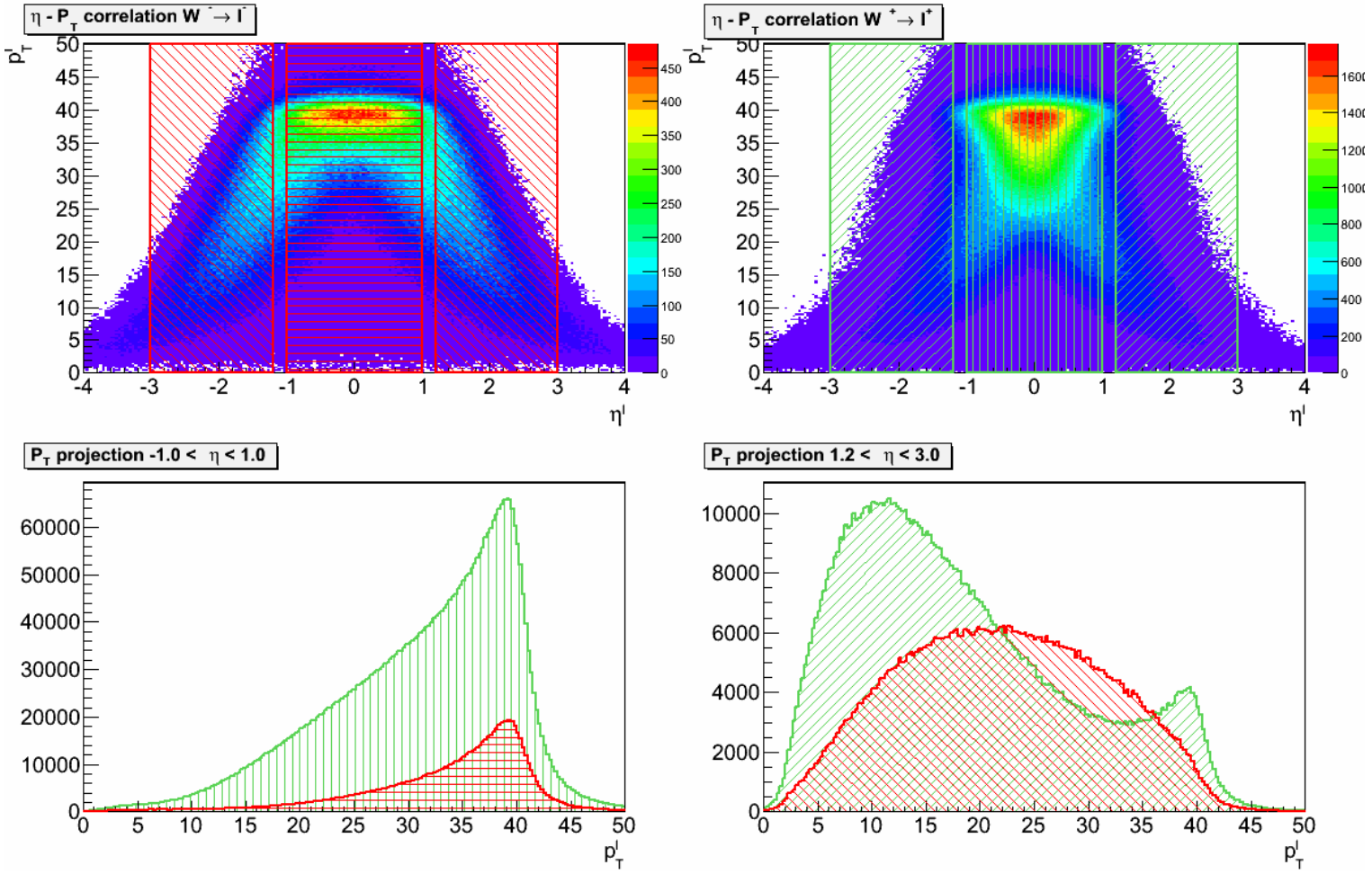
$$A_L^{W+} = \frac{u^-_-(x_1)\bar{d}^+(x_2) - u^-_+(x_1)\bar{d}^+(x_2)}{u^-_-(x_1)\bar{d}^+(x_2) + u^-_+(x_1)\bar{d}^+(x_2)}$$ ← 1. Δu is being probed





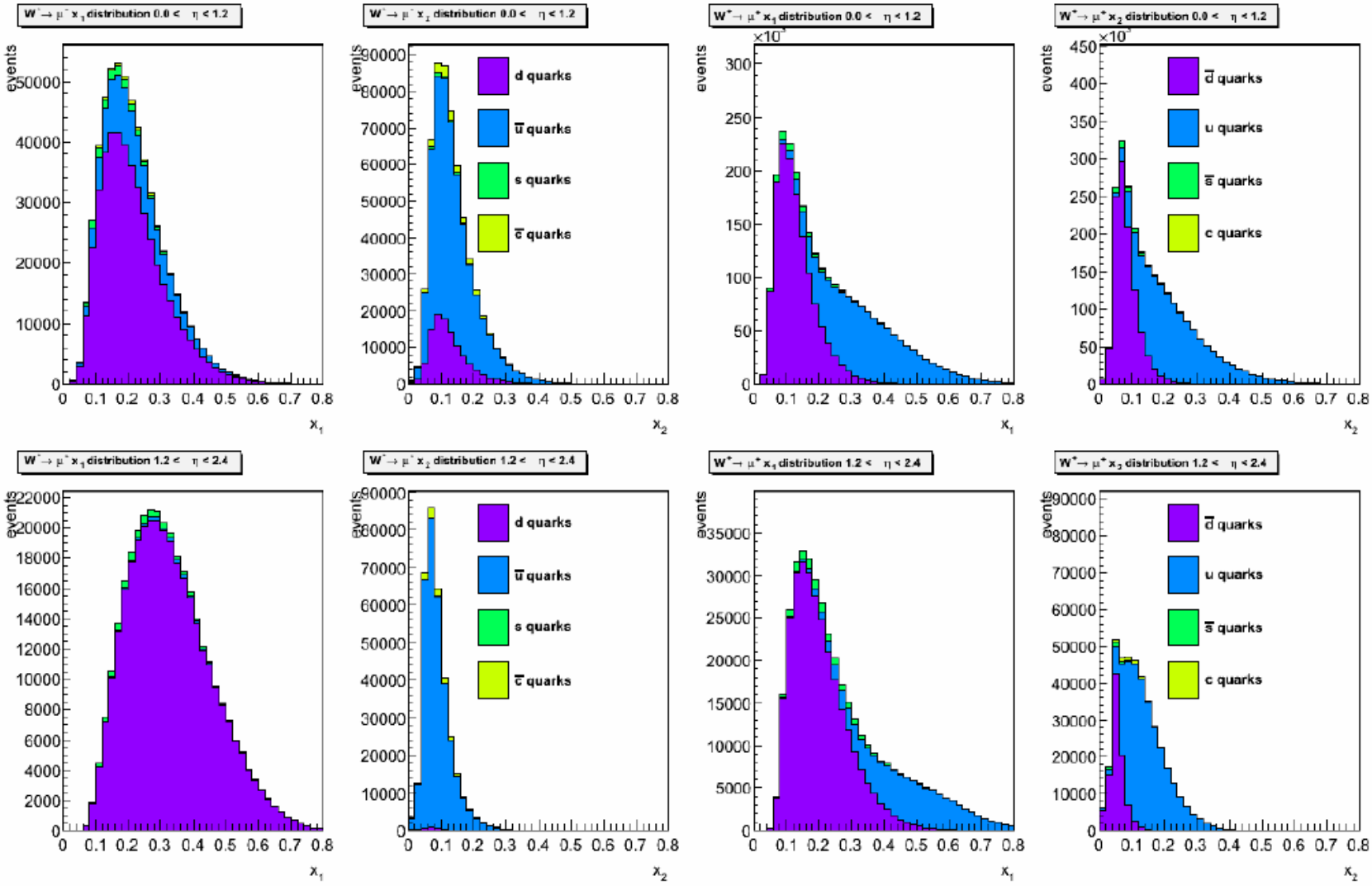
$$A_L^{W+} = \frac{\bar{d}^+_-(x_1)u^-(x_2) - \bar{d}^+_+(x_1)u^-(x_2)}{\bar{d}^+_-(x_1)u^-(x_2) + \bar{d}^+_+(x_1)u^-(x_2)}$$ ← 2. $\Delta\bar{d}$ is being probed

Backup *W* kinematics in PHENIX acceptance



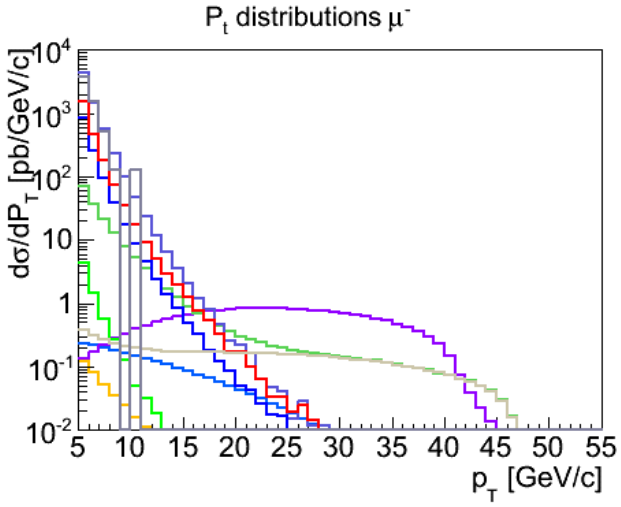
Backup

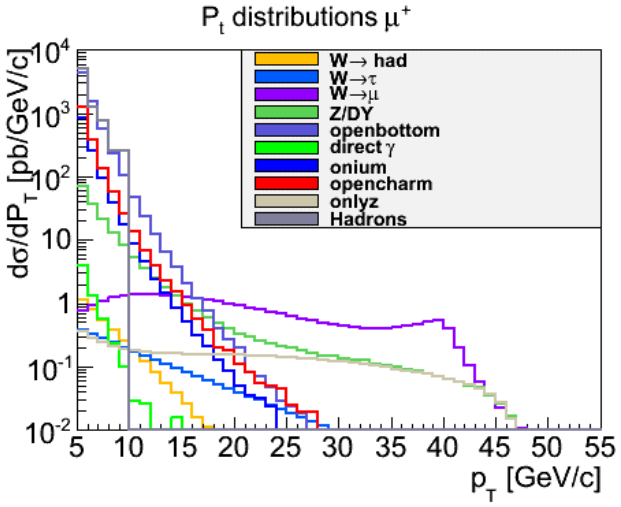
Bjorken x distributions of $W^{\pm}$

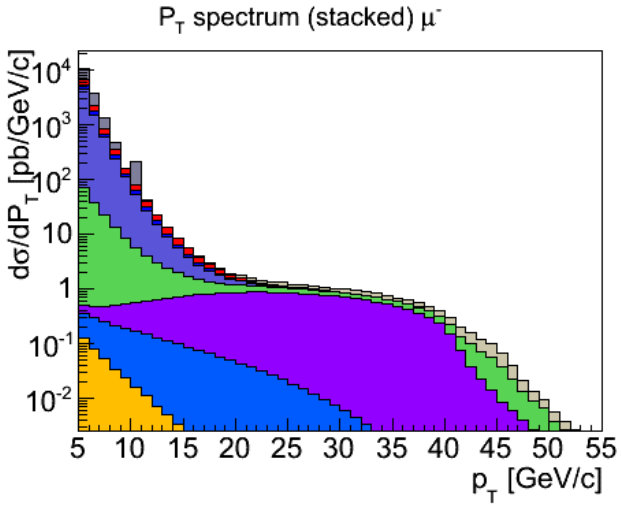


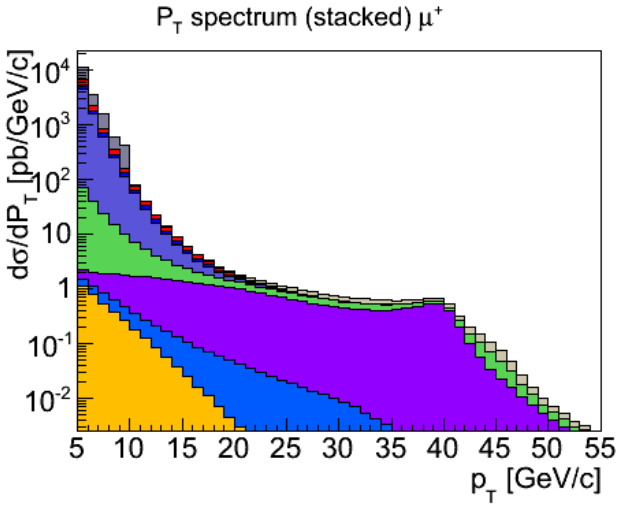
Backup

$W \rightarrow \mu$ muonic decay processes



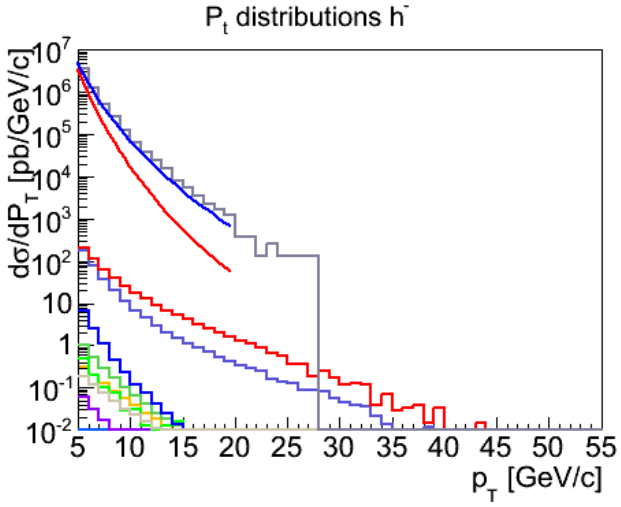


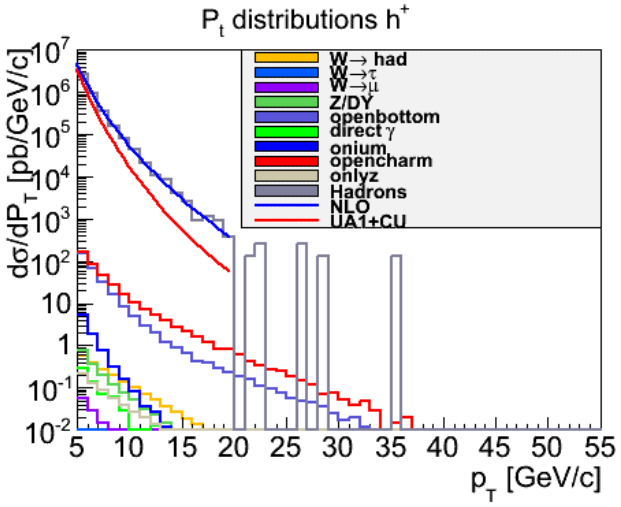


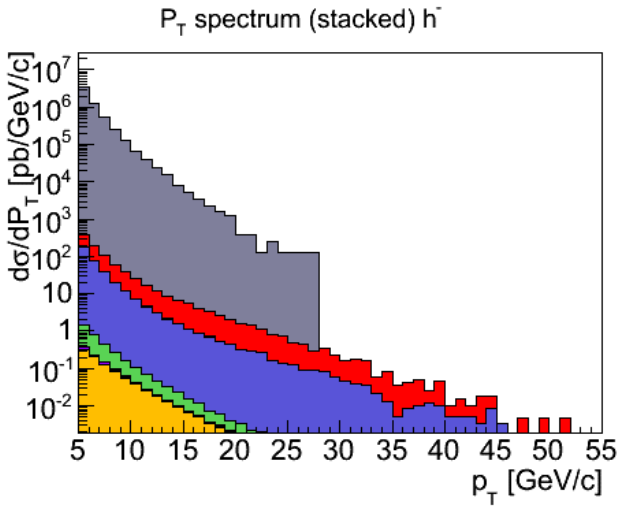


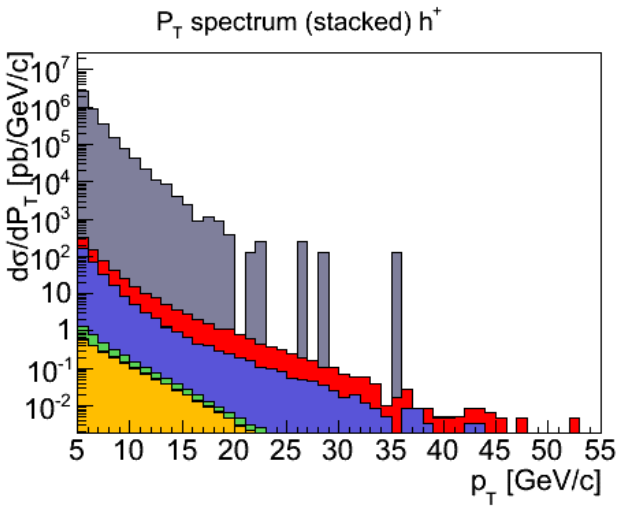
Backup

$W \rightarrow \mu$ hadronic decay processes



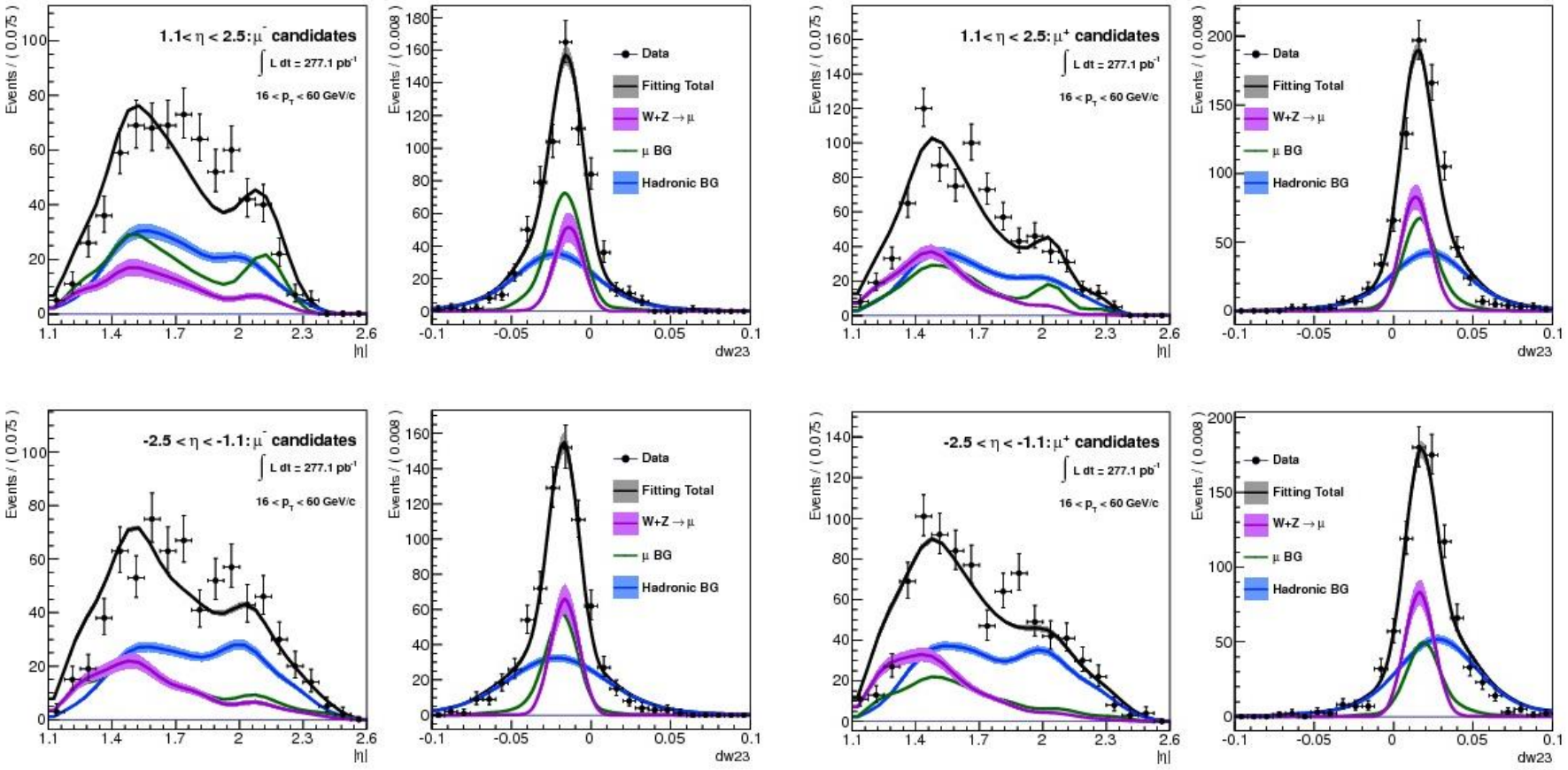






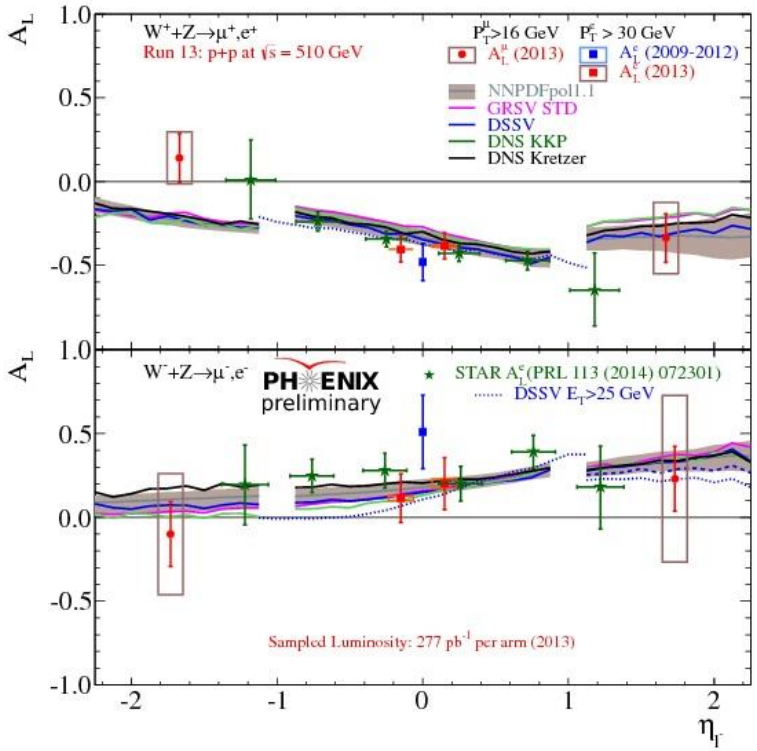
Backup

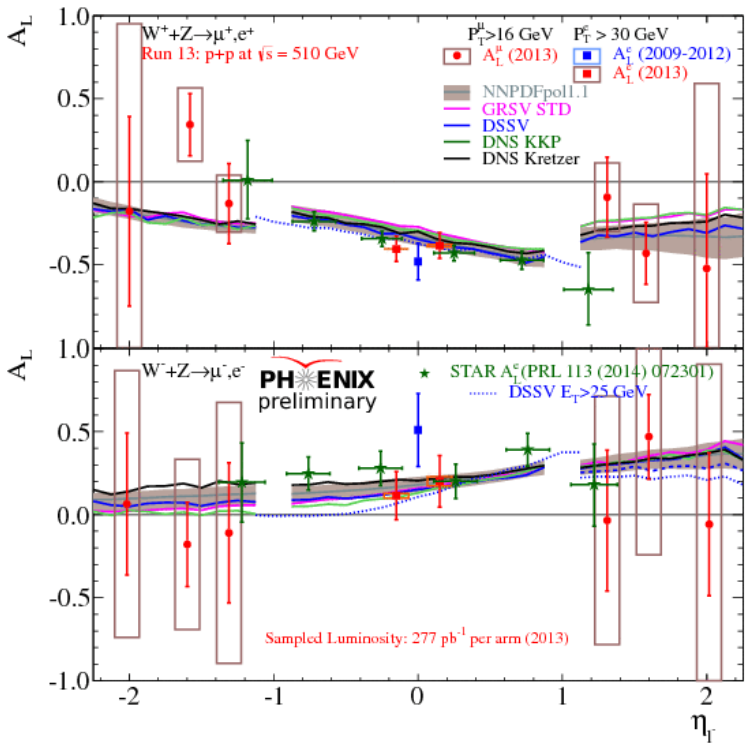
$W \rightarrow \mu$ signal extraction by unbinned max. likelihood fit



Backup

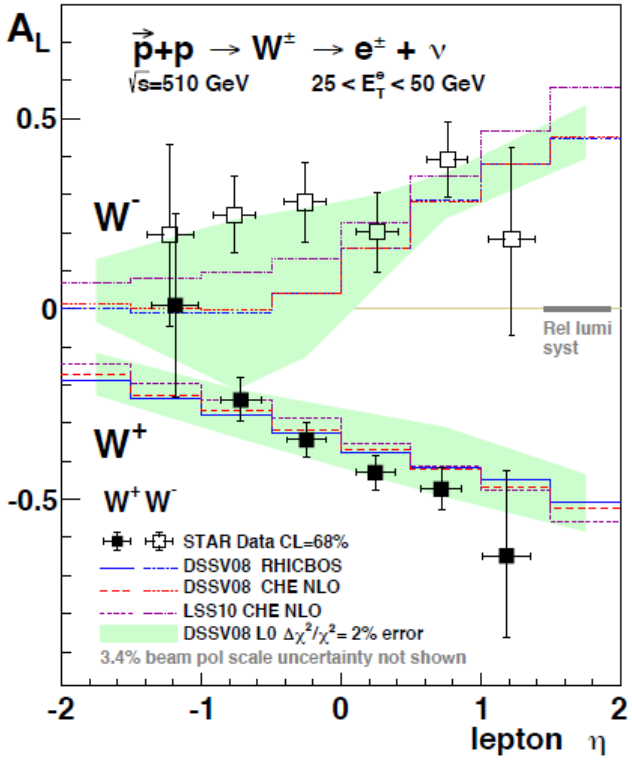
$W \rightarrow \mu$ Run13 preliminary with other results

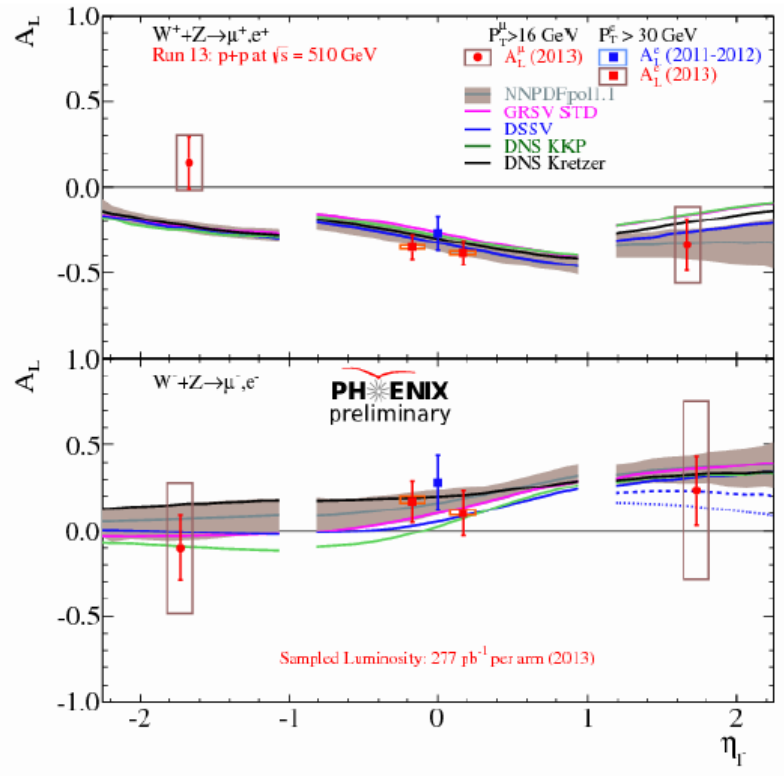




Backup *W* results comparison between PHENIX and STAR

arXiv: 1602.03922





Backup

Future RHIC data taking perspectives

arXiv: 1602.03922

	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^+ 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^+ 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^+ 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.