Recent Results on Proton Helicity Structure Studies from PHENIX

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for the PHENIX collaboration

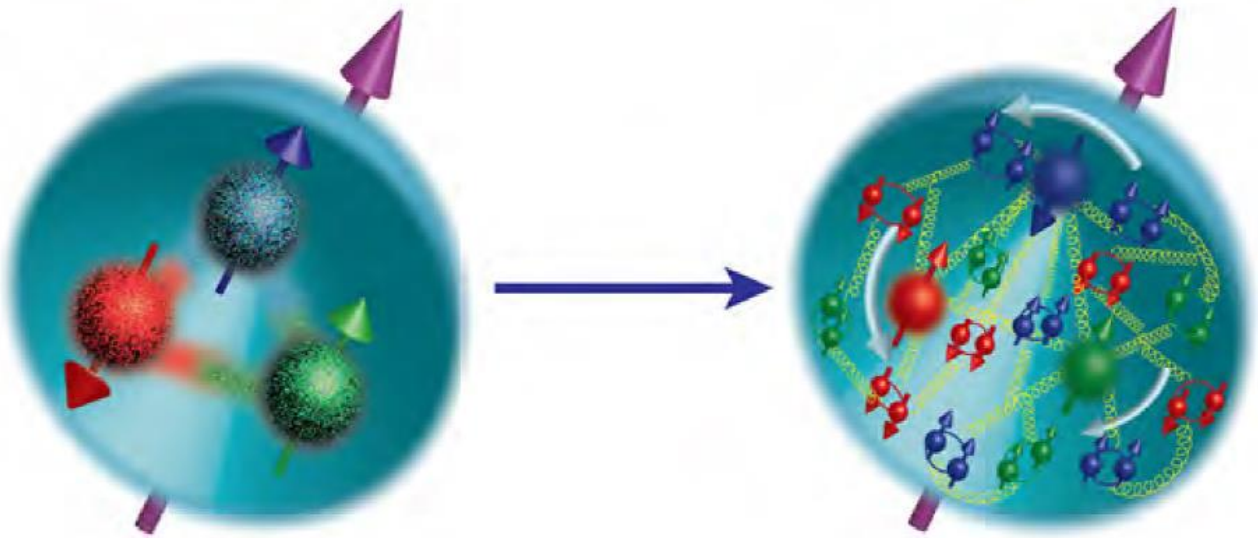
arXiv: 1501.01220

- RHIC Spin program
  - PHENIX and STAR
  - Longitudinal and Transverse
  - Achievements, Near term projections, and Future opportunities

Outline

- Introduction
  - Physics motivations
  - RHIC
  - PHENIX detectors
  - Recent longitudinal spin runs
- Proton helicity structure studies
  - Polarized gluon distributions (ΔG)
  - Polarized light sea quark distributions ($\Delta\bar{q}$)
- Summary and Outlook

Introduction Physics motivations

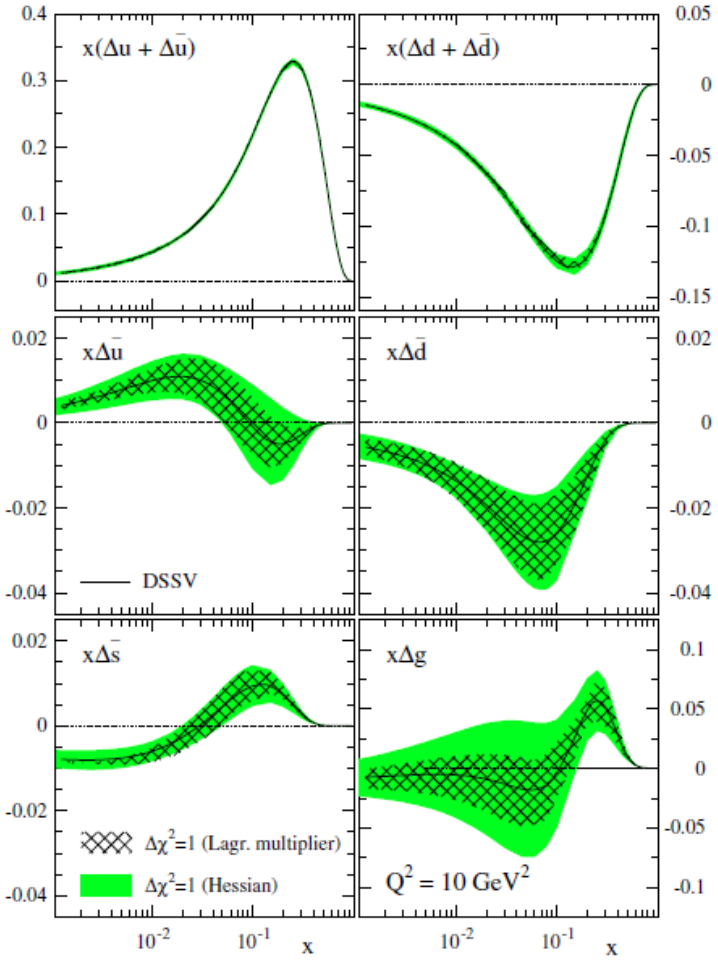


- It's not a big secret these days…
  - $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
  - PHENIX aims: both longitudinal spin structure and transverse spin phenomena

Tomorrow 11:30 AM by Dr. Yuji Goto

This talk

Introduction Physics motivations



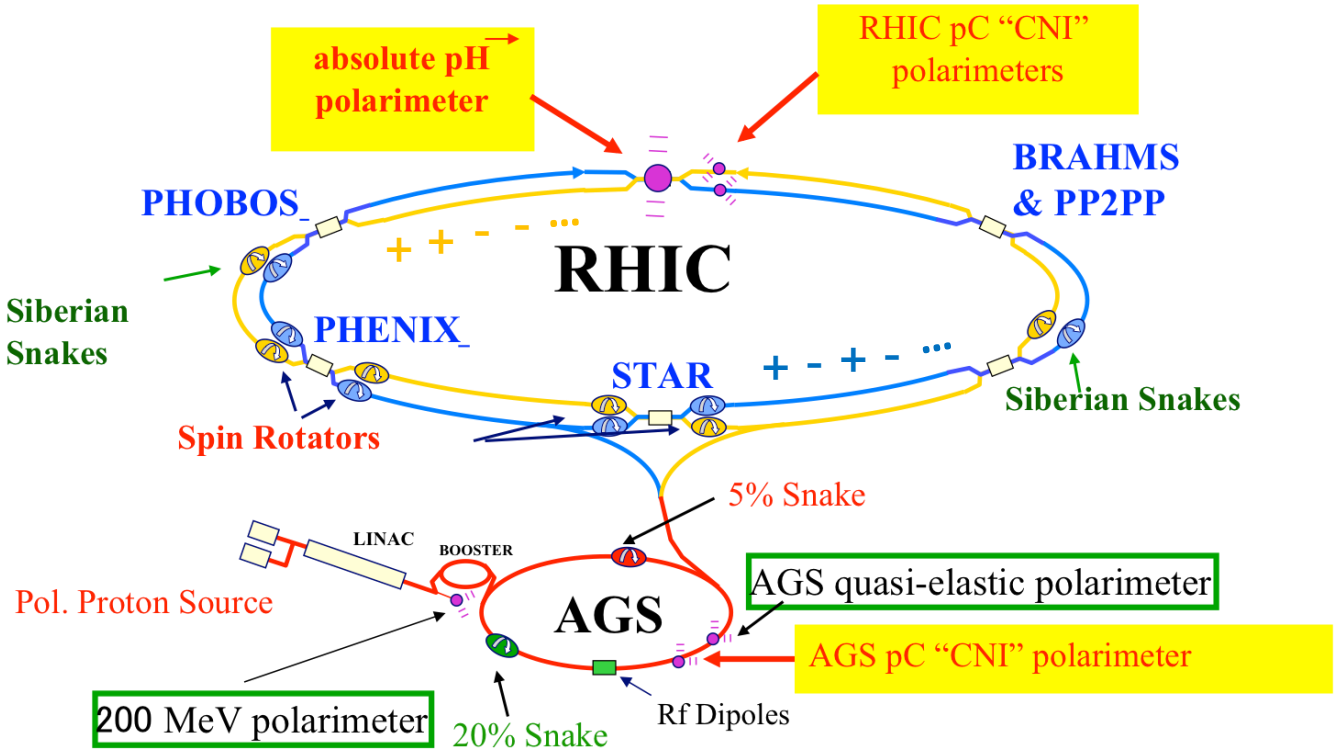
PRD80. 034030 (2009)

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

- $\Delta\Sigma = (\Delta q + \Delta\bar{q})$
  - $(\Delta q + \Delta\bar{q})$: well constrained thanks to DIS results
  - $\Delta\bar{q}$: large uncertainty from fragmentation processes
    → measure A_L by *W* decay leptons
- ΔG
  - Largely unconstrained
    → measure A_{LL} by various probes

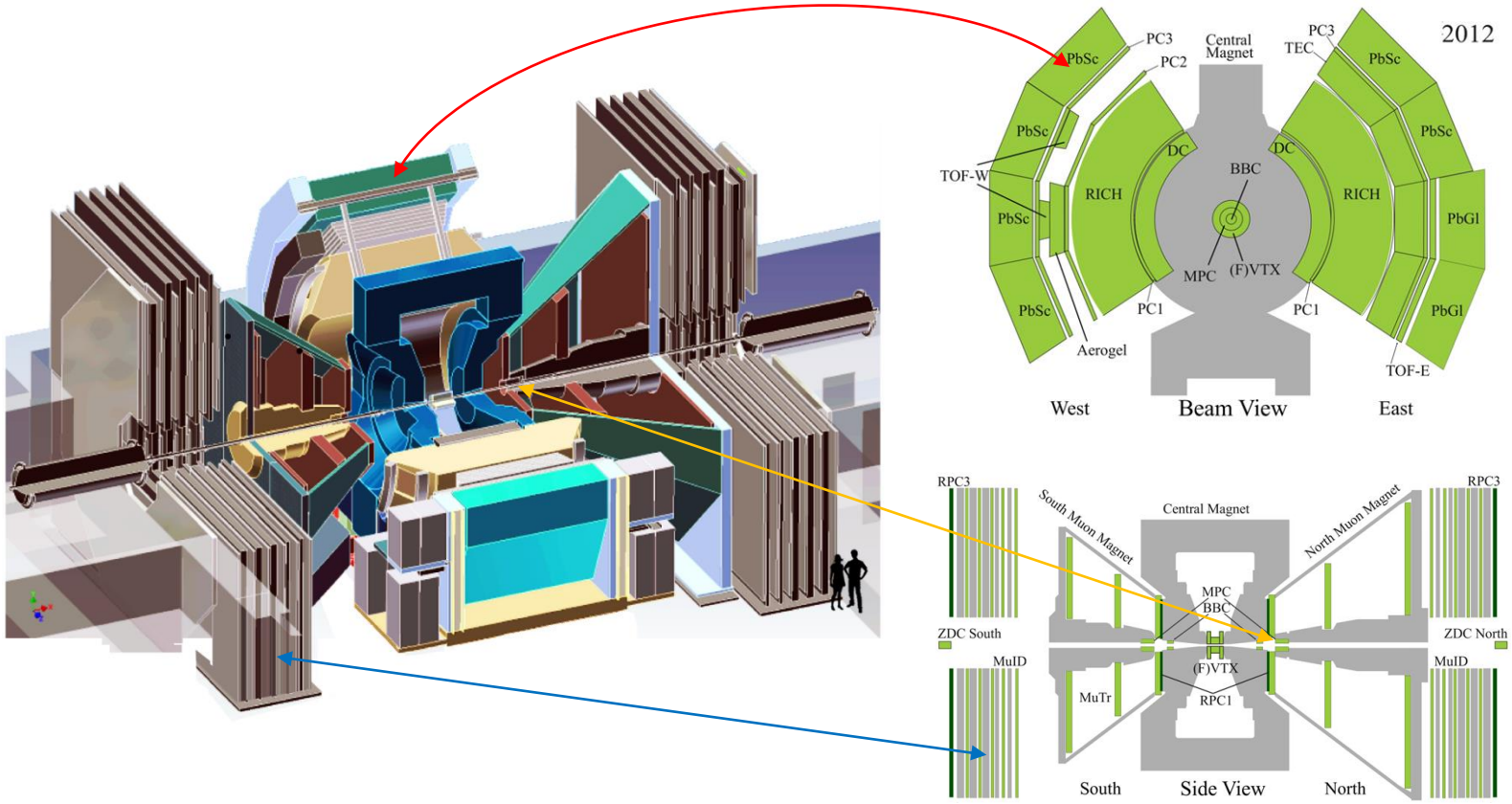
This talk mainly presents Run13 highlights

Introduction RHIC



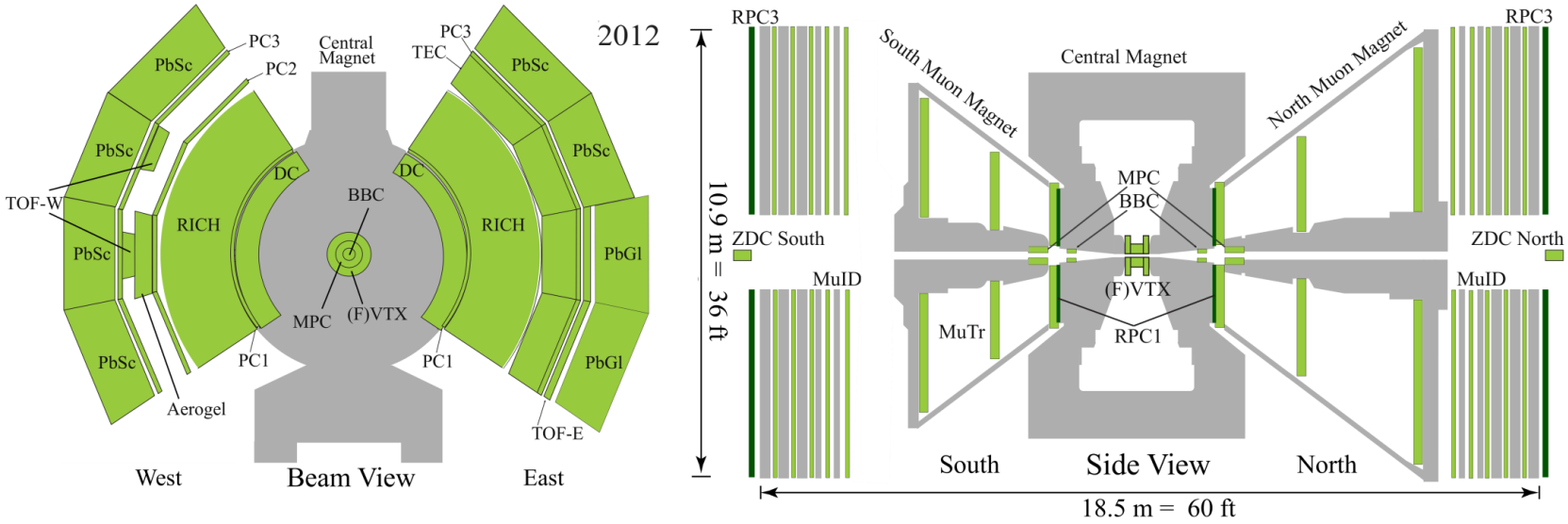
- RHIC @ Brookhaven Lab., NY
  - Polarized p + p at $\sqrt{s}$ = 62.5 - 510 (GeV)
  - max. $\langle P \rangle$ (avg. beam polarization) $\approx$ 60 %

Introduction PHENIX detectors



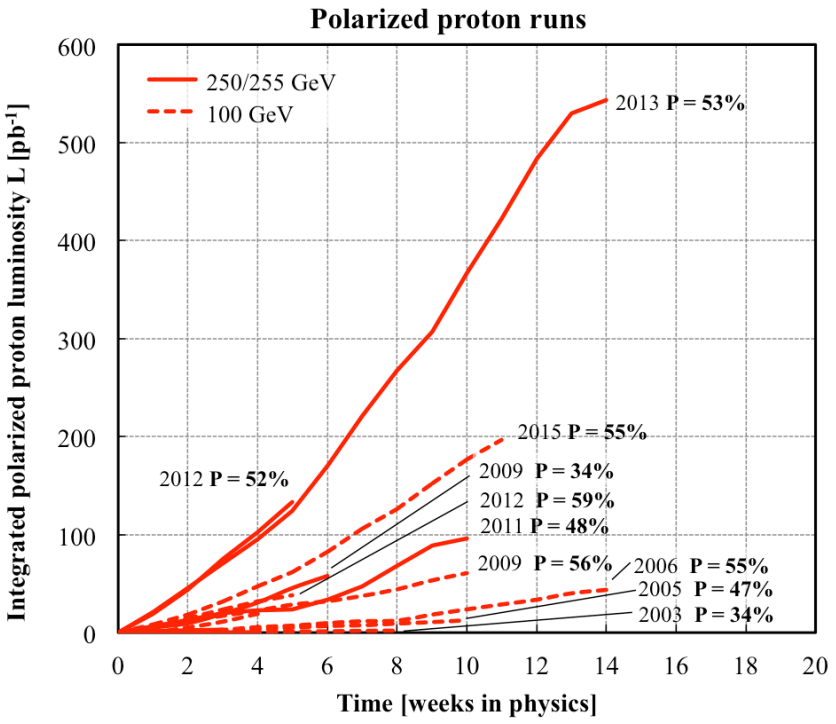
- PHENIX detector
  - High rate capability/granularity, Good mass resolution/pID, and Rare event triggers
  - Recent upgrades: forward muon trigger (2013) and inner tracking (VTX (2011) / FVTX (2012))

Introduction PHENIX detectors



- Central Arms (midrapidity)
  - $|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$
  - VTX (from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbSc, PbGl
- Muon Arms (forward rapidity)
  - $1.2 < \eta < 2.2$ (S) or 2.4 (N), $\Delta\phi = 2\pi$
  - FVTX (from 2012)
  - Tracking: MuTr
  - pID: MuID, RPCs (from 2011/2012)
- MPCs (forward EMCal)
  - $3.1 < |\eta| < 3.8$, $\Delta\phi = 2\pi$

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	500	14	33 / 36	1.66	0.20
	200	15.6	56 / 57	4.98	1.59
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**

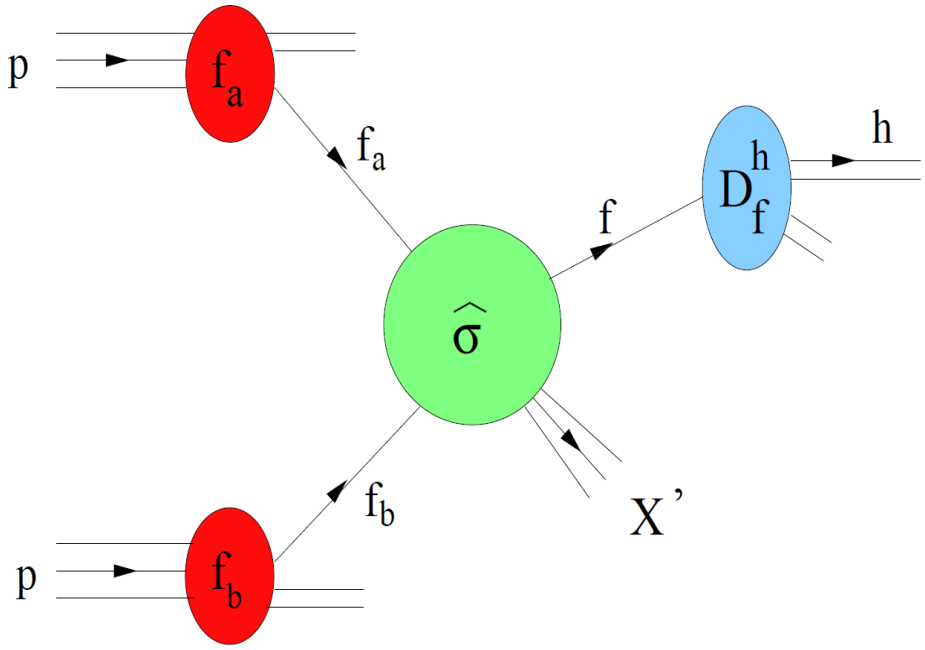
* MinBias with wide (no) vertex at PHENIX

- FoM1 = $L\cdot\langle P_B\rangle\cdot\langle P_Y\rangle$ ↔ Single spin asymmetry (A_L) ↔ $\Delta\bar{q}$
- FoM2 = $L\cdot\langle P_B\rangle^2\cdot\langle P_Y\rangle^2$ ↔ Double spin asymmetry (A_{LL}) ↔ ΔG

Polarized gluons (ΔG)

Observable: A_{LL}

ΔG Introduction



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

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

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

technically,

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

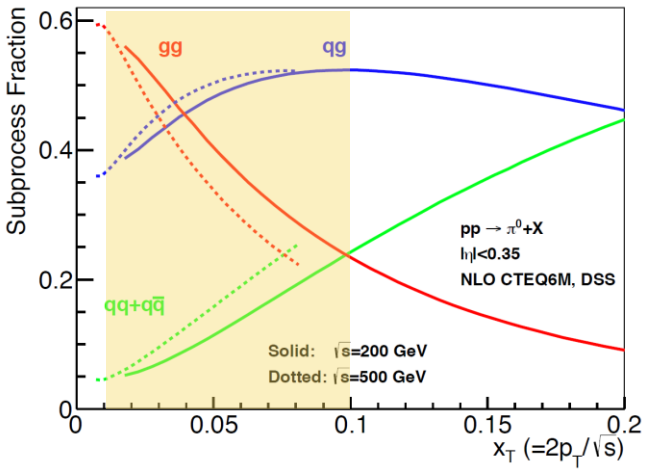
- P : avg. polarization of each beam
- N++ (N+-) : yields in same (opposite) helicity
- R ($\frac{L++}{L+-}$) : relative luminosity

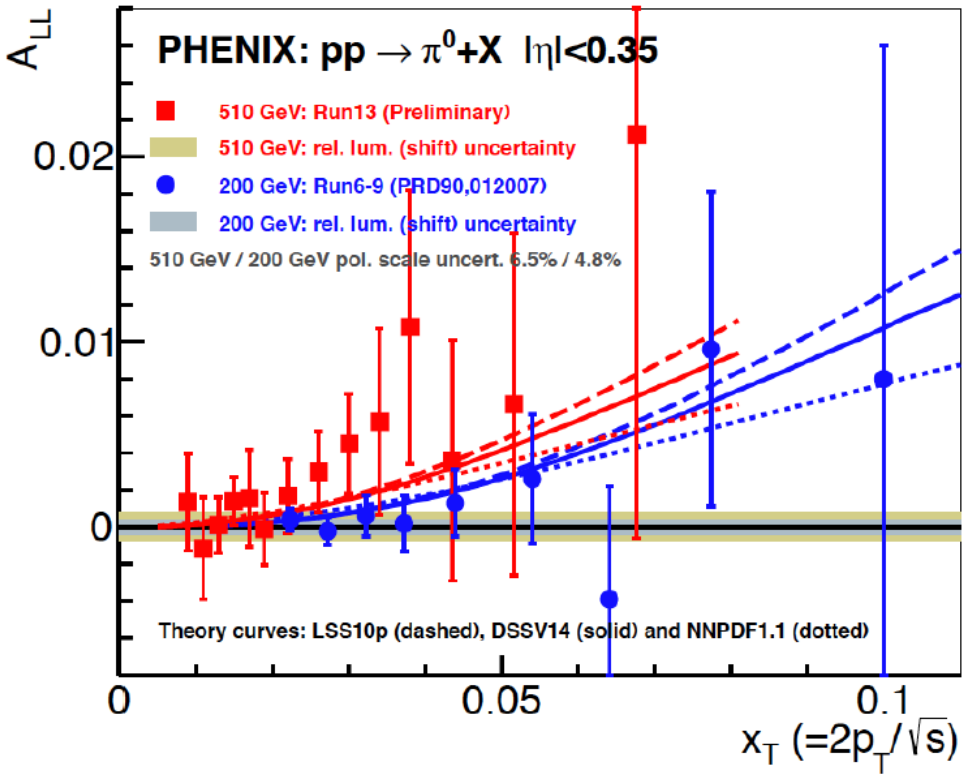
- ΔG measurement at PHENIX: via various probes
  - Midrapidity (Central Arms): γ, **π^0**, $\pi^{\pm}$, η, heavy flavor decay leptons
  - Forward (MPC): electromagnetic clusters

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

Will be officially published soon!

arXiv: 1501.01220

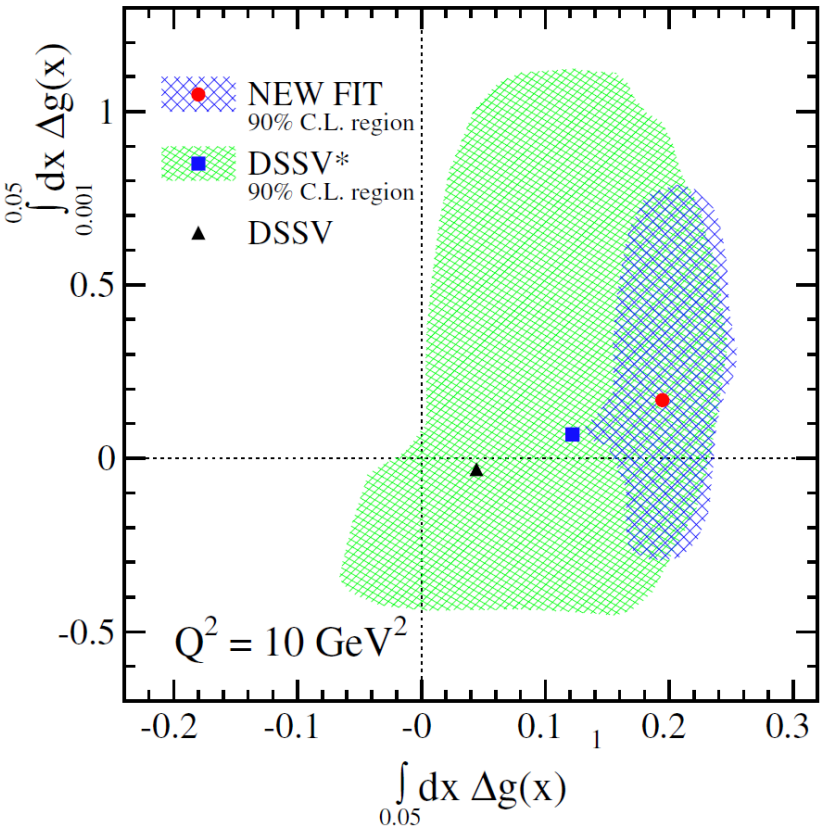




- Inclusive π^0 A_{LL} in Run 12-13 (Int. L = 20, 108 pb^{-1}) pp 510 GeV
  - First observation of significant non-zero A_{LL} (ΔG) in hadron production
    * of course, let's not forget 'first non-zero A_{LL}' was observed in STAR jet measurements
  - Extended Bjorken x coverage down to ~ 0.01

ΔG DIS + pp global pQCD fit (DSSV2014)

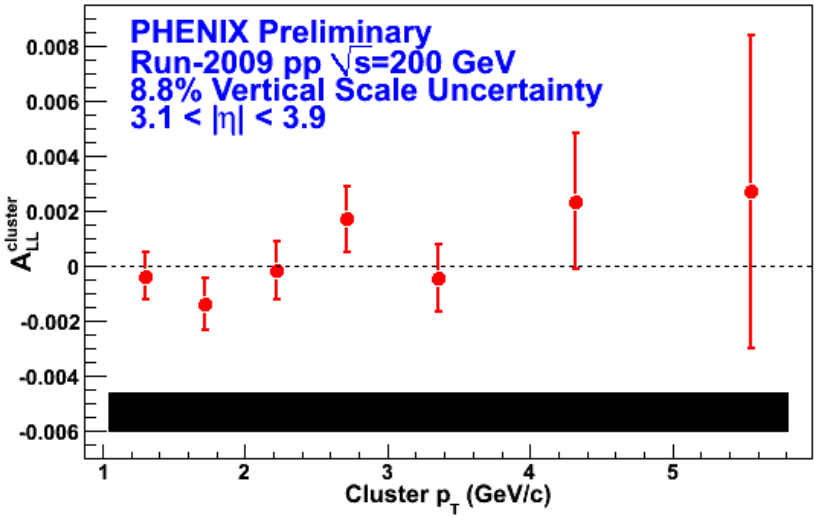
PRL113, 012001

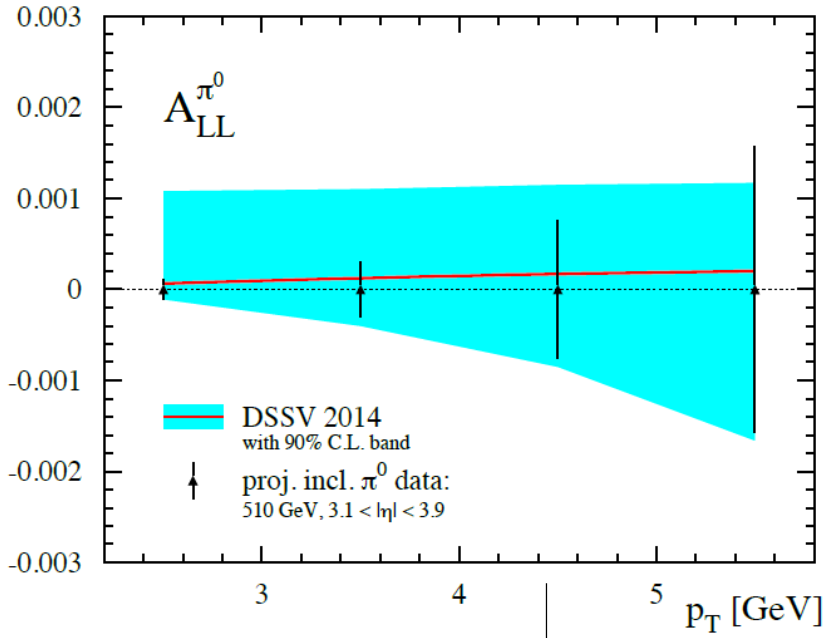


- DSSV2014 (DSSV* and New fit):
  - Included:
    RHIC data for original DSSV (before Run 9)
    New COMPASS (SI)DIS data sets
- $\int_{0.05}^{1} dx\ \Delta g\ (x)$
  - DSSV*: RHIC Run 9 data excluded
  - DSSV New fit: RHIC Run 9 data included
    a. $0.20\ ^{+0.06}_{-0.07}$ at 90 % C.L.
    b. LSS10p, DSSV, and NNPDF1.1 agree
- $\int_{0.001}^{0.05} dx\ \Delta g\ (x)$
  - Large uncertainty (no data points)
  - Upcoming forward data (next slide)

ΔG Other channels

arXiv: 1501.01220



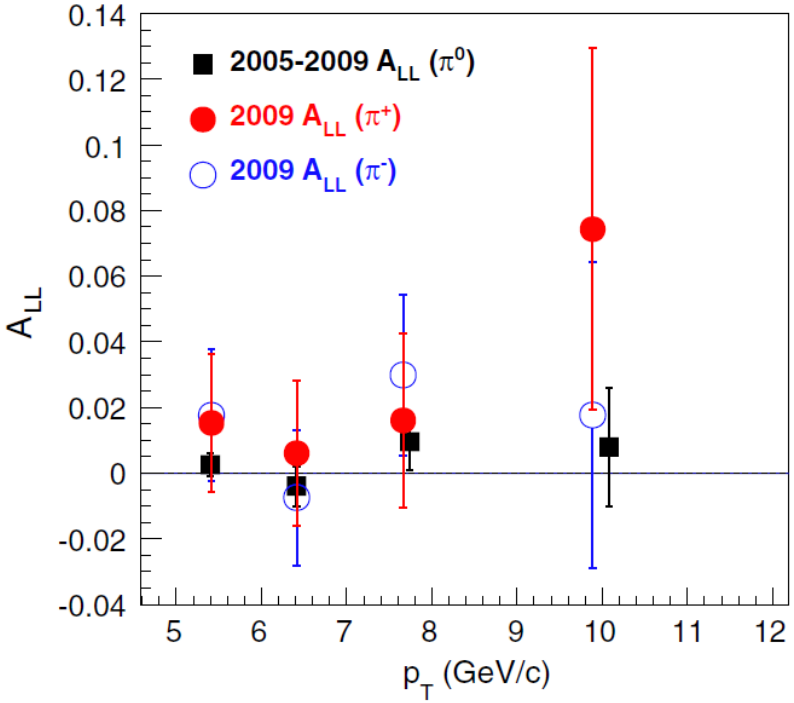


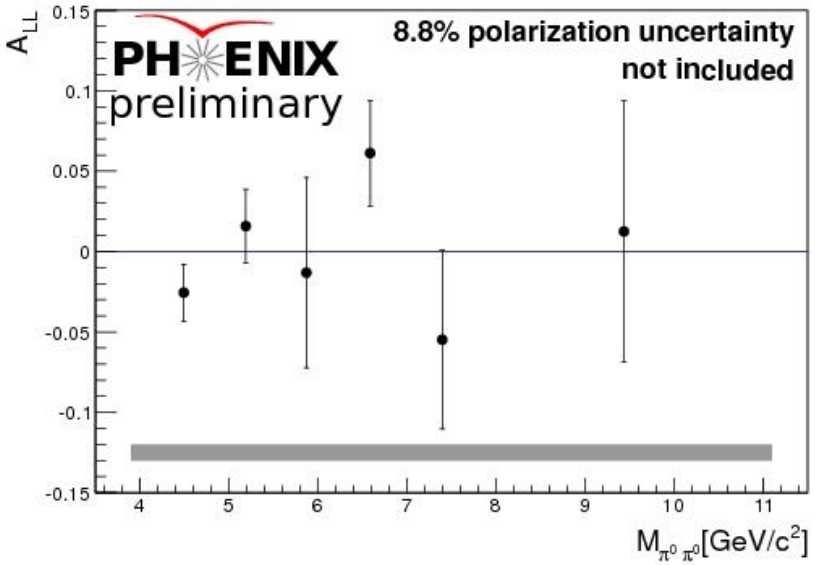
This is a projection

- A_{LL} at forward rapidity ($3.1 < \eta < 3.9$):
  - Run 9 data (left) / Run 13 projection (right, analysis is underway)
  - π^0 abundant (> 70 %) EM clusters
  - Probes Bjorken x down to ~ 0.001

ΔG Other channels

PRD91, 032001

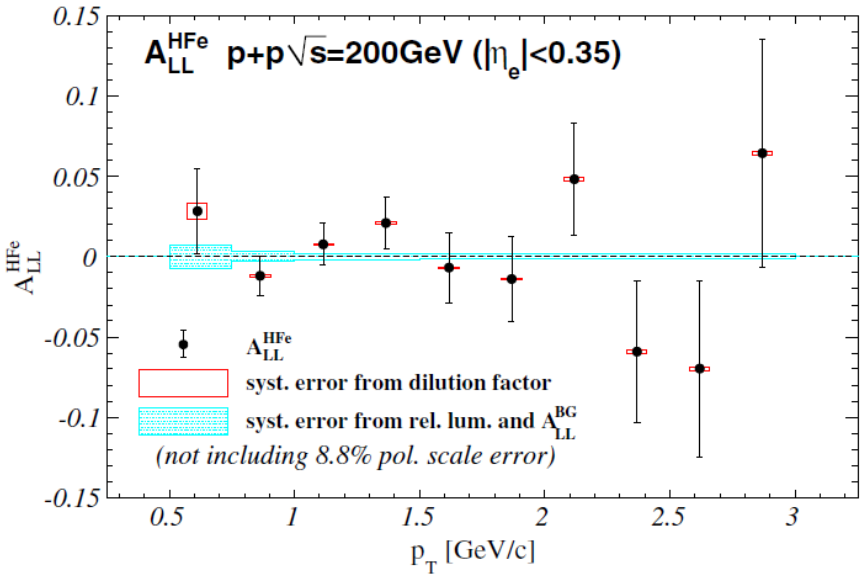


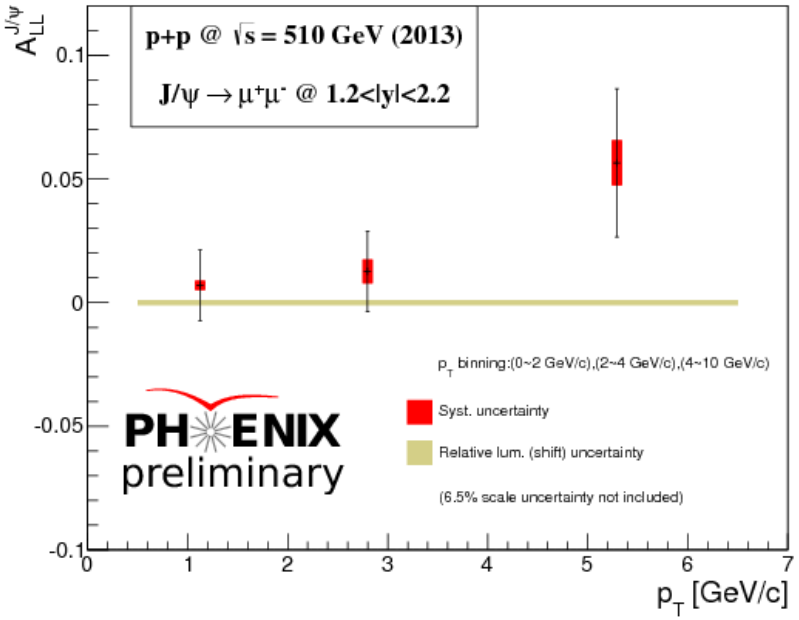


- $\pi^{\pm}$ (Charged pions)
  - Sensitive to the sign of ΔG
  - Run 13 analysis is underway
- π^0 pairs
  - Better Bjorken x determination
  - Run 9 analysis is underway

ΔG Other channels

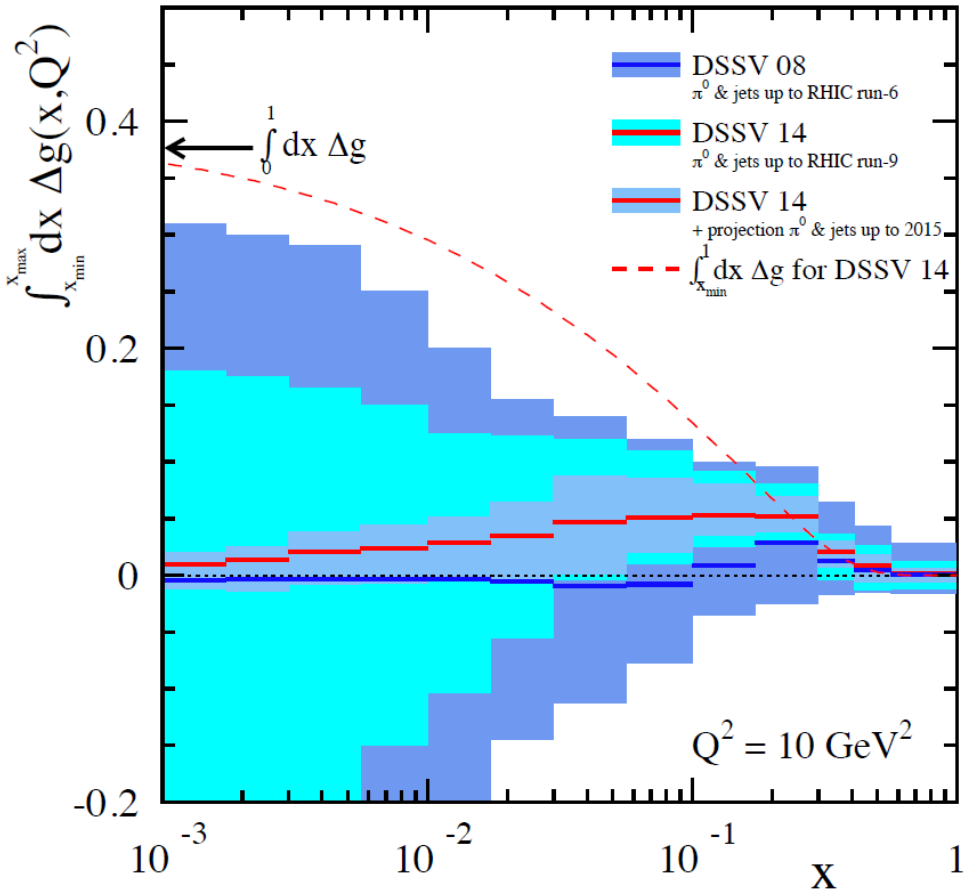
PRD87, 012001





- Heavy flavor decay
  - gg scat. dominated production
- Forward J/ψ
  - gg scat. dominated production
  - Reach ~ 2 - 3 × 10^{-3} Bjorken x

ΔG What's next?



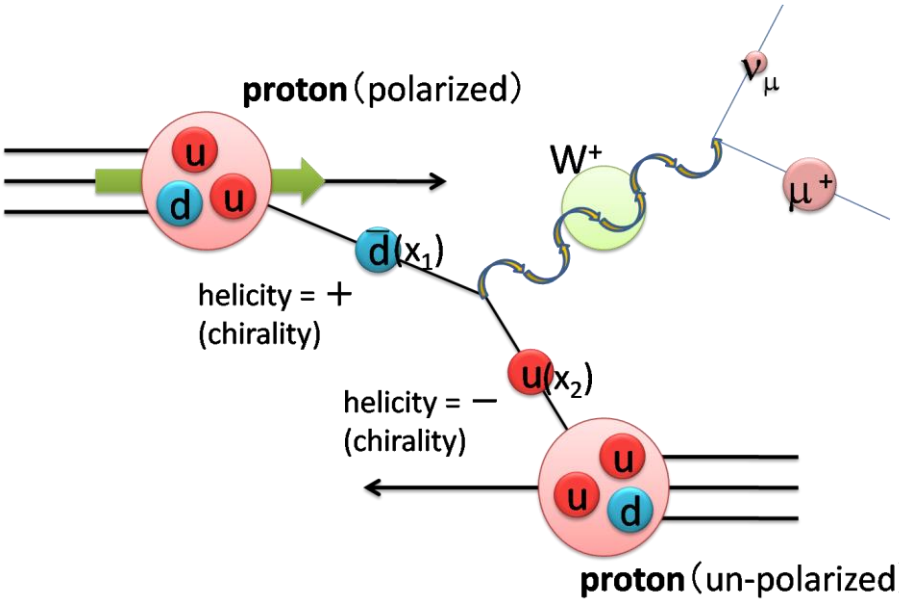
arXiv: 1501.01220

Bin by Bin Δg fit: significant improvement expected

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

Observable: A_L

$\Delta\bar{q}$ Introduction



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

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

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

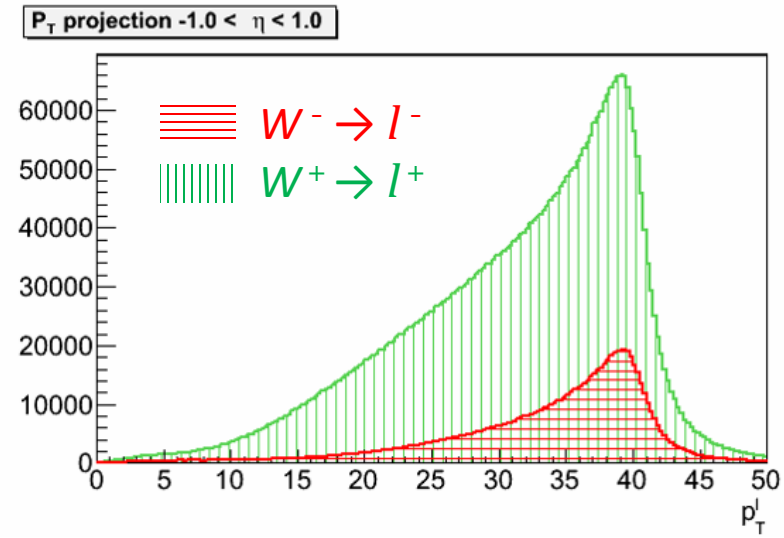
technically,

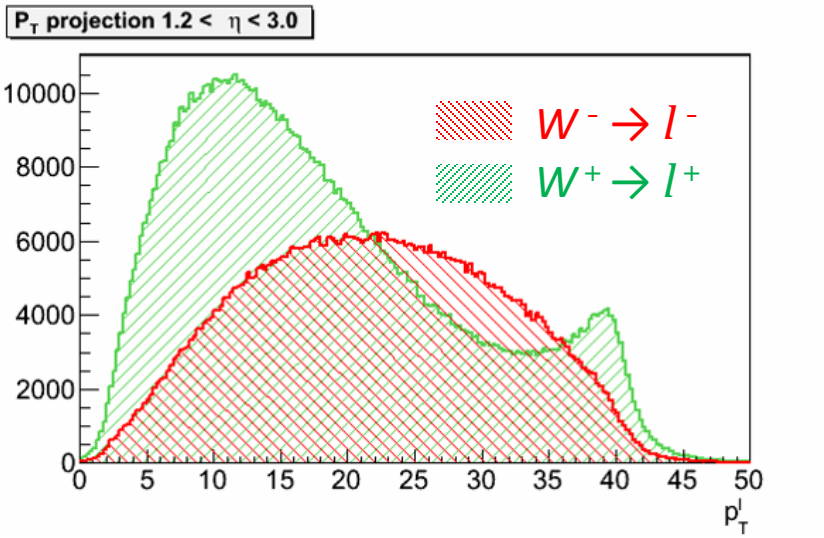
$$A_L^{W} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

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

- $\Delta\bar{q}$ measurement at PHENIX: by W/Z decay leptons
  - Midrapidity (Central Arms): electrons
  - Forward (Muon Arms): muons

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





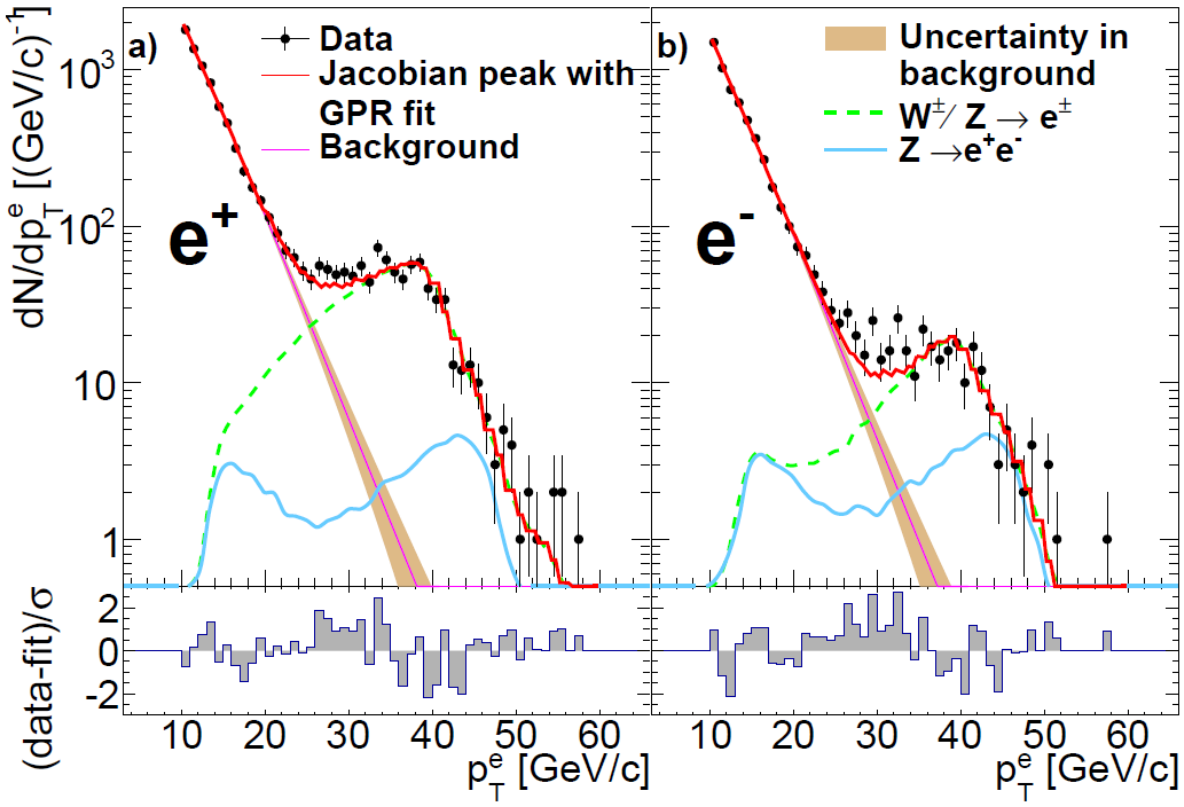
- $W^{\pm} \rightarrow e^{\pm}$ @ midrapidity
  - Central Arms ($|\eta| < 0.35$)
  - Distinct Jacobian peak

  Triggered by energy
  Momentum by energy
  Charge by tracking in B-field

- $W^{\pm} \rightarrow \mu^{\pm}$ @ forward rapidity
  - Muon Arms ($1.2 < |\eta| < 2.2$)
  - Suppressed/No Jacobian peak

  Triggered by momentum
  Momentum by tracking in B-field
  Charge by tracking in B-field

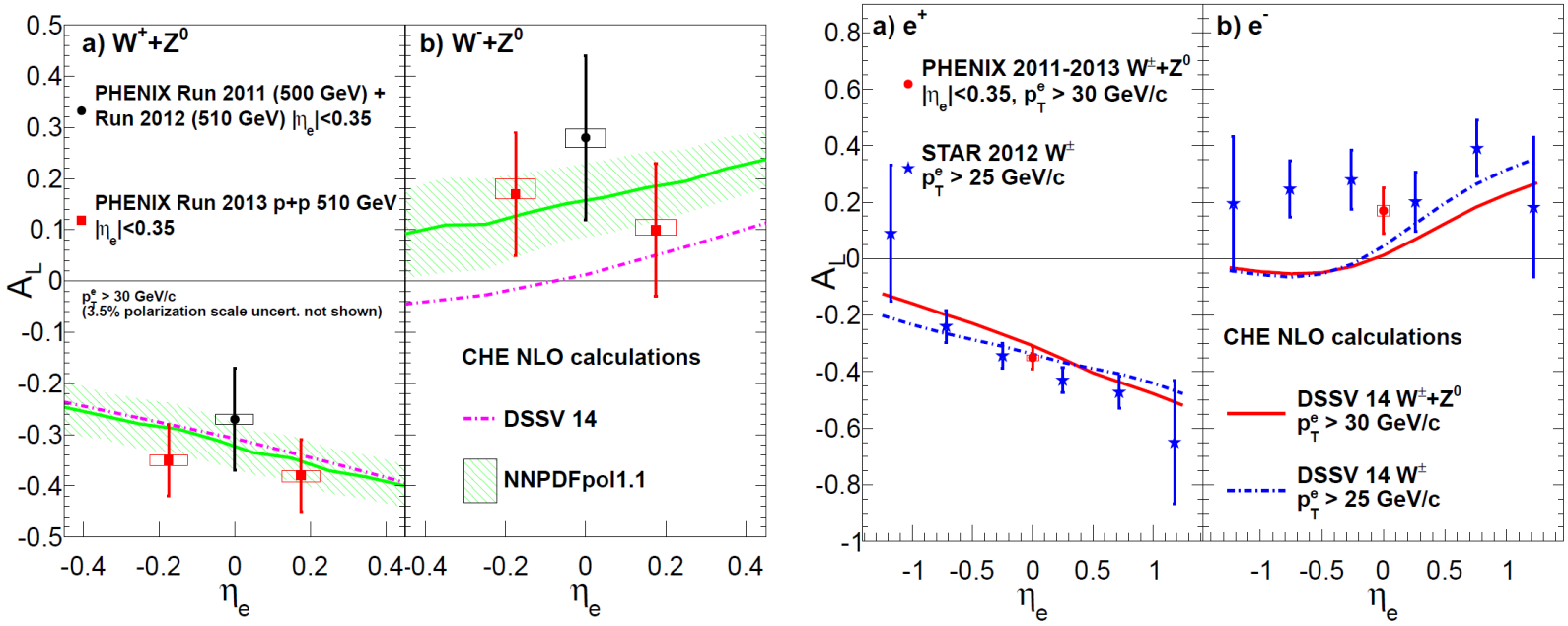
$\Delta\bar{q}$ $W^{\pm} \rightarrow e^{\pm}$ @ midrapidity ($|\eta| < 0.35$)



- W → e A_L in Run 11-13 (total Int. L = 240 pb^{-1}) pp 500/510 GeV
  - Charge isolation + Gaussian process regression

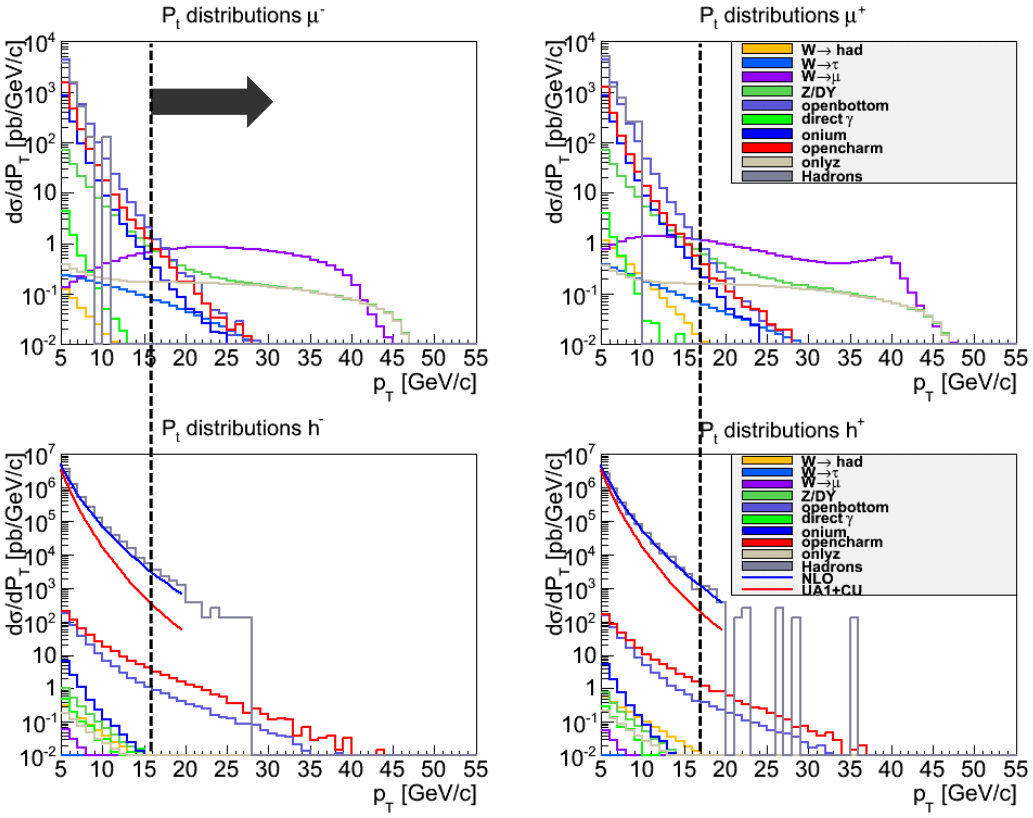
$\Delta\bar{q}$ $W^{\pm} \rightarrow e^{\pm}$ @ midrapidity ($|\eta| < 0.35$)

arXiv:1504.07451



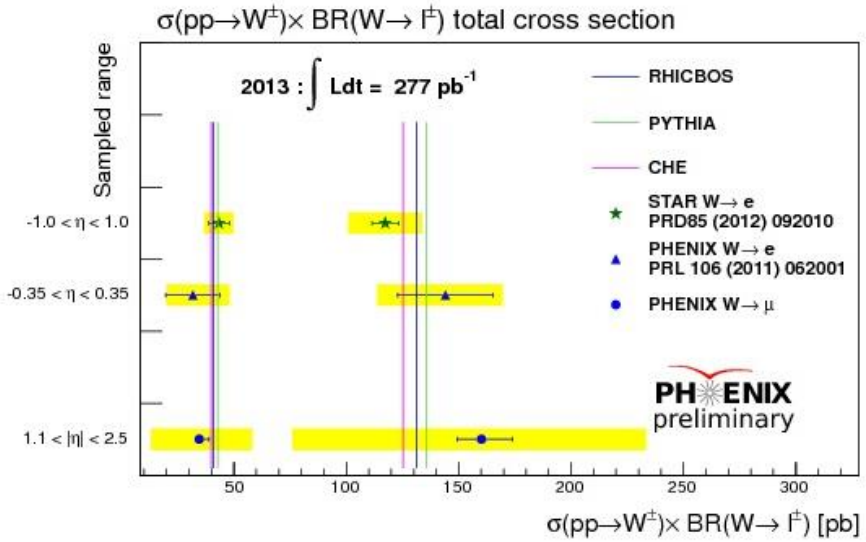
- W → e A_L in Run 11-13 pp 500/510 GeV
  - Probed Bjorken x : ~ 0.16
  - W^- suggests larger $\Delta\bar{u}$ contribution than theory in covered x range

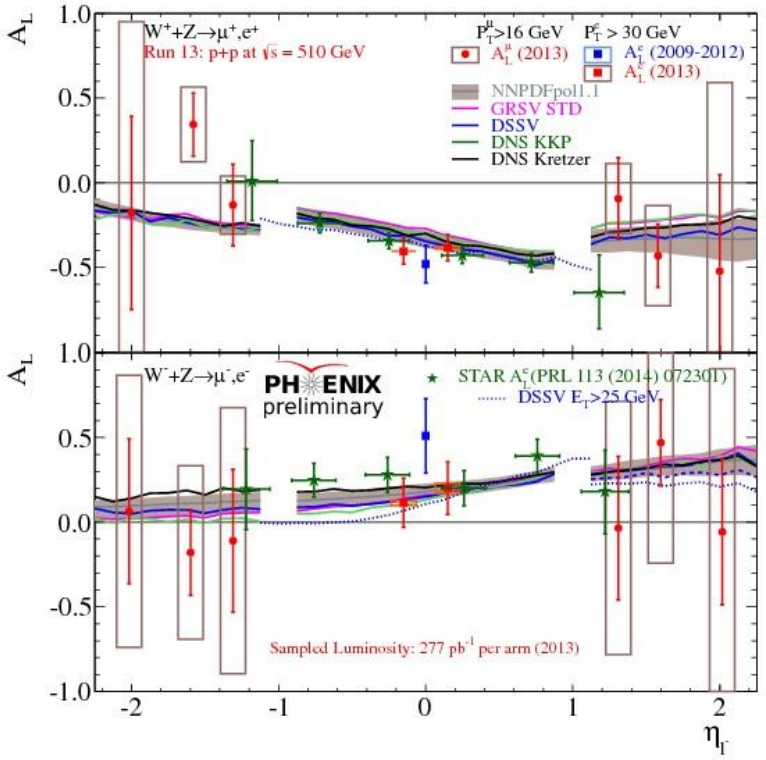
$\Delta\bar{q}$ $W^{\pm} \rightarrow \mu^{\pm}$ @ forward rapidity ($1.2 < \eta < 2.2 / 2.4$)



- W → μ A_L in Run 11-13 (Int. L = 27, 53, and 290 pb^{-1}) pp 500/510 GeV
  - Analysis challenges: BG abundance, p_T smearing, Limited acceptance…
  - Multivariate *W* likelihood based analysis

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

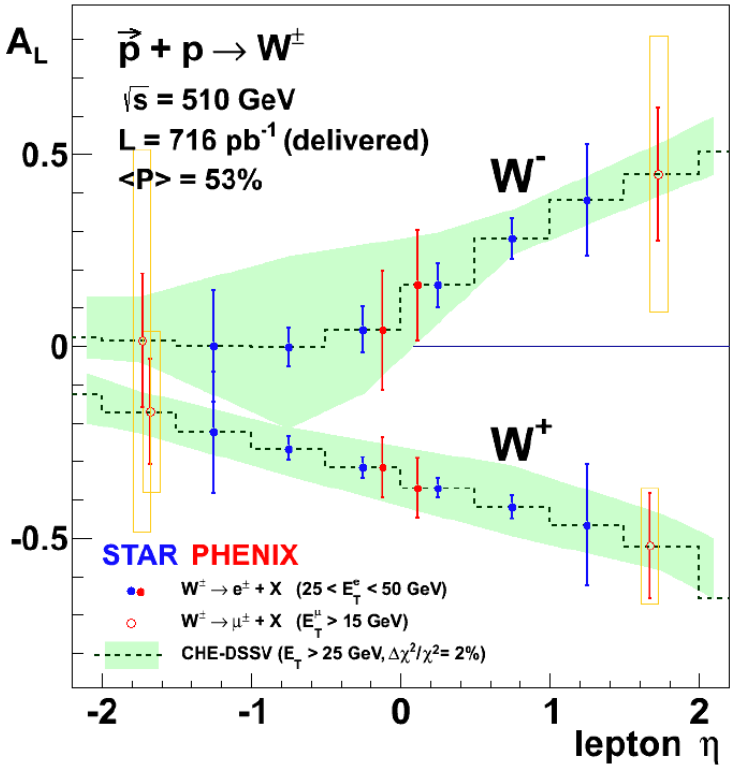


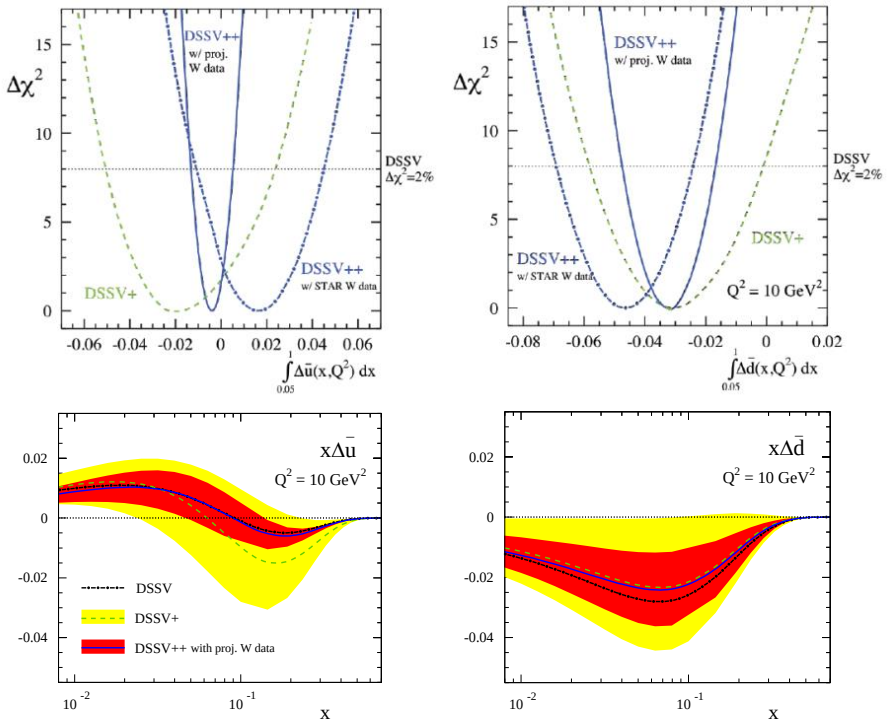


- $W \rightarrow \mu$ A_L in Run 13 pp 510 GeV
  - Cross section results agrees with calculations within large uncertainty
  - Still working on improving uncertainties:
    improve S/BG, tracking alignment, dead map update...

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

arXiv: 1501.01220





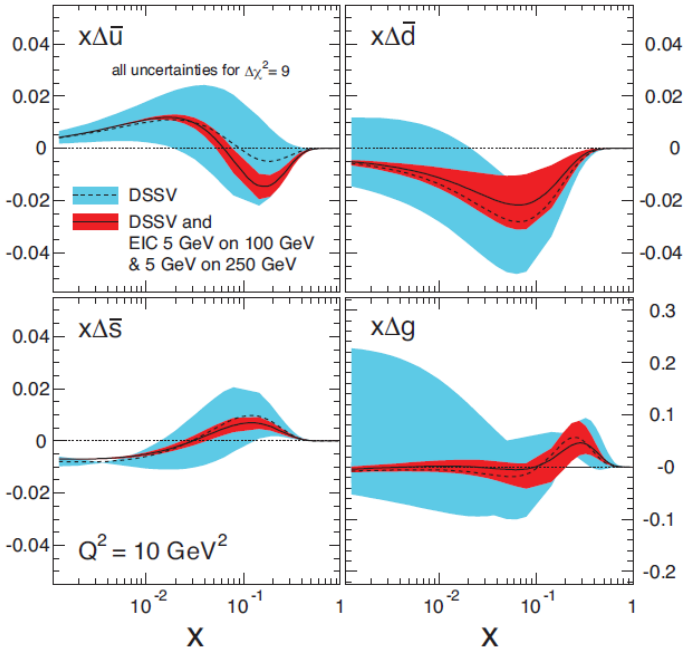
- DSSV++ projections with *W* data at RHIC
  - Significant constraint is expected in anti-quark polarization

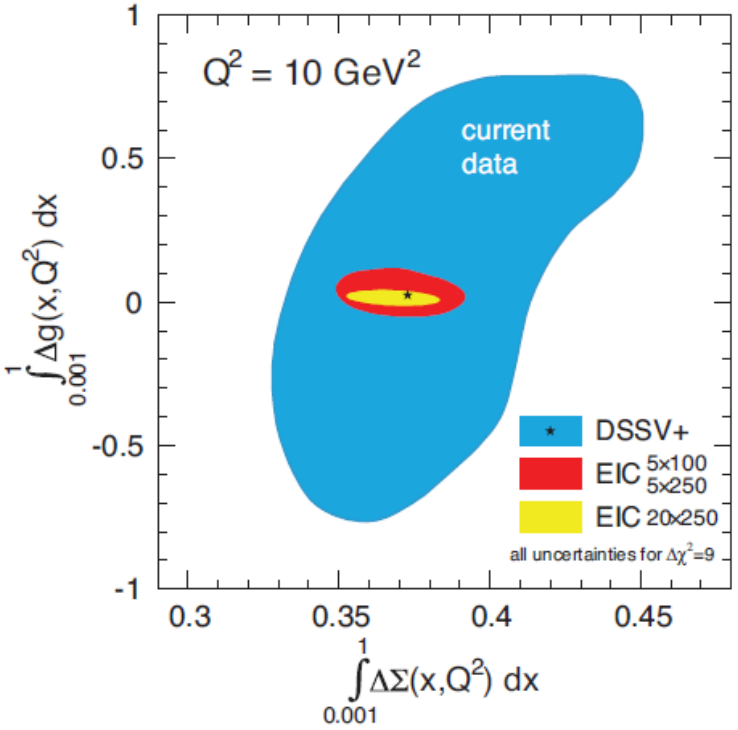
Summary and Outlook Helicity structure studies at PHENIX

- ΔG
  - Run 13 inclusive π^0 at √s = 510 GeV
    a. First non-zero A_{LL} observation in hadron production
    b. Extended Bjorken x constraint down to ~ 0.01
  - Upcoming forward π^0 rich EM clusters data: push x coverage down to ~ 0.001
  - Current DSSV14 fit: $0.20\ ^{+0.06}_{-0.07}$ at 90 % C.L in x > 0.05
    a. Includes only RHIC Run 6-9 data at √s = 62 and 200 GeV
    b. Room for improvement: recent (after Run 9) results are not included yet!
    in addition, not only π^0 / jet, but also many other probes exist to help reduce systematic uncertainty of the fit
- $\Delta\bar{q}$
  - Run 11 – 13 by *W* / Z → leptons
  - larger $\Delta\bar{u}$ contribution: possibility of symmetry breaking between $\bar{u} \leftrightarrow \bar{d}$?
  - DSSV++ fit suggests significant constraint

Summary and Outlook

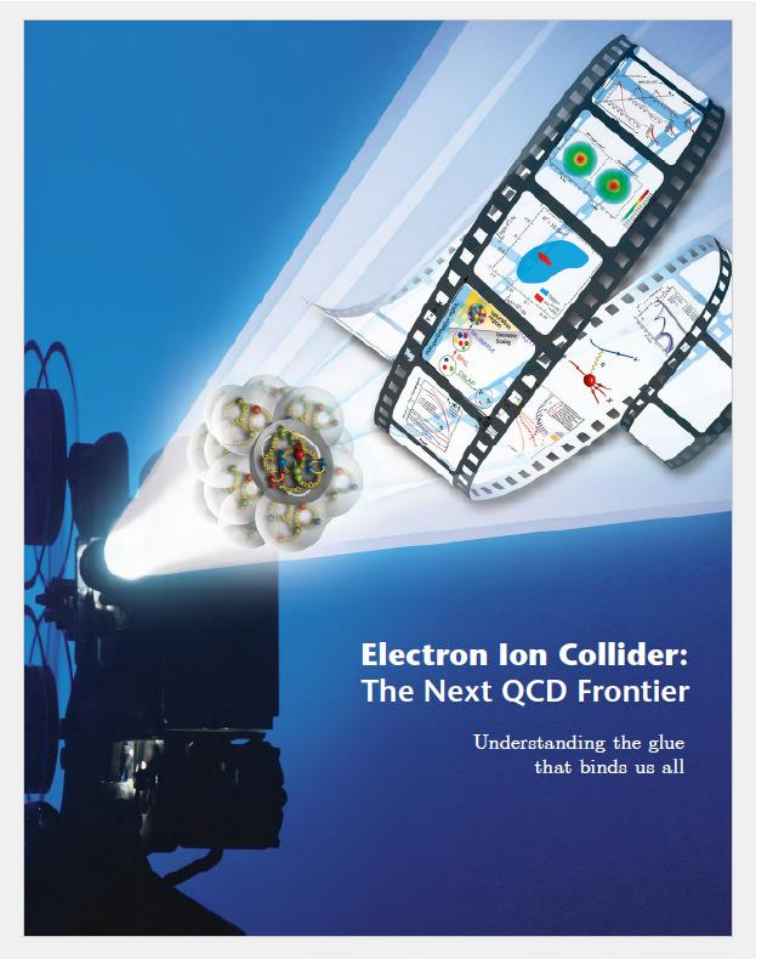
arXiv: 1212.1701





- Next?
  - PHENIX decommissions after Run 16
  - Transition to new detector system using the Babar solenoid
  - Upcoming Eletrcon-Ion Collider: back to DIS, but with much higher *L* and √s

arXiv: 1212.1701



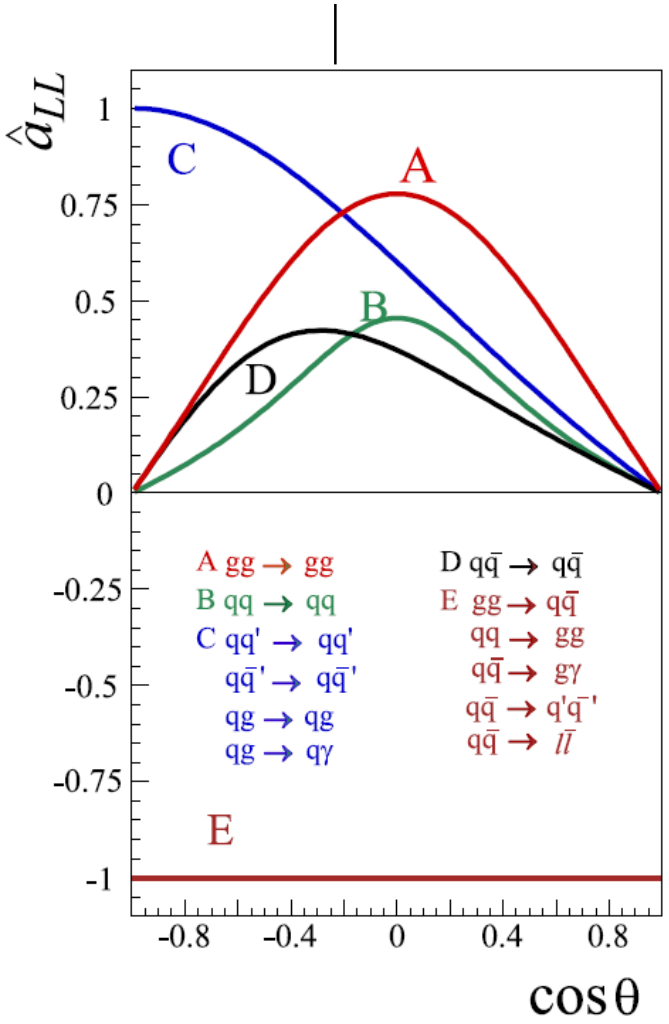
- If you're interested -

  all about upcoming Electron – Ion Collider (EIC)

Backup LO dominant partonic processes

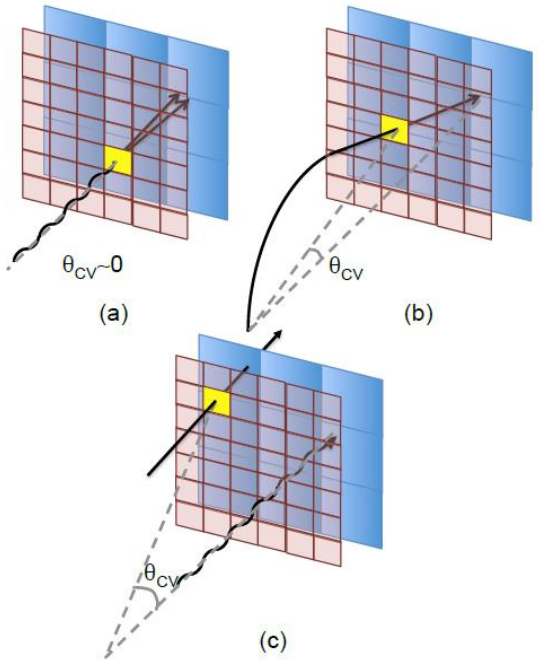
LO helicity dependent double spin asymmetries for partonic reactions at RHIC

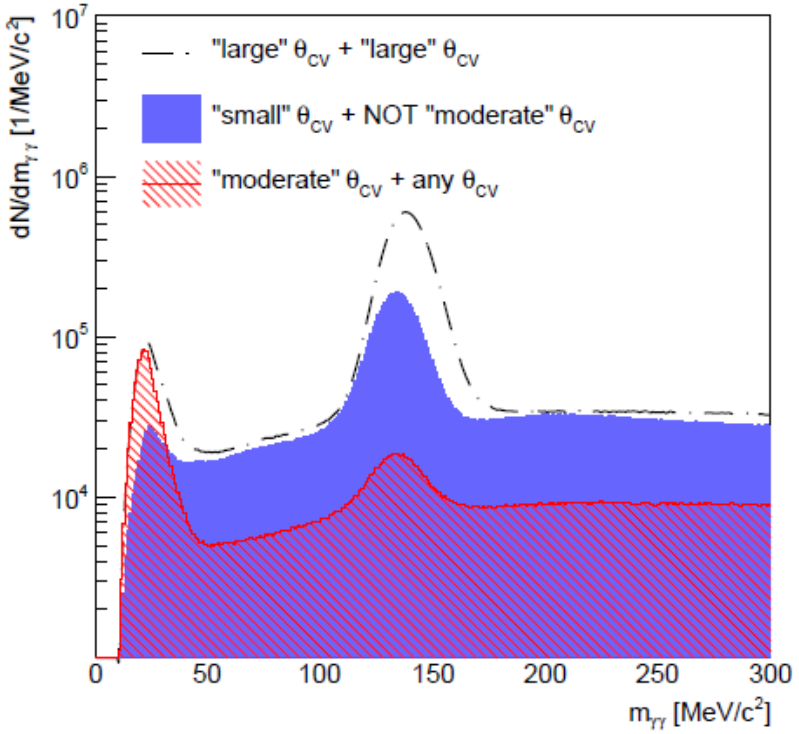
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [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 π^0 analysis

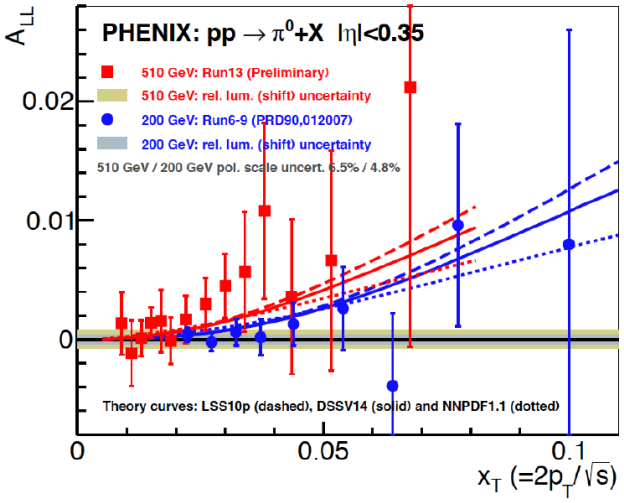
PRD90, 012007

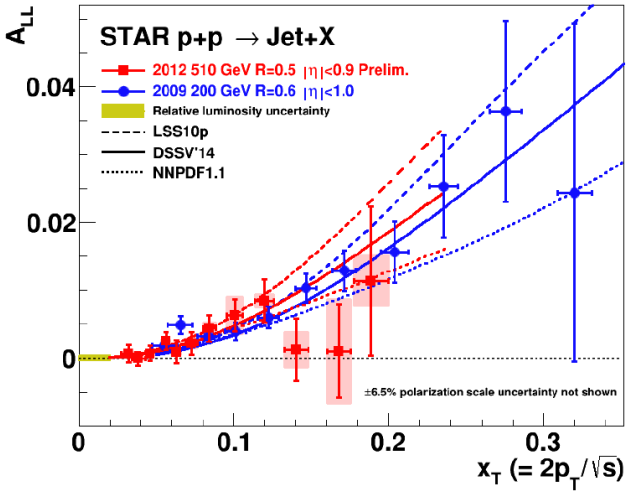


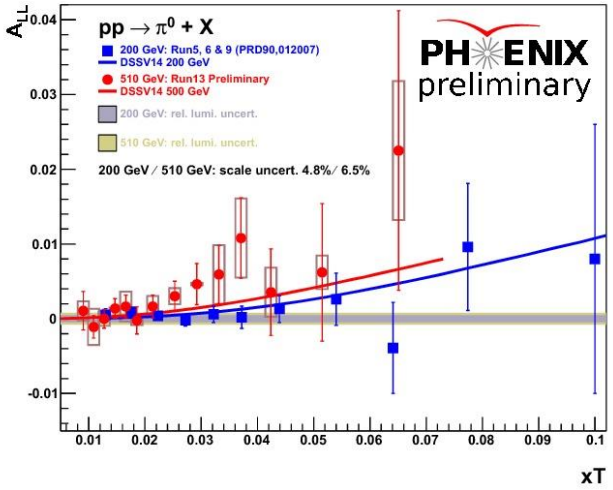


- Inclusive π^0 analysis
  - Charge veto (θ_{CV}) + Time of flight + Relative Luminosity correction + Background asymmetry correction (by background sampling)

Backup π^0 analysis results – PHENIX/STAR

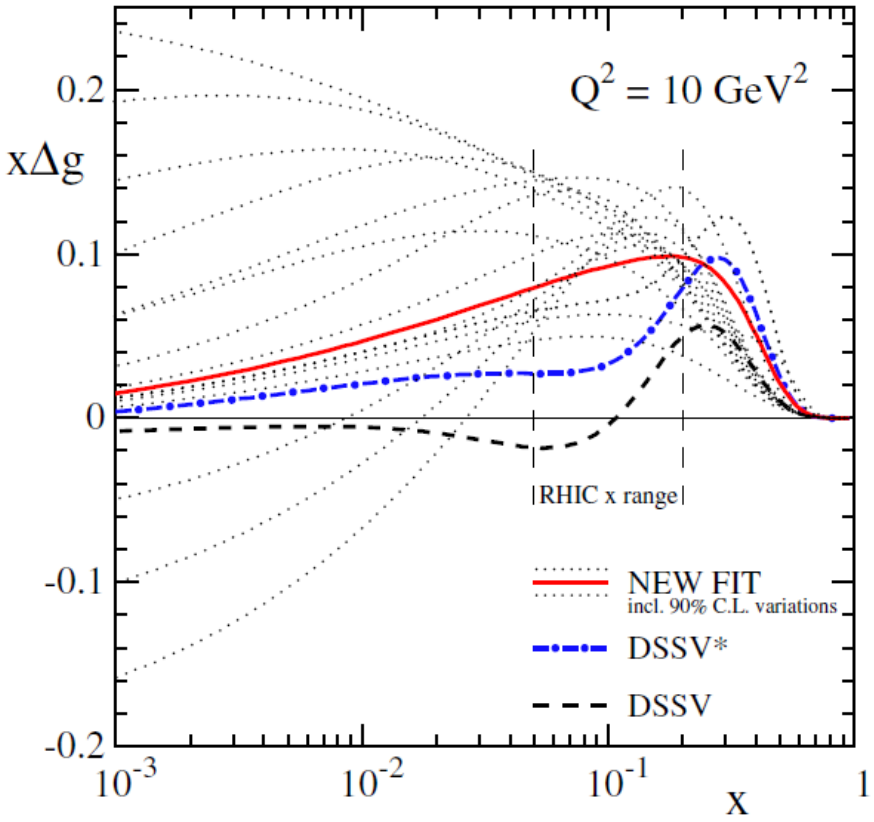






Backup DIS + pp global pQCD fit (DSSV2014) – xΔg vs. x

PRL113, 012001



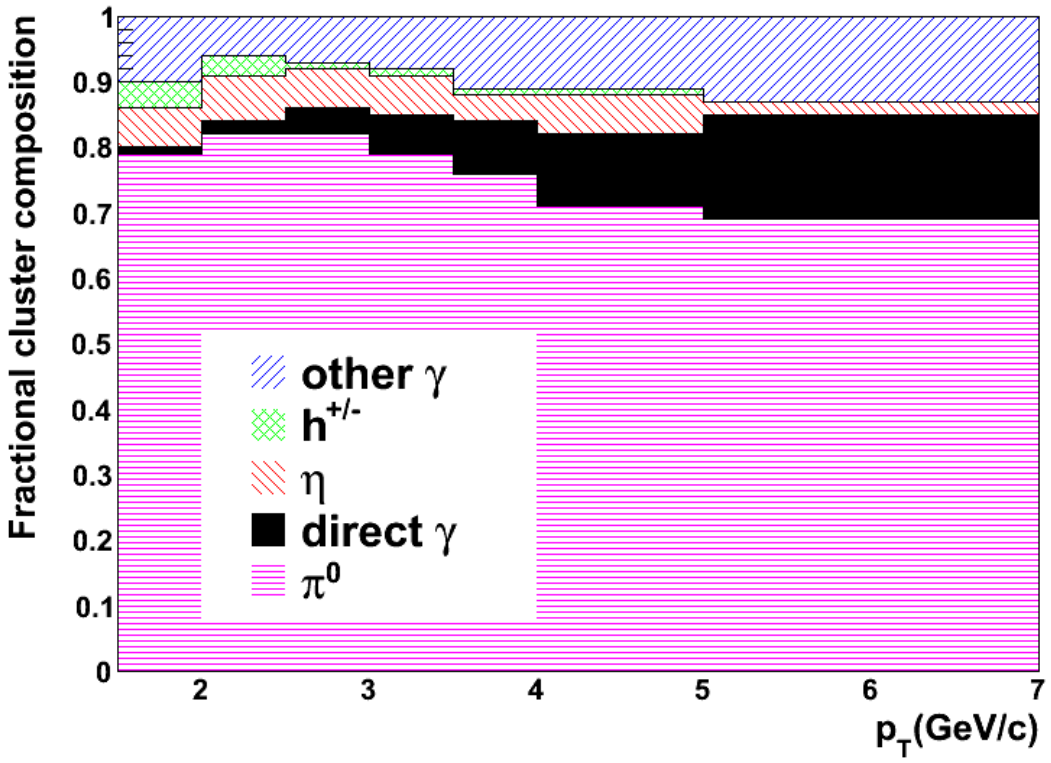
- DSSV2014 (DSSV* and New fit):
  - Included:

    RHIC data for original DSSV (before Run 9)

    New COMPASS (SI)DIS data sets

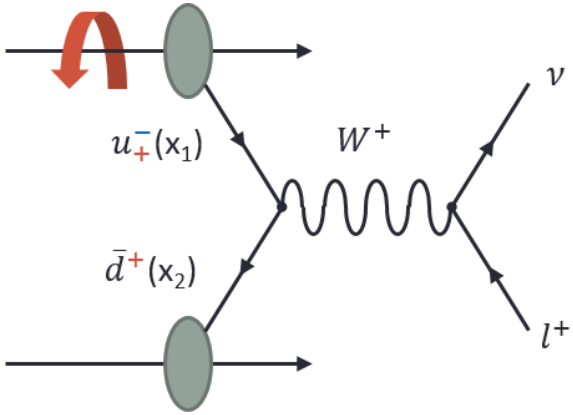
Backup π^0 abundance in forward EM clusters

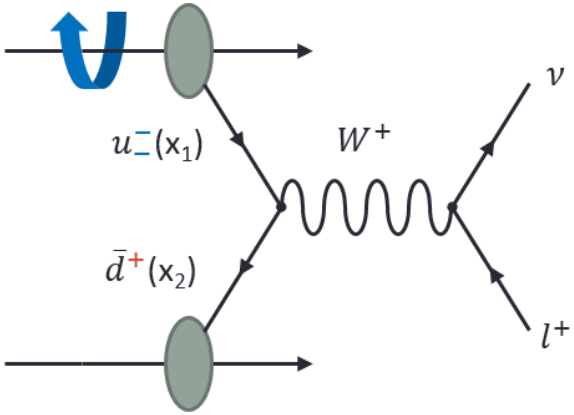
arXiv: 1312.1995v1



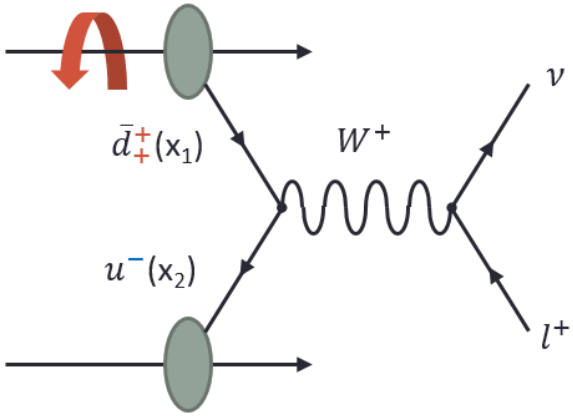
- MC simulation for √s = 200 GeV with full MPC
  - Kinematic cuts applied

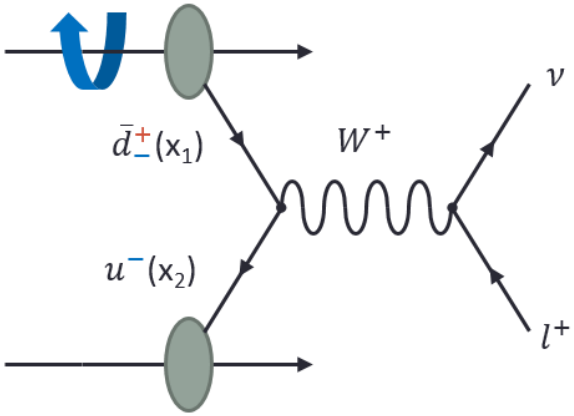
Backup *W* partonic process





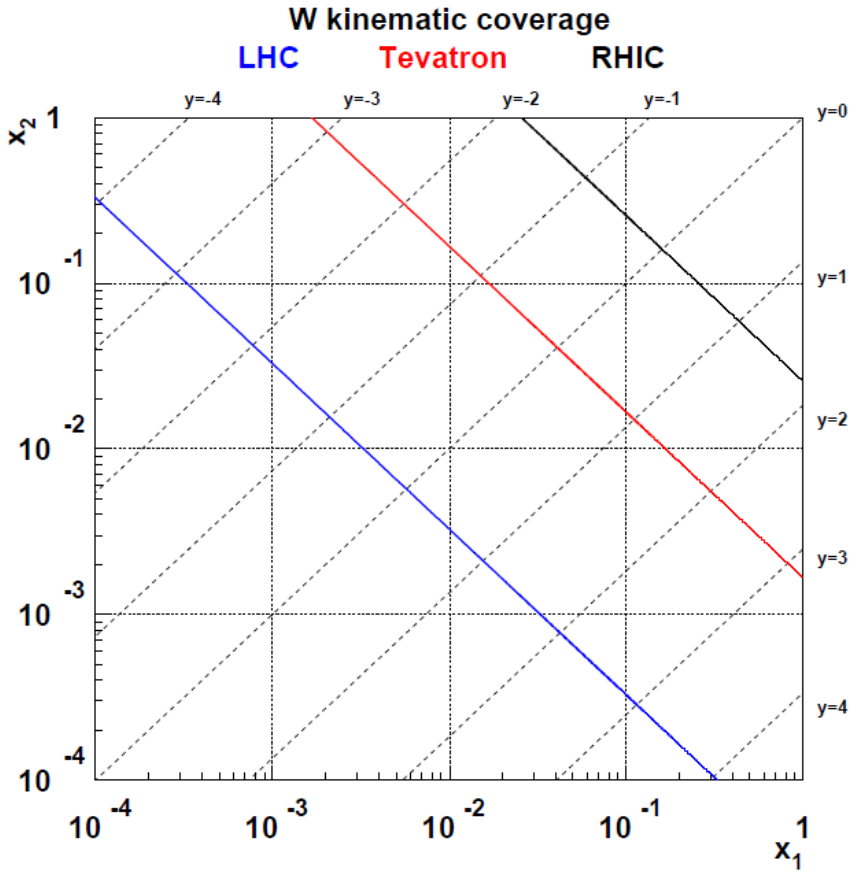
$$A_L^{W+} = \frac{u^-_-(x_1)\bar{d}^+(x_2) - u^-_+(x_1)\bar{d}^+(x_2)}{u^-_-(x_1)\bar{d}^+(x_2) + u^-_+(x_1)\bar{d}^+(x_2)}$$ ← 1. Δu is being probed



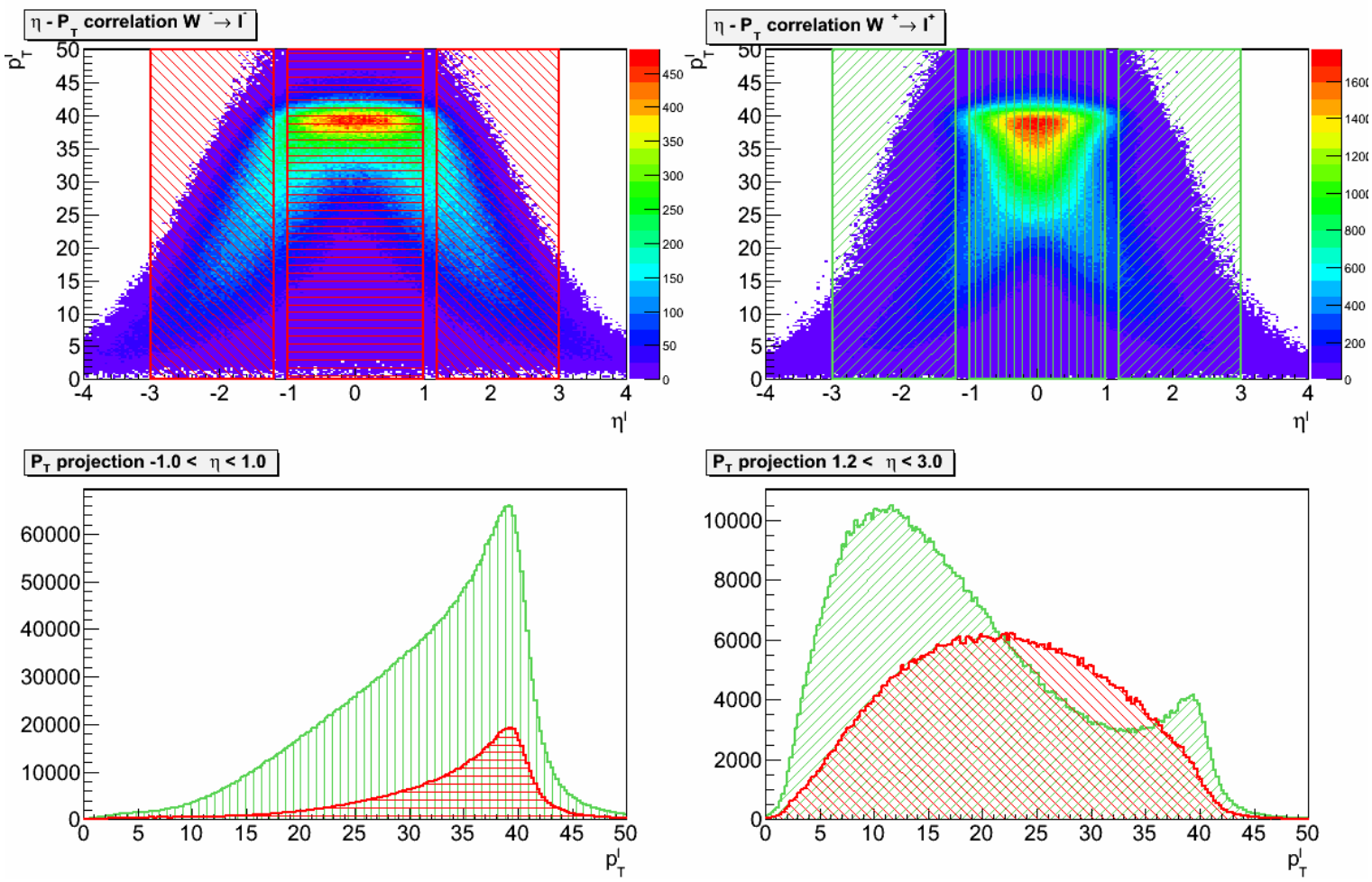


$$A_L^{W+} = \frac{\bar{d}^+_-(x_1)u^-(x_2) - \bar{d}^+_+(x_1)u^-(x_2)}{\bar{d}^+_-(x_1)u^-(x_2) + \bar{d}^+_+(x_1)u^-(x_2)}$$ ← 2. $\Delta\bar{d}$ is being probed

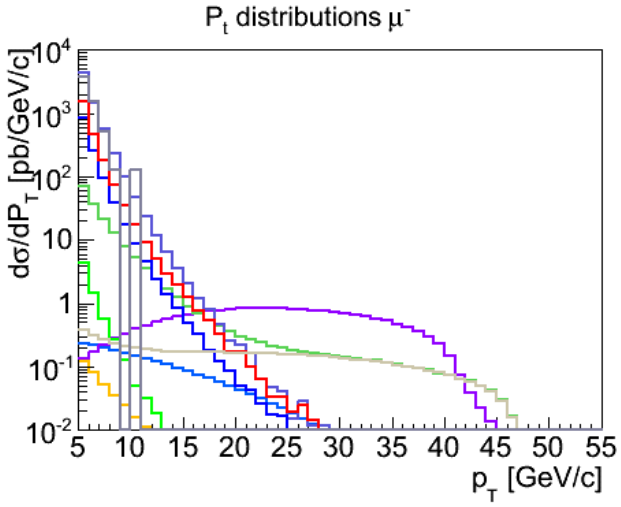
Backup *W* kinematic coverage

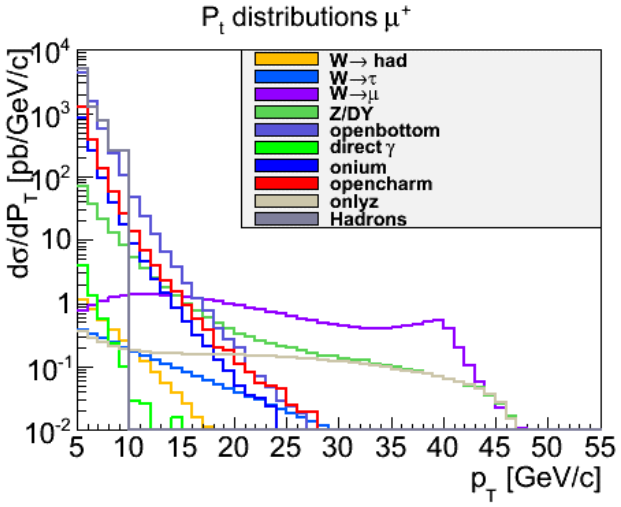


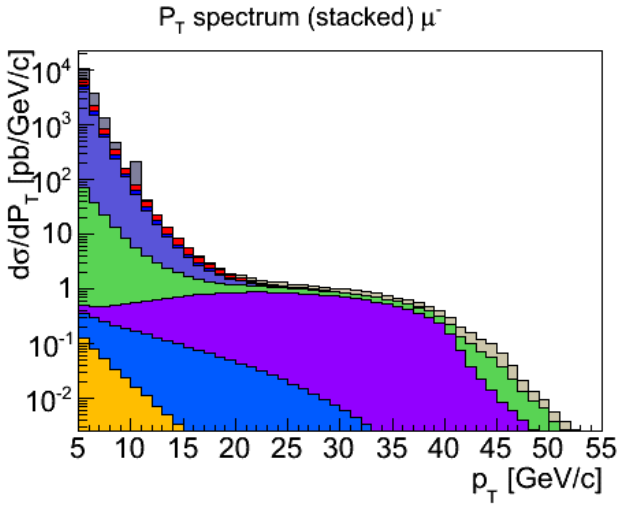
Backup *W* kinematics in PHENIX acceptance

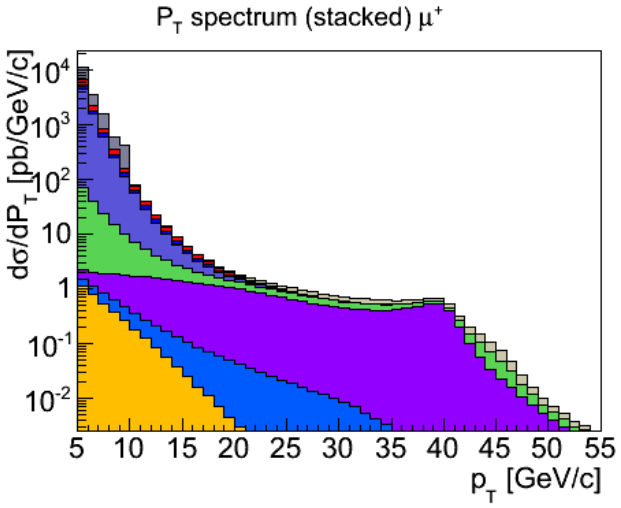


Backup $W \rightarrow \mu$ muonic processes

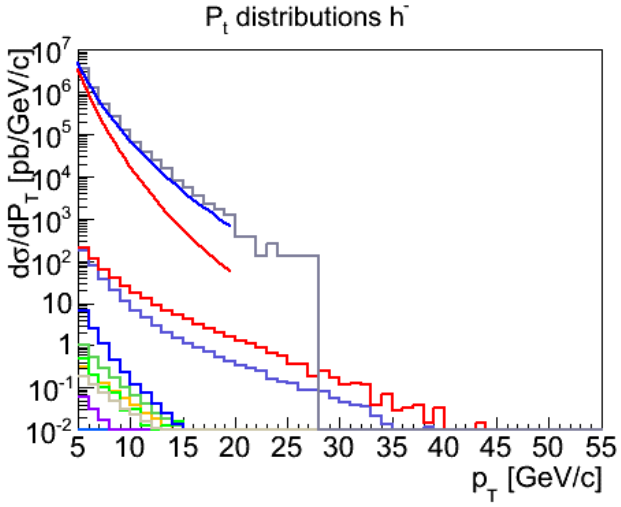


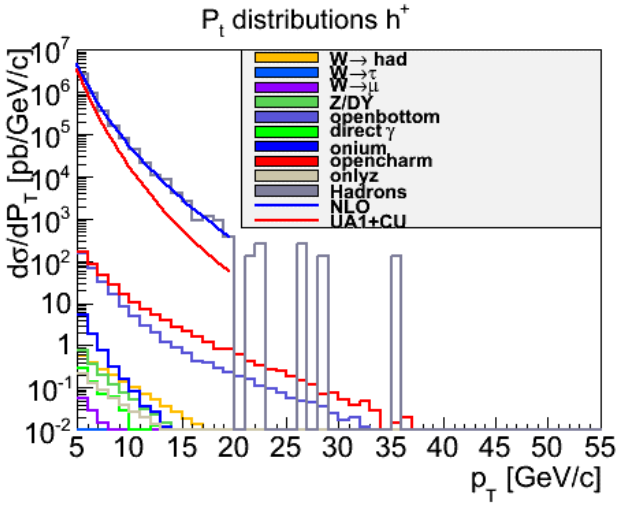


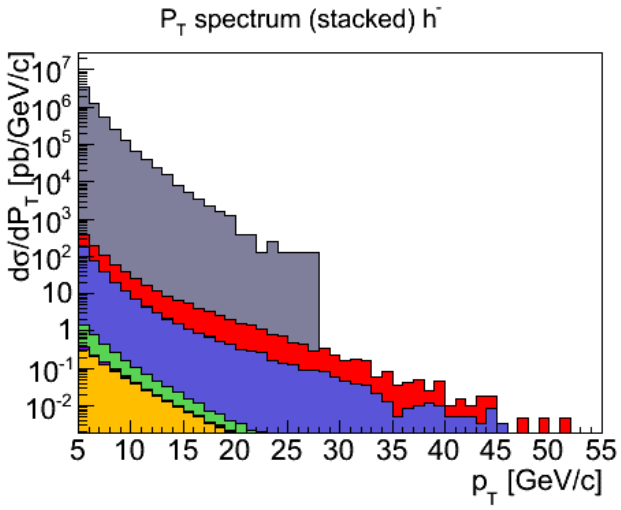


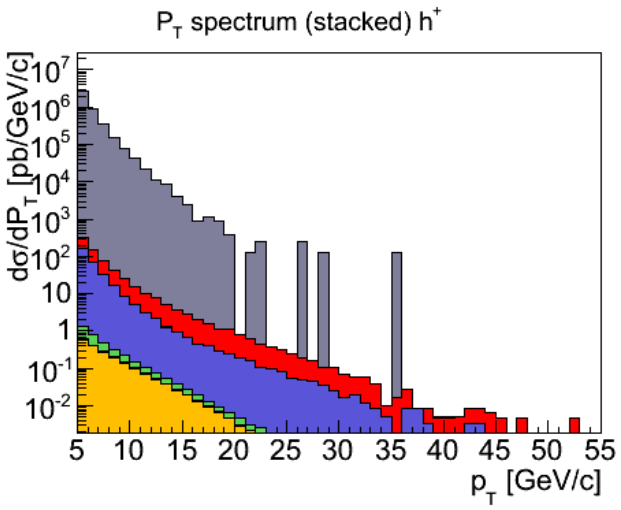


Backup $W \rightarrow \mu$ hadronic processes









Backup $W \rightarrow \mu$ S/BG extraction by unbinned max. likelihood fit