

# PHENIX Spin overview

6th International Conference on New Frontiers in Physics

**New Frontiers in Physics ICNFP 2017**

17-29 August 2017, Kolymbari, Crete, Greece

<http://indico.cern.ch/event/icnfp2017>

**Main topics of the Conference**

- High Energy Particle Physics
- Heavy Ion Physics, Critical phenomena
- Quantum Physics, Quantum Optics, Quantum Information
- Cosmology, Astrophysics, Gravity, Mathematical physics

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**Workshops**

- Continuous Variables and Relativistic Quantum Information
- Quantum Foundations and Quantum Information
- Exotic Hadrons
- New Searches in High Energy Particle Physics
- Highly Ionizing Avatars of New Physics
- Correlations and Fluctuations in Relativistic Heavy Ion Collisions
- Physics at FAIR-NICA-KSPS-BES-III-ETC
- Future of Fundamental Physics
- Noncommutative Geometry at the Forefront of Physics

**Special Sessions**

- QCD
- Astro-Cosmo-Gravity
- Super Heavy Elements
- Physics Education and Outreach
- Instruments and Methods in HEP

**Memorial Sessions**

- Walter Greiner
- Spartak Belyaev
- Helmuth Doscher
- Gunnar Lovhøiden

ICNFP 2017,  
Kolymbari, Greece

August 24,

Ralf Seidl(RIKEN)



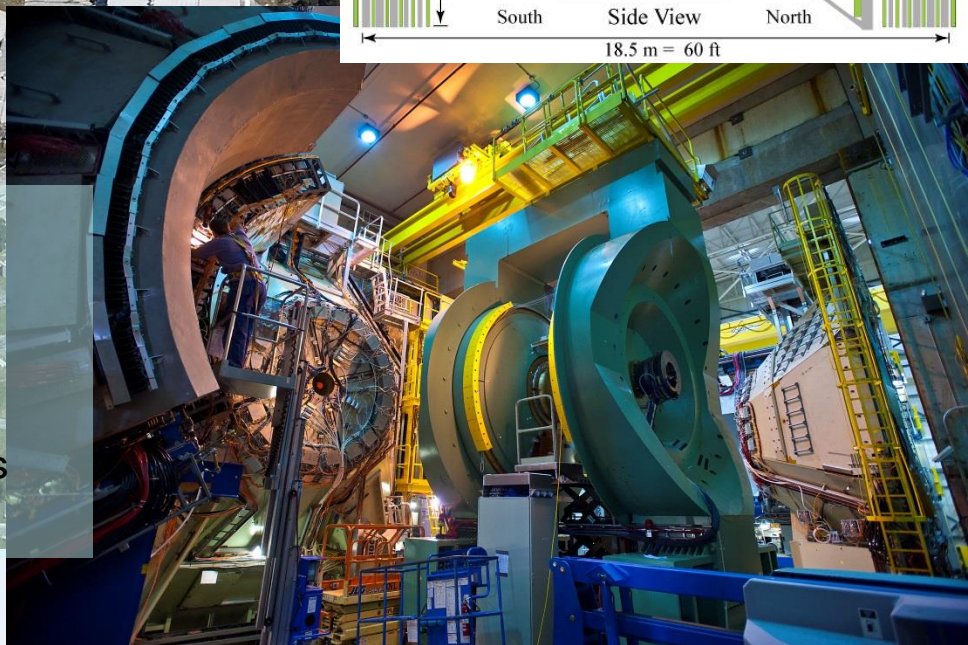
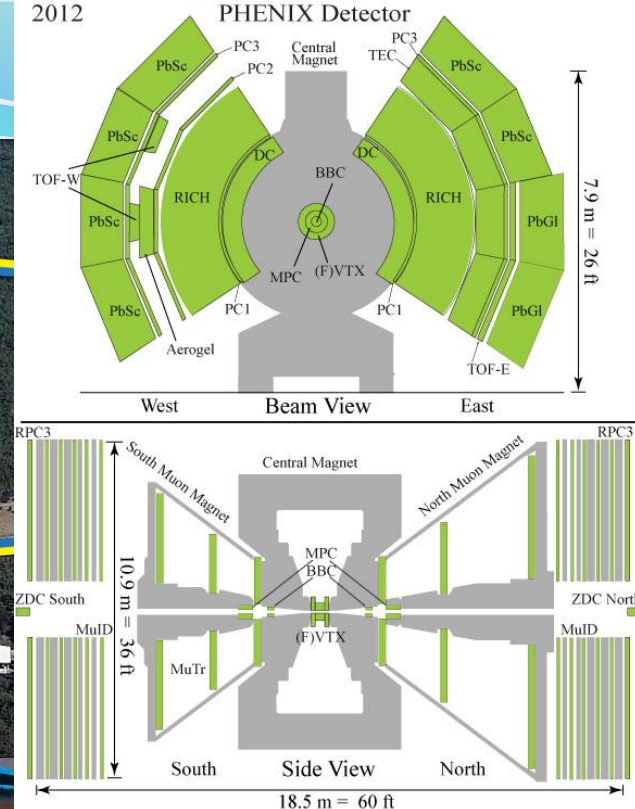
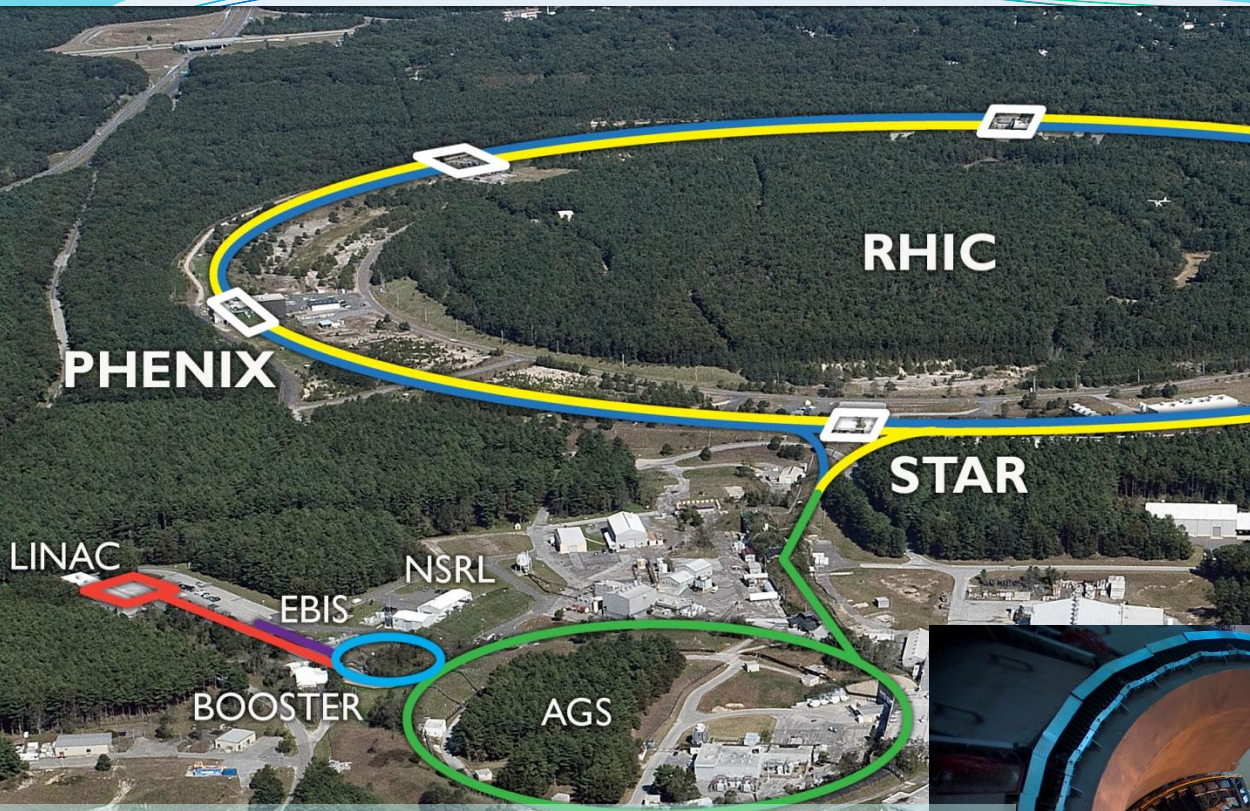
RIKEN



# Outline

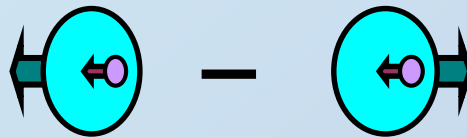
- Introduction to PHENIX
- Longitudinal spin physics:
  - Discovery of gluon spin contribution
  - Indication of asymmetric polarized light sea
- Transverse spin physics:
  - many surprises and new insights
- The Future of RHIC and eRHIC

# RHIC and PHENIX

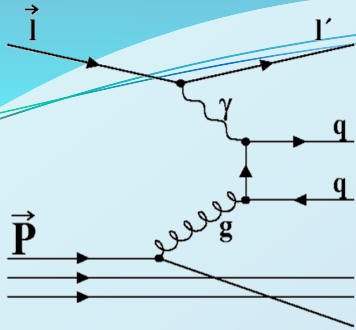


- Polarized proton beams from  $\sqrt{s}$  of 62–510 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
- Global and local polarimetry

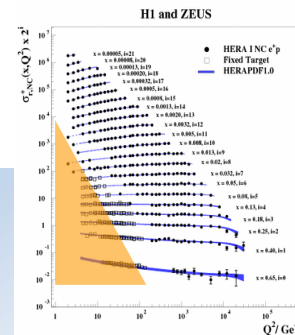
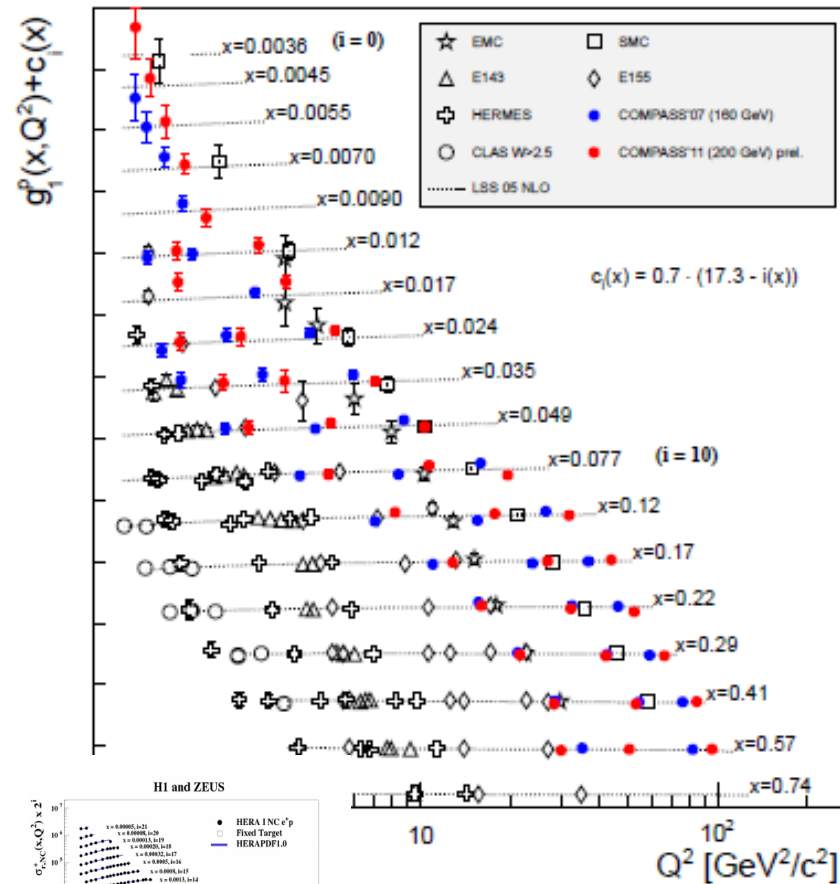
# Longitudinal Spin



# Gluon polarization

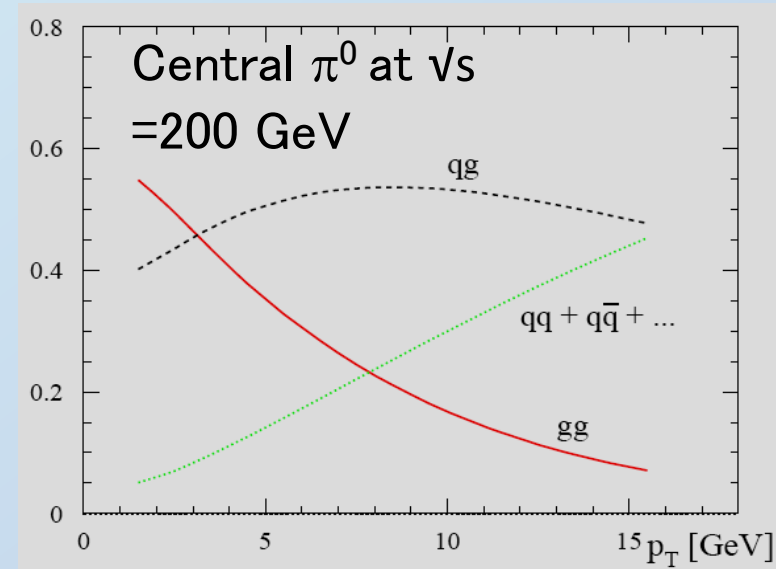


- Barely access via DIS data through DGLAP evolution (no large  $Q^2$  lever arm)
- Some access in SIDIS through high Pt hadrons and charmed mesons



# Gluon polarization

- Barely access via DIS data through DGLAP evolution (no large  $Q^2$  lever arm)
  - Some access in SIDIS through high  $P_T$  hadrons and charmed mesons
  - Polarized pp collisions at LO in  $\alpha_s$  sensitive to gluons
- long. double spin asymmetries  $A_{LL}$  access  $\Delta g$

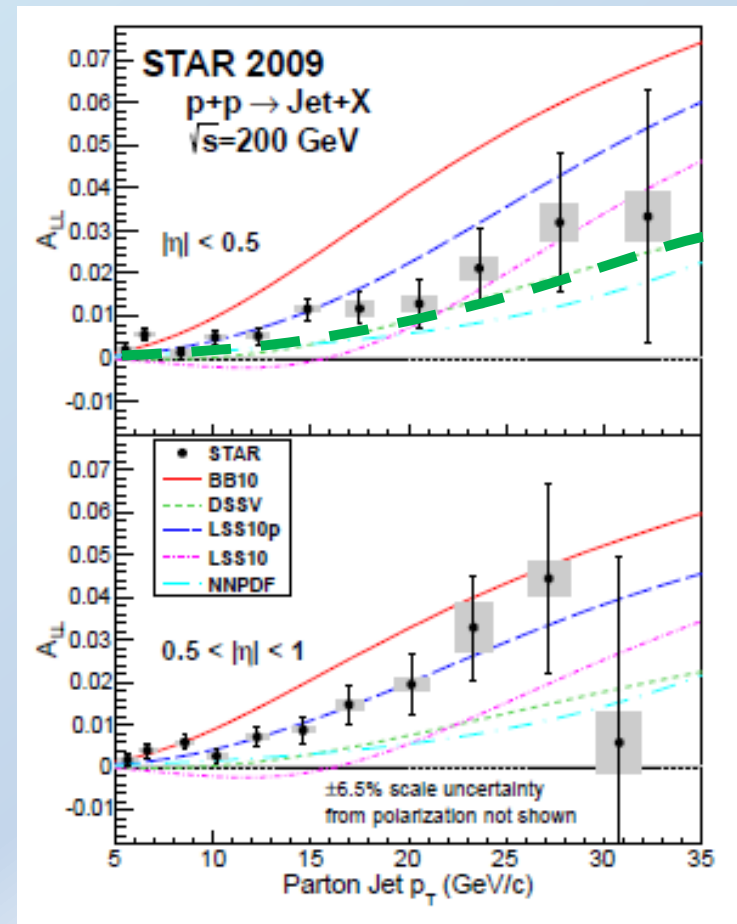
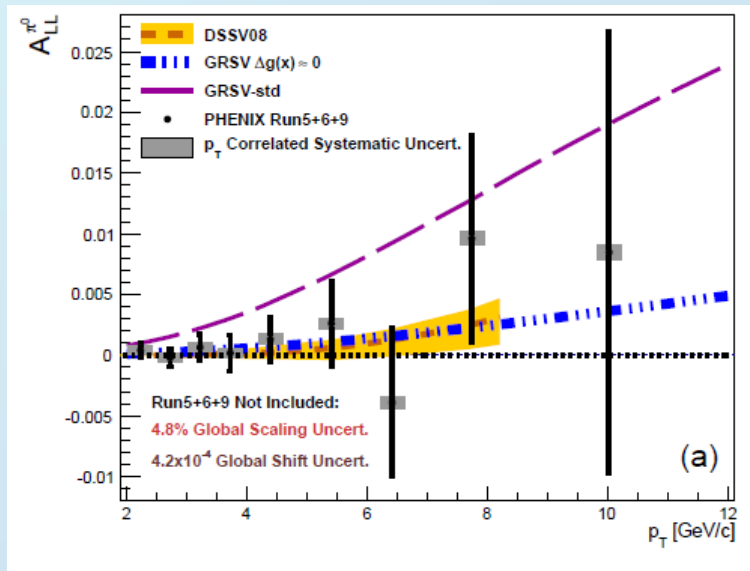


| Reaction                                                                                        | Dom. partonic process                                                          | probes                     | LO Feynman diagram |
|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------|--------------------|
| $\bar{p}\bar{p} \rightarrow \pi + X$                                                            | $\bar{g}\bar{g} \rightarrow gg$<br>$\bar{q}\bar{q} \rightarrow qg$             | $\Delta g$                 |                    |
| $\bar{p}\bar{p} \rightarrow \text{jet}(s) + X$                                                  | $\bar{g}\bar{g} \rightarrow gg$<br>$\bar{q}\bar{q} \rightarrow qg$             | $\Delta g$                 | (as above)         |
| $\bar{p}\bar{p} \rightarrow \gamma + X$<br>$\bar{p}\bar{p} \rightarrow \gamma + \text{jet} + X$ | $\bar{q}\bar{q} \rightarrow \gamma q$<br>$\bar{q}\bar{q} \rightarrow \gamma q$ | $\Delta g$<br>$\Delta g$   |                    |
| $\bar{p}\bar{p} \rightarrow \gamma\gamma + X$                                                   | $\bar{q}\bar{q} \rightarrow \gamma\gamma$                                      | $\Delta q, \Delta \bar{q}$ |                    |
| $\bar{p}\bar{p} \rightarrow DX, BX$                                                             | $\bar{g}\bar{g} \rightarrow c\bar{c}, b\bar{b}$                                | $\Delta g$                 |                    |

# $A_{LL}$ at 200 GeV

PHENIX: Phys.Rev. D90 (2014) 012007

STAR: arXiv:1405.5134

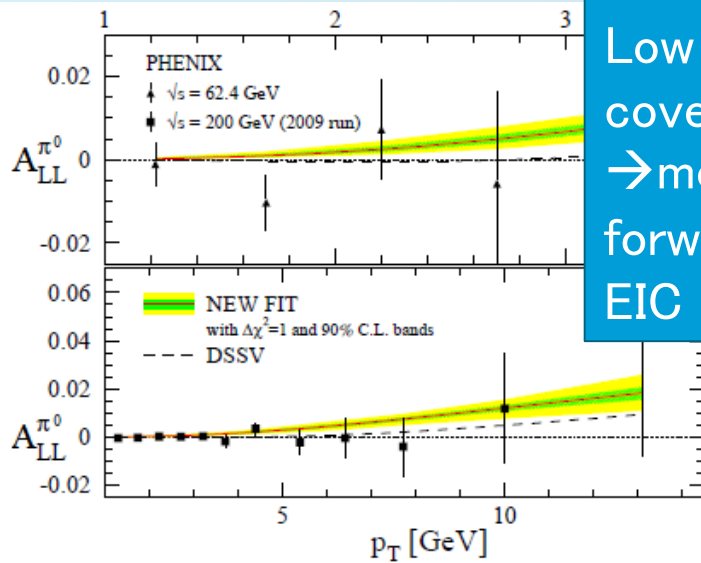


- 200 GeV up to 2009 did not show any large  $A_{LL}$
- First indications of nonzero gluons in 2009 data, especially Star's jet  $A_{LL}$ s

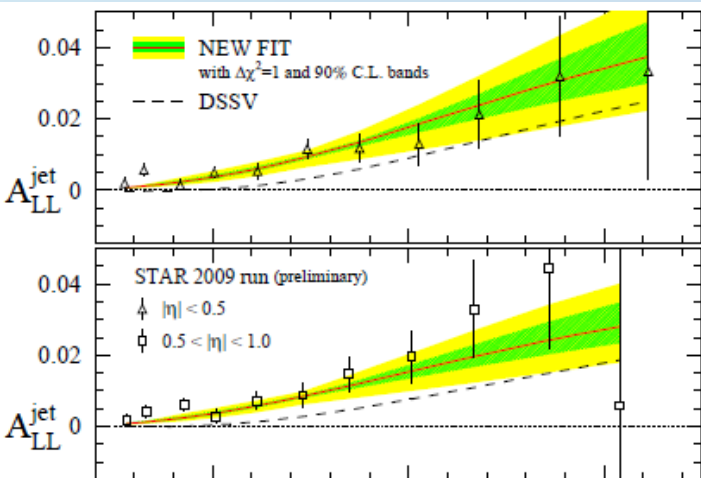
# First nonzero gluon spin indication

Also confirmed by NNPDFpol fit

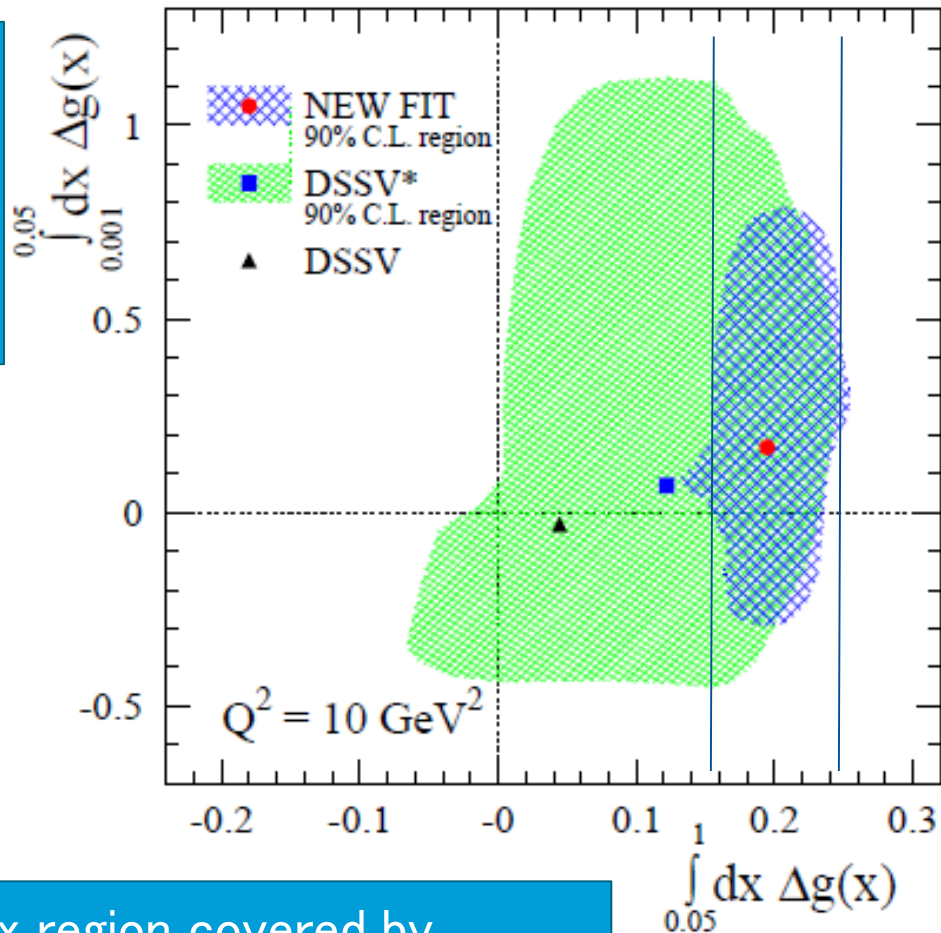
- DSSV: Phys.Rev.Lett. 113 (2014) 012001



Low x, not covered so far  
 → more forward pp, EIC



IX spin over

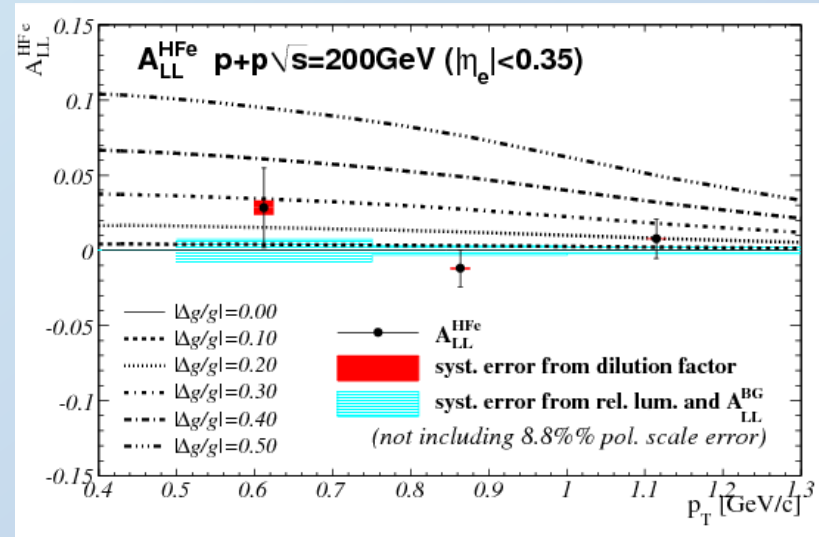
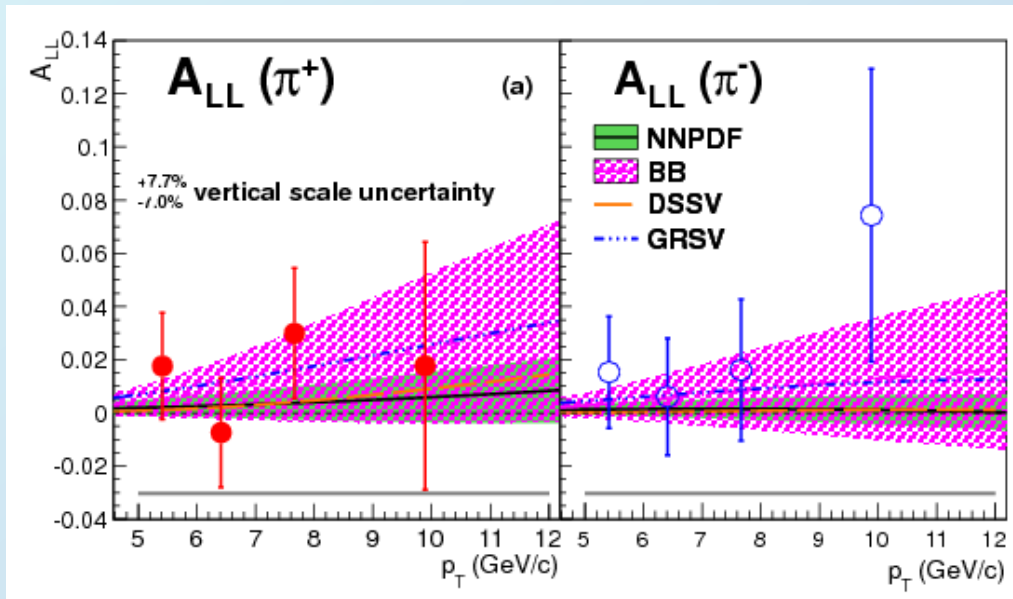


x region covered by 200GeV RHIC and DIS results

# Other 200 GeV results not yet used in global fit

Phys.Rev. D91 (2015) 3, 032001

Phys.Rev. D87 (2013) 012011

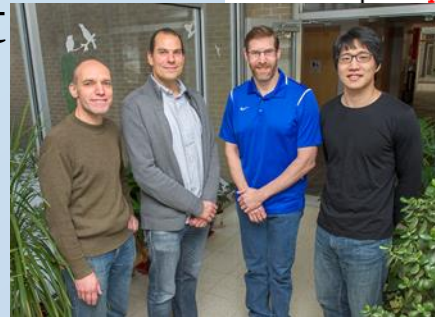
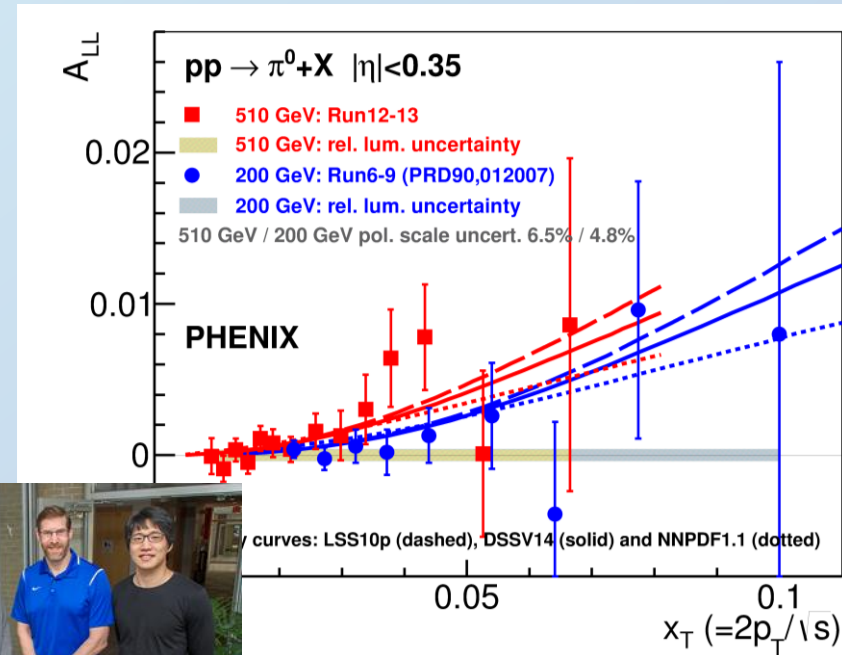


- Charged pions as potential direct indicator for sign of  $\Delta g$  via pion  $A_{LL}$  ordering
- 500 GeV analysis ongoing
- Reduced statistics compared to  $\pi^0$  due to triggering
- Also central  $\eta$

- Single electrons at central rapidity from heavy flavor production directly sensitive to gluon helicity
- Large scale given by the HF quark masses

# Gluon spin: To higher energies

- Nonzero gluon polarization established with RHIC  $\sqrt{s} = 200$  GeV data
- RHIC 510 GeV data (>2011) now confirms it in workhorse (jet, pion) measurements
- Extend access to lower  $x$  by higher energy (now  $\sim 10^{-2}$ )



PHENIX result:

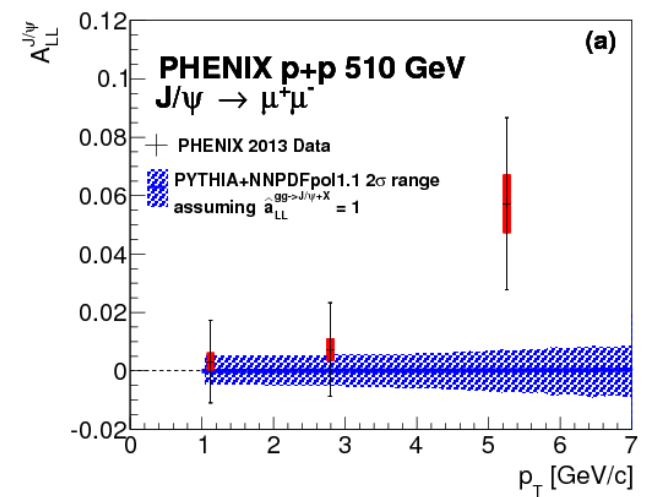
[RIKEN press release](#)

[BNL](#) and [DOE research highlights](#)

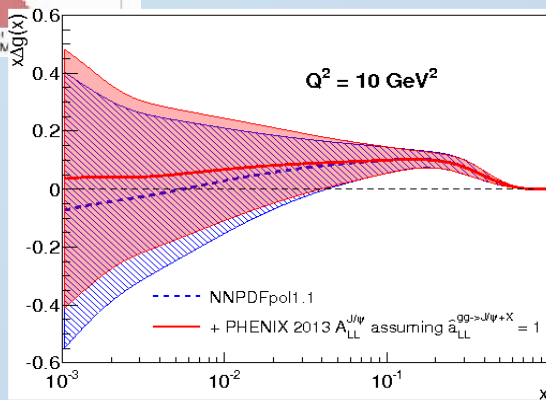
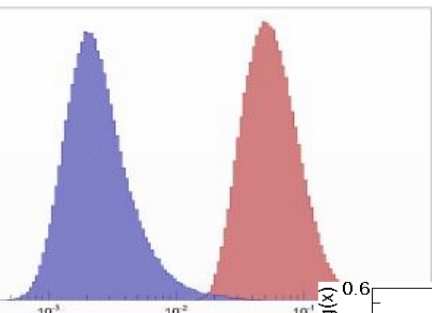
DOE labs 2016 research highlights  
[report](#)

# ...and lower x

Phys.Rev. D94 (2016)

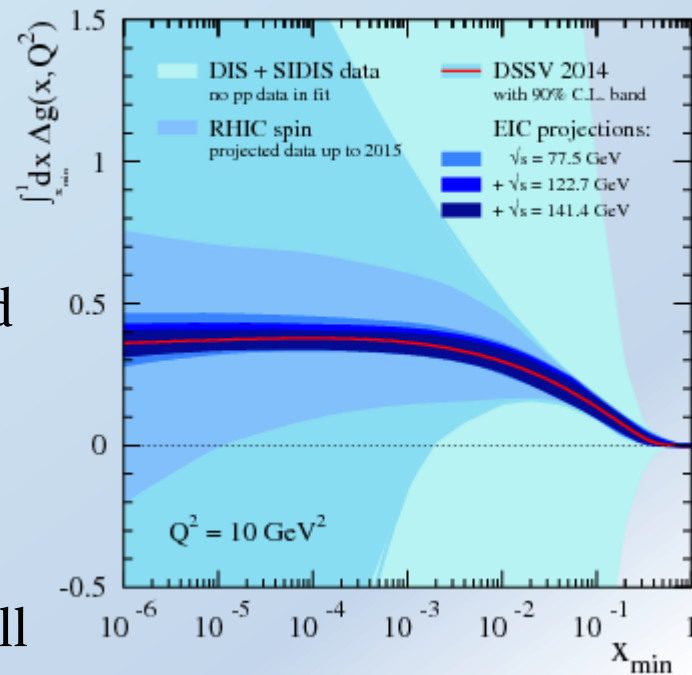


$J/\psi + X \rightarrow \mu^+\mu^- + X$  @ forward rapidity



- PHENIX forward  $J/\psi$  measurements reach close to  $x \sim 10^{-3}$
- Including feed-down almost entirely produced from  $gg$
- Due lack of knowing production mechanism interpretation still difficult

RPD 92 (2015) 094030



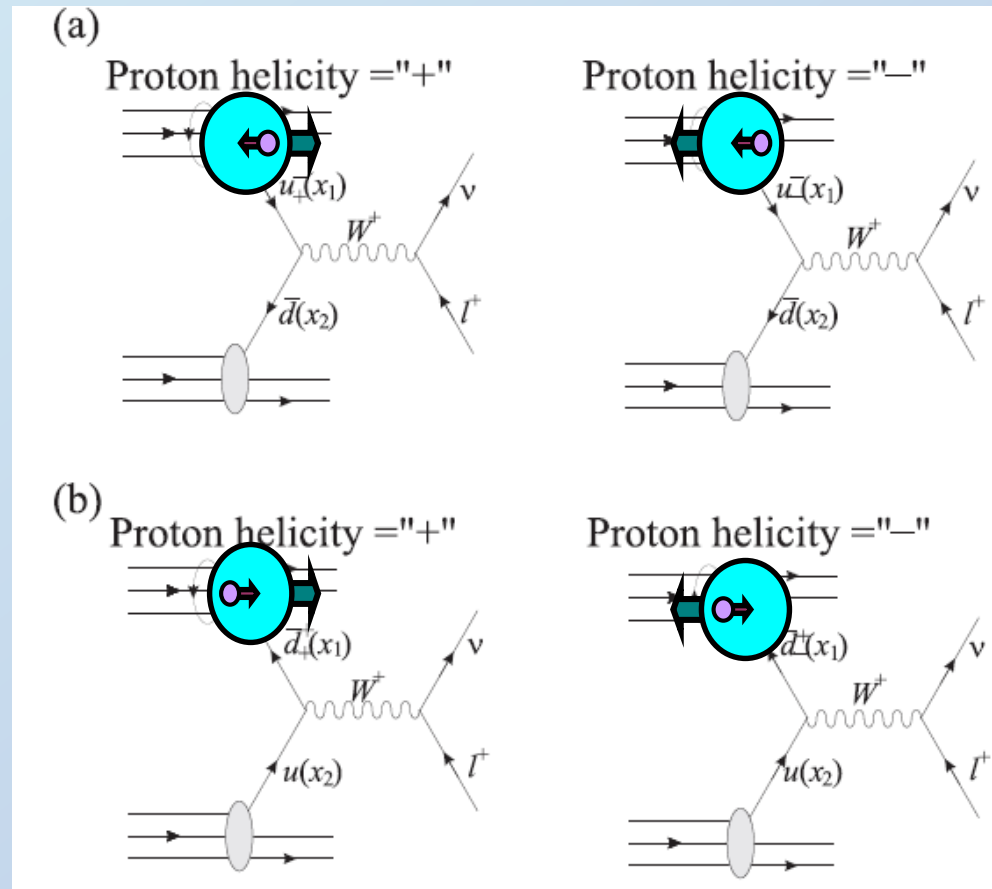
- Other forward  $\pi^0$  measurements ongoing to get better precision down to  $x \sim 10^{-3}$
- Eventually EIC to pin down integrals, strangeness and need for OAM

# Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only **lefthanded** quarks and **righthanded** antiquarks:
  - ➔ Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks
  - ➔ Difference of the cross sections gives quark helicities  $\Delta q(x)$
- No Fragmentation function required
- Very high scale defined by W mass

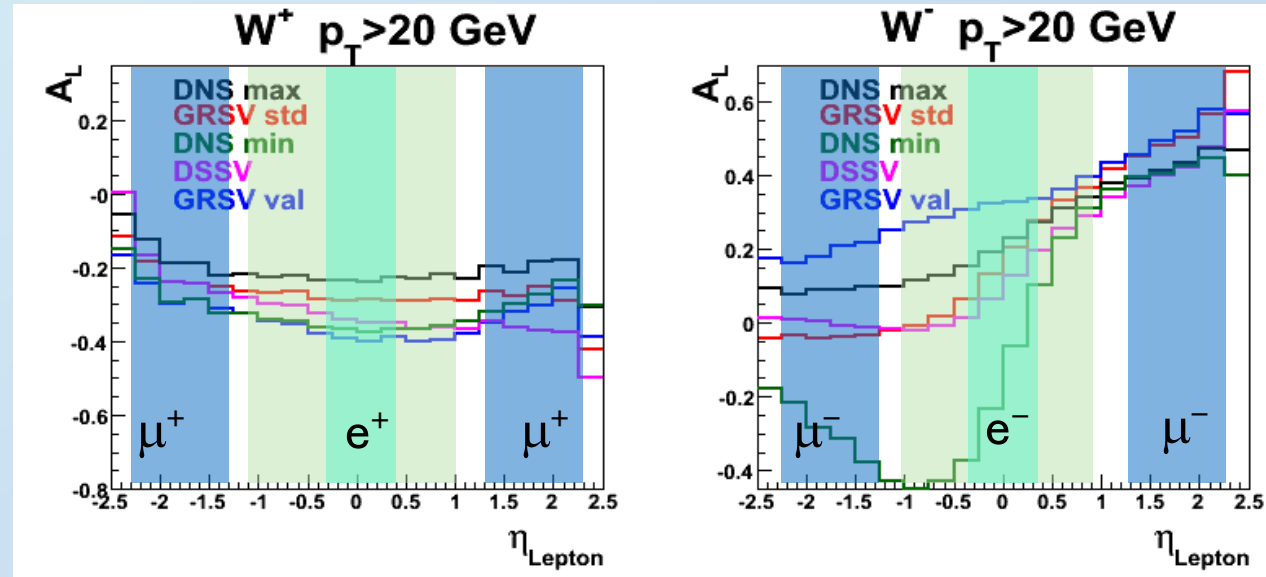
Bourelly , Soffer

Nucl.Phys. B423 (1994) 329–348



# Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics



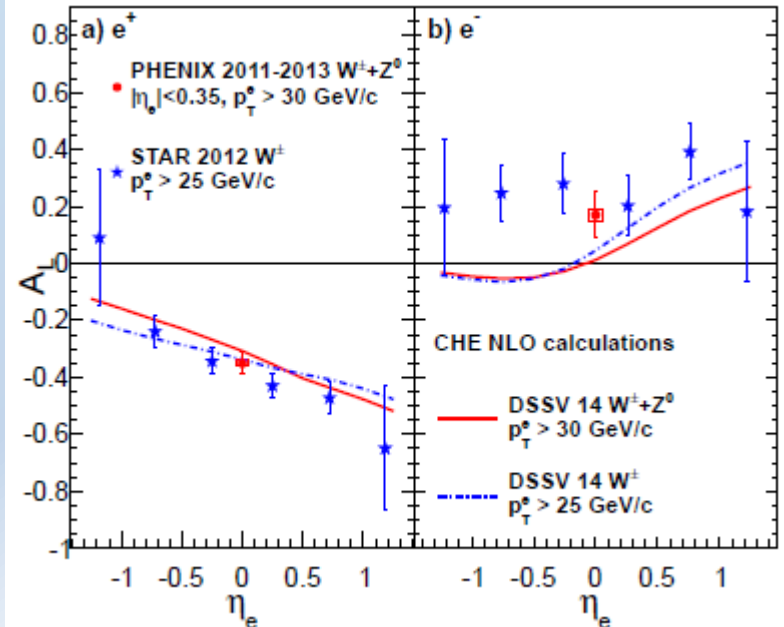
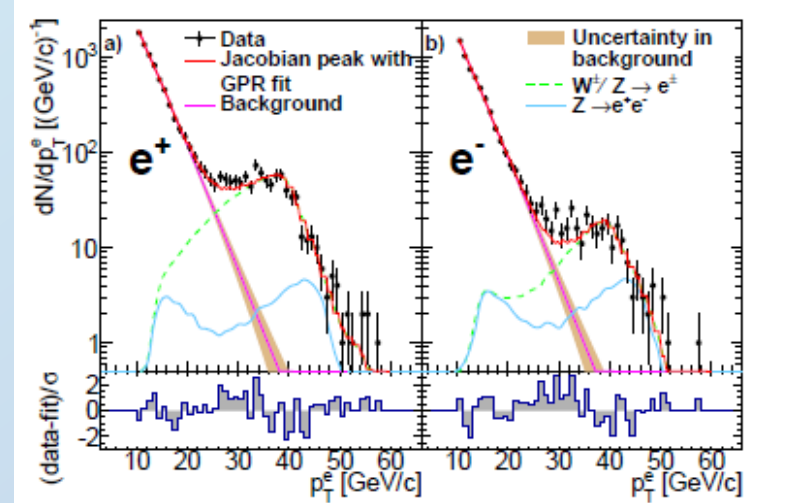
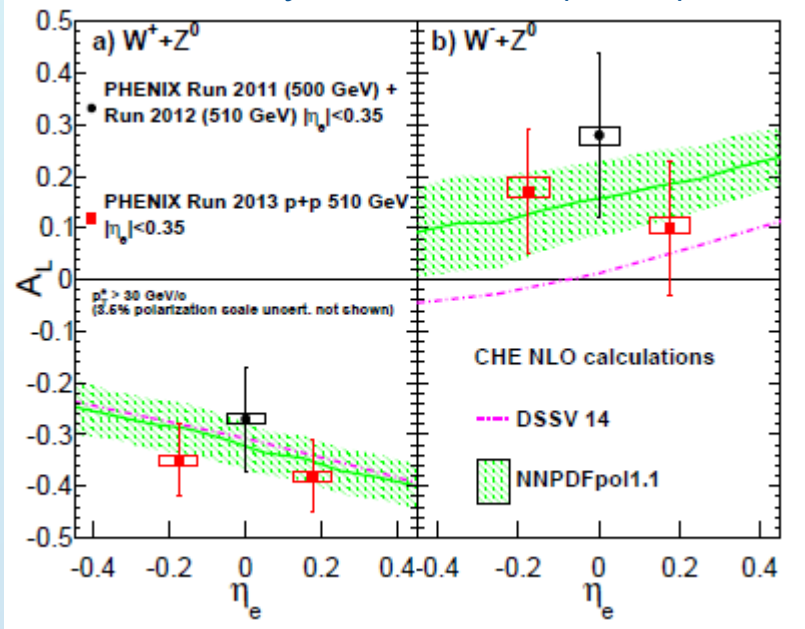
$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1 - \cos \theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1 + \cos \theta)^2}{u(x_1)\bar{d}(x_2)(1 - \cos \theta)^2 + \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2}$$

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

# Central $W+Z \rightarrow e$ asymmetries

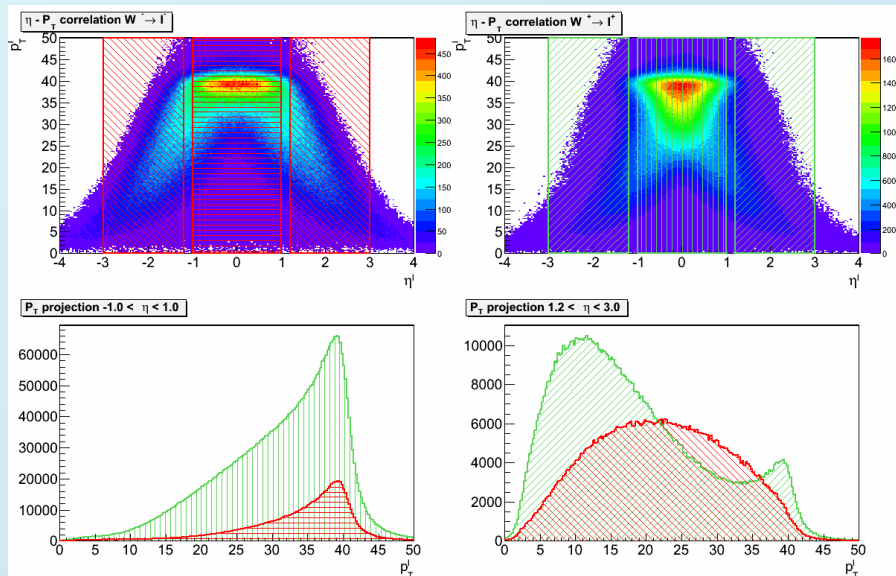
STAR: [Phys.Rev.Lett. 113 \(2014\) 072301](#)

PHENIX: [Phys.Rev. D93 \(2016\), 051103](#)

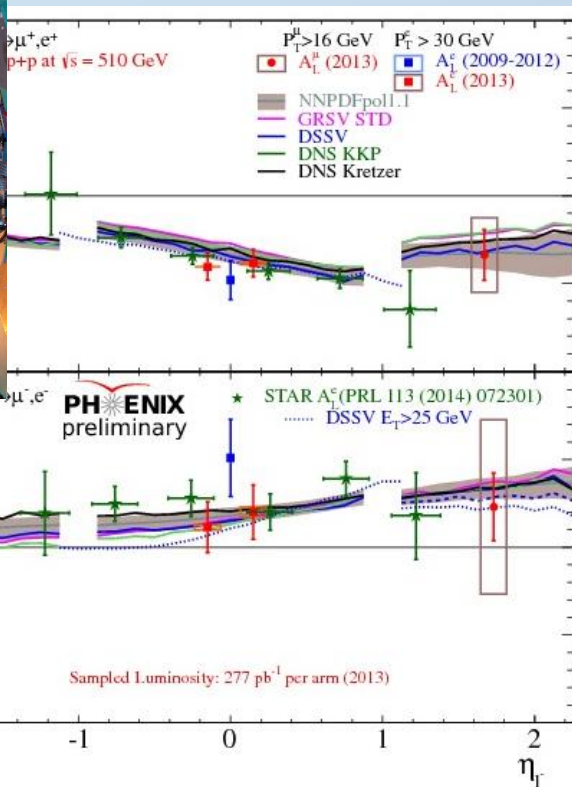


- Leptonic  $W$  decays very clearly visible via Jacobian peak
- Large asymmetries found, consistent between experiments
- $e^-$  significantly above latest global fit

# Forward $W+Z \rightarrow \mu$ asymmetries

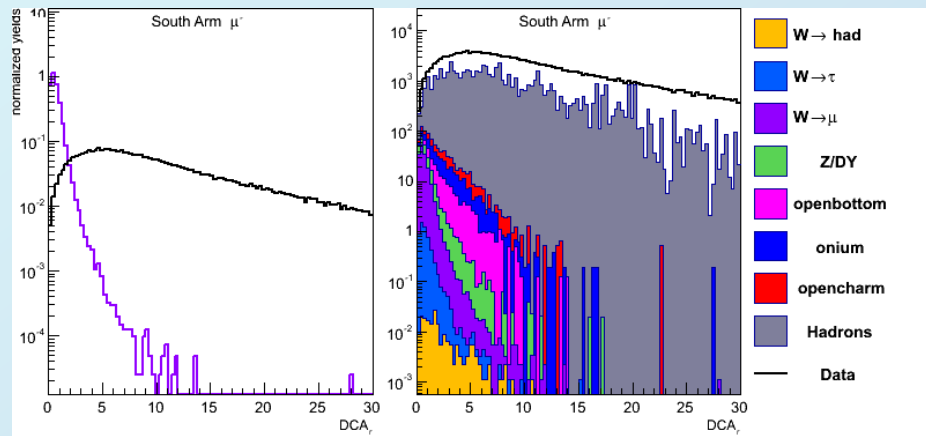


- At forward rapidities no Gaussian peak to identify W decay muons
- Lower  $P_T$  hadrons as fake high  $P_T$  “muons”
- Successfully performed unbinned max likelihood analysis to identify signal

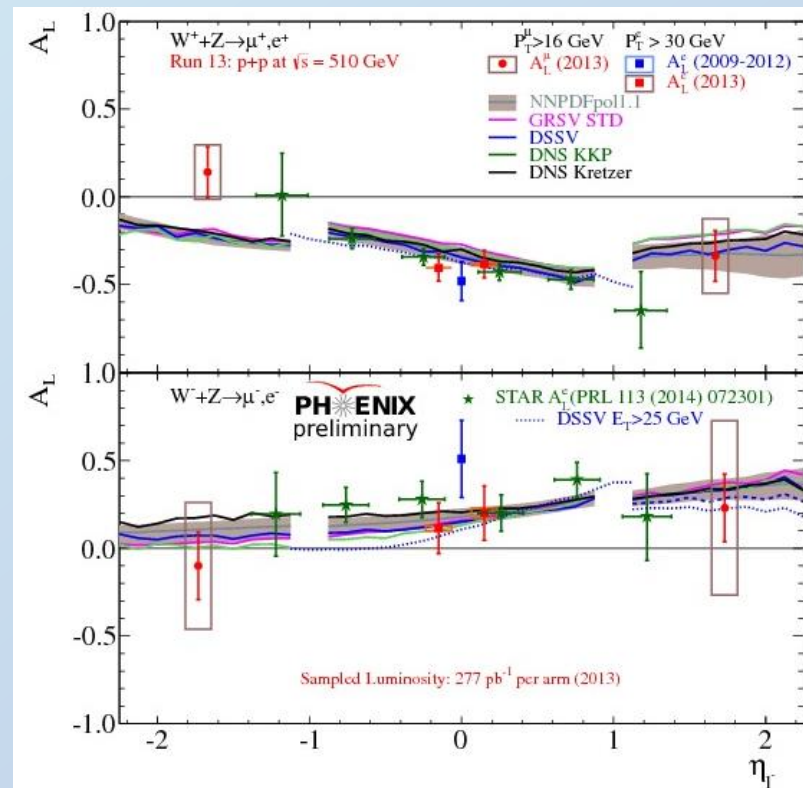


- Asymmetries as expected
- Still working on improving the uncertainties

# Forward $W+Z \rightarrow \mu$ asymmetries



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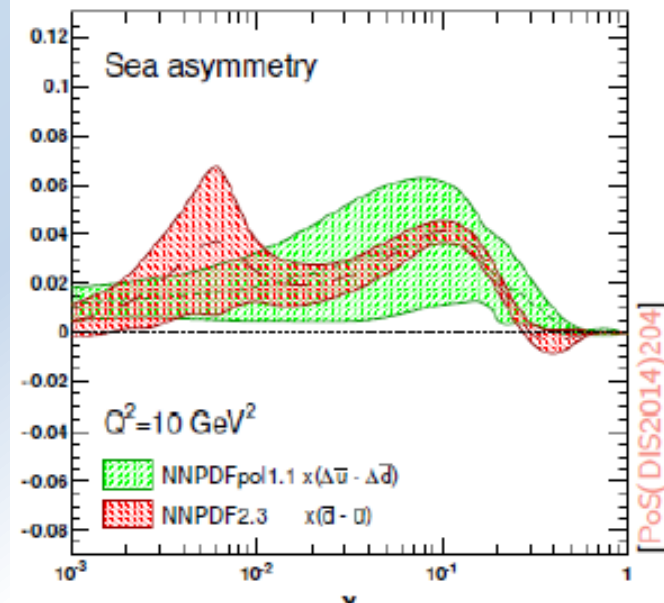
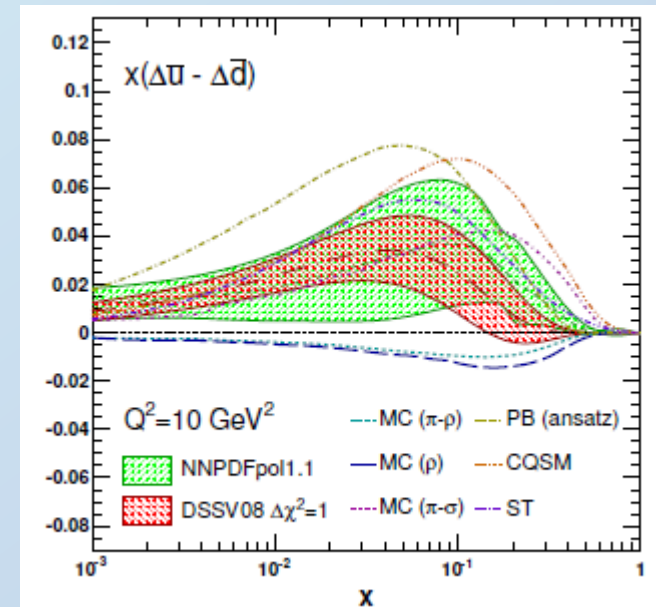


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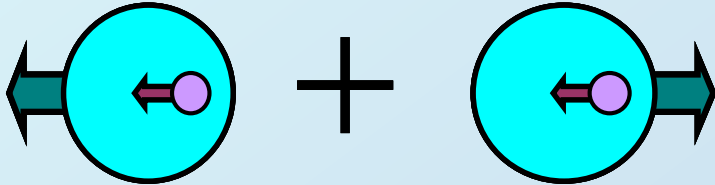
# Sea quark helicities

NNPDFpol1.1:  
[arXiv:1406.7122](https://arxiv.org/abs/1406.7122)

- STAR 2012 data at boundary of DSSV uncertainty bands
- Reweighted NNPDFpol1.1 shows substantial polarized light sea asymmetry
- opposite sign to most cloud models
- All central PHENIX data published,
- 2013 STAR data and forward PHENIX data pending

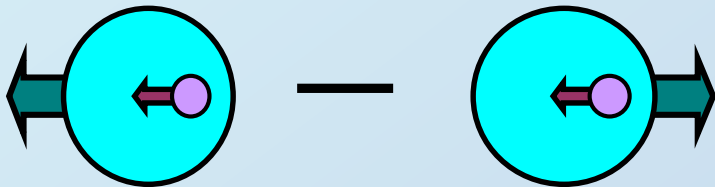


# Transverse quark polarization



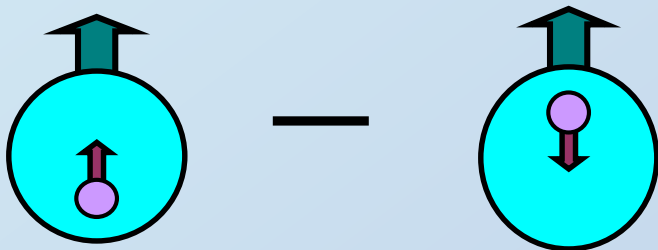
Unpolarized distribution function  $q(x)$

Sum of quarks with parallel and antiparallel polarization relative to proton spin  
(well known from Collider DIS experiments)



Helicity distribution function  $\Delta q(x)$

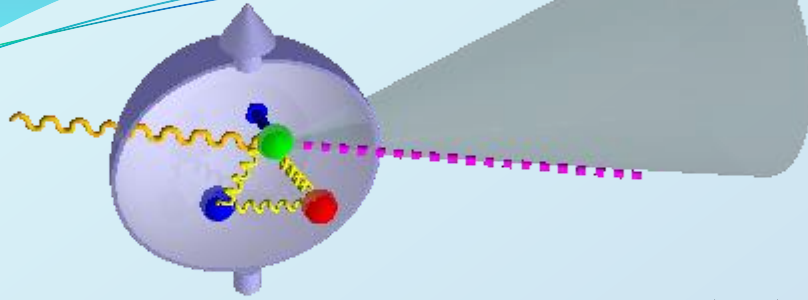
Difference of quarks with parallel and antiparallel polarization relative to **longitudinally** polarized proton  
(known from fixed target (SI)DIS experiments)



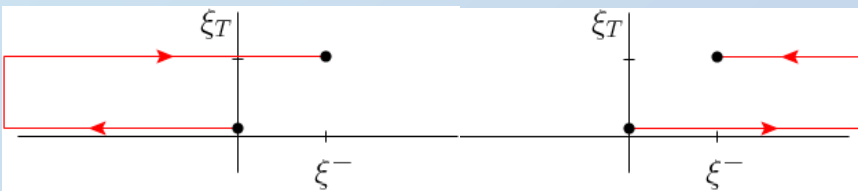
Transversity distribution function  $\delta q(x)$

Difference of quarks with parallel and antiparallel polarization relative to **transversely** polarized proton  
(first results from HERMES and COMPASS – with the help of Belle)

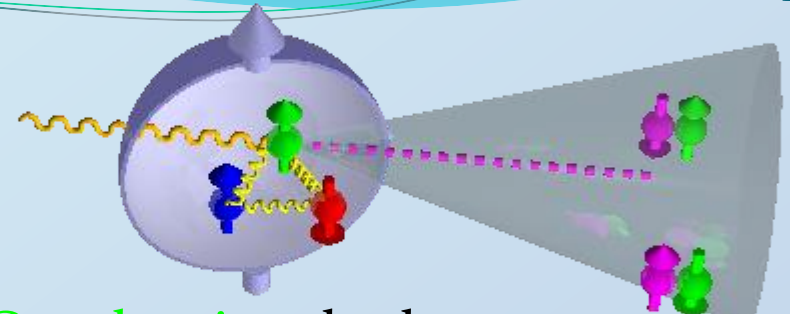
## Sivers Function



- Proton–spin – quark orbit ( $k_T$ ) correlation
- Suggested in '93 – dead due to time reversal
- Brodsky-Hwang-Schmid '02 model example of Sivers function using gauge links
- Belitsky-Yuan '02  $\rightarrow$  gauge links generally needed
- Collins  $\rightarrow$  function can exist, but modified universality (**the SIGN change**)



## Collins Function (x Transversity)

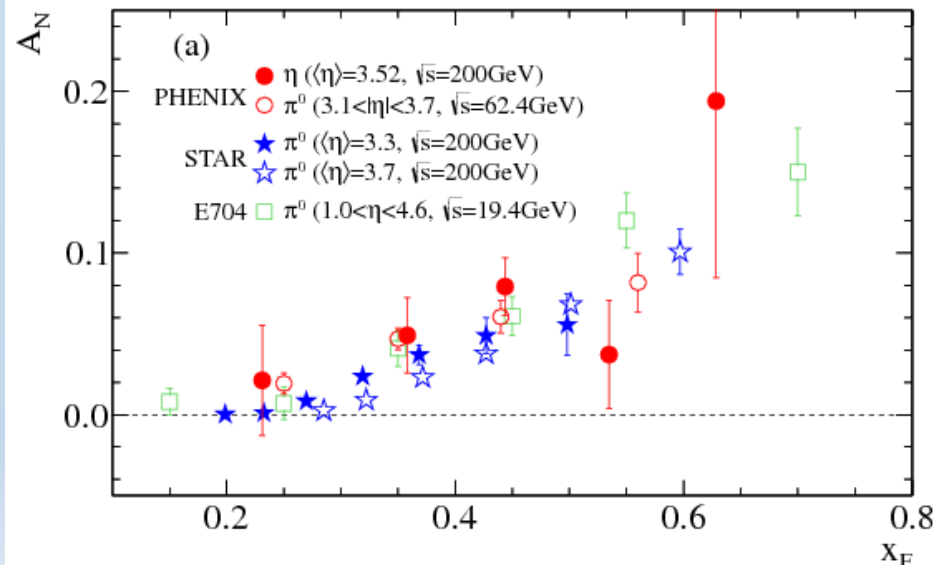


- **Quark spin** – hadron transverse momentum correlation (in fragmentation)
- Analyzer for quark transversity  $\rightarrow$  access to tensor charge (Lattice, BSM?)
- A polarized (ie signed) fragmentation function
- Transverse momentum conservation requires some compensation (Terayev-Schaefer)

# Inclusive single hadron left-right asymmetries in pp collisions

- Both **initial** state and **final** state effects contribute
  - Only one scale  $\rightarrow$  need to be described by collinear higher twist functions
  - Initial state higher twist effect related to  $k_t$  moment of Sivers TMD
  - Final state effect related to transversity and  $k_t$  moments of Collins fragmentation function
  - Some indications for potentially other origins
- Explicit hadron-in-jet and DY asymmetries directly related to TMDs
- Also study  $A$  dependence in pA collisions

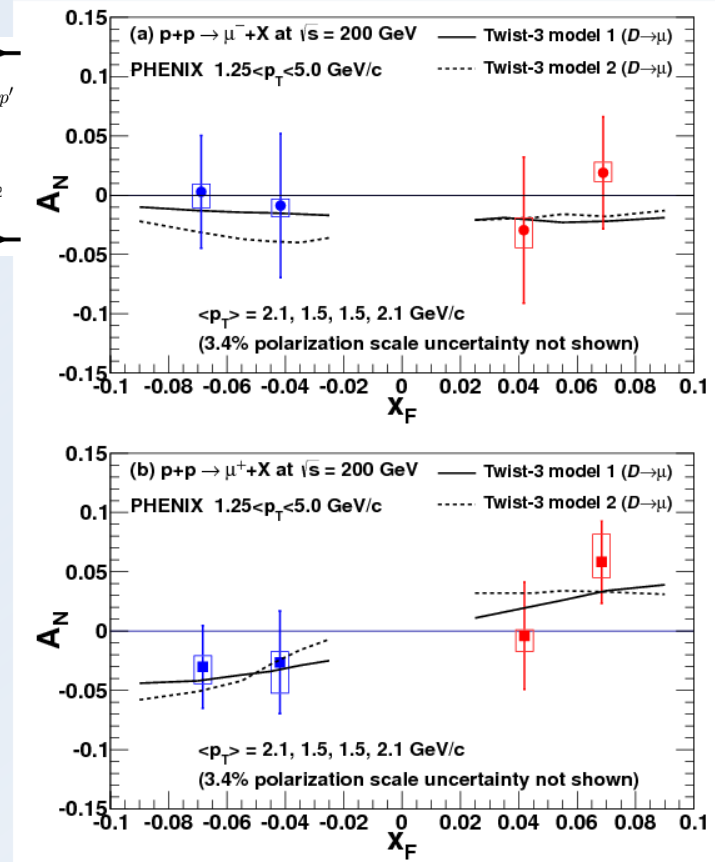
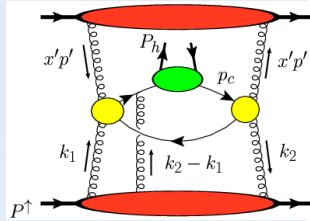
Phys.Rev. D90 (2014) 7, 072008  
Phys.Rev. D90 (2014) 1, 012006



# Heavy flavor asymmetries

[Phys.Rev. D95 \(2017\) 112001](#)

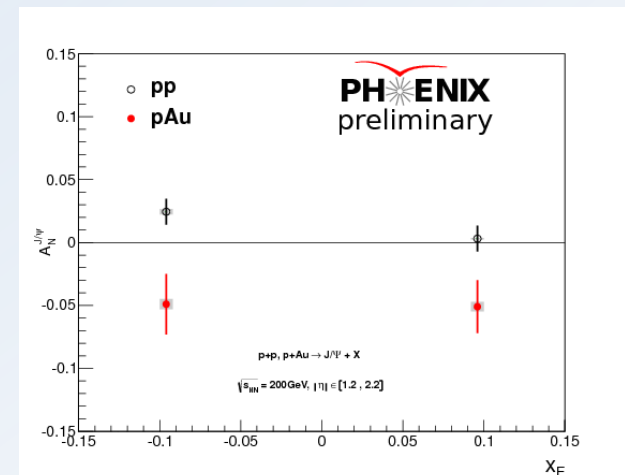
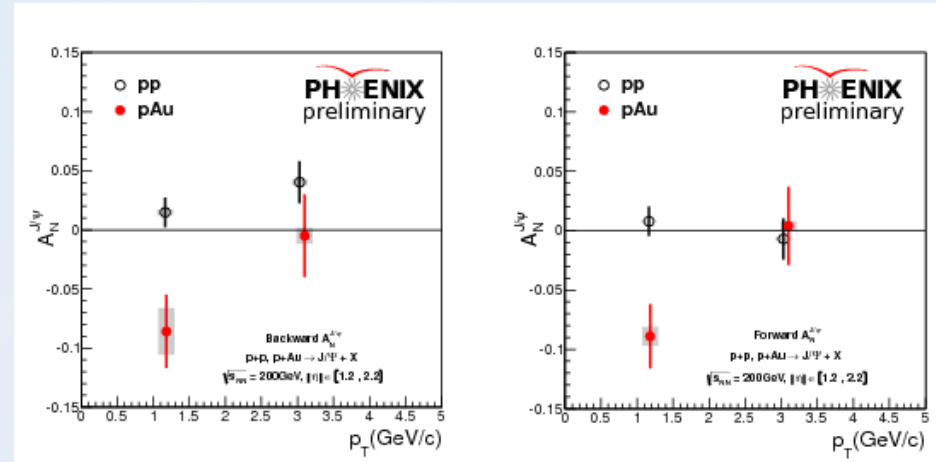
- Heavy flavor asymmetries most sensitive to Twist-3 counterpart of Gluon Sivers and tri-gluon correlator,
- no final state effects expected due to heavy quark mass
- Both contributions poorly known



Model calculations from: Koike et.al. [Phys.Rev. D84 \(2011\) 014026](#)

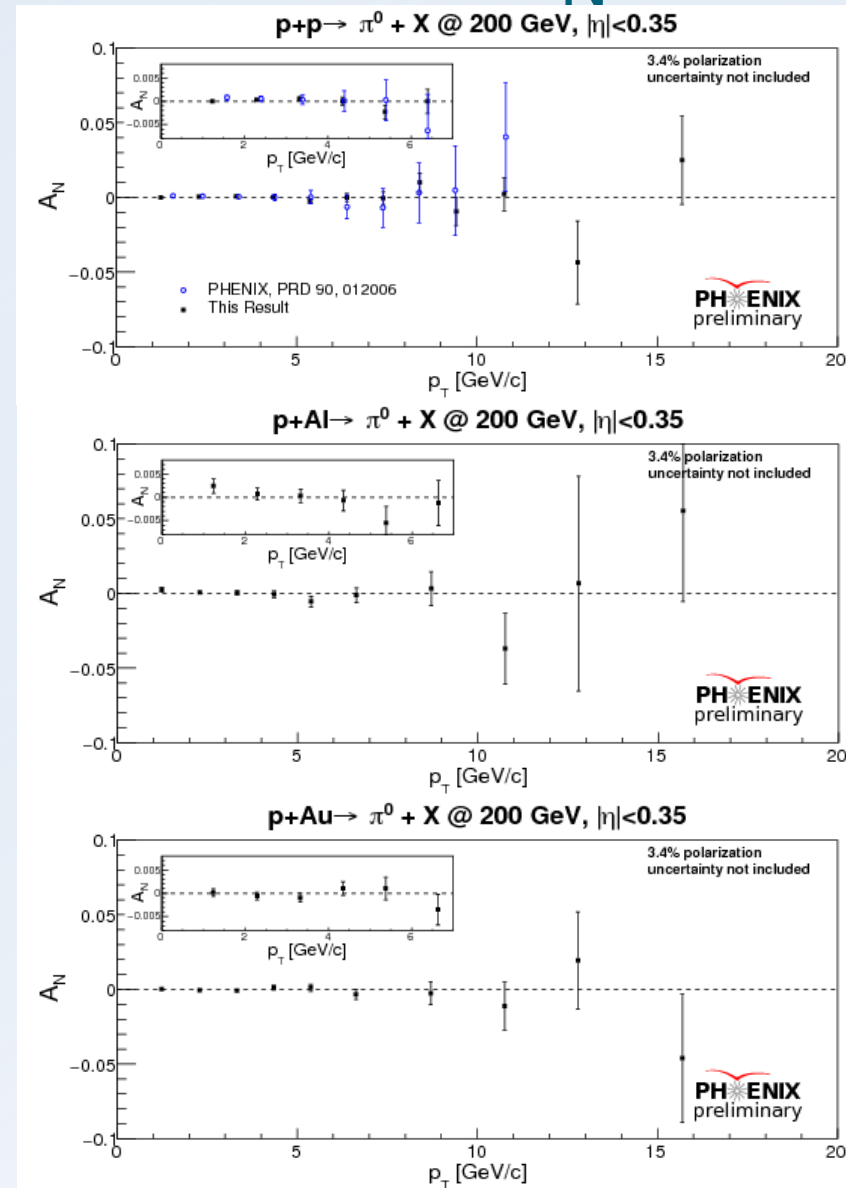
# J/Psi $A_N$ s

- Surprising nonzero J/Psi  $A_N$ s seen in pAu collisions while pp Asymmetries are mostly consistent with zero
- Nonzero effect only visible at the lowest available  $P_t$
- Diffractive effects as cause not very likely due to coincidence with hard collision trigger
- pA1 data is being analyzed



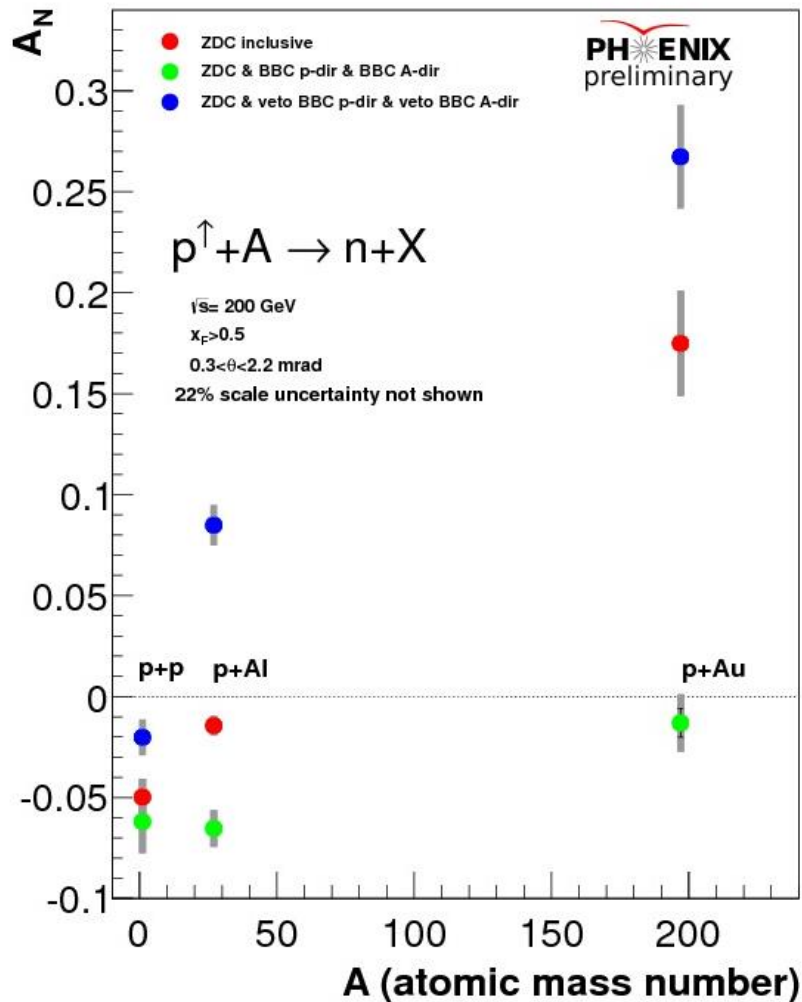
# A dependence of central $\pi^0$ $A_N$ s

- Central rapidity  $A_N$ s mostly sensitive to Gluon Sivers Twist-3 counterpart
- pp results consistent with zero at even higher precision
- No surprises in A dependence



# Forward neutron asymmetries

[arXiv:1703.10941](https://arxiv.org/abs/1703.10941)

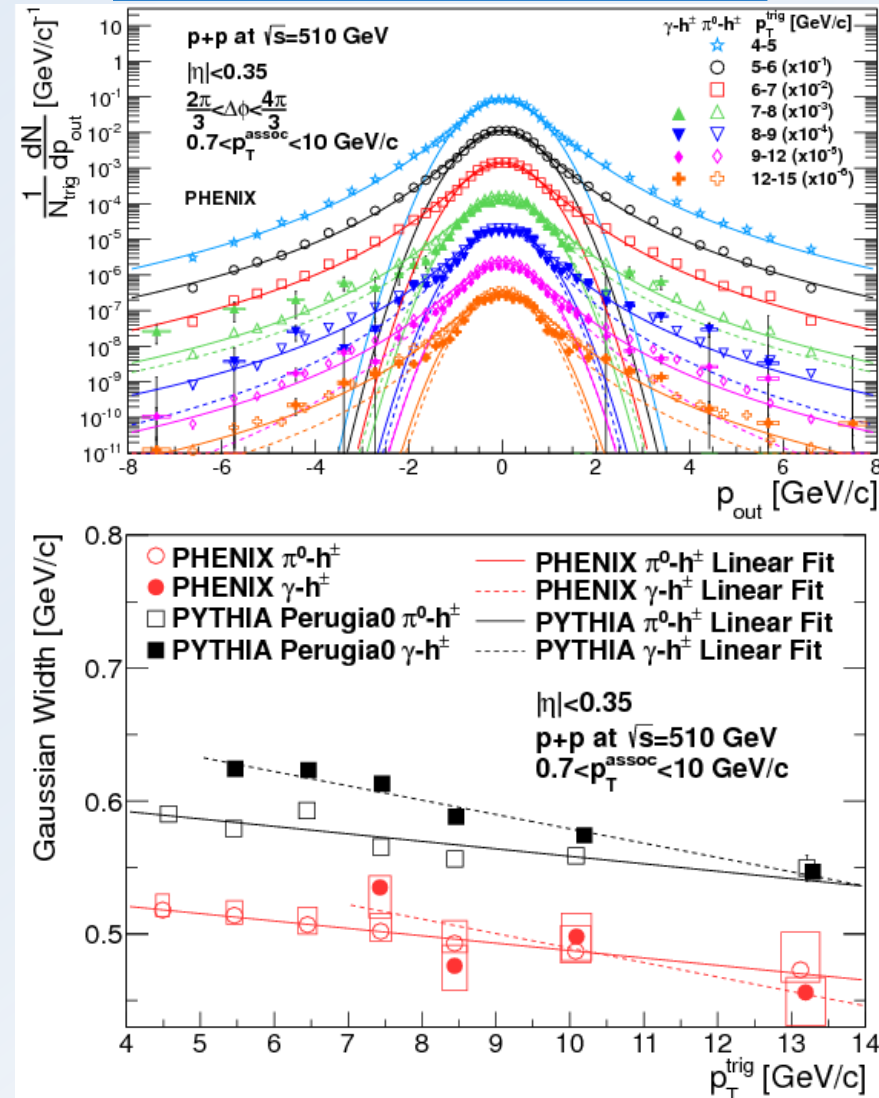


- Unexpectedly large  $A$  dependence in neutron asymmetries
- Sign change seen
- Possibility of ultra-peripheral collisions (UPC) effect, enhanced by  $Z^2$  for nuclei
- (anti-)Correlations with main Collision detector system enhance/reduce UPC contribution

# Di-hadron and h- $\gamma$ correlations

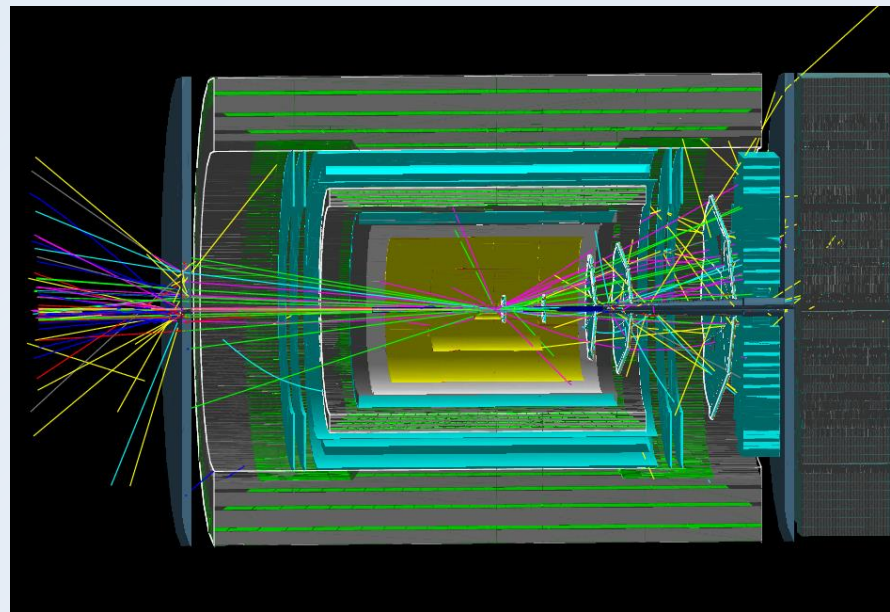
Phys.Rev. D95 (2017) 072002

- Look at angular correlation between nearly back-to-back particles
- Widths of Gaussian components seem to be decreasing with trigger particle momentum while increase is expected
- Pythia qualitatively describes this effect



# RHIC future (for spin and CNM physics)

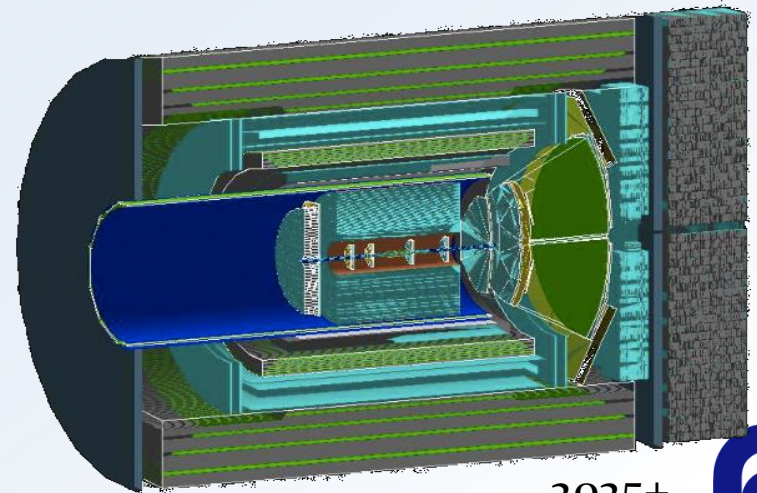
- Currently 510 GeV run ongoing in STAR for Sivers function measurements in Ws, Z and DY
- sPHENIX detector ( $-1.1 < \eta < 1.1$ ):
  - 1.4T Babar magnet
  - Central TPC + MAPS vertex tracker
  - EM+HCAL
  - CDo in Fall 2016
- For spin and CNM interest in **Forward** rapidities:
  - origin of large asymmetries,
  - high/low x reach
- fsPHENIX ( $2 < \eta < 4$ ):
  - Reused PHENIX EMCAL
  - New HCAL (joint development for STAR/fsPHENIX/EIC led by UCLA)
  - Tracking (GEMs or sTGCs)



- Most detectors directly useable for eRHIC
- Main Goals:
  - jet transverse asymmetries (flavor enhanced or Collins),
  - DY/photons in pA for nuclear /gluon PDFs
  - Hadronization in medium

# eRHIC

- 2015 NSAC long range plan highest priority new facility: electron Ion Collider (EIC)
- Currently National Academy of Science review ongoing
- DOE CD process starting soon
- 2 potential realizations:
  - JLAB (CEBAF+new pol. ion accelerator – concentration on first high intensity, lower CMS energy)
  - eRHIC (RHIC + new pol. electron beam – concentration on first high CMS energy, initially lower intensity)
  - ePHENIX (fsPHENIX + electron side+PID)



2025+

# Summary

- Gluon spin contribution confirmed at higher collision energies, started accessing lower  $x$
- Polarized light sea seems to be asymmetric and disfavors pion cloud models
- New information towards understanding transverse asymmetries in hadron collisions, but also new puzzles (such as  $A$  dependence)
- More to come in the future:
  - RHIC ([CNM 2017-23 plan](#))
- EIC

