Overview of PHENIX Spin Physics Program

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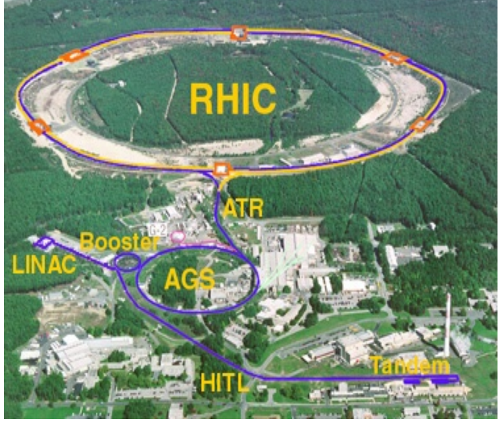
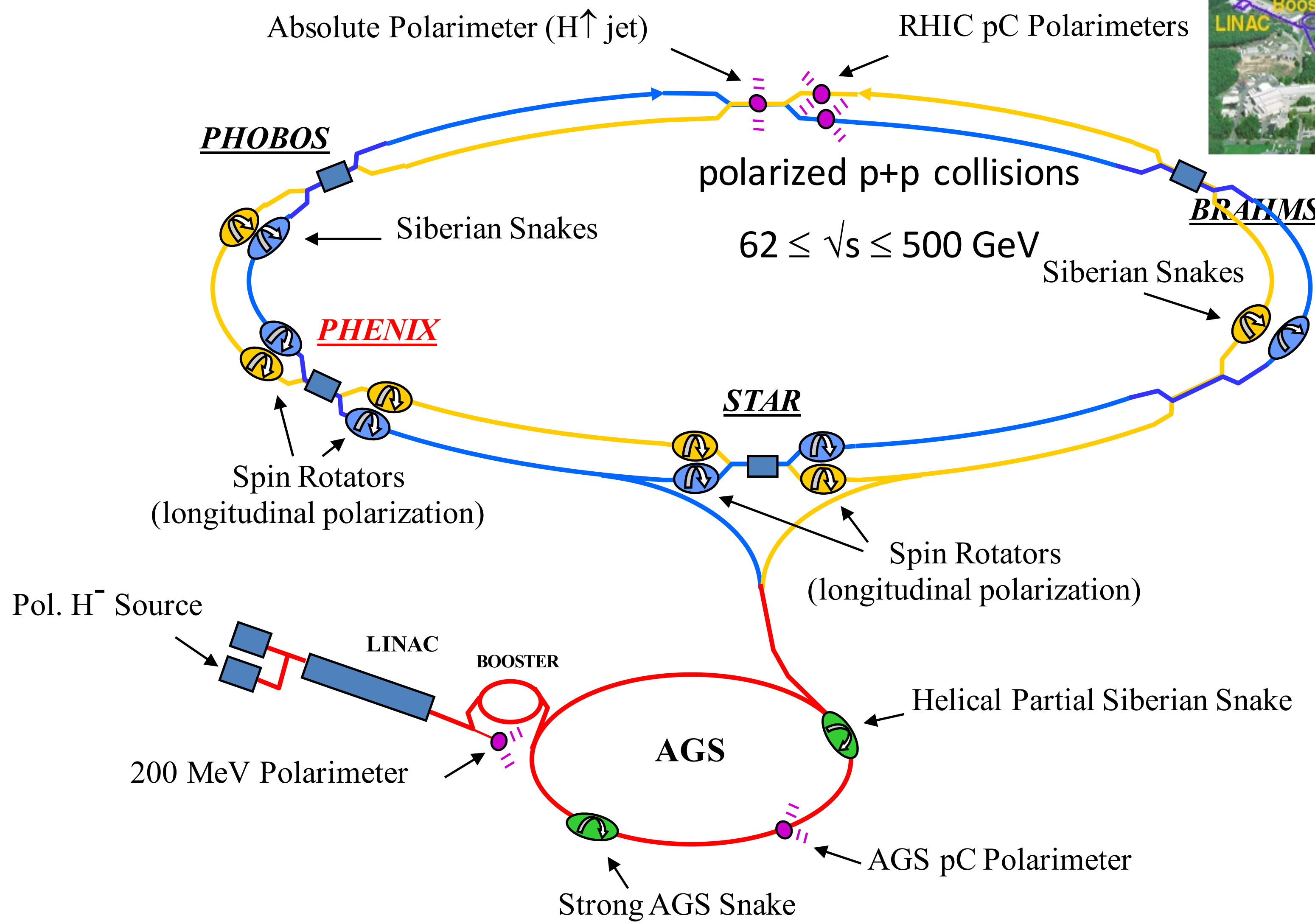
PHENIX

Outline

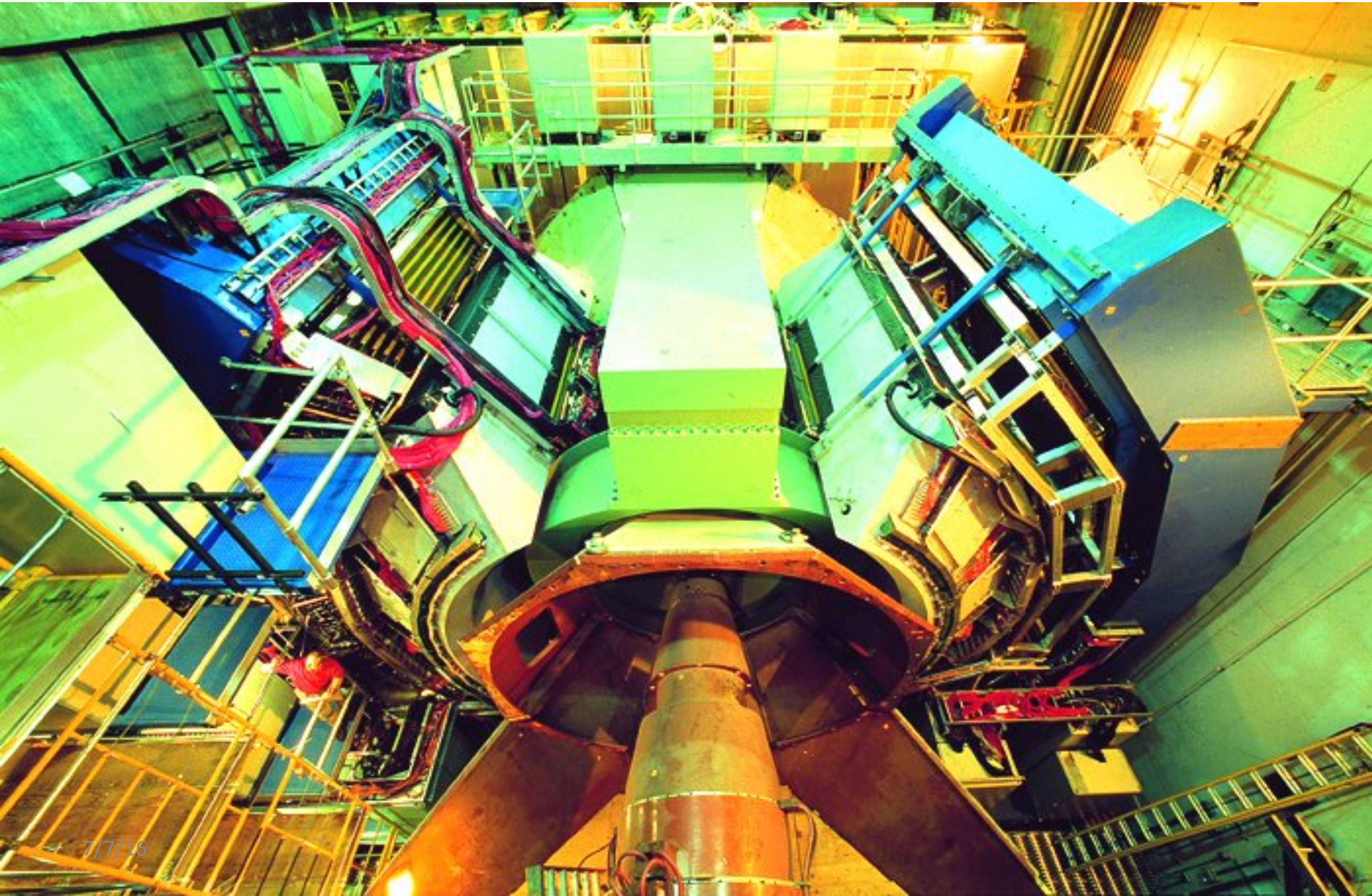
- PHENIX experiment at RHIC
- Longitudinal spin program
- Transverse spin program
- Outlook

Polarized Proton Collider at RHIC

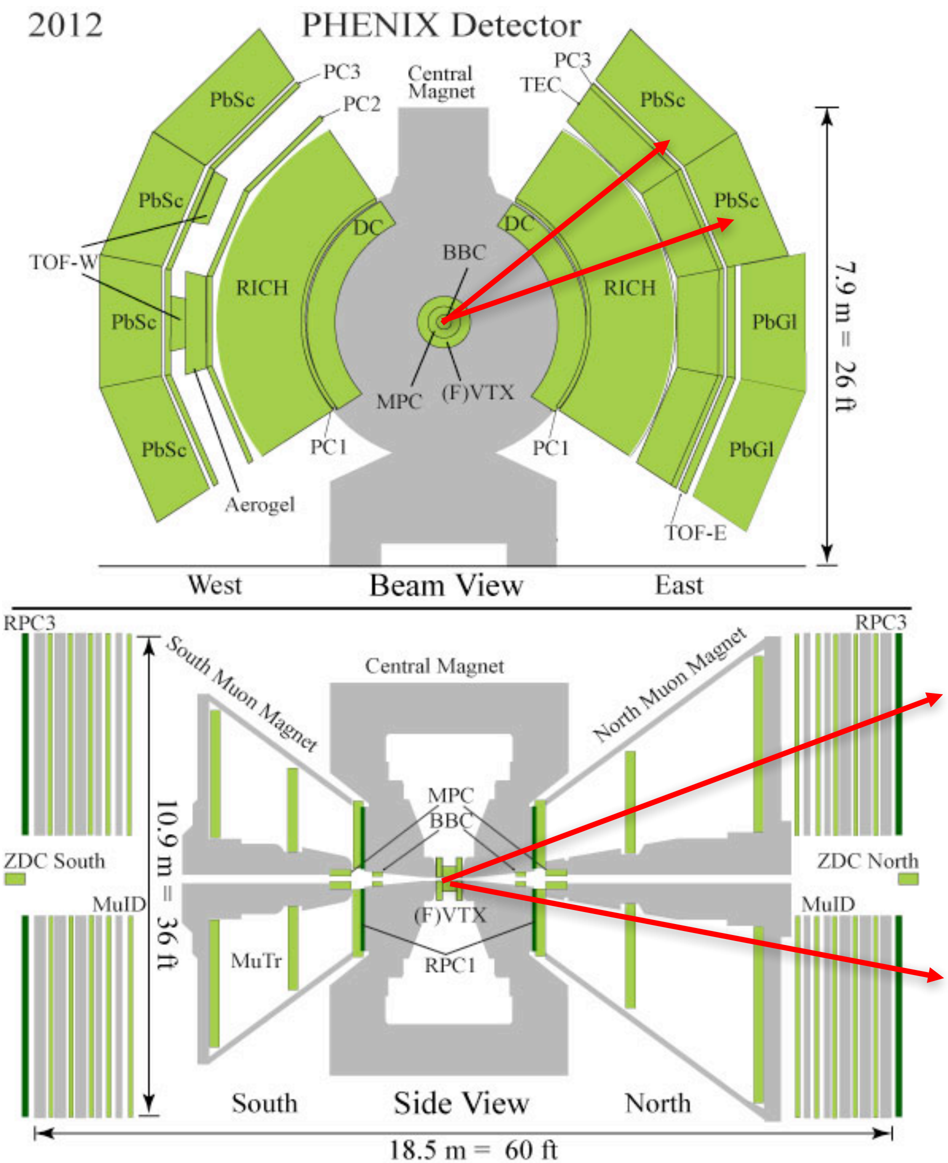




PHENIX Detector



PHENIX Detector at RHIC



Central Arms | η | < 0.35
- Identified charged hadrons
- Neutral Pions
- Direct Photon
- J/Psi
- Heavy Flavor

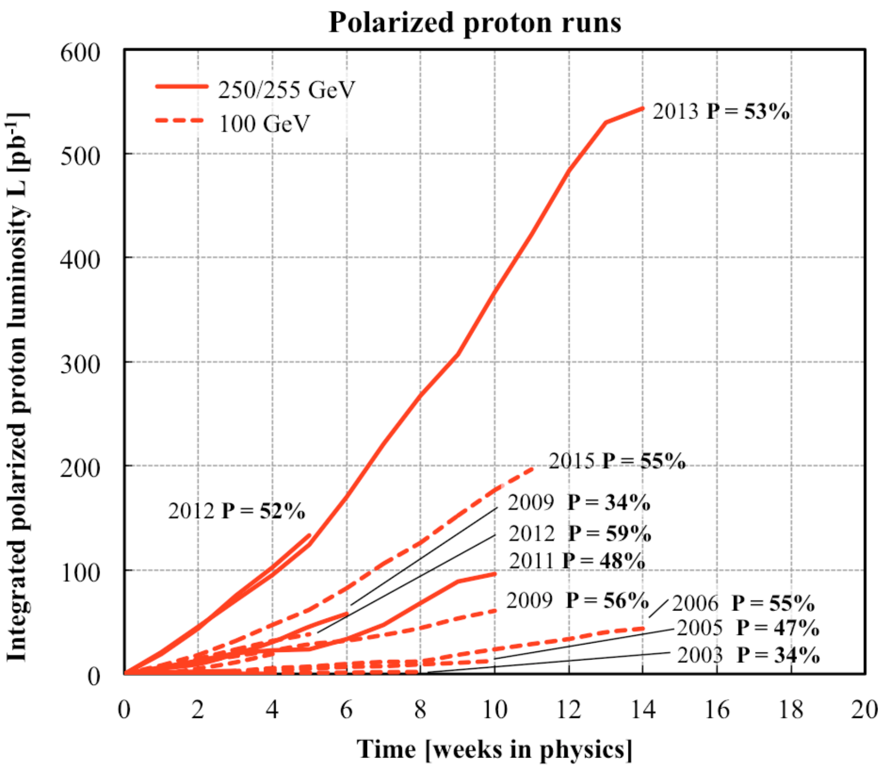
Muon Arms 1.2 < | η | < 2.4
- J/Psi
- Unidentified charged hadrons
- Heavy Flavor

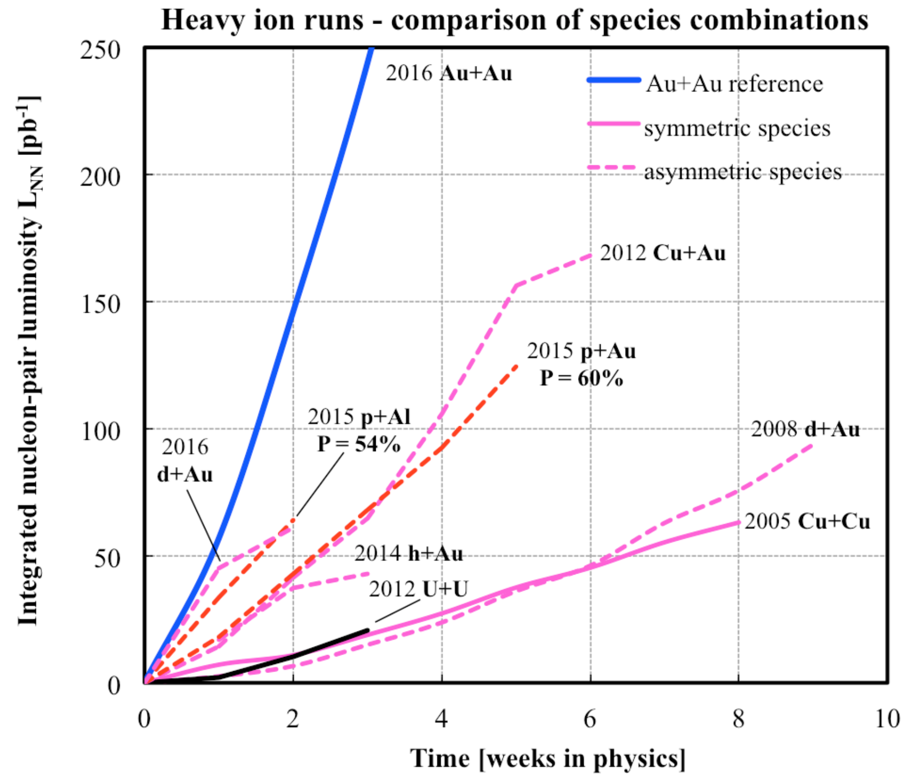
MPC 3.1 < | η | < 3.9
- Neutral Pion's
- Eta's

ZDC |η| ~ 5.9
- Neutrons

History of RHIC Spin Runs

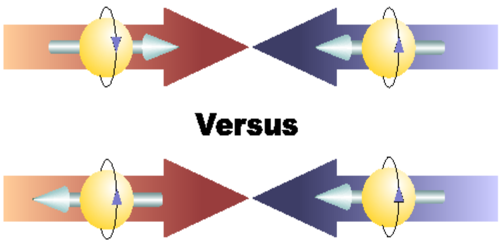
RHIC is capable of delivering the polarized p+p/A for precision spin physics

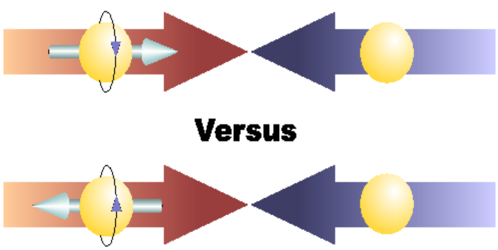


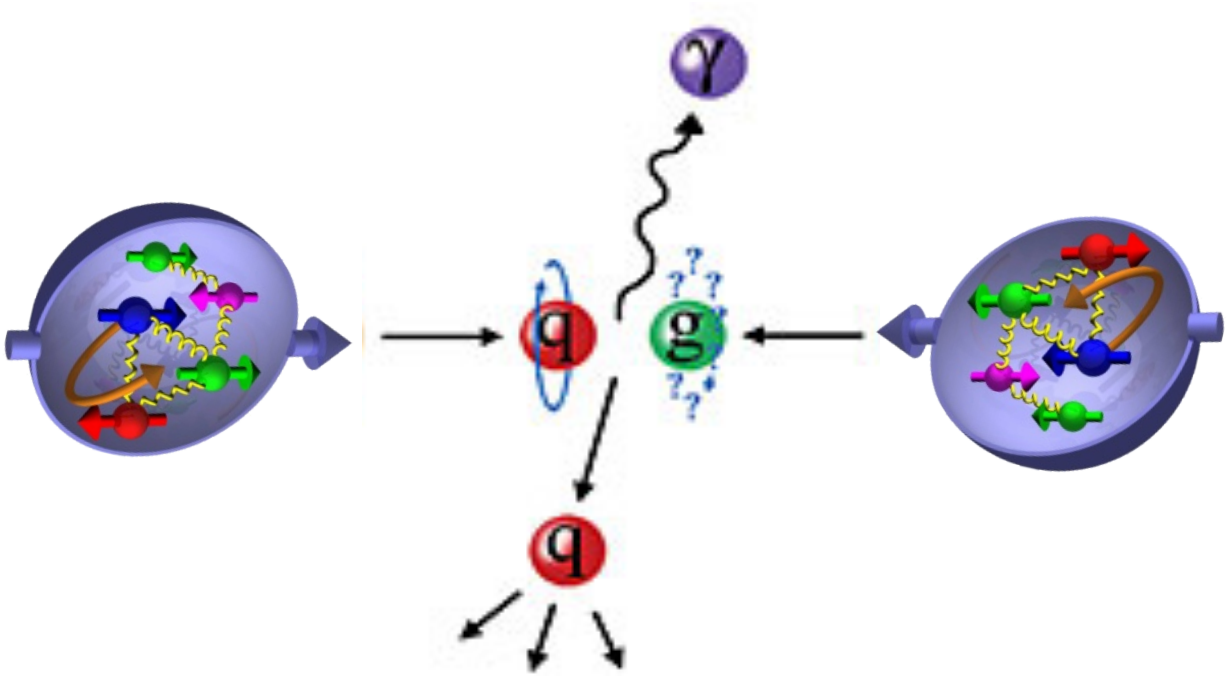


- A very challenging task to deliver polarized p+p, excellent performance from 2012+
- Outstanding Heavy Ion machine performance from the beginning
- Polarized p+p, p+Au and p+Al

Physics with Longitudinally Polarized p+p Collisions

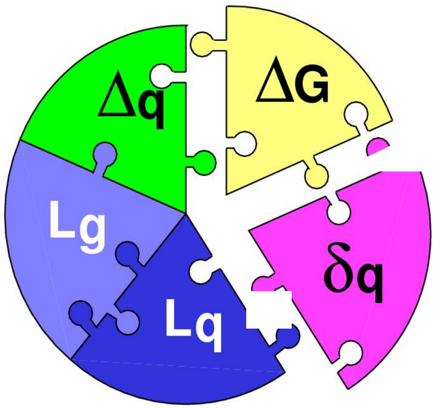






Three Decades of the Proton Spin Puzzle

- 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

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

$$\Delta q \sim 30\% \quad (pol.\, SIDIS)$$

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

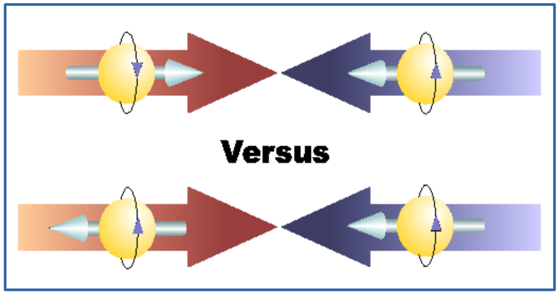
$$L \sim ? \quad (RHIC, FNAL?)$$

	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

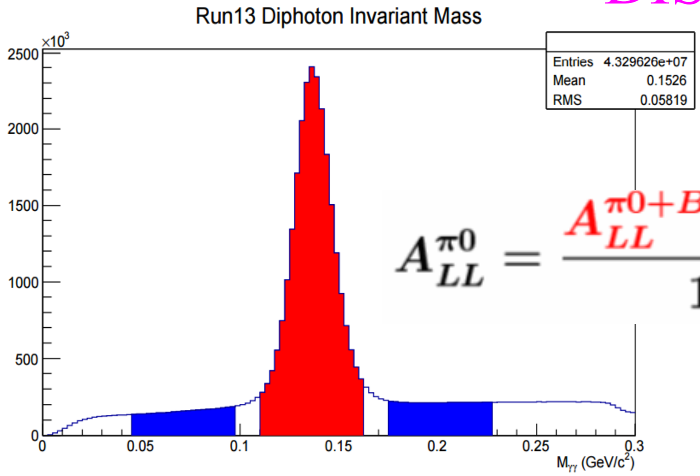
Gluon Polarization and π^0 A_{LL}



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

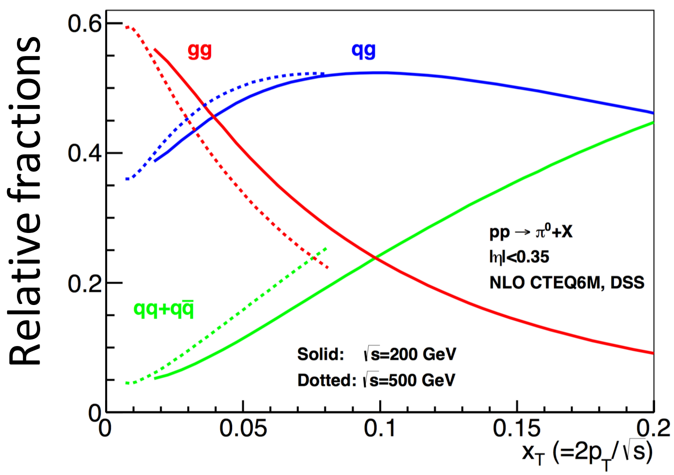
-- Parton distribution functions
-- Partonic hard scattering rates
-- Fragmentation functions

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



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

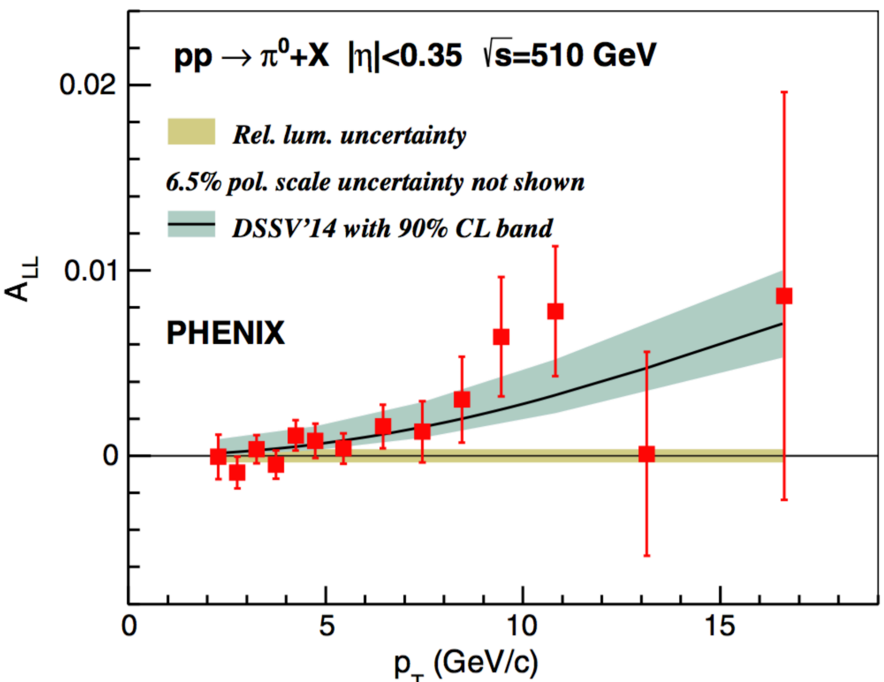
Di-photon mass: π^0 peak

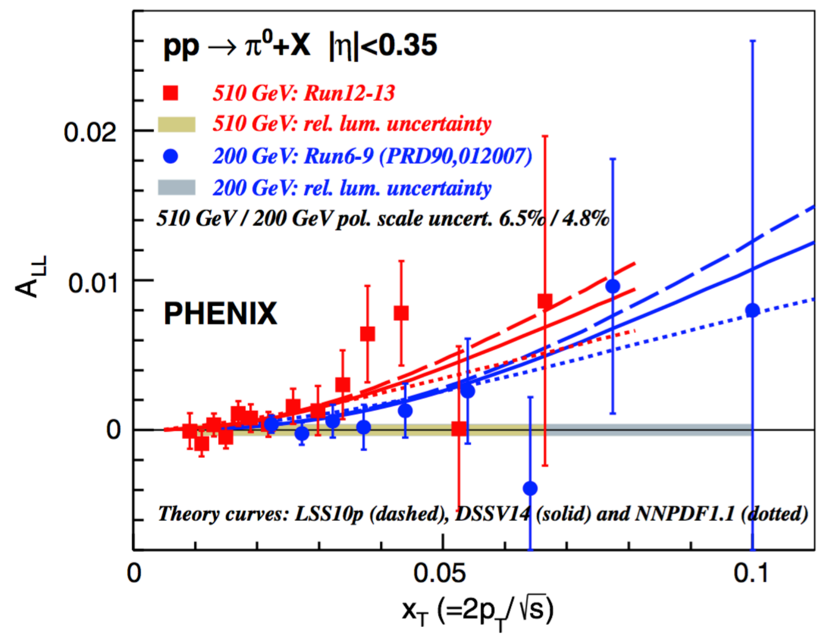


π^0 A_{LL} at central rapidity ($|\eta|<0.35$)

- Latest PHENIX publication PRD 93, 011501(R), (2016)
- Positive gluon polarization at moderate x ~ 0.05 - 0.2

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





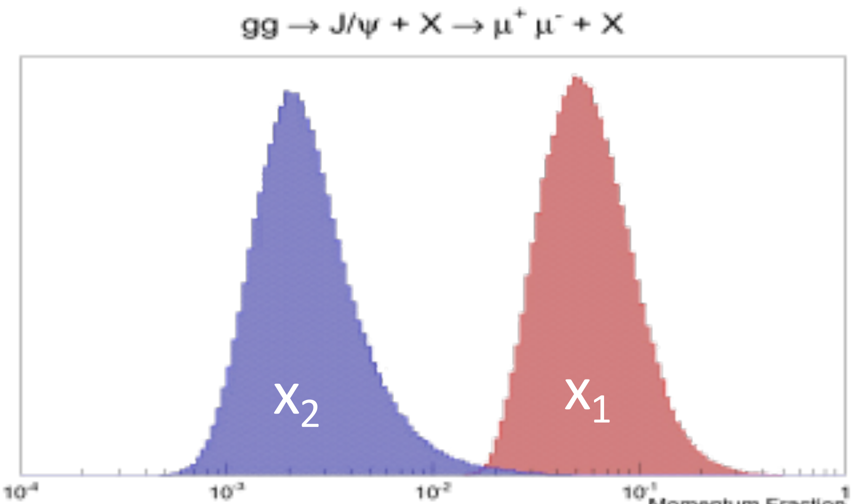
PHENIX+STAR data: $\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\,dx = 0.10^{+0.06}_{-0.07}$

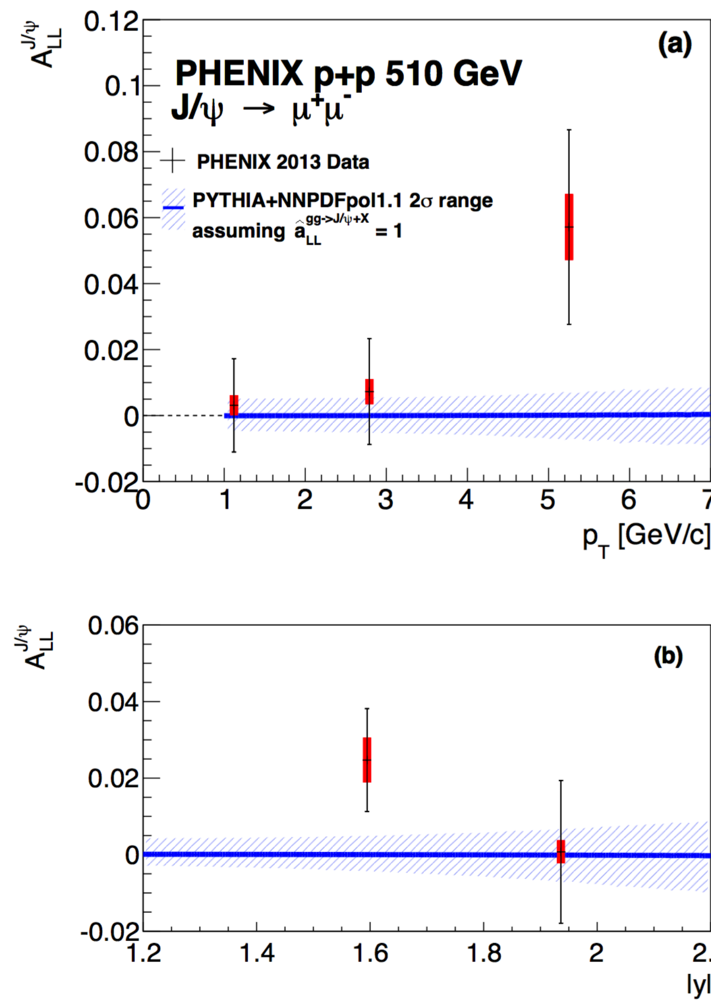
J/ψ A_{LL} at Forward Rapidity

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

The A_{LL} for J/ψ can be written (LO):

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

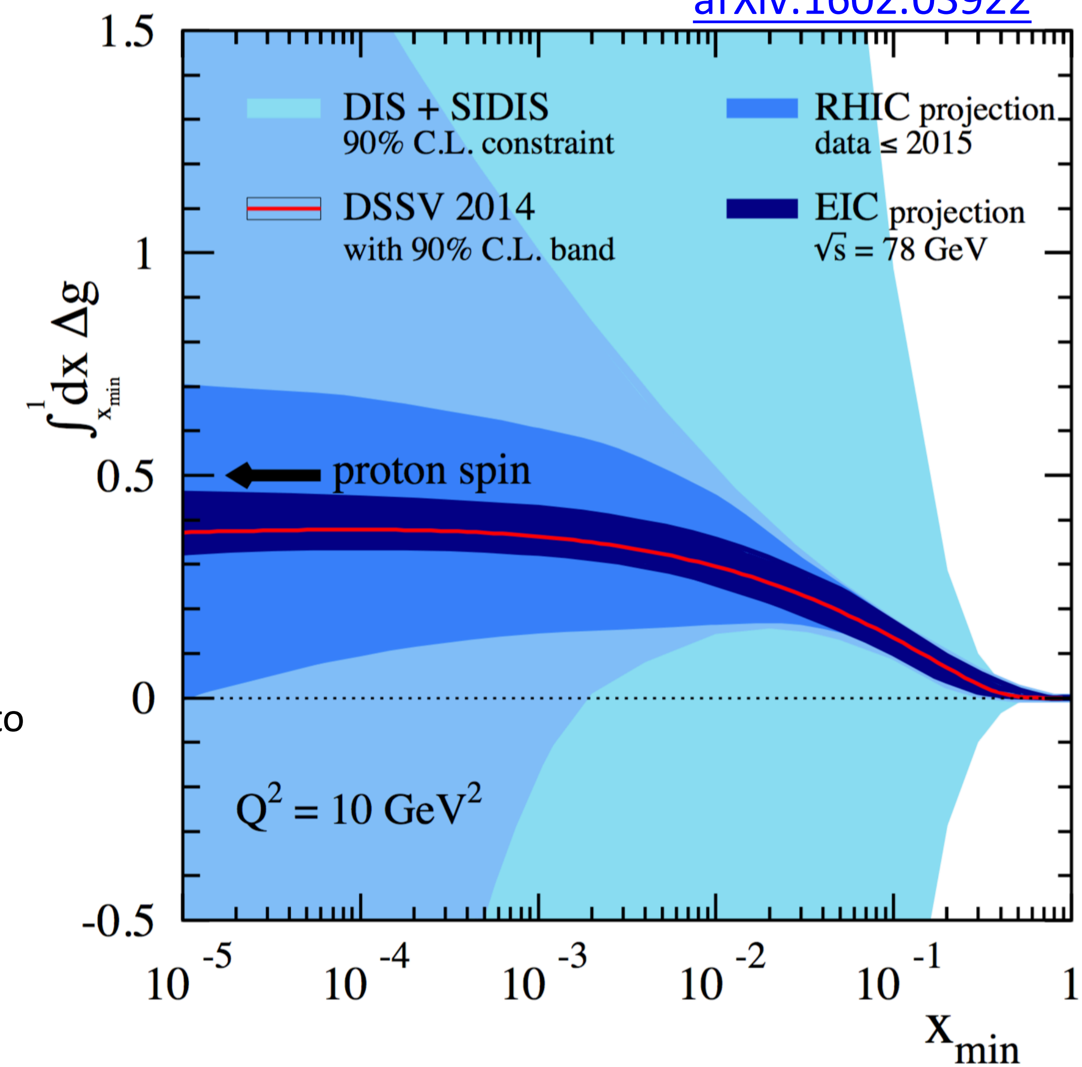




Impact of RHIC data on Gluon Polarization

- Favors positive gluon polarization
  - Published/Submitted:
    - Run9 200GeV Central π^0 A_{LL}
    - Run13 510GeV Central π^0 A_{LL}
    - Run13 510GeV Forward J/ψ A_{LL}
  - Ongoing analyses
    - Run11 500GeV Forward π^0 A_{LL}
    - Run13 510GeV Forward π^0 A_{LL}
    - Run13 510GeV Central $\pi^{\pm}$
    - Run13 510GeV Central direct photo
    - Run9, 11 di-π^0 A_{LL}
- Proposed EIC, 2025+

arXiv:1602.03922



Flavor Identified Sea Quark Polarization $\Delta u\ (x), \Delta d(x)$

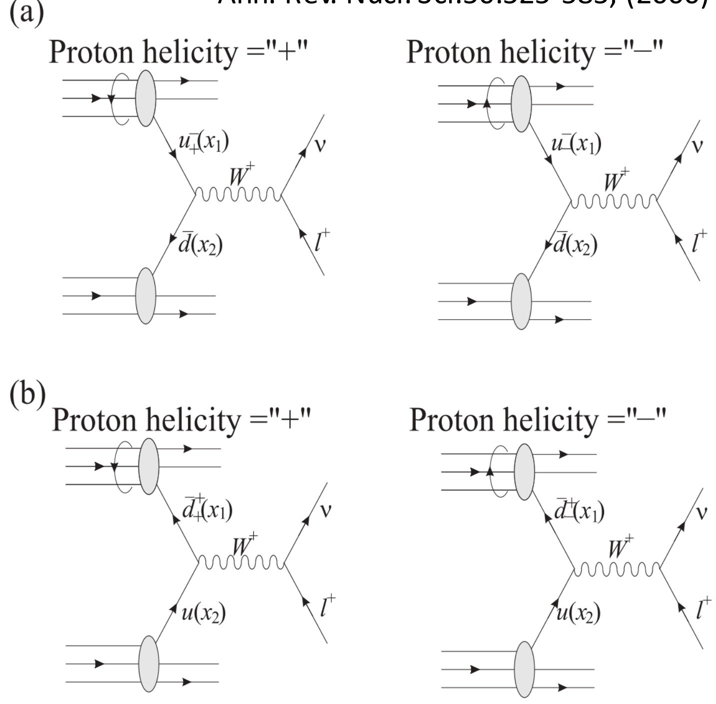
- Could sea-quark contribute significantly the total proton spin?
  - Polarized sea-quark distributions poorly known, SIDIS has limited sensitivity
- RHIC has unique access to flavor identified sea-quarks via $W^{+/-}$

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

$$A_L^{W^-} \approx \frac{\Delta d}{d}$$ (forward rapidity)

$$A_L^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}$$ (backward rapidity)

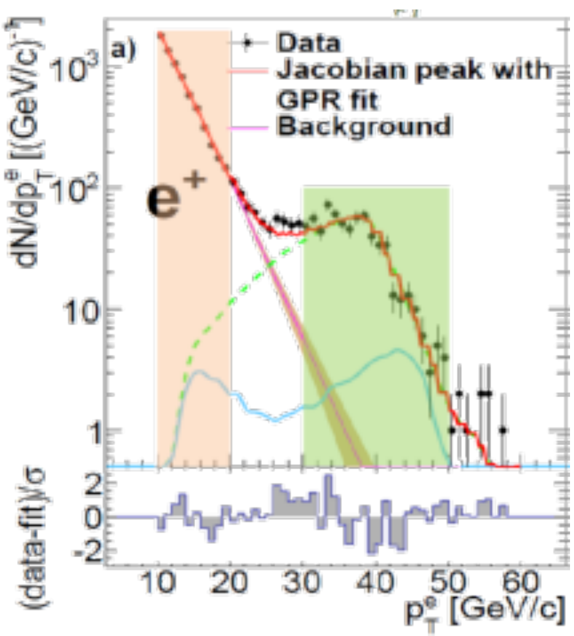
Ann. Rev. Nucl. Sci.50:525-585, (2000)

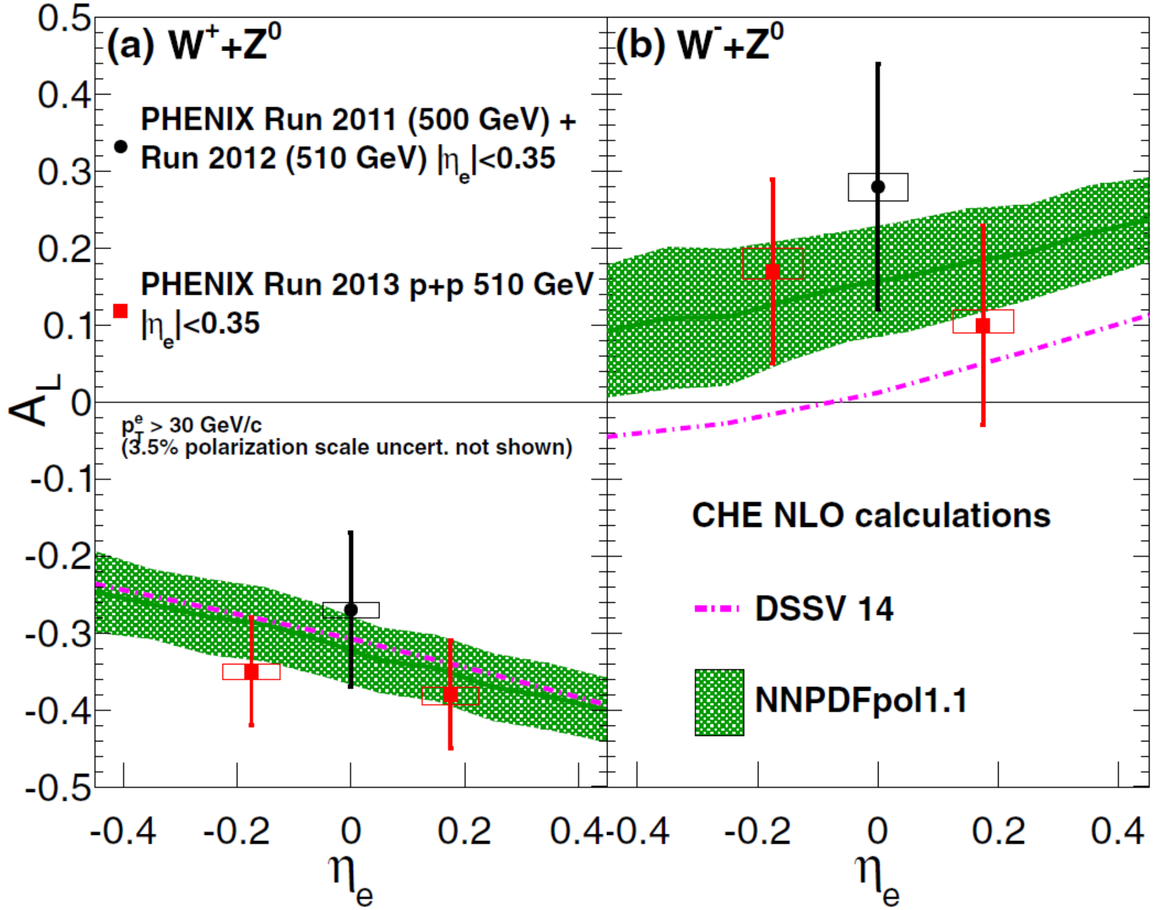


Run13 pp510GeV $W^{\pm} \rightarrow e^{\pm}$ A_L

Latest PHENIX publication: PRD 93, 051103(R)(2016)

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



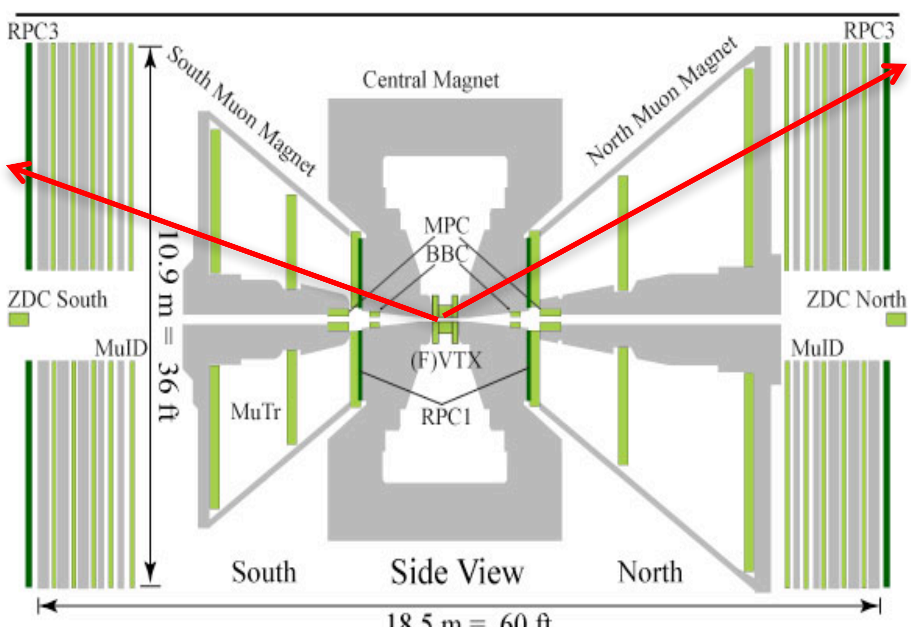


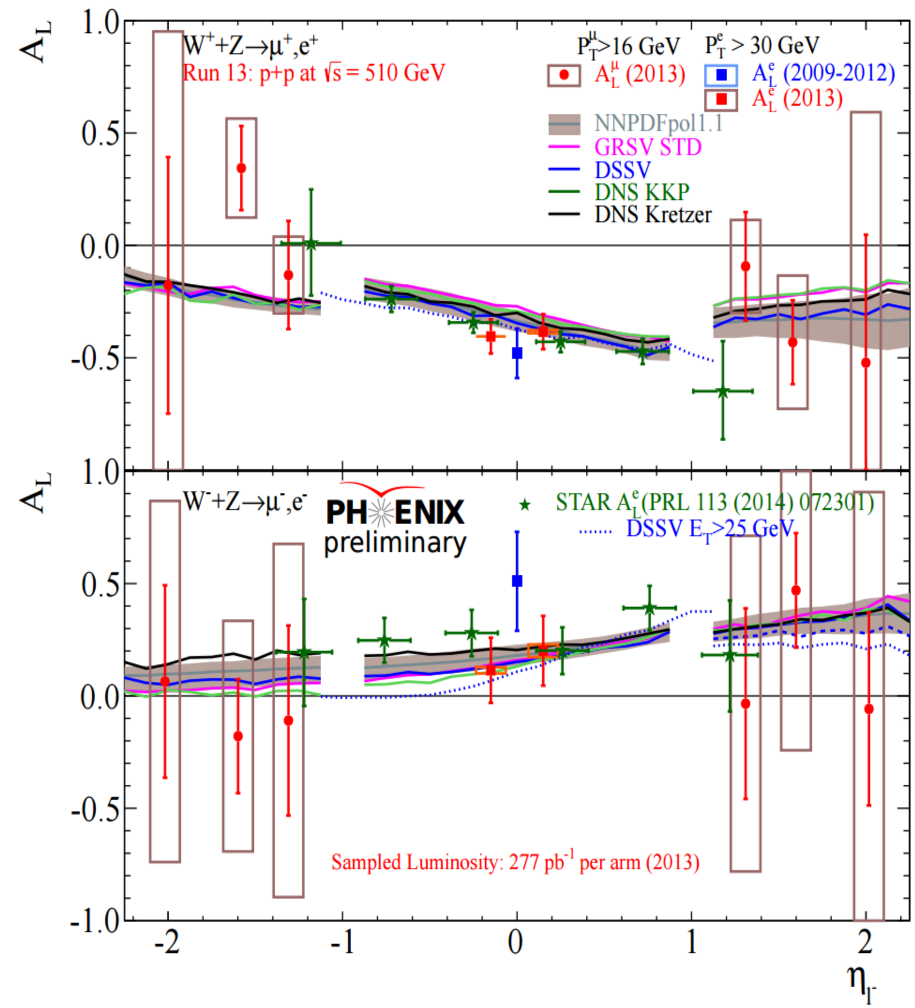
Add Forward $W^{\pm} \rightarrow \mu^{\pm} A_L$

- Forward Muons

$$A_L^{W^-} \approx \frac{\Delta d}{d}$$ (forward rapidity)

$$A_L^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}$$ (backward rapidity)

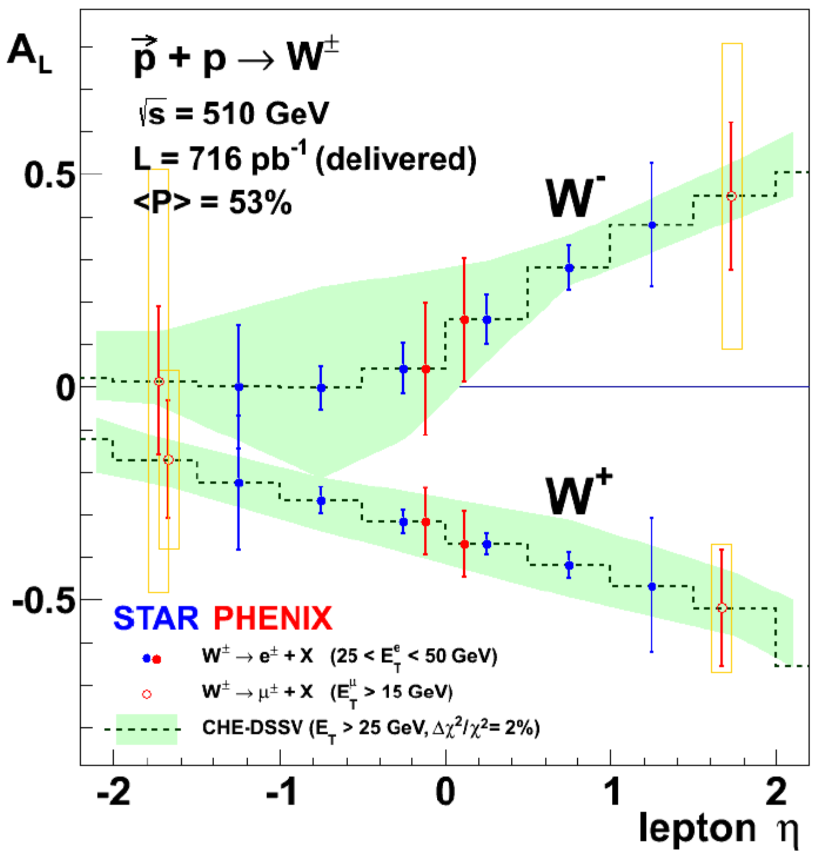


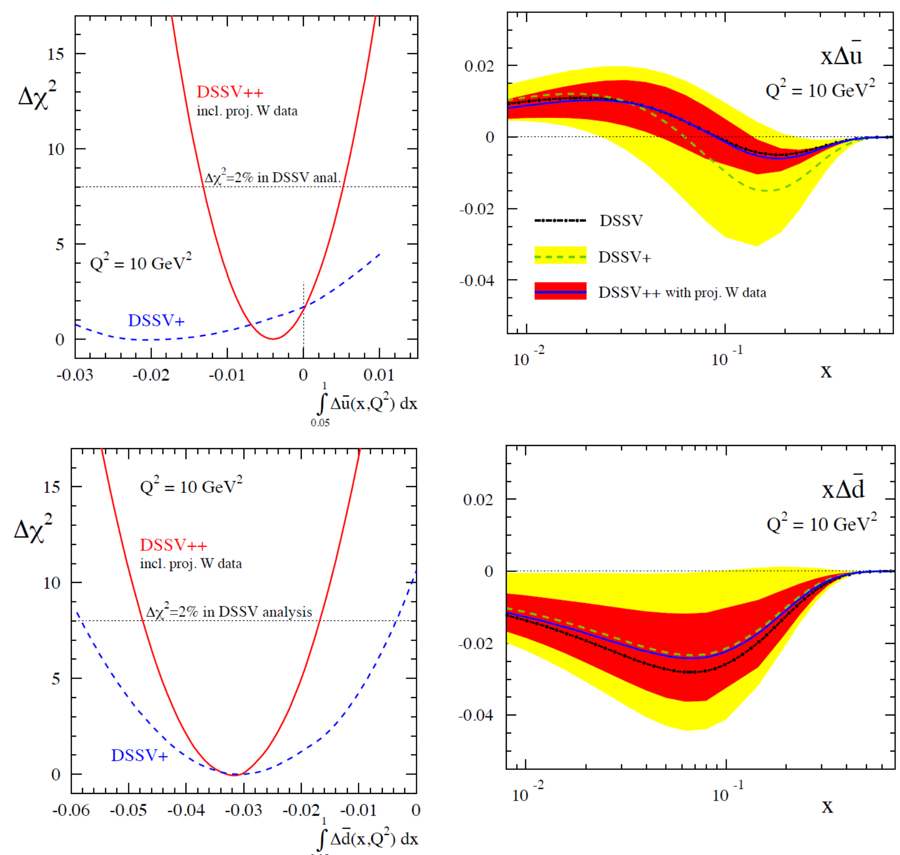


RHIC $W^{\pm} \rightarrow l^{\pm}$ data Impact on Sea Quark Polarization

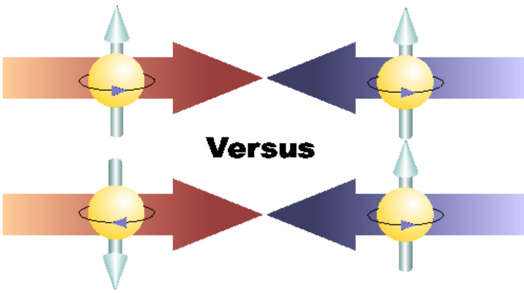
- Expect significant improvement of flavor identified sea quark polarization

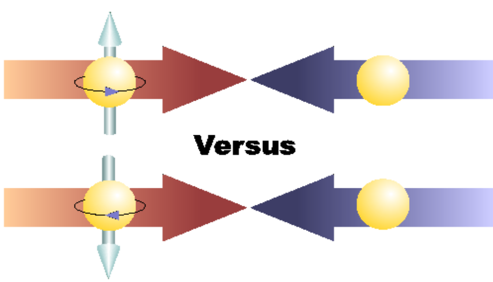
arXiv: 1501.01220

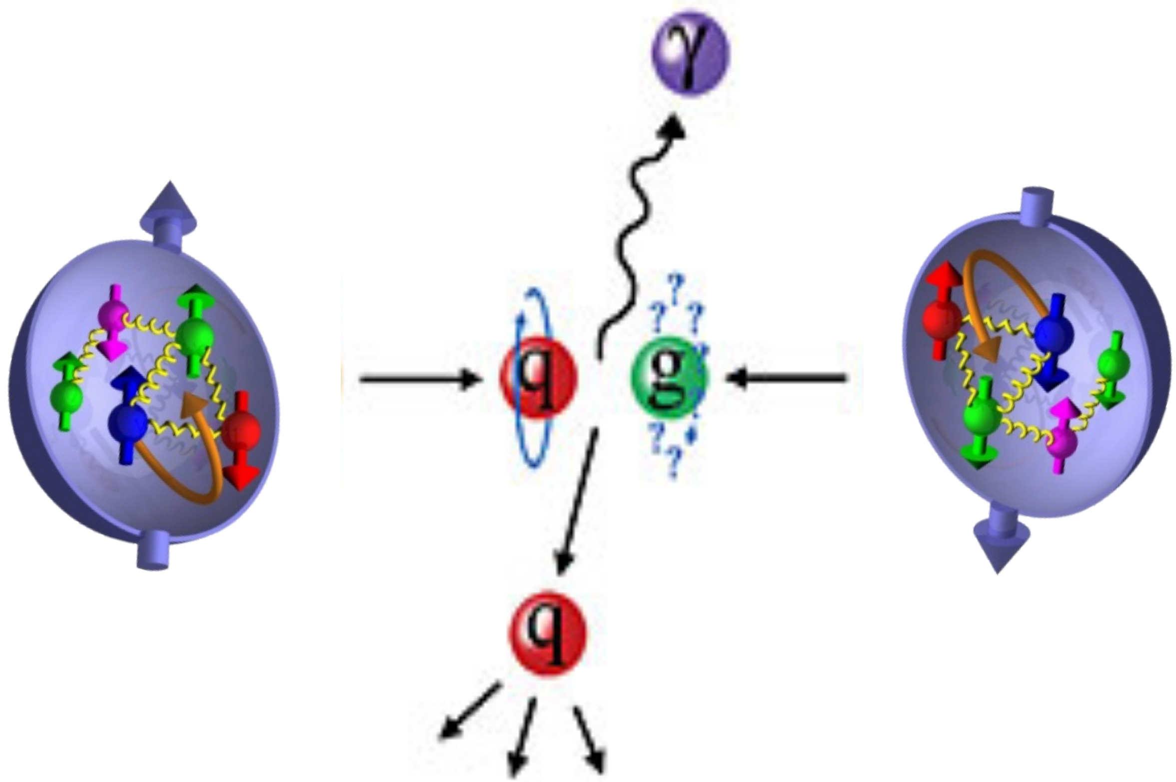




Physics with Transversely Polarized p+p Collisions



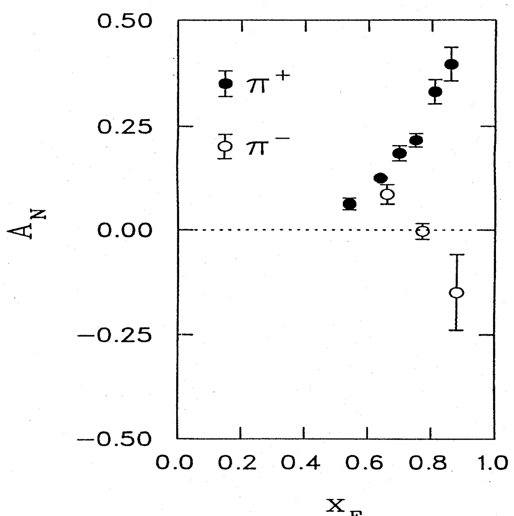




Do We Understand the Physics?

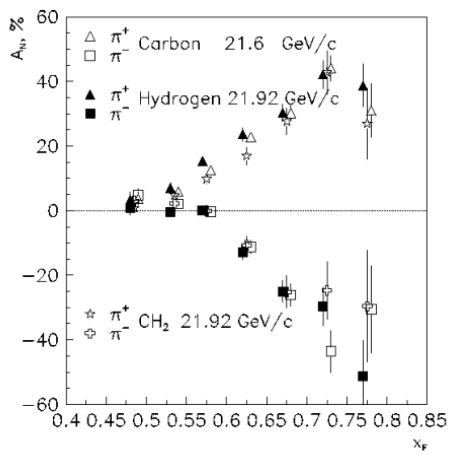
Large Transverse Single Spin Asymmetry (TSSA) in forward hadron production persists up to RHIC energy.

ZGS 12 GeV beam



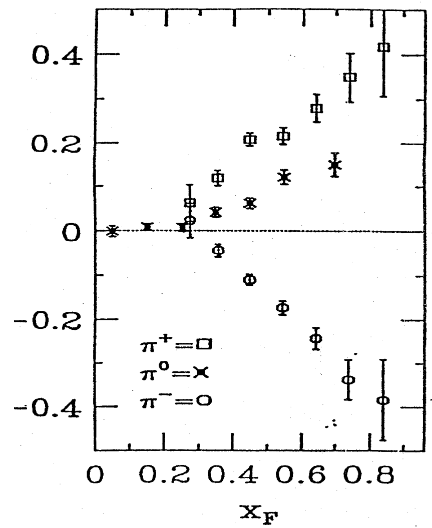
PRL36, 929 (1976)

AGS 22 GeV beam



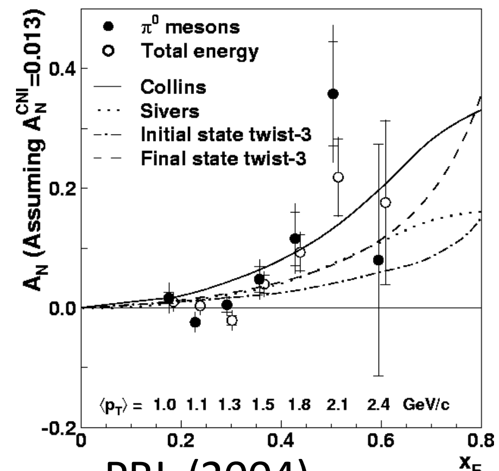
PRD65, 092008 (2002)

FNAL 200 GeV beam

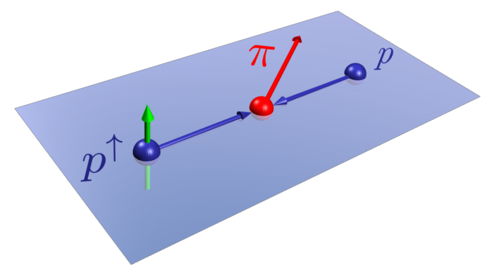


PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC 200 GeV CMS



PRL (2004)



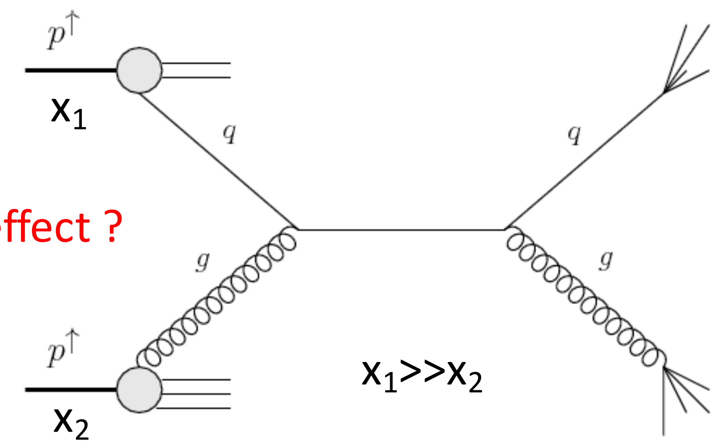
Sivers, Collins, Twist-3 ….

Non-Perturbative cross section → Perturbative cross section

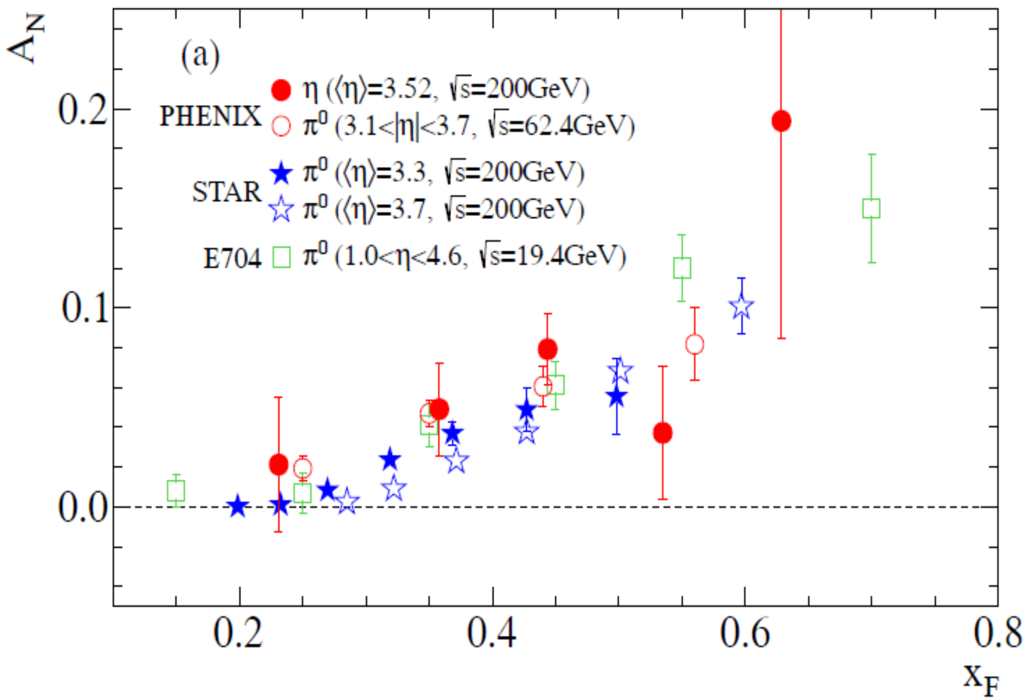
Large TSSA observed at Forward-Rapidity: π^0 and η

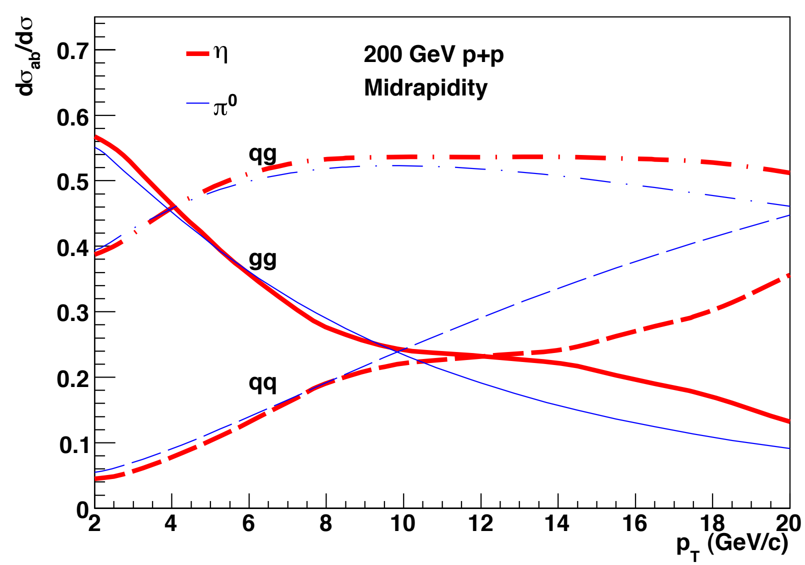
- Production well described by pQCD
- A_N is independent of collision energy
  - xF scaling?
- Similar for Pion and eta
  - No mass dependence?

Valance quark effect ?



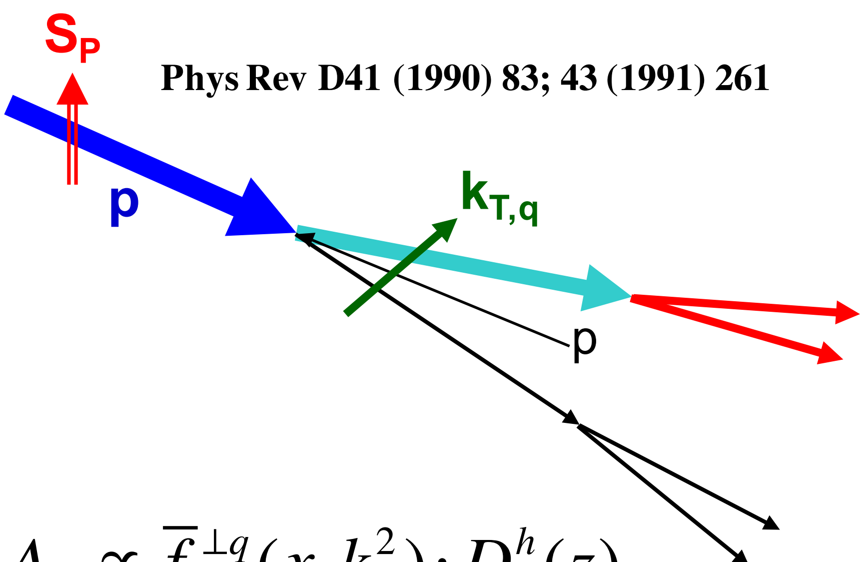
arXiv:1406.3541





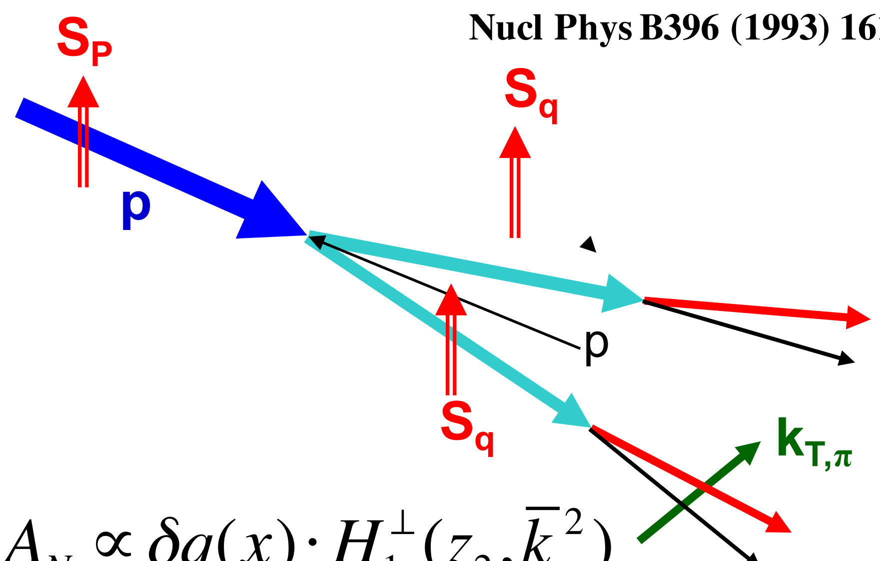
Probe the Underlying Physics via Hard Scatterings
TMD vs Collinear Twist-3 Factorizations

(i) Sivers mechanism:
correlation proton spin & parton k_T



$$A_N \propto \overline{f}_{1T}^{\perp q}(x, k_\perp^2) \cdot D_q^h(z)$$

(ii) Collins mechanism:
Transversity × spin-dep fragmentation



$$A_N \propto \delta q(x) \cdot H_1^\perp(z_2, \overline{k}_\perp^2)$$

Collinear Twist-3 (RHIC):

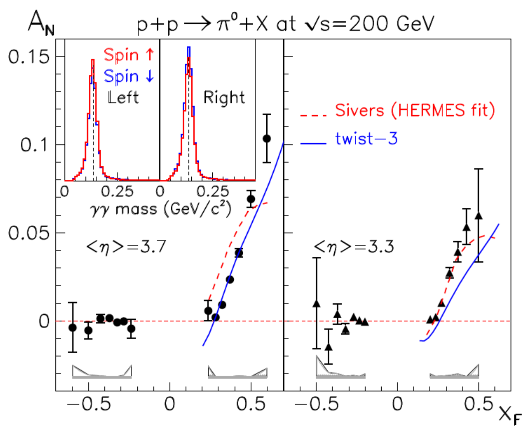
quark-gluon/gluon-gluon correlation

A Surprise: A_N Sign Mismatch?

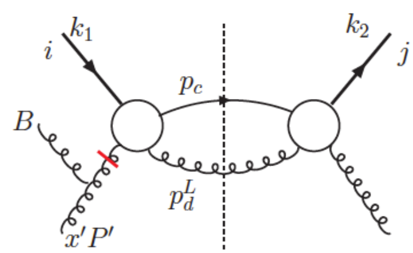
First attempt to check the "Universality of QCD description of TSSA"

- Kang, Qiu, Vogelsang, Yuan PRD 2011

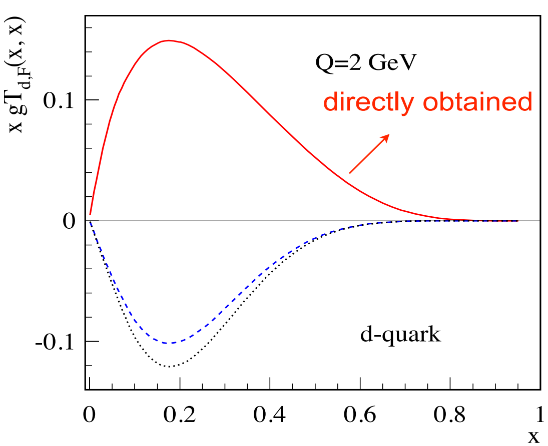
- Twist-3 (RHIC) v.s. Sivers (SIDIS)



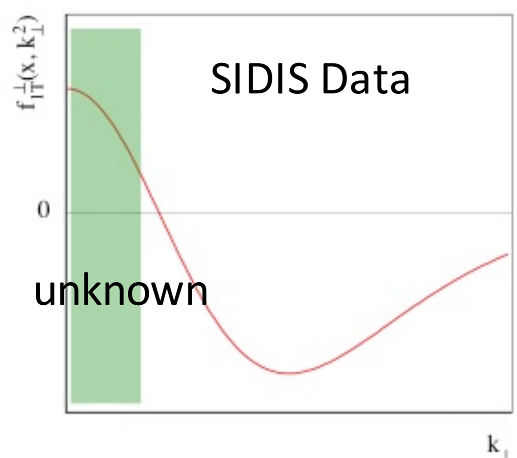
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$



Qiu,Sterman
Kouvaris et al.
Kanazawa,Koike
Kang,Prokudin



A possible solution? Kang, Prokudin PRD (2012)



Hadron TSSA in Twist-3 Framework

Qiu & Sterman PRD 59 (1998)

$$\Delta\sigma_{A+B\to\pi}(\vec{s}_T)=\sum_{abc}\underline{\phi^{(3)}_{a/A}(x_1,x_2,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H_{a+b\to c}(\vec{s}_T)\otimes D_{c\to\pi}(z)}$$

$$+\sum_{abc}\underline{\delta q^{(2)}_{a/A}(x,\vec{s}_T)\otimes\phi^{(3)}_{b/B}(x'_1,x'_2)\otimes H''_{a+b\to c}(\vec{s}_T)\otimes D_{c\to\pi}(z)}$$

$$+\sum_{abc}\underline{\delta q^{(2)}_{a/A}(x,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H'_{a+b\to c}(\vec{s}_T)\otimes D^{(3)}_{c\to\pi}(z_1,z_2)}$$

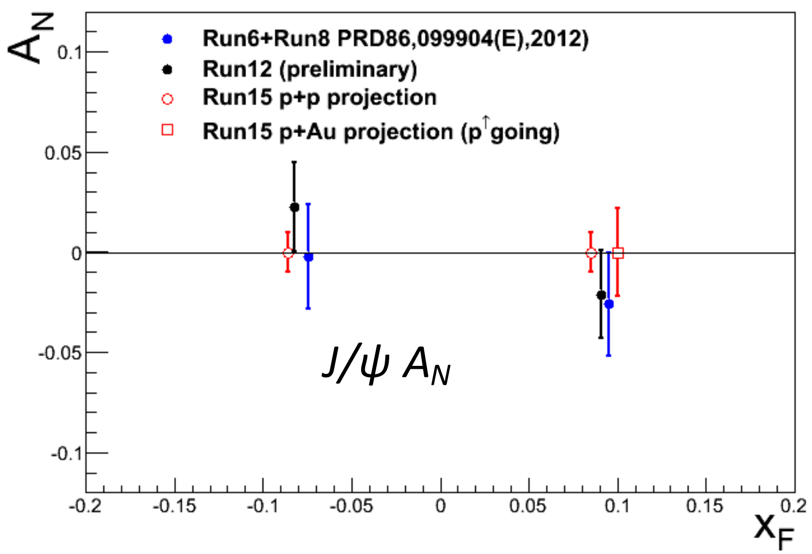
$$+\text{higher power corrections},$$

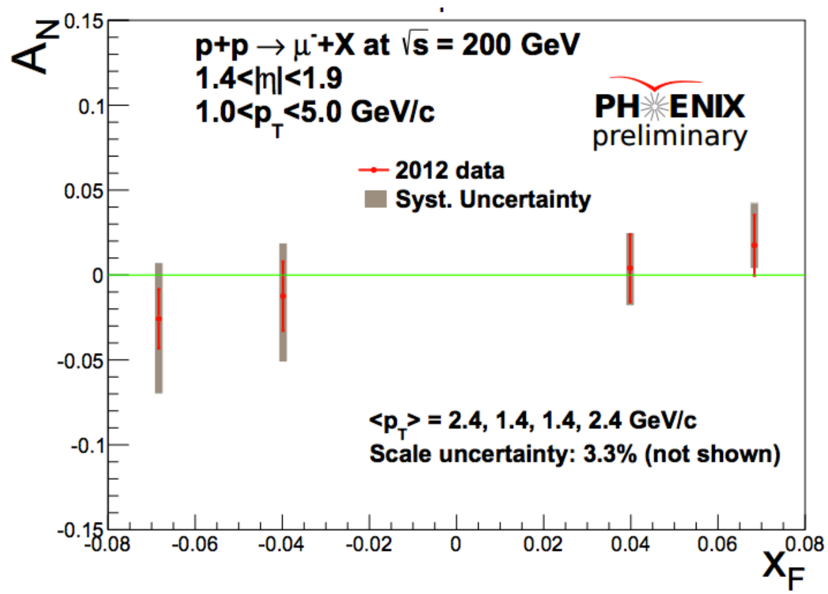
1st term: twsit-3 correlation functions, "Sivers"
2nd term: twist-2 transversity * twist-3 from unpol beam (expected small)
3rd term: twist-2 transversity * twist-3 FF, "Collins"

Need new direct measurements of Sivers and Collins TSSA in p+p!
Forward sPHENIX Upgrade Proposal

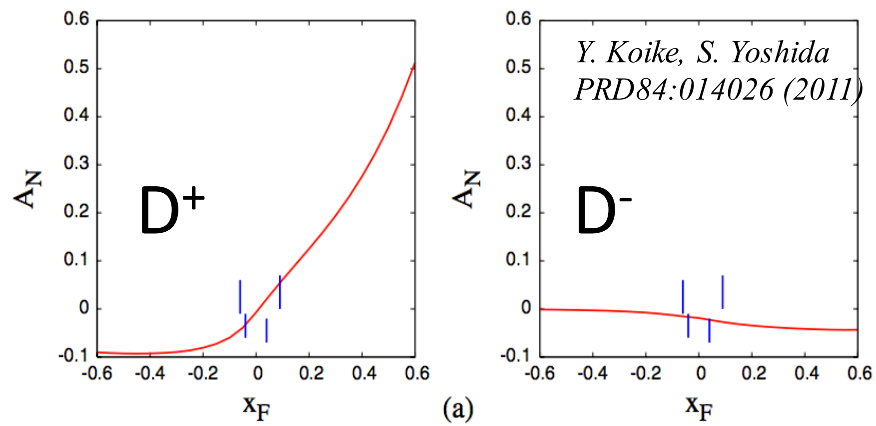
Gluons?: Forward Heavy Flavor A_N

- Heavy Flavor production is an ideal tool to investigate gluon distributions.



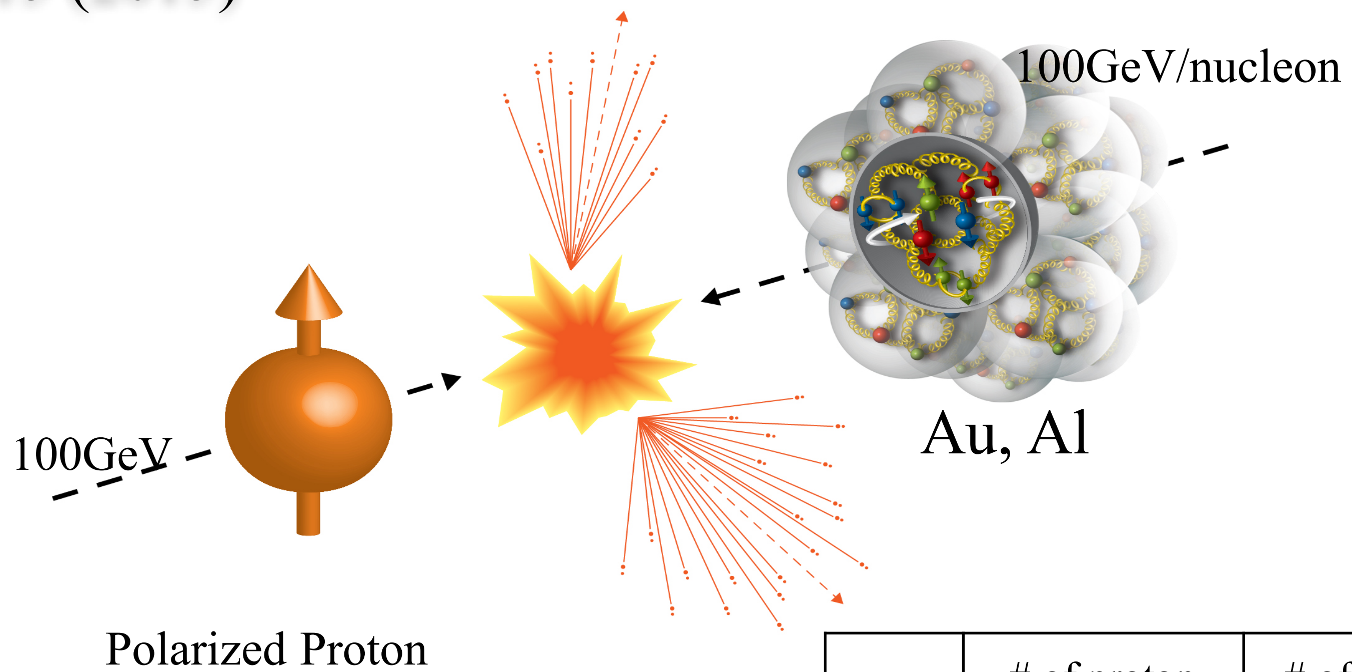


- We expect much improved result from ongoing Run15 *p+p* analysis (>5x statistics) as well as J/ψ A_N result in Run15 $p^\uparrow$+*A*



First Polarized p+A at RHIC

Run15 (2015)

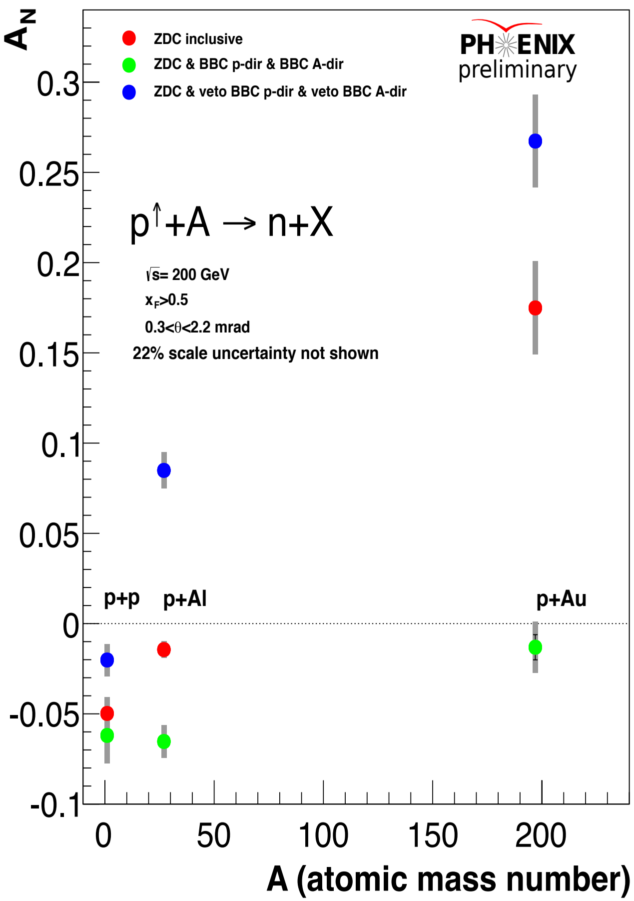


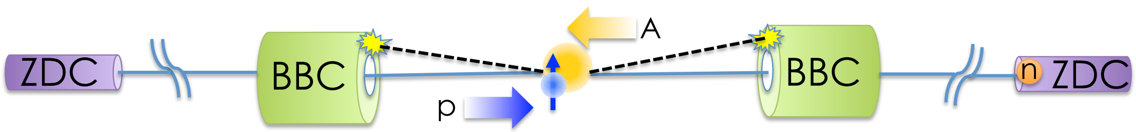
	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

Run15 p+Au: a Surprise!

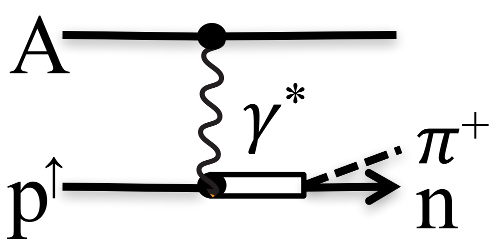
Itaru Nakagawa's talk, July 13

Unexpected pAu and pAl asymmetries observed compared to that of pp



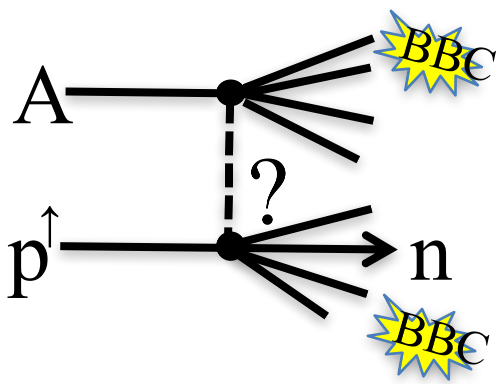


BBC Veto



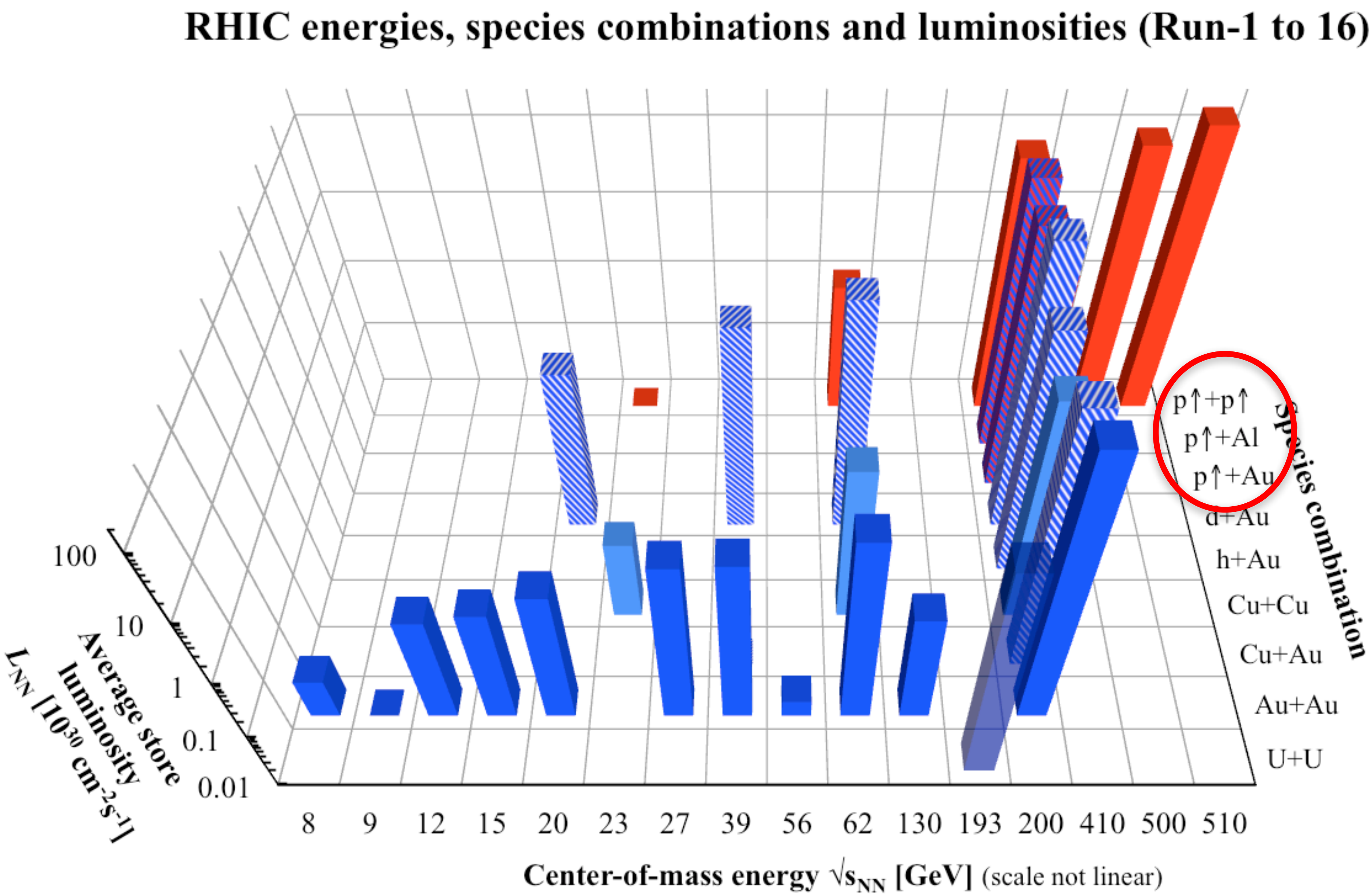
$A_N > 0$

BBC Tag



$A_N < 0$

Summary of PHENIX Runs: 2000-2016

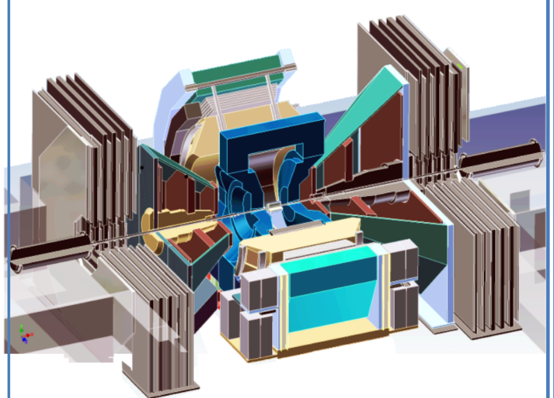


Outlook: PHENIX -> Forward/sPHENIX->ePHENIX

Documented: http://www.phenix.bnl.gov/plans.html

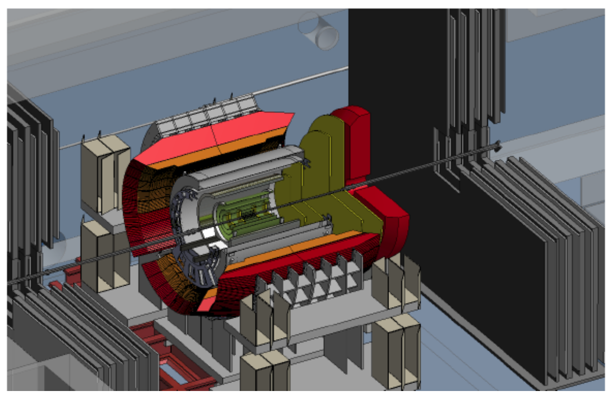
Current PHENIX

- PHENIX completed 2016
- 16y+ work
  100+M$ investment
- 130+ published papers to date



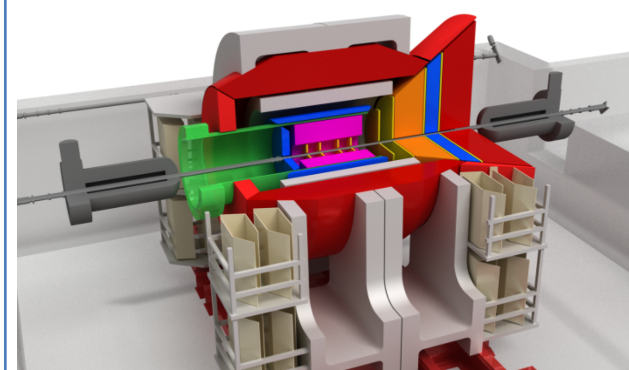
f/*s*PHENIX

- Comprehensive central upgrade based on BaBar magnet
- fsPHENIX: forward tracking, HCal and muon ID
- Key study of transverse spin
- New collaboration/new ideas



An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- New collaboration/new ideas



~2000 | 2017→2020 | ~2025 | Time

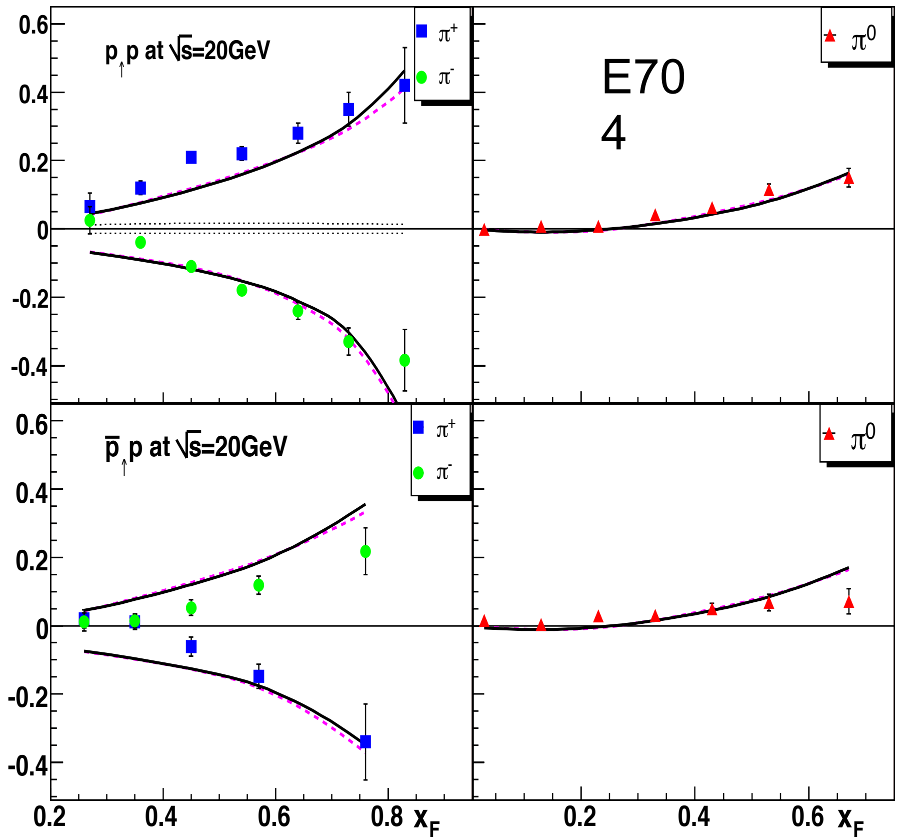
RHIC: A+A, polarized p+p, polarized p+A

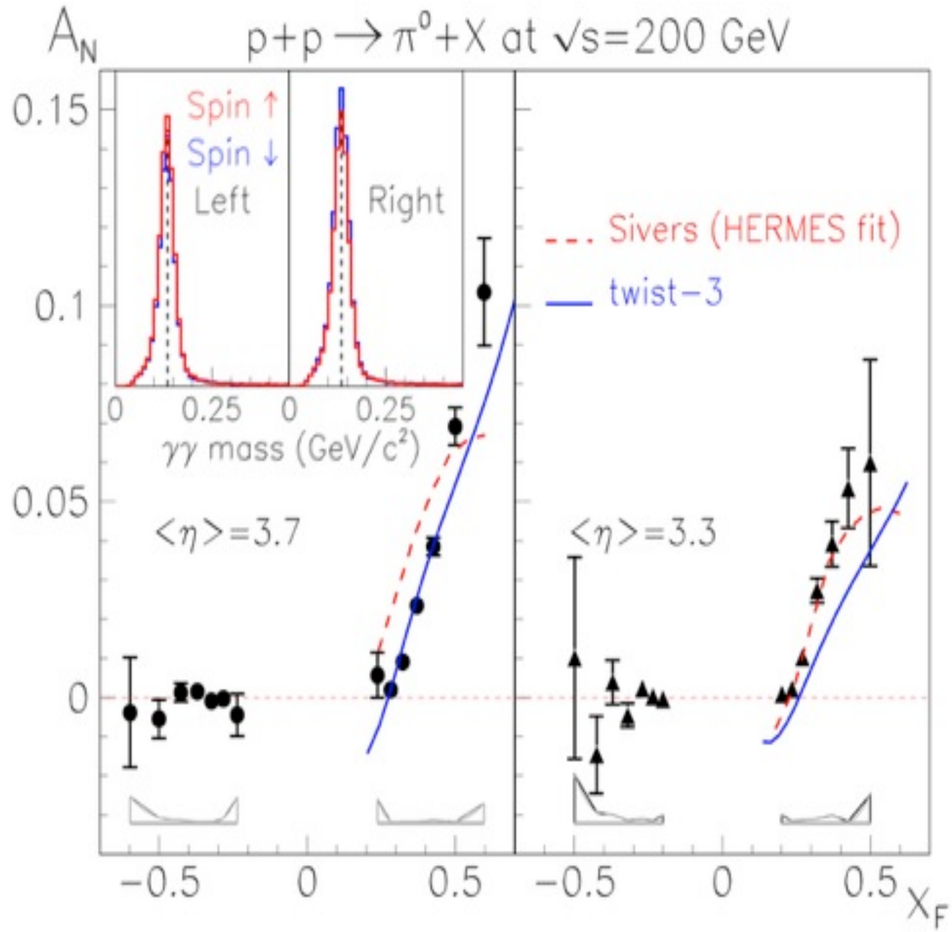
eRHIC: e+p, e+A

backup

Initial Success of TMD and Twist-3

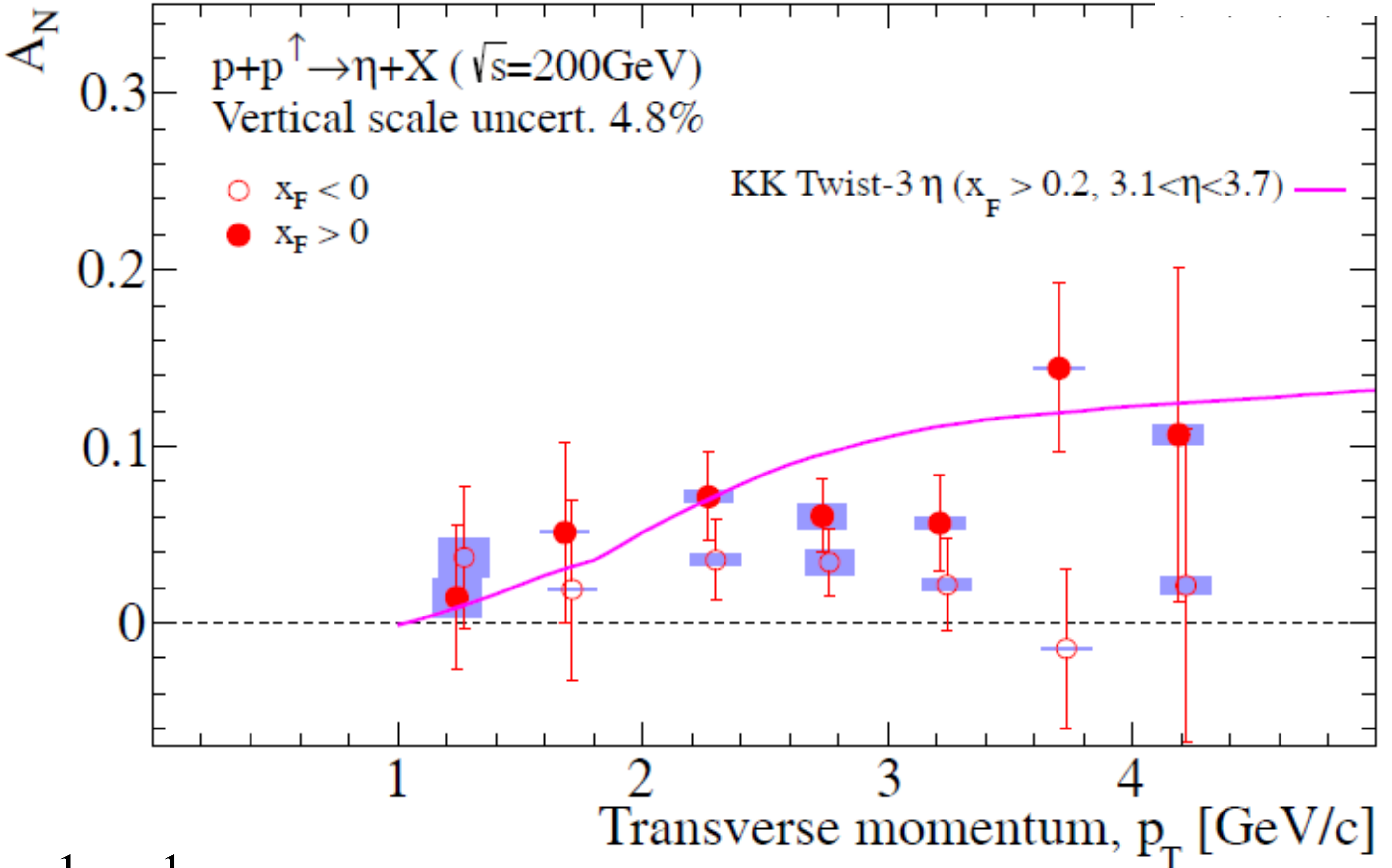
- Both describe pp data well, from fixed-target to RHIC





“Weak” p_T Dependence

arXiv:1406.3541



$$A_N \sim \frac{1}{Q} \sim \frac{1}{p_T} \quad @twist-3$$

Naïve expectation at high pT

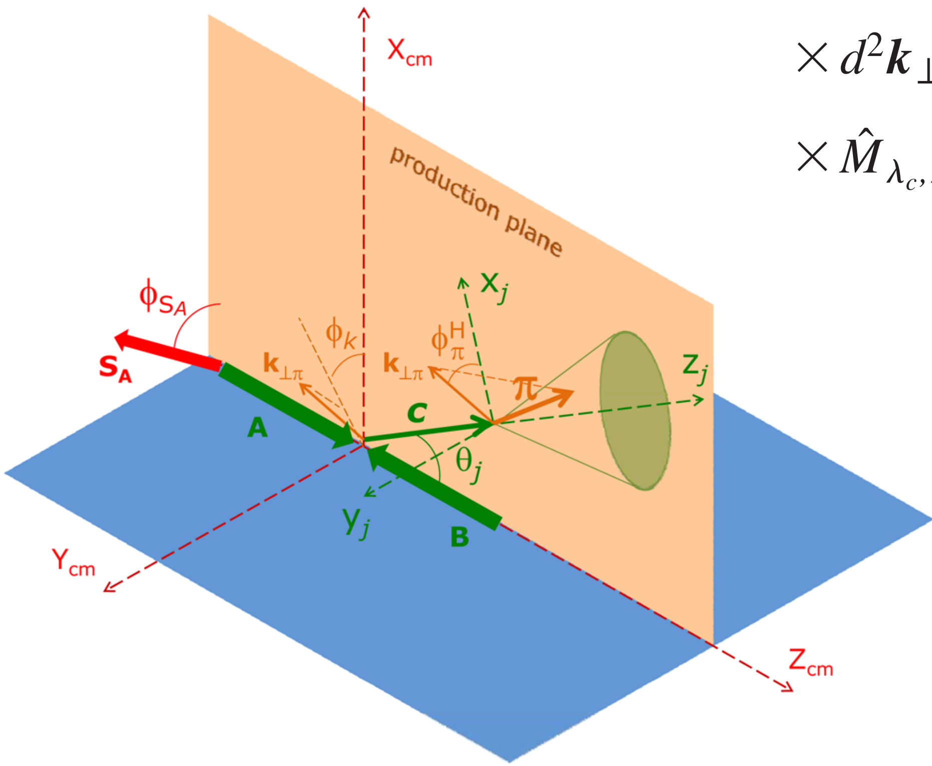
$$A_N \sim O\left(\frac{M_N P_T S}{UT}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

Recent work, Twist-3, Kanazawa & Koike

Access Sivers and Collins with Jet and Hadron Azimuthal Distributions in Transversely Polarized p+p Collisions

Feng Yuan, PRL 100, 032003 (2008)
Umberto D'Alesio et al PRD 83 034021 (2011)

$$\frac{E_j d\sigma^{A(S_A)B\to \mathrm{jet}+\pi+X}}{d^3\boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$
$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a \lambda'_a} \hat{f}_{a/A,S_A}(x_a, \boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b \lambda'_b} \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b})$$
$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z, \boldsymbol{k}_{\perp\pi}).$$



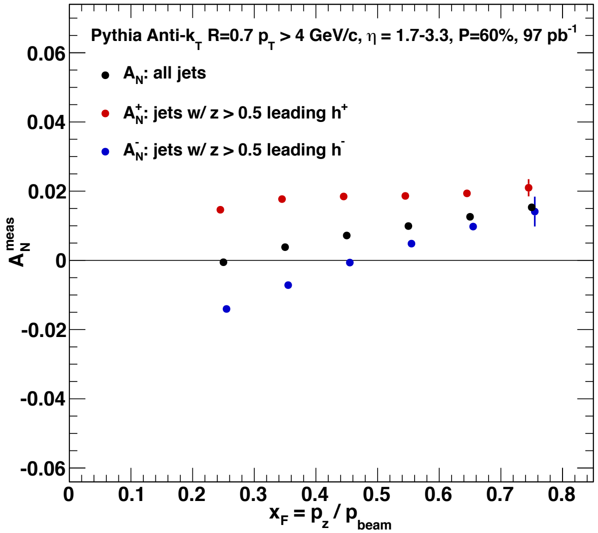
Experimental variables:
- Jet P_j, xF
- Hadron P_h , PID
- Beam polarization

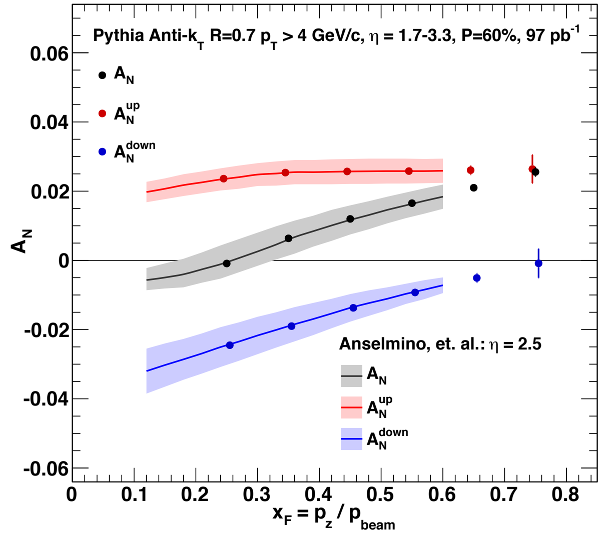
$A_N^{\sin\phi_{S_A}}$ → "Sivers-like"

$A_N^{\sin(\phi_{S_A} \mp \phi^H_\pi)}$ → "Collins-like"

fsPHENIX Projected Jet Sivers Asymmetries

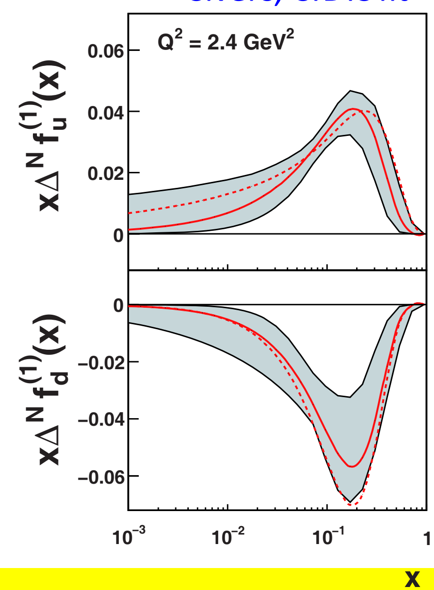
Test the universality of QCD description of TSSA: pp vs SIDIS

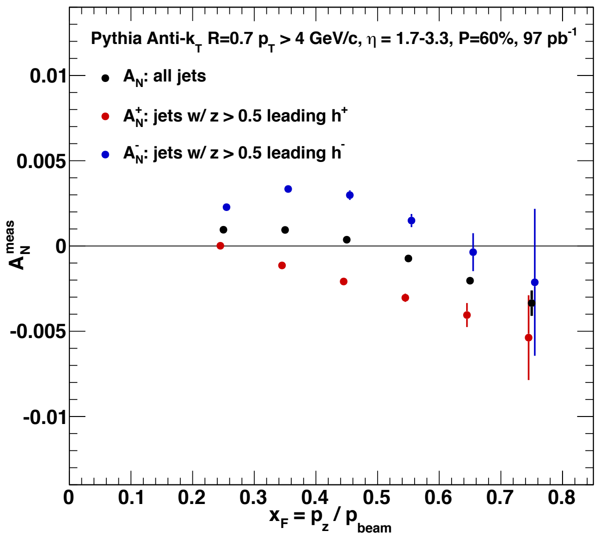


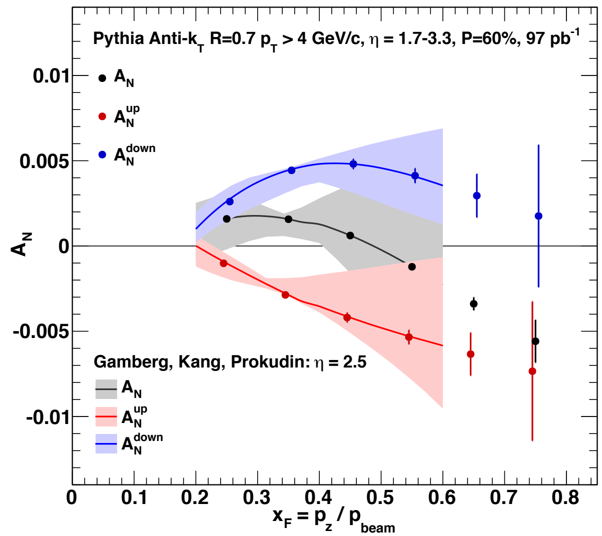


Naïve direct mapping from SIDIS Sivers (GPM)
- “u-quark jet” $A_N > 0$

Sivers, SIDIS fit







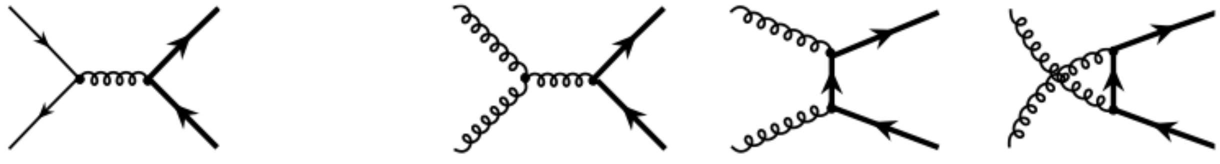
With process-dep from SIDIS Sivers (Twist-3)
- “u-quark jet” $A_N < 0$

TSSA in Heavy Quark Production in p+p

Kang, Qiu, Vogelsang, Yuan, PRD 2008

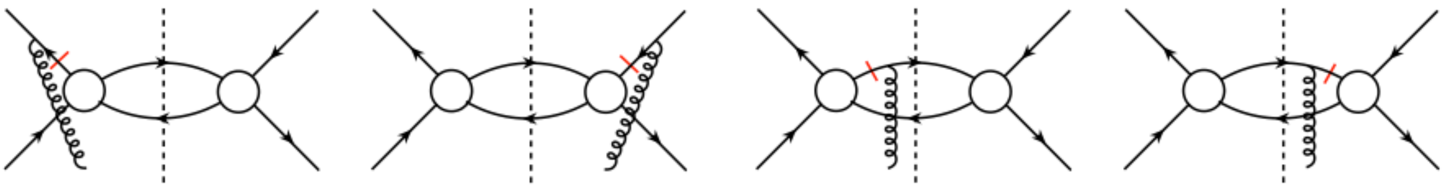
D-meson production in hadronic collisions

- Two partonic subprocesses:



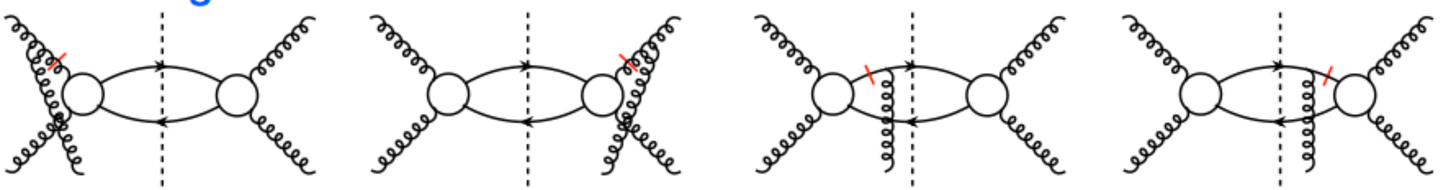
(a) (b)

- Quark-antiquark annihilation:



(a) (b) (c) (d)

- Gluon-gluon fusion:



(a) (b) (c) (d)

Open Charm TSSA in Twist-3 Approach

Factorized formula for D-meson production

Qiu, 2010

- Same factorized formula for both subprocesses:

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{q\bar{q}\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_q\int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{\bar{q}/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\boxed{\left(T_{q,F}(x,x)-x\frac{d}{dx}T_{q,F}(x,x)\right)}H_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})+T_{q,F}(x,x)\mathcal{H}_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})\right],$$

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{gg\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_{i=f,d}\int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{g/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\boxed{\left(T_G^{(i)}(x,x)-x\frac{d}{dx}T_G^{(i)}(x,x)\right)}H_{gg\to c}^{(i)}(\tilde{s},\tilde{t},\tilde{u})+T_G^{(i)}(x,x)\mathcal{H}_{gg\to c}^{(i)}(\tilde{s},\tilde{t},\tilde{u})\right],$$

- Hard parts:

$$H_{q\bar{q}\to c} = H_{q\bar{q}\to c}^{I} + H_{q\bar{q}\to c}^{F}\left(1+\frac{\tilde{u}}{\tilde{t}}\right) \qquad H_{gg\to c}^{(i)} = H_{gg\to c}^{I(i)} + H_{gg\to c}^{F(i)}\left(1+\frac{\tilde{u}}{\tilde{t}}\right)$$

All $\mathcal{H}_{q\bar{q}\to c}$ and $\mathcal{H}_{gg\to c}^{I(i)}$ and $\mathcal{H}_{gg\to c}^{F(i)}$ vanish as $m_c^2\to 0$

- Hard parts change sign for $T_G^{(d)}(x,x)$ when $c\to\bar{c}$

$$H_{gg\to\bar{c}}^{(f)} = H_{gg\to c}^{(f)}, \qquad H_{gg\to\bar{c}}^{(d)} = -H_{gg\to c}^{(d)},$$
$$\mathcal{H}_{gg\to\bar{c}}^{(f)} = \mathcal{H}_{gg\to c}^{(f)}, \qquad \mathcal{H}_{gg\to\bar{c}}^{(d)} = -\mathcal{H}_{gg\to c}^{(d)}.$$

Heavy Flavor to Access Gluons

- Sensitive to gluon Sivers function

  * probe gluon's orbital angular momentum?

  -- Minimize Collins' effects

  * heavy flavor production dominated by gluon gluon fusion at RHIC energy

  Pythia 6.1 simulation (LO)

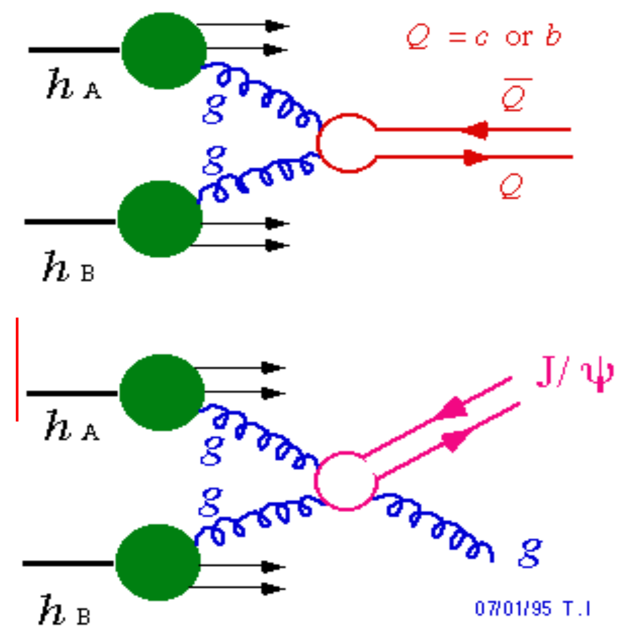
$c\bar{c}$: gg	$c\bar{c}$	95%
$b\bar{b}$: gg	$b\bar{b}$	85%

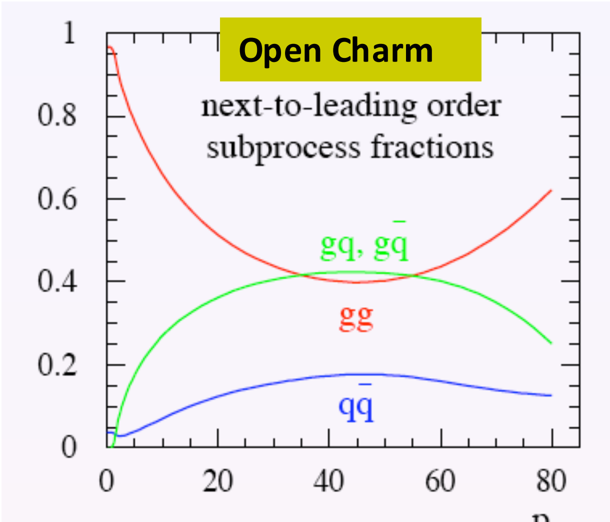
  * gluon has zero transversity

- Tri-gluon correlation functions

- Also sensitive to J/ψ production mechanisms and QCD dynamics

Gluon Fusion

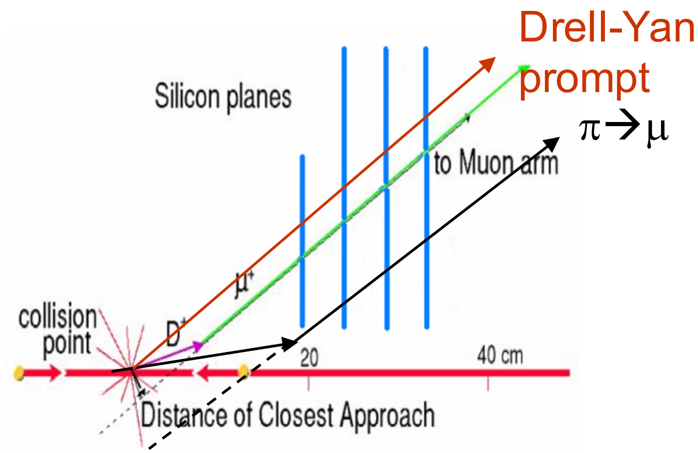




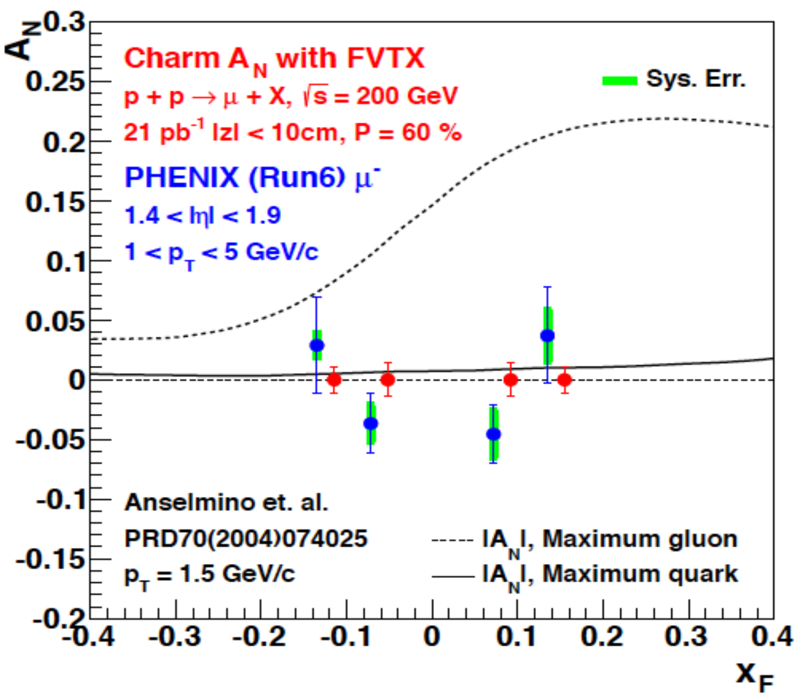
Johann Riedl, SPIN2008

Expectation from Run 2015 p+p & p+A with F/VTX

- Expect much improved results from Run 15
  - 110 pb^{-1}, Pol = 57% (Run15)
  - 10x FOM(Run12)



GTMD model



Twist-3 Approach