Studies on transverse spin properties of nucleons at PHENIX

Pacific Spin 2015

Academia Sinica in Taipei, Taiwan

October 8, 2015

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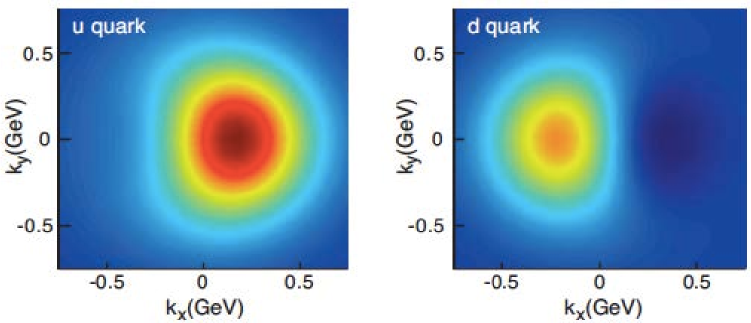
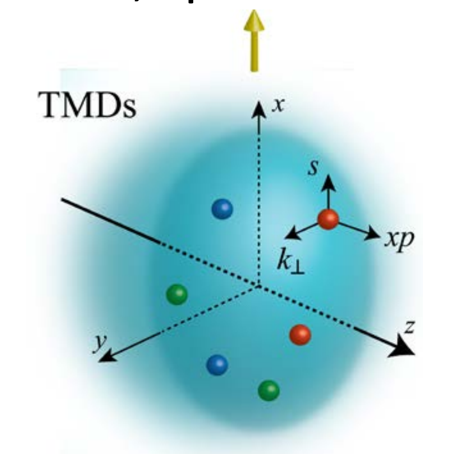
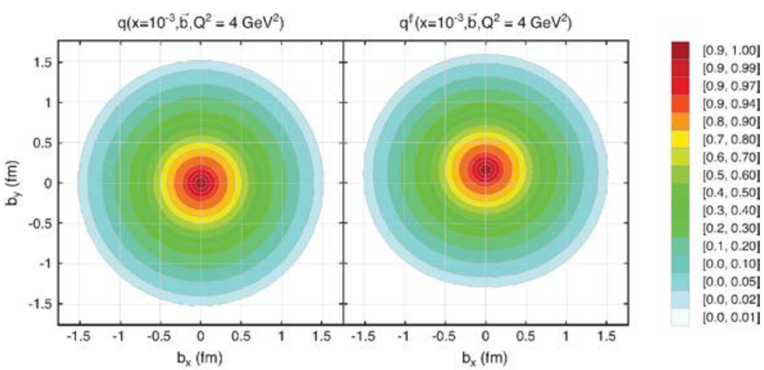
3D structure of the nucleon

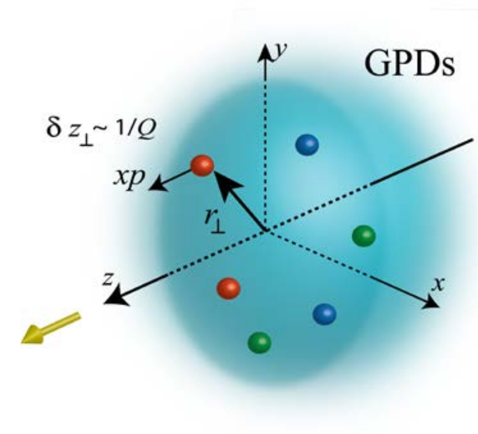
- Conclusive understanding of the nucleon spin
  - orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between transverse-momentum distribution, spin and orbital motion





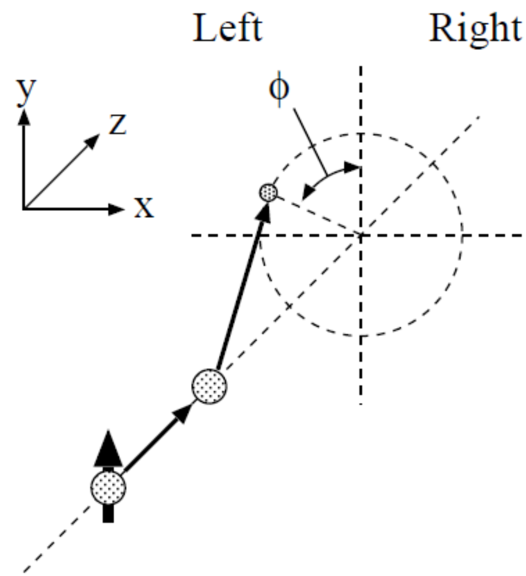
- GPD (Generalized Parton Distribution)
  - Spatial distribution or tomography





Transverse-spin asymmetry measurement

- Transverse single spin asymmetry (SSA)



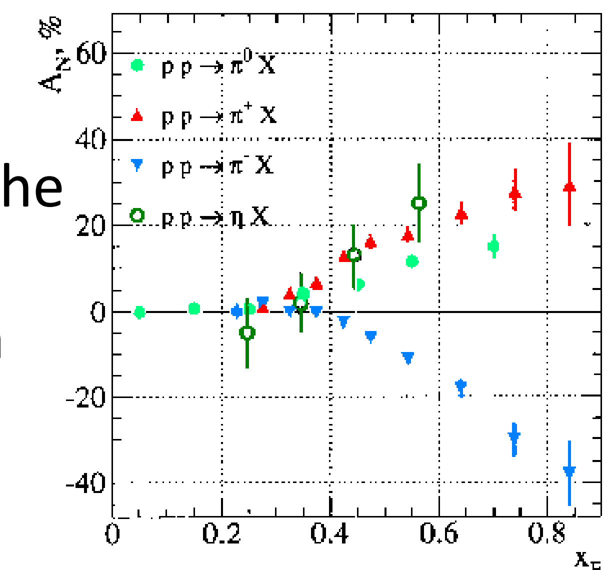
$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

  - Expected to be small in hard scattering at high energies

$$A_N \approx \frac{m_q \alpha_S}{p_T} \approx 0.001$$

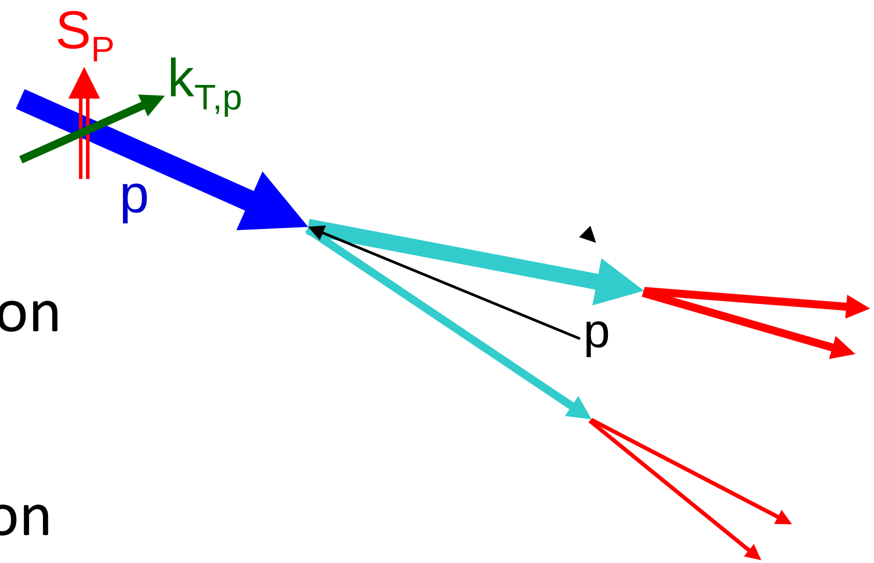
Kane, Pumplin, Repko
PRL 41 1689 (1978)

- FNAL-E704
  - Unexpected large asymmetry found in the forward-rapidity region
  - Development of many models based on perturbative QCD

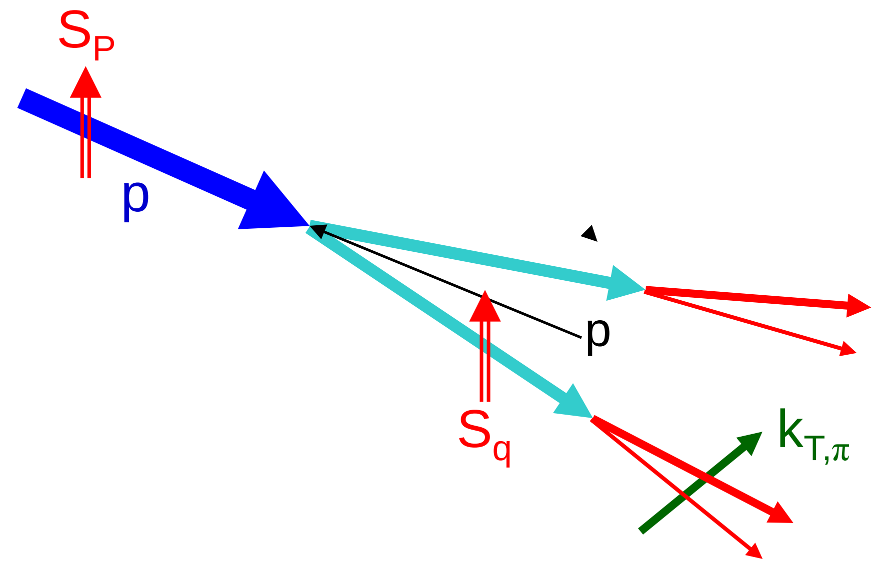


TMD and higher-twist

- Two theory frameworks
- "Sivers effect"
  - Initial-state effect
  - TMD (Sivers) distribution function
    - Need 2 scales (p_T and Q^2)
    - Drell-Yan, W/Z bosons
  - Higher-twist distribution function
    - Need 1 scale (p_T)
    - Hadron, photon, jet production



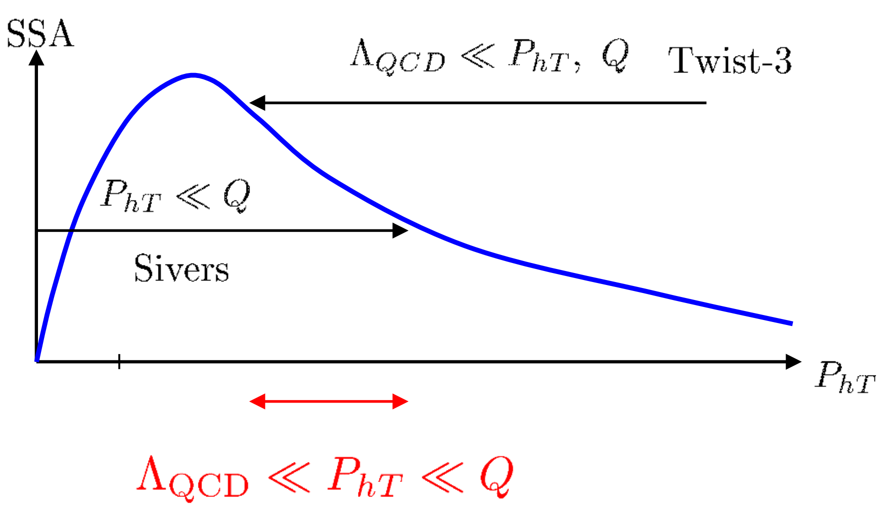
- "Collins effect"
  - Final-state effect
  - Transversity with TMD (Collins) fragmentation function
  - Transversity with higher-twist fragmentation function



TMD and higher-twist

- Theoretical description of SSA
  - TMD at low p_T and high Q^2
  - Higher twist at high p_T
  - Common description at medium p_T
- SSA description with initial state effect

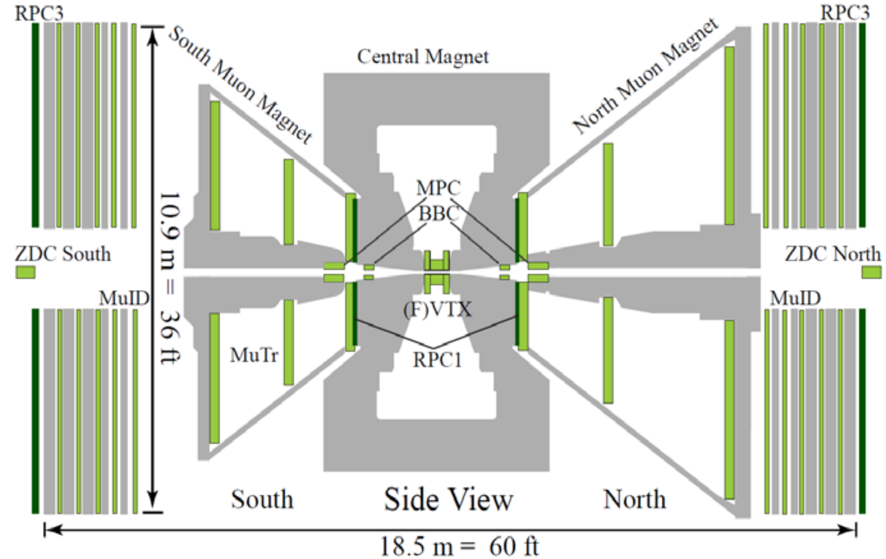
$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$



Twist-τ =
Suppressed by $\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)^{\tau-2}$

Transverse-polarization runs

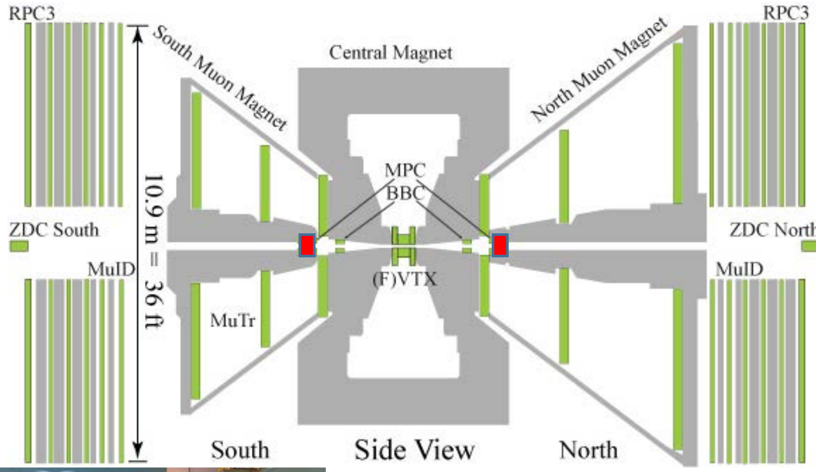
- Muon arm 2001-
- MPC 2006-
  - EM calorimeter
- FVTX 2012-
  - Silicon detector
- MPC-EX 2015-
  - Preshower detector

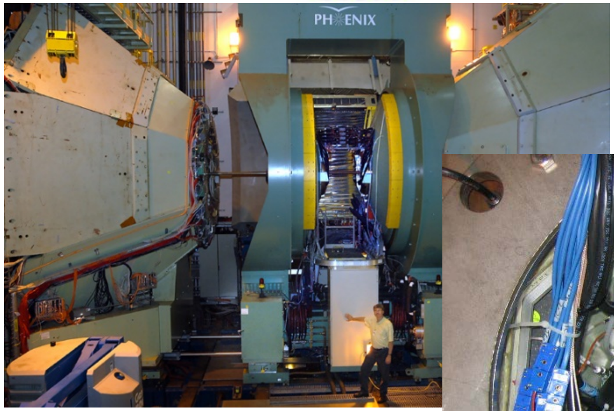


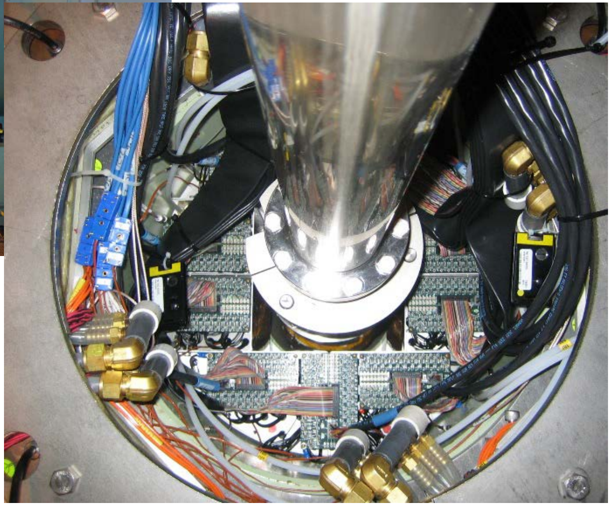
Year	Energy	Recorded Luminosity	Polarization	FoM (P^2L)
2001-2	200 GeV	0.15 pb^{-1}	15%	0.0034 pb^{-1}
2005	200 GeV	0.16 pb^{-1}	47%	0.035 pb^{-1}
2006	200 GeV	2.7 pb^{-1}	57%	0.88 pb^{-1}
2006	62.4 GeV	0.02 pb^{-1}	53%	0.0056 pb^{-1}
2008	200 GeV	5.2 pb^{-1}	45%	1.1 pb^{-1}
2012	200 GeV	9.2 pb^{-1}	59%	3.3 pb^{-1}
2015	200 GeV	110 pb^{-1}	57%	35 pb^{-1}

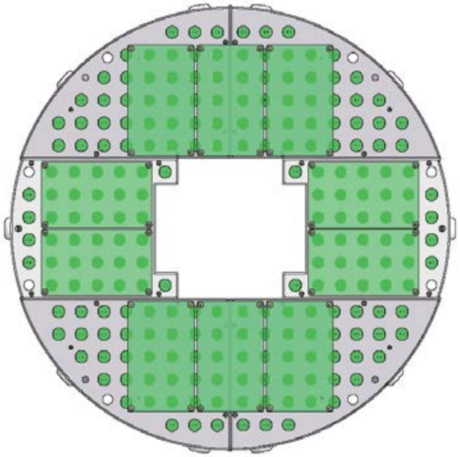
MPC

- Muon Piston Calorimeter
- EM calorimeter installed in the small cylindrical hole in muon magnet piston
  - $PbWO_4$ crystals
    - $2.2 \times 2.2 \times 18$ cm^3
  - 22.5 cm radius
  - 43.1 cm depth
  - $3.1 < |\eta| < 3.9$



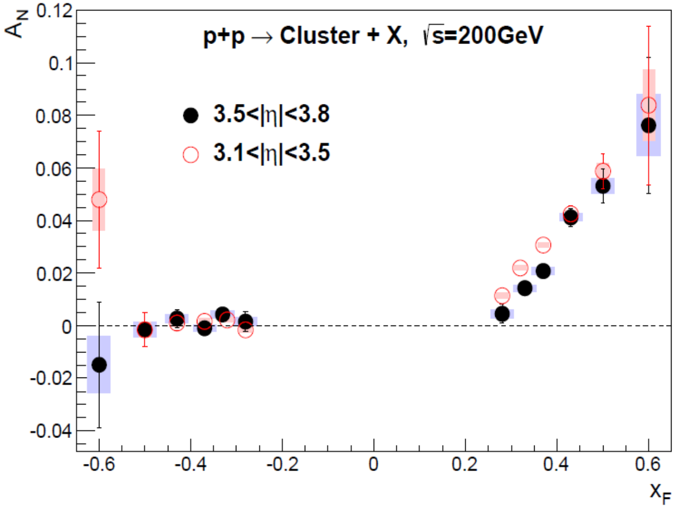


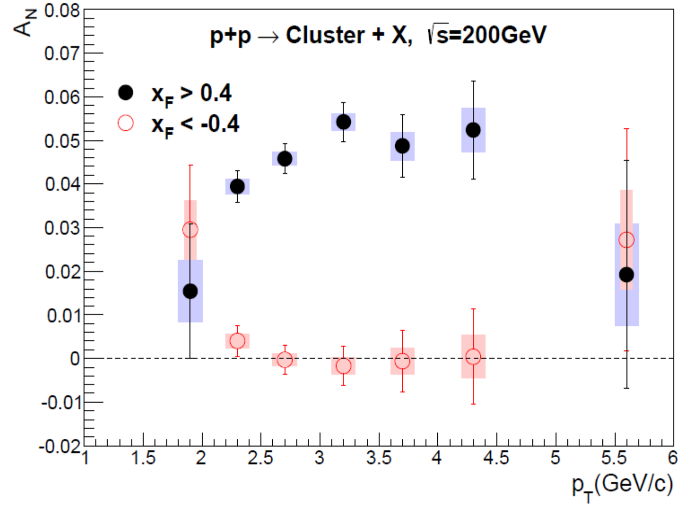




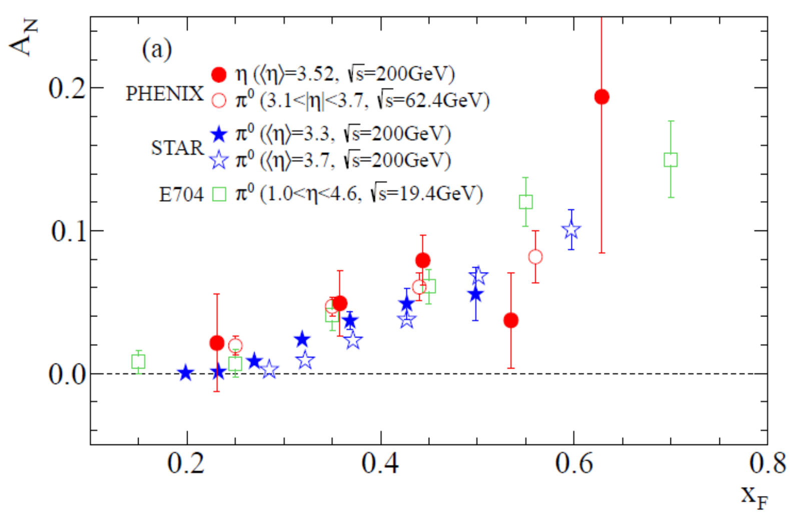
High-p_T measurements

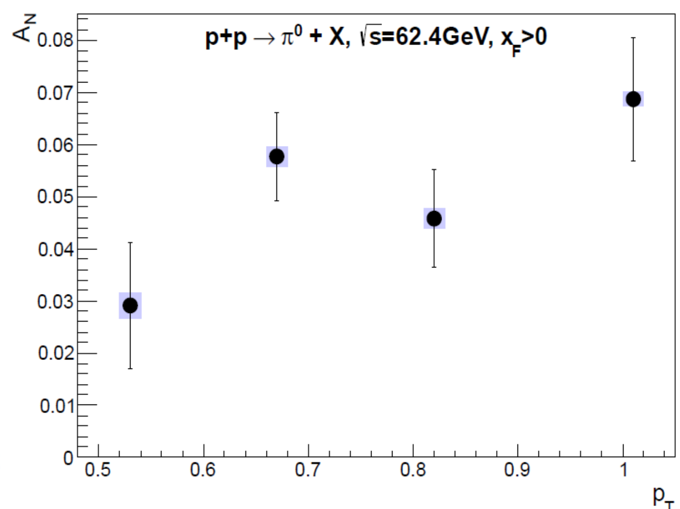
- Forward EM cluster at $\sqrt{s}$ = 200 GeV





- π^0 and η

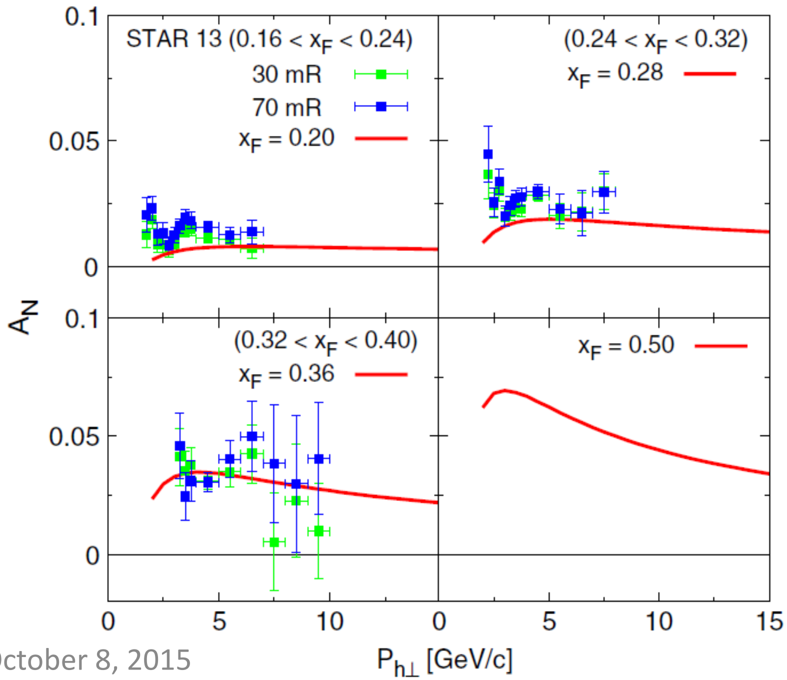


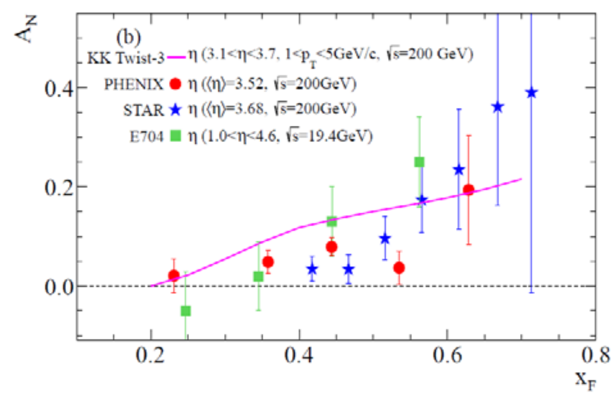


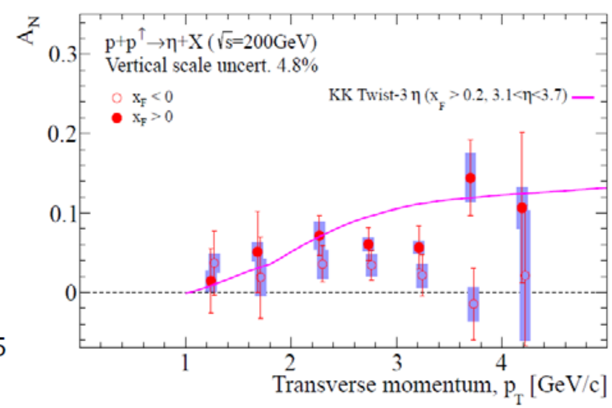
High-p_T measurements

- Measured SSA
  - No significant drop at high p_T
  - Not only initial state but also final state effect necessary
- Higher twist calculation of initial state and final state
  - Good fit with a new twist-3 fragmentation function

Kanazawa, Koike, Metz, Pitonyac:
PRD89, 111501 (2014)

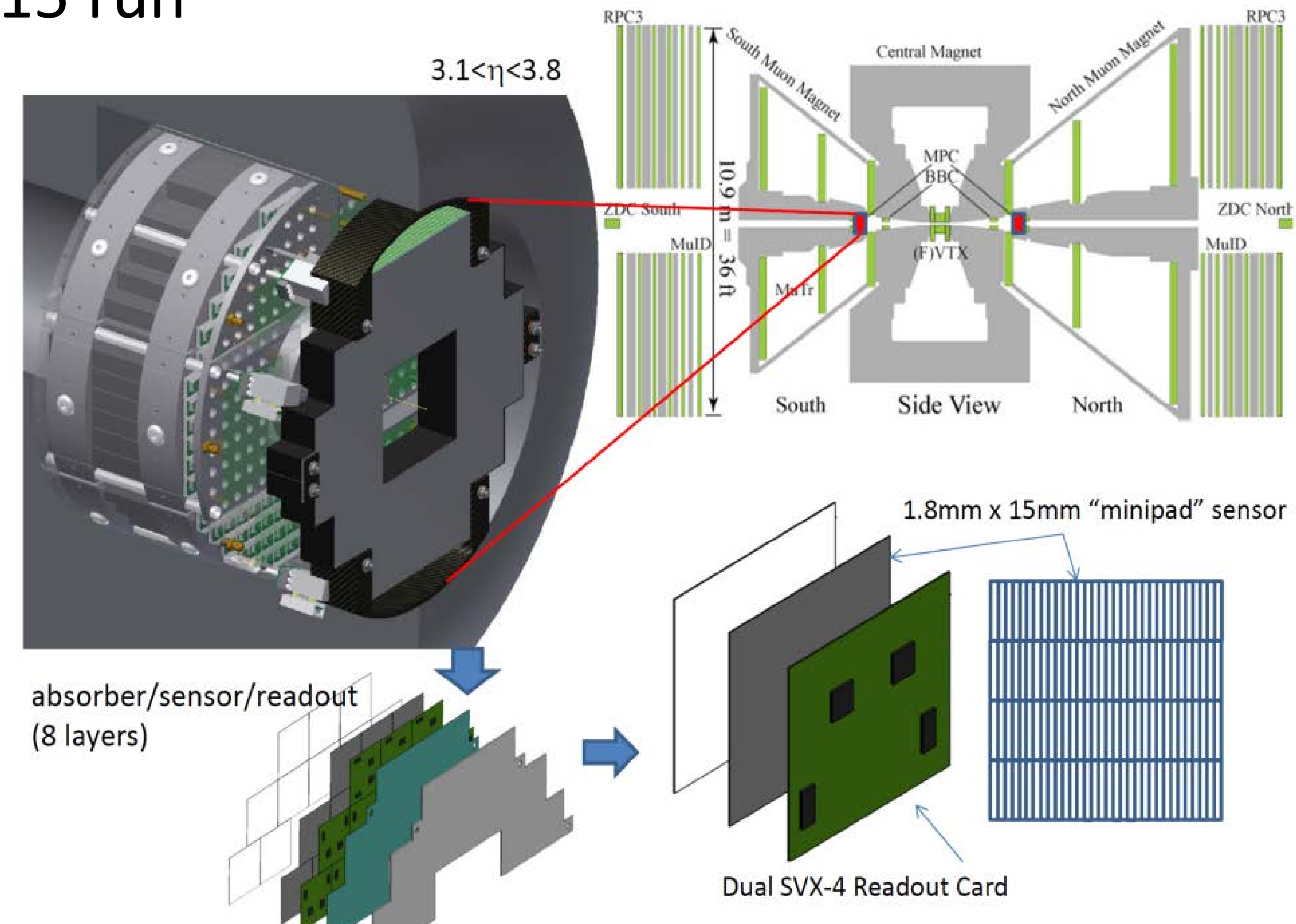






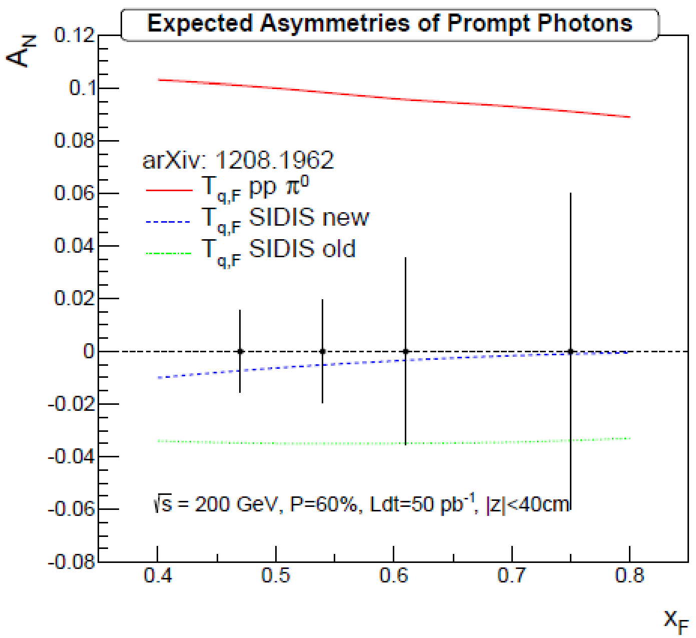
MPC-EX

- Pre-shower detector in front of MPC
  - Silicon mini-pad detectors with tungsten plates
- 2015 run

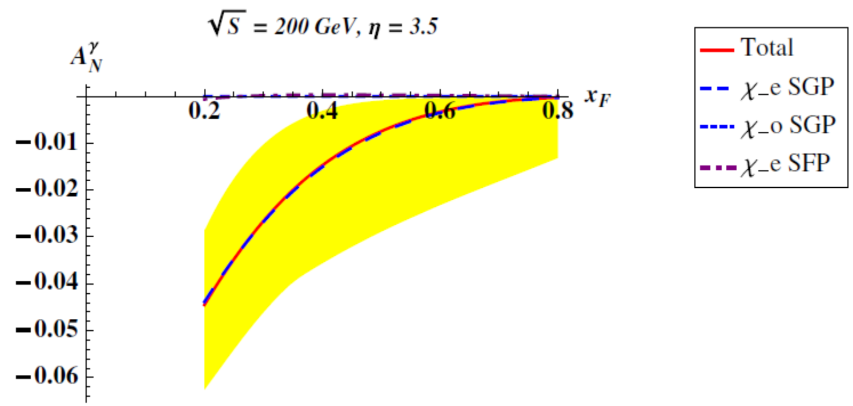


Direct photon

- Distinguish predicted higher-twist quark-gluon correlation functions
  - No final state effect



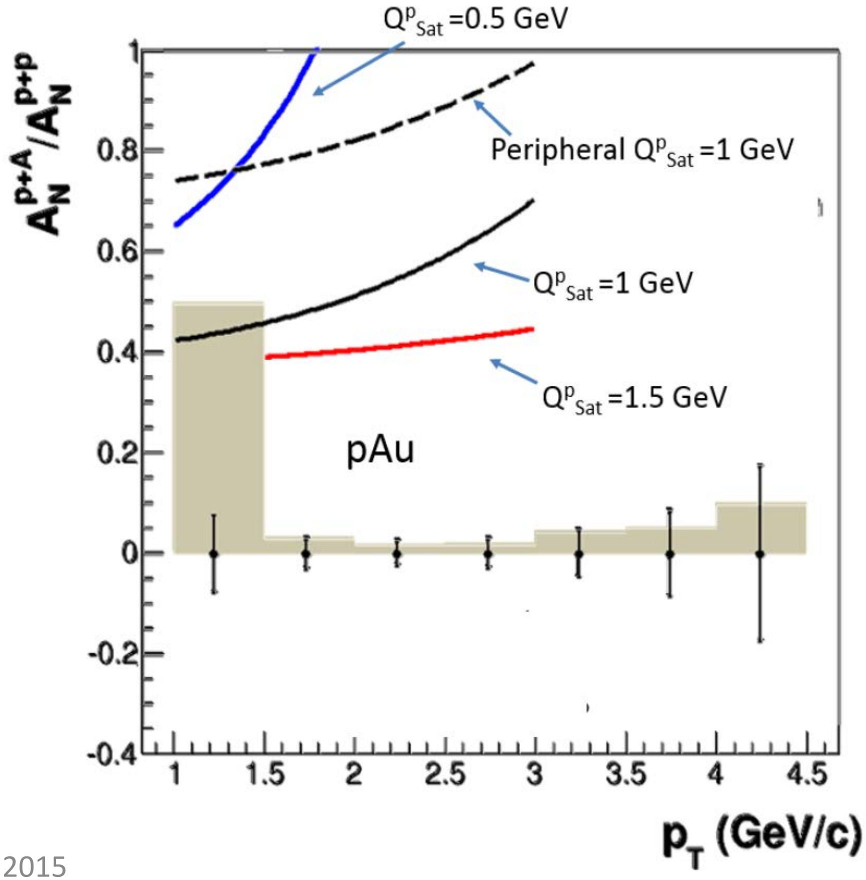
Kang, Qiu, Vogelsang and Yuan,
PRD 83 094001 (2011)
Gamberg and Kang,
arXiv 1208.1962v1 (2012)



Kanazawa, Koike, Metz and Pitonyak,
PRD 83 094001 (2015)

$p\uparrow + A$

- Unique capability of RHIC
- Polarization for probe to the gluon saturation (CGC)
  - Measurement of Q_s
- Projection for 2015 run



Z.-B.Kan and F.Yuan
PRD84, 034019 (2011)

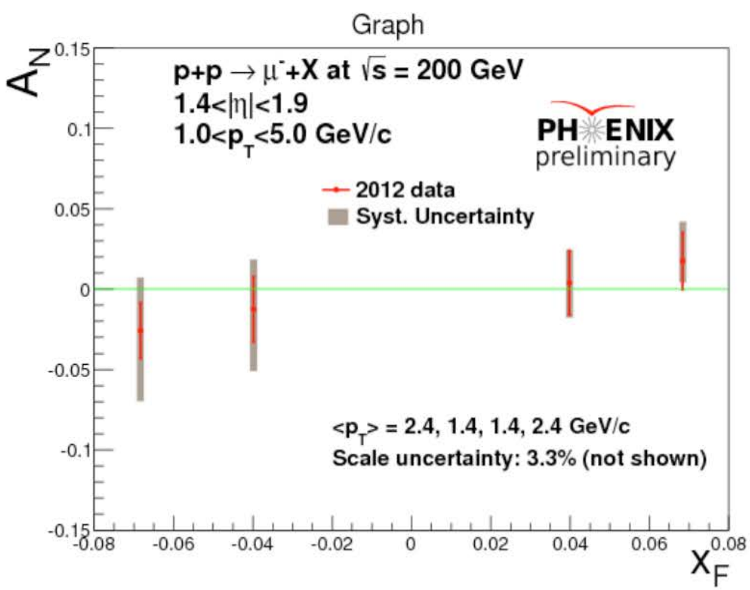
$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h << Q_s^2}{\approx} \frac{Q_{s,p}^2}{Q_{s,A}^2} f(p_T^h)$$

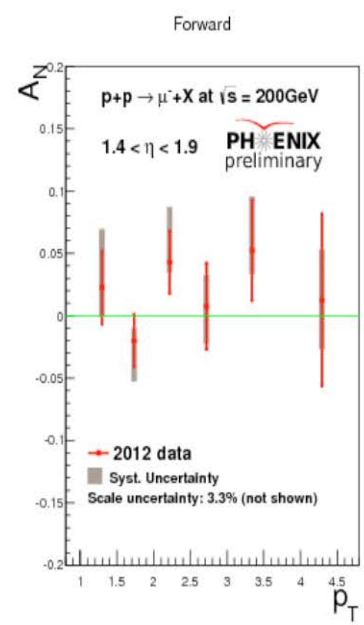
$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h >> Q_s^2}{\approx} 1$$

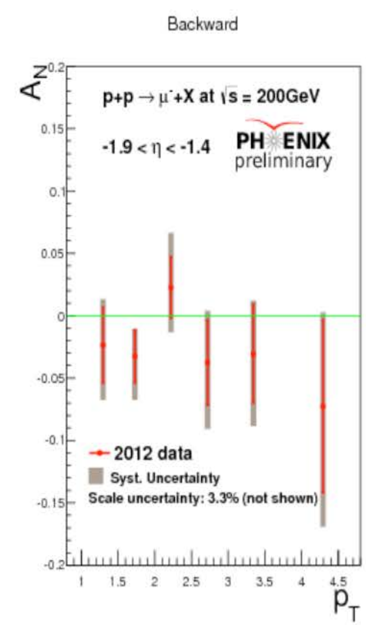
Odderon mechanism
(Kovchegov and Sievert)
predicts $\to 0$

Heavy-flavor measurements

- Gluon contribution
  - Quark sector good knowledge
    - Twist-3 quark-gluon correlation functions
  - Gluon sector largely unknown
    - Twist-3 tri-gluon correlation functions
- Heavy-flavor from gluon-gluon process
  - No final state effect
- Single muon SSA
  - 2012 run preliminary result

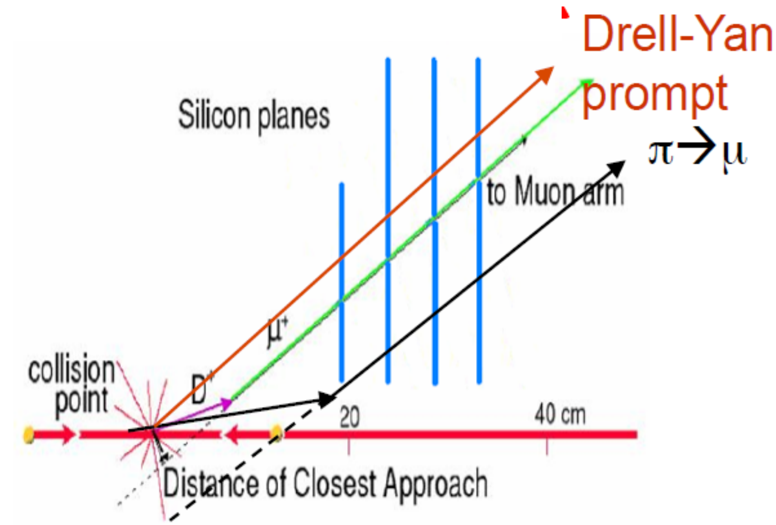




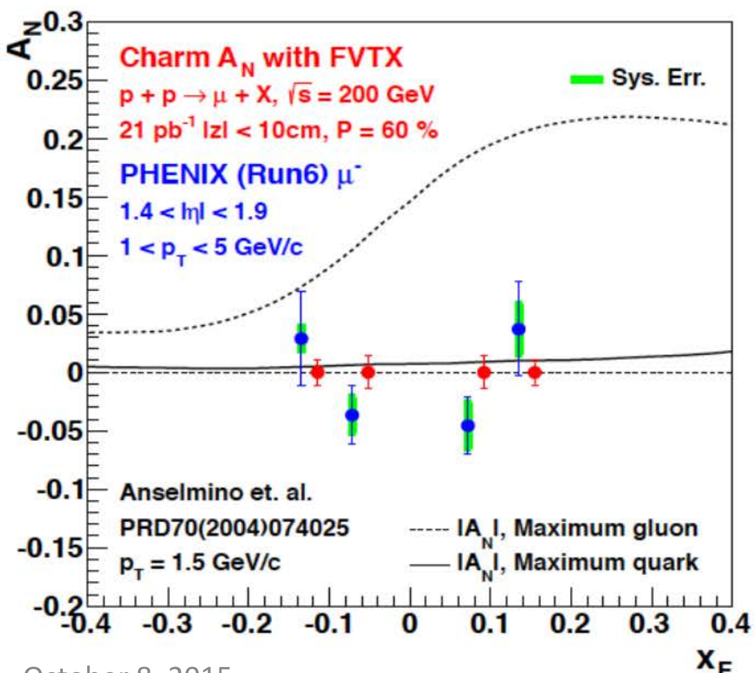


Single muon SSA

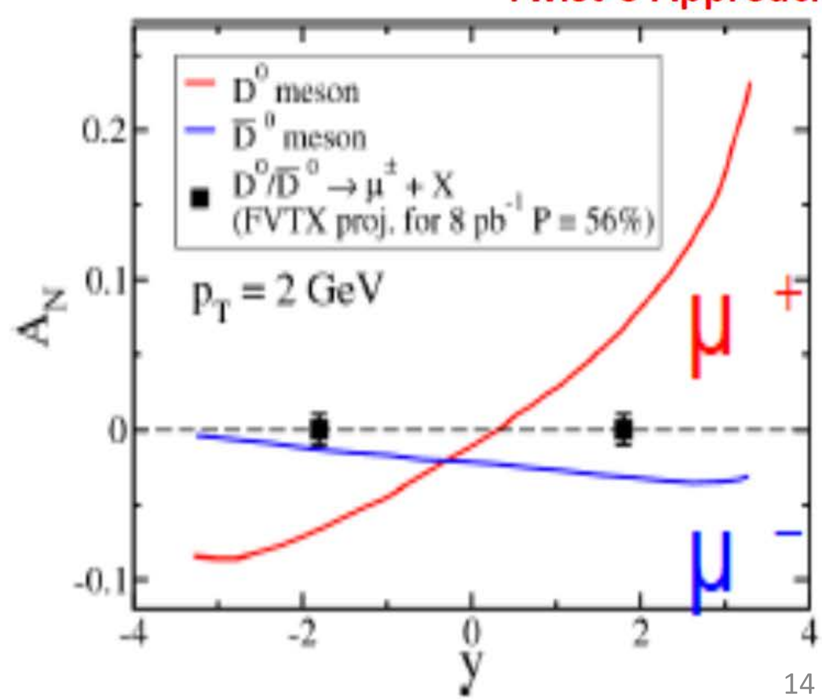
- Much improved results expected from 2015 run with VTX and FVTX



GTMD model

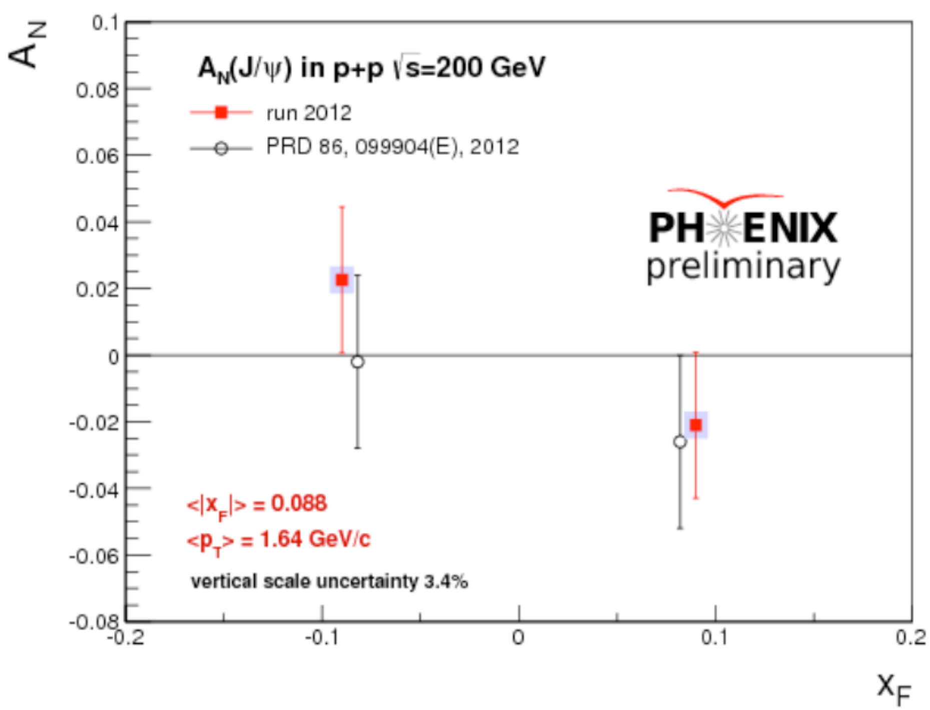


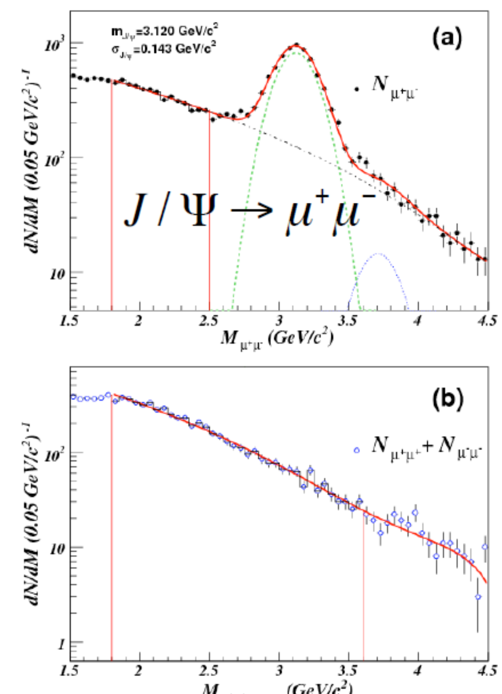
Twist-3 Approach



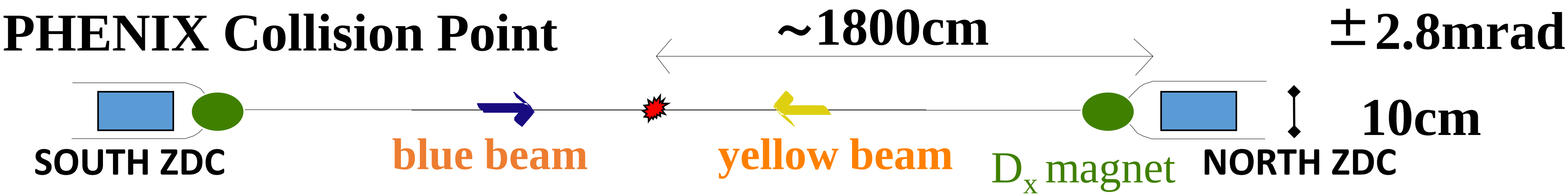
Forward J/ψ SSA

- 2012 run preliminary result
  - Asymmetry consistent with zero
  - More from 2015 run



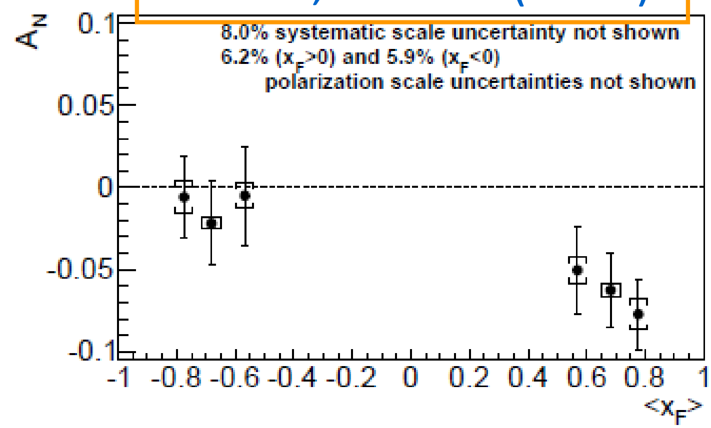


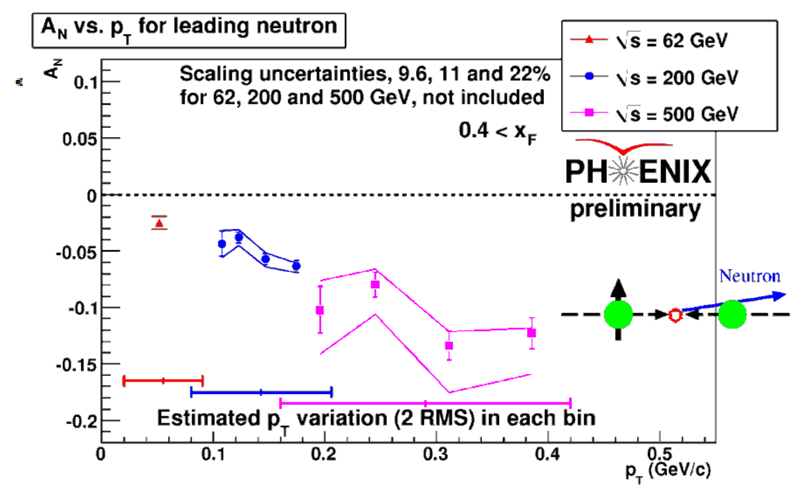
Forward neutron asymmetry



- ZDC + SMD
  - ZDC (Zero-Degree Calorimeter)
    - Hadron sampling calorimeter
  - SMD (Shower Maximum Detector)
    - Position measurement
- x_F distribution
  - Significant negative A_N in the forward region
    - No x_F dependence within the uncertainties
  - No significant backward asymmetry
- $\sqrt{s}$ dependence or p_T dependence

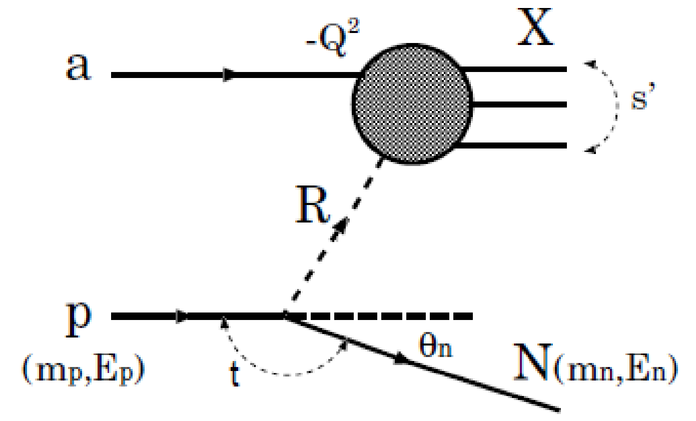
PRD 88, 032006 (2013)





Forward neutron production

- Cross section measurement
  - Forward peak in the x_F distribution around x_F~0.8
- OPE (one-pion exchange) model gives a reasonable description
- Asymmetry measurement
  - Interference between spin-flip and non-flip with a relative phase
  - Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012
  - Pion-a_1 interference: the data agree well with independence of energy
  - The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes



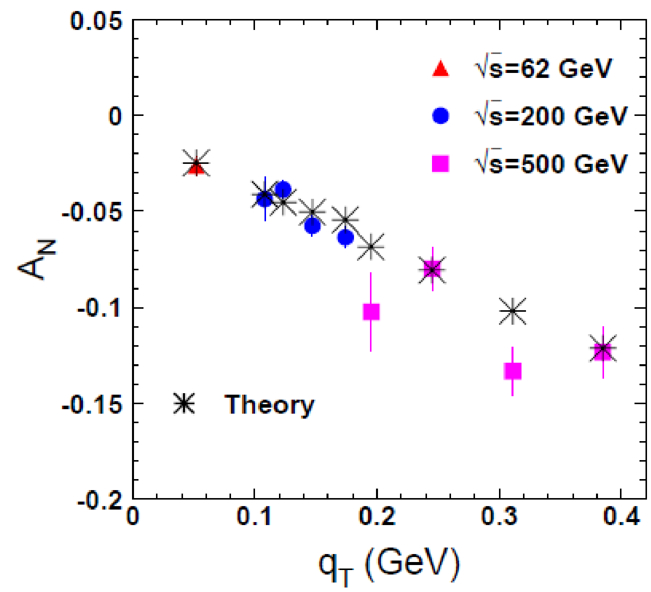
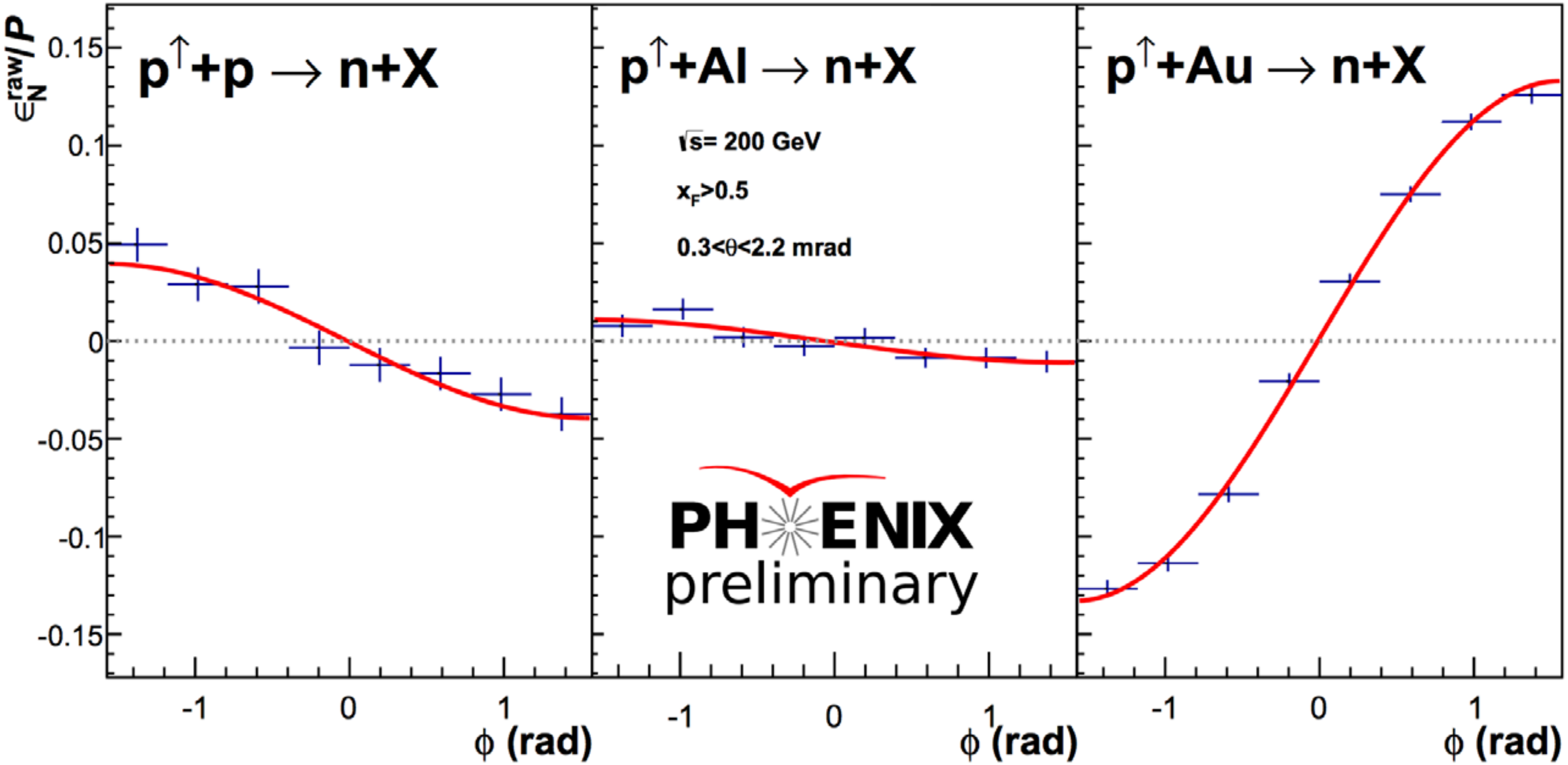


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500$ GeV [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).

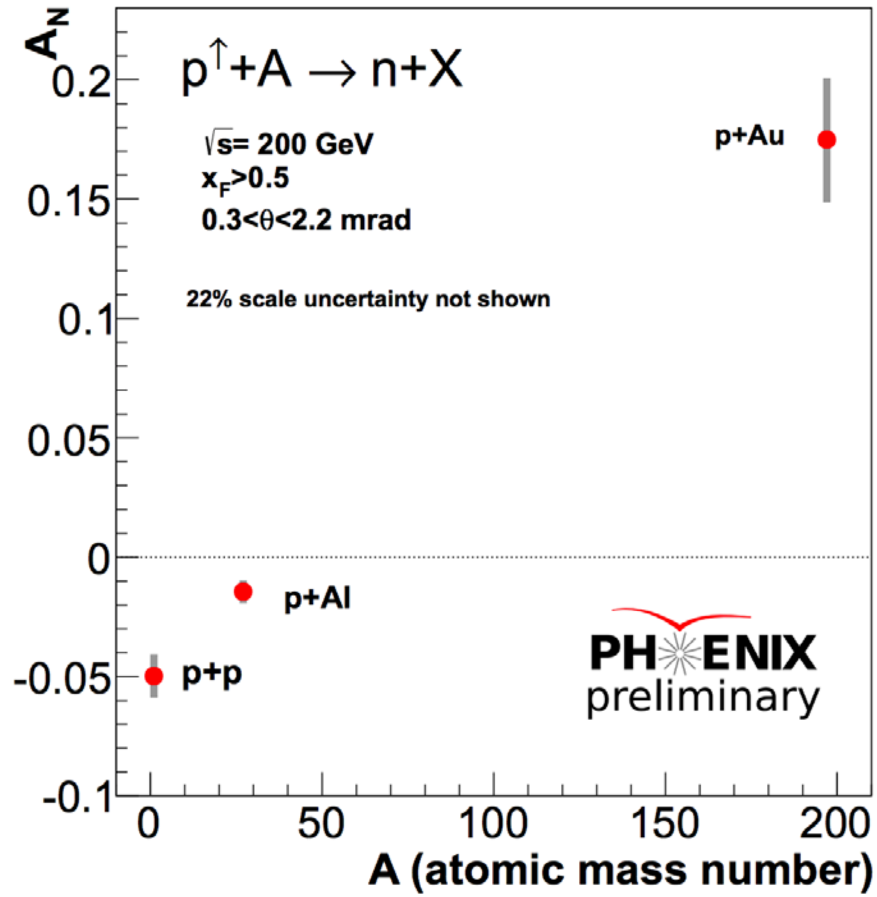
$p\uparrow + A$

- 2015 run preliminary result
  - ZDC trigger



A-dependence of neutron A_N

- Isospin effect?
- Nuclear effect?
  - Nucleus size
  - Neutron skin
  - Coherent effect
- Other trigger or offline event selection results to be obtained
- Inputs from theorists necessary



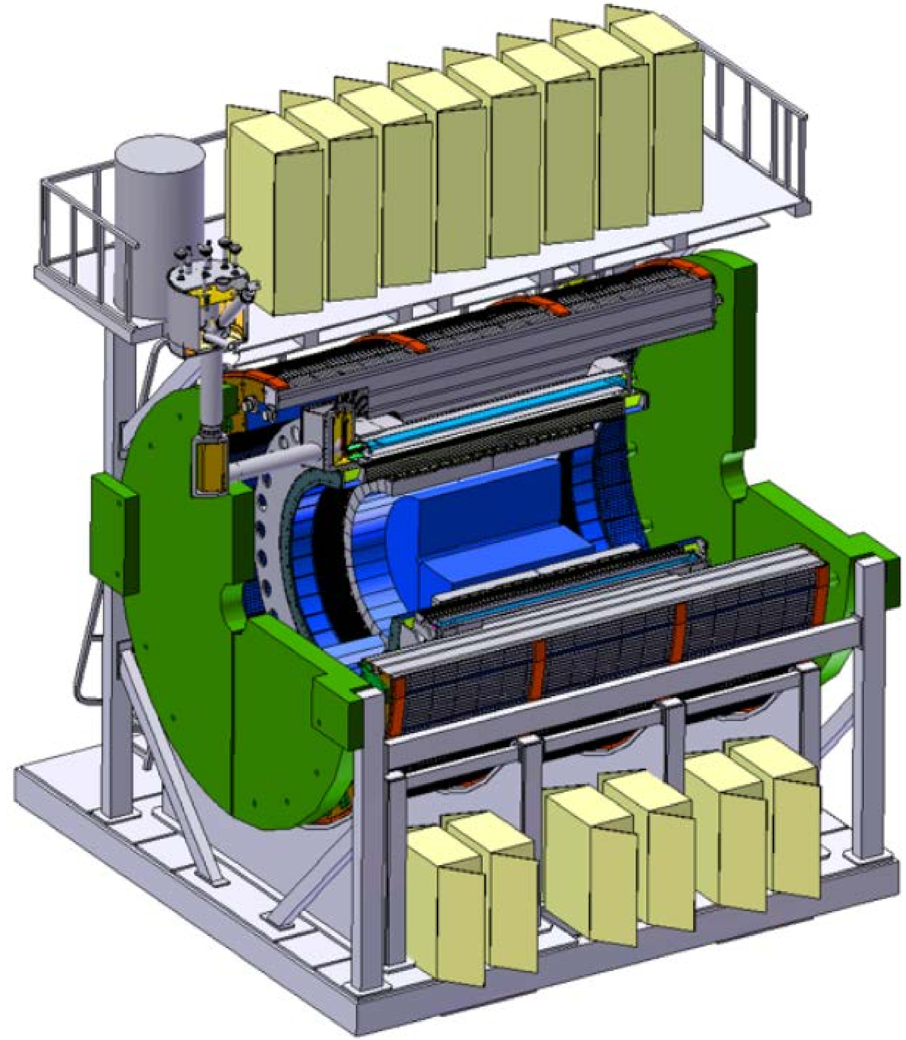
RHIC schedule

- PHENIX will end data taking after 2016 run
  - Polarized proton runs have already ended in 2015
- "sPHENIX" in 2021-22
  - Starting as a new collaboration
  - There will be polarized proton runs

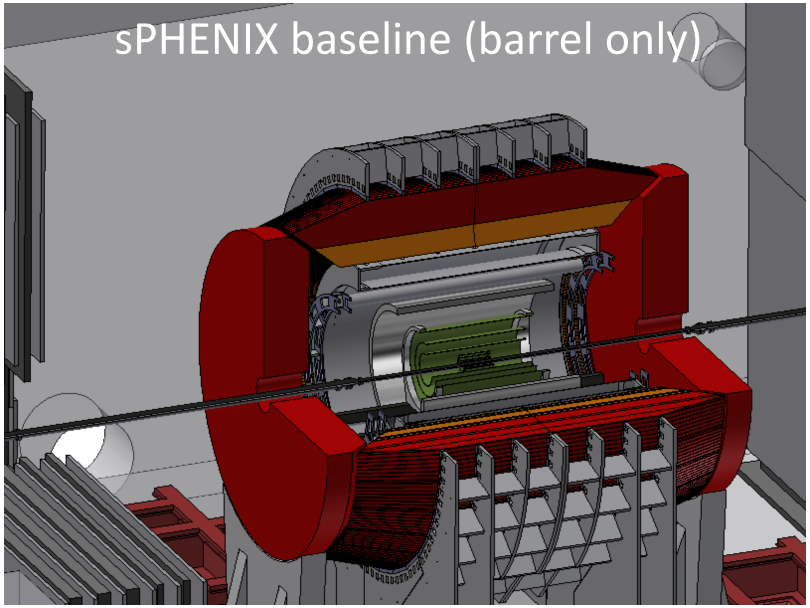
Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	$p^\uparrow+p^\uparrow$ at 200 GeV $p^\uparrow$+Au, $p^\uparrow$+Al at 200 GeV High statistics Au+Au Au+Au at 62 GeV ?	Extract $\eta/s(T)$ + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	$p^\uparrow+p^\uparrow$ at 510 GeV	Transverse spin physics Sign change in Sivers function	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2021-22	Au+Au at 200 GeV $p^\uparrow+p^\uparrow$, $p^\uparrow$+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

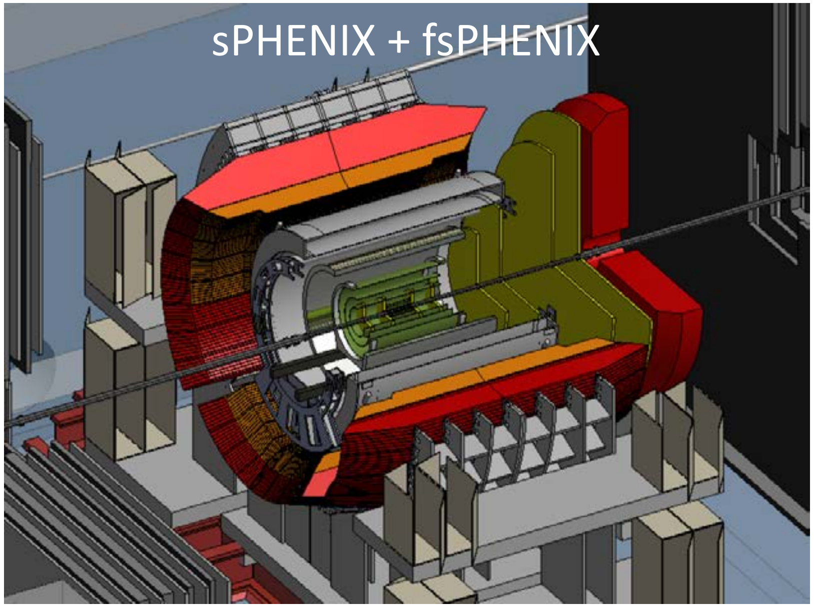
"sPHENIX"

- A new large-acceptance jet and Upsilon detector around the BaBar megnet
- Probe QGP with precision measurements of jet quenching and Upsilon suppression
- Spin physics and initial conditions at forward rapidities with p+p and p+A collisions



Forward "sPHENIX"

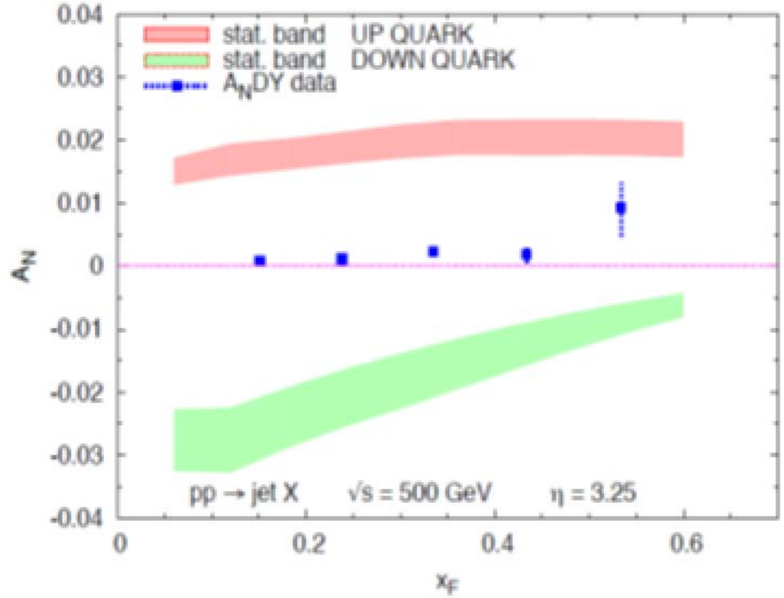


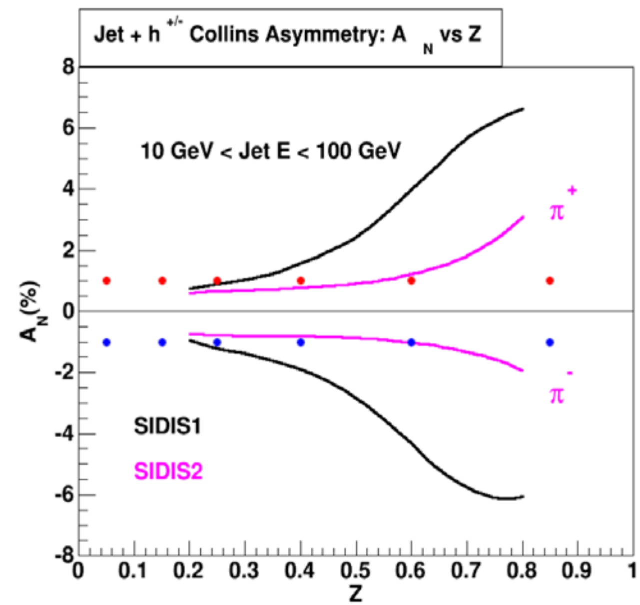


- Transverse spin physics
  - Transverse spin "puzzle"
  - Large single spin asymmetry (SSA) in the forward region
  - Understanding of the orbital motion
- p+A and p↑+A physics
  - Cold Nuclear Matter (CNM) effects
  - Polarization for probe to the gluon saturation

Jet measurements

- Small jet asymmetry measured by AnDY
  - Cancellation between u- and d-quarks
  - A cut on the charge of the leading hadron changes the composition of the jet sample
- Asymmetry measurement inside of jets
  - Transversity (initial state) + polarized fragmentation function (final state)





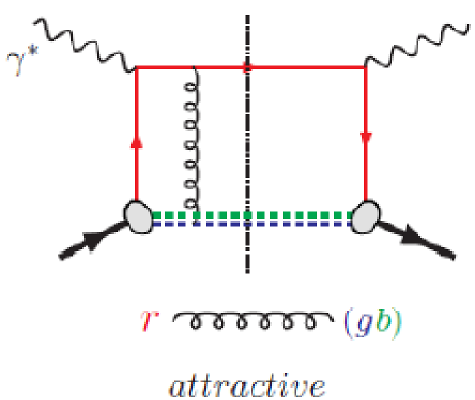
Drell-Yan measurement

- Establishment of non-universality of TMD distribution function
  - Opposite-sign contribution of TMD distribution function to SSA in SIDIS process and Drell-Yan process

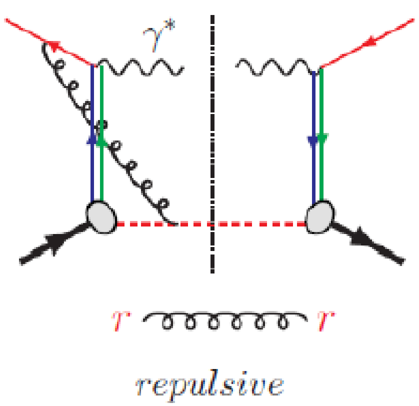
$$f_{1T}^{\perp q}|_{\mathrm{SIDIS}} = -f_{1T}^{\perp q}|_{\mathrm{DY}}$$

  - Fundamental property based on gauge invariance of QCD
  - Experimental verification required

SIDIS

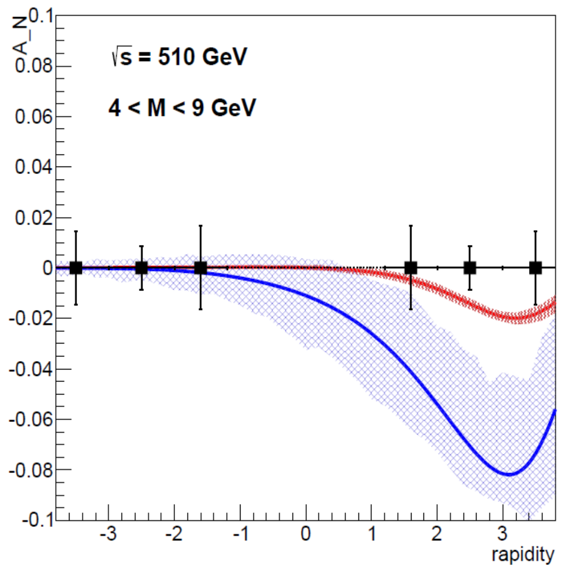


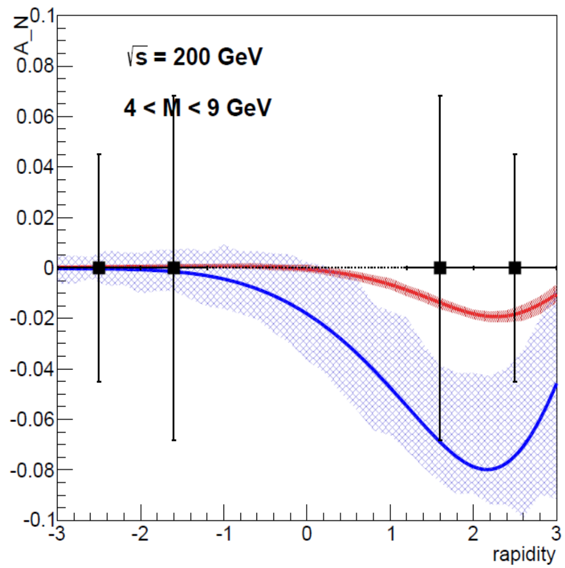
Drell-Yan



Drell-Yan measurement

- Statistical sensitivities
  - With and without Sivers function evolution
- Better S/B (lower heavy-flavor cross section) but reduced luminosity at √s = 200 GeV
- Higher luminosity (higher statistics) but higher background at √s = 510 GeV





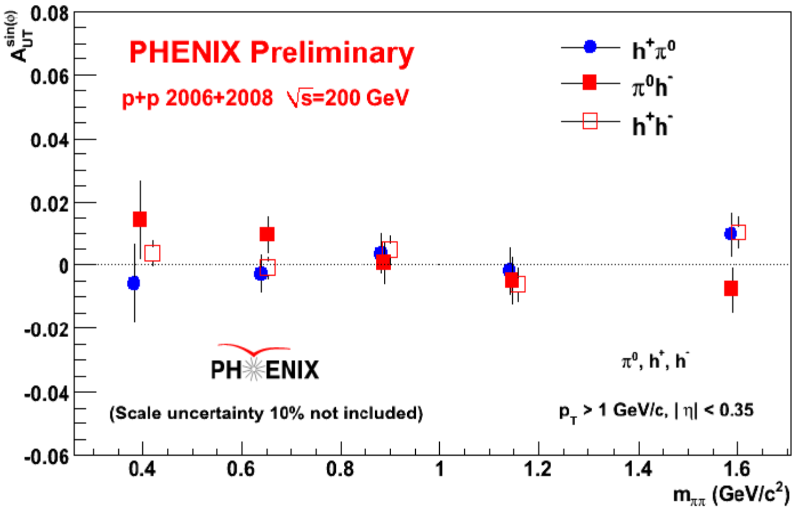
Summary

- Transverse-spin properties of the nucleon
  - Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon
  - Description with TMD and higher twist effect
  - Distinguish between initial state and final state effect
  - Forward measurements with MPC and MPC-EX
- p↑+A asymmetry measurement
  - Unique capability of RHIC
  - MPC-EX result to be obtained
  - Neutron asymmetry
- sPHENIX forward measurement
  - Jet and Drell-Yan asymmetry measurements
  - Support from the spin community important and necessary

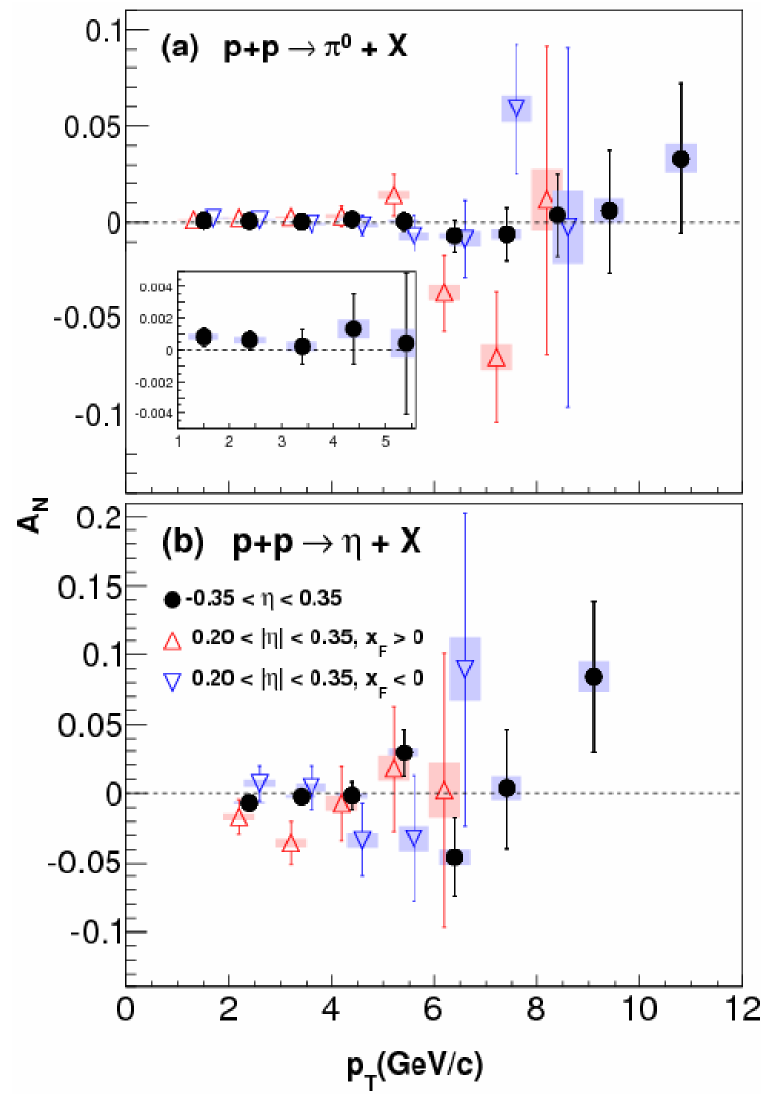
Backup slides

SSA at midrapidity

- Hadron pairs



- π^0 and η

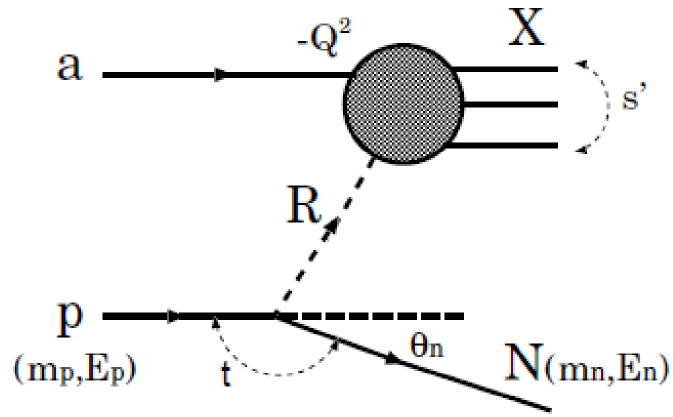


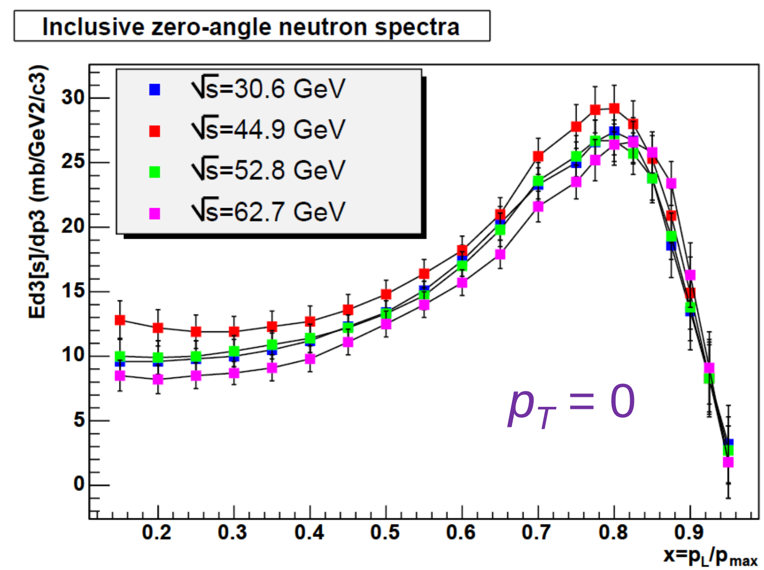
Drell-Yan measurement

	COMPASS-II	fsPHENIX 200 GeV	fsPHENIX 510 GeV
$L_{avg}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	1.18×10^{32}	0.76×10^{32}	6.48×10^{32}
Average L /week	14.3 pb^{-1}/week	18.7 pb^{-1}/week	128 pb^{-1}/week
Accelerator eff.	0.8	(included above)	(included above)
Detector up-time	0.85	0.6	0.6
Vertex cut	n/a	0.62	0.62
Sampled L /week	9.7 pb^{-1}/week	6.9 pb^{-1}/week	47.6 pb^{-1}/week
week/year	20	10	15
Sampled L /year	194 pb^{-1}/year	69 pb^{-1}/year	714 pb^{-1}/year
Dimuon trigger eff.	0.81	0.81	0.81
High mass: $4\,\mathrm{GeV}/c^2 < M < 9\,\mathrm{GeV}/c^2$			
Reconstruction eff.	0.8	0.312	0.305
Offline L /year	126 pb^{-1}/year	17.5 pb^{-1}/year	177 pb^{-1}/year
Cross section σ	1291 pb	1199 pb	2542 pb
Acceptance Ω	0.35	0.14	0.19
$\sigma\cdot\Omega$	452 pb	171 pb	478 pb
K factor (assumption)	2	1.38	1.38
Dimuon/year $L\cdot\sigma\cdot\Omega\cdot K$	115000/year	4150/year	117000/year
FoM/year	2230/year	747/year	14600/year
$\delta A_T^{\sin\phi_S} = 1/\sqrt{FoM}$	0.021	0.037	0.0083
Low mass: $2\,\mathrm{GeV}/c^2 < M < 2.5\,\mathrm{GeV}/c^2$			
Reconstruction eff.	0.8	0.285	0.272
Offline L /year	126 pb^{-1}/year	16.0 pb^{-1}/year	157 pb^{-1}/year
Cross section σ	6231 pb	2811 pb	4630pb
Acceptance Ω	0.43	0.22	0.21
$\sigma\cdot\Omega$	2679 pb	610 pb	955 pb
K factor (assumption)	2	1.38	1.38
Dimuon/year $L\cdot\sigma\cdot\Omega\cdot K$	674000/year	13500/year	207000/year
FoM/year	13200/year	2430/year	25900/year
$\delta A_T^{\sin\phi_S} = 1/\sqrt{FoM}$	0.0087	0.020	0.0062

Forward neutron production

- Cross section measurement at ISR/FNAL
  - Forward peak in the x_F distribution
    - around x_F~0.8
  - Only a small √s dependence
- OPE (one-pion exchange) model gives a reasonable description





- Cross section measurement at HERA(e+p)/NA49(p+p)
  - √*s* dependence indicated
  - Suppression of the forward x_F peak at high √*s*?
- More data necessary to understand the production mechanism
  - Asymmetry measurement as a new independent input

No cross section measurement performed at IP12 experiment
→ measurement at PHENIX

Forward neutron production

- Interference between spin-flip and non-flip with a relative phase

$$A_N \approx \frac{2\,\mathrm{Im}\left(fg^*\right)}{\left|f\right|^2 + \left|g\right|^2}$$

f : spin non-flip amplitude
g : spin flip amplitude

- Pion-a_1 interference: results
  - The data agree well with independence of energy
- The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

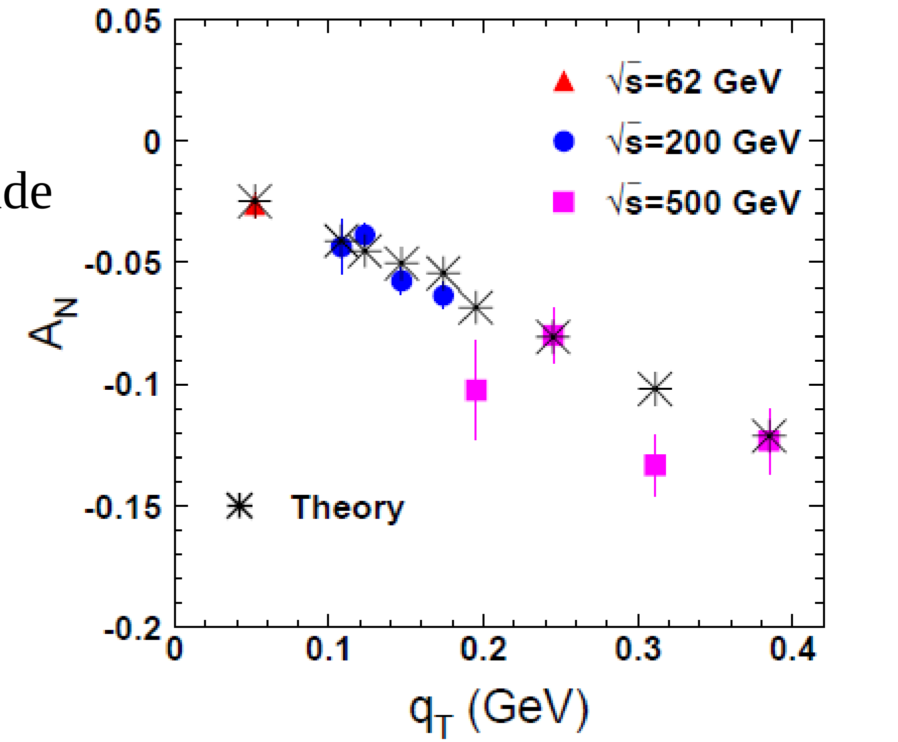


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500$ GeV [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).