Nucleon-Structure Physics by Proton-Proton Collisions

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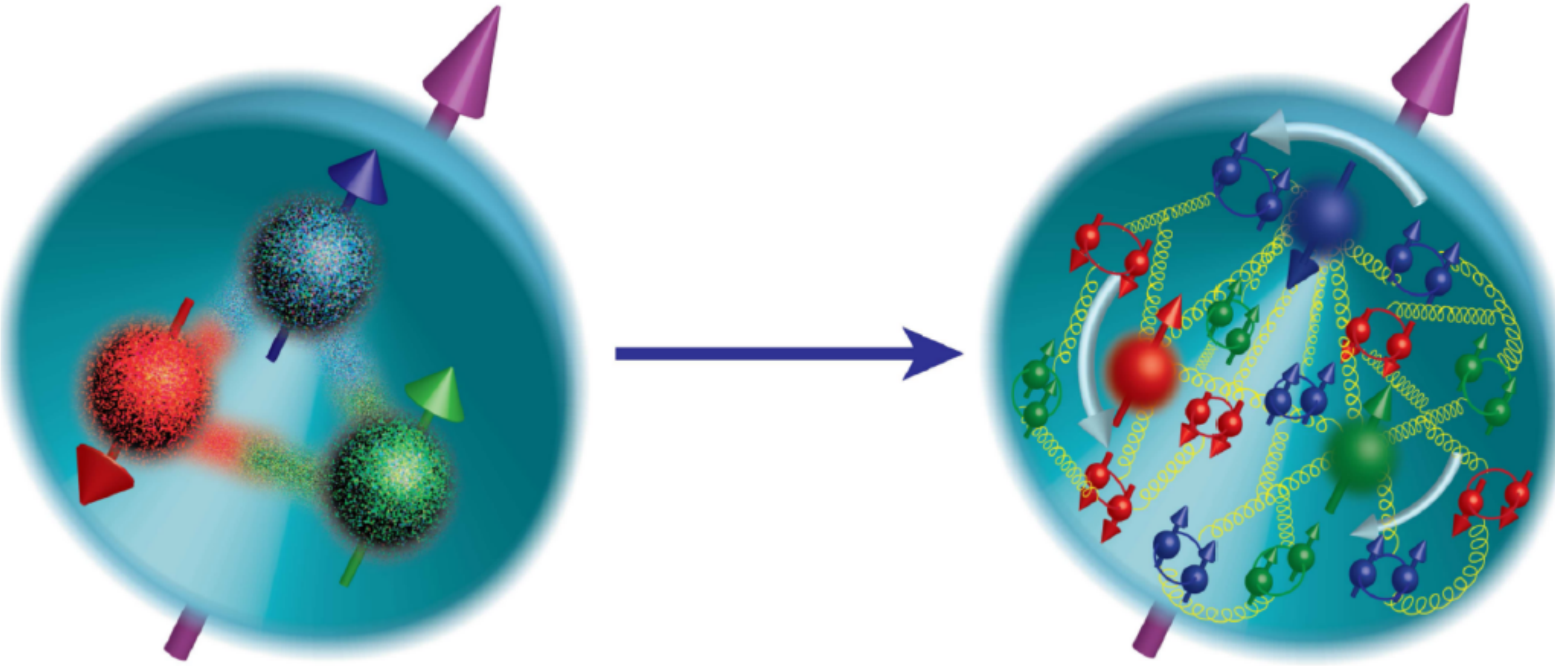
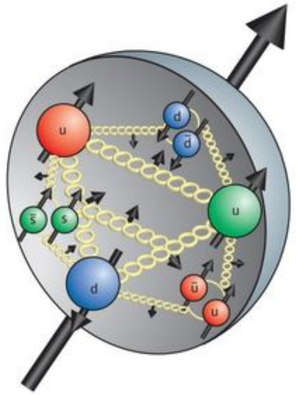
Tsukuba, Japan

Nucleon Structure and Interaction

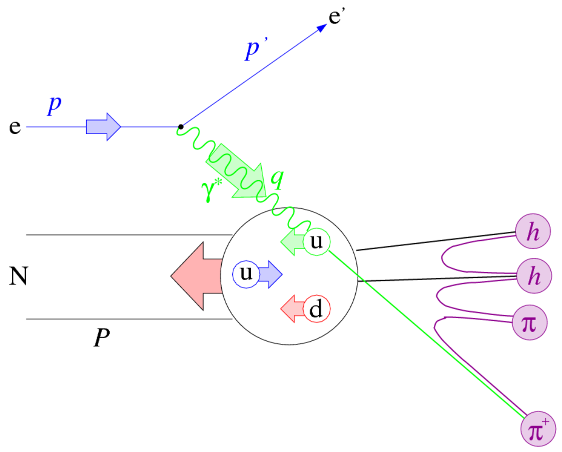
- A very rich dynamic environment, NOT a point particle
  - 3-D
  - scale-dependent
- Primary source of our knowledge about QCD and strong interaction phenomena

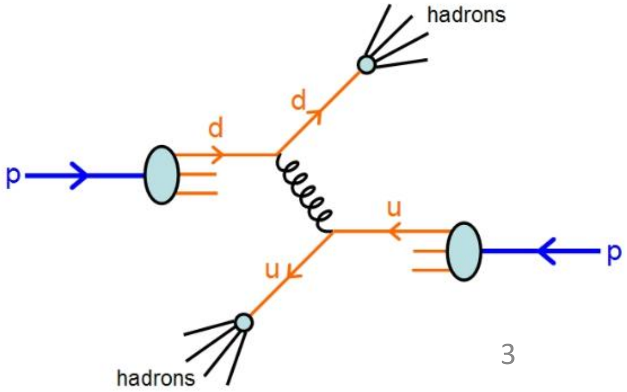


Physics of Nucleon Structures



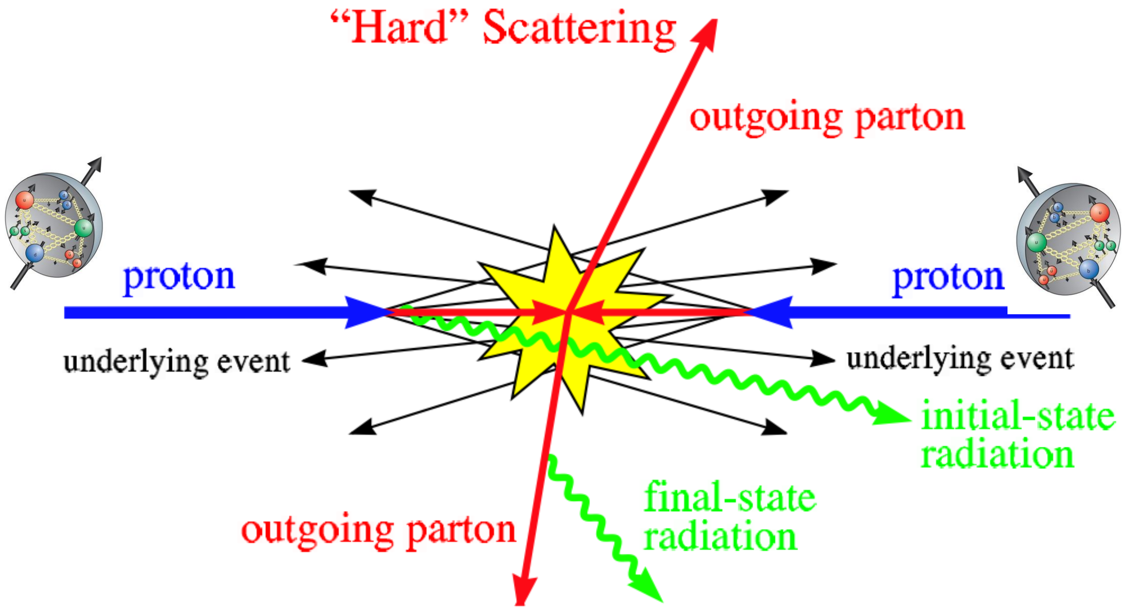
- How hadrons formed and interact from the fundamental quarks and gluons?
  - Space and momentum distributions of quarks and gluons
  - Spin degree of freedom
  - Probe scale dependence, Q2
- Our tools
  - Lepton probes - electrons, muons, neutrinos …
    - DIS experiments, HERMIES, COMPASS, EIC…
  - Hadron probes - proton, pion/Kaon…
    - RHIC, Fernilab, COMPASS …
  - Lattice QCD, pQCD …

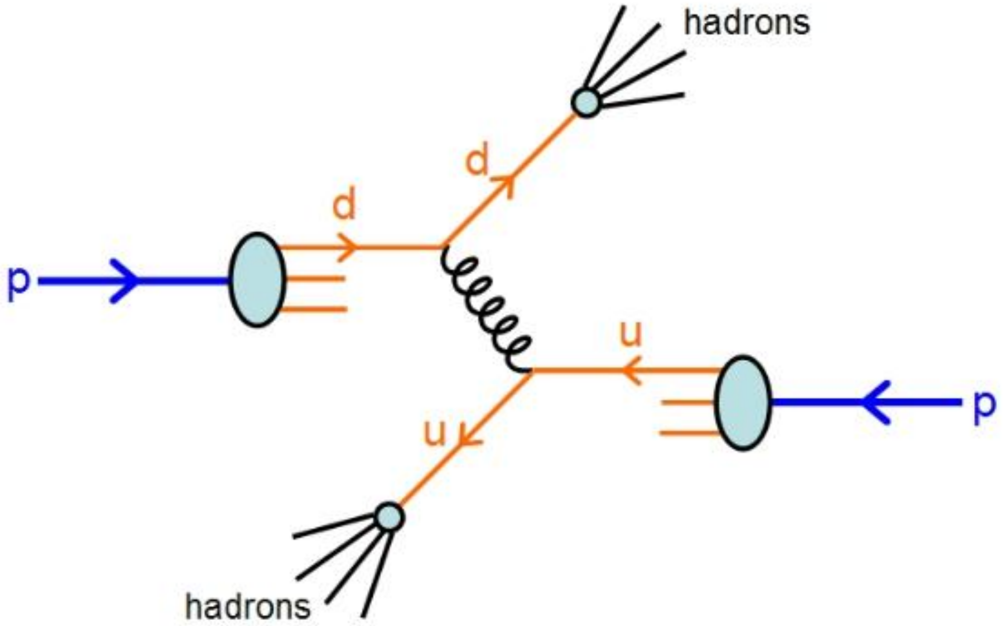




Study Nucleon Structure in Hadron Collisions

Very massy p-p collisions could be simplified for hard-scattering processes, pQCD applicable





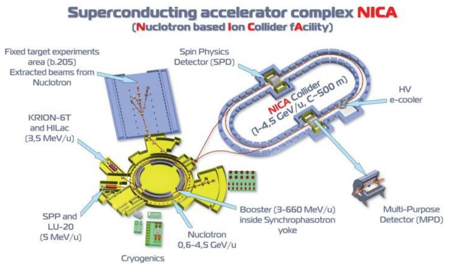
$$\sigma \sim f(x_1) \otimes f(x_2)\hat{\sigma}^{x_1+x_2\rightarrow h_1+h_2+X}$$

Selected Recent Highlights

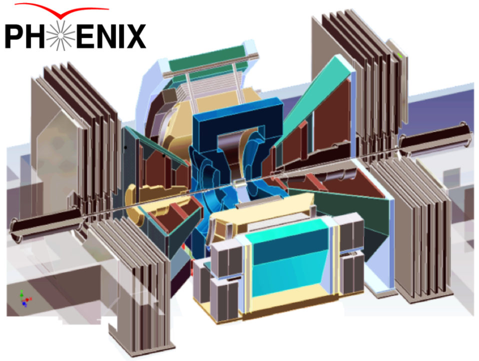
- Spin puzzle
  - RHIC –PHENIX, STAR
- TMD phenomena
  - RHIC/STAR, PHENIX
  - CERN/COMPASS
  - Fermilab/SeaQuest

NIKA/SPD

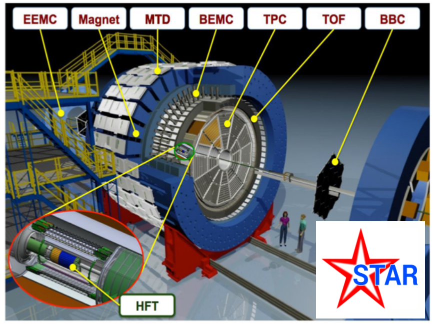
Alexey Guskov, Fri.



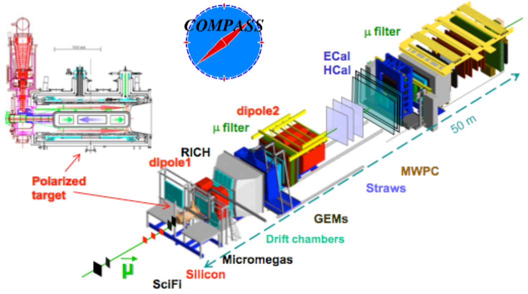
Itaru Nakagawa, Fri.



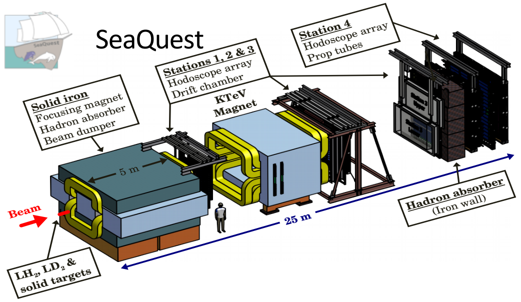
Ken Barish, Fri.



Marcia Quaresma, Wed.

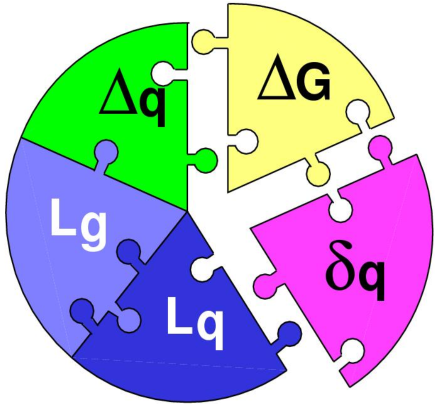


Kei Nagai &
Yoshiyuki Miyachi, Wed.



Part-I: Challenge of "Too Large"

Three Decades of the Proton Spin Puzzle



Spin Crisis: EMC, 1987

Early expectation:
Large gluon polarization,
Axial anomaly, Cheng & Li, PRL (1989)

$$\Delta\Sigma' = \Delta\Sigma - \frac{\alpha_s}{2\pi}\cdot\Delta G$$

$$\frac{\alpha_s}{2\pi}\cdot\Delta G = 0.3 \pm 0.1$$

Development of RHIC-Spin program in 90's

Today:

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

$\Delta\Sigma \sim 0.3$ (Pol. DIS)

$\Delta G \sim 0.2$ (RHIC-Spin)

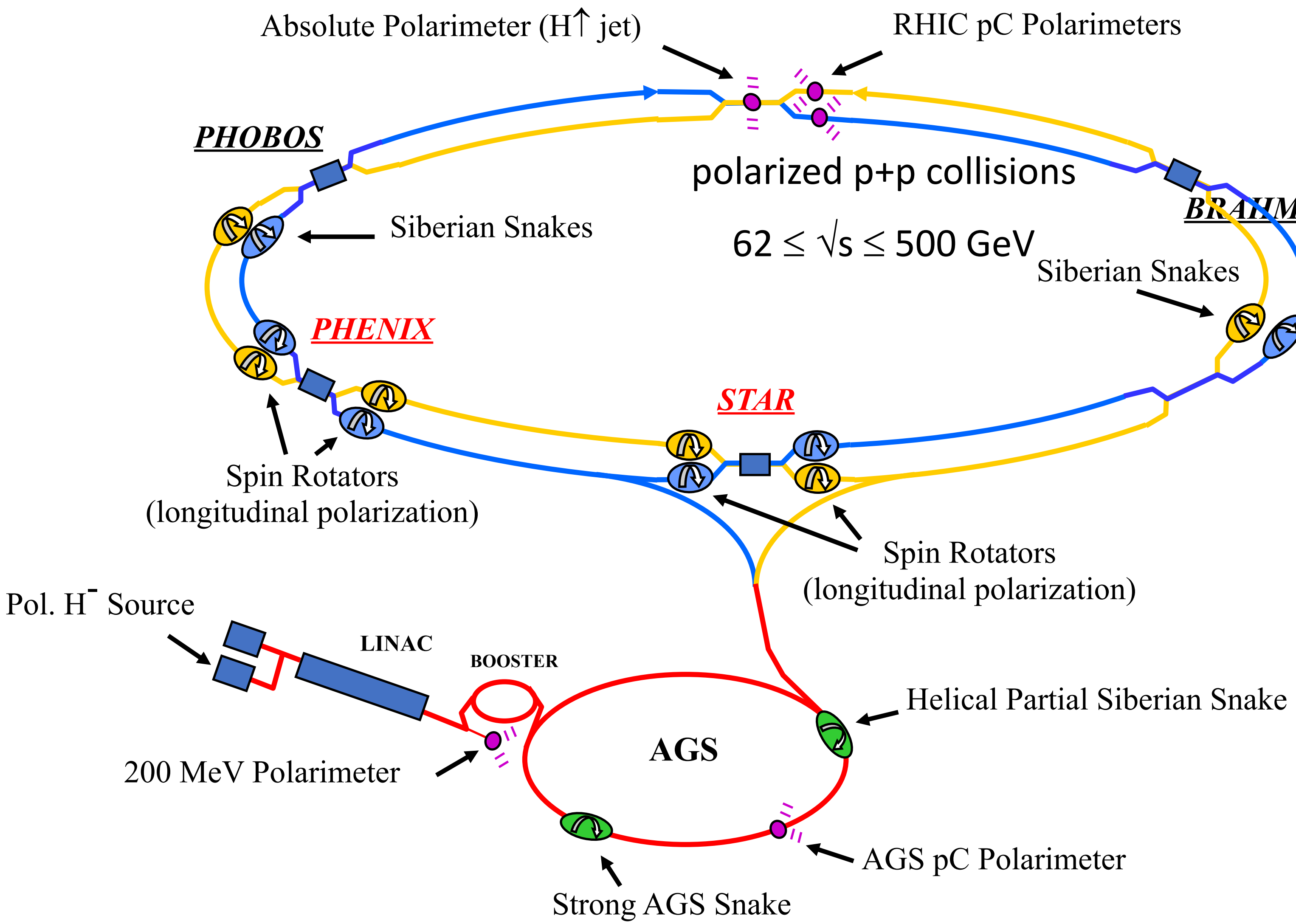
$L^z \sim ?$ (RHIC, FNAL?)

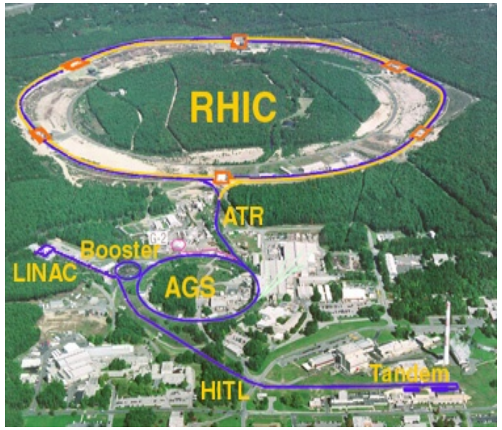
	Quark Spin	Gluon Spin
SLAC -> 2000	E80 – E155	
CERN ongoing	EMC, SMC, COMPASS	
DESY ->2007	HERMES	
JLab ongoing	Hall A,B,C	
RHIC ongoing	(BRAHMS), (PHENIX), STAR	

Orange: SIDIS/DIS

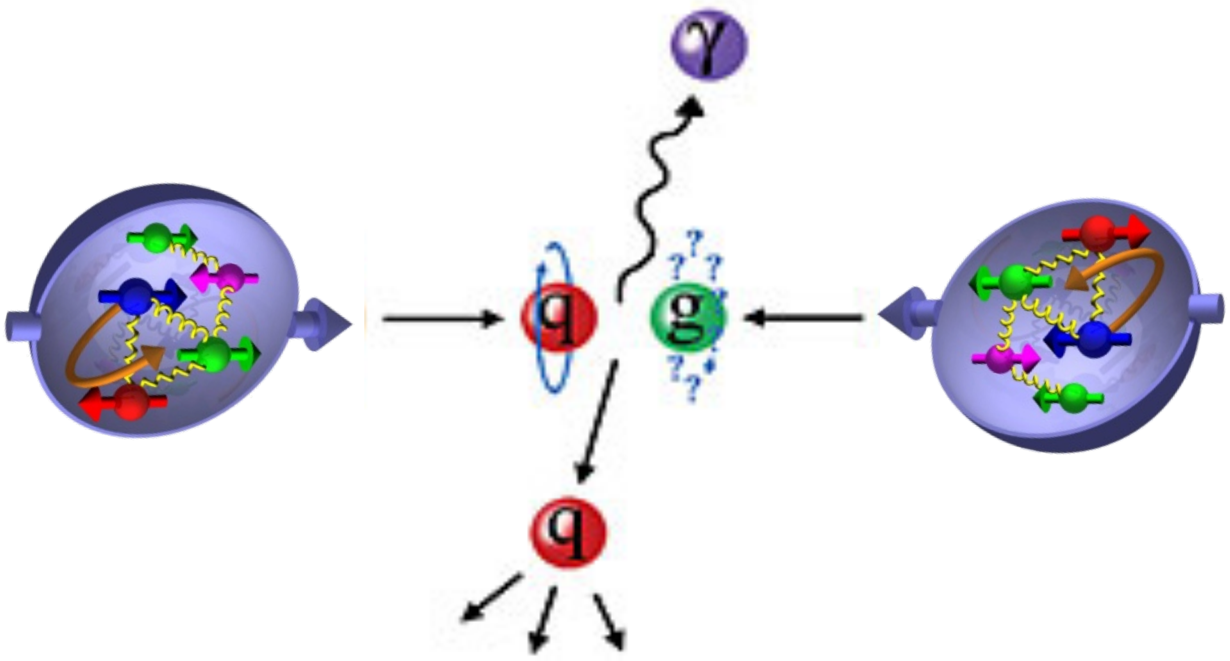
Green: Polarized p+p

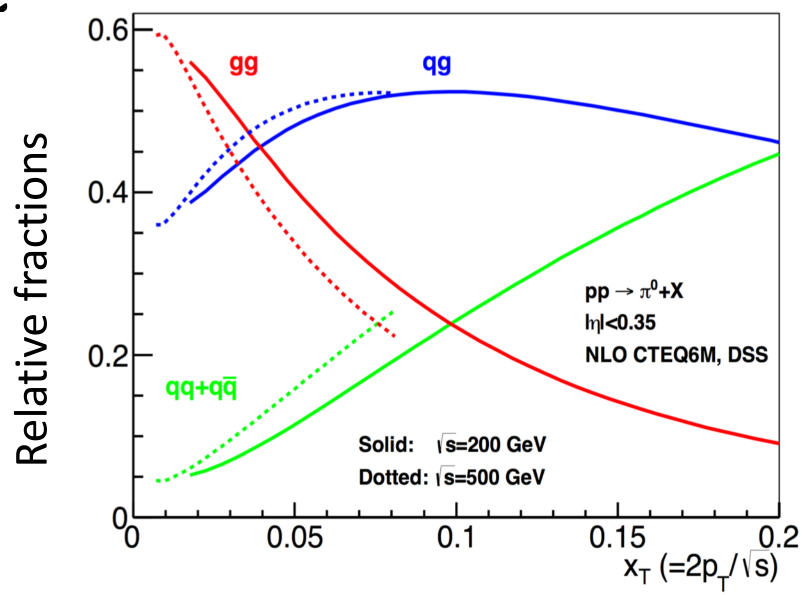
World First High-Energy Polarized Proton Collider at RHIC

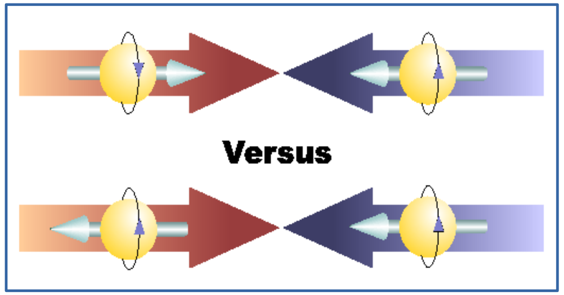




Study Gluon Polarization at RHIC





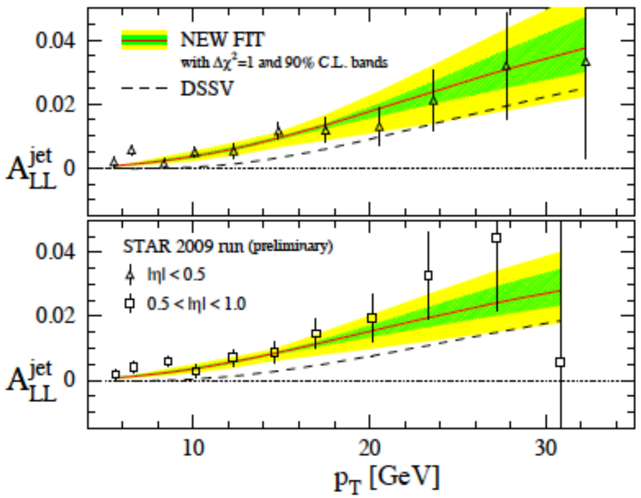


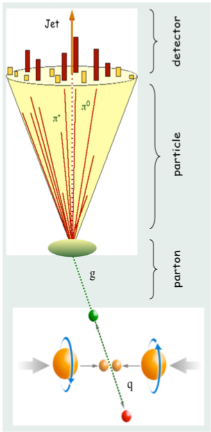
$A_{LL}=(N^{++}-N^{+-})/(N^{++}+N^{+-})$

$$\Delta\sigma(pp \to \pi^0 X) \approx \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)\ldots$$

First Hint of Non-zero Gluon Polarization from RHIC 2009 Data Set

STAR: PRL 115, 092002 (2015)

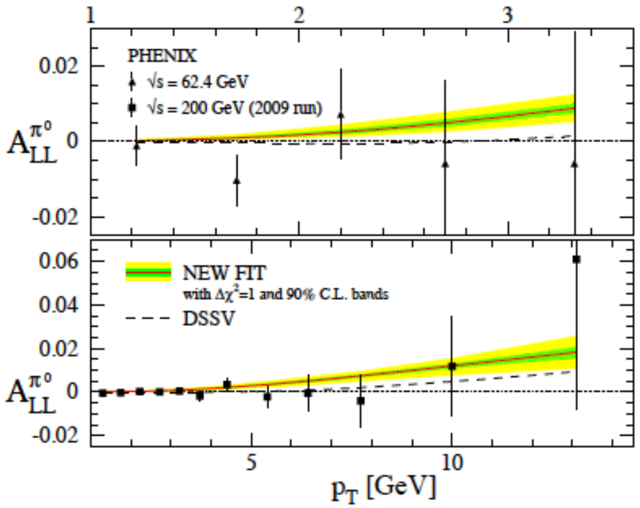


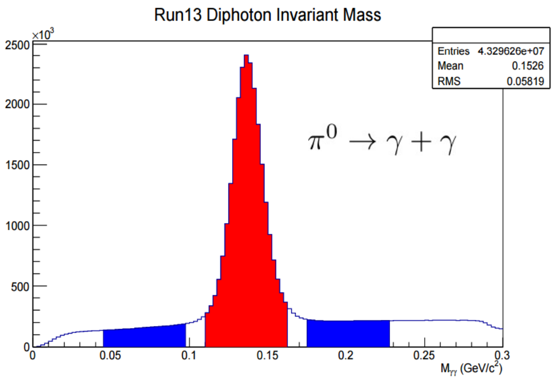


Run 2009

p+p@200GeV

PHENIX: PRD 90, 012007 (2014)

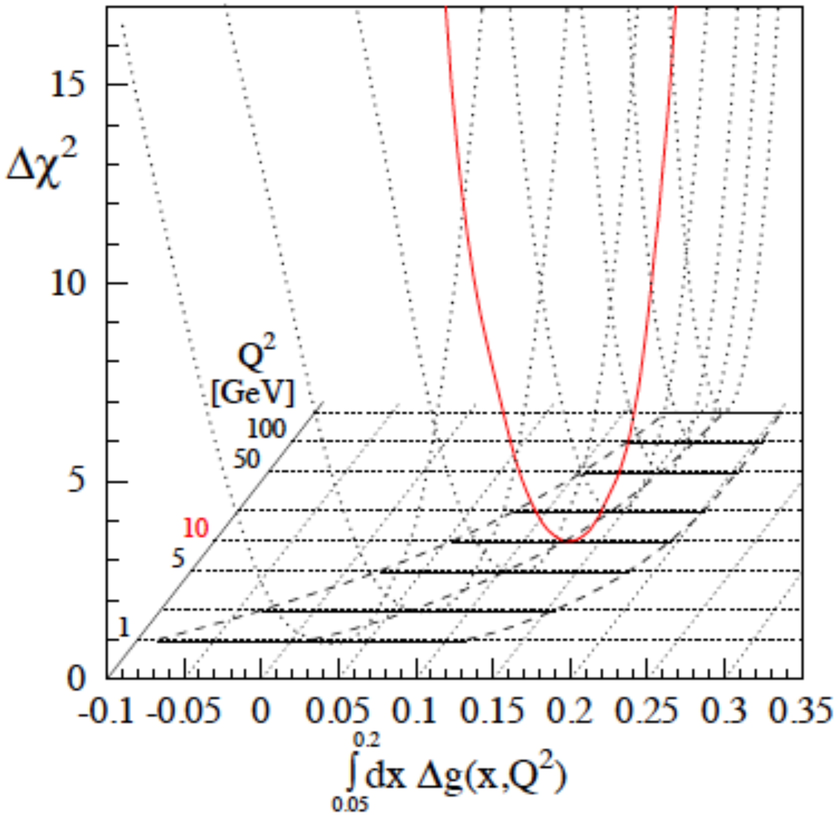




$$\int_{0.05}^{1} \Delta g(x, Q^2)\,dx = 0.2^{+0.06}_{-0.07}$$

@ Q^2 = 10 GeV^2

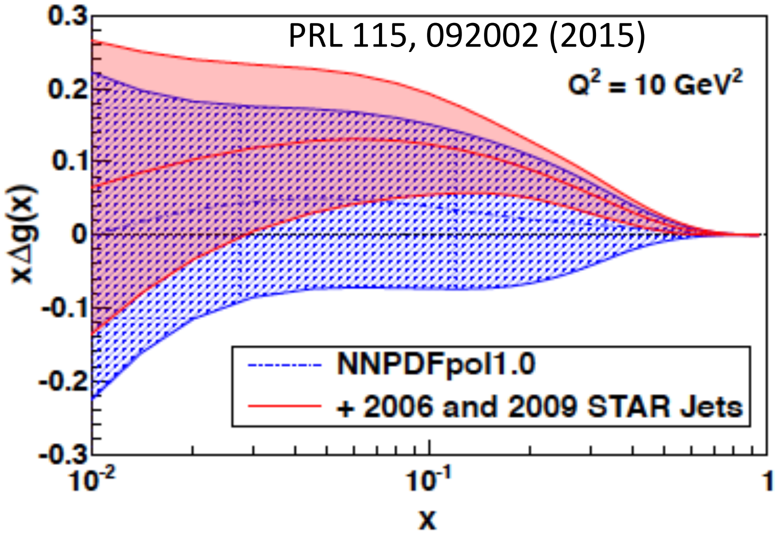
PRL 113, 012001 (2014), DSSV



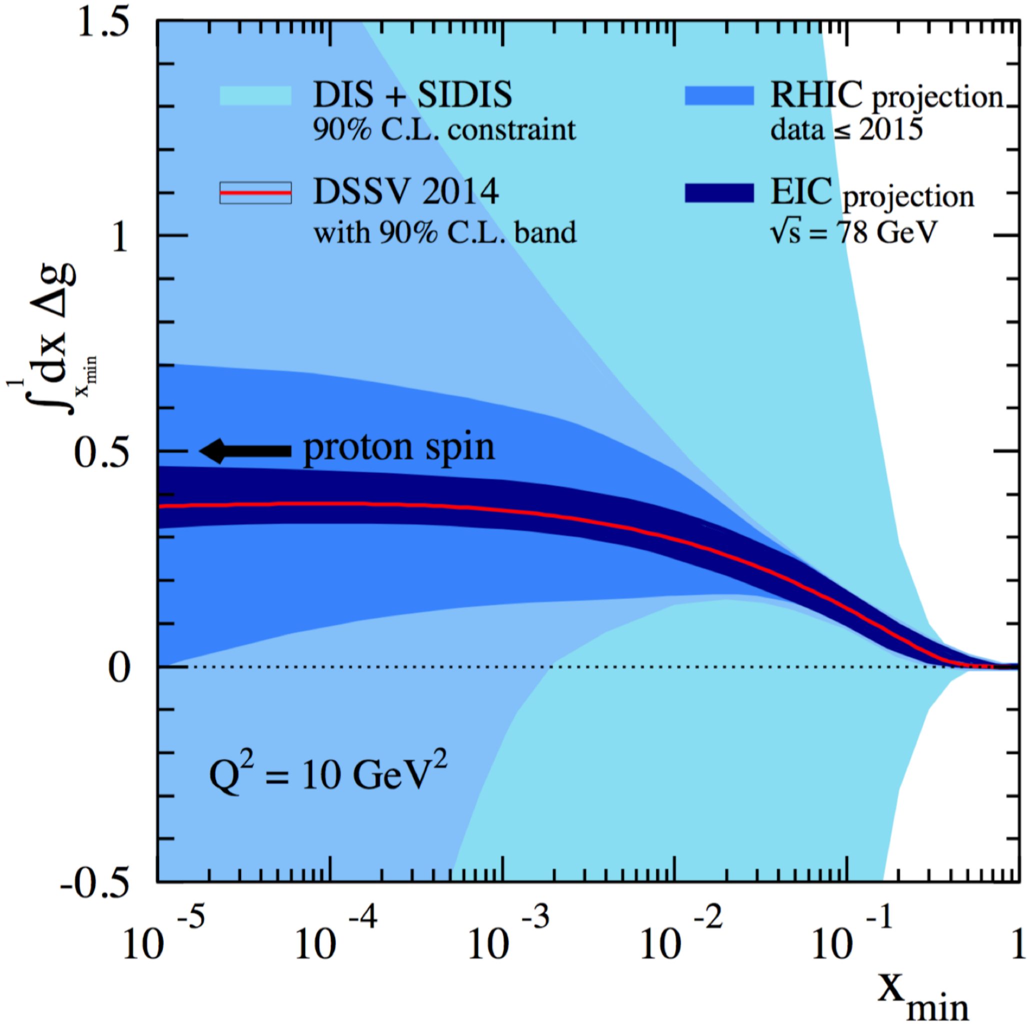
Projected Impact of RHIC data on Gluon Polarization

- Favors positive gluon polarization
  - PHENIX/STAR data:
    - 62GeV π^0 A_{LL}
    - 200GeV π^0 A_{LL}
    - 510GeV π^0 A_{LL}
    - 200/510GeV (di)jets A_{LL}

  Statistically limited but could be improved in the future high luminosity program:
    - 200/510GeV charged hadron A_{LL}
    - 200/510GeV HF A_{LL}
    - 200/510GeV J/ψ A_{LL}
- EIC future, 2027+

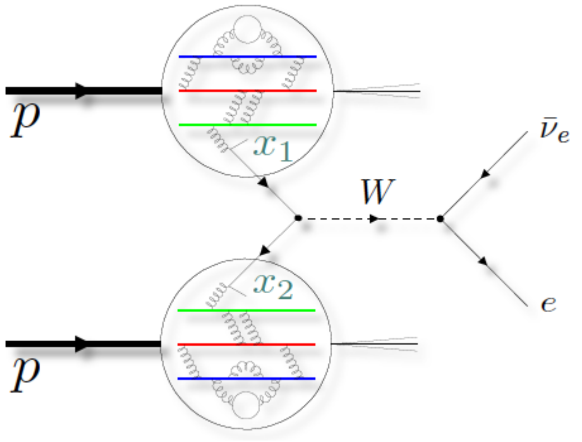


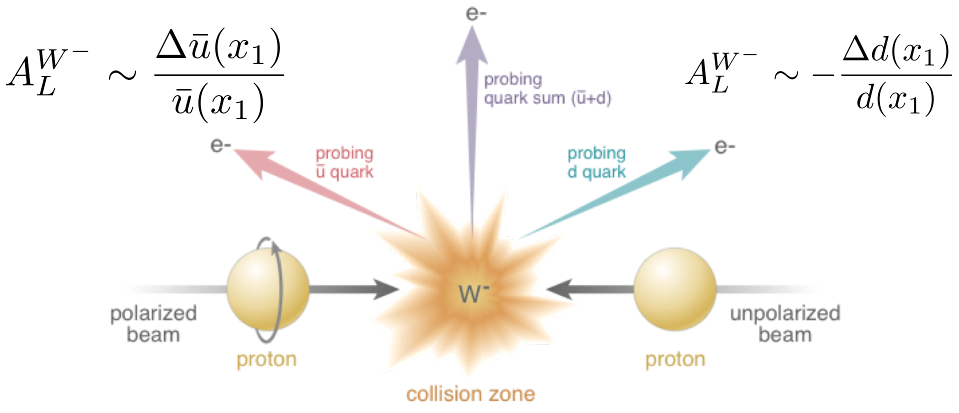
"RHIC Cold QCD Plan for 2017-2023", arXiv:1602.03922



Electroweak Probe for Sea Quarks at High Energy at RHIC

$$q(x_1) + \bar{q}'(x_2) \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu(\bar{\nu})$$





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

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

First Direct Measurements of Flavor Identified Sea Quark Polarization

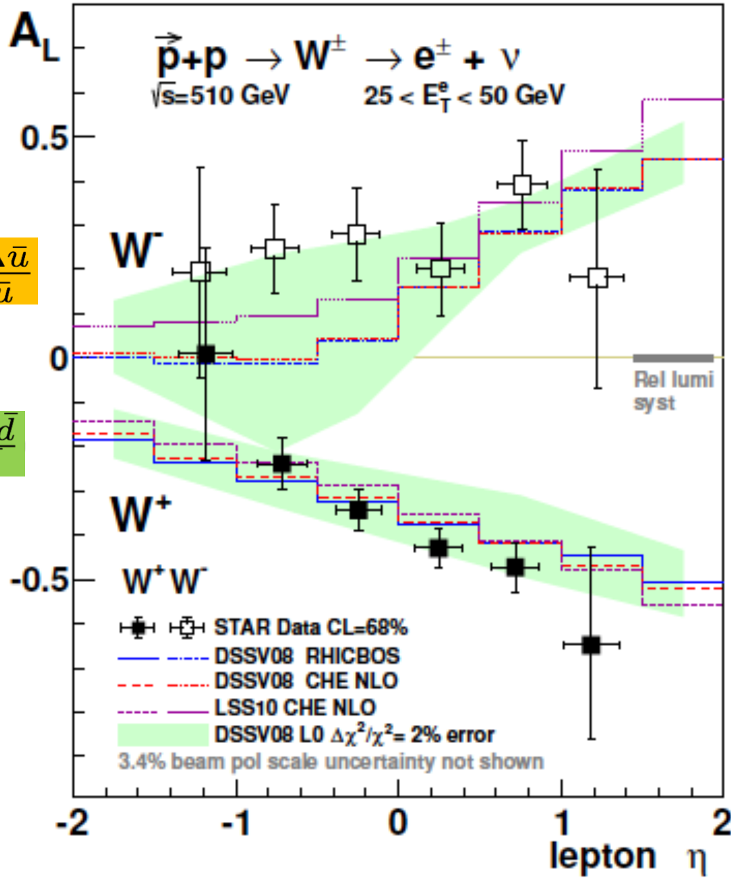
RHIC has unique access to flavor identified sea-quarks via real $W^{+/-}$

STAR: PRL 113, 072301 (2014)

Sea quarks

$A_L^{W^-} \sim \frac{\Delta \bar{u}}{\bar{u}}$

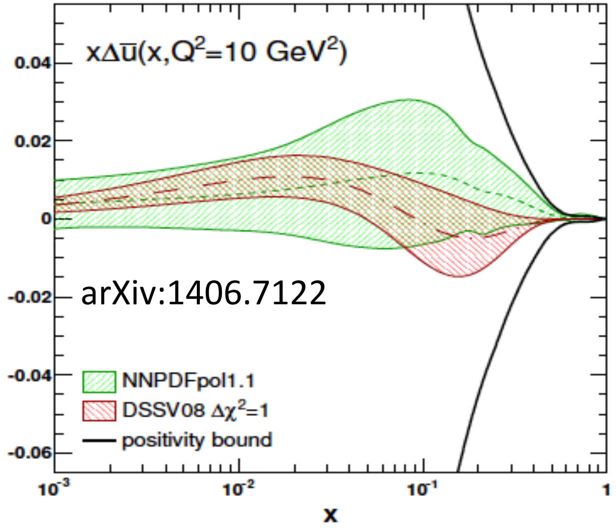
$A_L^{W^+} \sim \frac{\Delta \bar{d}}{\bar{d}}$

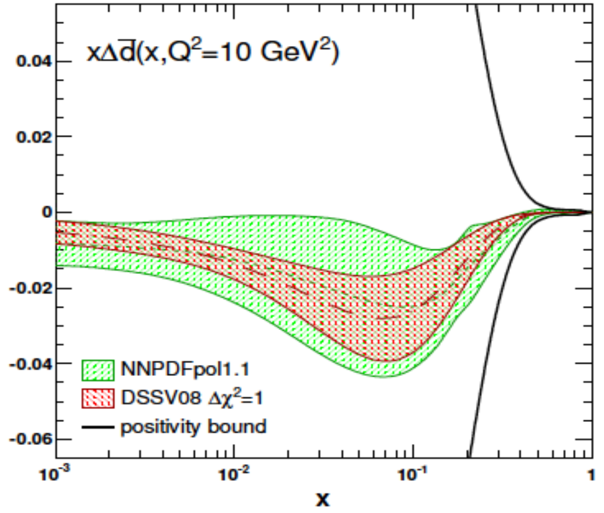


Valence quarks

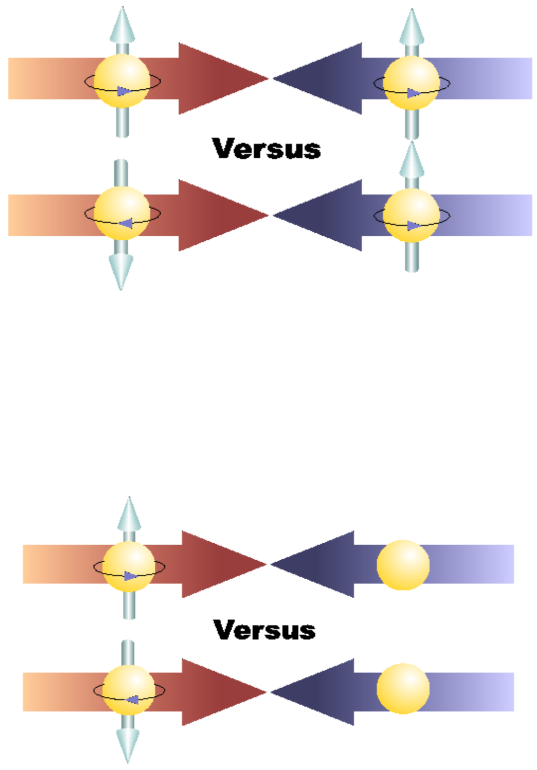
$A_L^{W^-} \sim -\frac{\Delta d}{d}$

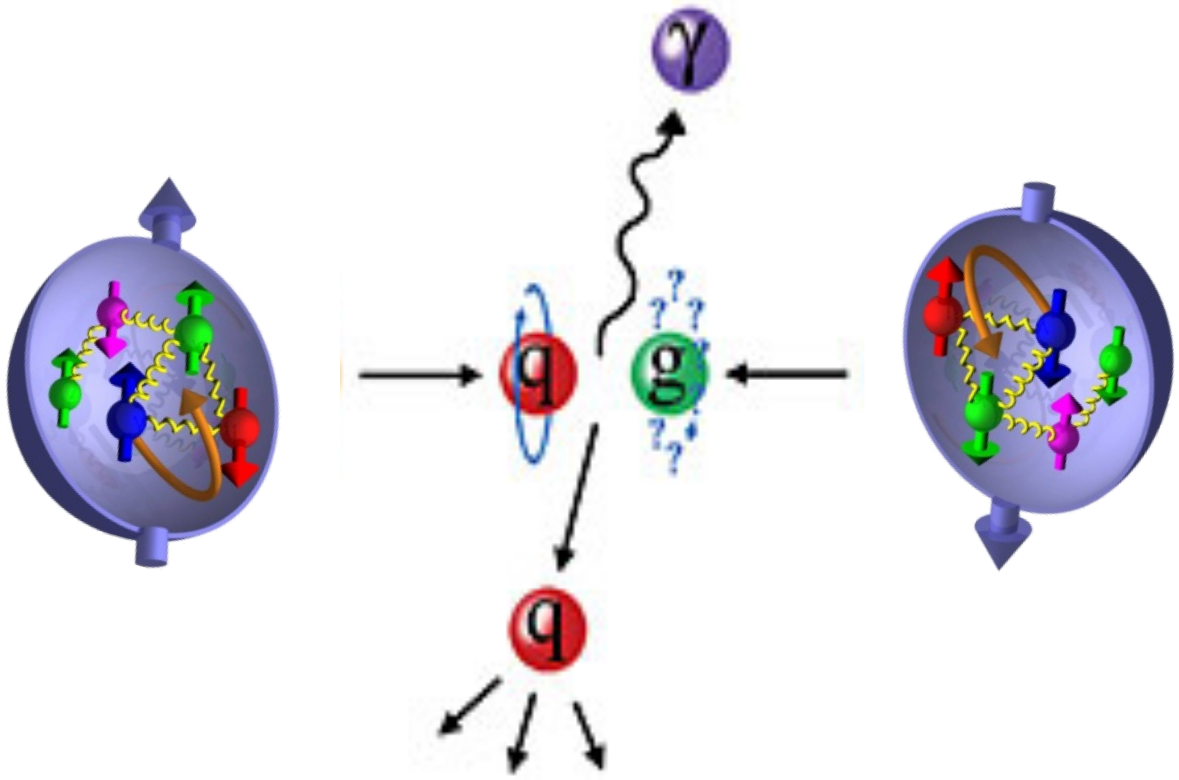
$A_L^{W^+} \sim -\frac{\Delta u}{u}$





Physics with Transversely Polarized p+p Collisions at RHIC

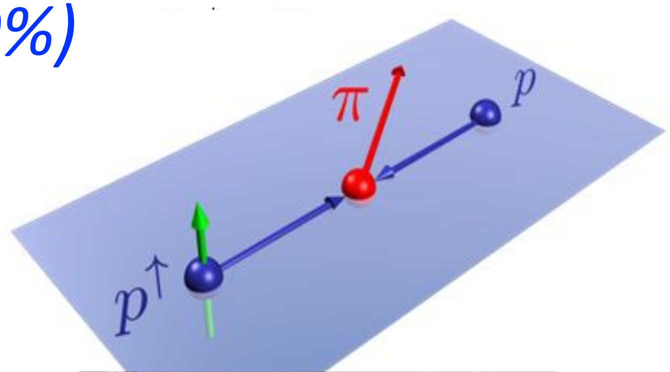




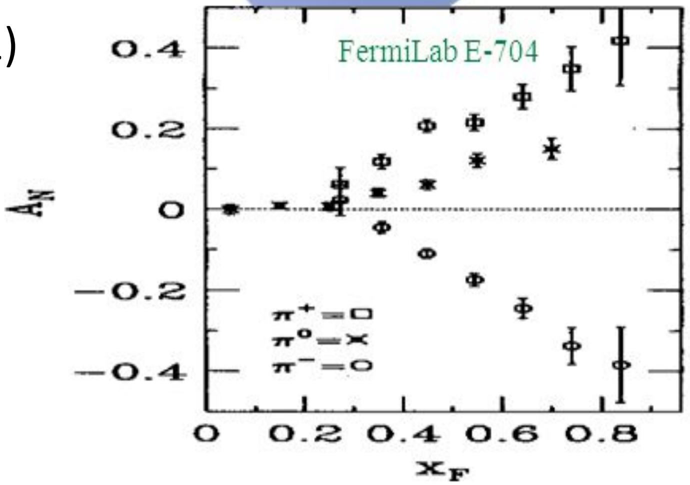
Part-II: The Challenge of "Too Large"

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

$A_N \sim O(10\%)$

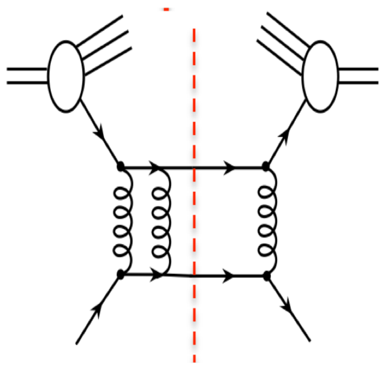


Fermilab
E704 (1991)



Kane, Pumplin, Repko (1978)

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



$$\propto \alpha_s \frac{m_q}{p_T}$$

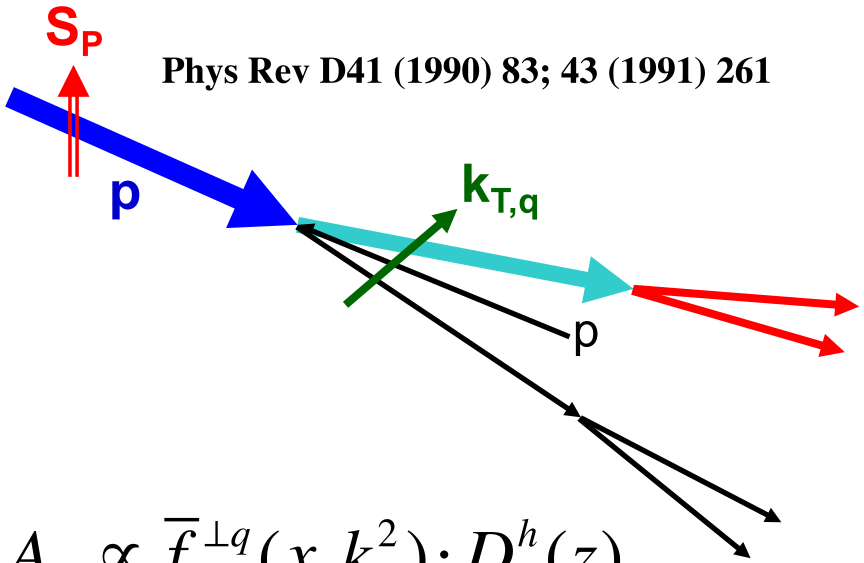
$$A_N^{(pred.)} \sim 0$$

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

(i) Sivers mechanism:

correlation proton spin & parton k_T

Phys Rev D41 (1990) 83; 43 (1991) 261

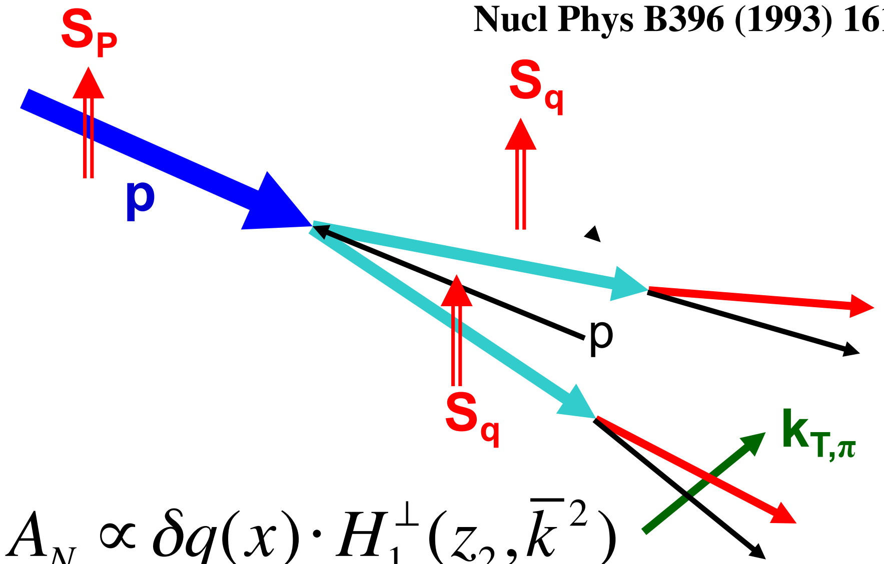


$$A_N \propto \overline{f}_{1T}^{\perp q}(x,k_\perp^2)\cdot D_q^h(z)$$

(ii) Collins mechanism:

Transversity × spin-dep fragmentation

Nucl Phys B396 (1993) 161



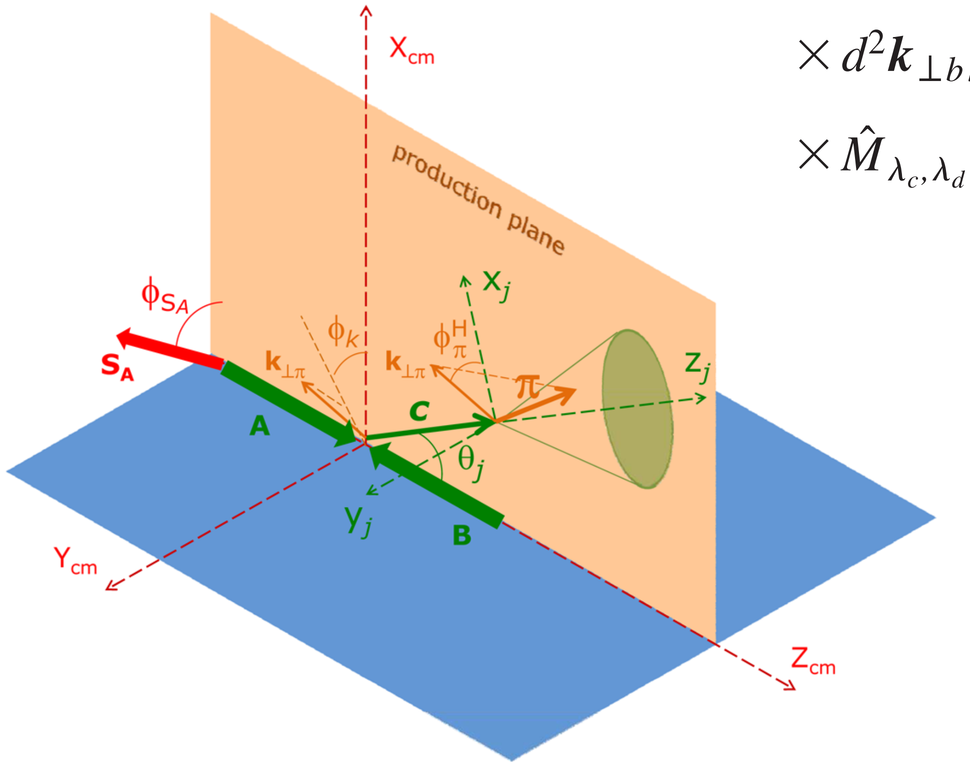
$$A_N \propto \delta q(x)\cdot H_1^{\perp}(z_2,\overline{k}_\perp^2)$$

Collinear Twist-3 (RHIC):

quark-gluon/gluon-gluon correlation

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

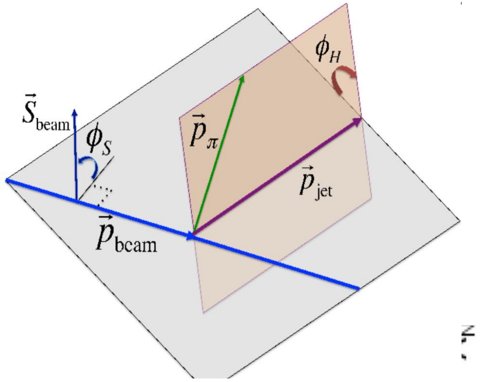
$A_N^{\sin\phi_{S_A}}$ → "Sivers-like"

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

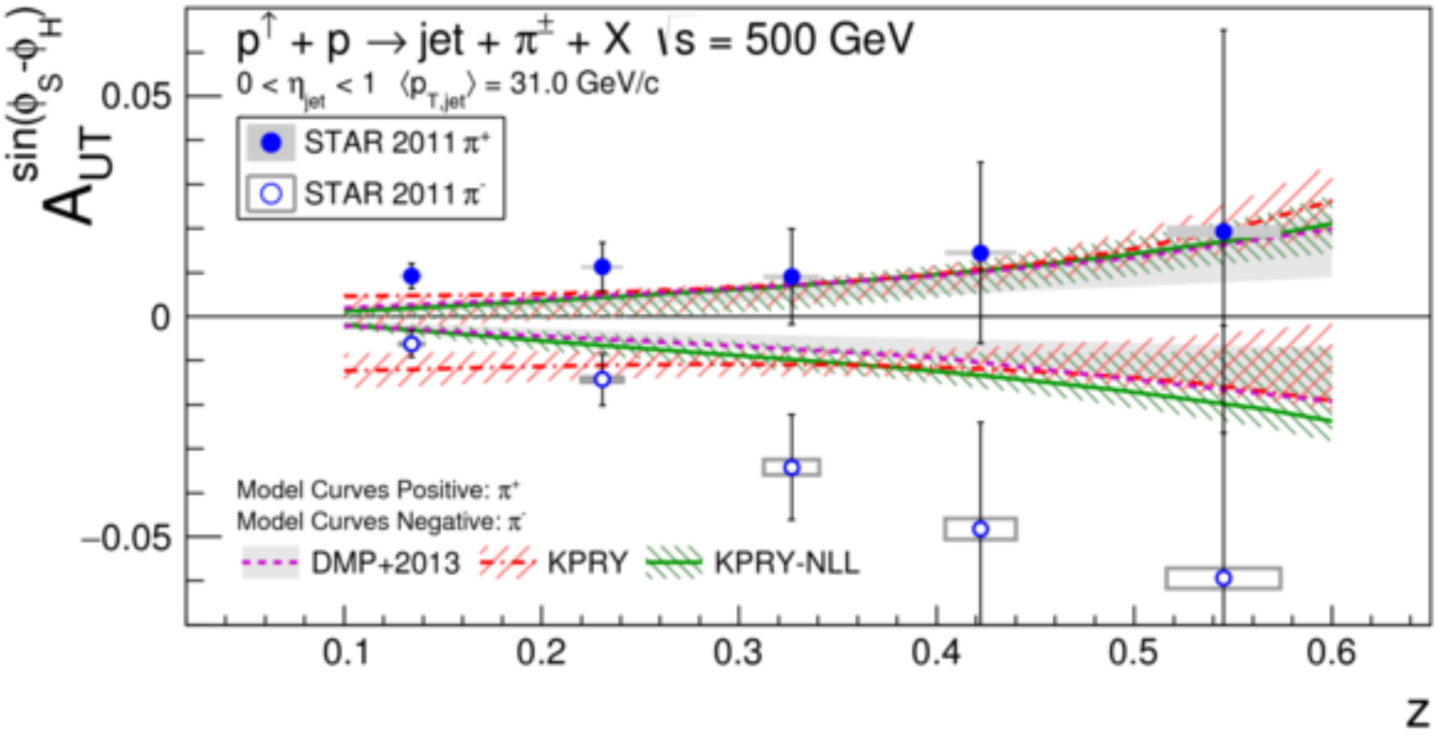
Collins Asymmetry in Jet

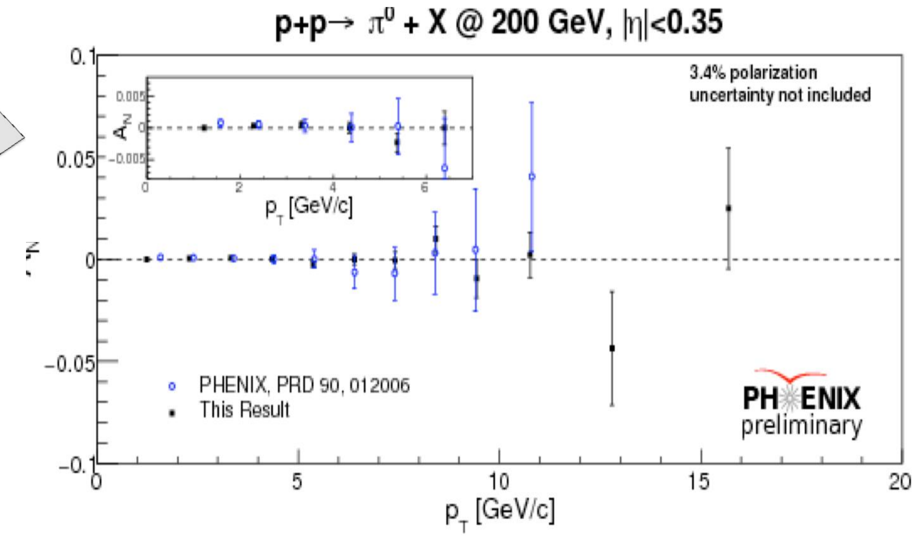
Inclusive A_N = 0 at central rapidity

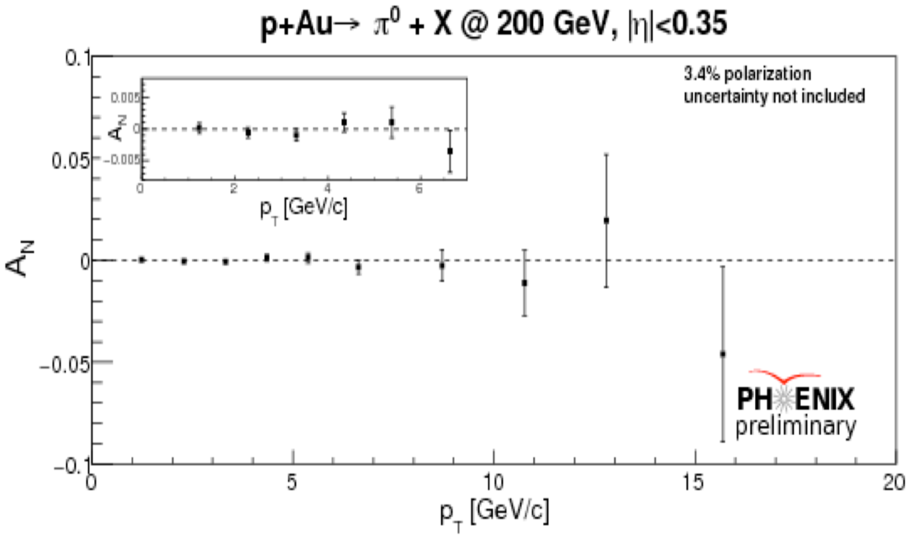
A_N at central rapidity: non-zero in jet!



Phys.Rev. D97, 032004 (2018)



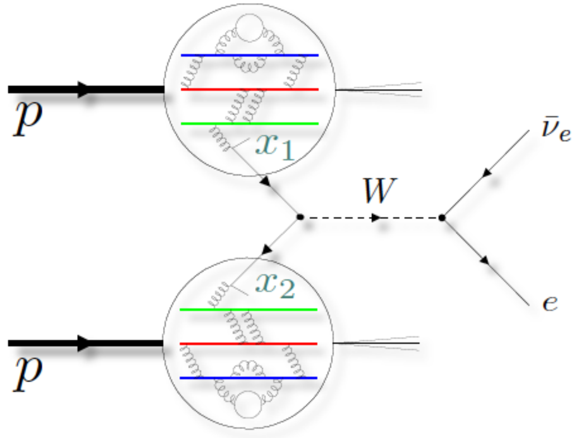




Sivers Asymmetry

- non-Universality, process dependent

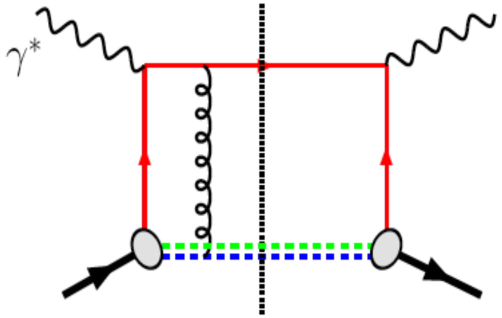
- Sign change prediction
- Drell-Yan and W/Z in p+p



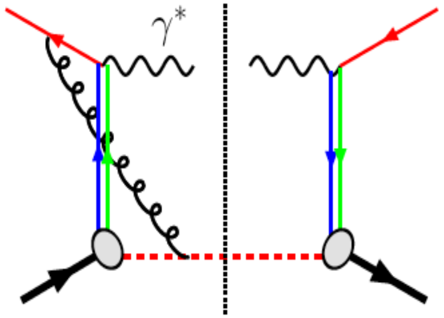
Phys. Rev. Lett. 116, 132301 (2016)

Comparison with Phys. Rev. Lett. 103, 172001

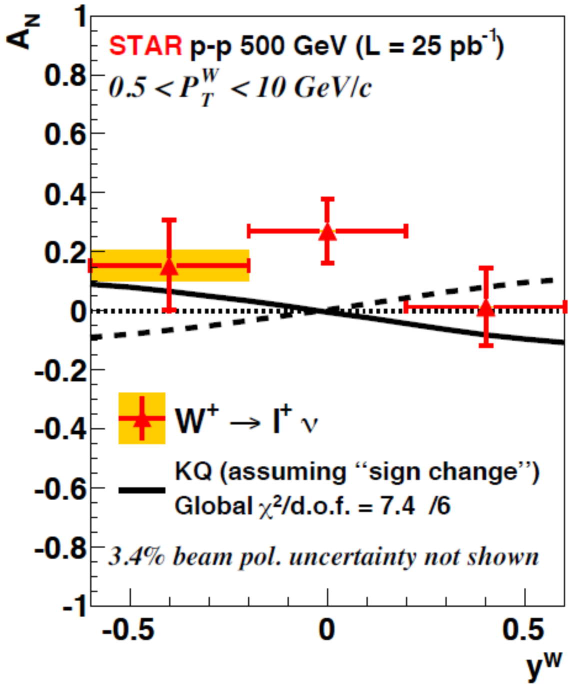
DIS: attractive

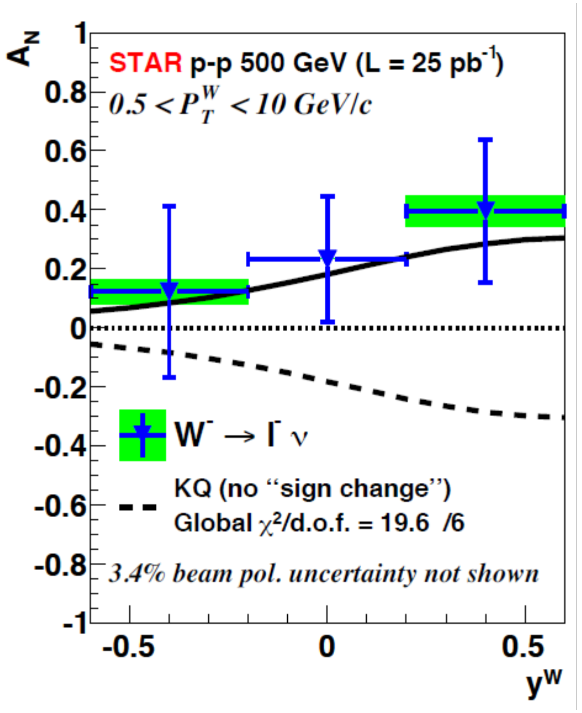


Drell-Yan: repulsive



$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

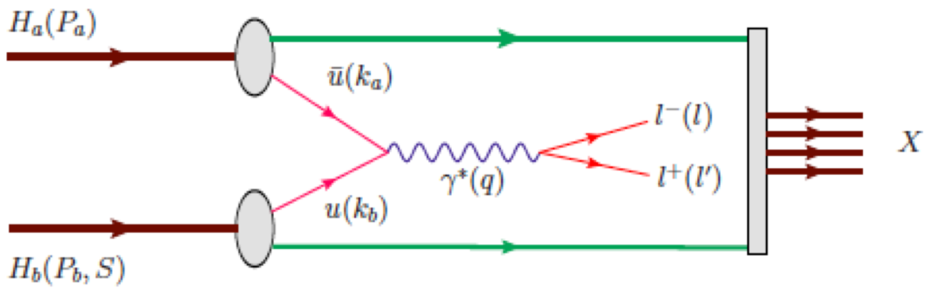




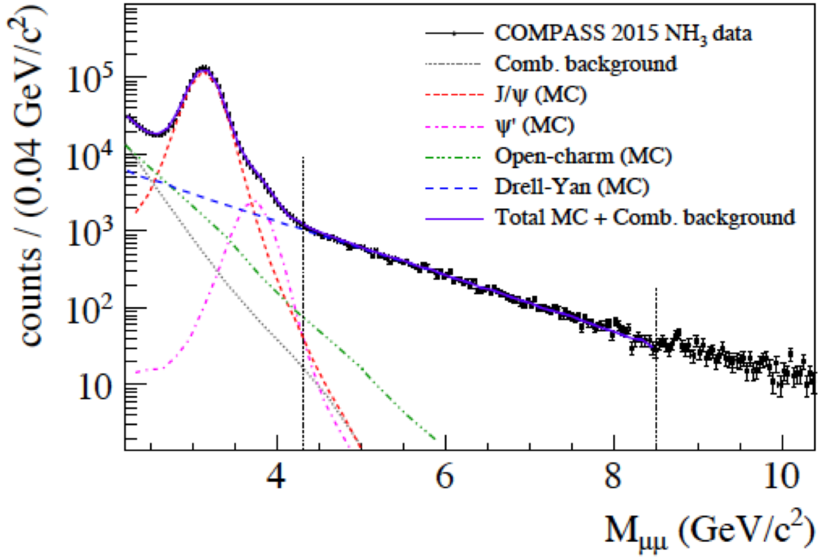
Drell-Yan from COMPASS Polarized Target

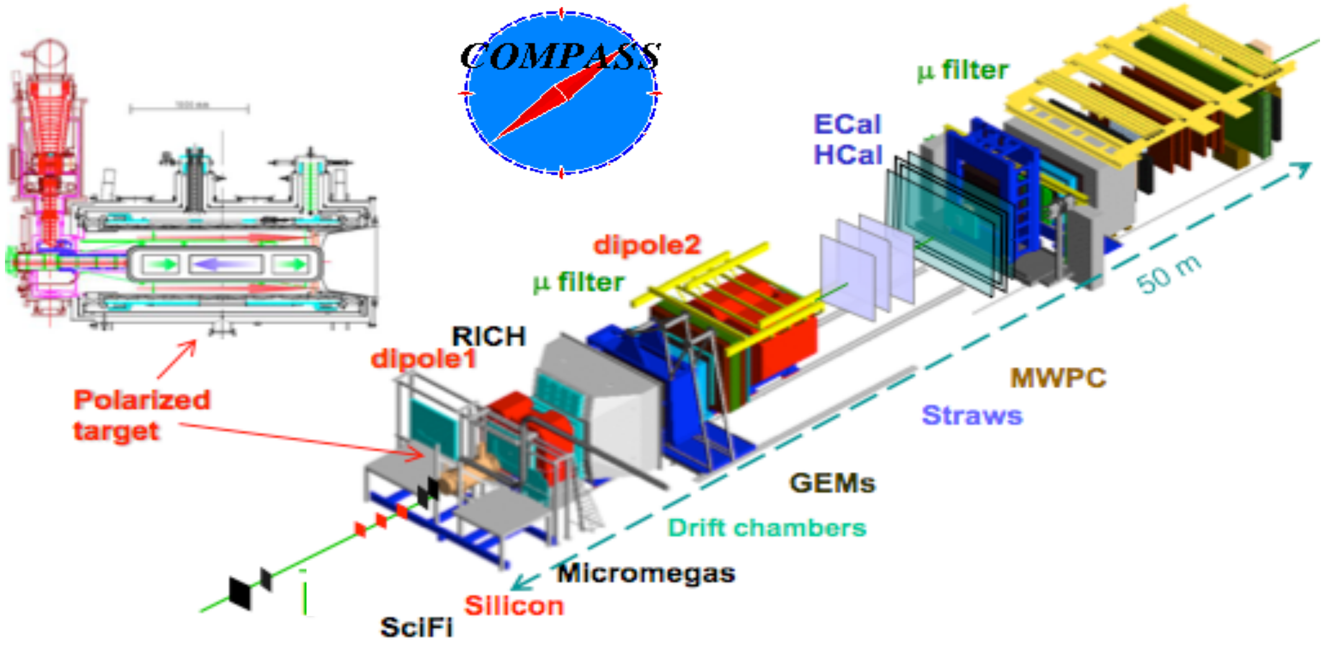
Beam: pi-

Polarized
Proton target



- J/ψ (NH_3) **~ 1.5M**
- HM DY (NH_3) **~40K**

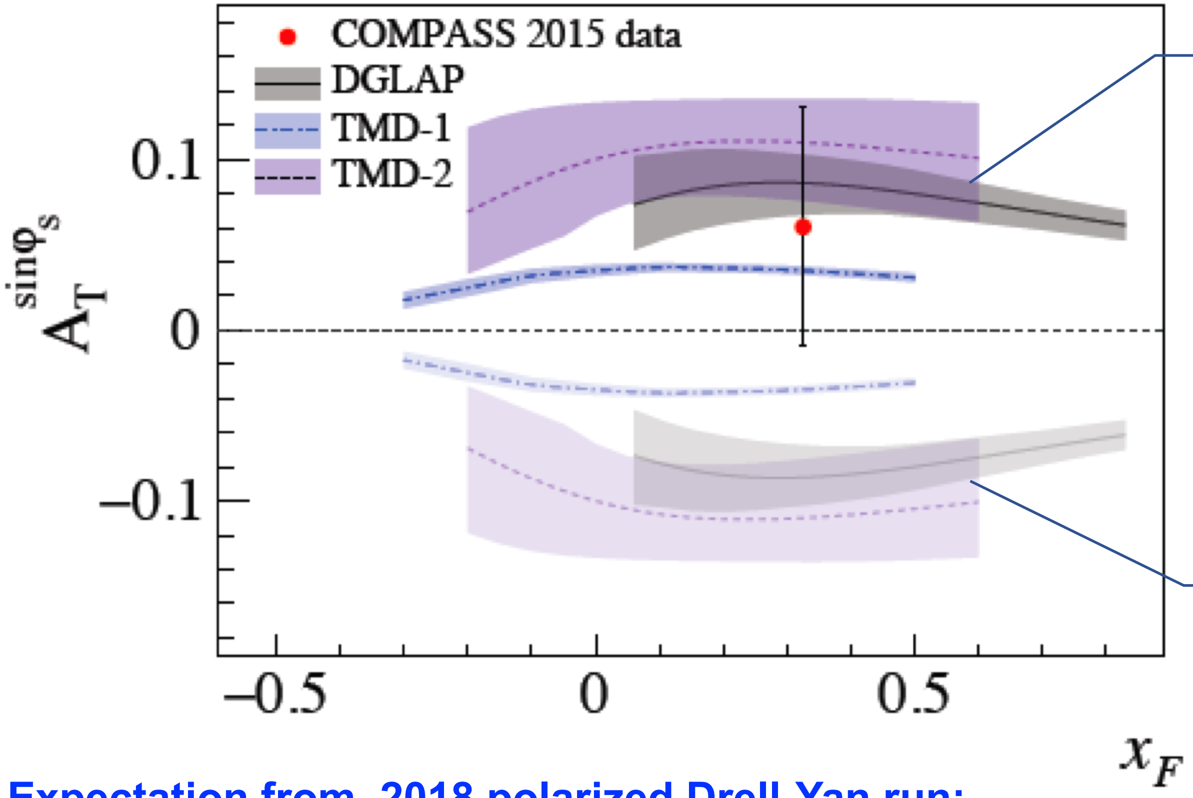




COMPASS Drell-Yan Run 2015 results

PRL 119, 112002 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

First Measurement of Transverse-Spin-Dependent Azimuthal Asymmetries in the Drell-Yan Process

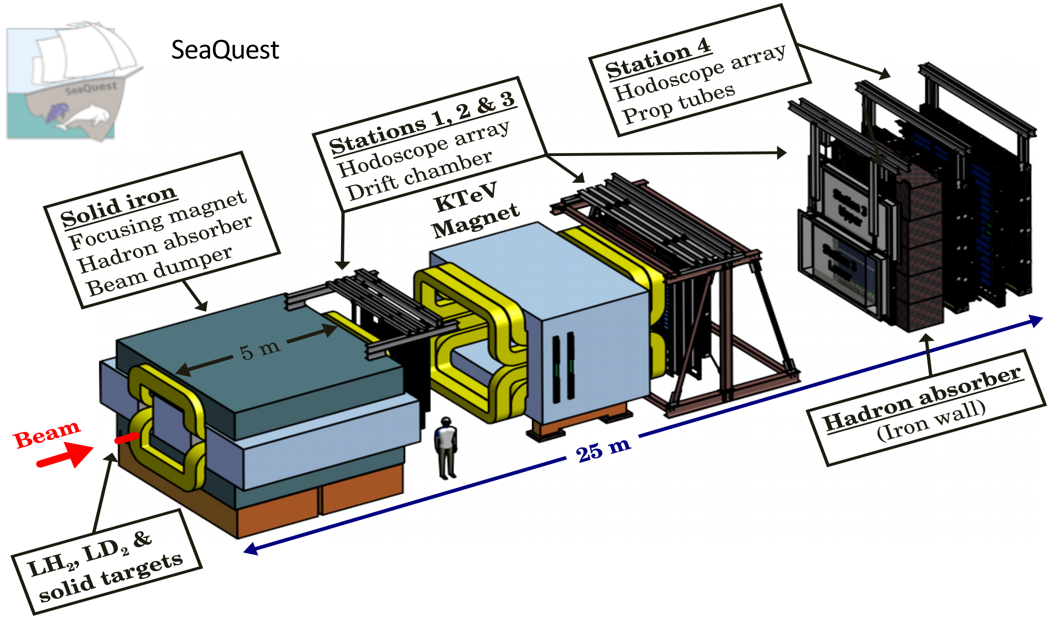


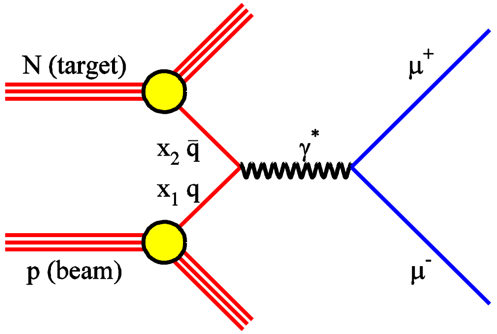
Sign change

NO Sign change

Expectation from 2018 polarized Drell-Yan run:
Unambiguous verification of the Sivers asymmetry sign change by reducing of the statistical error on Sivers TSA by a factor of ~2.

Drell-Yan @SeaQuest Fixed Target

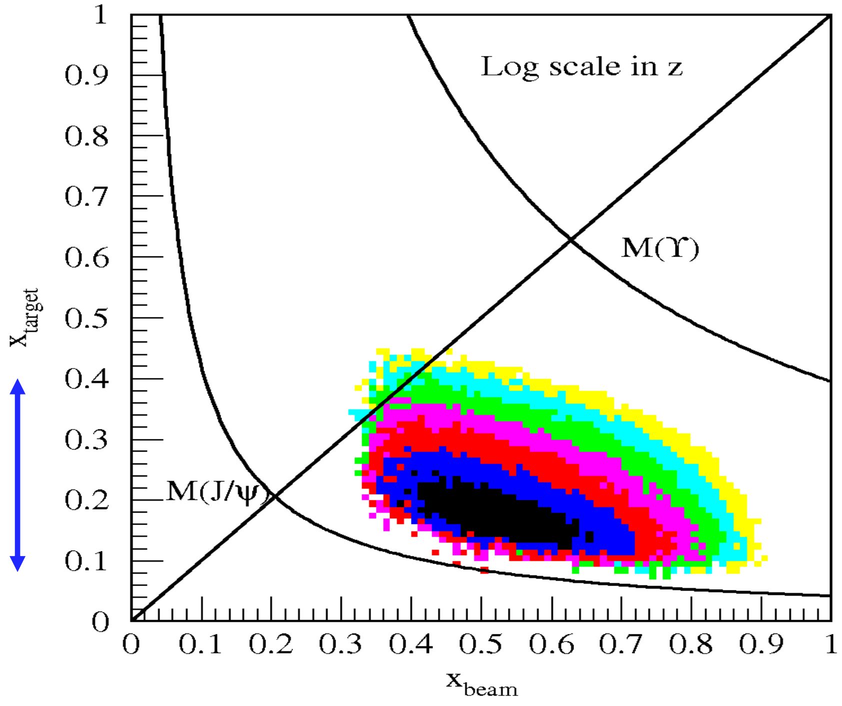




$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\underline{\bar{q}_t(x_t)} + \cancel{\bar{q}_b(x_b)q(x_t)}]$$

$$\approx \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q_b(x_b)\underline{\bar{q}_t(x_t)}]$$

SeaQuest



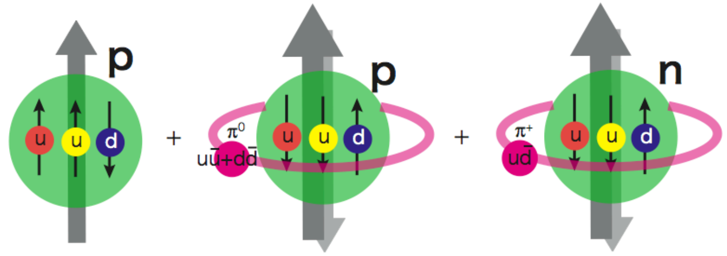
Kinematically favors sea-quarks from target – **a sea quark lab!**

Flavor Asymmetry of Sea Quarks at Intermediate x

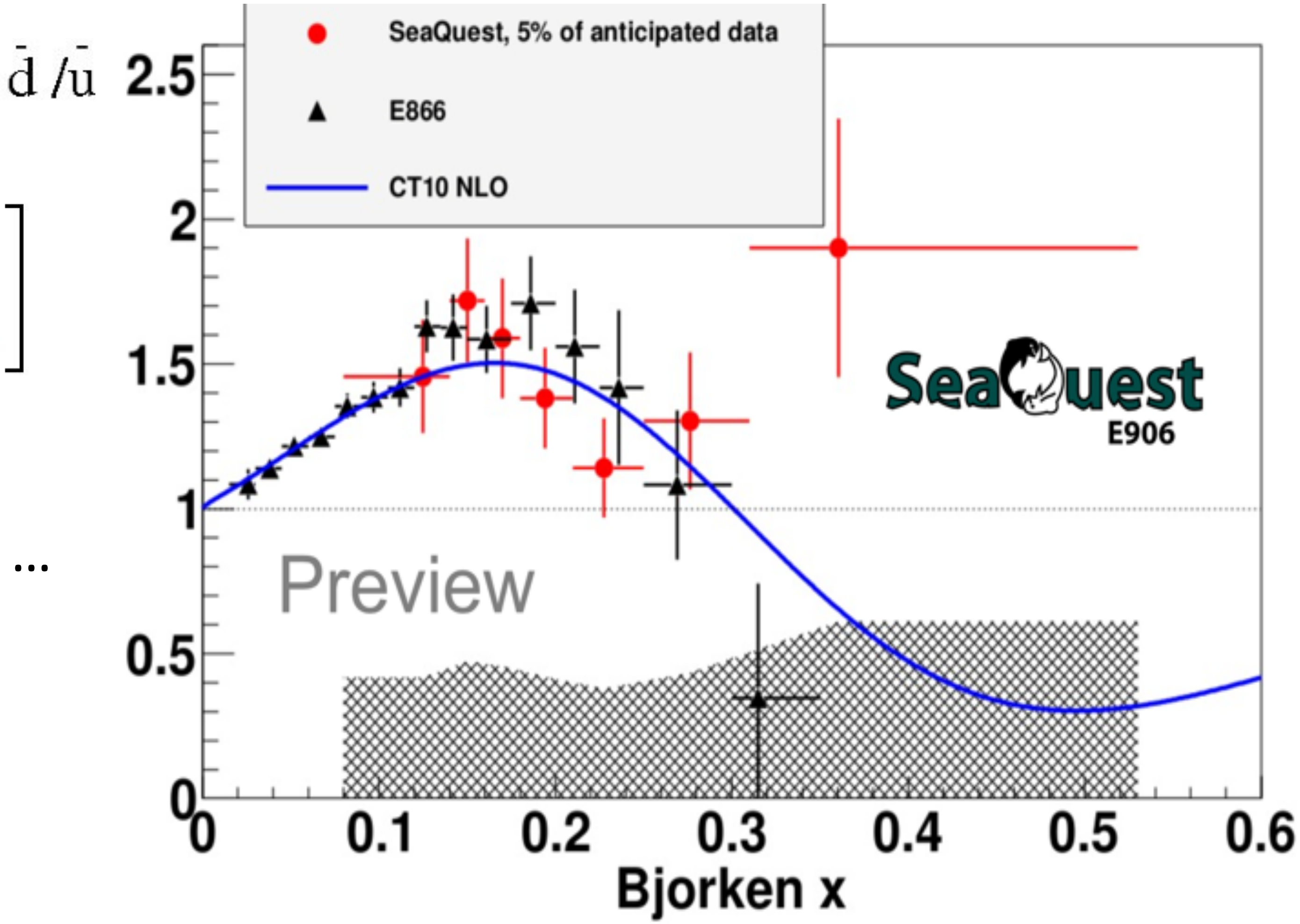
Proton vs “Neutron” targets:

$$\left.\frac{\sigma^{pd\to\mu^+\mu^-}}{\sigma^{pp\to\mu^+\mu^-}}\right|_{x_{\rm b}\gg x_{\rm t}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{\rm t})}{\bar{u}(x_{\rm t})}\right]$$

This could lead to a very interesting physics …

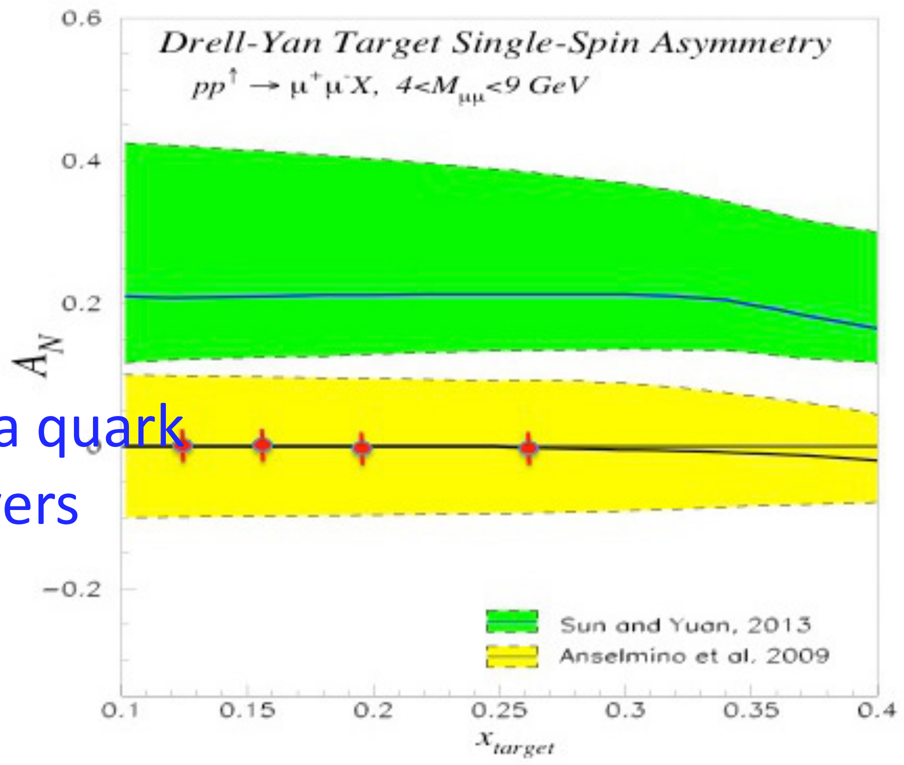


$|p\rangle = a|p_0\rangle + b|p_0 + pi^0\rangle + c|n+pi^+\rangle + \ldots$

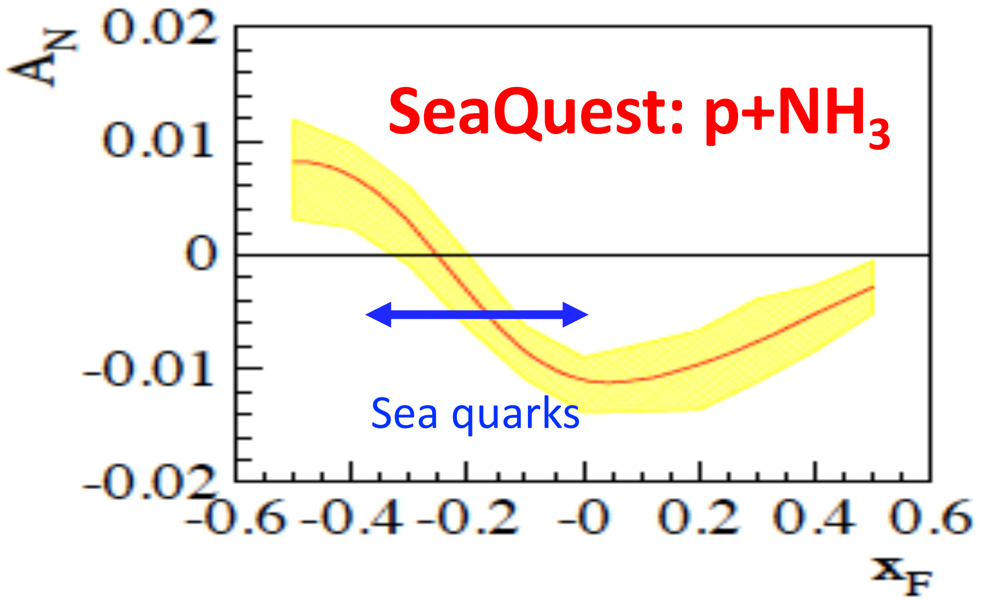


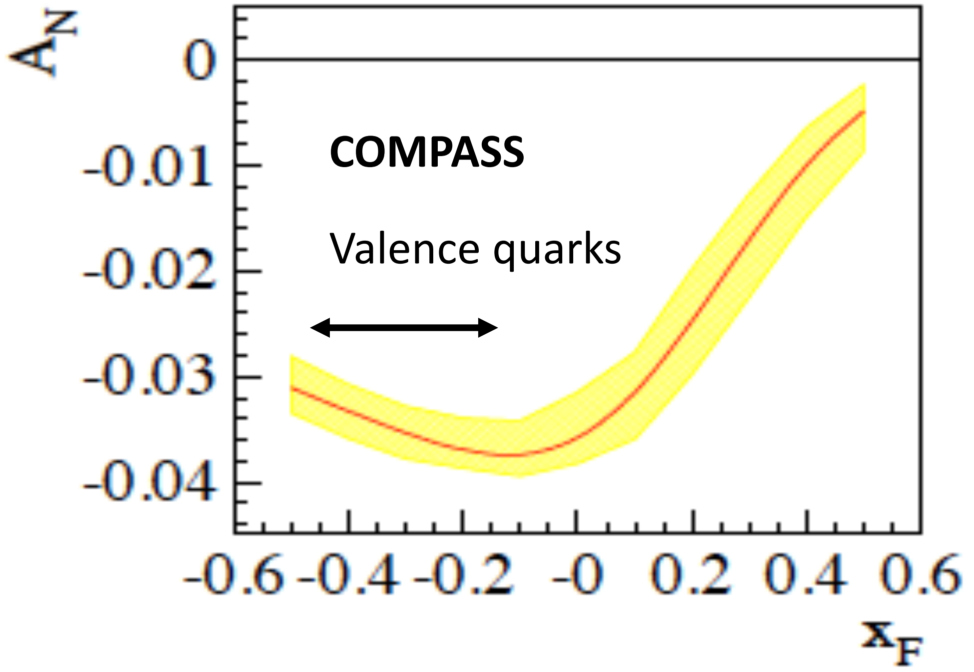
Projected Drell-Yan A_N

$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$



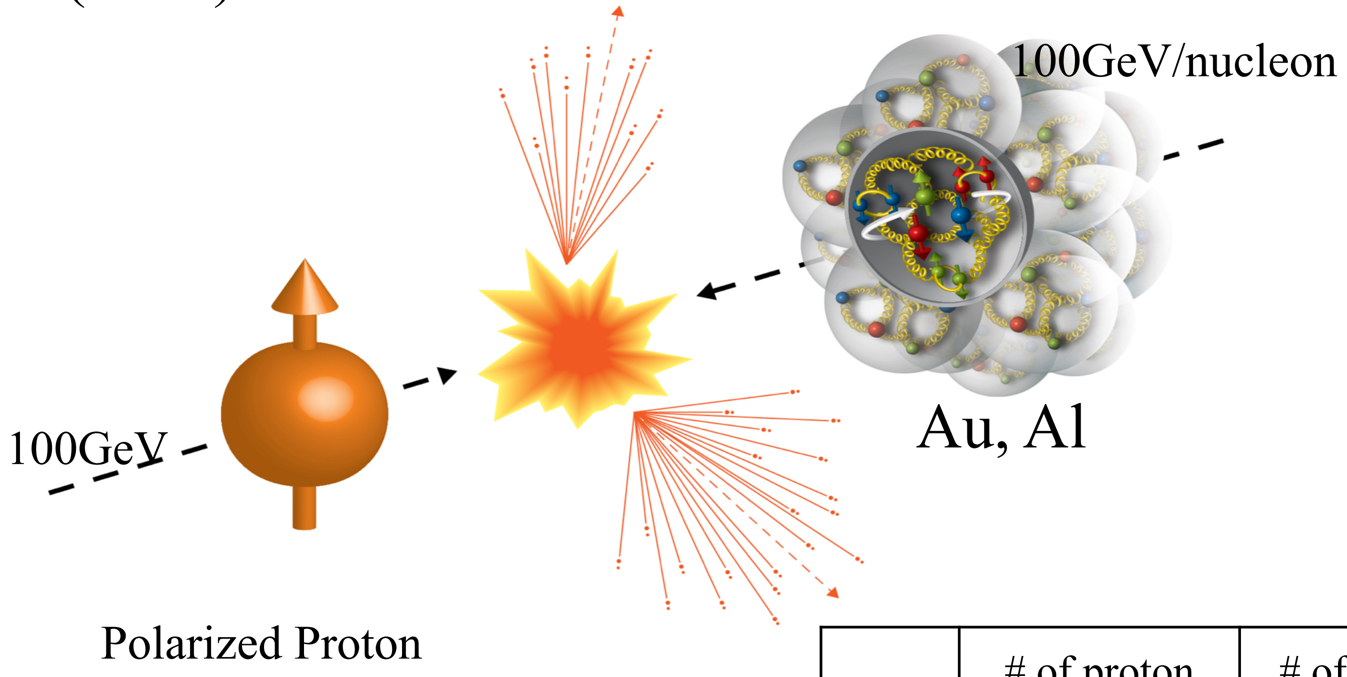
Sea quark
Sivers





First Polarized p+A at RHIC

Run15 (2015)

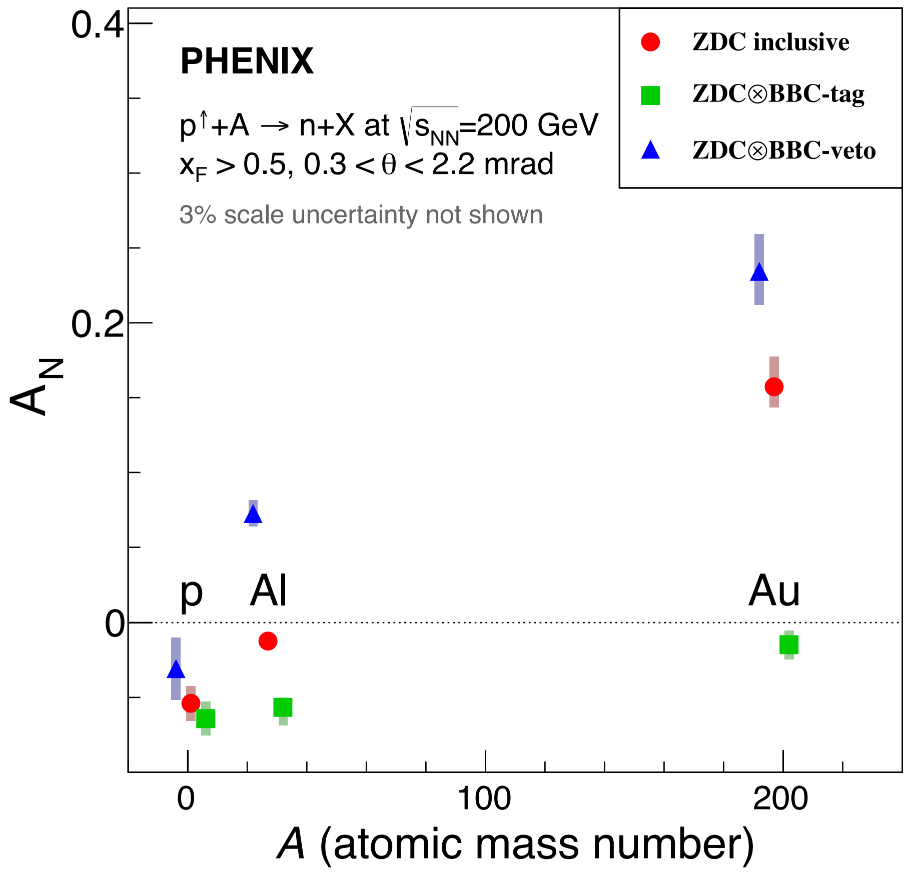


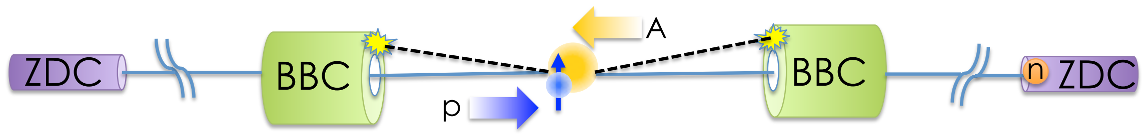
	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

Run15 p+Au: a Surprise!

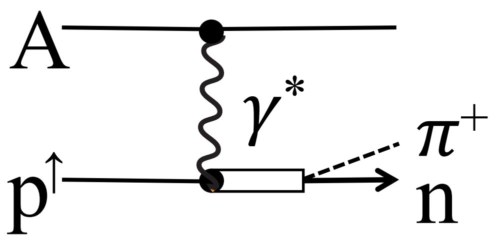
Unexpected pAu and pAl asymmetries observed compared to that of pp

[PRL 120 (2018) 022001]



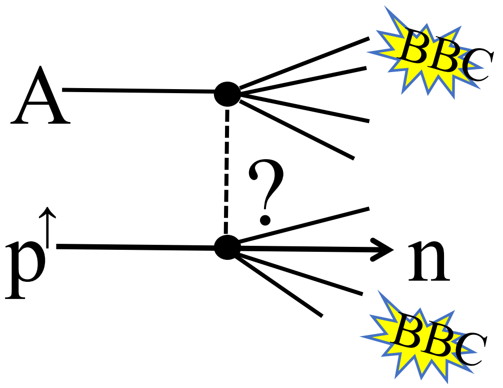


BBC Veto



$A_N > 0$

BBC Tag

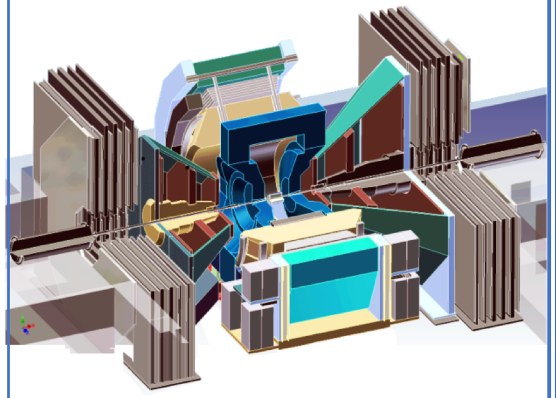


$A_N < 0$

Future at RHIC: PHENIX -> sPHENIX -> EIC@RHIC

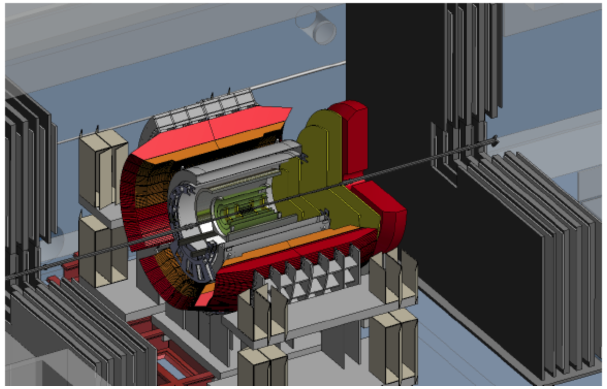
Current PHENIX

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



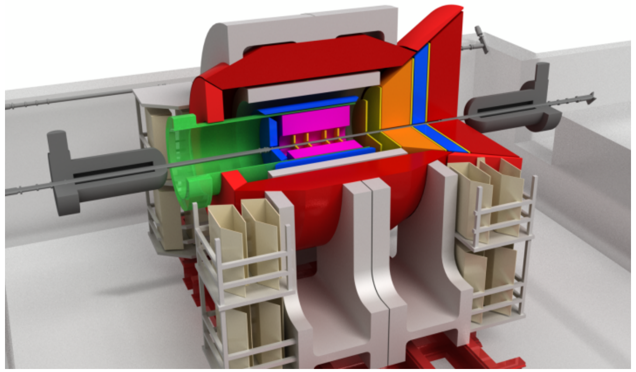
Forward sPHENIX

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



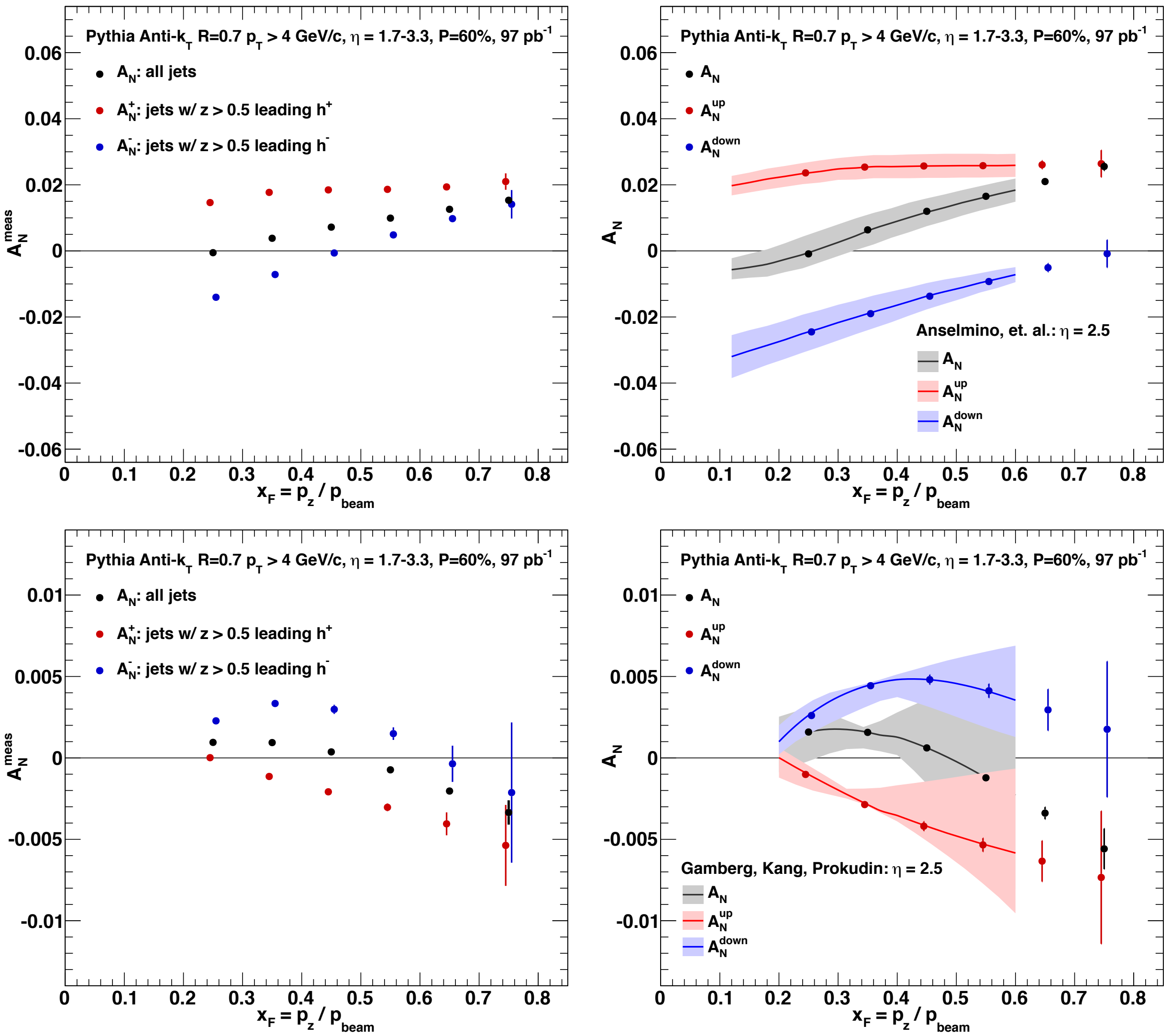
~2000 2017→2020 ~2025 Time

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

eRHIC: e+p, e+A

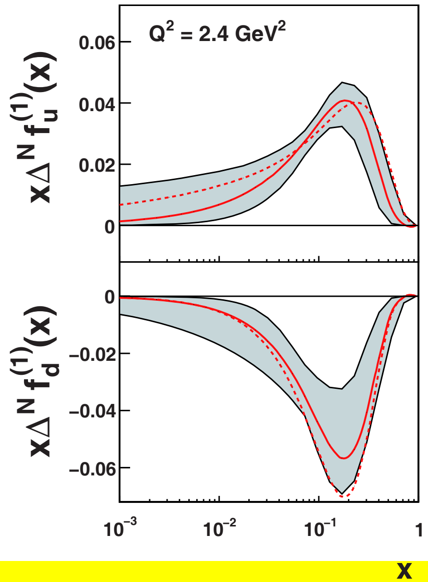
Forward sPHENIX Projected Jet Sivers Asymmetries

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



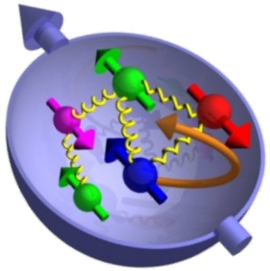
Naïve direct mapping from SIDIS Sivers (GPM)
- “u-quark jet” $A_N > 0$

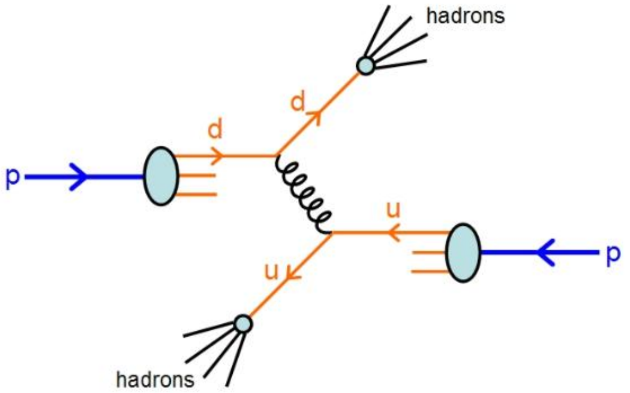
Sivers, SIDIS fit



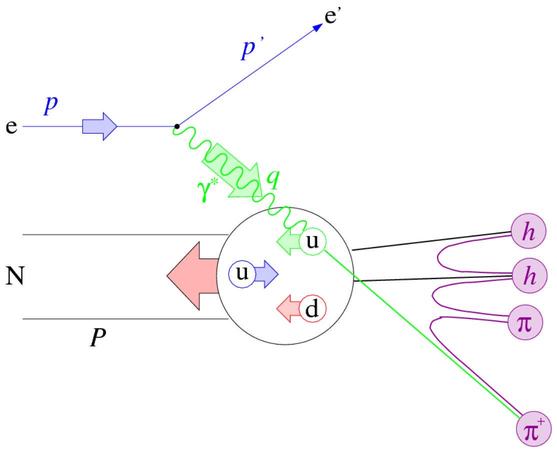
With process-dep from SIDIS Sivers (Twist-3)
- “u-quark jet” $A_N < 0$

Summary



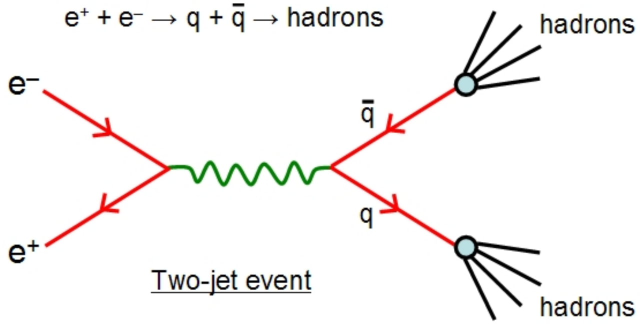


- QCD has been very successful in consistently interpreting and predicting high energy phenomena in
  - DIS vs p+p
  - Unified partonic description of nucleon structures and interactions



- Proton/Hadron collisions
  - Versatile physics program
  - Access a broad (x,Q^2) range

- Will continue playing a key role in exploring the fundamental nature of nucleon structure and strong interactions
  - Need all three experimental tools to complete the program
    - p+p, DIS, e^+e^-



Complementary test and validation of QCD description of hard processes

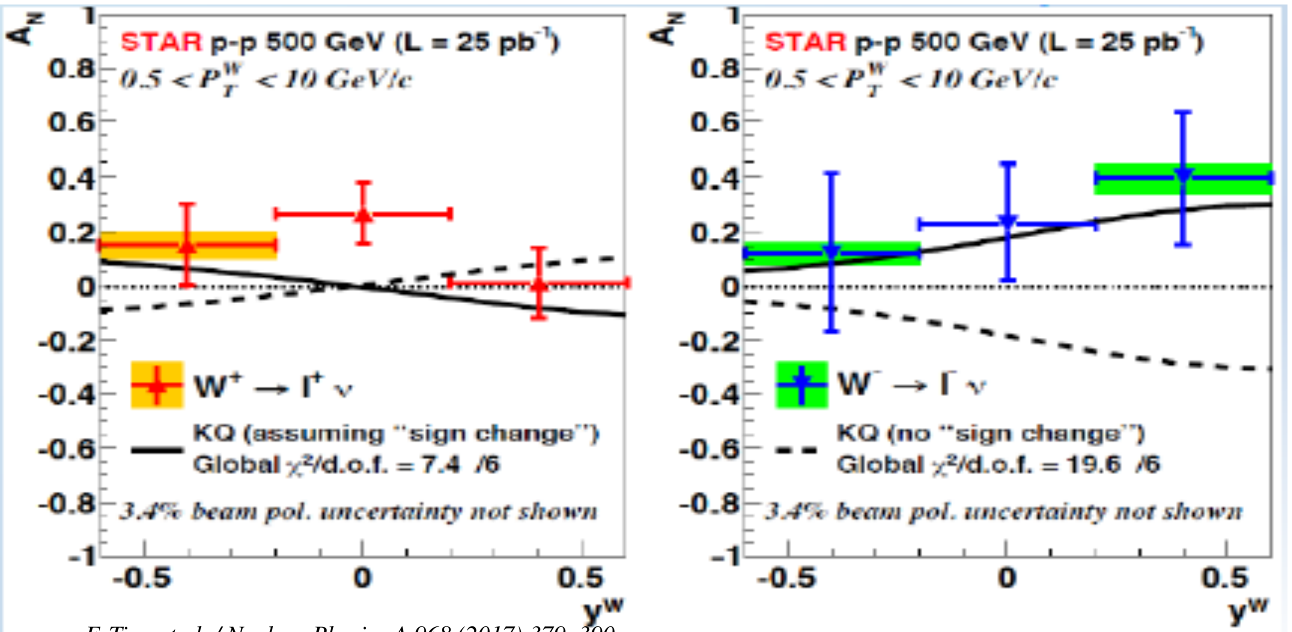
backup

Anselmino et al 2016

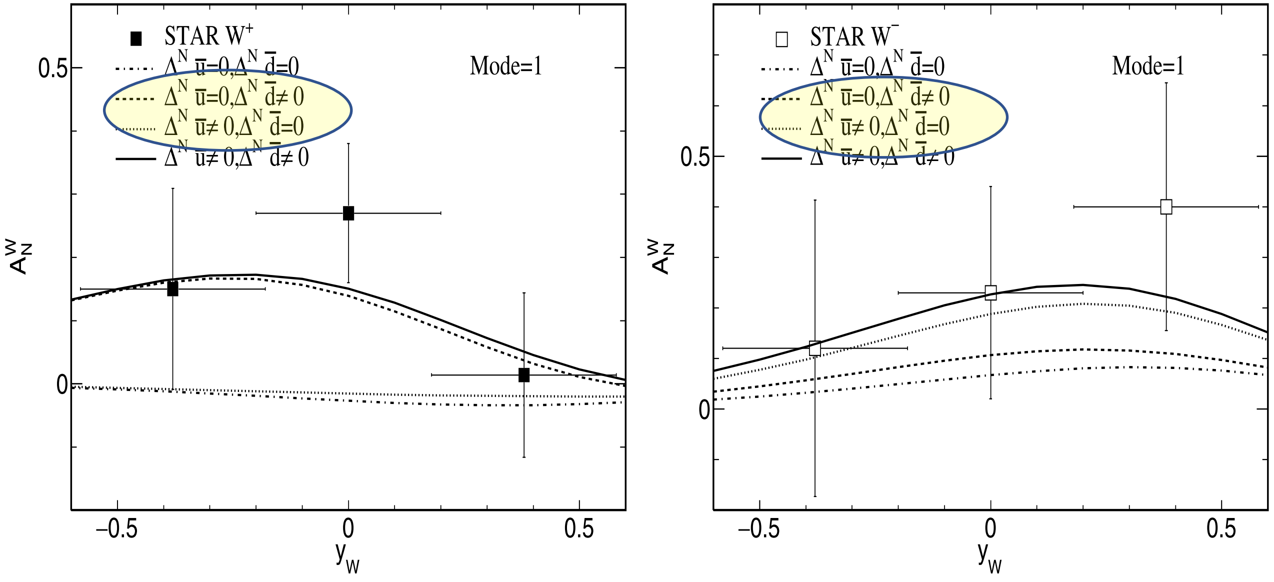
RHIC pp500GeV: $W^{+/-}$ A_N

$$A_N(W^+) \sim \left(\Delta^N f_{u/p^\uparrow} \otimes f_{\bar{d}/p} + \Delta^N f_{\bar{d}/p^\uparrow} \otimes f_{u/p}\right)$$

$$A_N(W^-) \sim \left(\Delta^N f_{\bar{u}/p^\uparrow} \otimes f_{d/p} + \Delta^N f_{d/p^\uparrow} \otimes f_{\bar{u}/p}\right)$$



F. Tian et al. / Nuclear Physics A 968 (2017) 379–390



(b) $A^N_{W^+}$.

(a) $A^N_{W^-}$.

RHIC data:

- A mix of valence and sea quark Sivers
- Quark flavor identified
- High Q^2
- Statistically limited, ~0(10%)
- **Possible large dbar Sivers contributions**

E1039:

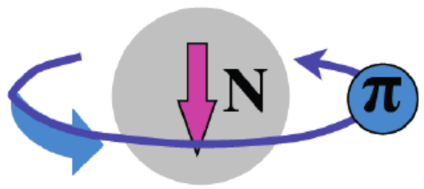
- low Q^2
- Good statistics, ~O(1%)

Unpolarized Sea Quark Distributions

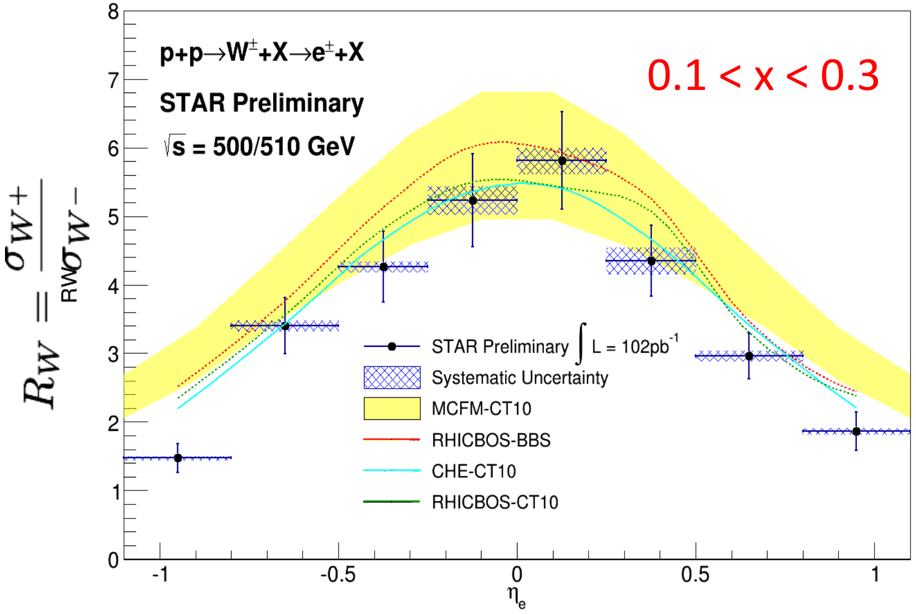
$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} =$$

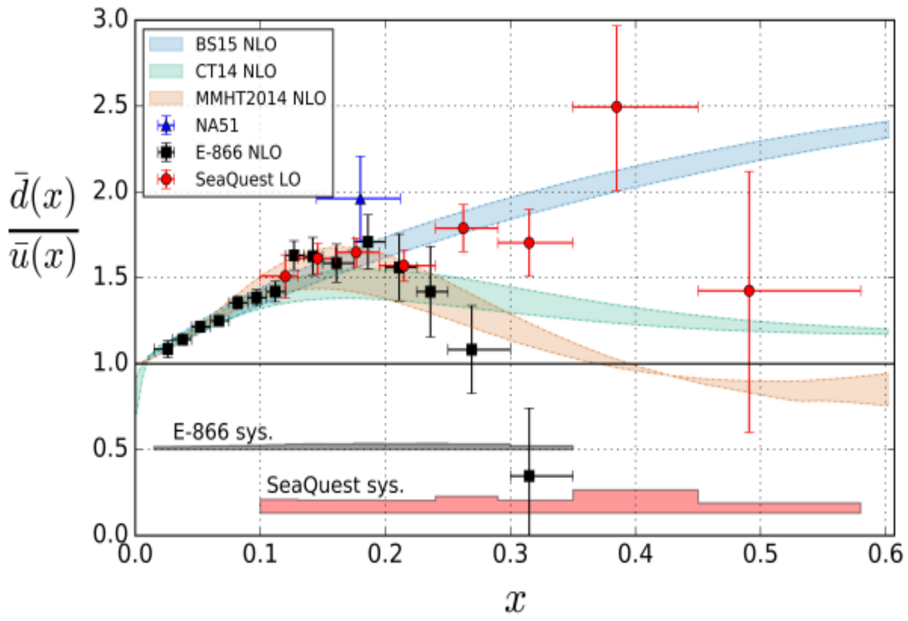
$$\frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

Sea quark flavor asymmetry and pion cloud model

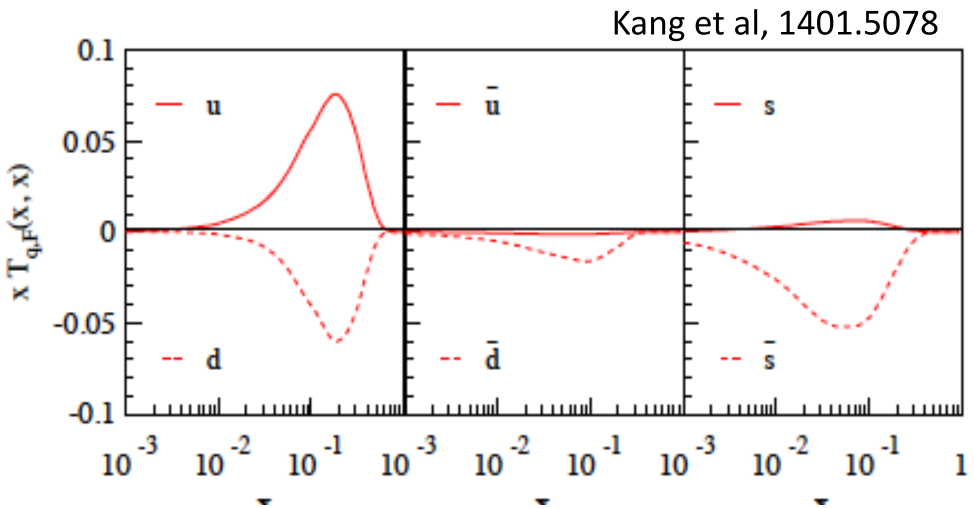


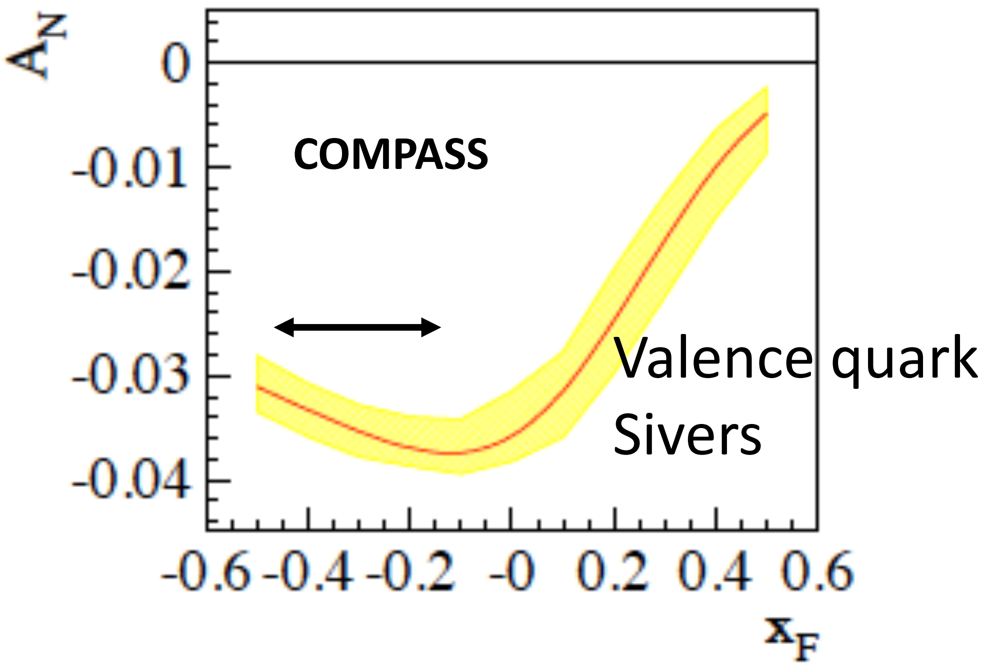
SeaQuest/E906 @Fermilab

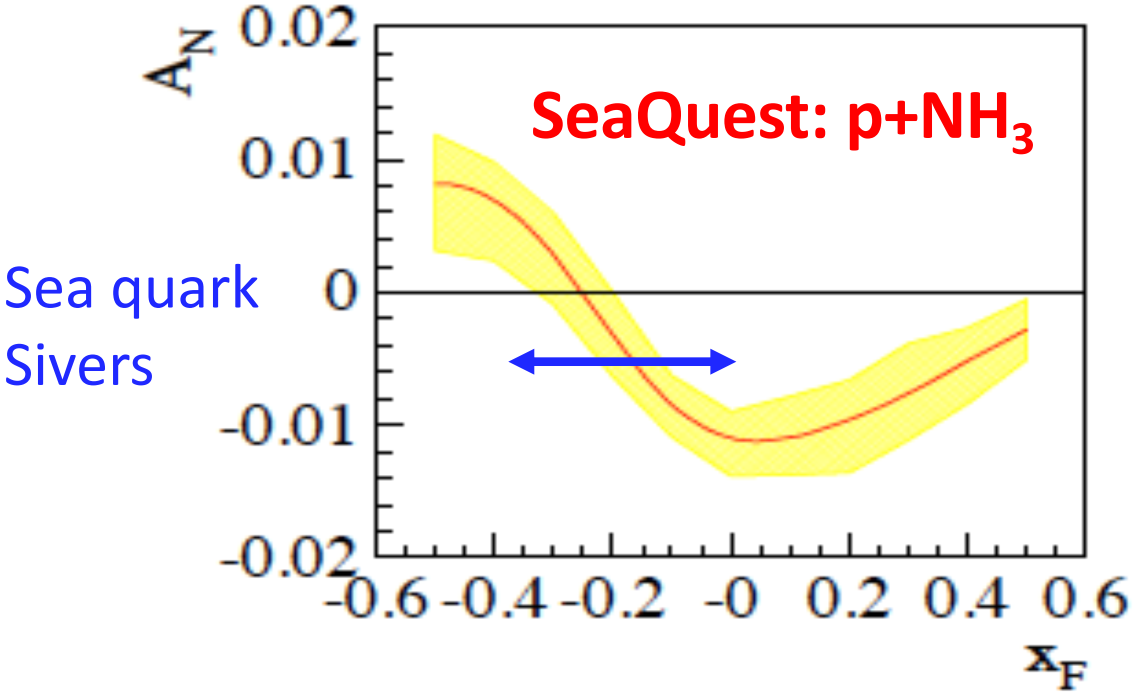


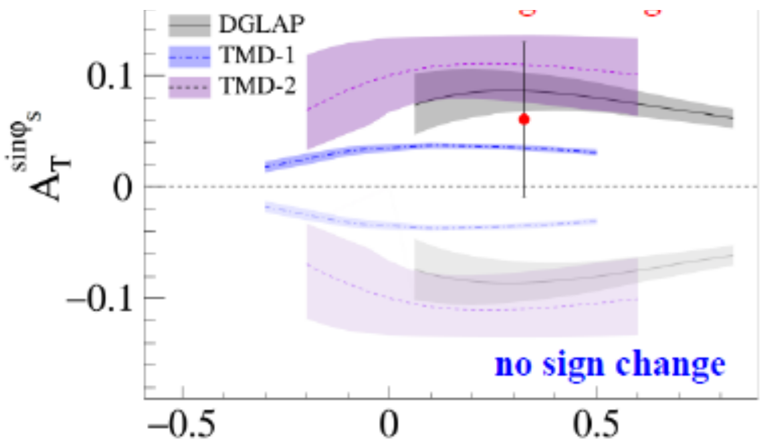


Drell-Yan Sivers Asymmetries w/ QCD Evolution





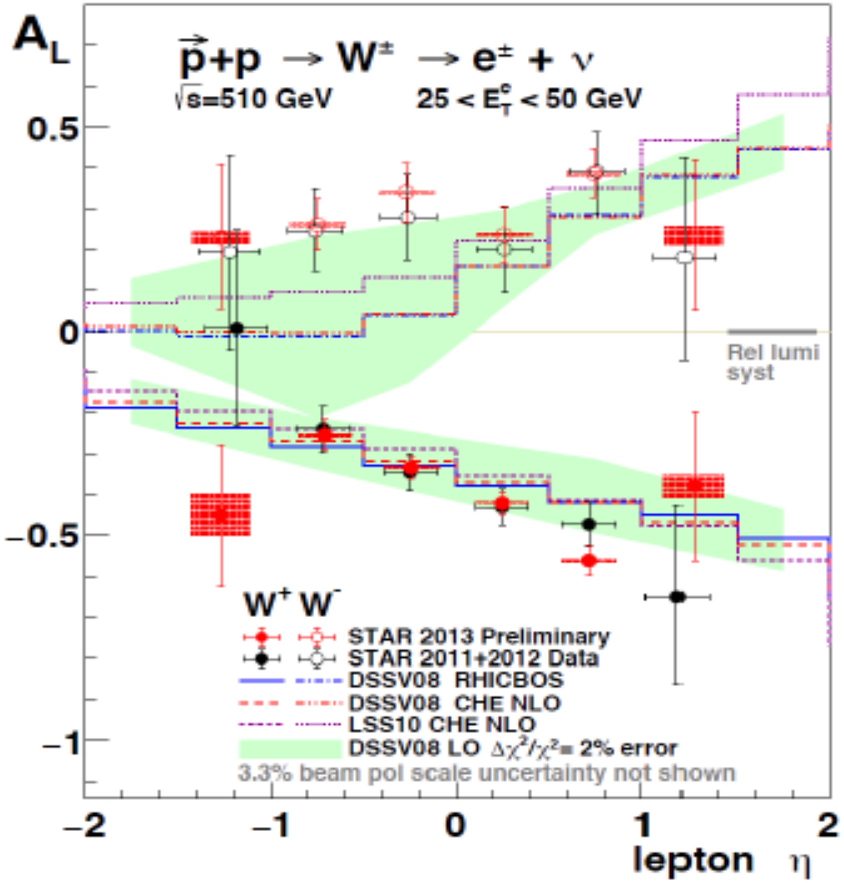




Latest $W^{+/-}$ A_L from STAR and PHENIX

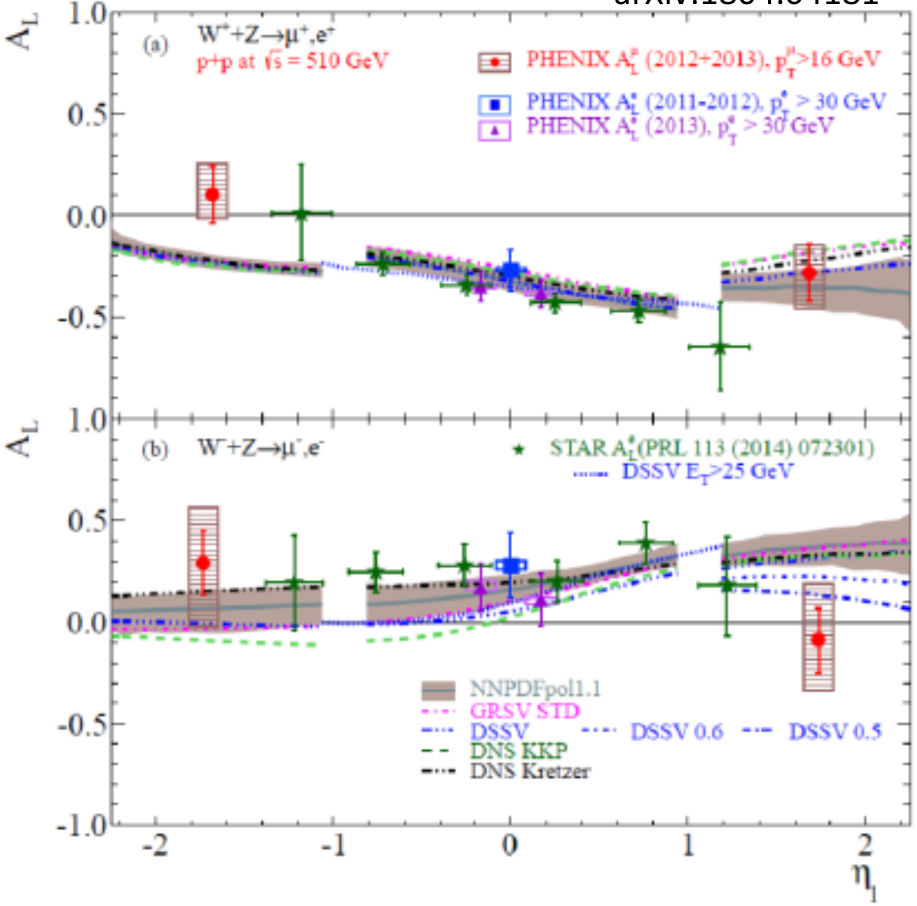
$p + p \rightarrow W^{\pm} \rightarrow e^{\pm}$

arXiv:1702.05077



$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm}$ $(e^{\pm})$

arXiv:1804.04181



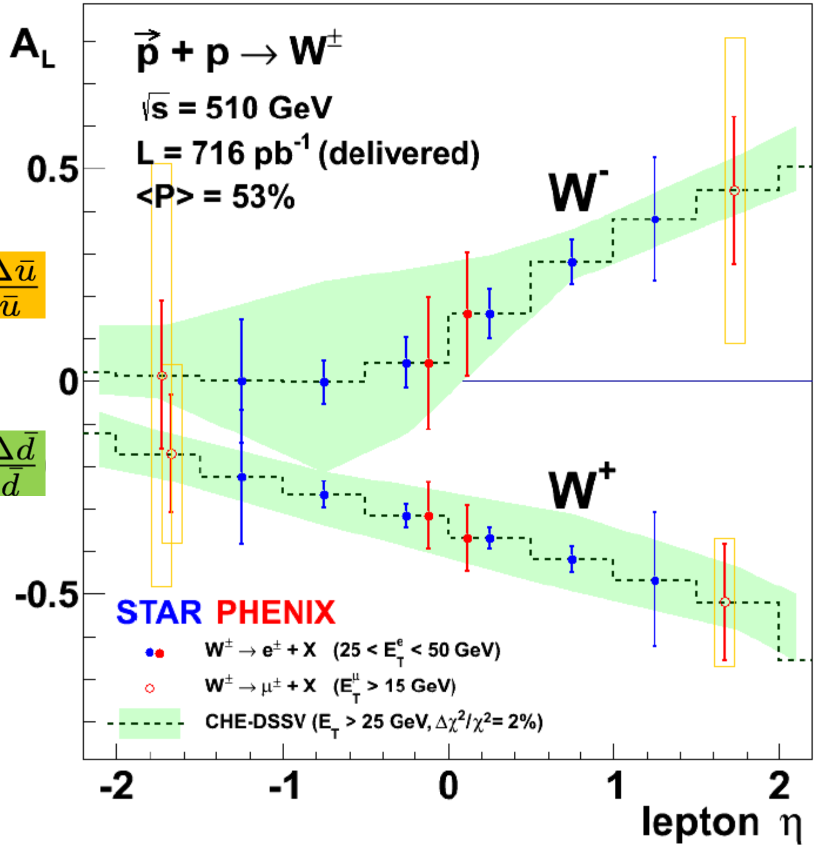
Projected RHIC $W^{\pm} \rightarrow l^{\pm}$ data Impact on Sea Quark Polarization Determination

- Expect significant improvement of flavor identified sea quark distributions

The RHIC Spin Program, arXiv: 1501.01220

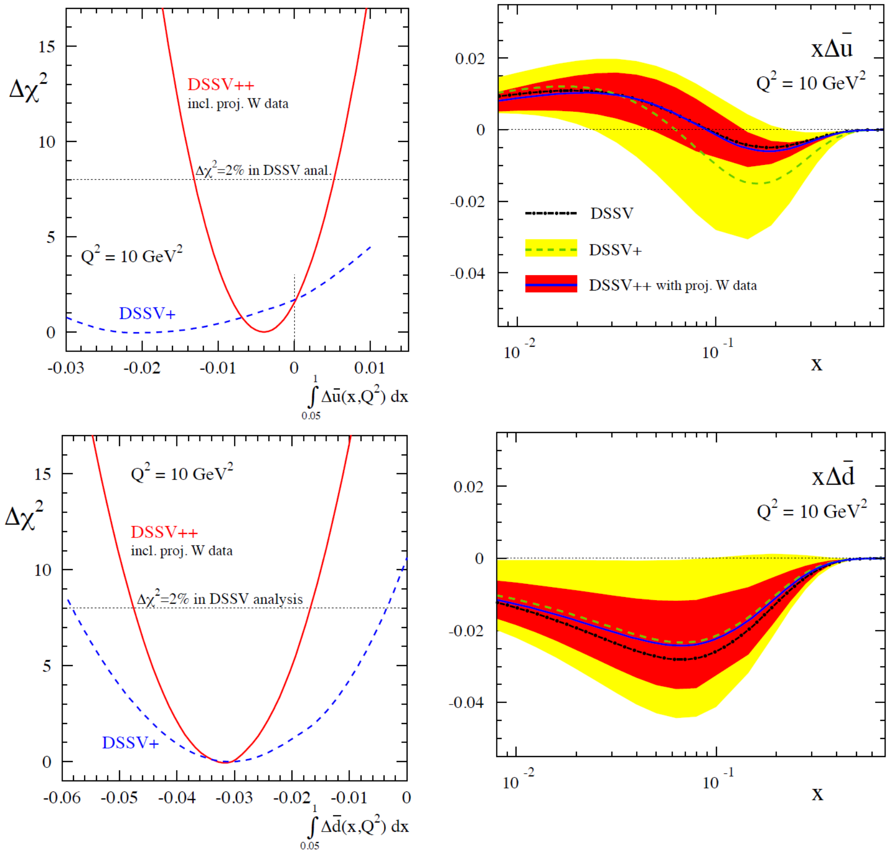
$A_L^{W^-} \sim \frac{\Delta \bar{u}}{\bar{u}}$

$A_L^{W^+} \sim \frac{\Delta \bar{d}}{\bar{d}}$



$A_L^{W^-} \sim -\frac{\Delta d}{d}$

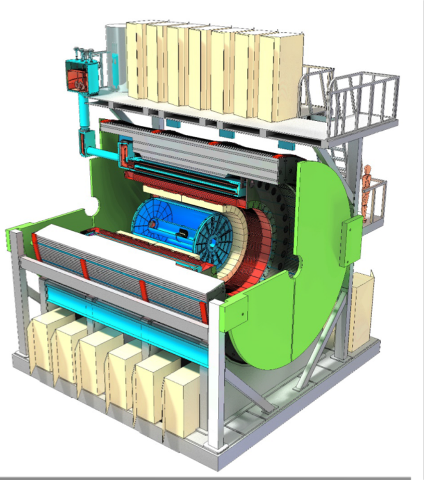
$A_L^{W^+} \sim -\frac{\Delta u}{u}$

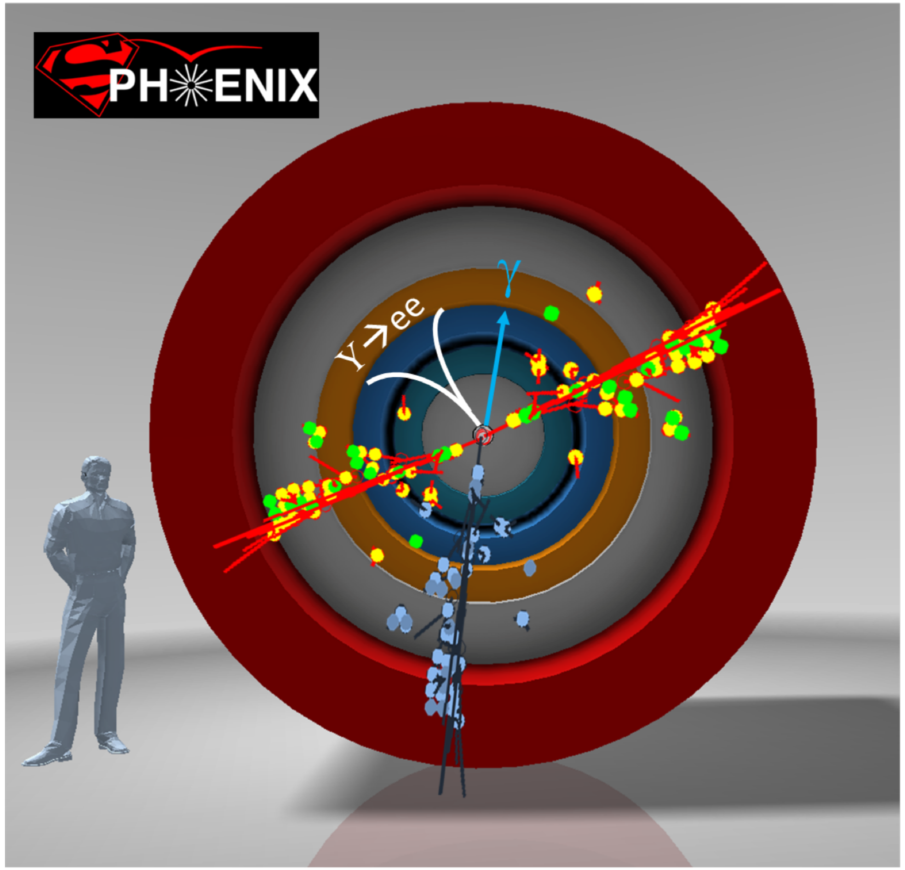


sPHENIX at RHIC

- Large acceptance, high rate next generation experiment at RHIC
  - QGP and Cold QCD physics with,
    - Jets
    - Heavy quarkonia
    - Open heavy flavor
  - Study p+p, p+A and Au+Au collisions at top energy 200GeV
    - Central barrel: |eta|<1, 2pi coverage
      - EMCal & HCal
      - MVTX/INTT/TPC
    - Forward upgrade being developed
    - DAQ rate: 15kHz

- Project Status
  - Granted DOE CD-0, 10/2016
  - CD-1 reviewed, 8/2018
  - Construction: 2018-2022
  - Day-1 physics, ~1/2023

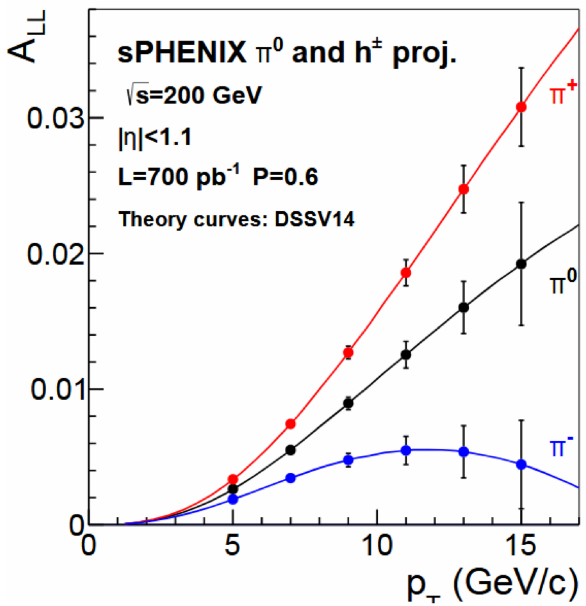




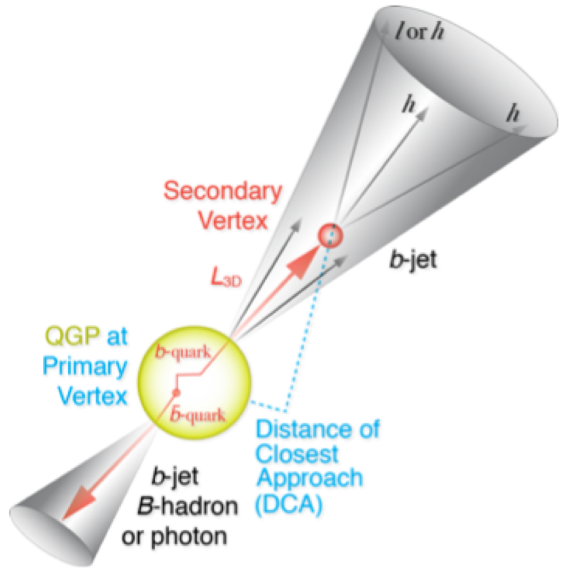
RHIC Multi-Year Plan: sPHENIX 2023-2027+

(Cold QCD plan under development now)

- Jets, hadrons and heavy flavor and more



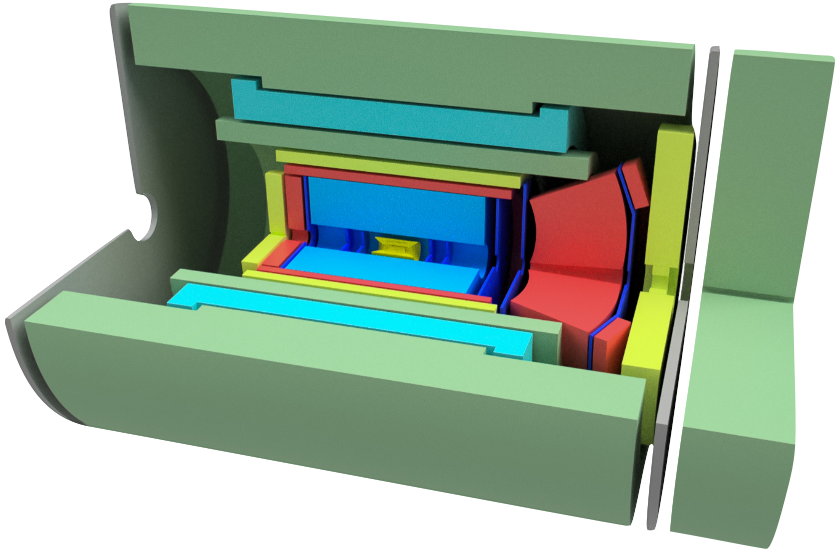
RHIC 2015 pp200
Recorded lumi ~50pb^{-1}



Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

Detector components, sPHENIX and EIC detector

- sPHENIX
  - HCal/Flux return
  - Solenoid
  - Central EMCal
  - Silicon strip tracking
  - TPC
  - MVTX



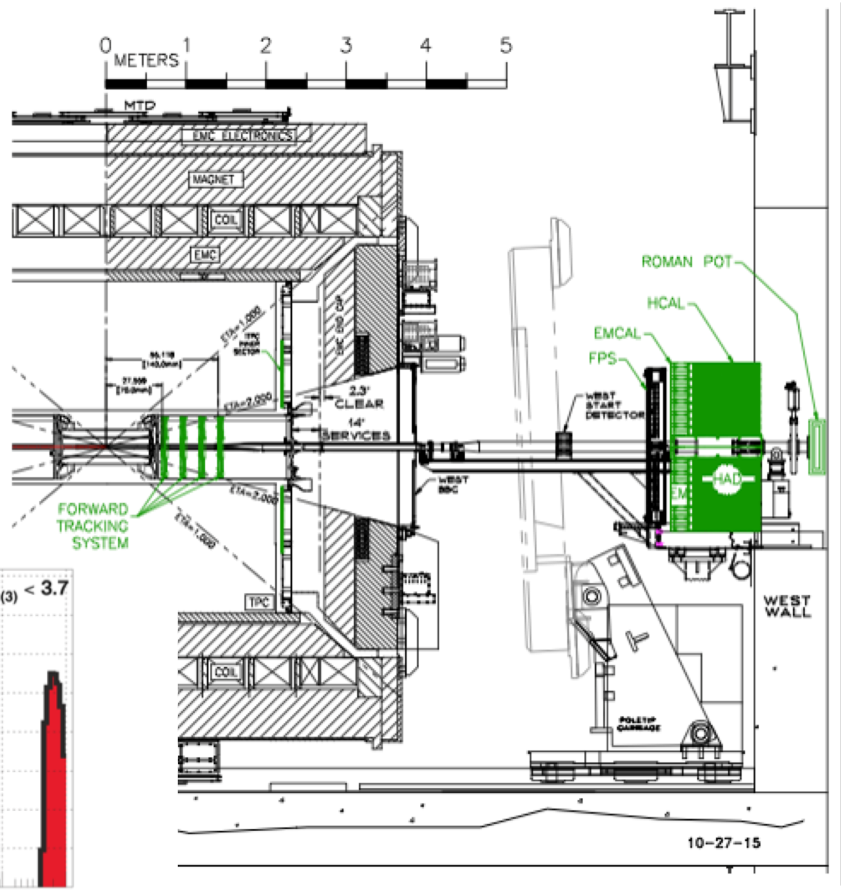
- EIC detector
  - HCal/Flux return
  - Solenoid
  - Extended Central EMCal
  - Central hadron PID
  - TPC
  - MAPS
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

Proposed STAR Forward Upgrade
Access small-x Gluons

To install a Forward Calorimeter System (FCS) in early 2020s:

- EMCal
- Hcal
- Tracking, charge separation

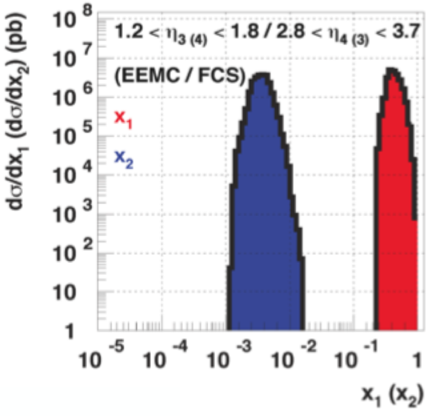
	p+p / p+A
ECAL	$\approx 10\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$

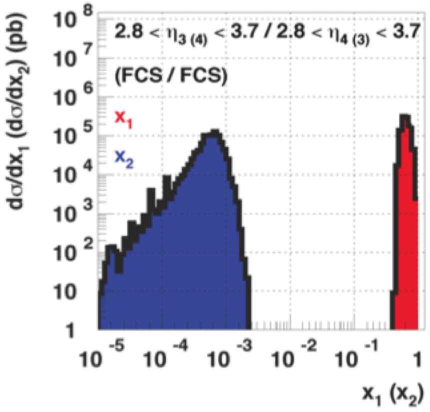


Di-jet in the forward region (2.8<eta<3.7)

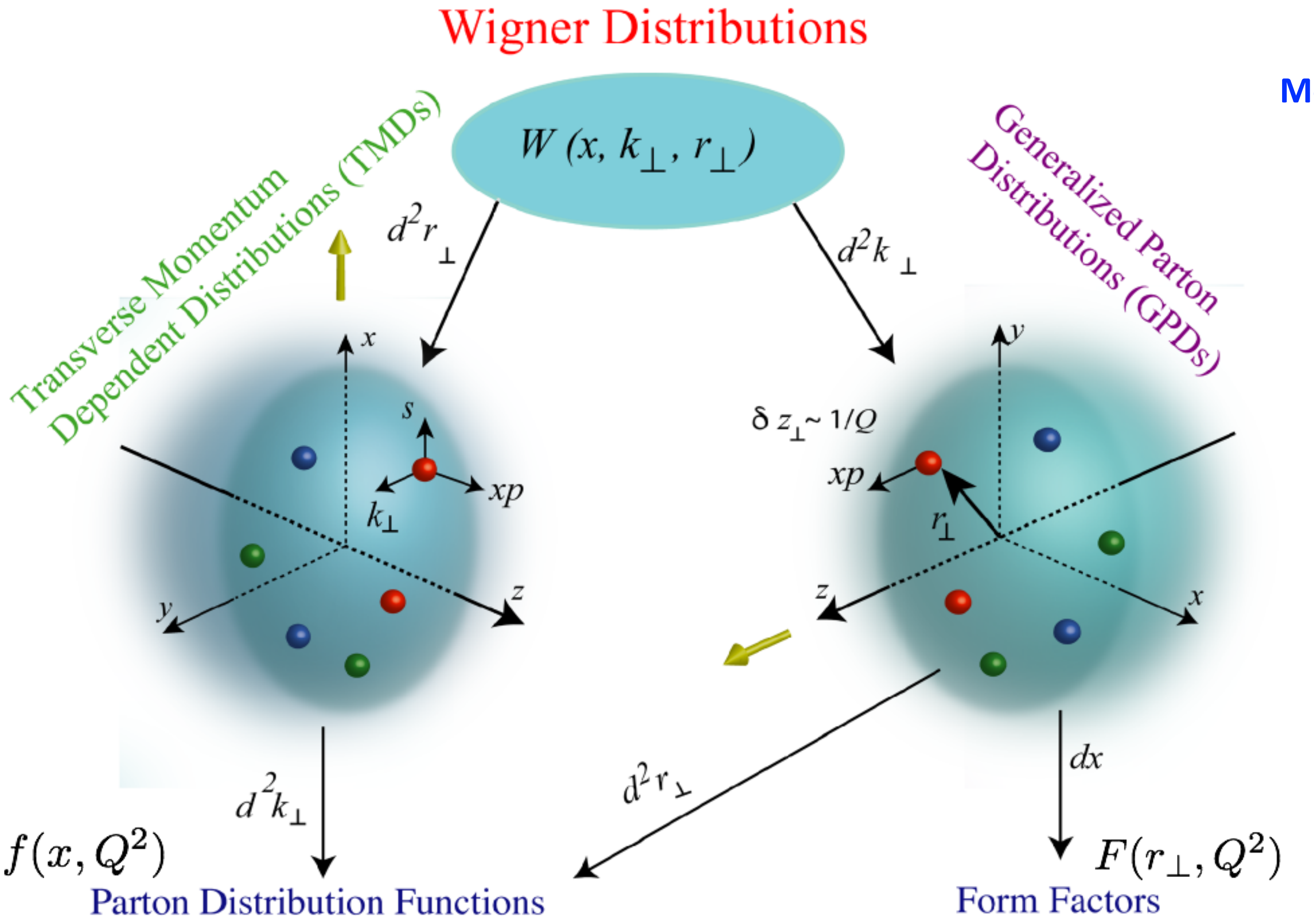
Access gluon polarization at low x:

- X ~ 5x10^-3 (central + forward)
- X~ <1x 10^-3 (forward - forward)





Toward a Unified Picture of Nucleon Structure



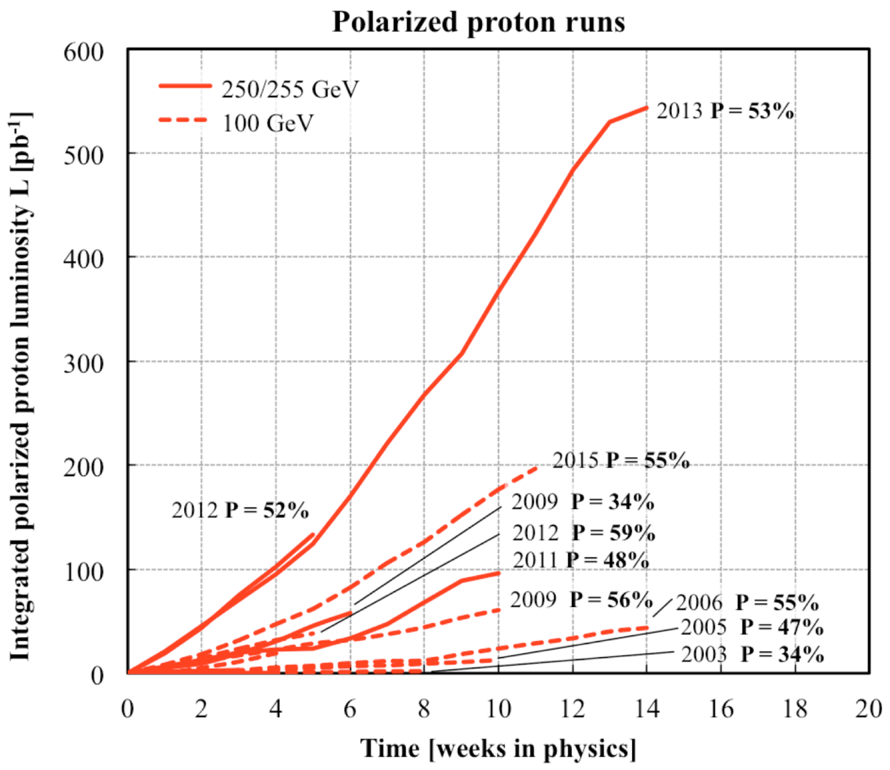
Momentum and Spatial Tomography

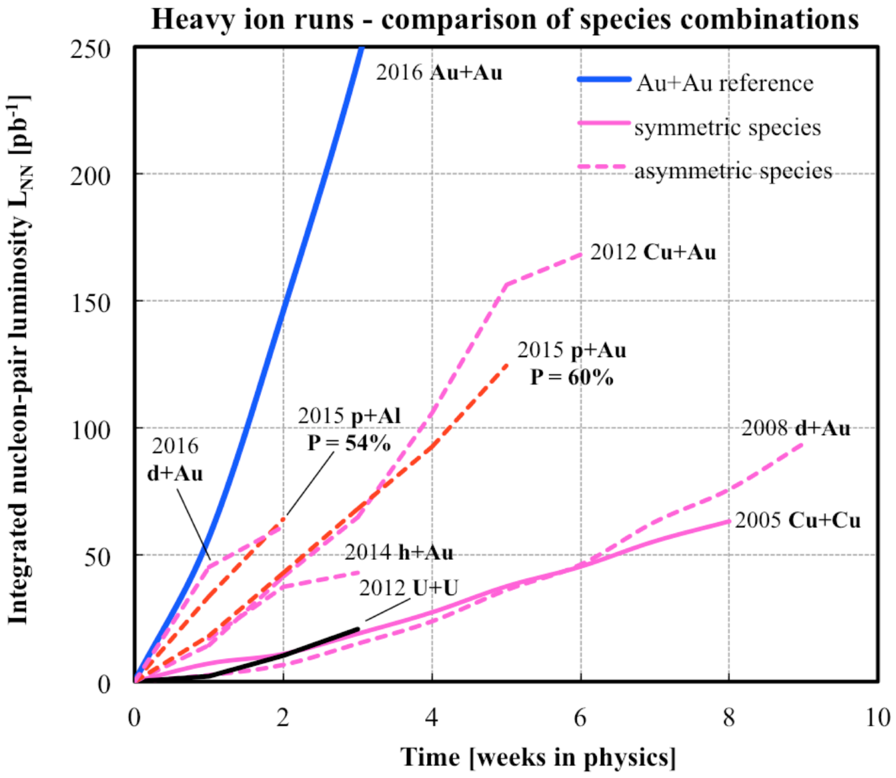
Some data, recent progress

Good data, long history

History of RHIC Spin Runs

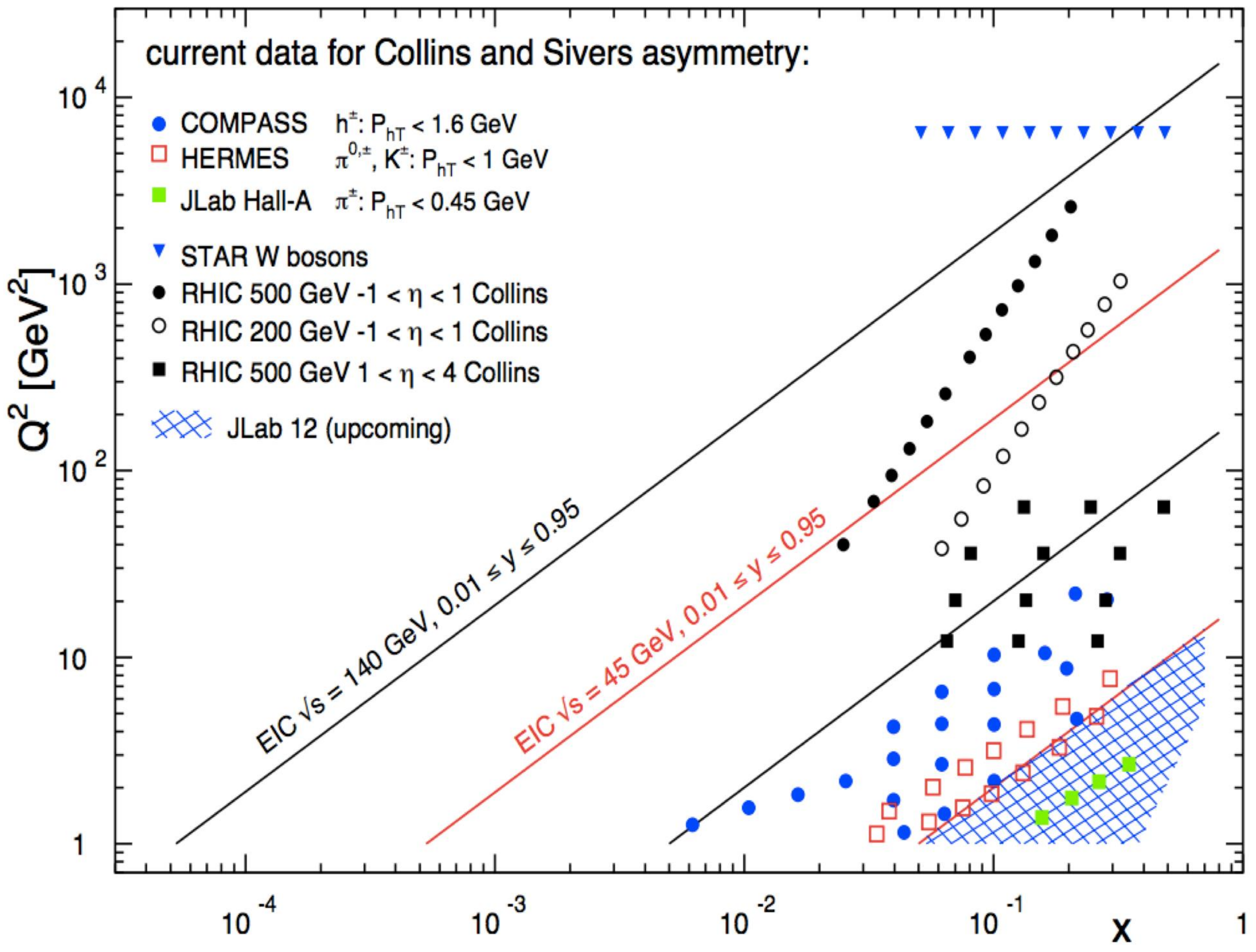
RHIC is capable of delivering the polarized p+p/A for precision spin physics



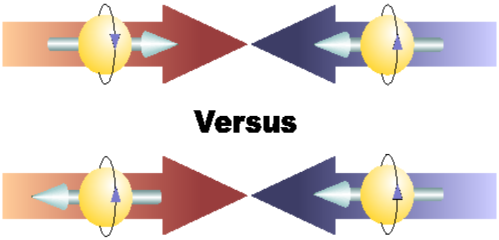


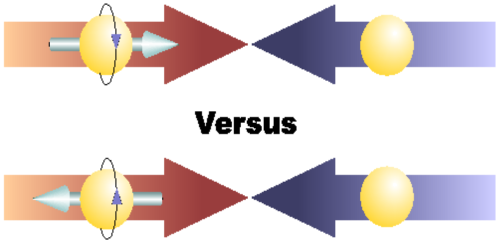
- A very challenging task to deliver polarized p+p, excellent performance from 2012+
- Outstanding Heavy Ion machine performance from the beginning
- Polarized p+p, p+Au and p+Al

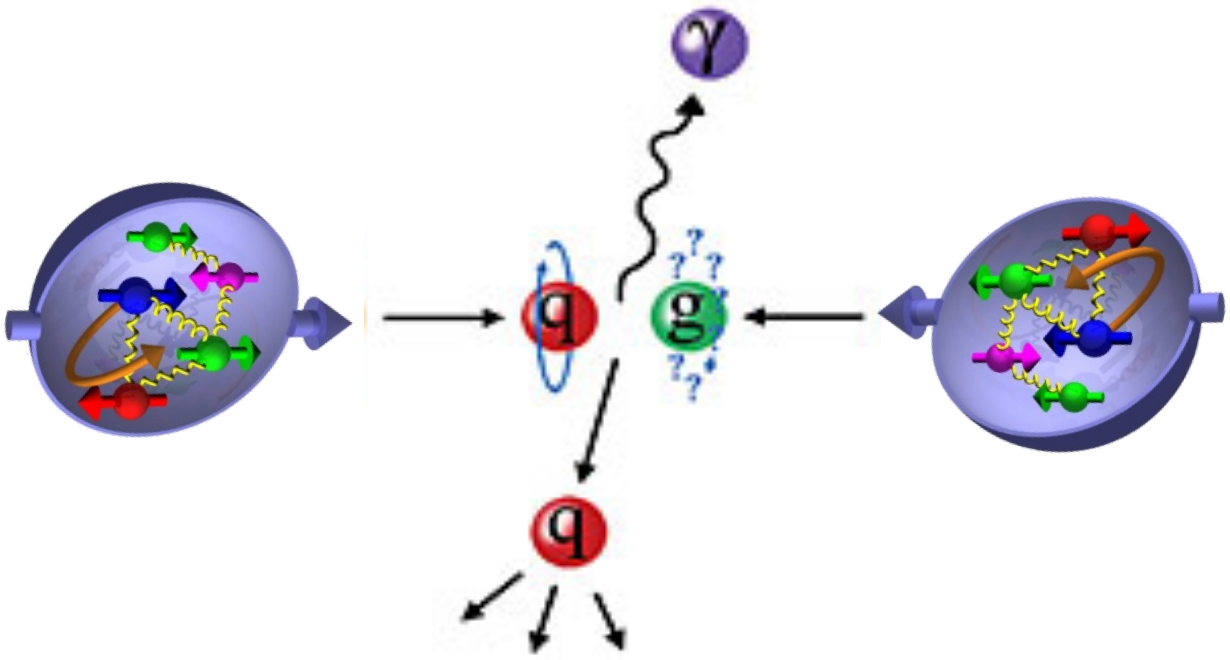
Work Wide Collins – (x, Q^2)



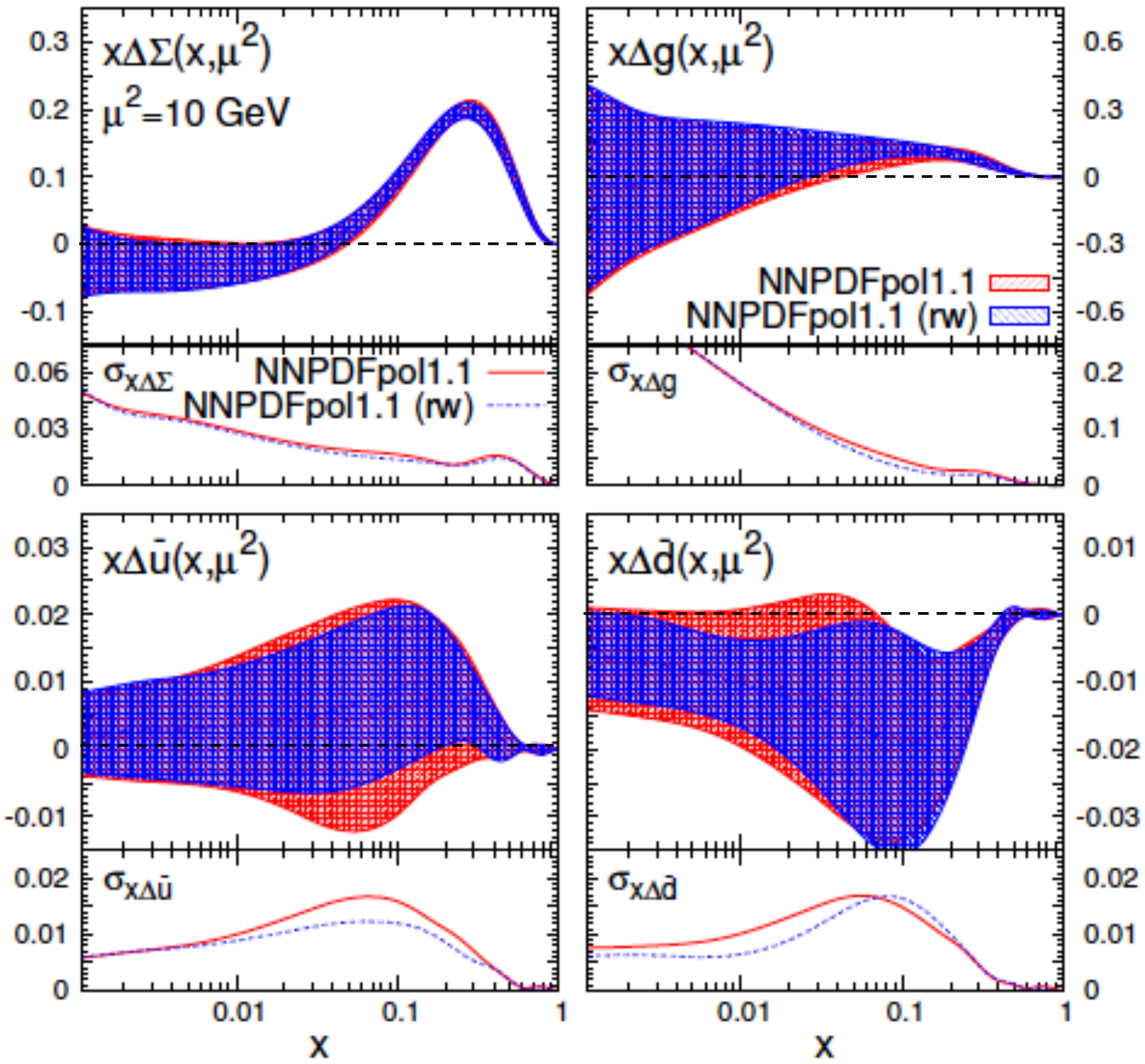
Physics with Longitudinally Polarized p+p Collisions







Latest Pol NNPDFPol Global Fit



arXiv:1702.05077

- -SI/DIS data
- -RHIC data

A New QCD Facility at M2 beam line of the SPS CERN (to be submitted in January 2019)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

October 15, 2018

http://arxiv.org/abs/1808.00848

[hep-ex] 15 Oct 2018

Letter of Intent (Draft 2.0)

A New QCD facility at the M2 beam line of the CERN SPS

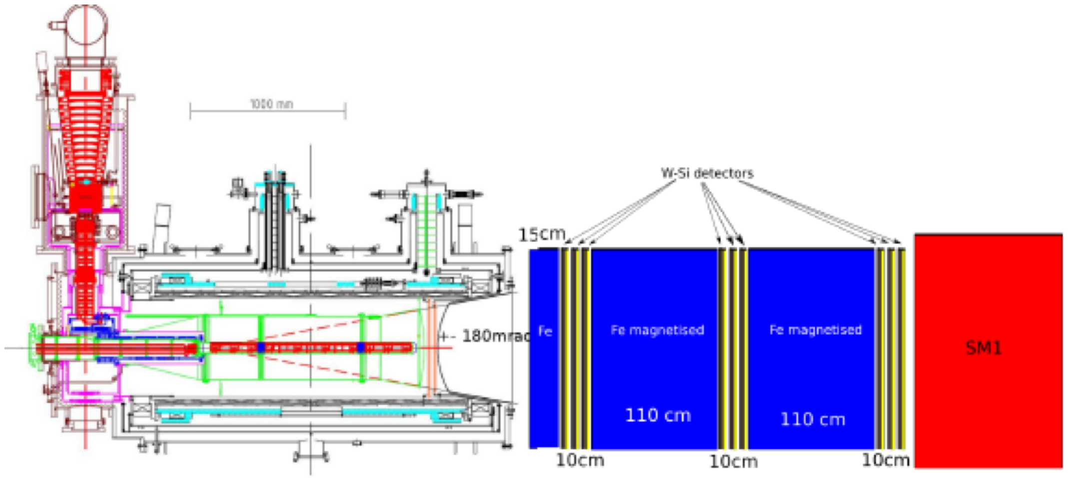
Letter of Intent working group*

A NQF@M2 beam line of the SPS CERN

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity $[s^{-1}]$	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

QCD facility – future fixed target experiment at M2
Spectrometer upgrades for Drell-Yan measurements with RF-separated beam



- Investigate the possibility to use W-Si detectors, a la PHENIX (NCC, MPC-EX)
- Dead zone with radius of 9 cm (12 cm) for angles below 90 mrad (120 mrad)
- Outter radius: 112 cm for angles up to 300 mrad

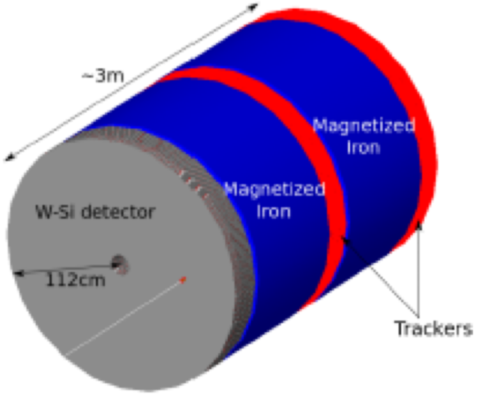
Initial detector consideration:

Combination of

- Baby-Mind detector

  M. Antonova *et al.* arXiv:1704.08079
- W-Si detectors, a la BNL

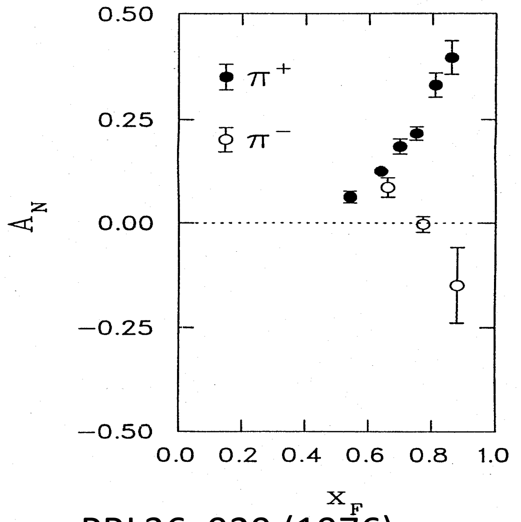
  AnDY | Phenix MPCEX | Phenix NCC



Do We Understand the Physics?

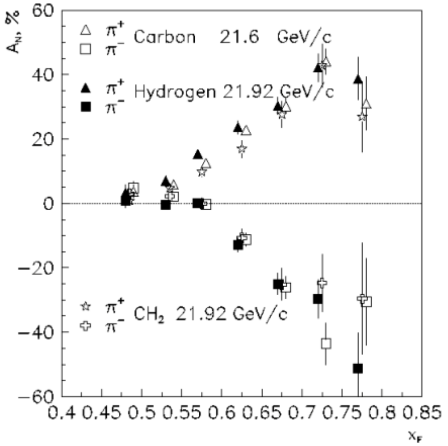
Large Transverse Single Spin Asymmetry (TSSA) in forward hadron production persists up to RHIC energy.

ZGS 12 GeV beam



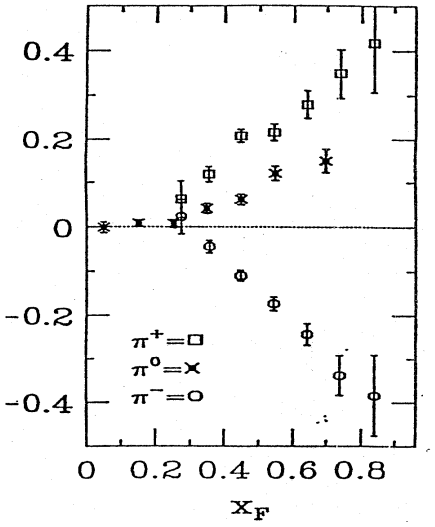
PRL36, 929 (1976)

AGS 22 GeV beam



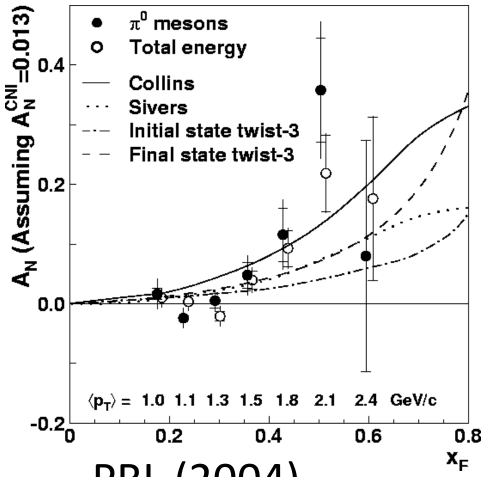
PRD65, 092008 (2002)

FNAL 200 GeV beam

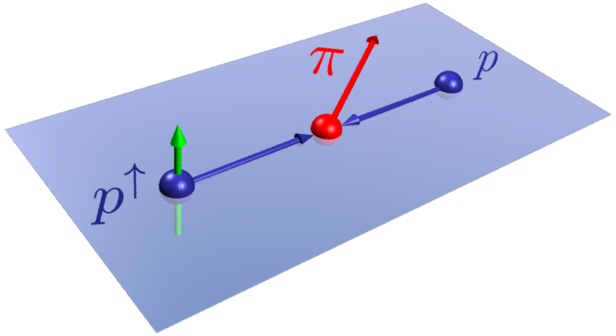


PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC 200 GeV CMS



PRL (2004)



Sivers, Collins, Twist-3 ….

Non-Perturbative cross section → Perturbative cross section

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