

# Nucleon-Structure Physics by Proton-Proton Collisions

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QNP 2018

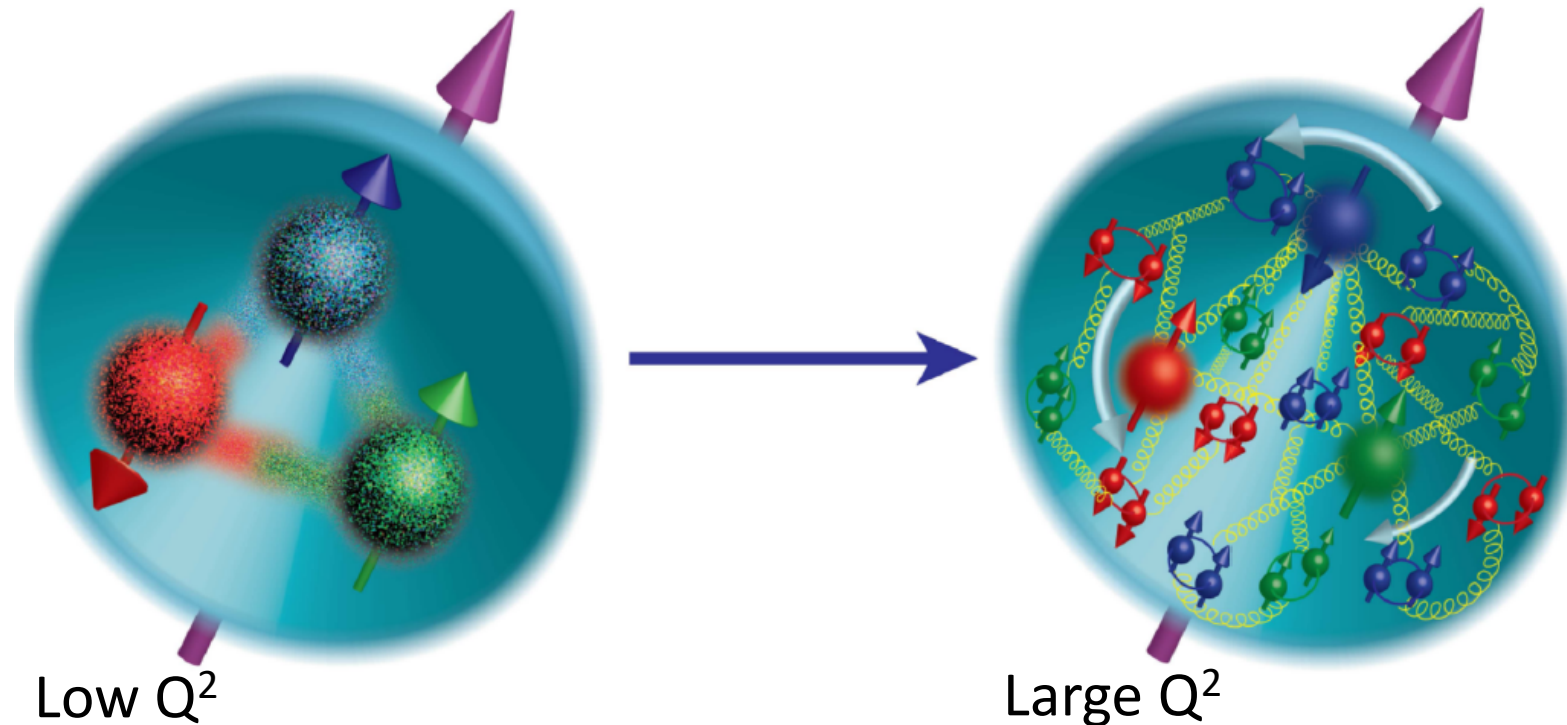
Tsukuba, Japan

# Nucleon Structure and Parton Interaction

- A very rich dynamic environment, NOT a point particle
  - “3-D” tomography
  - Probe scale-dependence, QCD evolution
- Source of many novel strong interaction phenomena

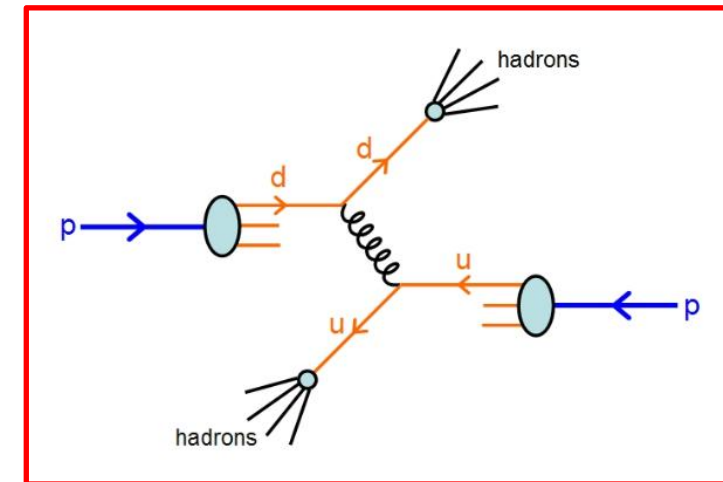
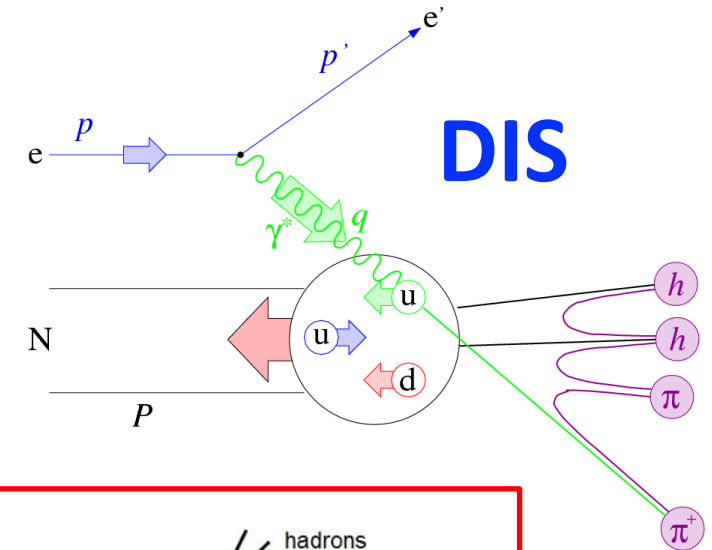
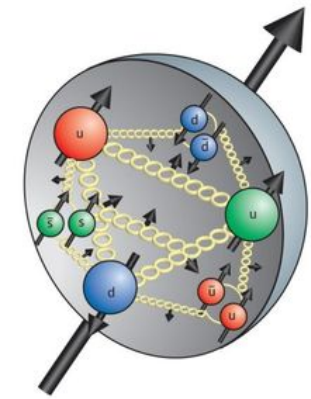
Probe resolution:

$$\lambda \sim 1/Q$$



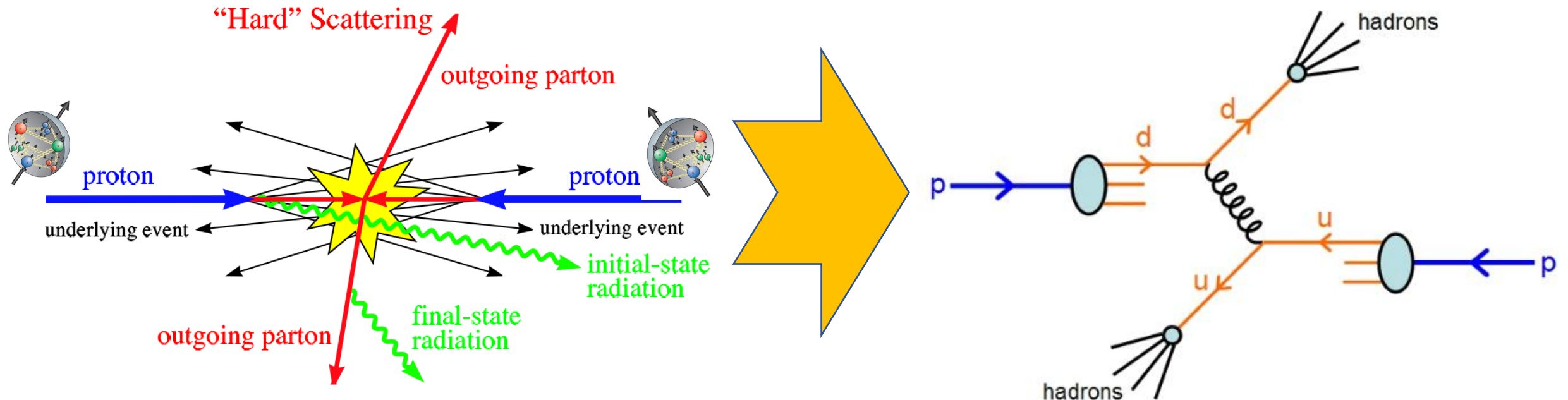
# Physics of Nucleon Parton Structures

- How hadrons formed and interact at fundamental level
  - Space and momentum distributions of quarks and gluons
  - Scale  $Q^2$  QCD evolution etc.
  - Parton correlations, spin degree of freedom etc.
- Tools
  - **Lepton probes** – DIS
    - HERMES, COMPASS, HERA, EIC...
  - **Hadron probes** – proton, pion/Kaon beams
    - RHIC, Fermilab, CERN, NIKA ...
  - Lattice QCD, pQCD ...



# Study Nucleon Structures in Hadronic Collisions

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



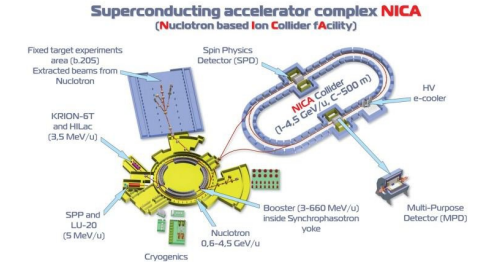
$$\sigma \sim f(x_1) \otimes f(x_2) \hat{\sigma}^{x_1+x_2 \rightarrow h_1+h_2+X}$$



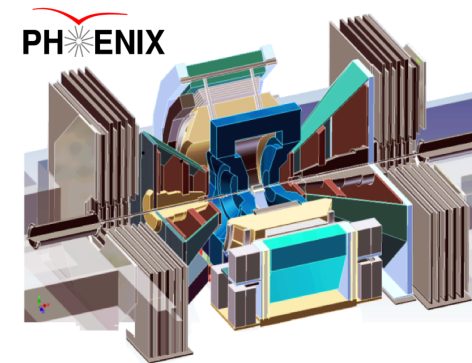
# Selected Recent Highlights

- Proton spin puzzle
  - RHIC –PHENIX, STAR
  - “Longitudinal spin phenomena”
- Transvers spin challenge
  - RHIC/PHENIX, STAR
  - CERN/COMPASS
  - Fermilab/SeaQuest
- “Transverse spin phenomena”

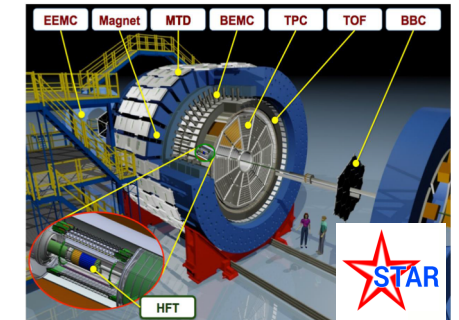
Alexey Guskov, Fri.



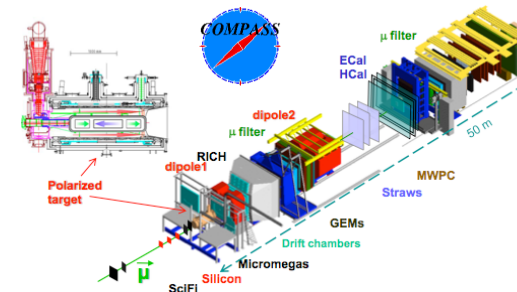
Itaru Nakagawa, Fri.



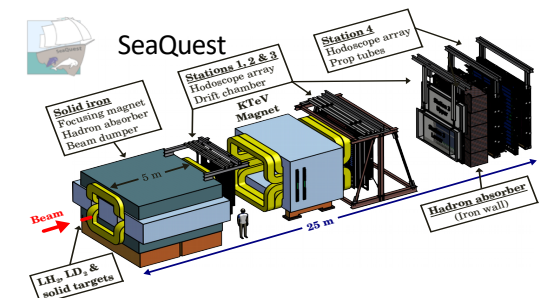
Ken Barish, Fri.



Marcia Quaresma, Wed.



Kei Nagai &  
Yoshiyuki Miyachi, Wed.



# Proton Spin Puzzle: the Challenge of “Too Small”



**“Spin Crisis”: EMC (1987)**  
**Quark contribution “small”**

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

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

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

Led to very active spin physics program in 90's  
 Development of RHIC-Spin program

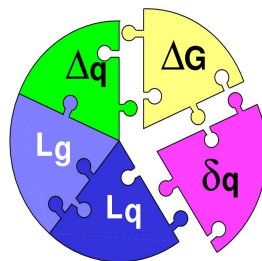
**Today:**

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

$$\Delta\Sigma \sim 0.3 \quad (\text{Pol. DIS})$$

$$\Delta G \sim 0.2 \quad (\text{RHIC-Spin})$$

$$L^z \sim ? \quad (\text{RHIC, FNAL?})$$



	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	

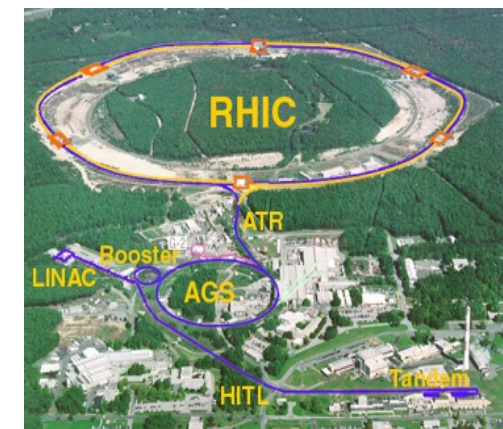
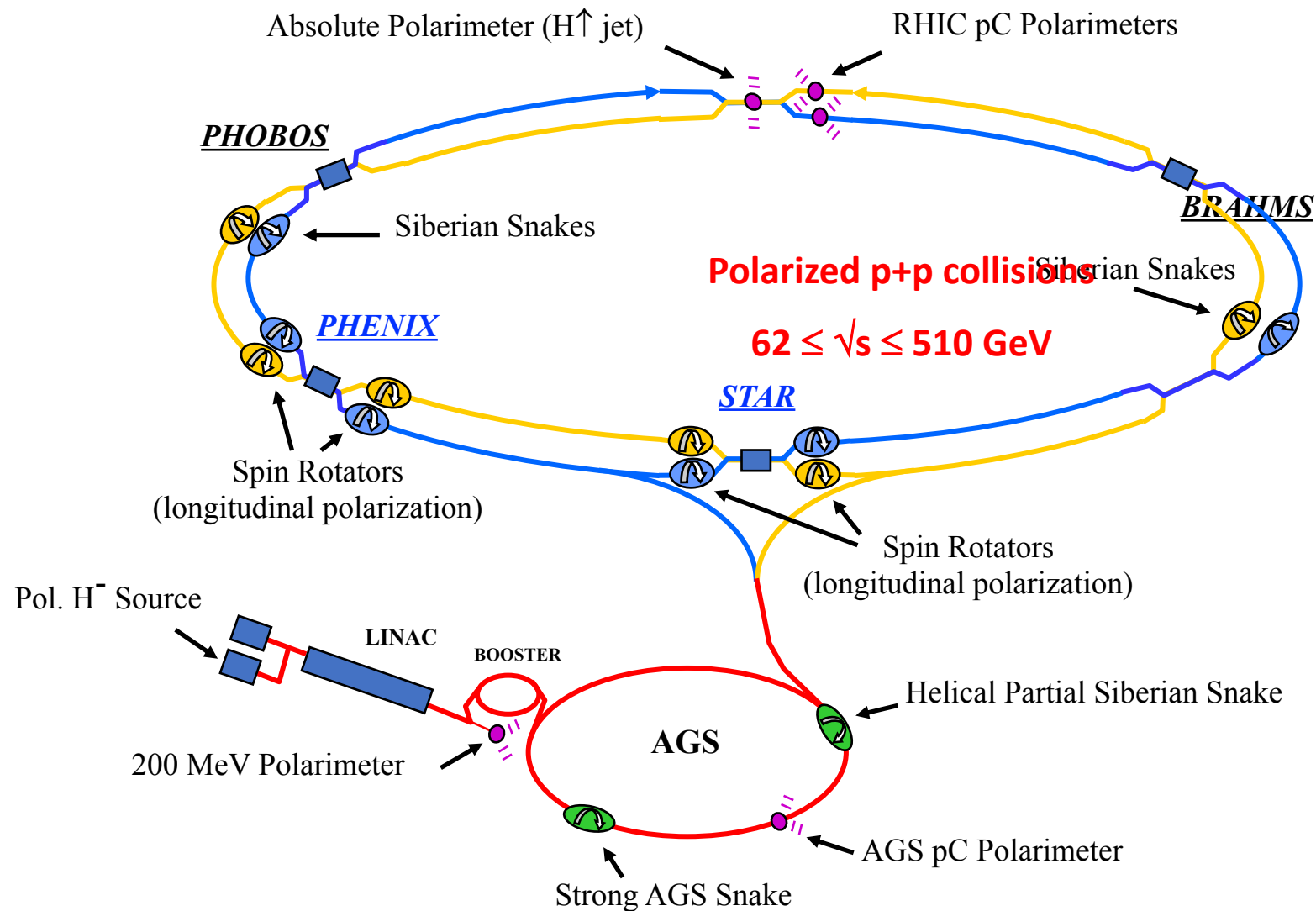


SIDIS/DIS



Polarized p+p

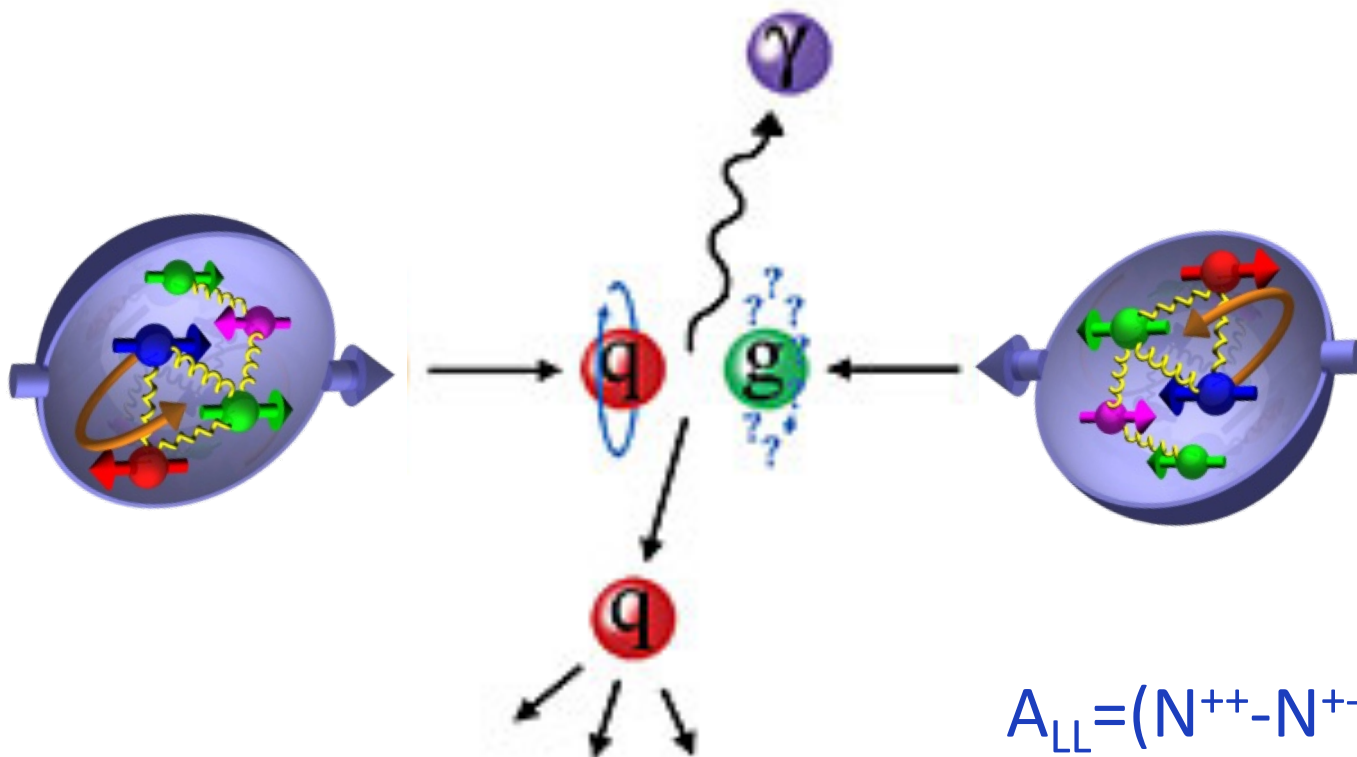
# The World First High-Energy Polarized Proton Collider at Relativistic Heavy Ion Collider



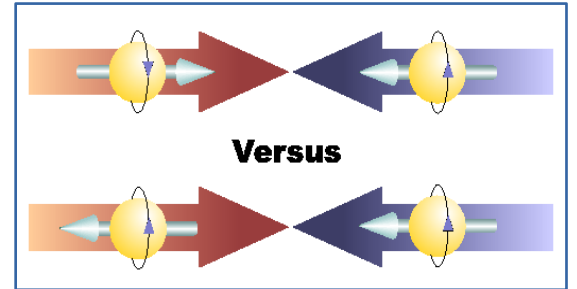
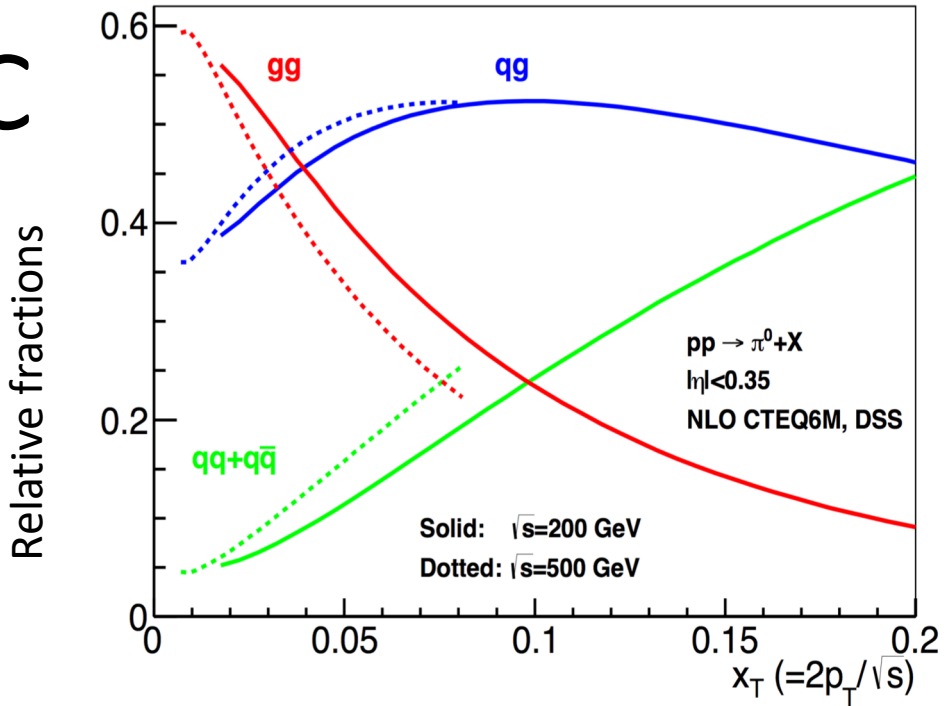
**RHIC-Spin  
Program:**

**2000-2017+**

# Study Gluon Polarization at RHIC



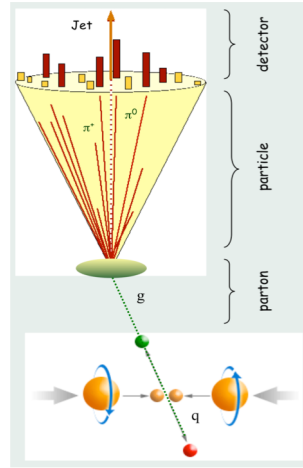
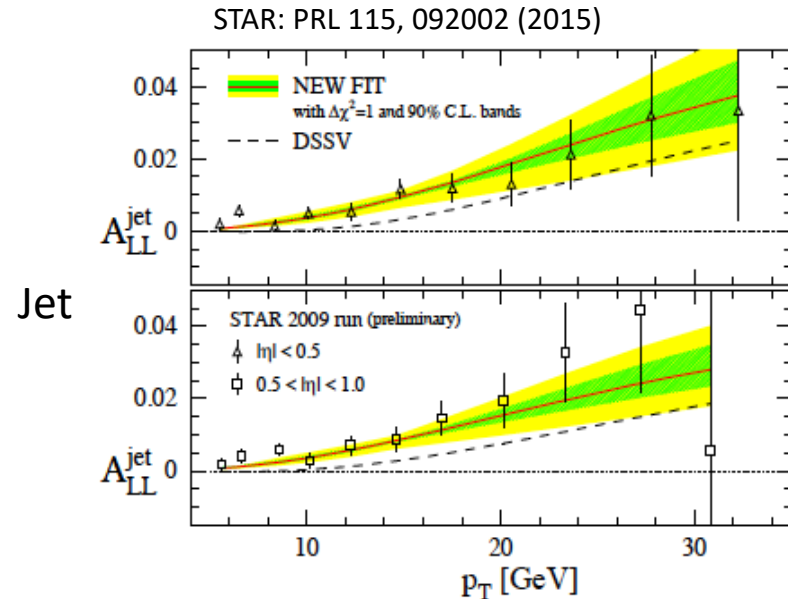
$$A_{LL} = (N^{++} - N^{+-}) / (N^{++} + N^{+-})$$



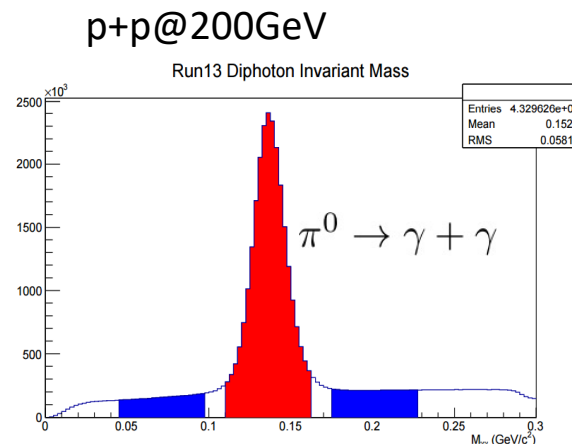
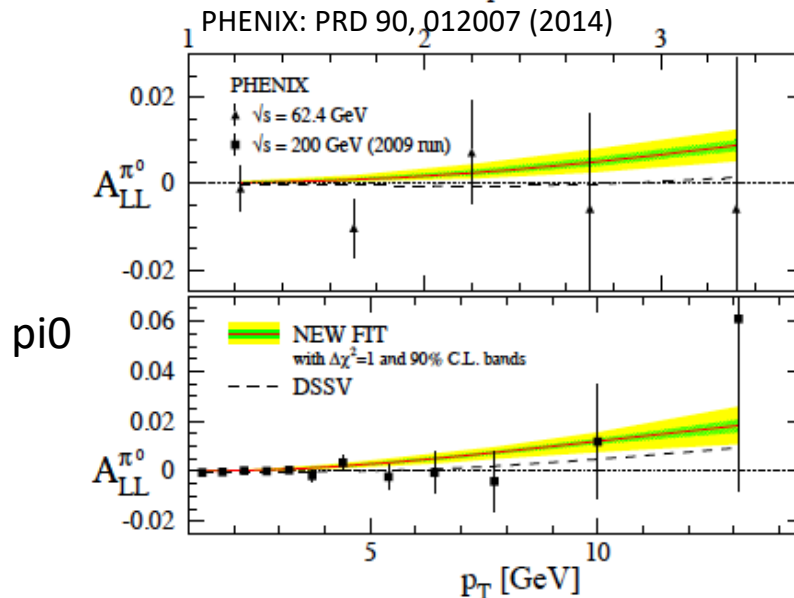
$$\Delta\sigma(pp \rightarrow \pi^0 X) \approx \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z) \dots$$

# First Hints of Non-zero Gluon Polarization from RHIC

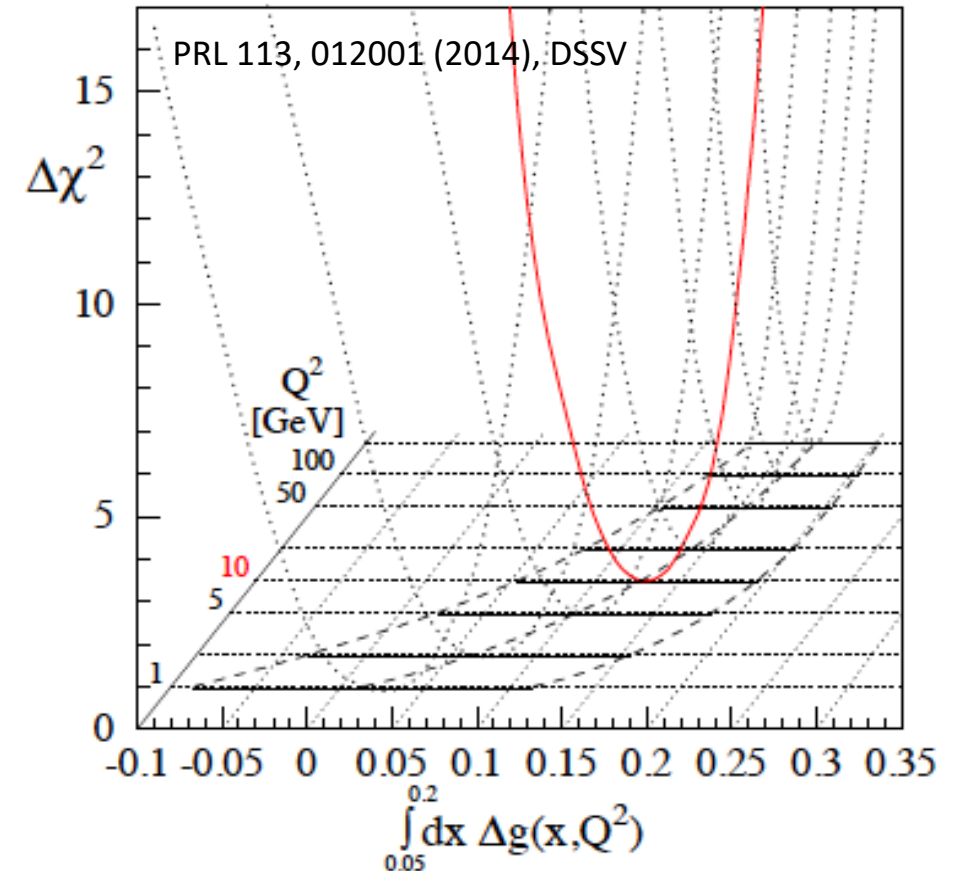
I. Nakagawa;  
K. Barish's talks



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



Ming Liu, QNP2018



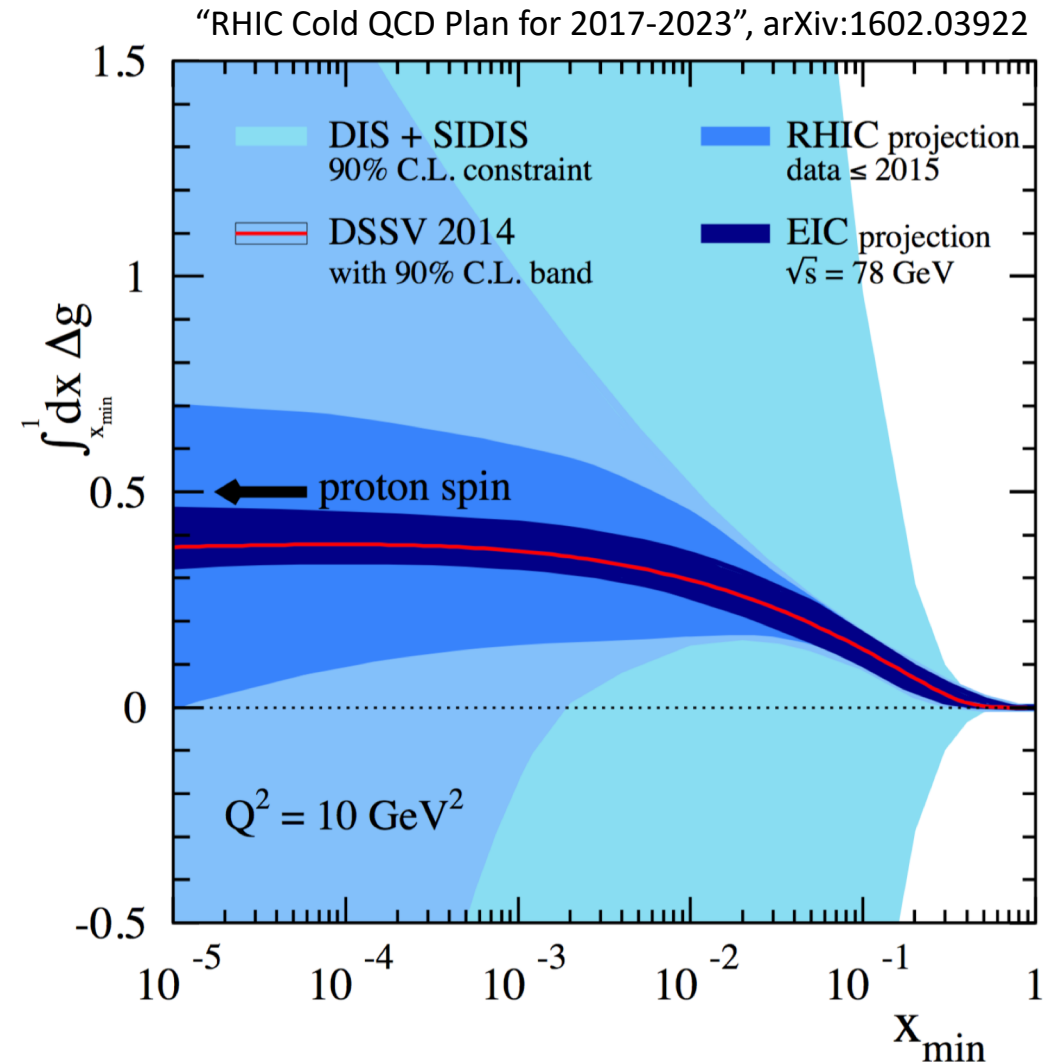
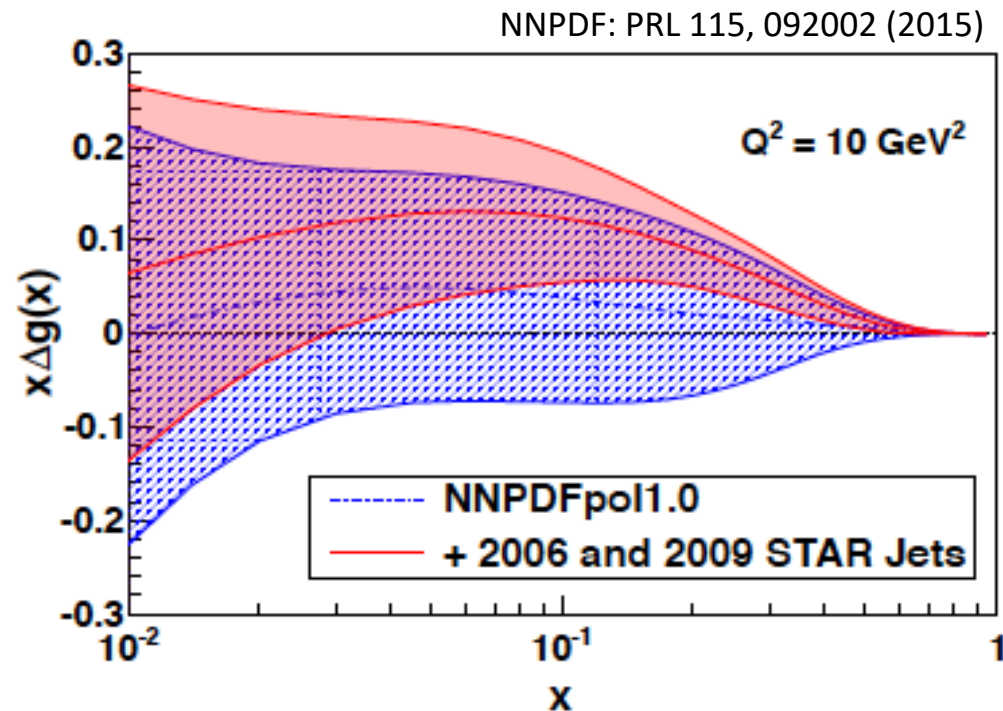


# Near Future: Projected Gluon Polarization Measurements

- Favors positive gluon polarization

- PHENIX/STAR data:
  - 62-510GeV  $\pi^0 A_{LL}$
  - 200/510GeV (di)jets  $A_{LL}$
  - and more ...*

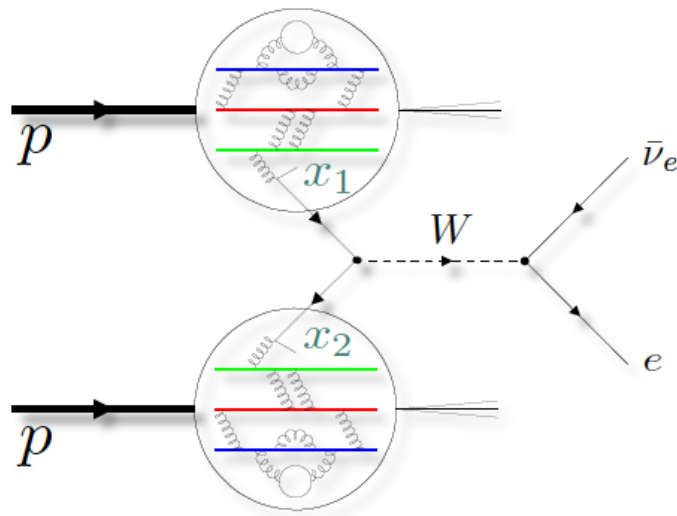
- EIC future, 2027+



# Electroweak Probes for (anti)Quarks at High Energy at RHIC

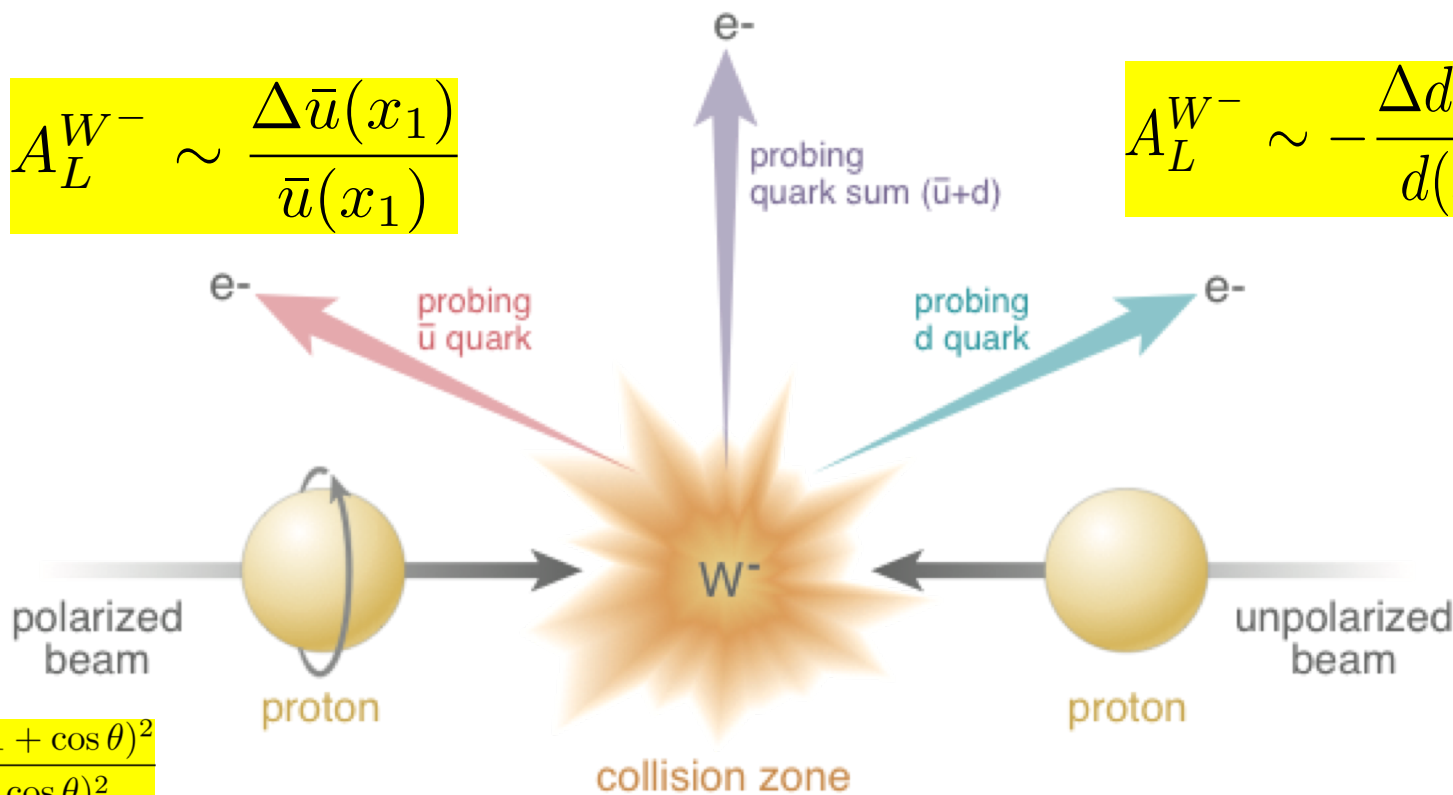
$$q(x_1) + \bar{q}'(x_2) \rightarrow W^\pm \rightarrow e^\pm + \nu(\bar{\nu})$$

“left-hand coupling”



$$A_L^{W^-} \sim \frac{\Delta \bar{u}(x_1)}{\bar{u}(x_1)}$$

$$A_L^{W^-} \sim -\frac{\Delta d(x_1)}{d(x_1)}$$

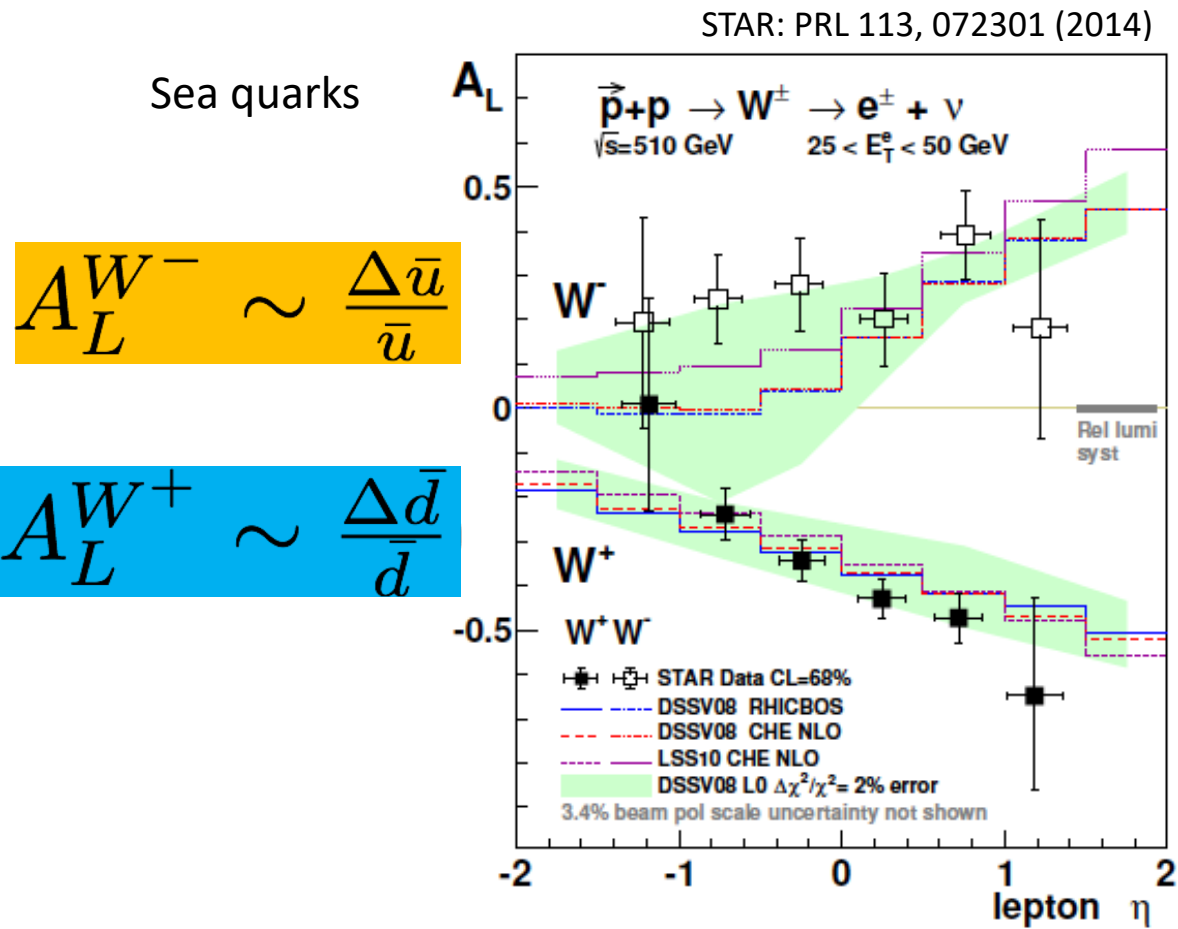


$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1 - \cos \theta)^2 + \Delta \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2}{u(x_1)\bar{d}(x_2)(1 - \cos \theta)^2 + \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2}$$

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

# First Measurements of Flavor Identified Sea-Quark Polarization

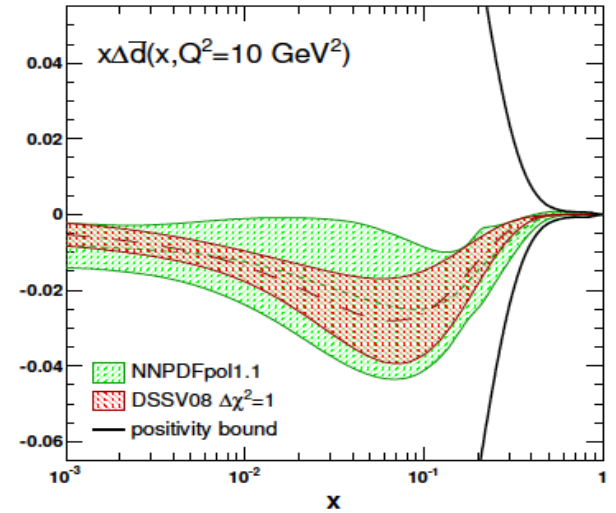
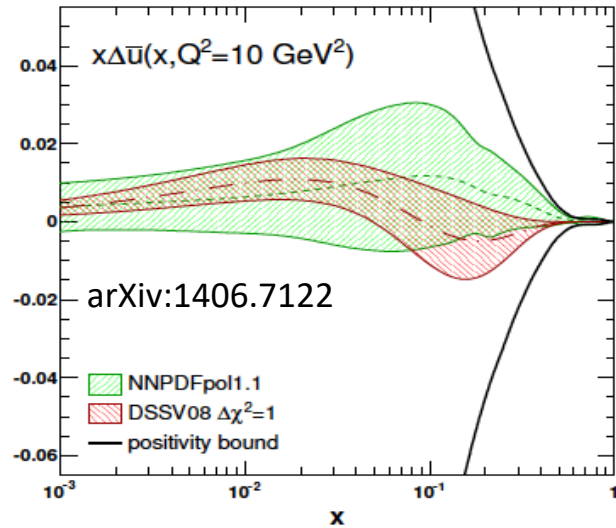
RHIC has unique access to flavor identified sea-quarks via real  $W^{+/-}$



Valence quarks

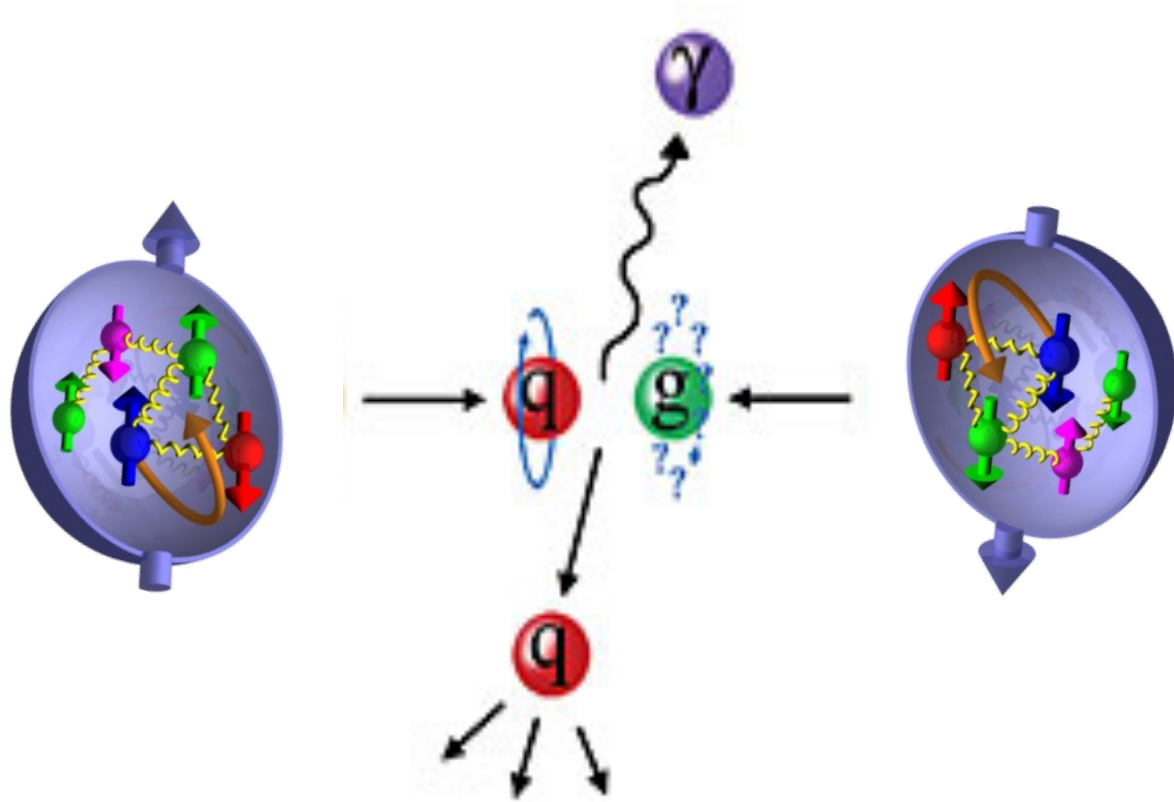
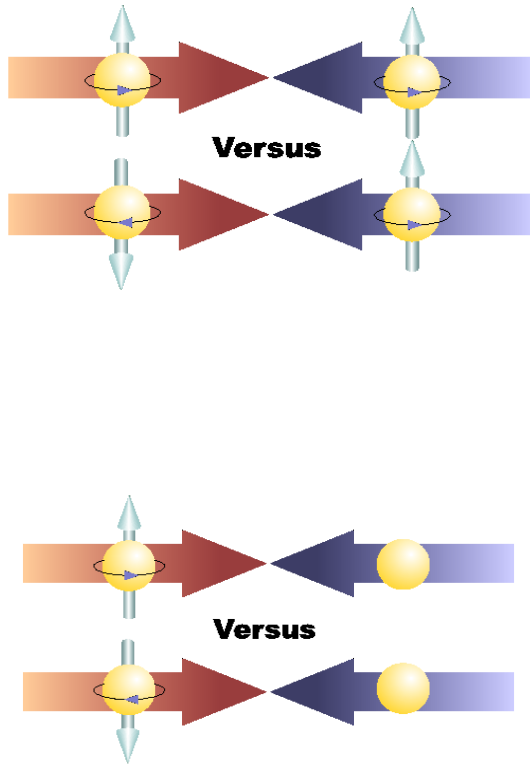
$$A_L^{W^-} \sim -\frac{\Delta d}{d}$$

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





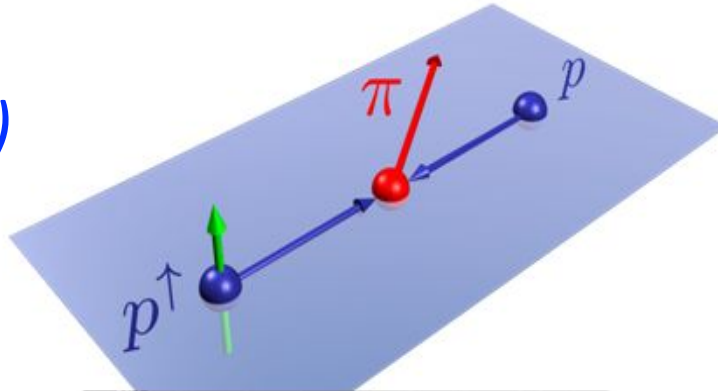
# Physics with Transversely Polarized p+p Collisions at RHIC



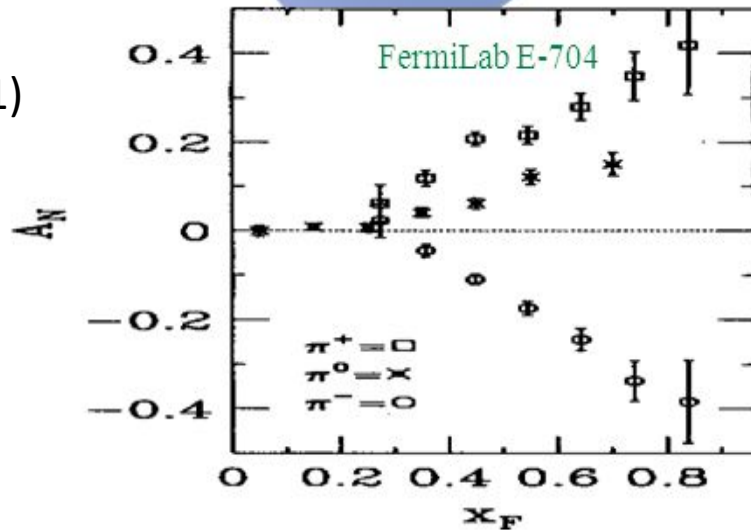
# “TMD” phenomena: The Challenge of “Too Large”

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

$$A_N \sim O(10\%)$$

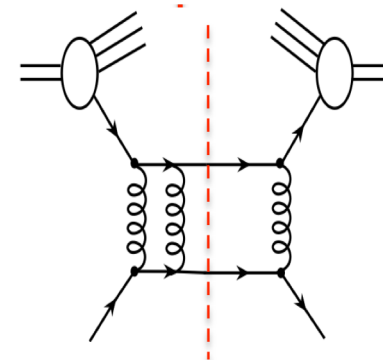


Fermilab  
E704 (1991)



Kane, Pumplin, Repko (1978)

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



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

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

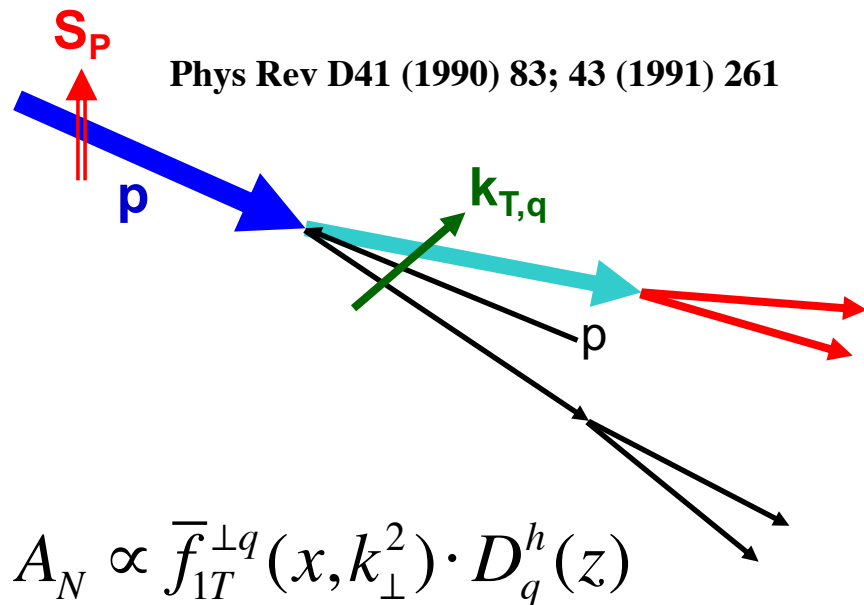
# Probe the Underlying Physics via Hard Scatterings

## TMD, Collinear Twist-3 Factorizations

### (i) **Sivers mechanism:**

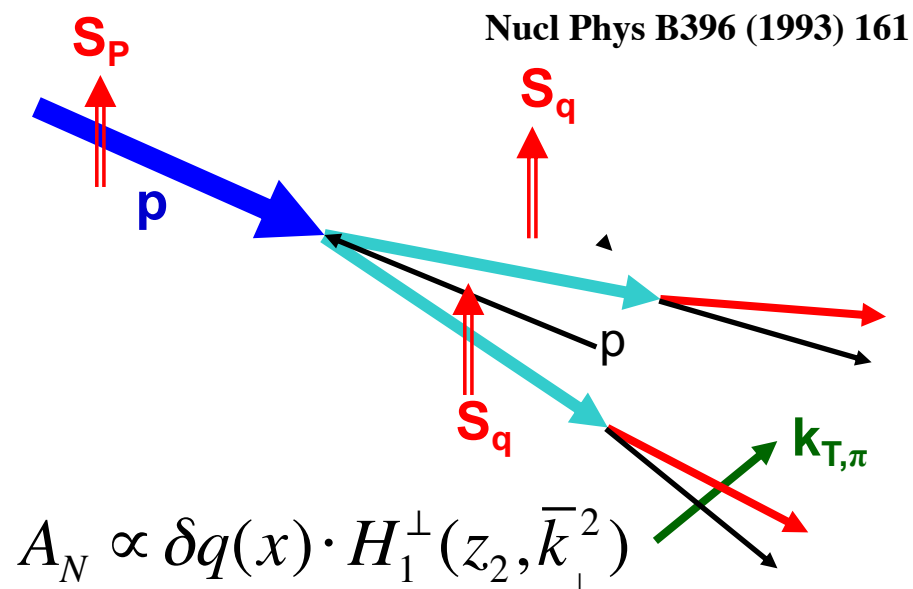
correlation proton spin & parton  $k_T$

**SIDIS:**



### (ii) **Collins mechanism:**

Transversity  $\times$  spin-dep fragmentation



**pp:**

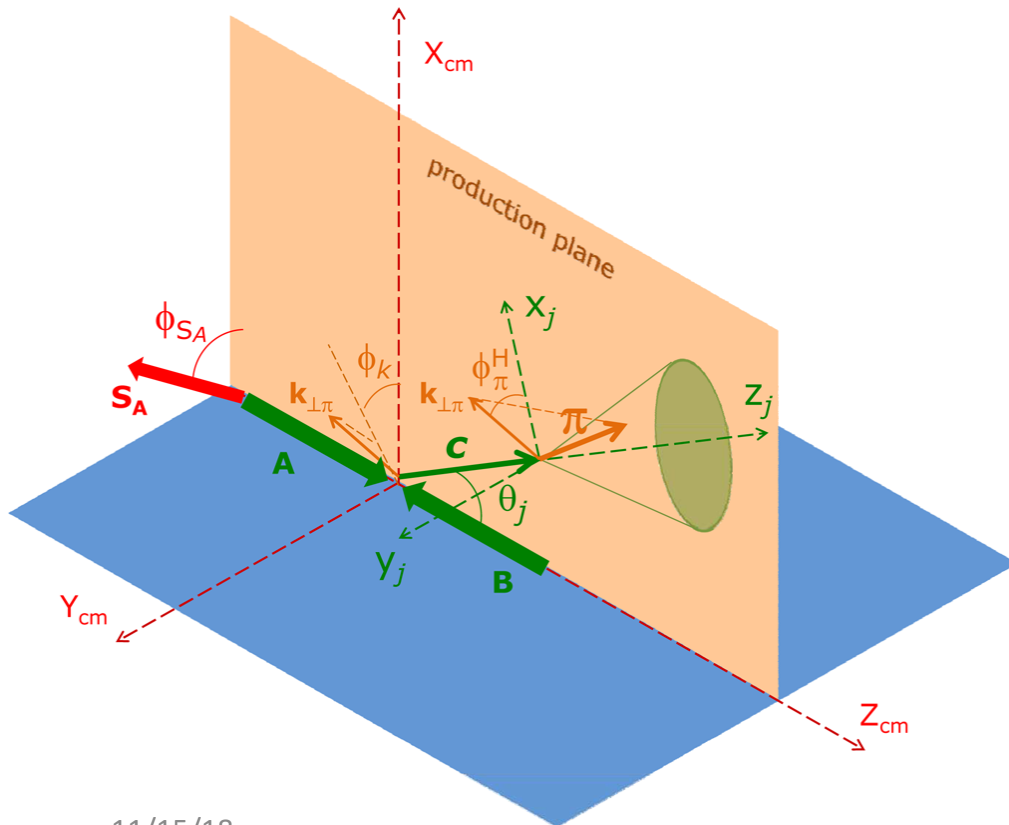
### **Collinear Twist-3 (RHIC):**

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)



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

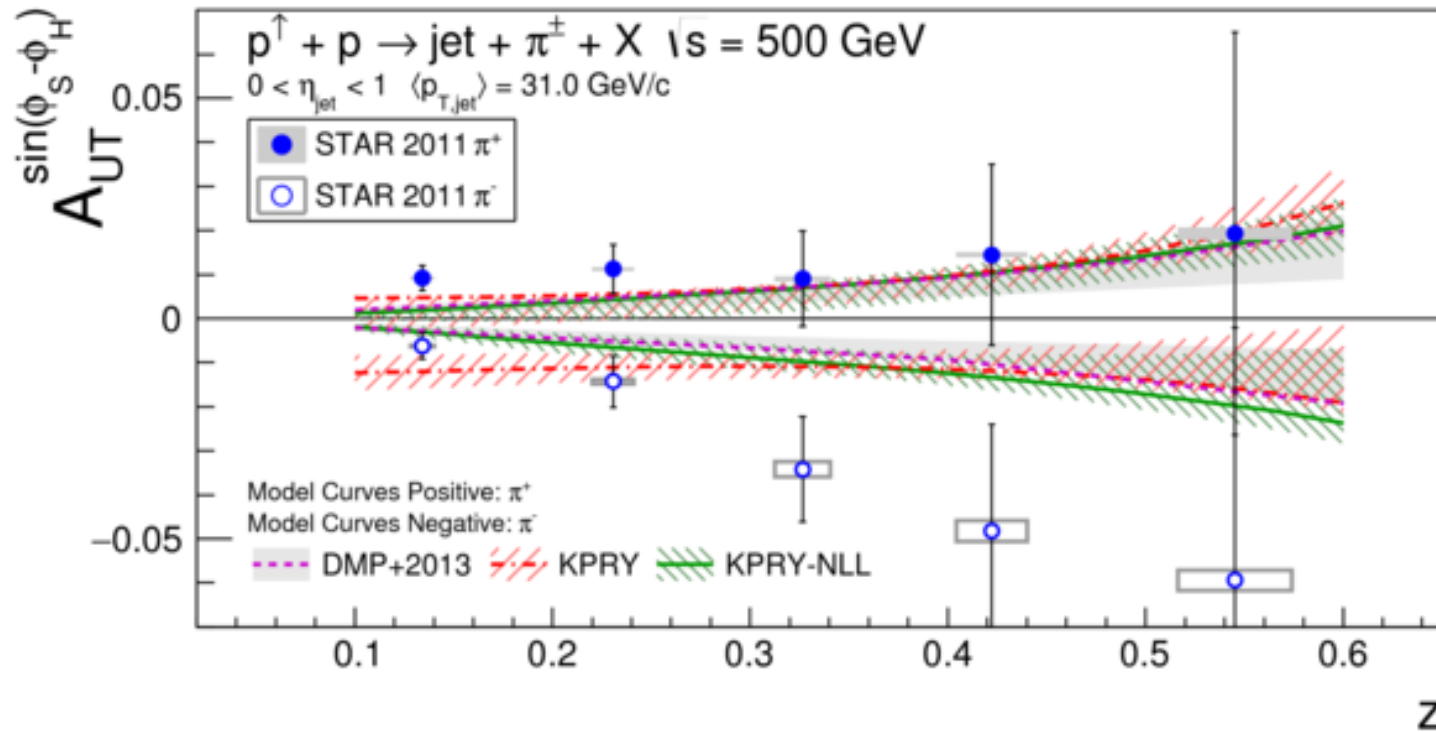
$$A_N^{\sin\phi_{S_A}} \rightarrow \text{“Sivers-like” (Jet)}$$

$$A_N^{\sin(\phi_{S_A} \mp \phi_{\pi}^H)} \rightarrow \text{“Collins-like” (hadron)}$$

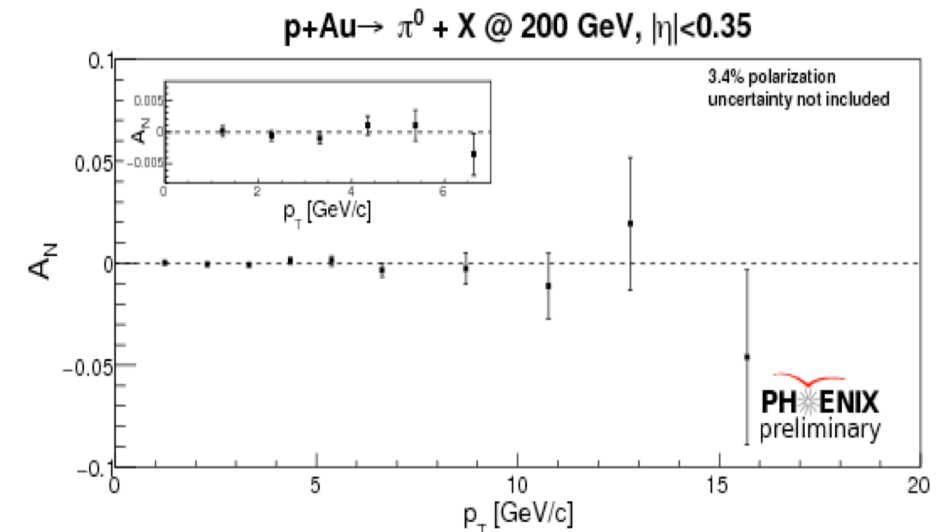
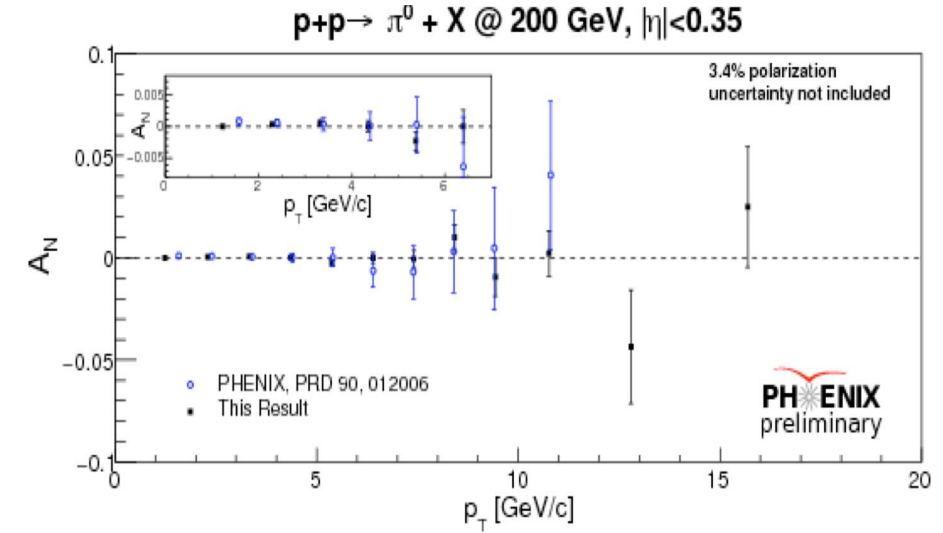
# Collins Asymmetry Observed in Jet in p+p Collisions

$A_N$  at central rapidity: non-zero in jet!

Phys.Rev. D97, 032004 (2018)



Inclusive  $A_N = 0$  at central rapidity



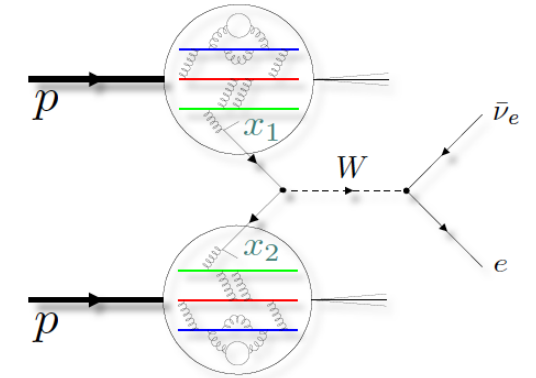
# Sivers Asymmetry – Initial State

Non-universality, process dependent

- Sign change prediction, QCD factorization

Can be tested in Drell-Yan and W/Z in p+p

K. Barish's Talk



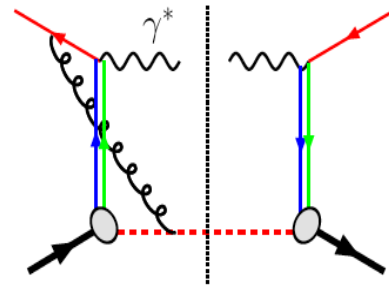
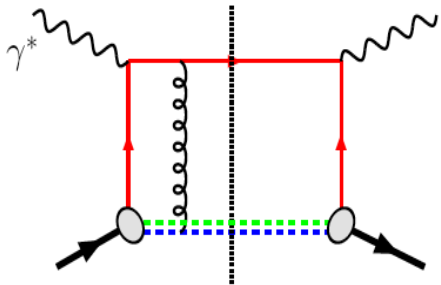
First hint of sign change from RHIC

More data, 350pb<sup>-1</sup>, from 2017 run

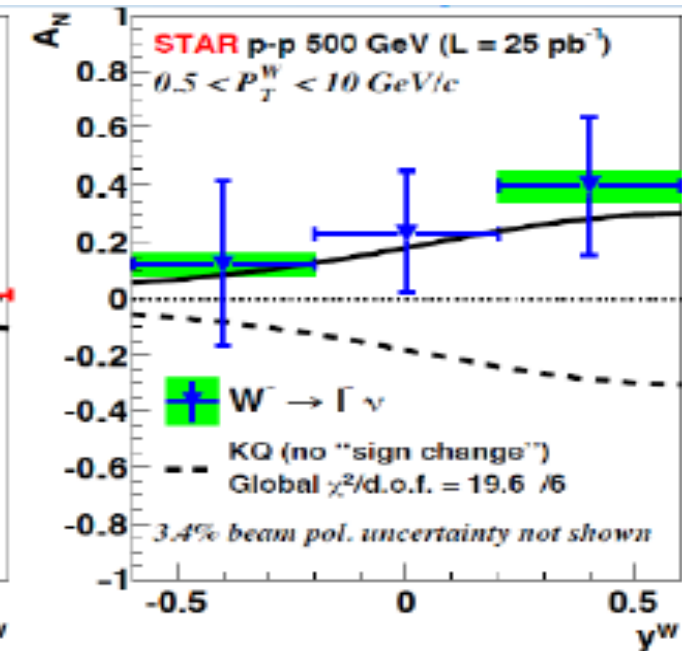
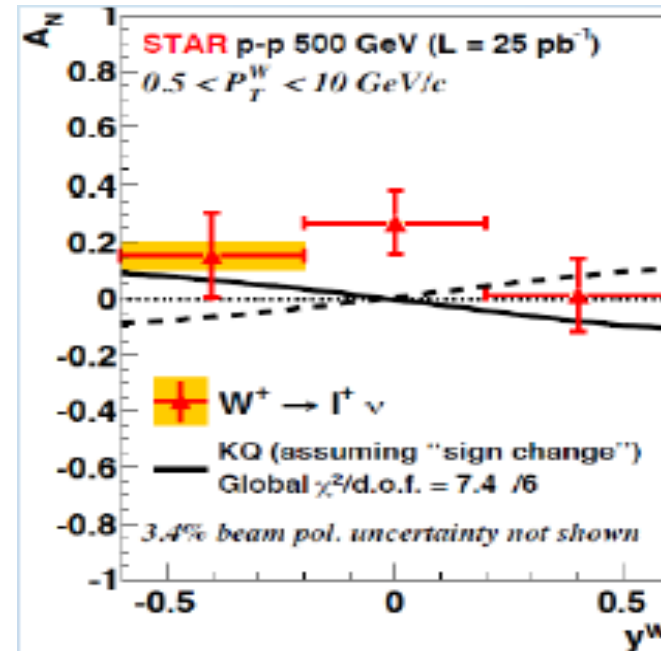
PRL 116, 132301 (2016)

DIS: attractive

Drell-Yan: repulsive



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

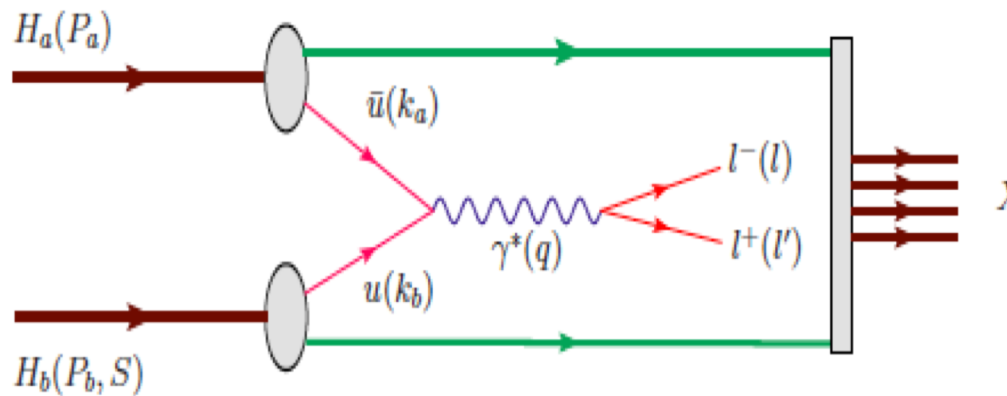


# Drell-Yan $A_N$ from COMPASS Polarized Target

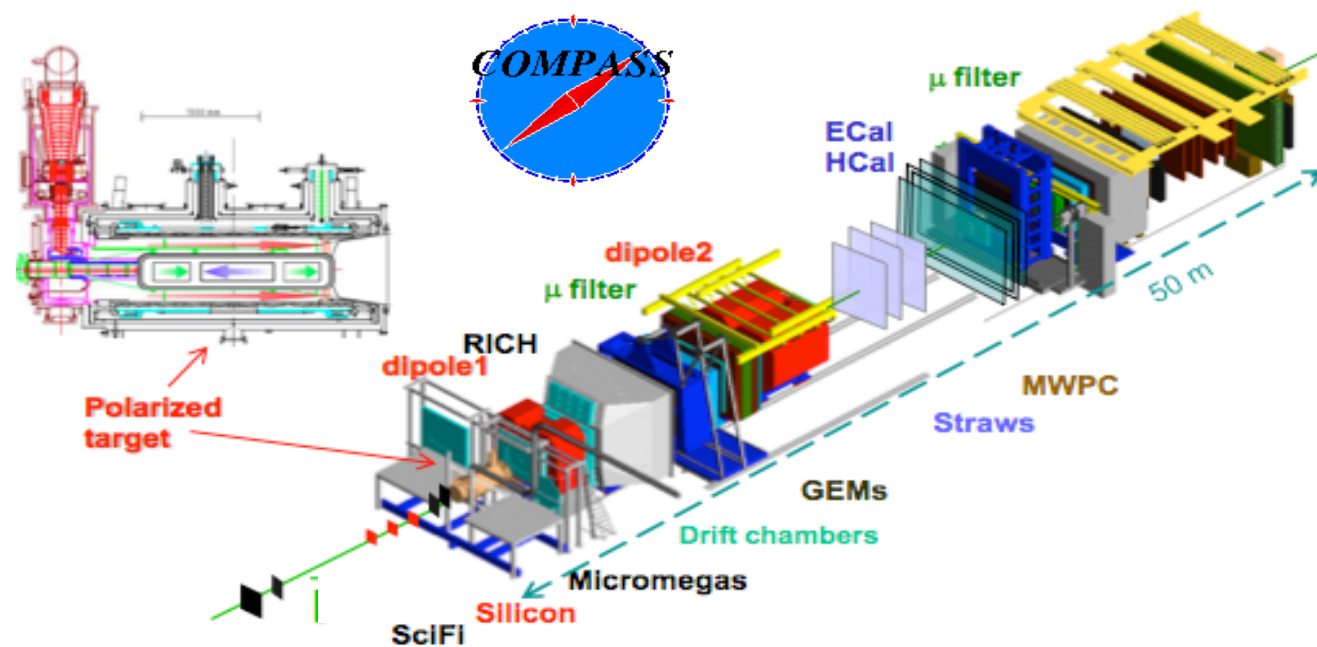
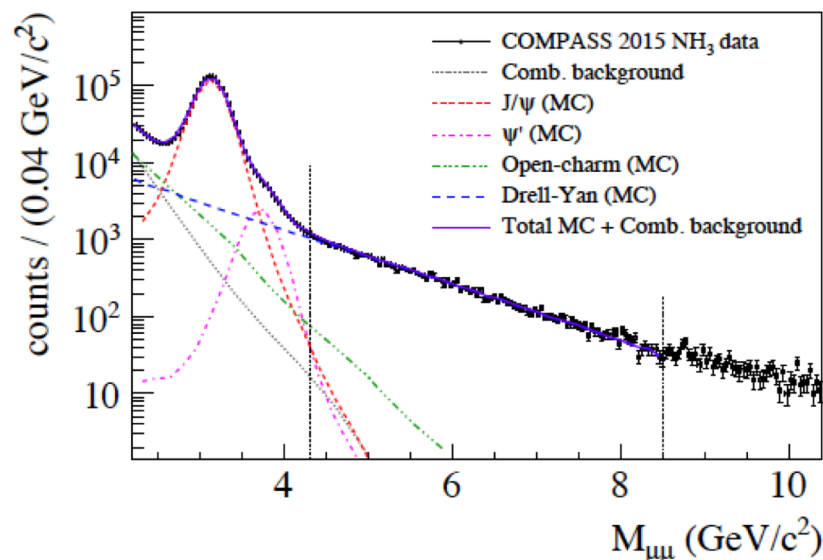
M. Quaresma's talk

Beam:  $\pi^-$   
190GeV

Polarized  
Proton target  $H_b(P_b, S)$



- $J/\psi$  ( $\text{NH}_3$ )  **$\sim 1.5\text{M}$**
- HM DY ( $\text{NH}_3$ )  **$\sim 35\text{K}$**





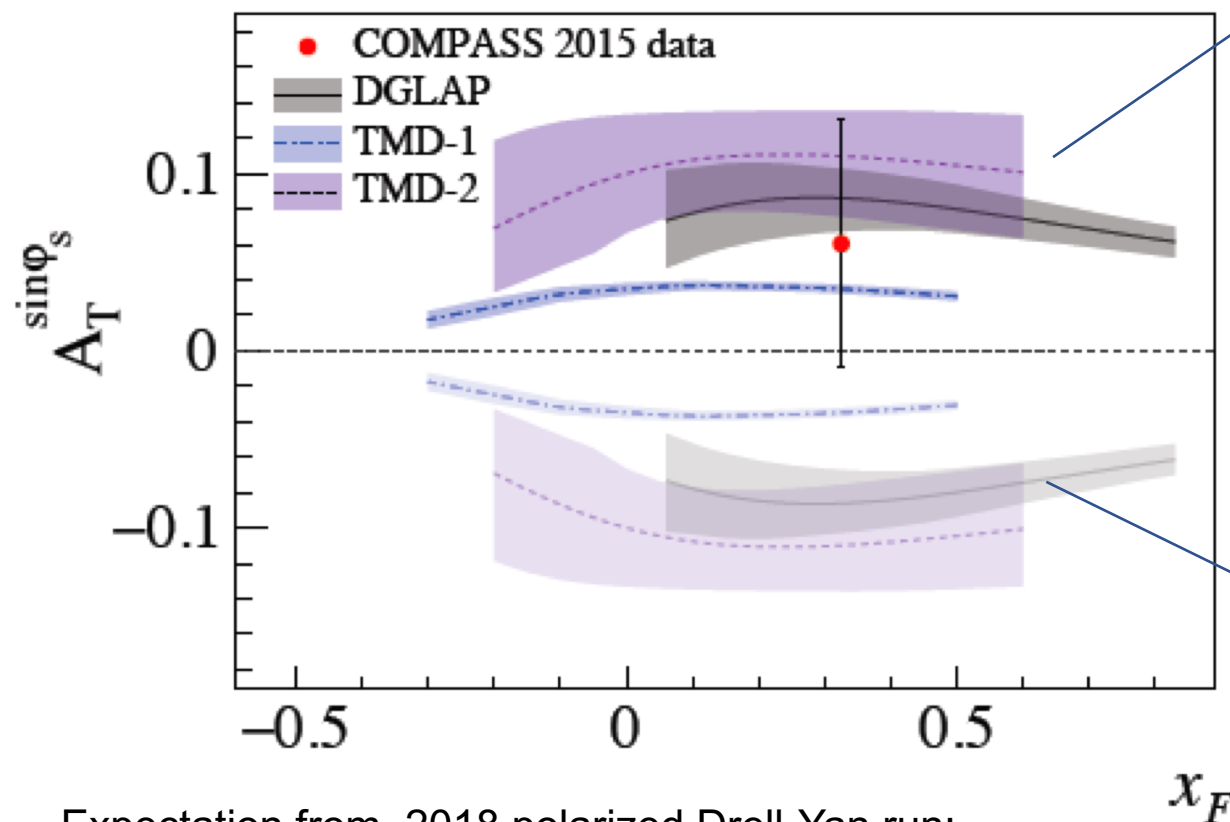
# COMPASS Drell-Yan Run 2015 Results

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



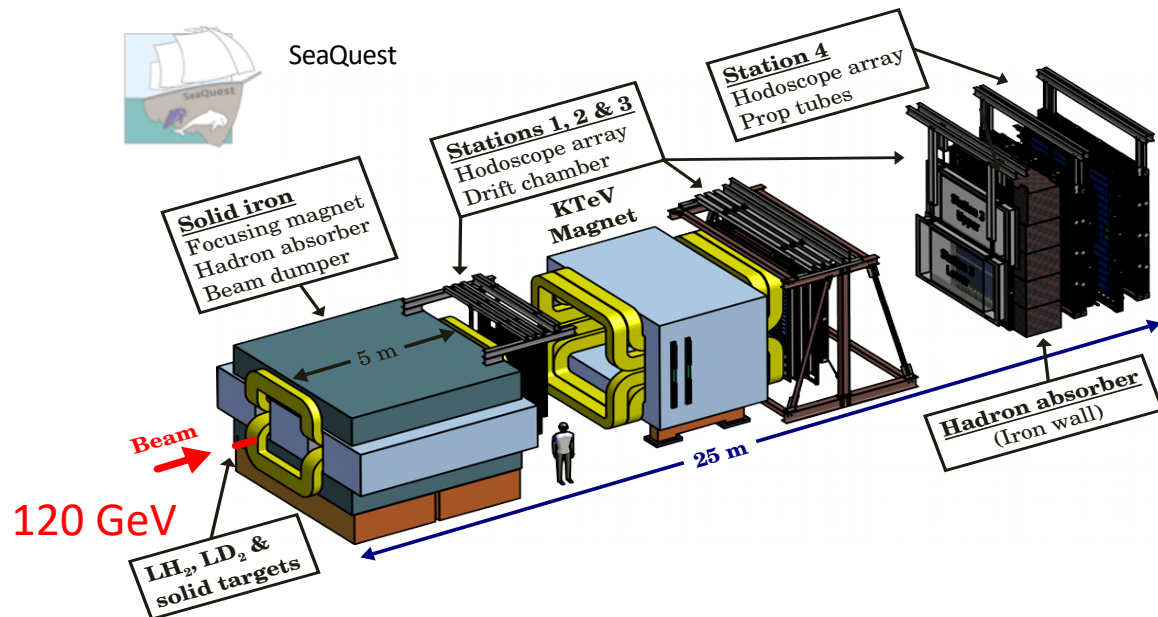
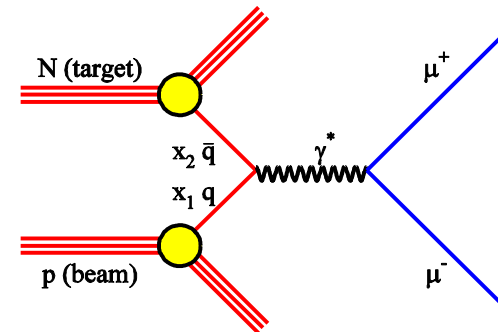
Sign change

NO Sign change

Expectation from 2018 polarized Drell-Yan run:  
Verification of the sign change by reducing of the error by a factor of  $\sim 1.5$ .



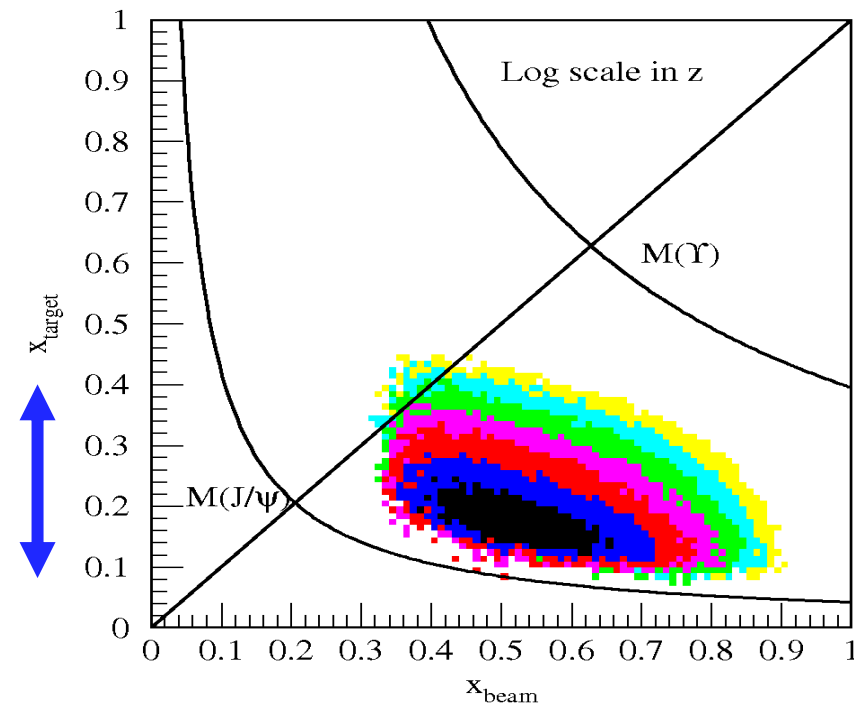
# Fermilab SeaQuest Fixed Target Drell-Yan



$$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [q_b(x_b) \bar{q}_t(x_t) + \bar{q}_b(x_b) q_t(x_t)]$$

$$\approx \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [q_b(x_b) \bar{q}_t(x_t)]$$

SeaQuest



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

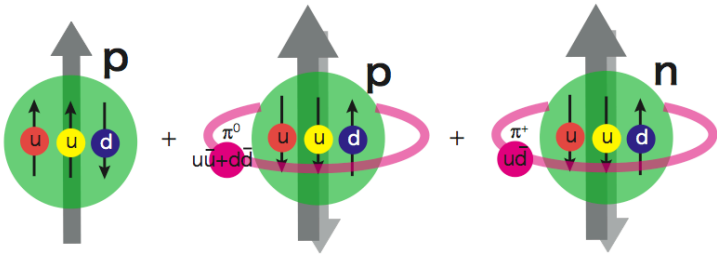
# Flavor Asymmetry of Sea Quarks at Intermediate x

Kei Nagai's talk

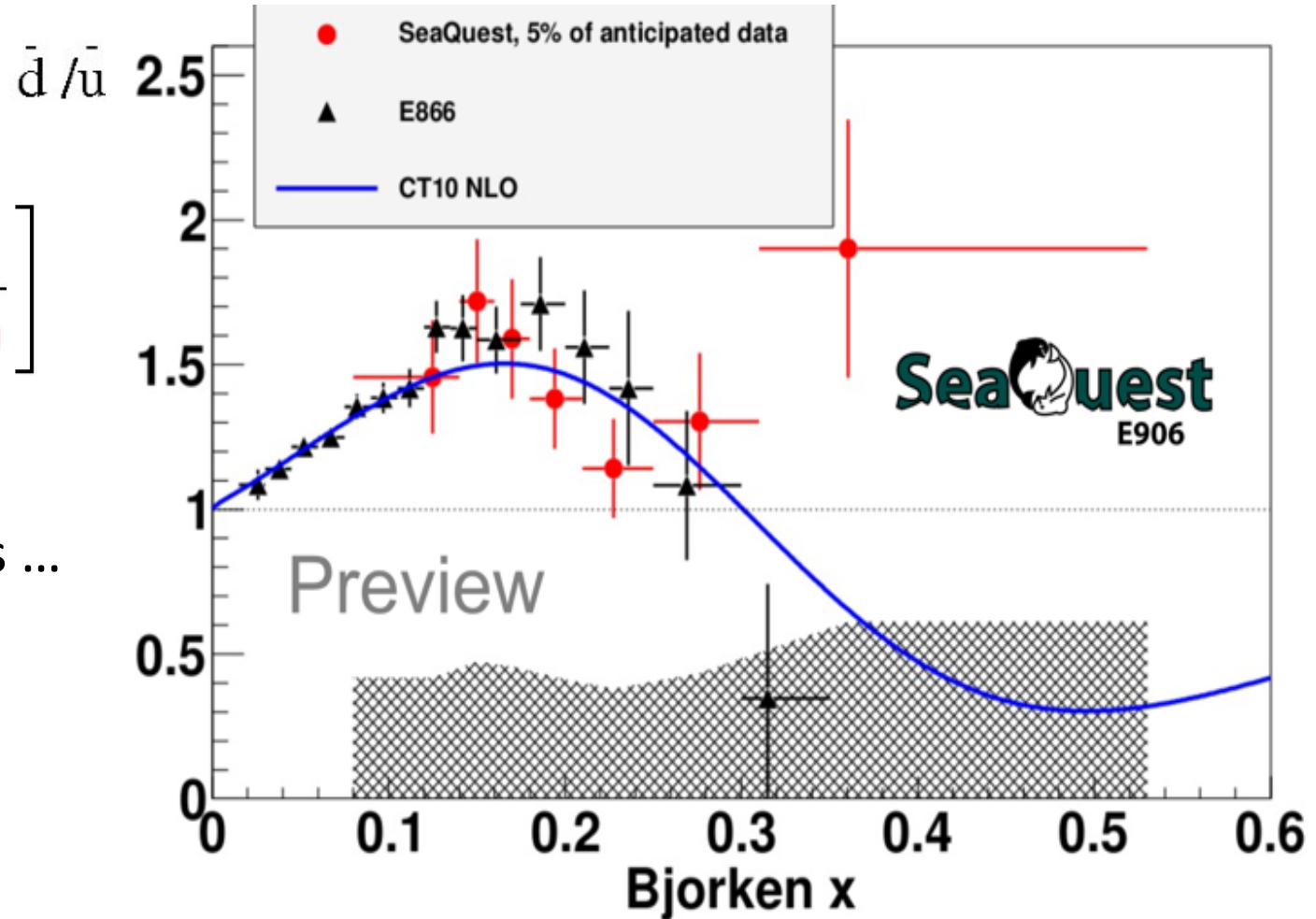
Proton vs “Neutron” targets:

$$\left. \frac{\sigma^{pd \rightarrow \mu^+ \mu^-}}{\sigma^{pp \rightarrow \mu^+ \mu^-}} \right|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]$$

This could lead to a very interesting physics ...



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



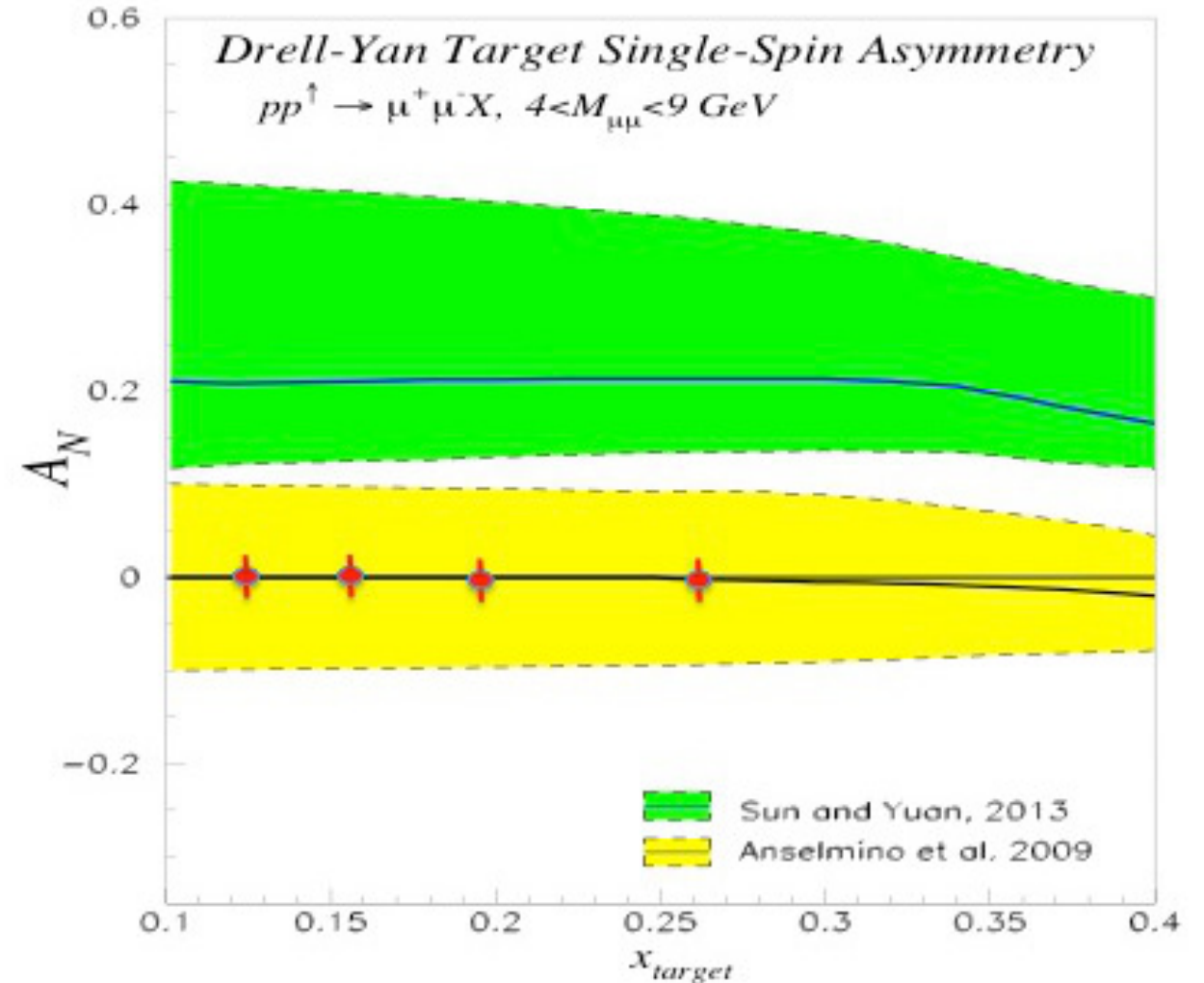
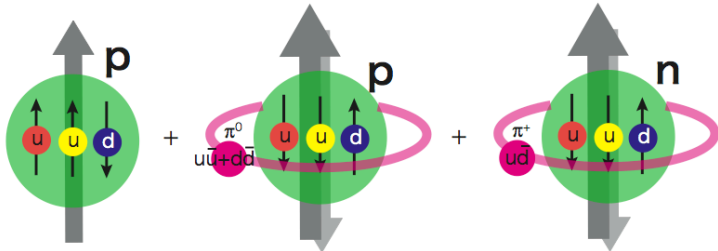
# SeaQuest/E1039 Projected Drell-Yan $A_N$

Y. Miyachi's talk

Sea quark Sivers:

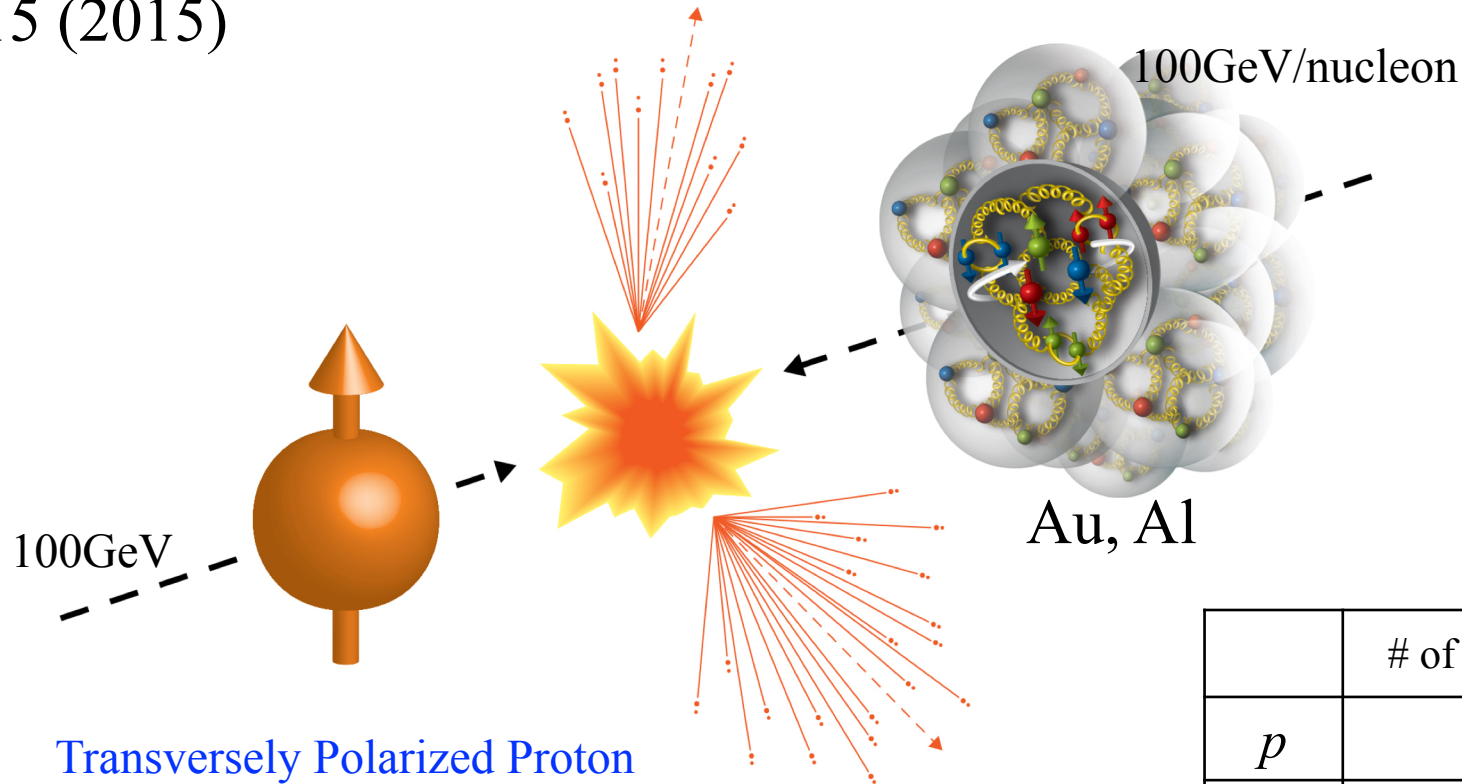
$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp, \bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Pion cloud model:



# First Transversely Polarized p+A collisions at RHIC

Run15 (2015)

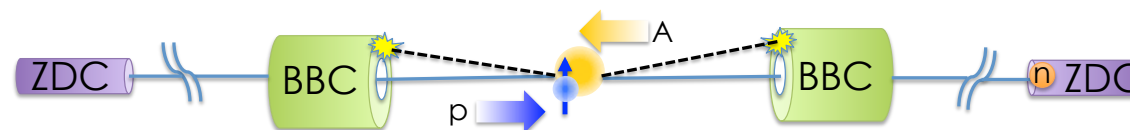
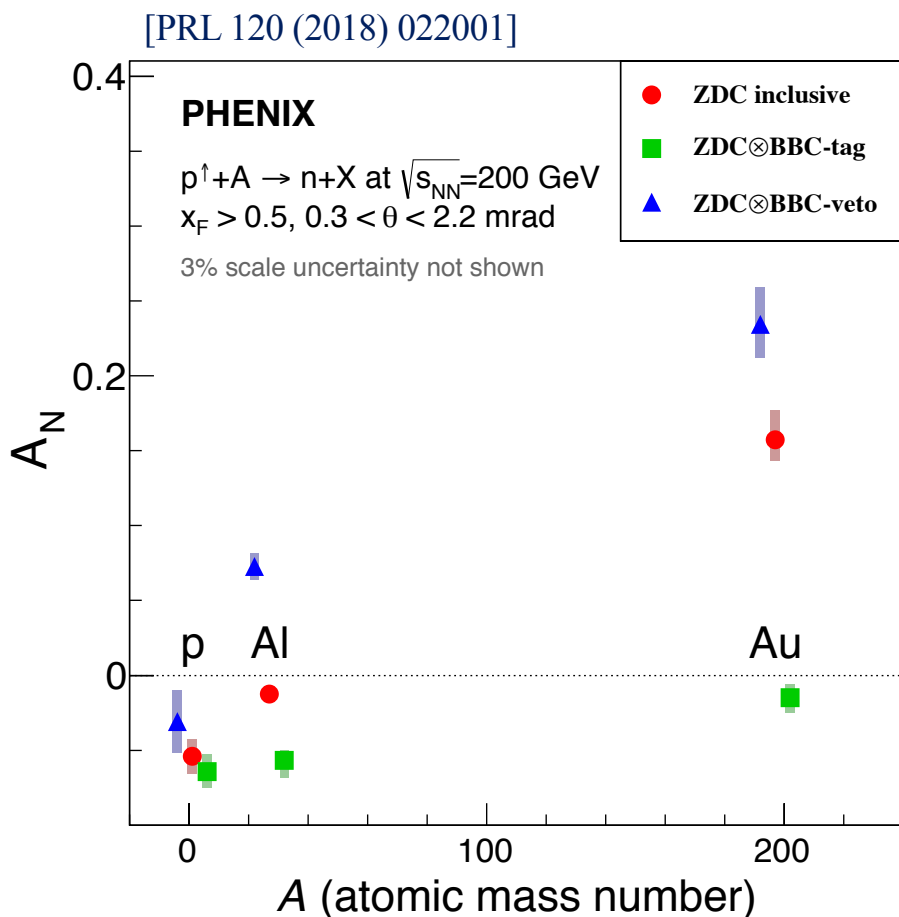


	# of proton	# of neutron
$p$	1	0
Al	13	14
Au	79	118

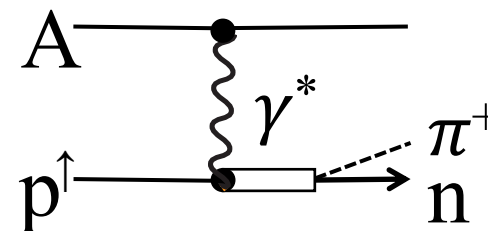
# Run15 p+Au: a Surprise!

I. Nakagawa's talk

Unexpected large pAu and pAl asymmetries observed compared to that of pp

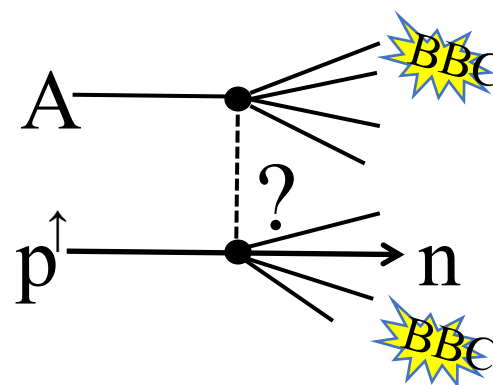


BBC Veto



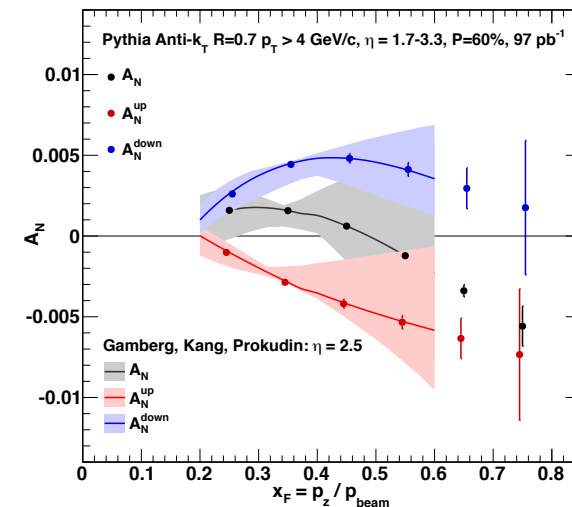
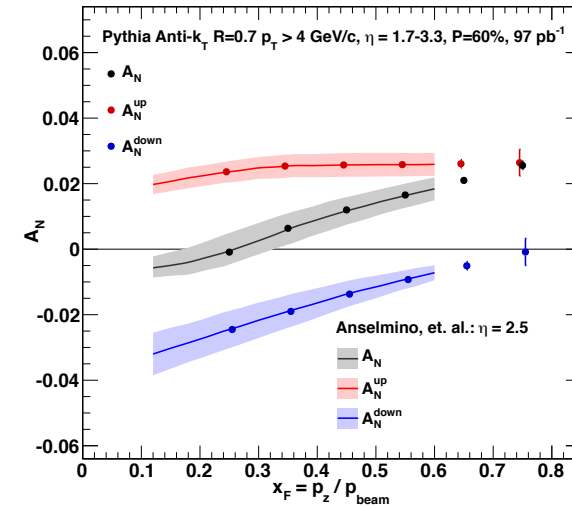
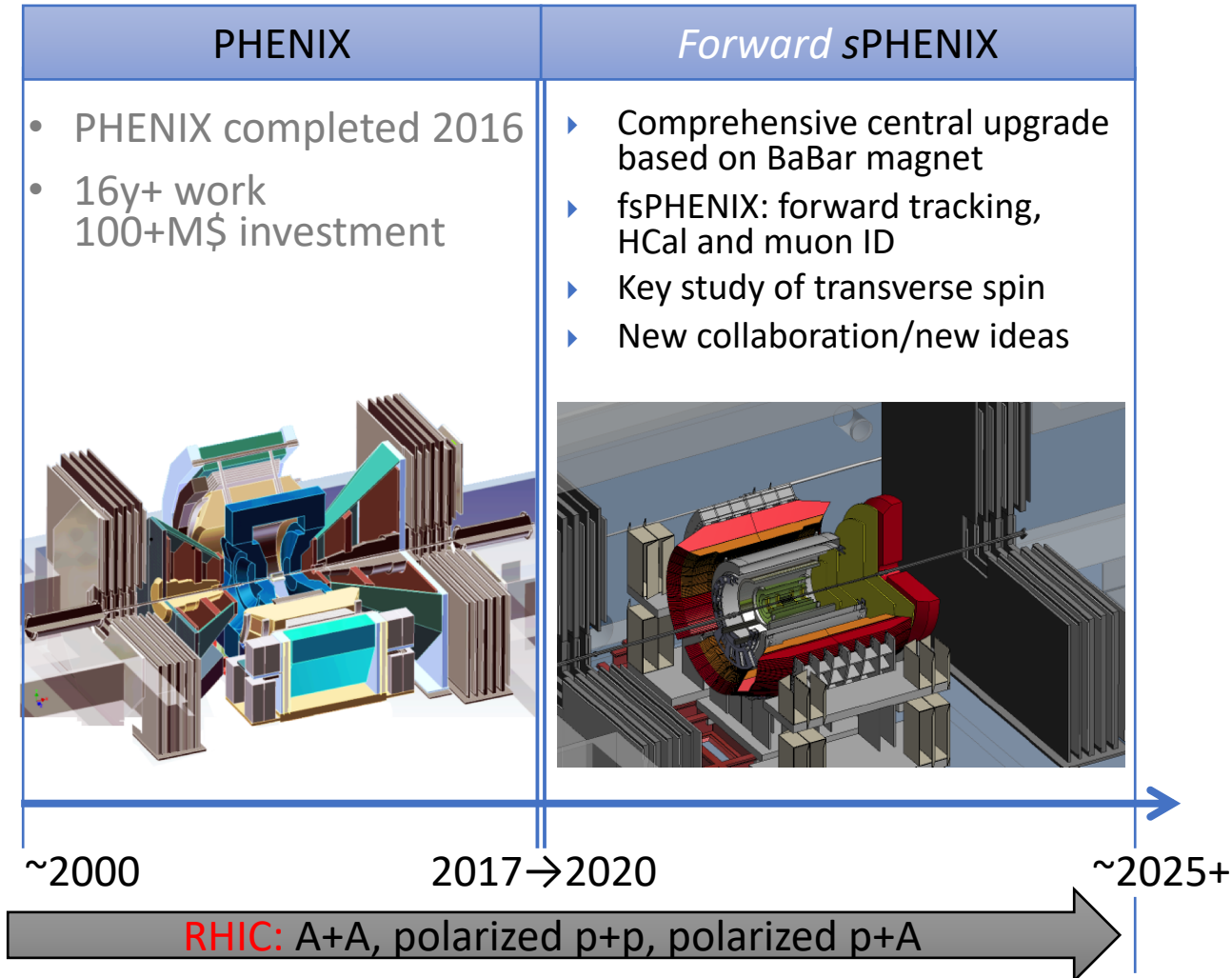
$$A_N > 0$$

BBC Tag



$$A_N < 0$$

# Future at RHIC: PHENIX -> sPHENIX (-> EIC@RHIC)





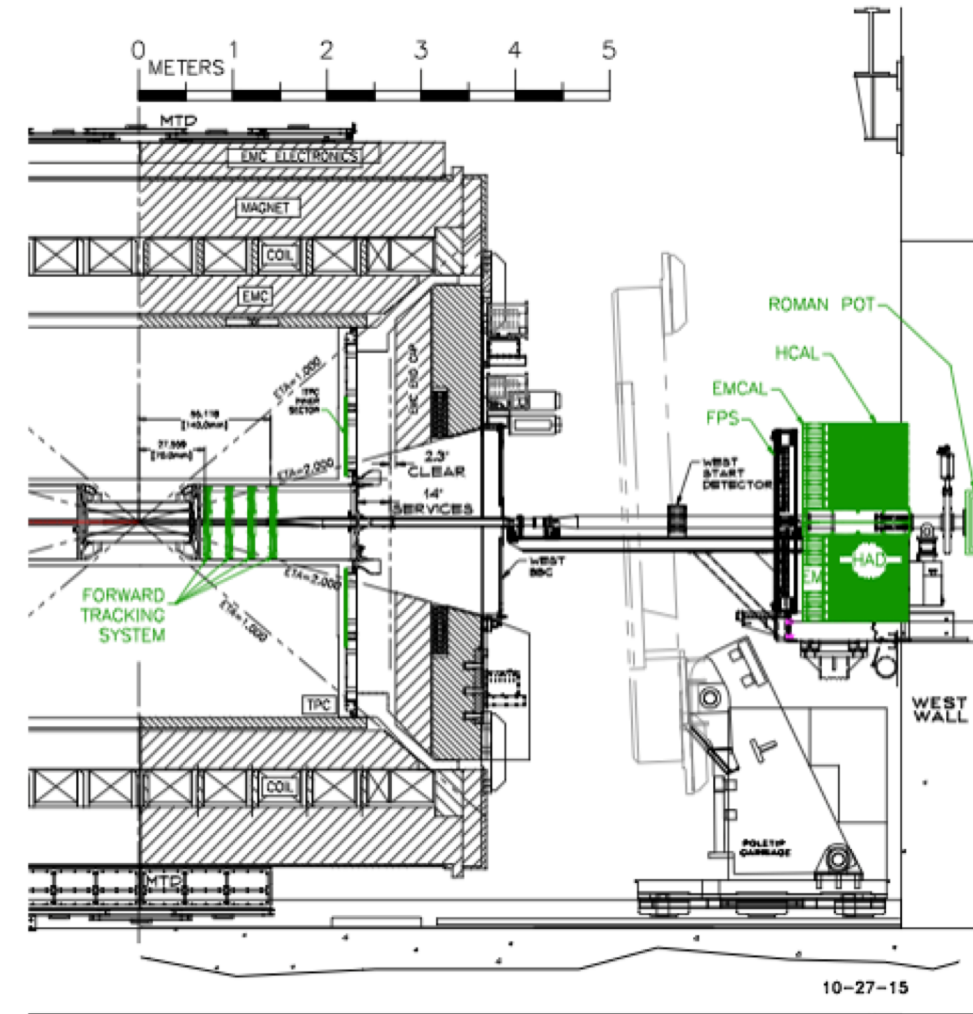
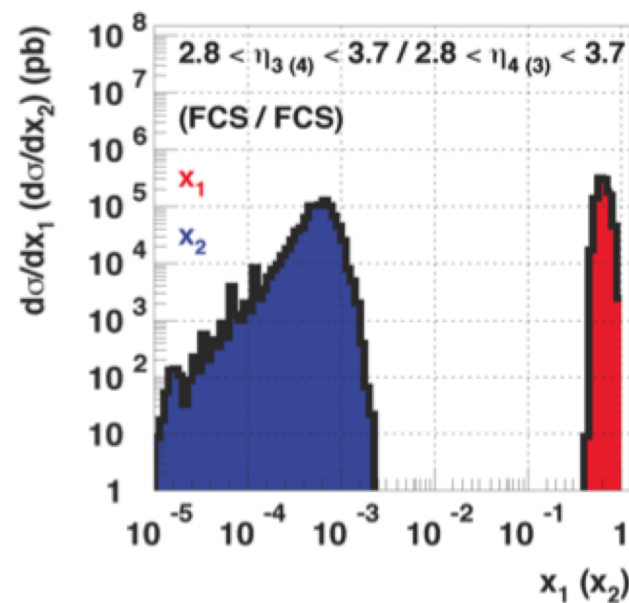
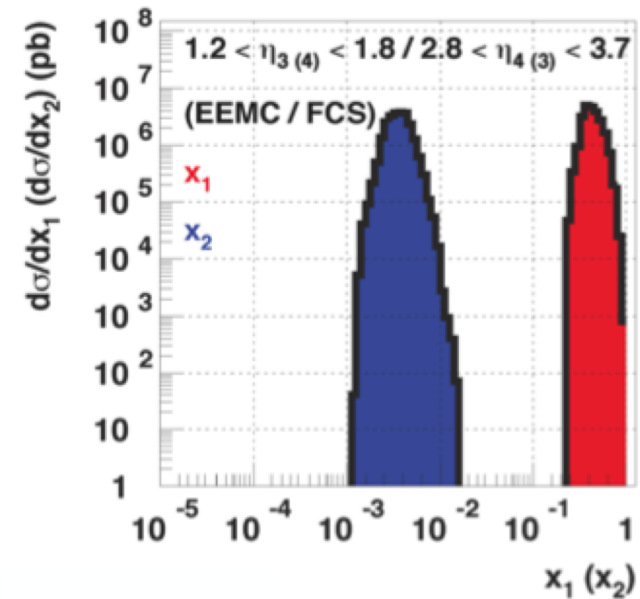
# STAR Forward Upgrade Proposal

## To 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	$\approx 60\%/\sqrt{E}$



# Other Future Facilities

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

SPD @NIKA

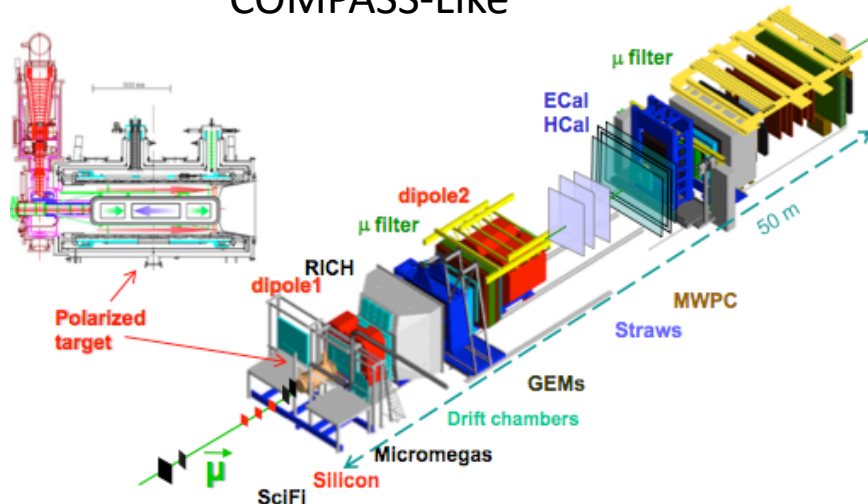


Letter of Intent (Draft 2.0)

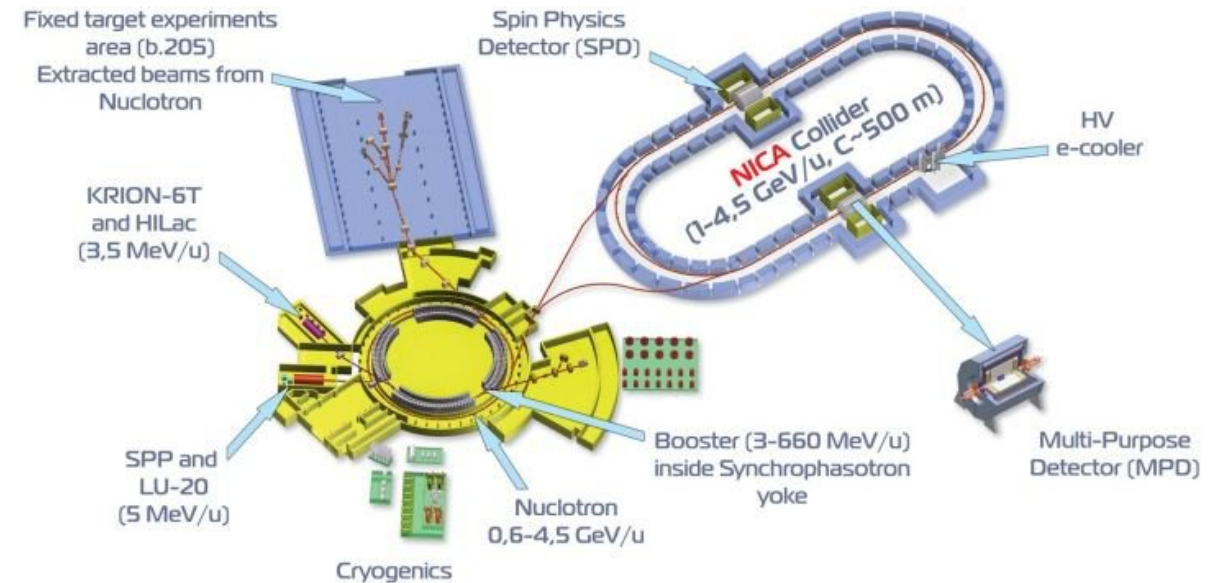
A New QCD facility at the M2 beam line of the CERN SPS

<http://arxiv.org/abs/1808.00848>

COMPASS-Like

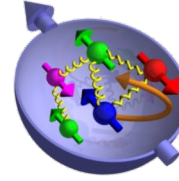


**Superconducting accelerator complex NICA**  
(Nuclotron based Ion Collider fAcility)

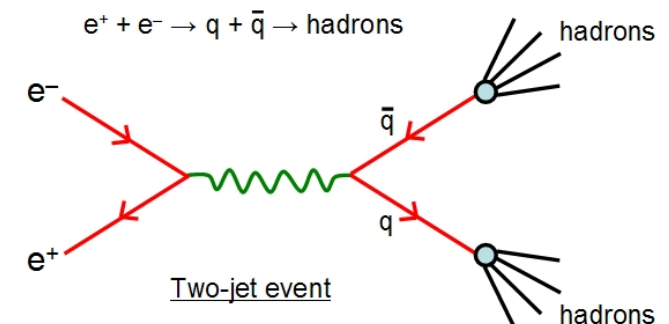
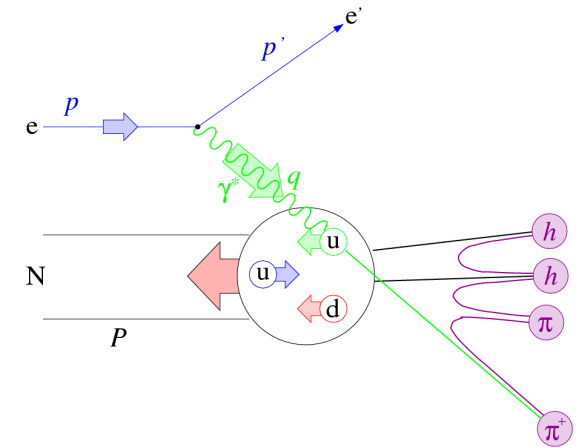
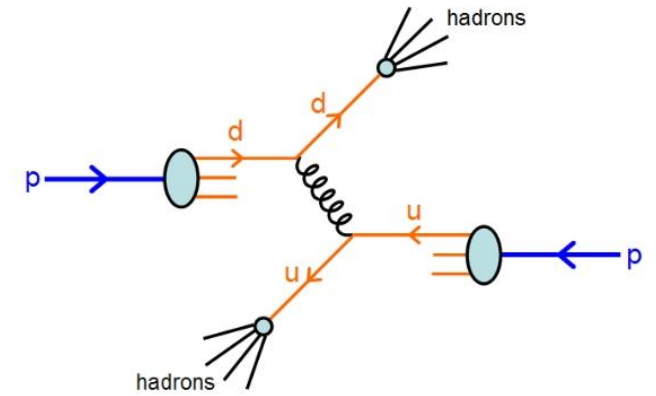




# Summary



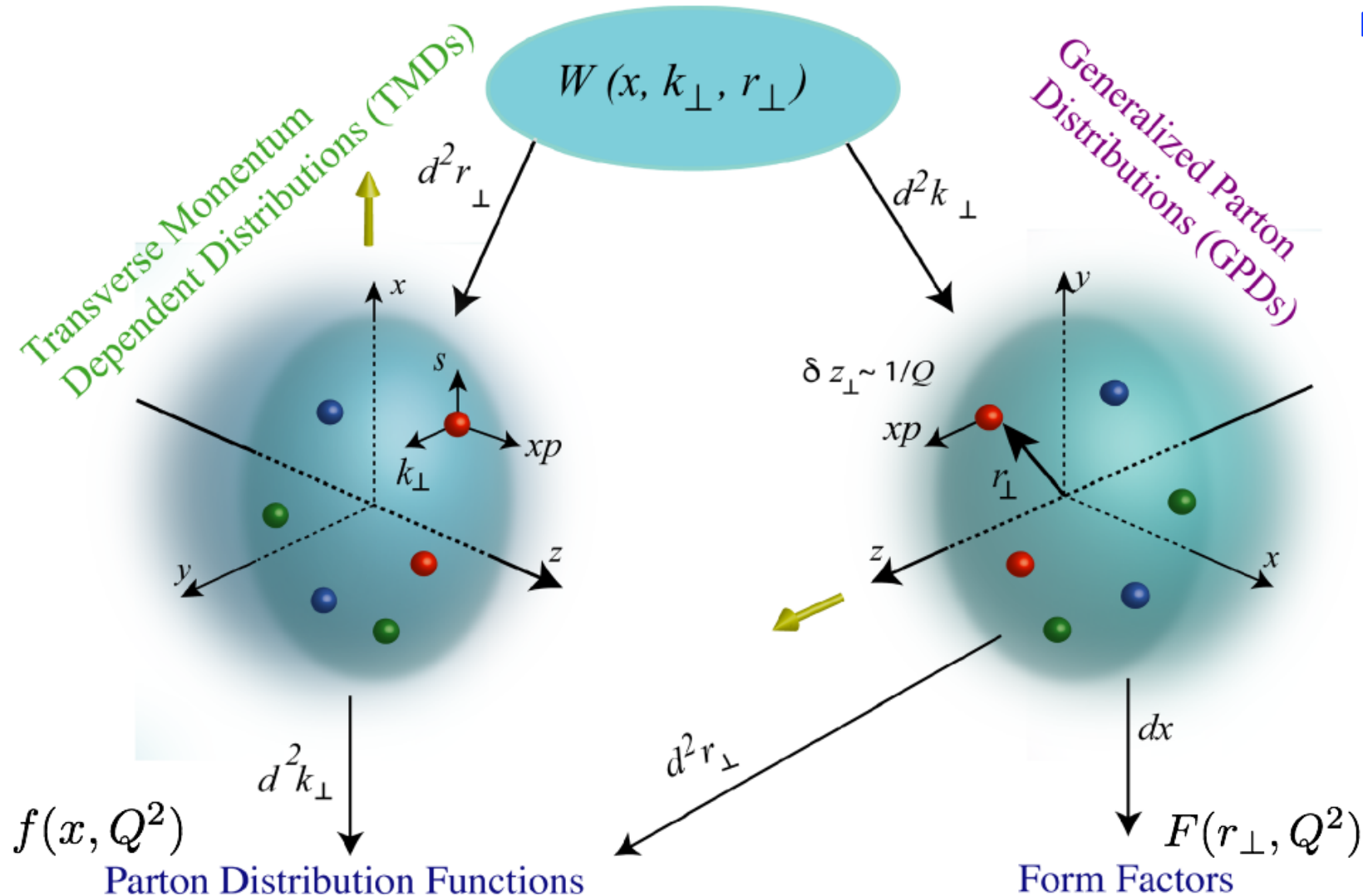
- Proton(hadron) collisions have provided:
  - Very rich & active nucleon structure physics program
    - RHIC, Fermilab, COMPASS ...
  - Unique electroweak probes at high energy @RHIC
  - Independent test of the universality of QCD description of strong phenomena in pp and DIS
- Will continue playing a key role in exploring the fundamental nature of nucleon structure and strong interactions
  - Complementary to future EIC program



# backup

# Toward a Unified Picture of Nucleon Structure

## Wigner Distributions



Momentum and Spatial Tomography

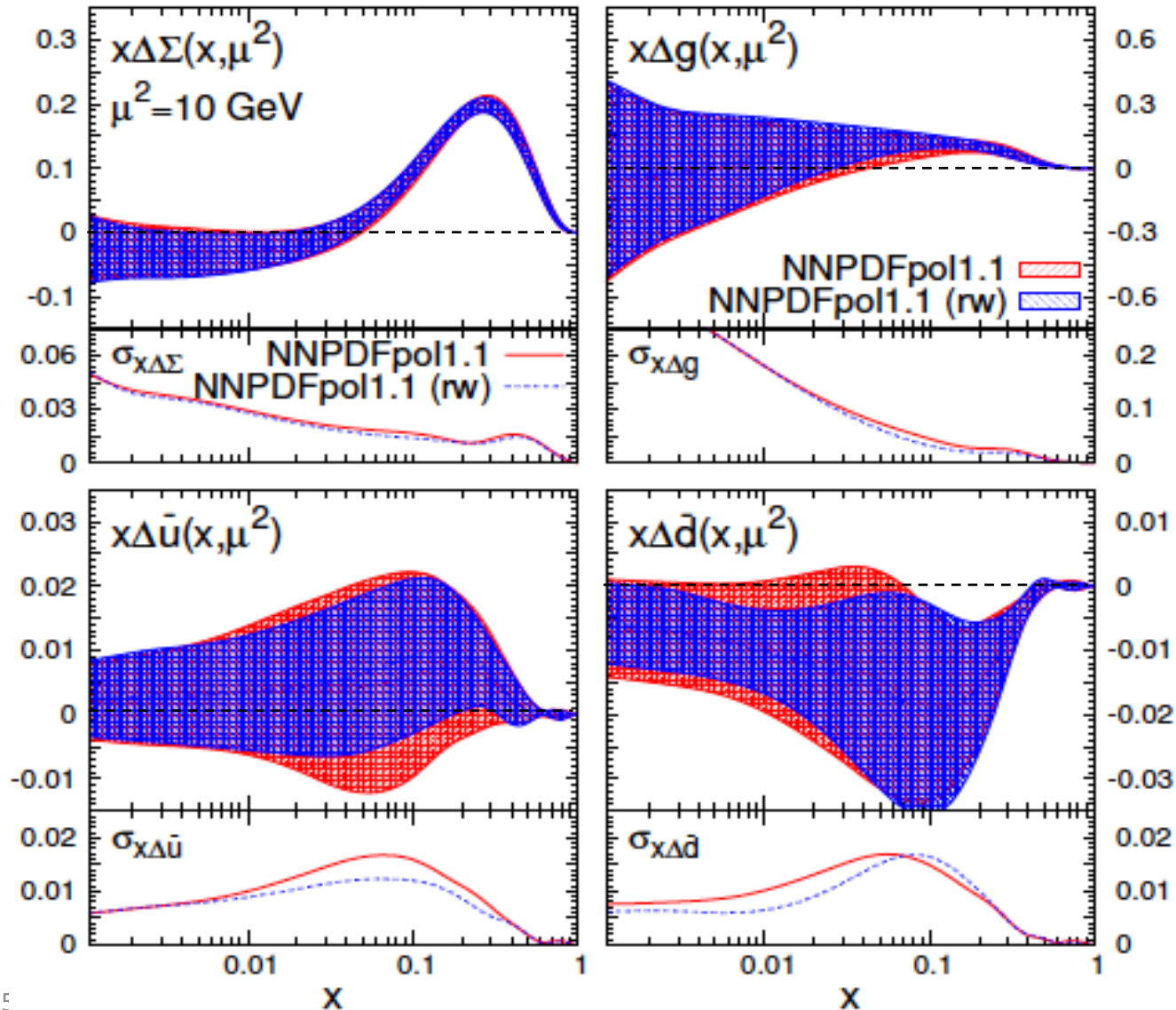
Some data, recent progress

Good data, long history

# Latest Pol NNPDFPol Global Fit

arXiv:1702.05077

-SI/DIS data  
-RHIC data



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

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

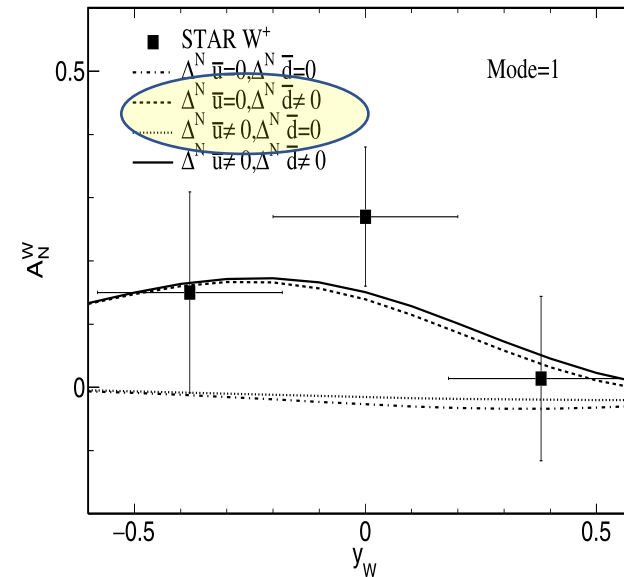
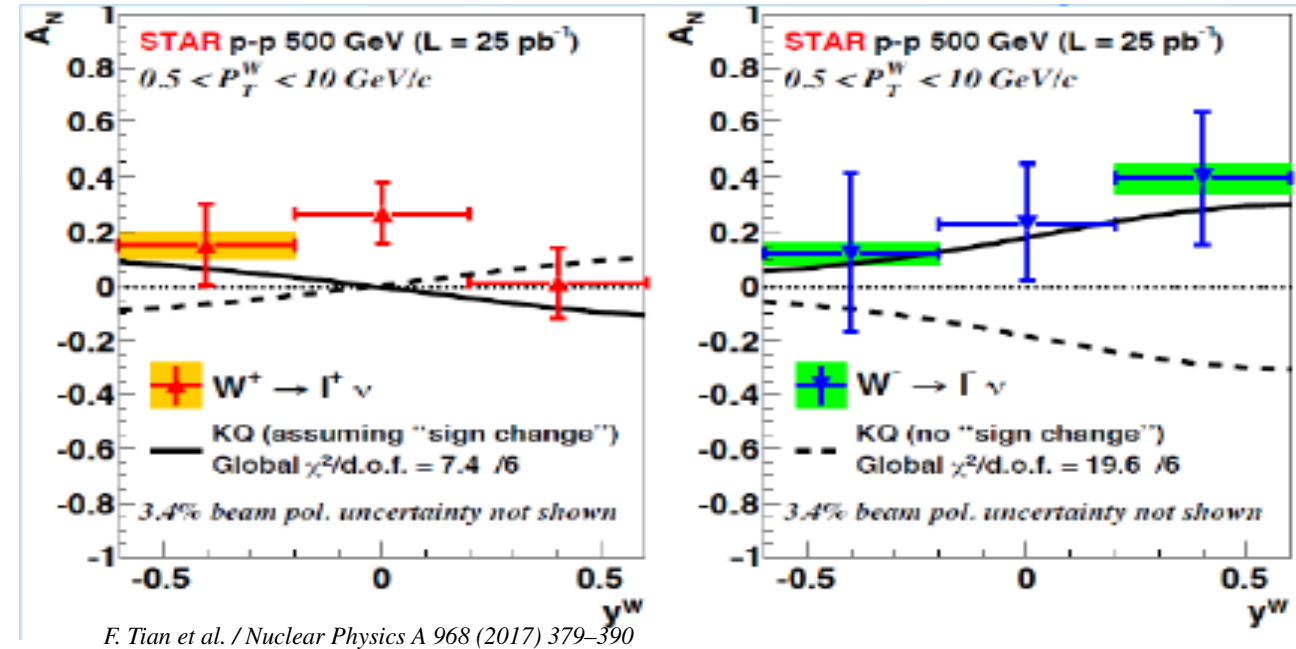
$$A_N(W^-) \sim \left( \Delta^N f_{\bar{u}/p^\uparrow} \otimes f_{d/p} + \Delta^N f_{d/p^\uparrow} \otimes f_{\bar{u}/p} \right)$$

## RHIC data:

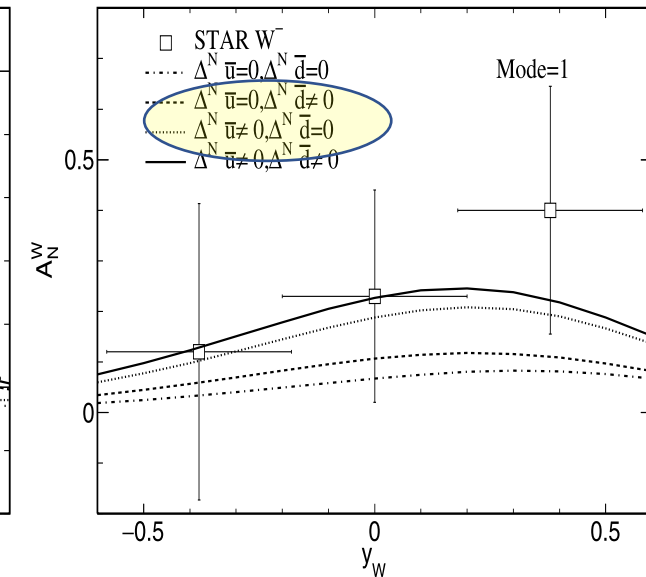
- A mix of valence and sea quark Sivers
- Quark flavor identified
- High  $Q^2$
- Statistically limited,  $\sim 10\%$
- **Possible large  $\bar{d}$  Sivers contributions**

## E1039:

- low  $Q^2$
- Good statistics,  $\sim 1\%$



(b)  $A_{W^+}^N$



(a)  $A_{W^-}^N$