Probing Hadron Structure at the Electron-Ion Collider, ICTS

# Hadron Structure in Experiments

## Part. 2

Sanghwa Park
(Jefferson Lab)

# Outline of the lecture

- What have we learned from Part. 1?
  - Basics of hadron structure experiments
    - Accelerators and particle detectors
    - Deep Inelastic Scattering experiments
    - DIS Kinematics reconstruction

- Part. 2: Collinear observables and measurements
  - Continue on DIS data - PDF extraction
  - Parton distributions at large-x
  - Flavor asymmetry of sea
  - Polarized spin structure

- Part. 3: Beyond collinear

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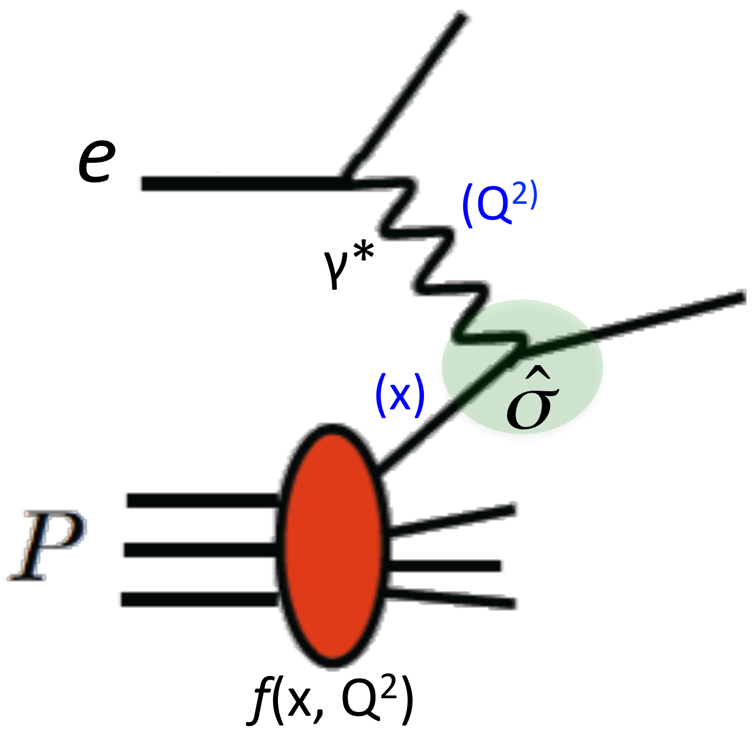
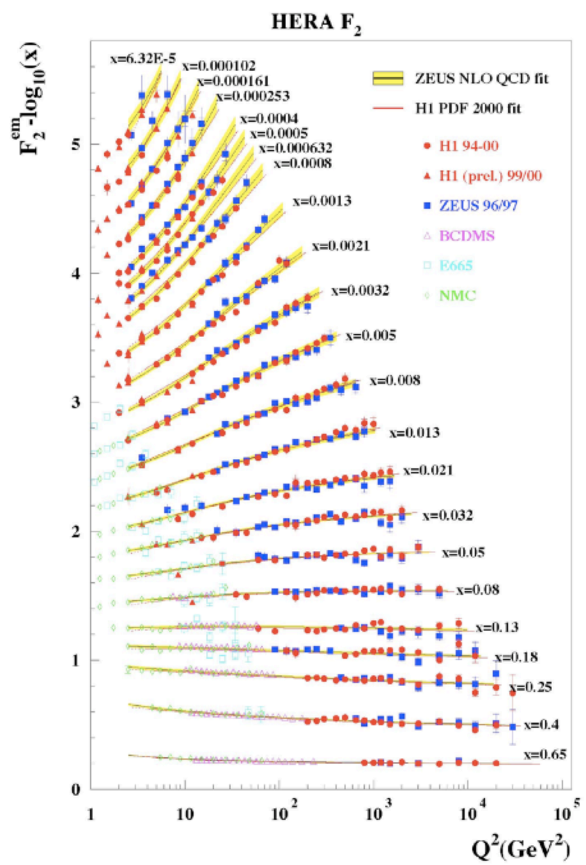
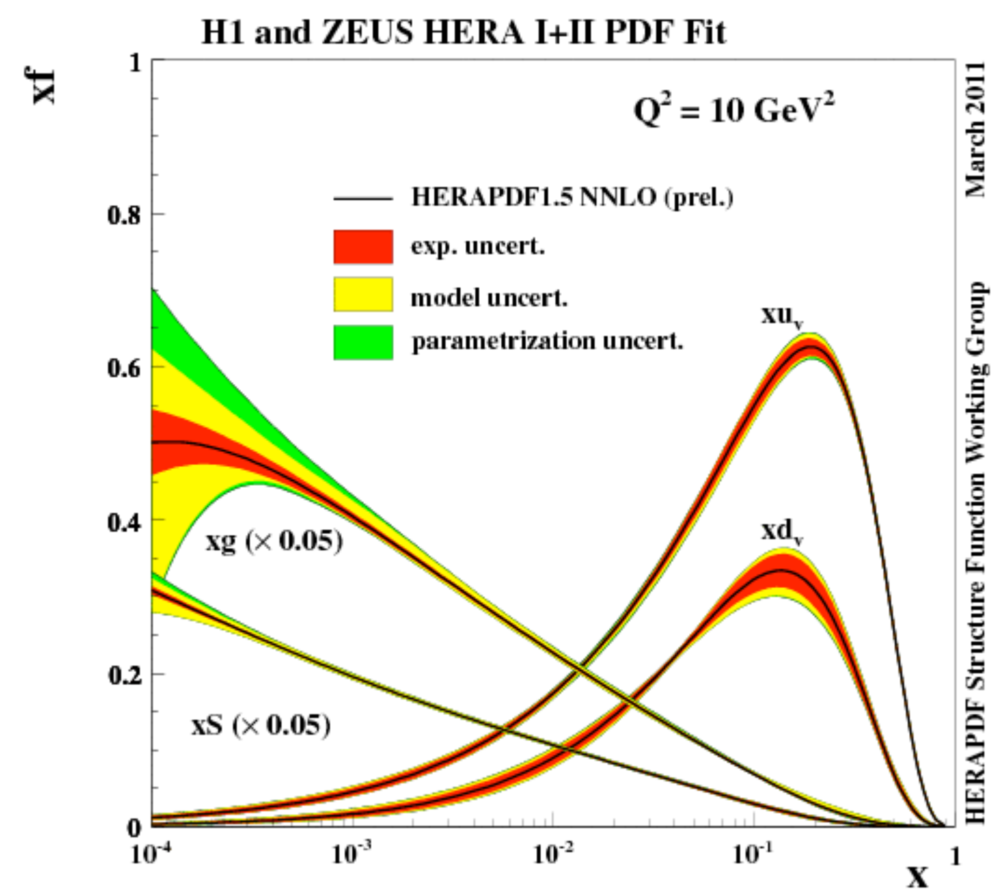
# Experimentalist's perspective on PDF extraction




**Hard probe** "see"s quarks with probability of $f(x, Q^2)$ for each flavor

Structure function extracted from the measured cross section (**observables**)

# Experimentalist's perspective on PDF extraction

- We want to know well about all quark flavors, and gluon
- DIS "sees" the collection of quarks
    - Strong constraint on u quark

$$F_2(X, Q^2) = \sum_i e_i^2 x f_i(x, Q^2)$$

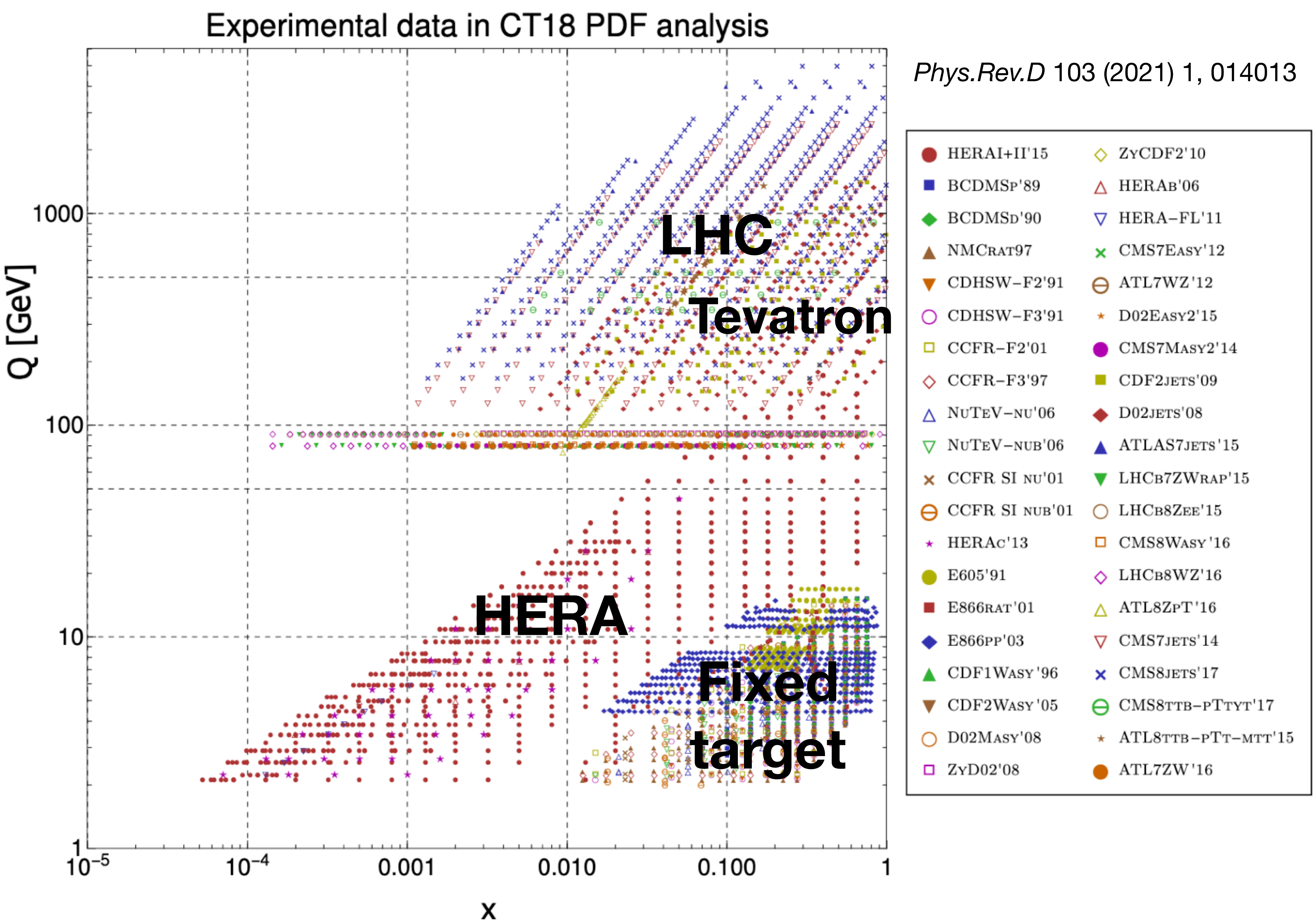
    - Gluons only indirectly accessed
    - Data only at a given set of $Q^2$

Quark-gluon coupling:
PDFs evolve with the scale!
(DGLAP equations)


- Increase x, $Q^2$ level arm with good precision data
- Flavor separation measurements
- Process directly sensitive to the gluon

# World Data for Global QCD Analysis

*Phys.Rev.D* 103 (2021) 1, 014013



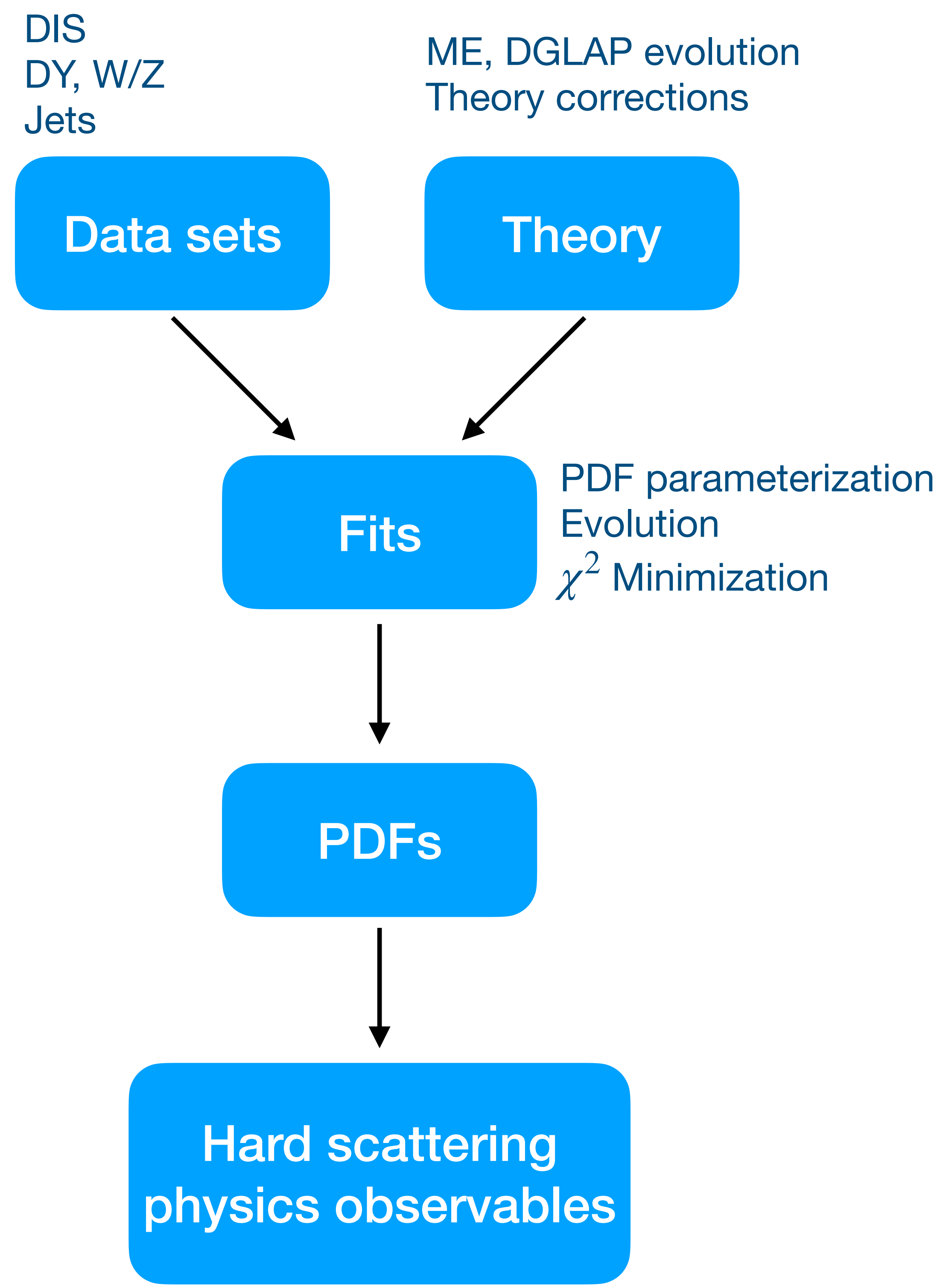
# Global QCD analysis in practice

- Traditional global fits assume PDFs in a parameterized form at initial scale $Q_0$ -> evolve to any other Q using DGLAP evolution
- Standard five parameter form for most parton species

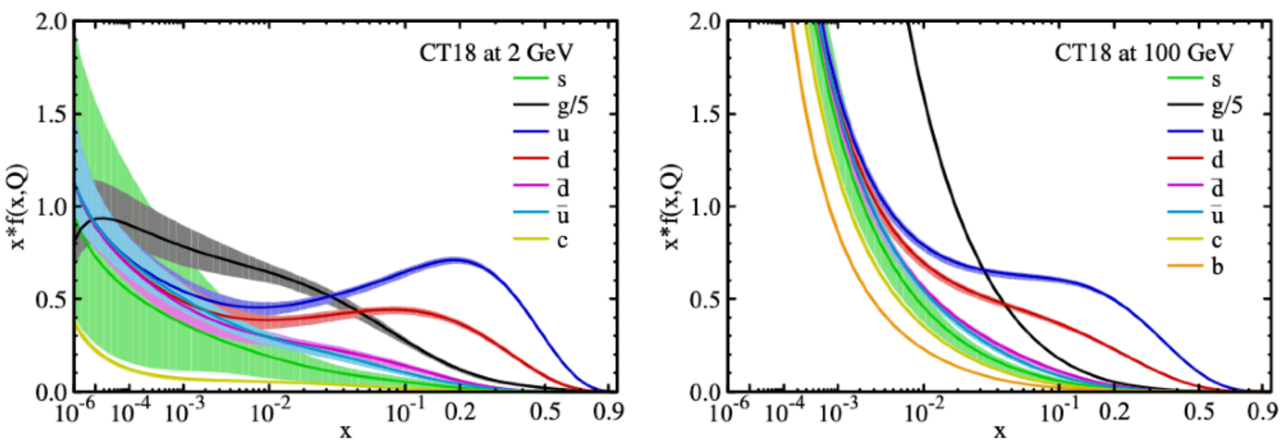
$$xf(x, Q_0^2) = Nx^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\delta x)$$

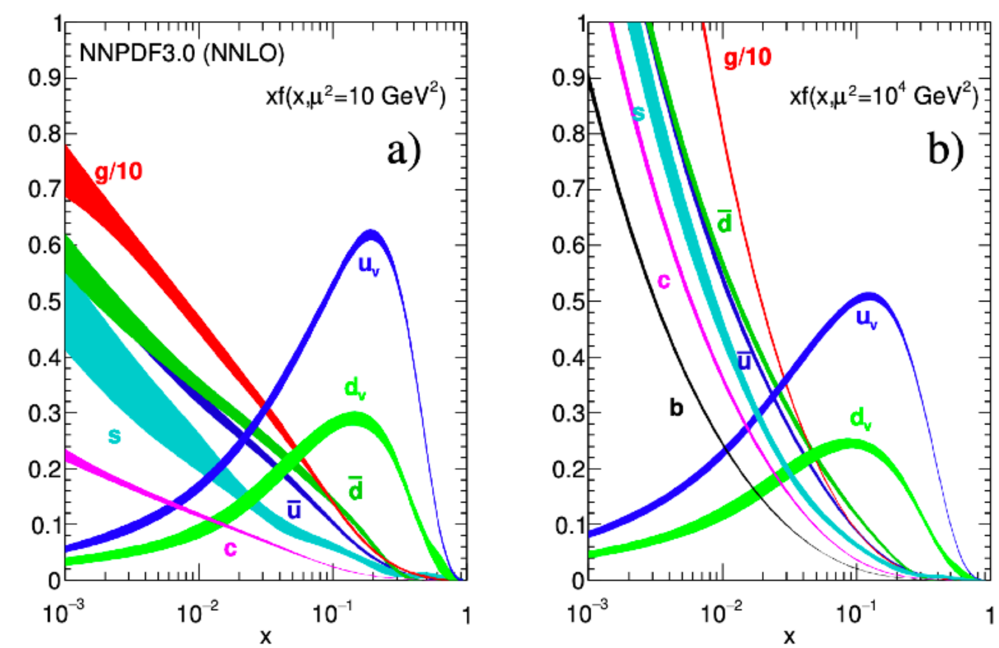
  - Some PDF parameters are prefixed/constrained. For example, normalization parameters for u, d are fixed by valence quark number sum rules and for gluon by the momentum sum rule.

- Number of free parameters to fit:
  -$\lambda_{QCD}$ and PDF parameters, other non-DGLAP parameters (e.g. nuclear corrections)
  - Data normalizations
- Use the PDFs to calculate the chosen hard scattering processes
- Vary the parameters to optimized the fits (iteration)



# Examples of global PDF fits

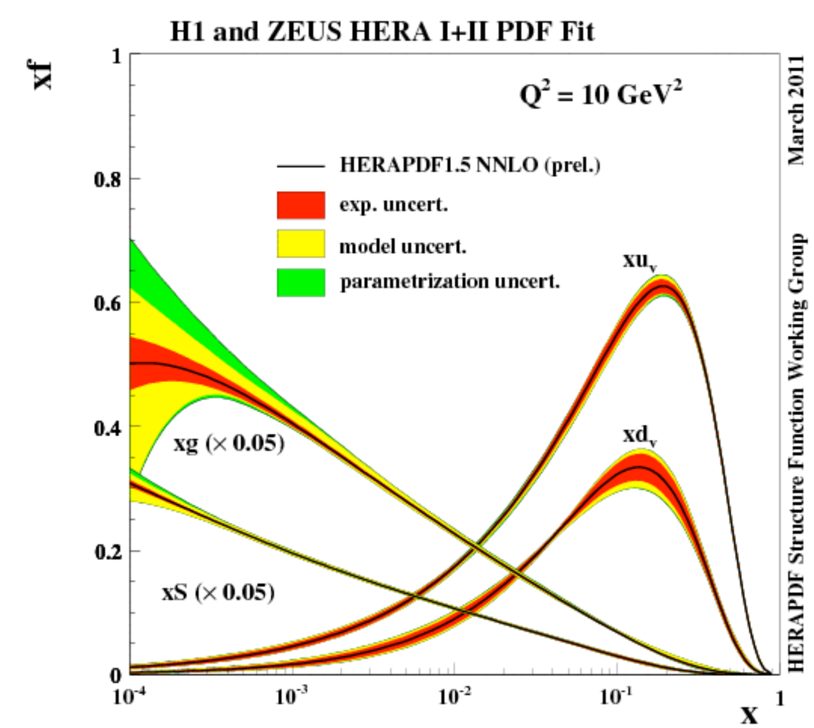


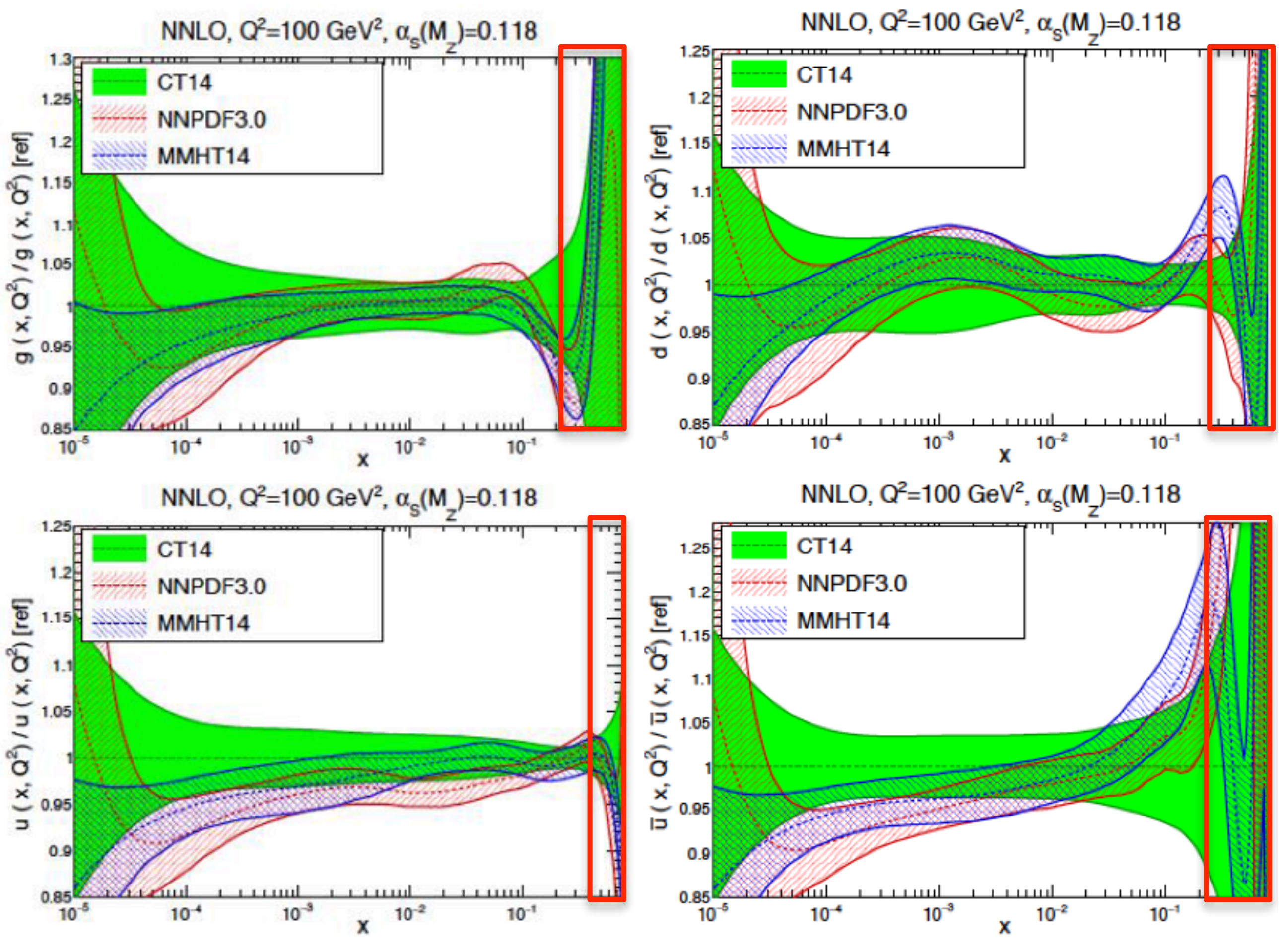

A. Accardi (HiX2019)

| | JLab & BONUS | HERMES | HERA I+II | Tevatron W,Z | LHC | ν+A di-μ | Large-x treatment: Nucl. & offsh | HT TMC | Flex *d* | low-W DIS |
|---|---|---|---|---|---|---|---|---|---|---|
| **CJ15 *** | ✓✓ | ✓ | ✓ | ✓ | *in prog.* | ✗ | ✓✓ | ✓ | ✓ | ✓ |
| CT18 | | | ✓ | ✓ ¤¤ | ✓ | ✓ | | | ✓ | |
| MMHT14 | | | ¤¤¤ | ✓ ¤¤ | ✓ | ✓ | ✓ | | | |
| NNPDF3.1 | | | ✓ | | ✓ | ✓ | | TMC only | | |
| JR14 | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | |
| **ABMP16/AKP** | | | | ✓ ¤¤ | ✓ | ✓ | ✓/✓ | ✓ | (✓) | ✓ |
| HERAPDF2.0 | | | ✓ | ¤ | | | | | | |

* NLO only ** No jet data ¤ see 1503.05221 ¤¤¤ see 1508.06621 ¤¤ no reconstructed W



# PDF uncertainties



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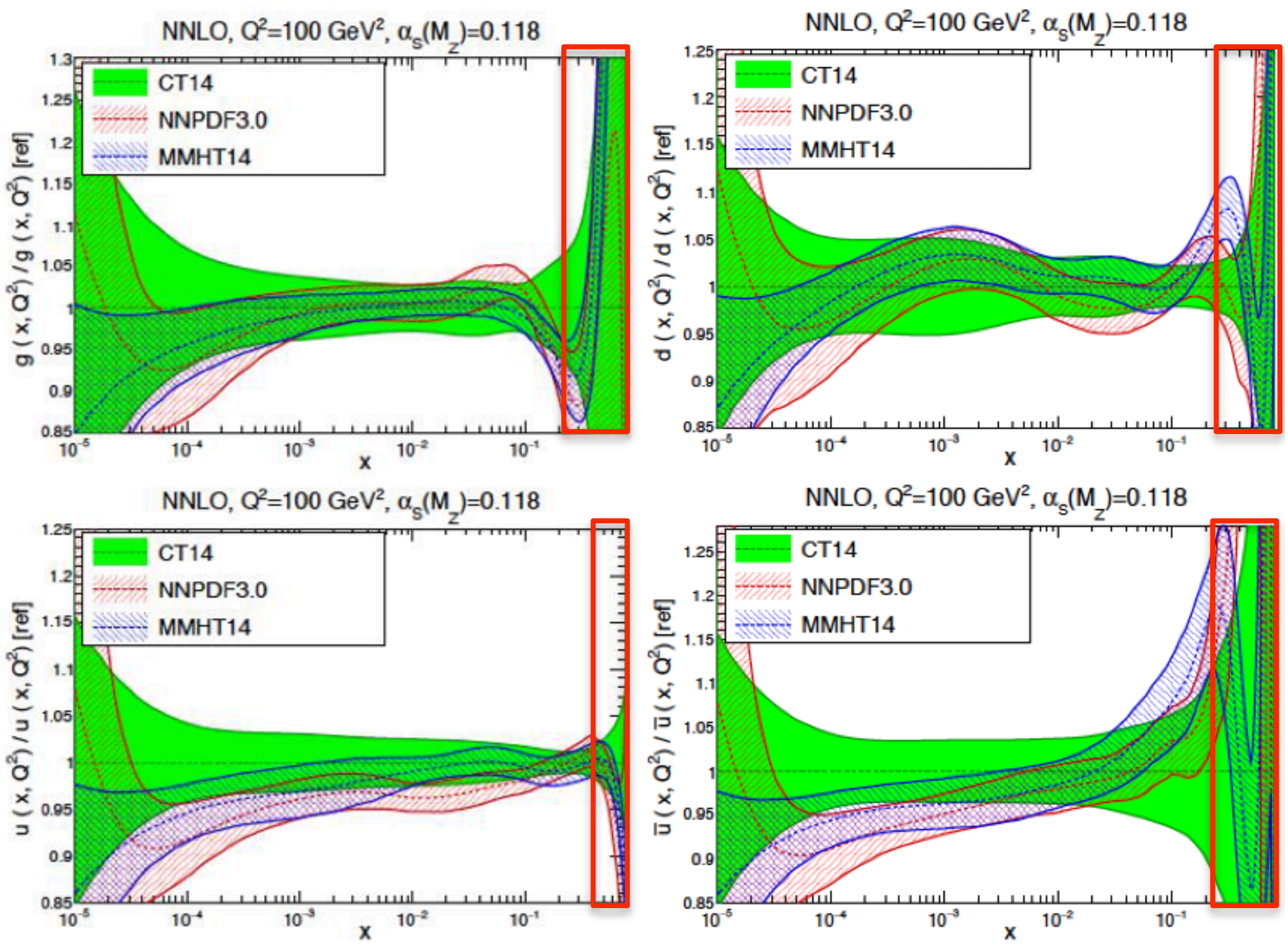
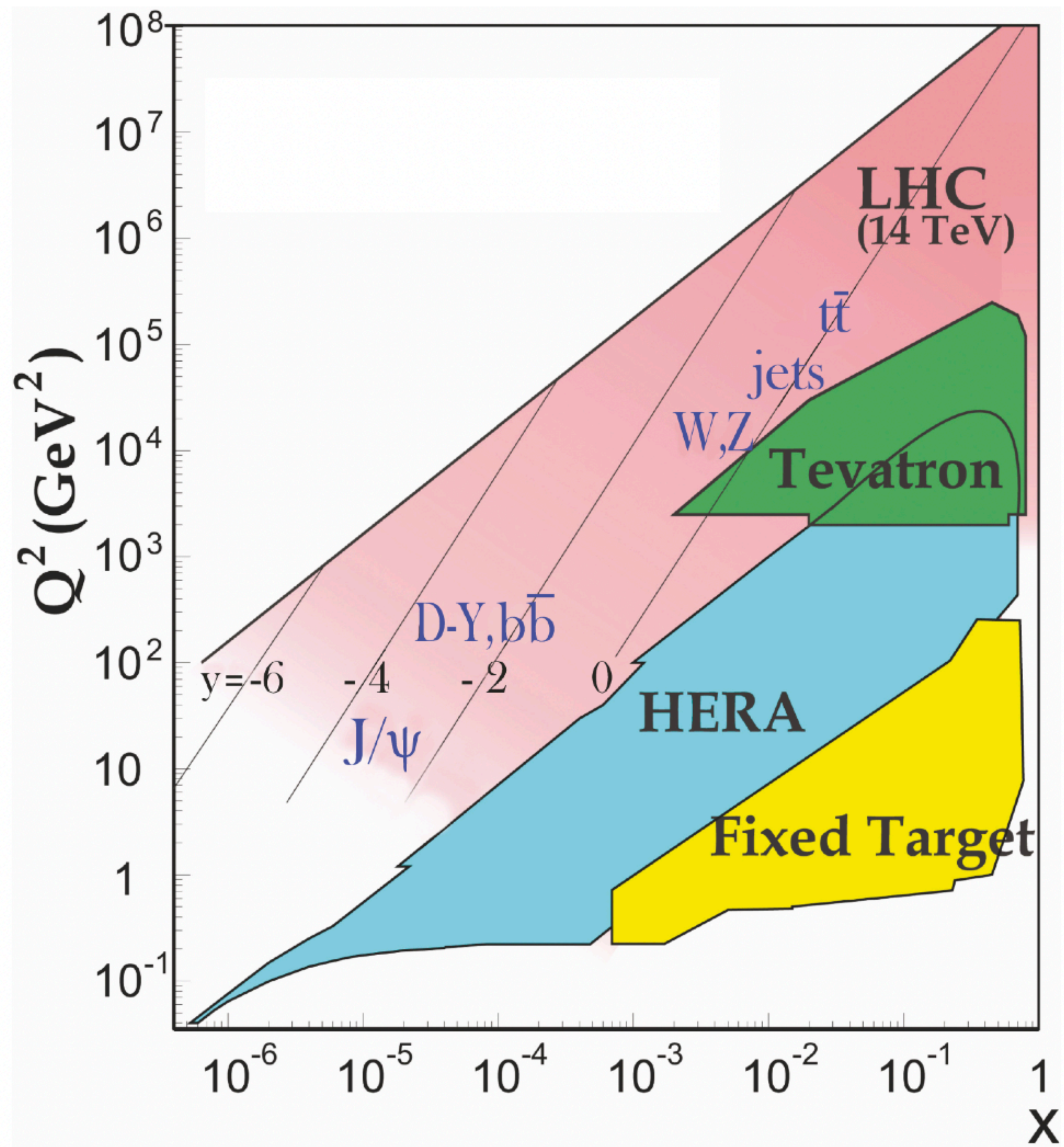



- Poorly constrained in small and large-x
  - Small-x:
    High energy physics at LHC
    Parton dynamics at high gluon density
  - Large-x:
    valence region
    Study non-perturbative dynamics of nucleon

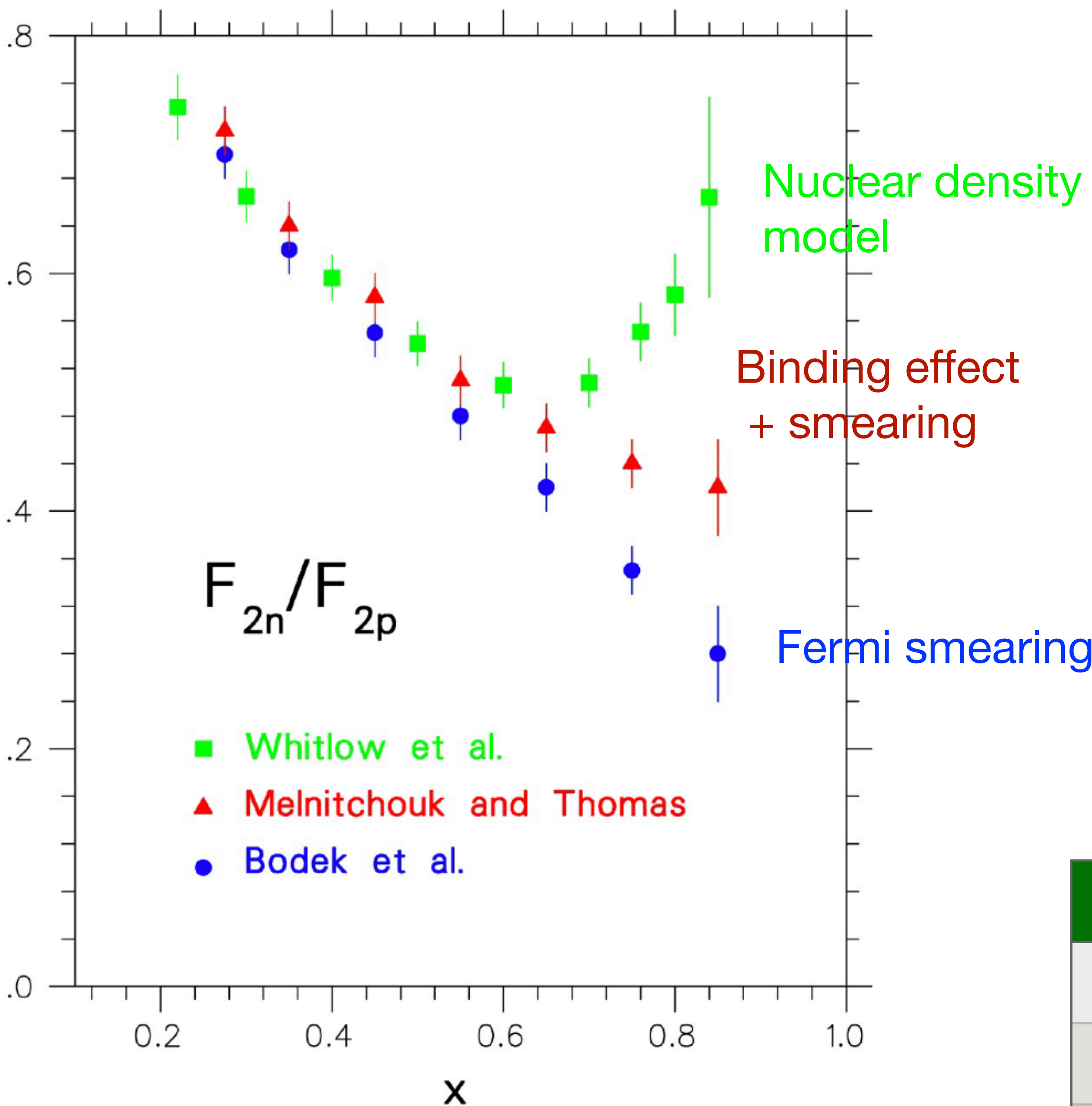
# Nucleon structure at large-x, low $Q^2$




- Fixed-target
- Valence structure of hadron
  - Partonic structure in the valence region defines a hadron
- F2n/F2p ratio (d/u ratio) at x-> 1 limit unknown
  - Predictions from different theory models
- Provide important input for PDF analysis at large-x
  Improve constraints on PDFs at large x, low Q2

-> (evolution) low x, high Q2

# Predictions for $F_2$(n/p), d/u at x→1




$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

**At large x,**

$$\frac{F_2^n}{F_2^p} \approx \frac{1+4(d/u)}{4+(d/u)}$$

**Testing ground for theory models**

| | $F_2$(n/p) | d/u |
|---|---|---|
| SU(6) | 2/3 | 1/2 |
| Diquark model/Feynman | 1/4 | 0 |
| Quark model/Isgur | 1/4 | 0 |
| pQCD | 3/7 | 1/5 |
| QCD counting rules | 3/7 | 1/5 |

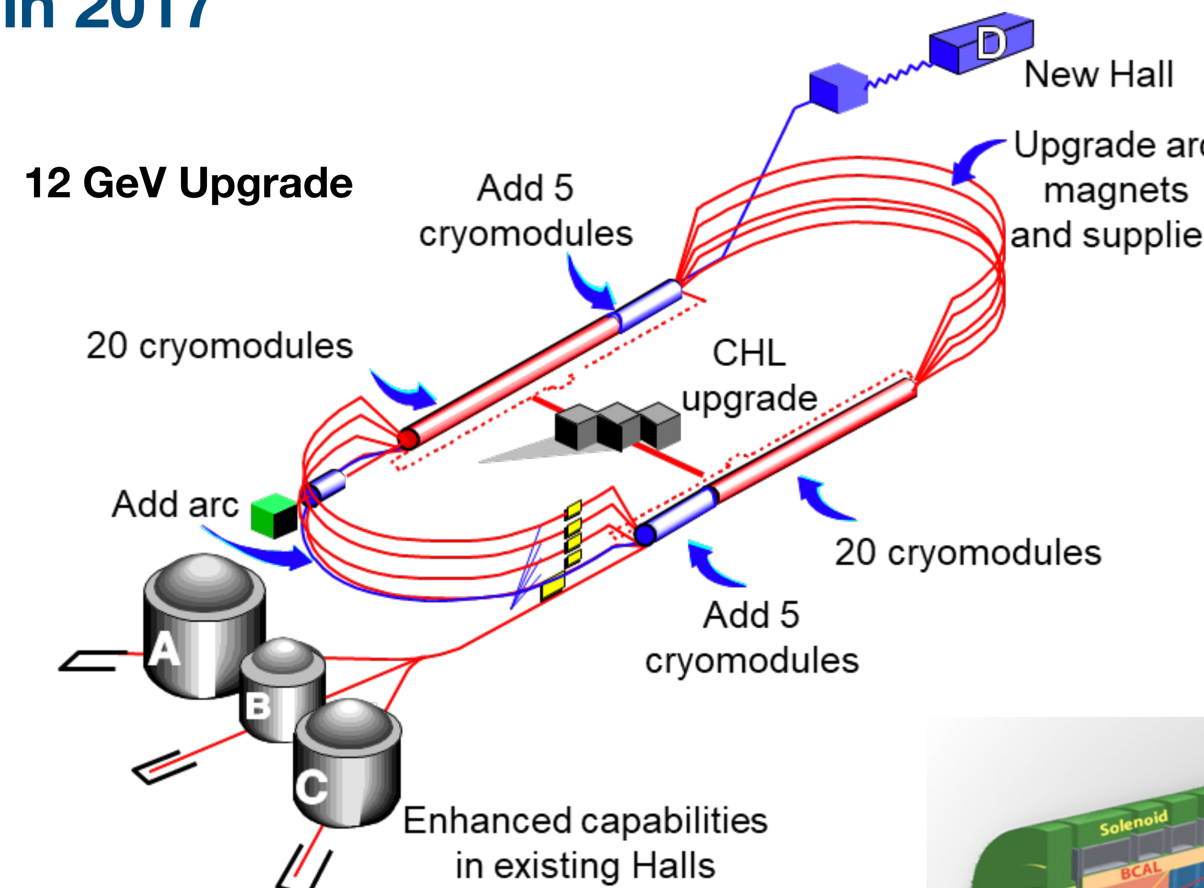
# The case of Neutron

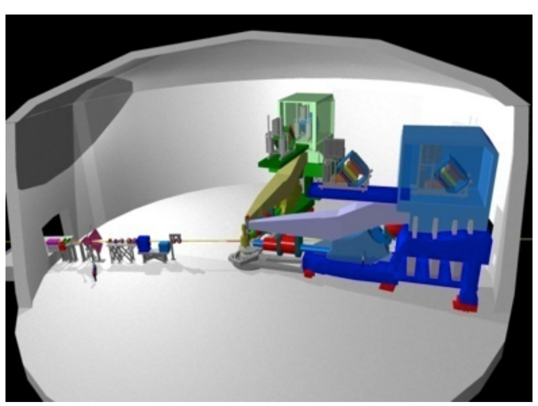
- No free neutron target exists
- Deuteron is a weakly bound system - chosen as effective neutron target
- But, $F2(d) \neq F2(n) + F2(p)$
- Large theory uncertainty from nuclear corrections
    - significant model dependence on deuteron wave function, off-shell corrections, ..

- Different approaches to extract the F2 ratio:
    - Model-dependent extraction from deuteron with precision data
    - Less model-dependence measurements:
        - 3H/3He DIS
        - Spectator tagging
    - Model-independent approach using parity-violating DIS (PVDIS)

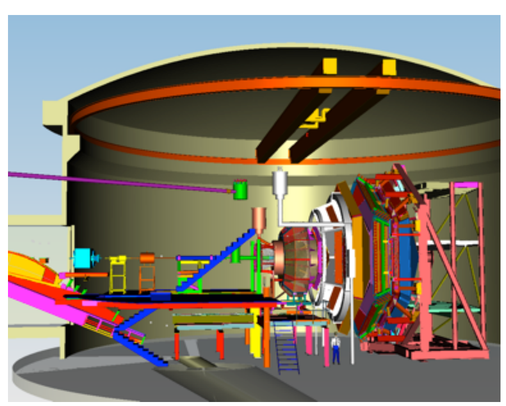
# CEBAF at Jefferson Lab

## Successfully completed 12 GeV upgrade in 2017

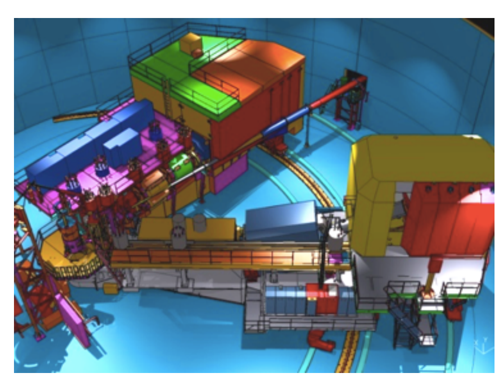


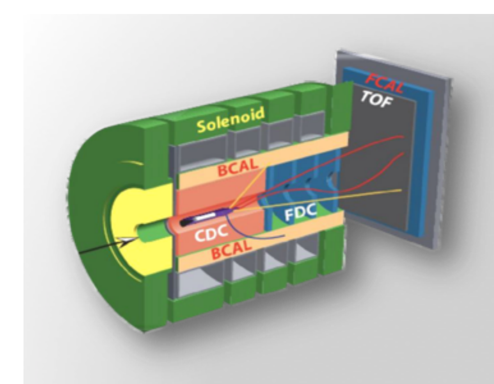
**Hall A: SRC, form factors, future new experiments (MOLLER, SoLID)**



**Hall B: understanding nucleon structure (GPDs and TMDs) CLAS12**

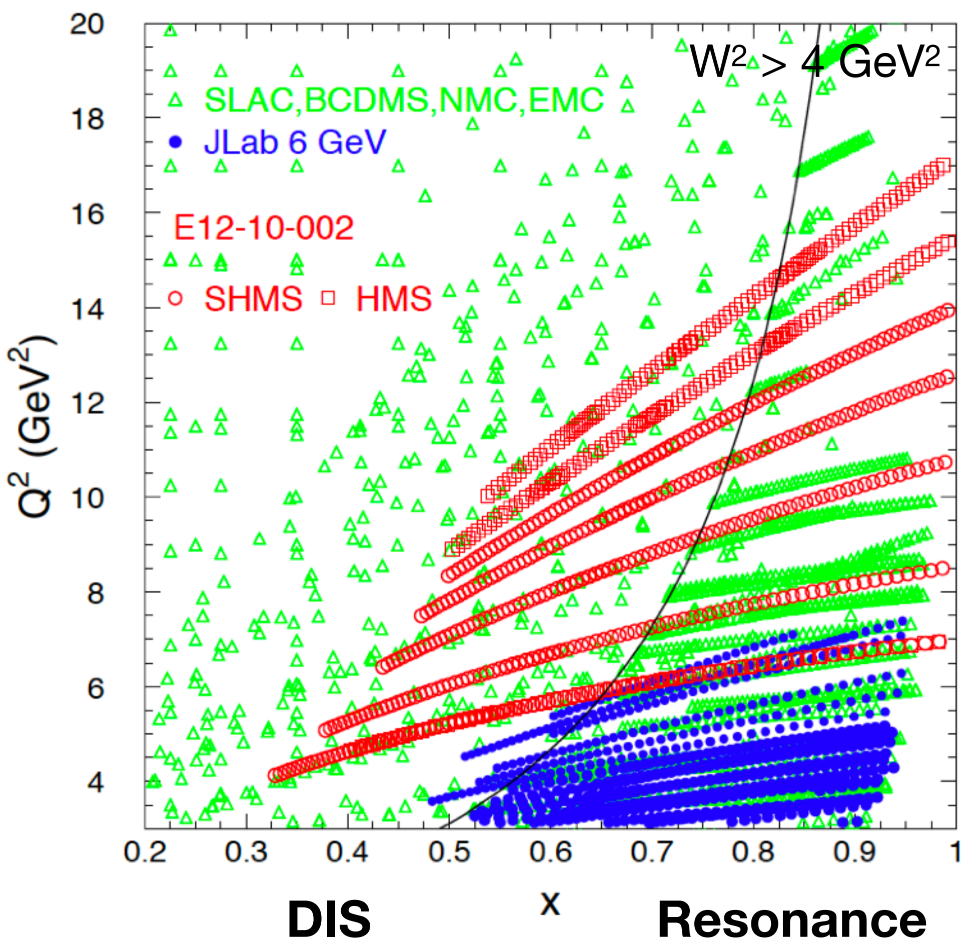


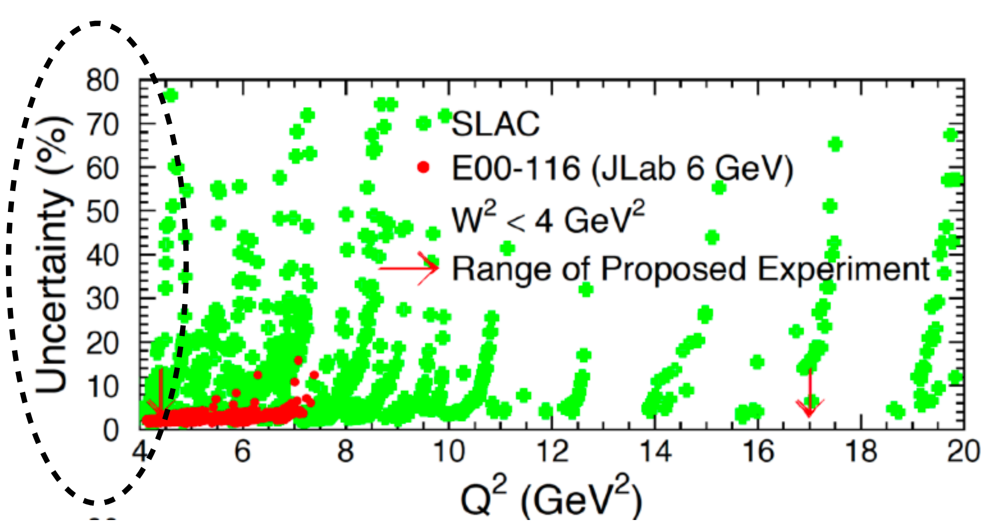
**Hall C: precision determination of valence quark properties of nucleons and nuclei**

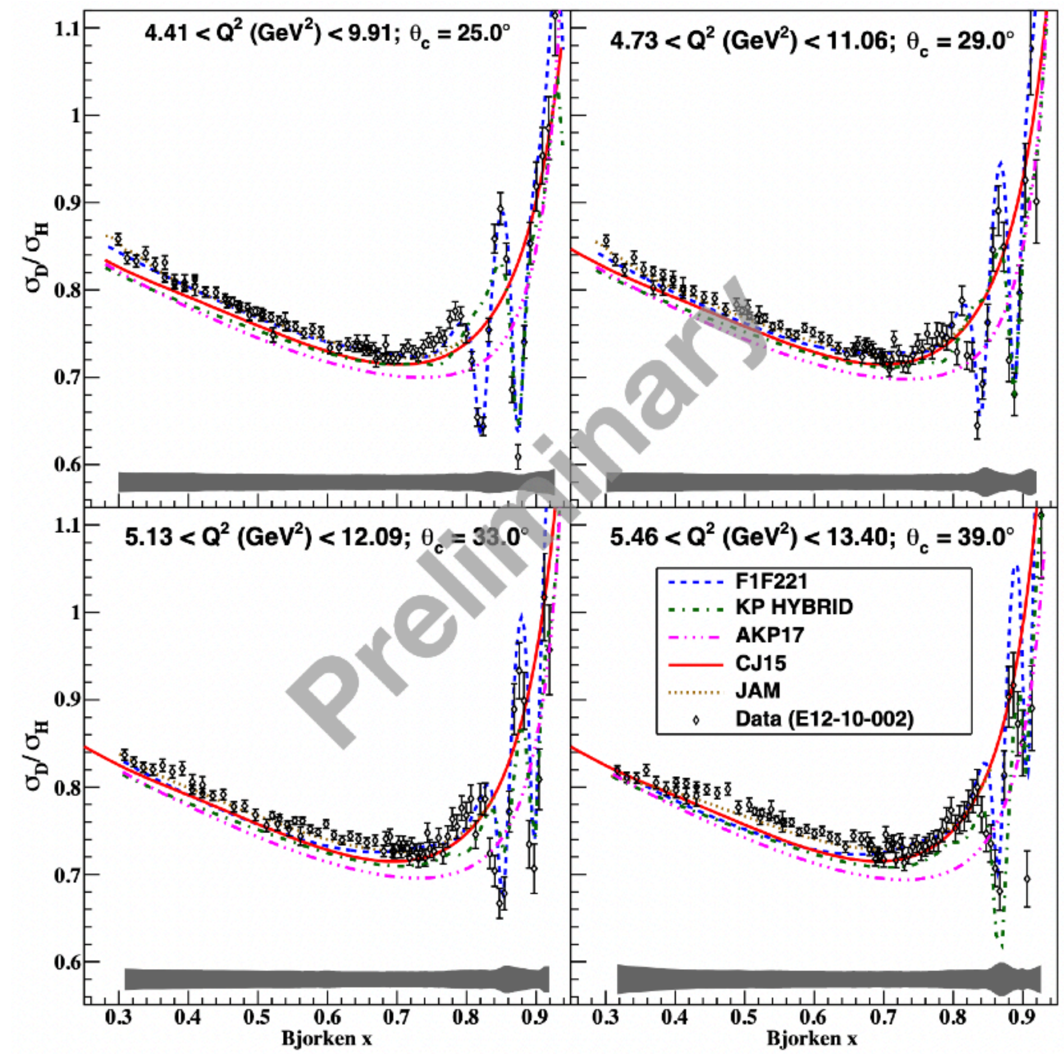


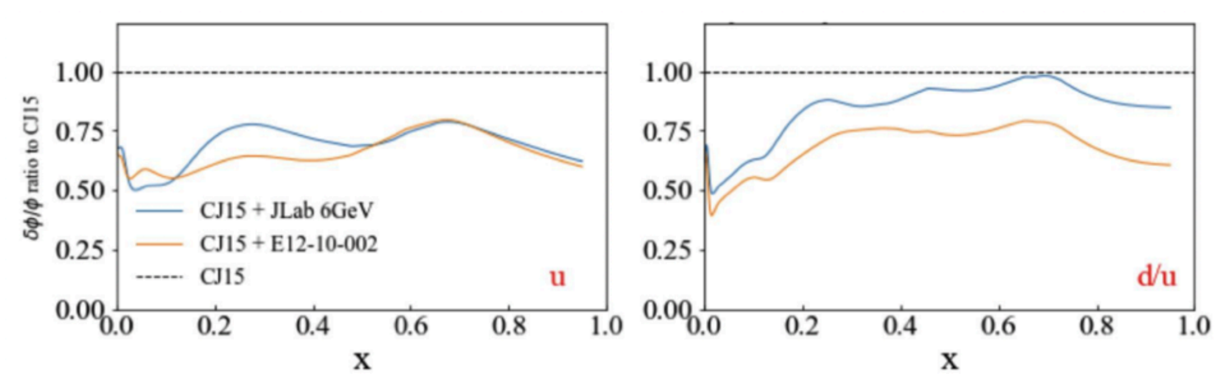

**Hall D: exploring origin of confinement by studying exotic mesons**

# Precision data on $F_2$ ratio



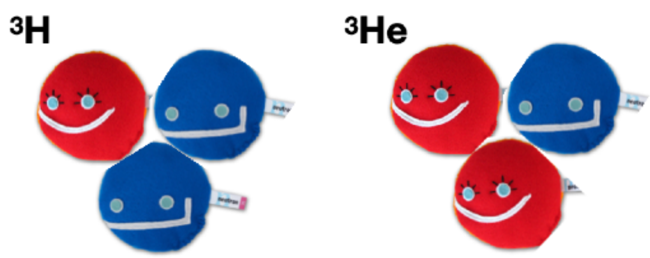



# 3H/3He DIS

A=3 mirror nuclei



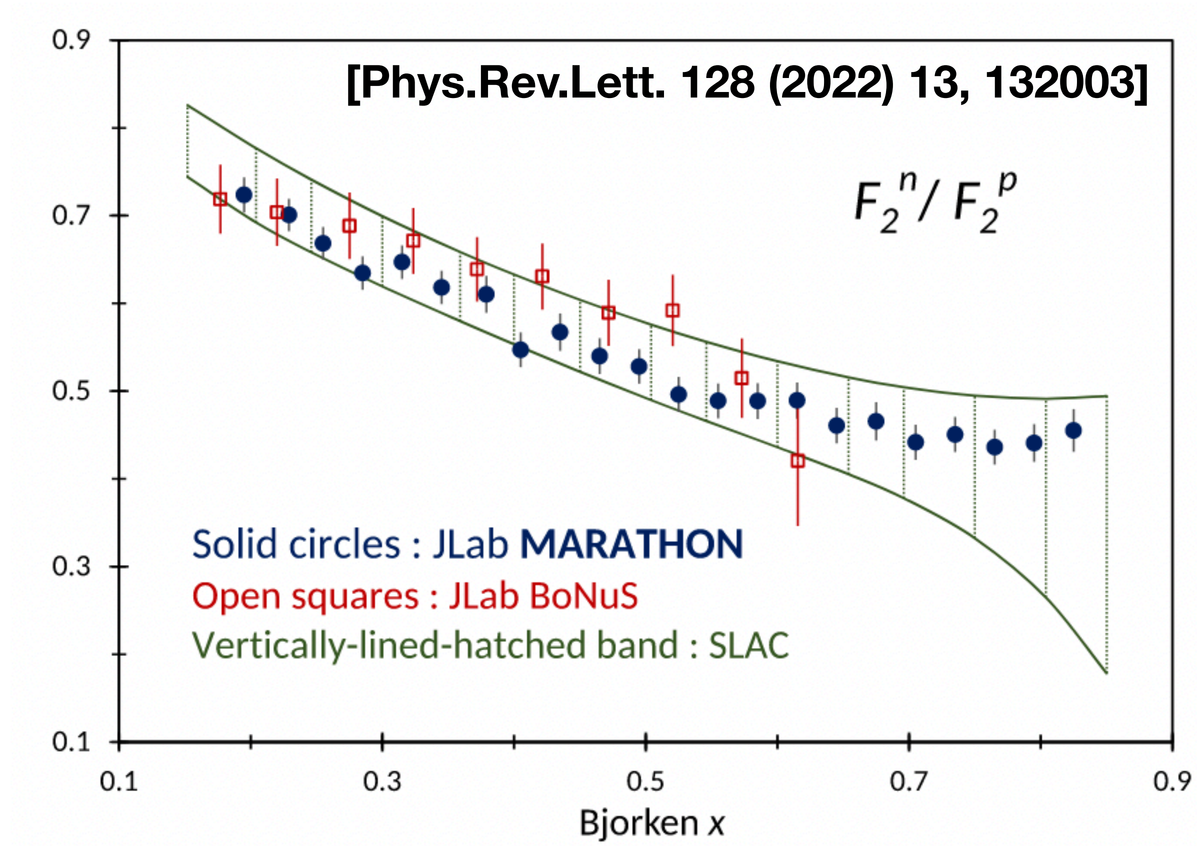

Form EMC-type ratios

$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

Form a super ratio $R^* = \dfrac{R(^3He)}{R(^3H)}$

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3He}/\sigma^{^3H}}{2\sigma^{^3He}/\sigma^{^3H} - R^*}$$

- 10.6 GeV beam, fixed scattered electron momentum (3.1 and 2.9 GeV), scattering angle 17-36 deg
- 3H, 3He, 2H, 1H targets
- Also measured EMC effects in 3He and 3H (first experimental data) and others




- JAM analysis including MARATHON data [Phys. Rev. Lett. 127, 242001]

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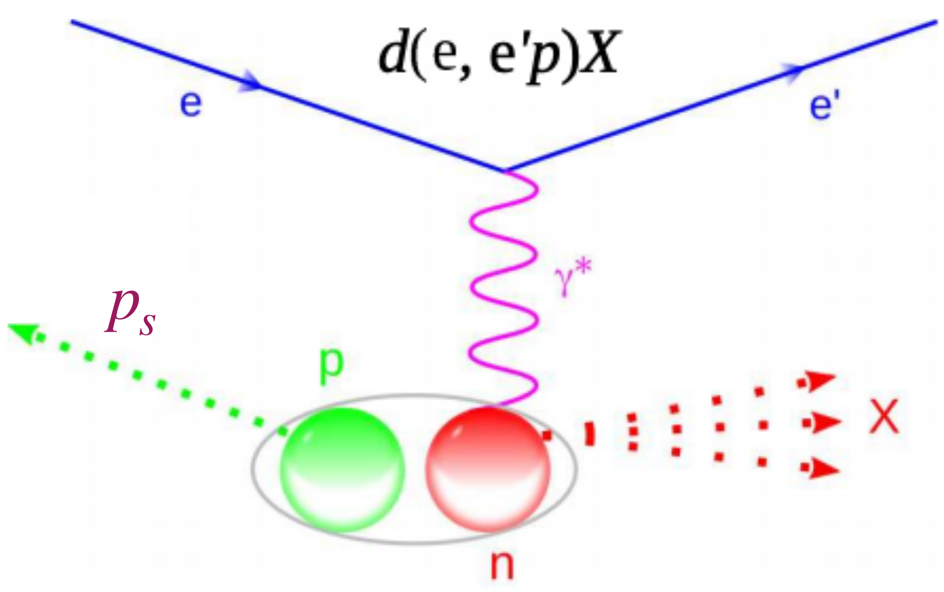
# Spectator tagging

Barely Off-shell Nucleon Structure experiment (@ Hall B)




Tagging spectator protons in coincidence with the scattered electrons

$$e + d \rightarrow e' + p_s + X$$

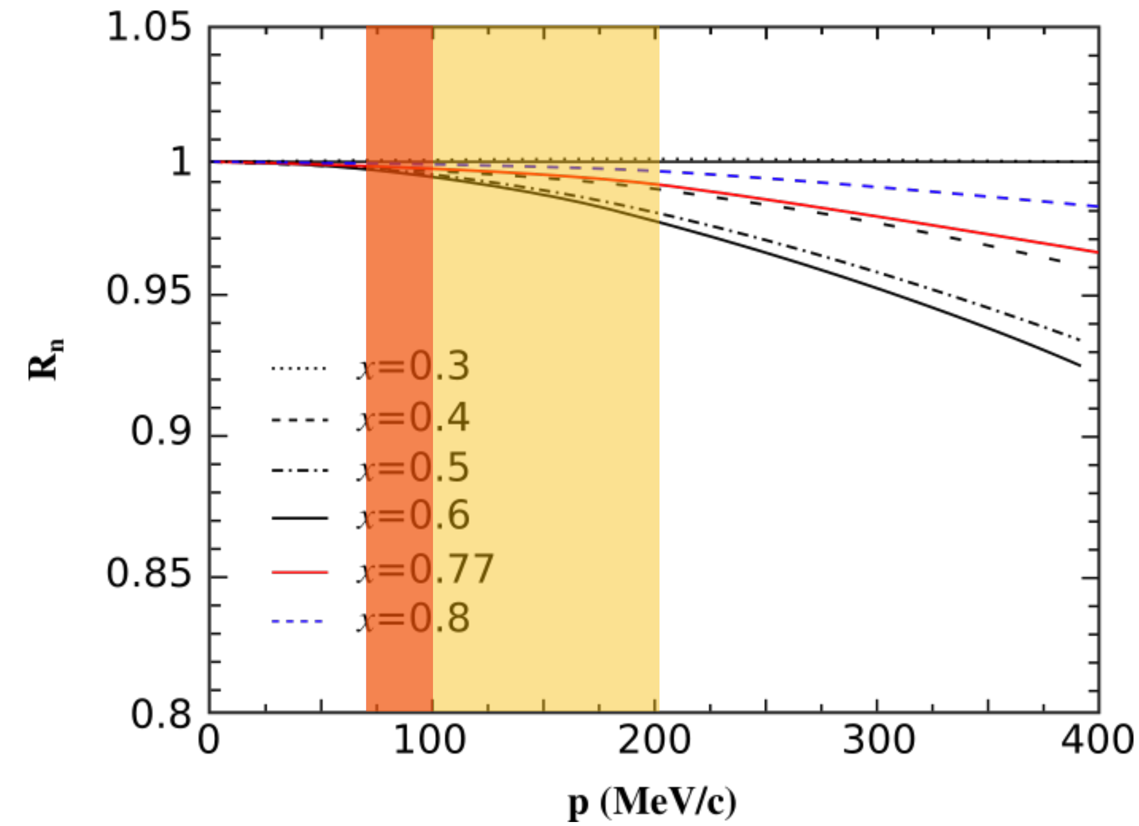
**Proton with small momentum in the backward hemisphere**

$$p_s \leq 100MeV$$

$$\theta_{pq} \geq 100$$

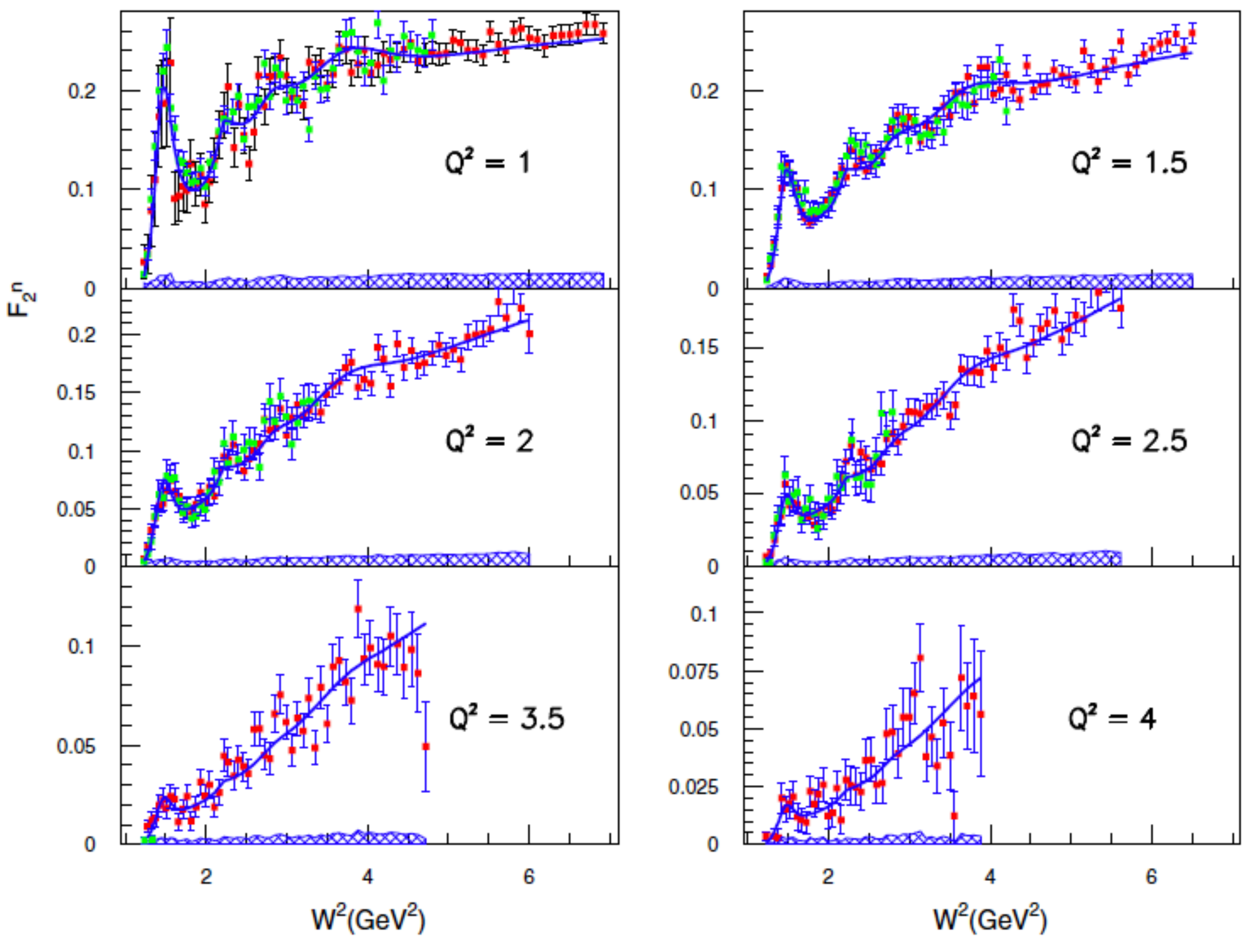
**→minimize probability of rescattering of spectator proton with hadronic debris**

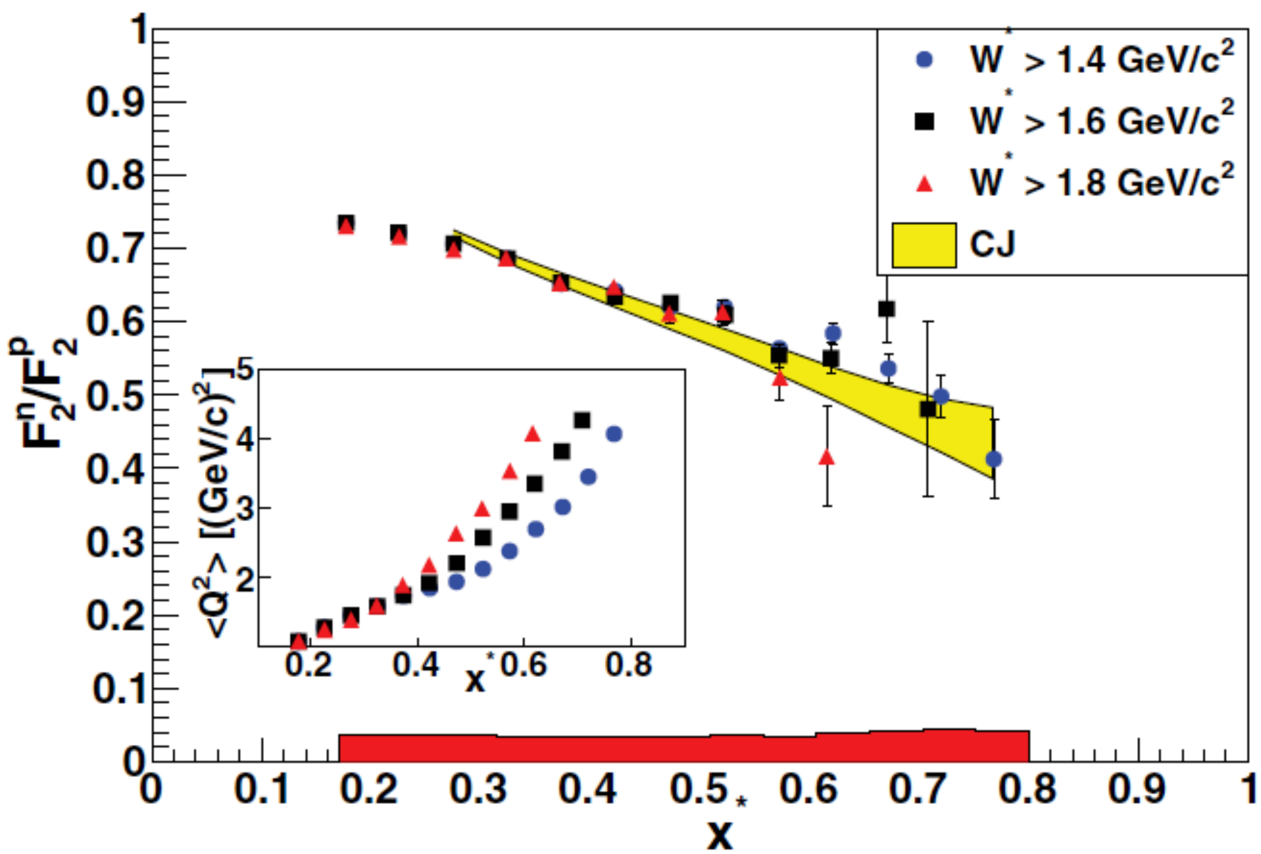
$R_n \equiv F_2^{n(\mathrm{eff})}/F_2^n$ W. Melnitchouk et al



# 6GeV results

S. Tkachenko et al., Phys. Rev. C 89, 045206 (2014)



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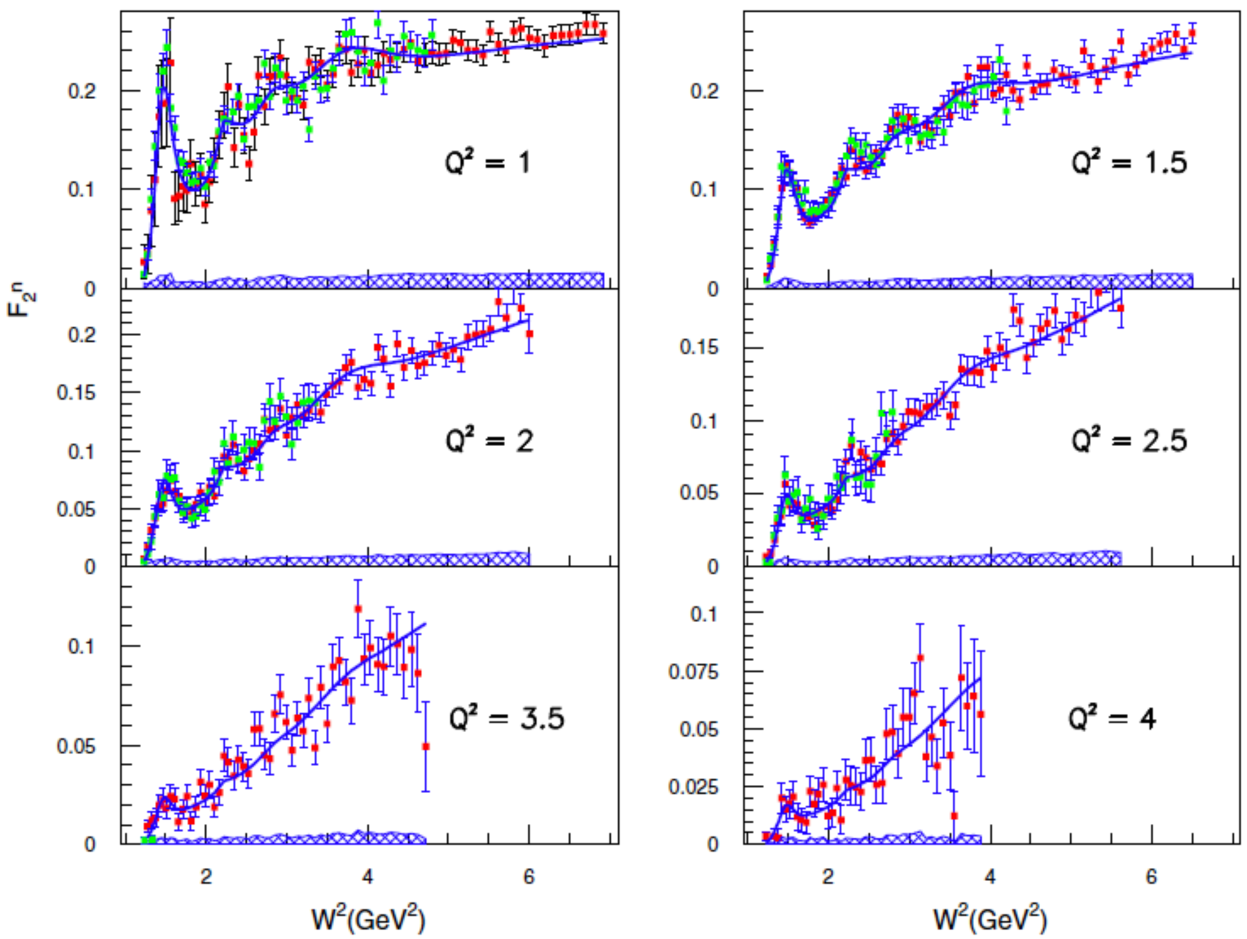
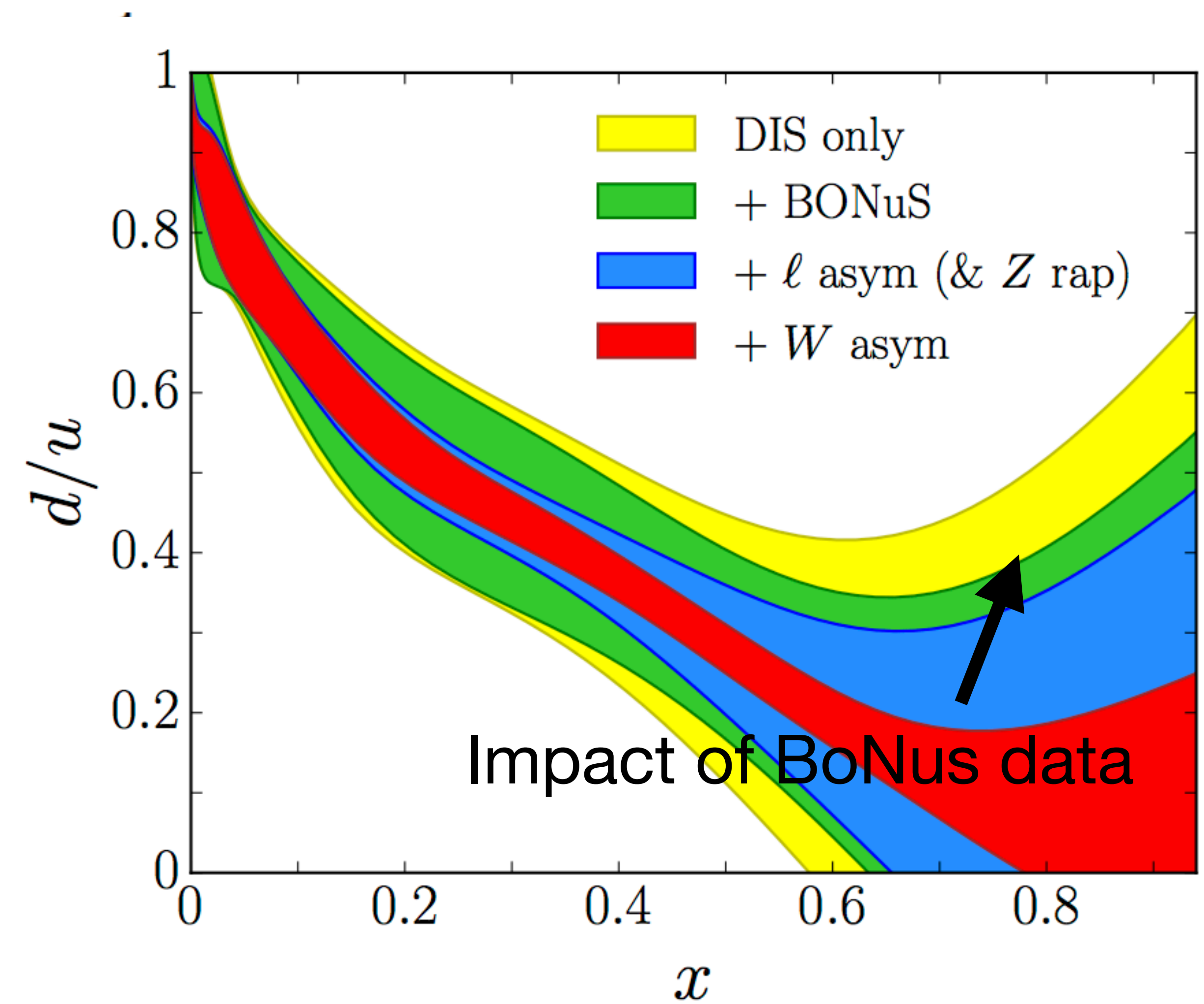


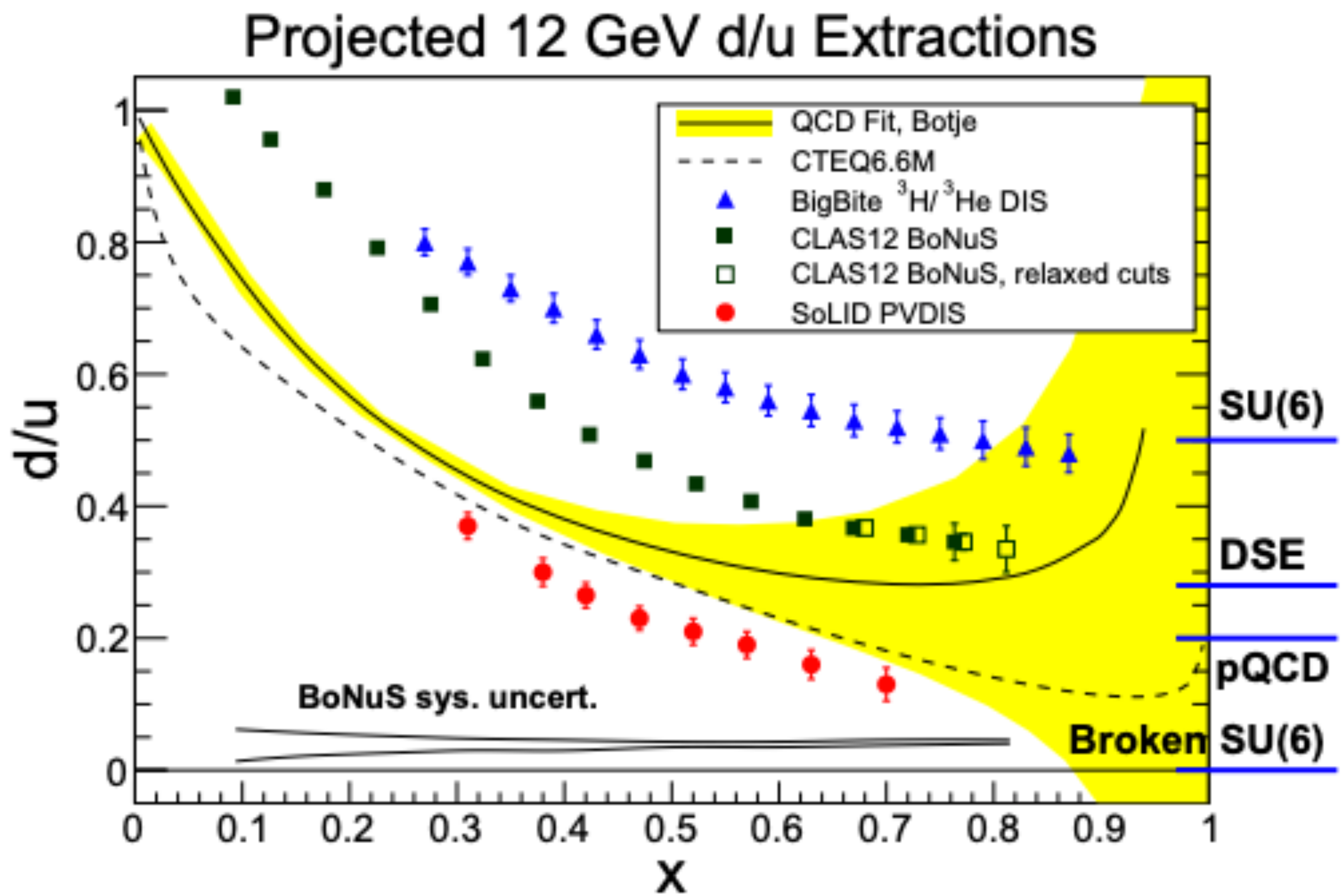




Successor experiment BoNus12 took data in 2020

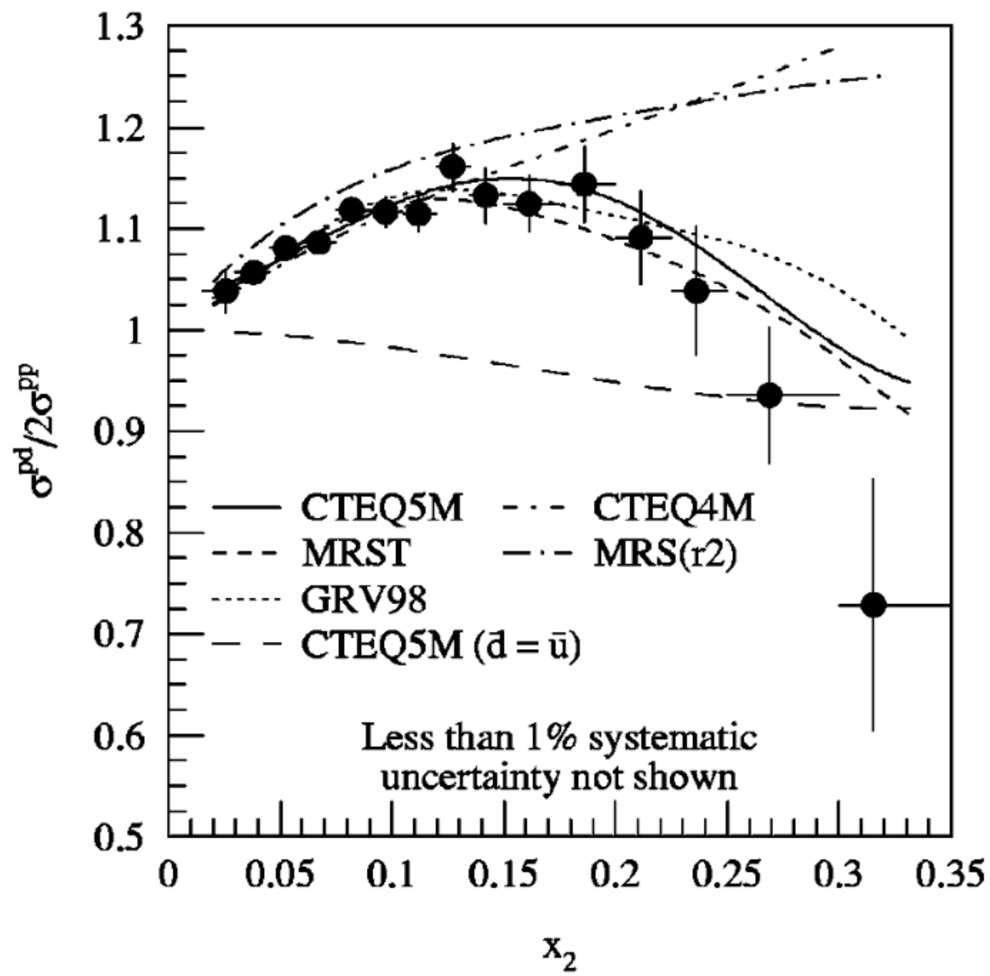
Extends kinematic coverage:

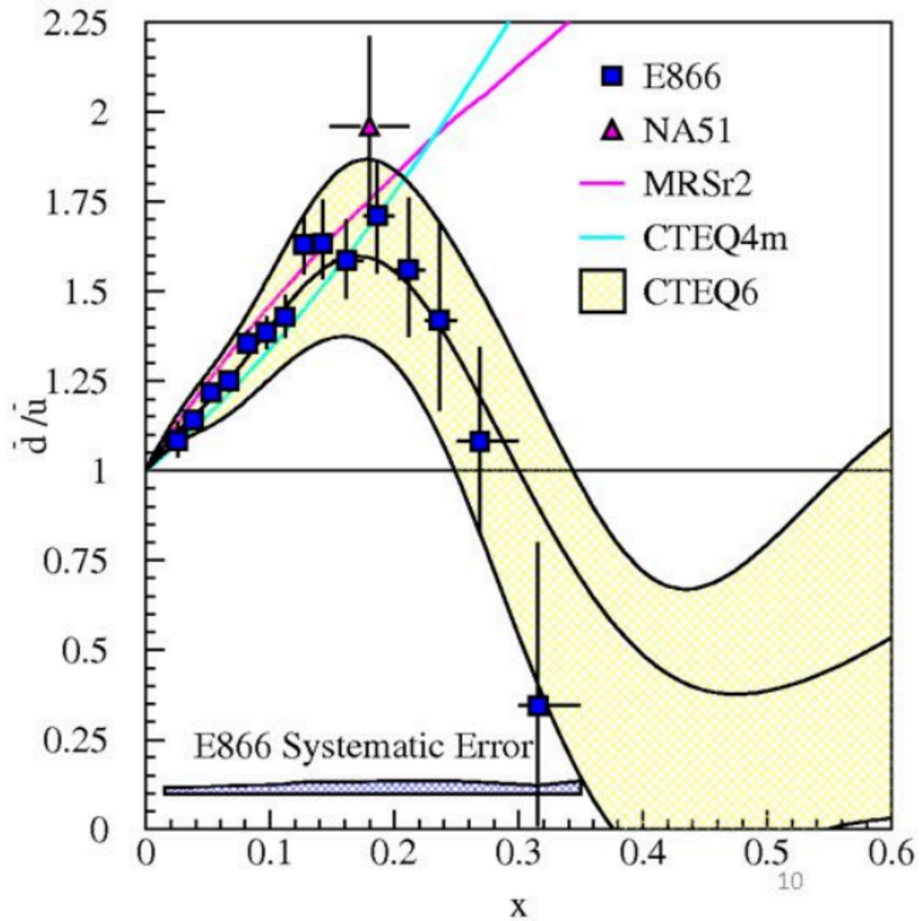
$0.1 < x < 0.8$, $Q^2$ of 1-14 GeV$^2$, W up to 4GeV

# Constraints on d/u from JLab 12GeV



# Sea Quarks and Flavor Asymmetry



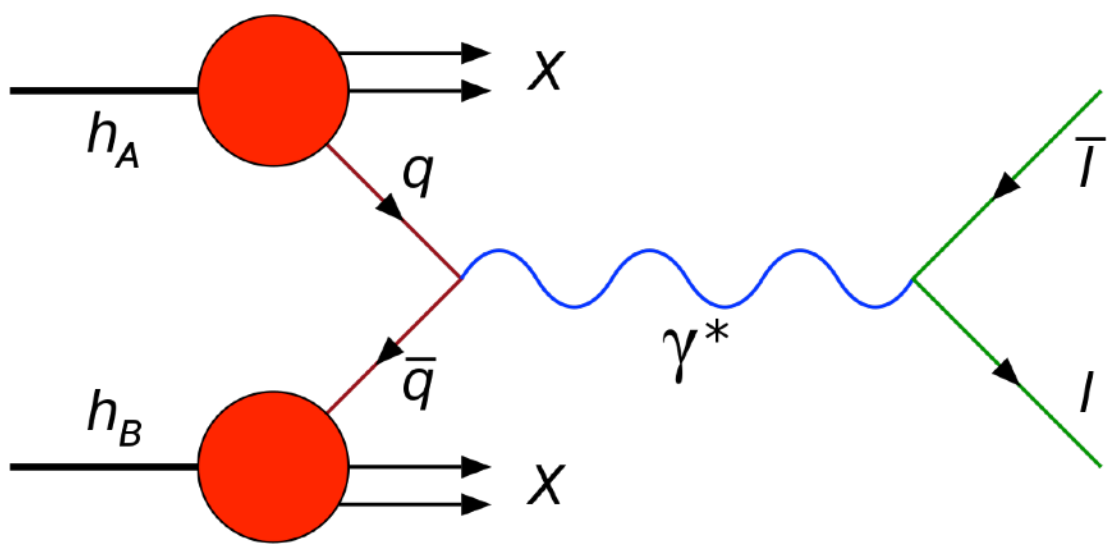




- First hint of asymmetric sea from NMC: [Phys. Rev. Lett. 66 (1991) 2712]

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}$$

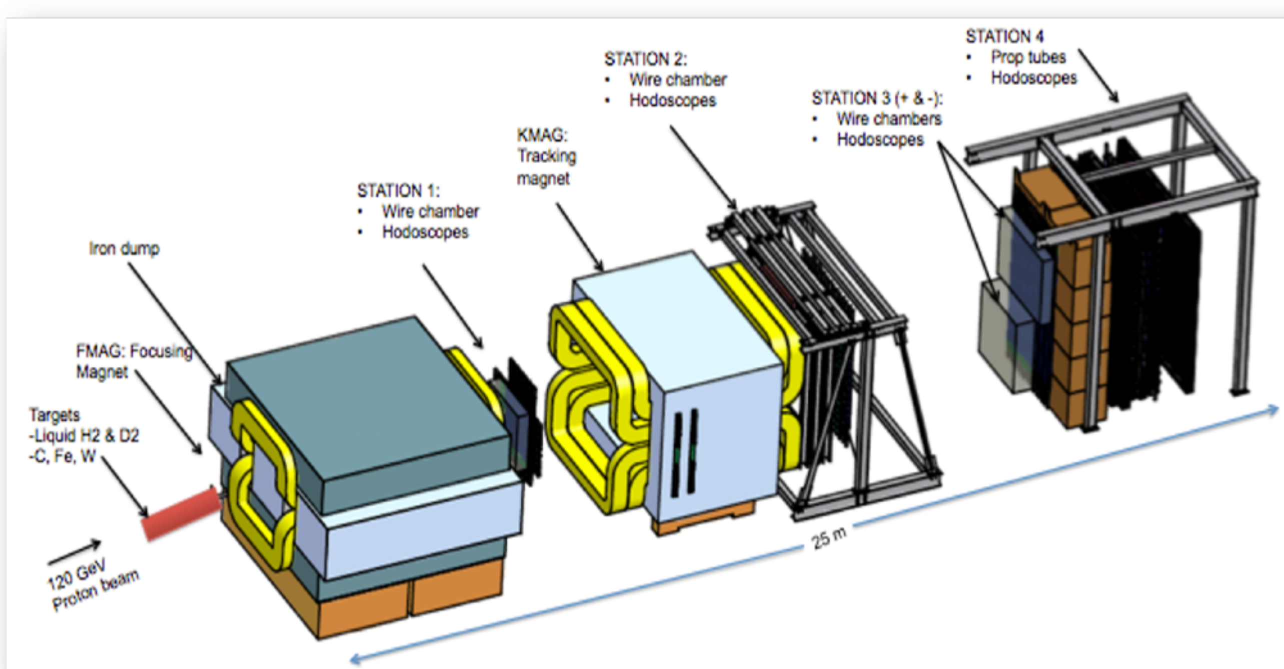
- Significant flavor asymmetry confirmed as well as x dependence by Drell-Yan data: NA51 (1994), E866 (1997) [Phys. Rev. D 64, 052002 ]

# Drell-Yan measurements at SeaQuest




- Quark from hadron annihilates with antiquark from another hadron
- Virtual photon is created
- Decays into a lepton + antilepton
- Unique sensitivity to the anti-quark distributions

SEAQUEST SPECTROMETER



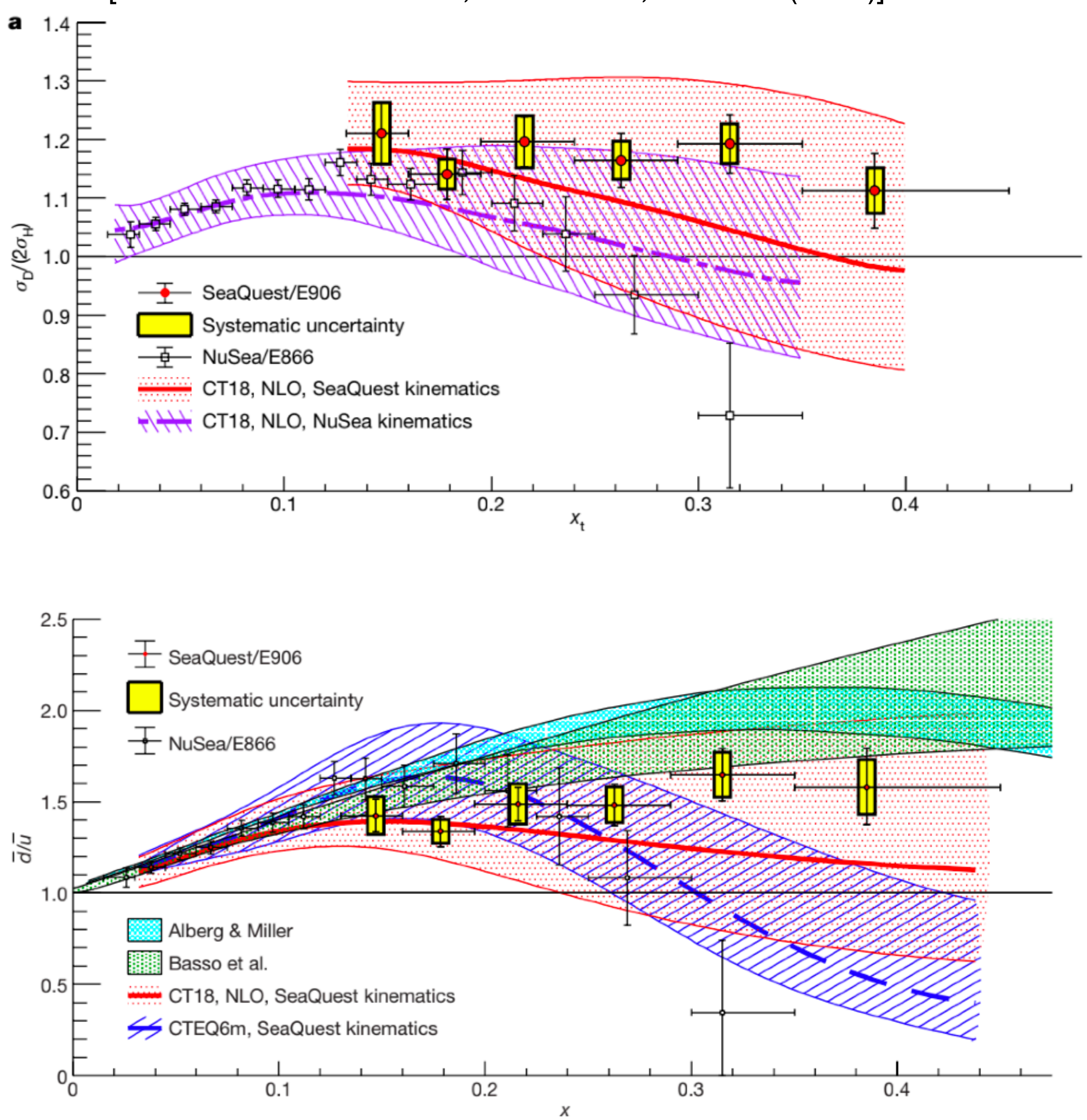

- New experiment with 120 GeV proton beam on LH2 and LD2

E866: $0.015 < x_t < 0.3$, average $Q^2$ of 54 $GeV^2$
SeaQueset: $0.1 < x_t < 0.45$, average $Q^2$ of 22-40 $GeV^2$

$$\frac{\sigma_{pd}}{\sigma_{pp}} \approx \frac{4 + \frac{d(x_b)}{u(x_b)}}{4 + \frac{d(x_b)}{u(x_b)} \frac{\bar{d}(x_t)}{\bar{u}(x_t))}} \left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

# SeaQuest Results

[SeaQuest Collaboration, Nature 590, 561-565 (2021)]




- SeaQuest results show that nature prefers dbar over ubar in the proton sea
- Non-perturbative mechanism other than gluon splitting must be the source
- Good agreement with meson baryon model and statistical parton distribution functions

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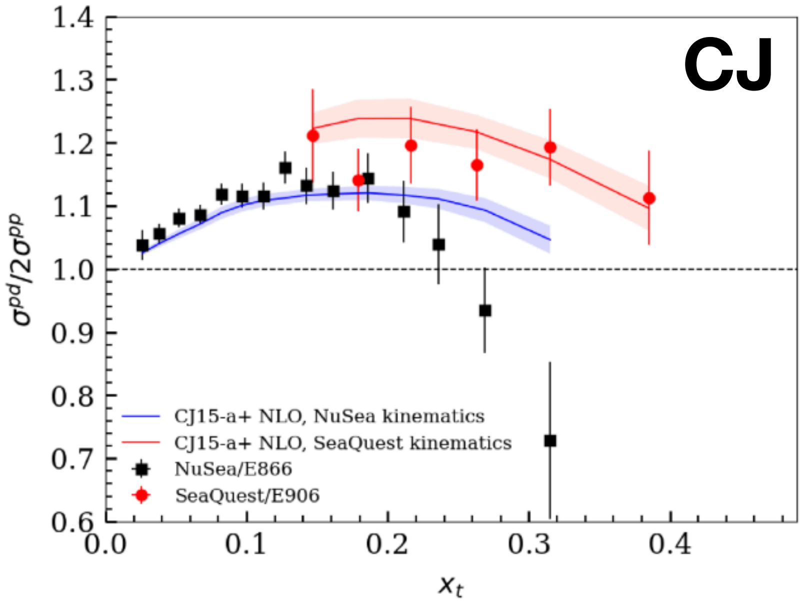
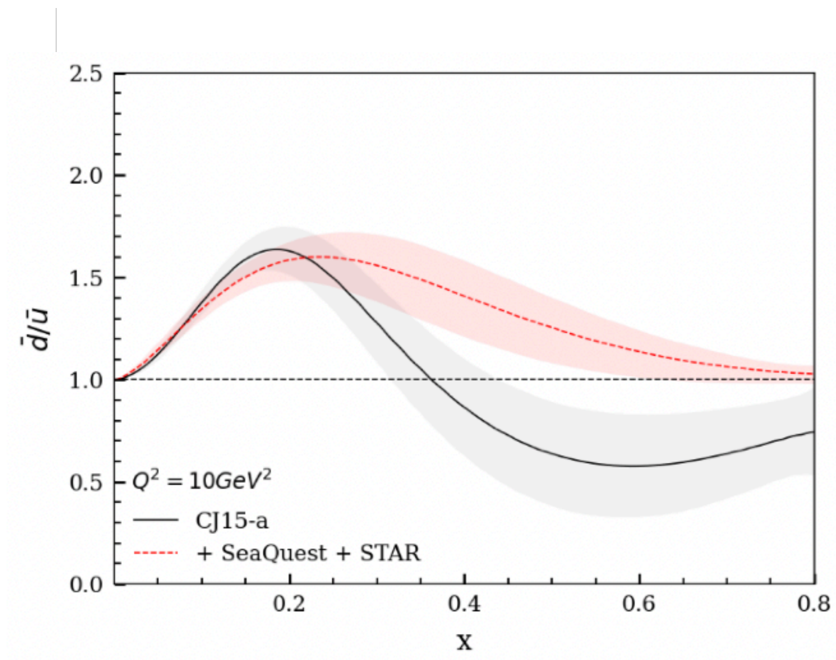
# SeaQuest data in Global PDF analysis

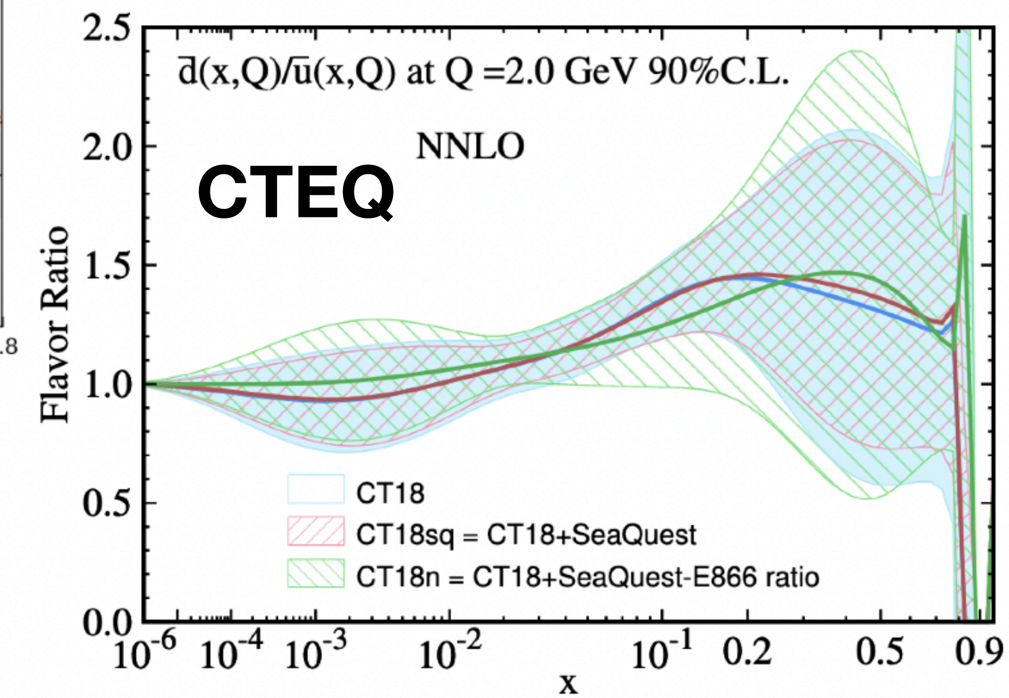
[CJ, arXiv:2108.05786]

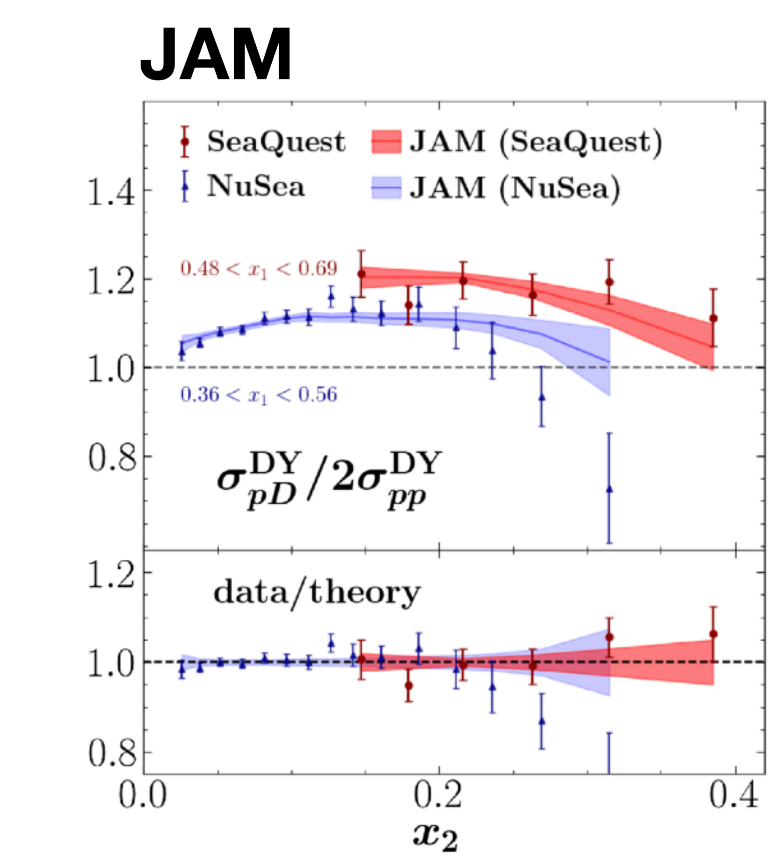
[JAM, Phys. Rev. D 104, no. 7, 074031 (2021)]

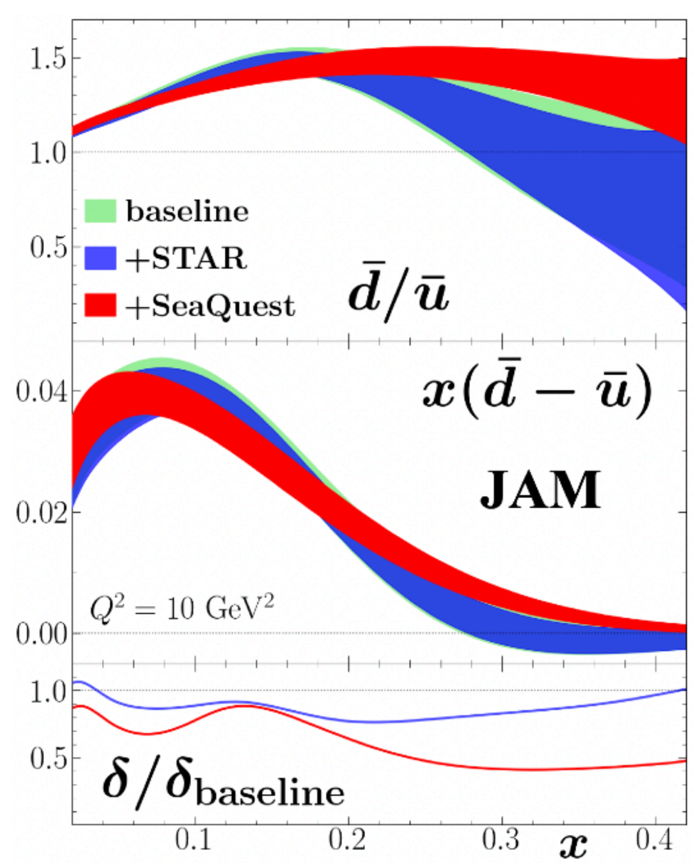
[CTEQ, SciPost Phys.Proc. 8 (2022) 005]




- Including SeaQuest data brings the $\bar{d}/\bar{u}$ ratio above 1 and reduces the uncertainty

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# Spin Structure of the Proton

# Polarized structure functions

- **Polarized structure functions g1, g2:**

$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 E}\left[\frac{E + E' cos\theta}{M\nu}\boxed{g_1(x, Q^2)} - \frac{Q^2}{M\nu}\boxed{g_2(x, Q^2)}\right]$$

In Quark parton model,

$$\boxed{g_1(x,Q^2) \sim \sum_q e_q^2 \Delta q(x,Q^2)}$$

quark spin distribution

$$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} - \sigma_{3/2}} \approx \frac{g_1(x, Q^2)}{F_1(x, Q^2)}$$

# Polarized structure functions

- **$g_2$ structure function and moment:**

No simple interpretation

Provides information on the quark-gluon correlations through higher twist effects

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

determined from twist-2 part of g1

higher twist term, not 1/Q suppressed w.r.t twist-2 term

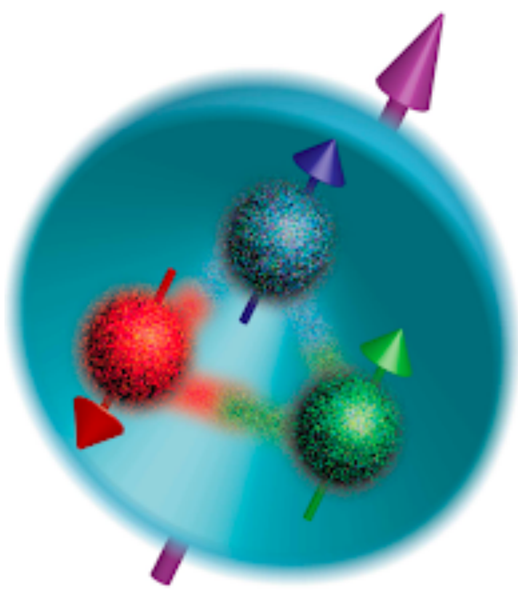
$x^2$ **weighted moment, d2:**

$$d_2(Q^2) = \int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$

Twist-3 matrix element, related to color polarizabilities
Calculable in lattice QCD

**Higher moments:** spin polarizabilities $\gamma_0$ (longitudinal), $\delta_{LT}$ (L-T) - benchmark for theory, lattice calculation and chiral perturbative theory at low $Q^2$

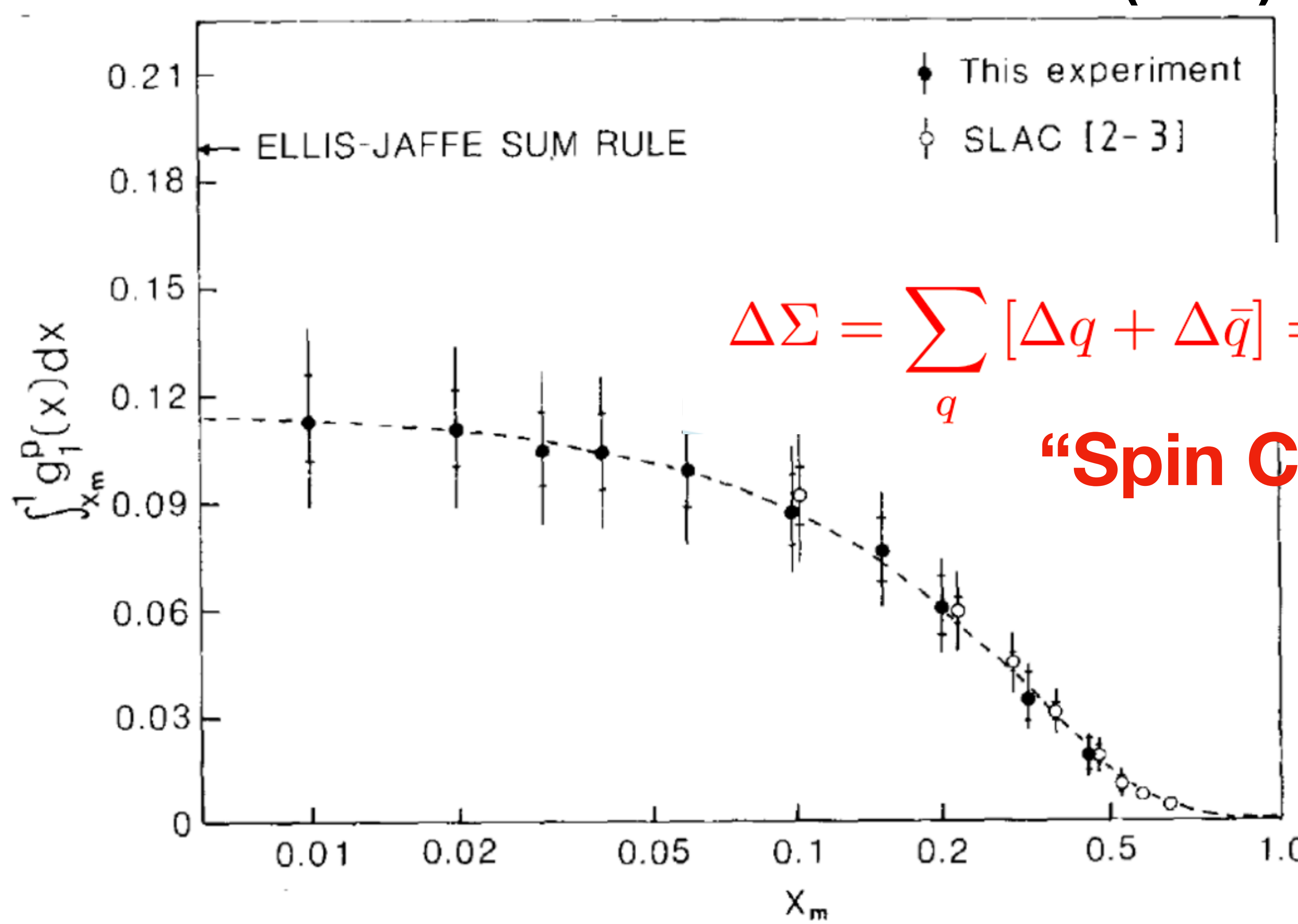
# Spin Surprise in 1980s



$$A_1^P = \frac{\sigma_{+-} - \sigma_{++}}{\sigma_{+-} + \sigma_{++}}$$

$$\sim \frac{g_1^p(x, Q^2)}{F_1^p(x, Q^2)}$$

**EMC (1989)**




$$\Delta\Sigma = \sum_q [\Delta q + \Delta\bar{q}] = 0.12 \pm 0.17$$

**"Spin Crisis"**

# We have better understanding than 30 years ago, but yet….

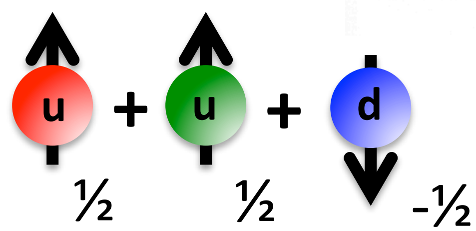
## How the spin of the proton is carried by its constituents inside?

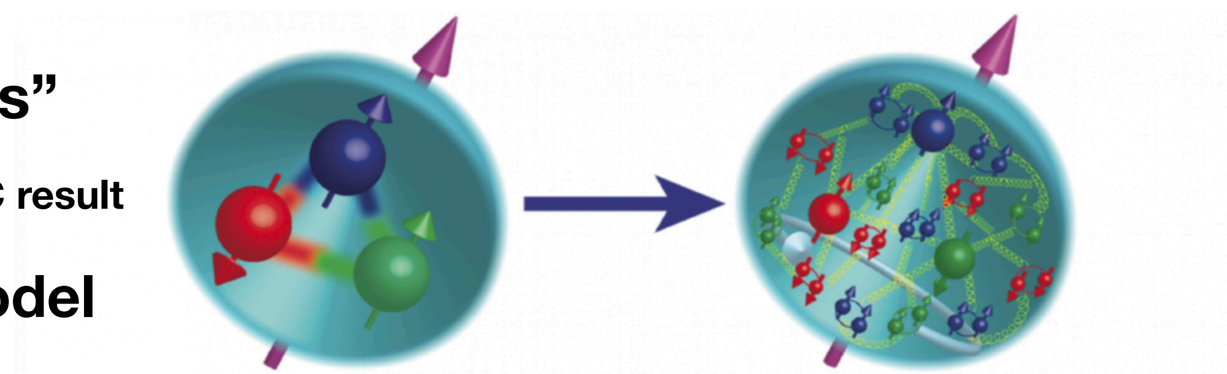
**Proton Spin Decomposition**

**“Proton spin crisis”**

**Naive interpretation of the EMC result**

**Naïve quark model**

$\frac{1}{2} \stackrel{?}{=}$ 

**1980s** **Now**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

**(Quark + antiquark) helicity contribution**

$$\frac{1}{2}\int dx(\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

~30%. Well constrained by polarized DIS

**Gluon helicity contribution**

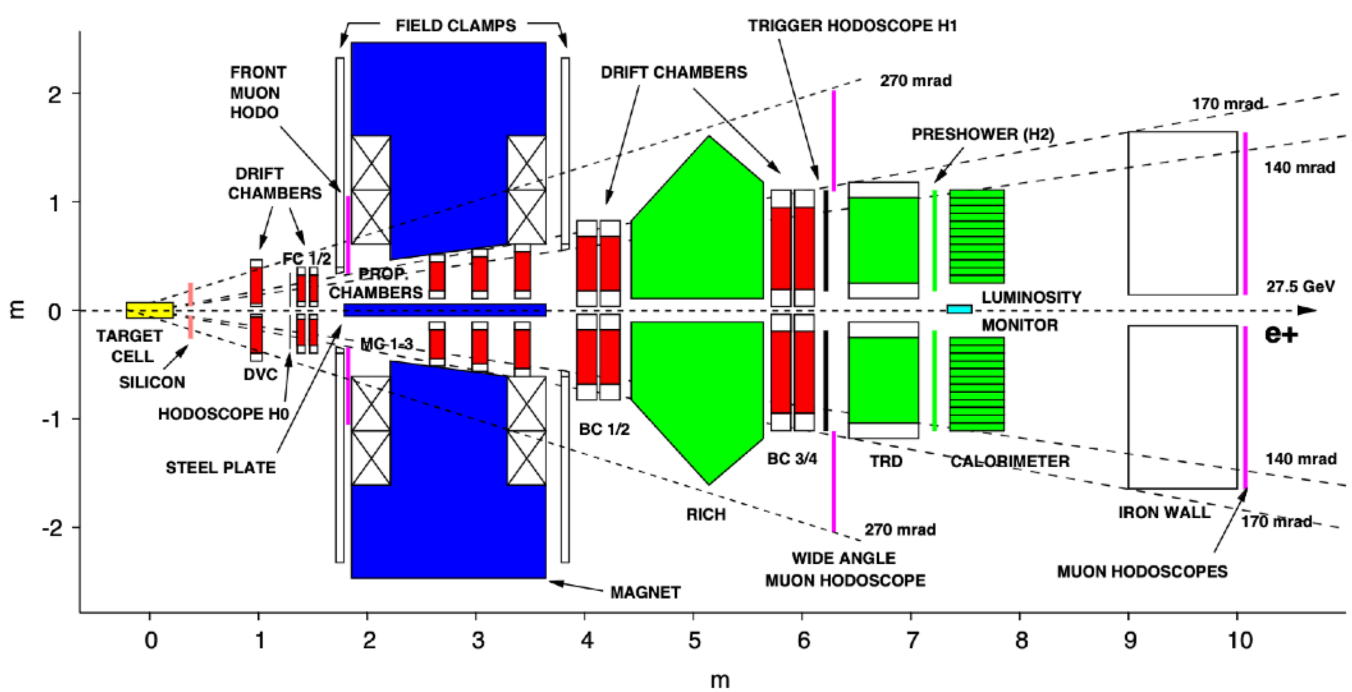
$$\Delta G = \int dx \Delta g(x)$$

Start to understand better with RHIC pp data

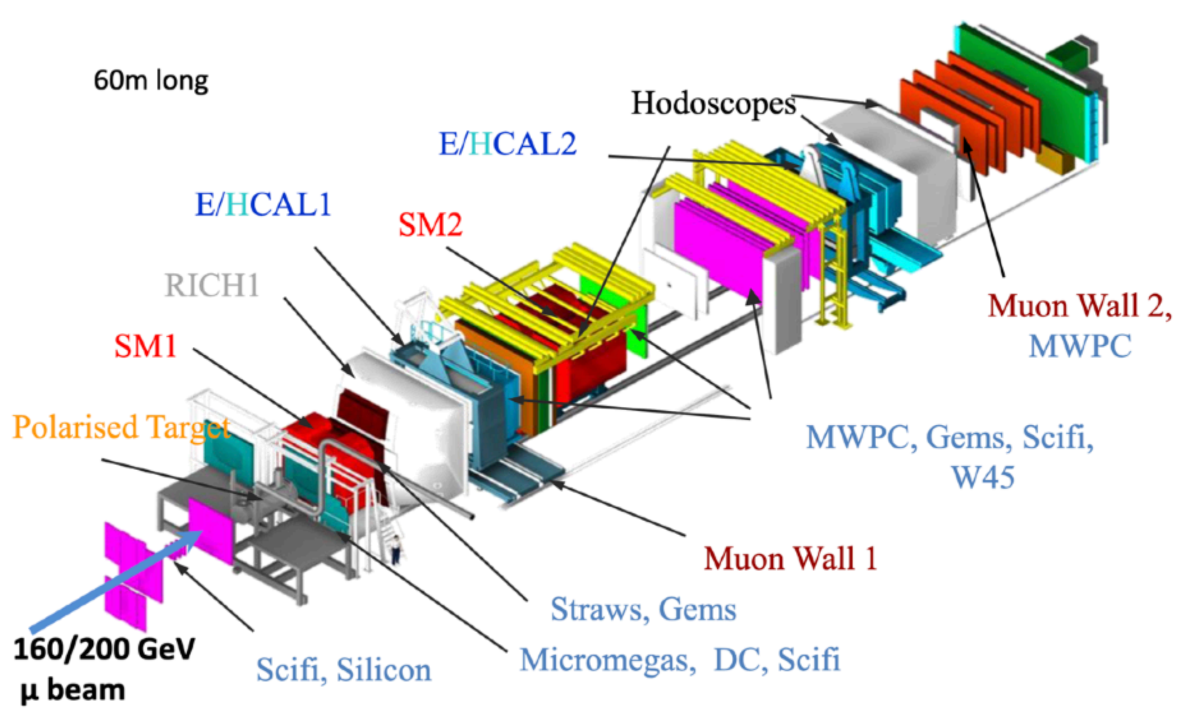
**Quark and gluon orbital angular momentum**

Very little known
Need to know 3D structure!

# HERMES and COMPASS

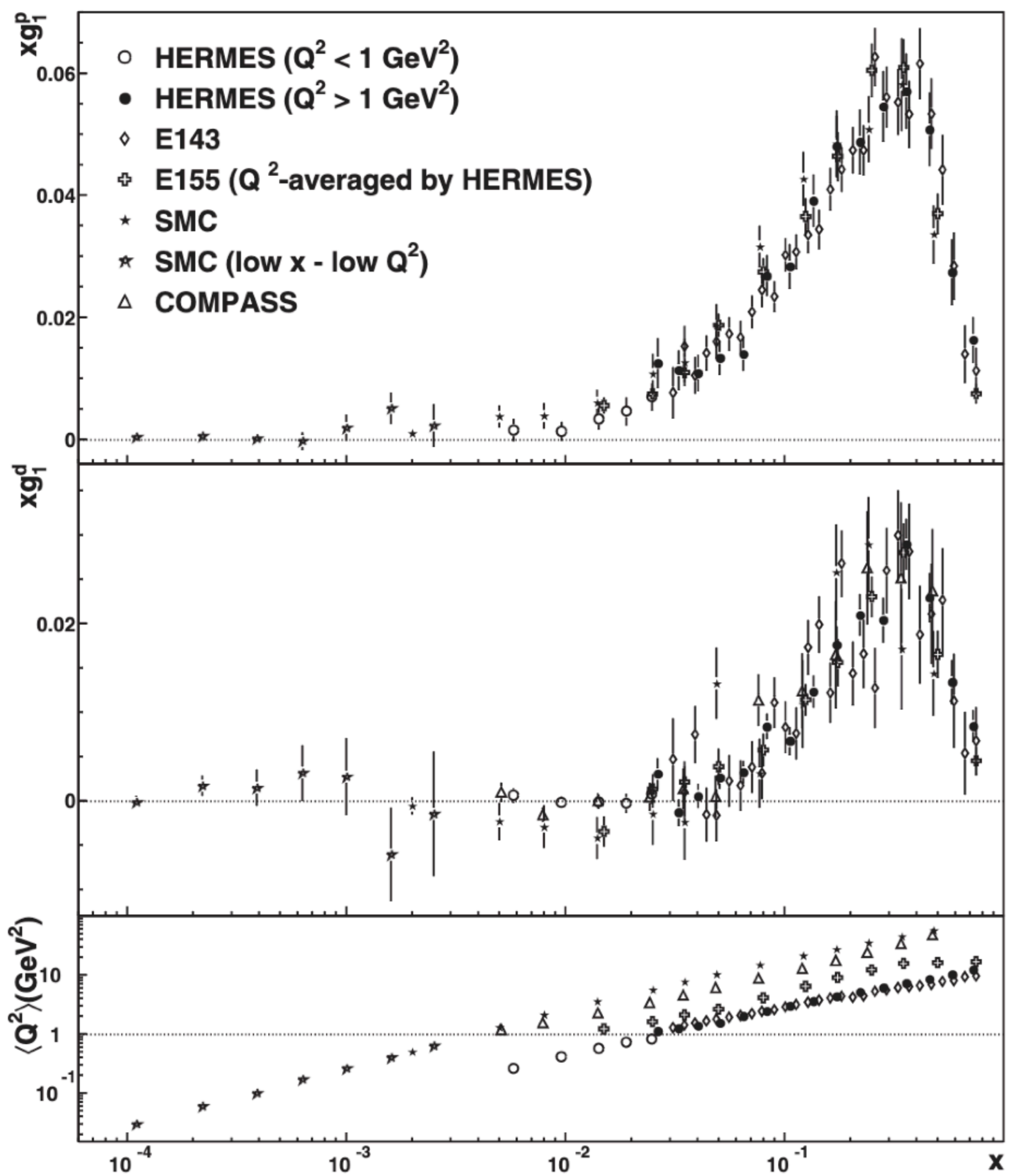


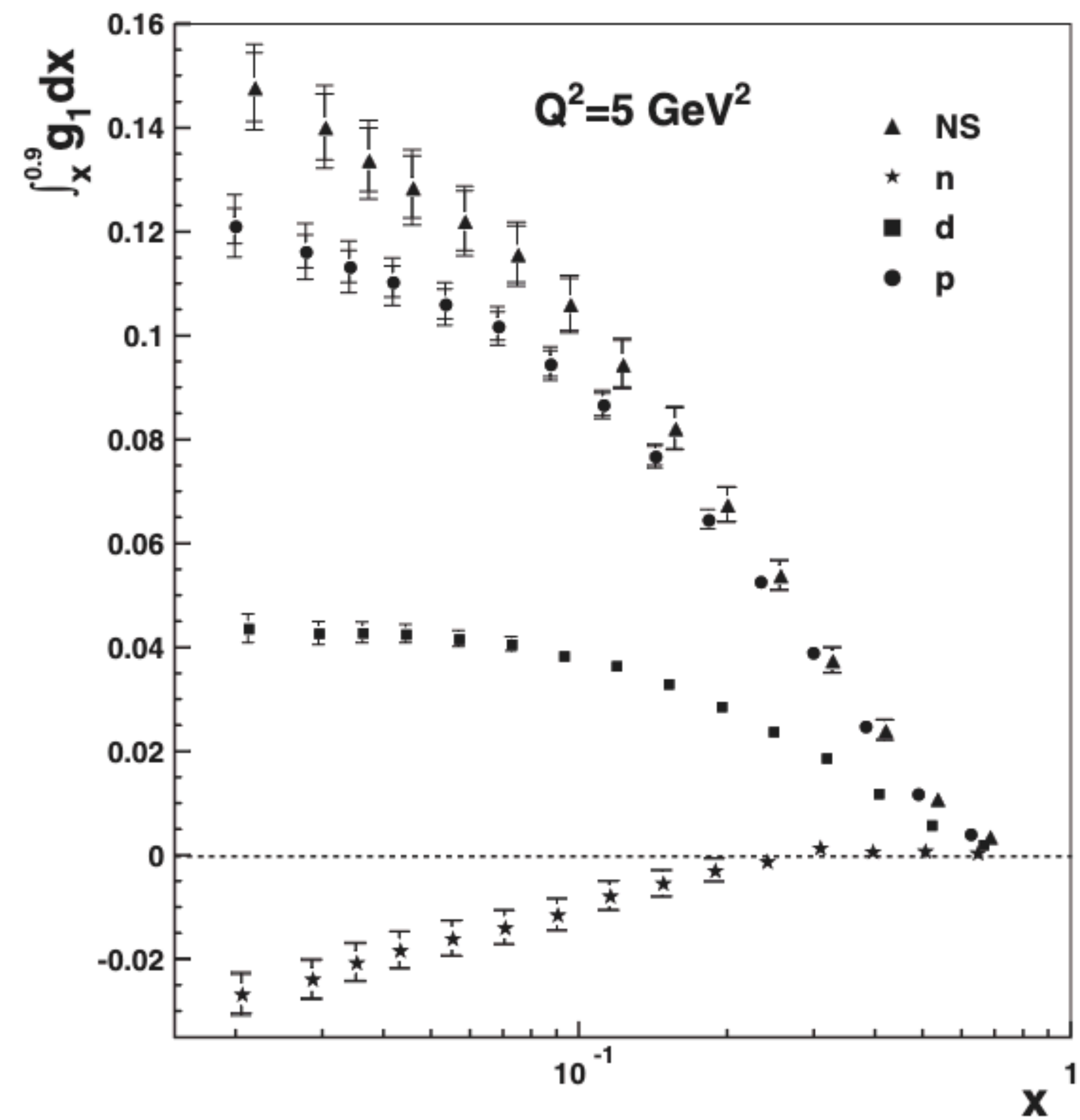

- HERMES @ HERA
  - Fixed-target experiment at HERA
  - Polarized lepton beam, 27.5 GeV (transverse<->longitudinal using spin rotator)
  - polarized gas target ($^1H, ^2H, ^3He$) with rapid spin reversal




- COMPASS @ CERN
  - Polarized muon beams from M2 beamline (80% pol.), 160/200 GeV
  - Solid polarized state targets: 6LiD (d) ~ 50% pol. NH3 (p) ~80% pol.

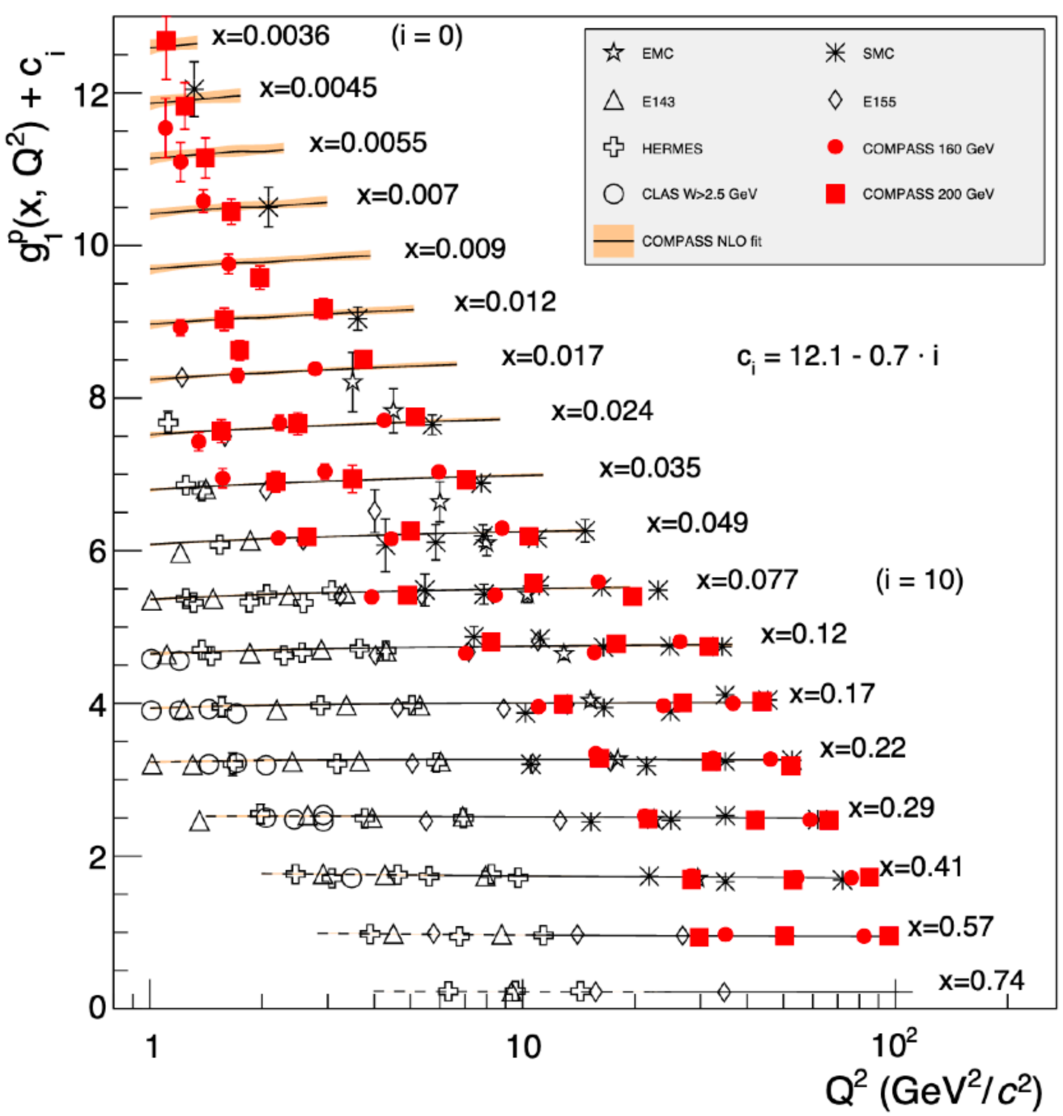
# g1 measurements



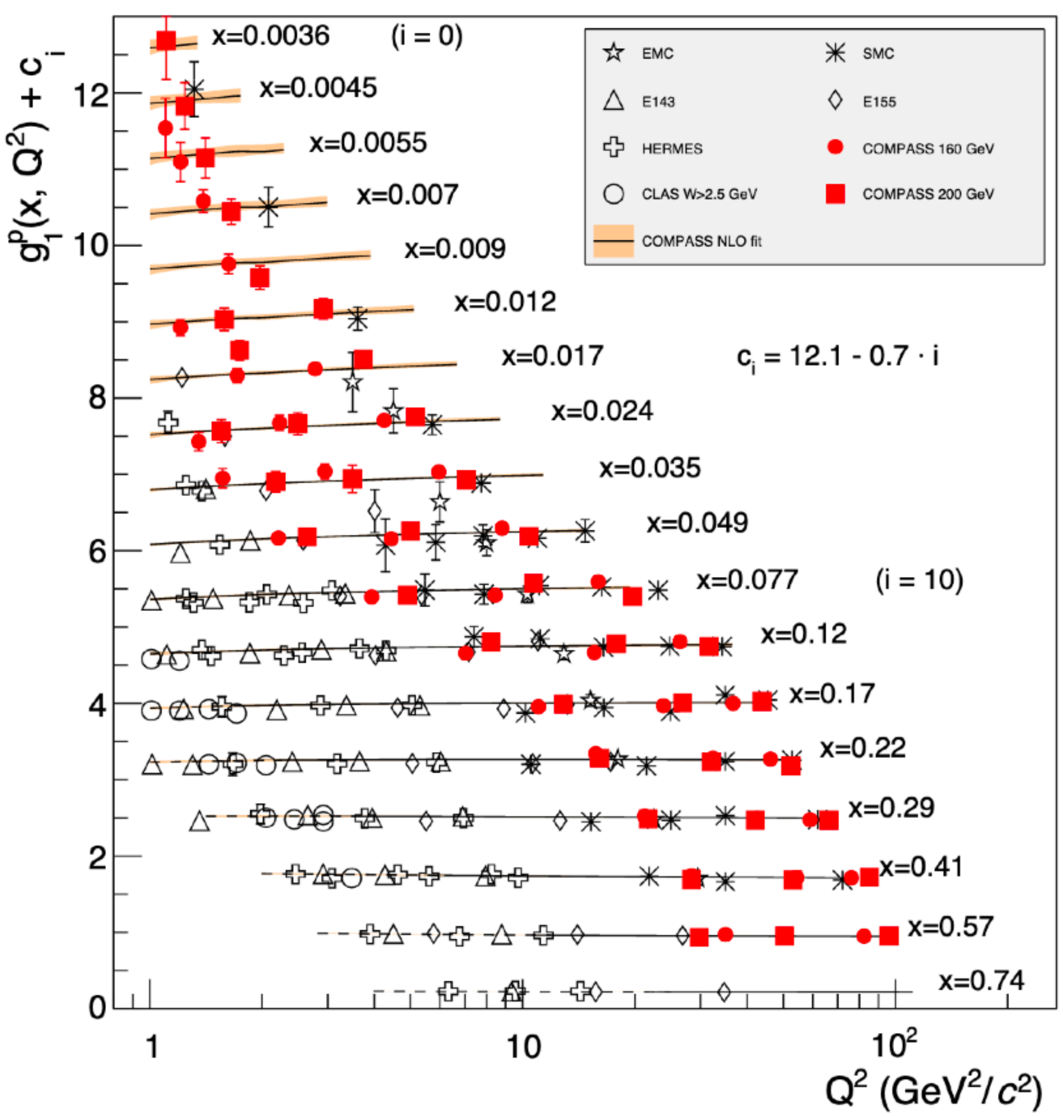
# g1 measurements

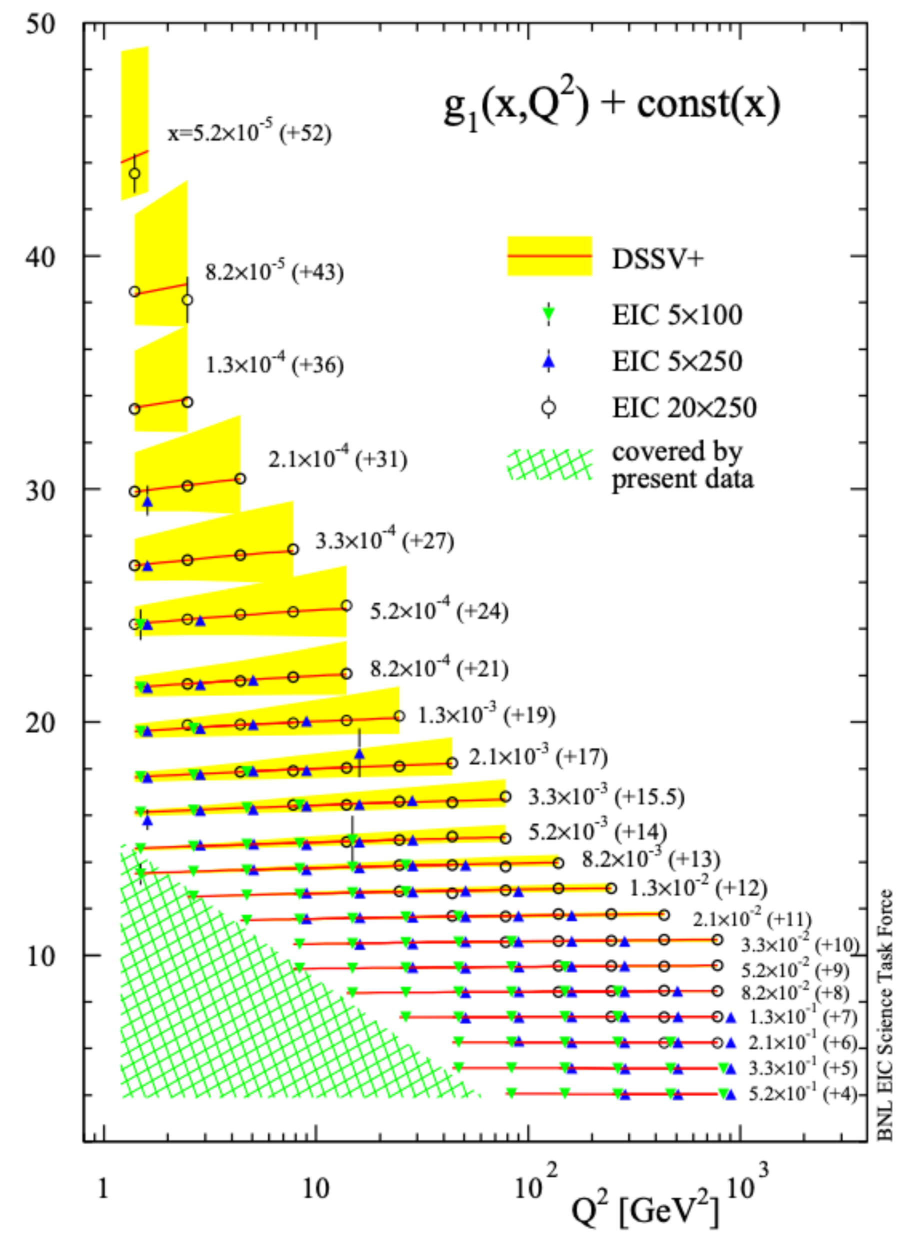
- World data of the polarized structure function $g^1$:
  Limited $(x,Q^2)$ level arm compared to the unpolarized case



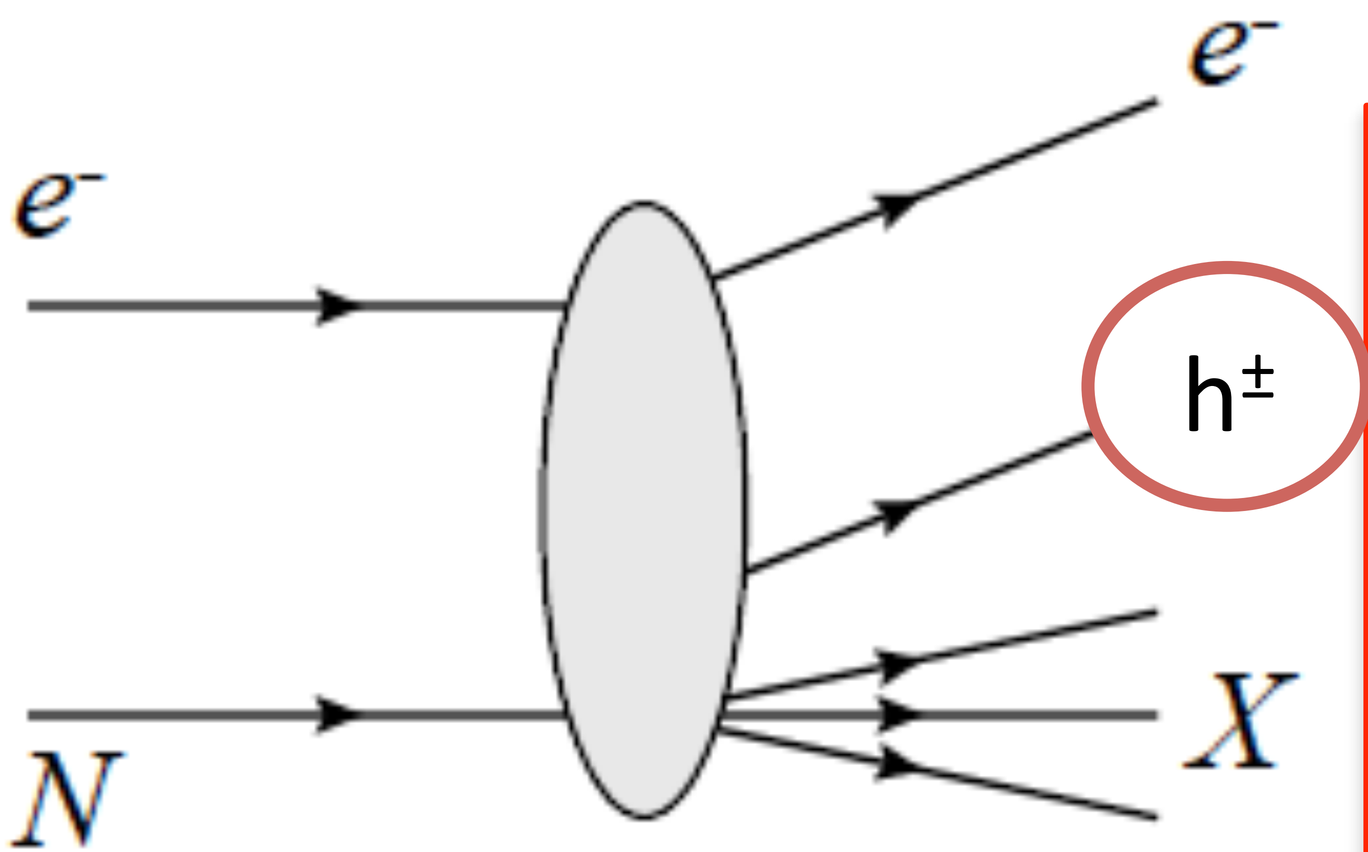
# g1 measurements

- World data of the polarized structure function g1:
  Limited (x,Q2) level arm compared to the unpolarized case



# Flavor separations with SIDIS



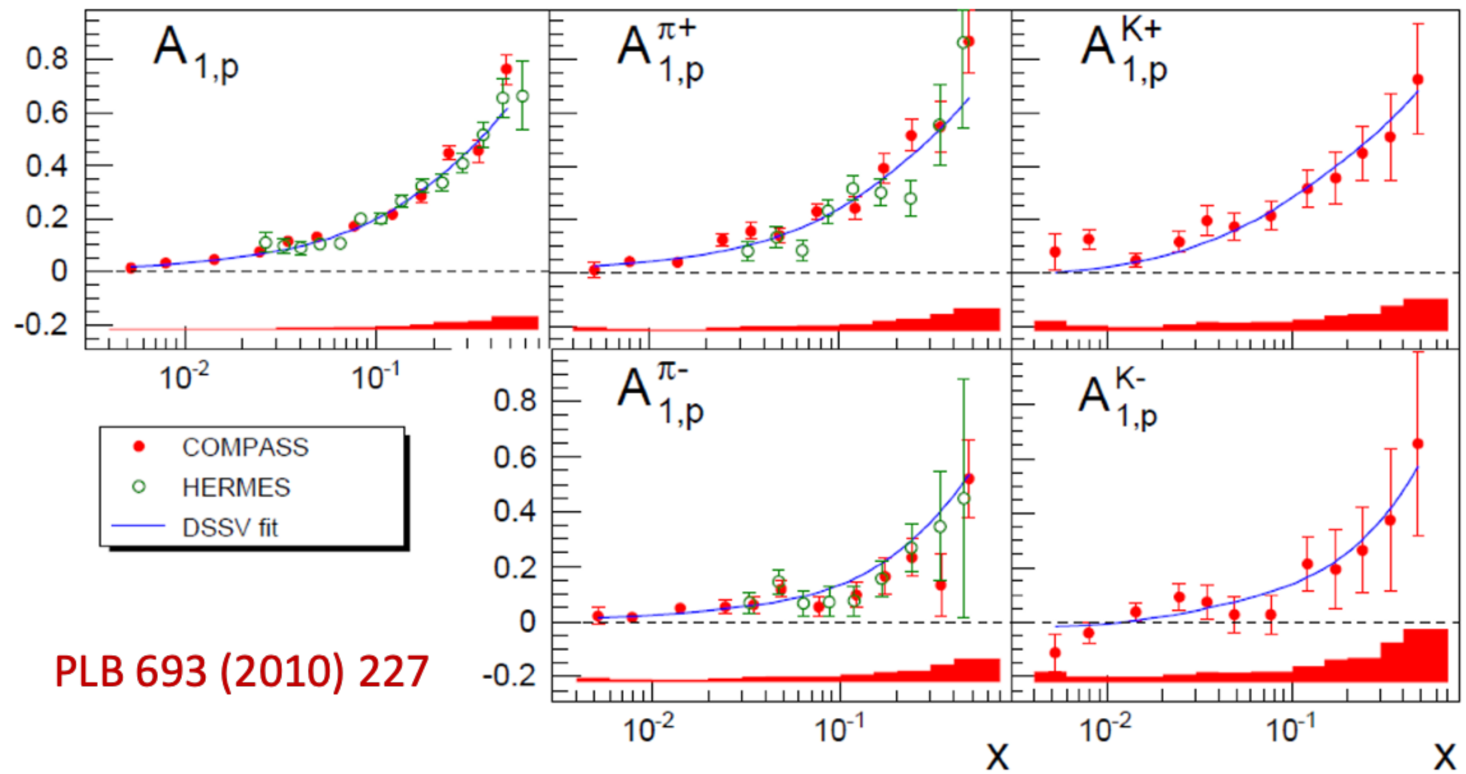

$\pi^+(u\bar{d})$

$\pi^-(\bar{u}d)$

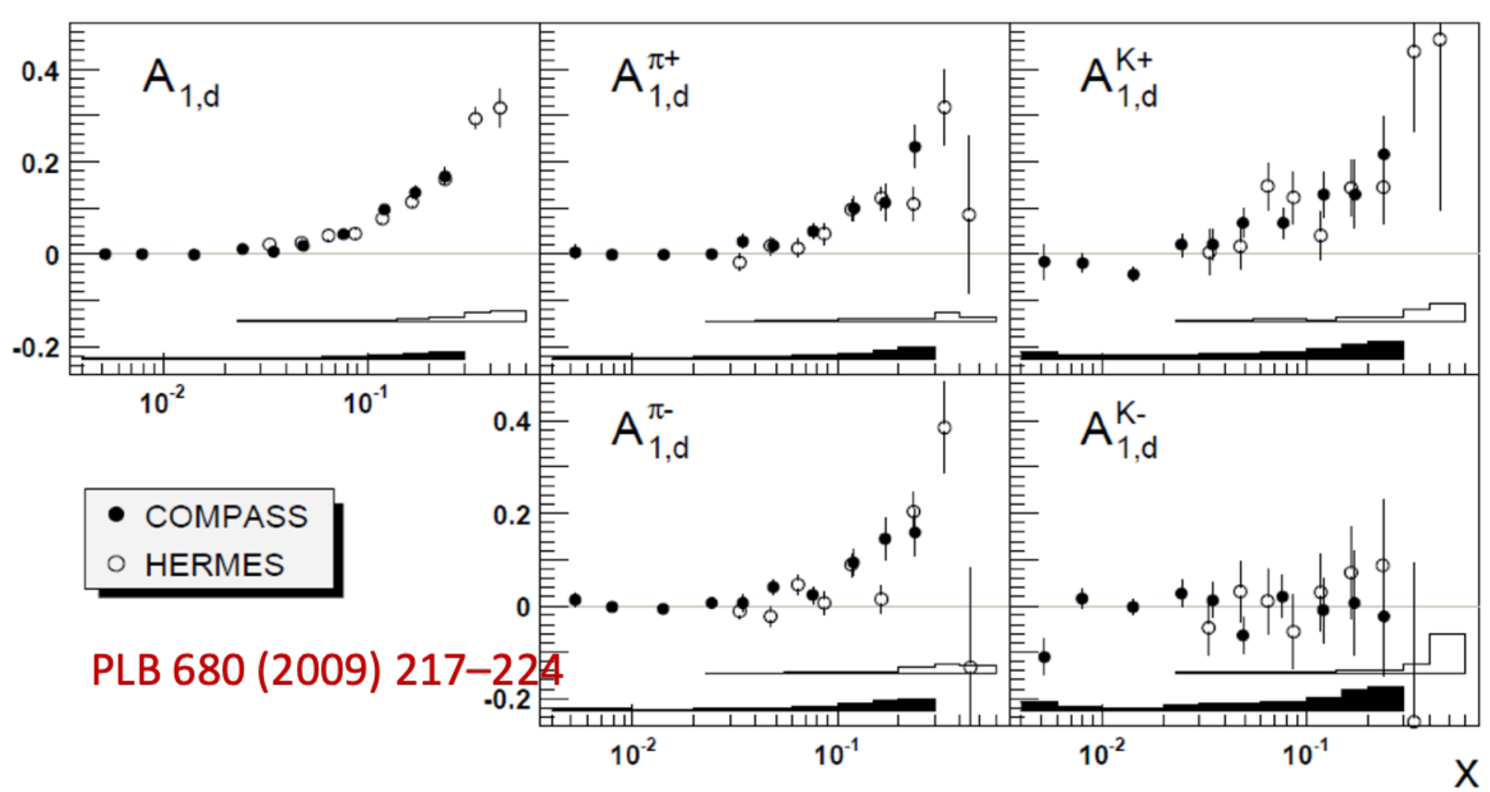
$K^+(u\bar{s})$

$K^-(s\bar{u})$

# Flavor separations with SIDIS




PLB 693 (2010) 227

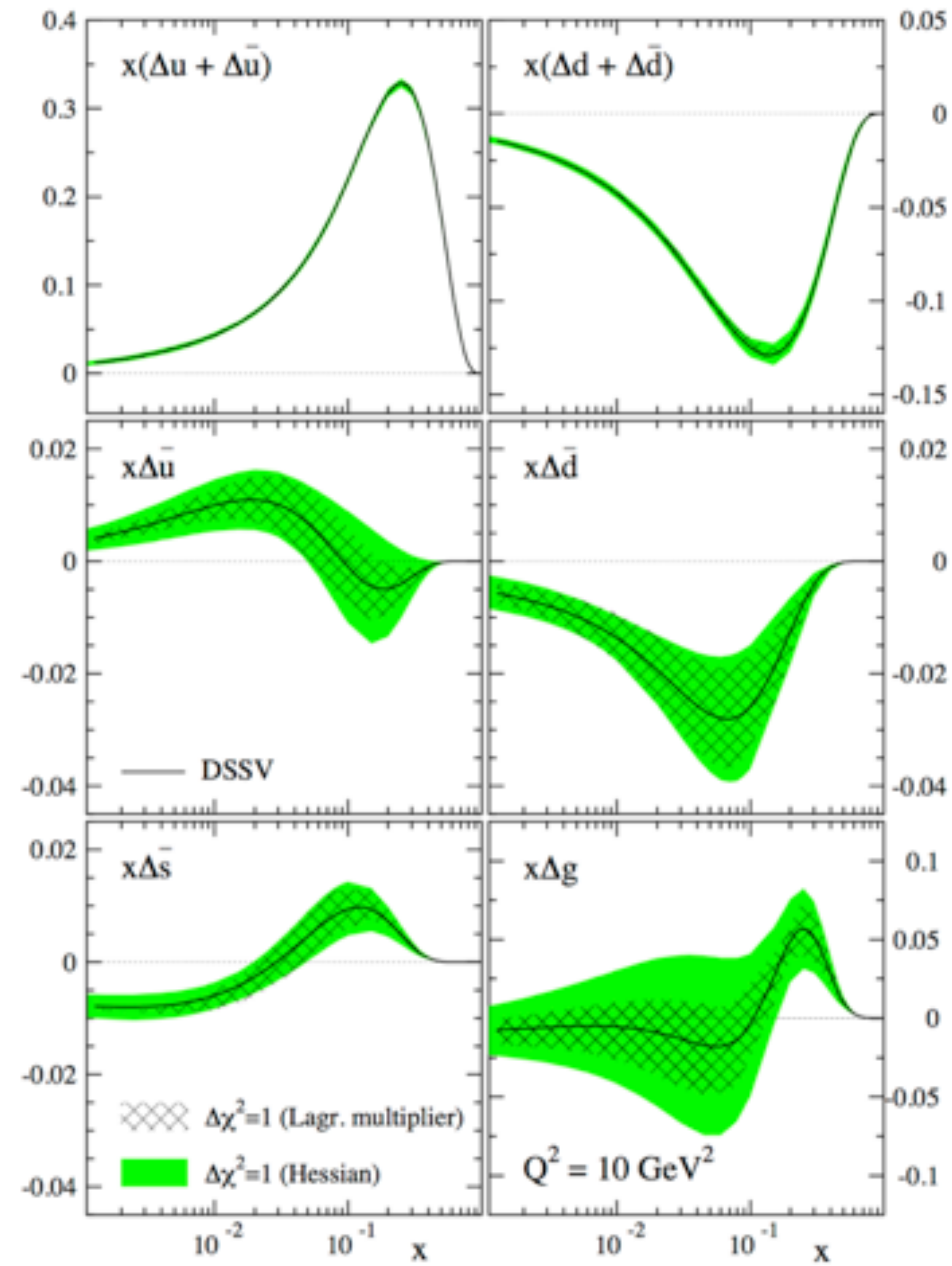



PLB 680 (2009) 217–224

# Helicity PDFs

- Combined quark and antiquark contribution well contained by polarized DIS data
- Antiquark mostly contained by SIDIS, but relatively large uncertainty due to the uncertainty on fragmentation functions
- Gluons only poorly contained by DIS (indirect access)

**-> RHIC Spin Program**




Phys. Rev. D80, 034030 (2009)

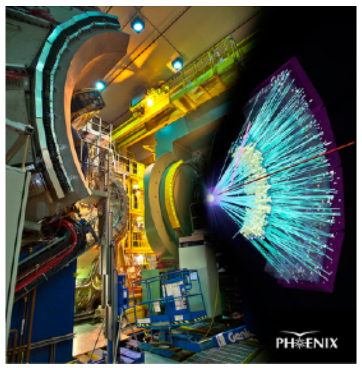

Prospects For Spin Physics at RHIC (2000)Ann.Rev.Nulc.Part.Sci.50:525-575

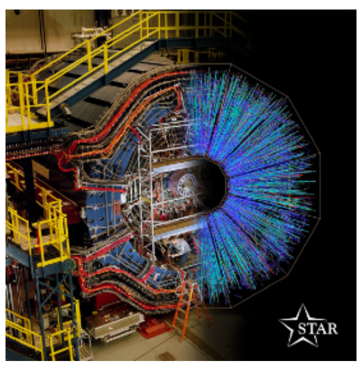
RHIC Spin White Paper (2015) https://arxiv.org/abs/1501.01220

RHIC Cold QCD Plan (2016) https://arxiv.org/abs/1602.03922

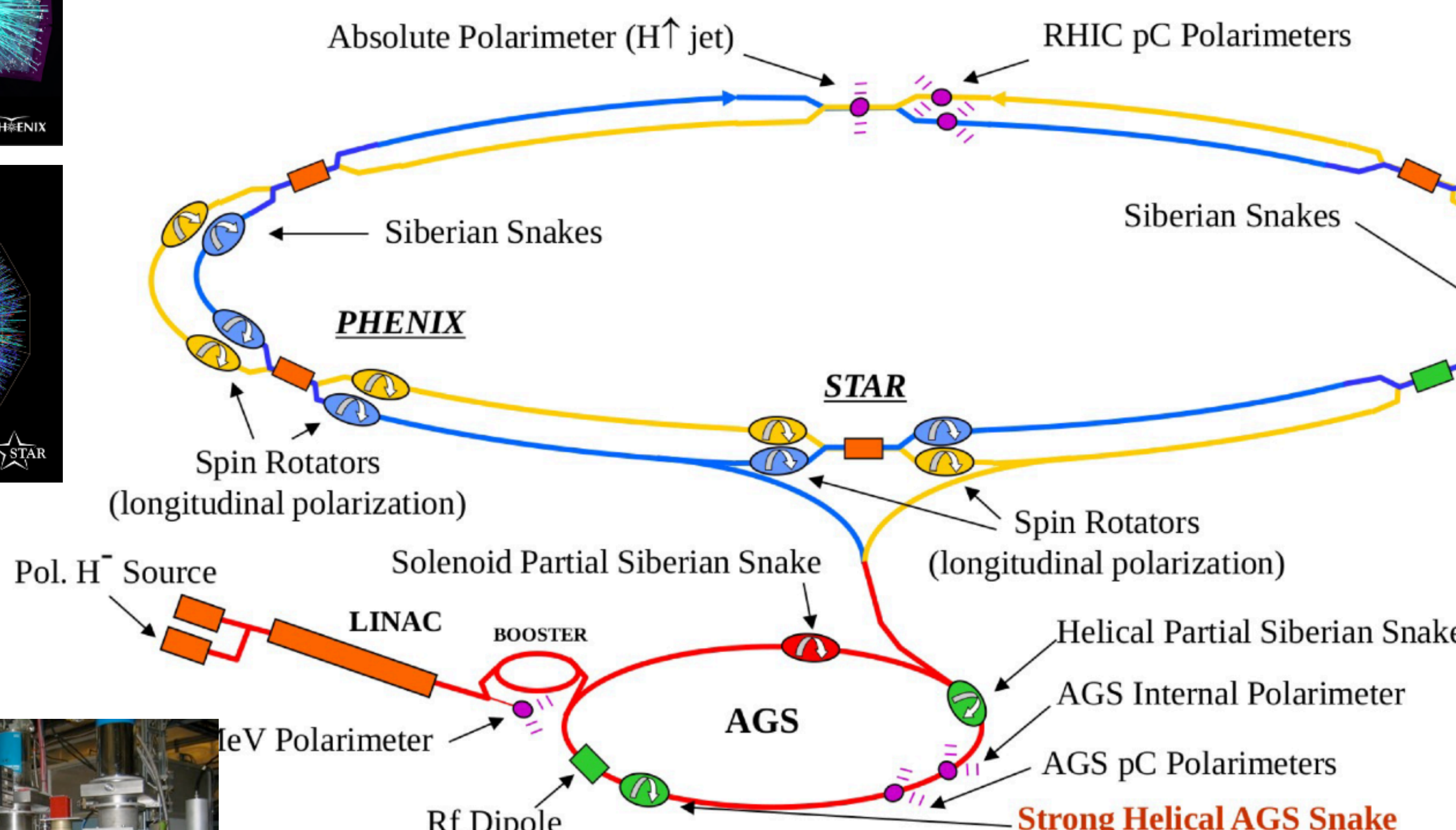
RHIC Cold QCD White Paper (2023) https://arxiv.org/abs/2302.00605

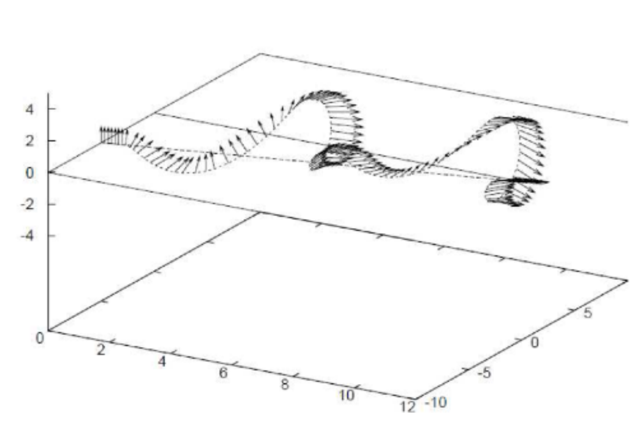
# Relativistic Heavy Ion Collider



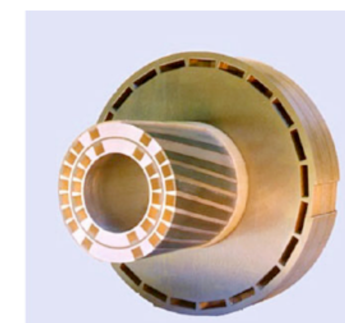


## Polarization measurements



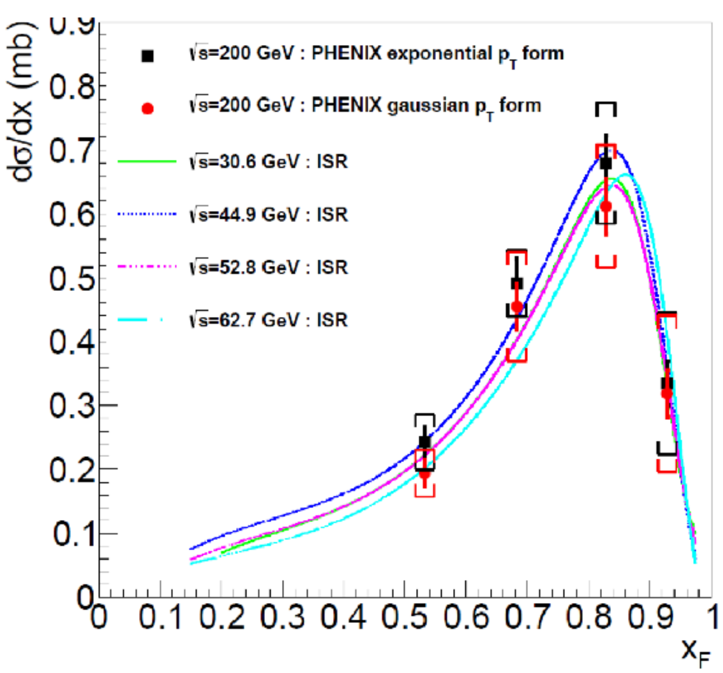
**Spin rotator**



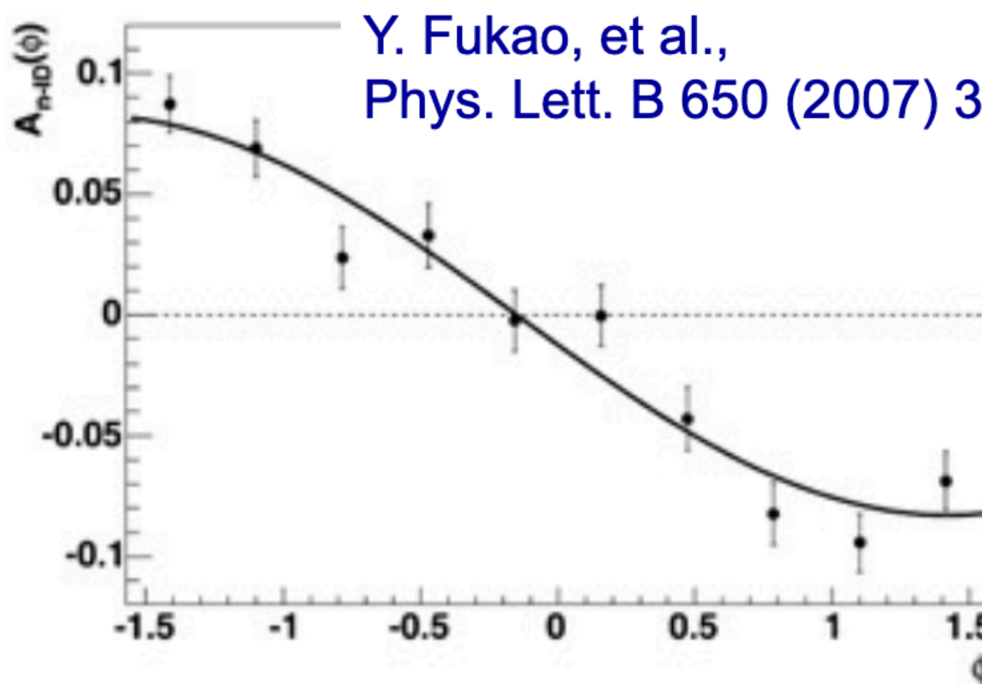
Polarized H- ion source
P = 80-85% (at 200 MeV)

# Local Polarimetry

- Monitoring the beam polarization around the interaction point. Polarization measurements for physics corrections done by RHIC polarimeters (HJet, pC).
- Very forward neutron production in p+p: cross sections (ISR and FNAL) and transverse spin asymmetries measured at RHIC (IP12)

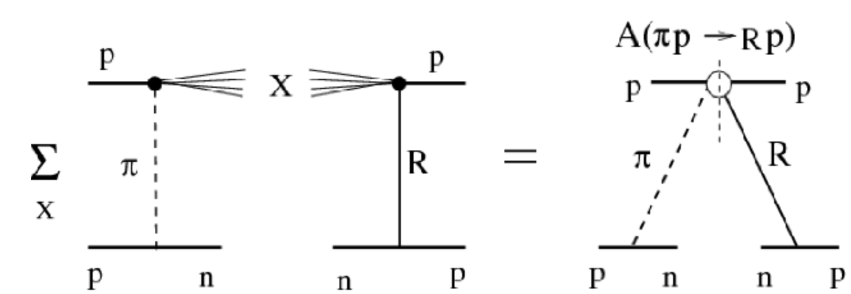



PRD 88 (2013) 032006



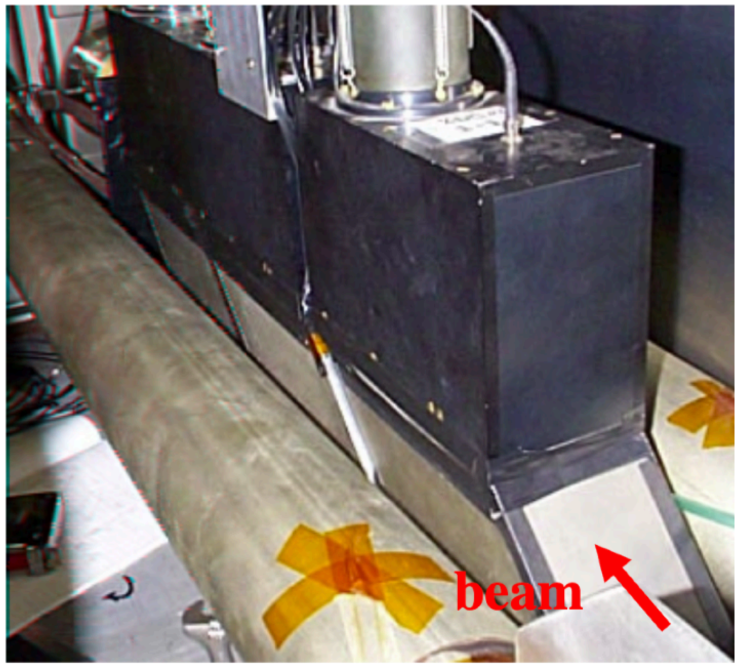

Y. Fukao, et al.,
Phys. Lett. B 650 (2007) 325.

(Extended) OPE model: Interference of pion and a1 Regge amplitudes can describe the asymmetry

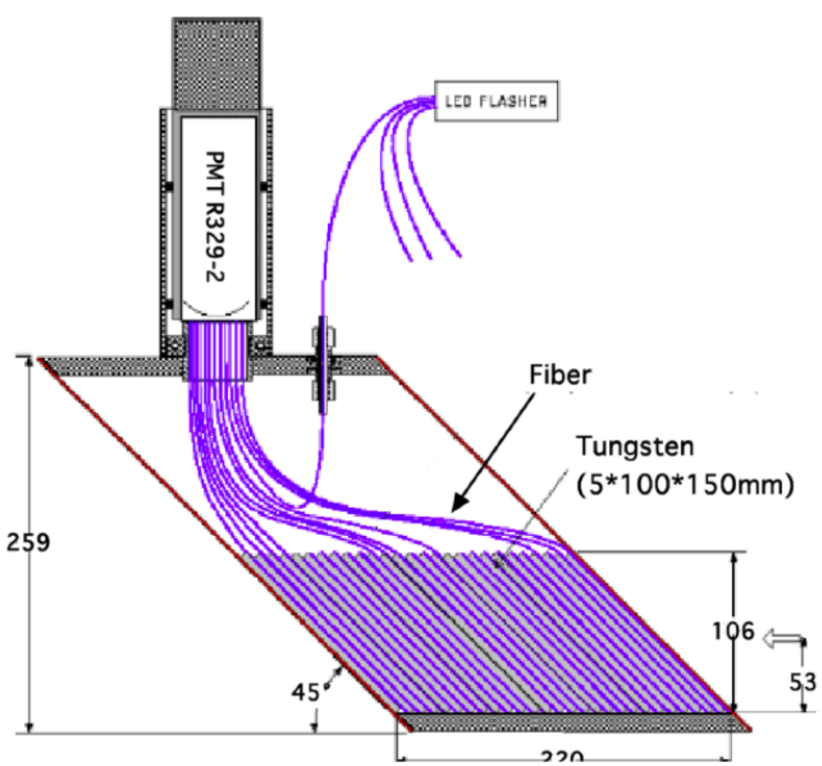


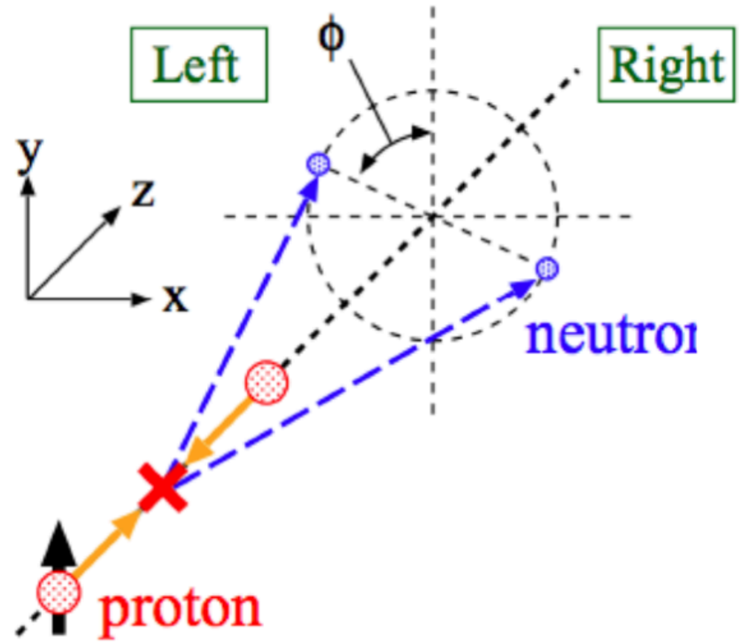
# Local Polarimetry

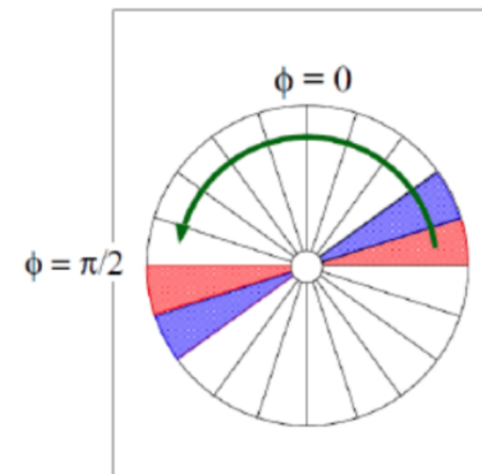
**18m from IP**



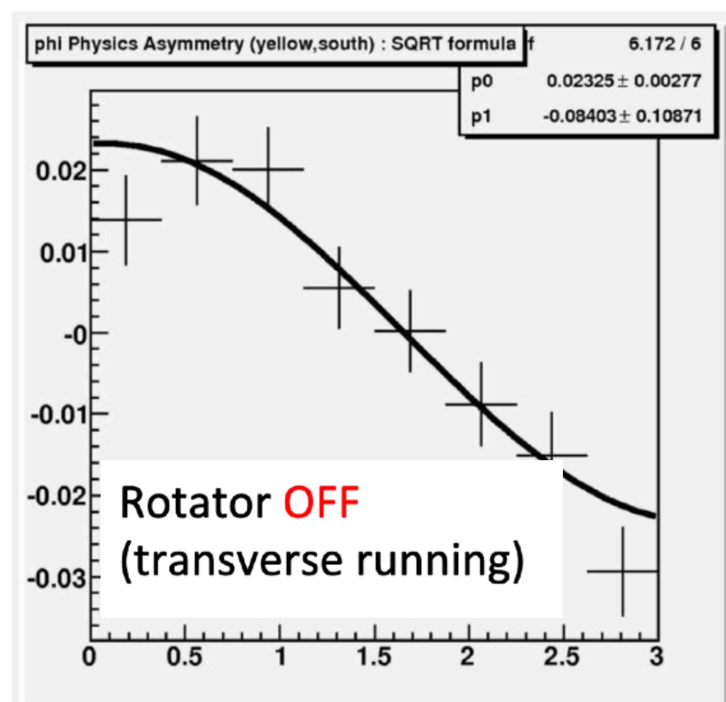

**ZDC (Zero Degree Calorimeter)**



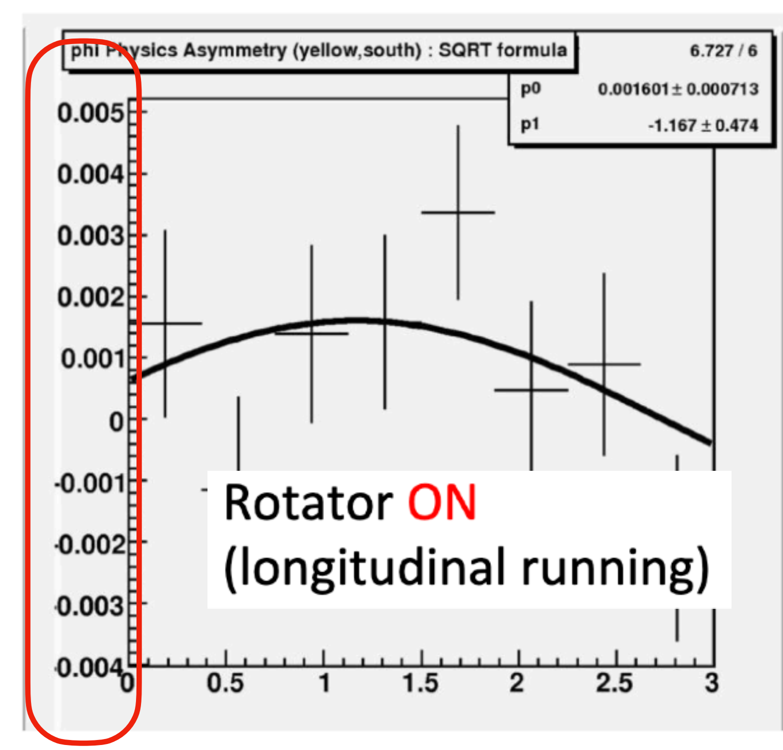




Azimuthal angle dependence
-> phi modulation

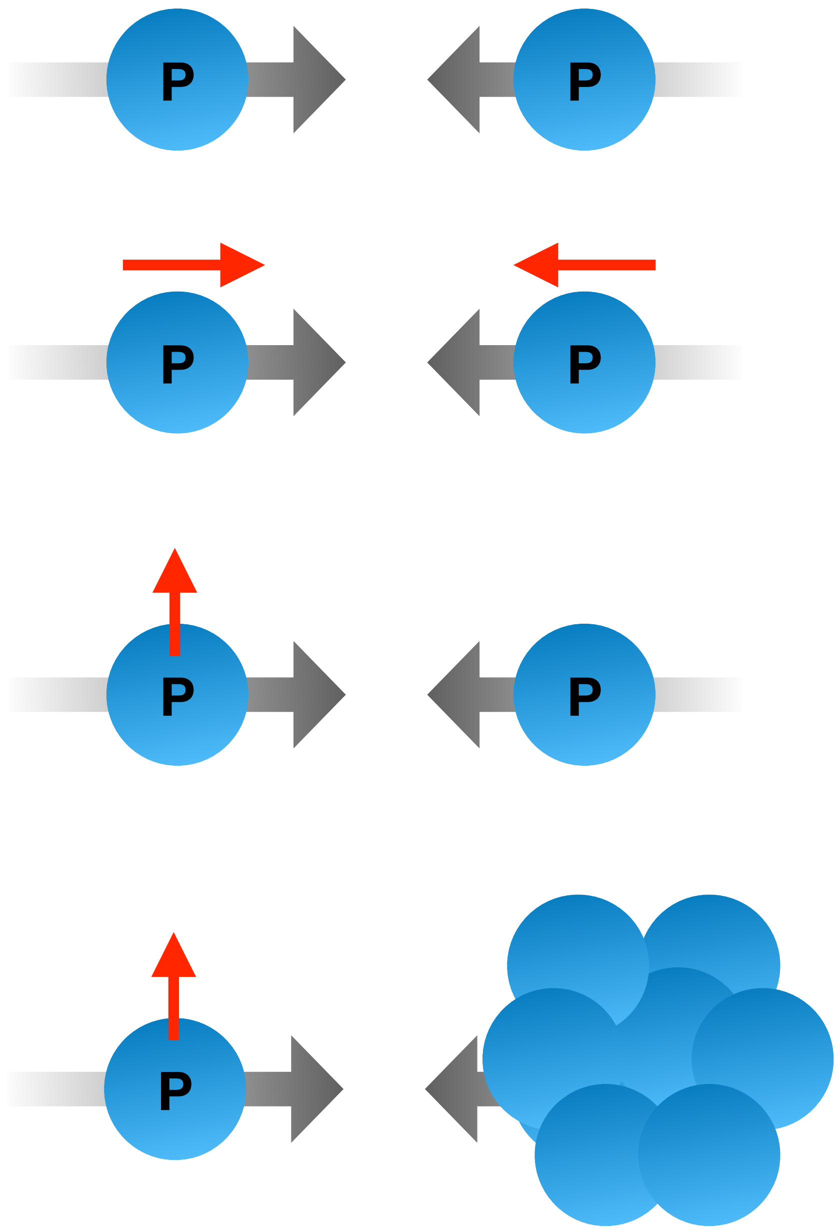



Yellow beam, phi asymmetry (Run11)




Yellow beam, phi asymmetry (Run11)

# p+A collisions at RHIC




Unpolarized anti-quark sea via W production. Provide baseline for heavy ion collisions

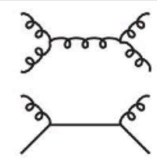
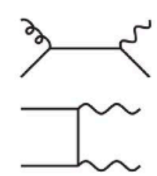
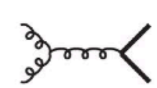
Gluon polarization inside the proton
Study sea quarks via W production

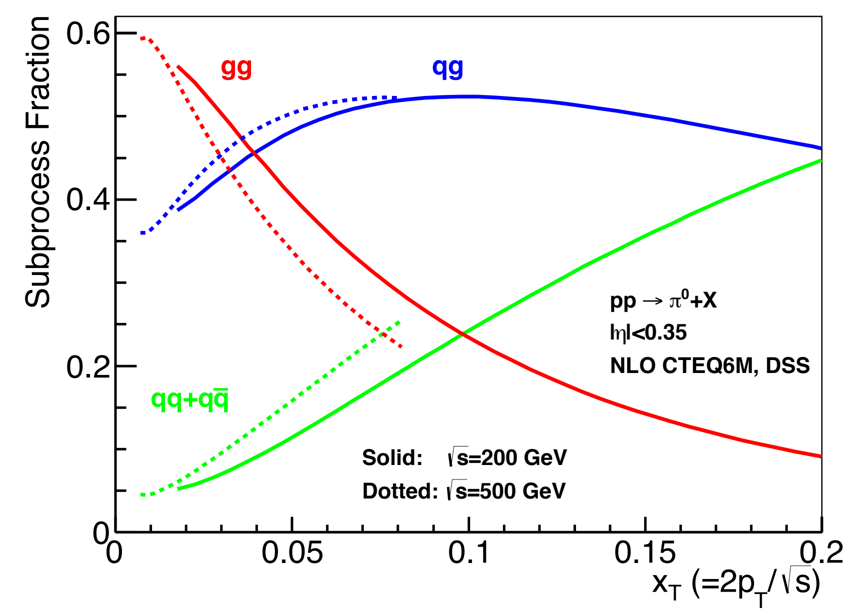
Origin of large transverse spin asymmetry
Transverse motion of partons inside the proton

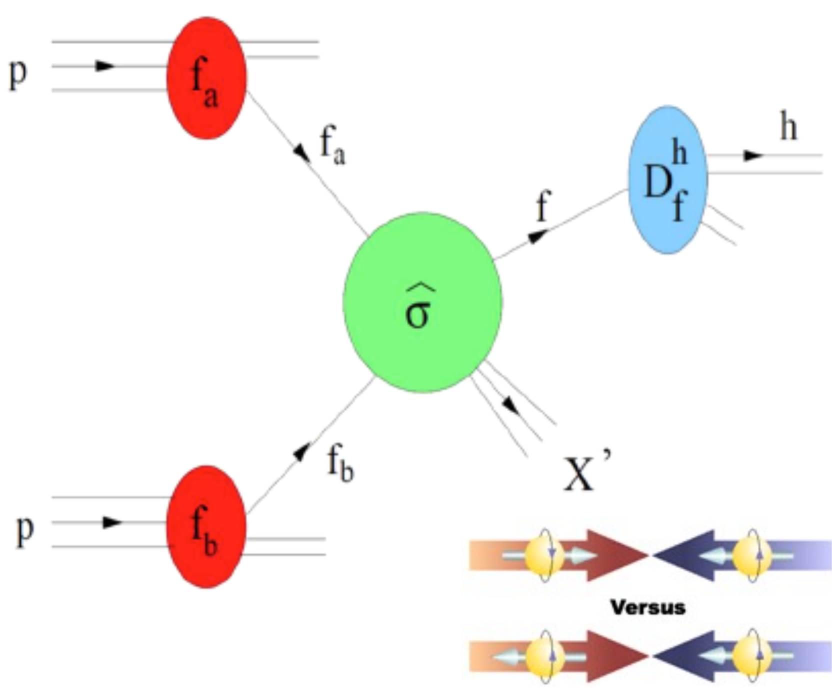
p+A Collisions provides unique opportunities to study nuclear effects to quarks and gluons distributions, and their interaction and correlations

# Direct access to gluons

- **gg and qg dominant at RHIC kenematics**
- **Access gluons at LO**

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




Polarized PDFs

Parton-level hard scattering cross section calculable in pQCD

$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{\pi^0}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{\pi^0}}$$

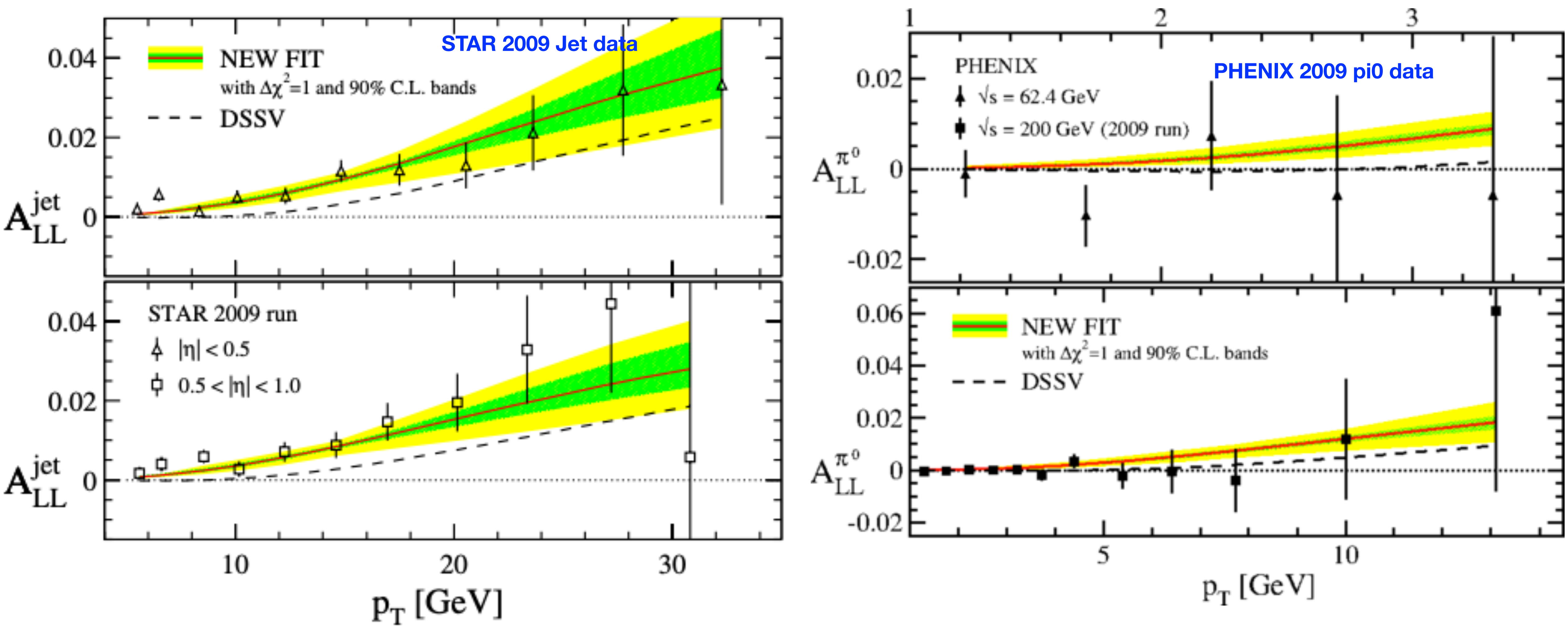
**What's measured**

Unpolarized PDFs

Fragmentation functions from e+e- scattering

# RHIC delivered:
# First evidence of non-zero gluon spin

Phys. Rev. Lett. 113 (2014) 012001




- Workhorse measurements: Inclusive jet and pion production
  - Productions dominated by gg and qg scatterings
- Non-zero asymmetries observed (especially STAR jets)

# Evidence of non-zero gluon polarization

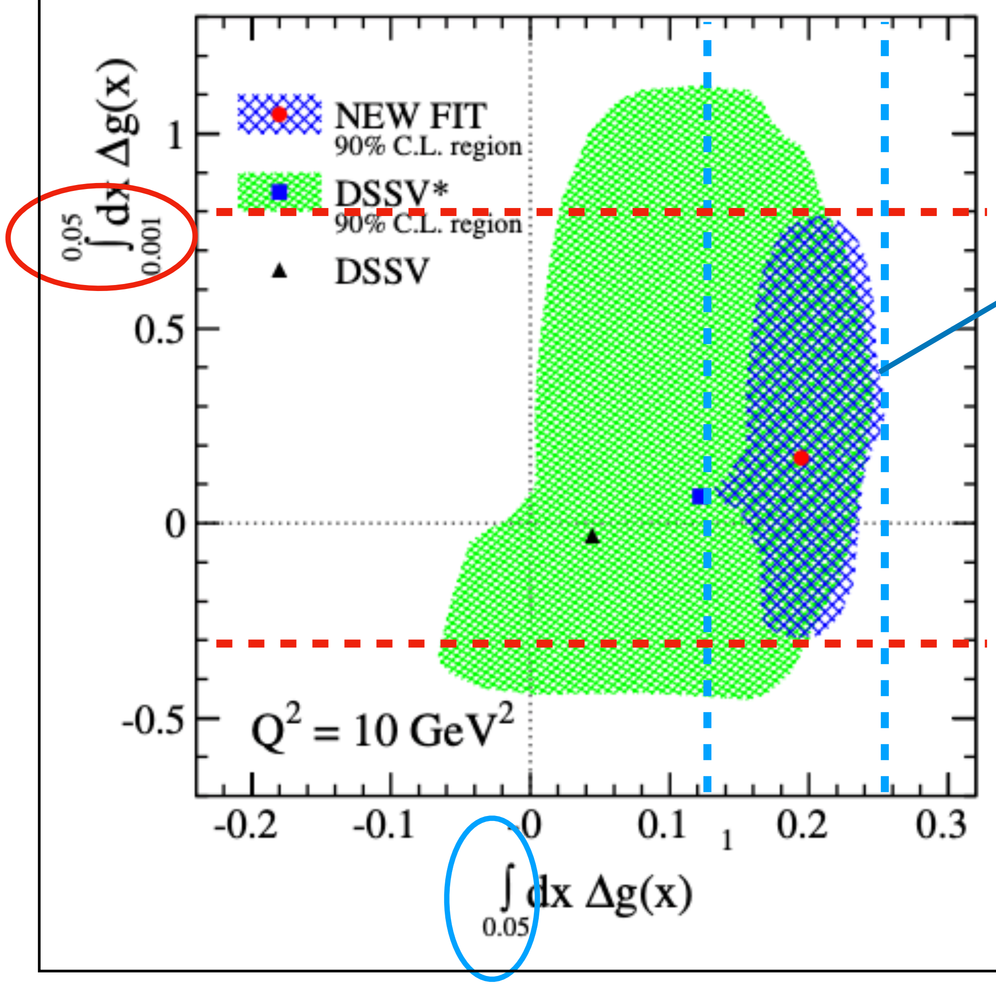
- **First evidence of non-zero gluon polarization in the proton for x > 0.05**

PRL 113, 012001 (2014) PHYSICAL REVIEW LETTERS week ending 4 JULY 2014

**Evidence for Polarization of Gluons in the Proton**

Daniel de Florian, Rodolfo Sassot, Marco Stratmann, and Werner Vogelsang

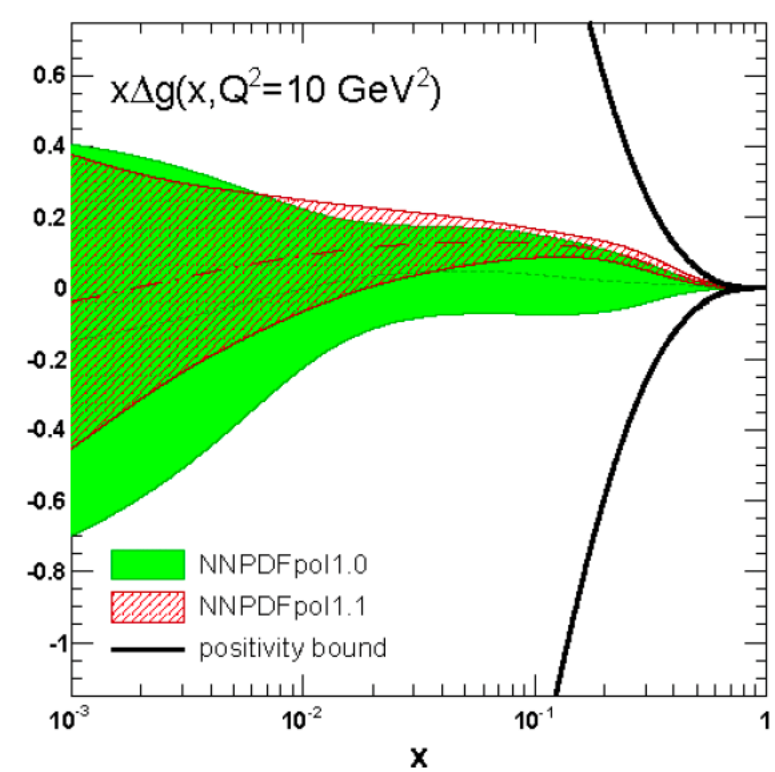
$$\int_{0.05}^{1} dx\Delta g(x) = 0.2^{+0.06}_{-0.07} (Q^2 = 10\mathrm{GeV}^2)$$




DIS data and 2009 200 GeV pp data only

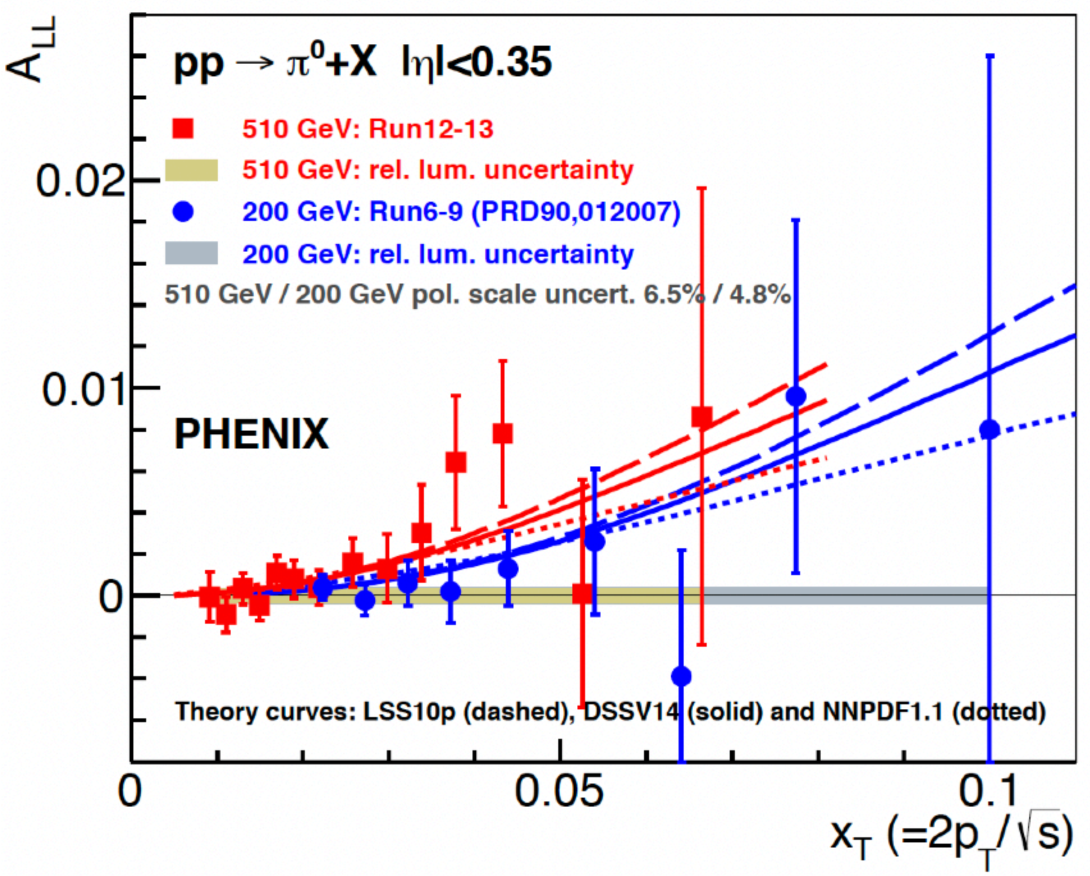
Similarly also confirmed by NNPDFpol

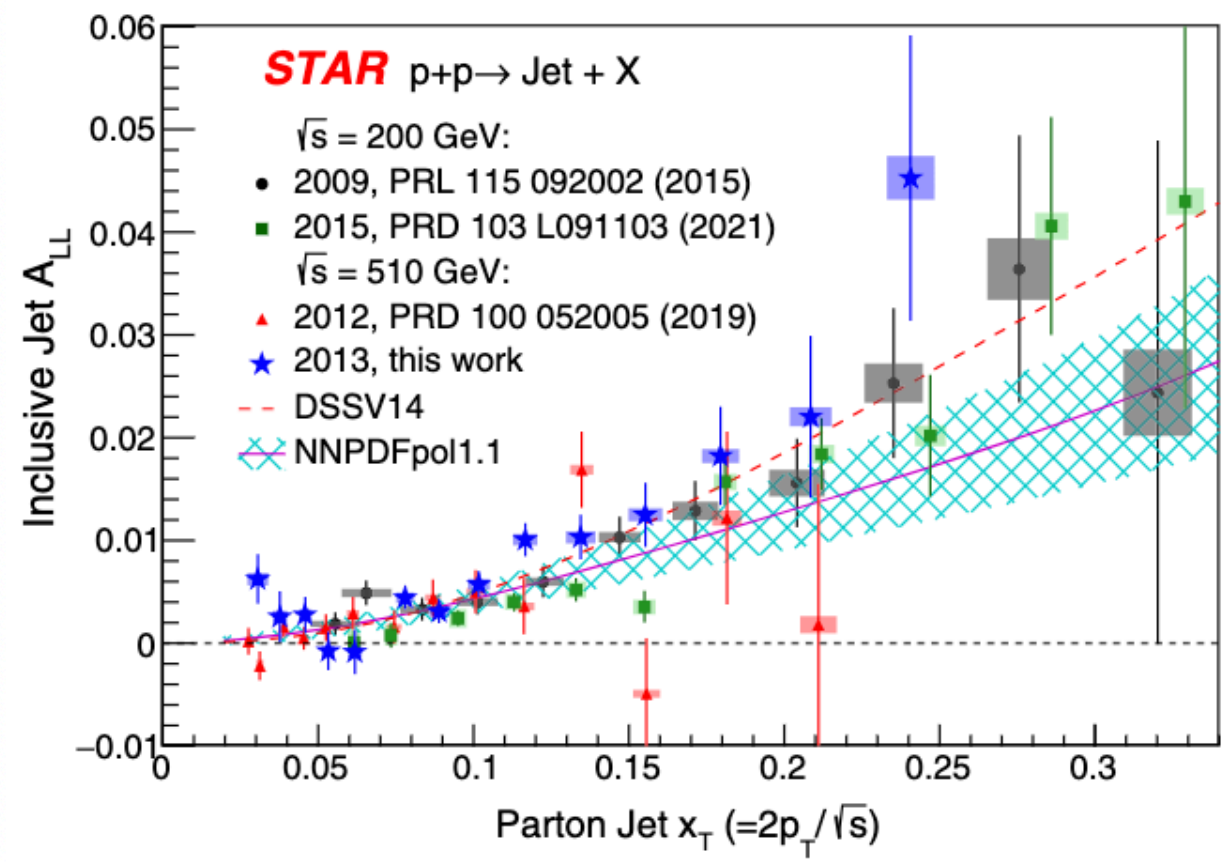
**NNPDF, NPB 887, 276 (2014)**



# Access low-x: Higher energy

Phys. Rev. D 93, 011501(R)
PRL 115, 092002 (2015)



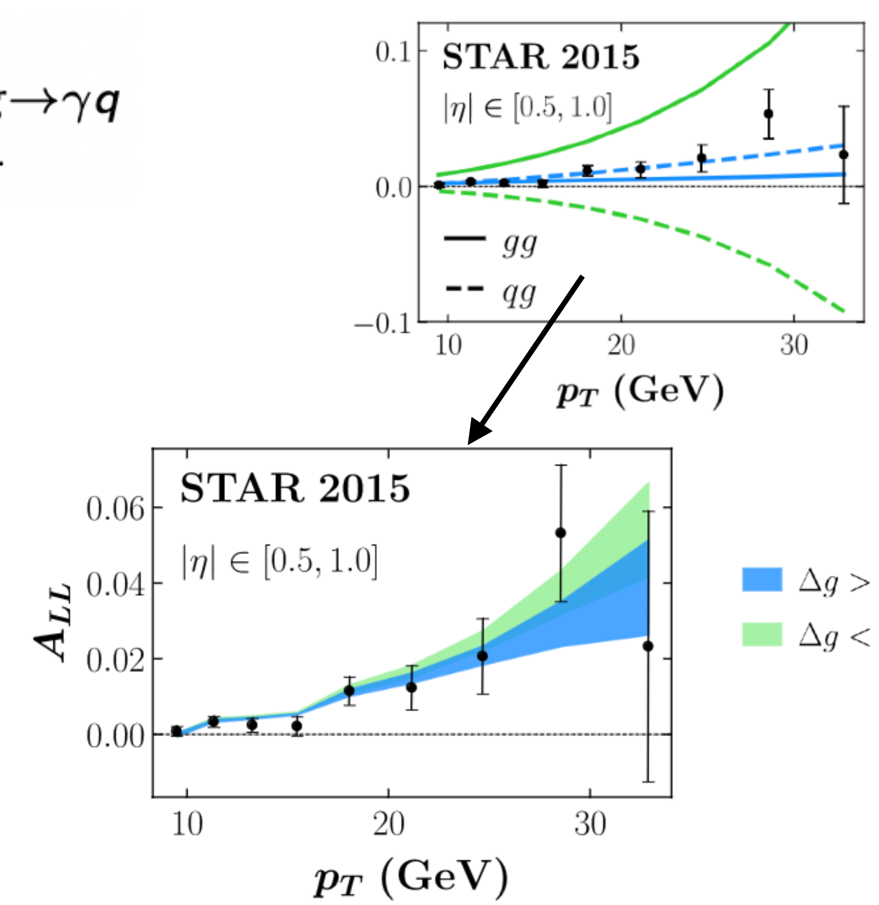




- **Non-zero $A_{LL}$ also confirmed by STAR jet and PHENIX pi0 at 510 GeV (x reach to ~$10^{-2}$)**

# Direct photon measurements

- Proposed as a *golden channel* to study the gluon spin (RHIC Spin Proposal, 1992)
- Theoretically clean measurement: only sensitive to initial partonic hard process and doesn't involve strong interaction
- Direct photons are produced dominantly by qg Compton scattering - linearly sensitive to gluon helicity distribution

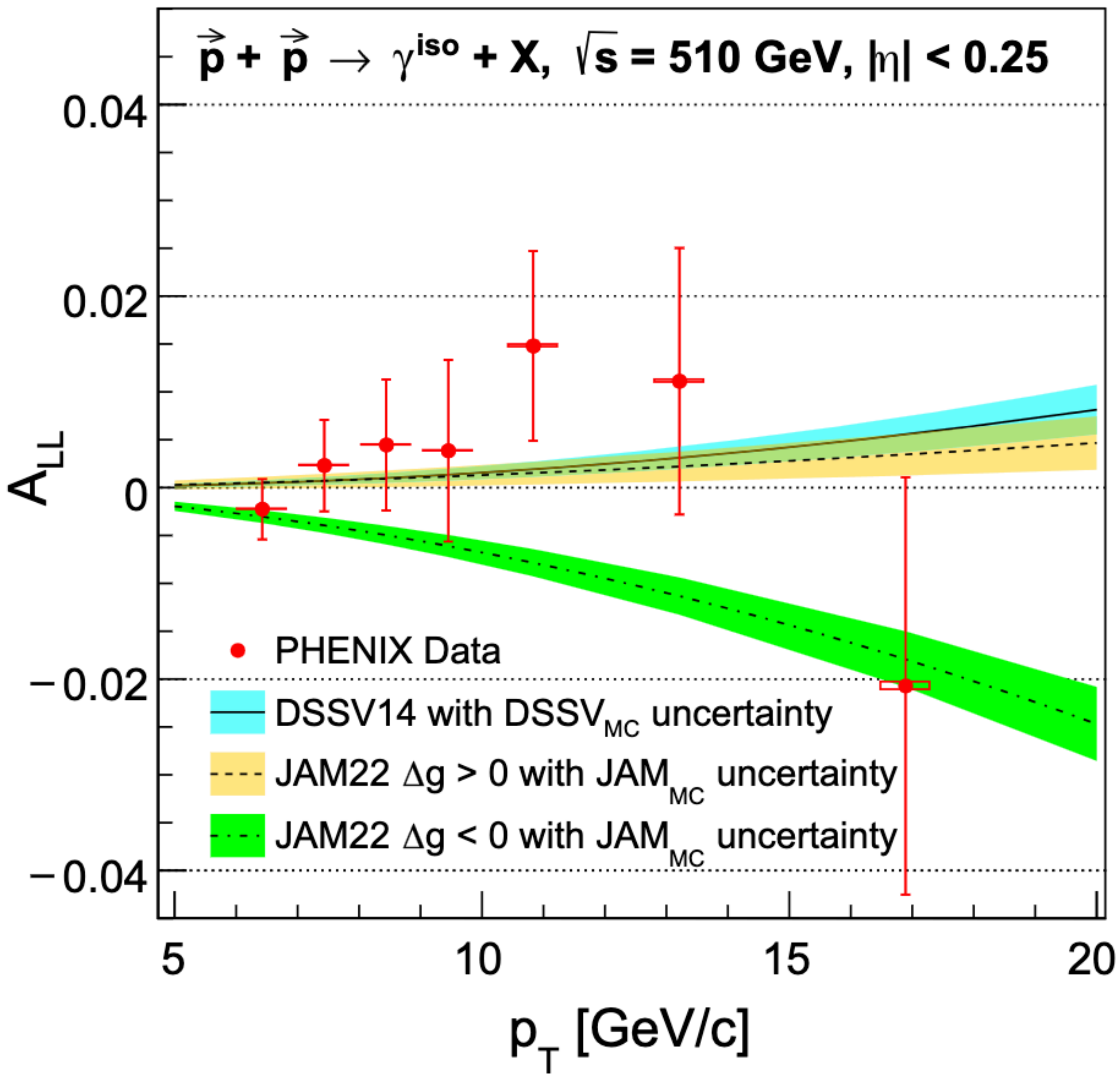
$$A_{LL}^{pp\to\gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{\Delta g(x_g)}{g(x_g)} \cdot a_{LL}^{qg\to\gamma q}$$




- Mixed gg and qg contributions: Recent analysis by JAM collaboration showed that existing data cannot rule out negative $\Delta g$ scenario [JAM, Phys. Rev. D 105, 074022 (2022)]

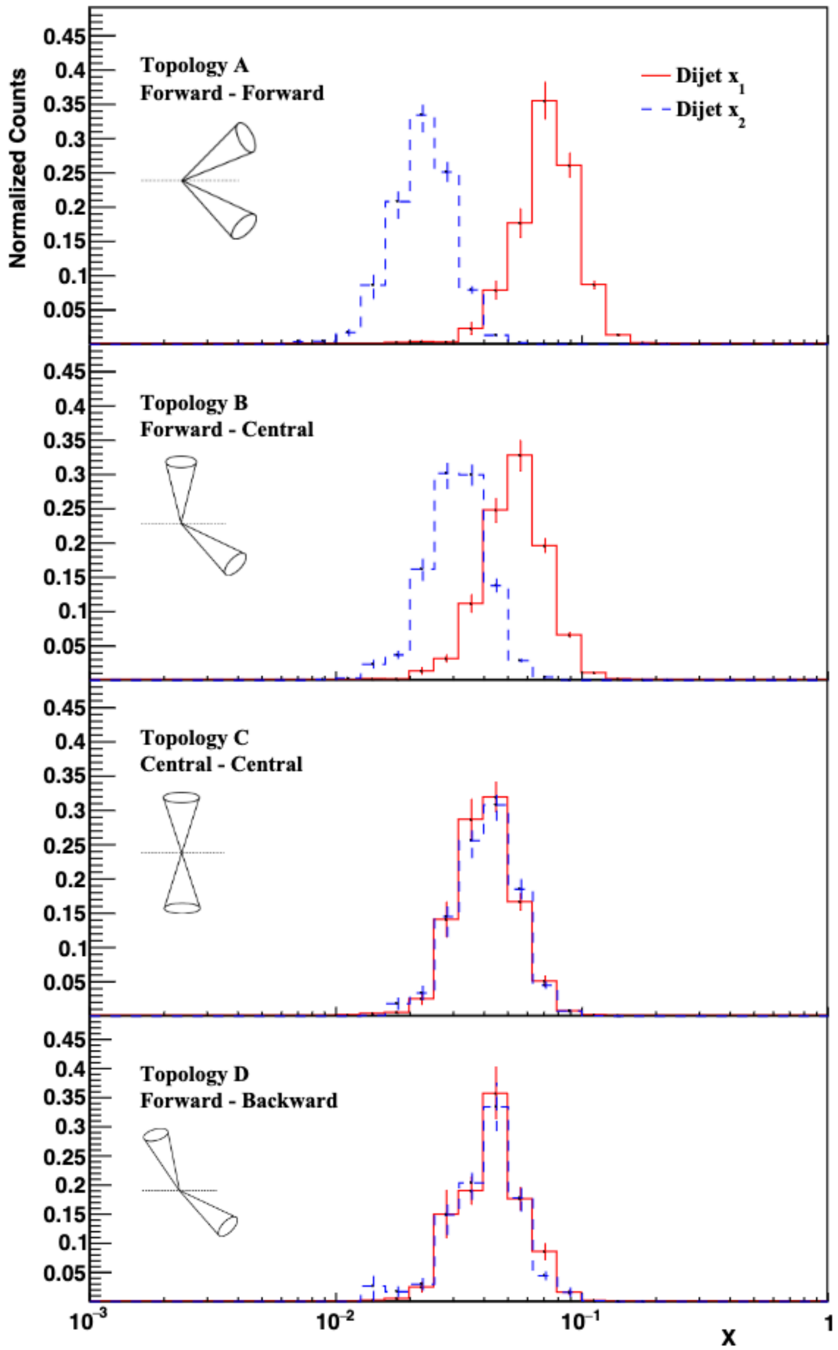
# Direct photon $A_{LL}$

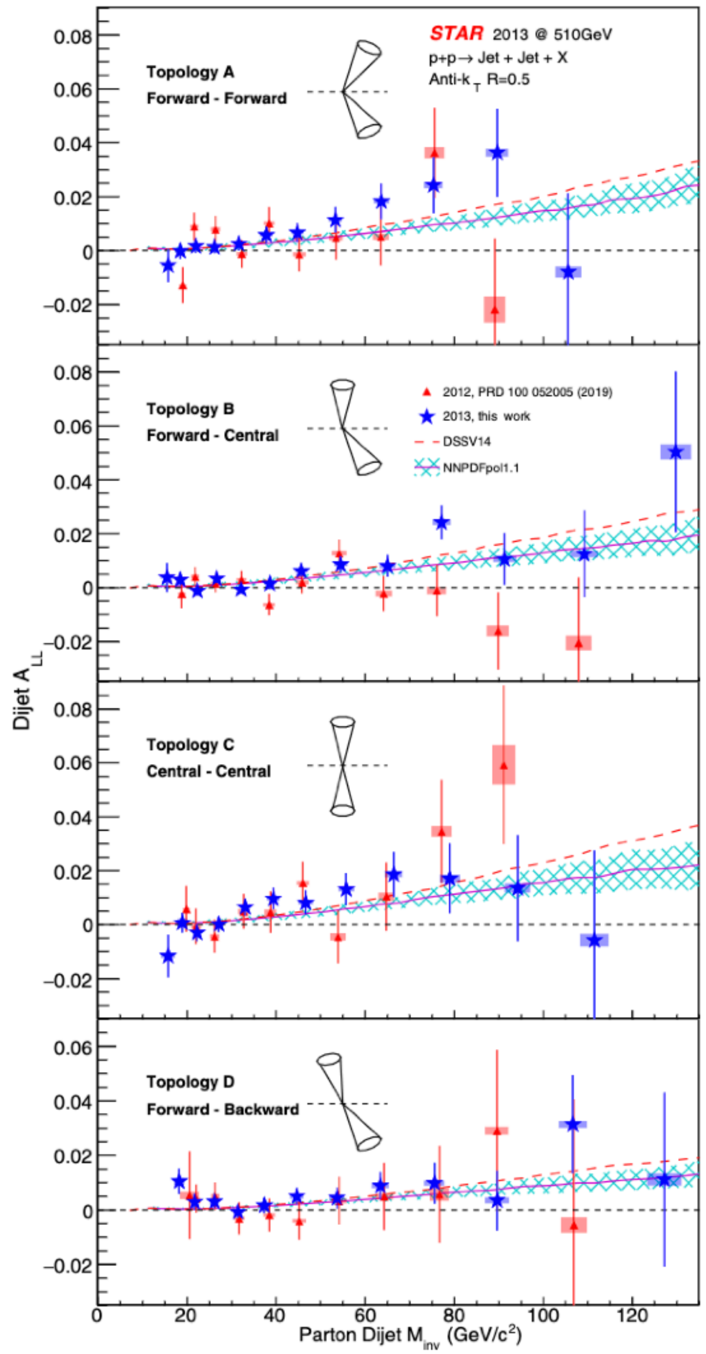
[Phys. Rev. Lett. 130, 251901 (2023)]




- First published measurement of direct photon $A_{LL}$
- Compared with two scenarios for gluon spin
- Data consistent with the positive gluon spin contributions and disfavor the negative $\Delta g$ scenario

# Dijet measurements



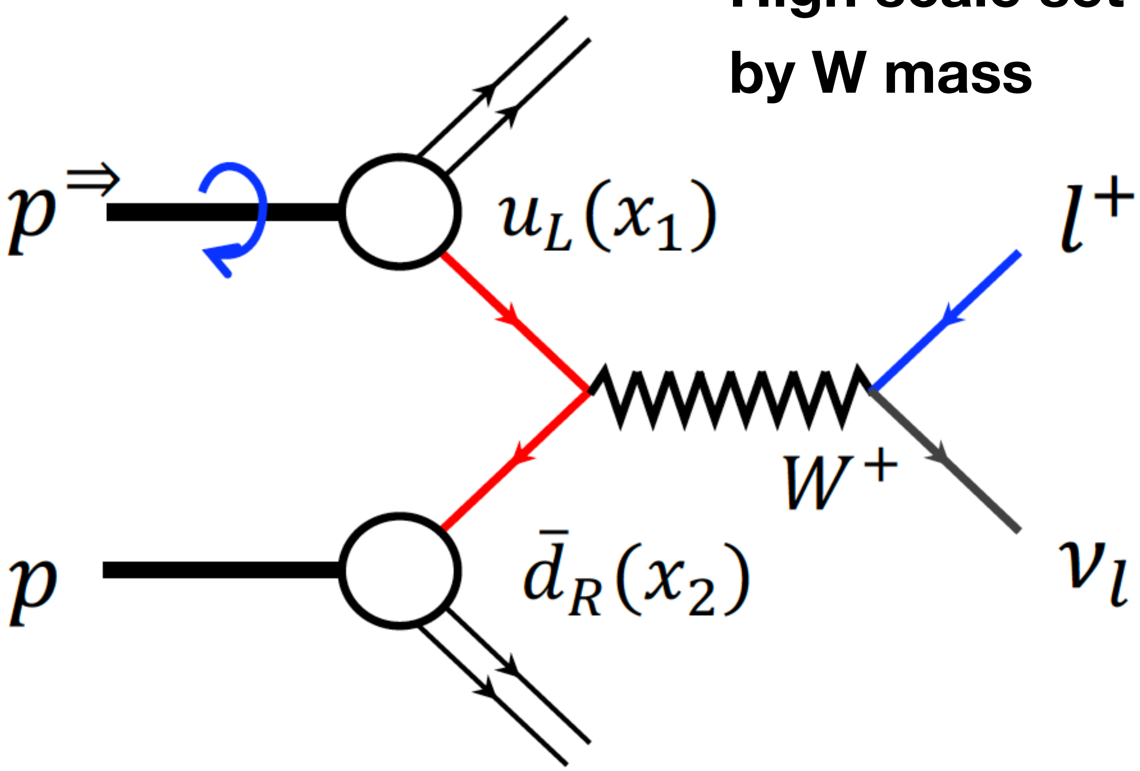

Correlation measurements allow one to access parton kinematics at LO

$$M = \sqrt{s}\sqrt{x_1 x_2}$$

$$\eta_3 + \eta_4 = \ln(x_1 / x_2)$$

# Flavor Separation: W production

**High scale set by W mass**



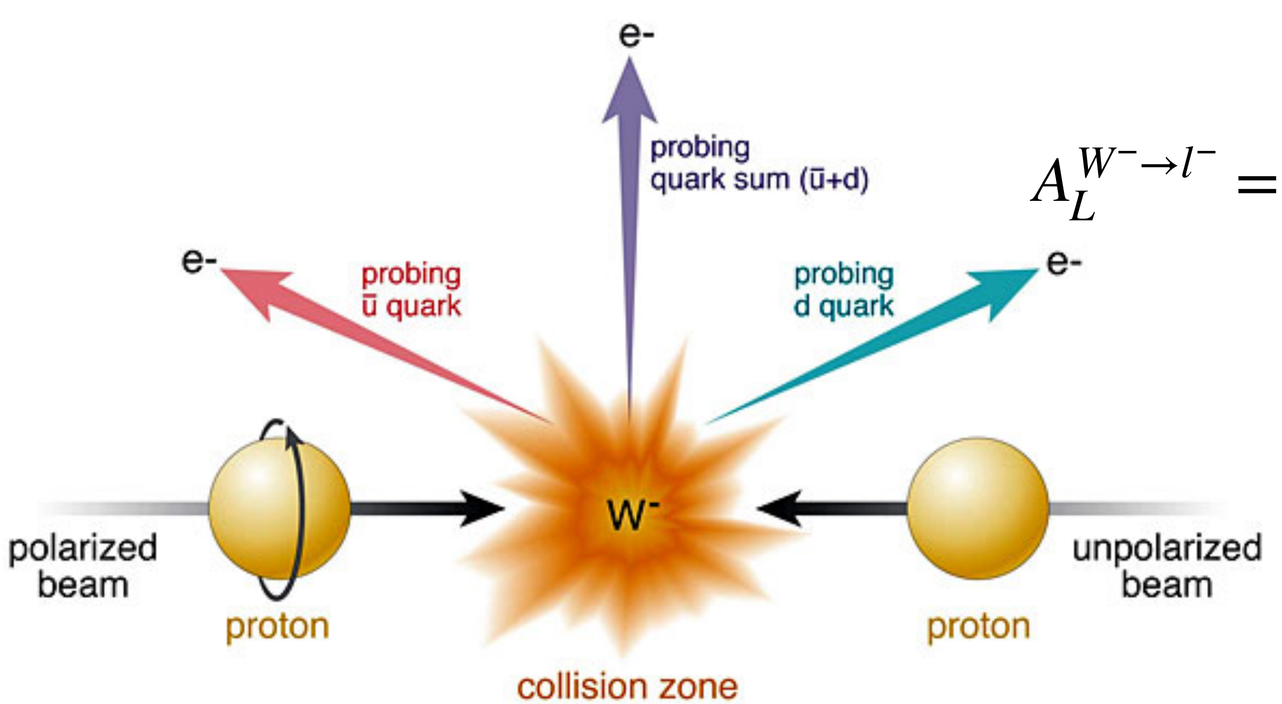

$$u_L \bar{d}_R \rightarrow W^+$$

$$d_L \bar{u}_R \rightarrow W^-$$

- Probing light quark sea via maximally parity violating W production
- W couples only to left-handed quark and right-handed antiquark
- $W^+/W^-$ distinguishes between quarks and antiquarks
- No fragmentation functions needed

# Parity violating spin asymmetry

- Parity violating spin asymmetries can directly access to quark helicities
- Combined with weak decay kinematics
  - Quark flavor mixed at mid-rapidity
  - Sensitive to antiquark at forward/backward rapidity



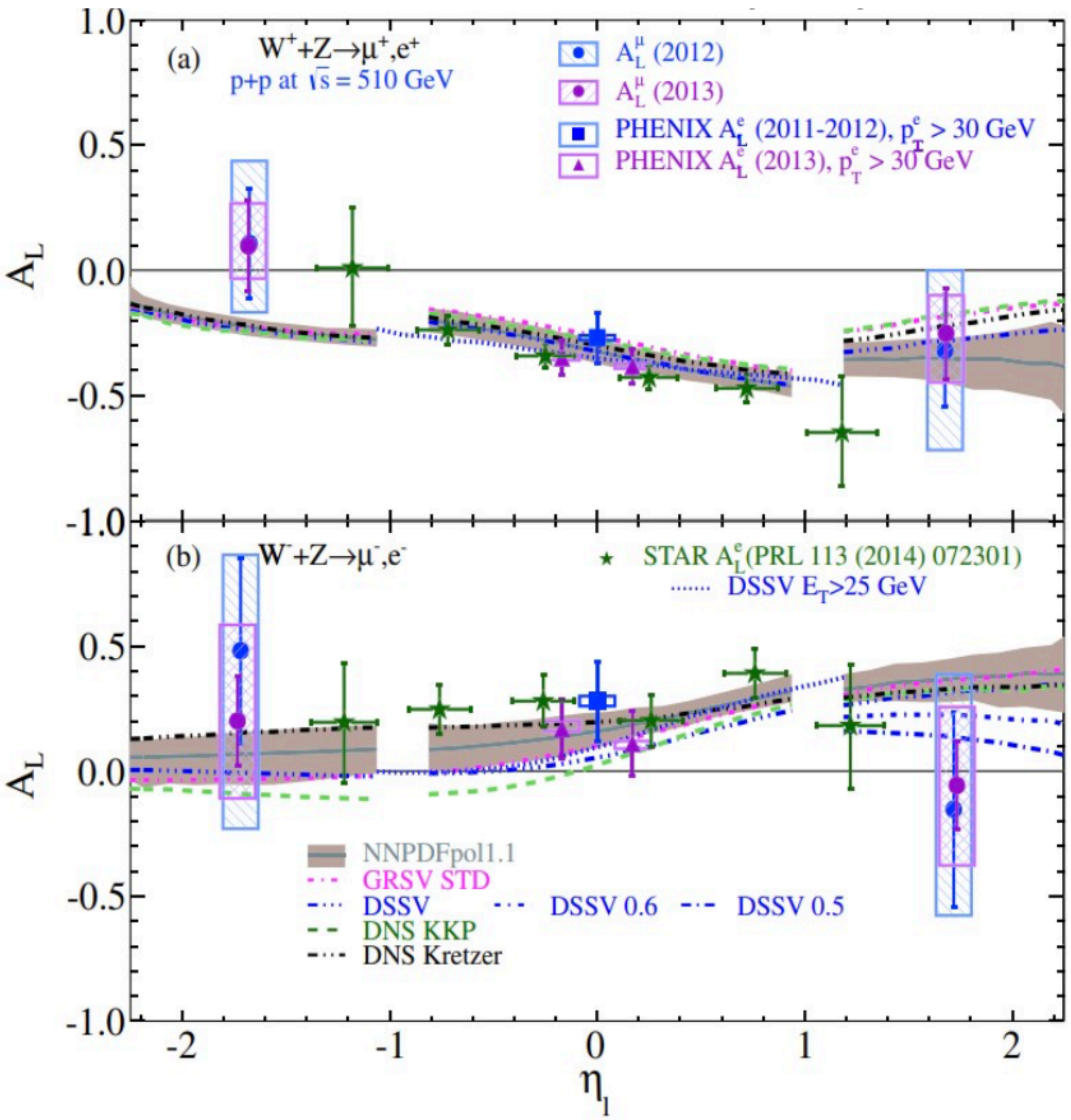

$$A_L^{W^-\to l^-} = \frac{-\Delta d(x_1)\bar{u}(x_2)(1+cos\theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1-cos\theta)^2}{d(x_1)\bar{u}(x_2)(1+cos\theta)^2 + \bar{u}(x_1)d(x_2)(1-cos\theta)^2}$$

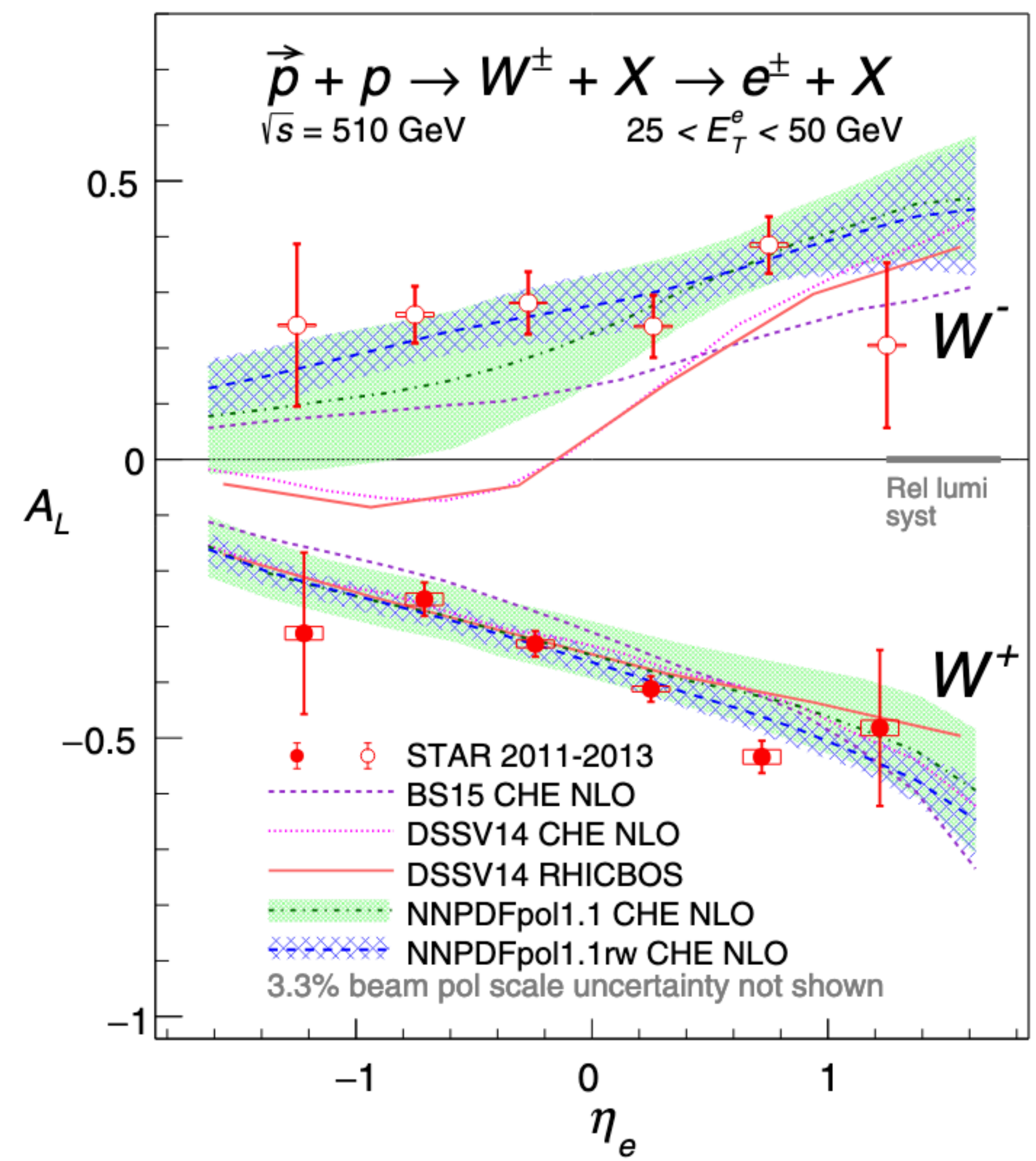
Similar for W+

$$A_L \equiv \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

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

# W single spin asymmetries



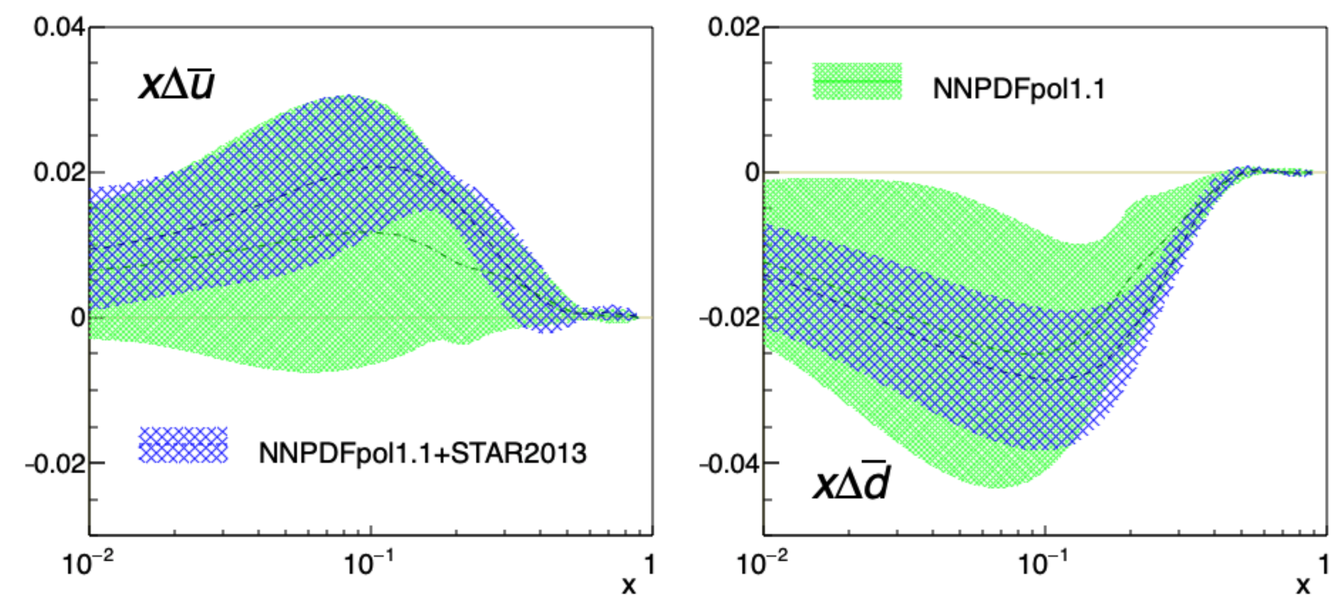

[PHENIX Phys. Rev. D93 051103 (2016)]

[PHENIX Phys. Rev. D 98, 032007 (2018)]

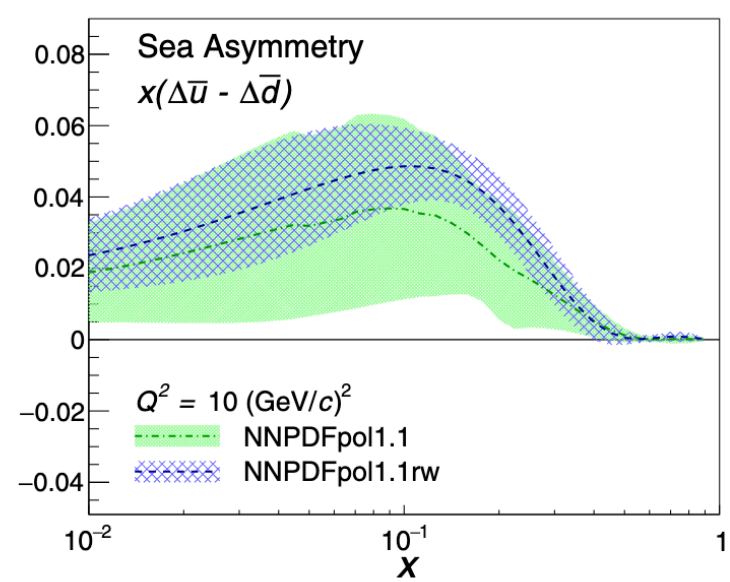
[STAR, Phys. Rev. D 99, 051102(R) (2019)]

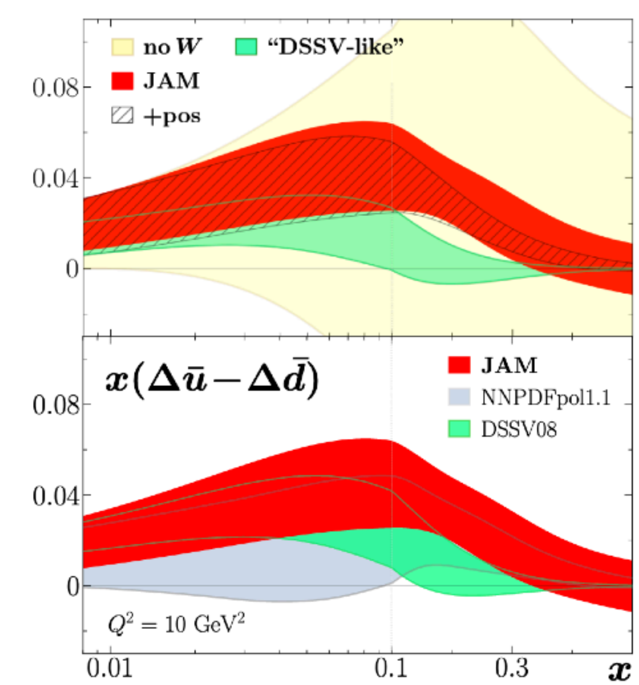
# Light sea quarks $\Delta\bar{u}$, $\Delta\bar{d}$

[STAR, Phys. Rev. D 99, 051102(R) (2019)]




**Asymmetric polarized light antiquark sea!**




[JAM, arXiv:2202.03372]