Center for Frontiers in Nuclear Science

Electron Ion Collider

Lecture 2 of 3

NNPSS 2021: UNAM/IU: Lectures on the Electron Ion Collider

Stony Brook University

Abhay Deshpande

Brookhaven National Laboratory

Overview of these lectures: Understanding the structure of matter

Lecture 2: Introduction to a Collider

- ***Polarized*** Relativistic Heavy Ion Collier (RHIC)
  - Longitudinal Spin: Gluon and anti-quark spin
  - The transverse spin puzzle

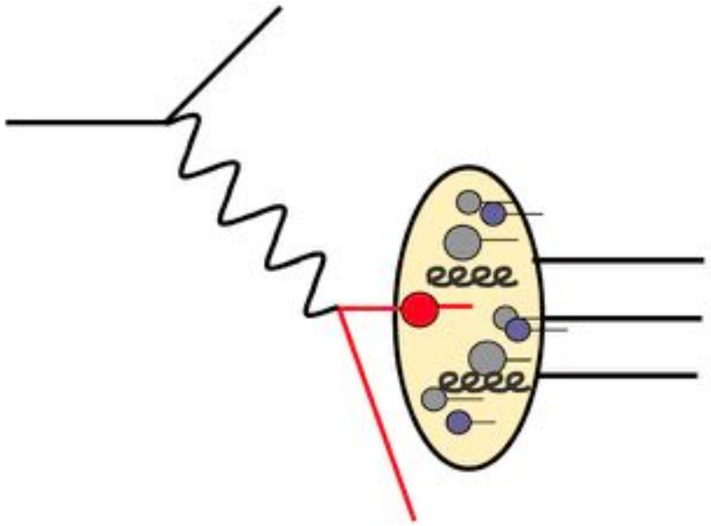
- Why do we need nuclei at a collider?

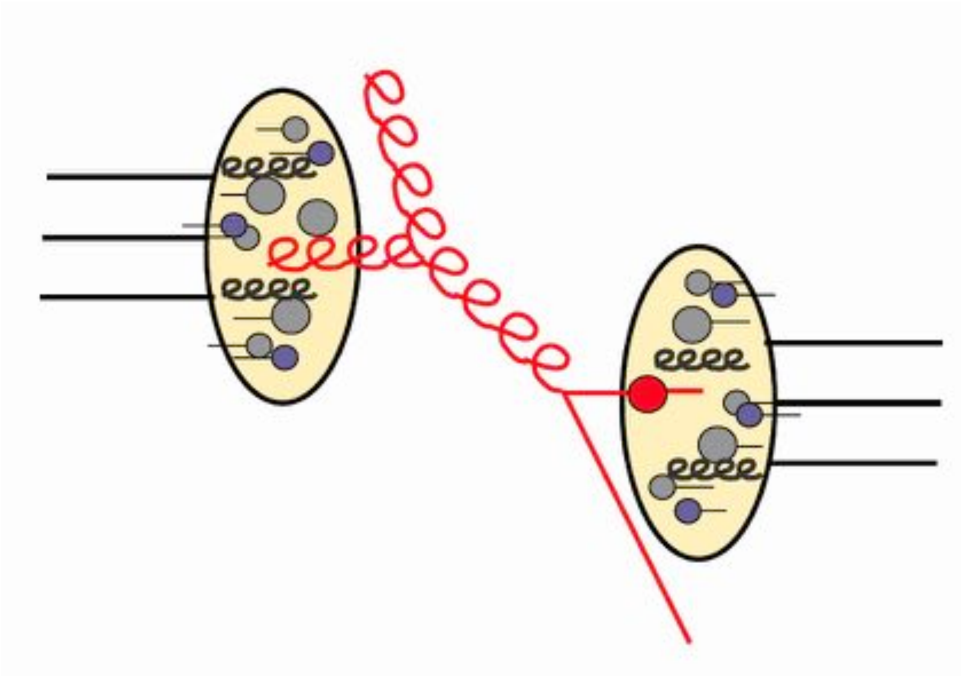
RHIC Spin program and the Transverse Spin puzzle

Pre-cursor to a polarized e-p collider

EIC lecture 2

Complementary techniques





Photons colorless: forced to interact at NLO with gluons

Can't distinguish between quarks and anti-quarks either

Why not use polarized quarks and gluons abundantly available in protons as probes ?

Seeds for RHIC Spin program:

Hadrons are almost full of gluons…. 95% of the mass of the hadrons comes from self interaction of gluons!

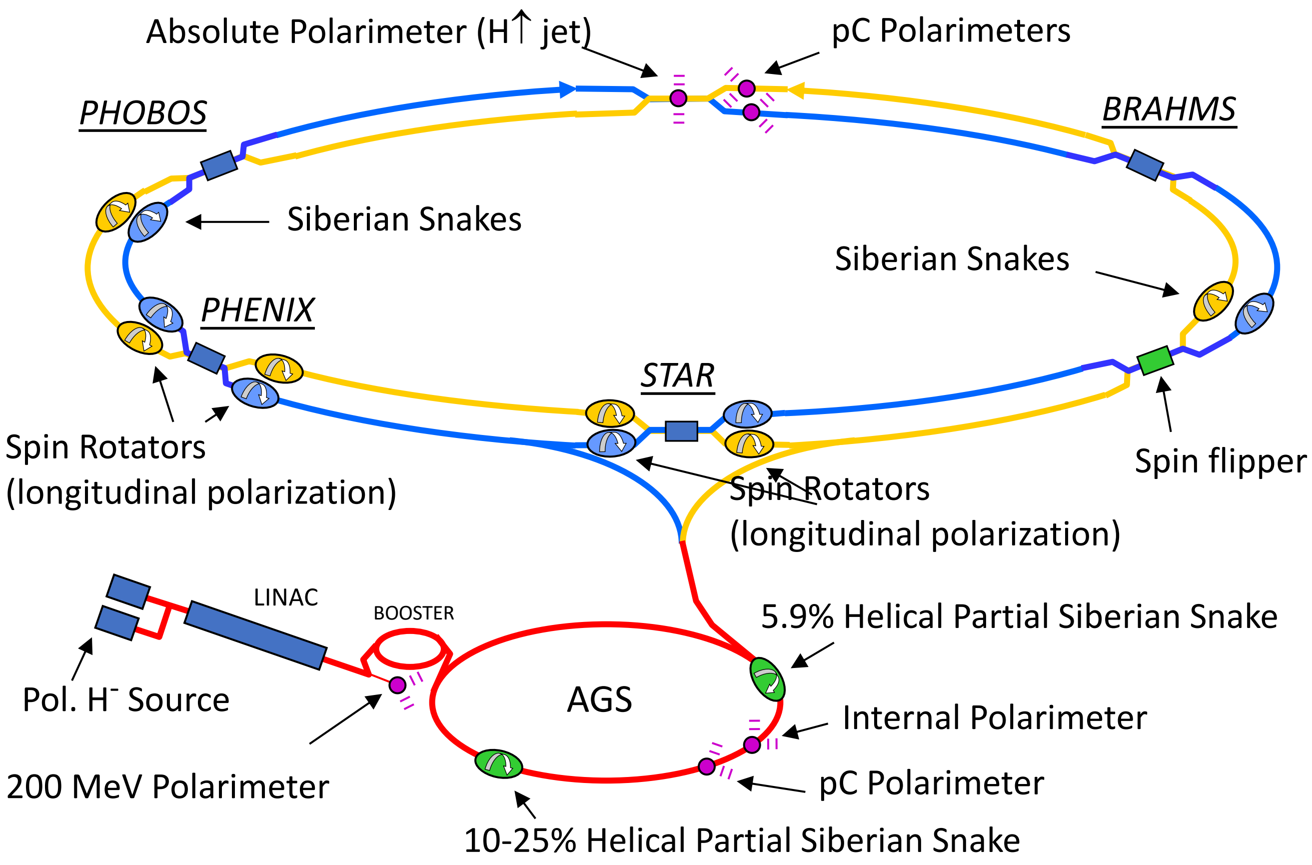
So if one wants to study gluons and their spin contribution to proton's spin, ***why not directly explore the gluon spin with polarized proton collisions?***

A very nice measurement of anti-quark polarization was suggested, which <u>did not require</u> fragmentation functions

Curious and bothersome transverse spin asymmetries in p-p scattering persistent in every experiment performed…. US physicists heavily involved… decided to investigate further

Technical know-how of polarizing proton beams at high energy became available!

RHIC as a Polarized Proton Collider



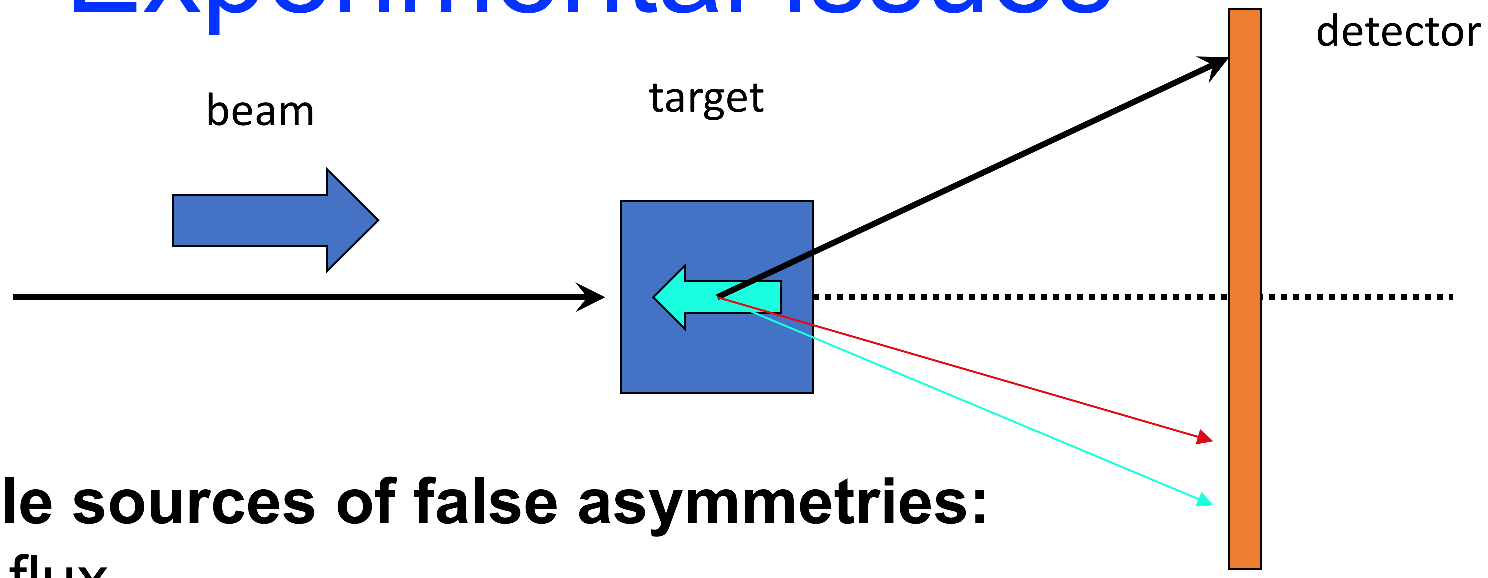
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances

With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances

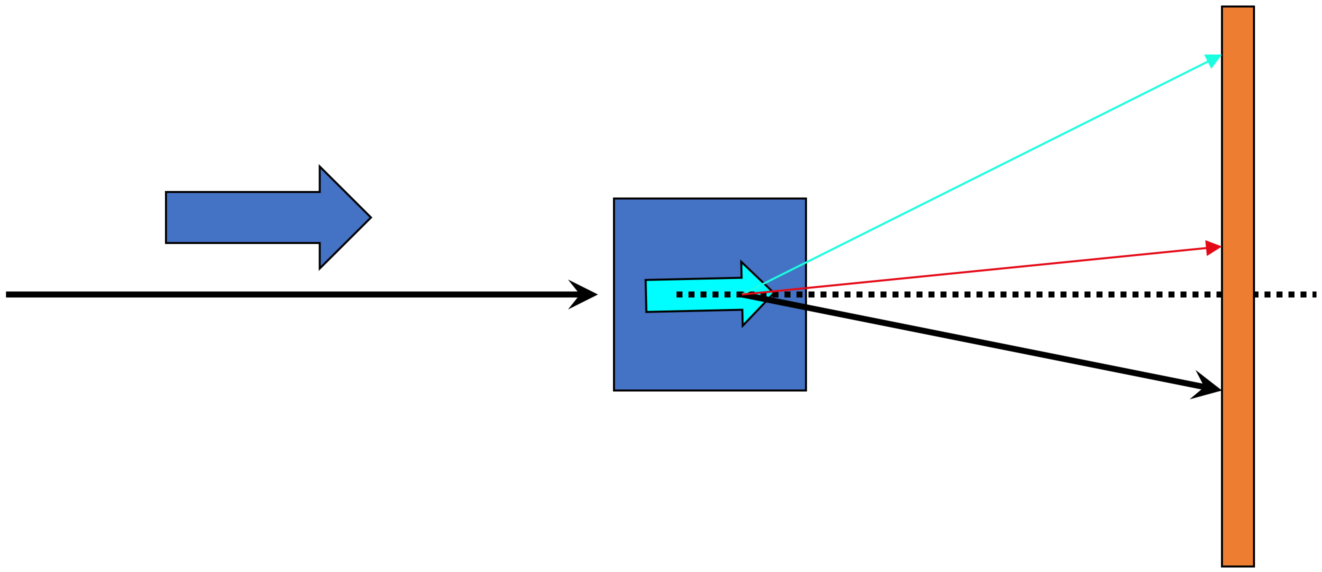
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

A diversion…

Experimental issues



Possible sources of false asymmetries:
- beam flux
- target size
- detector size
- detector efficiency



An Ideal Situation

$$A_{measured} = \frac{N^{\rightarrow\leftarrow} - N^{\rightarrow\rightarrow}}{N^{\rightarrow\leftarrow} + N^{\rightarrow\rightarrow}}$$

$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

If all other things are equal, they cancel in the ratio and….

$$A_{measured} = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

A Typical Setup

- Experiment setup (EMC, SMC, COMPASS@CERN)

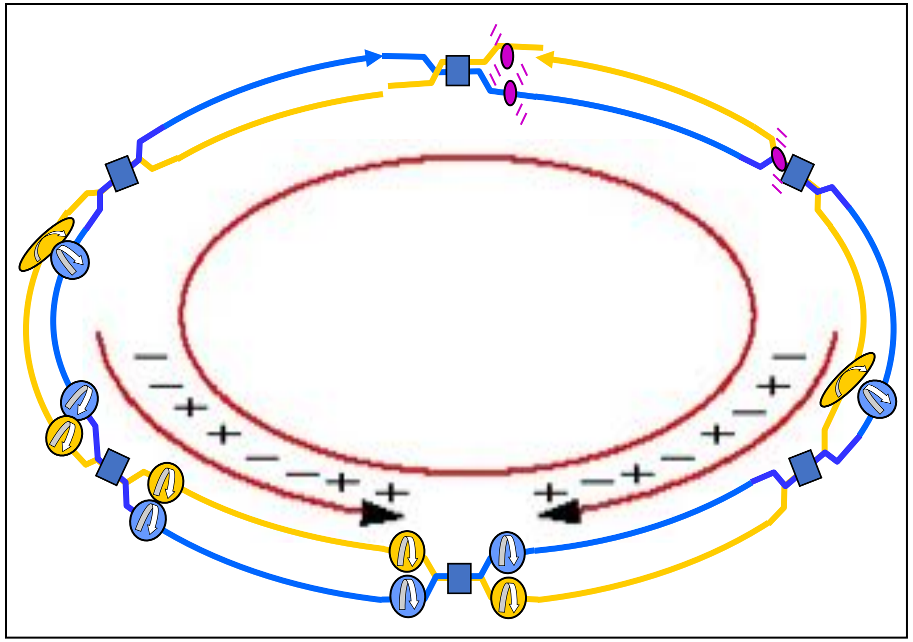
- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

Back to the Collider…

Advantage:
VERY small false asymmetries.

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$

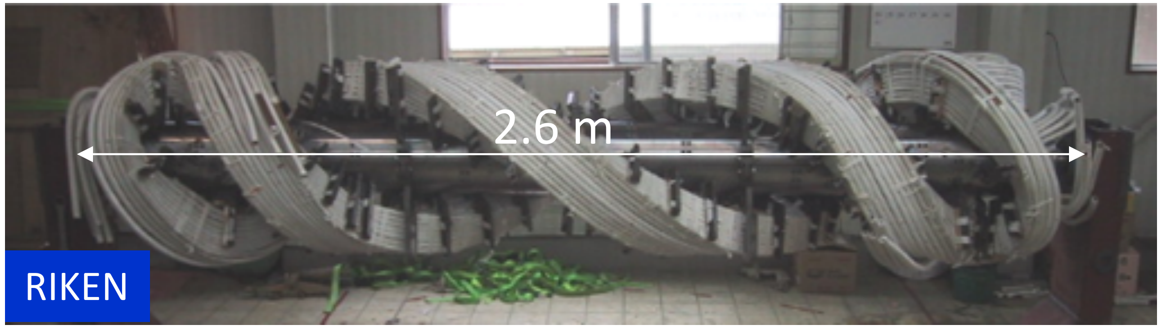


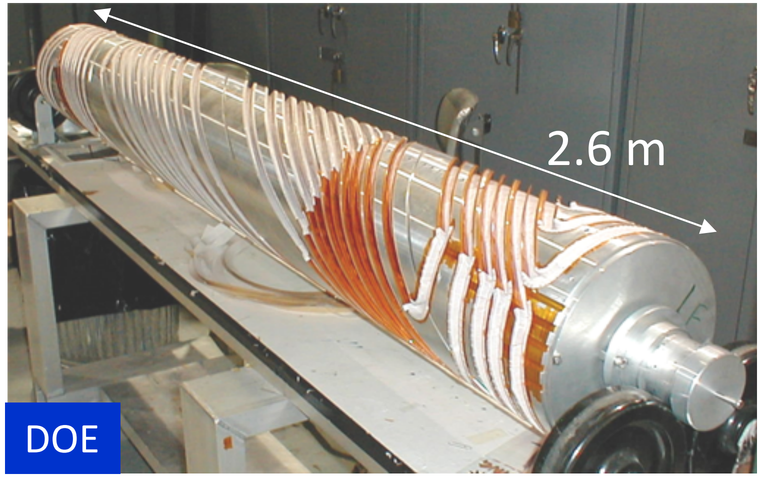
(N) Yield
(R) Relative Luminosity
(P) Polarization

Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

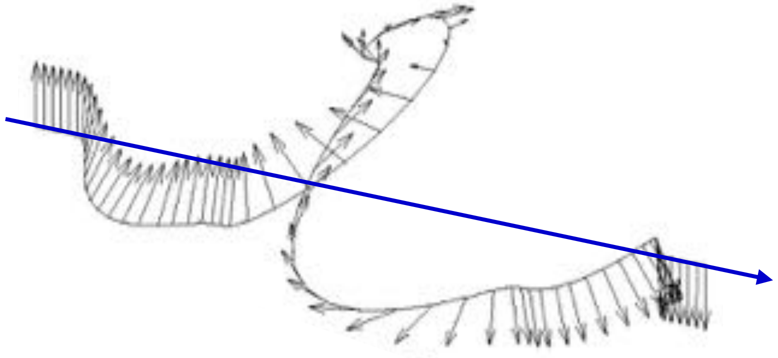
✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time
⇒ Possibility for false asymmetries are greatly reduced

Siberian Snakes

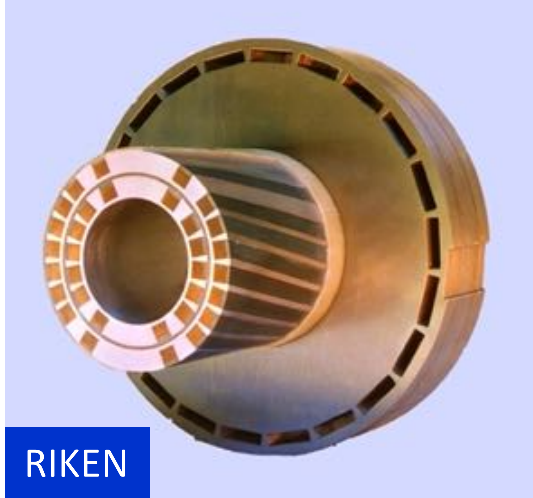




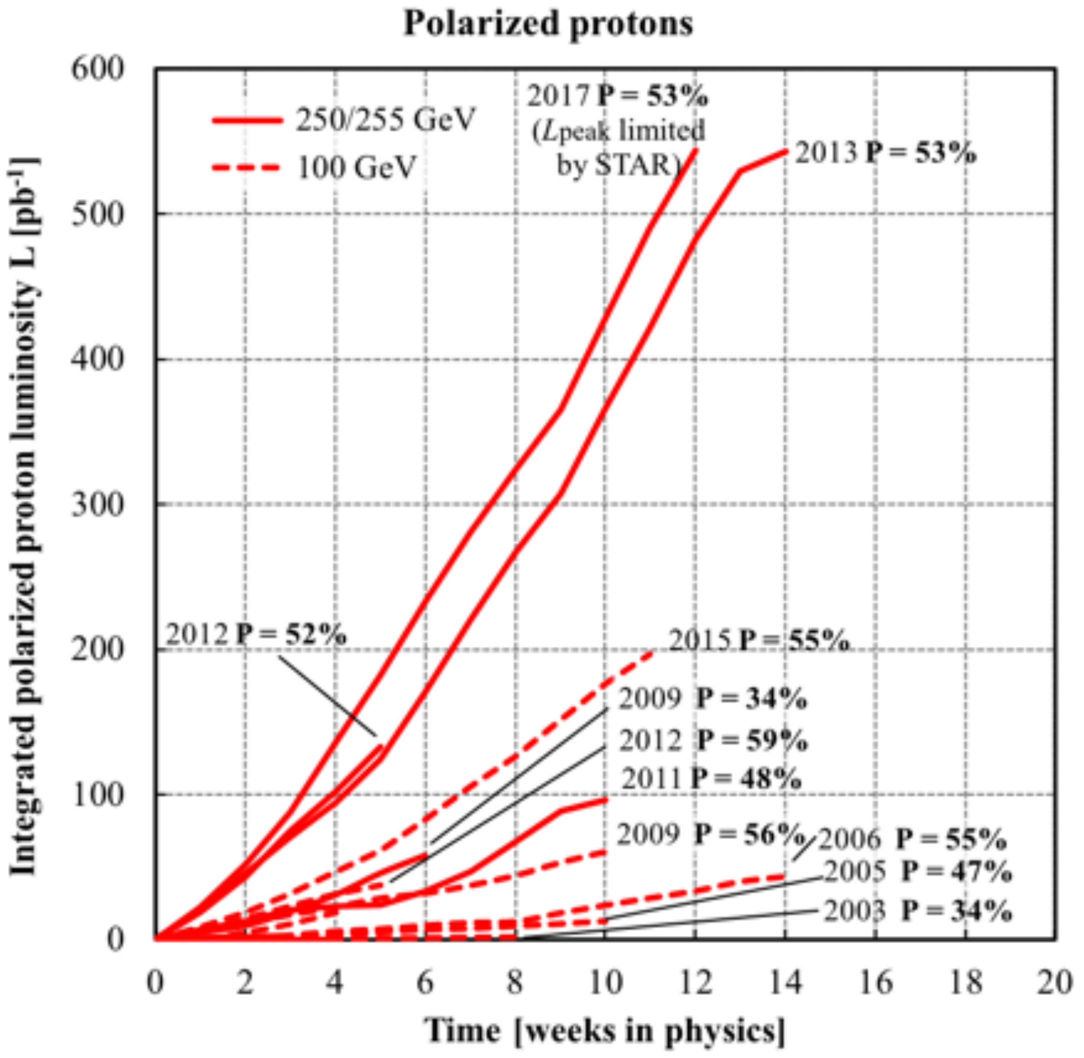
- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist

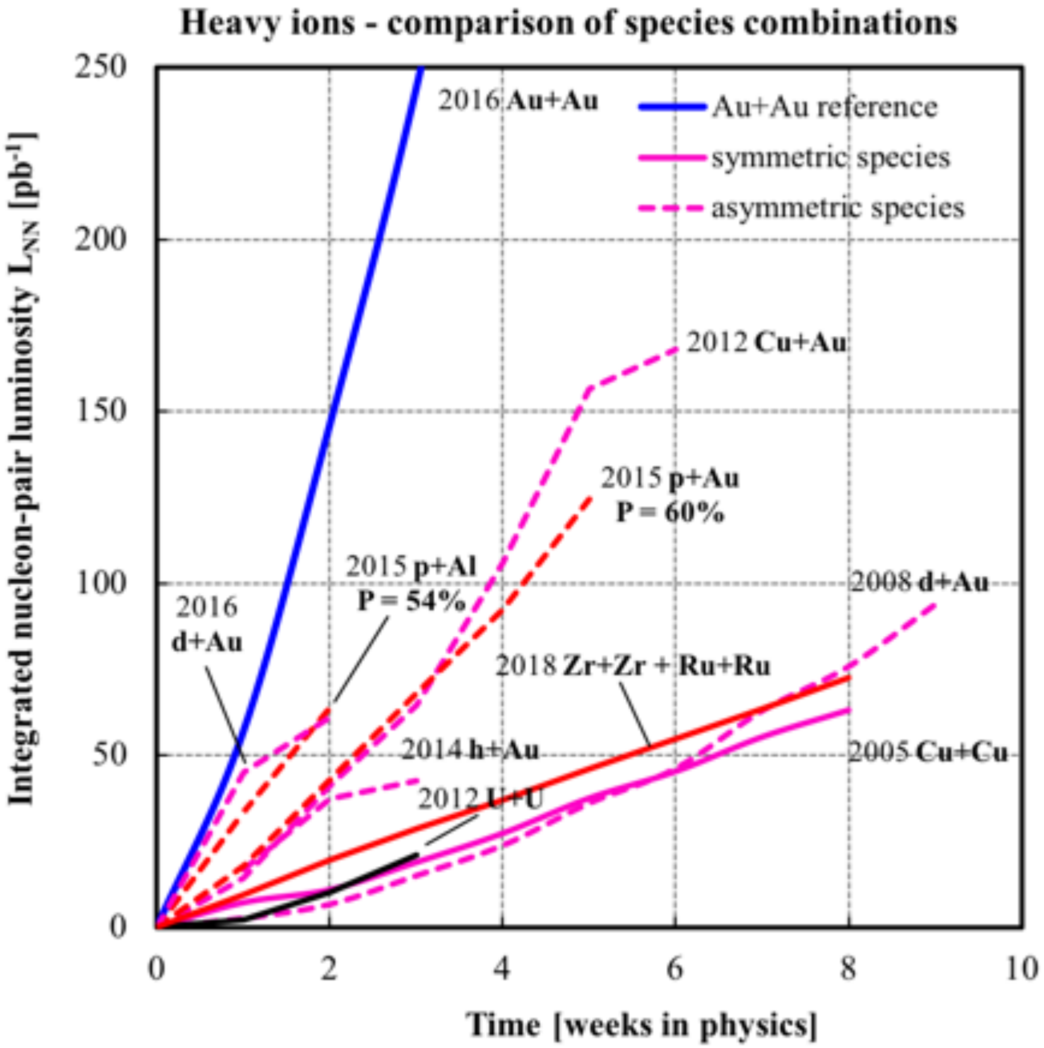


Courtesy of A. Luccio

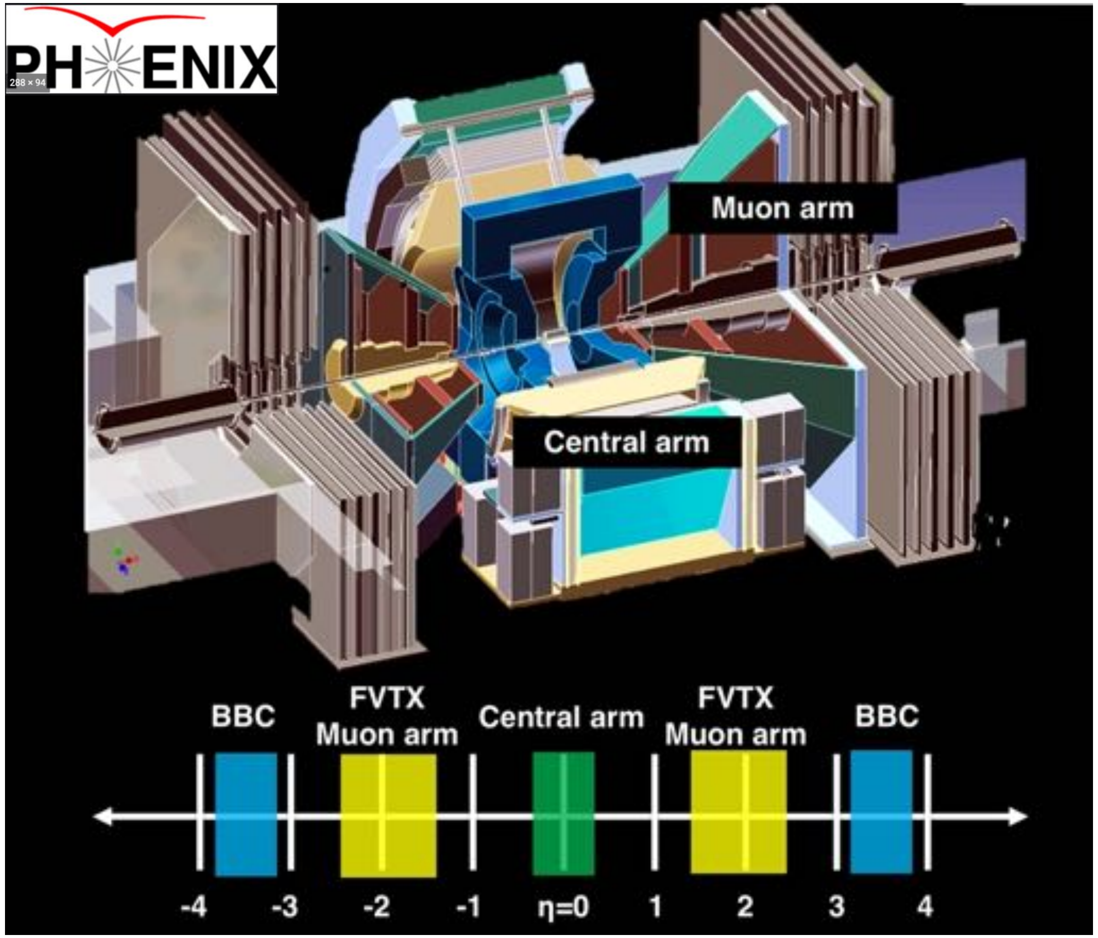


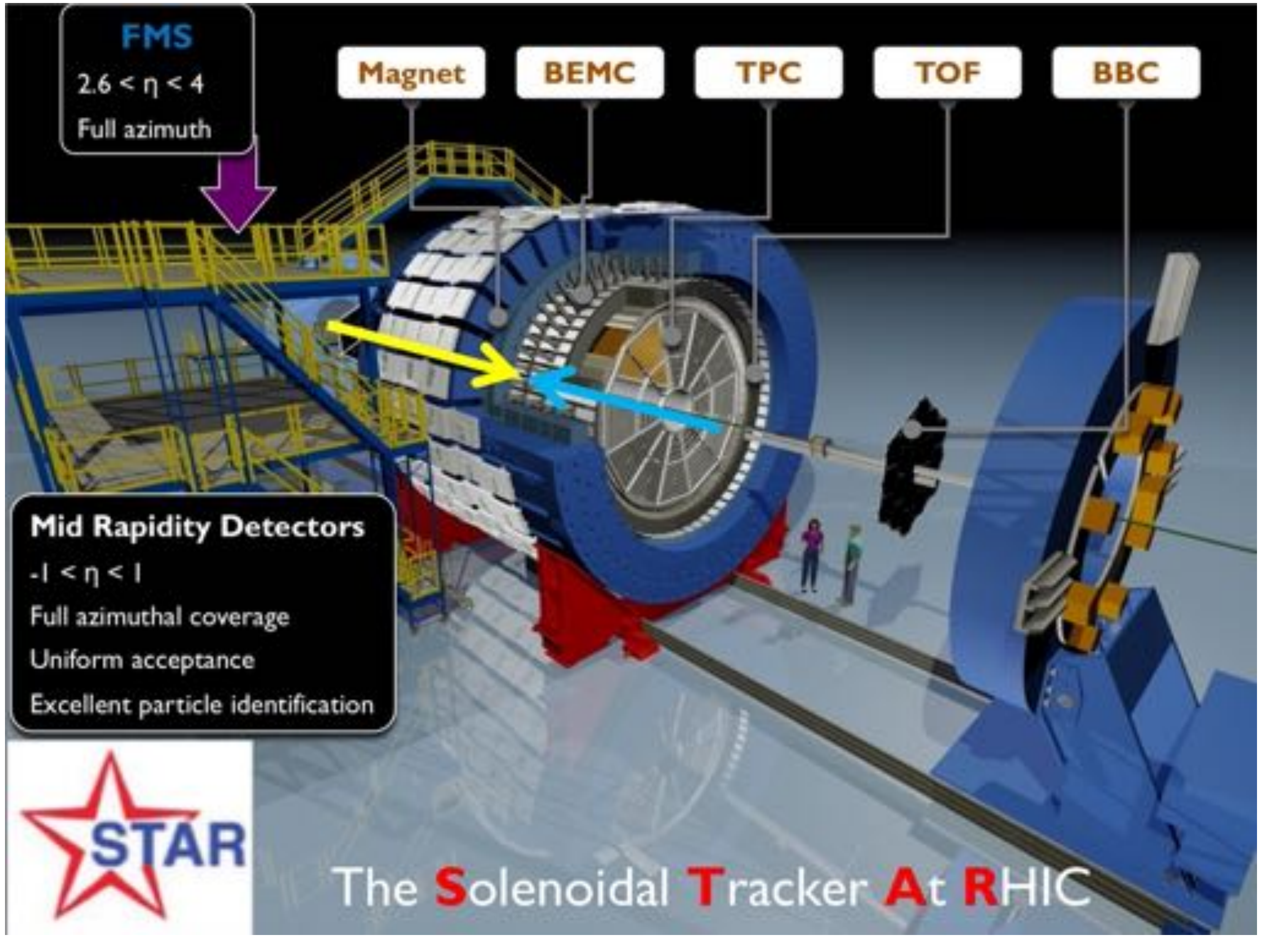
RHIC delivered





Two main detectors for spin studies





Accessing ΔG in p+p Collisions at RHIC

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{\pi/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{\pi/c}}$$

From ep (&pp) (HERA mostly)

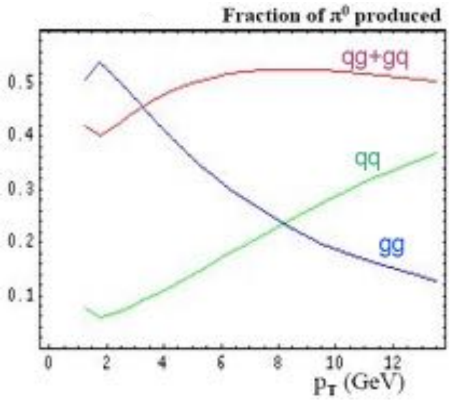
NLO pQCD

From e+e- (& SIDIS,pp)

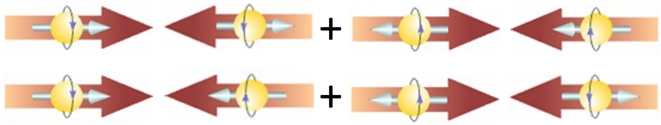
- If Δf = Δq, then we have this from pDIS
- So roughly, we have

$$A_{LL} \cong a_{gg}\Delta g^2 + b_{gq}\Delta g \Delta q + c_{qq}\Delta q^2$$

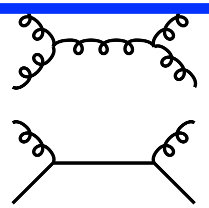
where the coefficients a, b and c depend on final state observable and event kinematics (η,p_T).



+- =
++ =



2009 RHIC data established non-zero ΔG

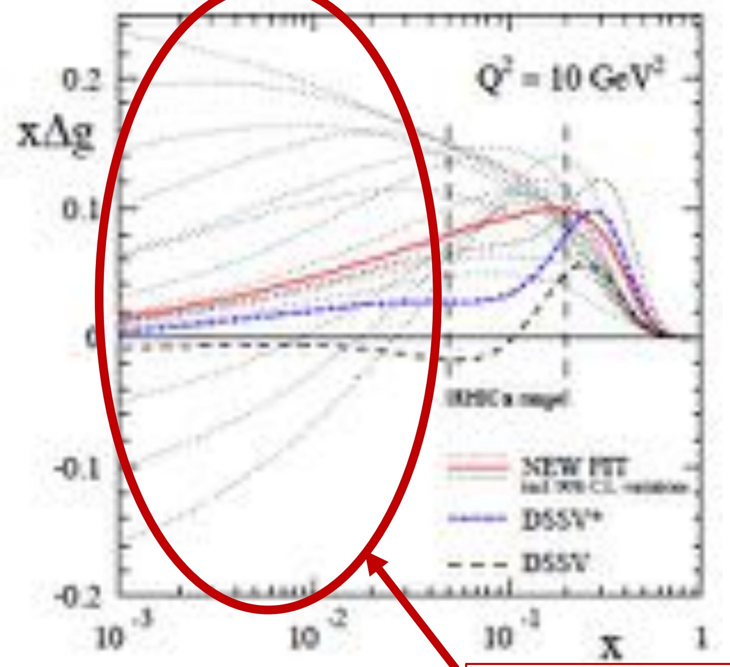
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \rightarrow \pi + X$ [61, 62]	$\vec{g}\vec{g} \rightarrow gg$ $\vec{q}\vec{g} \rightarrow qg$	Δg	
$\vec{p}\vec{p} \rightarrow \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \rightarrow gg$ $\vec{q}\vec{g} \rightarrow qg$	Δg	(as above)

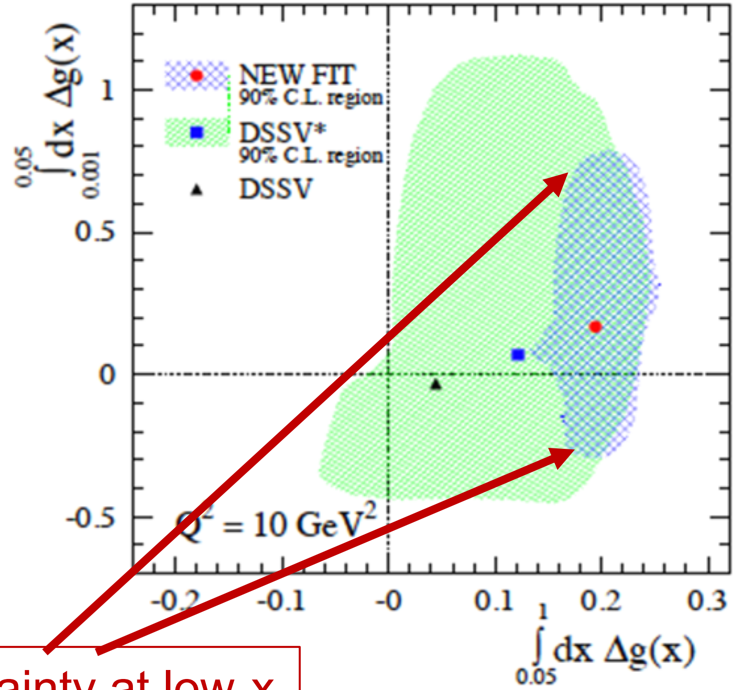
-- PHENIX 2005-9, PRD 90, 12007 (2014)

-- STAR 2009, PRL 115 (2015) 92002

-- DSSV PRL (113) 12001 (2014)

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ \text{GeV}^2$$

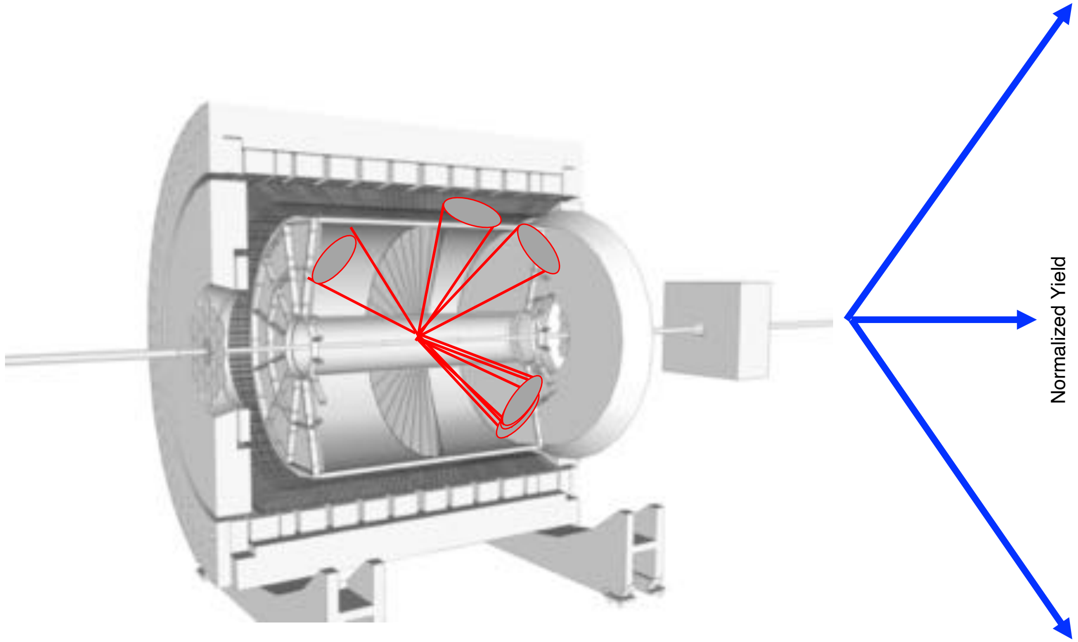


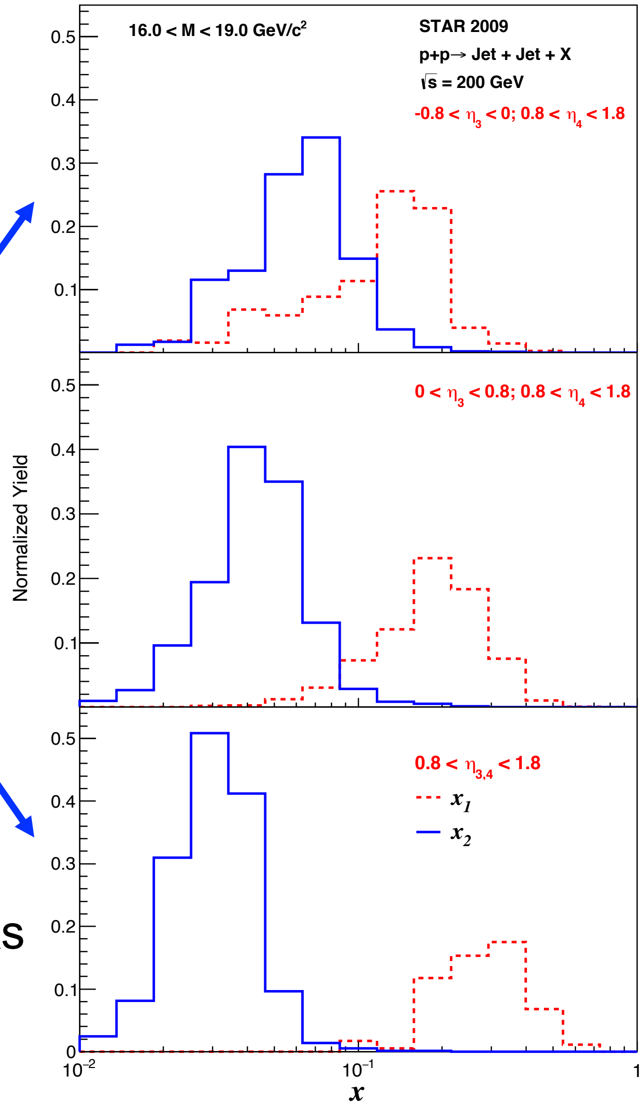


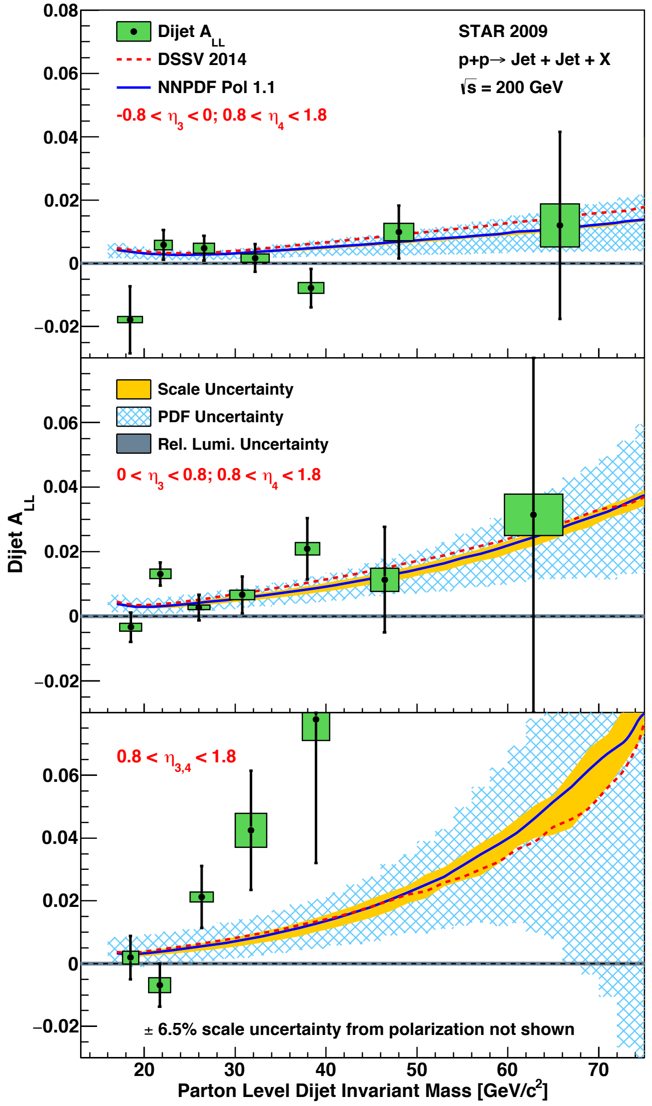
Large uncertainty at low-x

Advantage of large acceptance: STAR

Select event topology to access different regions of x







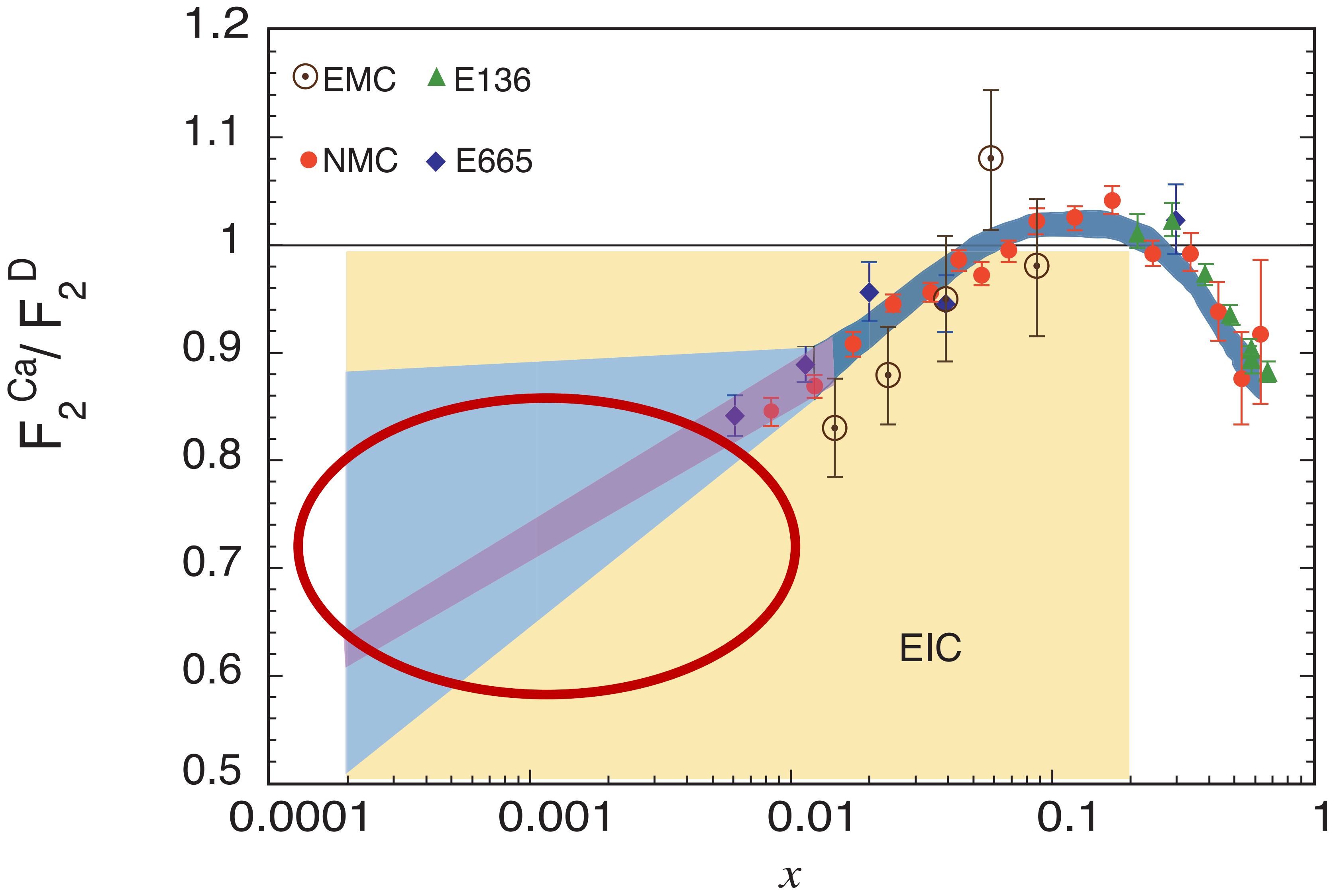
Measured asymmetries sample low & high x quarks
PRD 98 (2018) 32011
See arXiv: 1906.02740 for 510 GeV results

Event topology animation: E.C. Aschenauer

Lepton nucleus scattering for understanding the nuclear structure and dynamics:

Nuclear structure a known unknown….

PDFs in nuclei are different than in protons!



Since 1980's we know the ratio of F_2's of nuclei to that of Deuteron (or proton) are different.

Nuclear medium modifies the PDF's.

Fair understanding of what goes on, in the x > 0.01.

However, what happens at low x?

Does this ratio saturate? Or keep on going? – Physics would be very different depending on what is observed.

Data needed at low-x

Lessons learned:

- Proton and neutrons are not as easy to understand in terms of quarks, and gluons, as earlier anticipated:
  - Proton's spin is complex: alignment of quarks, gluons and possibly orbital motion
  - Proton mass: interactions amongst quarks and gluons, not discussed too much

- To fully understand proton structure (including the partonic dynamics) one needs to explore over a much broader x-Q2 range (not in fixed target but in collider experiment)

- e-p more precise than p-p as it probes with more experimental control and precision

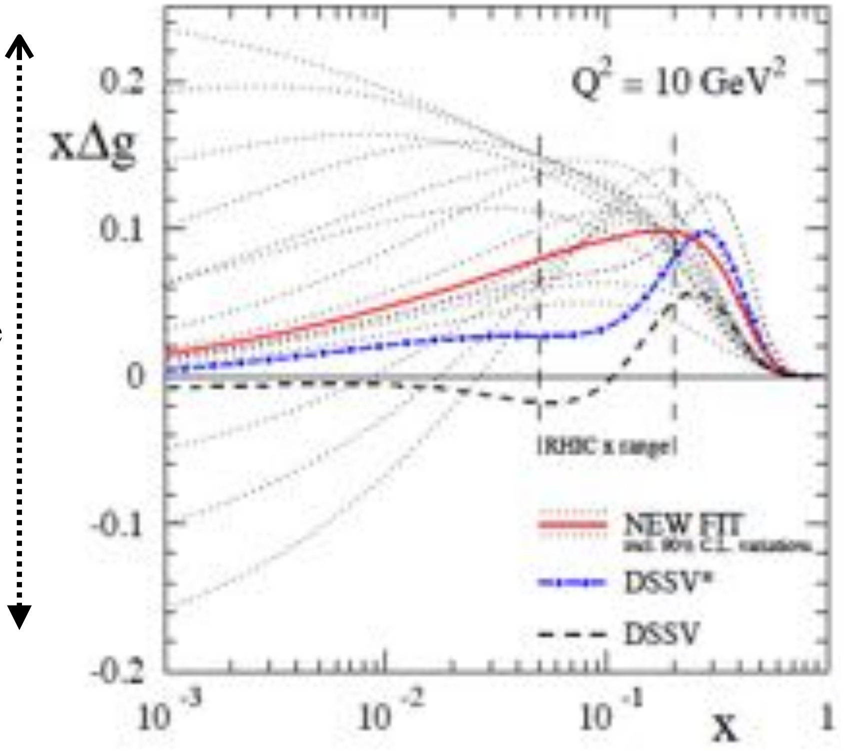
- Low-x behavior of gluons in proton intriguing; Precise measurements of gluons critical.

We need a new polarized collider….

Recent global analysis: DSSV

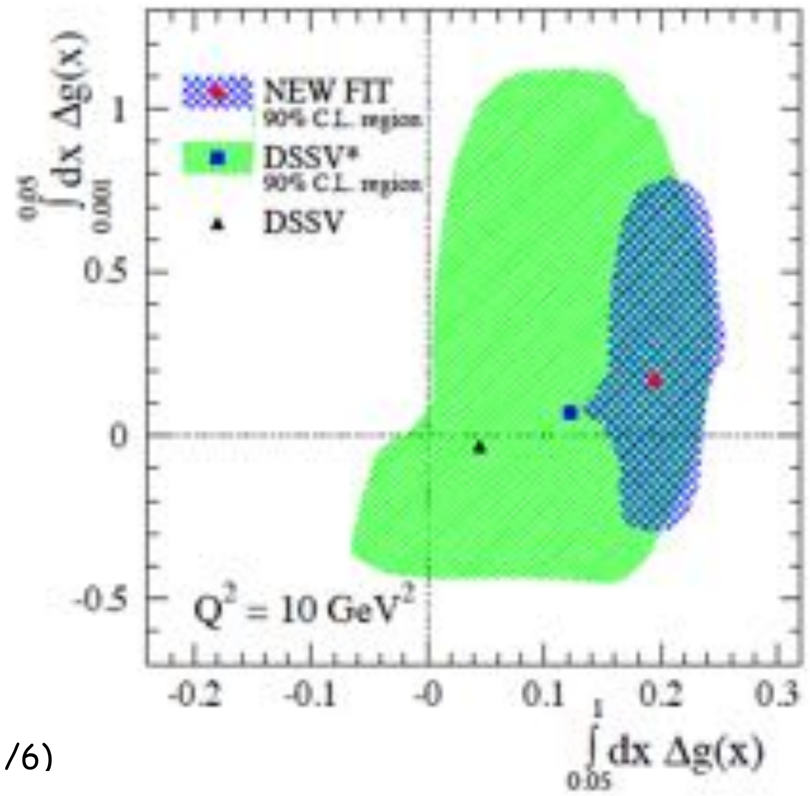
D. deFlorian et al., arXiv:1404.4293

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.



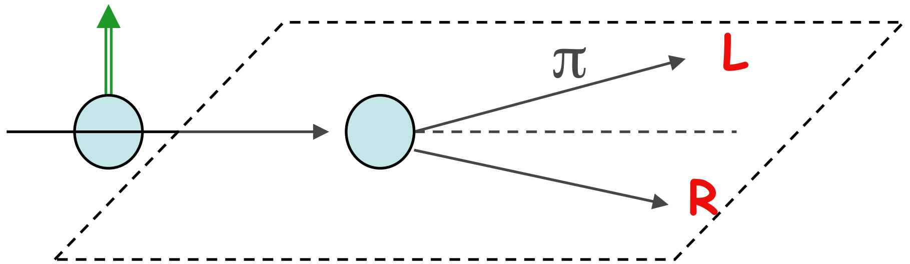
/6)

$\Delta G = 0.2 +/- 0.02 +/- 0.5$



While RHIC made a huge impact on ΔG
large uncertainties to remain in the low-x unmeasured region!

Transverse spin introduction



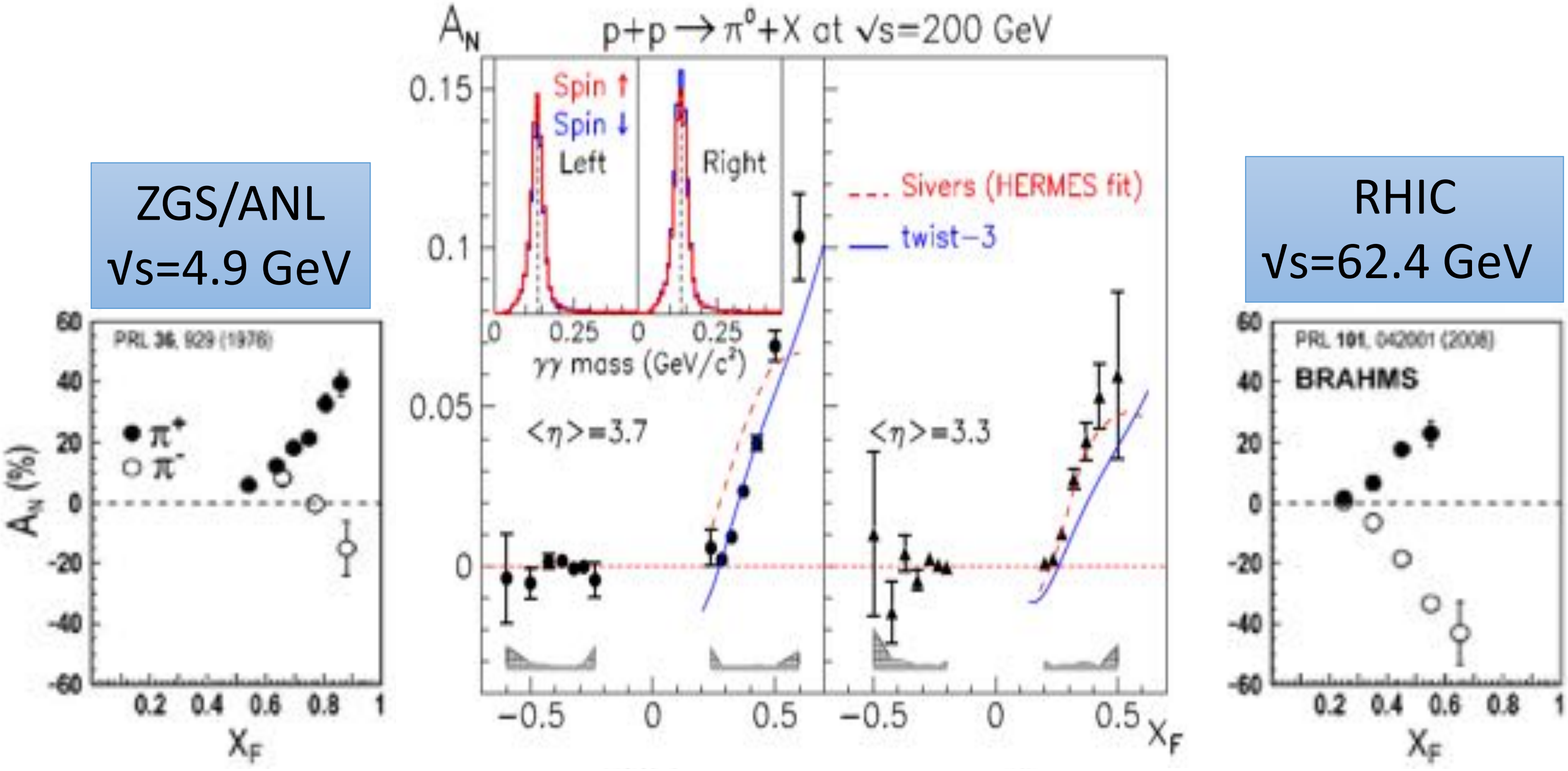
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

Kane, Pumplin and Repko
PRL 41 1689 (1978)

- Since people starved to measure effects at high p_T to interpret them in pQCD frameworks, this was "neglected" as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

Pion asymmetries: at most CM energies!

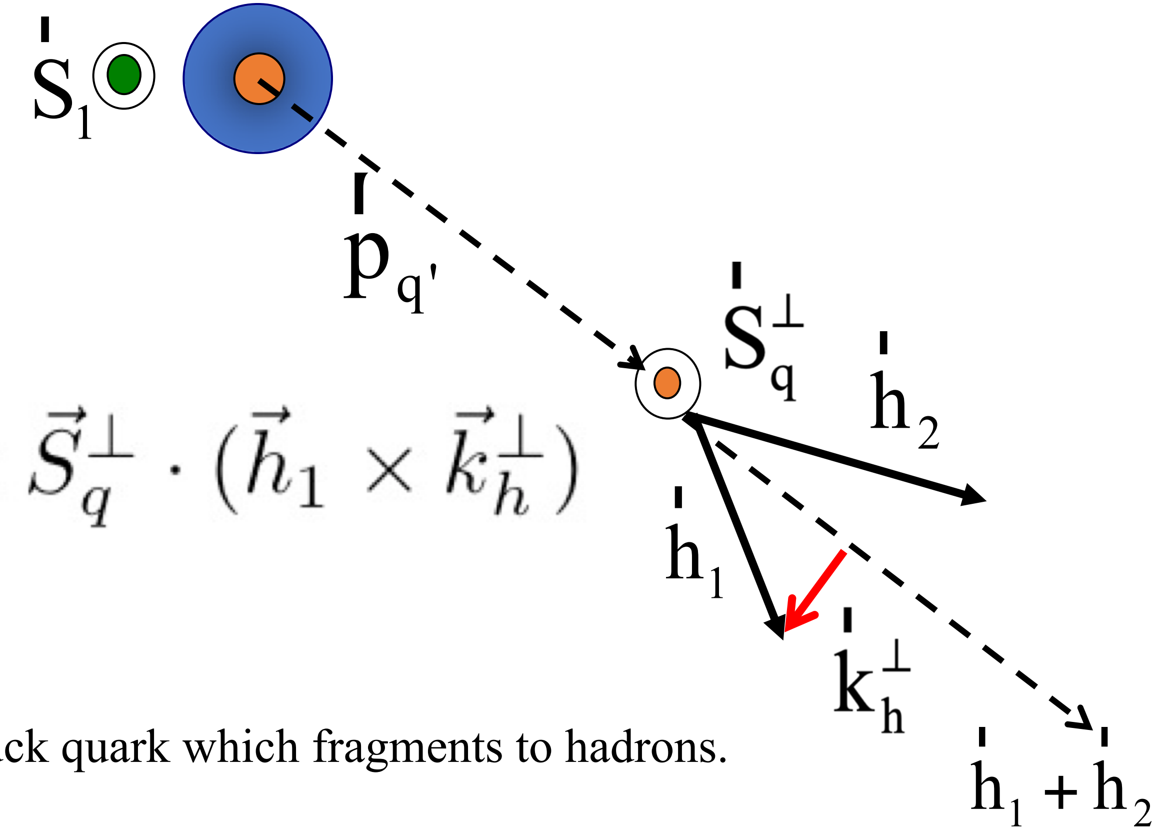


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

Example: $p^{\uparrow} + p \rightarrow h_1 + h_2 + X$

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

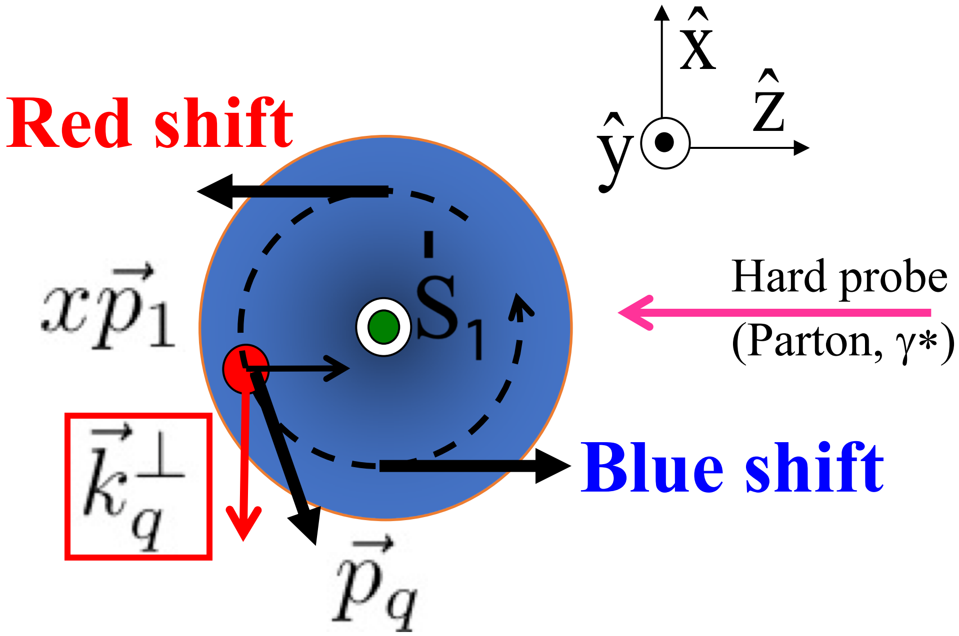


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

What does "Sivers effect" probe?

Top view, Breit frame



Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$.

PRD66 (2002) 114005

Parton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

Final **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$$f_{1T}^{\perp}(x, \vec{k}_q^{\perp})$$

hep-ph/ 0703176

Quark Orbital angular momentum

Generalized **P**arton **D**istribution Functions

PRD59 (1999) 014013

Lessons at the end of RHIC era

- Quarks carry small spin, gluons carry spin, precision not good enough… largest uncertainty comes from the
- Transverse momentum of quarks definitely plays a role, but what? How? What is the big picture?
- If TMDs play a role, so should transverse position. How? Where do they matter?