

Objectives for Spin Physics at RHIC

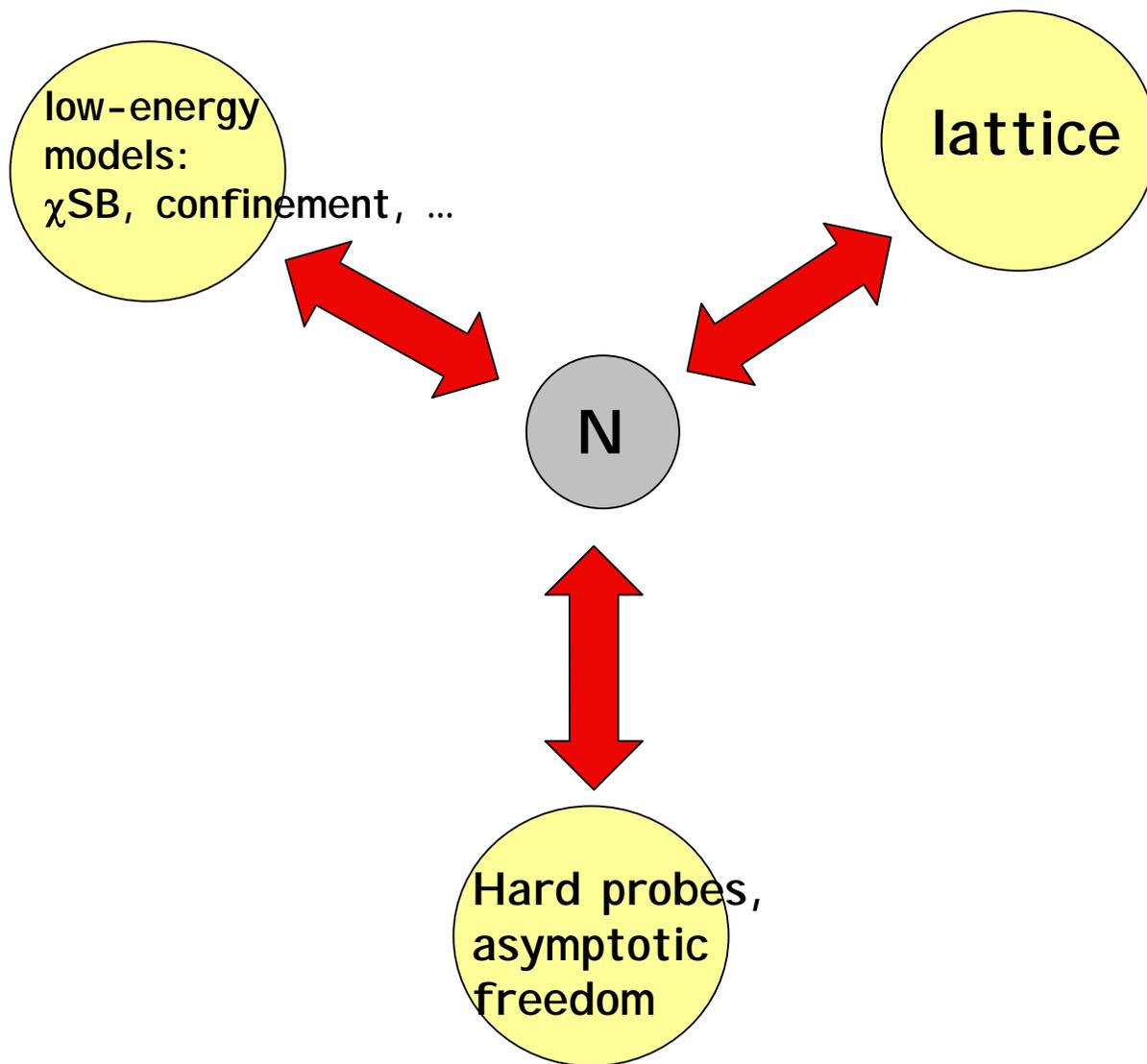
Werner Vogelsang
RBRC & BNL Nuclear Theory

NSAC Review Meeting 06/03

Outline:

- What have we learned so far?
- What are the challenges in QCD spin physics over the next ~ 10 years?
- **What do we expect from RHIC,
and what is the impact of other activities
?**

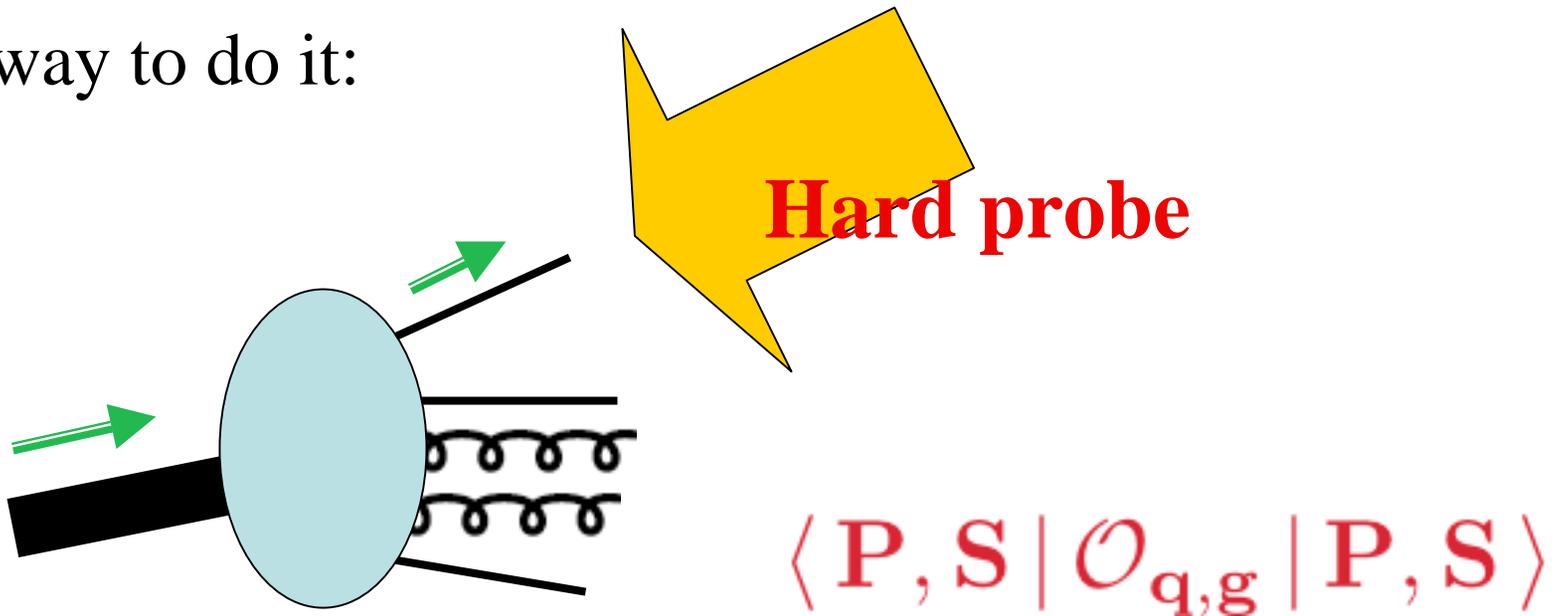
Exploring the nucleon: at the forefront of QCD



- Main goal of QCD spin physics:

To understand the spin structure of hadrons in terms of quarks and gluons

- The way to do it:



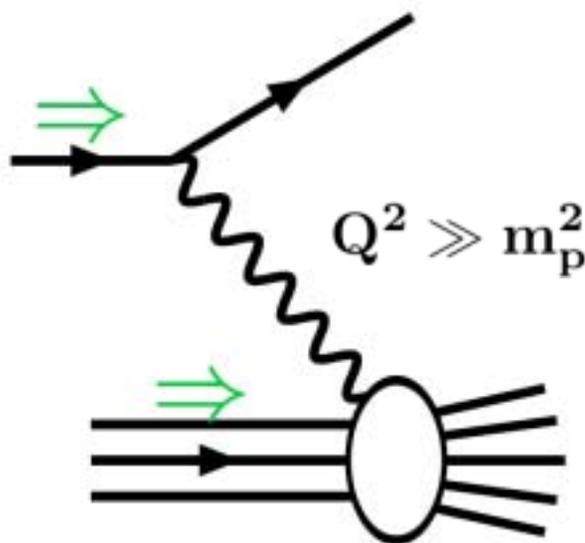
Famous examples:

$$\langle \mathbf{P}, \mathbf{S} | \bar{\mathbf{q}} \gamma^\mu \gamma^5 \mathbf{q} | \mathbf{P}, \mathbf{S} \rangle \propto \text{axial charge} \quad \text{quark spin}$$

$$\langle \mathbf{P}, \mathbf{S} | \bar{\mathbf{q}} i \sigma^{\mu\nu} \gamma^5 \mathbf{q} | \mathbf{P}, \mathbf{S} \rangle \propto \text{tensor charge} \quad \text{transversity}$$

What are the probes ?

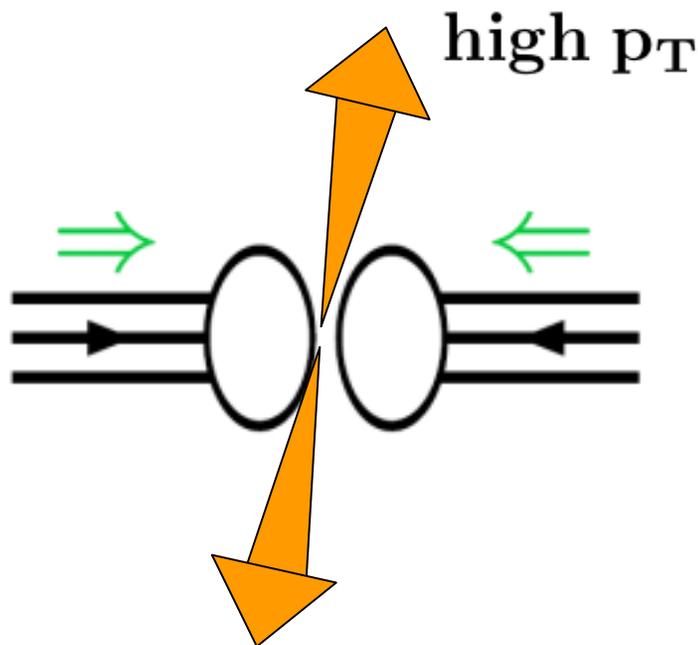
Polarized DIS



SLAC, CERN, DESY, Jlab, eRHIC

a powerful probe of quarks
(but sees gluons, too!)

pp scattering



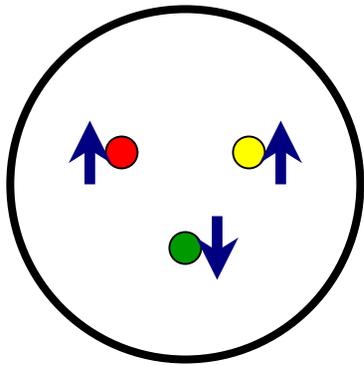
RHIC

a powerful probe of gluons
(but sees quarks, too!)

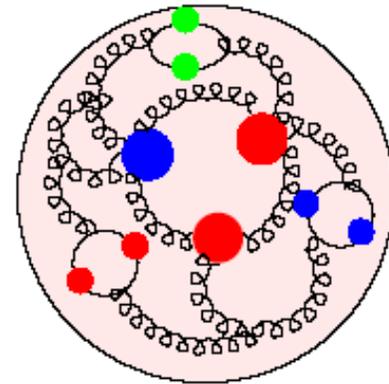
What have we learned so far ?

- **the main lesson:** **The nucleon spin is quite subtle !**

Quark Model



QCD

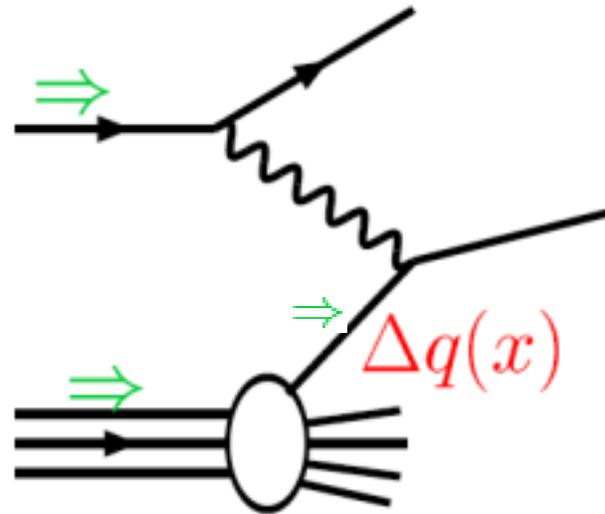


gluons, $q\bar{q}$ pairs, orbital, interactions, renormalization

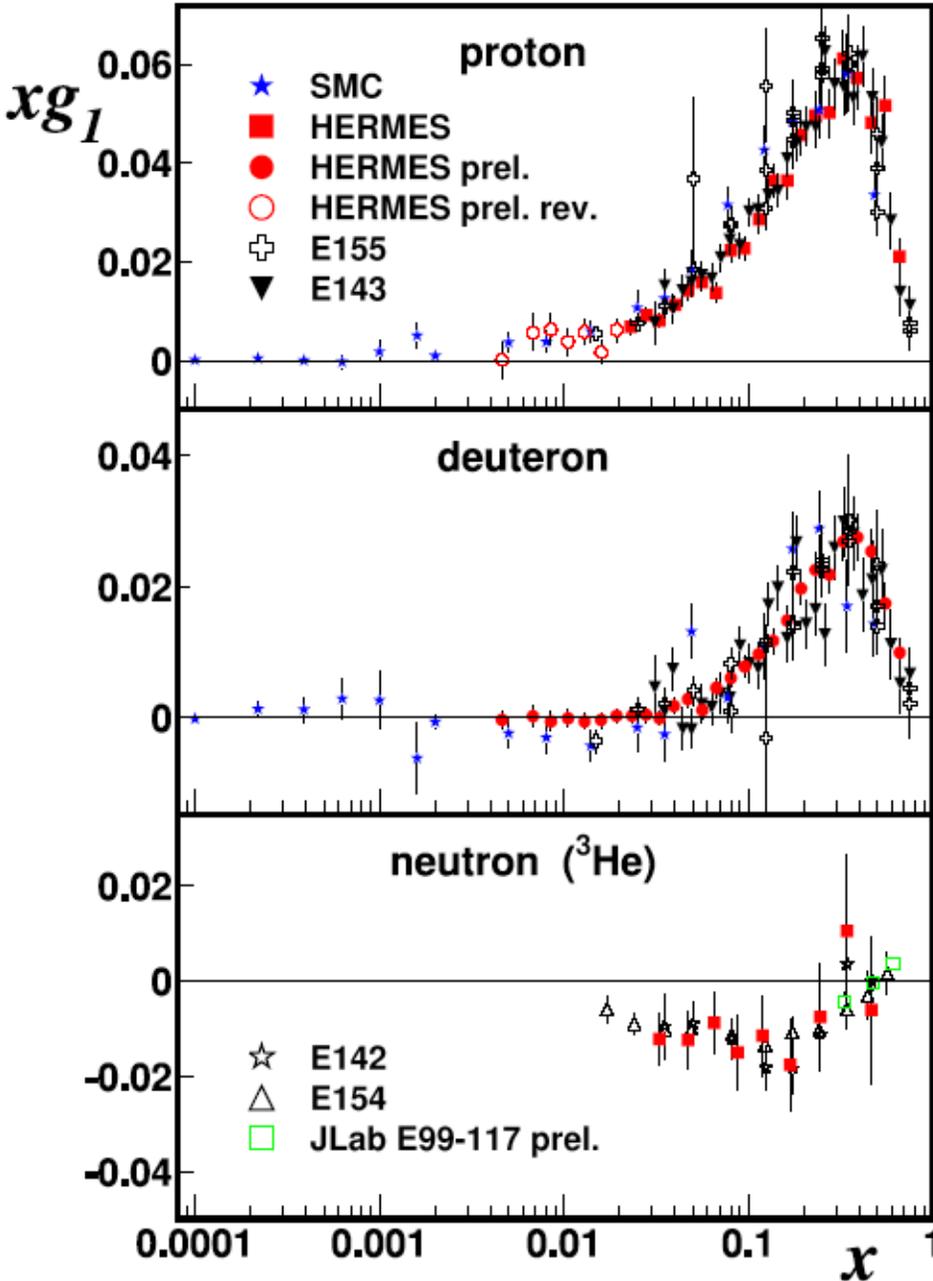
$$\frac{1}{2} = \langle \mathbf{S}_q \rangle + \langle \mathbf{S}_g \rangle + \langle \mathbf{L}_q \rangle + \langle \mathbf{L}_g \rangle \Big|_{Q^2}$$

\downarrow
 ≈ 0.1

* Result of the hugely successful program of **polarized DIS**



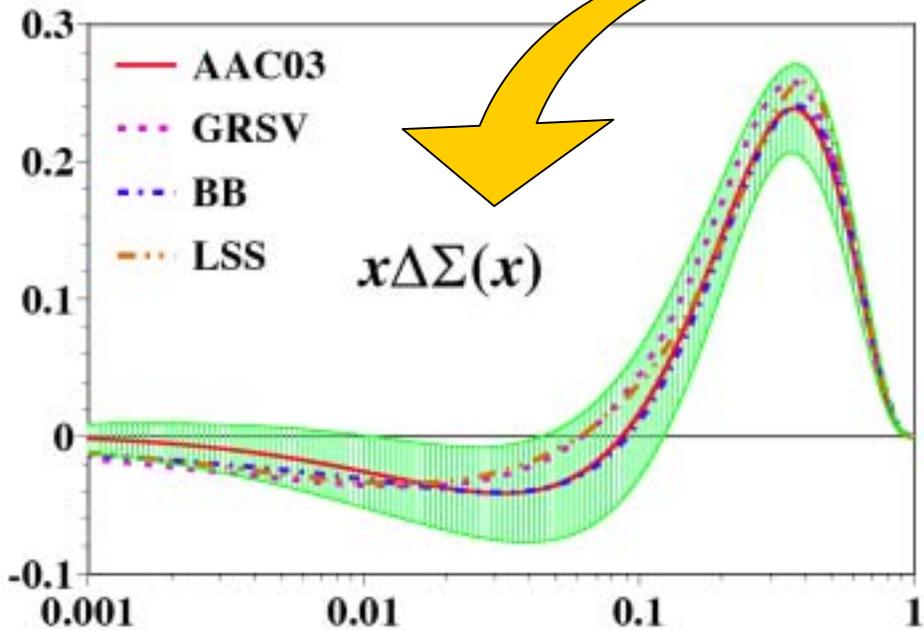
$$\Delta q(x) = \text{[Red circle with white dot and right-pointing yellow arrow]} \rightarrow \text{[Green arrow]} - \text{[Red circle with white dot and left-pointing yellow arrow]} \rightarrow \text{[Green arrow]}$$



$$g_1 \sim \sum_q e_q^2 [\Delta q(x) + \Delta \bar{q}(x)]$$

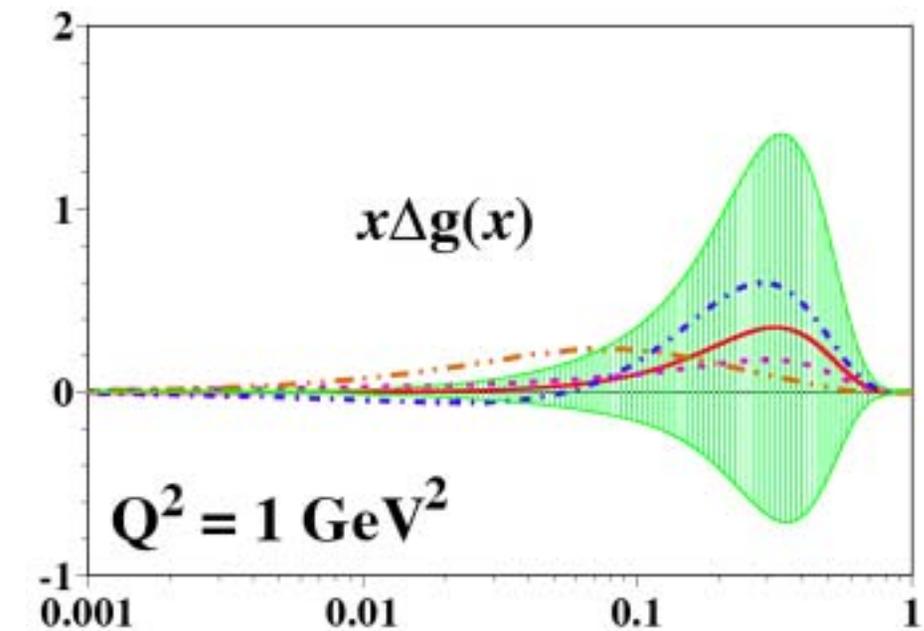
+ QCD scaling violations

Hirai, Kumano, Saito



$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

$$\langle S_q \rangle = \frac{1}{2} \int_0^1 dx \Delta\Sigma(x)$$



gluon polarization ?

$$\Delta g(x) = \text{[Diagram: gluon with right-pointing arrow]} - \text{[Diagram: gluon with left-pointing arrow]}$$

← weak constraint from scaling violations

Challenges in QCD spin physics



- **What else carries the proton spin ?**
 - How are gluons polarized ?
 - How large are parton orbital ang. mom. ?



“DVCS”
 $\gamma^* p \rightarrow \gamma p$

- **What are the detailed patterns of quark & antiquark polarizations ?**
 - Flavor asymmetries in sea ?



- **Is there significant transversity in the nucleon ?**



- **What are the origins of large observed single-spin asymmetries ?**
 - Correlations between transverse spin and parton k_T ?



Challenges in QCD spin physics

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Gluon polarization

- a key contributor to the proton spin ?

- $\langle S_g \rangle = \int_0^1 dx \Delta g(x, Q^2) \propto \frac{1}{\alpha_s(Q^2)}$ in QCD

- some model predictions ($Q \approx 0.5 \text{ GeV}$) :

$$\langle S_g \rangle = -0.4 \quad (\text{Jaffe, bag model})$$

$$\langle S_g \rangle = +0.25 \quad (\text{Barone et al., Isgur – Karl})$$

$$\langle S_g \rangle = +0.3 \quad (\text{Rho et al., chiral bag})$$

...

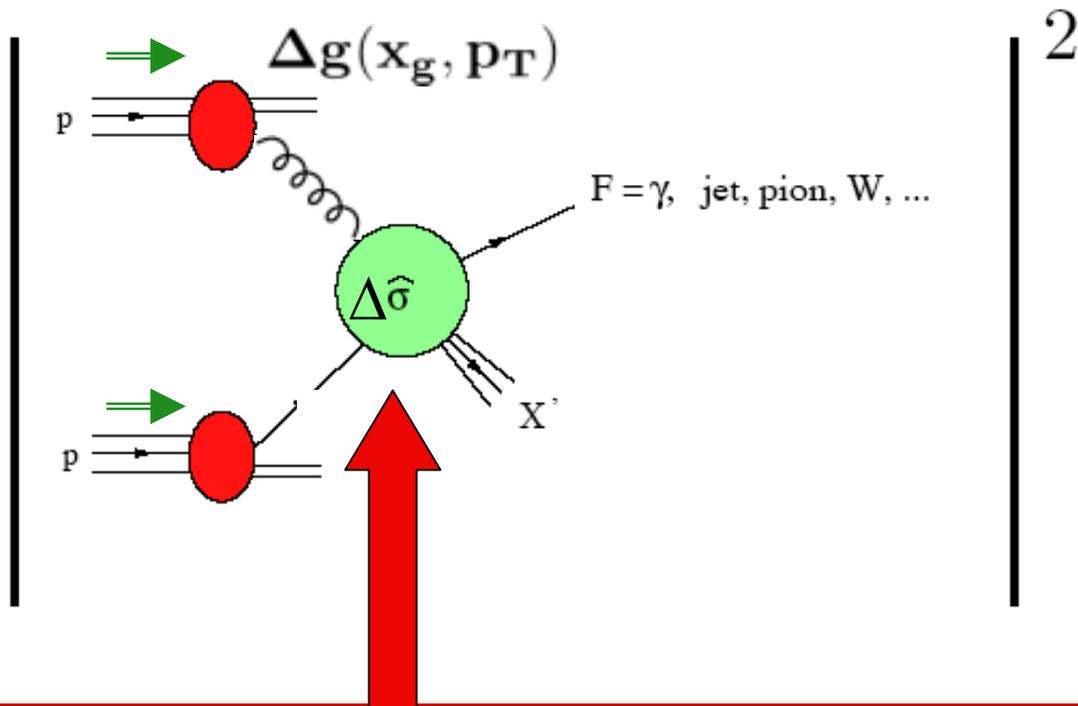
- **gluons subdominant in inclusive DIS**

- * Q^2 evolution \rightarrow need large lever arm

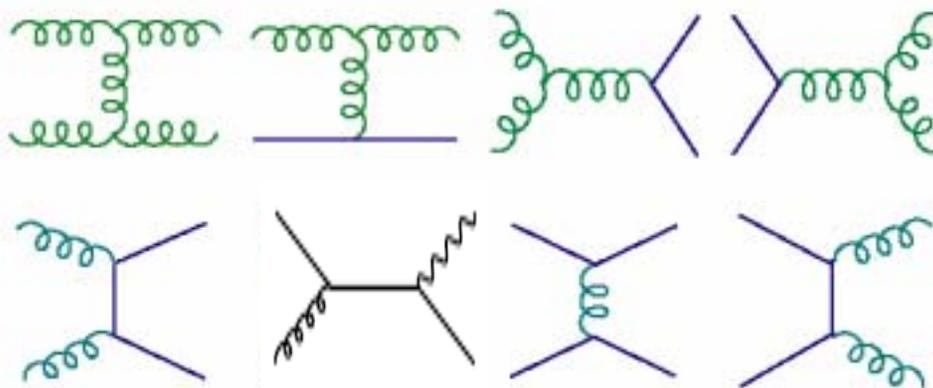
- * single out “photon-gluon fusion”

- $\gamma g \rightarrow c\bar{c}$, $\gamma g \rightarrow h^+ h^- X$ [very difficult theory !]

- **gluons are “leaders” at hadron colliders ...**

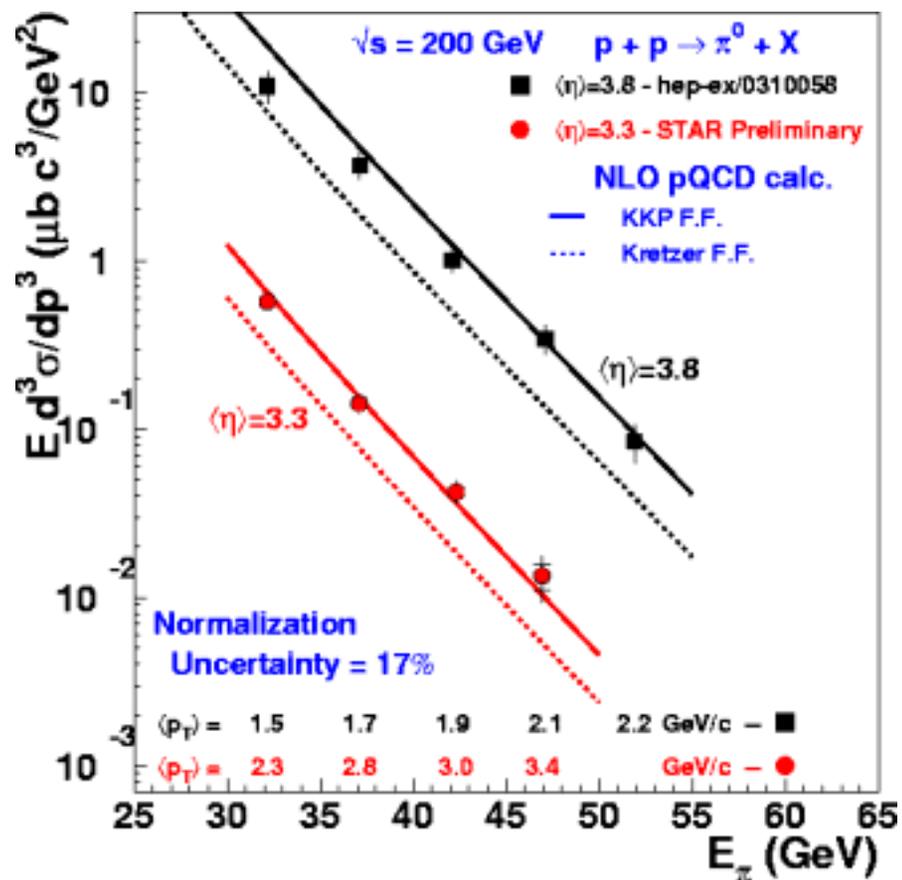
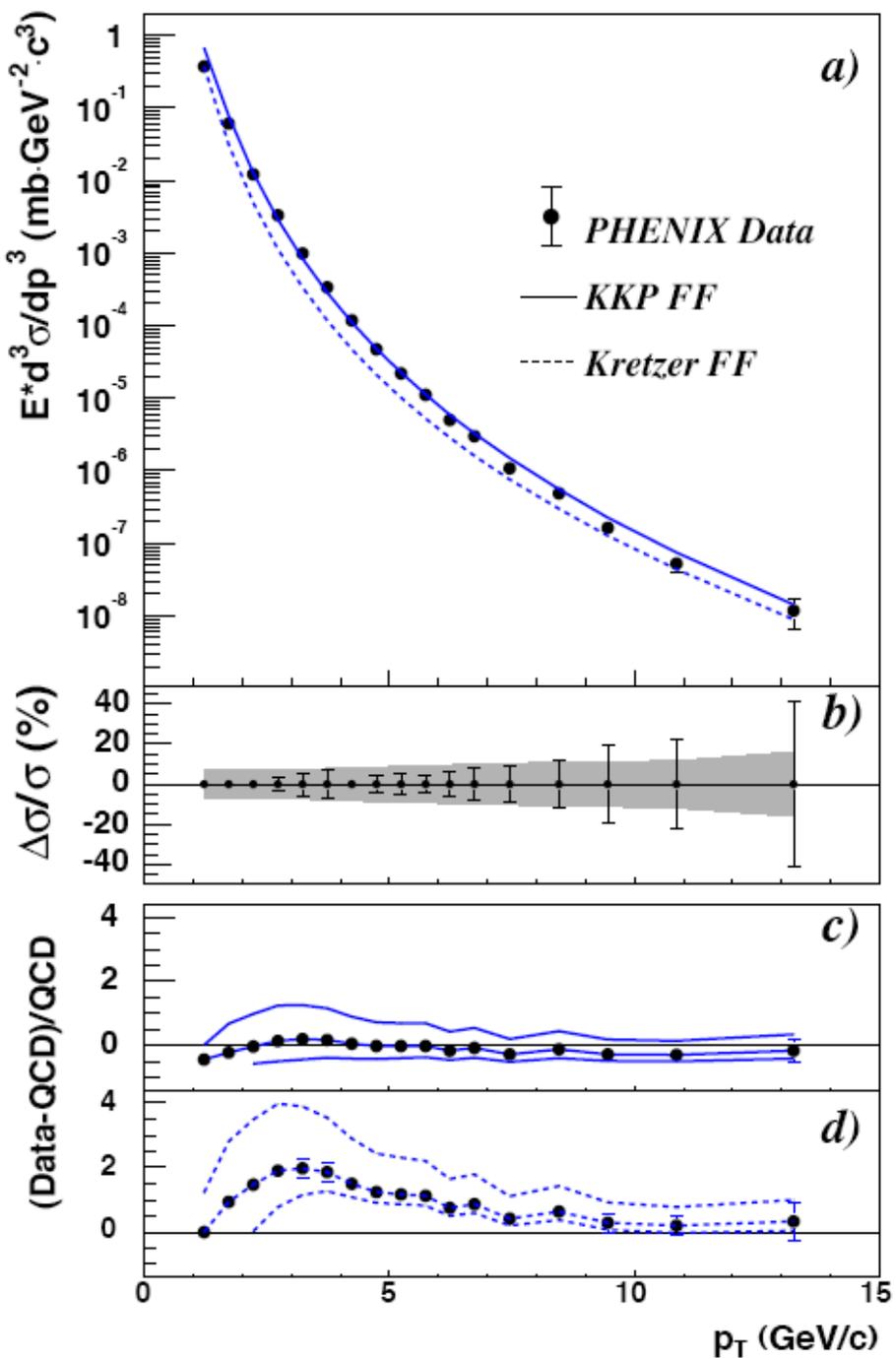


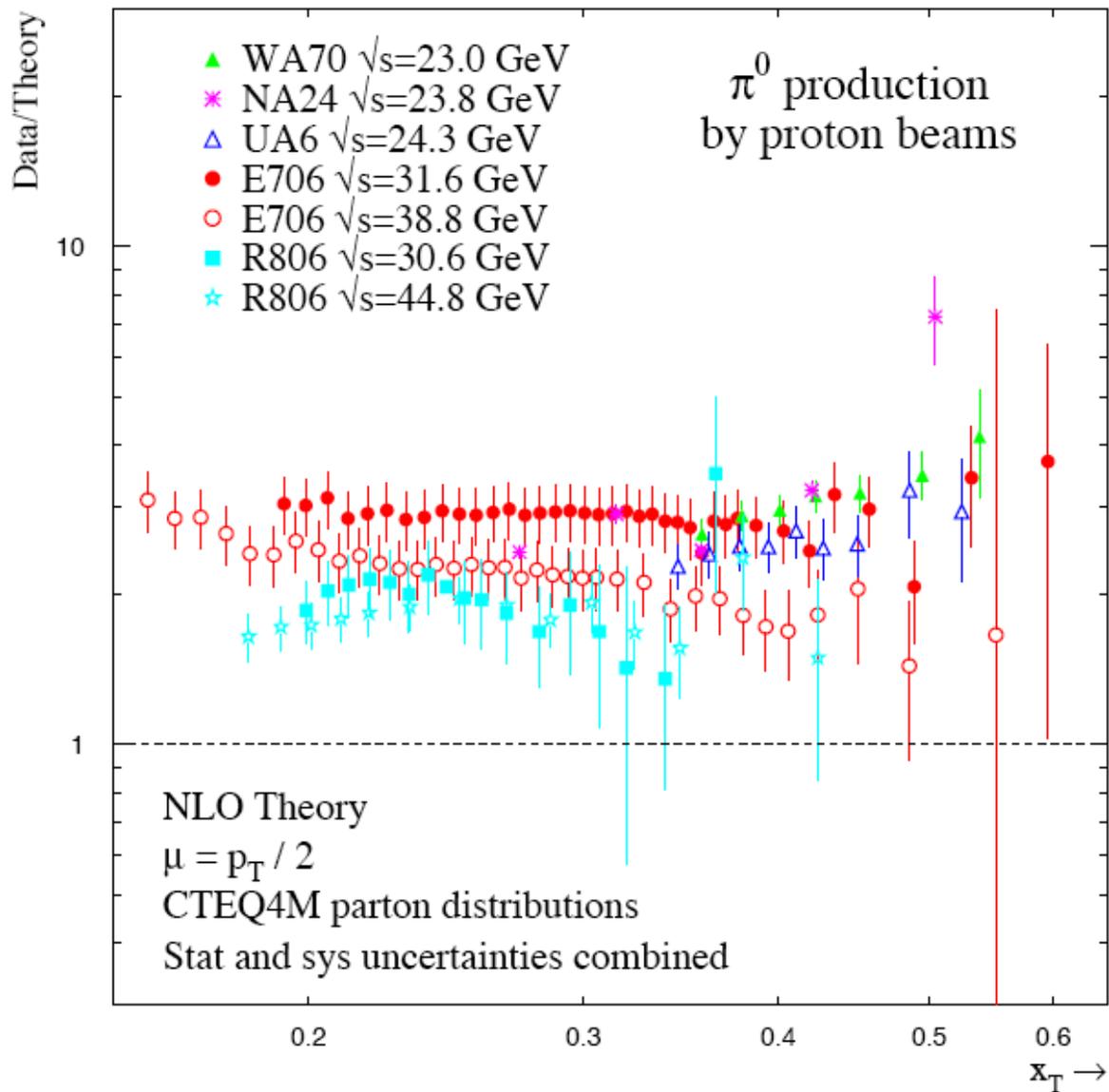
pQCD:



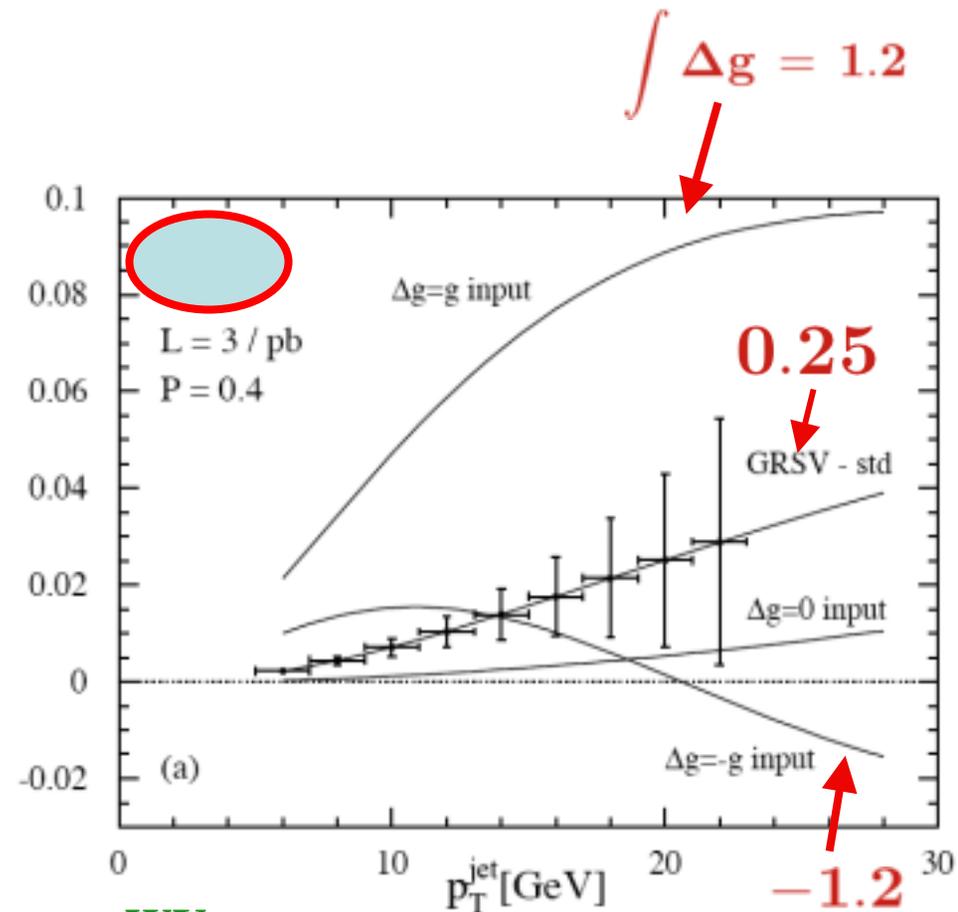
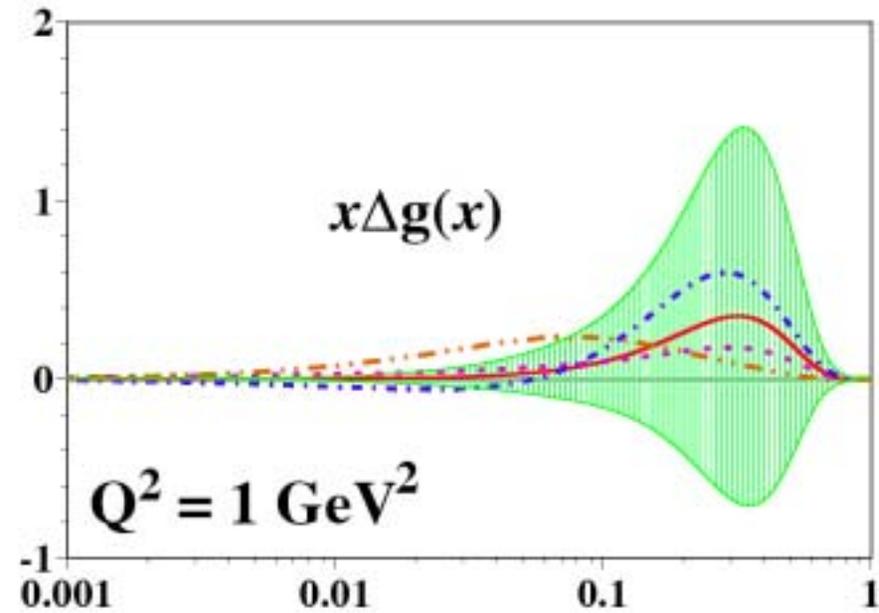
+NLO

$pp \rightarrow \text{jet } X, pp \rightarrow \pi X, pp \rightarrow \gamma X, pp \rightarrow Q\bar{Q} X, \dots$





Near-term example: spin asymmetry for jet production



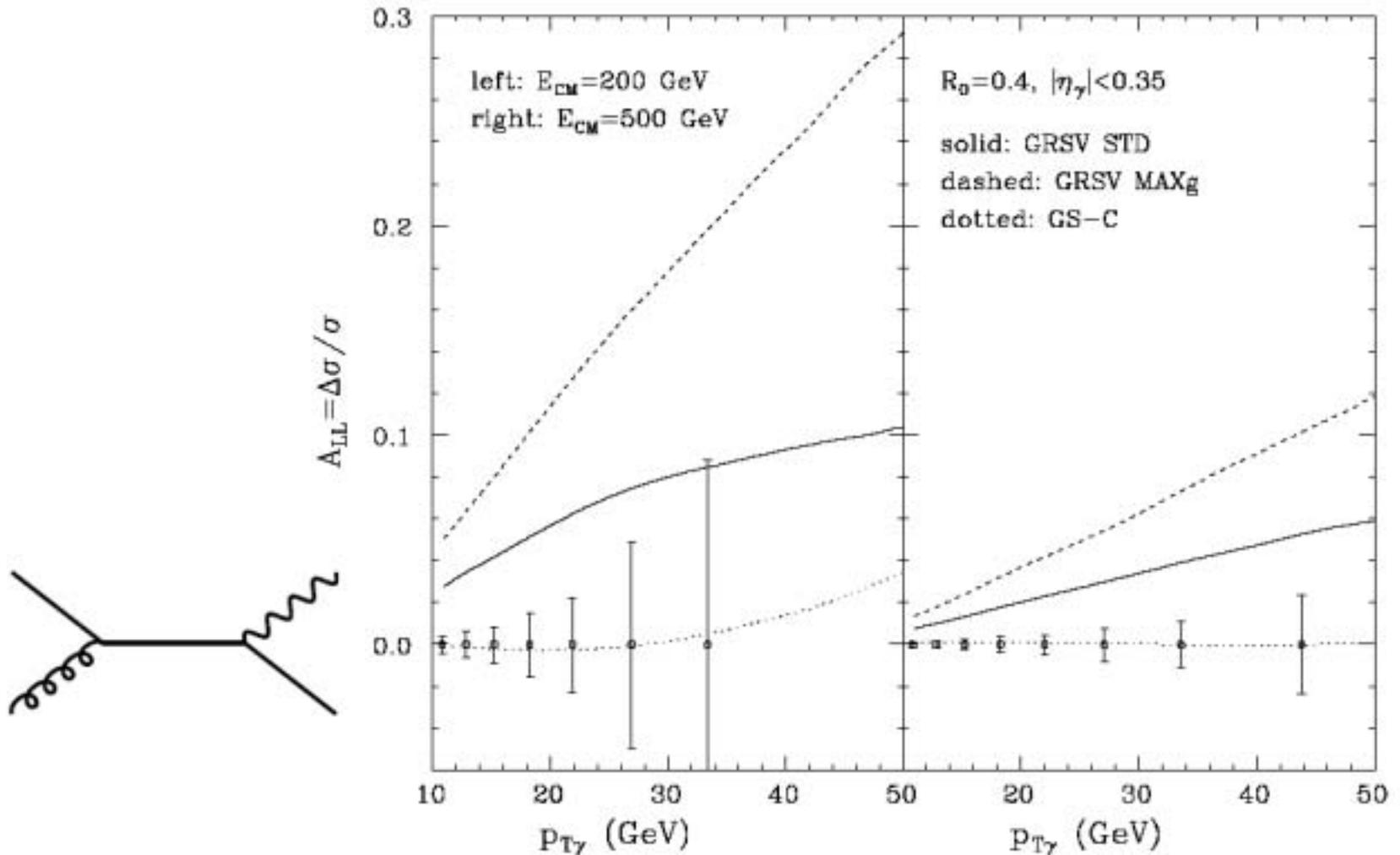
Mid / long-term at RHIC:

“rare probes”

- gluon polarization from $pp \rightarrow \gamma X$

$L=100/\text{pb}$

Frixione, WV



- main information is at $x_g \sim 2 p_T / \sqrt{s}$

typically, $0.025 < x_g < 0.3$ @ $\sqrt{s} = 200 \text{ GeV}$

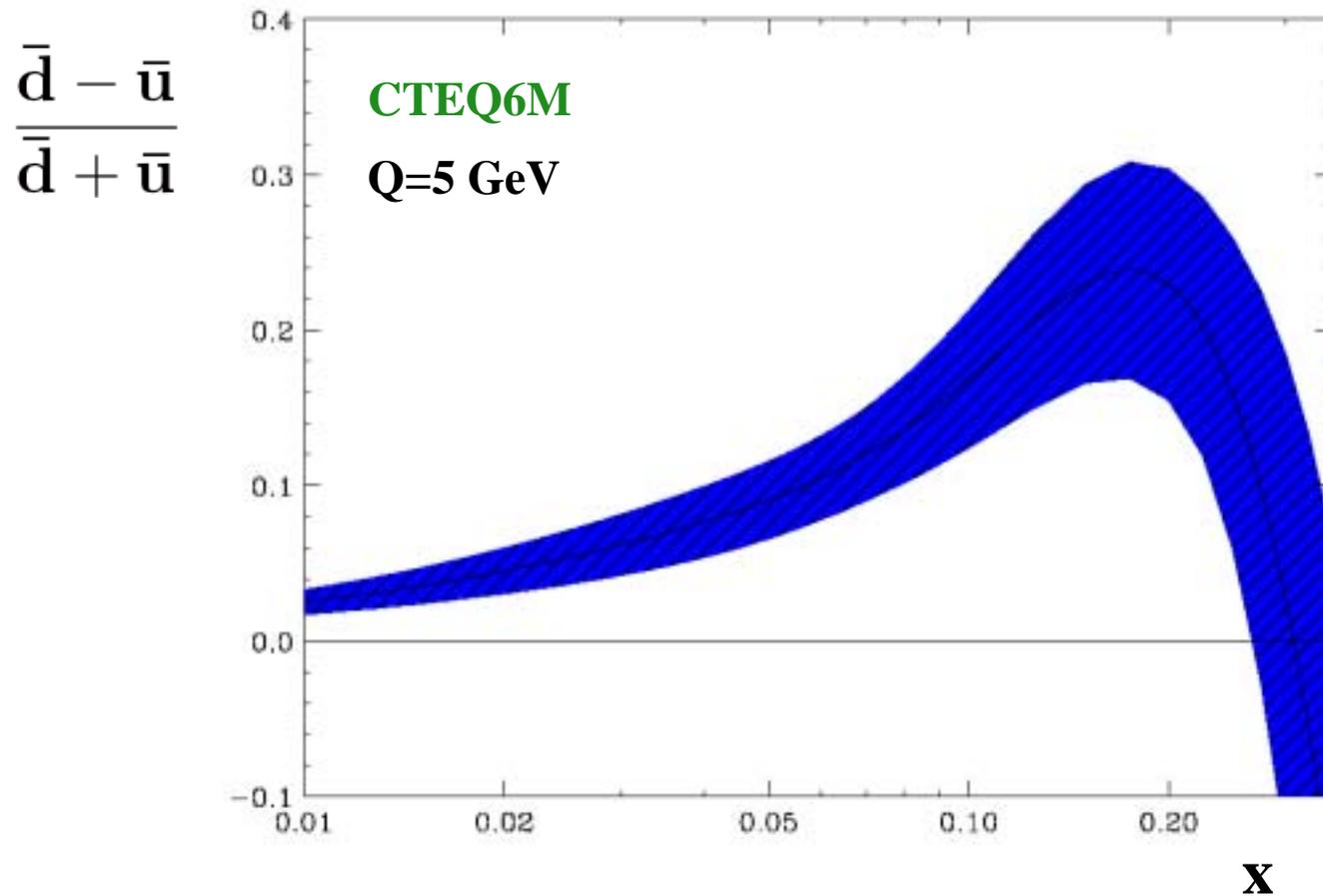
$0.01 < x_g < 0.1$ @ $\sqrt{s} = 500 \text{ GeV}$

- to get integral, may need to expand this:
 - * forward pp scattering
 - * scaling violations at small-x at **eRHIC**

Challenges in QCD spin physics

- What else carries the proton spin ?
 - How are gluons polarized ?
 - How large are parton orbital ang. mom. ?
- What are the detailed patterns of quark & antiquark polarizations ?
 - **Flavor asymmetries in sea ?**
- Is there significant transversity in the nucleon ?
- What are the origins of large observed single-spin asymmetries ?
 - Correlations between transverse spin and parton k_T ?

Detailed information on (anti)quarks



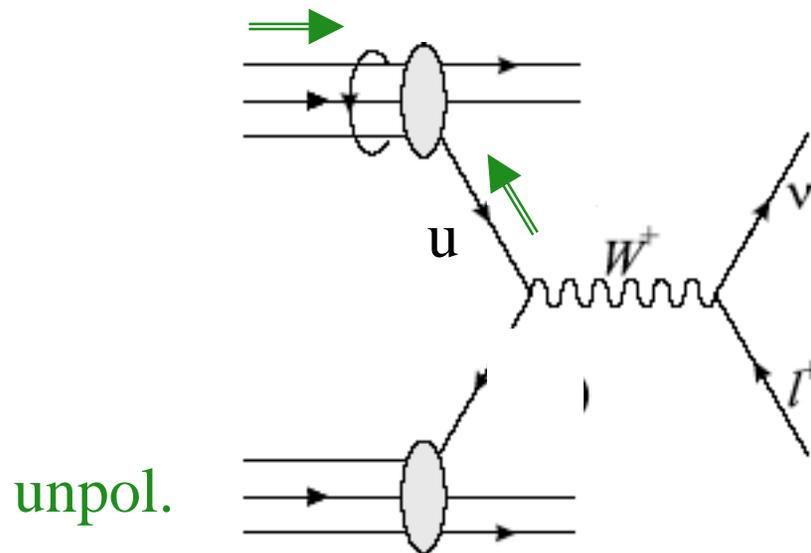
Polarized case: $\Delta\bar{u} - \Delta\bar{d} \begin{matrix} > \\ < \\ = \end{matrix} 0 ?$

most models predict $\Delta\bar{u} > 0$ $\Delta\bar{d} < 0$

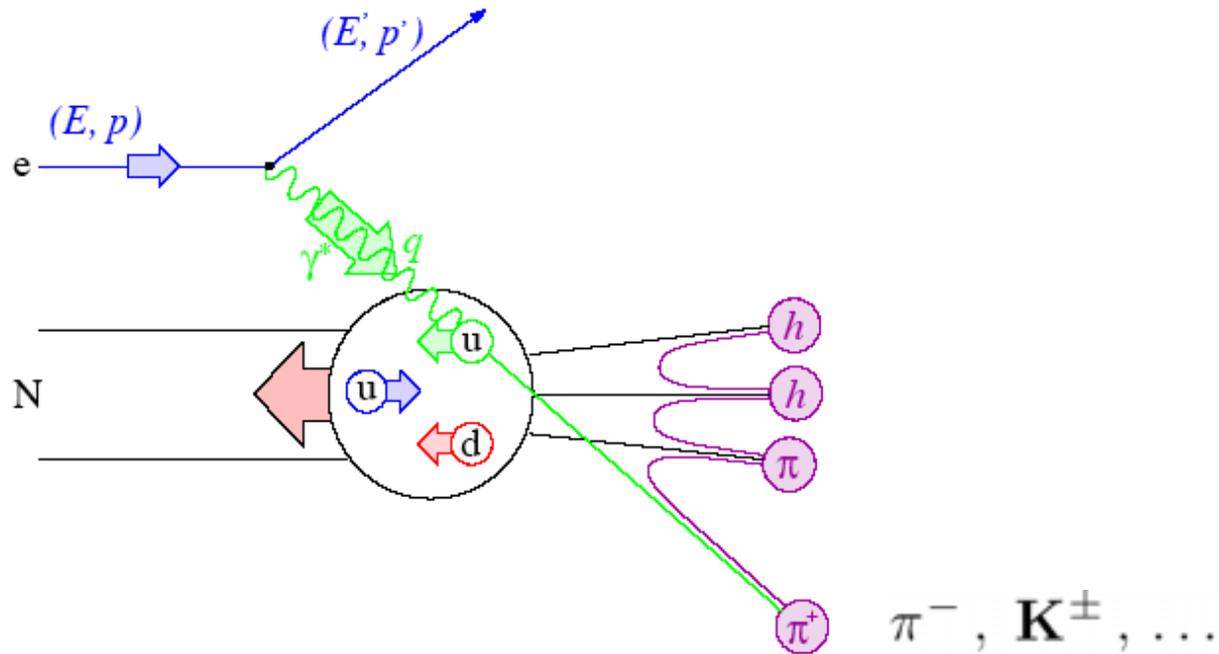
- remarkably, there is a very powerful way at RHIC:

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

parity violating



- **complementary to semi-inclusive DIS :**



HERMES, COMPASS, JLab \rightarrow eRHIC

- **probe properties of nucleon on very different scales !**

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Transversity

$$\Delta \mathbf{q}(\mathbf{x}) = \text{[Diagram 1]} - \text{[Diagram 2]}$$

The diagram shows two red circles representing nucleons. In the first circle, a white nucleon is on the left, and a yellow arrow points to the right. A green arrow points to the right from the center of the circle. In the second circle, a white nucleon is on the right, and a yellow arrow points to the left. A green arrow points to the right from the center of the circle.

$$\delta \mathbf{q}(\mathbf{x}) = \text{[Diagram 3]} - \text{[Diagram 4]}$$

The diagram shows two red circles representing nucleons. In the first circle, a white nucleon is at the bottom, and a yellow arrow points upwards. A green arrow points upwards from the center of the circle. In the second circle, a white nucleon is at the top, and a yellow arrow points downwards. A green arrow points upwards from the center of the circle.

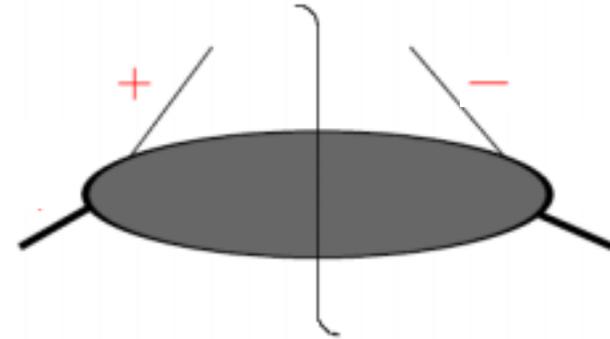
- the unknown “leading-twist” distribution functions

- **the physics involved:**

- * relativistic / dynamical effects

- * “odd chirality” → helicity-flip, χ SB

- * no mixing with gluons

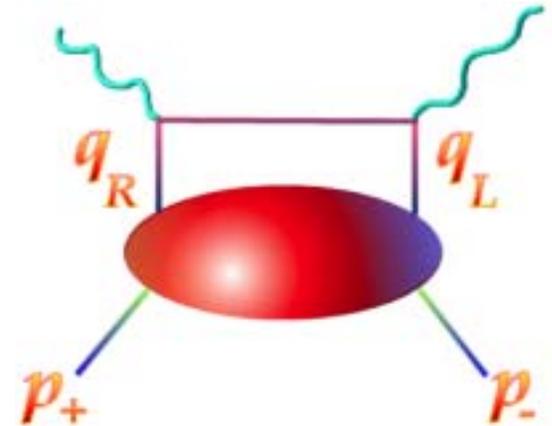
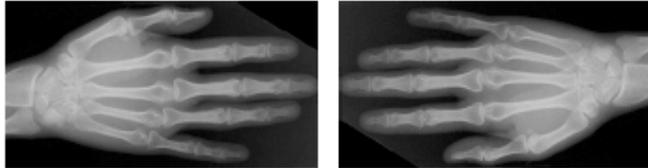


- * tensor charge (relevant for EDM)

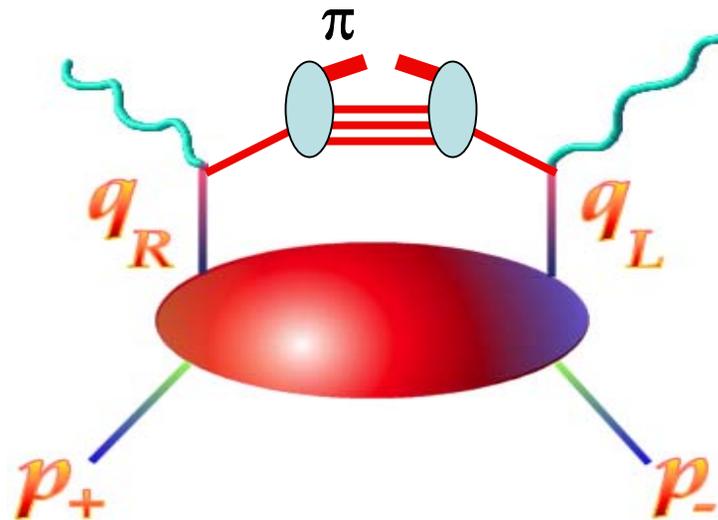
$$\langle \mathbf{P} | \bar{\mathbf{q}} \mathbf{i} \sigma^{\mu\nu} \gamma^5 \mathbf{q} | \mathbf{P} \rangle = \int_0^1 dx [\delta \mathbf{q}(x) - \delta \bar{\mathbf{q}}(x)]$$

• Opportunities for measurement ?

* not in inclusive DIS:



* helicity-flip from final-state effect ?



“Collins effect”

* opens numerous possibilities in ep^\uparrow & pp^\uparrow scattering

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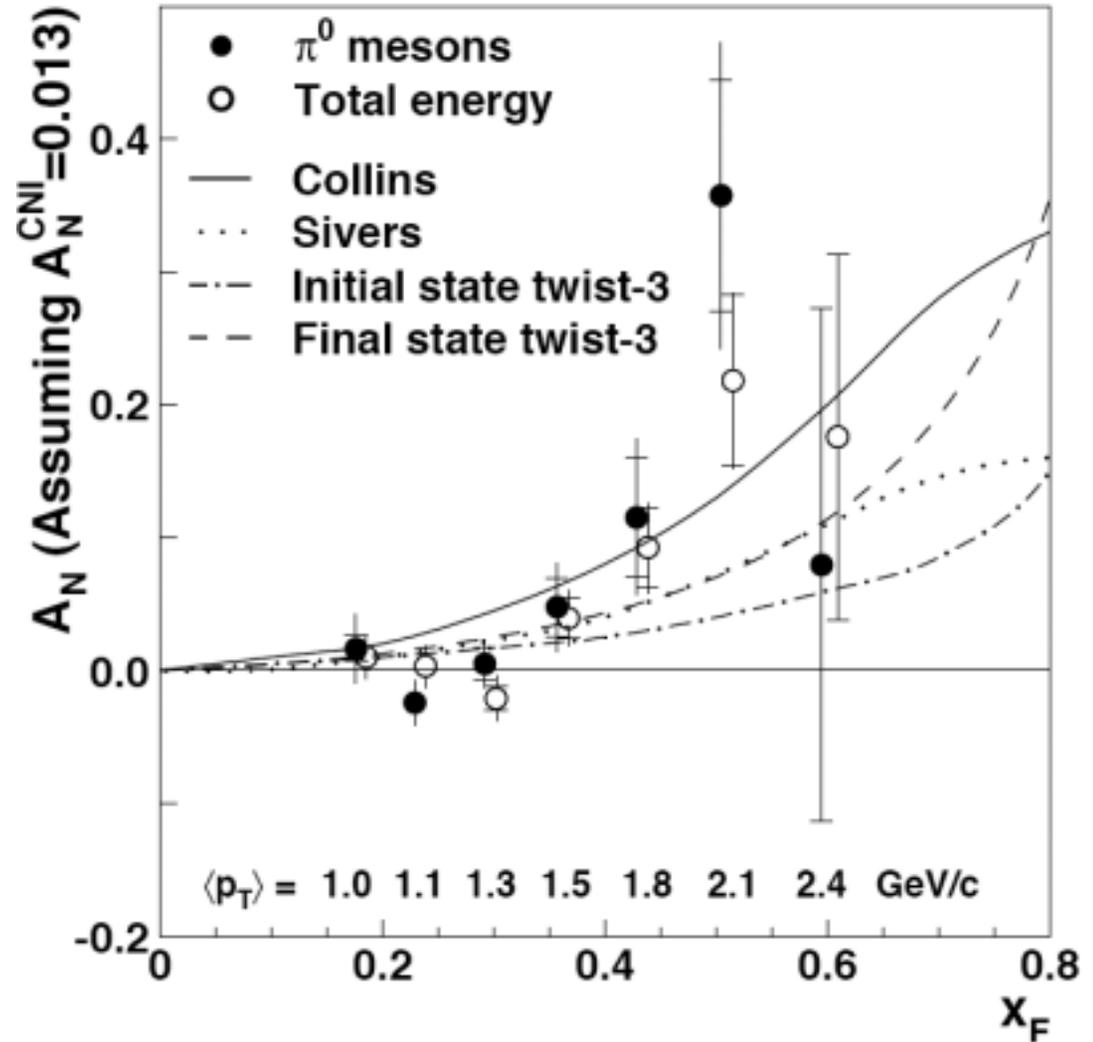
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STAR

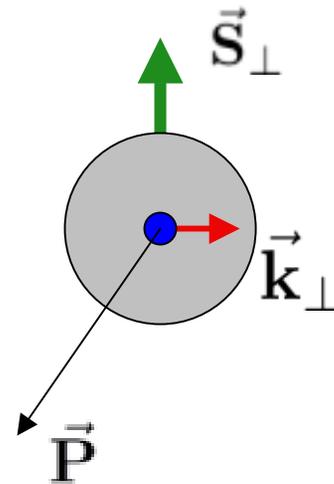
$$A_N = \frac{L - R}{L + R}$$



- **not really understood so far**

- * simple collinear hard scattering: **no asymmetry**
- * transversity & Collins effect are probably involved
- * multi-parton correlations ?
- * exciting possibility:

$$\vec{S}_{\perp} \cdot (\vec{P} \times \vec{k}_{\perp})$$



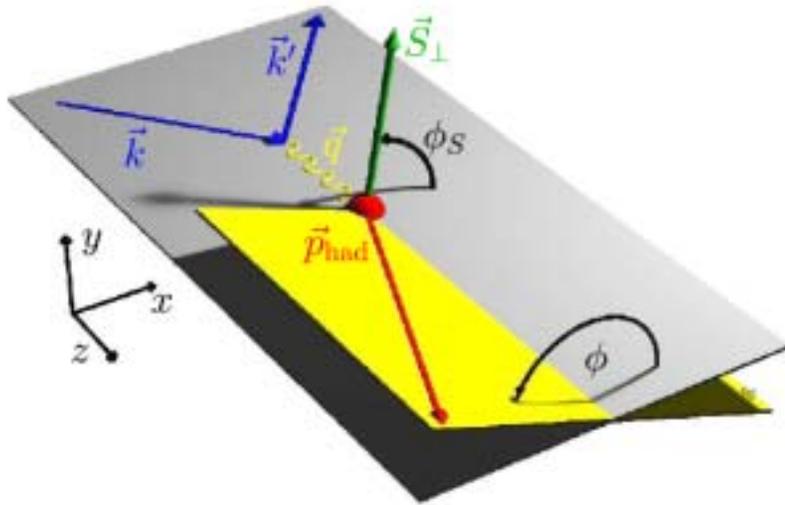
knows about **parton orbital angular momentum**

[connection to “generalized parton distributions” of DVCS ?]

- * many exciting theory issues: factorization, universality, ...

- **Excellent opportunities for direct measurement:**

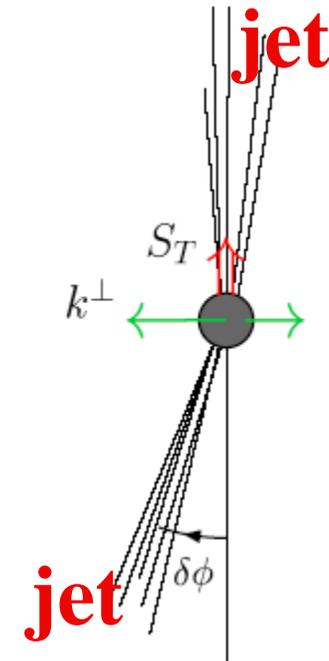
lepton-nucleon: $ep^\uparrow \rightarrow e\pi X$



Sivers $\leftrightarrow \sin(\Phi - \Phi_S)$

Collins $\leftrightarrow \sin(\Phi + \Phi_S)$

proton-proton:



+ **Drell-Yan, ...**

Conclusions

Over the next ~10 years, RHIC will provide new and groundbreaking information on most open questions

- **important interplay with:**
 - * **complementary information from lepton scattering**
fixed-target **HERMES, COMPASS, Jlab** → **eRHIC**
 - * **efforts to understand nucleon spin structure**
from QCD: lattice, models, ...