RHIC – Spin

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Workshop on
Forward Physics at RHIC and LHC
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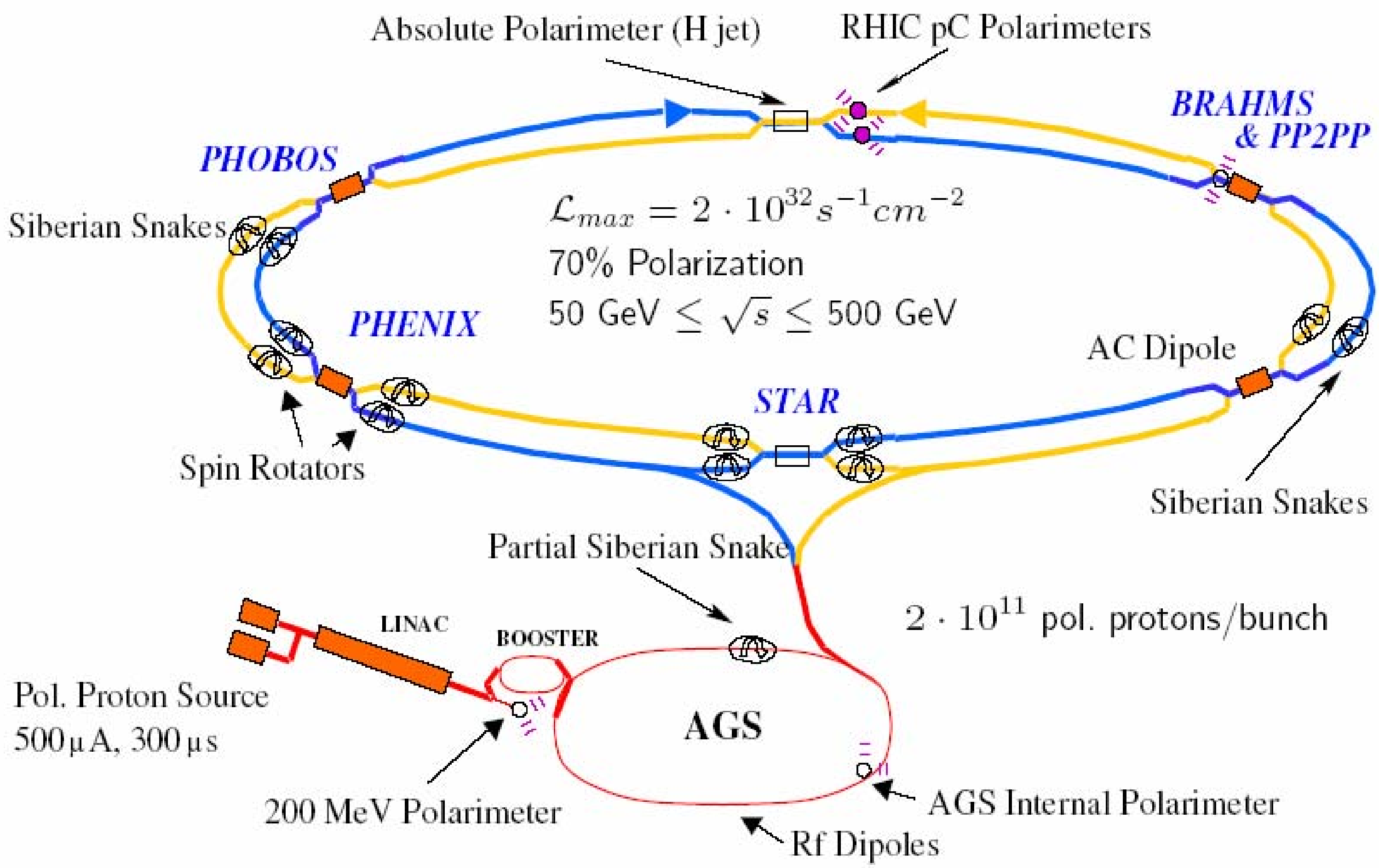
Outline

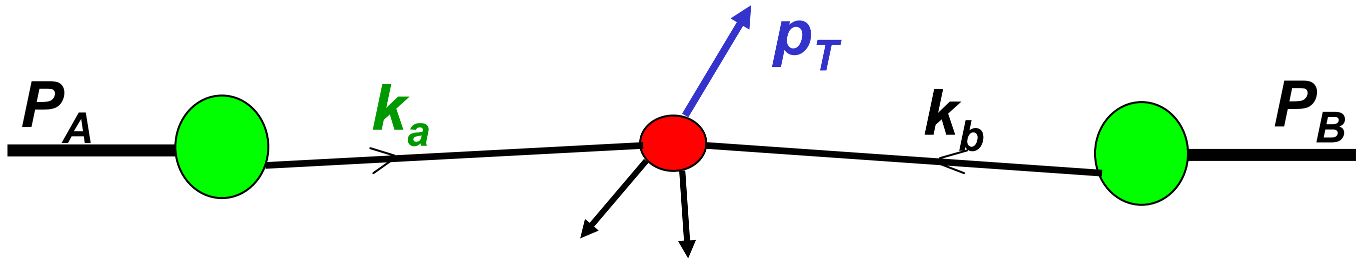
- ❑ RHIC - The machine
- ❑ Polarized parton distribution functions (PDF's)
- ❑ Spin – ½ sum rule
- ❑ What a RHIC spin program can achieve?
- ❑ Beyond the PDF's – Single spin asymmetries
- ❑ Summary and outlook

Relativistic Heavy Ion Collider



First polarized *pp* collider

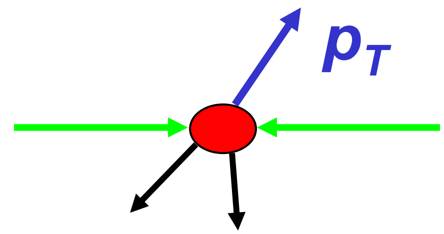
Hadronic Hard Collisions



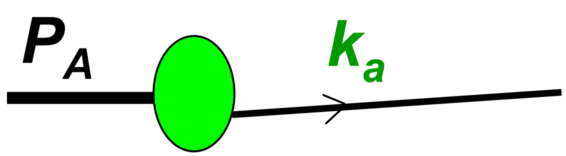
❑ Collinear factorization – approximation:

❖ **Hard part:**

$$\left| \; k_a \approx x_a P_A \quad \text{[diagram]} \quad k_b \approx x_b P_B \; \right|^2$$



❖ **PDF:**



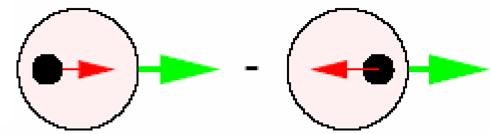
$$\left| \; \cdots \; \right|^2 d^4k_a \; \delta\left(x_a - \frac{k_a \cdot P_B}{P_A \cdot P_B} \right)$$

❑ Factorized cross section:

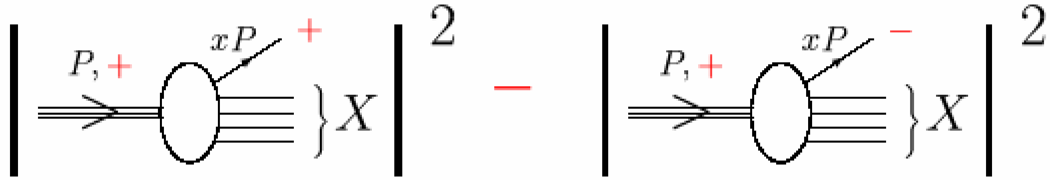
$$d\sigma_{AB} = \sum_{a,b} f_{a/A}(x_a) \otimes f_{b/B}(x_b) \otimes d\hat{\sigma}_{ab} + O\left(\left(\frac{\langle k_T \rangle}{p_T} \right)^2 \right)$$

Polarized parton distributions

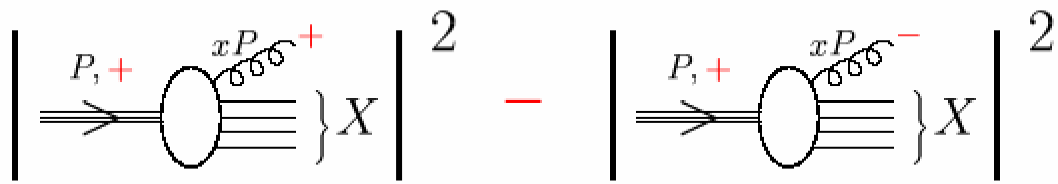
- **Longitudinally polarized nucleon:**



$\Delta q(x) =$



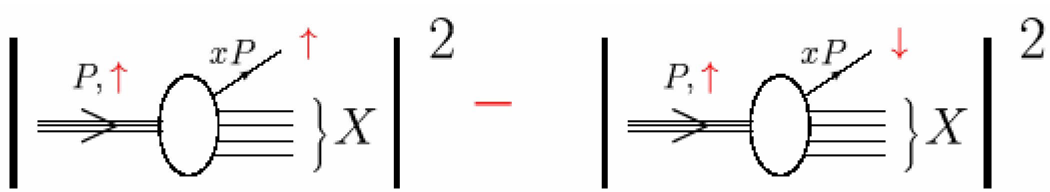
$\Delta g(x) =$



with the parton's transverse momentum integrated

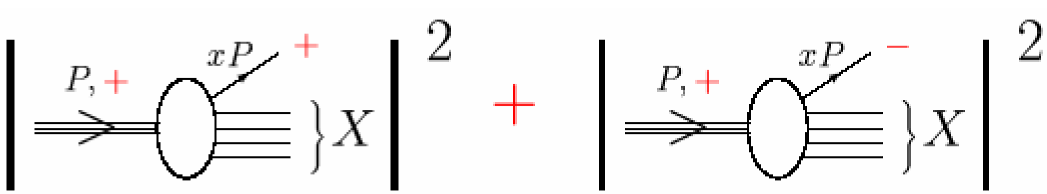
- **Transversely polarized nucleon:**

$\delta q(x) =$



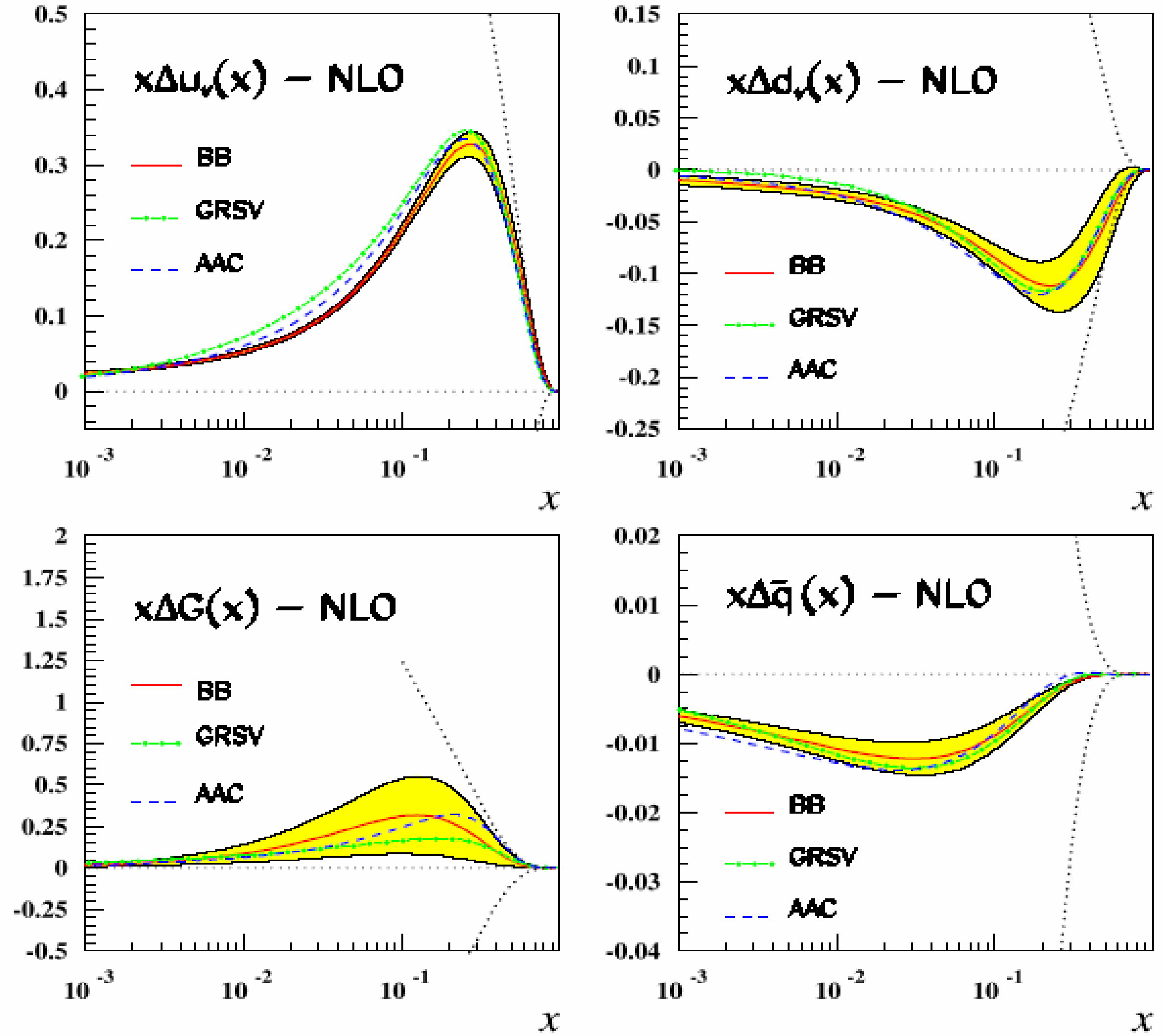
- **unpolarized parton distribution:**

$q(x) =$

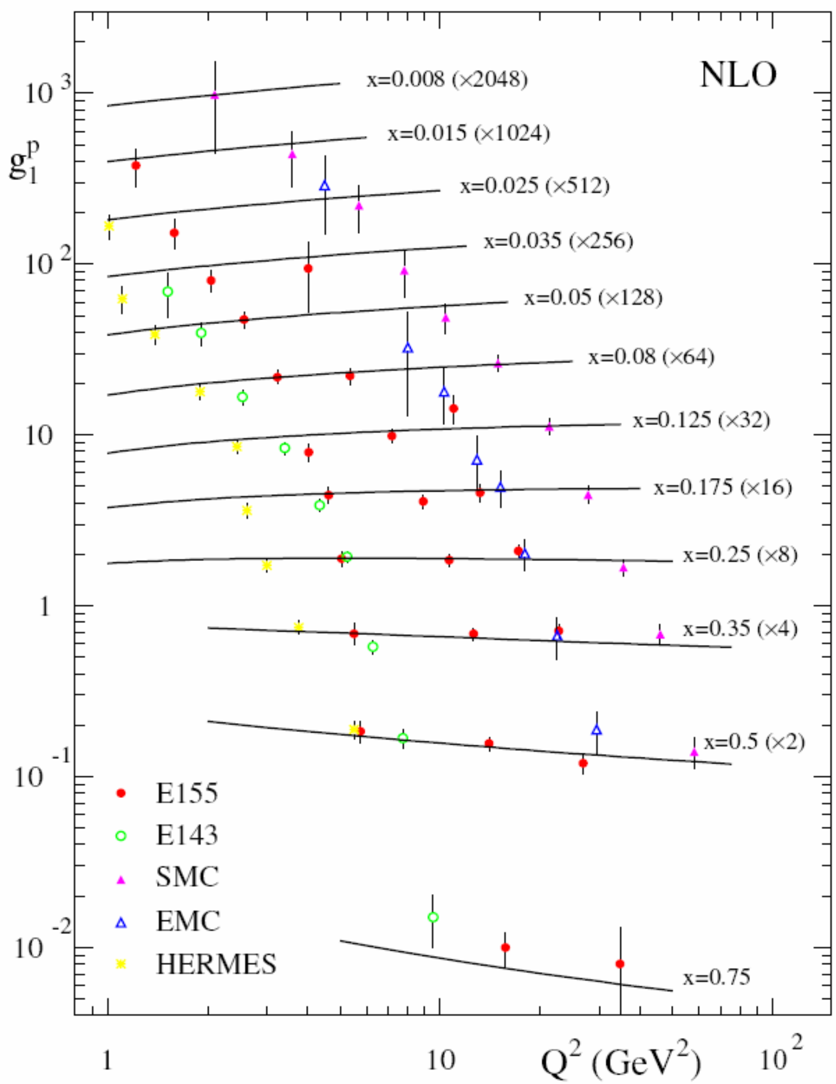


Polarized parton distributions - II

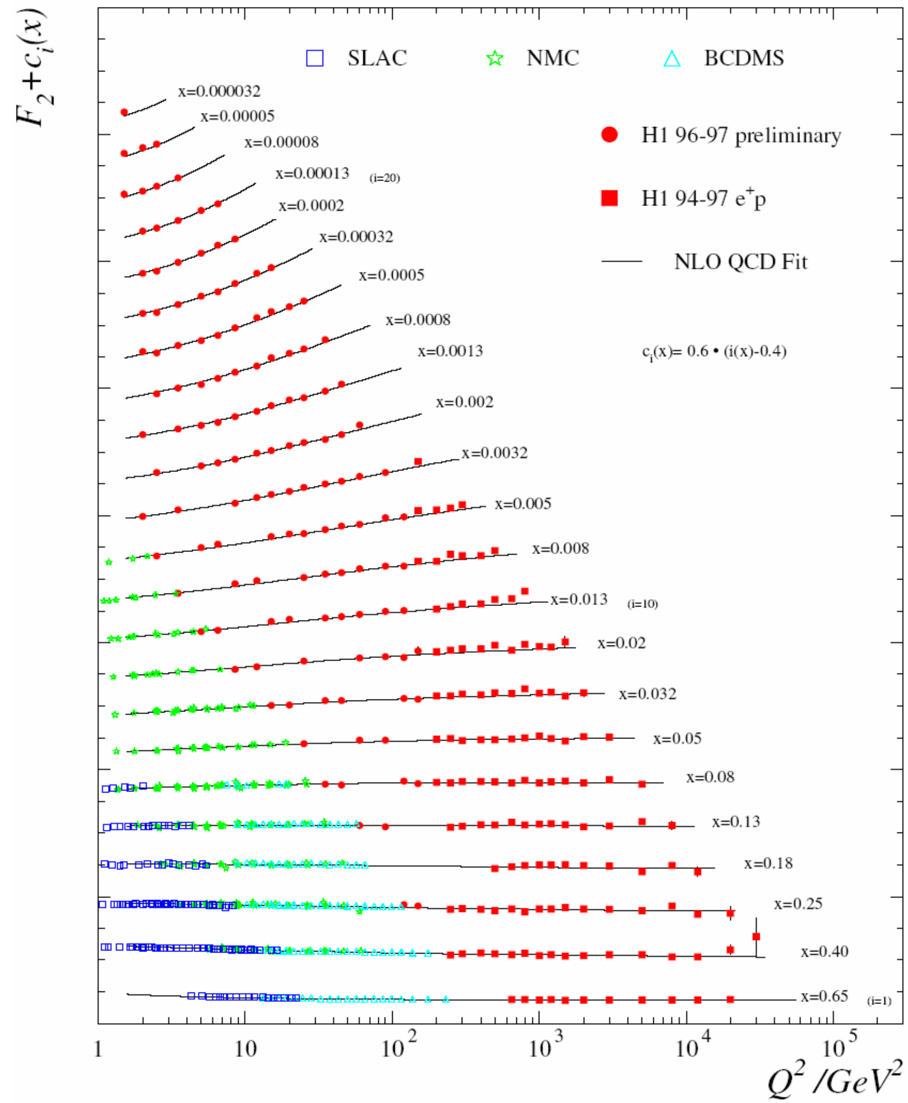
❑ Current knowledge of Δf exclusively from low energy DIS:



Polarized vs. unpolarized



NLO QCD fit: Glück, Reya, Vogelsang, MS (2000 update)



Spin – ½ sum rule

- First moment of polarized parton distribution:

$$\Delta f \equiv \int_0^1 dx\, \Delta f(x)$$

= helicity carried by the parton of flavor ***f***

- Quark spin contribution to proton's spin:

$$\frac{1}{2}\Delta\Sigma \equiv \frac{1}{2}\left[\Delta U + \Delta\bar{U} + \Delta D + \Delta\bar{D} + \Delta S + \Delta\bar{S}\right]$$

$$\tfrac{1}{2}\Delta\Sigma \approx 0.08 \pm 0.04 \quad \ll \tfrac{1}{2}$$ "spin crisis"

- Nucleon spin – ½ sum rule:

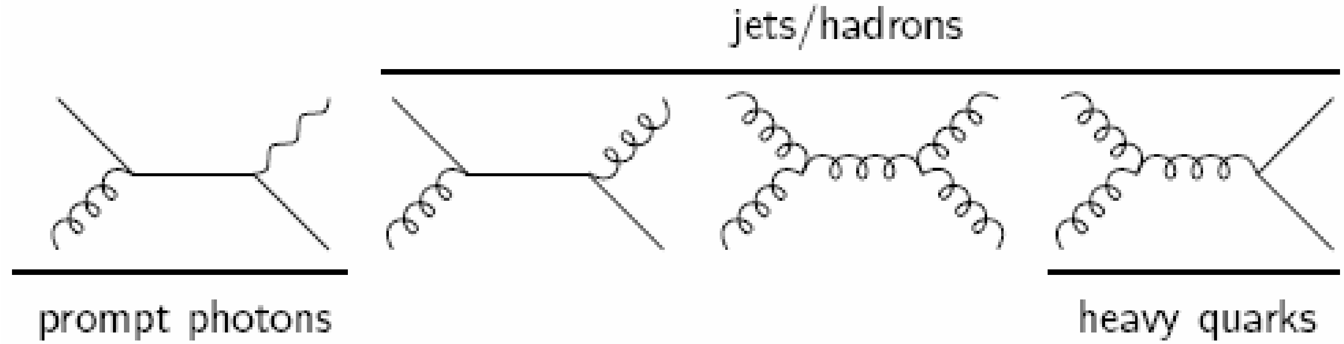
$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

What a RHIC spin program can do?

- ❑ **Measure polarized parton distributions:**
  - ❖ Many more physical processes (or probes)
  - ❖ wider range of x and Q
  - ❖ Better quark flavor separation
  - ❖ Direct information on polarized gluon distribution
- ❑ **Check the universality of the parton distributions**
  - ❖ Test of the QCD factorization theorem
- ❑ **Asymmetries with transversely polarized beams**
  - ❖ Measure the transversity distributions: $\delta q(x)$
  - ❖ Go beyond the collinear factorization:
    - – multi-parton correlation, Collins and Sivers functions, …
- ❑ **Test QCD dynamics in its spin sector**

Probes for polarized PDFs

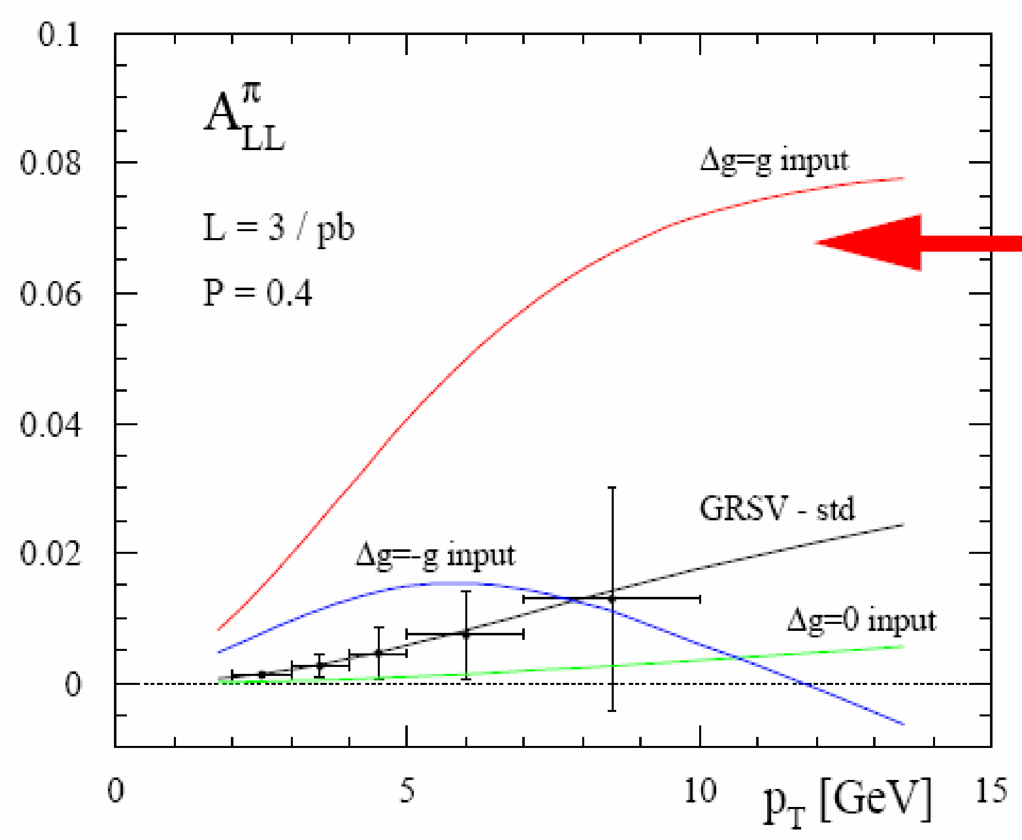
- **Gluon distribution enters at the Leading Order (LO):**

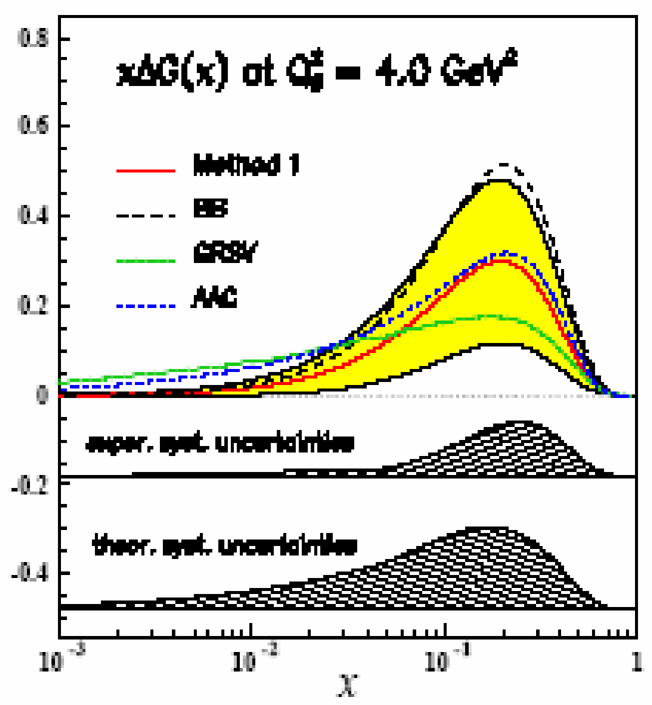


reaction	LO subprocesses	partons probed	x-range
$pp \to \text{jets}\ X$	$q\bar{q}, qq, qg, gg \to \text{jet}\ X$	Δq, Δg	$x \gtrsim 0.03$
$pp \to \pi X$	$q\bar{q}, qq, qg, gg \to \pi X$	Δq, Δg	$x \gtrsim 0.03$
$pp \to \gamma X$	$qg \to q\gamma$, $q\bar{q} \to g\gamma$	Δg	$x \gtrsim 0.03$
$pp \to Q\bar{Q}X$	$gg \to Q\bar{Q}$, $q\bar{q} \to Q\bar{Q}$	Δg	$x \gtrsim 0.01$
$pp \to W^{\pm}X$	$q\bar{q}' \to W^{\pm}$	Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$	$x \gtrsim 0.06$

Sensitivity on Δ*g*

❑ **Predictions for very different Δ*g*:**

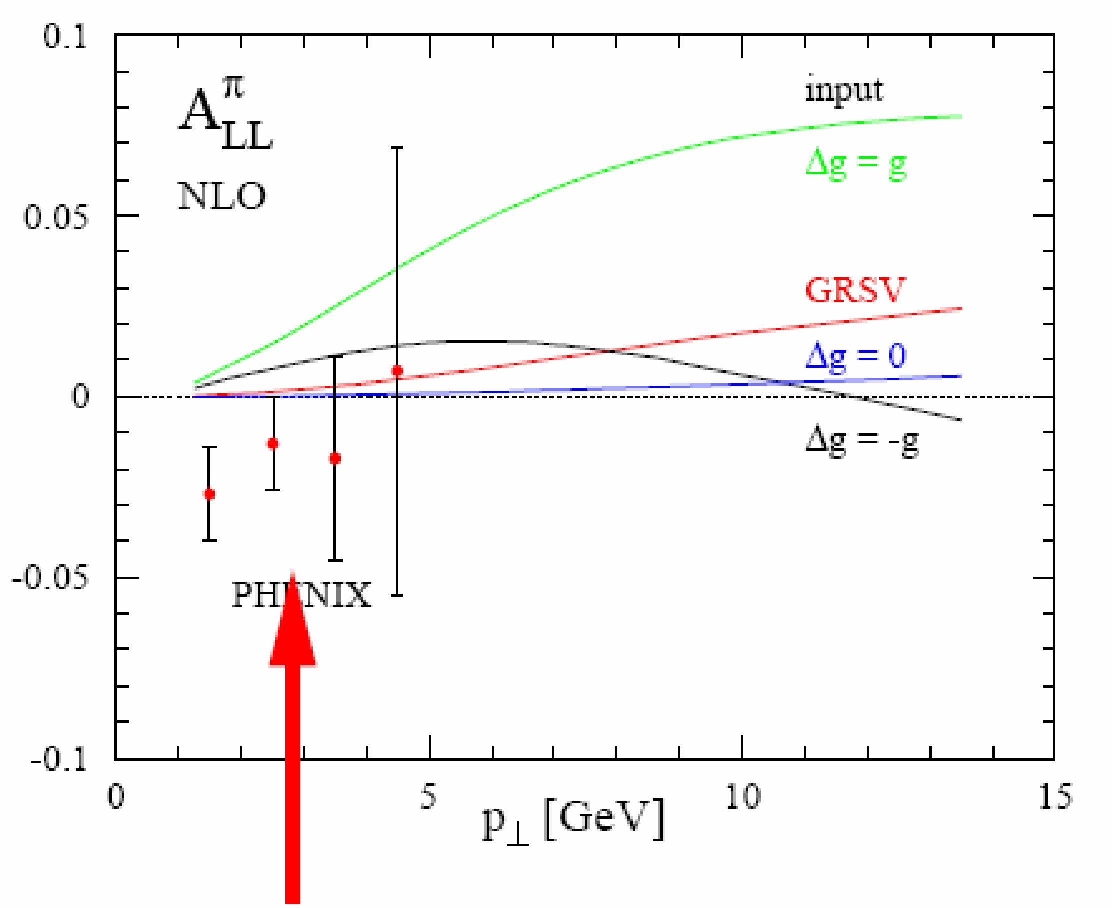




Error estimate based on 3 pb^{-1}

All these different Δ*g* are consistent with DIS data

First results on A_{LL} by PHENIX



trend for $A_{\mathrm{LL}} < 0$ at small p_T contrary to expectations

B. Jäger *et al.* Phys. Rev. Lett. **92**, 121803 (2004)

Is it possible to have a negative A_{LL}?

- **Un-polarized cross section is positive definite**
  - **Need a negative polarized cross section:** $A_{LL} = \frac{\Delta\sigma}{\sigma} < 0$
- **Factorized cross section:**

$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, \Delta f_a(x_a,\mu_f)\, \Delta f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu'_f) \times \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu'_f, \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

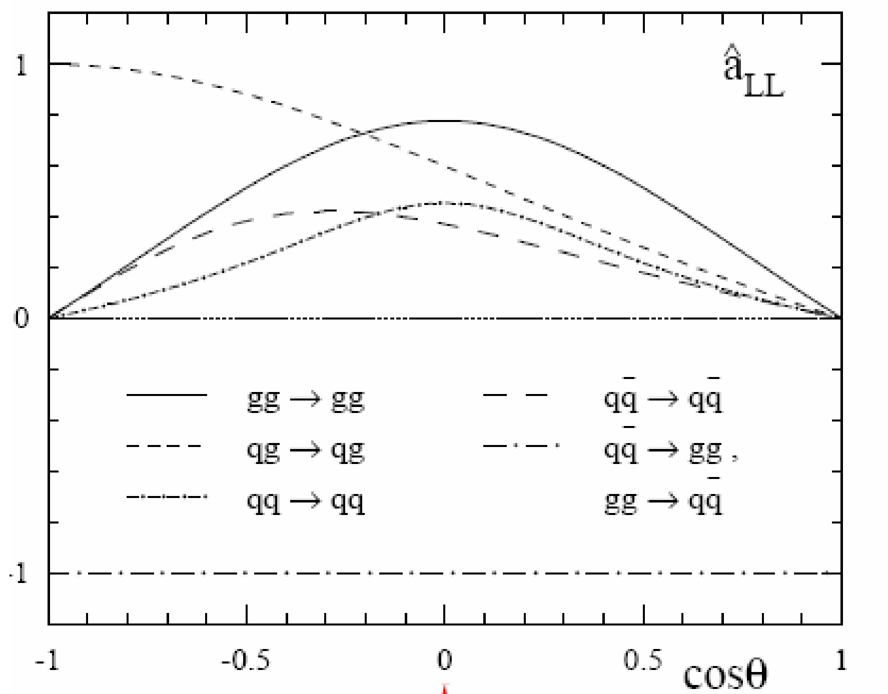
- **Negative polarized cross section requires:**
  - **Negative polarized parton distributions**
  - **Negative polarized partonic cross section**

The answer is YES, in principle

How likely to have a negative A_{LL}?

B. Jäger *et al.* Phys. Rev. Lett. **92**, 121803 (2004)

- Partonic asymmetries:



PHENIX measures at central rapidities

$gg \to gg \quad \hat{a}_{LL} > 0$

$gg \to q\bar{q} \quad \hat{a}_{LL} = -1$

$gq \to gq \quad \hat{a}_{LL} > 0$

Negative A^{π}_{LL} from:

$q\bar{q} \to gg$

$gg \to q\bar{q}$

subprocesses

BUT

$$\Delta\hat{\sigma}_{gg\to gg} \underset{(\eta\simeq 0)}{\simeq} 160\, \Delta\hat{\sigma}_{gg\to q\bar{q}}$$

$$(\Delta g)^2 > 0$$

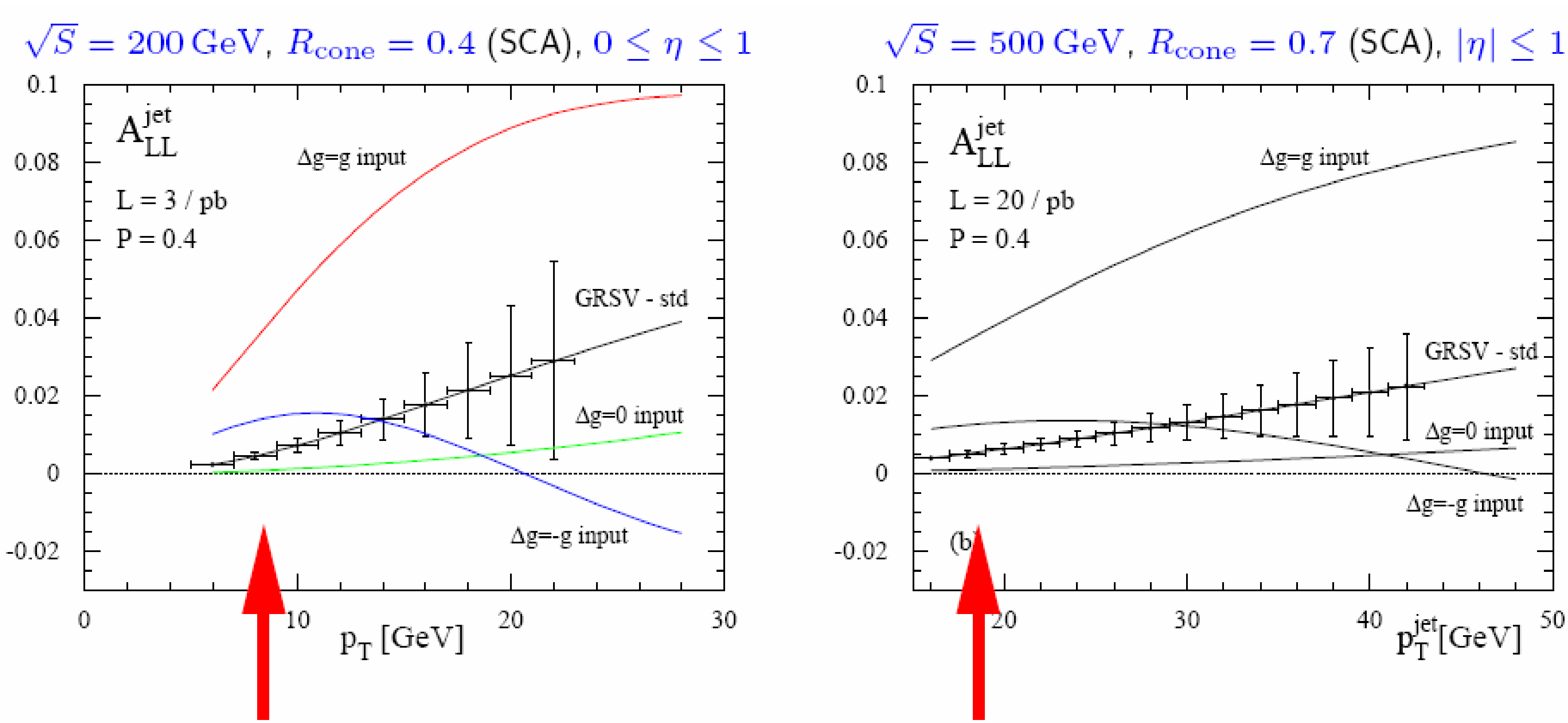
The answer is NOT likely

Need more measurements

- π^0 **at different rapidity:**
  - At large rapidity, qg subprocess becomes more important
  - qg subprocess is sensitive to the sign of Δg
- π^+ **or** π^- **production:**
  - More sensitive to Δg because of the differences in fragmentation functions
- **Other observables:**
  - Direct photon dominated by qg Compton subprocess
  - Low mass Drell-Yan at $p_T > Q/2$
  - …

High p_T Jets

- Sensitive to gluon polarization Δg :



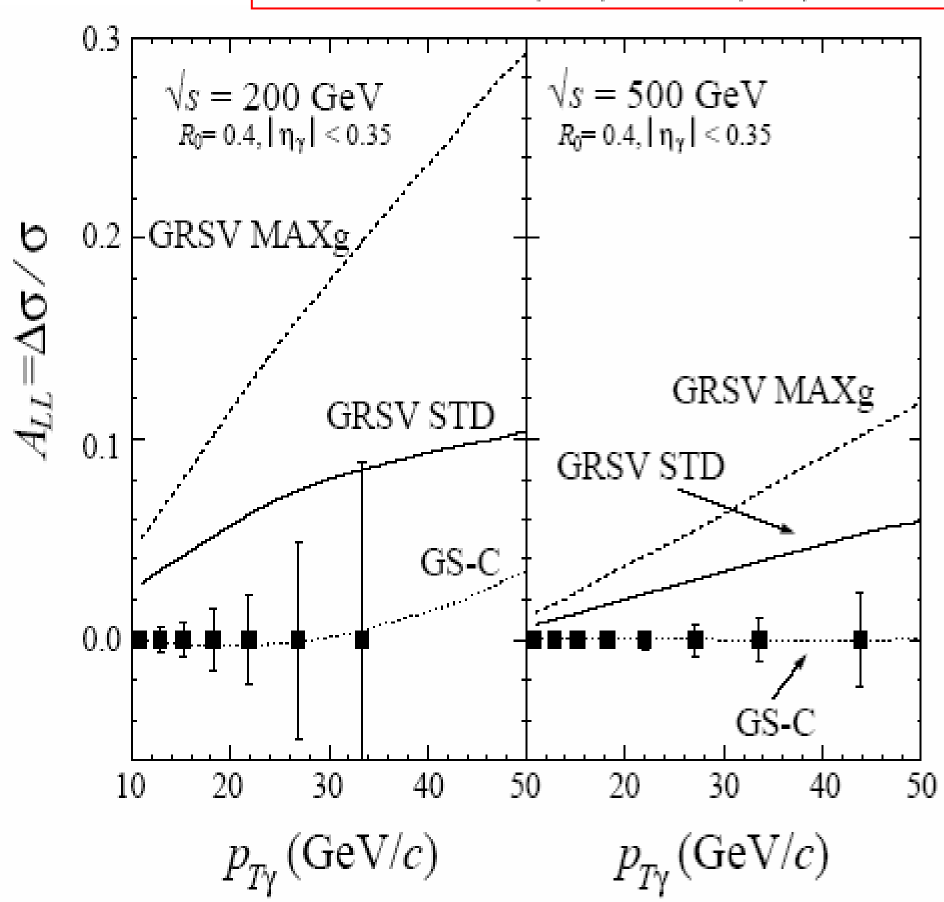
But, not sensitive to the sign of Δg (gg sub. dominates)

Figures taken from Stratmann's talk at BNL Spin Summer School

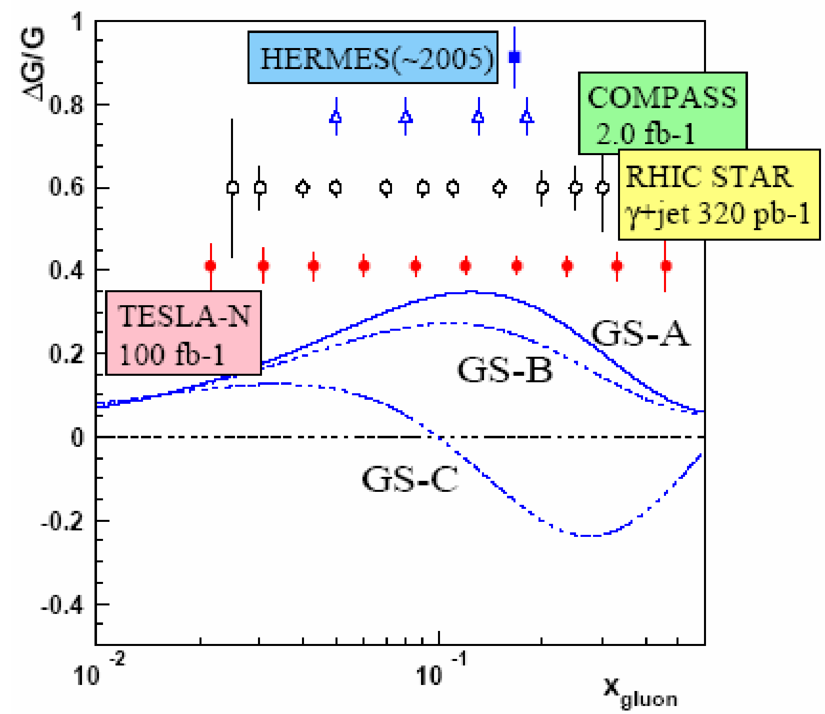
Direct photons

- Sensitive to gluon polarization Δg and its sign :

$$A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \frac{g_1(x_2)}{F_1(x_2)} \hat{A}_{LL}(gq \to \gamma q) + (1 \leftrightarrow 2)$$



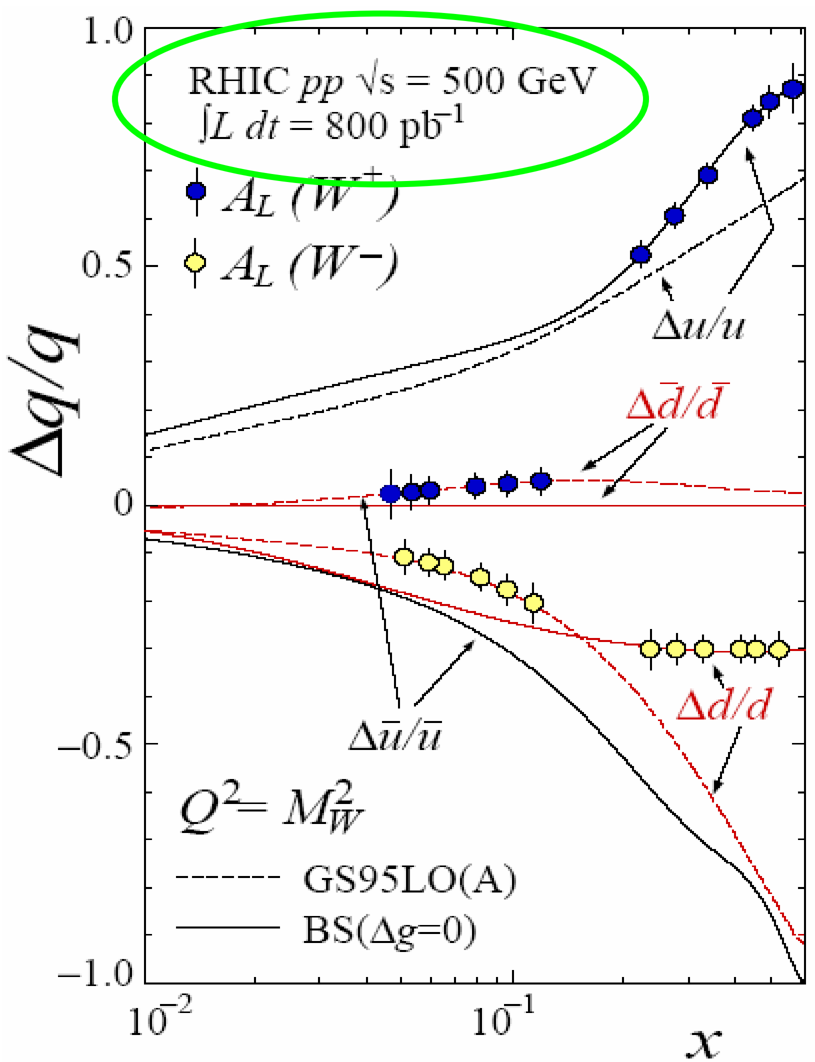
[fig. taken from Frixione, Vogelsang]



projected accuracy for $\Delta g/g$ from
$\gamma + \text{jet}$ measurement at STAR
(only including $\sqrt{S} = 200$ GeV)

Flavor separation – A_L

- Take advantage of the pure V-A interaction for $W^{\pm}$



$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}}\,e^{+y}, \quad x_2 = \frac{M_W}{\sqrt{s}}\,e^{-y}$$

- *y*-dependence to separate Δu from Δd
- Detector issues:

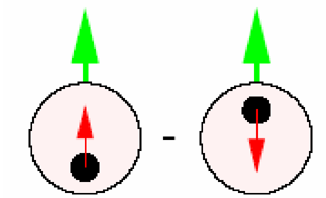
  missing ET cannot be reconstructed
- Get *y*(W) only from the *y* of the charged lepton

  NLO lepton-level MC available (Nadolsky, Yuan)

Transversity distribution – $\delta q(x)$

Ralston, Soper; Artru, Mekhfi; Jaffe, Ji

- Rotate the beam polarization by 90^0 :

$\delta q(x) =$  = Chiral-odd helicity-flip density

Cannot be derived from knowing q(x) and Δq(x) because

boosts and rotations do not commute

- Soffer inequality : $$|\delta q(x)| \leq \frac{1}{2}\left[q(x) + \Delta q(x)\right]$$

- Require two of these for physical observables: A_{TT}

- Drell-Yan : Ralston & Soper, Nucl. Phys. B152 (1979) 109; ...

$$A_{TT} = \frac{\sum_q e_q^2\, \delta q(x_1,M)\delta\bar{q}(x_2,M)+(1\leftrightarrow 2)}{\sum_q e_q^2\, q(x_1,M)\bar{q}(x_2,M)+(1\leftrightarrow 2)}\, \hat{a}_{TT}$$

Expect $A_{TT} \sim 1 – 2\ \%$

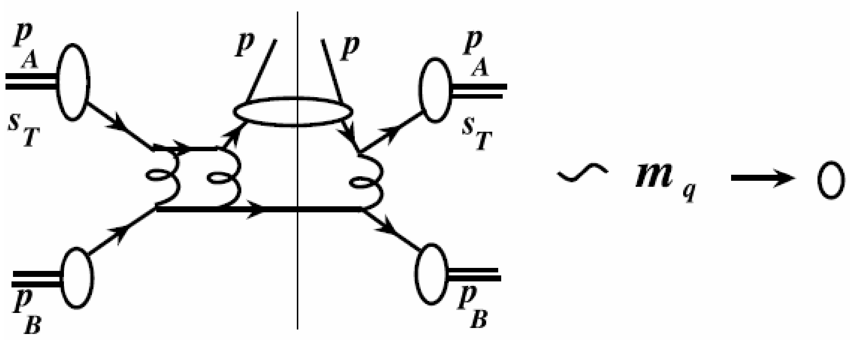
Single transverse spin asymmetry – A_N

- process – only one hadron is transversely polarized:

$$A(p, \vec{s}_T) + B(p') \to C(l) + X \text{ with } C \text{ `=' high-}p_T\ \pi, \gamma, \ldots$$

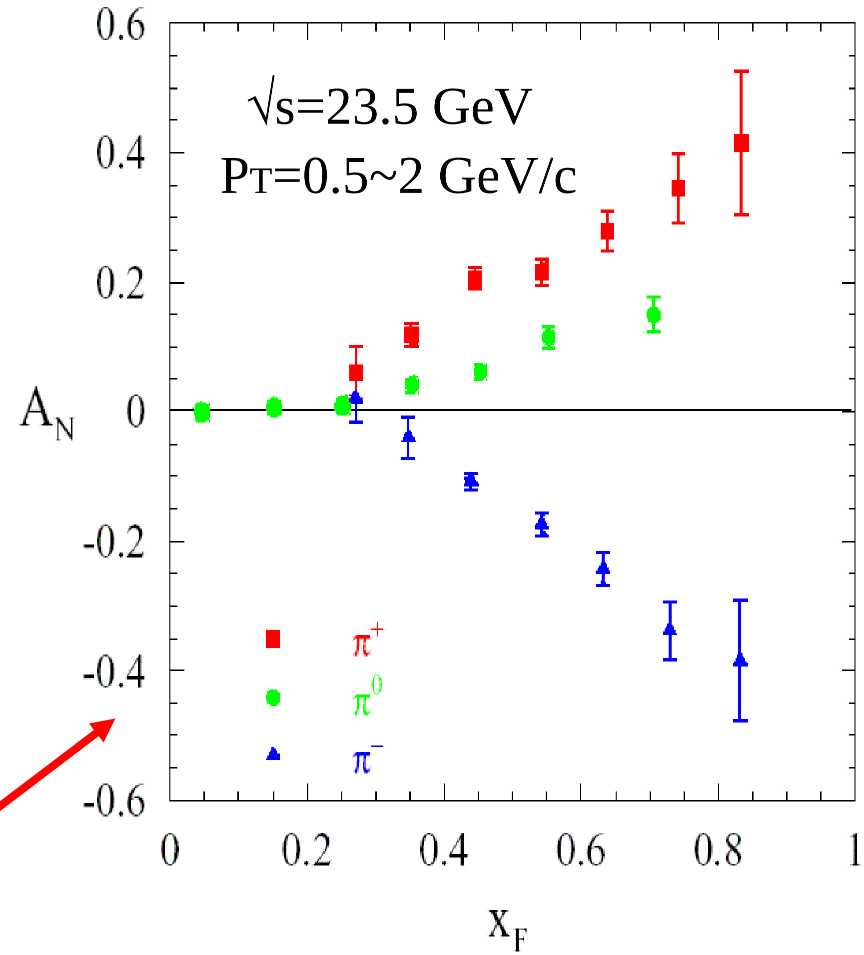
- Asymmetries: $A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$

- Collinear formalism:



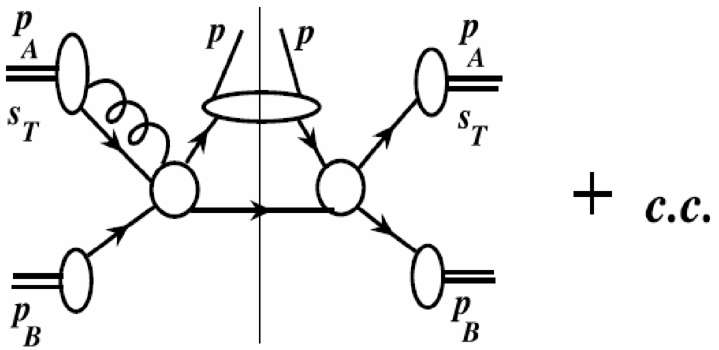
- Large asymmetries A_N observed in hadron collisions:
  - decay of Λ
  - production of π's

FNAL - E704



Beyond the collinear twist-2 formalism

- **Twist-3 contribution in collinear factorization**
  - **leading corrections from parton correlation (minimal approach)**

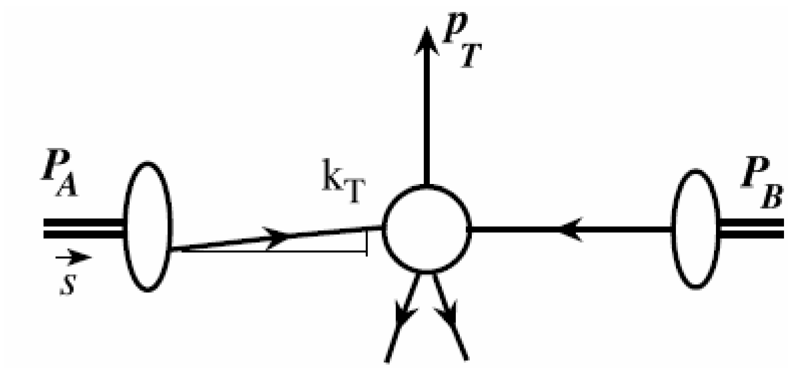


$$A_N \propto \frac{1}{S}\varepsilon^{p_A p_B s_T p_T}\frac{1}{T}\frac{-x\frac{\partial}{\partial x}T^{(3)}(x)}{\phi(x)}$$

$$\Rightarrow \frac{1}{p_T}\left(-x\frac{\partial}{\partial x}T^{(3)}(x)\right)$$

$$\frac{d\Delta\sigma}{dy\,dp_T^2} = \sum_{abc} T^{(3)}_{a/A}(x_1)\otimes\phi_{b/B}(x_2)\otimes H_{abc}\otimes D_c(z)+\ldots$$

- **Effect of non-vanish parton k_T (when $k_T \sim p_T$):**



$$A_N \propto \frac{1}{S}\varepsilon^{p_A p_B s_T p_T}\frac{1}{M}f^{\perp}(x)\Rightarrow\frac{p_T}{M}$$

M = Non-perturbative scale, e.g., di-quark mass, …

What is the $T^{(3)}(x)$?

- Twist-3 correlation $T_F(x,x)$:

$$T_F(x,x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+y_1^-} \times \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma^+ \left[\int dy_2^- \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

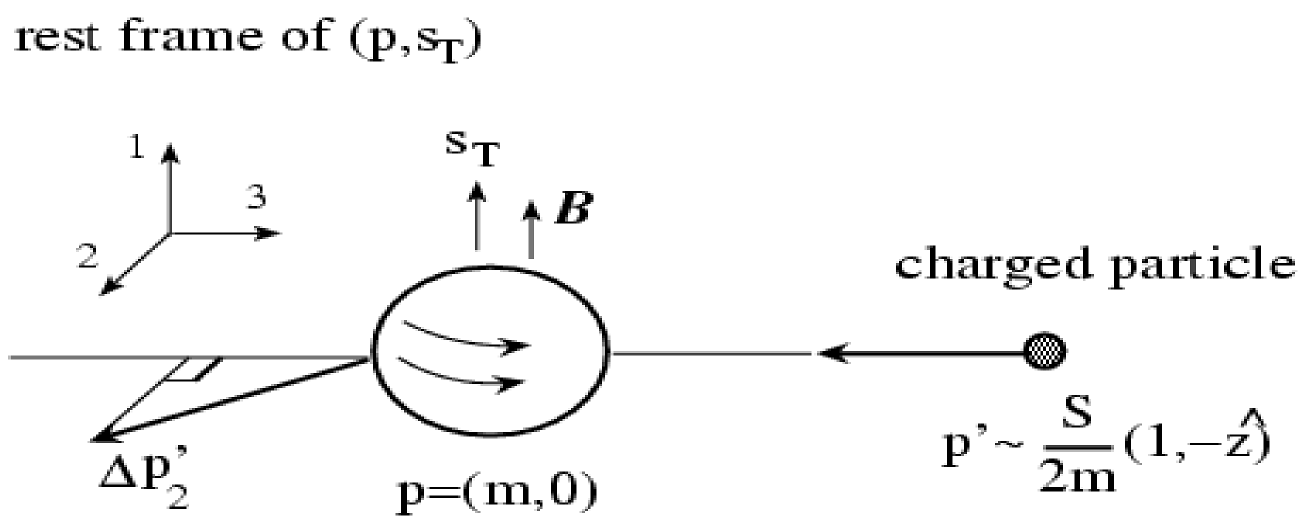
- Twist-2 quark distribution:

$$q(x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+y_1^-} \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma^+ \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

T_F **Represents a fundamental quantum correlation between quark and gluon inside a hadron**

What the $T^{(3)}(x)$ tries to tells us?

- **Consider a classical (Abelian) situation:**



– change of transverse momentum

$$\frac{d}{dt}p_2' = e(\vec{v}' \times \vec{B})_2 = -ev_3B_1 = ev_3F_{23}$$

– in the c.m. frame

$$(m, \vec{0}) \to \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \to n = (0, 1, 0_T)$$

$$\Longrightarrow \quad \frac{d}{dt}p_2' = e\, \epsilon^{s_T \sigma n \bar{n}}\, F_{\sigma}{}^{+}$$

– total change: $\Delta p_2' = e \int dy^- \epsilon^{s_T \sigma n \bar{n}}\, F_{\sigma}{}^{+}(y^-)$

Model for $T_F(x,x)$

- T_F (x,x) tells us something about quark's transverse motion in a transversely polarized hadron

- It is non-perturbative, has unknown **x**-dependence

$$T_F(x,x) \propto \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \left[\int dy_2^- \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Model for $T_F(x,x)$ of quark flavor a:

$$T_{F_a}(x,x) \equiv \kappa_a \, \lambda \, q_a(x)$$

with $\kappa_u = +1$ and $k_d = -1$ for proton

Fitting parameter $\lambda \sim O(\Lambda_{\rm QCD})$

⇒

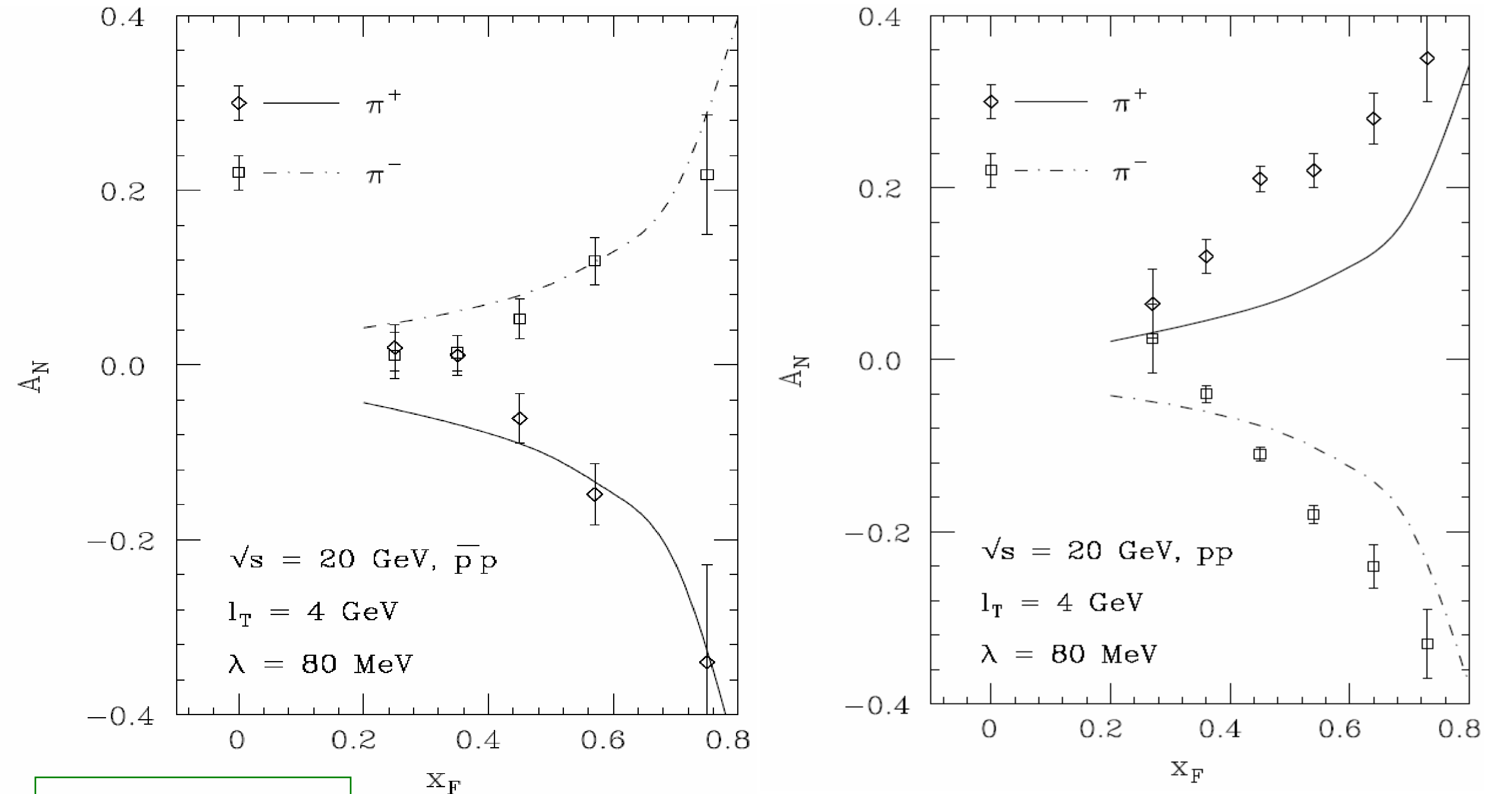
$$A_N \propto \left(\frac{\ell_\perp}{-\hat{u}} \right) \frac{n}{1-x}$$

if $T_F(x,x) \propto q(x) \propto (1-x)^n$

One parameter and one sign!

Numerical results – (I)

(compare apples with oranges)

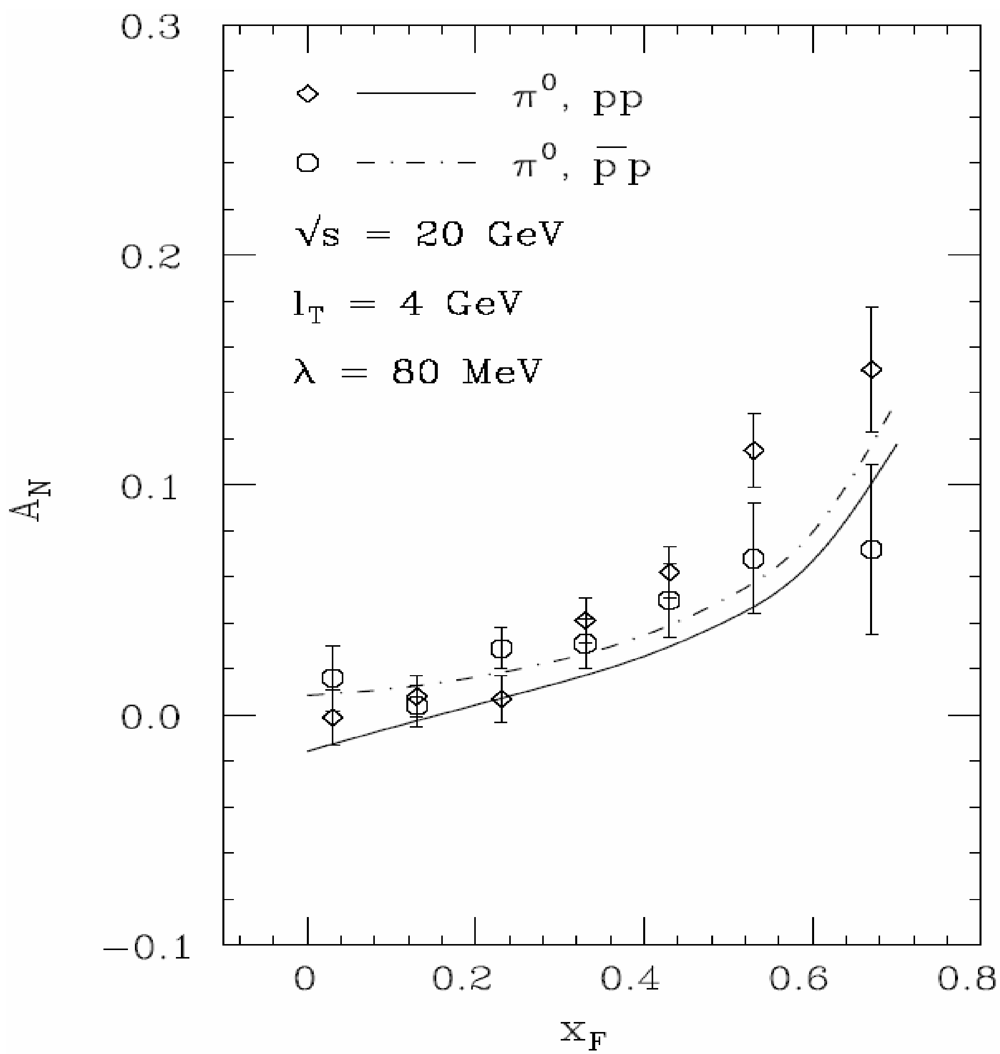


Qiu and Sterman
Phy. Rev. D, 1999

Fermilab data with ℓ_T up to 1.5 GeV

Numerical results – (II)

(compare apples with oranges)

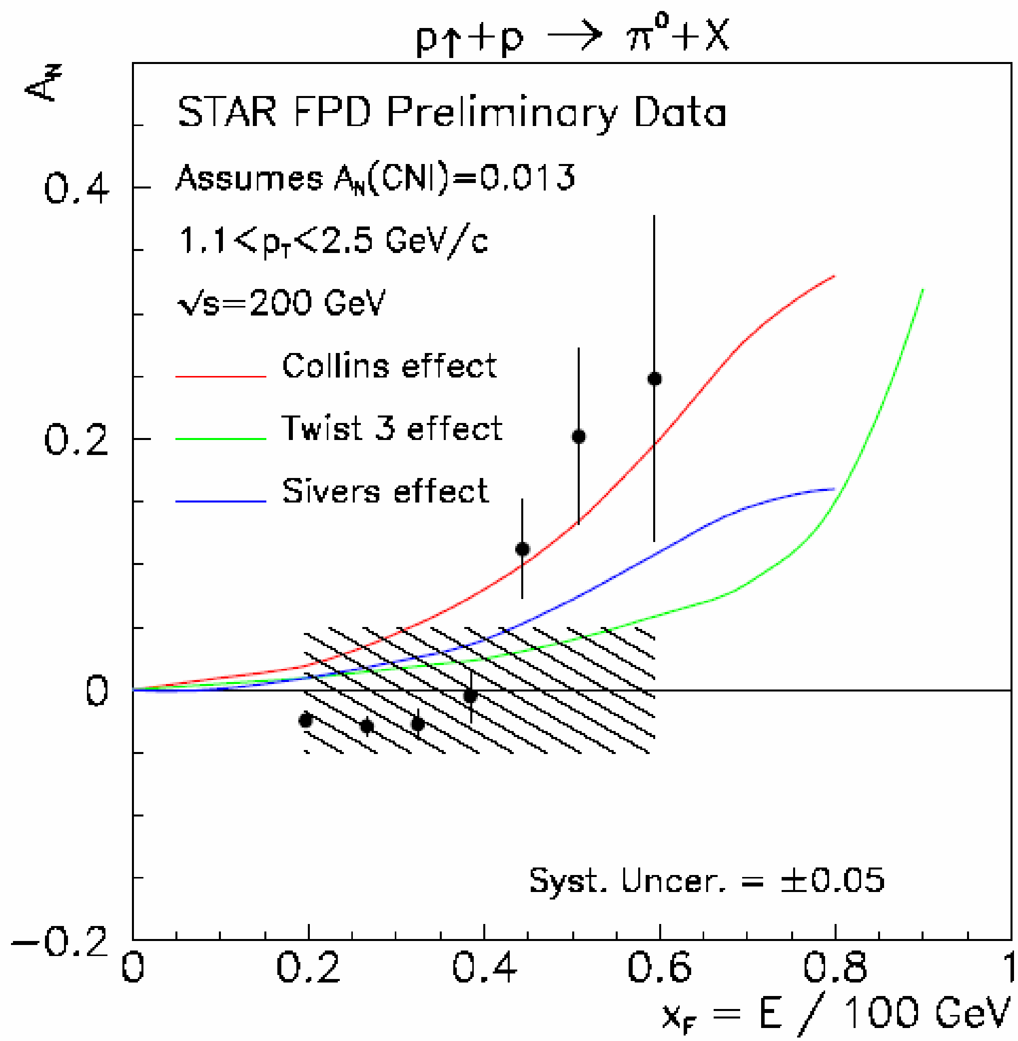


Qiu and Sterman
Phy. Rev. D, 1999

Numerical results – (IV)
(compare apples with oranges)

STAR

Rakness



Sivers' functions

❖ **Sivers' functions:** $f_{1T}^{\perp}(x)$

$$q(x,k_\perp,\vec{s}_\perp)-q(x,k_\perp,-\vec{s}_\perp)=f_{1T}^{\perp}(x)\ \varepsilon_{\mu\nu\rho\sigma}\frac{\gamma^\mu n^\nu k_\perp^\rho s_\perp^\sigma}{M}$$

Sivers' functions are connected to a polarized hadron beam

Sivers' functions are T- odd, but do not need another T- odd function to produce nonvanish asymmetries – the extracted proportional factor is T- odd, proportional to A_N

❖ **Polarized SIDIS cross section:**

$$\Delta\sigma(x,Q,p_\perp)\propto[q(x,k_\perp,\vec{s}_\perp)-q(x,k_\perp,-\vec{s}_\perp)]\otimes D(z)$$

$$\propto\left(\varepsilon_{\mu\nu\rho\sigma}P^\mu n^\nu k_\perp^\rho s_\perp^\sigma\right)\ f_{1T}^{\perp}(x)\otimes D(z)$$

Collins' functions

❖ **Collins' functions:** $H_1^{\perp}(x)$

$$D(z,k_\perp,\vec{s}_\perp)+D(x,k_\perp,-\vec{s}_\perp)=H_1^{\perp}(z)\ \sigma_{\mu\nu}\frac{k_\perp^\mu \overline{n}^\nu}{M}$$

Collins' functions are connected to the unpolarized Fragmentation contributions to a hadron

Collins' functions are T- odd, need another T- odd function to produce nonvanish asymmetries

❖ **Polarized SIDIS cross section:**

$$\Delta\sigma(x,Q,p_\perp)\propto\delta q(x,\vec{s}_\perp)\otimes[D(z,k_\perp,\vec{s}_\perp)+D(z,k_\perp,-\vec{s}_\perp)]$$

$$\propto\left(\sigma_{\mu\nu}k_\perp^\mu\overline{n}^\nu\right)\ \delta q(x,\vec{s}_\perp)\otimes H_1^{\perp}(z)$$

Summary and outlook

❑ **The machine – running schedule (STAR):**

pp Run	2002	2003	2004	2005 Expected	> 2006 LongTermGoals	
CM Energy	200 GeV				200 GeV	500 GeV
$\langle P_b \rangle$ and direction at STAR	0.15 T	0.3 T/L	0.4 L	0.45 L/T	0.7 L/T	0.7 L/T
L_{max} [10^{30} $s^{-1}cm^{-2}$]	2	6	6	16	80	200
L_{int} [pb^{-1}] at STAR	0.3	0.5 / 0.4	0.4	14 / 8	320	800

Joanna Kiryluk- ICHEP04

❑ **Measure polarized parton distributions, and**
- test the twist-2 pQCD dynamics in the spin sector

❑ **Study multiple parton correlation functions,**
and QCD dynamics beyond the PDF's
– the "probability distribution"

Backup transparencies

Asymmetries

- **Single longitudinal spin asymmetries:**

$$A_L = \frac{\sigma_{\rightarrow} - \sigma_{\leftarrow}}{\sigma_{\rightarrow} + \sigma_{\leftarrow}} \equiv \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}}$$

- **Double longitudinal spin asymmetries:**

$$A_{LL} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$

Reduce under parity to:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

- **Single transverse spin asymmetries:**

$$A_N = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}}$$

- **Double transverse spin asymmetries:**

$$A_{TT} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}}$$

Open questions and discussion

❖ **Dynamics for single transverse spin asymmetries:**

❑ **Connection between the twist-3 and finite k_T approach?**

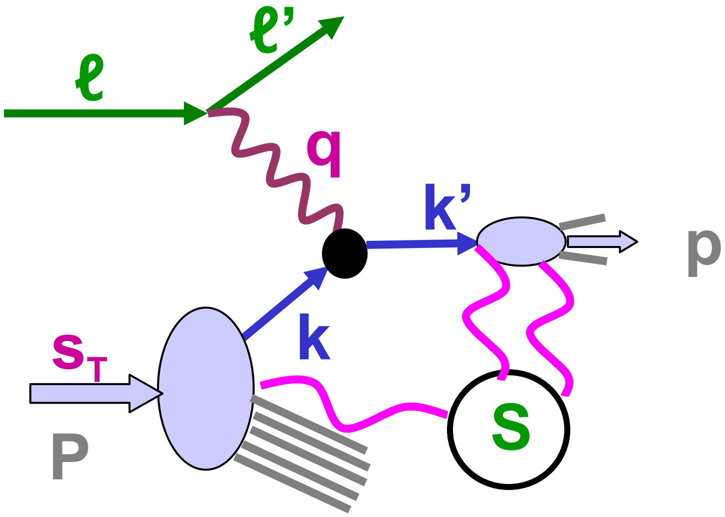
❑ **Transition between the k_T approach at low p_T and twist-3 mechanism at high p_T?**

	k_T approach	Twist-3
Sivers:	$f_{1T}^{\perp}(x)$	$T_F(x,x)$
Collins:	$H_1^{\perp}(z)$	$D^{(3)}(z,z)$

❖ **Asymmetries vs absolute cross sections:**

PQCD NLO formalism does not fit low energy π data!

K_T - Factorization



In q-P frame, if $k_T \sim p_T \ll Q$

- ❖ we can neglect k^2 in partonic part
- ❖ But, we cannot neglect k_T in partonic part

$$k^\mu = xP^\mu + k_\perp^\mu + \frac{k_T^2}{2k \cdot n} n^\mu$$

- ❑ One can define k_T-dependent and gauge invariant parton distributions $\neq$ factorization
- ❑ Soft interaction between the hadrons can spoil factorization
- ❑ Sudakov resummation done in b-space, and need nonperturbative information for coming back to momentum space

- If there is no K_T – factorization, how universal are Sivers and Collins functions?

  - KT – factorization in SIDIS and Drell-Yan might be a reasonable approximation due to a large scale Q and $P_T \sim K_T \ll Q$

  - It is very unlikely to have the K_T – factorization in hadronic collisions when $P_T \sim K_T$ due to a lack of perturbative scale

- What these nonperturbative functions try to tell us?

- K_T – dependent distributions do include information on power corrections in a twist expansion
  How much are not included in the K_T – distributions?

- … …

Initial success of RHIC pp runs

- ❑ π^0 **cross section measured over 8 order of magnitude [PRL 91, 241803 (2003)]**
- ❑ **Good agreement with NLO pQCD calculation at low p_T**
- ❑ Can be used in interpretation of spin-dependent results

9.6% normalization error not shown