Some relevant cases for studying high-p$_T$ physics at the RHIC pp collider

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Outline

- Introduction
- Double helicity asymmetries A_{LL}
  Quark and Gluon helicity distributions
- Double transverse spin asymmetries A_{TT}
  Positivity, Quark transversity distributions
- Spin transfers in Λ production
  Positivity, fragmentation functions
- Single spin asymmetries A_N
  Sivers function
- Search for new physics at RHIC

Introduction

- Spin occurs in all particle processes
- By ignoring this fundamental quantum number, we will miss a relevant part of the story

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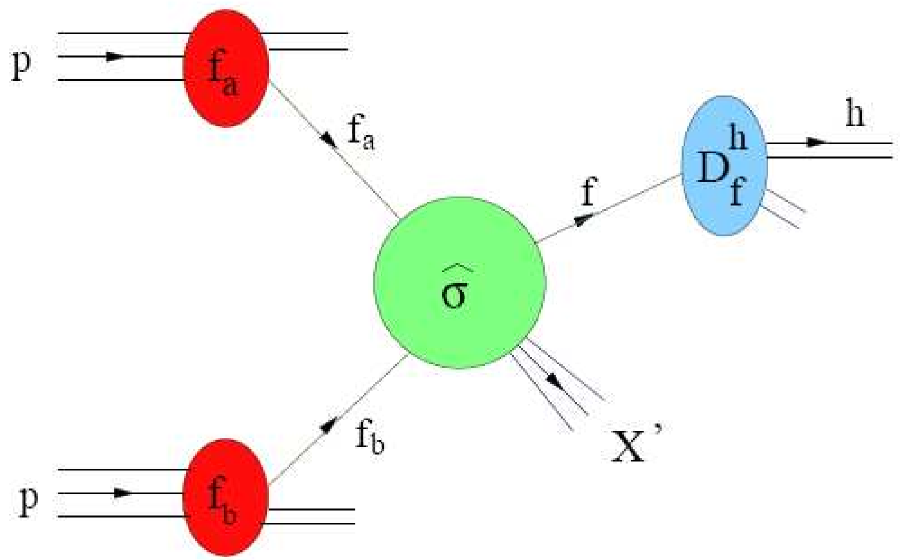
- Spin occurs in all particle processes
- By ignoring this fundamental quantum number, we will miss a relevant part of the story
- Spin observables allow a deeper understanding of the underlying dynamics
- This sometimes leads to uncover new important tools
- Remember also that spin sector of pQCD must be carefully checked
- High-p$_T$ region is most appropriate

A collision $p + p \to A + X$ in QCD partonic picture

$$\sigma \equiv \frac{Ed^3\sigma}{dp^3} = \sum_{abcd} \int_{\bar{x}_a}^{1} dx_a \int_{\bar{x}_b}^{1} dx_b f_a^{p_1}(x_a, Q^2) f_b^{p_2}(x_b, Q^2) D_c^A(z, Q^2) \frac{1}{\pi z} \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) \ ,$$



Double helicity asymmetry A_{LL} for $\overrightarrow{p}_1 + \overrightarrow{p}_2 \to A + X$

The corresponding double helicity asymmetry A_{LL} defined as

$$A_{LL} = \frac{\sigma(s_{p_1}, s_{p_2}) - \sigma(s_{p_1}, -s_{p_2})}{\sigma(s_{p_1}, s_{p_2}) + \sigma(s_{p_1}, -s_{p_2})} = \frac{\Delta\sigma}{\sigma}$$

where $\Delta\sigma$ reads

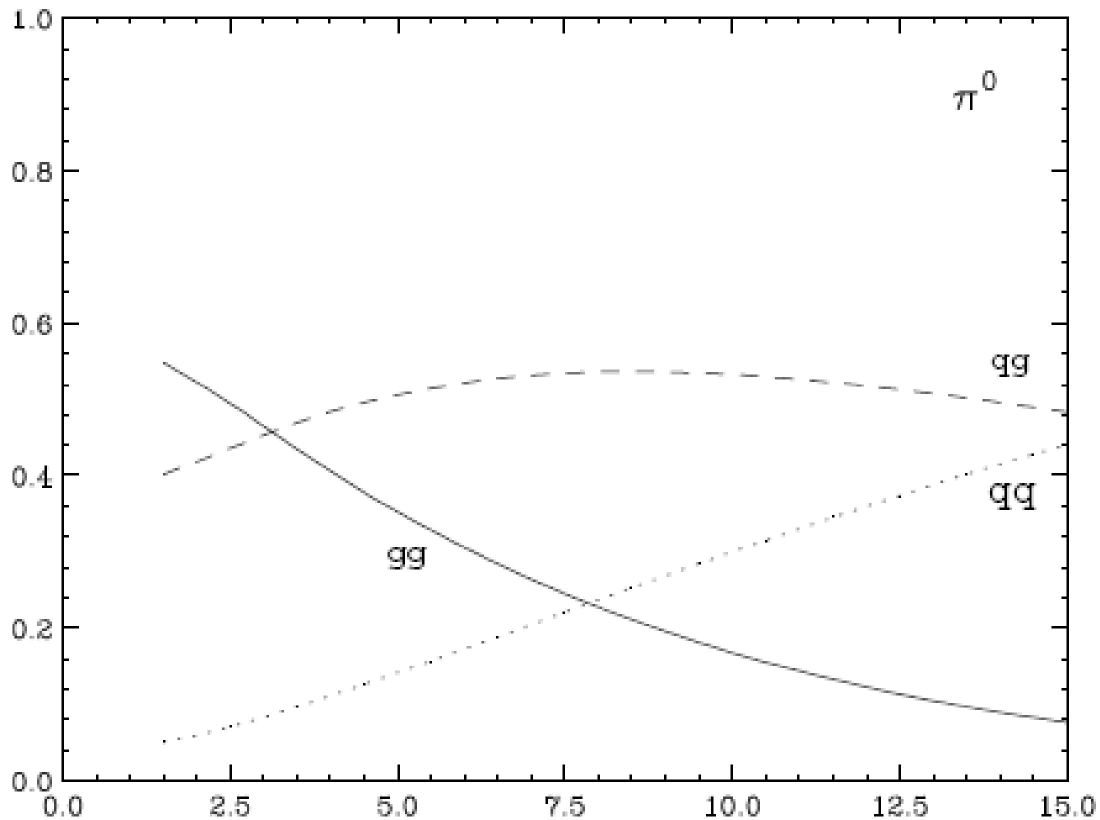
$$\Delta\sigma \equiv \frac{E\Delta d^3\sigma}{dp^3} = \sum_{abcd} \int_{\bar{x}_a}^1 dx_a \int_{\bar{x}_b}^1 dx_b \Delta f_a^{p_1}(x_a, Q^2) \Delta f_b^{p_2}(x_b, Q^2) D_c^A(z, Q^2) \frac{1}{\pi z} \frac{\Delta d\hat{\sigma}}{d\hat{t}}(ab \to cd) \, ,$$

with

$$\bar{x}_a = \frac{x_T e^y}{2 - x_T e^{-y}} \, , \; \bar{x}_b = \frac{x_a x_T e^{-y}}{2x_a - x_T e^y} \, , \; z = \frac{x_T}{2x_b} e^{-y} + \frac{x_T}{2x_a} e^y \, ,$$

where $x_T = 2p_T/\sqrt{s}$, $\sqrt{s}$ is the center of mass energy of the pp collision, and $\hat{t} = -x_a p_T \sqrt{s} e^{-y}/z$ is the Mandelstam variable at the parton level.

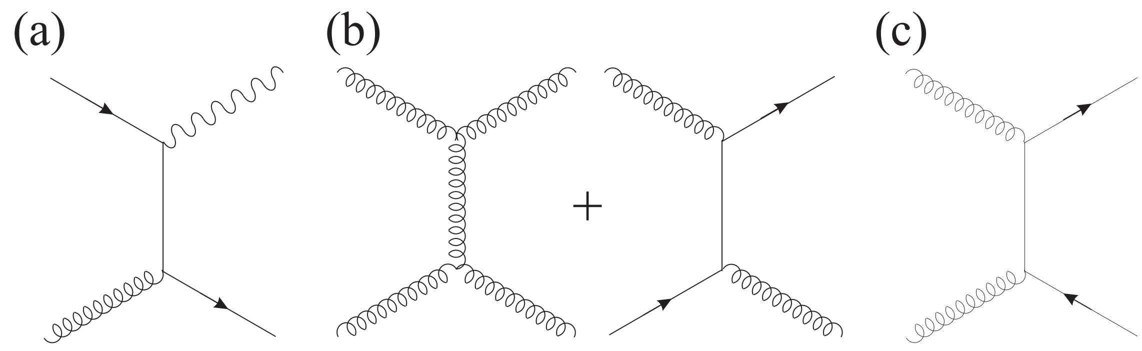
Decomposition of the partonic cross sections



Double helicity asymmetries A_{LL}

Lowest-order diagrams with initial gluons

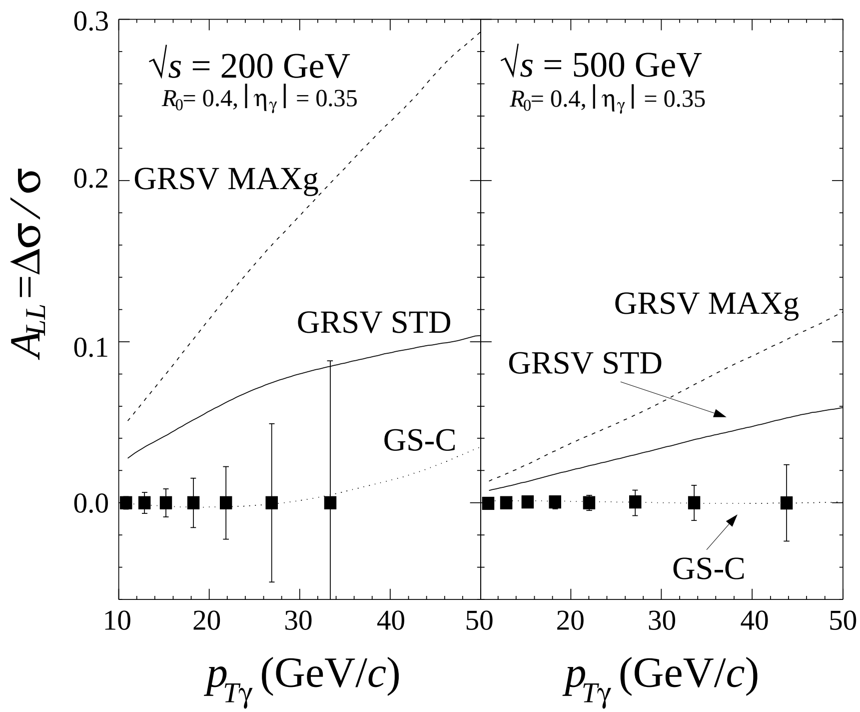
How to check in pp collisions that Δg is small as a first "‘indication"’ from DIS?



- High-p$_T$ photon production (a)
- Jets production (b)
- Heavy-flavor production (c)

Prompt photon production at RHIC

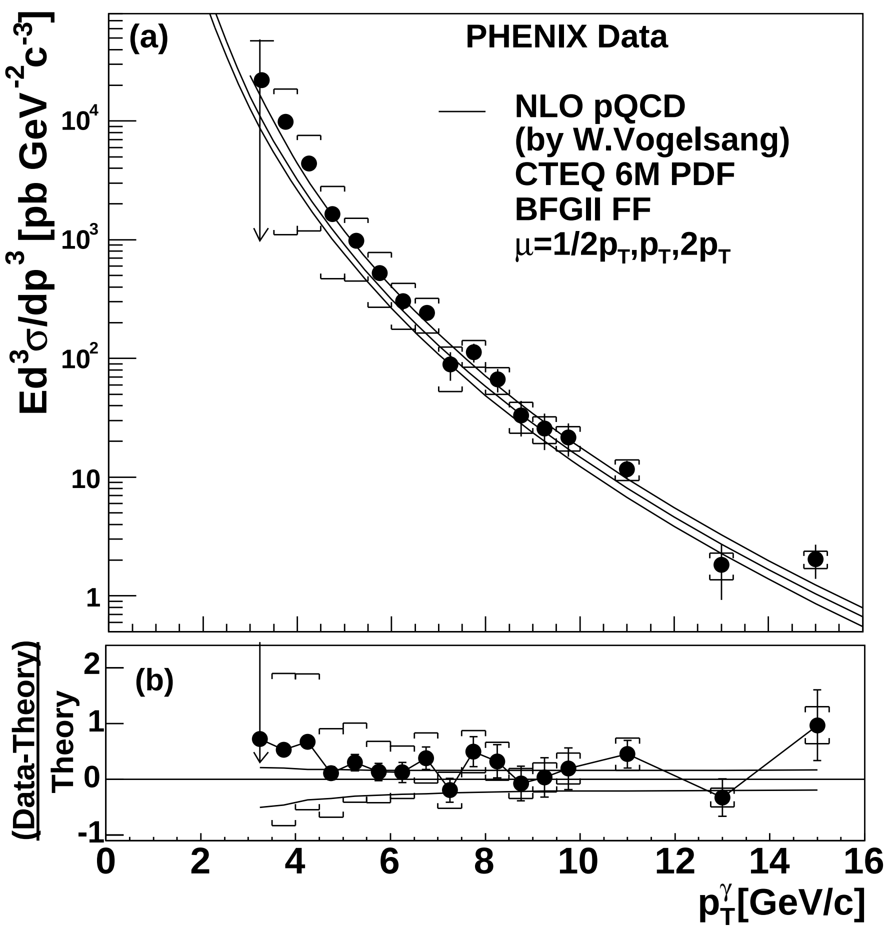
$$A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \left[\frac{\sum_i e_i^2 \left[\Delta q_i(x_2) + \Delta\bar{q}_i(x_2)\right]}{\sum_i e_i^2 \left[q_i(x_2) + \bar{q}_i(x_2)\right]} \right] \otimes \hat{a}_{LL}(gq \to \gamma q) + (1 \leftrightarrow 2)$$



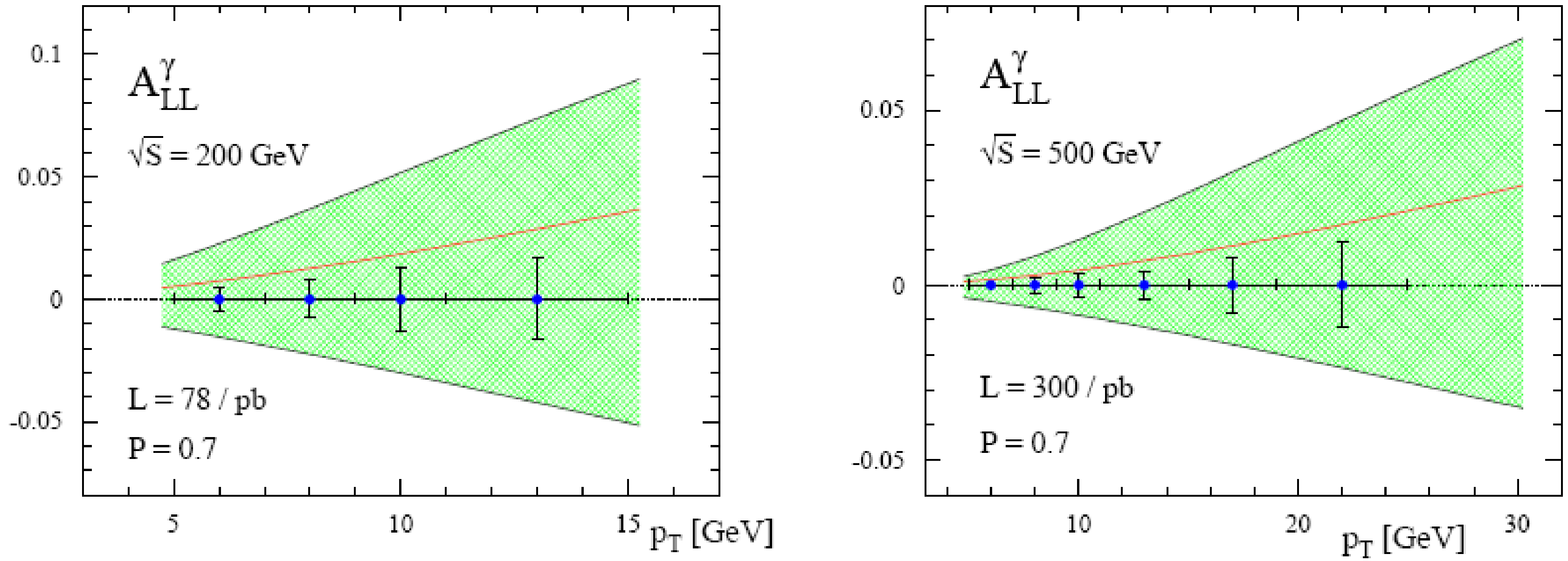
To avoid convolution should consider $pp \to \gamma + jet + X$

It is also on the shopping list

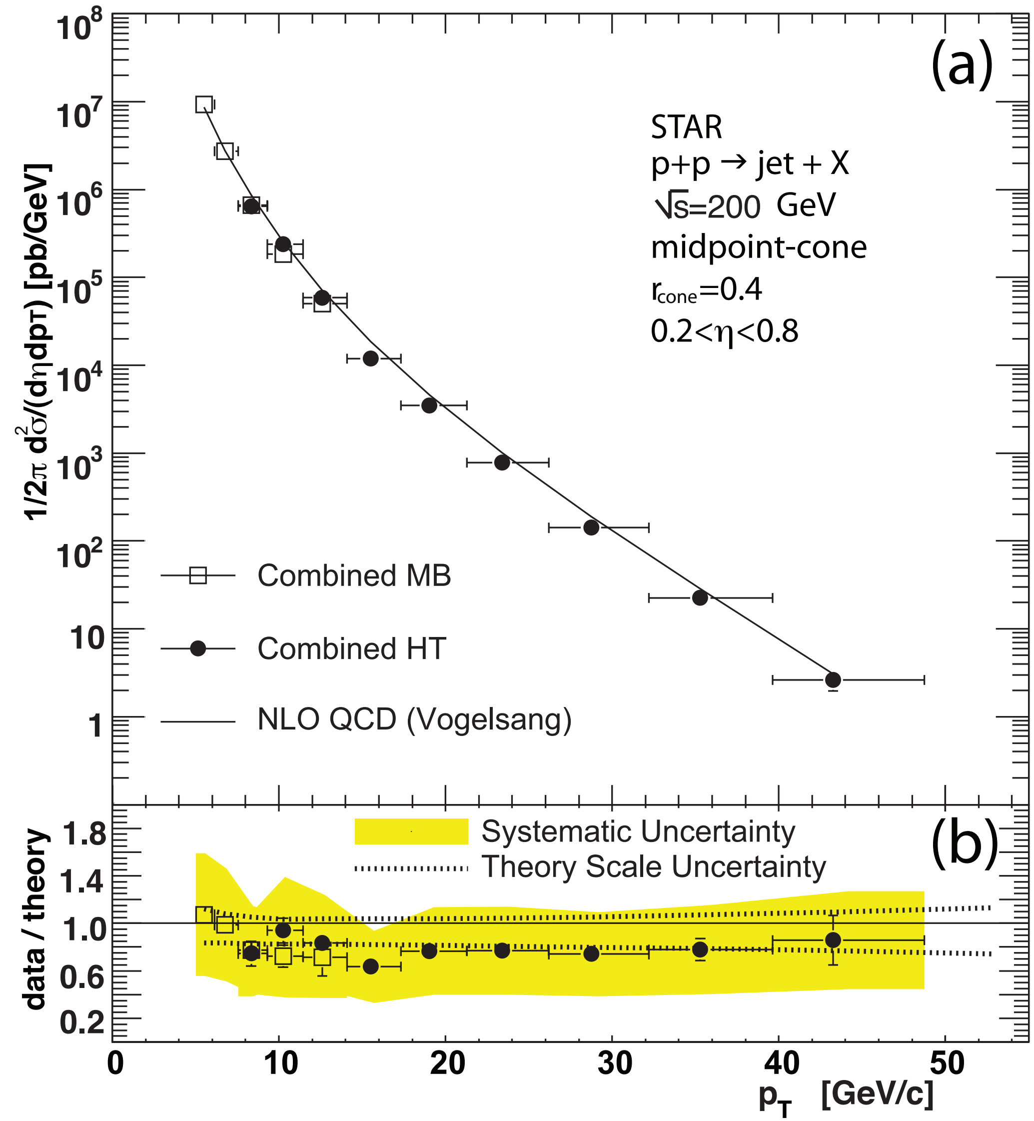
PHENIX data on γ production at RHIC



Expected high-p_T A_{LL} data on γ production at RHIC

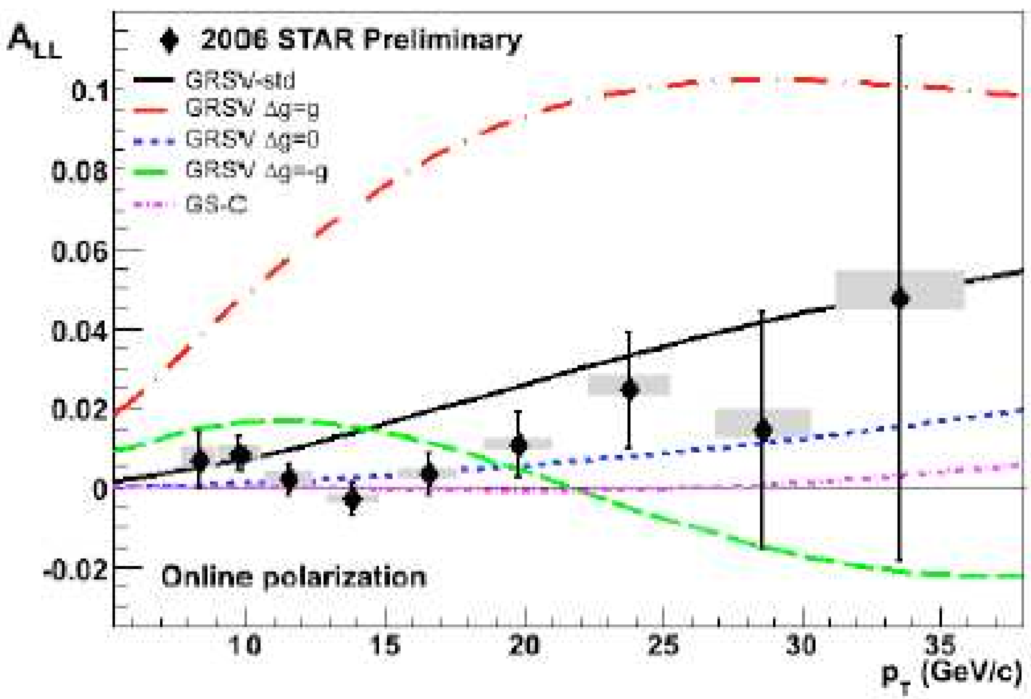


STAR data on jet production at RHIC

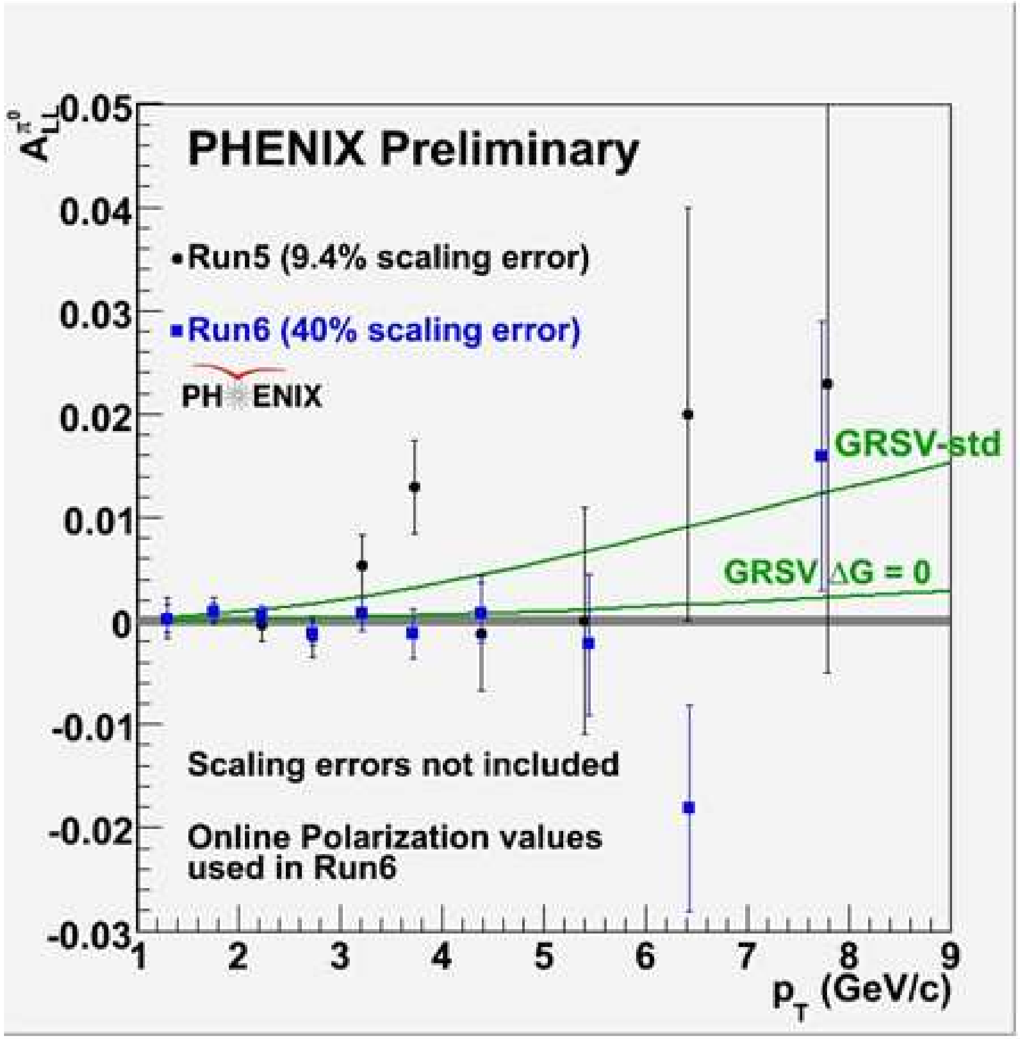


STAR data on jet production at RHIC

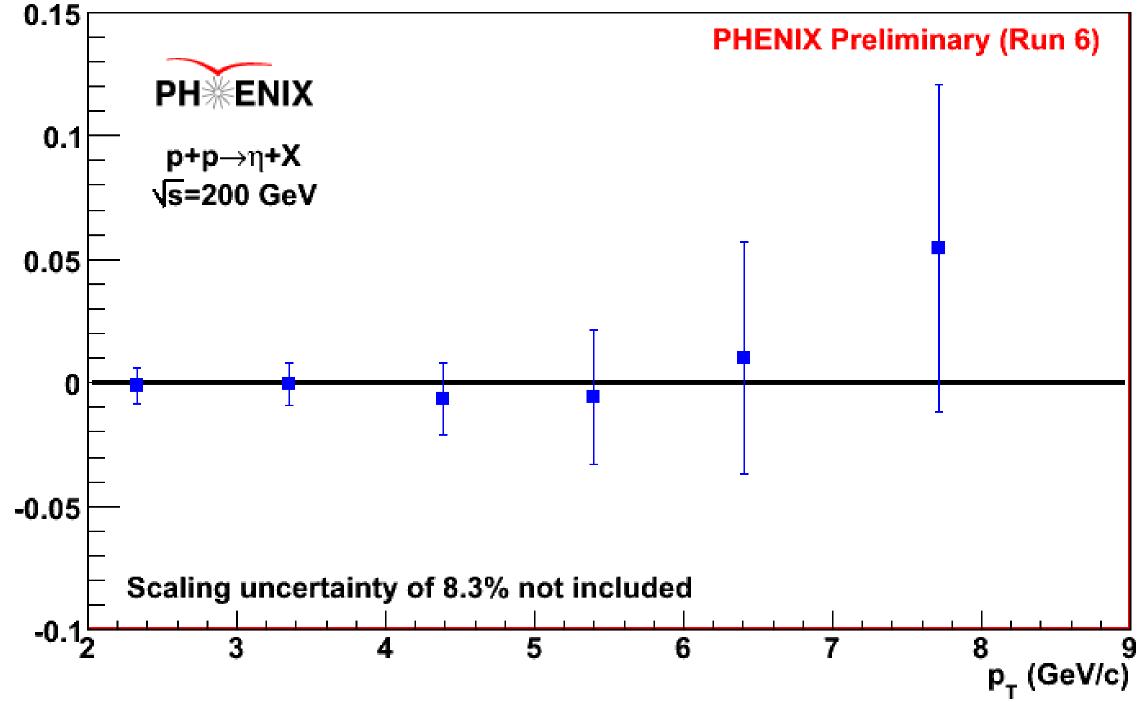
Sensitivity to Δg only in the medium p$_T$ region, dominated by $gq \to gq$. Low p$_T$ region dominated by gg collisions. High p$_T$ region dominated by qq collisions.
Extreme cases $\Delta g(x) = \pm g(x)$ are already excluded.
A_{LL} is expected to be small $\leq 10\%$ even at high-p$_T$.



PHENIX data on π^0 and η production at RHIC

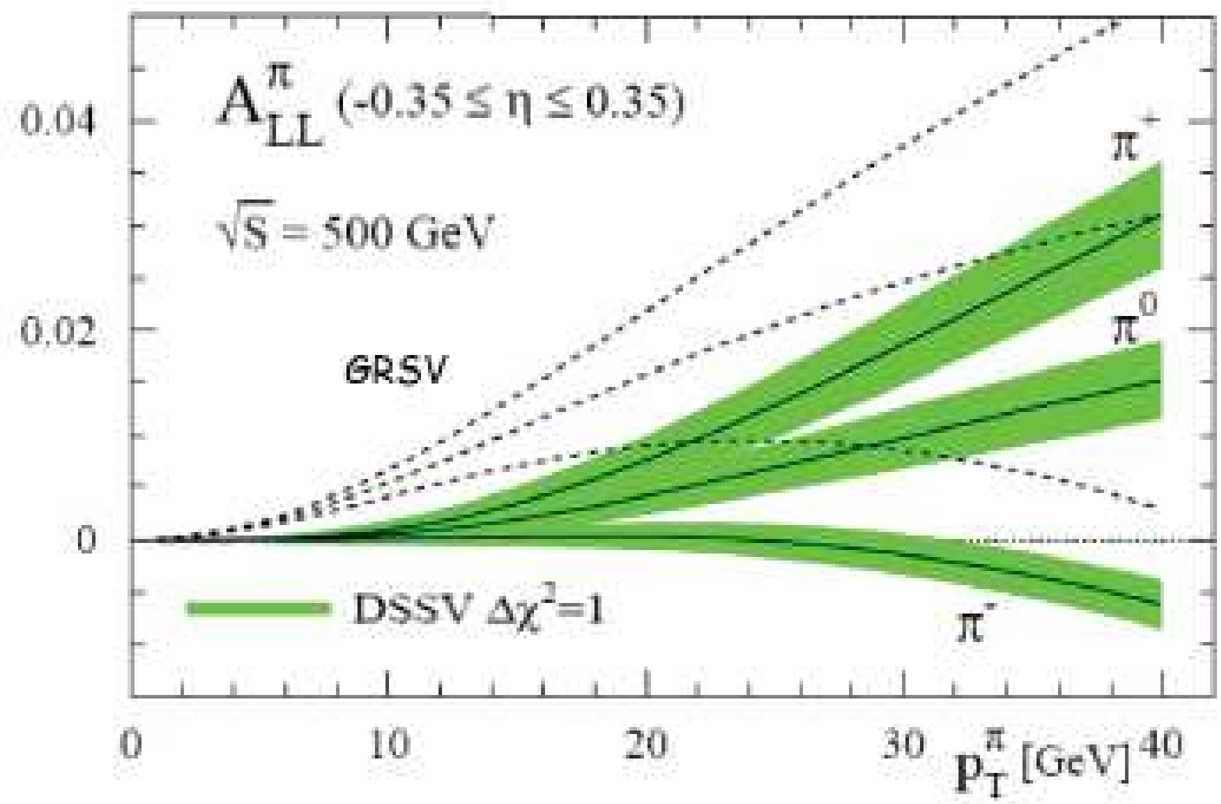


PHENIX data on π^0 and η production at RHIC



Predictions for larger p$_T$

Expect $A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-)$ if $\Delta G > 0$



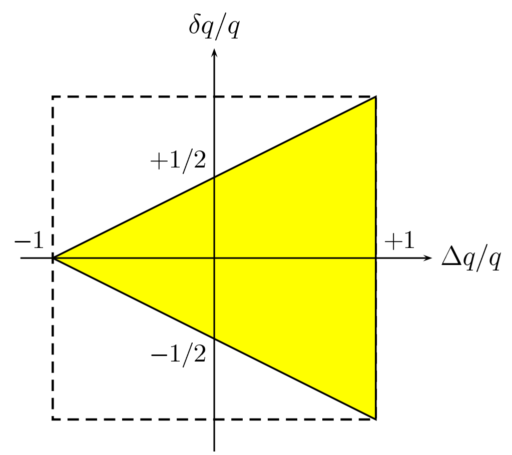
Quark Transversity Distribution $\delta q(x,Q^2)$

It was first mentioned by Ralston and Soper in 1979, in $pp \to \mu^+\mu^- X$ with transversely polarized protons, but forgotten until 1990, where it was realized that it completes the description of the quark distribution in a nucleon as a density matrix

$$\mathcal{Q}(x,Q^2) = q(x,Q^2) I \otimes I + \Delta q(x,Q^2)\sigma_3 \otimes \sigma_3 + \delta q(x,Q^2)(\sigma_+ \otimes \sigma_- + \sigma_- \otimes \sigma_+)$$

This new distribution function $\delta q(x,Q^2)$ is chiral odd, leading twist and decouples from DIS. Only recently, it has been extracted indirectly, for the first time.
There is a positivity bound (J.S., PRL 74,1292,1995) survives up to NLO corrections

$$q(x,Q^2) + \Delta q(x,Q^2) \geq 2|\delta q(x,Q^2)|$$



First determination of the quark Transversity Distribution $\delta q(x, Q^2)$

Current status on transversity

Anselmino et al, arXiv:0812.4366

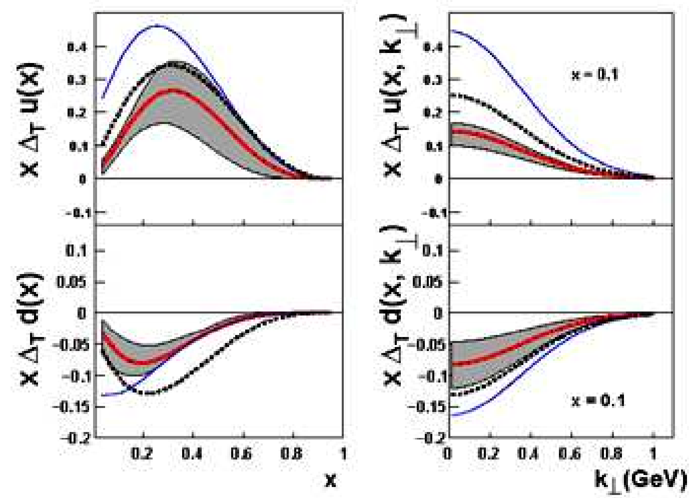
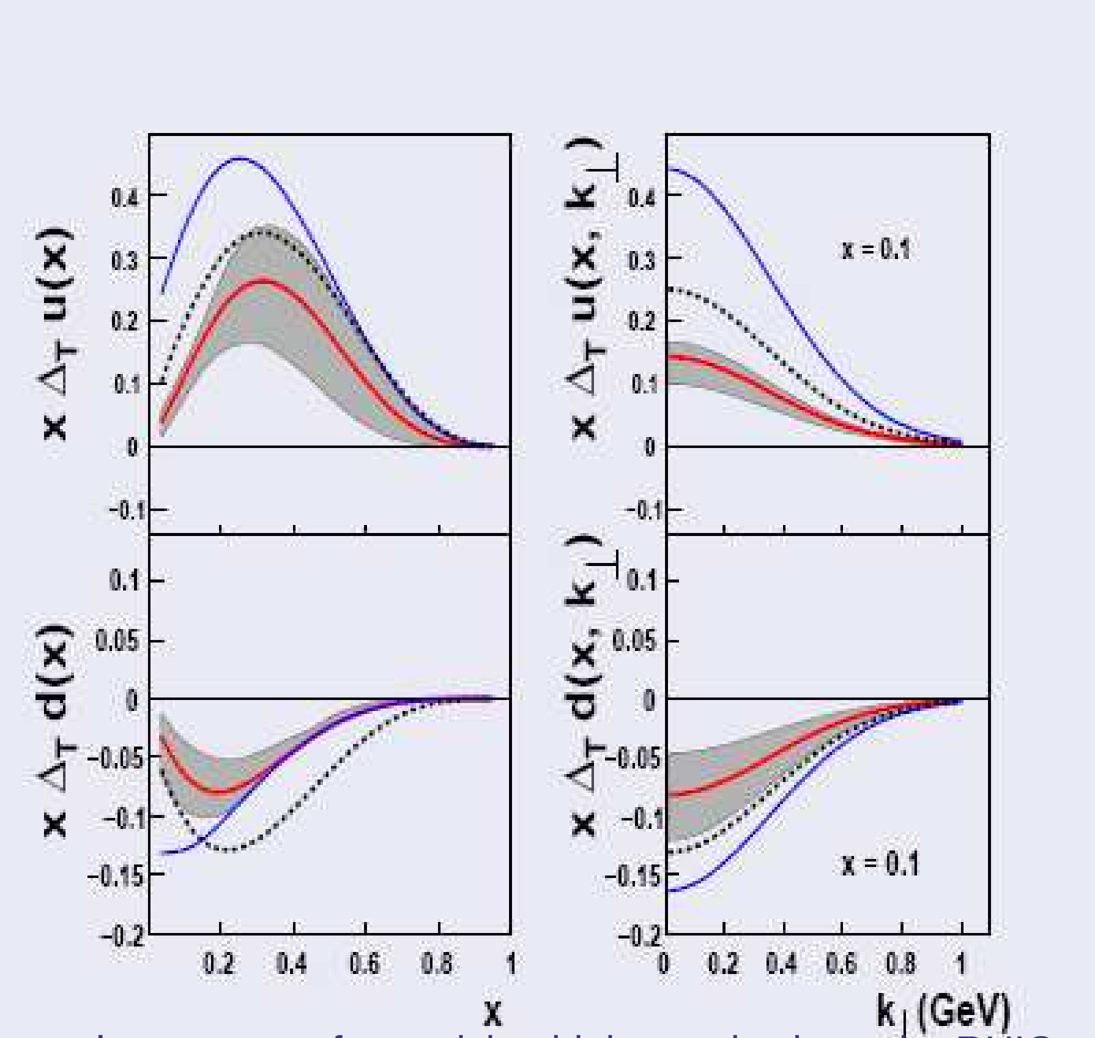


Figure 7. Comparison of the extracted transversity (solid line) with the helicity distribution (dashed line) at $Q^2 = 2.4$ GeV^2. The Soffer bound [46] (blue solid line) is also shown.

- Global analysis combining Collins effect measurements in SIDIS from HERMES and COMPASS with measurements of the Collins fragmentation function by BELLE

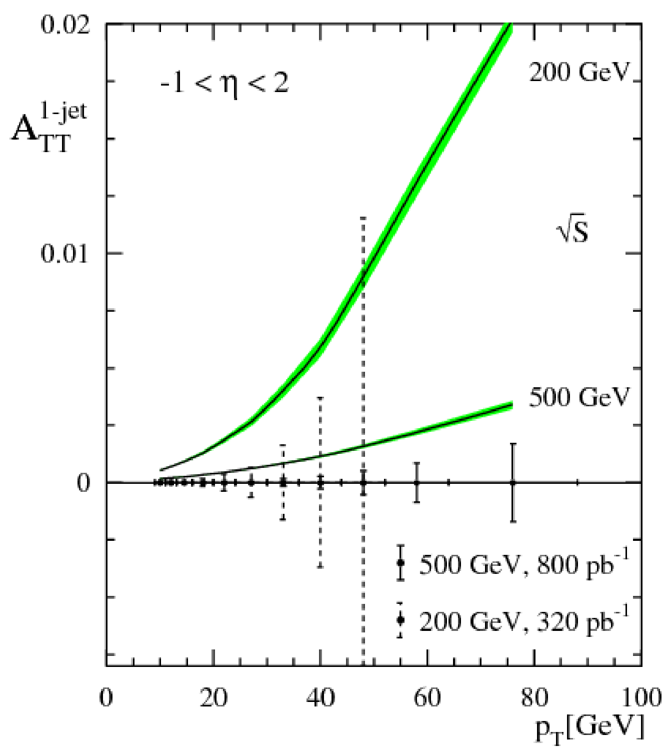
First determination of the quark Transversity Distribution $\delta q(x, Q^2)$

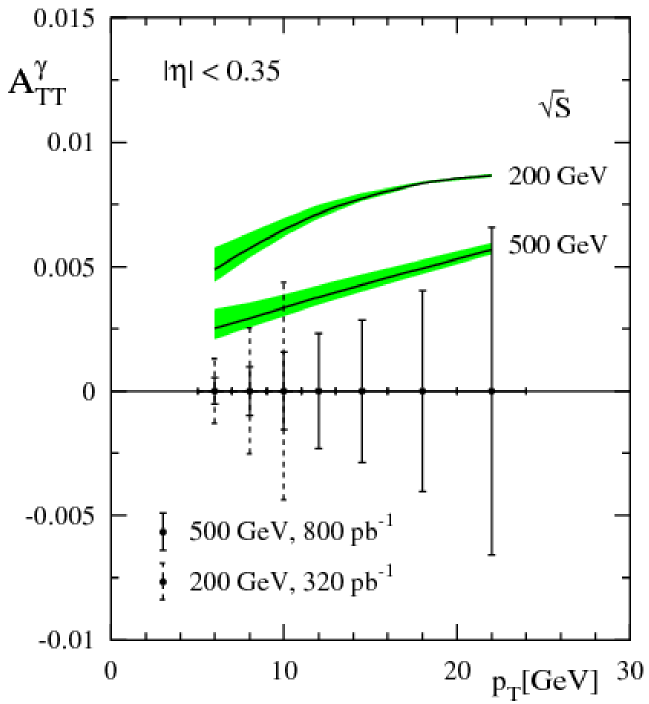
Helicity > Transversity for u and d - Positivity saturated for d at high x ?



Upper bounds on A_{TT} in jet and γ production

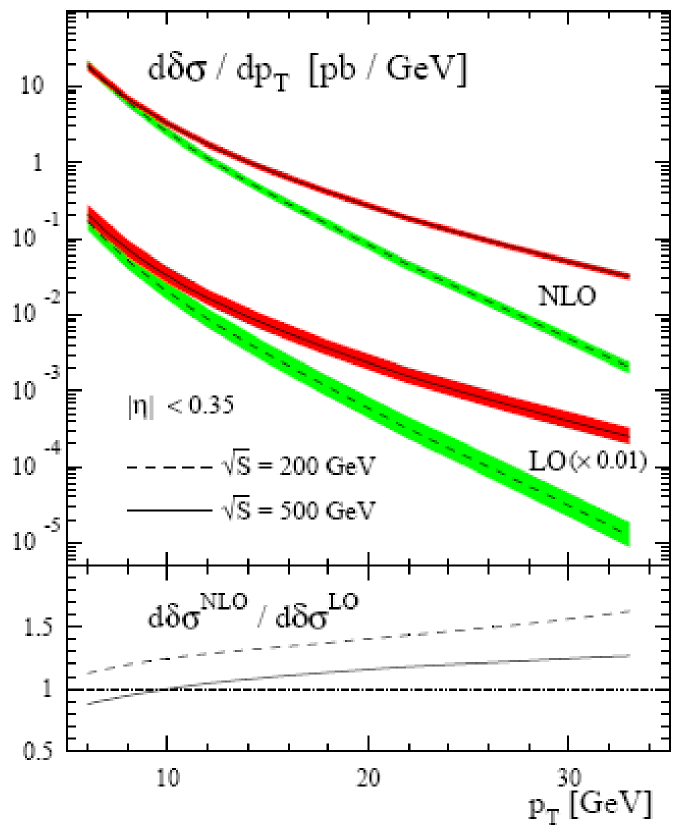
Since NO GLUON TRANSVERSITY, sensitivity to δq only in the high p_T region, dominated by $qq \to qq$. Several reasons to expect $|A_{TT}| << |A_{LL}|$ and it is important to verify the theoretical expectation

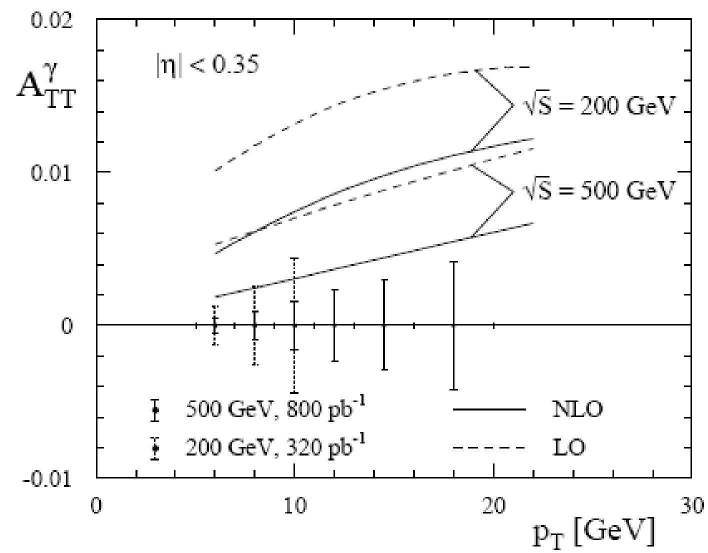




J. S., M. Stratmann, W. Vogelsang, PRD 65, 114024, (2002)

NLO predictions for γ production at RHIC





A. Mukherjee, M. Stratmann, W. Vogelsang, PRD 67, 114006, (2003)

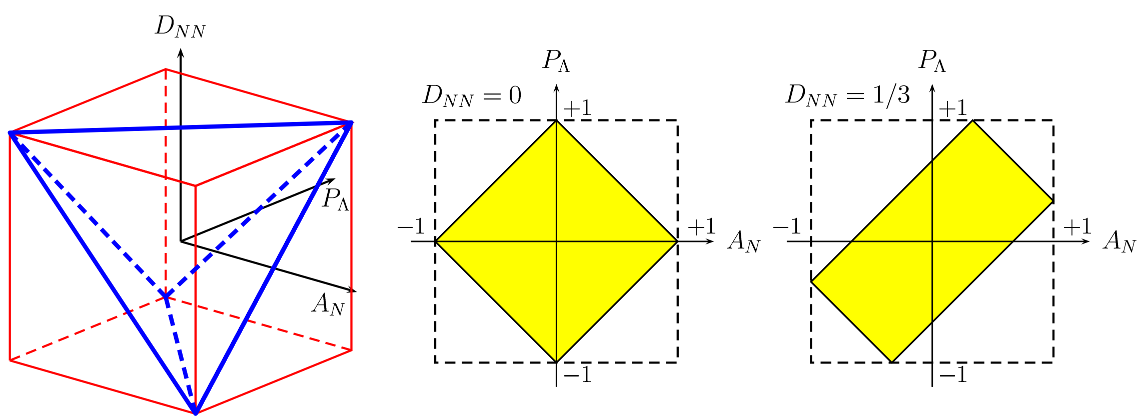
Cross section increases, so A_{TT} decreases

Spin transfer observables

* Consider a parity conserving inclusive reaction of the type,
$a(spin1/2) + b(unpol.) \rightarrow c(spin1/2) + X$.
* One can define eight observables, which must satisfy

$$(1 \pm D_{NN})^2 \geq (P_{cN} \pm A_{aN})^2 + (D_{LL} \pm D_{SS})^2 + (D_{LS} \mp D_{SL})^2$$

NOTE: The eight TMD quark distributions obey the same constraints since they are related to $nucleon(p, S) \rightarrow quark(k, S') + X$
If we concentrate for the moment on the case where the particle spins are normal to the scattering, for example for $p^\uparrow p \rightarrow \Lambda^\uparrow X$, one has $1 \pm D_{NN} \geq |P_\Lambda \pm A_N|$



Spin transfer for $\overrightarrow{p} + p \to \overrightarrow{\Lambda} + X$

$$D_{PP} \equiv \frac{\sigma(s_p, s_\Lambda) - \sigma(s_p, -s_\Lambda)}{\sigma(s_p, s_\Lambda) + \sigma(s_p, -s_\Lambda)} \ , \qquad (P = L, S, N) \ ,$$

An analogous positivity bound for the fragmentation functions of a quark q into a hadron h holds, namely

$$2|\Delta_T D_q^h(x)| \leq D_q^h(x) + \Delta_L D_q^h(x) \ .$$

It allows to put a bound on the transverse spin transfer D_{NN}^{Λ}

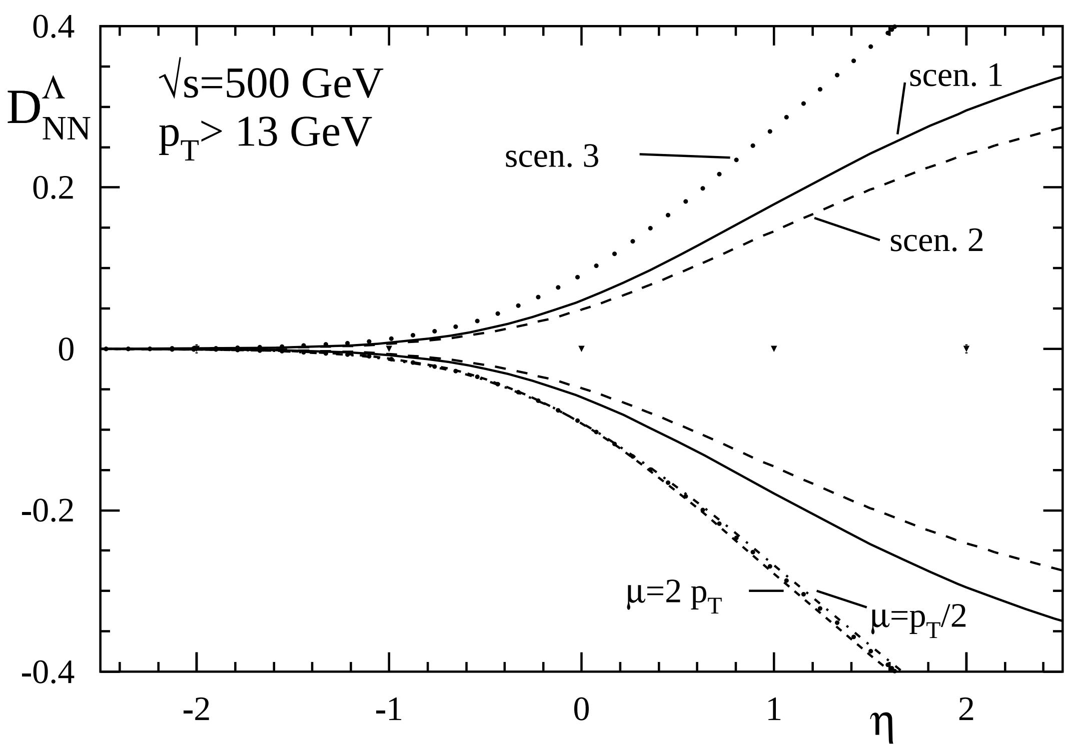
Consider 3 scenarios for the fragmentation:

1- only strange quarks contribute

2- a sizeable contribution from u and d quarks

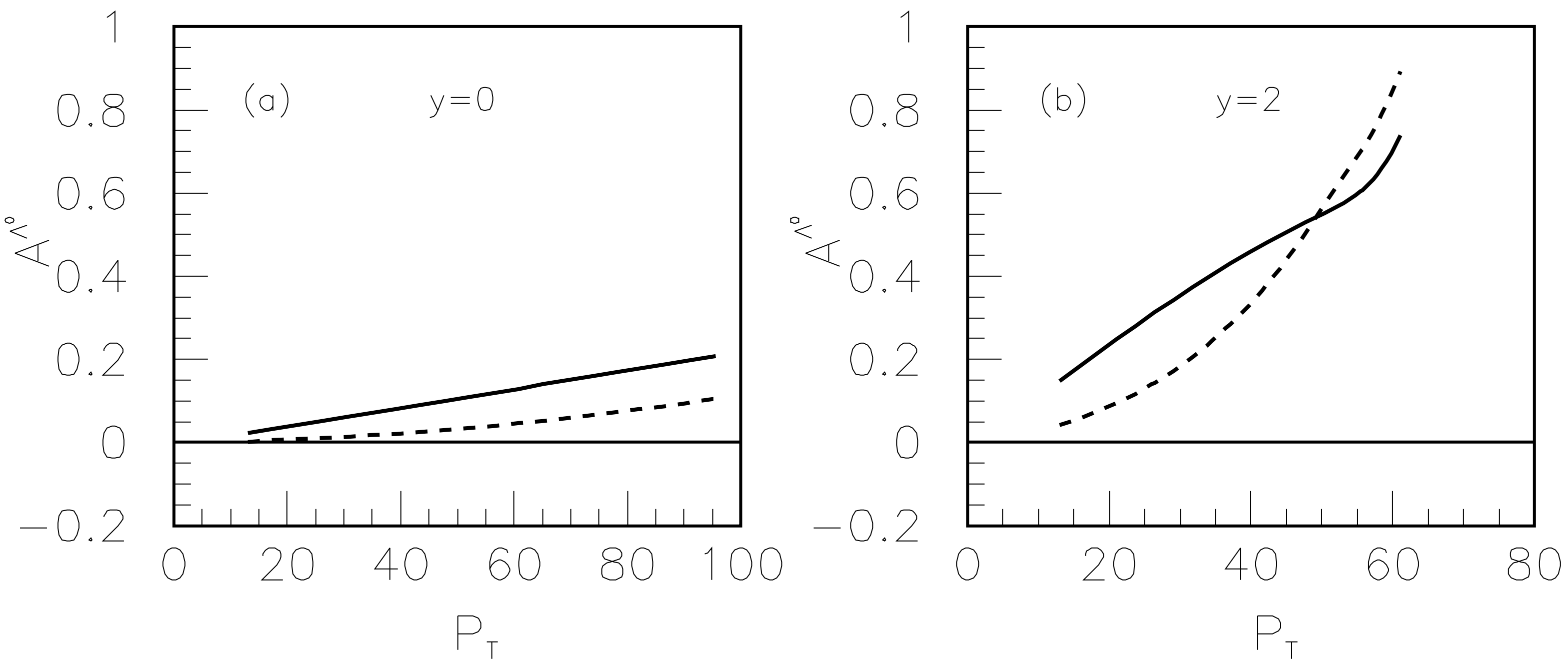
3- all quarks contribute equally

Upper bounds for the transverse spin transfer of Λ



D. de Florian, J.S., M. Stratmann, W. Vogelsang, Phys. Lett. B439, 176 (1998)

Longitudinal spin transfer D_{LL} for $\overrightarrow{p} + p \rightarrow \overrightarrow{\Lambda} + X$



Dashed curves: SU(6) quark-diquark spectator model

Solid curves: pQCD counting rules

Fragmentation functions via Gribov-Lipatov relation

Larger effect for higher y

B.Q. Ma, I. Schmidt, J.S. and J.J. Yang, Nucl. Phys. A703, 346 (2002)

Single spin asymmetry A_N

What is a single spin asymmetry (SSA)?

Consider the pp collision with one proton of momentum $\overrightarrow{p}$, carrying a transverse spin $\overrightarrow{s_T}$ and producing an outgoing hadron with transverse momentum $\overrightarrow{k_T}$. The SSA defined as

$$A_N = \frac{d\sigma(\overrightarrow{s_T}) - d\sigma(-\overrightarrow{s_T})}{d\sigma(\overrightarrow{s_T}) + d\sigma(-\overrightarrow{s_T})}$$

is zero, unless the cross section contains a term $\overrightarrow{s_T} \cdot (\overrightarrow{p} \times \overrightarrow{k_T})$

It can be shown that this requires the existence of an helicity flip and final state interactions, which generate a phase difference between the flip and the non-flip amplitudes, to avoid violation of time reversal invariance.

In the NAIVE parton model one expects very small SSA, because of the double suppression $\alpha_s m_q/Q$.

Single spin asymmetry A_N in QCD

Two QCD mechanisms

- Introduce Transverse Momentum Dependence (TMD)
  - TMD parton distributions $\Rightarrow$ Sivers effect 1990
  - TMD fragmentation distributions $\Rightarrow$ Collins effect 1993
- Consider higher twist operators
  - In collinear approach introduce quark-gluon correlators (Efremov-Teryaev 1982, Qiu-Sterman 1991, Vogelsang, Yuan, etc..)

The gauge-invariance properties of the TMD PDF have been first clarified (S. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett.B 530,99 (2002)) for DIS and Drell-Yan processes.
In general both Sivers and Collins effects contribute to a specific reaction, although there are some cases in which only one of them contributes. For example in SIDIS, the Collins effect is the only mechanism that can lead to asymmetries A_{UT} and A_{UL}. On the other hand, it does not appear in some electroweak interaction processes, where there is only the Sivers effect. For direct photon production in pp collisions, which is dominated by $qg \longrightarrow q\gamma$, the SSA is sensitive to both the quark and the gluon Sivers functions, according to x_F of the photon. (I. Schmidt, J. S. and J. J. Yang, Phys. Lett.B 612, 258 (2005)).

What positivity can bring into this game?

New general positivity bounds were derived (J.S.,PRL 91,092005,2003), among the spin observables in a single particle inclusive reaction, where the two initial particles carry a spin-1/2. In particular for $y = 0$ one has

$$1 - A_{TT}(y = 0, p_T) \geq 2|A_N(y = 0, p_T)|$$

for any value of $\sqrt{s}$ and p_T. From the previous results $A_{TT} \sim 0$ for $pp \to \gamma X$ and $pp \to jetX$, we get a strong bound e.g. $|A_N| \leq 1/2$.

(See also a recent review on positivity: X. Artru, M. Elchikh, J.M. Richard, J.S., O. Teryaev, Phys. Reports, 470, 1 (2009))

Single spin asymmetry A_N in $W^\pm$ production

Consider the collision $p^\uparrow p$ with a proton p of momentum $\overrightarrow{p}$, carrying a transverse spin $\overrightarrow{s}_p$ producing a $W^\pm$ of transverse momentum $\mathbf{p_T}$.
The SSA in first approximation factorizes and then it reads

$$A_N^{W^\pm}(\sqrt{s}, y, \mathbf{p}_T) = H(p_T) A^\pm(\sqrt{s}, y) \mathbf{S}_p \cdot \hat{\mathbf{p}} \times \mathbf{p}_T, \tag{1}$$

where $\mathbf{p}_T$ is the transverse momentum of the $W^\pm$ produced at the c.m. energy $\sqrt{s}$ and $H(p_T)$ is a function of p_T, the magnitude of $\mathbf{p}_T$. For W^+ we have

$$A^+(\sqrt{s}, y) = \frac{\Delta^N u(x_a)\bar{d}(x_b) + \Delta^N \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}, \tag{2}$$

where y denotes the W^+ rapidity, which is related to x_a and x_b. Actually we have $x_a = \sqrt{\tau}e^y$ and $x_b = \sqrt{\tau}e^{-y}$, with $\tau = M_W^2/s$, and we note that a similar expression for $A_N^{W^-}$, the SSA corresponding to W^- production, is obtained by permuting u and d.
This allows to perform a flavor separation of the Sivers functions.

Single spin asymmetry A_N in $W^{\pm}$ production

For the y-dependent part of the SSA, one gets for $y = 0$

$$A^{+} = \frac{1}{2}\left(\frac{\Delta^N u}{u} + \frac{\Delta^N \bar{d}}{\bar{d}}\right) \quad \text{and} \quad A^{-} = \frac{1}{2}\left(\frac{\Delta^N d}{d} + \frac{\Delta^N \bar{u}}{\bar{u}}\right) \tag{3}$$

Get positivity bounds on Sivers functions for $y = 0$, since one has $A_{TT}^{W} = 0$, following from the weak couplings and therefore $|A_N^{\pm}| \leq 1/2$

So one has

$$\left|\frac{\Delta^N u(x)}{u(x)} + \frac{\Delta^N \bar{d}(x)}{\bar{d}(x)}\right| \leq 1 \quad \text{and} \quad \left|\frac{\Delta^N d(x)}{d(x)} + \frac{\Delta^N \bar{u}(x)}{\bar{u}(x)}\right| \leq 1$$

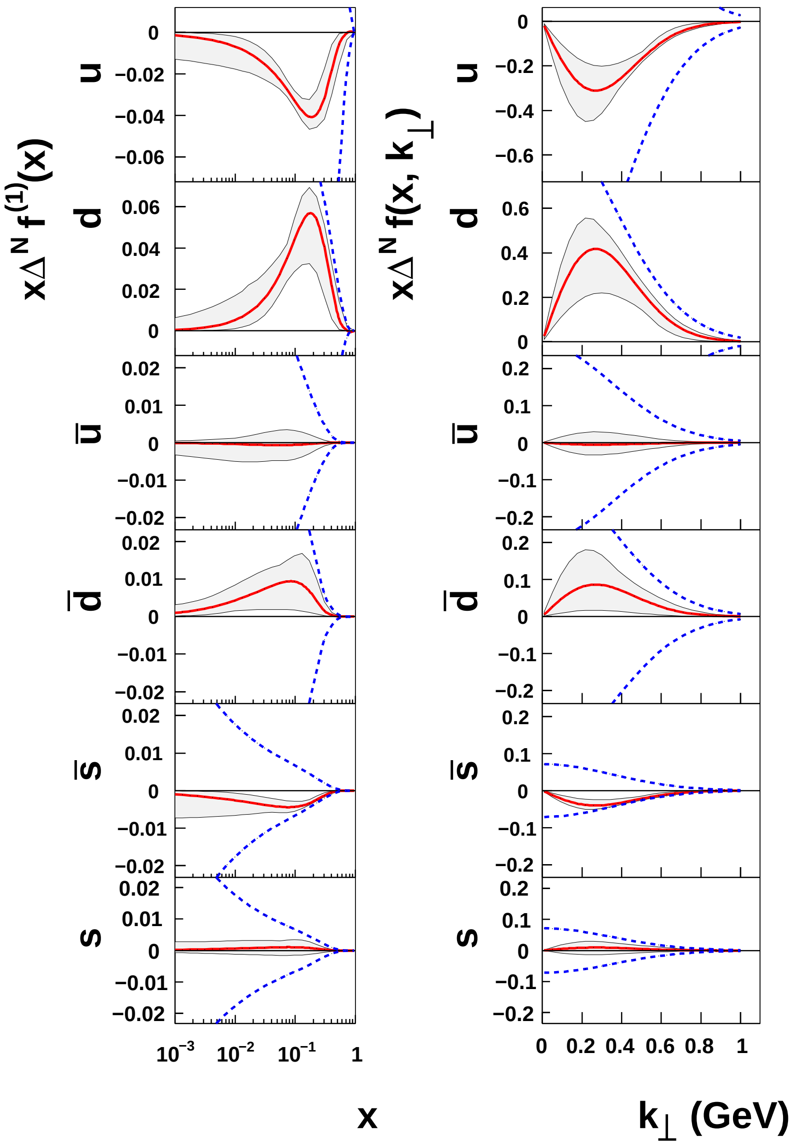
Different from the trivial ones

$$\left|\frac{\Delta^N q(x)}{2q(x)}\right| \leq 1$$

and certainly much more restrictive if $\Delta^N \bar{q}(x) = 0$.

Sivers functions from a fit:

Anselmino et al. PRD 79, 054010 (2009)



Single spin asymmetry A_N in direct photon production

$$d\sigma = \sum_i \int_{x_{min}}^{1} dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})e^y} [q_i(x_a, \mathbf{k}_{Ta}) G(x_b, \mathbf{k}_{Tb}) \times \frac{d\hat{\sigma}}{d\hat{t}}(q_i G \to q_i \gamma) + G(x_a, \mathbf{k}_{Ta})\, q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(G q_i \to q_i \gamma) \Big] ,$$

where $q_i(x, \mathbf{k}_T)$ [$G(x, \mathbf{k}_T)$] is the quark [gluon] distribution function with given $\mathbf{k}_T$, and

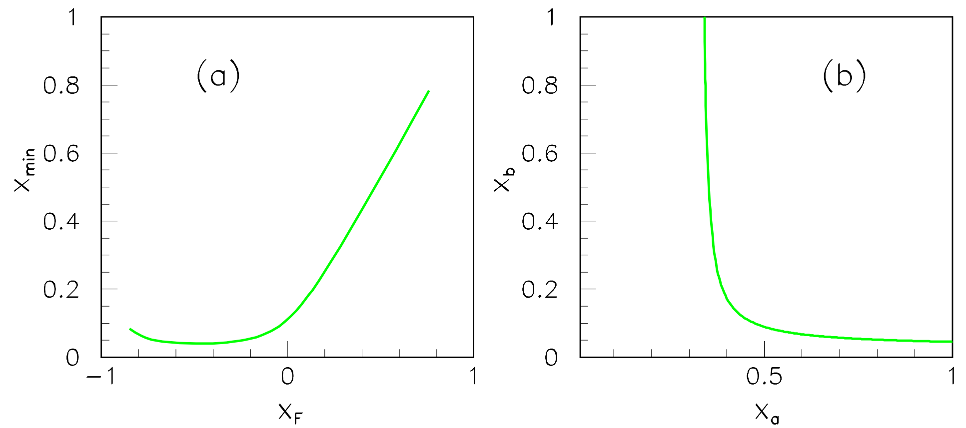
$$x_b = \frac{x_a (p_T/\sqrt{s})\, e^{-y}}{x_a - (p_T/\sqrt{s})\, e^y} \;, \quad x_{min} = \frac{(p_T/\sqrt{s})\, e^y}{1 - (p_T/\sqrt{s})\, e^y} \;, x_F = 2 sinh y (p_T/\sqrt{s}).$$

$$d\Delta_N \sigma = \sum_i \int_{x_{min}}^{1} dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})\, e^y} [q_i(x_a, \mathbf{k}_{Ta}) \Delta_N G(x_b, \mathbf{k}_{Tb}) \times \frac{d\hat{\sigma}}{d\hat{t}}(q_i G \to q_i \gamma) + G(x_a, \mathbf{k}_{Ta}) \Delta_N q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(G q_i \to q_i \gamma) \Big] \;.$$

$$A_N^{\gamma} = \frac{d\Delta_N \sigma}{d\sigma} \;,$$

Single spin asymmetry A_N in direct photon production

Both Sivers functions for quarks and gluons are involved, but the gluon Sivers function dominates in the large x_F region



For $p_T = 20GeV$ and $\sqrt{s} = 200GeV$. $x_{min} \approx x_F$ in the region $x_F > 0.3$. On the other hand, x_b versus x_a is shown above and we see that when x_a is integrated over the range [x_{min}, 1], the main contribution comes from the low x_b values. Therefore, when we look at large x_F region, where x_a is large but x_b is small, the asymmetry can be approximately expressed as

$$A^\gamma(s, x_F) = \frac{\langle \Delta_N G \rangle}{\langle G \rangle} \ ,$$

Search for New Physics at RHIC

- Why ? : polarized protons at RHIC may discover a new pure hadronic interaction of weak strength. New interactions involving leptons would have been discovered at other facilities (LEP, HERA, Tevatron-(Drell-Yan)).
- $\vec{p}\vec{p}$ RHIC facility :
  highest Energy ($\sqrt{s} = 500\ GeV$)
  + highest Luminosity ($L = 800\ pb^{-1}$)
  + highest Polarisation ($P = 70$ %).

The relevant observable

- one-spin Parity Violating asymmetry for jet production

$$A_L = \frac{d\sigma_{(-)} - d\sigma_{(+)}}{d\sigma_{(-)} + d\sigma_{(+)}}$$

- basic QCD property : $A_L(QCD) = 0$ ($A_L(SM) \neq 0$)
- If new physics is PV (in general it is) we may have strong PV effects

SM effects at lowest order

- virtual Z.g(70%) and W.g(30%) interferencies :

$$A_L \approx \alpha_s \alpha_z (C^2_{u,L} - C^2_{u,R})[u \cdot \Delta u + \Delta u \cdot u]$$

(There are also real Z and W productions)

- denominator is QCD jet production => A_L is small (few % level) but measurable at RHIC
- Uncertainties for pol. pdf's have to be strongly reduced from other processes for the new physics program to be done
- SM have large NLO corrections

(see S.Moretti, M. Nolten, D. Ross, PLB643,86 (2006), NPB759, 50 (2006))

New physics models

- qq Contact Interactions:

$$\mathcal{L}_{qq} = \epsilon \frac{\pi}{2\Lambda^2} \bar{\Psi}\gamma_\mu(1-\eta\gamma_5)\Psi.\bar{\Psi}\gamma^\mu(1-\eta\gamma_5)\Psi \tag{4}$$

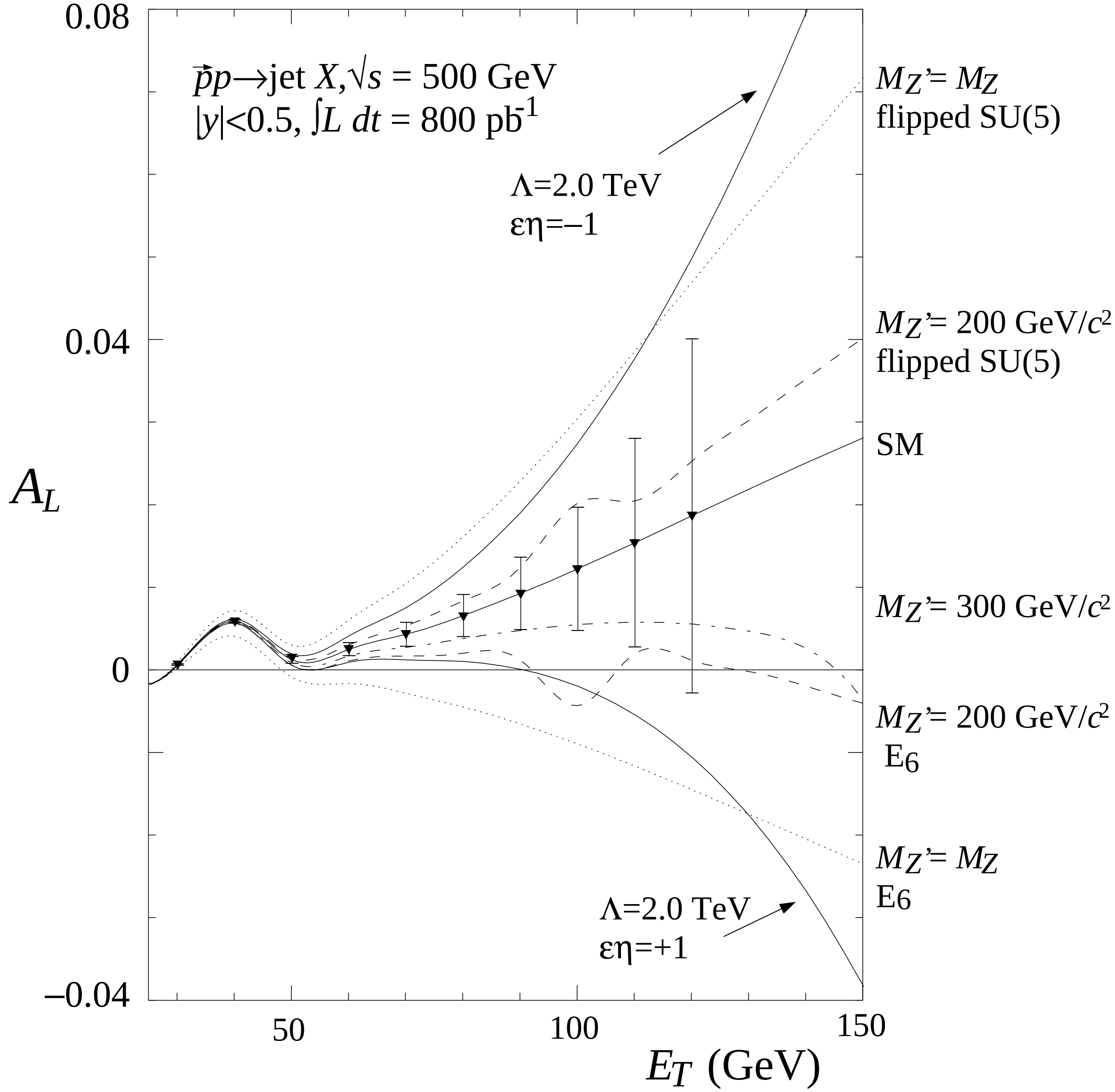
$\Psi\equiv$quark doublet, $\epsilon=\pm1$, $\eta=\pm1,0$ (chiral structure), $\Lambda\equiv$compositeness scale.

- leptophobic Z':

$$\mathcal{L}_{Z'} = \kappa\frac{g}{2\cos\theta_W} Z'^\mu\bar{\Psi}\gamma_\mu[C_L^q(1-\gamma_5)\ +\ C_R^q(1+\gamma_5)]\Psi$$

$\kappa=g_{Z'}/g_Z\approx1$. Numerous models, SUSY or not, may be constructed.

$A_L(SM + NP)$ at RHIC



qq Contact Interactions Constraints

RHIC with $\sqrt{s} = 500\ GeV$ and $L = 800\ pb^{-1}$:
$\Lambda^{lim} = 3.2\ TeV$.
Similar to expectations from TEVATRON with $\sqrt{s} = 2\ TeV$ and $L = 1\ fb^{-1}$.
However, RHIC limits increase fast with $\sqrt{s}$ or L but systematics should be controlled (i.e. 10% assumed here).
E.g. with $L = 10\ fb^{-1}$ we get $\Lambda^{lim} = 5.4\ TeV$ at RHIC whereas it is $\Lambda^{lim} = 3.7\ TeV$ at TEVATRON.
RHIC is competitive with Tevatron and give unique informations on the chiral structure.

Keep doing this good work
We will stay tuned

Thank you !