Spin: a powerful tool for physics at RHIC

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Outline

- How to improve our knowledge on PDF?
- Hyperon production at RHIC
- Physics beyond the Standard Model

u/d from the charge asymmetry in $\bar{p}p$ collisions

- The forward-backward charge asymmetry provides an important test of the ratio u/d. Since $u(x) > d(x)$, W^+ is boosted forward in p direction

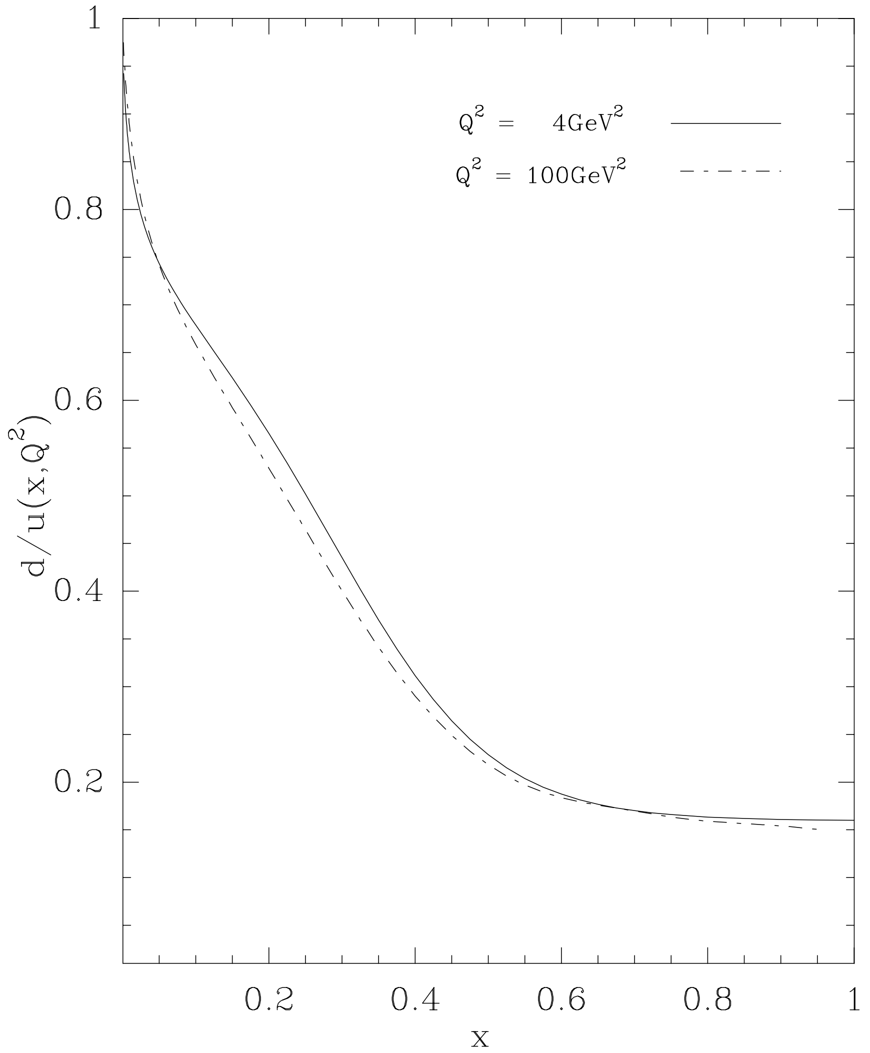
$$A(y_W) = \frac{d\sigma^{W^+}/dy_W - d\sigma^{W^-}/dy_W}{d\sigma^{W^+}/dy_W + d\sigma^{W^-}/dy_W} = \frac{u(x_a)d(x_b) - d(x_a)u(x_b)}{d(x_a)u(x_b) + u(x_a)d(x_b)}$$

  where $x_a = \sqrt{\tau}e^y$, $x_b = \sqrt{\tau}e^{-y}$ and $\tau = M_W^2/s$. One has $A(y_W) = -A(-y_W)$ and if $u(x)/d(x) = k$, $A = 0$.

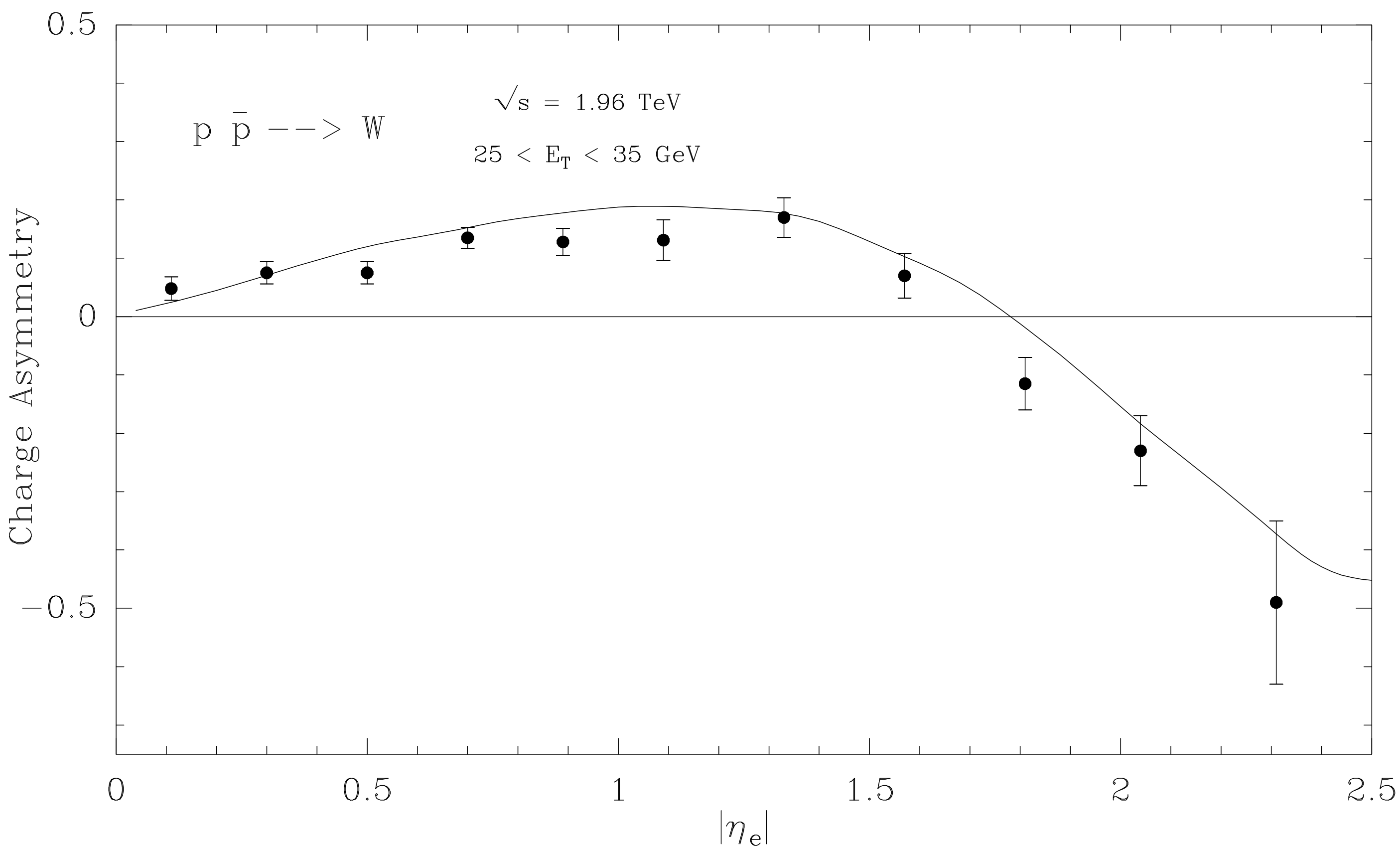
- Since one selects the leptonic decay $W \to e\nu$

$$A(\eta_e) = \frac{d\sigma(e^+)/d\eta_e - d\sigma(e^-)/d\eta_e}{d\sigma(e^+)/d\eta_e + d\sigma(e^-)/d\eta_e}$$

d/u in the statistical PDF



CDF data PRD71,051104(R) 2005(using RhicBos)



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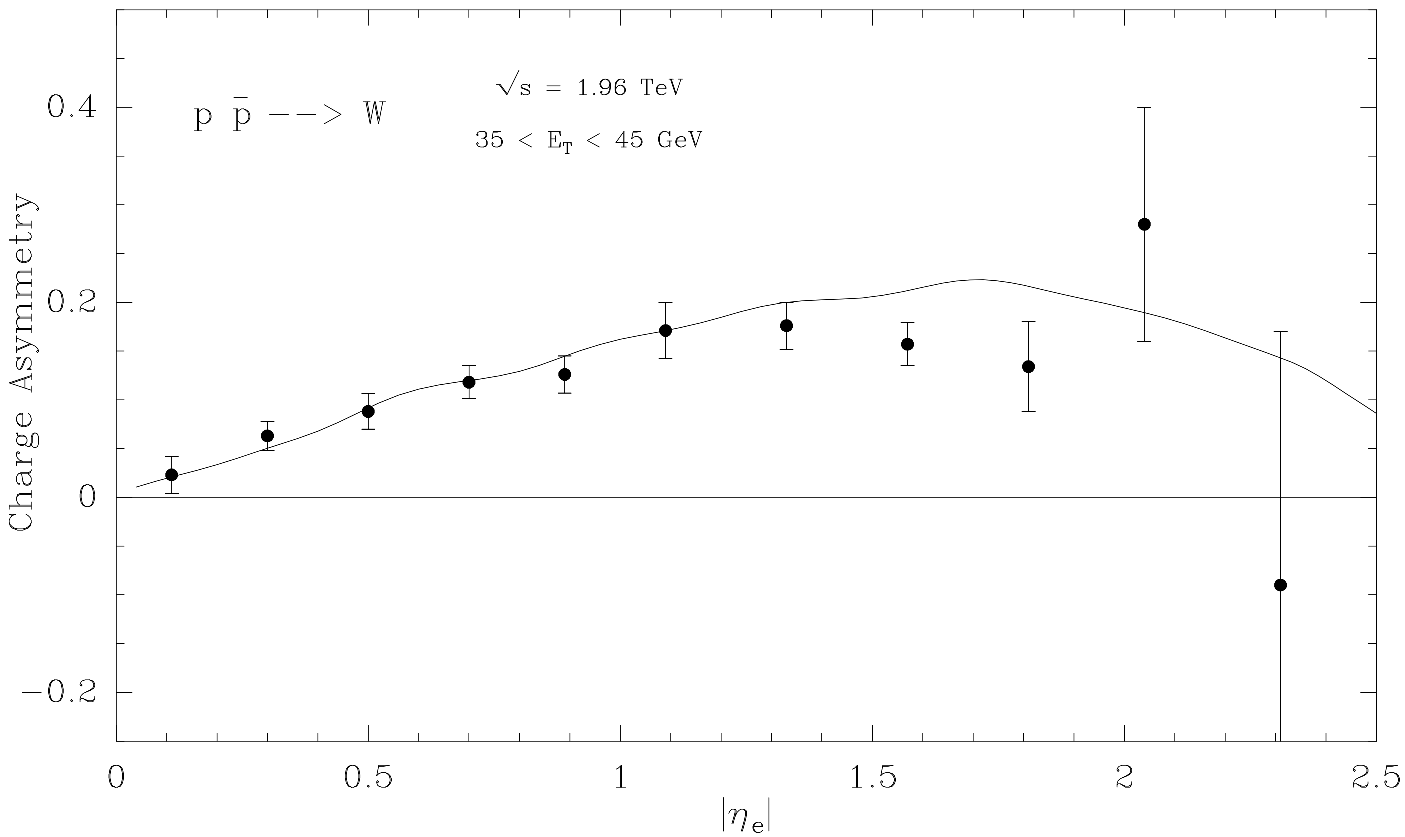
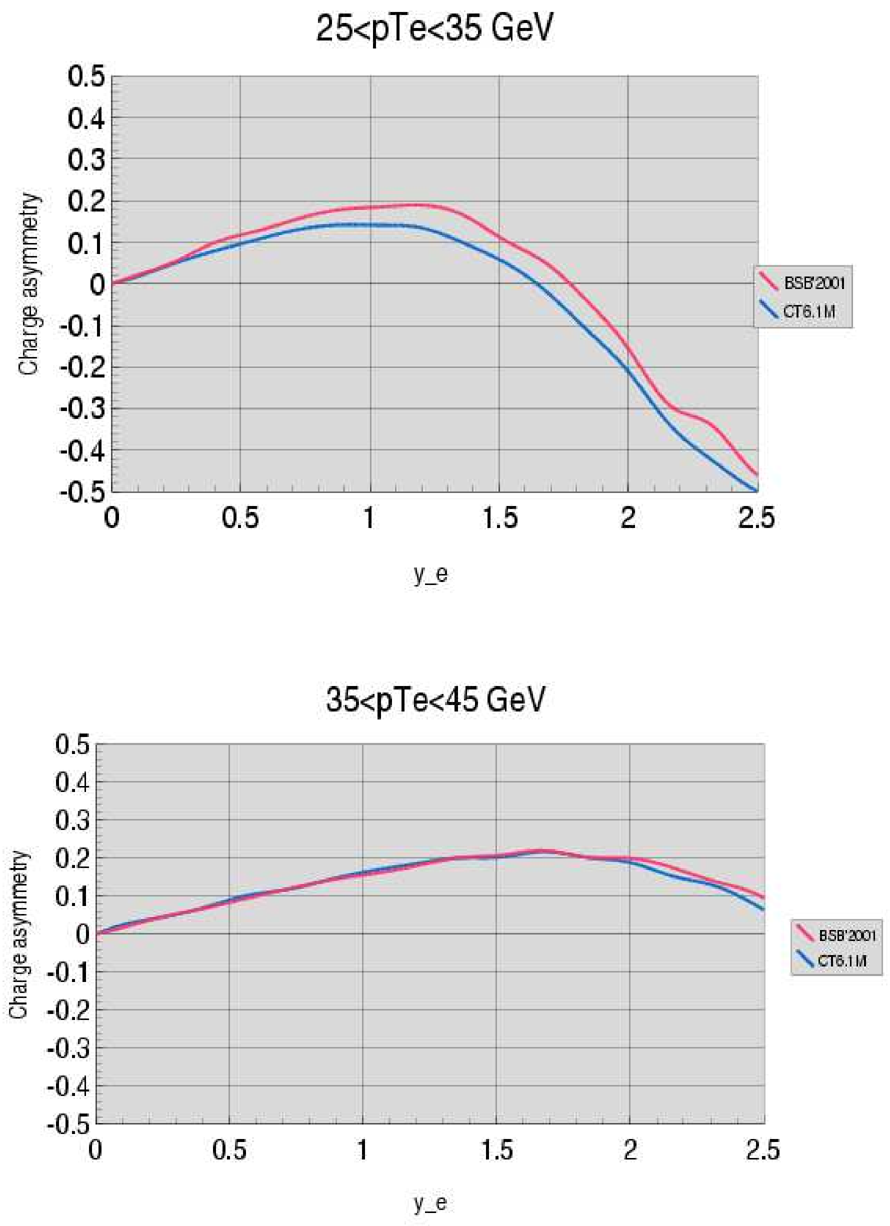
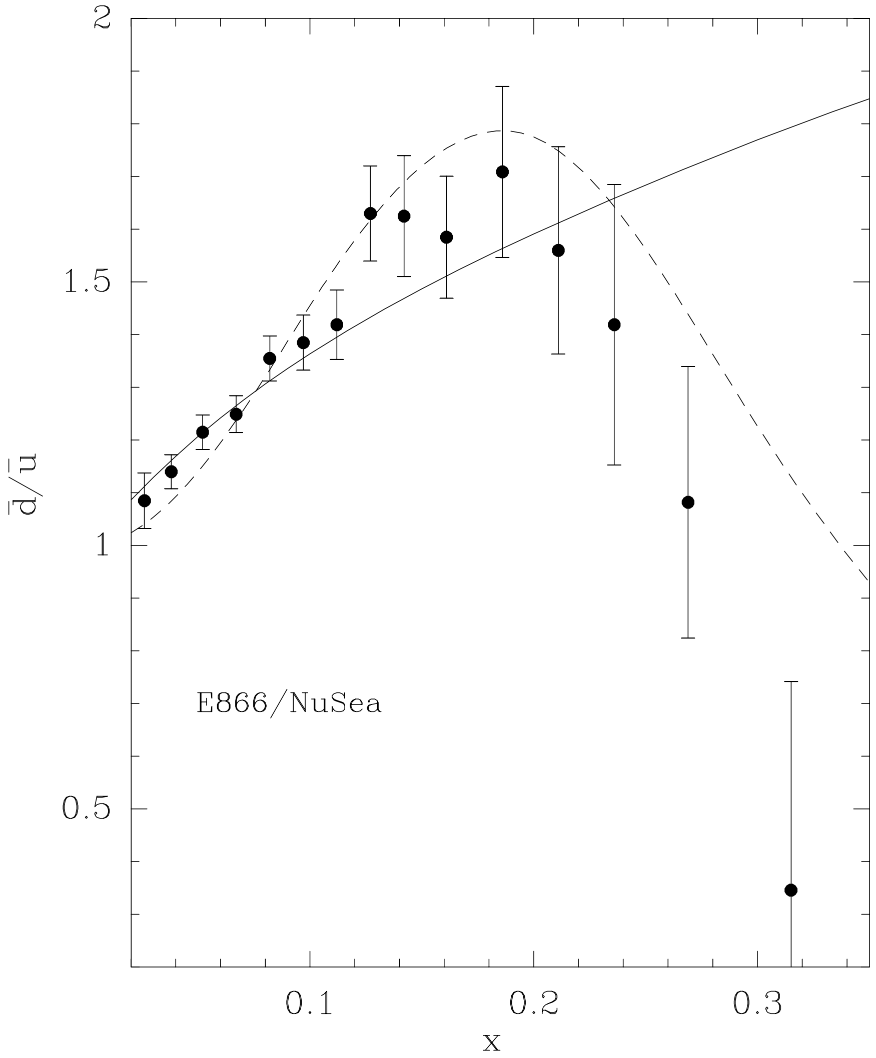


BBS versus CTEQ6 (thanks to P. Nadolski)



Behavior of $\bar{d}/\bar{u}$ at high x ?



Light sea quarks asymmetry in $pp \to W^{\pm}$

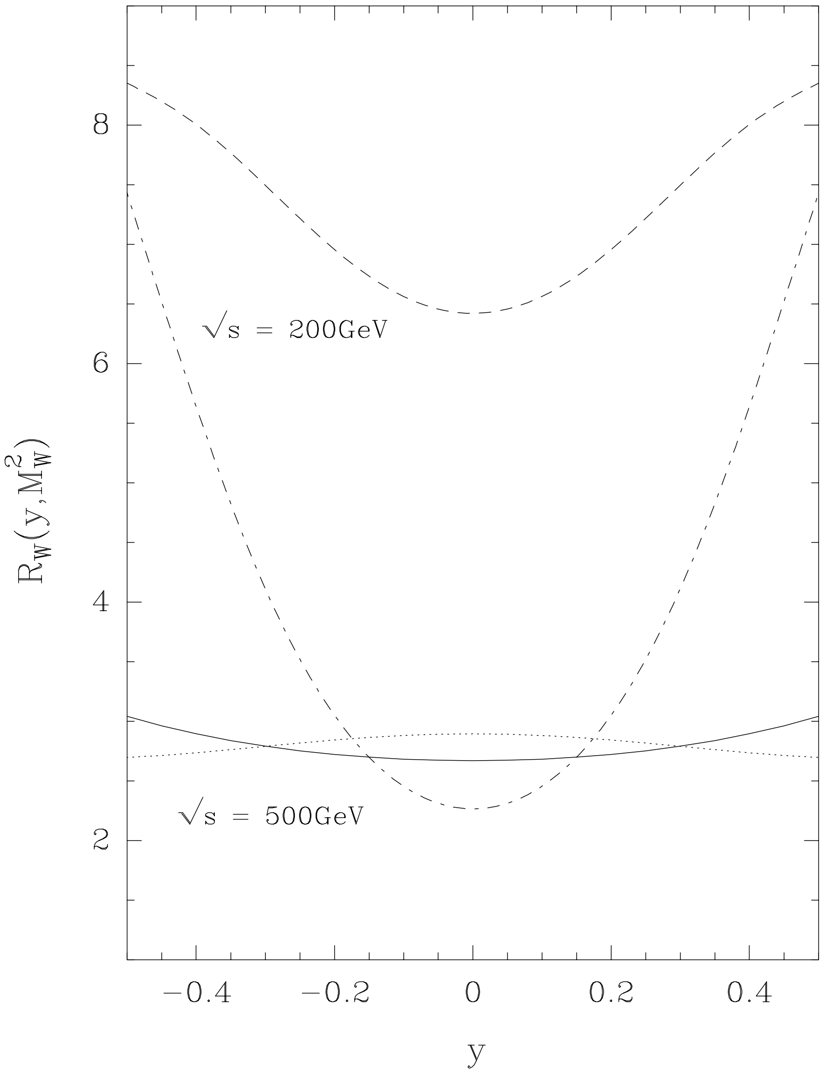
- Consider $R_W(y) = (d\sigma^{W^+}/dy)/(d\sigma^{W^-}/dy)$ which reads in lowest order

$$R_W(y, M_W^2) = \frac{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}{d(x_a)\bar{u}(x_b) + \bar{u}(x_a)d(x_b)} ,$$

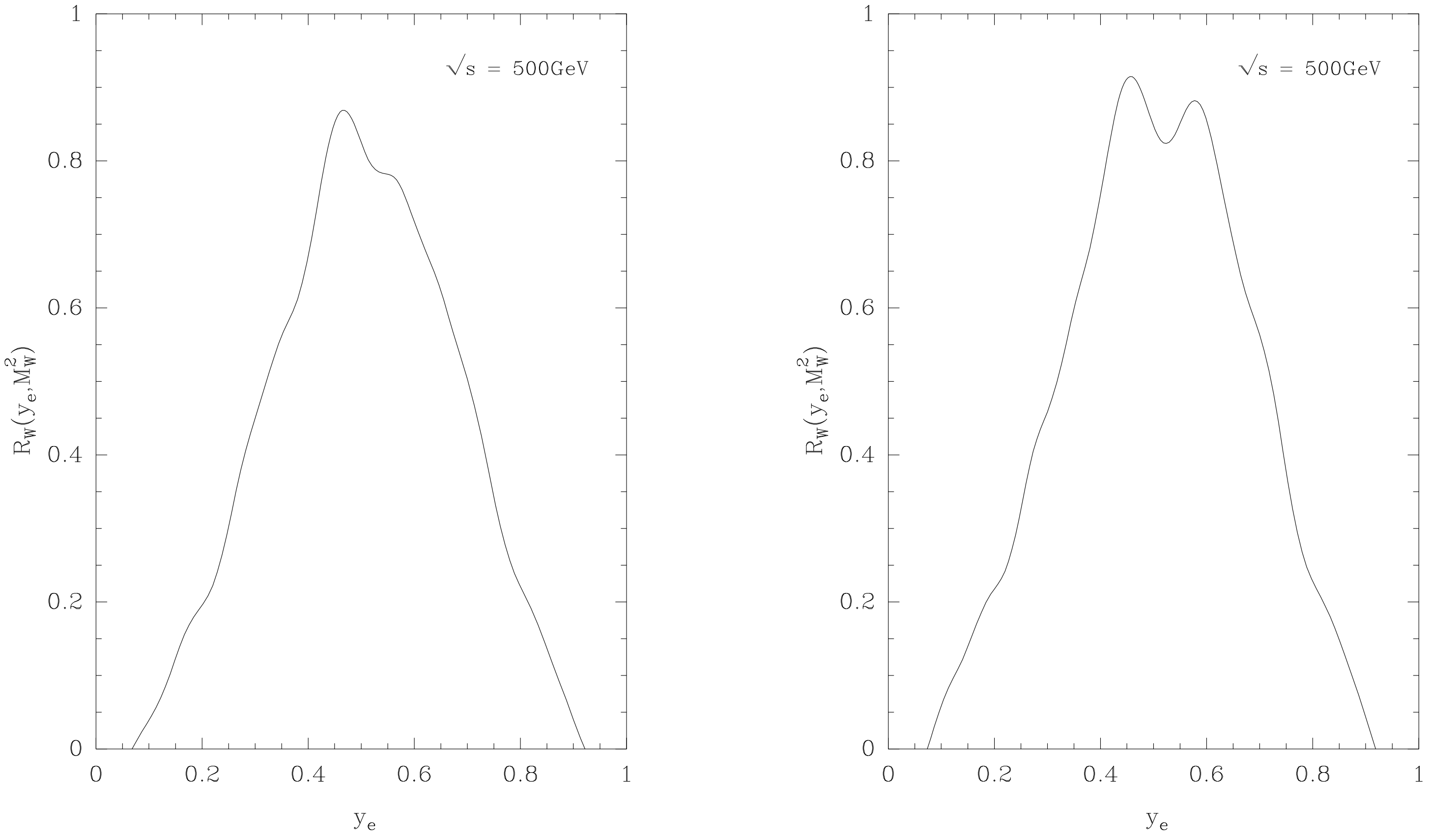
  where $x_a = \sqrt{\tau}e^y$, $x_b = \sqrt{\tau}e^{-y}$ and $\tau = M_W^2/s$.

- At $\sqrt{s} = 500$GeV for $y = 0$, we have $x_a = x_b = 0.16$. So $R_W(0, M_W^2)$ probes the $\bar{d}(x)/\bar{u}(x)$ ratio at $x = 0.16$.
  At $\sqrt{s} = 200$GeV for $y = 0$, we have $x_a = x_b = 0.40$
  Better test but the production rate is lower.

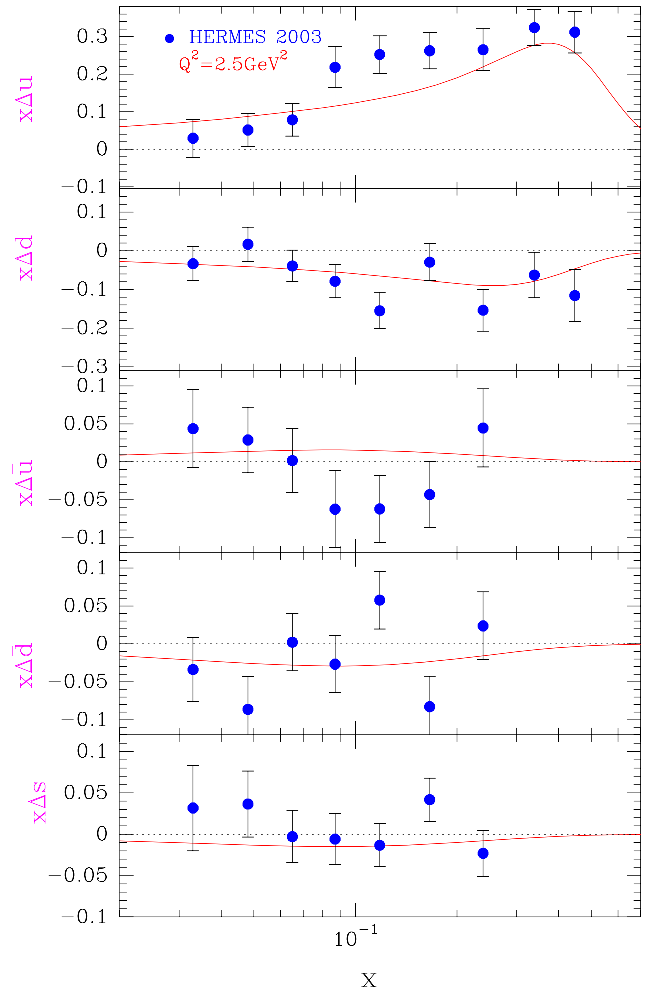
Decisive test at RHIC



BBS (left) versus CTEQ (right)



Δq and $\Delta\bar{q}$ flavor separation from SIDIS



Δq and $\Delta \bar{q}$ flavor separation from $W^{\pm}$ production

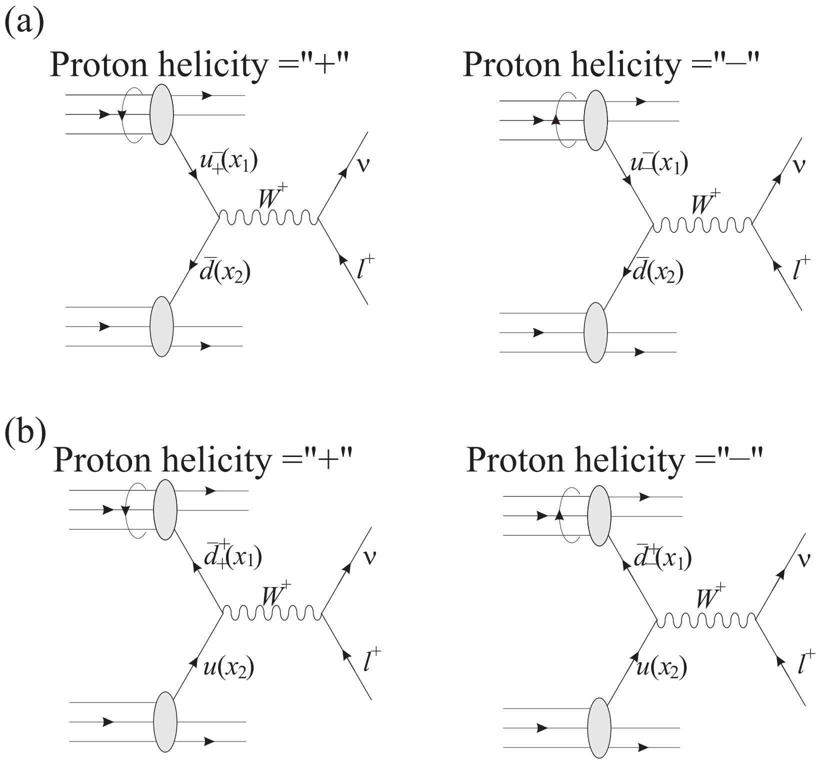
Consider the parity-violating helicity asymmetry $A_L^{PV}(W)$

$$A_L^{PV}(W) = \frac{\Delta d\sigma/dy}{d\sigma/dy} = \frac{d\sigma_-^W/dy - d\sigma_+^W/dy}{d\sigma_-^W/dy + d\sigma_+^W/dy} ,$$

where $\pm$ stands for the helicity of one polarized proton beam. For W^+, at the lowest order of the Drell-Yan production mechanism, it reads

$$A_L^{PV}(W^+) = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} ,$$

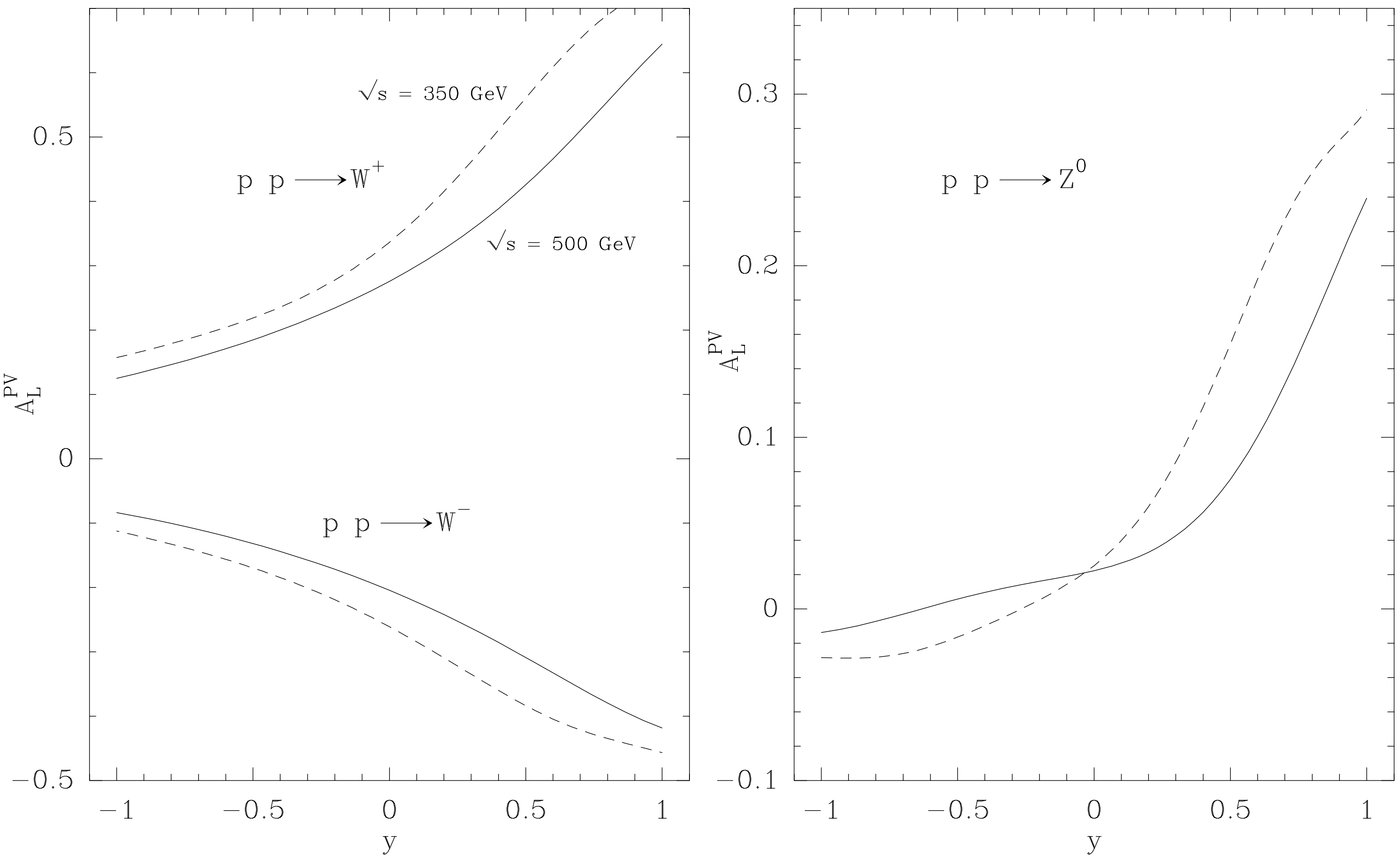
W^+ production in polarized pp collisions



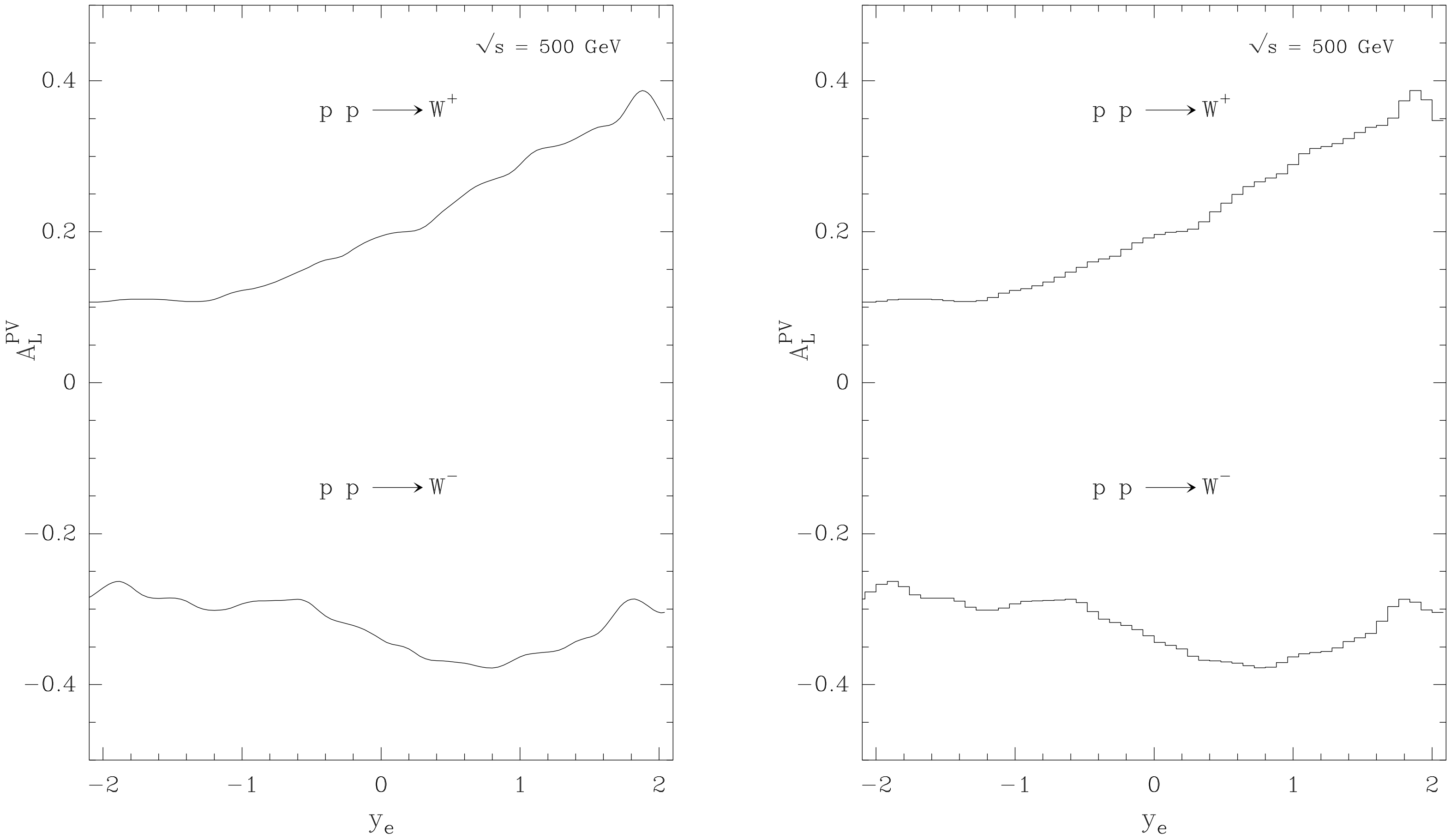
Polarized quarks flavor separation

For W^- production one interchanges u and d. The general trend of $A_L^{PV}(W)$ can be easily understood and, for example at $\sqrt{s} = 500$GeV near $y = +1$, $A_L^{PV}(W^+) \sim \Delta u/u$ and $A_L^{PV}(W^-) \sim \Delta d/d$, evaluated at $x = 0.435$. Similarly for near $y = -1$, $A_L^{PV}(W^+) \sim -\Delta \bar{d}/\bar{d}$ and $A_L^{PV}(W^-) \sim -\Delta \bar{u}/\bar{u}$, evaluated at $x = 0.059$.

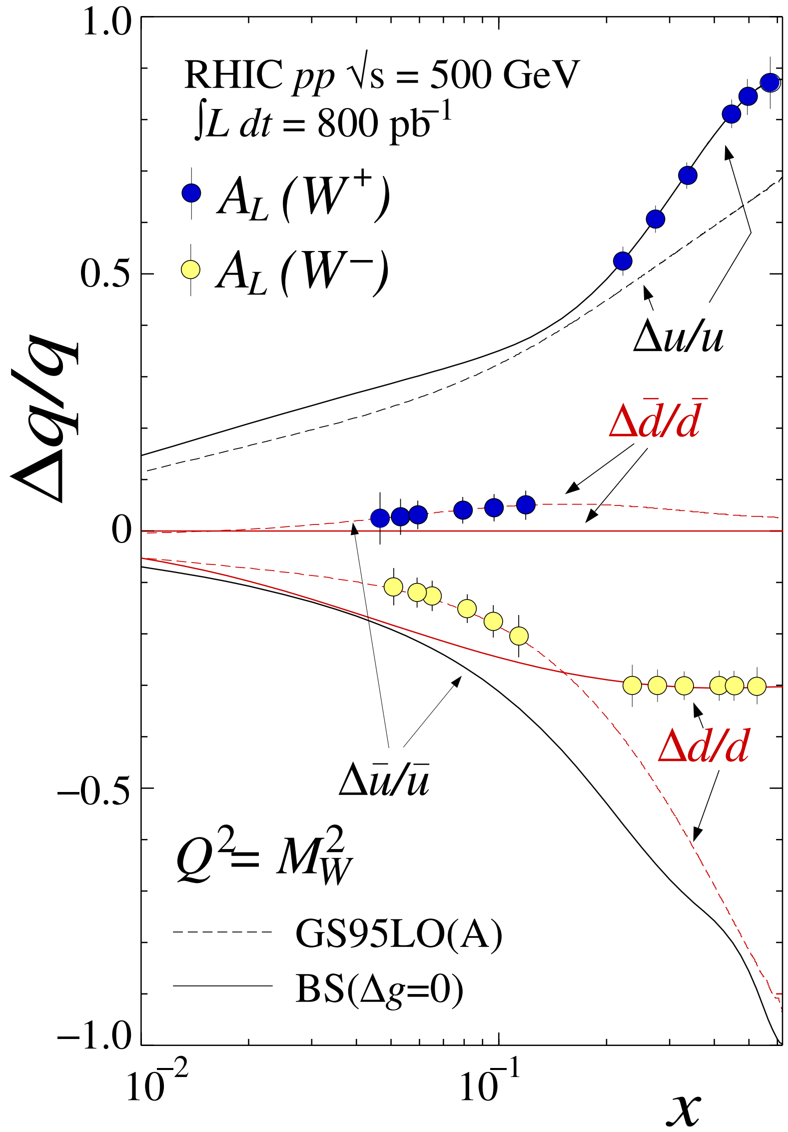
Parity-violating asymmetries



Parity-violating asymmetries(using RhicBos)



Expected sensitivity for the polarized PDF



Gluon Polarization $\Delta g(x)$ at RHIC

- From pure DIS, the Q^2 evolution does NOT allow a determination of $\Delta g(x)$.
- From DIS with 2 hadrons in the final state one has at $x = 0.095$

$$\Delta g(x)/g(x) = 0.024 \pm 0.089(stat) \pm 0.057(syst)$$

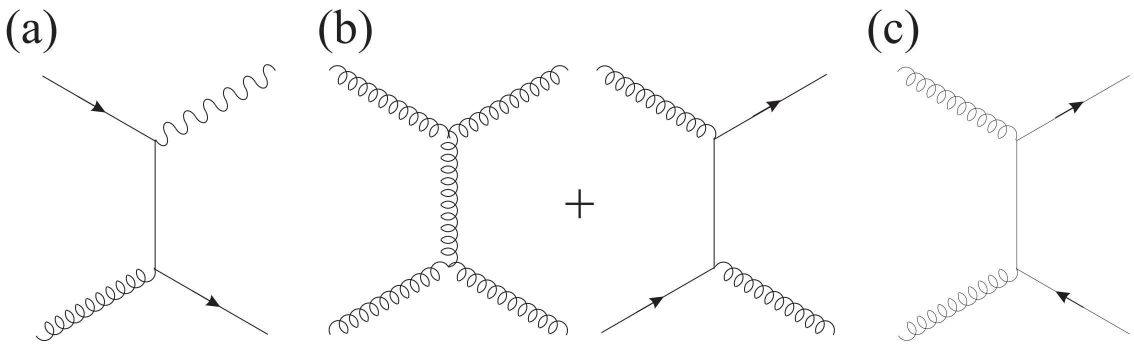
- From quasi-photoproduction of open charm, a new result from COMPASS gives for $x = 0.15 \pm 0.08$

$$\Delta g(x)/g(x) = -0.22 \pm 0.48 \ \ (non \quad official!!!)$$

- Hermes has a positive result 0.40 ± 0.20

Lowest-order diagrams with initial gluons

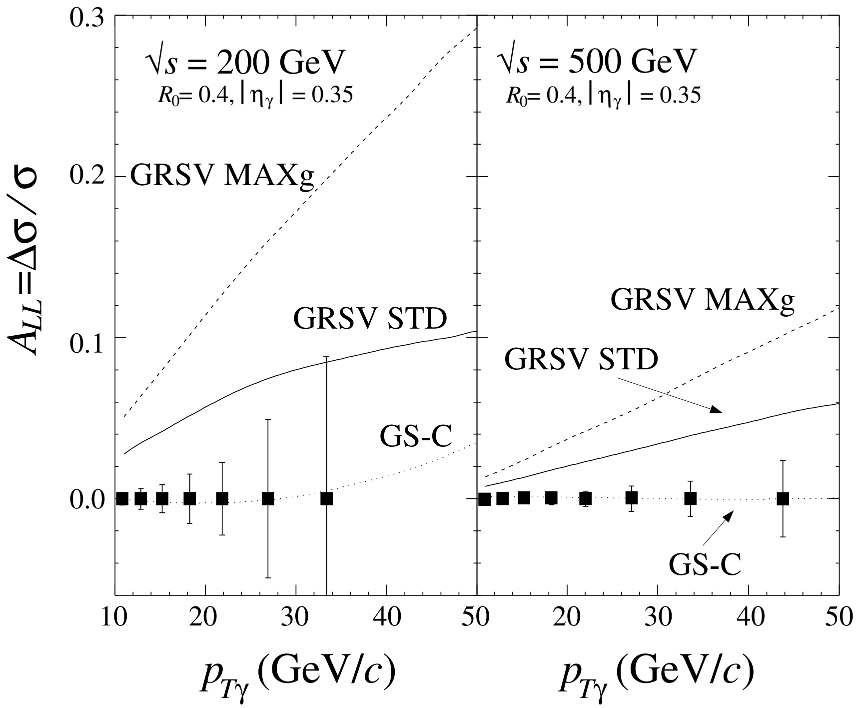
How to check this first "‘indication"’ that Δg is small?



- High-p_T photon production (a)
- Jets production (b)
- Heavy-flavor production (c)

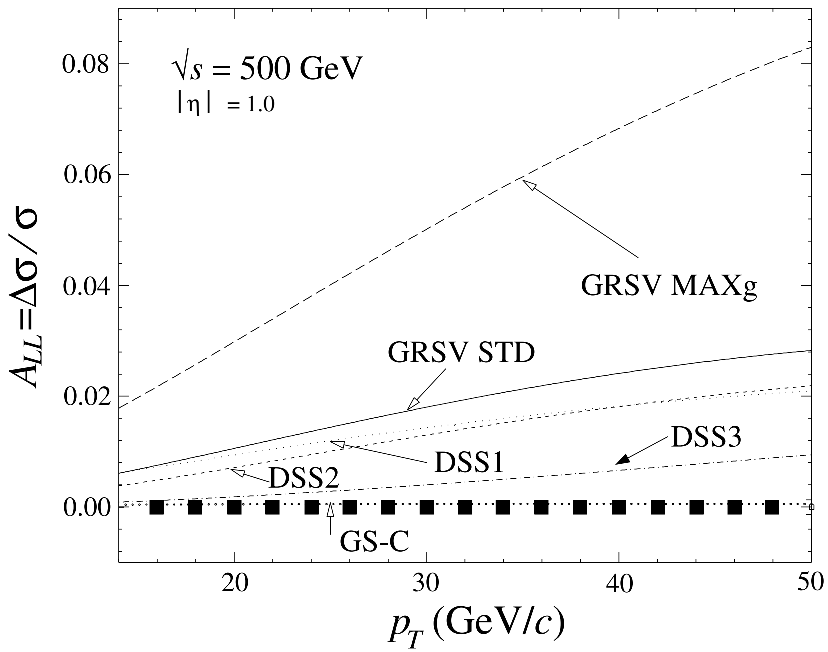
Prompt photon production at RHIC

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

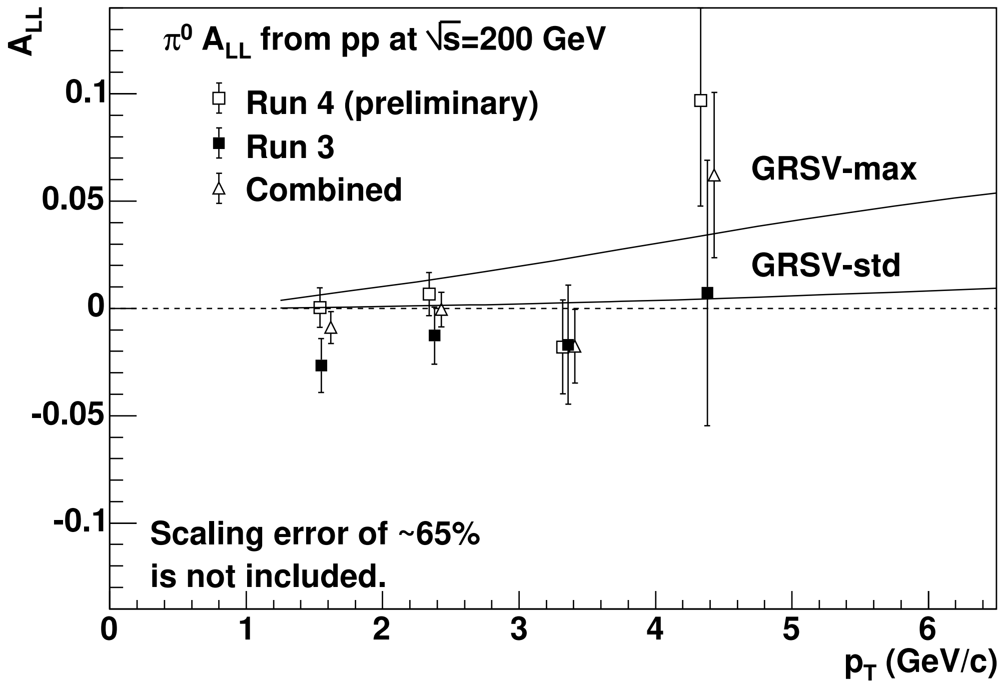


Jet production at RHIC

Sensitivity to Δg only in the medium p_T region, dominated by $gq \to gq$. Low p_T region dominated by gg collisions



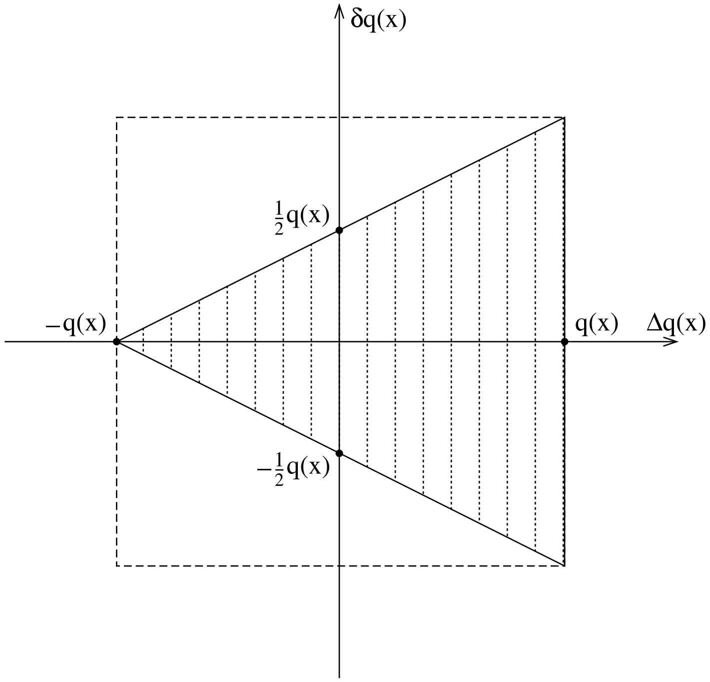
Data on π^0 production at RHIC at low p_T



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

There is a new distribution function $\delta q(x, Q^2)$, chiral odd, leading twist, which decouples from DIS. This bound survives up to NLO corrections

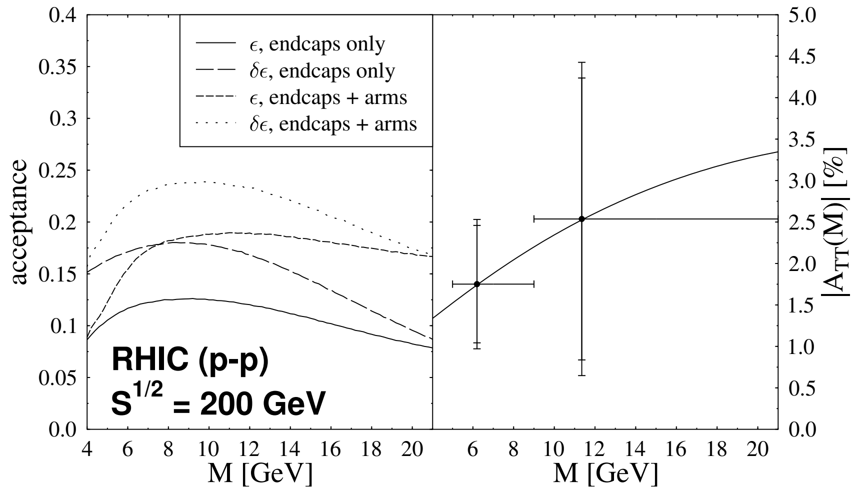
$$q(x, Q^2) + \Delta q(x, Q^2) \geq 2|\delta q(x, Q^2)|$$



A_{TT} in Drell-Yan dimuon production

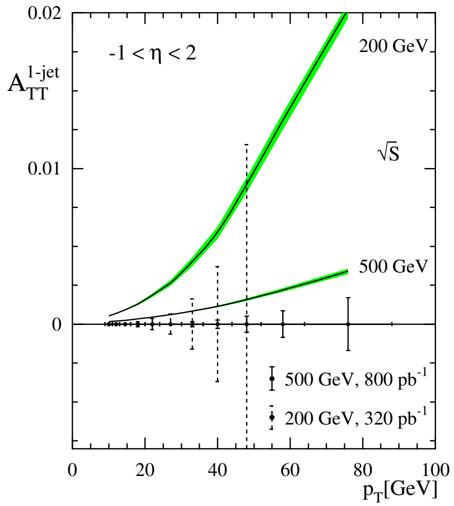
It can be measured in Drell-Yan dimuon production

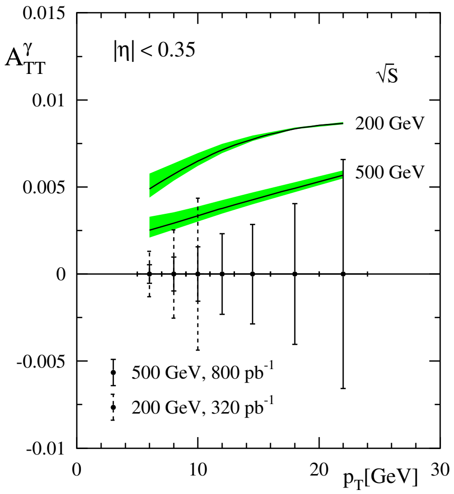
$$A_{TT} = \widehat{a}_{TT} \frac{\sum_q e_q^2 \delta q(x_1, M^2) \delta \bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}.$$



Upper bounds on A_{TT} in Jet and prompt photon productions

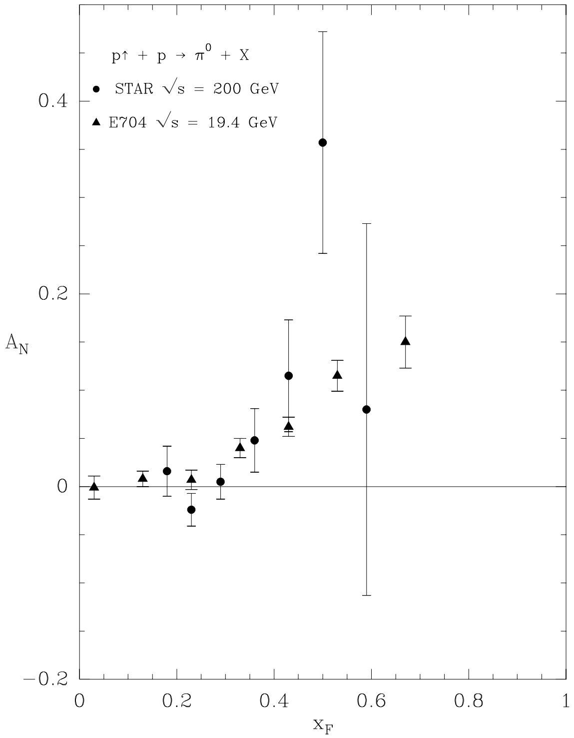
Sensitivity to δq only in the high p_T region, dominated by $qq \to qq$. Use positivity bound. Expect $|A_{TT}| << |A_{LL}|$



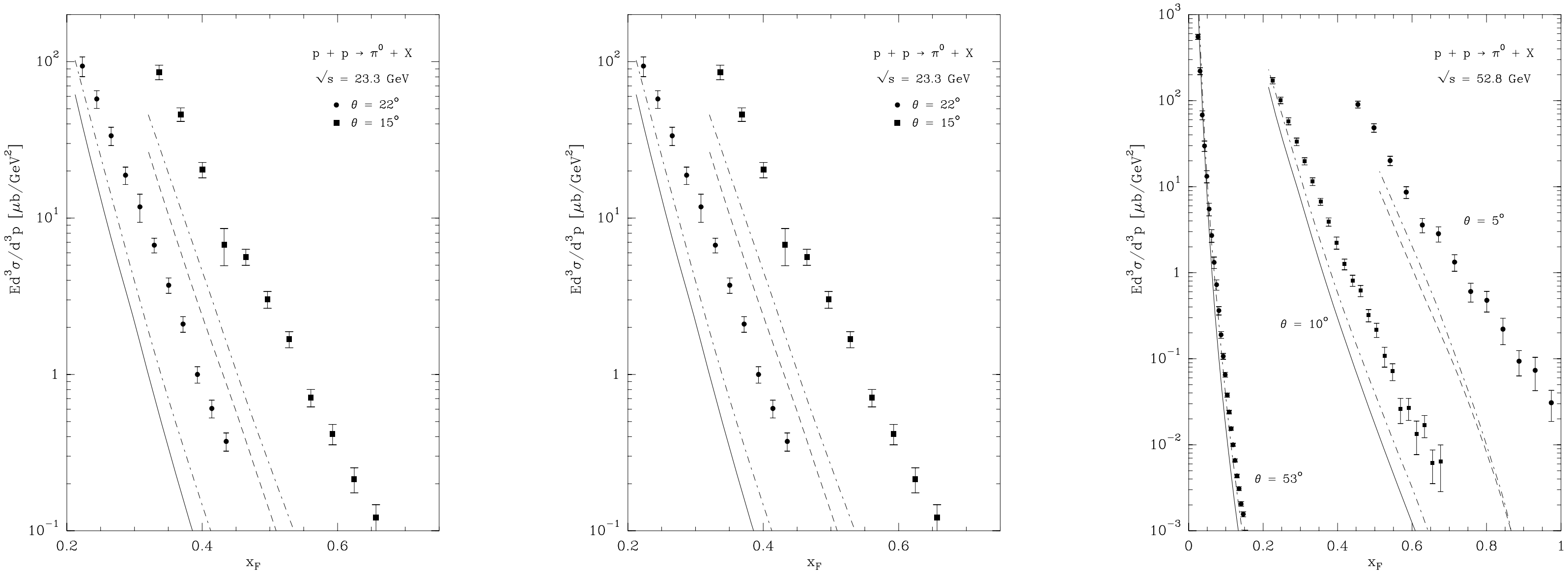


Single spin asymmetry A_N in π^0 production

Do we understand this asymmetry, given the fact that STAR is at very small angle 2.6° and E704 at 9°to 64°?

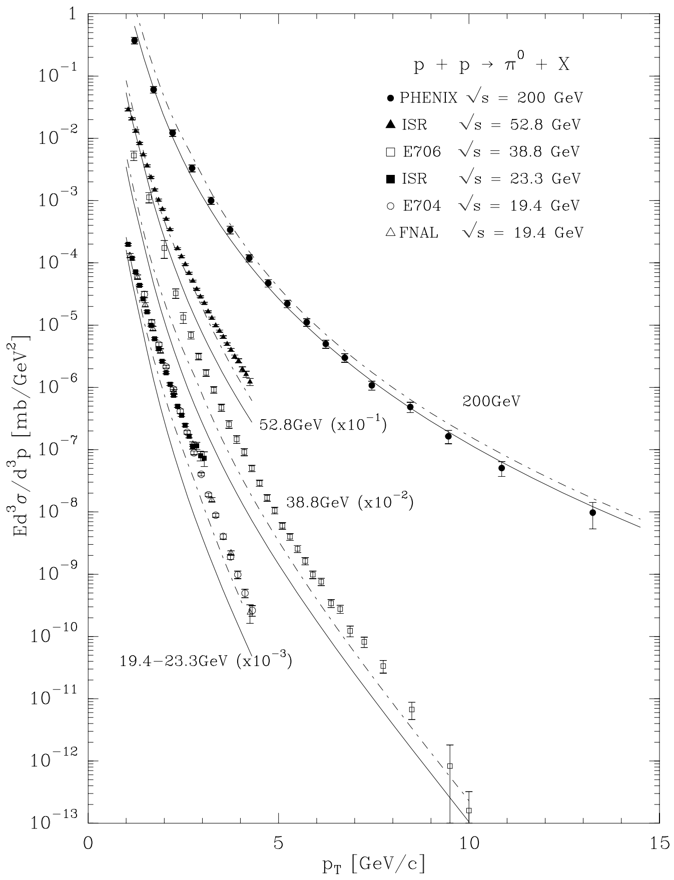


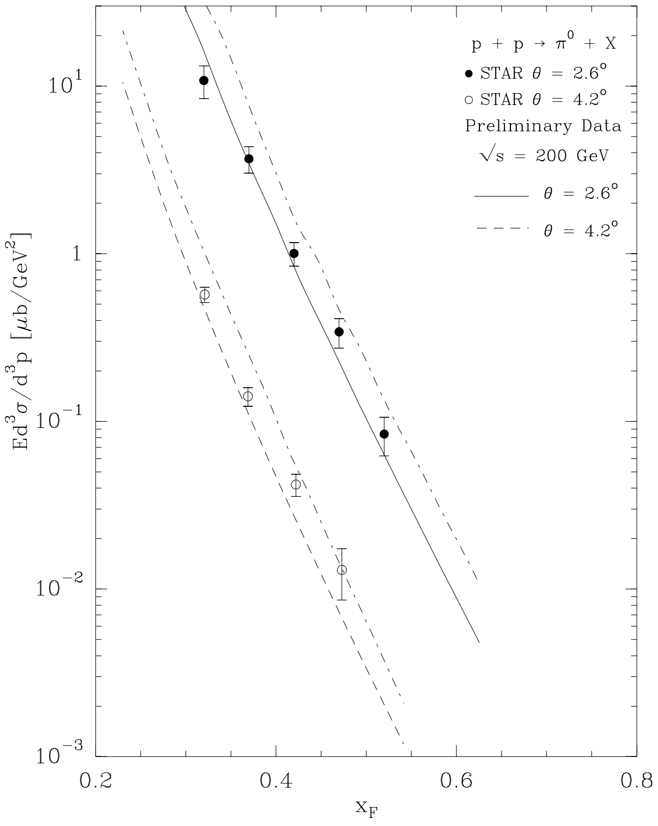
Single spin asymmetry A_N in π^0 production



The pQCD calculation underestimates the cross section at low energies and small angles. This is not the case at 90° and at small angles at high energy, which is the STAR kinematic range.

Single spin asymmetry A_N in π^0 production





Single spin asymmetries A_N Sivers vs Collins

In practice, two mechanisms have been proposed in order to explain the SSA. The first one is to generalize the parton distribution functions by considering distributions that depend on the transverse momenta k_T of these partons, and the second is to take into account higher twist operators. Recently it was shown that there is a direct relation between these two approaches, so in fact they are expected to produce very similar effects. In the case of the k_T dependent distribution functions, the SSA can be produced either by quark distributions, which is called the Sivers effect proposed long time ago, or by quark fragmentation functions, which is called the Collins effect. In general both the Sivers and the Collins effects will be present in a specific reaction, although there are some cases in which only one of them contributes. For example, the Collins effect is the only mechanism that can lead to asymmetries A_{UT} and A_{UL}, in SIDIS. On the other hand, it does not appear in some electroweak interaction processes, where there is only the Sivers effect. In direct photon production in pp collisions, which is dominated by $qg \rightarrow q\gamma$, the SSA is sensitive to both the quark and the gluon Sivers functions, according to x_F of the photon, as we will see.

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 specified $\mathbf{k}_T$, and

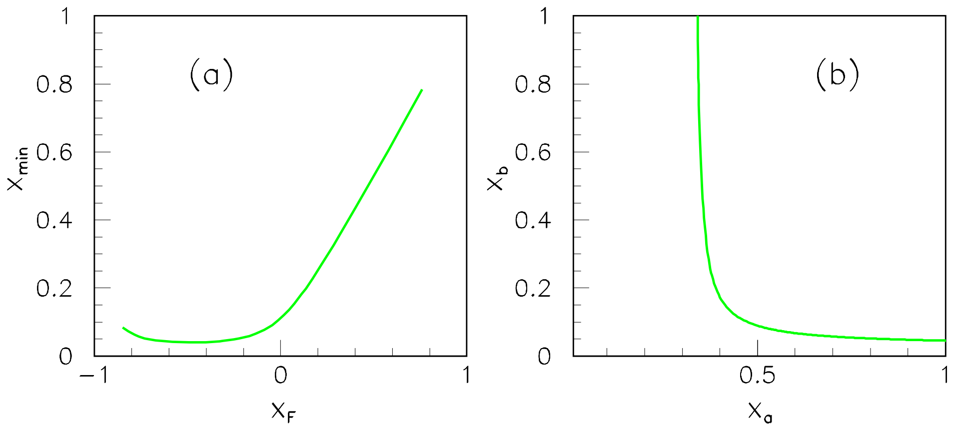
$$x_b = \frac{x_a (p_T/\sqrt{s})\, e^{-y}}{x_a - (p_T/\sqrt{s})\, e^y}, \quad x_{min} = \frac{(p_T/\sqrt{s})\, e^y}{1 - (p_T/\sqrt{s})\, e^y}, x_F = 2sinhy(p_T/\sqrt{s}).$$

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

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

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

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

Hyperon production at RHIC

First, we are interested in the reaction $\overrightarrow{p}p \to \overrightarrow{\Lambda}X$, where both the initial proton and the produced Λ are longitudinaly polarized and we consider the helicity transfer parameter D^{Λ}_{LL} defined as follows

$$D^{\Lambda}_{LL}(\eta, p_T) = (d\sigma_{++} - d\sigma_{+-})/(d\sigma_{++} + d\sigma_{+-}) \ ,$$

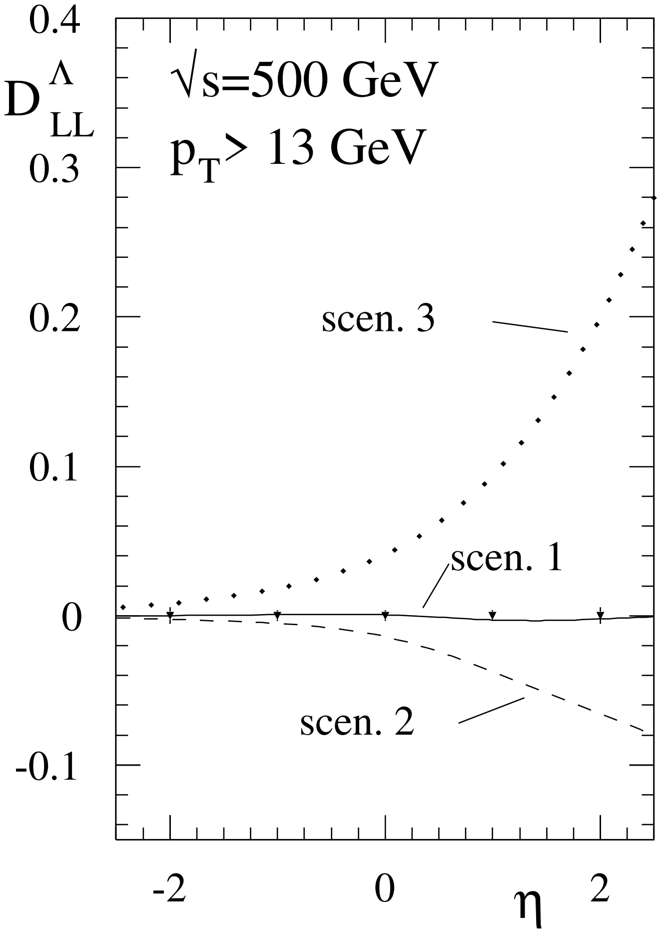
where η and p_T are the rapidity and the transverse momentum of the outgoing Λ. $d\sigma_{++}$ [$d\sigma_{+-}$] denotes the cross section where the proton and the Λ helicities have the same [opposite] sign. When η is positive the Λ has the direction of $\overrightarrow{p}$ and p_T is always assumed to be large. D^{Λ}_{LL} is directly related to the $\Delta D^{\Lambda}_f\ 's$, the analogue of Δq for the fragmentation functions $D^{\Lambda}_f\ 's$. Although these FF are reasonably known, we have to make models for ΔD^{Λ}_f, and also for the other hyperons.

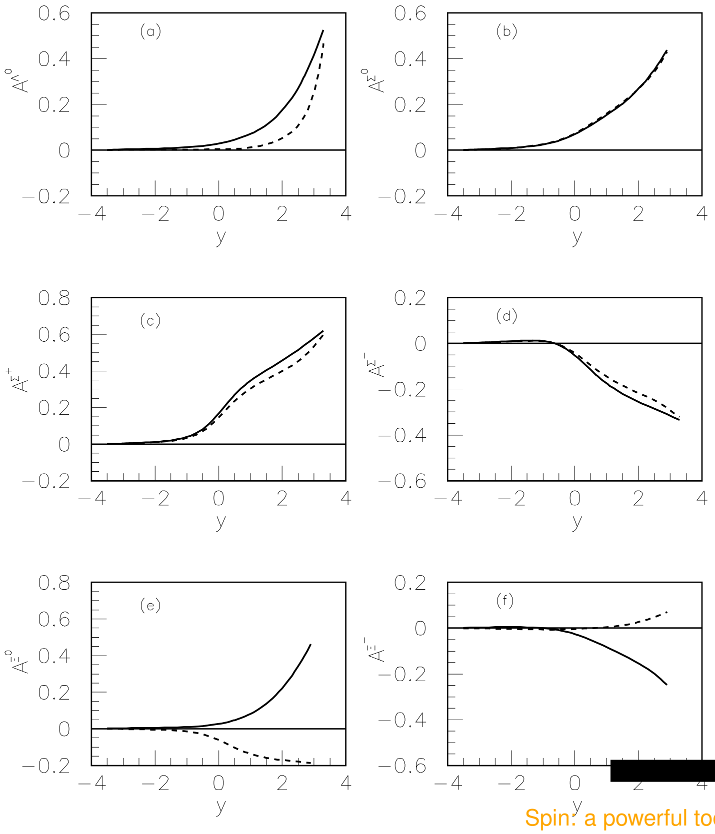
$$\Delta D^{\Lambda}_u = \Delta D^{\Lambda}_d = N_u \Delta D^{\Lambda}_s \ \text{ and } \ \Delta D^{\Lambda}_s = z^{\alpha} D_s \ ,$$

in terms of *two* new parameters α and N_u at a given scale. To cover a wide range of plausible models, they consider three different scenarios:

Helicity transfer D_{LL}^{Y} (A^{Y})

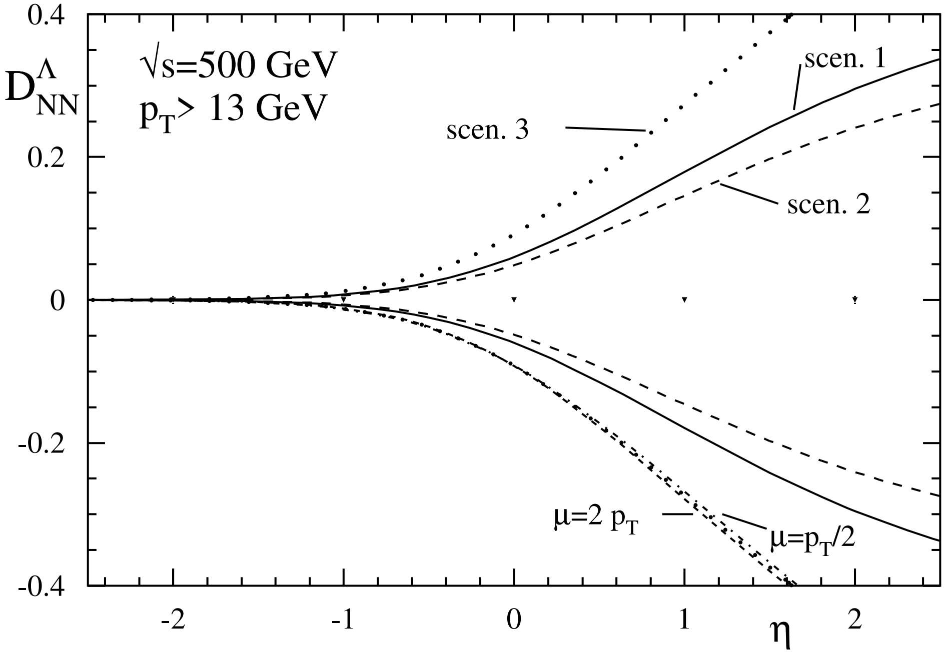
1) In the non-relativistic quark model, only strange quarks contribute, so $N_u = 0$.
2) By transposing an estimate for the polarized u and d quark distributions in a Λ, to the polarized fragmentation functions, one gets $N_u = -0.2$.
3) By assuming that all polarized fragmentation functions are equal, which is an extreme case, one gets $N_u = 1$.





Bounds for the Spin transfer D^{Λ}_{NN}

$$2|\Delta_T D_q^H(z,Q^2)| \leq D_q^H(z,Q^2) + \Delta D_q^H(z,Q^2) \ .$$



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 ($P = 70$ %).

Observables

- 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 :

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

(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 effects at NLO are underway (see S.Moretti et al. works, hep-ph/0509254, hudge corrections

New physics models

- qq Contact Interactions:

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

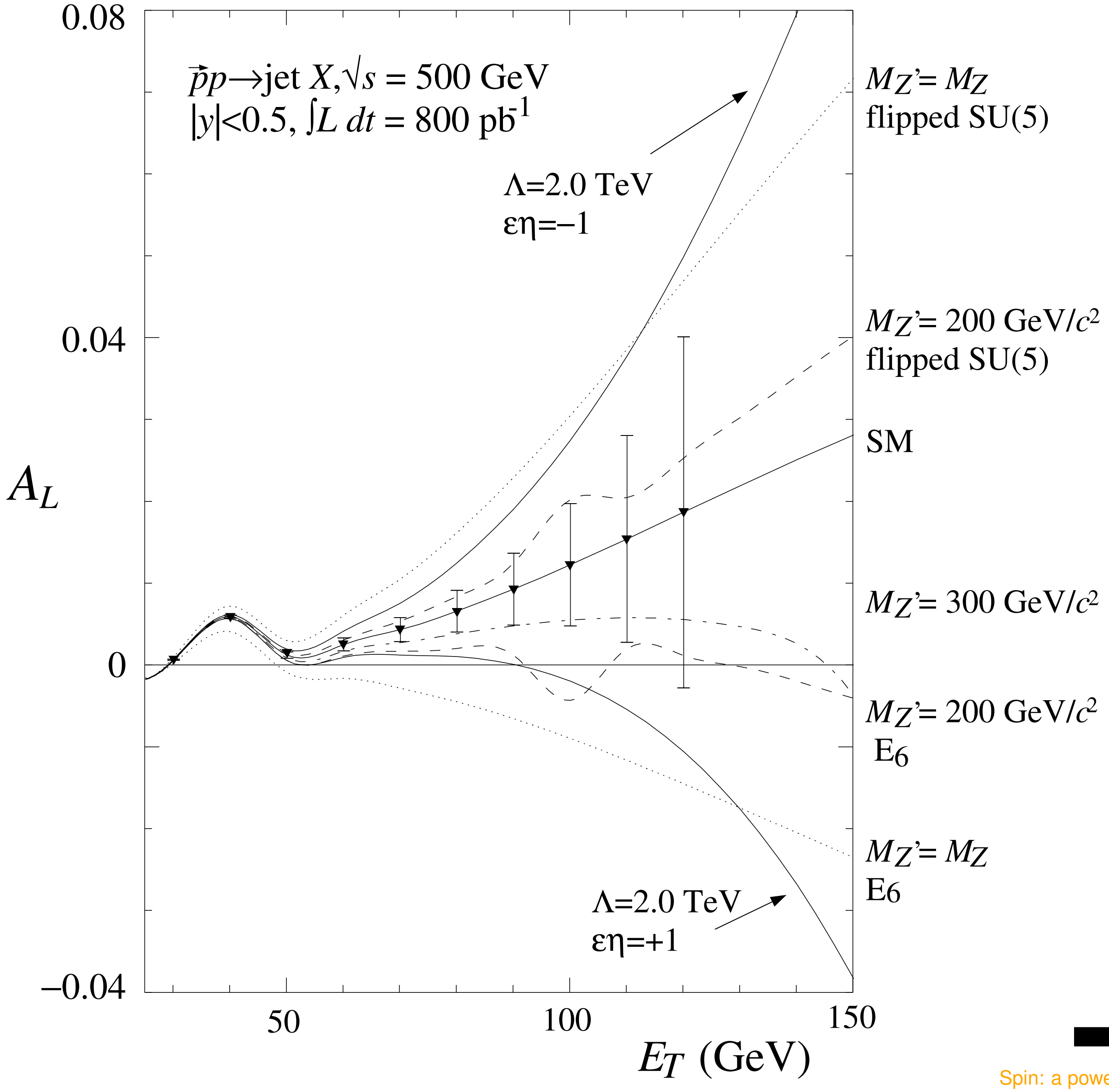
  $\Psi \equiv$quark doublet, $\epsilon = \pm 1$, $\eta = \pm 1, 0$ (chiral structure), $\Lambda \equiv$compositeness scale.

- leptophobic Z':

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

  $\kappa = g_{Z'}/g_Z \approx 1$. Numerous models, SUSY or not, may be constructed.

$A_L(SM + NP)$ at RHIC

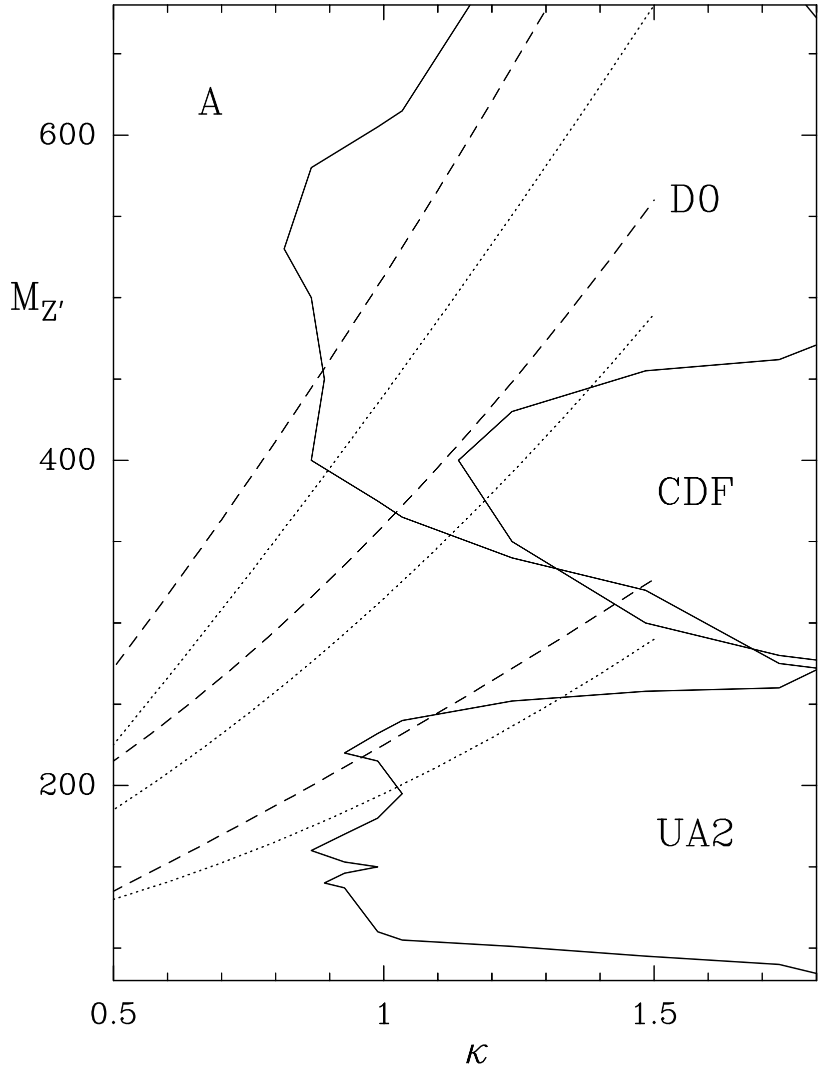


qq Contact Interactions Constraints

RHIC with $\sqrt{s} = 500\ GeV$+$L = 800\ pb^{-1}$:
$\Lambda^{lim} = 3.2\ TeV$.
Similar to expectations from TEVATRON with $\sqrt{s} = 2\ TeV$+$L = 1\ fb^{-1}$.
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.

Leptophobic Z' Constraints

dotted(dashed) $\sqrt{s} = 500(650)\ GeV$, bottom to top : $L = 1,\ 10,\ 100 fb^{-1}$



$\kappa < 1$, $M_{Z'} \approx M_Z$, $M_{Z'} \approx 300\ GeV$: unconstrained, RHIC only!

Conclusions for new physics at RHIC

- RHIC is competitive with TEVATRON to discover a new interaction which belongs to the pure quark sector.
- If the strength is weak ($\kappa < 1$) RHIC is the unique place for discovery.
- High energy, High luminosity, High polarisation and small systematics are mandatory ...

Keep doing all this good work!

THANK YOU