Gluon Polarization in the Nucleon

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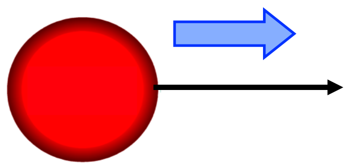
Outline:

- Brief review of Δg
- Where are we now ?
- Where do we go from here ?
- Some ideas for the future

Brief review of Δg



$$\frac{1}{2} = \langle P, \frac{1}{2} \,|\, \hat{J}_z \,|\, P, \frac{1}{2} \rangle$$

$$\hat{J}_z = \int d^3x \left[\frac{1}{2}\,\bar{\psi}\,\gamma_z \gamma_5\,\psi \;-\; i\psi^\dagger \left(\vec{x} \times \vec{\nabla}\right)_z \psi \;+\; \left(\vec{E} \times \vec{A}\right)_z \;+\; E_i \left(\vec{x} \times \vec{\nabla}\right)_z A_i \right]$$

- gauge-invariant way of writing J_z :

$$\hat{J}_z = \int d^3x \left[\frac{1}{2}\,\bar{\psi}\,\gamma_z \gamma_5\,\psi \;-\; i\psi^\dagger \left(\vec{x} \times \vec{D}\right)_z \psi \;+\; \left[\vec{x} \times \left(\vec{E} \times \vec{B}\right)\right]_z \right]$$

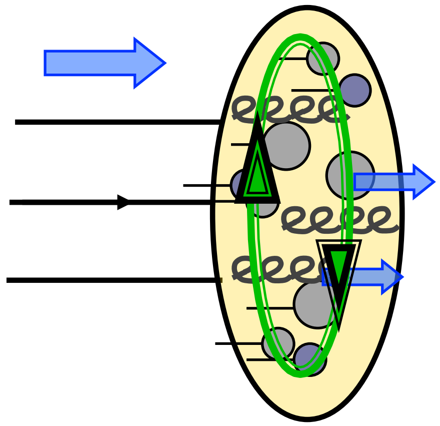
leads to

$$\frac{1}{2} = J_q + J_g$$

X. Ji

(measurable in DVCS & related)

- **alternatively, Parton Model (inf. momentum fr., $A^+=0$):**



Jaffe, Manohar; Jaffe, Bashinsky; Brodsky; Chen et al.

$$\hat{J}_z = \int d^3x \left[\frac{1}{2} q_+^\dagger \gamma_5 \, q_+ + \frac{1}{2} q_+^\dagger \left(\vec{x} \times \vec{\nabla} \right)_3 q_+ \right.$$
$$\left. + \left[A^1 F^{+2} - A^2 F^{+1} \right] + F^{+j} \left(\vec{x} \times \vec{\nabla} \right)_3 A^j \right]$$

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

- one can access the q and g spin contributions:

  do high energy scattering at large momentum transfer !

$$\Delta\Sigma = \int_0^1 dx \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x)$$

$$\Delta G = \int_0^1 dx\, \Delta g(x)$$

$\Delta g(x) =$

$$\Delta g(x) = \frac{1}{4\pi x P^+} \int dy^- \, \mathrm{e}^{-iy^- xP^+} \langle P, S \,|\, F^{+\alpha}\left(0, y^-, \mathbf{0}_\perp\right) \tilde{F}_\alpha{}^{+}(0) \,|\, P, S \rangle$$

Collins, Soper; Manohar

- **DGLAP evolution:**

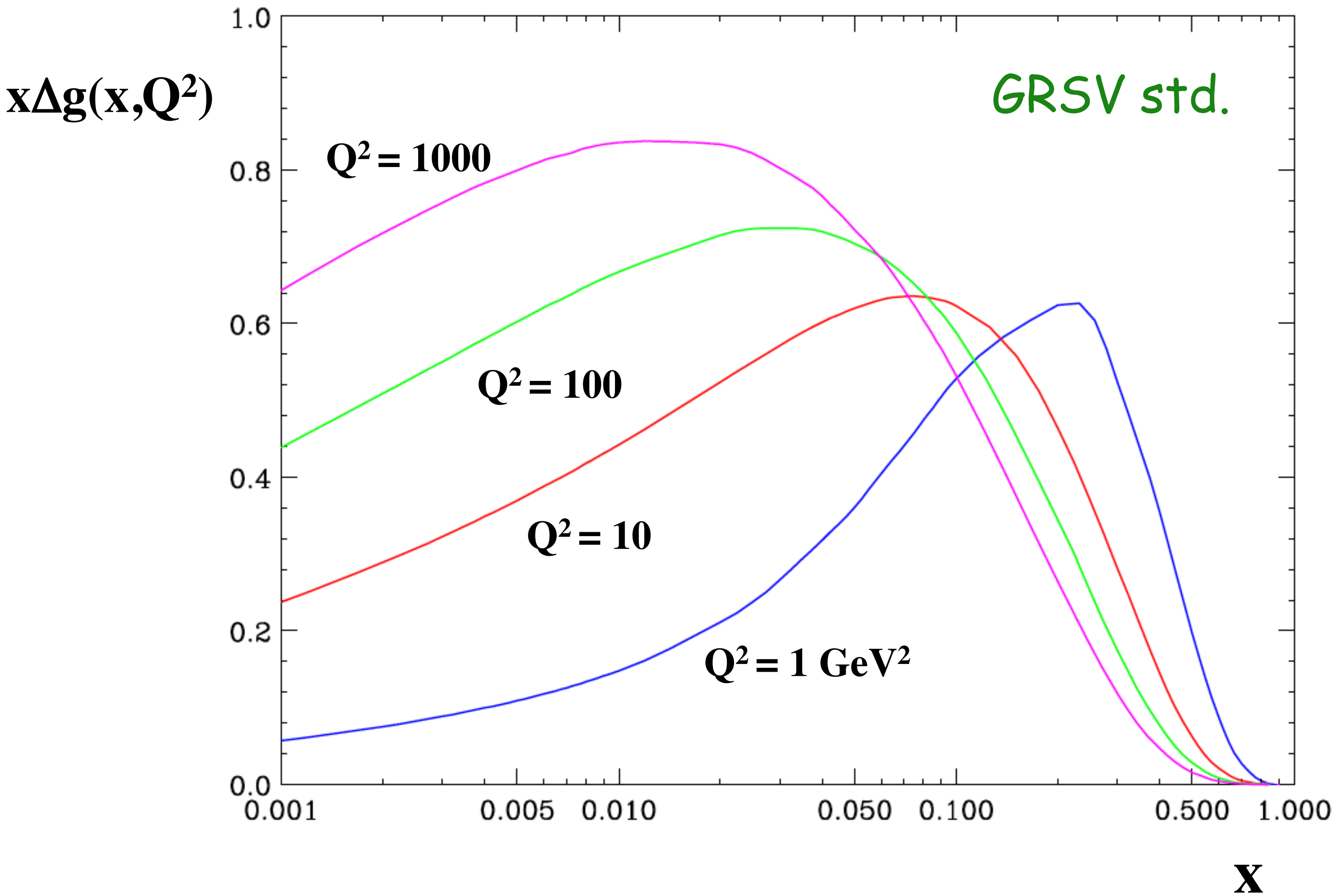
$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} \begin{pmatrix} \Delta q(x,\mu^2) \\ \Delta g(x,\mu^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} \left(\frac{x}{z},\mu^2\right)$$

$$\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta\mathcal{P}_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta\mathcal{P}_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta\mathcal{P}_{ij}^{\mathrm{NNLO}} + \ldots$$

Ahmed, Ross
Altarelli, Parisi, …

Mertig, van Neerven
WV

Moch, Rogal,
Vermaseren, Vogt
(ij = qq, qg)



Glück, Reya, Stratmann, WV '96 / '00

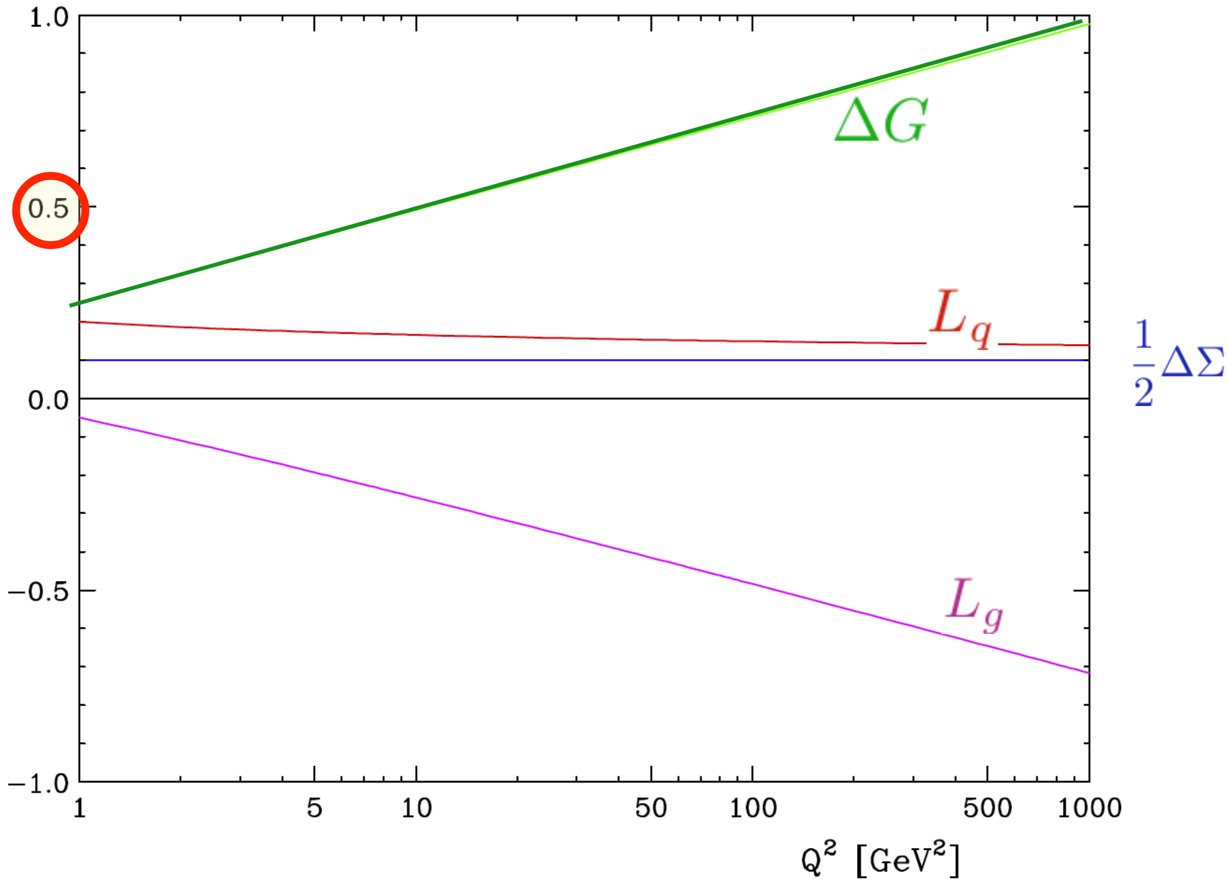
Evolution of first moment:

$$\frac{d}{d\log(Q^2)}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}0 & 0\\ \frac{3}{2}C_F & \frac{\beta_0}{2}\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}$$

$\Delta\Sigma \;=$ **const. at LO**

$$\Delta G(Q^2) = \frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\Delta G(Q_0^2) + \frac{3C_F}{\beta_0}\left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)} - 1\right)\Delta\Sigma$$

Increase ~Log(Q^2) as you look "deeper into the proton" !



Hoodbhoy, Ji;
Hägler, Schäfer

Asymptotically :

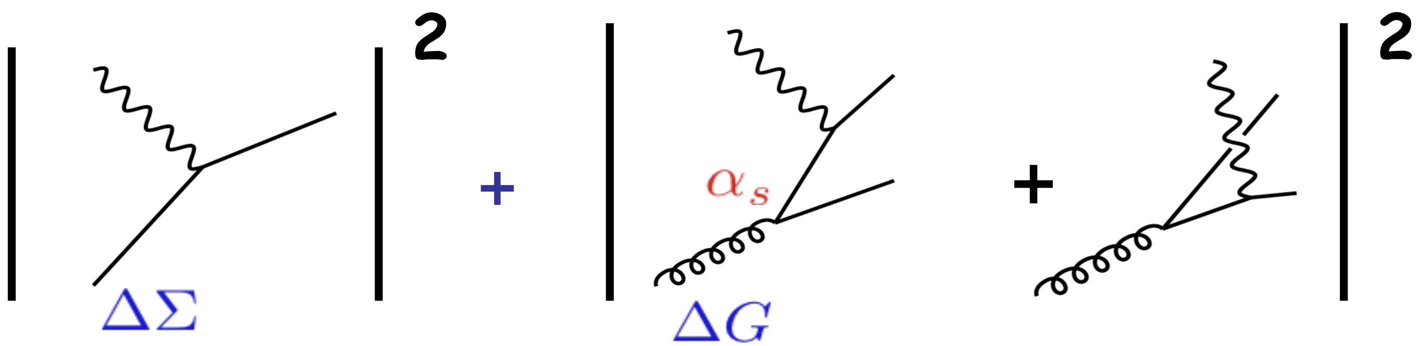
$$L_q + \frac{1}{2}\Delta\Sigma \approx L_g + \Delta G$$

Ji

- **early expectations of a large ΔG :**

Altarelli, Ross;
Altarelli, Stirling;
Carlitz, Collins, Mueller; …

$$\Delta\Sigma \;\to\; \Delta\Sigma - n_f\,\underbrace{\frac{\alpha_s(Q^2)}{2\pi}\,\Delta G(Q^2)}_{\text{does not vanish at large } Q^2\,!}$$

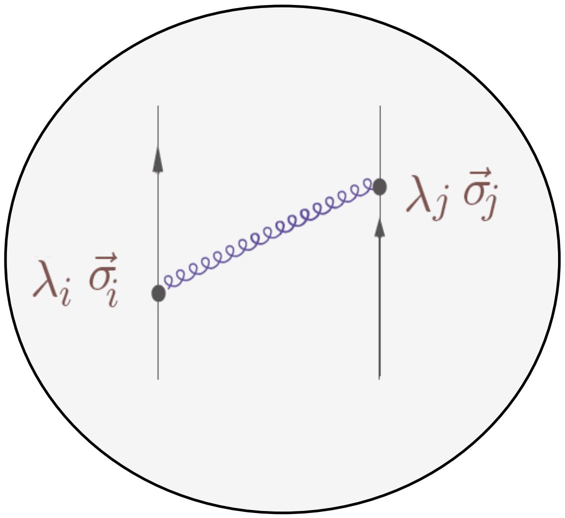


factorization scheme motivated by axial anomaly

- $\Delta\Sigma \approx 0.6$ if $\Delta G(Q^2 = 1\,\mathrm{GeV}^2) \approx 1.5 - 2$

Model expectations for Δg

Jaffe; Barone, Calarco, Drago; Lee, Min, Park, Rho, Vento;
Ji, Chen

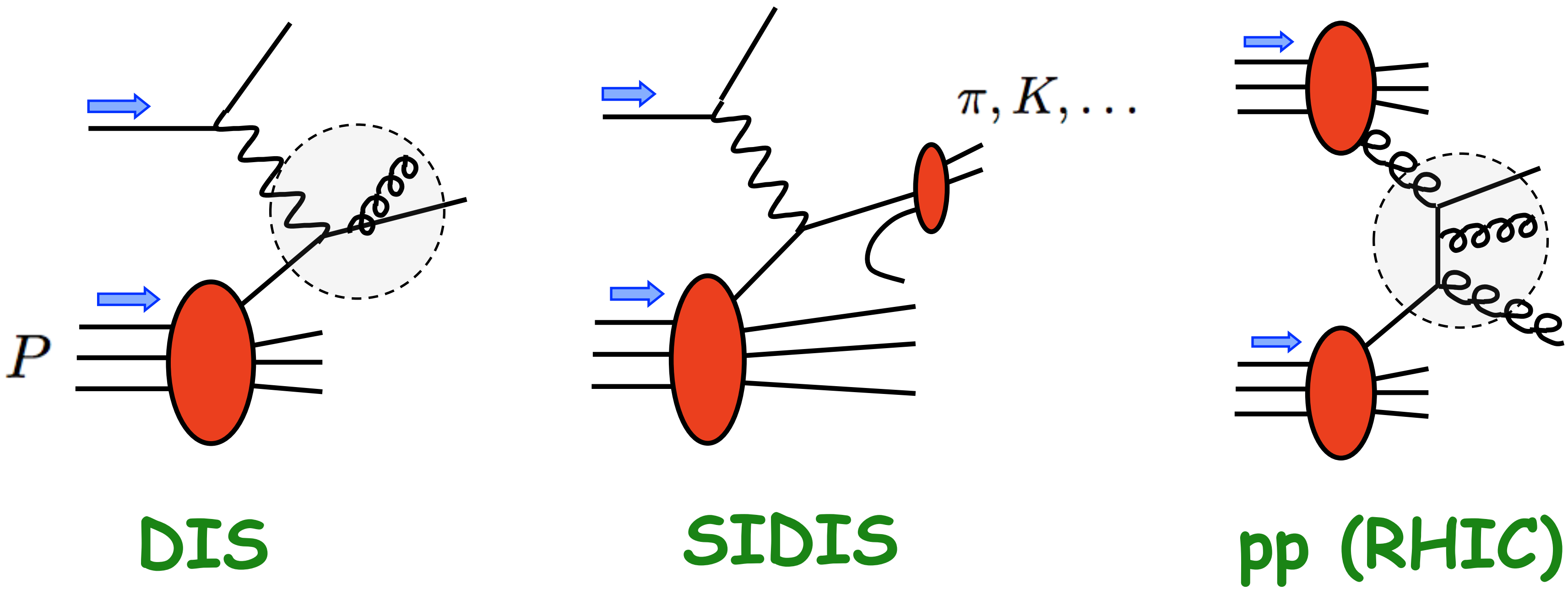


$$\Delta G = \langle p \uparrow | \int d^3x \, 2\mathrm{Tr}\left\{ \left(\vec{E} \times \vec{A} \right)_z + \vec{A}_\perp \cdot \vec{B}_\perp \right\} | p \uparrow \rangle$$

- typically $\Delta g \sim 0.2$ (positive !)

Where are we now ?

The probes of nucleon helicity structure :

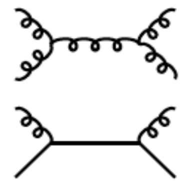
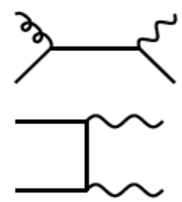
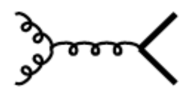


DIS $$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \Delta f(x,Q^2)\, \Delta\hat{\sigma}^f(xP, \alpha_s(Q^2)) + \ldots$$

pp $$\Delta\sigma = \sum_{a,b=q,\bar{q},g} \int dx_a\, \Delta f_a(x_a, p_\perp^2) \int dx_b\, \Delta f_b(x_b, p_\perp^2) \Delta\hat{\sigma}^{ab}(x_a P, x_b P', \alpha_s(p_\perp^2)) + \ldots$$

$$\Delta\hat{\sigma} = \Delta\hat{\sigma}_{\mathrm{LO}} + \alpha_s \Delta\hat{\sigma}_{\mathrm{NLO}} + \ldots$$

Polarized pp scattering (RHIC) :

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

NLO:

Jäger, Schäfer, Stratmann, WV

Jäger, Stratmann, WV; Signer et al.

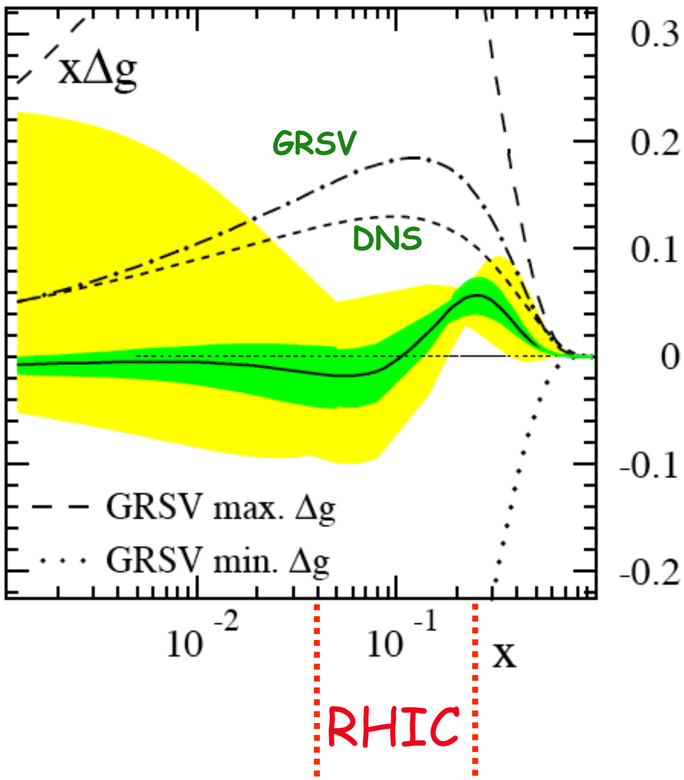
Gordon, WV; Contogouris et al.; Gordon, Coriano; Frixione. WV

Stratmann, Bojak

The latest:

Hadron+jet production D. de Florian, 0904.4402 [hep-ph]
(gamma+hadron in preparation)

Heavy quark correlations Riedl, Schäfer, Stratmann, 0911.2146



$Q^2 = 10\ \mathrm{GeV}^2$

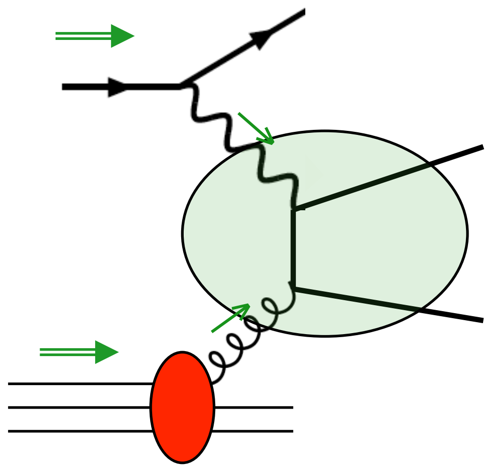
DSSV

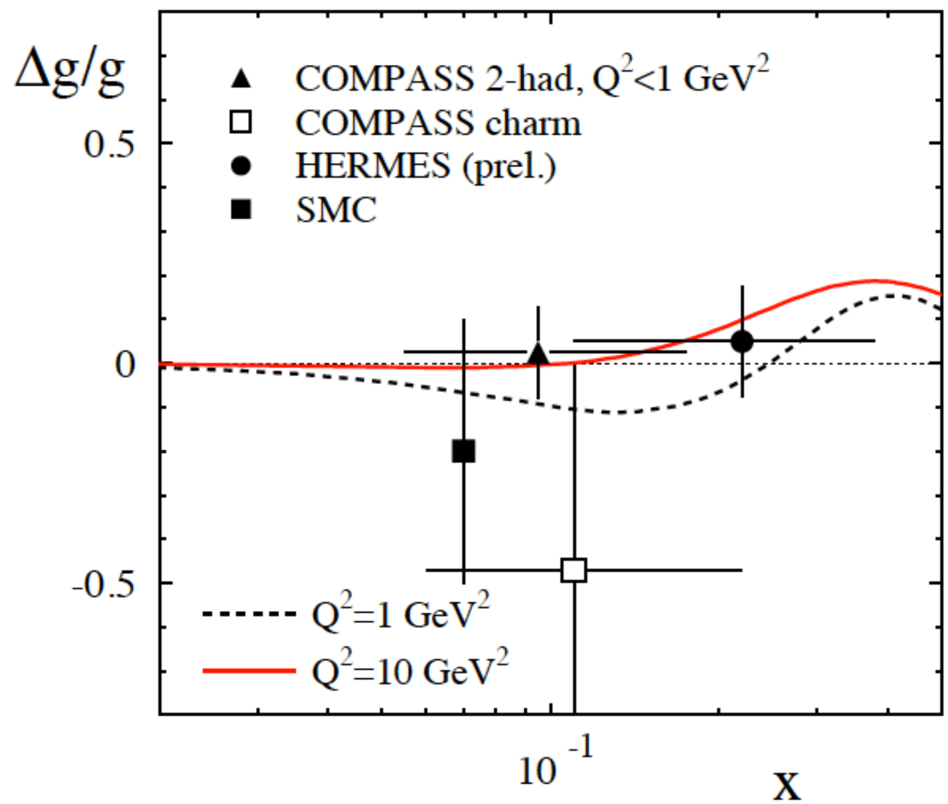
$$\int_{0.05}^{0.2} dx\, \Delta g \;=\; 0.006 \pm 0.06 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx\, \Delta g \;=\; -0.084 \pm ?$$

- there could still be significant contribution to proton spin

HERMES, COMPASS:





(not yet included in DSSV)

LO evolution of first moment:

$$\frac{d}{d\log(Q^2)}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}0 & 0\\ \frac{3}{2}C_F & \frac{\beta_0}{2}\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}$$

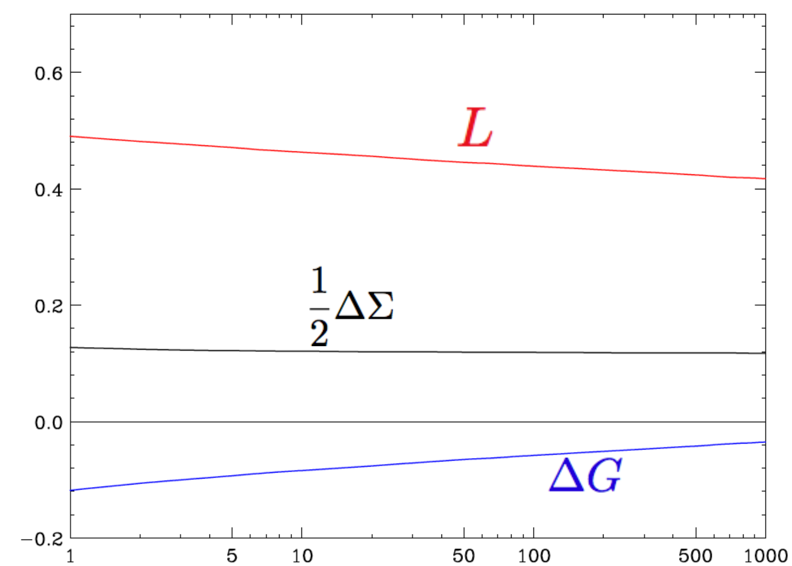
$$\Delta G(Q^2) = \frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\Delta G(Q_0^2) + \frac{3C_F}{\beta_0}\left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)} - 1\right)\Delta\Sigma$$

ΔG **does not evolve if** $\Delta G(Q_0^2) = -\frac{3C_F}{\beta_0}\Delta\Sigma \sim -\frac{1}{2}\Delta\Sigma$

DSSV has that:

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

$\approx 0\,?$



Where to go from here ?

"Discovery phase

$\longrightarrow$ precision phase"

Progress on various fronts:

(1) map out presently accessible x-range with better precision

(2) extend x-range (vary energy / kinematics, study correlations)

(3) look at variety of probes
(every channel can make impact in global analysis.
We are studying polarized QCD hard scattering !)

(4) find new observables (?)

Smaller x? **Larger x?**

Small x ? $x \leq 0.01$

- Quite possibly relevant for integral.
  With present information, Δg story is not complete!
- not so easy to access experimentally
- relatively little known from theoretical point of view
- does not mean it's not worth exploring !

- **what does DGLAP evolution tell us ?**

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \begin{pmatrix} \Delta\Sigma(x,\mu^2) \\ \Delta g(x,\mu^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix}_{(z,\alpha_s(\mu))} \cdot \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix} \left(\frac{x}{z},\mu^2\right)$$

- **at $x \to 0$ (and to lowest order):**

$$\begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix} (x,\alpha_s) \approx \frac{\alpha_s}{2\pi} \begin{pmatrix} C_F & -n_f \\ 2C_F & 4C_A \end{pmatrix} + \mathcal{O}(x)$$

- **compare unpolarized case:**

$$\begin{pmatrix} \mathcal{P}_{qq} & \mathcal{P}_{qg} \\ \mathcal{P}_{gq} & \mathcal{P}_{gg} \end{pmatrix} \approx \frac{\alpha_s}{2\pi} \frac{1}{x} \begin{pmatrix} 0 & 0 \\ 2C_F & 2C_A \end{pmatrix} + \mathcal{O}(1)$$

- solution (double-log approx. DLA):

Berera
Ball, Forte, Ridolfi
Gehrmann, Stirling

- interplay between input and pert. evolution:

  * "flat" input : small-x behavior driven by evolution

$$\Delta g(x,Q^2) \;\propto\; \frac{1}{\sqrt{4\pi\gamma_+\sqrt{\ln\frac{x_0}{x}\ln\frac{t}{t_0}}}}\,\exp\left[2\gamma_+\sqrt{\ln\frac{x_0}{x}\ln\frac{t}{t_0}}\;-\;\delta\ln\frac{t}{t_0}\right]$$

$$\gamma_+ \approx 2.5$$

  * power-like input $\Delta\Sigma\,,\,\Delta g \;\sim\; x^{-\alpha}$
    preserved under evolution -- rise indep. of Q^2

- for first case:

$$\frac{\Delta g(x,Q^2)}{xg(x,Q^2)} \;\propto\; \exp\left[2(\gamma_+-\gamma_u)\sqrt{\ln\frac{x_0}{x}\ln\frac{t}{t_0}}\;+\;\ldots\right]$$

- higher orders in the splitting functions at small x :

$$\Delta P(x) = \frac{\alpha_s}{2\pi} c_0 + \left(\frac{\alpha_s}{2\pi}\right)^2 c_1 \ln^2 x + \ldots + \left(\frac{\alpha_s}{2\pi}\right)^{k+1} c_k \ln^{2k} x + \ldots$$

- compare unpolarized case: (gq, gg spl. fcts.)

$$P(x) = \frac{\alpha_s}{2\pi} \frac{c_0'}{x} + \left(\frac{\alpha_s}{2\pi}\right)^2 c_1' \frac{\ln x}{x} + \ldots + \left(\frac{\alpha_s}{2\pi}\right)^{k+1} c_k' \frac{\ln^k x}{x} + \ldots$$

- all-order resummation in polarized case:

  Kirschner,Lipatov; Bartels,Ermolaev,Ryskin; Kwiecinski,Ziaja; Ermolaev,Greco,Troyan; Maul

- typically predict (steep) power-like rise

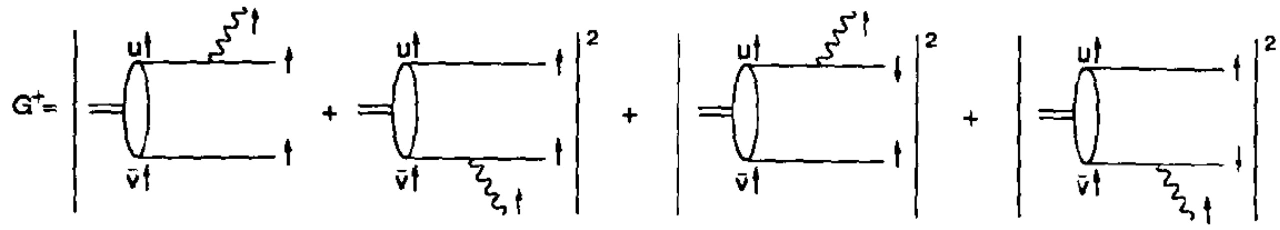
- however, subleading terms probably remain crucial

  Blümlein,Riemersma,Vogt

- model approach:

Brodsky, Schmidt

positronium



(a)

- argue that $\Delta g(x) \approx x g(x) \qquad x \to 0$

- CTEQ6M:

$$\int_0^{0.01} dx \, x \, g(x, Q^2 = 10) \; = \; 0.065 \qquad -0.1$$

$$\int_{0.3}^{1} dx \; g(x, Q^2 = 10) \; = \; 0.096 \qquad 0.017$$

$\int \Delta g$ [DSSV]

Large x ? $x \geq 0.2$

- not so easy to access experimentally
  (even in unpolarized case uncertainties large)

- expectation that ultimately $\Delta g/g \rightarrow 1$ as $x \rightarrow 1$

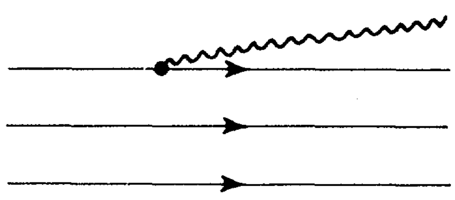
- nucleon wave function $\Delta f/f \rightarrow 1 \quad (x \rightarrow 1)$

  $Q^2 \sim Q_0^2$

  Brodsky, Burkardt, Schmidt

- evolution: $Q^2 > Q_0^2$

  Close, Sivers '77



$$g^+ \sim (1-x)\, q^+ \sim (1-x)^4$$

$$g^- \sim (1-x)^6$$

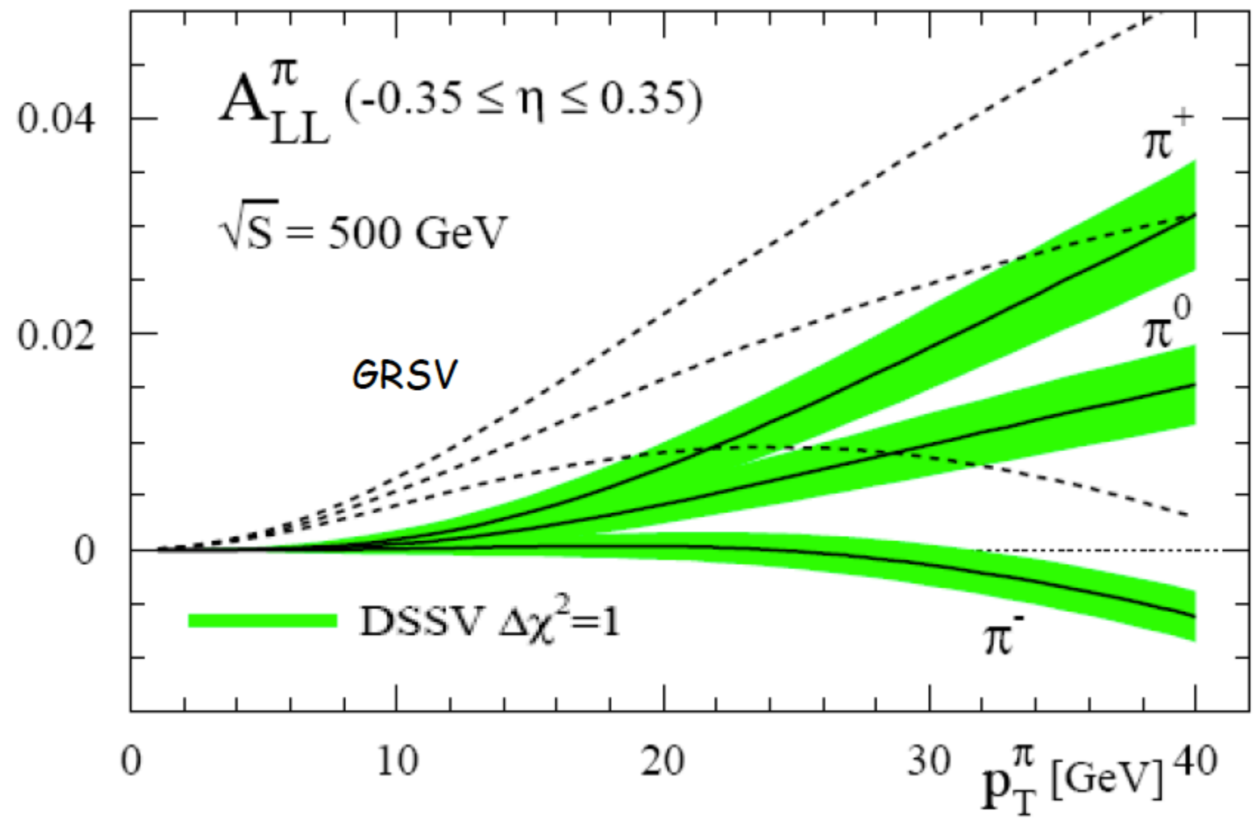
Some ideas for the future

(1) map out presently accessible x-range with better precision

(2) extend x-range

(3) look at variety of probes

(4) find new observables



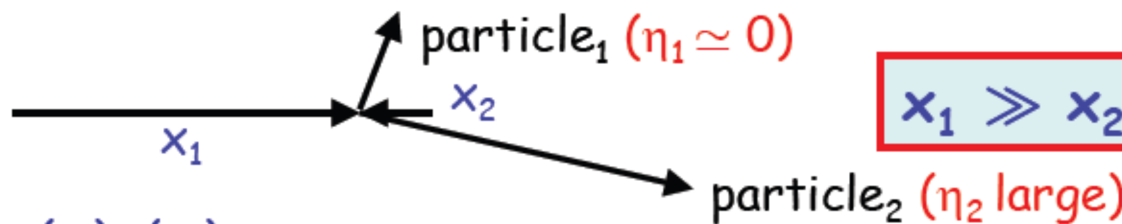
$$[\Delta u \otimes D_u^\pi + \Delta \bar{u} \otimes D_{\bar{u}}^\pi + \Delta d \otimes D_d^\pi + \Delta \bar{d} \otimes D_{\bar{d}}^\pi] \otimes \Delta g \xrightarrow[\text{expect}]{\text{properties of FFs}} A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-)$$

+ Photons, heavy flavors,…

- the obvious:
  higher energy <-> access to lower x
  lower energy <-> access to higher x

- **going beyond 1-inclusive: particle correlations**

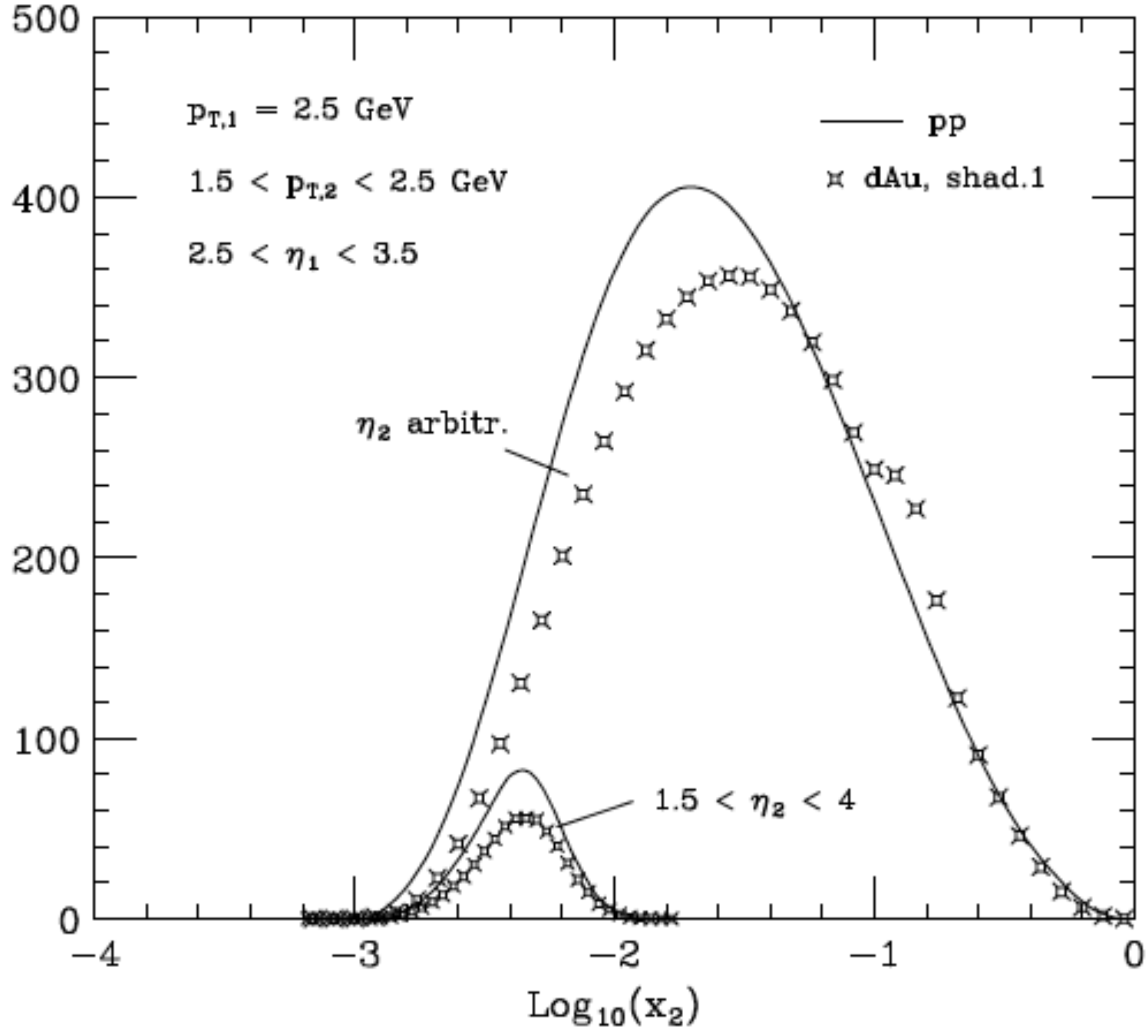
idea:
forward-central correlations



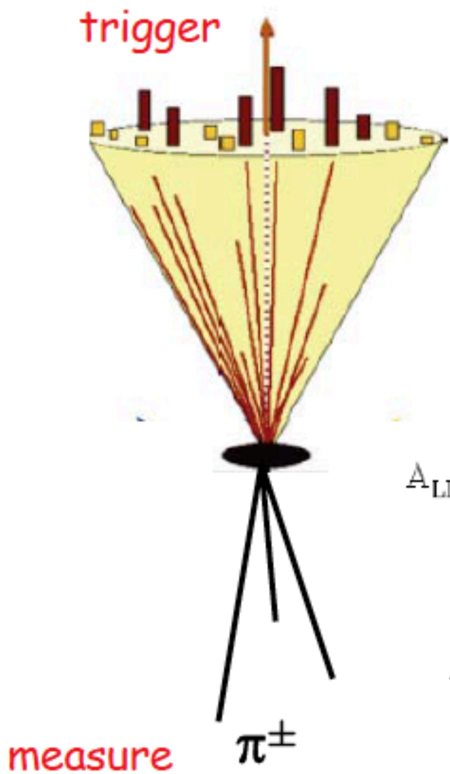
$\boxed{x_1 \gg x_2}$

$\rightarrow$ mainly qg-scatt.: $q(x_1)\, g(x_2)$

Guzey,Strikman,WV

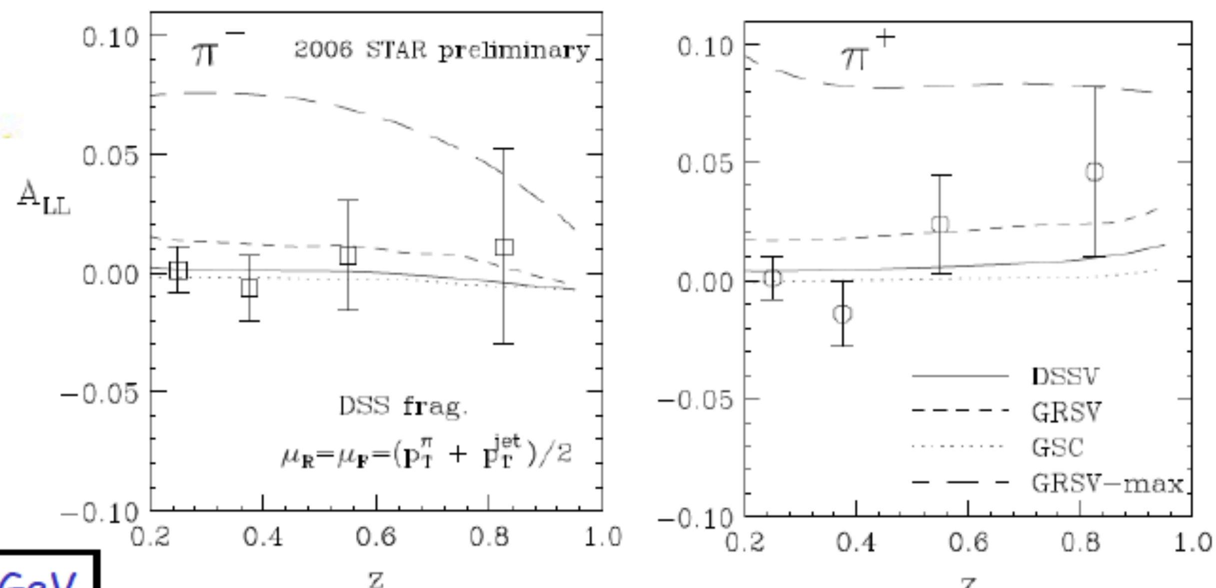


o 1st promising result from STAR: mid-rapidity $\pi^{\pm}$ w/ jet patch trigger



data compare well with a recent NLO calculation using DSS FFs & DSSV PDFs

de Florian, arXiv:0904.4402



$|\eta| \leq 1$; $p_T^{\pi} > 2$ GeV
$25 > p_T^{jet} > 10$ GeV

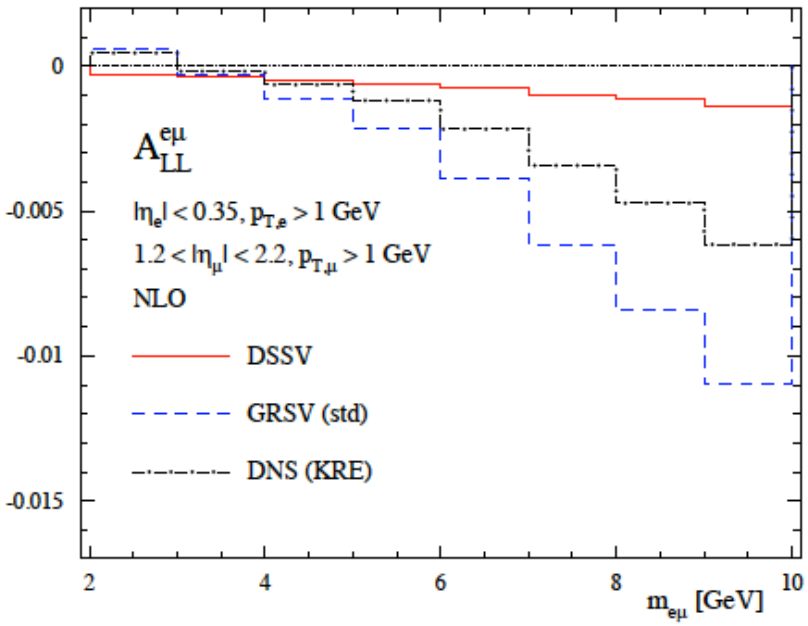
$z \simeq p_T^{\pi}/p_T^{jet}$

(courtesy M. Stratmann)

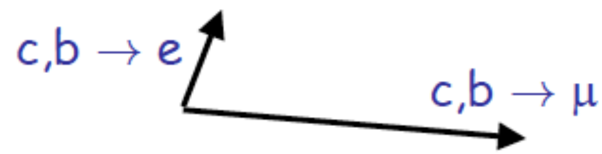
o expectations for heavy flavor correlations

Riedl, Schafer, MS

obtained with new flexible NLO MC code; includes hadronization and leptonic decays

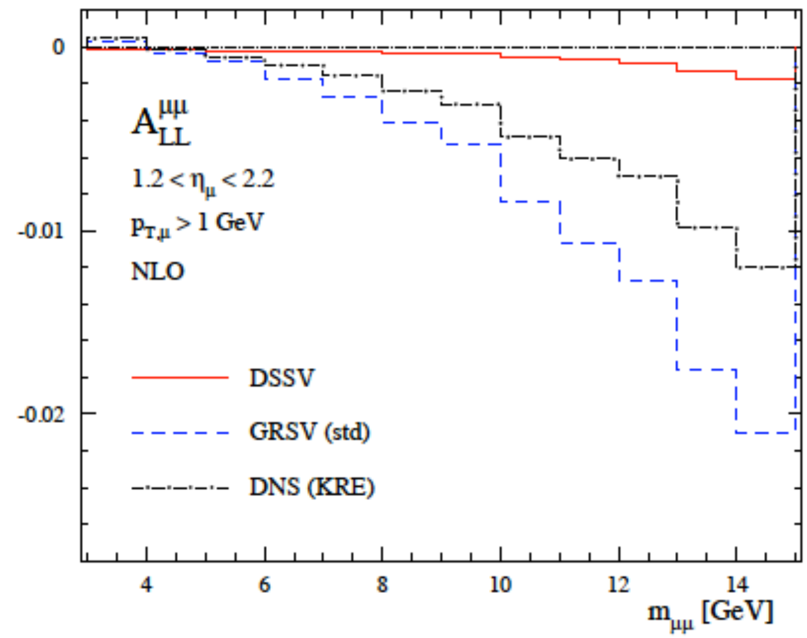


forward-central e-μ coincidences



note: single-e & single-μ have tiny A_{LL}'s

forward-backward μ-μ coincidences



(courtesy M. Stratmann)

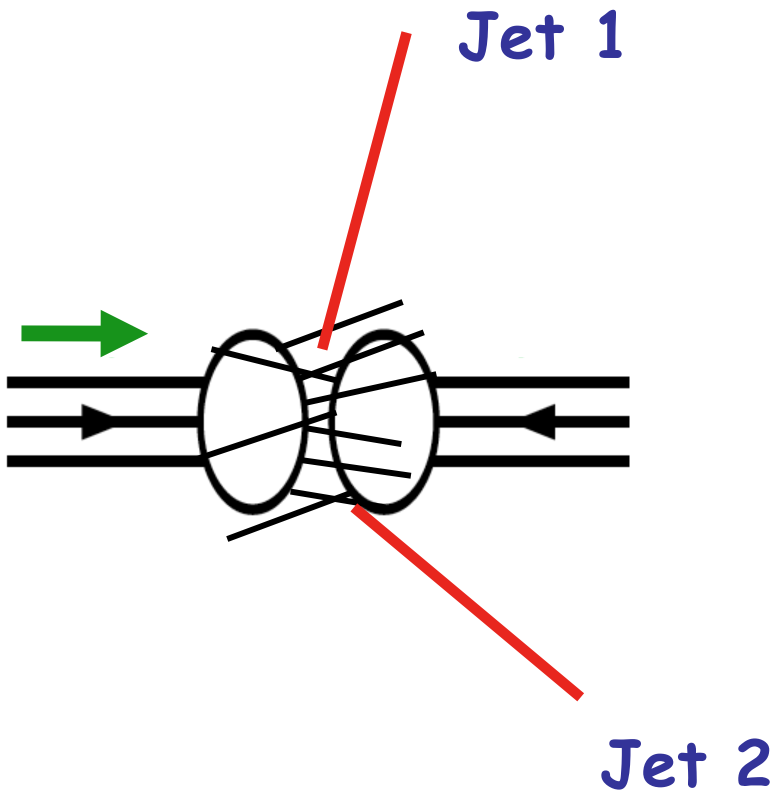
(4) find new observables:

An example …

We all know that with Parity Violation we can have

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$

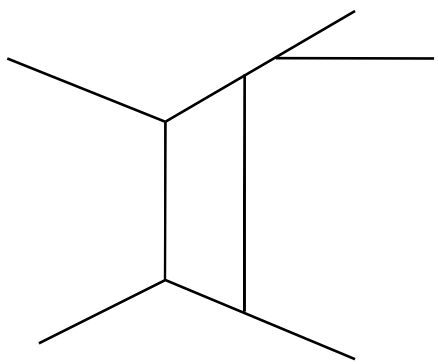
However, the converse is not necessarily true



$$\vec{S}_L \cdot \left(\vec{P}_{T,1} \times \vec{P}_{T,2}\right)$$

$$\vec{P}_{T,1} + \vec{P}_{T,2} \neq 0$$

- parity conserving
- jets must not be back-to-back
- however, T-odd can arise from loops



Conclusions & Outlook:

- We have learned a lot !
- But we are not there yet.

  (1) map out presently accessible x-range with better precision

  (2) extend x-range

  (3) look at variety of probes

  (4) find new observables

- Keep in mind, the integral ΔG is only one aspect