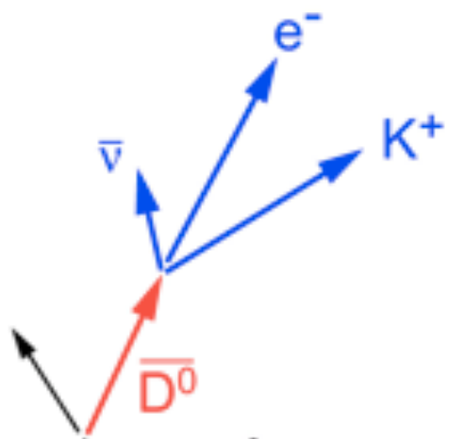
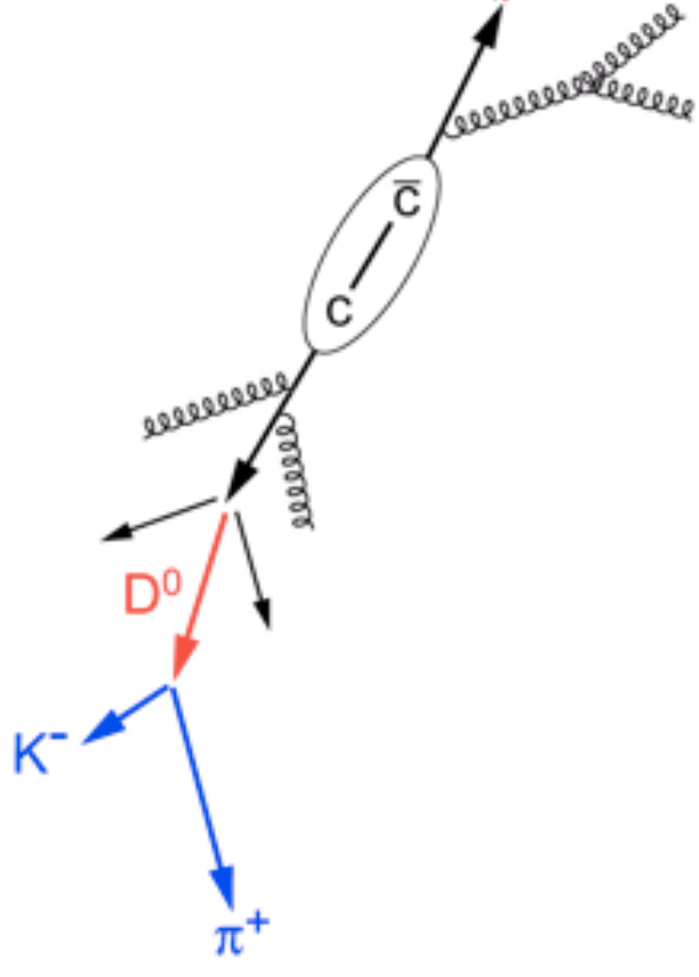
Heavy Quarks and Nucleon Spin Structure

Ernst Sichtermann (LBNL)

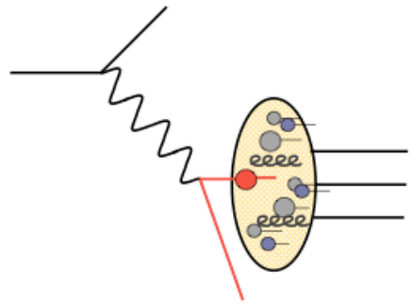


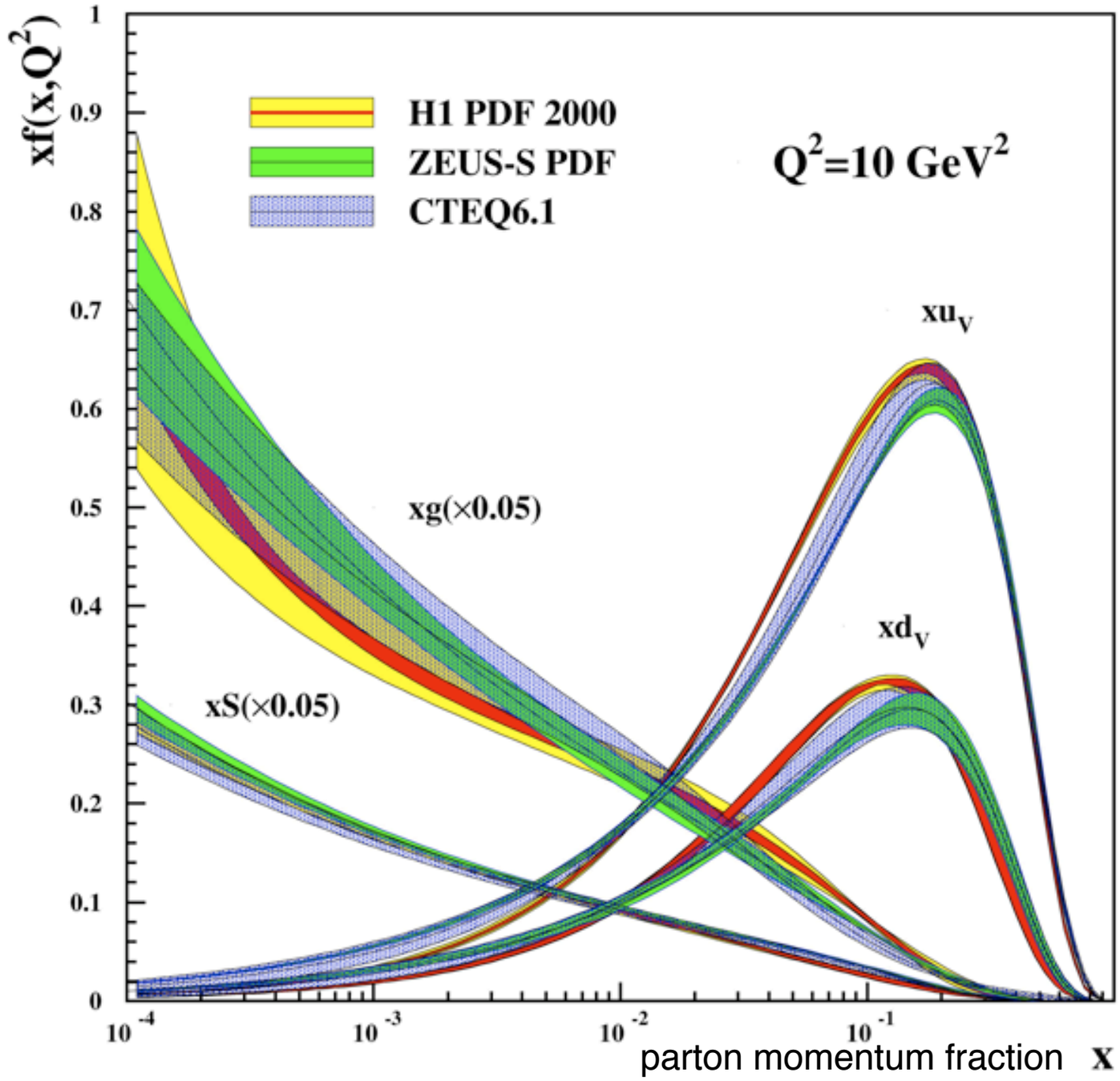
With thanks to:
Feng Yuan,
Xin Dong
Wei Zhou
Qinghua Xu
Ming Liu
and many others...



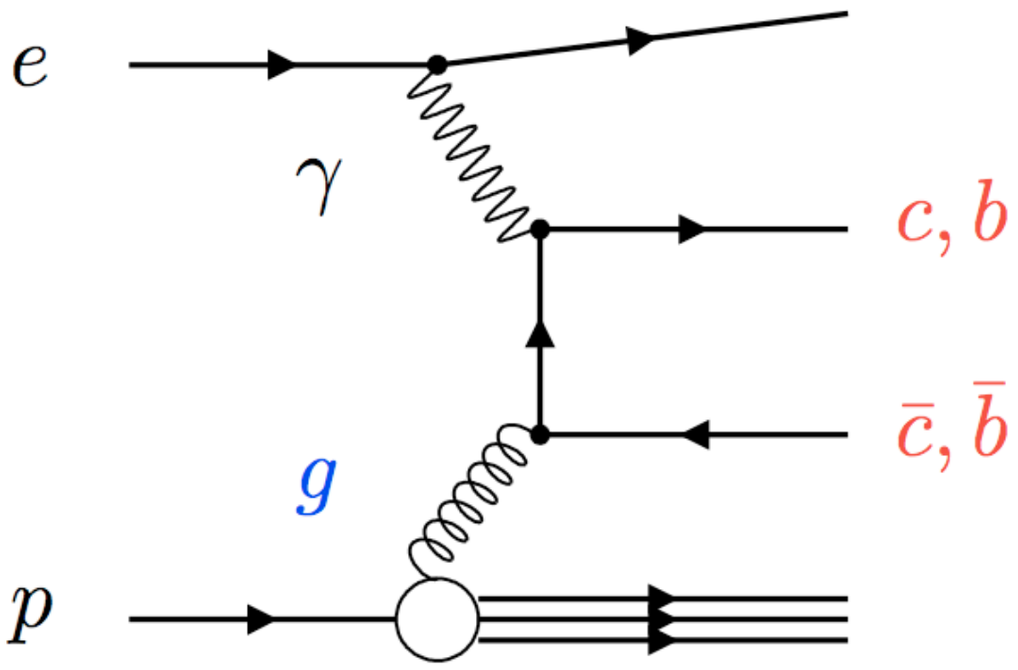
Nucleon Structure

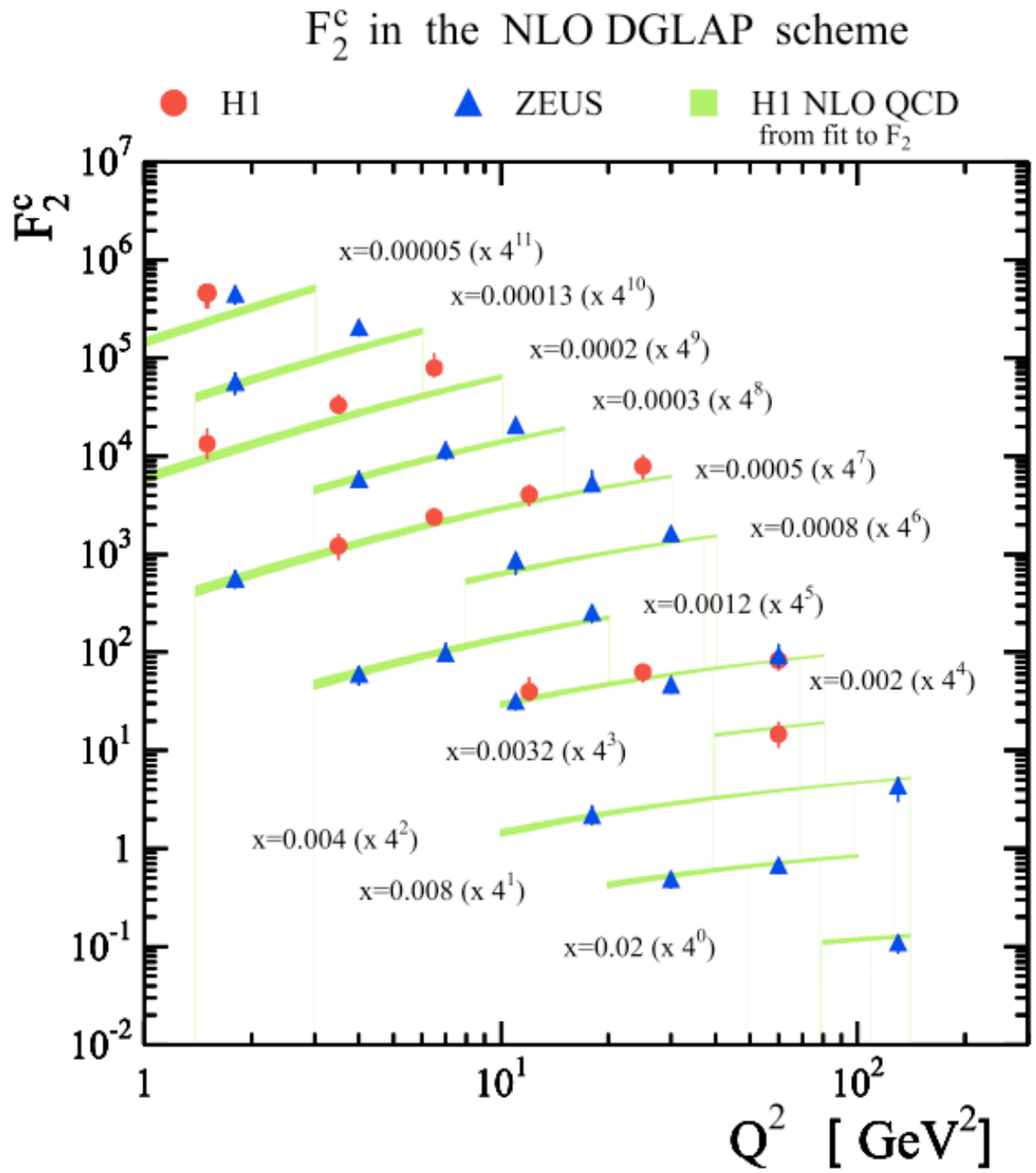
DIS





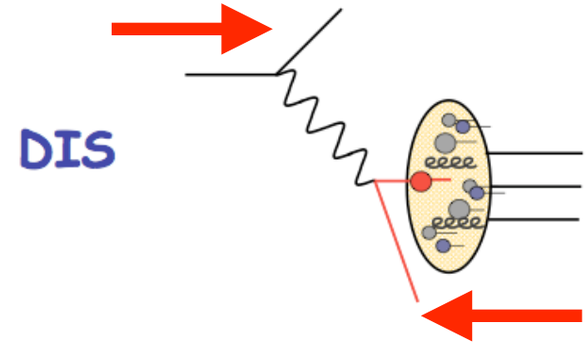
Heavy Quarks - Nucleon Structure





Major limitation for *spin* structure: proton *beam* at HERA not polarized,
however, HERMES had a polarized internal target.

Spin - Weak Decay



In probing the *polarized* proton,

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x = \int_0^1 \left(\frac{1}{2}\sum e_q^2 \Delta q(x)\right)\mathrm{d}x = \frac{1}{2}\left(\frac{4}{9}\Delta_1 u + \frac{1}{9}\Delta_1 d + \frac{1}{9}\Delta_1 s\right)$$

$$= \frac{1}{12}\left(\Delta_1 u - \Delta_1 d\right) + \frac{1}{36}\left(\Delta_1 u + \Delta_1 d - 2\Delta_1 s\right) + \frac{1}{9}\left(\Delta_1 u + \Delta_1 d + \Delta_1 s\right)$$

Known from weak neutron to proton decay

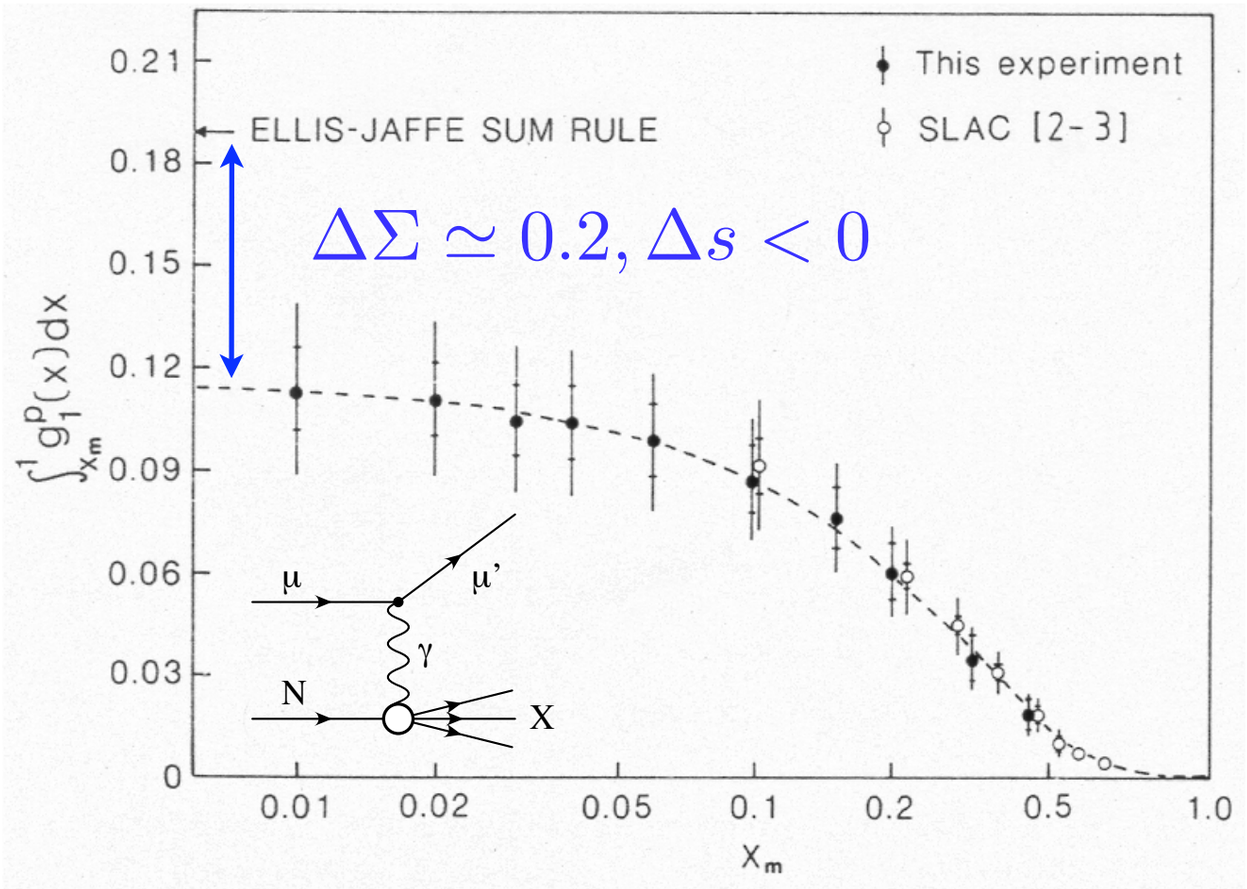
Known from weak neutron to proton decay, combined with weak ∑ to neutron decay

Unique to DIS

This becomes a prediction if $\Delta_1 s = 0$, i.e.
if strange quark spins do not contribute.

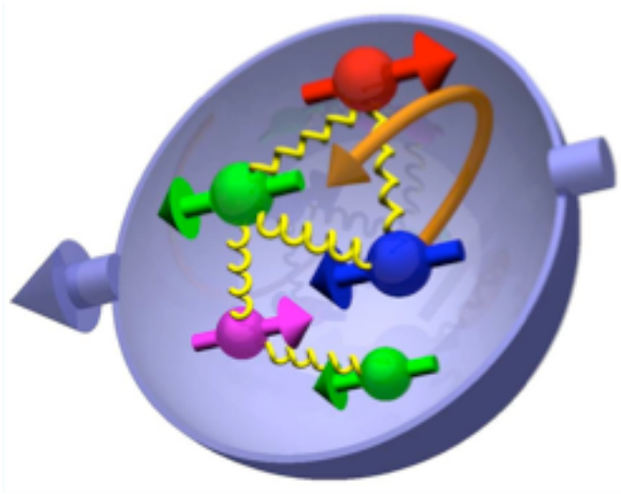
Proton Spin Structure - circa 1985

- Polarized DIS - European Muon Collaboration:



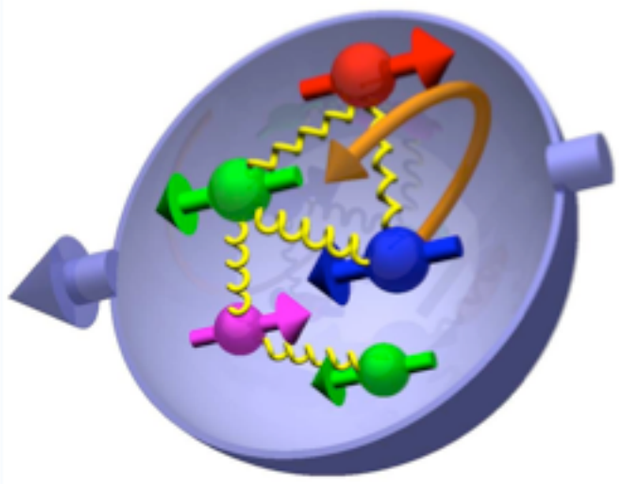
- *Quark spins carry only a small fraction of the proton spin,*
- *Strange sea is negatively polarized.*

- SMC, E142, E143, E155, and Hermes have since confirmed the EMC data.
- have tested the Bjorken Sum to ~7% precision.



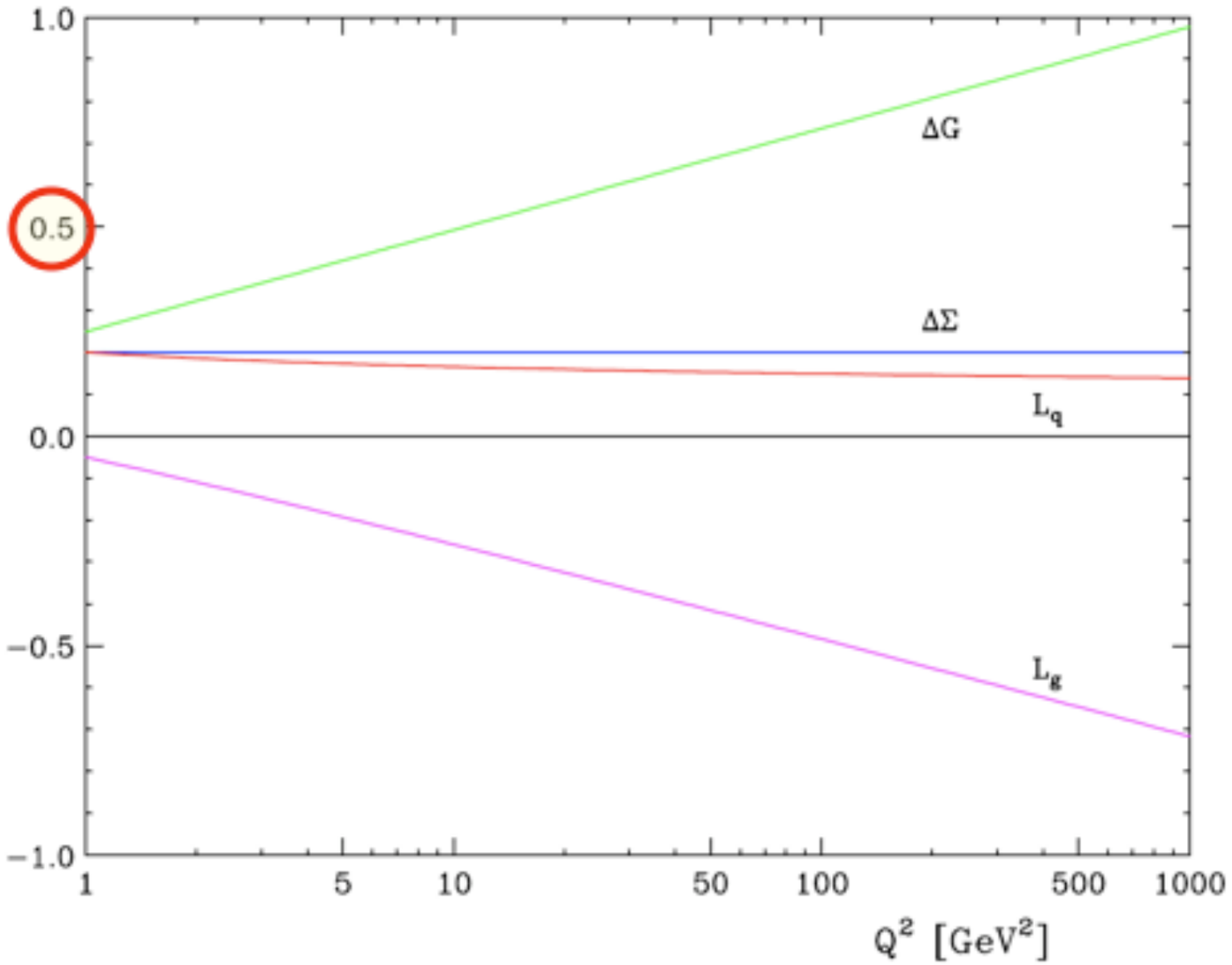
Some Open Questions

- Is the extrapolation over unmeasured small x justified?
- What does gluon polarization contribute to the proton spin?
- What are the quark and anti-quark polarizations by flavor?
- What orbital angular momenta do quarks and gluons carry?
- What is the role of transverse spins?



Asymptotic Conjectures*,

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



$$J_q = L_q + \frac{1}{2}\Delta\Sigma \to \frac{1}{2}\,\frac{3n_f}{16+3n_f}$$

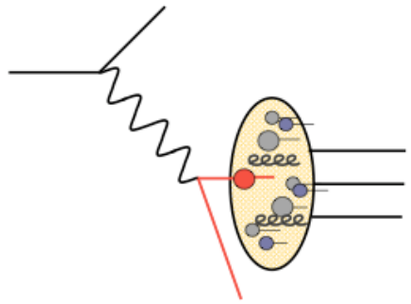
$$J_g = L_g + \Delta G \to \frac{1}{2}\,\frac{16}{16+3n_f}$$

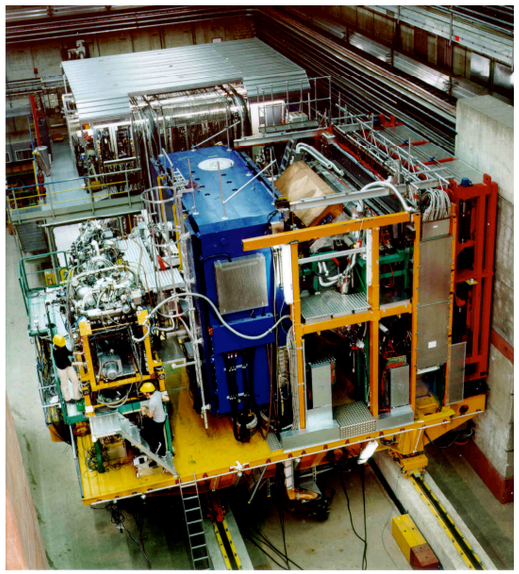
X. Ji

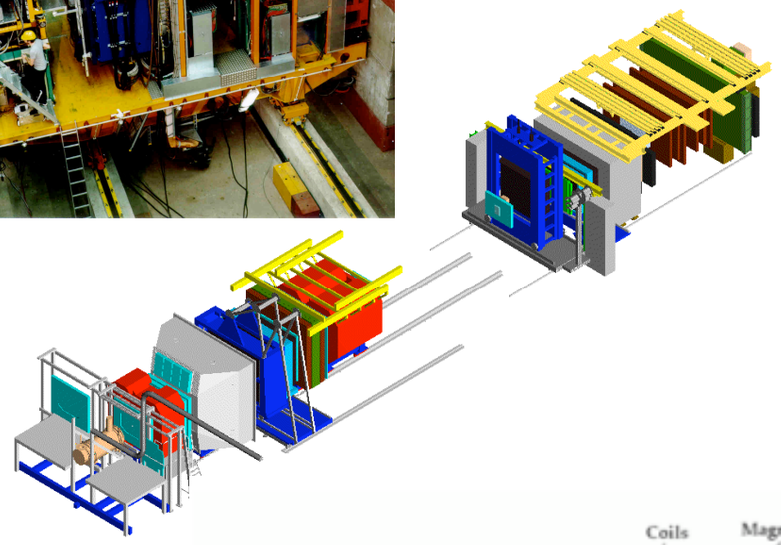
* in leading order, if the intrinsic contributions do not overwhelm radiatively generated contributions, ...
i.e. *perhaps*.

Active Spin Experiments

DIS



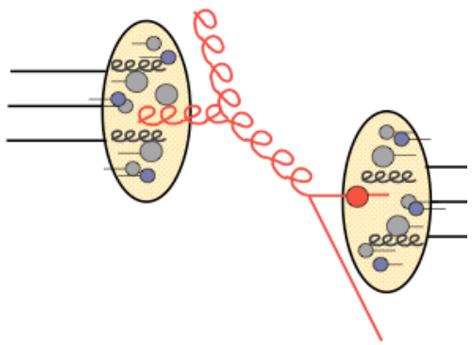


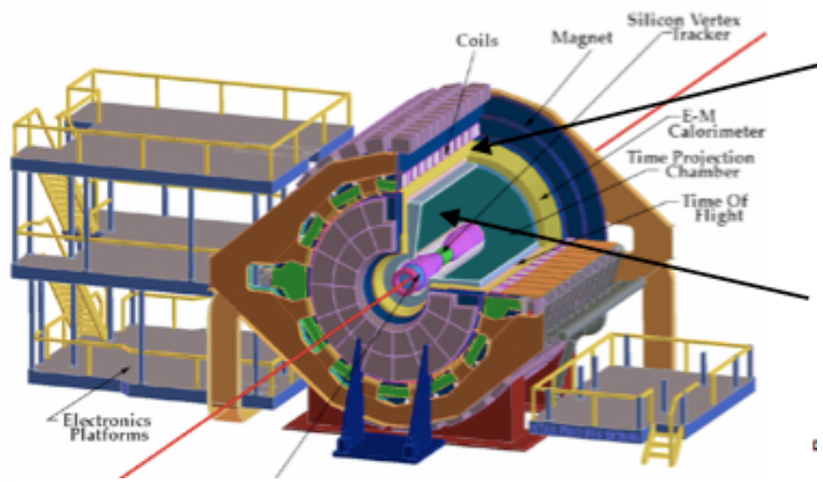


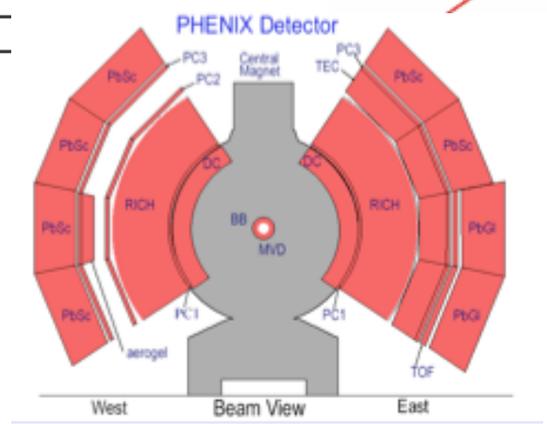
HERMES at DESY:
- 27 GeV electron beam,
- fixed target,
- PID

COMPASS at CERN:
- 160 GeV muon beam,
- fixed target,
- open spectrometer

pp



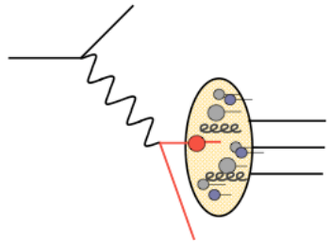


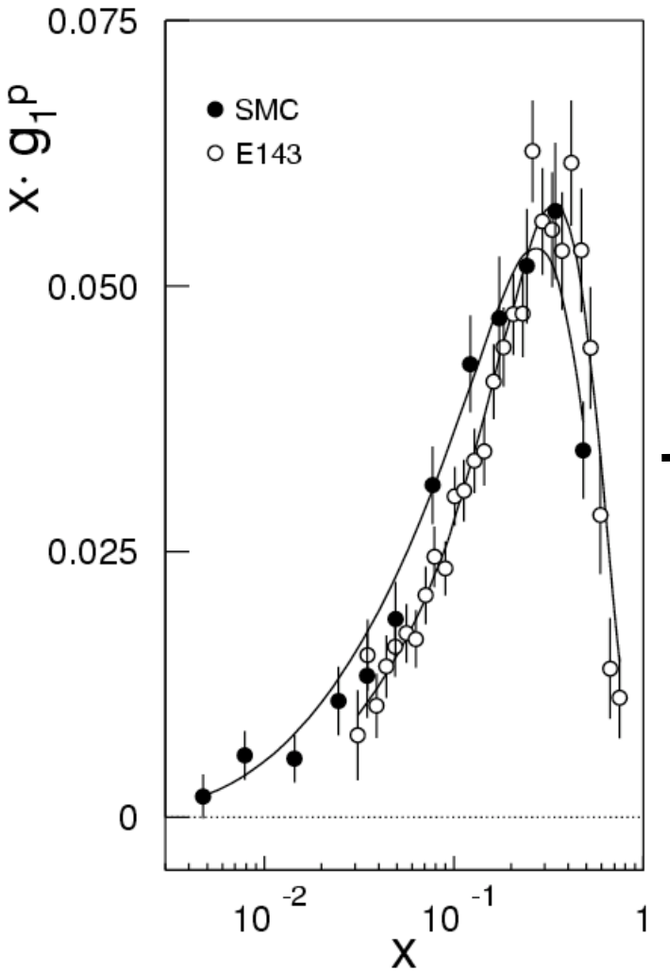


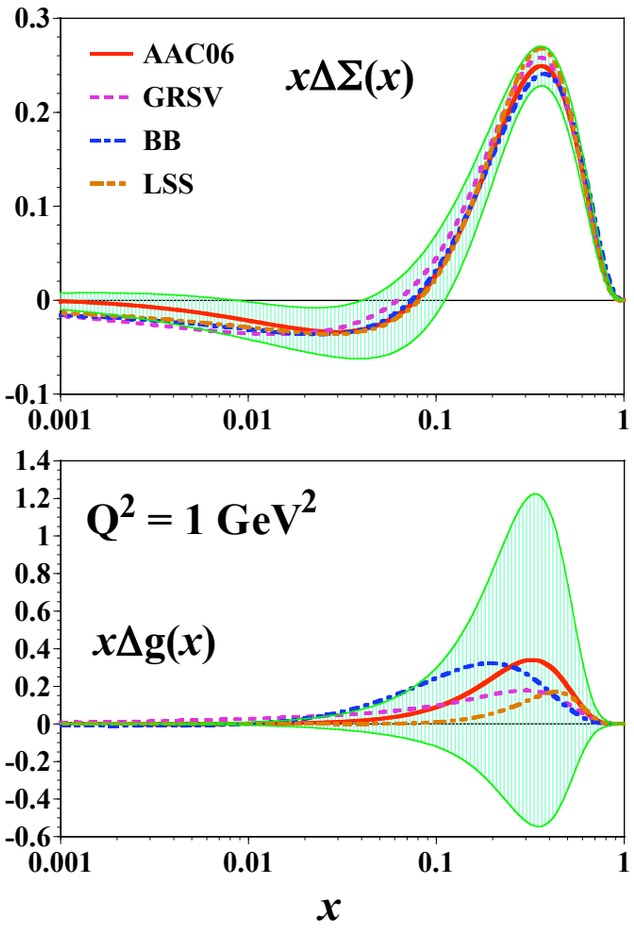
STAR at RHIC:
- 200-500 GeV E_{cms},
- large acceptance

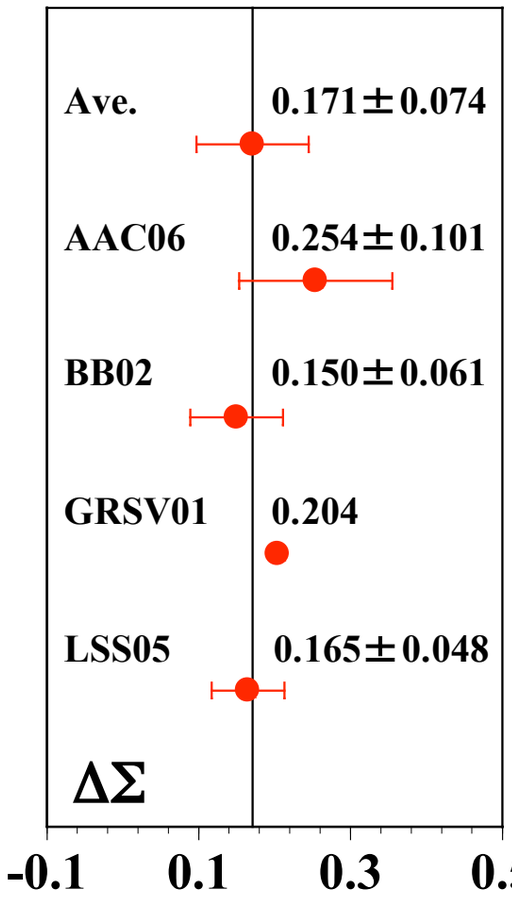
PHENIX at RHIC:
- high resolution,
- high rate

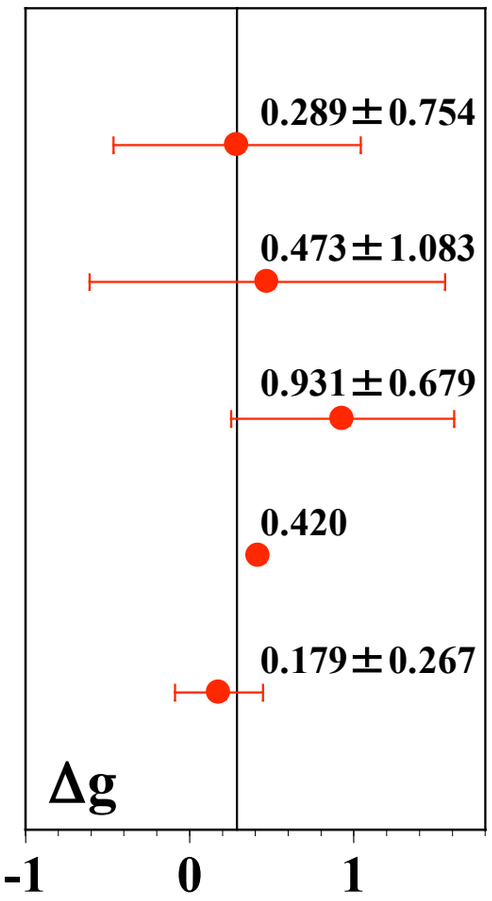
Polarized DIS - Scale Dependence





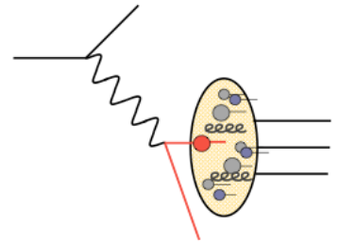


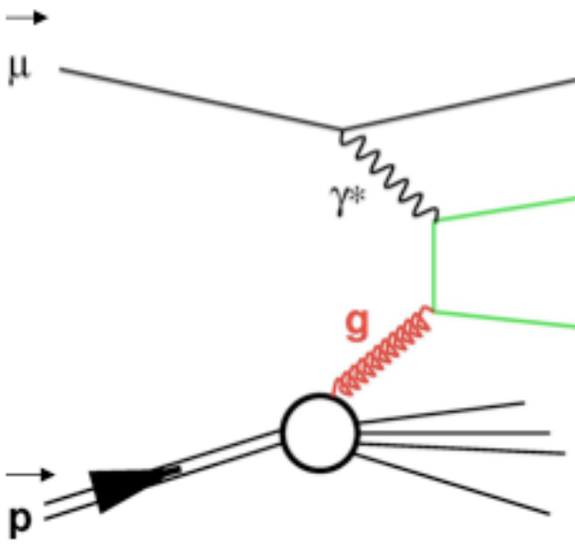


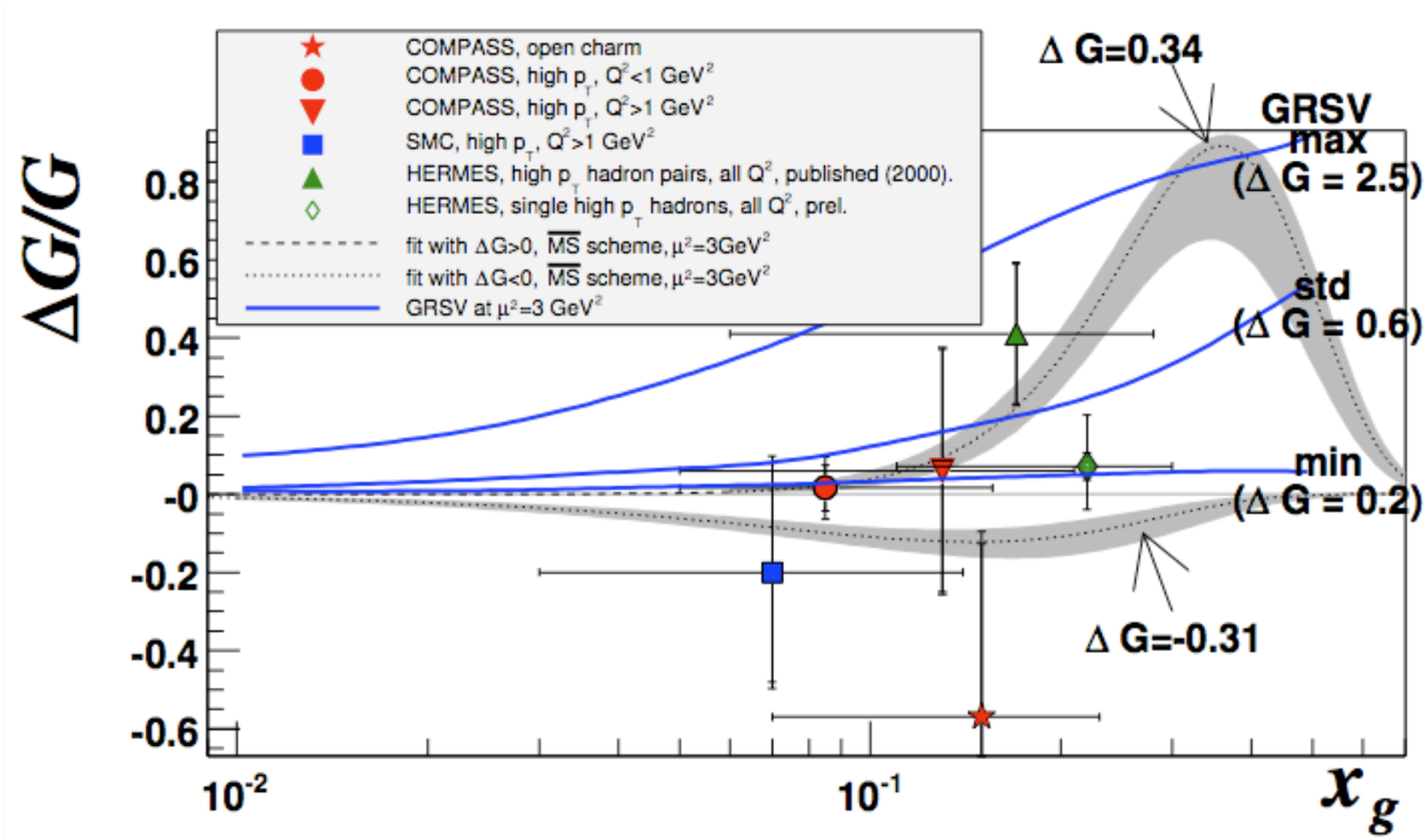


$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\begin{pmatrix}\Delta q(x,\mu^2)\\ \Delta g(x,\mu^2)\end{pmatrix} = \int_x^1 \frac{dz}{z}\begin{pmatrix}\Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg}\\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg}\end{pmatrix}_{(z,\alpha_s(\mu))} \cdot \begin{pmatrix}\Delta q\\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

Polarized DIS - Heavy Quarks





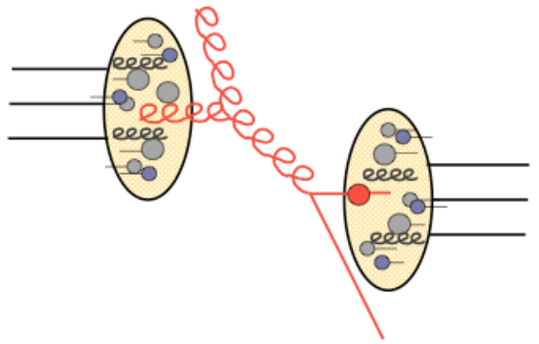


Measurements of:

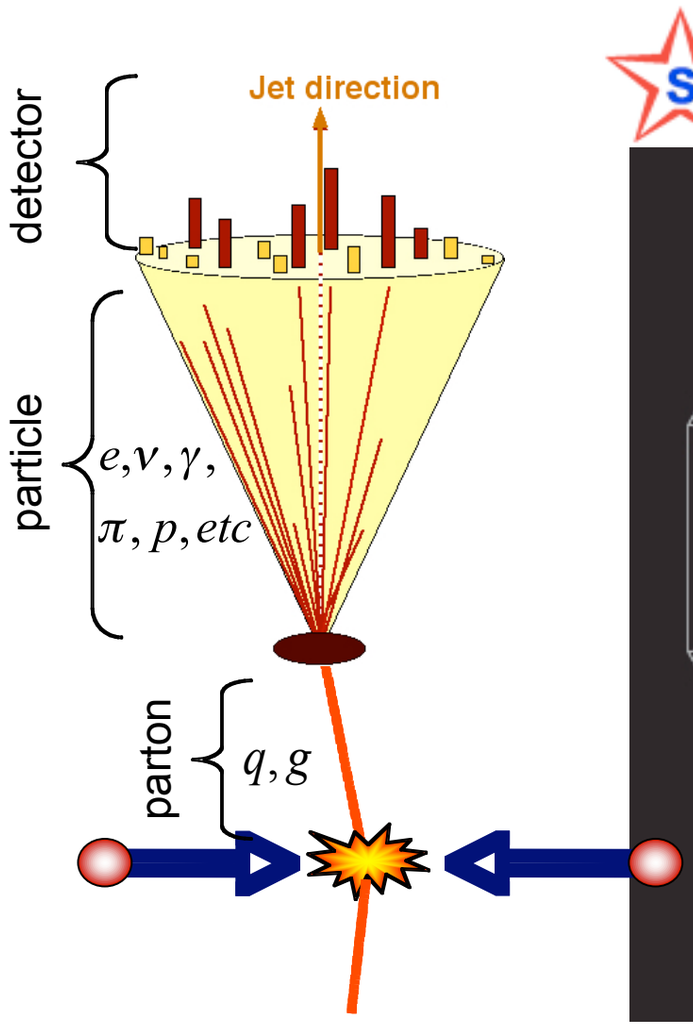
- open charm (clean, but rare), and

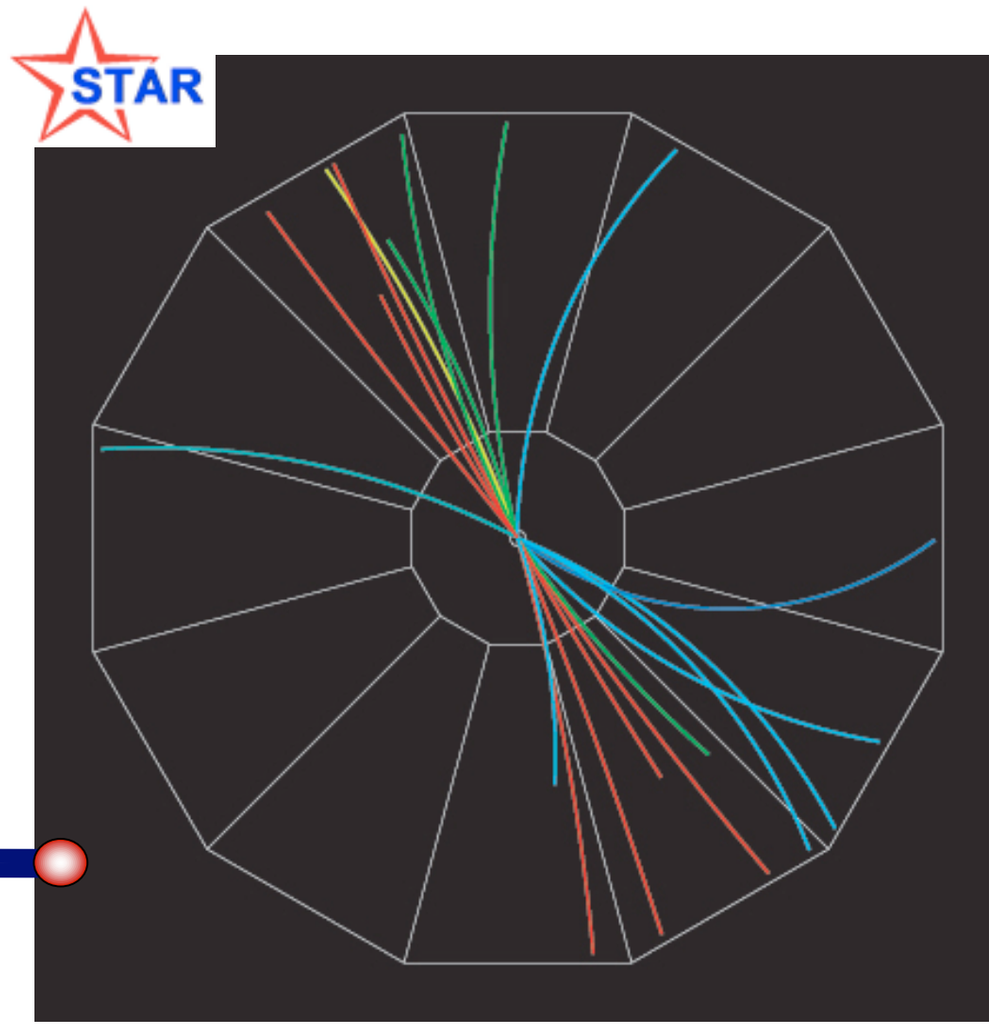
- high-p_T hadron pairs (high and low Q^2)

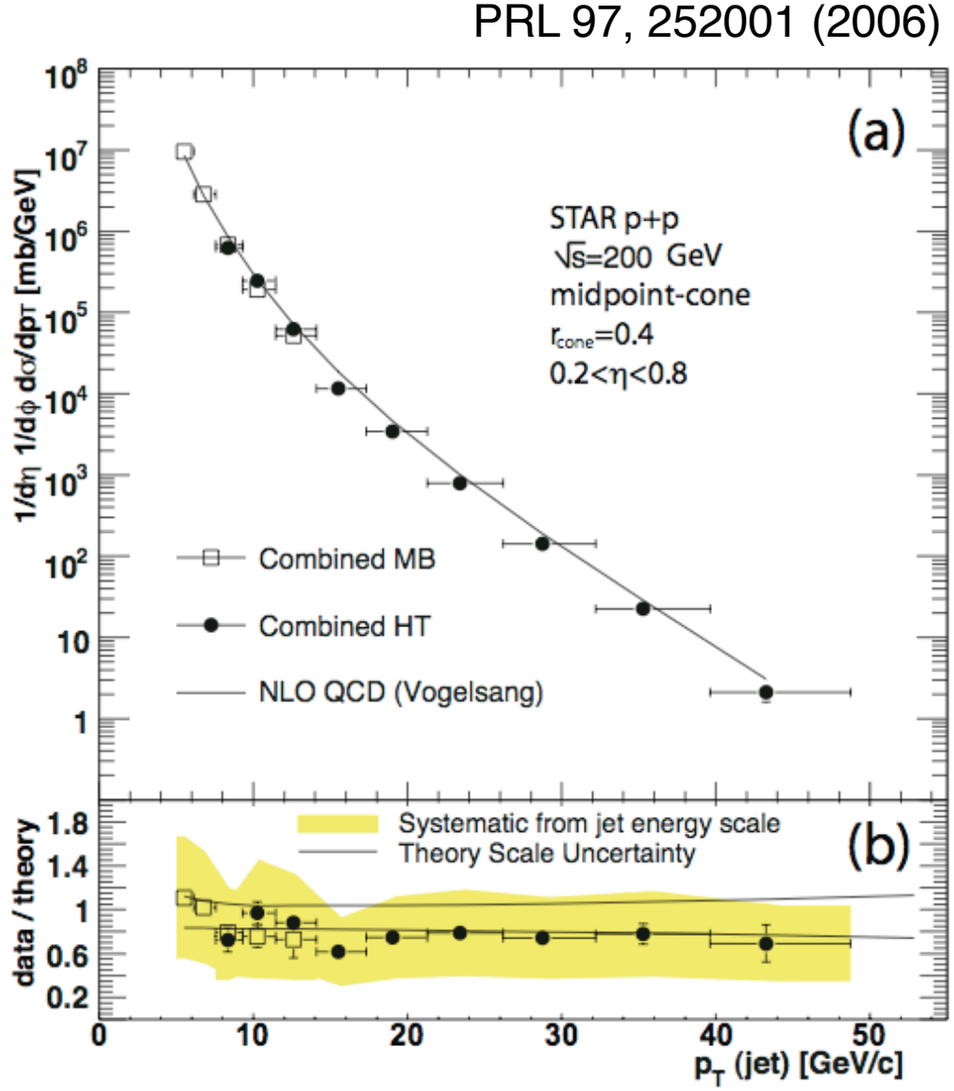
Polarized Proton Collisions at RHIC



PRL 97, 252001 (2006)

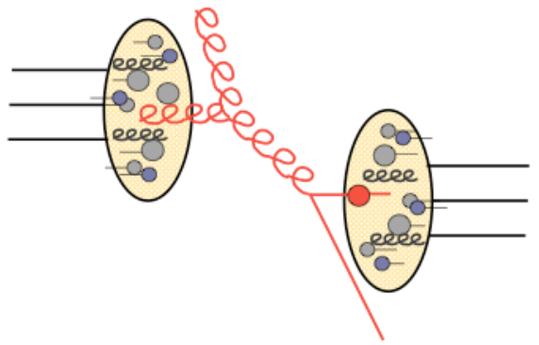






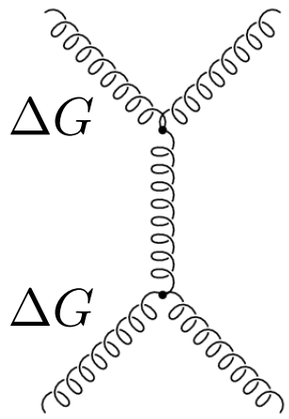
$$(\Delta)\sigma \propto (\Delta)f \otimes (\Delta)g \otimes (\Delta)\hat{\sigma}$$

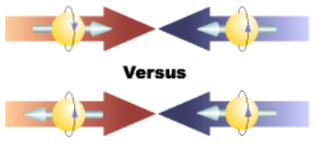
Polarized Proton Collisions at RHIC

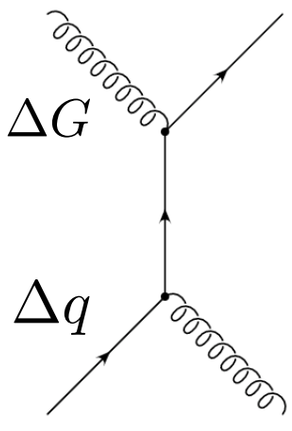


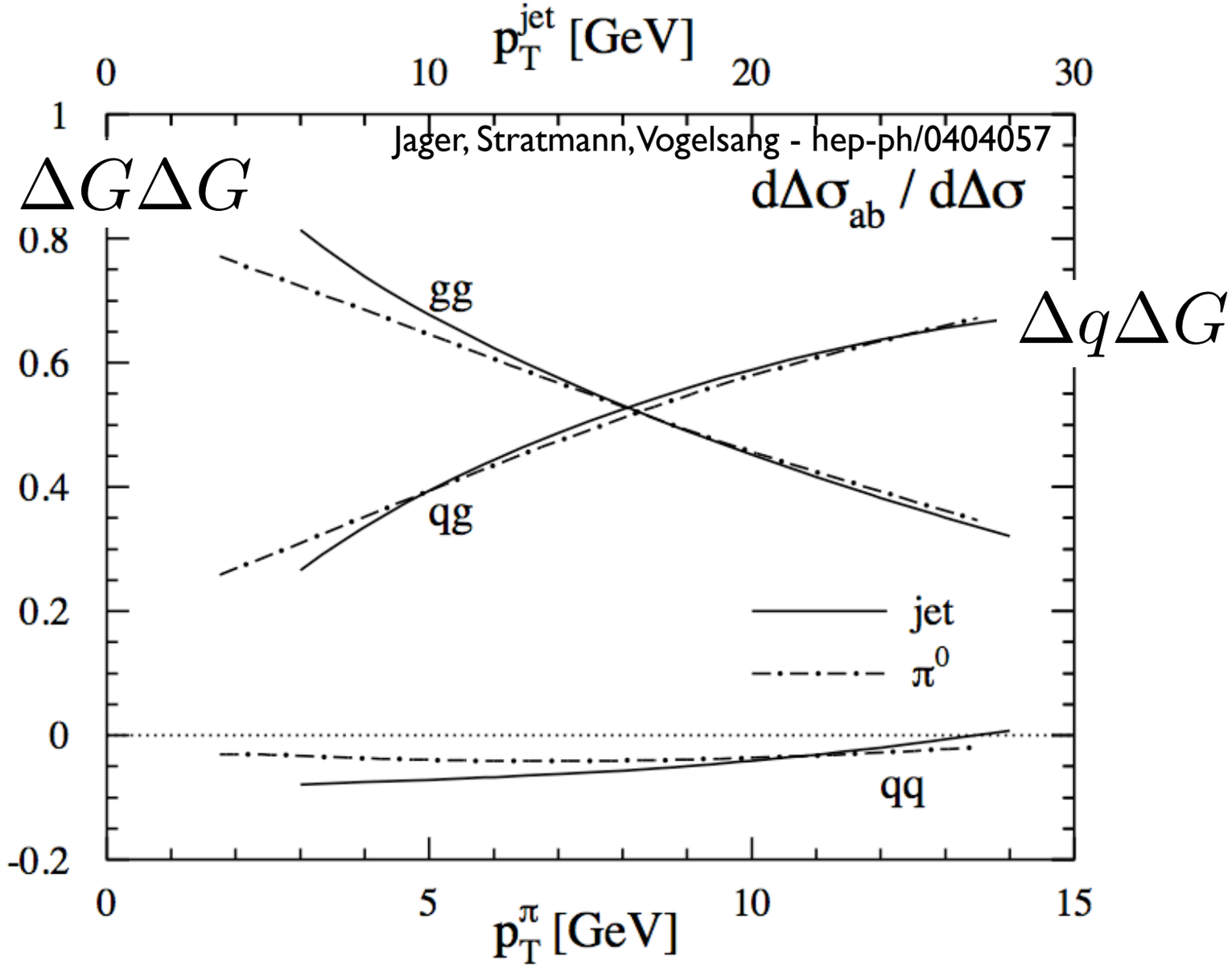
$$\vec{p} + \vec{p} \rightarrow \text{jet(s) or } \pi^0(s) + X$$

$$A_{LL} \propto$$



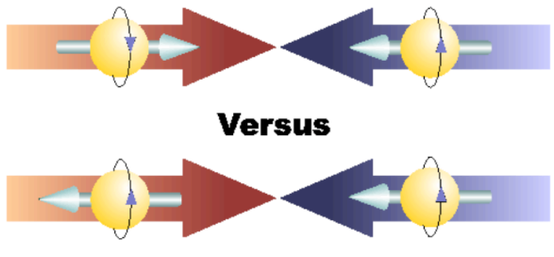


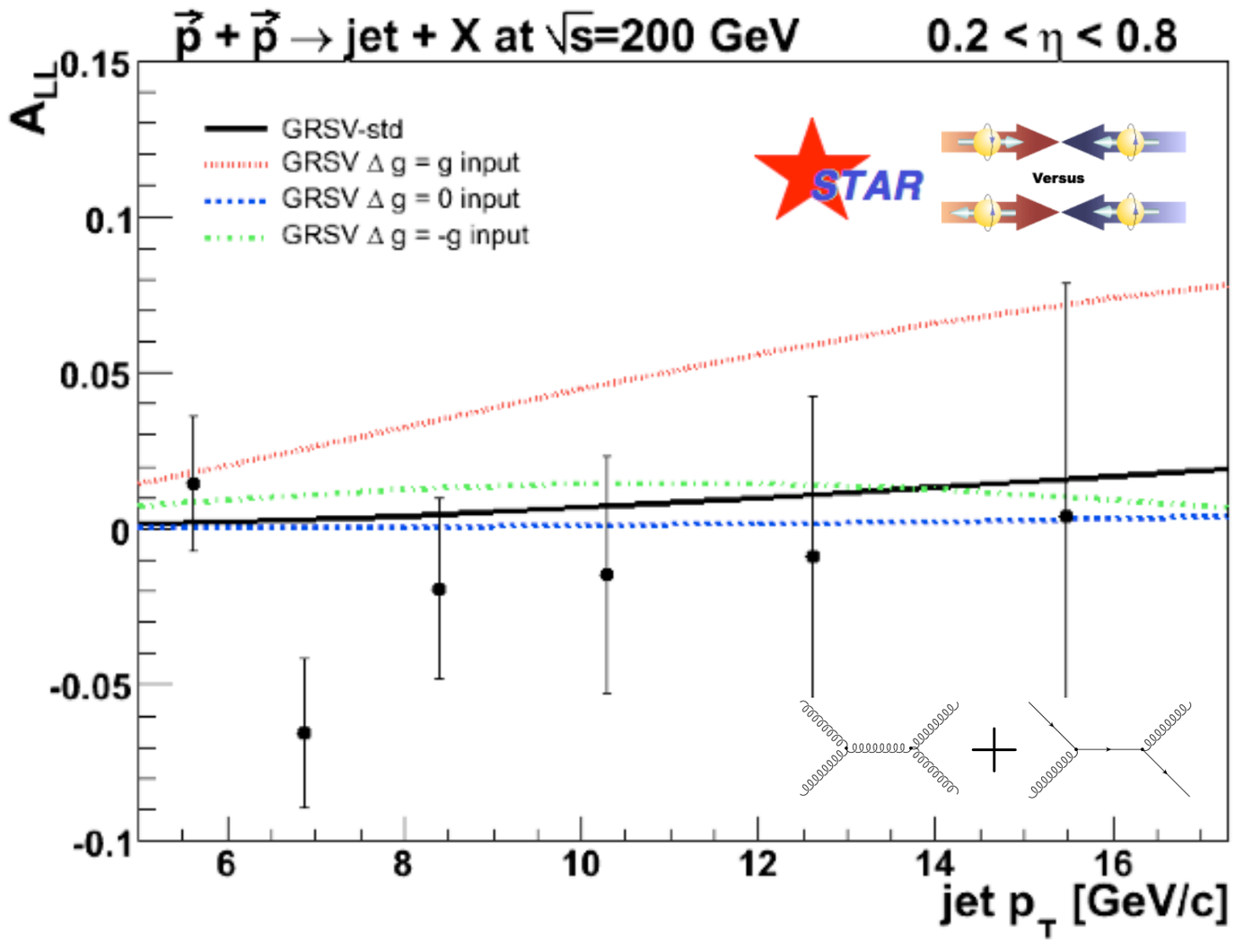




First Longitudinal Double-Spin Asymmetries from STAR

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





- Consistent with DIS and disfavors large values for ΔG
- Statistics limited measurement; systematics ~0.015
- Improved statistics 2005 (2006)
- Similar PHENIX results on inclusive neutral pion production

STAR - B. Abelev et al, hep-ex /0608030 PRL 97:252001 (2006)

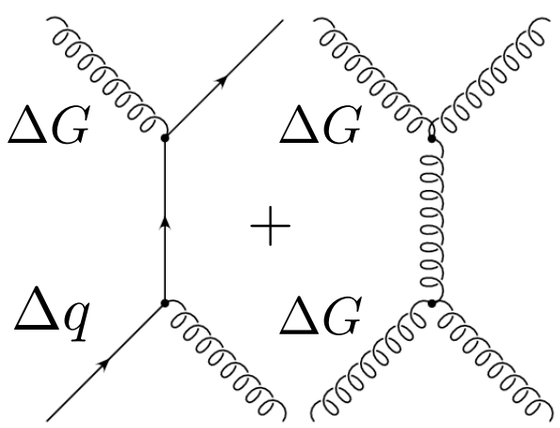
GRSV - Gluck et al, PR D63 094005 (2001).

Future Polarized Proton Collisions at RHIC

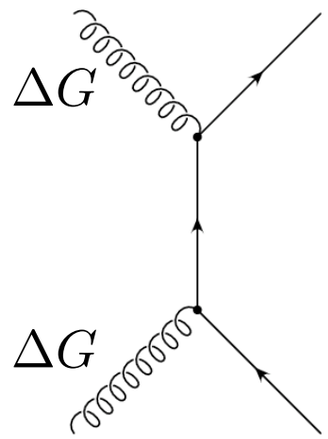
Clear need for data that are *kinematically complete* and *process selective*,

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

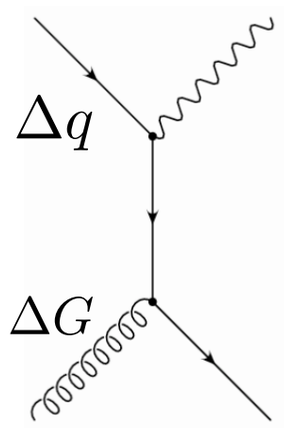
$\vec{p} + \vec{p} \rightarrow \text{jet(s)} + X$



$\vec{p} + \vec{p} \rightarrow c\bar{c}, b\bar{b} + X$



$\vec{p} + \vec{p} \rightarrow \gamma + \text{jet}$



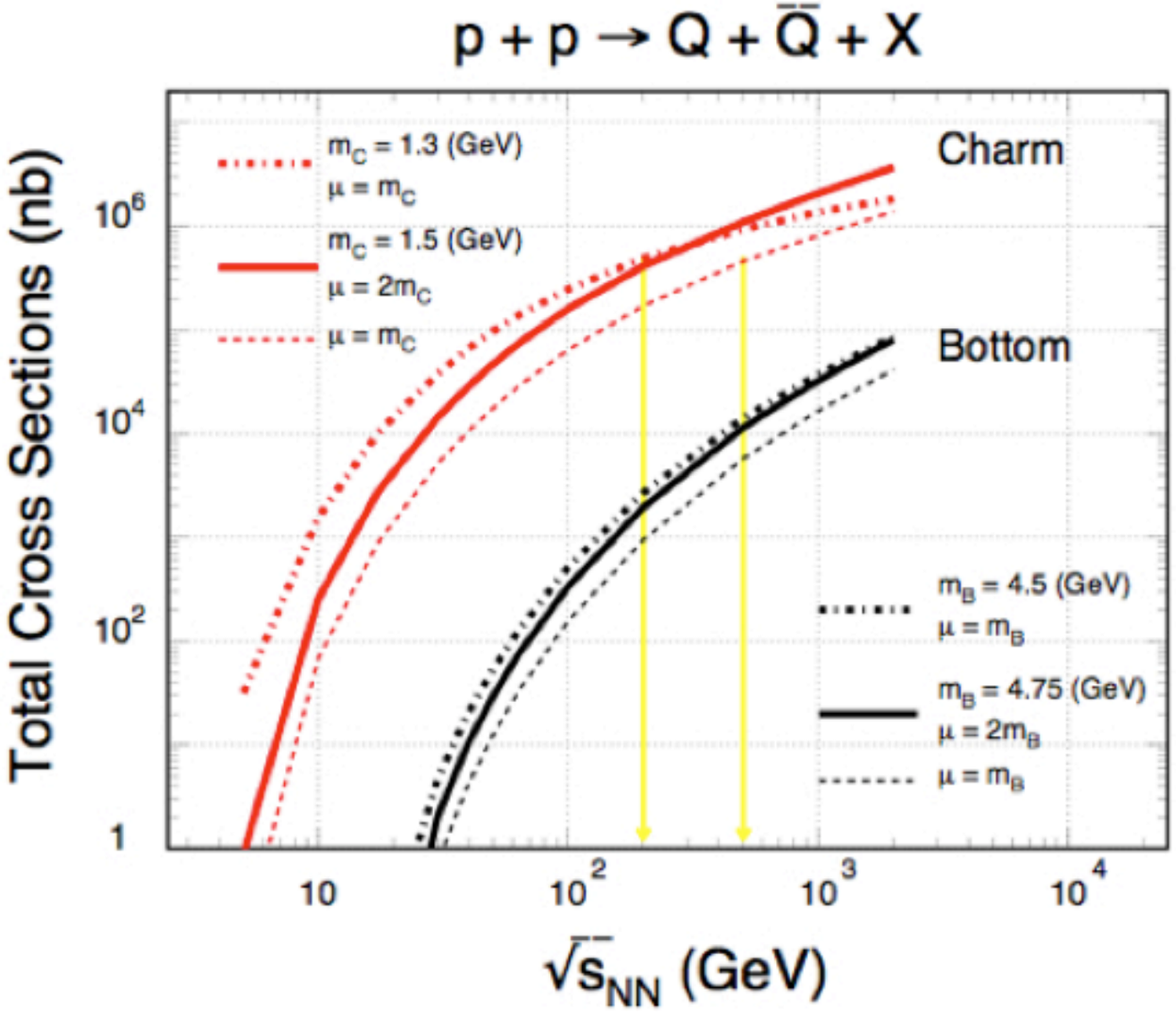
$\mathcal{L} \simeq 3 - 8 \cdot 10^2\,\text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500\,\text{GeV}$

time

Clear need for data that are *kinematically complete* and *process selective*,

Heavy Quark and Prompt Photon Production are *complementary.*

Heavy Quark Total Cross Section



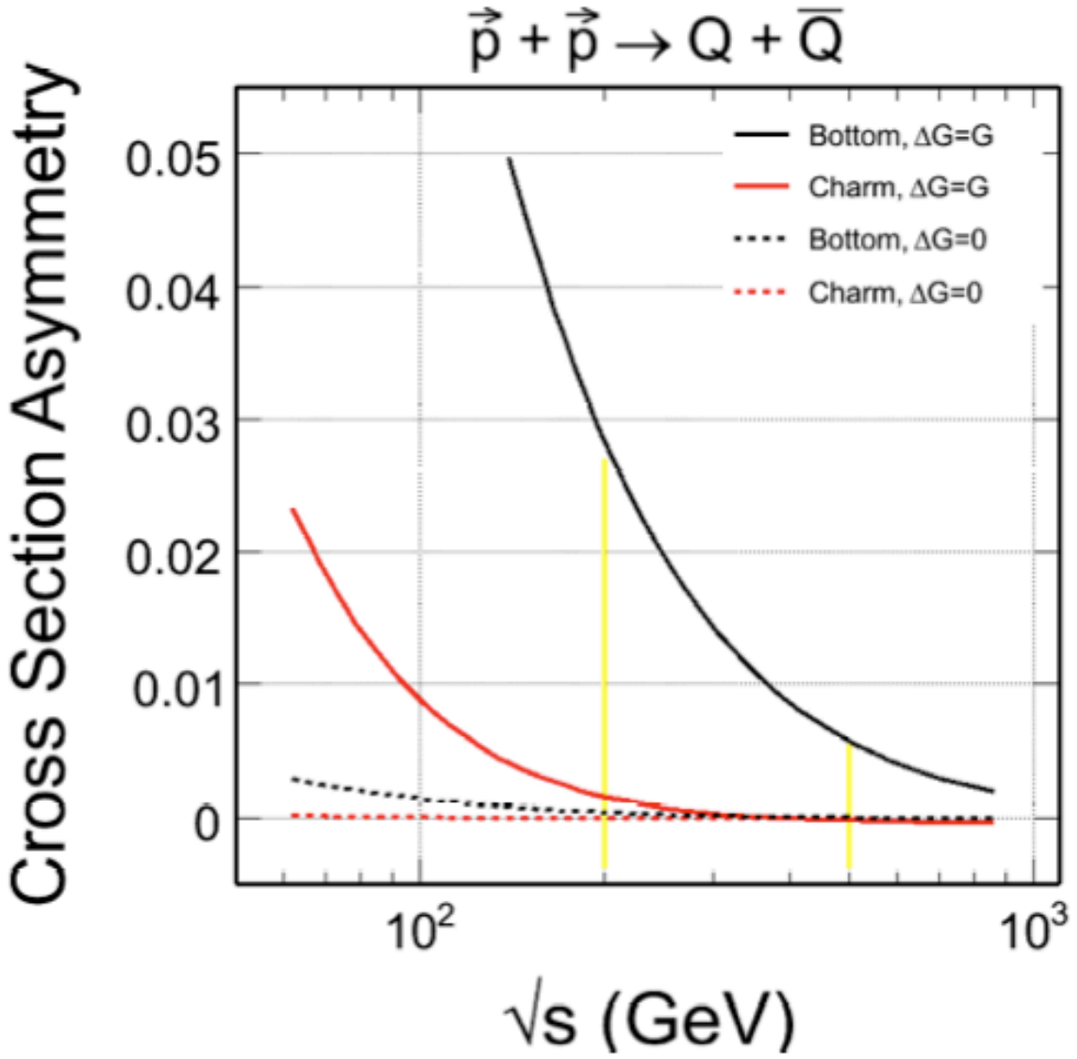
Total cross section, e.g.
P. Nason et al., NPB 303 (1988) 607

Quarkonium, e.g.
G. Bodwin et al., PR D51 (1995) 1125;
erratum ibid D55 (1997) 5883

Friday morning session at this workshop

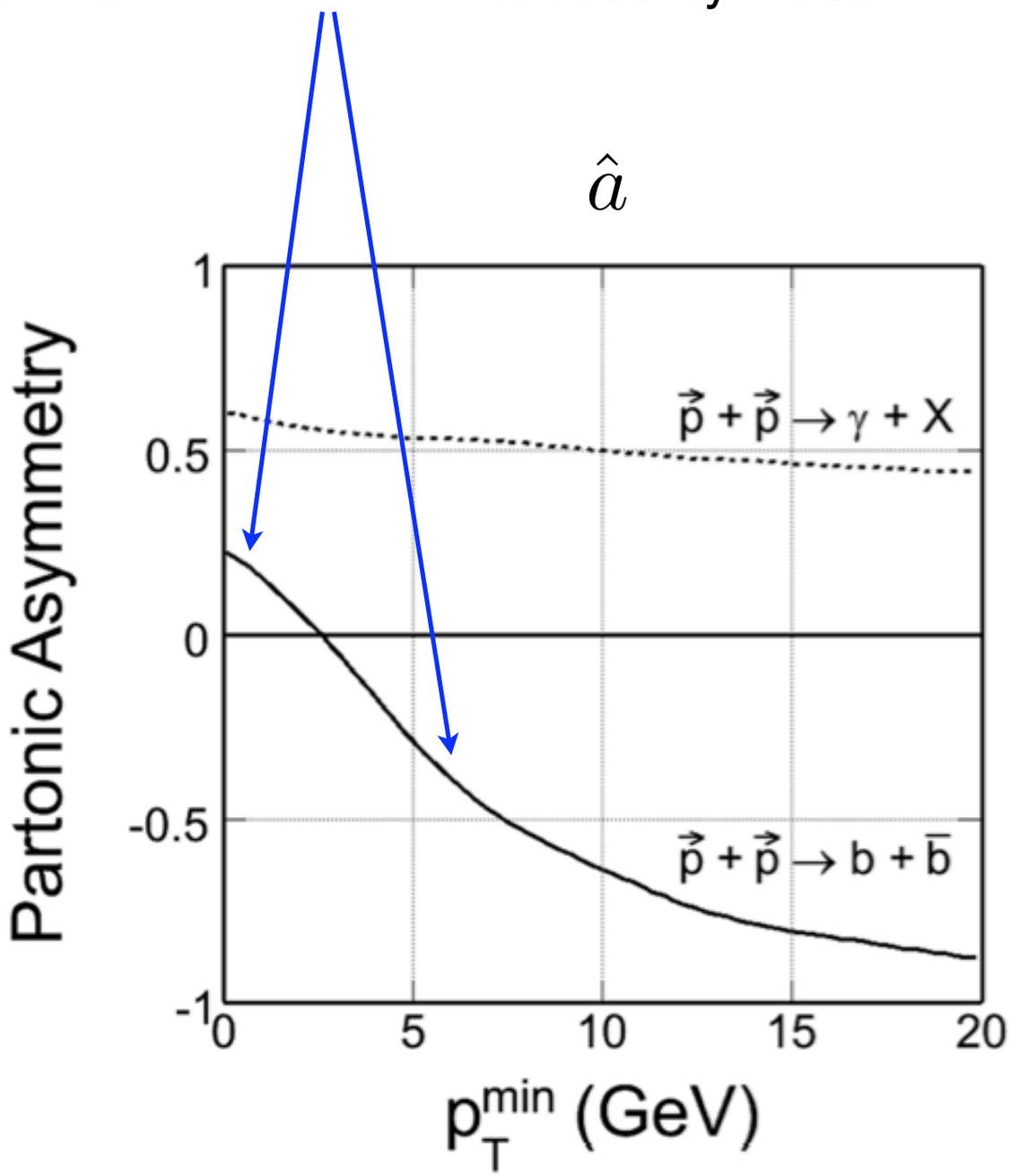
... and its Spin Dependence

$$A \propto \Delta f \otimes \Delta g \otimes \hat{a}$$

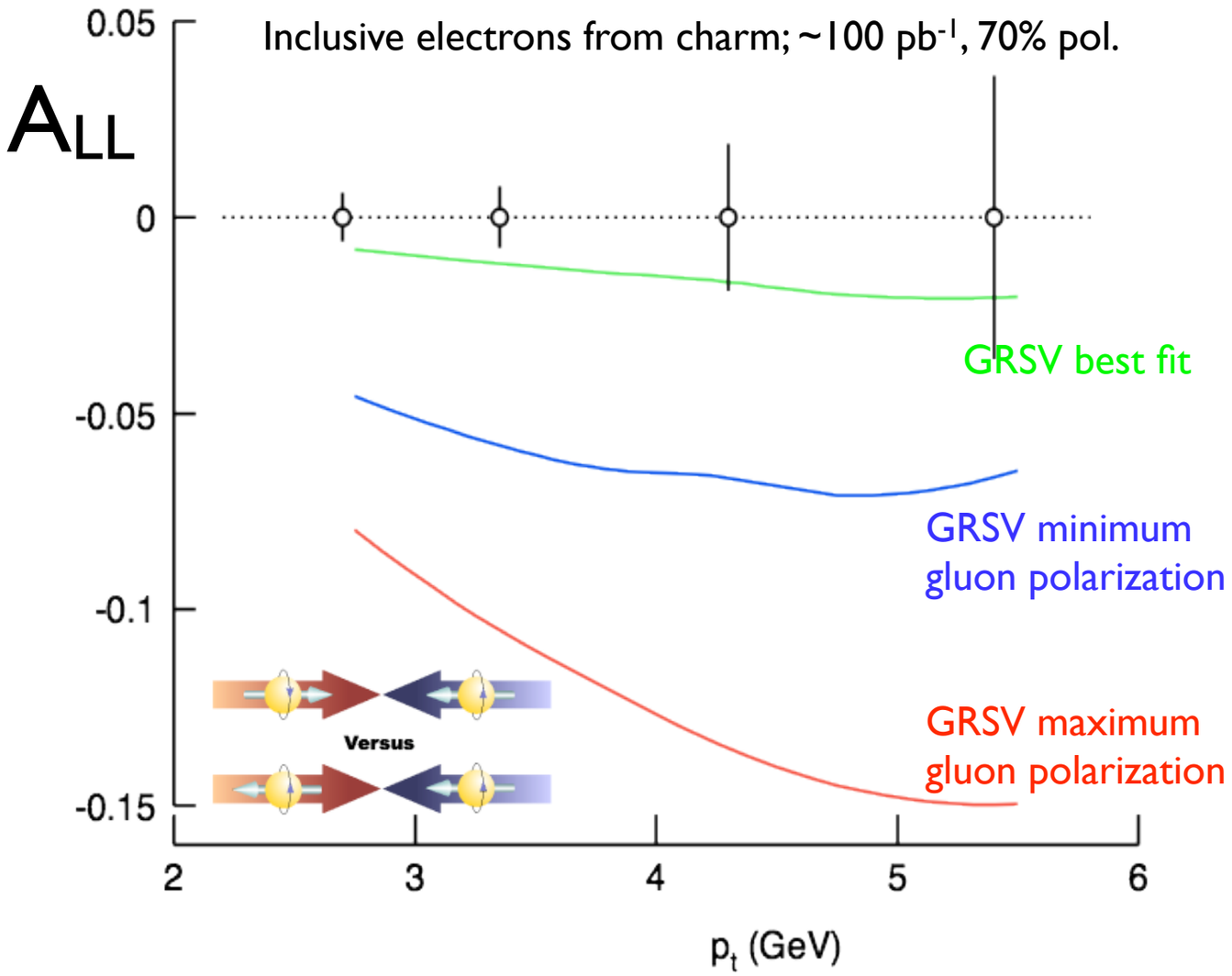


Contogouris et al., PLB 246 (1990) 523
Karliner and Robinett, PLB 324 (1994) 209
Lampe and Reya, Phys. Rept. 332 (2000) 1
Bojak and Stratmann, PR D67 (2003) 034010

Small total cross section asymmetry is a result from *cancellation* caused by mass.

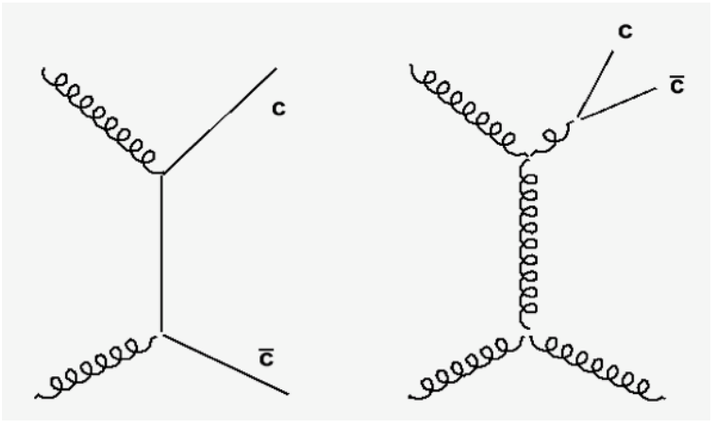


Displaced Electrons from Charm in STAR



Beauty lasymmetriesl are generally smaller at small p_T

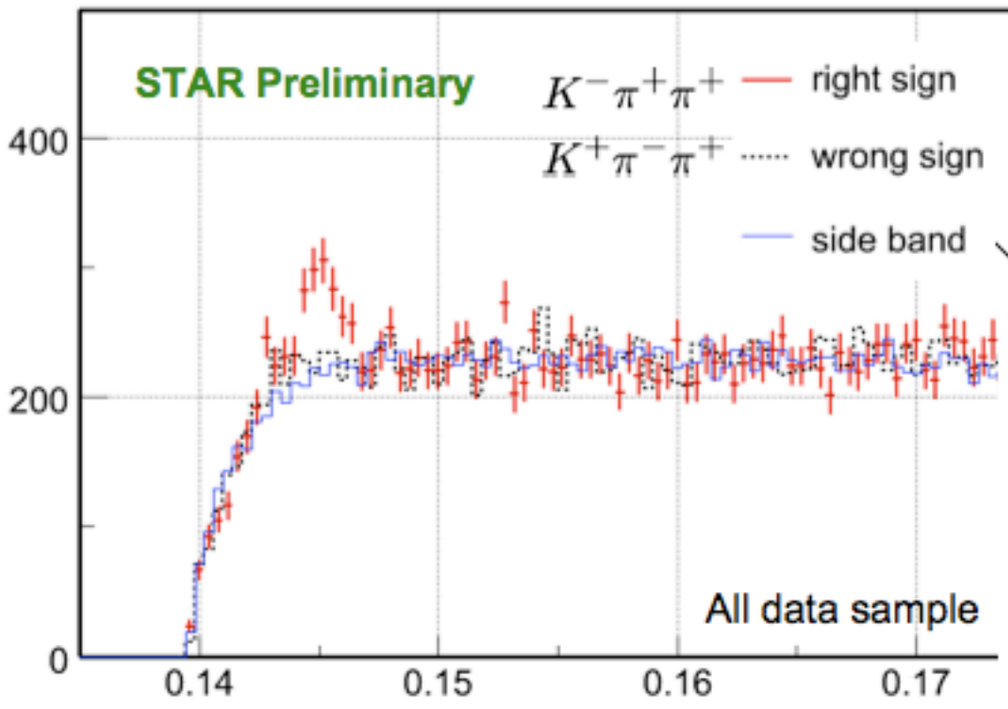
Heavy Quark Content of Jets

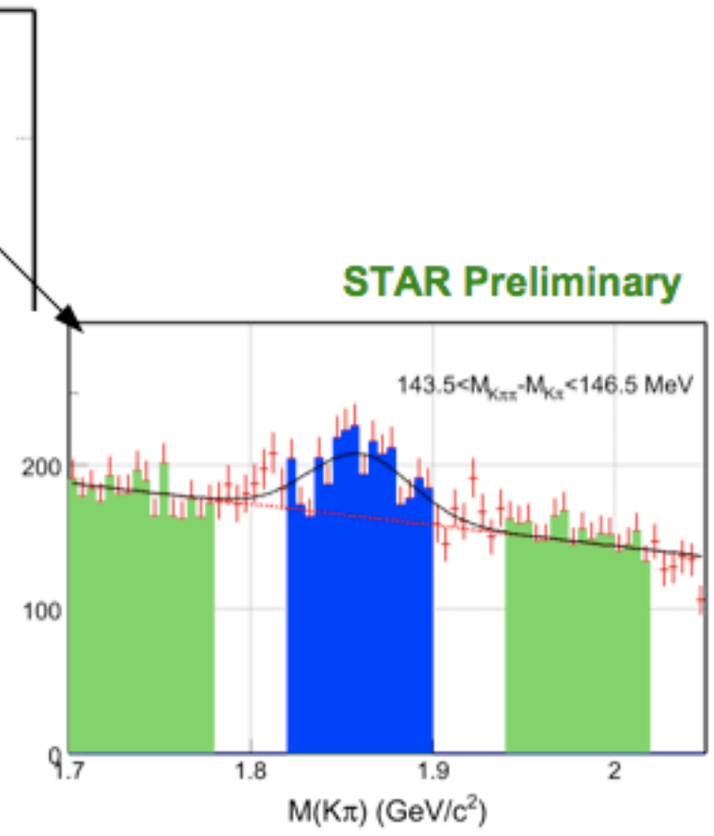


UA1, PLB 244 (1990) 566
CDF, PRL 64 (1990) 348

STAR

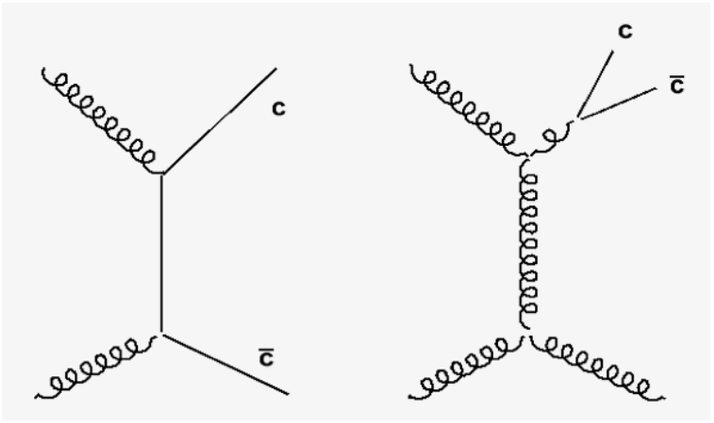
Raw signal





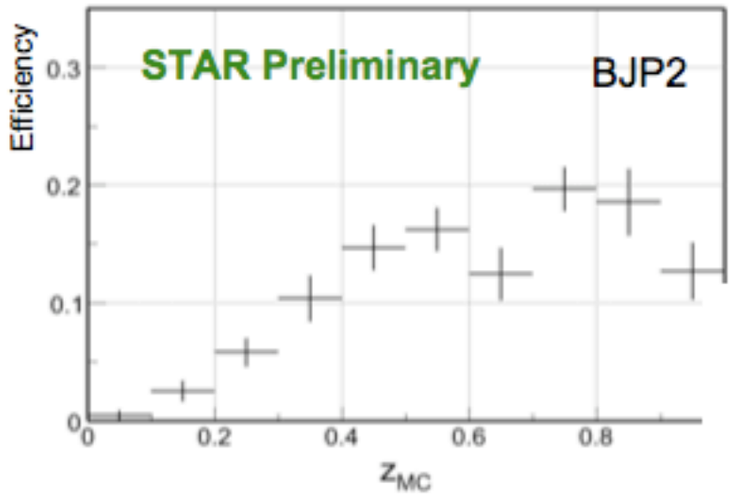
➢ wrong sign combination and side-band methods describe the background shape very well.

Heavy Quark Content of Jets



UA1, PLB 244 (1990) 566
CDF, PRL 64 (1990) 348

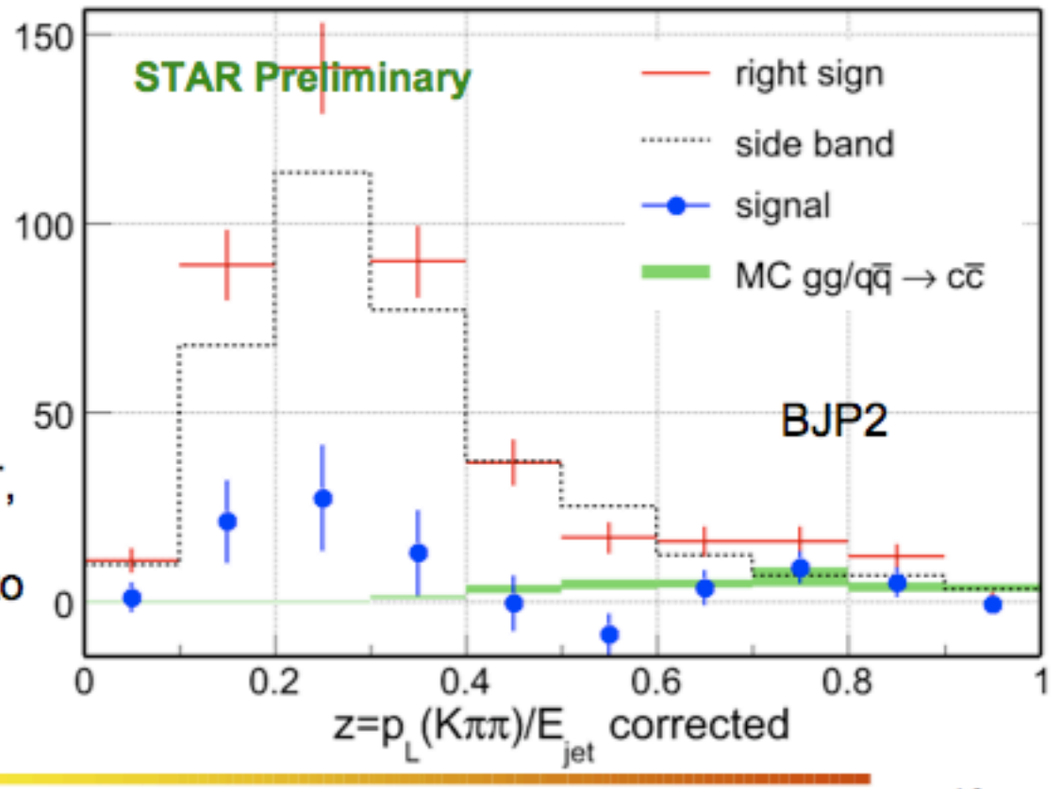
Efficiency & Trigger



Efficiency of reconstructing the D* in a reconstructed jet

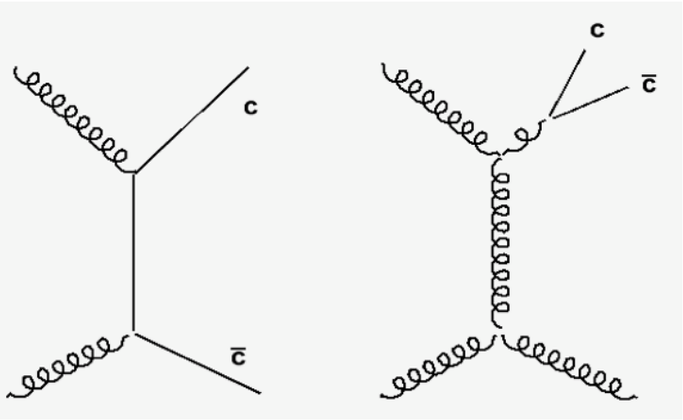
JP or HT triggers suppress the high z production.

Excess at low z region is from gluon splitting



Efficiency is calculated in (z, jet pT, D* multiplicity in jet) 3-D "plane". Then folded into z axis according to real jet pT and D* multiplicity in jet distributions from data.

Heavy Quark Content of Jets

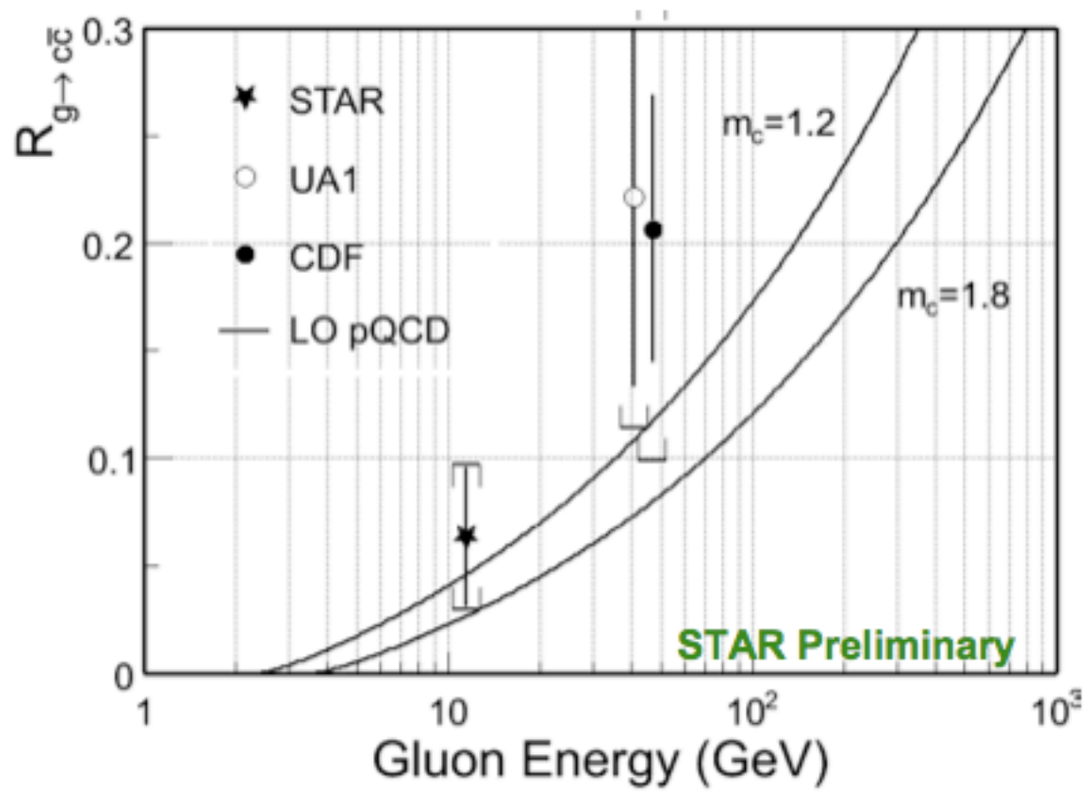


UA1, PLB 244 (1990) 566
CDF, PRL 64 (1990) 348

Results and Discussion

$N(D^{*+}+D^{*-})/N(jets) = (1.5 \pm 0.8 \pm 0.5) \times 10^{-2}$

$0.2<z<0.5$, $\langle E_T \rangle \sim 11$ GeV



Mueller & Nason PLB 157 (1985) 226 --- LO pQCD

Assumptions:

c->D* fraction
3/8 for all

gluon jets fraction

CDF	75%
UA1	70%
STAR	60%

z coverage fraction

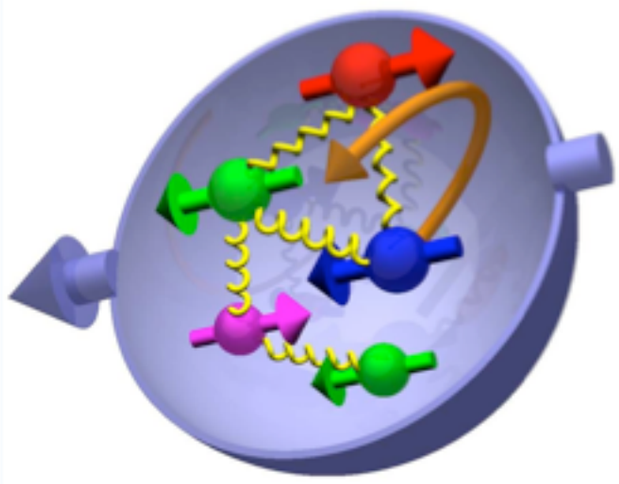
CDF	83% for (0.1, 1.0)
UA1	83% for (0.1, 1.0)
STAR	51% for (0.2, 0.5)

Total uncertainty from above: ~45%

The gluon splitting rate is consistent with LO pQCD calculations!

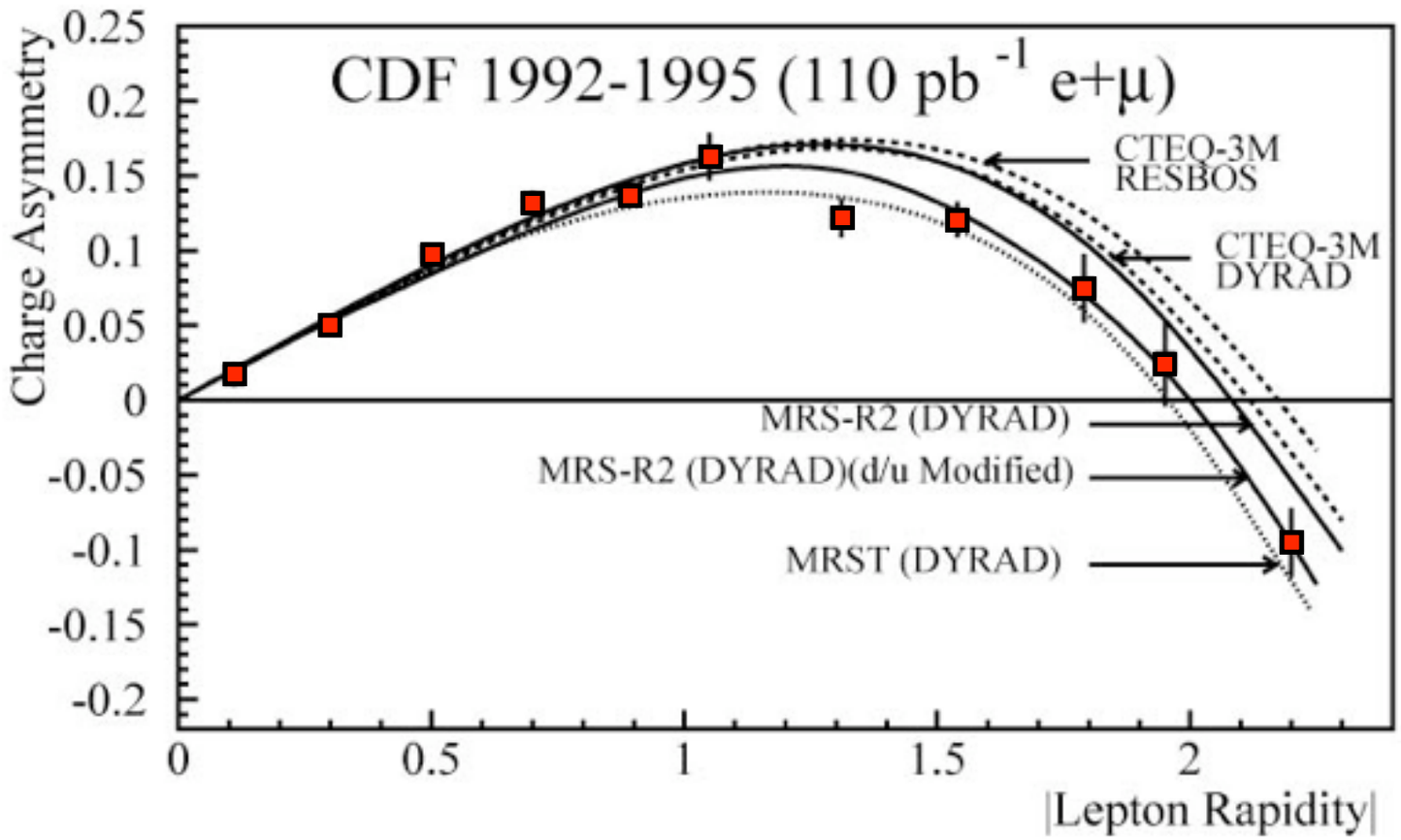
Some Open Questions

- Is the extrapolation over unmeasured small x justified?
- What does gluon polarization contribute to the proton spin?
- What are the quark and anti-quark polarizations by flavor?
- What orbital angular momenta do quarks and gluons carry?
- What is the role of transverse spins?



Quark Structure at Hadron Colliders - Leptonic W-boson Decays

CDF Collaboration, *Measurement of the lepton charge asymmetry in W boson decays produced by ppbar collisions*, PRL 81, 5754 (1998).



$$u + d \rightarrow W \rightarrow l + \nu$$

$$A_{\text{charge}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Clean measurement:

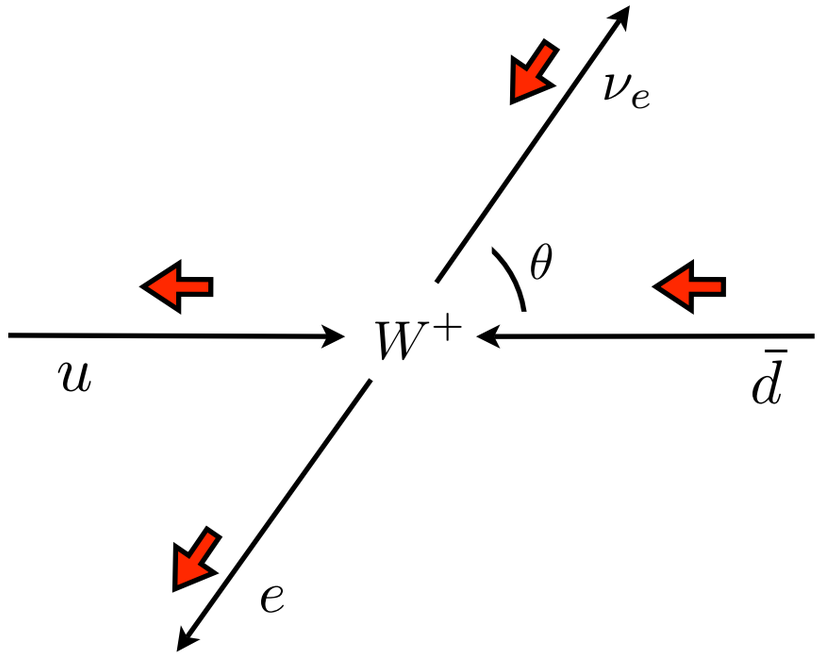
- hard scale,
- convolution with calculable V-A decay,
- sensitive, at large lLepton Rapidityl

More recent measurements (Phys.Rev.D71 - 2005):

- transverse energy E_T dependence

Quark Polarimetry at RHIC - Leptonic W-boson Decays

Quark polarimetry with W-bosons:



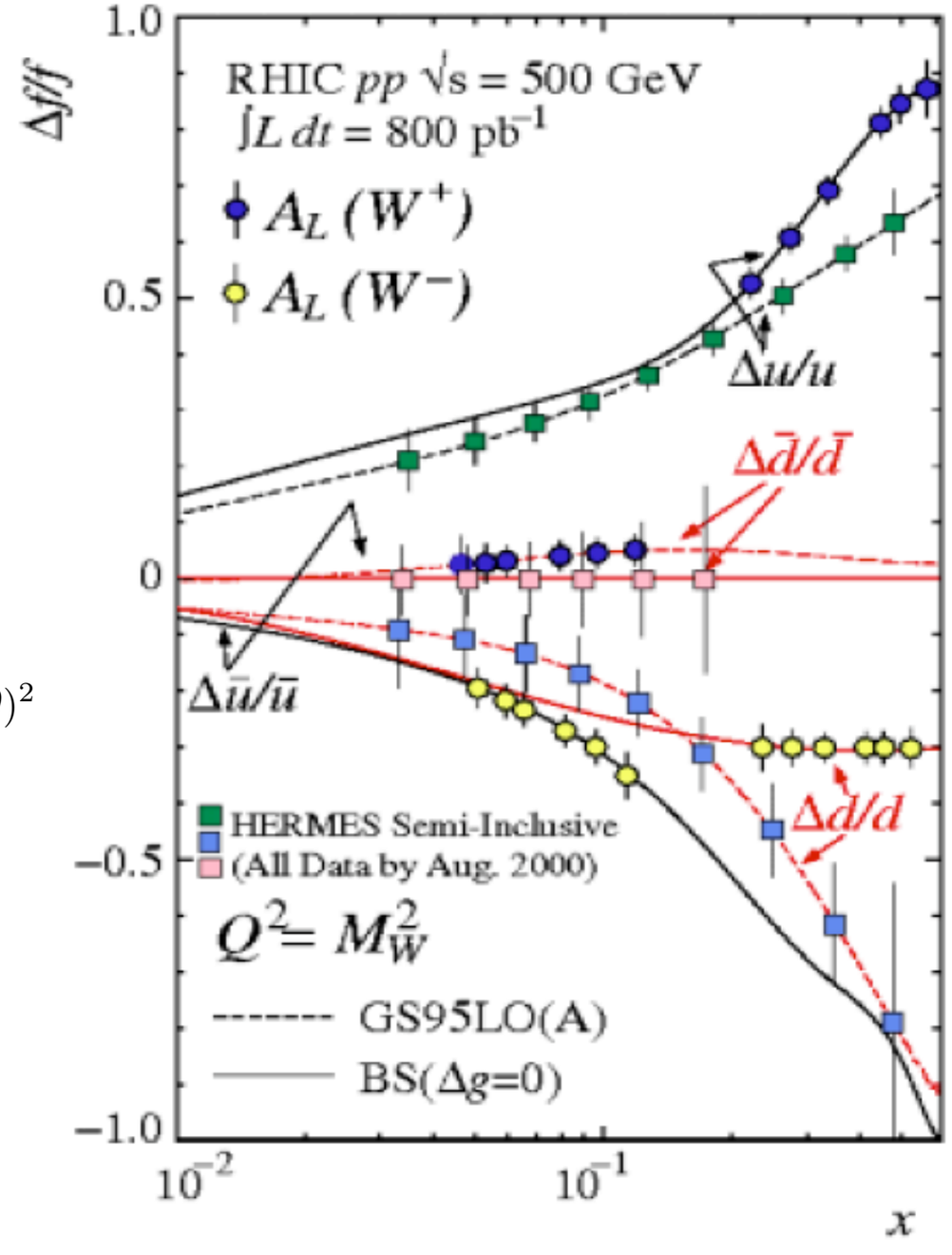
$$\Delta\sigma^{\rm Born}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

Spin measurements:

$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

PHENIX projections



Requires:

- PHENIX and STAR upgrades
- high integrated luminosity

Quark Polarimetry at RHIC - Heavy Quark W-boson Decays?

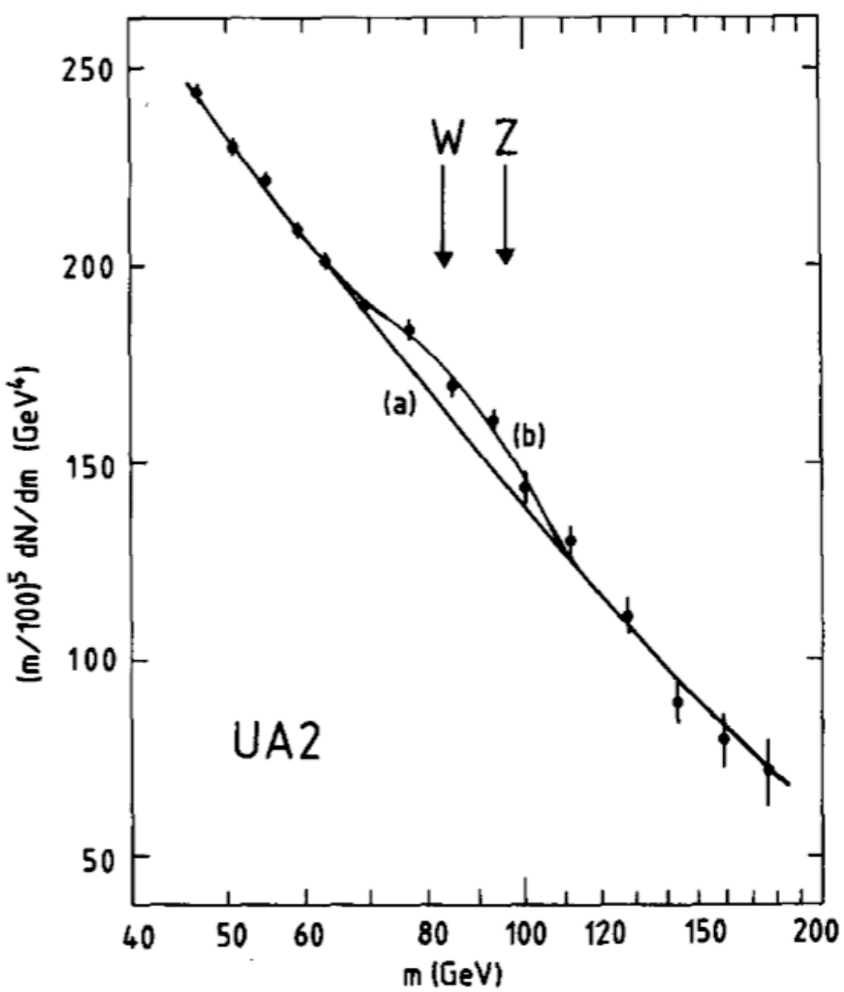
Hadronic decays:

+ are 6x more abundant,

+ are kinematically complete,

- have challenging QCD backgrounds.

UA2, PLB 186 (1987) 452.



Quark Polarimetry at RHIC - Heavy Quark W-boson Decays?

Hadronic decays:

+ are 6x more abundant,

+ are kinematically complete,

- have challenging QCD backgrounds.

↓

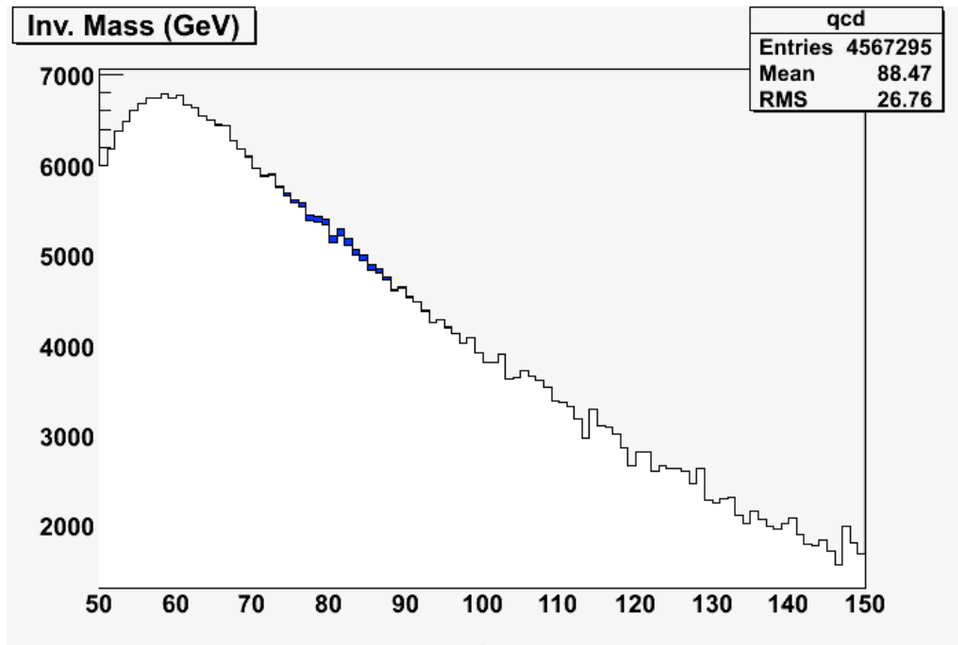
The requirement of charm

+ reduces QCD background > 10x,

+ reduces Z background 5x,

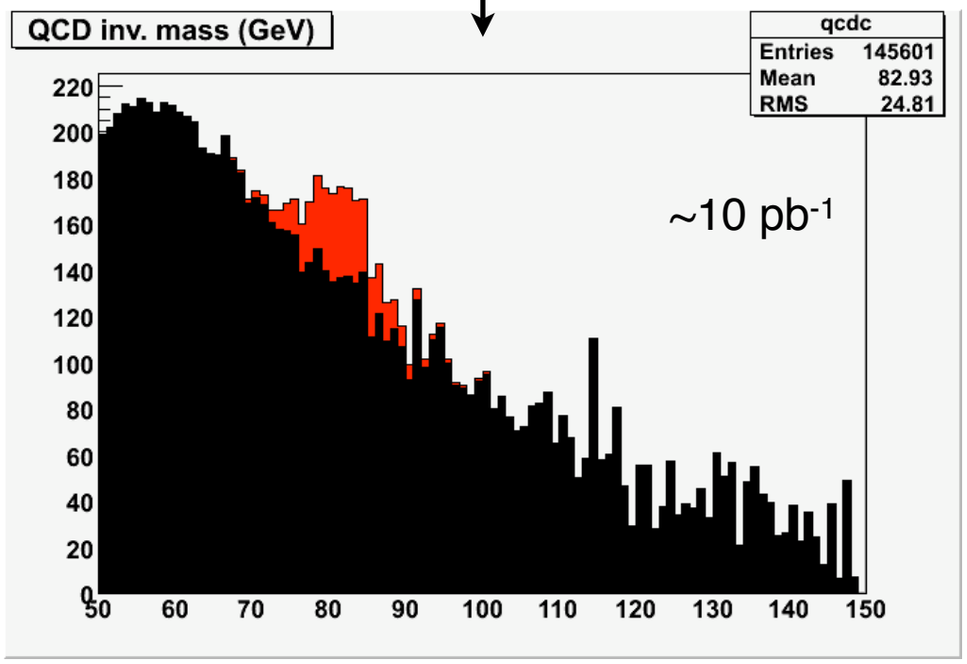
- reduces signal 2x.

RHIC



mass [GeV]

↓



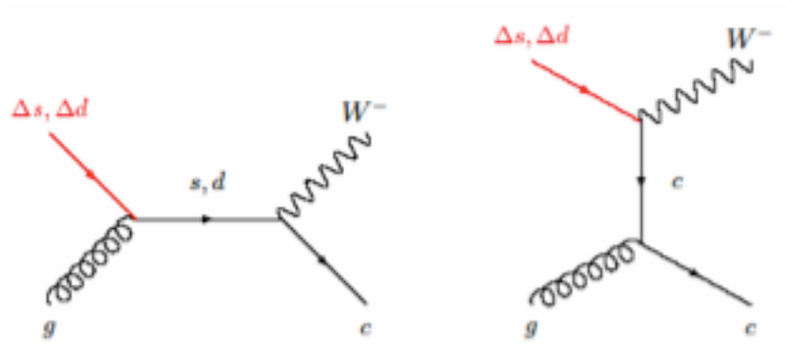
mass [GeV]

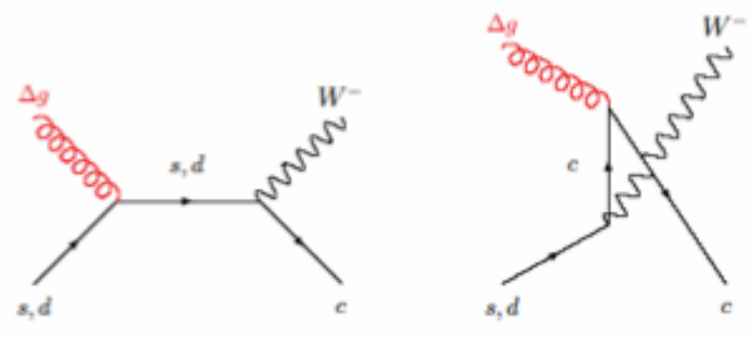
$A_L^{QCD} = 0$, $A_L^{W} \sim 0.2$, S/B can be optimized, W charge?

W. Zhou (LBNL), E.S.

W-boson Processes - Higher Orders...

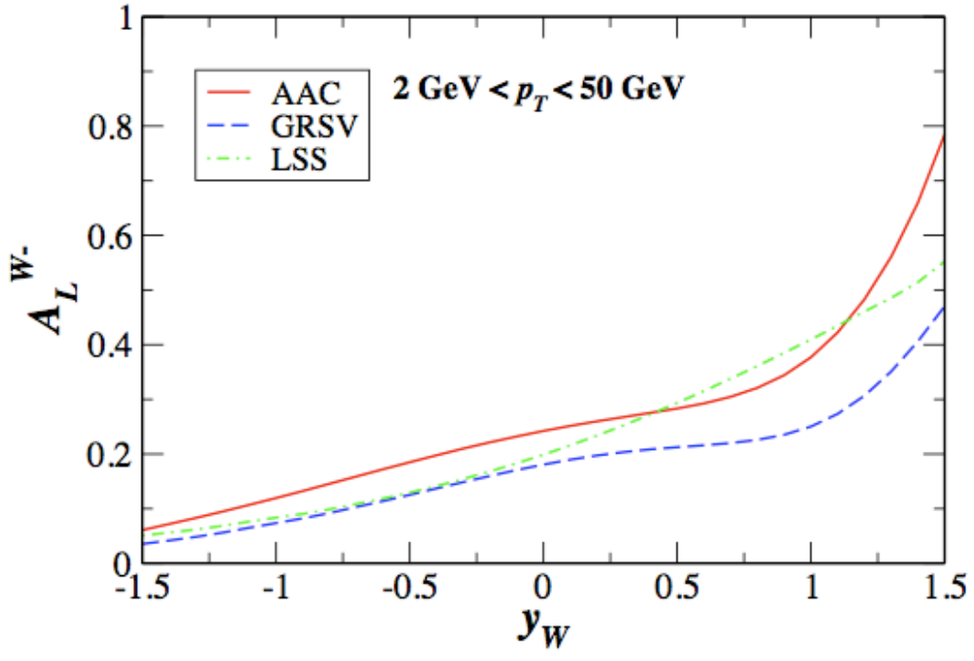
- Charm-associated W-boson production,

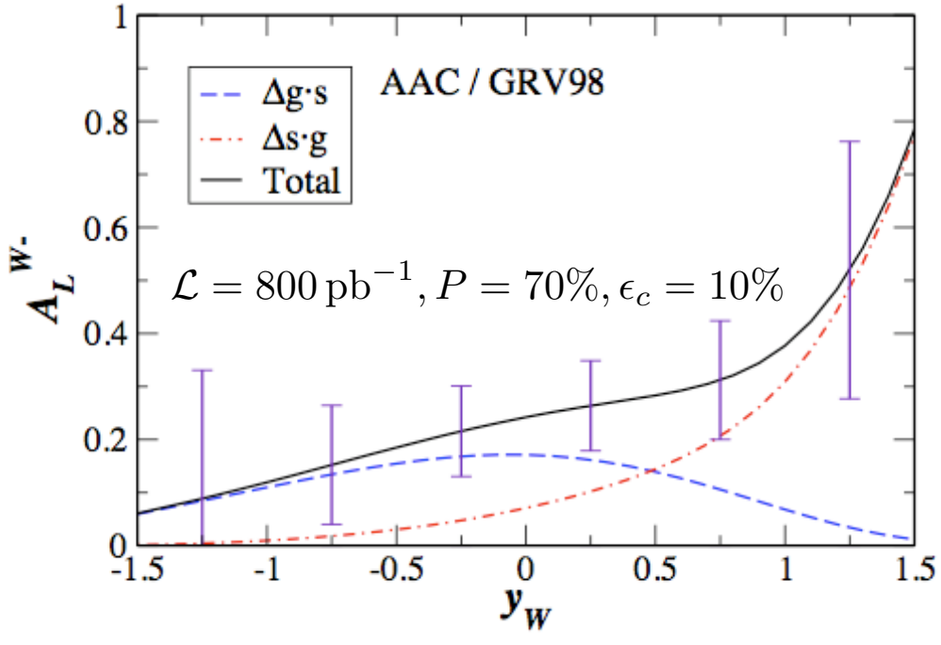




gives *some* sensitivity to $\Delta s, \Delta \bar{s}$

K. Sudoh, RHIC-II Science Workshop (2005)

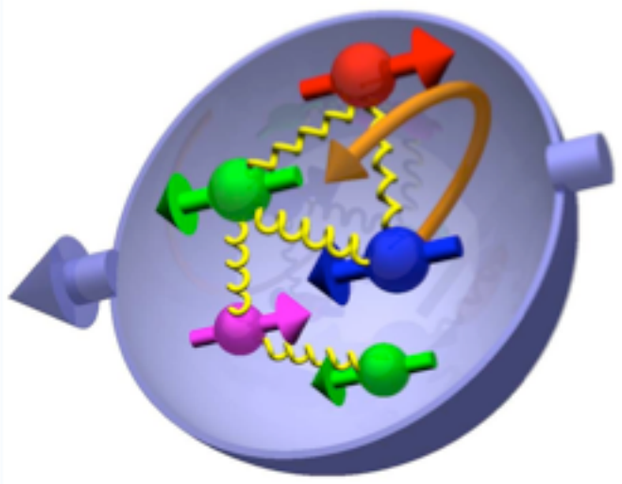




- Hyperon spin transfer at RHIC (Q.H. Xu, E.S.), elastic neutrino scattering (BNL E734), semi-inclusive DIS at a future Electron Ion Collider

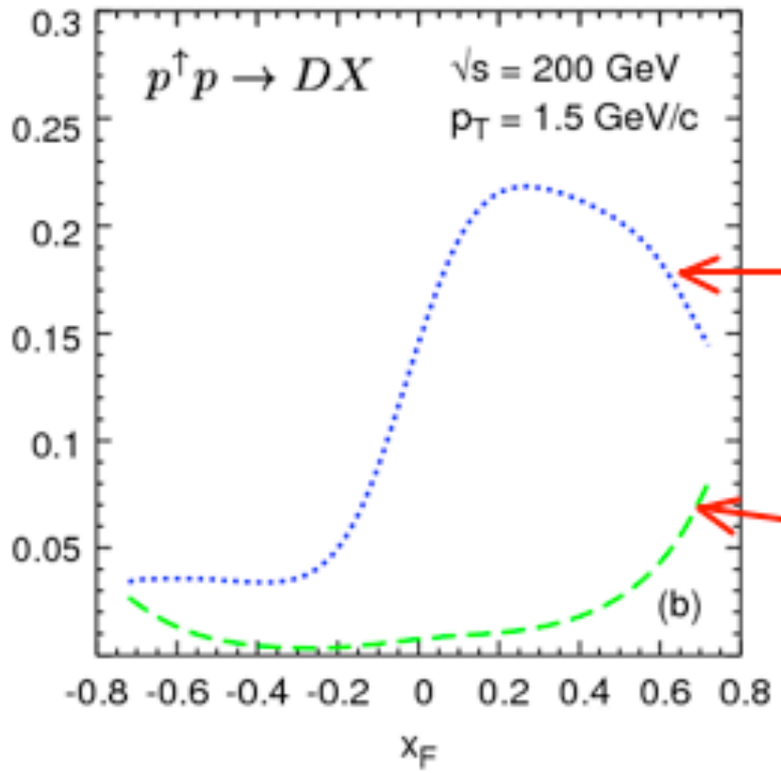
Some Open Questions

- Is the extrapolation over unmeasured small x justified?
- What does gluon polarization contribute to the proton spin?
- What are the quark and anti-quark polarizations by flavor?
- What orbital angular momenta do quarks and gluons carry?
- What is the role of transverse spins?



Heavy flavor for transverse spin physics

- Can probe the gluon "Sivers" function

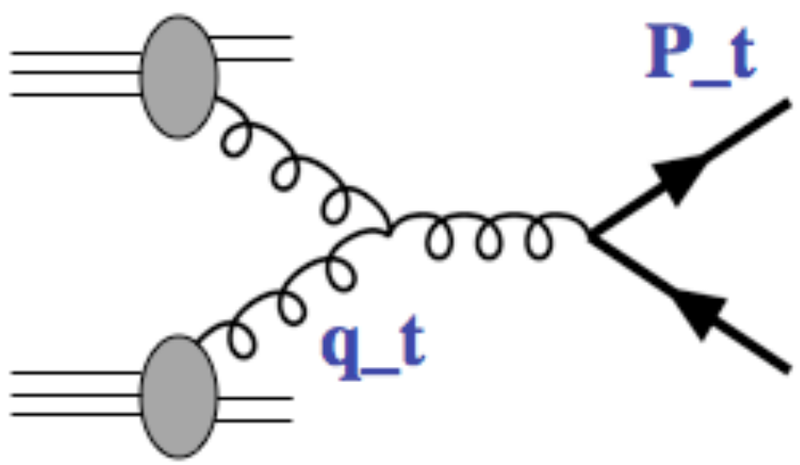


Max. gluon Sivers

Max. quark Sivers

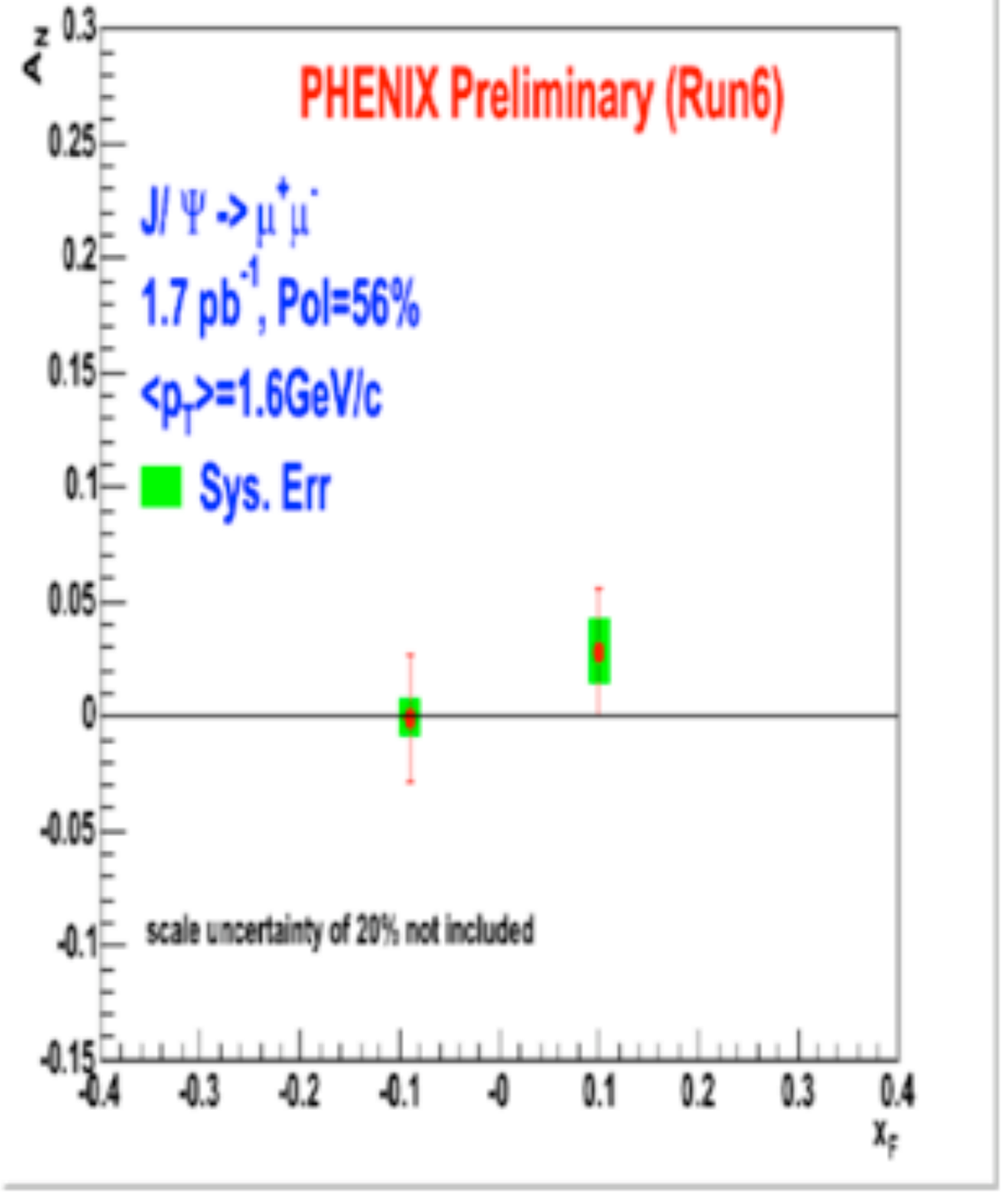
Anselmino, et al., 2004

Some comments



- Indirect connection between P_t and q_t
  - Different from Drell-Yan process
- Suitable framework should be twist-3
  - Qiu-Sterman approach
  - The asymmetry can be calculated down to zero P_t, work in progress, F.Yuan et al.

Phenix preliminary

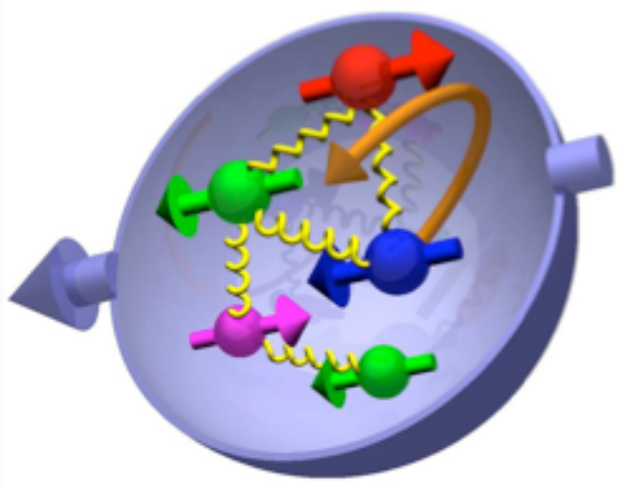


Han Liu, spin 2006

Feng Yuan

Some Open Questions

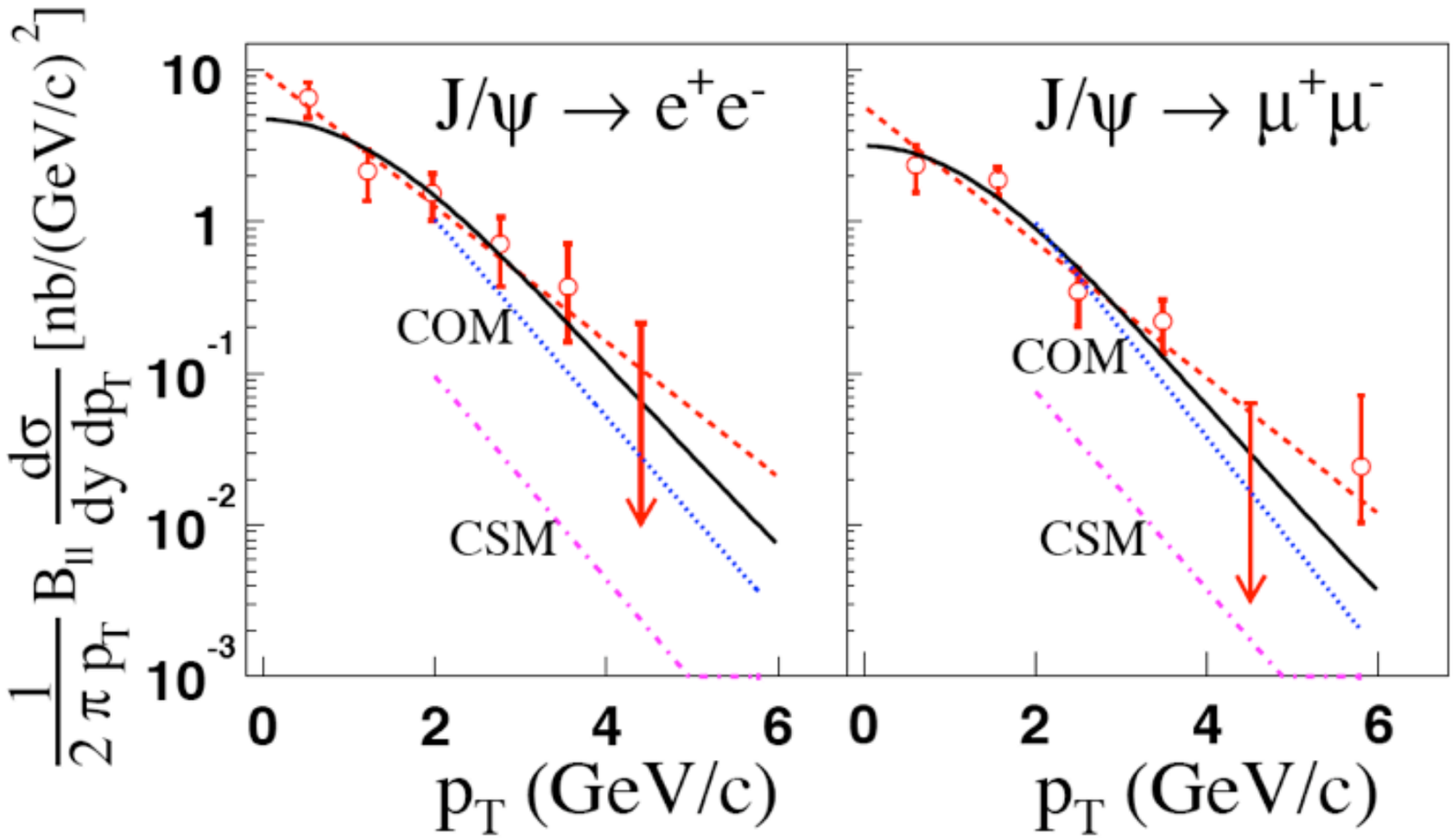
- Is the extrapolation over unmeasured small x justified?
- What does gluon polarization contribute to the proton spin?
- What are the quark and anti-quark polarizations by flavor?
- What orbital angular momenta do quarks and gluons carry?
- What is the role of transverse spins?
- Other



Quarkonia

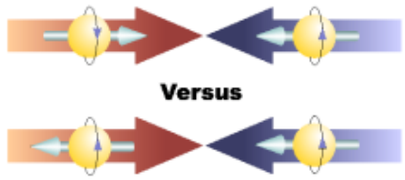
- Considerable effort to understand the production mechanism

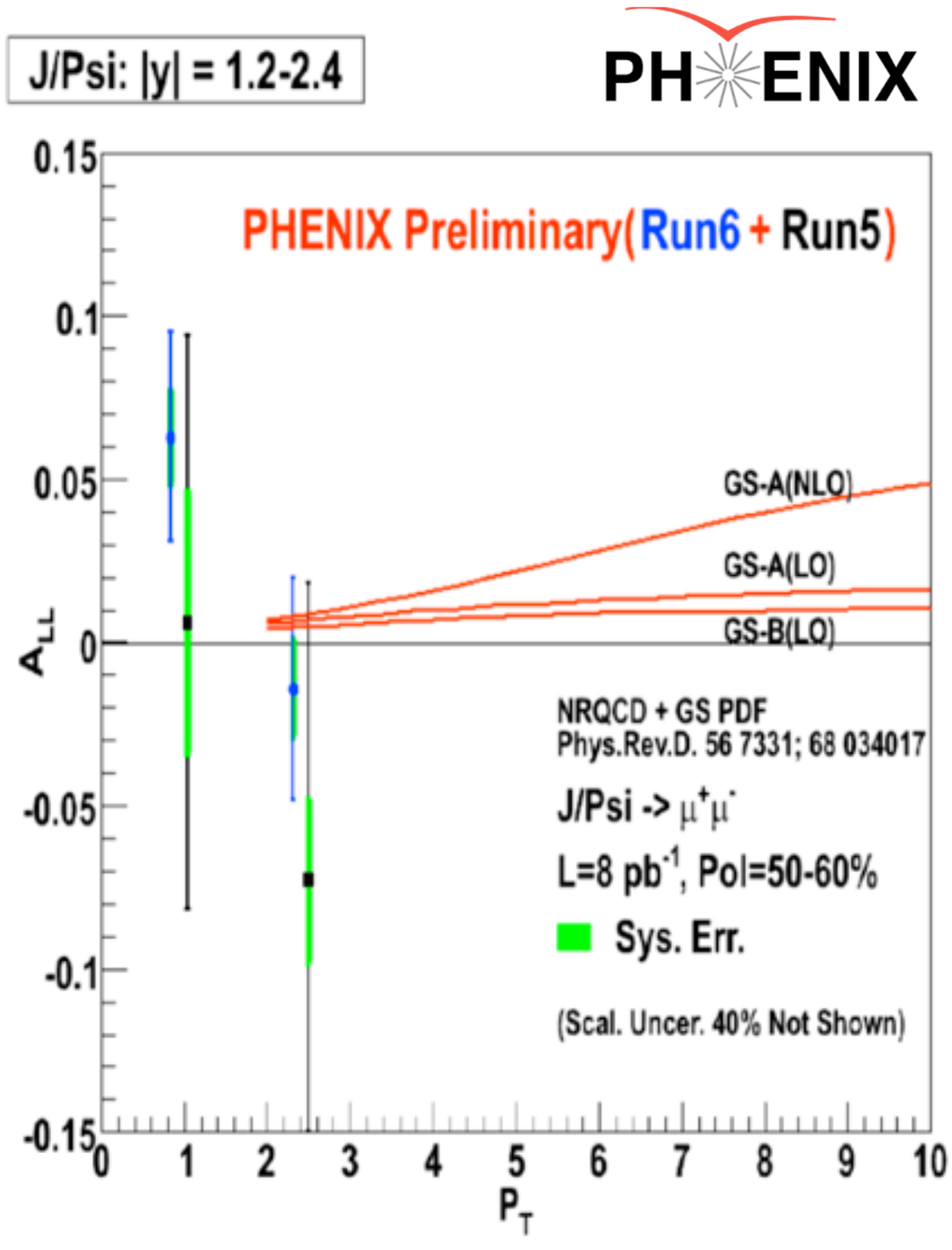
  e.g. Cooper, Liu, Nayak



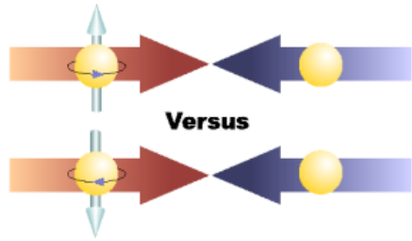
- Any spin observables?

Quarkonia





M.Liu, Spin 2006



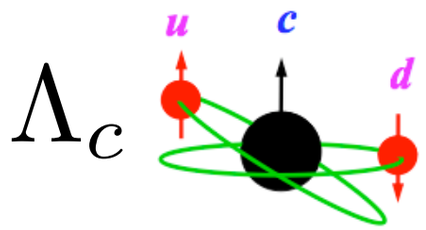
Transverse spin asymmetry in heavy quarkonium

- Color-singlet model
  - Only initial state interactions, can be calculated from the quark splitting
- Color-octet model
  - Both initial and final state interactions, but they cancel out to all orders (surprisingly!!)
  - Maybe that's why it is small

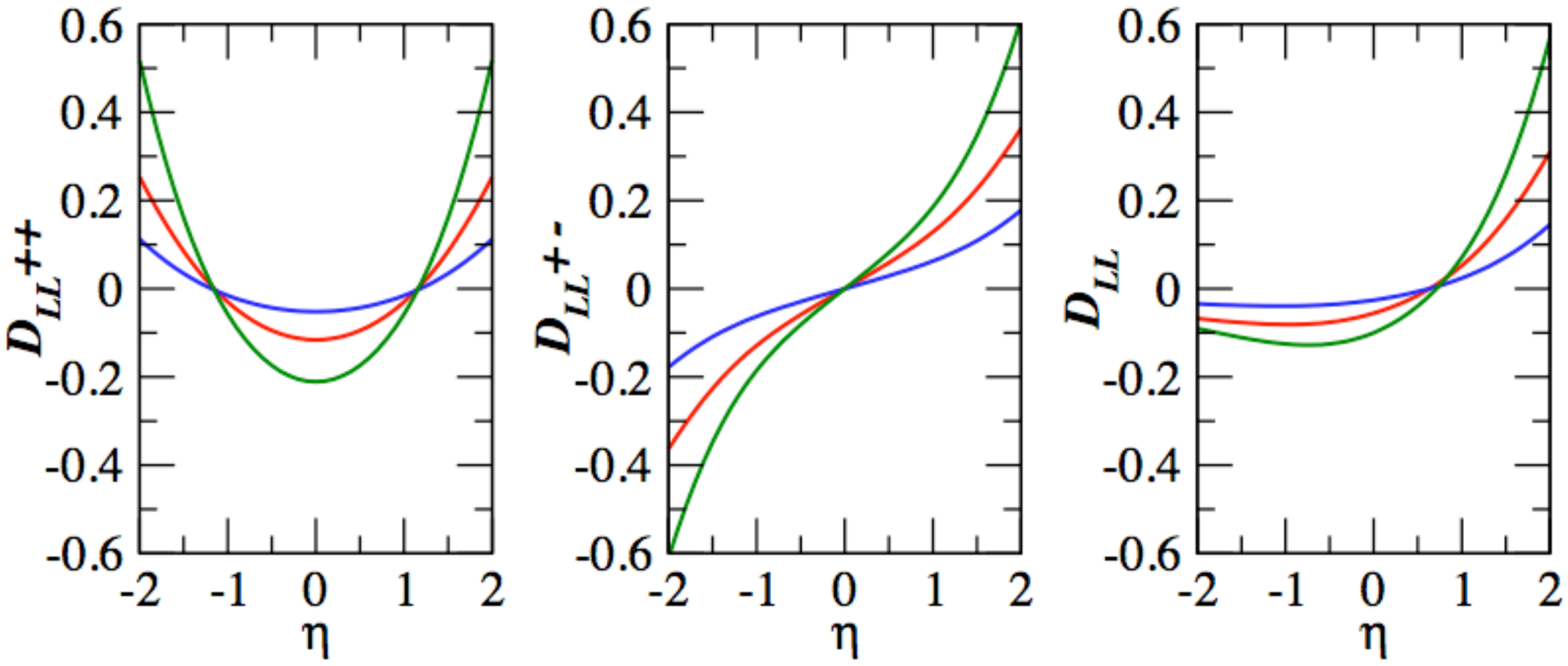
F.Yuan, to appear

Spin Transfer - Λ_c

A correlation between the spins of initial and final particles.



K. Sudoh, RHIC-II Science Workshop (2005)



AAC: Y. Goto, *et al.*, *Phys. Rev.* D62, 034017 (2000).
GRSV: M. Gl"uck, *et al.*, *Phys. Rev.* D63, 094005 (2001).
BB: J. Bl"umlein, *et al.*, *Nucl. Phys.* B636, 225 (2002).

Thanks!