Parton Distributions
at
Short Distances and High Energy

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Iowa State University

APS Division of Nuclear Physics: 2007 Long Range Plan
Joint Town Meetings on Quantum Chromodynamics
Rutgers University, January 12-15, 2007

Assignment

Parton distributions at short distances and high energy

❖ to review the progress since last Long Range exercise

❖ What should be expected in the next 5-6 years?

❖ What are the need and future opportunities?

See also A. Deshpande et al, Ann. Rev. Nucl. Part. Sci. 55, 165 (2005)

Hadron structure at short distance

- Known fact:

  Hadrons are made of quarks and gluons, or partons

- Question:

  How to understand hadron properties and structure in terms of partonic dynamics?

- "snap shot" of a hadron

  \- seen by a hard probe at a short-distance

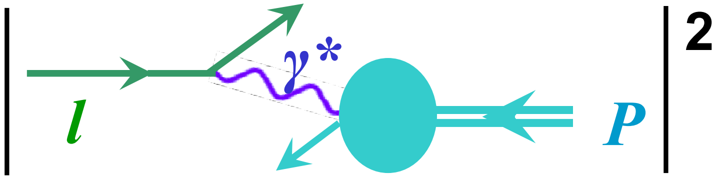
  Parton number densities and momentum distributions,
  Parton helicity or spin-dependent distributions,
  Multi-parton correlation functions, and etc.

Parton distribution functions (PDFs)

Defined as a consequence of QCD factorization

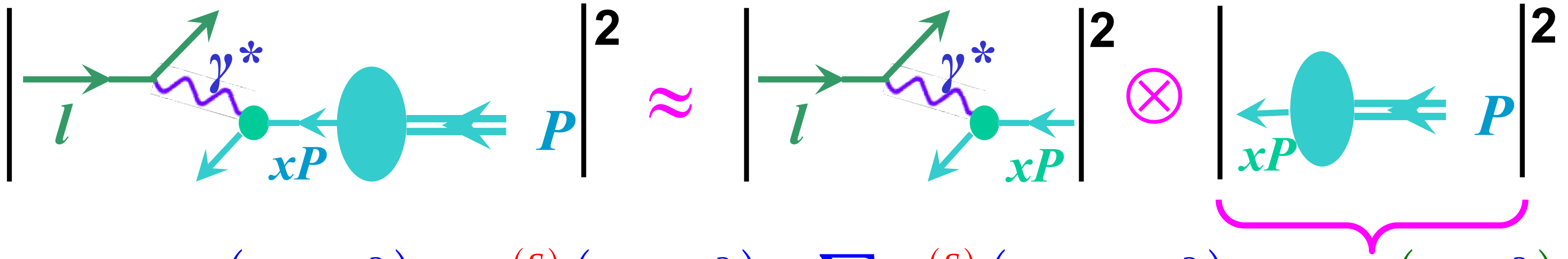
❖ Experiments measure cross sections

Inclusive DIS: $\sigma_{\ell A}\left(x_B, Q^2\right) \propto$



❖ DIS cross section measures PDFs

if the collision is dominated by a single hard scattering:



$$\longrightarrow \quad \sigma_{\ell A}\left(x_B, Q^2\right) \approx \sigma_{\ell A}^{(S)}\left(x_B, Q^2\right) = \sum_f \hat{\sigma}_{\ell f}^{(S)}\left(x_B, x, Q^2\right) \otimes \varphi_{f/A} \underbrace{\left(x, Q^2\right)}_{\text{PDFs}}$$

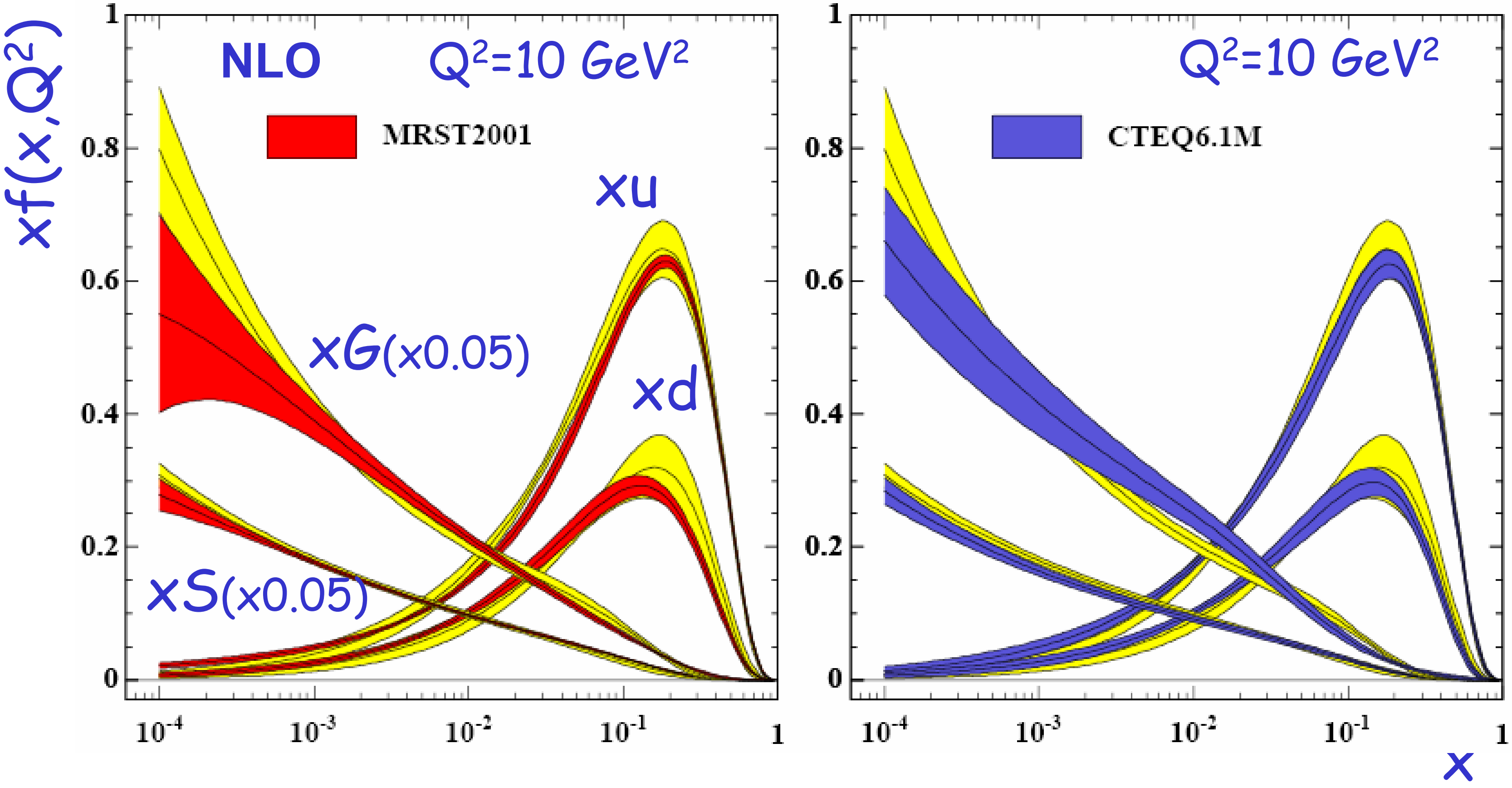
❖ PDFs are non-perturbative, but universal

⟶ **Information on hadron structure at short-distance**

Spin-averaged PDFs of a proton

- ❖ Oever 20 years effort of QCD Global fits:

→ **Modern sets of PDFs with uncertainties**



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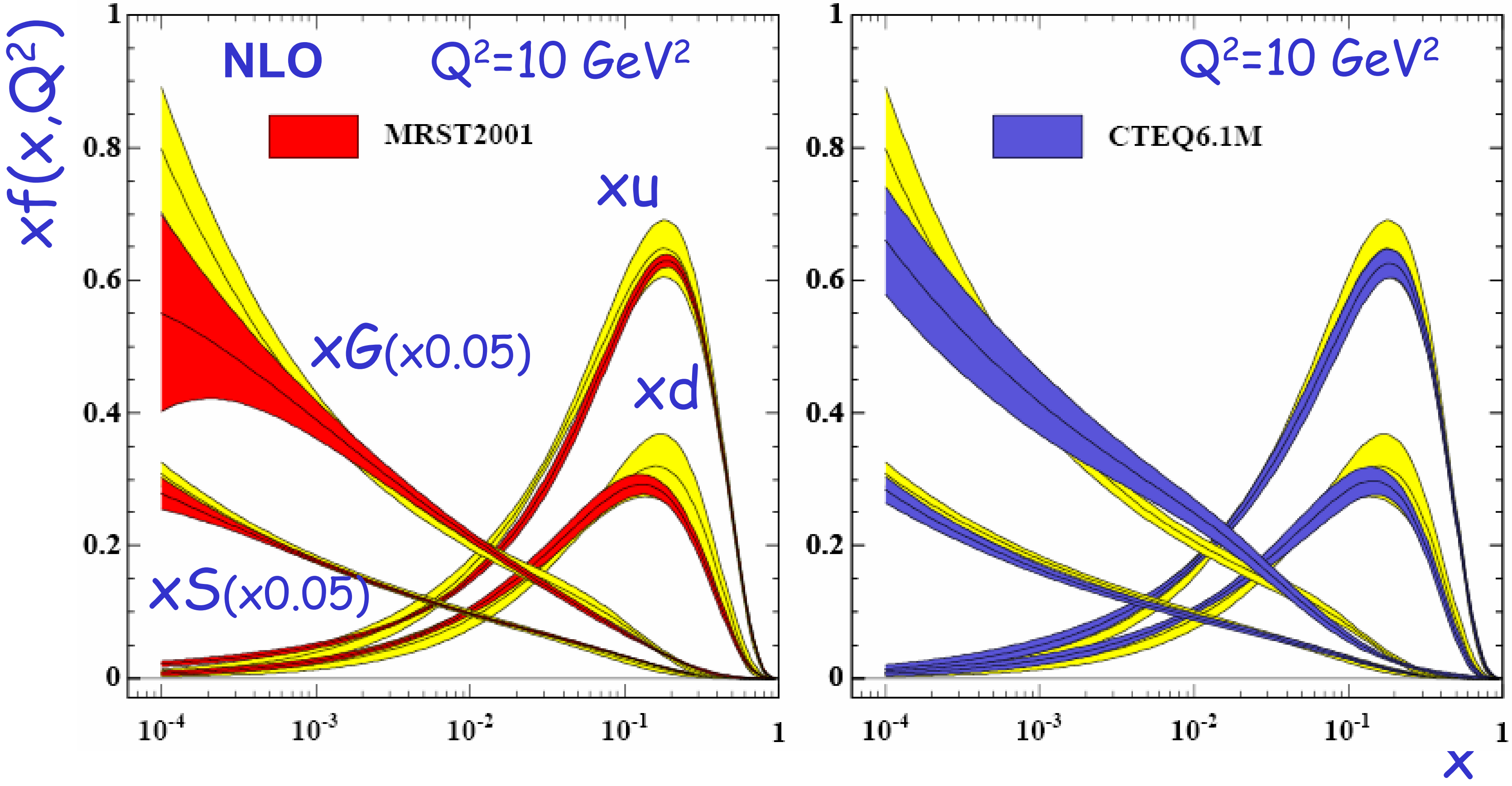
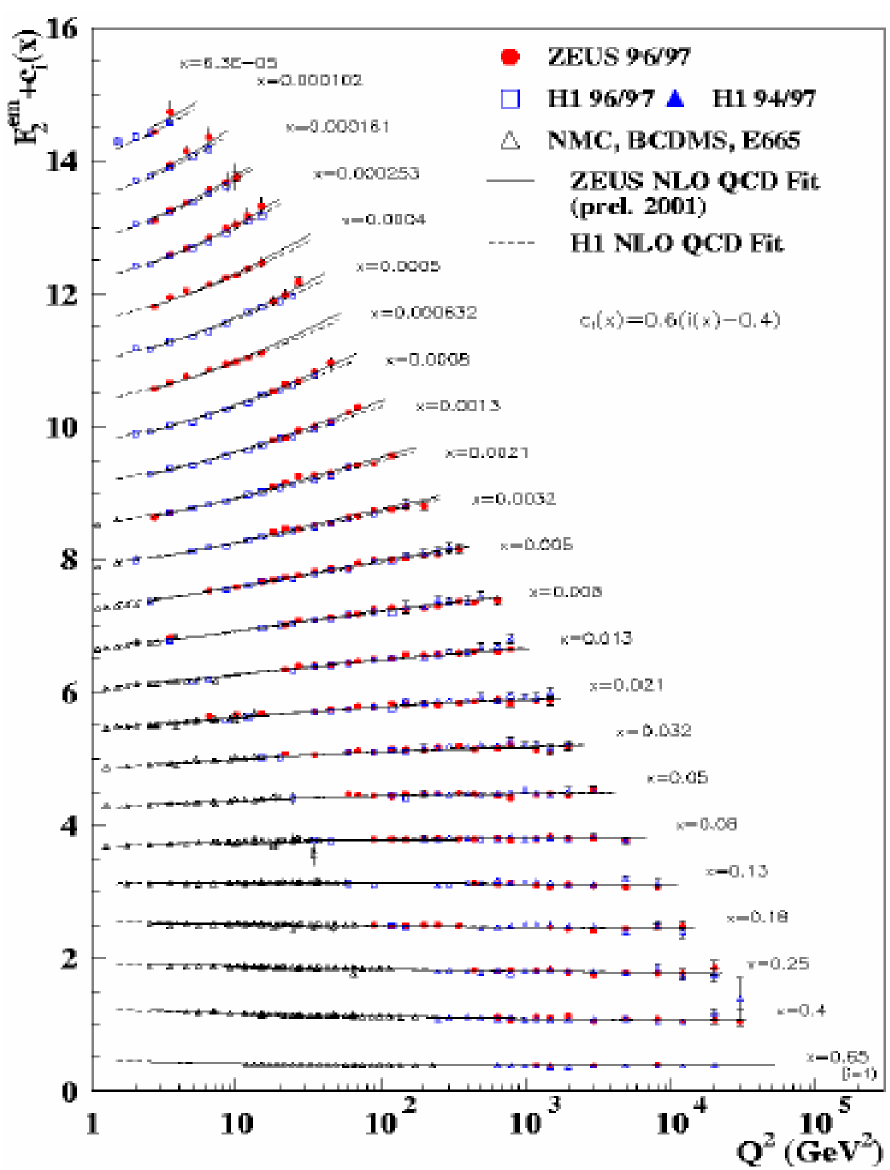
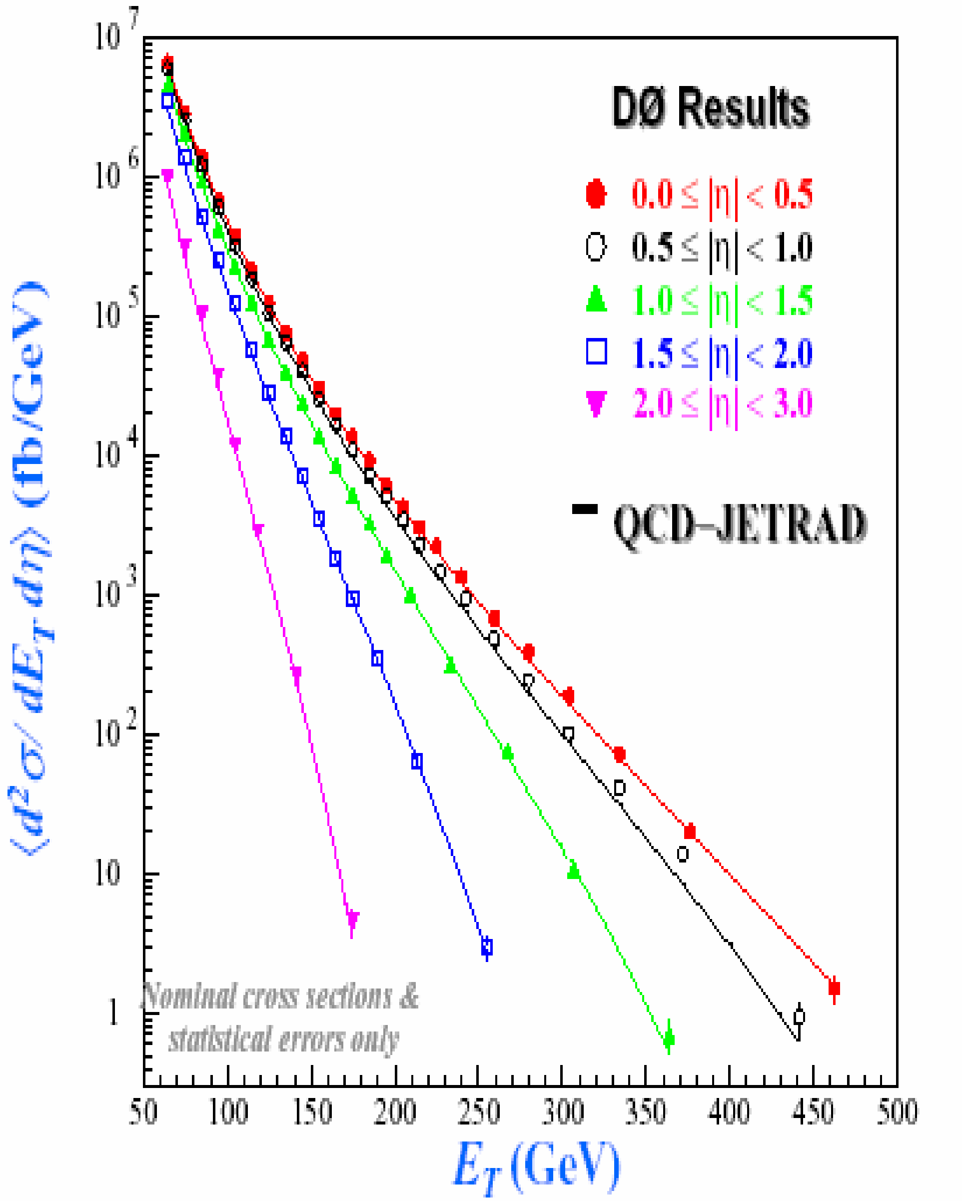


Consistently fit almost all data with Q > 2GeV

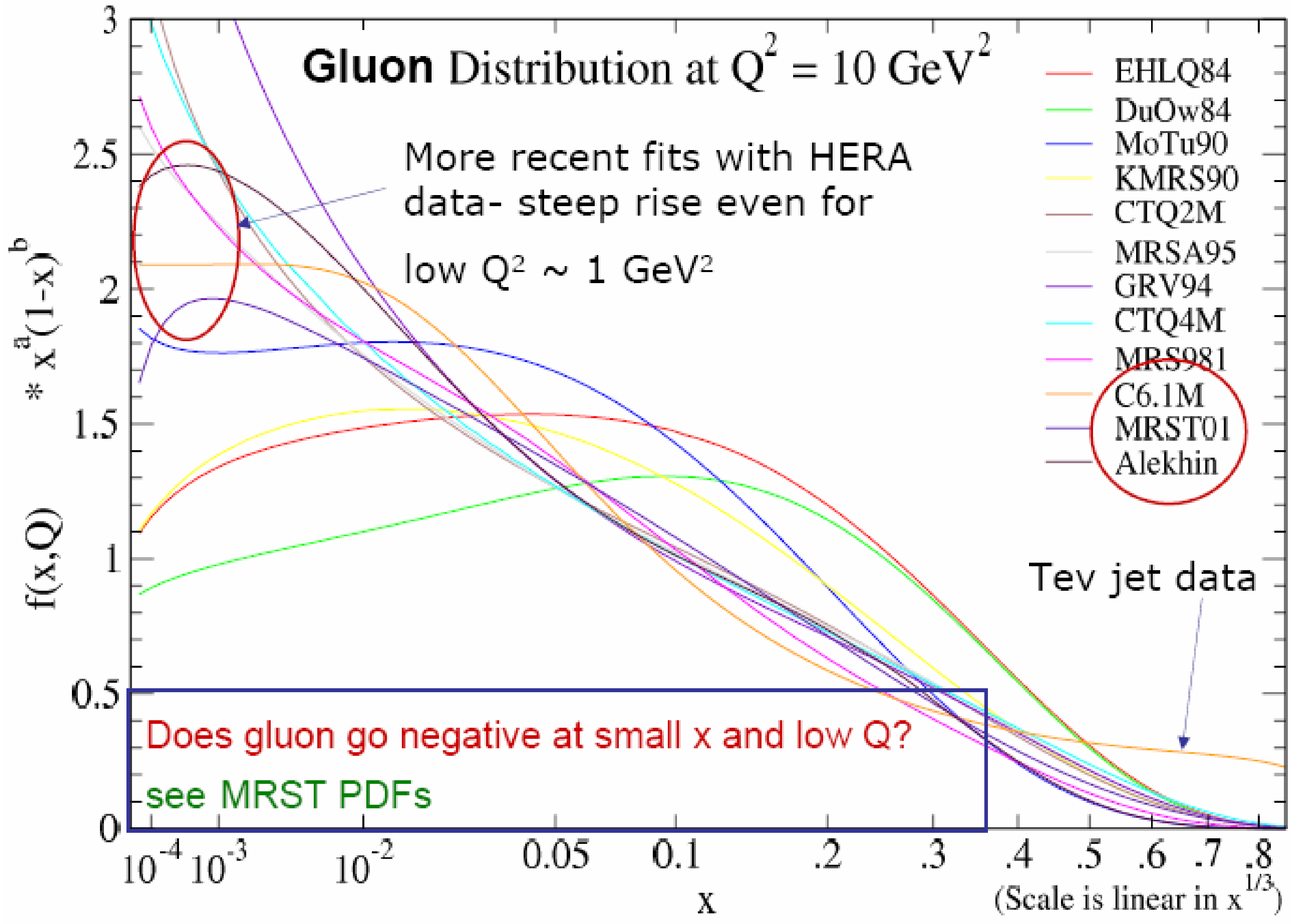
DIS structure function



Inclusive jet at Tevatron



Gluon distribution over 20 years



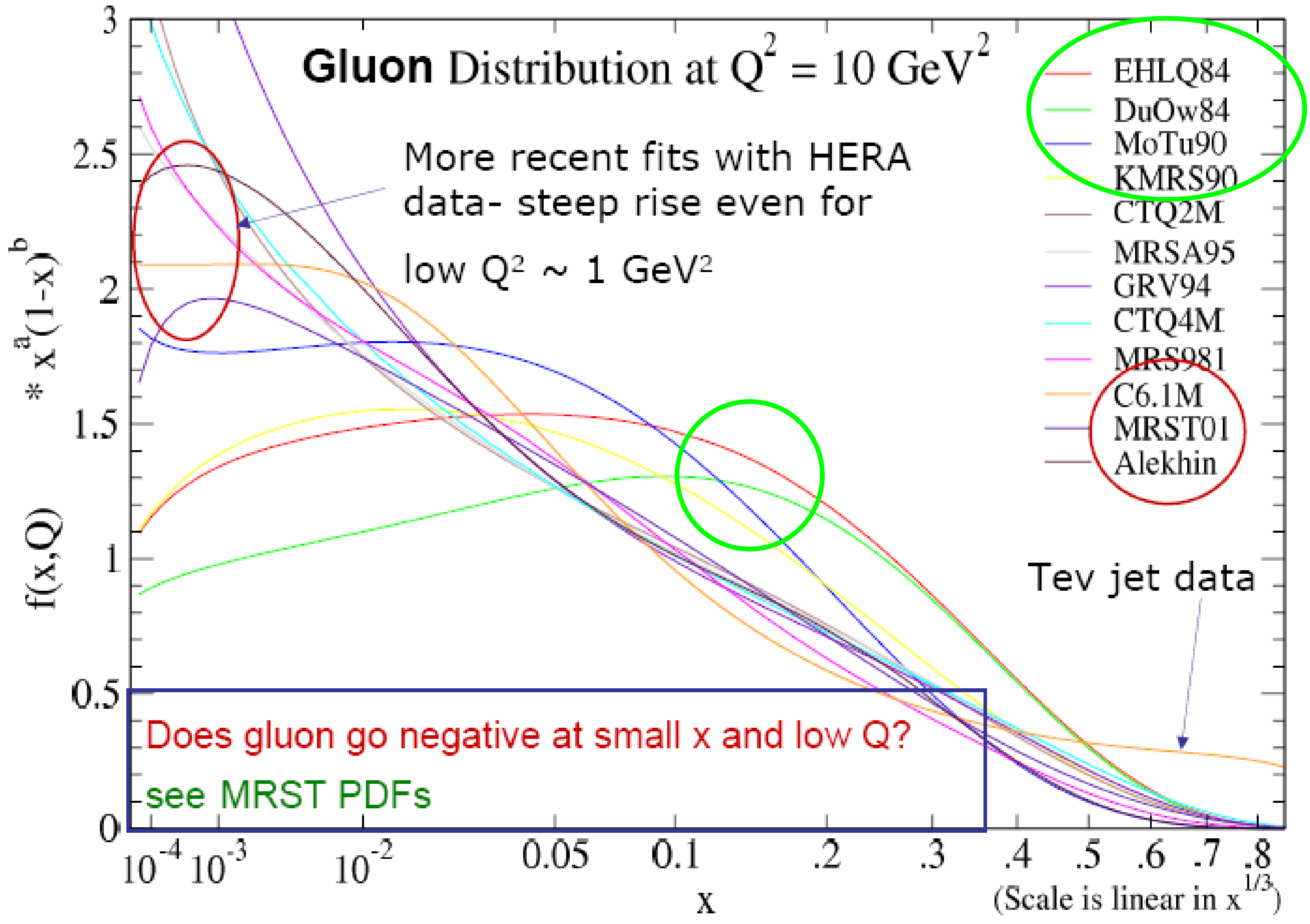
More recent fits with HERA data- steep rise even for low $Q^2 \sim 1$ GeV^2

Tev jet data

Does gluon go negative at small x and low Q?

see MRST PDFs

Gluon distribution over 20 years



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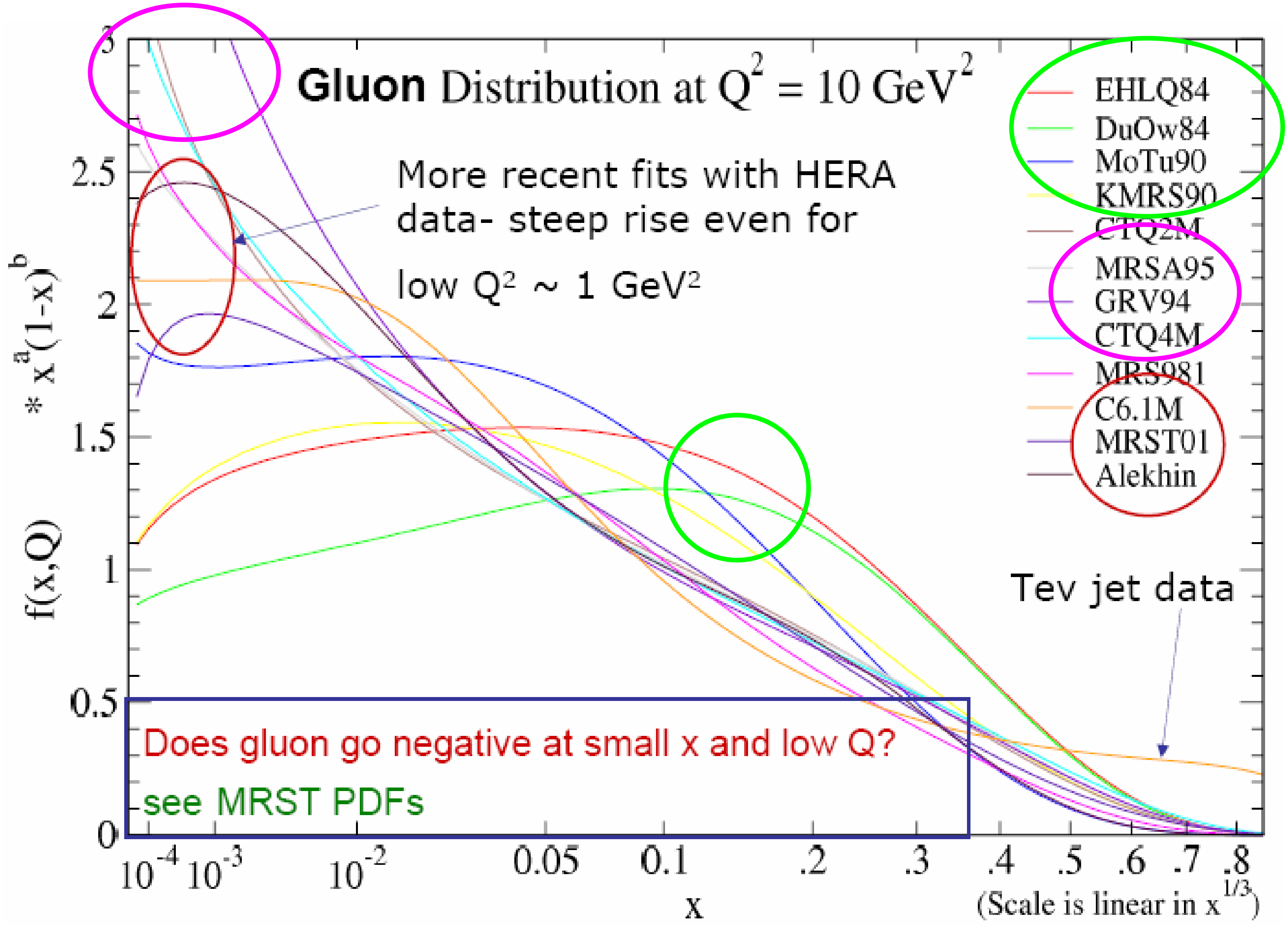

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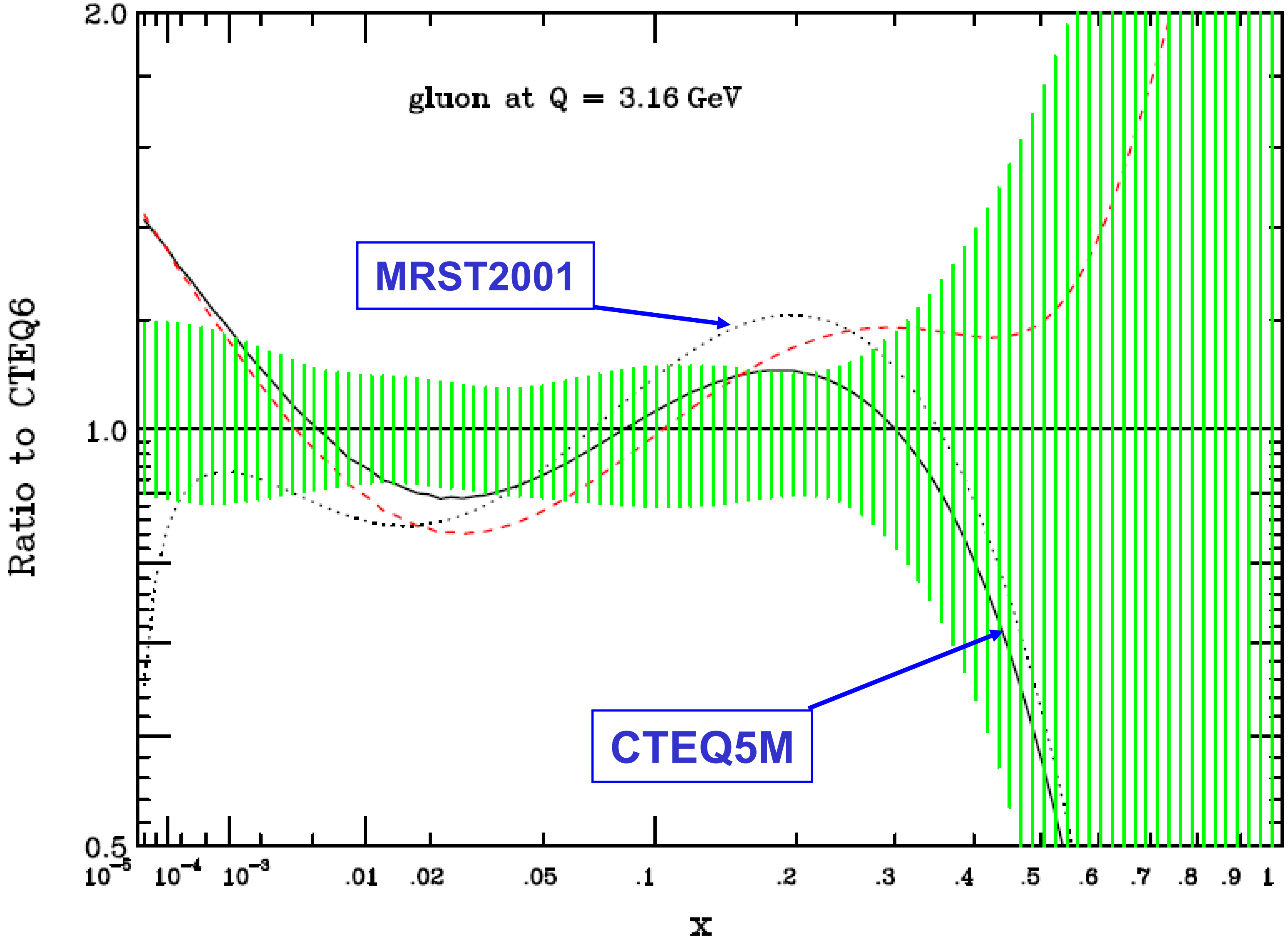
Uncertainties of gluon distribution

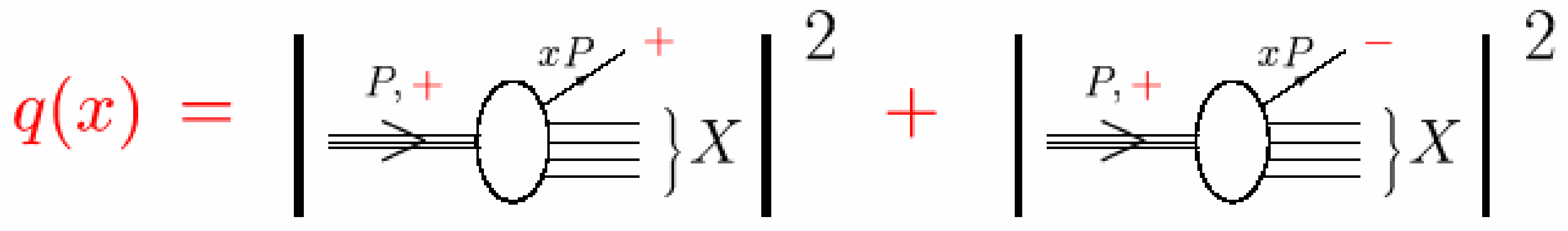


MRST2001

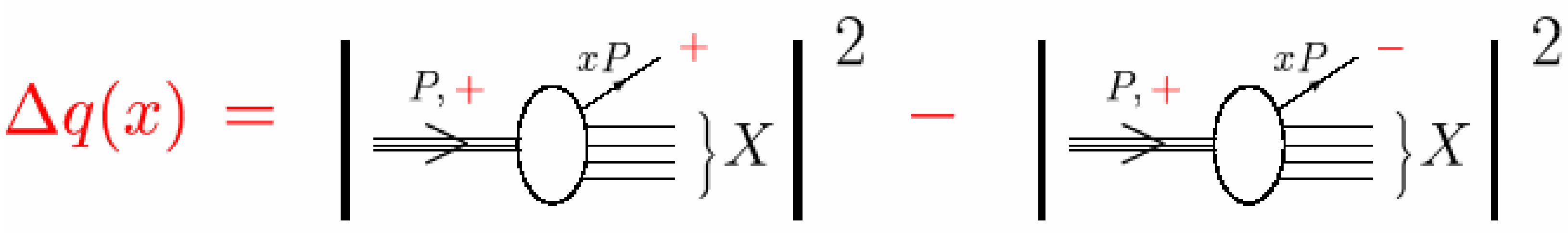
CTEQ5M

Spin dependence of PDFs

- **Spin-averaged PDFs:**



- **Spin-dependent PDFs:**

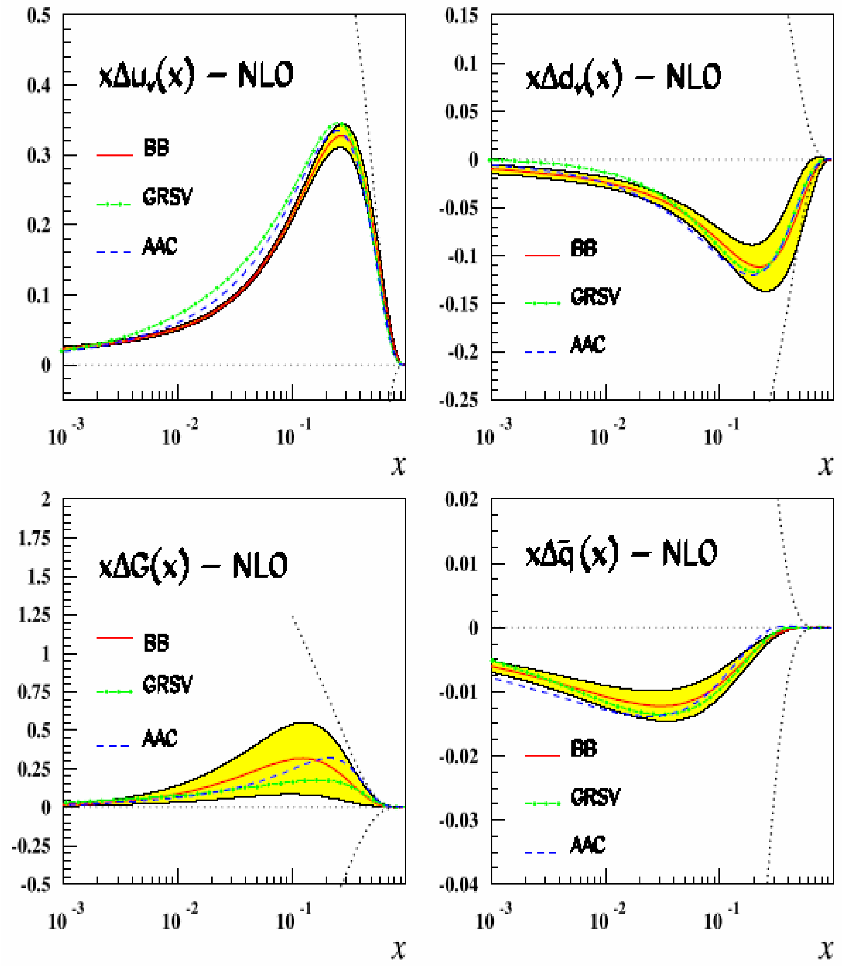


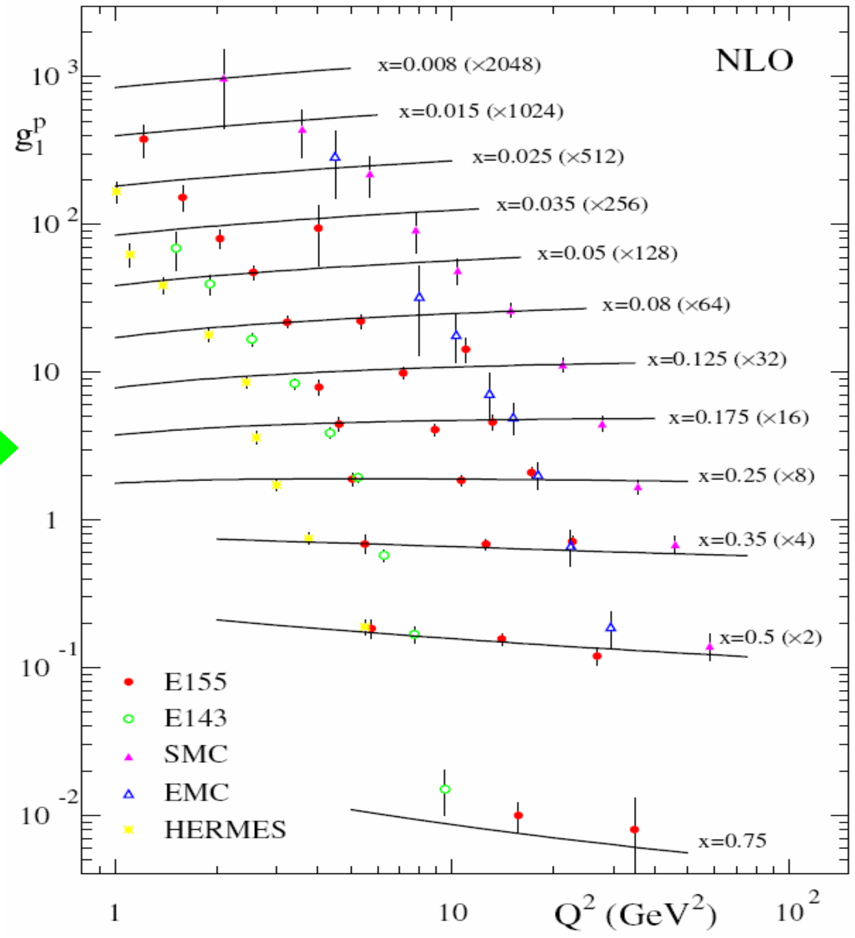
(transversity, GPDs, and etc - covered by other talks)

- **Not much information, as well as people's effort on spin-dependent PDFs until recently**

Spin-dependent PDFs of a proton

❖ DIS data on g1 + QCD global fits:





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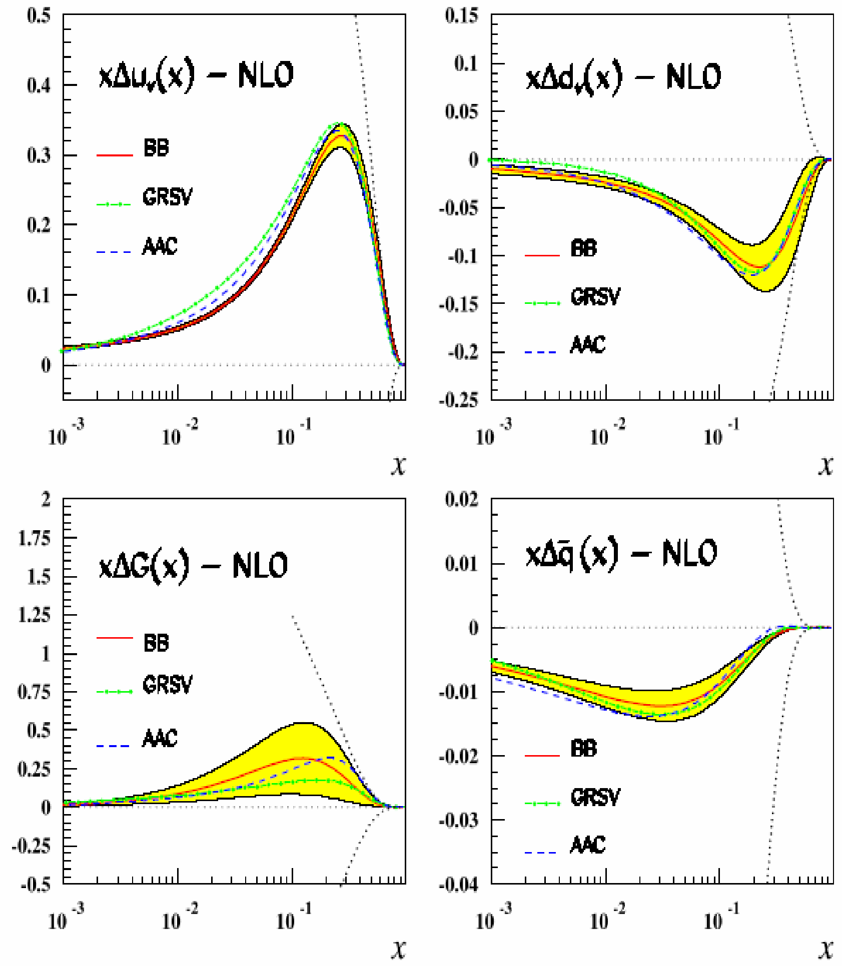
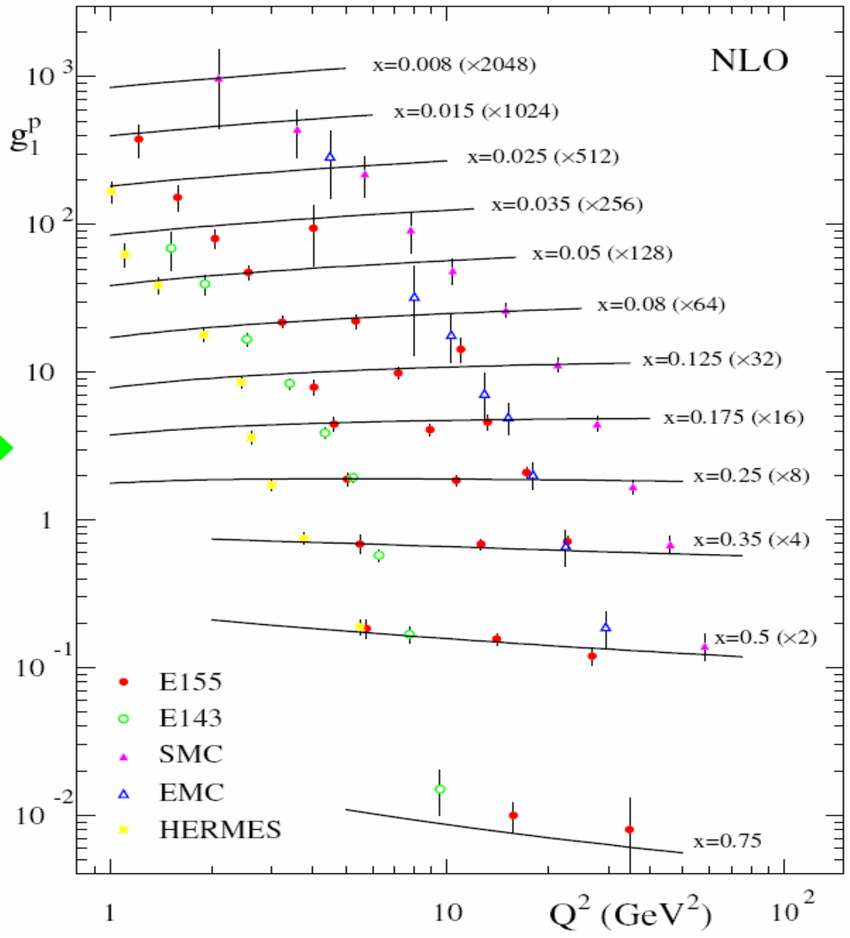


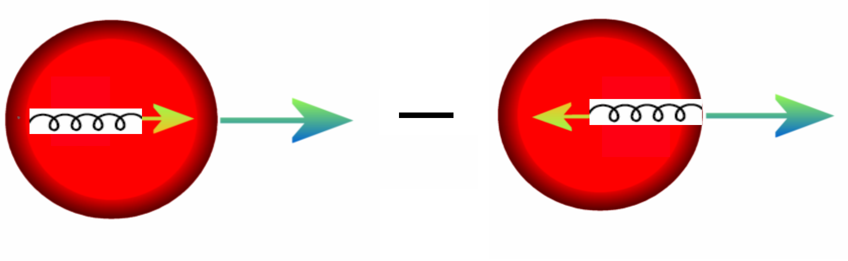


Current DIS data ➡ Very limited constraints on the glue!

Spin-dependent gluon distribution

❖ **Spin-dependent gluon distribution:**

$$\Delta g(x) =$$



❖ **Net gluon helicity:**

$$\Delta G(Q^2) = \int_0^1 dx\, \Delta g(x, Q^2)$$

❖ **Proton helicity sum rule:**

Covered by other talks

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

Quark spin
≈ 0.1

EMC, SMC, E142-155, HERMES

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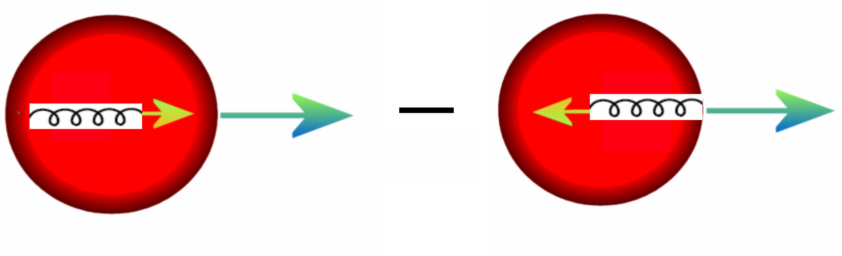

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Covered by other talks

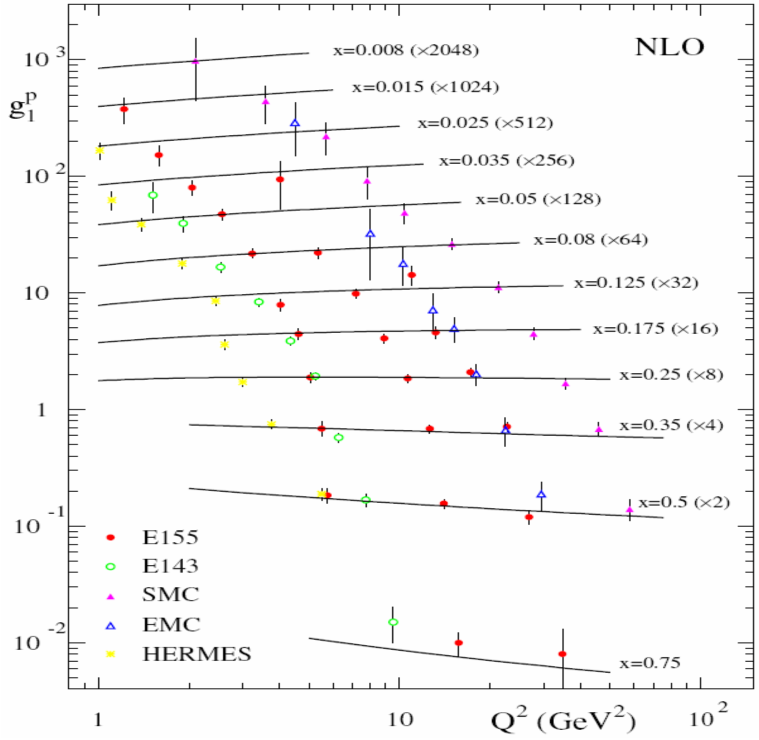
Extensive effort at RHIC, HERMES, COMPASS

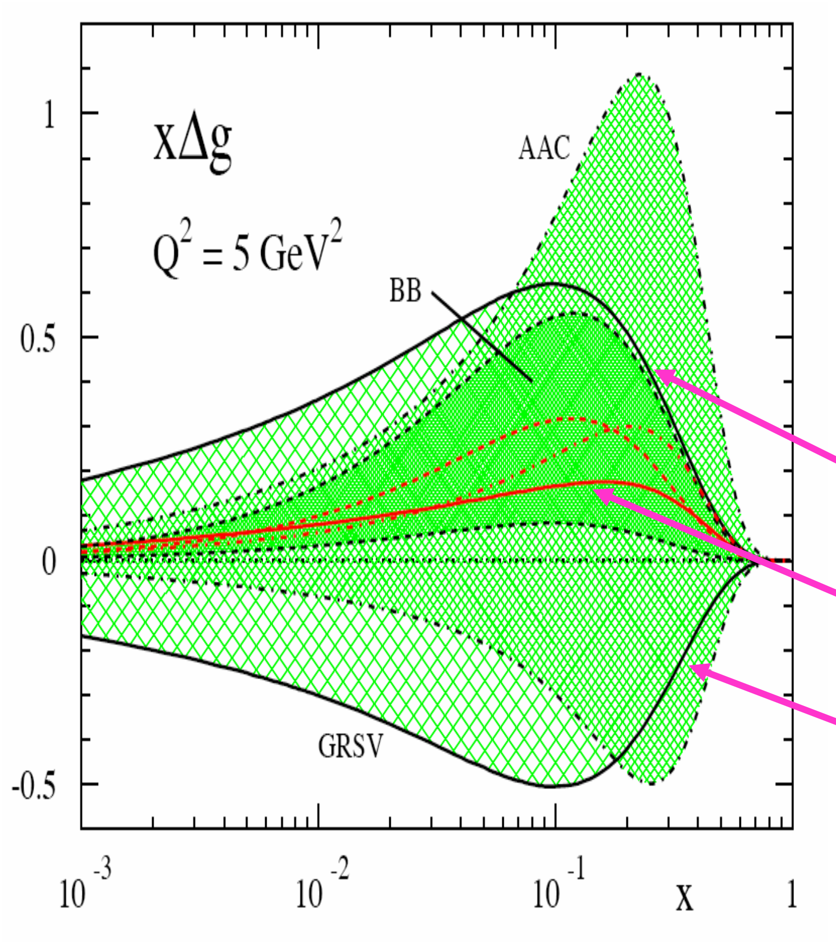
Quark spin
≈ 0.1

EMC, SMC, E142-155, HERMES

Existing inclusive DIS data

- **Very limited information on the glue:**





GRSV, …

$$\Delta G(1\,\mathrm{GeV}^2) \approx 1.8$$

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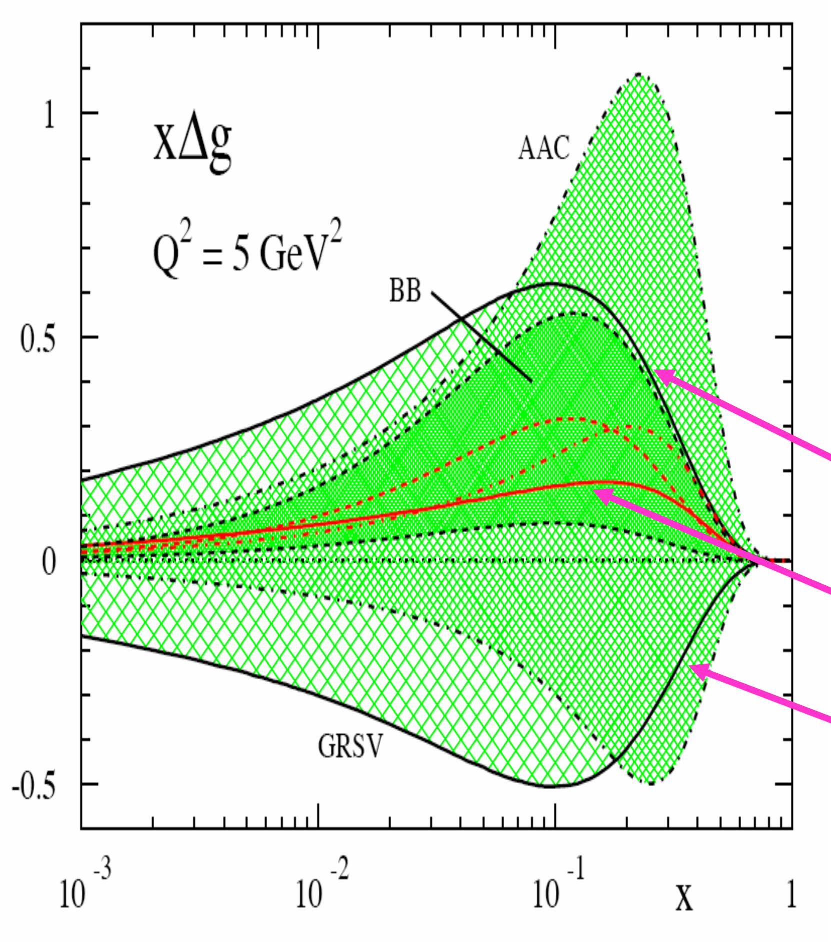

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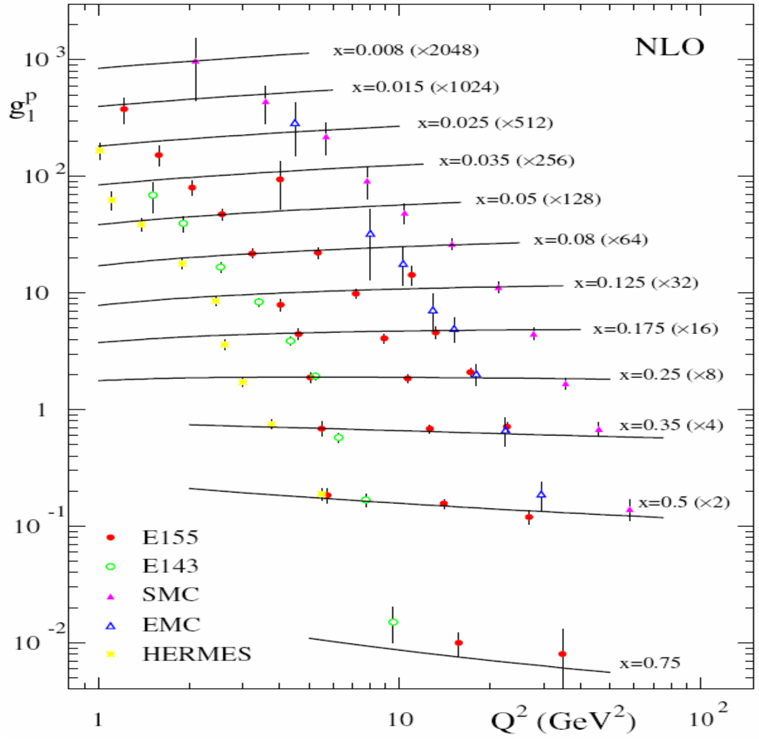

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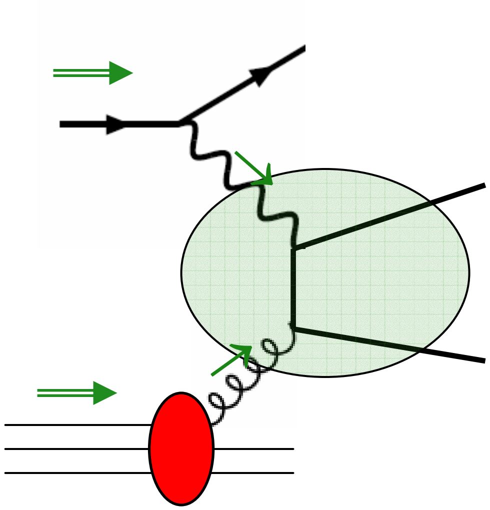
Need more glue sensitive probes!

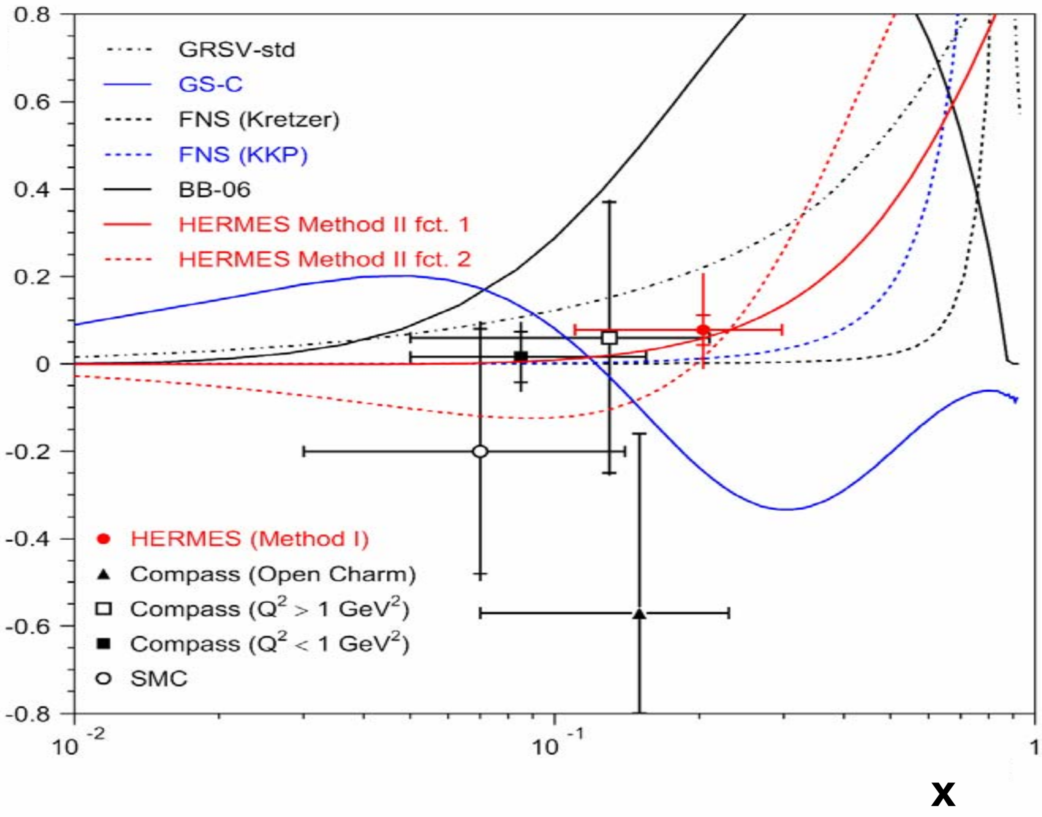
Semi-inclusive DIS



jet(s), $c\bar{c}$, . . .

$\Delta g / g$

HERMES, COMPASS



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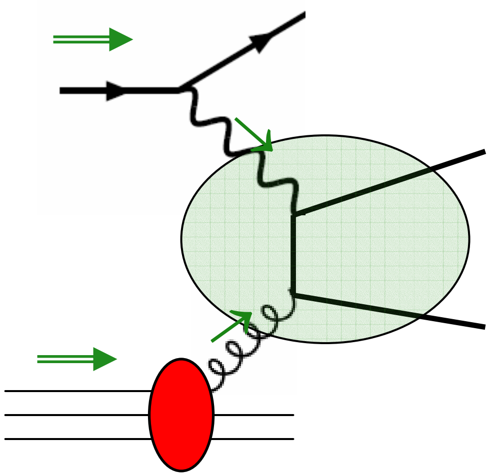
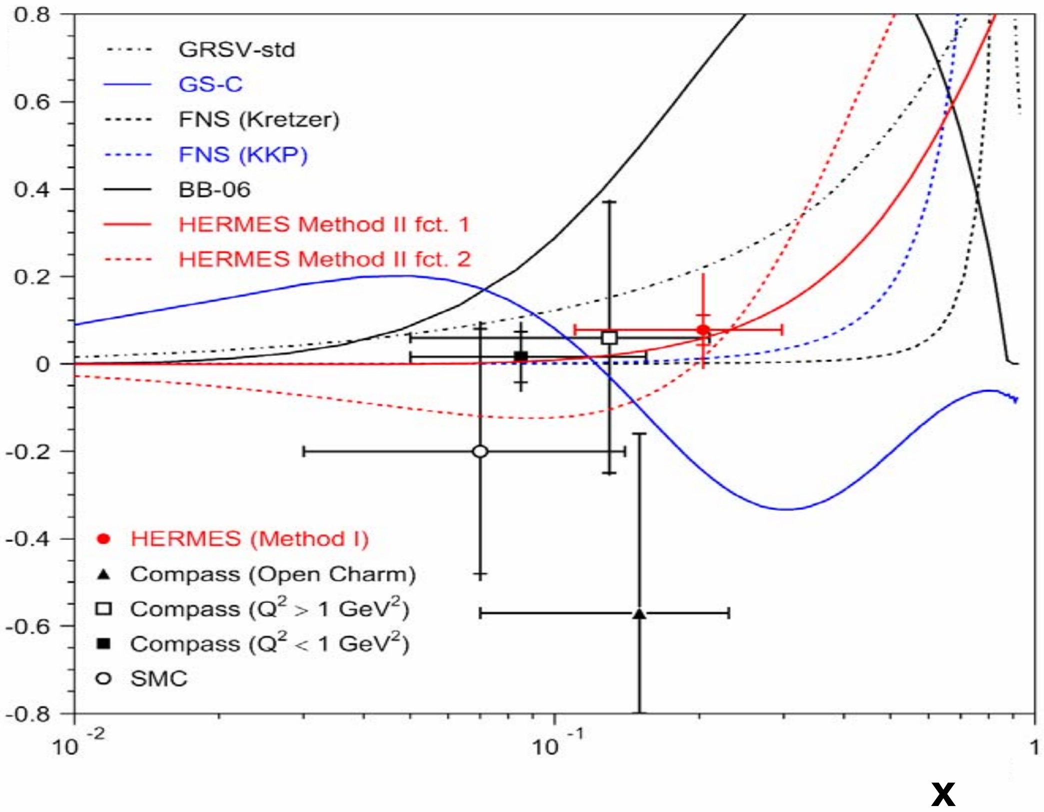


$\mathrm{jet(s)},\, c\bar{c},\, \ldots$

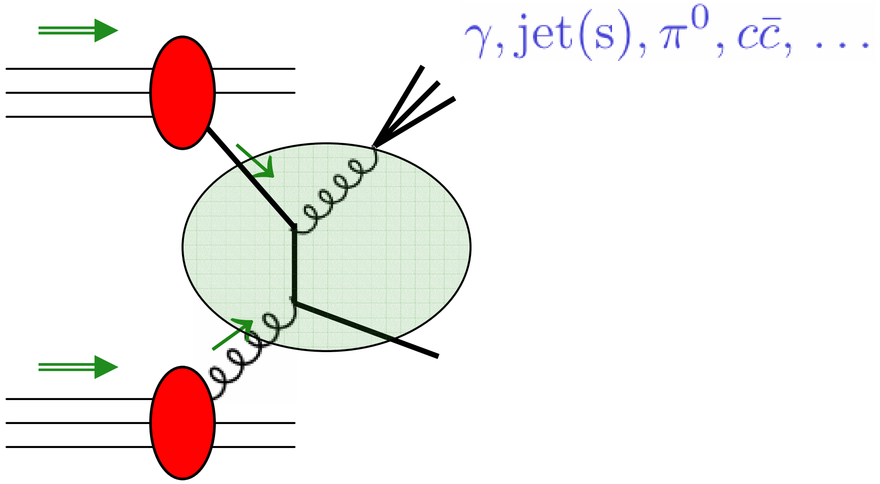
HERMES, COMPASS

$\Delta g/g$



Limited reach
due to
statistics and
collision energy

Polarized hadronic collision - RHIC



PHENIX, STAR

Very rich final states

Variable collision energies

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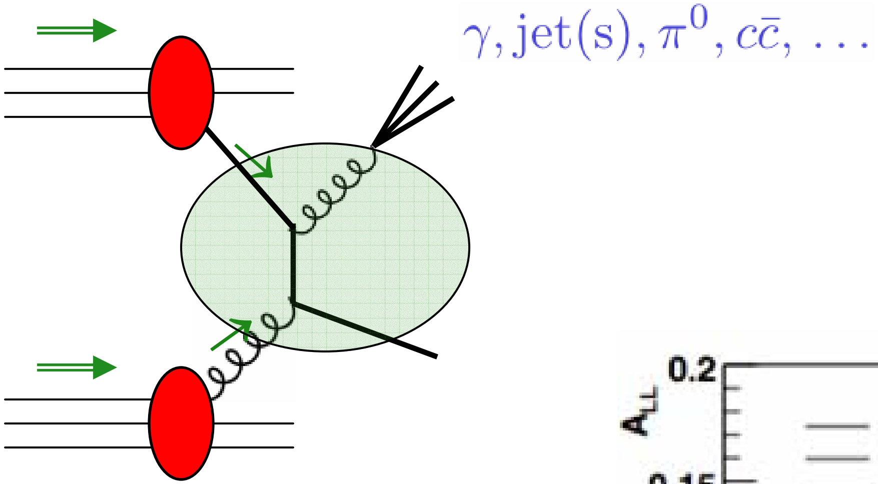

$\gamma, \mathrm{jet(s)}, \pi^0, c\bar{c}, \ldots$

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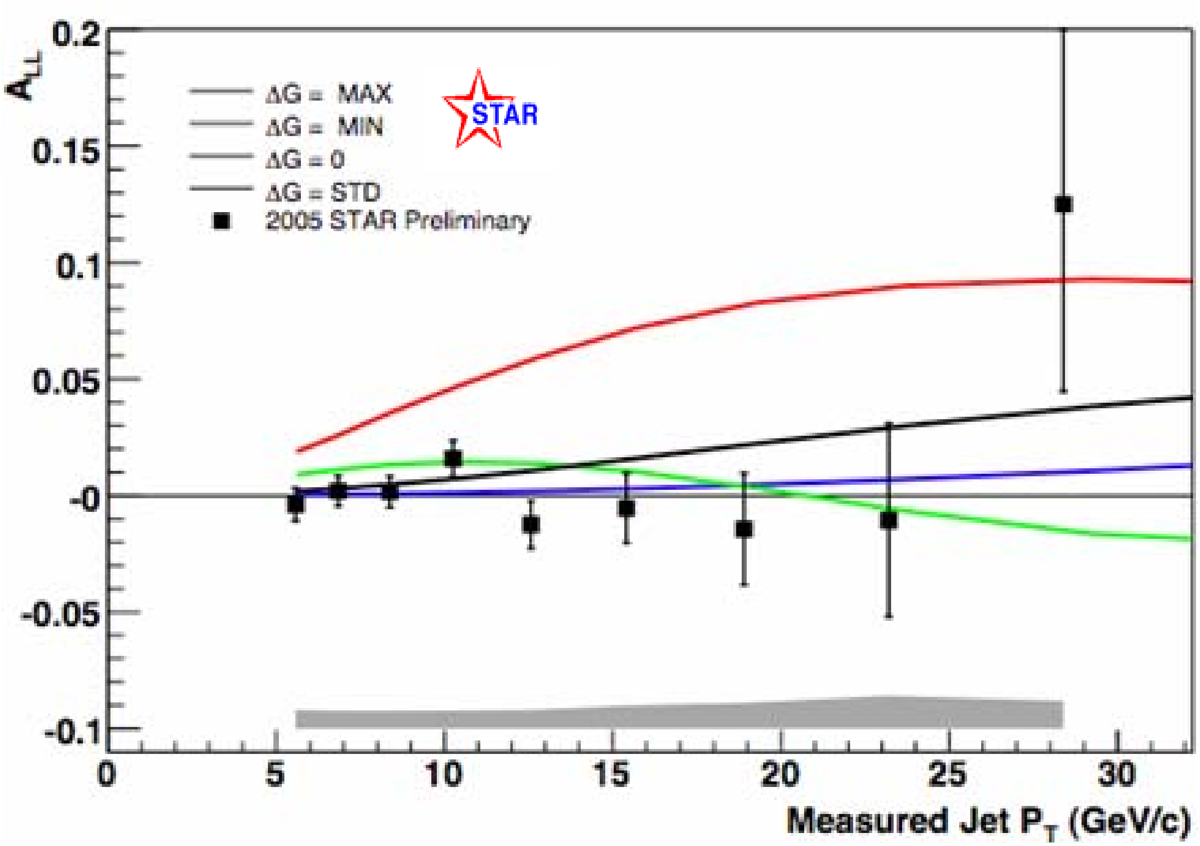
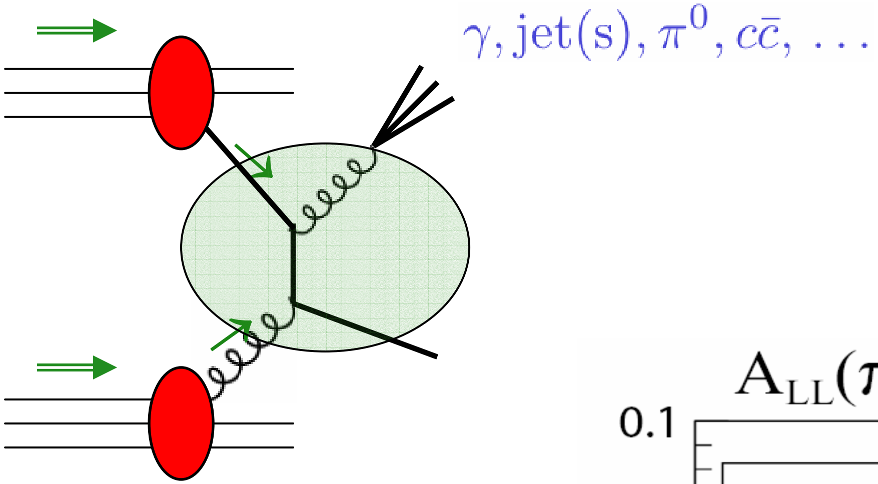


STAR - jets
200 GeV

Polarized hadronic collision - RHIC



PHENIX, STAR

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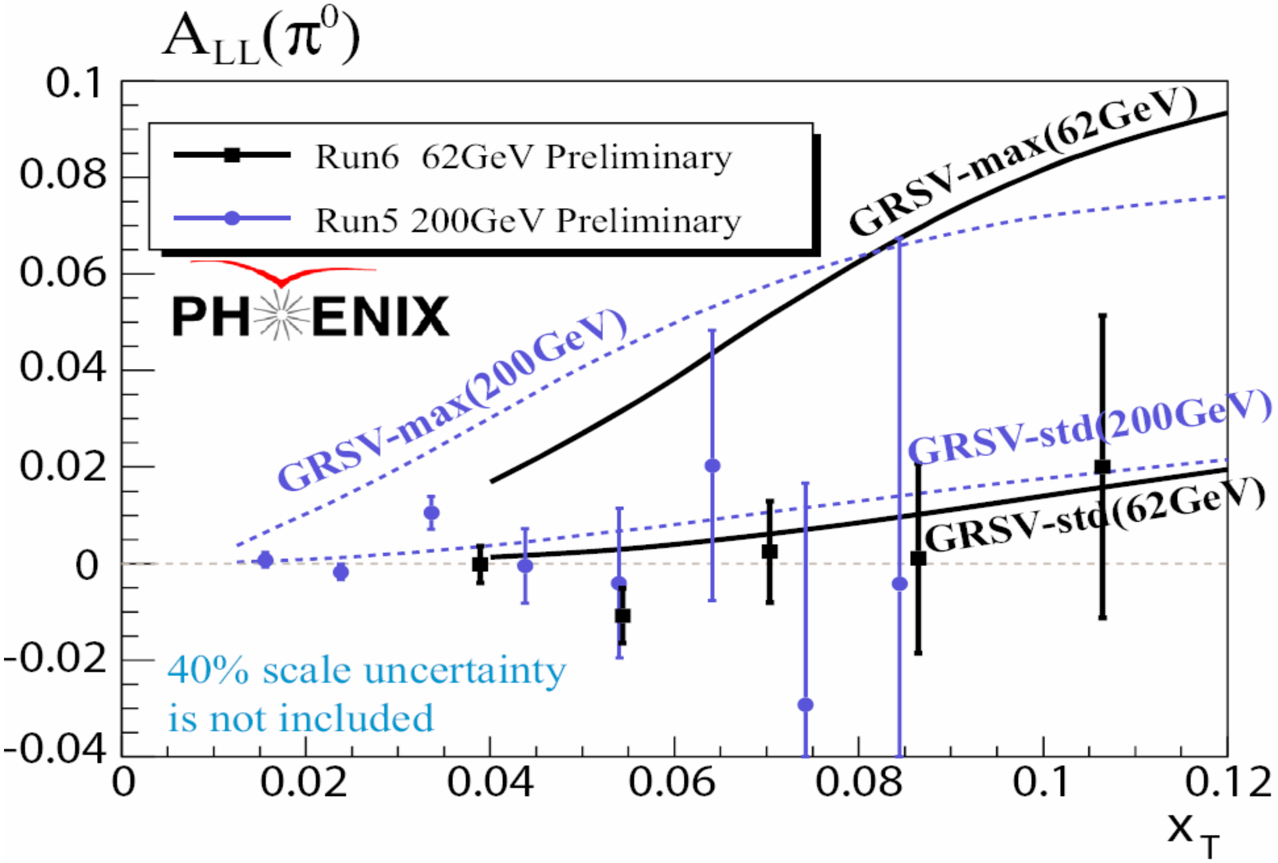
Variable collision energies

PHENIX - π^0

200, 62 GeV



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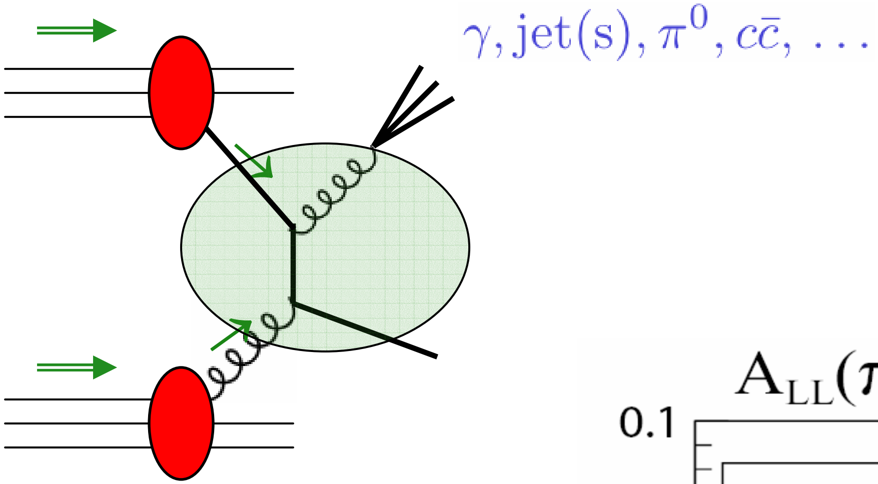

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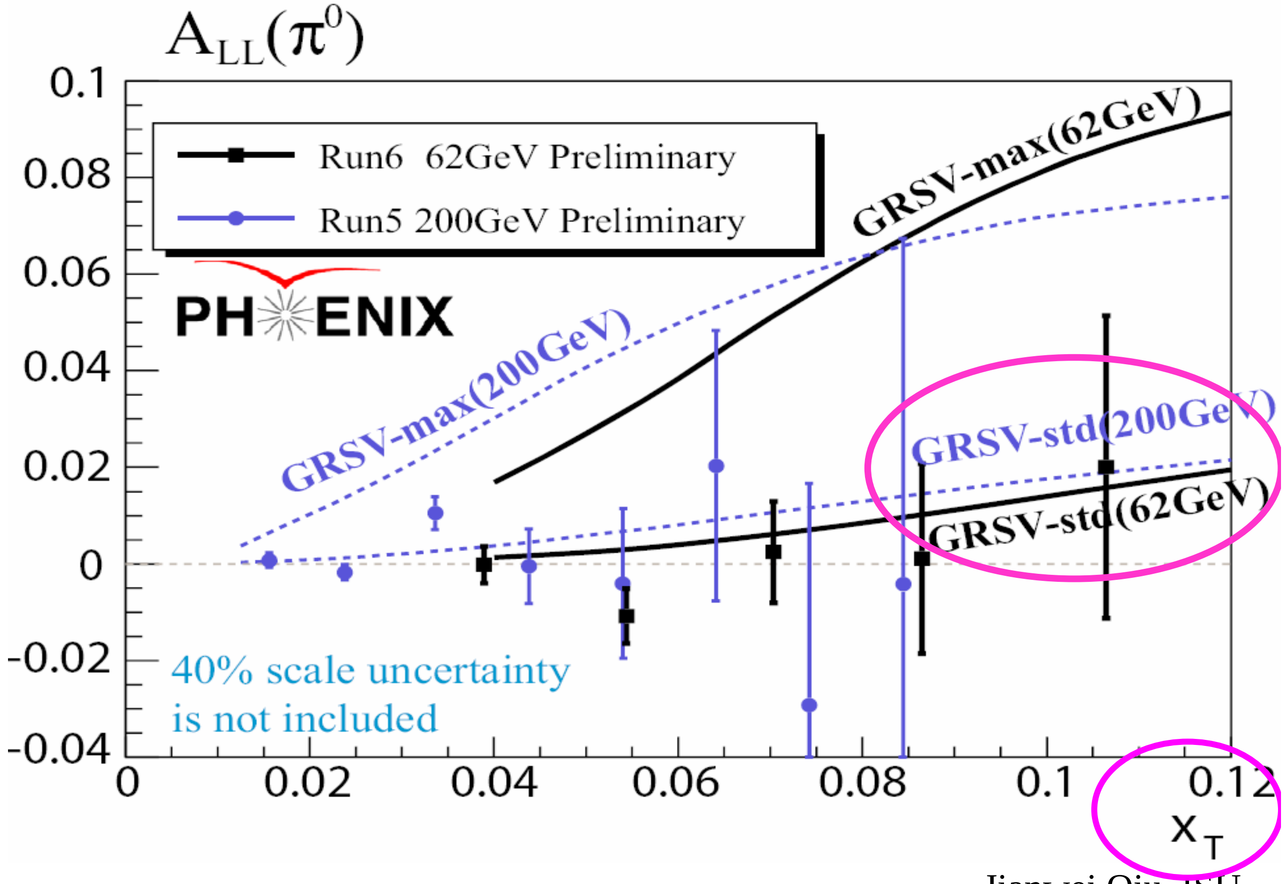


What have we learned so far about Δg?

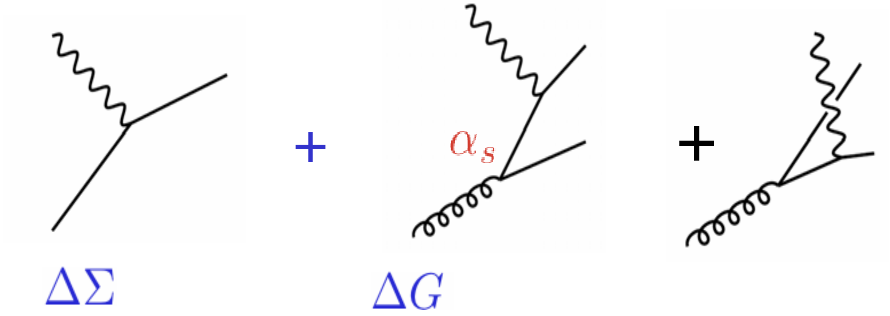
- Δg probably "small" in the accessible x-range:

Consistent with $\Delta g(x) \propto x g(x)$

$$\longrightarrow \quad \Delta G = \int_0^1 dx\, \Delta g(x) \propto \int_0^1 dx\, x g(x) \sim 0.5$$

- No indication of huge integral ΔG ~ 2

Needed to explain the small g1 while keeping Δq large



$$\Delta\Sigma - \underbrace{n_f \frac{\alpha_s(Q^2)}{2\pi} \Delta G(Q^2)}$$

Does not vanish at large Q^2!

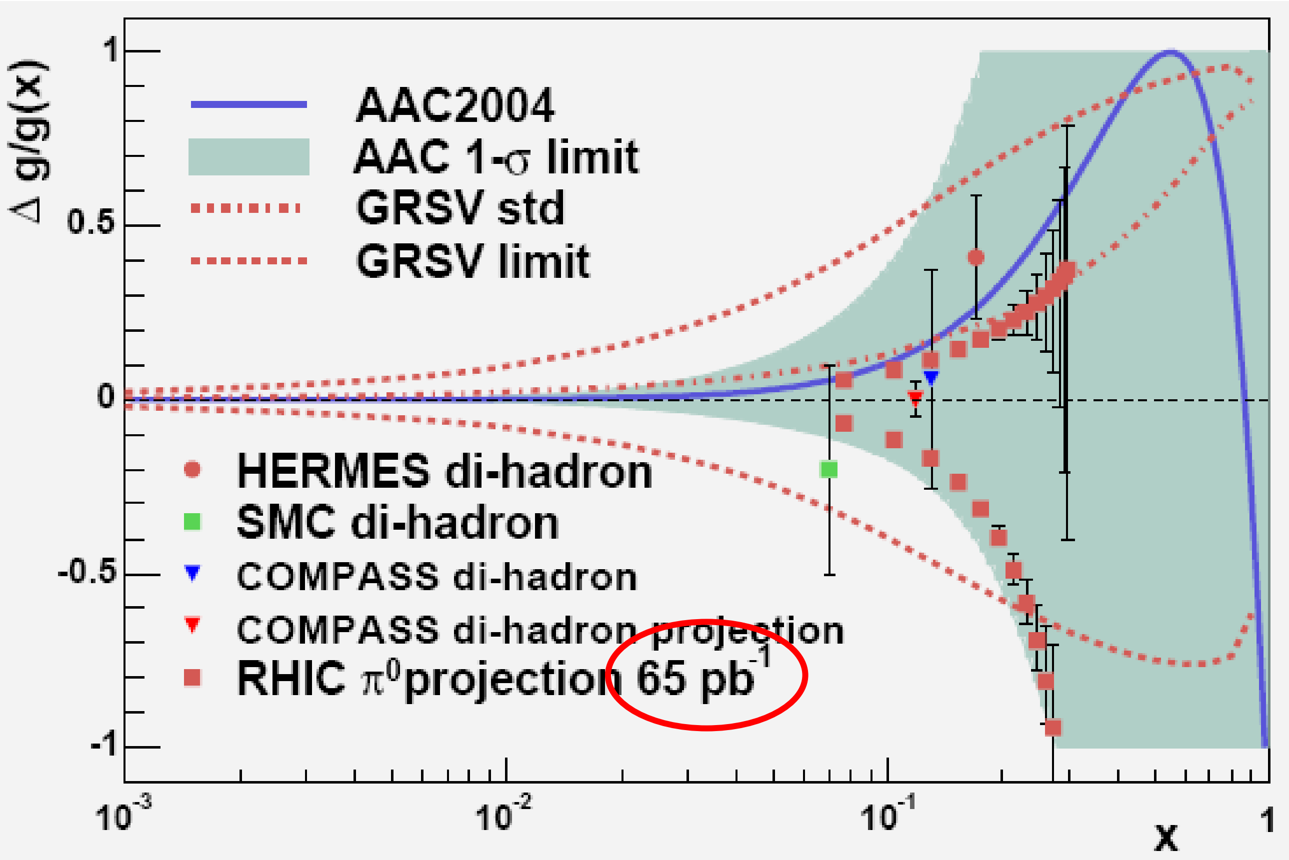
- Challenge: sign, x-dependence of Δg(x), and

why? - model calculations

Werner's talk

More from RHIC

- **PHENIX – ALL(π^0):** $\sqrt{S} = 200$ GeV



More from RHIC

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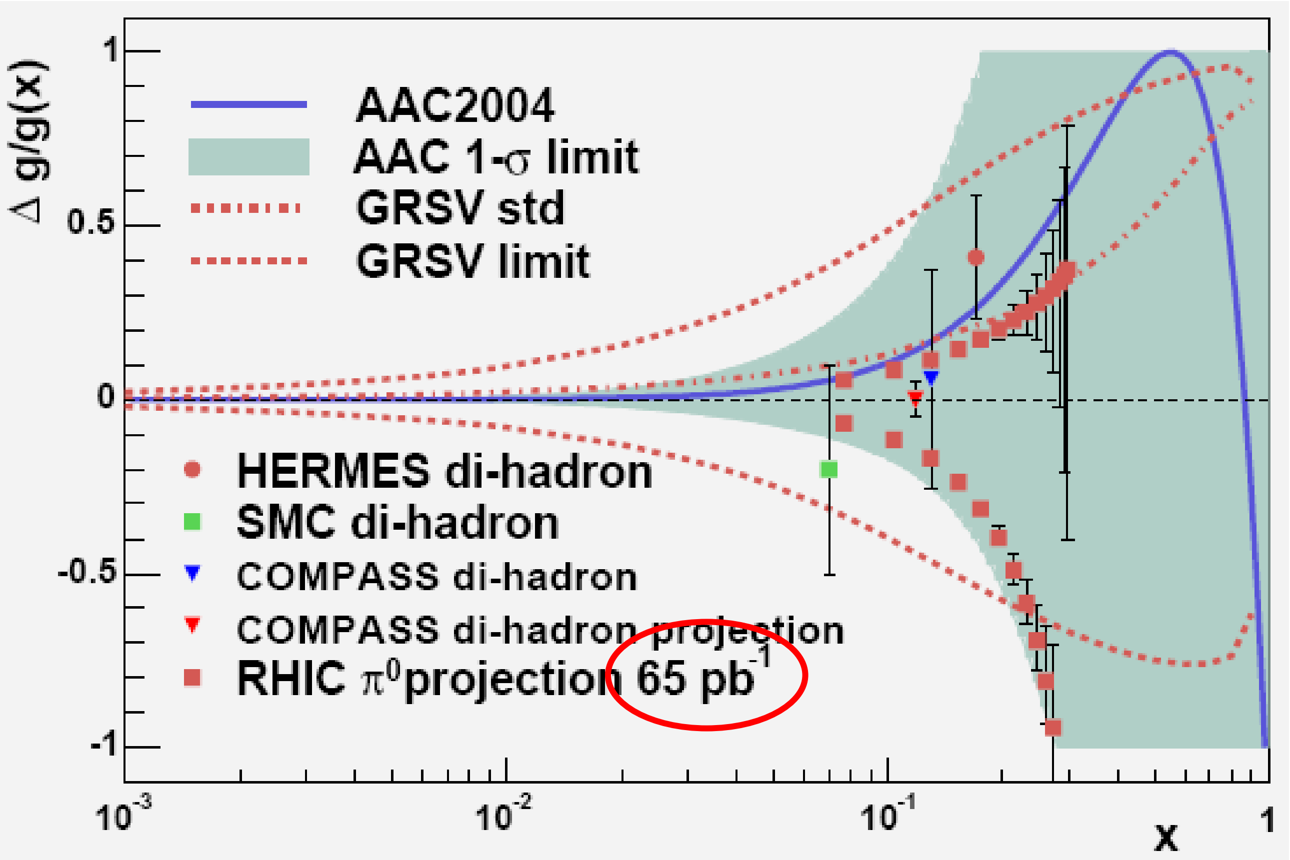


Dominated by gg subprocesses: $A_{LL}\left(\pi^0\right) \propto [\Delta g]^2$

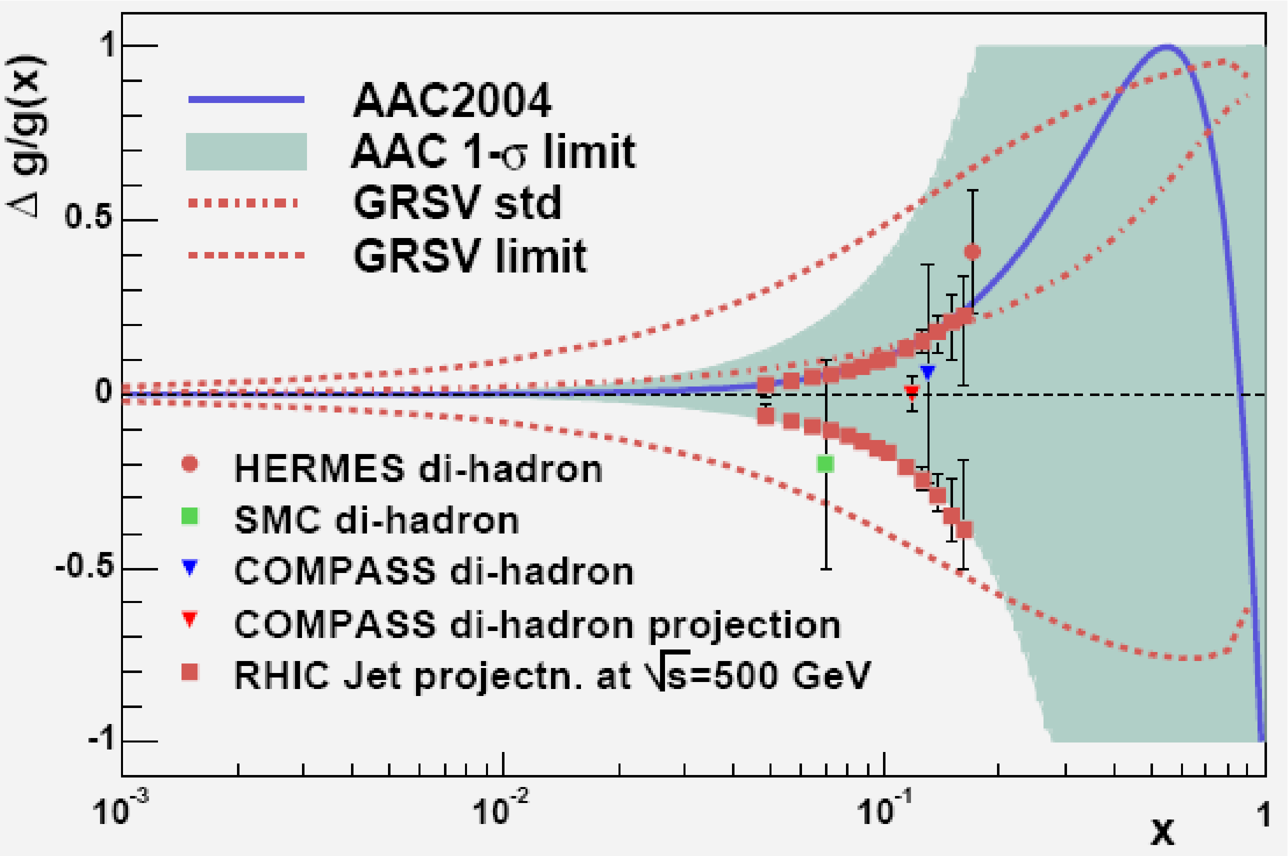
Sign of Δg?

January 12, 2007

Jianwei Qiu, ISU

More from RHIC

- **STAR - jets:** $\sqrt{S} = 500\ \text{GeV}$



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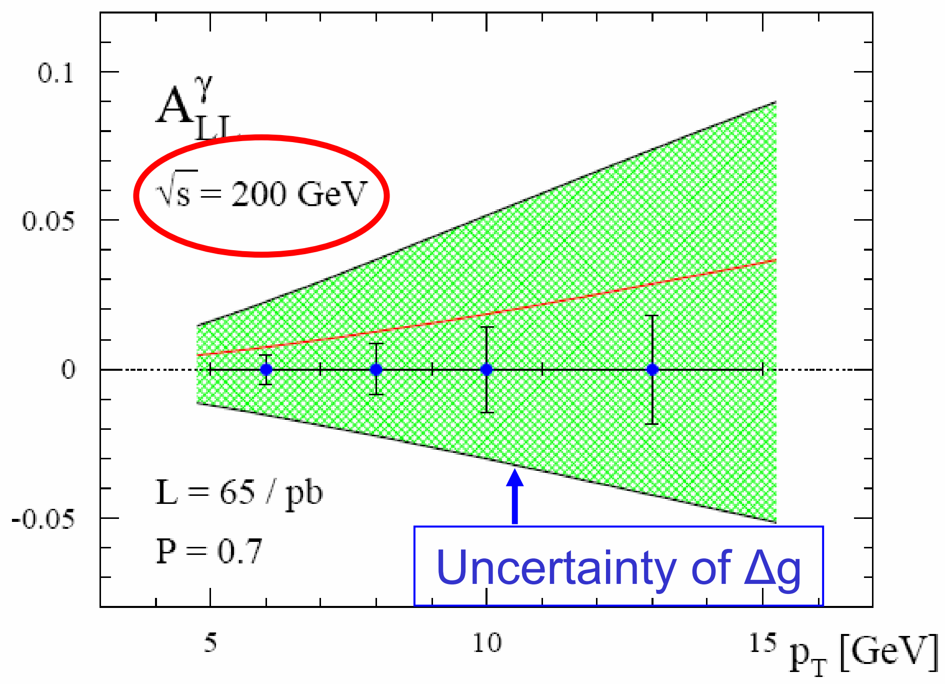
Sign of Δg?

More on Δg from RHIC

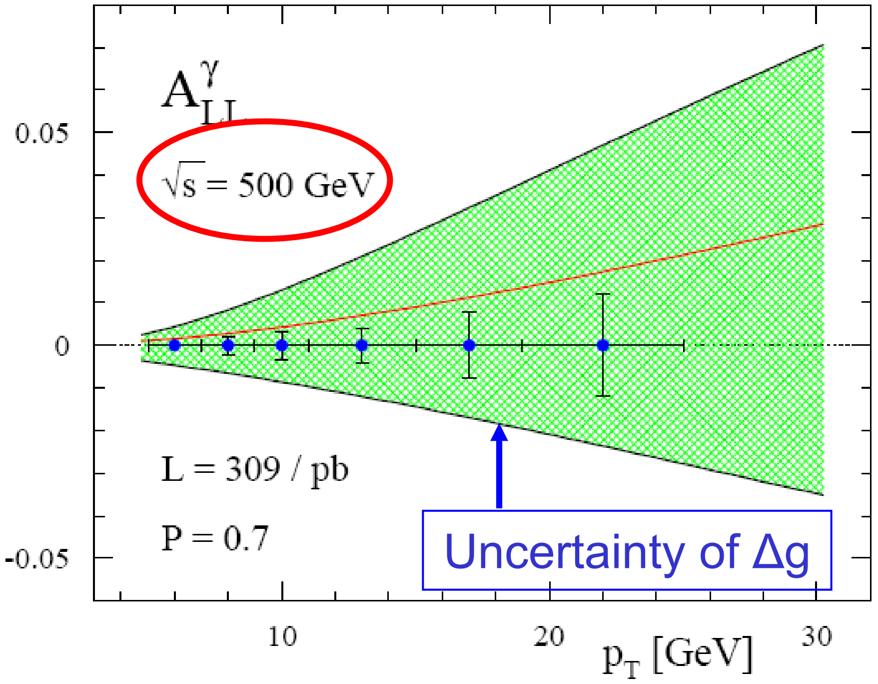
- direct photon – dominated by “Compton” subprocess:

$$A_{LL}(\gamma) \propto \left[\frac{g_1^p \otimes \Delta g \otimes \Delta\hat{\sigma}}{F_1^p \otimes g \otimes \hat{\sigma}}\right] + \ldots$$

Sensitive to sign of Δg



Uncertainty of Δg

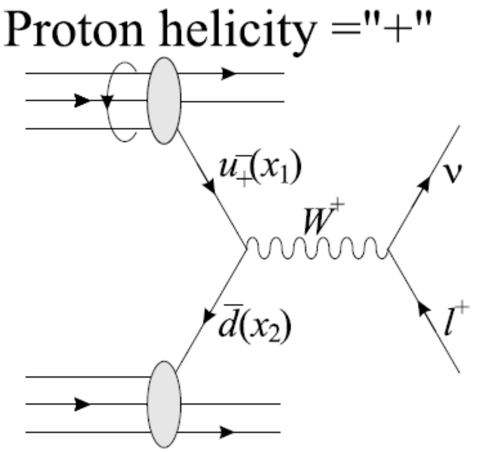


Uncertainty of Δg

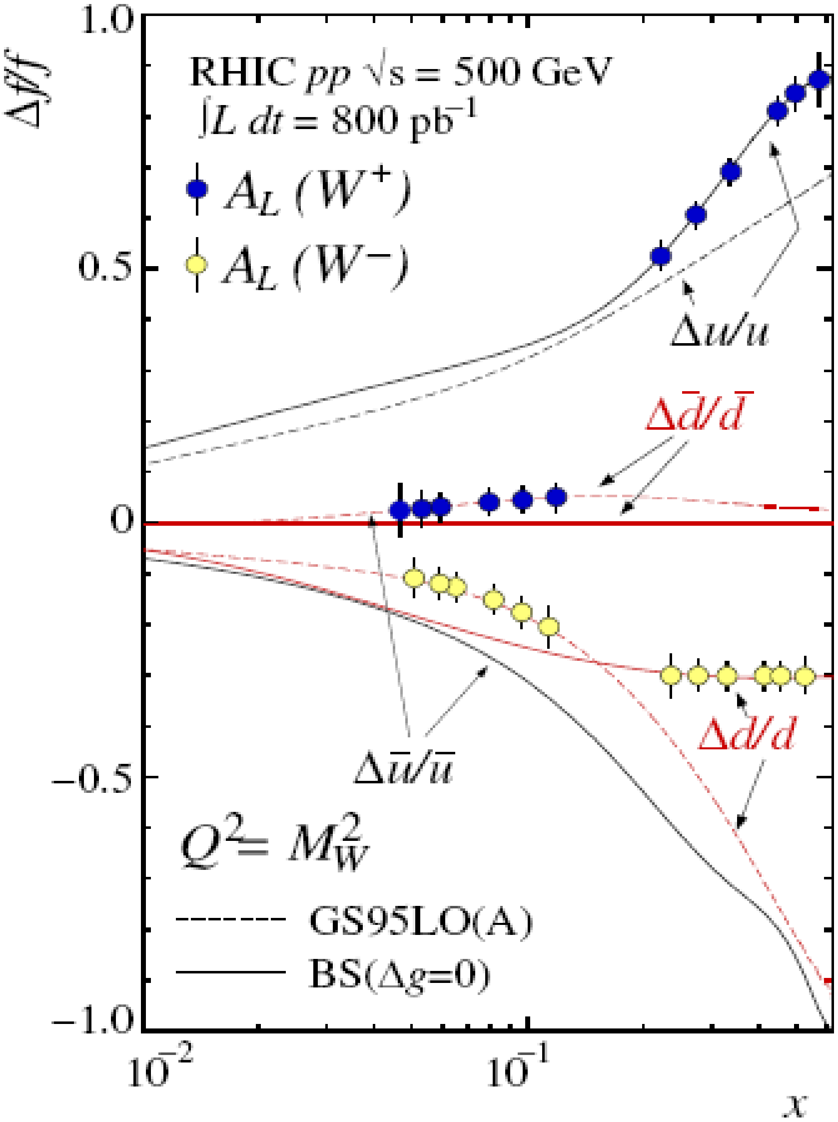
Photon + jet, etc

Flavor separation of Δq from RHIC

- **W-production at 500 GeV:**



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



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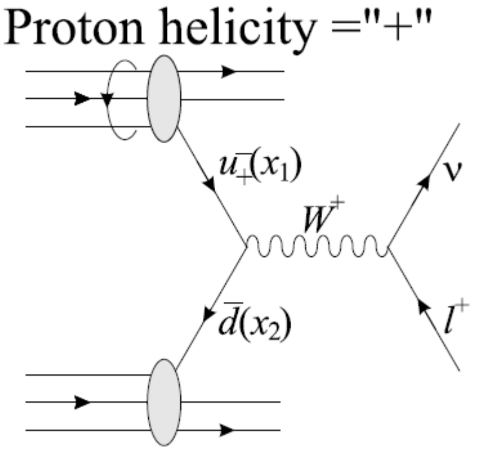

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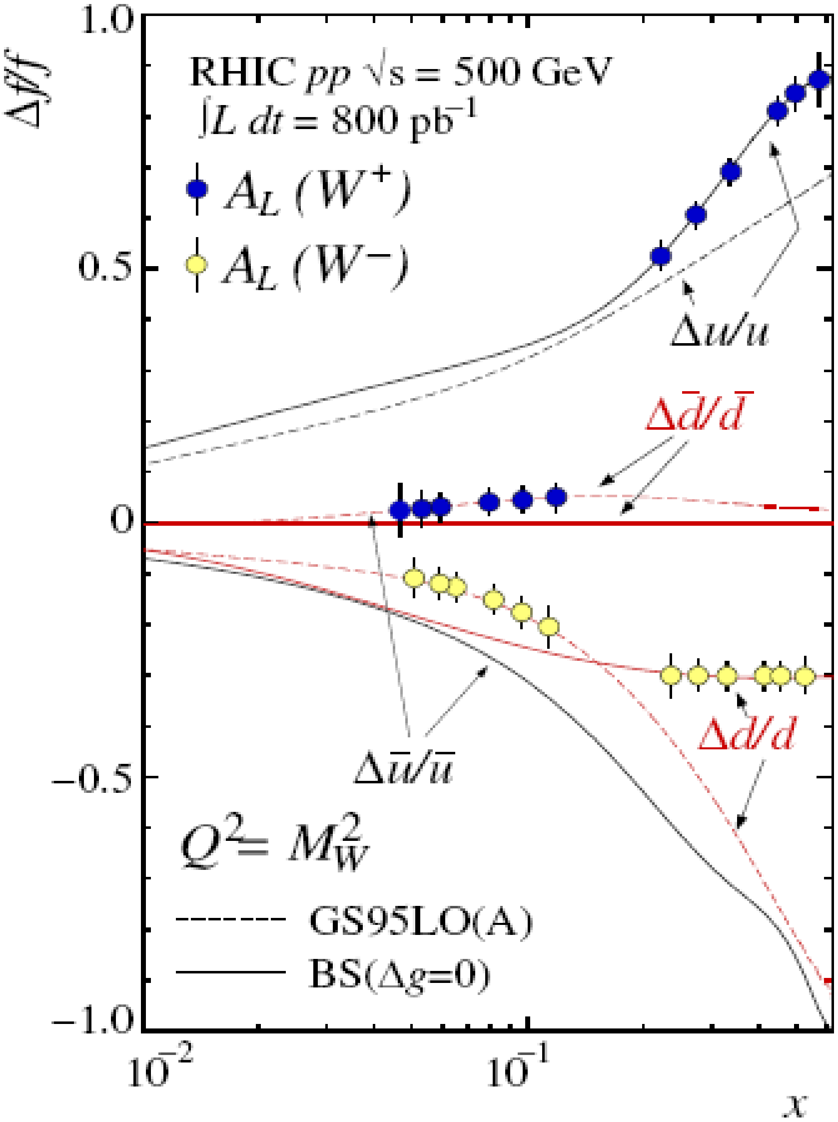
➡ $\frac{\Delta u(x_1)}{u(x_1)}$ as $x_2 \to 0$



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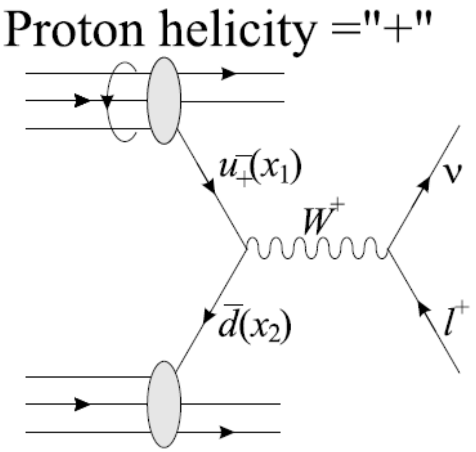

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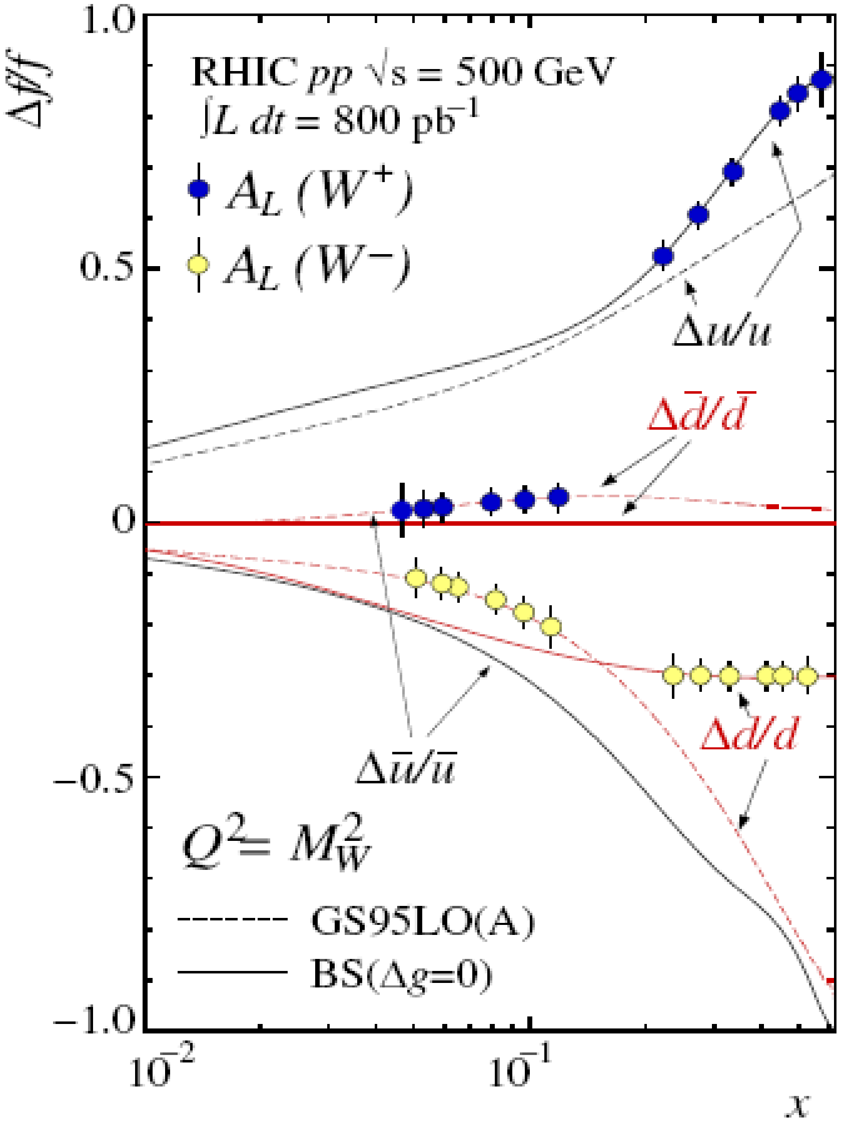
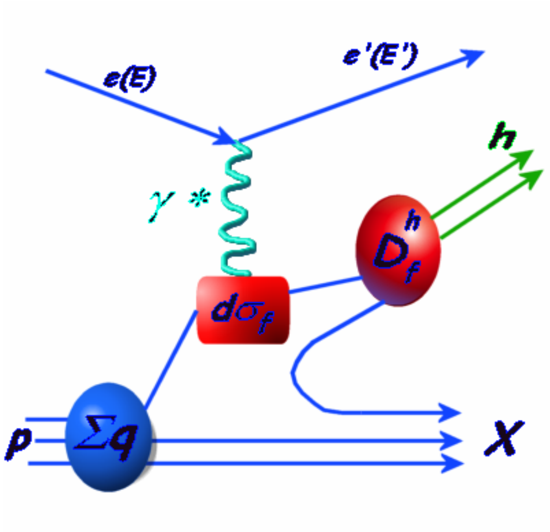
➡ $\frac{\Delta u(x_1)}{u(x_1)}$ *as* $x_2 \to 0$

➡ $-\frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$ *as* $x_2 \to 1$



SIDIS at HERMES

- **Hadron flavor tagging:**



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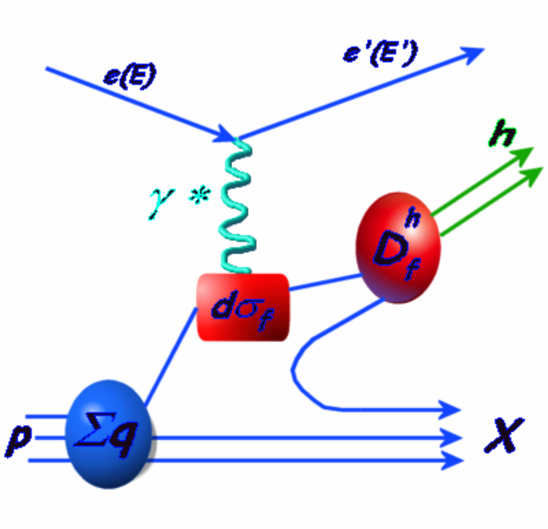

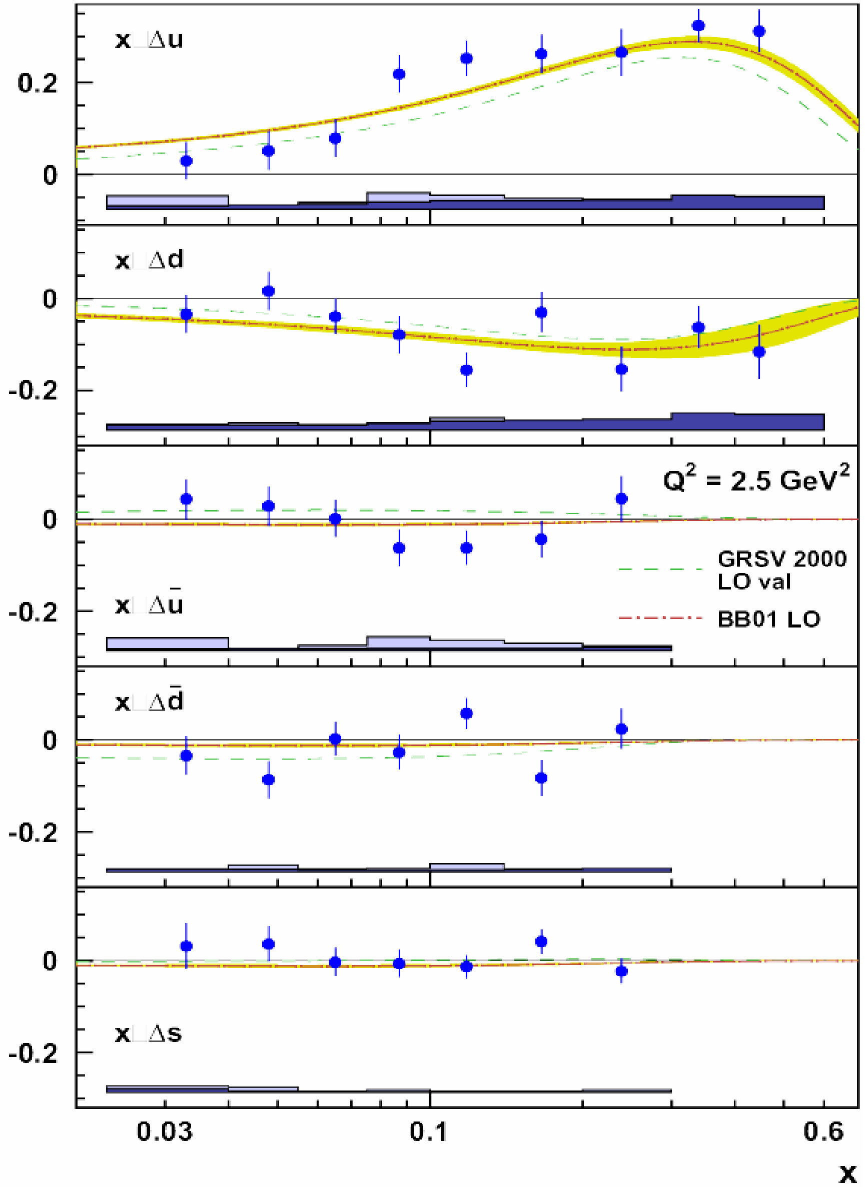

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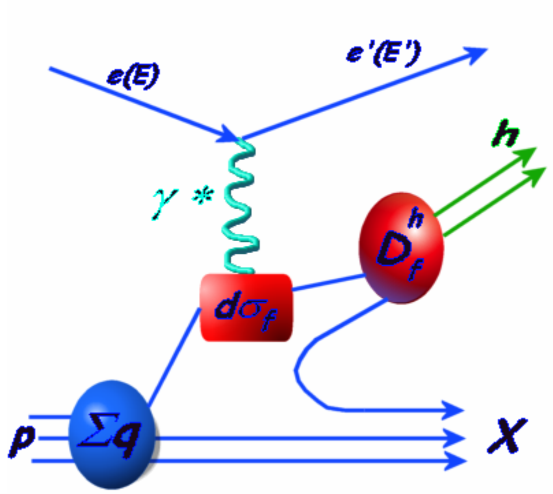
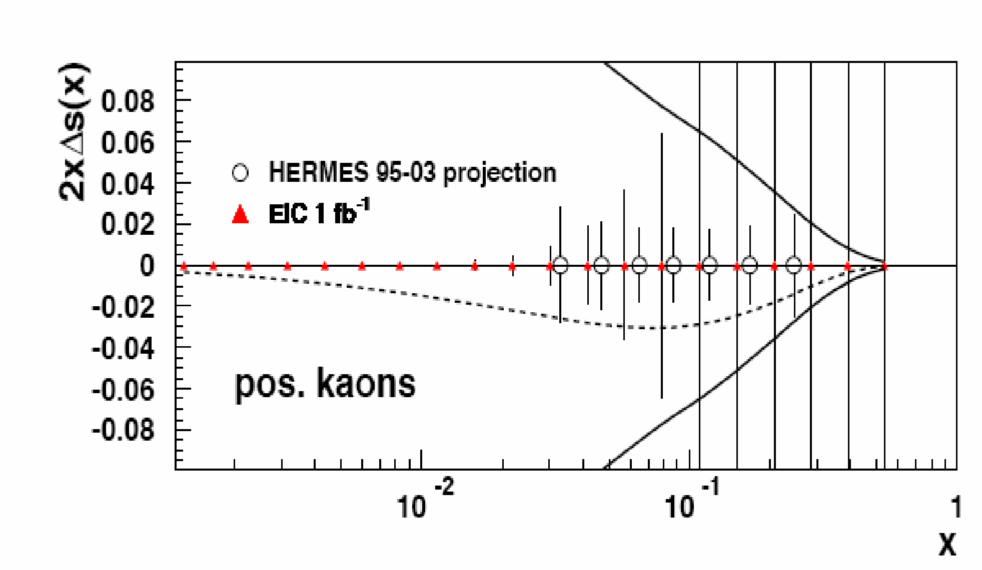
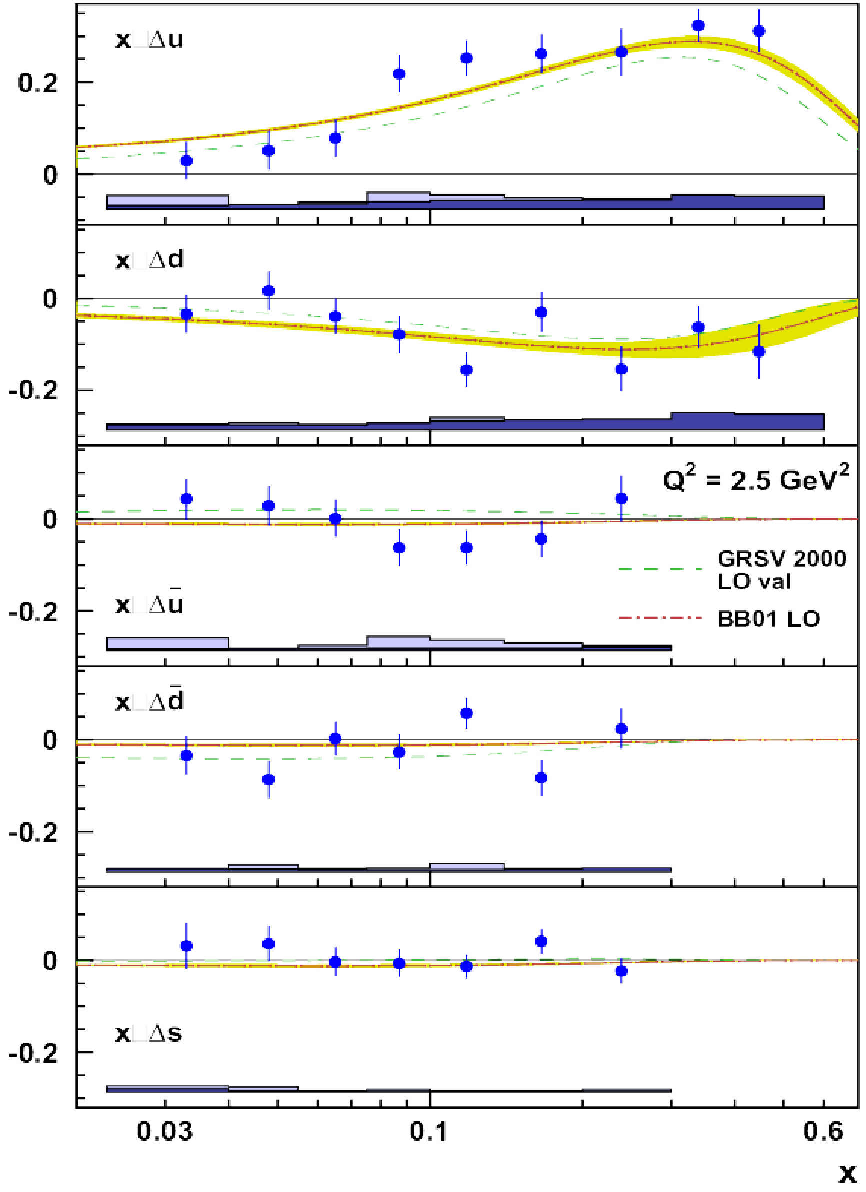
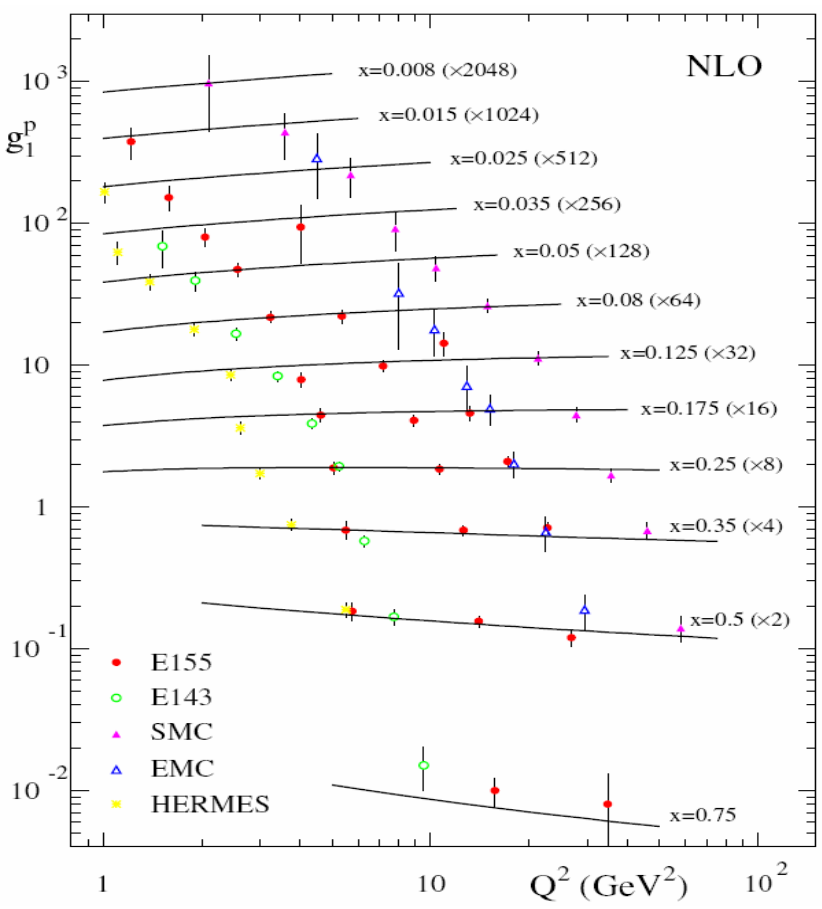


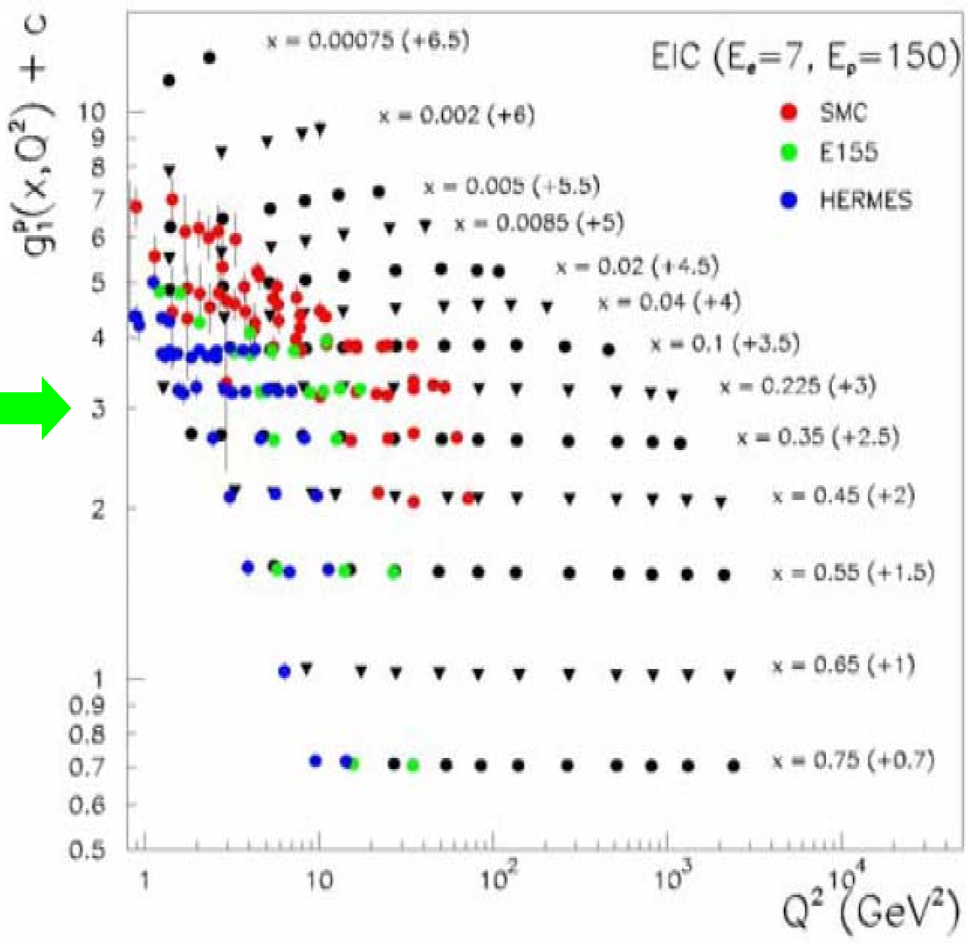




Opportunities at future EIC

- Much improved inclusive DIS g_1 measurement (5fb^{-1}):





Opportunities at future EIC

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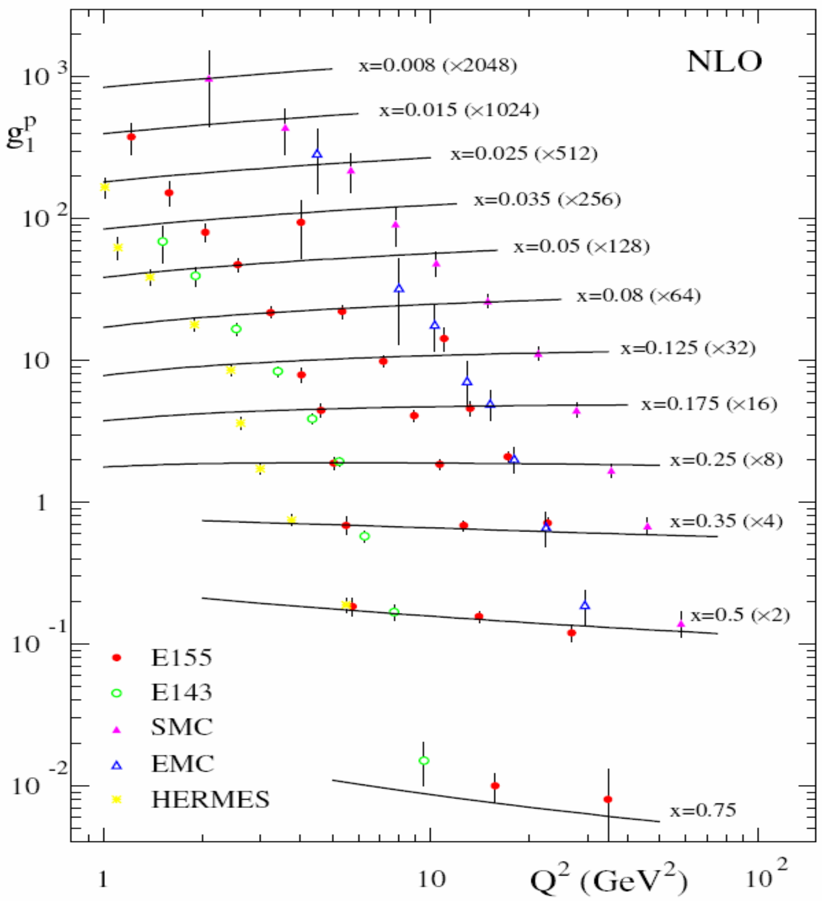

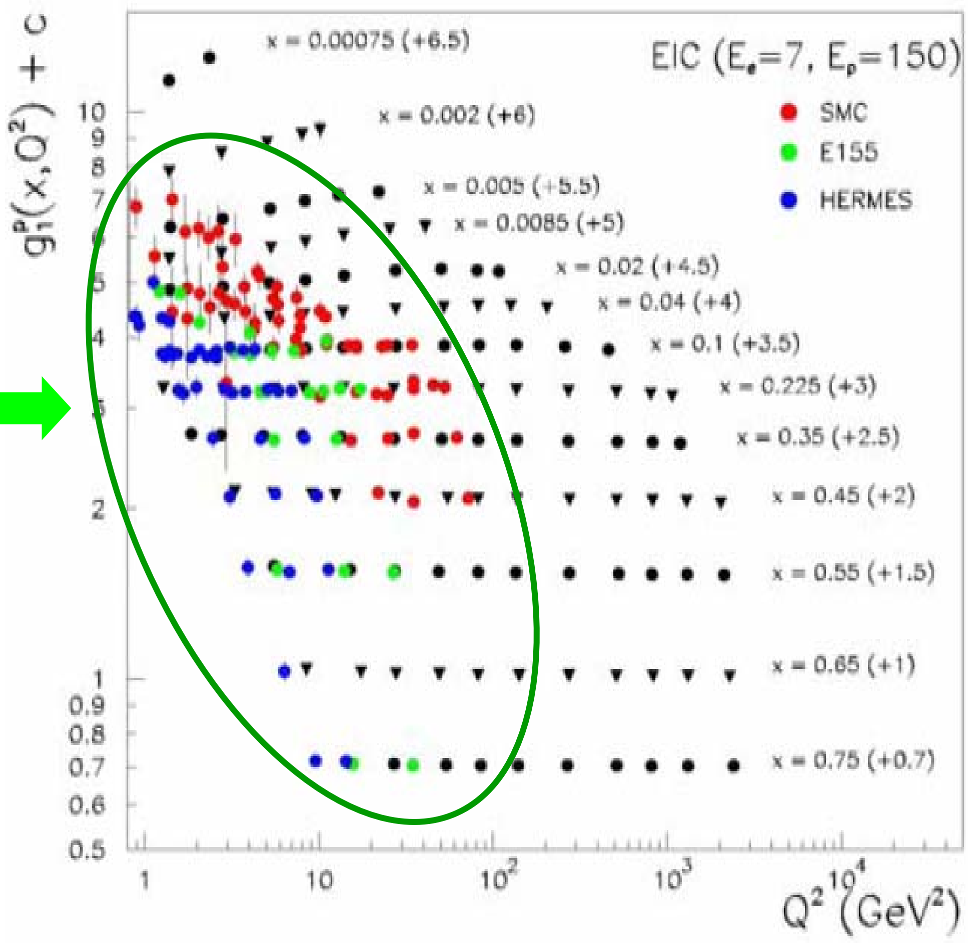

Many more bins and better statistics

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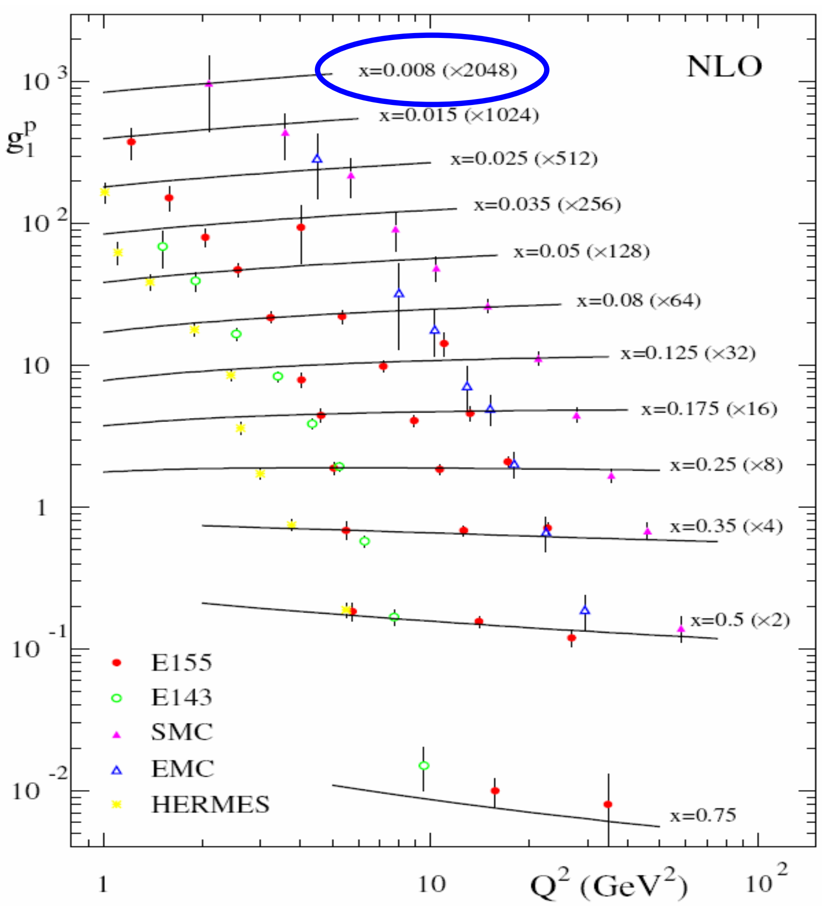
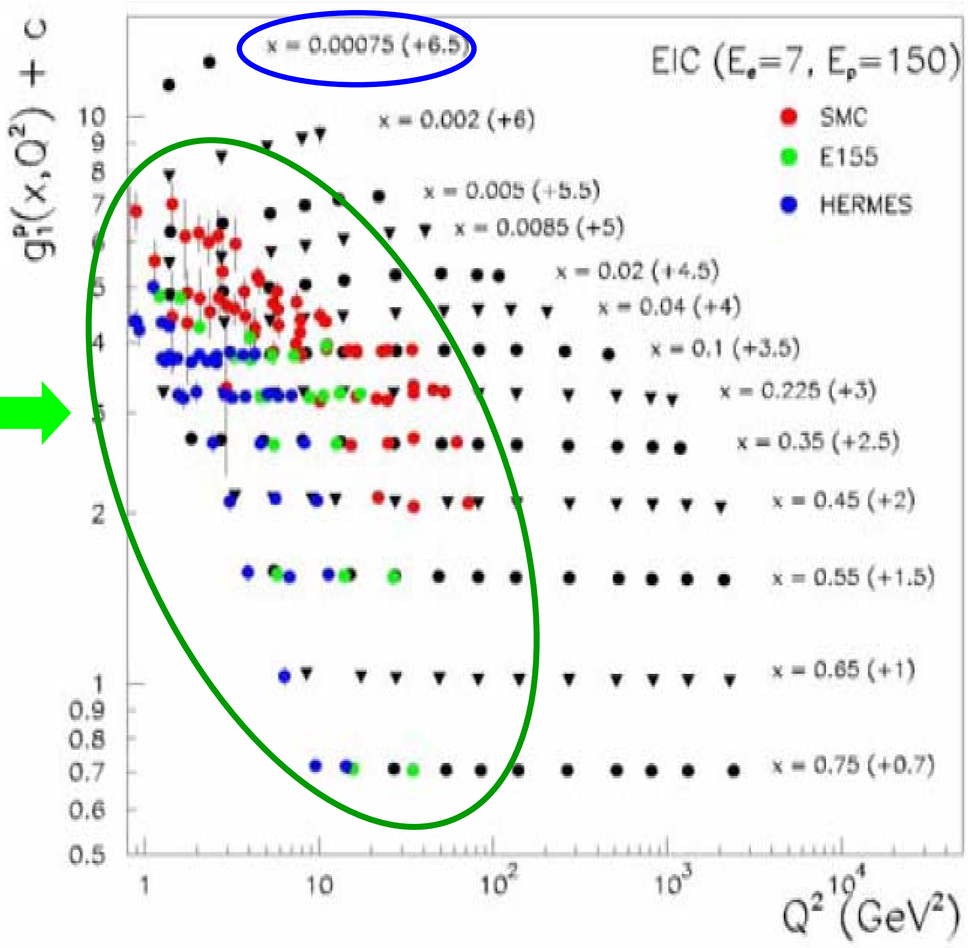


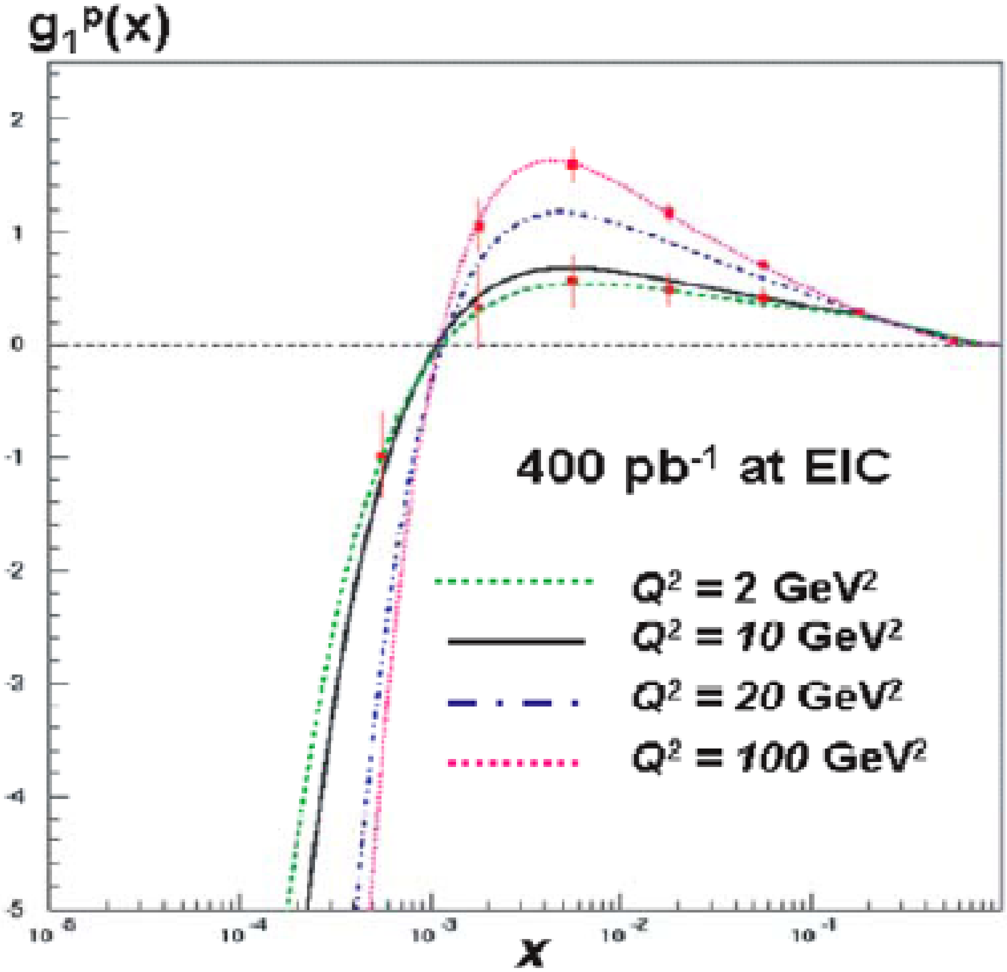


Many more bins and better statistics

Small x: from 10^{-2} to 10^{-3}

Q^2-dependence of inclusive g_1 at EIC

(10 GeV x 250 GeV with $0.4 fb^{-1}$ and a big positive Δg)



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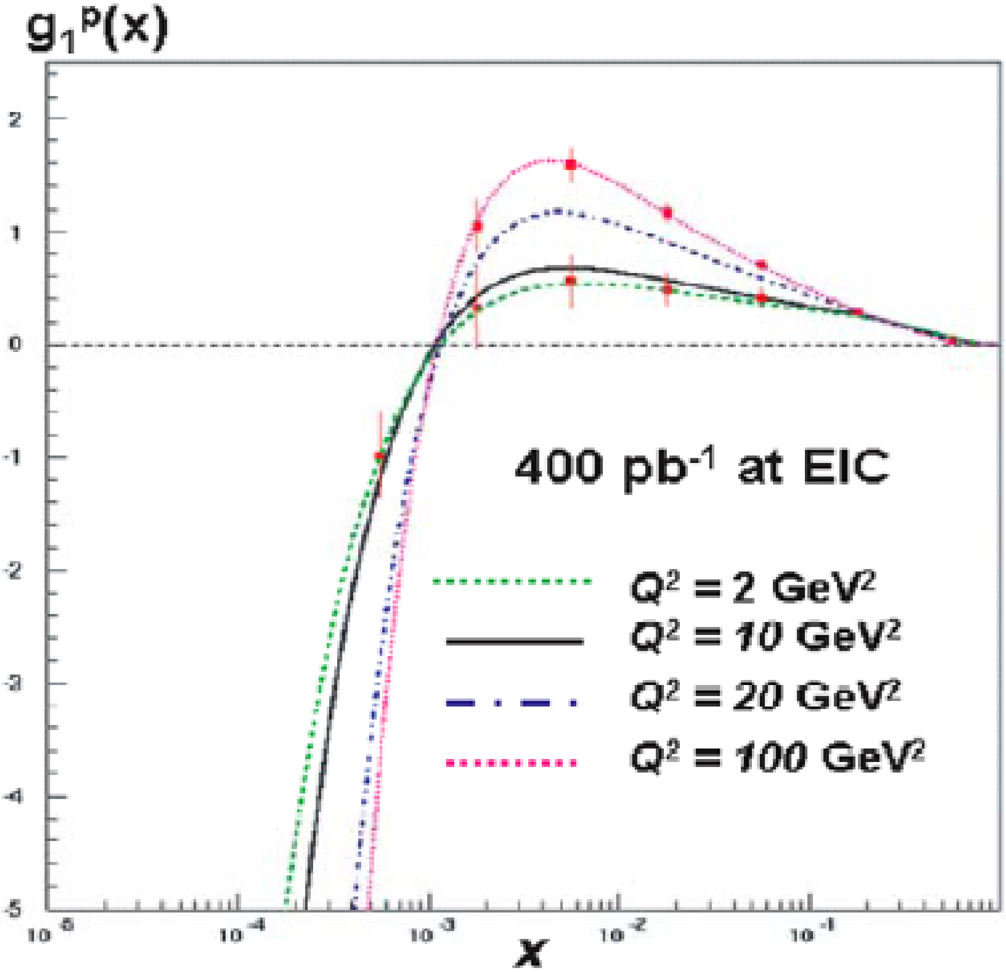
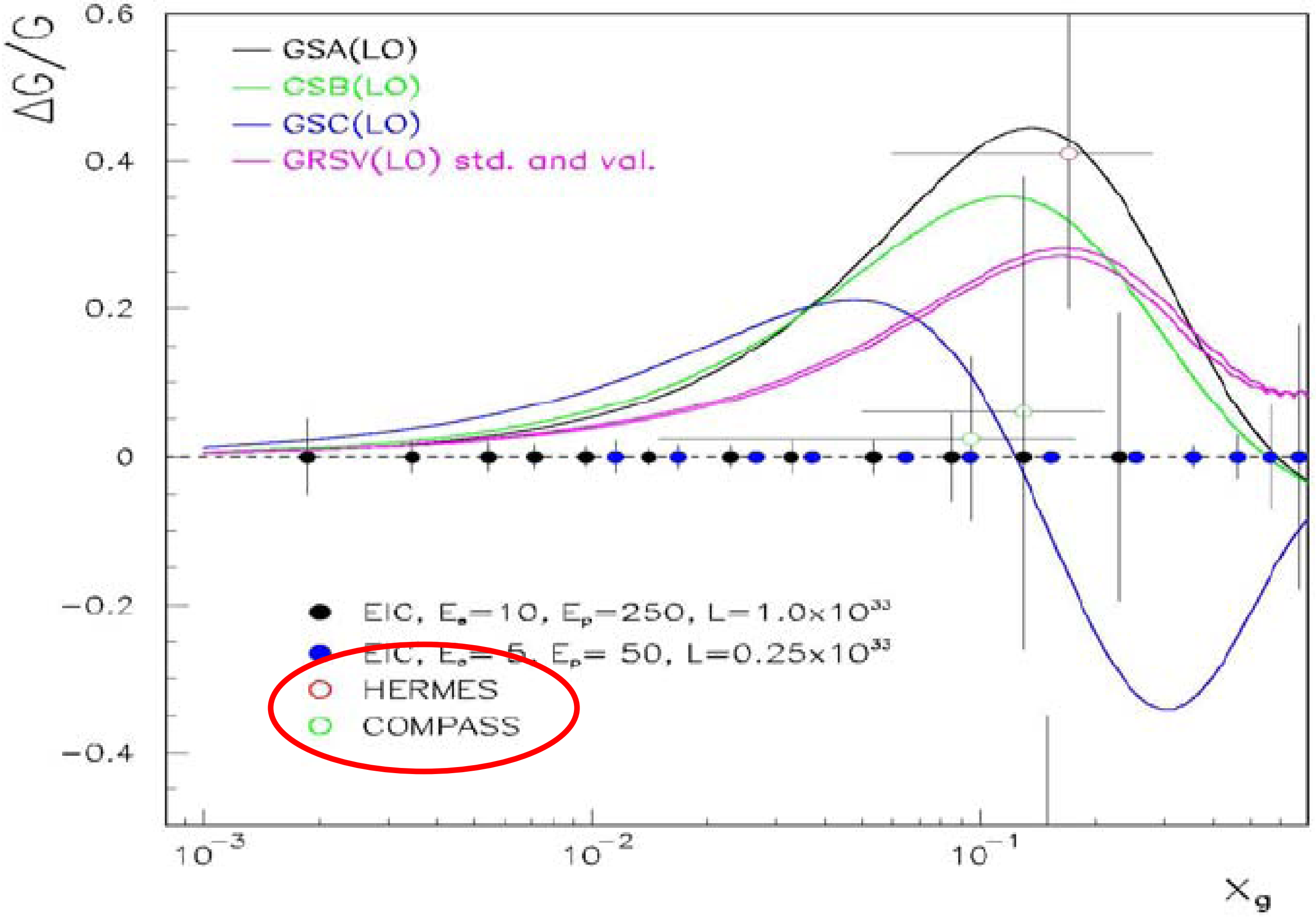


Test QCD's scaling violation, extraction of Δg

Charm production at EIC

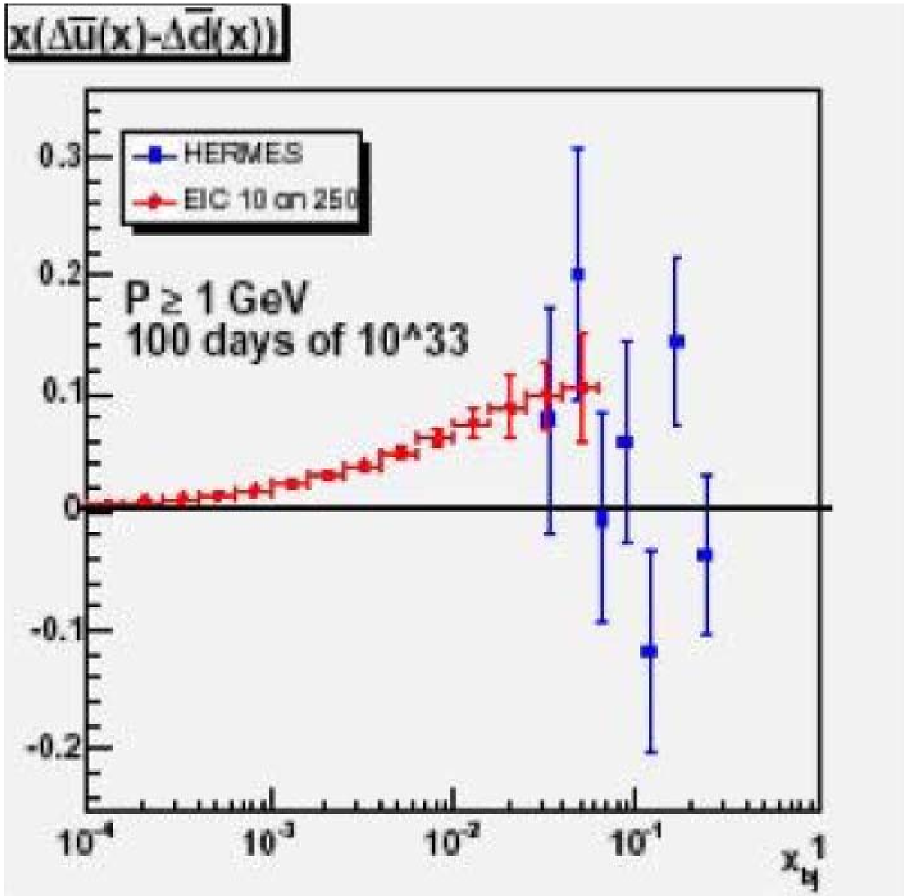
- $\gamma g \longrightarrow c\bar{c}$ and $D^0 \longrightarrow K^-\pi^+$:

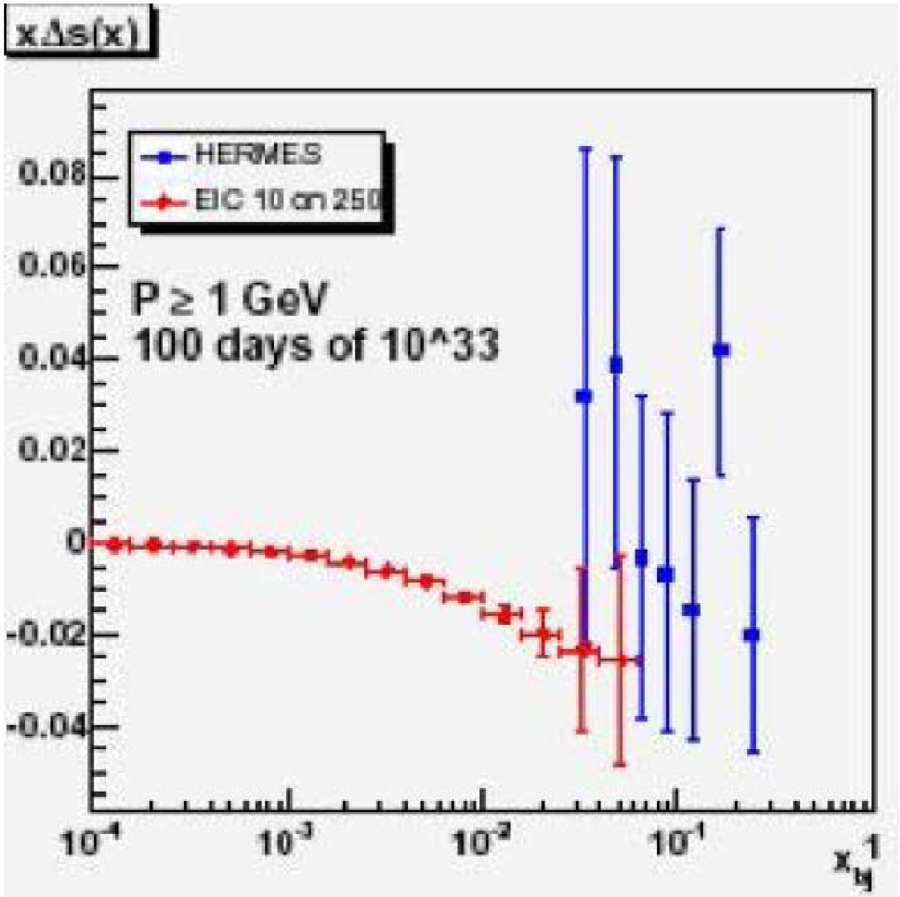


10 fb^{-1} for 10x250GeV, and 2.5 fb^{-1} for 5x50GeV

Flavor separation at EIC

- SIDIS on π's, K's, parity violating structure functions:





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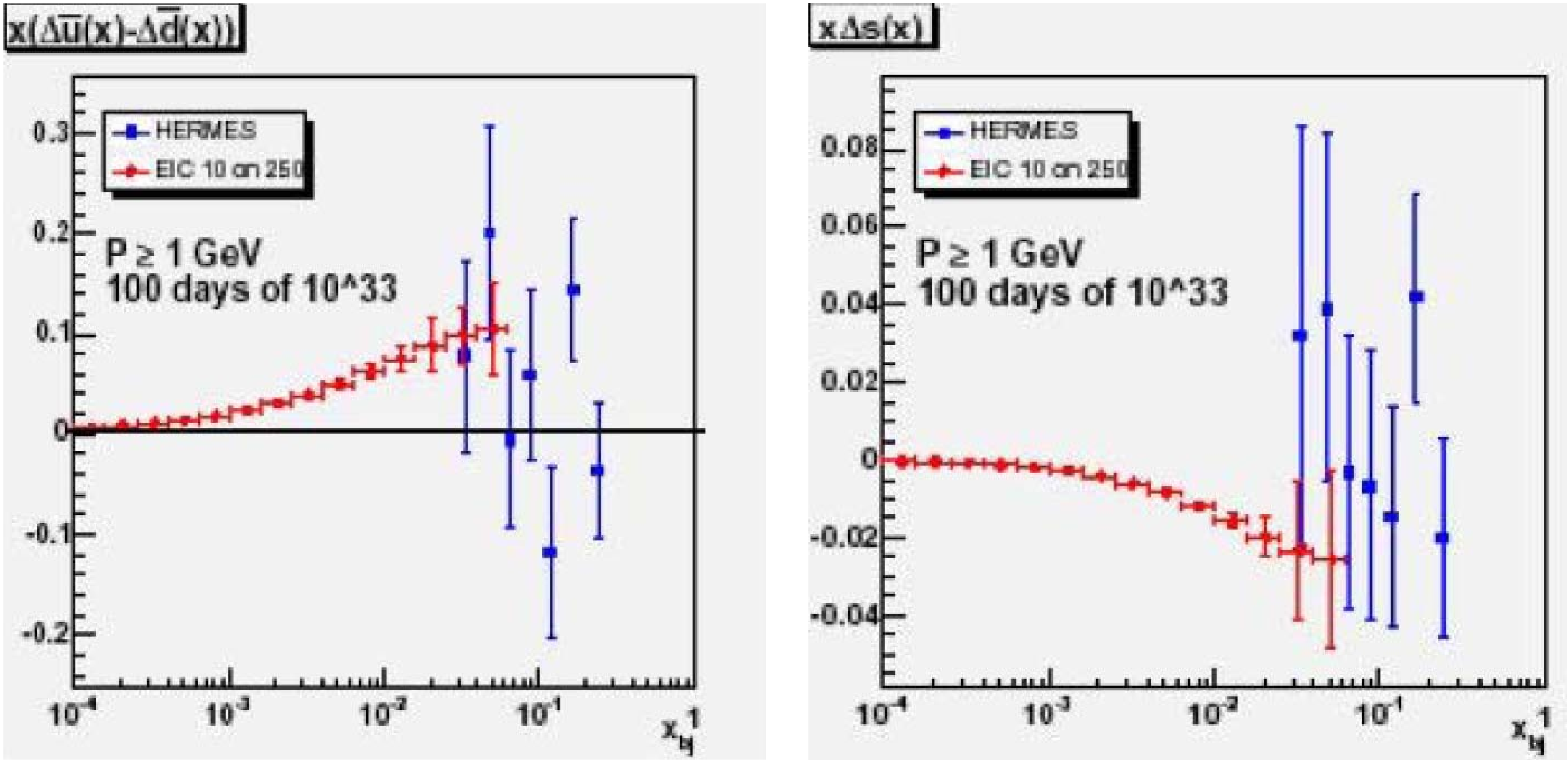

Much better reach (to 10^{-4}) and much smaller error bars

Conclusions

- QCD factorization + PDFs generated by QCD global fits have successfully interpreted all existing high energy unpolarized ep, $p\overset{(-)}{p}$ data with momentum exchange > 2 GeV
- For polarized PDFs, a great deal has been learned
  But, a lot remains to be explored
- RHIC has produced important constraint on Δg – small?
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Future EIC will provide the better and complementary measurements of both Δg, Δq, and help to determine the parton's helicity contribution to proton's spin