# Topics on QCD and Spin Physics

(sixth lecture)

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# Spin (revisited)

naive quark spin $\overset{?}{\approx}$ parton spin $\overset{?}{\approx}$ QCD parton spin

polarized DIS:

EMC experiment: not the naive picture

strange quarks polarization?

gluon polarization?

from moments to parton densities:

first moments $\approx$ sum rules

flavor symmetry & models

parton densities $\approx$ more insight

more observables!

# More spin dependent observables:

inclusive DIS

$g_1^p(x,Q^2)$ $g_1^n(x,Q^2)$

unknowns

$\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s, \Delta\bar{s}, \Delta g$

$$g_1^N(x,Q^2) = \left(\pm\frac{1}{12}\Delta q_3^{NS} + \frac{1}{36}\Delta q_8^{NS} + \frac{1}{9}\Delta\Sigma\right) \otimes \left(1 + \frac{\alpha_s}{2\pi}\Delta C_q\right) + \sum_q e_q^2 \frac{\alpha_s}{2\pi}\Delta g \otimes \Delta C_g.$$

$$\begin{aligned}
\Delta q_3^{NS} &\equiv (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d}) \\
\Delta q_8^{NS} &\equiv (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s}) \\
\Delta\Sigma &\equiv (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})
\end{aligned}$$

$$\frac{d}{d\ln Q^2}\Delta q^{NS} = \frac{\alpha_s}{2\pi}\Delta P_{qq}^1 \otimes \Delta q^{NS}$$

$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}\Delta P_{qq}^1 & 2fP_{qg}^1 \\ \Delta P_{gq}^1 & P_{gg}^1\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix}$$

# More spin dependent observables:

## SIDIS asymmetries

$$A_1^{N\,h}(x,Q^2)_Z \simeq \frac{\int_Z dz\, g_1^{N\,h}(x,z,Q^2)}{\int_Z dz\, F_1^{N\,h}(x,z,Q^2)}$$

$N = p, D, He$
$h = \pi^\pm, K^\pm, h^\pm$

$$g_1^{N\,h}(x,z,Q^2) = \sum_{q,\bar{q}} e_i^2 \left\{ \Delta q_i(x,Q^2) D_{q_i}^h(z,Q^2) \right. \qquad \text{LO}$$

$$+ \frac{\alpha_s(Q^2)}{2\pi} [\Delta q_i \otimes \Delta C_{ij} \otimes D_{q_j}^h + \Delta q_i \otimes \Delta C_{ig} \otimes D_g^h + \Delta g \otimes \Delta C_{gj} \otimes D_{q_j}^h] \qquad \text{NLO}$$

$$D_1 = D_u^{\pi^+} = D_{\bar{d}}^{\pi^+}$$
$$D_2 = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+}$$
$$D_3 = D_s^{\pi^+} = D_{\bar{s}}^{\pi^+}$$

$$2g_{1p}^{\pi+(-)} \sim \frac{4}{9}(\Delta u + \Delta\bar{u}) \otimes D_{1(2)}^\pi + \frac{1}{9}(\Delta d + \Delta\bar{d}) \otimes D_{2(1)}^\pi$$
$$+ \frac{1}{9}(\Delta\bar{d} - 4\Delta\bar{u}) \otimes (D_{1(2)}^\pi - D_{2(1)}^\pi)$$

# More spin dependent observables:

polarized pp collisions

$$A_{\rm LL} \equiv \frac{d\Delta\sigma}{d\sigma} \equiv \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

$$\begin{aligned} d\Delta\sigma &= \sum_{ab} \int dx_a \int dx_b \, \Delta f_a(x_a, Q^2) \Delta f_b(x_b, Q^2) \\ &\quad \times d\Delta\hat{\sigma}_{ab}(x_a, x_b, p_T). \end{aligned}$$

jets

$$\begin{aligned} d\Delta\sigma &= \sum_{ab} \int dx_a \int dx_b \int dz \, \Delta f_a(x_a, Q^2) \Delta f_b(x_b, Q^2) D_c^h(z, Q^2) \\ &\quad \times d\Delta\hat{\sigma}_{abc}(x_a, x_b, z, p_T) \end{aligned}$$

hadrons

numerically involved: Mellin tricks

# DSSV helicity distributions:

D.de Florian, R.S., M. Stratmann, W. Vogelsang 2008

| | experiment | data type | data points |
|---|---|---|---|
| inclusive DIS data | EMC, SMC, | DIS | 34 |
| | COMPASS | DIS | 15 |
| | E142, E143, E154, E155 | DIS | 123 |
| $\sim \Delta q + \Delta\bar{q}$ | HERMES | DIS | 39 |
| | HALL-A | DIS | 3 |
| | CLAS | DIS | 20 |
| SIDIS data | SMC | SIDIS $h^{\pm}$ | 48 |
| | HERMES | SIDIS $h^{\pm}$ | 54 |
| | | SIDIS, $\pi^{\pm}$ | 36 |
| $\sim$ flavor separation | | SIDIS, $K^{\pm}$ | 27 |
| | COMPASS | SIDIS, $h^{\pm}$ | 24 |
| RHIC data $\sim \Delta g$ | PHENIX | 200 GeV pp, $\pi^0$ | 20 |
| | PHENIX | 62 GeV pp, $\pi^0$ | 5 |
| | STAR | 200 GeV pp, jet | 19 |
| | **TOTAL:** | | 467 |

DIS $\sim 50\%$
SIDIS $\sim 40\%$
RHIC $\sim 10\%$

# DSSV helicity distributions: parameterization

$$x(\Delta q + \Delta\overline{q})(x, Q_0^2) = N_q x^{\alpha_q}(1-x)^{\beta_q}(1+\gamma_q\sqrt{x}+\eta_q x)$$

$$x\Delta\overline{q}(x, Q_0^2) = N_{\overline{q}} x^{\alpha_{\overline{q}}}(1-x)^{\beta_{\overline{q}}}(1+\eta_{\overline{q}} x)$$

$$x\Delta g(x, Q_0^2) = N_g x^{\alpha_g}(1-x)^{\beta_g}(1+\eta_g x) \qquad Q_0^2 = 1\mathrm{GeV}^2$$

NLO evolution $\alpha_s$ MRST

$$\alpha_{\overline{u}} = \alpha_{u+\overline{u}} \qquad \alpha_{\overline{d}} = \alpha_{d+\overline{d}} \qquad \Delta s = \Delta\overline{s}$$

$$(\Delta u^1 + \Delta\overline{u}^1) - (\Delta d^1 + \Delta\overline{d}^1) = (F+D)[1+\epsilon_{SU(2)}]$$

$$(\Delta u^1 + \Delta\overline{u}^1) + (\Delta d^1 + \Delta\overline{d}^1) - 2(\Delta s^1 + \Delta\overline{s}^1) = (3F-D)[1+\epsilon_{SU(3)}]$$

# DSSV helicity distributions: scheme

$$A_{LL}^{NLO-\overline{MS}}(DSSV) \equiv A_{LL}^{EXP}$$

$$\frac{g_1^{NLO-\overline{MS}}(DSSV)}{F_1^{NLO-\overline{MS}}(MRST)} \equiv A_1^{EXP}$$

not "unique": $F_1(x, Q^2)$ from data

from parameterization

from $F_2(x, Q^2)$ and $R(x, Q^2)$

fit just $g_1(x, Q^2)$

approximation:

$$\frac{g_1^{NLO-\overline{MS}}}{F_1^{NLO-\overline{MS}}} + \mathcal{O}(\frac{1}{Q^2}, \alpha_s^2) = A_1$$

# DSSV helicity distributions:

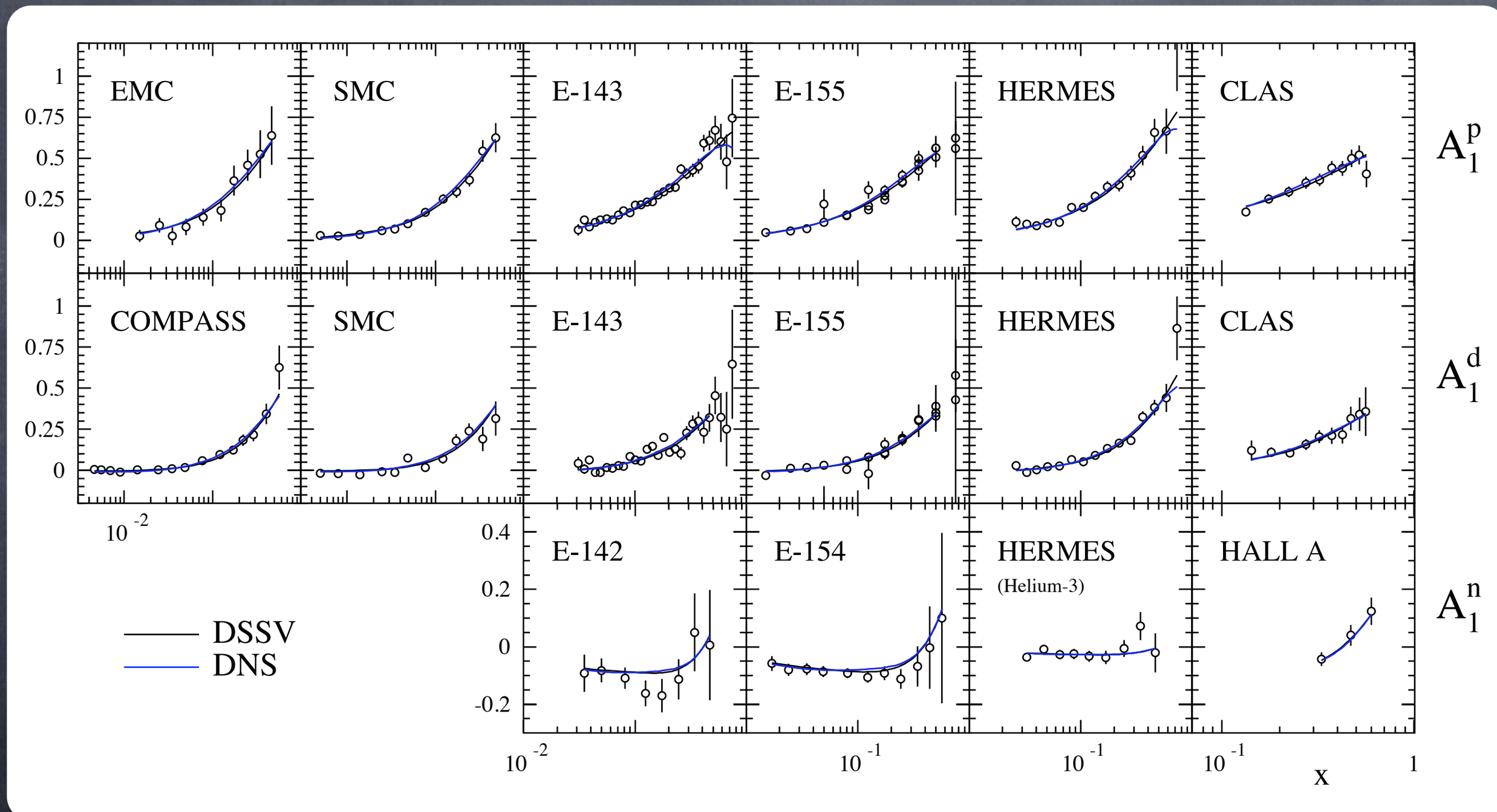
very good!

no significant tension

$$\chi^2/d.of. \simeq 0.88$$

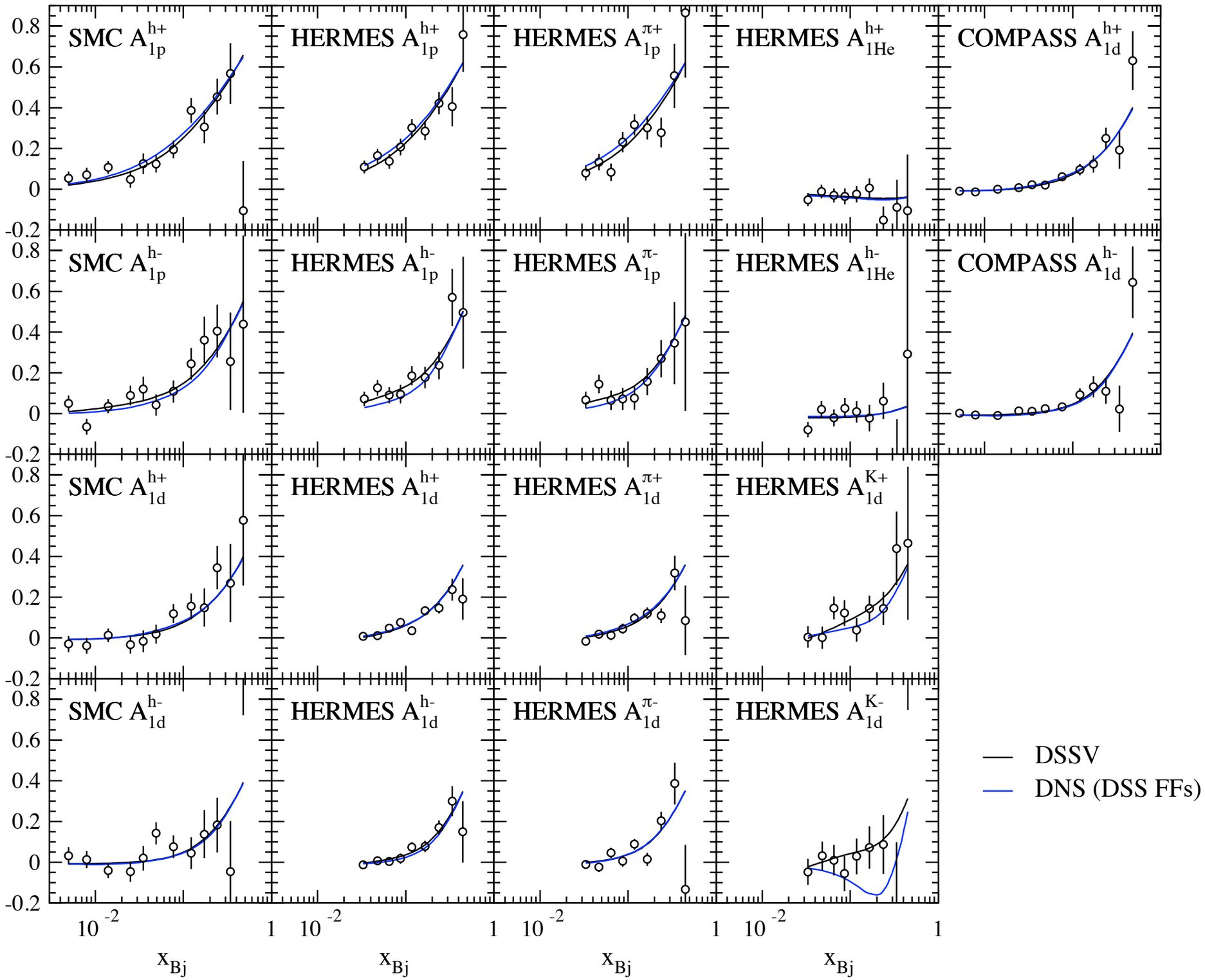
| experiment | process | $N_{\rm data}$ | $\chi^2$ |
|---|---|---|---|
| EMC [?] | DIS (p) | 10 | 3.9 |
| SMC [?] | DIS (p) | 12 | 3.4 |
| SMC [?] | DIS (d) | 12 | 18.4 |
| COMPASS [?] | DIS (d) | 15 | 8.1 |
| E142 [?] | DIS (n) | 8 | 5.6 |
| E143 [?] | DIS (p) | 28 | 19.3 |
| E143 [?] | DIS (d) | 28 | 40.8 |
| E154 [?] | DIS (n) | 11 | 4.5 |
| E155 [?] | DIS (p) | 24 | 22.6 |
| E155 [?] | DIS (d) | 24 | 17.1 |
| HERMES [?] | DIS (He) | 9 | 6.3 |
| HERMES [?] | DIS (p) | 15 | 10.5 |
| HERMES [?] | DIS (d) | 15 | 16.9 |
| HALL-A [?] | DIS (n) | 3 | 0.2 |
| CLAS [?] | DIS (p) | 10 | 5.9 |
| CLAS [?] | DIS (d) | 10 | 2.5 |
| SMC [?] | SIDIS (p, $h^+$) | 12 | 18.7 |
| SMC [?] | SIDIS (p, $h^-$) | 12 | 10.6 |
| SMC [?] | SIDIS (d, $h^+$) | 12 | 7.3 |
| SMC [?] | SIDIS (d, $h^-$) | 12 | 14.1 |
| HERMES [?] | SIDIS (p, $h^+$) | 9 | 6.4 |
| HERMES [?] | SIDIS (p, $h^-$) | 9 | 4.9 |
| HERMES [?] | SIDIS (d, $h^+$) | 9 | 11.4 |
| HERMES [?] | SIDIS (d, $h^-$) | 9 | 4.5 |
| HERMES [?] | SIDIS (He, $h^+$) | 9 | 4.7 |
| HERMES [?] | SIDIS (He, $h^-$) | 9 | 6.9 |
| HERMES [?] | SIDIS (p, $\pi^+$) | 9 | 9.6 |
| HERMES [?] | SIDIS (p, $\pi^-$) | 9 | 4.9 |
| HERMES [?] | SIDIS (d, $\pi^+$) | 9 | 9.4 |
| HERMES [?] | SIDIS (d, $\pi^-$) | 9 | 19.5 |
| HERMES [?] | SIDIS (d, $K^+$) | 9 | 6.2 |
| HERMES [?] | SIDIS (d, $K^-$) | 9 | 5.8 |
| HERMES [?] | SIDIS (d, $K^+$+$K^-$) | 9 | 3.4 |
| COMPASS [?] | SIDIS (d, $h^+$) | 12 | 6.2 |
| COMPASS [?] | SIDIS (d, $h^-$) | 12 | 12.0 |
| PHENIX [?] | pp (200 GeV, $\pi^0$) | 10 | 14.2 |
| PHENIX [?] | pp (200 GeV, $\pi^0$) | 10 | 7.1 [13.8] [1] |
| PHENIX [?] | pp (62 GeV, $\pi^0$) | 5 | 3.1 [2.8] [a] |
| STAR [?] | pp (200 GeV, jet) | 10 | 8.8 |
| STAR (prel.) [?] | pp (200 GeV, jet) | 9 | 6.9 |
| **TOTAL:** | | 467 | 392.6 |

# DSSV helicity distributions: DIS data



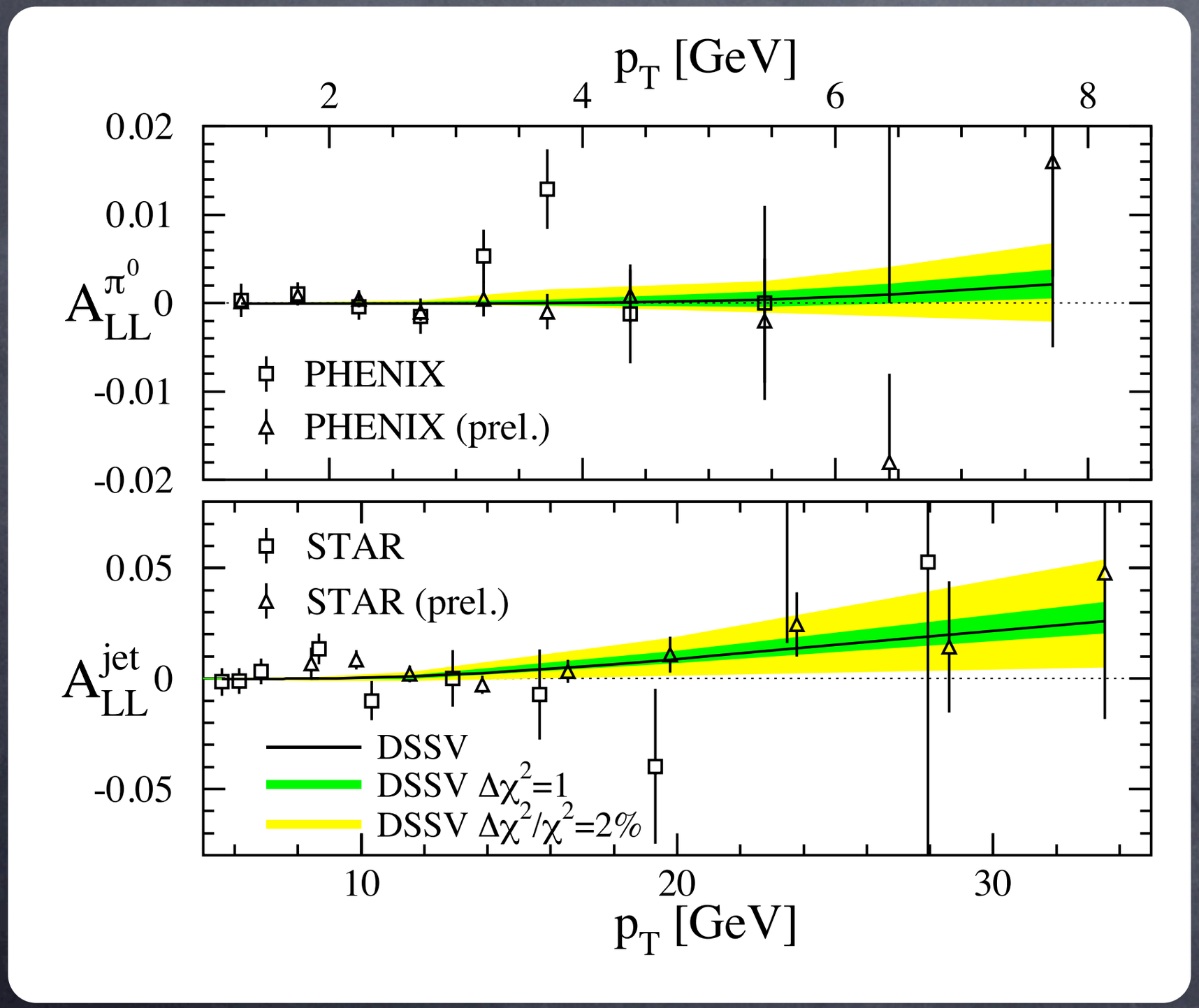

new compass data also in good agreement

# DSSV helicity distributions: SIDIS data




new compass data also in good agreement

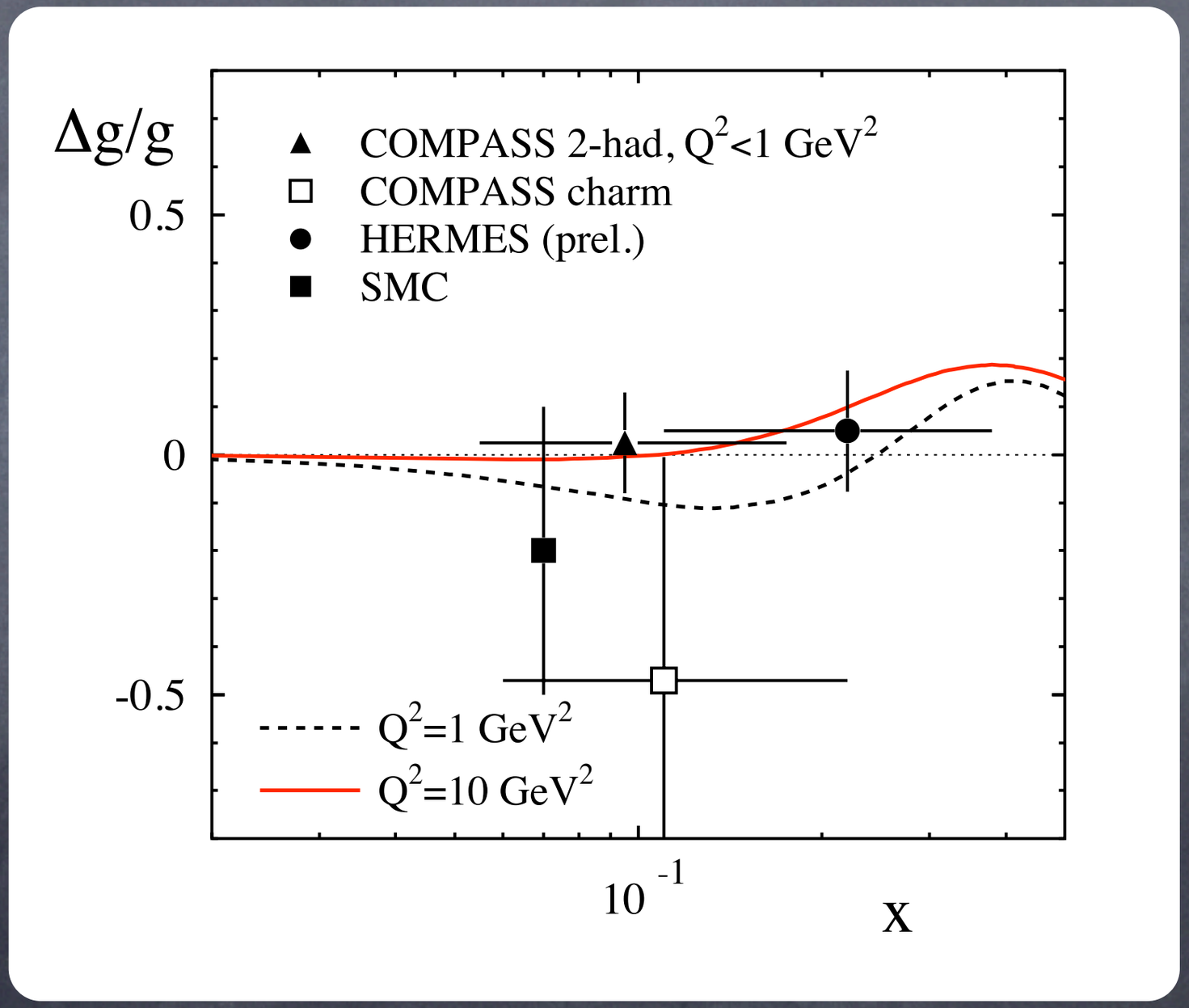
# DSSV helicity distributions: RHIC data



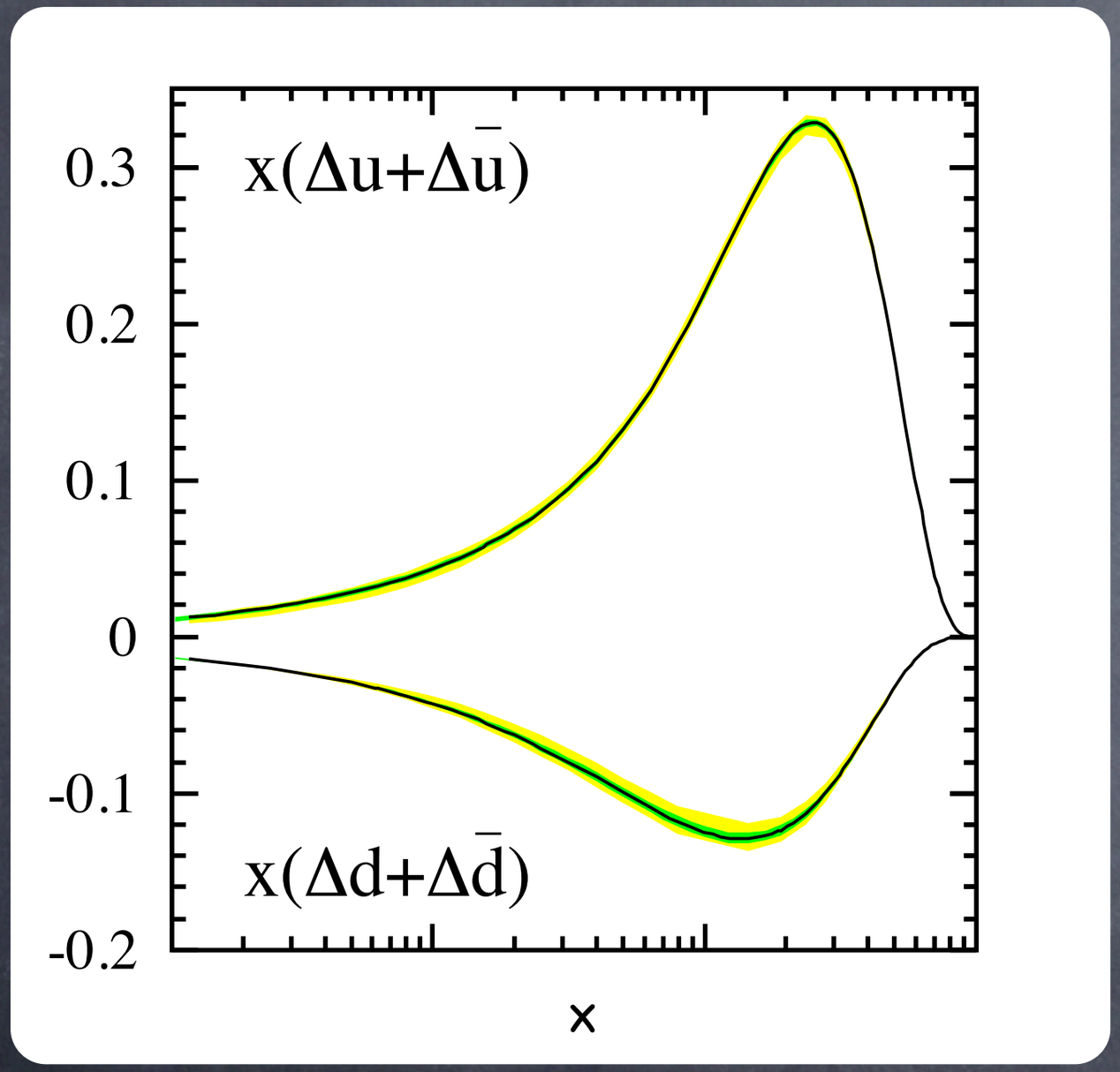

important constraint on gluons despite large uncertainties

# Not included

no NLO yet...



# DSSV helicity distributions: utot dtot

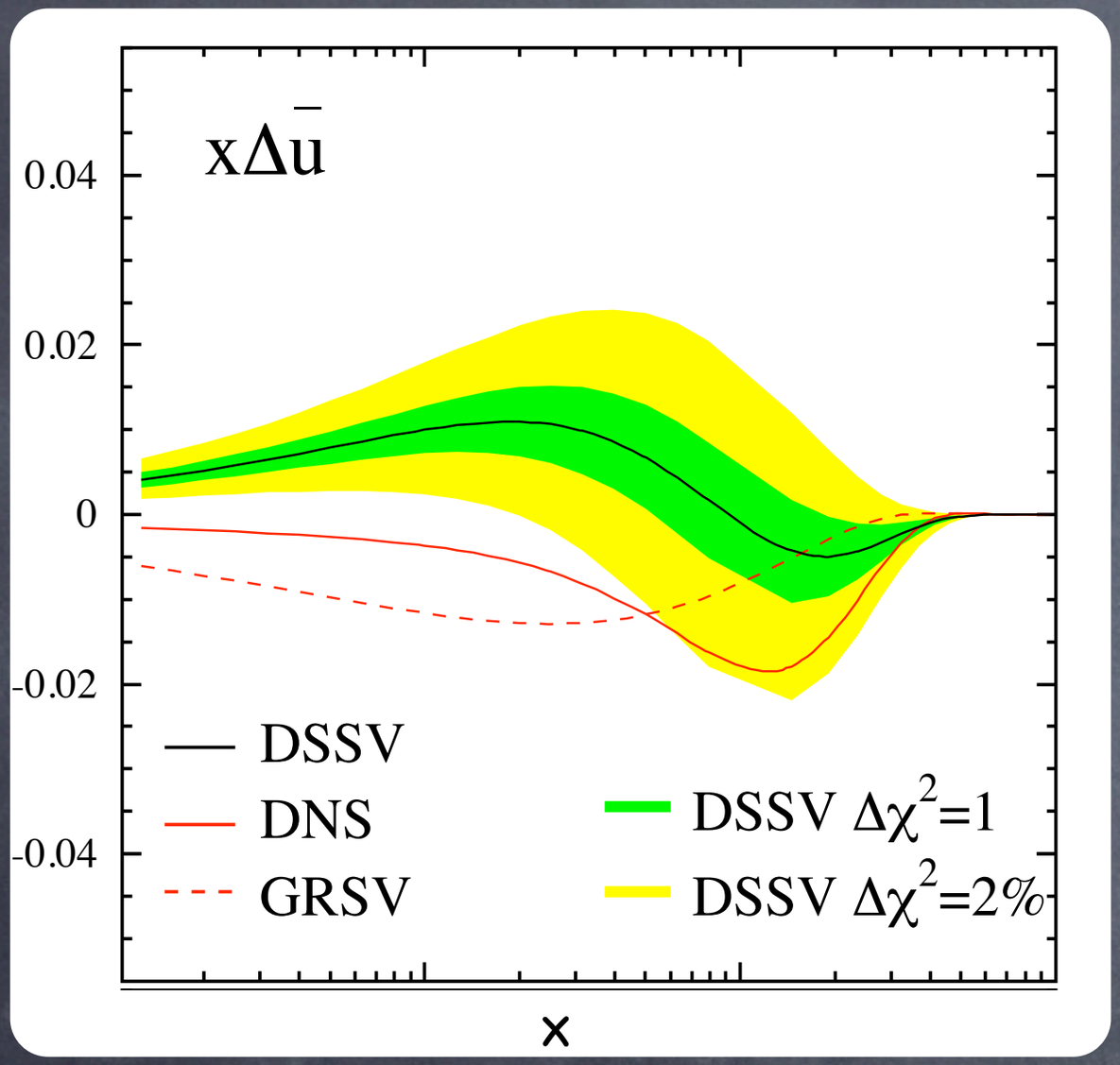


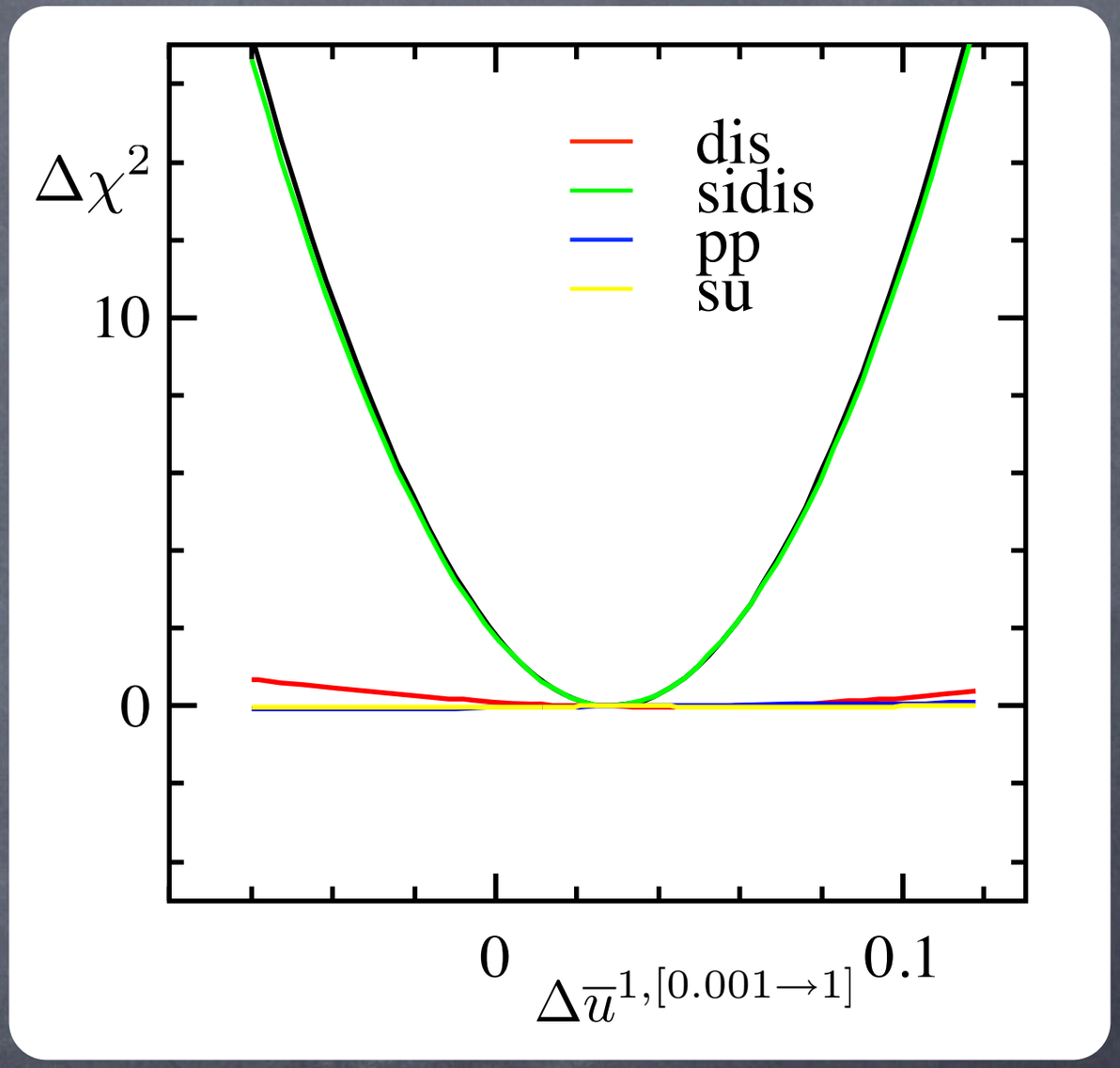

very well constrained

agrees with DIS-only fits

valence-like behavior

# DSSV helicity distributions: ubar



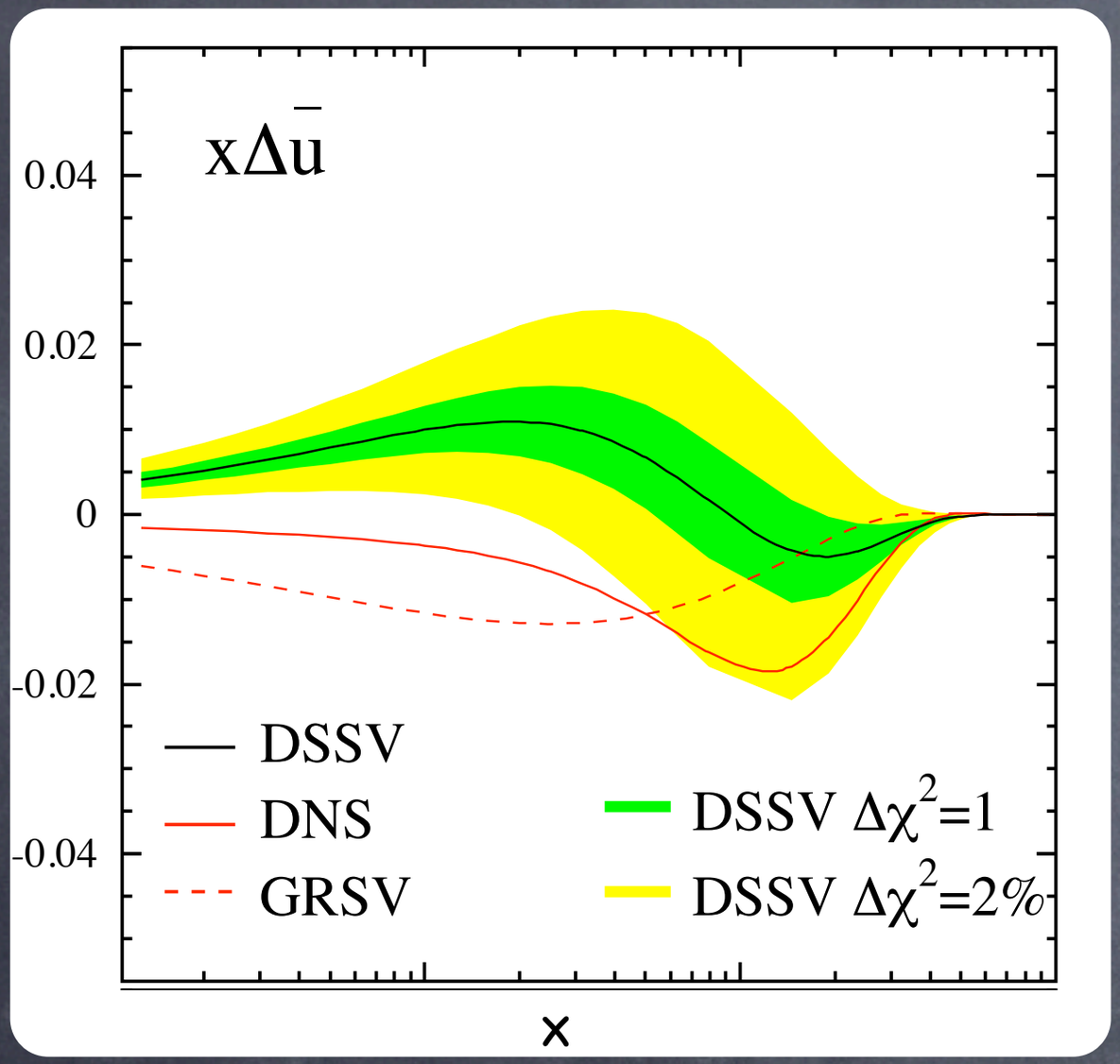



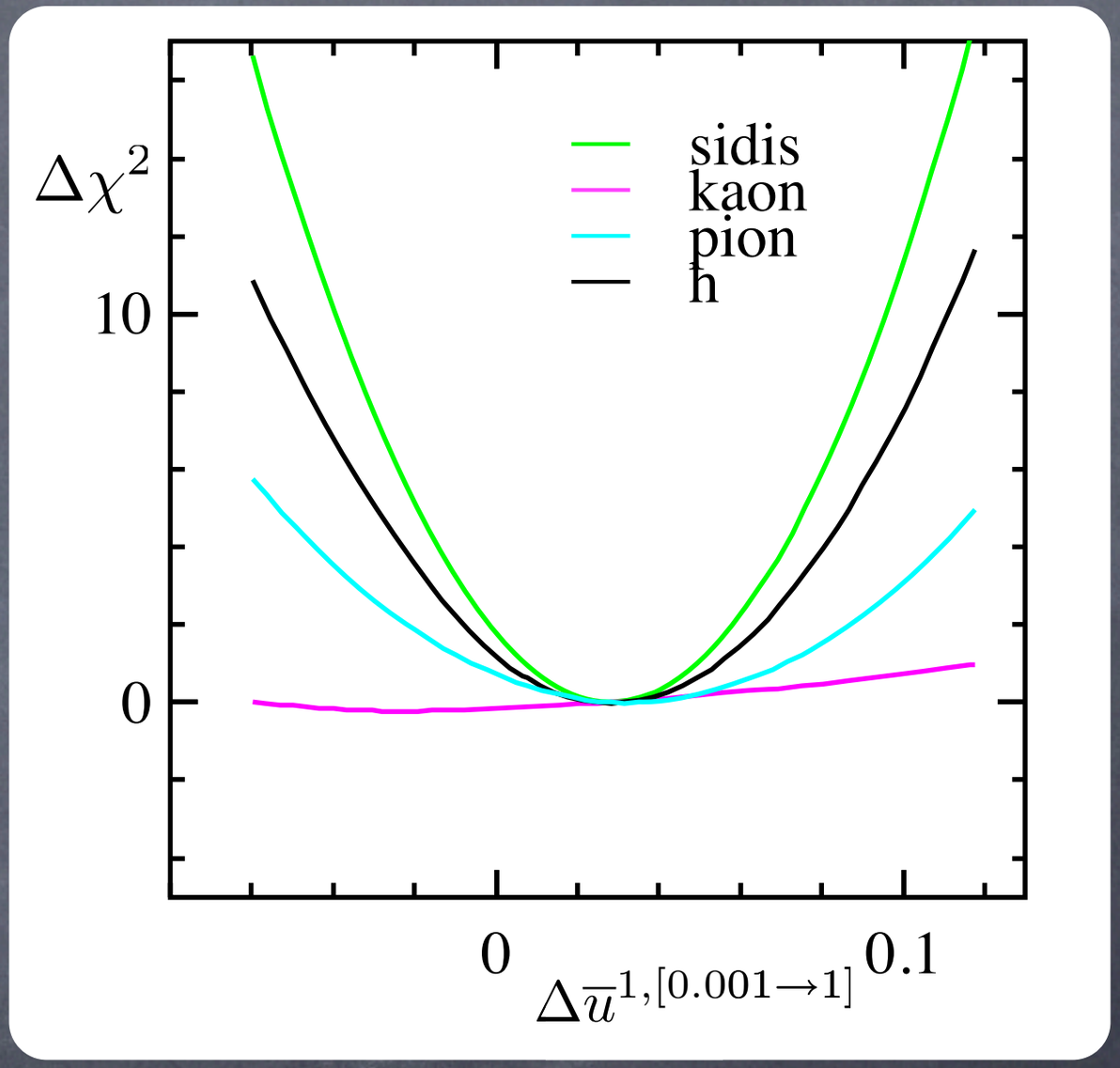

small and positive?

large uncertainties

sidis driven

# DSSV helicity distributions: ubar



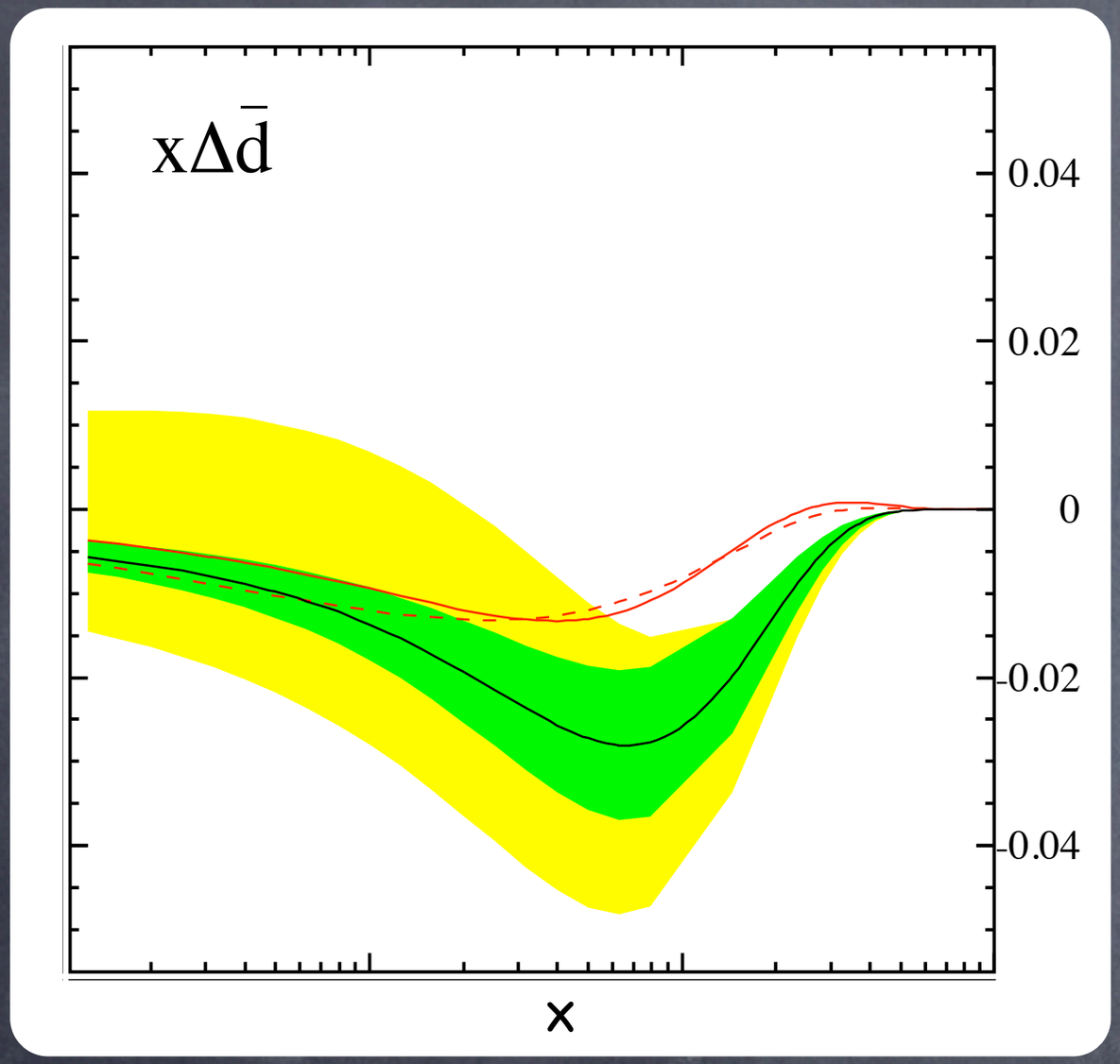



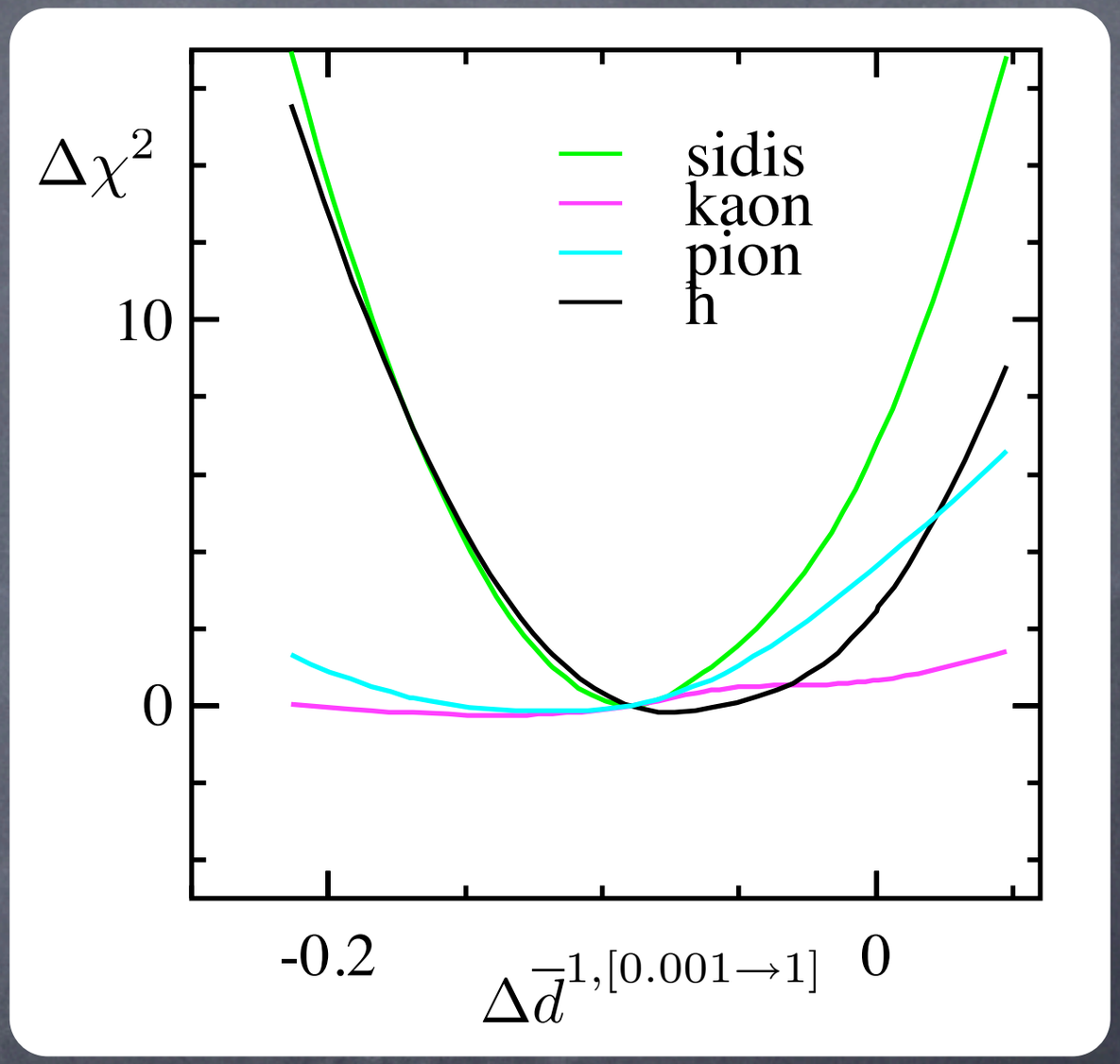

small and positive?

large uncertainties

sidis driven

# DSSV helicity distributions: dbar



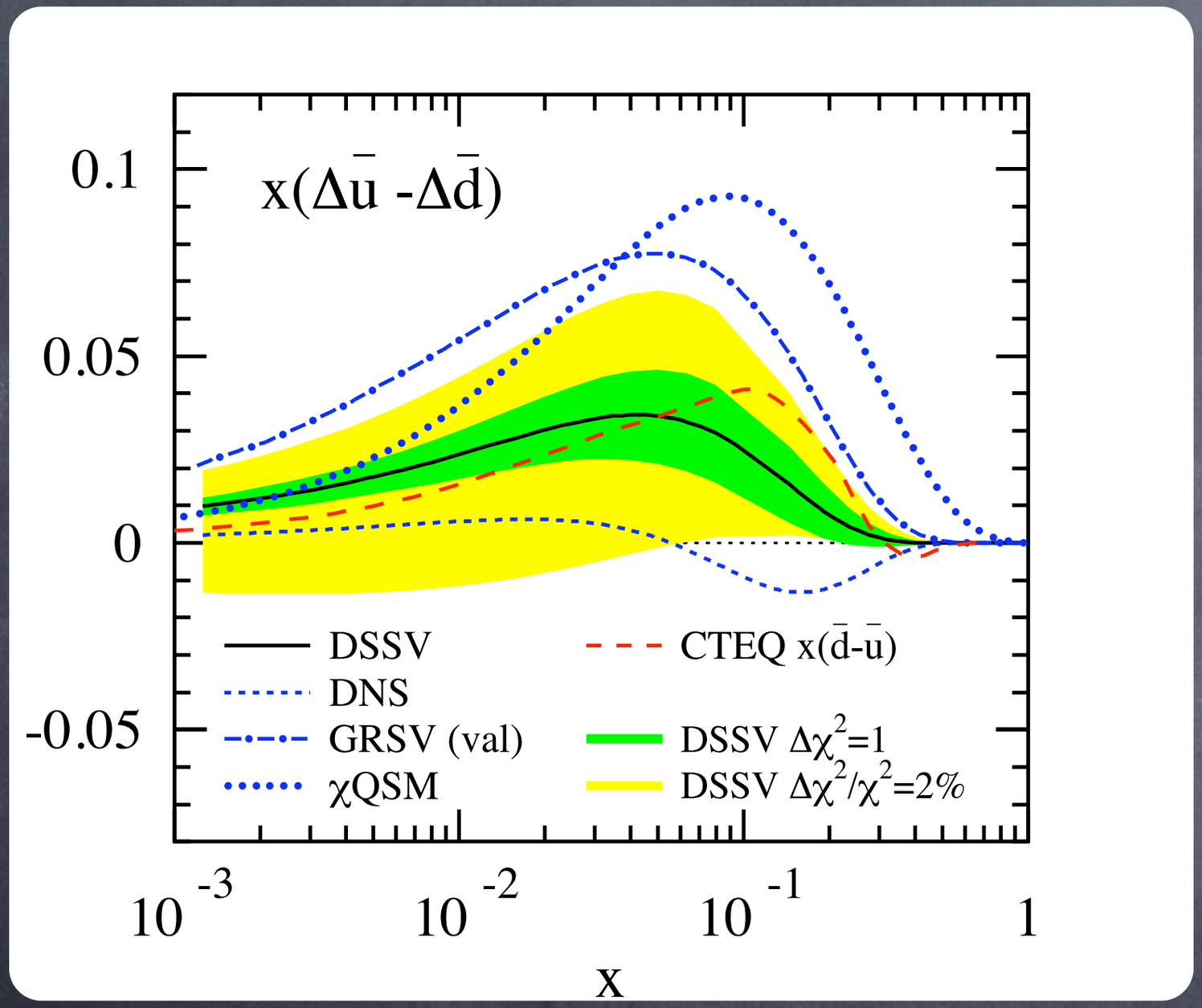




larger and negative?

larger uncertainties

h/pi tension?

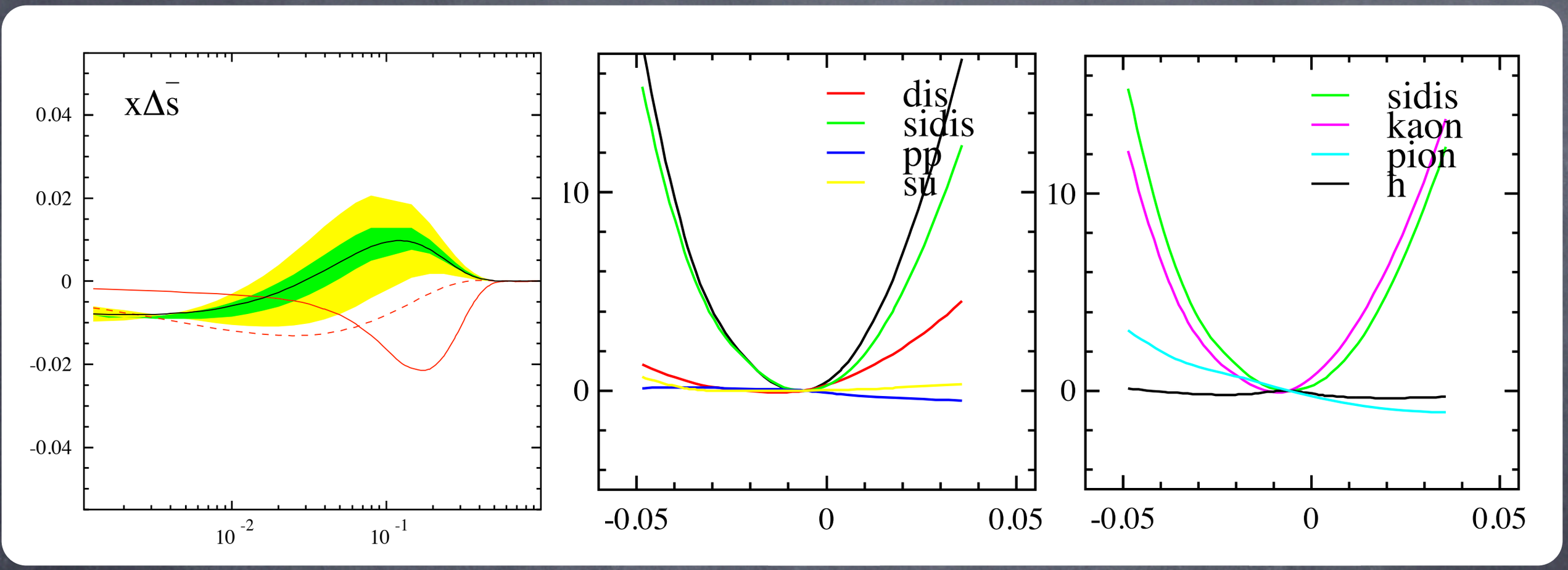
# DSSV helicity distributions: SU(2) breaking




breaking similar to unpolarized case

similar patterns in many models

# DSSV helicity distributions: strangeness

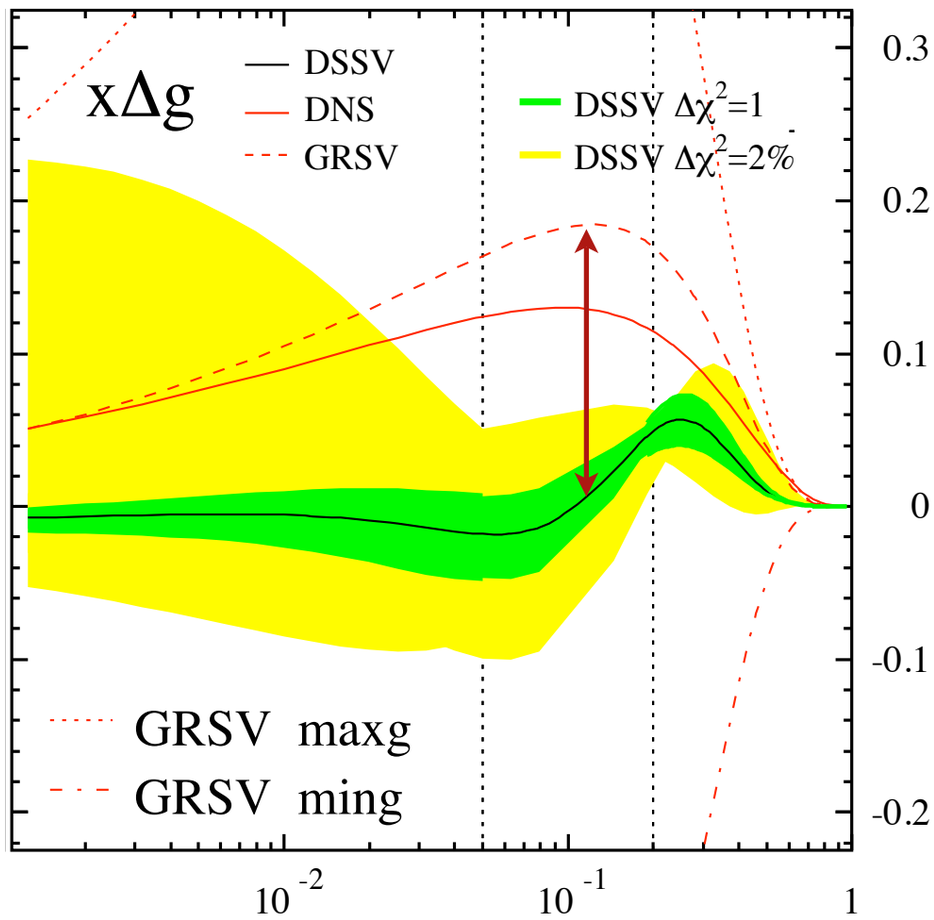


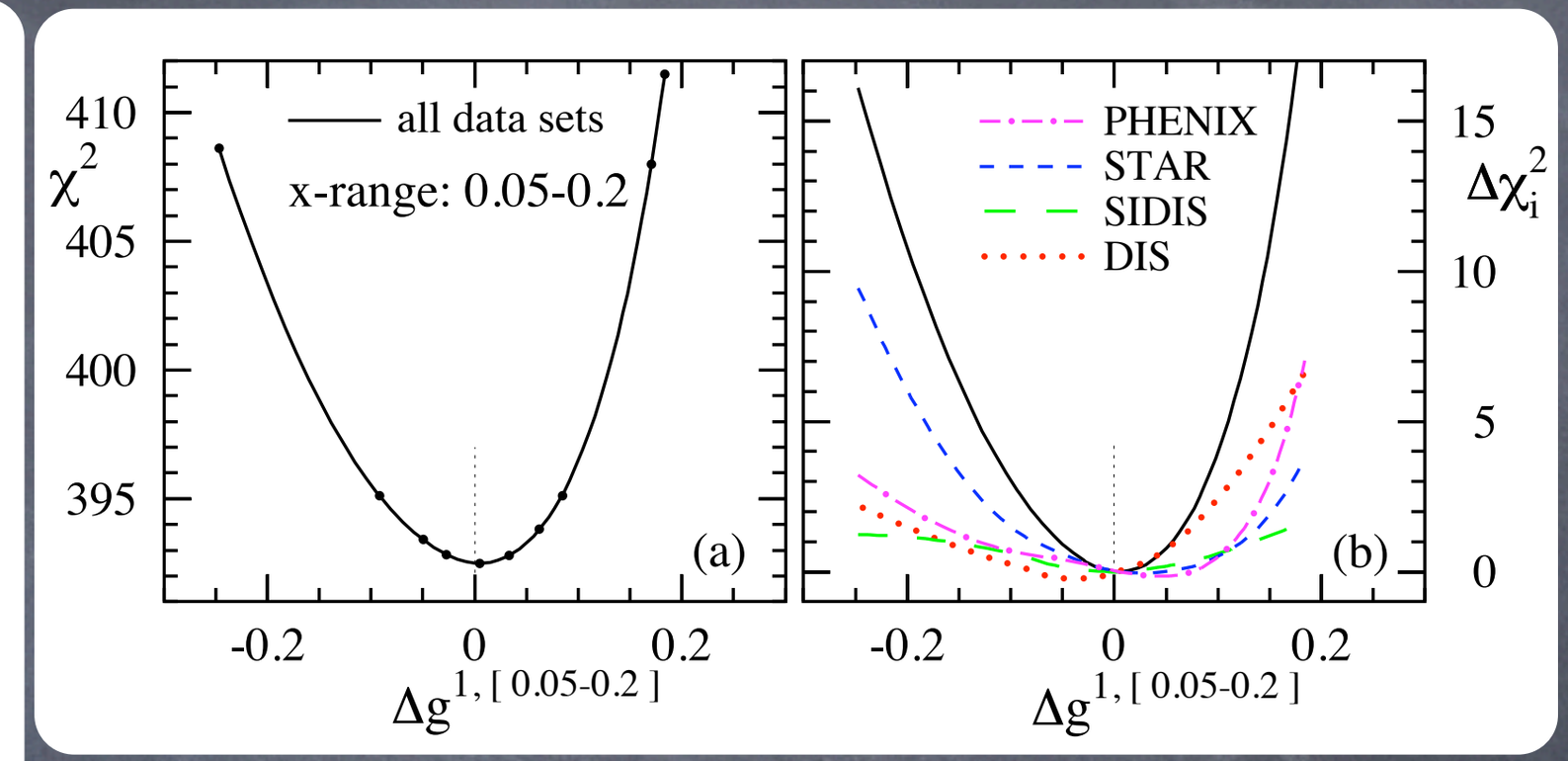

always though to be negative...

mainly determined by sidis (kaon)

becomes negative at small x?

# DSSV helicity distributions: gluons




measured region

$$\Delta g^{1,[0.05\to 0.2]} \equiv \int_{0.05}^{0.2} \Delta g \, dx$$

RHIC region

| | $[0.0-1.0]$ best fit | $[0.001-1.0]$ $\Delta\chi^2=1$ | $[0.001-1.0]$ $\Delta\chi^2/\chi^2=2\%$ |
|---|---|---|---|
| $\Delta u+\Delta\bar{u}$ | 0.813 | $0.793^{+0.011}_{-0.012}$ | $0.793^{+0.028}_{-0.034}$ |
| $\Delta d+\Delta\bar{d}$ | -0.458 | $-0.416^{+0.011}_{-0.009}$ | $-0.416^{+0.035}_{-0.025}$ |
| $\Delta\bar{u}$ | 0.036 | $0.028^{+0.021}_{-0.020}$ | $0.028^{+0.059}_{-0.059}$ |
| $\Delta\bar{d}$ | -0.115 | $-0.089^{+0.029}_{-0.029}$ | $-0.089^{+0.090}_{-0.080}$ |
| $\Delta\bar{s}$ | -0.057 | $-0.006^{+0.010}_{-0.012}$ | $-0.006^{+0.028}_{-0.031}$ |
| $\Delta g$ | -0.084 | $0.013^{+0.106}_{-0.120}$ | $0.013^{+0.702}_{-0.314}$ |
| $\Delta\Sigma$ | 0.242 | $0.366^{+0.015}_{-0.018}$ | $0.366^{+0.042}_{-0.062}$ |

low x extrapolation

# QCD and Spin Physics

a collection of topics that highlight the link
between theory and experiment

many "surprises", lively discussions, still learning...

pQCD as a tool to connect phenomena
relates experiment to the underlying protagonists

step by step approach: changing picture

just the first steps...