Spin-dependent parton distributions and QCD threshold resummation

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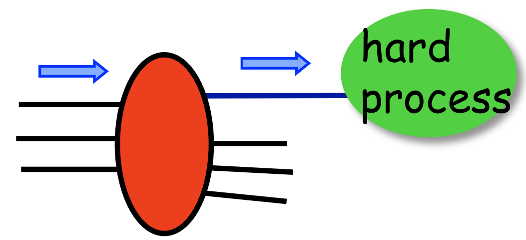
Zeuthen, 03.10.2011

Today:

Helicity structure of the nucleon

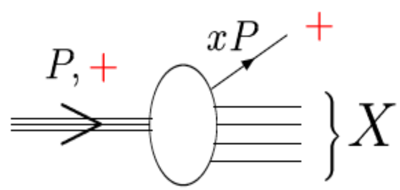
- Helicity parton distributions and their physics
- Present knowledge
- Latest results and developments

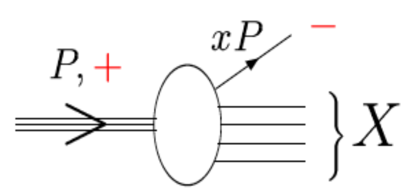


Applications of threshold resummation

- Drell-Yan process in πN scattering
- Photoproduction of high-p_T hadrons

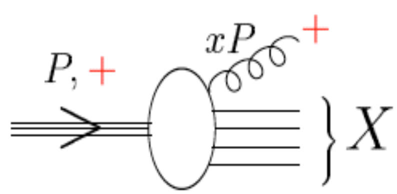
Helicity Parton Distributions

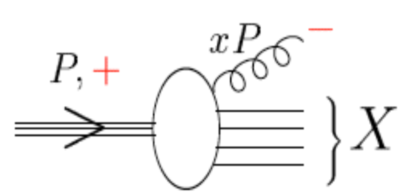
$\Delta q(x) = \Big|$ 

$\Big|^2 - \Big|$ 

$\Big|^2$

$$\Delta\, q(x) \;=\; \frac{1}{4\pi} \int dy^- \, \mathrm{e}^{-iy^- xP^+} \, \langle\, P, S \,|\, \bar{\psi}\,(0, y^-, \mathbf{0}_\perp)\; \gamma^+ \gamma_5 \, \psi(0) \,|\, P, S \,\rangle$$

$\Delta g(x) = \Big|$ 

$\Big|^2 - \Big|$ 

$\Big|^2$

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

Collins, Soper; Manohar

Measured in numerous experiments:

SLAC

E142, E143,
E154, E155

CERN

EMC, SMC,
COMPASS

DESY

HERMES

JLab

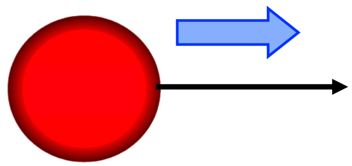
Hall A, CLAS

BNL

PHENIX, STAR

pp collisions at
200 & 500 GeV

(1) Δq, Δg and the proton spin



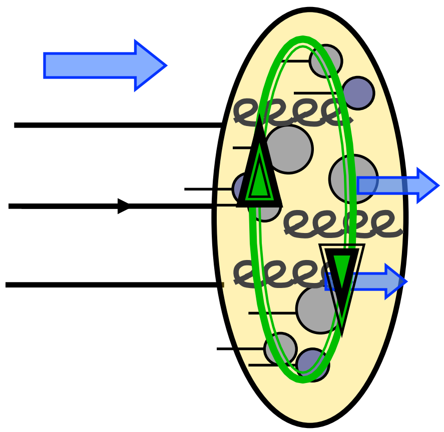
$$\frac{1}{2} = \langle P, \frac{1}{2} \,|\, J_{QCD} \,|\, P, \frac{1}{2} \rangle$$

$$\boldsymbol{J}_{QCD} \;=\; \boldsymbol{S}^q \;+\; \boldsymbol{L}^q \;+\; \boldsymbol{S}^g \;+\; \boldsymbol{L}^g$$

$$\begin{aligned}
\boldsymbol{S}^q &= \int \psi^\dagger \, \frac{1}{2} \boldsymbol{\Sigma} \, \psi \, d^3x, \\
\boldsymbol{L}^q &= \int \psi \, \boldsymbol{x} \times (\boldsymbol{p} - g\,\boldsymbol{A}) \, \psi \, d^3x, \\
\boldsymbol{S}^g &= \int \boldsymbol{E}^a \times \boldsymbol{A}^a_{phys} \, d^3x, \\
\boldsymbol{L}^g &= \int E^{aj} \, (\boldsymbol{x} \times \nabla) \, A^{aj}_{phys} \, d^3x \;+\; g \int \psi^\dagger \, \boldsymbol{x} \times \boldsymbol{A}_{phys} \, \psi \, d^3x
\end{aligned}$$

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

- gives rise to proton helicity ("spin") sum rule:



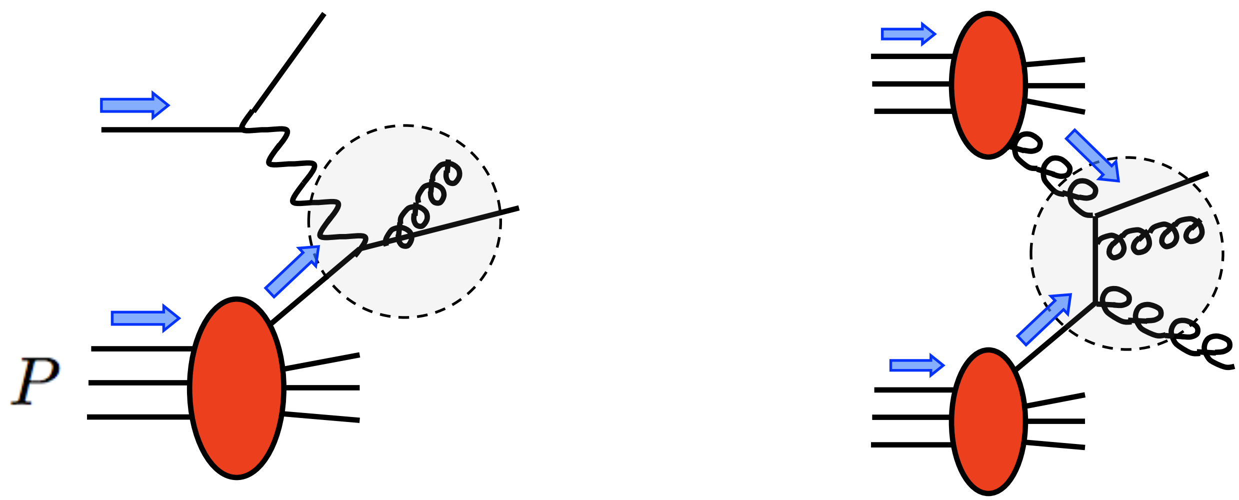
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

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

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

- known for past ~25 years: $\Delta\Sigma \sim 0.25 \ll 1$

(2) Δq, Δg and short-distance QCD



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

universal !

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

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

- Many higher-order calculations for polarized ep, pp:

  Jäger,Schäfer,Stratmann,WV; Signer et al.; Gordon, WV; Contogouris et al.;Blümlein et al. Stratmann,Bojak; Gehrmann; Kamal; Smith,van Neerven,Ravindran;Nadolsky, Yuan ...

- 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,...
1977

Mertig, van Neerven
WV 1995

Moch, Rogal, Vogt,
Vermaseren 2008
(ij = qq,qg)

- by now, complete NLO framework available

(3) Δq, Δg "beyond the proton spin sum rule"

Models of nucleon structure, e.g.:

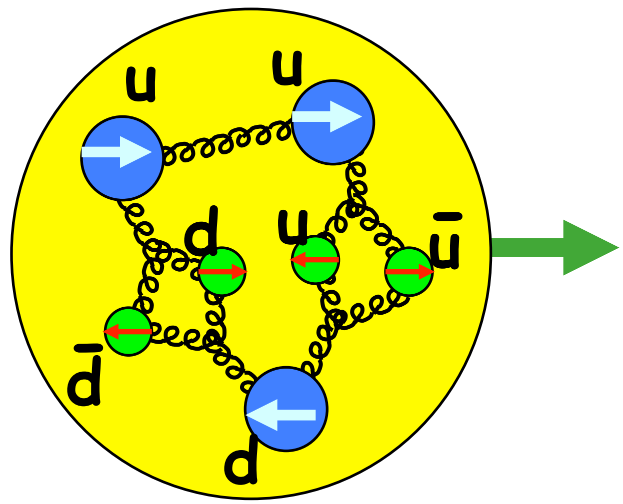
- valence region

$$\frac{\Delta d}{d} \xrightarrow{x \to 1} \begin{cases} 1 & \text{counting rules/pQCD} \\ -1/3 & \text{constituent quark model} \end{cases}$$

- flavor / sea structure

$$\Delta\bar{u} \;\text{ vs. }\; \Delta\bar{d}$$

large-N_c,
chiral quark models,
meson cloud,...



Lattice

- connection to hyperon β decays, SU(3)

$$\Delta\Sigma_q \equiv \int_0^1 dx\,(\Delta q + \Delta\bar{q})\,(x, Q^2) \;\; \propto \; \langle\, P, s\,|\,\bar{\psi}_q\,\gamma^\mu\gamma_5\,\psi_q\,|\,P, s\,\rangle$$

(axial charges)

Bjorken;
Ellis, Jaffe;
Sehgal;
Karliner, Lipkin;
Ratcliffe;…

$$\Delta\Sigma_u - \Delta\Sigma_d \;=\; g_A = 1.257 \pm \ldots$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s \;=\; 3F - D \;=\; 0.58 \pm 0.03 \quad ?$$

- strangeness?

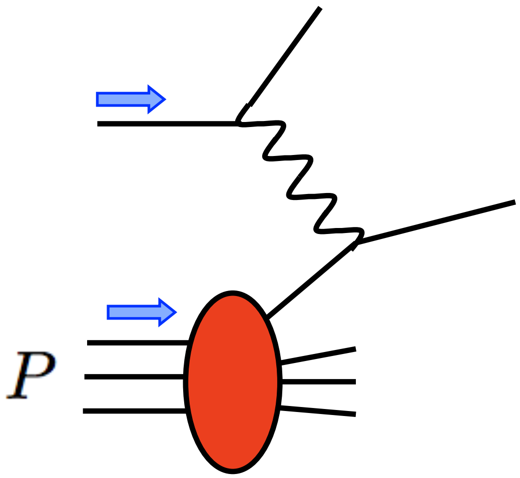
$$\Delta\Sigma \;=\; \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s \;=\; 3F - D \;+\; 3\Delta\Sigma_s$$

$\Delta q, \Delta g$: "Global analysis"

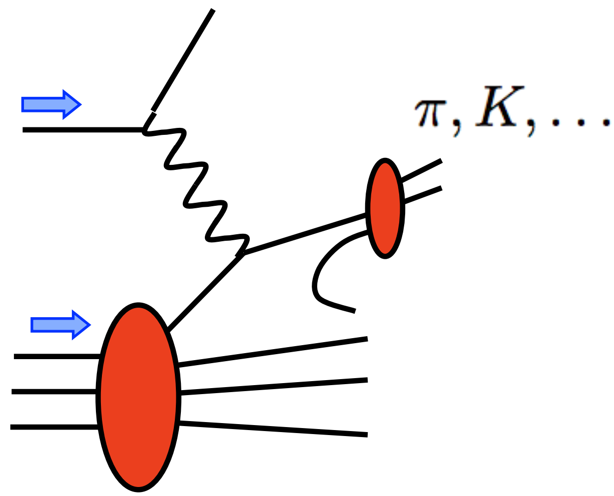
First NLO ($\overline{\text{MS}}$) "global analysis" of all DIS & RHIC data sets:

"DSSV" de Florian, Sassot, Stratmann, WV PRL 101, 2008

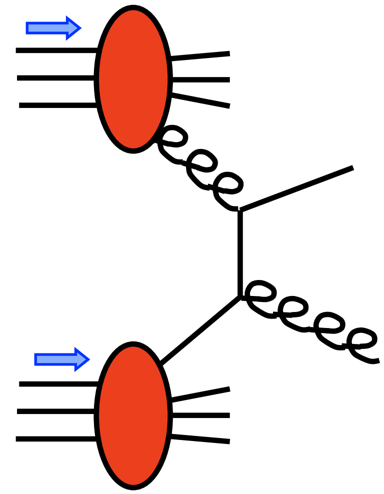
PRD 80, 2009



DIS



SIDIS



pp

- other recent analyses of DIS data :

  Blümlein, Böttcher; Leader, Stamenov, Sidorov; Forte et al.

- earlier: Glück ,Reya et al., Gehrmann,Stirling, Kumano,Saito et al. , …

Mellin method : example pp→πX

Stratmann, WV; Berger, Graudenz, Hampel, Vogt; Kosover

$$\Delta\sigma = \sum_{abc} \int dx_a \int dx_b \int dz_c \, \Delta f_a(x_a) \, \Delta f_b(x_b) \, \Delta\hat{\sigma}_{ab\to cX} \, D_c(z_c)$$

$$\frac{1}{2\pi i} \int_{\mathcal{C}} dn \; x_a^{-n} \, \Delta f_a^n \qquad\qquad \frac{1}{2\pi i} \int_{\mathcal{C}_m} dm \; x_b^{-m} \, \Delta f_b^m$$

$$\frac{1}{(2\pi i)^2} \sum_{abc} \int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm \; \boxed{\Delta f_a^n \, \Delta f_b^m} \; \boxed{\int dx_a \int dx_b \int dz_c \; x_a^{-n} \, x_b^{-m} \, \Delta\hat{\sigma}_{ab\to cX} \, D_c(z_c)}$$

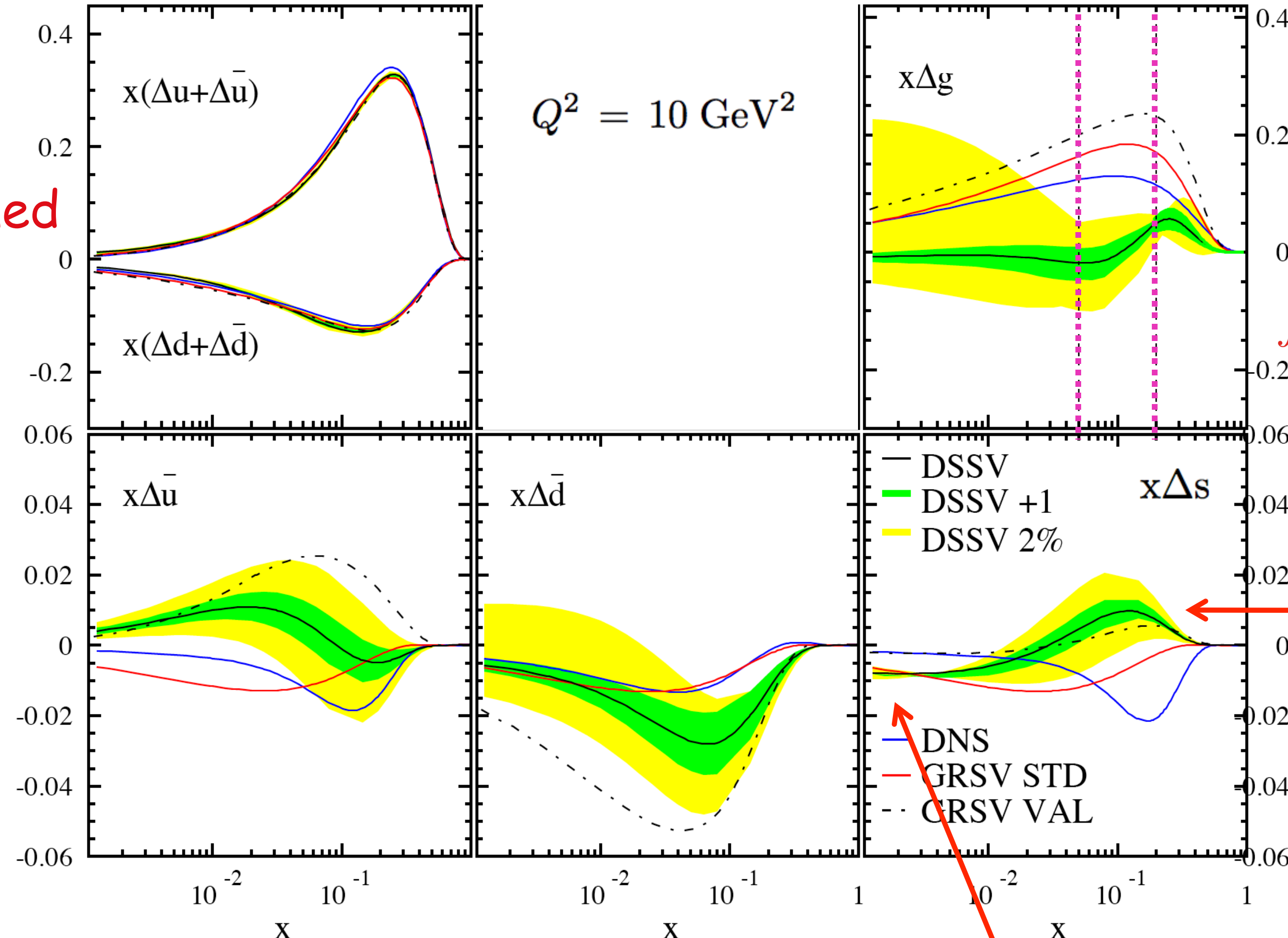
Contains all dependence on fit parameters

Completely independent of pdfs. Can be "pre-calculated" prior to fit

Status ~ 2009 :

best constrained

driven by SIDIS



small in measured regime !

$$\int_{0.05}^{0.2} dx\, \Delta g \approx 0$$

SIDIS

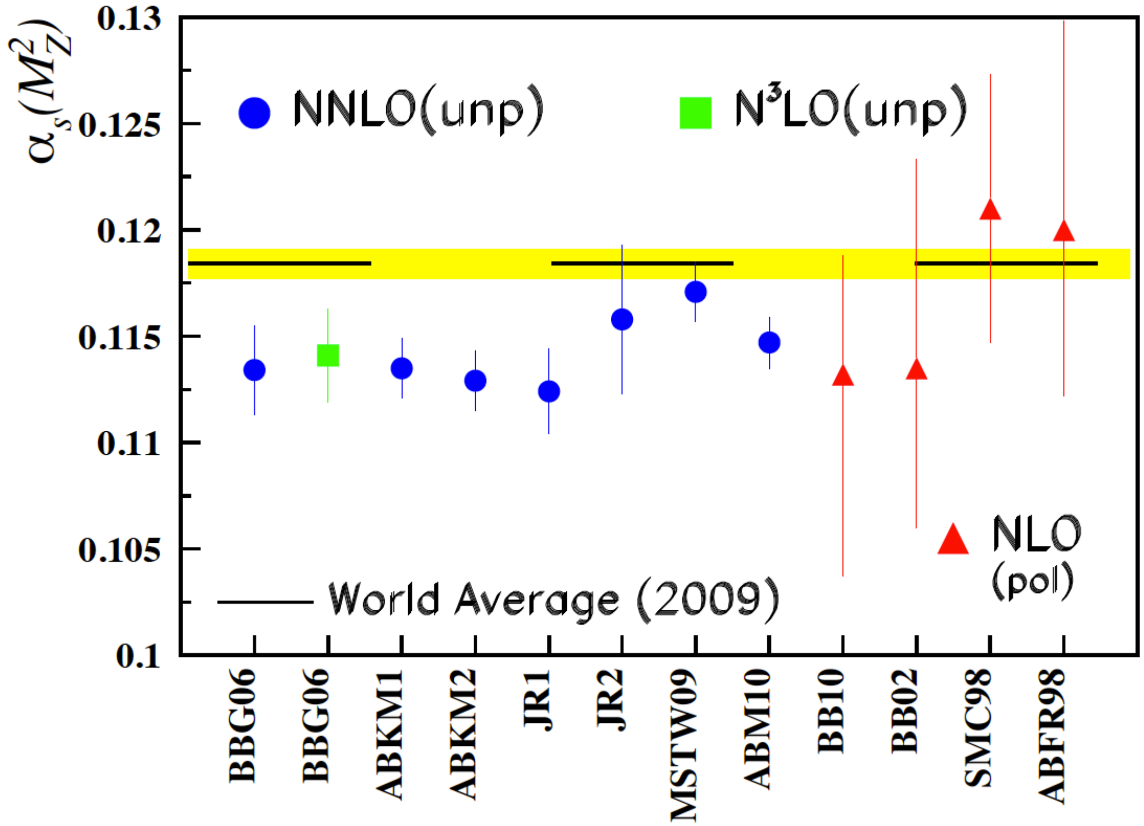
indications for $\Delta\bar{u} > 0$ $\Delta\bar{d} < 0$

DIS + SU(3)

strangeness puzzle?

- other analyses of polarized-DIS data (incl. new data):

Focus on target-mass corrections, higher-twist, α_s



Blümlein, Böttcher

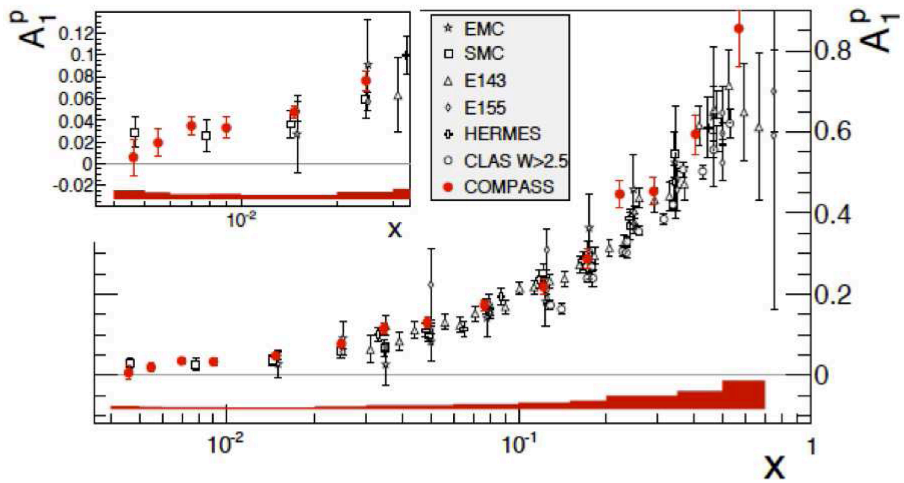
Latest developments …

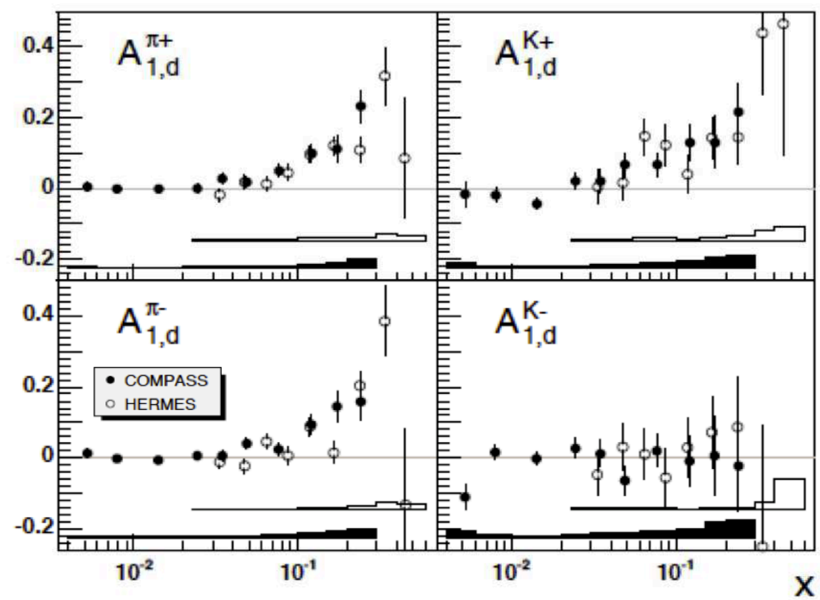
New data !

(1) Precise COMPASS DIS and SIDIS data:

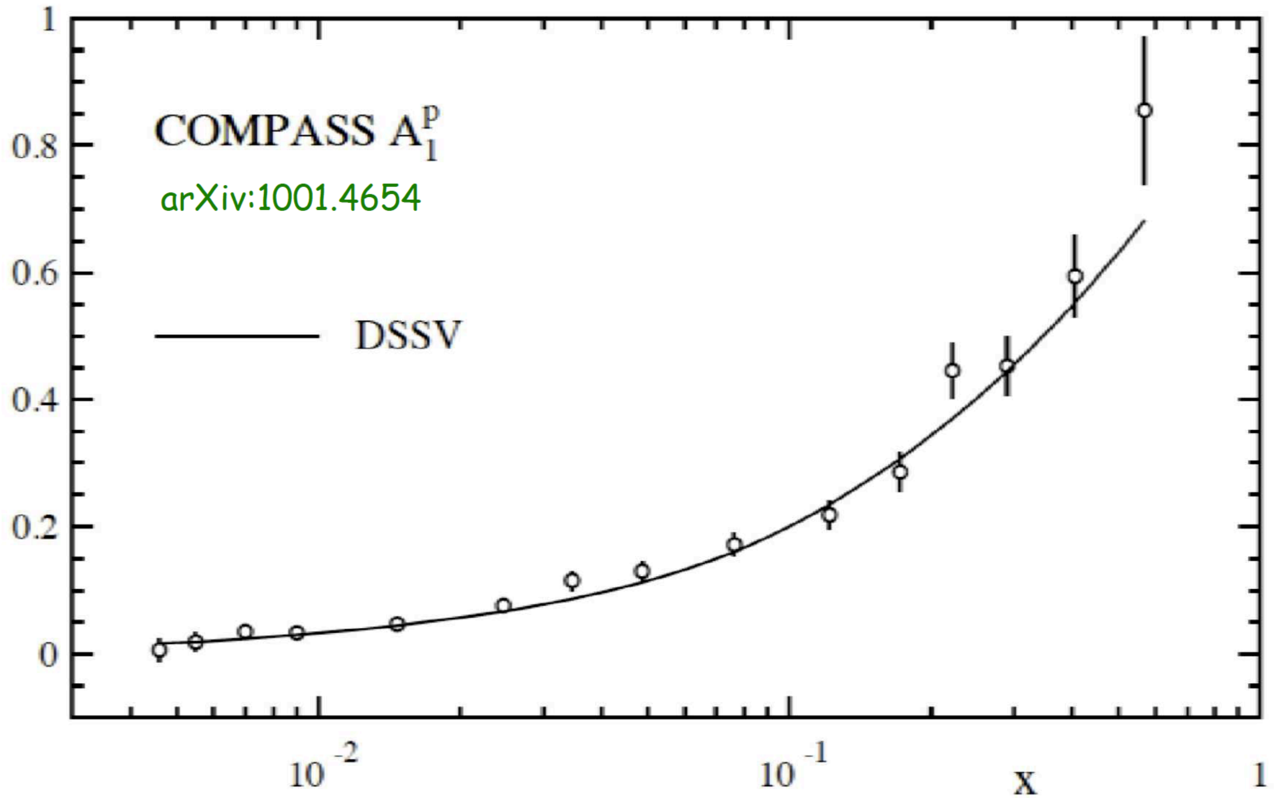
- **DIS:** A_1^p from COMPASS
  arXiv:1001.4654
- **SIDIS:** $A_{1,d}^{\pi,K}$ from COMPASS
  arXiv:0905.2828
- **SIDIS:** $A_{1,p}^{\pi,K}$ from COMPASS
  arXiv:1007.4061

extended x coverage w.r.t. HERMES



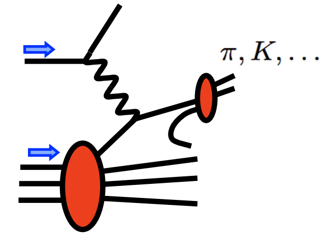


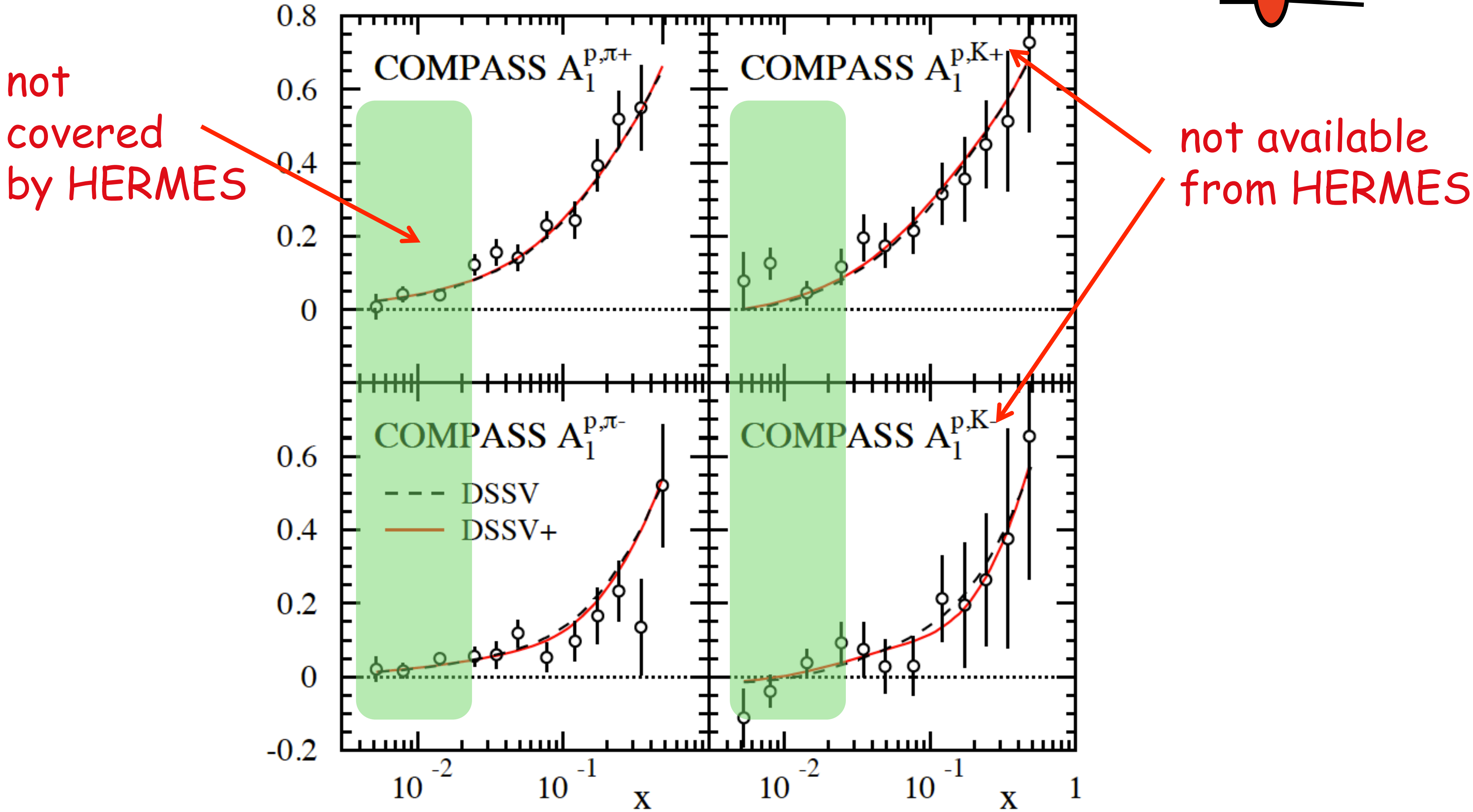
(M.Stratmann at DIS 2011)



✔

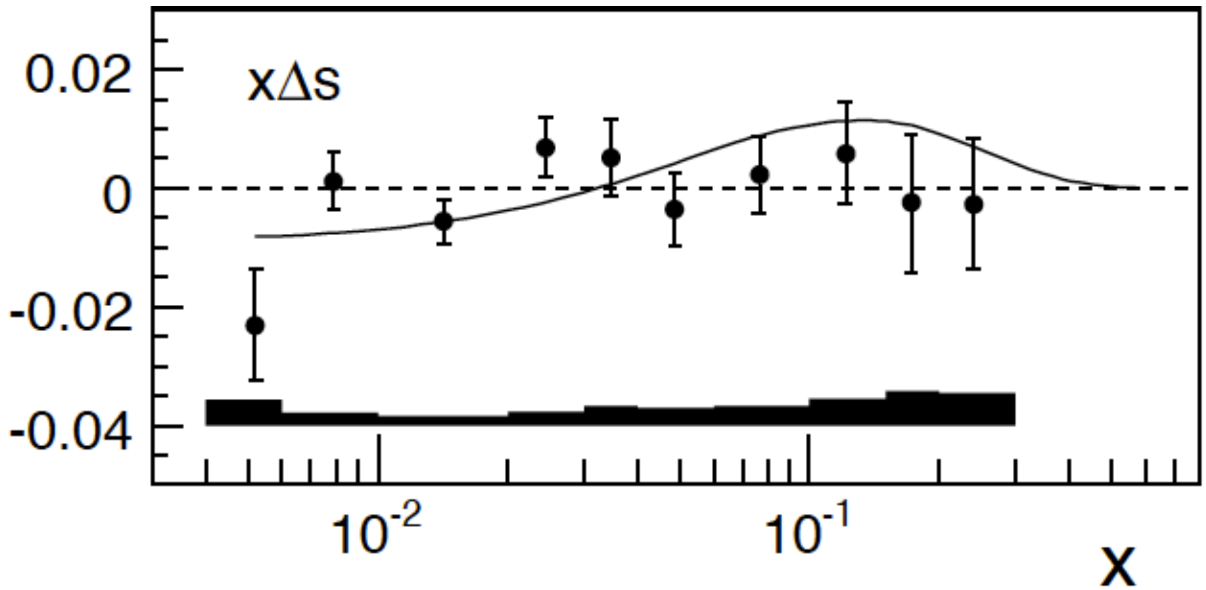
- COMPASS semi-inclusive data:





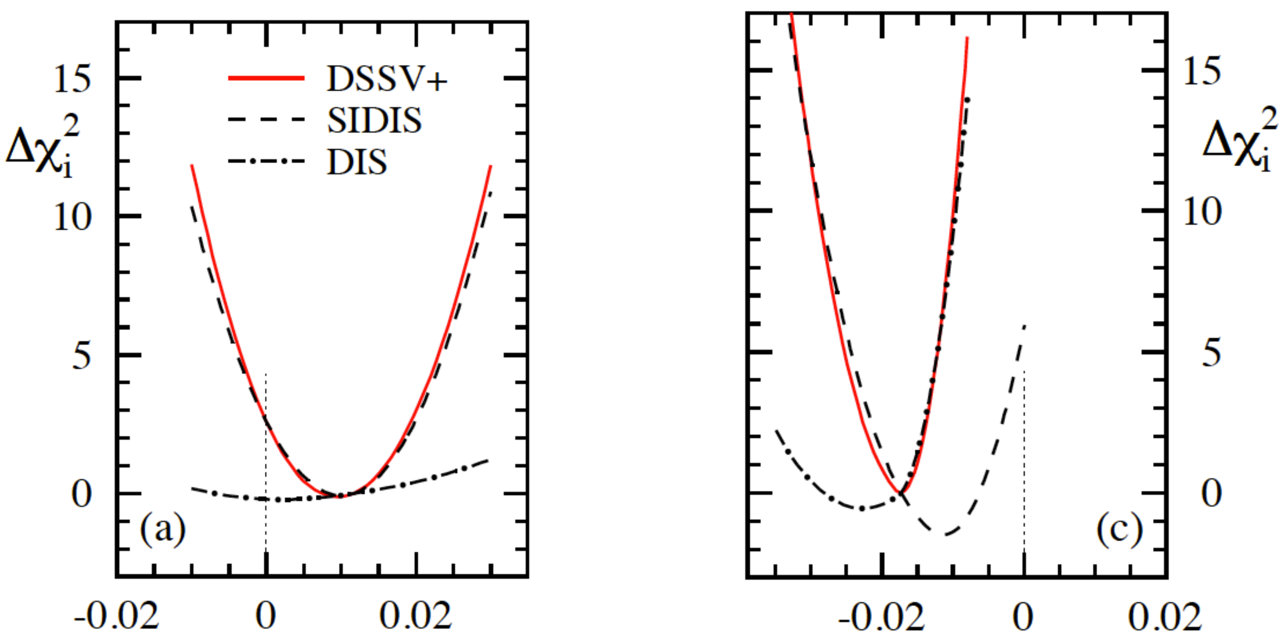
- refit: trend for $\Delta\bar{u} - \Delta\bar{d} \neq 0$ now less pronounced

- implications for Δs ?



(COMPASS LO extraction)

(M.Stratmann at DIS 2011)



$$\int_{0.02}^{1} dx\,\Delta s \qquad\qquad \int_{0.001}^{0.02} dx\,\Delta s$$

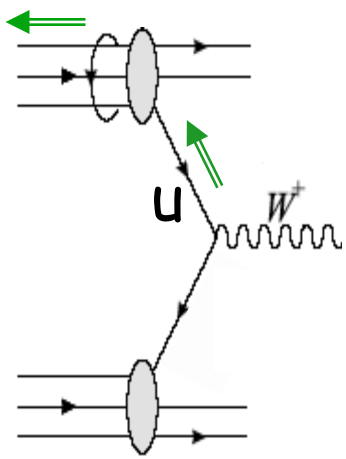
- tendency toward negative low-x Δs also from SIDIS ?
- lattice ?

$$\Delta\Sigma_s \sim -0.02$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s \sim 0.5$$

Bali,Collins,Schäfer (QCDSF)

(2) RHIC sees W bosons !

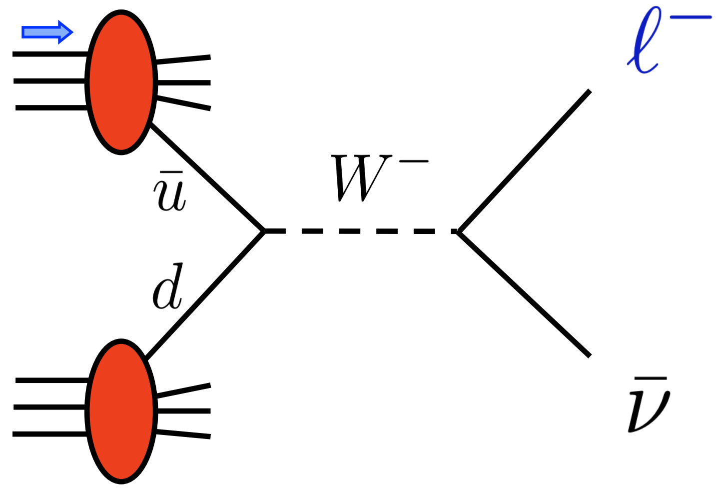


unpol.

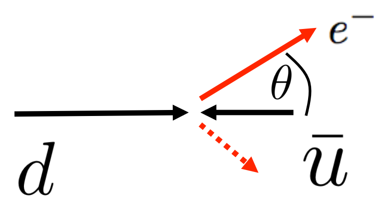
$$\sqrt{s} = 500 \text{ GeV}$$

- large Parity Violation effect $$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$

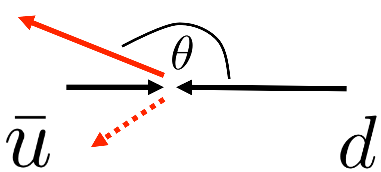
- new NLO for polarized case: de Florian, WV



$$A_L^{e^-} \sim \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

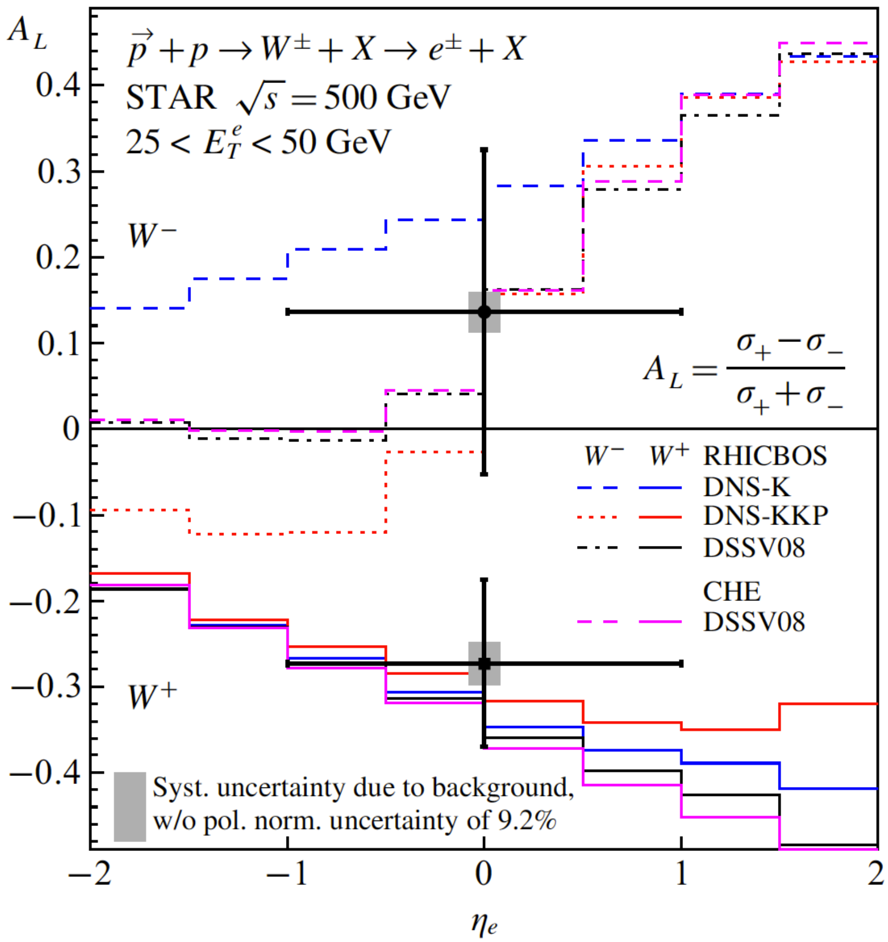


$$\sim (1+\cos\theta)^2$$



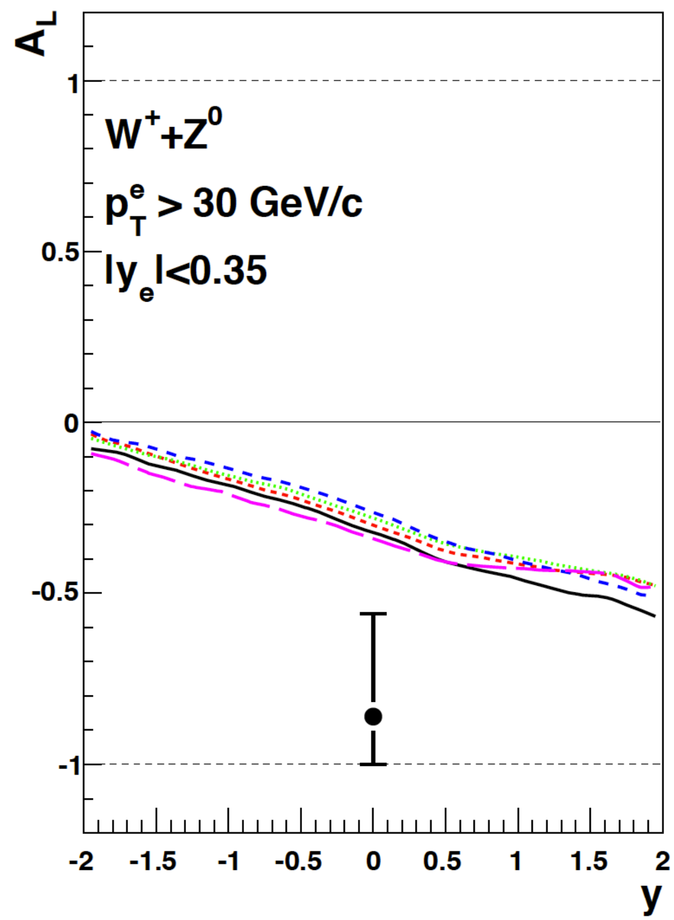
$$\sim (1-\cos\theta)^2$$

STAR



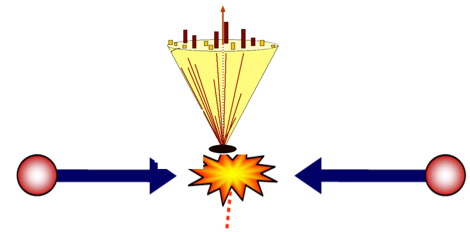
$\vec{p}+p \rightarrow W^{\pm}+X \rightarrow e^{\pm}+X$
STAR $\sqrt{s}=500$ GeV
$25 < E_T^e < 50$ GeV
A_L
W^-
W^+
$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
W^- W^+ RHICBOS
DNS-K
DNS-KKP
DSSV08
CHE
DSSV08
Syst. uncertainty due to background,
w/o pol. norm. uncertainty of 9.2%
η_e

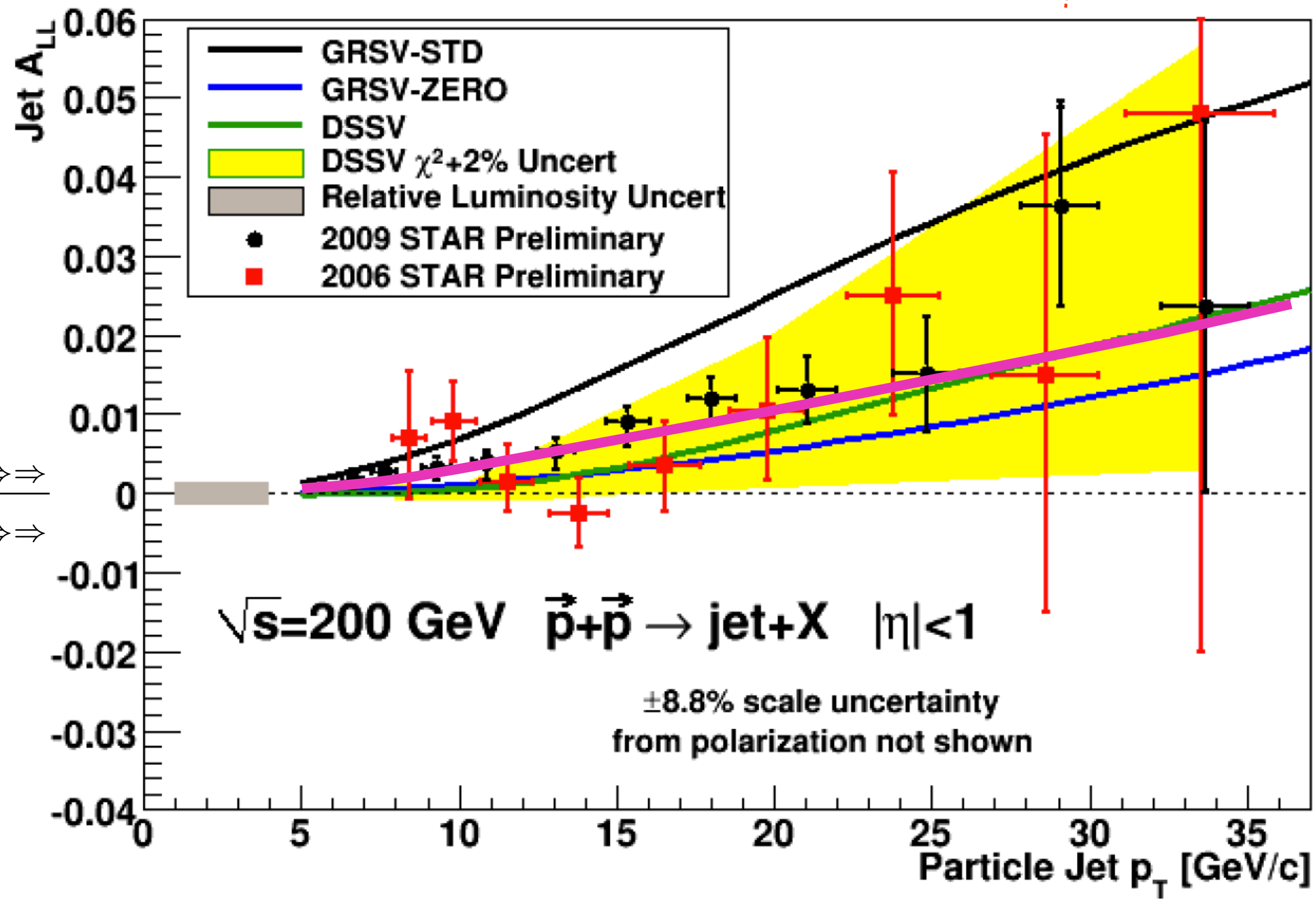
Phenix



A_L
$W^+ + Z^0$
$p_T^e > 30$ GeV/c
$|y_e| < 0.35$
y

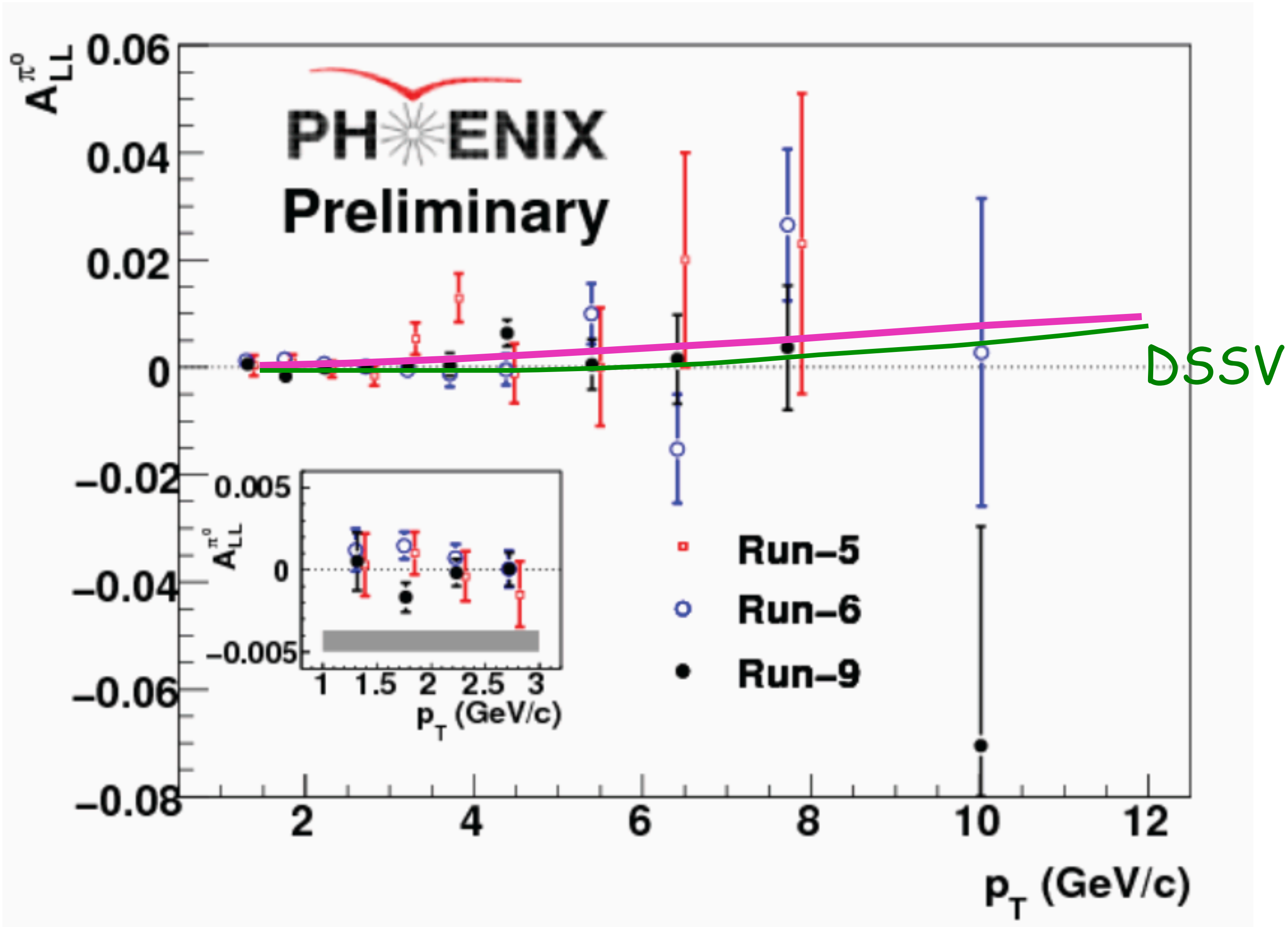
(3) New devlopments on Δg





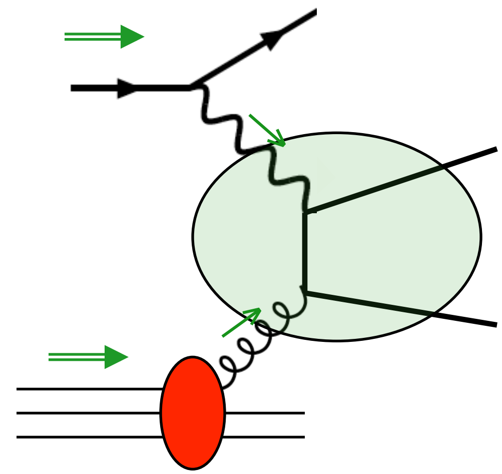
$$A_{LL} = \frac{\sigma_{\Rightarrow\Leftarrow} - \sigma_{\Rightarrow\Rightarrow}}{\sigma_{\Rightarrow\Leftarrow} + \sigma_{\Rightarrow\Rightarrow}}$$

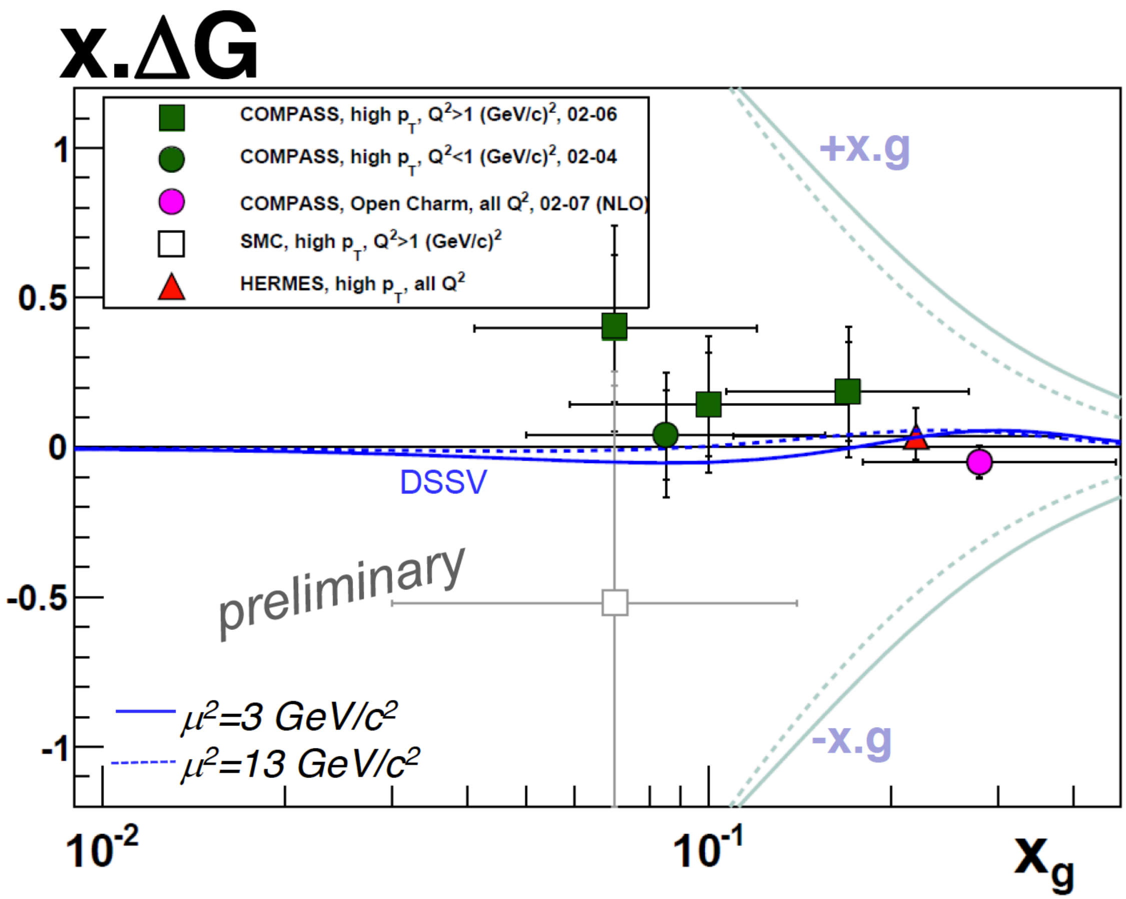
- gives gluon with $\displaystyle\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$



PHENIX
Preliminary
$A_{LL}^{\pi^0}$
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
2
4
6
8
10
12
p_T (GeV/c)
0.005
0
−0.005
1
1.5
2
2.5
3
Run−5
Run−6
Run−9
DSSV

Most recent COMPASS data:

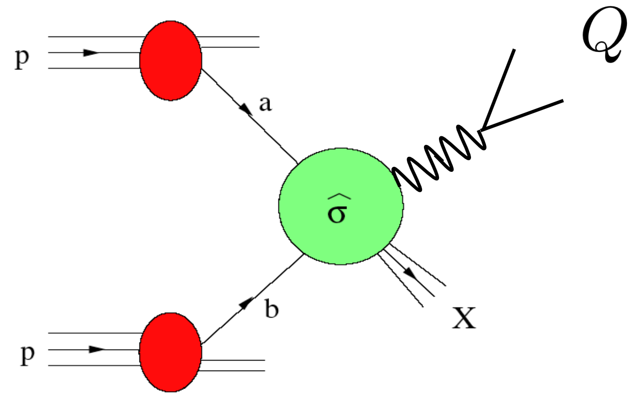




yet to be included in global analysis

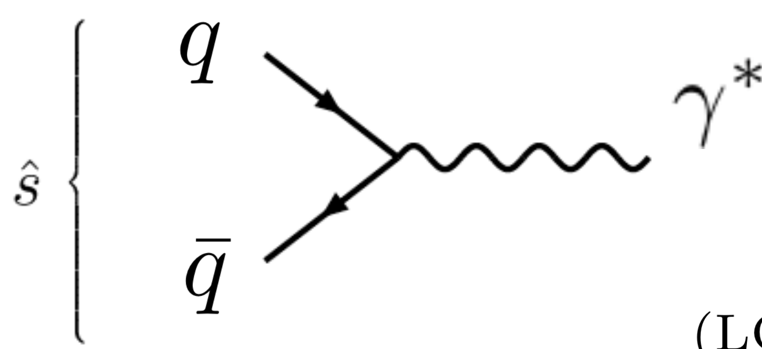
Applications of QCD Threshold Resummation

The archetype: Drell-Yan



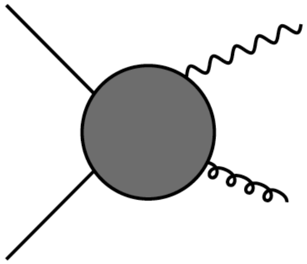
$$Q^2 d\sigma \;=\; \sum_{ab} \int dx_a dx_b \, f_a(x_a,\mu)\, f_b(x_b,\mu)\; \omega_{ab}\left(z=\frac{Q^2}{\hat{s}}, \alpha_s(\mu), \frac{Q}{\mu}\right) \;+\; \ldots$$

LO :



$$\omega_{ab}^{(\mathrm{LO})} \;\propto\; \delta(1-z)$$

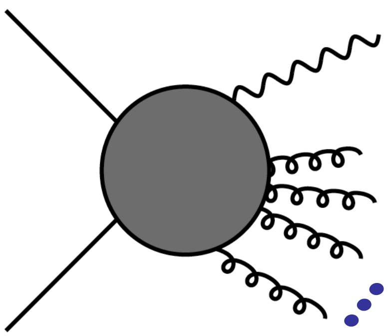
- NLO correction:



$$z \to 1:$$

$$\omega_{ab}^{(\mathrm{NLO})} \propto \alpha_s \left(\frac{\log(1-z)}{1-z} \right)_+ + \ldots$$

- higher orders:



$$\omega_{ab}^{(\mathrm{N^kLO})} \propto \alpha_s^k \left(\frac{\log^{2k-1}(1-z)}{1-z} \right)_+ + \ldots$$

"threshold logarithms"

- for z->1 real radiation inhibited

- logs emphasized by parton distributions :

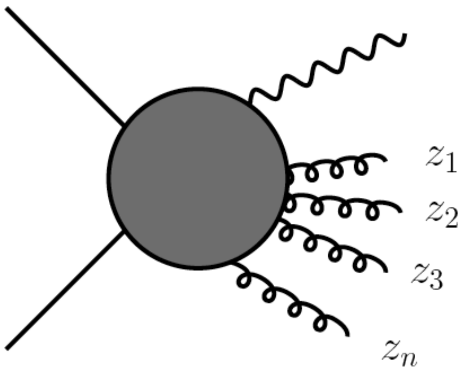
$$d\sigma \sim \int_{\tau}^{1} \frac{dz}{z} \mathcal{L}_{q\bar{q}} \left(\frac{\tau}{z} \right) \omega_{q\bar{q}}(z) \qquad \tau = \frac{Q^2}{S}$$

z = 1 relevant,
in particular as $\tau \rightarrow 1$

Large logs can be resummed to all orders

Catani, Trentadue; Sterman; ...

- factorization of matrix elements
- and of phase space when integral transform is taken:



$$\delta\left(1 - z - \sum_{i=1}^{n} z_i\right) = \frac{1}{2\pi i}\int_C dN\, e^{N\left(1-z-\sum_{i=1}^{n} z_i\right)}$$

$$z_i = \frac{2E_i}{\sqrt{\hat{s}}}$$

$\overline{\text{MS}}$ scheme

$$\hat{\sigma}_{q\bar{q}}^{\text{res}}(N) \propto \exp\left[2\int_0^1 dy\, \frac{y^N - 1}{1-y}\int_{\mu^2}^{Q^2(1-y)^2} \frac{dk_\perp^2}{k_\perp^2} A_q\left(\alpha_s(k_\perp^2)\right) + \ldots\right]$$

Kodaira,Trentadue

$$A_q(\alpha_s) = C_F\left\{\frac{\alpha_s}{\pi} + \left(\frac{\alpha_s}{\pi}\right)^2\left[\frac{C_A}{2}\left(\frac{67}{18} - \zeta(2)\right) - \frac{5}{9}T_R n_f\right] + \ldots\right\}$$

- they enhance cross sec. !

$$\hat{\sigma}_{q\bar{q}} \propto \exp\left[+\frac{2C_F}{\pi}\alpha_s \ln^2(N)\right] > 1$$

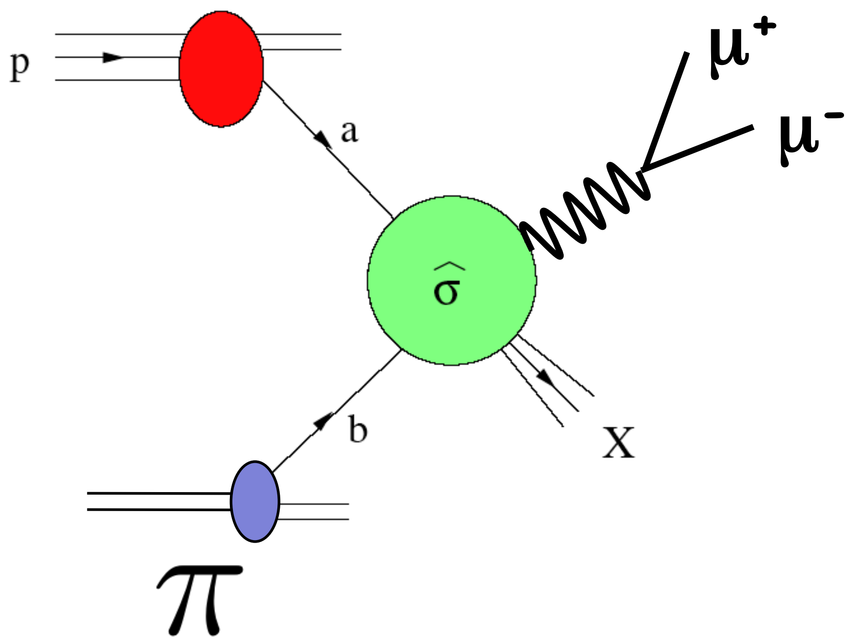
Drell-Yan is key focus in nucleon structure physics:

- in pp, pN: probe of anti-quark distributions
- in πN: probe of pion structure
- probe of spin phenomena: TMDs, Sivers effect

Currently:	E906	ongoing
	RHIC, COMPASS	near-term plans
	J-PARC, FAIR	future possibilities

- Drell-Yan process has been main source of information on pion structure:

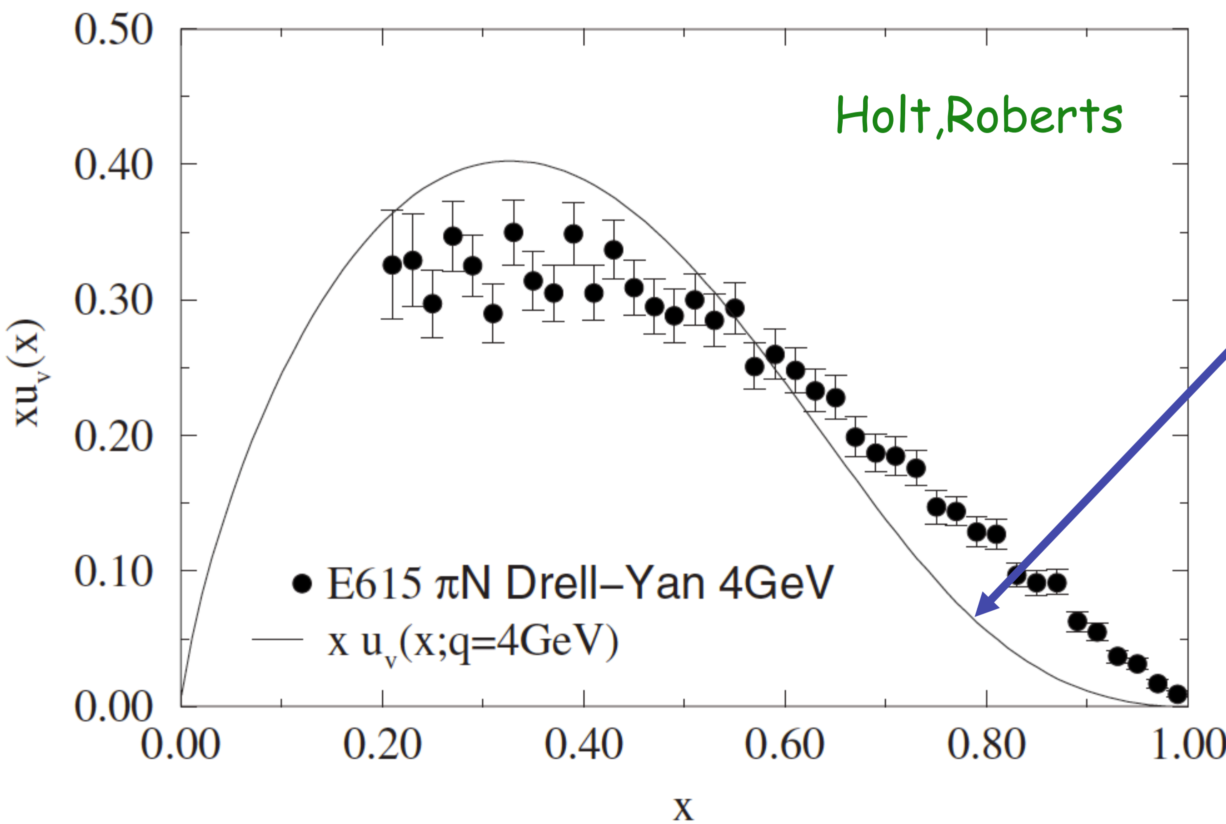
E615, NA10



$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a^{\pi}(x_a, \mu) f_b(x_b, \mu) \, d\hat{\sigma}_{ab}(x_a P_a, x_b P_b, Q, \alpha_s(\mu), \mu)$$

- Kinematics such that data mostly probe valence region: ~200 GeV pion beam on fixed target $\frac{Q}{\sqrt{S}} \sim 0.4$

- LO extraction of u_v from E615 data: $\sqrt{S} = 21.75\,\mathrm{GeV}$



$\sim (1-x)^2$

QCD counting rules

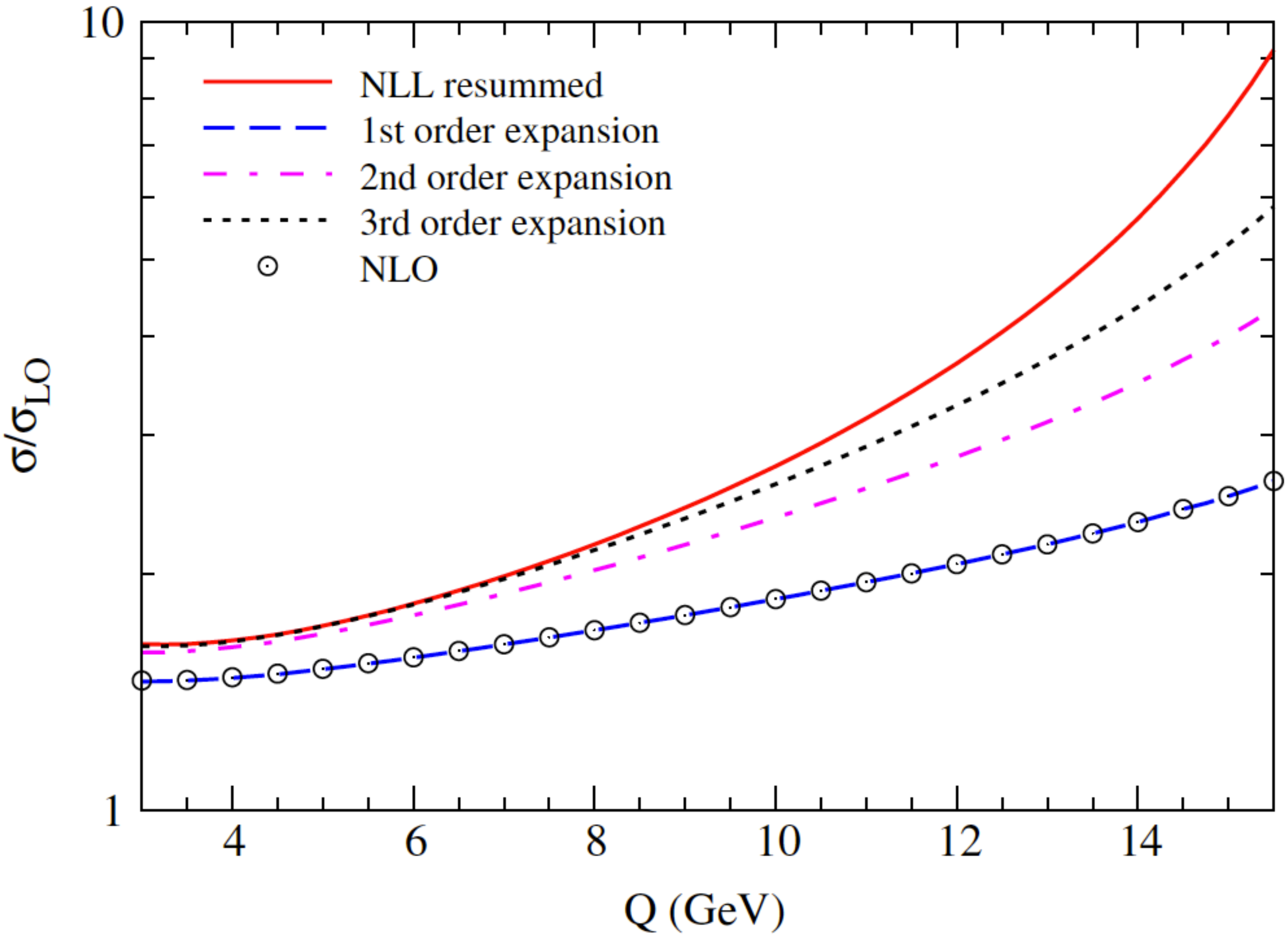
Farrar,Jackson;
Berger, Brodsky; Yuan
Blankenbecler,Gunion,
Nason

Dyson-Schwinger

Hecht et al.

(Compass kinematics)

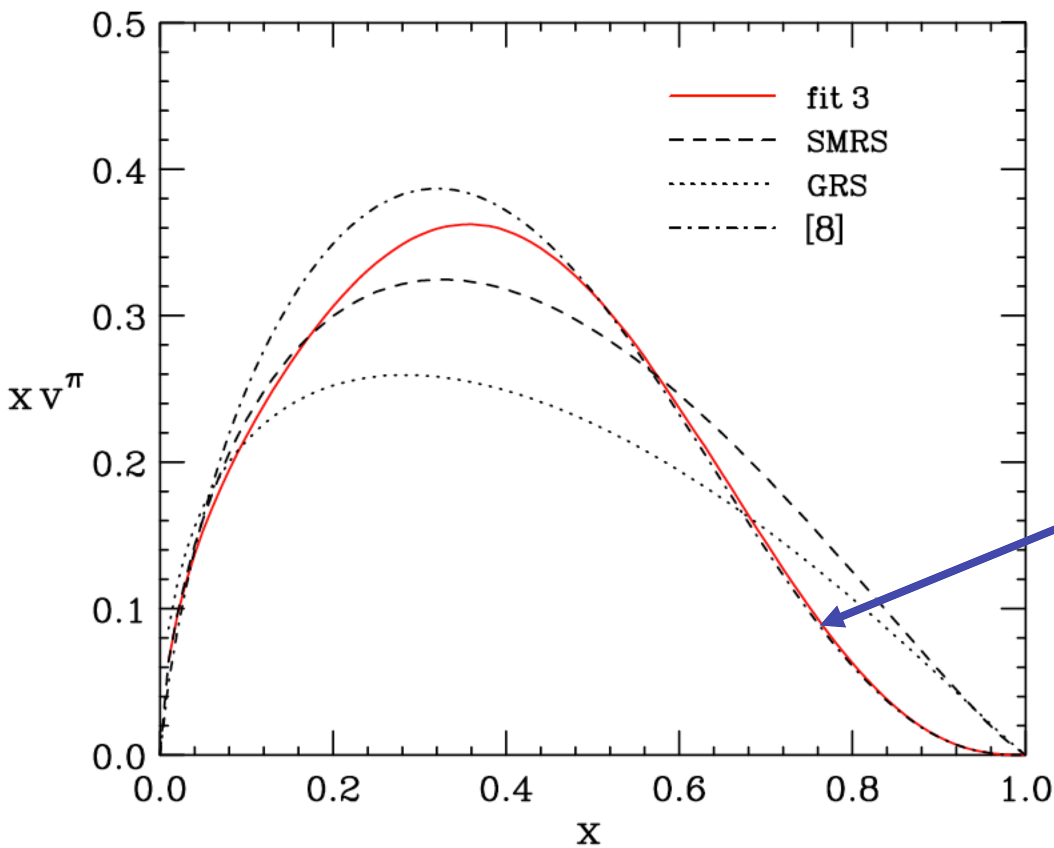
$\sqrt{S} = 19\,\mathrm{GeV}$



Aicher,Schäfer, WV
(earlier studies: Shimizu,Sterman,WV,Yokoya)

$$xv^{\pi}(x, Q_0^2) = N_v x^{\alpha}(1-x)^{\beta}(1+\gamma x^{\delta})$$

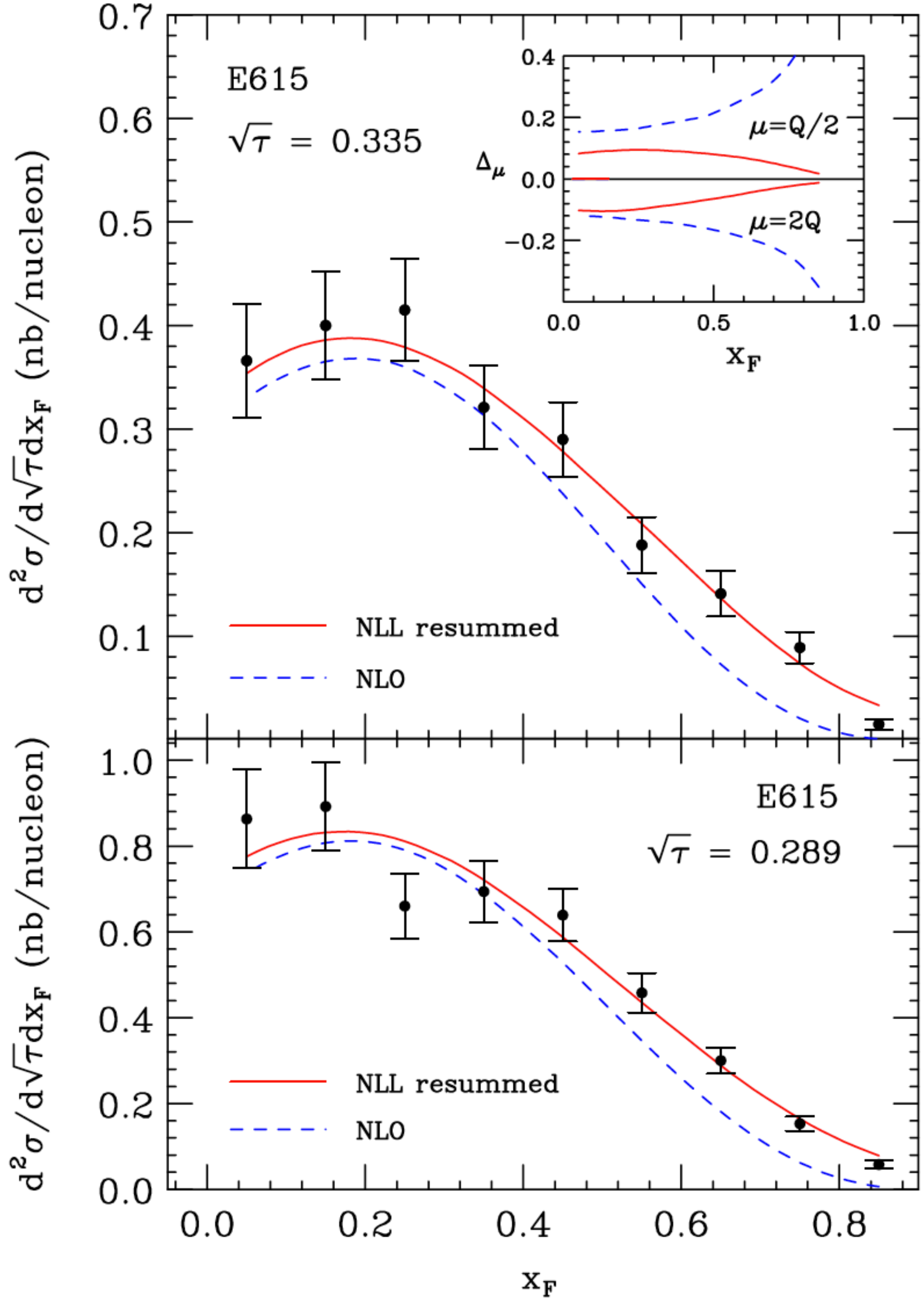
Fit	$2\langle xv^{\pi}\rangle$	α	β	γ	K	χ^2 (no. of points)
1	0.55	0.15 ± 0.04	1.75 ± 0.04	89.4	0.999 ± 0.011	82.8 (70)
2	0.60	0.44 ± 0.07	1.93 ± 0.03	25.5	0.968 ± 0.011	80.9 (70)
3	0.65	0.70 ± 0.07	2.03 ± 0.06	13.8	0.919 ± 0.009	80.1 (70)
4	0.7	1.06 ± 0.05	2.12 ± 0.06	6.7	0.868 ± 0.009	81.0 (70)



$Q = 4\ \mathrm{GeV}$

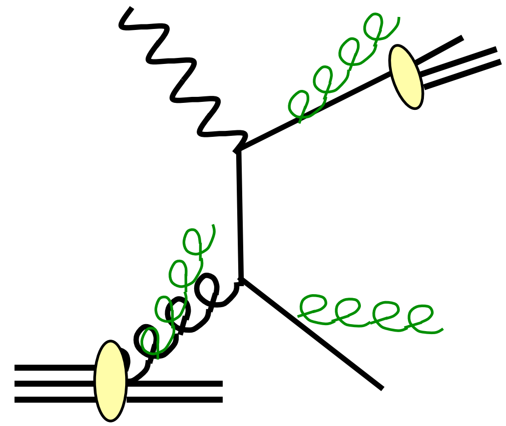
$\sim (1-x)^{2.34}$

M. Aicher, A.Schäfer, WV



M. Aicher,
A.Schäfer, WV

Logarithms also present in high-p_T processes:



$$p_T^3 \frac{d\hat{\sigma}_{ab}}{dp_T} = p_T^3 \frac{d\hat{\sigma}_{ab}^{\text{Born}}}{dp_T} \left[1 + \underbrace{\mathcal{A}_1\, \alpha_s\, \ln^2\left(1-\hat{x}_T^2\right) + \mathcal{B}_1\, \alpha_s\, \ln\left(1-\hat{x}_T^2\right)}_{\text{NLO}} \right.$$

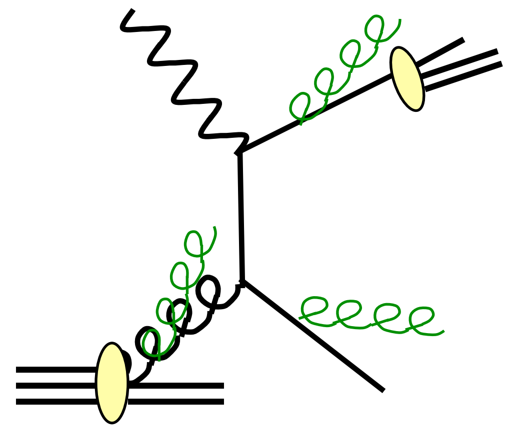
$$\left. + \ldots + \mathcal{A}_k\, \alpha_s^k\, \ln^{2k}\left(1-\hat{x}_T^2\right) + \ldots \right] + \ldots$$

$$\hat{x}_T \equiv \frac{2p_T}{\sqrt{\hat{s}}}$$

All-order resummation:

Laenen, Oderda, Sterman; Catani et al.;
Kidonakis, Sterman; Bonciani et al.;
de Florian, WV;
Almeida, Sterman, WV

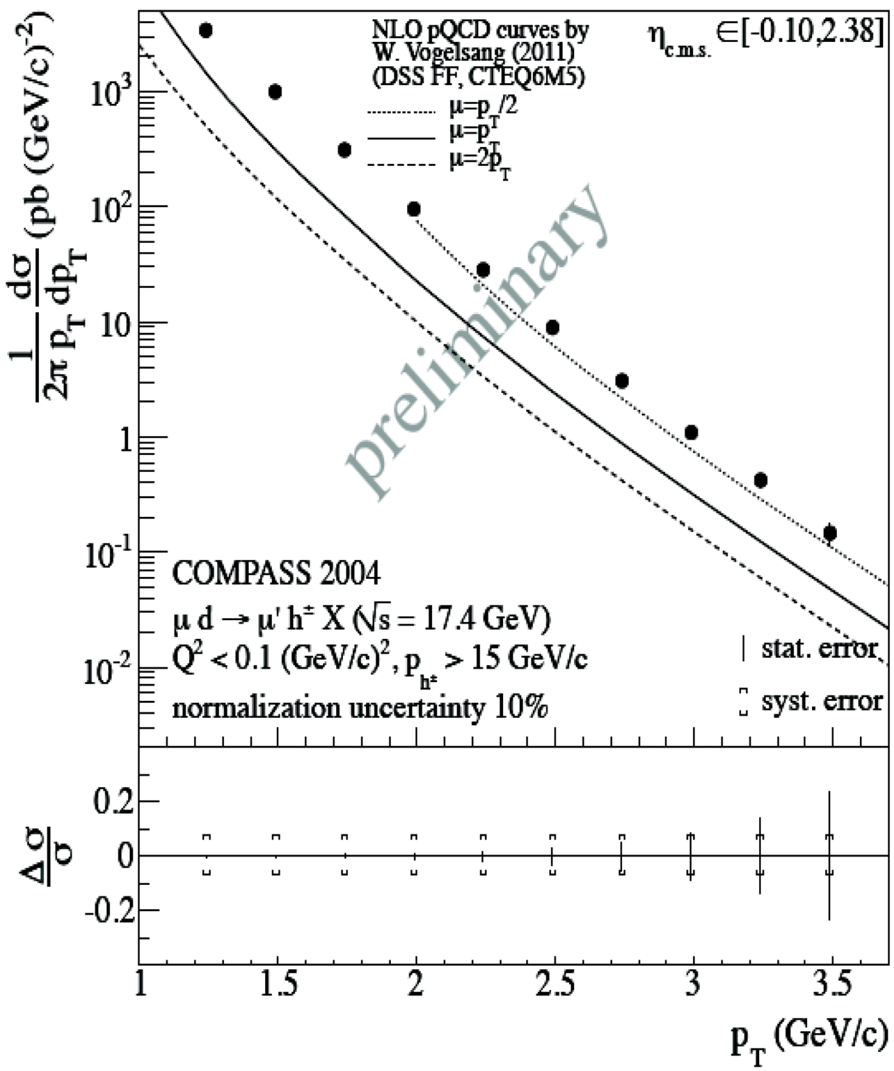
$$\gamma g \to q\bar{q}$$



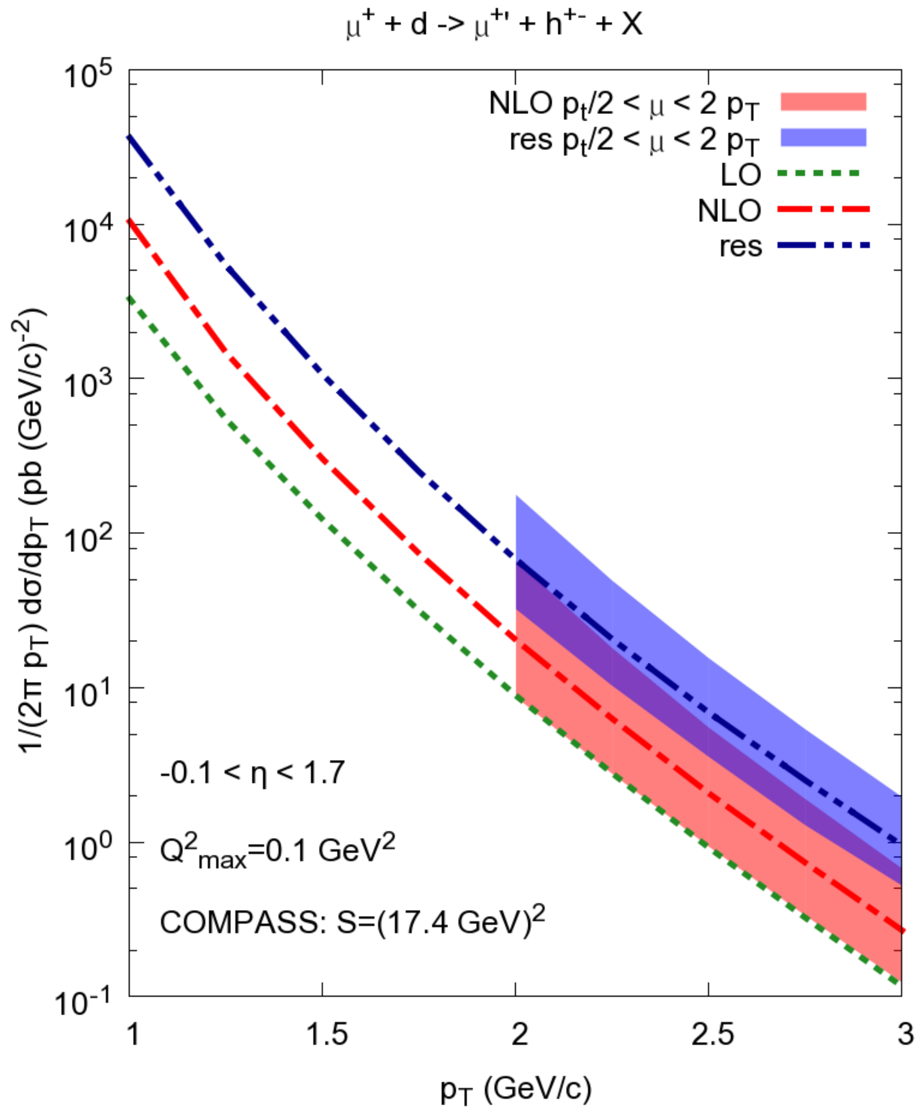
Leading logarithms:

$$\sigma_{\rm res}^{\gamma g} \sim \exp\left[\left(C_A + C_F - \frac{1}{2}C_F\right)\frac{\alpha_s}{\pi}\ln^2 N\right]$$

(NLL far more complicated, but known)



COMPASS
(C.Hoeppner,A.Morreale)



de Florian, Pfeuffer,
Schäfer, WV (prel.)

Conclusions:

- ever-improving picture of nucleon's helicity distributions
- yet, many open questions remain:
  - are gluons polarized after all ?
  - are there flavor asymmetries in pol. sea ?
  - what exactly is the role of strangeness ?
  - AND:

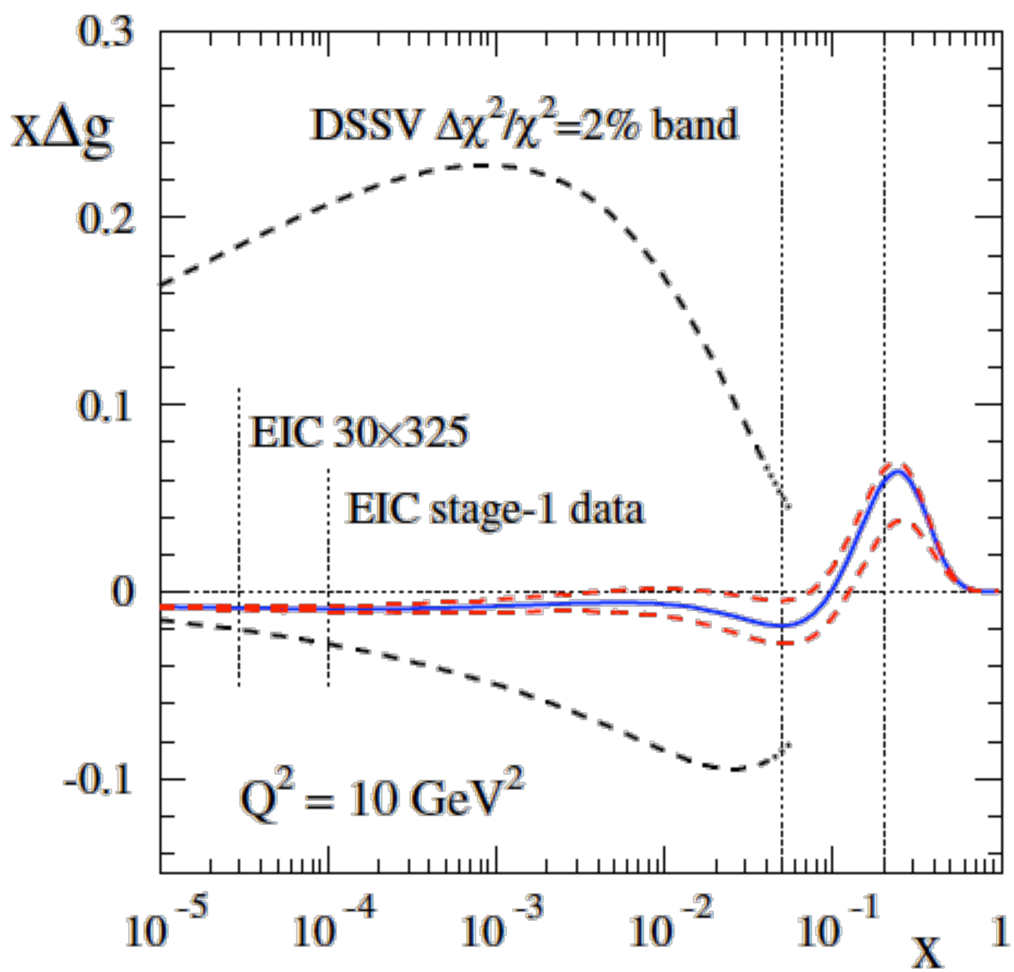
What *is* the nucleon's partonic spin budget ?

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

25-30% 20% ??

- relevance of threshold resummation toward lower energies

- the future: Electron-Ion Collider (EIC) ?



Sassot, Stratmann