Spin-dependent parton distributions of the nucleon

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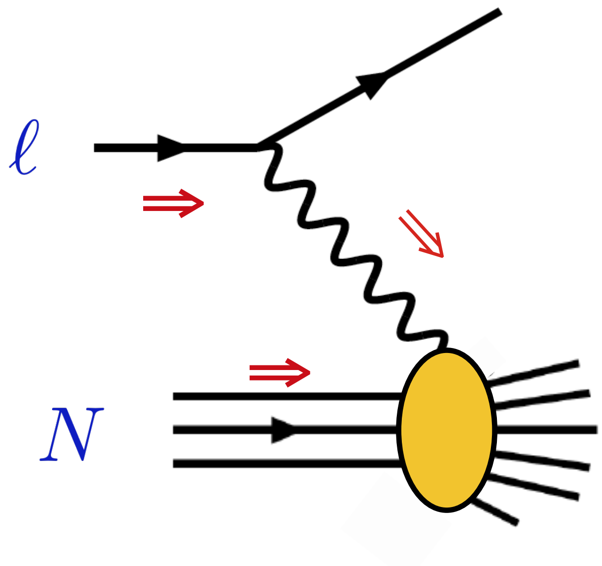
Outline:

- Introduction: Nucleon helicity structure
- Polarized high-energy collisions in QCD
- Global analysis of pol. parton distributions
- Applications of QCD resummation
- Conclusions & Outlook

Introduction:
Nucleon Helicity Structure

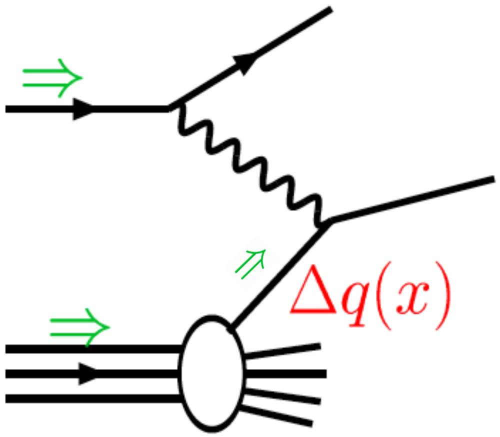
Mid '70s: "Polarized DIS"



$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \sim \frac{g_1(x, Q^2)}{F_1(x, Q^2)}$$

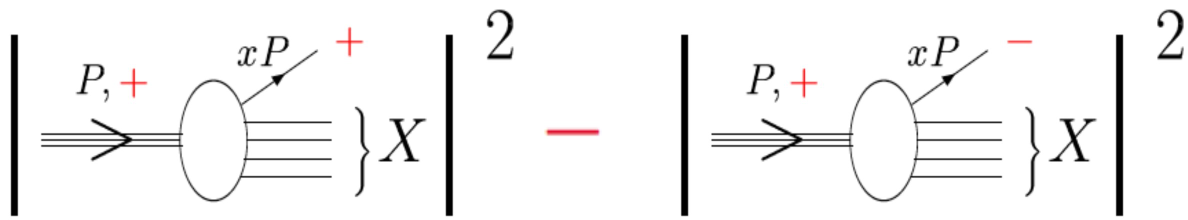
First at SLAC, later CERN, DESY, Jefferson Lab

Parton Model:



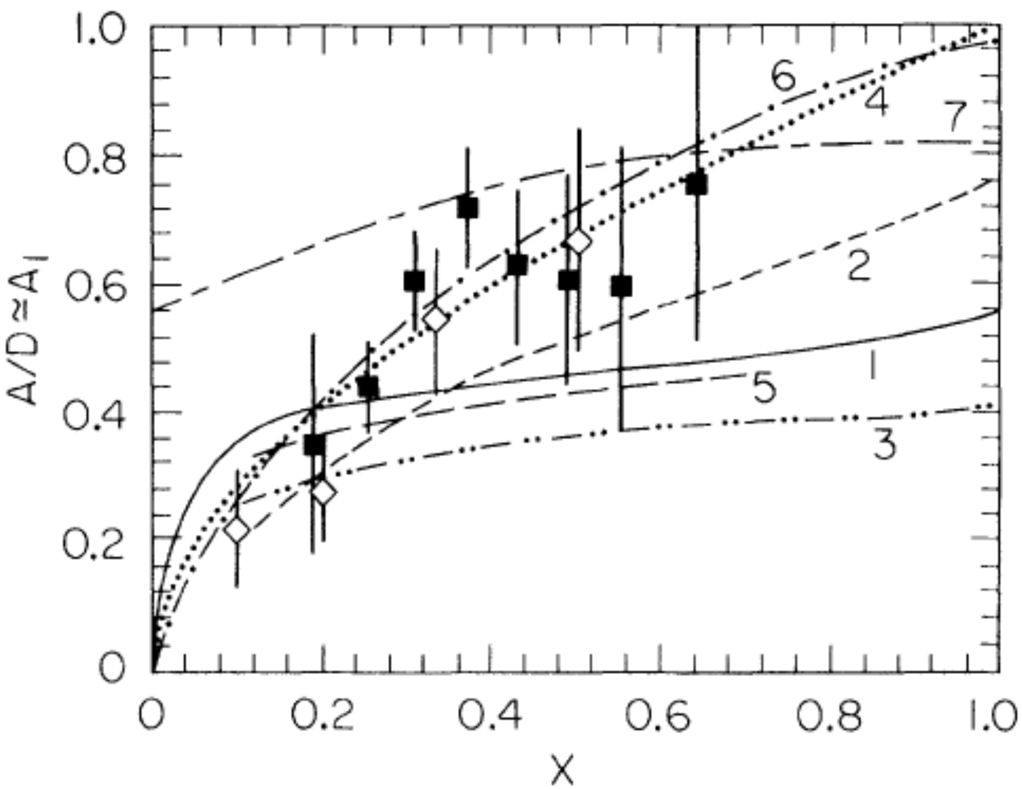
$$A_1 = \frac{\sum_q e_q^2 \, [\, \Delta q(x) \, + \, \Delta \bar{q}(x) \,]}{\sum_q e_q^2 \, [\, q(x) \, + \, \bar{q}(x) \,]}$$

$\Delta q(x) =$



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

All was well … initially…

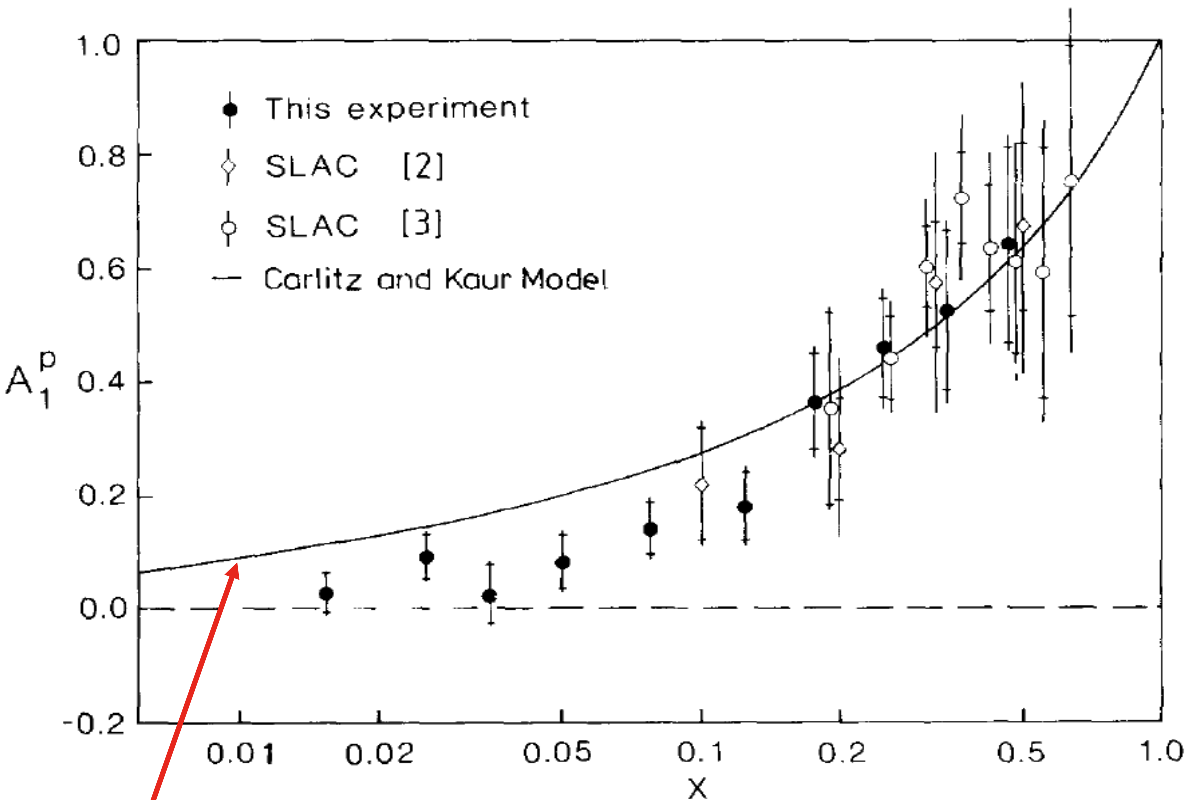


SLAC-E80, E130

(1976-83)

But then:

EMC (1987)



If quarks and anti-quarks carried ~70% of the proton spin…

$$2\int_0^1 dx\, g_1(x,Q^2) = \frac{4}{9}\Delta\Sigma_u + \frac{1}{9}\Delta\Sigma_d + \frac{1}{9}\Delta\Sigma_s$$

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

(axial charges)

use SU(3) to obtain *non-singlet* combinations from baryon decays:

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

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

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

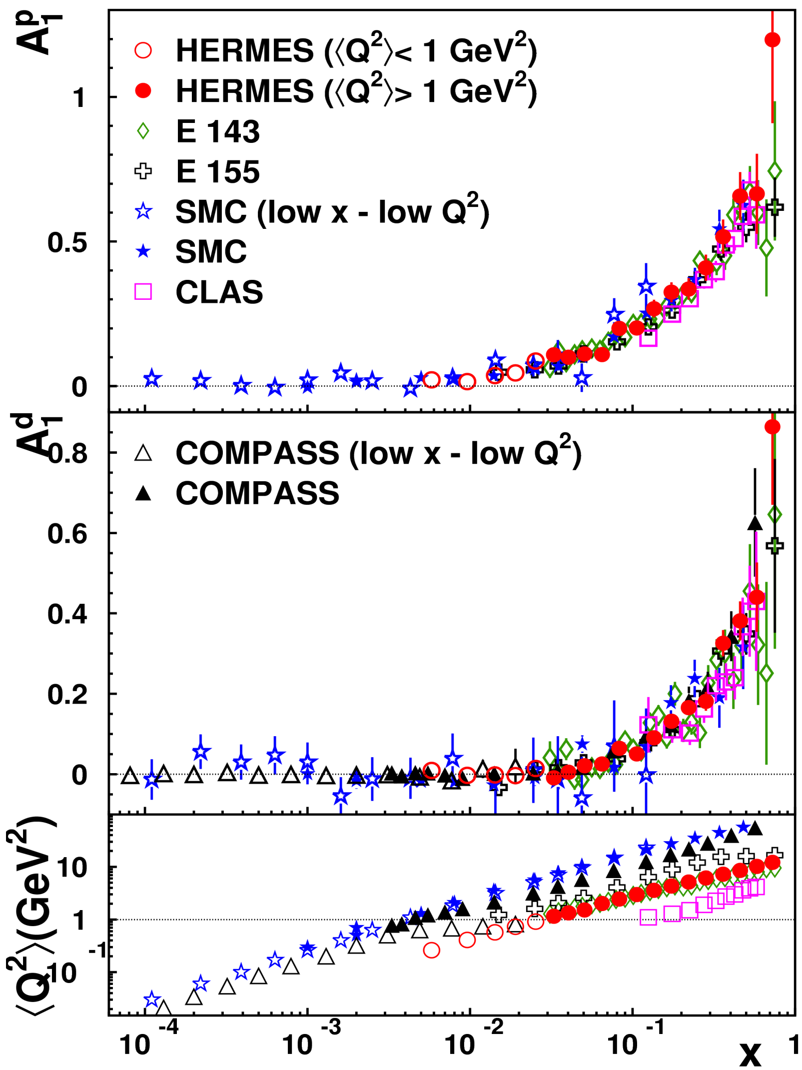
$$\Delta\Sigma = \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s = 0.12 \pm 0.17$$

EMC '89

- Note,

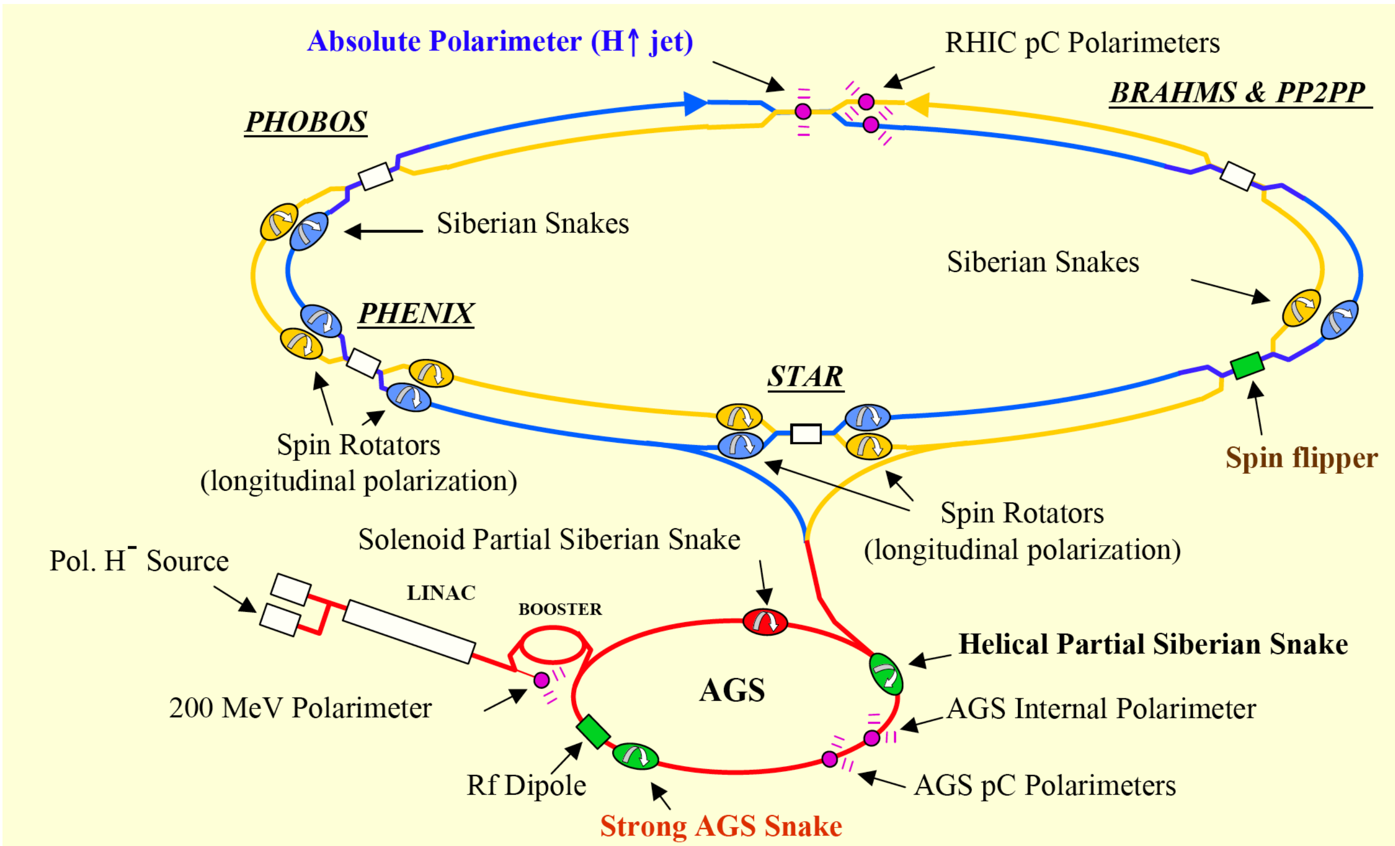
$$\Delta\Sigma = \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s = 3F - D + 3\Delta\Sigma_s$$

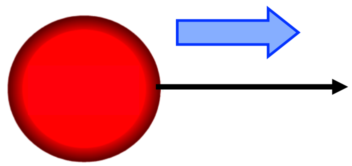
Today:



A_1^p
HERMES (⟨Q²⟩< 1 GeV²)
HERMES (⟨Q²⟩> 1 GeV²)
E 143
E 155
SMC (low x - low Q²)
SMC
CLAS
1
0.5
0
A_1^d
COMPASS (low x - low Q²)
COMPASS
0.8
0.6
0.4
0.2
0
⟨Q²⟩(GeV²)
10
1
10⁻¹
10⁻⁴
10⁻³
10⁻²
10⁻¹
x
1

Plus: polarized pp at RHIC

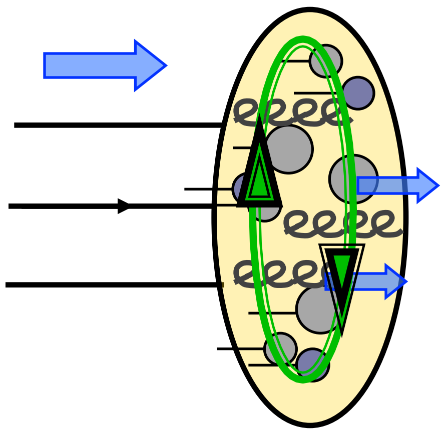




$$\frac{1}{2} = \langle P, \frac{1}{2} | \hat{J}_z | P, \frac{1}{2} \rangle$$

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

- Gives rise to proton spin sum rule:



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

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

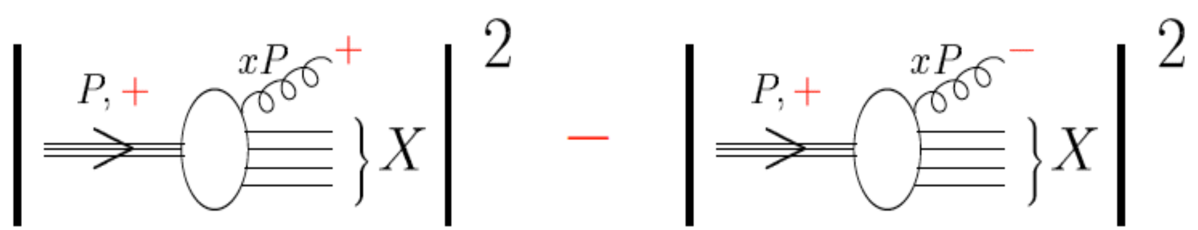
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- one can access the q and g spin contributions:

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

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

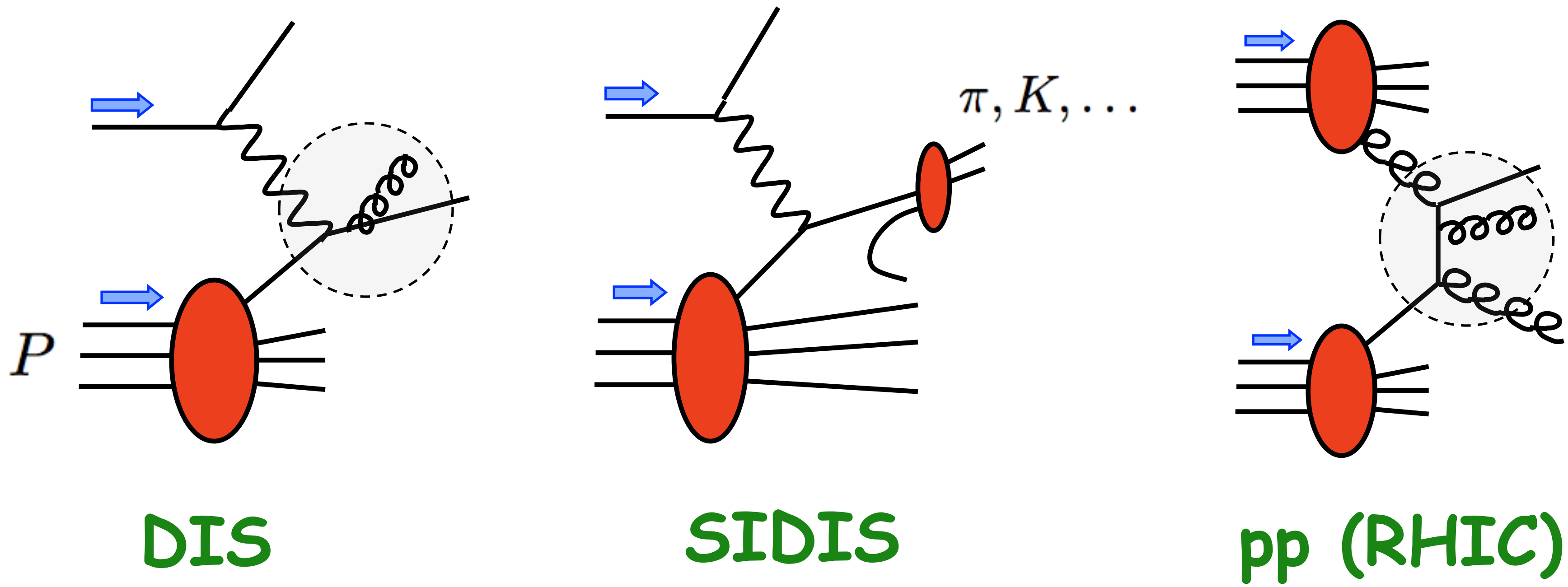
$\Delta g(x) =$



- pol. high energy scattering at large momentum transfer !

Polarized high-energy collisions in QCD

The probes of nucleon helicity structure :



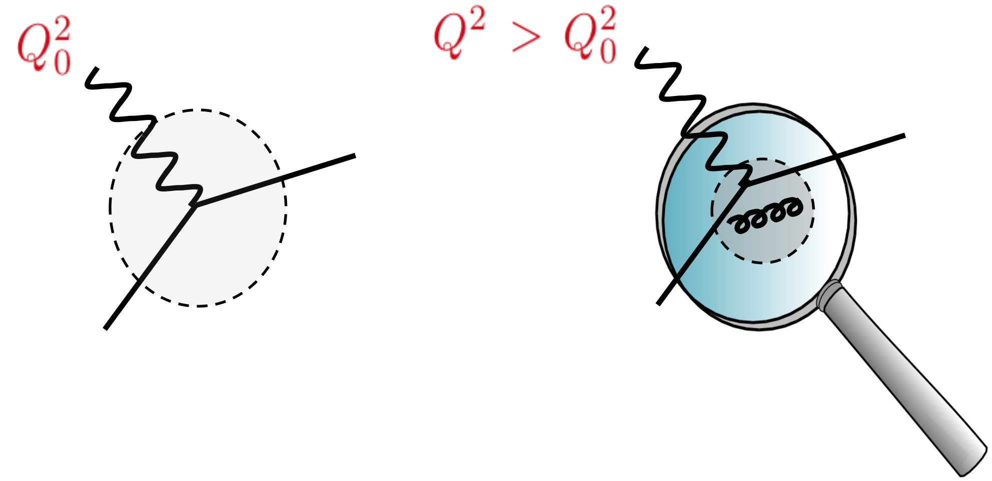
DIS $$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \Delta f(x,Q^2)\, \Delta\hat{\sigma}^f(xP, \alpha_s(Q^2)) + \ldots$$

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

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

A lot of theory work:

- **DGLAP evolution:**



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

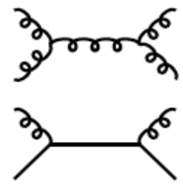
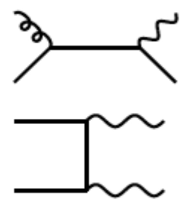
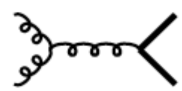
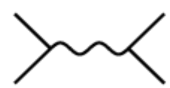
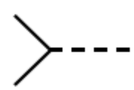
$$\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi} \Delta\mathcal{P}_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta\mathcal{P}_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta\mathcal{P}_{ij}^{\mathrm{NNLO}} + \ldots$$

Ahmed, Ross
Altarelli, Parisi, …

Mertig, van Neerven
WV

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

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	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\bar{\vec{q}} \to \gamma\gamma$	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	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\bar{\vec{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\bar{\vec{q}} \to Z^0,\ \vec{q}'\bar{\vec{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm,\ q'\bar{\vec{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

NLO:

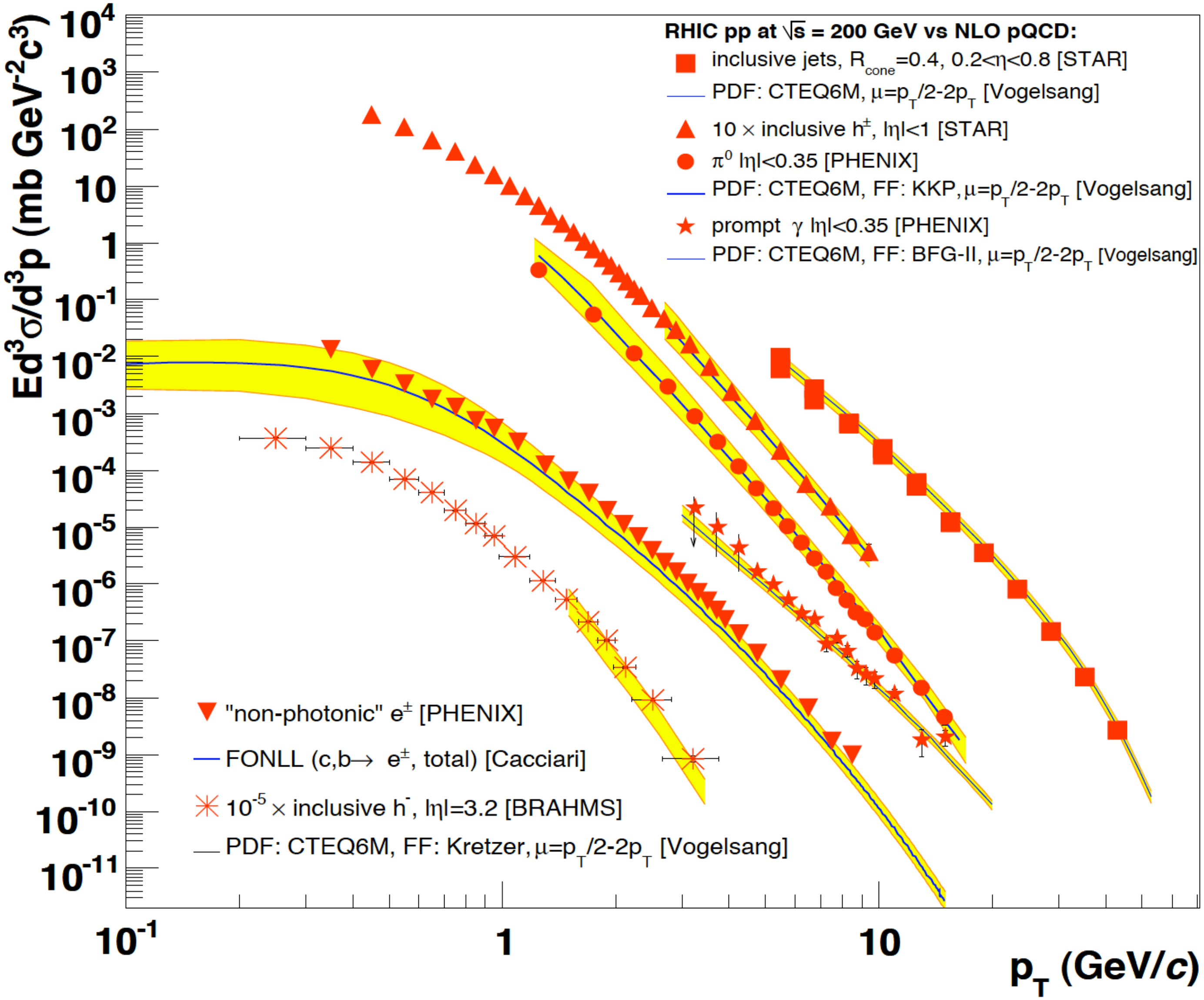
Jäger, Schäfer, Stratmann, WV

Jäger,Stratmann, WV; Signer et al.

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

Stratmann, Bojak

Weber; Gehrmann; Kamal; Smith, van Neerven, Ravindran; Nadolsky, Yuan; de Florian, WV



RHIC pp at √s = 200 GeV vs NLO pQCD:
inclusive jets, R_cone=0.4, 0.2<η<0.8 [STAR]
PDF: CTEQ6M, μ=p_T/2-2p_T [Vogelsang]
10 × inclusive h±, |η|<1 [STAR]
π0 |η|<0.35 [PHENIX]
PDF: CTEQ6M, FF: KKP, μ=p_T/2-2p_T [Vogelsang]
prompt γ |η|<0.35 [PHENIX]
PDF: CTEQ6M, FF: BFG-II, μ=p_T/2-2p_T [Vogelsang]
"non-photonic" e± [PHENIX]
FONLL (c,b→ e±, total) [Cacciari]
10^-5 × inclusive h-, |η|=3.2 [BRAHMS]
PDF: CTEQ6M, FF: Kretzer, μ=p_T/2-2p_T [Vogelsang]
Ed³σ/d³p (mb GeV^-2c^3)
p_T (GeV/c)

Global analysis of polarized parton distributions: technique

Long history of NLO QCD analyses of helicity parton distributions in DIS:

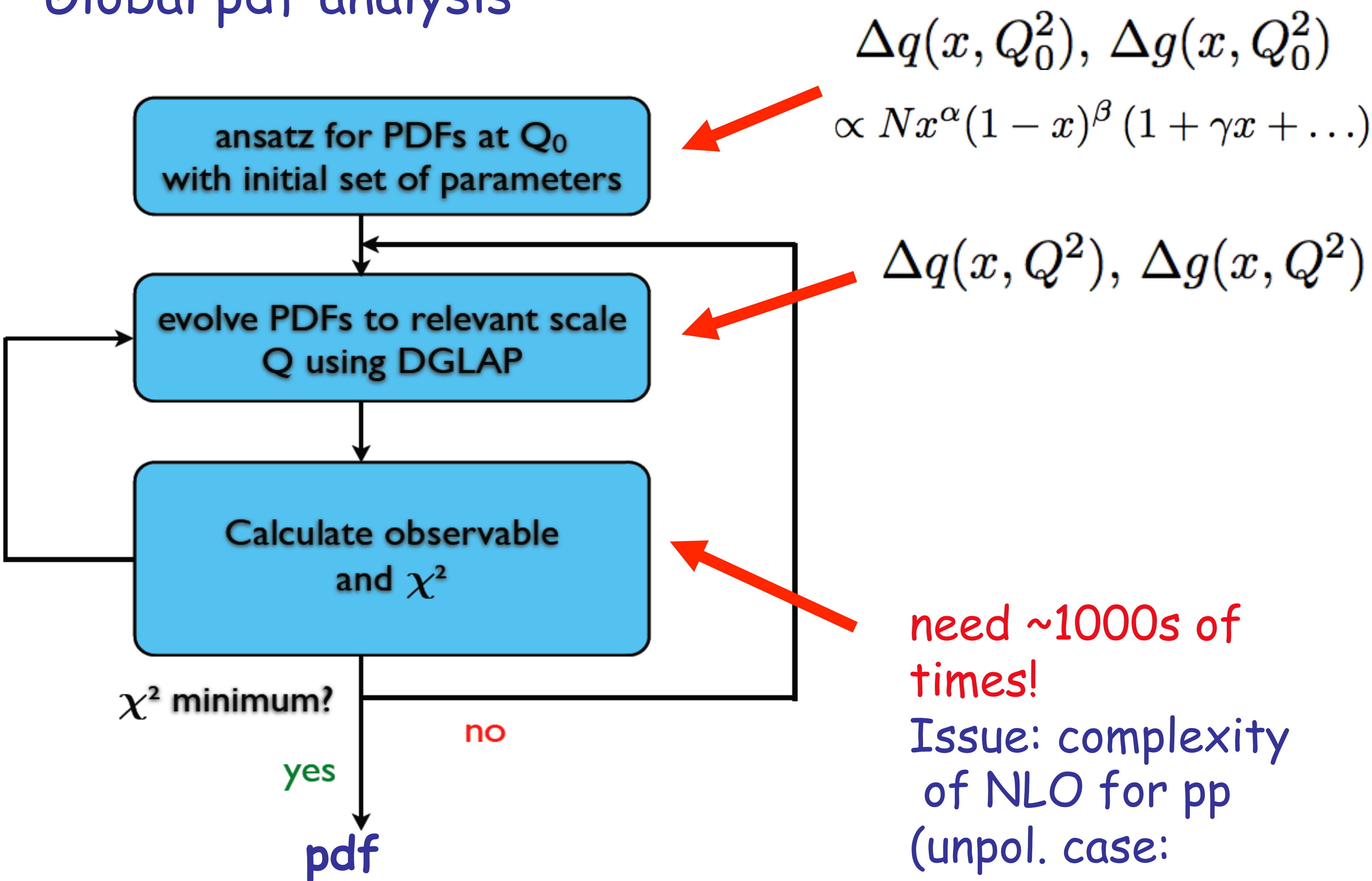
GRSV	Glück, Reya, Stratmann, WV
GS	Gehrmann, Stirling
ABFR	Altarelli, Ball, Forte, Ridolfi
BB	Blümlein, Böttcher
BBS	Bourrely, Buccella, Soffer
LSS	Leader, Sidorov, Stamenov
AAC	Hirai, Kumano, Saito
DNS	de Florian,Navarro,Sassot

...

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

DSSV de Florian, Sassot, Stratmann, WV

"Global pdf analysis"



Issue: complexity of NLO for pp (unpol. case: K factor method)

Typical example $pp \to \pi X$:

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

One evaluation @ NLO: ~ O(10 sec.)

Assume ~10 data points and 5,000 calls during fit:

→ Time = $O(10^6$ sec.)

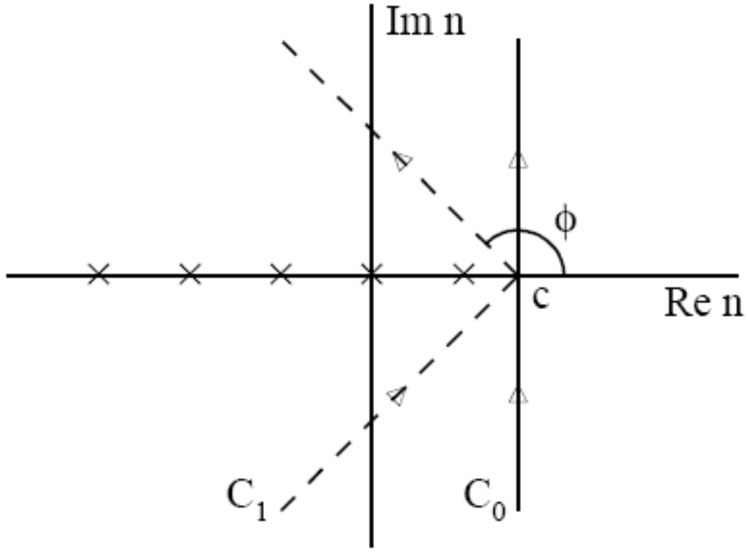
(typically need 100s of fits)

Mellin moments of a function f(x) :

$$f^n \equiv \int_0^1 dx\, x^{n-1}\, f(x)$$

Inverse transformation :

$$f(x) = \frac{1}{2\pi i} \int_C dn\, x^{-n}\, f^n$$



Mellin method for pp scattering : example pp→πX

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

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

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

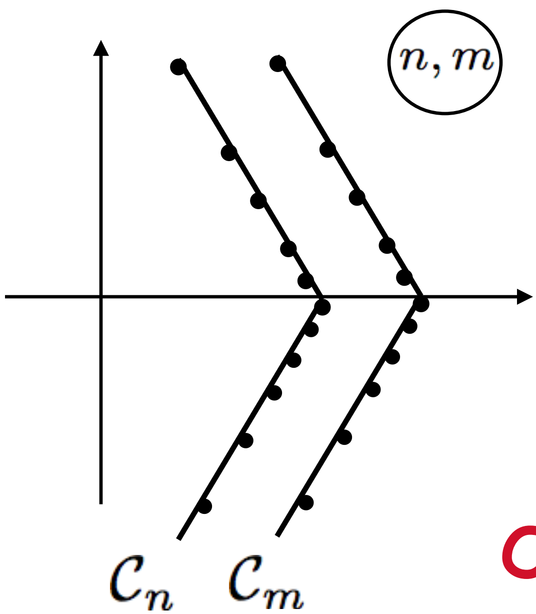
$$= \frac{1}{(2\pi i)^2} \sum_{abc} \int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm \;\; \Delta f_a^n \, \Delta f_b^m \;\; \int dx_a \int dx_b \int dz_c \, x_a^{-n} \, x_b^{-m} \, \Delta\hat{\sigma}_{ab\to cX} \, D_c(z_c)$$

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

Standard Mellin inverses

Contains all dependence on fit parameters

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



Discretize for (Gaussian) integration: 64 × 64 positions

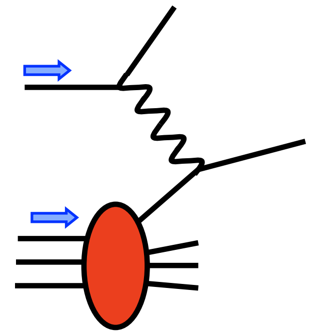
Evaluate "matrix"

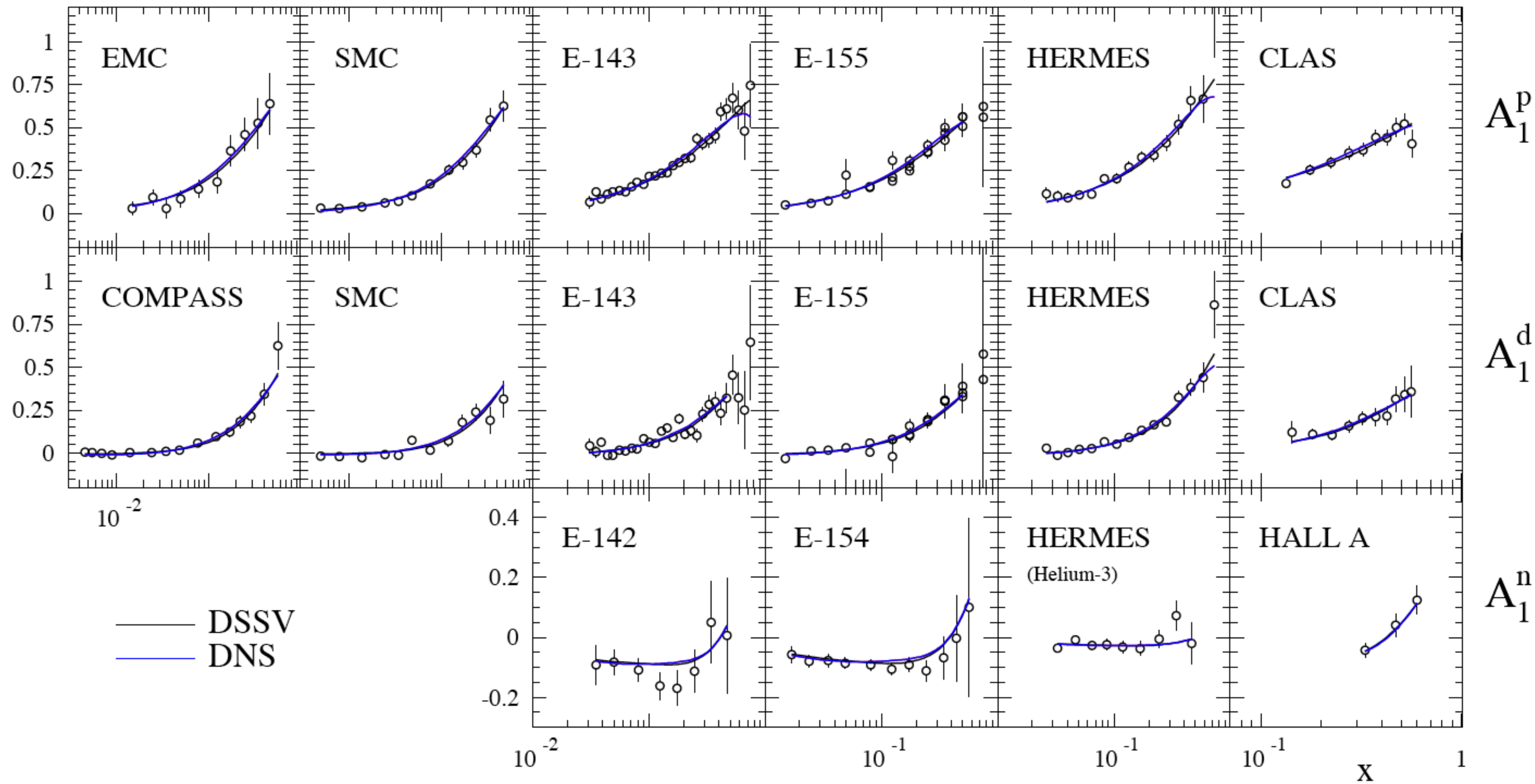
$$\left(\Delta\tilde{\sigma}_{ab\to cX}\right)_{n_i m_j}$$

O(10 sec.) /point → O(1 msec.)/point

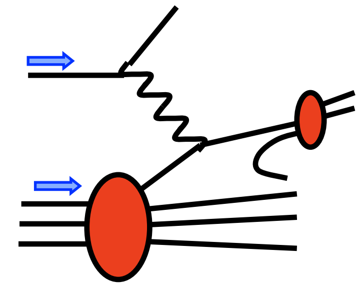
Global analysis: results

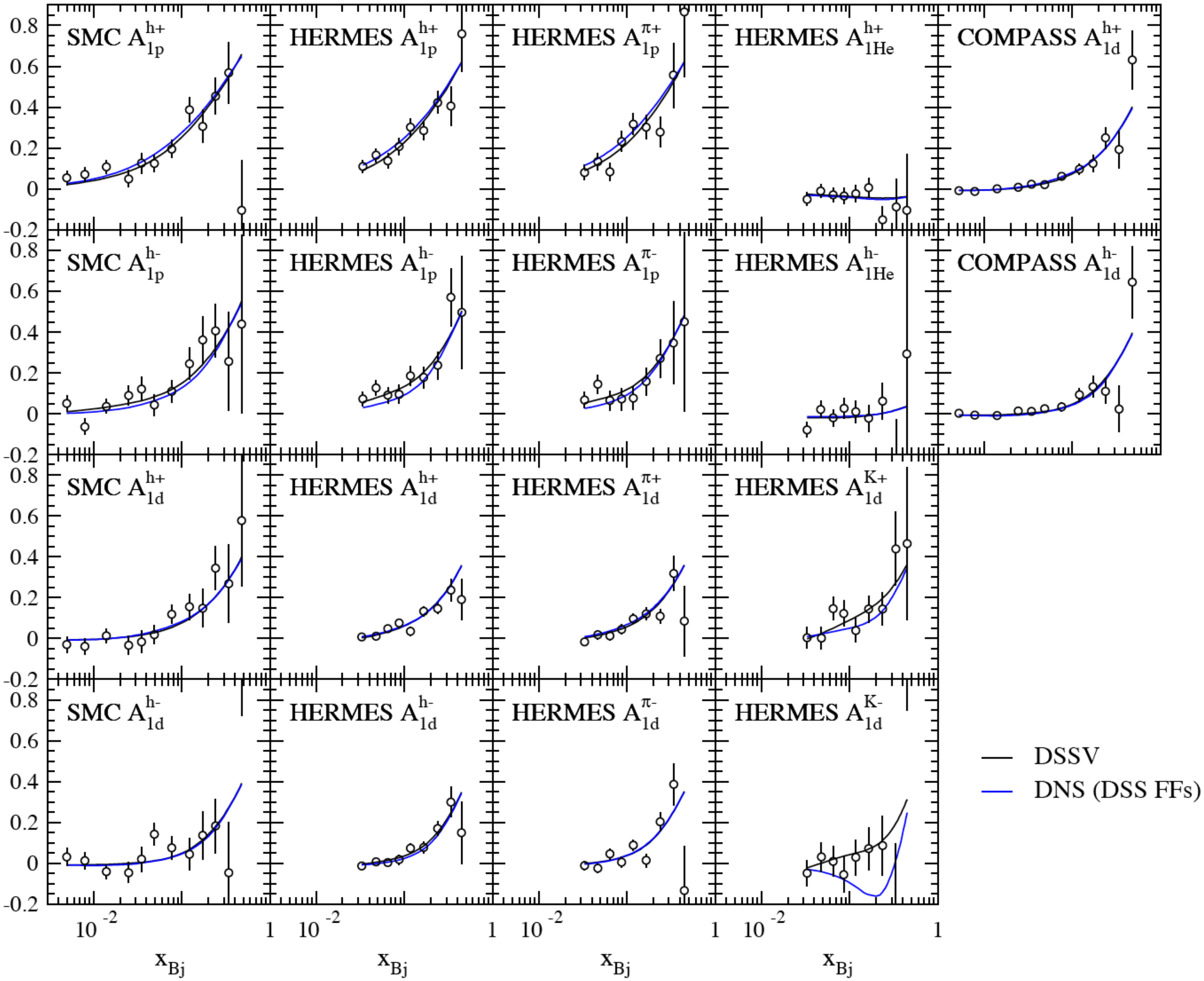
Spin asymmetries in inclusive DIS:





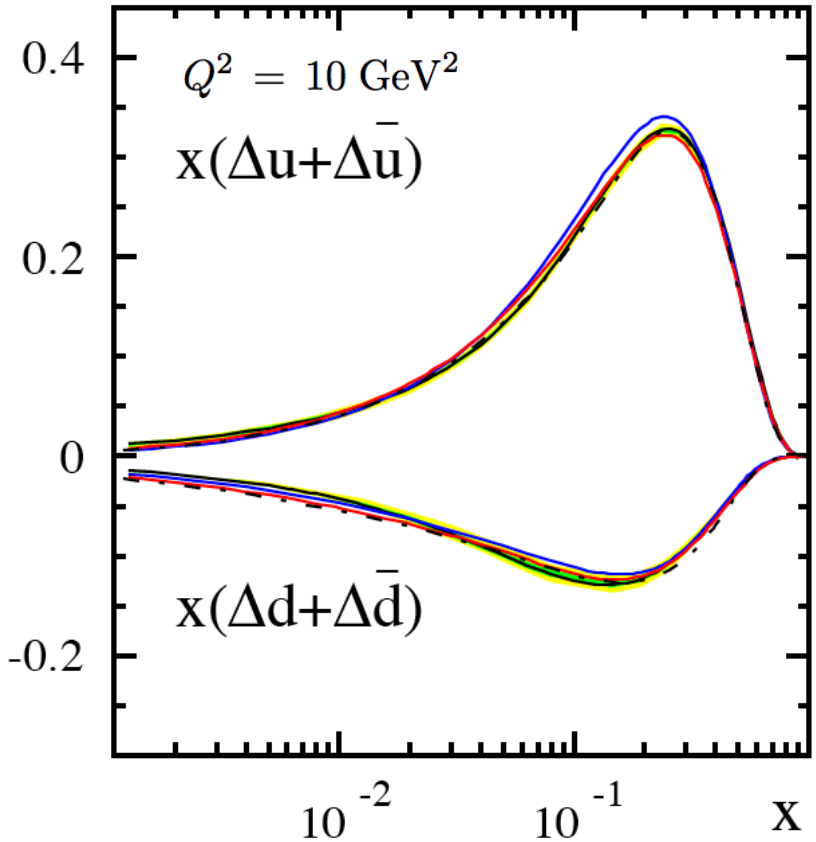
Spin asymmetries in semi-inclusive DIS:





What's the emerging picture ?

- best determined: $\Delta u + \Delta \bar{u}$, $\Delta d + \Delta \bar{d}$



Comparison with:
DNS de Florian,Navarro,Sassot
GRSV Glück, Reya, Stratmann, WV

Similar results:
Leader, Stamenov, Sidorov
Blümlein, Böttcher; & HERMES
Hirai, Kumano, Saito (AAC)
COMPASS

- first moments agree with lattice:

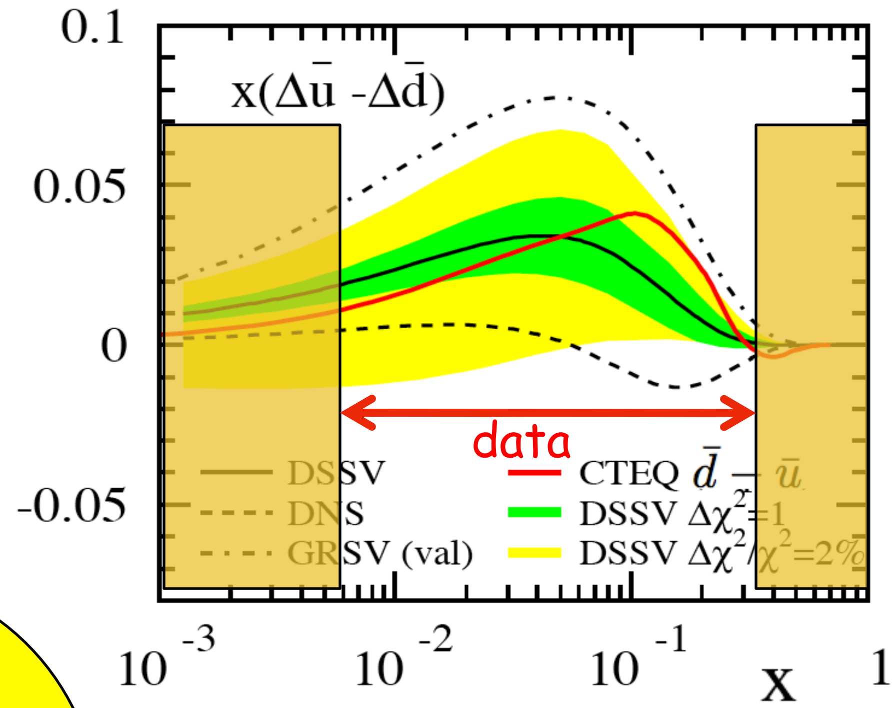
  gives confidence in small-x extrapolations (?)

- light flavor sea :

driven by SIDIS

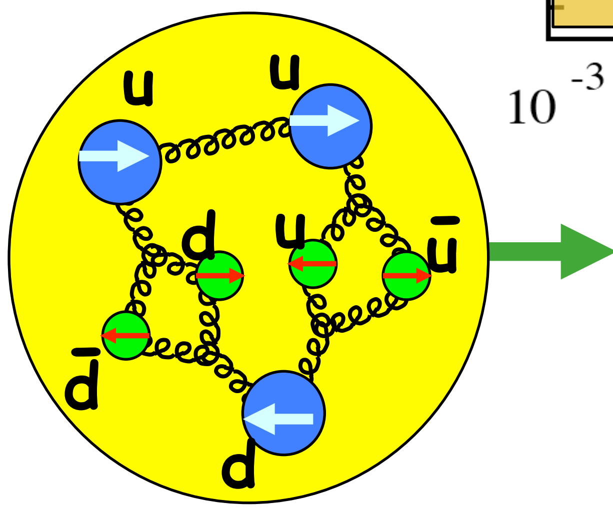
$$\Delta\bar{u} > 0$$

$$\Delta\bar{d} < 0$$



- qualitatively:

Glück,Reya;...

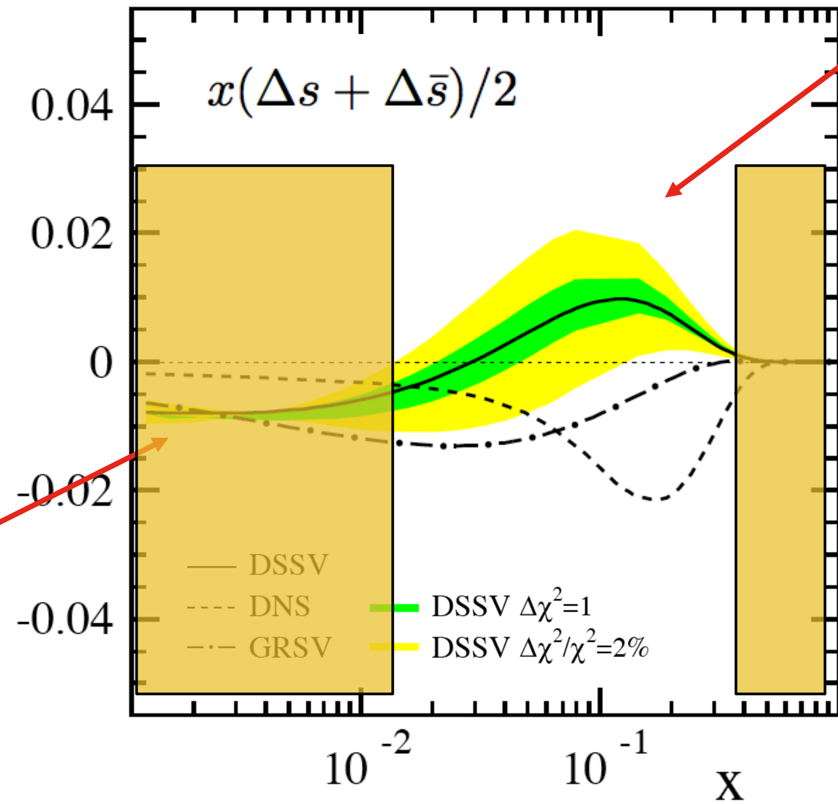


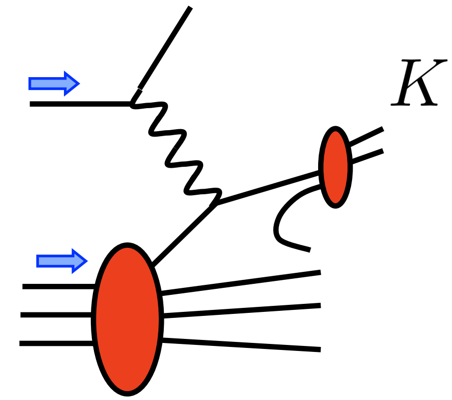
- large-N_c, chiral quark models, meson cloud

Thomas,Signal,Cao; Holtmann,Speth,Fässler; Diakonov,Polyakov,Weiss; Schäfer,Fries; Kumano; Wakamatsu; Bourrely, Soffer ...

- strangeness :

kaon SIDIS





driven by
SU(3) (3F-D)

$$\int_{0.001}^{1} dx\, \Delta s(x) \;=\; -0.006 \pm 0.01 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx\, \Delta s(x) \;=\; -0.057 \pm ?$$

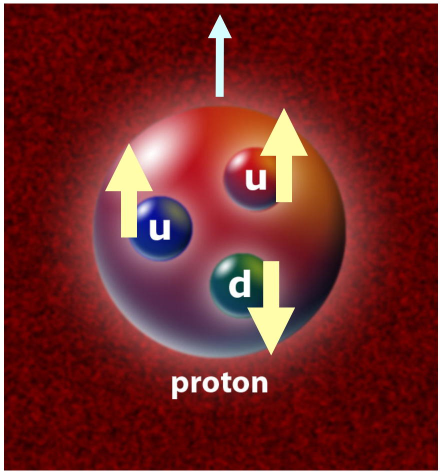
using F,D and SU(3)

- total quark and anti-quark spin contribution :

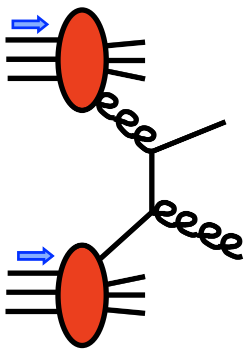
$$\int_{0.001}^{1} dx \Delta\Sigma = 0.366 \pm 0.016 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx \Delta\Sigma = 0.242 \pm ?$$

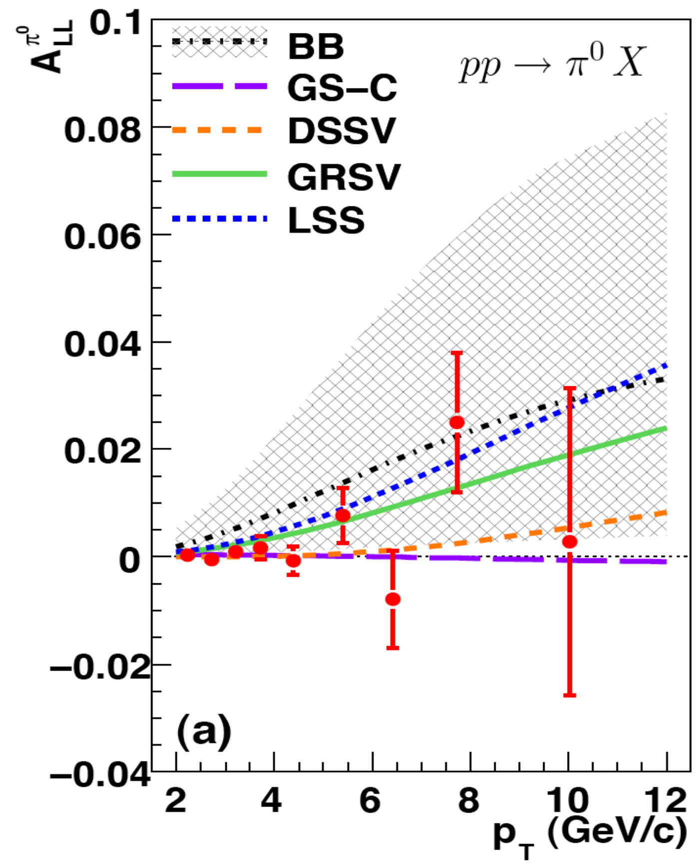
- in any case, $\Delta\Sigma \ll 1$



- polarized glue ?



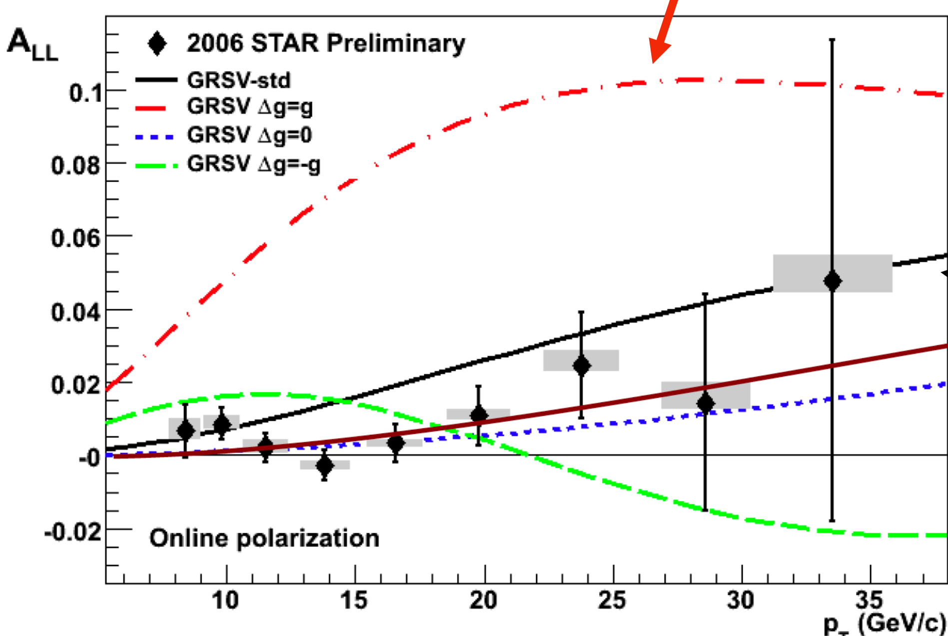
PHENIX



(Altarelli et al.)

$\Delta G \approx 1.8$

$pp \to \text{jet}\, X$

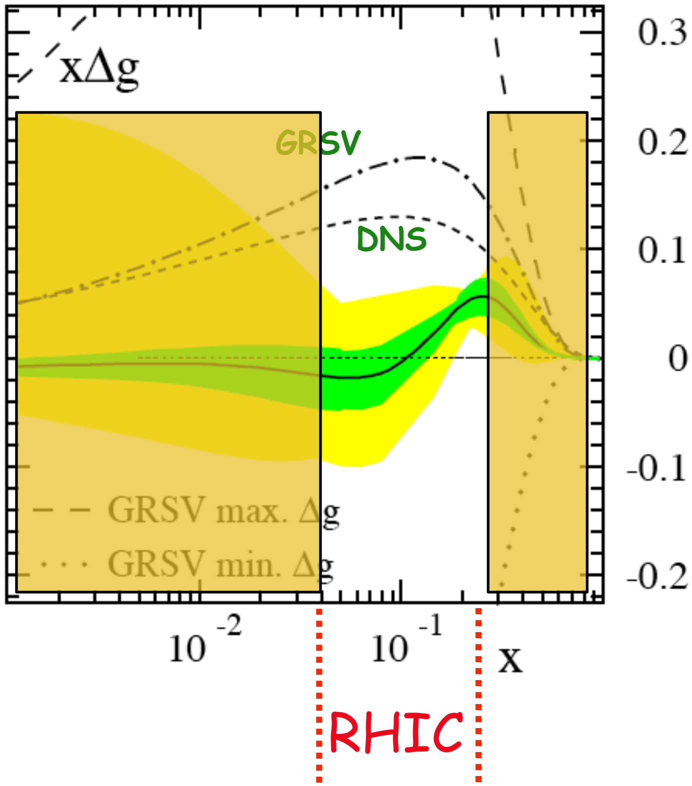


$\Delta G \approx 0.4 \quad (Q^2 = 1\,\text{GeV}^2)$

DSSV

$\Delta G = 0$

STAR

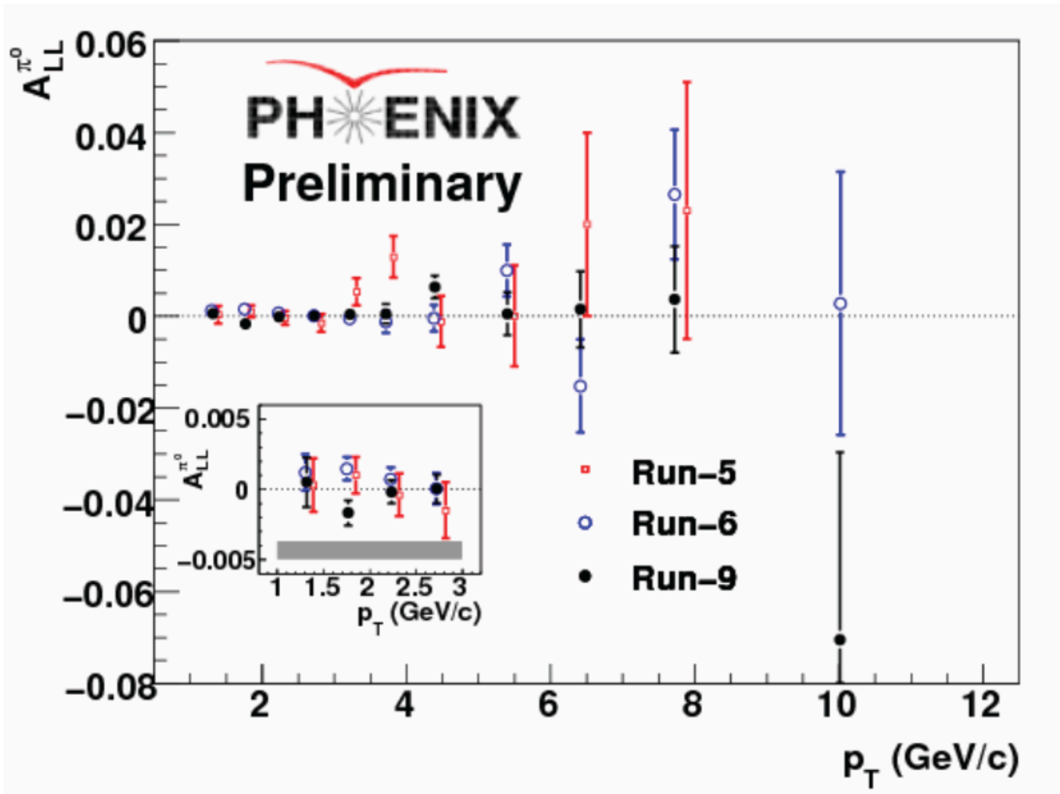


$$\int_{0.05}^{0.2} dx\, \Delta g \;=\; 0.006 \pm 0.06 \qquad (\Delta\chi^2 = 1)$$

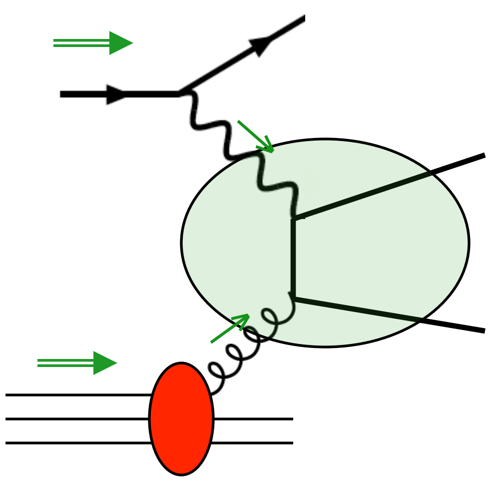
$$\int_0^1 dx\, \Delta g \;=\; -0.084 \pm ? \qquad \frac{1}{2}\Delta\Sigma + \Delta G \approx 0 \qquad ?$$

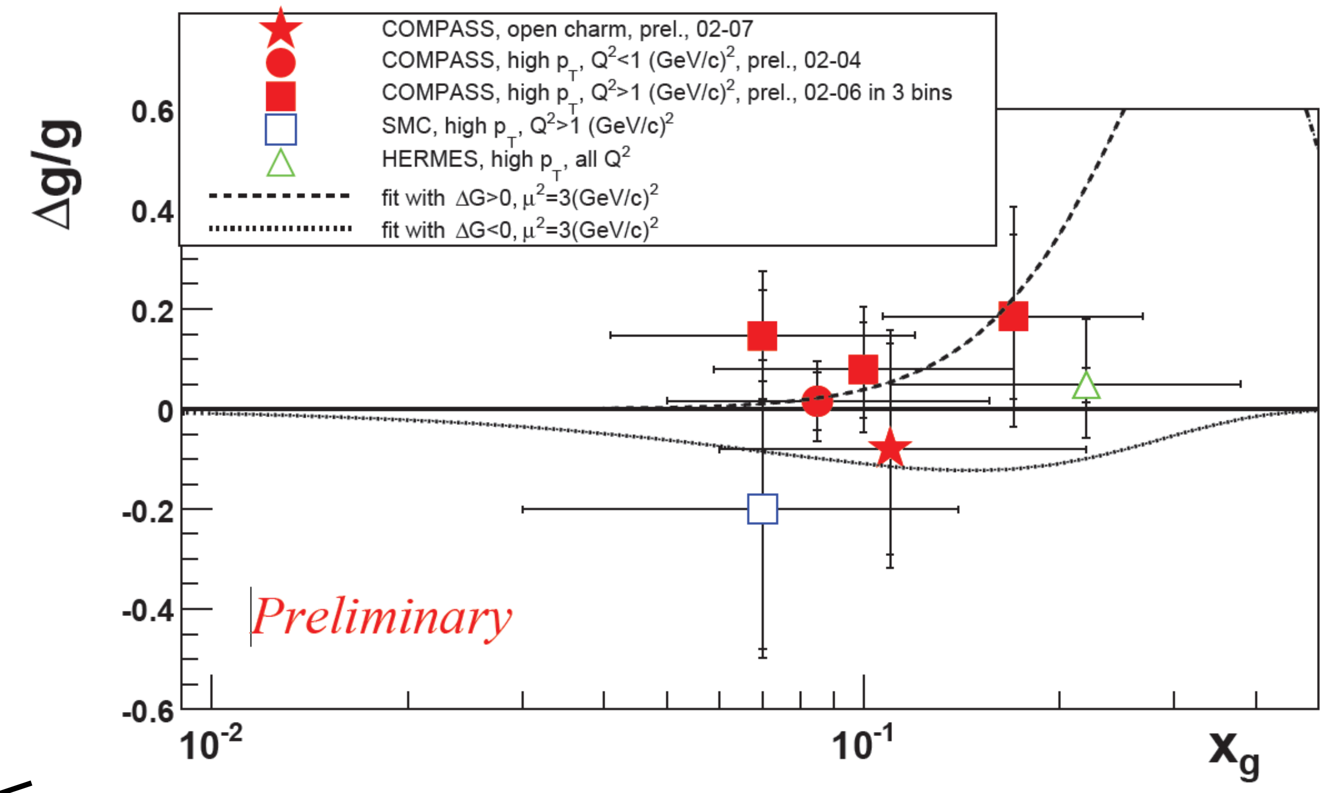
- there could still be significant contribution to proton spin
- constraints become better with new data

Most recent data:

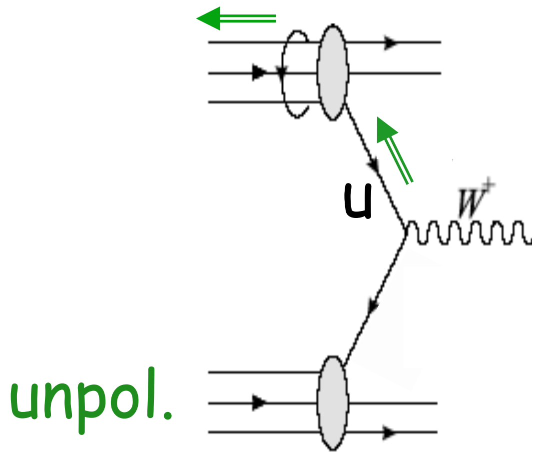


Recent COMPASS data:





- **W production in pp:**



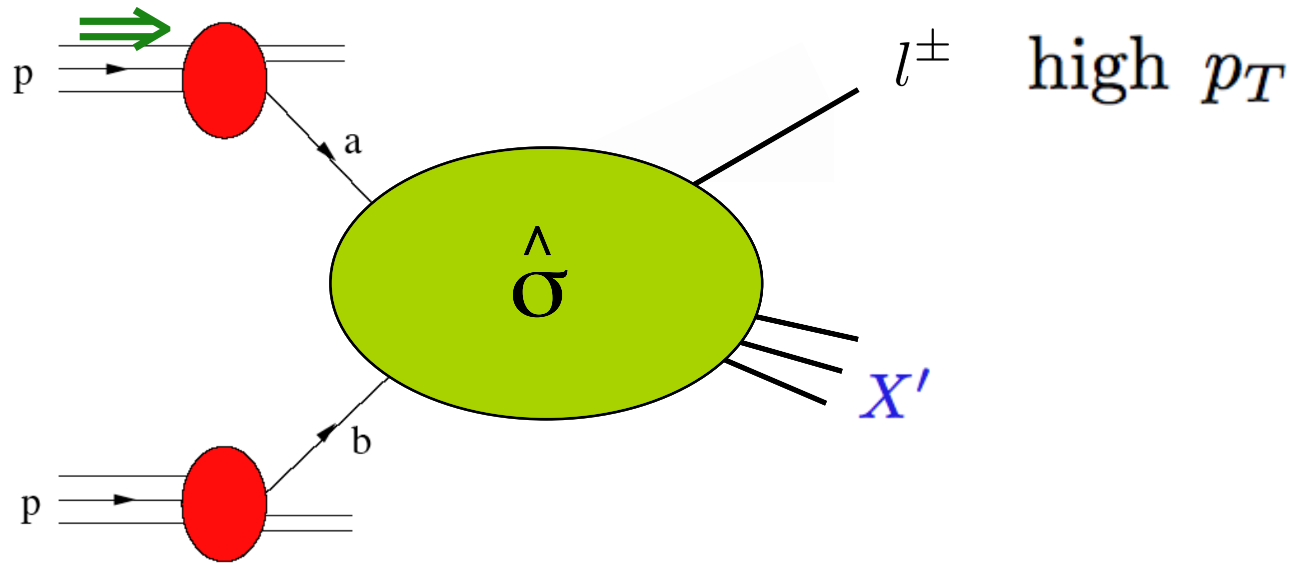
Parity violation:

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

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)} \qquad x_{1,2} = \frac{M_W}{\sqrt{S}}\,\mathrm{e}^{\pm y_W}$$

- **large scale $Q \sim M_W$: pQCD**

In practice:



$$d\sigma^+ - d\sigma^- = \sum_{a,b} \int dx_a dx_b \, \Delta f_a(x_a,\mu) \, f_b(x_b,\mu) \, \left[d\hat{\sigma}^+ - d\hat{\sigma}^-\right]_{ab\to W\to l} + \text{power corr.}$$

smear out
x_a, x_b

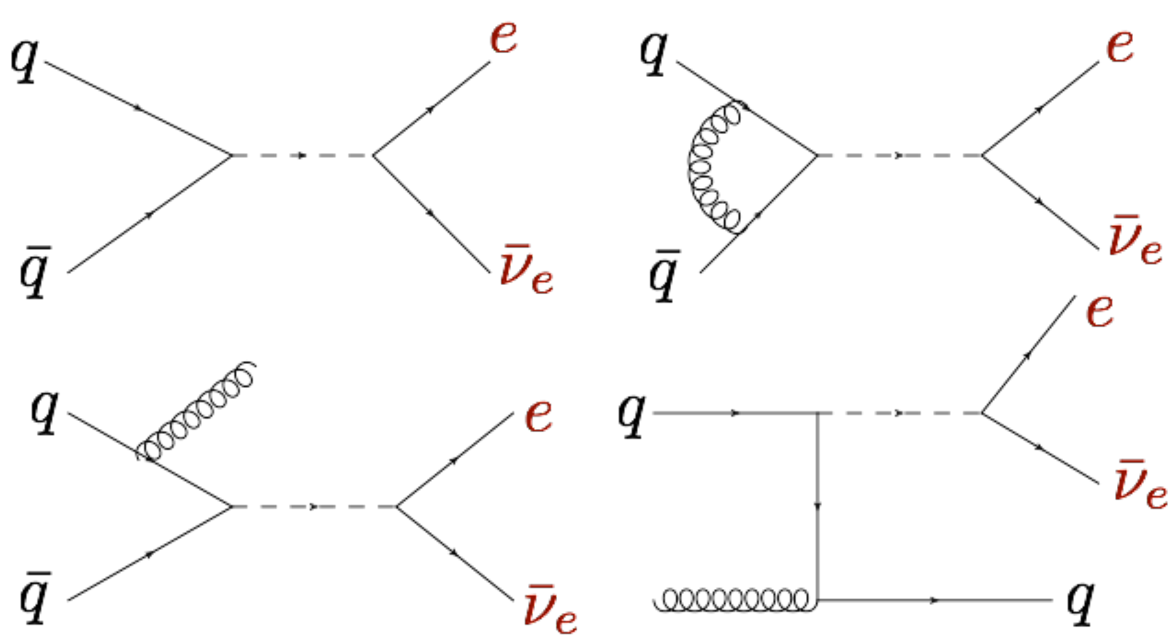
perturbative QCD

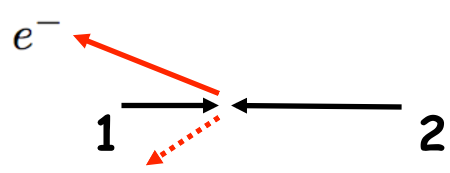
$$\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_s \, \hat{\sigma}^{(1)} + \ldots$$

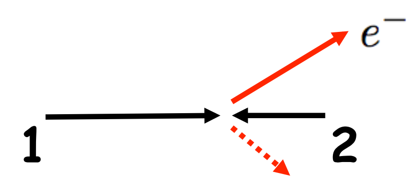
- **new NLO for polarized case:** de Florian, WV channels at NLO

$$
\begin{aligned}
\Delta\bar{q}\; q &\longrightarrow e\,\bar{\nu}_e \\
\Delta q\; \bar{q} &\longrightarrow e\,\bar{\nu}_e \\
\Delta\bar{q}\; g &\longrightarrow e\,\bar{\nu}_e\,\bar{q} \\
\Delta g\; \bar{q} &\longrightarrow e\,\bar{\nu}_e\,\bar{q} \\
\Delta q\; g &\longrightarrow e\,\bar{\nu}_e\,g \\
\Delta g\; q &\longrightarrow e\,\bar{\nu}_e\,g
\end{aligned}
$$

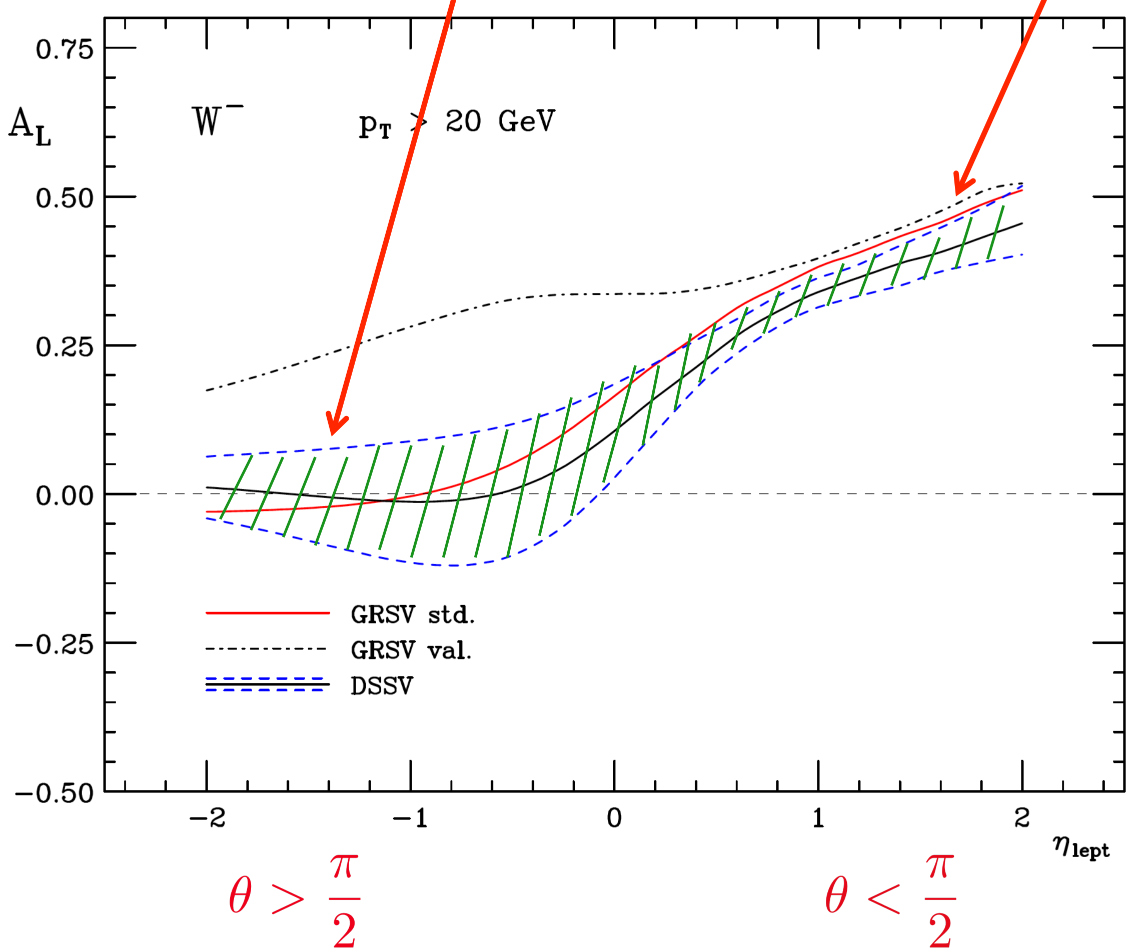
Some diagrams

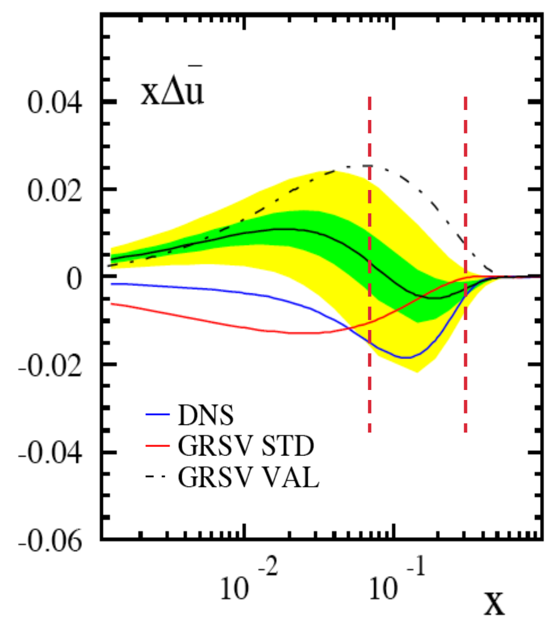


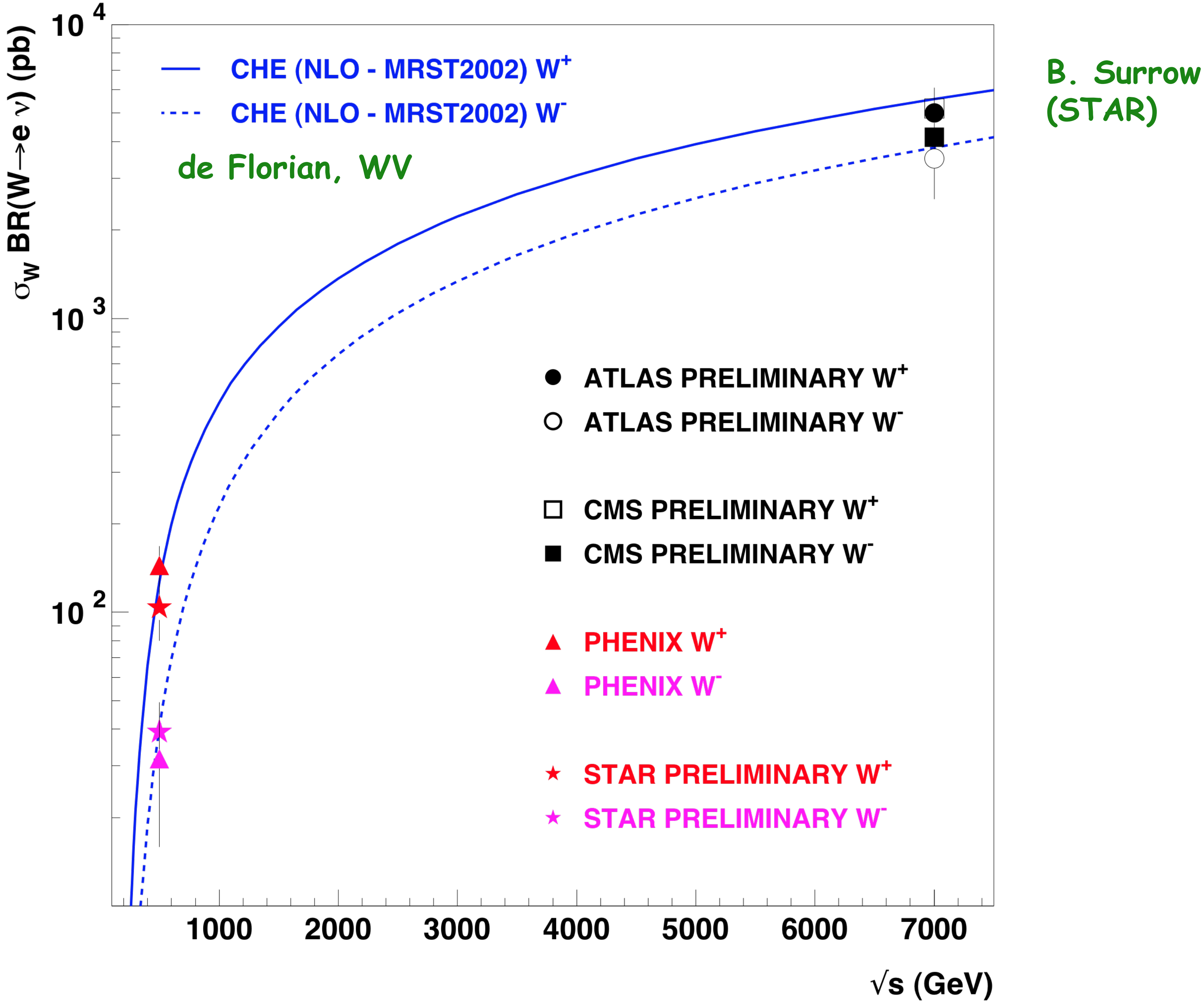




$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1) d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1) d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$

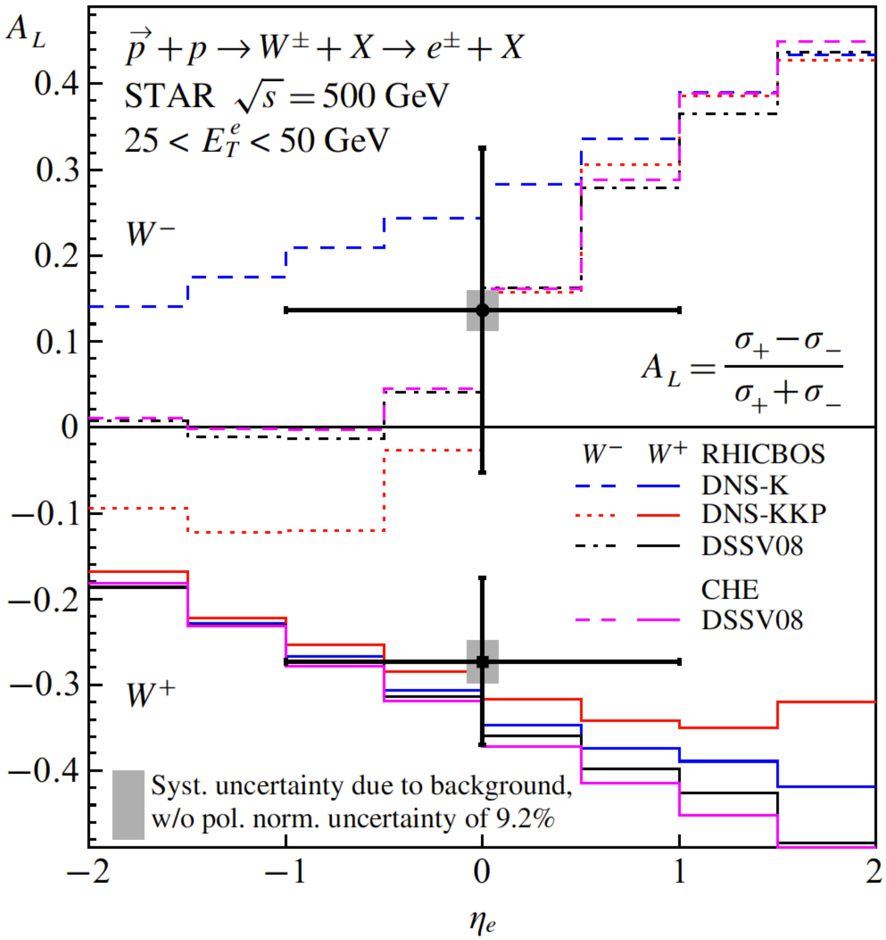




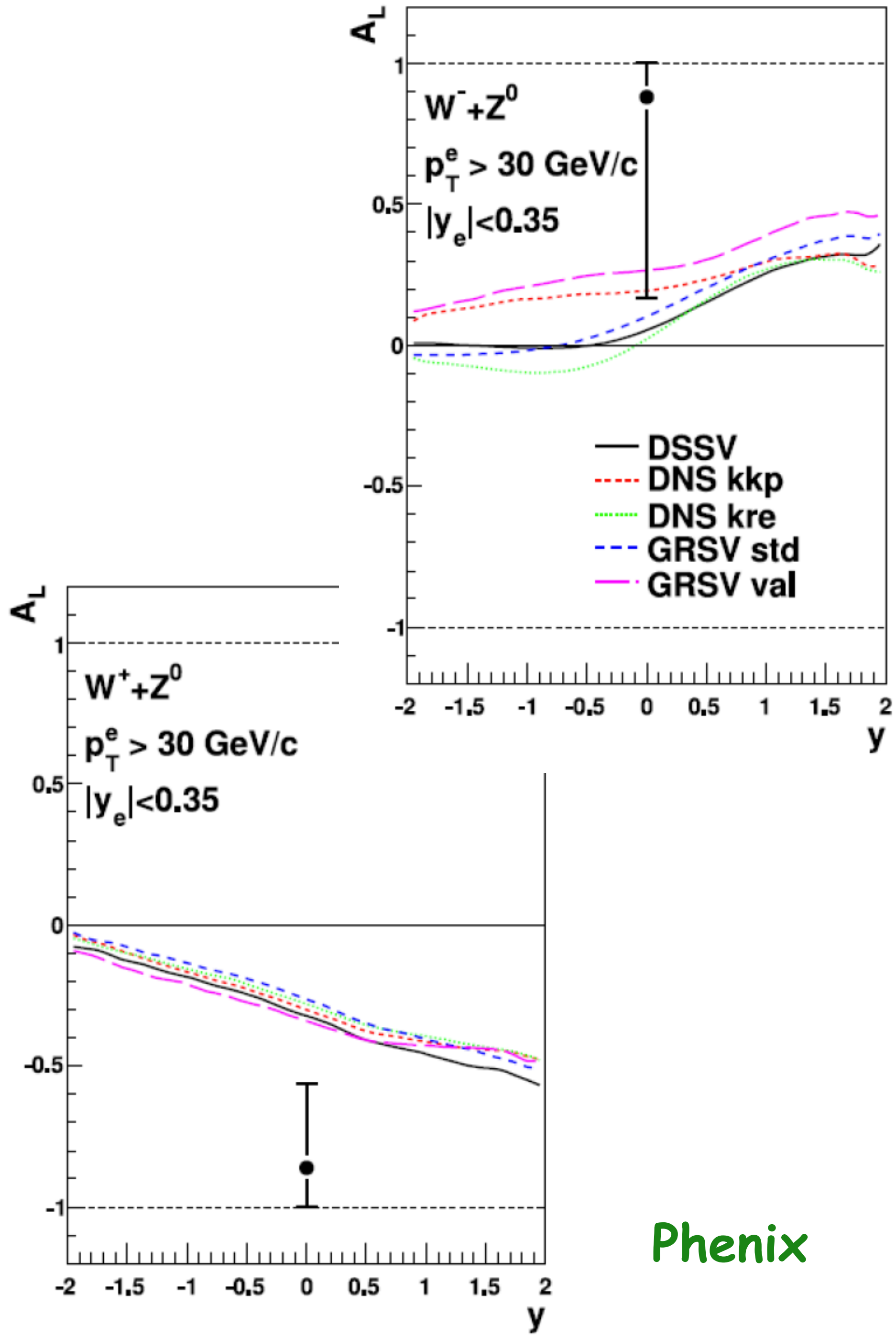


σ_W BR(W→e ν) (pb)
10^4
10^3
10^2
CHE (NLO - MRST2002) W^+
CHE (NLO - MRST2002) W^-
de Florian, WV
B. Surrow (STAR)
ATLAS PRELIMINARY W^+
ATLAS PRELIMINARY W^-
CMS PRELIMINARY W^+
CMS PRELIMINARY W^-
PHENIX W^+
PHENIX W^-
STAR PRELIMINARY W^+
STAR PRELIMINARY W^-
1000
2000
3000
4000
5000
6000
7000
√s (GeV)

STAR



A_L
$\vec{p}+p \to W^{\pm}+X \to e^{\pm}+X$
STAR $\sqrt{s}=500$ GeV
$25 < E_T^e < 50$ GeV
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%
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−2
−1
0
1
2
η_e

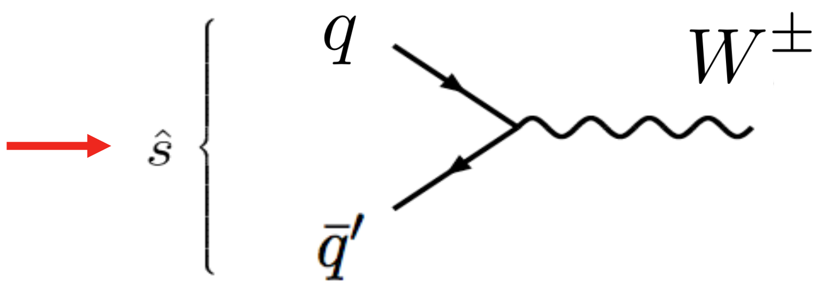


A_L
W^-+Z^0
$p_T^e > 30$ GeV/c
$|y_e|<0.35$
DSSV
DNS kkp
DNS kre
GRSV std
GRSV val
1
0.5
0
-0.5
-1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
y
A_L
W^++Z^0
$p_T^e > 30$ GeV/c
$|y_e|<0.35$
1
0.5
0
-0.5
-1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
y

Phenix

Applications of QCD resummation

"Threshold resummation"



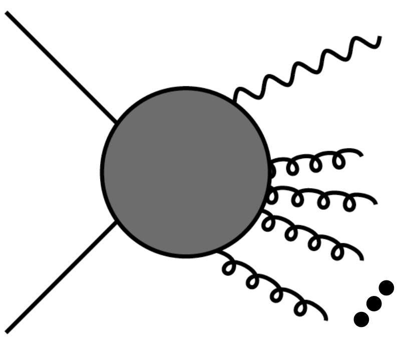
inv. mass M_W

$$\hat{s} = M_W^2 \; , \quad z \equiv \frac{M_W^2}{\hat{s}} = 1$$

- partonic cross section :

$$\hat{\sigma}_{q\bar{q}}^{(0)} \propto \delta(1-z)$$

- higher orders :



$$\hat{\sigma}_{q\bar{q}}^{(k)} \propto \alpha_s^k \left[\frac{\ln^{2k-1}(1-z)}{1-z} \right]_+ + \ldots$$

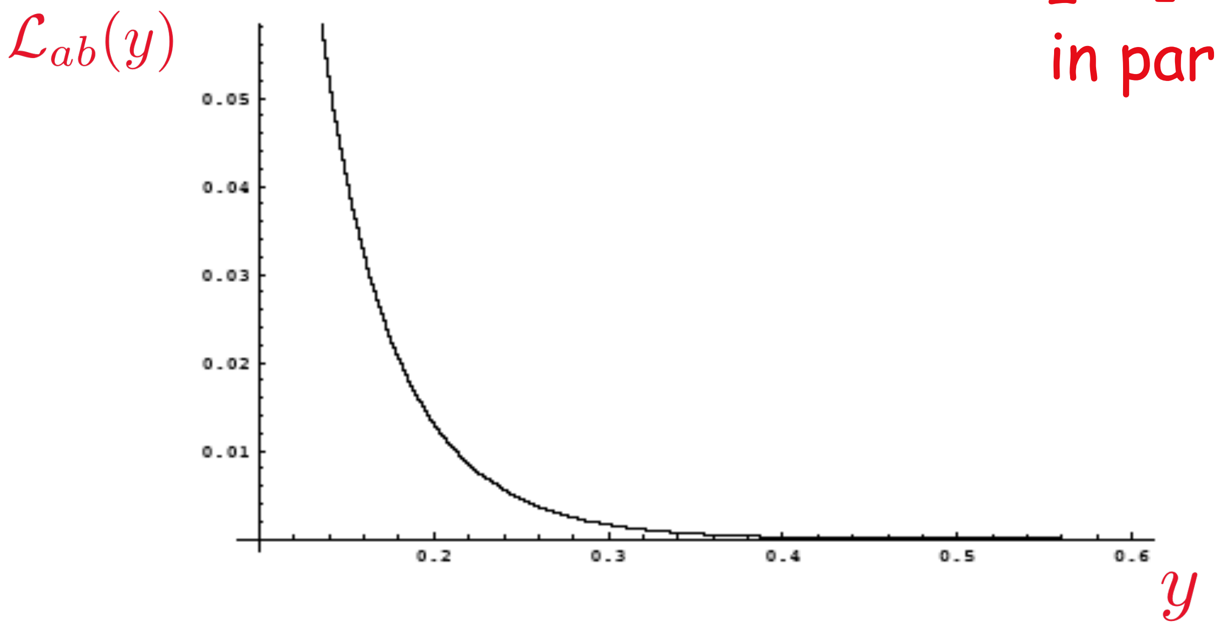
"Threshold logarithms"

- interplay with parton distributions : $\tau = M_W^2/s$

$$\sigma^W \propto \sum_{a,b} \int_\tau^1 \frac{dx_a}{x_a} f_a(x_a) \int_{\tau/x_a}^1 \frac{dx_b}{x_b} f_b(x_b)\ \hat{\sigma}_{ab}(z = \tau/(x_a x_b))$$

$$= \sum_{a,b} \int_\tau^1 \frac{dz}{z}\ \mathcal{L}_{ab}\left(\frac{\tau}{z}\right)\ \hat{\sigma}_{ab}(z)$$

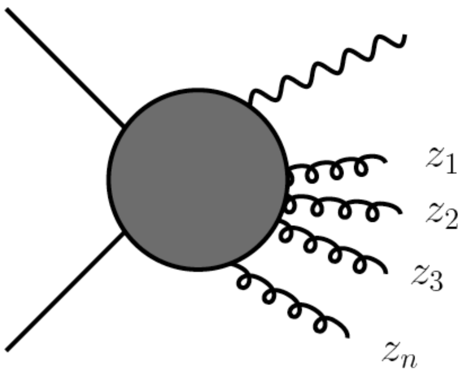
z = 1 emphasized,
in particular as τ→1



Large logs can be resummed to all orders

Sterman; Catani, Trentadue; ...

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



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

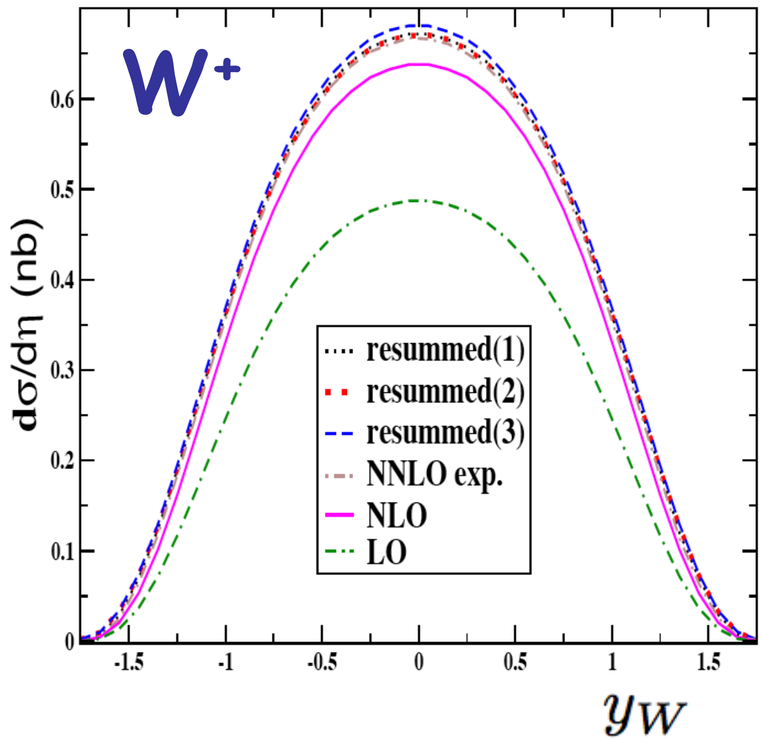
$$z_i = \frac{2E_i}{\sqrt{\hat{s}}}$$

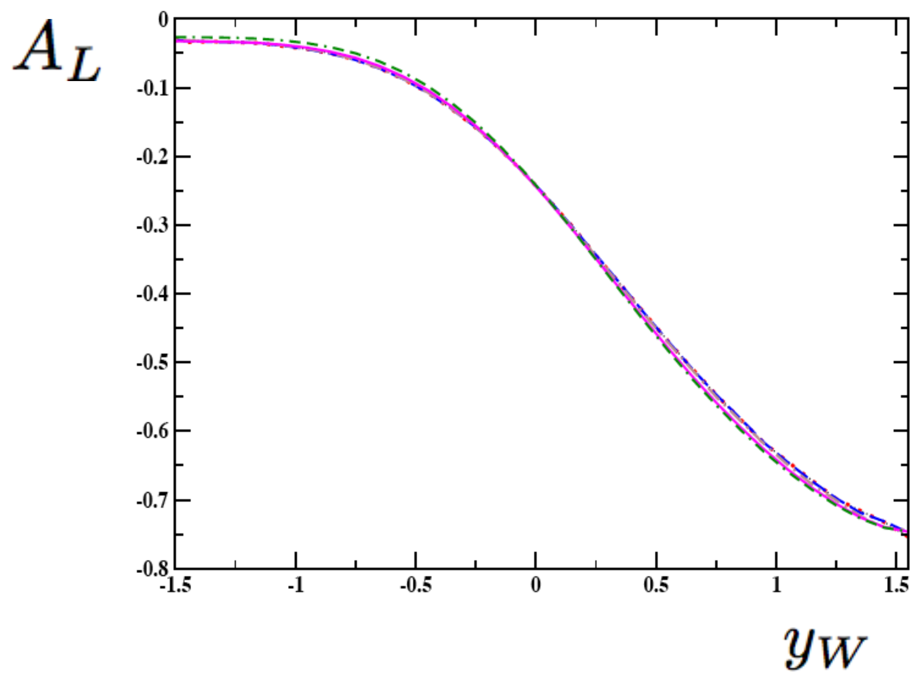
$$\hat{\sigma}_{q\bar{q}} \propto \exp\left[2\int_0^1 dy\, \frac{y^N - 1}{1-y}\int_{\mu_F^2}^{Q^2(1-y)^2} \frac{dk_\perp^2}{k_\perp^2} A_q\left(\alpha_s(k_\perp^2)\right) + \ldots\right]$$

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

- they enhance cross sec. ! $\hat{\sigma}_{q\bar{q}} \propto \exp\left[+\frac{2\,C_F}{\pi}\alpha_s \ln^2(N)\right] > 1$

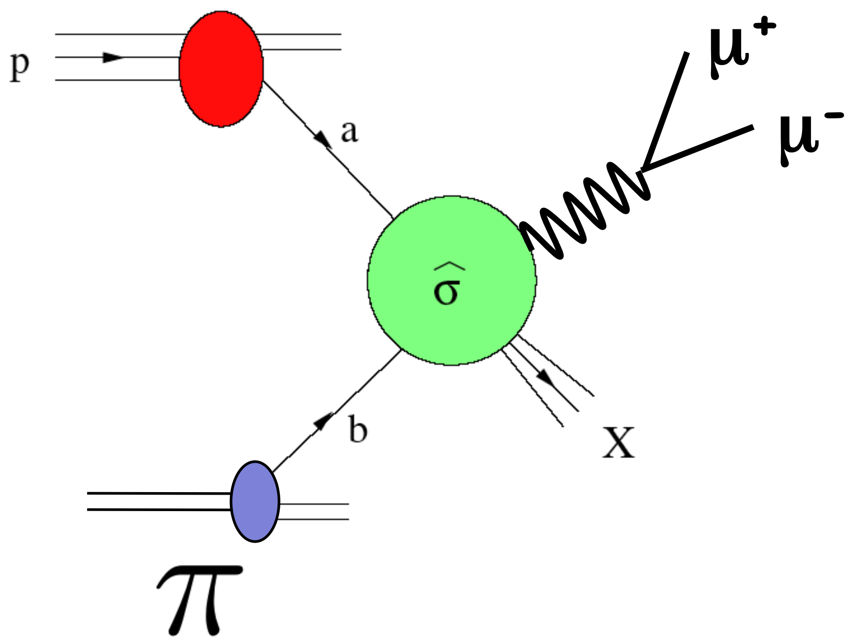
Mukherjee, WV





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

E615, NA10

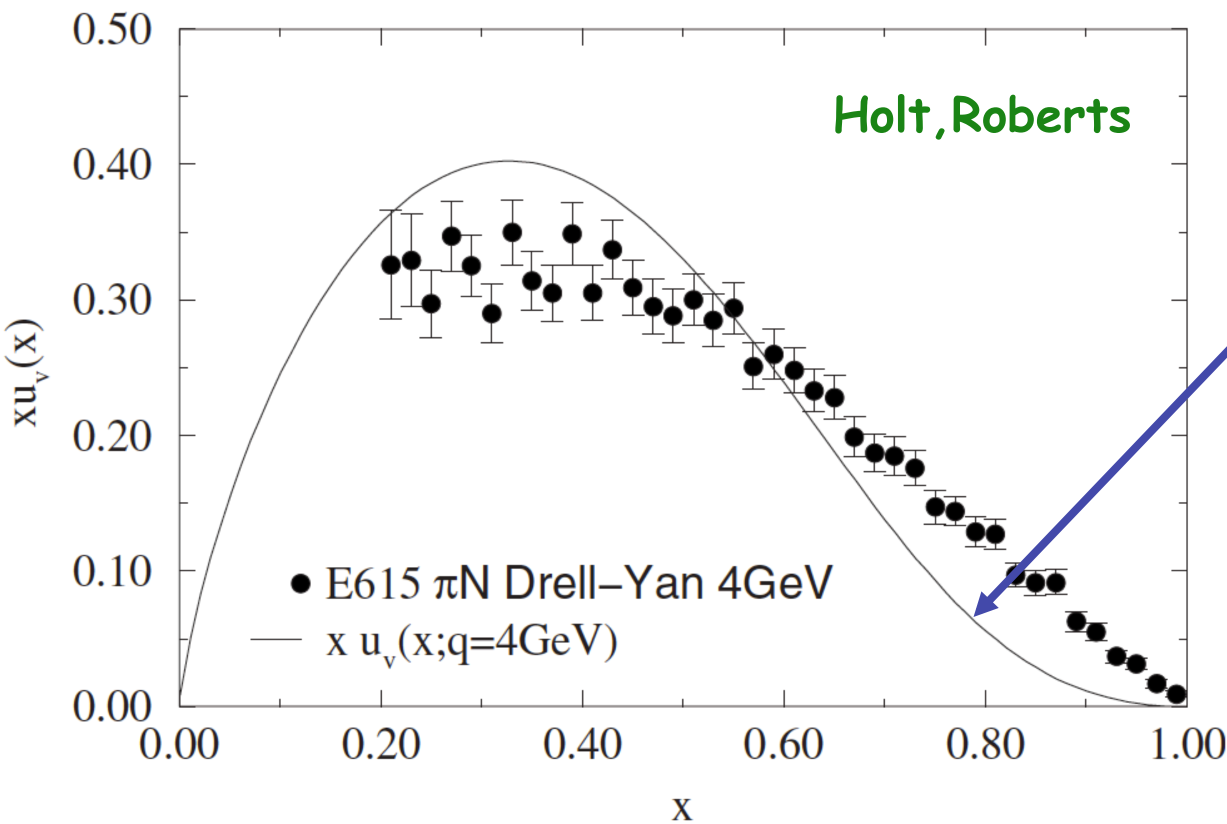


partonic hard scatt.
perturbative QCD

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

• Kinematics such that data mostly probe valence region: ~200 GeV pion beam on fixed target

- LO extraction of u_v from E615 data:



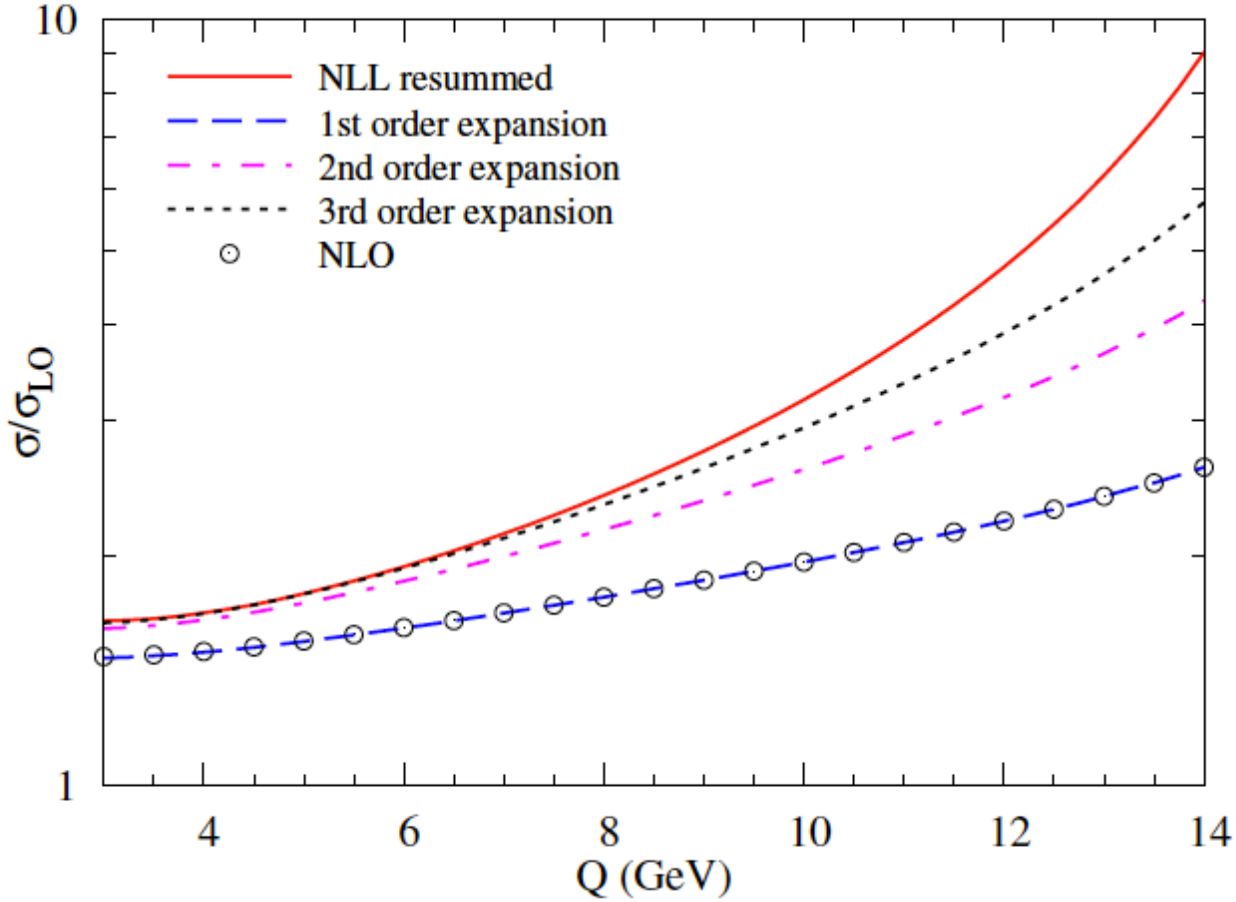
$\sim \ (1-x)^2$

QCD counting rules

Farrar,Jackson;
Berger, Brodsky; Yuan

Dyson-Schwinger

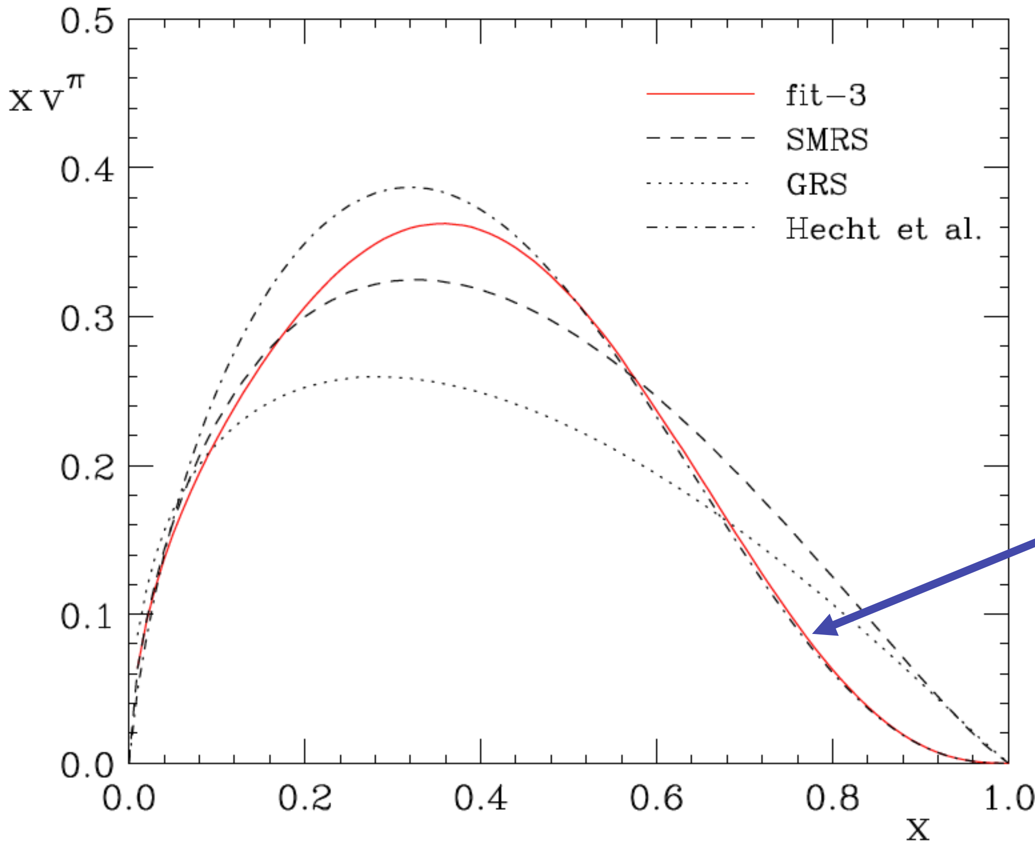
Hecht et al.



Aicher, Schäfer, WV

(Compass kinematics)

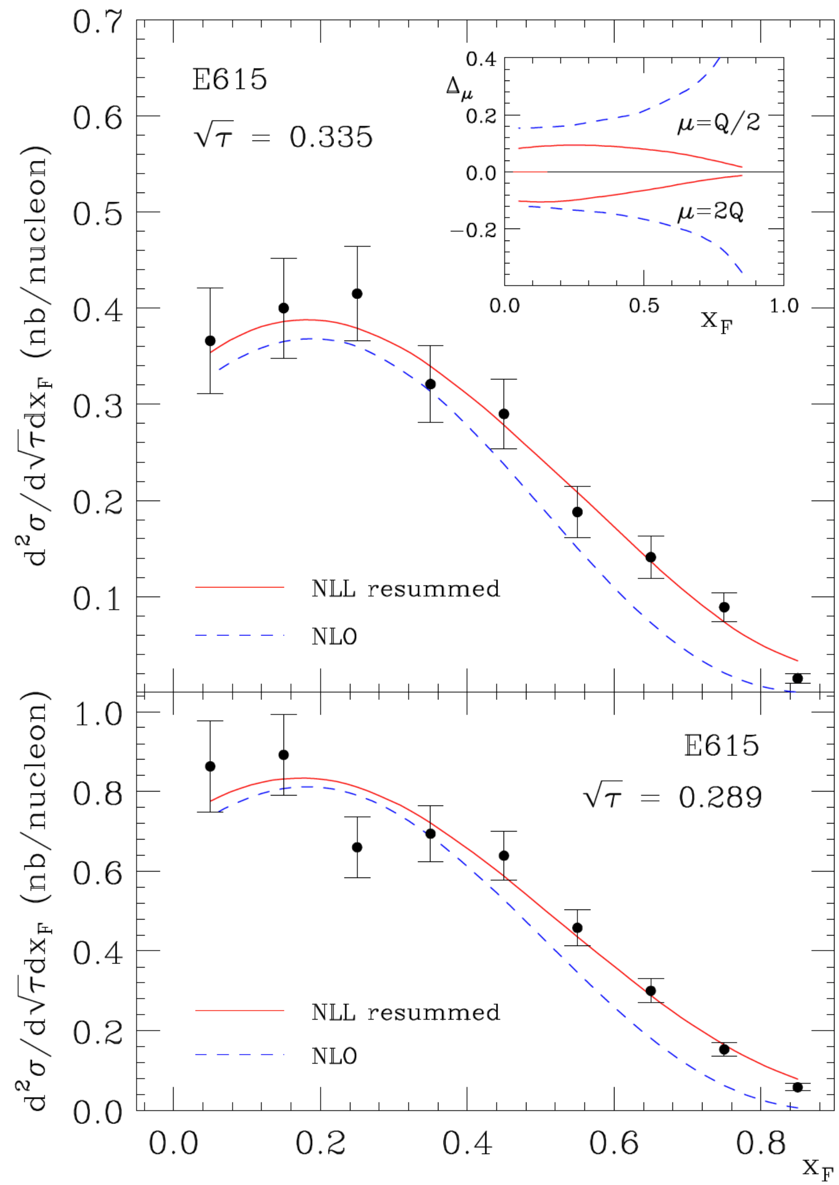
$$\sqrt{S} = 17\,\mathrm{GeV}$$



$Q = 4$ GeV

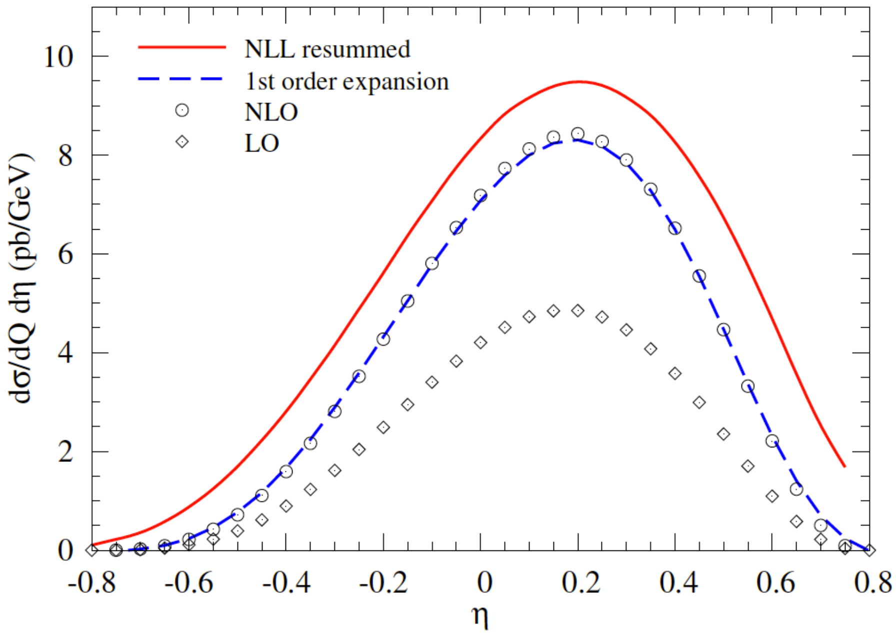
$\sim\ (1-x)^{2.34}$

Aicher, Schäfer, WV

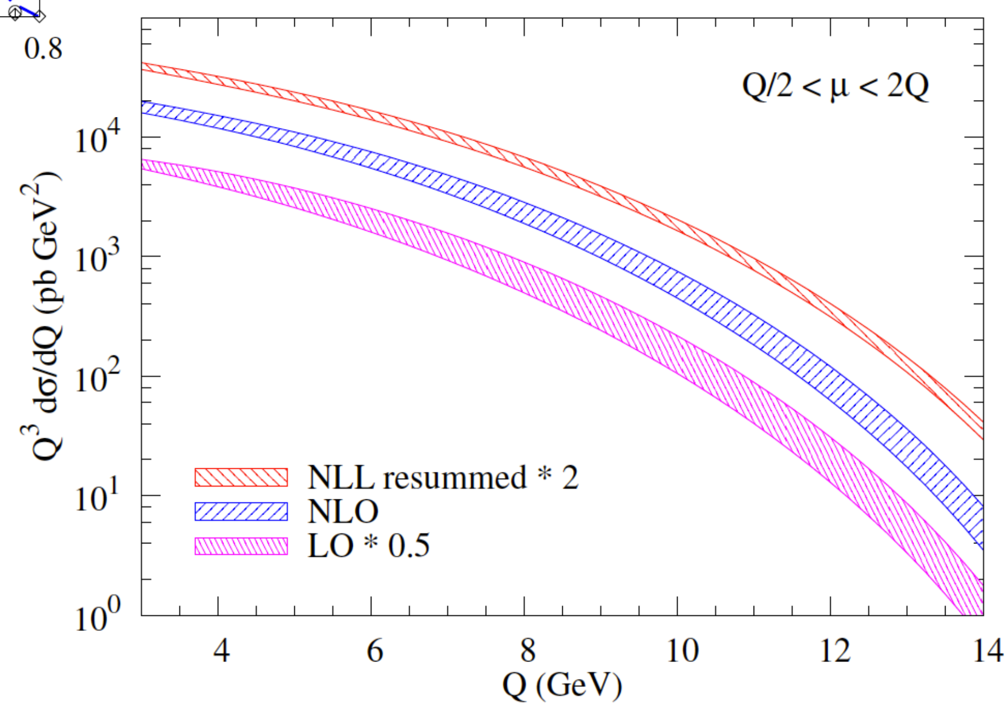


E615
$\sqrt{\tau}$ = 0.335
Δ_μ
μ=Q/2
μ=2Q
x_F
NLL resummed
NLO
E615
$\sqrt{\tau}$ = 0.289
$d^2\sigma/d\sqrt{\tau}dx_F$ (nb/nucleon)
x_F

Equally relevant for COMPASS:

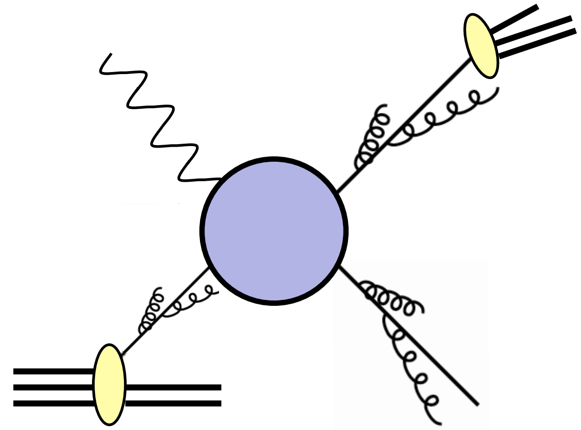


$$\frac{Q}{\sqrt{S}} = 0.45$$



Aicher, Schäfer, WV

Logarithms also present in high-p_T processes:



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

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

$$\hat{\mathbf{x}}_{\mathbf{T}} \equiv \frac{2\mathbf{p}_{\mathbf{T}}}{\sqrt{\hat{\mathbf{s}}}}$$

"threshold" logarithms

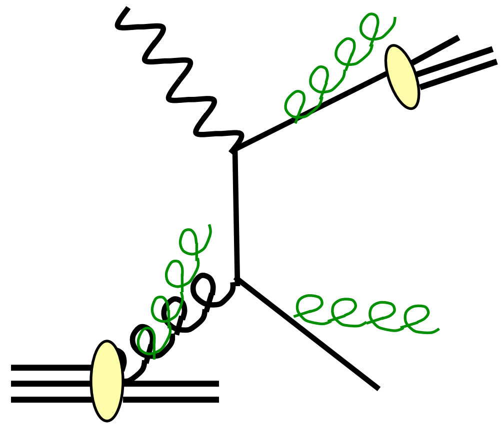
$\hat{\mathbf{x}}_{\mathbf{T}} \rightarrow 1$: only soft/collinear gluons allowed

All-order resummation:

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

- soft-gluon effects exponentiate :

$$\gamma g \longrightarrow qg$$

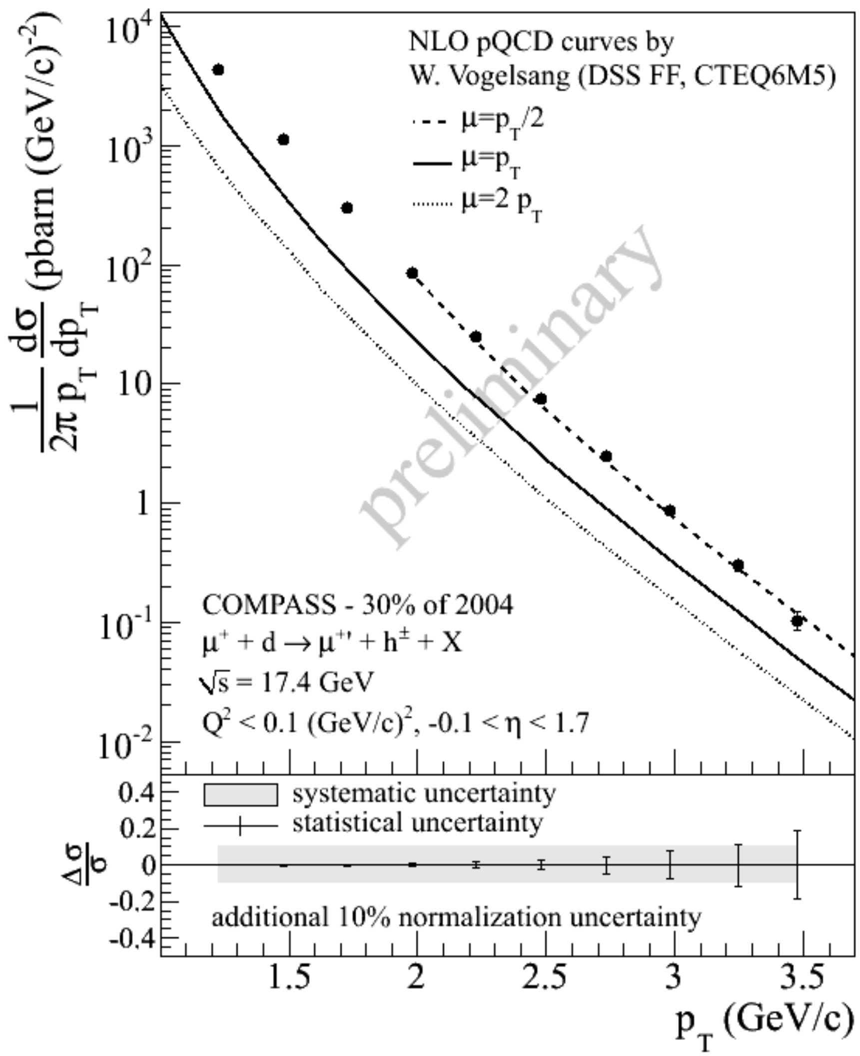


Mellin moment in $\hat{\mathbf{x}}_{\mathbf{T}}^{2}$

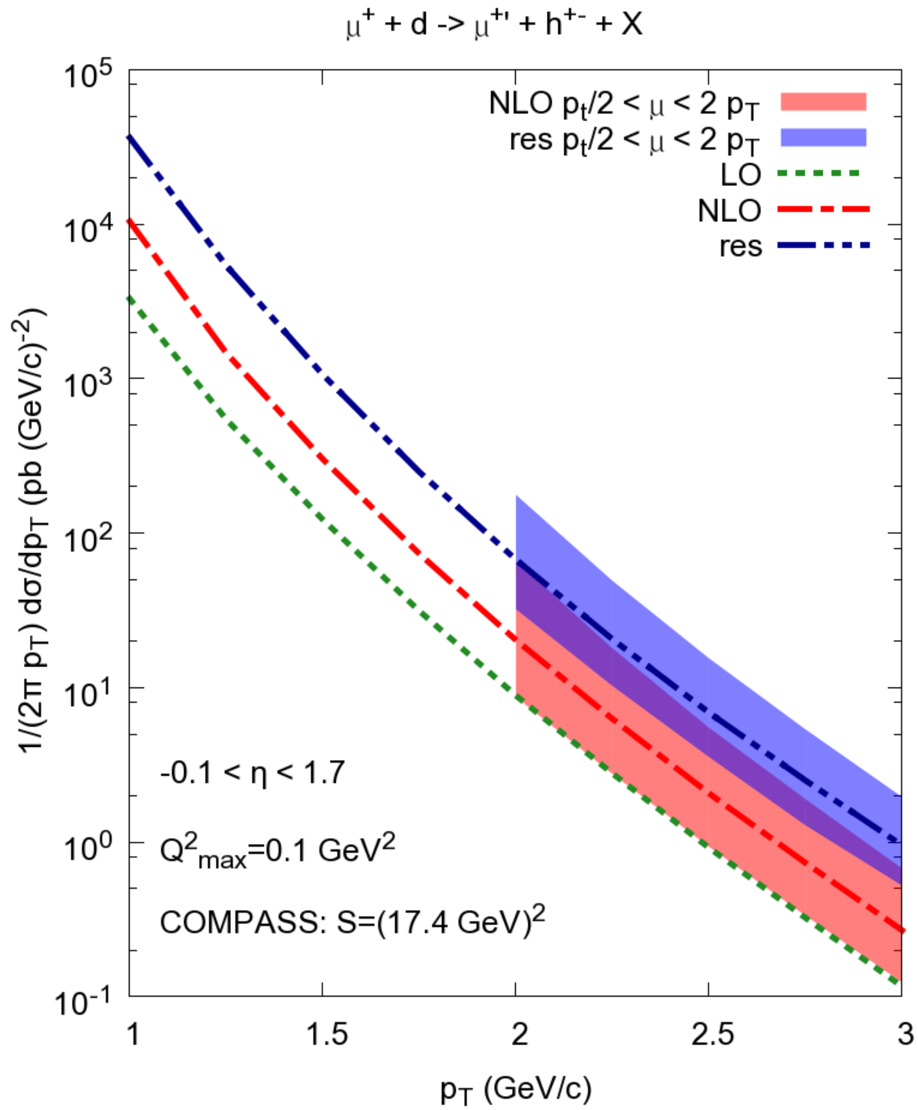
Leading logarithms:

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

(NLL far more complicated, but known)



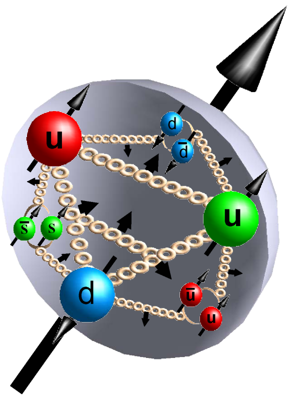
COMPASS

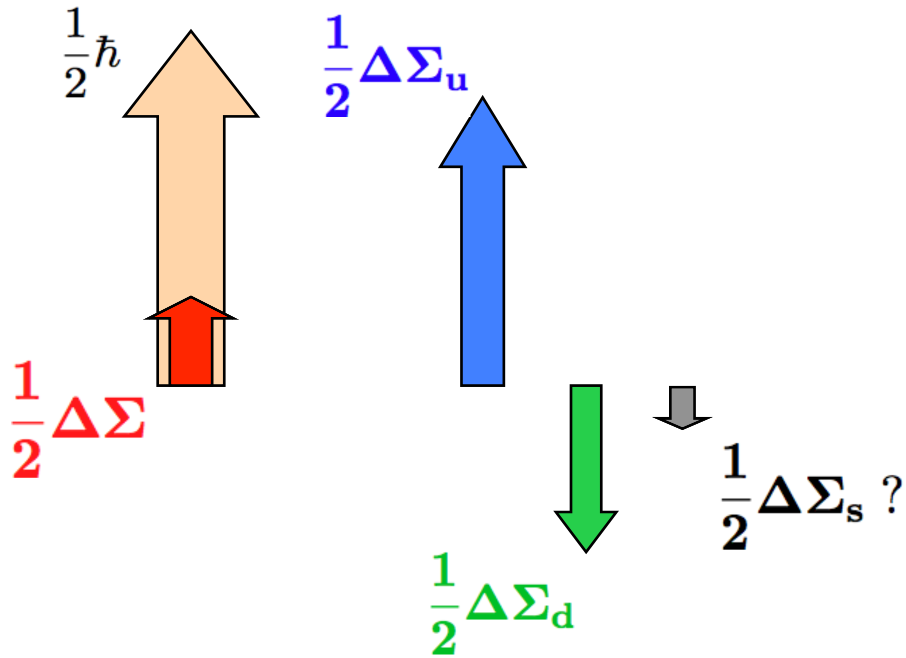


de Florian, Pfeuffer, Schäfer, WV (prel.)

Conclusions:

- first global QCD analysis of DIS, SIDIS, RHIC data





- RHIC (& HERMES,COMPASS) closing in on Δg :
  small in accessible x-region. Small overall ?

- flavor asymmetry $\Delta\bar{u} - \Delta\bar{d} > 0$? Strangeness puzzle?

- many applications of QCD resummation