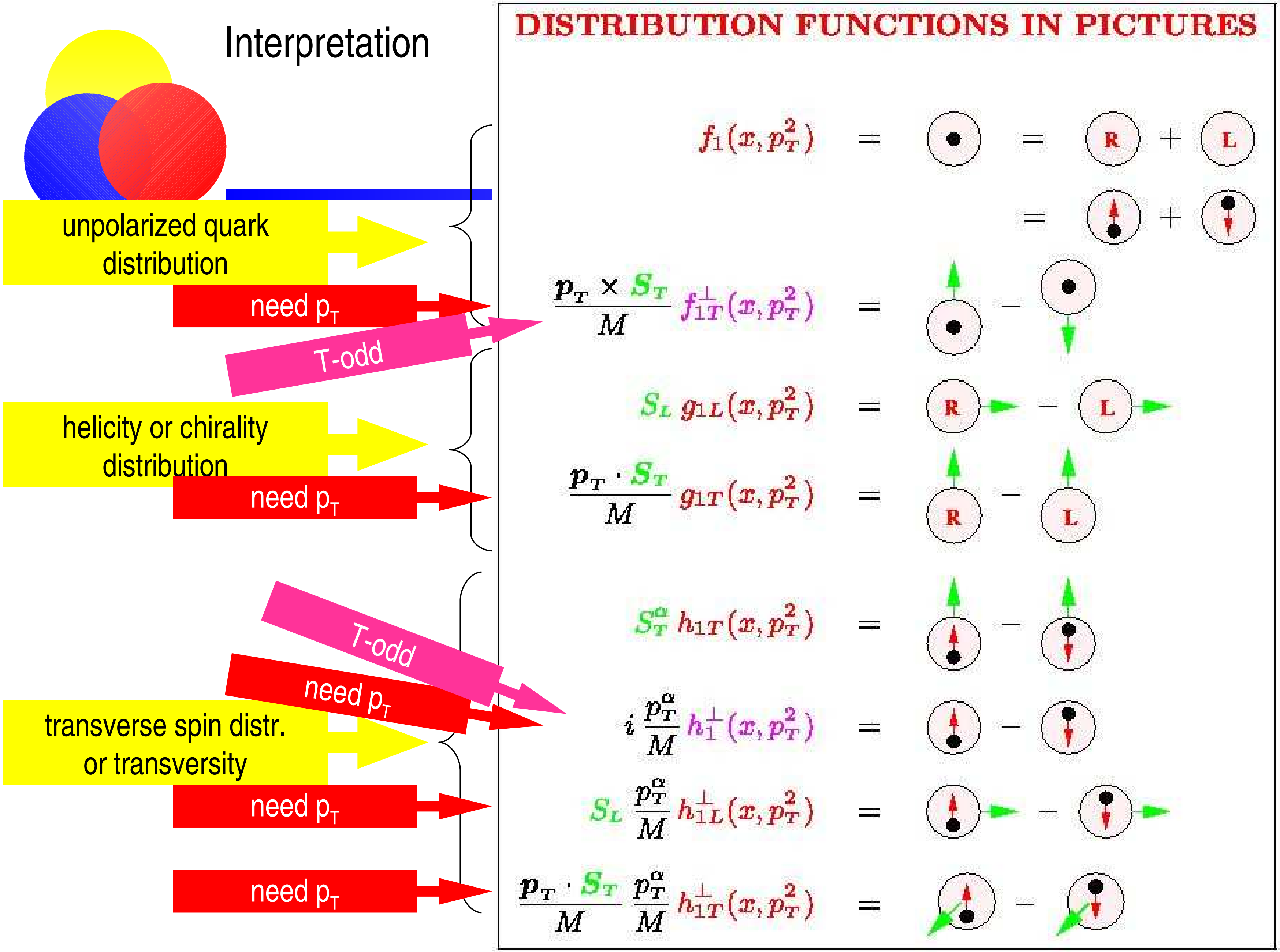
# SPIN WORKING GROUP:

# THEORY

CONVENOR: S. Forte (Milan)

SPEAKERS: M. Ehrenfried (Giessen)
L. Gamberg (Penn State Berks)
M. Hirai (Titech)
H. Kawamura (RIKEN)
Y. Koike (Niigata)
E. Leader (Imperial)
P. Mulders (Amsterdam)
R. Sassot (Buenos Aires)
M. Stratmann (Regensburg)
M. Stolarski (Warsaw)
H. Yokoya (Hiroshima)
F. Yuan (BNL)

# THE PLAYERS




**P. MULDERS**

# THE NAME OF THE GAME

- PARTON DISTRIBUTIONS: THE NUCLEON SPIN PROBLEM
  (Ehrenfried, Hirai, Leader, Sassot, Stratmann, Stolarski)
  - $\Delta g$: POLARIZED GLUE
  - $\Delta s$: POLARIZED STRANGENESS
- HIGHER ORDER CALCULATIONS: POLARIZED RESUMMATION
  (Kawamura, Koike, Yokoya)
  - THRESHOLD RESUMMATION
  - $p_t$ RESUMMATION
- STRETCHING THE PERTURBATIVE DOMAIN: TRANSVERSITY
  (Gamberg, Mulders, Yuan)
  - TWIST-3 & TRANSVERSE FACTN. UNIFICATION
  - UNIVERSALITY

# THE NUCLEON SPIN PROBLEM

# THE NUCLEON SPIN: WHAT IS THE PROBLEM?

$$\Delta\Sigma s^{\mu} \equiv (\Delta u + \Delta d + \Delta s) s^{m} u = \langle p, s | j_5^{\mu} | p, s \rangle << \langle p, s | j_{5\ 8}^{\mu} | p, s \rangle = (\Delta u + \Delta d - 2\Delta s) s^{\mu} \equiv a_8$$

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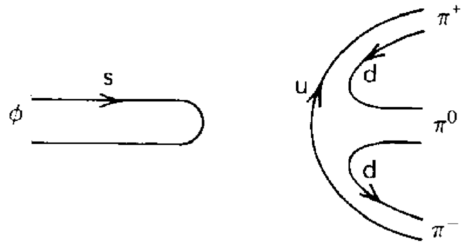
## OZI VIOLATION!

OZI RULE:

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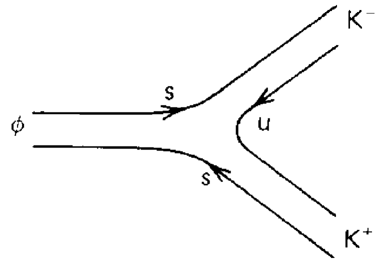
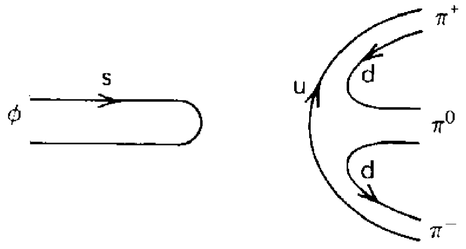


# THE NUCLEON SPIN: WHAT IS THE PROBLEM?

$$\Delta\Sigma s^\mu \equiv (\Delta u{+}\Delta d{+}\Delta s)s^m u = \langle p, s|j_5^\mu|p, s\rangle << \langle p, s|j^\mu_{5\,8}|p, s\rangle = (\Delta u + \Delta d - 2\Delta s)s^\mu \equiv a_8$$

## OZI VIOLATION!

OZI RULE:

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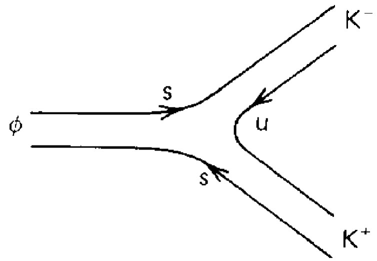



## SOLUTIONS

- THE SINGLET AXIAL CHANNEL IS SPECIAL BECAUSE OF THE ANOMALY ⇒ POLARIZED GLUONS $\Delta g$
  (scheme and scale dependence, instantons,. . . )
- THE OCTET AXIAL CHANNEL IS SPECIAL BECAUSE OF SU(3) SPIN STRUCTURE ⇒ POLARIZED STRANGENESS $\Delta s$
  (sea polarization, skyrmions,. . . )

# TROUBLE

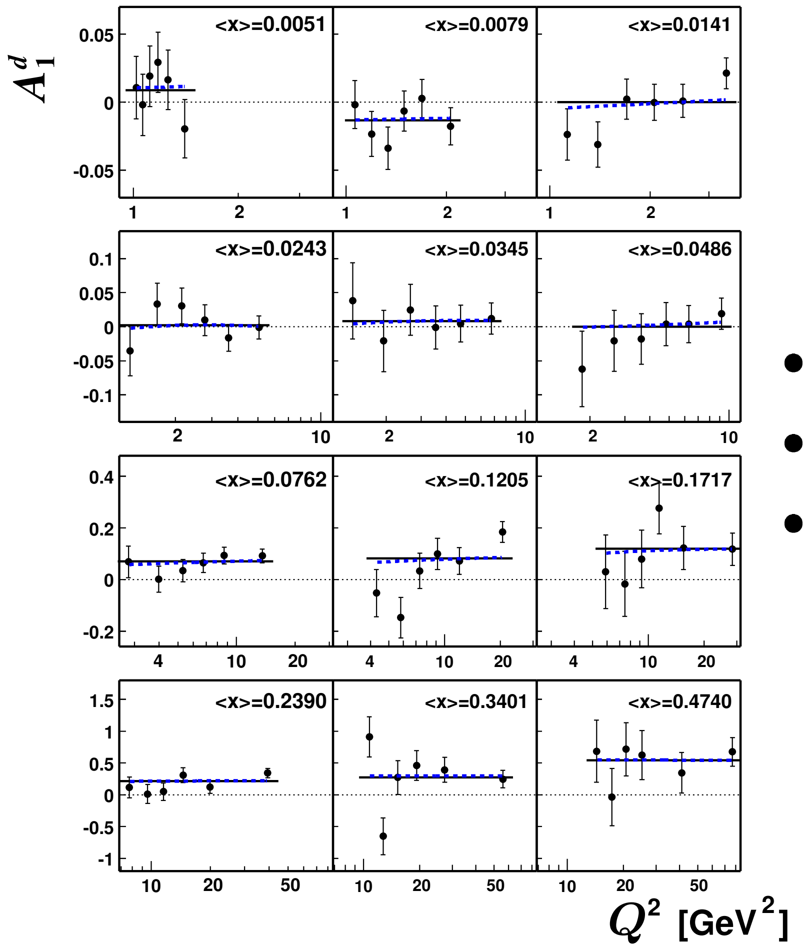
IN COMPARISON TO UNPOLARIZED CASE, TWO MAIN PROBLEMS

- $\Delta G$: GLUON DETERMINED MOSTLY BY SCALING VIOLATIONS, BUT SMALL $Q^2$ RANGE AVAILABLE IN POLARIZED CASE
- $\Delta s$: NO POLARIZED NEUTRINO DATA

SEMI-INCLUSIVE DIS AND VARIOUS HADRONIC CHANNELS ($W$, DY, JETS...) PLAY/WILL PLAY A MAJOR ROLE

# FIT TO DIS DATA ONLY....

## COMPASS QCD ANALYSIS




- $\Delta\Sigma = 0.25 \pm 0.02$ (stat.); $Q^2 = 3$ GeV$^2$
- $\Delta G = 0.4 \pm 0.2$ (stat.); $Q^2 = 3$ GeV$^2$
- without COMPASS:
  $\Delta\Sigma = 0.22 \pm 0.03$ (stat.); $Q^2 = 3$ GeV$^2$

**M. STOLARSKI**

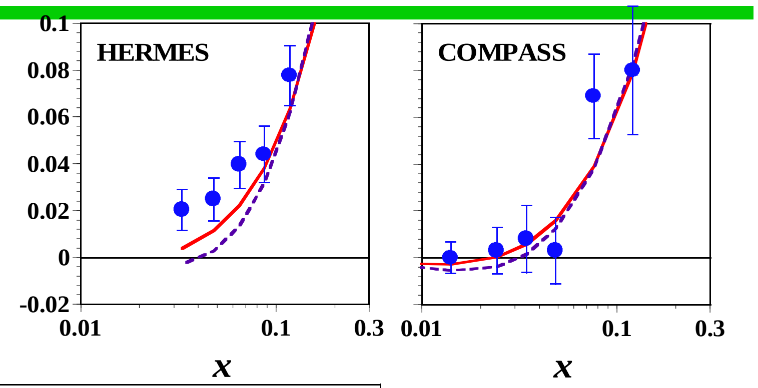
- STRANGENESS CANNOT BE DETERMINED
- ERROR DUE TO FUNCT. FORM & EXTRAP. $\Delta G \approx \pm \sim 1.0$; $\Delta\Sigma \approx \pm \sim 0.1$

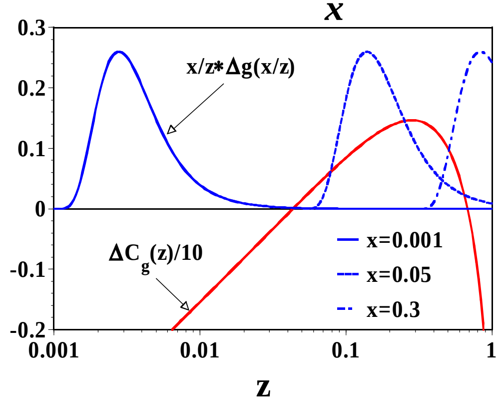
(Altarelli, Ball, S.F., Ridolfi)

# LOOKING FOR POLARIZED GLUE...

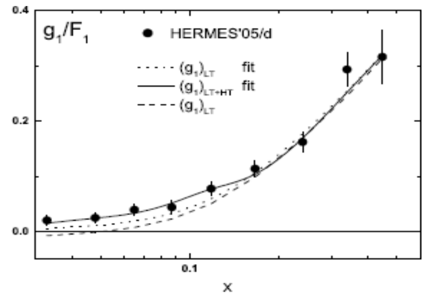
## Constraint on large-x behavior of $\Delta g(x)$

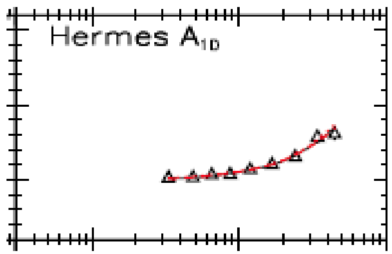
- Positive $\Delta g(x)/g(x)$ at large-x
  - HERMES $A_1^d$
    - $0.03 < x_{Bj} < 0.07$, $1.2 < Q^2 < 1.7$
    - COMPASS-d: $4.5 < Q^2 < 8.6$
  - NLO gluon term
    - Positive contribution
    - Relative increasing for $g_1^D$
      - $e_{uv}^2$: 4/9(P) → 2.5/9(D)
    - Positive $\Delta g(x)$ at large-x
- Other DOF for HERMES-d ?
  - Higher Twist effects
    - LSS, PRD73(2006)034023
  - Antiquark $SU_f(3)$ aymmetry
    - D. de Florian, et al., PRD71(2005)094018




$$\Delta C(x) \otimes x\Delta g(x) = \int_x^1 \frac{dz}{z} \Delta C_g(z)\, x\Delta g\left(\frac{x}{z}\right)$$






M. HIRAI

# LOOKING FOR POLARIZED STRANGENESS...

Asymmetry expressed with purities: $A_1^{K^\pm}(x,z) = \sum_q \mathcal{P}_q^{K^\pm}(x,z)\frac{\Delta q(x)}{q(x)}$

with $\mathcal{P}_q^{K^\pm}(x,z) = \frac{e_q^2\, q(x)\, D_q^{K^\pm}(z)}{\sum_{q'} e_{q'}^2\, q'(x)\, D_{q'}^{K^\pm}(z)}$

"Probability that the virtual photon struck a quark of flavour $q$ in the nucleon when a $K^\pm$ is detected."

Simple linear relationship between the two measured asymmetries and the total non-strange quark distribution $Q(x) \equiv u(x) + \overline{u}(x) + d(x) + \overline{d}(x)$ and total strange quark distribution $S(x) \equiv s(x) + \overline{s}(x)$ :

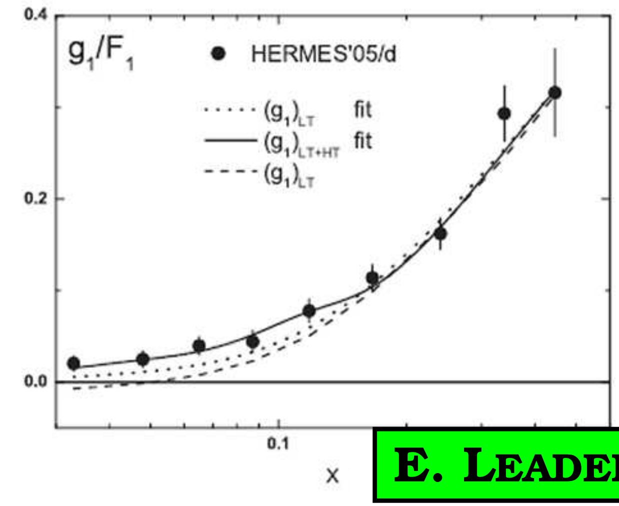
$$\begin{pmatrix} A_{1,d}(x) \\ A_{1,d}^{K^\pm}(x) \end{pmatrix} \propto \begin{pmatrix} \mathcal{P}_Q(x) & \mathcal{P}_S(x) \\ \mathcal{P}_Q^{K^\pm}(x) & \mathcal{P}_S^{K^\pm}(x) \end{pmatrix} \begin{pmatrix} \Delta Q(x)/Q(x) \\ \Delta S(x)/S(x) \end{pmatrix}$$

M. EHRENSFRIED

# MORE TROUBLE...

## HIGHER TWISTS AT LOW $Q^2$

- $g_1$ IN HERMES REGION SIGNIFICANTLY AFFECTED BY HIGHER TWISTS
- HERMES - COMPASS DIFFERENCE CAN BE EXPLAINED BY HIGHER TWISTS INSTEAD OF $\Delta g$




E. LEADER

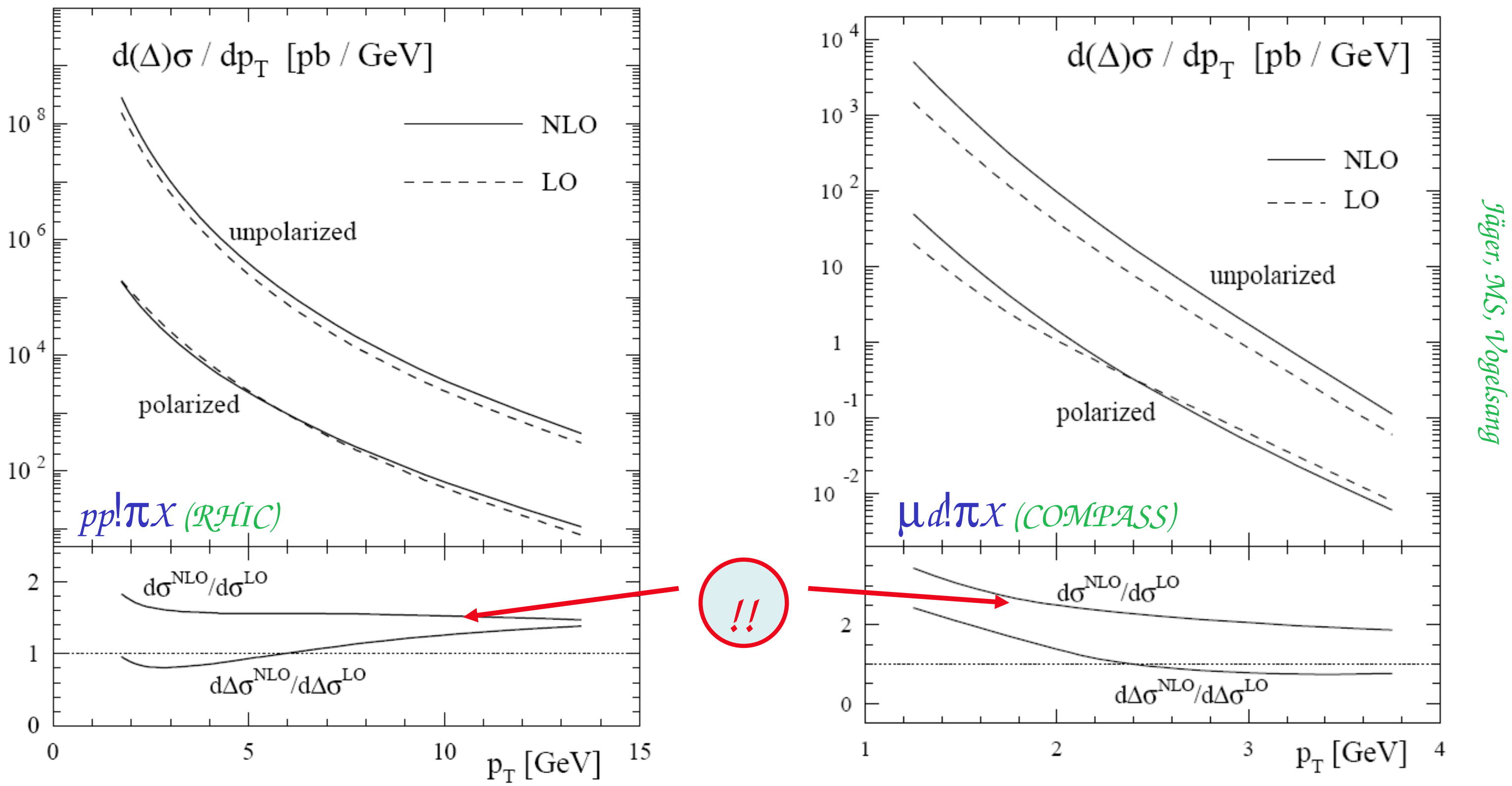
## SU(3) CONSTRAINTS

- ASSUMING SU(3), OCTET CHARGE RELATED TO BARYON DECAY CONSTANTS $\Delta u + \Delta d - 2\Delta s = 3F - D = 0.585 \pm 0.025$
- $\Delta s > 0$ REQUIRES $a_8 \lesssim 0.2 \to$ 60% SU(3) VIOLATION (Leader and Stamenov)

# AND NLO CORRECTIONS!

## K-factor myth

*often it is assumed that NLO corrections drop out in $A_{LL}$ or that K=const*




**assumptions about K factors can be quite misleading**



M. STRATMANN

# A SOLUTION: GLOBAL FITS TO DIS+SIDIS

how do we deal with pSIDIS data?

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

$$g_1^{N\,h}(x_{Bj},z,Q^2) = \frac{1}{2}\Sigma e_q^2 \Big\{ \Delta q\, D_q^h + \frac{\alpha_s}{2\pi}\Big[C_{qq}\otimes \Delta q \otimes D_q^h + C_{gq}\otimes \Delta q \otimes D_g^h + C_{qg}\otimes \Delta g \otimes D_q^h\Big]\Big\}$$

D. de Florian et al. Nuc.Phys.B470 (1996) 195
M. Stratmann W.Vogelsang Phys.Rev.D64 (2001) 114007

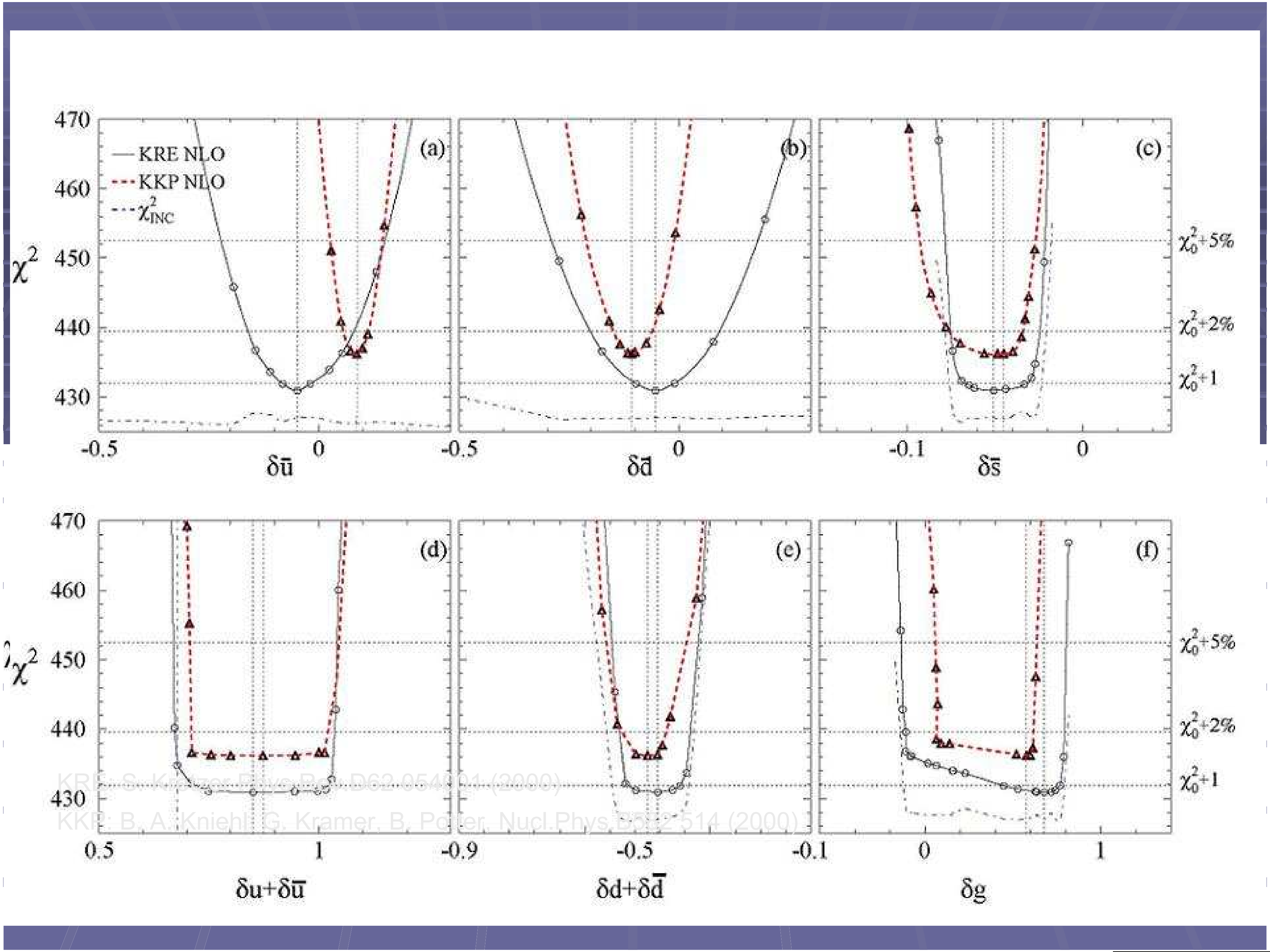
$$2\, g_1^{p\,\pi^{+(-)}} \sim \frac{4}{9}(\Delta u + \Delta\overline{u})\, D^{\pi}_{1(2)} + \frac{1}{9}(\Delta d + \Delta\overline{d})\, D^{\pi}_{2(1)} + \frac{1}{9}(\Delta\overline{d} - 4\Delta\overline{u})\left(D^{\pi}_{1(2)} - D^{\pi}_{2(1)}\right) + \frac{1}{9}(\Delta s + \Delta\overline{s})\, D^{\pi}_{s}$$

$$D_u^{\pi^+} = D_d^{\pi^-} \equiv D_1^{\pi}$$

$$D_d^{\pi^+} = D_u^{\pi^-} \equiv D_2^{\pi}$$

$$D_{\overline{u}}^{\pi^+}(z,Q_0^2) = (1-z)\, D_u^{\pi^+}(z,Q_0^2)$$

# RESULTS




KRE: S. Kretzer Phys.Rev.D62 054001 (2000)
KKP: B. A. Kniehl, G. Kramer, B. Potter, Nucl.Phys.B582 514 (2000)

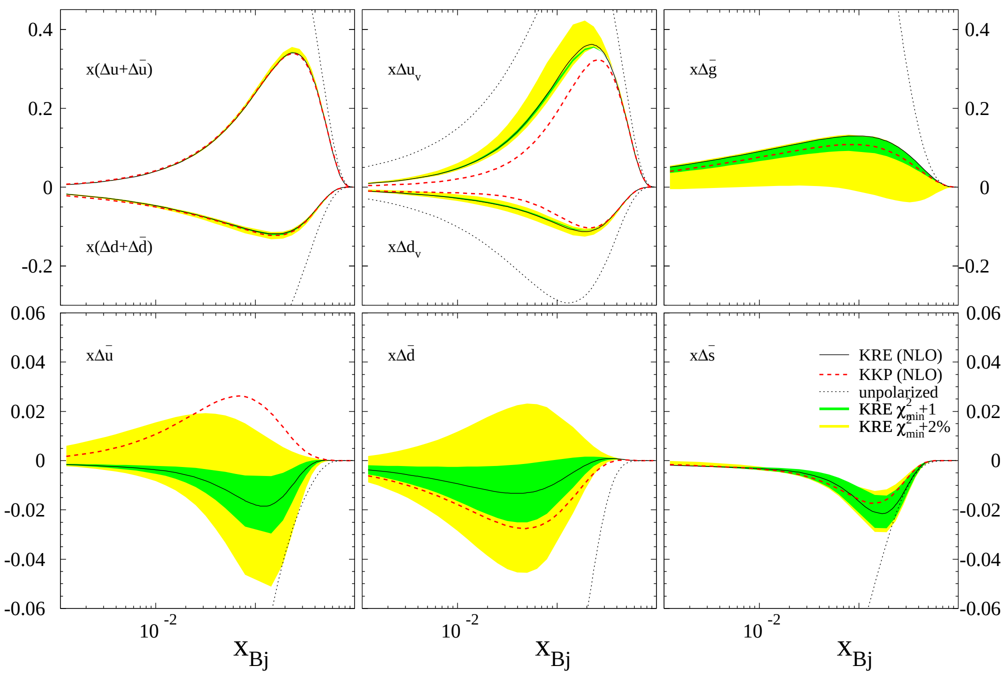
- QUARK: THEORETICAL UNCERTAINTIES LARGER THAN ONE-$\sigma$ ERRORS
- GLUON: NON-GAUSSIAN ERRORS

**R. SASSOT**

# THE IMPACT OF NEXT-TO-LEADING-ORDER CORRECTIONS

## THE GLOBAL FIT OF DE FLORIAN, NAVARRO AND SASSOT

| set | | $\chi^2$ | $\chi^2_{DIS}$ | $\chi^2_{SIDIS}$ | $\delta\bar{u}$ | $\delta\bar{d}$ | $\delta\bar{s}$ | $\delta g$ | $\delta\Sigma$ |
|---|---|---|---|---|---|---|---|---|---|
| NLO | KRE | 430.91 | 206.01 | 224.90 | -0.0487 | -0.0545 | -0.0508 | 0.680 | 0.284 |
| | KKP | 436.17 | 205.66 | 230.51 | 0.0866 | -0.107 | -0.0454 | 0.574 | 0.311 |
| LO | KRE | 457.54 | 213.48 | 244.06 | -0.0136 | -0.0432 | -0.0415 | 0.121 | 0.252 |
| | KKP | 448.71 | 219.72 | 228.99 | 0.0497 | -0.0608 | -0.0365 | 0.187 | 0.271 |

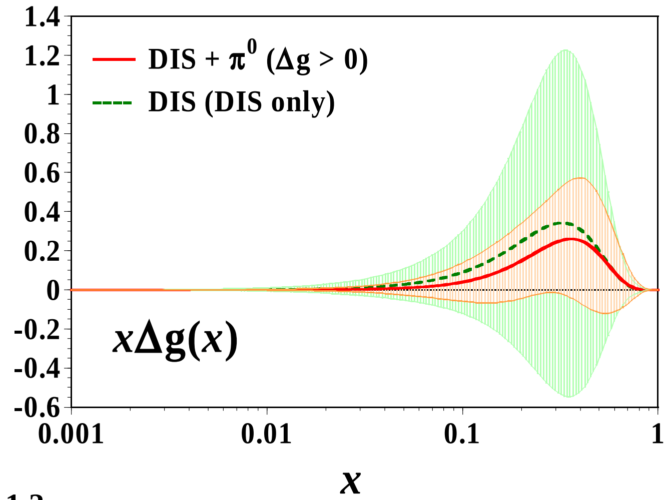


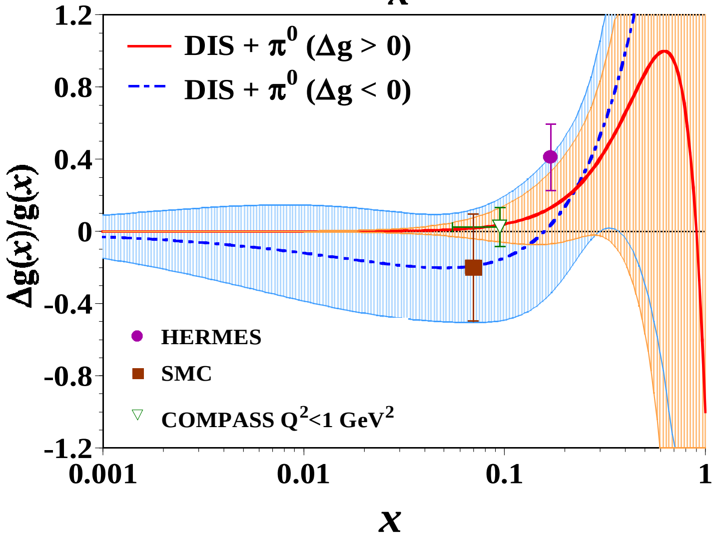

- SEA QUARK DISTRIBUTIONS CHANGE BETWEEN 20% ($\Delta s$) AND A FACTOR OF SEVERAL ($\Delta\bar{u}$) FROM LO TO NLO
- $\Delta\chi^2 = 2\% \approx 9$ SUGGESTED $\Rightarrow$ LARGE GLUON UNCERTAINTY

# $\Delta g$: THE ROLE OF HADRONIC DATA

## Δg from $\pi^0$ production (RUN05)

- 1st moment Δg
  - $0.31 \pm 0.32$ (DIS+$\pi^0$)
  - $0.47 \pm 1.08$ (DIS only)
- Significant reduction of the Δg uncertainty
- Sign problem
  - gg process dominates
    - $\Delta\sigma \propto [\Delta g(x)]^2$
    - Positive or negative Δg?
    - $\chi^2_{\pi 0}$: 11.18(Δg>0) vs. 11.05 (Δg<0) (8 data points)
- Consistent results
  - 1st moment ($0.1<x_{Bj}<1$)
    - Δg>0: $0.30 \pm 0.30$
    - Δg<0: $0.32 \pm 0.42$
  - DIS + $\pi^0$ data covered
  - Large-x is positive






DIS CONSTRAINS LOW MOMENTS

$\pi^0$ CONSTRAINS VALUE IN NARROW $x$ RANGE

$\Rightarrow$ LARGE ERROR REDUCTION IF COMBINED

**M. HIRAI**

# NEED FOR A GLOBAL FIT!

## global analysis

### unpolarized pdfs:

*CTEQ, MRST*

- *gluon constrained by scaling-violations*
- *$2^{nd}$ moment constrained (mom. sum)*
- *pp data only for fine-tuning pdfs*

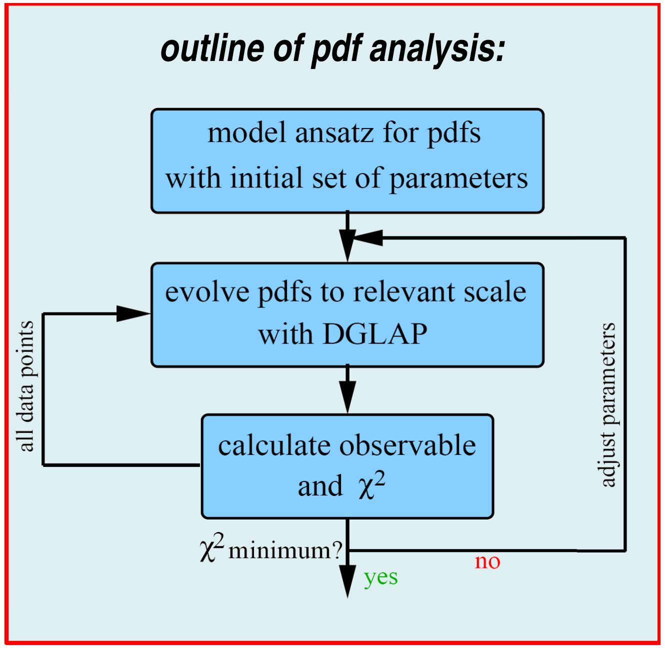
**K-factor approx., etc. often reasonable**

### polarized pdfs:

*completely different situation!*

- *gluon unconstrained by existing DIS data*
- *no momentum sum rule; pol. pdfs can have nodes*
- *pp data determine $\Delta g$ and other aspects of pdfs*

**full NLO global analysis mandatory; approximations often misleading**






M. STRATMANN

# (NO) CONCLUSION ON NUCLEON SPIN

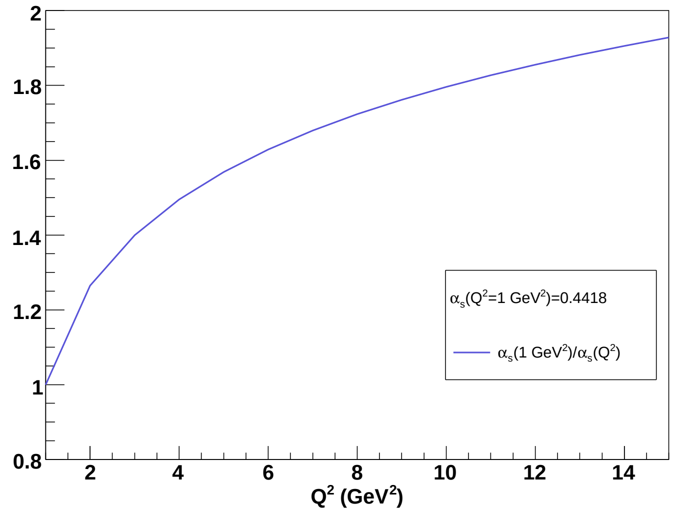
$\Delta G$ PROBABLY SMALL $\left(\frac{N_f}{2\pi}\right)\alpha_s(Q^2)\Delta G \lesssim \frac{1}{2}\Delta\Sigma$, PERHAPS ZERO

$\Delta s$ PROBABLY NEGATIVE, PERHAPS SMALL

# (NO) CONCLUSION ON NUCLEON SPIN YET

## EXISTING RESULTS VERY HARD TO COMPARE:

- SOME LO, SOME NLO: DIFFERENCE TYPICALLY 20%




- $\Delta G$ DEPENDS STRONGLY ON SCALE:
  $\Delta G \sim \frac{1}{\alpha_s(Q^2)}$, SO
  $\Delta G(2m_c) \sim 2\Delta G(1\ \mathrm{GeV})$

- LARGE SCHEME DEPENDENCE OF $\Delta\Sigma$, $O\left(\frac{N_f}{2\pi}\right)\alpha_s(Q^2)\Delta G$
- ERRORS DETERMINED WITH $\Delta\chi^2 = 1$ UP TO $\Delta\chi^2 = 12$
- MANY TH. ERRORS DIFFICULT TO ESTIMATE/NOT INCLUDED

$\Delta G$ PROBABLY SMALL $\left(\frac{N_f}{2\pi}\right)\alpha_s(Q^2)\Delta G \lesssim \frac{1}{2}\Delta\Sigma$, PERHAPS ZERO

$\Delta s$ PROBABLY NEGATIVE, PERHAPS SMALL

# RESUMMATION

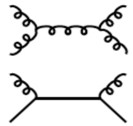
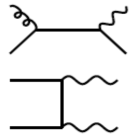
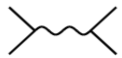
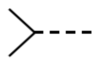
# HIGHER ORDER CALCULATIONS….

## avail. NLO results

**RHIC spin:**

$\Delta g$

$\Delta \bar{q}$

| Reaction | Dom. partonic process | probes | LO Feynman diagram |
|---|---|---|---|
| $\vec{p}\vec{p} \to \pi + X$ [61, 62] | $\vec{g}\vec{g} \to gg$<br>$\vec{q}\vec{g} \to qg$ | $\Delta g$ |  |
| $\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72] | $\vec{g}\vec{g} \to gg$<br>$\vec{q}\vec{g} \to qg$ | $\Delta g$ | (as above) |
| $\vec{p}\vec{p} \to \gamma + X$<br>$\vec{p}\vec{p} \to \gamma + \text{jet} + X$<br>$\vec{p}\vec{p} \to \gamma\gamma + X$<br>[67, 73, 74, 75, 76] | $\vec{q}\vec{g} \to \gamma q$<br>$\vec{q}\vec{g} \to \gamma q$<br>$\vec{q}\vec{\bar{q}} \to \gamma\gamma$ | $\Delta g$<br>$\Delta g$<br>$\Delta q, \Delta\bar{q}$ |  |
| $\vec{p}\vec{p} \to DX, BX$ [77] | $\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$ | $\Delta g$ |  |
| $\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80] | $\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$ | $\Delta q, \Delta\bar{q}$ |  |
| $\vec{p}\vec{p} \to (Z^0, W^\pm)X$<br>$p\vec{p} \to (Z^0, W^\pm)X$<br>[78] | $\vec{q}\vec{\bar{q}} \to Z^0$, $\vec{q}'\vec{\bar{q}} \to W^\pm$<br>$\vec{q}'\bar{q} \to W^\pm$, $q'\vec{\bar{q}} \to W^\pm$ | $\Delta q, \Delta\bar{q}$ |  |

*Jäger,Schäfer, MS, Vogelsang; de Florian*

*Jäger,MS,Vogelsang; Signer et al.*

*Gordon,Vogelsang; Contogouris et al.; Gordon, Coriano*

*Bojak, MS*

*Weber; Gehrmann; Kamal; Smith et al.*

**NLO for polarized lepton-proton scattering** *(COMPASS, HERMES):*

*only photoproduction of single-hadrons and heavy flavors available*

*Jäger,MS,Vogelsang* *Bojak, MS*



**M. STRATMANN**

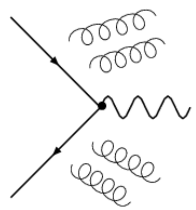
## Threshold logs

Large corrections come from the partonic threshold region (z~1)

- ✓ real emission suppressed by the phase space restriction
- ✓ imbalance occurs between real and virtual gluon corrections
  (after the cancellation of IR pole)

[redacted] → only soft gluon can be emitted

→ soft gluon (eikonal) approximation
to treat these logs up to all orders



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# IMPACT OF THRESHOLD RESUMMATION



## Double Transverse Spin Asymmetry

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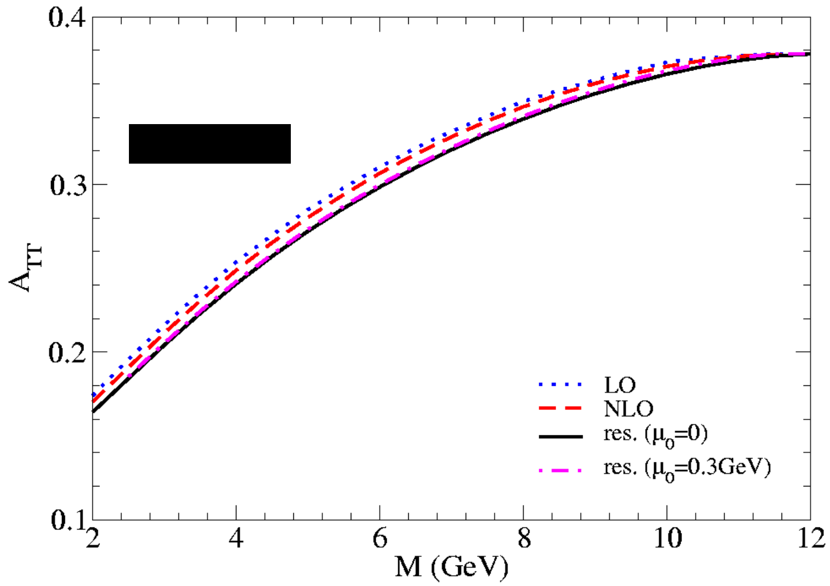


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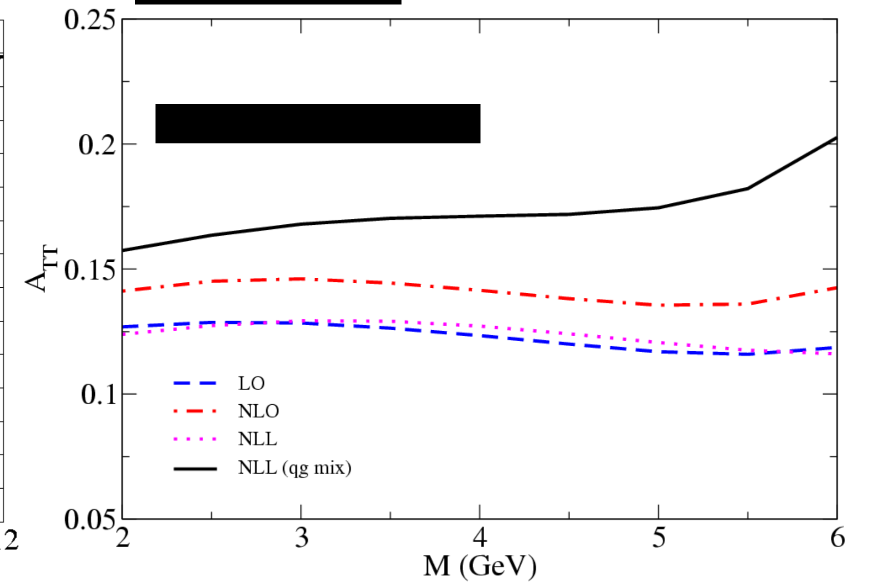


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Model of Transverse PDFs → upper limit of Soffer's inequality with GRV&GRSV

[redacted]

Martin,Schafer, Stratmann,Vogelsang

IMPACT OF RESUMMATION SIZABLE, BUT LARGELY CANCELS IN ASYMMETRY

**H. Yokoya**

# $p_T$ RESUMMATION

$Q_T$ resummation

*Collins, Soper '81*
*Collins, Soper, Sterman '85*

*Next-to-leading logarithmic (NLL) resummation in tDY :*

*H.K, Kodaira, Shimizu, Tanaka : hep-ph/0512137*

$$\frac{\Delta_T d\sigma}{dQ^2 dy d\phi dQ_T^2} = \frac{\alpha^2}{3N_c S Q^2}\cos(2\phi)\left[\frac{1}{2}\int d\vec{b} e^{i\vec{b}\cdot\vec{Q}_T}\ e^{S(b,Q)} R(b,Q,y) + Y(Q_T^2, Q^2, y)\right]$$

*b : impact parameter*

*Sudakov factor*

$$S(b,Q) = -\int_{1/b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left\{\ln\frac{Q^2}{\mu^2} A(\alpha_s(\mu^2)) + B(\alpha_s(\mu^2))\right\} \quad \Leftrightarrow$$

[redacted]

$$A(\alpha_s) = C_F\frac{\alpha_s}{\pi} + \frac{1}{2}C_F\left\{\left(\frac{67}{18} - \frac{\pi^2}{6}\right) - \frac{5}{9}N_f\right\}\left(\frac{\alpha_s}{\pi}\right)^2$$

$$B(\alpha_s) = -\frac{3}{2}C_F\frac{\alpha_s}{\pi}$$

*universal* *Catani et al. '01*

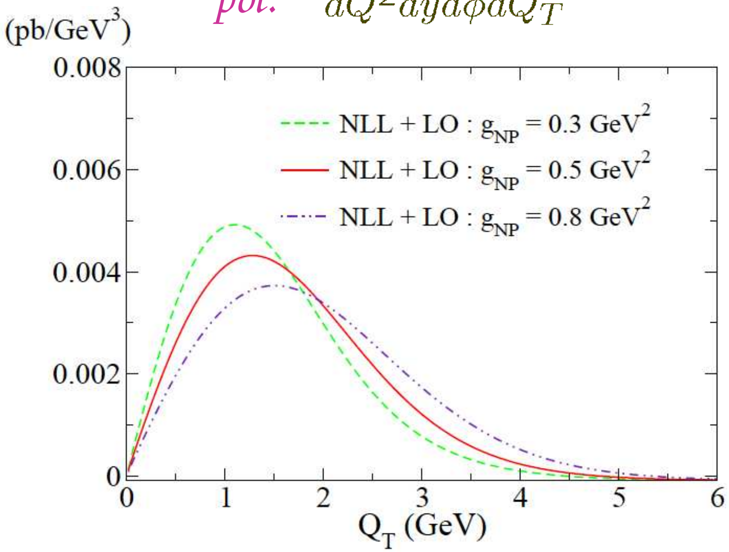
$$R(b,Q,y) = \sum_i C_i \otimes \delta q_i\left(x_1^0, \frac{1}{b}\right)\cdot C_{\bar{i}} \otimes \delta q_{\bar{i}}\left(x_2^0, \frac{1}{b}\right)$$

$$C_i(z,\alpha_s) = \delta(1-z)\left\{1 + \frac{\alpha_s}{4\pi}C_F(\pi^2 - 8)\right\}$$ *coeff. function*

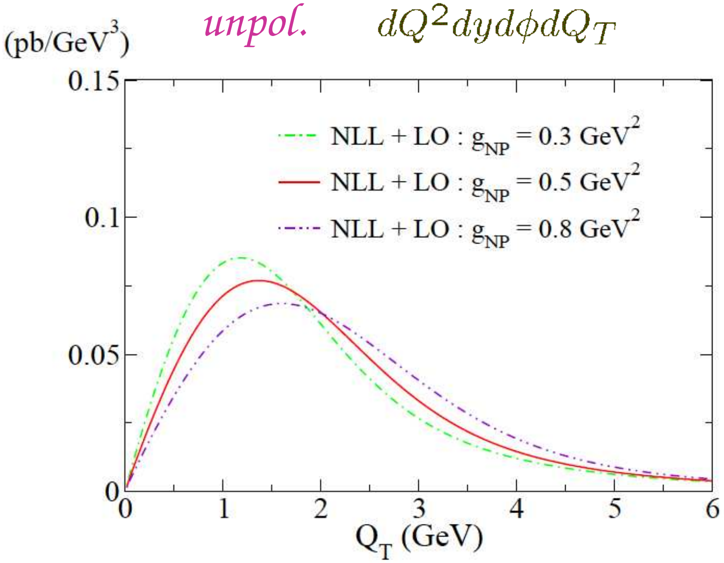
# STABILIZATION: DRELL-YAN

*$Q_T$ spectrum*

*pol.* $\frac{\Delta_T d\sigma}{dQ^2 dy d\phi dQ_T}$




*unpol.* $\frac{d\sigma}{dQ^2 dy d\phi dQ_T}$




*pp collision @ RHIC*

$\sqrt{s}$ = 200 GeV, Q = 8 GeV, y=2, =0

$$F^{NP}(b) = e^{-g_{NP}b^2}$$

$g_{NP}$ = 0.3, 0.5, 0.8GeV²

$\leftrightarrow$ $< k_T >$ = 0.7, 0.9, 1.1 GeV

RESUMMATION REMOVES SINGULARITY AS $q_t \to 0$

**H. KAWAMURA**

Hiroyuki Kawamura (RIKEN)

# THE CASE OF SIDIS

⋆ Structure of the lowest order cross section

Cf. Y.K. & J. Nagashima, NPB 660 ('03) 269, (E) 742('06) 312.

- $$\frac{d^5\sigma^{\rm LO}}{dQ^2 dx_{bj} dz_f dq_T^2 d\phi} = \sigma_0 + \cos(\phi)\sigma_1 + \cos(2\phi)\sigma_2,$$ $p_T = z_f q_T$

  for $ep \to e\pi X$, $e\vec{p} \to e\vec{\Lambda}X$.

- $$\frac{d^5\sigma^{\rm LO}}{dQ^2 dx_{bj} dz_f dq_T^2 d\phi} = \sigma_0 + \cos(\phi)\sigma_1,$$ for $\vec{e}\vec{p} \to e\pi X$, $\vec{e}p \to e\vec{\Lambda}X$.

- $$\frac{d^5\sigma_T^{\rm LO}}{dQ^2 dx_{bj} dz_f dq_T^2 d\phi} = \cos(\Phi_A - \Phi_B - 2\phi)\sigma_0^T + \cos(\Phi_A - \Phi_B - \phi)\sigma_1^T + \cos(\Phi_A - \Phi_B)\sigma_2^T,$$

  for $ep^\uparrow \to e\Lambda^\uparrow X$.

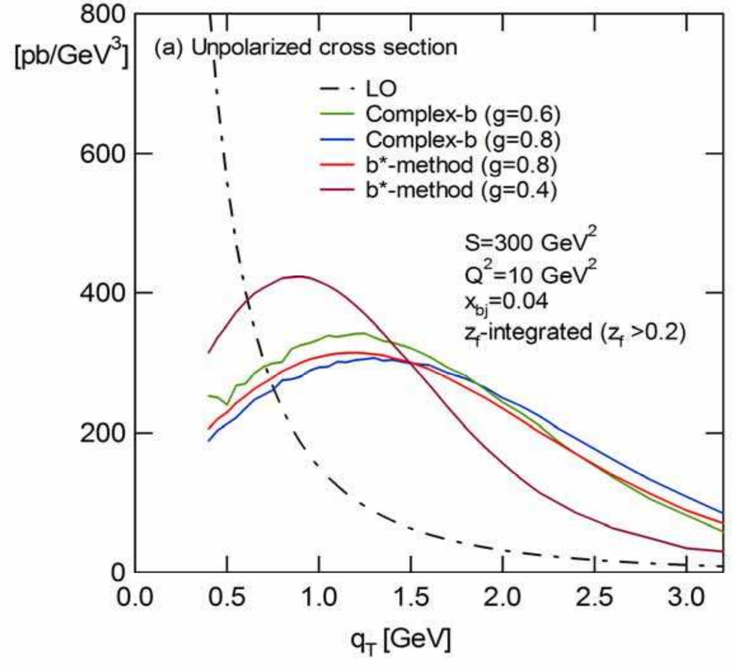
($\Phi_{A,B}$=azimuth. of $S_{\perp A,B}$ around $\vec{p}_{A,B}$ measured from the *hadron* plane.)

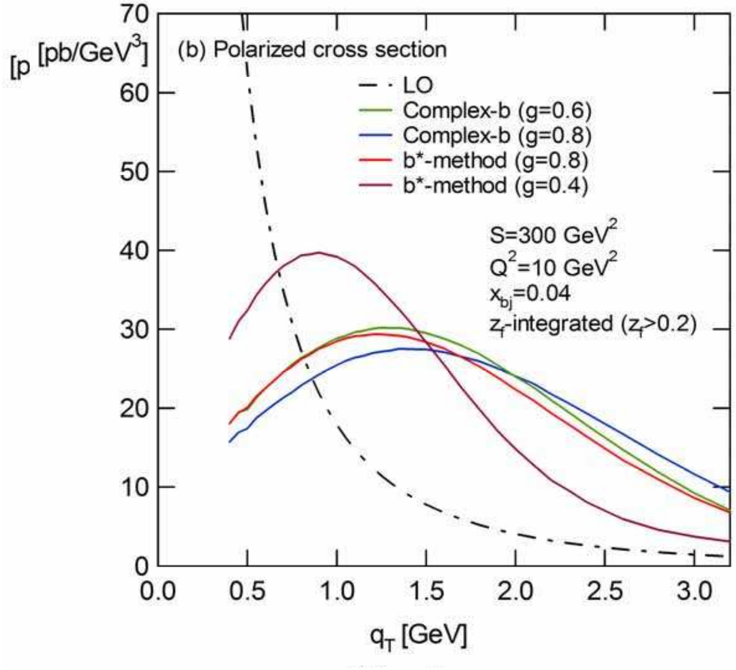
⋆ $\sigma_0,\ \sigma_0^T \sim \frac{1}{q_T^2}\ln\left(\frac{Q^2}{q_T^2}\right)$ as $q_T \to 0$. $\longrightarrow$ We focus on the resummation of this part.

$\sigma_1,\ \sigma_1^T \sim \frac{1}{q_T}\ln\left(\frac{Q^2}{q_T^2}\right)$, $\sigma_2,\ \sigma_2^T \sim \ln\left(\frac{Q^2}{q_T^2}\right)$

Less singular. Could be resummable. But not in this work.

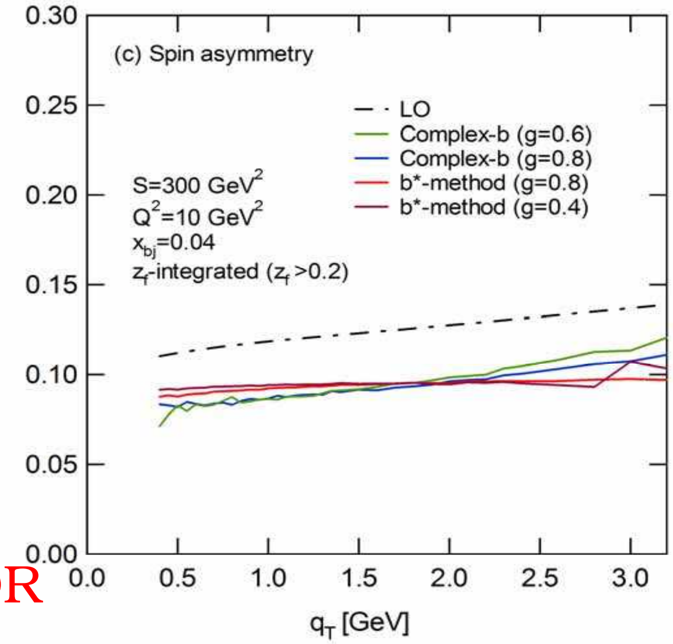
# RESUMMATION AND NON-PERTURBATIVE TERMS




COMPASS kinematics

$$p_T = z_f q_T$$




SIZABLE DEPENDENCE ON
NONPERTURBATIVE REGULATOR

**Y. Koike**

# TRANSVERSITY

# Naïve Parton Model Fails to Explain Large SSAs

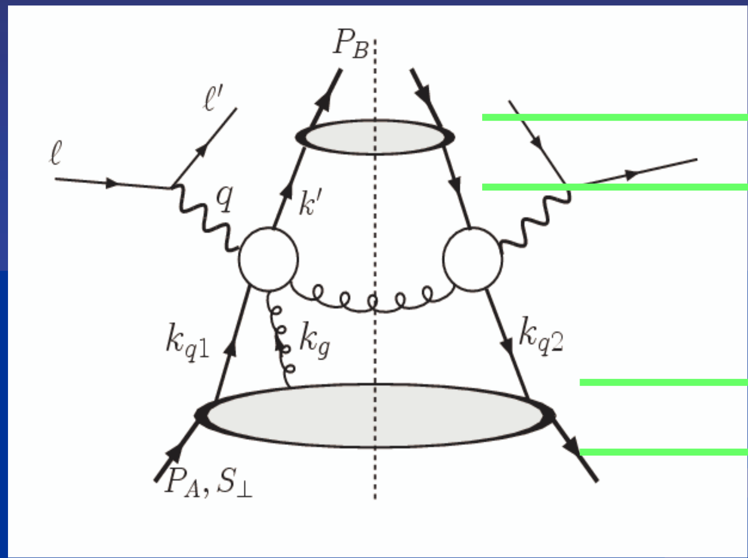
- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, PRL41, 1978)
  - It is in general suppressed by $\alpha_S\, m_q/Q$
- We have to go beyond the naïve parton model to understand the large SSAs observed in hadronic reactions

# …AND THEIR ORIGIN

## Two Mechanisms in QCD

- Transverse Momentum Dependent Parton Distributions
  - Sivers function, Sivers 90
  - Collins function, Collins 93
  - Gauge invariant definition of the TMDs: Brodsky, Hwang, Schmidt 02; Collins 02 ; Belitsky, Ji, Yuan 02; Boer, Mulders, Pijman, 03
  - The QCD factorization: Ji, Ma, Yuan, 04; Collins, Metz, 04
- Twist-three Correlations (collinear factorization)
  - Efremov-Teryaev, 82, 84
  - Qiu-Sterman, 91,98

# A General Diagram in Twist-3




**Collinear Factorization:**

$$d\sigma \propto \epsilon^{\beta\alpha} S_{\perp\beta} P_{h\perp\alpha} \int \frac{dx}{x}\frac{dz}{z} \widehat{q}(z) T_F(x, x - xg) \times \cdots$$

Qiu,Sterman, 91

# TMD Factorization

- When $q_\perp \ll Q$, a TMD factorization holds,

$$\frac{d^3\triangle\sigma(S_\perp)}{dx_B dz_h d^2P_{h\perp}} = \frac{\epsilon^{\alpha\beta}S_{\perp\alpha}P_{h\perp\beta}}{M_P}\int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\lambda}_\perp \quad H(Q) \times\frac{\vec{k}_\perp\cdot\vec{P}_{h\perp}}{P_{h\perp}^2}\,\delta^{(2)}(z_h\vec{k}_\perp+\vec{p}_\perp+\vec{\lambda}_\perp-\vec{q}_\perp) \times q_T(x_B,k_\perp,\zeta)\,\hat{q}(z_h,p_\perp,\hat{\zeta})\,(S(\lambda_\perp))^{-1}$$

- When $q_\perp \gg \Lambda_{QCD}$, all distributions and soft factor can be calculated from pQCD, by radiating a hard gluon

# Sivers Function at Large $k_\perp$

$$q_T(x,k_\perp) = -\frac{\alpha_s}{4\pi^2}\frac{2M_p}{(k_\perp^2)^2}\int\frac{dx}{x}\{A + C_F T_F(x) \times \delta(\xi-1)\left(\ln\zeta^2/\vec{k}_\perp^2 - 1\right)\}$$

- $1/k_\perp^4$ follows a power counting
- Drell-Yan Sivers function has opposite sign
- Plugging this into the factorization formula, we indeed reproduce the polarized cross section calculated from twist-3 correlation

# PROCESS-DEPENDENT COEFFICIENTS…

## Gluonic poles

- Thus

  $\Phi_\partial^{[\pm]\alpha}(x) = \Phi_\partial^{\alpha}(x) + C_G^{[\pm]}\,\pi\Phi_G^{\alpha}(x,x)$
- $C_G^{[\pm]} = \pm 1$
- with universal functions in gluonic pole m.e. (T-odd for distributions)
- There is only one function $h_1^{\perp(1)}(x)$ [Boer-Mulders] and (for transversely polarized hadrons) only one function $f_{1T}^{\perp(1)}(x)$ [Sivers] contained in $\pi\Phi_G$
- These functions appear with a process-dependent sign
- Situation for FF is more complicated because there are no T constraints

What about other hard processes (in particular pp scattering)?

Efremov and Teryaev 1982; Qiu and Sterman 1991
Boer, Mulders, Pijlman, NPB 667 (2003) 201

P. MULDERS

# …AND UNIVERSAL PARTONIC QUANTITIES

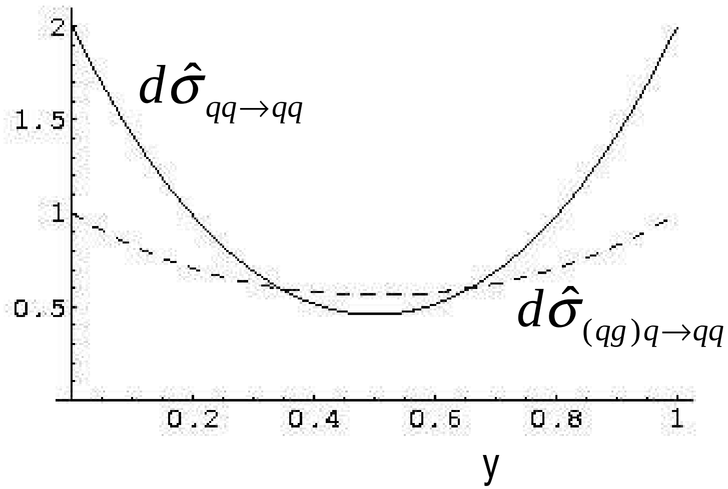
## Gluonic pole cross sections

- In order to absorb the factors $C_G^{[U]}$, one can define specific hard cross sections for gluonic poles (to be used with functions in transverse moments)
- for pp:

$$\hat{\sigma}_{qq\to qq} = \sum_{[D]} \hat{\sigma}^{[D]} \qquad \hat{\sigma}_{(qg)q\to qq} = \sum_{[D]} C_G^{[D]} \hat{\sigma}^{[D]}$$

etc.

(gluonic pole cross section)




- for SIDIS:

$$\hat{\sigma}_{\ell(qg)\to \ell q} = +\hat{\sigma}_{\ell q\to \ell q}$$

for DY:

$$\hat{\sigma}_{(qg)\bar{q}\to \ell\bar{\ell}} = -\hat{\sigma}_{q\bar{q}\to \ell\bar{\ell}}$$

- Similarly for gluon processes

Bomhof, Mulders, Pijlman, EPJ; hep-ph/0601171

HADRONIC QUANTITIES CAN BE EXPRESSED
IN TERMS OF UNIVERSAL PARTONIC MATRIX ELEMENTS…

**P. MULDERS**

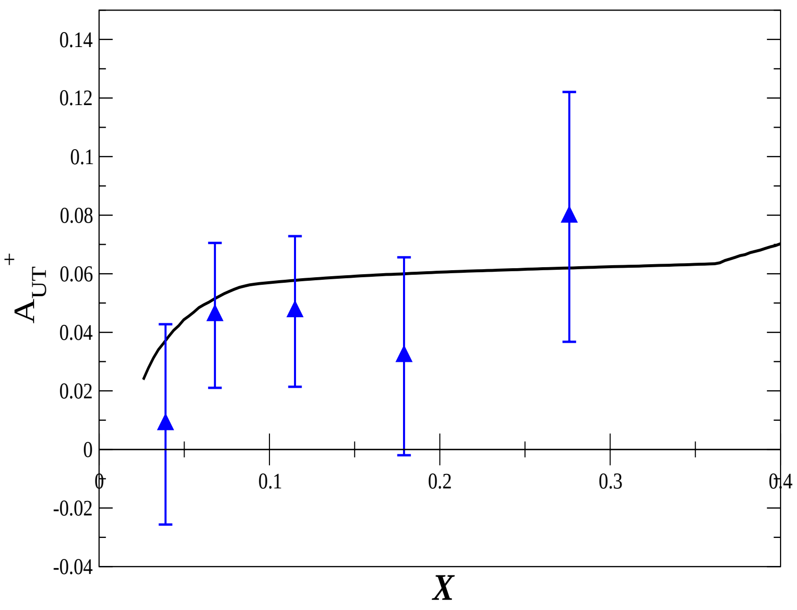
# Collins Asymmetry

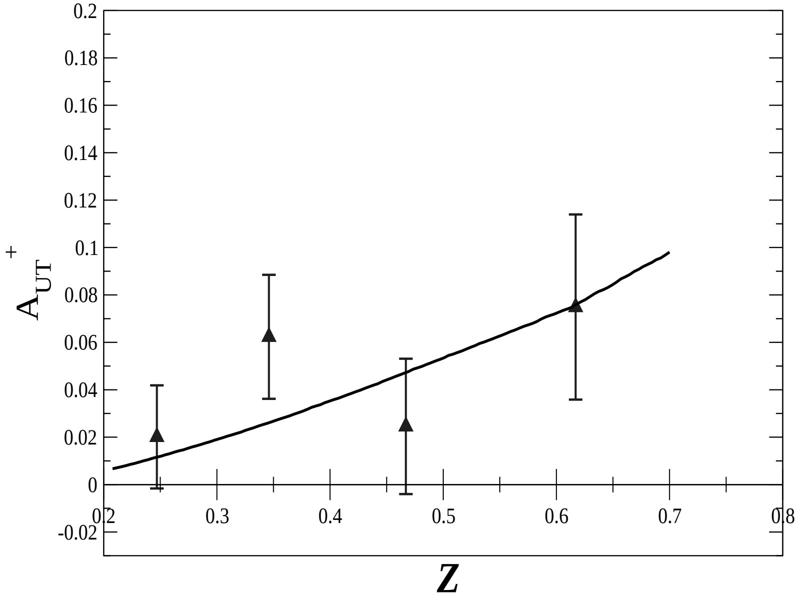
L.G., Goldstein, Oganessyan PRD 2003: updated For the HERMES kinematics

1 GeV$^2 \leq Q^2 \leq 15$ GeV$^2$, 4.5 GeV $\leq E_\pi \leq 13.5$ GeV, $0.2 \leq x \leq 0.41$, $0.2 \leq z \leq 0.7$, $0.2 \leq y \leq 0.8$, $< P_{h\perp}^2 >= 0.25$ GeV$^2$

$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT} = |S_T| \frac{2(1-y)\sum_q e_q^2 h_1(x) z H_1^{\perp(1)}(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x) D_1(z)}.$$

Data from A. Airapetian et al. PRL94,2005



# SUMMARY

- A DRAMATIC IMPROVEMENT OF OUR UNDERSTANDING OF NUCLEON SPIN IS BEHIND THE CORNER, DUE TO COMBINATION OF HERMES, COMPASS & RHIC DATA WITH FULL NLO ANALYSIS

- NLO AND RESUMMED RESULTS ALREADY AVAILABLE FOR MOST INTERESTING POLARIZED PROCESS

- FACTORIZATION OF COLLINS, SIVERS AND BOER-MULDERS PROCESSES UNDERSTOOD IN QCD

# SUMMARY

- A DRAMATIC IMPROVEMENT OF OUR UNDERSTANDING OF NUCLEON SPIN IS BEHIND THE CORNER, DUE TO COMBINATION OF HERMES, COMPASS & RHIC DATA WITH FULL NLO ANALYSIS

  NEED A FULL CONSISTENT GLOBAL FIT

- NLO AND RESUMMED RESULTS ALREADY AVAILABLE FOR MOST INTERESTING POLARIZED PROCESS

  SOME EXPERIMENTALLY RELEVANT PROCESSES MISSING: E.G. TWO LARGE $p_t$ HADRONS

- FACTORIZATION OF COLLINS, SIVERS AND BOER-MULDERS PROCESSES UNDERSTOOD IN QCD

  NEED SYSTEMATIC PHENOMENOLOGY

# OUTLOOK

SPIN PHYSICS CHALLENGES OUR KNOWLEDGE OF QCD AT A FUNDAMENTAL LEVEL

IT IS THE ULTIMATE TESTING GROUND OF OUR UNDERSTANDING OF ITS THEORY AND PHENOMENOLOGY