Summary of the spin physics sessions - theory part

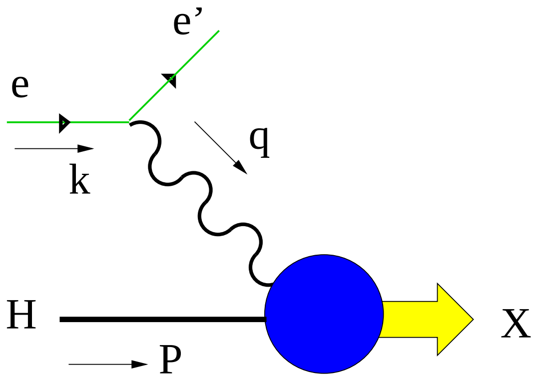
Convenors of WG: Daniël Boer, Delia Hasch, Gerhard Mallot

Spin physics WG has expanded considerably w.r.t. other years
7 + 2 sessions (2 joined with Diffraction & Vector Mesons WG)
Number of theory talks: 14 (5 long. vs 9 transv.)+3

Transverse spin phenomena receive increased attention
Also from a theory perspective they are quite challenging
Recent years have seen quite some unexpected developments concerning TMDs

[The usual disclaimer for summary talks applies]

Polarized DIS: $\vec{\ell}\,\vec{p} \to \ell' X$



$$W_A^{\mu\nu} = \frac{i\epsilon^{\mu\nu\rho\sigma} q_\rho}{P \cdot q} \left[S_\sigma g_1(x_B, Q^2) + \left(S_\sigma - \frac{S \cdot q}{P \cdot q} P_\sigma \right) g_2(x_B, Q^2) \right]$$

$$x_B = Q^2/2P \cdot q \qquad Q^2 = -q^2$$

$$\Gamma_1^{p/n}(Q^2) = \int_0^1 dx\; g_1^{p/n}(x, Q^2) = \frac{1}{36} \left(4\Delta\Sigma \pm 3\Delta q_3 + \Delta q_8\right) \left(1 + \frac{\alpha_s}{\pi}\right) + \mathcal{O}(\alpha_s^2)$$

The famous spin crisis/puzzle

The sum of quark contributions to the proton spin:

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s$$

The number of quarks and antiquarks of flavor q with helicity $+$ minus $-$:

$$\Delta q = (q_+ - q_-) + (\bar{q}_+ - \bar{q}_-)$$

$\Delta\Sigma$ can be extracted from polarized DIS (using input from β-decay processes)

European Muon Collaboration [1989] ($\langle Q^2 \rangle = 10.7$ GeV^2): $\Delta\Sigma = 0.12 \pm 0.17$

Spin Muon Collaboration [1998] ($Q^2 = 1$ GeV^2): $\Delta\Sigma = 0.19 \pm 0.06$

The quarks and antiquarks together contribute very little to the proton spin!

Polarized DIS off p, n, d

At DIS 2007 we heard the latest results from COMPASS and HERMES

COMPASS [Kurek]

$$\Delta\Sigma = 0.35 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.}) \qquad Q^2 = 3\ \text{GeV}^2$$

HERMES [DeNardo]

$$\Delta\Sigma = 0.330 \pm 0.025(\text{exp.}) \pm 0.028(\text{evol.}) \pm 0.011(\text{theo.}) \qquad Q^2 = 5\ \text{GeV}^2$$

Almost twenty years after EMC the conclusion remains essentially the same!

Spin sum rule

In general, one expects the following "spin sum rule" to hold

$$\text{proton spin} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

$$\Delta G = \int dx\, \Delta G(x) = \int dx\, [G_+ - G_-]$$

Inclusive DIS is sensitive to $\Delta G(x)$ through Q^2 dependence of g_1:

$$\begin{aligned} g_1^{p/n}(x,Q^2) &= \frac{1}{36}\left(4\Delta\Sigma \pm 3\Delta q_3^{\rm NS} + \Delta q_8^{\rm NS}\right) \otimes \left(1 + \frac{\alpha_s}{2\pi}\Delta C_q\right) \\ &+ \sum_q e_q^2 \frac{\alpha_s}{2\pi}\Delta G \otimes \Delta C_g + \mathcal{O}(\alpha_s^2) \end{aligned}$$

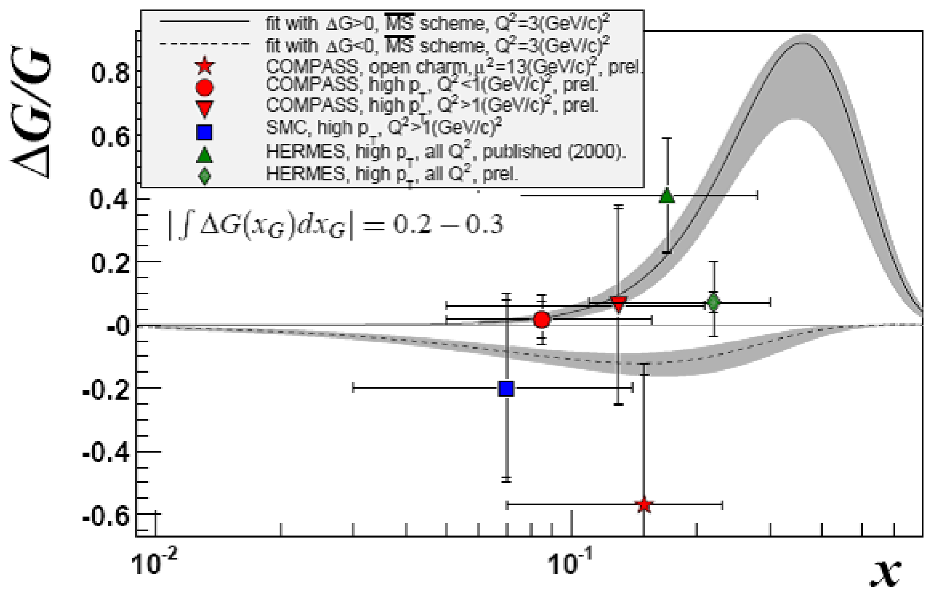
Stamenov: inclusion of $Q^2 \approx 1 - 5$ GeV^2 data of CLAS & COMPASS, higher twist

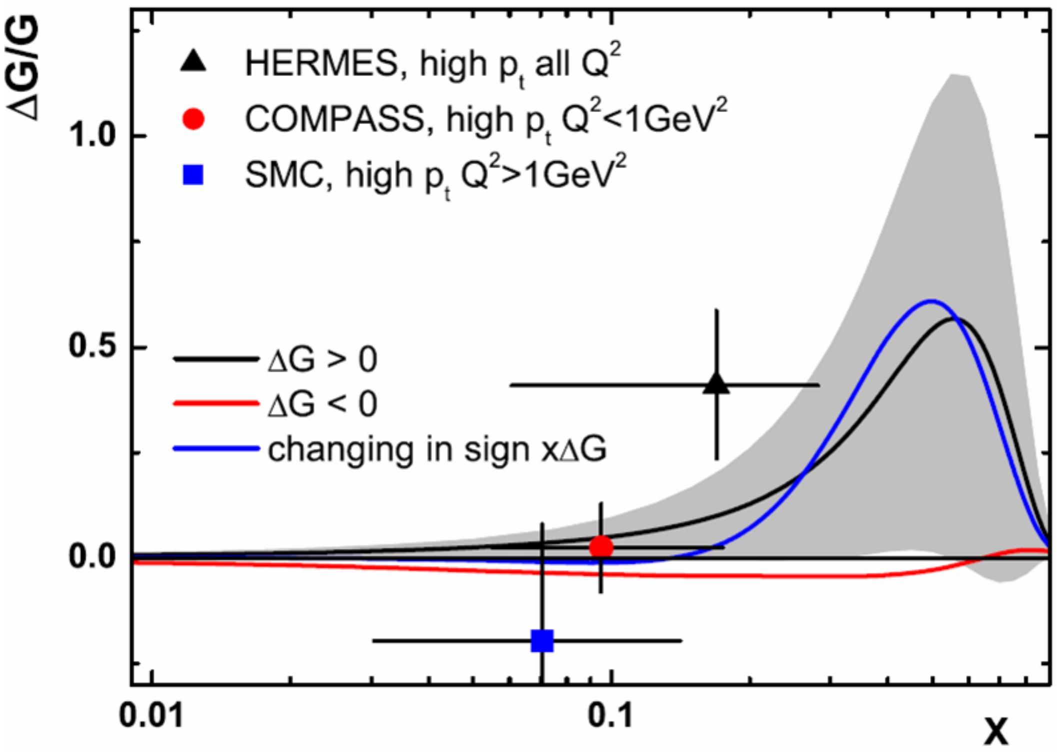
Ermolaev: study $2P{\cdot}q$ dependence of g_1 to estimate impact of initial gluon density

$\Delta G(x)$ from inclusive DIS

Many groups have extracted fits of the polarized pdf's (GRSV, BB, AAC, LSS, ...)

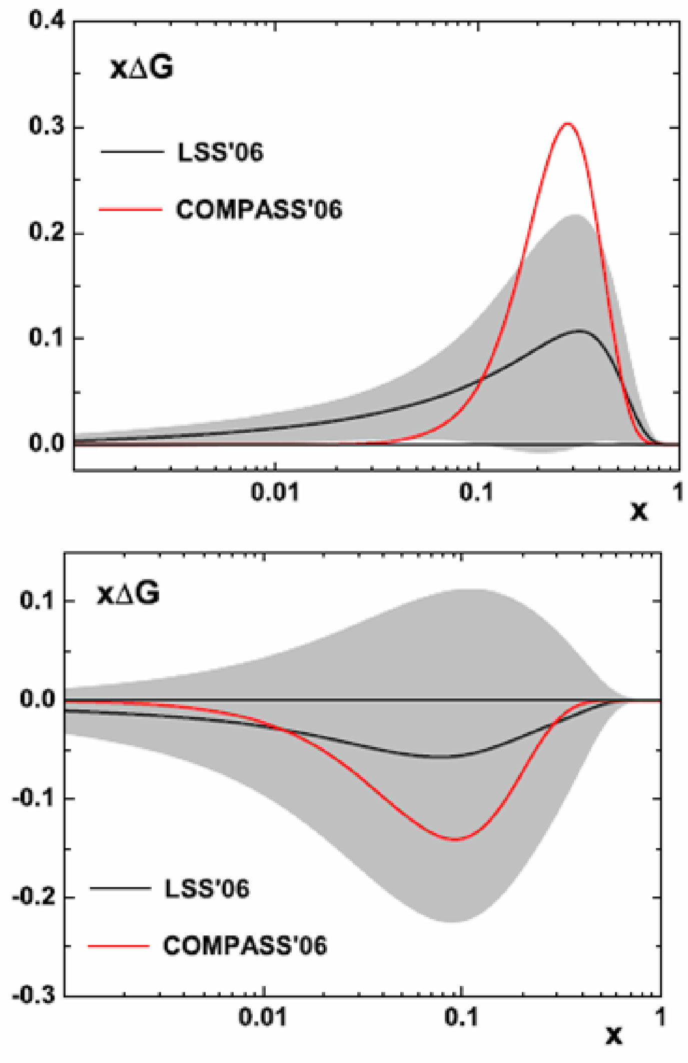
COMPASS 2006 fit to world data of g_1 [Kurek] and LSS06 [Stamenov]



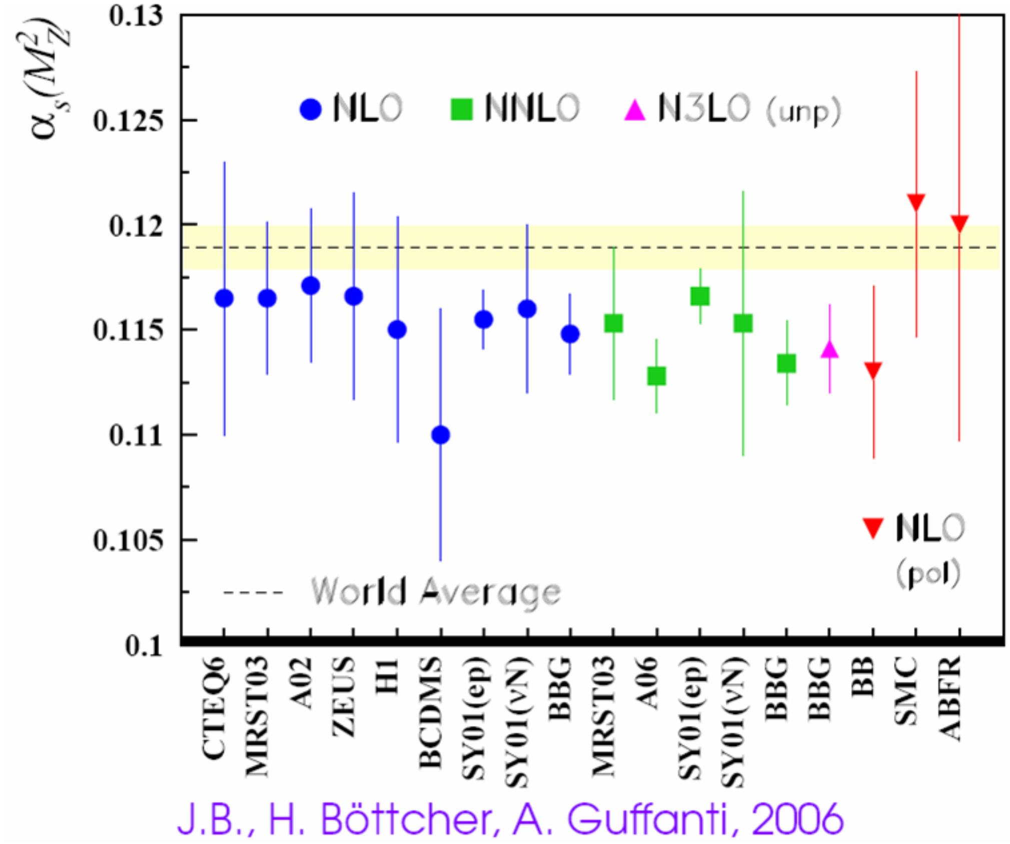


$\Delta G(x)$ from inclusive DIS

Stamenov also compared the fits



Blümlein: correlated fit of $\Lambda_{\rm QCD}$ and $\Delta G(x)$ is mandatory



$\Delta G(x)$ from other processes

At present $\Delta G(x)$ is under active experimental investigation using other processes:

- polarized semi-inclusive DIS

Liebing - HERMES: high-p_T inclusive charged hadrons
Koblitz - COMPASS: open charm

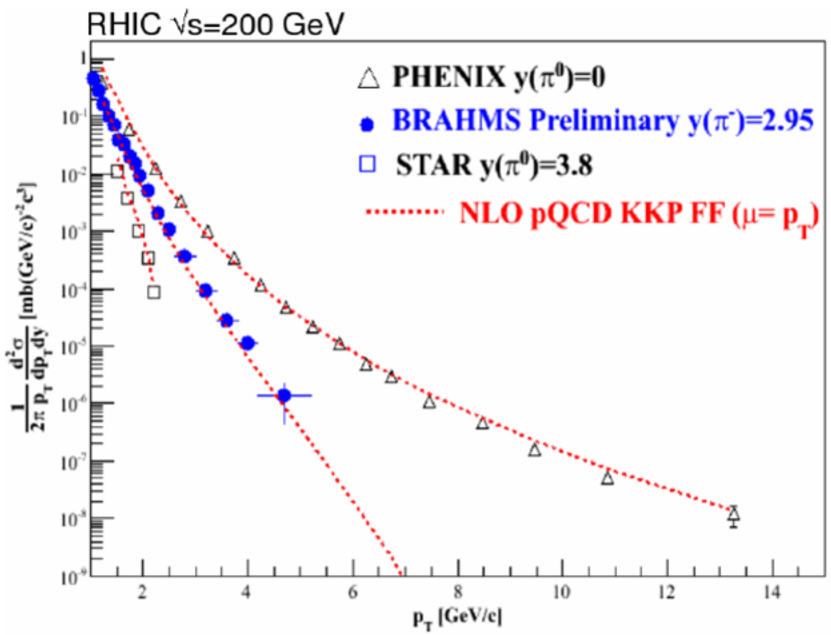
- polarized $p\,p$ collisions at RHIC (data at $\sqrt{s} = 200$ GeV indicate $\Delta G(x) \ll G(x)$)

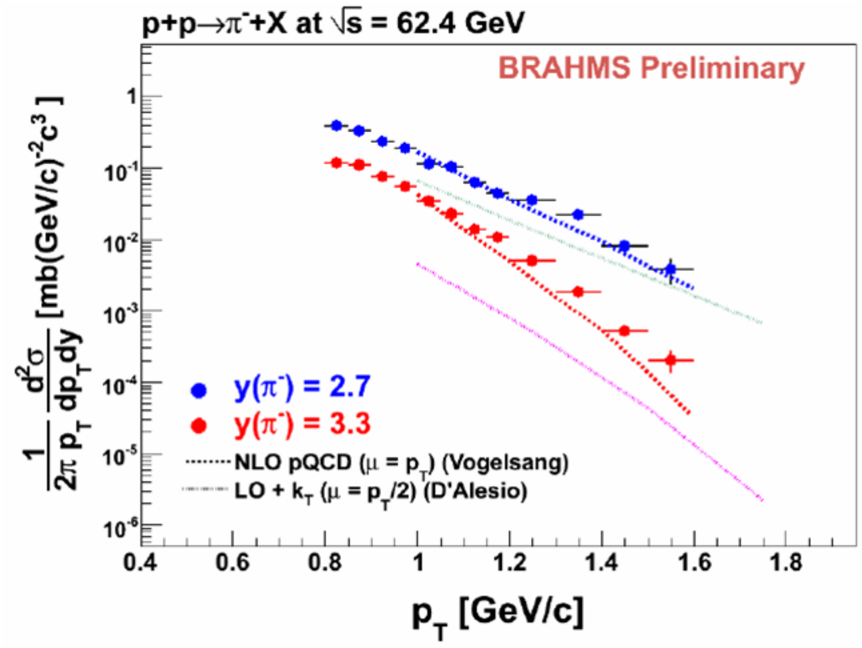
Okada - PHENIX: A_{LL} in π^0 production
Fatemi - STAR: A_{LL} in jet production
Simon -STAR: A_{LL} in $\pi^0, \pi^\pm$ production

For all observables one first has to make sure the cross sections are well-described

Concerning $\Delta G(x)$ from A_{LL} in pp

For PHENIX [Okada] and STAR [Fatemi] at $\sqrt{s} = 200$ GeV the cross section is well described by NLO pQCD using KKP fragmentation functions



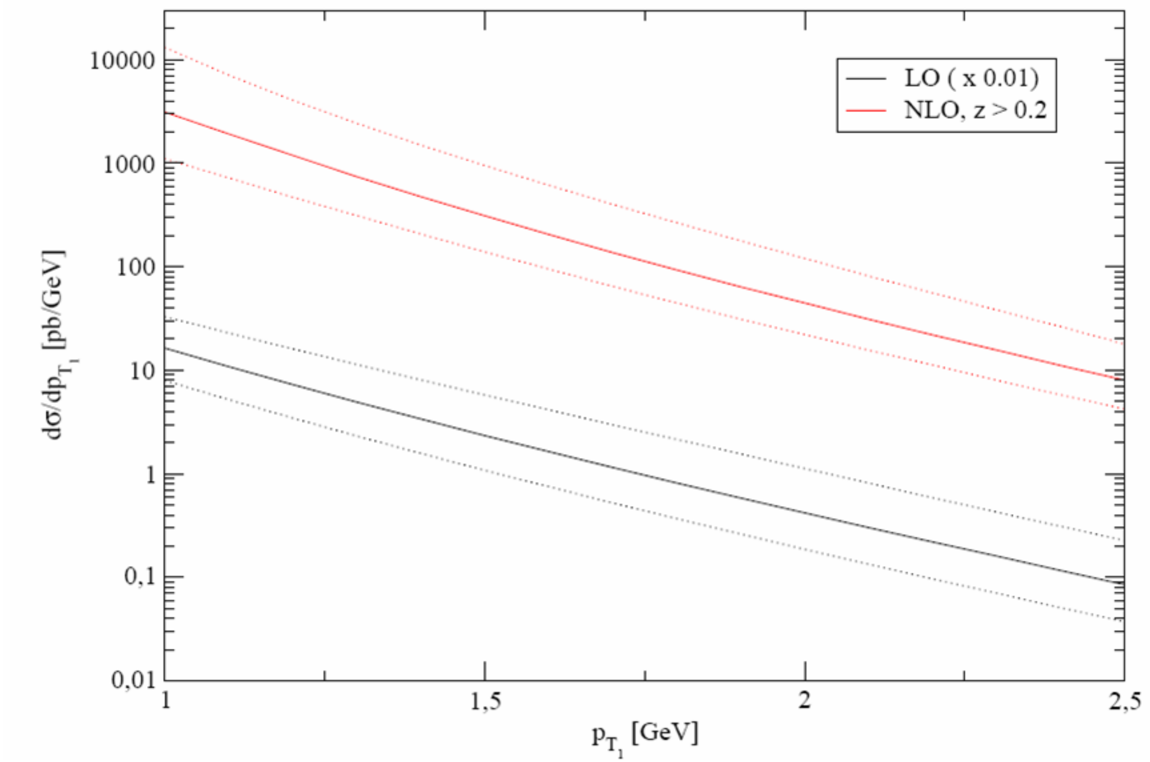


Plots presented by J.H. Lee [Brahms] since also relevant for transverse spin asymmetries

Concerning $\Delta G(x)$ from high-p_T hadron pairs

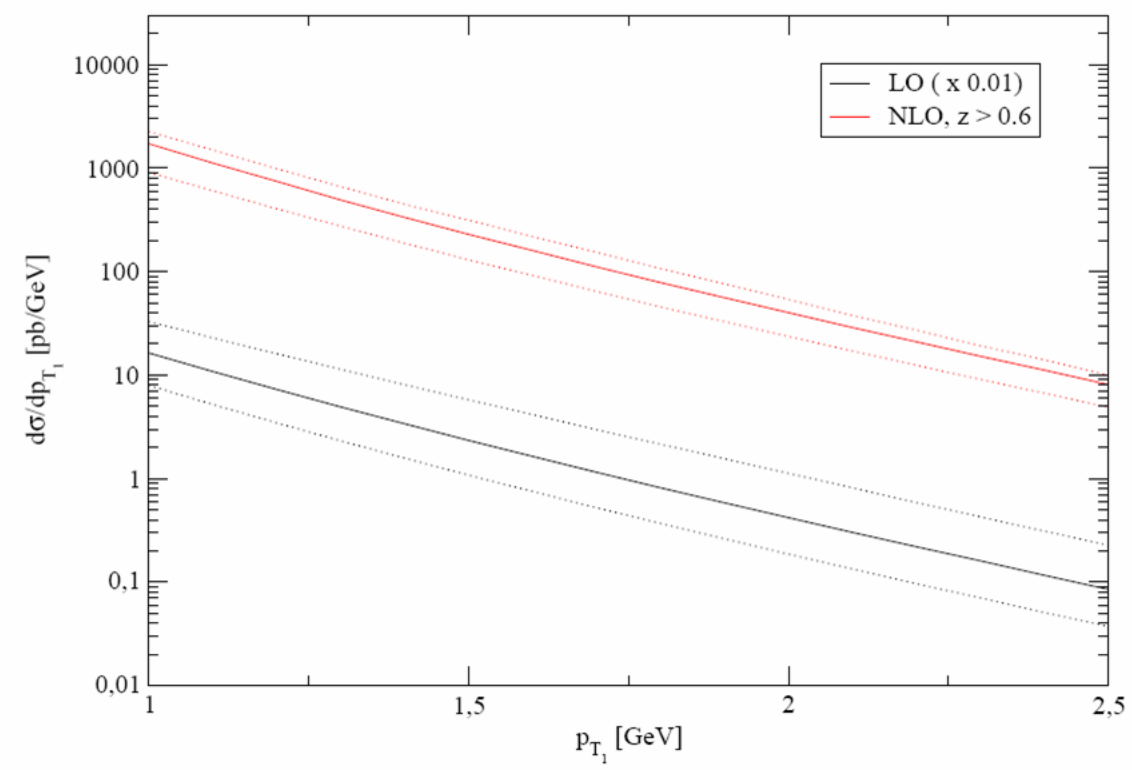
Hendlmeier: Photoproduction of hadron pairs with high transverse momenta
Application to COMPASS and HERMES situation
Scale dependence at NLO generally not smaller than at LO

Cross section for
COMPASS kinematics



ΔG from high-p_T hadron pairs

Scale dependence can be reduced by putting a lower cut on $z = -\vec{P}_{T,3} \cdot \vec{P}_{T,4} / \vec{P}^2_{T,3}$ (works for COMPASS, not for HERMES though)



Large scale dependence is of course reflected by the large error bars on extractions

L_z

All data seem to be consistent with $|\Delta G| \lesssim 0.3$

For $\Delta G \sim 0.3$ the spin sum rule can still be satisfied with small L_z

Renormalization scheme and scale dependent statement

However, for $\Delta G \sim -0.2$, $|L_z| \gtrsim \Delta\Sigma, |\Delta G|$

Lattice indicates: $L_q^u \approx -L_q^d$, hence $L_q \approx 0$

Importance of L_z remains to be seen

Future input:
- better ΔG determination especially from RHIC at $\sqrt{s} = 500$ GeV
- more lattice results
- L_q from forward extrapolations of GPD extractions

Transverse polarization

Just as the axial charge Δq is defined as:

$$\langle P,S|\overline{\psi}_q \gamma^\mu \gamma_5 \psi_q(0)|P,S\rangle \sim \Delta q\, S^\mu$$

For a transversely polarized proton the tensor charge is defined as:

$$\langle P,S|\overline{\psi}_q [\gamma^\mu,\gamma^\nu]\gamma_5 \psi_q(0)|P,S\rangle \sim \delta q\, [P^\mu S^\nu - P^\nu S^\mu]$$

$$\delta q = \int dx\, h_1^q(x) \qquad h_1(x) \text{ is called transversity}$$

h_1 contains completely new information on the proton spin structure

Theoretically most safe extractions can come from:

- A_{TT} in $p^\uparrow \bar{p}^\uparrow \to e^+ e^- X$ (GSI/FAIR)
- the use of two-hadron fragmentation functions [Seidl - BELLE, Schill - COMPASS]

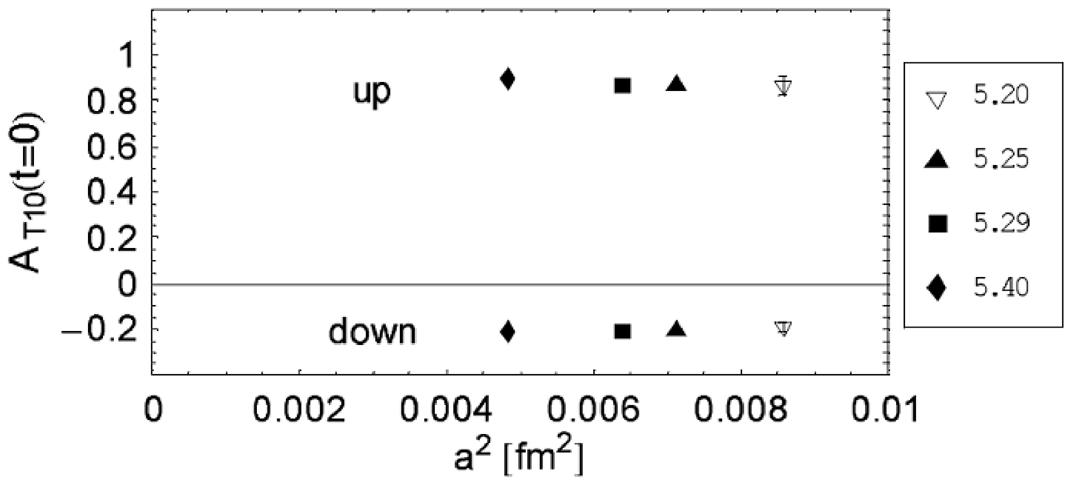
Transverse polarization - theory talks

Radici: Evolution equations for two-hadron fragmentation functions

Hägler: Transverse spin structure of hadrons from lattice QCD, tensor GPDs
Update on earlier determination with dynamical quarks and obtained at $\mu^2 = 4$ GeV^2:

$$\delta u = 0.857 \pm 0.013, \quad \delta d = -0.212 \pm 0.005$$

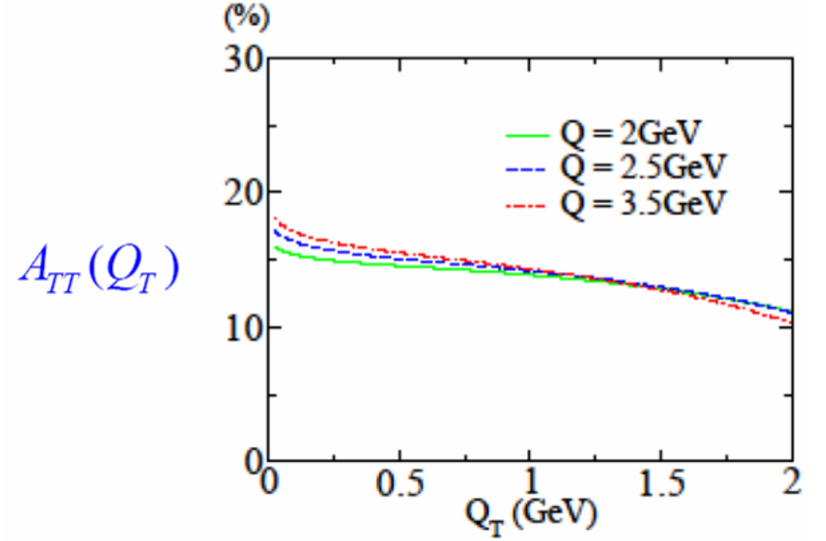
QCDSF and UKQCD Collab., Göckeler *et al.*, PLB 627 (2005) 113

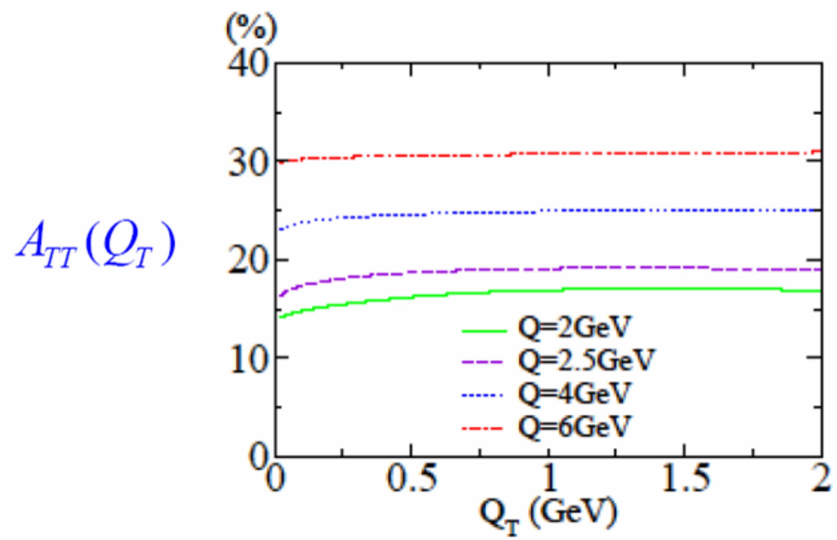


Transverse polarization - theory talks

Kawamura: Soft gluon resummation for $A_{TT}(Q_T) \sim h_1\, h_1$

Left: $p^{\uparrow}p^{\uparrow}$ at J-PARC; Right: $p^{\uparrow}\bar{p}^{\uparrow}$ at GSI (both $\sqrt{s} = 10$ GeV)



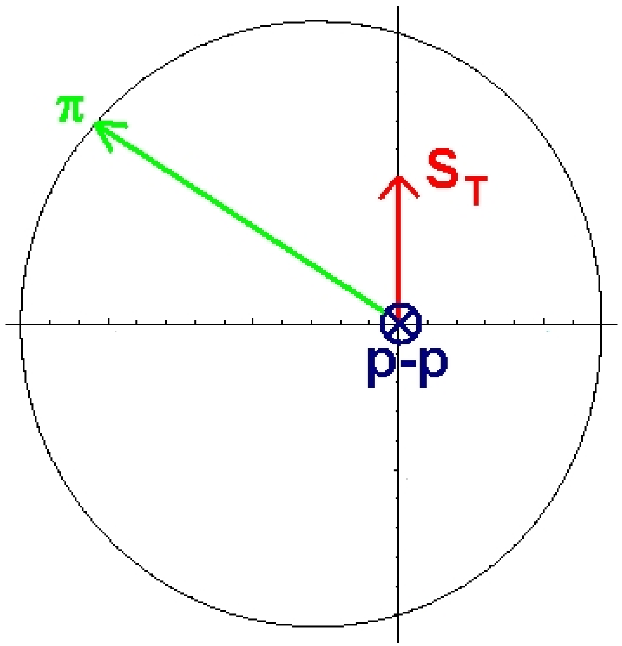


Left-right asymmetries

Transverse polarization has another trick up its sleeve...

Large single spin asymmetries in $p\,p^{\uparrow} \rightarrow \pi\,X$ have been observed

E704 Collab. ('91); AGS ('99); STAR ('02); BRAHMS ('05); ...



A left-right asymmetry

Pion distribution is asymmetric depending on transverse spin direction and on pion charge

What is the explanation at the quark-gluon level?

Twist-3 formalism

One suggestion is to describe the left-right asymmetry A_N at twist-3 level
Qiu-Sterman effect (PRL 67 (1991) 2264; PRD 59 (1999) 014004)

A matrix element of the type:

$$G_F \sim \langle P, S_T |\, \overline{\psi}(0) \int d\eta^- \; F^{+\alpha}(\eta^-) \, \gamma^+ \, \psi(\xi^-) \, | P, S_T \rangle$$

Formalism applies at high-p_T

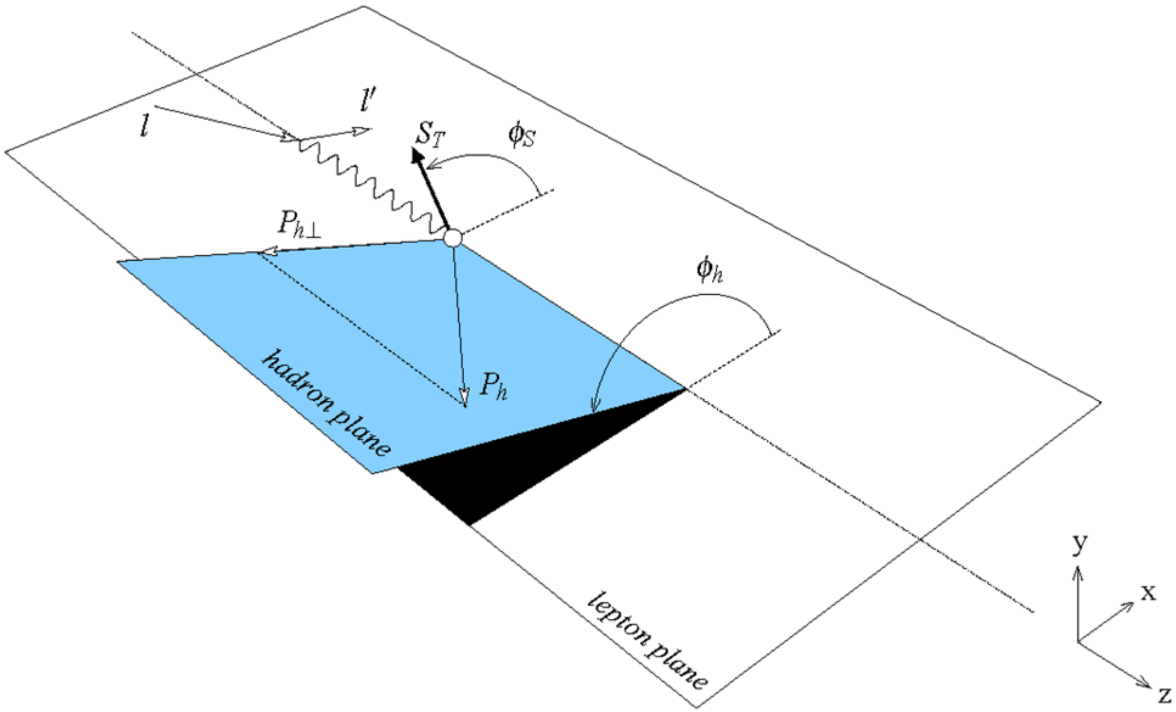
Koike: showed twist-3 factorization and gauge invariance of A_N expression

Tanaka: novel master formula for A_N in various processes
Twist-3 SSA obtained from twist-2 unpolarized cross section
Provides an understanding of why the combination $G_F - x\, dG_F/dx$ always appears

Transverse momentum of quarks

A_N can also be described by a natural but quite nontrivial extension of $q(x) \to q(x, \boldsymbol{k}_T)$

k_T-dependent pdfs (TMDs) can be probed in experiments, such as in semi-inclusive DIS



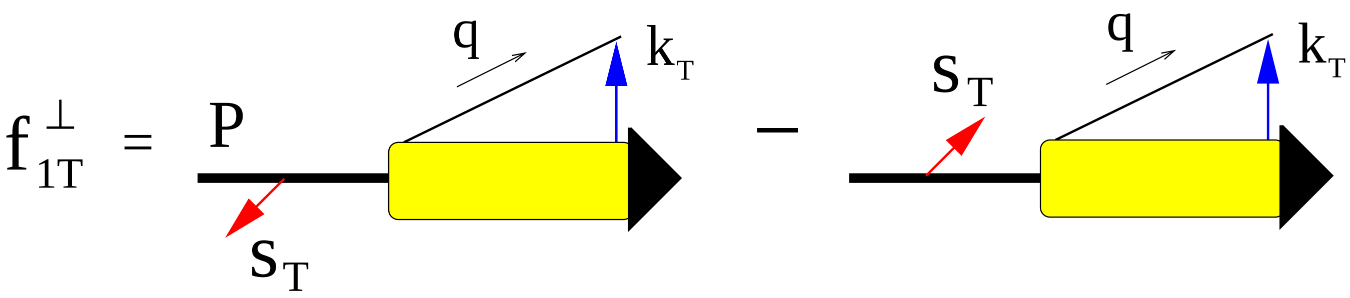
Sivers asymmetry: $\sin(\phi_h - \phi_S)$; Collins asymmetry: $\sin(\phi_h + \phi_S)$

Diefenthaler - HERMES; Bressan - COMPASS; Kotzinian - COMPASS

Spin dependent TMDs

$$f_1(x) \Longrightarrow f_1(x,\boldsymbol{k}_T^2) + \frac{\boldsymbol{P}\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)}{M}\, f_{1T}^{\perp}(x,\boldsymbol{k}_T^2)$$

Upon integration over transverse momentum the Sivers function $f_{1T}^{\perp}$ drops out



Sivers, PRD 41 (1990) 83

Sivers $\sin(\phi_h - \phi_S)$ asymmetry in $e\,p^{\uparrow} \to e'\,\pi\,X \propto f_{1T}^{\perp} D_1$

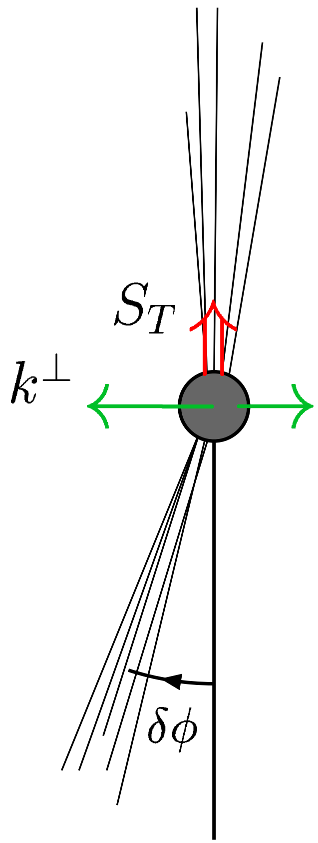
Bacchetta: complete expressions of all 18 SIDIS structure functions in terms of TMDs

Measuring the Sivers effect in $p^\uparrow p$

Asymmetric jet or hadron correlations in $p^\uparrow p \to h_1 h_2 X$

D.B. & Vogelsang, PRD 69 (2004) 094025

Bacchetta *et al.*, PRD 72 (2005) 034030



A closely related asymmetry has been measured by STAR [Balewski]

Process dependence of TMDs

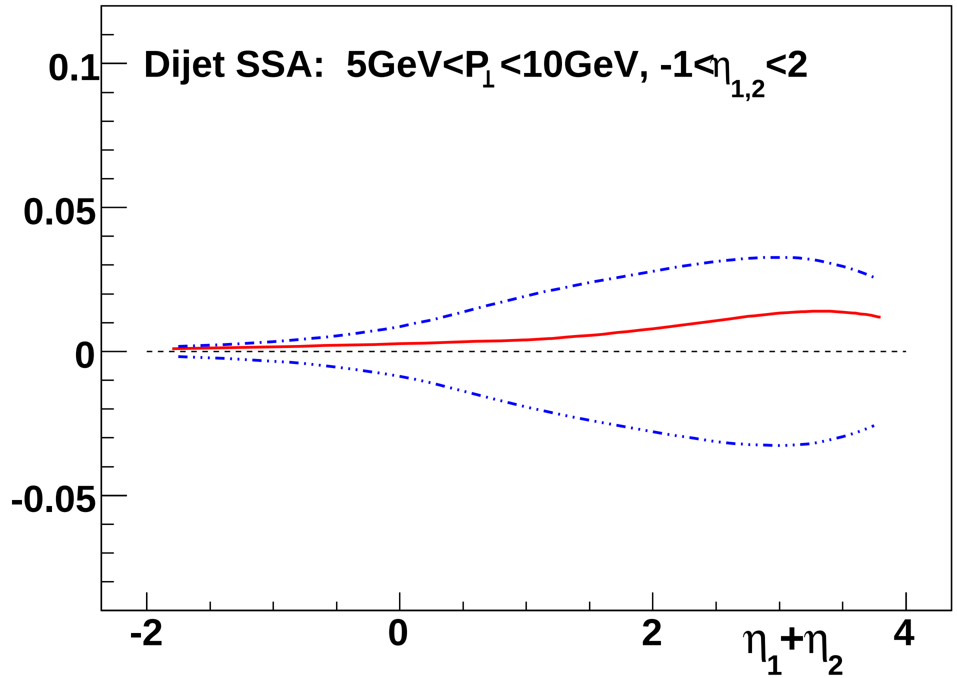
TMDs have a *calculable* process dependence (Collins, PLB 536 (2002) 43):

$$(f_{1T}^{\perp})_{\text{SIDIS}} \quad = \quad -(f_{1T}^{\perp})_{\text{DY}}$$

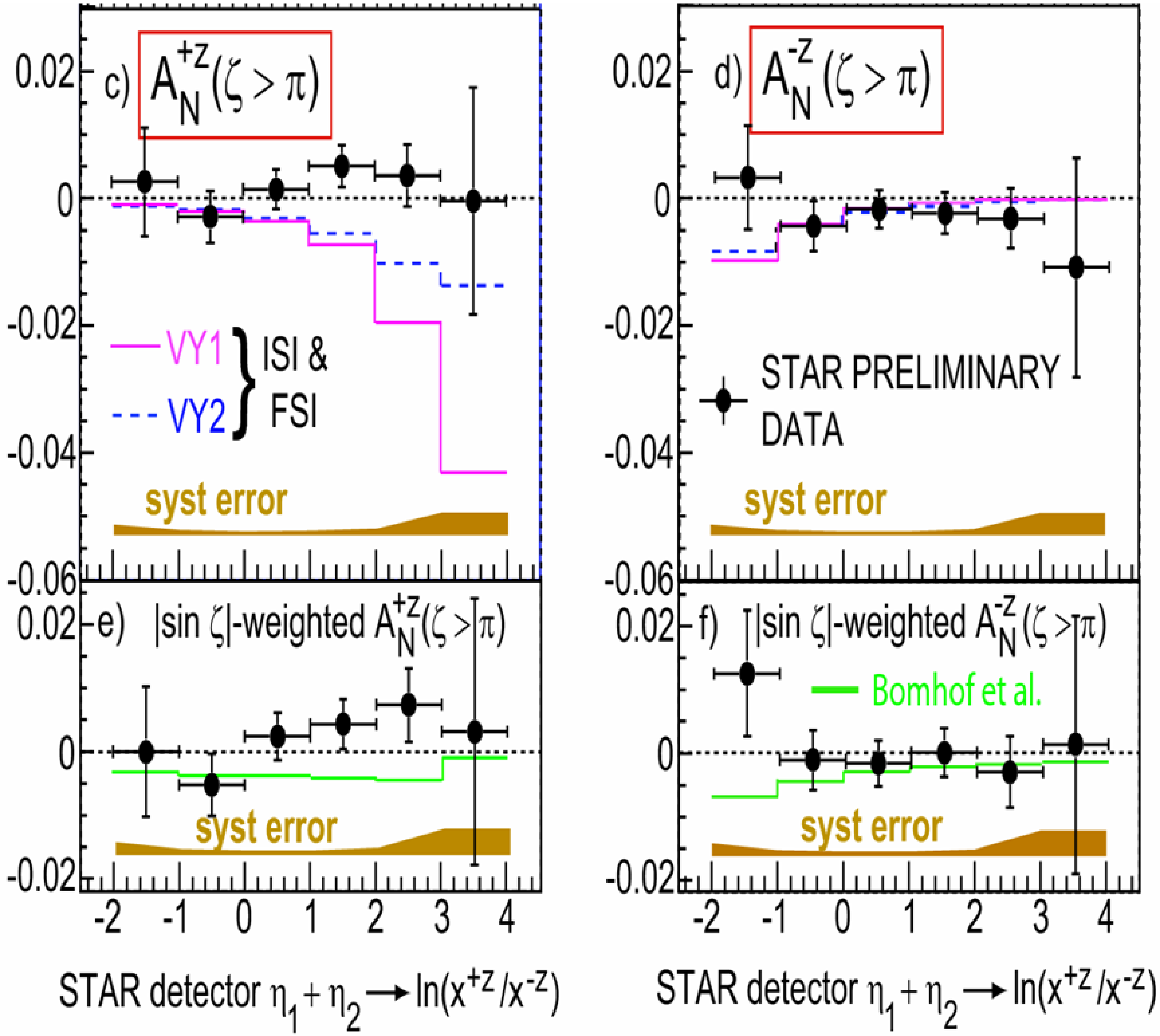
The color flow of a process is crucial
The more hadrons are observed, the more complicated the end result

Bomhof: $p^{\uparrow} p \longrightarrow \text{jet} + \text{jet} + X \; (\propto f_{1T}^{\perp})$

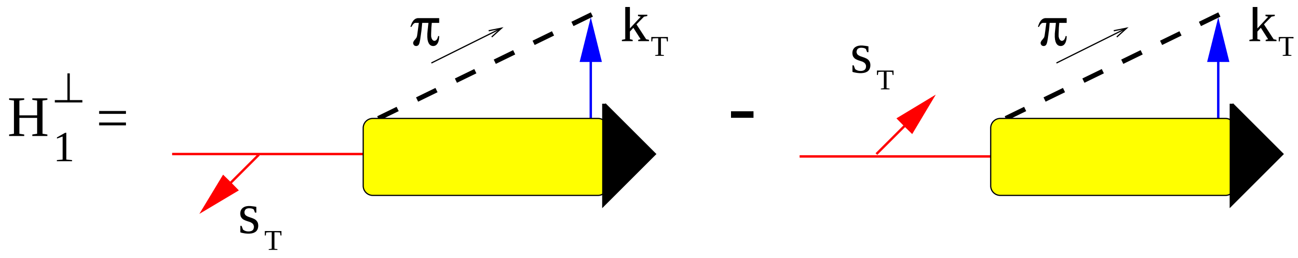
$$f_{1T}^{u\perp(1/2)}(x) \quad = \quad -0.75\, x(1-x)\, u(x)$$
$$f_{1T}^{u\perp(1/2)}(x) \quad = \quad 2.76\, x(1-x)\, d(x)$$



Dijet Asymmetry at STAR [Balewski]



Collins fragmentation function



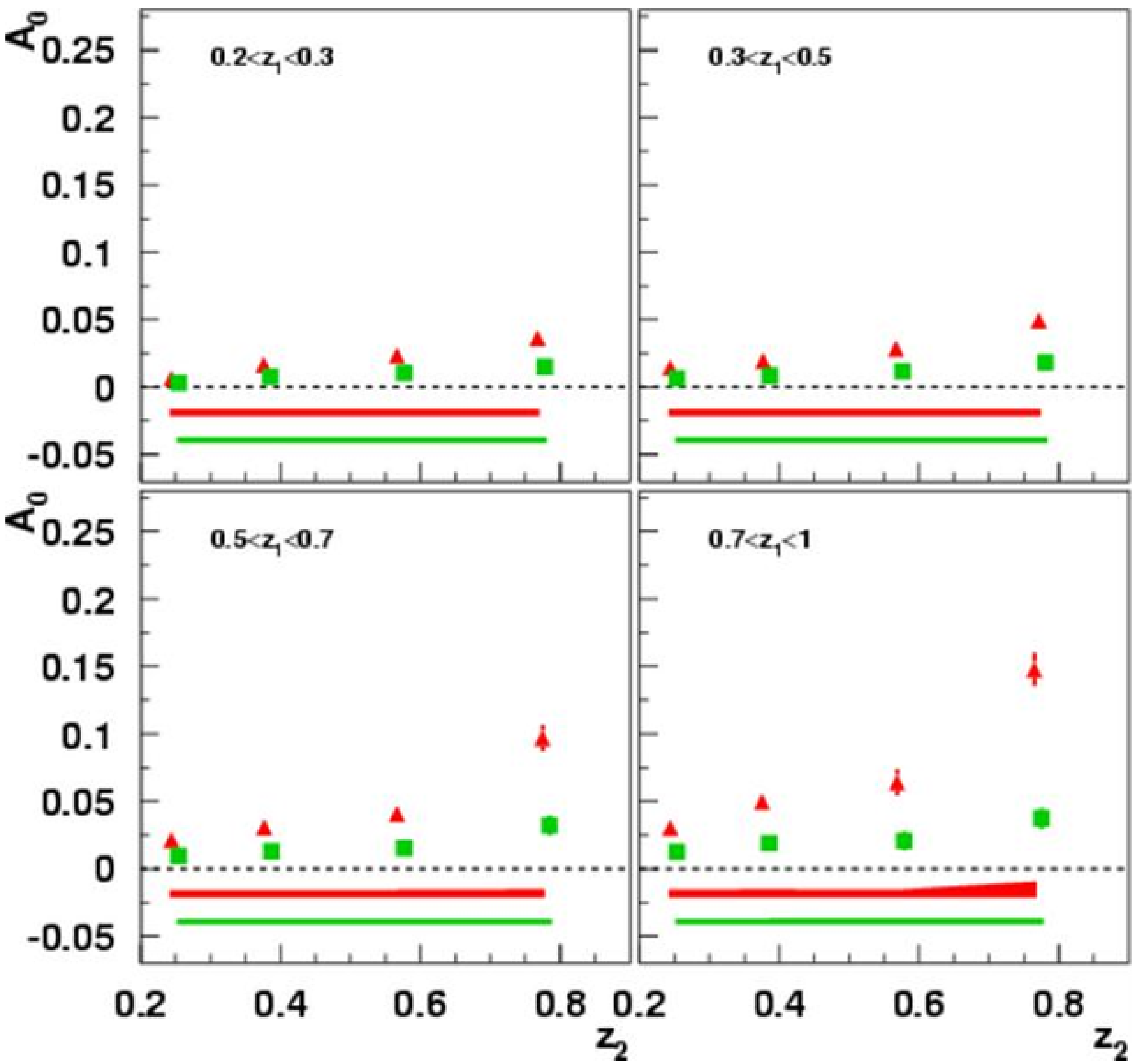
Collins, NPB 396 (1993) 161

It can be extracted from $e^+\ e^- \to \pi^+\ \pi^-\ X$: $\langle\cos(2\phi)\rangle \propto (H_1^\perp)^2$
D.B., Jakob & Mulders, NPB 504 (1997) 345

This has been done using BELLE data, K. Abe *et al.*, PRL 96 (2006) 232002 [Seidl]

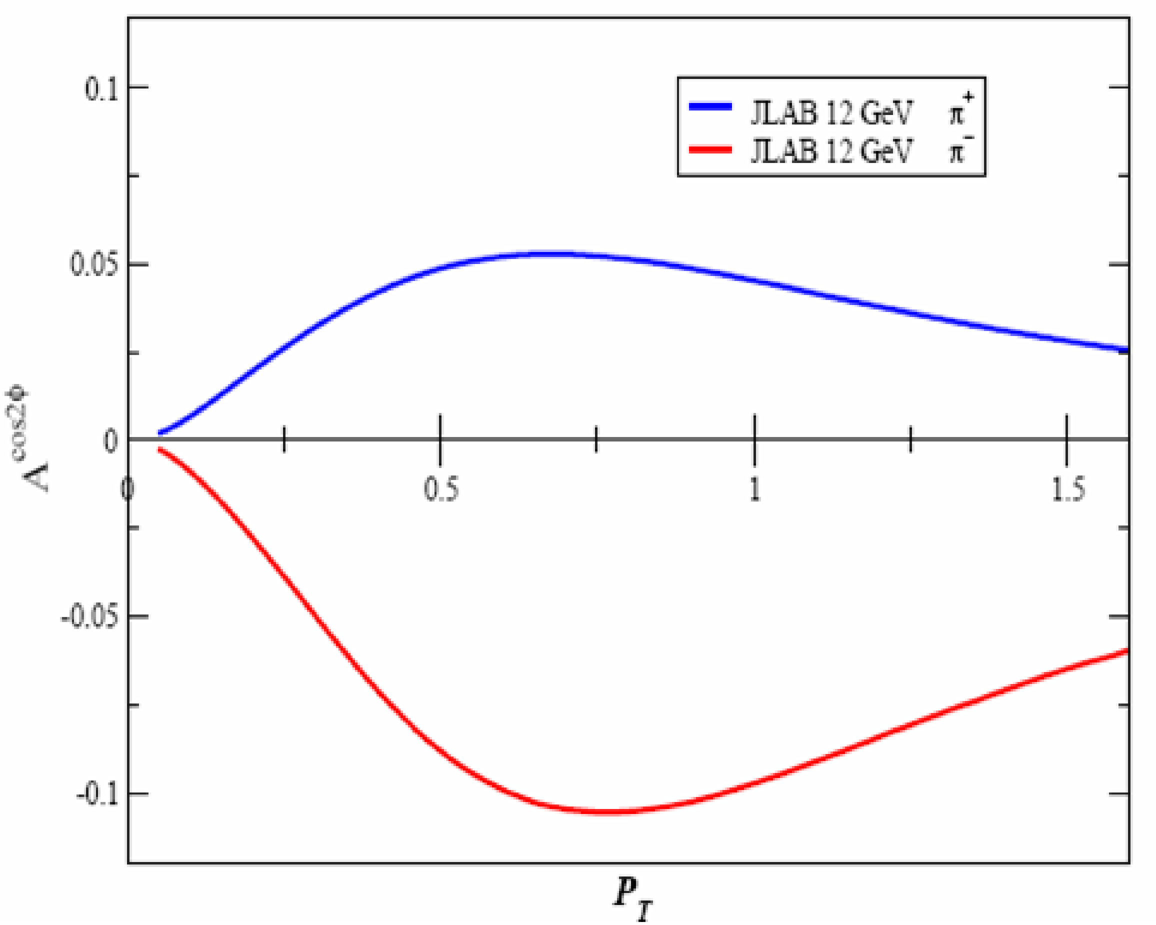
D'Alesio: h_1 and Collins functions ($H_1^\perp$): from e^+e^- ($\propto H_1^\perp H_1^\perp$) to SIDIS processes ($\propto h_1 H_1^\perp$), all data can be simultaneously described

$\cos 2\phi$ asymmetry in $e^+ e^- \to \pi^+ \pi^- X$ [Seidl]



$\cos 2\phi$ asymmetry in unpolarized SIDIS

Gamberg: model prediction of $\cos 2\phi$ asymmetry in unpolarized SIDIS ($\propto h_1^{\perp} H_1^{\perp}$)



Relation between TMDs and GPDs?

One may expect a relation of the Sivers effect with OAM and hence with GPDs

A model dependent relation between $f_{1T}^{\perp(1)}$ and the GPD E has been put forward

Burkardt, NPA 635 (2004) 185; Burkardt & Hwang, PRD 69 (2004) 074032

$$f_{1T}^{\perp(1)}(x) \propto \epsilon_{ij} S_T^i b_\perp^j \int db_\perp^2 \boldsymbol{I}(b_\perp^2) \frac{\partial}{\partial b_\perp^2} E(x, b_\perp^2)$$

The factor $\boldsymbol{I}(b_\perp^2)$ not analytically calculable, has to be modeled

Allows to link the Sivers function to the anomalous magnetic moment of u, d

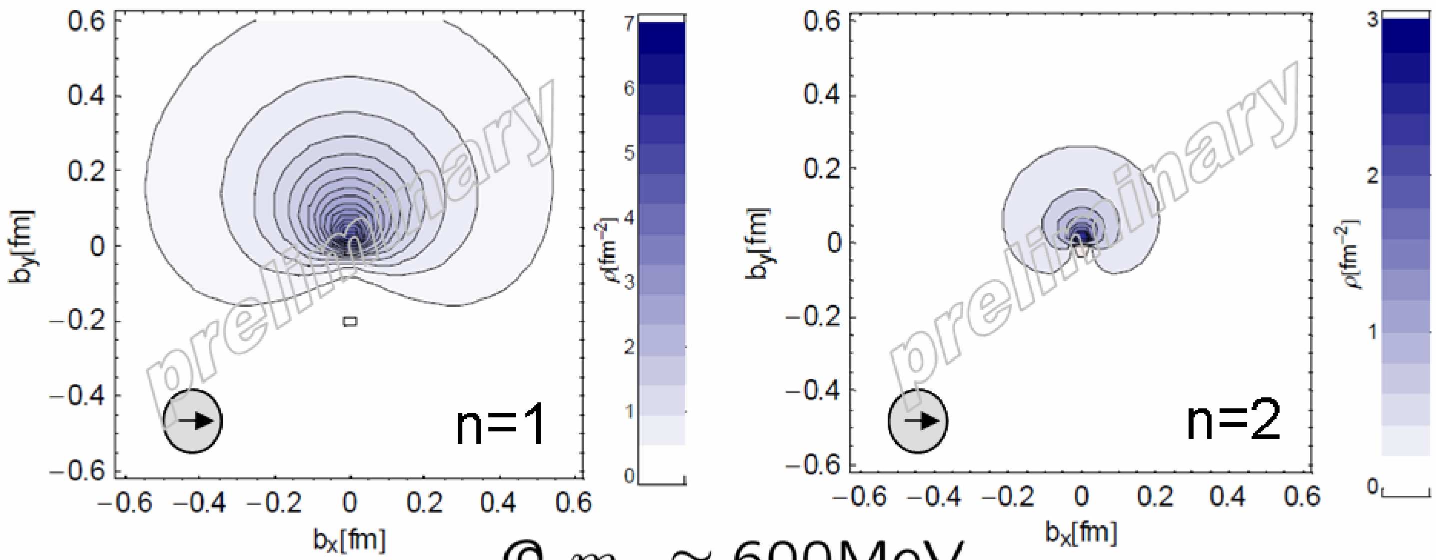
Metz extended this type of model-dependent but nontrivial relations to all TMDs

Transverse quark spin structure of the pion

Hägler showed the first lattice result relevant for $h_1^\perp$ of the pion

$$\rho_T(x, b_\perp; s_\perp) = \frac{1}{2}\left\{H^\pi(x, b_\perp^2) - \epsilon_{ij} s_\perp^i b_\perp^i \frac{1}{m_\pi} E_T^{\pi\prime}\right\}$$

but is $E_T^{\pi\prime}$ non-zero?



@ $m_\pi \approx 600$MeV

the pion has a very surprising non-trivial transverse spin structure!