Spin Physics - Summary (Theory)

Conveners: Abhay Deshpande, Sergey Yaschenko, Kresimir Kumericki, Marc Schlegel

Sketch of main results, Apologies to those missed

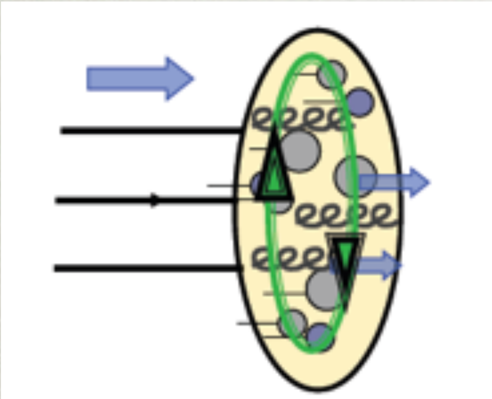
DIS 2012 - 30.03.2012 - Bonn, Germany

Content of WG Spin Physics Session

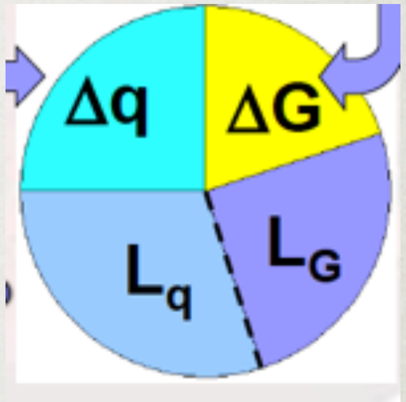
- Longitudinal Spin Physics - 14 talks
  - ➥ Long. DSA (A_{LL}), Helicity Parton Distributions, ΔG, ...
  - ➥ Partonic Orbital Angular Momentum
- Transverse Spin Physics - 15 talks
  - ➥ Transverse SSA, collinear formalism, ...
  - ➥ TMD - factorization, Sivers/Collins effect, transversity ...
- Exclusive Processes - 9 talks
  - ➥ GPDs, DVCS, TCS ...
  - ➥ Lattice calculations of spin observables ➙ 1 overview talk

Orbital Angular Momentum

(Overview talk by F. Yuan)



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



- (Long.) Spin Sum rule: many versions: Jaffe, Manohar; Ji; Leader; Chen et al.; Hatta
- Dedicated Workshop: INT-Workshop "Orbital Angular Momentum in QCD"

Quark spin : $$\Delta\Sigma(Q^2) = \int_0^1 dx\, [\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}]\,(x, Q^2)$$

Gluon spin: $$\Delta G(Q^2) = \int_0^1 dx\, \Delta g(x, Q^2)$$

➙ polarized ep, pp - collisions

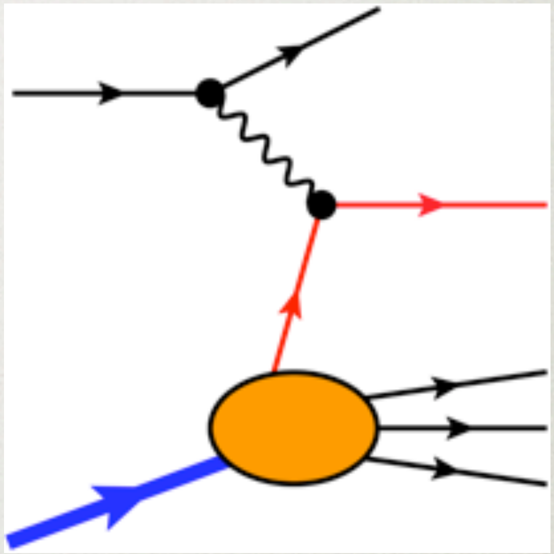
Quark Orbital Angular Moment: $$J_q = \frac{1}{2}\sum_i \int dx\, x\, [q_i(x) + E_i(x, 0, 0)]$$

➙ exclusive processes

Longitudinal Spin Physics

Talks by Vogelsang, Stratmann, Collins, Nocera, Kataev, Pfeuffer, ...

<u>Collinear Factorization in pQCD:</u>



- Cross Section at high energies ➙ (hard part) × (soft part)
- Hard Part ➙ pQCD ; Soft Part ➙ Universal
- Soft Part ➙ collinear Parton Distributions (1-dimensional)

quarks:

$$q(x,\mu),\ \Delta q(x,\mu),\ \delta q(x,\mu)$$

gluons:

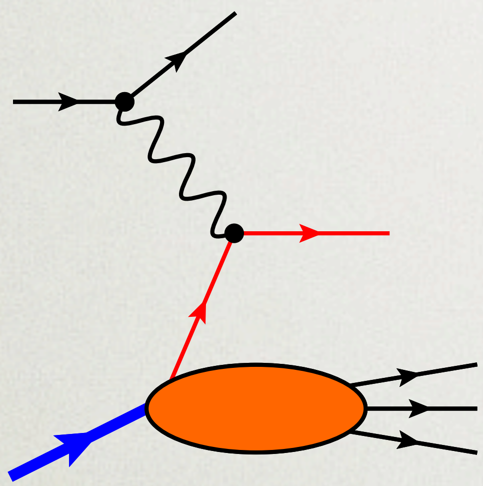
$$G(x,\mu),\ \Delta G(x,\mu)$$

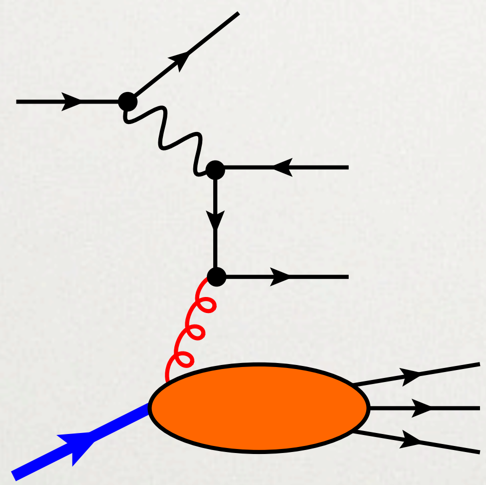
➡ Helicity distributions: Information on the longitudinal spin structure of hadrons

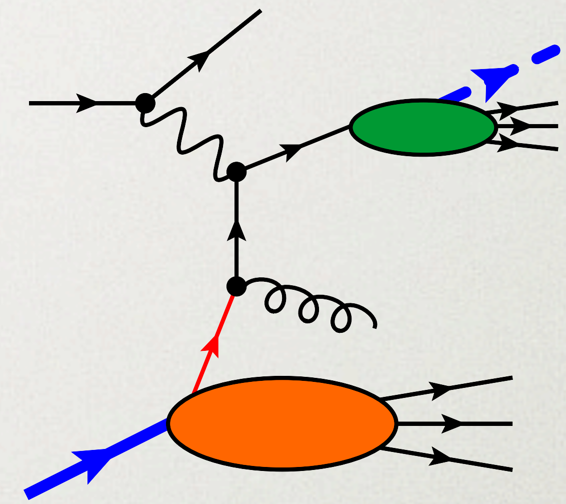
Long. Spin: Observables

Inclusive DIS: Structure function g_1 ➙ HERMES, COMPASS, JLab, ...

Semi-Inclusive DIS (SIDIS) at large P_T or P_T-integrated ➙ investigation of flavor

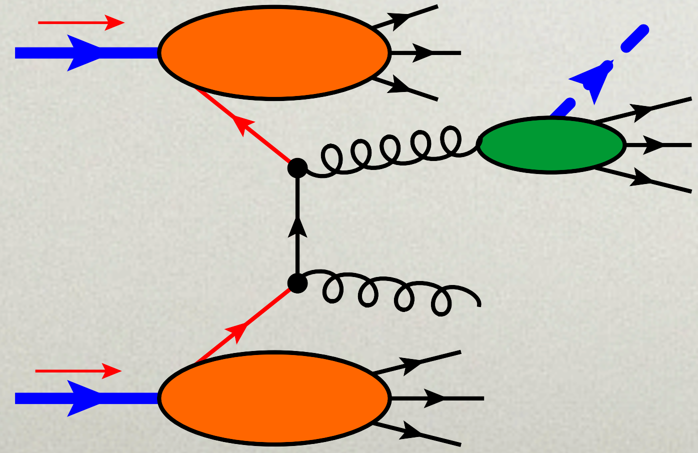


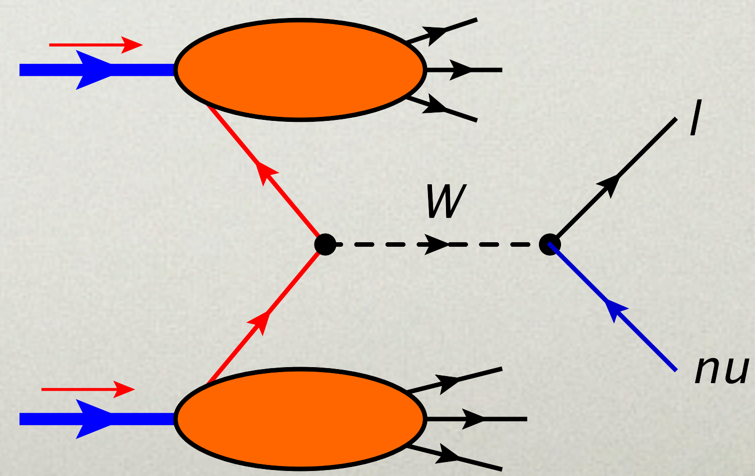




polarized pp - collisions (A_{LL}) ➙ RHIC

Pion - production, Drell-Yan leptoproduction, *new RHIC W-program*



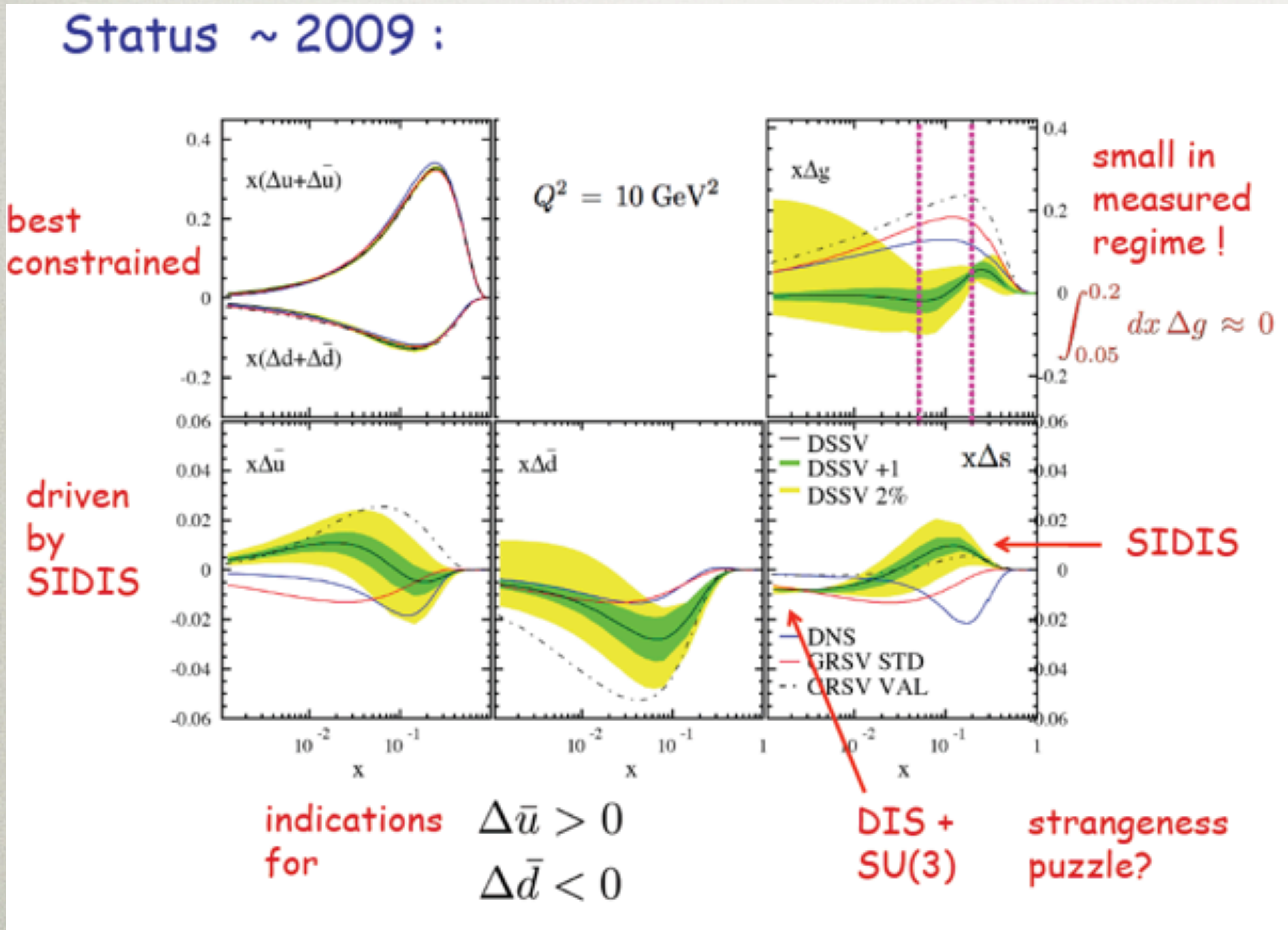


$$\frac{\Delta u}{u}, \frac{\Delta d}{d}$$

Helicity Distributions

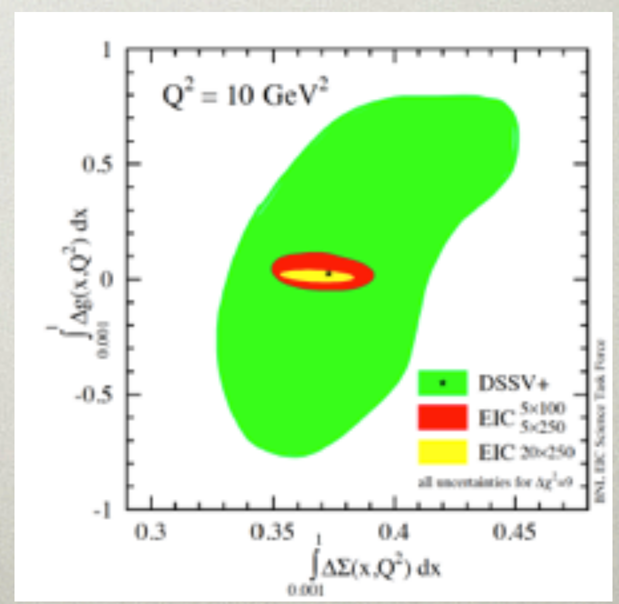
(W. Vogelsang, M. Stratmann)

Report on DSSV "global QCD analysis" on polarized DIS, SIDIS and RHIC data



- new COMPASS data: minor modification of analysis

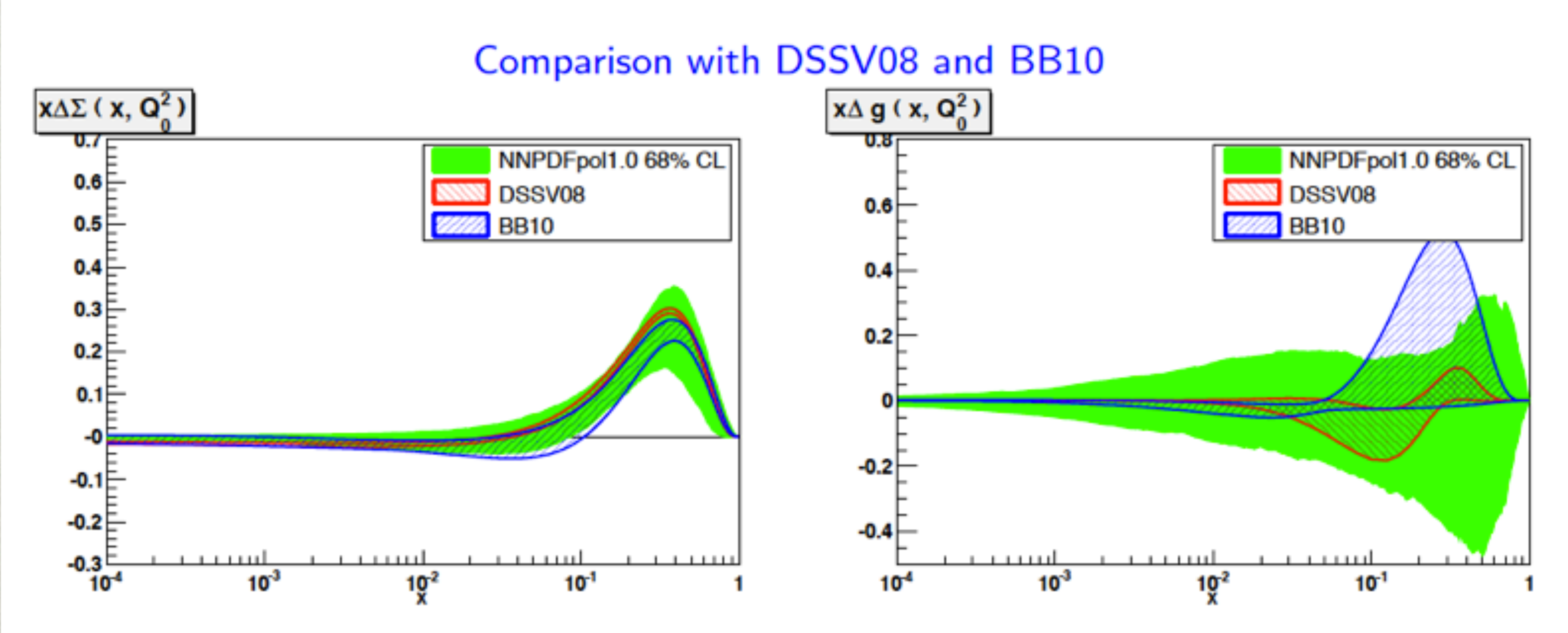
- DSSV analysis for an EIC: mock data + error projection (M. Stratmann): error band for Δg dramatically reduced



NNPDF fits of helicity PDFs

(E. Nocera)

- Conventional fits from global analyses (DSSV and others) ➞ assume functional form, bias
- unbiased fits ➞ neural networks



- larger error bands, in particular on Δg
- Only DIS data included, no SIDIS or RHIC data
- certain inconsistencies with BB10 fits,
  in agreement with DSSV

$$\langle S_z \rangle = \frac{1}{2}\langle \Delta\Sigma \rangle + \langle \Delta g \rangle + L_q + L_g$$

$$\frac{1}{2} = (-0.1 \pm 1.1) + L_q + L_g$$

Lattice Calculation for Helicities & OAM

(S. Collins, QCDSF)

Calculations of moments on the lattice

$$\frac{\Delta q}{2} \quad s_\mu \quad = \quad \frac{1}{m_N}\langle N, s|\bar{q}\gamma_\mu\gamma_5\frac{1}{2}q|N, s\rangle$$

Focus on polarized strange quark distribution Δs: include "disconnected contributions"

Lattice specifications:
improved Clover fermions, lattice spacing a=0.072 fm, pion mass m_π=285 MeV

need to match continuum renormalization:

$$\Delta q^{\overline{MS}}(\mu) = Z_A^{ns}(1 + b_A a m_q)\Delta q^{\mathrm{lat}} + \frac{z(\mu)}{2}(\Delta u + \Delta d)^{\mathrm{lat}}$$

Main result:

$$\begin{aligned} \Delta\Sigma = \Delta u + \Delta d + \Delta s \quad &= \quad 0.45(4)(9) \\ \Delta s \quad &= \quad -0.020(10)(4) \end{aligned}$$

negative strange quark polarization ➙
disagreement with DSSV analysis

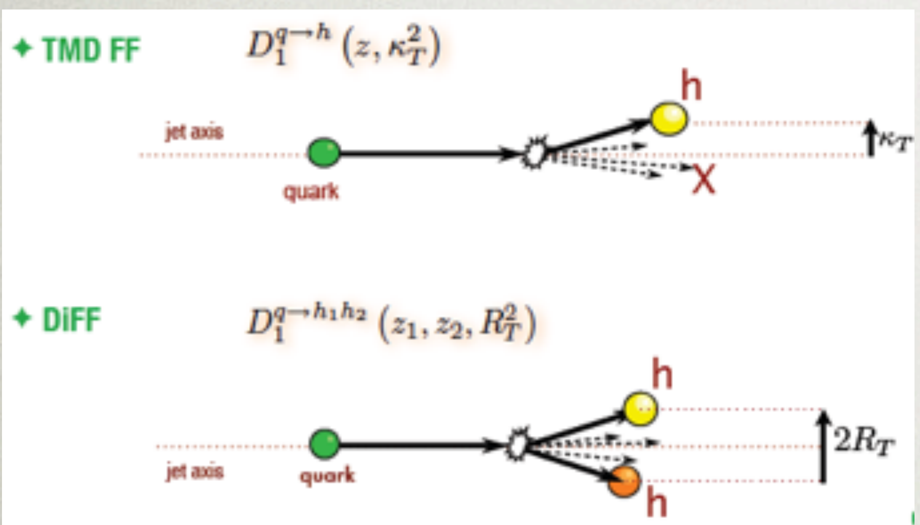
Transverse Spin Physics - Transversity via IFF

(A. Courtoy)

Motivation: Study of the transversity distribution δq(x) ➞ absent in inclusive DIS ➞ SIDIS

1-hadron fragmentation ➞ Collins effect (TMD fact.) $h_1 \otimes H_1^{\perp}$

2-hadron fragmentation ➞ Interference FF (coll. fact.) $h_1 \otimes H_1^{\angle}$

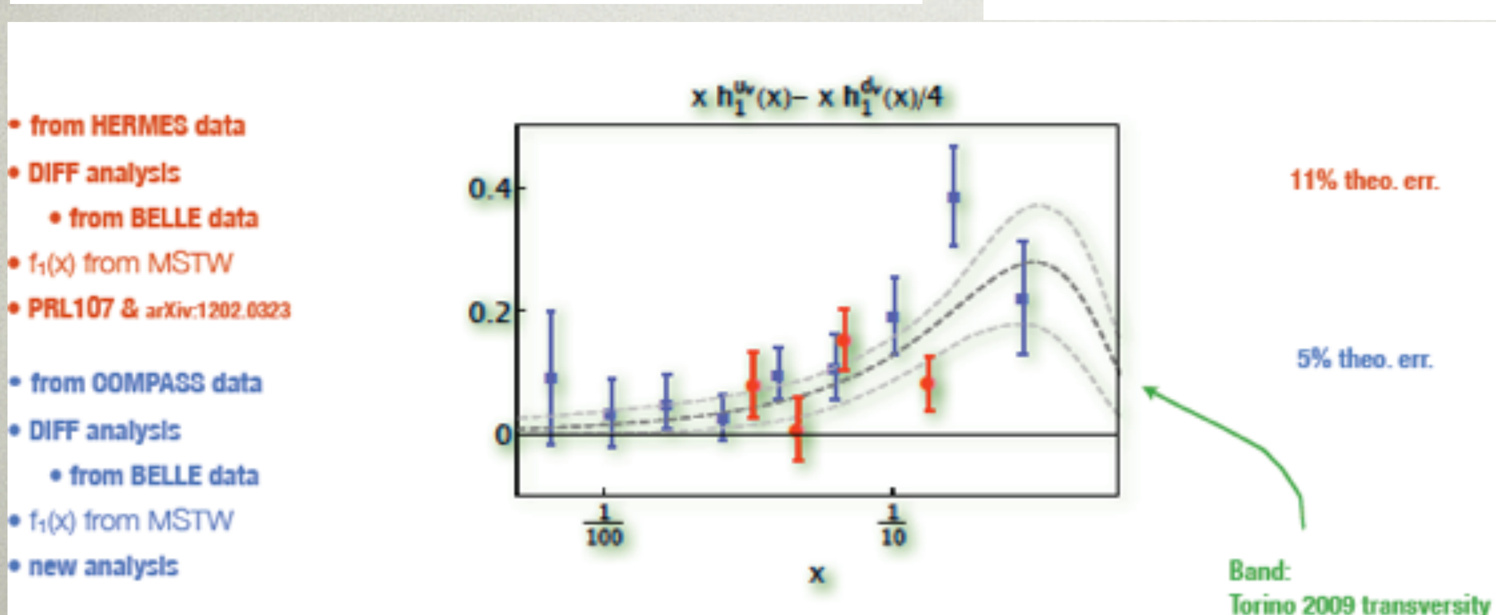


Transverse SSA in 2-hadron DIS at LO:

$$A_{\rm DIS}(x,z,M_h^2,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\,\frac{|\vec R|}{M_h}\, H_{1,sp}^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\quad D_1^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}$$

$$x h_1^{u_v}(x,Q^2) - \frac{1}{4}\, x h_1^{d_v}(x,Q^2) = -C_y^{-1}\, A_{\rm DIS}(x,Q^2)\,\frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar q}(x,Q^2)$$

HERMES range: -0.251^{-1} (± 9% theo. err.) from BELLE

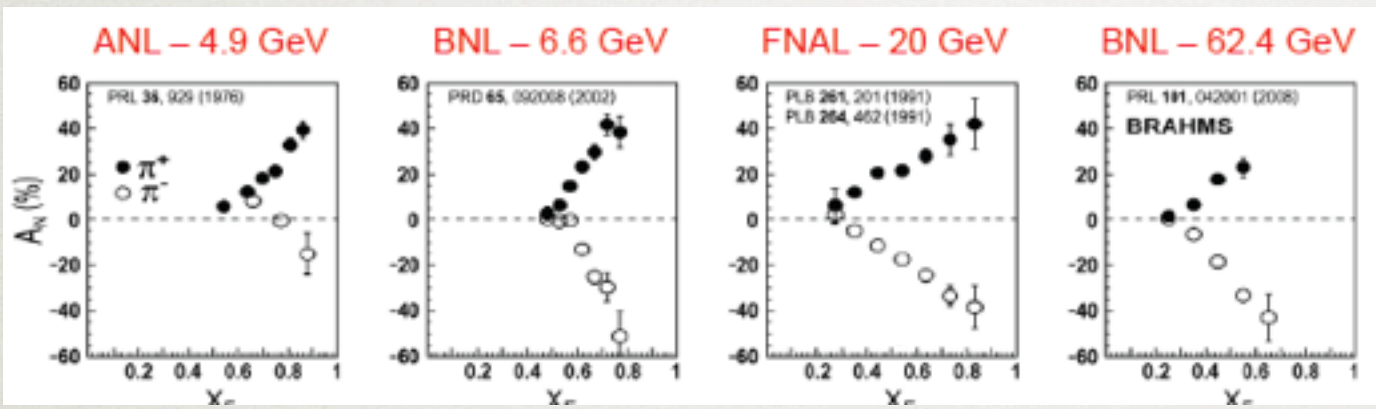


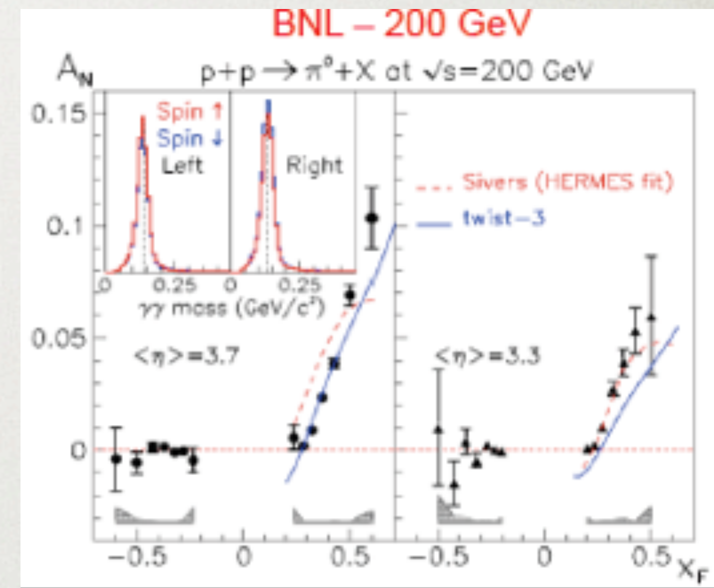
- Consistent with extraction from Collins effect
- Fit: work in progress

Transverse SSA - twist-3 coll. Approach

(J.-W. Qiu)

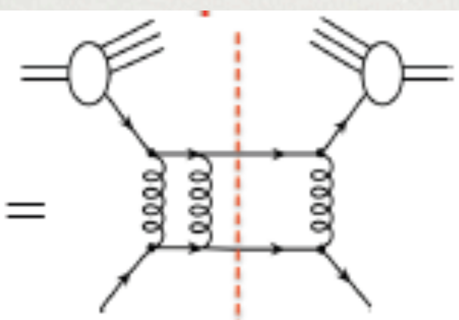
Long history of large transverse spin asymmetries in pp - collisions:





Simple parton model explanation fails:

$$\sigma_{AB}(p_T,\vec{s}) - \sigma_{AB}(p_T,-\vec{s}) =$$



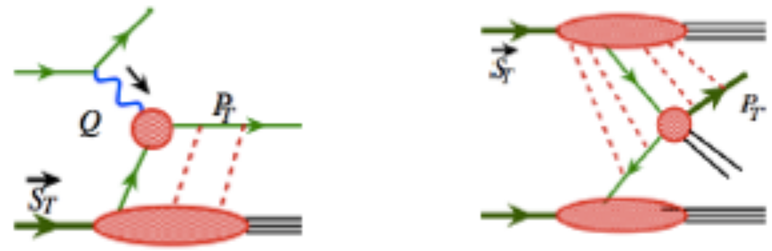
$$\propto \alpha_s \frac{m_q}{p_T}$$

Too small to explain available data!

→ need multi-parton correlations (twist-3)

Twist-3 approach for 1-scale processes

❑ **One scale observables – $Q >> \Lambda_{QCD}$:**



SIDIS: $Q \sim P_T$ Jet, Particle: P_T

➡ **Collinear factorization**
Twist-3 distributions

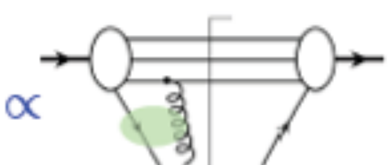
Transverse SSA ➙ Quark-Gluon-Quark correlation

$$\langle P,s|\overline{\psi}(0)\gamma^+ \left[\epsilon_\perp^{\alpha\beta} s_{T\alpha} \int dy_2^- F_\beta{}^+(y_2^-)\right] \psi(y^-)|P,s\rangle$$

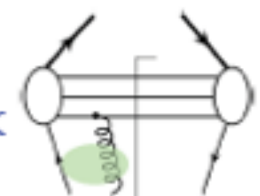
❑ **Single transverse spin asymmetry:**

Efremov, Teryaev, 82;
Qiu, Sterman, 91, etc.

$$\Delta\sigma(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z) + \ldots$$

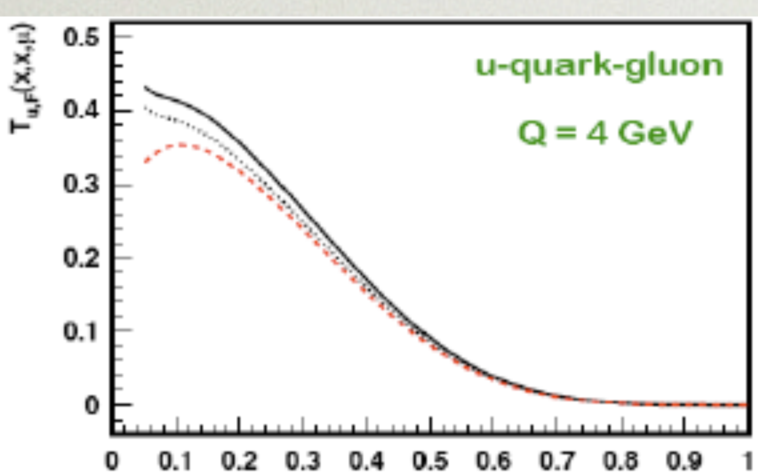
$T^{(3)}(x,x) \propto$ 

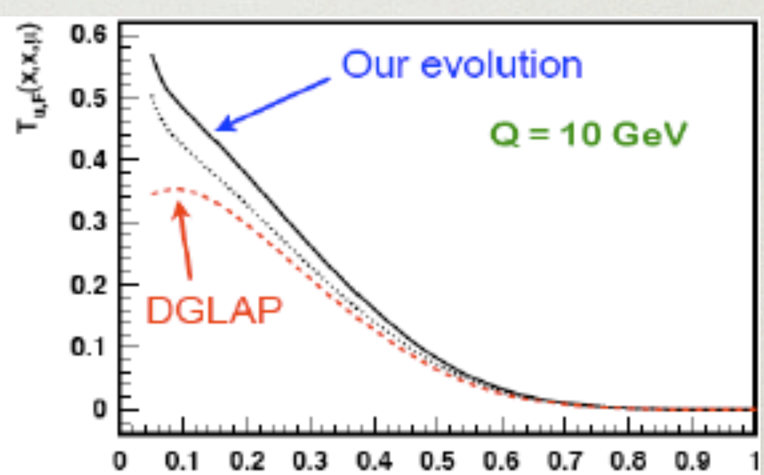
Qiu, Sterman, 1991, …

$D^{(3)}(z,z) \propto$ 

Kang, Yuan, Zhou, 2010

Evolution of $T_F(x,x)$ studied by different groups ➙ inconsistencies resolved





- like DGLAP at large x
- differences at smaller x

TMD factorization

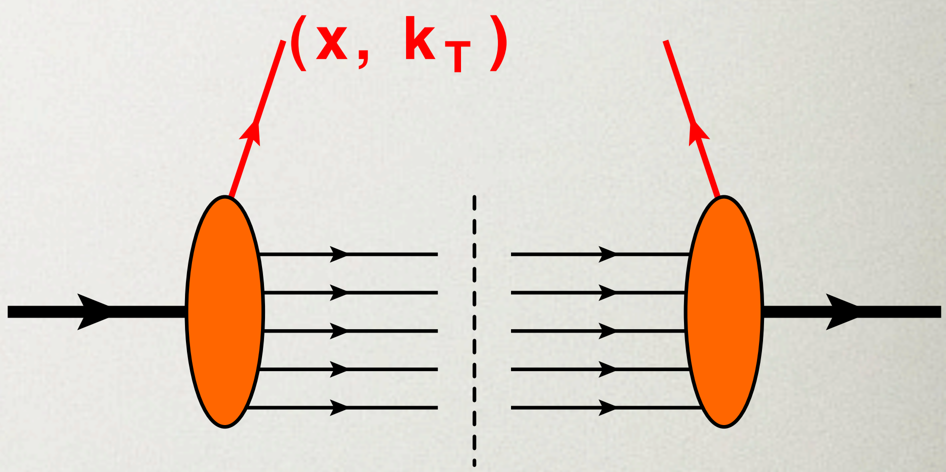
Talks by Mulders, Bacchetta, Yuan, Boglione, Mukherjee, Zhou, den Dunnen, ...

Idea of TMDs:

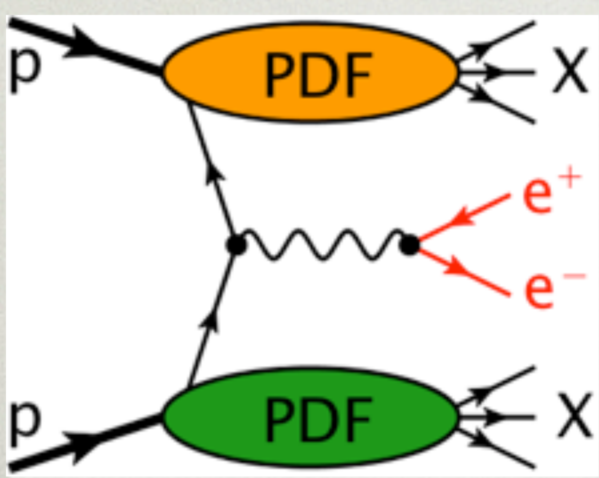
Implement "intrinsic" transverse parton momentum k_T

➙ different kind of factorization

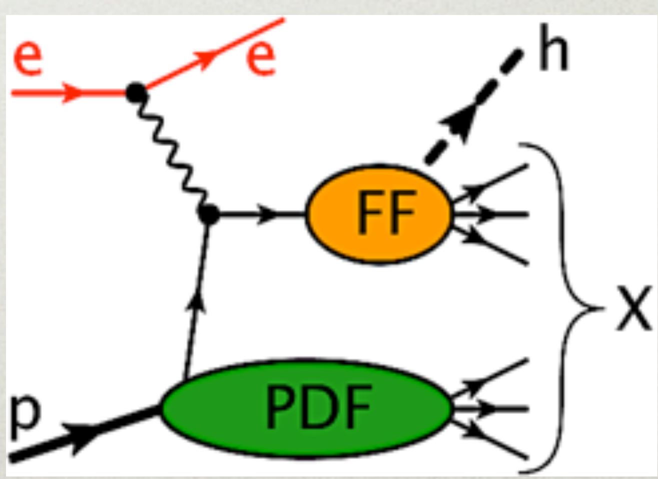
➙ opportunity to study different aspects of hadron spin structure (e.g. spin-orbit correlations, overlap rep. etc.)



"intrinsic" transverse parton momentum through small final state transverse momenta



$q_T \ll Q$



$P_{hT} \ll Q$

(Naive) definition of the quark TMD correlator

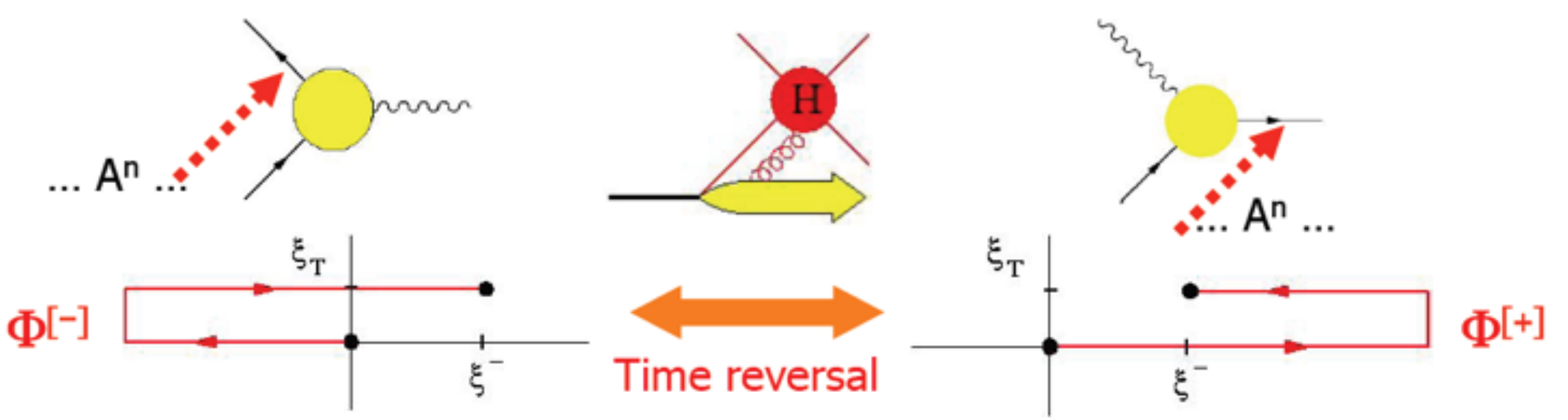
$$\Phi_{ij}(x,\vec{k}_T;S) = \int \frac{dz^- d^2 z_T}{2(2\pi)^3}\, e^{ik\cdot z} \langle P,S|\, \bar{\psi}_j(0) \mathcal{W}_{\mathrm{SIDIS/DY}}[0,z]\, \psi_i(z)\, |P,S\rangle \Big|_{z^+=0}$$

(talk by P. Mulders)

- $$\Phi(x,p_T) \underset{p_T^2 > \mu^2}{\longrightarrow} \frac{1}{\pi p_T^2} \frac{\alpha_s(p_T^2)}{2\pi} \int_x^1 \frac{dy}{y} P\left(\frac{x}{y}\right) \Phi(y;p_T^2)$$
- Consistent matching to collinear situation: CSS formalism

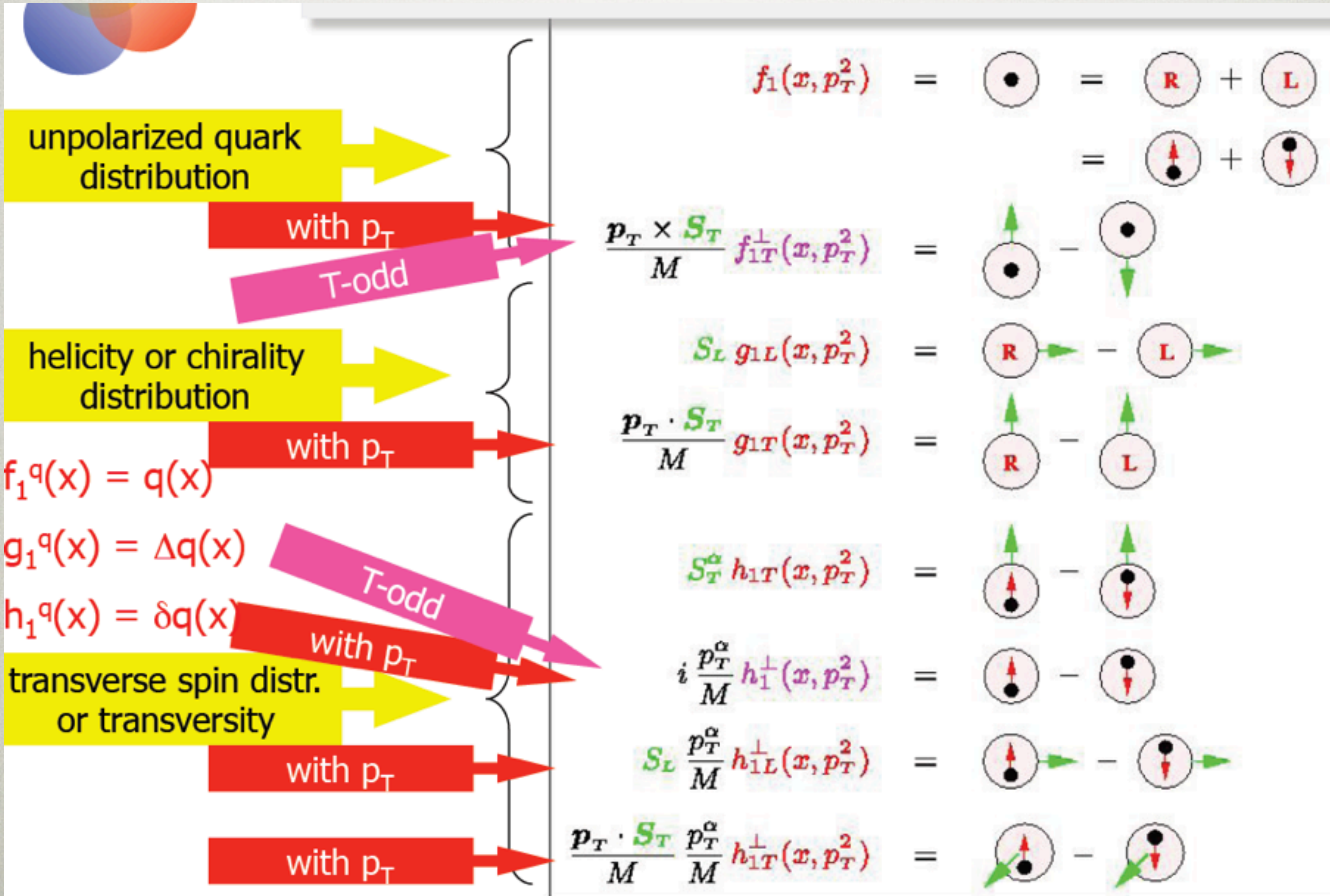
JC Collins, DE Soper and GF Sterman, NP B 250 (1985) 199

- Gauge links for TMD correlators process-dependent with simplest cases



Color entanglement ➞ TMD factorization broken for more complicated processes

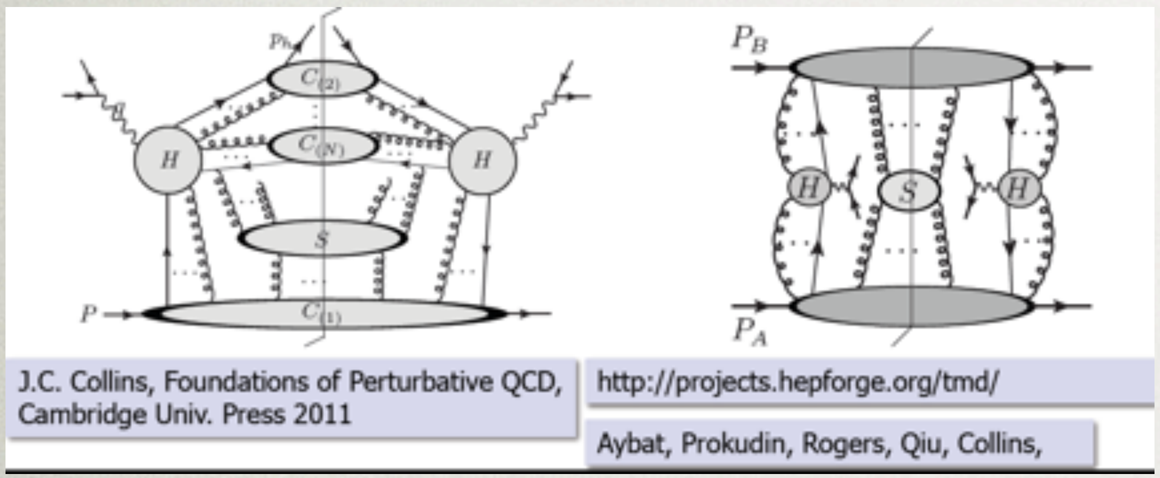
Eight leading twist TMDs

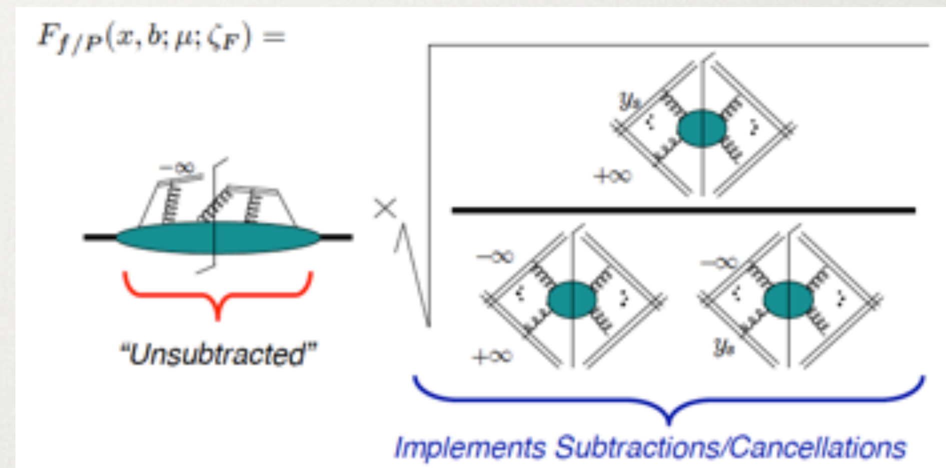


Evolution of TMDs

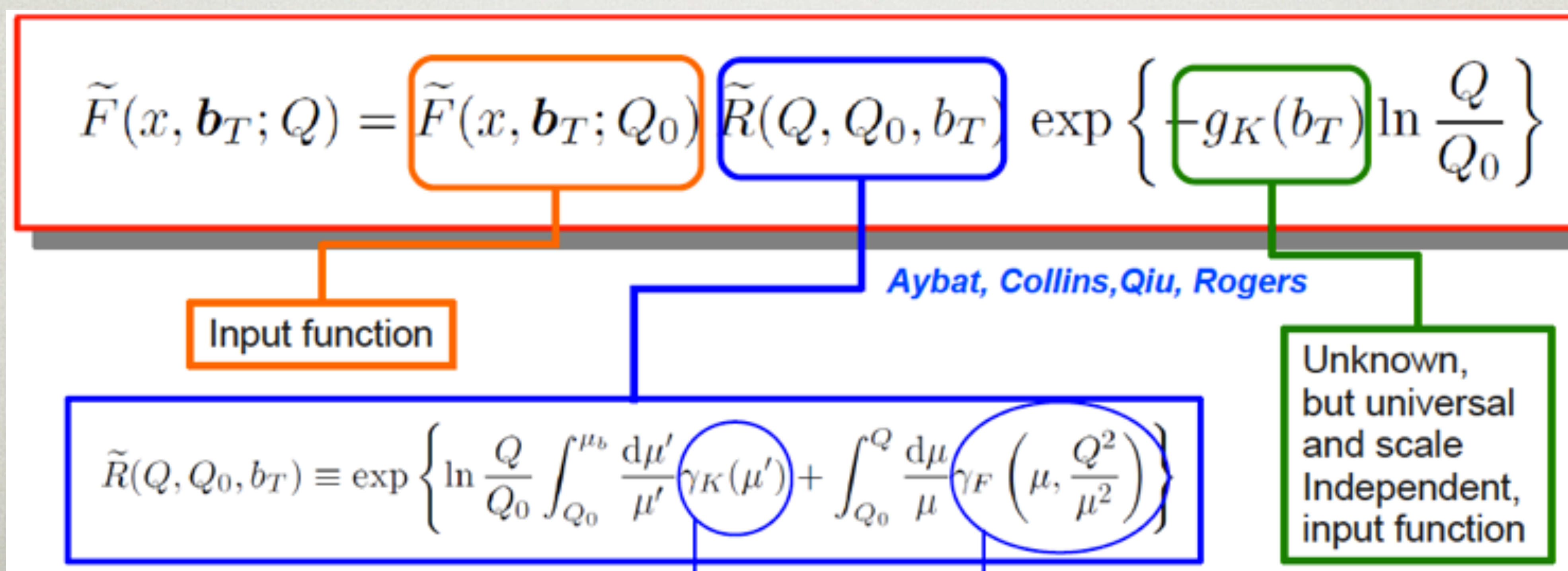
(talks by M. Boglione, F. Yuan)

all-order TMD factorization theorems include soft factor, non-lightlike Wilson lines





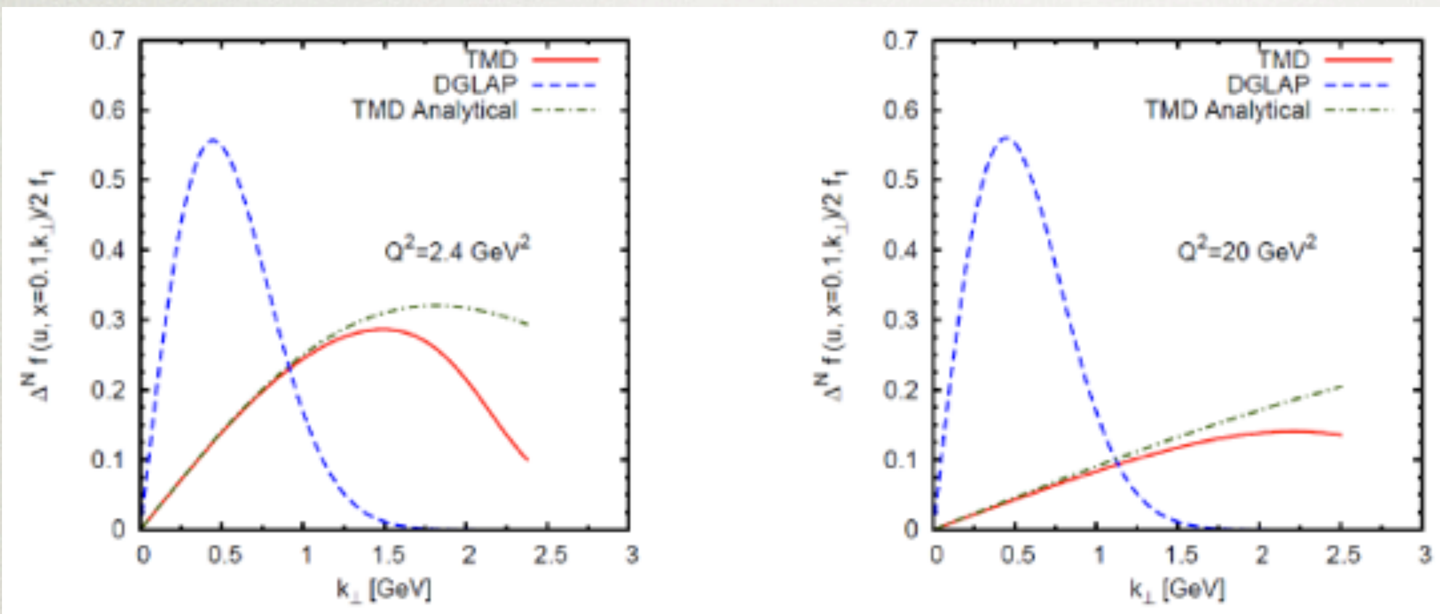
$\Phi_{ij}(x,\vec{k}_T;S;\xi,\mu)$ Collins-Soper evolution equations for ξ, μ



Sivers effect with evolution

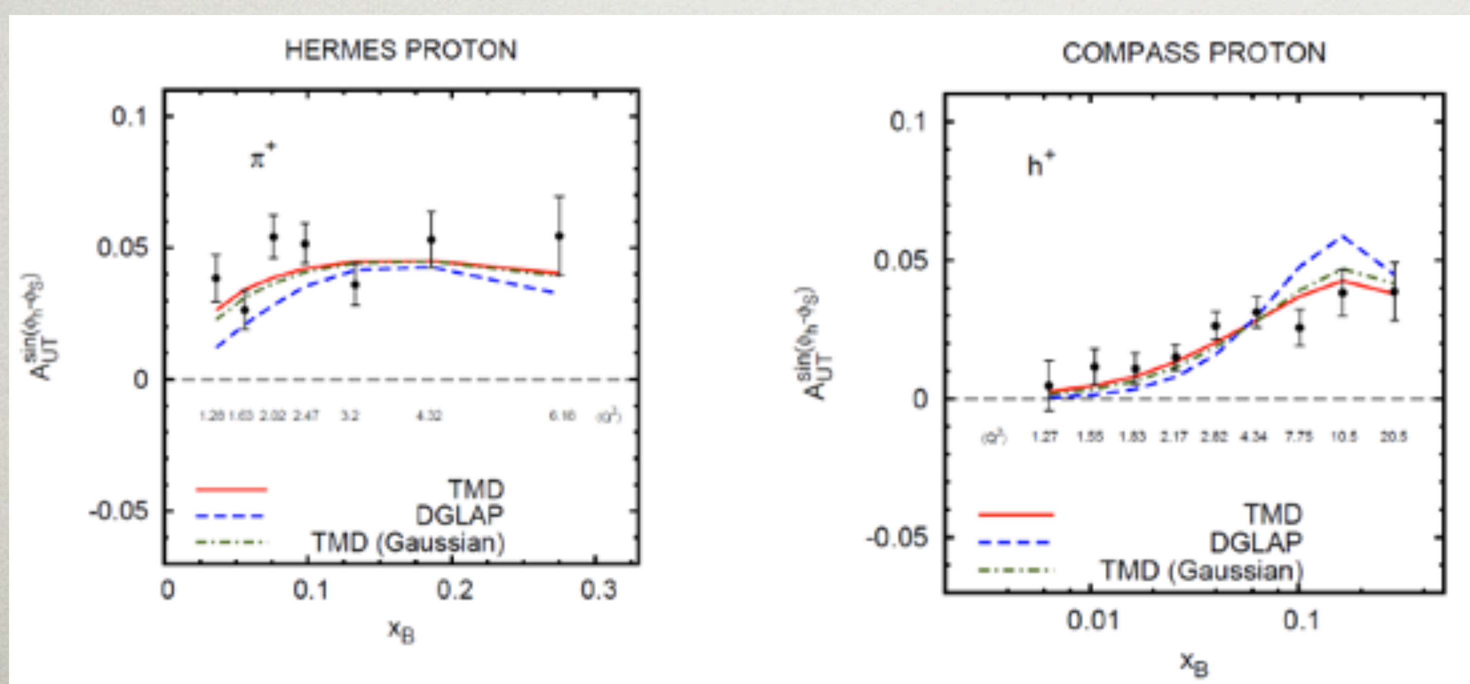
Sivers effect: Transverse SSA in SIDIS, Drell-Yan,...

$$A_{UT} \propto \sin(\phi - \phi_s) \frac{f_{1T}^{\perp q} \otimes D_1^q}{f_1^q \otimes D_1^q}$$



Evolved Sivers functions

- DGLAP-evolution slow
- TMD evolution: big effects



Data fits with evolution

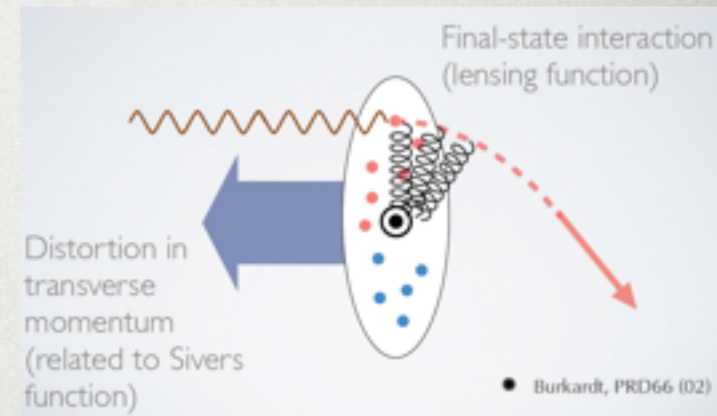
- improved fits
- χ^2 reduced by factor ~3

OAM and the Sivers effect

(A. Bacchetta) Idea: use SIDIS data to constrain OAM

(model-inspired) fit ansatz for the Sivers function (lensing picture)

$$f_{1T}^{\perp(0)a}(x;Q_L^2) = -L(x)\,E^a(x,0,0;Q_L^2)$$



- Lensing function constraint by anomalous magnetic moments

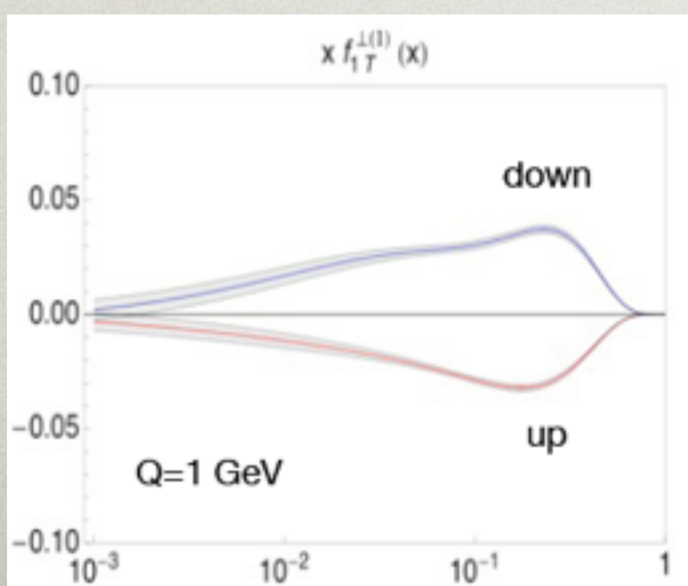
$$L(x) = \frac{K}{(1-x)^{\eta}}$$

$$\kappa^p = \int_0^1 \frac{dx}{3}\left[2E^{u_v}(x,0,0) - E^{d_v}(x,0,0) - E^{s_v}(x,0,0)\right]$$

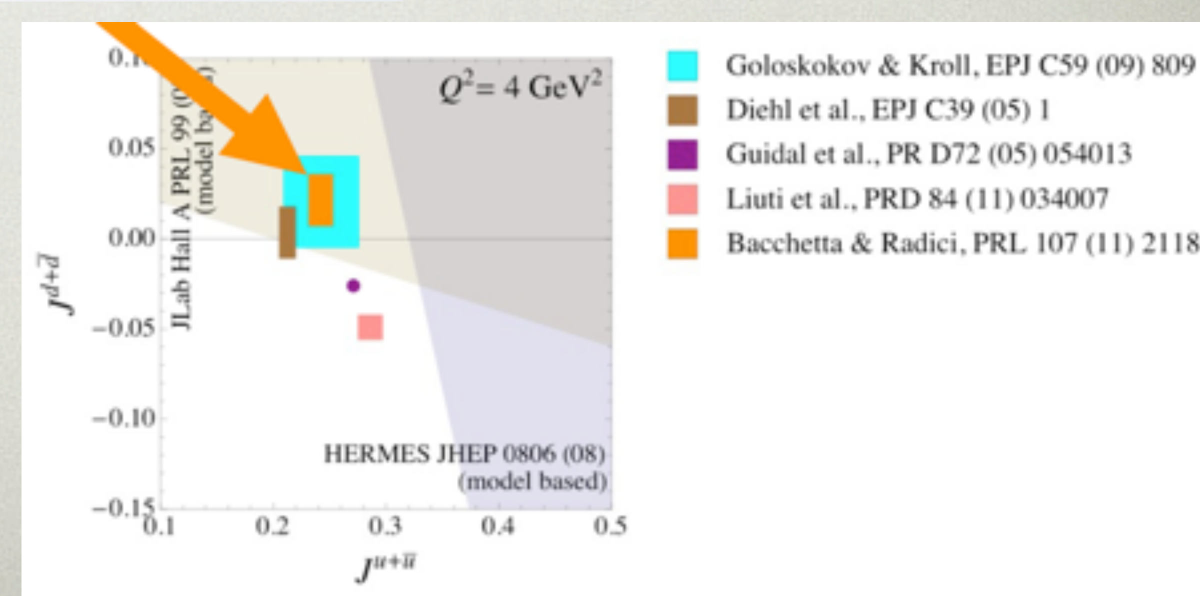
$$\kappa^n = \int_0^1 \frac{dx}{3}\left[2E^{d_v}(x,0,0) - E^{u_v}(x,0,0) - E^{s_v}(x,0,0)\right]$$

- Sivers function: fit from HERMES, COMPASS, JLab data

$$f_{1T}^{\perp q_v}(x,p_T^2) \propto C^{q_v}\,(1 - x/\alpha^{q_v})\,(1-x) f_1^{q_v}(x)\, e^{-p_T^2/M_1^2}\, e^{-p_T^2/\langle p_T^2\rangle}$$



OAM



Linearly polarized Gluons

(J. Zhou, W. den Dunnen)

Define gluon TMDs through gluonic field-strength tensor

$$\int \frac{dr^- d^2 r_\perp}{(2\pi)^3 P^+} e^{-ix_1 P^+ r^- + i\vec{k}_{1\perp}\cdot\vec{r}_\perp} \langle A| F^{+i}(r^-+y^-, r_\perp+y_\perp)\, L^\dagger\, L\, F^{+j}(y^-,y_\perp)|A\rangle$$
$$= \frac{\delta_\perp^{ij}}{2} x_1 G(x_1,k_{1\perp}) + \left(\hat{k}_{1\perp}^i \hat{k}_{1\perp}^j - \frac{1}{2} \delta_\perp^{ij}\right) x_1 h_1^{\perp g}(x_1,k_{1\perp}), \qquad \delta_\perp^{ij} = -g^{ij} + (p^i n^j + p^j n^i)/p\cdot n$$

Connection: gluon TMDs - small x physics in large nuclei

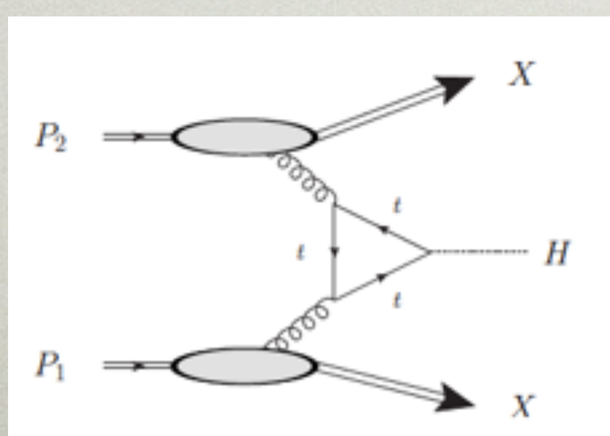
Calculation of Distribution of lin. pol. gluons in Color Dipole Model, Weizsäcker-William Model, ...
➙ (partial) saturation of positivity bound

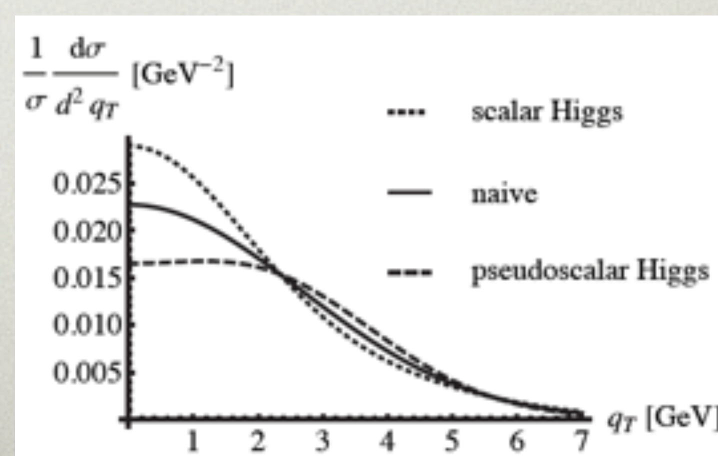
$$xh^{\perp g}_{1,WW}(x,k_\perp) \simeq S_\perp \frac{N_c^2-1}{4\pi^3}\frac{\mu_A}{Q_s^2} \qquad xG^g_{WW}(x,k_\perp) \simeq S_\perp \frac{N_c^2-1}{4\pi^3}\frac{1}{\alpha_s N_c}\ln\frac{Q_s^2}{k_\perp^2}$$

$$xh^{\perp g}_{1,DP}(x,k_\perp) = xG^g_{DP}(x,k_\perp)$$

Connection: gluon TMDs - Higgs physics

linearly polarized gluons sensitive to Higgs parity ➙ measure q_T distribution at small q_T

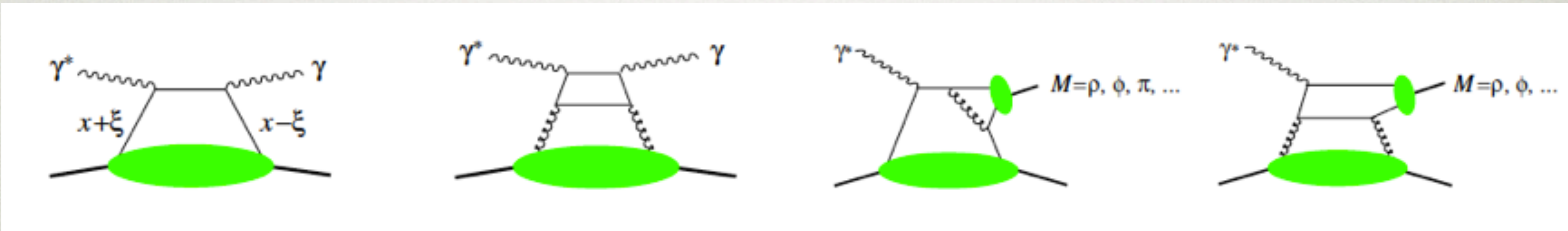




Parton Structure in hard exclusive Processes

(Theory overview by M. Diehl)

Generalized Parton Distribution from DVCS, Meson Production, ...



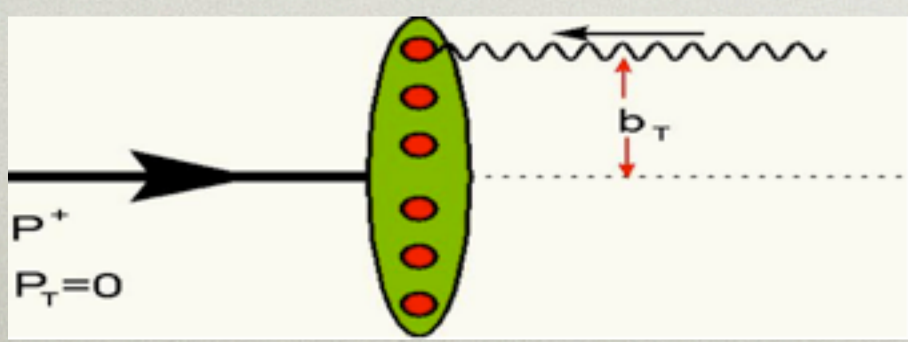
$\Delta = p' - p$ $\Delta^+ = -2\xi P^+$ $t = \Delta^2$ → GPD (x, ξ, t, μ)

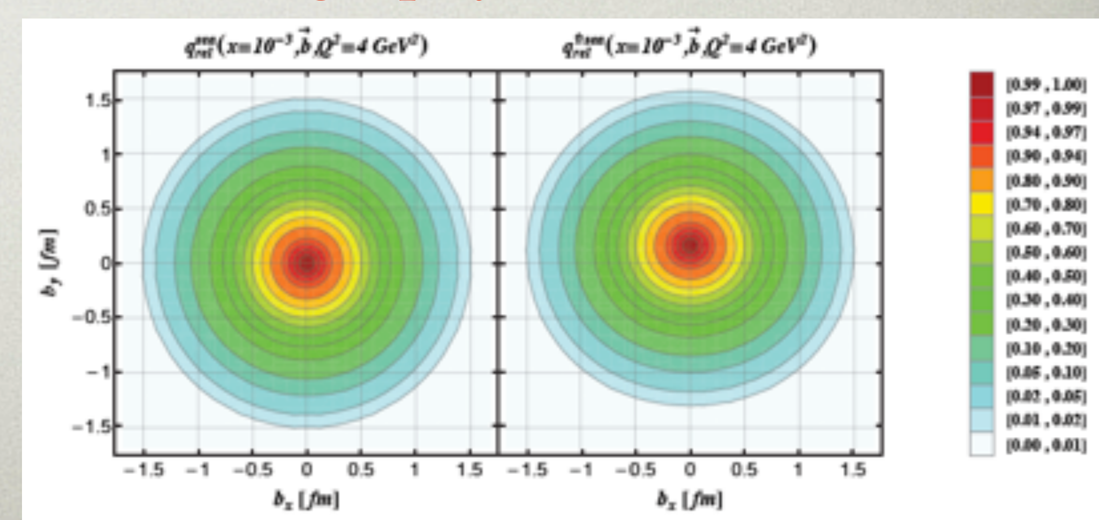
DVCS amplitude

$$T_{\text{DVCS}} \sim \int_{-1}^{1} dx \frac{\text{GPD}(x,\xi,t)}{x-\xi+i\epsilon} \longrightarrow \Re T \sim \mathcal{P}\int_{-1}^{1} dx \frac{\text{GPD}(x,\xi,t)}{x-\xi}\,,\ \Im T \sim \text{GPD}(\xi,\xi,t)$$

Impact parameter Parton Distributions → "Hadron Tomography"

$$\mathcal{F}_{ij}(x,\vec{b}_T) = \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{-i\vec{\Delta}_T\cdot\vec{b}_T}\, F_{ij}(x,0,\vec{\Delta}_T)$$



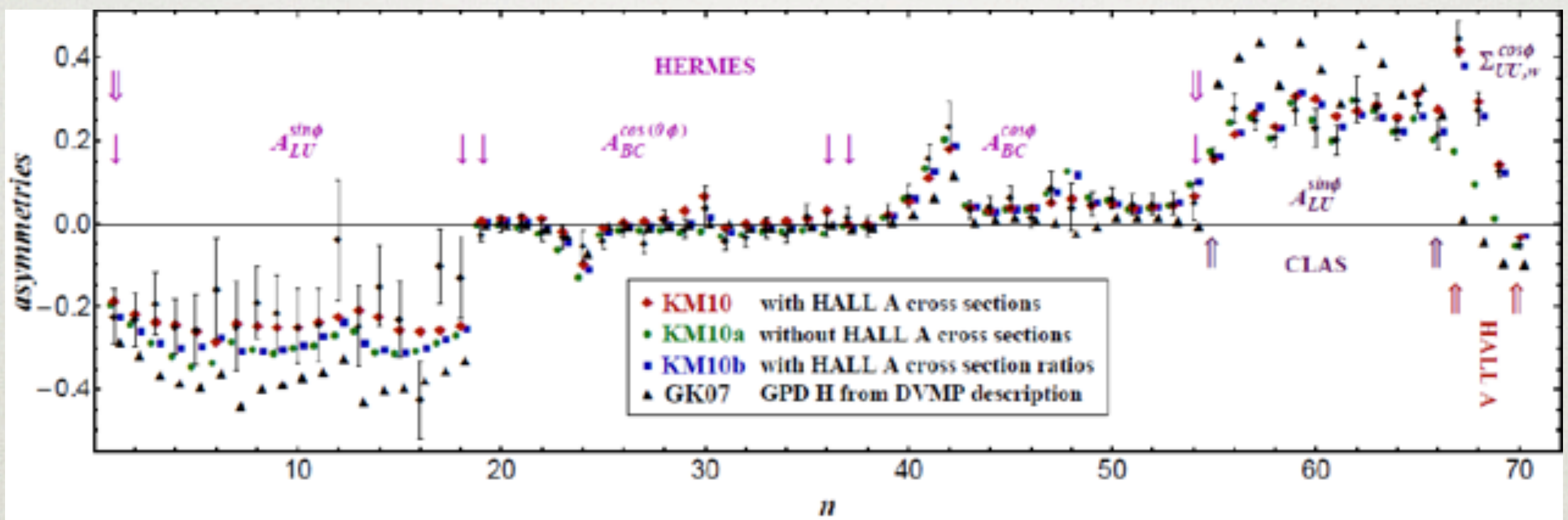


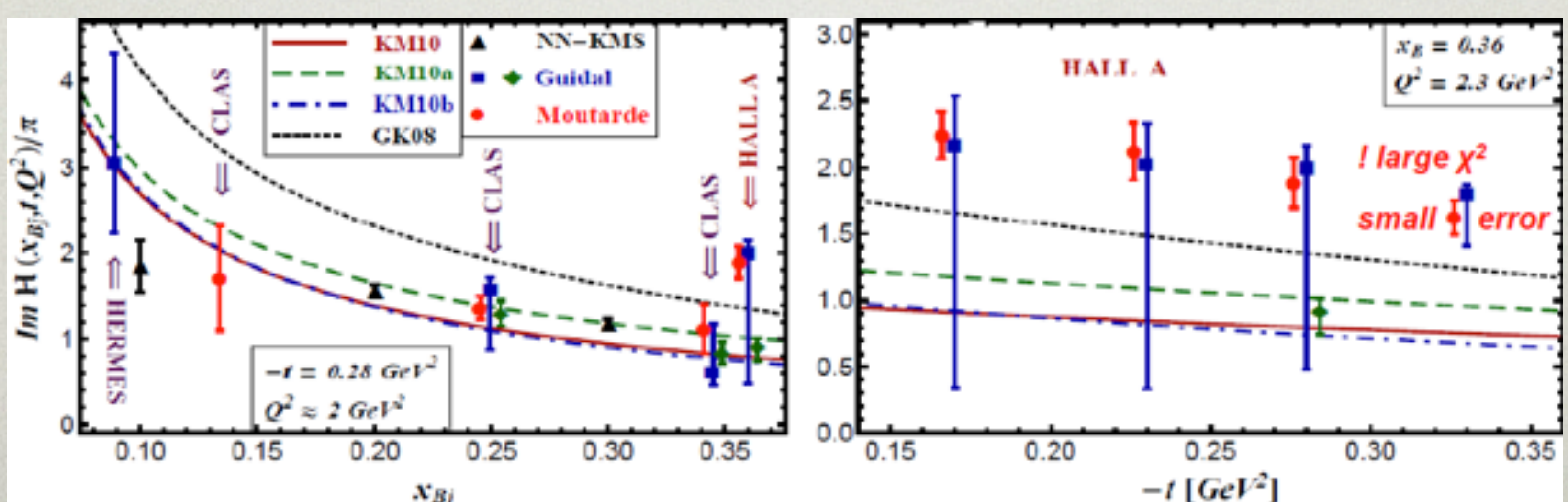
DVCS and GPD fits

(D. Müller)

Overview on extraction of GPDs from DVCS and Meson Production using global fits and neural networks

Asymmetry / Compton Form Factor fits of HERMES, JLab data

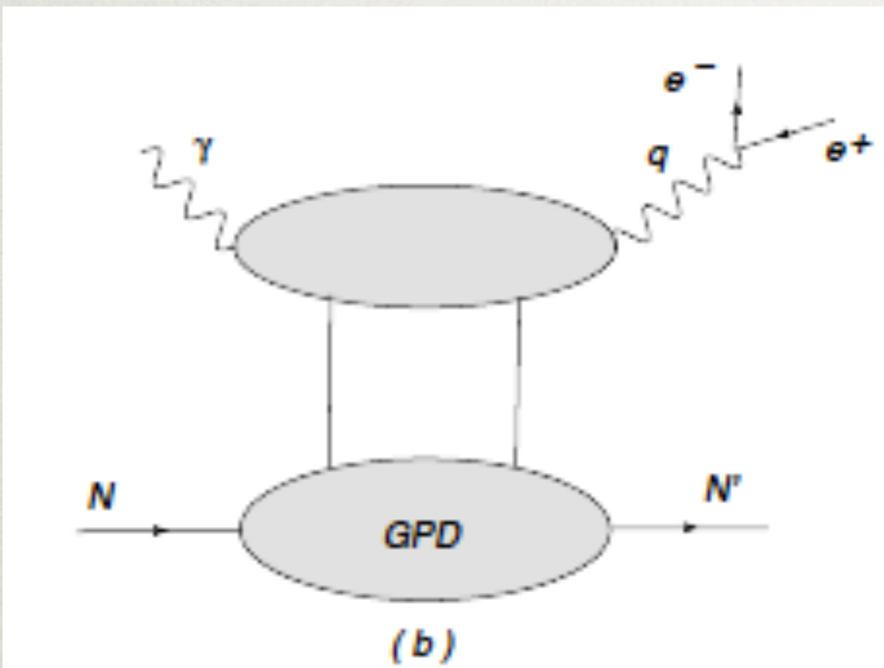




Time-like Compton Scattering

(H. Moutarde, J. Wagner)

Complementary process to DVCS: "crossed process" TCS $\gamma p \to l^- l^+ p'$

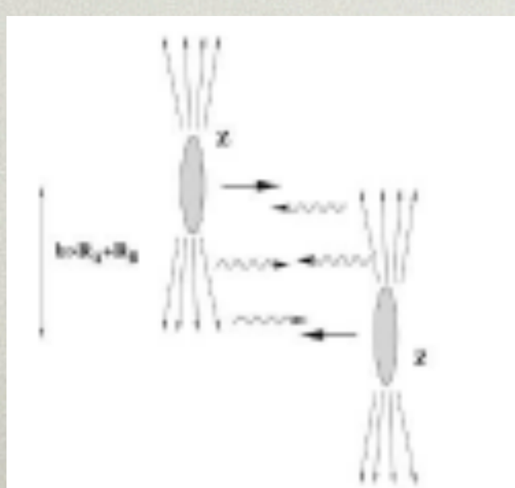


DVCS: $q_{in}^2 < 0 \,, \quad q_{out}^2 = 0$

TCS: $q_{in}^2 = 0 \,, \quad q_{out}^2 > 0$

- Measurable at JLab 6, 12
- can test universality of GPDs
- NLO-corrections studied: large effects from gluons

feasible also in ultraperipherical hadron/nuclei collisions at RHIC



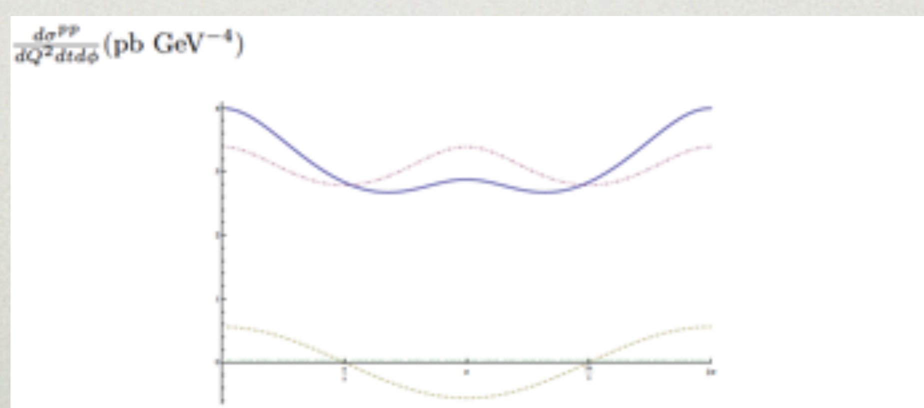


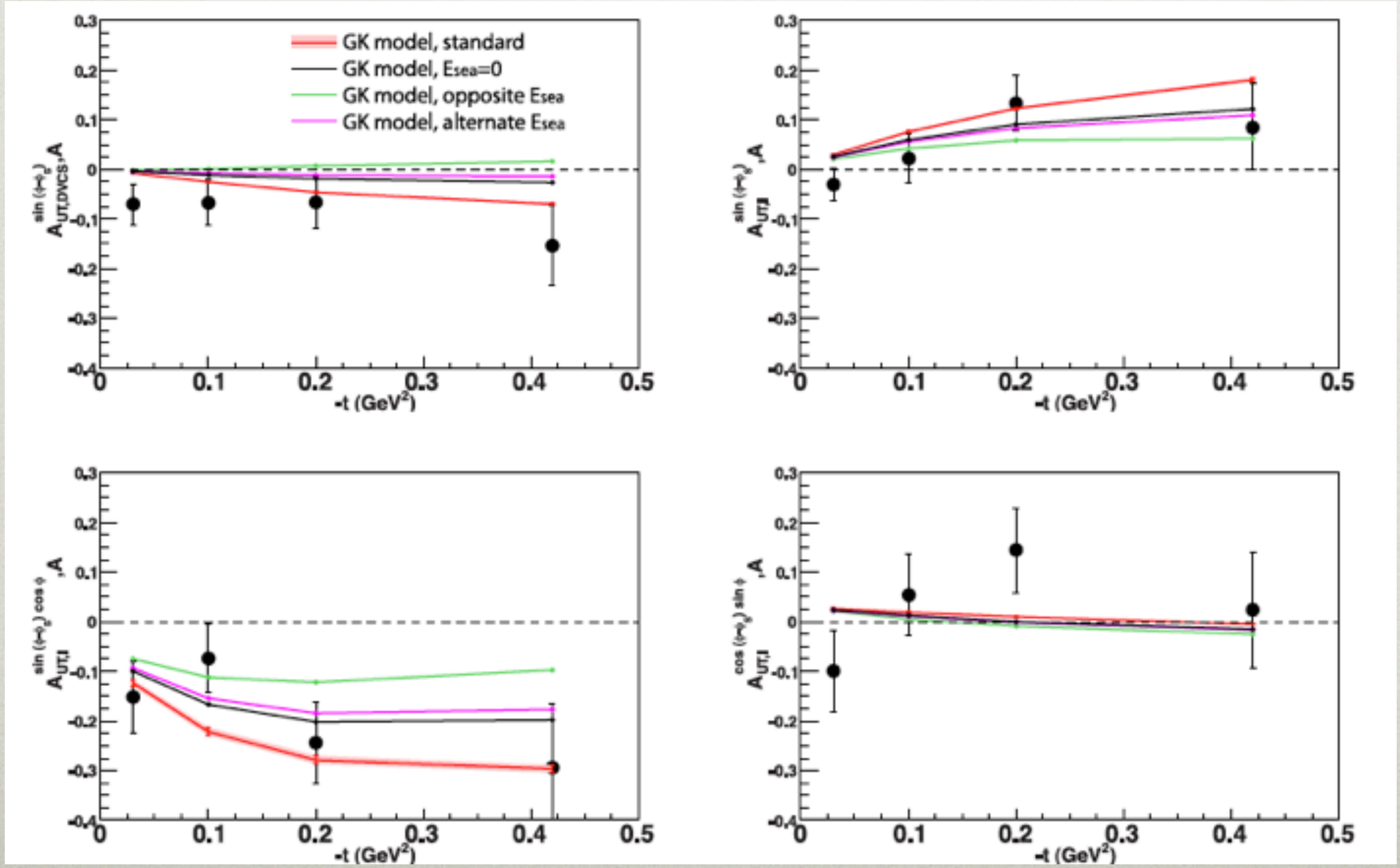
Figure: The differential cross sections (solid lines) for $t = -0.1\,\mathrm{GeV}^2$, $Q'^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

RHIC estimates for Bethe-Heitler, Compton, Interference

Compton Form Factors in GK-Model

(H. Moutarde)

Goloskokov-Kroll model designed to describe meson production data
➙ application to DVCS and TCS also describes data reasonably well
➙ supports universality of GPDs



Summary

- Nice data on polarized processes from COMPASS, HERMES, RHIC, JLab,...
- Future EIC can reduce error bands on data fits for all branches of spin physics.
- Progress in Theory: Global fits, evolution of twist-3 objects, TMDs
- Thanks to all the speakers!