Fourth International Workshop on Transverse Polarisation Phenomena in Hard Processes

(Transversity 2014)

Chia (CA), 9-13th June 2014

Transverse spin physics: overview

M. Anselmino, Torino University & INFN

Transversity 2005

The International Workshop on Transverse Polarisation Phenomena in Hard Processes (Transversity 2005)

Villa Olmo (Como), 7–10th. September 2005

Transversity 2008

Second International Workshop on Transverse Polarisation Phenomena in Hard Processes

May 28-31, Ferrara

TRANSVERSITY 2011

Third International Workshop on

TRANSVERSE POLARIZATION PHENOMENA IN HARD SCATTERING

29 August - 2 September 2011

Veli Lošinj, Croatia

ECSAC

EUROPEAN CENTRE FOR SCIENCE ARTS AND CULTURE transverse spin physics: not only understanding puzzling spin asymmetries and the transversity distribution, but exploring the nucleon structure beyond collinear configuration

3D imaging in momentum (and co-ordinate) space

brief history of TMDs (Sivers and Collins)

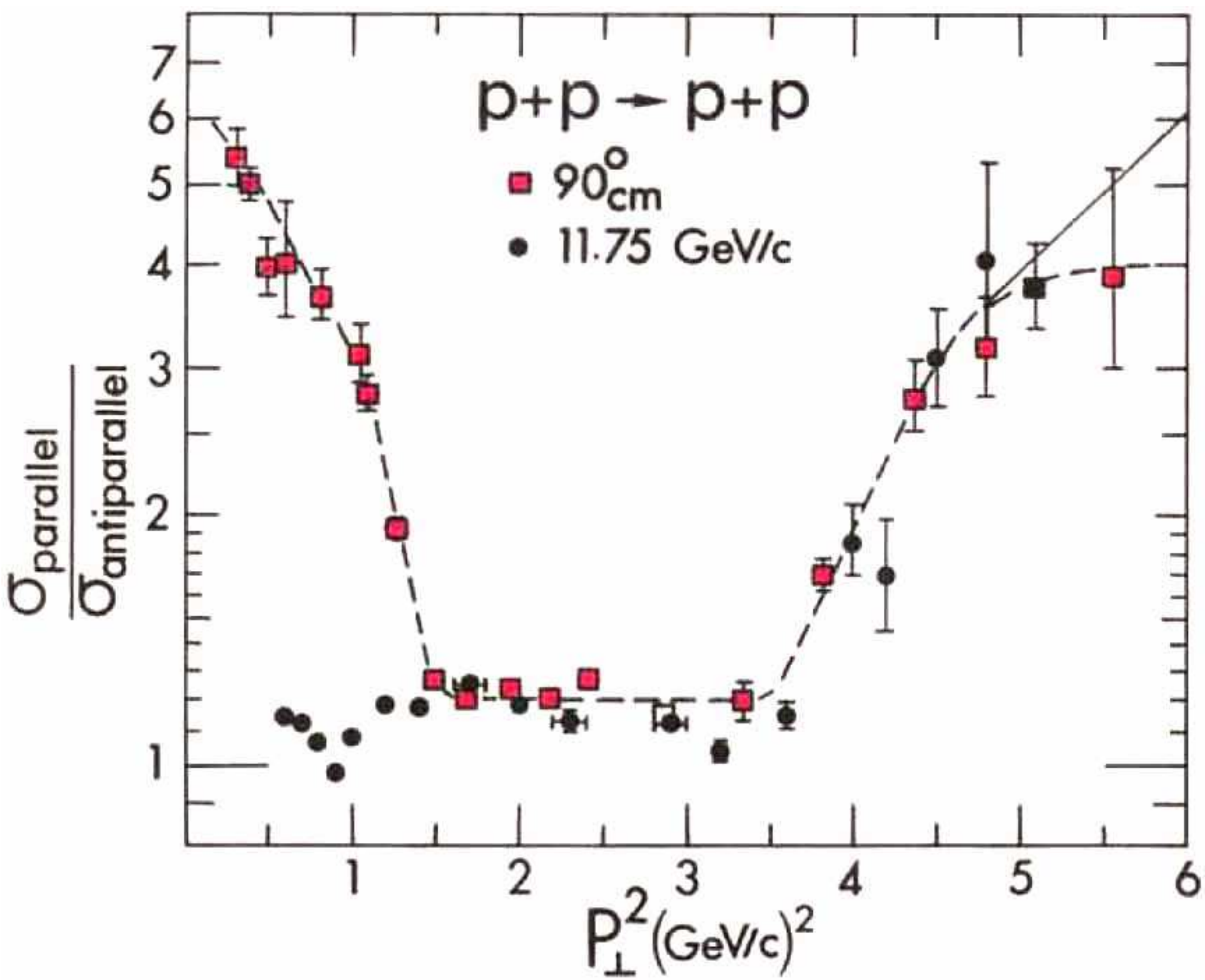
TMDs in SIDIS and in pp inclusive processes

TMD phenomenology - phase 1

TMDs from QCD, TMD phenomenology - phase 2

future experiments

long tradition of astonishing data with transverse spin
(Argonne ZGS, elastic pp scattering, ~1977)



$$p^{\uparrow} p^{\uparrow} \rightarrow p\, p$$

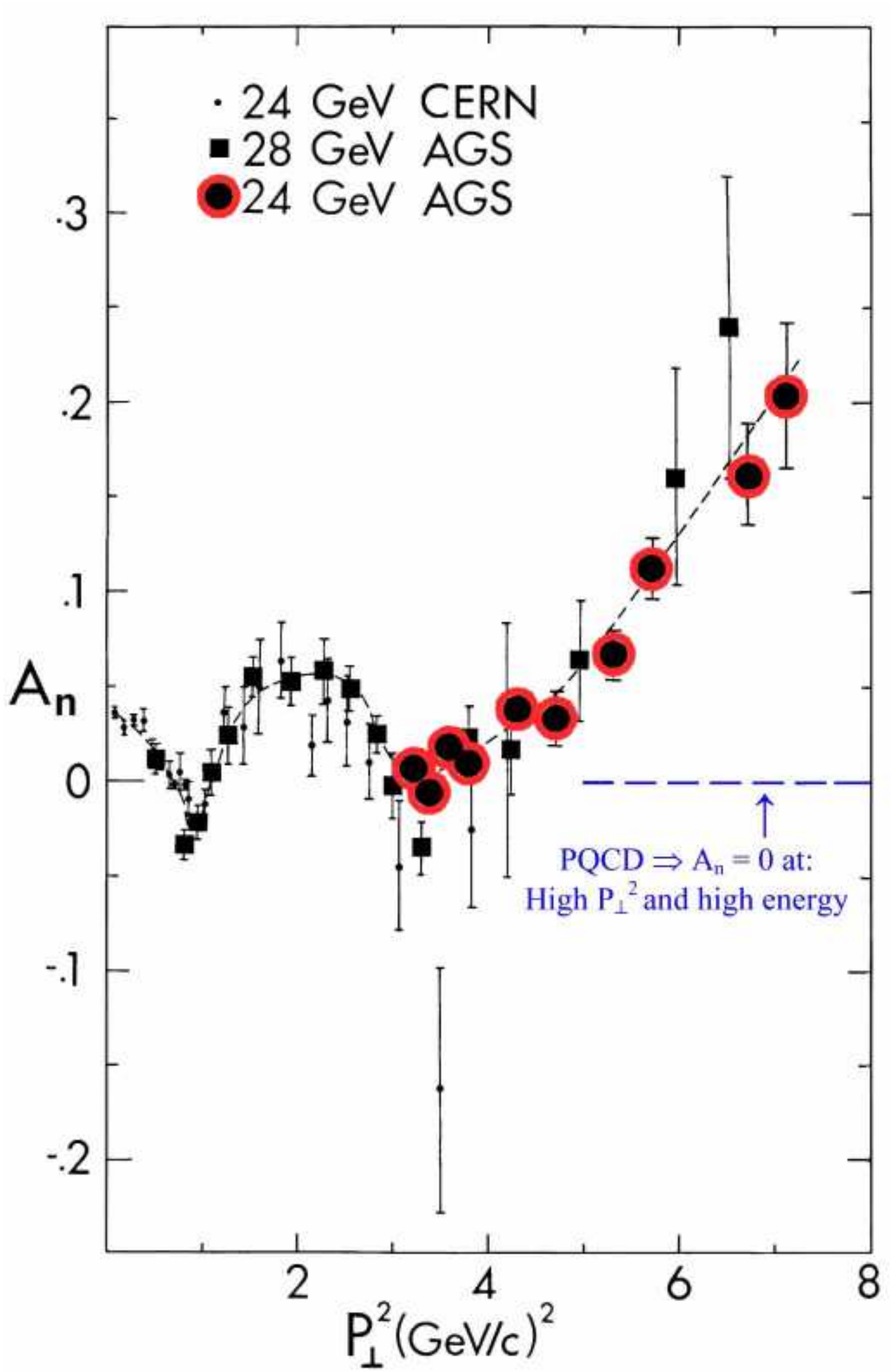
versus

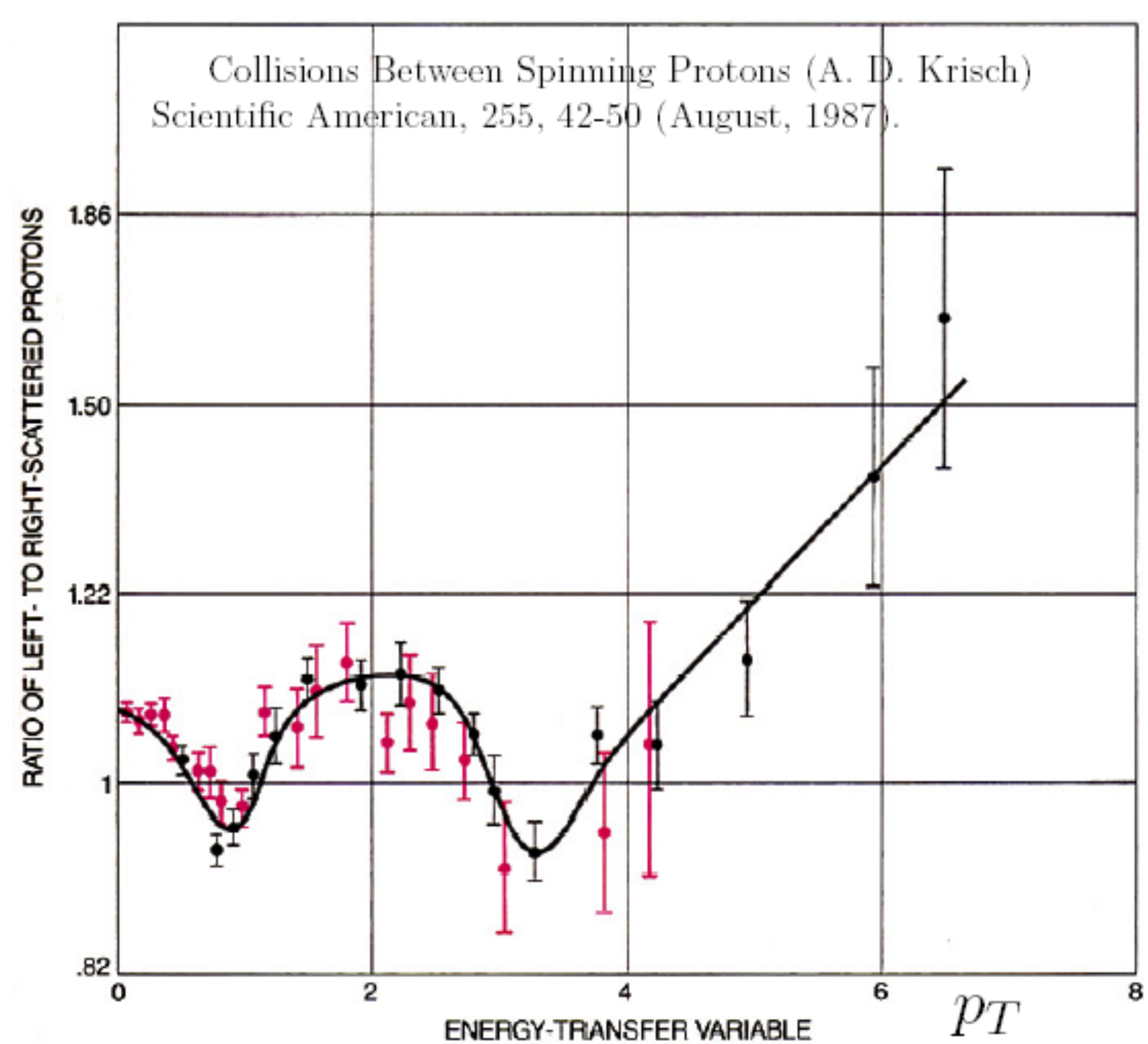
$$p^{\uparrow} p^{\downarrow} \rightarrow p\, p$$

for a summary see A. Krisch, EPJA 31 (2007) 417

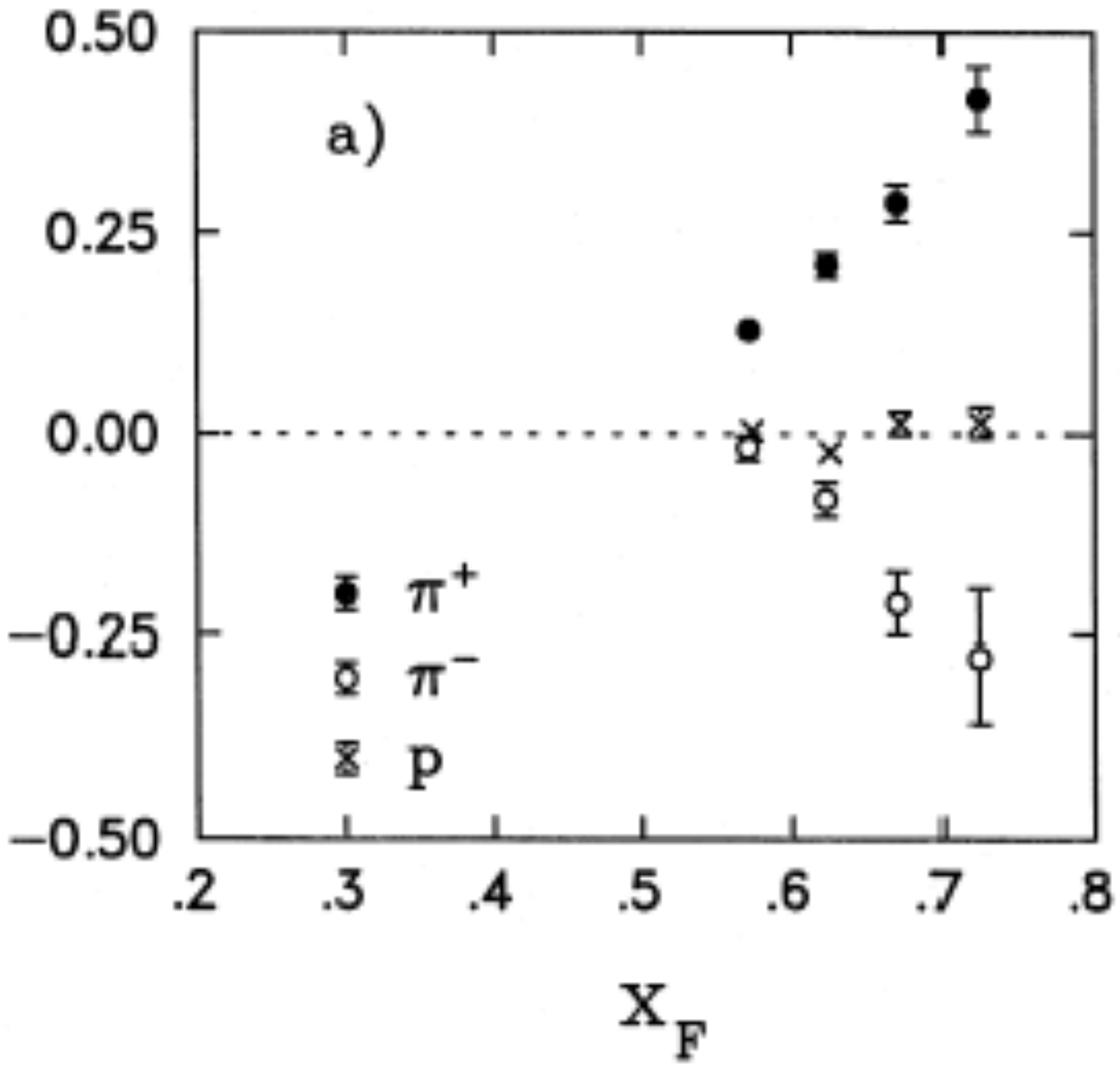
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$p^{\uparrow}p \to p\,p$ versus $p^{\downarrow}p \to p\,p$





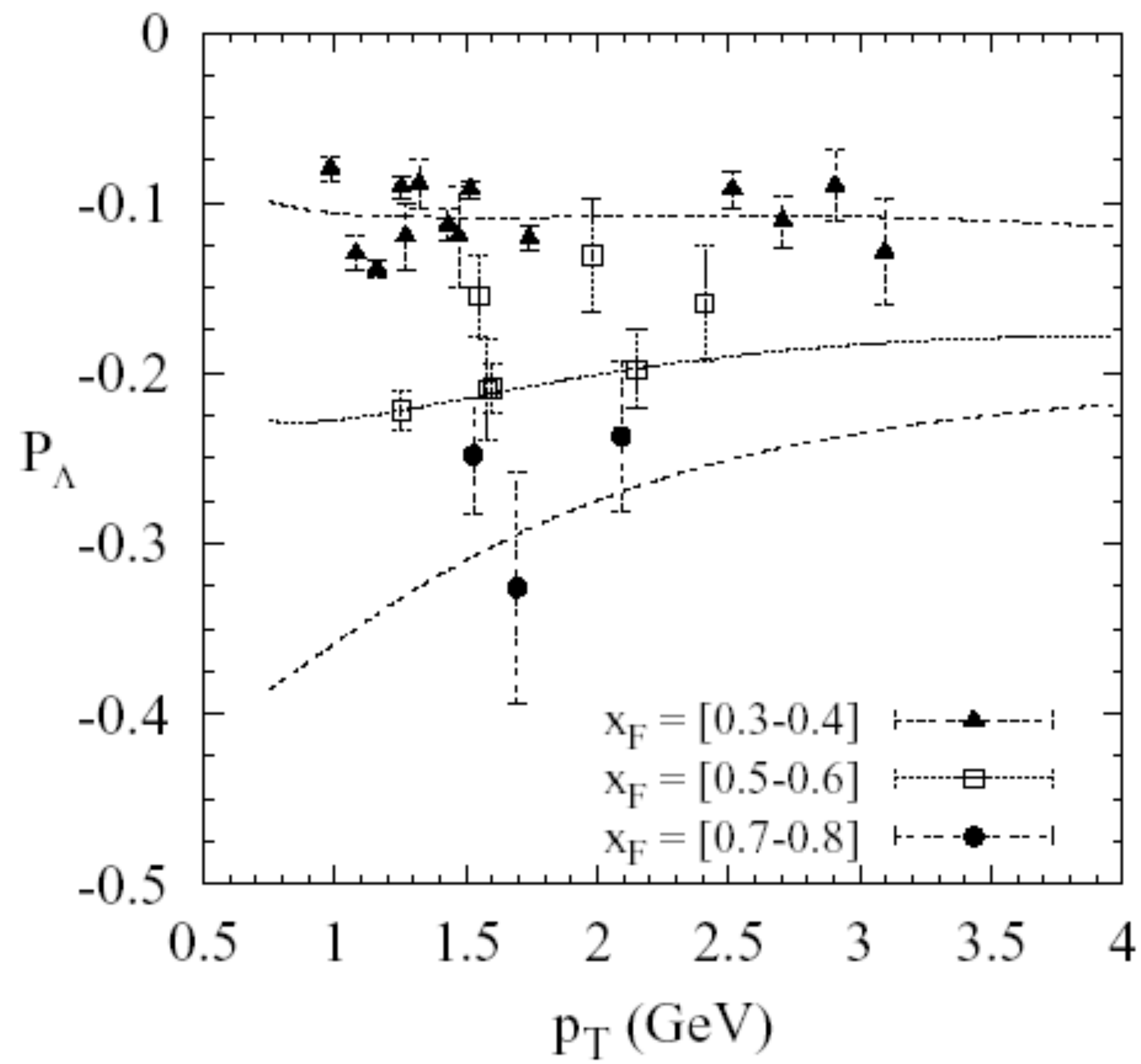
$p^{\uparrow}\, p \to \pi\, X$



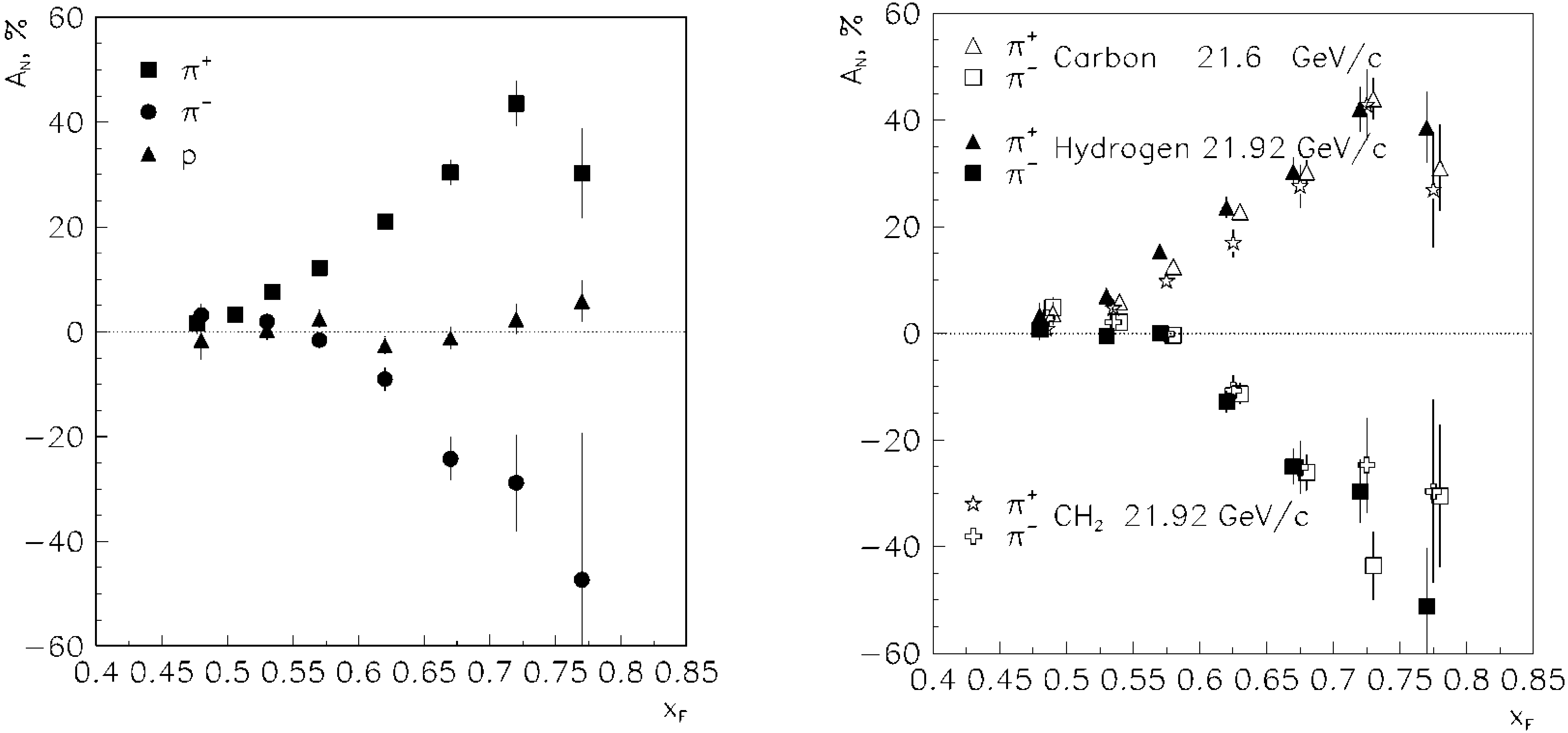
BNL-AGS
√s = 6.6 GeV
0.6 < p_T < 1.2

$$\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$p\, N \to \Lambda^{\uparrow}\, X$



Transverse Λ polarization in unpolarized p-Be scattering at Fermilab



$$P_T \leq 1\,\mathrm{GeV}$$

E925, BNL AGS, 22 GeV

PRD 65 (2002) 092008

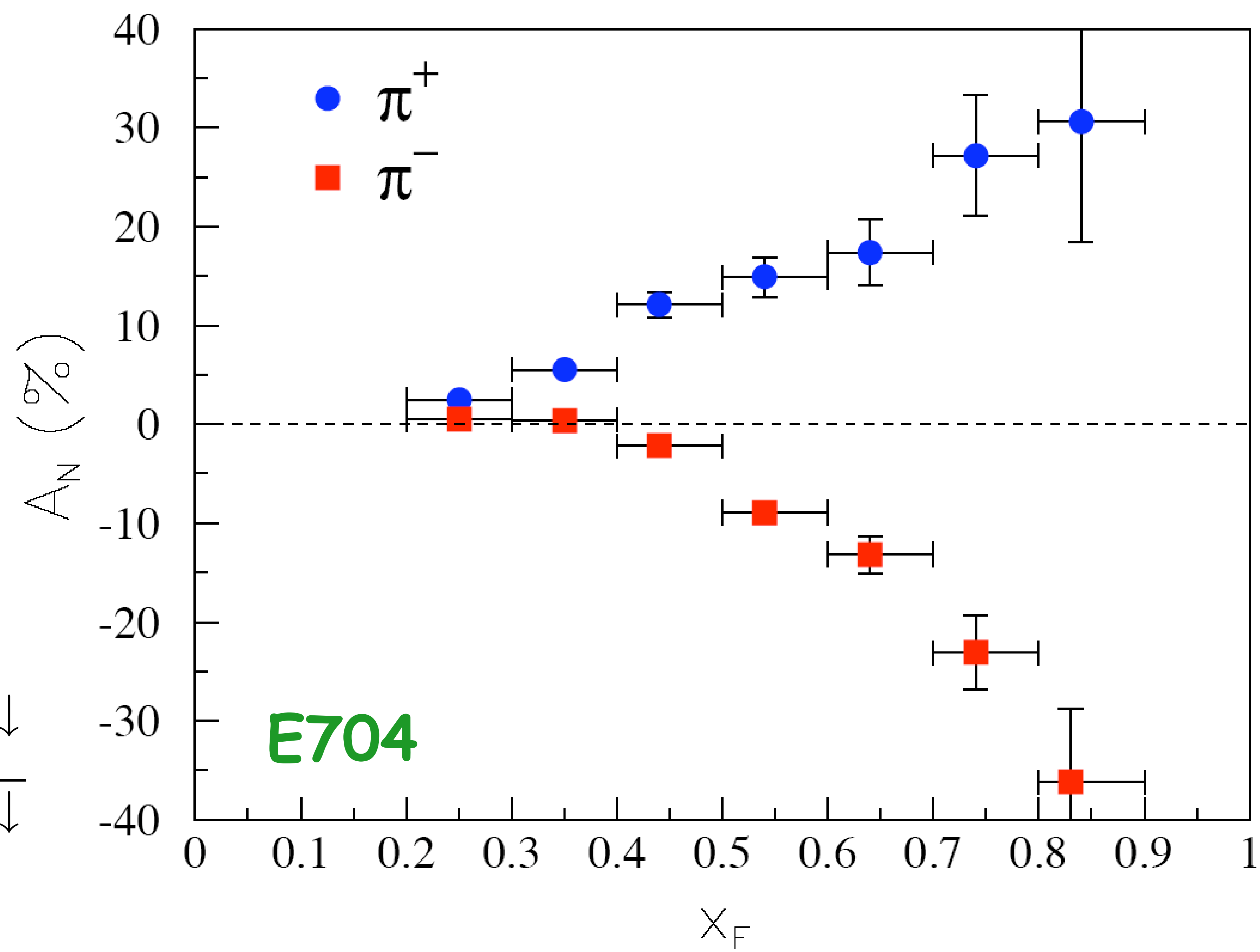
where TMDs started from ... (1991)

large P_T

$$p^{\uparrow}\, p \rightarrow \pi\, X$$

Single Spin Asymmetry

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



E704 $\sqrt{s}$ = 20 GeV $0.7 < p_T < 2.0$

The birth of TMDs (as phenomenological quantities): D. Sivers, PRD 41 (1990) 83

$$G_{a/p}(x;\mu^2) \to G_{a/p}(x,\boldsymbol{k}_T;\mu^2)$$

The relevance of the transverse momentum for the asymmetry can be seen from the venerable Chou-Yang[1] model of the constituent structure of a transversely polarized proton. If we assume a correlation between the spin of the proton and the orbital motion of its constituents, Chou and Yang showed the existence of a nontrivial A_N in elastic scattering. The coherent dynamics which correlates the spin of the proton with the orbital angular momentum of the quarks and gluons can also produce a constituent-level asymmetry in transverse momentum:

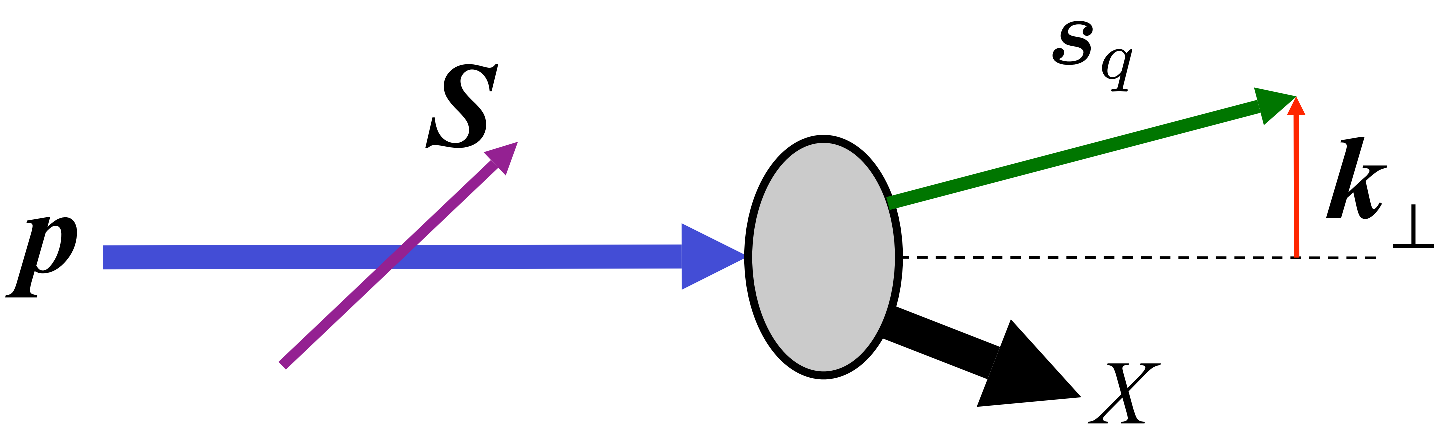
$$\Delta^N G_{a/p(\uparrow)}(x,\boldsymbol{k}_T;\mu^2) = \sum_h \left[G_{a(h)/p(\uparrow)}(x,\boldsymbol{k}_T;\mu^2) - G_{a(h)/p(\downarrow)}(x,\boldsymbol{k}_T;\mu^2)\right]$$

$$= \sum_h \left[G_{a(h)/p(\uparrow)}(x,\boldsymbol{k}_T;\mu^2) - G_{a(h)/p(\uparrow)}(x,-\boldsymbol{k}_T;\mu^2)\right]$$

1 T. T. Chou and C. N. Yang, Nucl. Phys. B107, 1 (1976)

$$A_N \left[E \frac{d^3\sigma}{d^3p}(pp_\uparrow \to mX) \right] \simeq \sum_{ab\to cd} \int d^2\boldsymbol{k}_T^a \, dx_a \int d^2\boldsymbol{k}_T^b \, dx_b \int d^2\boldsymbol{k}_{TC} \frac{dx_c}{x_c^2} \Delta^N G_{a/p_\uparrow}(x_a, k_T^a; \mu^2)$$
$$\times \, G_{b/p}(x_b, k_T^b; \mu^2) \, D_{m/c}(x_c, k_T^c : \mu^2) \times \tilde{s} \, \frac{d\sigma}{d\tilde{t}}(ab \to cd) \, \delta(\tilde{s} + \tilde{t} + \tilde{u})$$

.... this equation corresponds to a probabilistic formula in the original spirit of the parton model where the unknown soft nonperturbative dynamics have been absorbed into the specification of the density $\Delta^N G$ ...



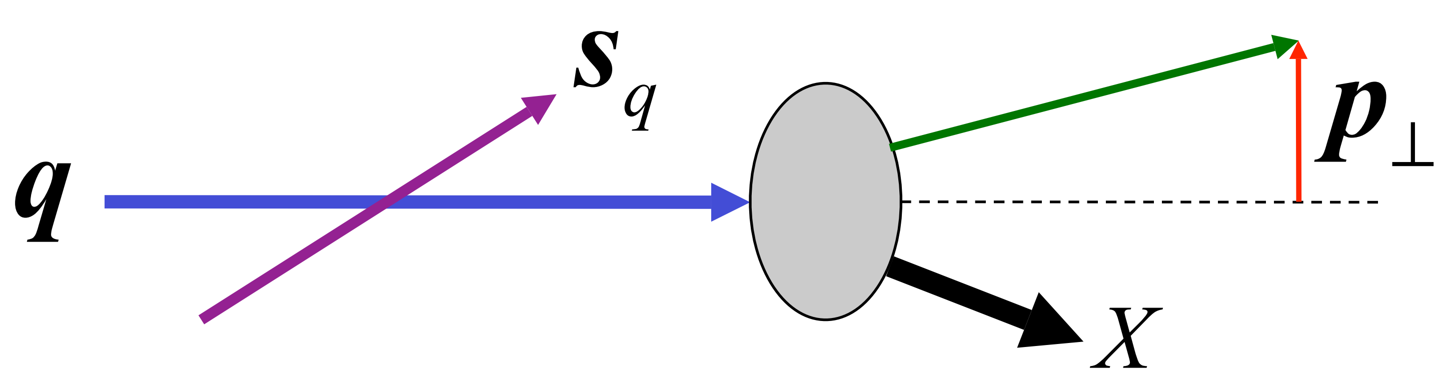
Sivers function

$$f_{q/p,\boldsymbol{S}}(x, \boldsymbol{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2} \Delta^N f_{q/p^\uparrow}(x, k_\perp) \, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$
$$= f_{q/p}(x, k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x, k_\perp) \, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

Collins fragmentation function

Nucl. Phys. B396 (1993) 161

It is shown that the azimuthal dependence of the distribution of hadrons in a quark jet is a probe of the transverse spin of the quark initiating the jet. This results in a new spin-dependent fragmentation function that acts at the twist-2 level.

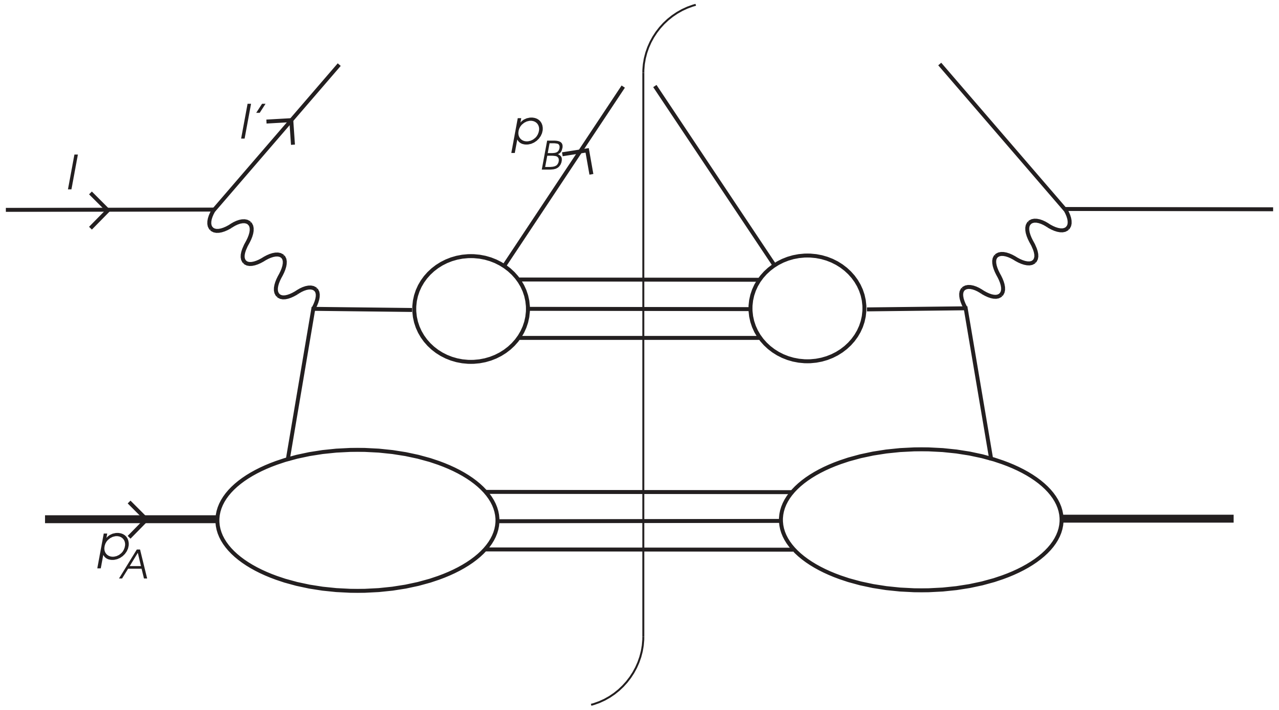


Collins function

$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

$$= D_{h/q}(z,p_\perp) + \frac{p_\perp}{zM_h} H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

TMD factorization



unpolarized cross section

$$E' E_B \frac{d\sigma}{d^3l'\, d^3p_B} = \frac{4x_{\rm Bj}}{Q^2} \sum_a \int d^2k_{a\perp}\, \hat{f}_{a/A}(x_{\rm Bj}, k_{a\perp})\ \frac{d\hat{\sigma}}{d\Omega}\, \hat{D}_{B/a}(z, k_{a\perp} + q_\perp)$$

$$+ Y(x_{\rm Bj}, Q, z, q_\perp/Q).$$

polarized cross section

$$E' E_B \frac{d\sigma}{d^3l'\, d^3p_B} = \frac{4x_{\rm Bj}}{Q^2} \sum_a \int d^2k_{a\perp}\, \hat{f}_{a/A}(x_{\rm Bj}, k_{a\perp})\, \rho_{\alpha\alpha'}\ \frac{d\hat{\sigma}_{\alpha\alpha';\beta\beta'}}{d\Omega}\, \hat{D}_{\beta\beta';B/a}(z, k_{a\perp} + q_\perp)$$

$$+ Y(x_{\rm Bj}, Q, z, q_\perp/Q).$$

Collins, Nucl. Phys. B396 (1993) 161

It follows from the parity and time-reversal invariance of QCD that the number density of quarks is independent of the spin state of the initial hadron, so that we have

$$\hat{f}_{a/A}(x, |k_\perp|) \equiv \int \frac{\mathrm{d}y^- \, \mathrm{d}^2 y_\perp}{(2\pi)^3} \mathrm{e}^{-ixp^+y^- + ik_\perp \cdot y_\perp} \langle p| \, \bar{\psi}_i(0, y^-, y_\perp) \, \frac{\gamma^+}{2} \, \psi_i(0) \, |p\rangle$$

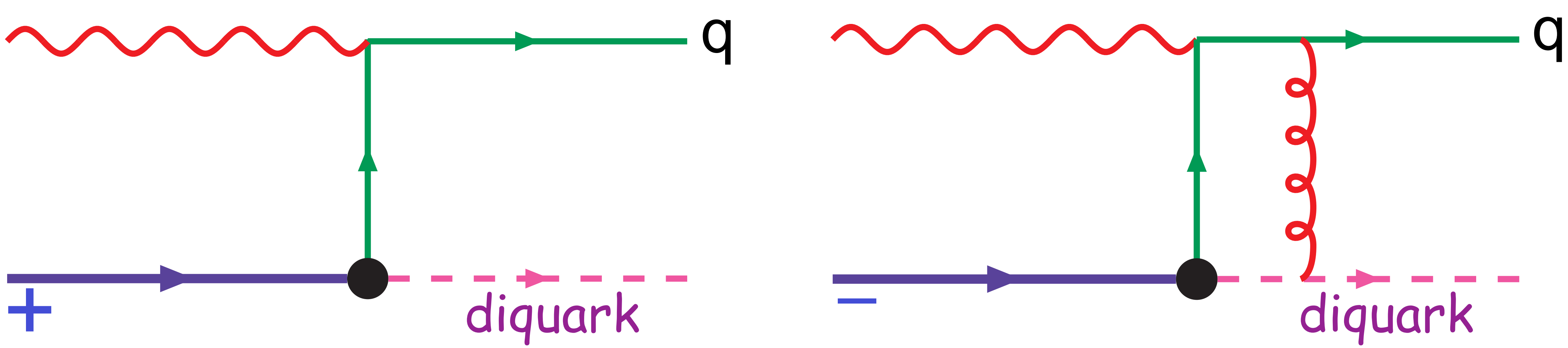
We have ignored here the subtleties needed to make this a gauge invariant definition: an appropriate path ordered exponential of the gluon field is needed [18].

Sivers suggested that the $k_\perp$ distribution of the quark could have an azimuthal asymmetry when the initial hadron has transverse polarization. However, such an asymmetry is prohibited because QCD is time-reversal invariant....

premature death of Sivers effect?

gauge links have physical consequences; quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

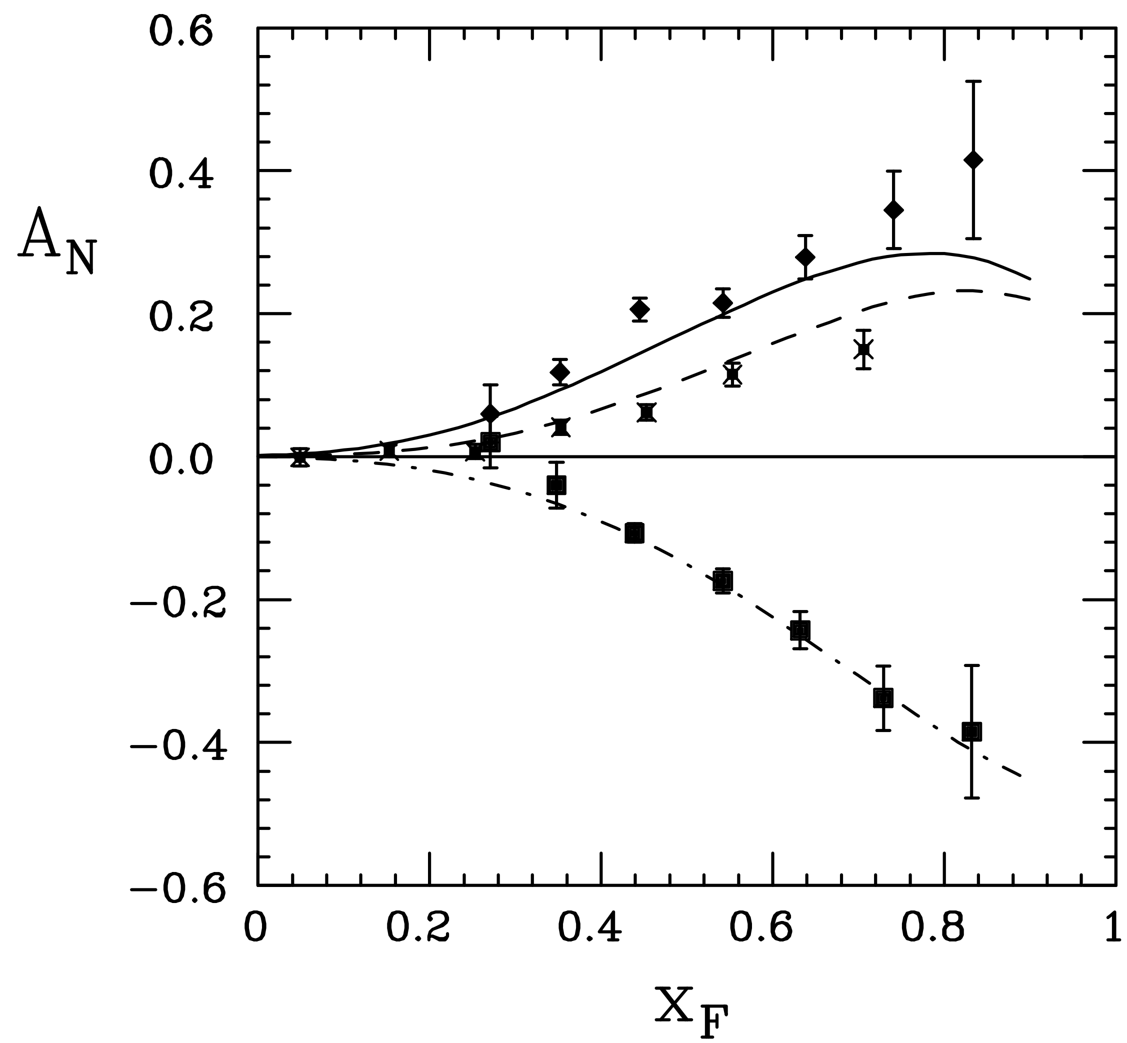
$$[f_{1T}^{q\perp}]_{\mathrm{SIDIS}} = -[f_{1T}^{q\perp}]_{\mathrm{DY}}$$

early A_N phenomenology with Sivers function

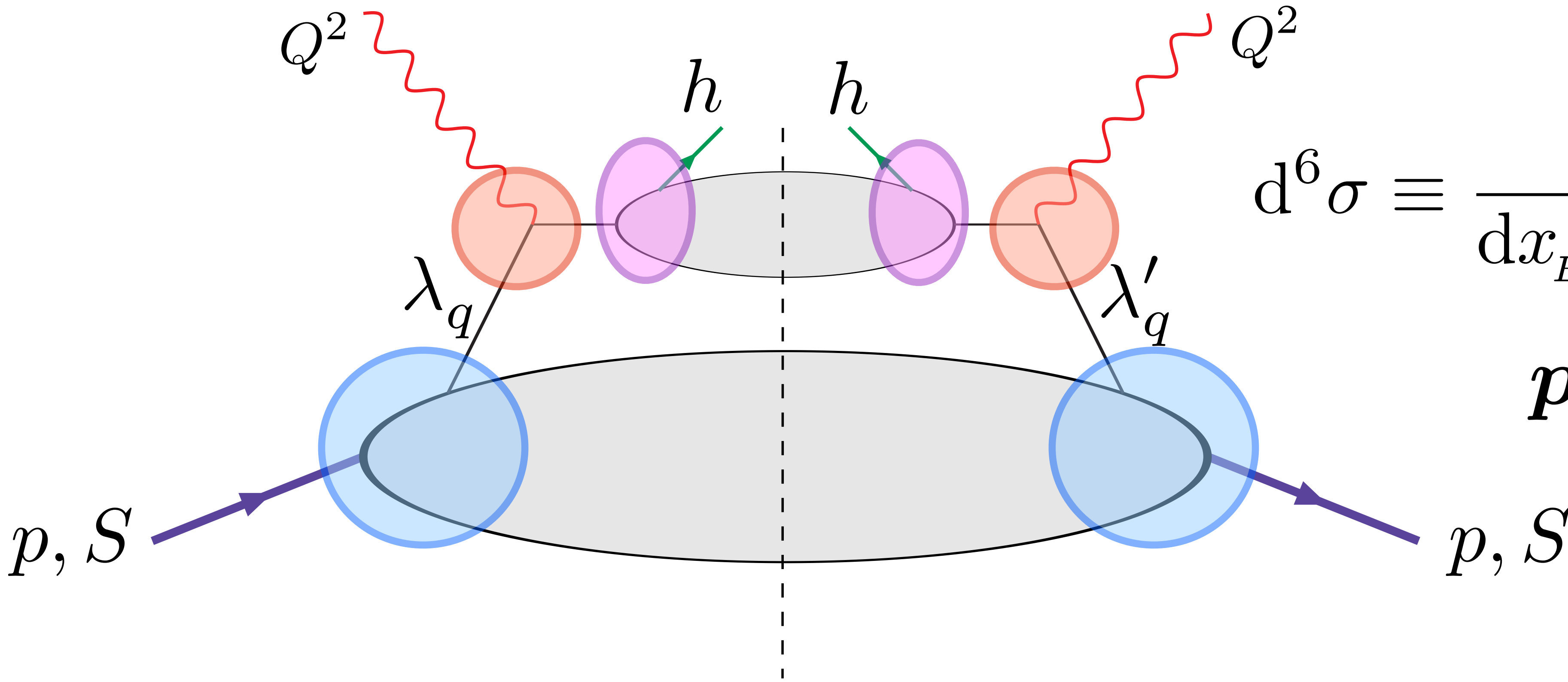
(M.A., M. Boglione and F. Murgia, PL B 362 (1995) 164)

$$\frac{E_\pi \, d\sigma^{p^\uparrow p \to \pi X}}{d^3 \boldsymbol{p}_\pi} \sim \frac{1}{2} \sum_{a,b,c,d} \sum_{\lambda_a, \lambda'_a; \lambda_b; \lambda_c, \lambda'_c; \lambda_d} \int d^2 \boldsymbol{k}_{\perp a} dx_a \, dx_b \, \frac{1}{z}$$

$$\rho^{a/p^\uparrow}_{\lambda_a, \lambda'_a} \, \hat{f}_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a}) \, f_{b/p}(x_b) \, \hat{M}_{\lambda_c, \lambda_d; \lambda_a, \lambda_b} \, \hat{M}^*_{\lambda'_c, \lambda_d; \lambda'_a, \lambda_b} \, D^{\lambda_c, \lambda'_c}_{\pi/c}(z)$$



SSAs and TMDs in SIDIS



$$d^6\sigma \equiv \frac{d^6\sigma^{\ell p^\uparrow \to \ell h X}}{dx_B \, dQ^2 \, dz_h \, d^2\boldsymbol{P}_T \, d\phi_S}$$

$$\boldsymbol{p}_\perp \simeq \boldsymbol{P}_T - z_h \, \boldsymbol{k}_\perp$$

TMD factorization holds at large Q^2, and $P_T \approx k_\perp \approx \Lambda_{QCD}$

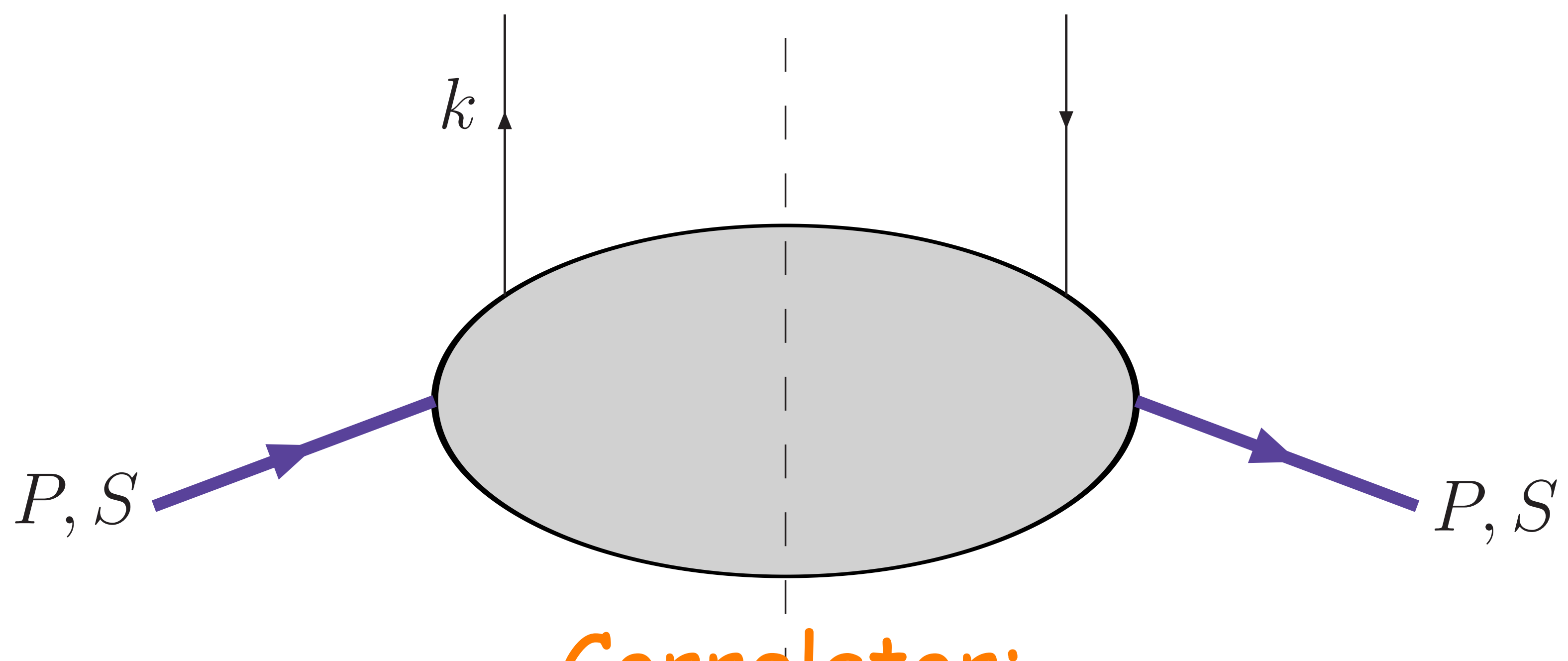
Two scales: $P_T \ll Q^2$

TMD-PDFs — hard scattering — TMD-FFs

$$d\sigma^{\ell p \to \ell h X} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q \to \ell q}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

(Collins, Soper, Ji, J.P. Ma, Yuan, Qiu, Vogelsang, Collins, Metz...)

The nucleon, as probed in DIS, in collinear configuration: 3 distribution functions



Correlator:

$$\Phi_{ij}(k;P,S) = \sum_X \int \frac{d^3 \boldsymbol{P}_X}{(2\pi)^3\, 2E_X} (2\pi)^4\, \delta^4(P-k-P_X) \langle PS|\overline{\Psi}_j(0)|X\rangle\langle X|\Psi_i(0)|PS\rangle$$

$$= \int d^4\xi\, e^{ik\cdot\xi} \langle PS|\overline{\Psi}_j(0)\Psi_i(\xi)|PS\rangle$$

$$\Phi(x,S) = \frac{1}{2}\left[f_1(x)\, \not{n}_+ + S_L\, g_{1L}(x)\, \gamma^5\, \not{n}_+ + h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]$$

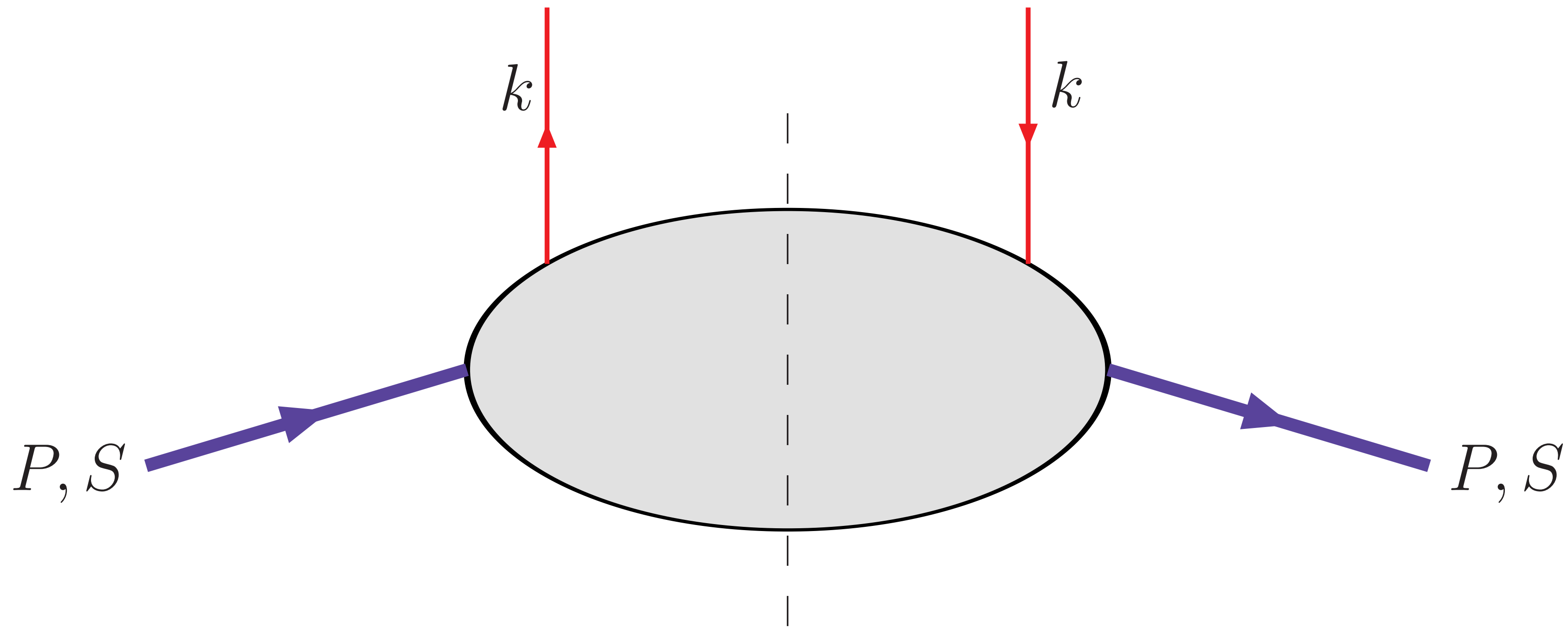
q (f_1), Δq (g_{1L}), $\Delta_T q$ (h_{1T})

TMD-PDFs: the leading-twist correlator, with intrinsic k⊥, contains 8 independent functions

$$\Phi(x, \boldsymbol{k}_\perp) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \Big(S_L g_{1L} + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} g_{1T}^\perp \Big) \gamma^5 \not{n}_+$$

$$+ h_{1T} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \Big(S_L h_{1L}^\perp + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} h_{1T}^\perp \Big) \frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M}$$

$$+ h_1^\perp \frac{\sigma_{\mu\nu} k_\perp^\mu n_+^\nu}{M} \Big]$$



with partonic interpretation

talk by Buffing

there are 8 independent TMD-PDFs

(partonic structure of the nucleon in momentum space)

$f_1^q(x, \boldsymbol{k}_\perp^2)$ unpolarized quarks in unpolarized protons
unintegrated unpolarized distribution

$g_{1L}^q(x, \boldsymbol{k}_\perp^2)$ correlate s_L of quark with S_L of proton
unintegrated helicity distribution

$h_{1T}^q(x, \boldsymbol{k}_\perp^2)$ correlate s_T of quark with S_T of proton
unintegrated transversity distribution

only these survive in the collinear limit

$f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$ correlate $k_\perp$ of quark with S_T of proton (Sivers)

$h_1^{\perp q}(x, \boldsymbol{k}_\perp^2)$ correlate $k_\perp$ and s_T of quark (Boer-Mulders)

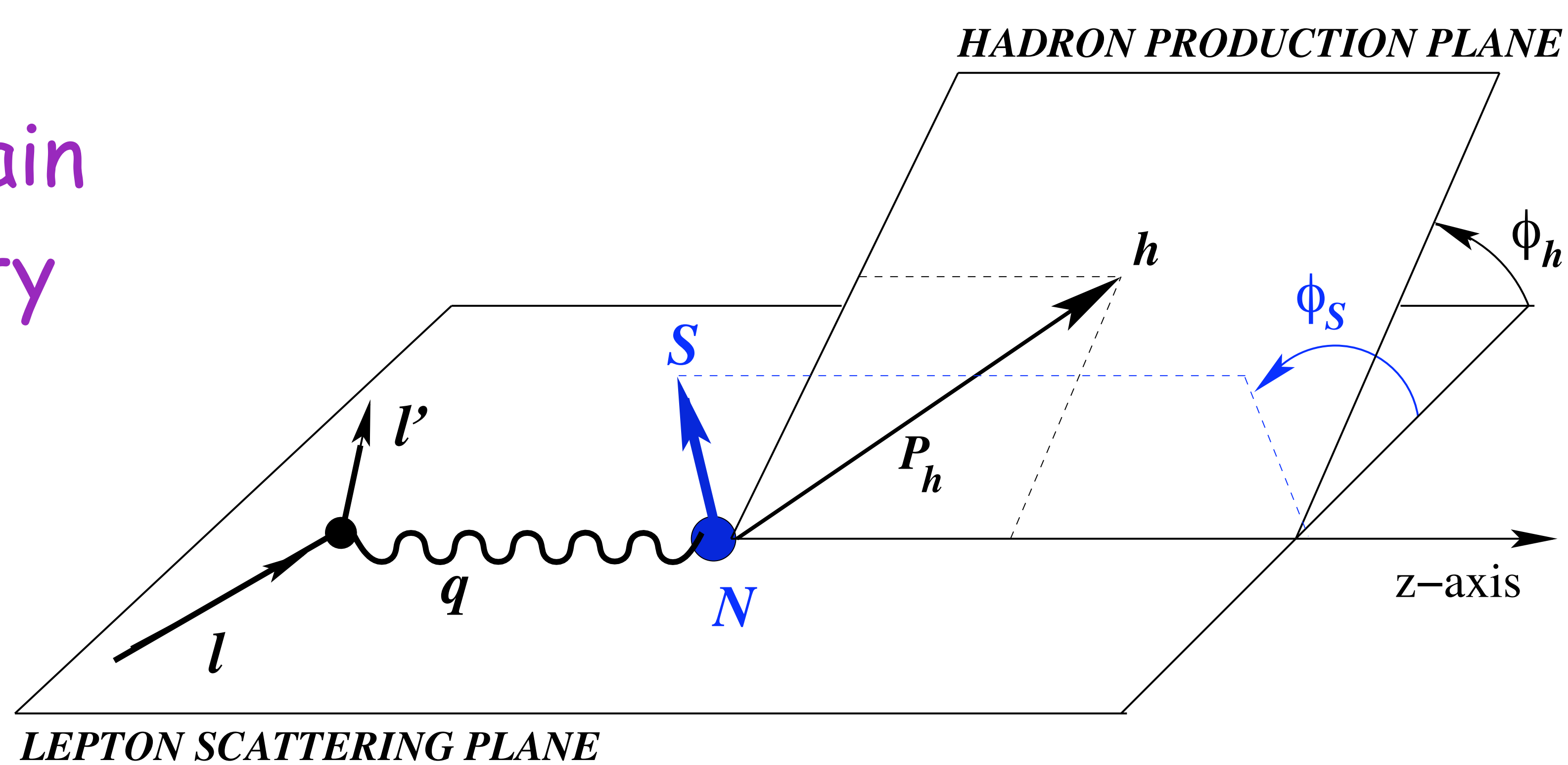
$g_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2) \quad h_{1L}^{\perp q}(x, \boldsymbol{k}_\perp^2) \quad h_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$

different double-spin correlations

(+ gluon TMDs, talk by Schlegel for linearly polarised gluons)

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \;=\;& F_{UU} + \cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \frac{1}{Q}\,\cos\phi\, F_{UU}^{\cos\phi} + \lambda\,\frac{1}{Q}\,\sin\phi\, F_{LU}^{\sin\phi} \\
&+ S_L\left\{\sin(2\phi)\, F_{UL}^{\sin(2\phi)} + \frac{1}{Q}\,\sin\phi\, F_{UL}^{\sin\phi} + \lambda\left[F_{LL} + \frac{1}{Q}\,\cos\phi\, F_{LL}^{\cos\phi}\right]\right\} \\
&+ S_T\left\{\underbrace{\sin(\phi-\phi_S)\, F_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers}} + \underbrace{\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins}} + \sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}\right. \\
&+ \frac{1}{Q}\left[\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)} + \sin\phi_S\, F_{UT}^{\sin\phi_S}\right] \\
&\left.+ \lambda\left[\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \frac{1}{Q}\left(\cos\phi_S\, F_{LT}^{\cos\phi_S} + \cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\right)\right]\right\}
\end{aligned}
$$

the $F^{(\cdots)}_{S_B\,S_T}$ contain the TMDs; plenty of Spin Asymmetries

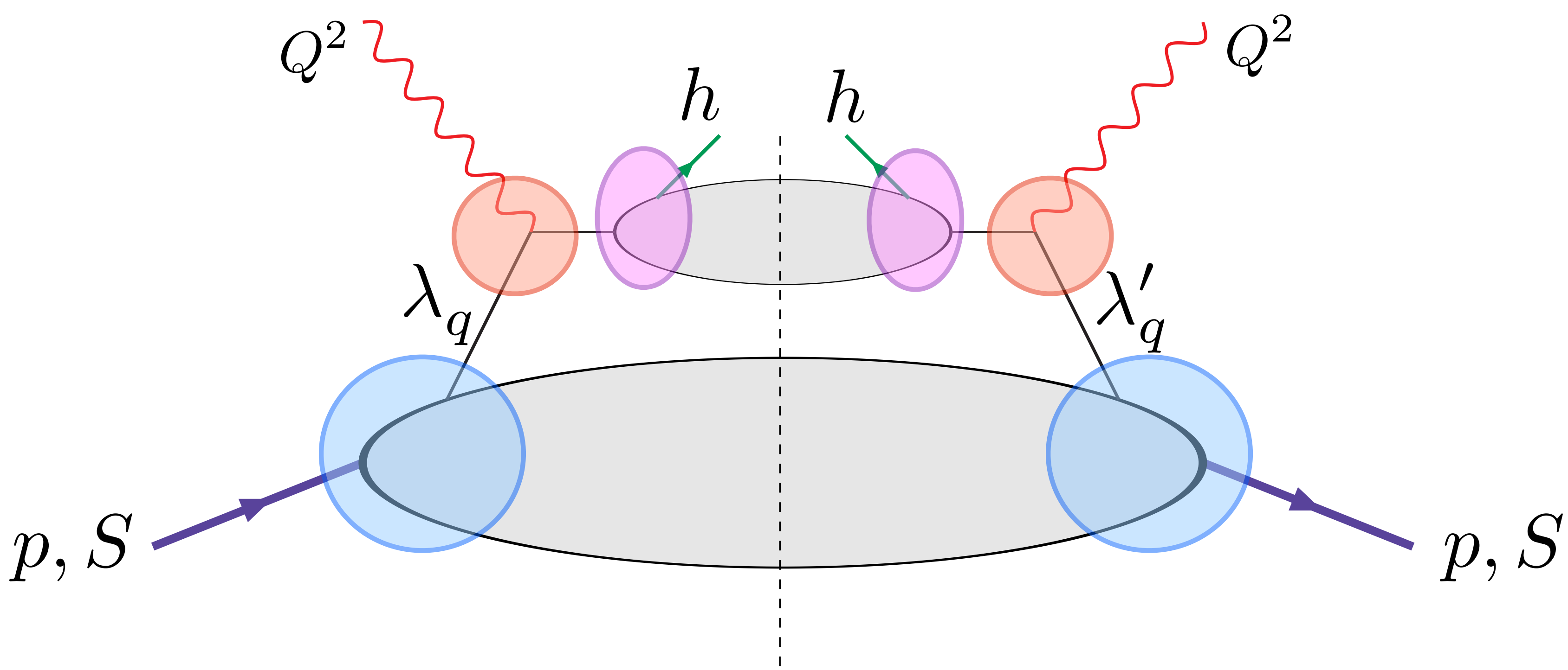


exactly the same results can be obtained at $\mathcal{O}(P_T/Q)$ from

$$\frac{d\sigma^{\ell(S_\ell)\,p(S)\to\ell' hX}}{dx_{_B}\,dQ^2\,dz_h\,d^2\boldsymbol{P}_T\,d\phi_S} \simeq \frac{1}{2\pi}\sum_q\sum_{\{\lambda\}}\frac{1}{16\,\pi\,(x_{_B}\,s)^2}\int d^2\boldsymbol{k}_\perp\,d^2\boldsymbol{p}_\perp\,\delta(\boldsymbol{P}_T - z_h\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)$$
$$\times\ \rho^{\ell(S_\ell)}_{\lambda_\ell\lambda'_\ell}\,\rho^{q/p,S}_{\lambda_q\lambda'_q}\,\hat f_{q/p,S}(x,\boldsymbol{k}_\perp)\,\hat M_{\lambda_\ell\lambda_q;\lambda_\ell\lambda_q}\,\hat M^*_{\lambda_\ell\lambda'_q;\lambda_\ell\lambda'_q}\,\hat D^h_{\lambda_q\lambda'_q}(z,\boldsymbol{p}_\perp)$$

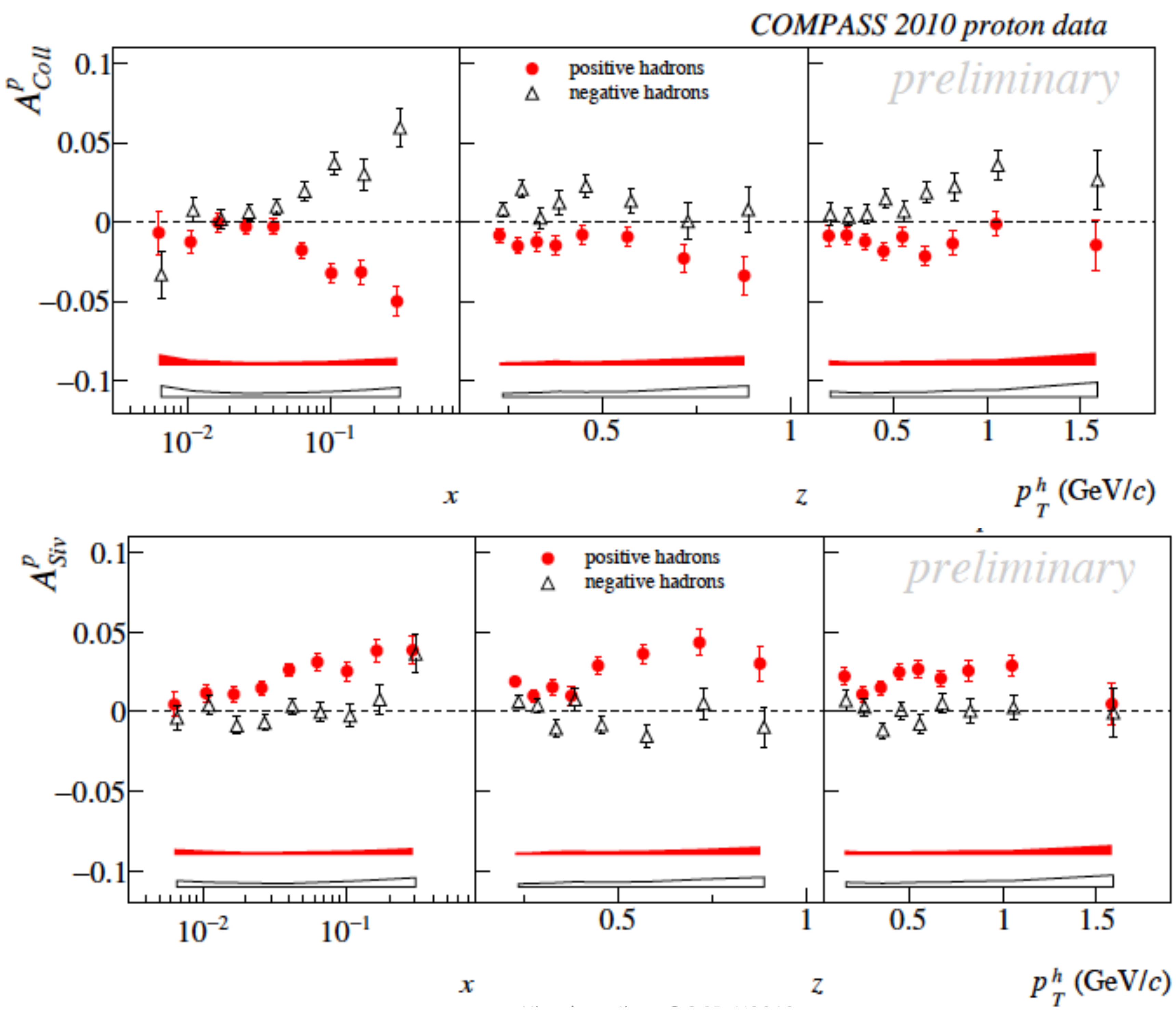
using general properties of helicity amplitudes and elementary interactions

(M.A, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, E. Nocera, A. Prokudin, PRD83 (2011) 114019)



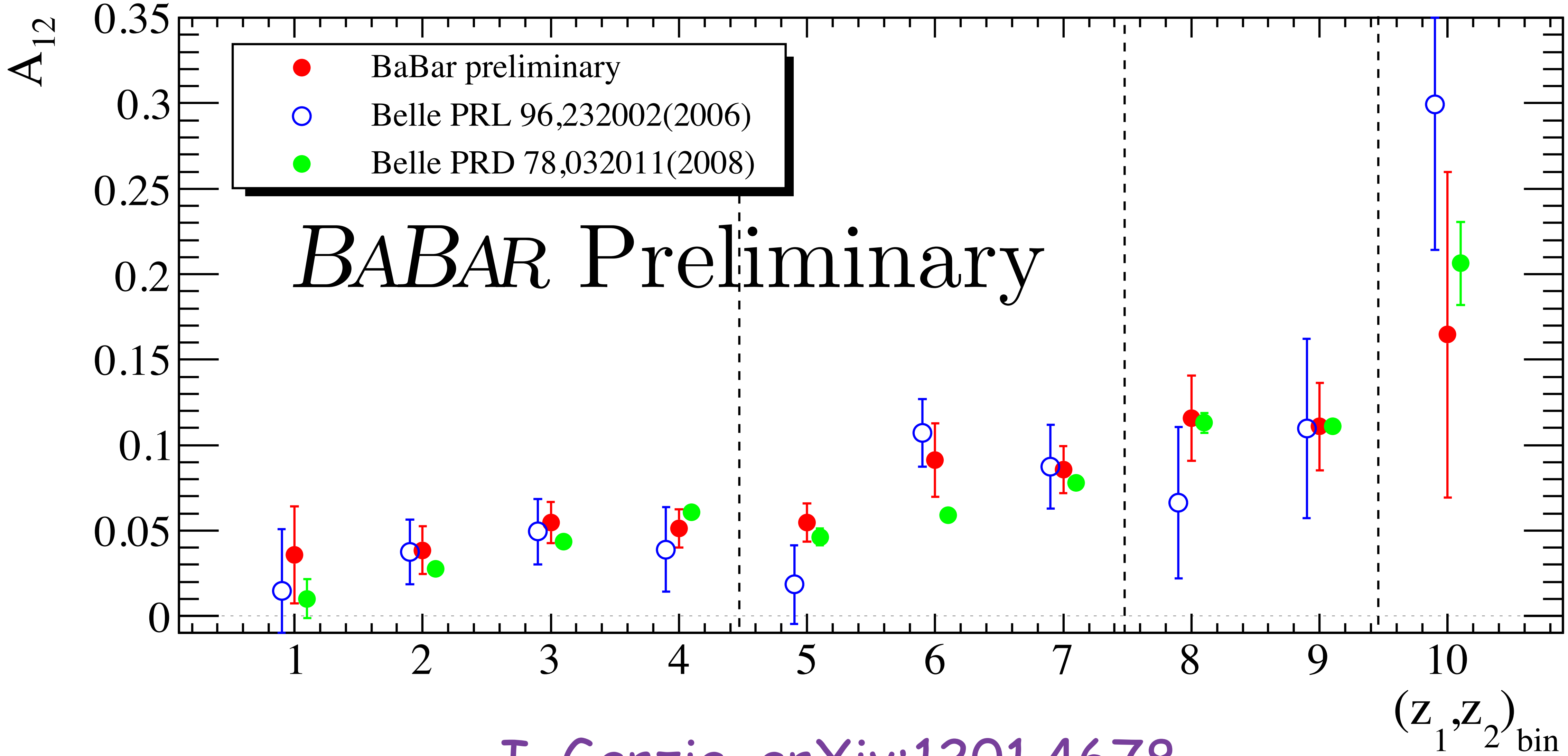
Clear evidence for Sivers and Collins effects from SIDIS data (HERMES, COMPASS, JLab)

talks by Melis, Contalbrigo, Bressan, Szabelski, Prokudin, Burkardt, Braun, Parsamyan, Van Huise, Puckett, Avakian, Schnell, Radici, Kotzinian, Pace, …



independent evidence for Collins effect from e^+e^- data at Belle and BaBar

$$A_{12}(z_1, z_2) \sim \Delta^N D_{h_1/q^\uparrow}(z_1) \otimes \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)$$



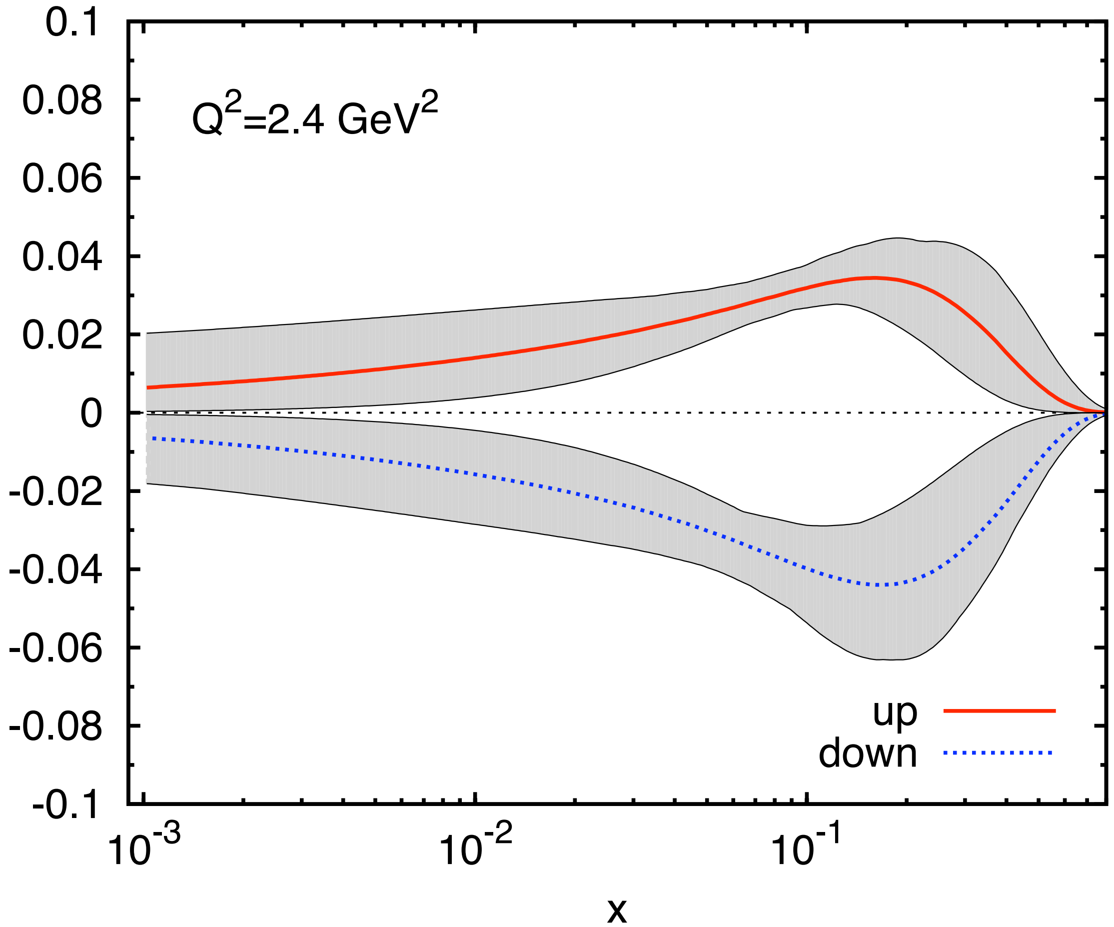
I. Garzia, arXiv:1201.4678

talks by Garzia, Giordano, Perdekamp

extraction of u and d Sivers functions - first phase

M.A, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin
(in agreement with several other groups)

$x\,\Delta^N f_q^{(1)}(x,Q)$

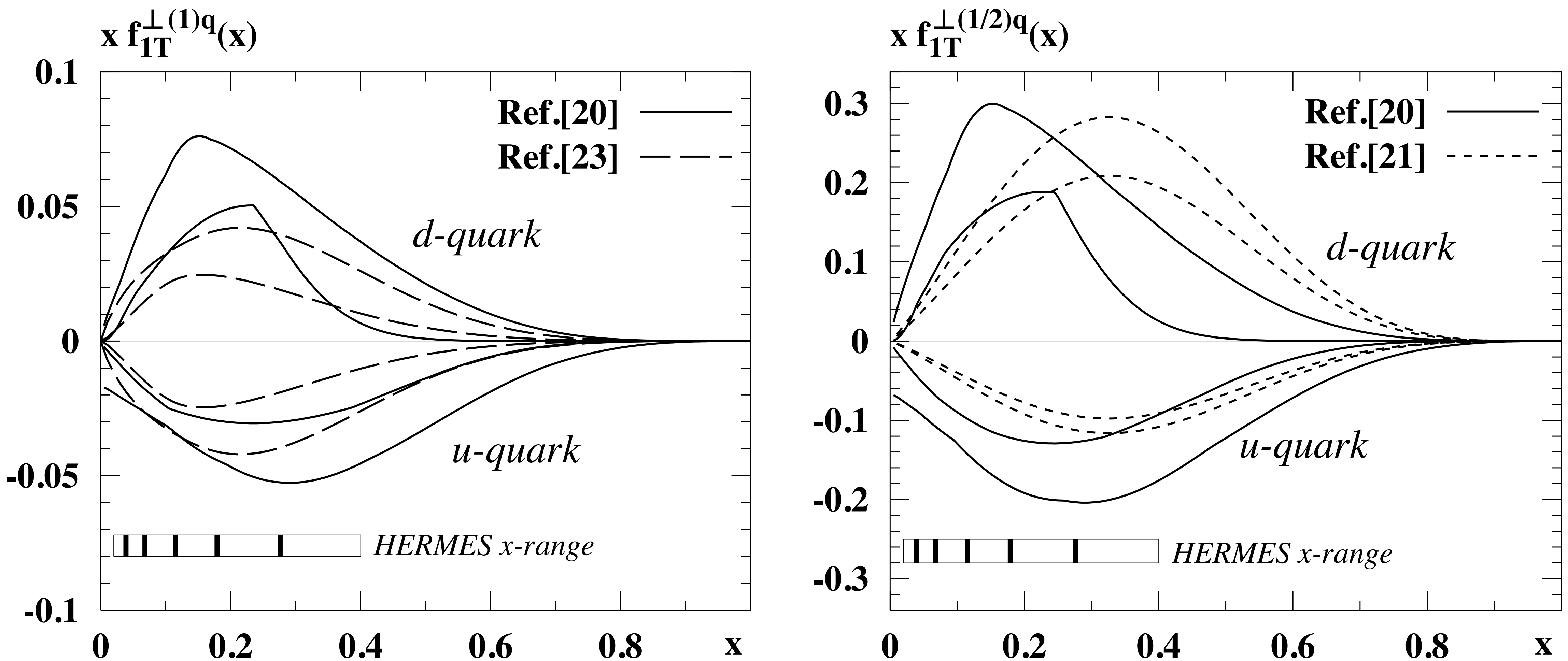


$$\Delta^N f_q^{(1)}(x,Q) = \int d^2\boldsymbol{k}_\perp \, \frac{k_\perp}{4M_p} \, \Delta^N \widehat{f}_{q/p^\uparrow}(x,k_\perp;Q) = -f_{1T}^{\perp(1)q}(x,Q)$$

parameterization of the Sivers function:

$$\Delta^N \widehat{f}_{q/p^\uparrow}(x,k_\perp;Q) = 2\,\mathcal{N}(x)\,h(k_\perp)\,f_q(x,Q)\,\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

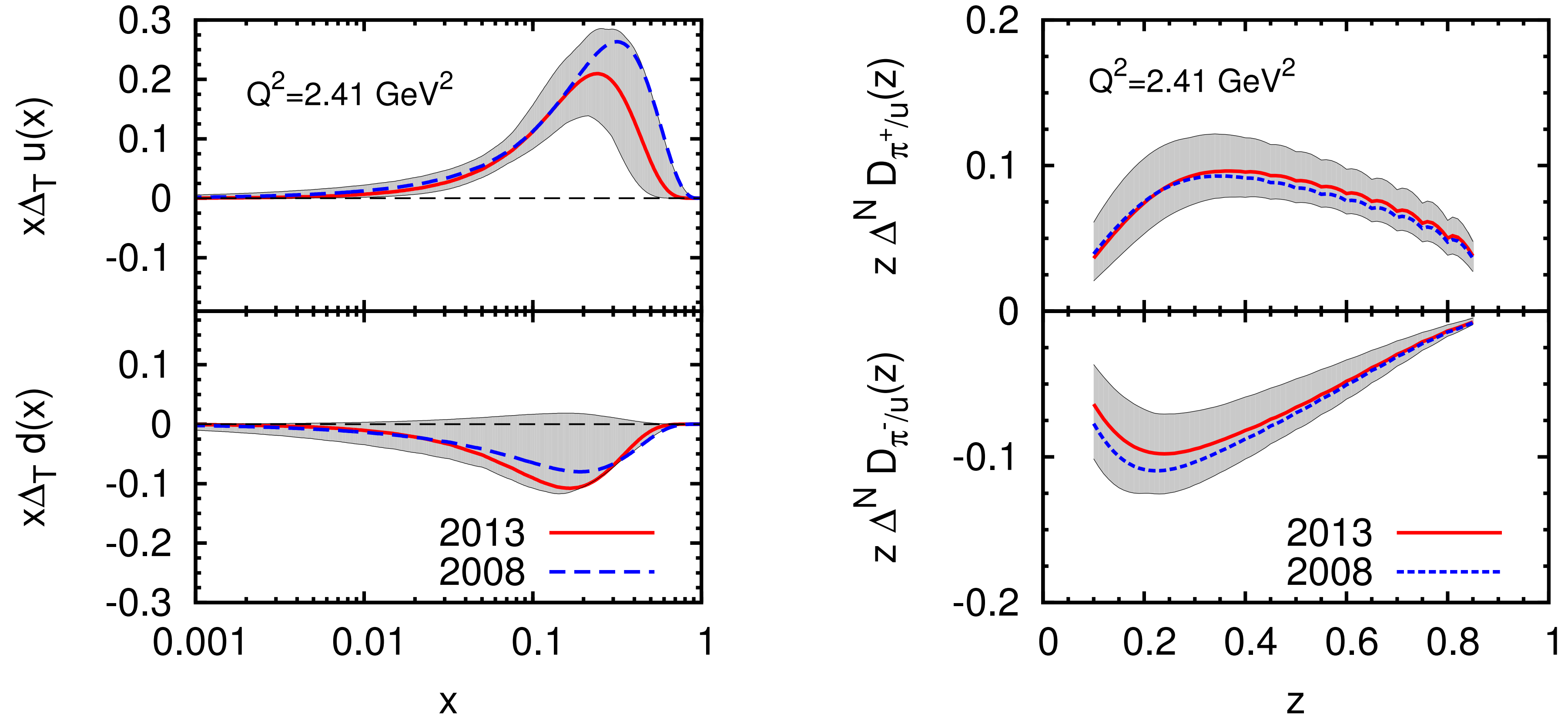
Q^2 evolution only taken into account in the collinear part (usual PDF) from: Como International Workshop on Transverse Polarization Phenomena in Hard Processes (Transversity 2005)



[20] Torino - Cagliari
[21] Vogelsang - Yuan
[23] Bochum

extraction of transversity and Collins functions

M. A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, PRD 87 (2013) 094019



$$\Delta_T q(x, k_\perp) \;=\; \frac{1}{2}\,\mathcal{N}_q^T(x)\,[f_{q/p}(x) + \Delta q(x)]\;\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T}$$

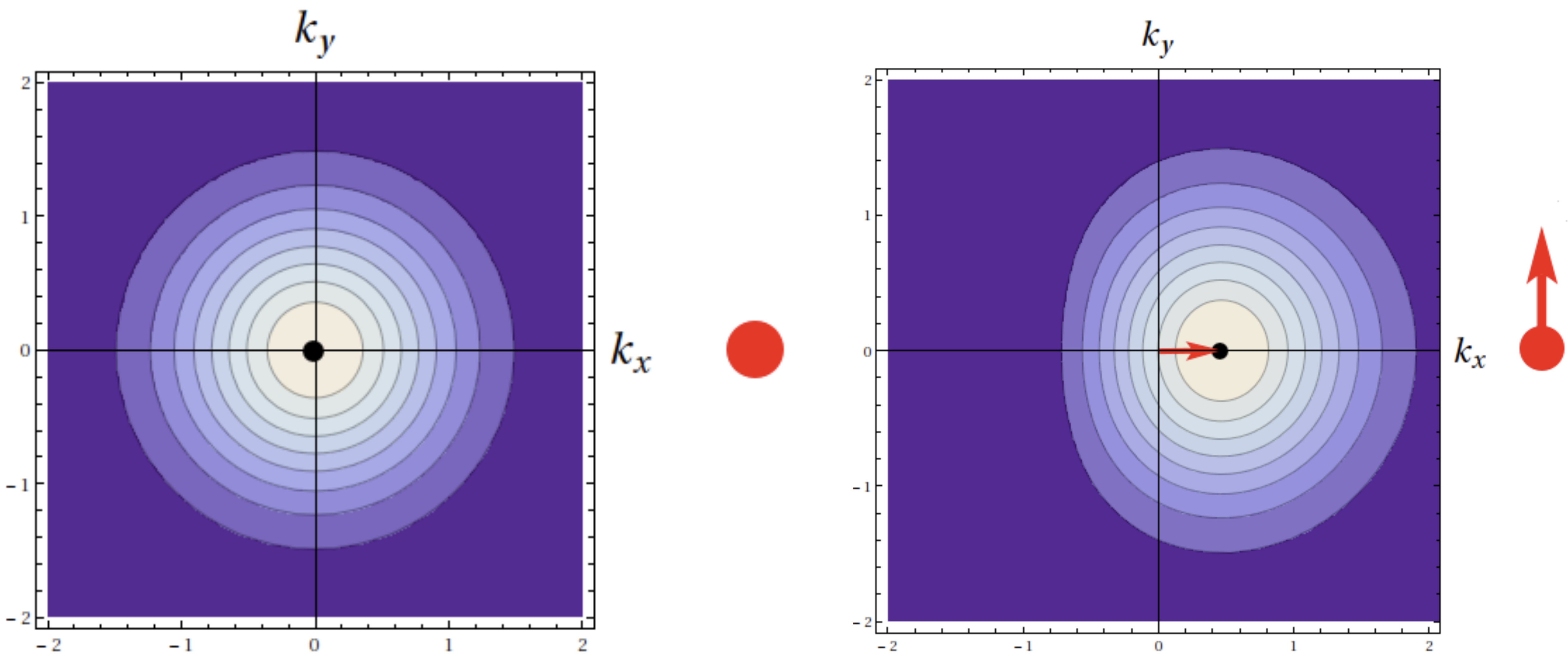
$$\Delta^N D_{h/q^\uparrow}(z, p_\perp) \;=\; 2\,\mathcal{N}_q^C(z)\,D_{h/q}(z)\,h(p_\perp)\;\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$$

simple parameterization, no TMD evolution, agreement with extraction using di-hadron FF (talks by Radici, Braun,...)

what do we learn from the Sivers function?
dipole deformation

$$\widehat{f}_{q/p^\uparrow}(x, \boldsymbol{k}_\perp, S\,\hat{\boldsymbol{j}}; Q) = \widehat{f}_{q/p}(x, k_\perp; Q) - \widehat{f}_{1T}^{\perp q}(x, k_\perp; Q)\, \frac{k_\perp^x}{M_p}$$

$\boldsymbol{S} = 0$ u quark $\boldsymbol{S} = S\,\hat{\boldsymbol{j}}$



courtesy of Alexei Prokudin

Sivers function and angular momentum

(talks by Leader, Mukherjee, Zavada)

Ji's sum rule

forward limit of GPDs

$$J^q = \frac{1}{2}\int_0^1 dx\, x\,[H^q(x,0,0) + E^q(x,0,0)]$$

usual PDF $q(x)$

cannot be measured directly

anomalous magnetic moments

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

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

$$(E^{q_v} = E^q - E^{\bar{q}})$$

Sivers function and angular momentum

assume

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

$$f_{1T}^{\perp(0)a}(x,Q) = \int d^2\boldsymbol{k}_\perp \, \widehat{f}_{1T}^{\perp a}(x,k_\perp;Q)$$

L(x) = lensing function
(unknown, can be computed in models)

parameterize Sivers and lensing functions

fit SIDIS and magnetic moment data

obtain E^q and estimate total angular momentum

results at $Q^2 = 4$ GeV^2: $J^u \approx 0.23$, $J^{q \neq u} \approx 0$

Bacchetta, Radici, PRL 107 (2011) 212001

TMDs and QCD - TMD evolution

study of the QCD evolution of TMDs and TMD factorisation in rapid development

Collins-Soper-Sterman resummation - NP B250 (1985) 199

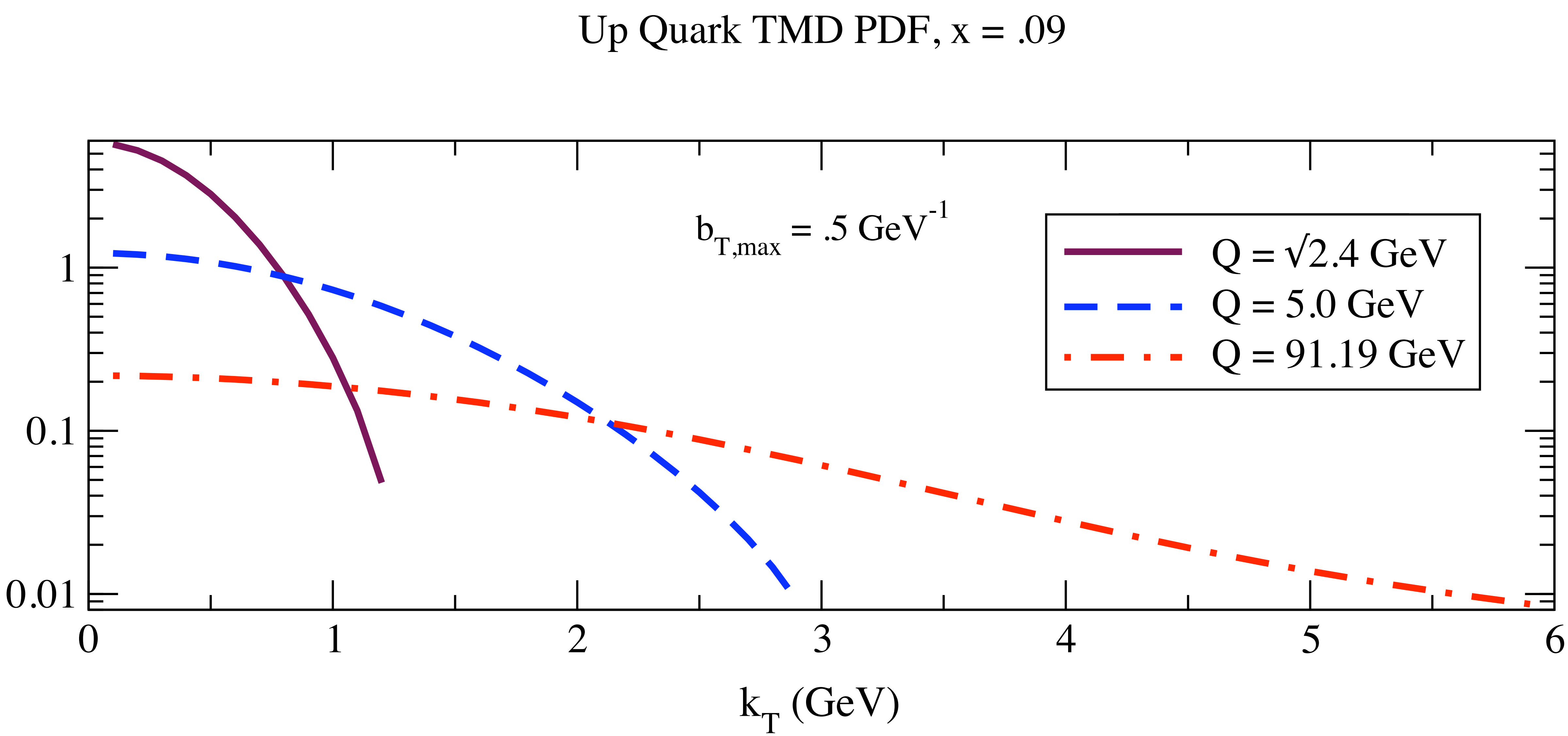
Idilbi, Ji, Ma, Yuan - PL B 597, 299 (2004); PR D70 (2004) 074021
Ji, Ma, Yuan - P. L. B597 (2004) 299; P. R. D71 (2005) 034005

Collins, "Foundations of perturbative QCD", Cambridge University Press (2011)
Aybat, Rogers, PR D83 (2011) 114042
Aybat, Collins, Qiu, Rogers, PR D85 (2011) 034043
Echevarria, Idilbi, Schafer, Scimemi, arXiv:1208.1281
Echevarria, Idilbi, Scimemi, JHEP 1207 (2012) 002
+ many more authors...

dedicated workshops, QCD evolution 2011, 2012, 2013, 2014

TMD phenomenology - phase 2

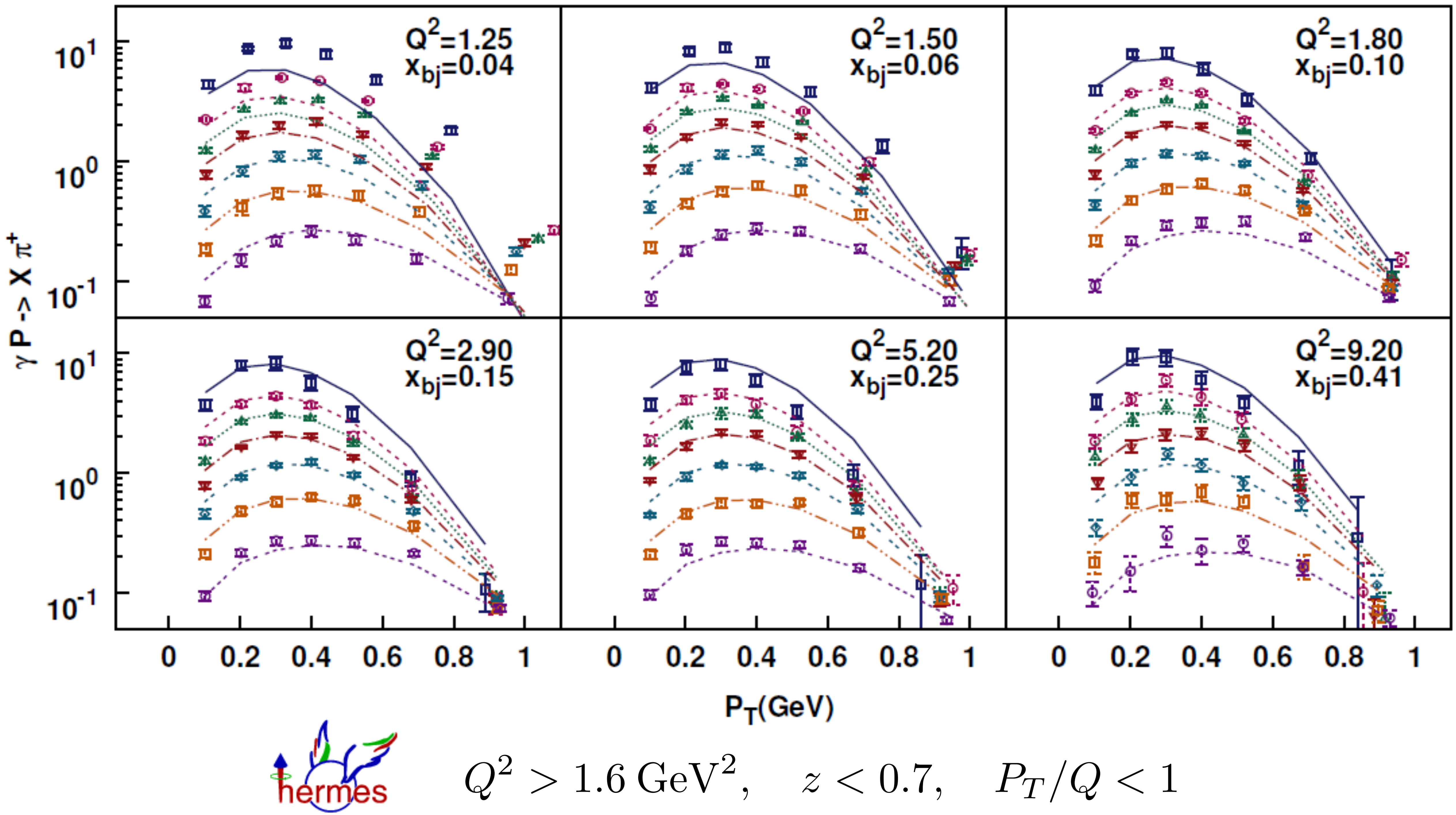
Aybat, Rogers, PR D83, 114042 (2011); arXiv:1101.5057



many talks on TMD evolution: Collins, Vogelsang, Gamberg, Scimemi, Van der Veken, Echevarria, Prokudin, round table....

first test: transverse momentum dependence of the unpolarized SIDIS cross section

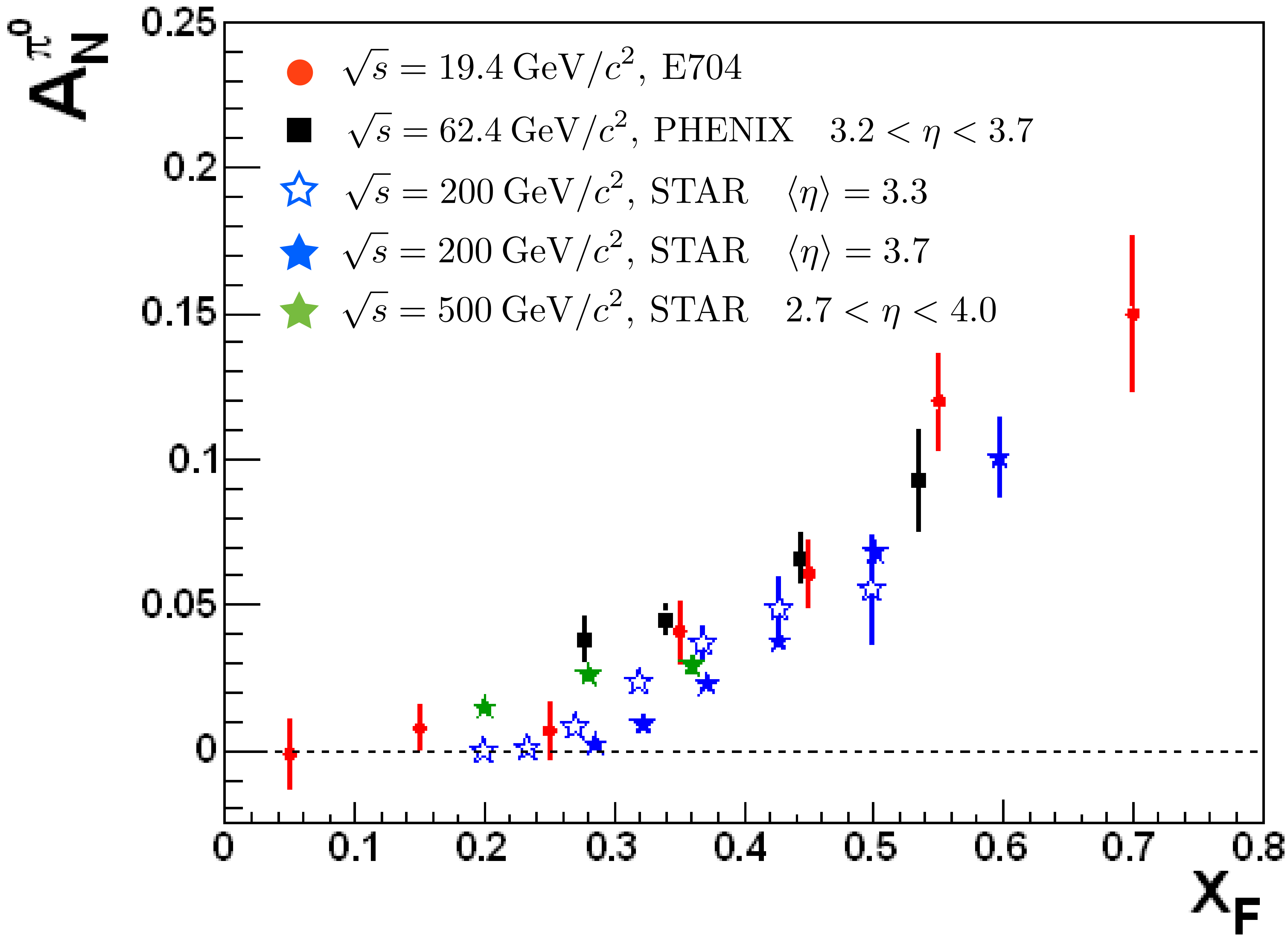
(multi-dimensional analysis sensitive to $\langle k_\perp^2 \rangle$ and evolution)



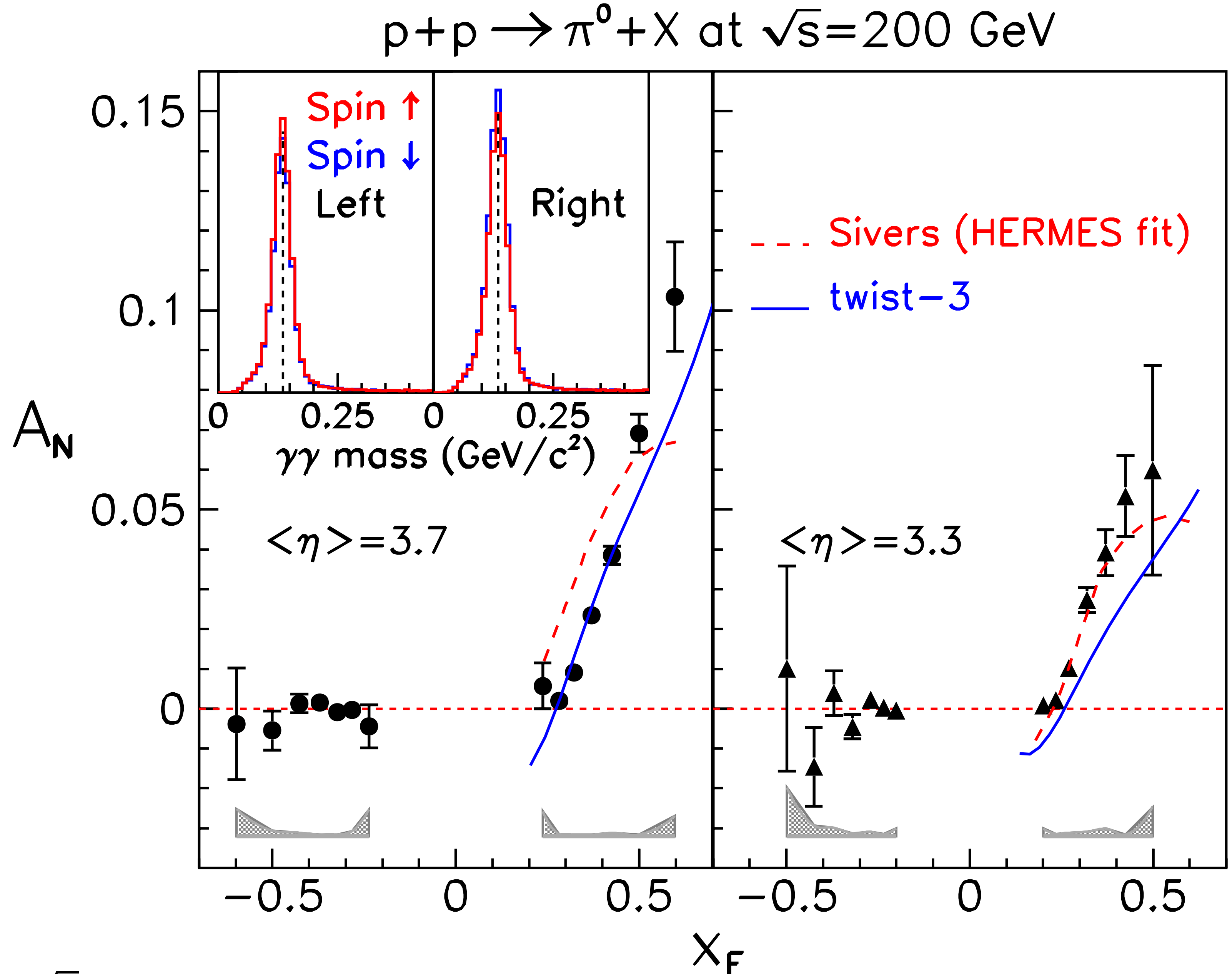
$$Q^2 > 1.6\,\mathrm{GeV}^2, \quad z < 0.7, \quad P_T/Q < 1$$

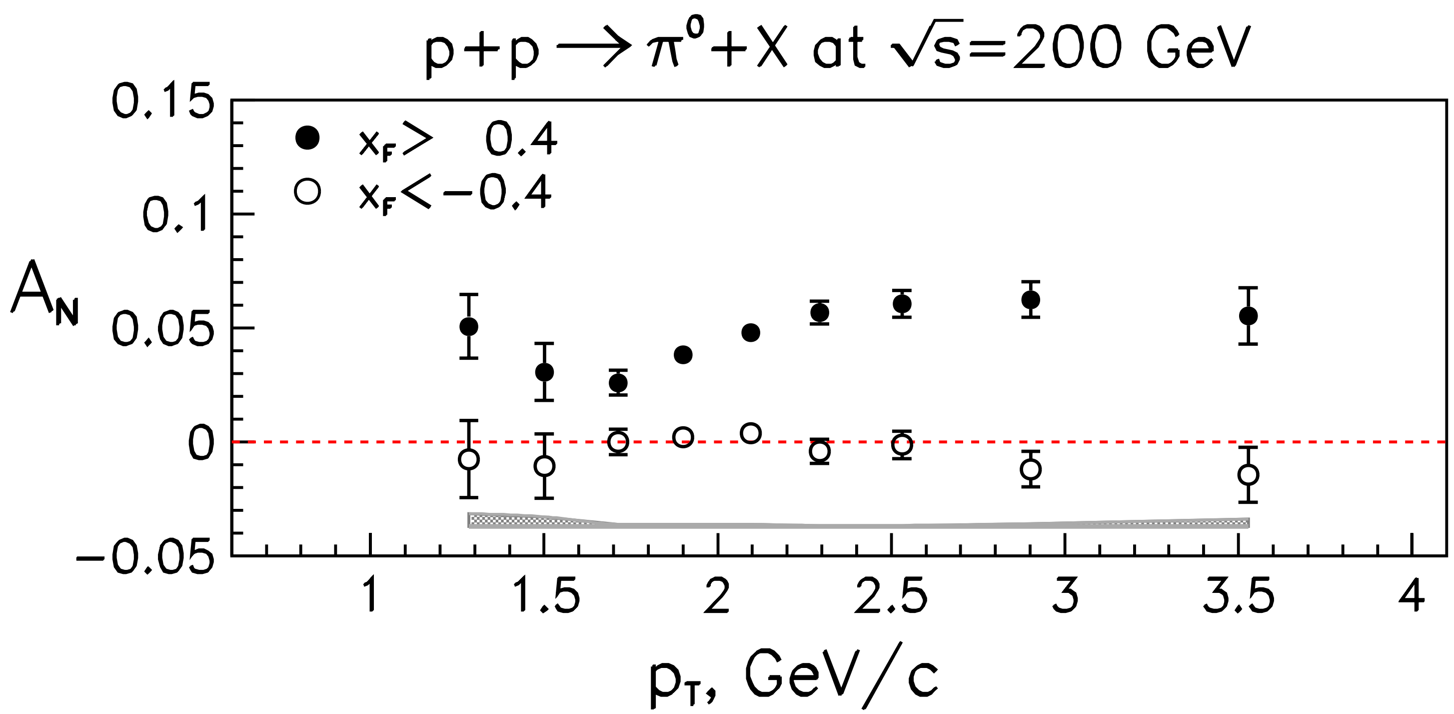
talks by Karyan, Makke, Gonzalez and Signori

meanwhile, what happened to A_N?
it remained, of course ....

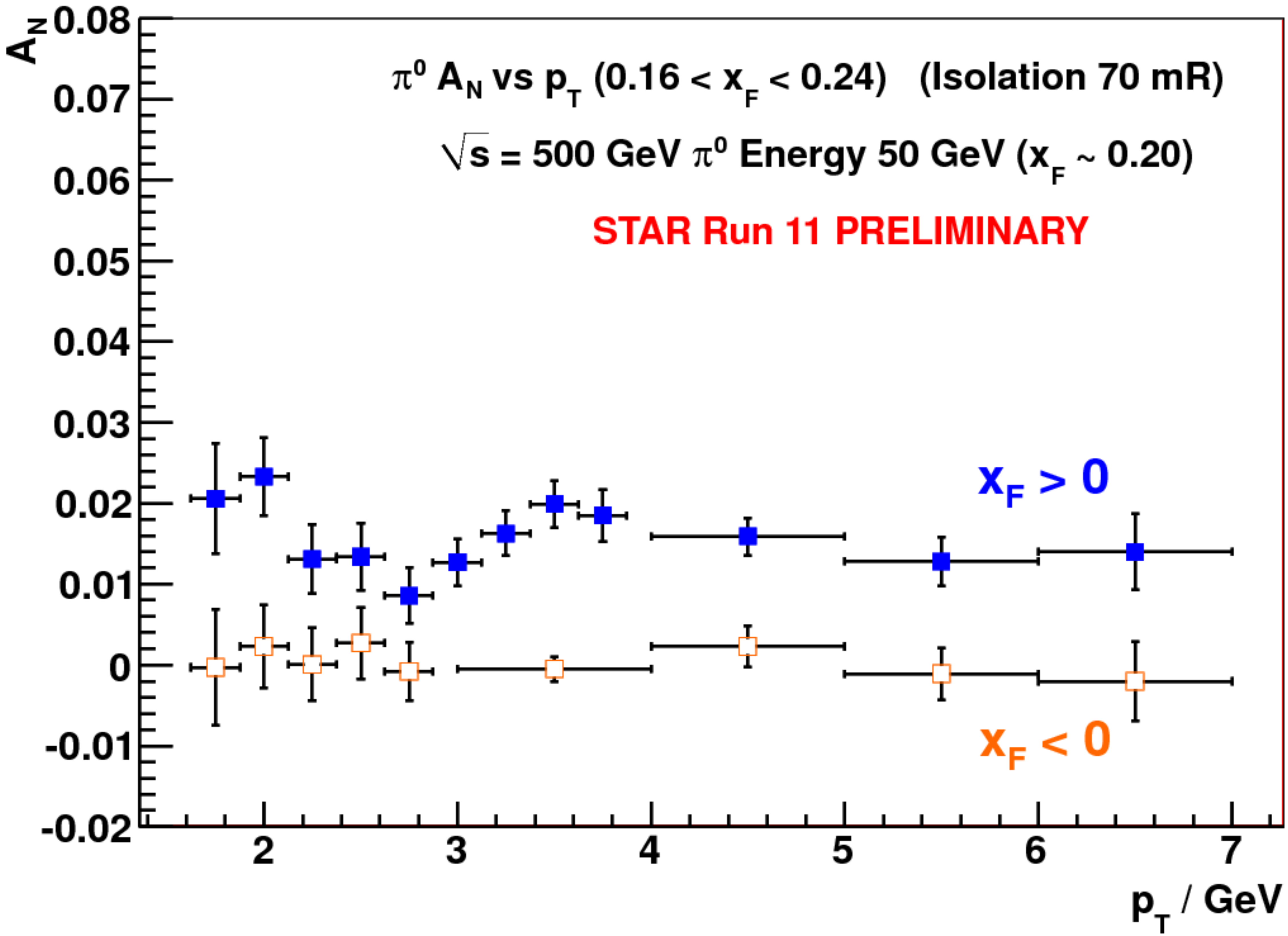


STAR data





PRL 101, 222001 (2008)

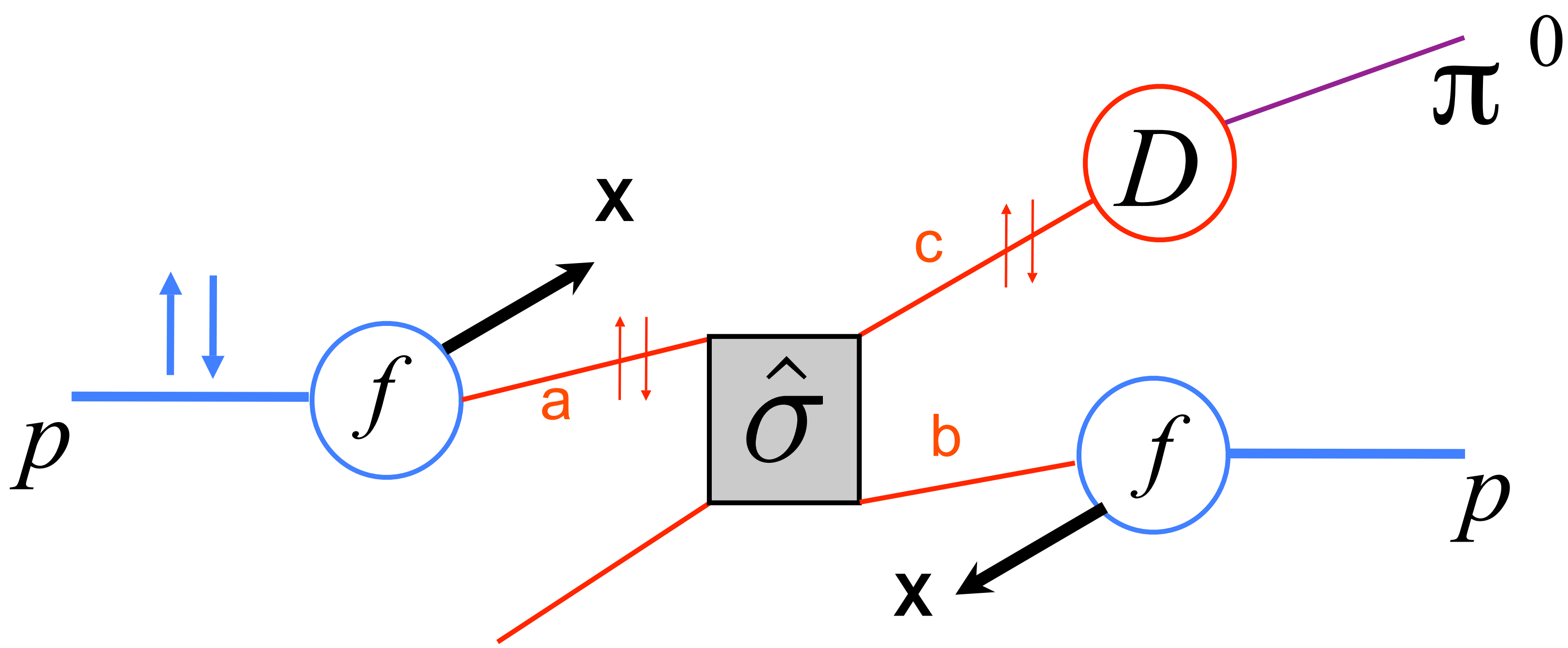


talks by Bland, Kleinjan, Vossen, Ogawa

SSA in hadronic processes: TMDs, higher-twist correlations?

Two main different (?) approaches

1. Simple generalization of collinear scheme
(assuming TMD factorization)



$$d\sigma^\uparrow = \sum_{a,b,c=q,\bar{q},g} \underbrace{f_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a})} \otimes \underbrace{f_{b/p}(x_b, \boldsymbol{k}_{\perp b})} \otimes d\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \underbrace{D_{\pi/c}(z, \boldsymbol{p}_{\perp \pi})}$$

single spin effects in TMDs

M.A., M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, ...

Field-Feynman

possible TMD contributions to A_N

$$
\begin{aligned}
d\sigma^{\uparrow} - d\sigma^{\uparrow} \quad = \quad & \sum_{a,b,c} \Big\{ \Delta^N f_{a/p^{\uparrow}}(\boldsymbol{k}_\perp) \otimes f_{b/p} \otimes d\hat{\sigma}(\boldsymbol{k}_\perp) \otimes D_{\pi/c} \\
+ \quad & h_1^{a/p} \otimes f_{b/p} \otimes d\Delta\hat{\sigma}(\boldsymbol{k}_\perp) \otimes \Delta^N D_{\pi/c^{\uparrow}}(\boldsymbol{k}_\perp) \\
+ \quad & h_1^{a/p} \otimes \Delta^N f_{b^{\uparrow}/p}(\boldsymbol{k}_\perp) \otimes d\Delta'\hat{\sigma}(\boldsymbol{k}_\perp) \otimes D_{\pi/c} \Big\}
\end{aligned}
$$

(1) Sivers effect

(2) transversity $\otimes$ Collins

(3) transversity $\otimes$ Boer - Mulders

main contribution from Sivers effect, can explain qualitatively most SIDIS and A_N data

(M.A. M. Boglione, D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, PRD86 (2012) 074032; PRD88 (2013) 054023)

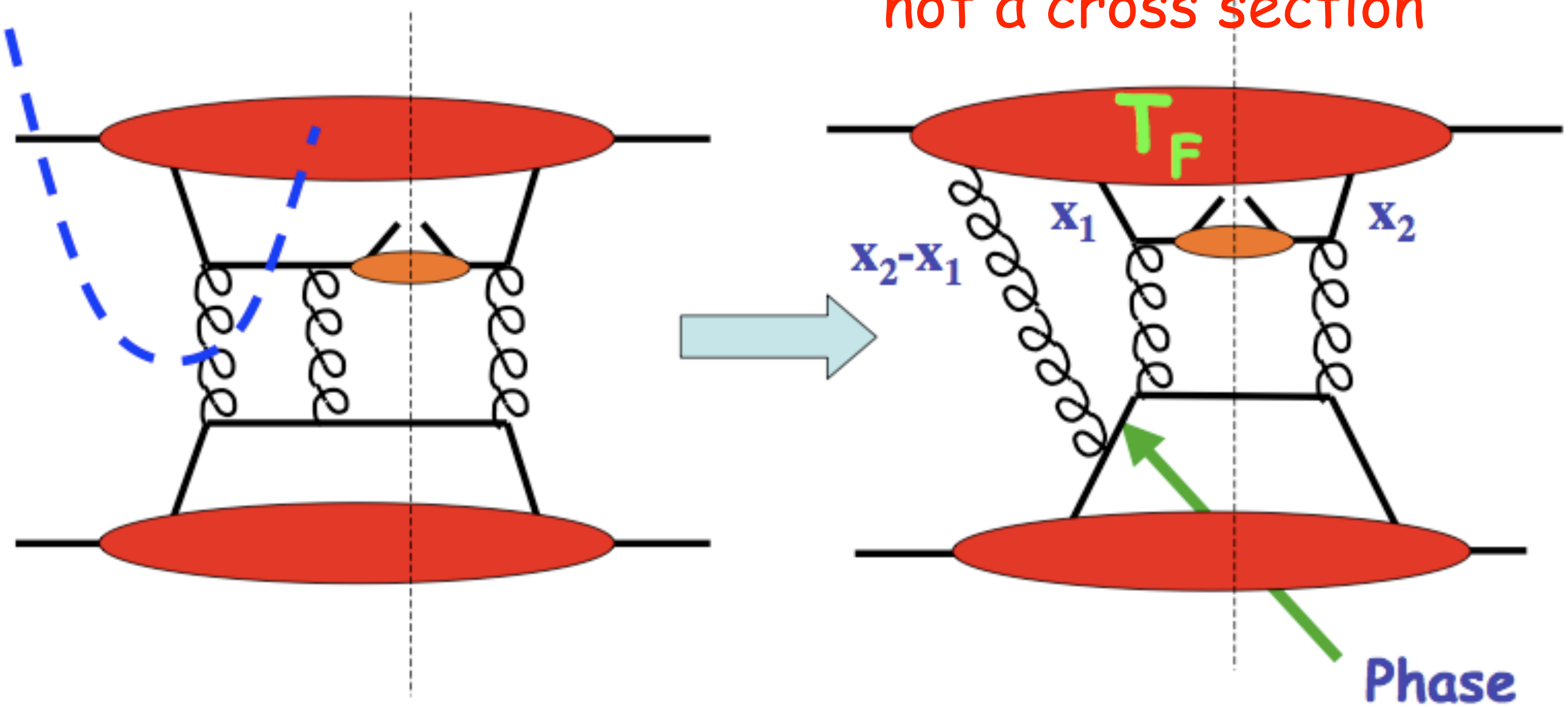
(talk by C. Pisano for pp → (π+jet) X)

2. Higher-twist partonic correlations

(Efremov, Teryaev, Ratcliffe; Qiu, Sterman; Kouvaris, Vogelsang, Yuan; Bacchetta, Bomhof, Mulders, Pijlman; Koike; Gamberg, Kang...)

higher-twist partonic correlations - factorization OK

$$\mathrm{d}\Delta\sigma \propto \sum_{a,b,c} \underbrace{T_a(k_1, k_2, \boldsymbol{S}_\perp)}_{\text{twist-3 functions}} \otimes f_{b/B}(x_b) \otimes \underbrace{H^{ab\to c}(k_1, k_2)}_{\text{hard interaction, not a cross section}} \otimes D_{h/c}(z)$$



the twist-3 function T_F is related to the Sivers function

(figure courtesy of W. Vogelsang)

possible higher-twist contributions to A_N

$$d\sigma(\vec{S}_\perp) = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}$$

(1) Twist-3 contribution related to Sivers function

(2) Twist-3 contribution related to Boer-Mulders function

(3) Twist-3 fragmentation: has two contributions, one related to Collins function + a new one

the first contribution with a twist-3 quark-gluon-quark correlator was expected to be the dominant one, but ....

sign mismatch

(Kang, Qiu, Vogelsang, Yuan, PR D83 (2011) 094001)

using the SIDIS Sivers function to build the twist-3 q-g-q correlator $T_{q,F}$

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$

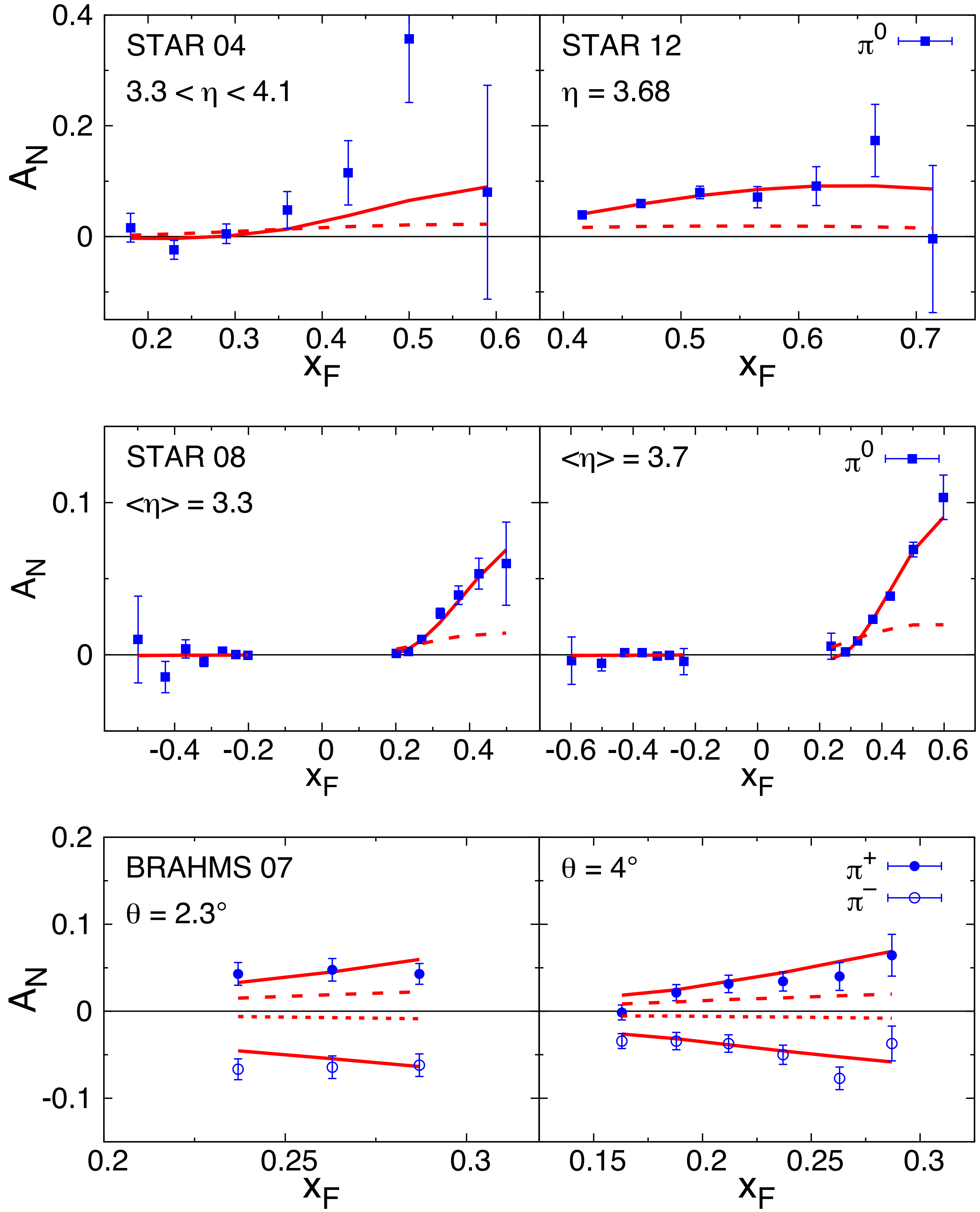
leads to sizeable value of A_N, but with the wrong sign....

the same mismatch does not occur adopting TMD factorization; the reason is that the hard scattering part in higher-twist factorization is negative

(see talks by Koike and Pitonyak)

A_N from twist-3 fragmentation functions

(Kanazawa, Koike, Metz, Pitoniak, arXiv:1404.1033)



good fit of A_N mainly due to the new twist-3 fragmentation function

(talk by Pitonyak)

compare with A_N in

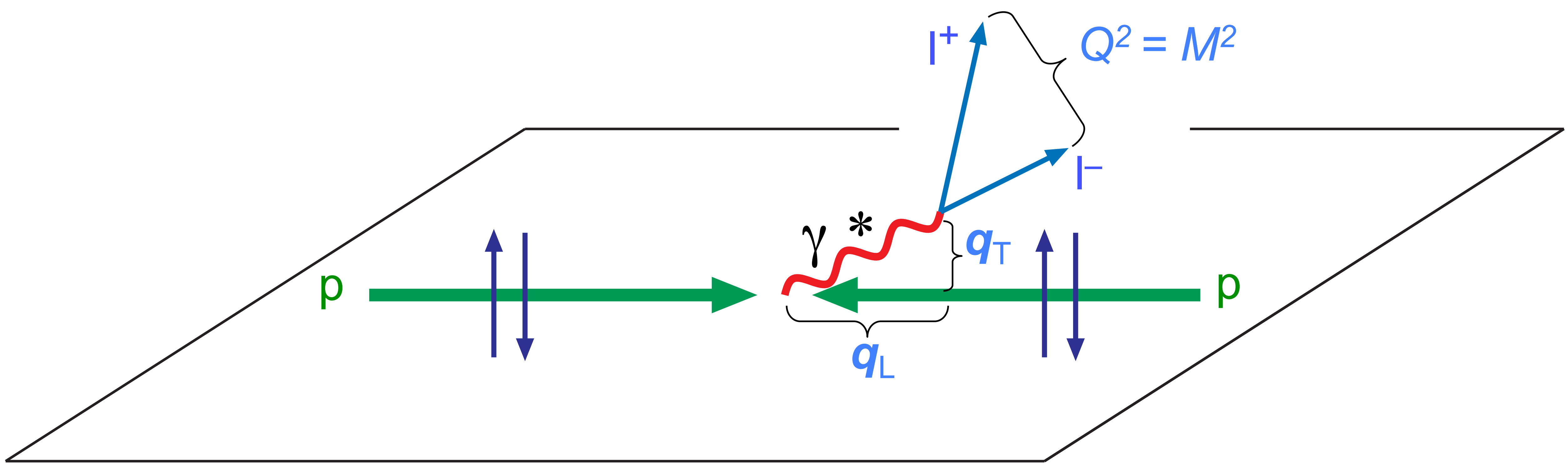
$l\, p \rightarrow \pi\, X$

processes

(talk by Prokudin)

Future: TMDs in Drell-Yan processes

COMPASS, RHIC, Fermilab, NICA, AFTER...
(talks by Peng, Chiosso, Lansberg, Teryaev)



factorization holds, two scales, M^2, and $q_T \ll M$

$$d\sigma^{D-Y} = \sum_a f_q(x_1, \boldsymbol{k}_{\perp 1}; Q^2) \otimes f_{\bar{q}}(x_2, \boldsymbol{k}_{\perp 2}; Q^2)\, d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}$$

direct product of TMDs, no fragmentation process

cross-section: most general pp leading-twist expression

S. Arnold, A. Metz and M. Schlegel, PR D79 (2009) 034005

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{F\,q^2}\times$$

$$\begin{aligned}
&\Big\{\Big((1+\cos^2\theta)\,F_{UU}^1 + (1-\cos^2\theta)\,F_{UU}^2 + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\Big)\\
&+ S_{aL}\Big(\sin 2\theta\sin\phi\,F_{LU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LU}^{\sin 2\phi}\Big)\\
&+ S_{bL}\Big(\sin 2\theta\sin\phi\,F_{UL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UL}^{\sin 2\phi}\Big)\\
&+ |\vec{S}_{aT}|\Big[\sin\phi_a\Big((1+\cos^2\theta)\,F_{TU}^1 + (1-\cos^2\theta)\,F_{TU}^2 + \sin 2\theta\cos\phi\,F_{TU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TU}^{\cos 2\phi}\Big)\\
&\qquad + \cos\phi_a\Big(\sin 2\theta\sin\phi\,F_{TU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TU}^{\sin 2\phi}\Big)\Big]\\
&+ |\vec{S}_{bT}|\Big[\sin\phi_b\Big((1+\cos^2\theta)\,F_{UT}^1 + (1-\cos^2\theta)\,F_{UT}^2 + \sin 2\theta\cos\phi\,F_{UT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UT}^{\cos 2\phi}\Big)\\
&\qquad + \cos\phi_b\Big(\sin 2\theta\sin\phi\,F_{UT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UT}^{\sin 2\phi}\Big)\Big]\\
&+ S_{aL}\,S_{bL}\Big((1+\cos^2\theta)\,F_{LL}^1 + (1-\cos^2\theta)\,F_{LL}^2 + \sin 2\theta\cos\phi\,F_{LL}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LL}^{\cos 2\phi}\Big)\\
&+ S_{aL}\,|\vec{S}_{bT}|\Big[\cos\phi_b\Big((1+\cos^2\theta)\,F_{LT}^1 + (1-\cos^2\theta)\,F_{LT}^2 + \sin 2\theta\cos\phi\,F_{LT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LT}^{\cos 2\phi}\Big)\\
&\qquad + \sin\phi_b\Big(\sin 2\theta\sin\phi\,F_{LT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LT}^{\sin 2\phi}\Big)\Big]\\
&+ |\vec{S}_{aT}|\,S_{bL}\Big[\cos\phi_a\Big((1+\cos^2\theta)\,F_{TL}^1 + (1-\cos^2\theta)\,F_{TL}^2 + \sin 2\theta\cos\phi\,F_{TL}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TL}^{\cos 2\phi}\Big)\\
&\qquad + \sin\phi_a\Big(\sin 2\theta\sin\phi\,F_{TL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TL}^{\sin 2\phi}\Big)\Big]\\
&+ |\vec{S}_{aT}|\,|\vec{S}_{bT}|\Big[\cos(\phi_a+\phi_b)\Big((1+\cos^2\theta)\,F_{TT}^1 + (1-\cos^2\theta)\,F_{TT}^2 + \sin 2\theta\cos\phi\,F_{TT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TT}^{\cos 2\phi}\Big)\\
&\qquad + \cos(\phi_a-\phi_b)\Big((1+\cos^2\theta)\,\bar{F}_{TT}^1 + (1-\cos^2\theta)\,\bar{F}_{TT}^2 + \sin 2\theta\cos\phi\,\bar{F}_{TT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,\bar{F}_{TT}^{\cos 2\phi}\Big)\\
&\qquad + \sin(\phi_a+\phi_b)\Big(\sin 2\theta\sin\phi\,F_{TT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TT}^{\sin 2\phi}\Big)\\
&\qquad + \sin(\phi_a-\phi_b)\Big(\sin 2\theta\sin\phi\,\bar{F}_{TT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,\bar{F}_{TT}^{\sin 2\phi}\Big)\Big]\Big\}
\end{aligned}$$

Drell-Yan

48 structure functions ...

Case of one polarized nucleon only

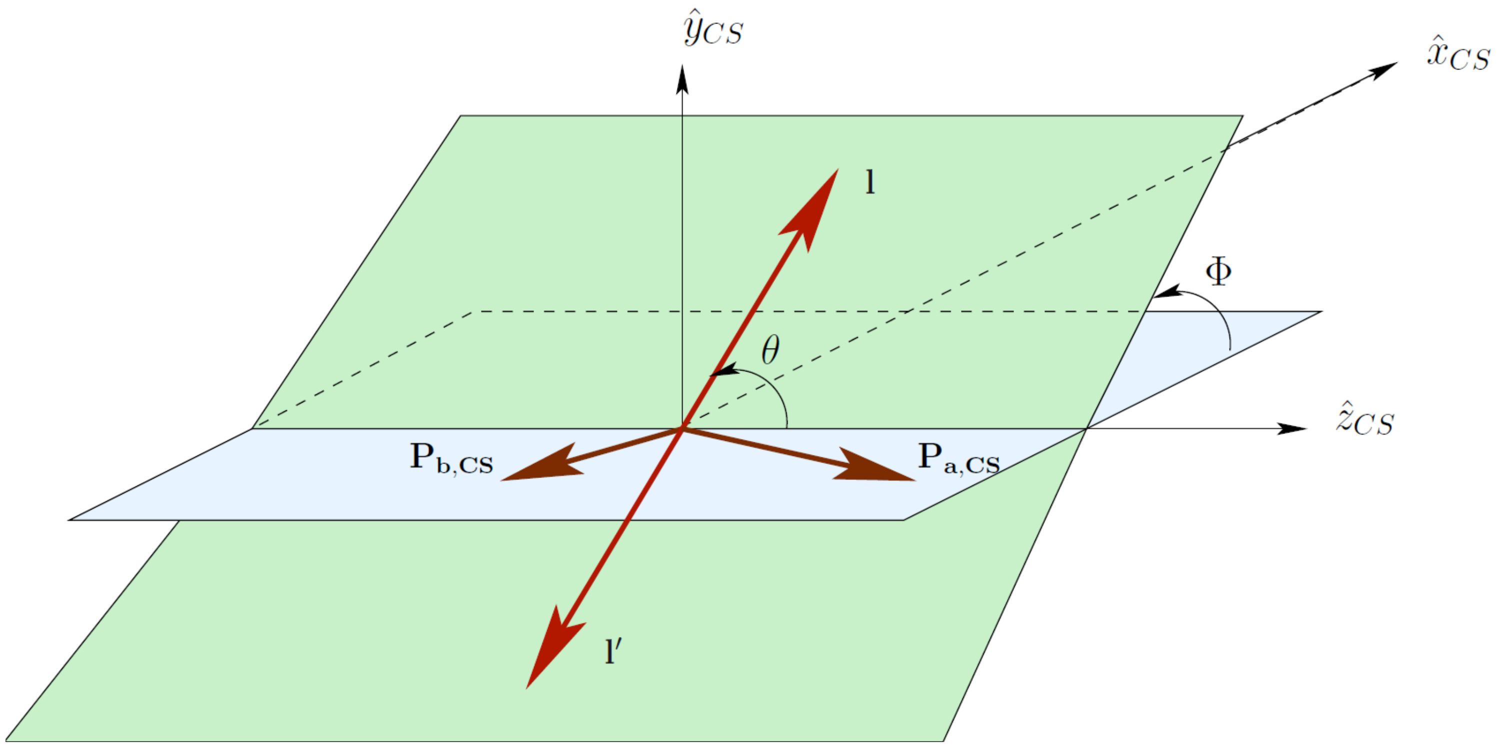
$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha^2}{\Phi\, q^2}\Big\{(1+\cos^2\theta)\, F_U^1 + (1-\cos^2\theta)\, F_U^2 + \sin 2\theta \cos\phi\, F_U^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_U^{\cos 2\phi}$$

$$+\ S_L \left(\sin 2\theta \sin\phi\, F_L^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_L^{\sin 2\phi}\right)$$

$$+\ S_T \Big[\left(F_T^{\sin\phi_S} + cos^2\theta\, \tilde{F}_T^{\sin\phi_S}\right)\sin\phi_S + \sin 2\theta \Big(\sin(\phi+\phi_S)\, F_T^{\sin(\phi+\phi_S)}$$

$$+\ \sin(\phi-\phi_S)\, F_T^{\sin(\phi-\phi_S)}\Big)$$

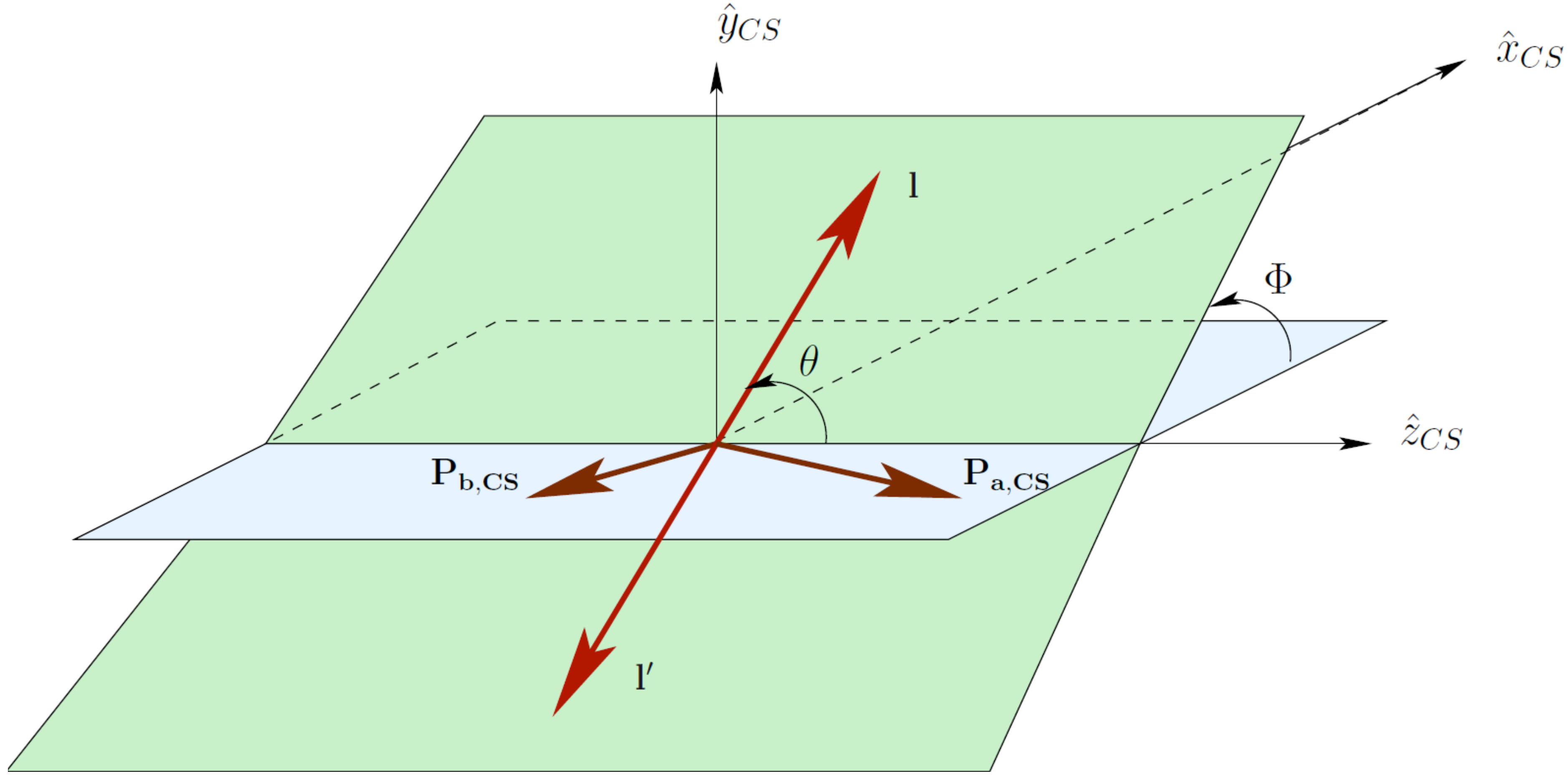
$$+\ \sin^2\theta \left(\sin(2\phi+\phi_S)\, F_T^{\sin(2\phi+\phi_S)} + \sin(2\phi-\phi_S)\, F_T^{\sin(2\phi-\phi_S)}\right)\Big]\Big\}$$



Collins-Soper frame

Unpolarized cross section already very interesting

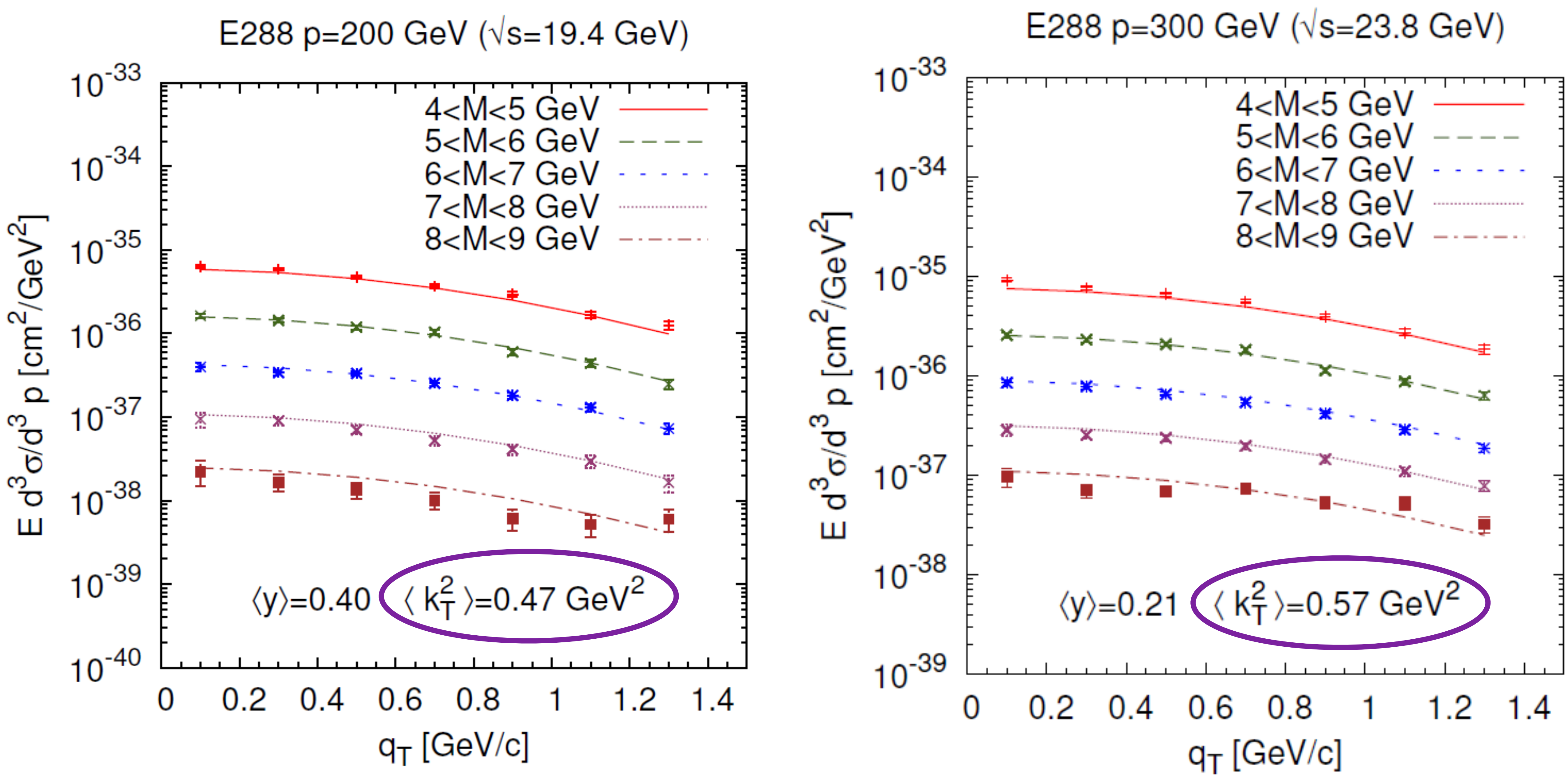
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\,\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$



Collins-Soper frame

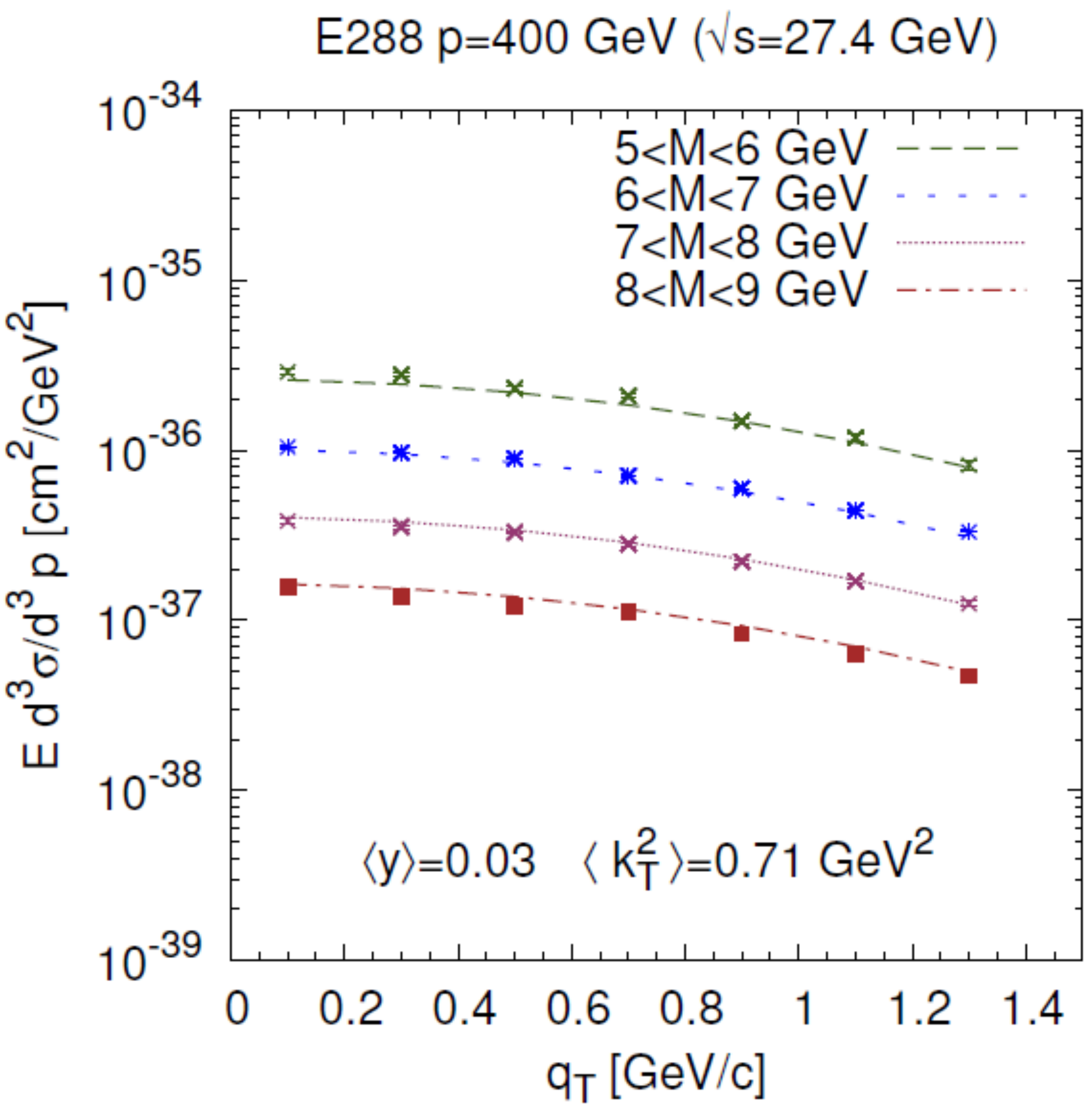
naive collinear parton model: $\lambda = 1 \quad \mu = \nu = 0$

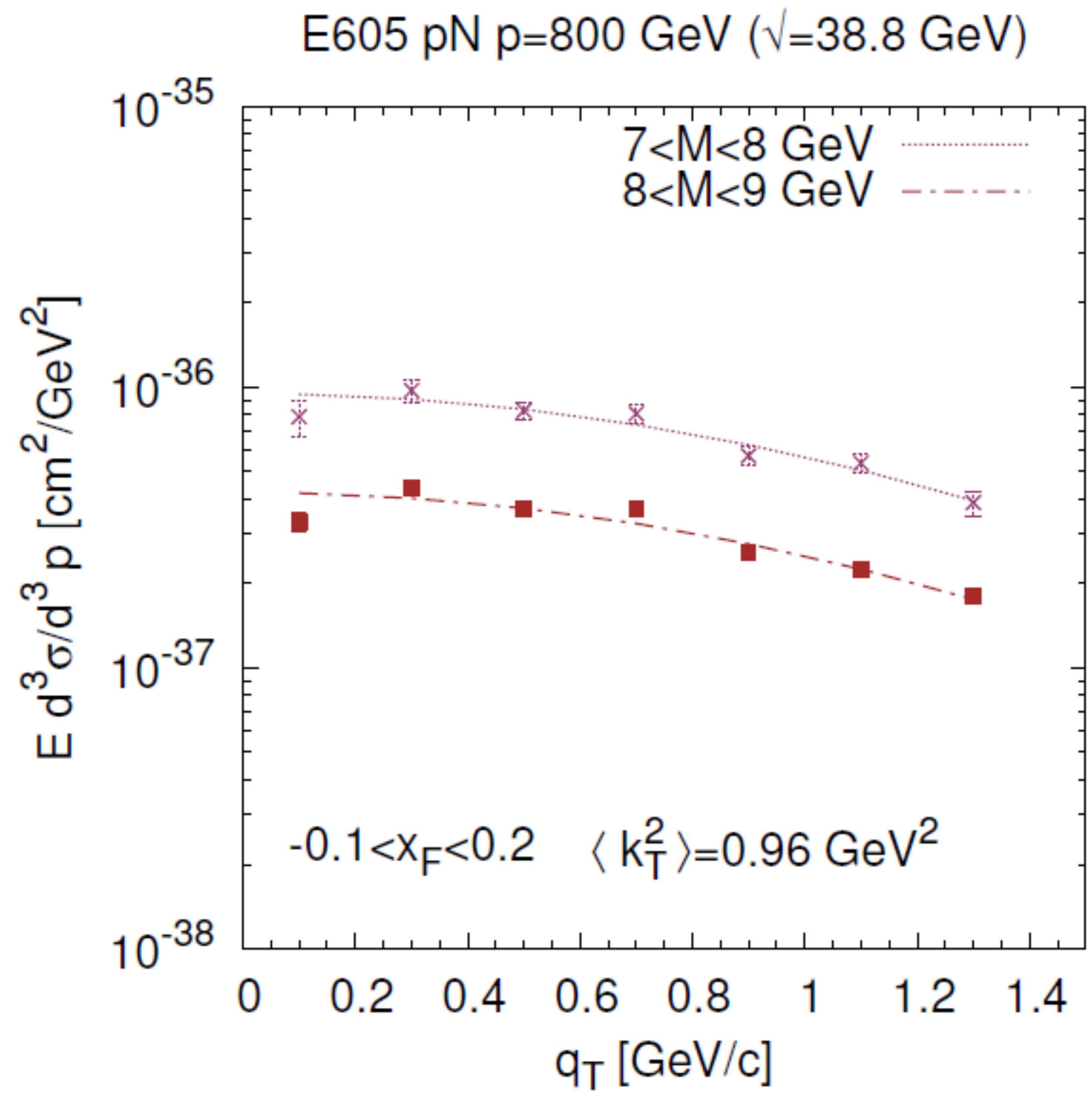
fit of unpolarized D-Y data, S. Melis, preliminary results



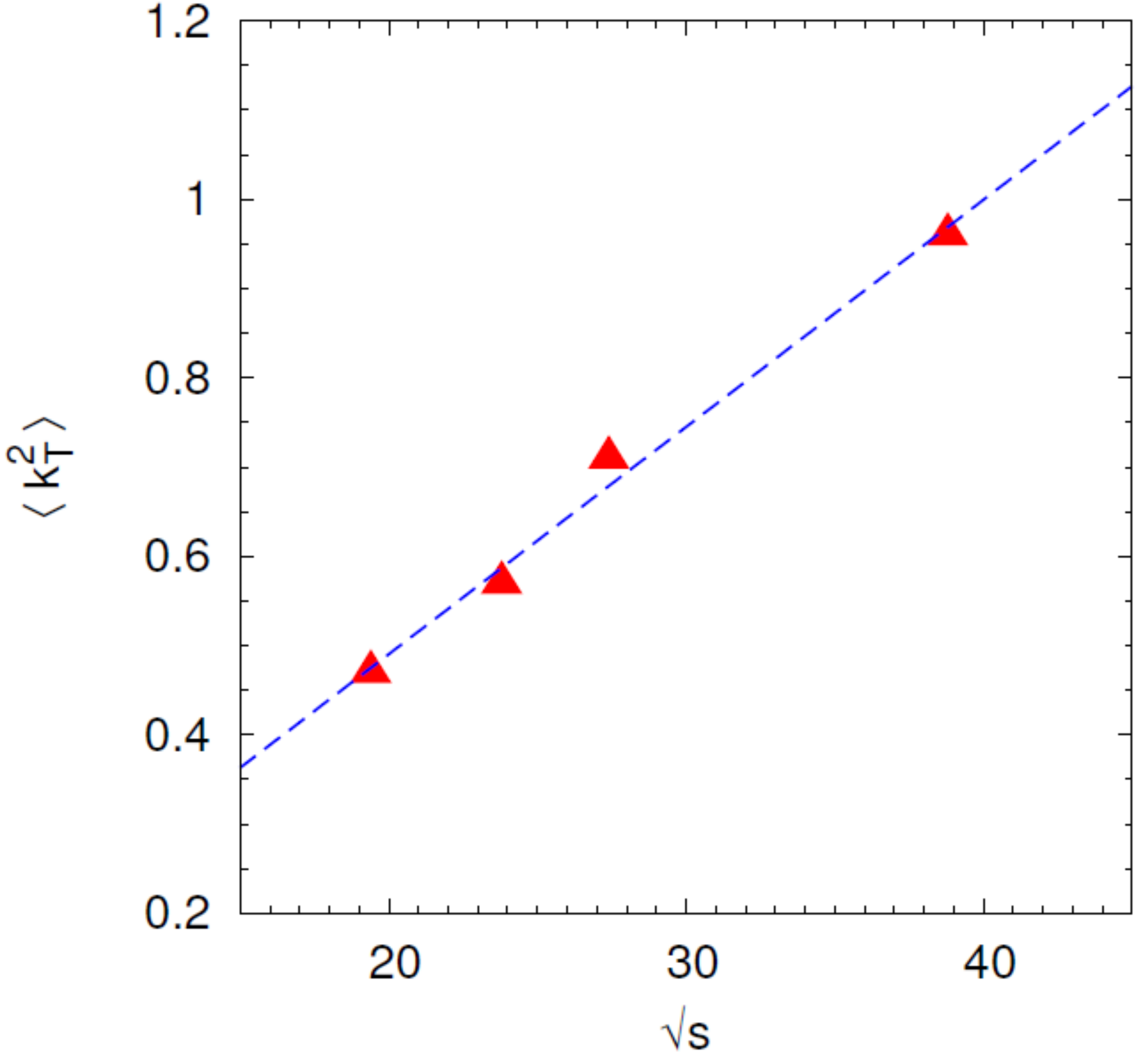
$$\hat{f}_{q/p}(x, k_\perp; Q) = f_{q/p}(x; Q)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

a different $\langle k_\perp^2\rangle$ for each set of data





dependence of $\langle k_\perp^2 \rangle$ with energy?



talk by Melis, see also Peng, Qiu, arXiv:1401.0934

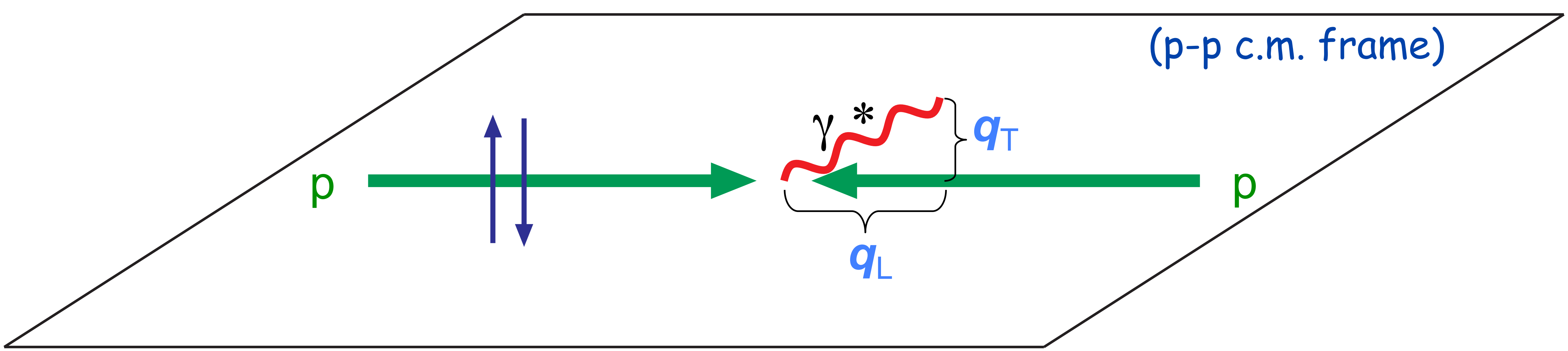
Sivers effect in D-Y processes

By looking at the $d^4\sigma/d^4q$ cross section one can single out the Sivers effect in D-Y processes

$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow \propto \sum_q \Delta^N f_{q/p^\uparrow}(x_1, \boldsymbol{k}_{\perp 1}) \otimes f_{\bar{q}/p}(x_2, k_{\perp 2}) \otimes \mathrm{d}\hat{\sigma}$$

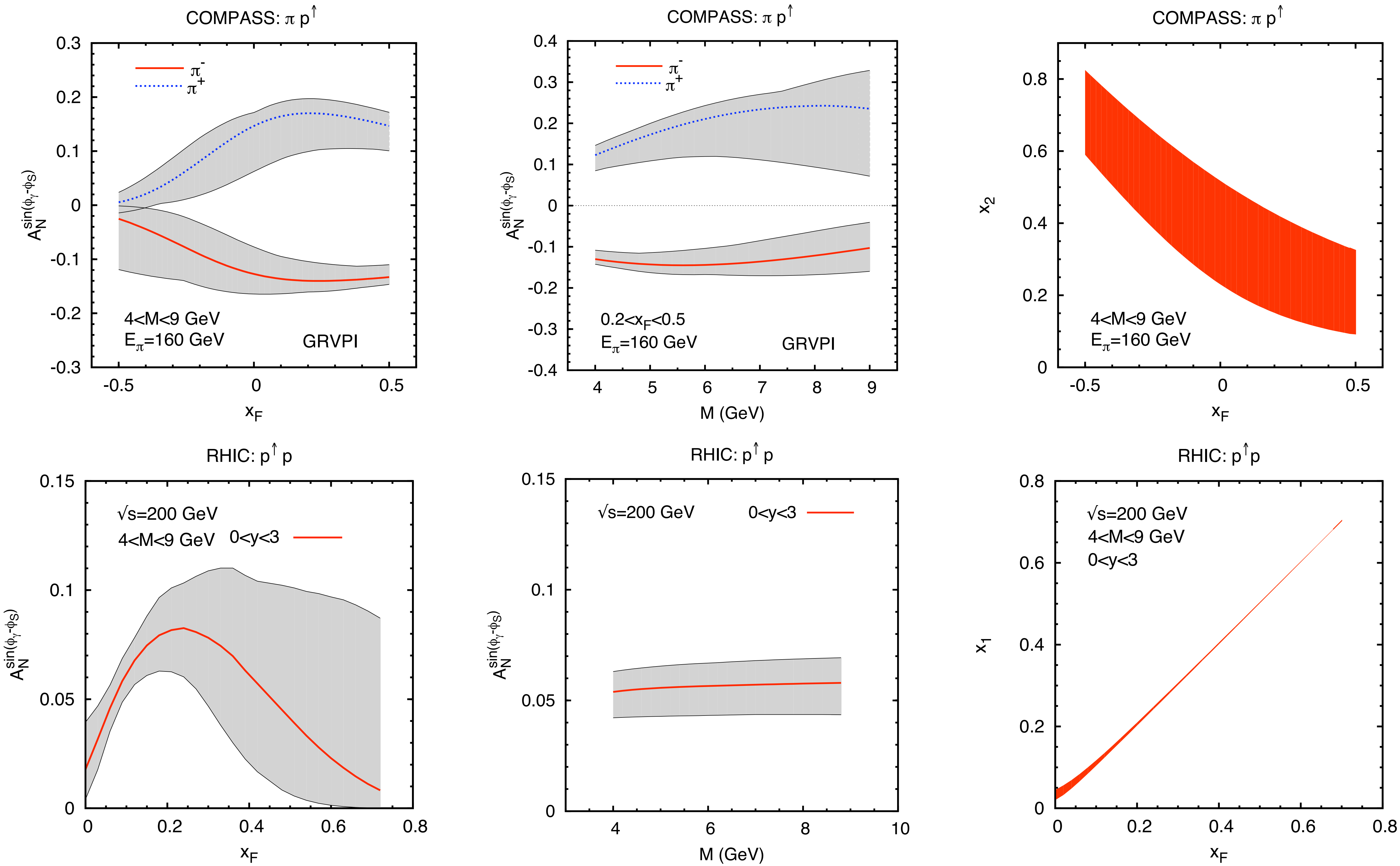
$$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$$

$$A_N^{\sin(\phi_S - \phi_\gamma)} \equiv \frac{2\int_0^{2\pi} \mathrm{d}\phi_\gamma \, [\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow] \, \sin(\phi_S - \phi_\gamma)}{\int_0^{2\pi} \mathrm{d}\phi_\gamma \, [\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow]}$$



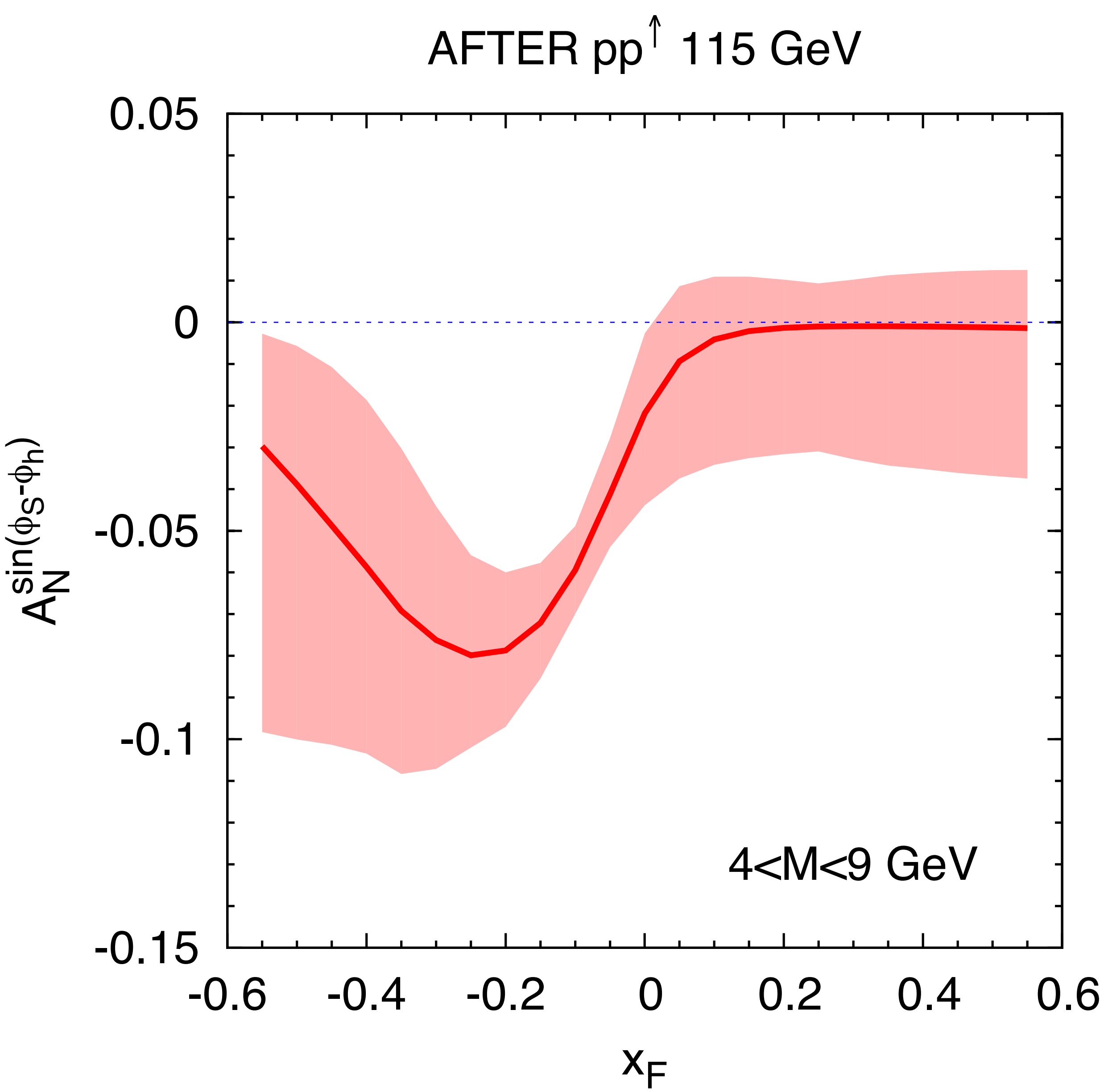
Predictions for A_N - no TMD evolution

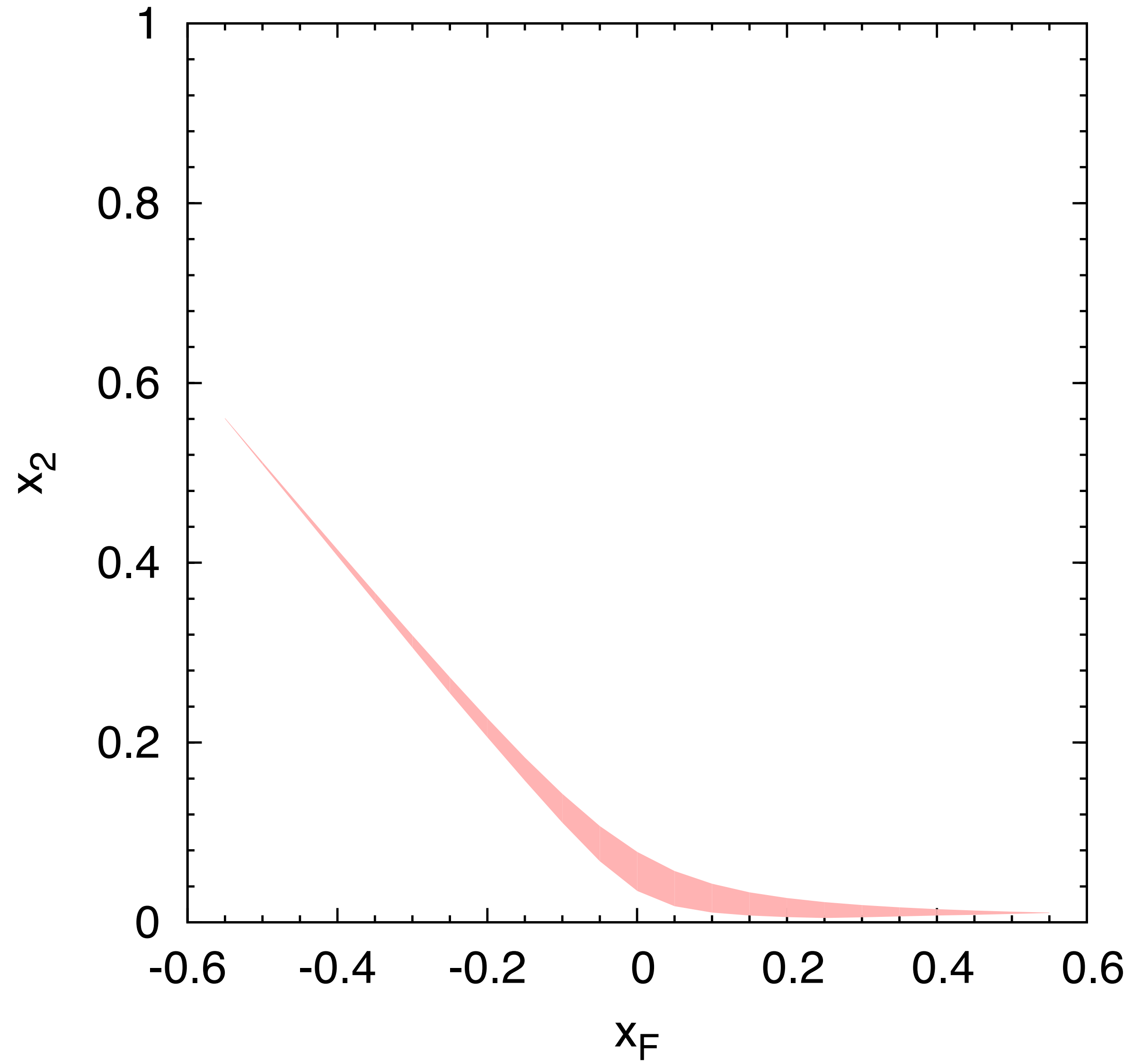
Sivers functions as extracted from SIDIS data, **with opposite sign**



M.A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, PR D79 (2009) 054010

expected Sivers asymmetry in D-Y@AFTER, sign change, no TMD evolution

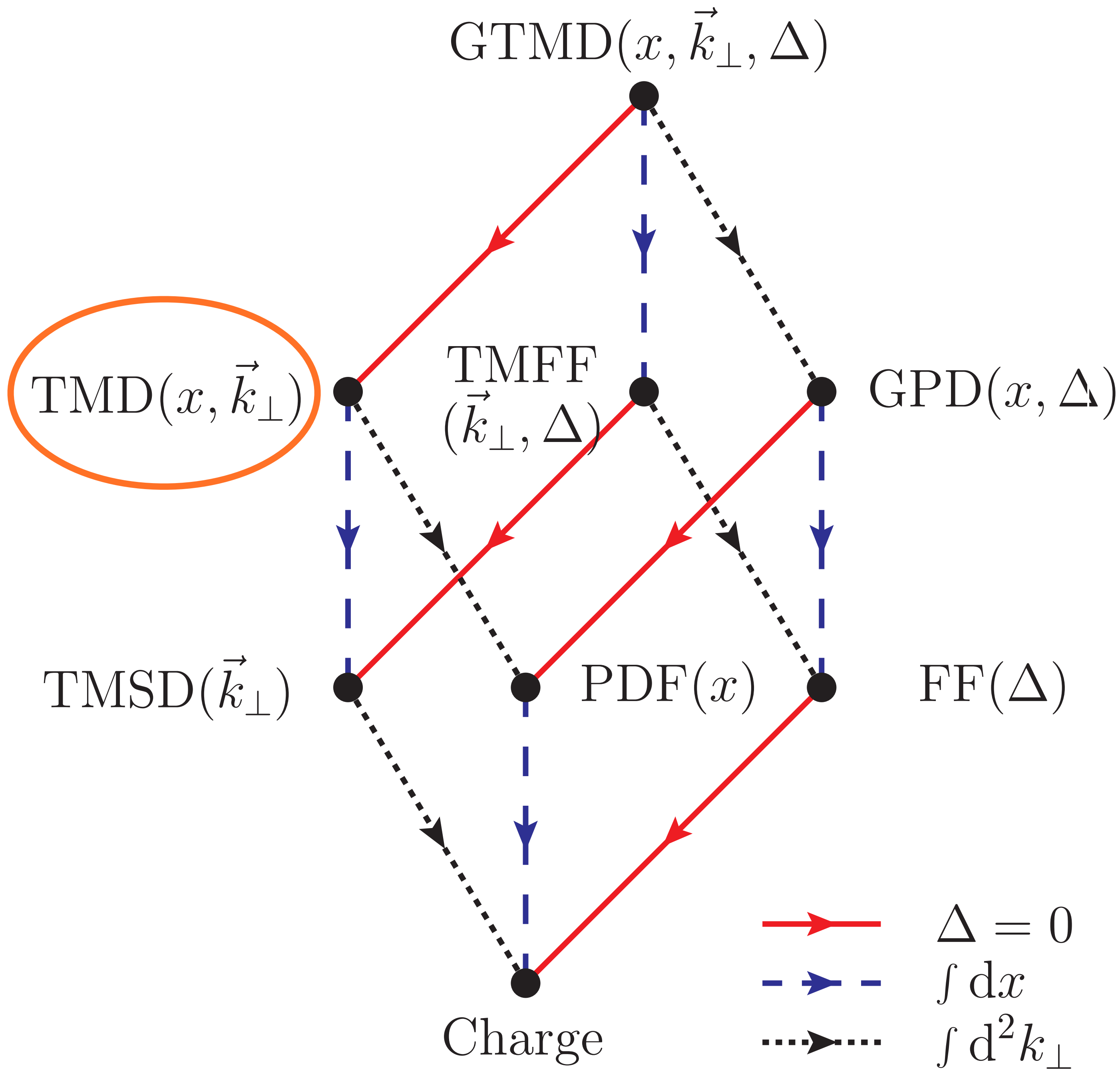




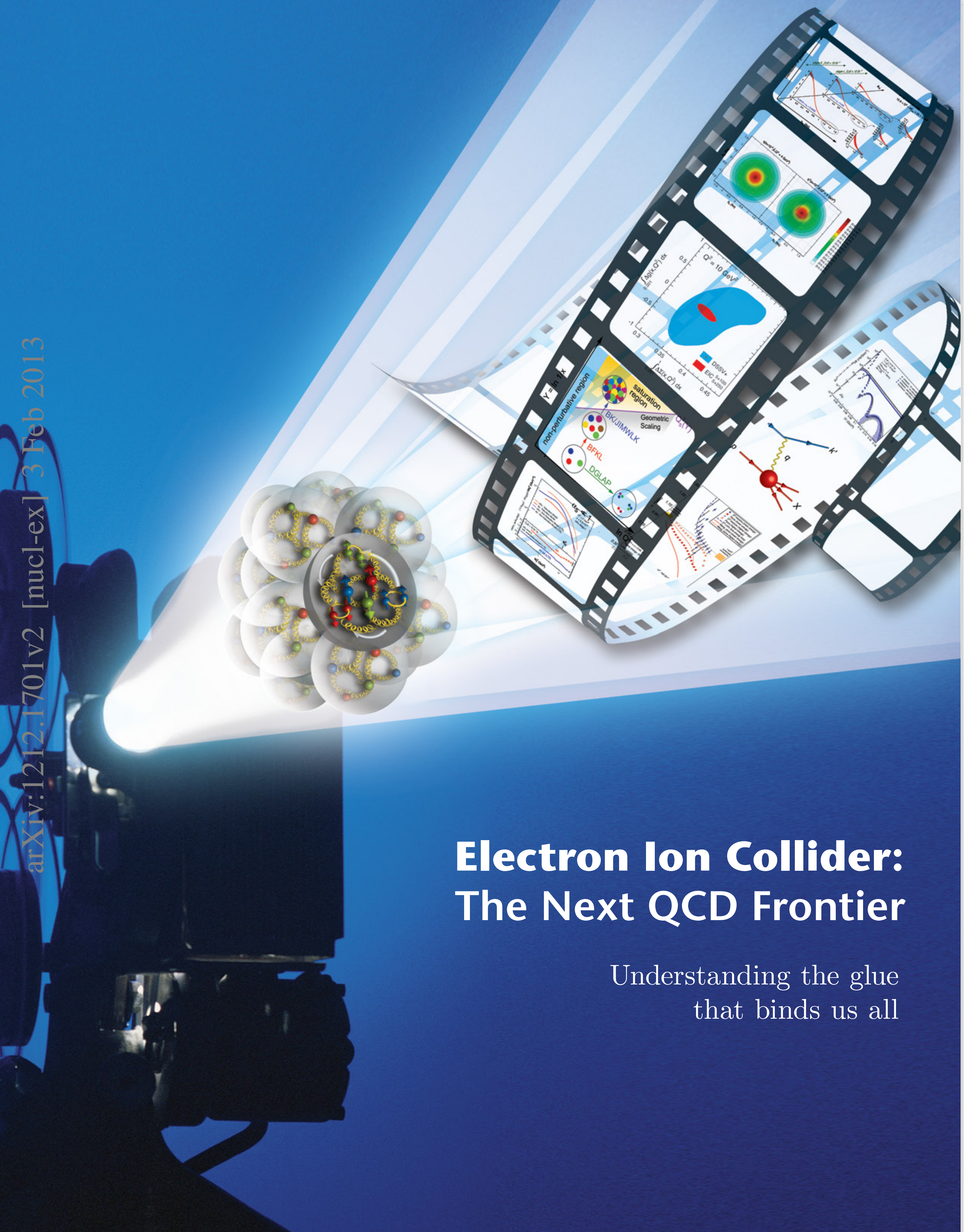
courtesy of U. D'Alesio

TMDs are only part of the full story ...

(talks by d'Hose, Kroll, Goldstein, Kim, Movsisyan,...)



C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (2011) 041



future facilities
and experiments:

D-Y @ COMPASS

(talks by Peng, Chiosso)

JLAB 12 GeV

(talk by S. Pisano)

EIC

(talk by Eyser)

BESIII

(talk by Guan)

AFTER

(talk by Lansberg)

NICA-SPD

(talk by Teryaev)

....

Conclusions

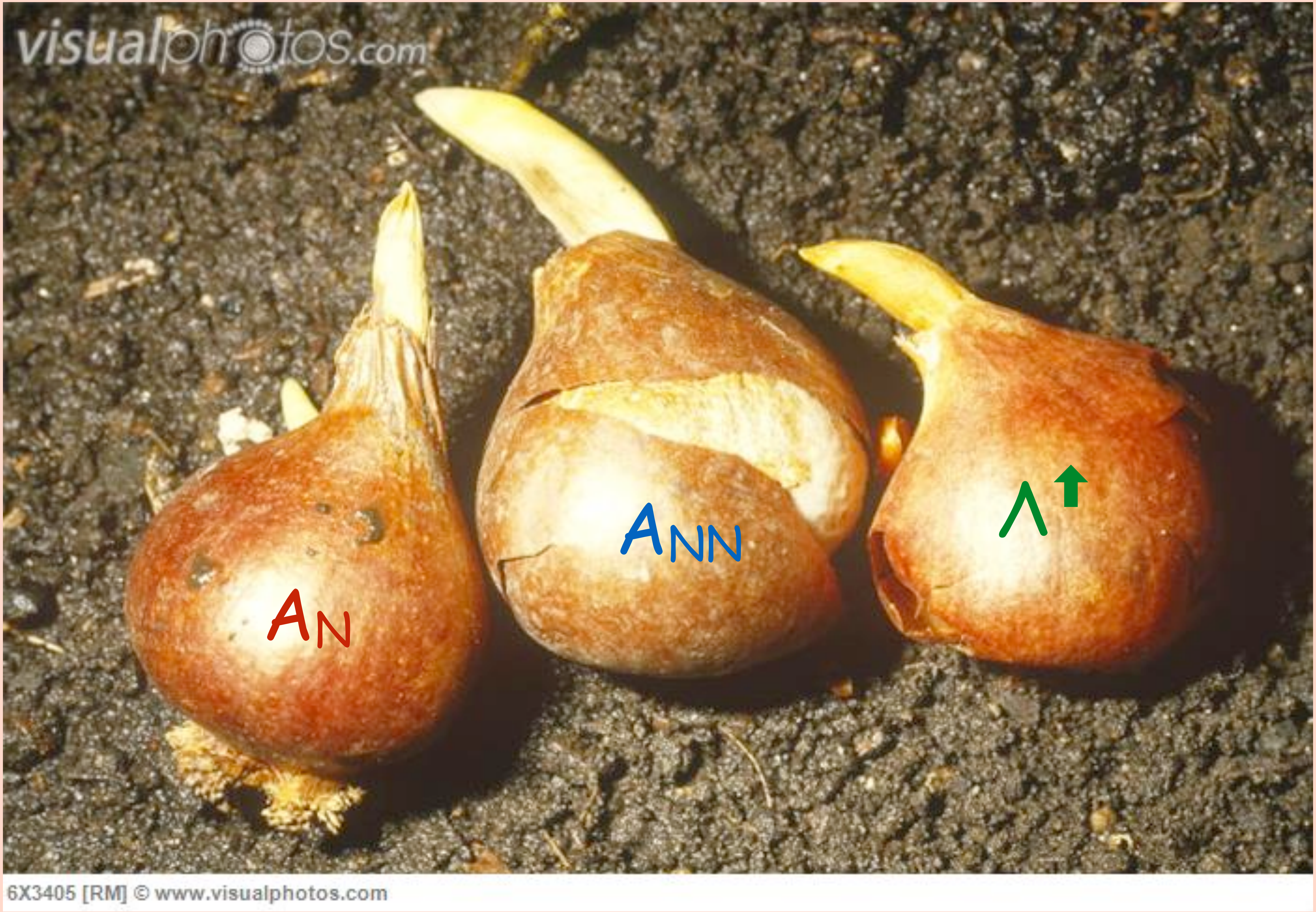
physical interpretations of TMDs, models of the proton wave function, orbital motion and TMDs, 3D imaging in momentum and coordinate space...

global fits of SIDIS, D-Y and e+e- data, with TMD evolution; check sign change of Sivers function, understand A_N and partonic origin of TMDs, predictions for next measurements...

future experiments and machines, new data, combined efforts of theory and experiments...

it is a blooming field....

(new ideas from Sivers, Teryaev)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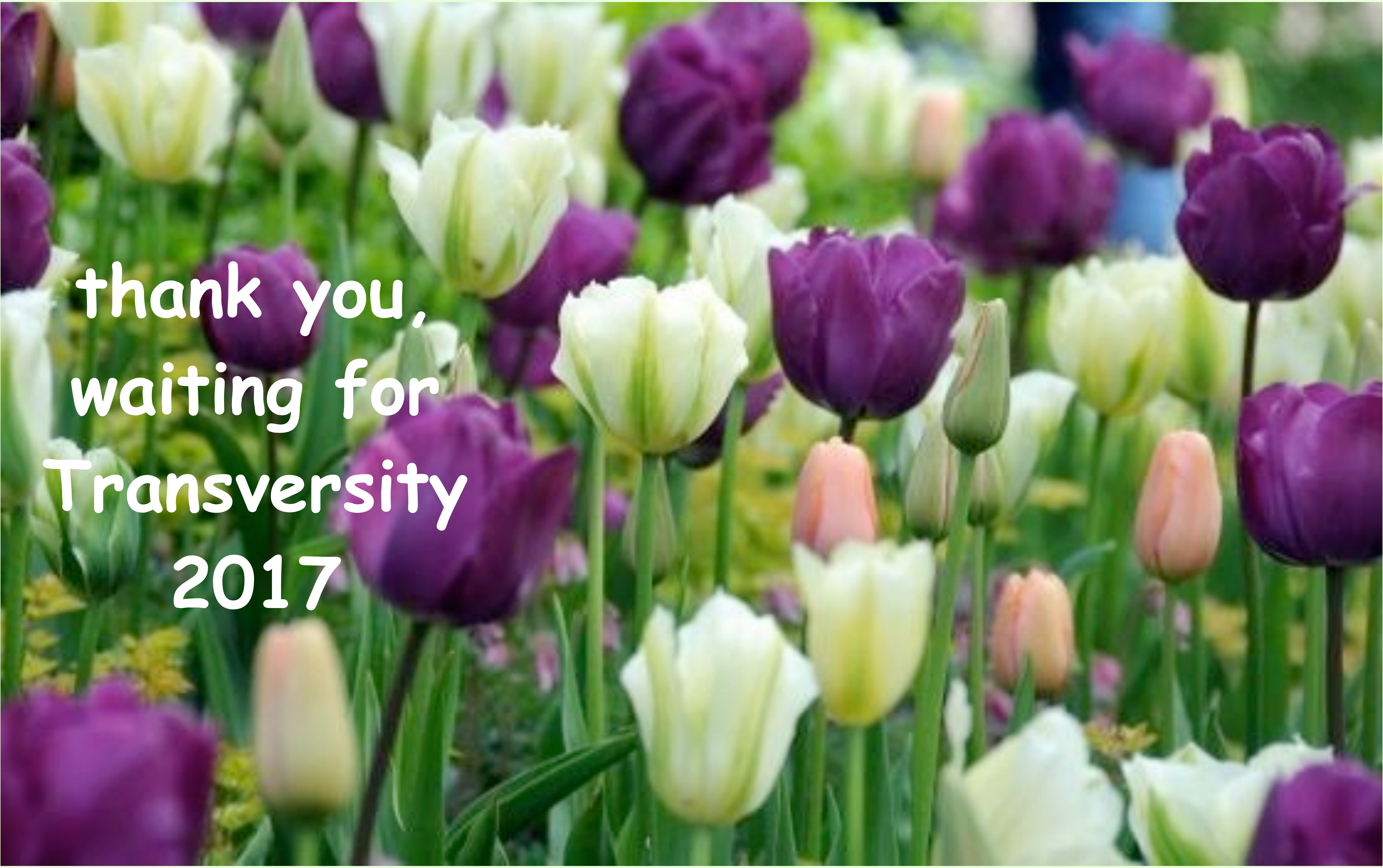
thank you,
waiting for
Transversity
2017