Transversity and Transverse-momentum distributions

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Some goals of hadronic physics

- Understand CONFINEMENT
- Study the STRUCTURE of the proton, e.g.,
  - 3D structure
  - Spin
  - Flavor
- Test QCD in all its aspects, e.g.,
  - Factorization
  - Evolution
  - Lattice

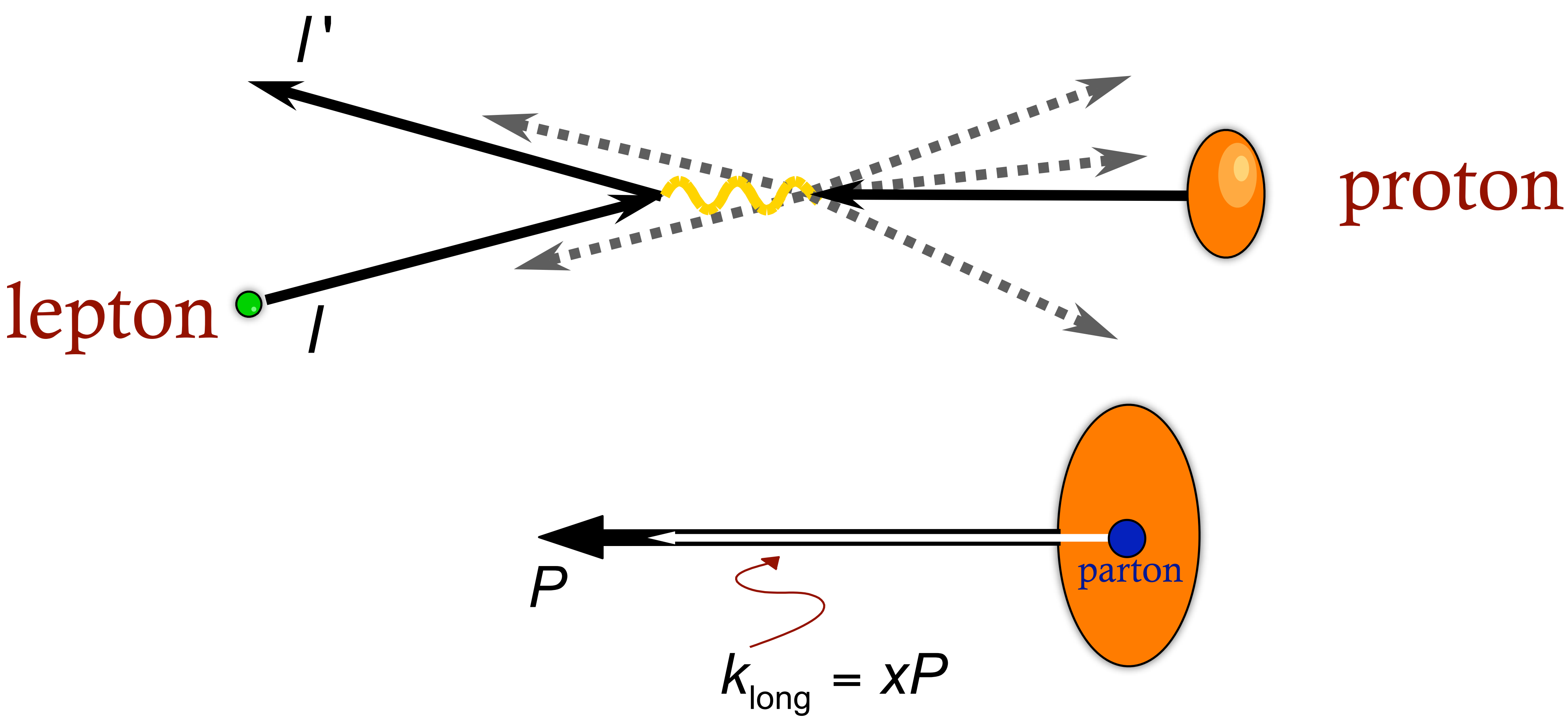
TMDs and transversity are relevant for all of these issues

Parton distribution functions essentials

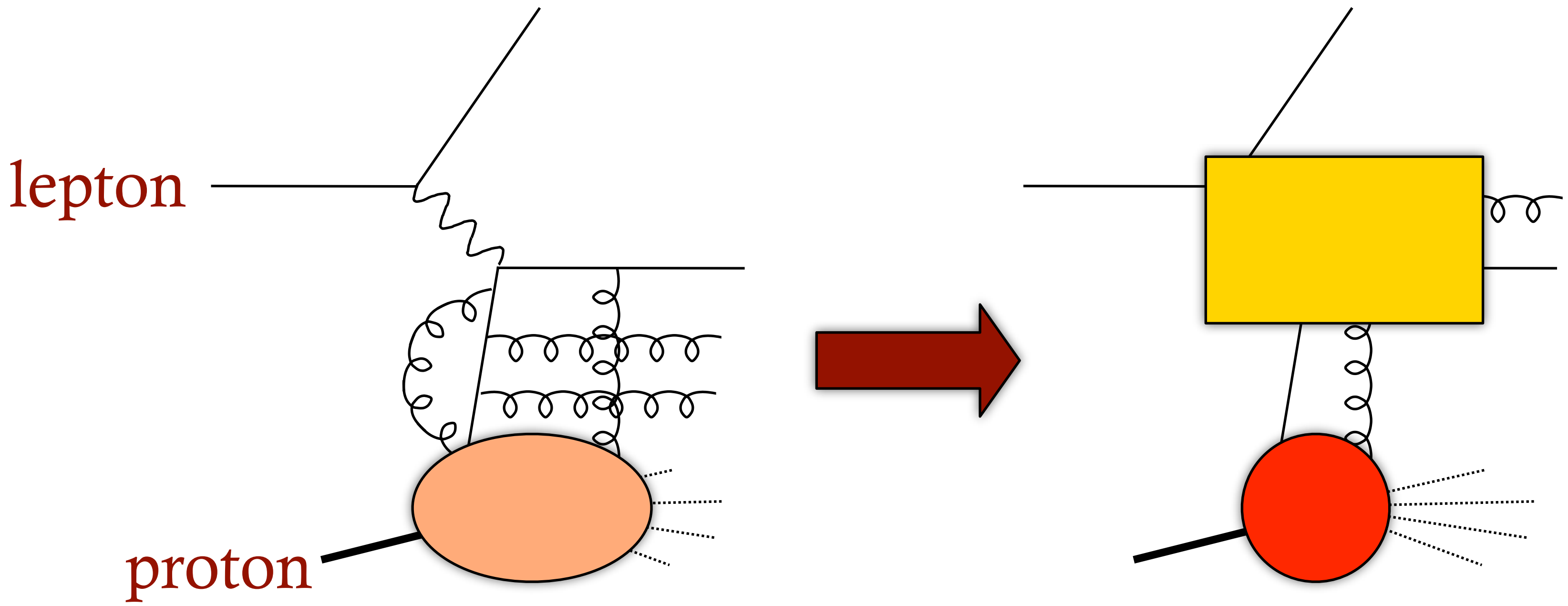
Deep inelastic scattering (DIS)

$-(l - l')^2 = Q^2 =$ virtuality of photon

$$x = \frac{Q^2}{2P \cdot (l - l')}$$



Factorization



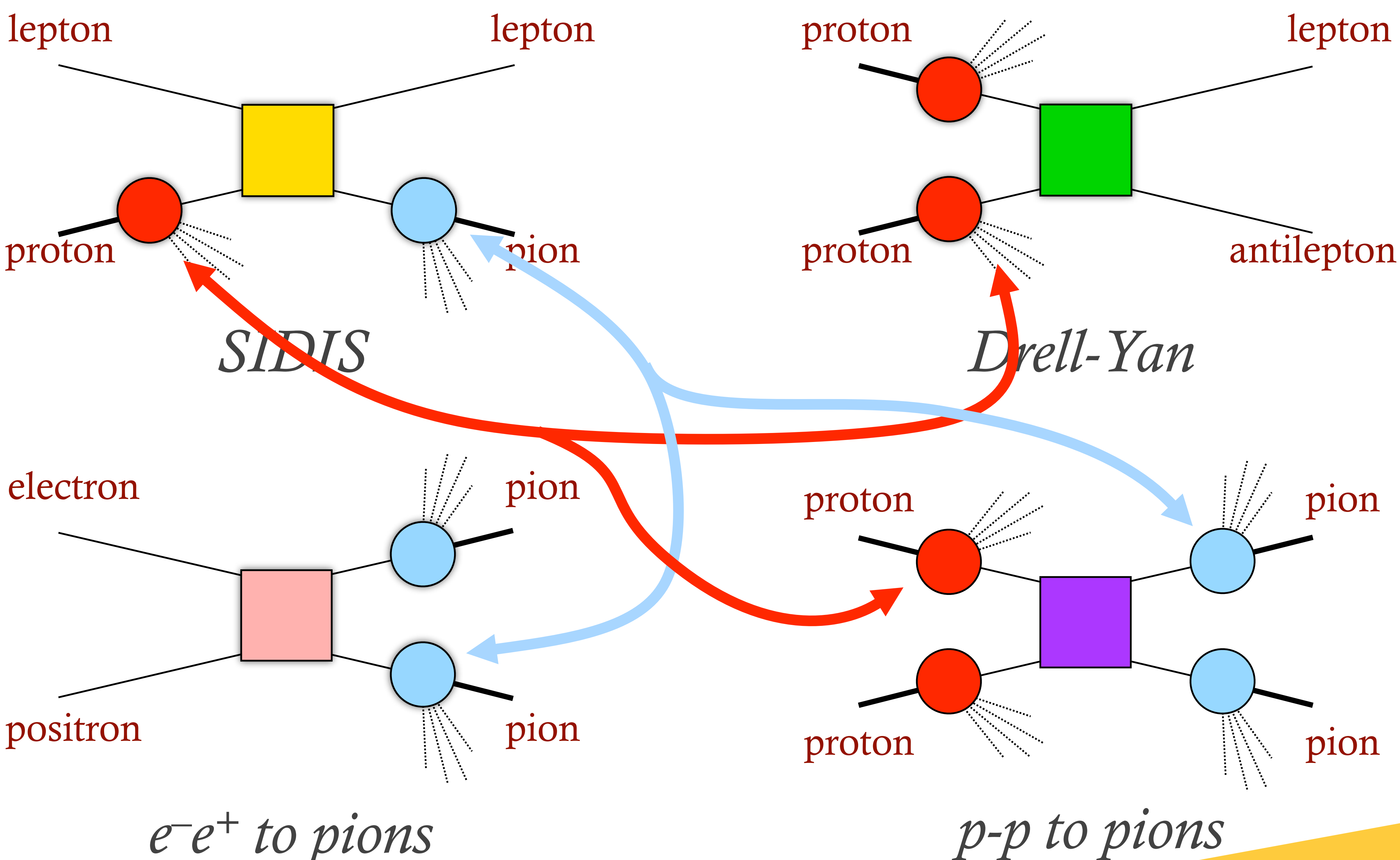
Partonic scattering amplitude

Distribution amplitude

H *f*

Key result of QCD

Universality



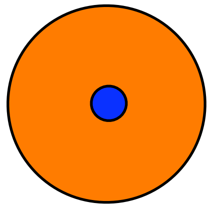
Key result of QCD

Parton distribution functions

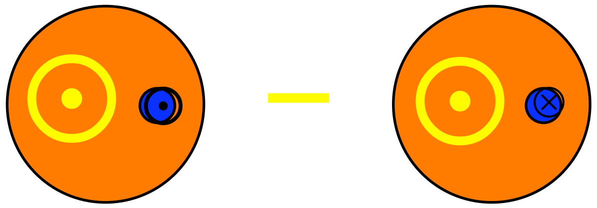
Parton distribution functions (PDFs) are probability densities to find a parton with a given longitudinal momentum and a given spin

Photon moves into the screen/ proton moves out of the screen

$$f_1^q(x) = q(x) =$$

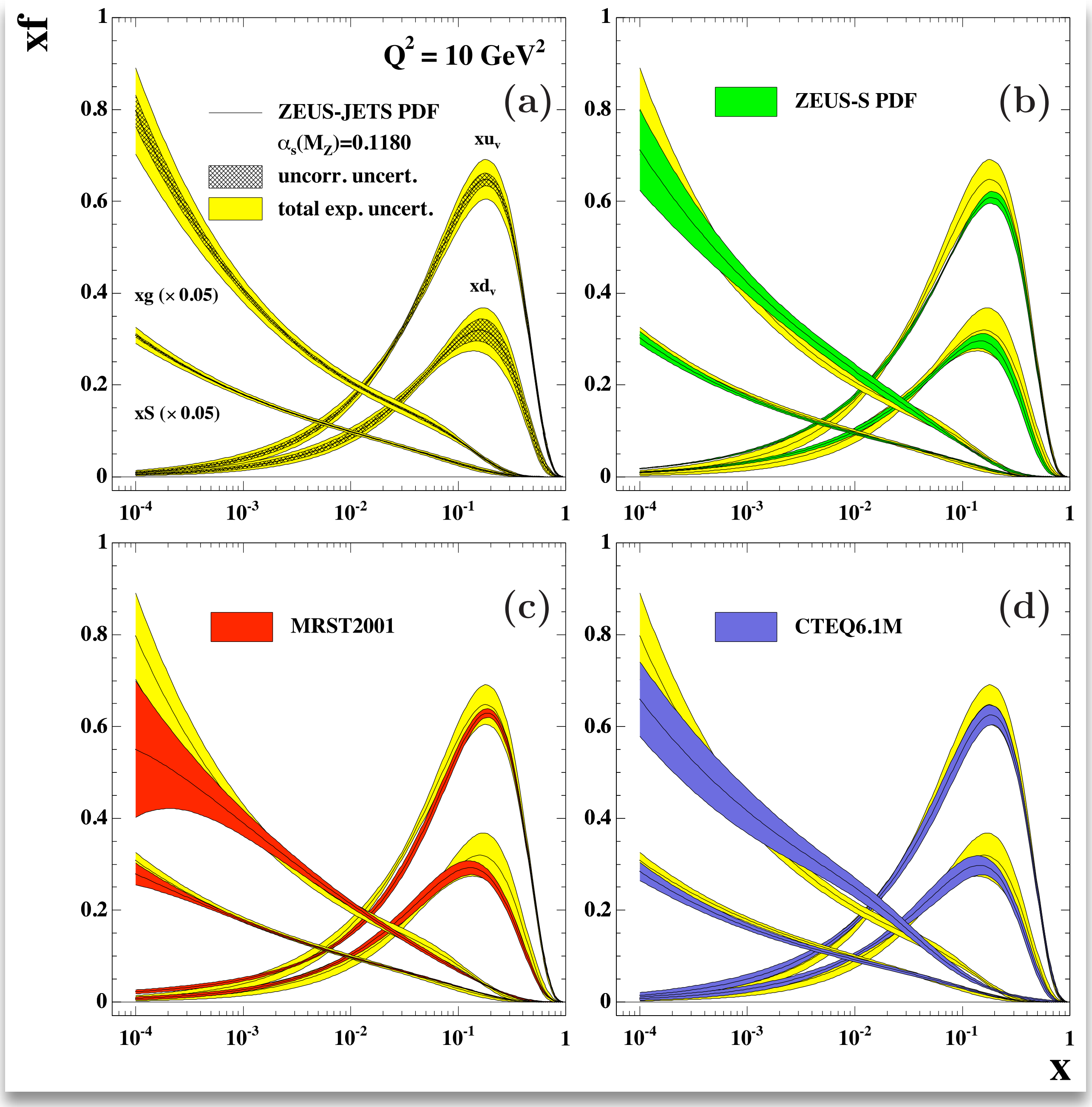


$$g_1^q(x) = \Delta q(x) =$$



PDFs from global fits

x q(x)

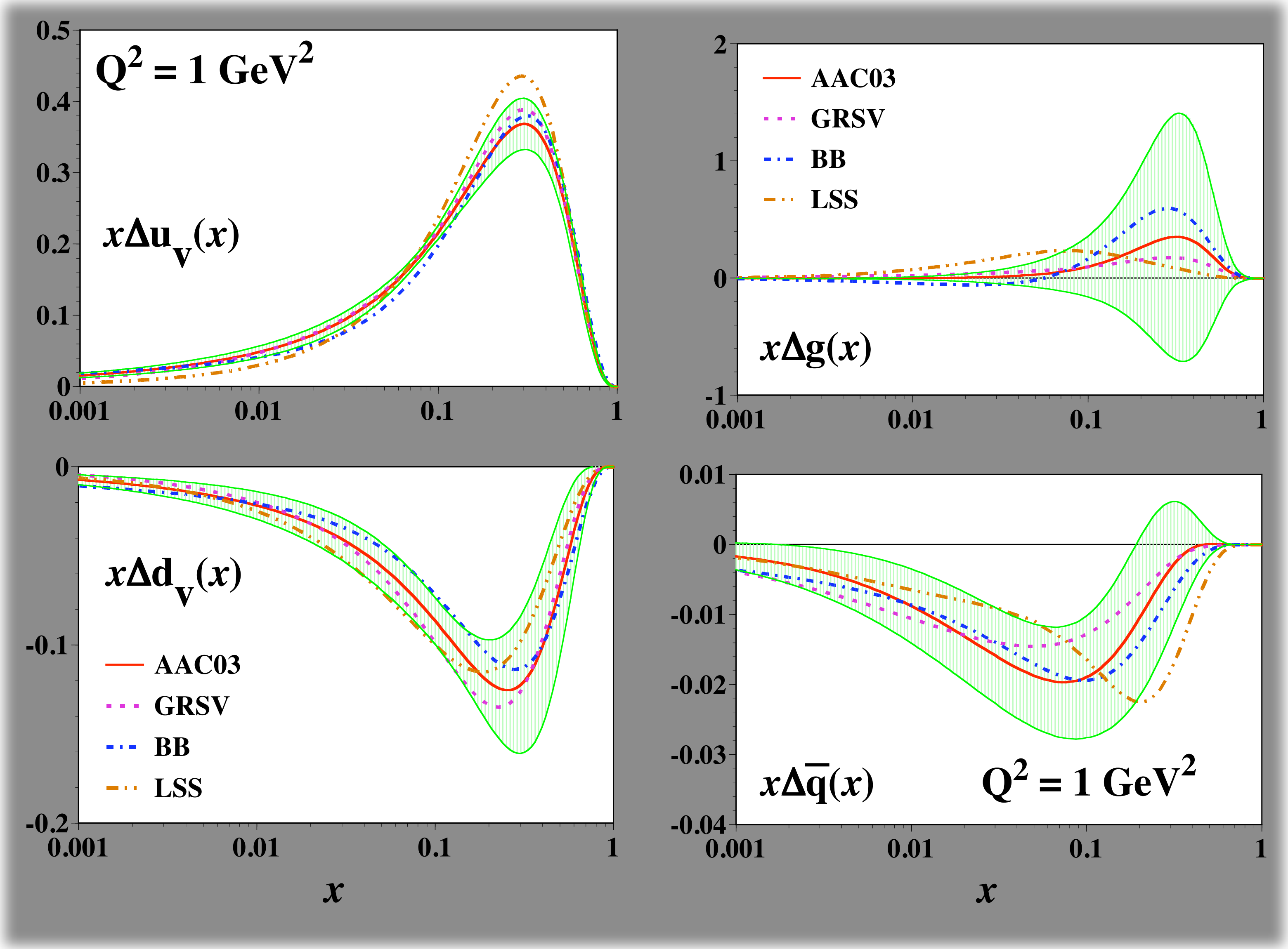


ZEUS Coll, EPJ C42 (05)

Helicity PDFs from global fits

see talk by S. Kuhn this morning

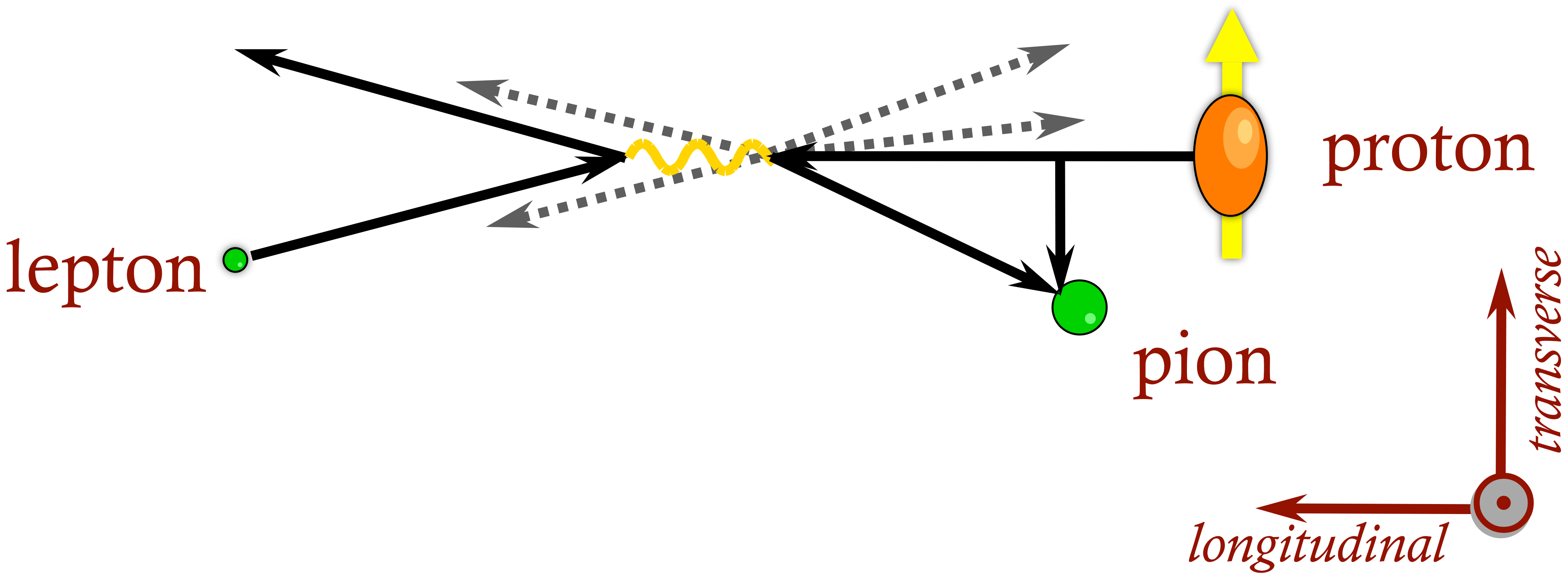
$x\,\Delta q(x)$



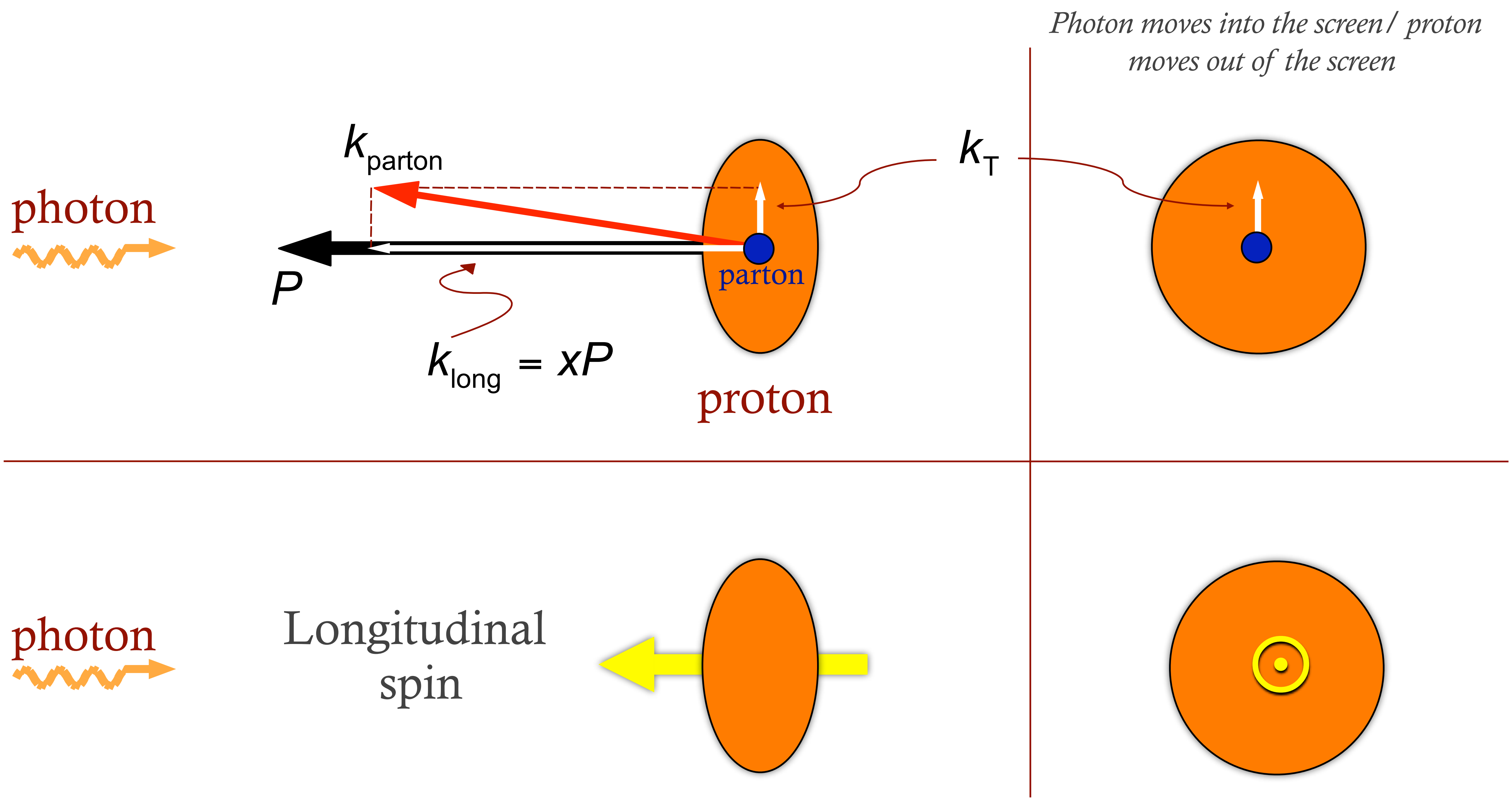
AAC, Hirai et al. PRD69 (04)

Transverse parton distribution functions

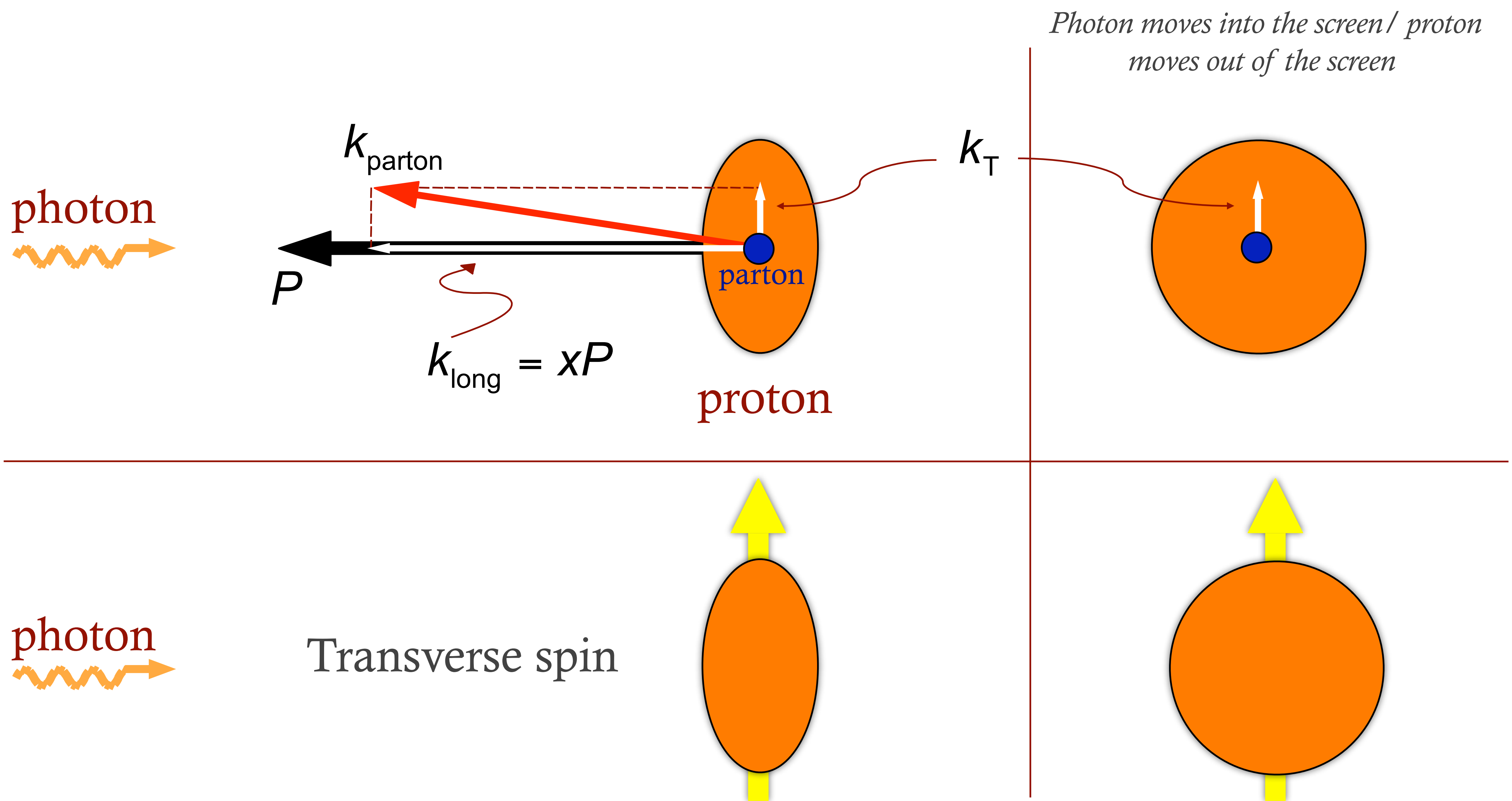
Transverse vs. longitudinal



Transverse vs. longitudinal



Transverse vs. longitudinal

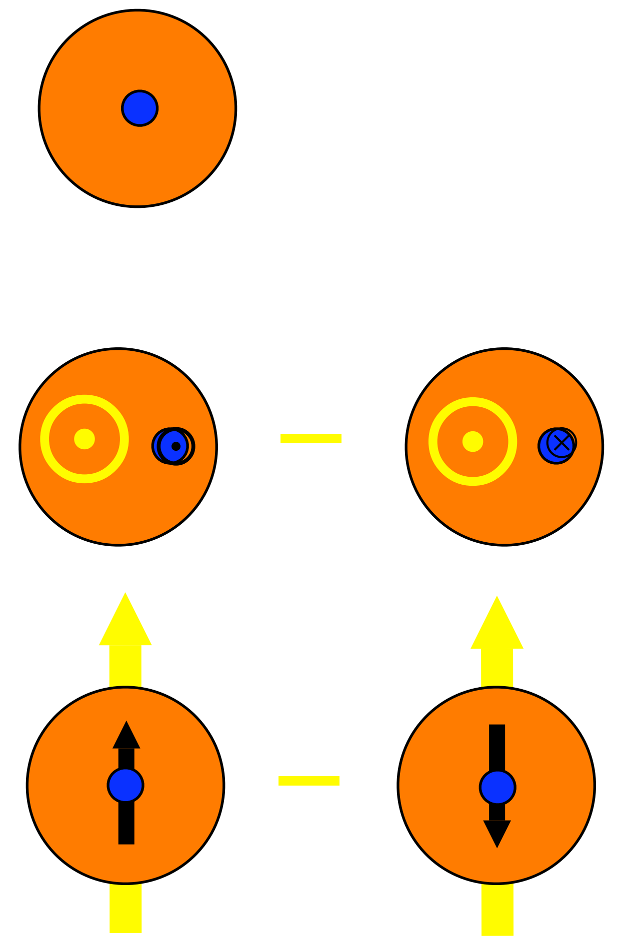


Transversity

$$f_1^q(x) = q(x) =$$

$$g_1^q(x) = \Delta q(x) =$$

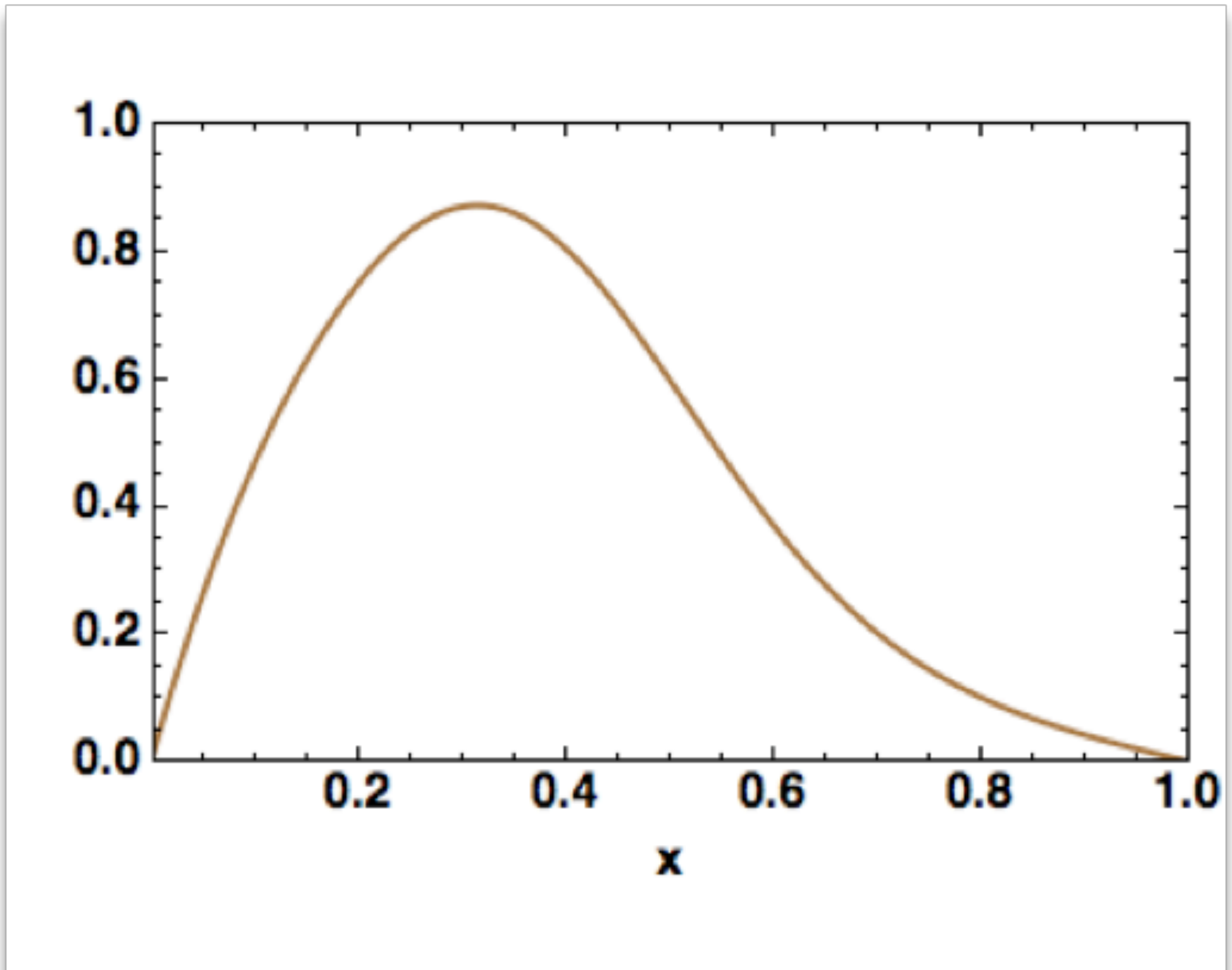
$$h_1^q(x) = \Delta_T q(x) =$$



Transverse momentum distributions

up quarks

$x\,q(x)$



Orbital angular momentum

Jaffe, Manohar, NPB 337 (90)

$$\frac{1}{2} = \frac{1}{2}\int dx\, g_1^{q+\bar{q}}(x) + L_z^{q+\bar{q}} + \int dx\, g_1^{g}(x) + L_z^{g}$$

Gauge invariant

Gauge dependent
not directly measurable

$$\frac{1}{2} = J_z^{q+\bar{q}} + J_z^{g}$$

Ji, PRL 78 (97)

Transversity

Transversity vs Helicity

- Different due to relativistic effects
- Different integral (tensor vs axial charge)

$$\delta\Sigma = 0.56$$
$$\Delta\Sigma = 0.18$$

Aoki et al., PRD 56 (97)

- Different evolution (no gluons vs gluons)

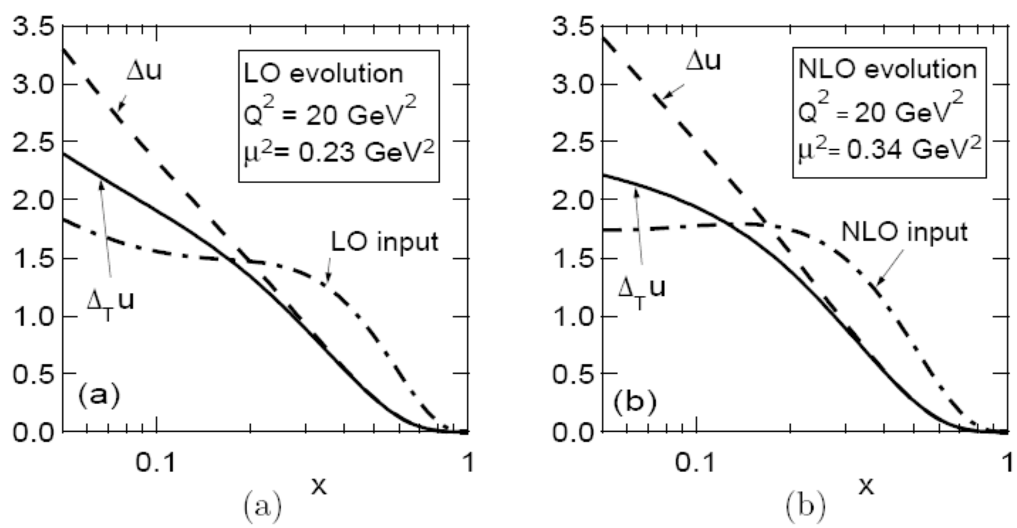
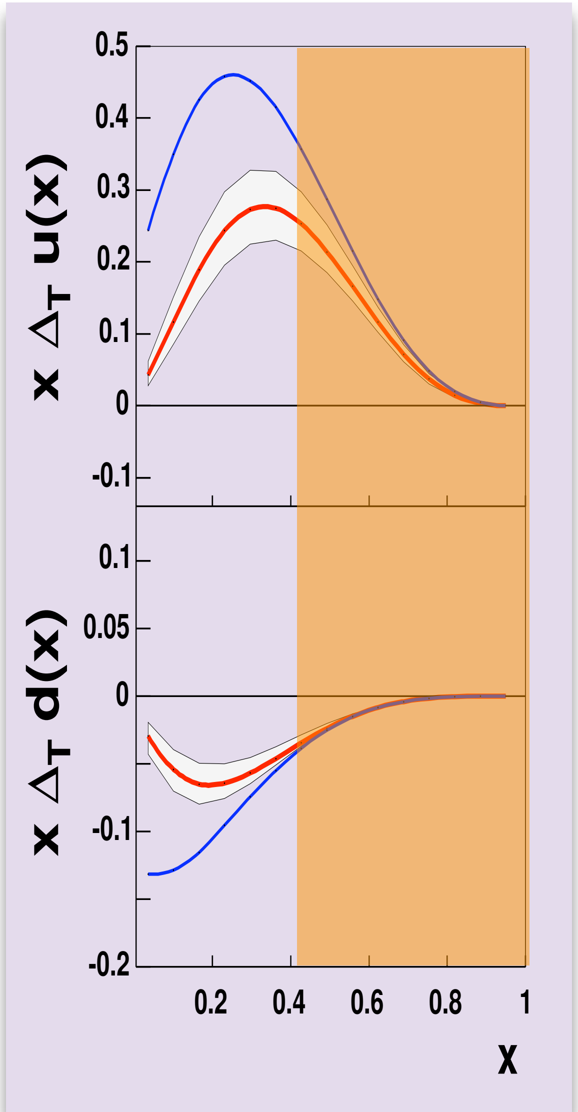


Fig. 19. Comparison of the Q^2-evolution of $\Delta_T u(x, Q^2)$ and $\Delta u(x, Q^2)$ at (a) LO and (b) NLO, from [72].

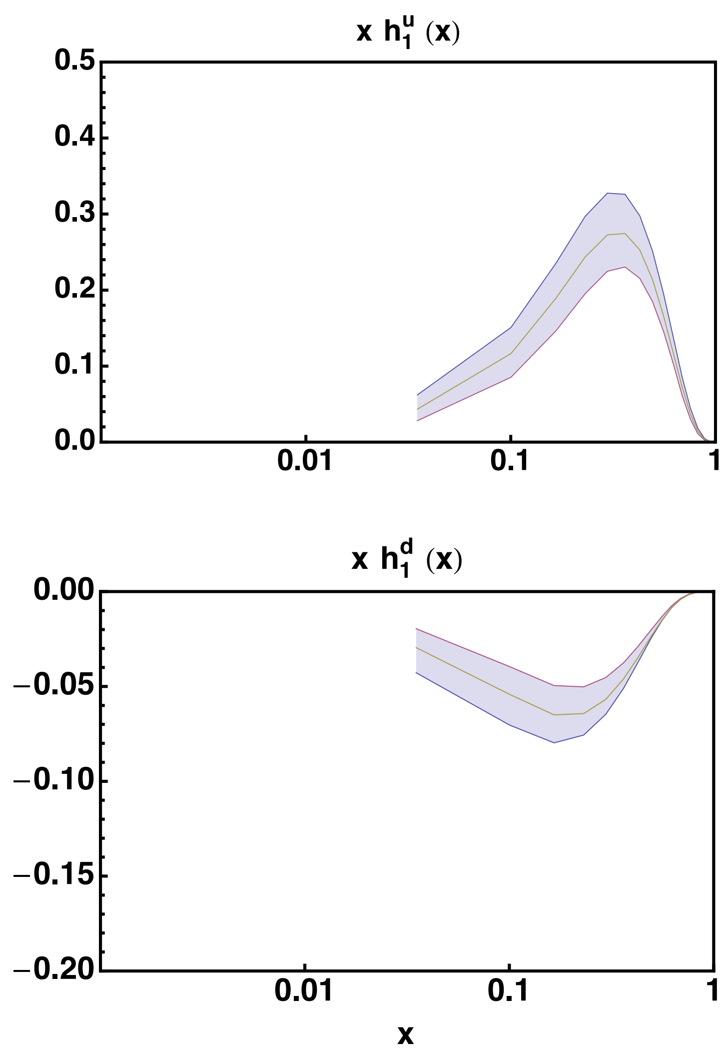
Extraction of transversity



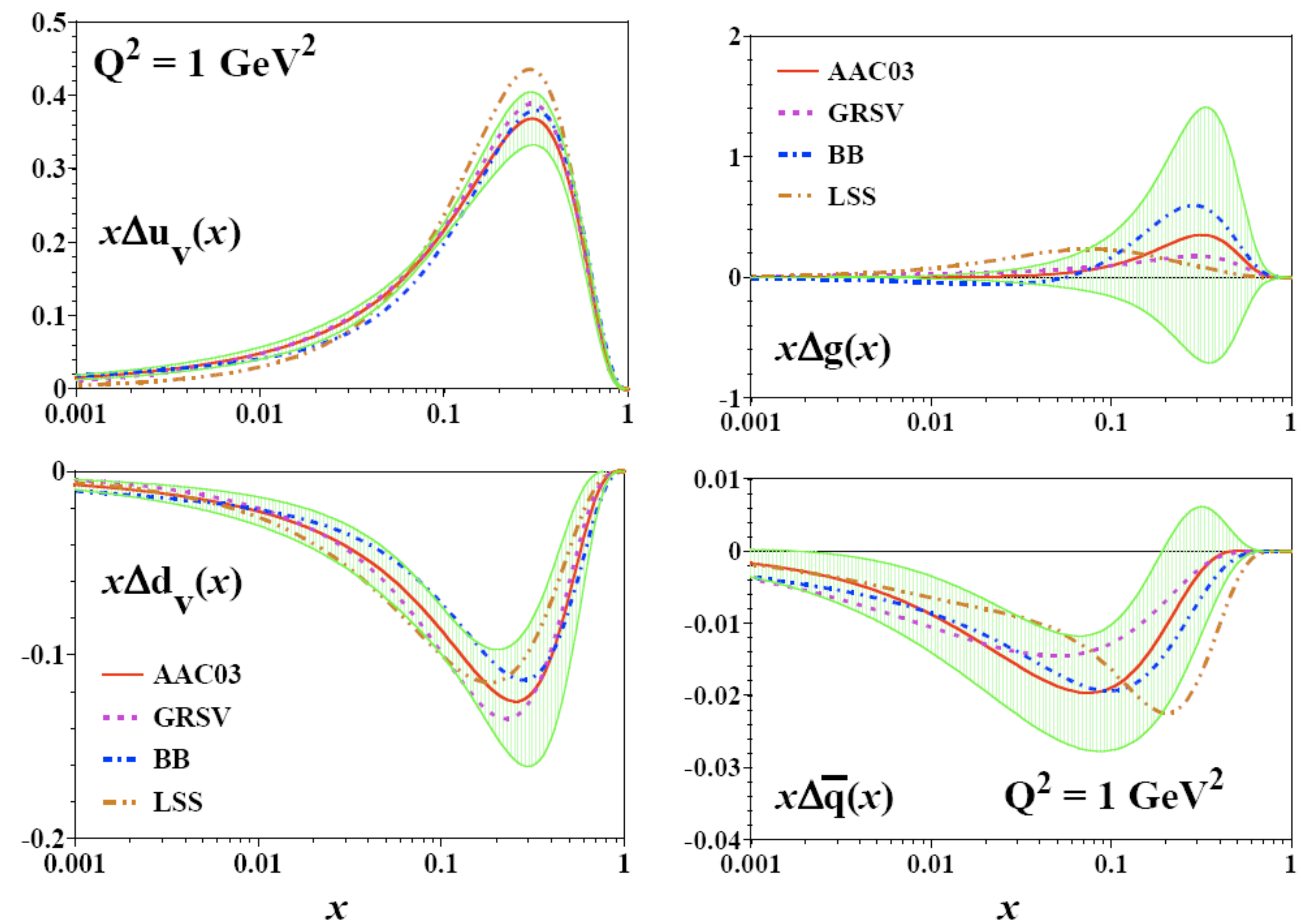
- Data from HERMES, COMPASS, BELLE
- 96 data points (cf. 467 points for Δq fits)
- $\chi^2 \approx 1.4$
- Statistical uncertainty only ($\Delta\chi^2 \approx 17$)

A. Prokudin, talk at DIS08 (Anselmino et al, 0807.0173)

Comparison with helicity

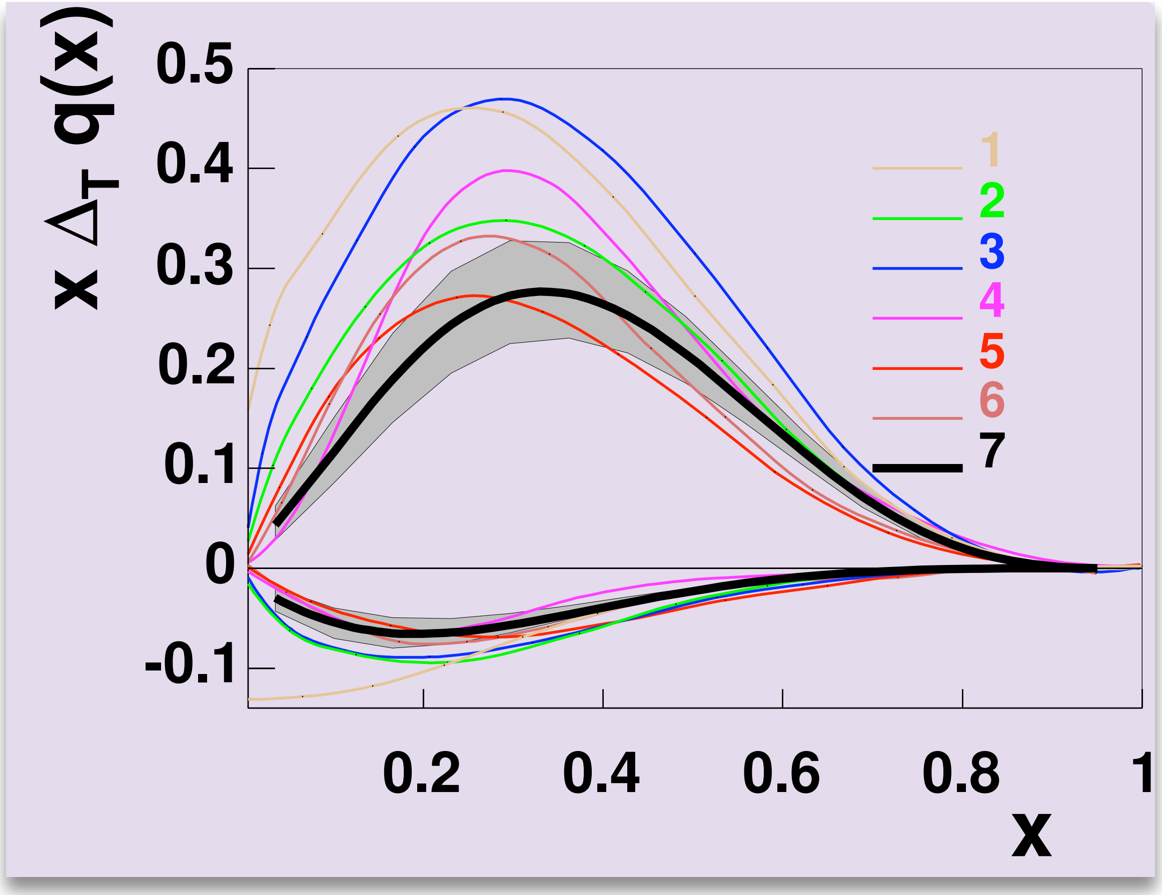


Anselmino et al, 0807.0173



AAC, Hirai et al. PRD 69 (04)

Comparison with models



[1] *Soffer et al. PRD 65 (02)*

[2] *Korotkov et al. EPJC 18 (01)*

[3] *Schweitzer et al., PRD 64 (01)*

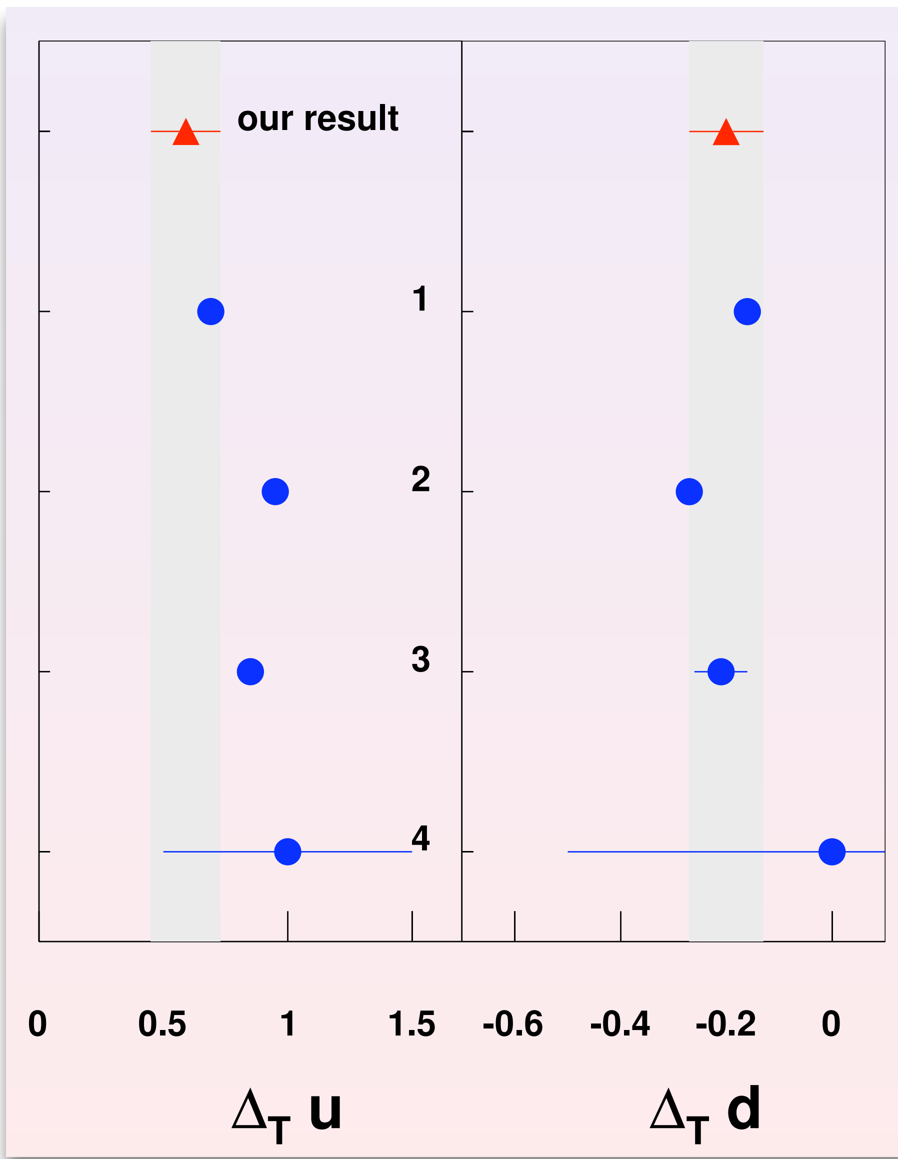
[4] *Wakamatsu, PLB 509 (01)*

[5] *Pasquini et al., PRD 72 (05)*

[6] *Cloet, Bentz, Thomas, PLB 659 (08)*

Nucleon tensor charges

Integrals over x of transversity



[our result] Anselmino et al. DIS 08

[1] Diquark spectator model, Cloet, Bentz, Thomas, PLB 659 (08)

[2] Chiral quark soliton model, Wakamatsu, PLB 653 (07)

[3] Lattice QCD, Goekeler et al. PLB 627 (05)

[4] QCD sum rules, He, Ji, PRD 52 (95)

Transverse momentum distributions (TMDs)

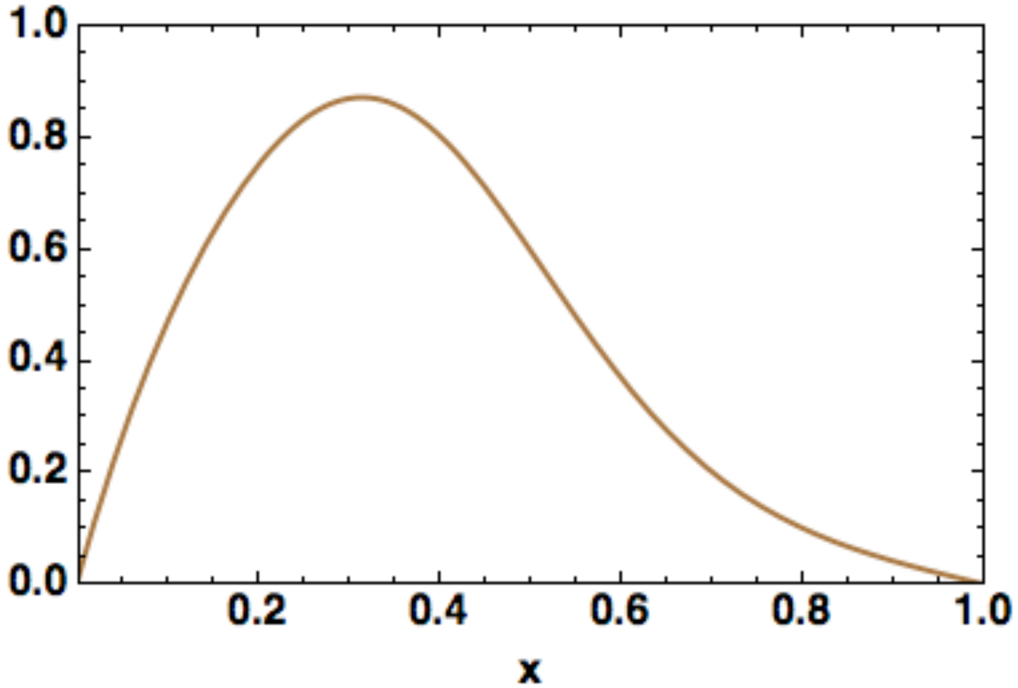
Relation to GPDs

- In general, parton distributions are 6 dimensional (Wigner distributions)
  - 3 dim. in coordinate space (GPDs)
  - 3 dim. in momentum space (TMDs)

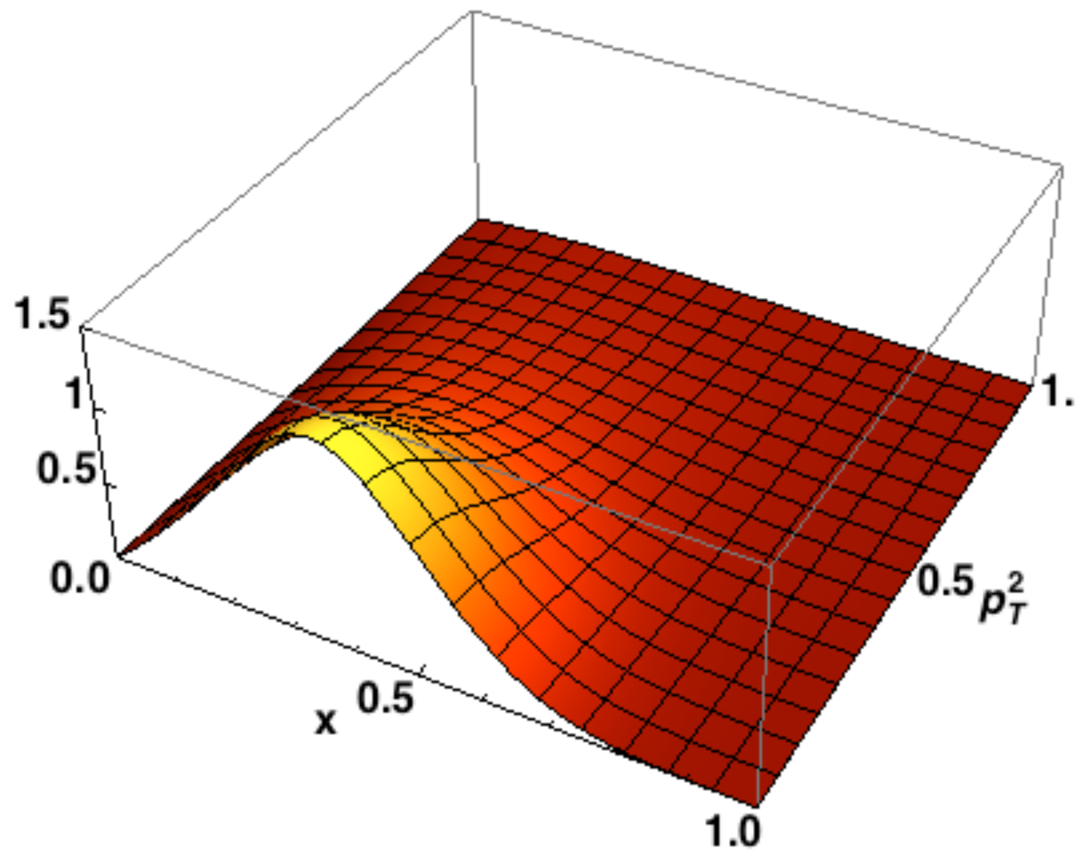
X. Ji, PRL 91 (03), Meissner et al. arXiv:0805.3165
for even more dim. (8), see Collins, Rogers, Stasto, PRD77 (08)

Transverse momentum distributions

$x f_1^u(x)$

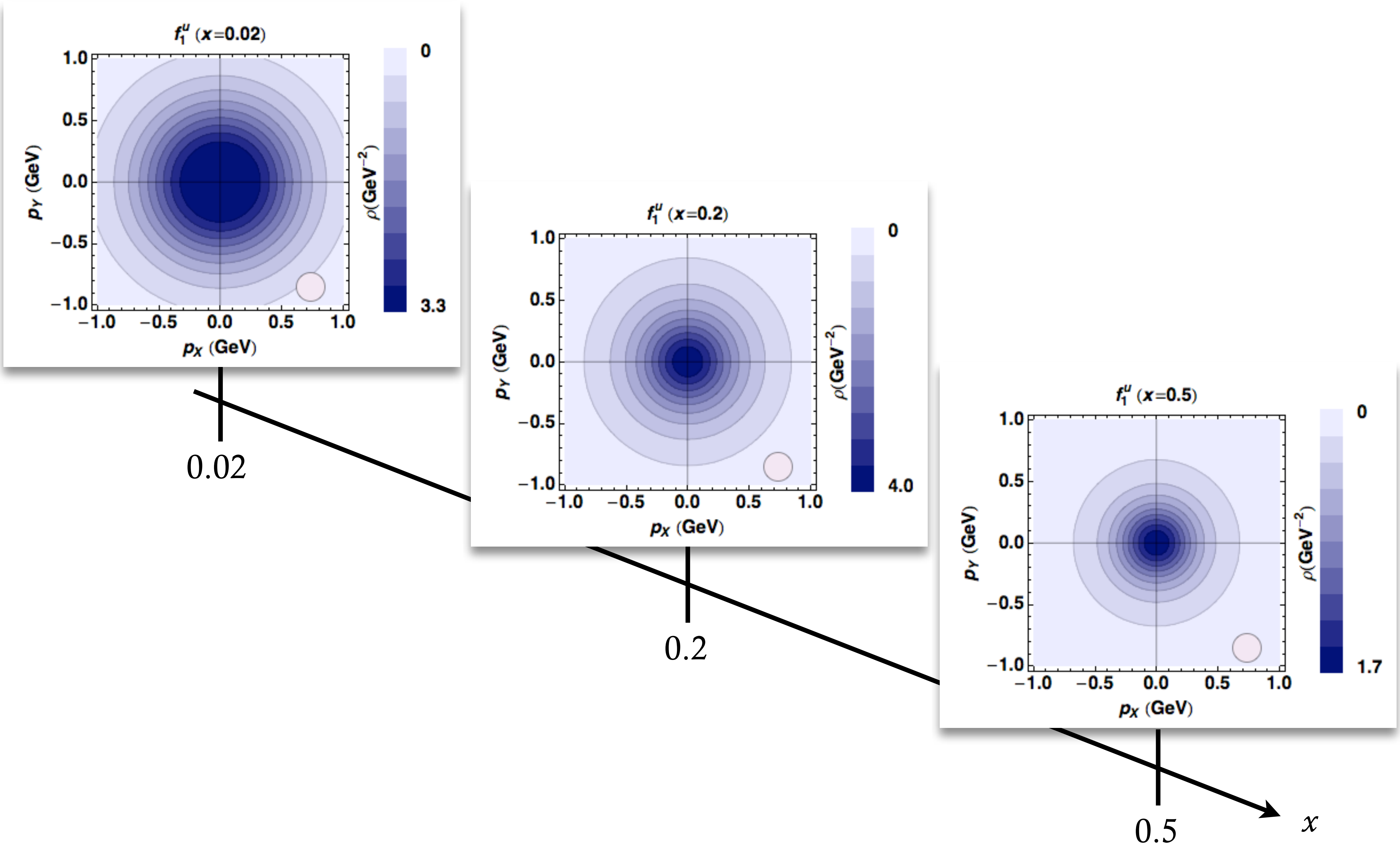


$x f_1^u(x, p_T^2)$

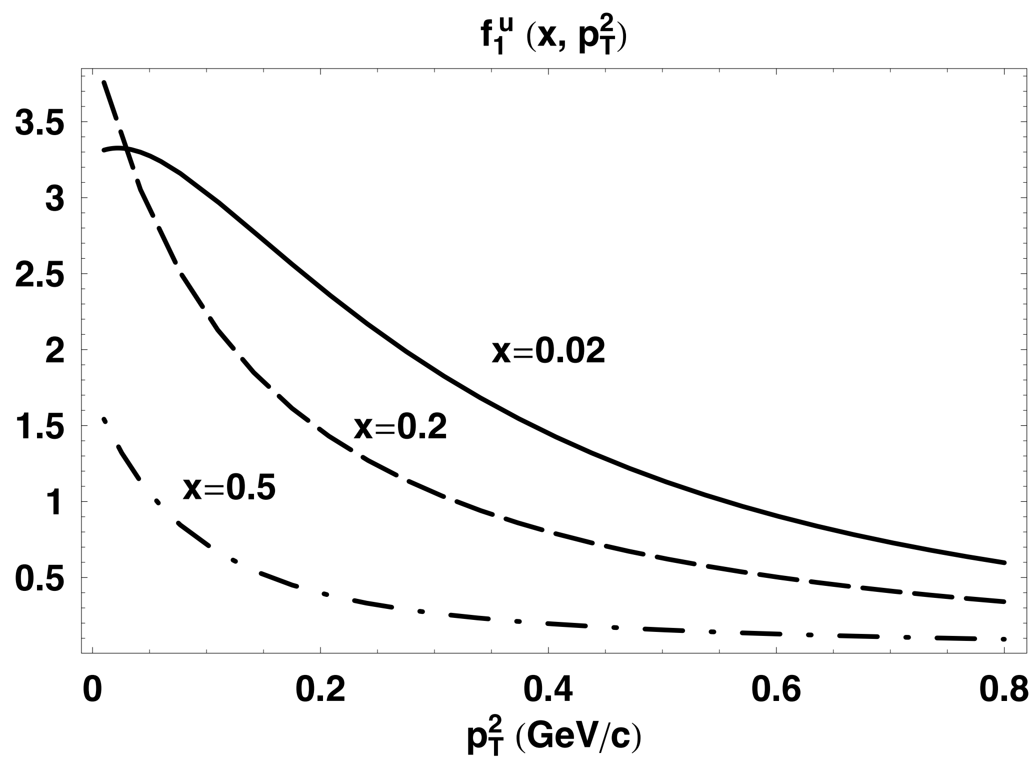


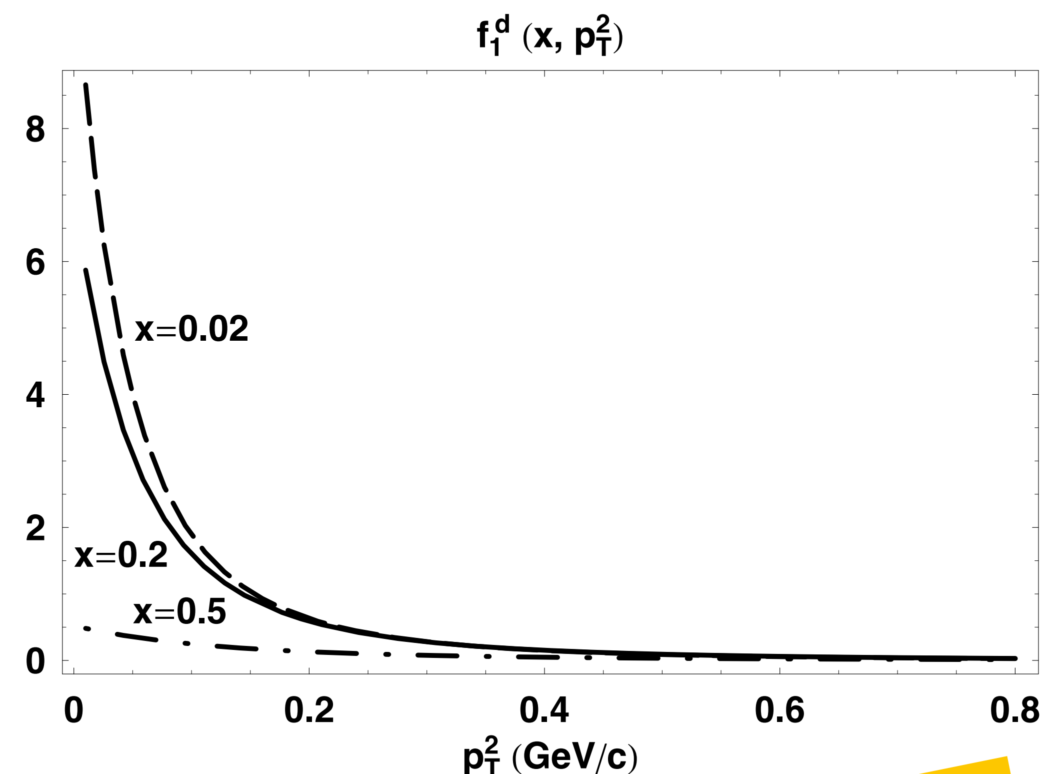
A.B., F. Conti, M. Radici, arXiv:0807.0323

Nucleon tomography in momentum space



Nontrivial features





Simple model calculations suggests

- *x*-dependence
- flavor dependence
- deviation from a simple Gaussian

Fundamental information on the nucleon structure almost as important as standard collinear PDFs

Experimental results

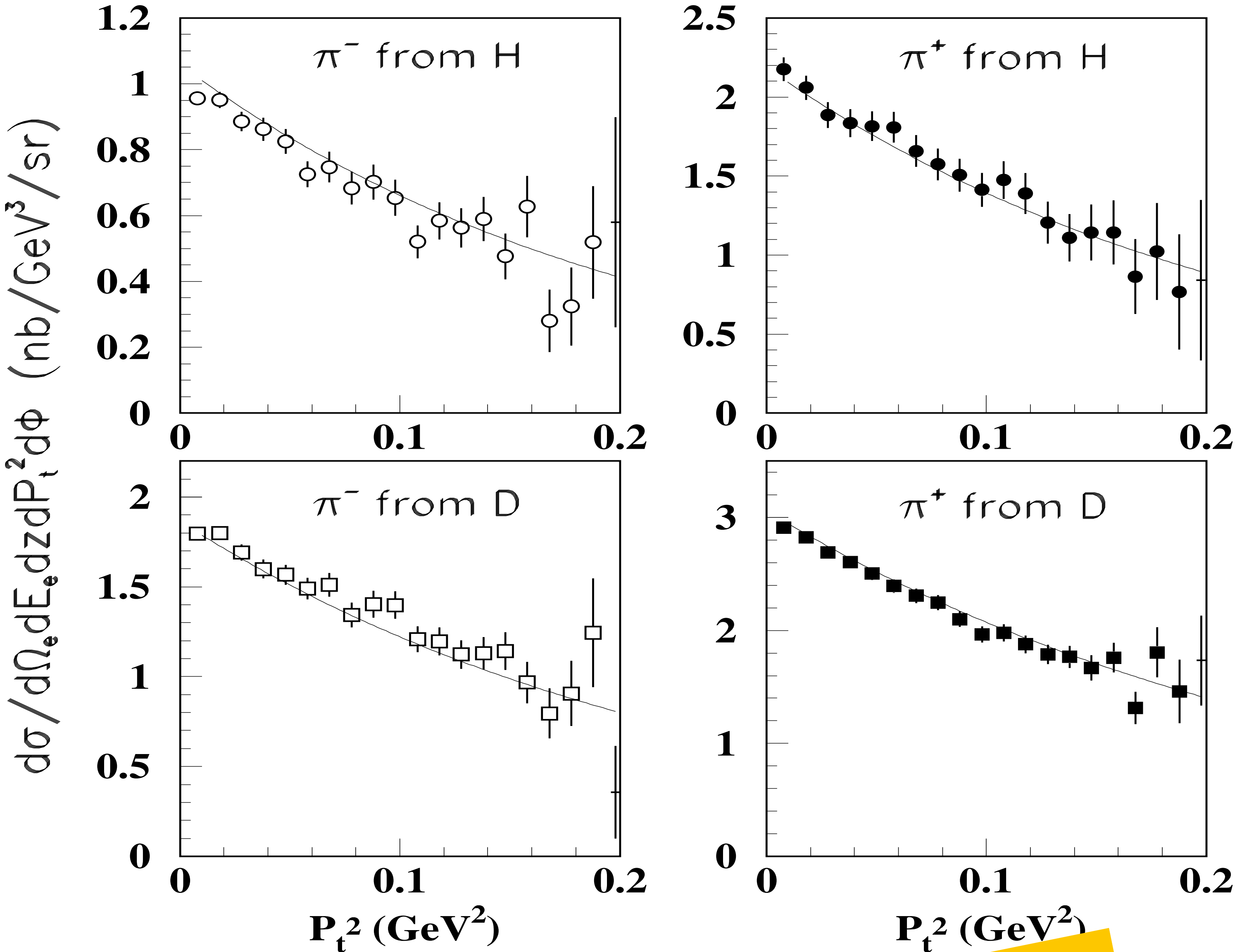
- There are several different approaches to study unpolarized TMDs: nonperturbative contribution only, nonperturbative +resummation, nonperturbative+parton shower from Monte Carlo generators...

- So far, essentially all analyses consider simple Gaussians with flavor-independent and usually also *x*-independent widths. Mostly Drell--Yan.

- Interesting analysis done at JLab Hall C: down quarks have higher transverse momentum than up quarks

Mkrtchyan et al., arXiv: 0709.3020

SIDIS data with hadron identification

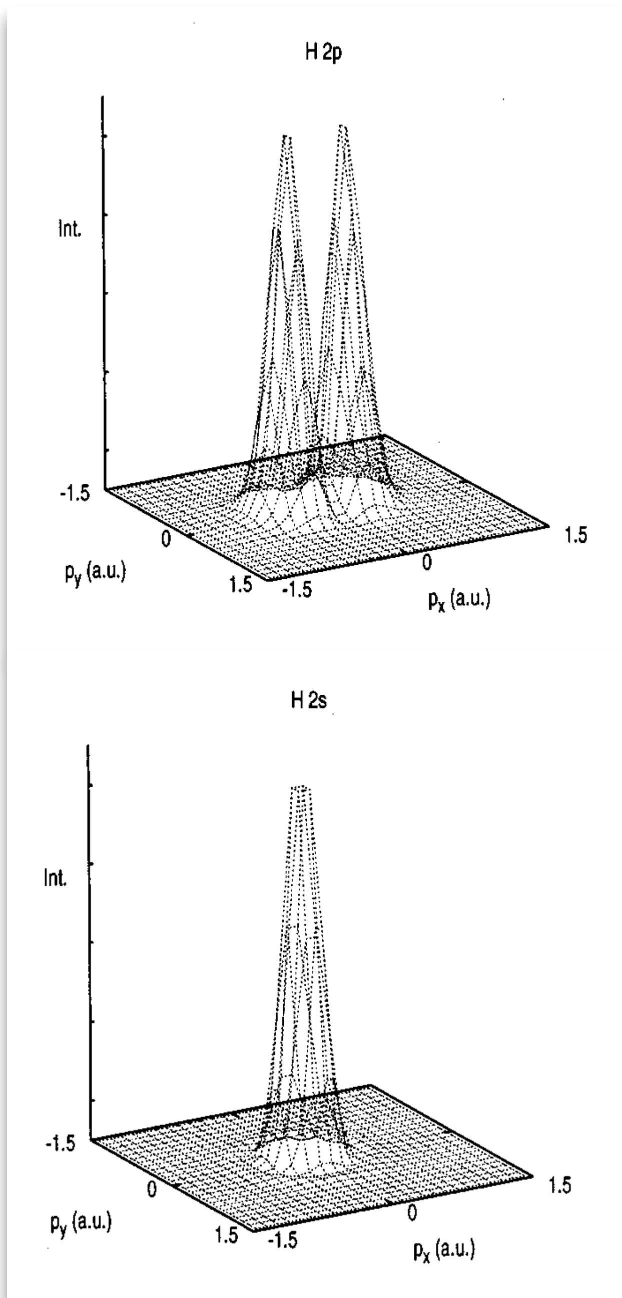


Essential to study flavor structure

JLab Hall C, Mkrtchyan et al., PLB665 (08)

Orbital angular momentum

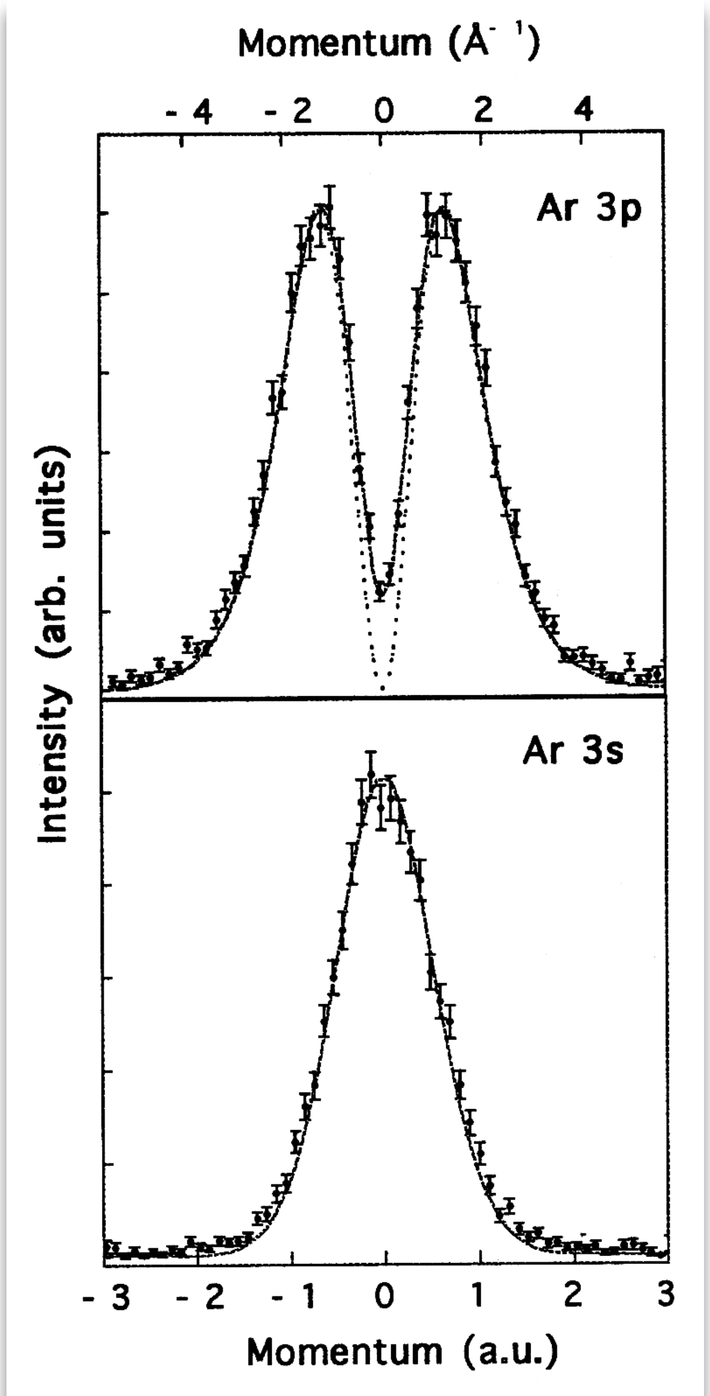
Hidrogen atom wavefunctions
in momentum space



- In atomic physics, wavefunctions with orbital angular momentum have distinct shapes

Vos, McCarthy, Am. J. Phys. 65 (97), 544

Orbital angular momentum



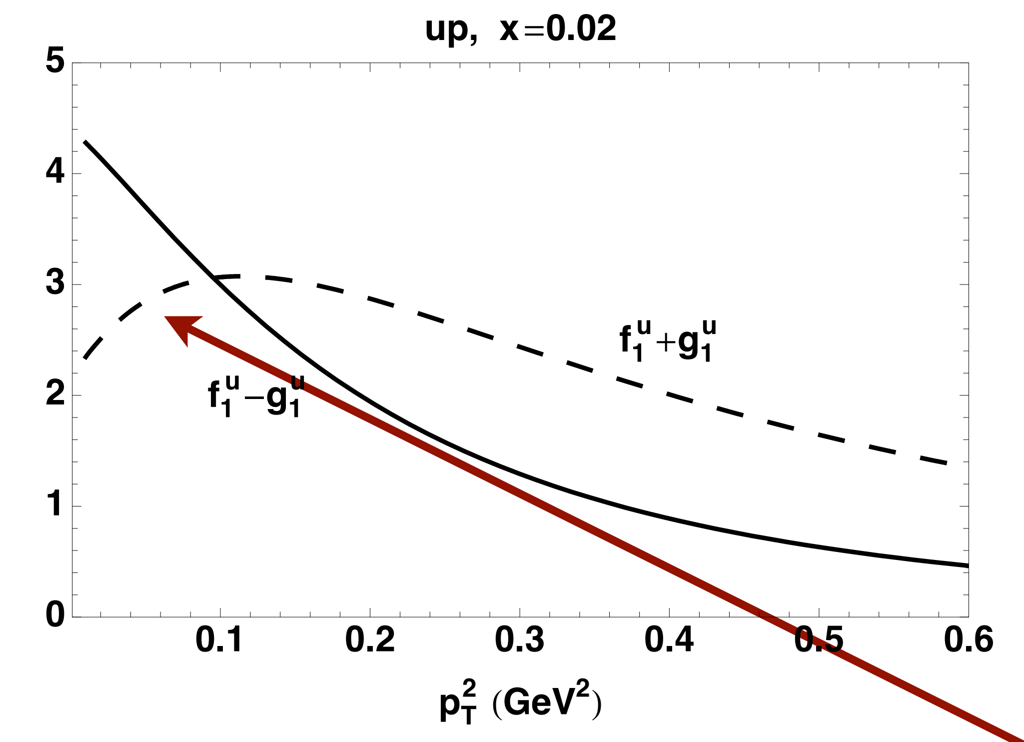
Vos, McCarthy, Am. J. Phys. 65 (97), 544

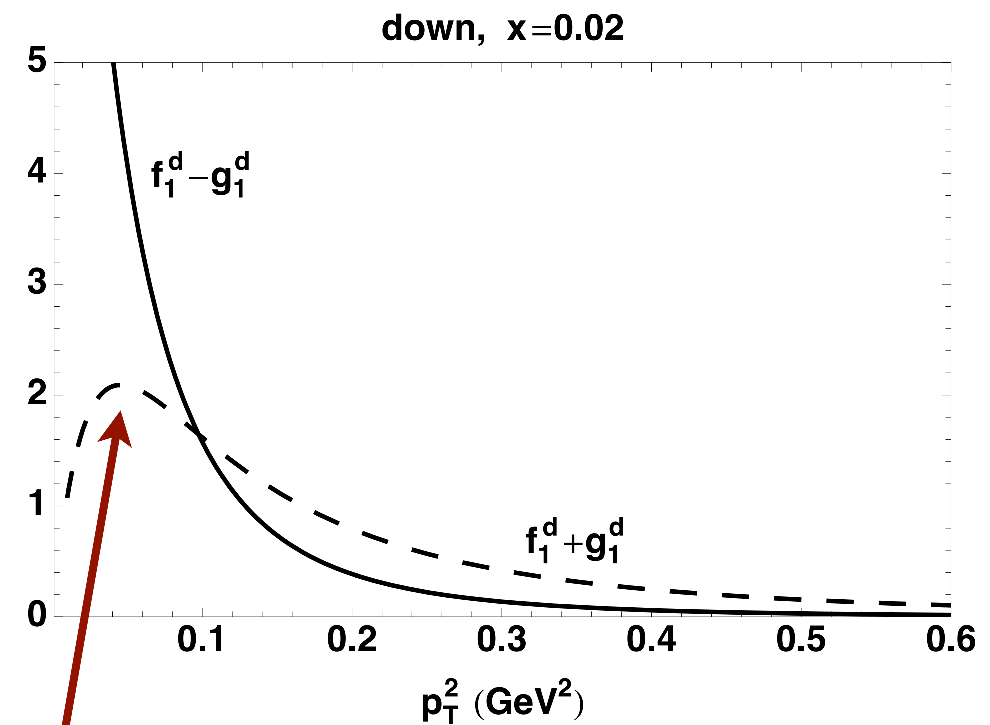
- In atomic physics, wavefunctions with orbital angular momentum have distinct shapes
- The most direct visualization of these shapes is provided by scattering experiments and is in momentum space

$$f_1(x, p_T^2) = |\psi_{s-\text{wave}}|^2 + |\psi_{p-\text{wave}}|^2 + \ldots$$

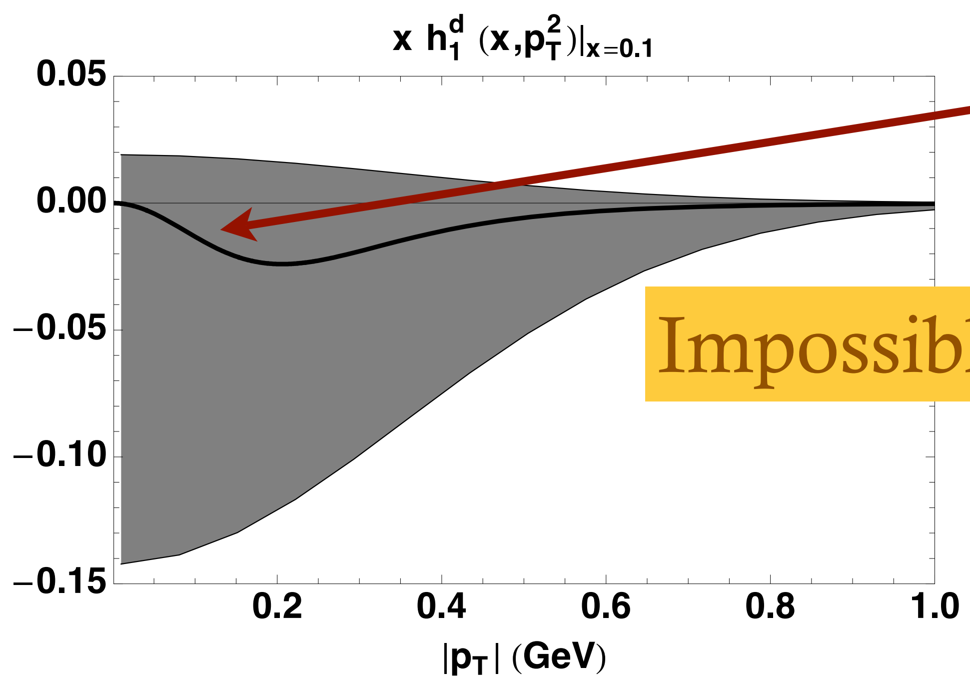
At low p_T $|\psi_{p-\text{wave}}|^2 \sim p_T^2$

TMDs and orbital angular mom.





Signs of orbital ang. mom.



Impossible to reproduce using simple Gaussians

A.B., F. Conti, M. Radici, in preparation

TMDs and orbital angular mom.

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Twist-2 TMDs

- Some TMDs vanish if there is no quark orbital angular momentum, e.g., Sivers function, g_{1T},…
- Any quantitative statement about the total orbital angular momentum is model-dependent

Sivers function

Two ingredients

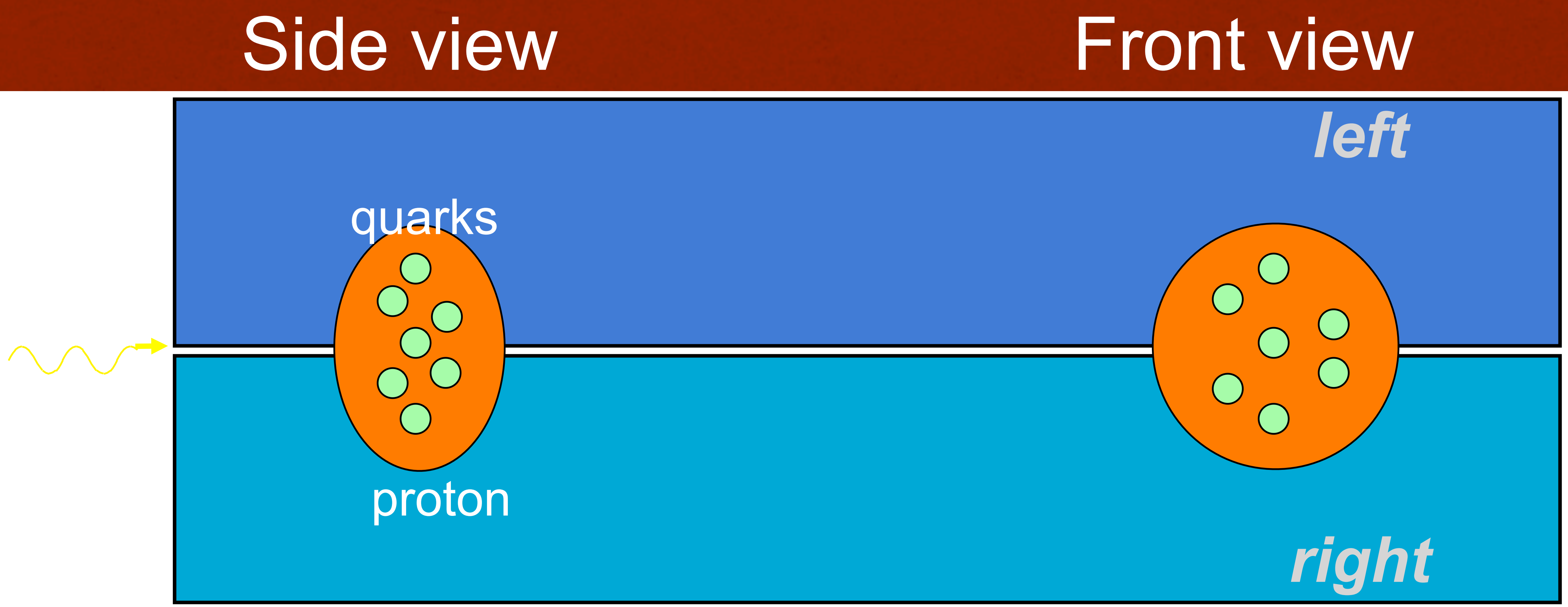
- Final-state interactions (included in the gauge link)

  Ji, Yuan, PLB 543 (02); Belitsky, Ji, Yuan, NPB656 (03)

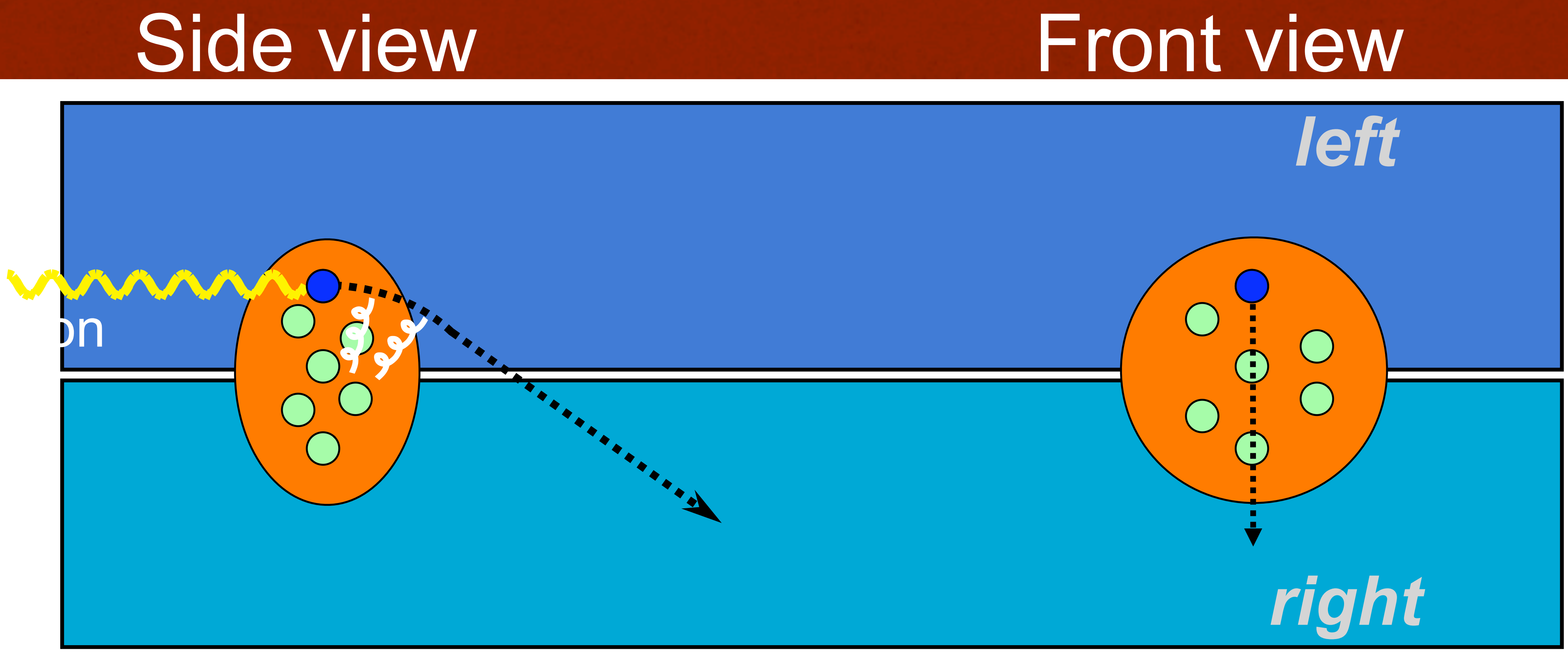
- Transverse-spin dependent distribution of quarks in transverse space

  Burkardt, PRD 66 (02); Diehl, EPJ C25 (02); Diehl, Hägler, EPJ C44 (05)

Final-state interactions

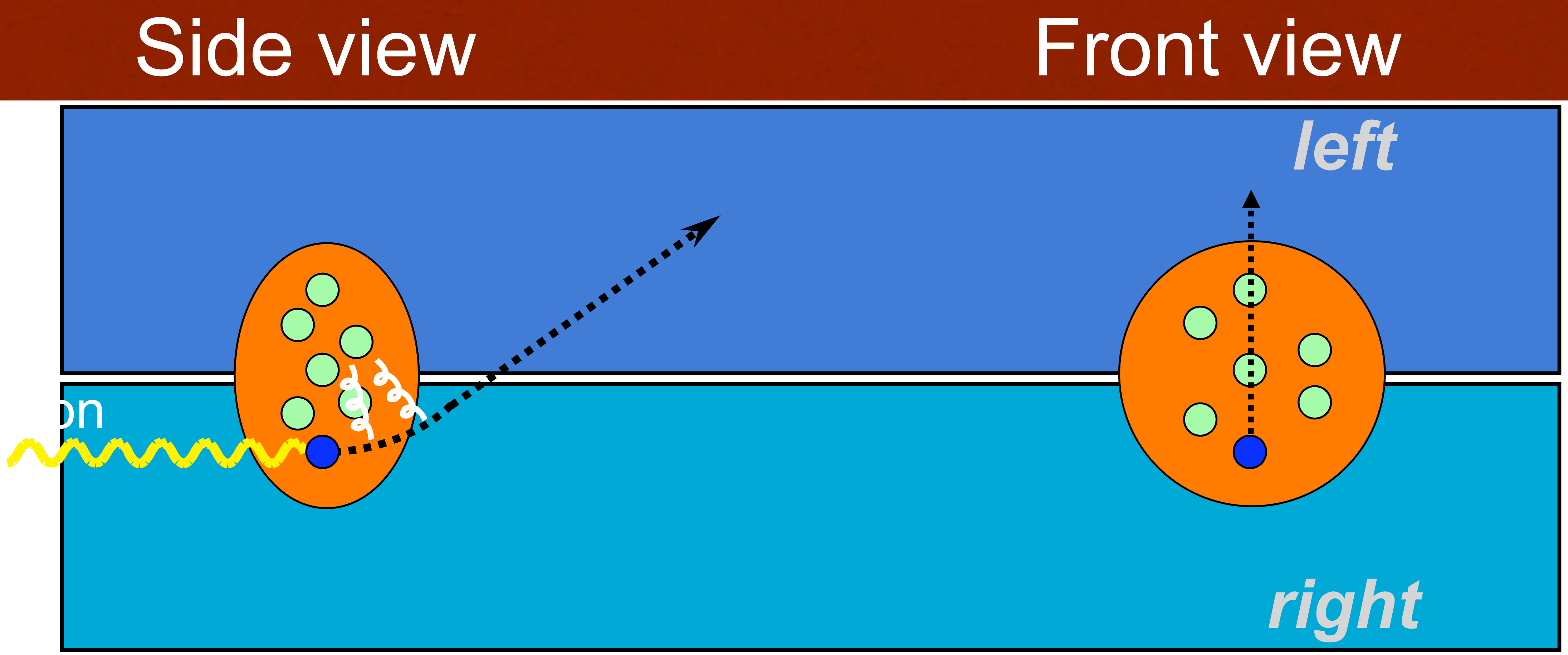


Final-state interactions



NOTE: QCD tells us that the FSI has to be attractive, since quark and remnants form a color antisymmetric state

Final-state interactions

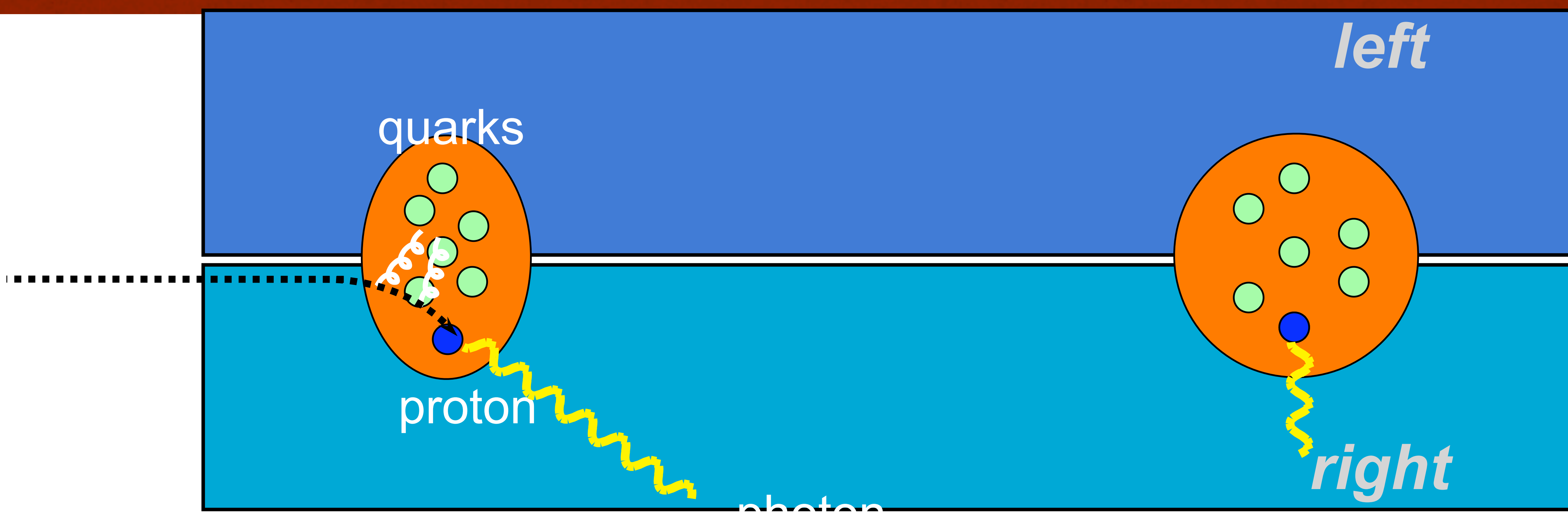


Chromodynamic lensing

Burkardt, PRD 66 (02)

Change of sign in Drell-Yan

Side view Front view



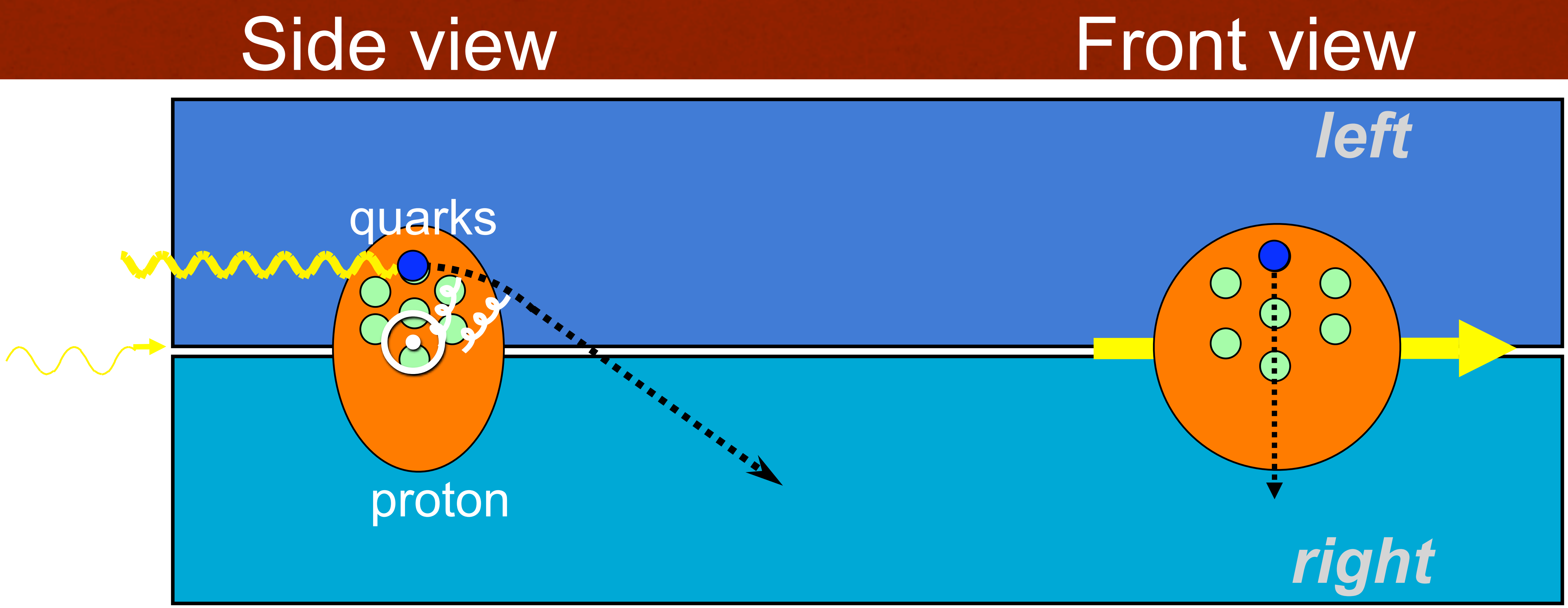
Clear-cut prediction of QCD

Collins, PLB 536 (02)

Distortions in transverse space

Side view | Front view

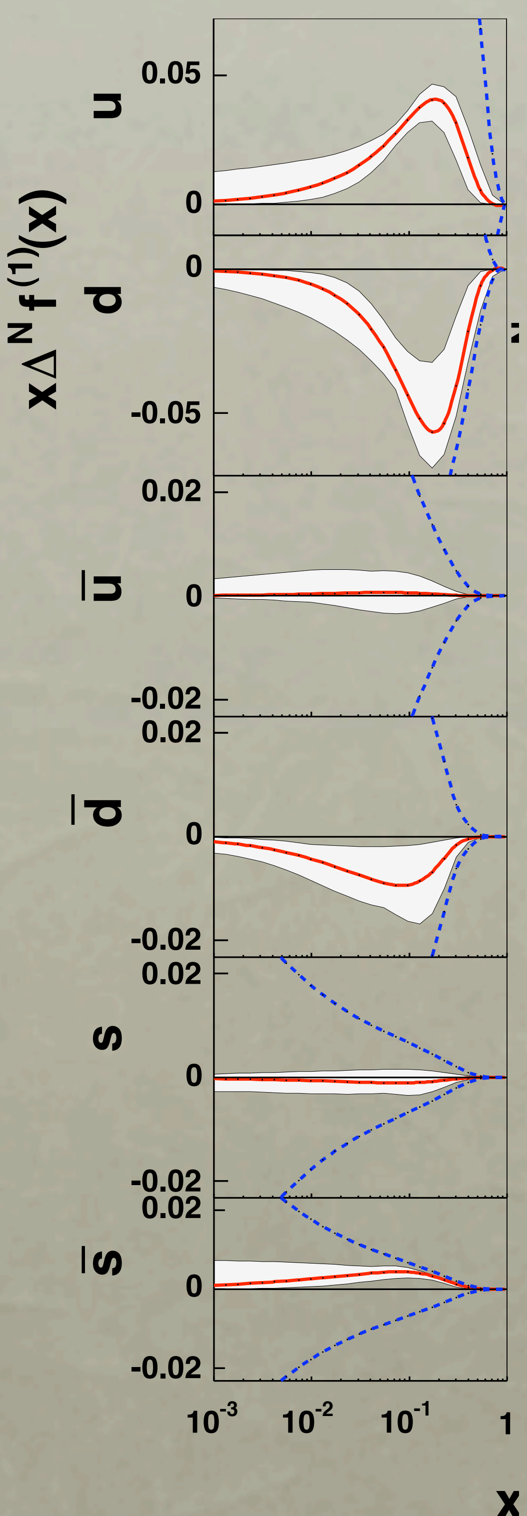
Distortions in transverse space



The presence of spin can distort the distribution of quarks in transverse space (orbital angular momentum of quarks is required)

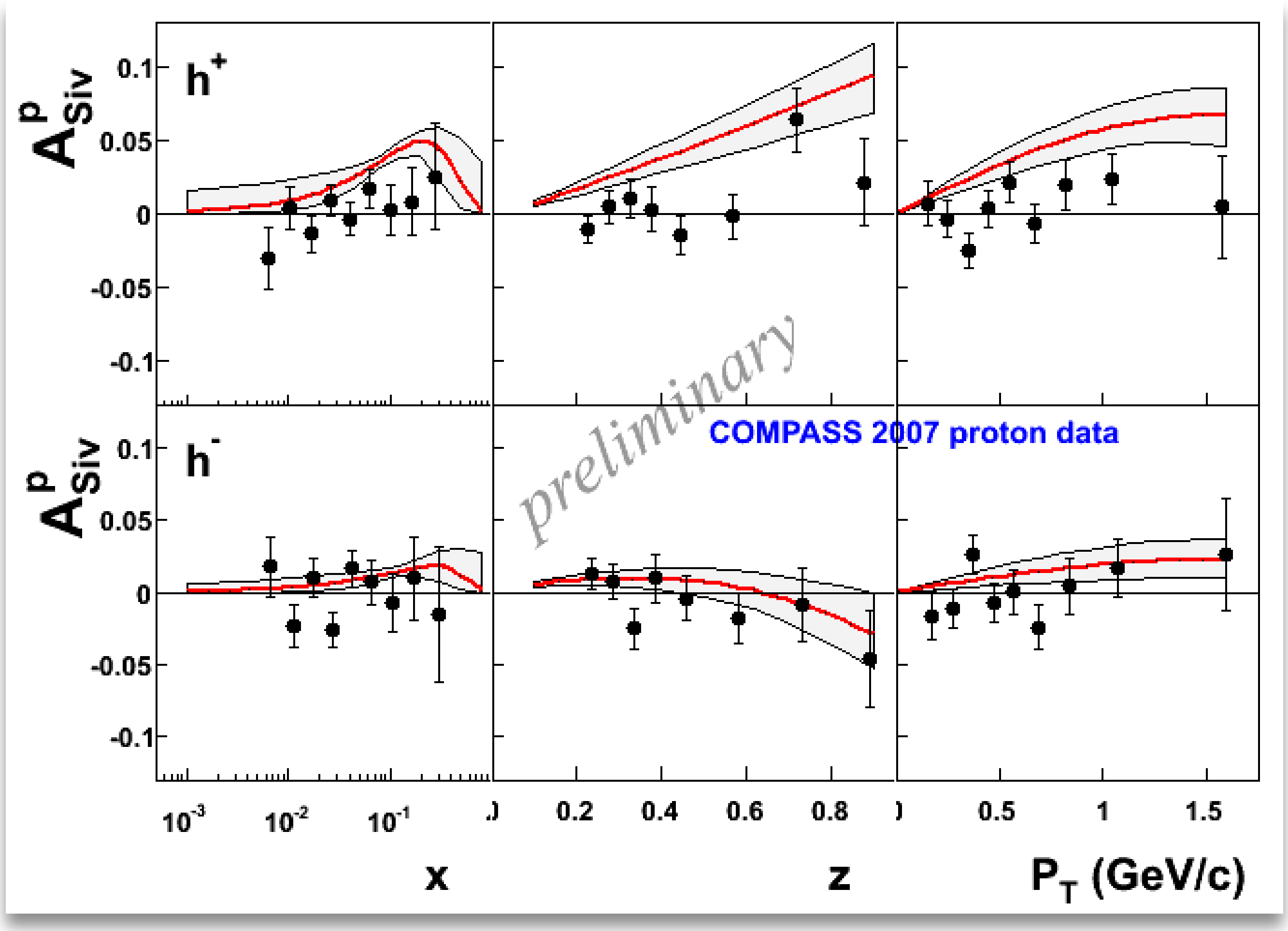
A distortion in the distribution of quarks in transverse space can give rise to a nonzero Sivers function

Sivers function extraction



- Data from HERMES, COMPASS (deuteron)
- 96 data points (cf. 467 points for Δq fits)
- $\chi^2 \approx 1.0$
- Statistical uncertainty only ($\Delta\chi^2 \approx 17$)

Sivers function: COMPASS



data: S. Levorato, Transversity 08
prediction: Anselmino et al., 0805.2677

Main messages

- We have a first estimate of transversity, but we have to go from exploration to precision
- TMDs allow a 3D momentum tomography
- All transverse-momentum dependences, starting from that of f_1, are interesting and largely unknown
- Strong indirect connections with orbital angular momentum
- We are going from exploration to precision