Jefferson Lab

mini lecture series

“transverse thinking”: an introduction to TMDs

Alessandro Bacchetta

TMDs

TMDs stands for Transverse Momentum Distributions

Sometimes it is used also for Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs) and Fragmentation Functions (TMD FFs)

Often in the literature they are called also Unintegrated Parton Distribution Functions (uPDFs)

Some organization details

- On Wednesdays, once every two weeks
- About 90 min each
- Schedule will be advertised through mailing lists
- Comments, questions more than welcome. My office is B200A (in front of director’s office). E-mail: alessandro.bacchetta@jlab.org
- There will be some upcoming theory seminars on the topic, namely
  - Z. Kang, Mar 9
  - F. Yuan, Apr 27

Preliminary plan

- Introduction
- Semi-inclusive DIS
- Theory of TMDs 1 (definition, interpretation, gauge link)
- Theory of TMDs 2 (high pT, resummation, evolution)
- Phenomenology of unpolarized SIDIS
- Phenomenology of polarized SIDIS

mini lecture series

“transverse thinking”: an introduction to TMDs

Part 1: Introduction

Some goals of hadronic physics

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

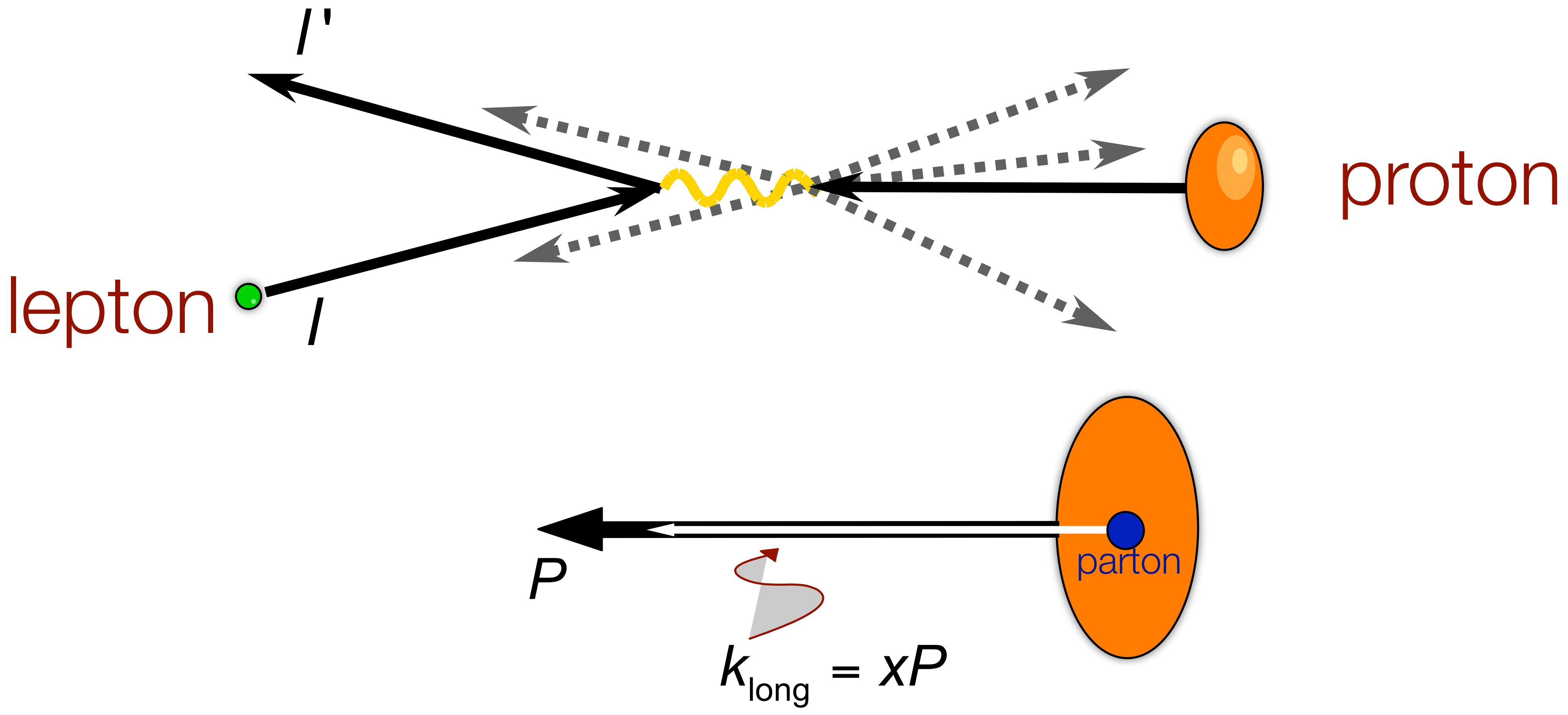
TMDs are relevant
for all of these issues

Parton distribution functions essentials

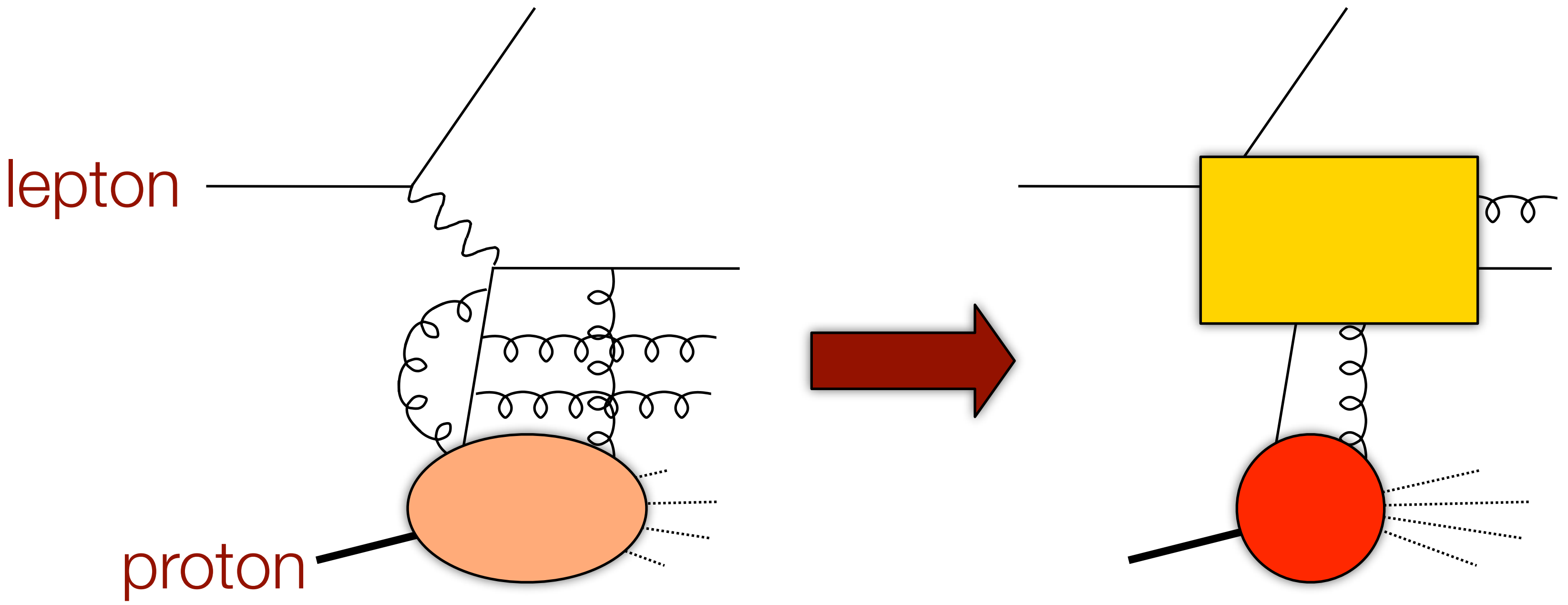
Deep inelastic scattering (DIS)

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

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



Factorization



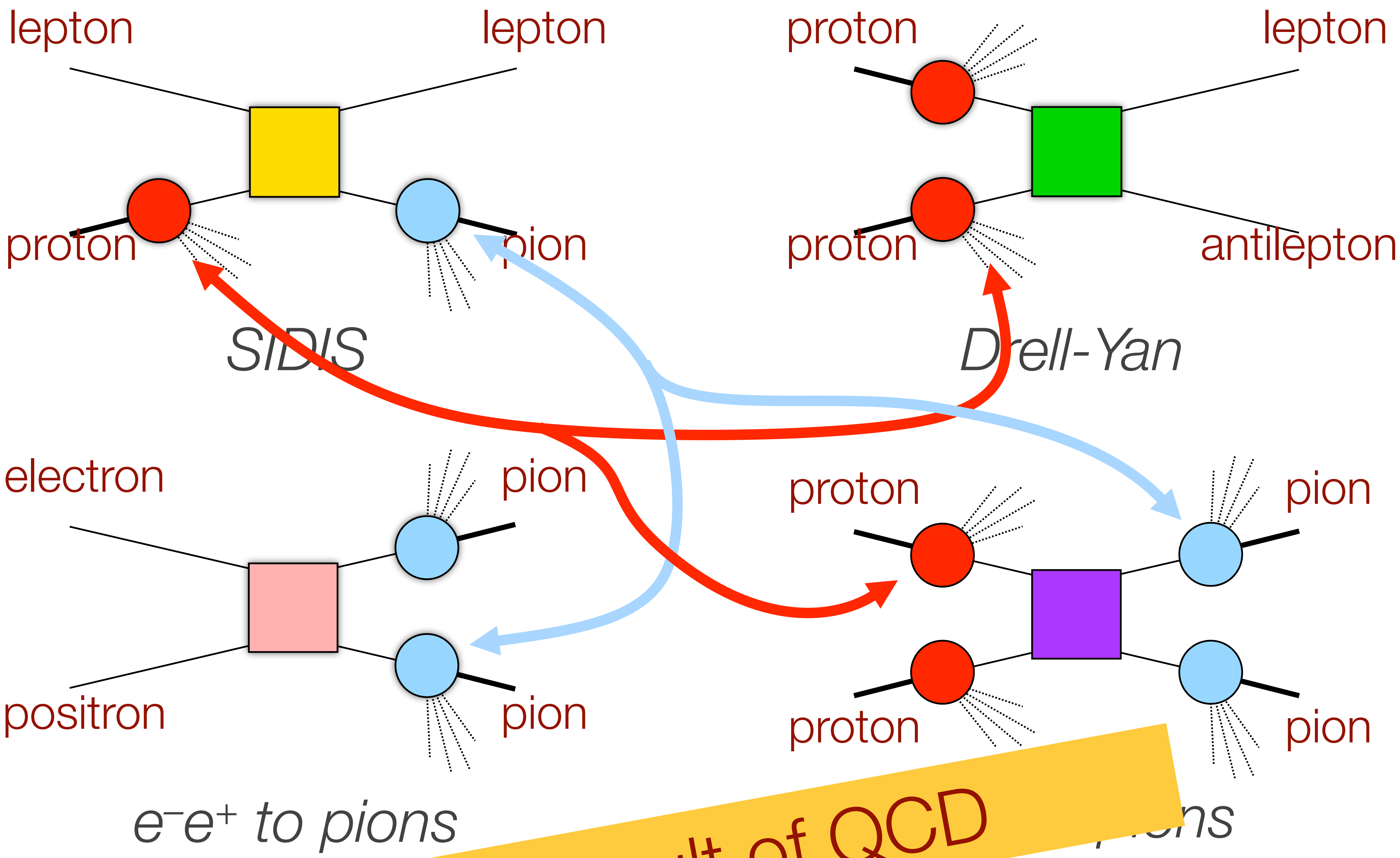
🟨 Partonic scattering amplitude

🔴 Distribution amplitude

$$d\sigma \sim H \otimes f$$

Key result of QCD

Universality



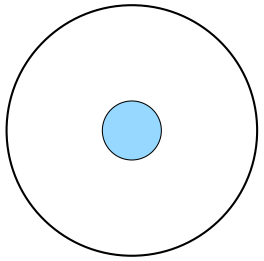
Key result of QCD

Parton distribution functions

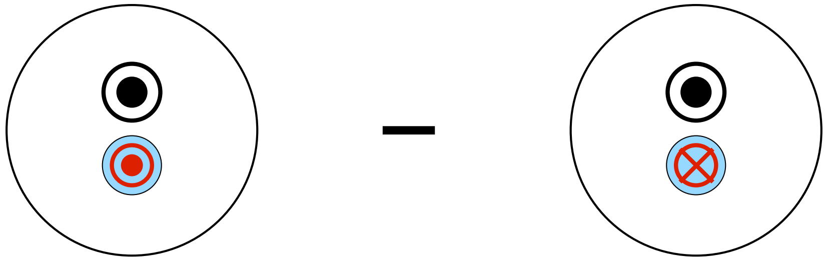
Parton distribution functions (PDFs) are probability densities to find a parton with a given longitudinal momentum and a given spin

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

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



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



Caveats

- The hard probe “sees” only some components of the partonic fields (good fields), or in an equivalent way PDFs are pictures of partons in a specific frame of reference (infinite momentum frame)

Pictures in the infinite momentum frame

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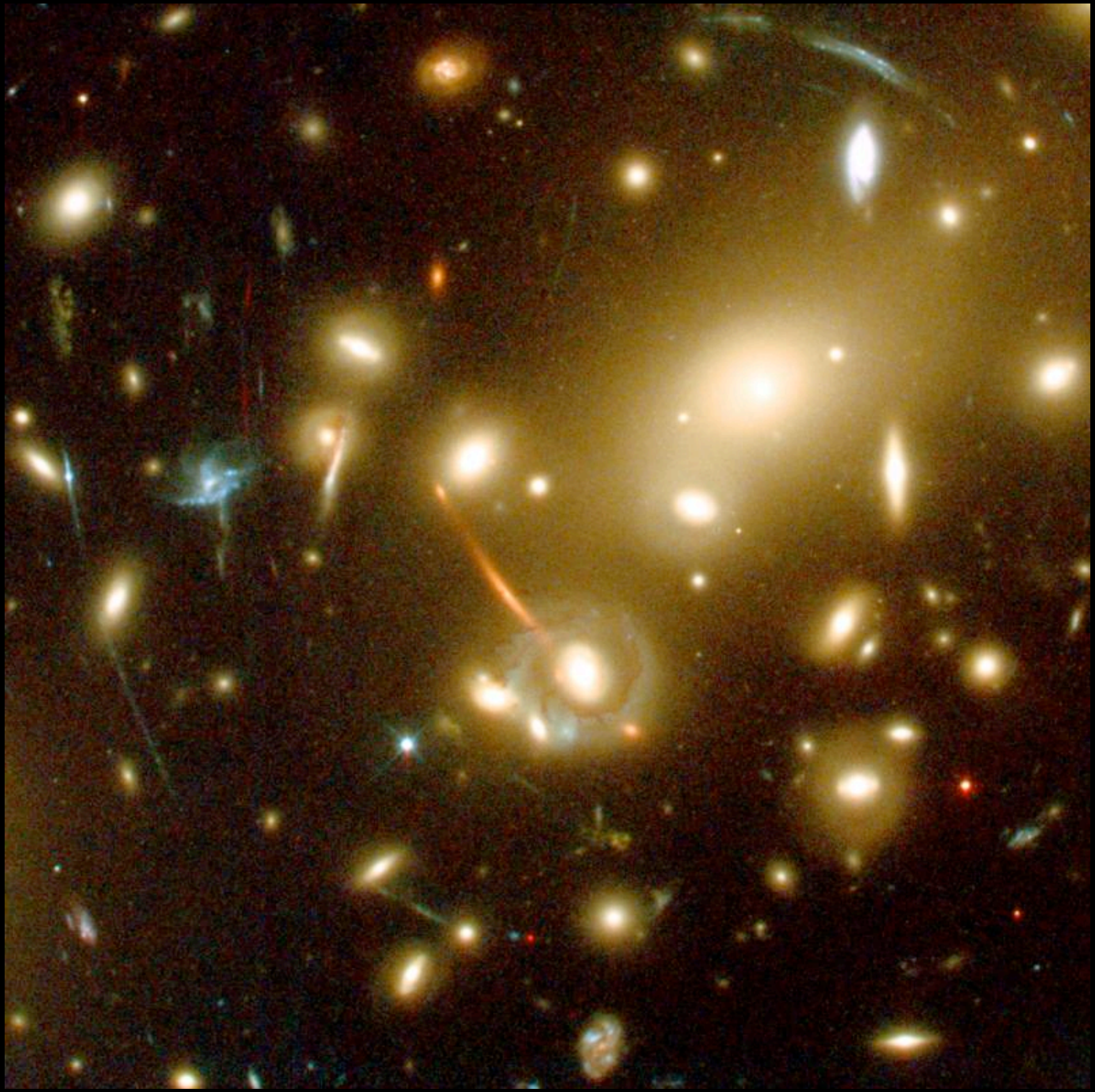
- Some final state interactions are included inside the PDFs

Pictures with final state interactions

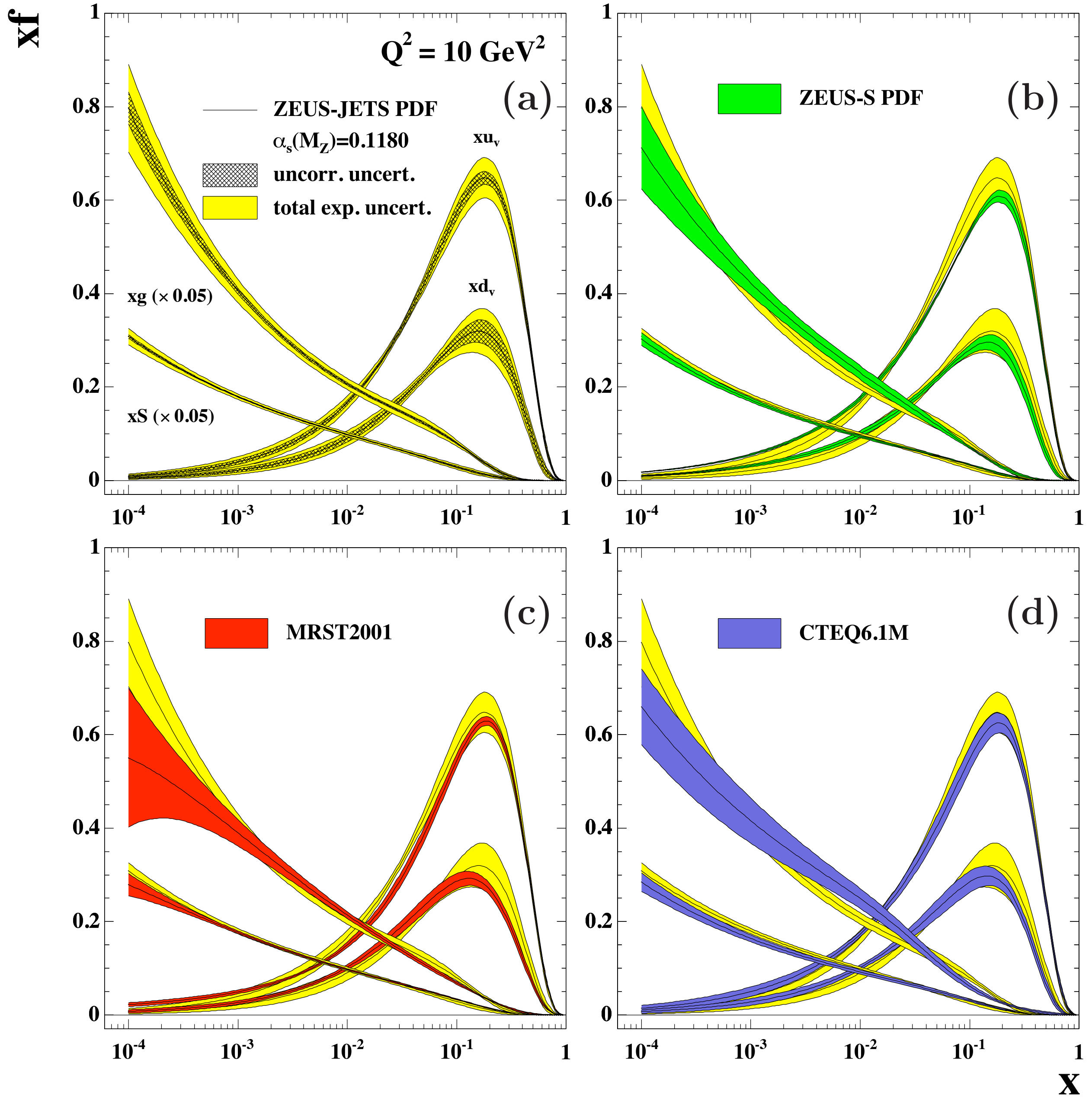


Caveats

- The hard probe “sees” only some components of the partonic fields (good fields), or in an equivalent way PDFs are pictures of partons in a specific frame of reference (infinite momentum frame)
- Some final state interactions are included inside the PDFs
- The intuitive interpretation of the PDFs is not rigorously true. For instance, PDFs depend on the factorization scheme, which is inconsistent with the idea that they are probability densities
- Formally, we can say that PDFs are nonperturbative objects, they give information on the internal structure of the nucleon, they can be defined through factorization theorems, they can be extracted from data and used to make predictions
- Factorization does not overthrow the “parton model” picture, but modifies it, while preserving much of the intuitive framework

PDFs from global fits

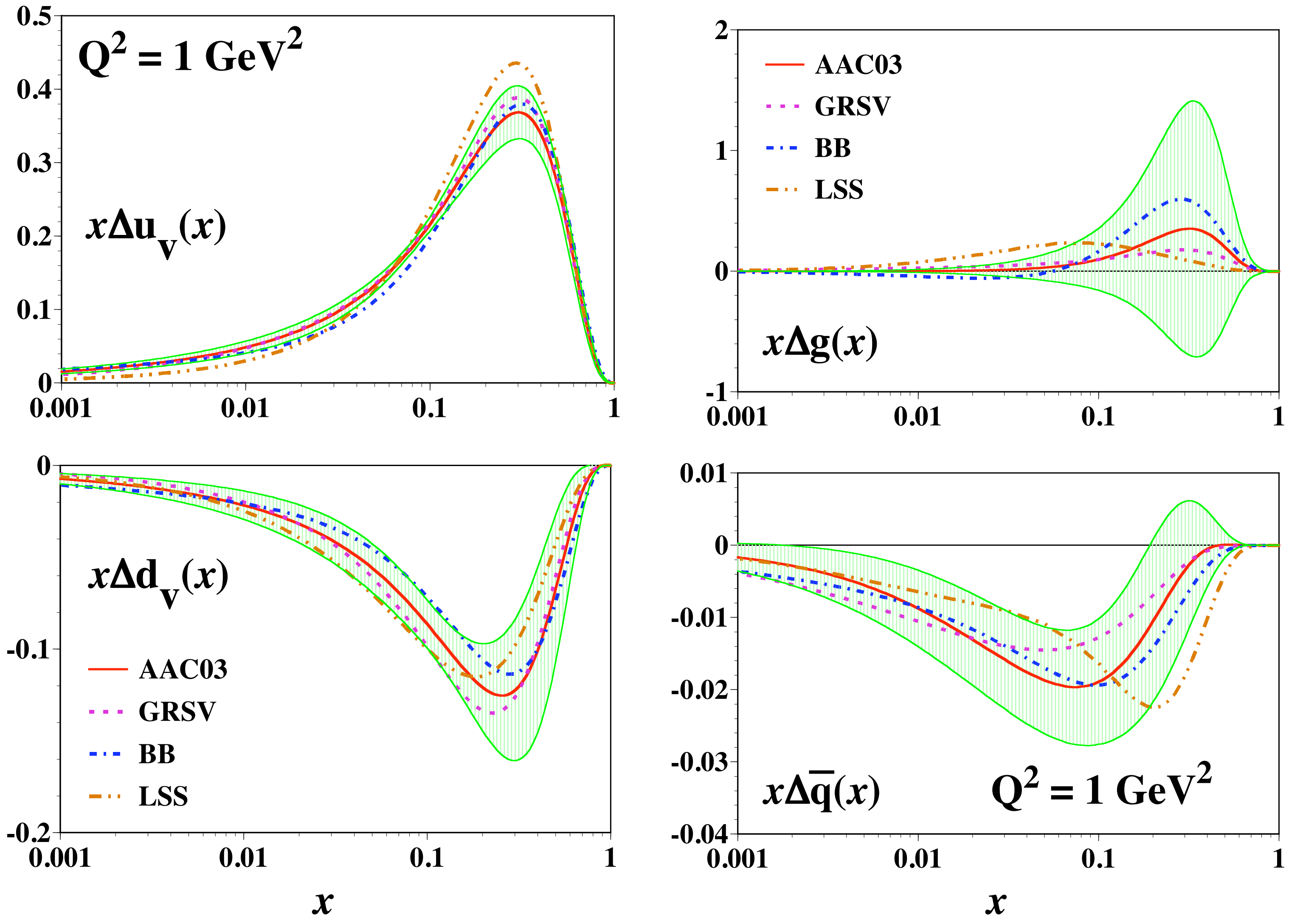
$$xq(x)$$



ZEUS Coll, EPJ C42 (05)

Helicity PDFs from global fits

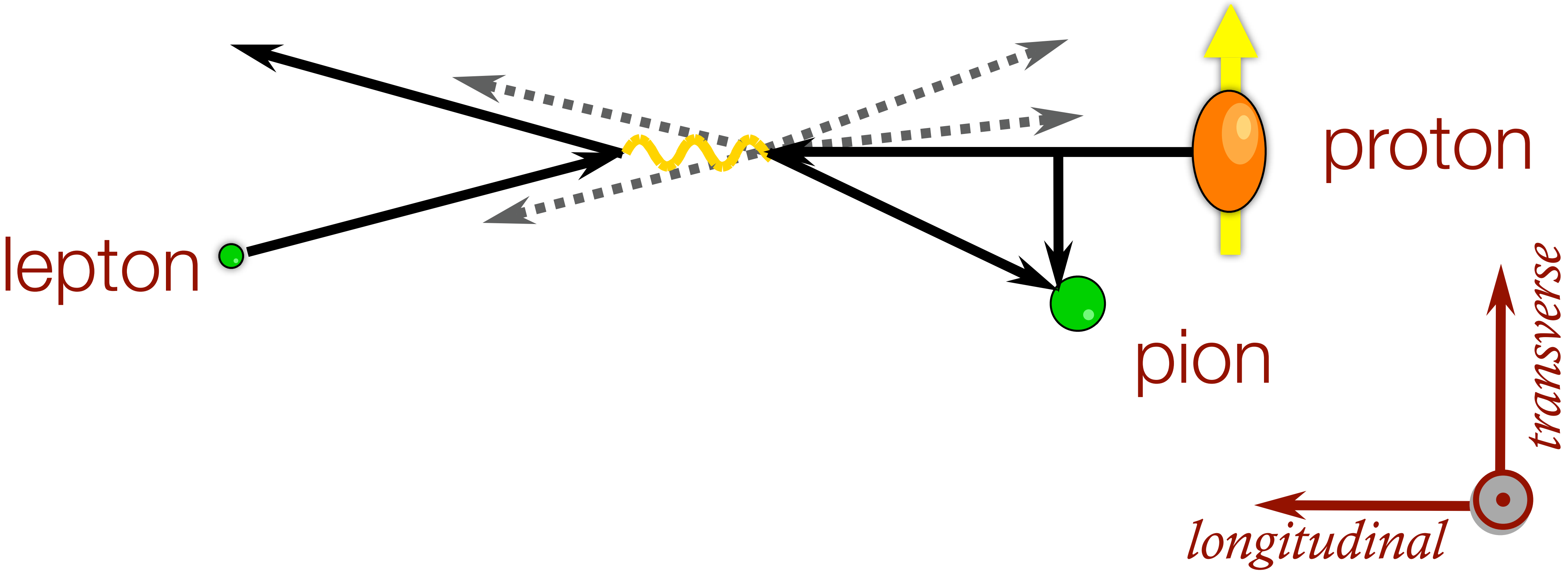
$$x\Delta q(x)$$



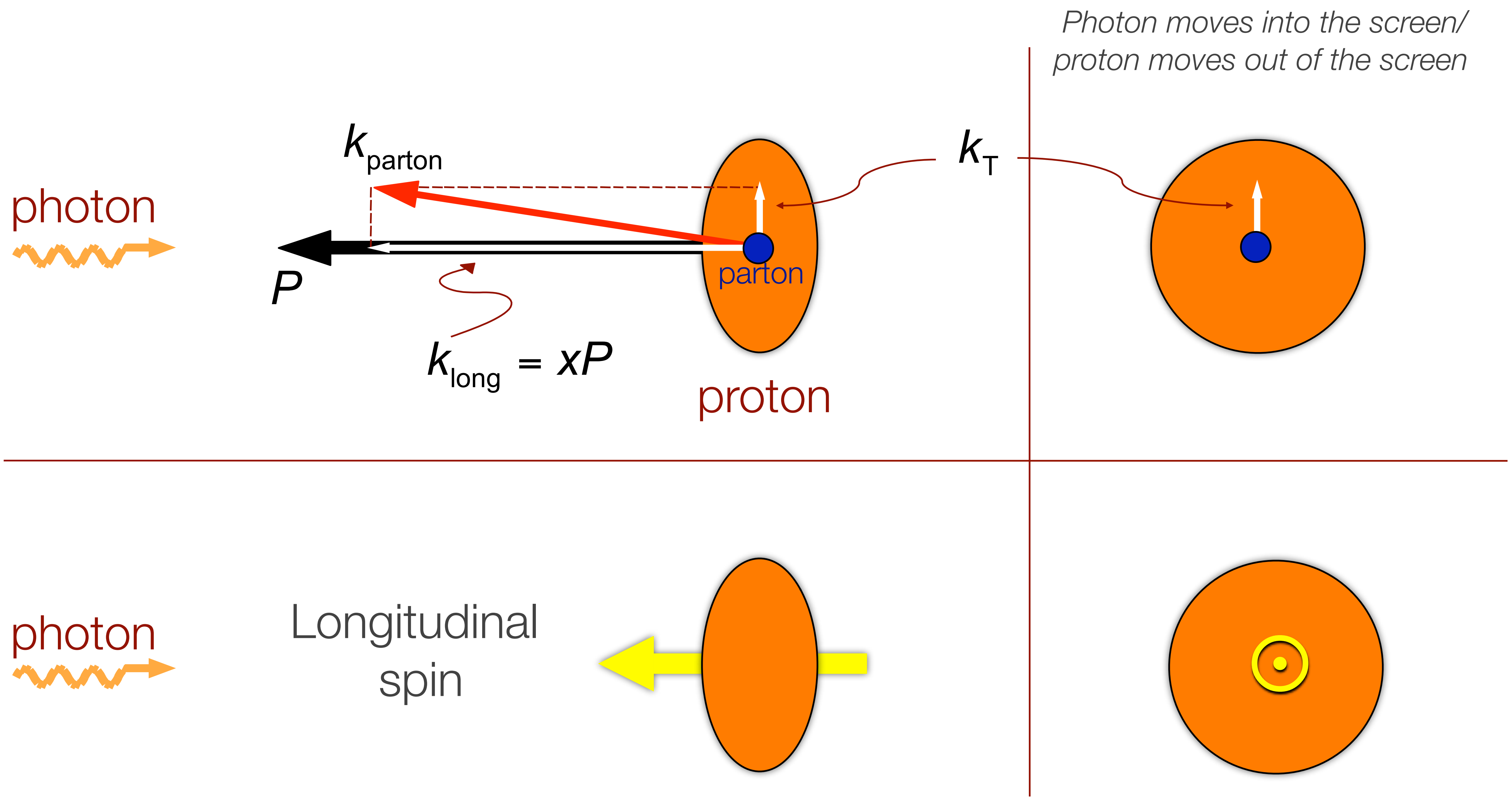
AAC, Hirai et al. PRD69 (04)

Transverse momentum dependent parton distribution functions

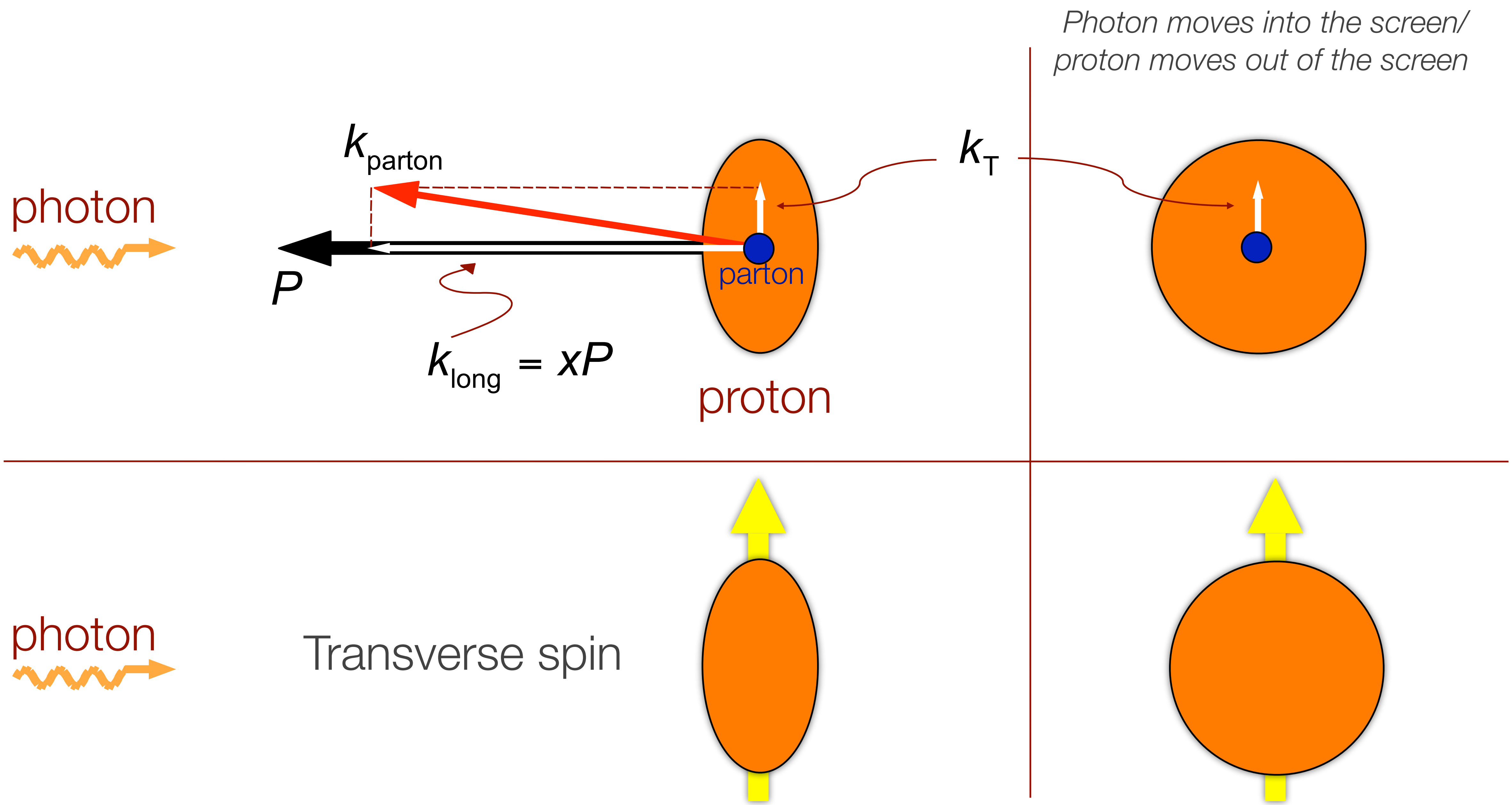
Transverse vs. longitudinal



Transverse vs. longitudinal



Transverse vs. longitudinal



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

photon

k_{parton}

k_T

P

parton

$k_{\text{long}} = xP$

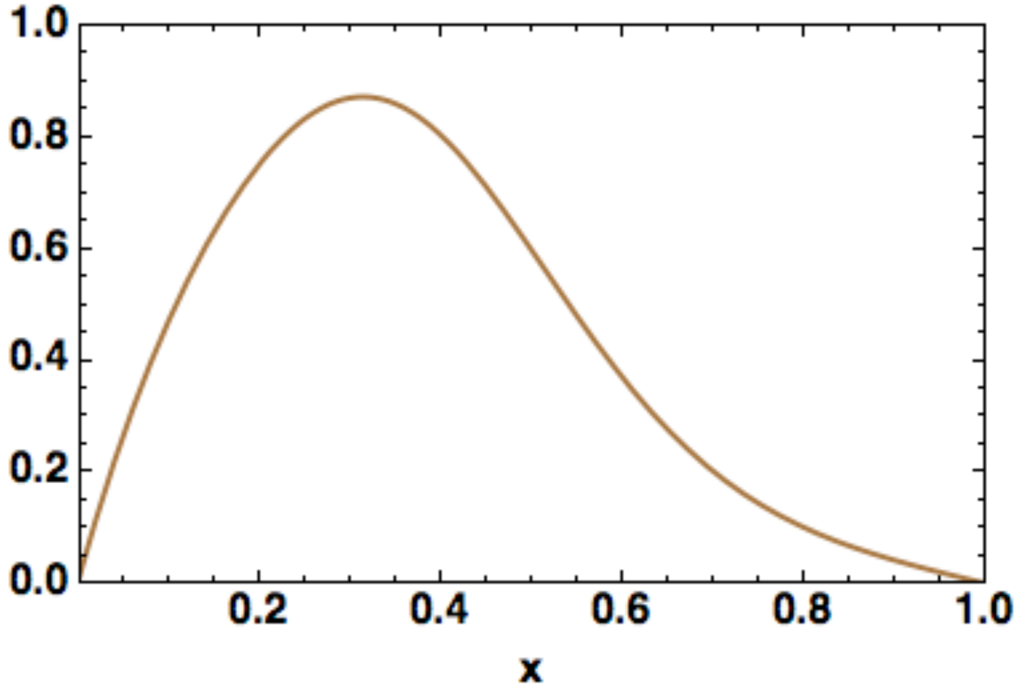
proton

photon

Transverse spin

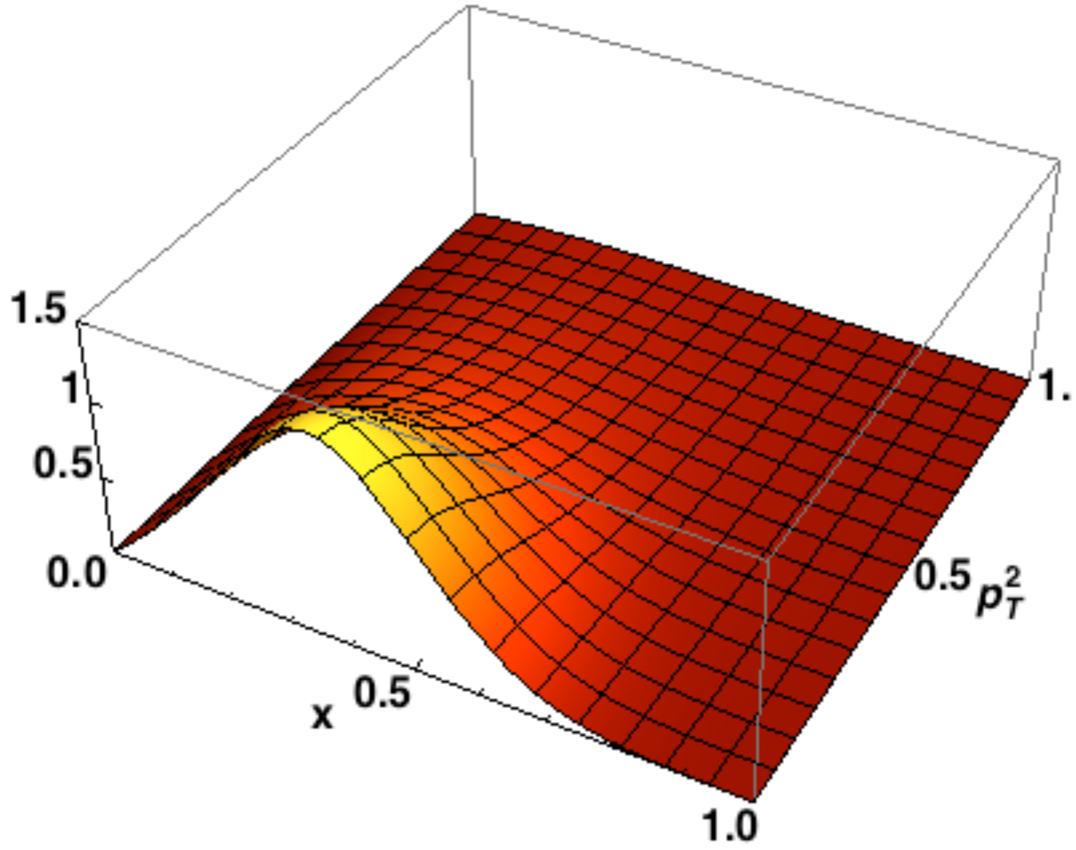
Transverse momentum distributions

$x f_1^u(x)$



Standard collinear PDF

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



TMD

A.B., F. Conti, M. Radici, PRD78 (08)

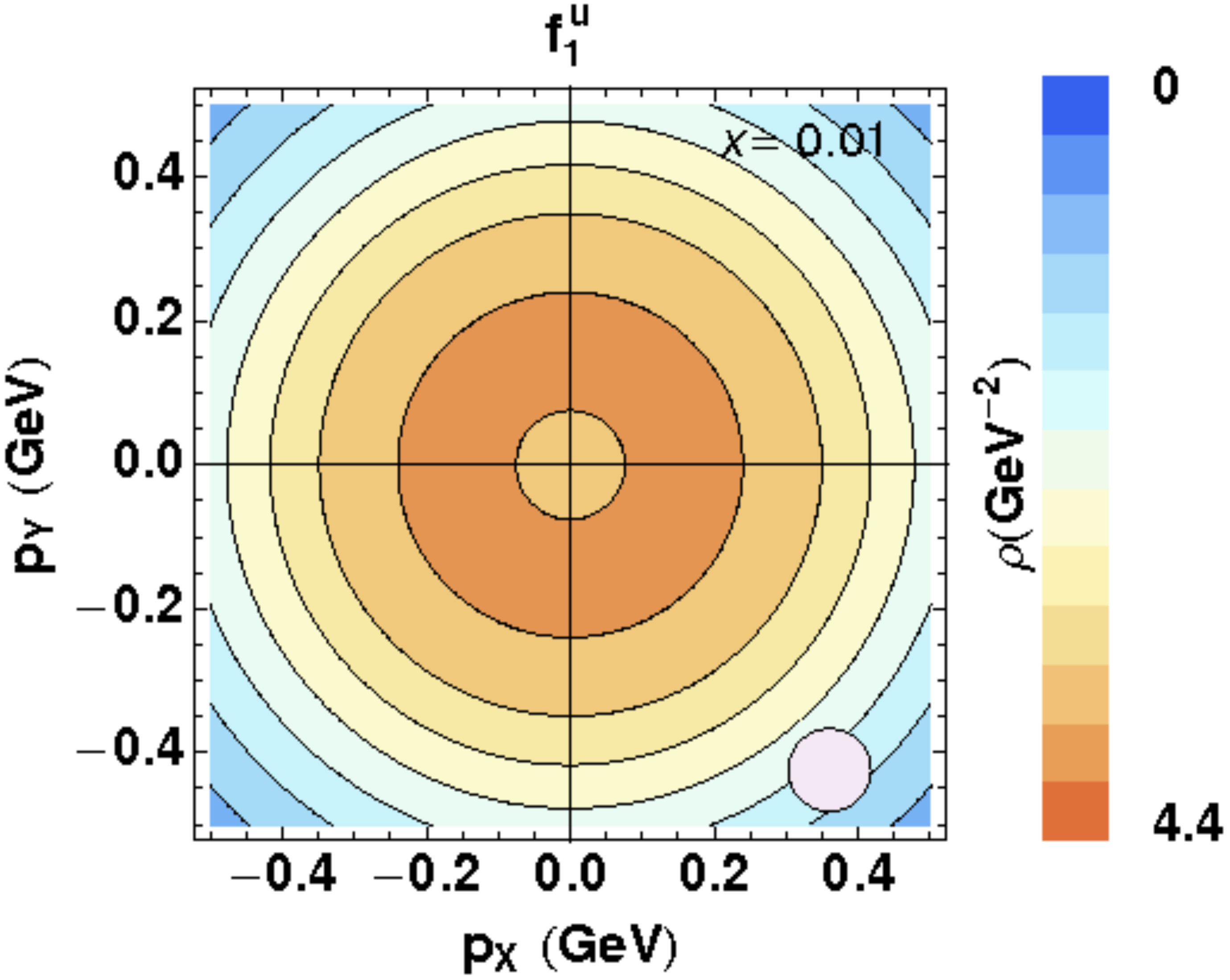
Relation to GPDs

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

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

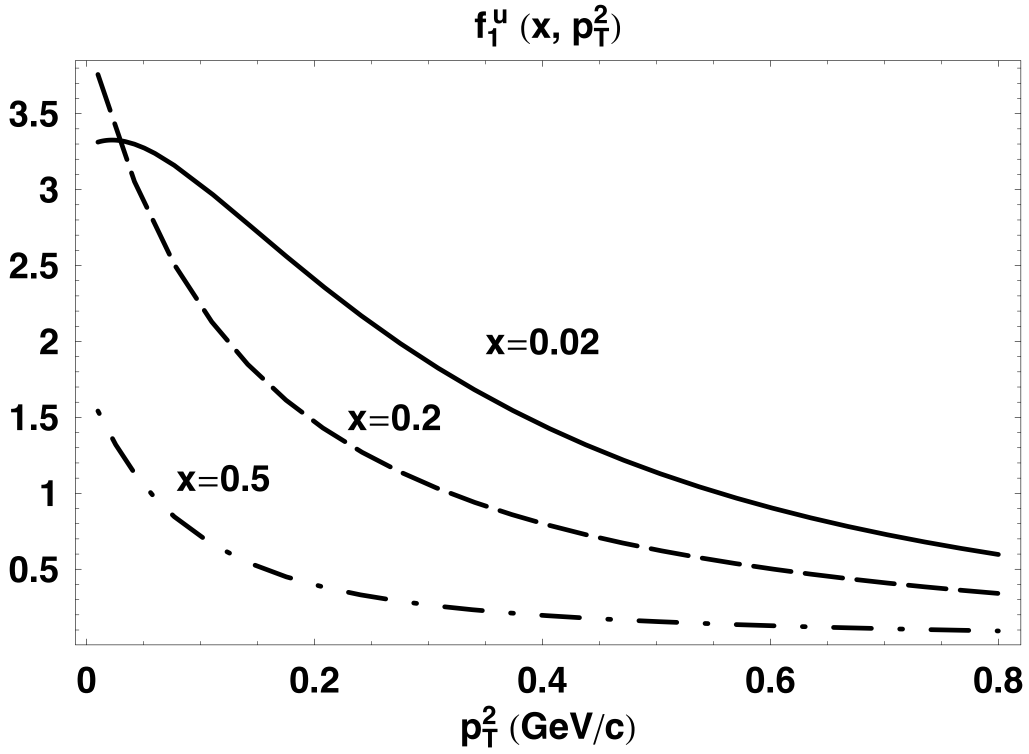
- GPDs in impact parameter space can be interpreted as probability densities in 2 transverse coordinates and 1 longitudinal momentum
- TMDs can be interpreted as probability densities in 3 momentum space
- Similar caveats as standard collinear PDFs

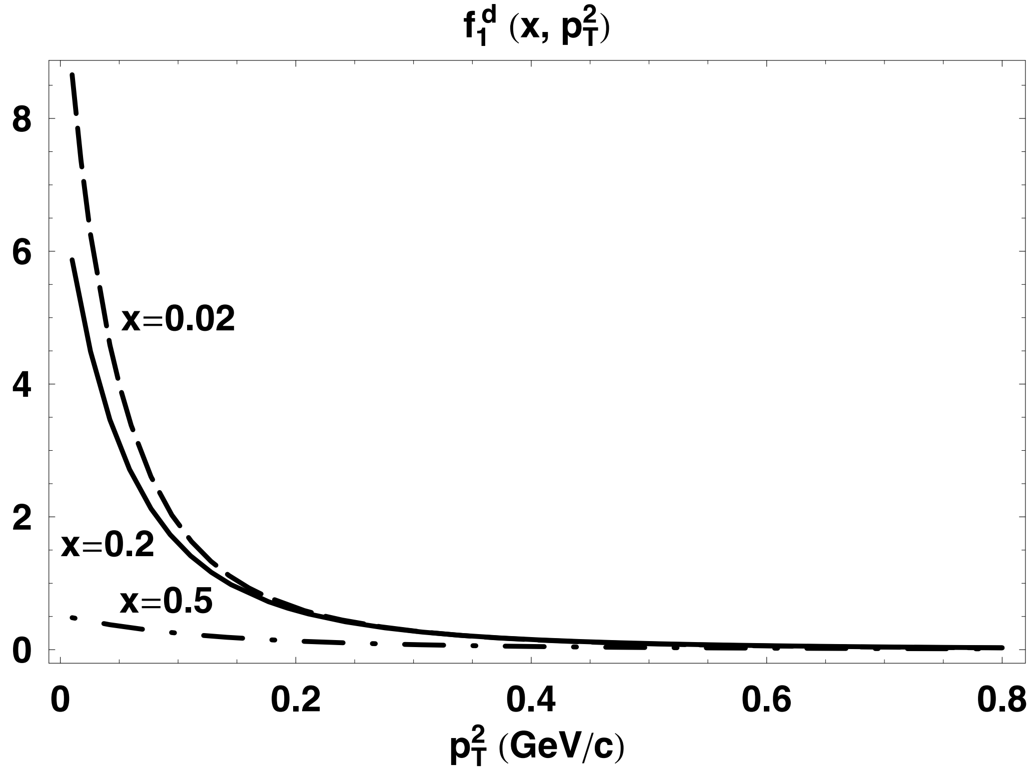
Nucleon tomography in momentum space



A.B., F. Conti, M. Radici, PRD78 (08)

Nontrivial features





A.B., F. C

Simple model calculations suggests

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

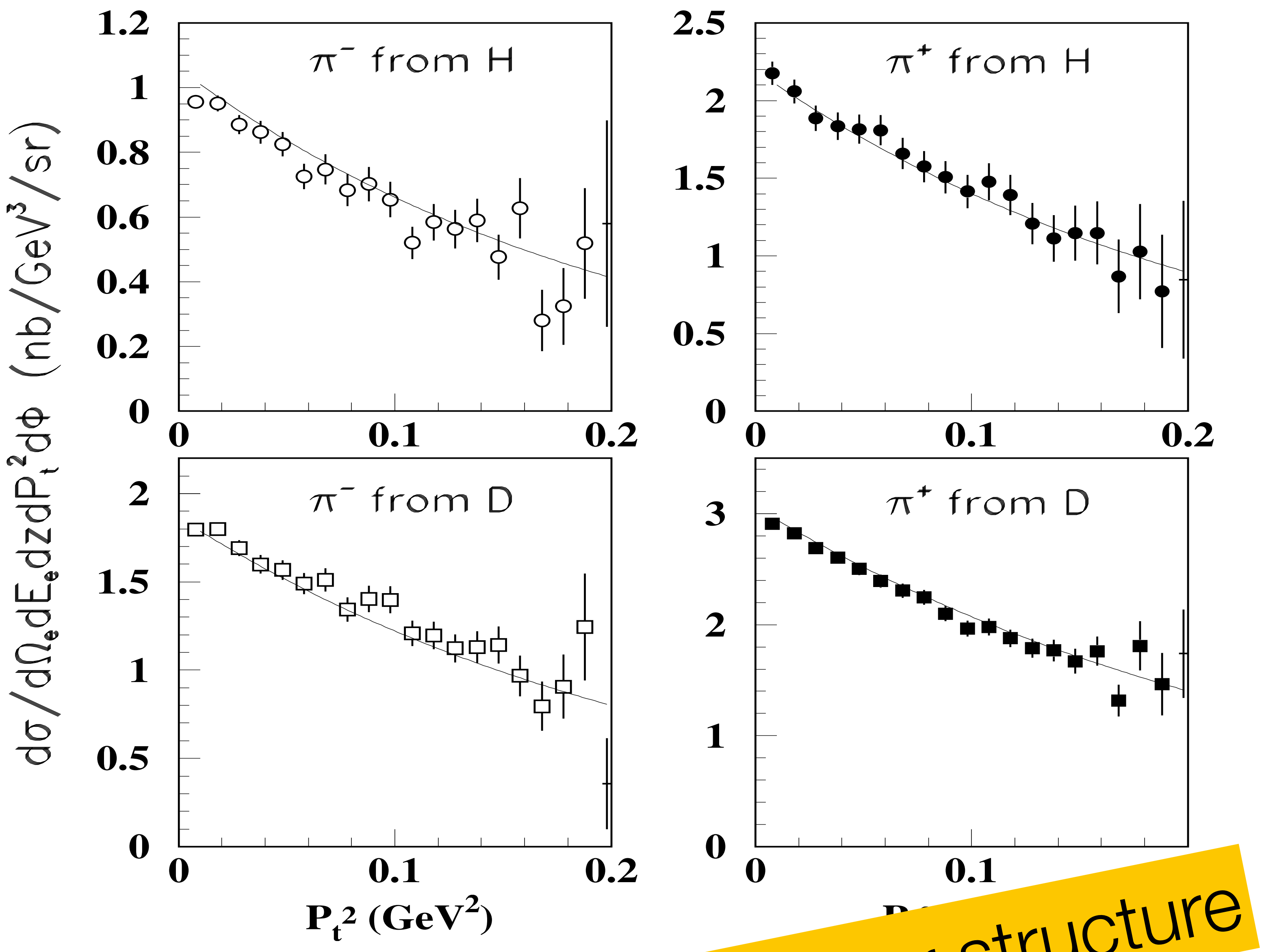
Fundamental information on the nucleon structure
almost as important as standard collinear PDFs

Phenomenological 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., PLB 665 (08)

SIDIS data with hadron identification

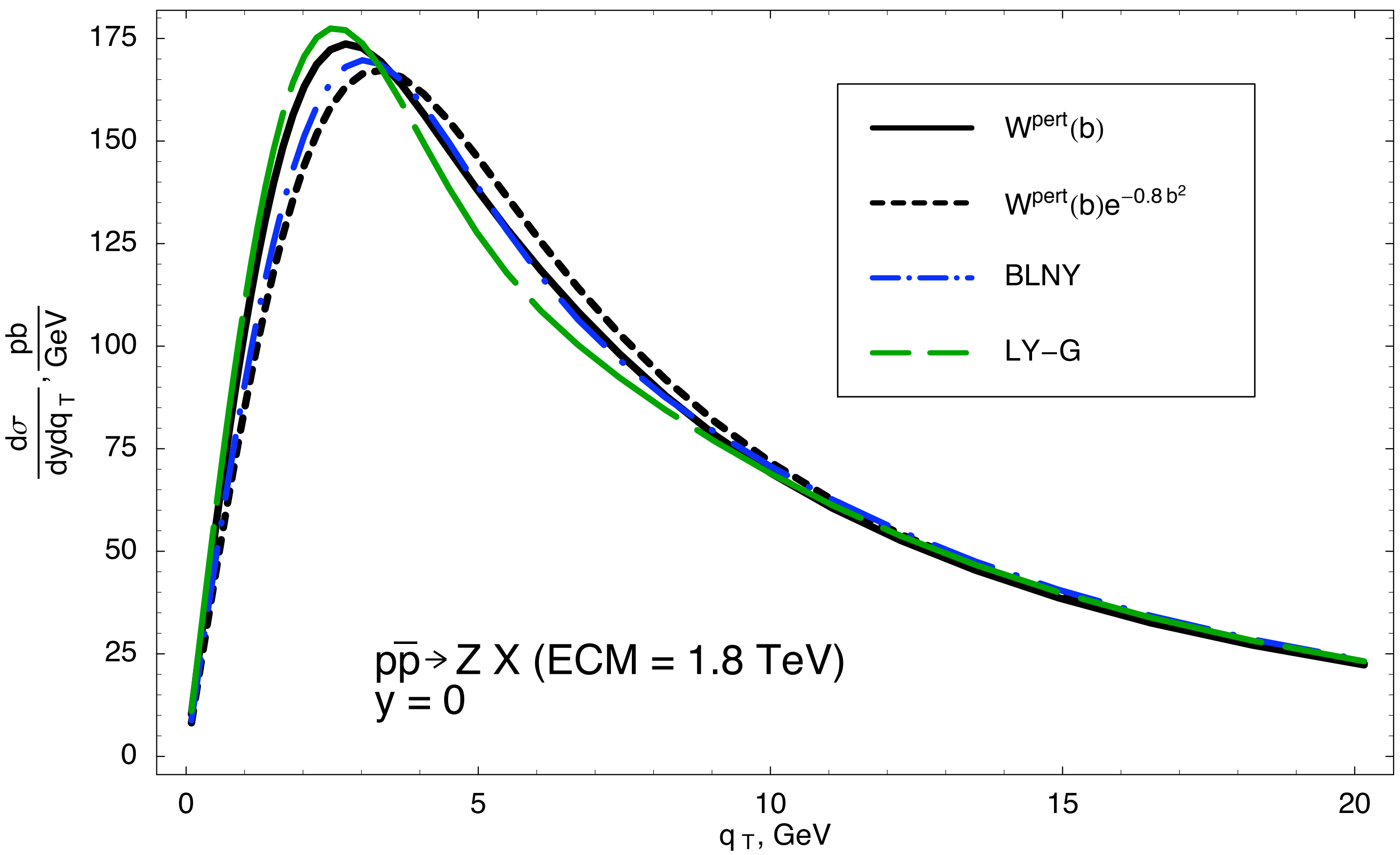


Essential to study flavor structure

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

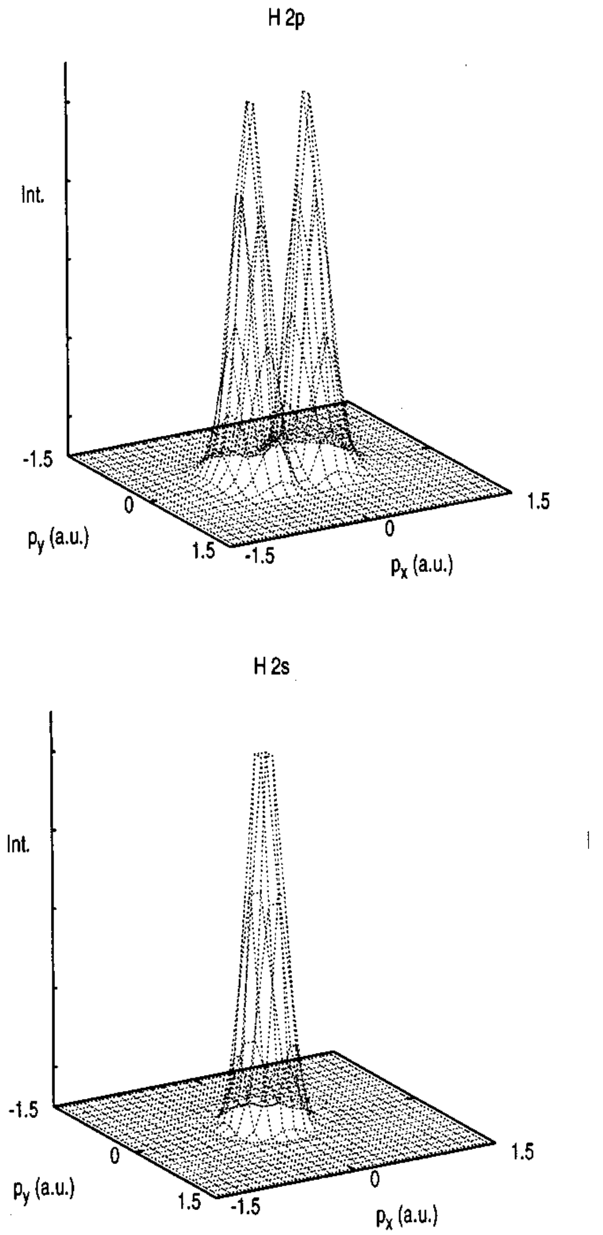
Impact on high-energy physics

P. Nadolsky, hep-ph/0412146



Orbital angular momentum

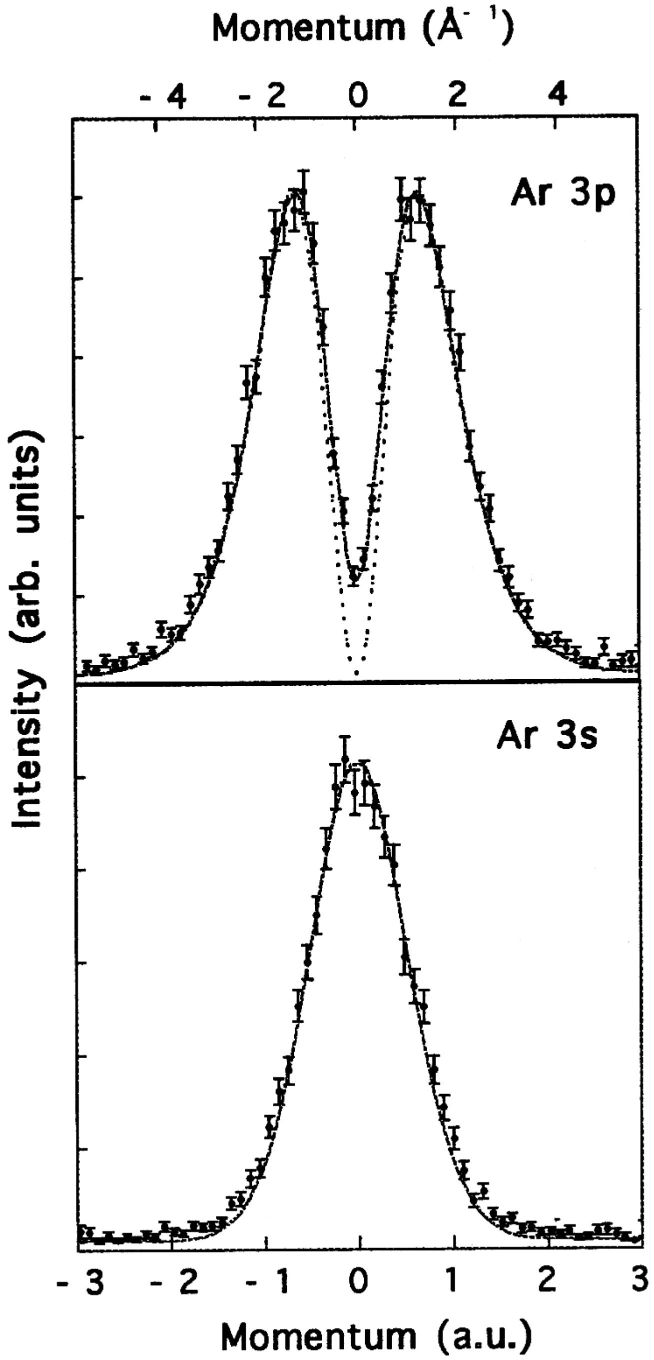
Hydrogen atom wavefunctions
in momentum space



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

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

Orbital angular momentum



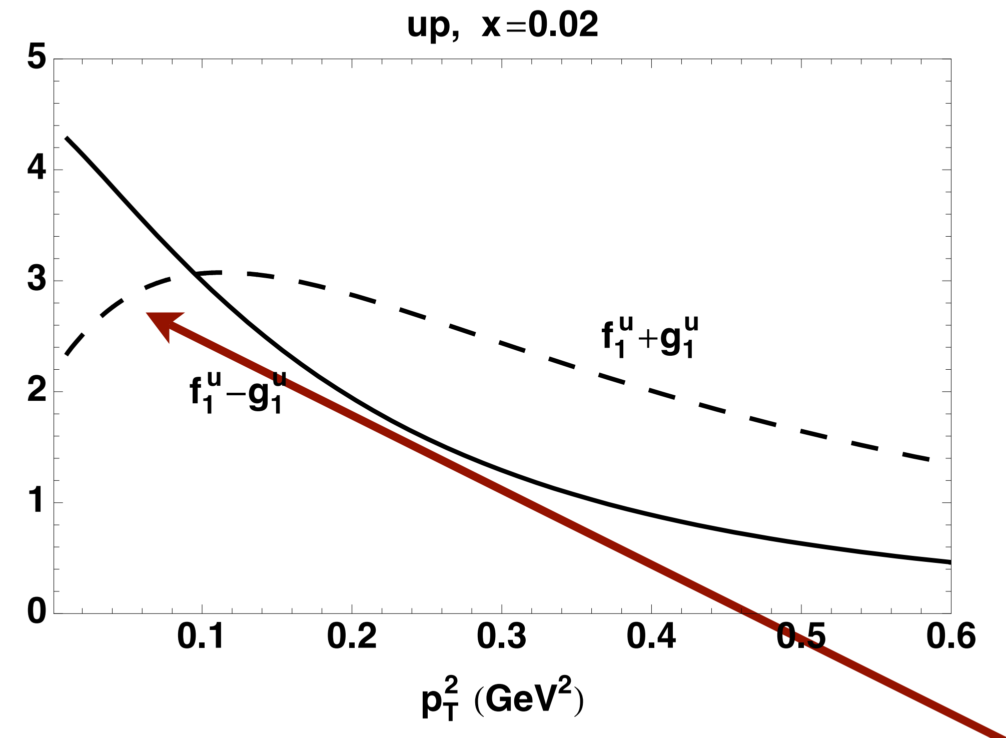
Vos, McCarthy, Am. J. Phys. 65 (97), 544

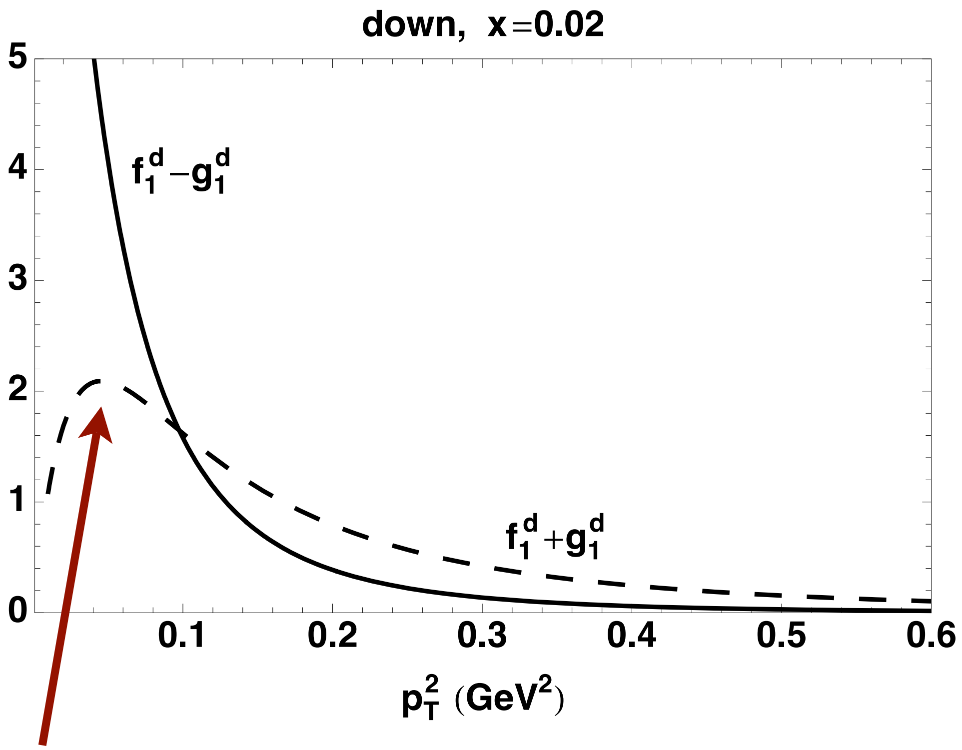
- In atomic physics, wavefunctions with orbital angular momentum have distinct shapes
- The most direct visualization of these shapes is provided by scattering experiments and is in momentum space

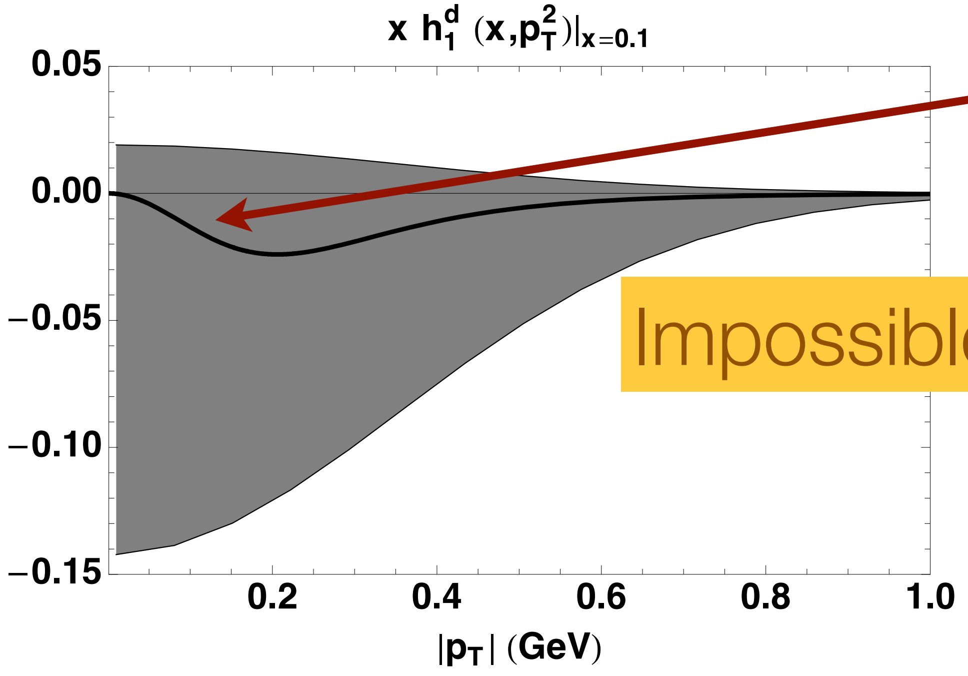
$$f_1(x, p_T^2) = |\psi_{s-\mathrm{wave}}|^2 + |\psi_{p-\mathrm{wave}}|^2 + \ldots$$

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

TMDs and orbital angular mom.





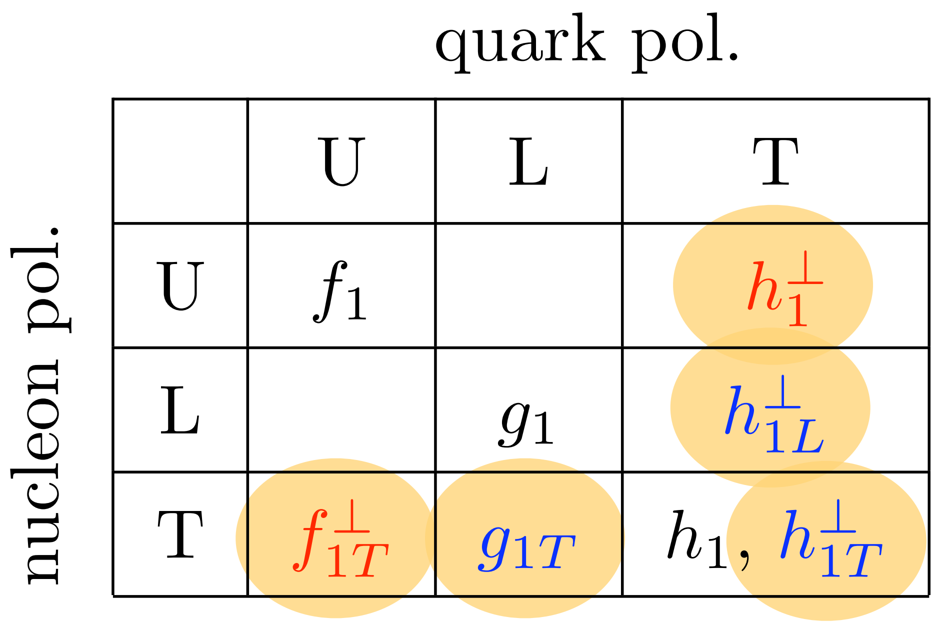


Signs of orbital ang. mom.

Impossible to reproduce using simple Gaussians

A.B., F. Conti, M. Radici, PRD78 (08)

TMDs and orbital angular momentum



quark pol.

nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Twist-2 TMDs

- All colored TMDs vanish if there is no quark orbital angular momentum
- Any quantitative statement about the total orbital angular momentum is model-dependent

Main messages

- 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