Transversity and Transverse-momentum distributions

Alessandro Bacchetta

Jefferson Lab
N. Isgur Fellowship

Some goals of hadronic physics

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- Understand CONFINEMENT

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- Study the STRUCTURE of the proton, e.g.,
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  - Spin
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TMDs and transversity are relevant for all of these issues

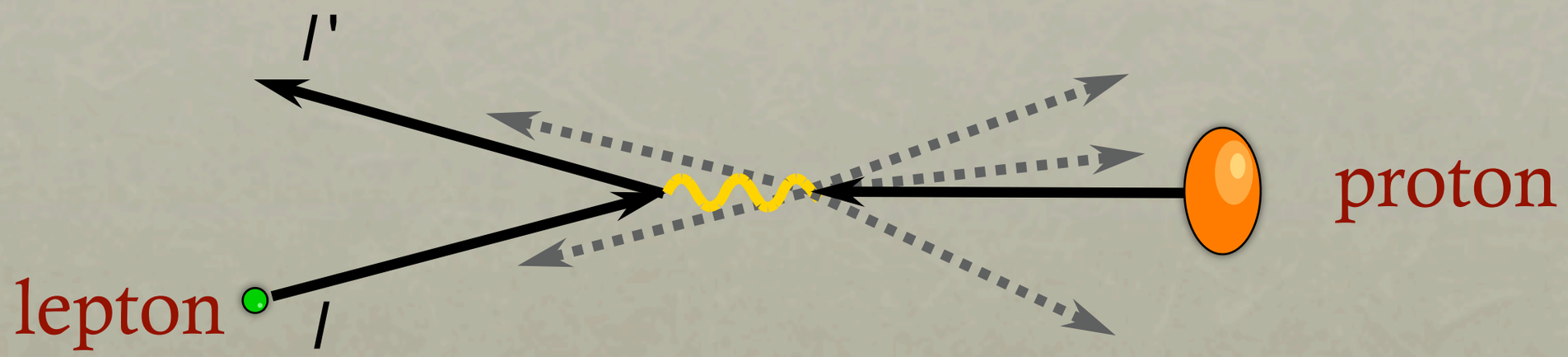
Parton distribution functions

essentials

Deep inelastic scattering (DIS)

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

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



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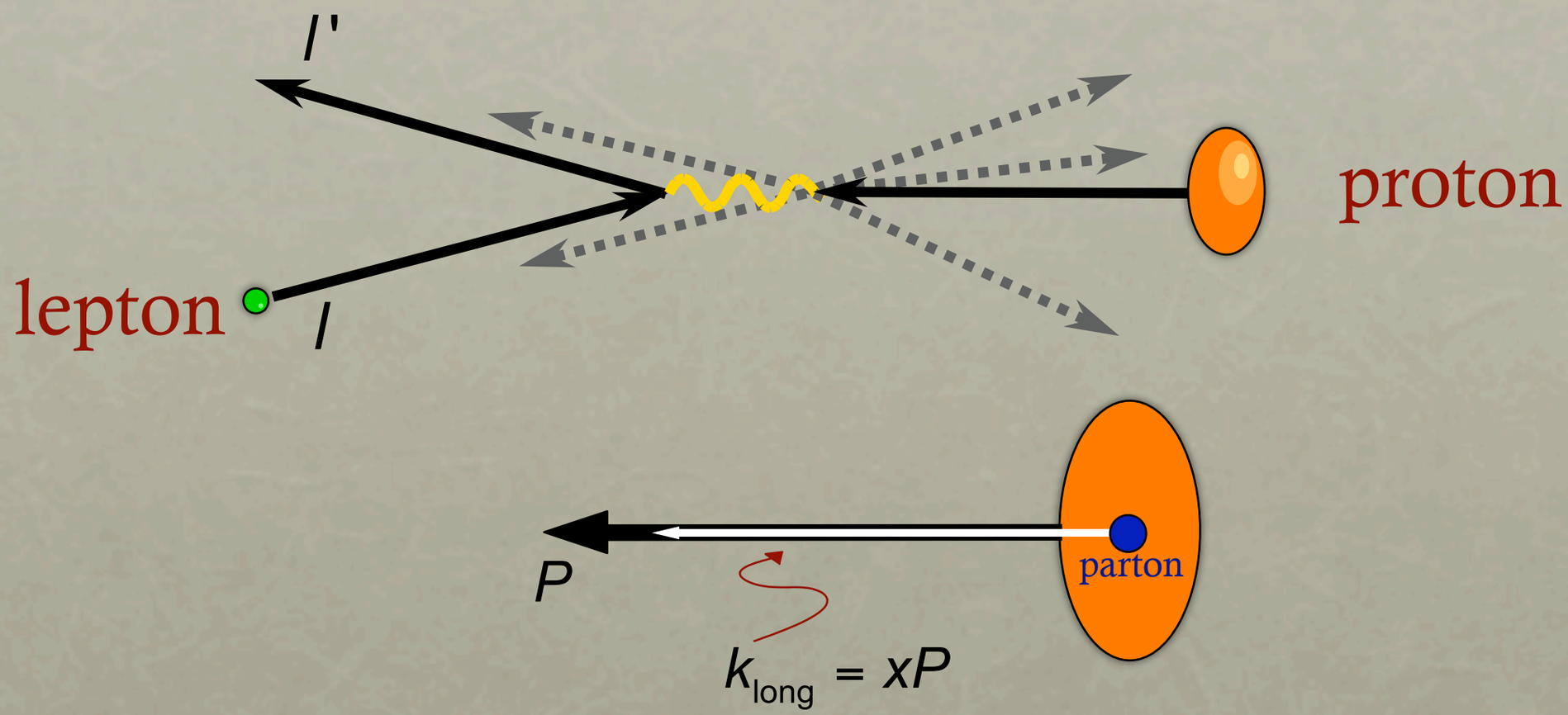

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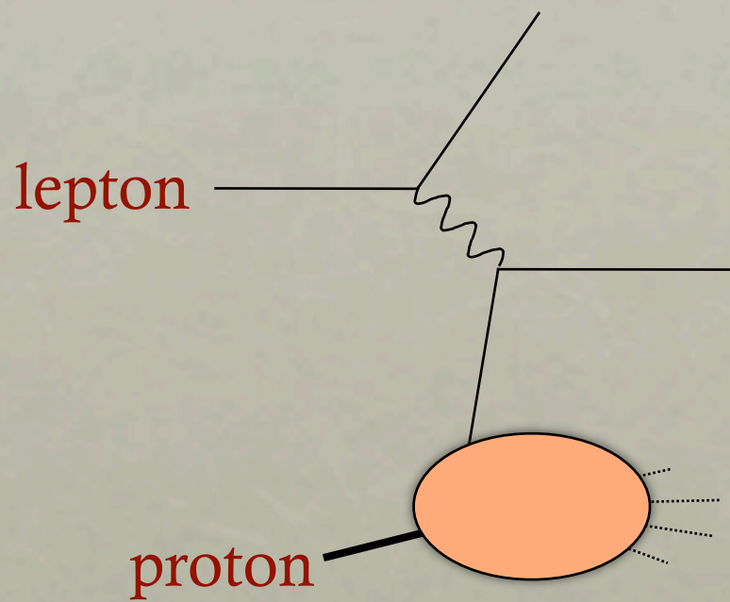

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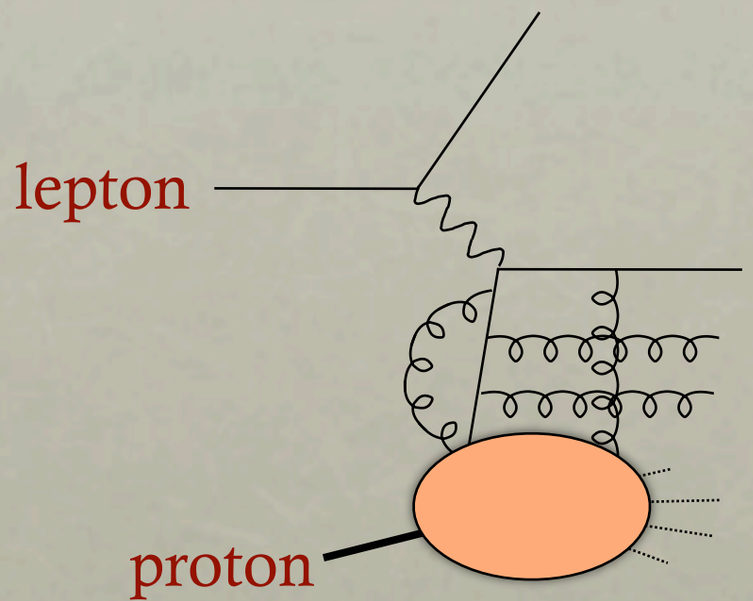

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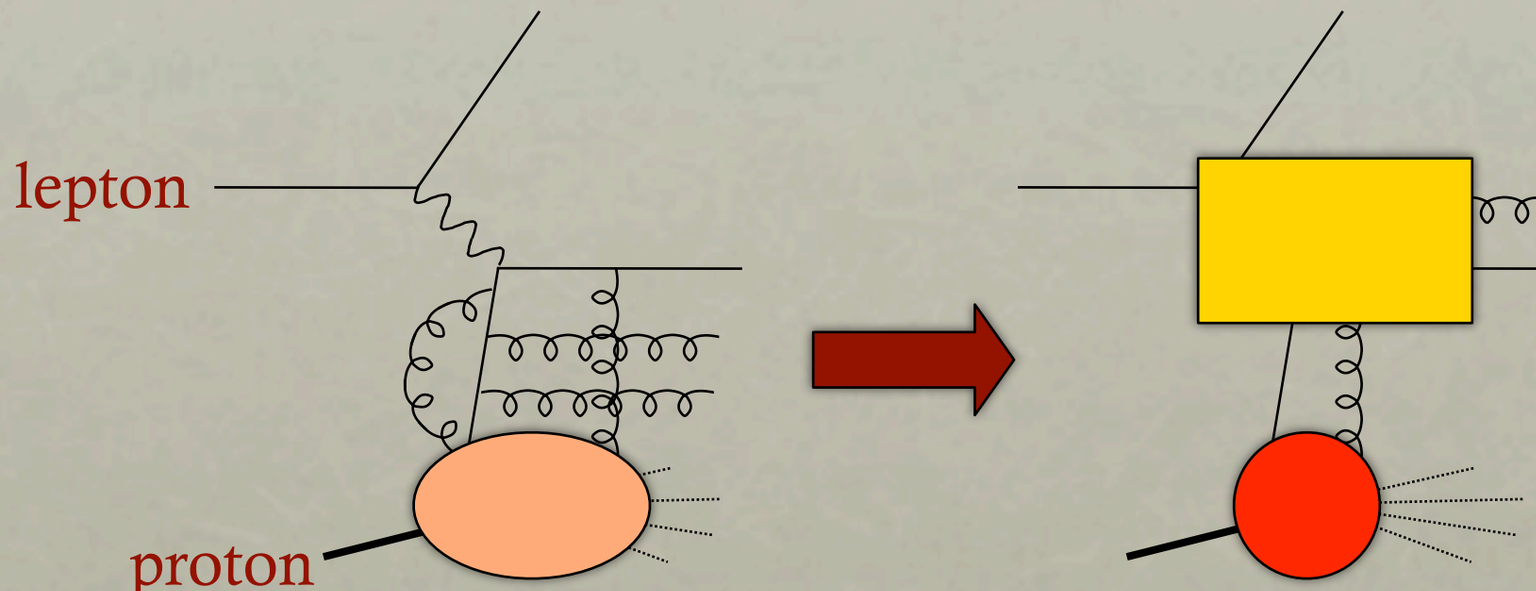

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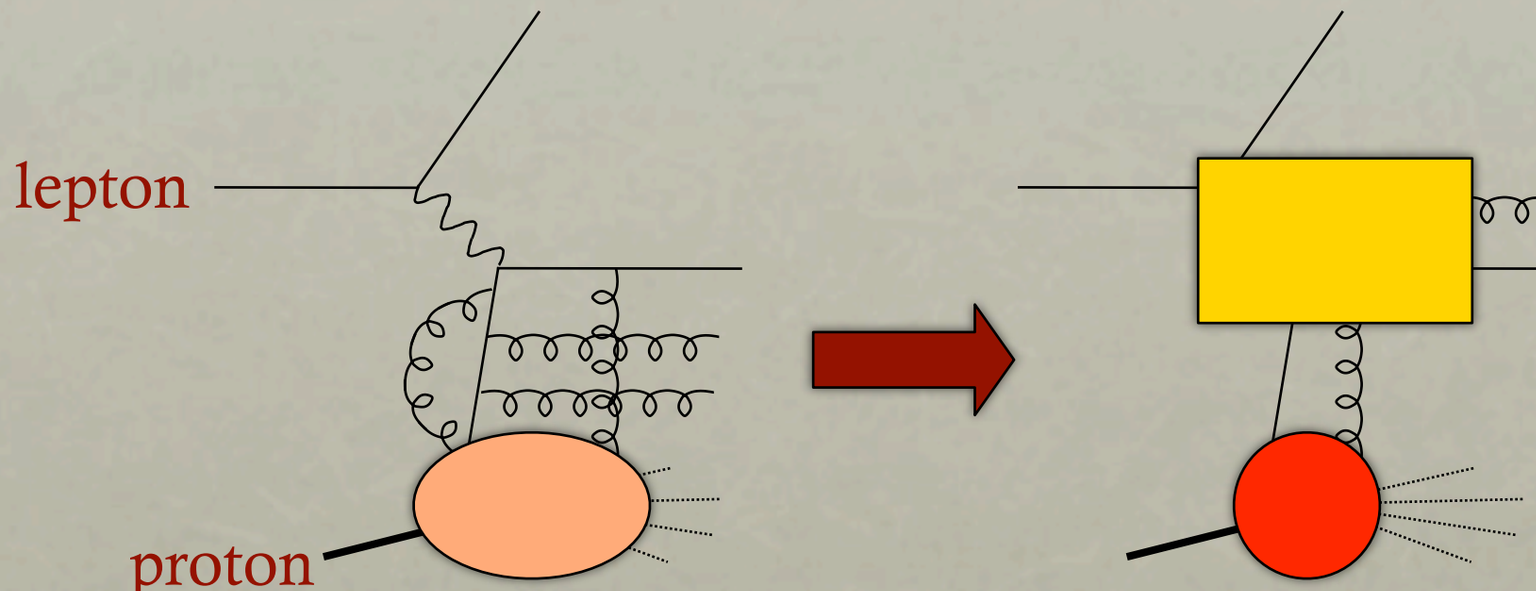
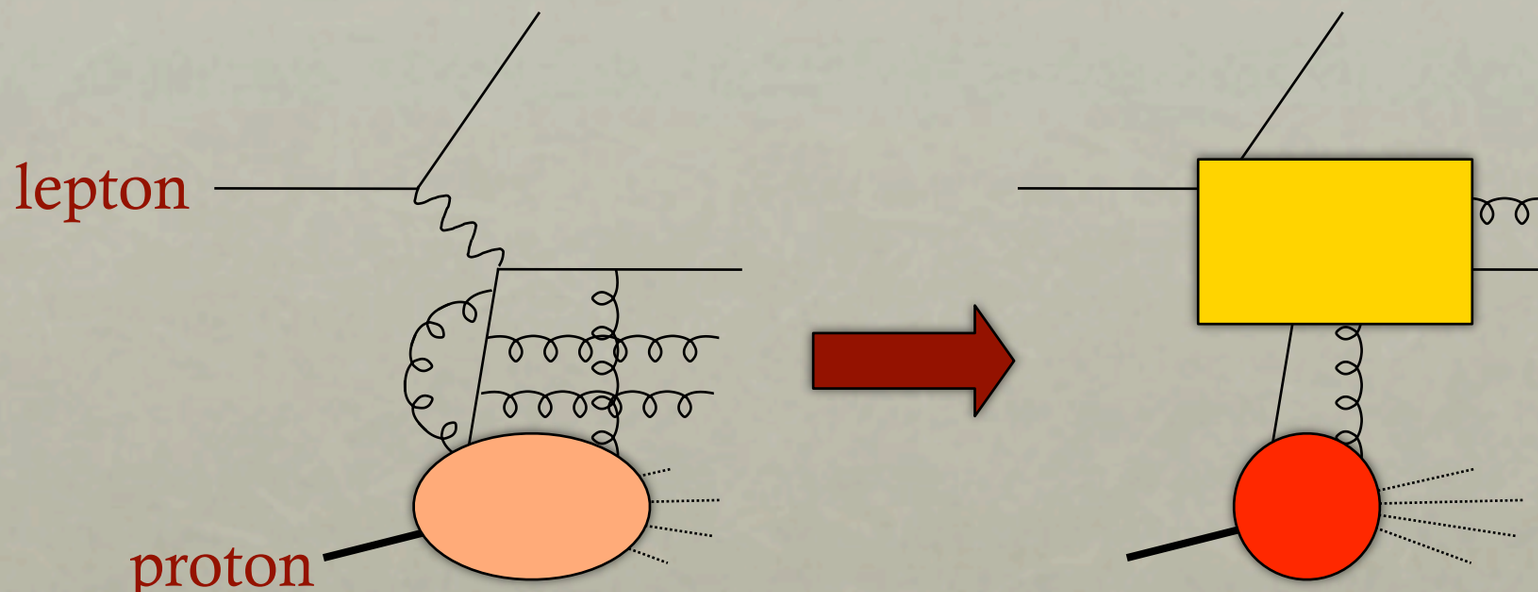


Partonic scattering amplitude

Distribution amplitude

Factorization



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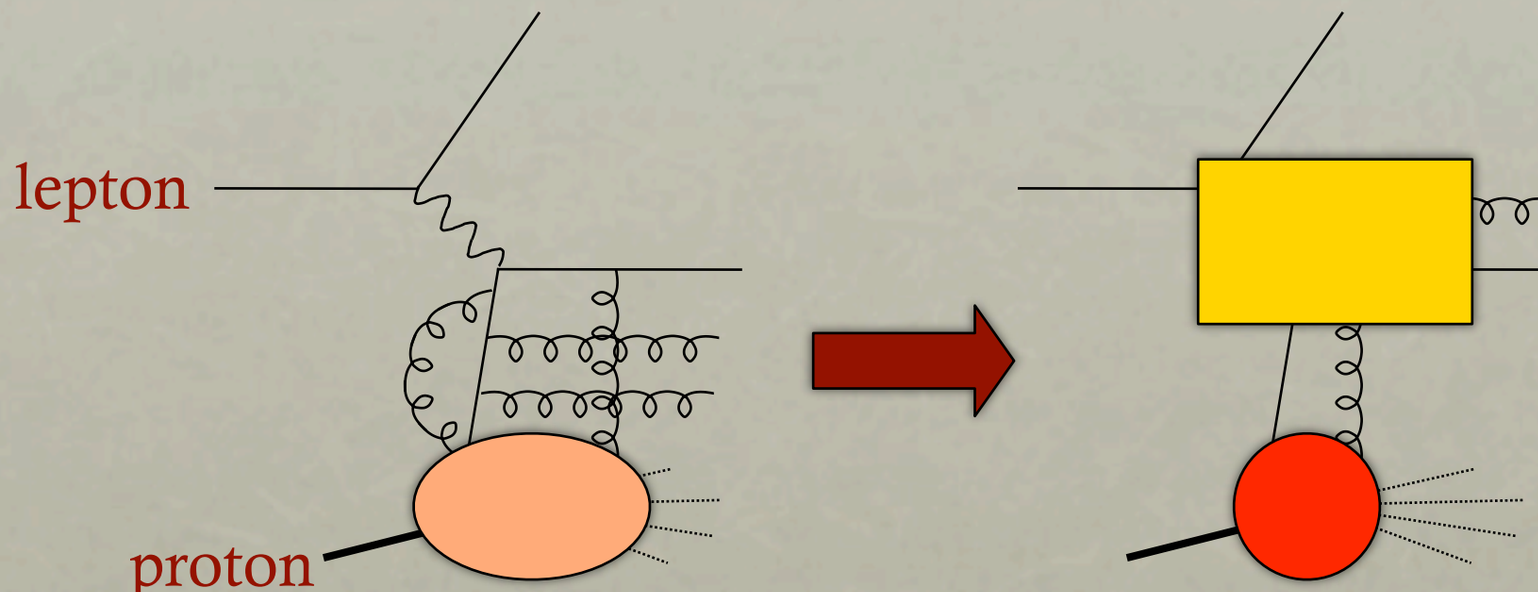
Distribution amplitude

$$d\sigma = H \otimes f$$

Factorization



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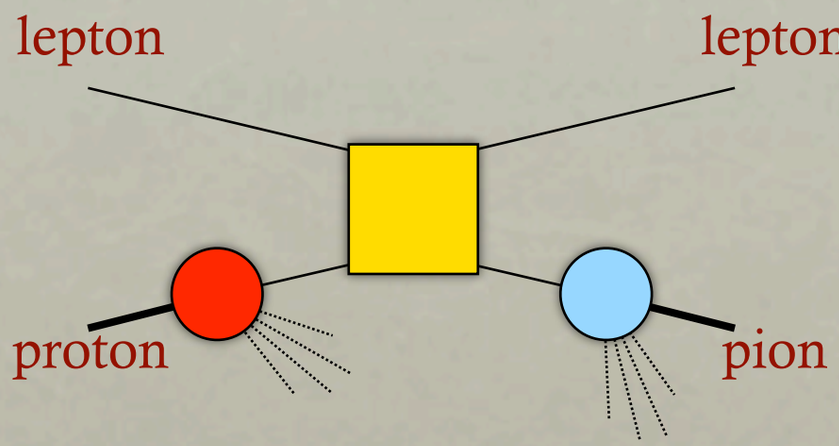
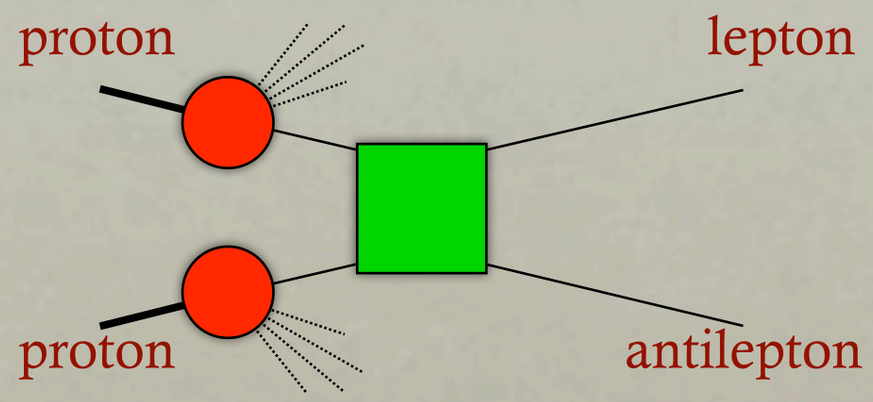
Key result of QCD

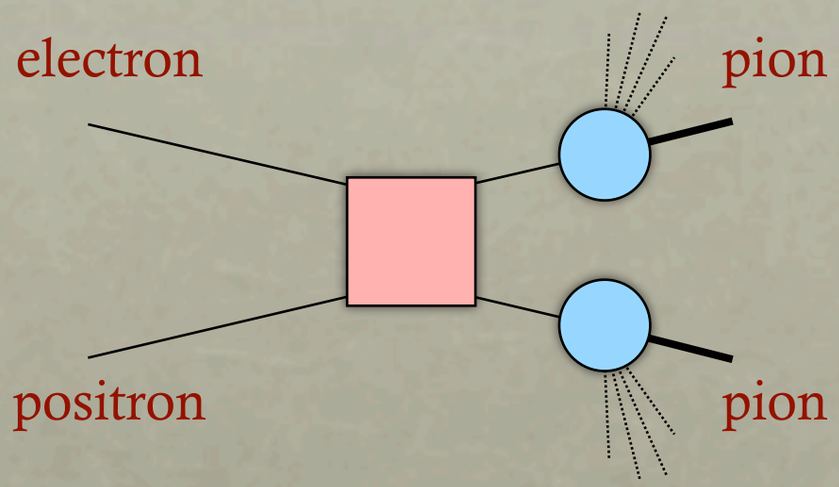
Universality



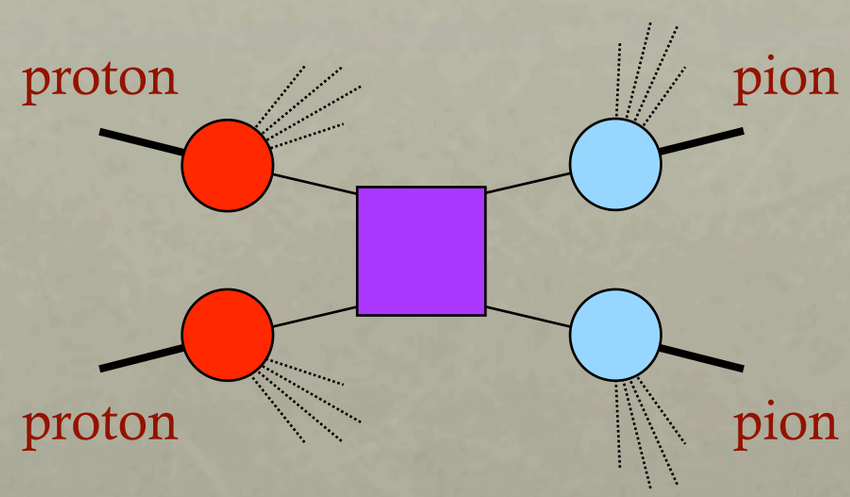
SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions



p-p to pions

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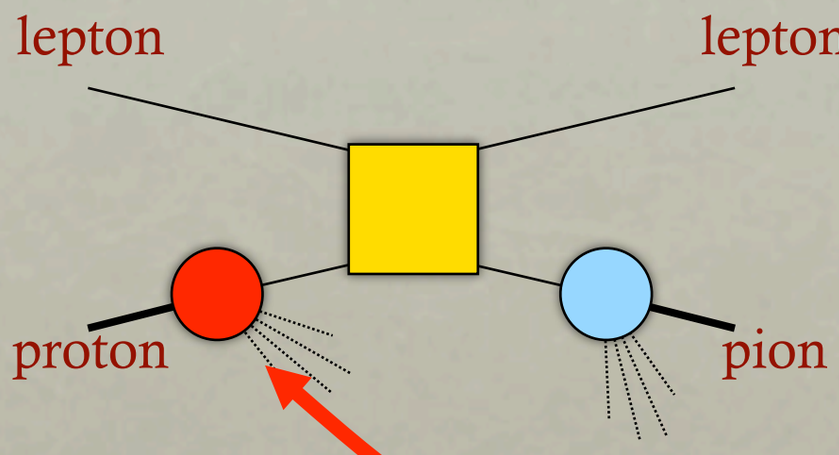

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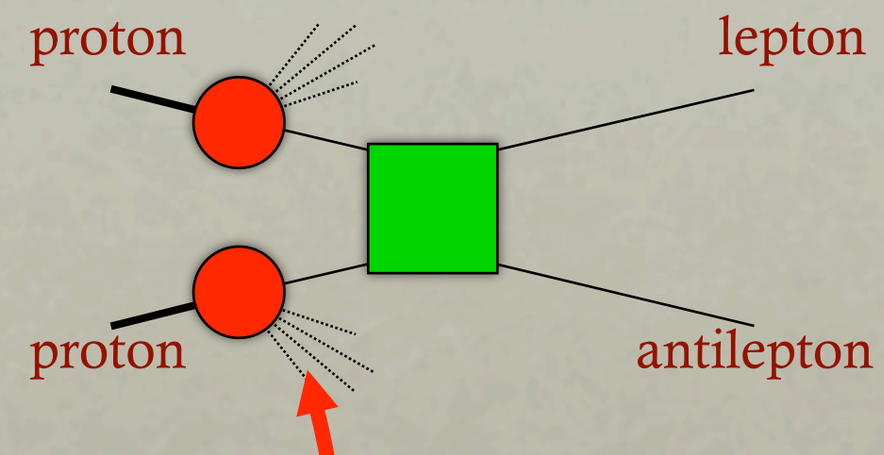

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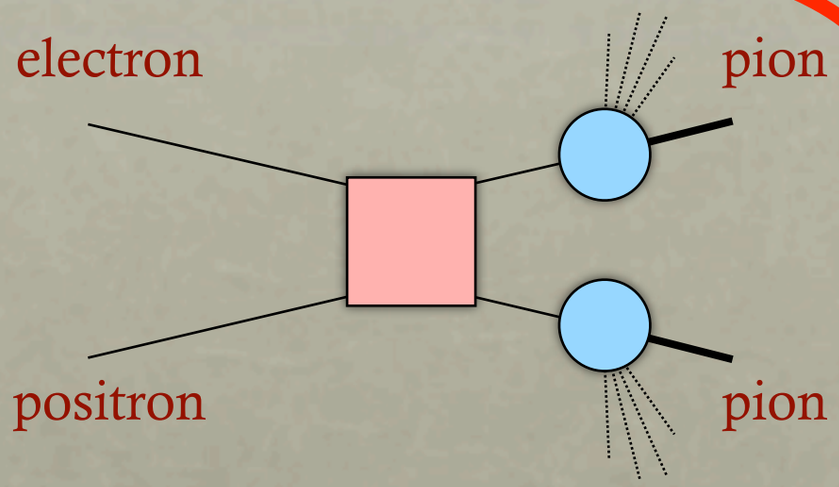

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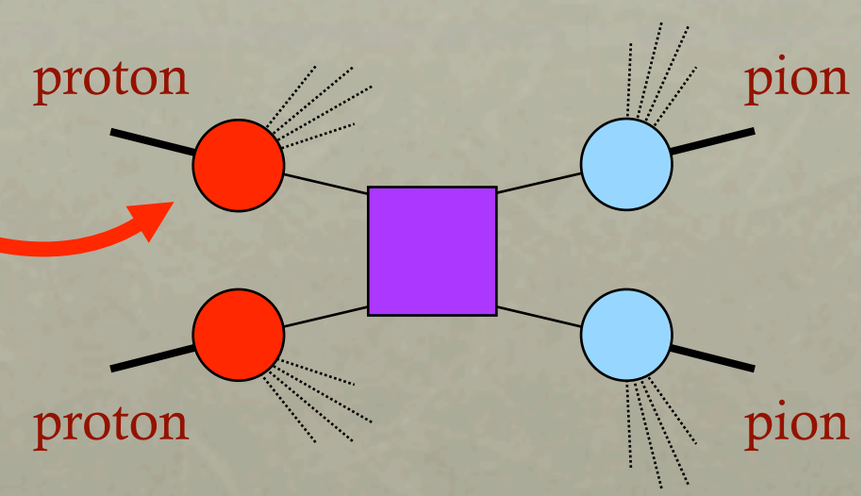

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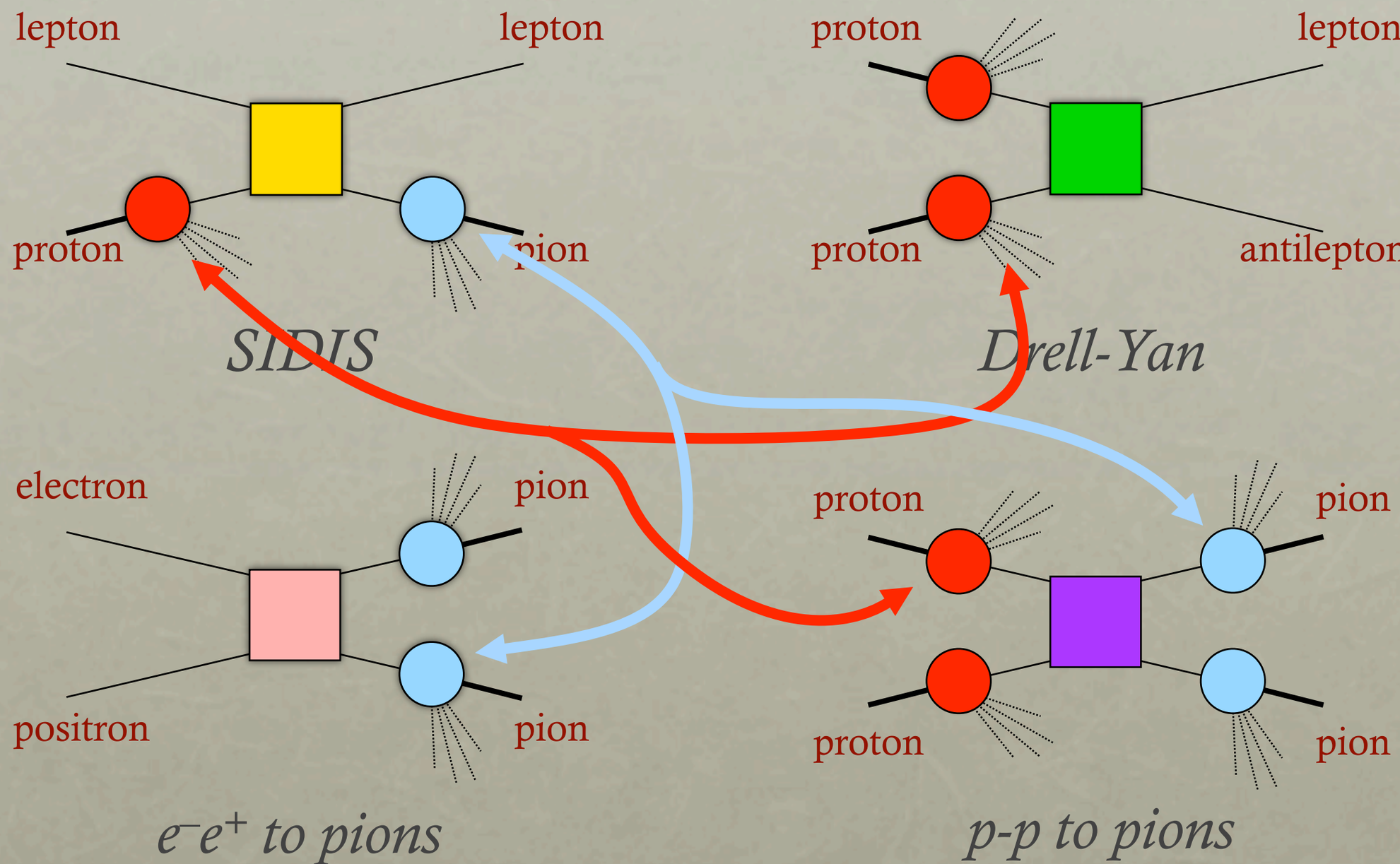

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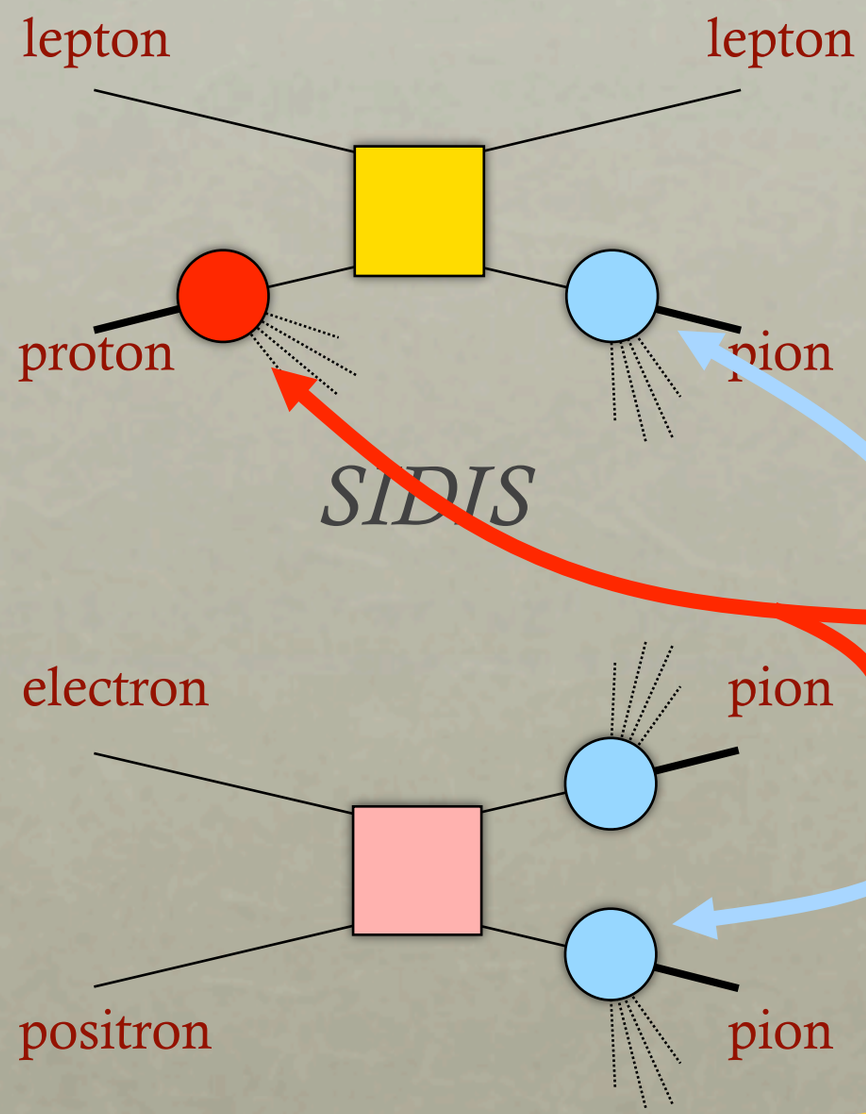
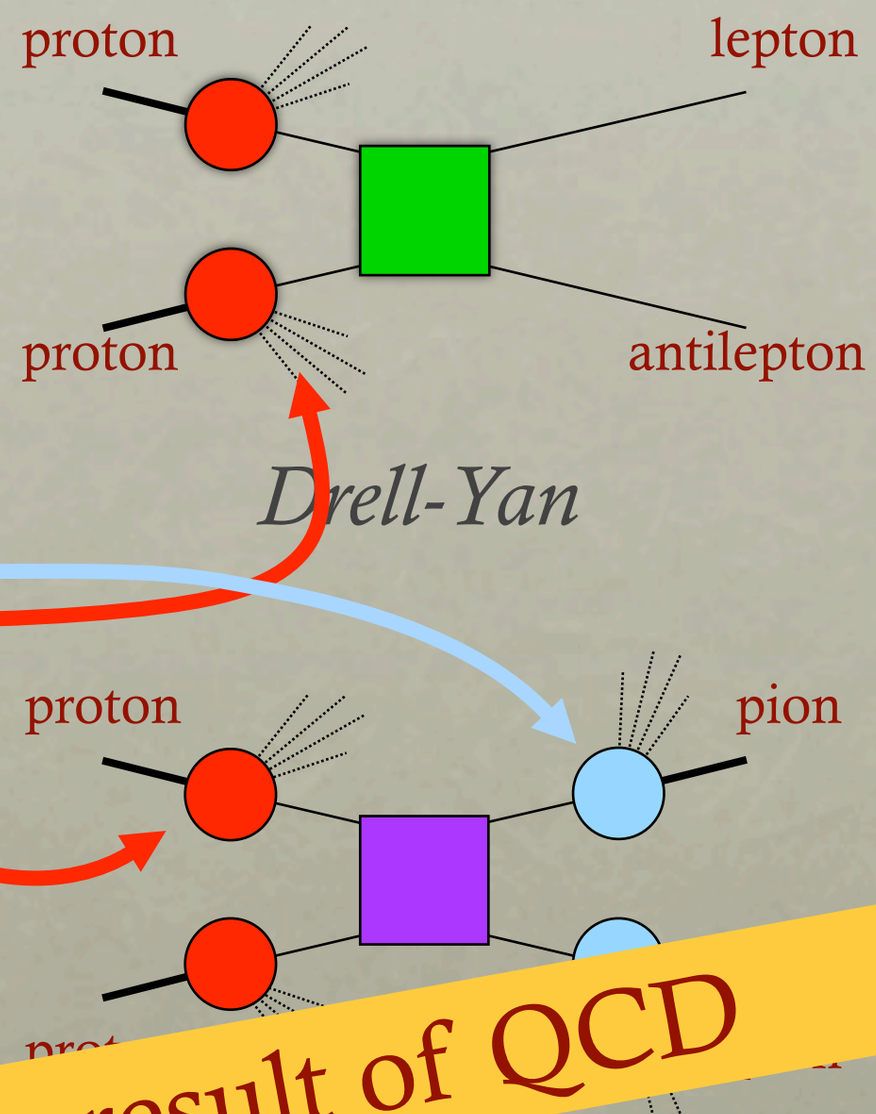




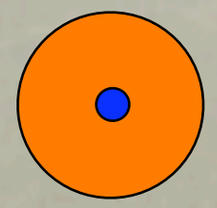
$e^- e^+$ *to pions*

p-p to pions

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

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

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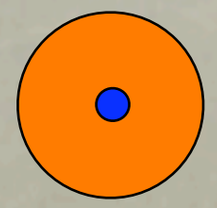
$$f_1^q(x) = q(x) =$$ 

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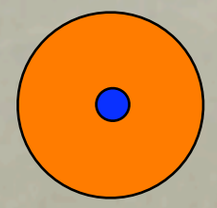
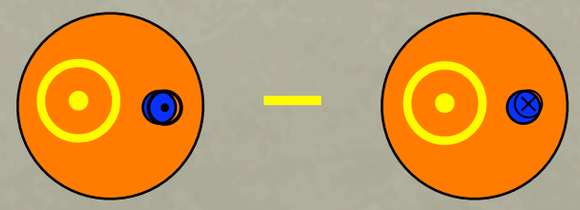
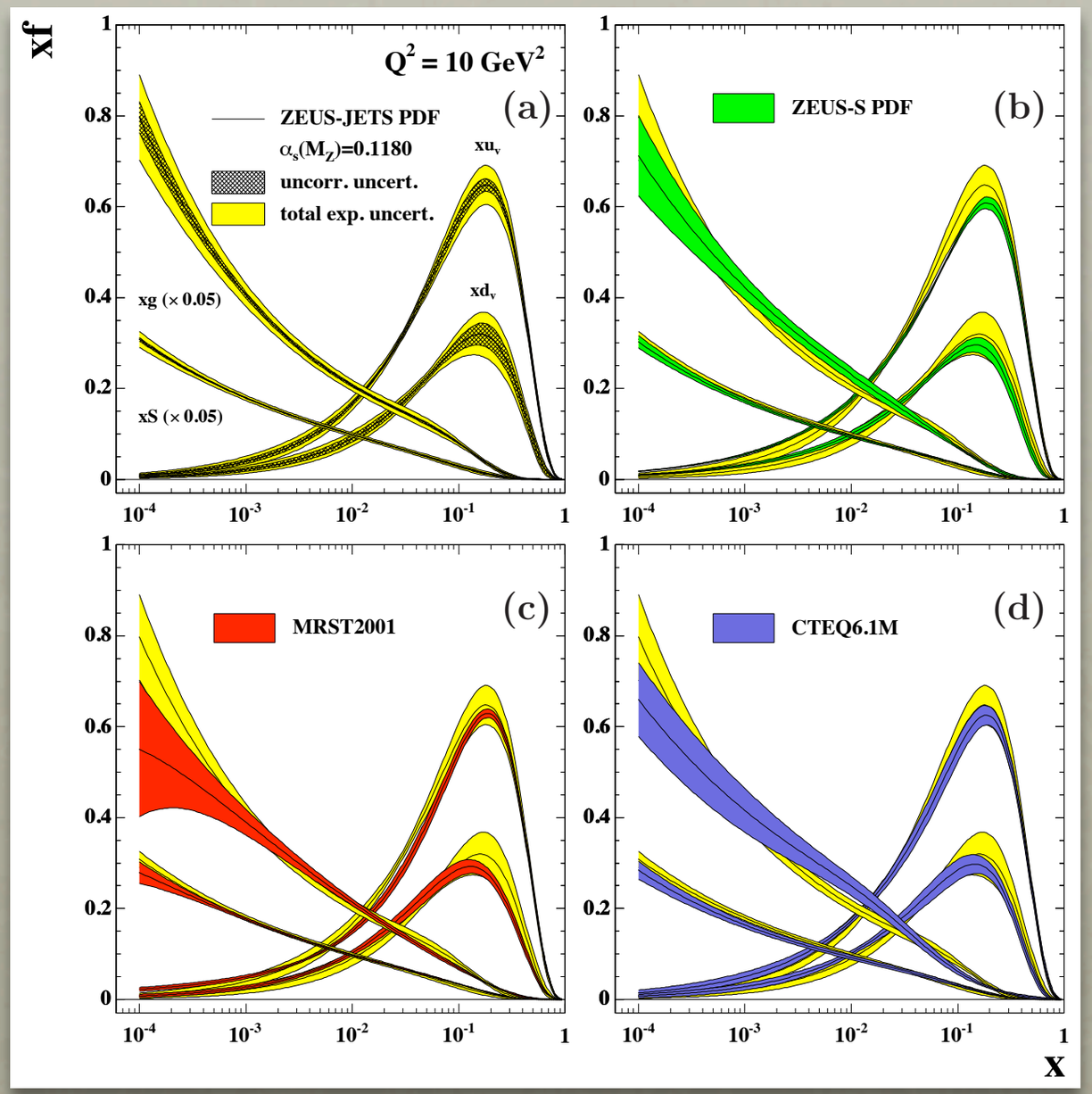
$$f_1^q(x) = q(x) =$$ 

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

PDFs from global fits

x q(x)

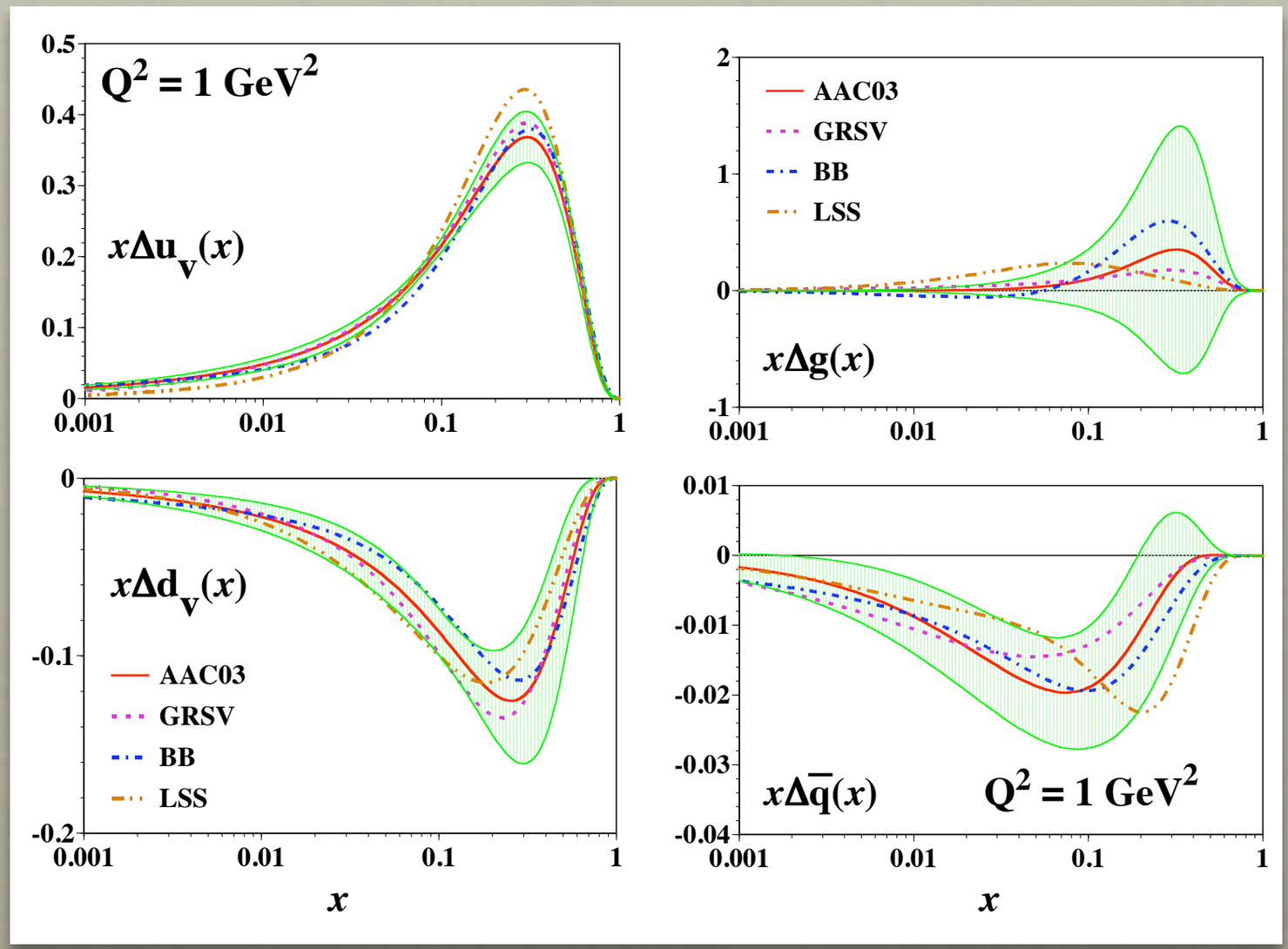


ZEUS Coll, EPJ C42 (05)

Helicity PDFs from global fits

see talk by S. Kuhn this morning

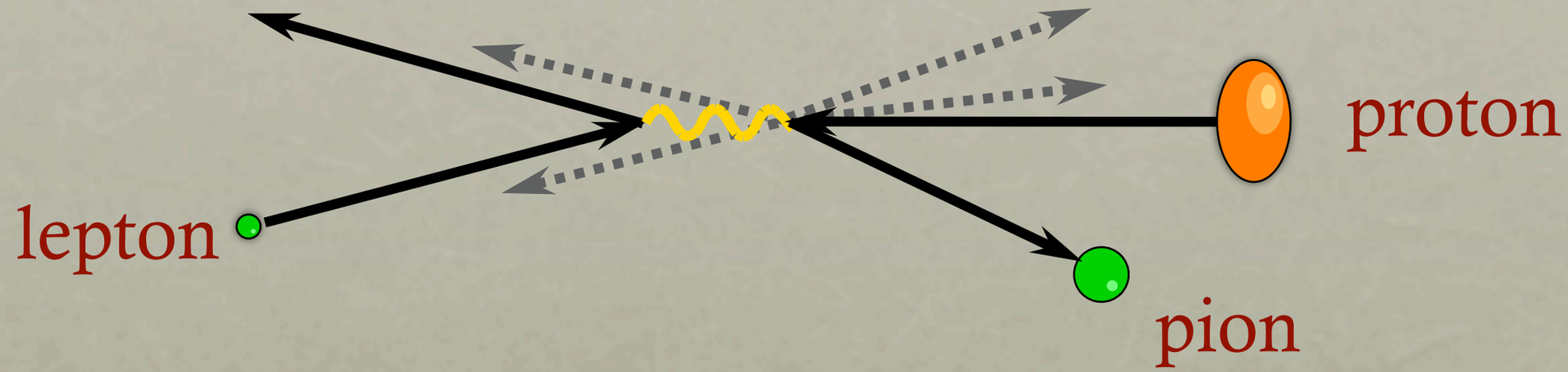
$x\,\Delta q(x)$



AAC, Hirai et al. PRD69 (04)

Transverse parton distribution functions

Transverse vs. longitudinal



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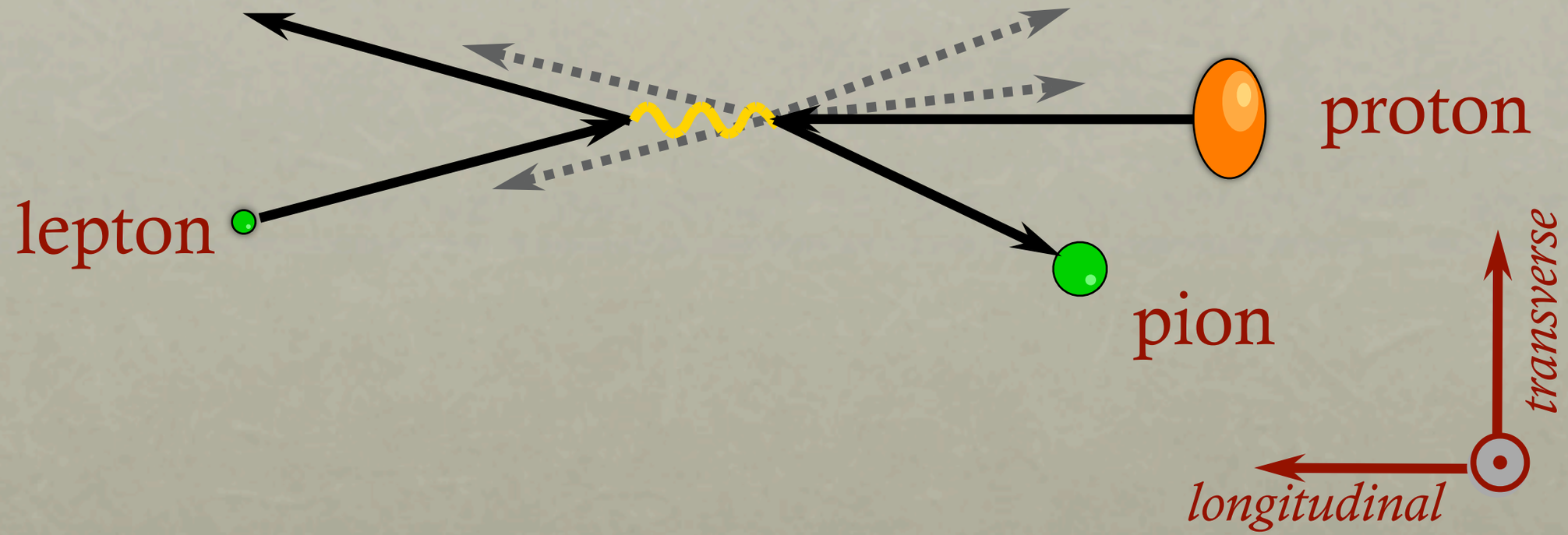

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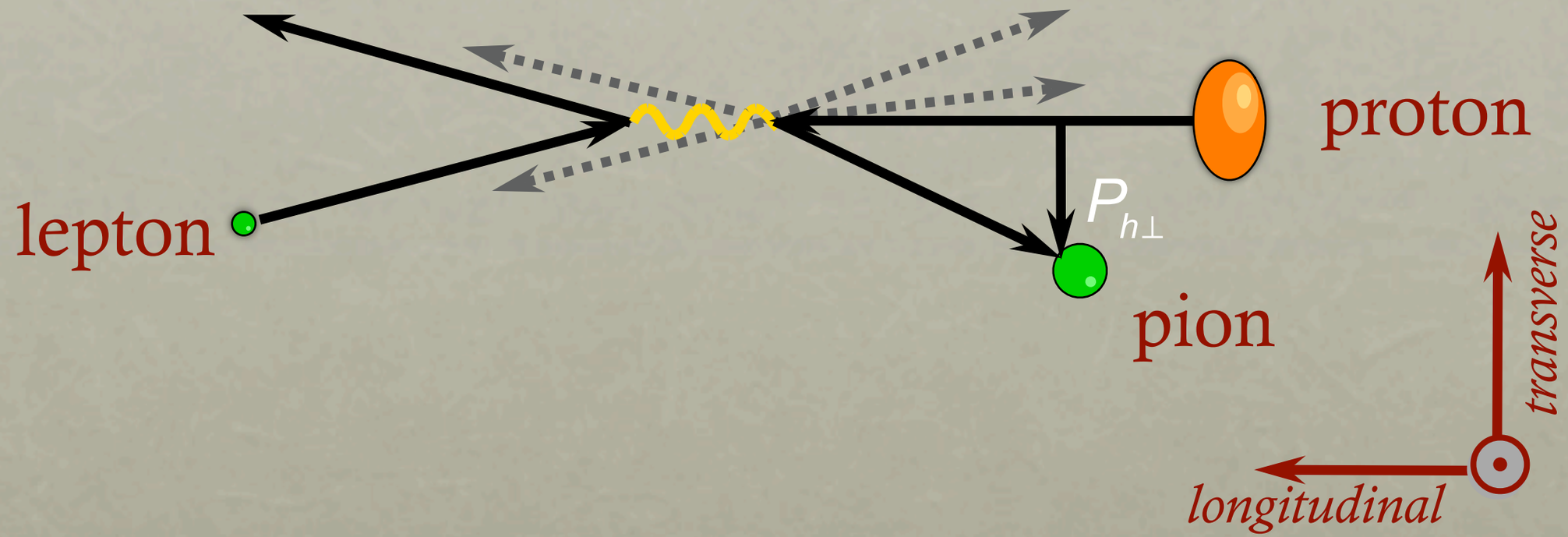

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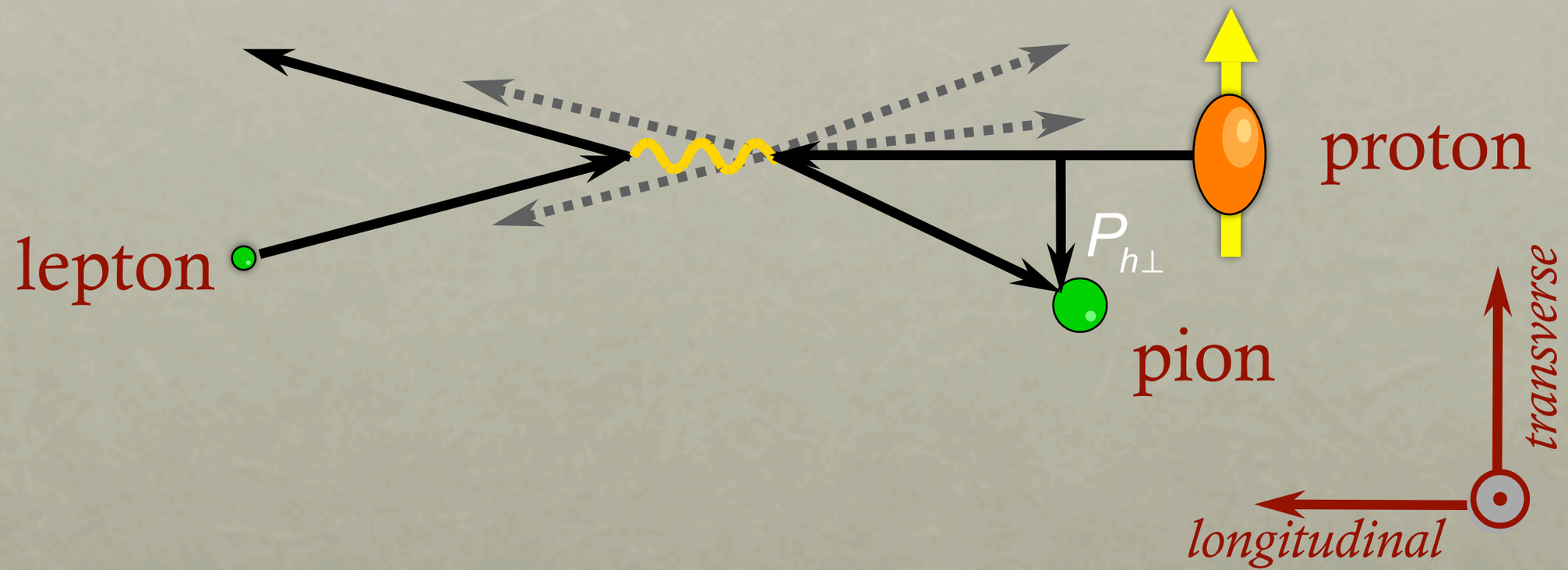

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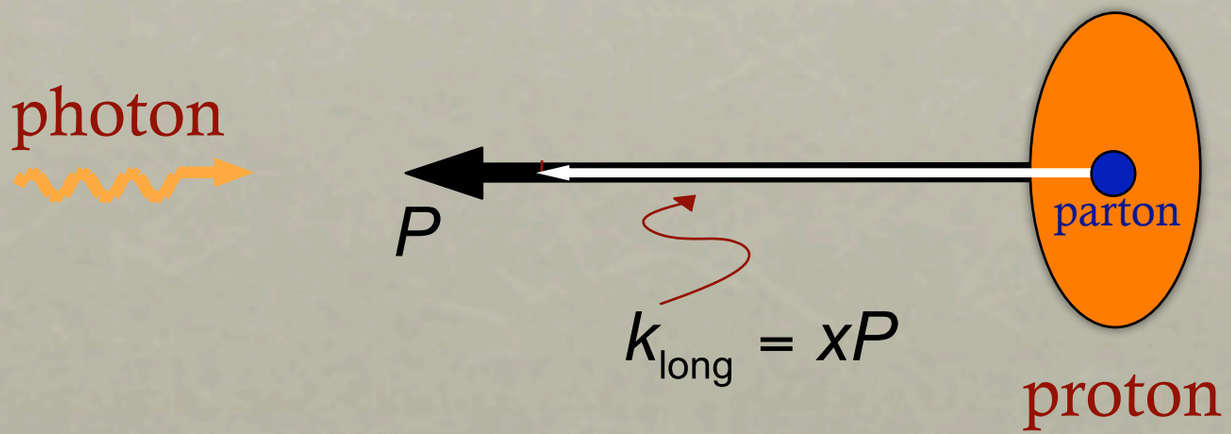

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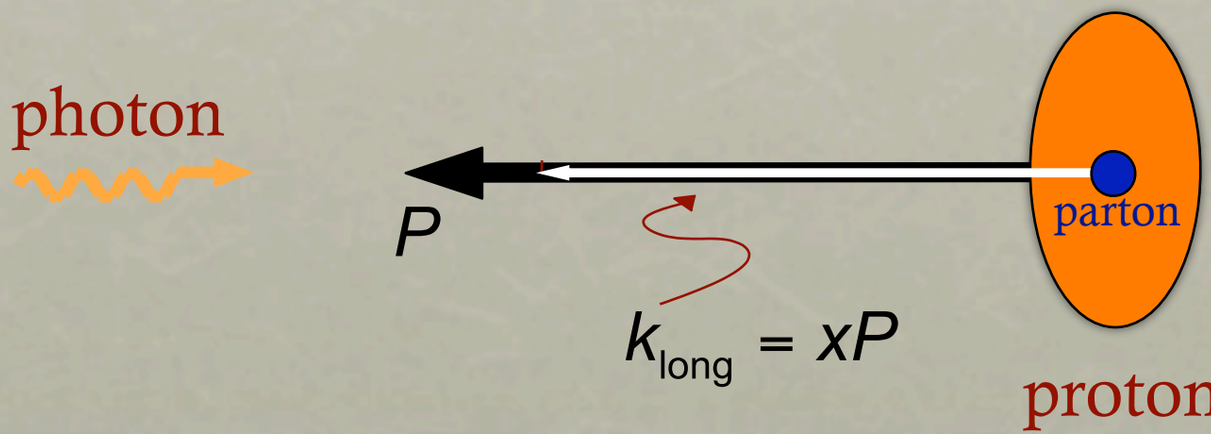

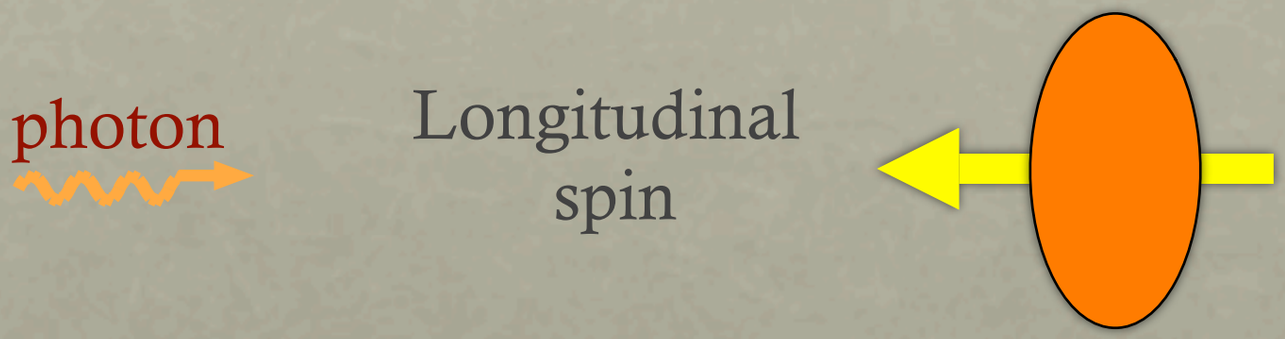

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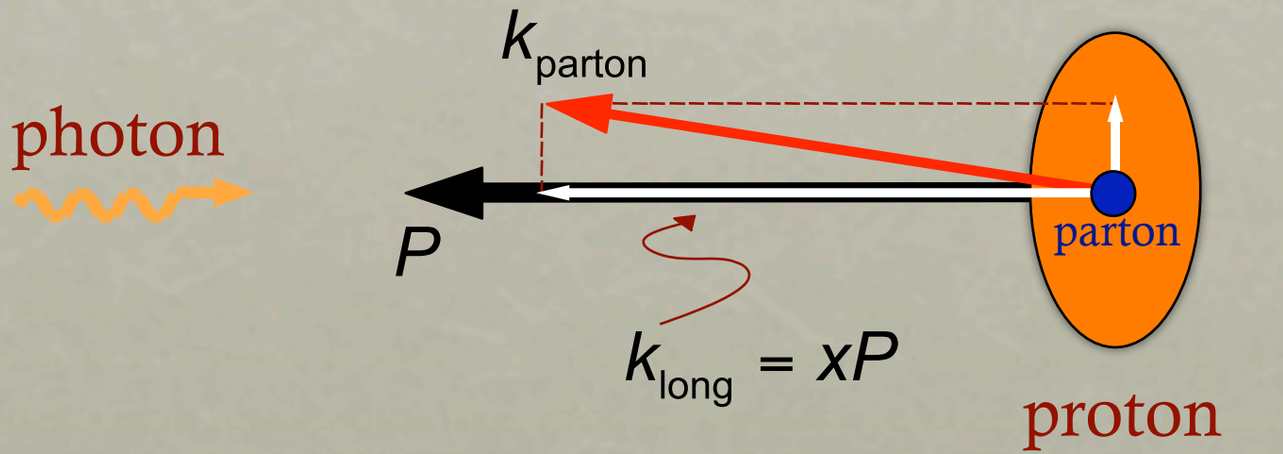

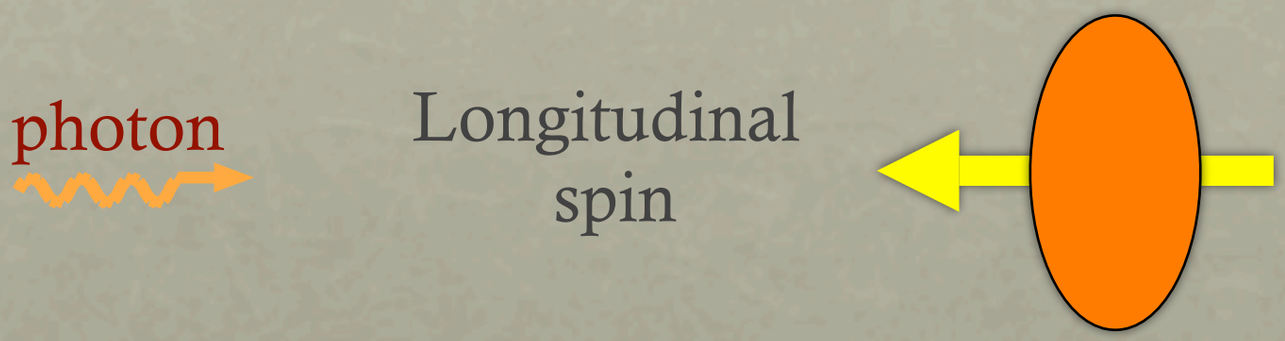

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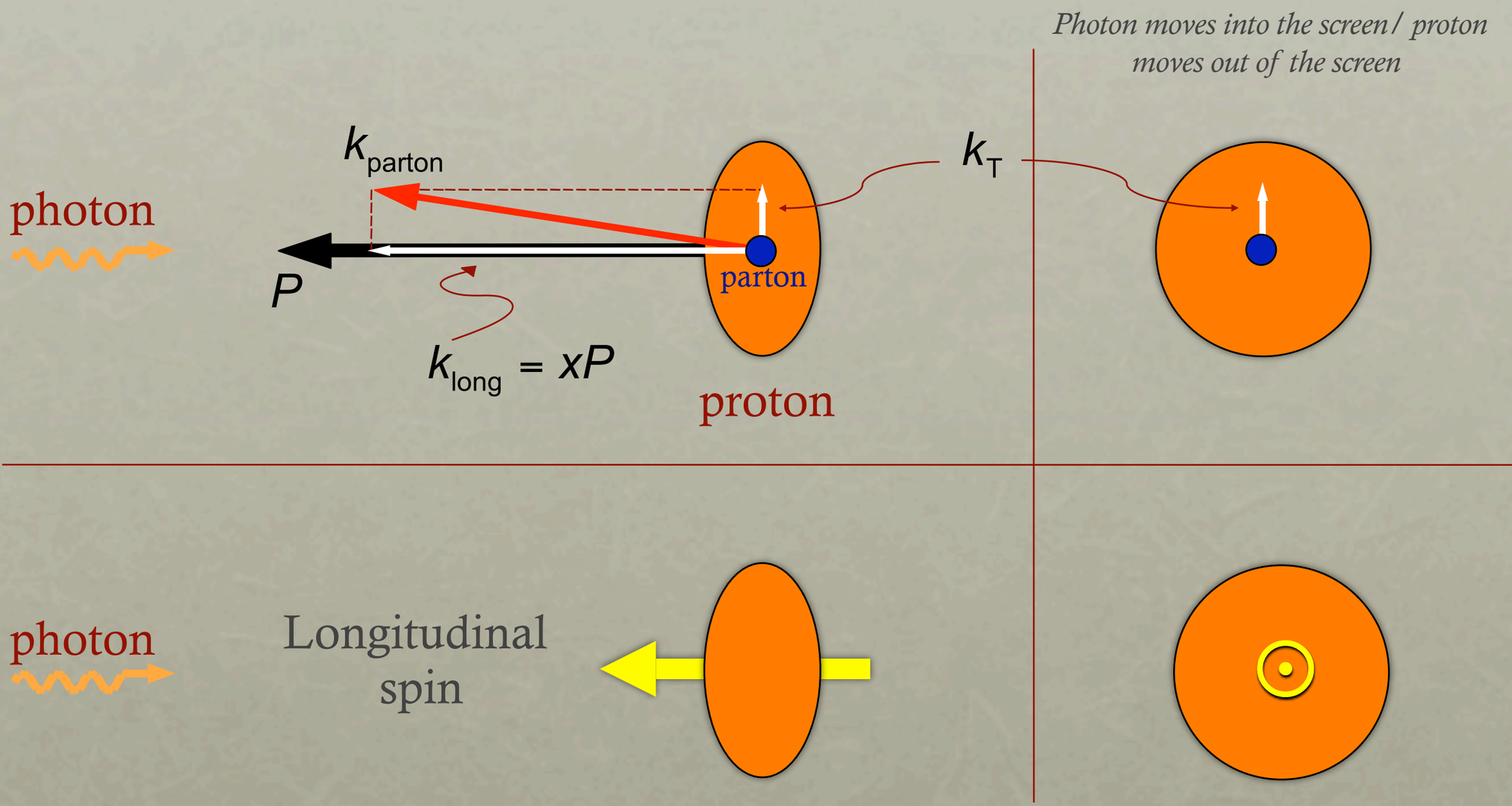

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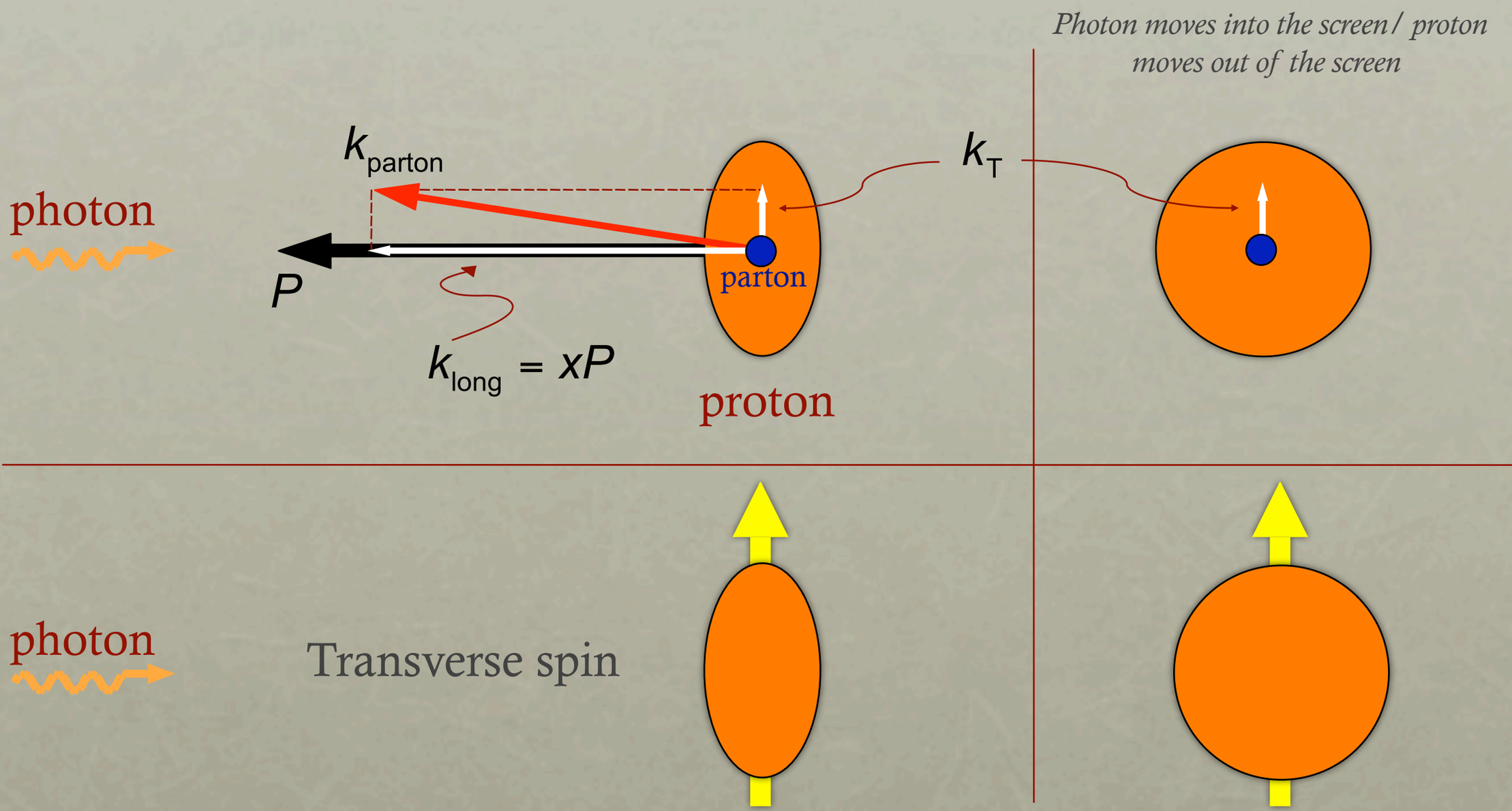
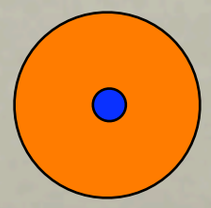


Transversity

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

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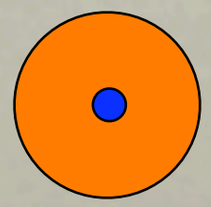
$f_1^q(x) = q(x) =$ 

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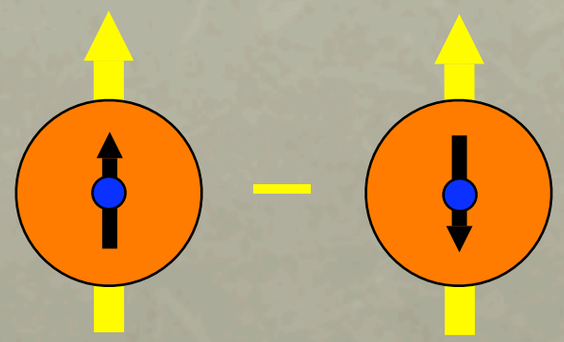
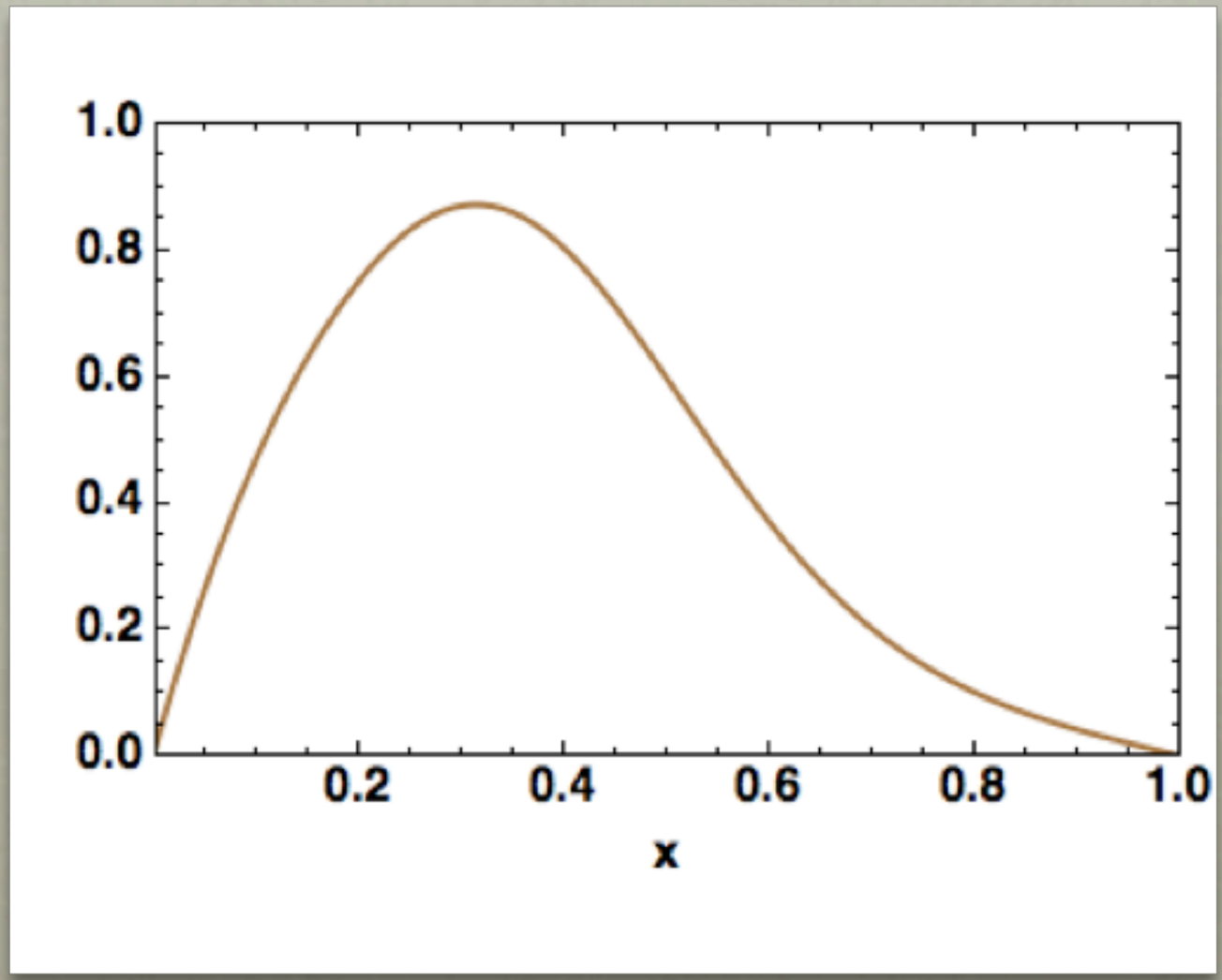
$h_1^q(x) = \Delta_T q(x) =$ 

Transverse momentum distributions

up quarks



Transverse momentum distributions

up quarks

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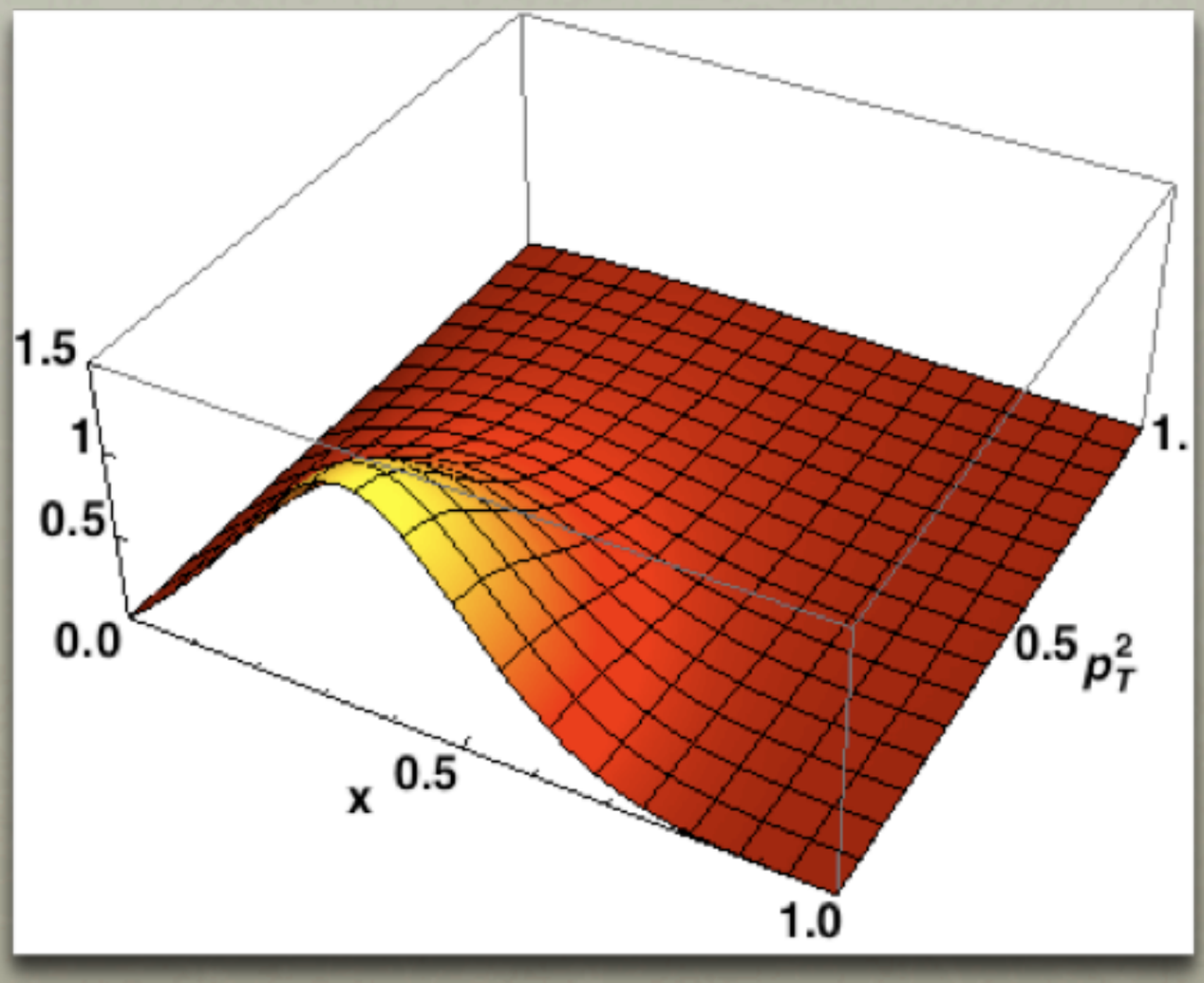

Orbital angular momentum

Jaffe, Manohar, NPB 337 (90)

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

Ji, PRL 78 (97)

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Ji, PRL 78 (97)

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Gauge invariant

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

Ji, PRL 78 (97)

Transversity

Transversity vs Helicity

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

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

- Different evolution (no gluons vs gluons)

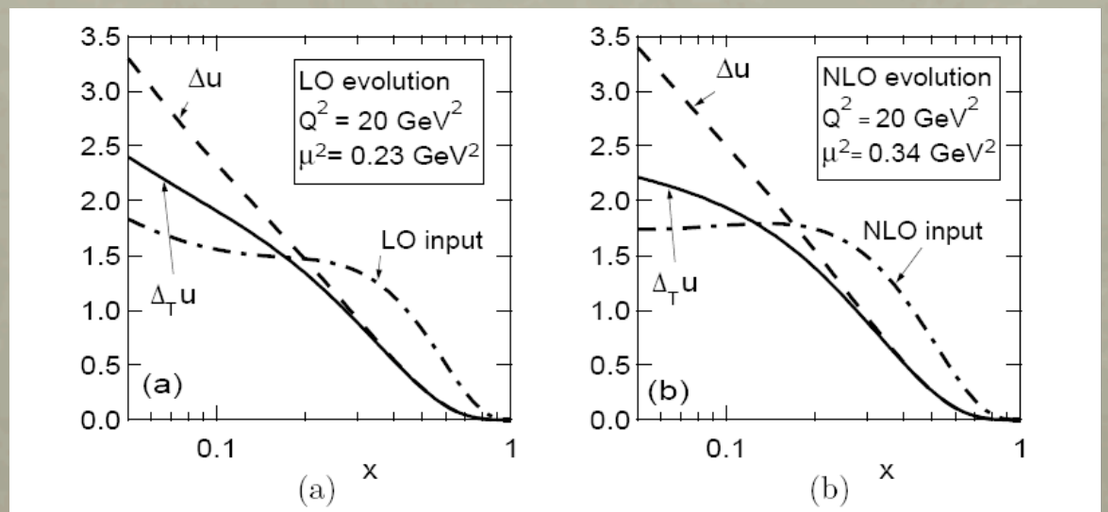

Fig. 19. Comparison of the Q^2-evolution of $\Delta_T u(x, Q^2)$ and $\Delta u(x, Q^2)$ at (a) LO and (b) NLO, from [72].

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Aoki et al., PRD 56 (97)

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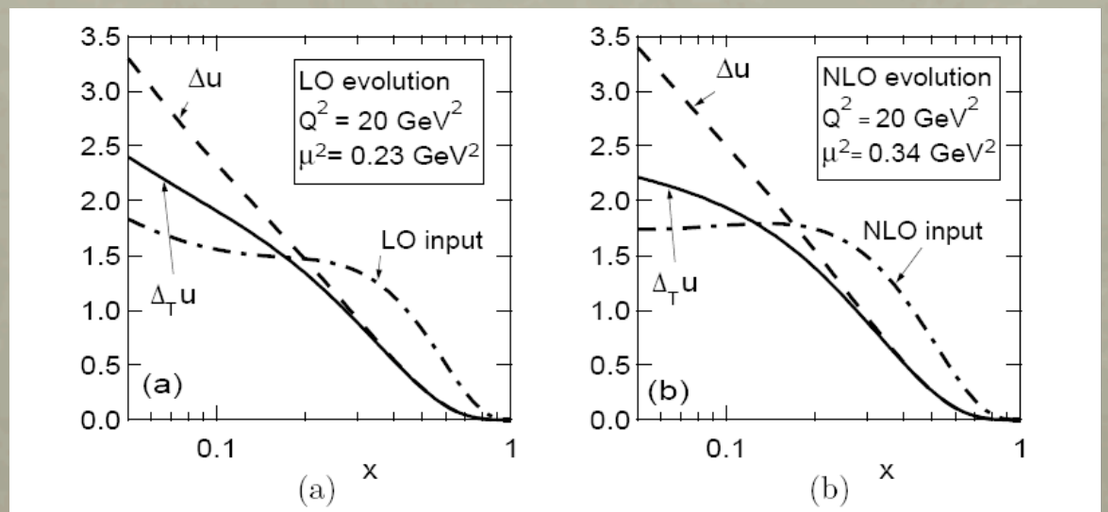

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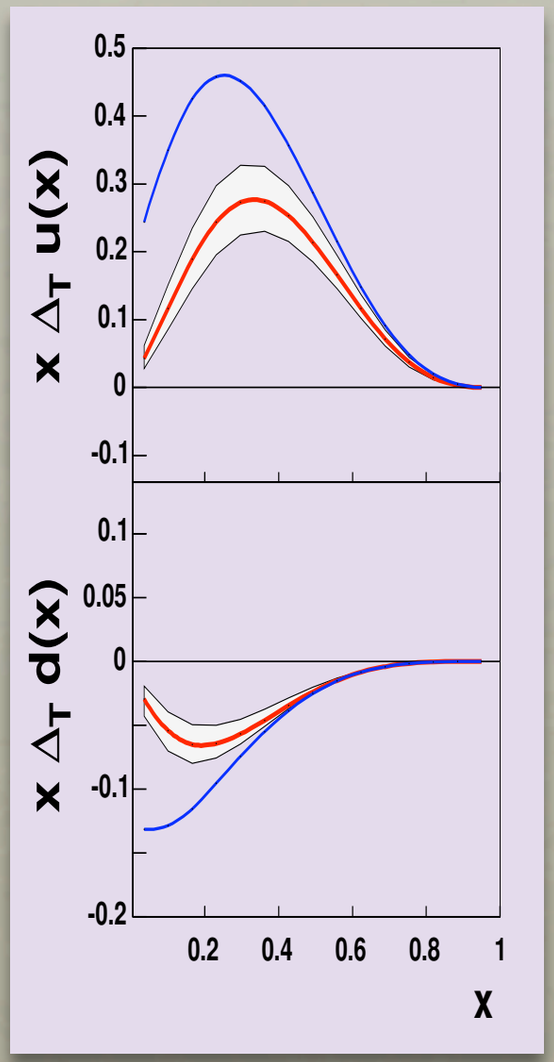
Extraction of transversity



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

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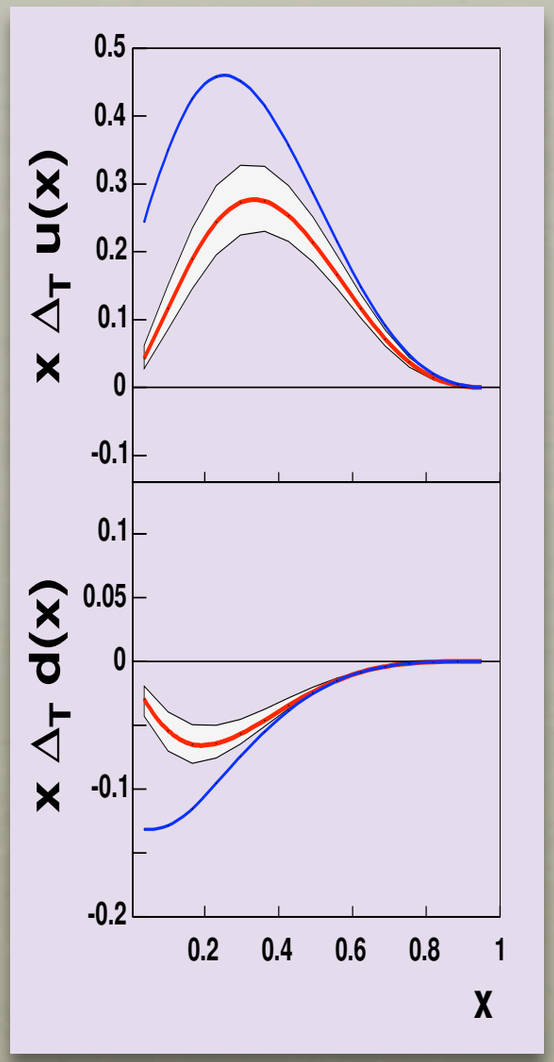

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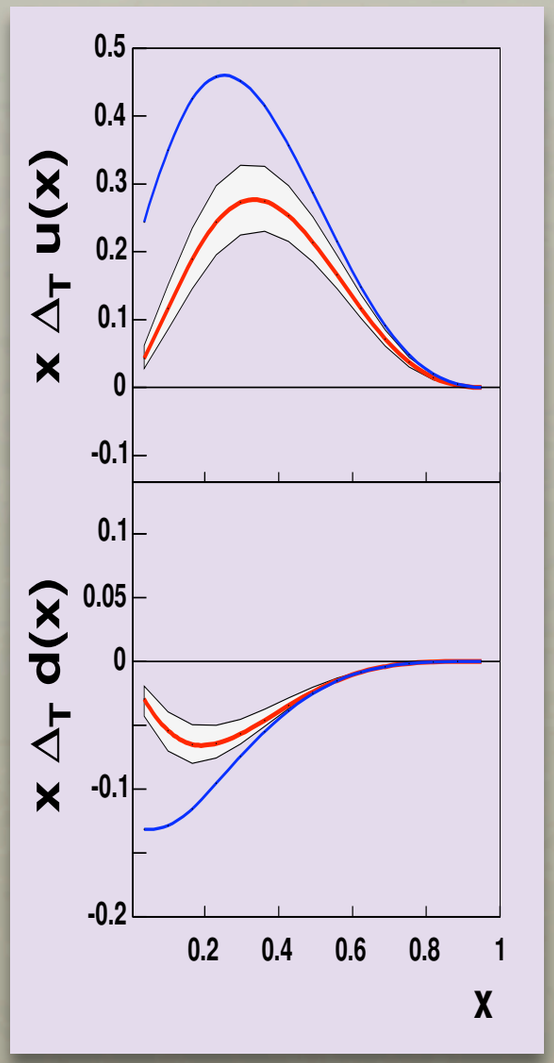

- Data from HERMES, COMPASS, BELLE
- 96 data points (cf. 467 points for Δq fits)

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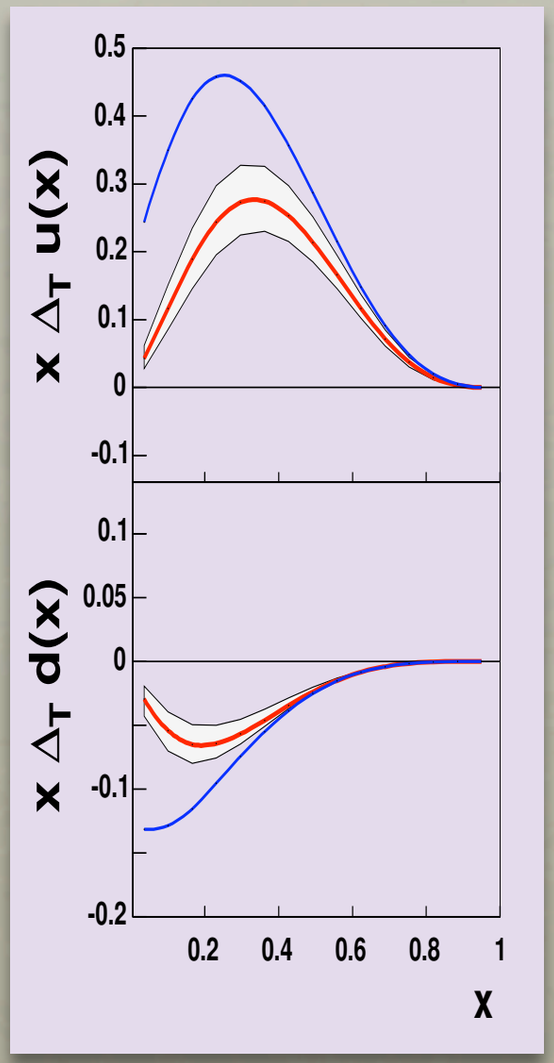

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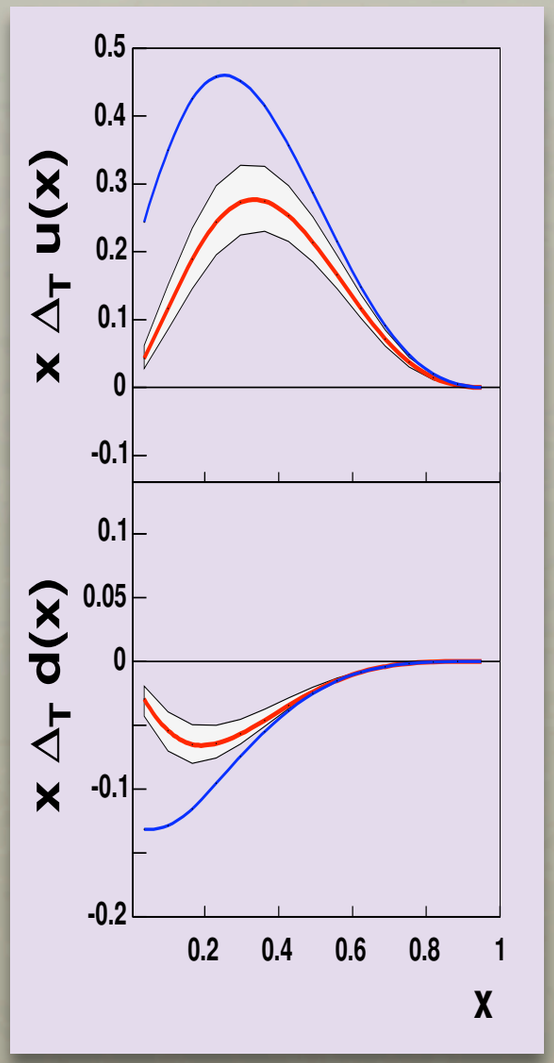
A. Prokudin, talk at DIS08 (Anselmino et al, 0807.0173)

Extraction of transversity



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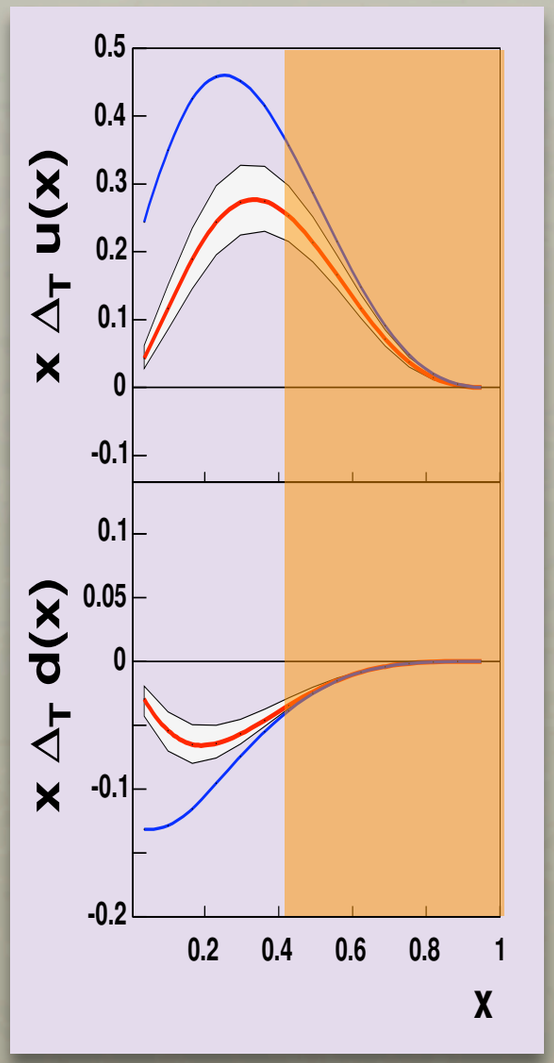

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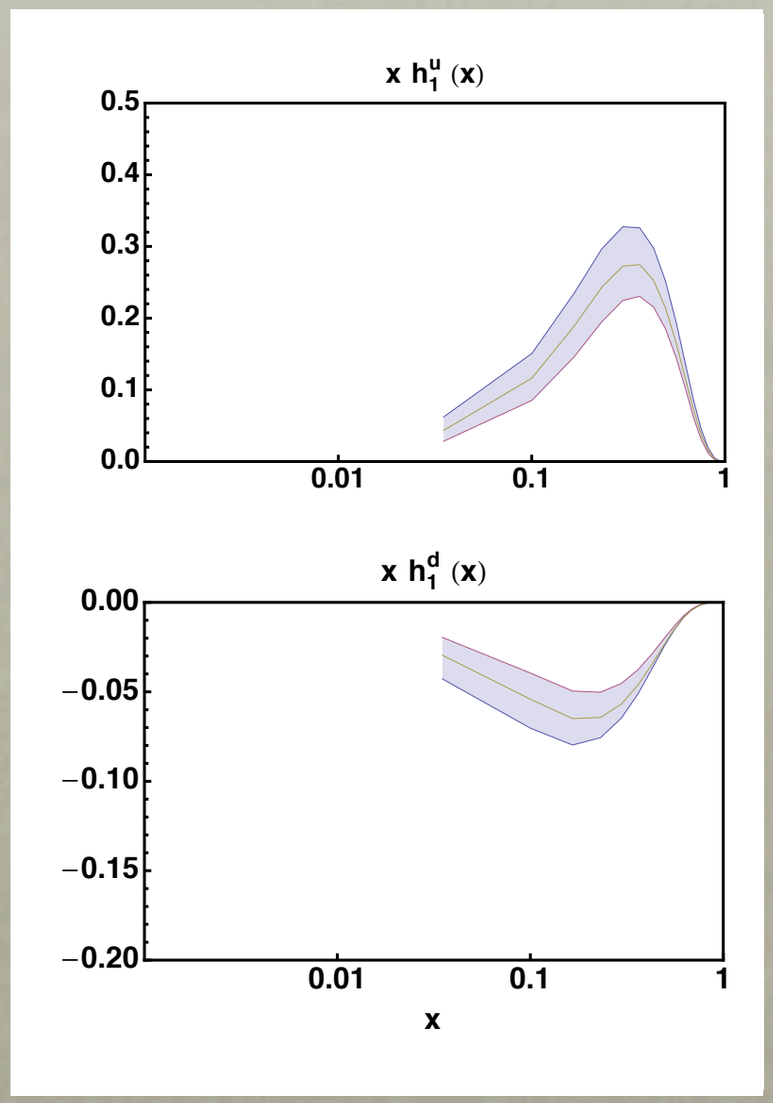

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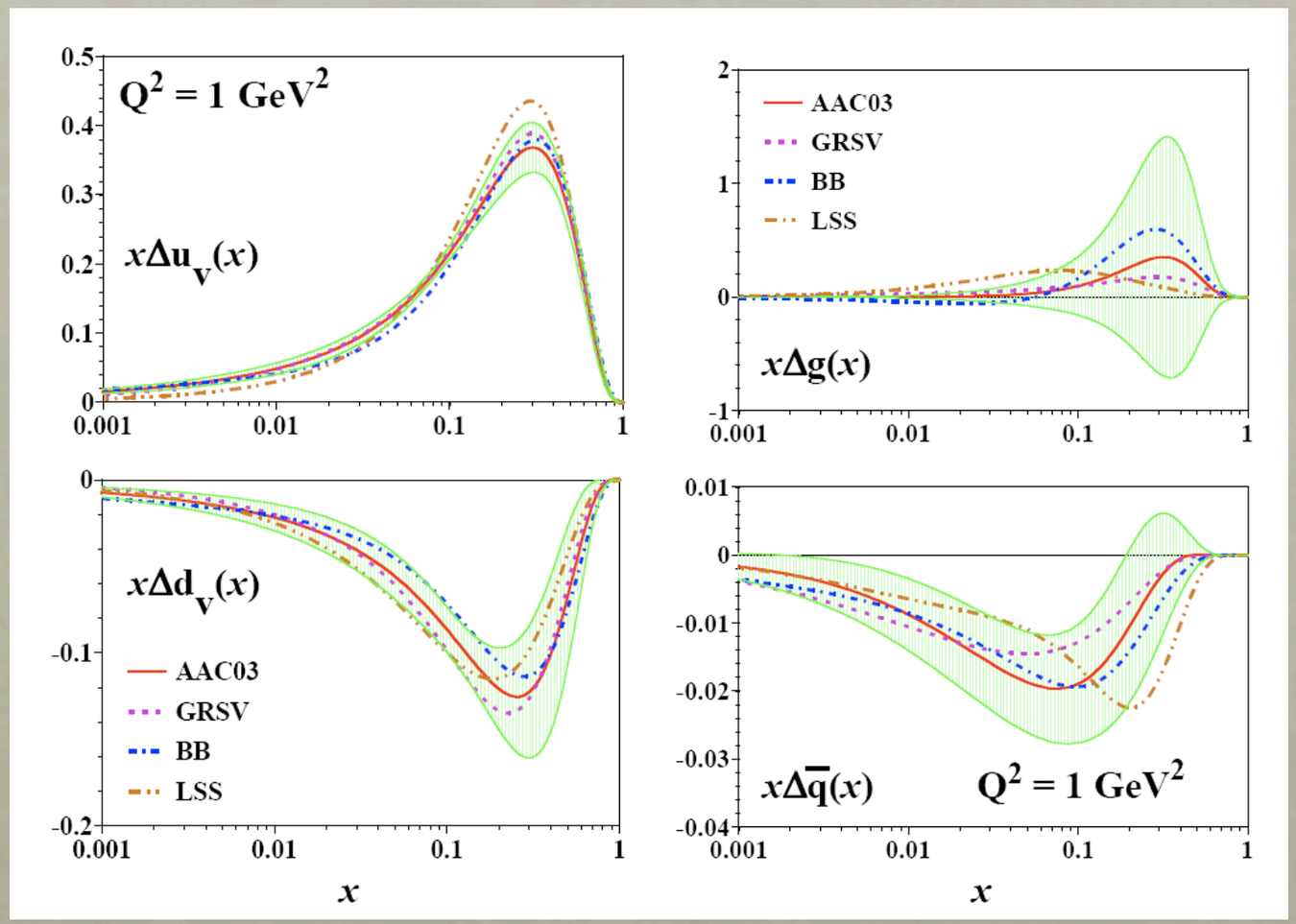
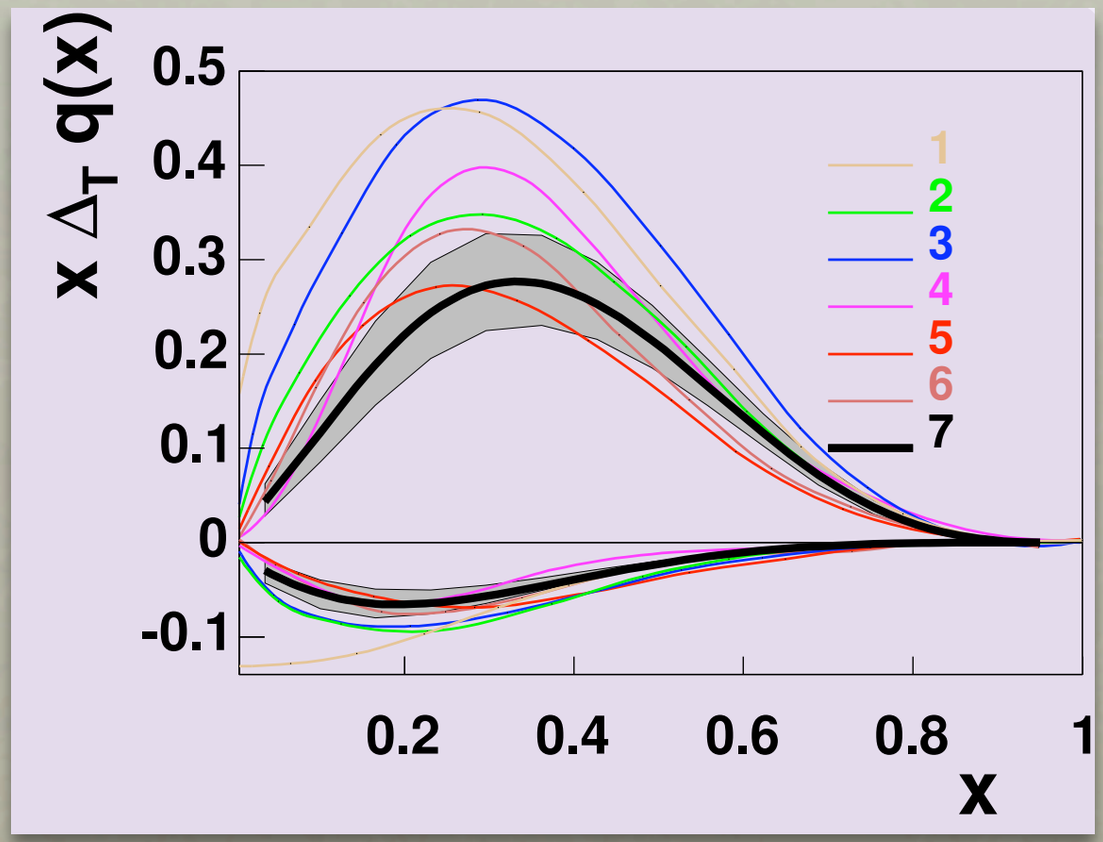


AAC, Hirai et al. PRD 69 (04)

Comparison with models



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

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

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

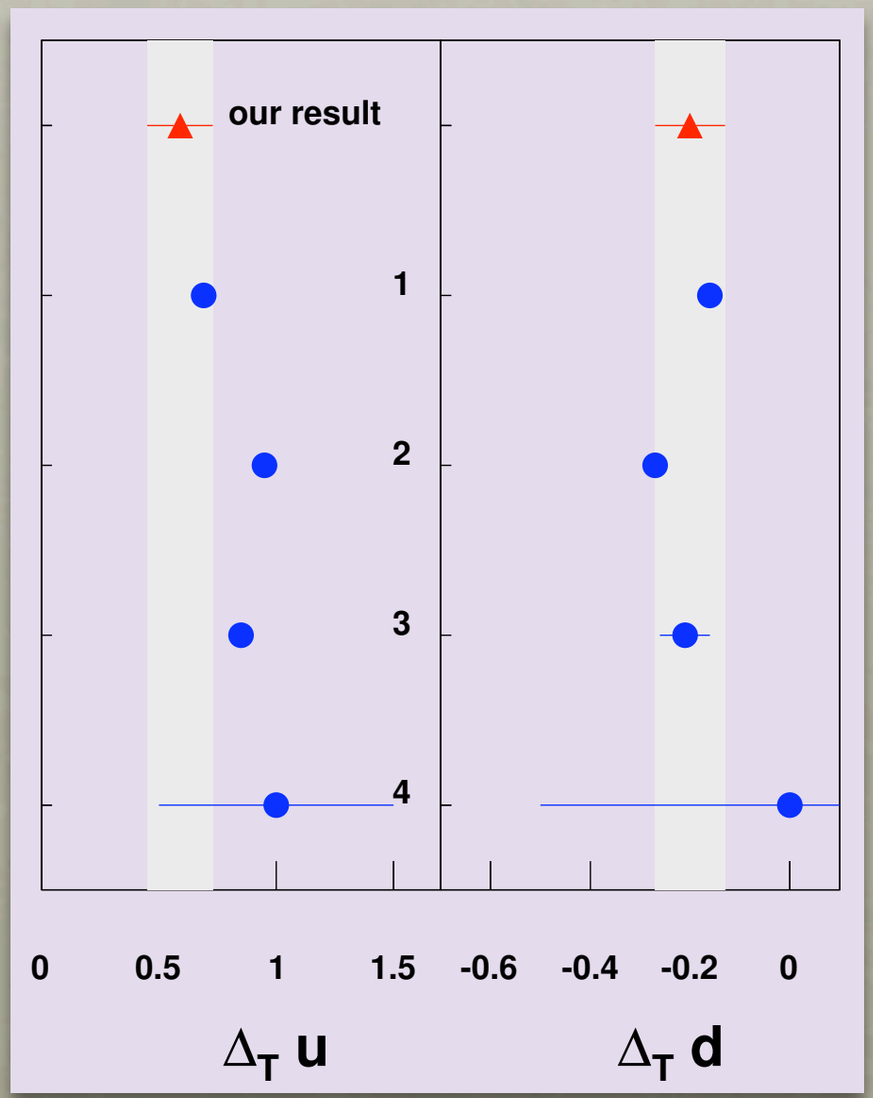
[4] Wakamatsu, PLB 509 (01)

[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

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- In general, parton distributions are 6 dimensional (Wigner distributions)

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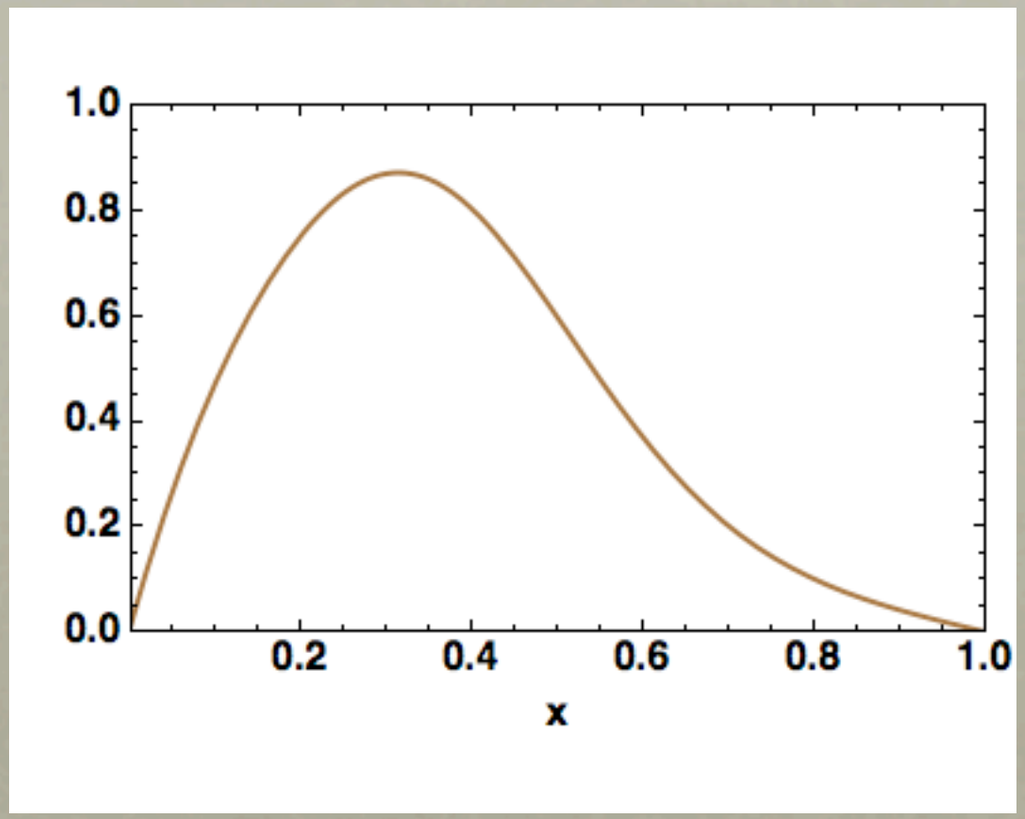
X. Ji, PRL 91 (03), Meissner et al. arXiv:0805.3165
for even more dim. (8), see Collins, Rogers, Stasto, PRD77 (08)

Transverse momentum distributions

$x f_1^u(x)$



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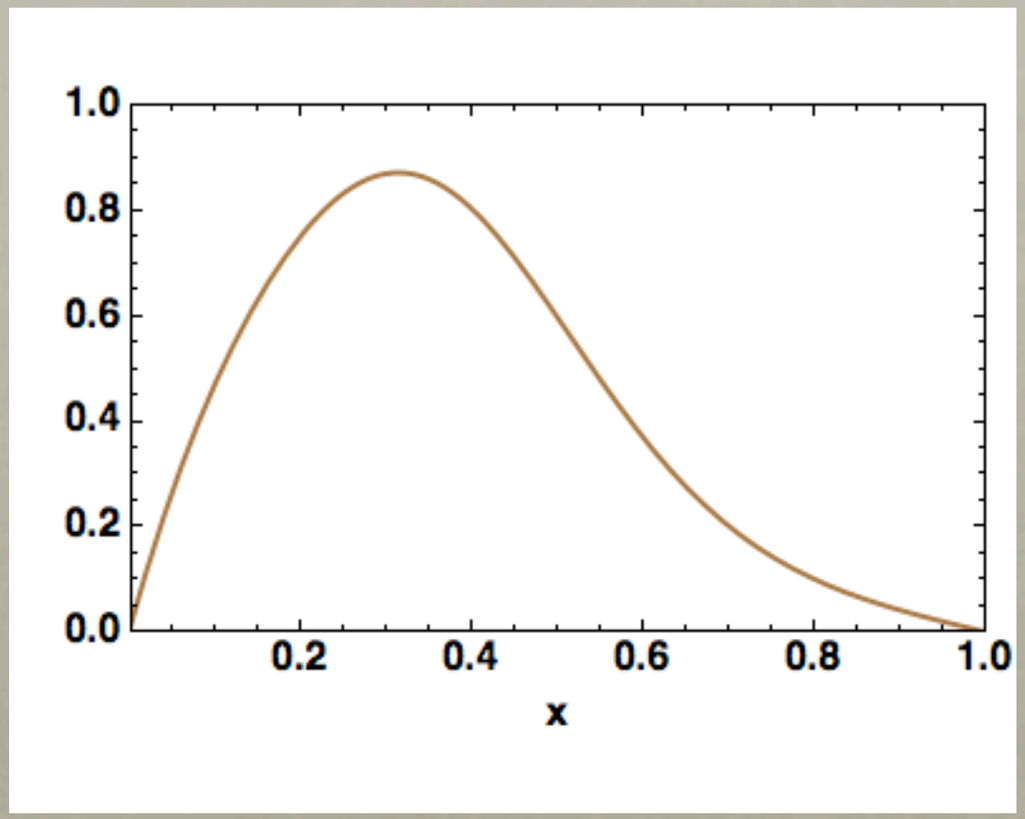
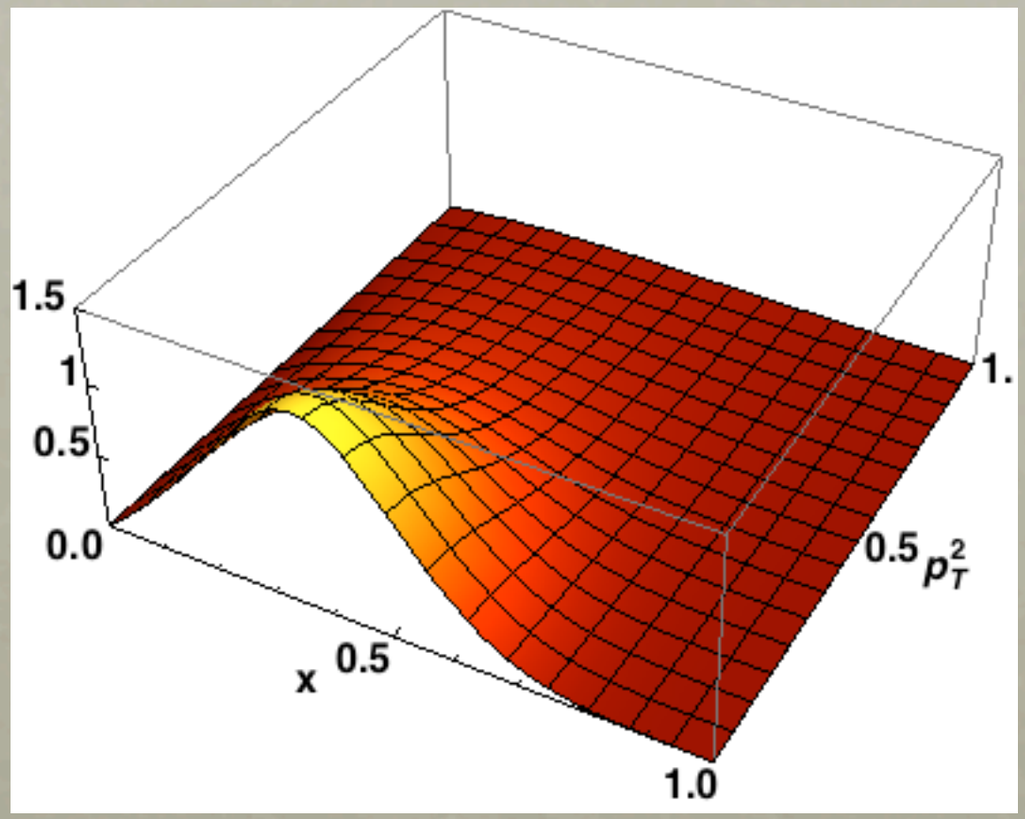


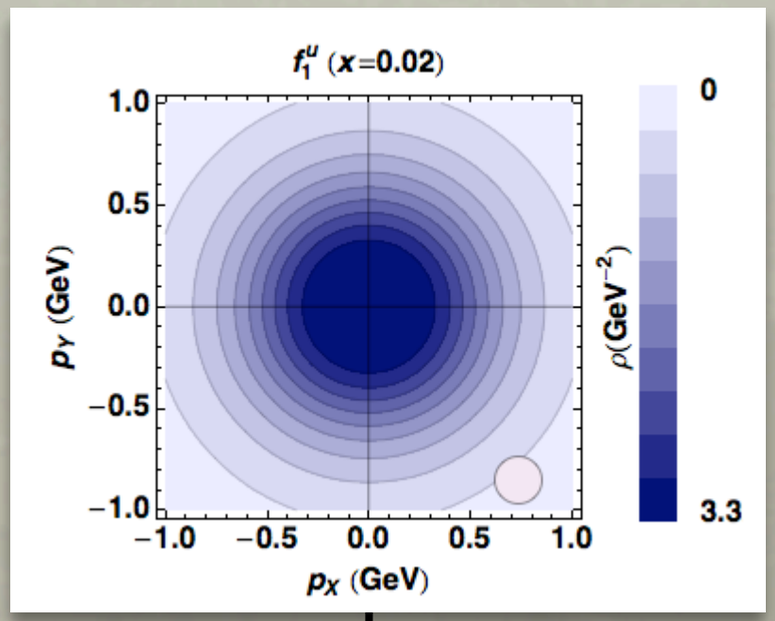
$x f_1^u(x, p_T^2)$



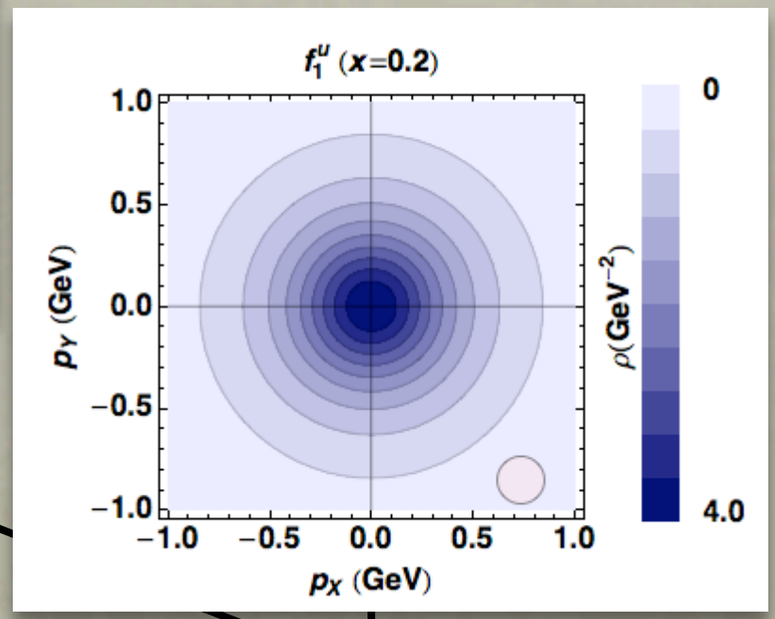
A.B., F. Conti, M. Radici, arXiv:0807.0323

see also talk by B. Pasquini

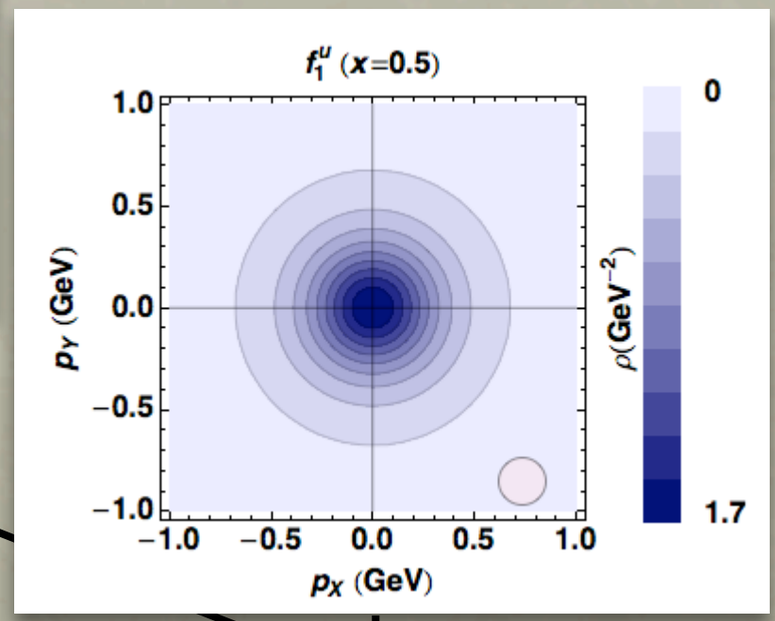
Nucleon tomography in momentum space



0.02



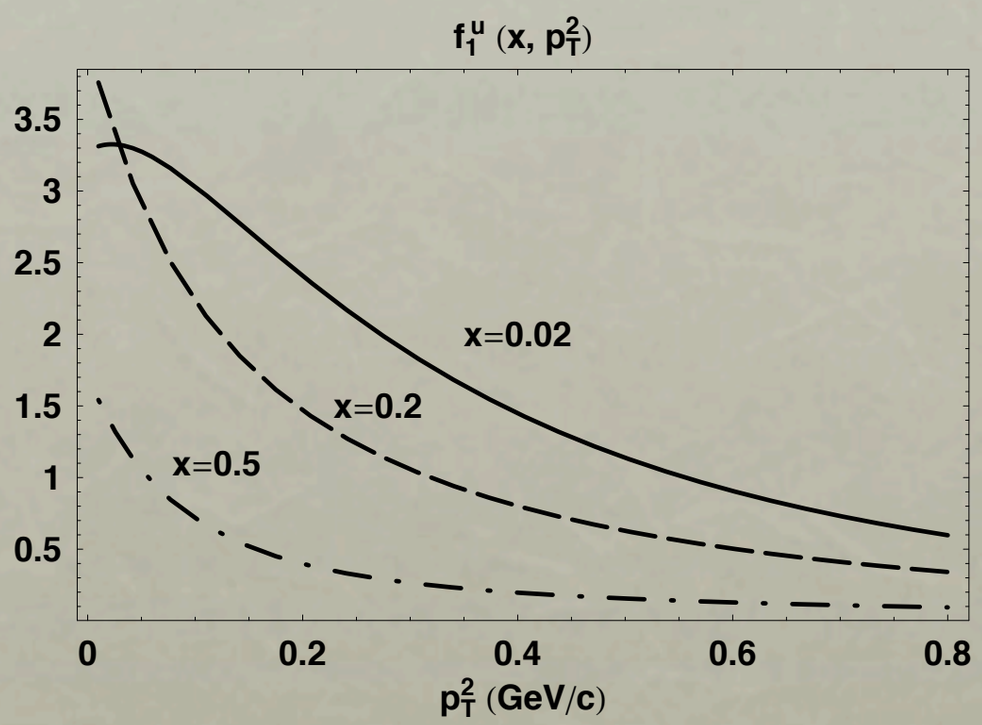
0.2

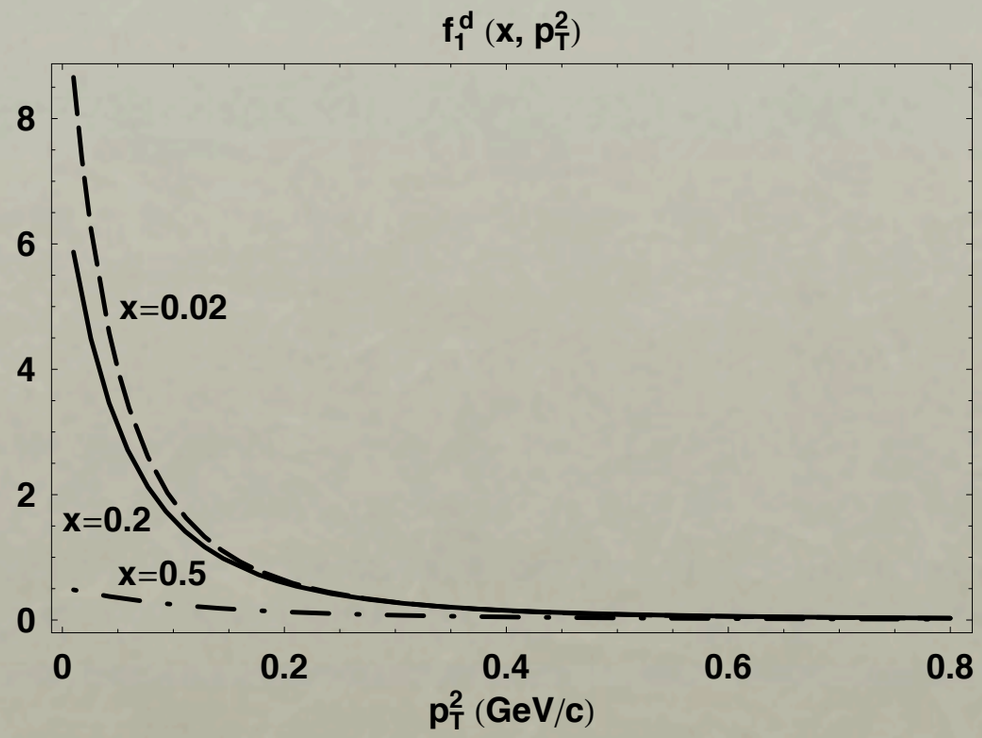


0.5

x

Nontrivial features





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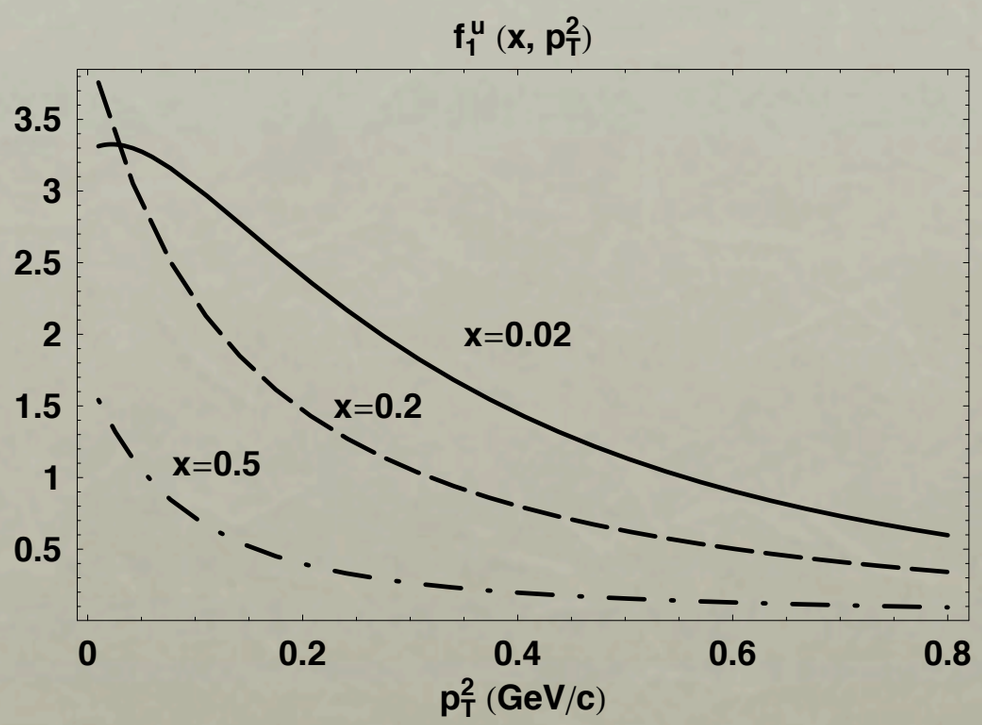

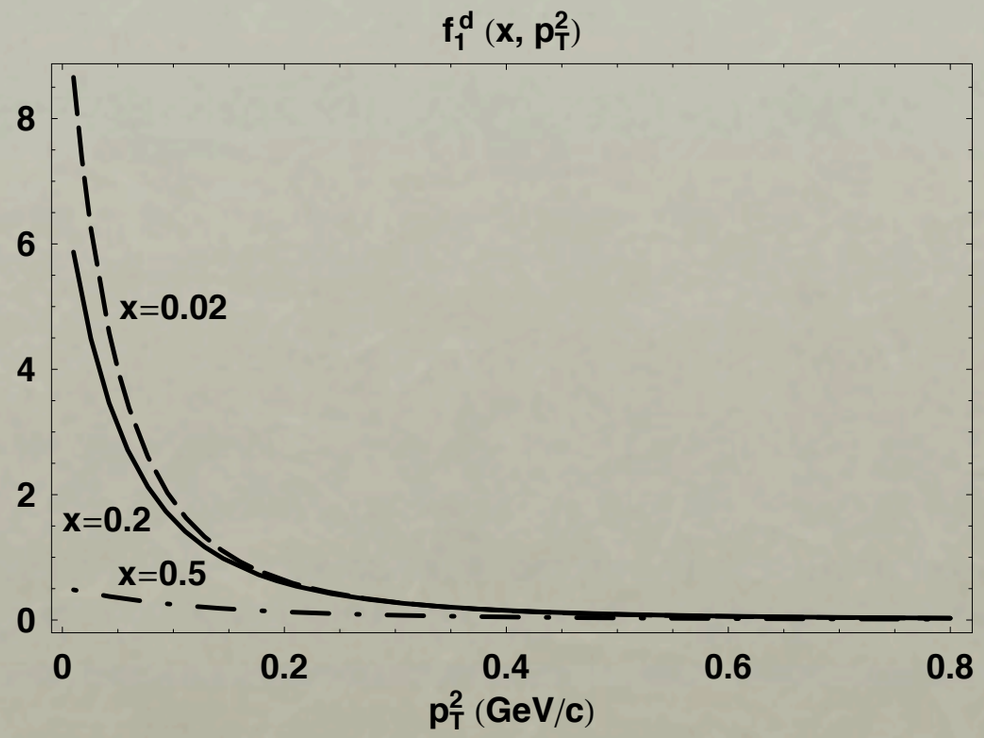

Simple model calculations suggests

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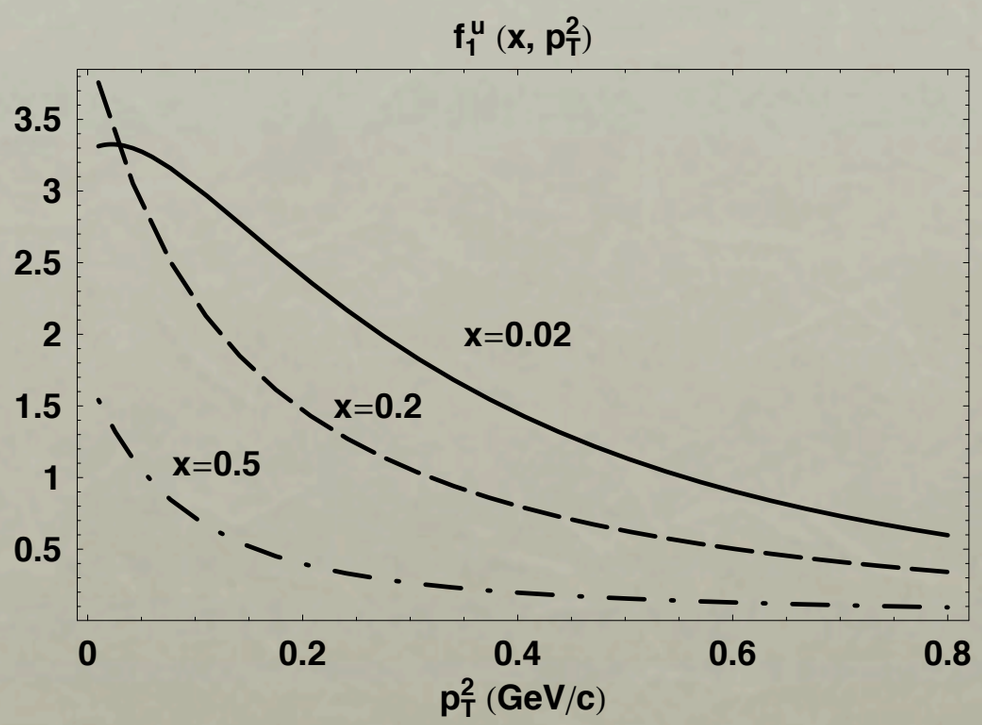

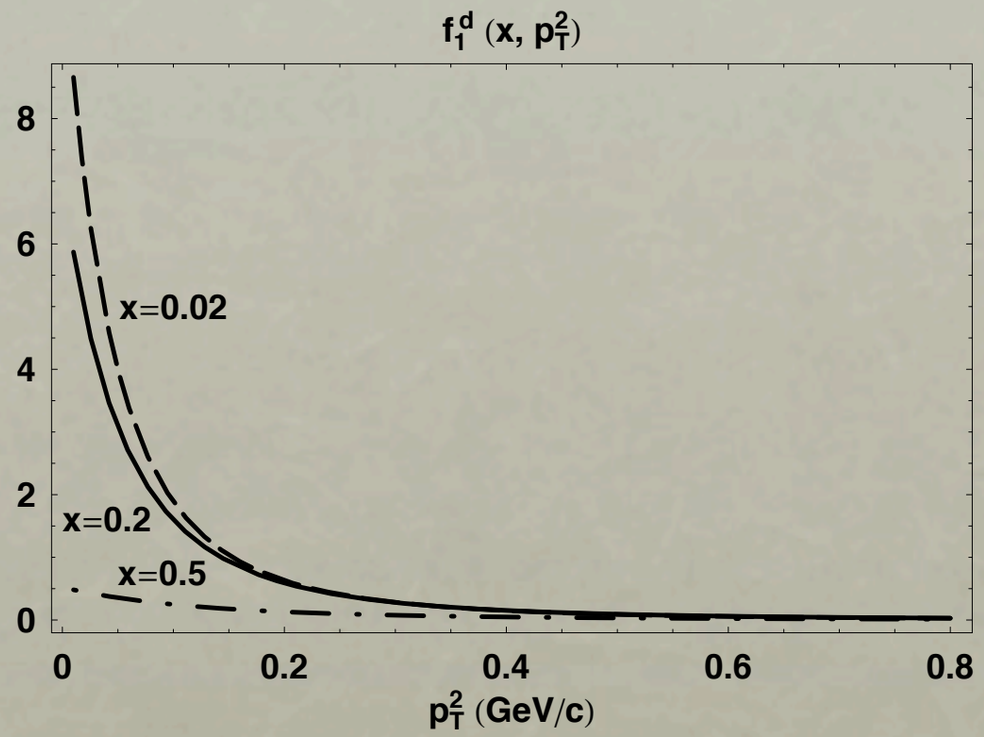

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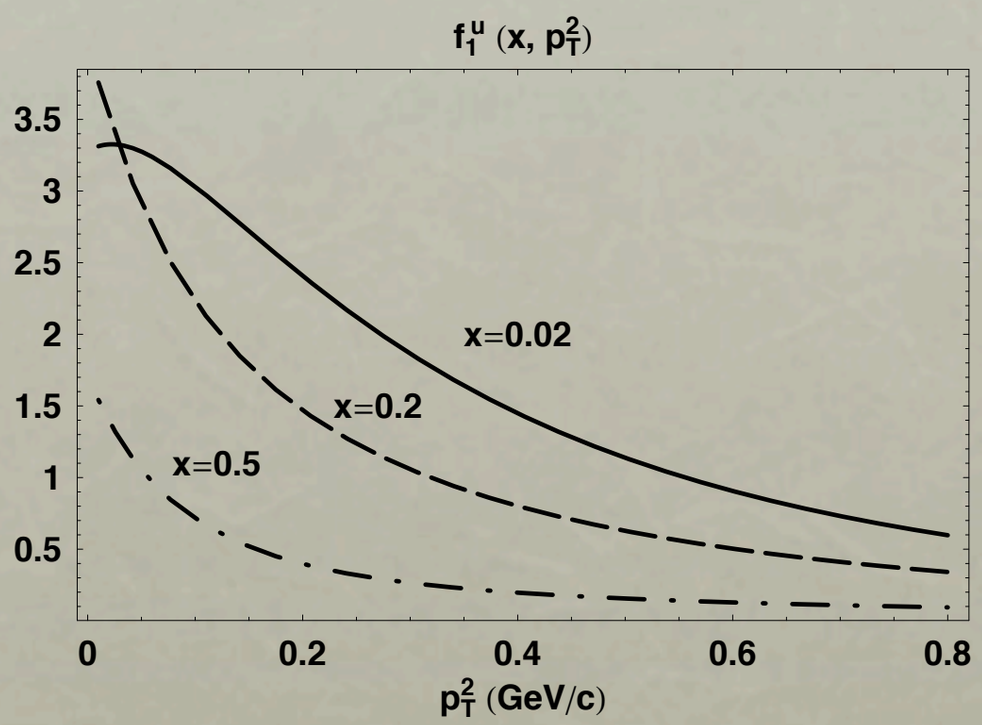

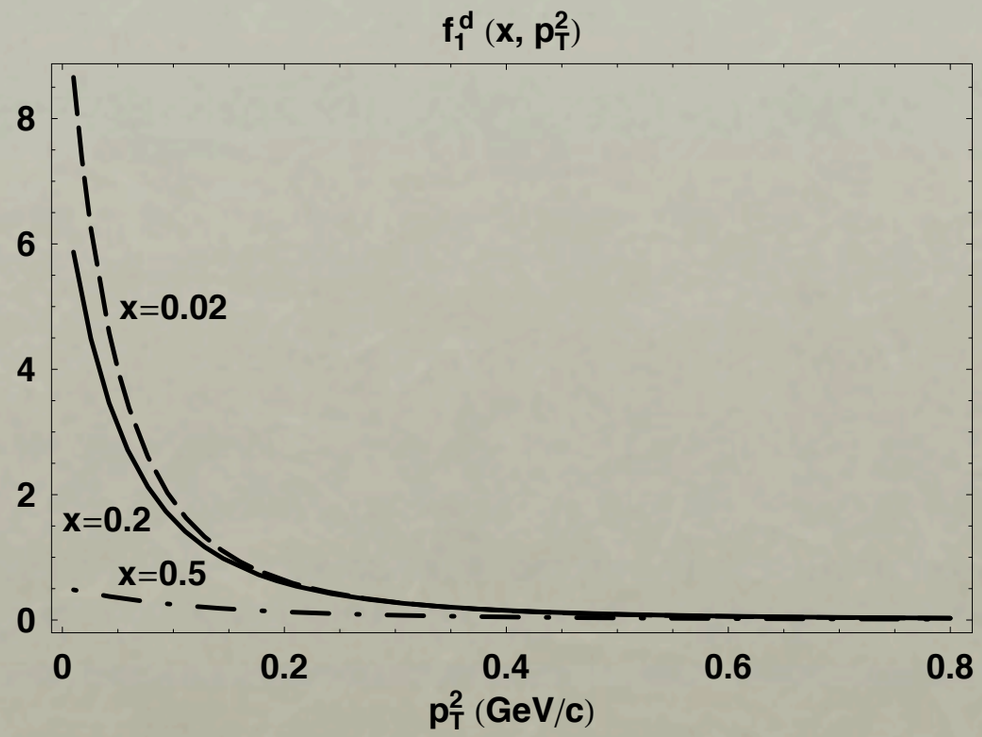

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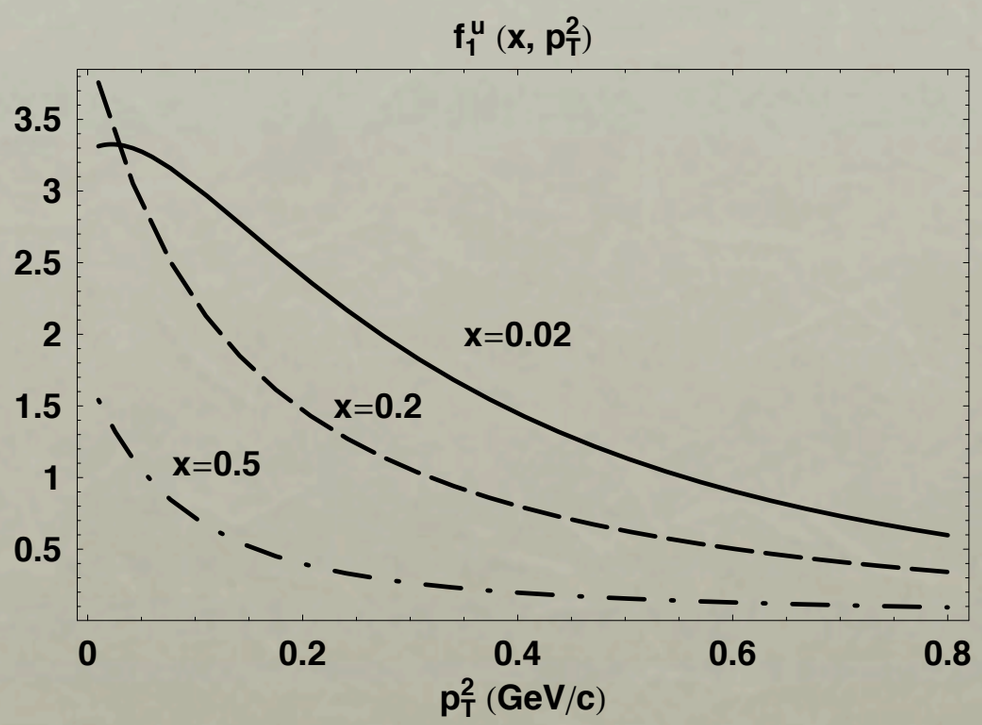

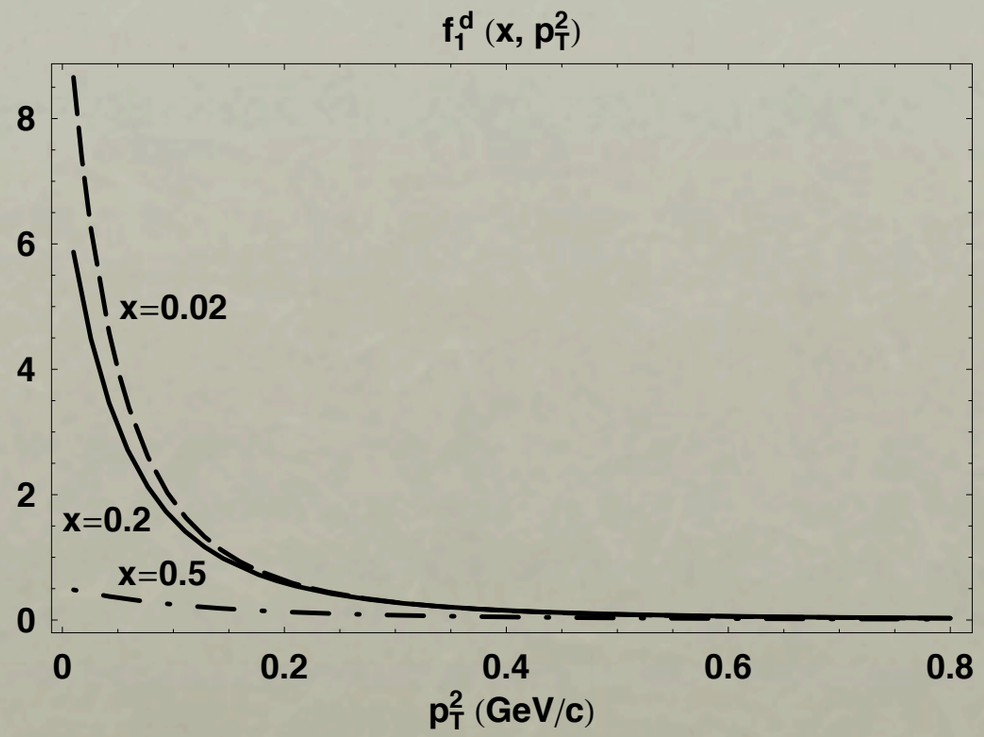

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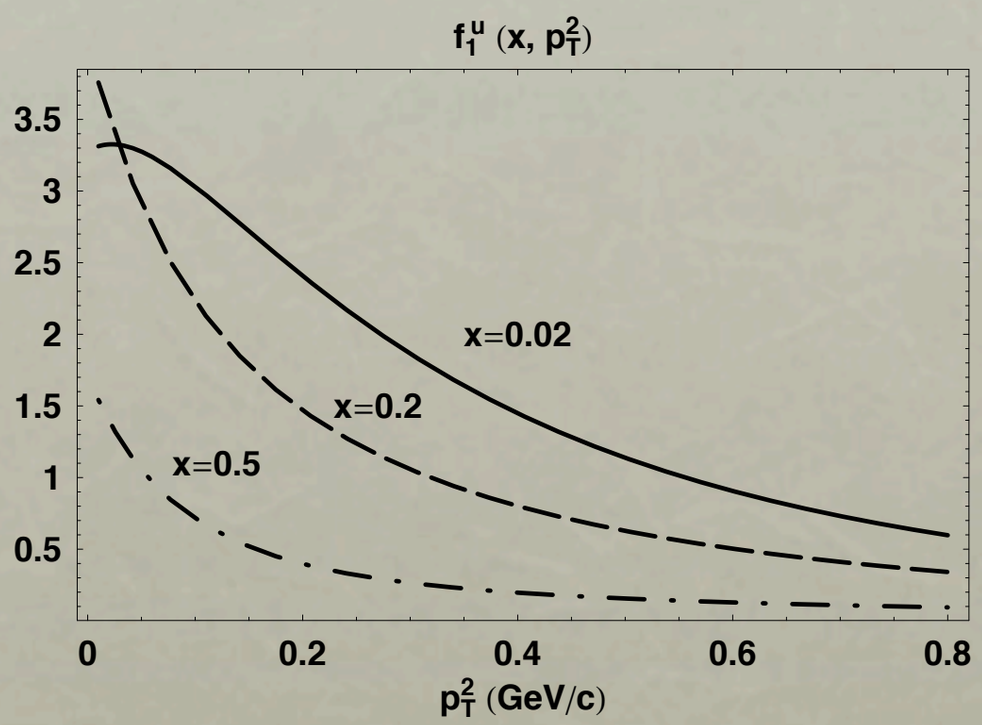

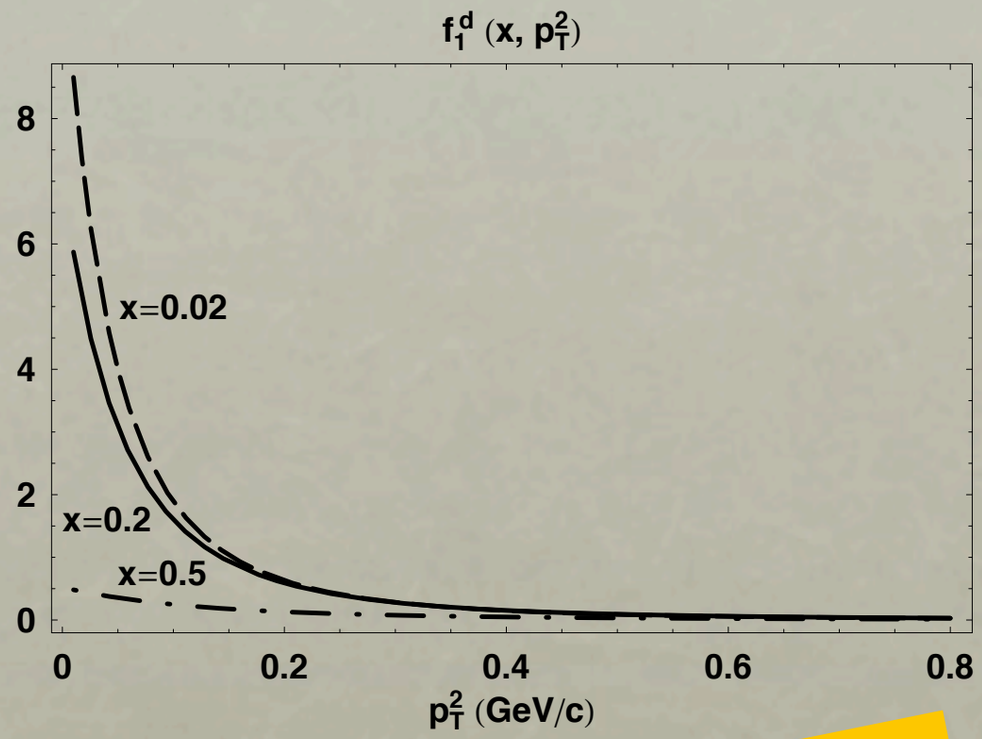

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Fundamental information on the nucleon structure almost as important as standard collinear PDFs

Experimental results

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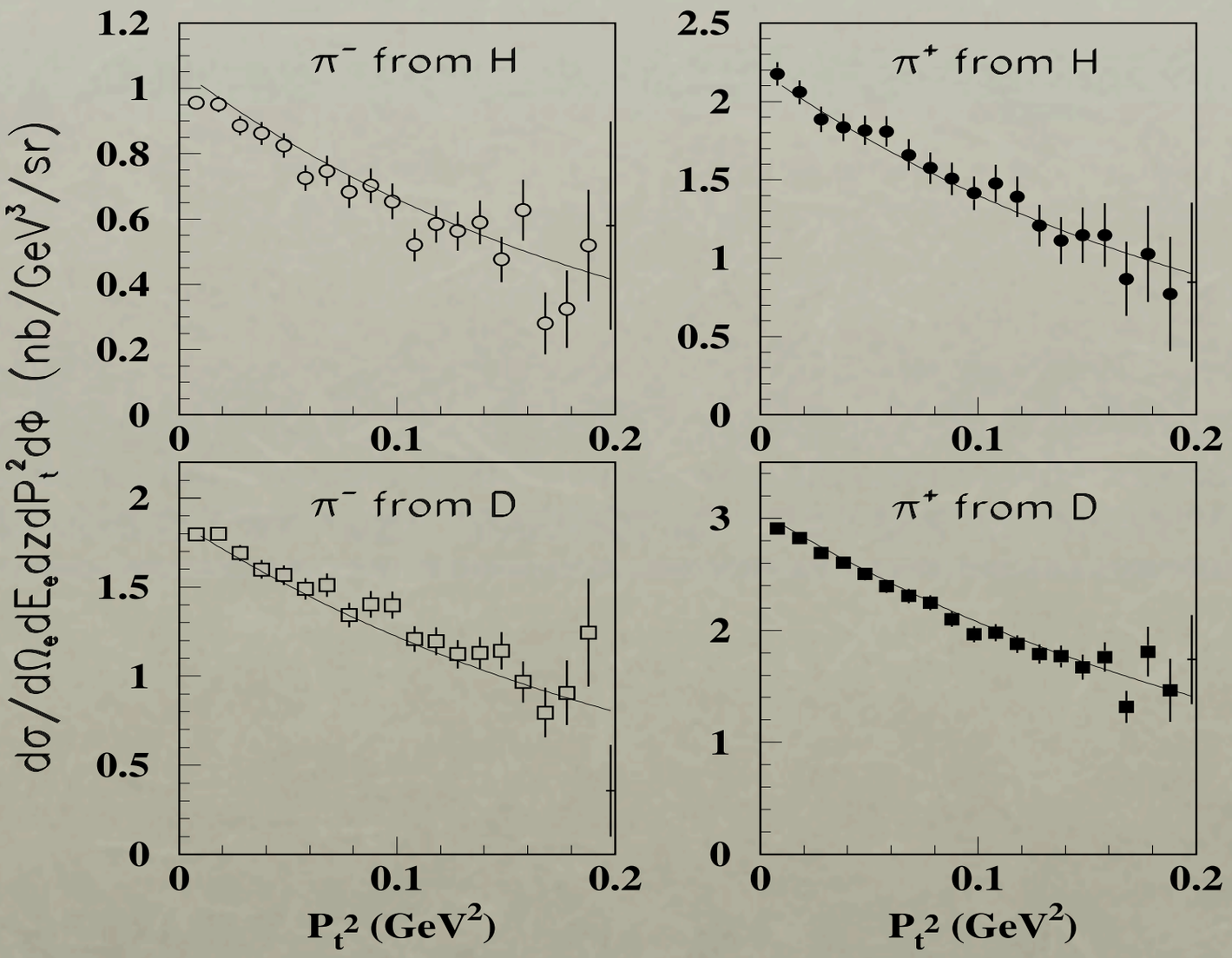
- Interesting analysis done at JLab Hall C: down quarks have higher transverse momentum than up quarks

Mkrtchyan et al., arXiv: 0709.3020

SIDIS data with hadron identification



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

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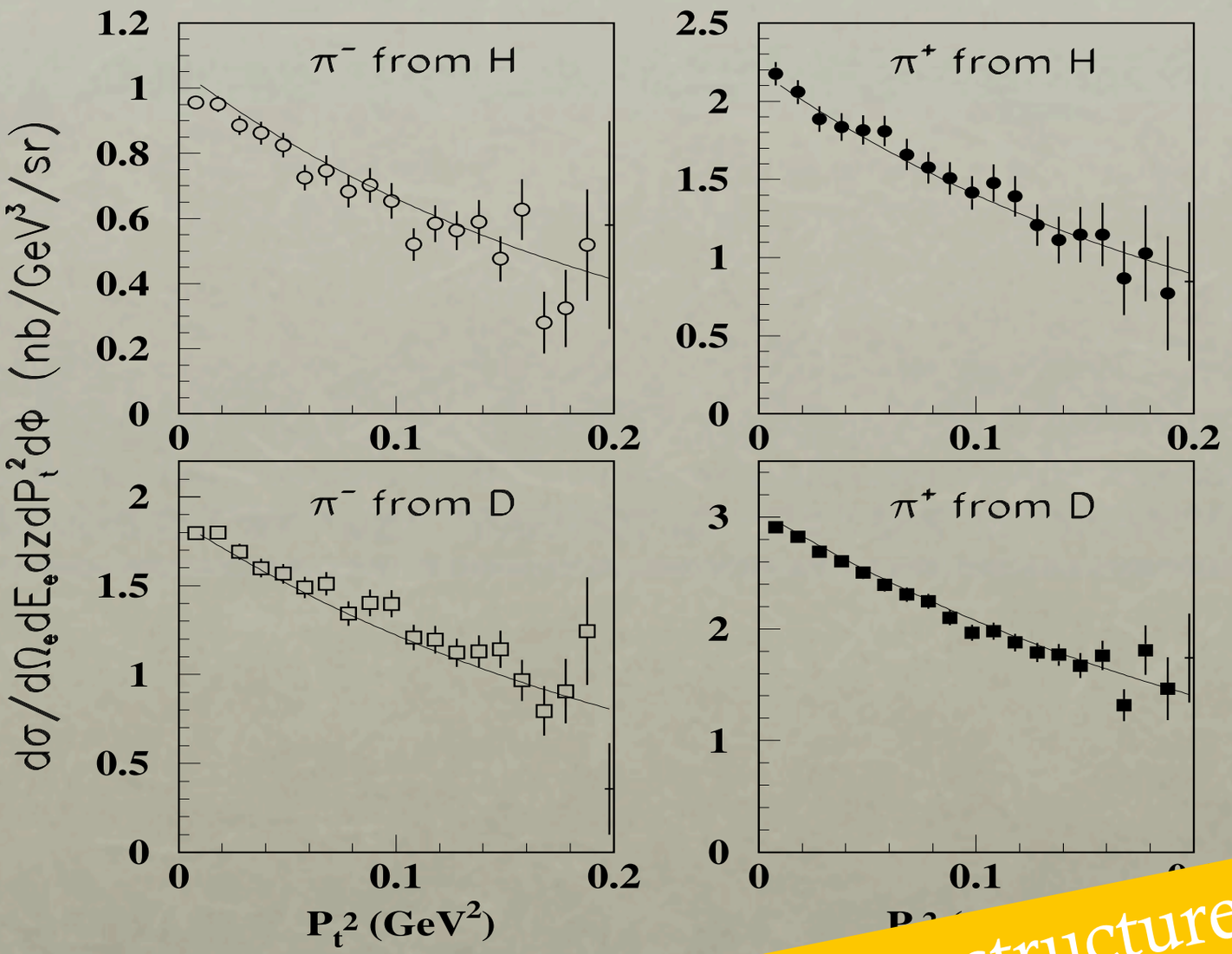
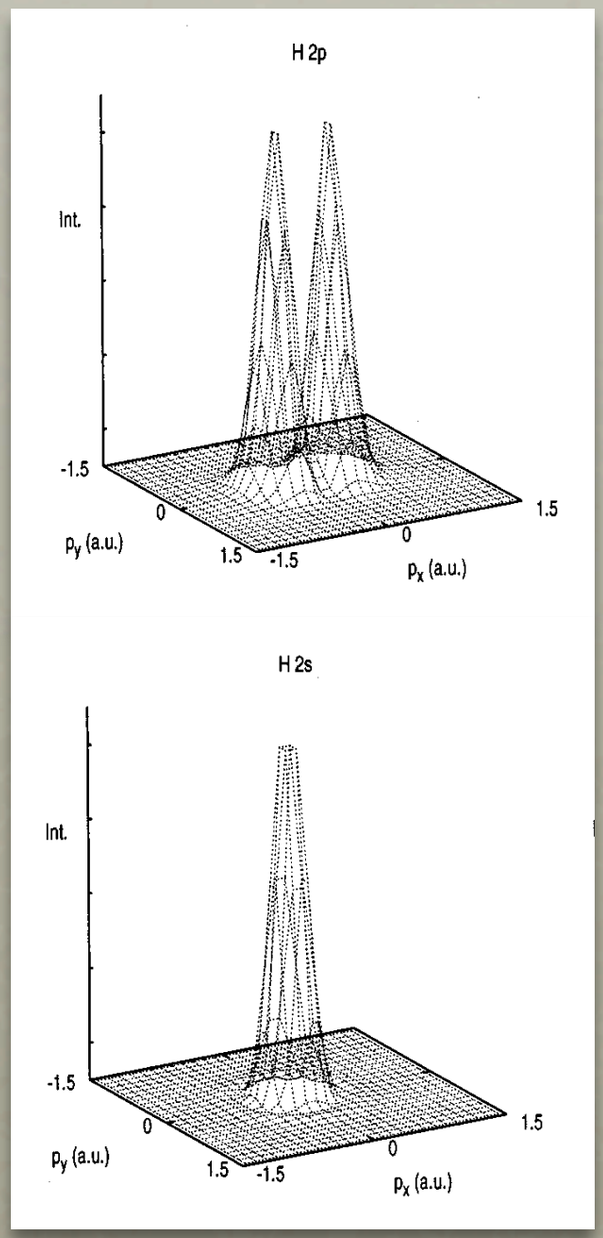


Essential to study flavor structure

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

Orbital angular momentum

Hidrogen atom wavefunctions
in momentum space



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

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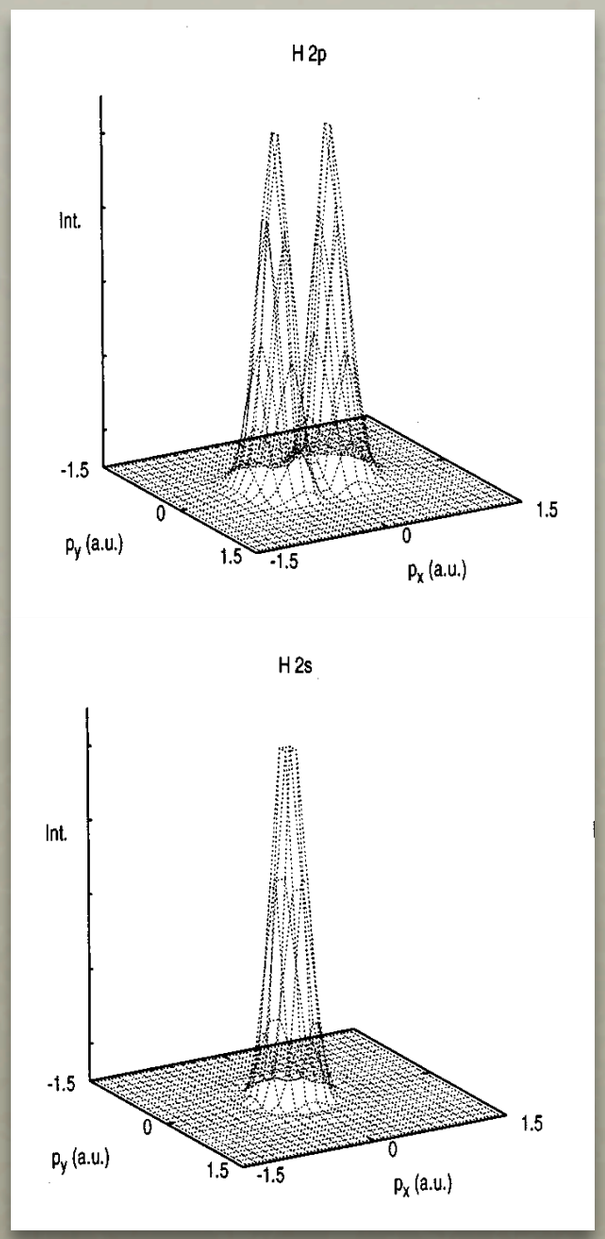

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Vos, McCarthy, Am. J. Phys. 65 (97), 544

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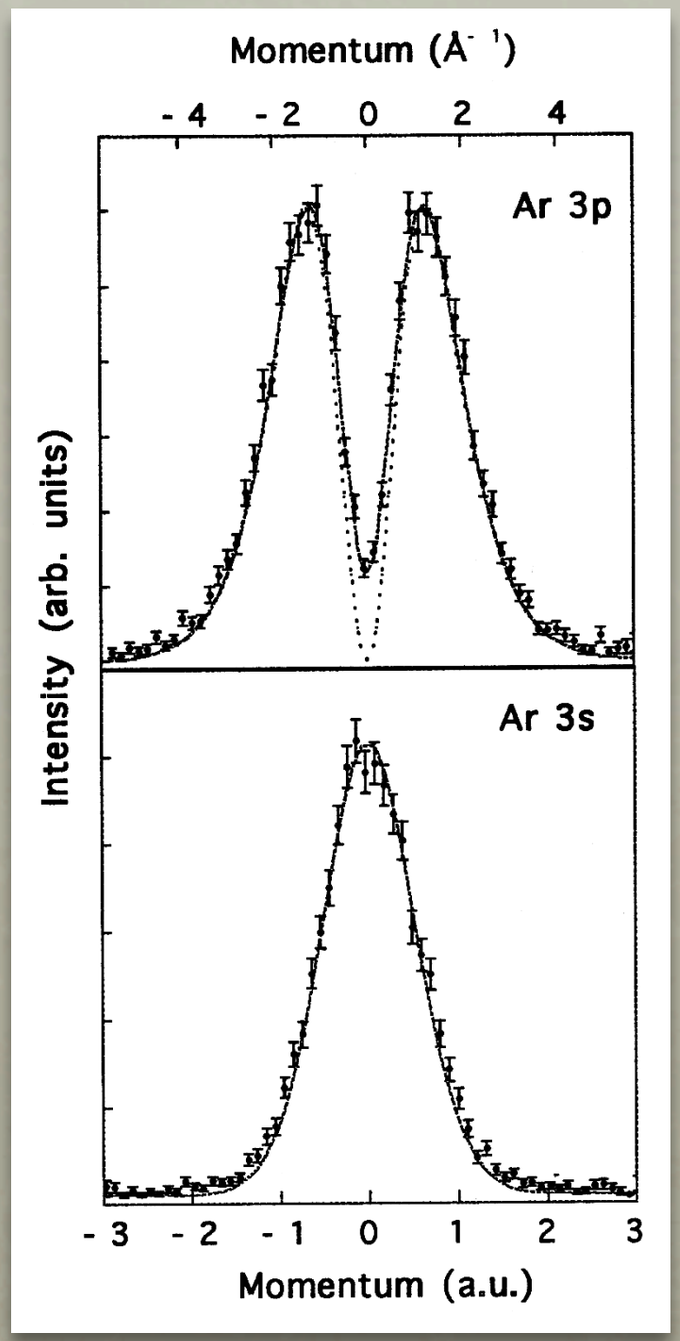

Vos, McCarthy, Am. J. Phys. 65 (97), 544

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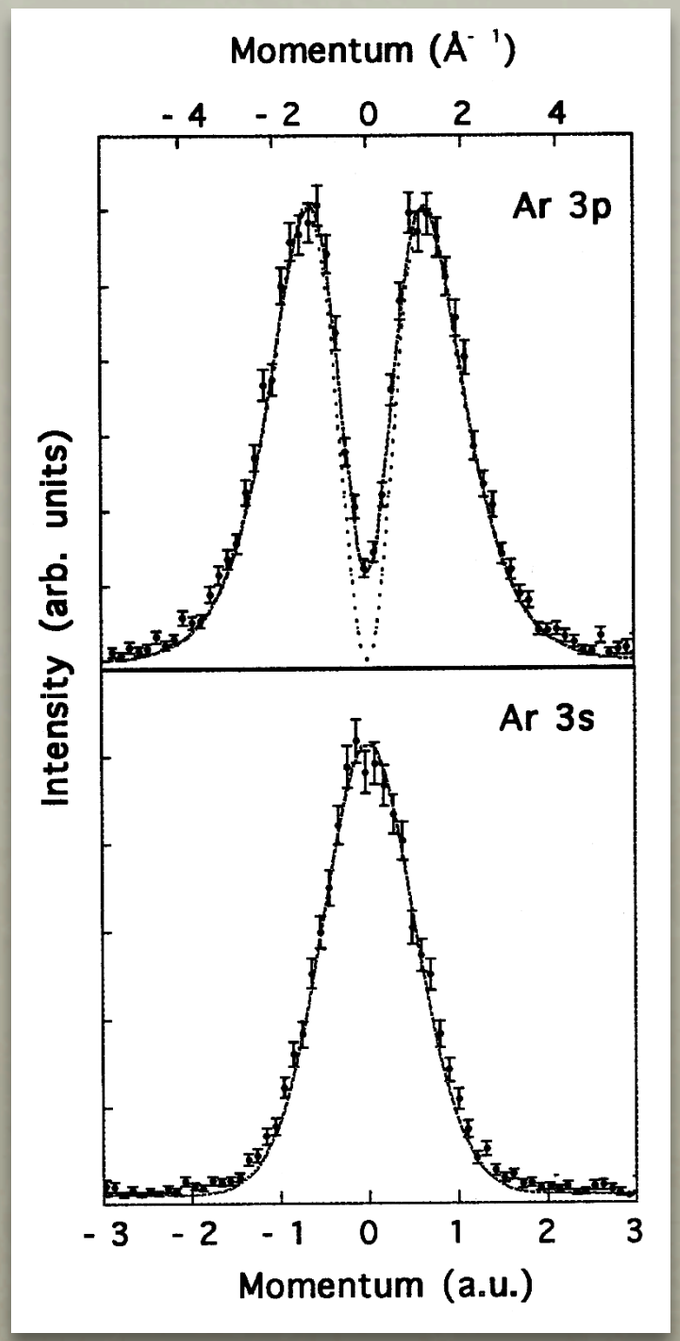

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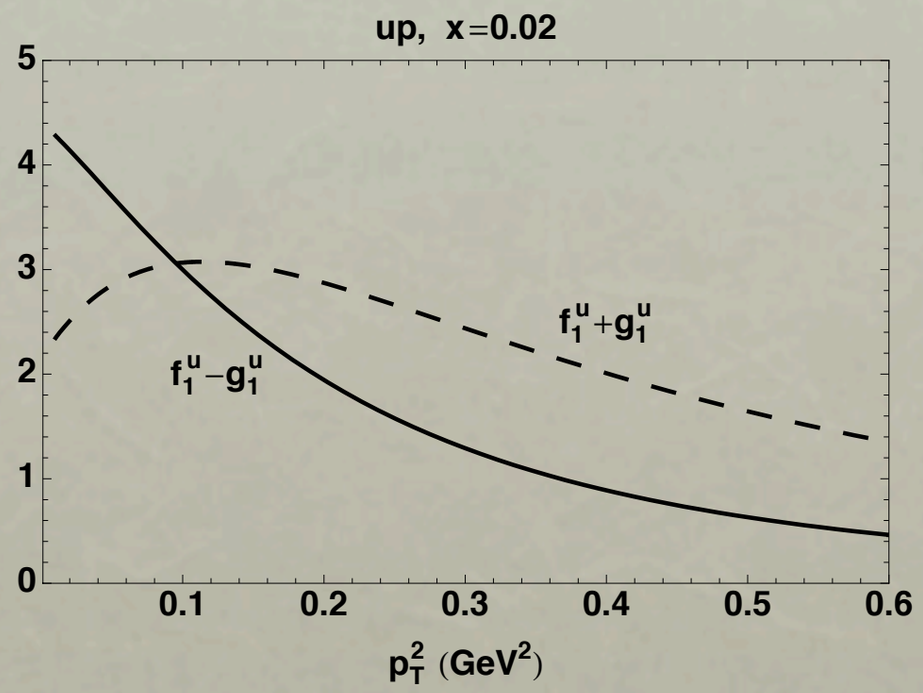
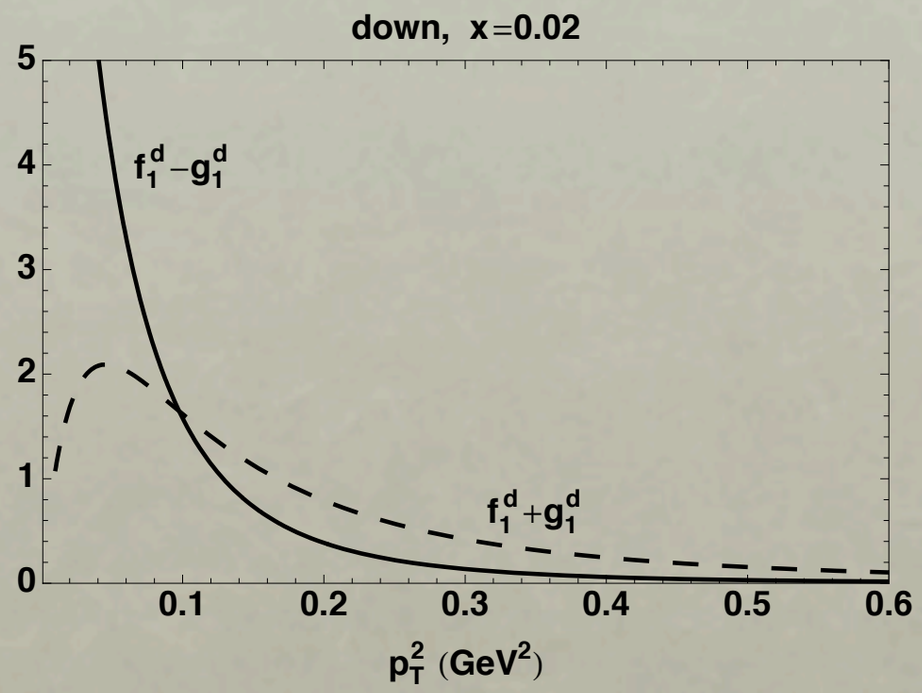
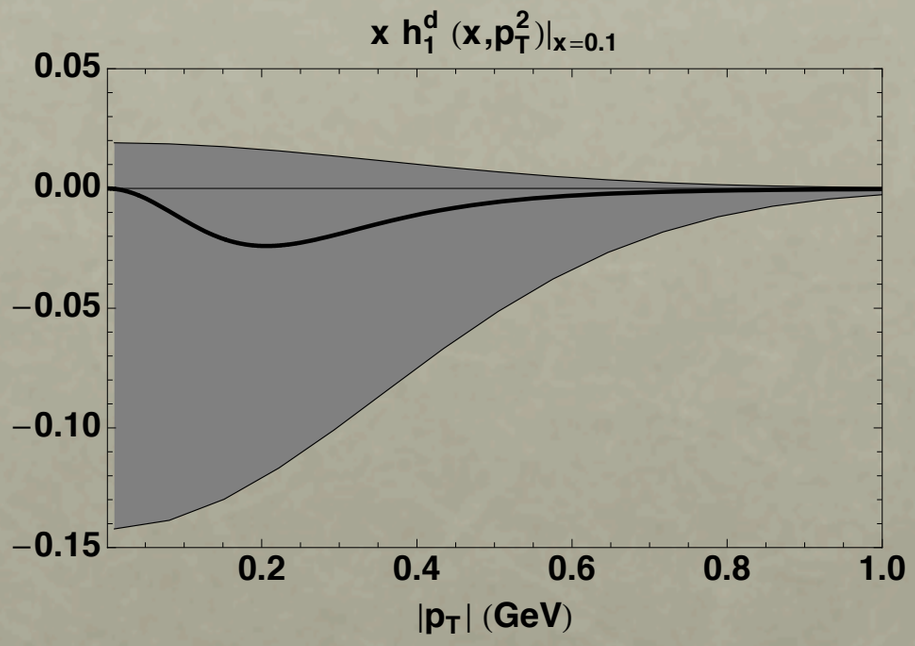
$$\text{At low } p_T \ |\psi_{p-\text{wave}}|^2 \sim p_T^2$$

TMDs and orbital angular mom.







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

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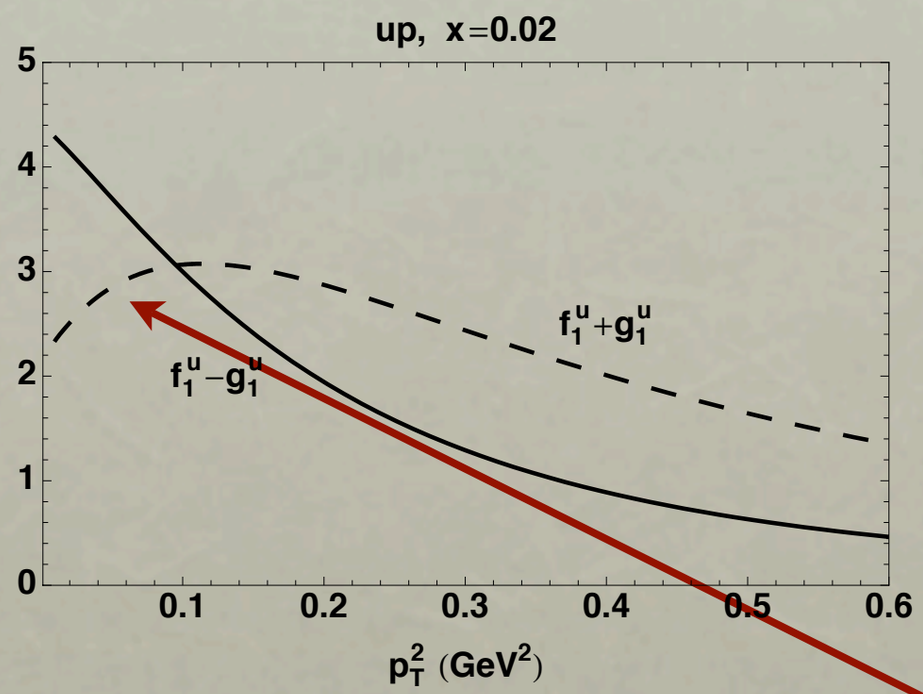

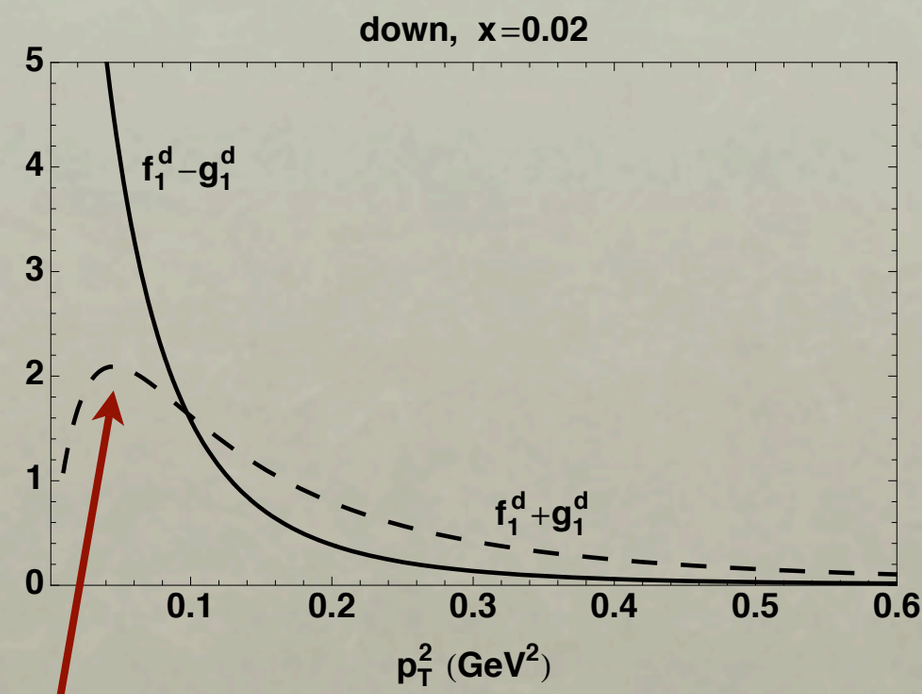

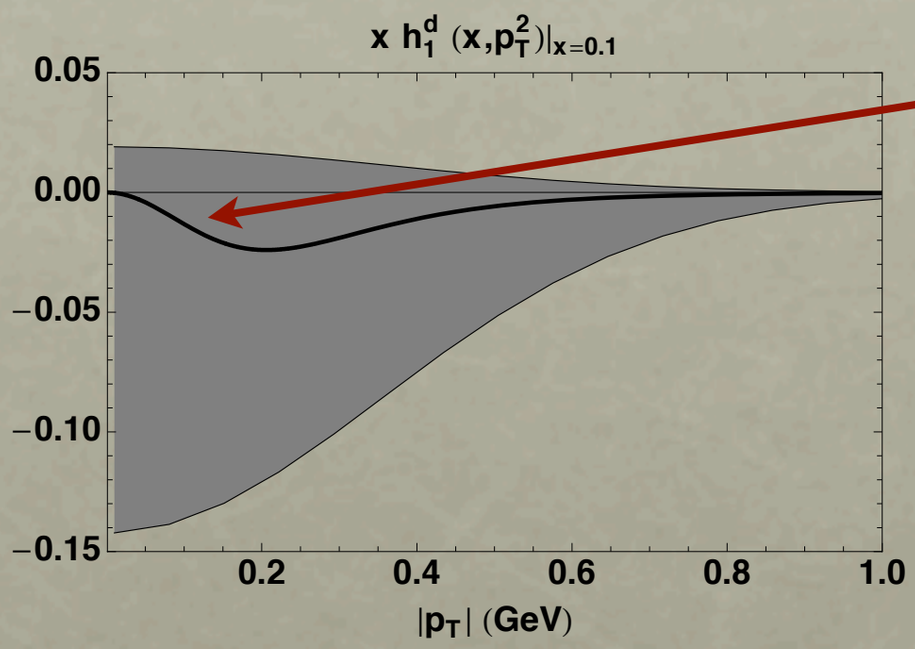

Signs of orbital ang. mom.

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

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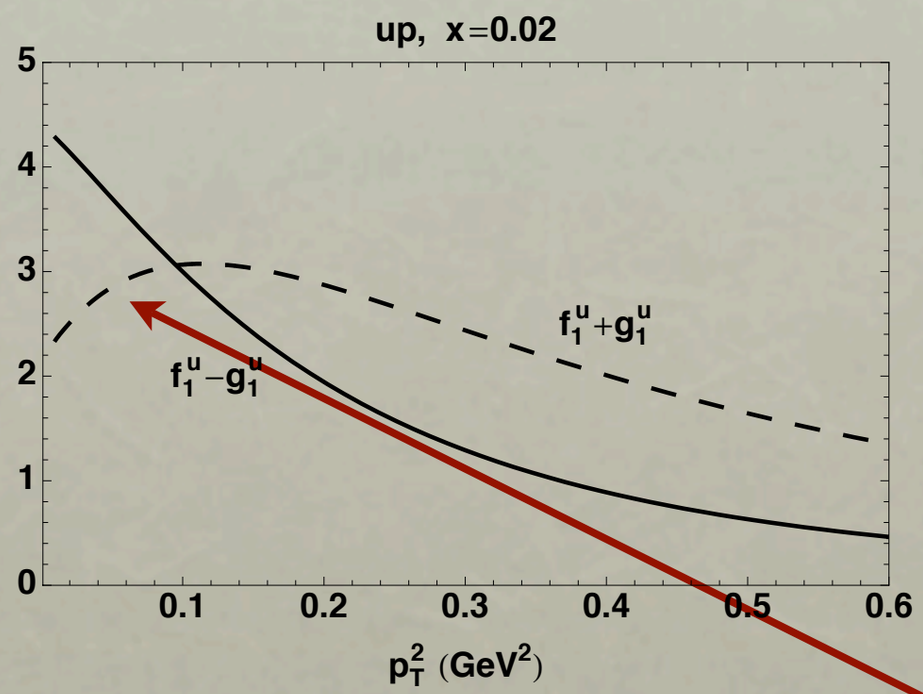

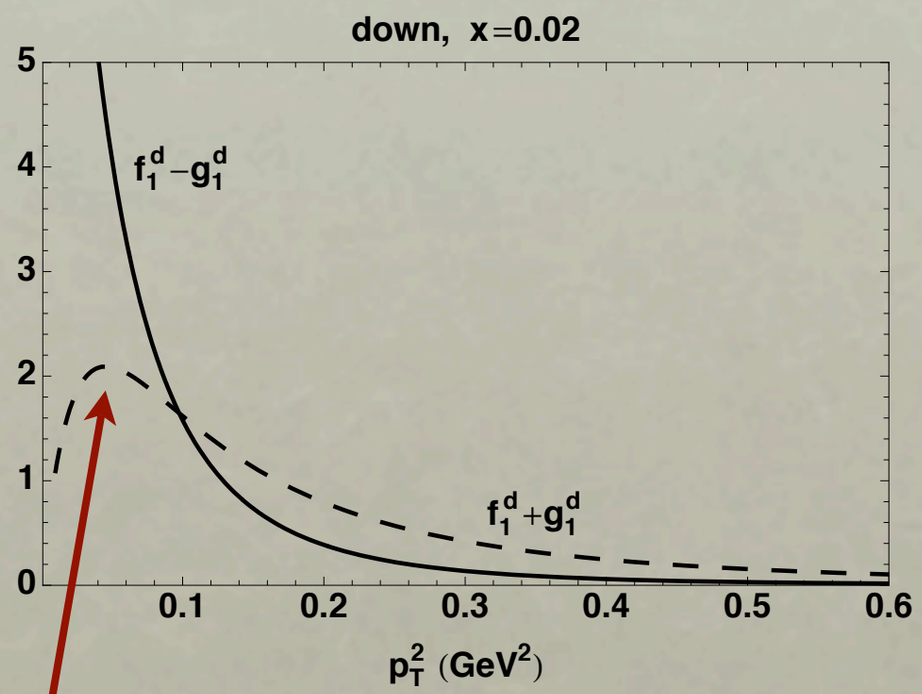

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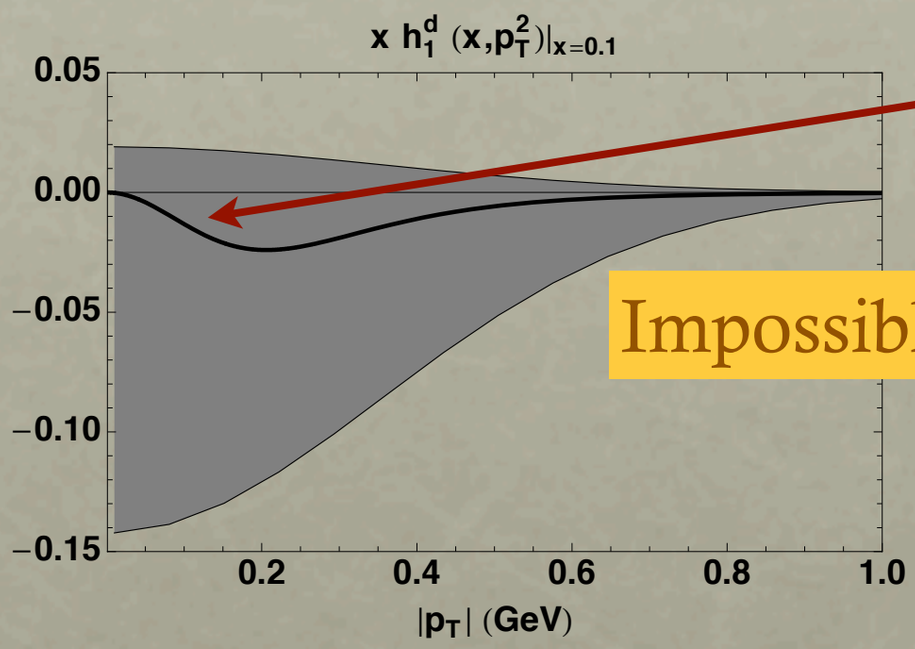

Impossible to reproduce using simple Gaussians

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

TMDs and orbital angular mom.

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Twist-2 TMDs

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TMDs and orbital angular mom.

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Twist-2 TMDs

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- Any quantitative statement about the total orbital angular momentum is model-dependent

Sivers function

Two ingredients

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

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

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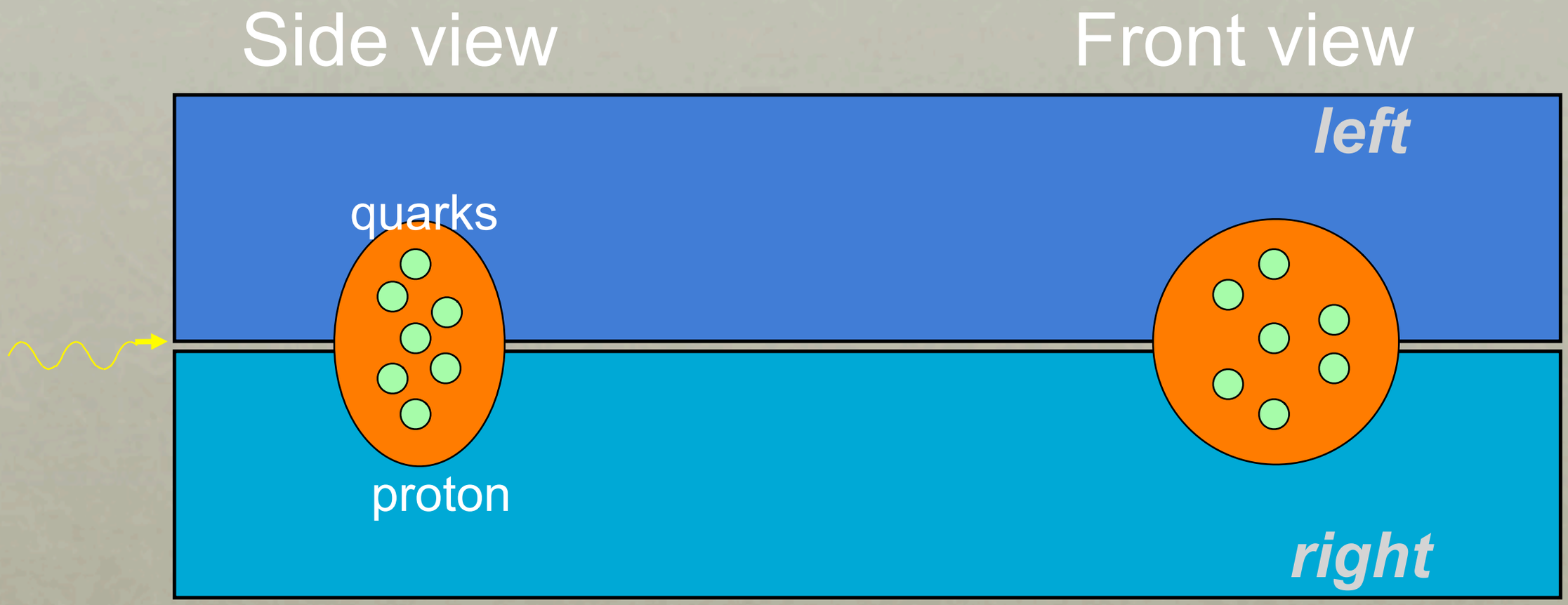
Burkardt, PRD 66 (02); Diehl, EPJ C25 (02); Diehl, Hägler, EPJ C44 (05)

Final-state interactions

Side view

Front view

Final-state interactions



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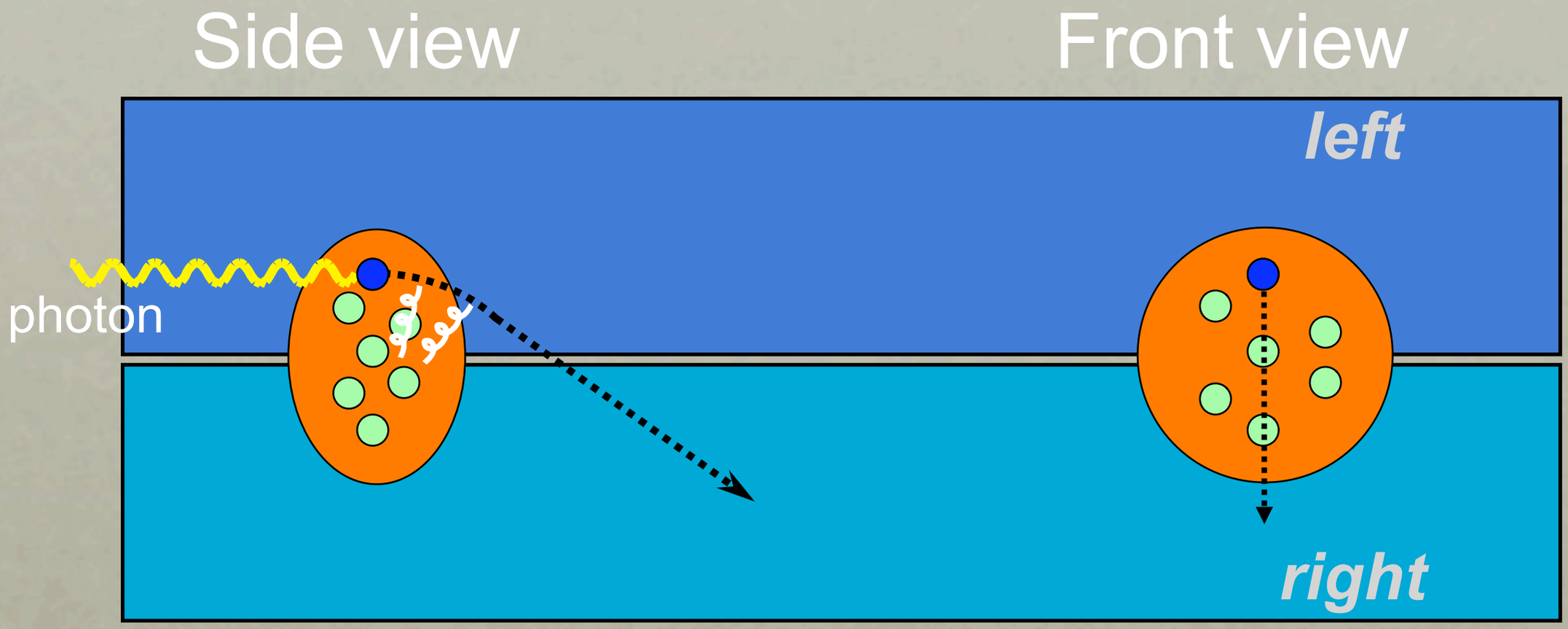
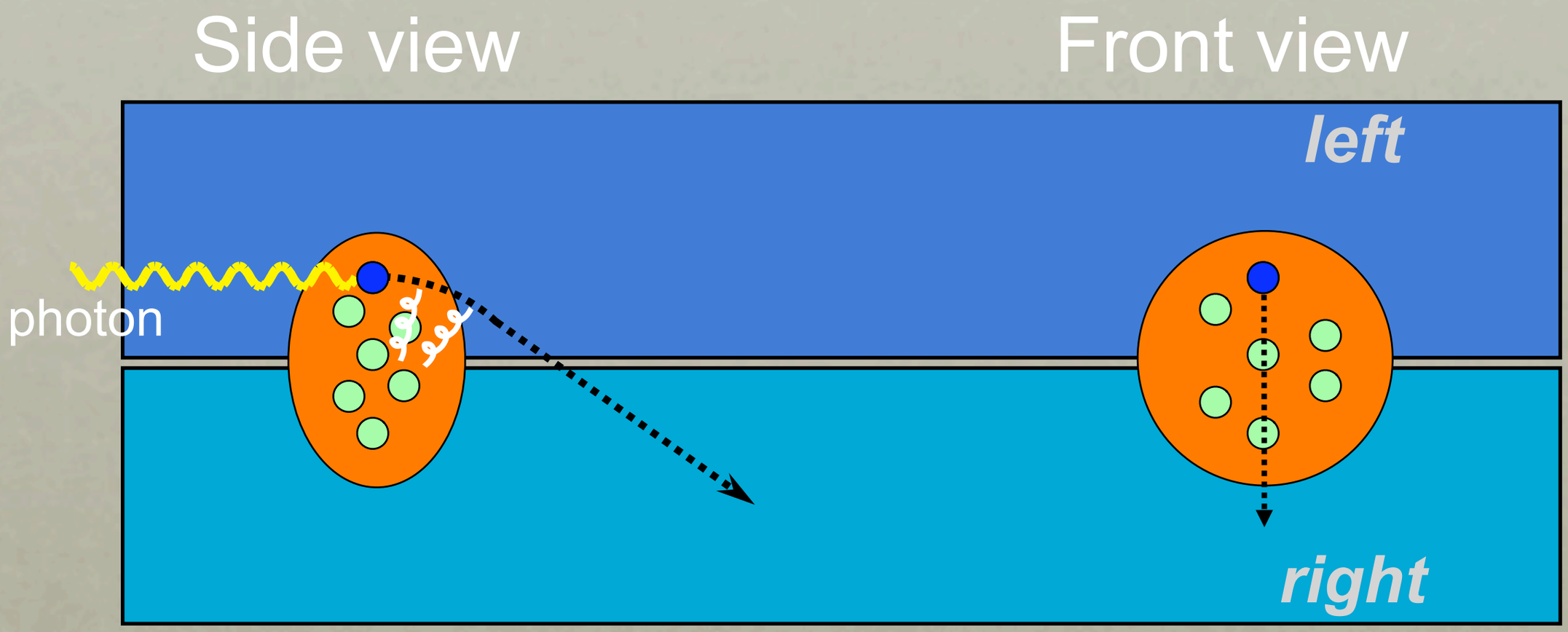
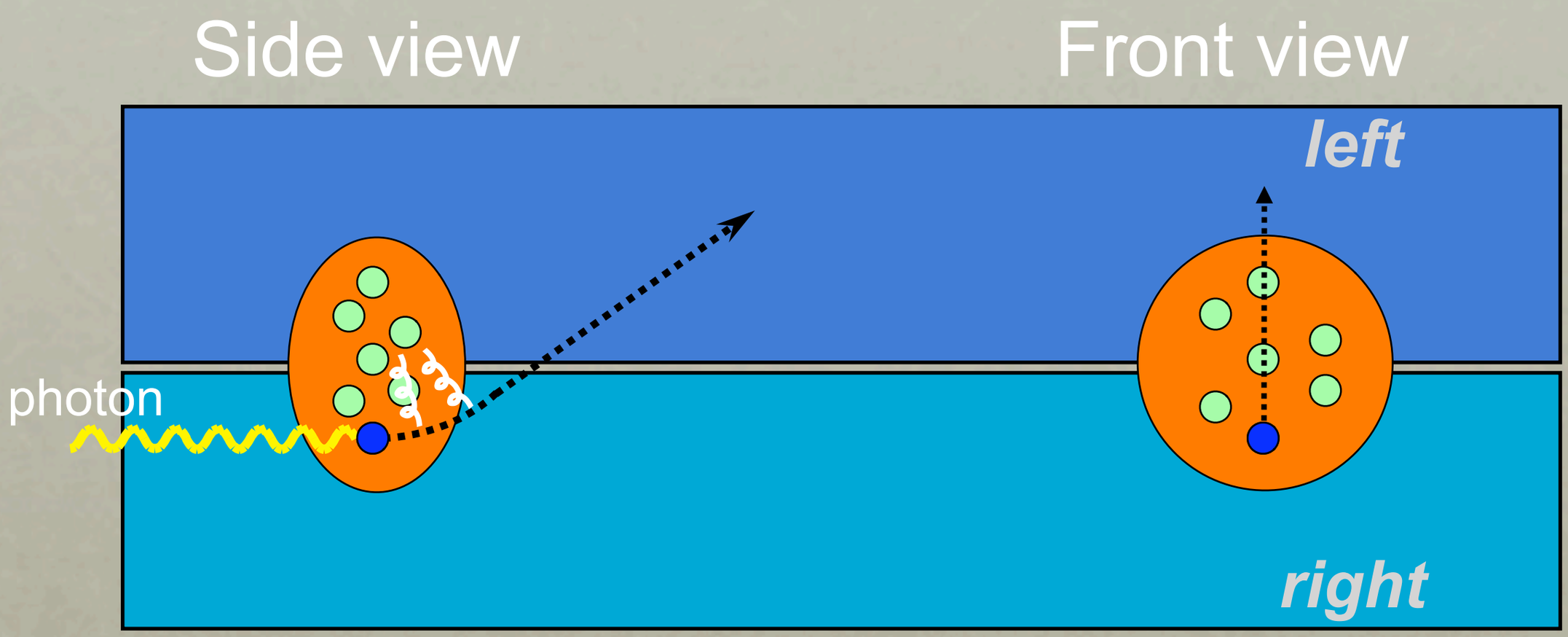


Final-state interactions



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

Final-state interactions



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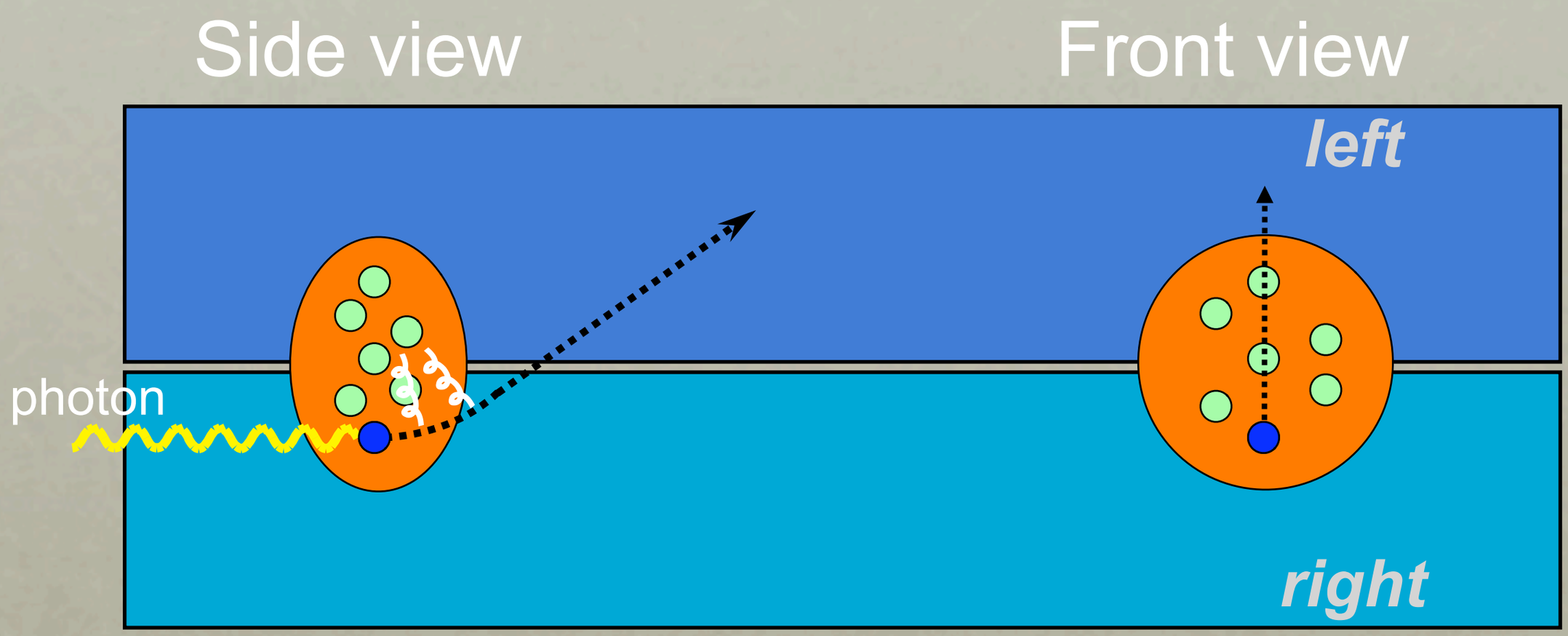
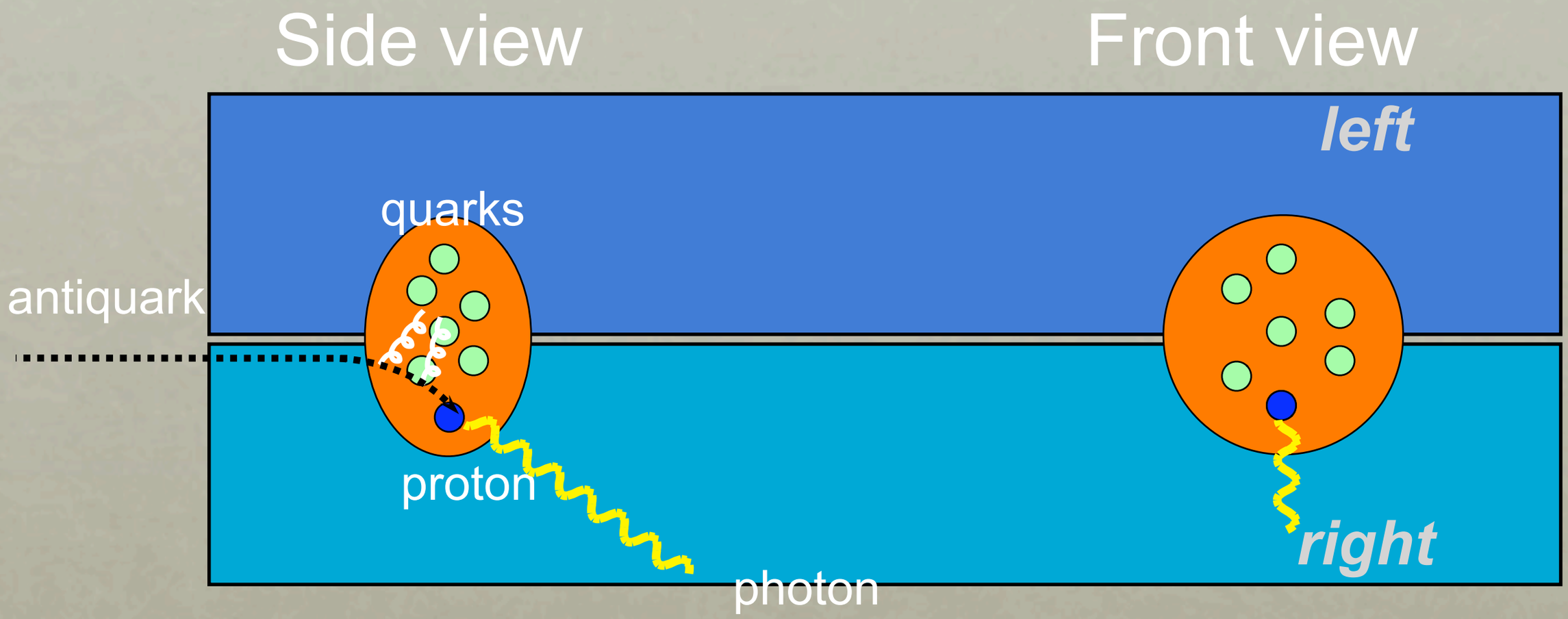


Chromodynamic lensing

Burkardt, PRD 66 (02)

Change of sign in Drell-Yan



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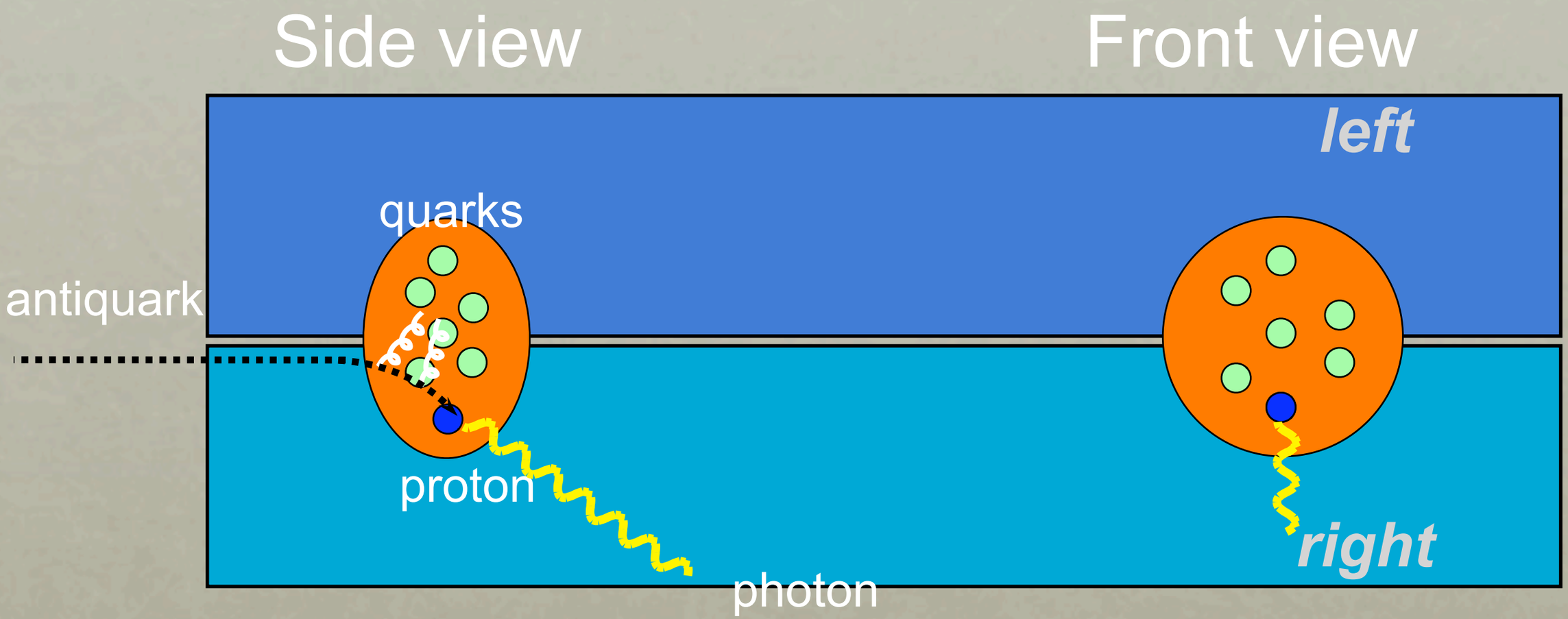
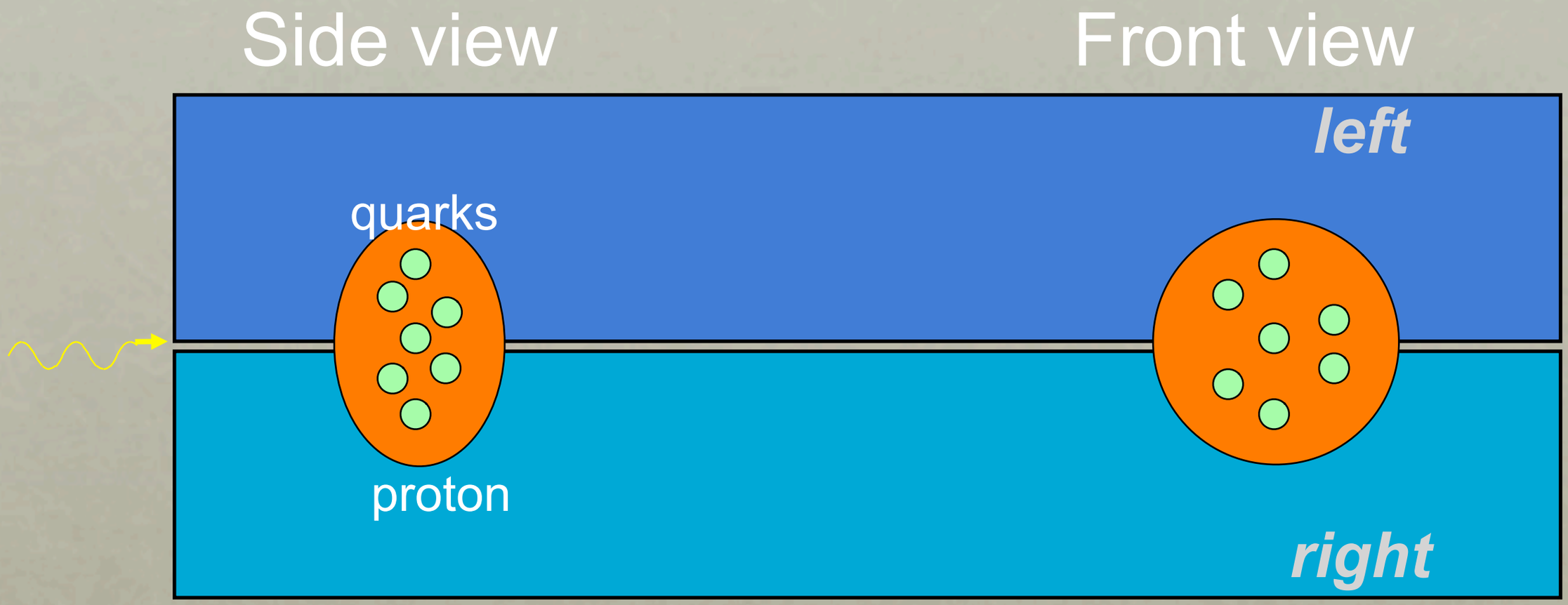


Clear-cut prediction of QCD

Collins, PLB 536 (02)

Distortions in transverse space



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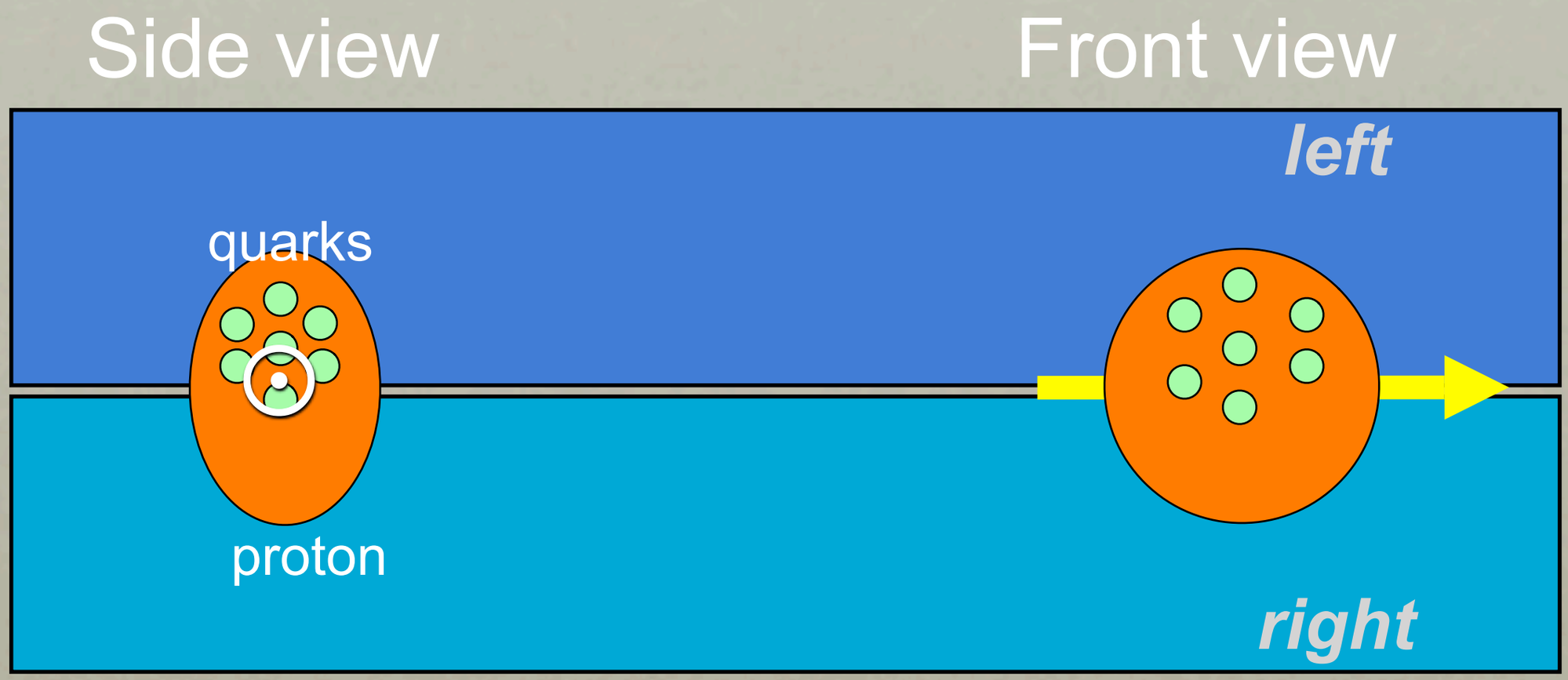

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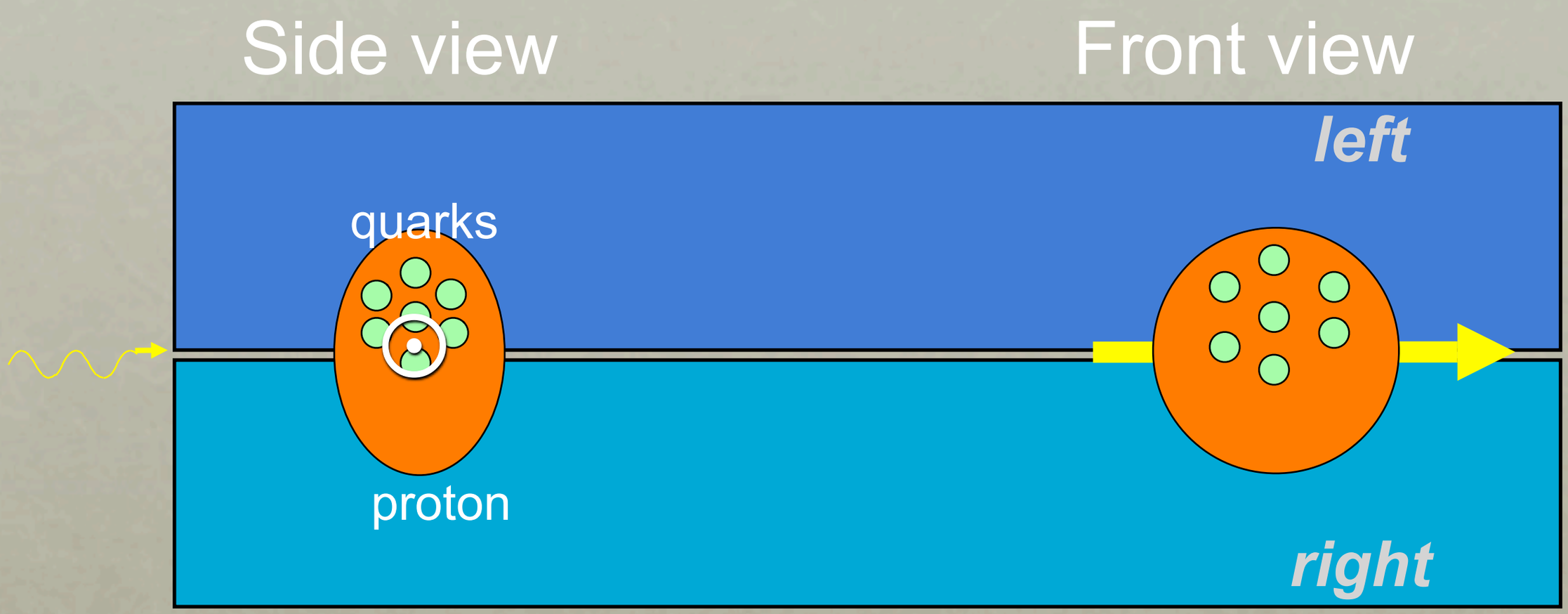

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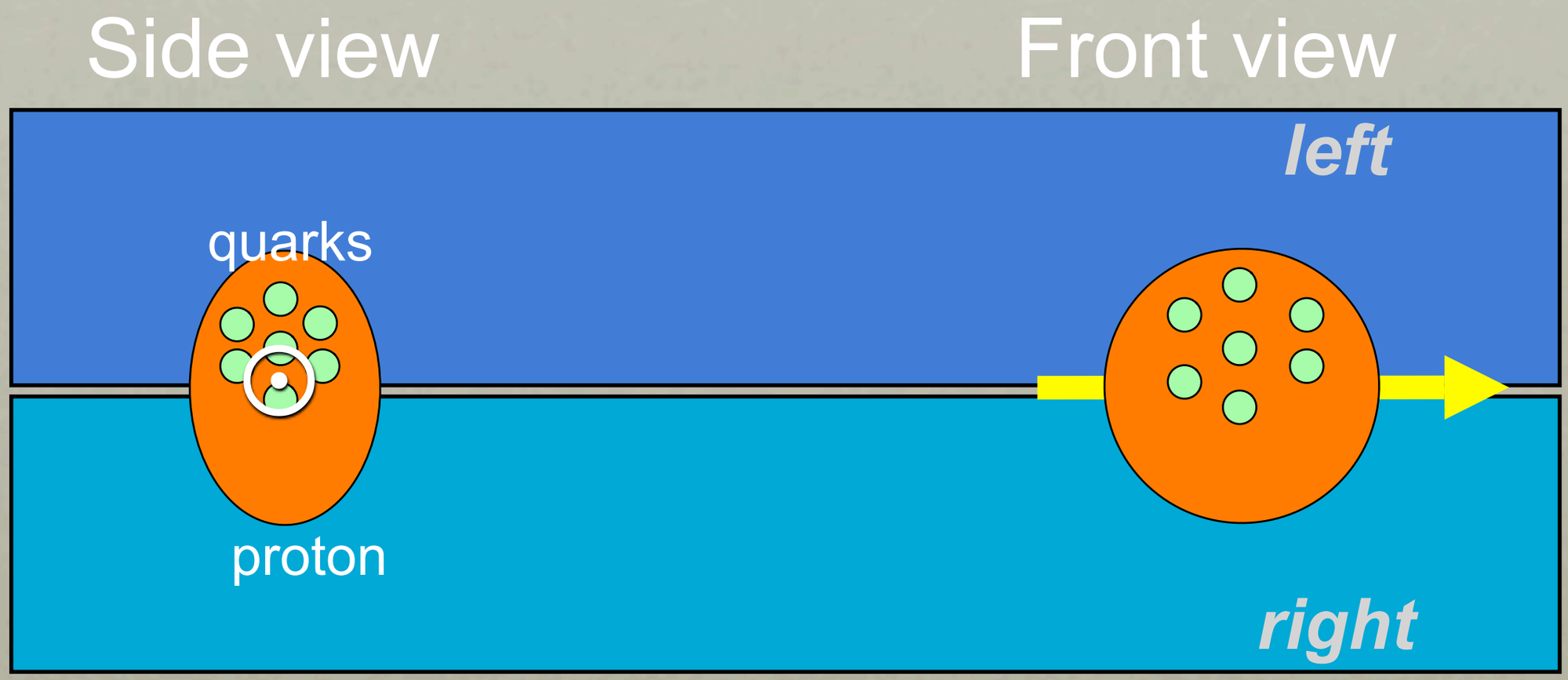

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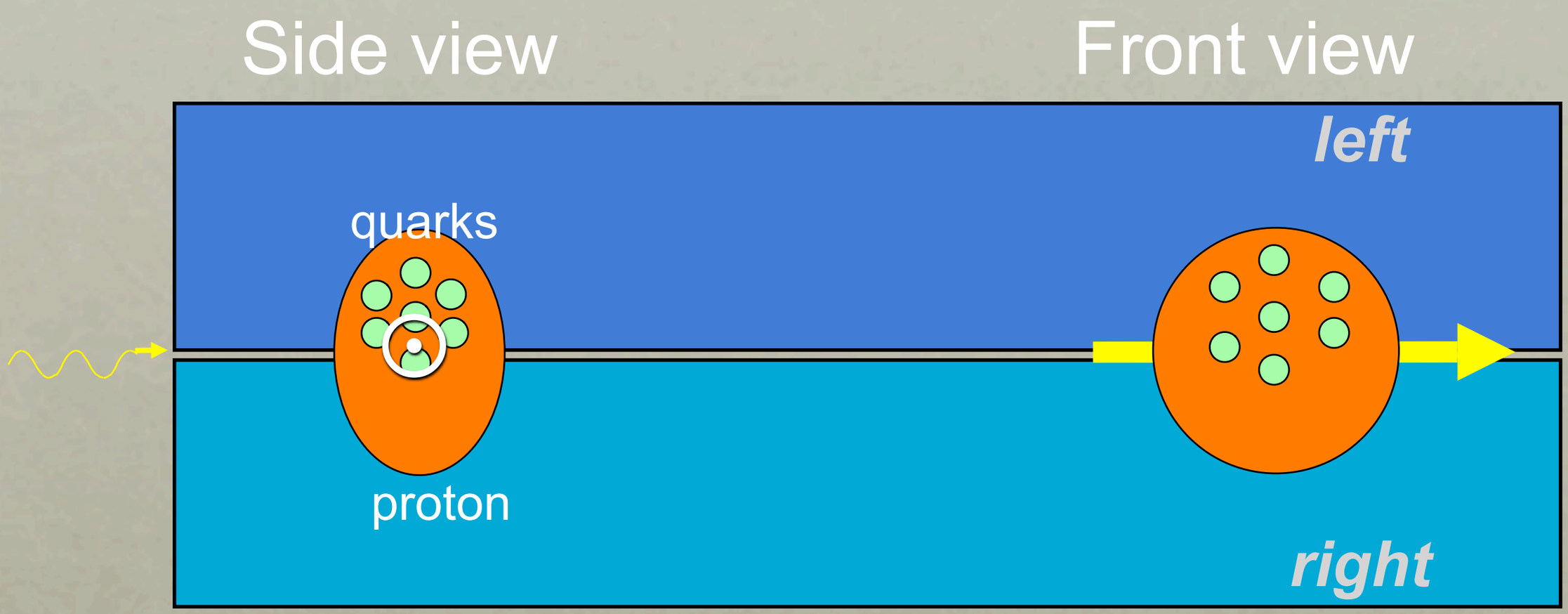
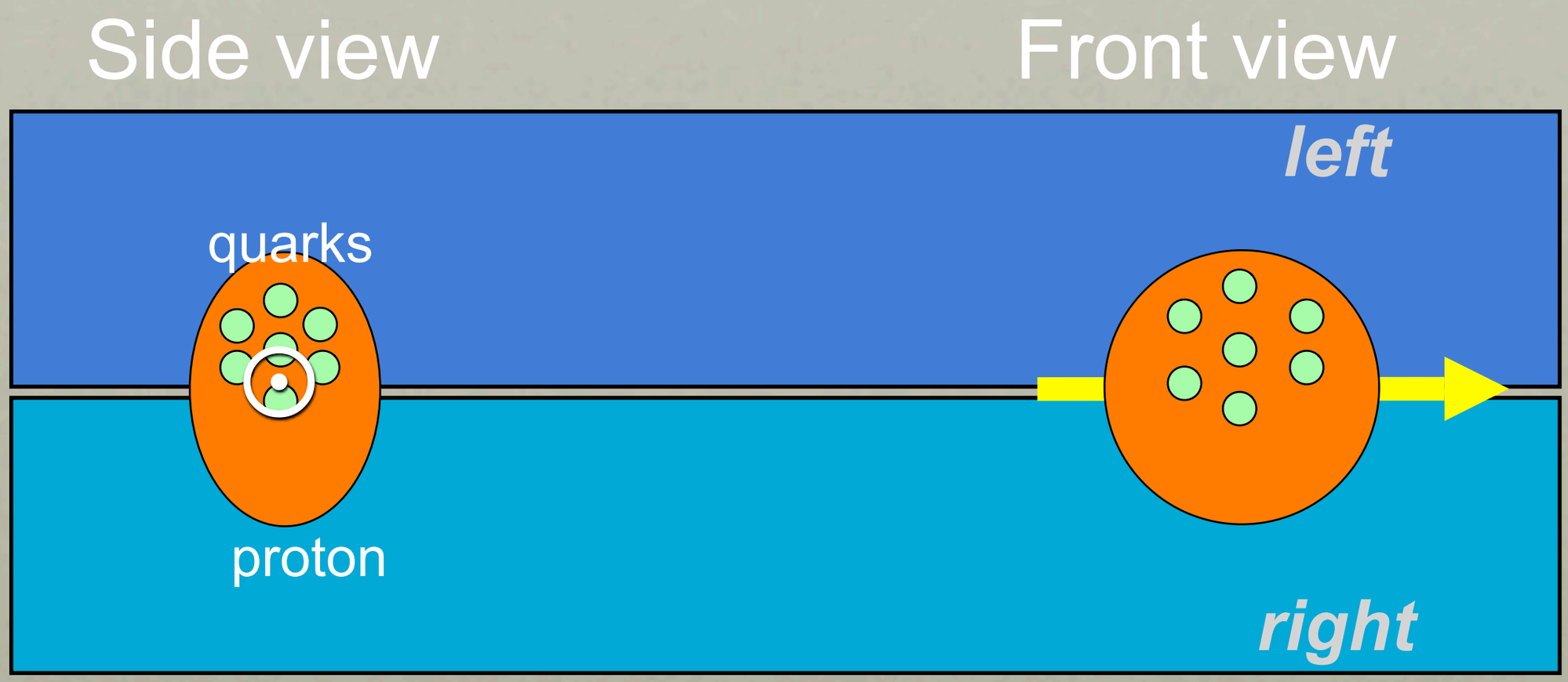


The presence of spin can distort the distribution of quarks in transverse space (orbital angular momentum of quarks is required)

Distortions in transverse space



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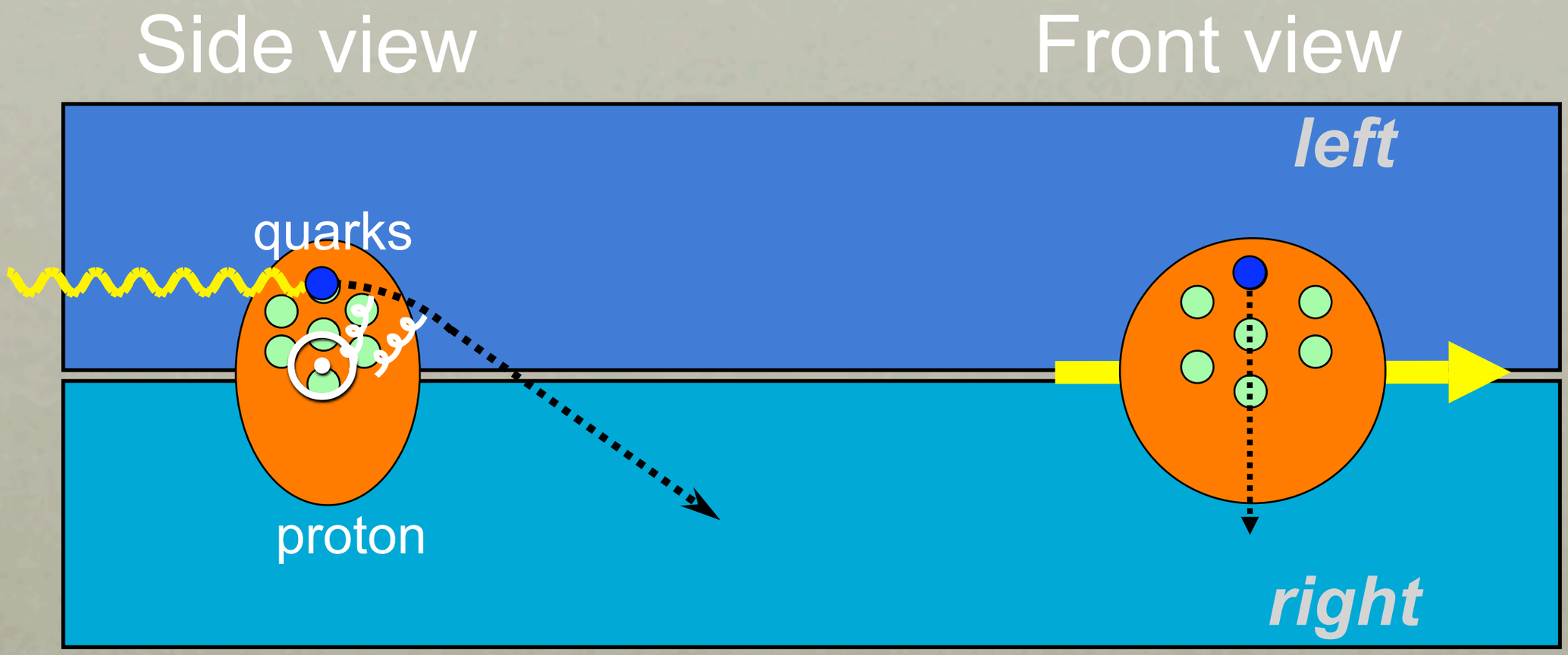

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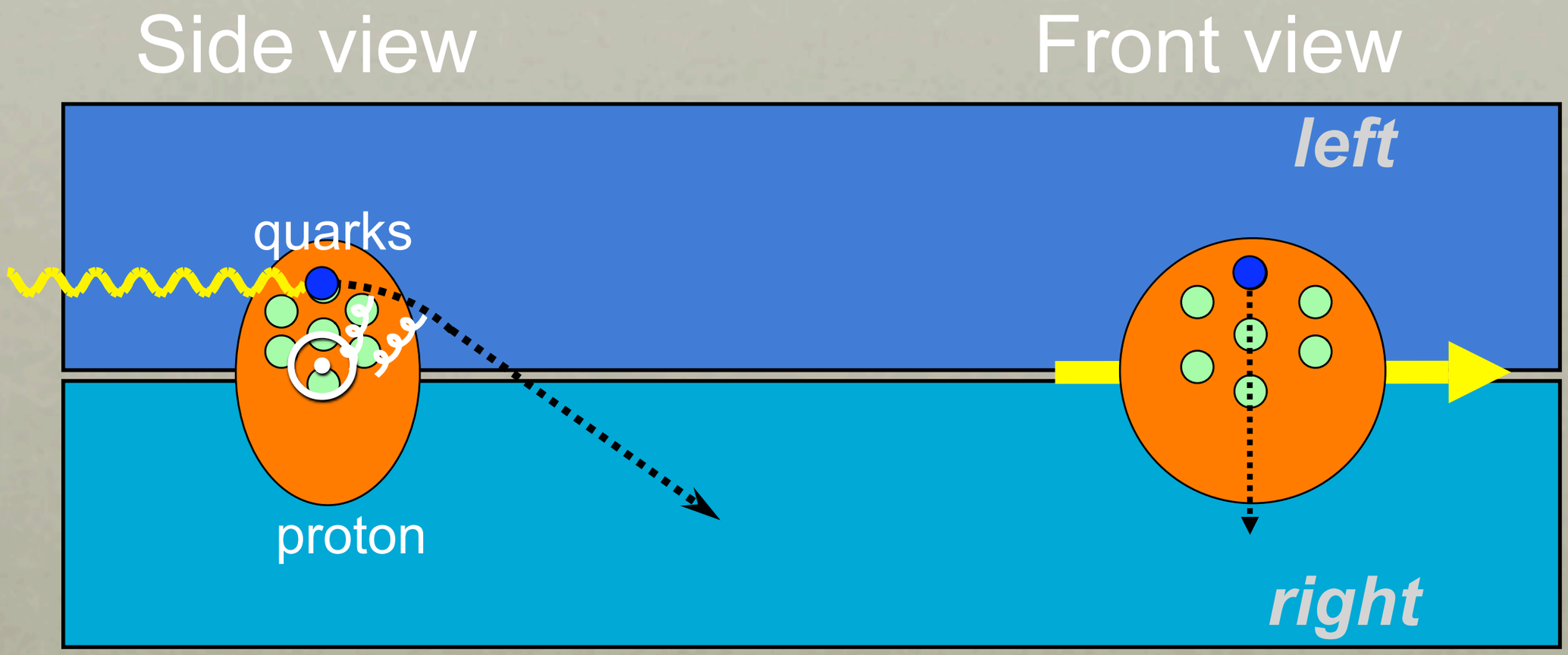
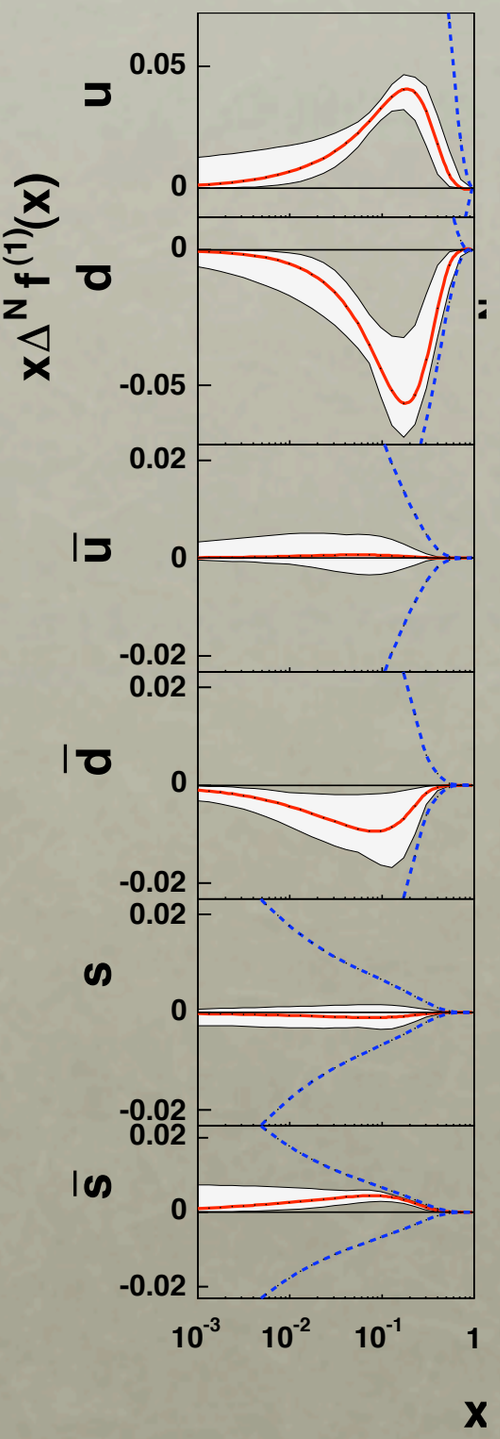


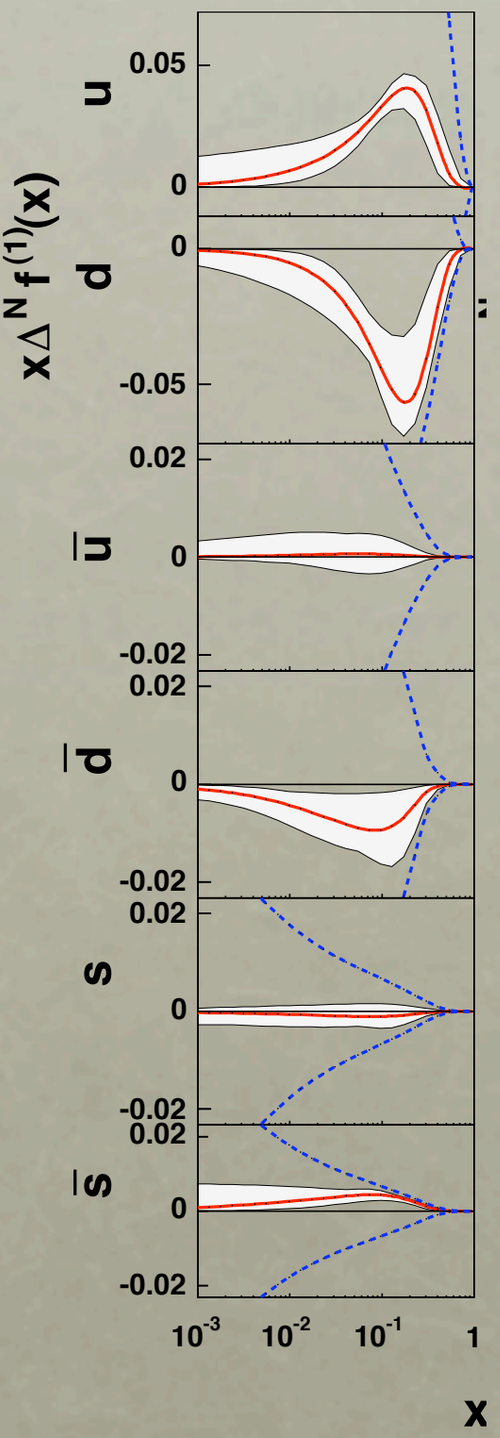
The presence of spin can distort the distribution of quarks in transverse space (orbital angular momentum of quarks is required)

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

Sivers function extraction

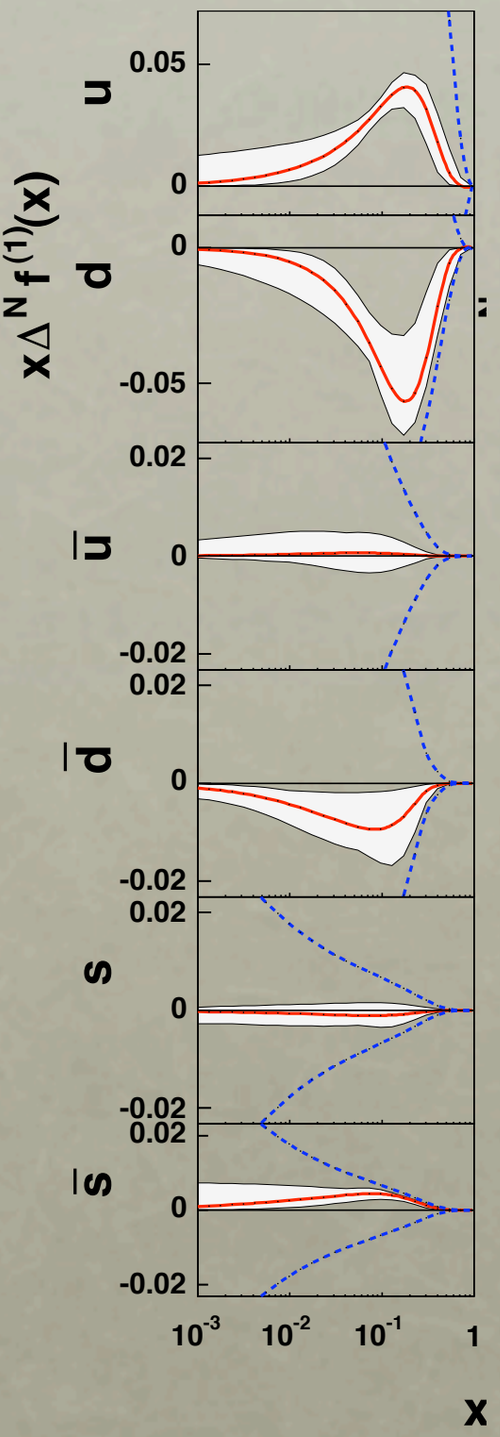


Sivers function extraction



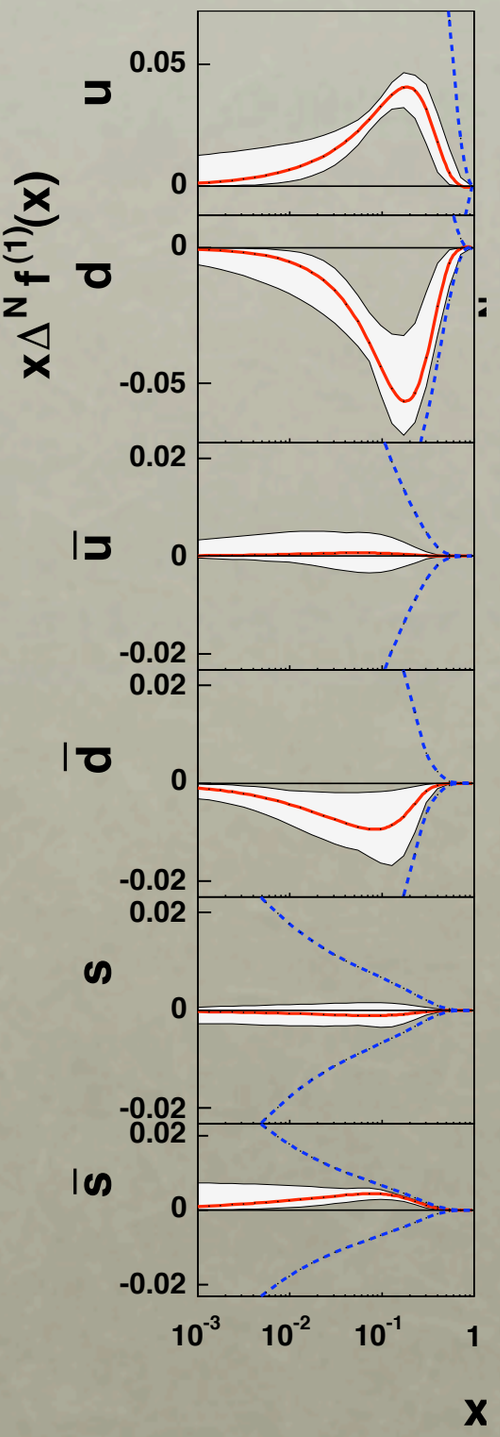
- Data from HERMES, COMPASS (deuteron)

Sivers function extraction



- Data from HERMES, COMPASS (deuteron)
- 96 data points (cf. 467 points for Δq fits)

Sivers function extraction



- Data from HERMES, COMPASS (deuteron)
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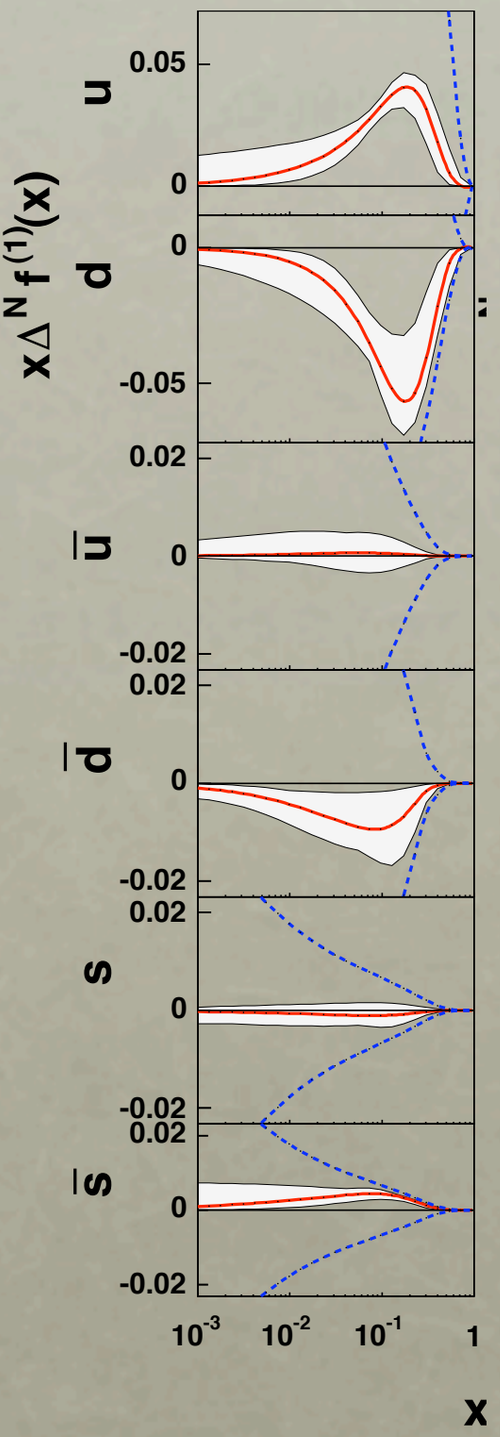
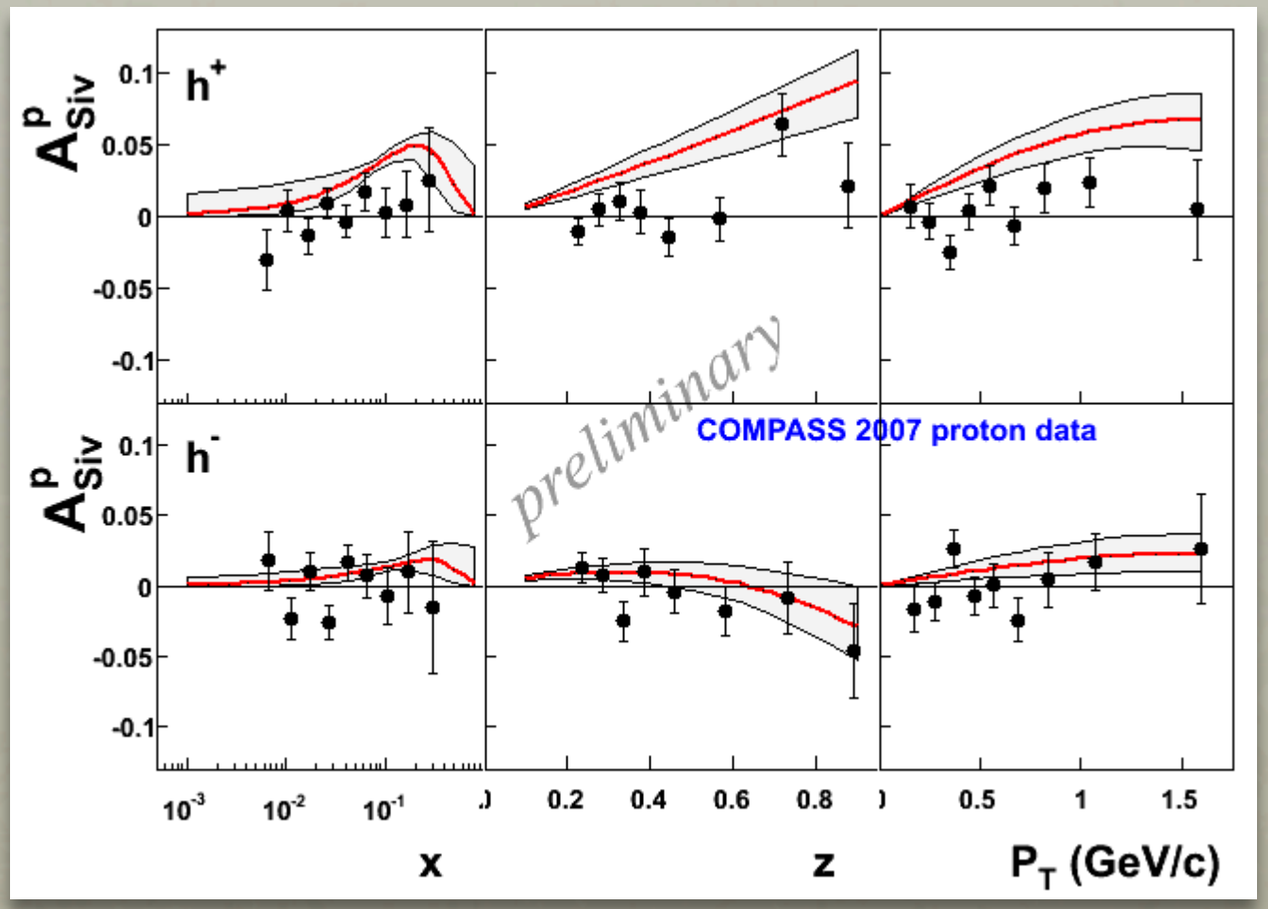


- Data from HERMES, COMPASS (deuteron)
- 96 data points (cf. 467 points for Δq fits)
- $\chi^2 \approx 1.0$
- Statistical uncertainty only ($\Delta\chi^2 \approx 17$)

Sivers function: COMPASS



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

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