What can we learn from TMDs measurements?

Alessandro Bacchetta

Jefferson Lab
N. Isgur Fellowship

Outline

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- 3D structure of the nucleon in momentum space

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- Orbital angular momentum

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- Many interesting topics will be left out
- Many topics were already touched in the talks by M. Burkardt, M. Anselmino, F. Yuan, R. Joosten, N. Makins and several others
- A consensus on the relevance of TMDs is growing

Transverse Momentum Distributions (TMDs)

$$f_1^q(x, p_T^2) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle\Big|_{\xi^+=0}$$

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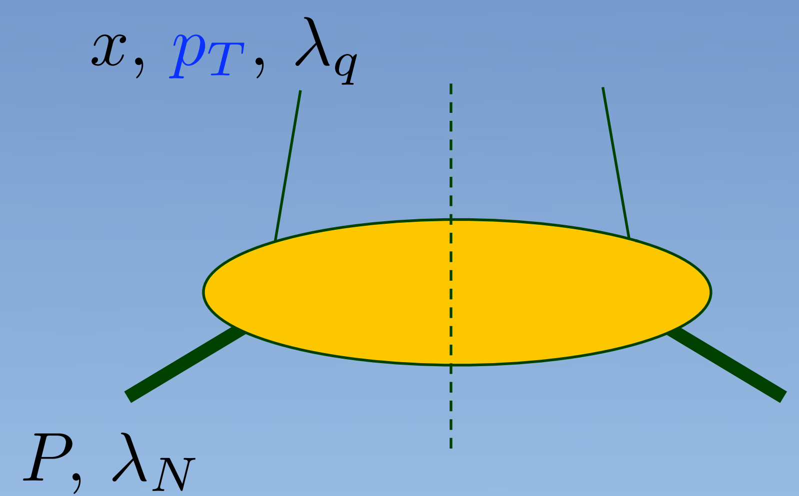

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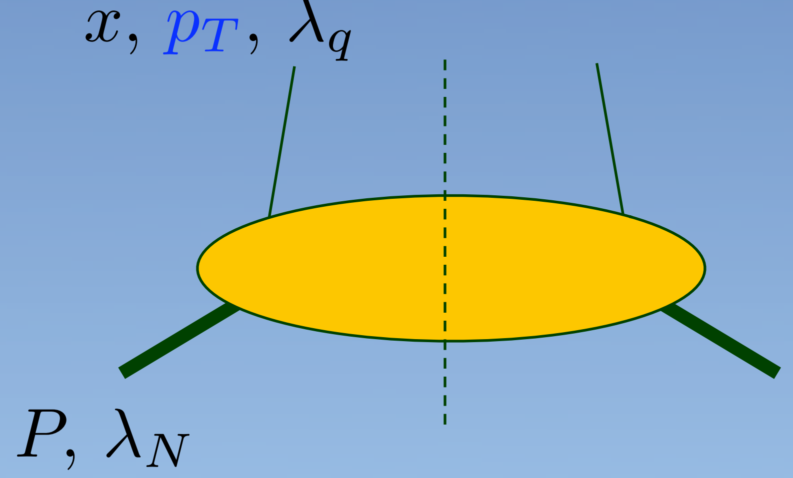

$$f_1(x, p_T^2) = \frac{1}{16\pi^2}\left(|\psi_+^+(x, p_T)|^2 + |\psi_-^+(x, p_T)|^2\right)$$

Transverse Momentum Distributions

see e.g. A.B., Diehl, Goeke, Metz, Mulders, Schlegel, JHEP093 (07)

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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

TMDs in black survive transverse-momentum integration
TMDs in red are T-odd

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quark pol. (columns) / nucleon pol. (rows)

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Twist-2 TMDs

quark pol. (columns) / nucleon pol. (rows)

	U	L	T
U	$f^\perp$	$g^\perp$	$h,\ e$
L	$f_L^\perp$	$g_L^\perp$	$h_L,\ e_L$
T	$f_T,\ f_T^\perp$	$g_T,\ g_T^\perp$	$h_T,\ h_T^\perp,\ e_T,\ e_T^\perp$

Twist-3 TMDs

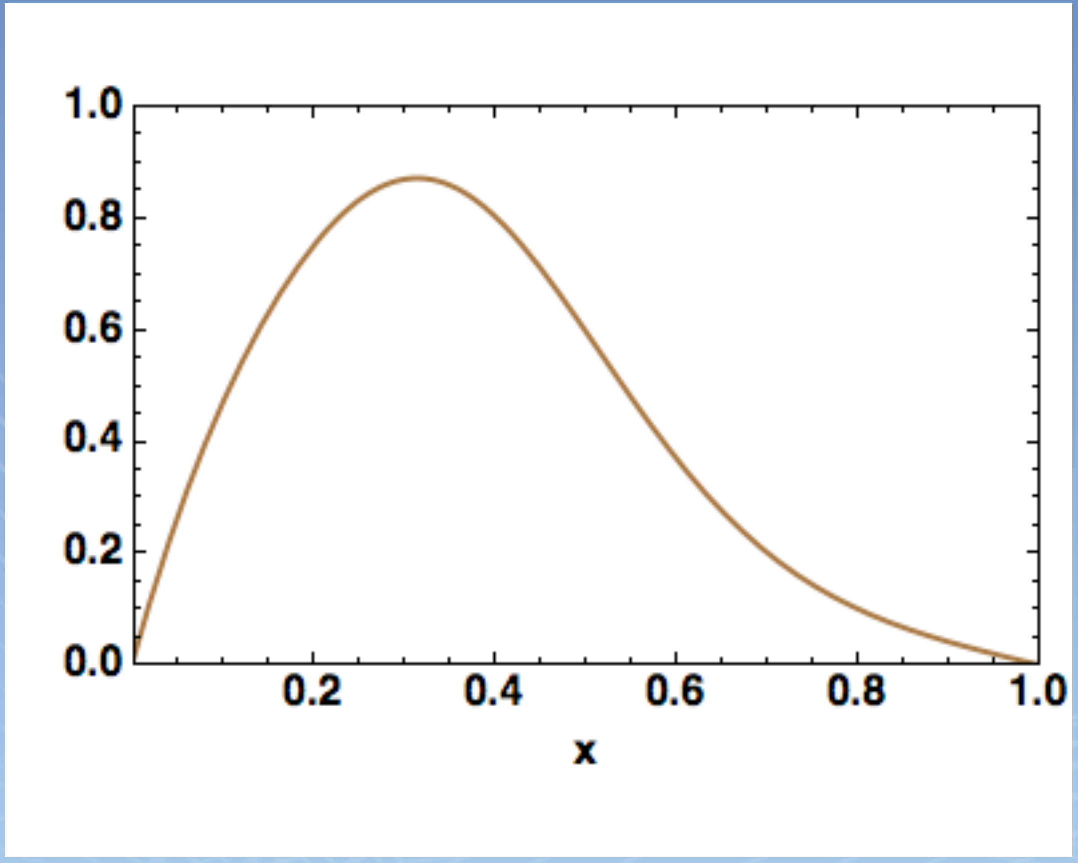
TMDs in black survive transverse-momentum integration
TMDs in red are T-odd

For effects related to twist-3 TMDs, see talks by
M. Burkardt, F. Giordano, M. Aghasyan, K. Tanaka, Y. Koike...

Unpolarized TMDs

Transverse momentum distributions

$xf_1^u(x)$



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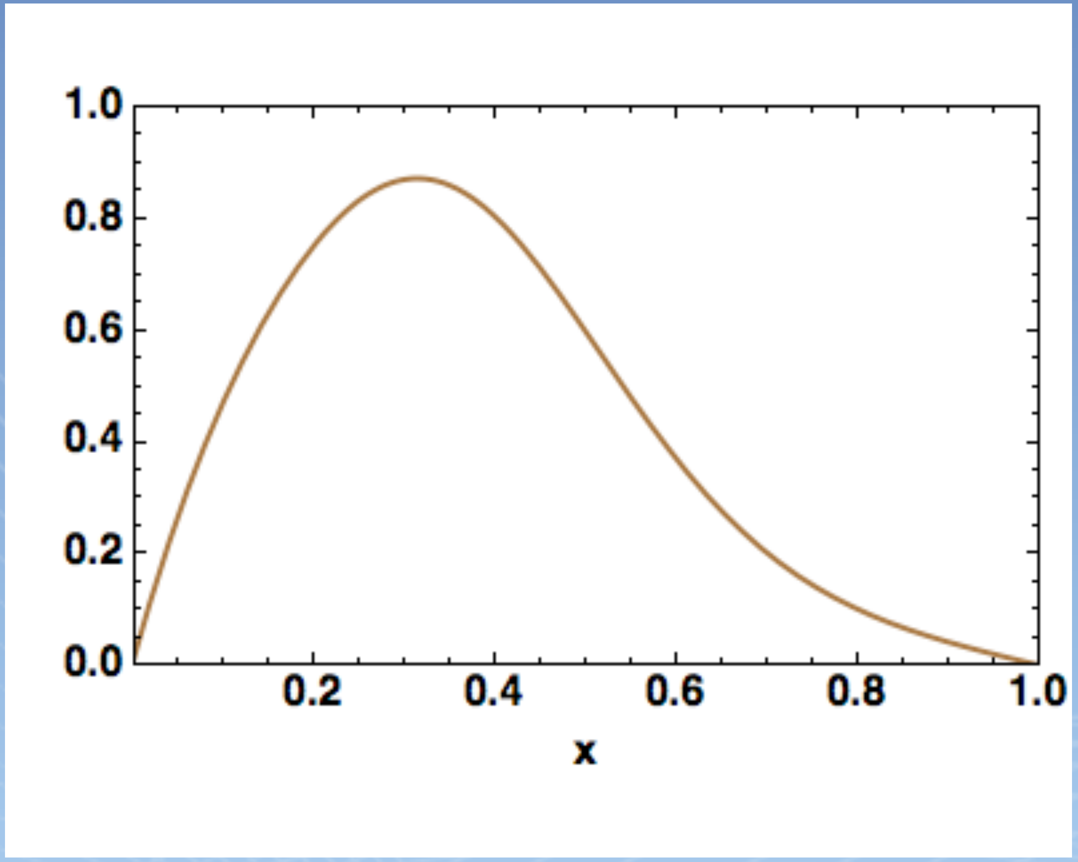
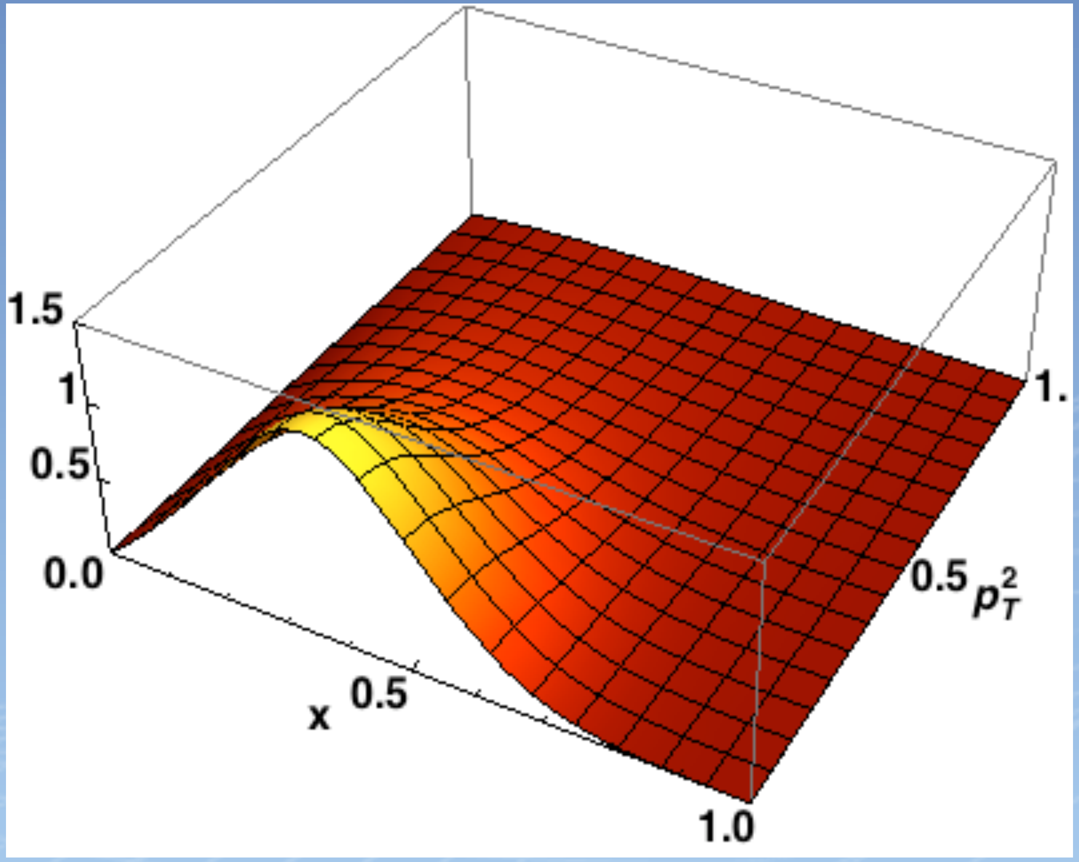


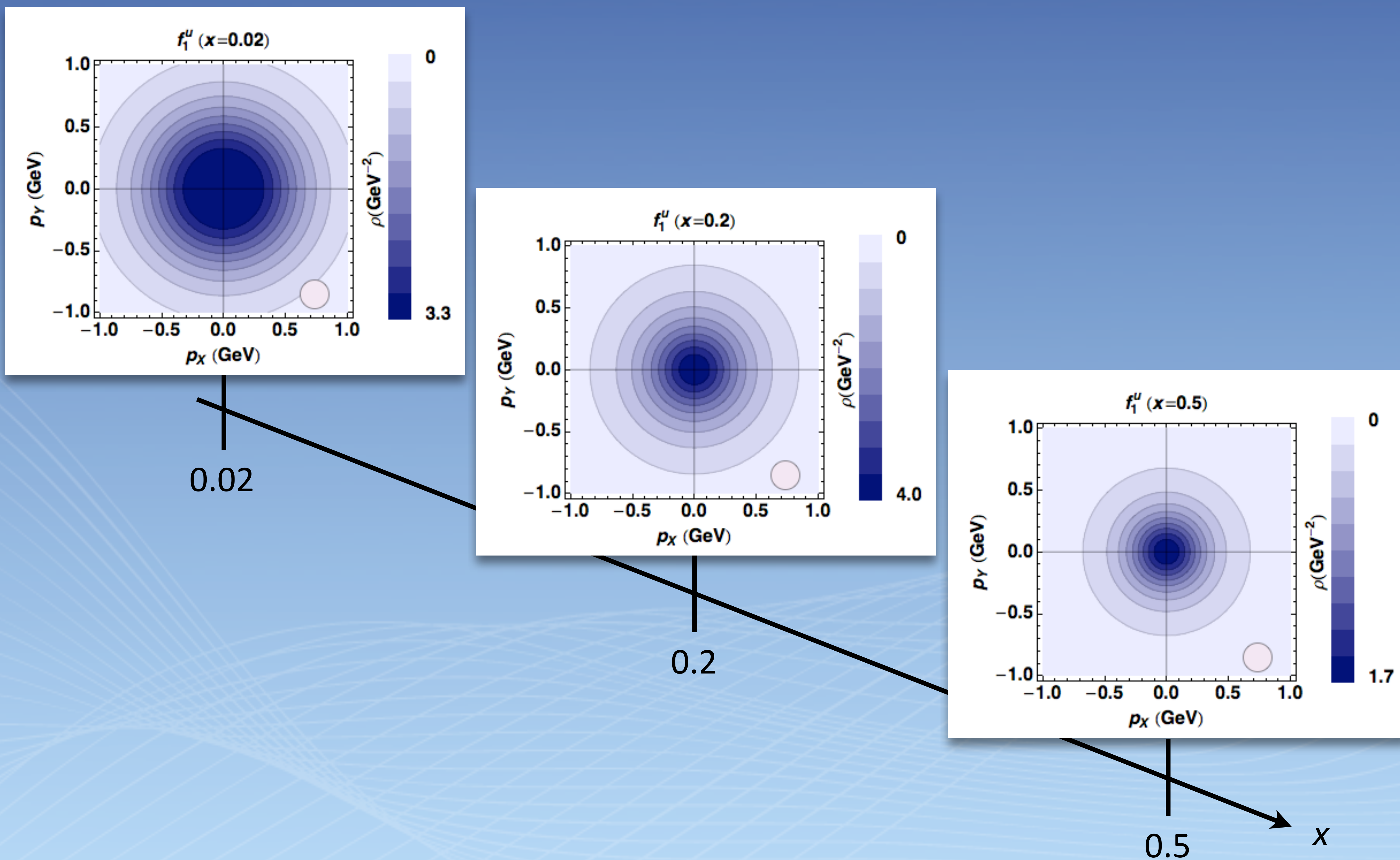
$x f_1^u(x, p_T^2)$



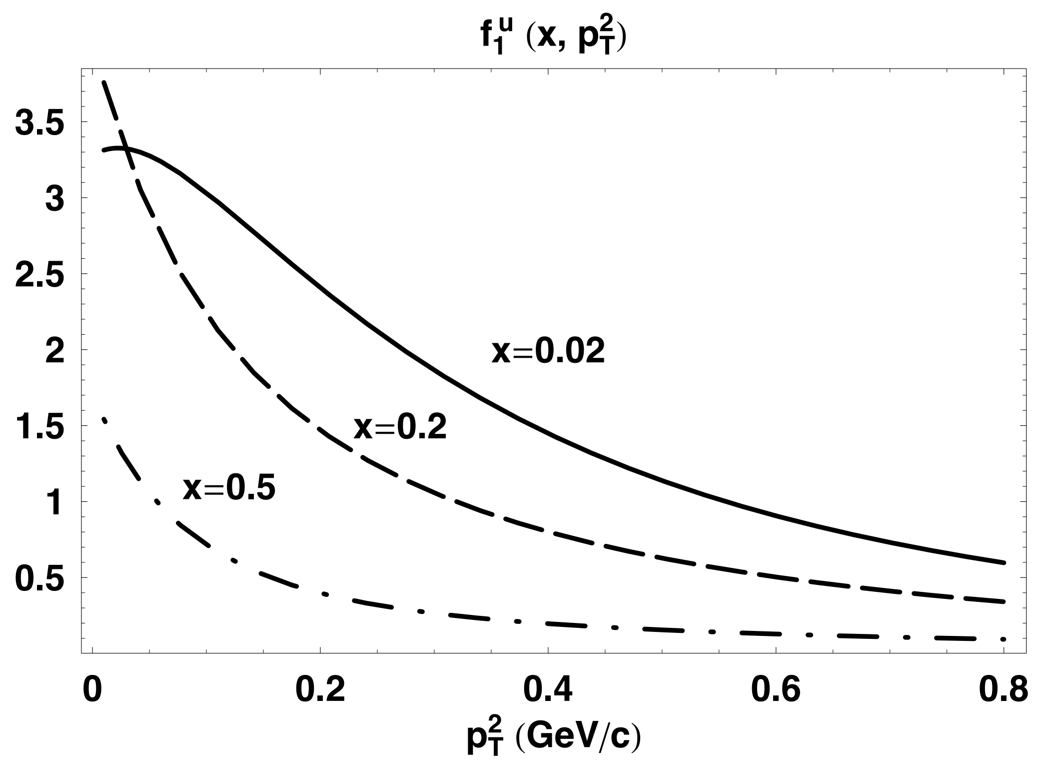
A.B., F. Conti, M. Radici, arXiv:0807.0323

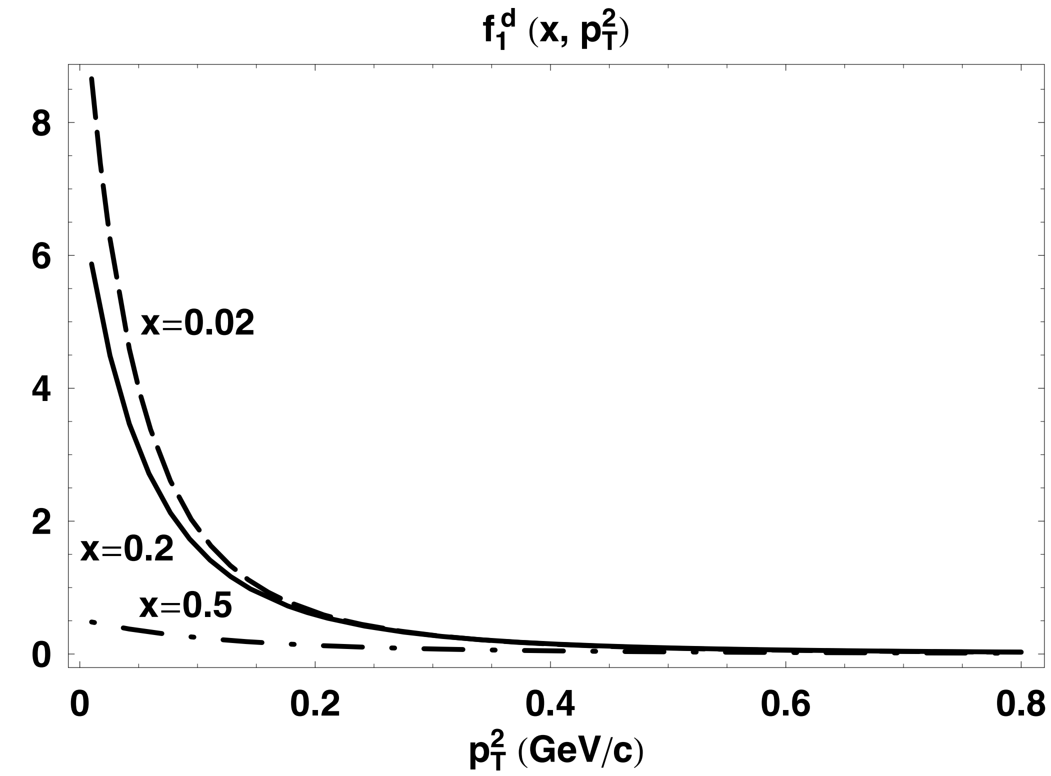
see also talk by B. Pasquini

Nucleon tomography in momentum space



Nontrivial features





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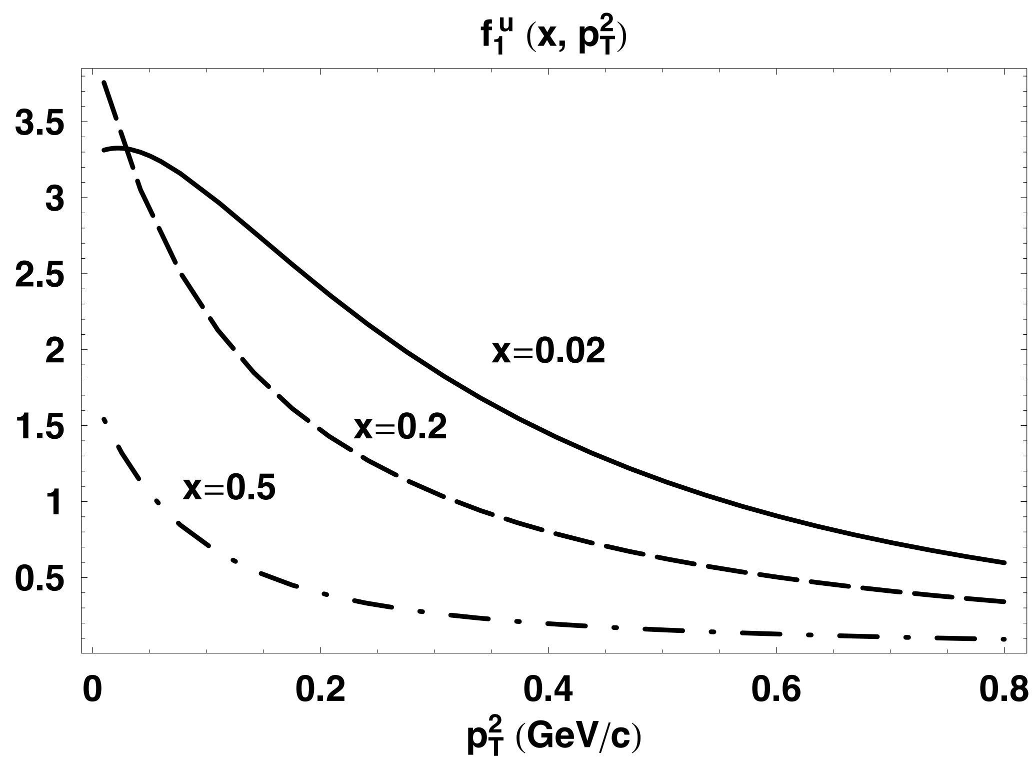

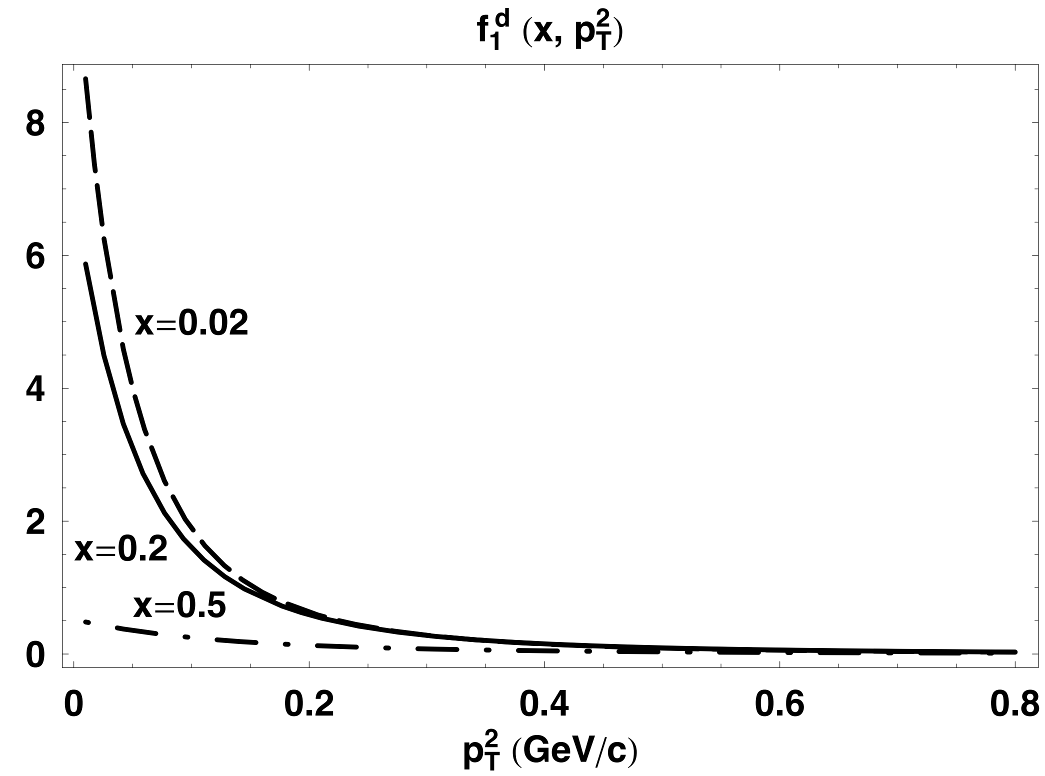

Simple model calculations suggests

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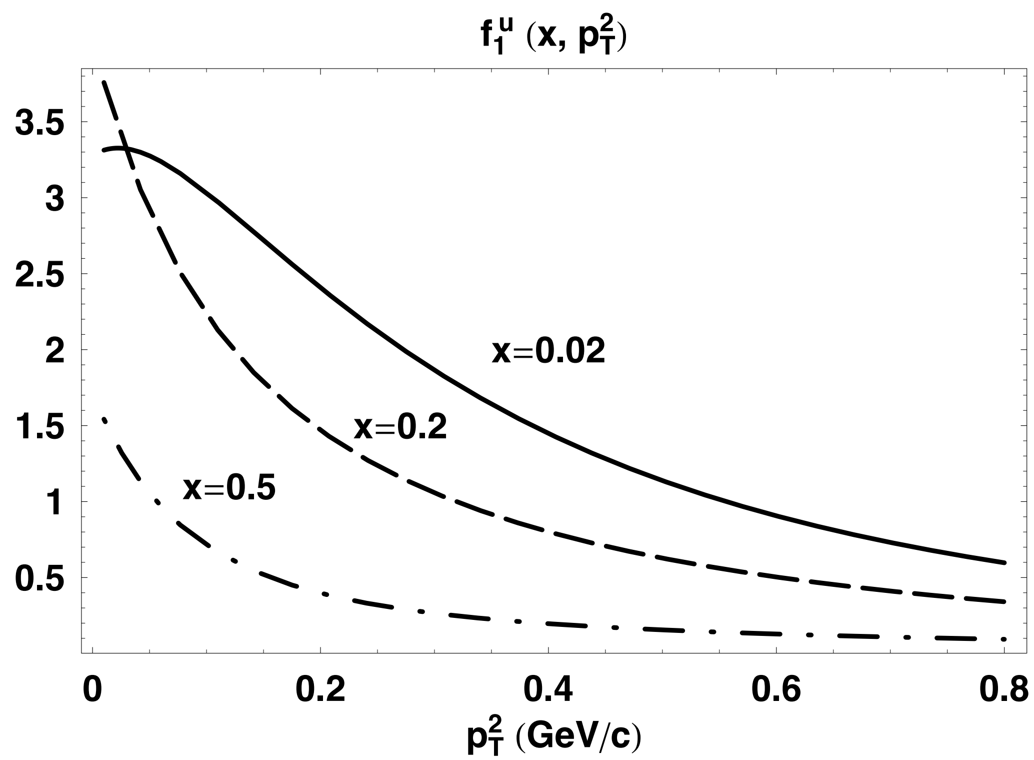

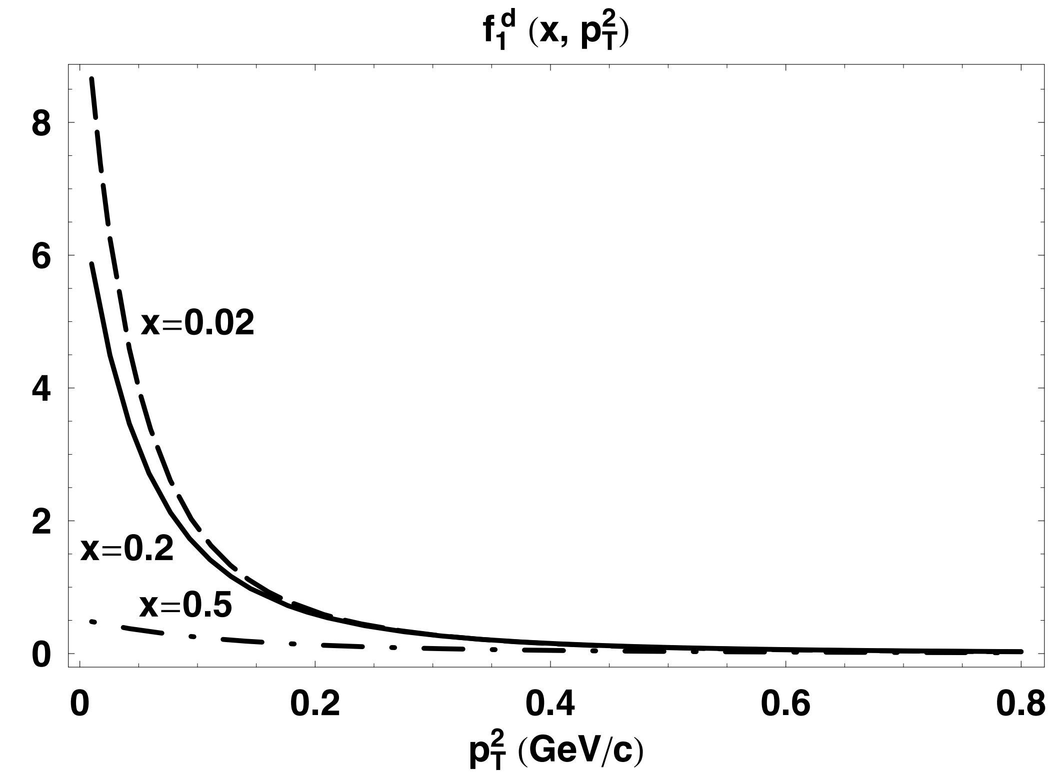

Simple model calculations suggests

- *x*-dependence

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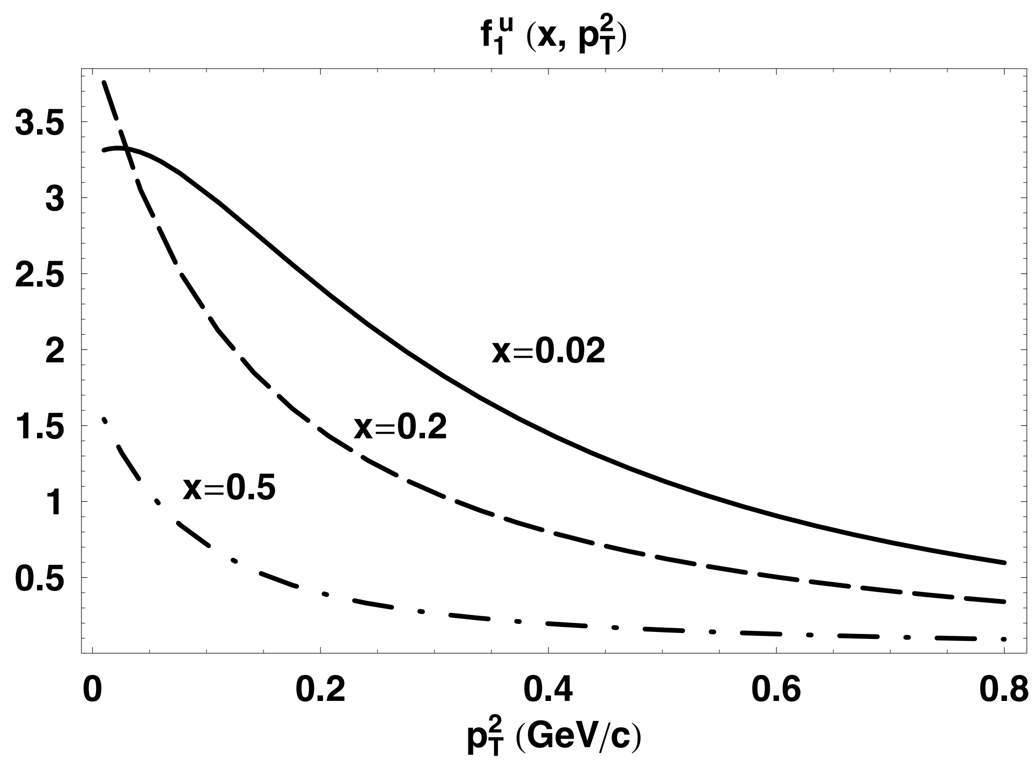

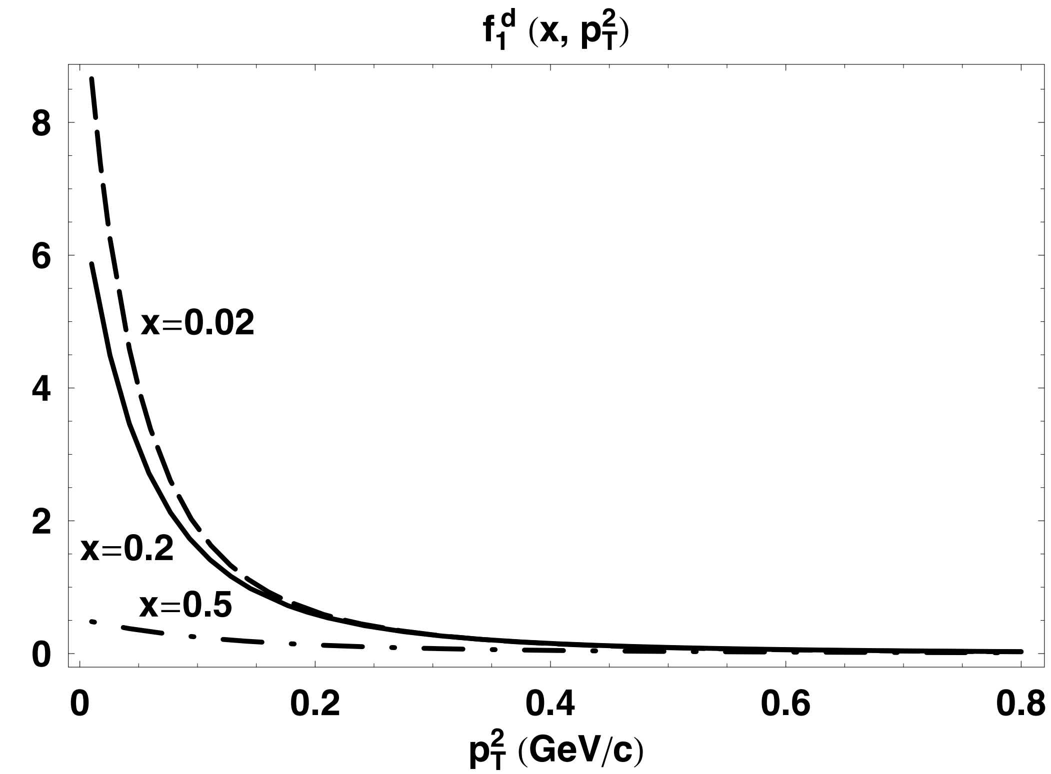

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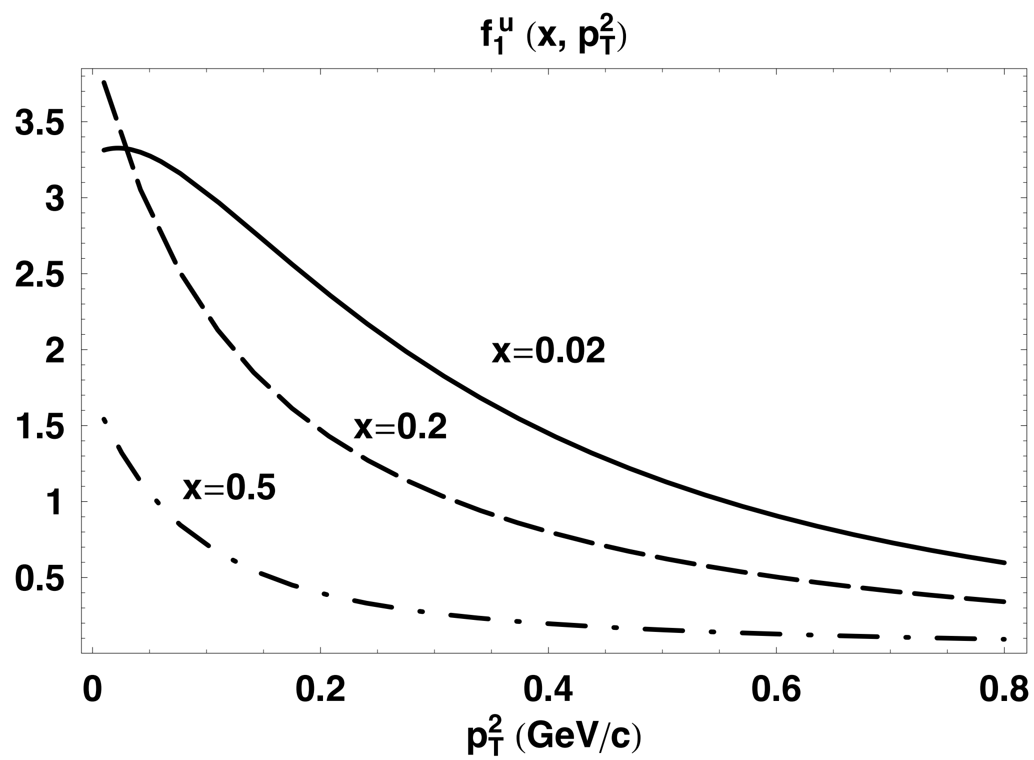

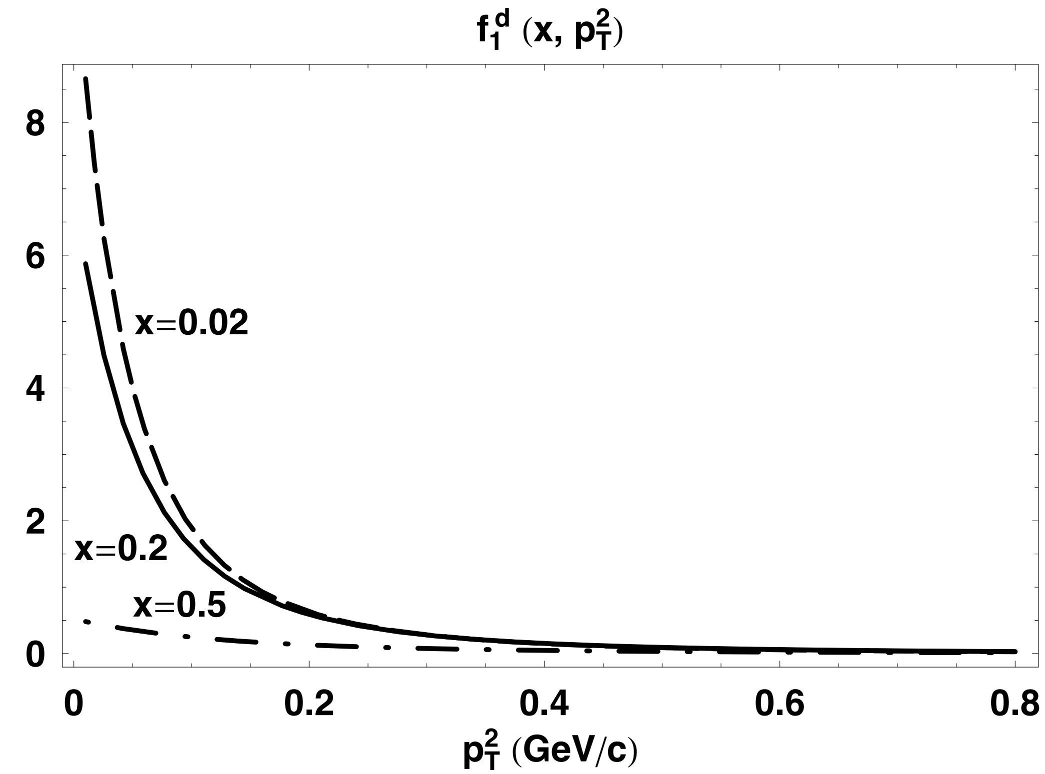

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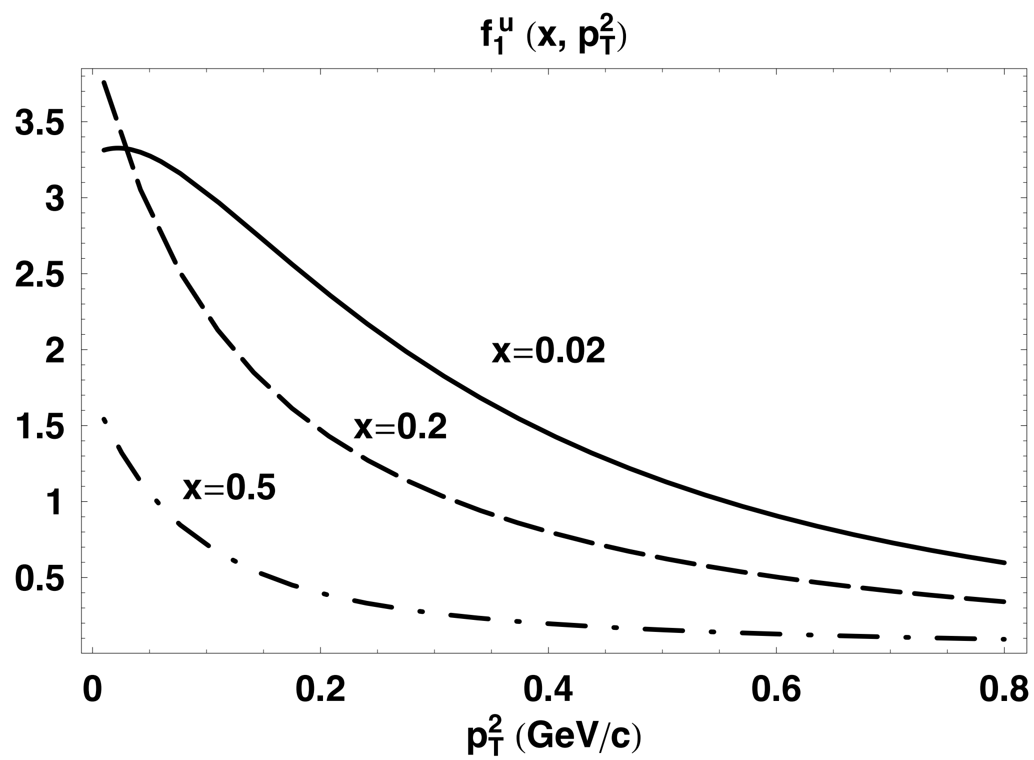

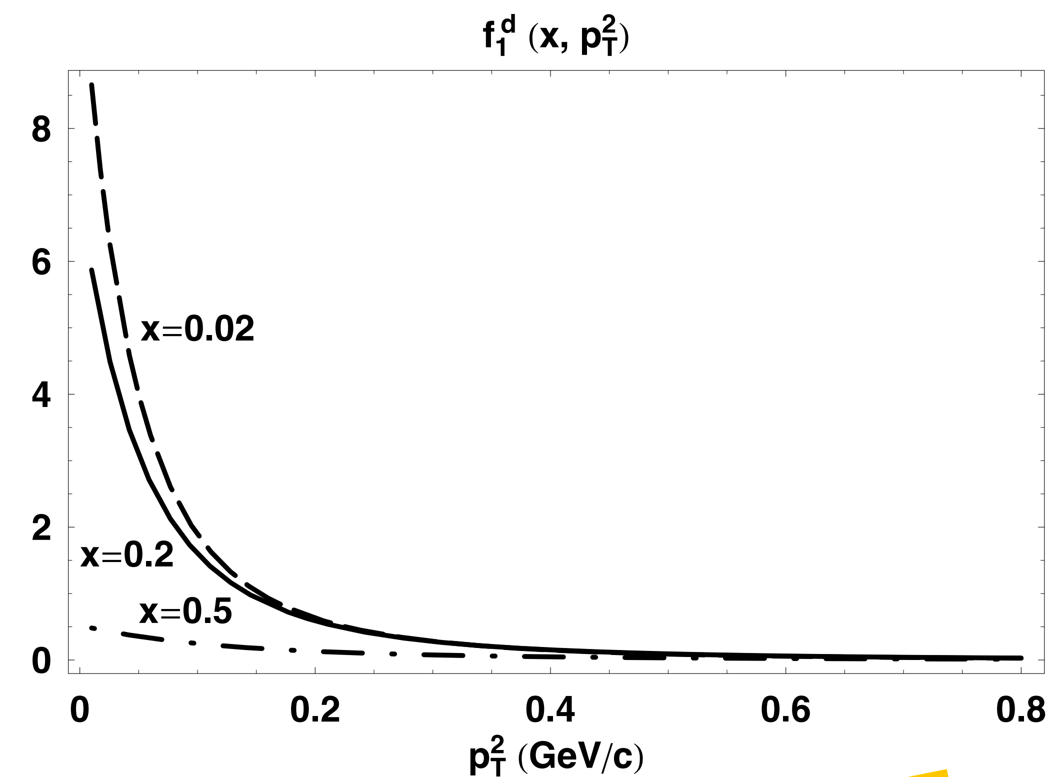

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Fundamental information on the nucleon structure almost as importan as standard collinear PDFs

Extractions from experiments

Drell-Yan

$$\frac{d\sigma}{dq_T^2} \sim \sum_q e_q^2\, f_1^q(x, p_T^2) \otimes f_1^{\bar{q}}(\bar{x}, \bar{p}_T^2)$$

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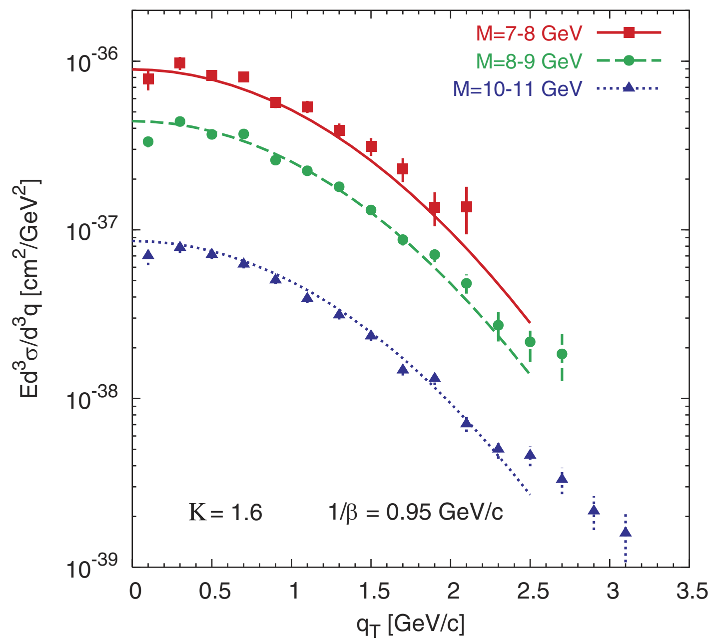
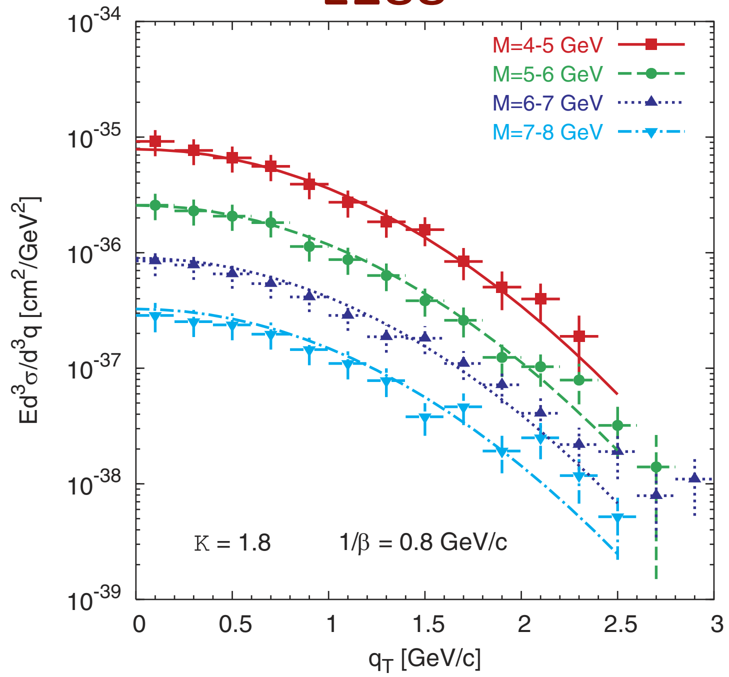
Analyses of Drell-Yan data

E605



E288

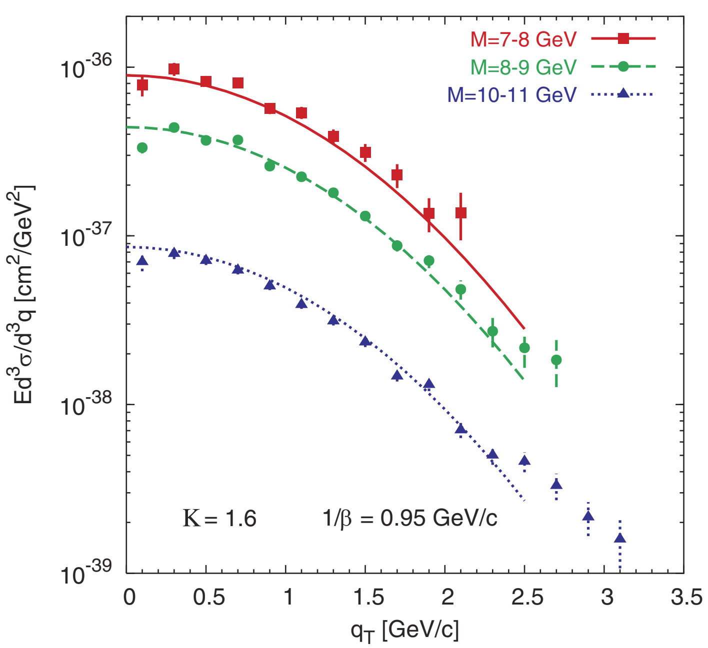


Gaussians

D'Alesio, Murgia, PRD70 (04)

Analyses of Drell-Yan data

E605



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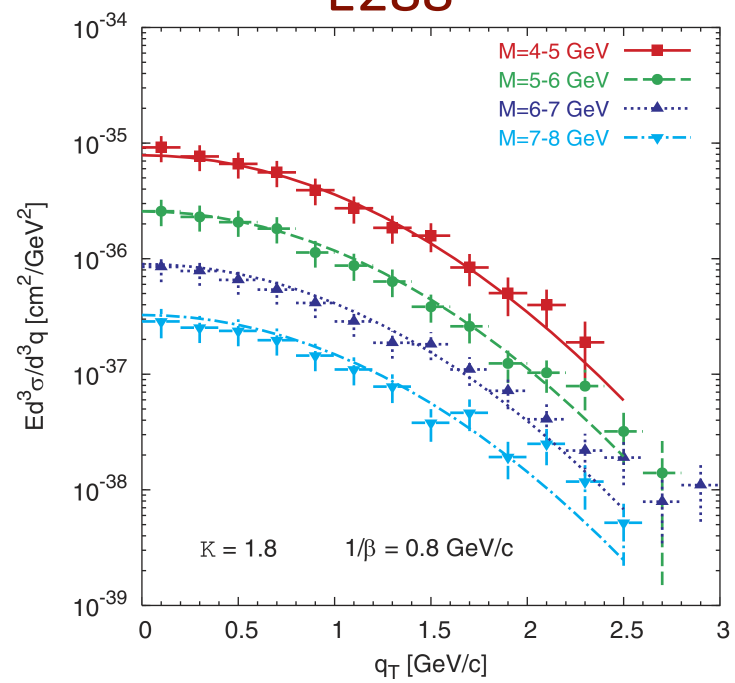

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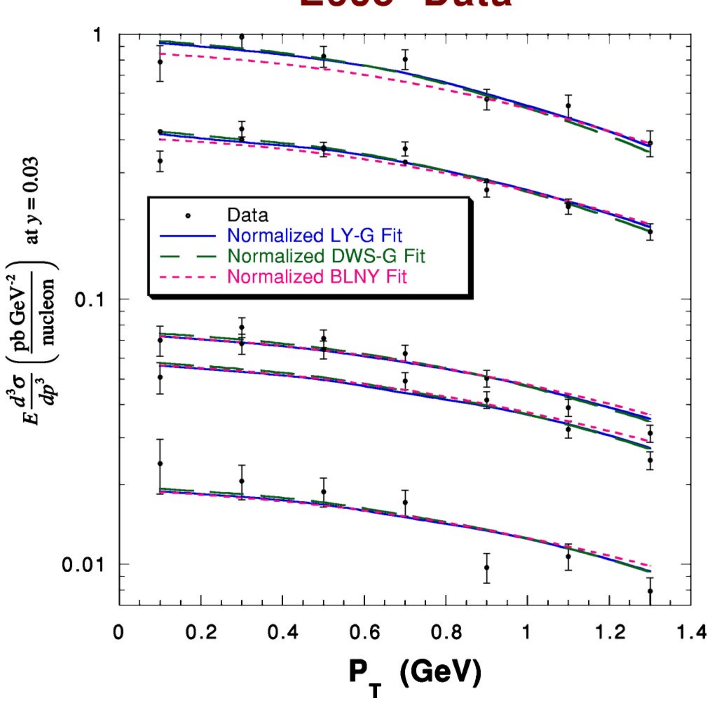

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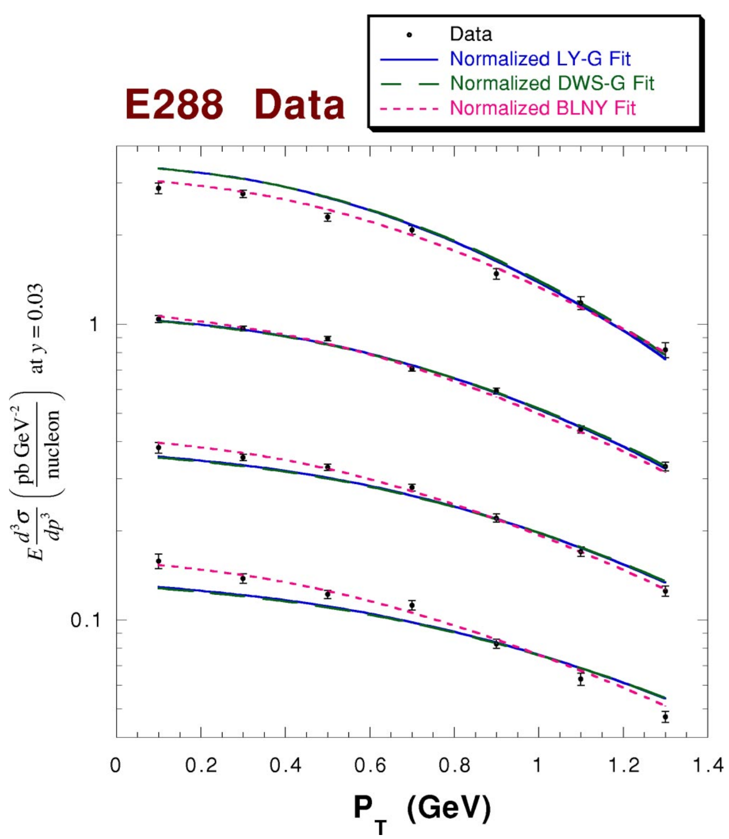
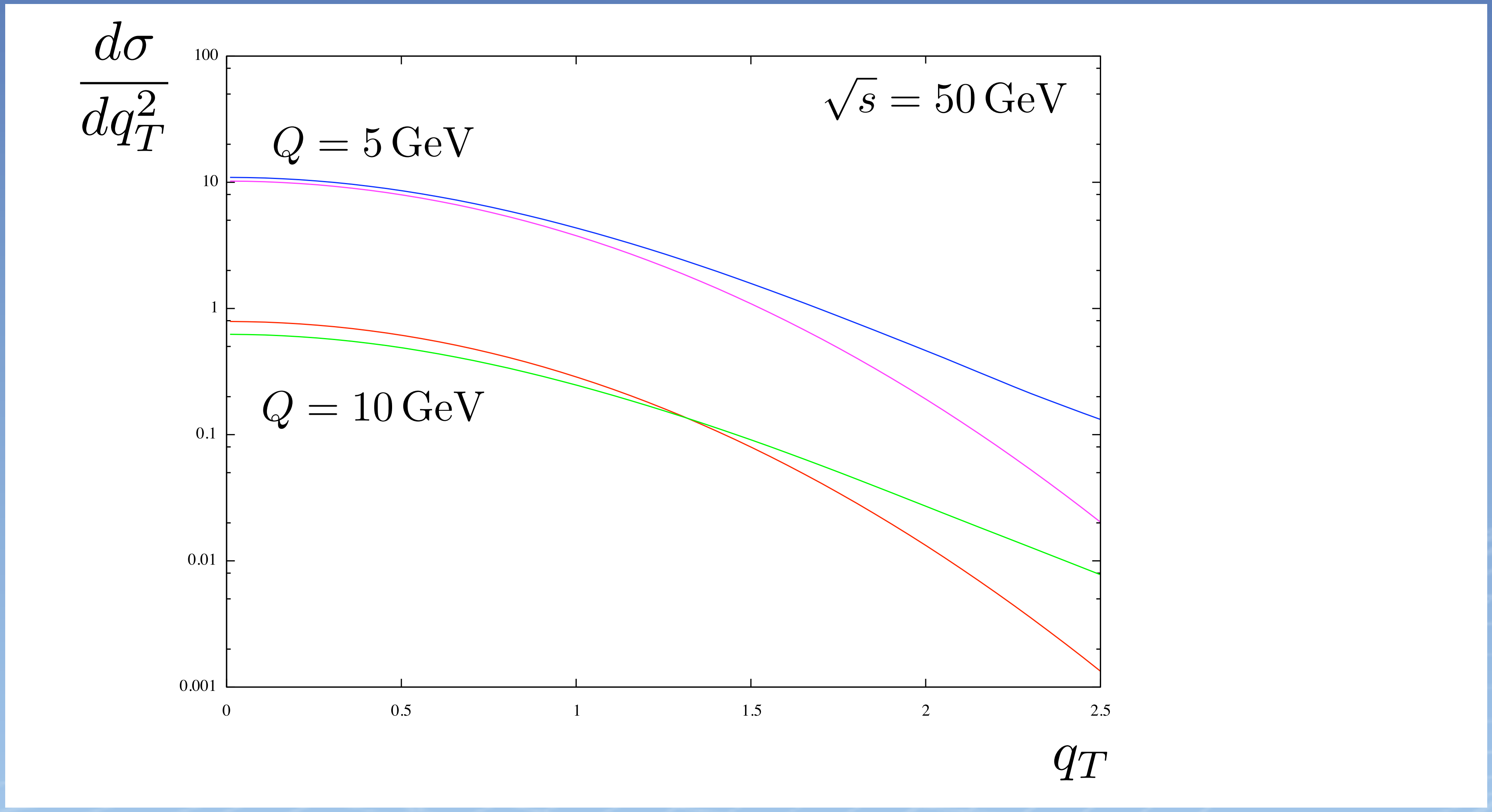


Gaussians
+ kT resummation

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

Resummation



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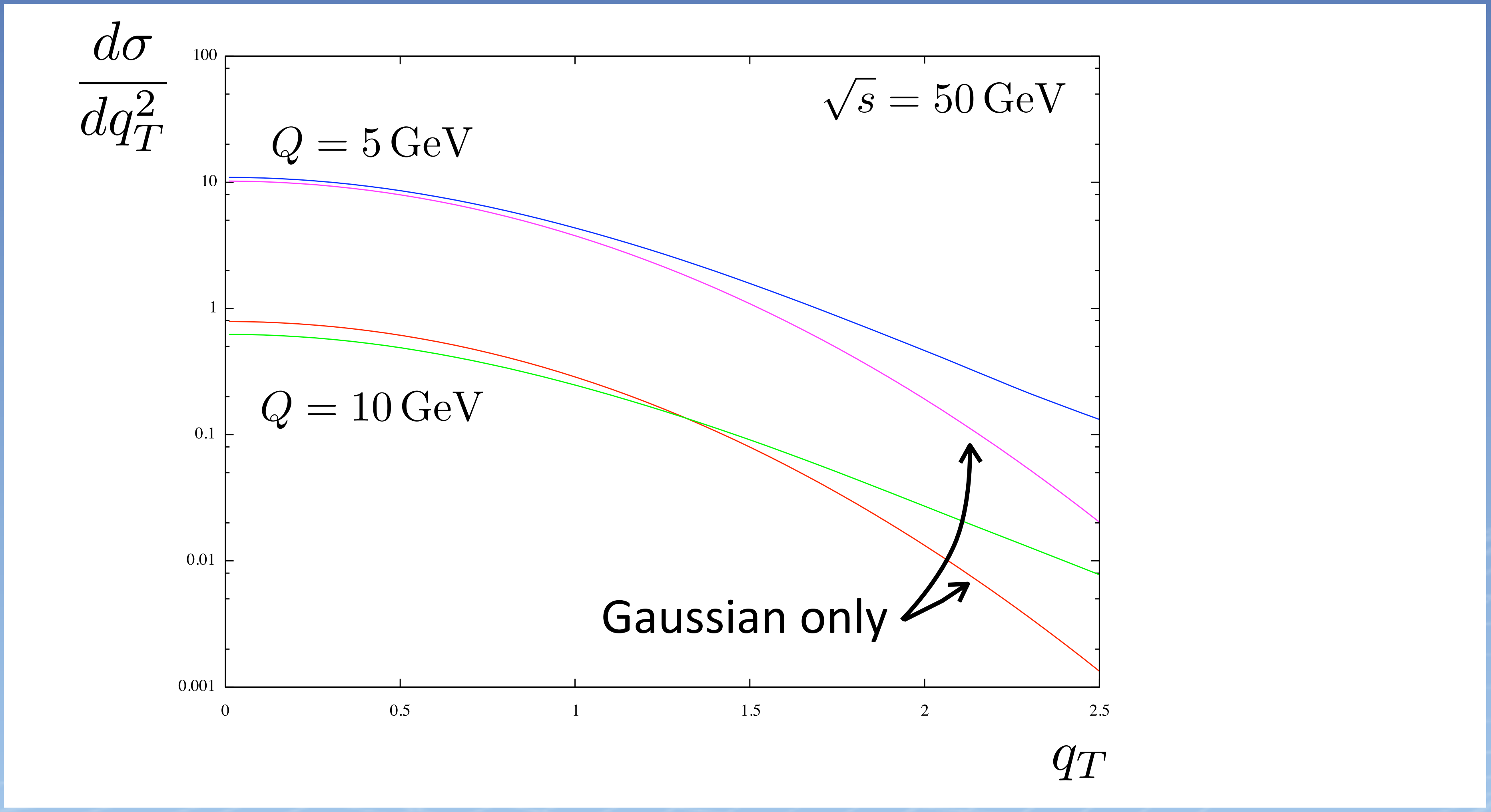

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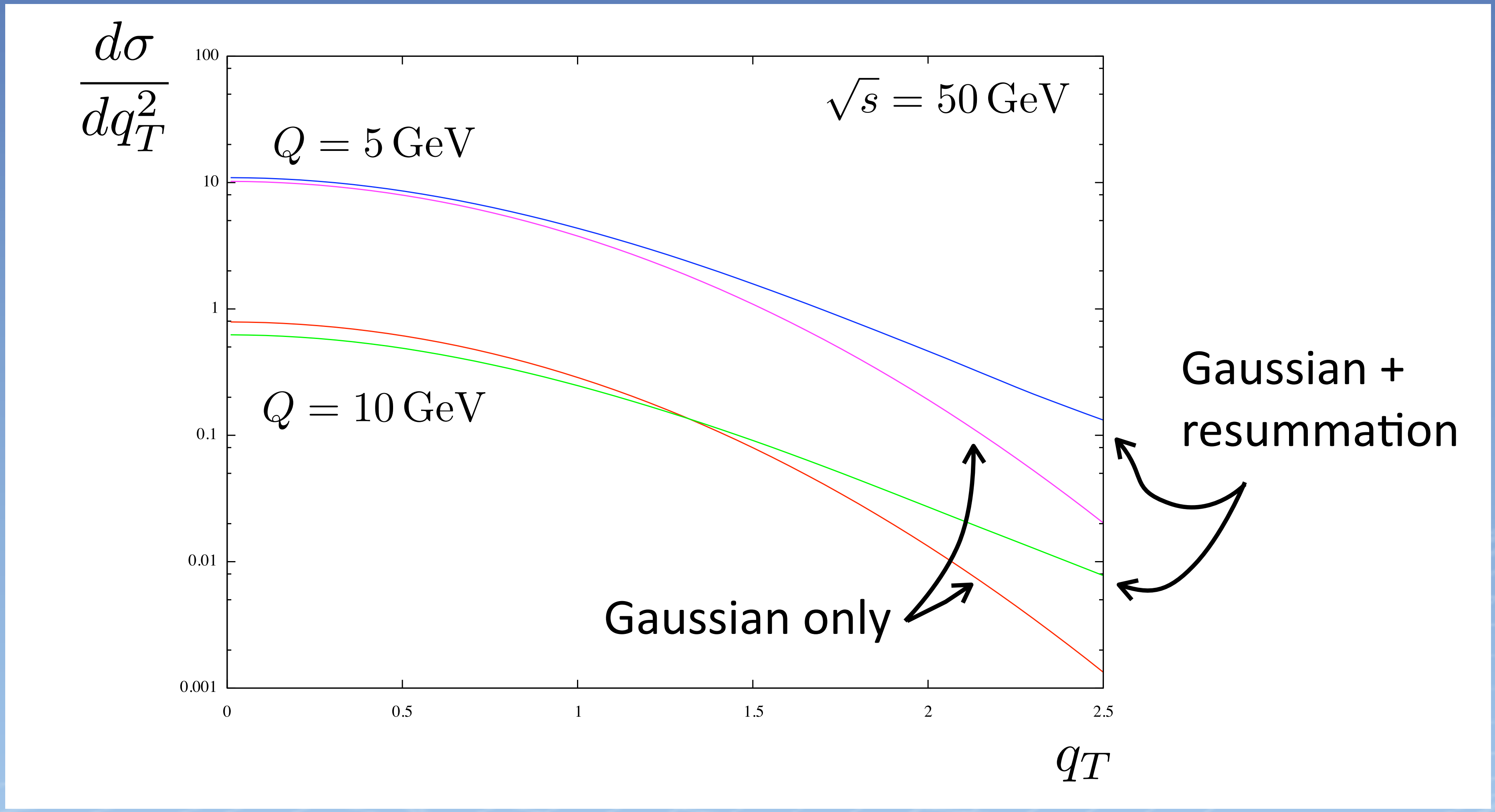

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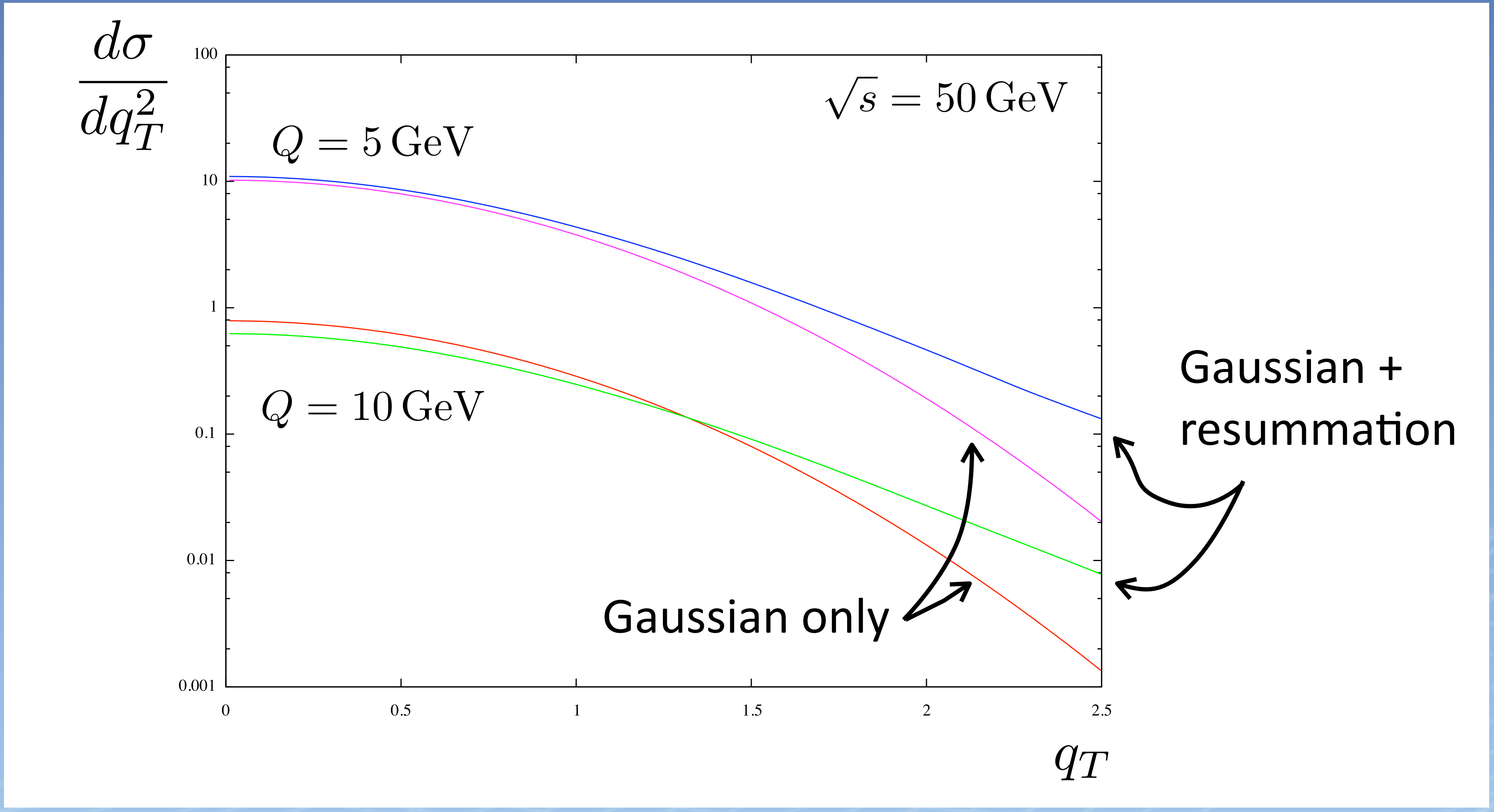
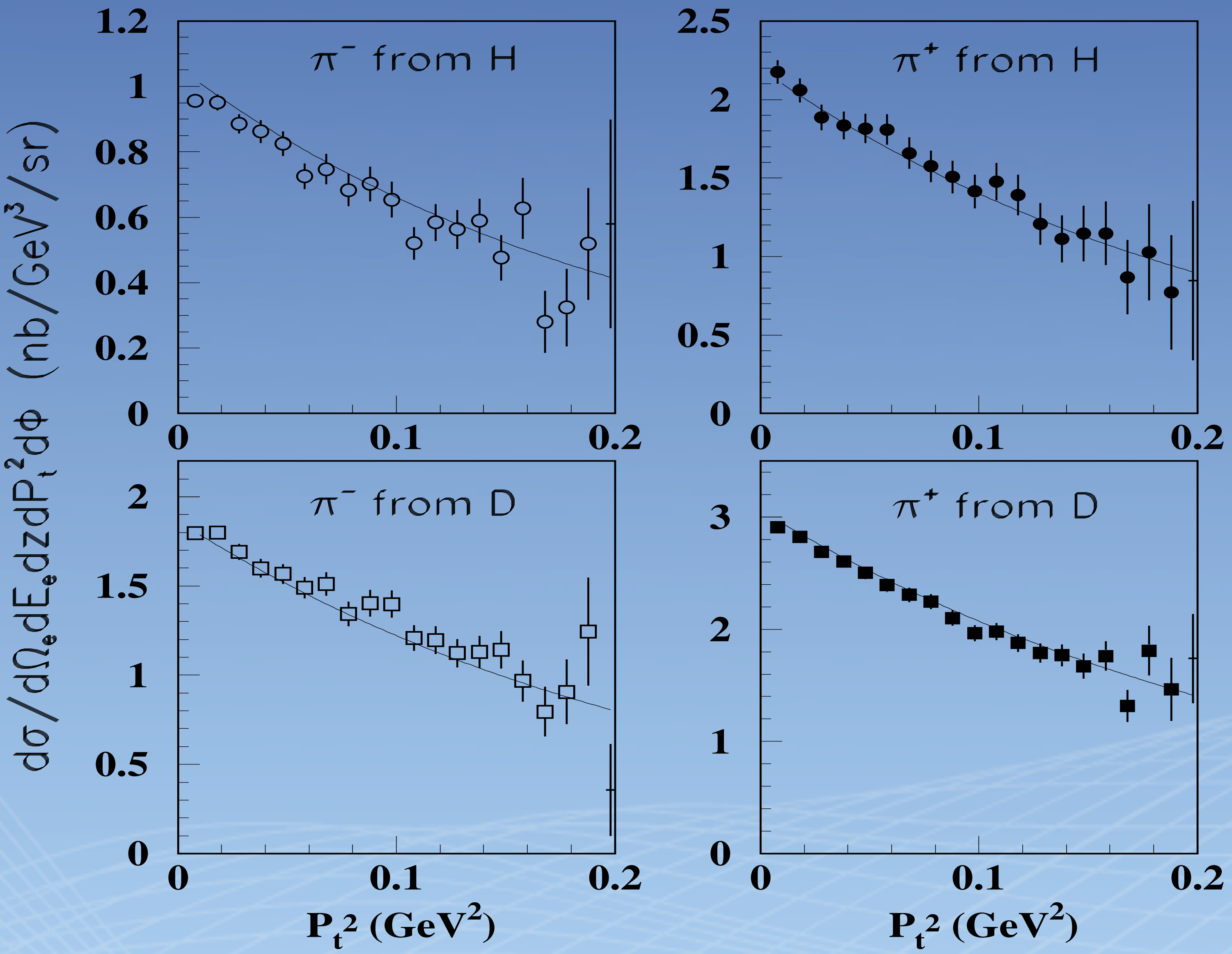


Resummation typically gives larger transverse momentum (requires smaller intrinsic transverse momentum) and a specific dependence on Q

Even data at Tevatron can be described!

SIDIS data with hadron identification



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

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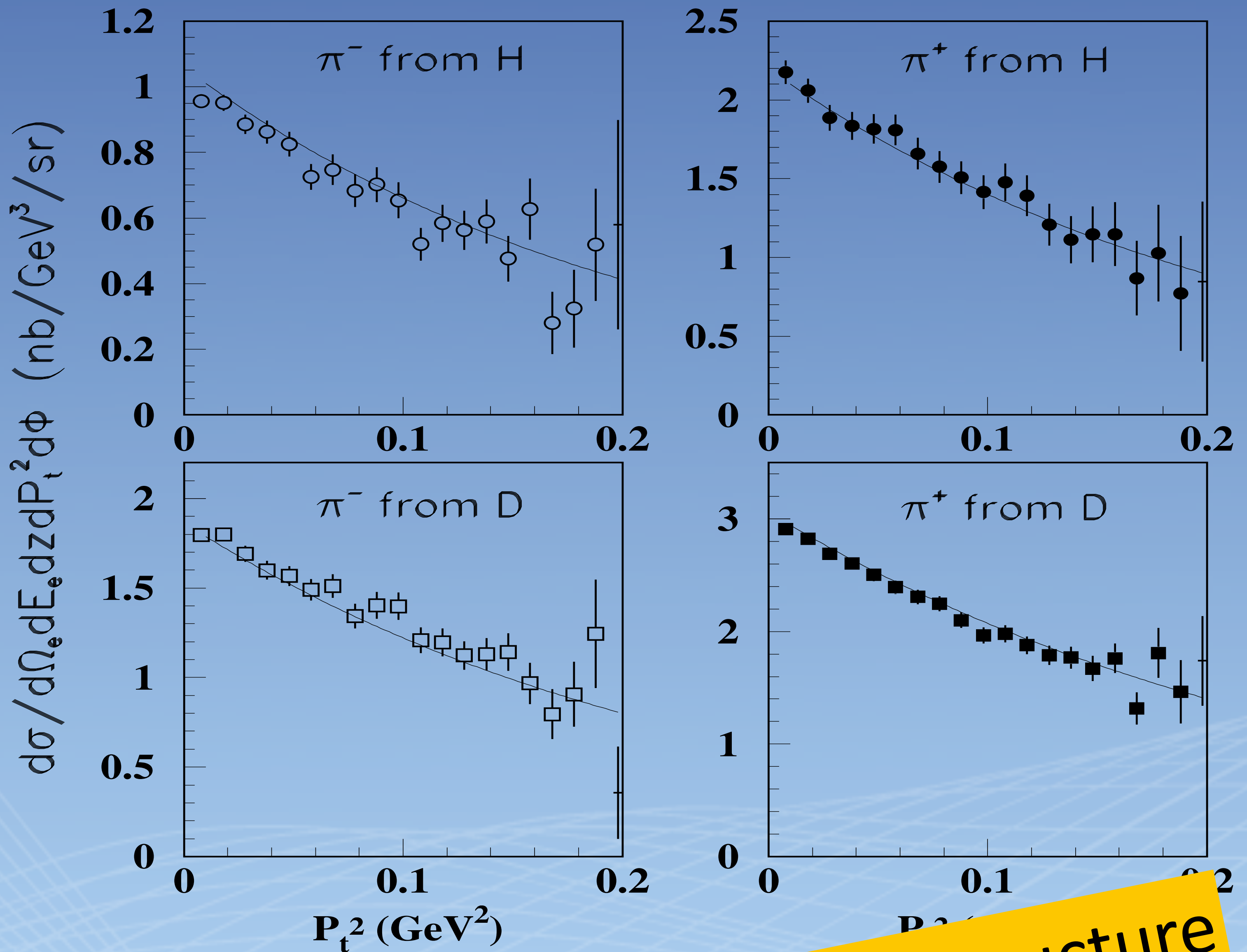

Essential to study flavor structure

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

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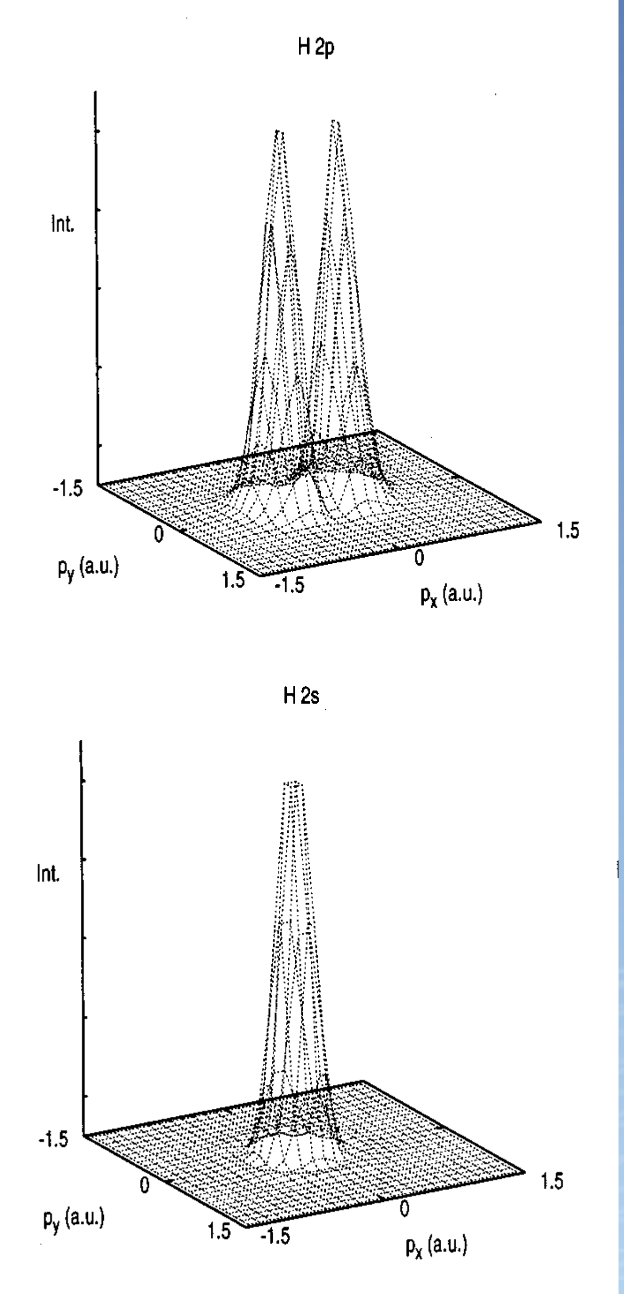
- Try to abandon simple Gaussians
- Use resummation

Orbital angular momentum

Orbital angular momentum in atoms

Hidrogen atom wavefunctions
in momentum space



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

Orbital angular momentum in atoms

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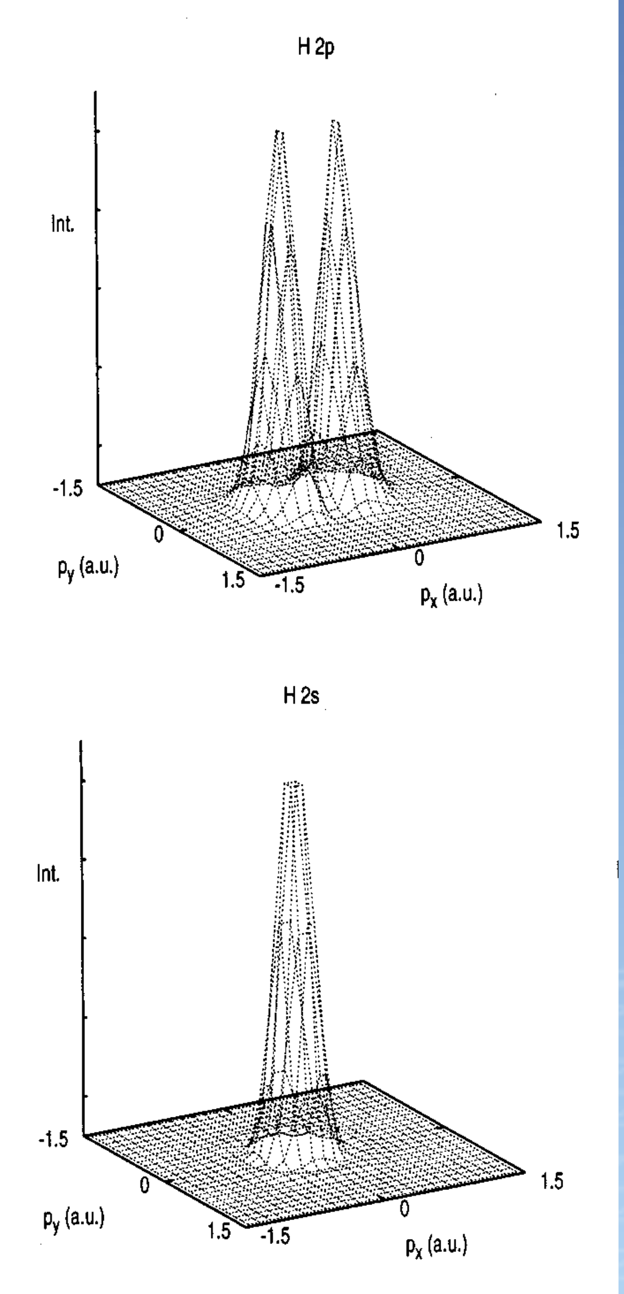

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Vos, McCarthy, Am. J. Phys. 65 (97), 544

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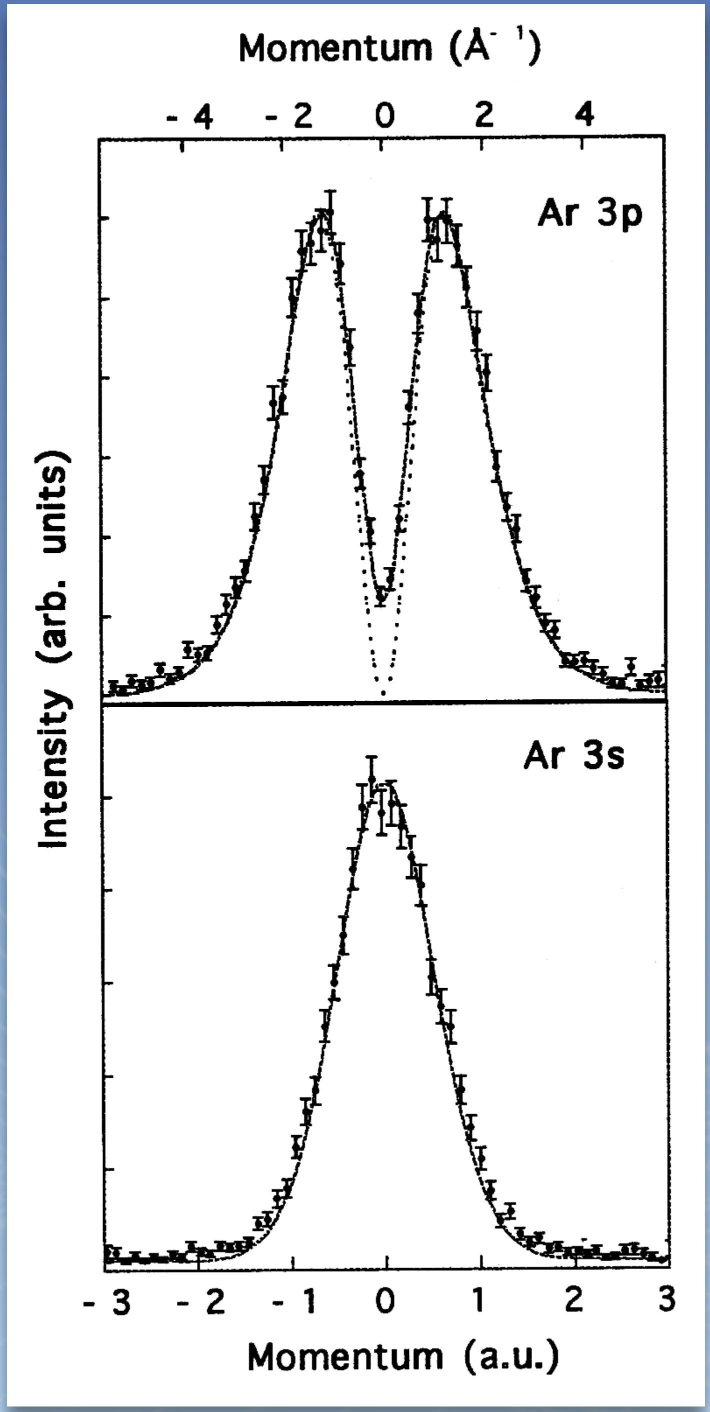

Vos, McCarthy, Am. J. Phys. 65 (97), 544

- 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

Signs of orbital angular momentum

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

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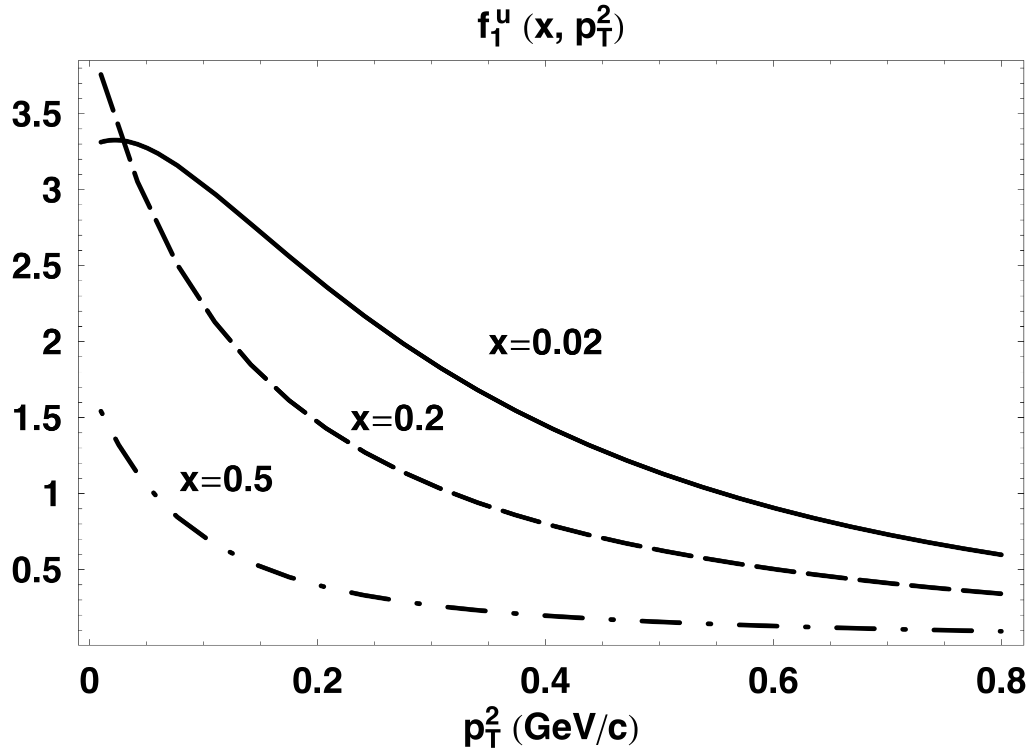

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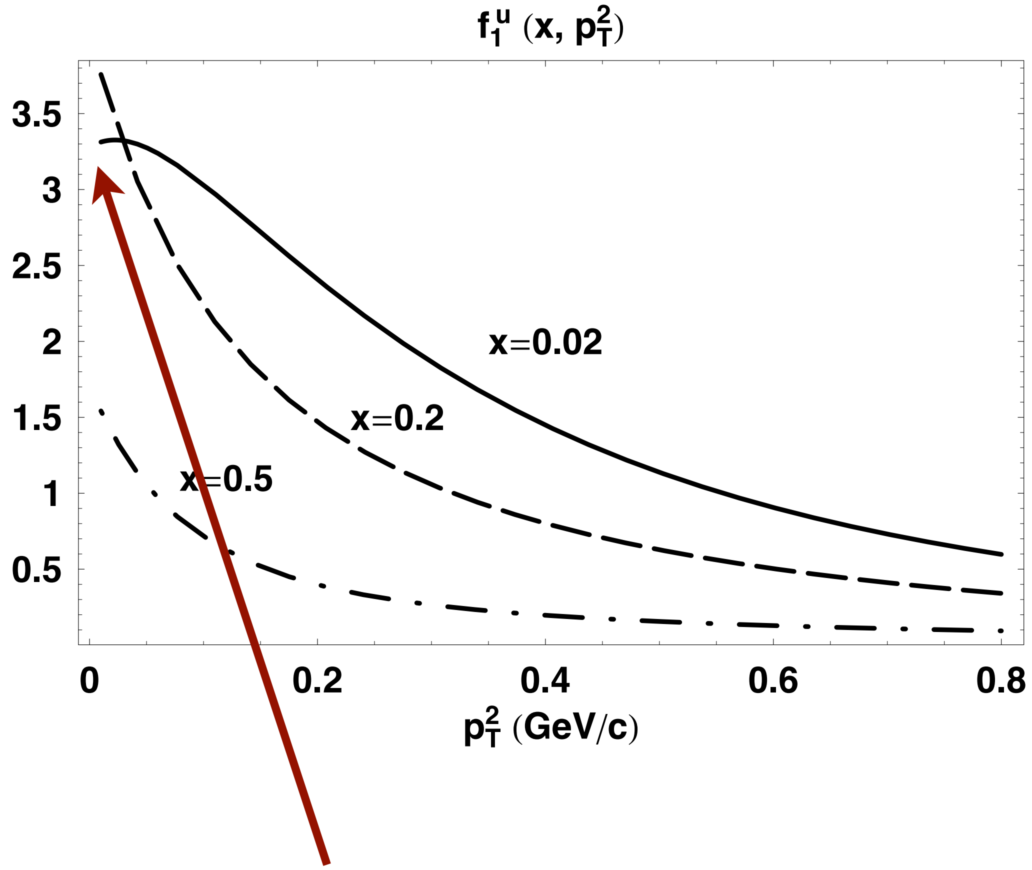

Turning down of TMDs can be generated only by contributions of wavefunctions with nonzero orbital angular momentum

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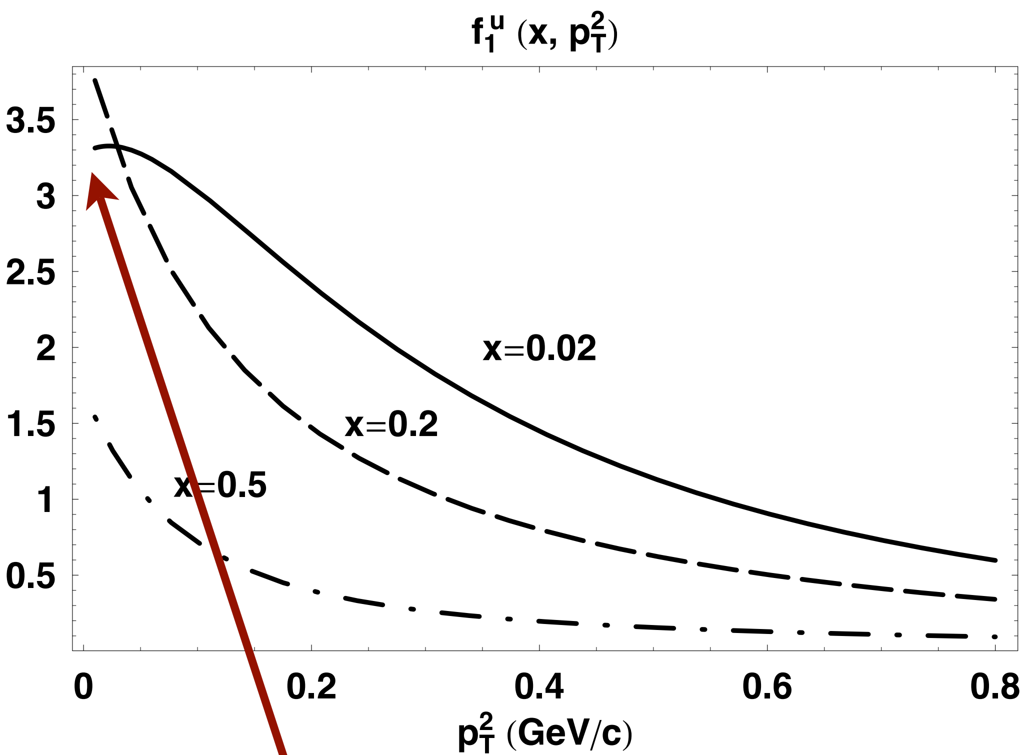

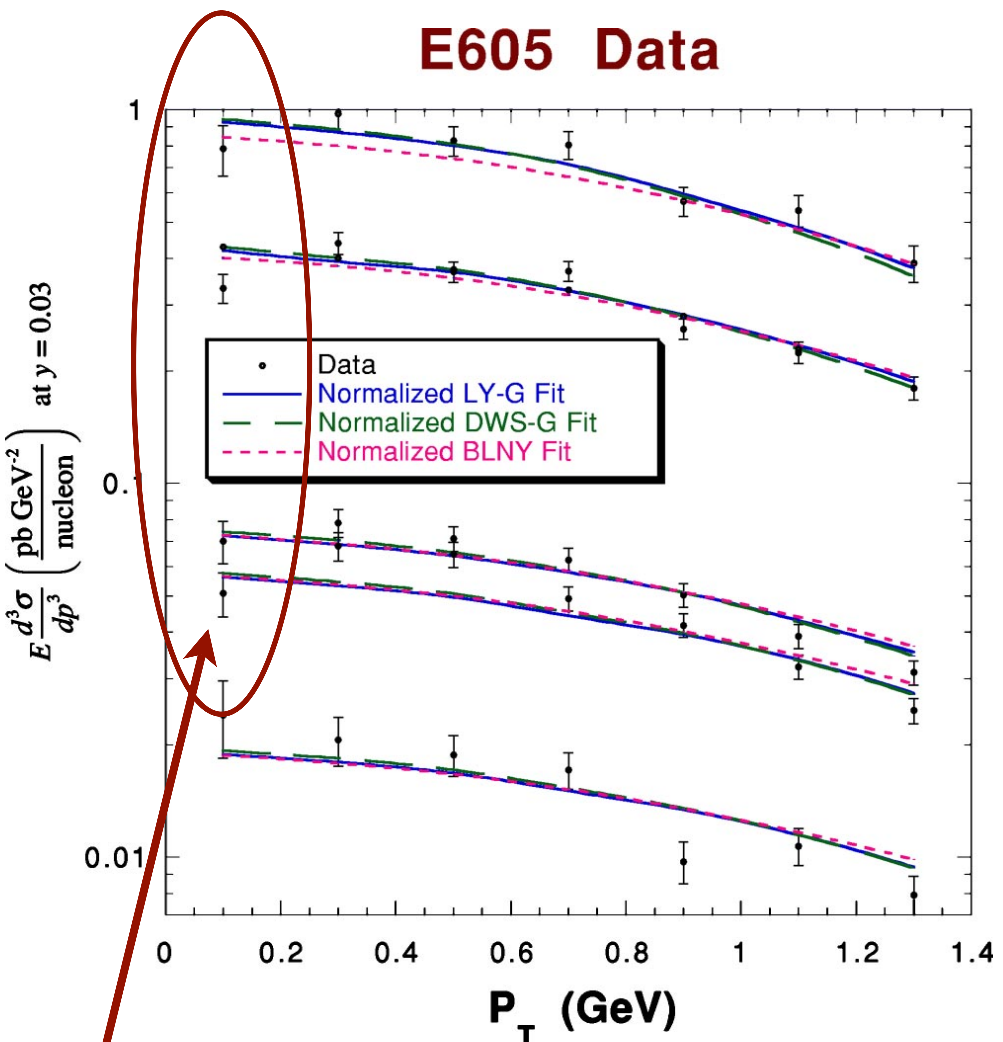

Turning down of TMDs can be generated only by contributions of wavefunctions with nonzero orbital angular momentum

Is it already seen in data?

OAM and polarized TMDs

quark pol. / nucleon pol.

	U	L	T
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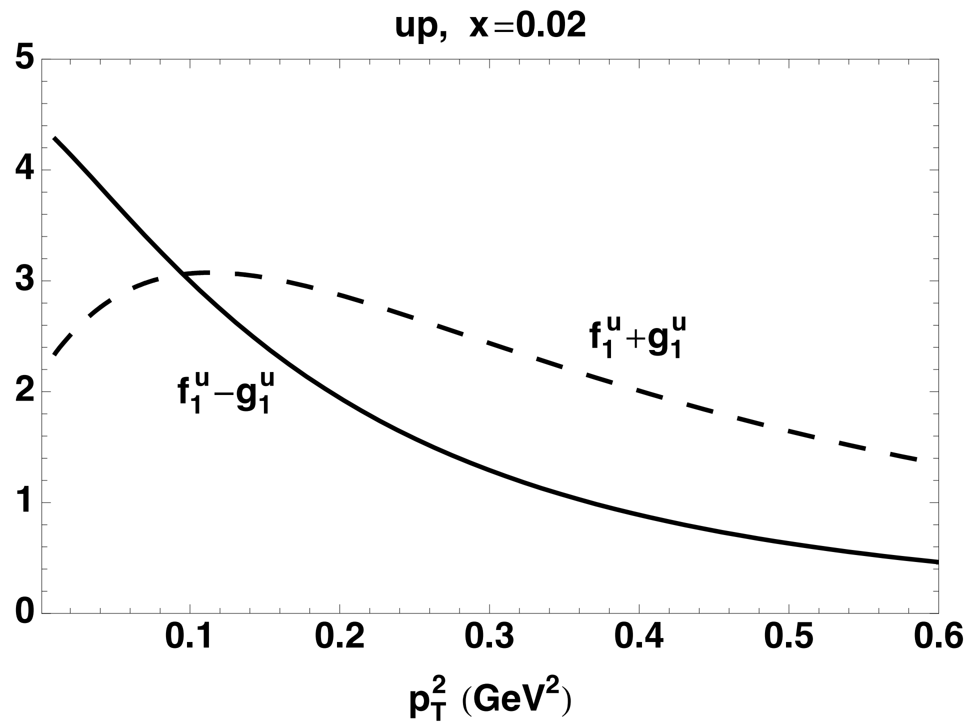
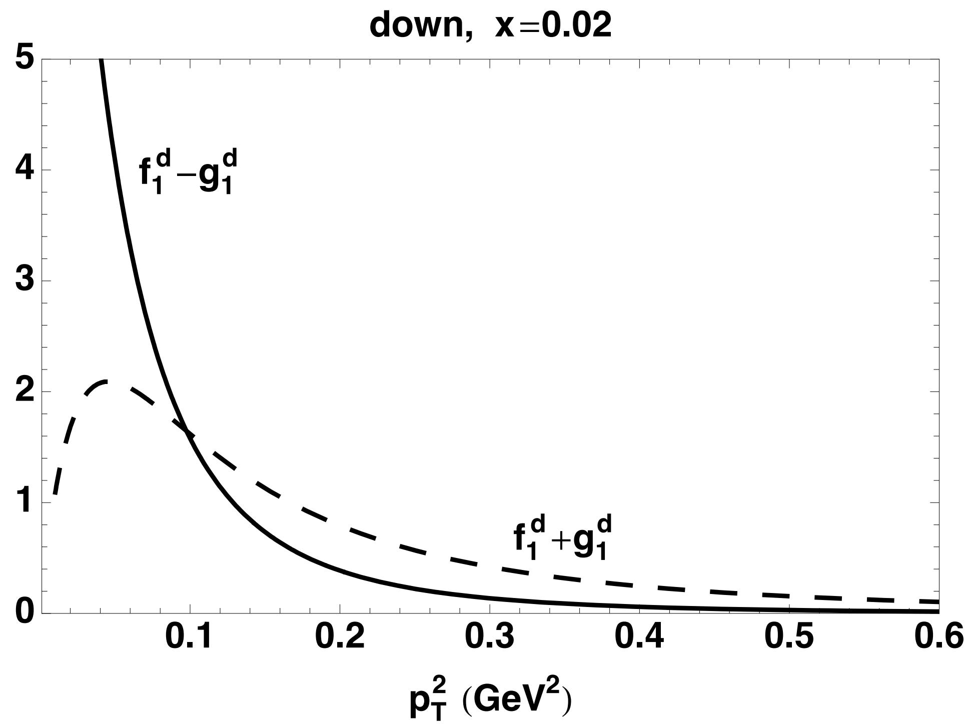
Twist-2 TMDs

Signs of OAM in polarized TMDs





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

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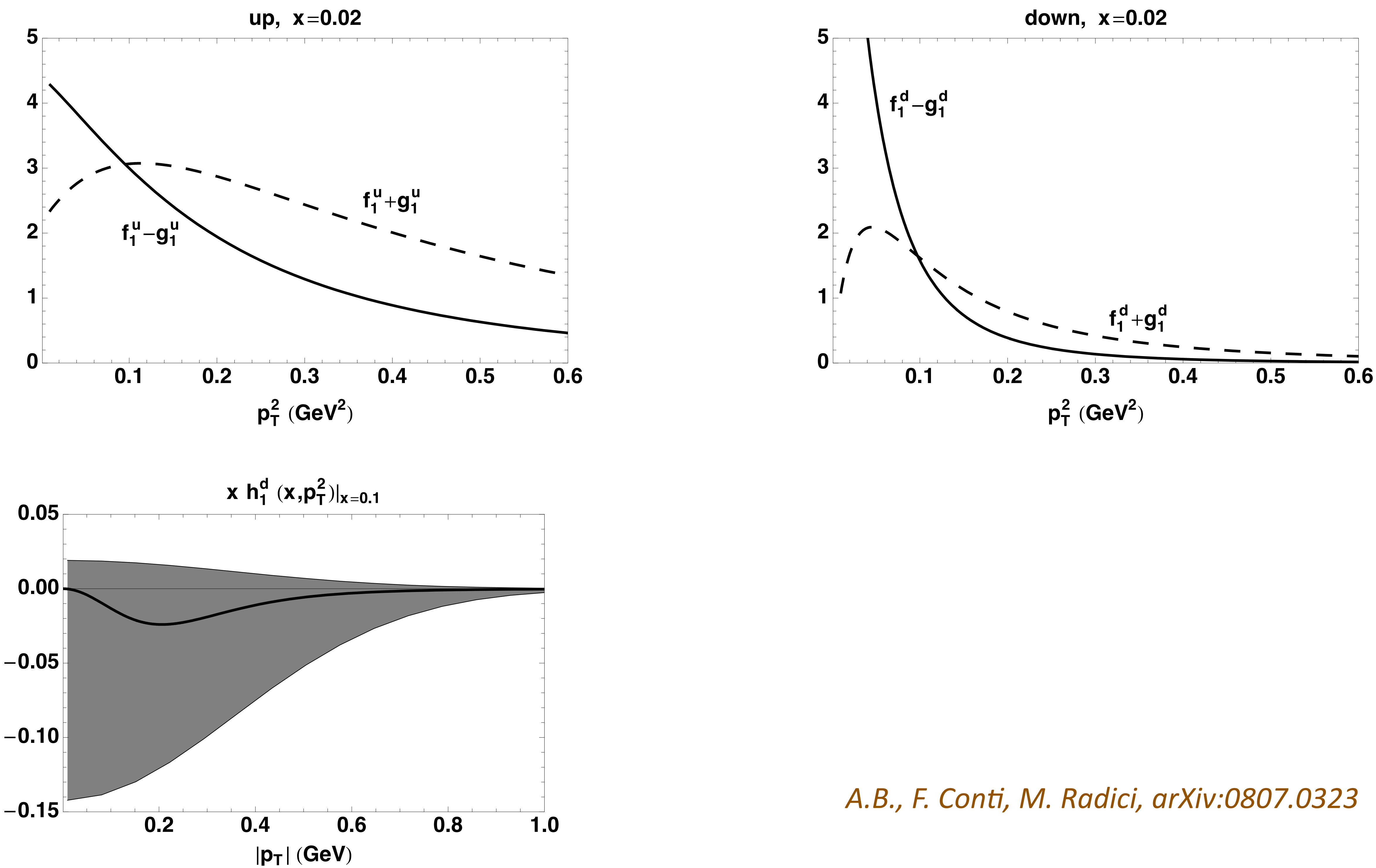

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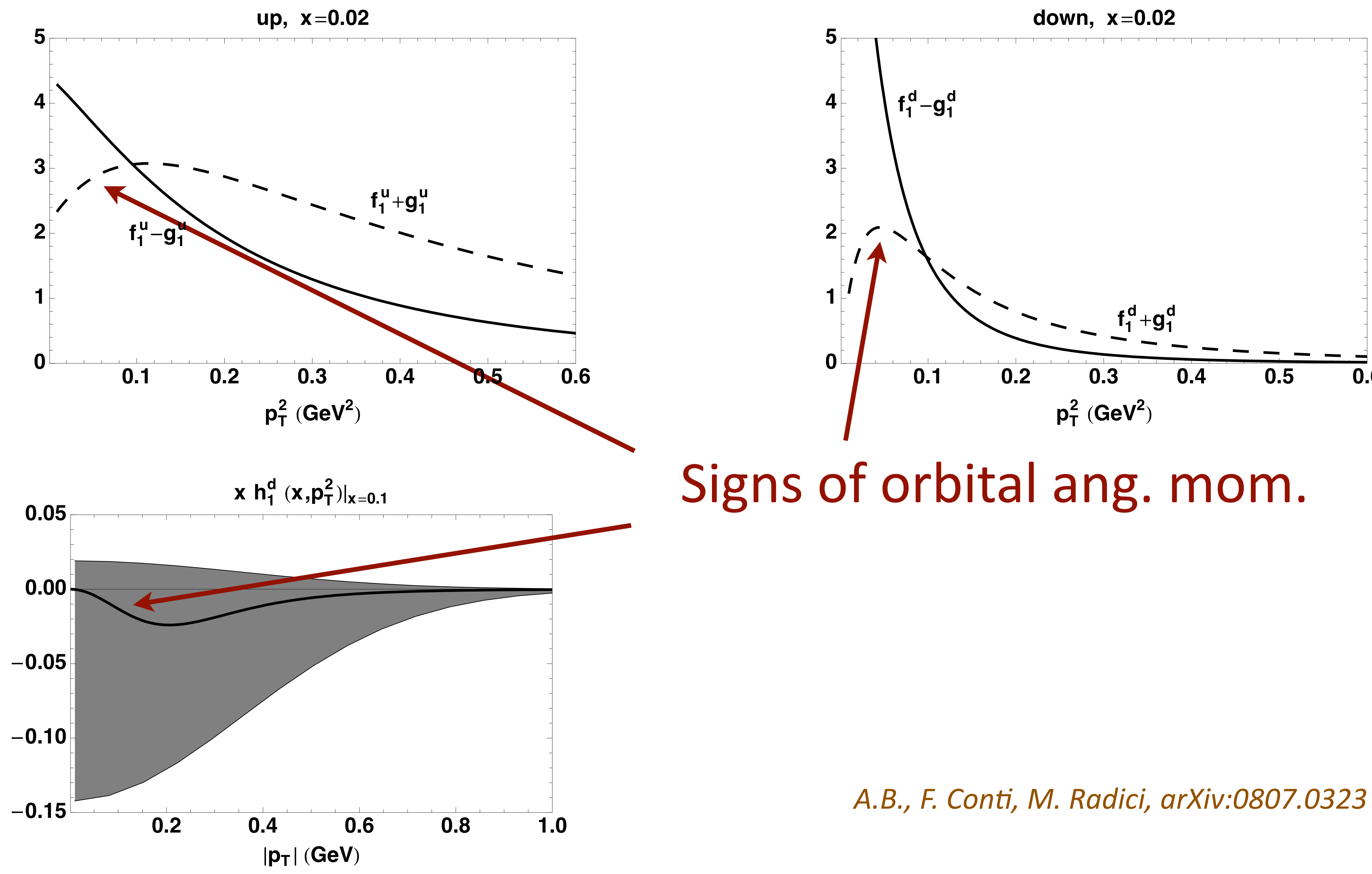

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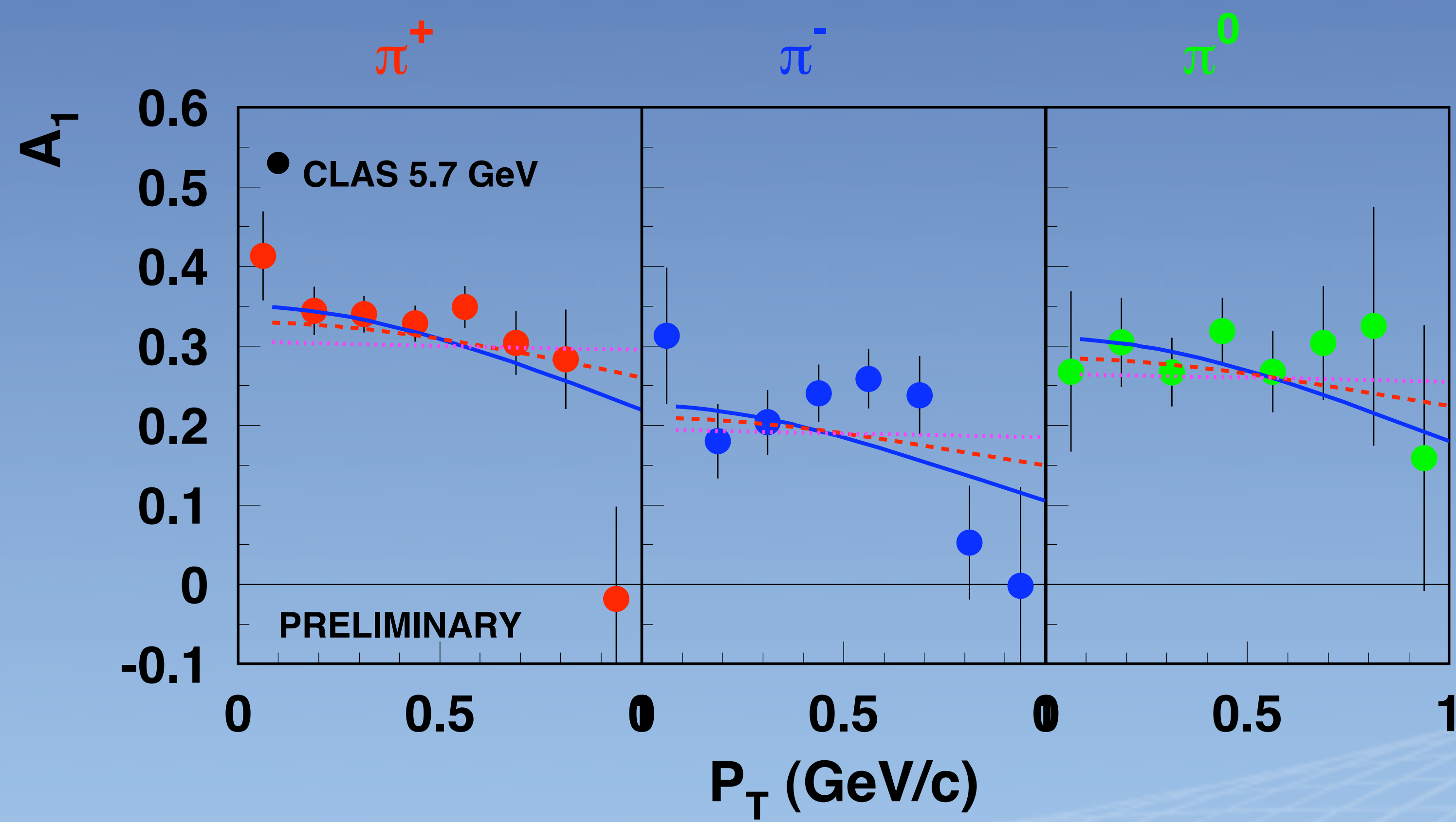
Longitudinal polarization measurements



see talk by P. Bosted

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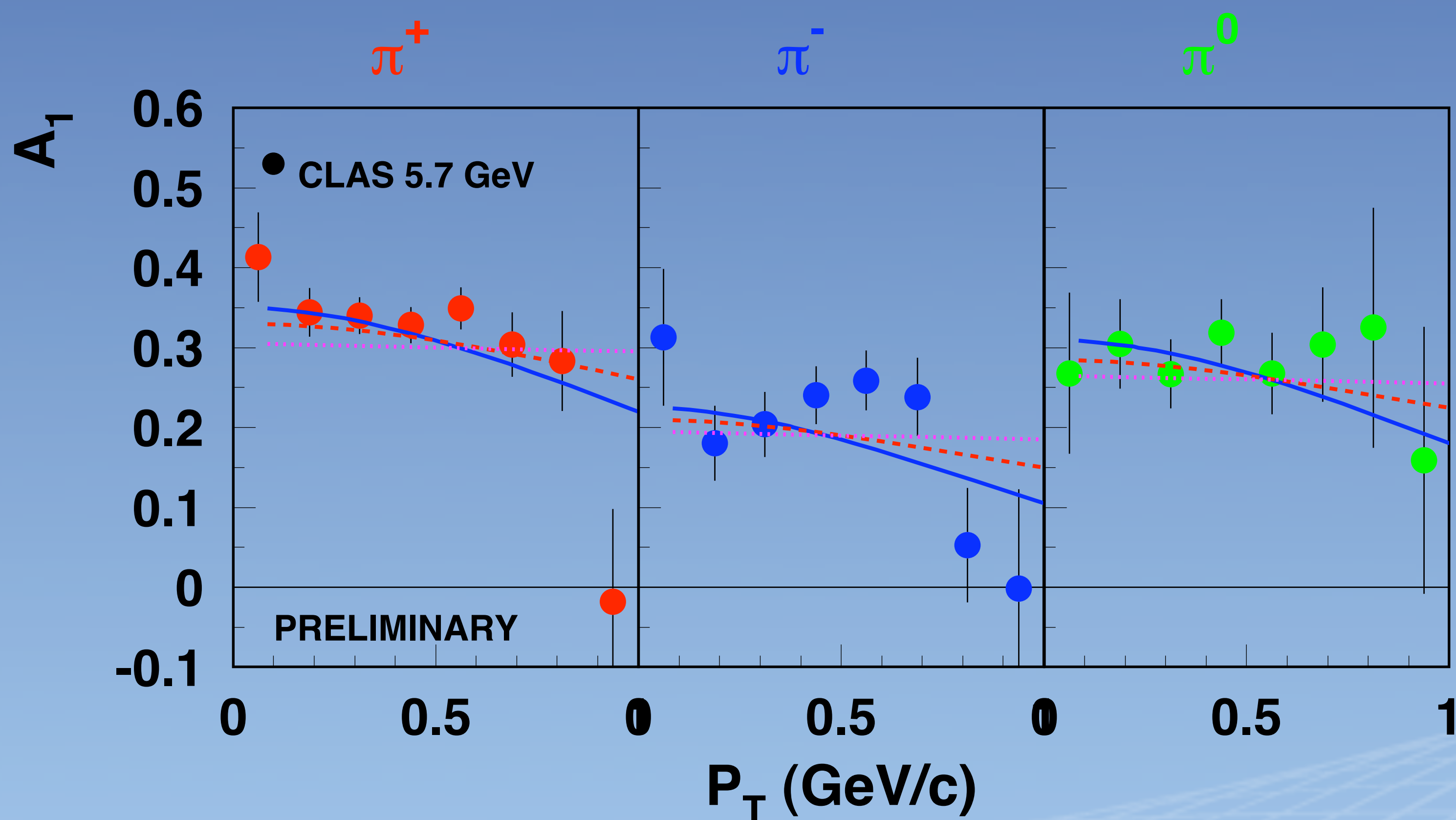

◉ Non-flat behavior indicates that polarized TMDs are different from unpolarized ones

see talk by P. Bosted

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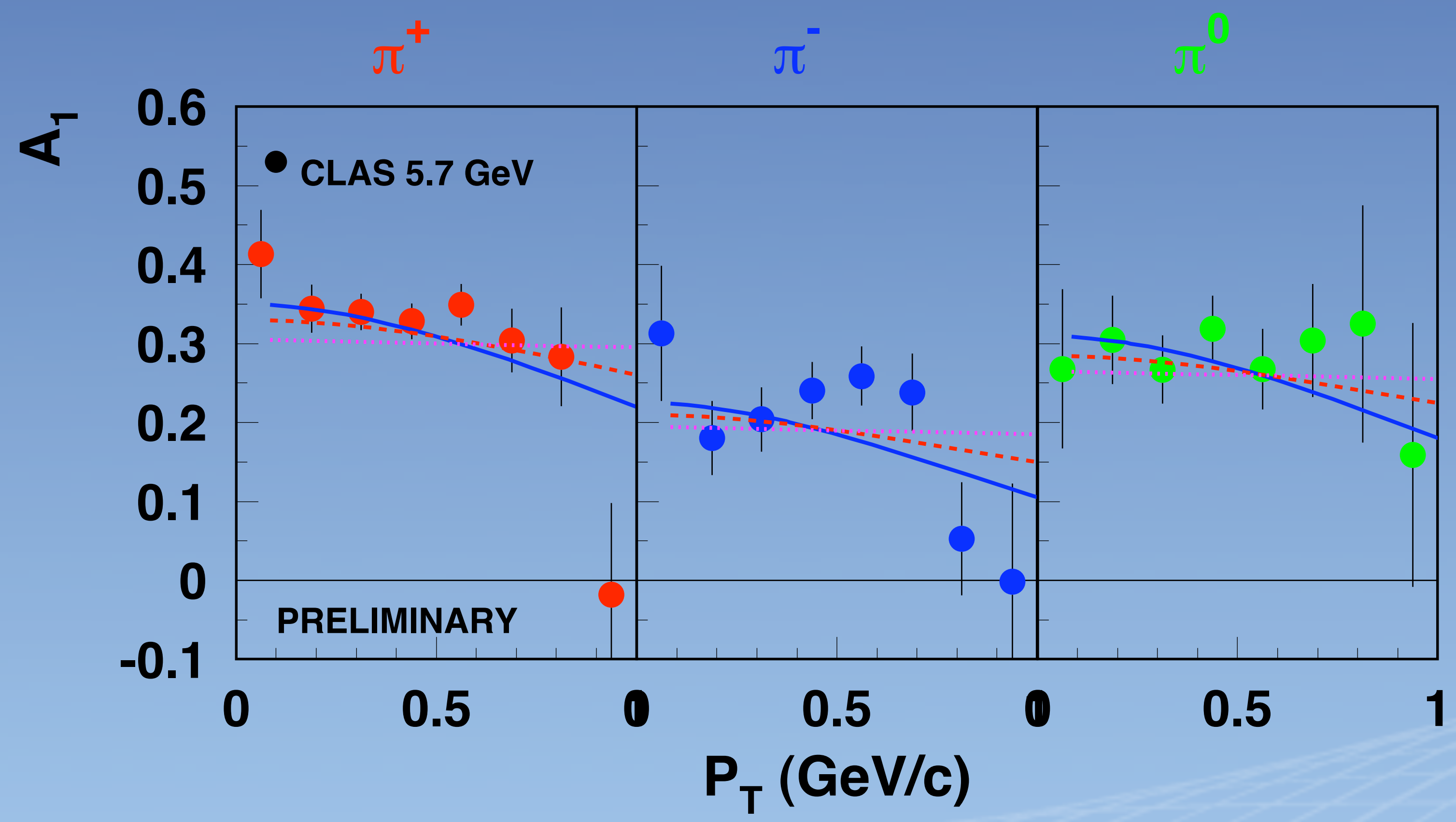

◉ Non-flat behavior indicates that polarized TMDs are different from unpolarized ones

◉ Non-monotonic behavior is a sign of orbital angular momentum

see talk by P. Bosted

OAM and polarized TMDs

quark pol. (columns) / nucleon pol. (rows)

	U	L	T
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L		g_{1L}	$h_{1L}^\perp$
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Twist-2 TMDs

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Twist-2 TMDs

- All off-diagonal TMDs vanish in the absence of orbital angular momentum

OAM and polarized TMDs

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

see also talks by B. Pasquini, P. Zavada

- All off-diagonal TMDs vanish in the absence of orbital angular momentum
- In general, quantitative relations between TMDs and orbital angular momentum are model-dependent

OAM and polarized TMDs

quark pol. / nucleon pol.

	U	L	T
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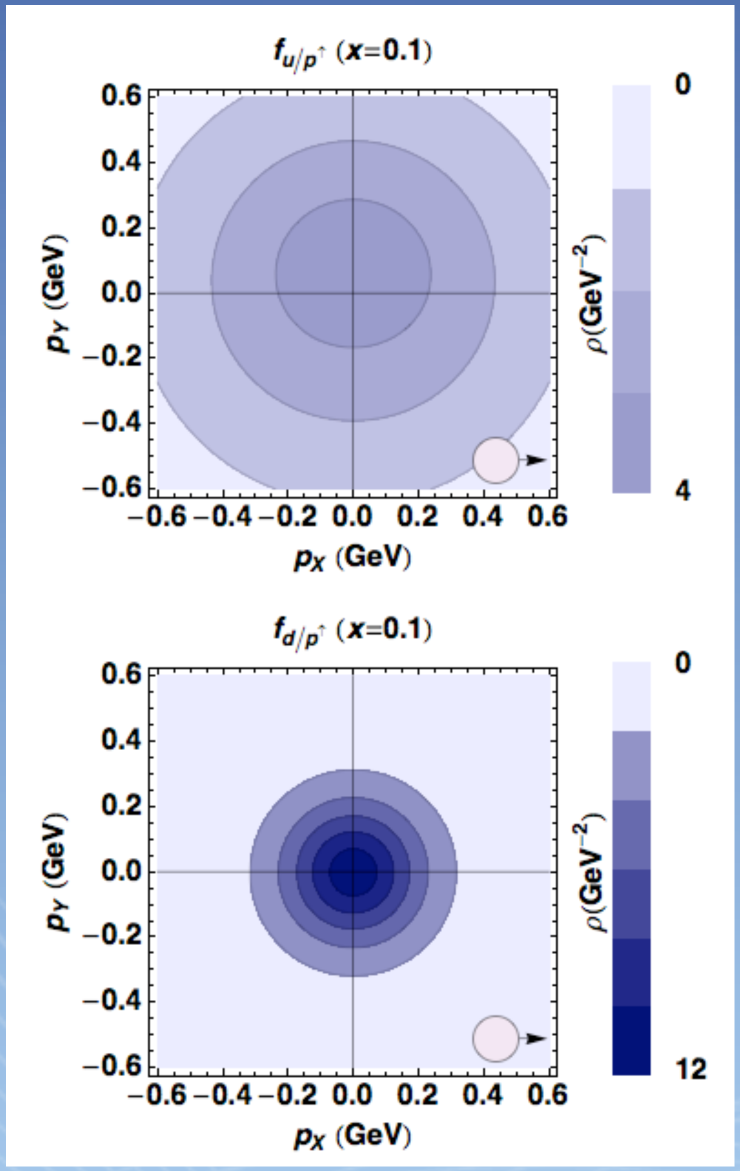
Sivers function



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

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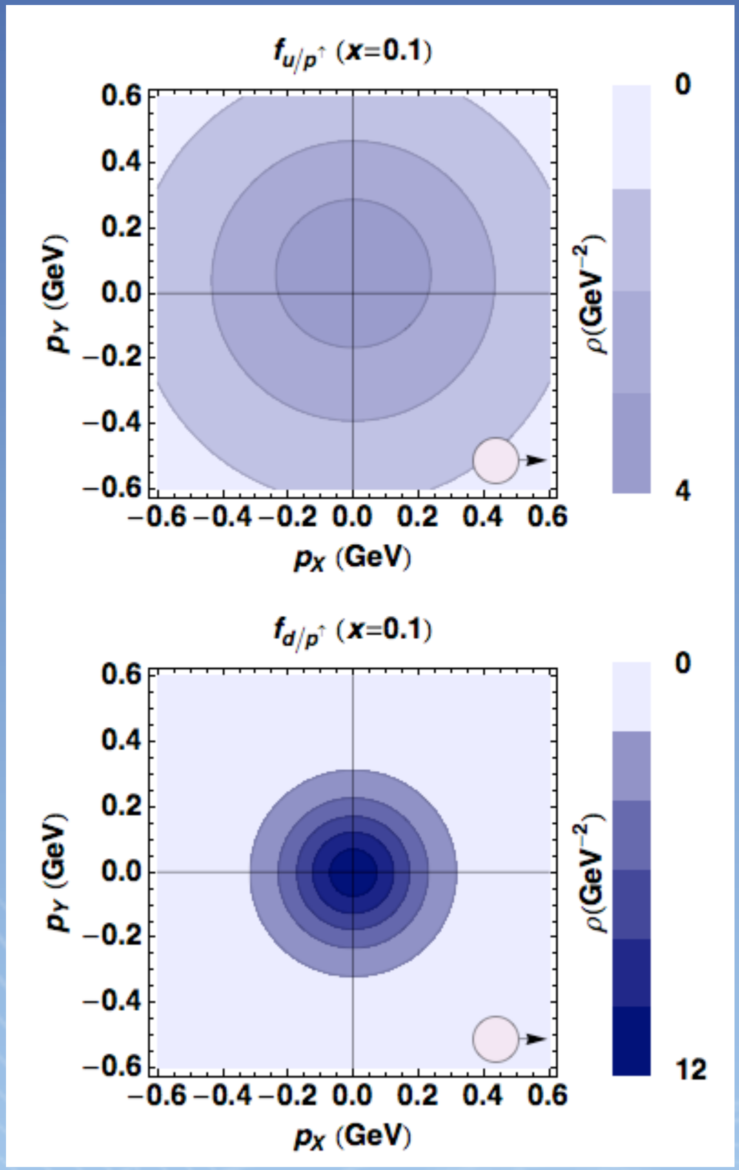

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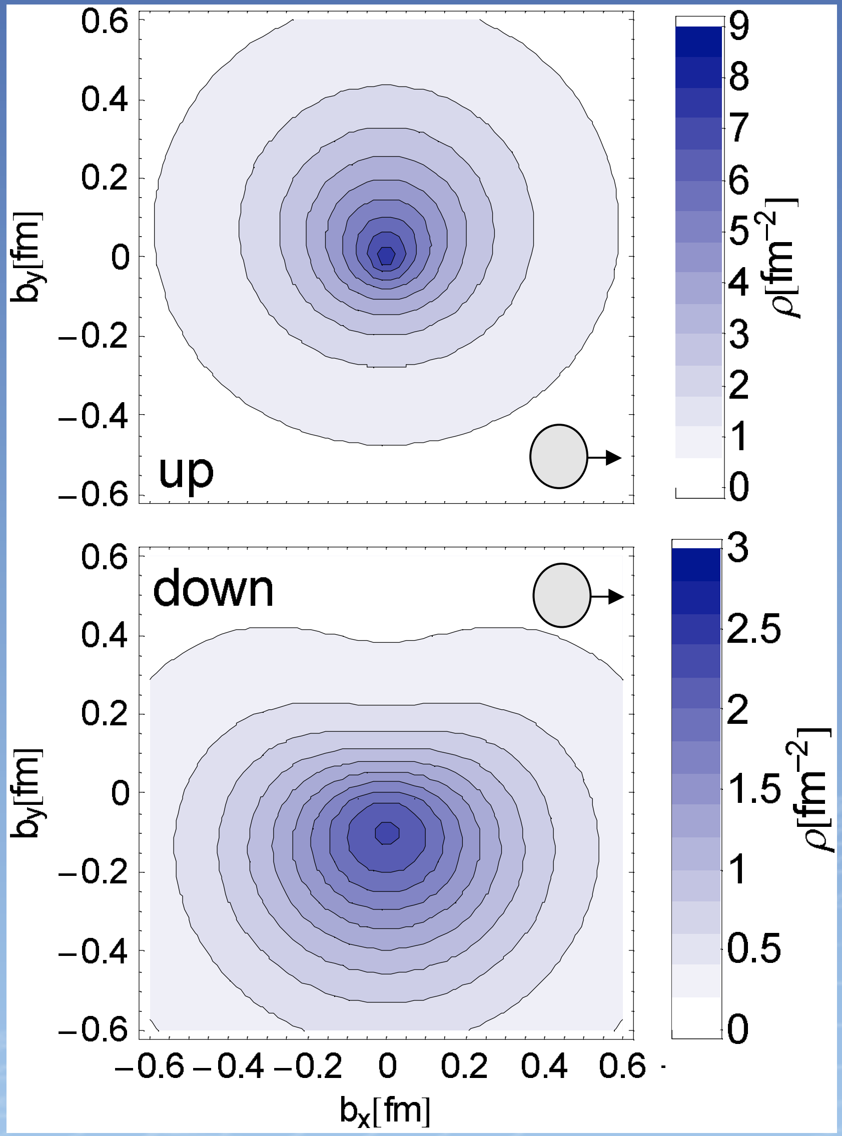

QCDSF/UKQCD, PRL 98 (07)

Sivers function and OAM

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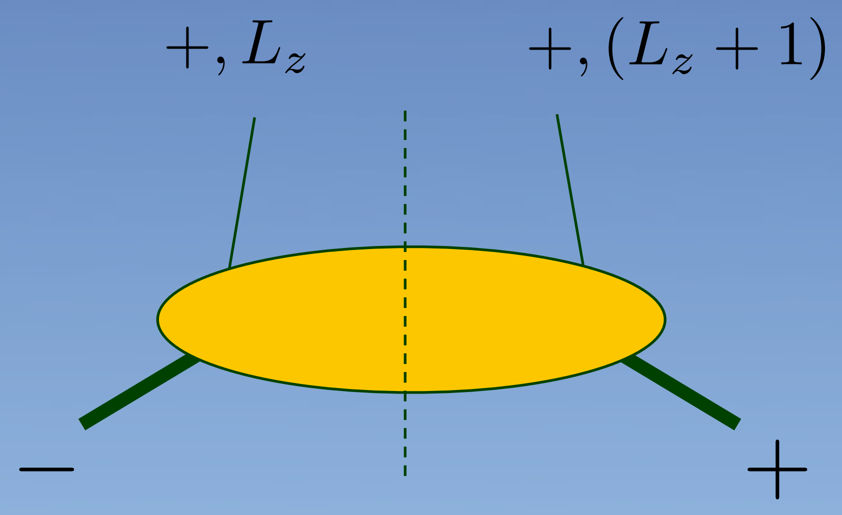

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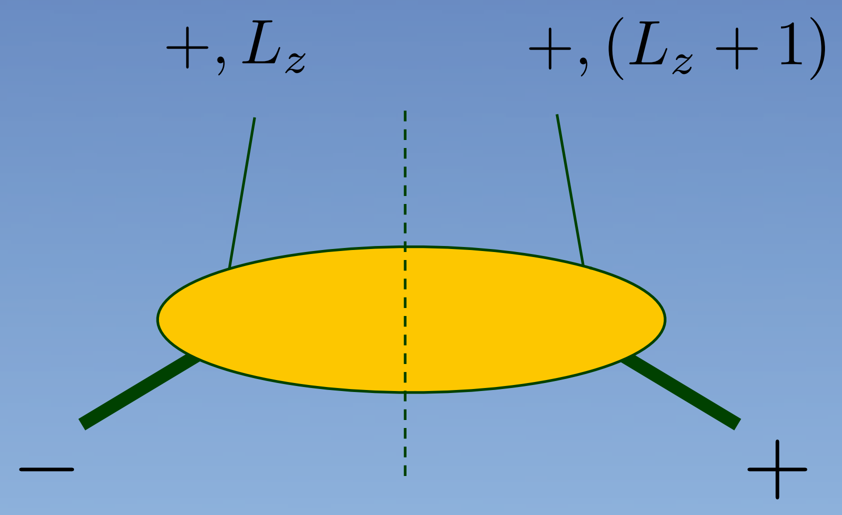

$$E(x,0,0) = \lim_{q_T\to 0}\left(-\frac{1}{q_x - iq_y}\frac{1}{16\pi^3}\big[(\psi_+^+)^*\psi_+^- + (\psi_-^+)^*\psi_-^-\big]\right)$$

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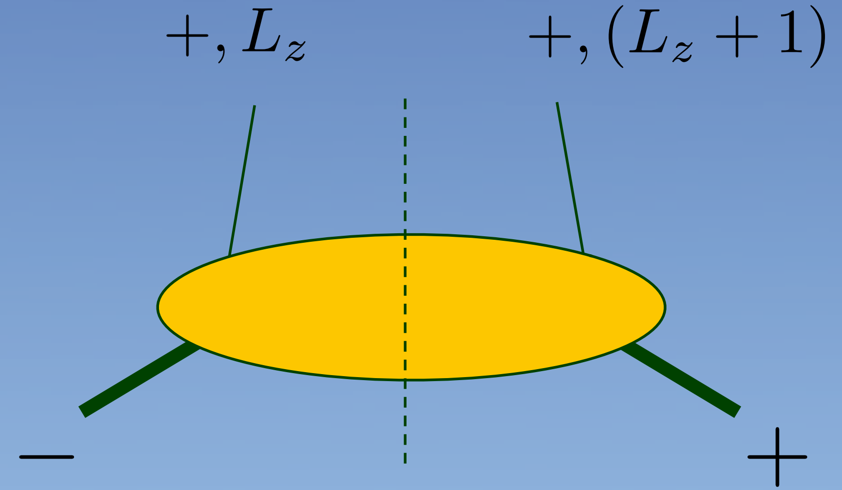

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$$J_q = \int_0^1 dx\, x\left(H_q(x,0,0) + E_q(x,0,0)\right)$$ Ji's sum rule

Sivers function and OAM

Model statement

$$(1-x) f_{1T}^{\perp q}(x) = -\frac{3}{2} M C_F \alpha_S \, E^q(x,0,0)$$

$$\int_0^1 dx (1-x) f_{1T}^{\perp q}(x) = -\frac{3}{2} M C_F \alpha_S \, \kappa^q$$

Burkardt, Hwang, PRD69 (04)
Lu, Schmidt, PRD75 (07)
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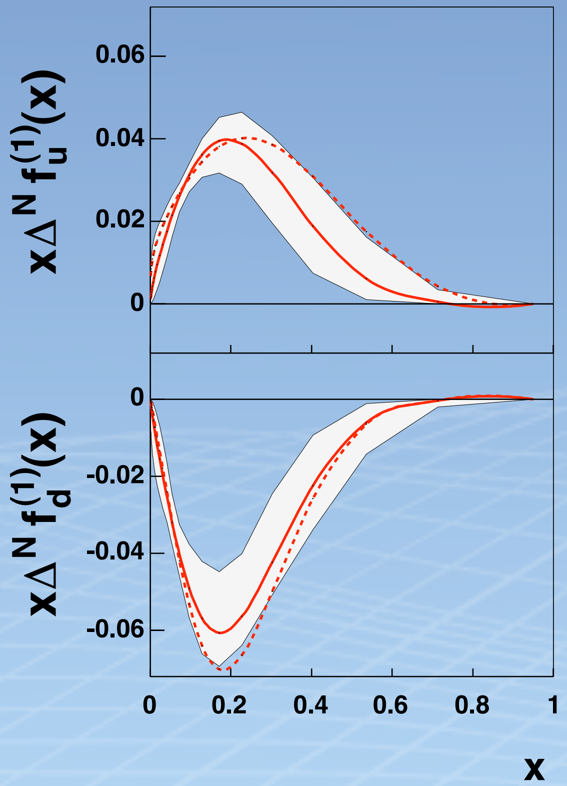

Anselmino et al., 0805.2677,
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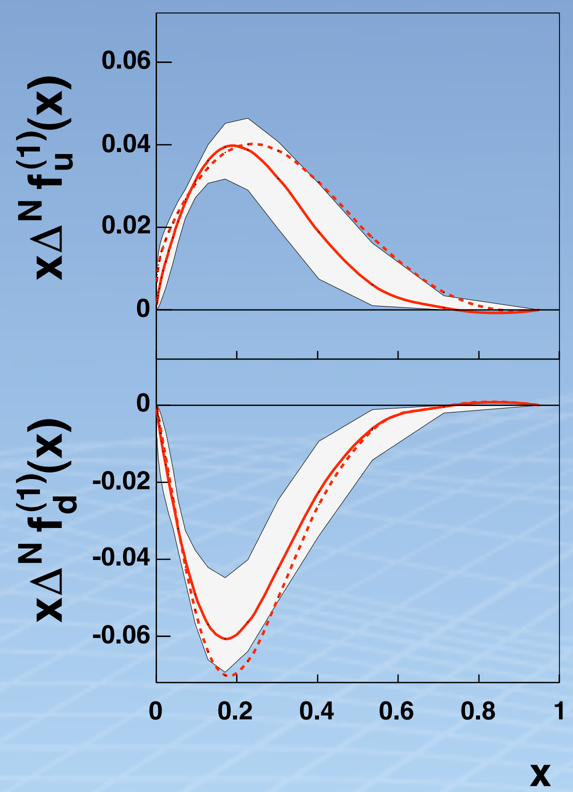
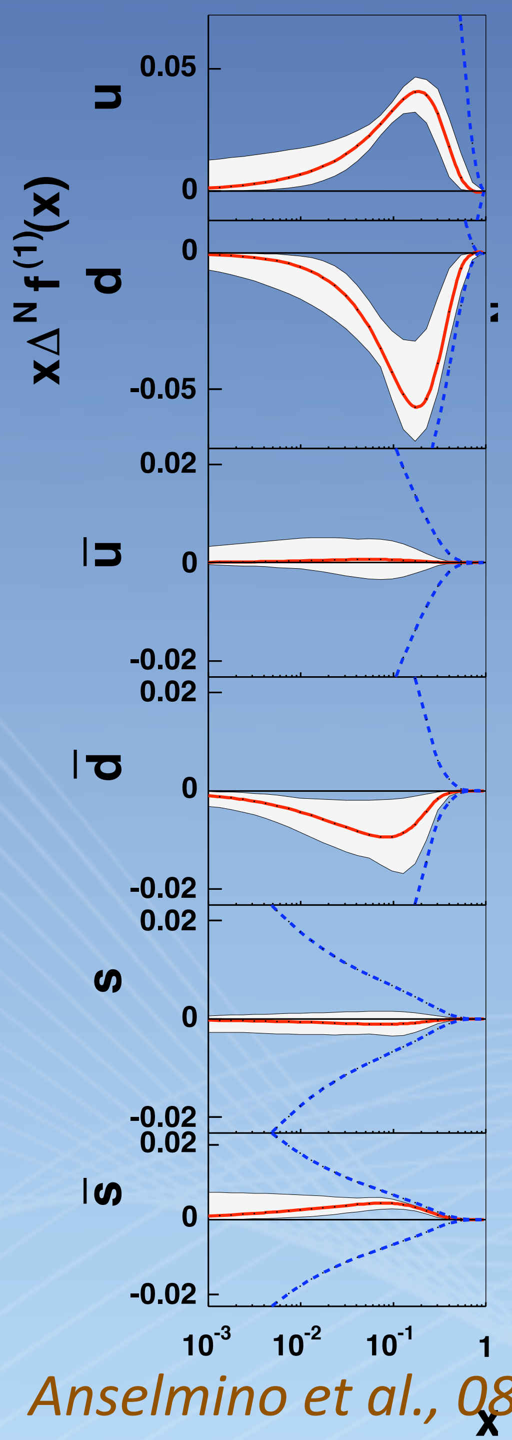


Anselmino et al., 0805.2677,
Arnold et al. , 0805.2137

The relation is not general

see talk by S. Meissner

Sivers function and OAM



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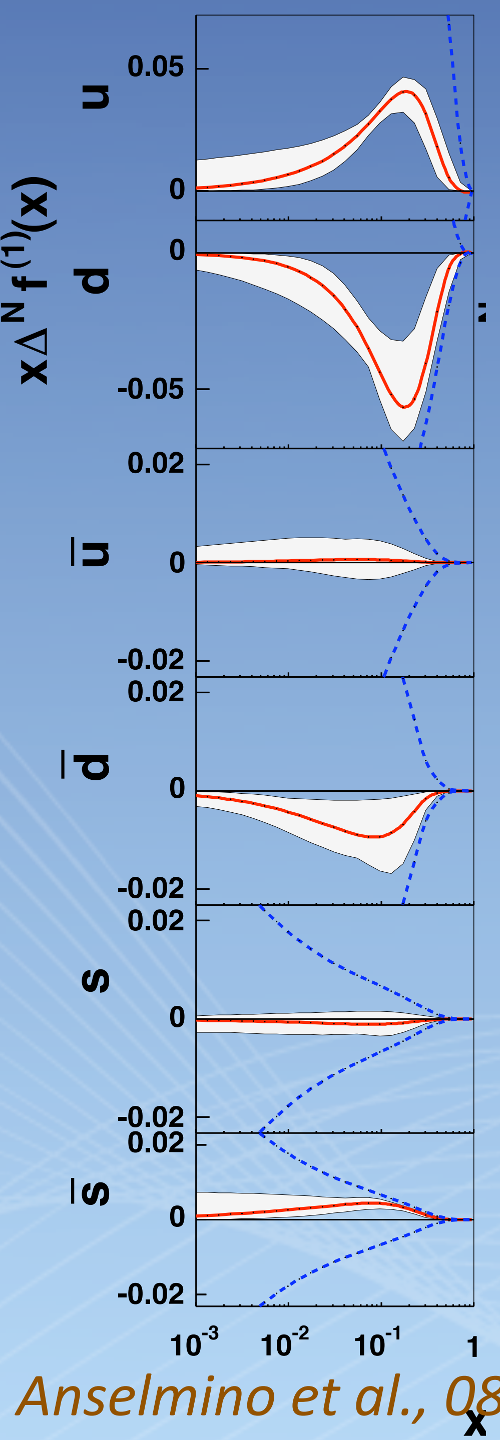
Sivers function and OAM



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Anselmino et al., 0805.2677, see talk by A. Prokudin

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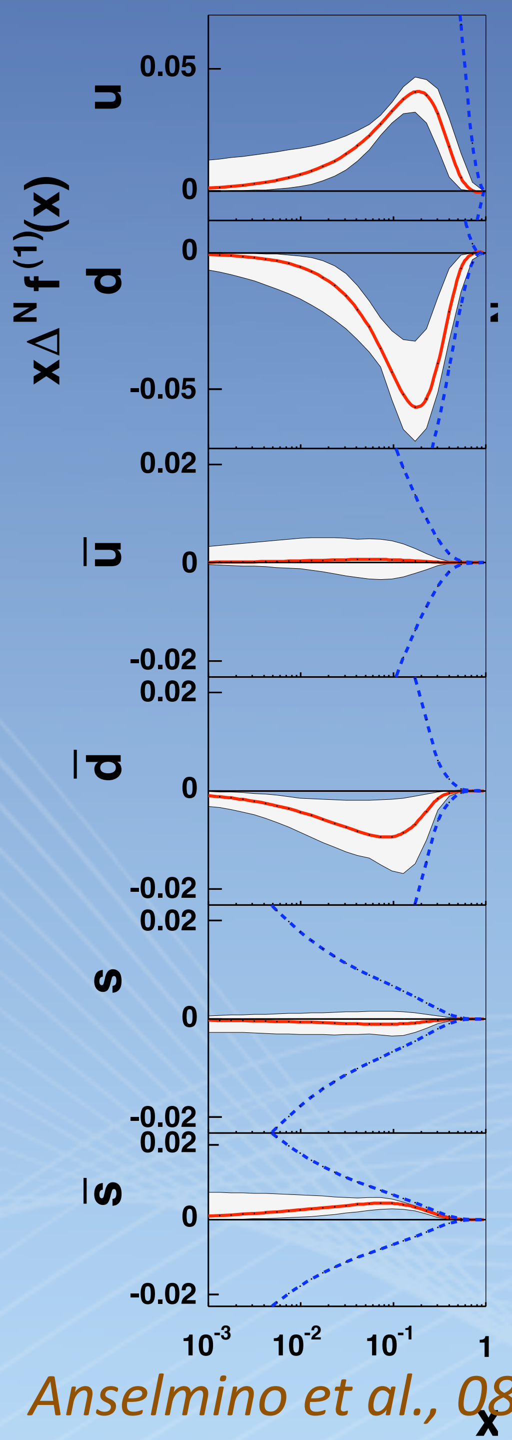

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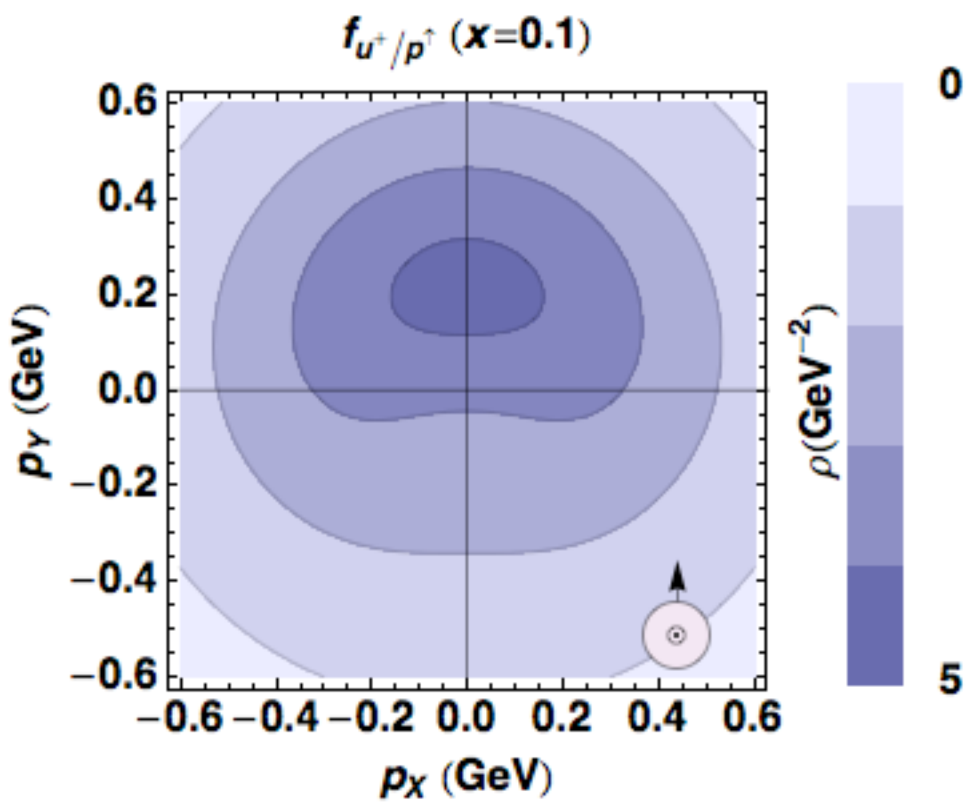
- Can the Sivers measurements provide an effective way to do a flavor decomposition of the anomalous magnetic moment?
- Can it become one of the most important sources of information also on gluon angular momentum?

g_{1T}: another interesting function



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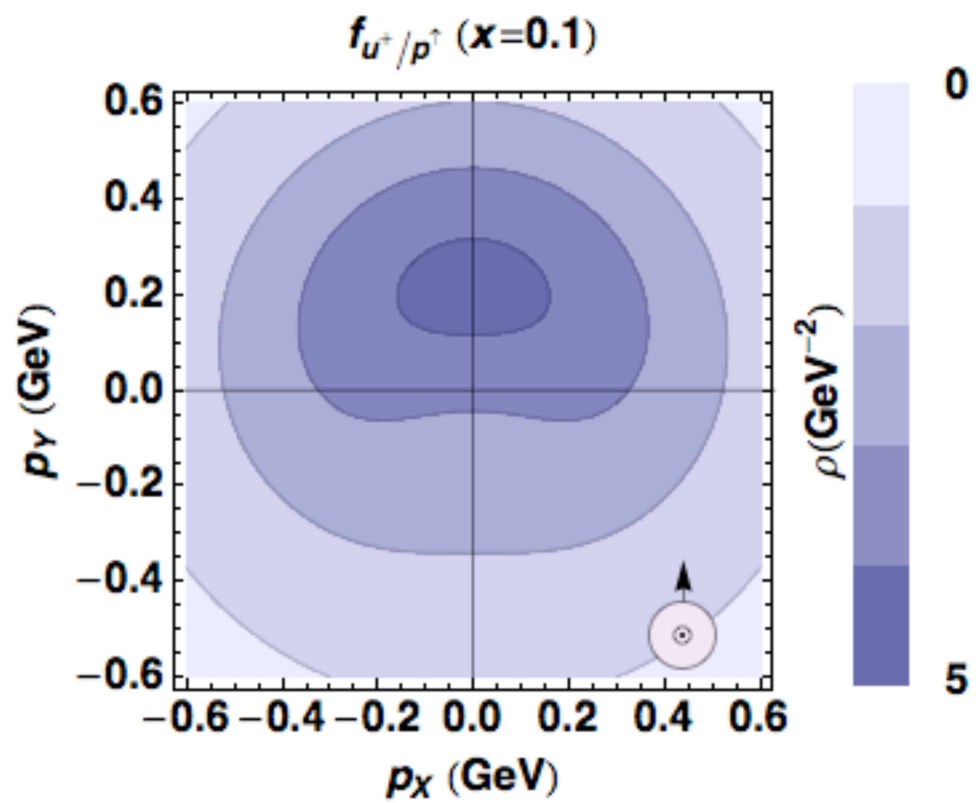
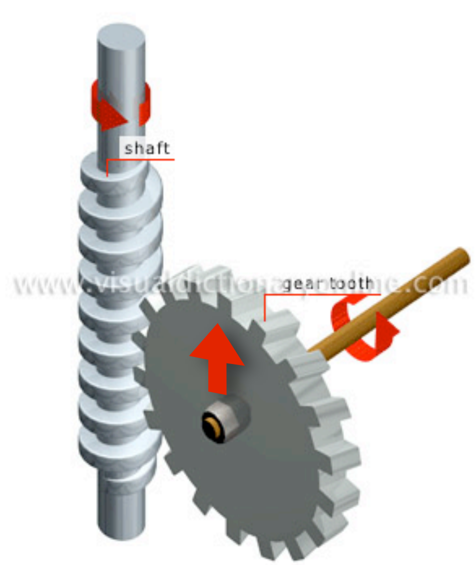


Worm gear



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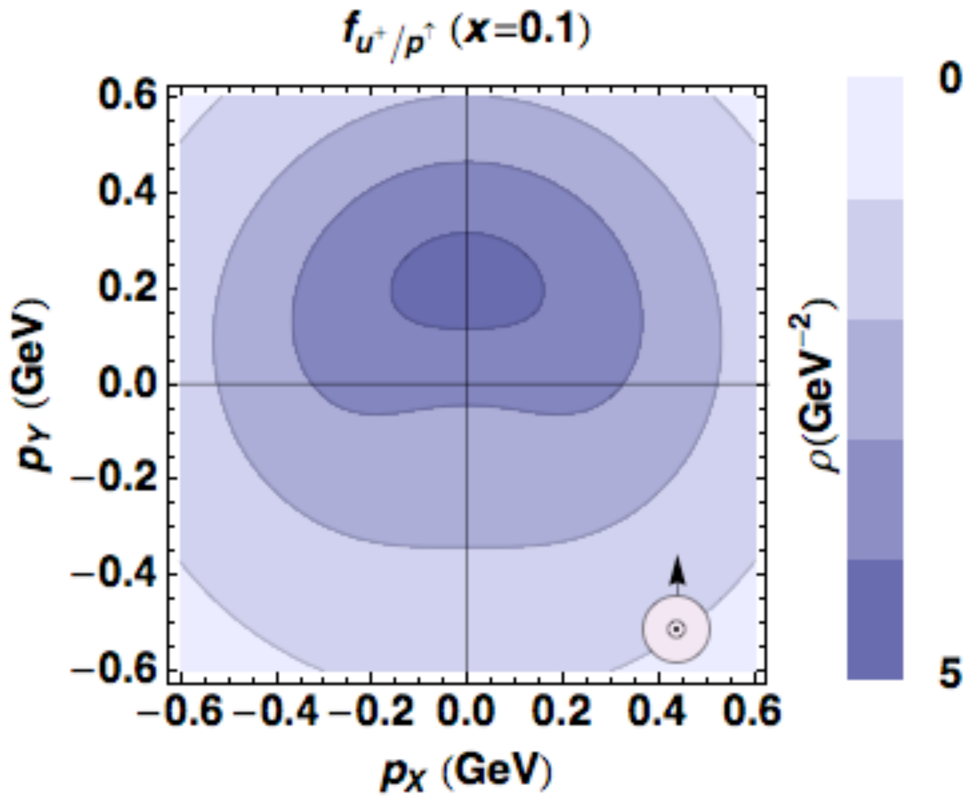

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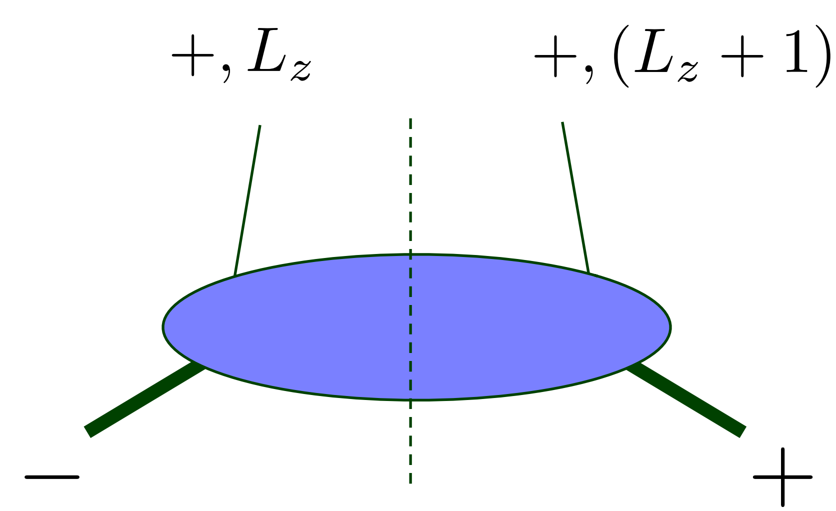

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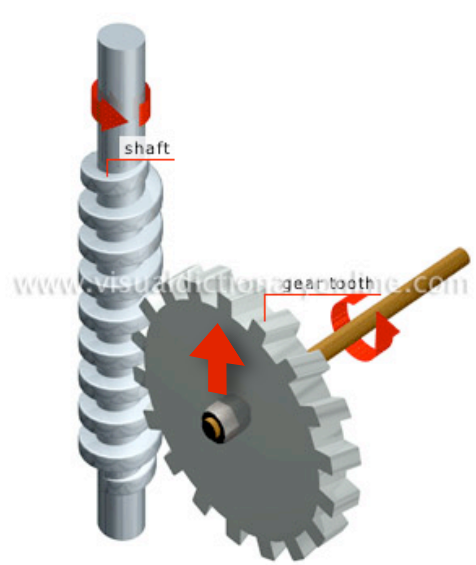

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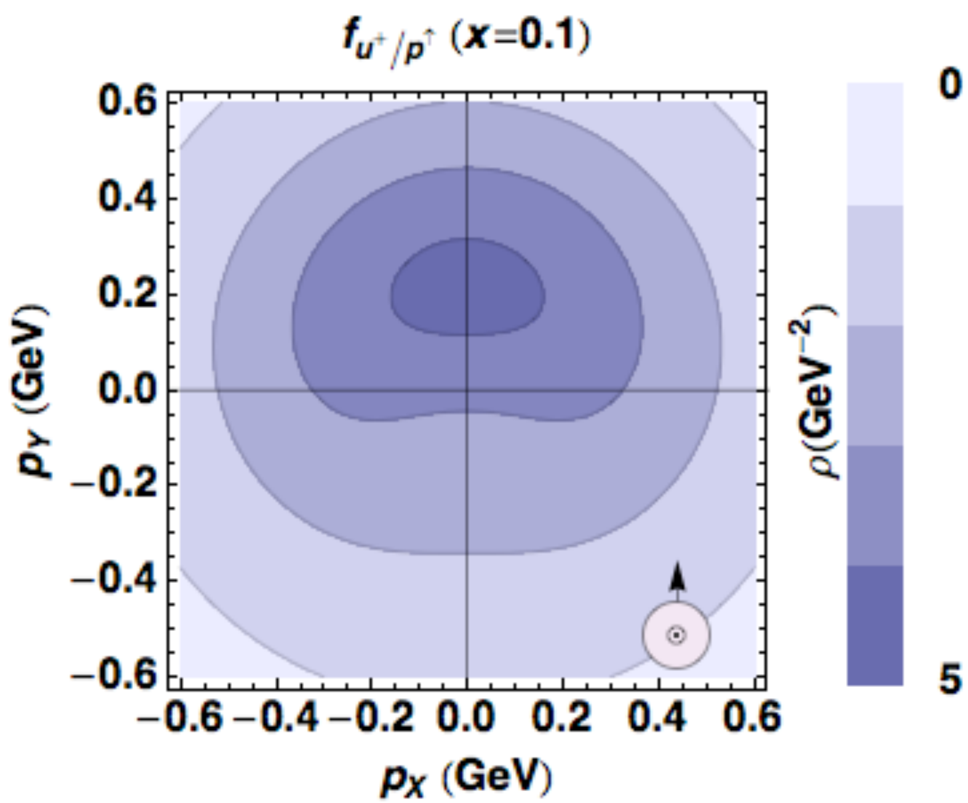

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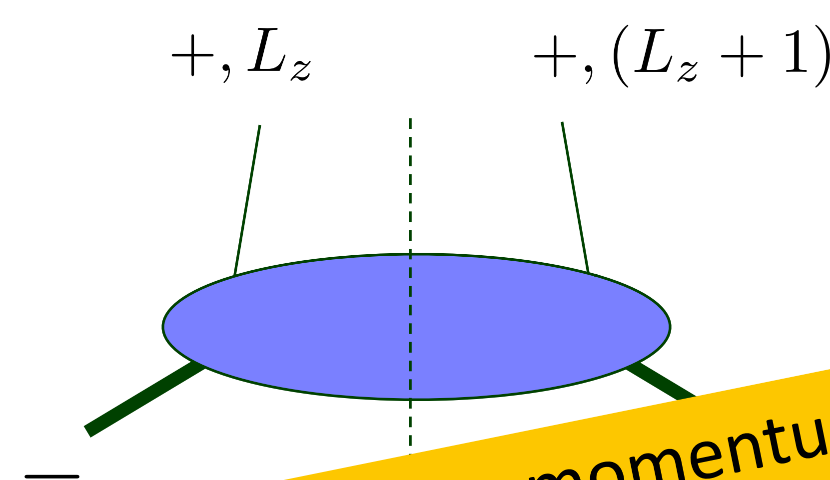

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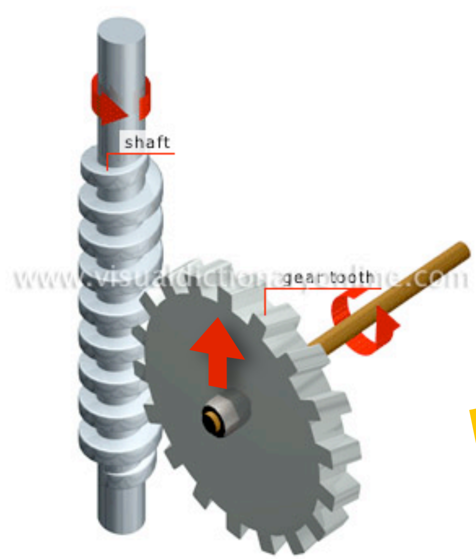

Another way to access angular-momentum information without final-state interactions

Factorization

Gauge links

$$\Phi_{ij}(x, p_T) = \int \frac{d\xi^- d^2\xi_T}{8\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi)|P\rangle\Big|_{\xi^+=0}$$

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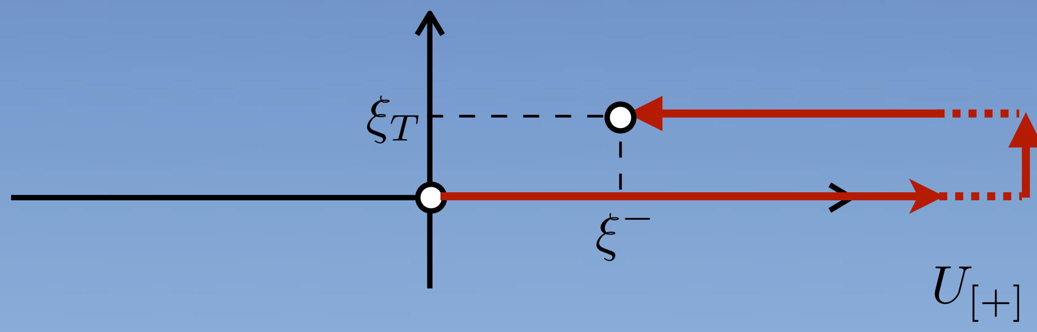

$U_{[+]}$

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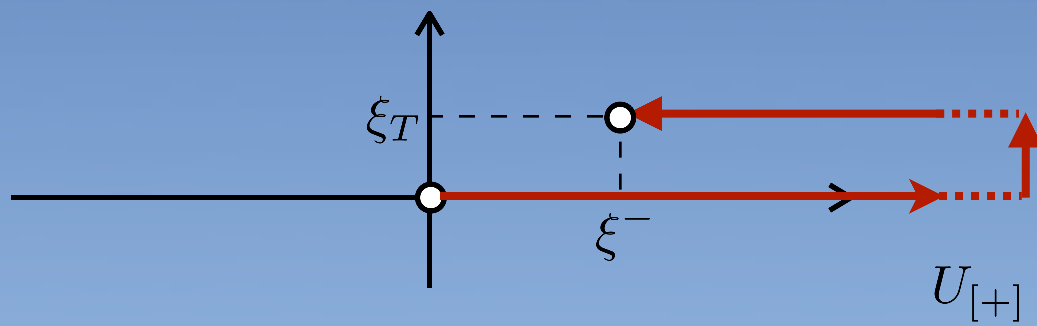
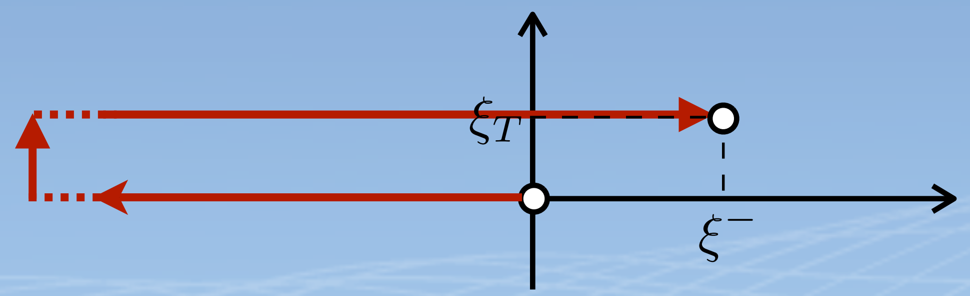


$U_{[+]}$

Drell-Yan



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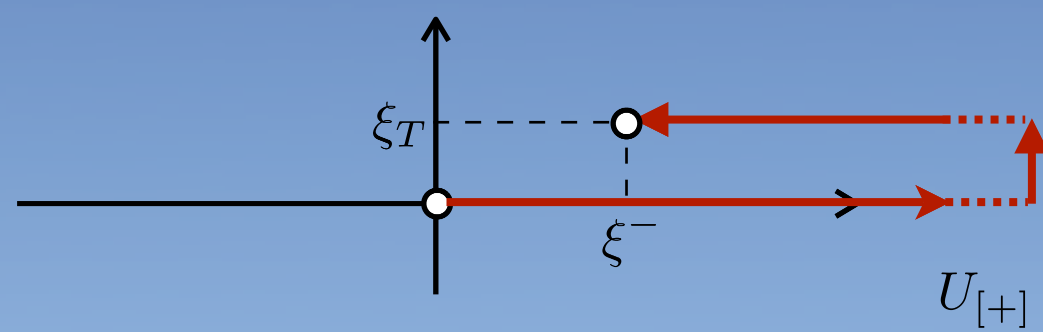

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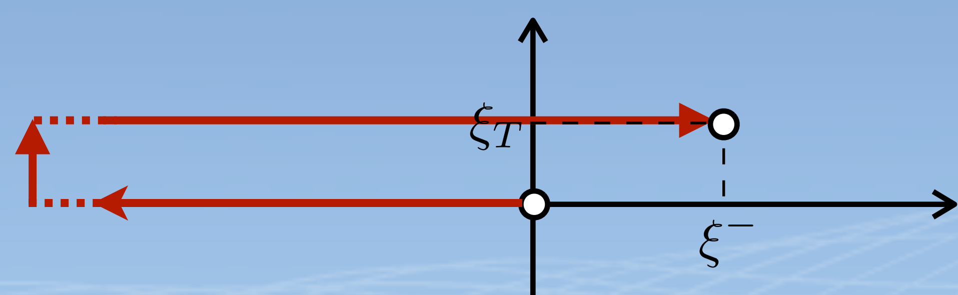
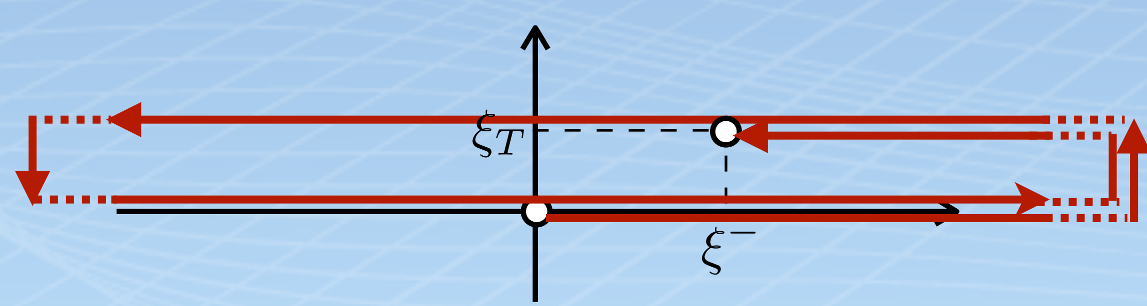


$U_{[-]}$

pp to hadrons



$U_{[\square]} U_{[+]}$

\+ several others

Generalized universality

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Collins, PLB 536 (02)
Bomhof, Mulders, Pijlman, PLB 596 (04)
A.B., Bomhof, Mulders, Pijlman, PRD 72 (05)
Collins, Qiu, PRD 75 (07)
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RHIC measurements are vital to check and understand these issues

…(02)
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- With assumptions, TMDs can be used to give extra constraints on orbital angular momentum
- TMDs pose some nice challenges from the theoretical point of view