Transverse-momentum-dependent parton distributions (TMDs)

Alessandro Bacchetta
University of Pavia and INFN

On behalf of an *exceptional* TMD community

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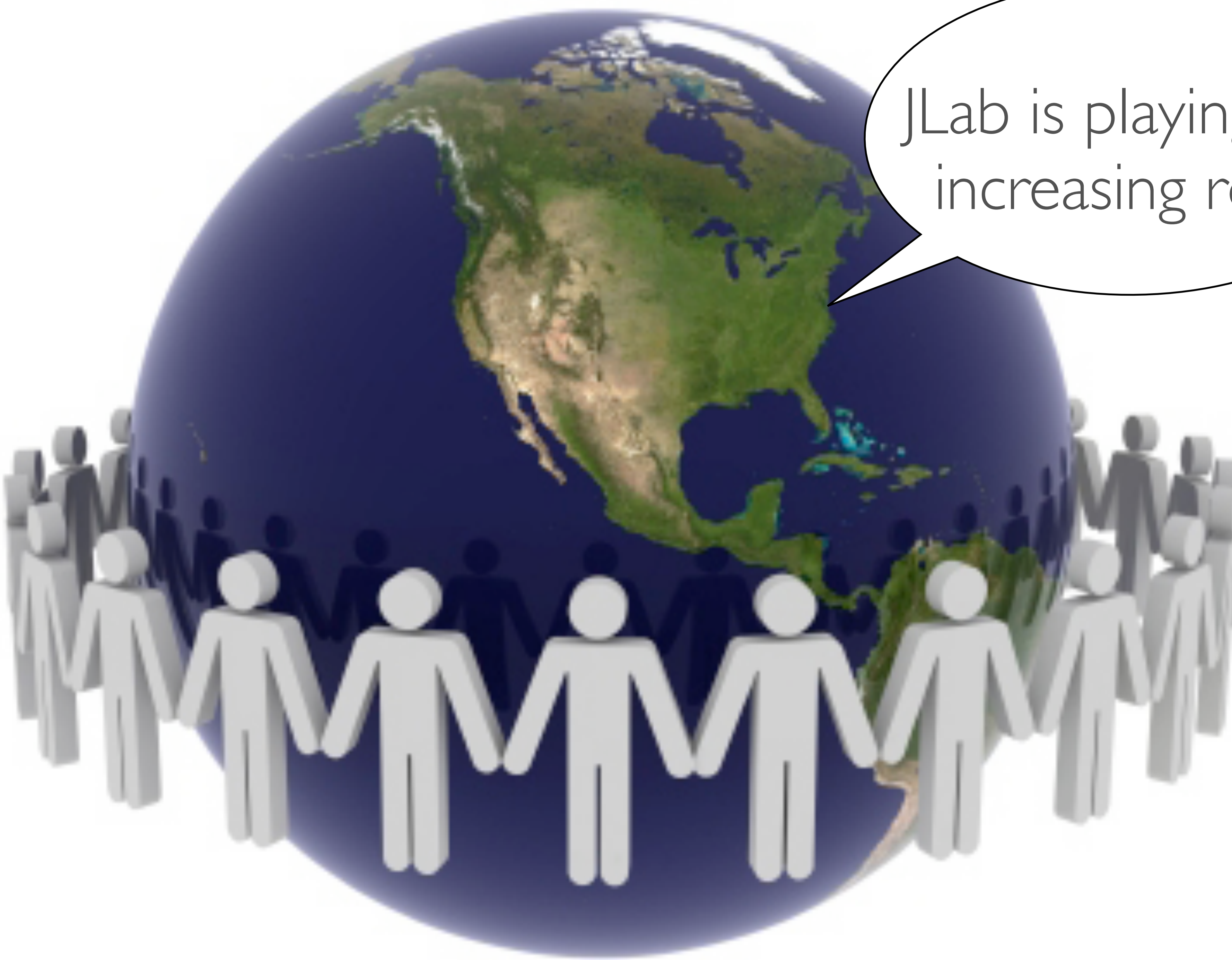


JLab is playing an increasing role

Steady progress over last years

Steady progress over last years

- Theory

Steady progress over last years

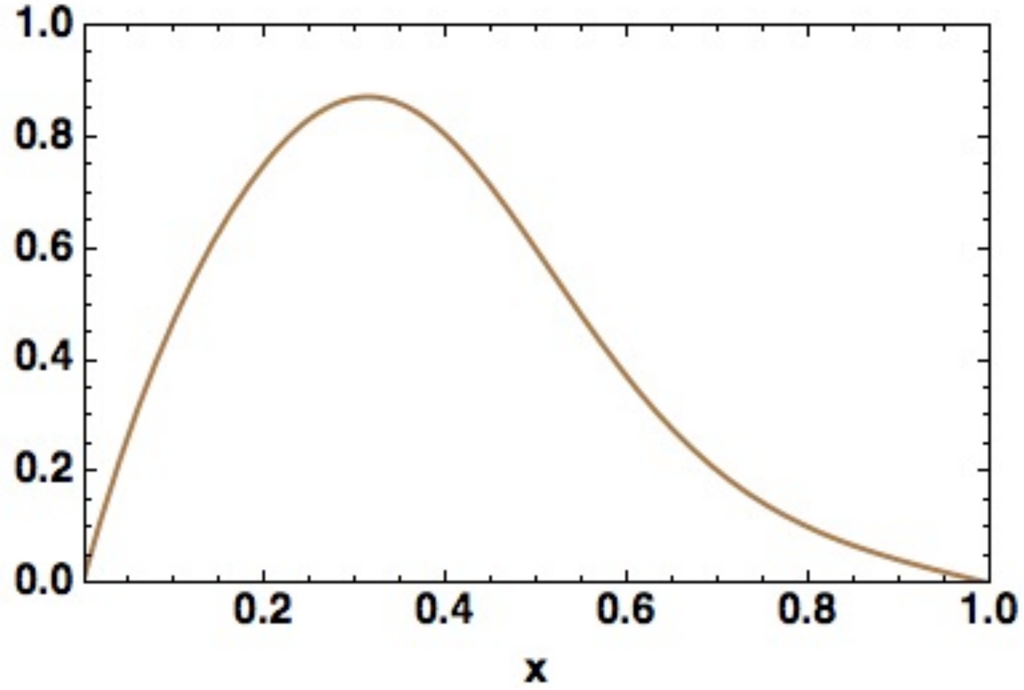
- Theory
- Experiment

Steady progress over last years

- Theory
- Experiment
- Phenomenology

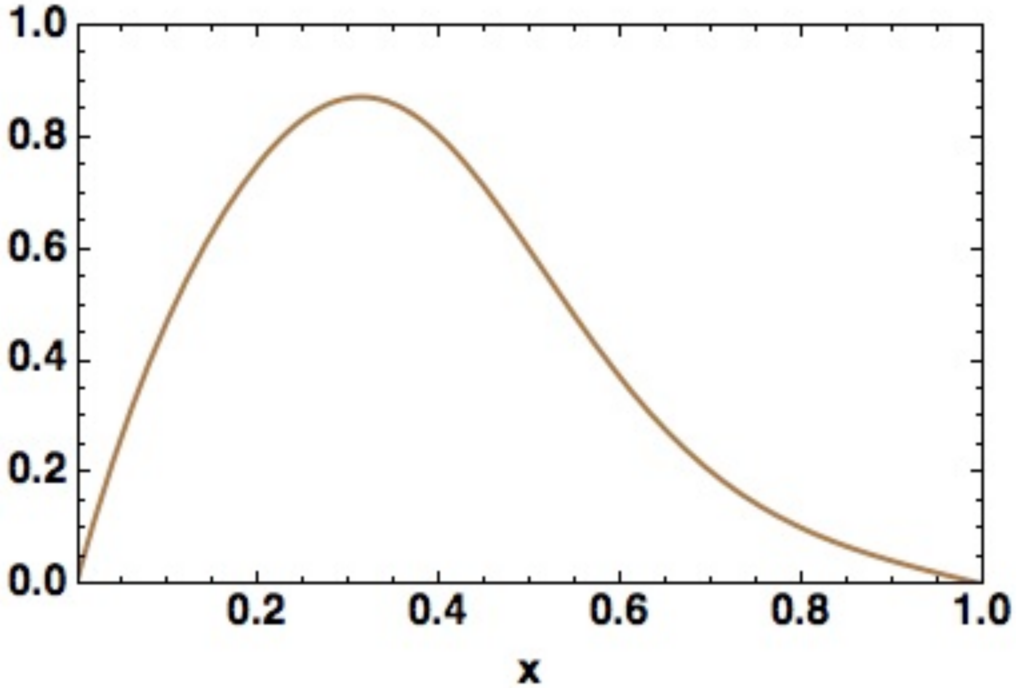
Intro

$$xf_1^u(x)$$



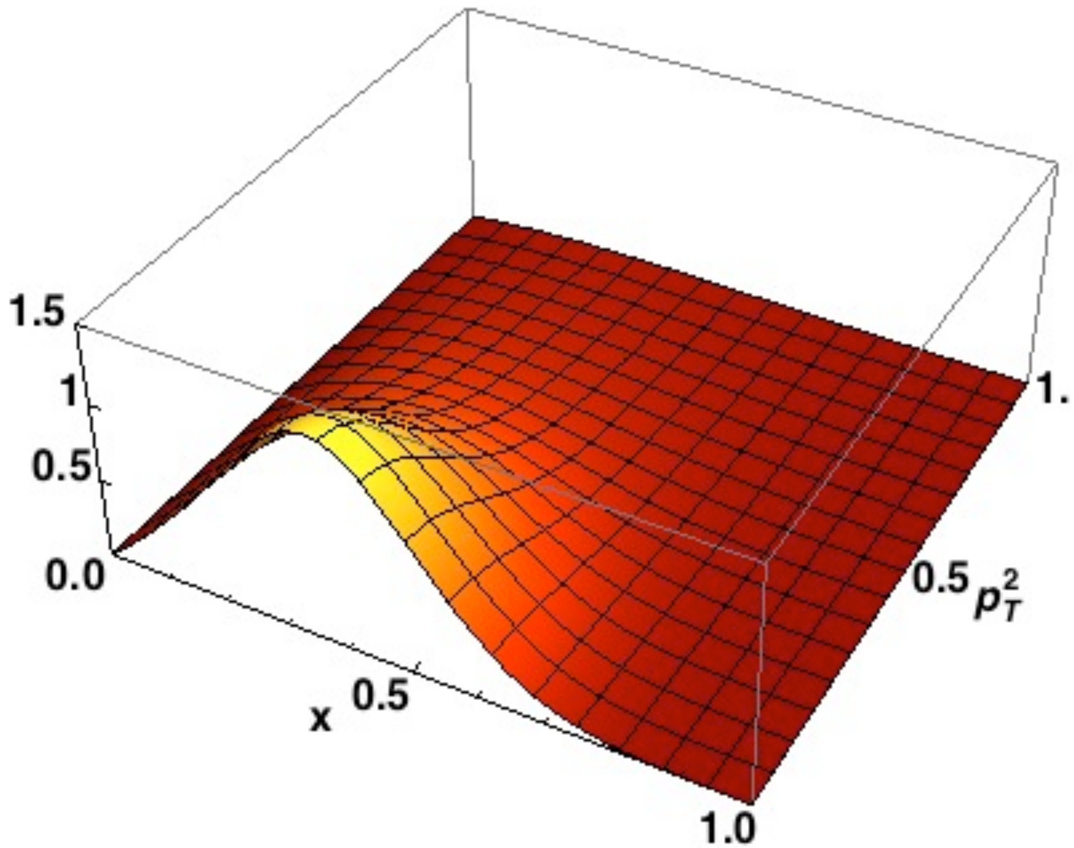
Standard collinear PDF

$xf_1^u(x)$



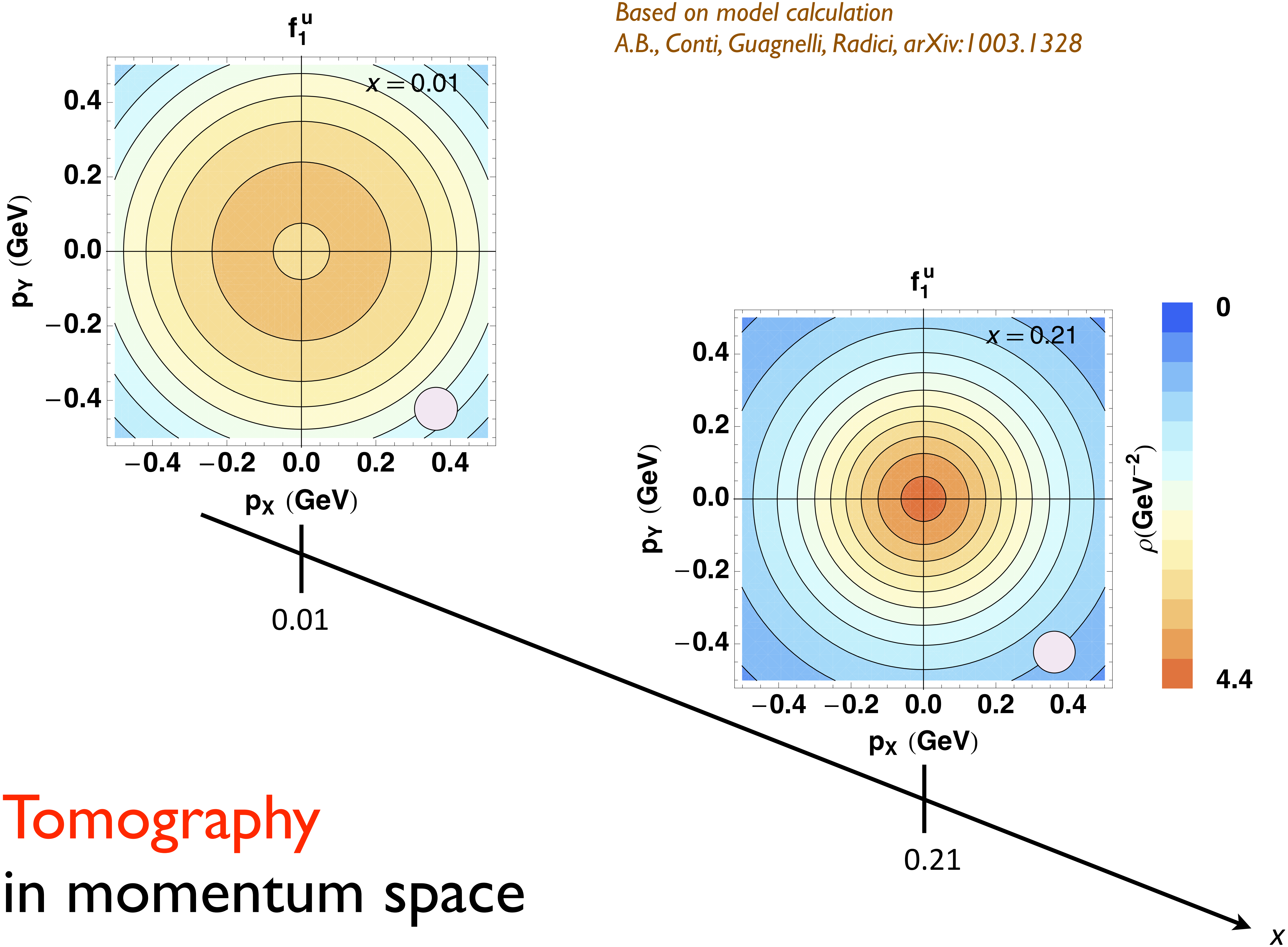
Standard collinear PDF

$xf_1^u(x, p_T^2)$



Transverse momentum distribution (TMD)

Based on model calculation
A.B., Conti, Guagnelli, Radici, arXiv:1003.1328



Tomography
in momentum space

Based on model calculation
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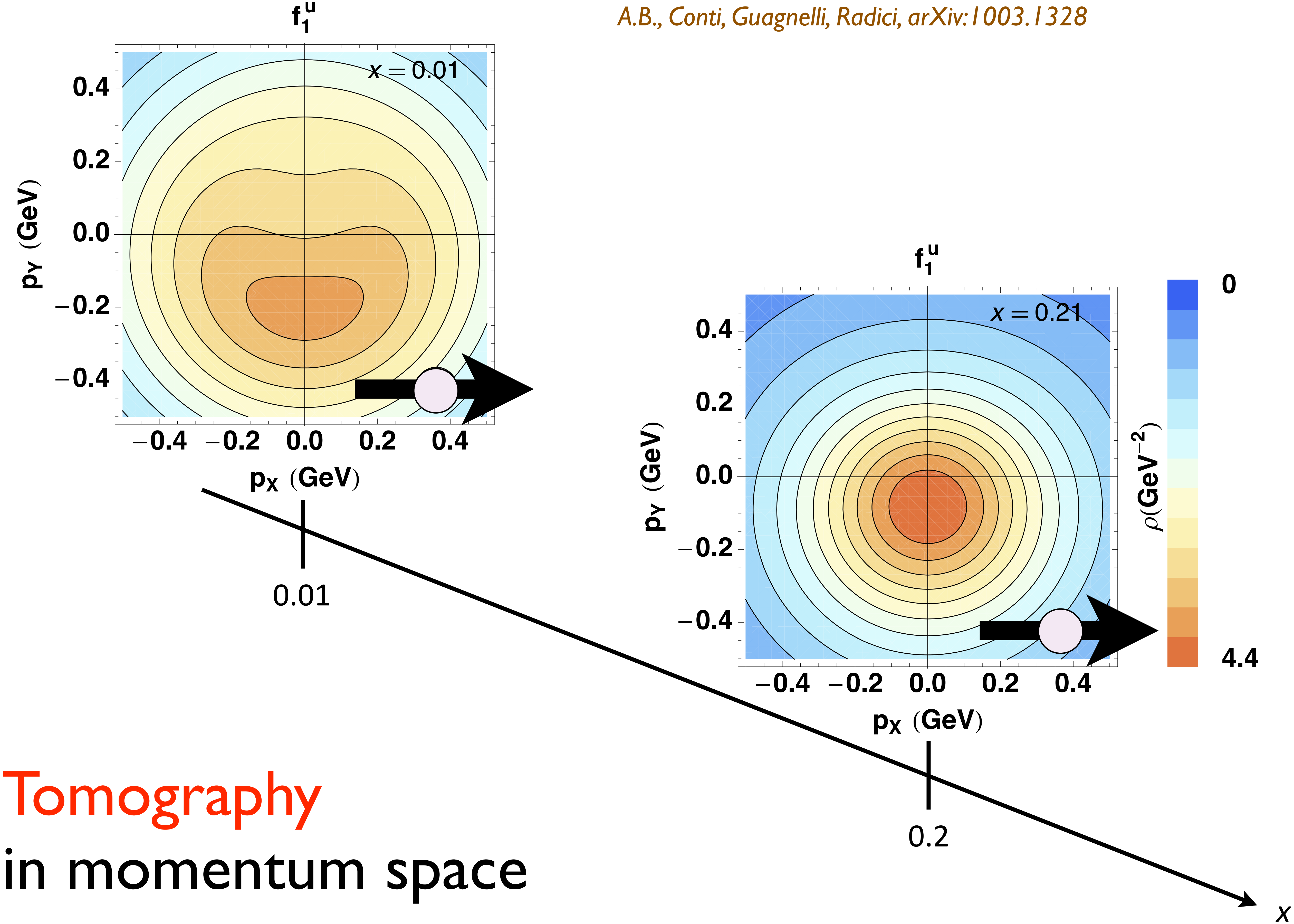
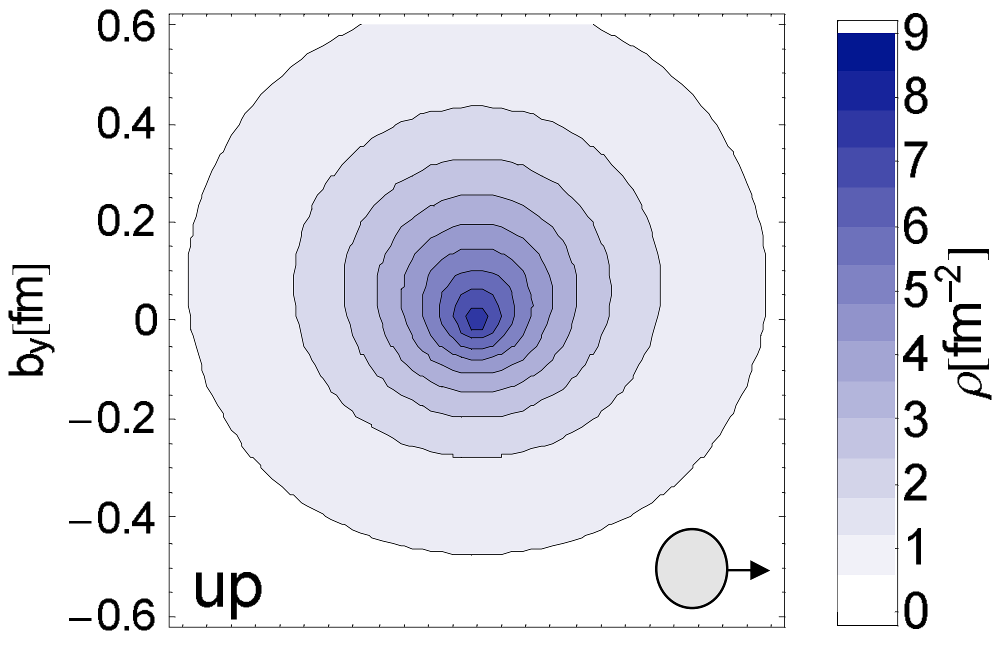


Tomography
in momentum space

Sister distributions

Generalized parton distribution functions

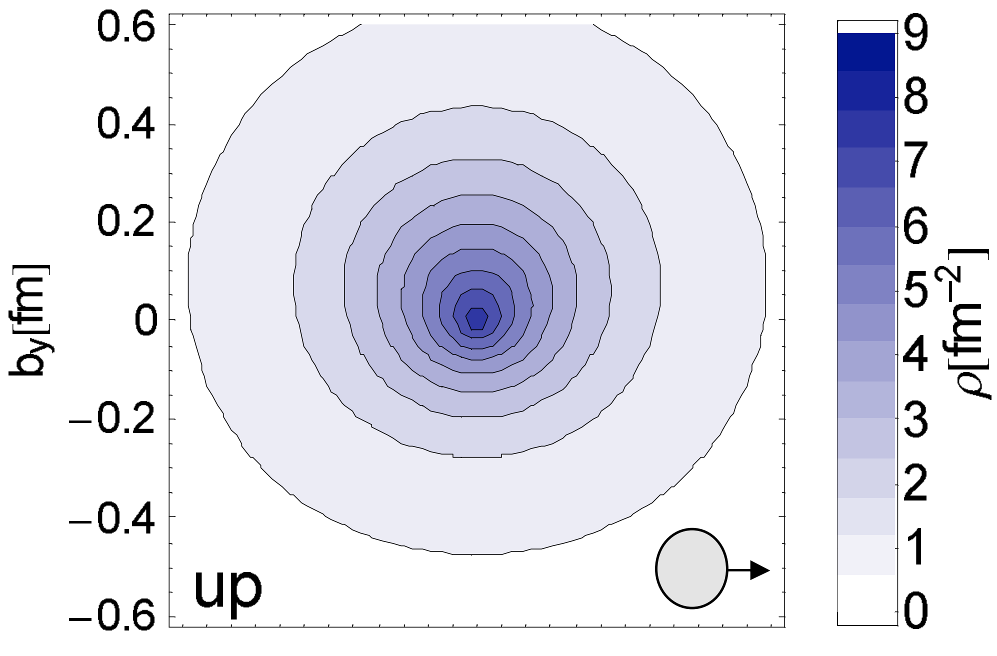


QCDSF/UKQCD, PRL 98 (07)

Coordinate space

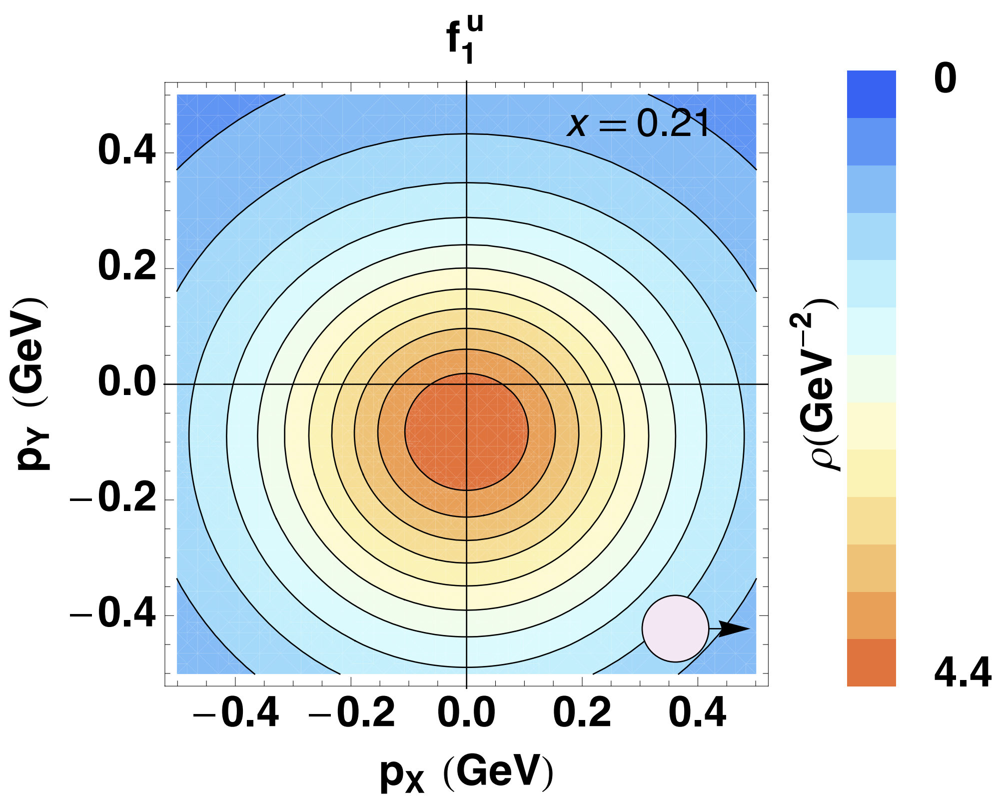
Sister distributions

Generalized parton distribution functions



QCDSF/UKQCD, PRL 98 (07)

TMDs



Based on A.B., Conti, Guagnelli, Radici, arXiv:1003.1328

Coordinate space **Momentum space**

This is a picture of an orchestra in coordinate space.

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Adding momentum we get the full experience...

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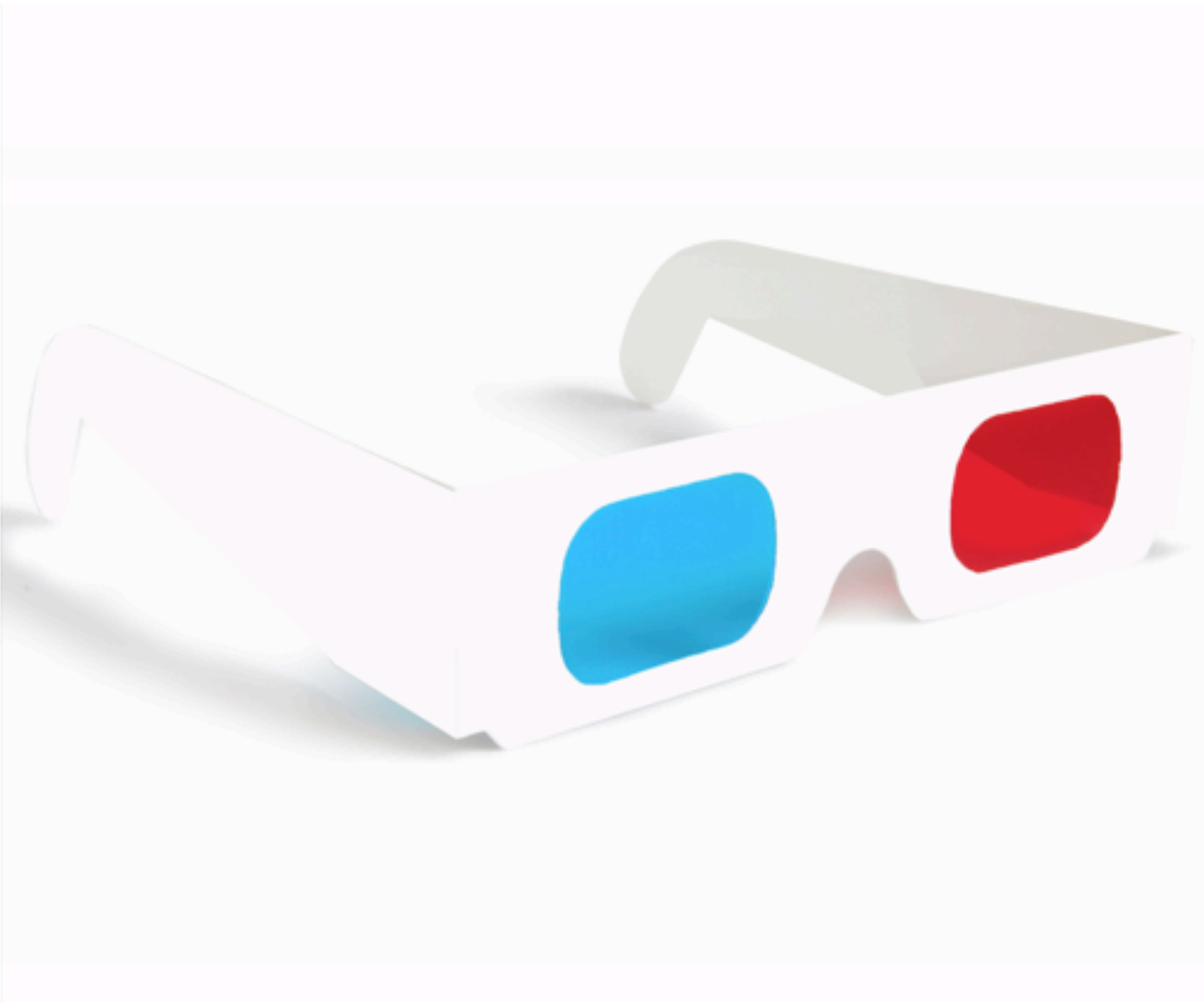
Adding momentum we get the full experience...



TMDs: multidimensional structure of the nucleon in momentum space

8 leading-twist 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

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

8 leading-twist TMDs

helicity

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

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

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Twist-2 TMDs

transversity

TMDs in black survive transverse-momentum integration

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8 leading-twist TMDs

helicity

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Sivers

Twist-2 TMDs

transversity

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8 leading-twist TMDs

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

nucleon pol. \ quark 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

helicity → g_{1L}

Boer-Mulders → $h_1^\perp$

Sivers → $f_{1T}^\perp$

transversity → h_1

TMDs in black survive transverse-momentum integration

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8 leading-twist TMDs

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

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Twist-2 TMDs

helicity (g_{1L})
Boer-Mulders ($h_1^\perp$)
Sivers ($f_{1T}^\perp$)
transversity (h_1)
pretzelosity ($h_{1T}^\perp$)

TMDs in black survive transverse-momentum integration
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8 leading-twist TMDs

quark pol.

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Twist-2 TMDs

helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

TMDs in black survive transverse-momentum integration

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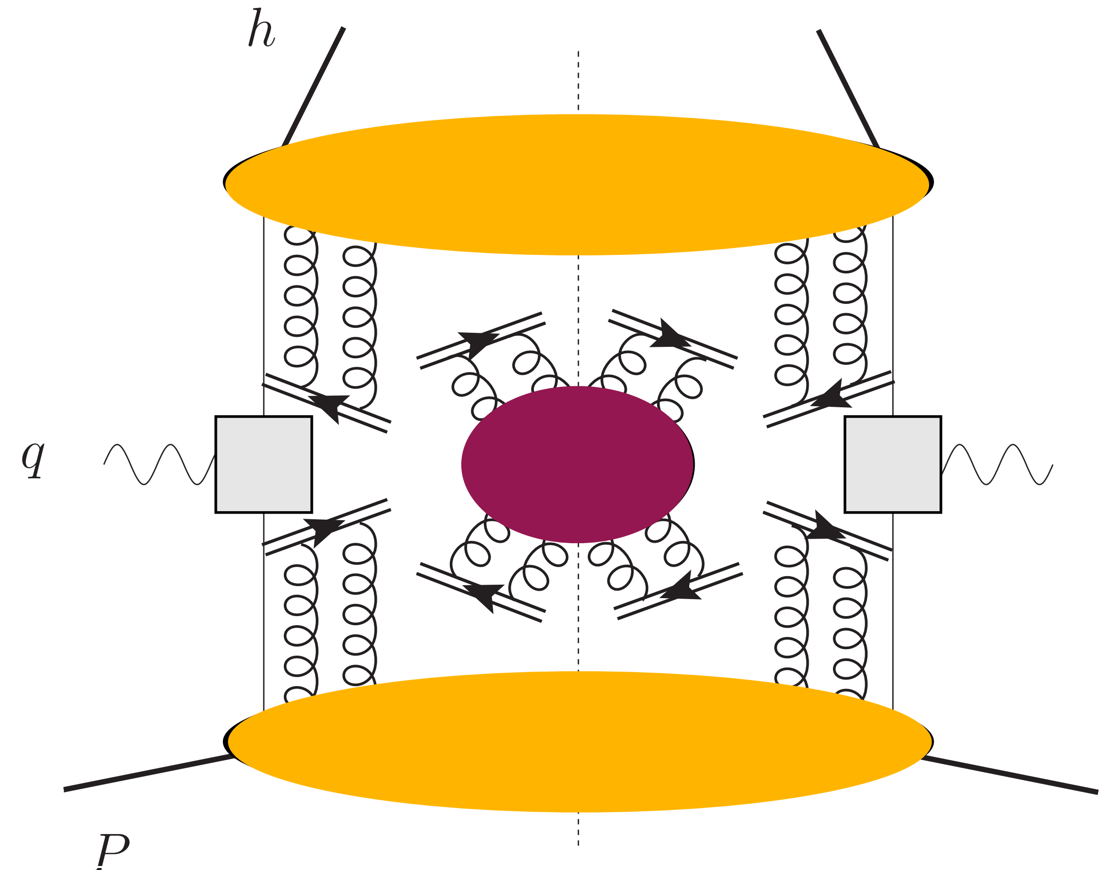
What have we learned about TMDs ?

TMD factorization



Collins, Soper, NPB 193 (81)
Ji, Ma, Yuan, PRD 71 (05)

$$F_{UU,T}(x,z,P_{h\perp}^2,Q^2) = \mathcal{C}'\left[f_1 D_1\right]$$

$$= H(Q^2,\mu^2,\zeta,\zeta_h)\int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, d^2\boldsymbol{l}_T\, \delta^{(2)}\big(\boldsymbol{p}_T - \boldsymbol{k}_T + \boldsymbol{l}_T - \boldsymbol{P}_{h\perp}/z\big)$$

$$x\sum_a e_a^2\, f_1^a(x,p_T^2,\mu^2,\zeta)\, D_1^a(z,k_T^2,\mu^2,\zeta_h)\, U(l_T^2,\mu^2,\zeta\zeta_h)$$

TMD factorization

Collins, Soper, NPB 193 (81)
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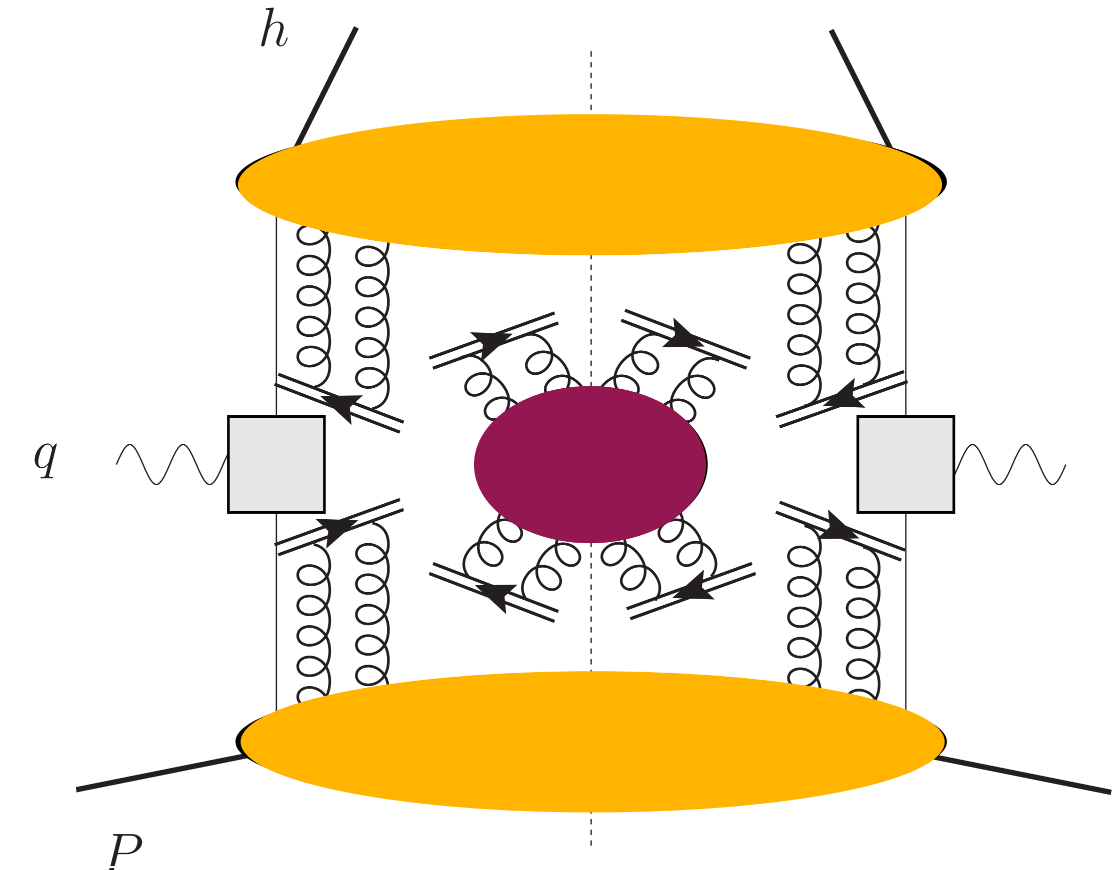

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$$x\sum_a e_a^2\, f_1^a(x,p_T^2,\mu^2,\zeta)\, D_1^a(z,k_T^2,\mu^2,\zeta_h)\, U(l_T^2,\mu^2,\zeta\zeta_h)$$

Hard part

TMD PDF

TMD FF

Soft factor

New concepts

New concepts

- Generalized factorization

New concepts

- Generalized factorization
- Soft factors

New concepts

- Generalized factorization
- Soft factors
- Rapidity divergences

New concepts

- Generalized factorization
- Soft factors
- Rapidity divergences
- Nondiagonal evolution equations

Unpolarized distribution

quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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Twist-2 TMDs

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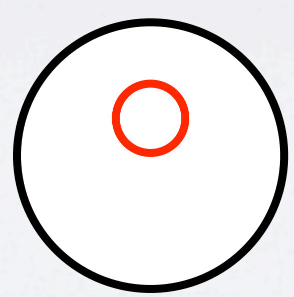
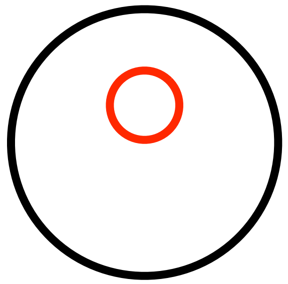
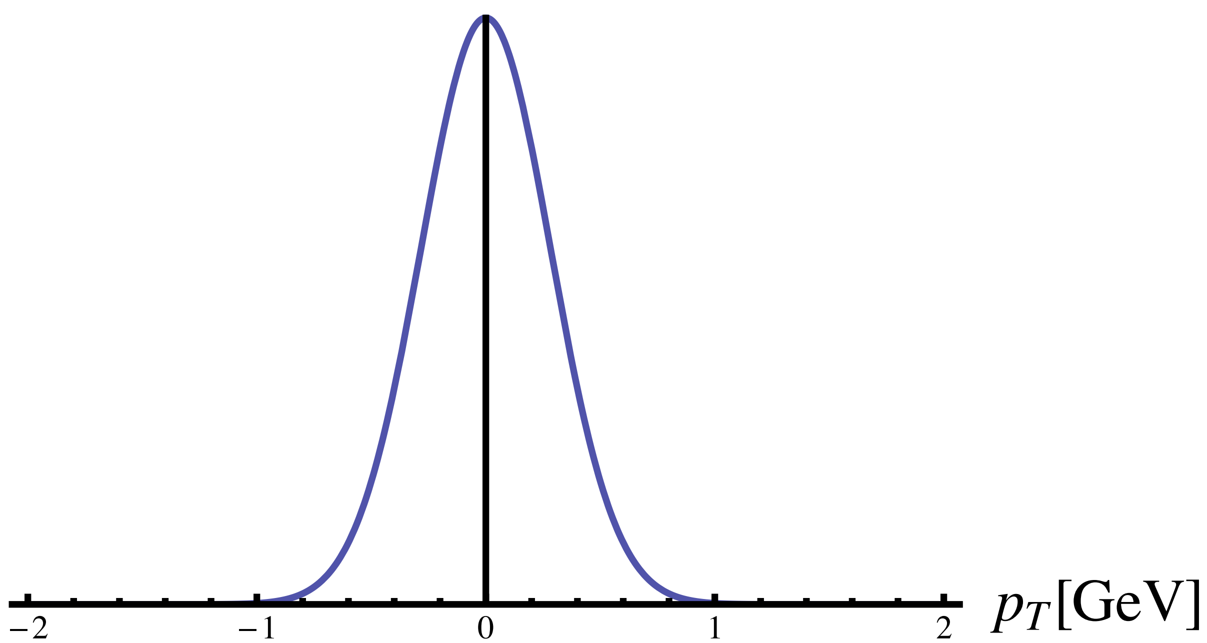
Twist-2 TMDs

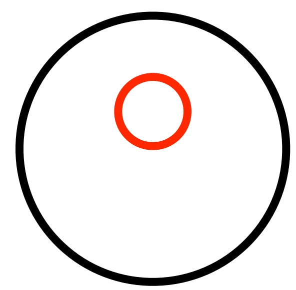


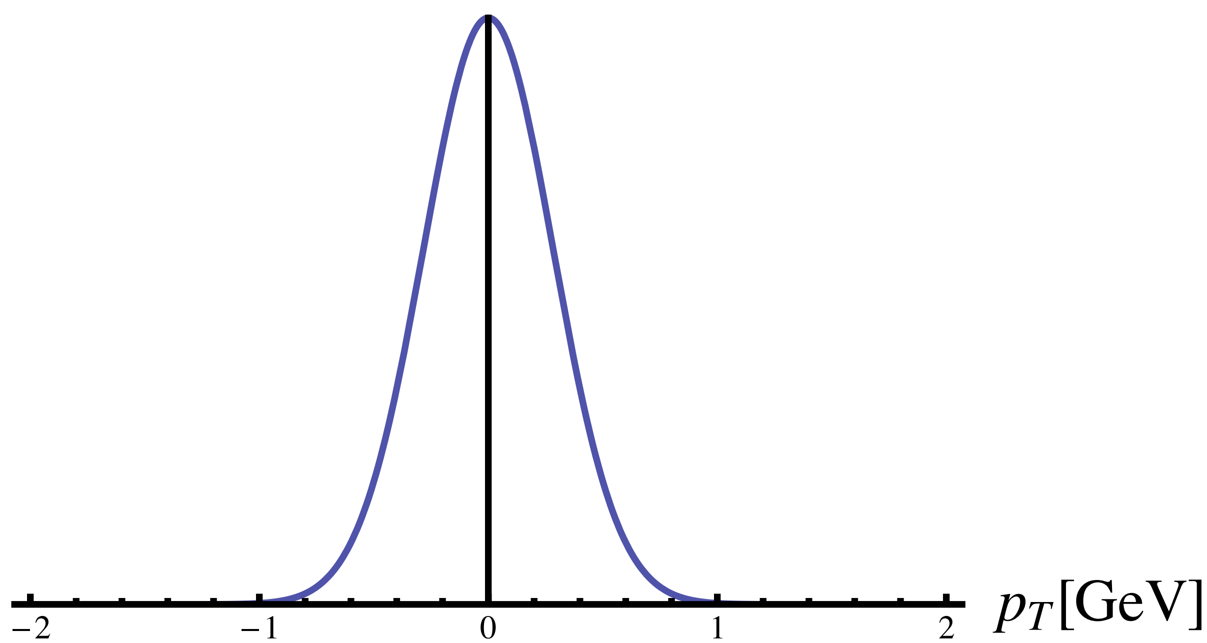
Unpolarized TMD width





Unpolarized TMD width

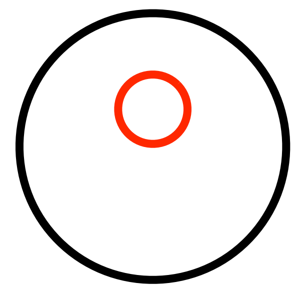


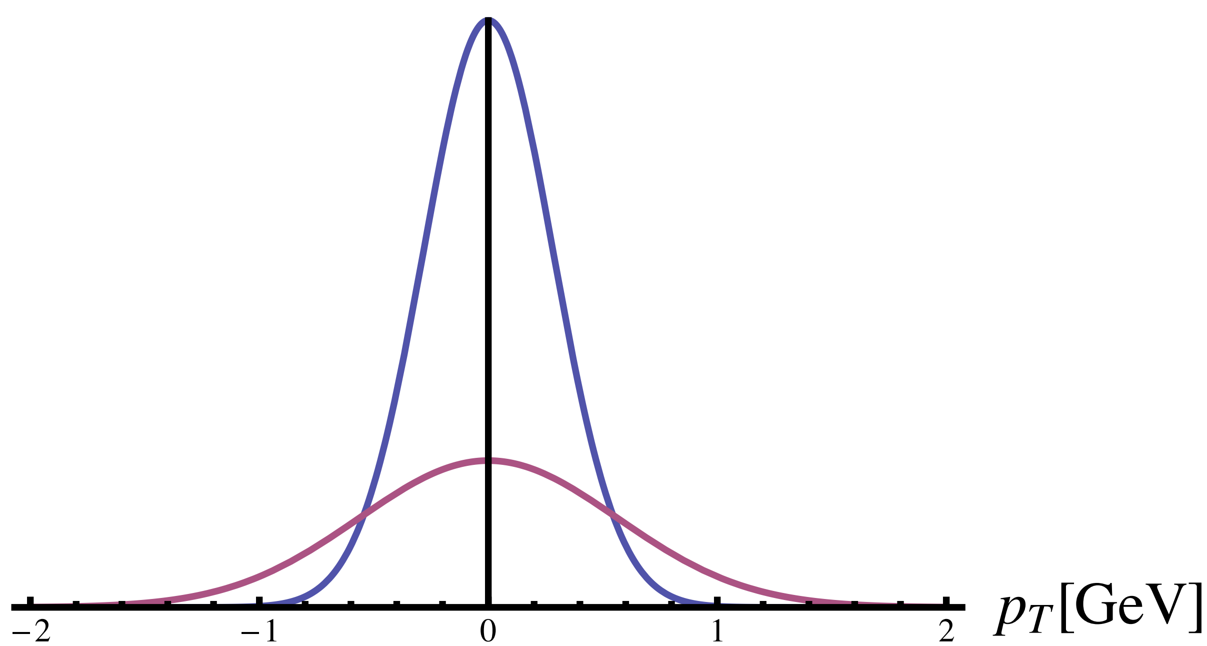


$$\sqrt{\langle p_T^2 \rangle} \approx 0.4 - 0.8 \text{ GeV}$$

depending on kinematics

Unpolarized TMD width



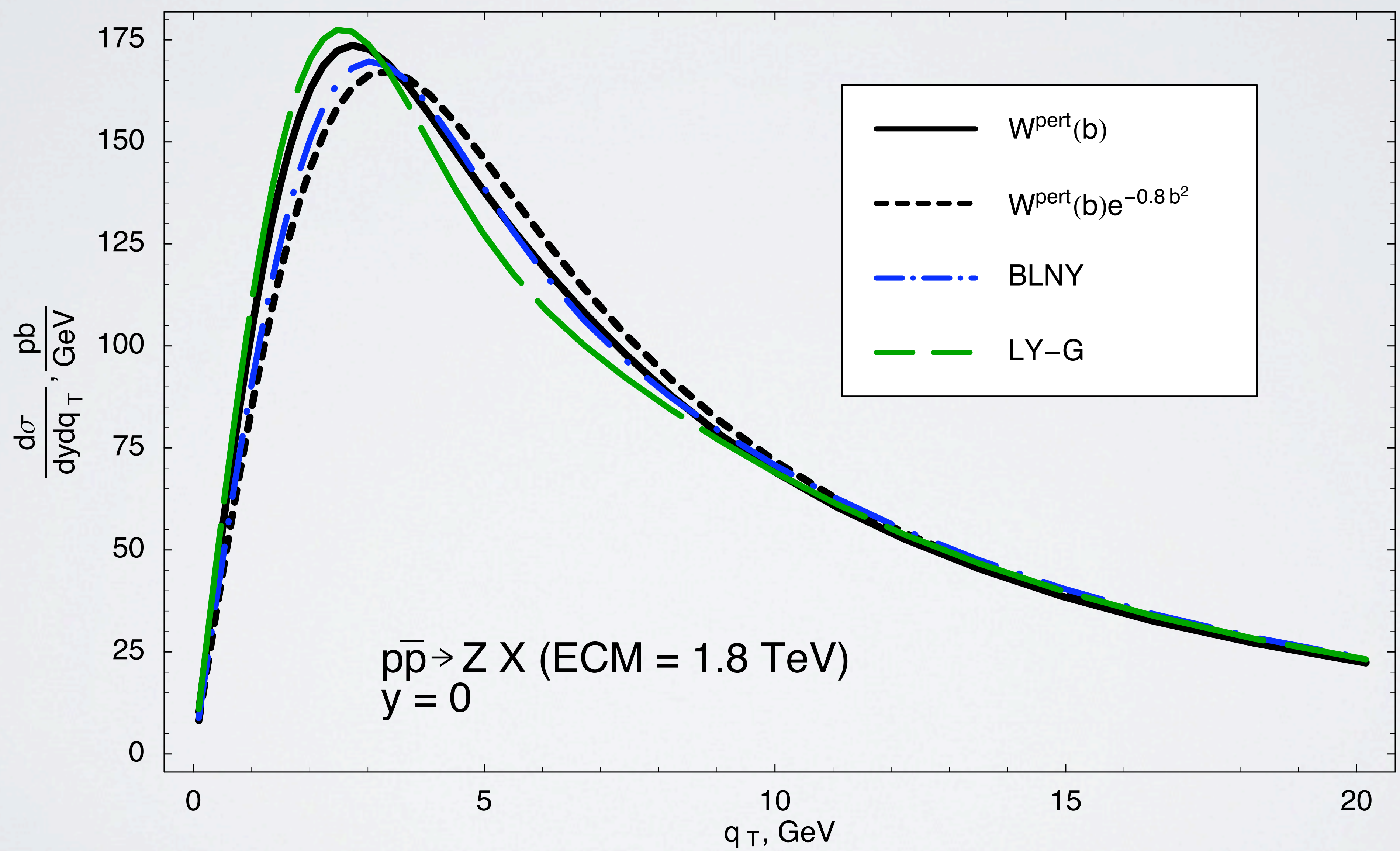


$$\sqrt{\langle p_T^2 \rangle} \approx 0.4 - 0.8 \text{ GeV}$$

depending on kinematics

Impact on high-energy physics

P. Nadolsky, hep-ph/0412146



TMDs and determination of W mass

CDF collaboration, PRD77 (08)

TABLE XVI. Systematic uncertainties in units of MeV on the combination of the six fits in the electron and muon channels. Each uncertainty has been estimated by removing its covariance and repeating the sixfold combination.

Source	Uncertainty (MeV)
Lepton scale	23.1
Lepton resolution	4.4
Lepton efficiency	1.7
Lepton tower removal	6.3
Recoil energy scale	8.3
Recoil energy resolution	9.6
Backgrounds	6.4
PDFs	12.6
W boson p_T	3.9
Photon radiation	11.6

$$m_W = 80.398 \pm 0.025 \text{ GeV}. \quad (53)$$

Transversity

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

talk by Xiaodong Jiang

Transversity

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

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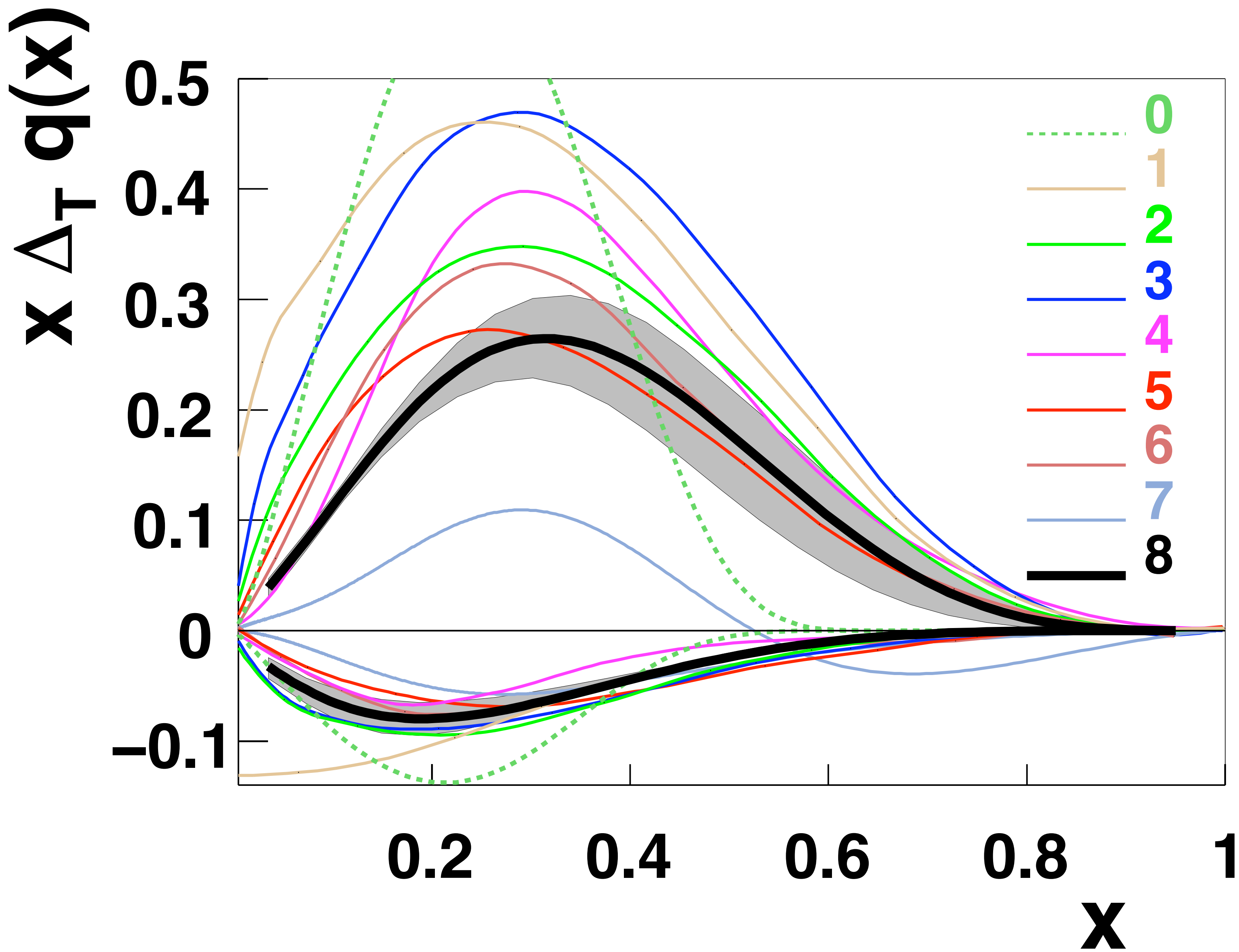
Twist-2 TMDs

Successful use of TMD observables to extract transversity

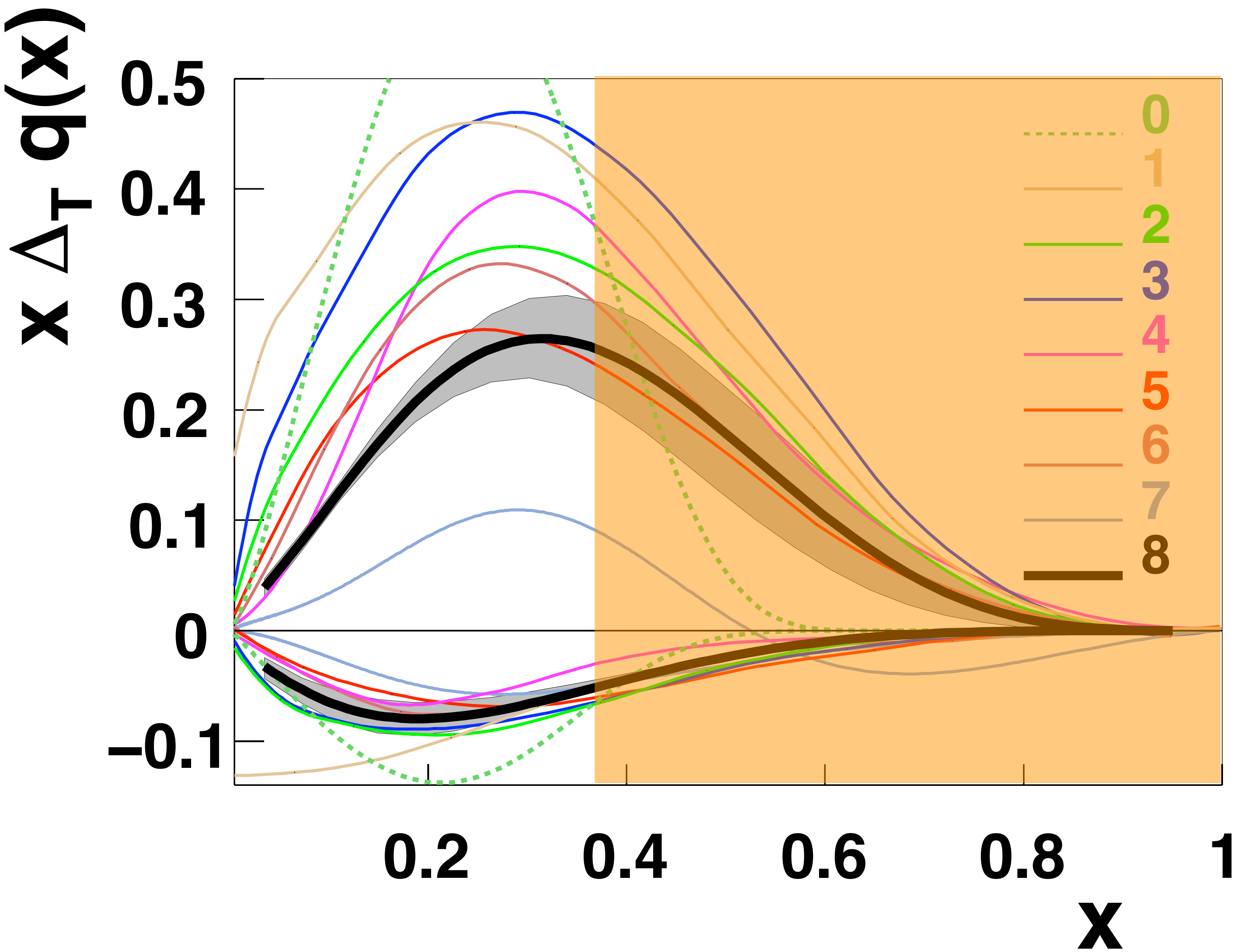
talk by Xiaodong Jiang

Extraction vs models



1-7 models, 8 extraction *talk by Alexei Prokudin*

Extraction vs models



1-7 models, 8 extraction

talk by Alexei Prokudin

Sivers function

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Twist-2 TMDs

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Twist-2 TMDs

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Twist-2 TMDs

The Sivers function is nonzero.

Sivers function

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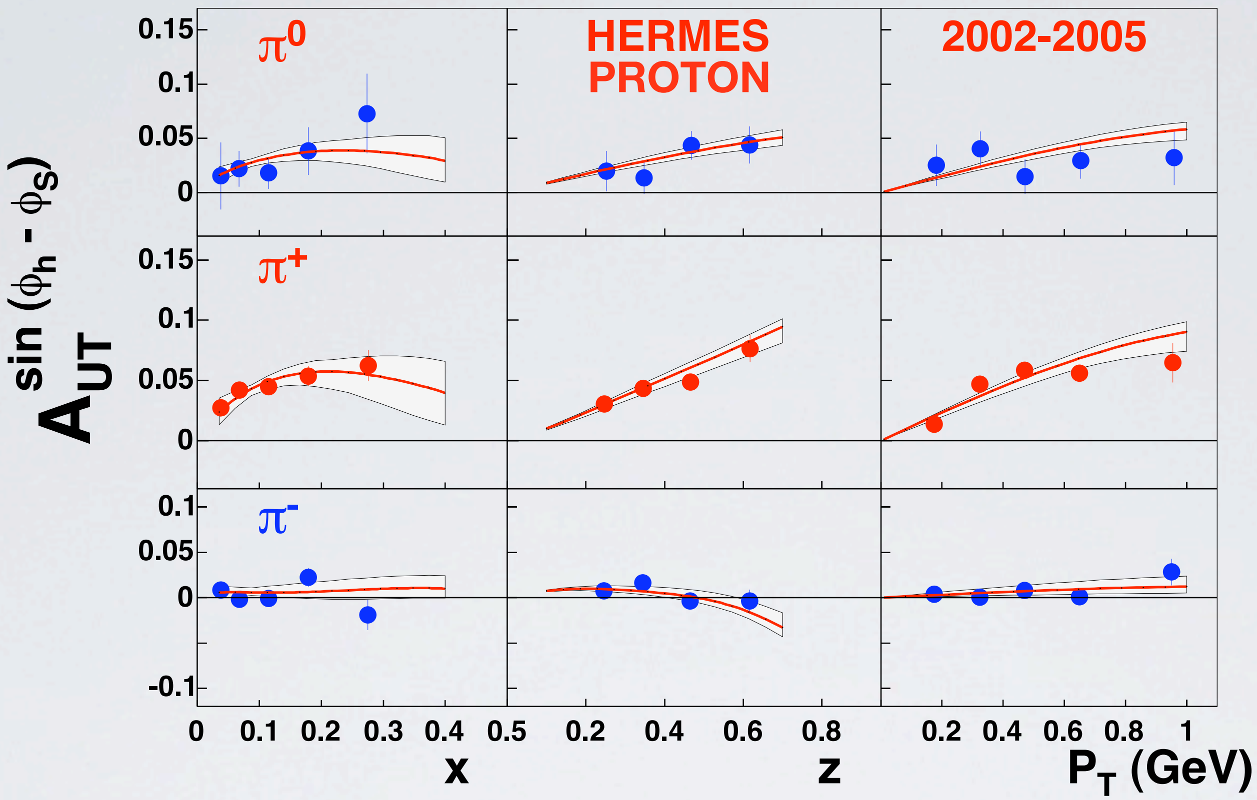
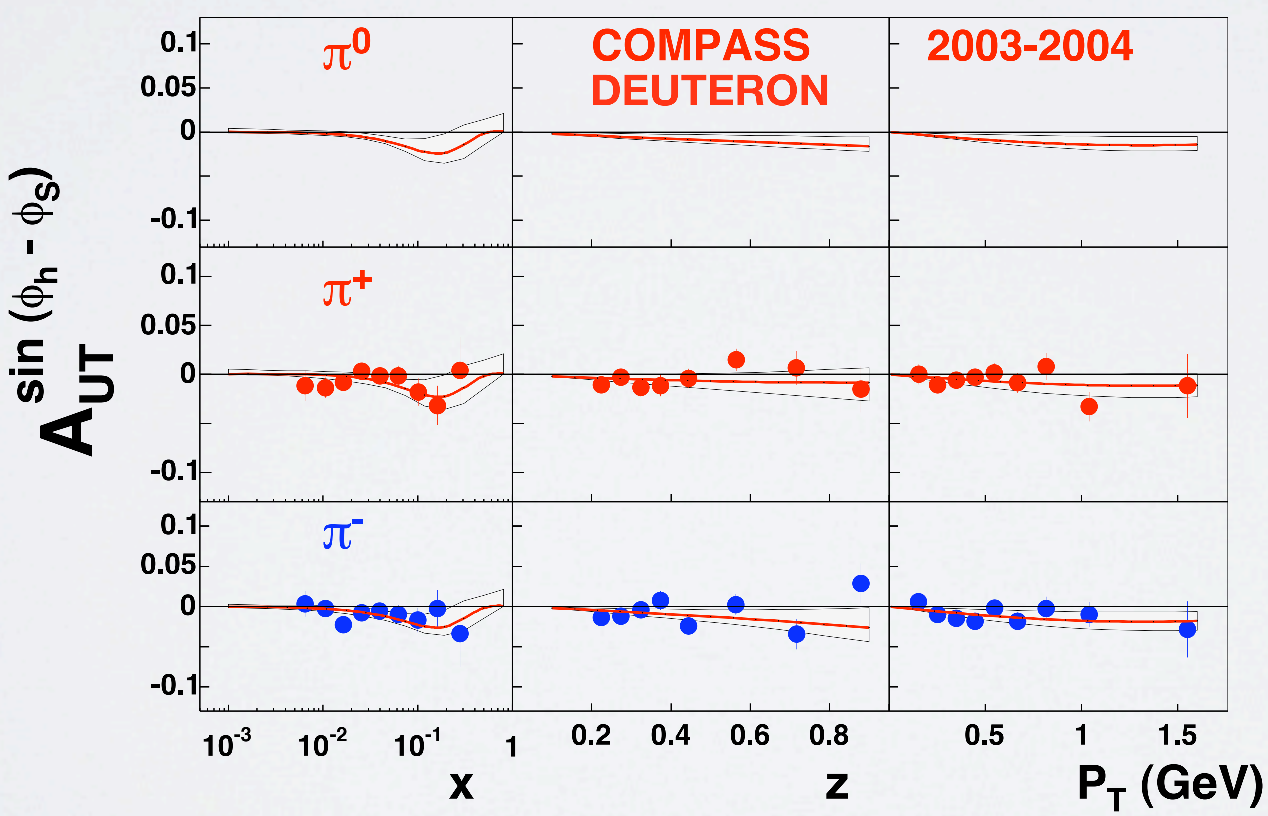
Twist-2 TMDs

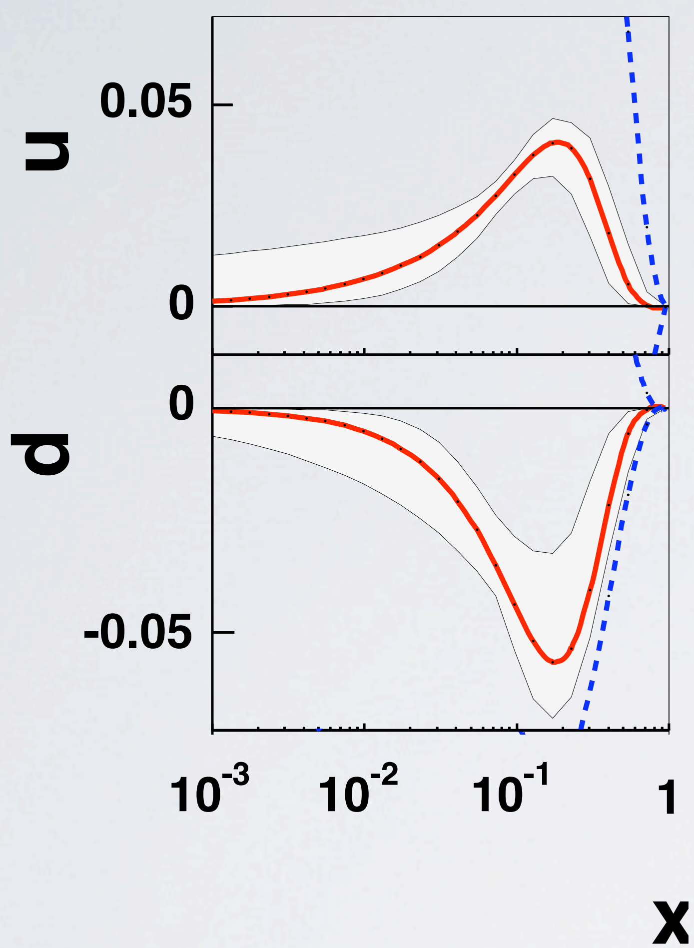
The Sivers function is nonzero.
Indication of the presence of quark orbital angular momentum.

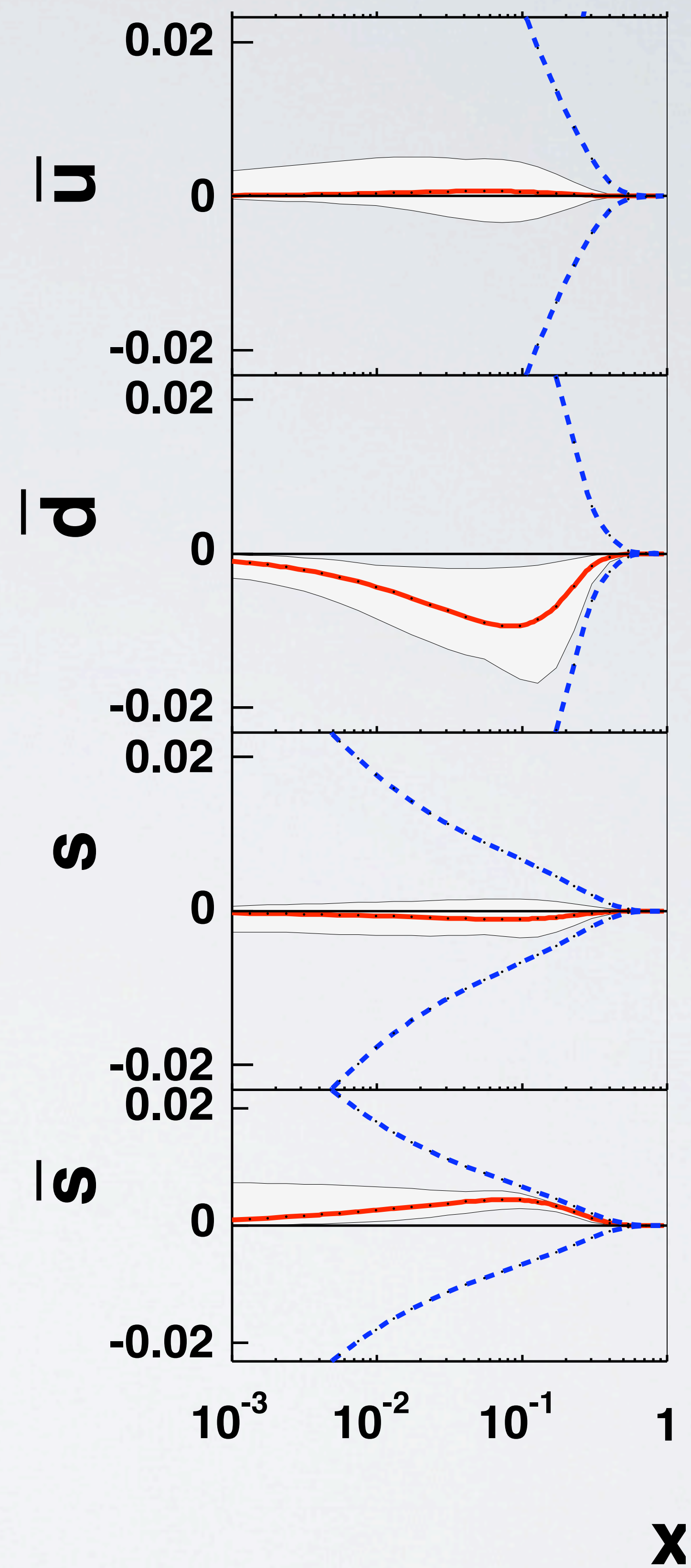




data: HERMES and COMPASS, fit: Anselmino et al., EPJA39(09)
talk by Alexei Prokudin

Sivers function





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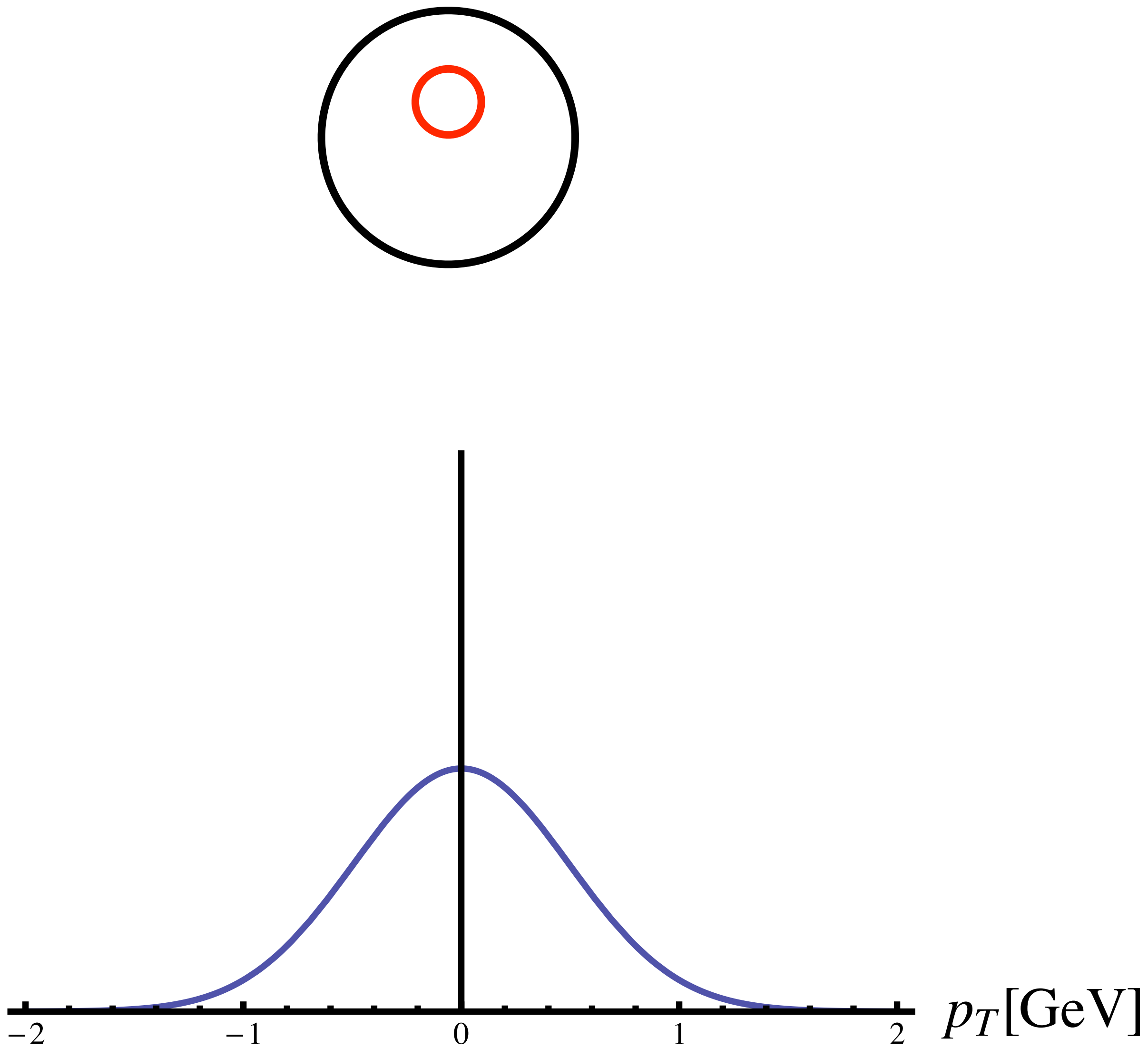
talk by Alexei Prokudin

Transverse spin dependence



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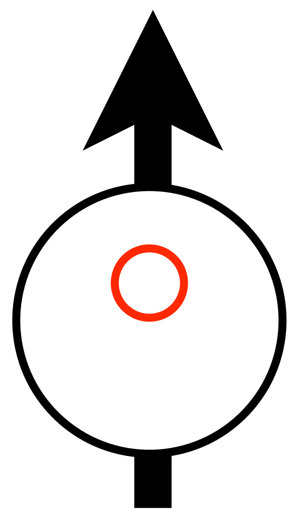
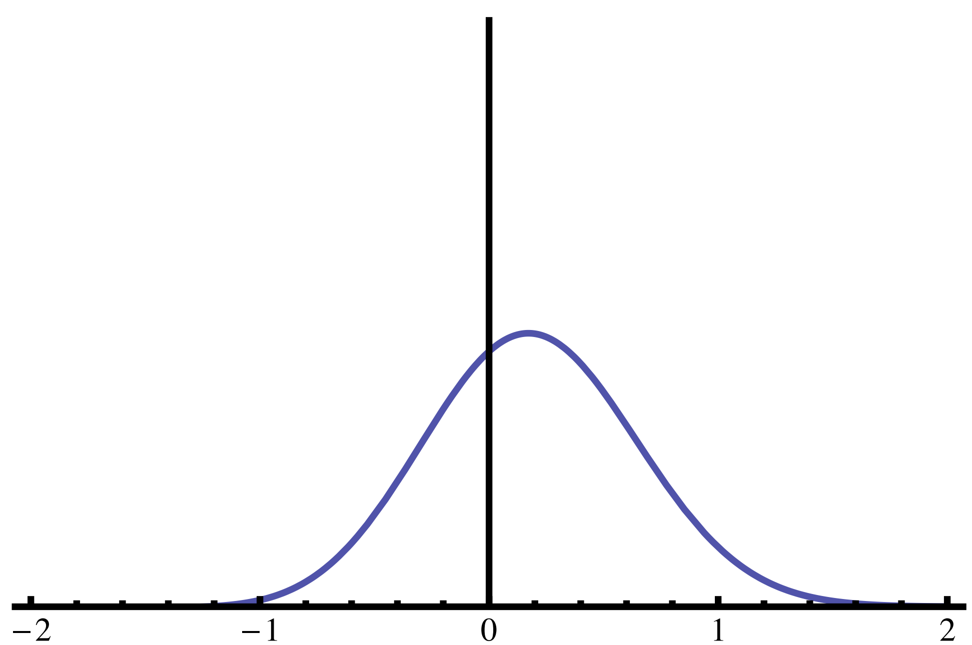
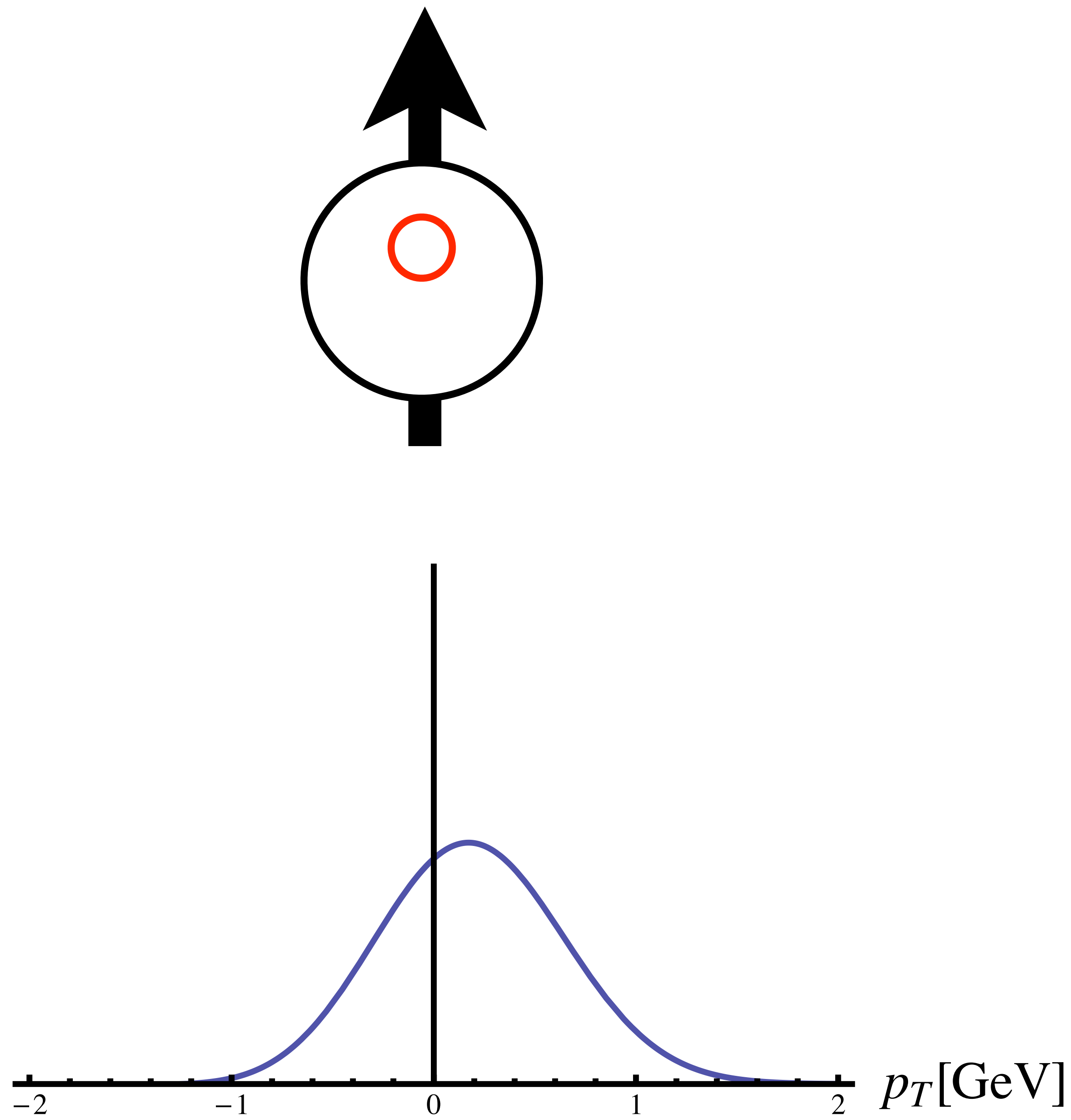


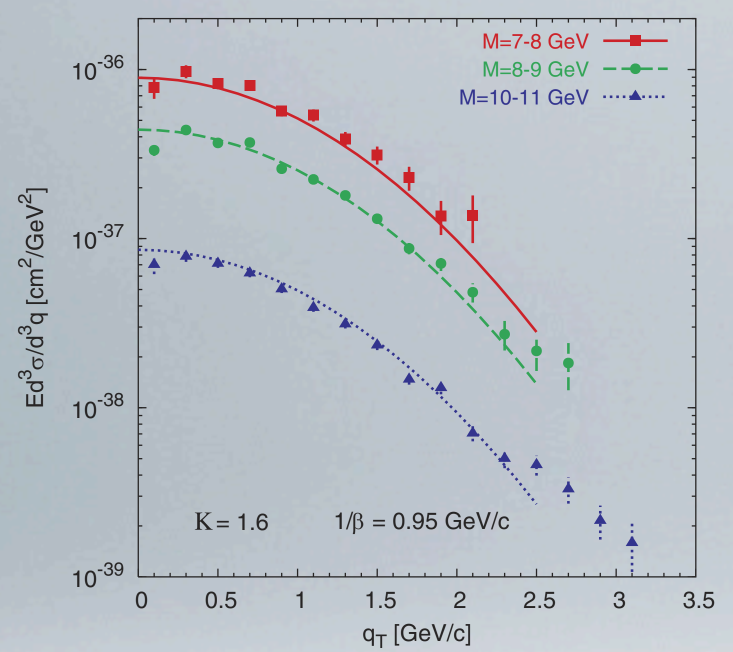


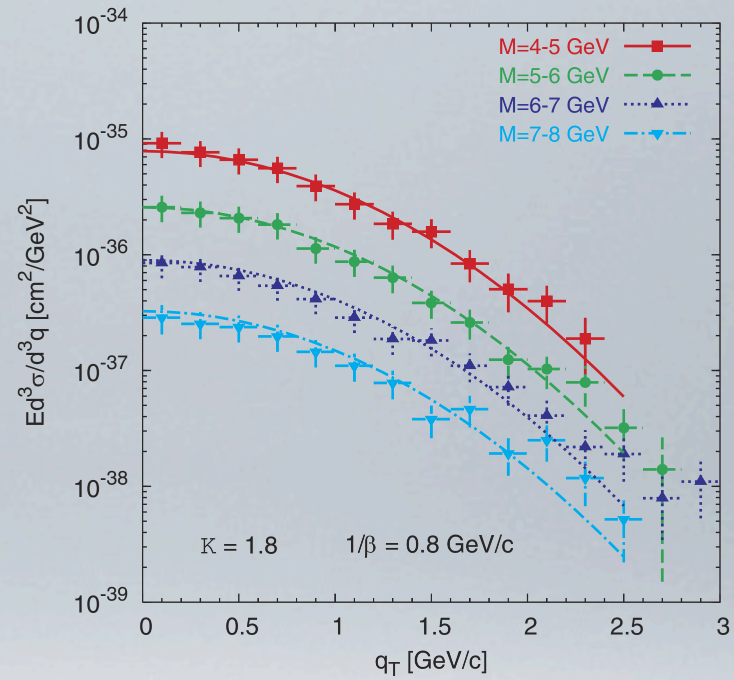
Transverse spin dependence



What we still *don't* know about TMDs ?

What's the precise shape





D'Alesio, Murgia, PRD70 (04)

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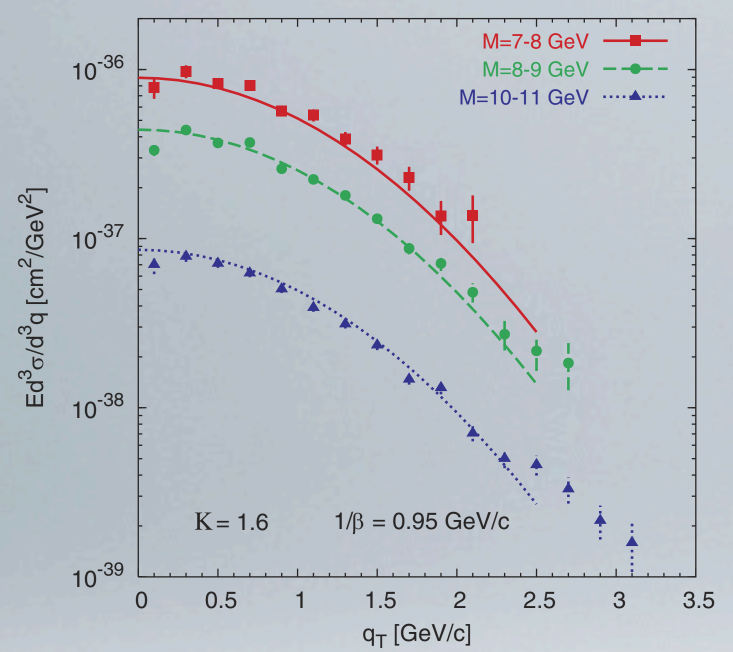

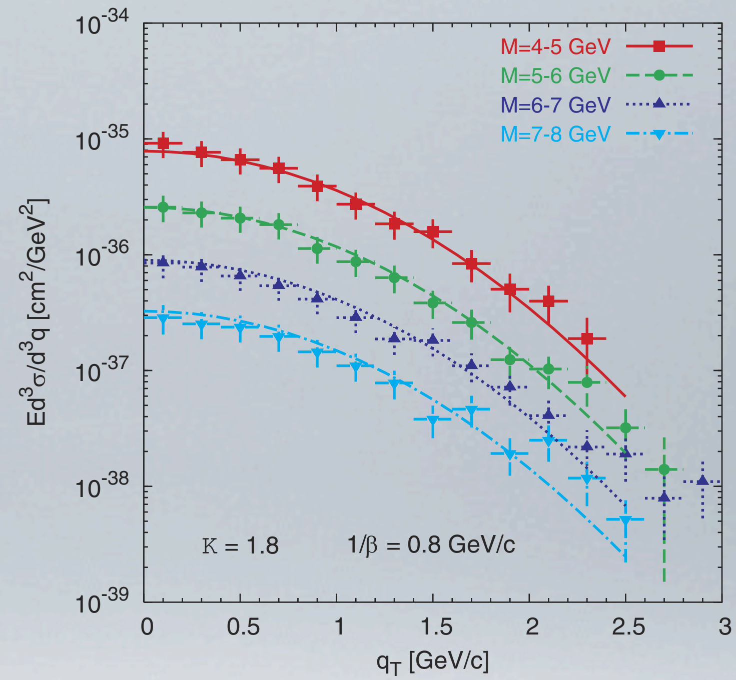

D'Alesio, Murgia, PRD70 (04)

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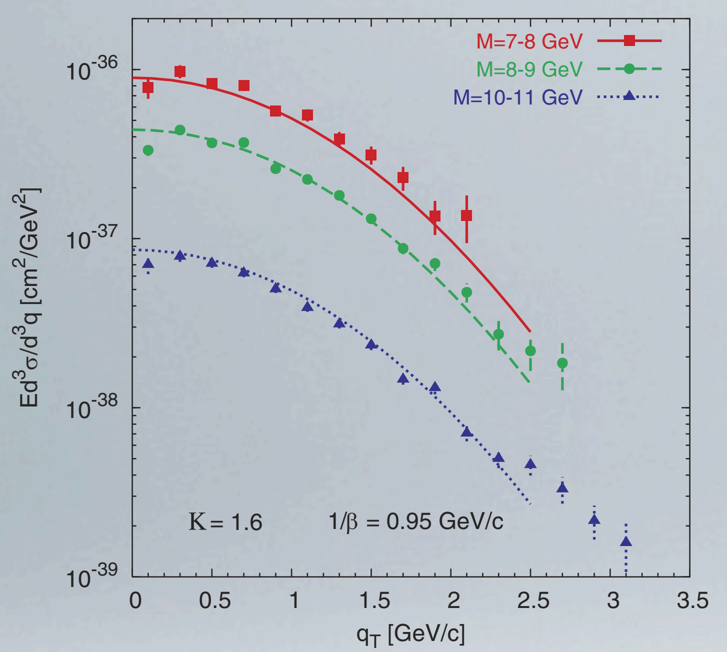
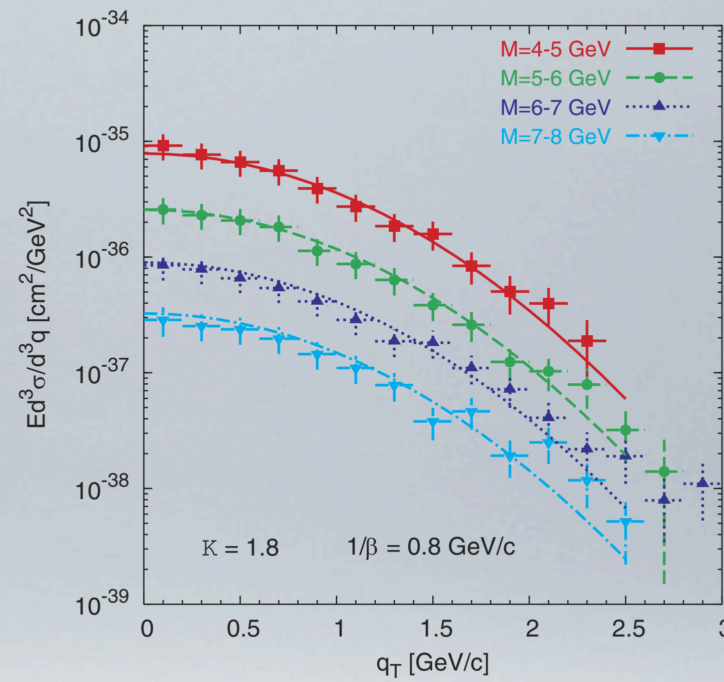


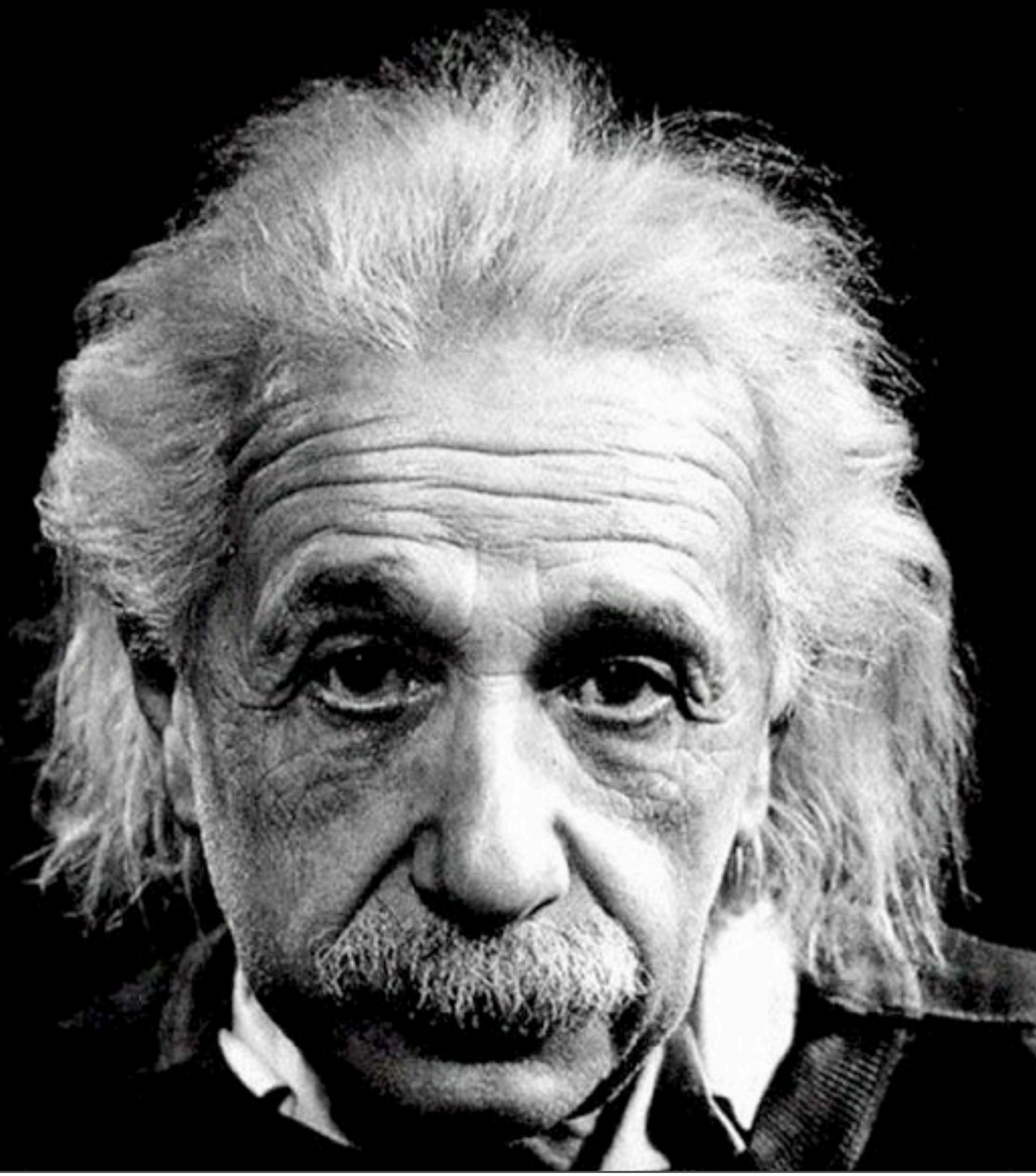


D'Alesio, Murgia, PRD70 (04)

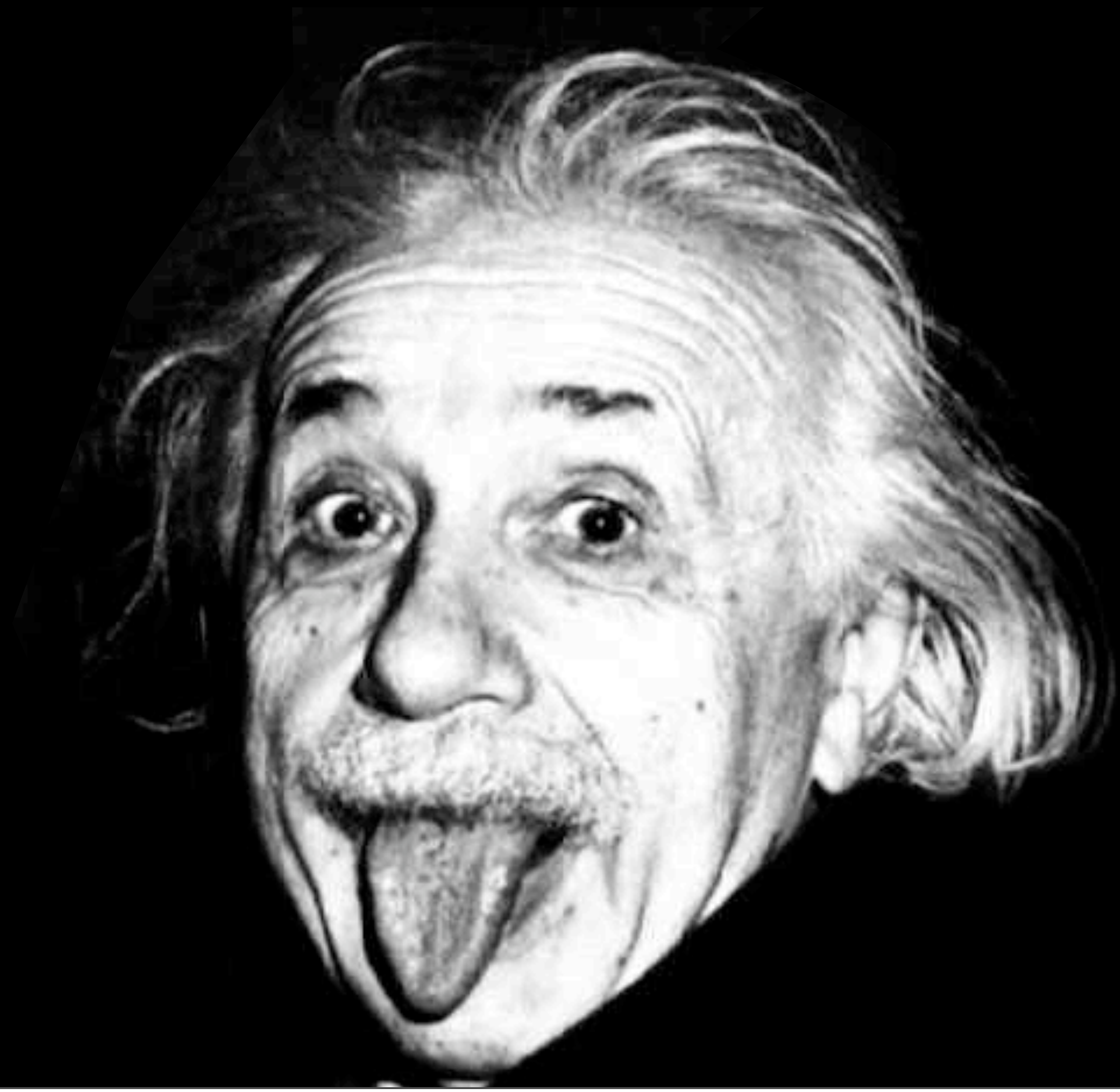
A good amount of data can be described using Gaussians independent of flavor, spin, and often x and Q^2

see nice discussion in P. Schweitzer, T. Teckentrup, A. Metz, PRD81(10)

“Things should be made as simple as possible...”

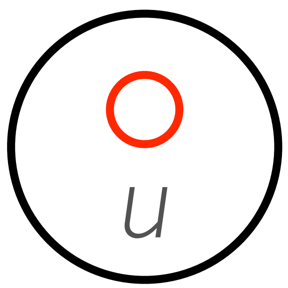


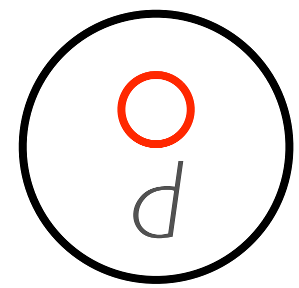
“Things should be made as simple as possible, *but not any simpler*”

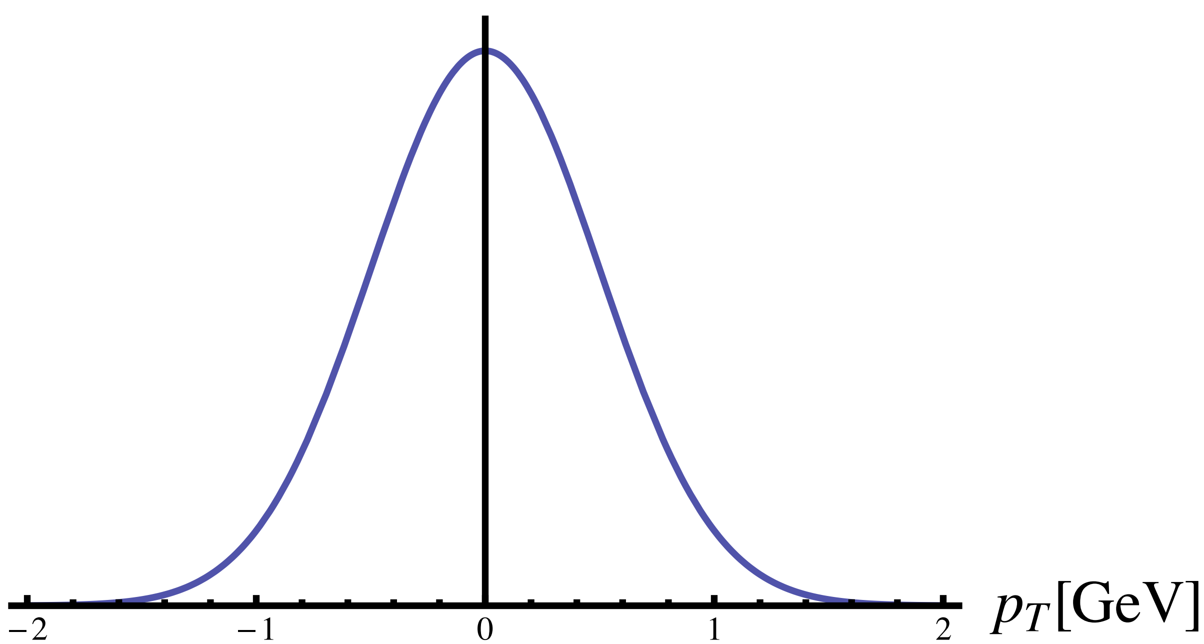


Can flavor influence TMDs?

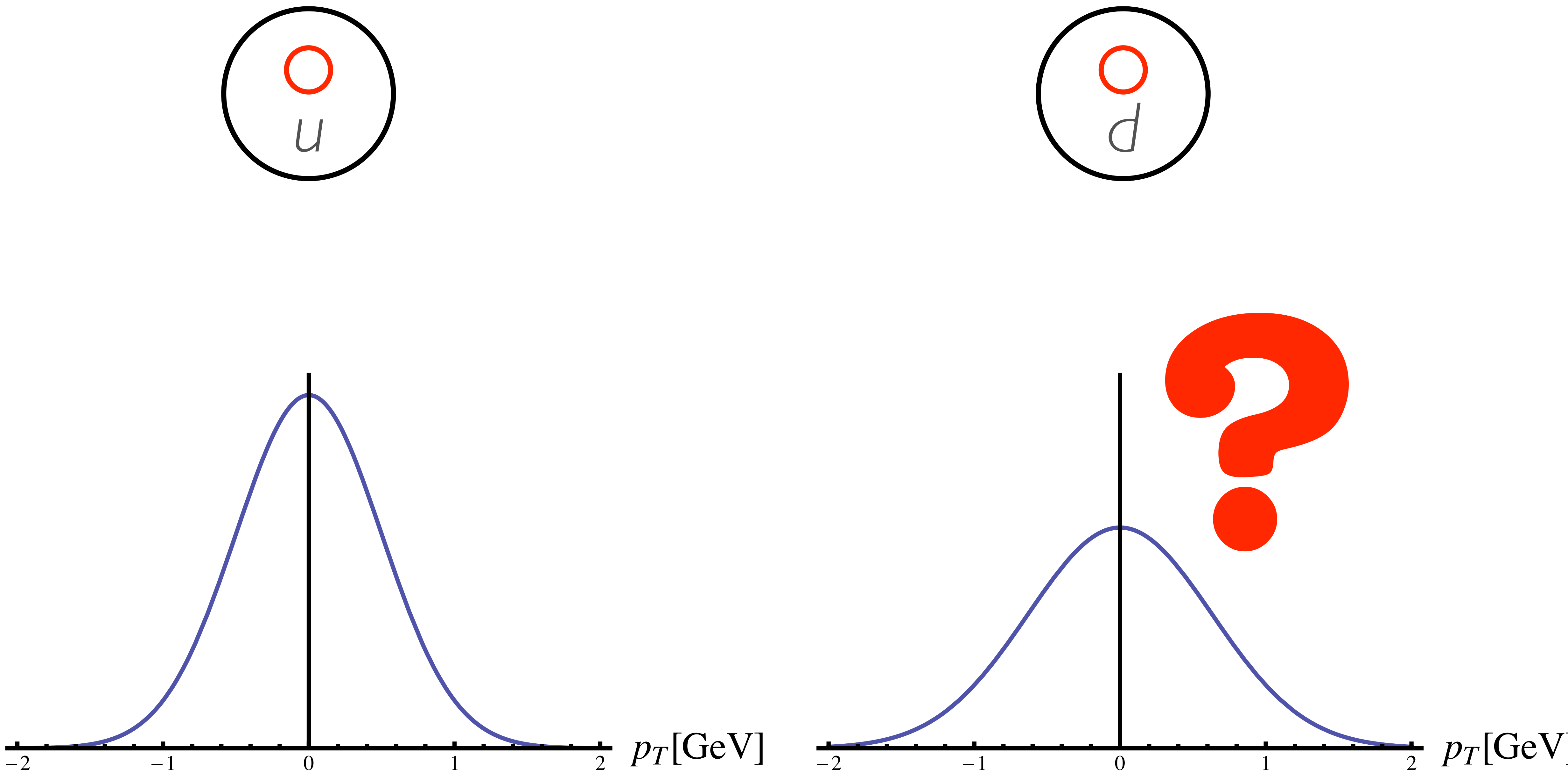
TMDs may be flavor dependent







TMDs may be flavor dependent



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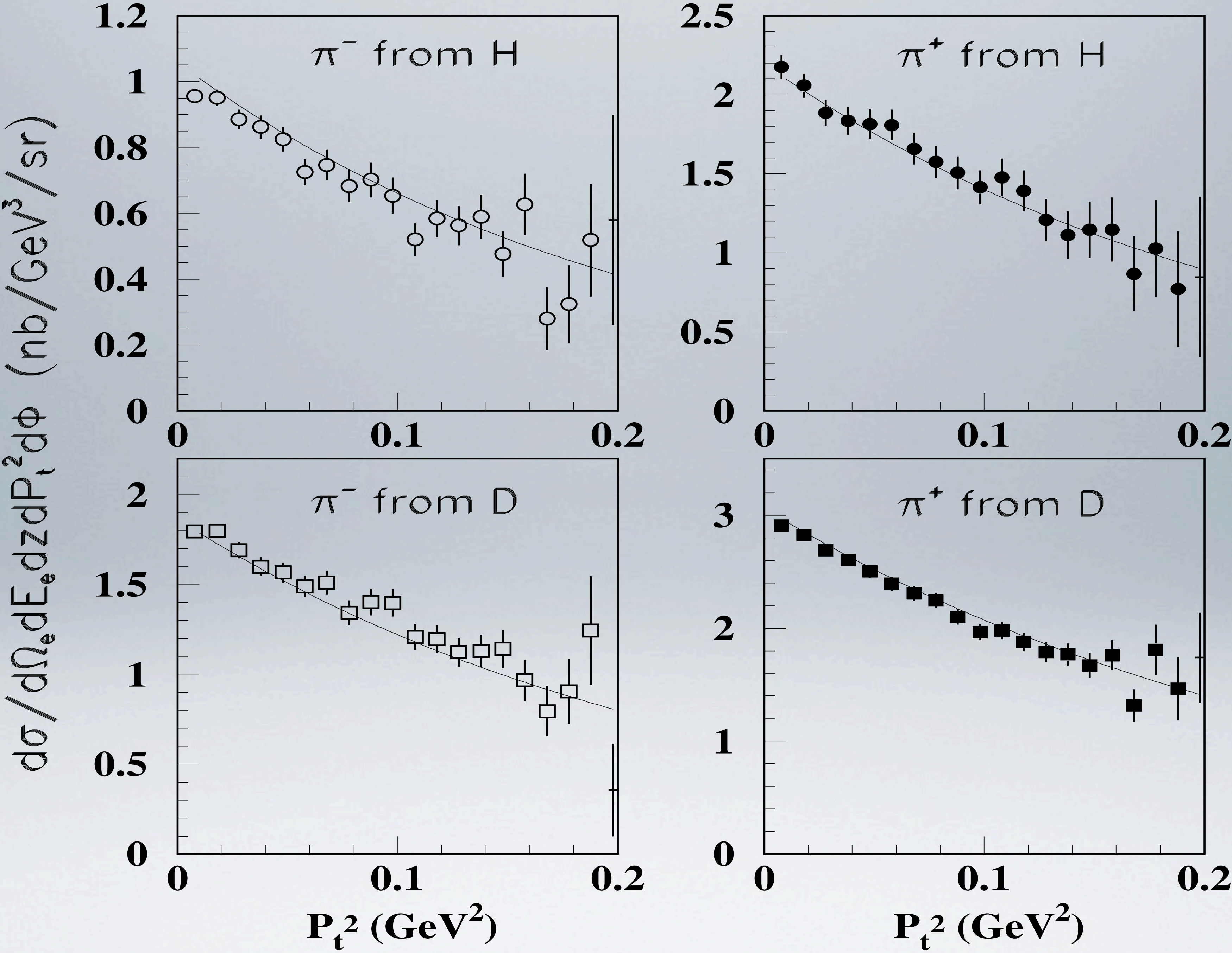
Hall C, Mkrtchyan et al., PLB665 (08)



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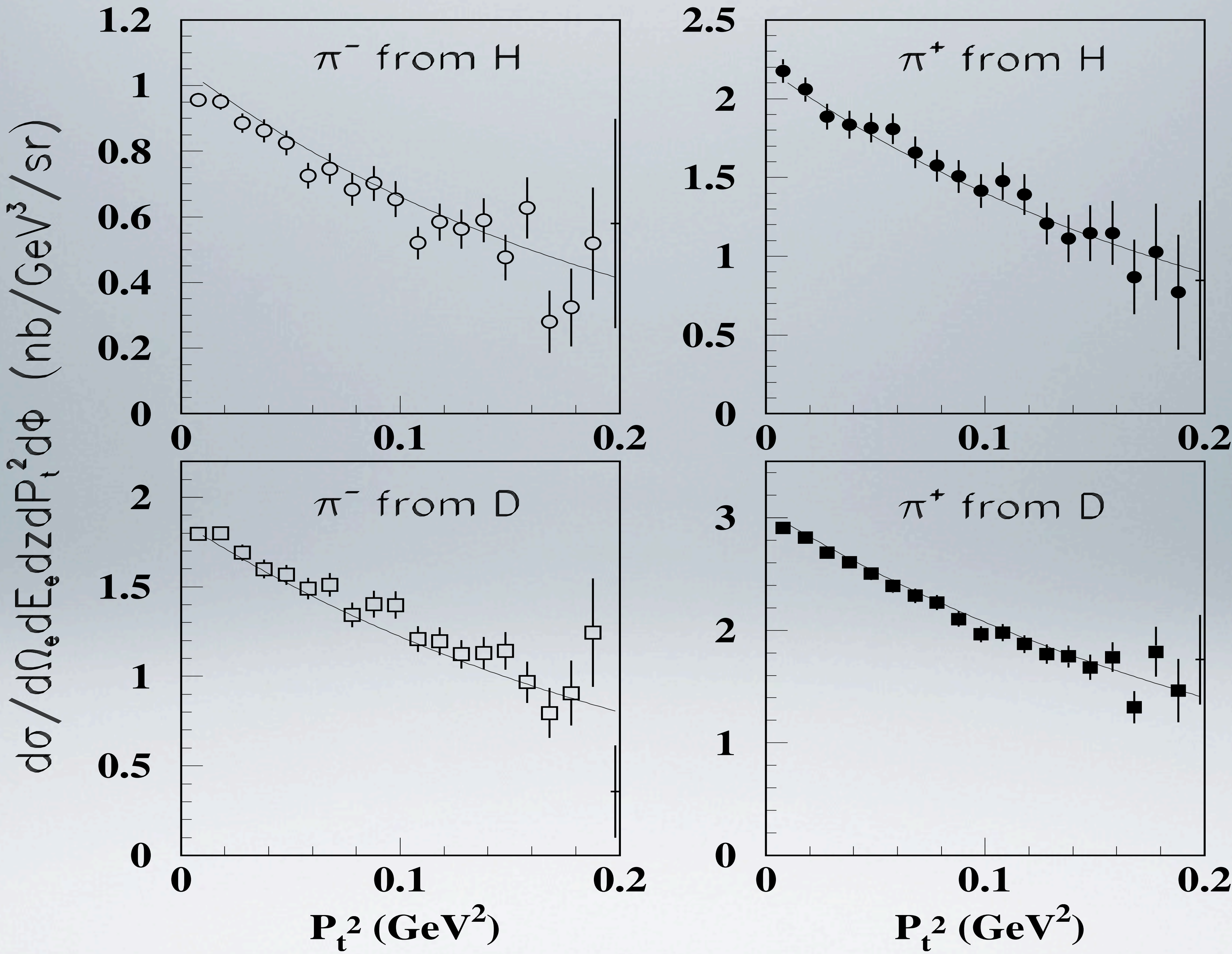
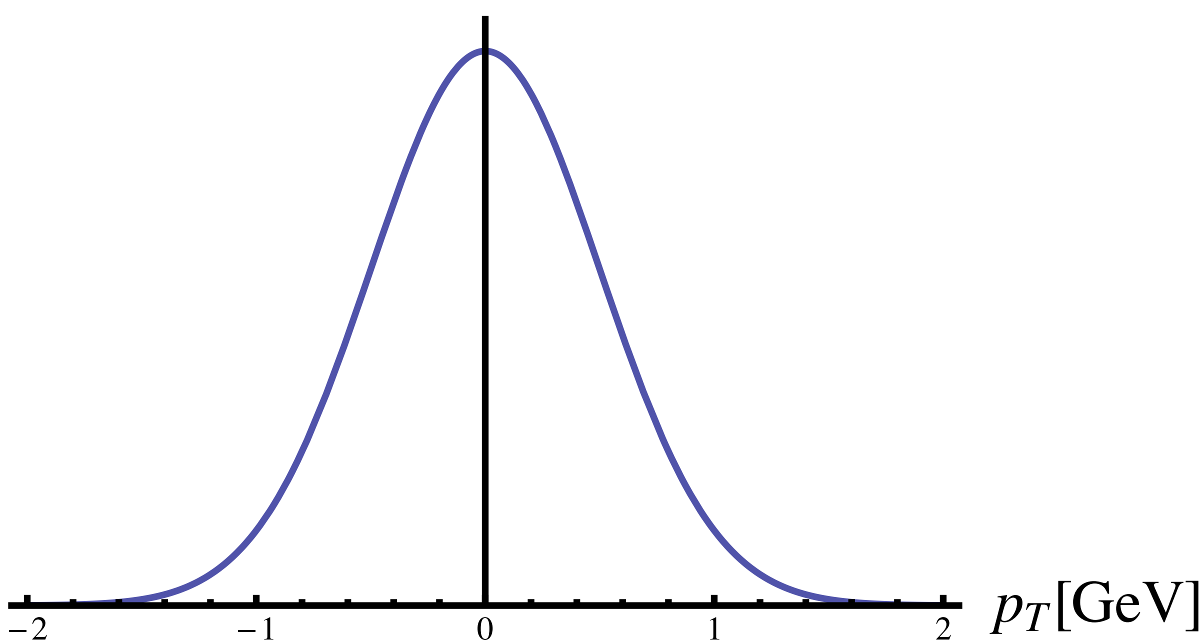
Hall C, Mkrtchyan et al., PLB665 (08)



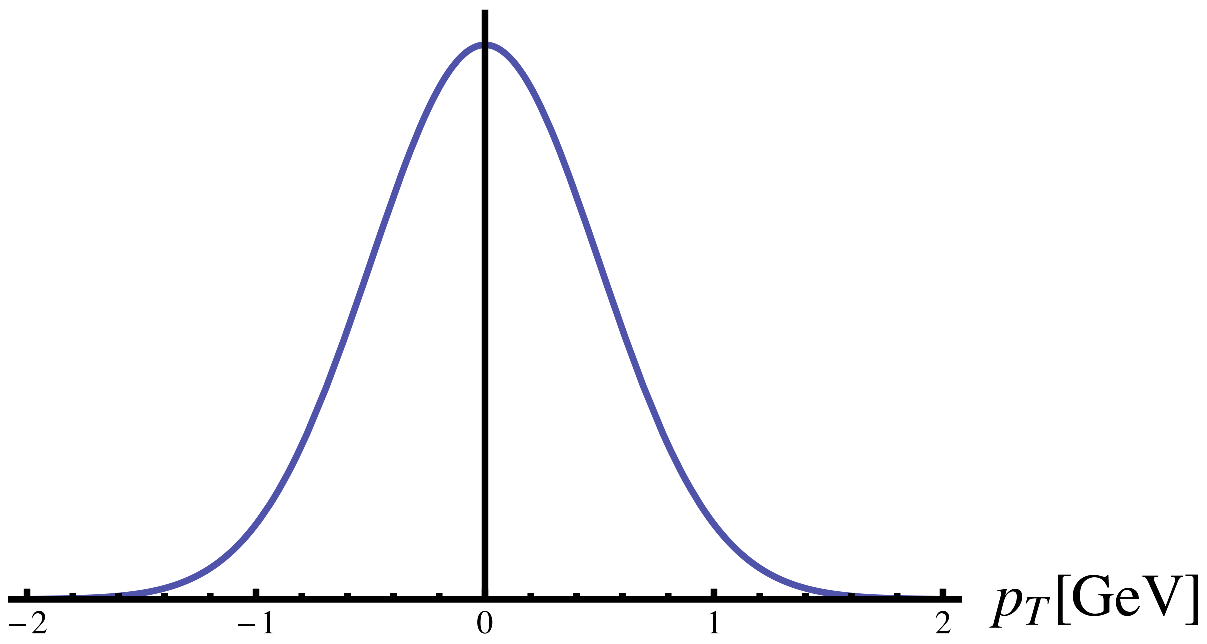
Indication of a nontrivial flavor dependence

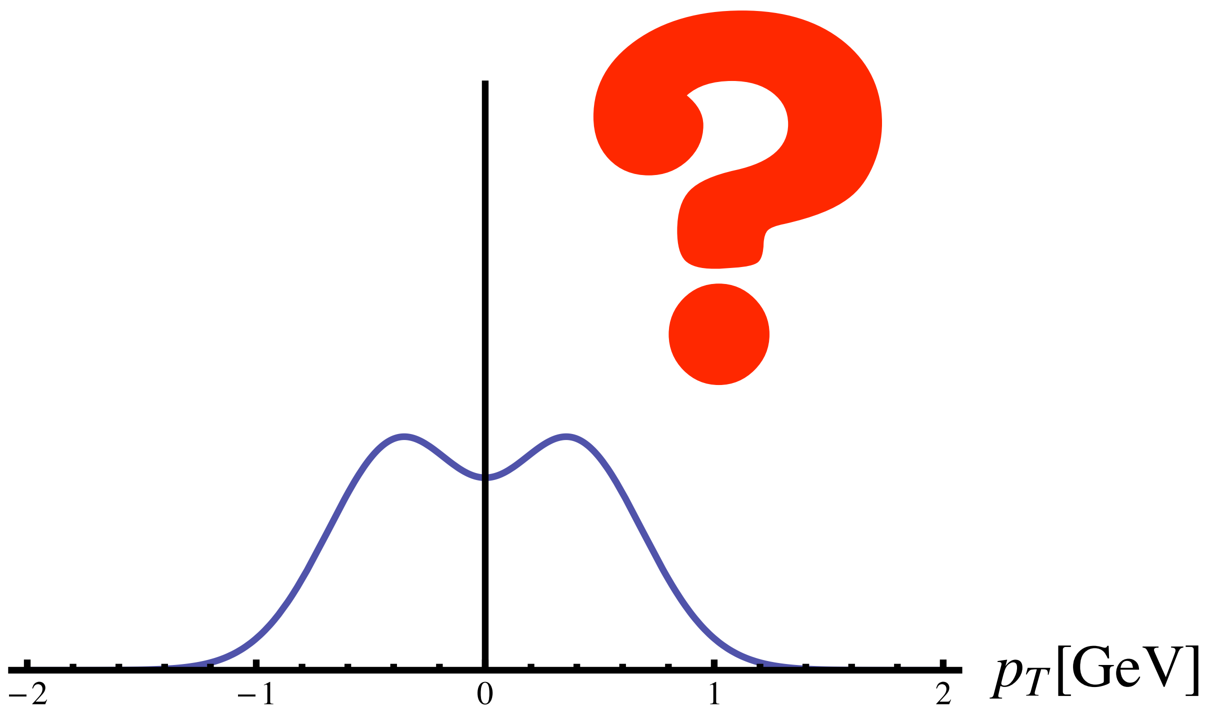
Can TMDs be non-Gaussian?

Non-Gaussian TMDs

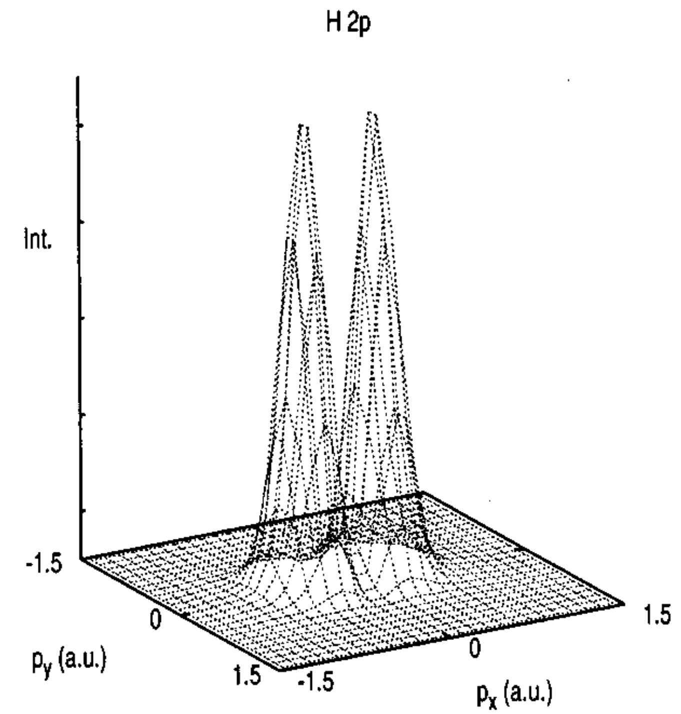


Non-Gaussian TMDs

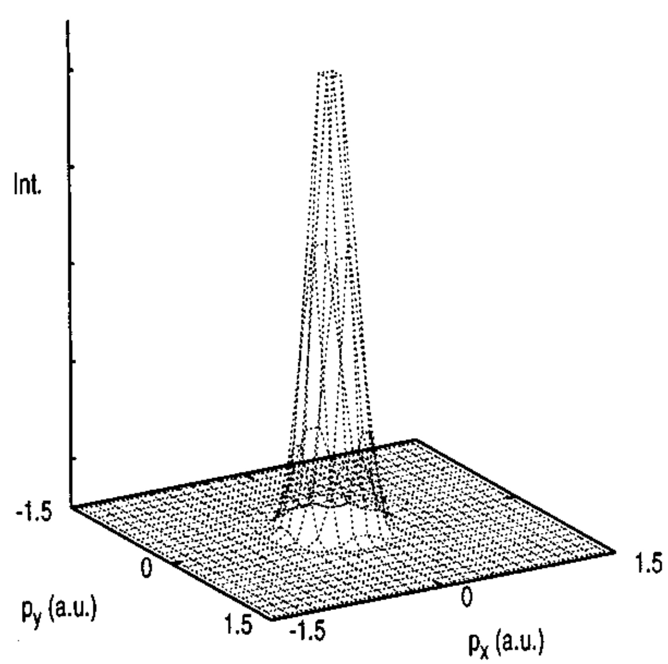




Shape of atomic orbitals

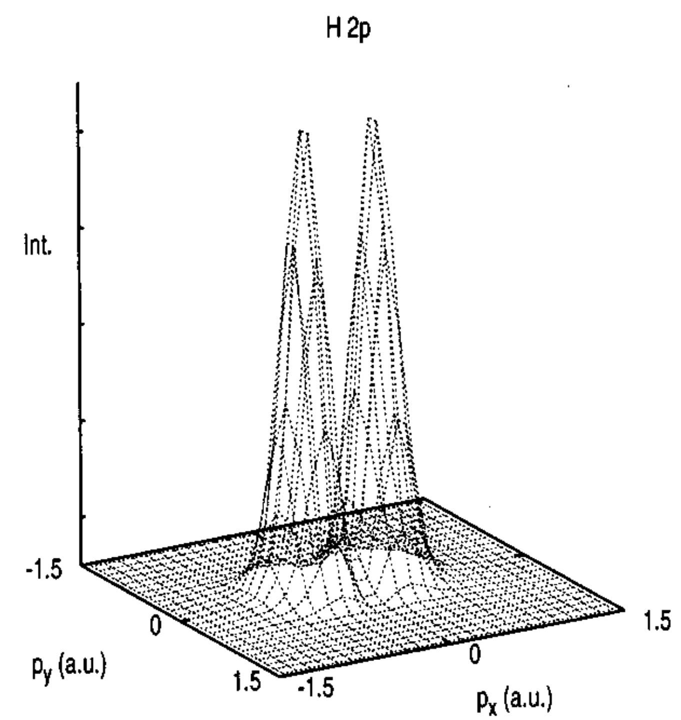


p-wave

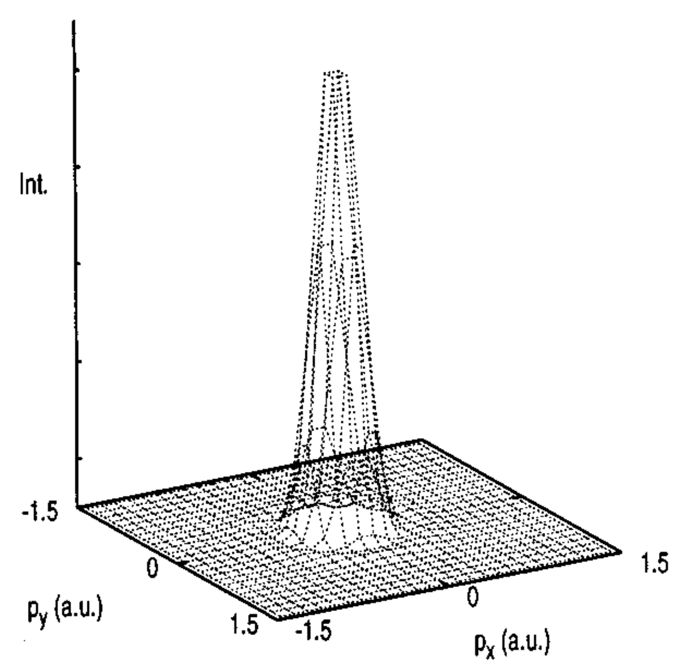


s-wave

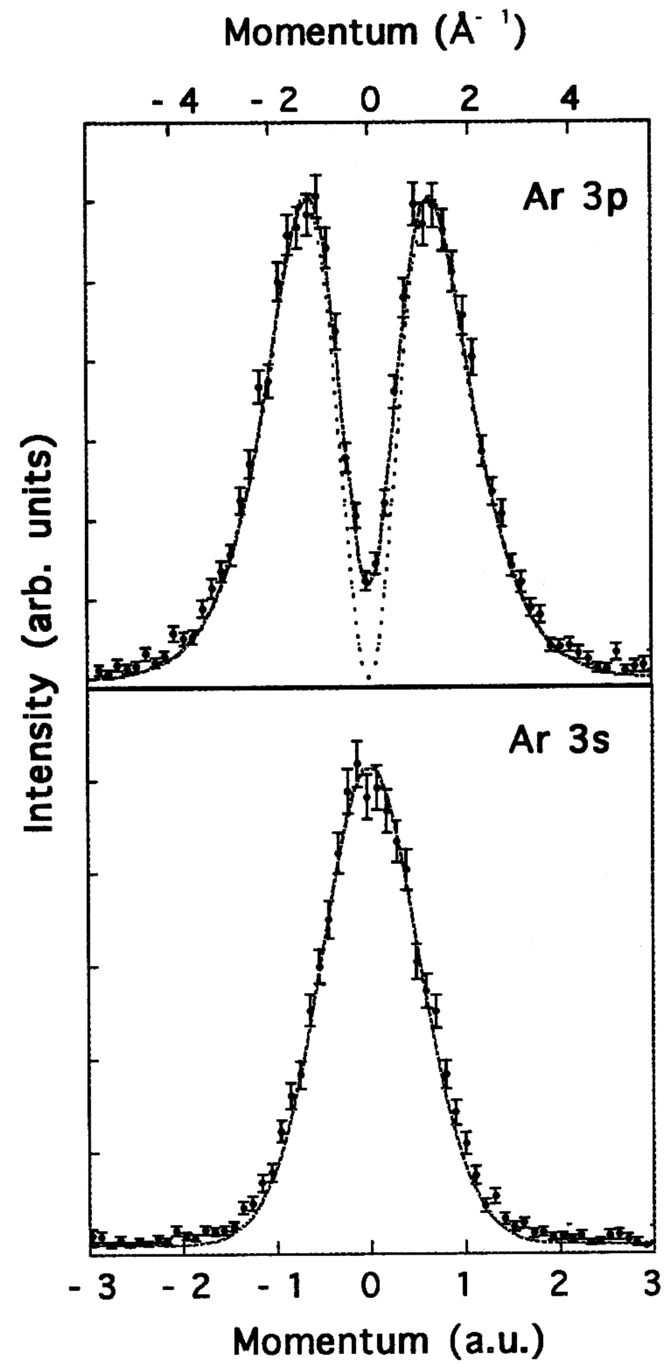
Shape of atomic orbitals



p-wave



s-wave



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

Orbital angular momentum and shape of TMDs

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

Orbital angular momentum and shape of TMDs

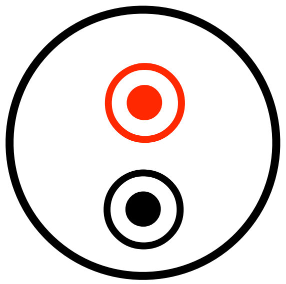
$$f_1(x, p_T^2) = |\psi_{s-\mathrm{wave}}|^2 + |\psi_{p-\mathrm{wave}}|^2 + \dots$$

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

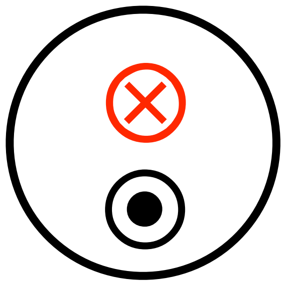
With orbital angular momentum, TMDs cannot be Gaussians!

Does spin influence TMDs?

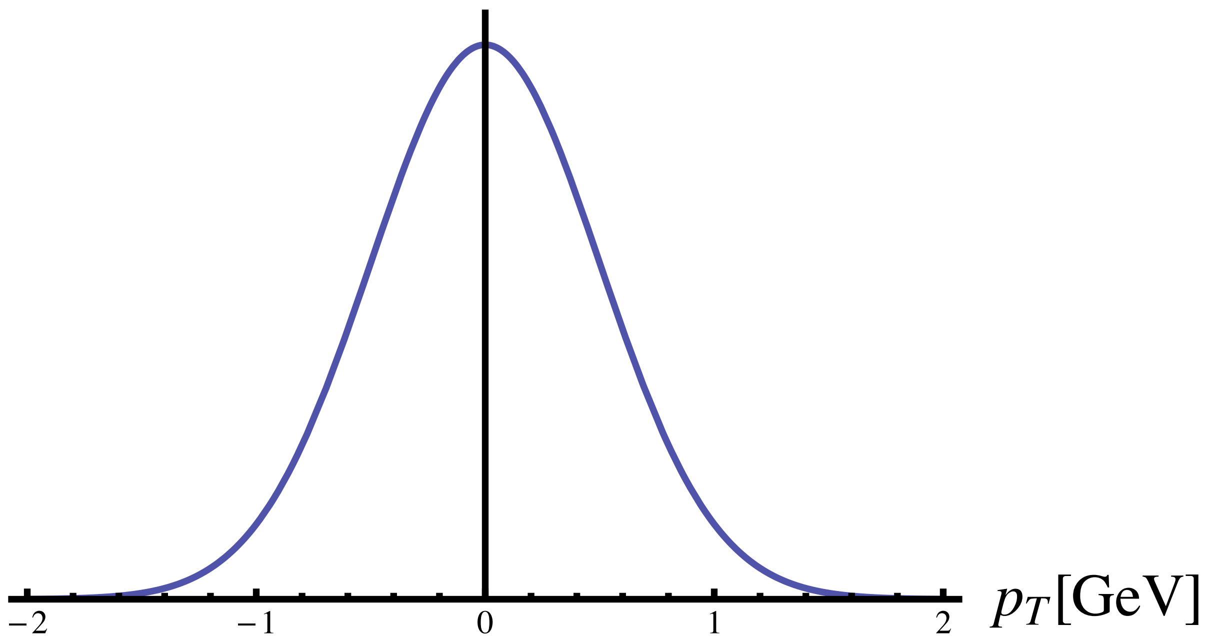
Longitudinal spin dependence



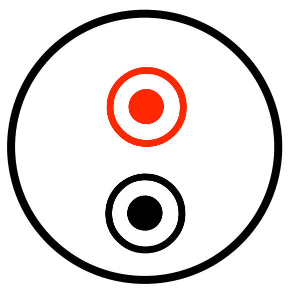
longitudinal parallel spins



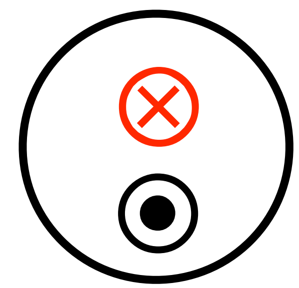
long. antiparallel spins



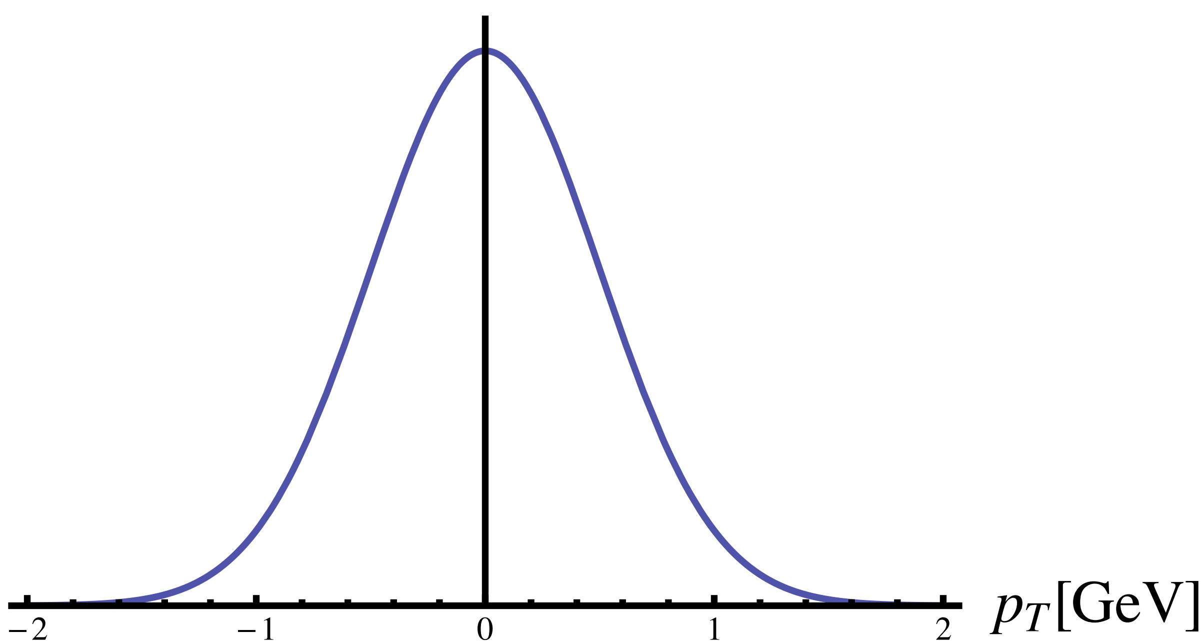
Longitudinal spin dependence

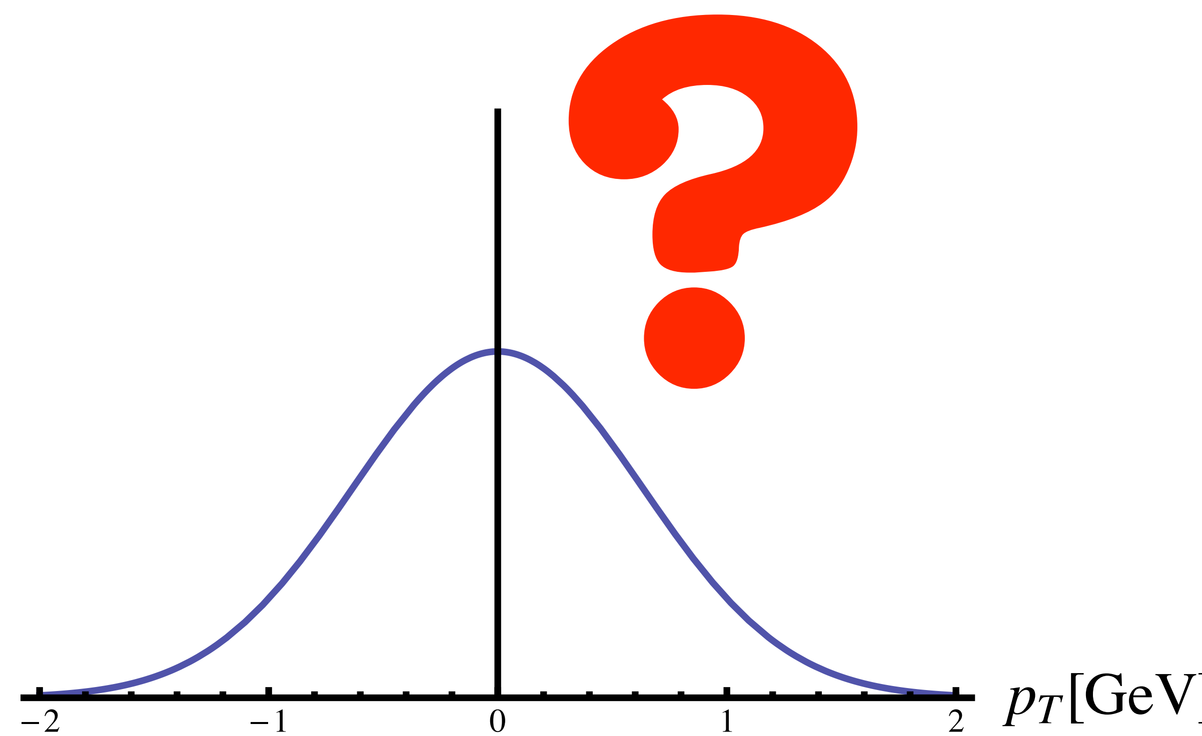


longitudinal parallel spins

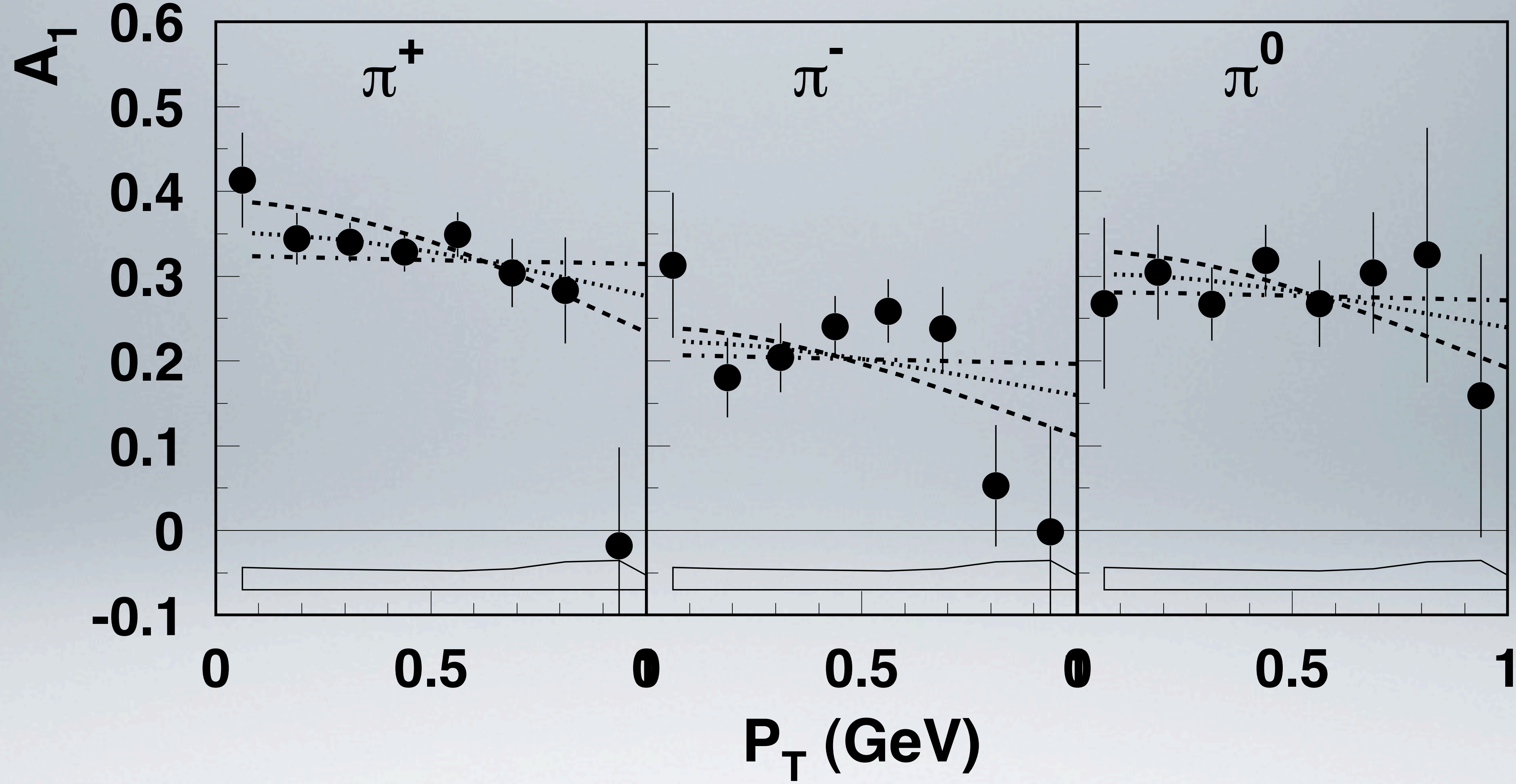


long. antiparallel spins





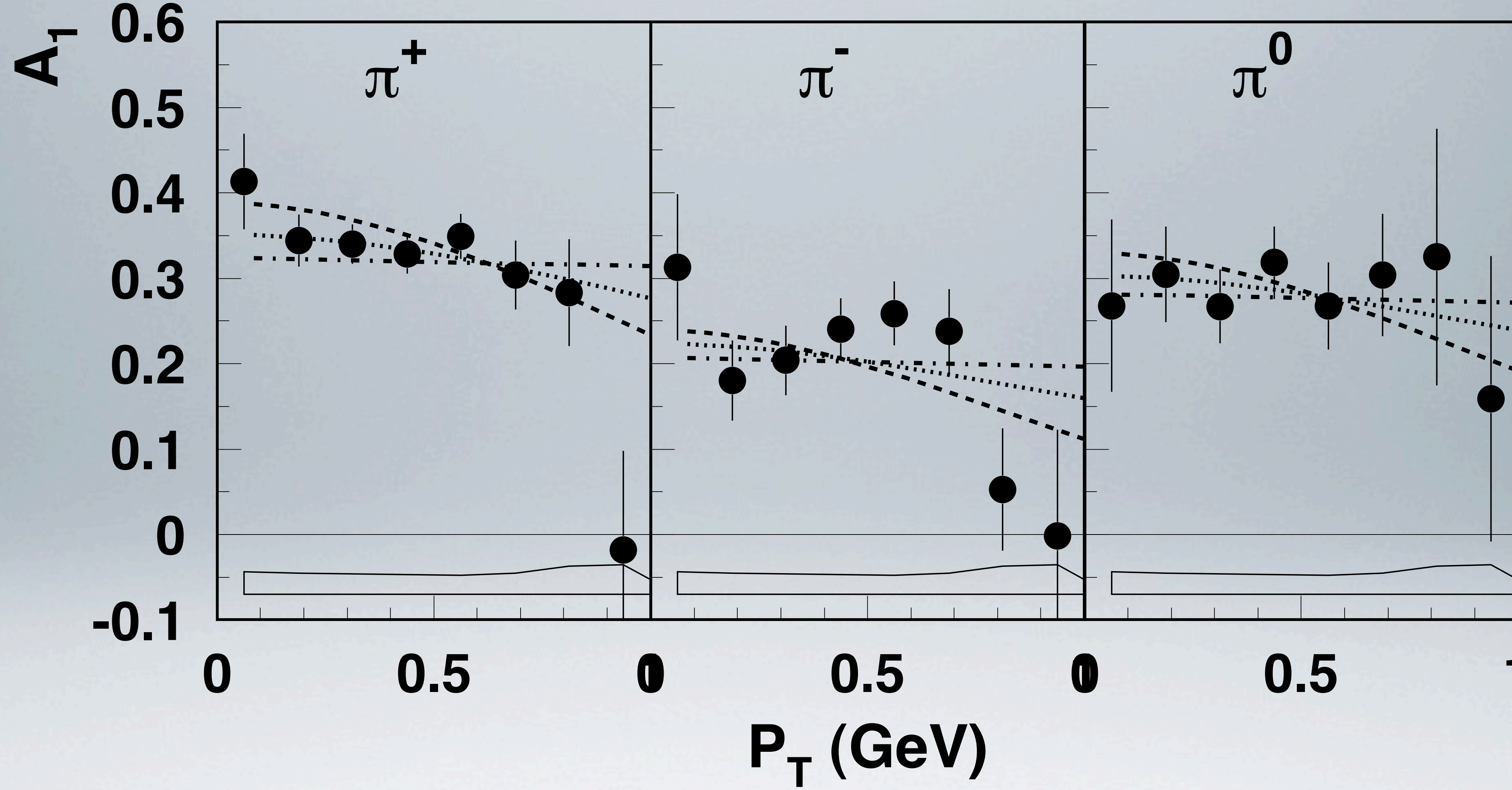
CLAS, arXiv:1003.4549
talk by Patrizia Rossi



Thursday, 3 June 2010

Jefferson Lab

CLAS, arXiv:1003.4549
talk by Patrizia Rossi



Non-flat behavior means that polarization affects TMDs

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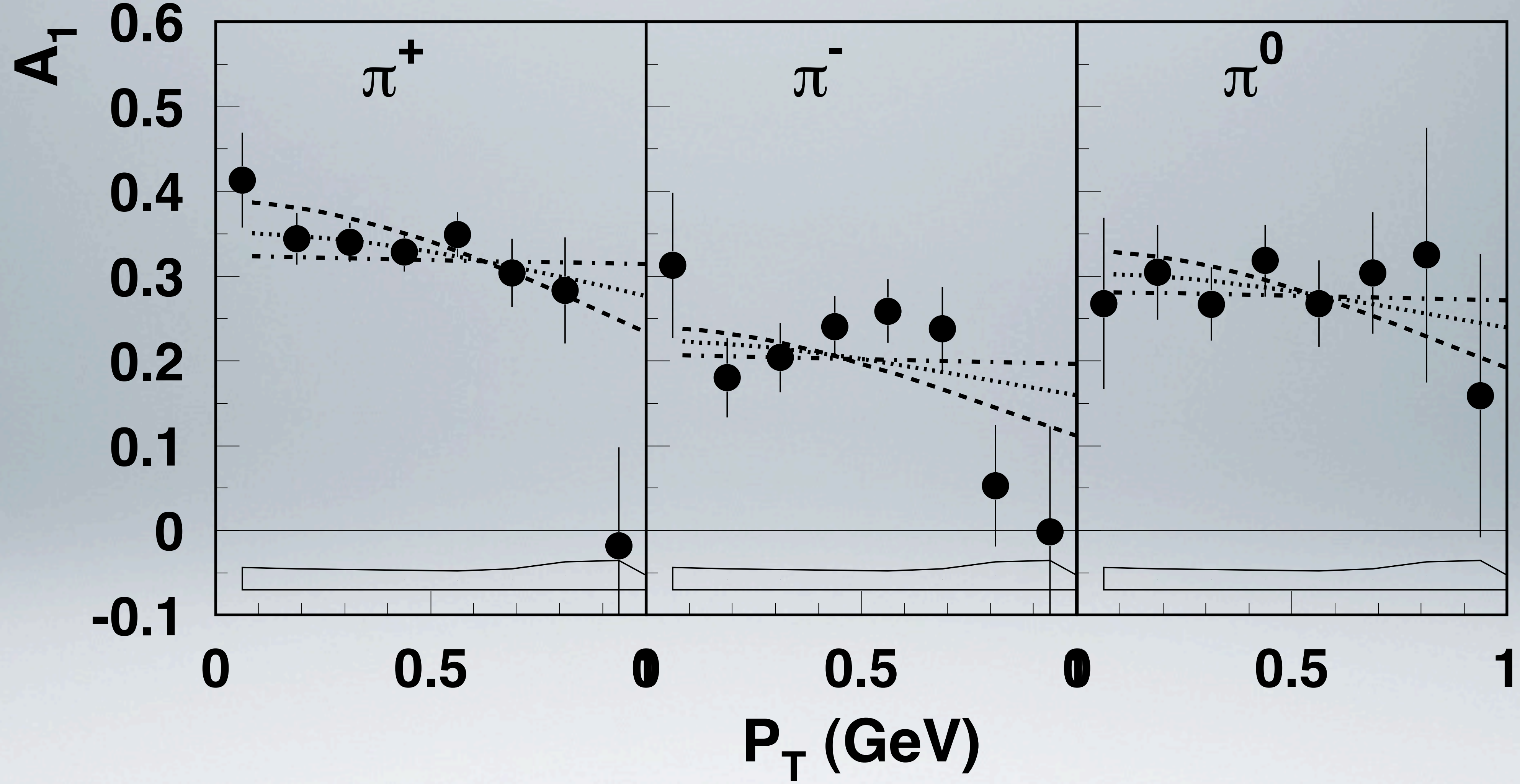
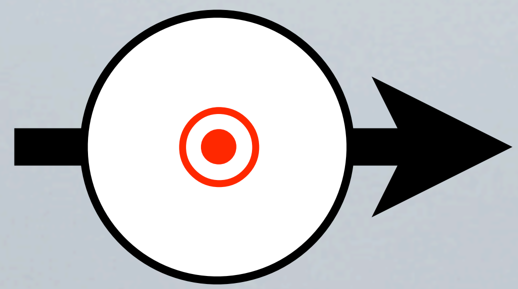
CLAS, arXiv:1003.4549
talk by Patrizia Rossi

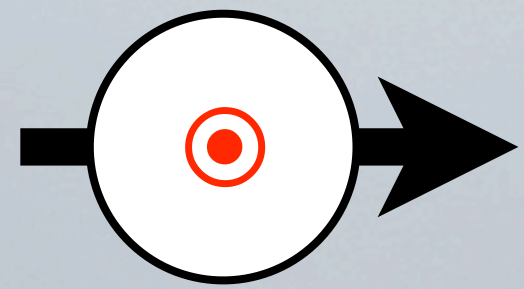


Non-flat behavior means that polarization affects TMDs
Non-monotonic behavior may be a sign of orbital angular momentum

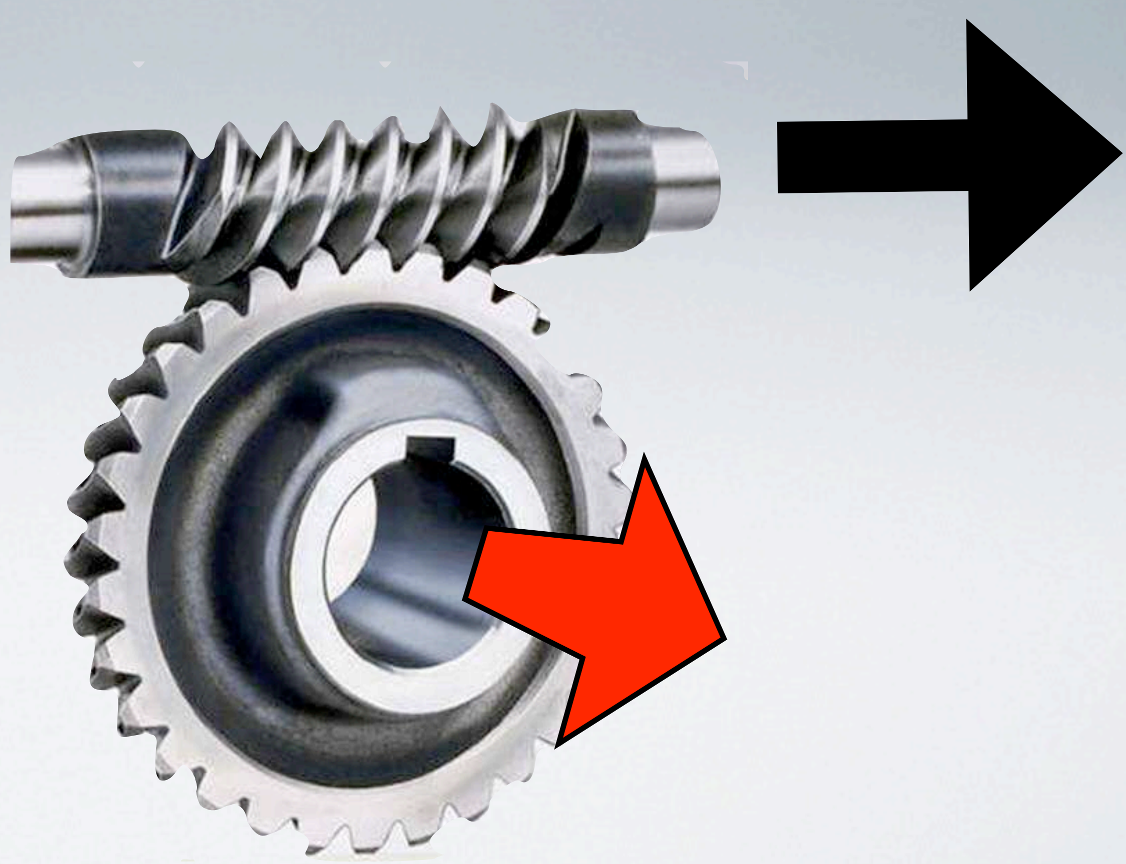
Transverse-longitudinal spin



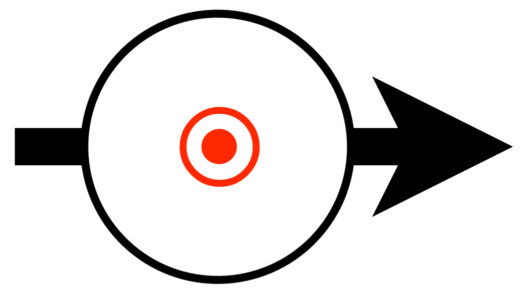
Transverse-longitudinal spin

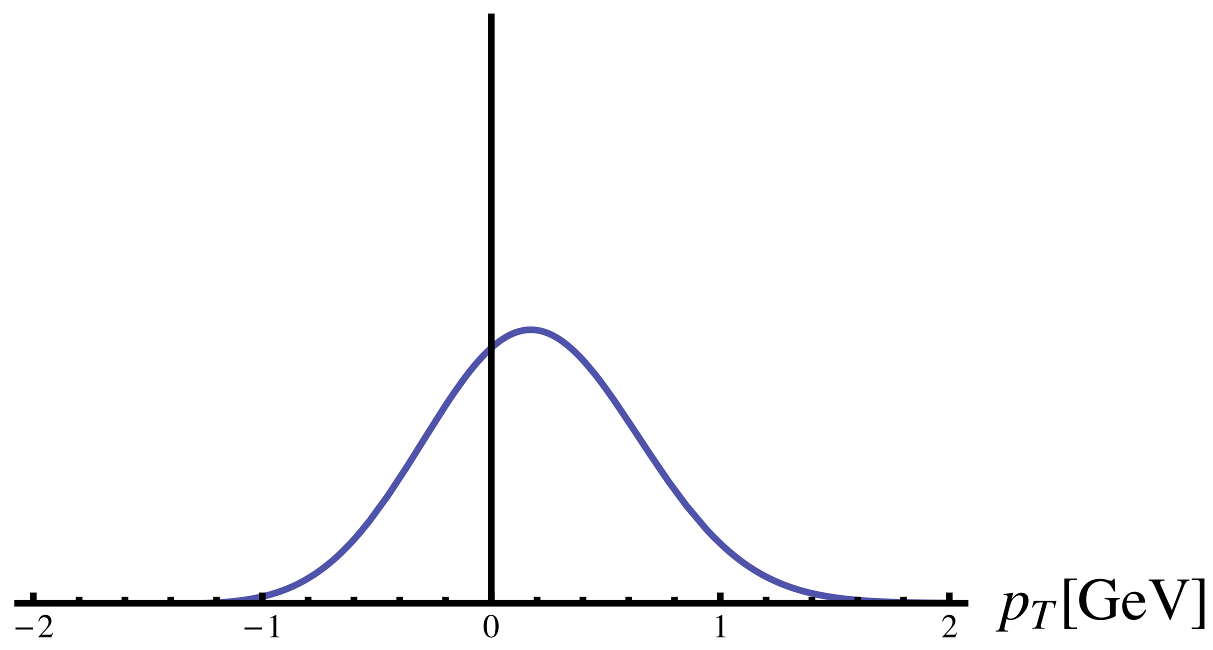


Reminiscent of
a worm gear

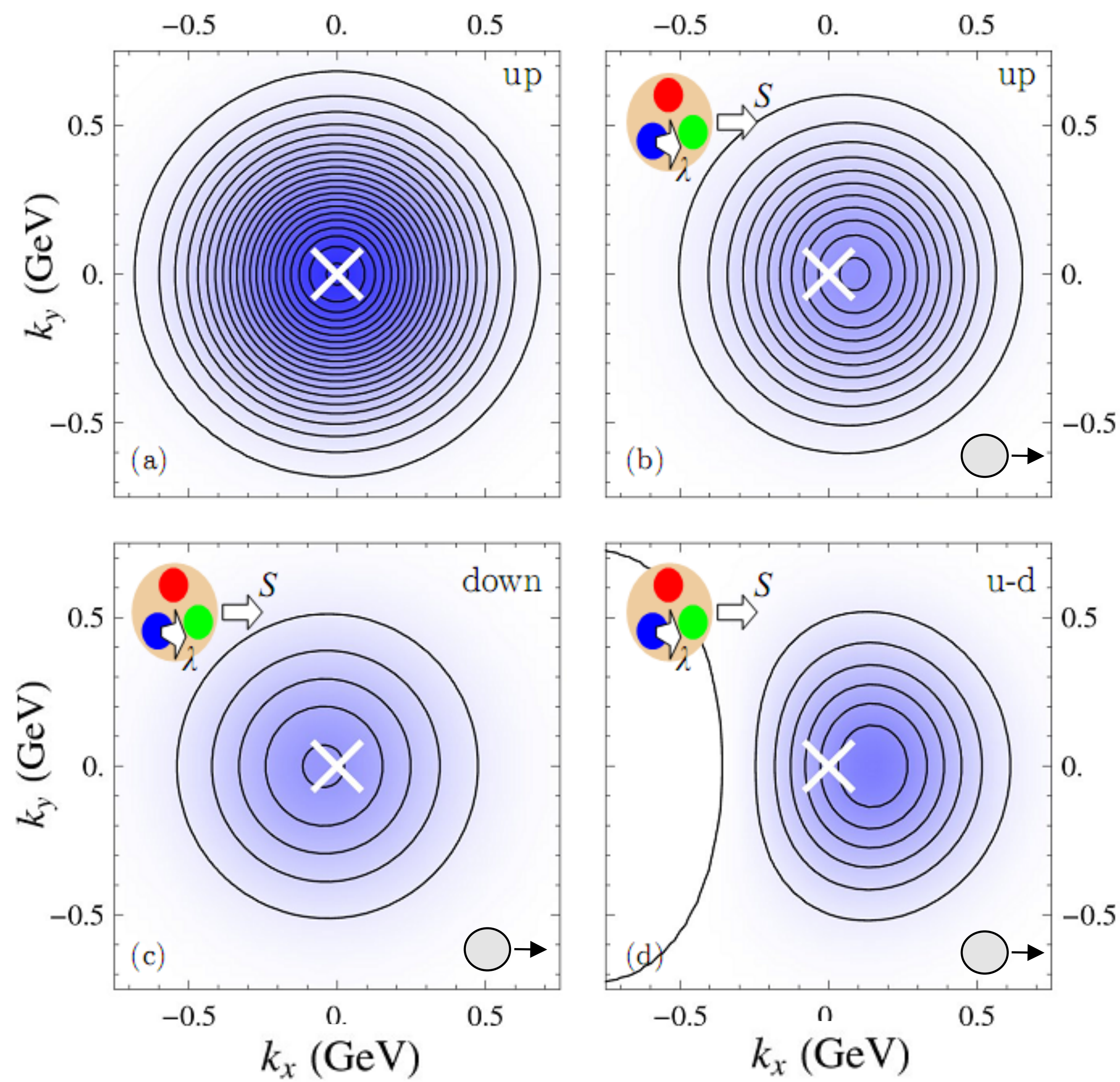


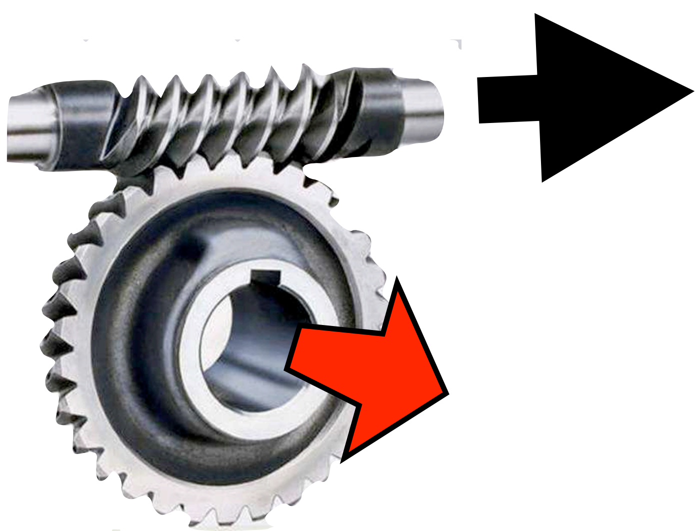
Transverse-longitudinal spin





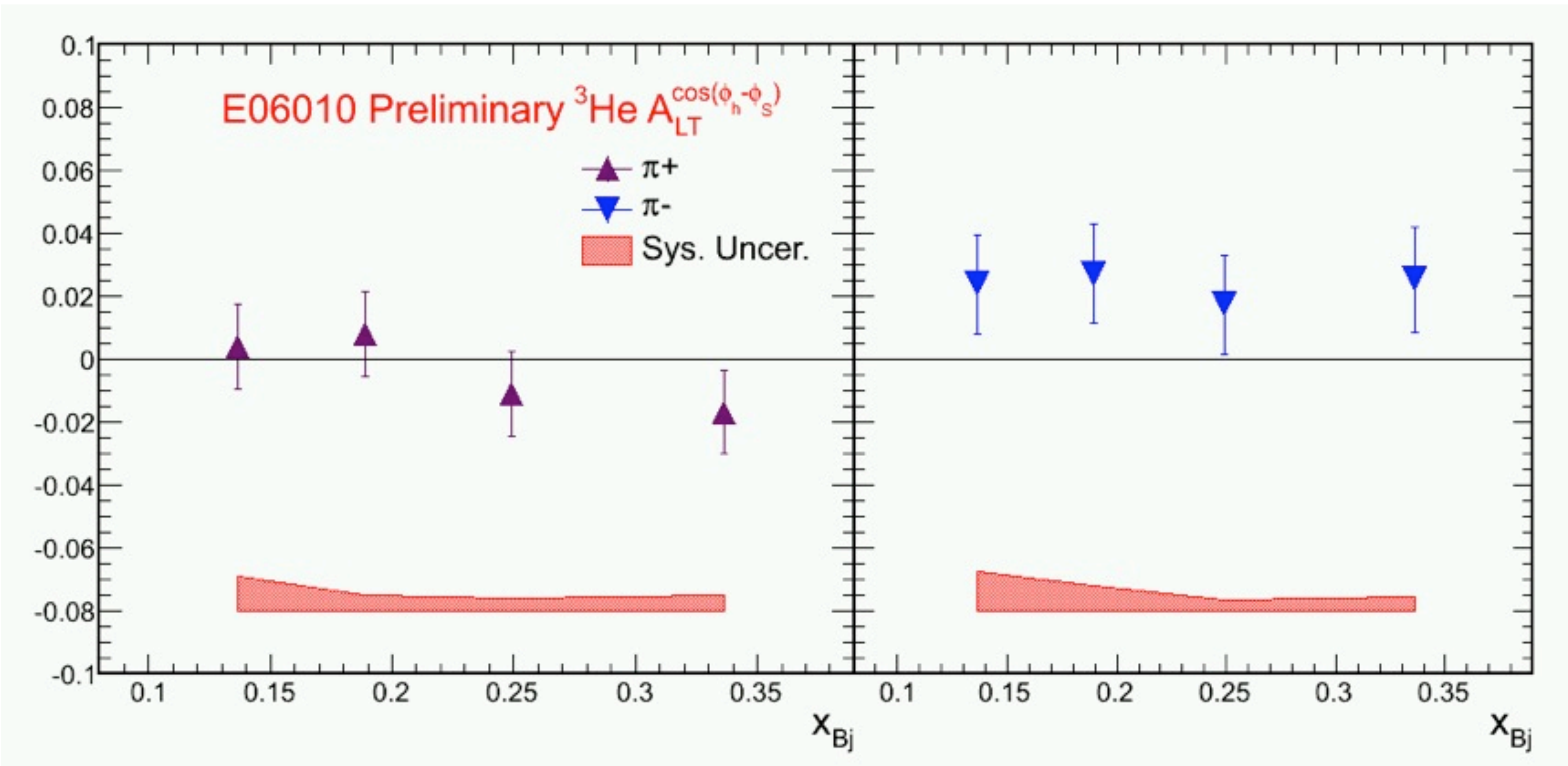
Worm gears on the lattice





Talk by Bernhard Musch

Worm gear signal in experiments



Hall A, talk by Jin Huang

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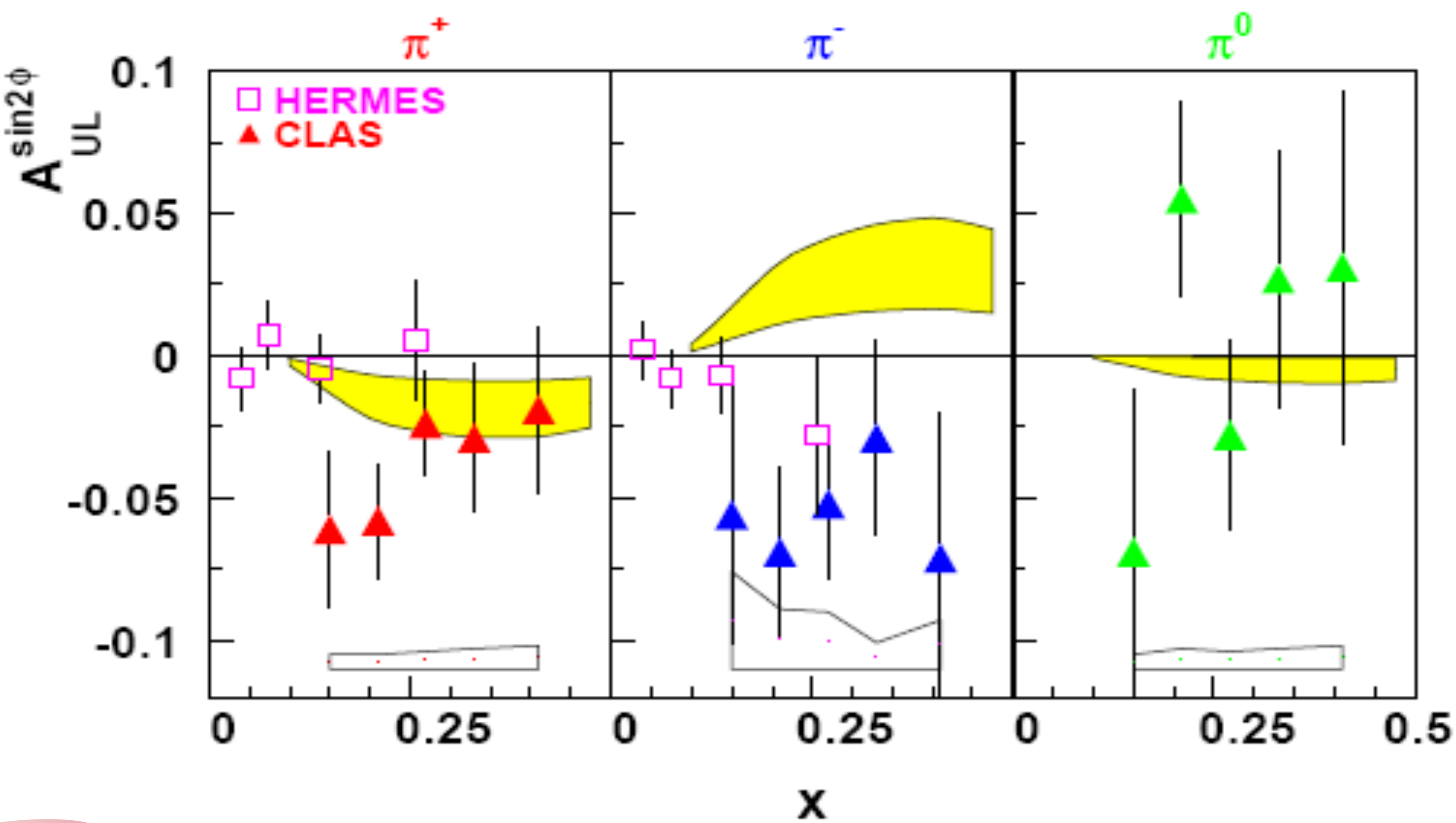
Worm gear signal in experiments



CLAS, arXiv:1003.4549
talk by Patrizia Rossi

Jefferson Lab

We have achieved a lot.

We have achieved a lot.
We have a lot to achieve.

Coming up: TMD2010 workshop (June 21-25)

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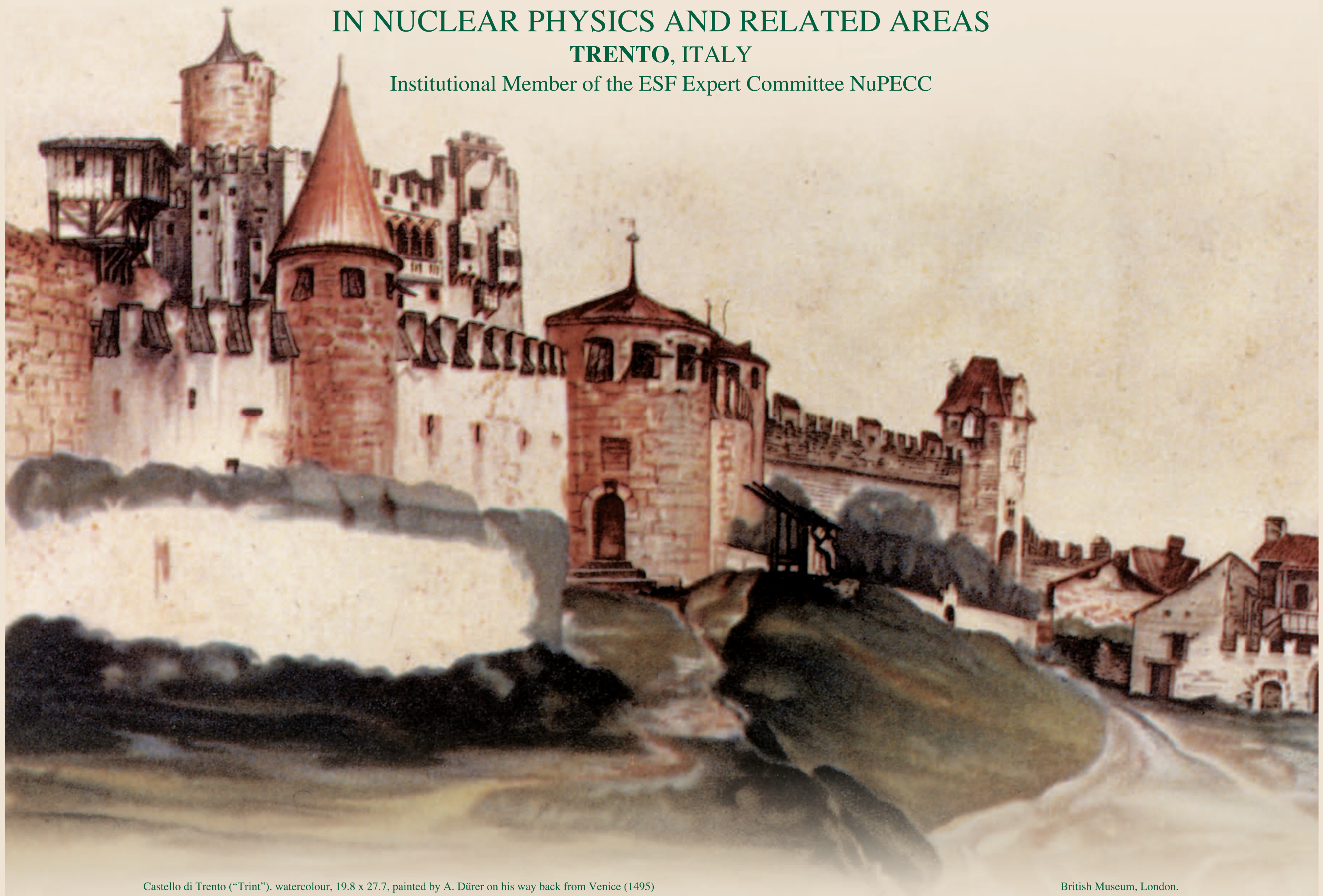

Castello di Trento ("Trint"). watercolour, 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495) British Museum, London.

Transverse Momentum Distributions (TMD 2010)

Trento, June 21-25, 2010

INFN Istituto Nazionale di Fisica Nucleare

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