Transverse Momentum Distributions: status and perspectives

Alessandro Bacchetta

Funded by

3DSPIN
MAPPING THE PROTON IN 3D

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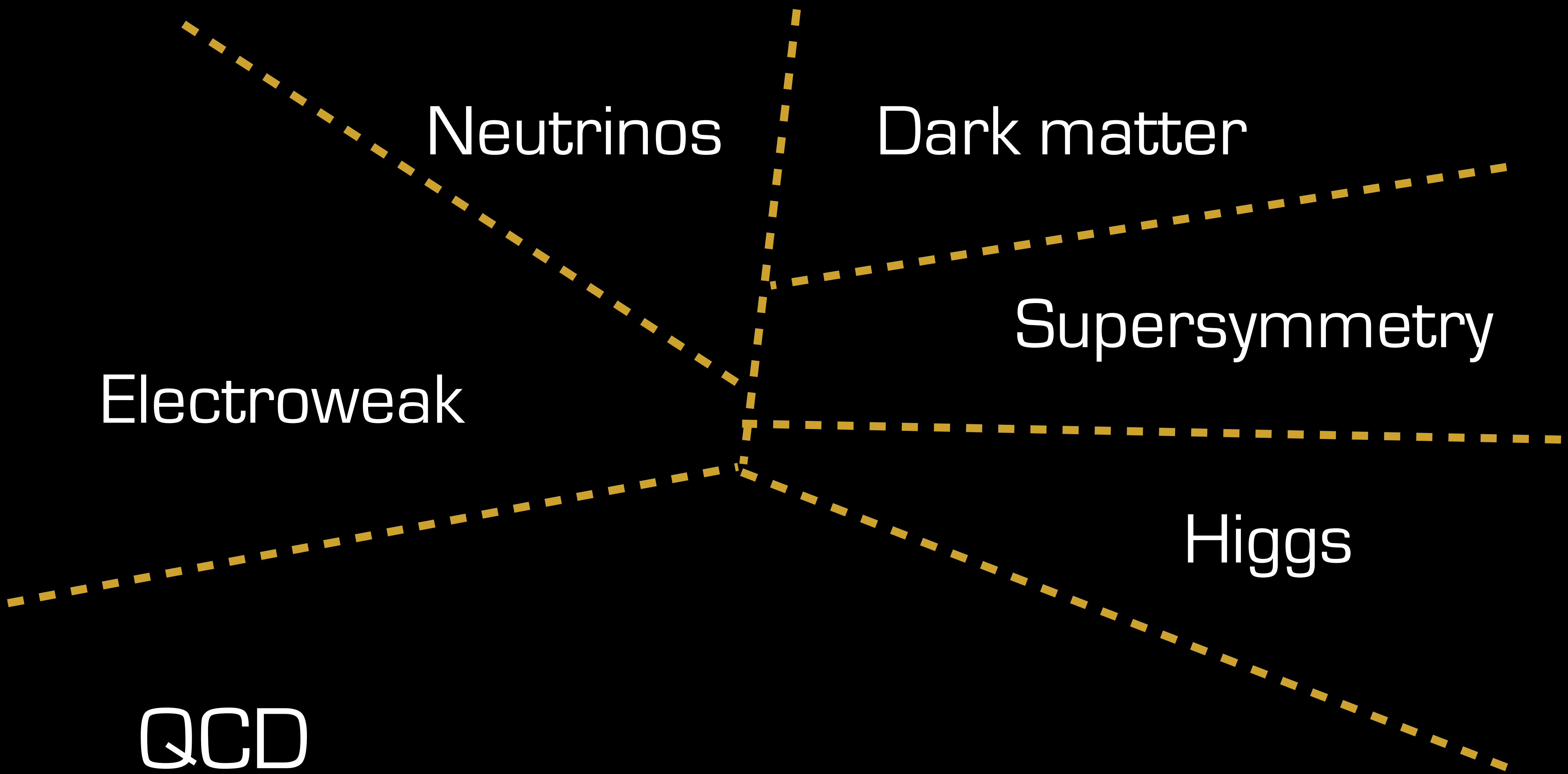
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

The Standard Model and beyond



$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not\partial - g \not{A} + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

QCD: the WILD SIDE of the SM

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not{\partial} - g \not{A} + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

The goal of hadronic physics

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The goal of hadronic physics

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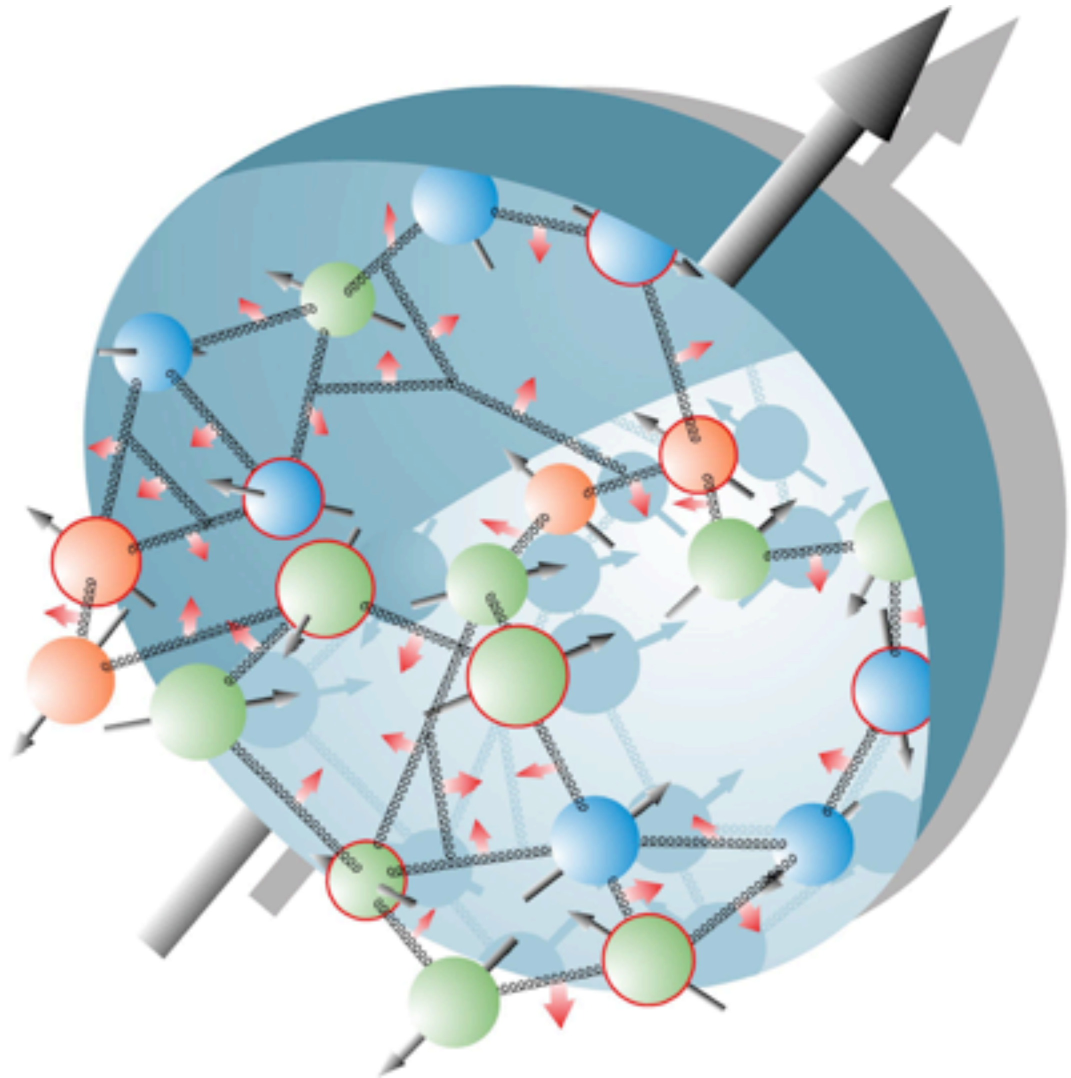
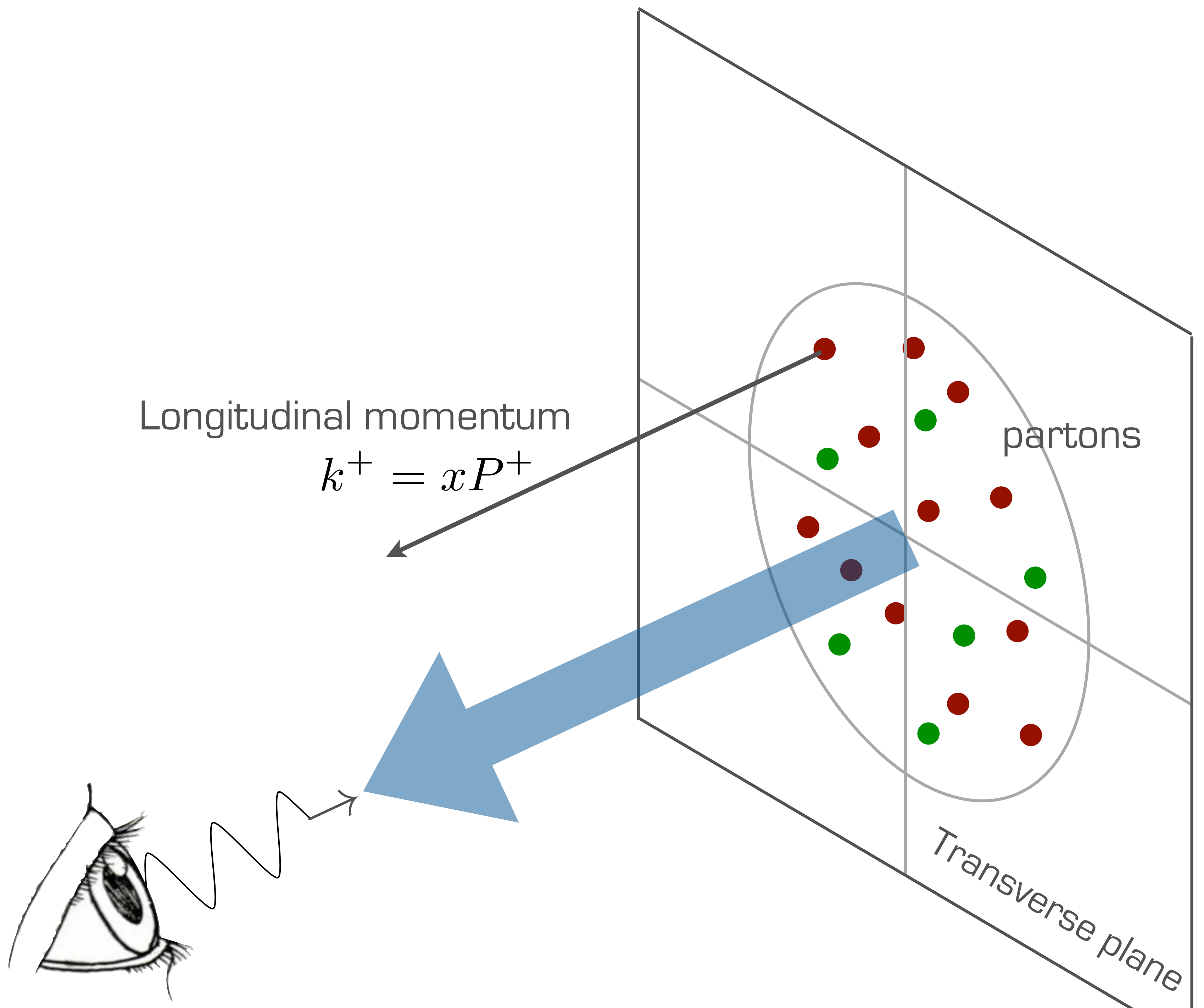
The goal of hadronic physics



$$\mathcal{L}_{\rm QCD} = \sum_q \overline{\psi}_q (i \not\partial - g \not A + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

Mapping the structure of the proton



1D structure of the proton

Encoded in Parton Distribution Functions (PDFs)

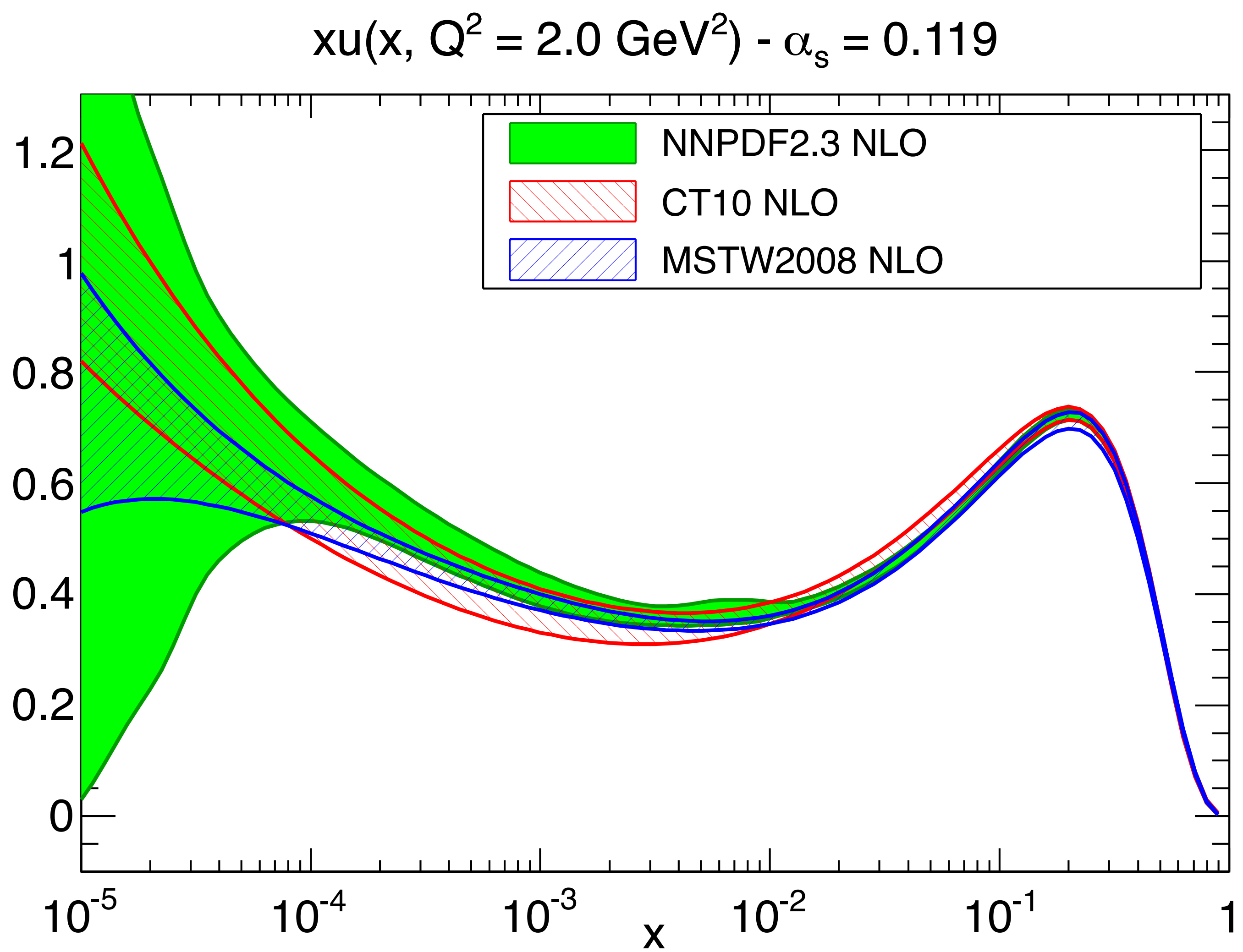


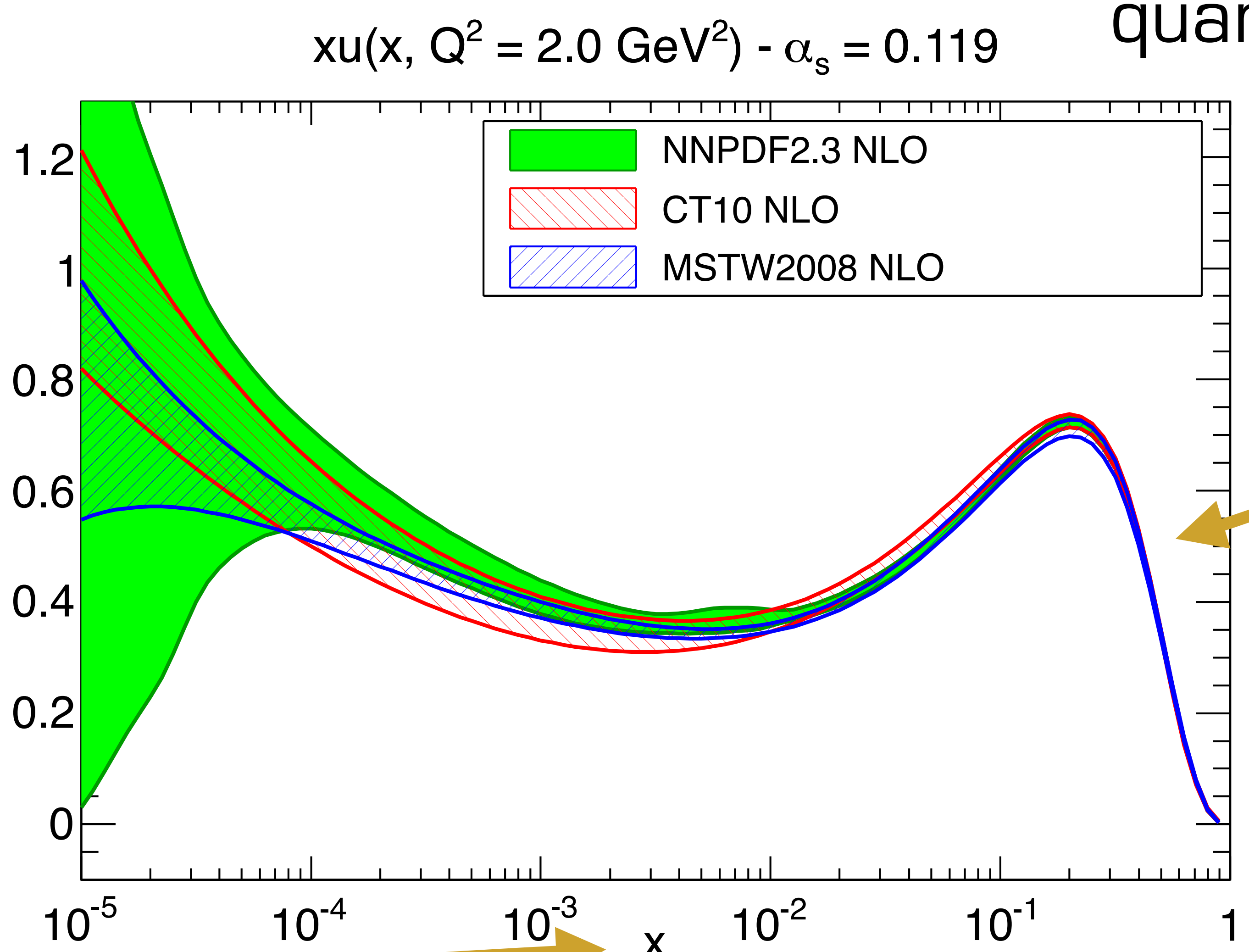
image from: NNPDF http://nnpdf.hepforge.org

see e.g., talks by C. Keppel, S. Platchkov

1D structure of the proton

Encoded in Parton Distribution Functions (PDFs)

Density distribution of quarks in the proton



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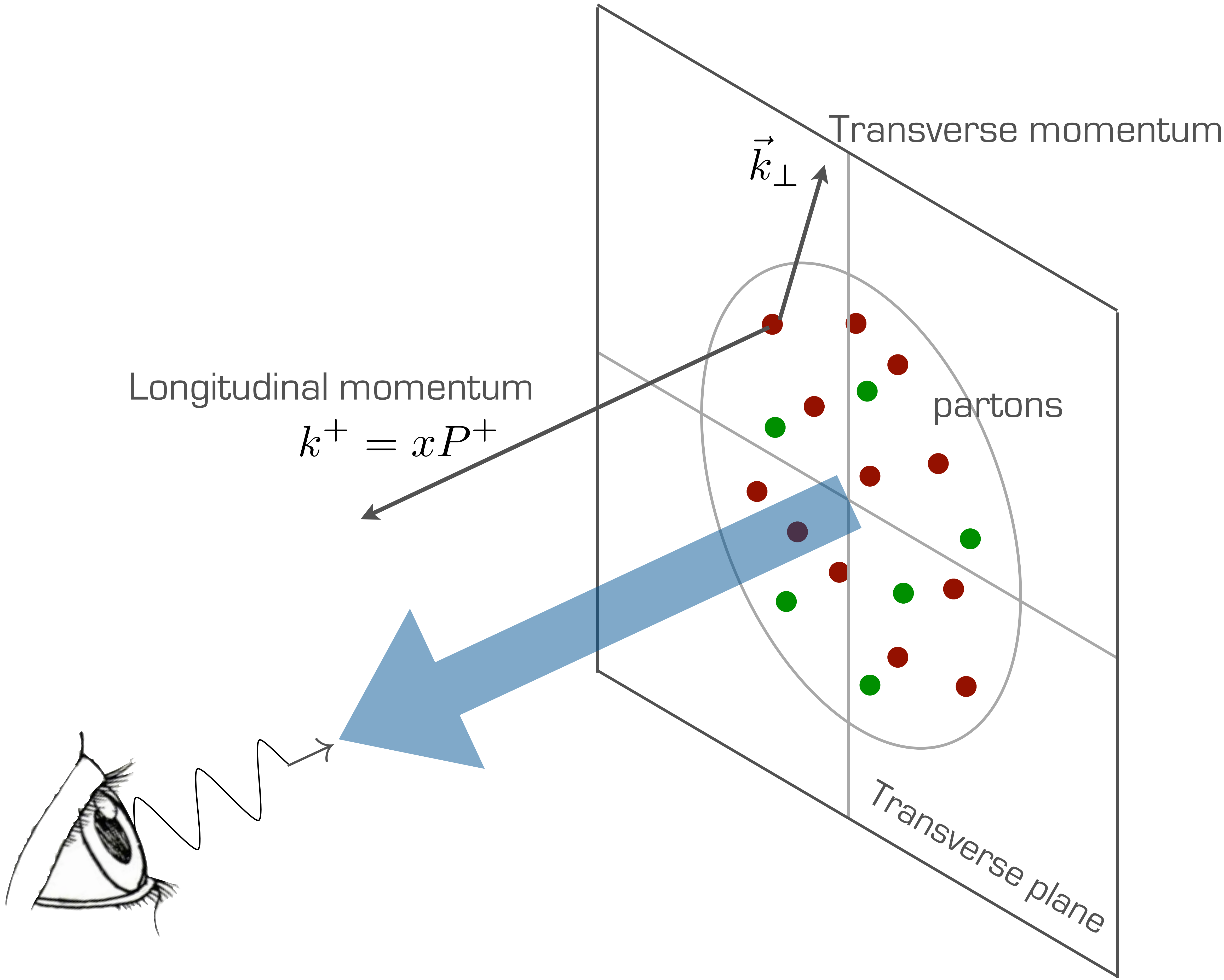
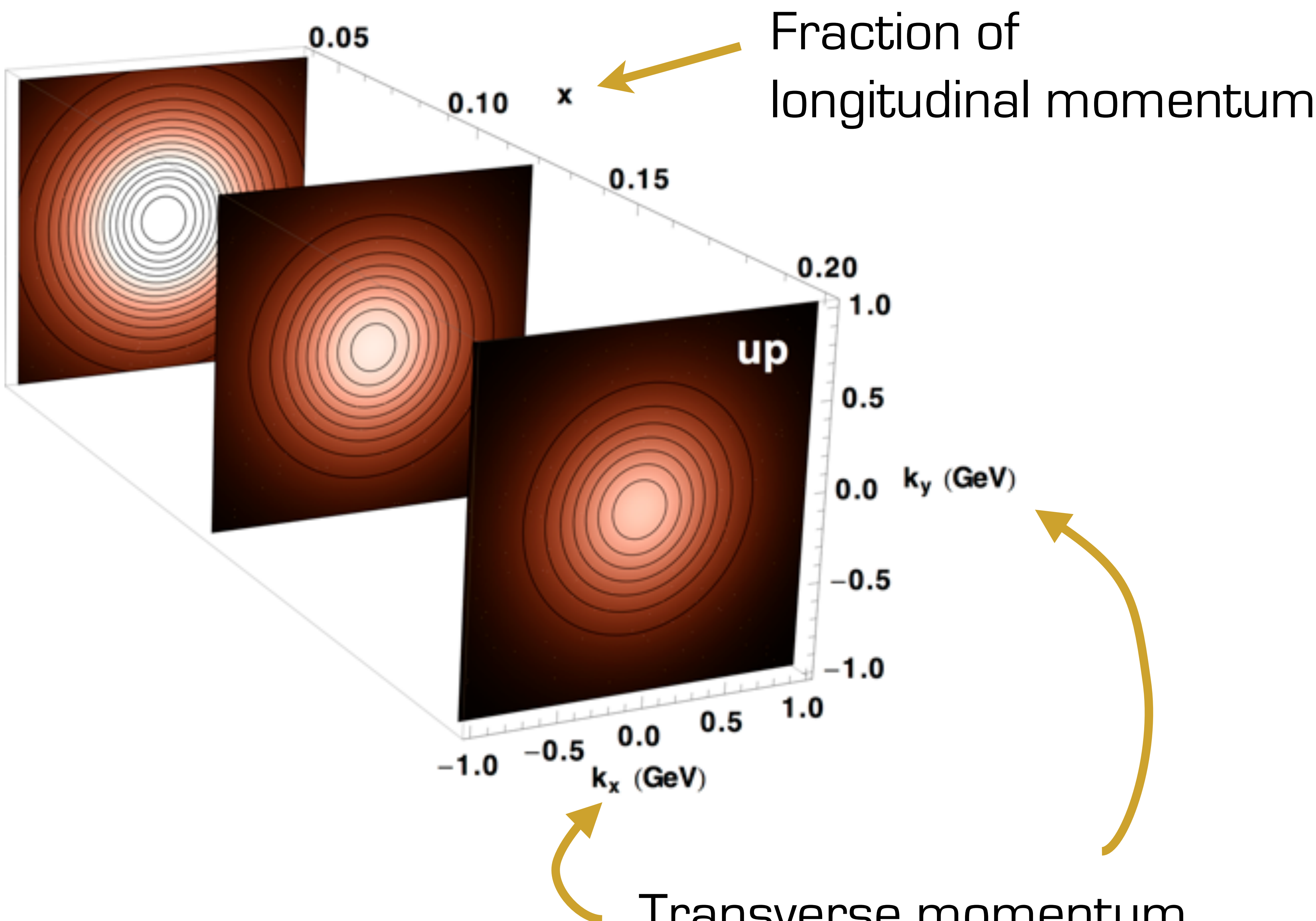
Fraction of longitudinal momentum

see e.g., talks by C. Keppel, S. Platchkov



Transverse momentum
$\vec{k}_\perp$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

3D structure of the nucleon



3D structure of the nucleon

Fraction of
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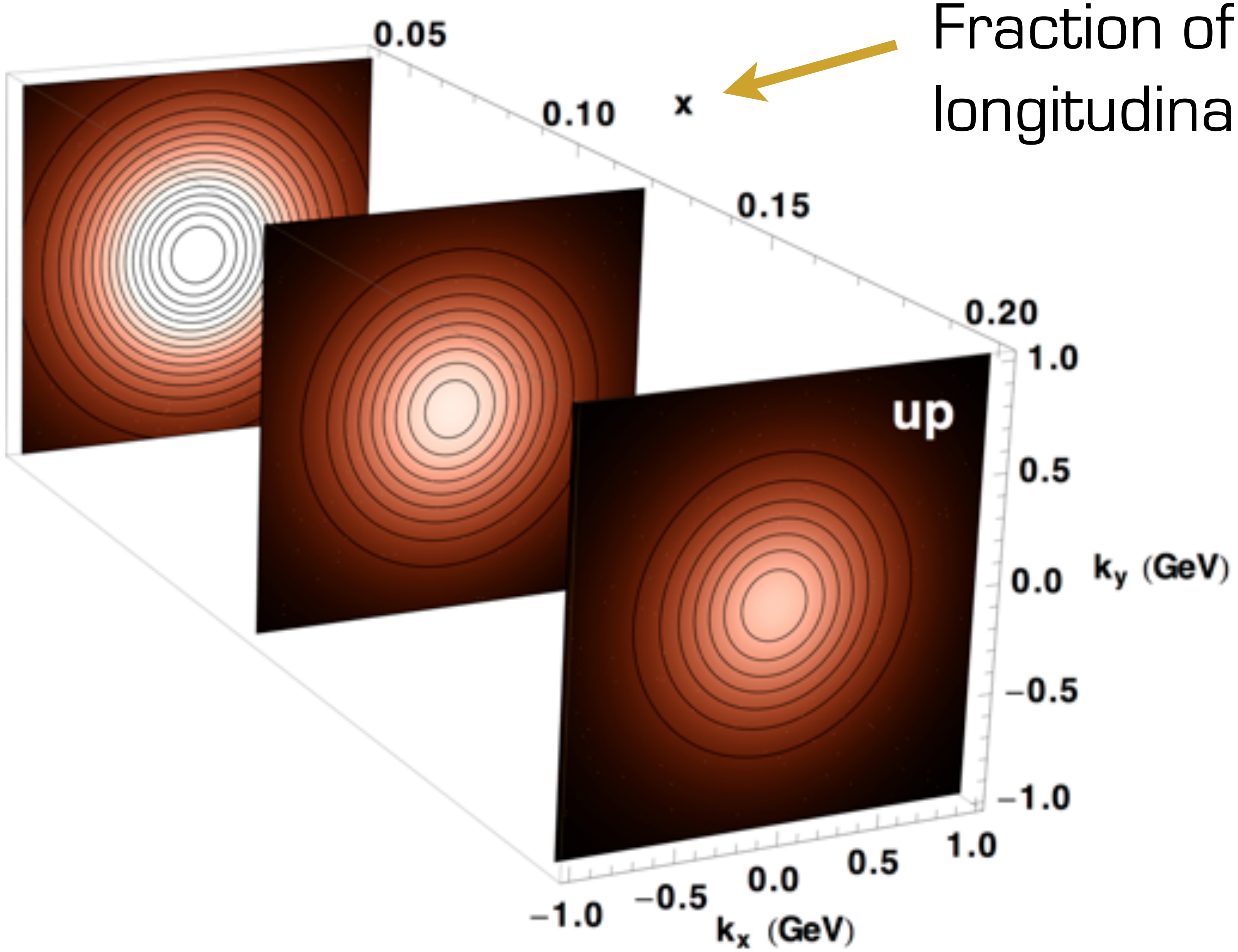
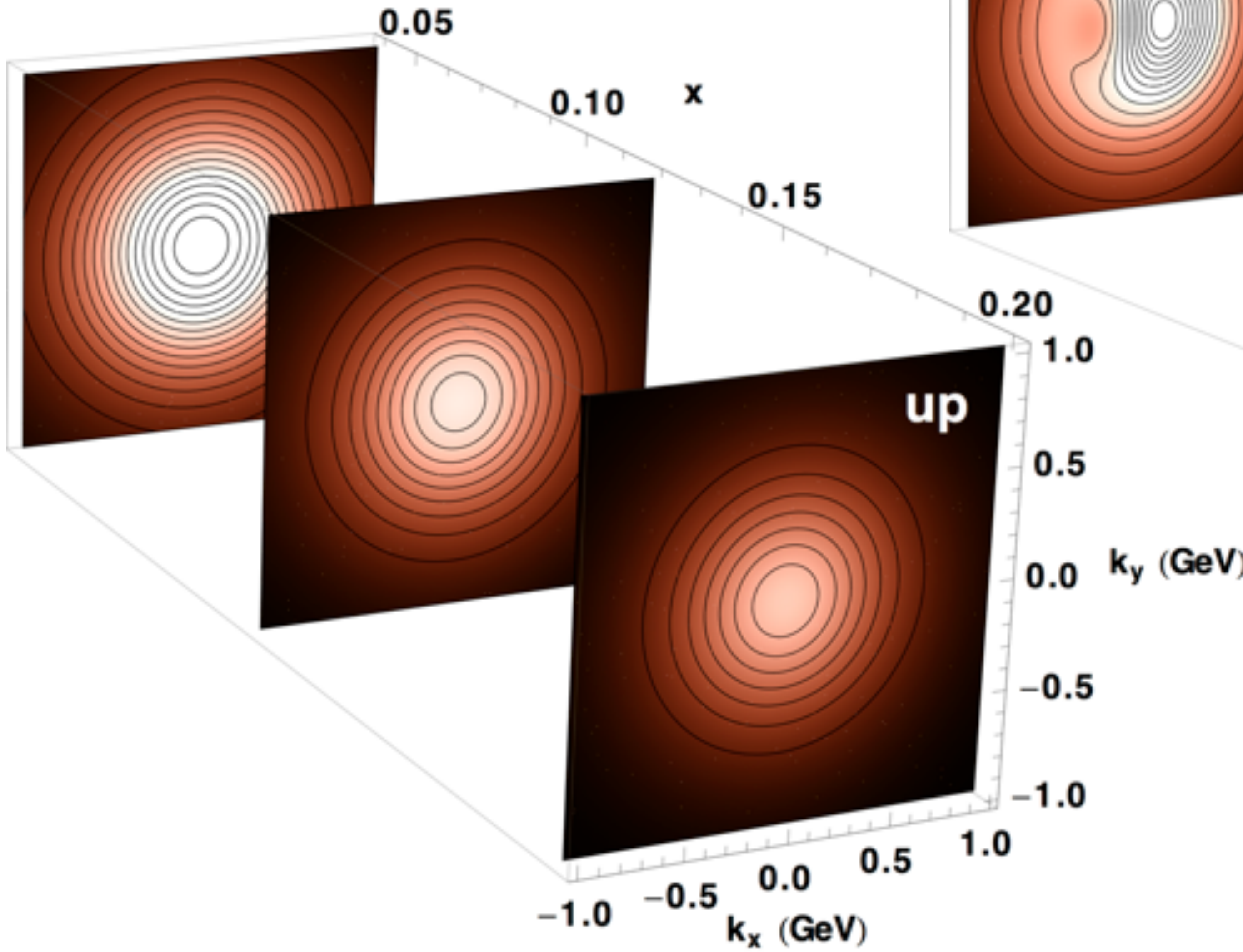
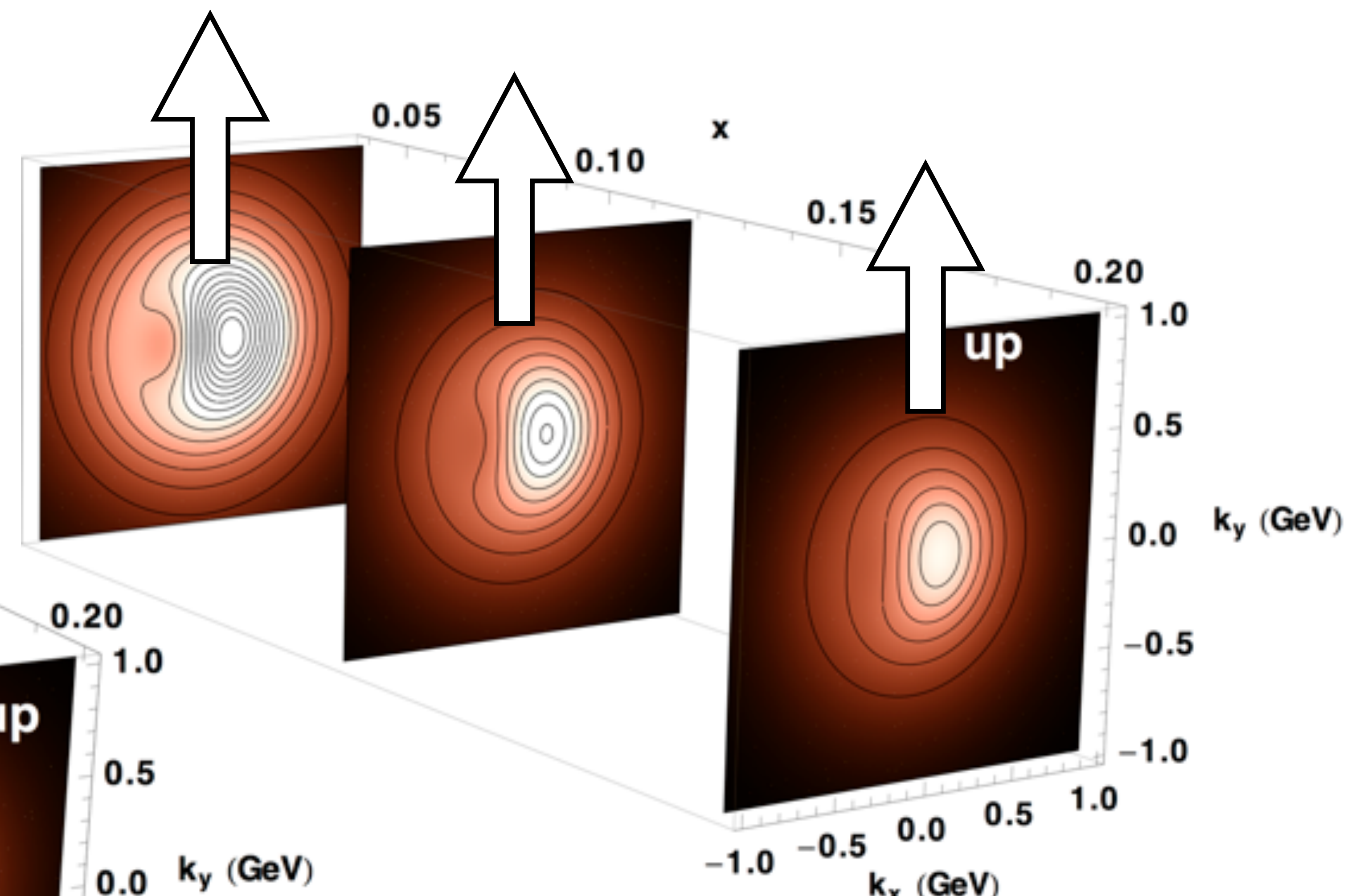


Encoded in Transverse
Momentum Distributions (TMDs)

Transverse momentum

3D structure of the nucleon

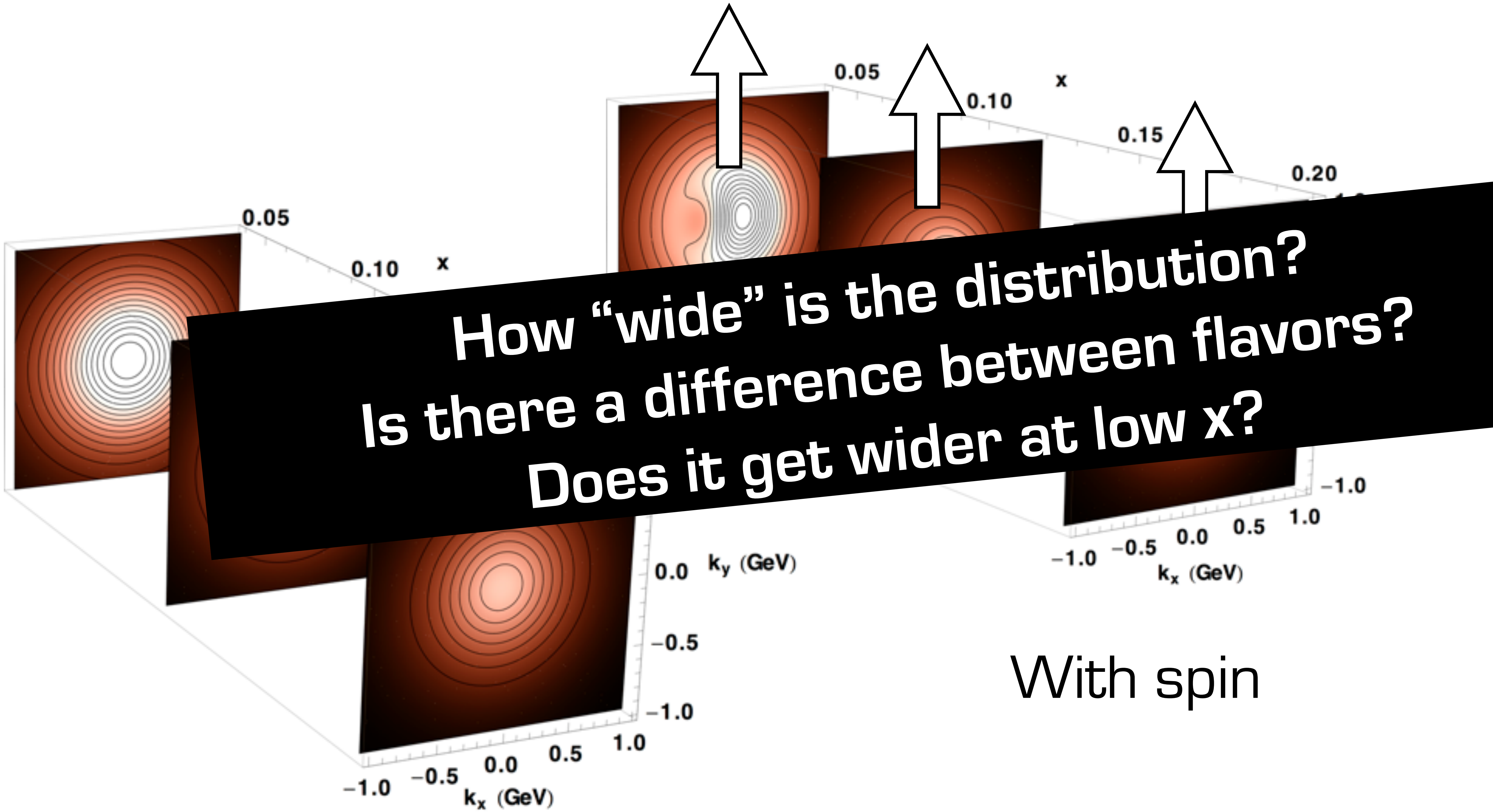




With spin

Encoded in Transverse Momentum Distributions (PDFs)

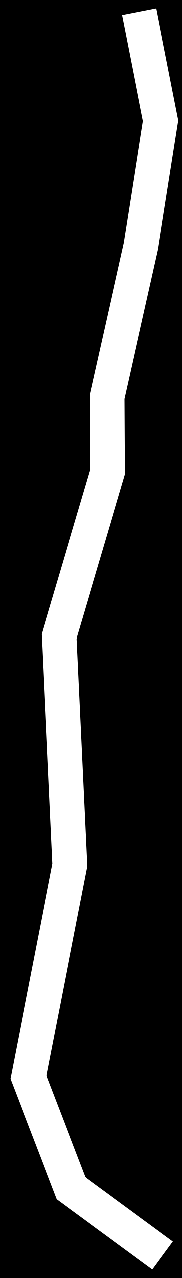
3D structure of the nucleon



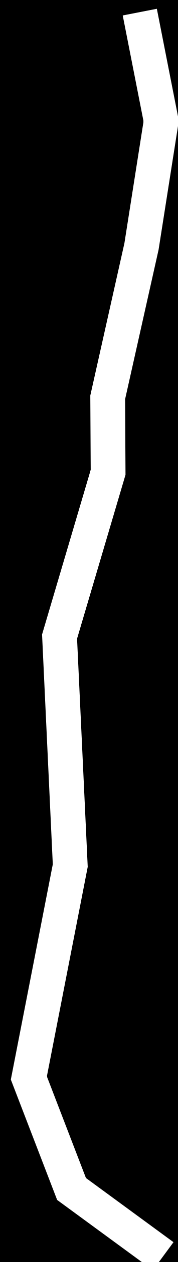
How "wide" is the distribution?
Is there a difference between flavors?
Does it get wider at low x?

With spin

Encoded in Transverse Momentum Distributions (PDFs)



Chile in 1D (?)



Chile in 1D (?)

Chile in 3D

Table of twist-2 TMDs with polarization

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, $h_{1T}^\perp$

Twist-2 TMDs

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)
AB, Diehl, Goeke, Metz, Mulders, Schlegel, JHEP093 (07)

Table of twist-2 TMDs with polarization

helicity

quark pol.

nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
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Twist-2 TMDs

transversity

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Table of twist-2 TMDs with polarization

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Sivers

Twist-2 TMDs

transversity

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)
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Table of twist-2 TMDs with polarization

helicity

quark pol.

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

Boer-Mulders

Sivers

Twist-2 TMDs

transversity

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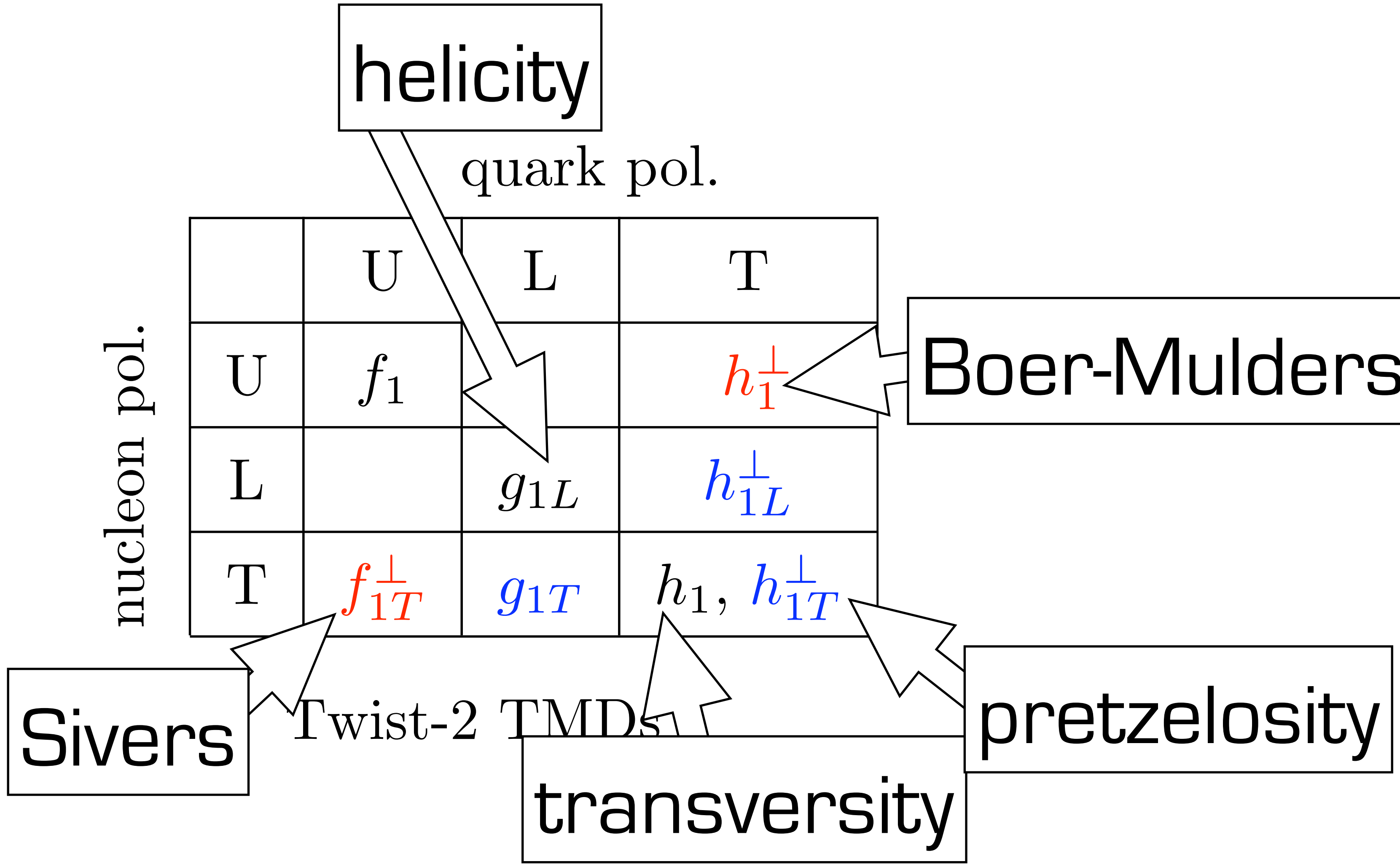

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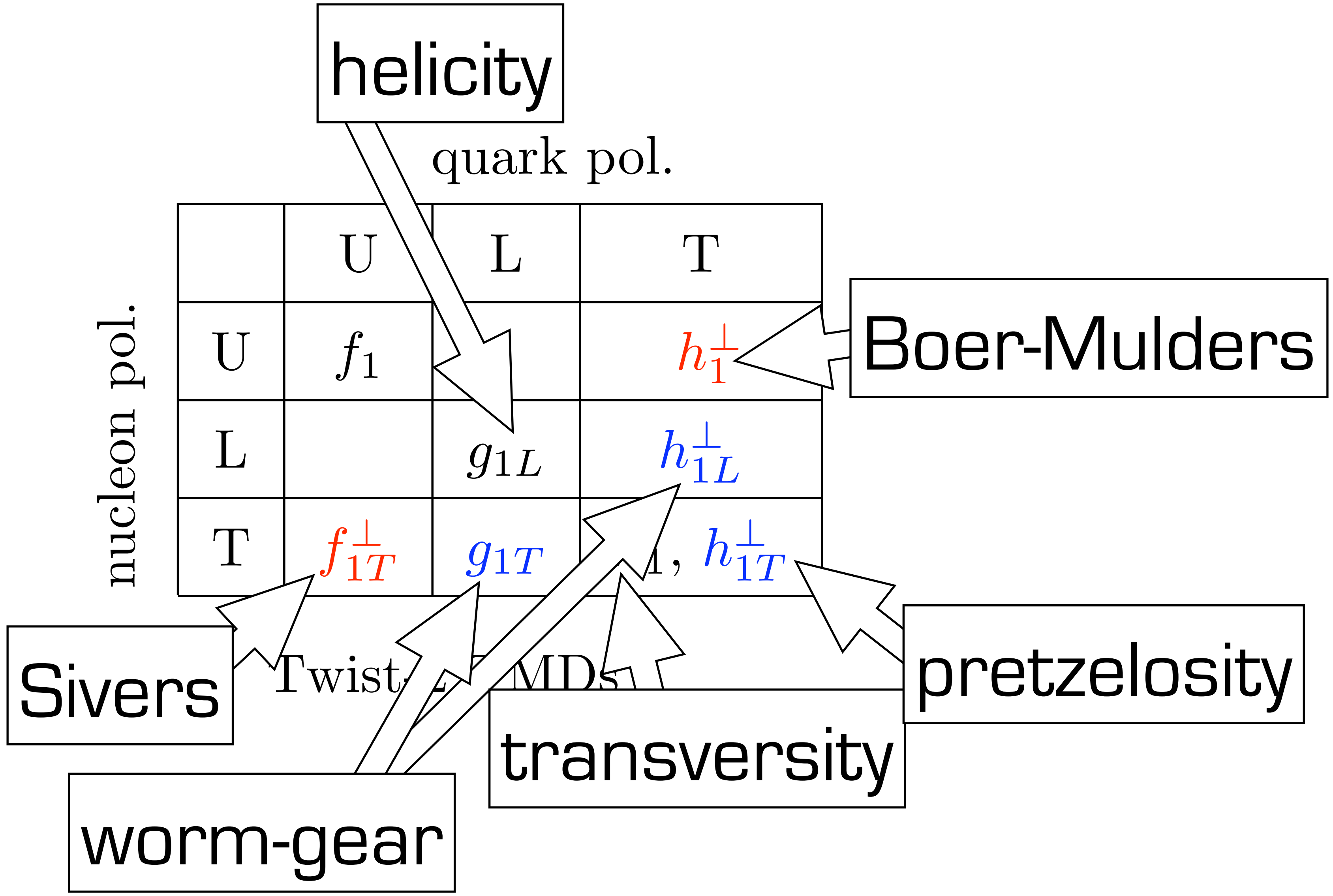

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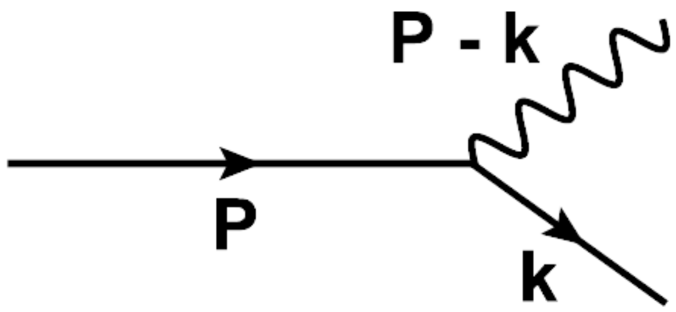
TMDs in QED

dressed electron

[Bacchetta, Mantovani, Pasquini, arXiv:1508.06964]



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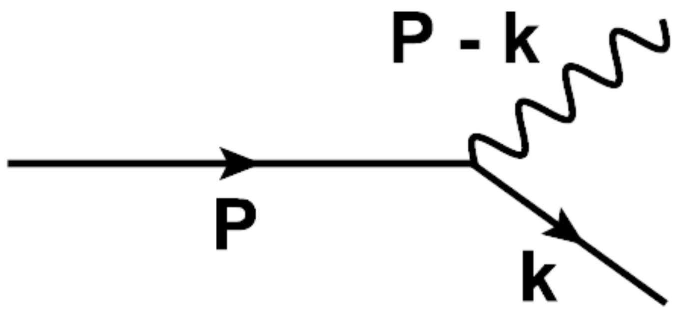
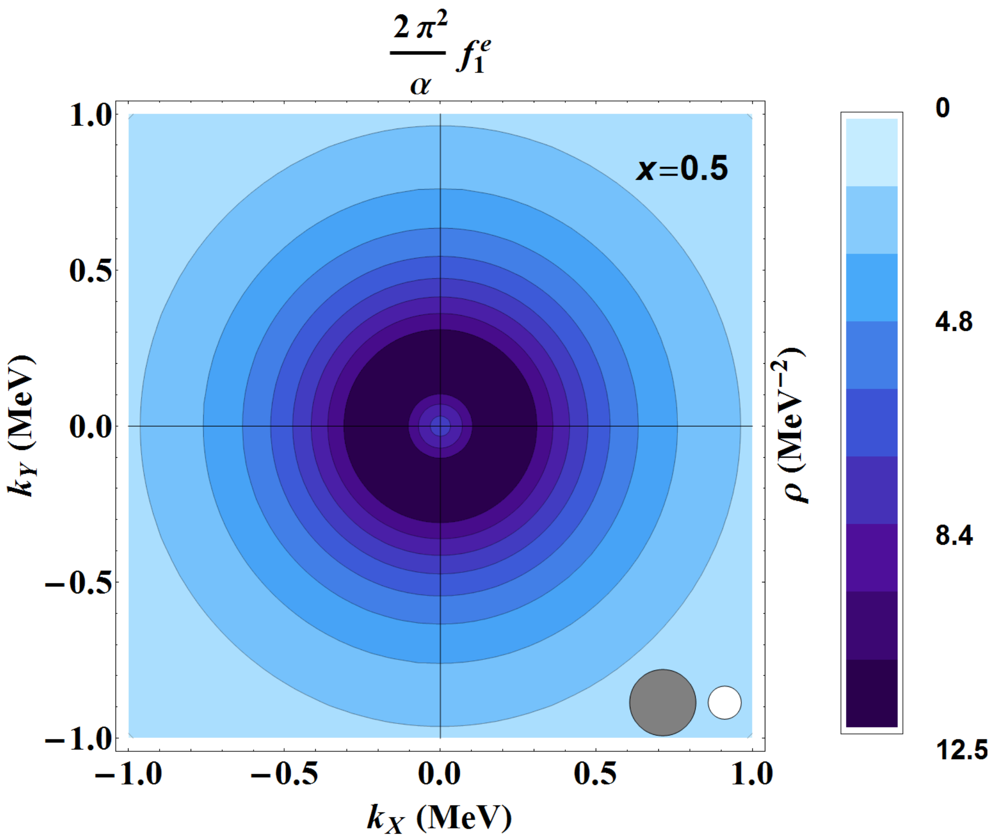


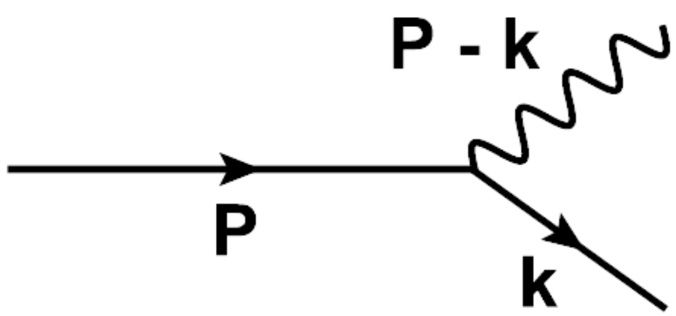


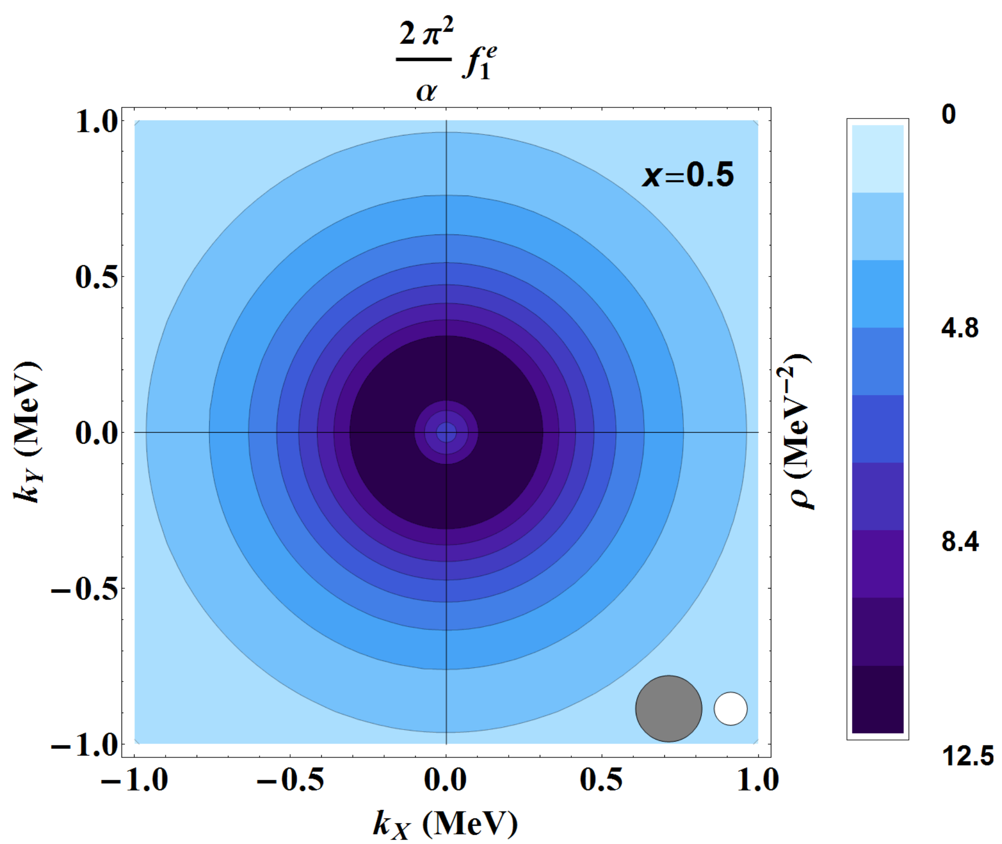
electron density inside a dressed electron

TMDs in QED

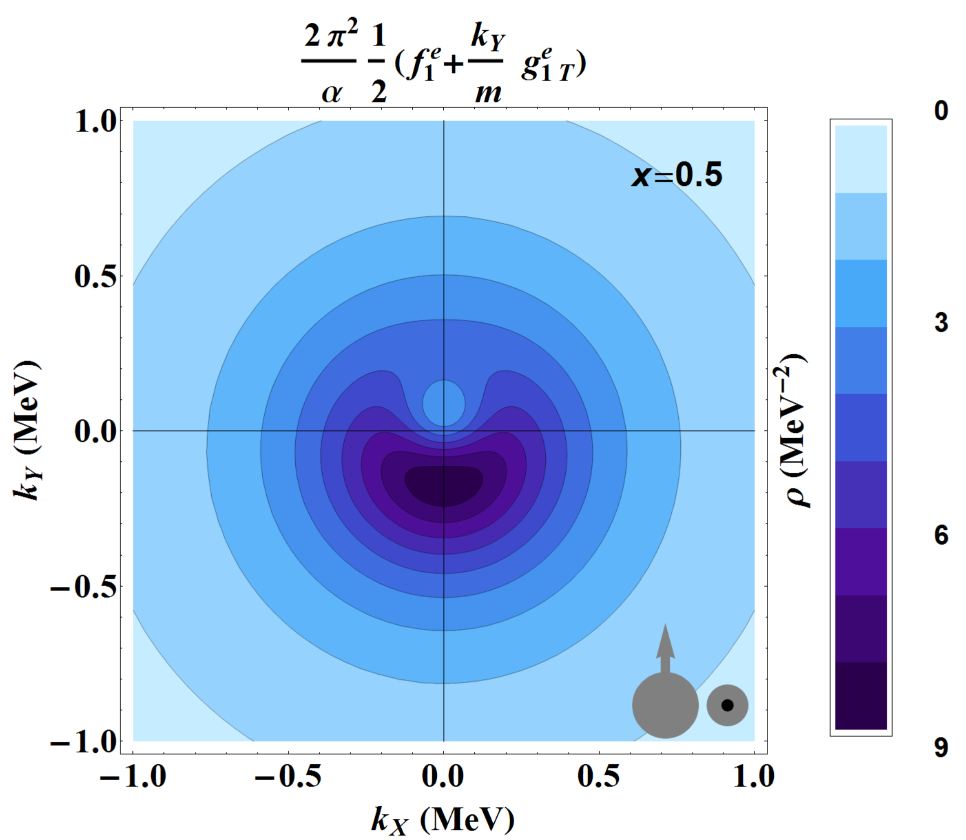
dressed electron

Bacchetta, Mantovani, Pasquini, arXiv:1508.06964





electron density
inside a dressed electron

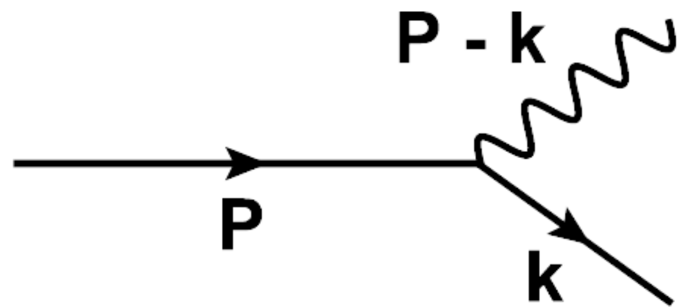


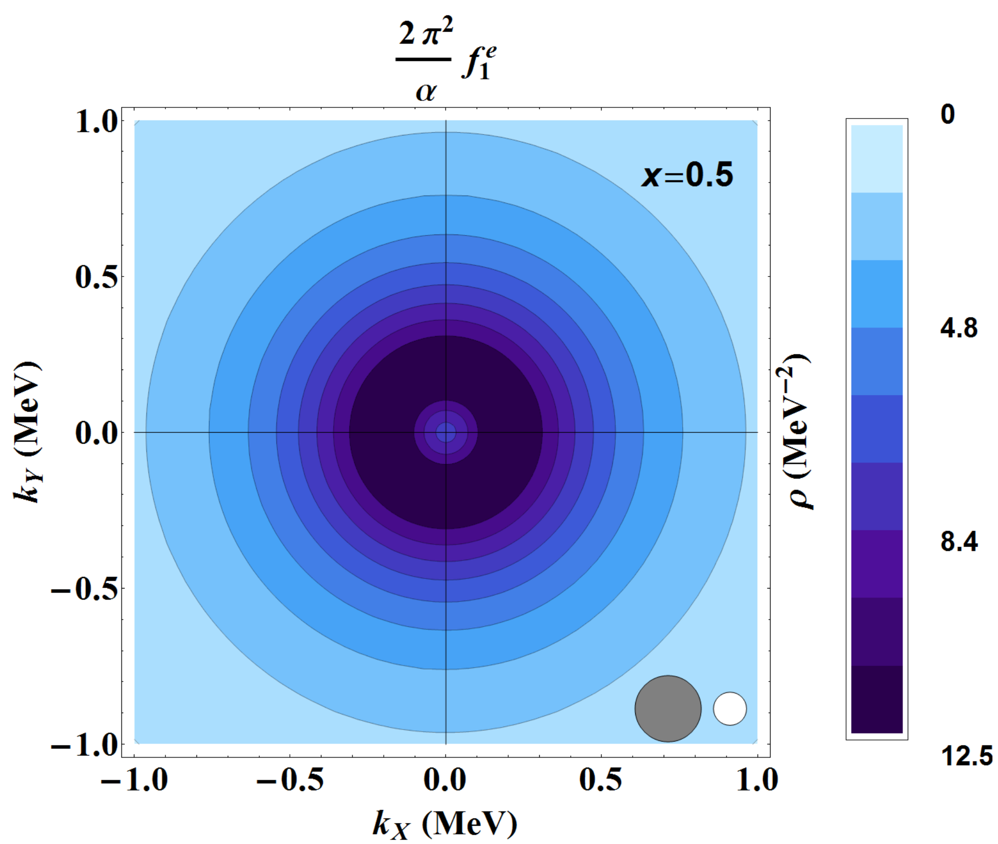
electron “worm-gear” TMD

TMDs in QED

dressed electron

Bacchetta, Mantovani, Pasquini, arXiv:1508.06964





electron density

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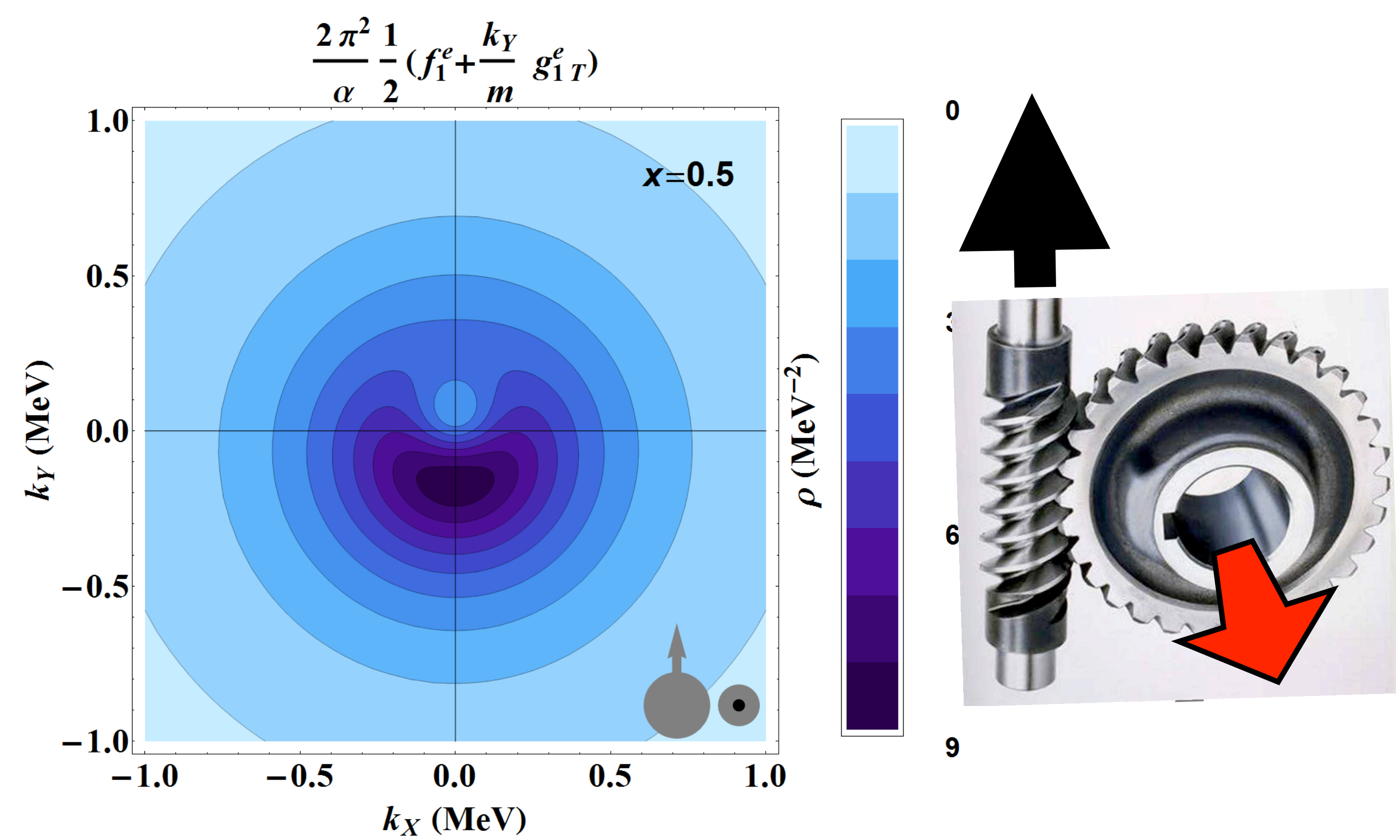
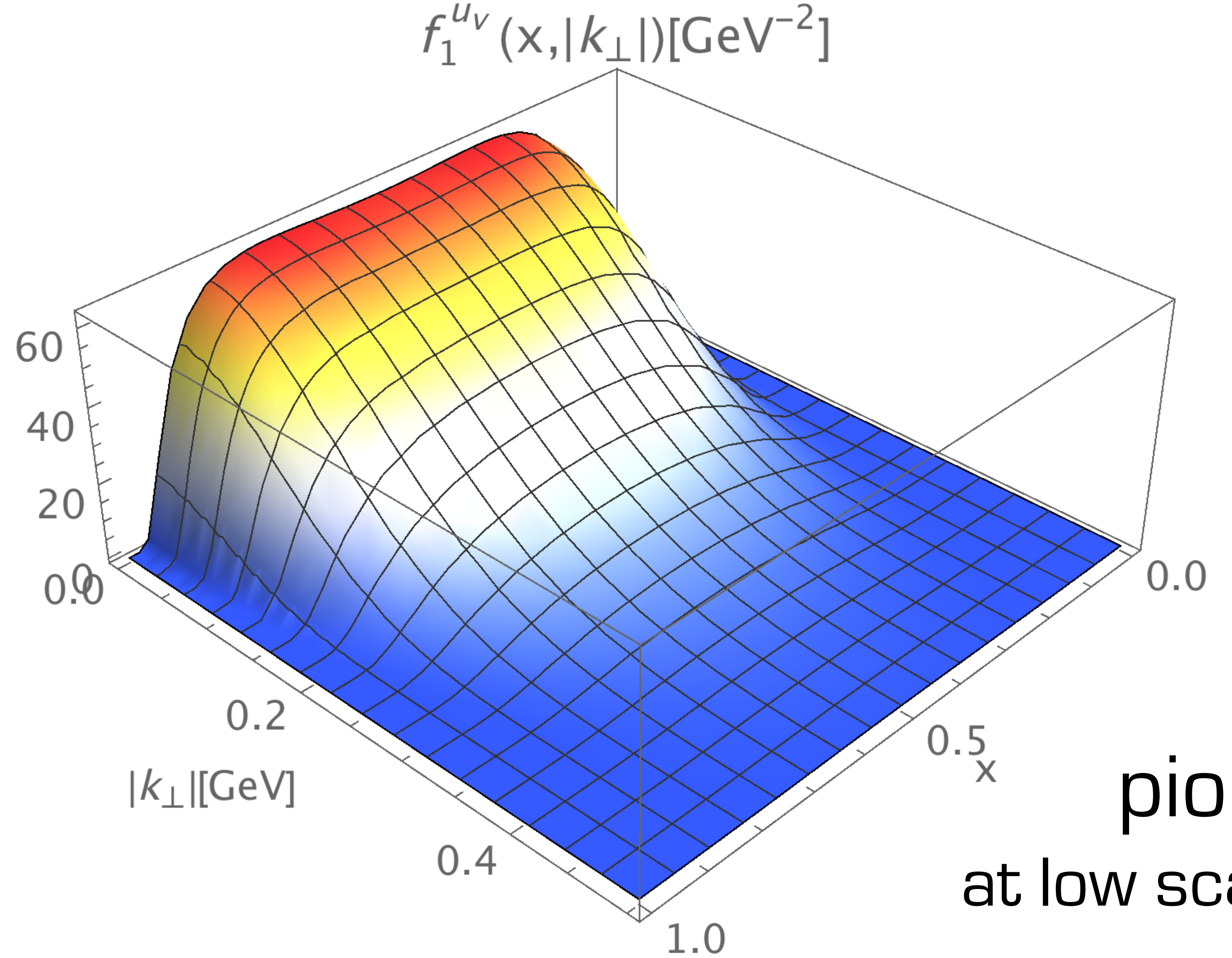


electron “worm-gear” TMD

TMD in AdS/QCD

talk by S. Cotogno at LC2015

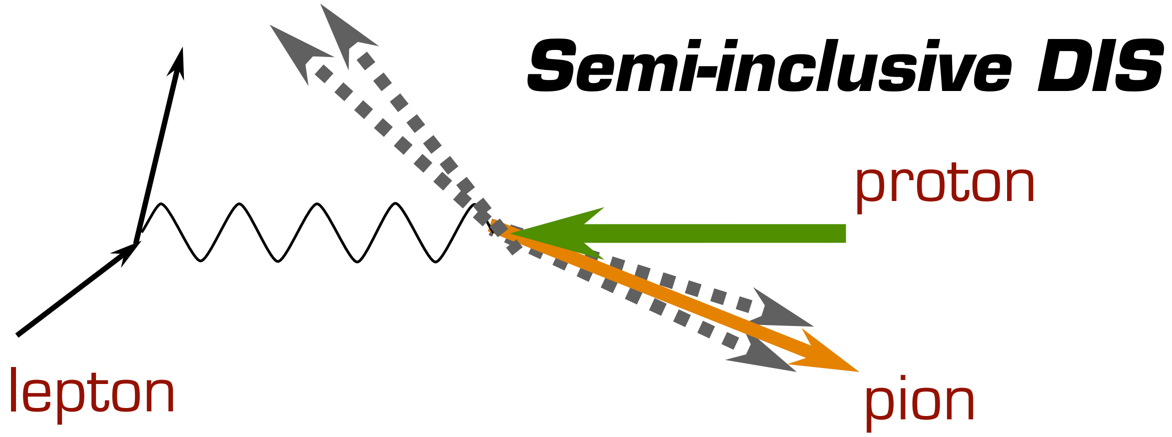


pion TMD

at low scale (0.5 GeV^2)

see also talks by S. Brodsky, A. Vega and V. Lyubovistky

Where can we access TMDs?



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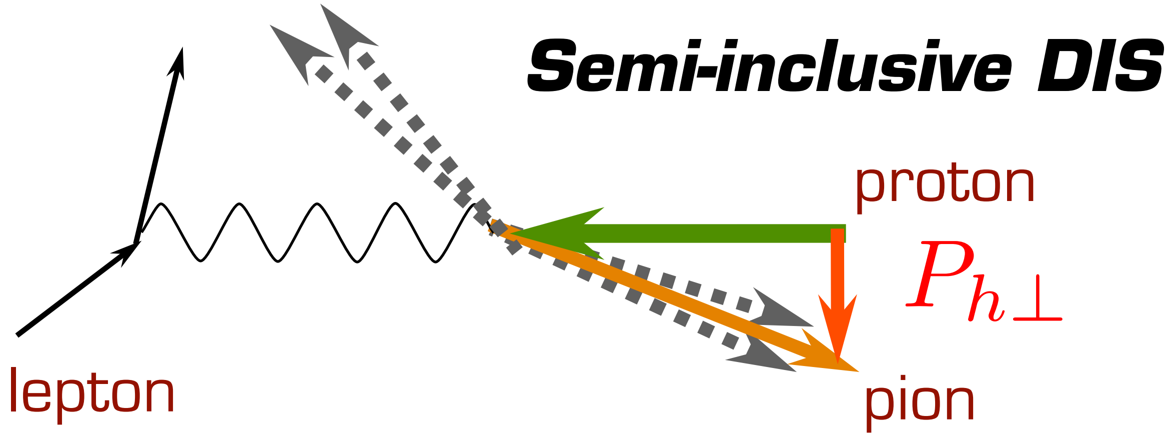
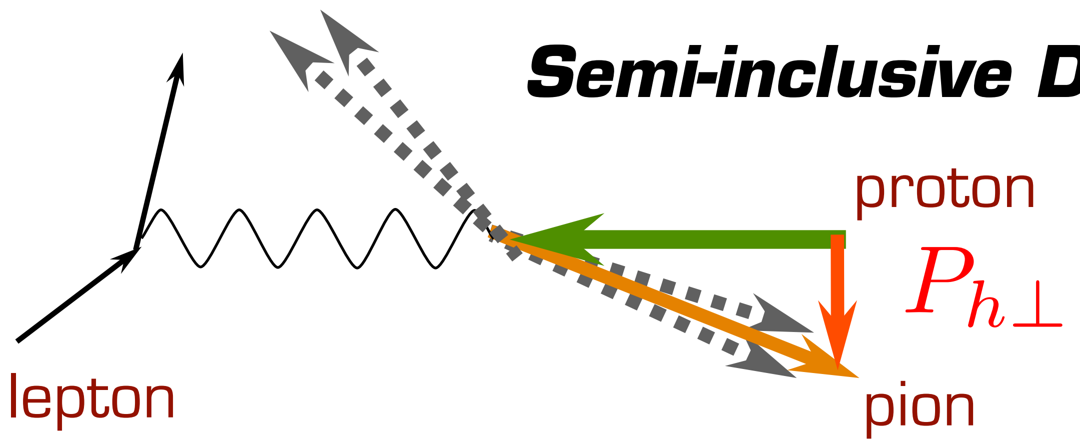
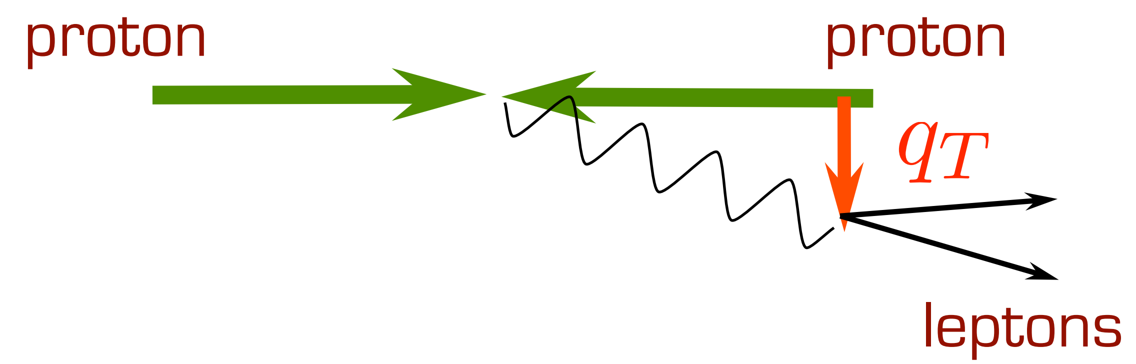


Where can we access TMDs?

Semi-inclusive DIS



Drell-Yan



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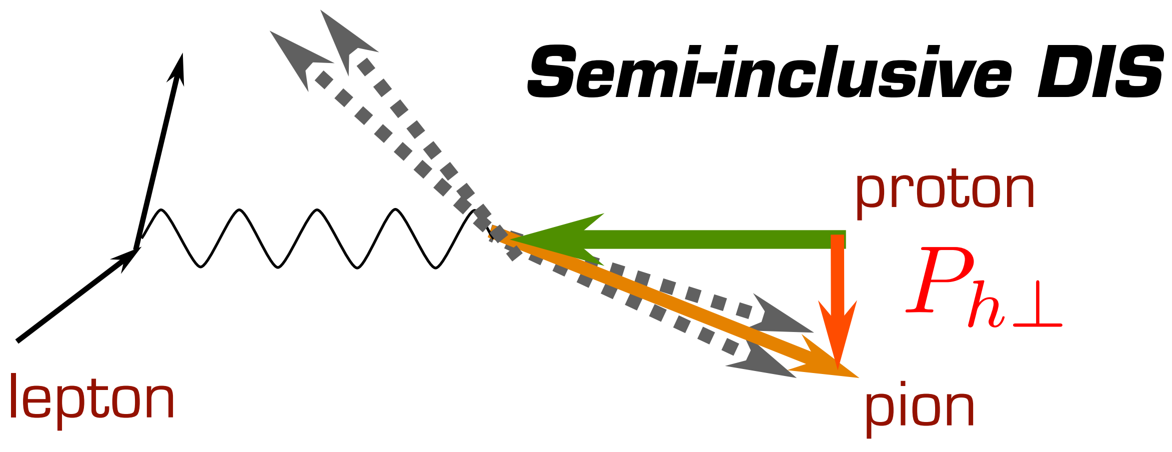

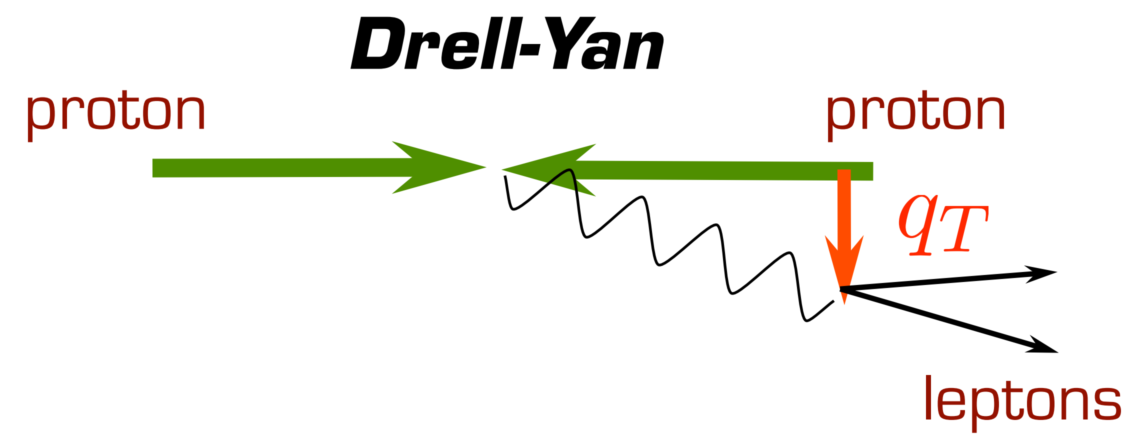

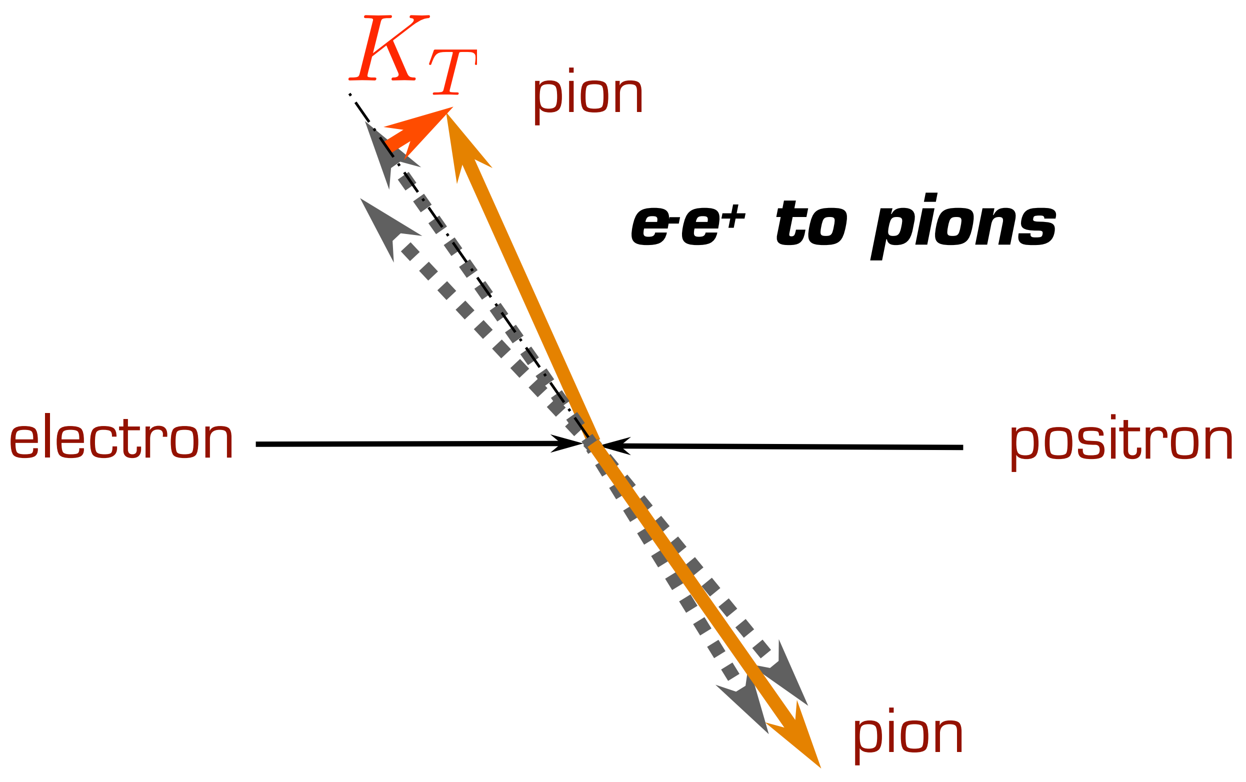

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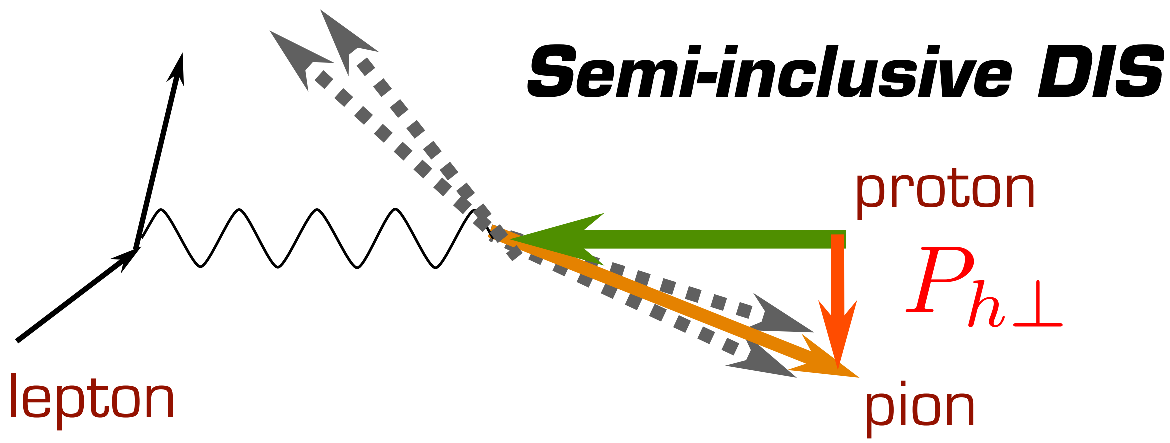
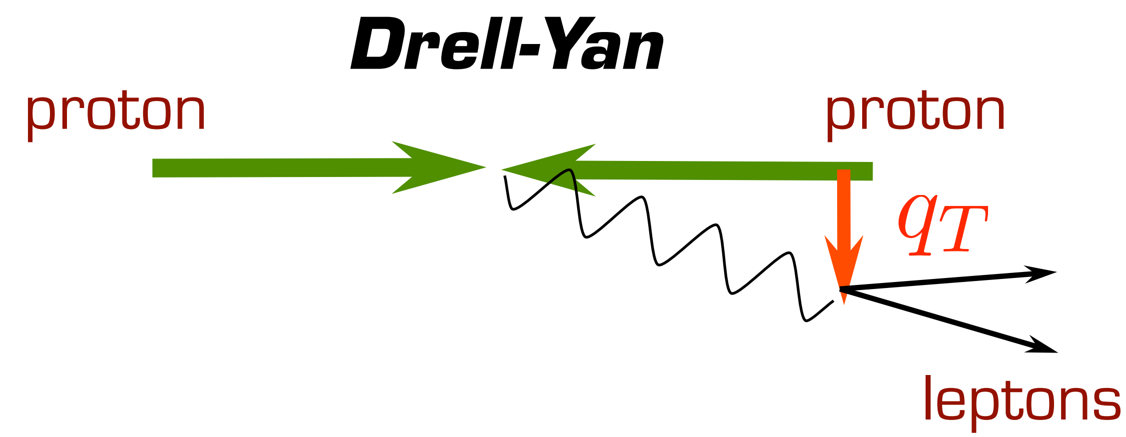
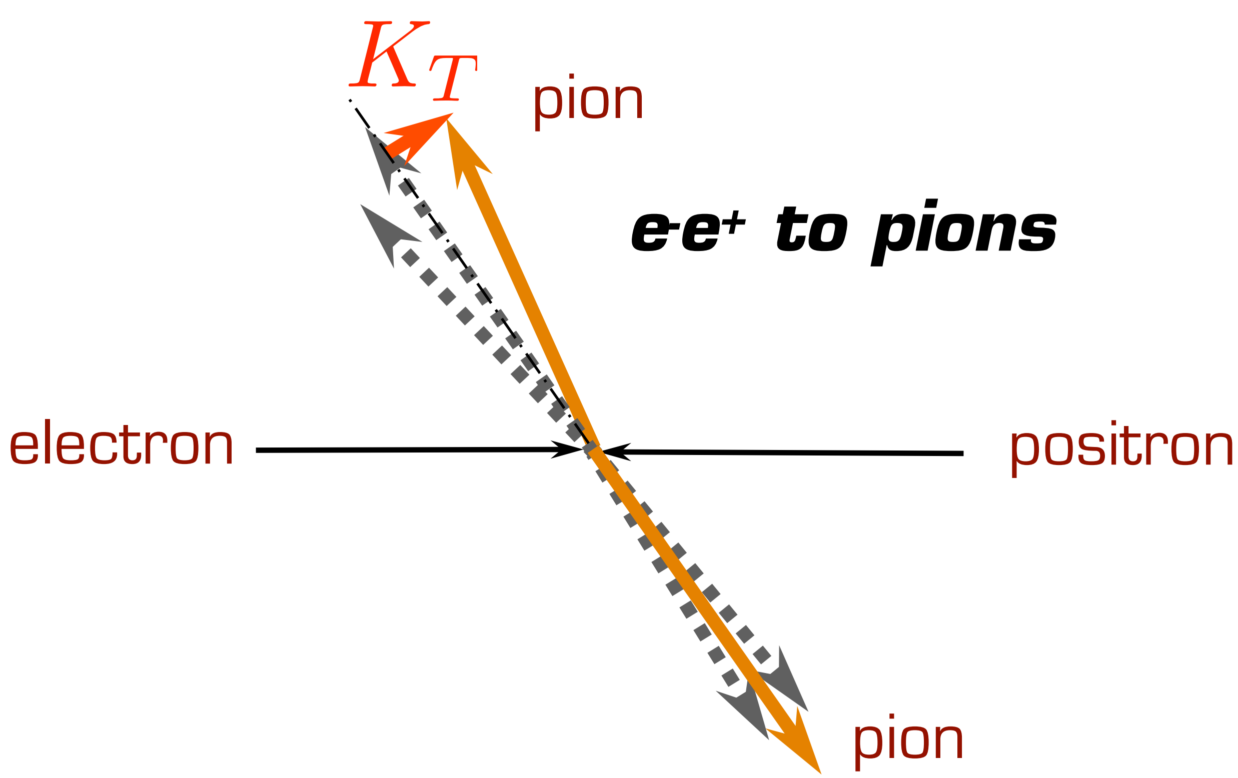
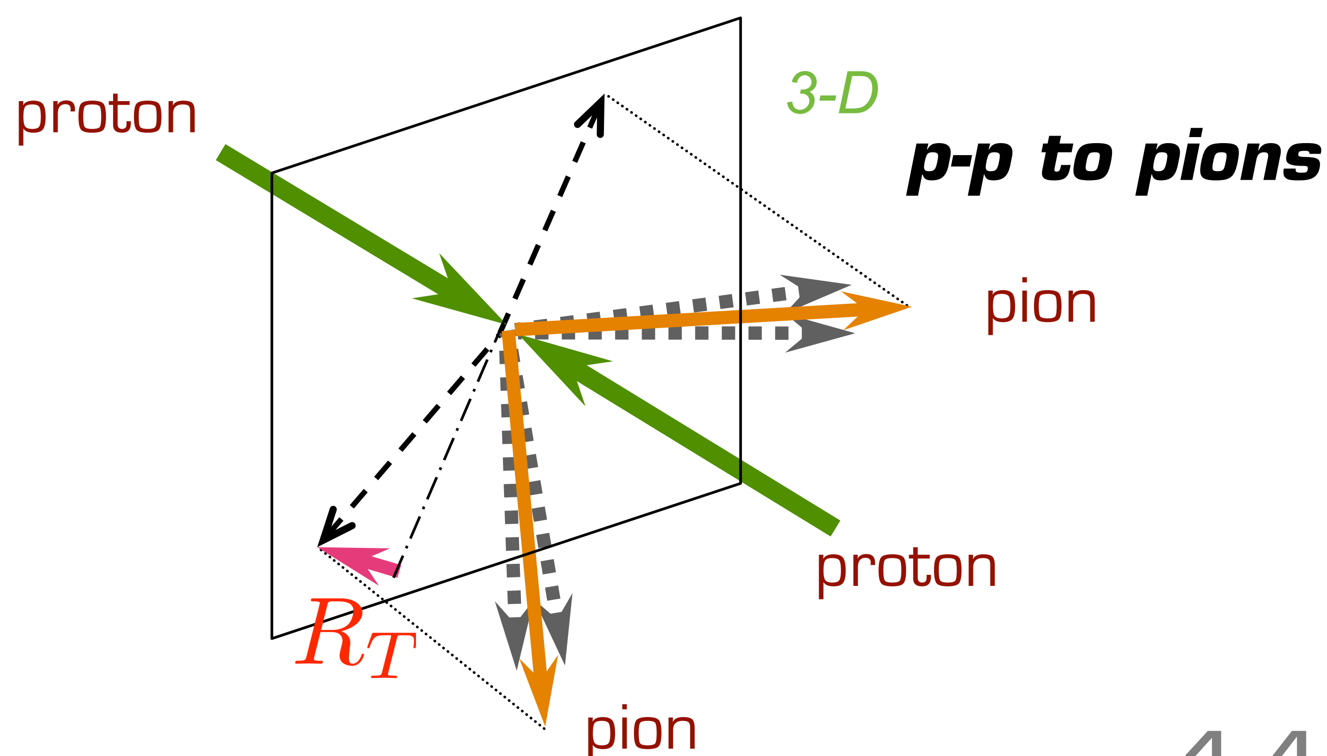








Where can we access TMDs?

Semi-inclusive DIS — hermes, Jefferson Lab, COMPASS

see talk by S. Platchkov

Drell-Yan — Fermilab

p-p to pions — BROOKHAVEN NATIONAL LABORATORY, LHC

e-e+ to pions — BELLE, BABAR, BESIII

Where can we access TMDs?

Semi-inclusive DIS

see talk by S. Platchkov

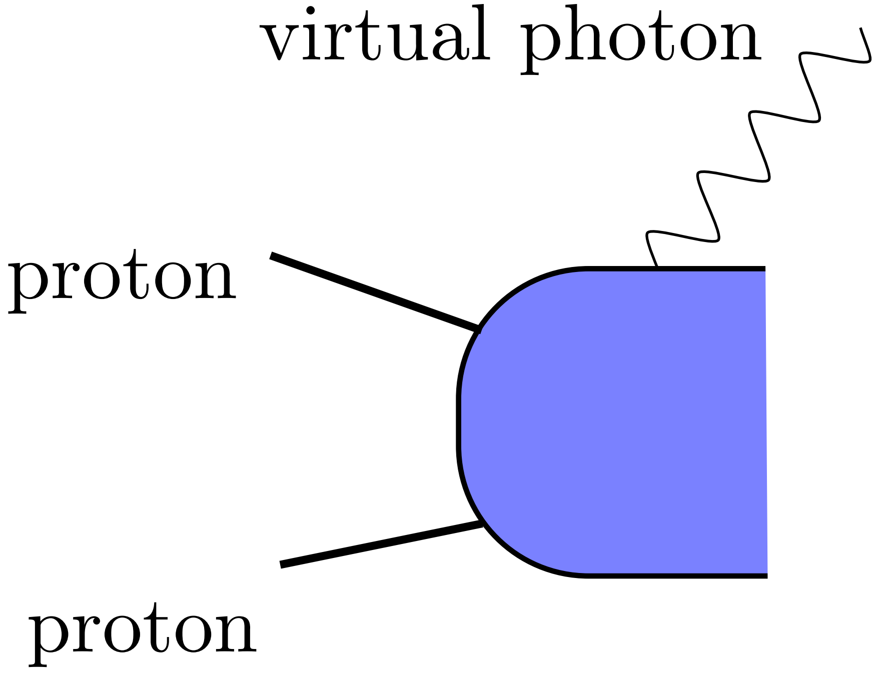
Drell-Yan

p-p to pions

e^-e^+ to pions

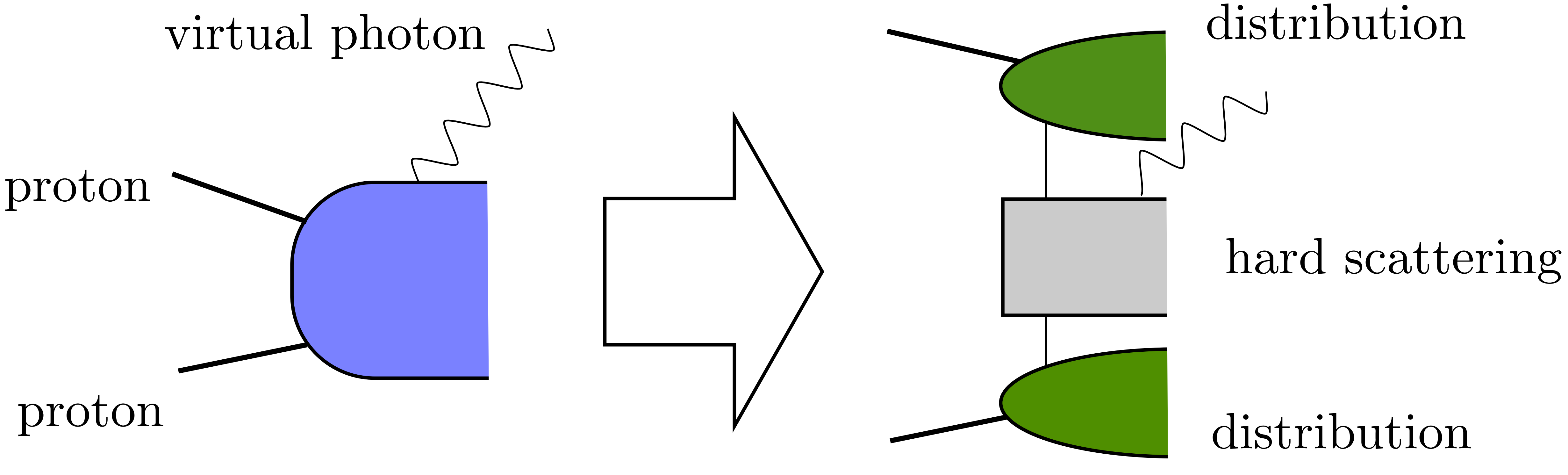
Factorization

Drell-Yan



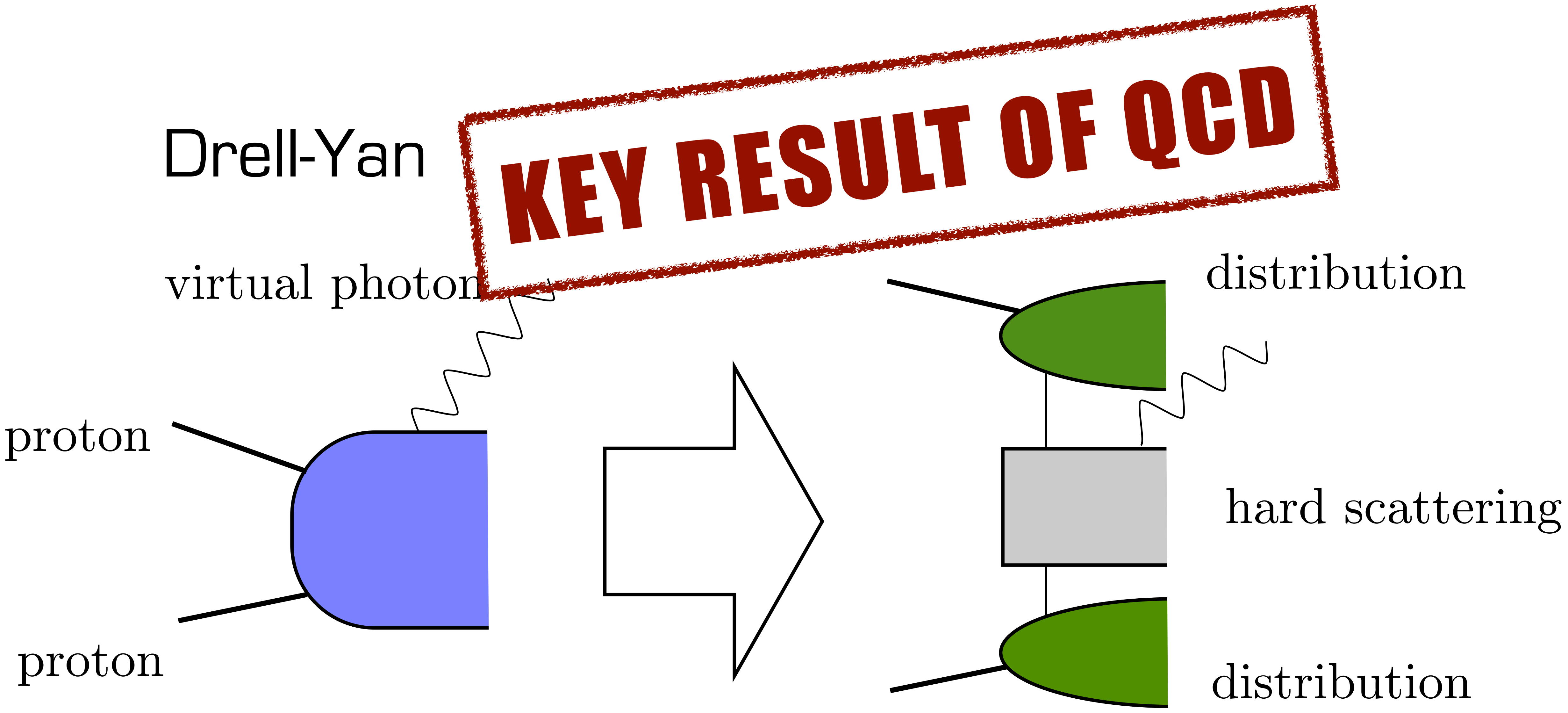
Factorization

Drell-Yan



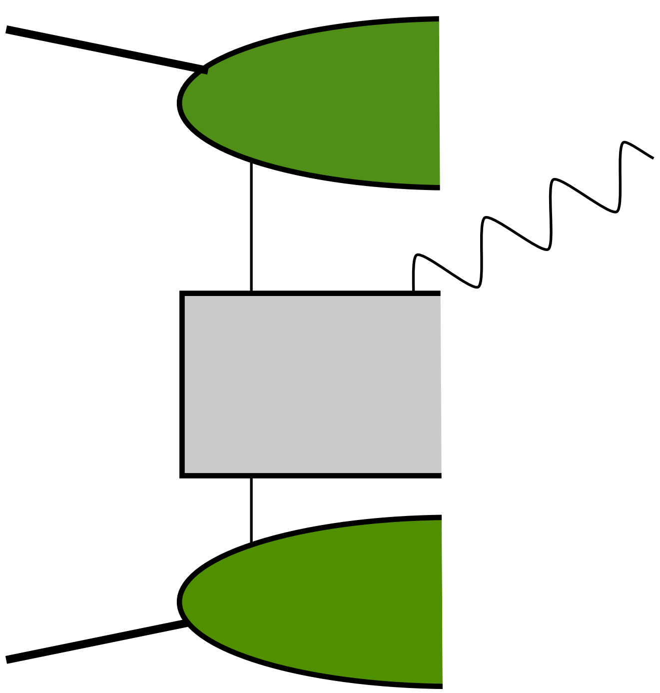
Factorization

Drell-Yan



Universality

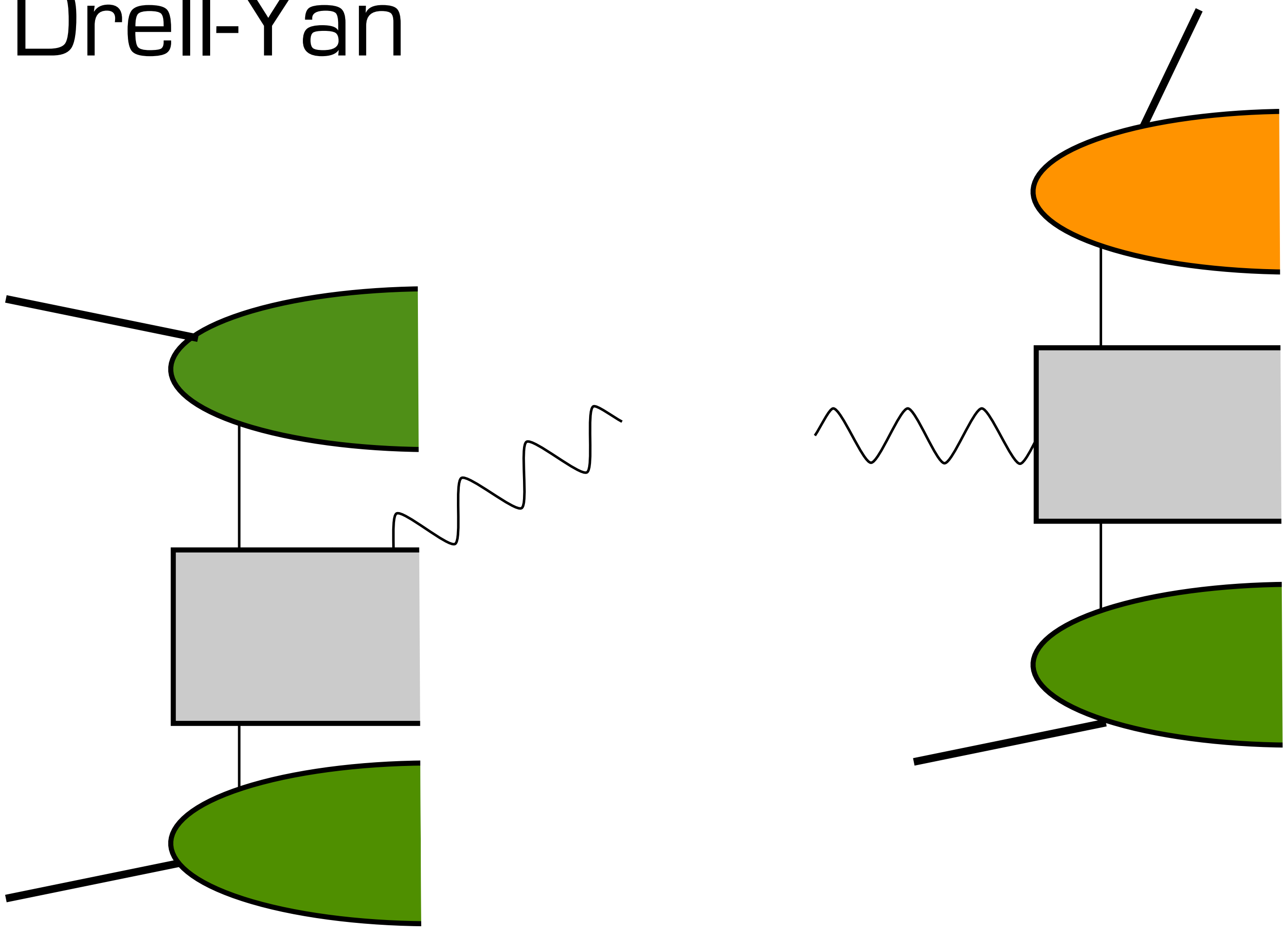
Drell-Yan



Universality

SIDIS

Drell-Yan



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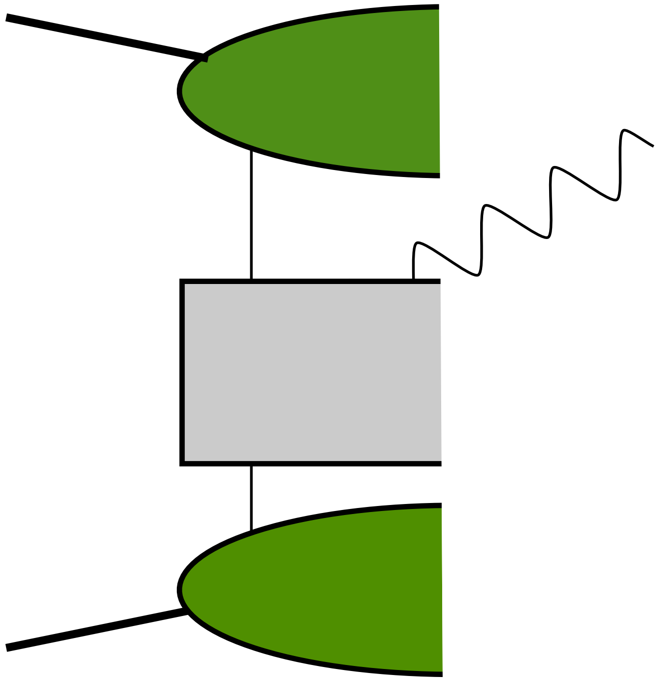

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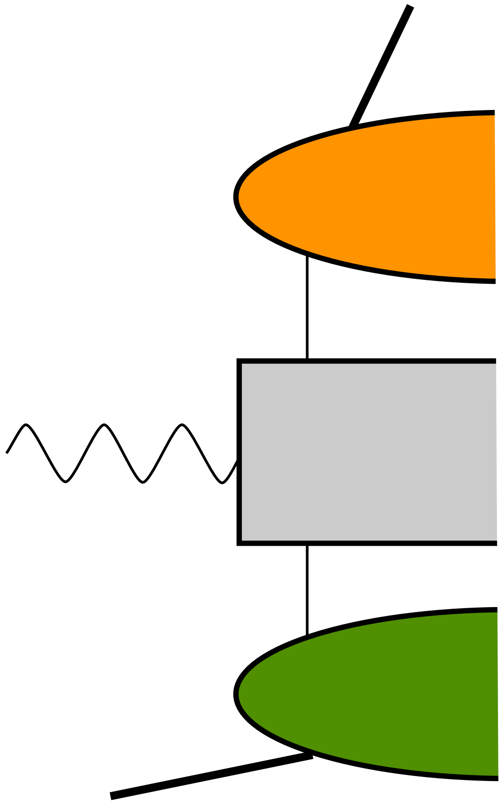
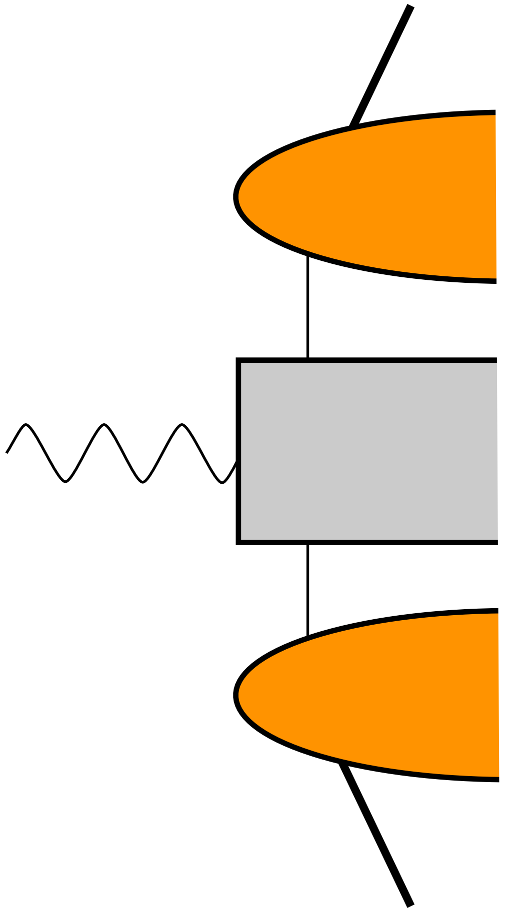


e^-e^+ to pions



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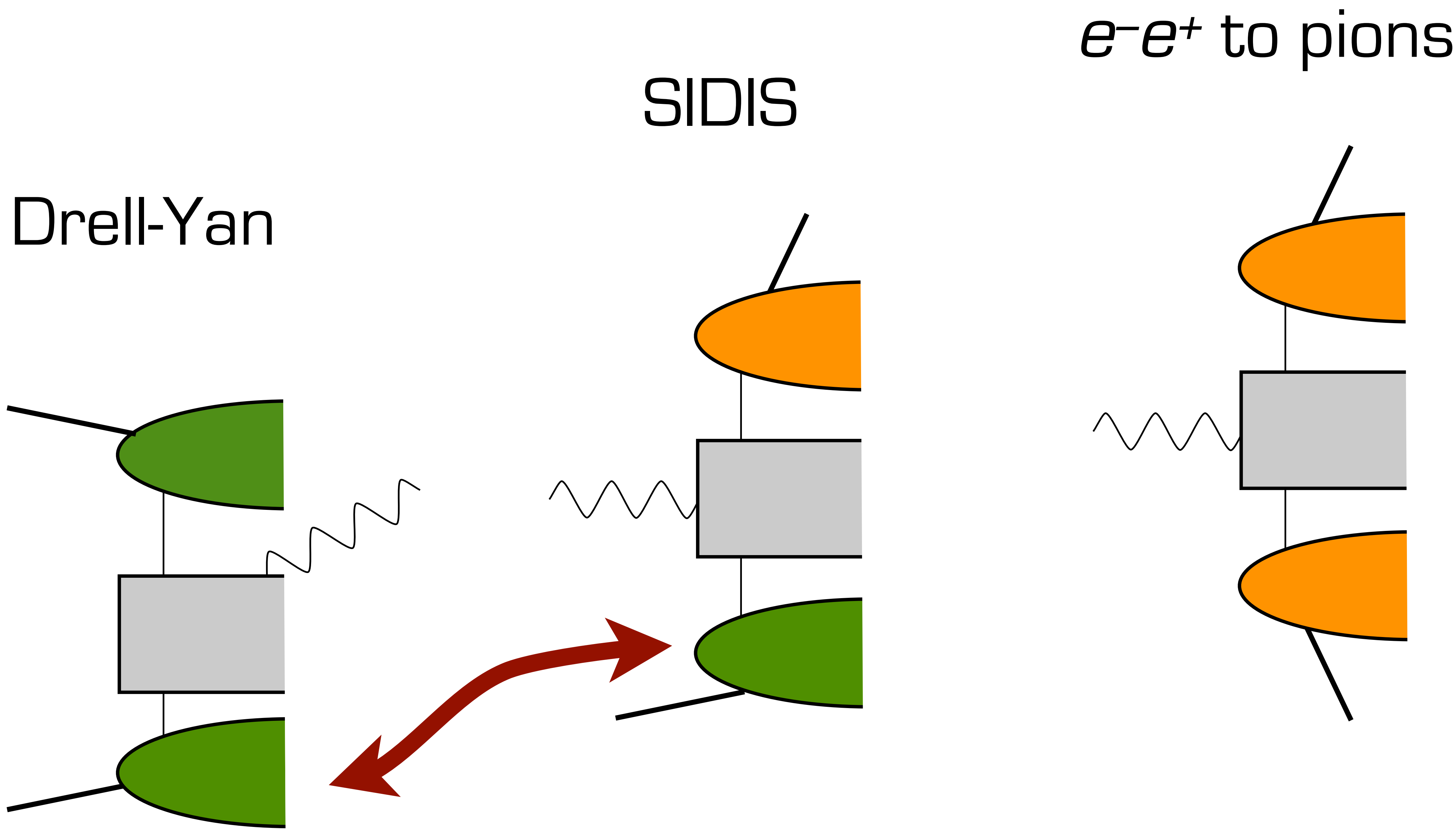

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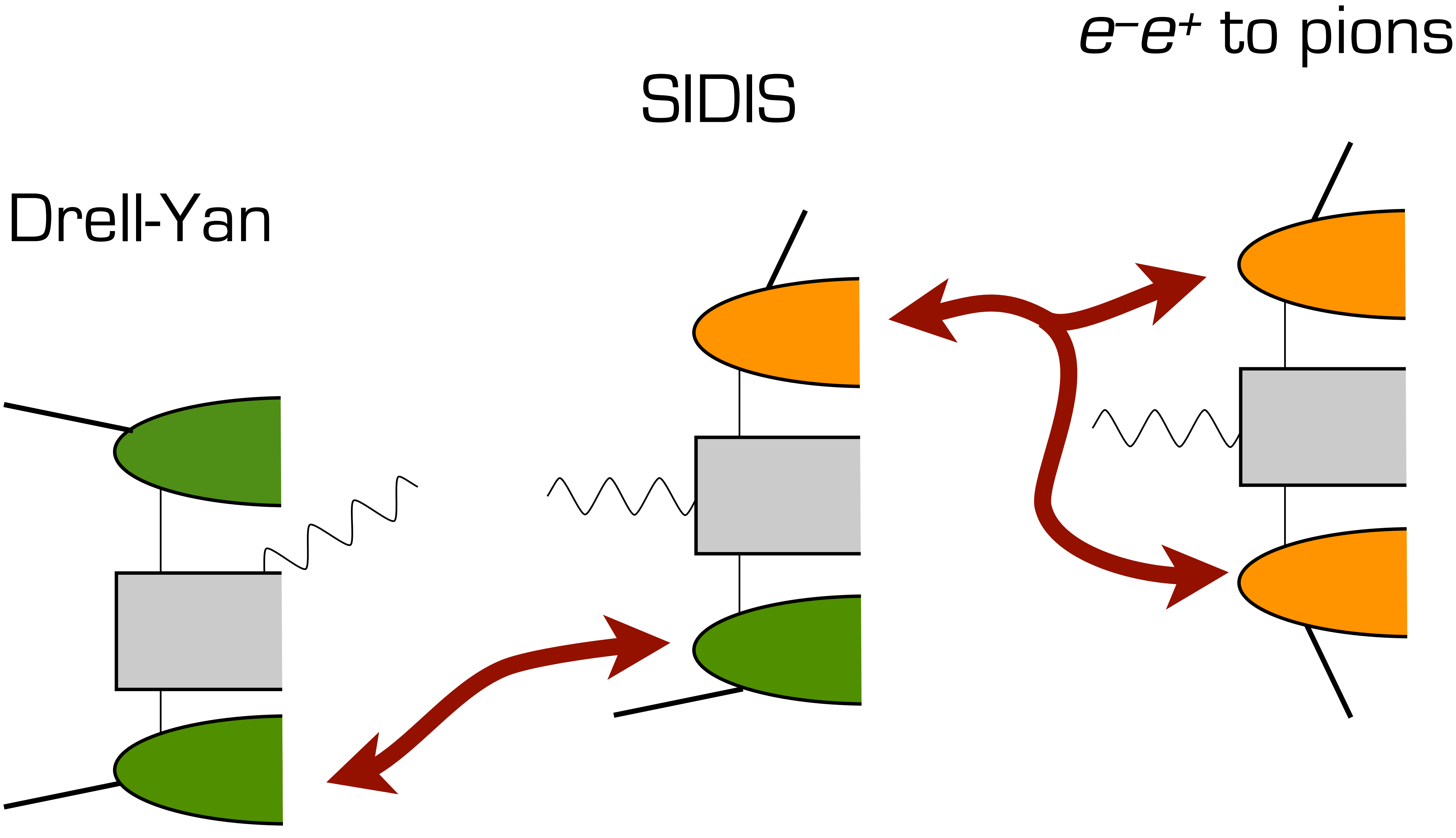

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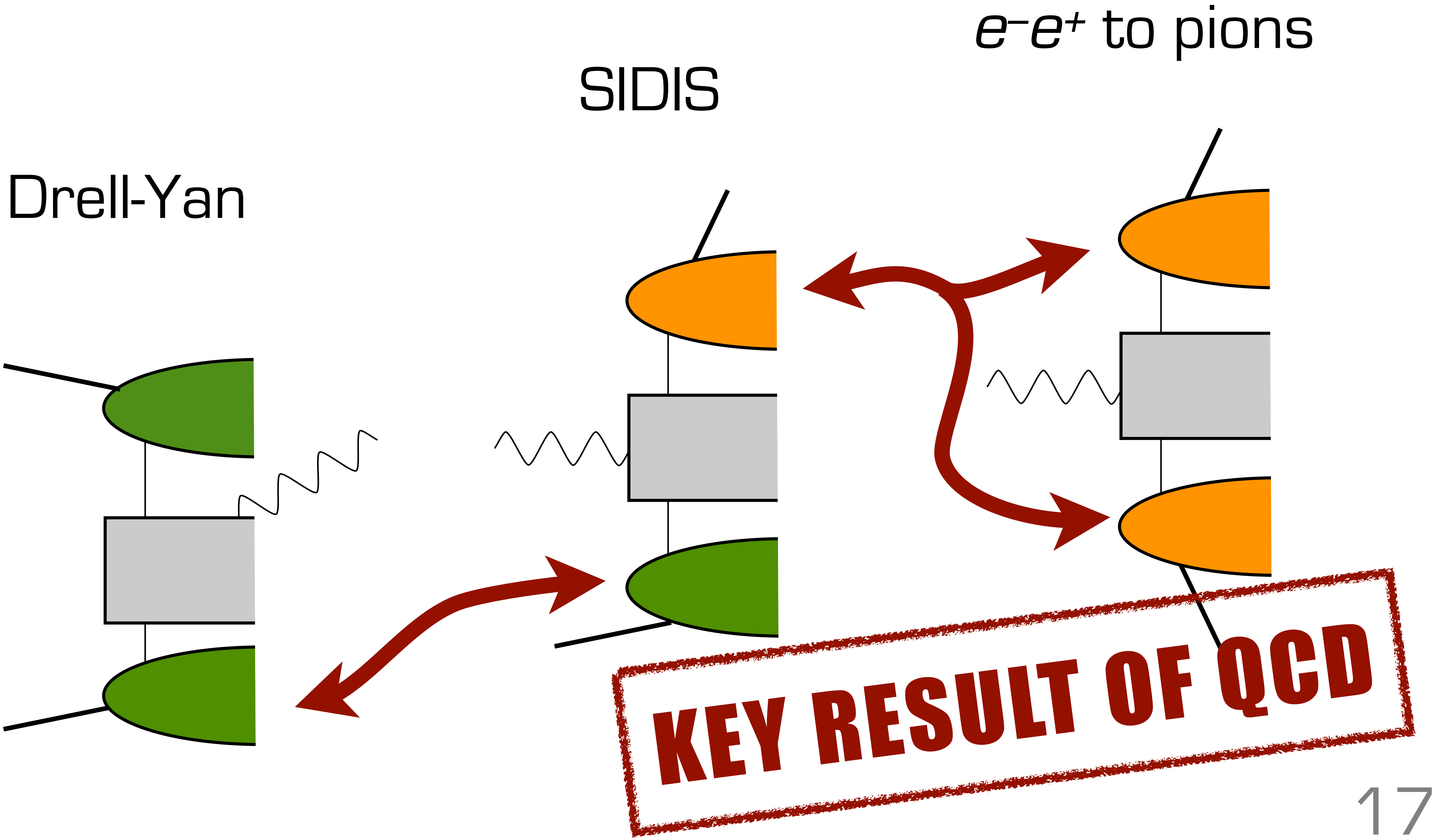
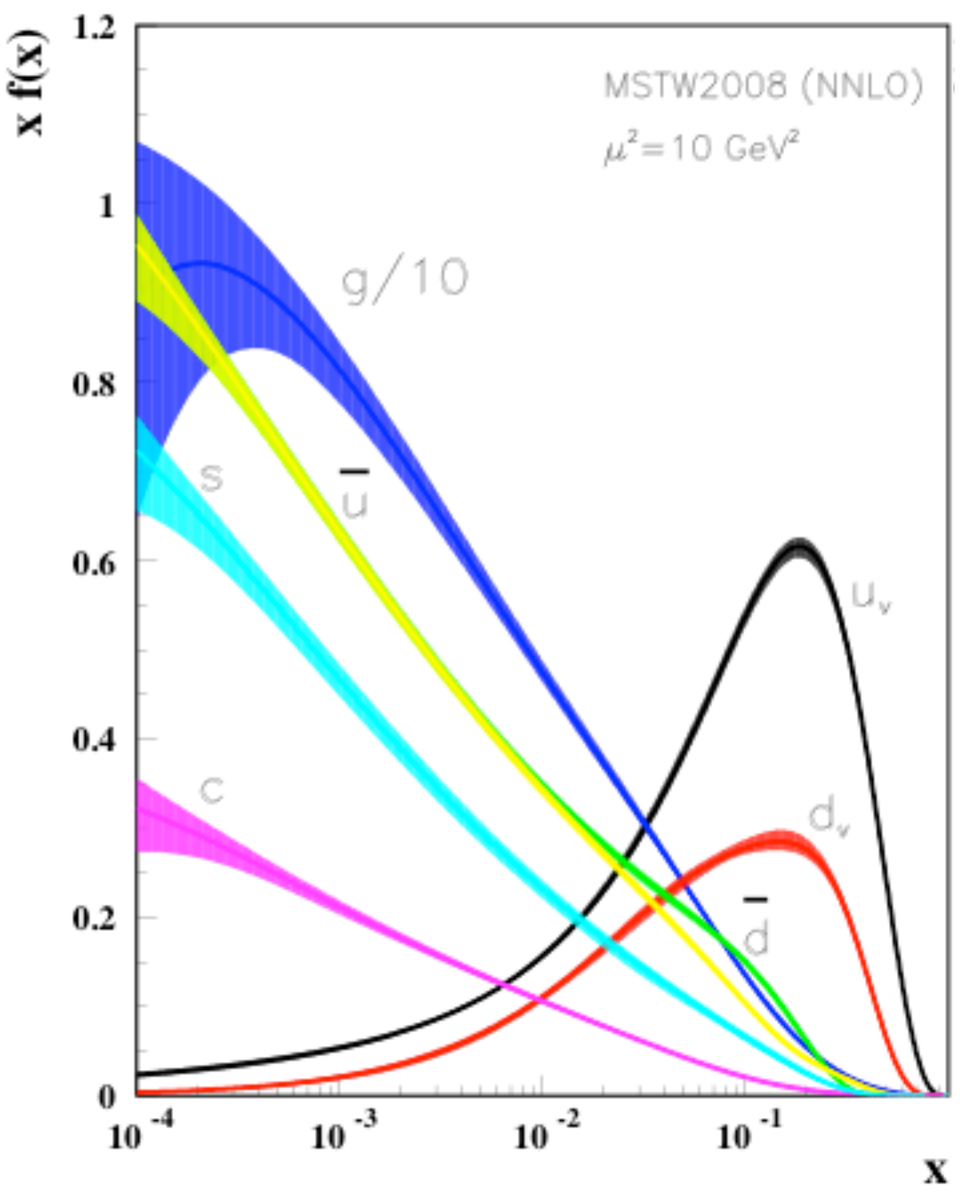
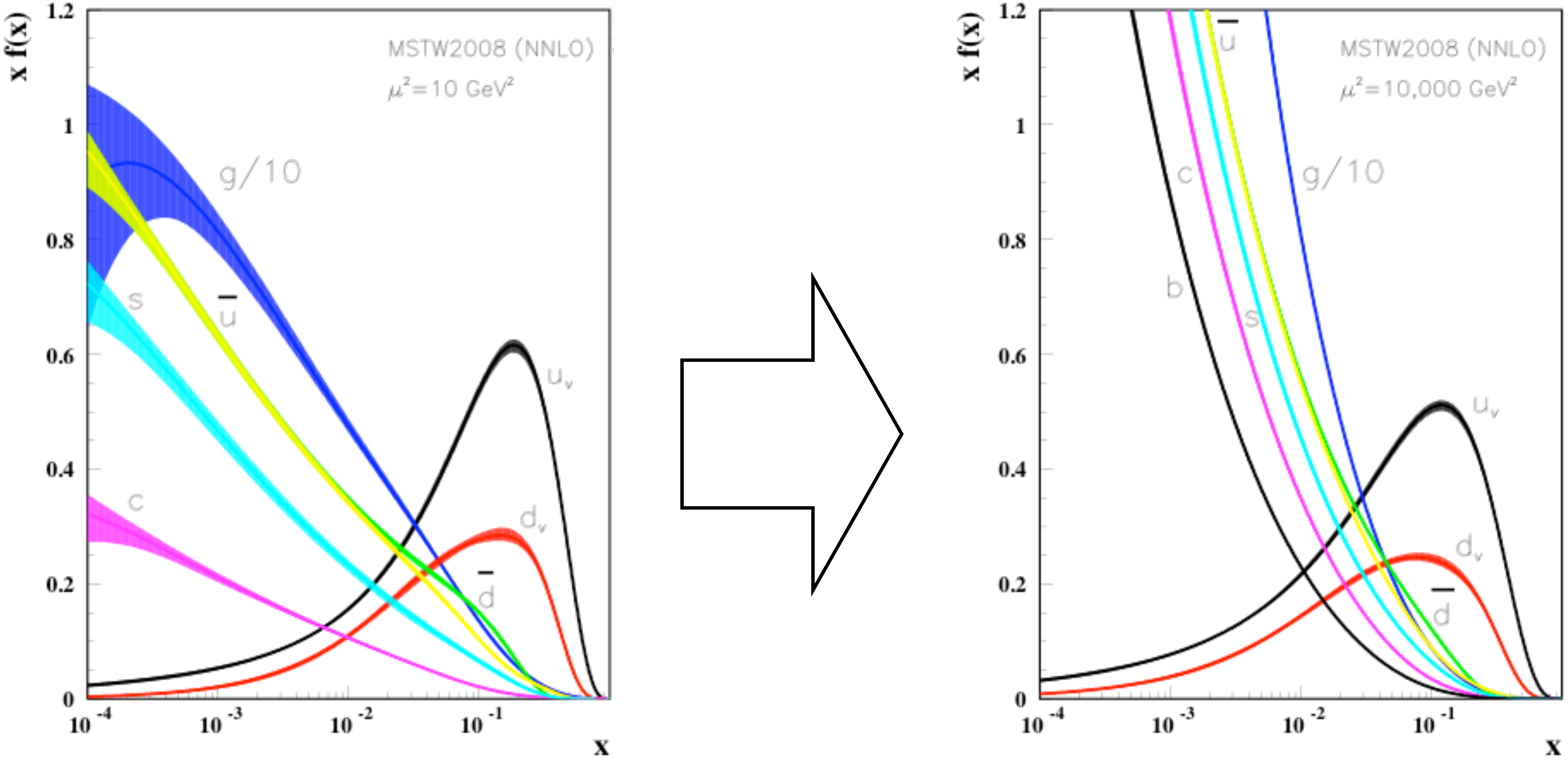


Evolution



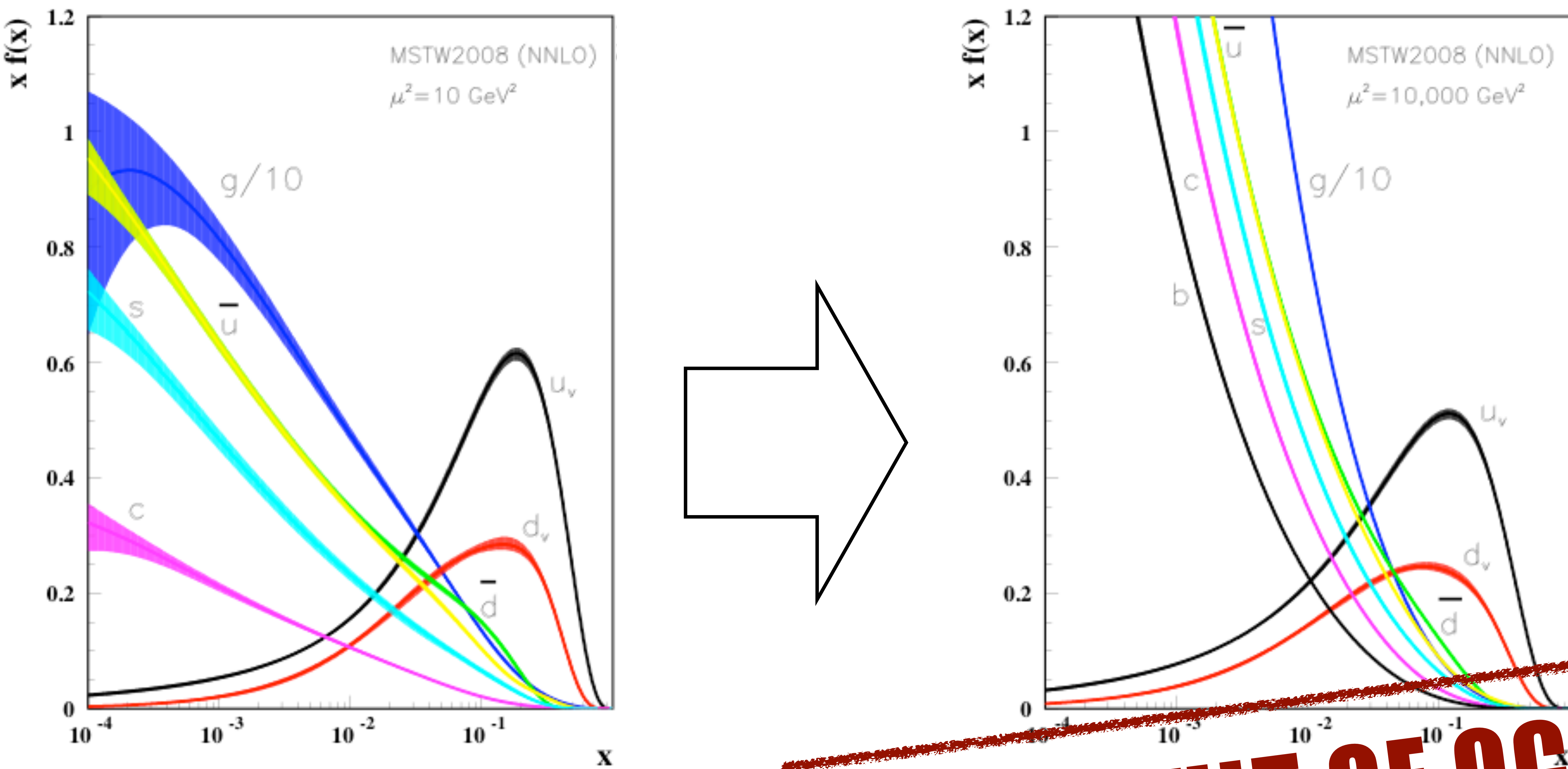
x f(x)
1.2
1
0.8
0.6
0.4
0.2
0
MSTW2008 (NNLO)
μ^2=10 GeV^2
g/10
s
$\bar{u}$
c
u_v
d_v
$\bar{d}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

Evolution



MSTW2008 (NNLO)
μ^2=10 GeV^2
g/10
s
$\bar{u}$
c
u_v
d_v
$\bar{d}$
x f(x)
x
MSTW2008 (NNLO)
μ^2=10,000 GeV^2
g/10
c
b
s
$\bar{u}$
u_v
d_v
$\bar{d}$
x f(x)
x

Evolution



KEY RESULT OF QCD

It has been necessary to review

all of these issues

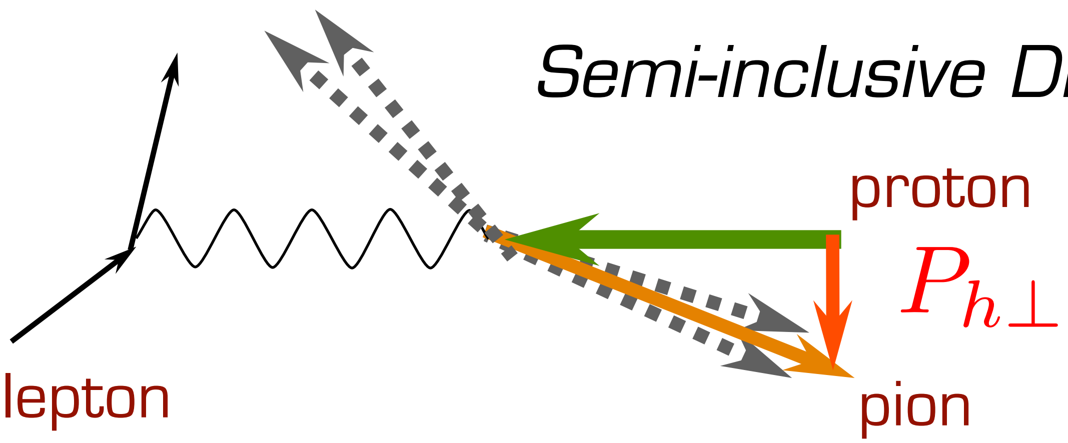
for TMDs

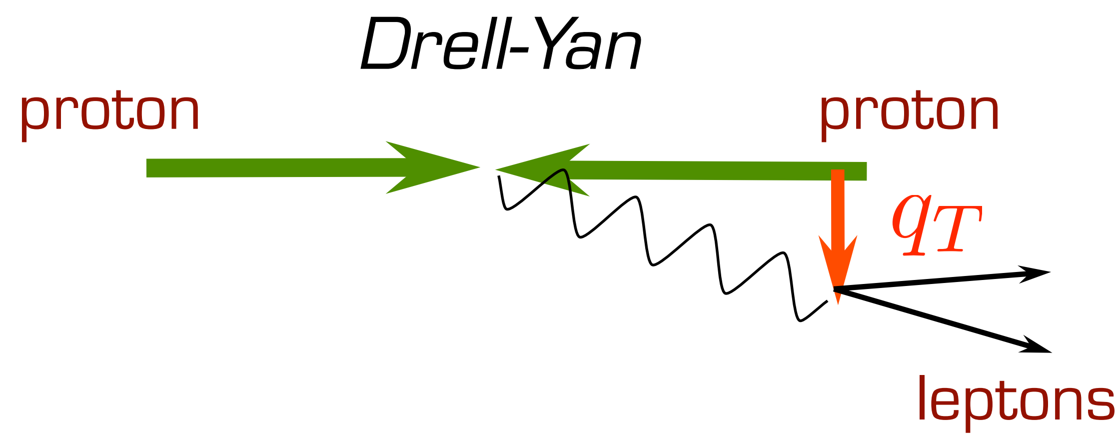
(and the process is still ongoing)

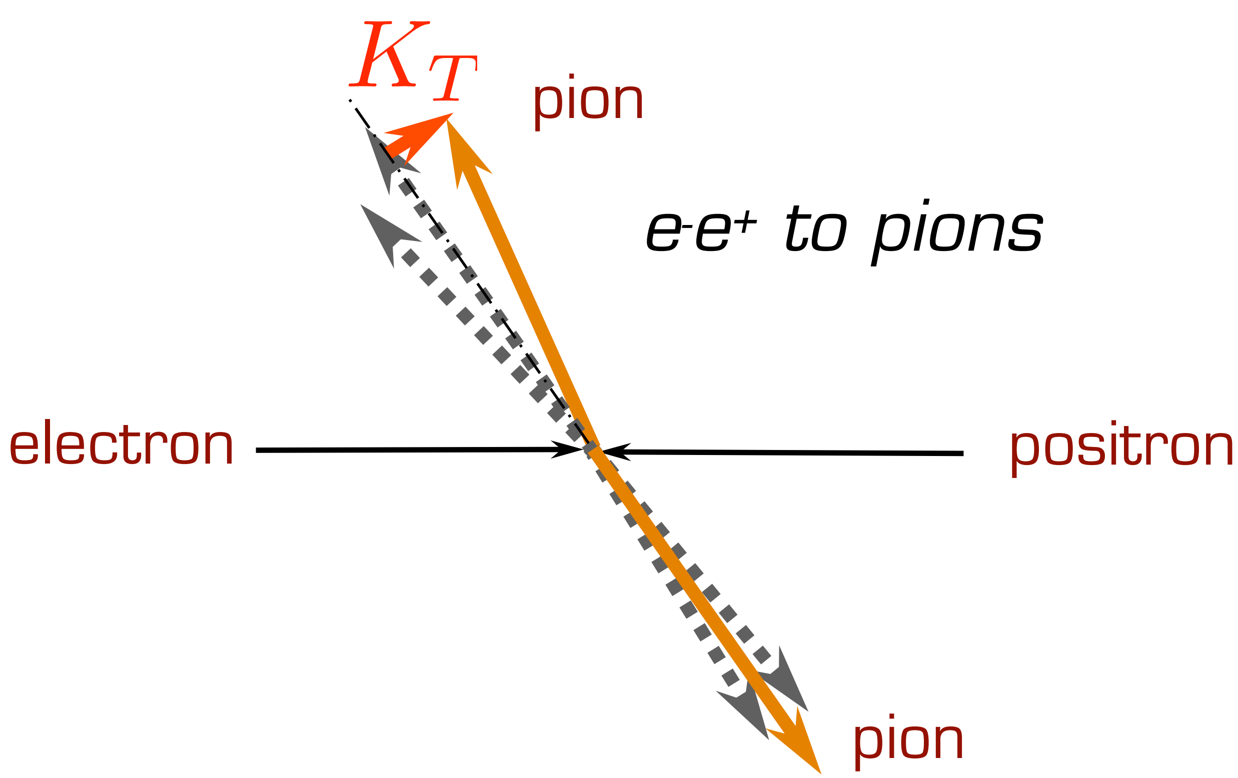
Some references:
Rogers arXiv:1509.04766 and references therein
Ji, Ma, Yuan
Collins, "Foundations of Perturbative QCD" (11)
Echevarria, Idilbi, Scimemi
Boer, Mulders, Buffing et al.

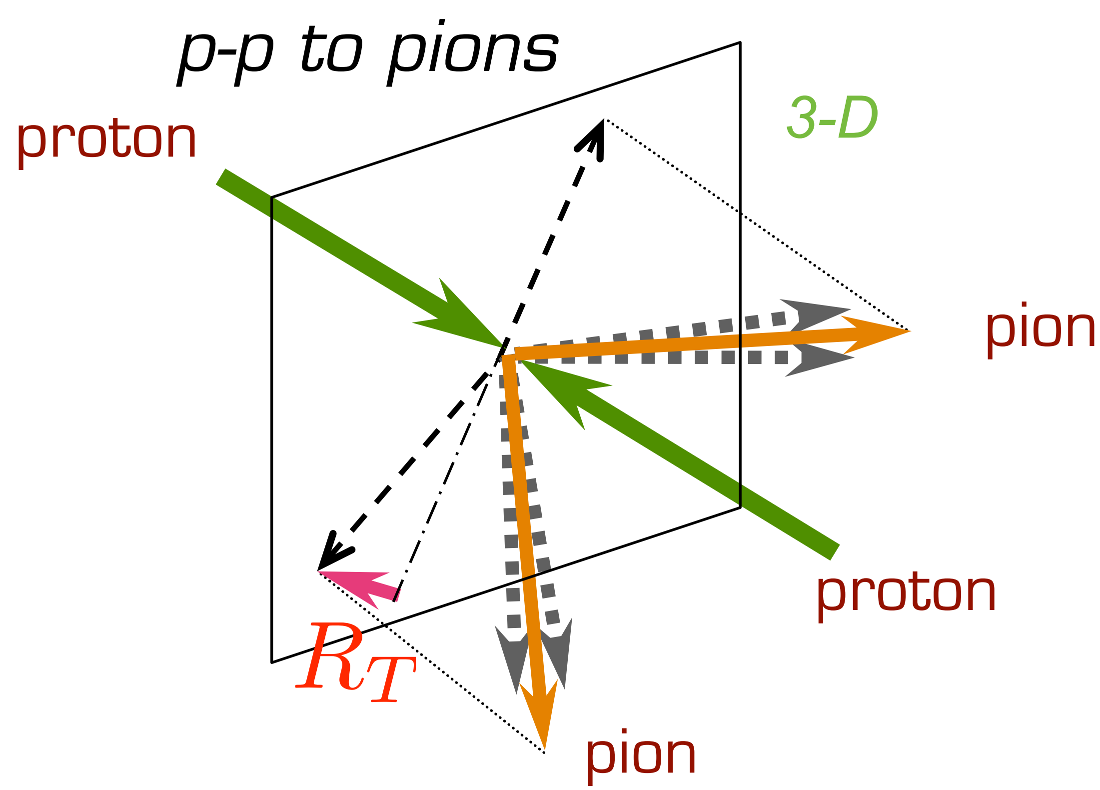
Connection with TMDs at low x (see I. Balitsky's talk) still to be understood

TMD factorization

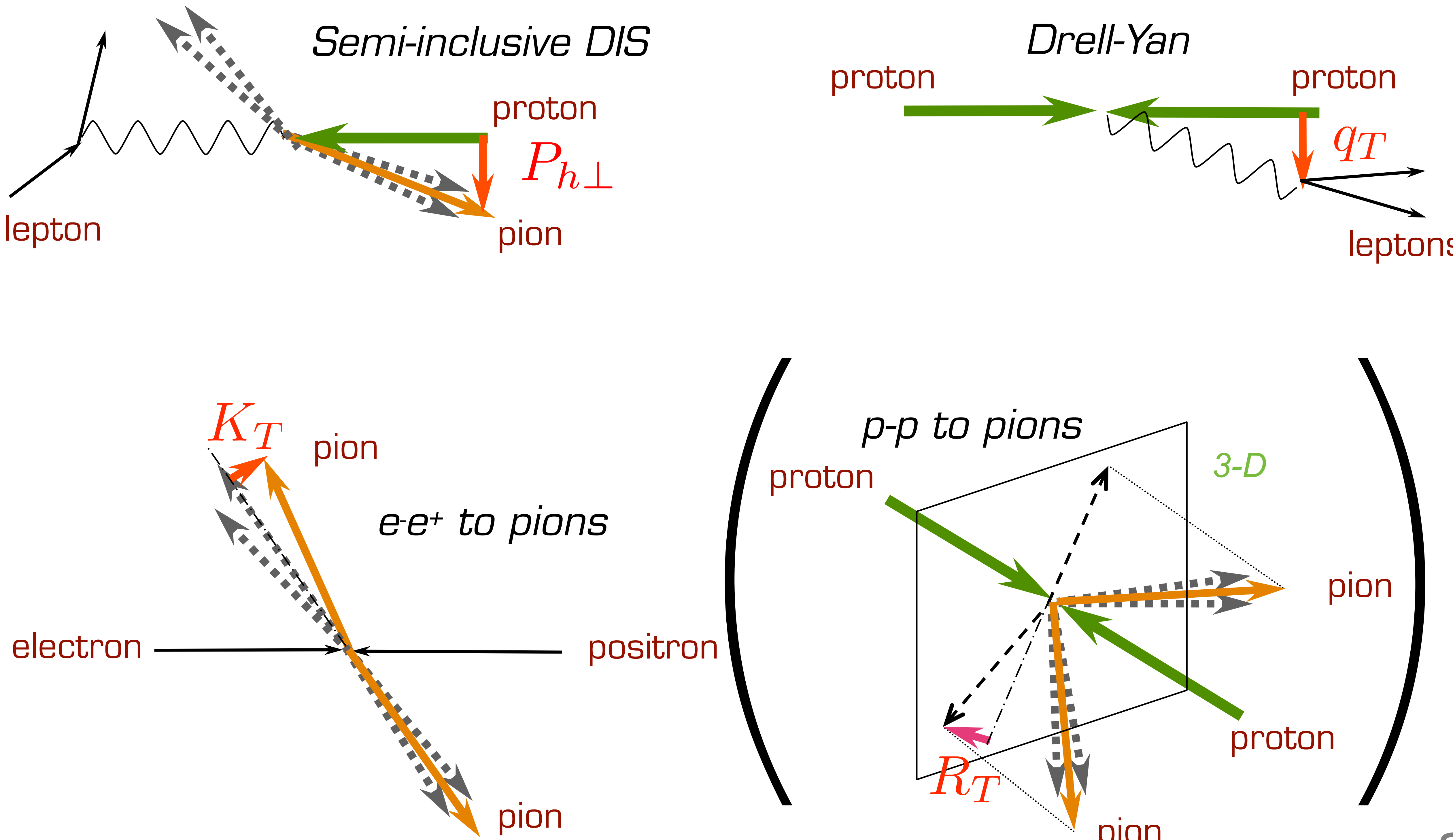






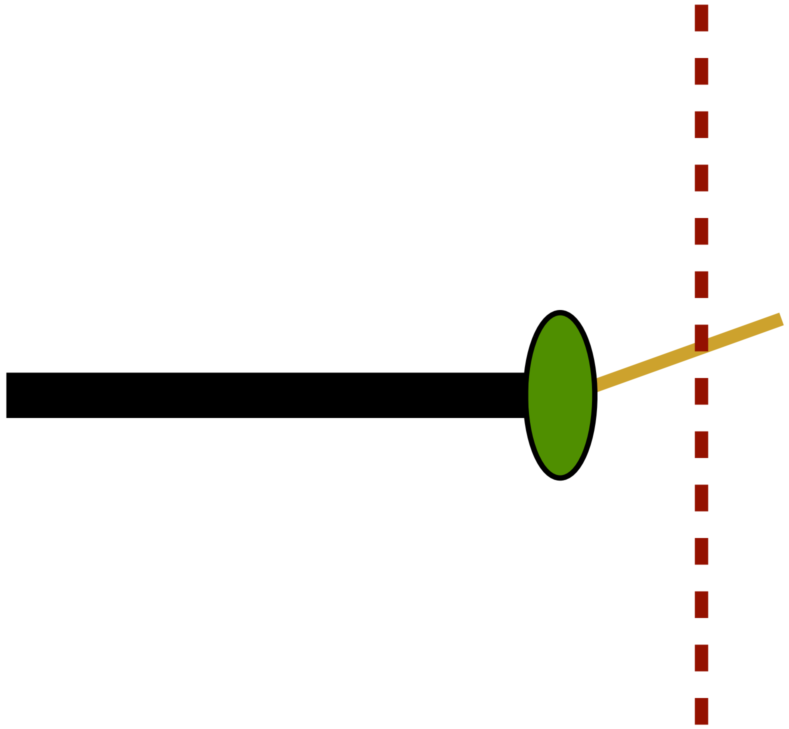


TMD factorization



TMD evolution

"intrinsic" transverse momentum

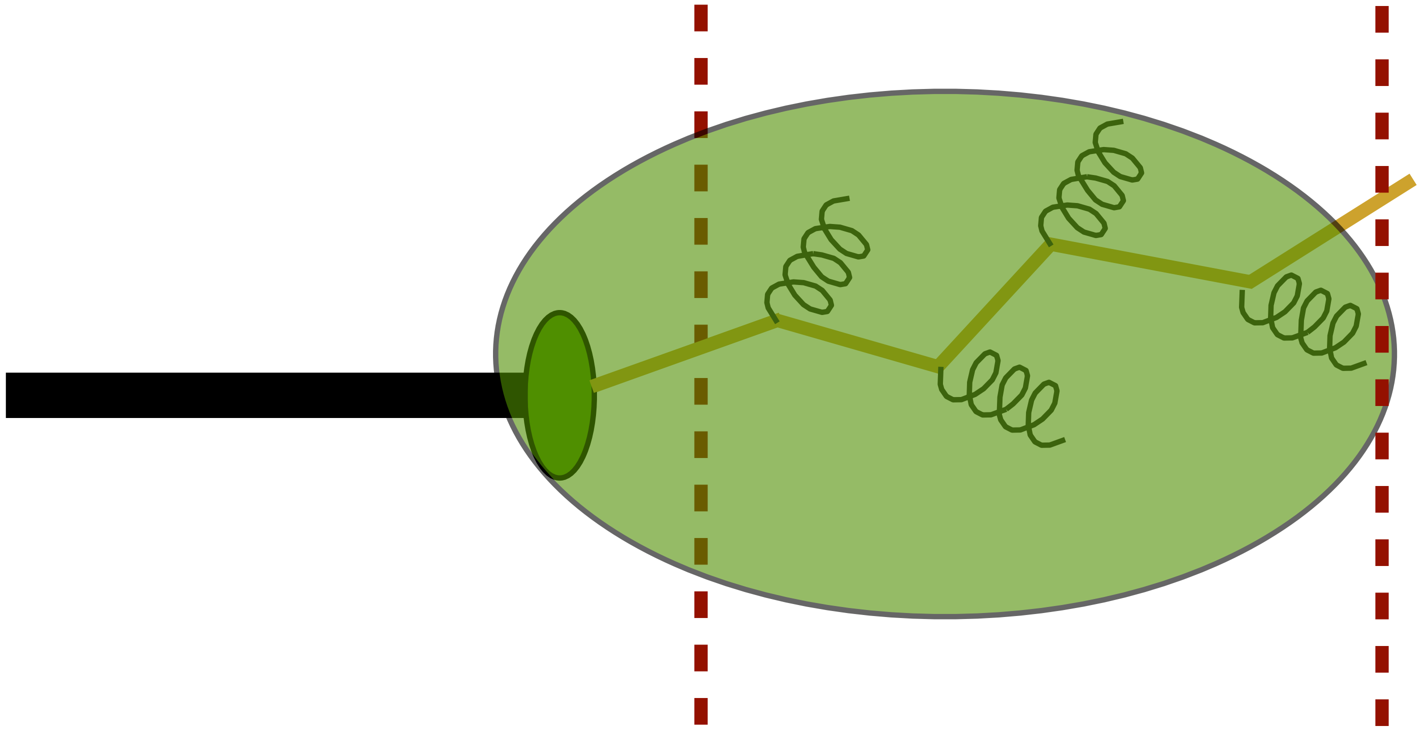


$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

TMD evolution

"intrinsic" transverse momentum

soft and collinear gluon radiation



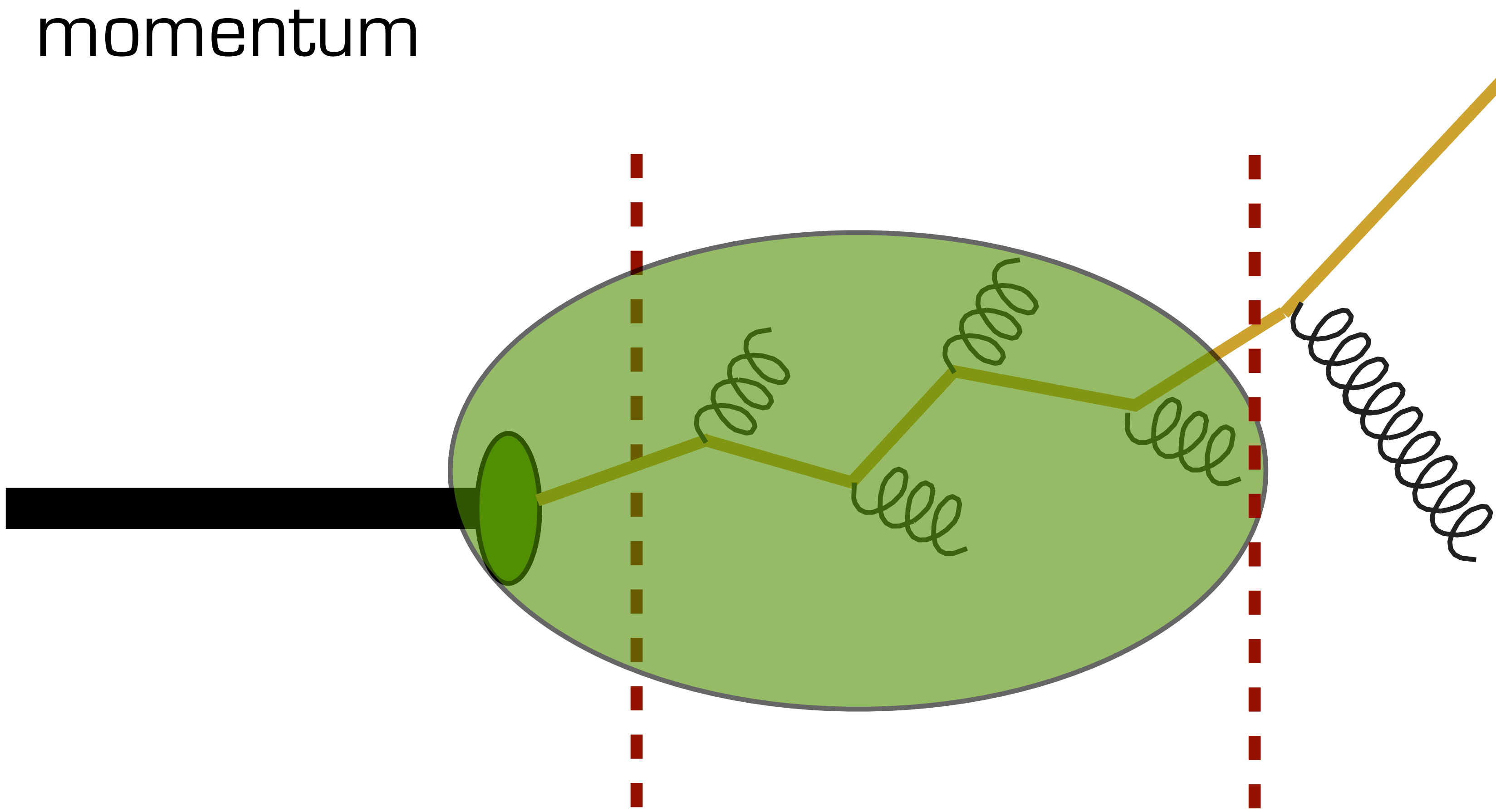
$|k_\perp| \sim \Lambda_{\rm QCD}$ $\qquad$ $|k_\perp| \ll Q$

TMD evolution

"intrinsic" transverse momentum

soft and collinear gluon radiation

hard gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

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$|k_\perp| \sim Q$

TMD evolution: Fourier transform

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-ib_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

Rogers, Aybat, PRD 83 (11)
Collins, "Foundations of Perturbative QCD" (11)

possible schemes, e.g.,
Collins, Soper, Sterman, NPB250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

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collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

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Choice

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Choice Choice Choice

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collinear PDF

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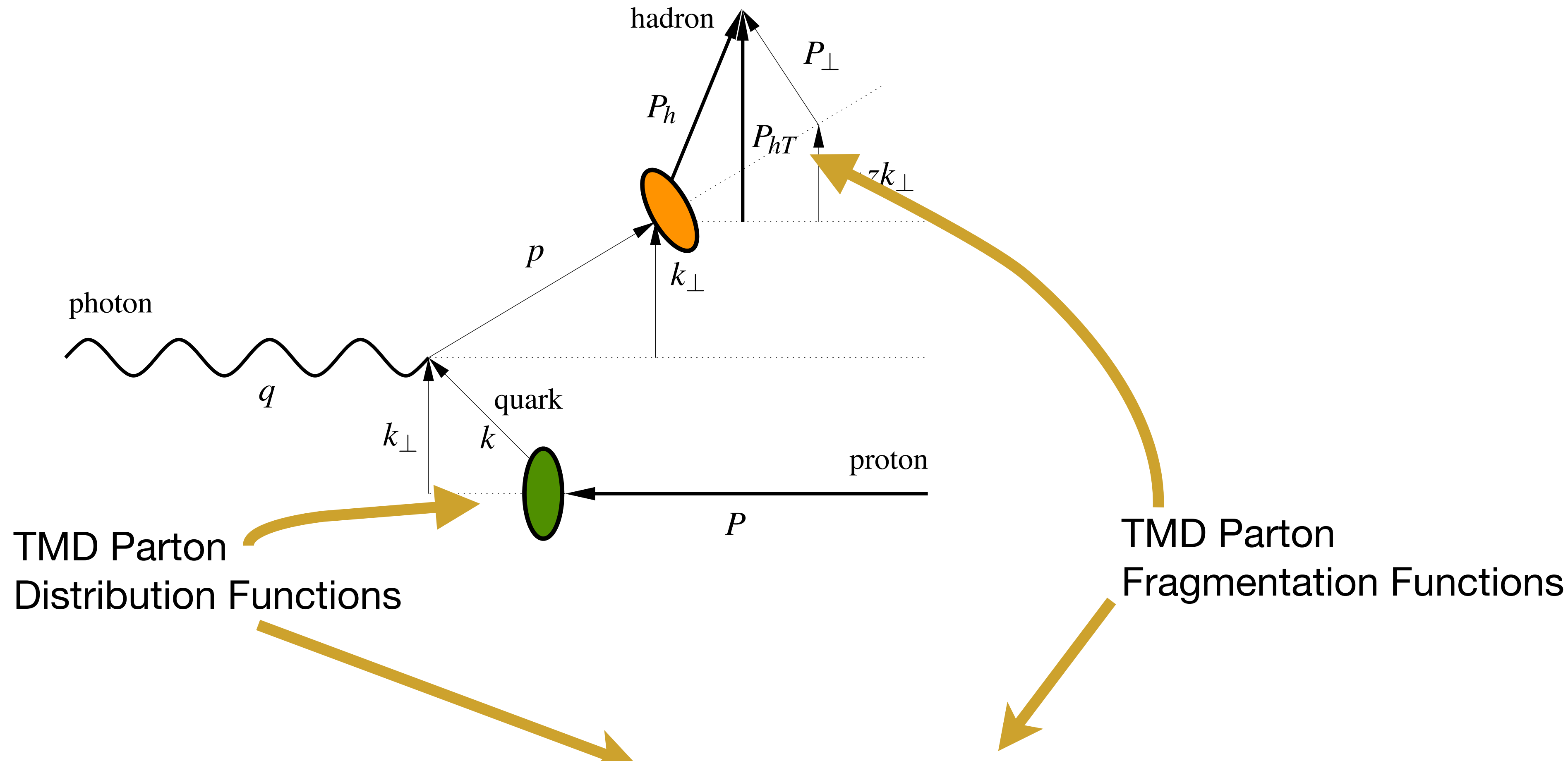
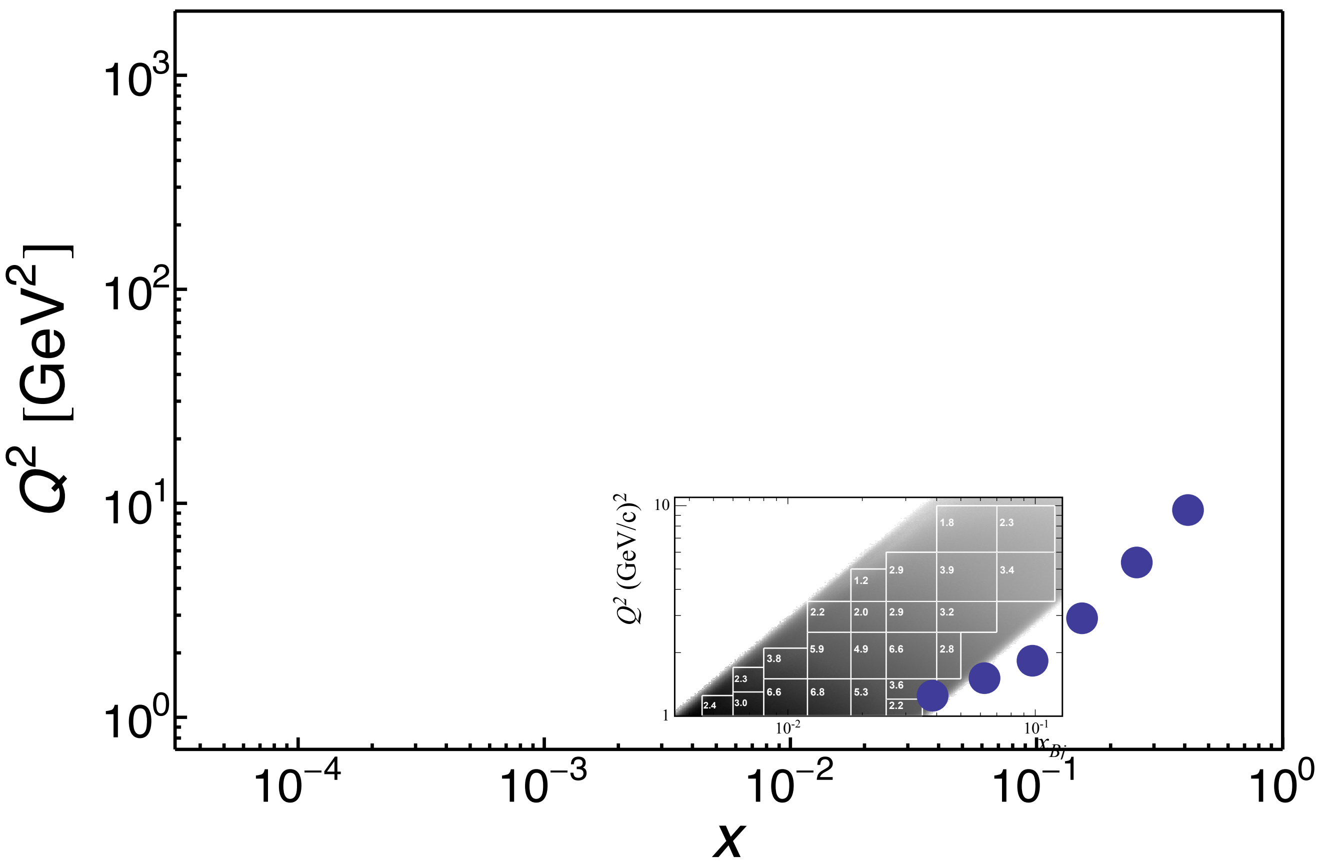
Transverse-momentum convolutions



$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int d\boldsymbol{k}_\perp \, d\boldsymbol{P}_\perp \, f_1^a\big(x,\boldsymbol{k}_\perp^2;\mu^2\big)\, D_1^{a\to h}\big(z,\boldsymbol{P}_\perp^2;\mu^2\big)\, \delta\big(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\big)$$
$$+ Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

Existing data



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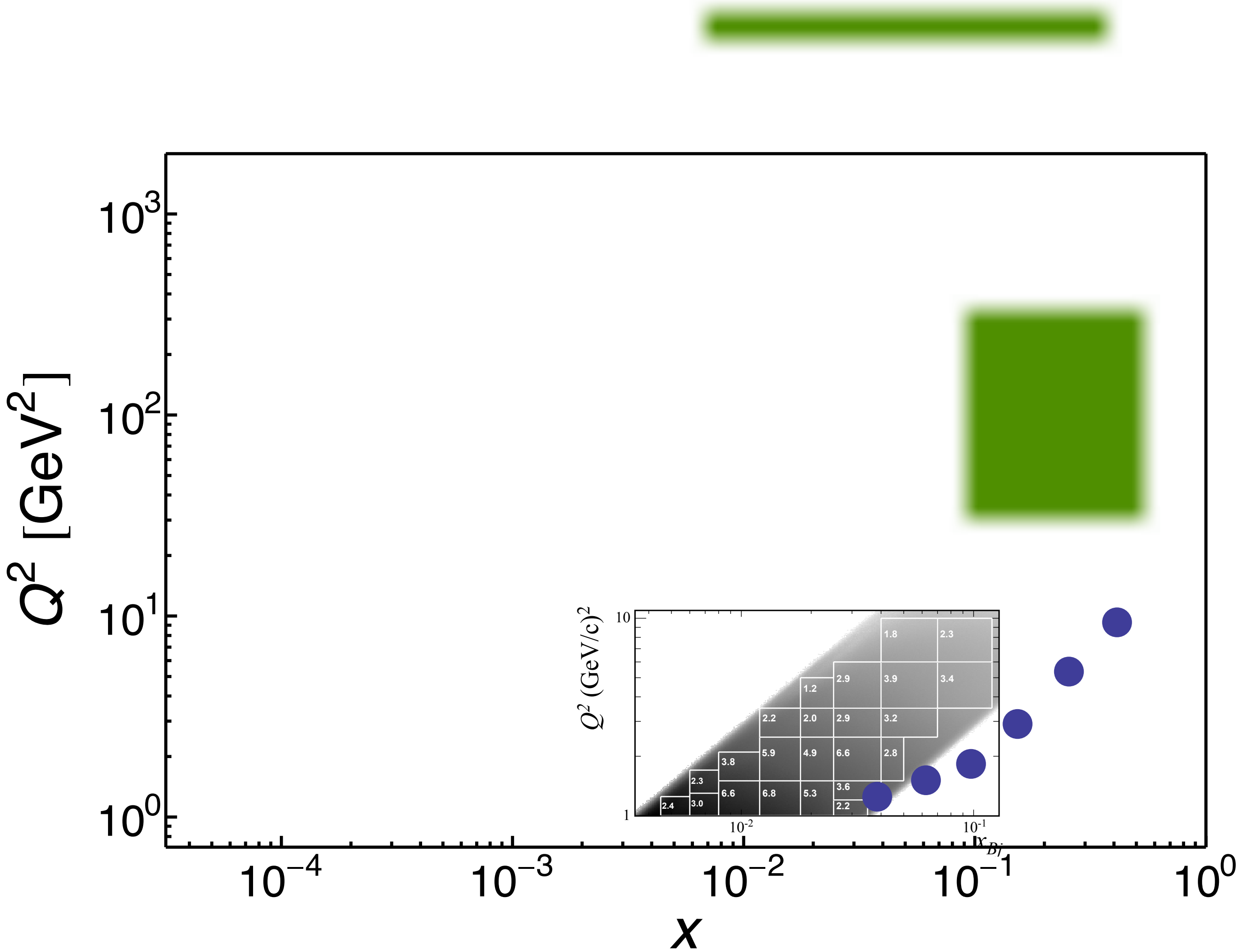
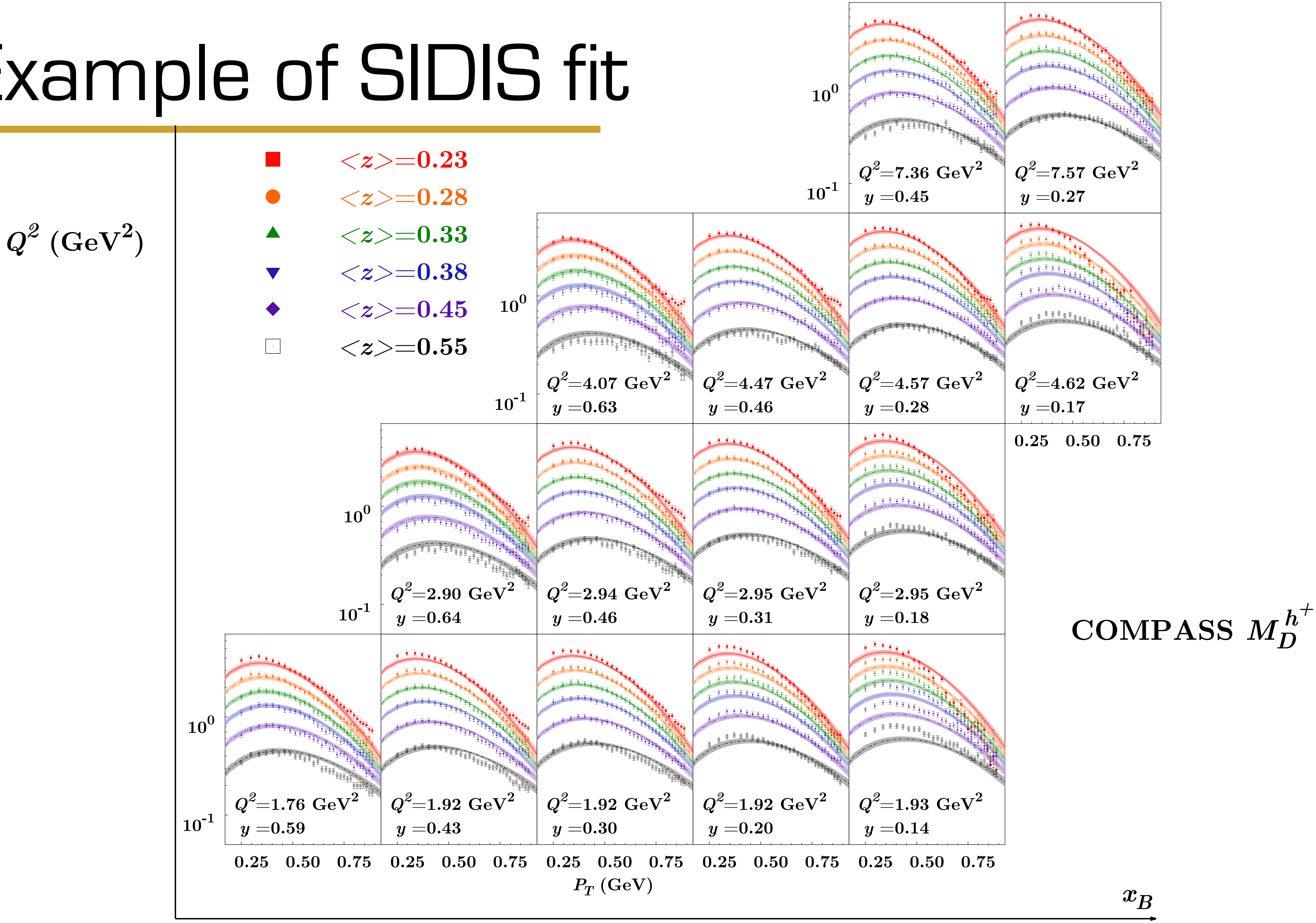


Drell-Yan@

Fermilab

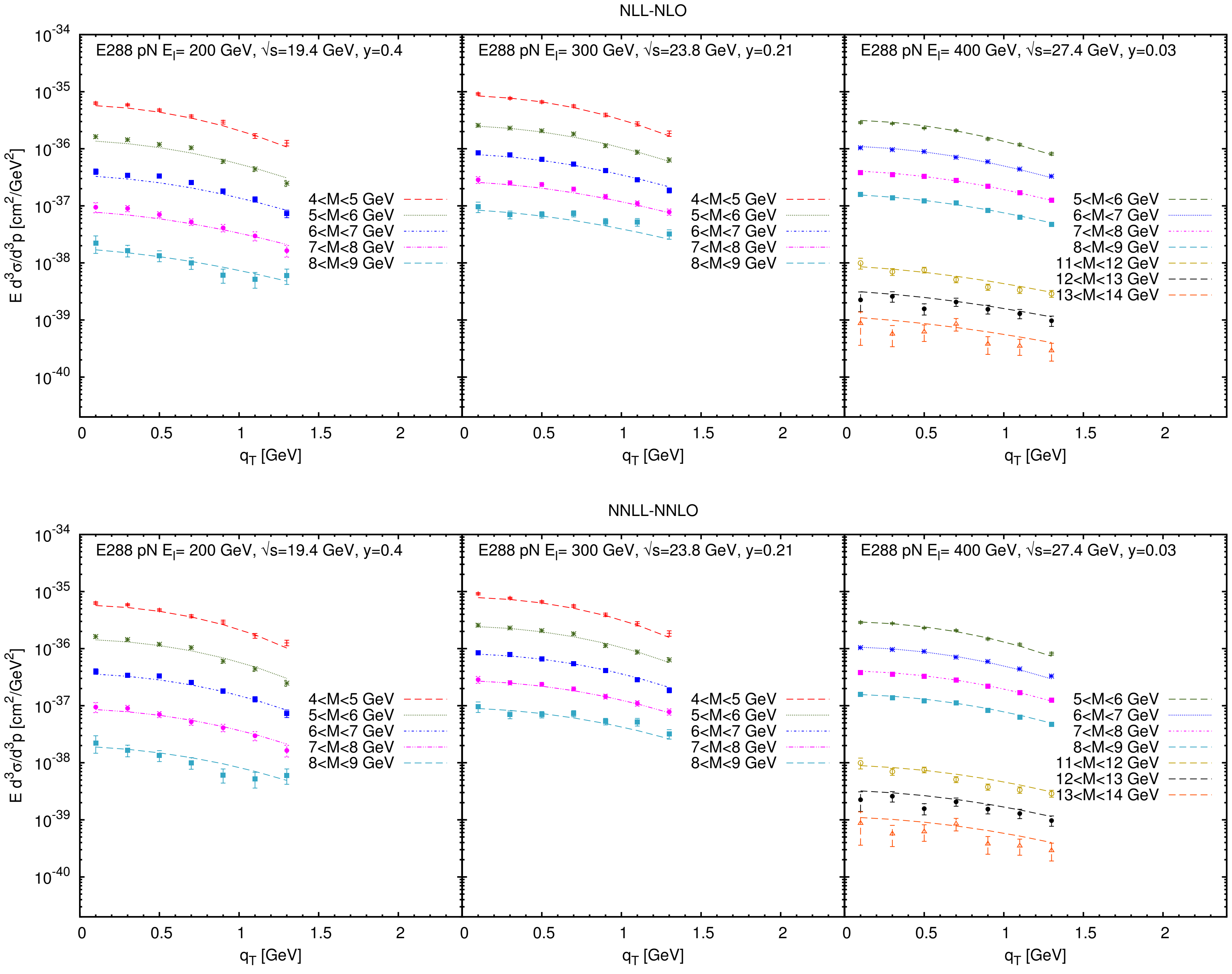
Example of SIDIS fit



Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

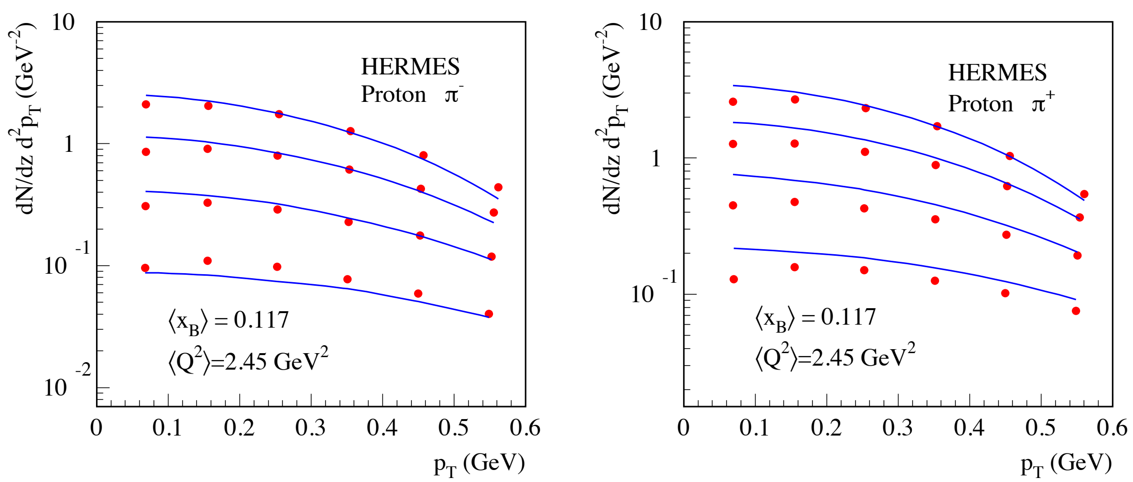
Example of Drell-Yan fit

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)

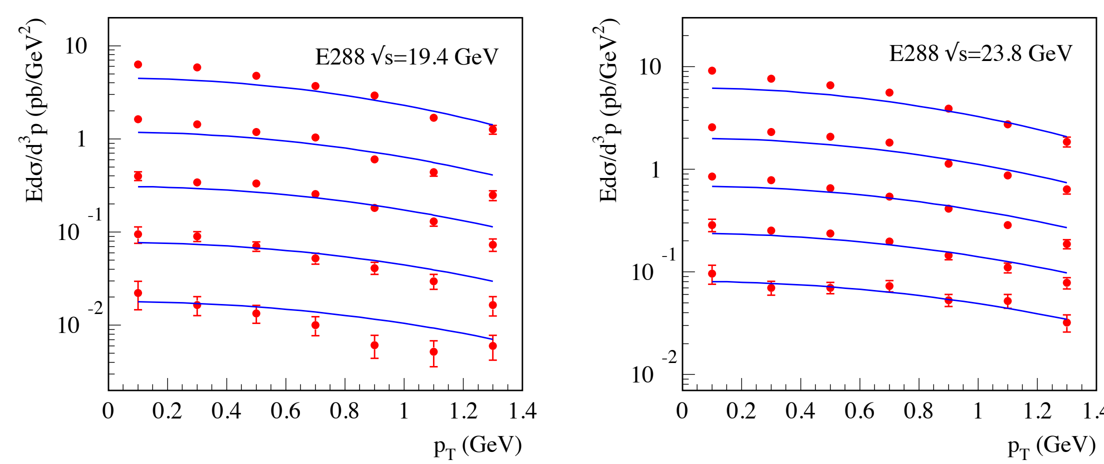


First attempts to put them together

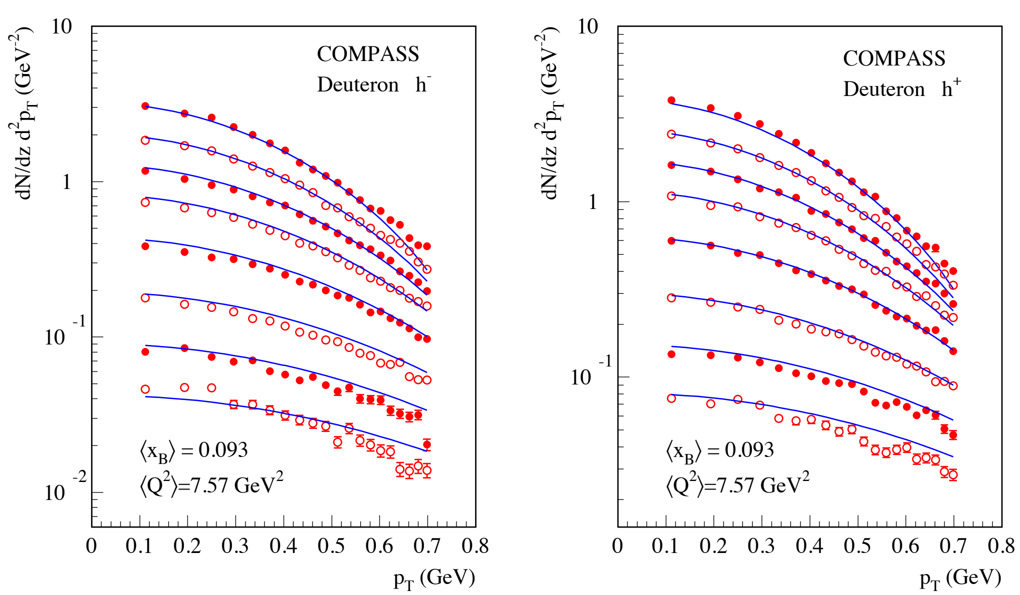
SIDIS



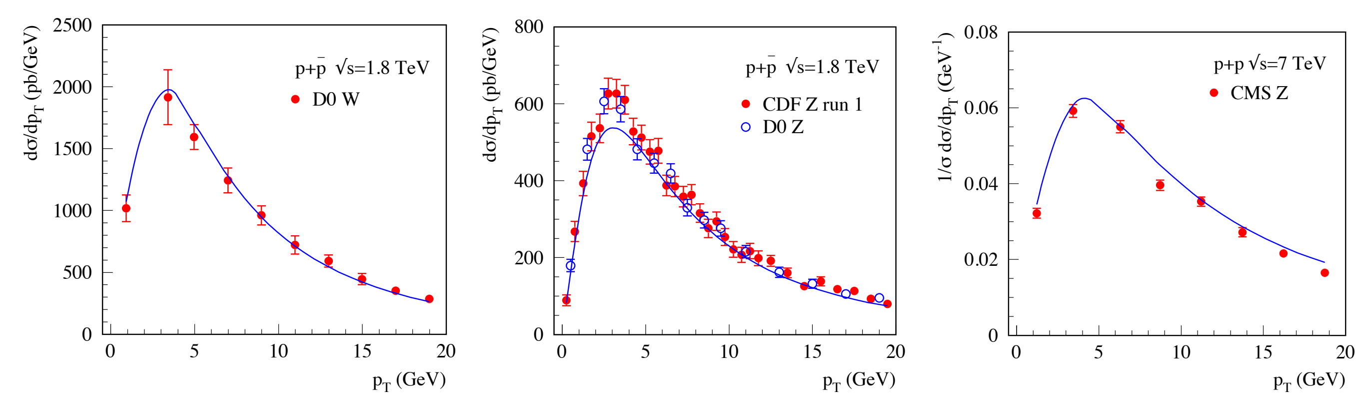
DRELL-YAN



SIDIS

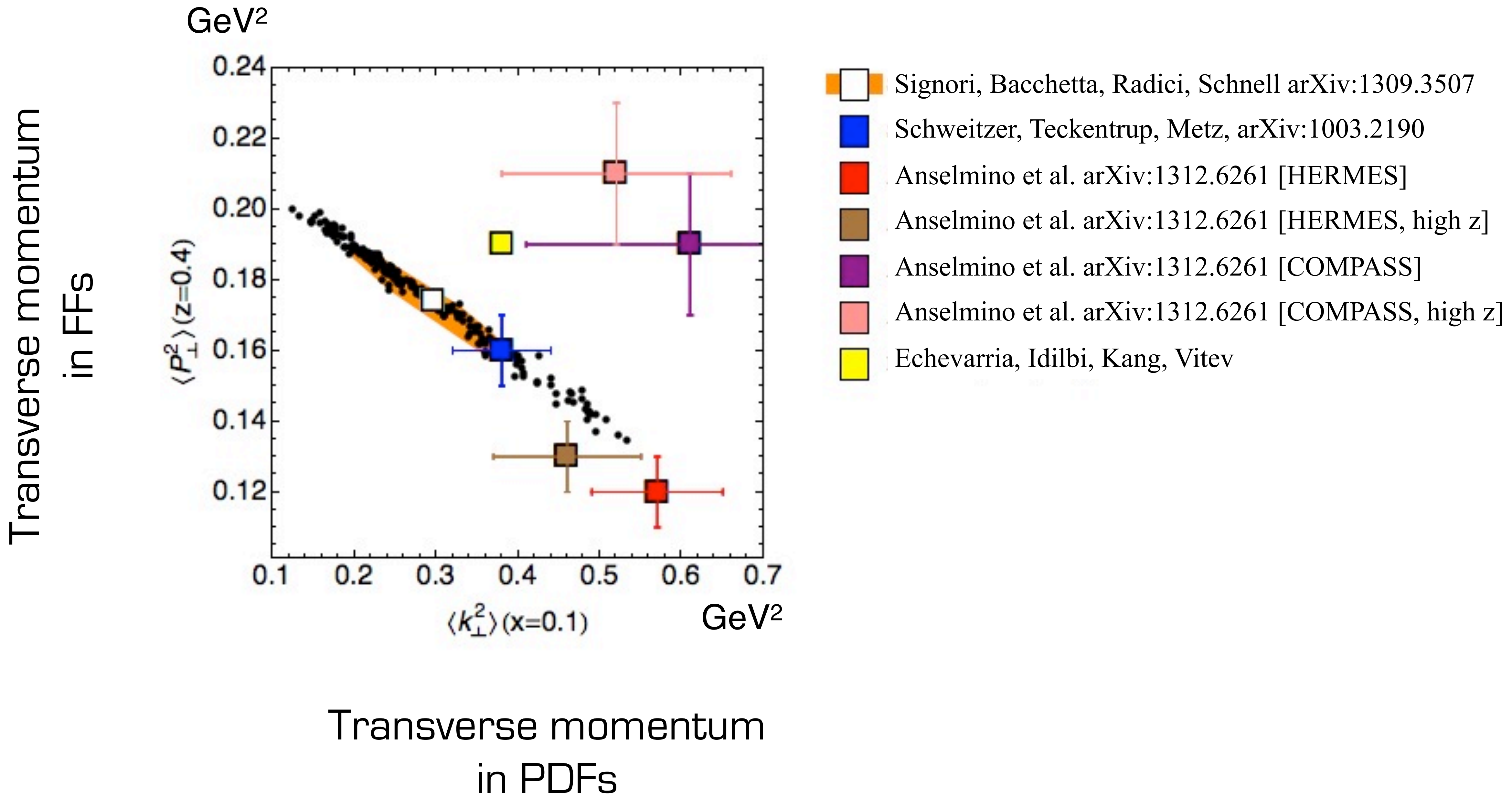


W AND Z PRODUCTION



Echevarria et al. arXiv:1401.5078

Transverse momentum “size”



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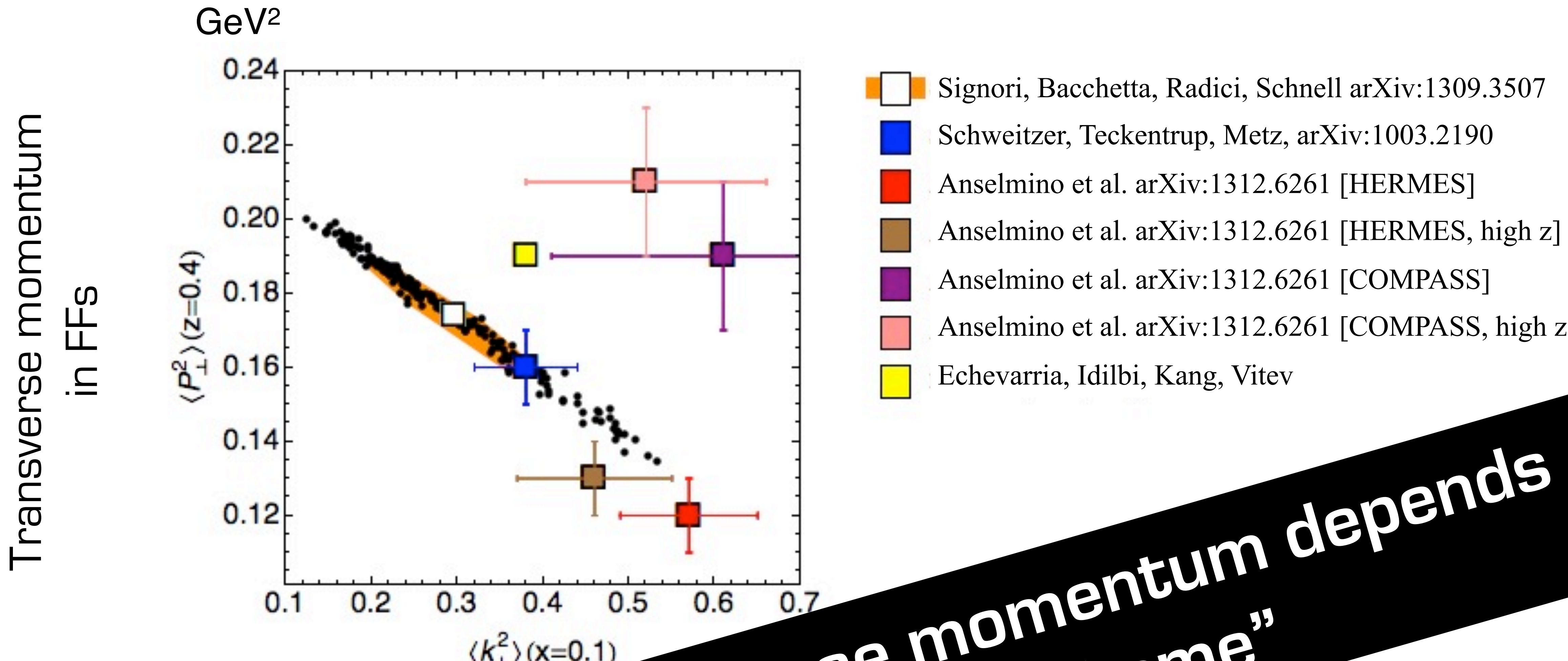
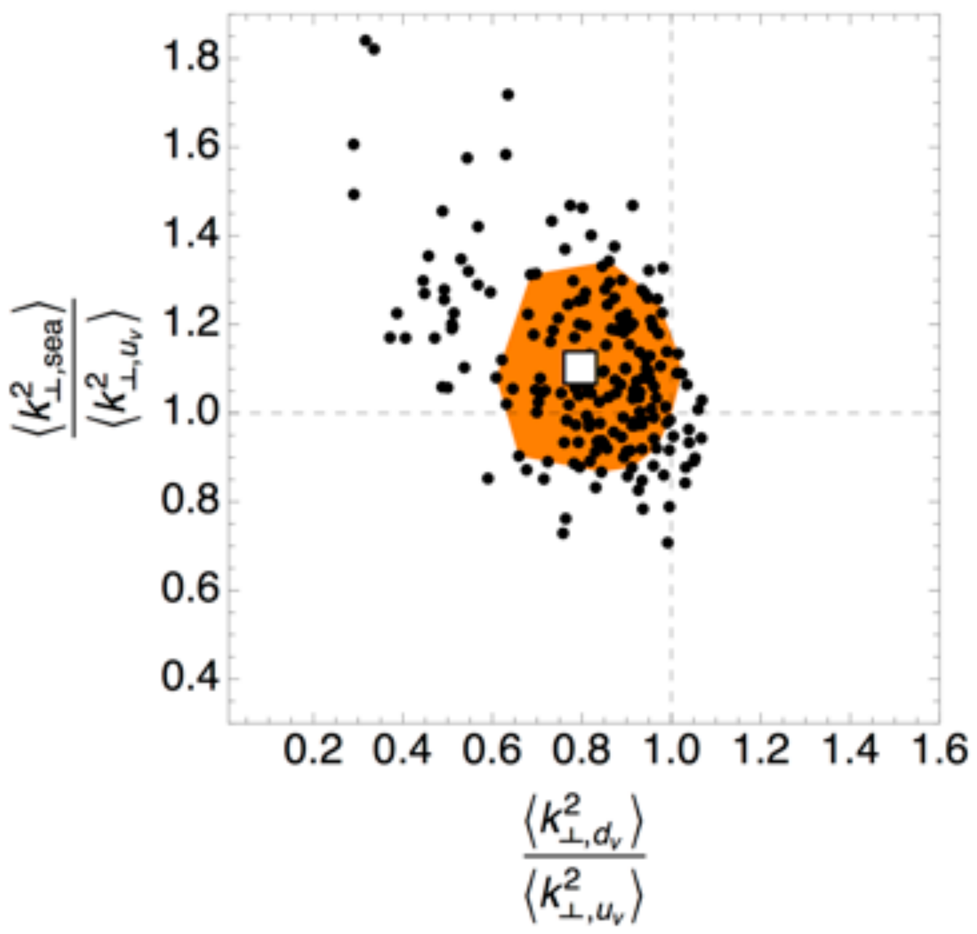


CAVEAT: intrinsic transverse momentum depends on the TMD evolution “scheme”

Flavor structure of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea / width of up valence



Ratio width of down valence/ width of up valence

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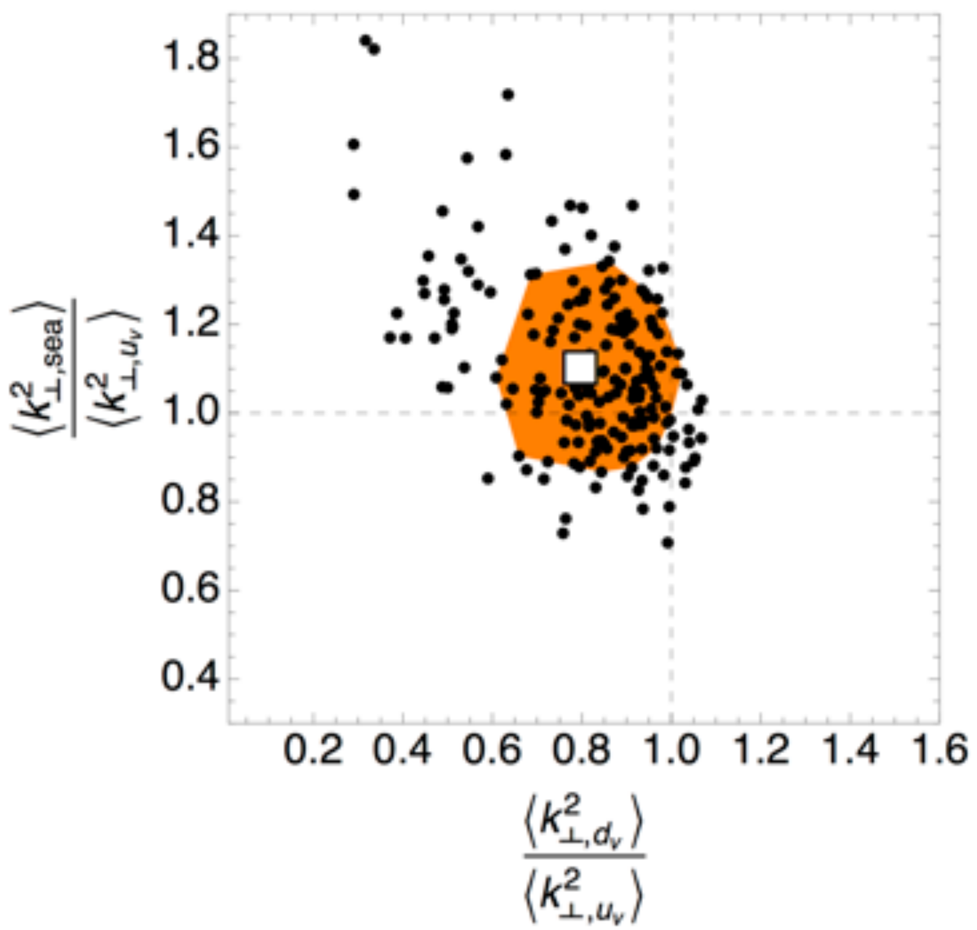

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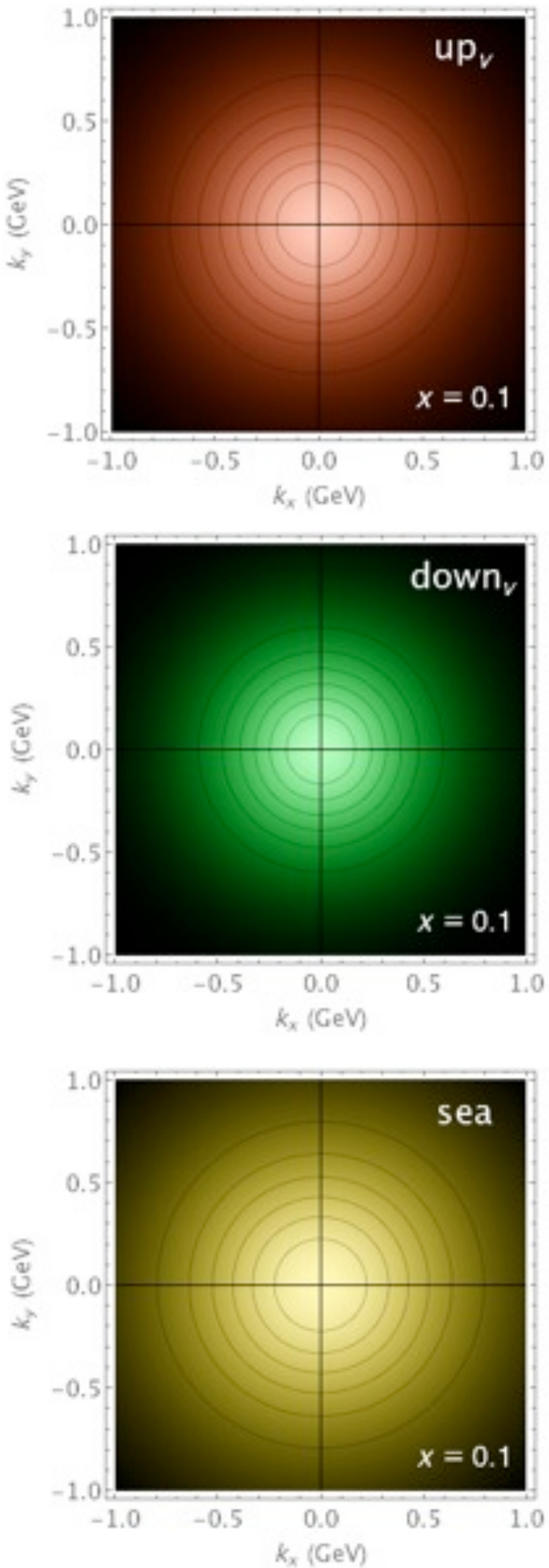

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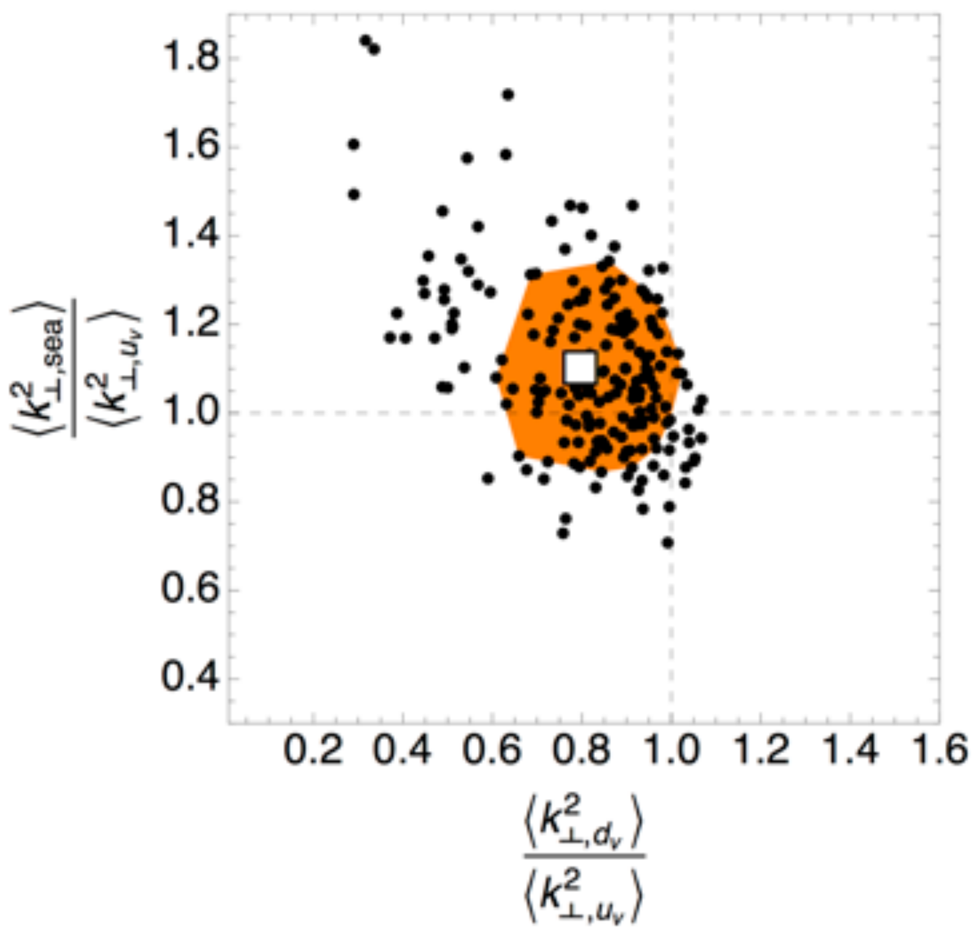

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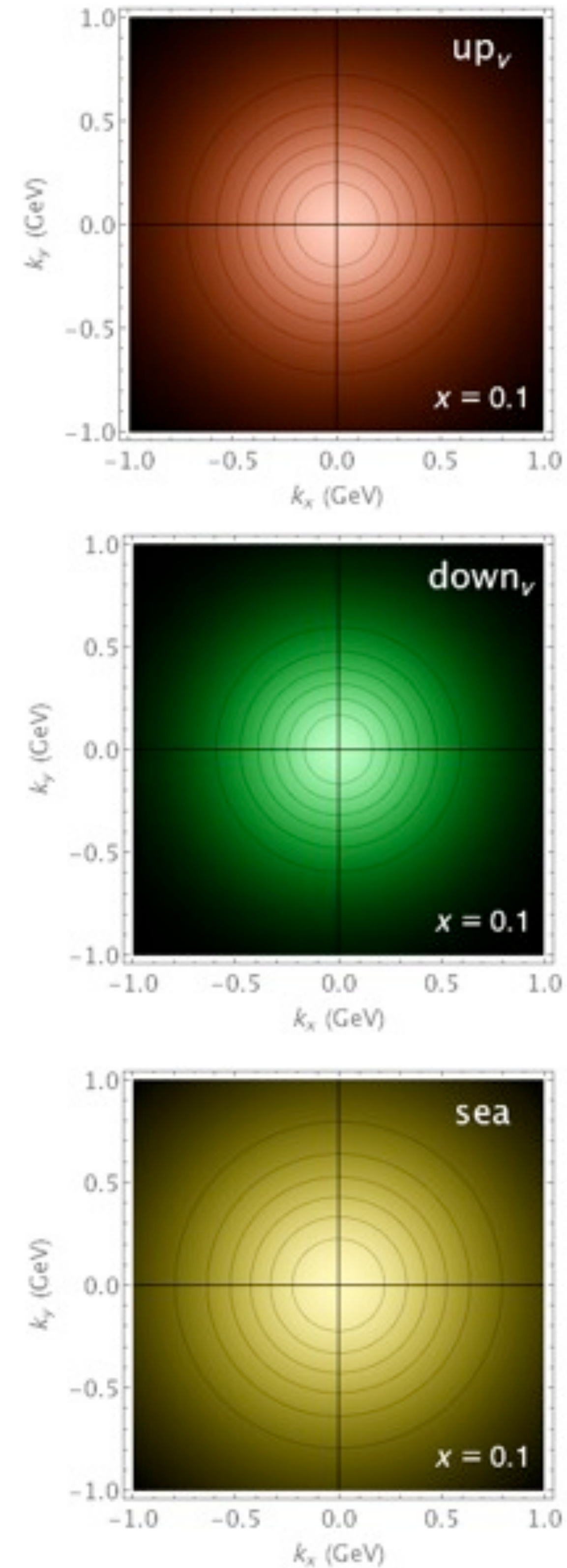

Indications that width of down < up < sea

Flavor structure of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

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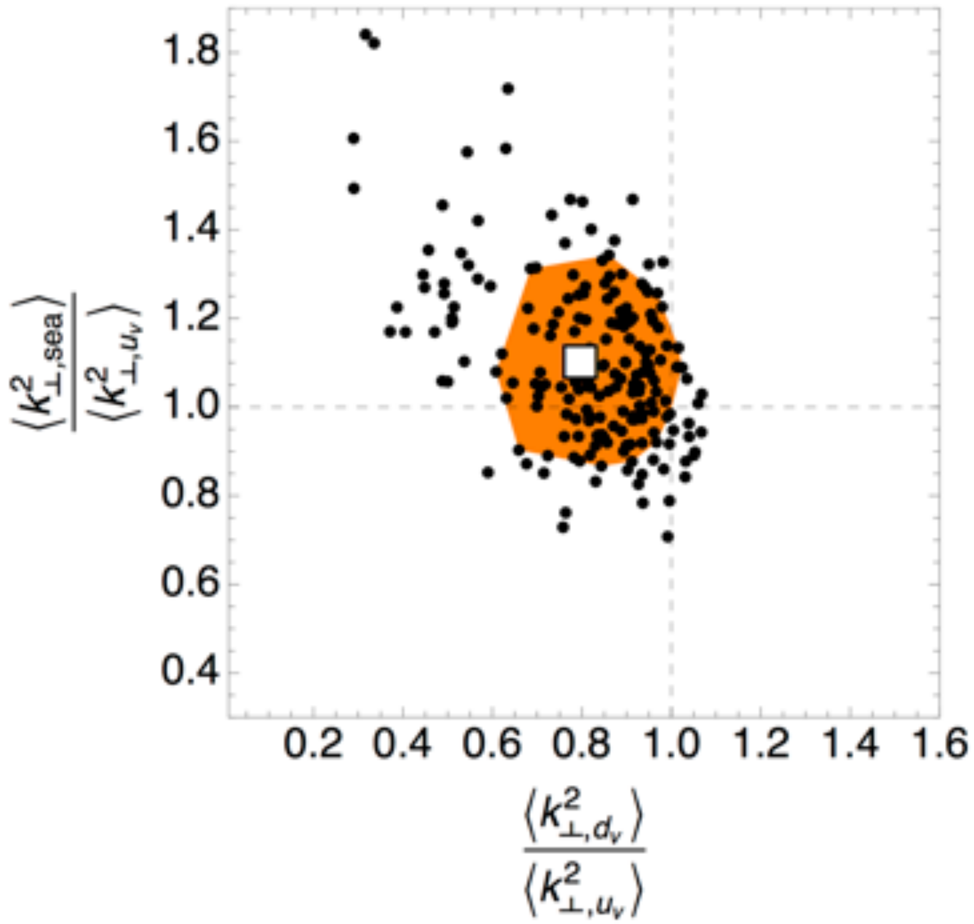

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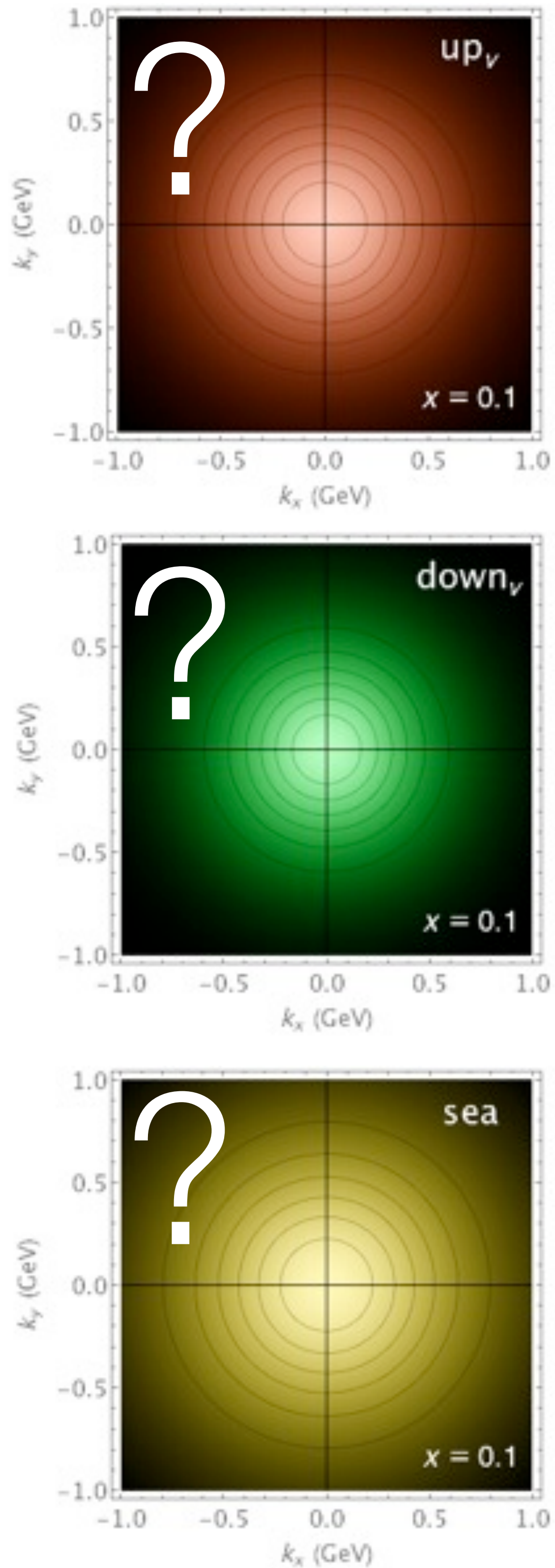
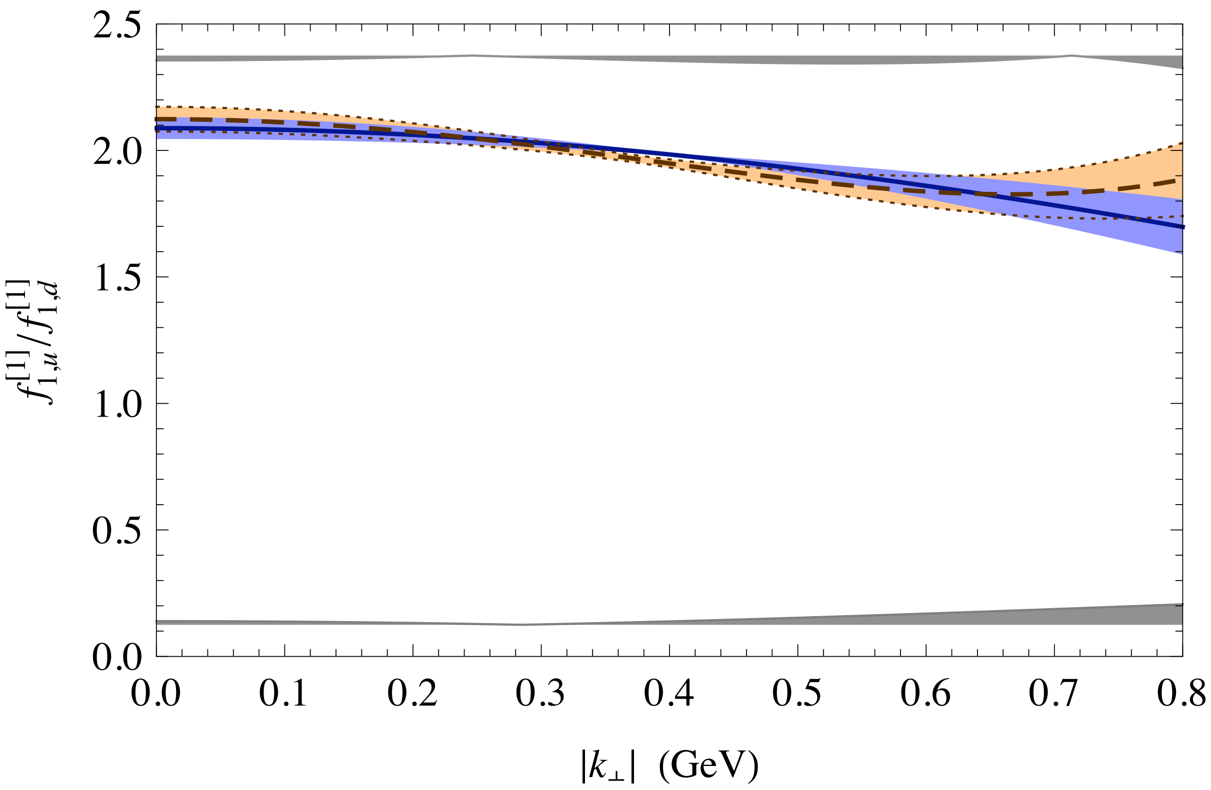


Indications that width of down < up < sea

Indications from lattice QCD



Musch, Hagler, Negele, Schafer, PRD 83 (11)

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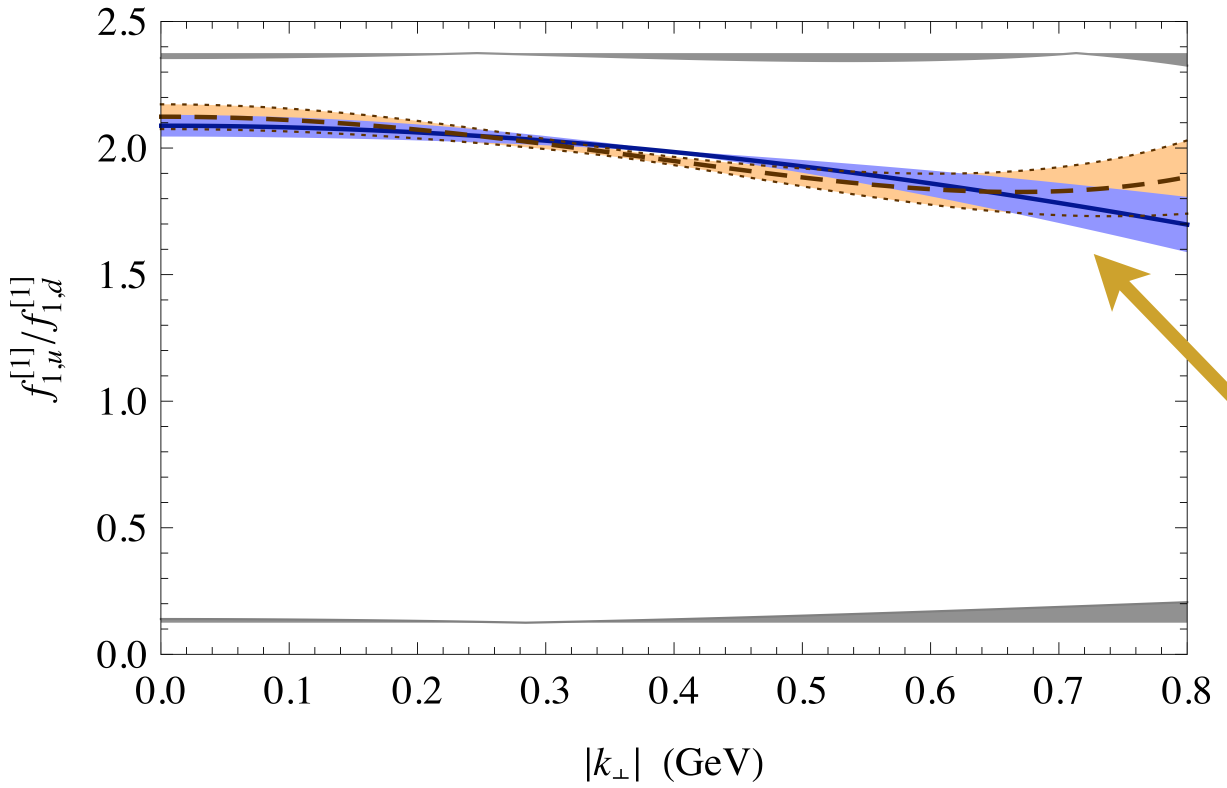

"less" up quarks

Musch, Hagler, Negele, Schafer, PRD 83 (11)

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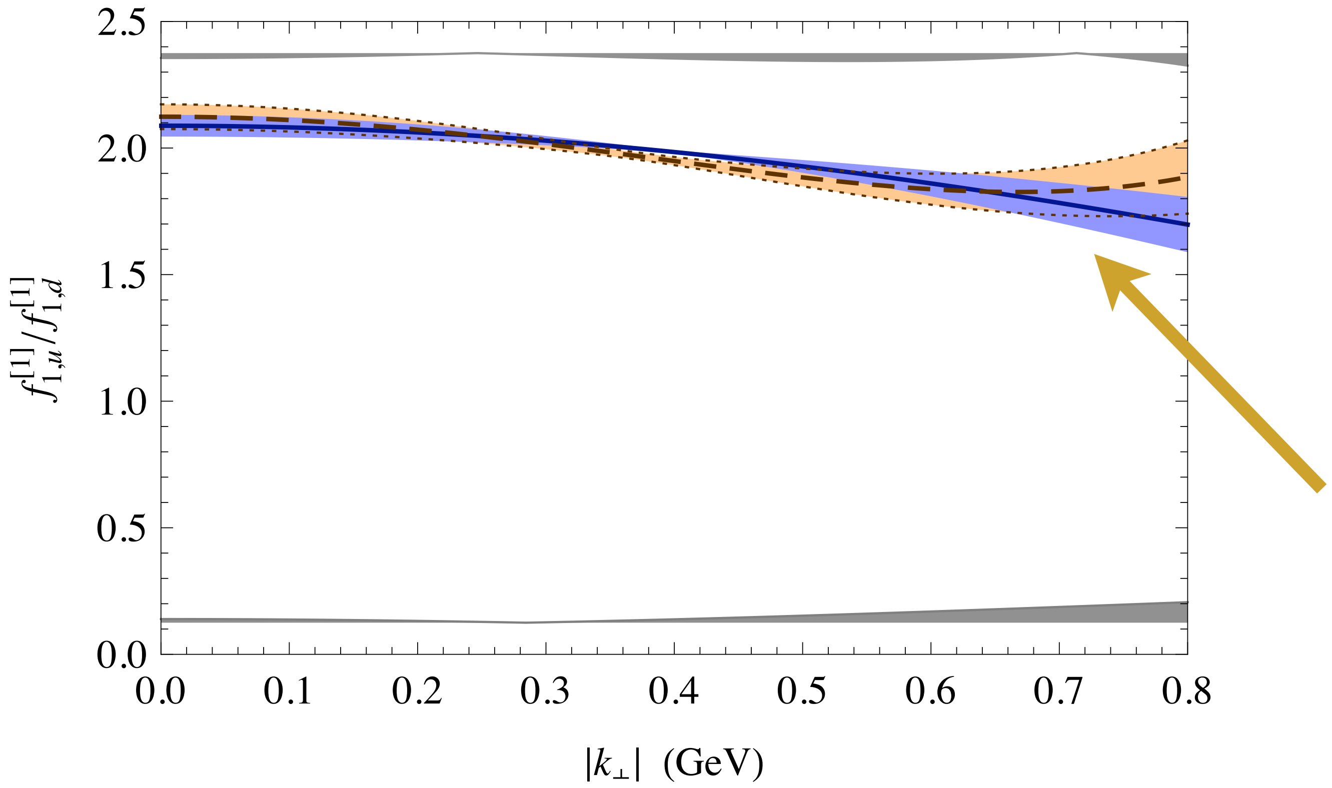


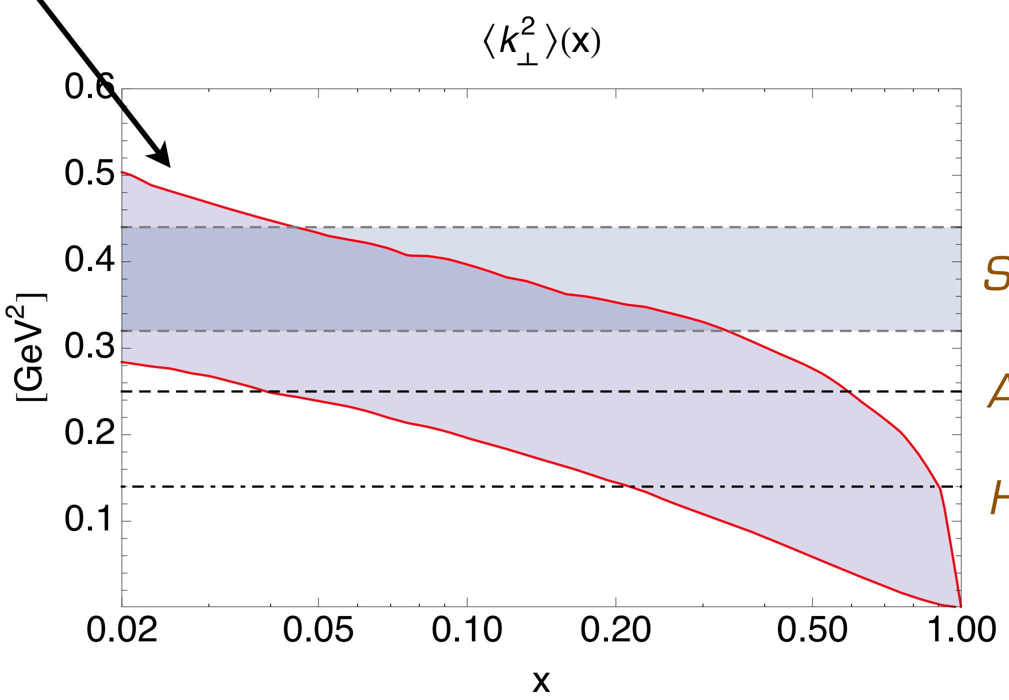
“less” up quarks

Musch, Hagler, Negele, Schafer, PRD 83 (11)

Pioneering lattice-QCD studies hint at a down distribution being wider than up

x-behavior of TMDs

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)



Schweitzer, Teckentrup, Metz, PRD 81 (2010)

Anselmino et al., PRD 71 (2005)

HERMES gmc_trans

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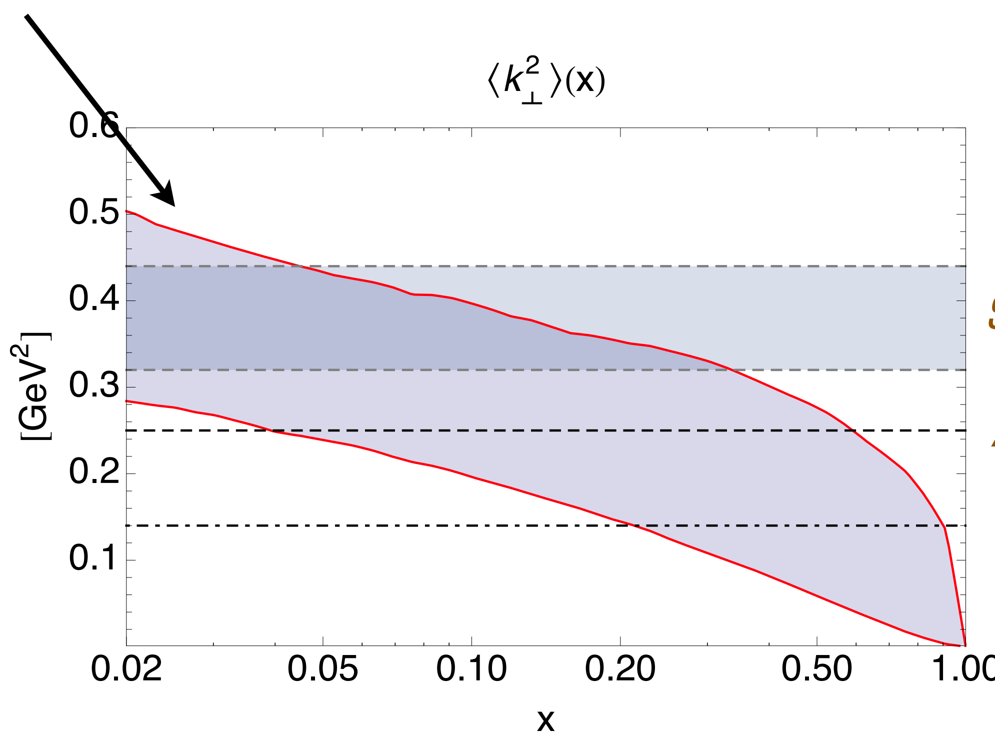
Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)



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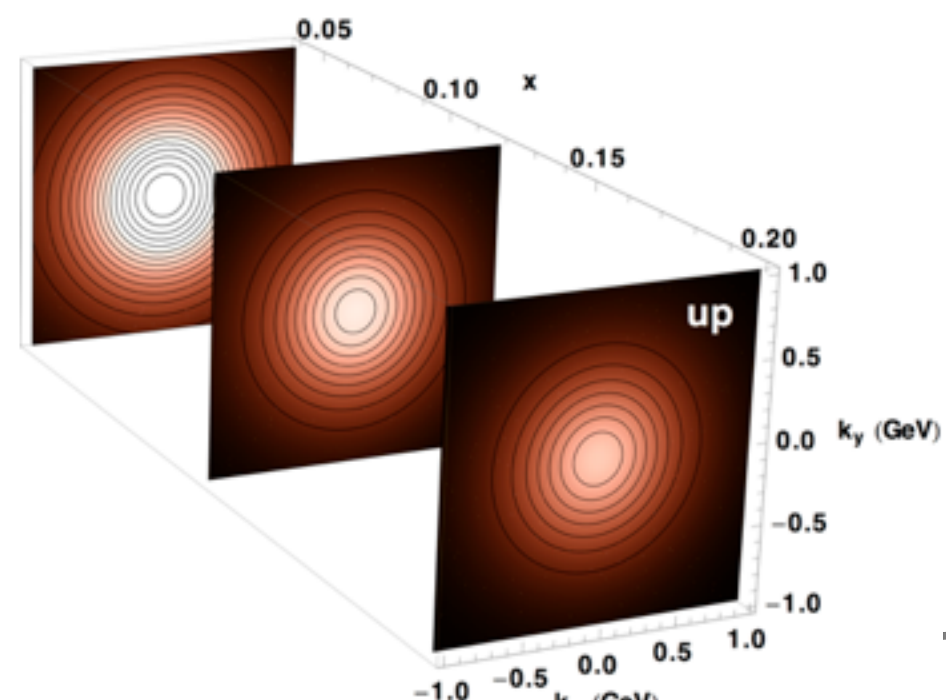
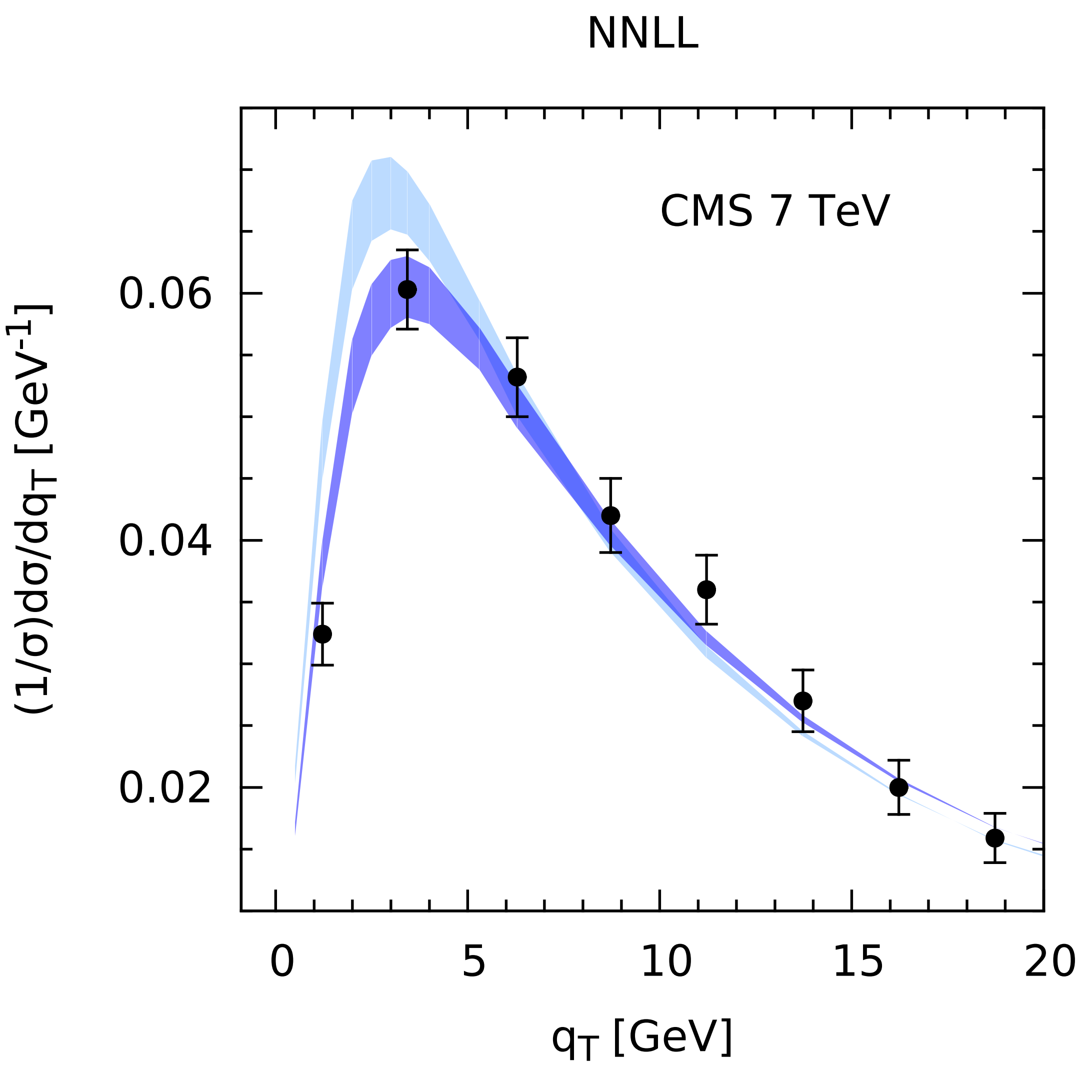


Still difficult to say, but possibly a widening at lower x

TMDs at LHC

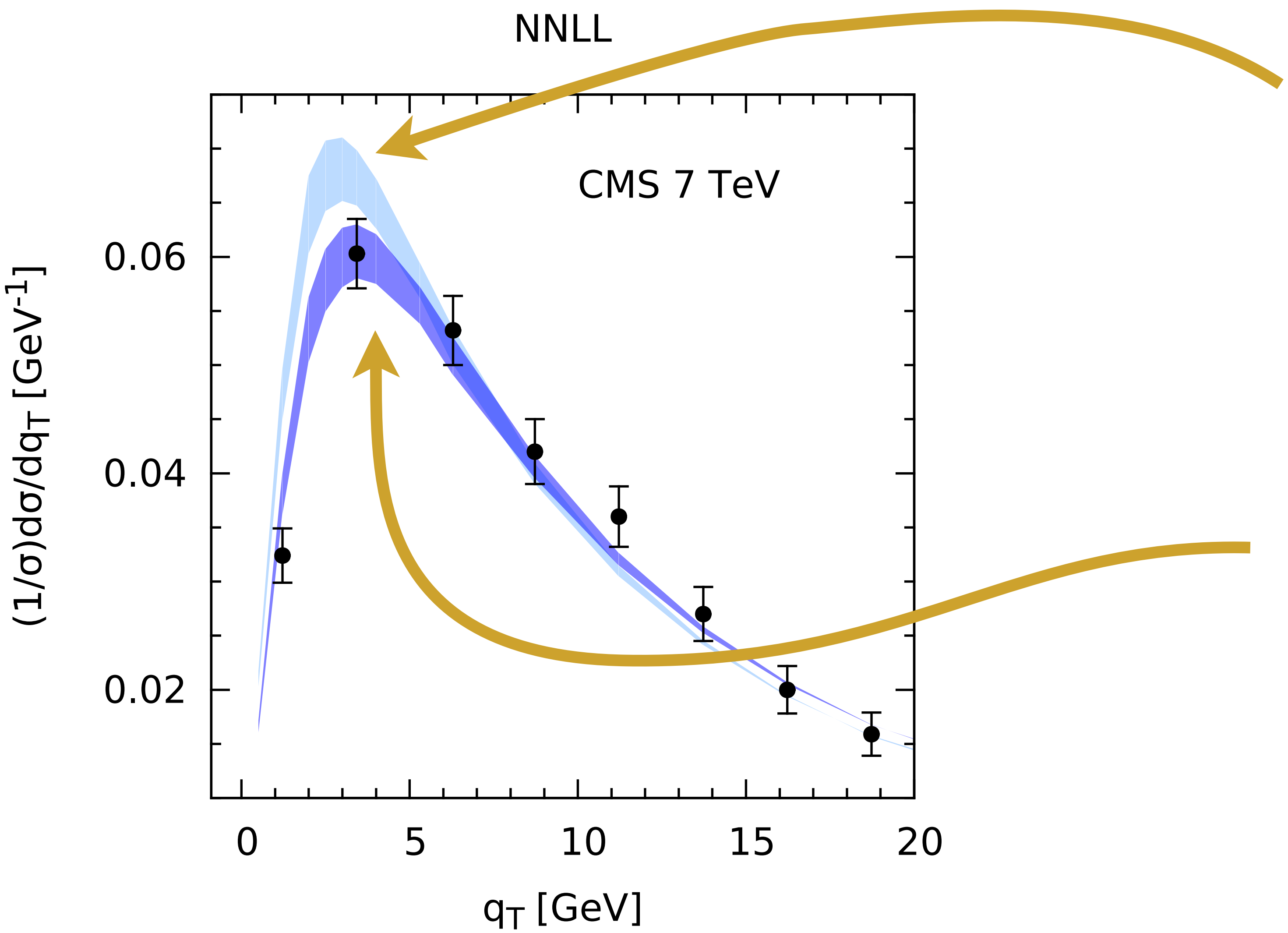
Z transverse momentum



D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)

TMDs at LHC

Z transverse momentum



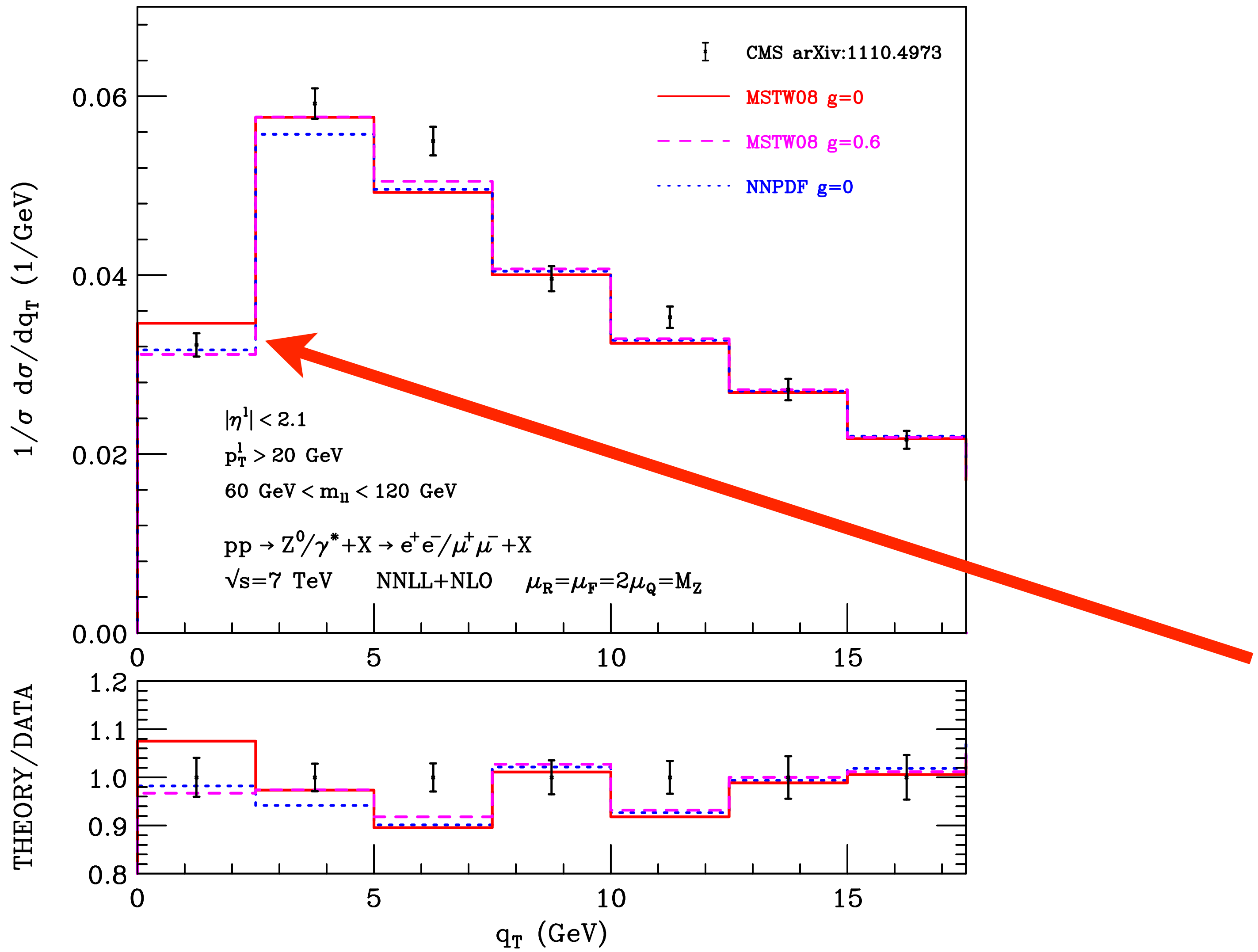
Perturbative transverse momentum only

With intrinsic transverse momentum

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)

TMDs a LHC

Z transverse momentum

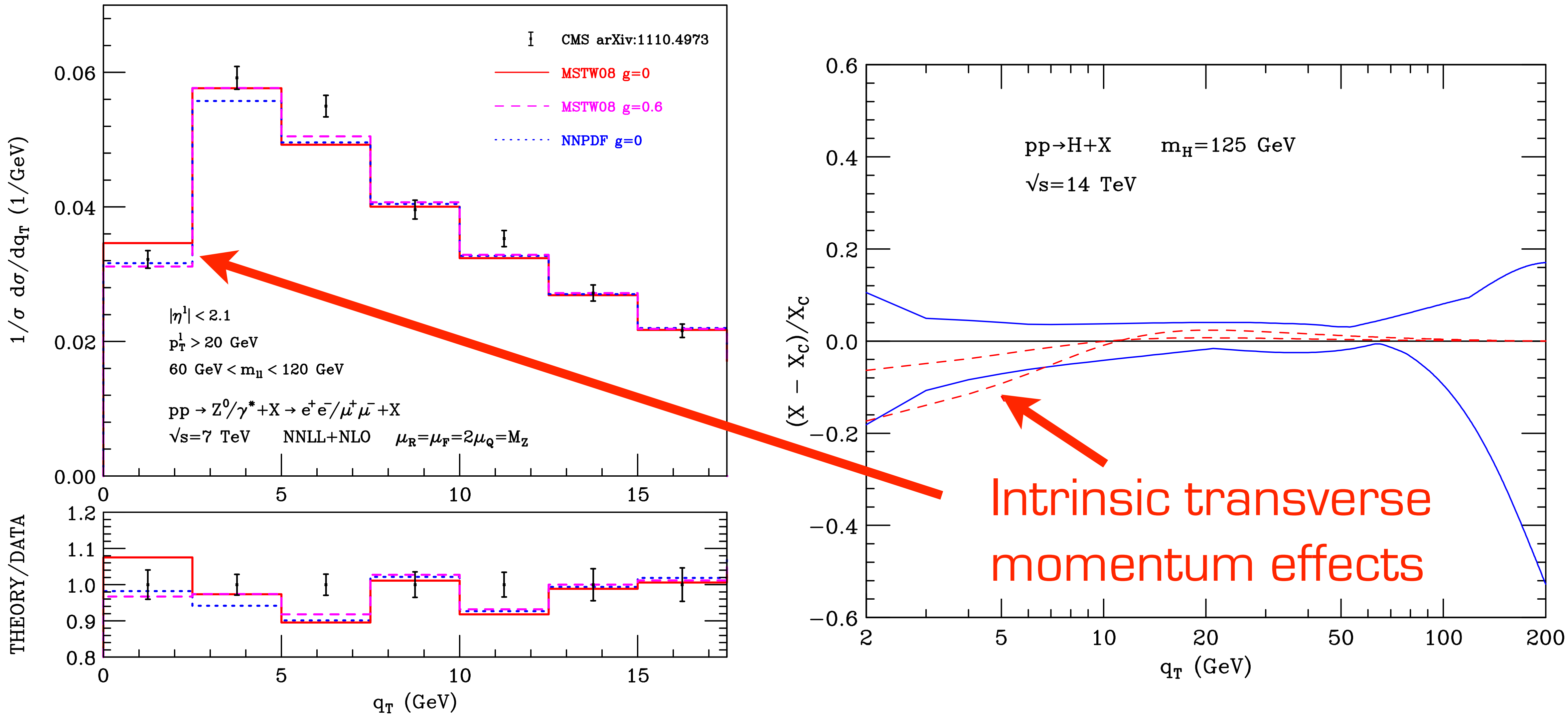


G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/

TMDs a LHC

Z transverse momentum

Higgs transverse momentum



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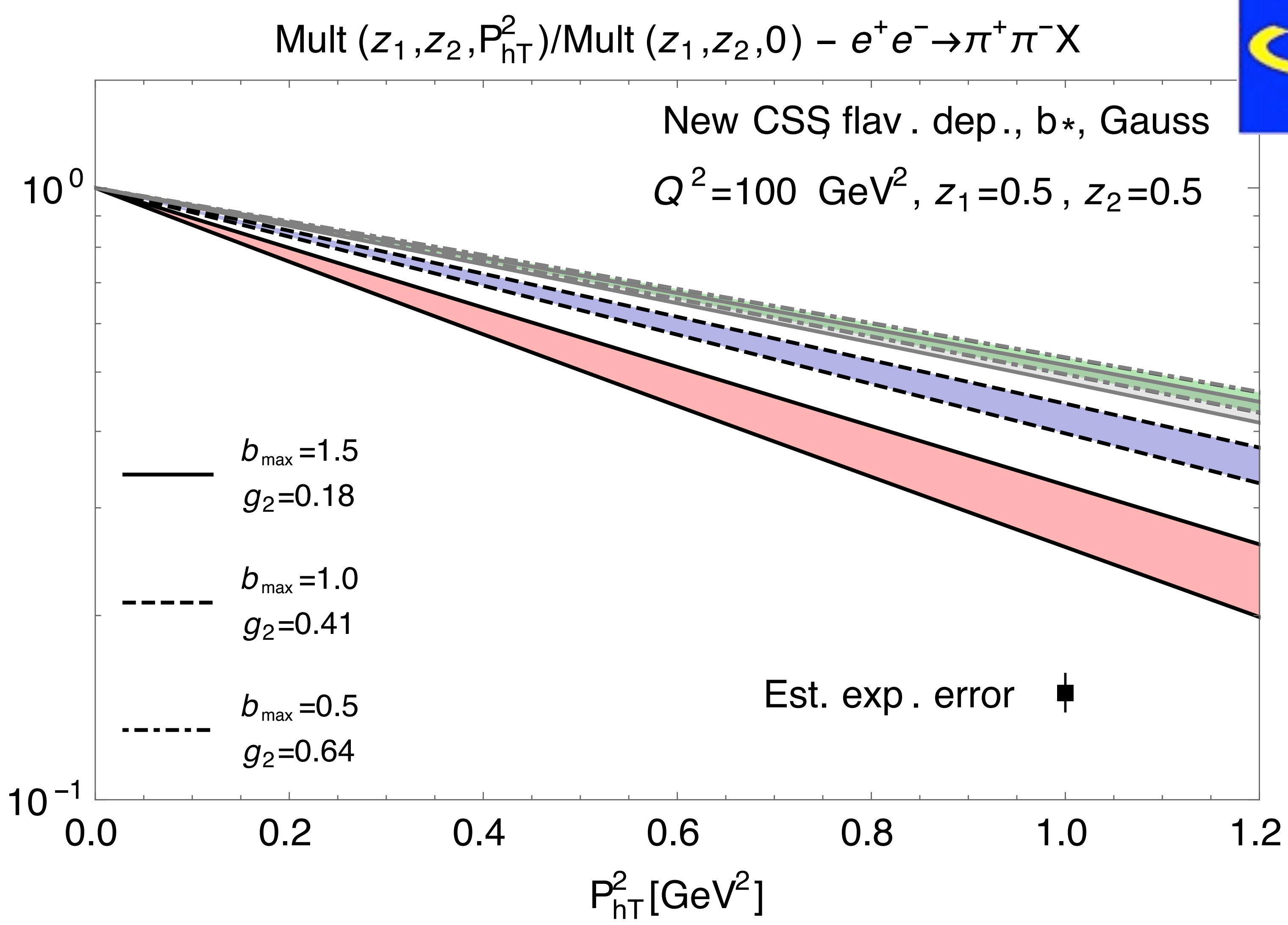
TMDs in electron-positron annihilation



Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

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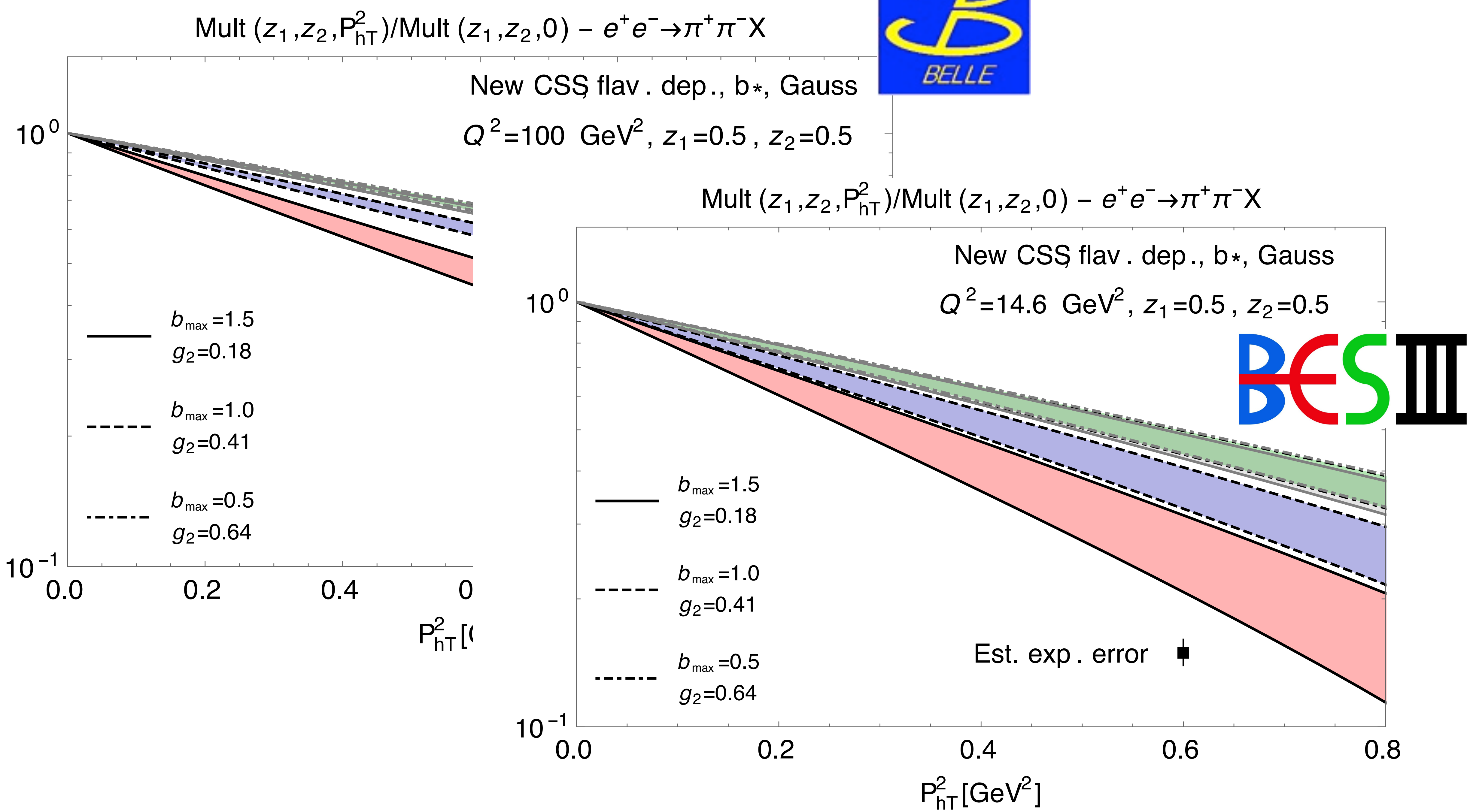

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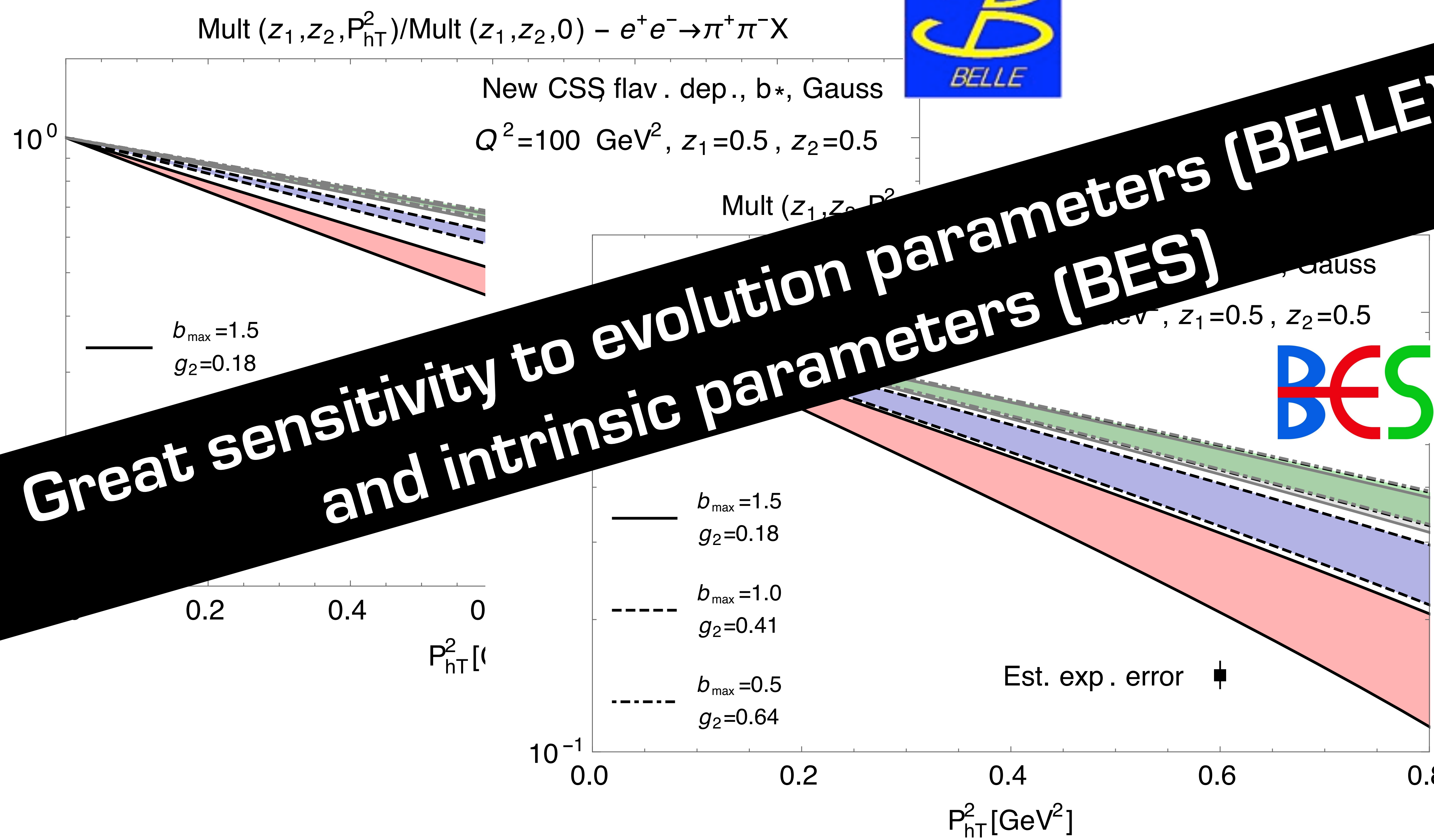


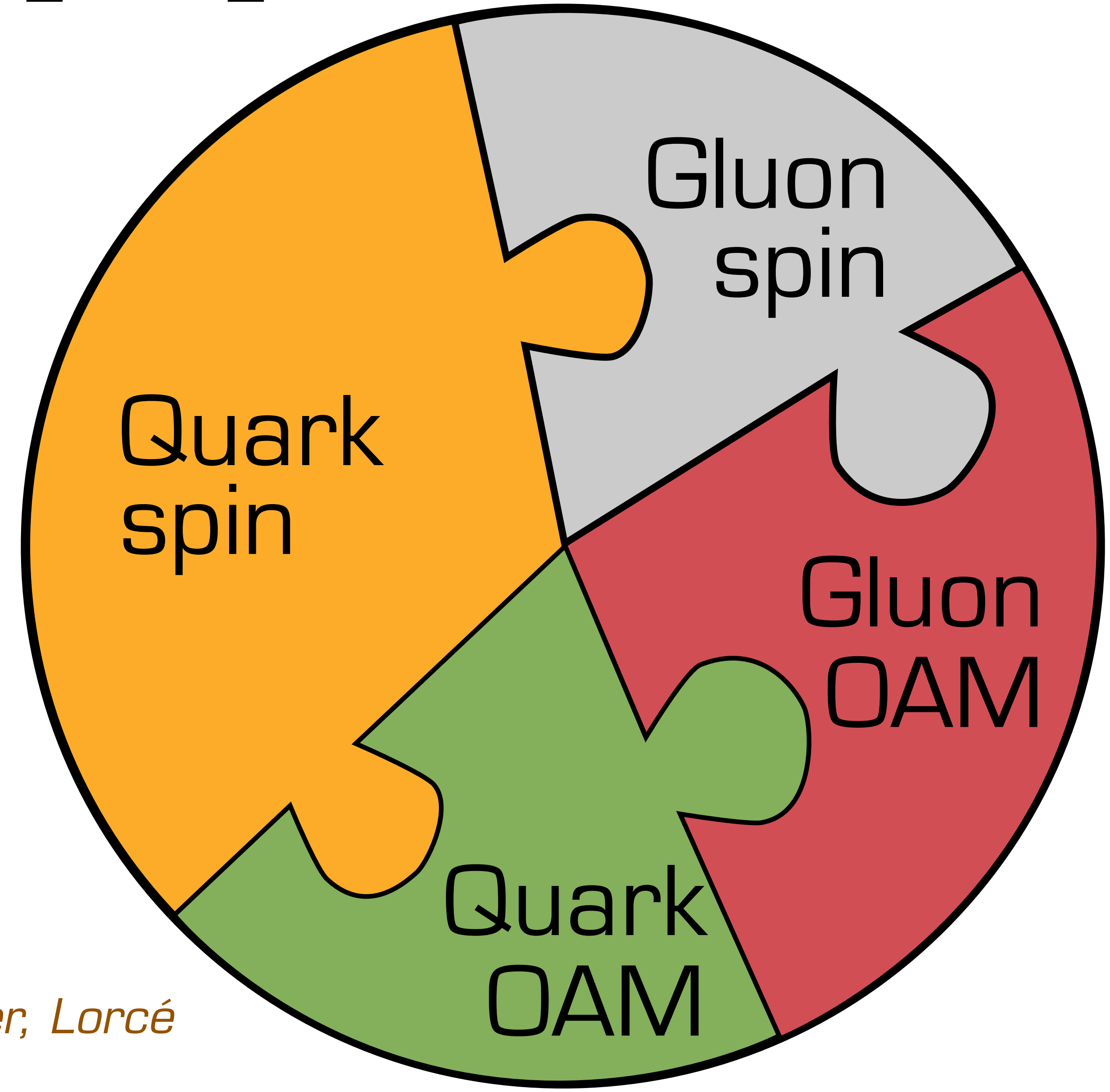
Great sensitivity to evolution parameters (BELLE) and intrinsic parameters (BES)

Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

A few slides on proton's spin

The proton spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

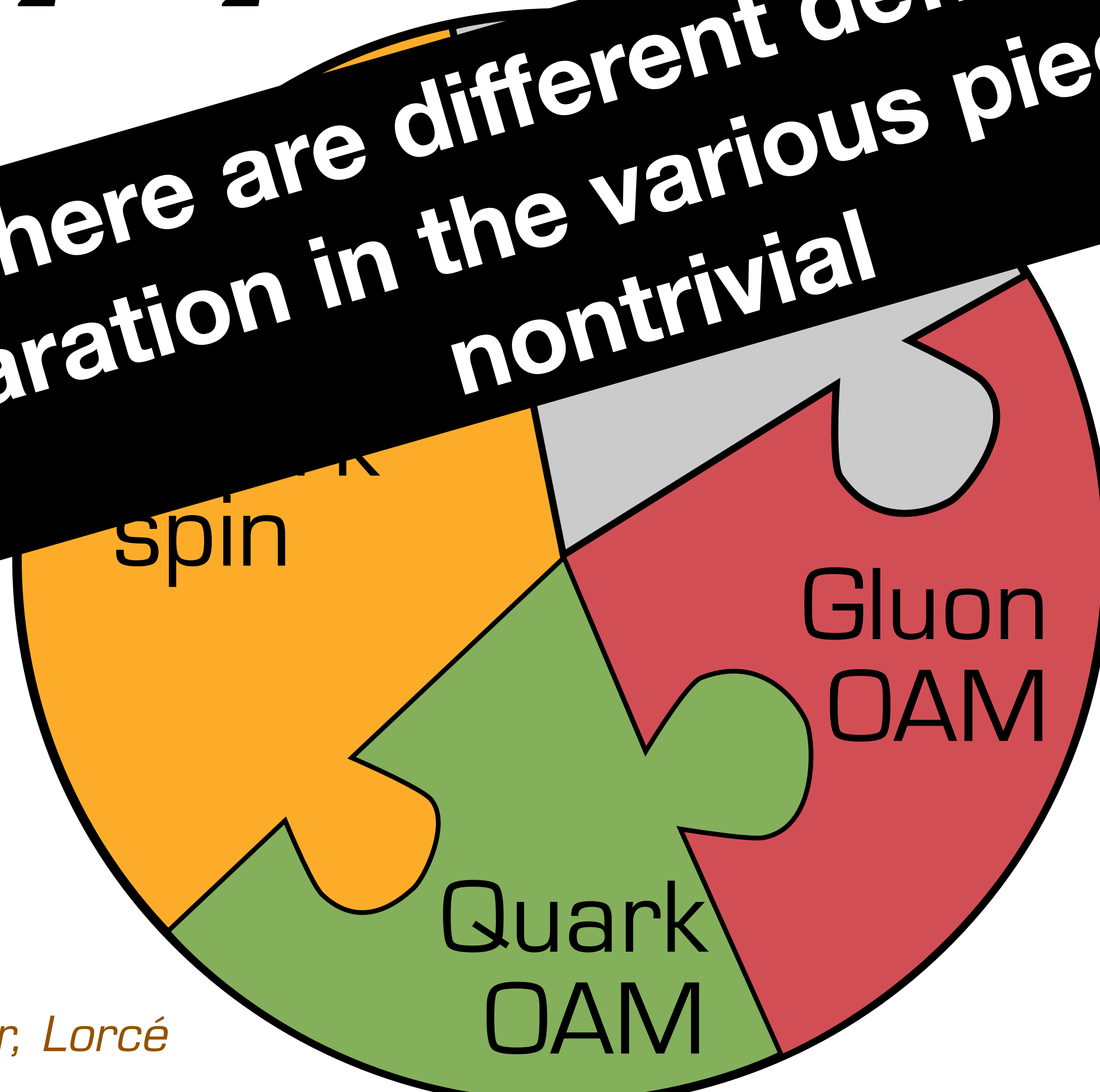


see, e.g., review by Leader, Lorcé
arXiv:1309.4235

The proton spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

CAVEAT: there are different definitions of OAM
The separation in the various pieces is highly nontrivial



see, e.g., review by Leader, Lorcé
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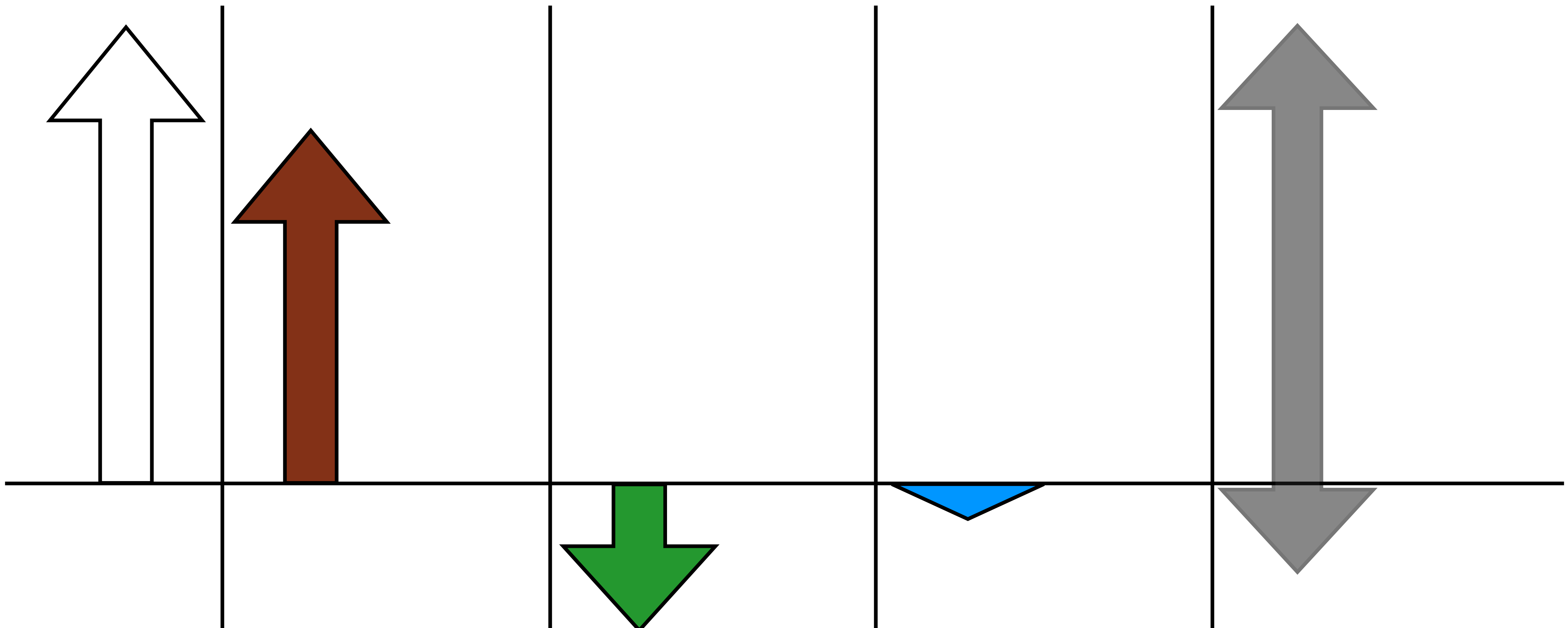
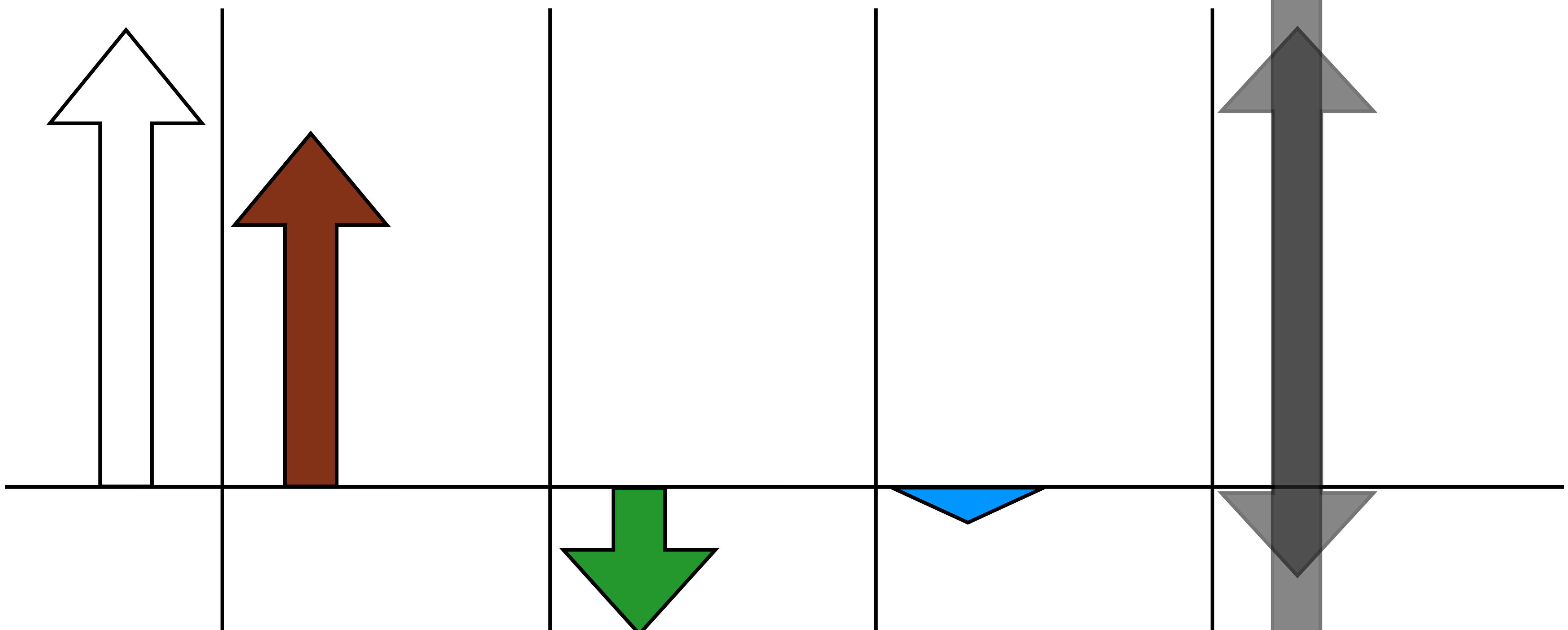
Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)

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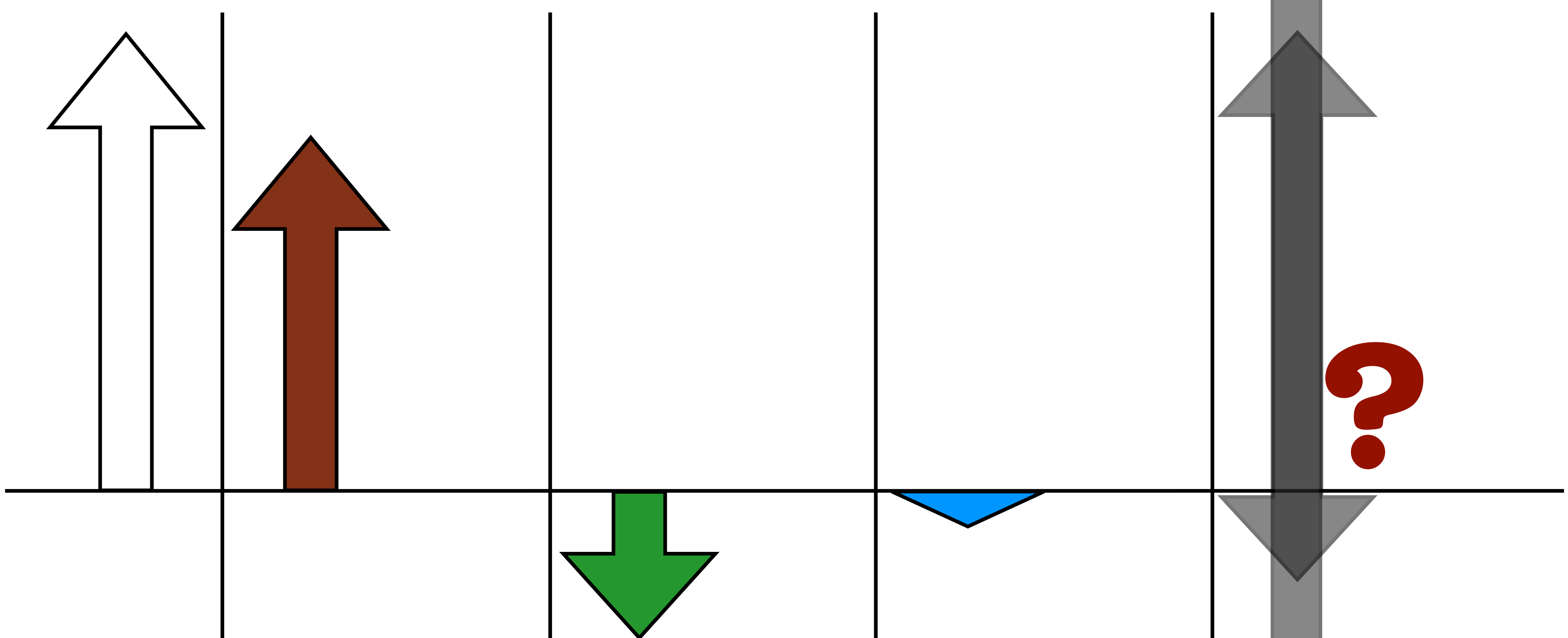

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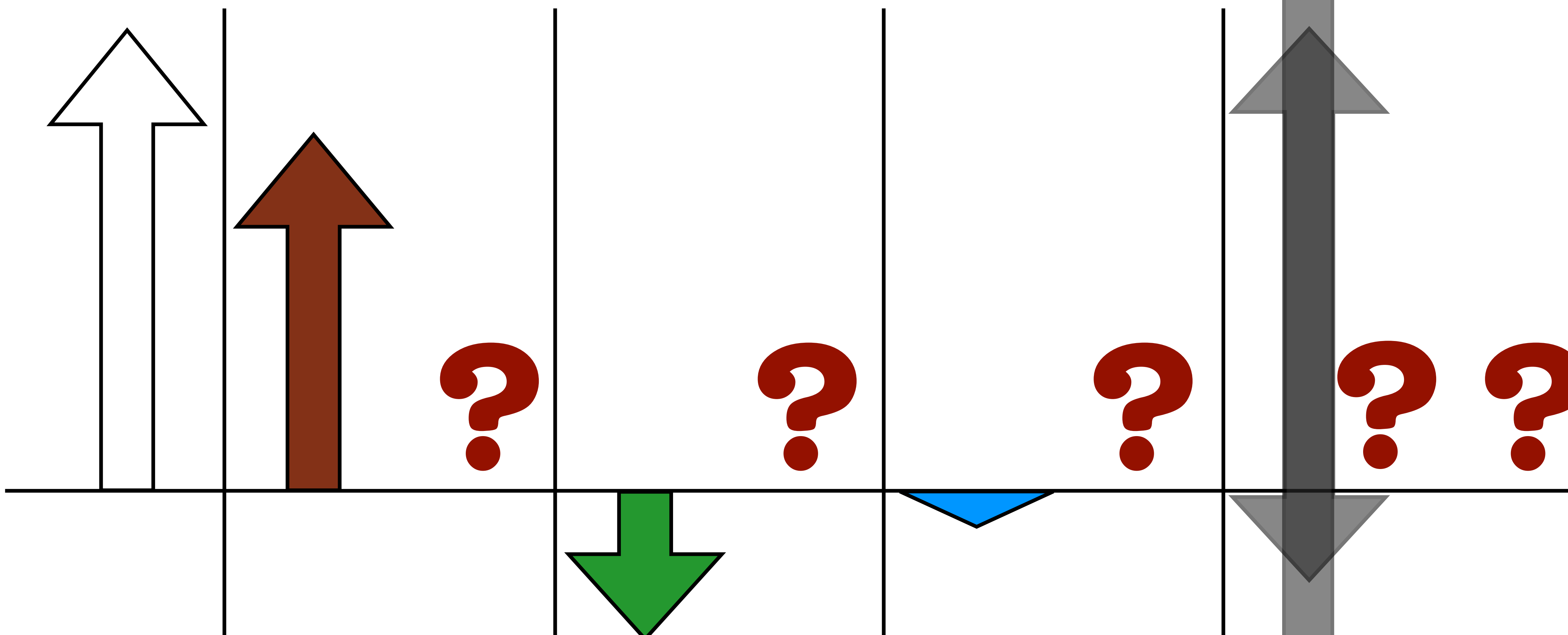

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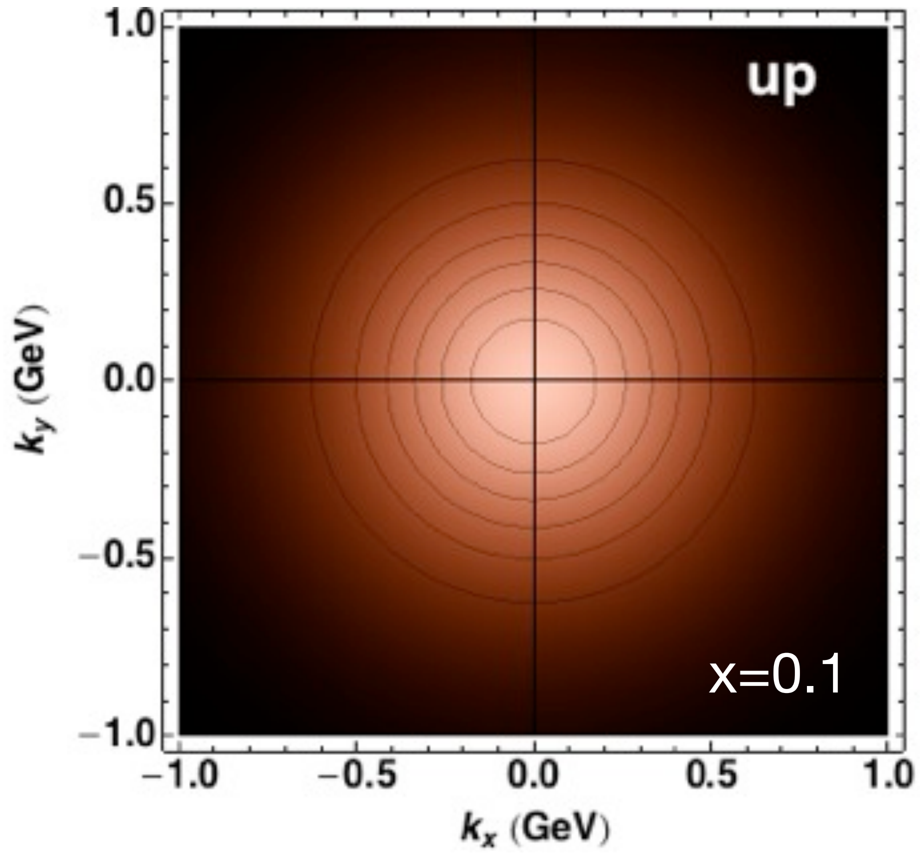
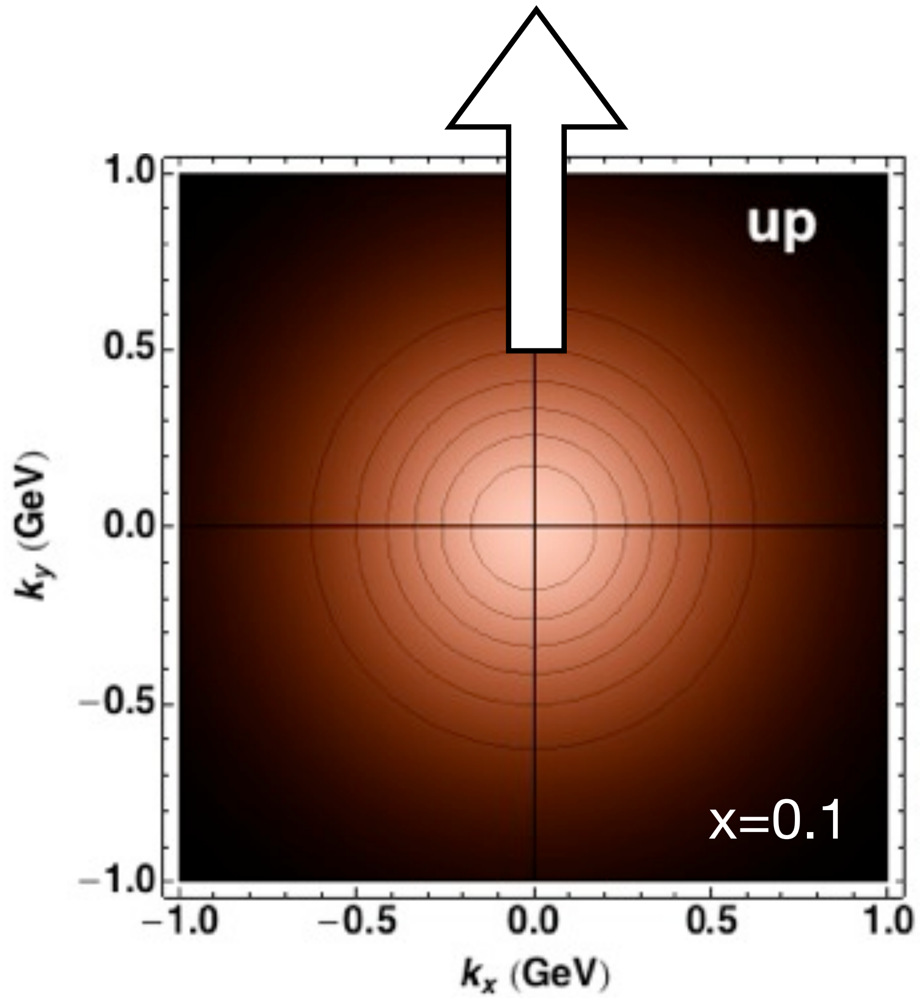
Transverse maps and orbital angular momentum



Transverse maps and orbital angular momentum

Transverse spin

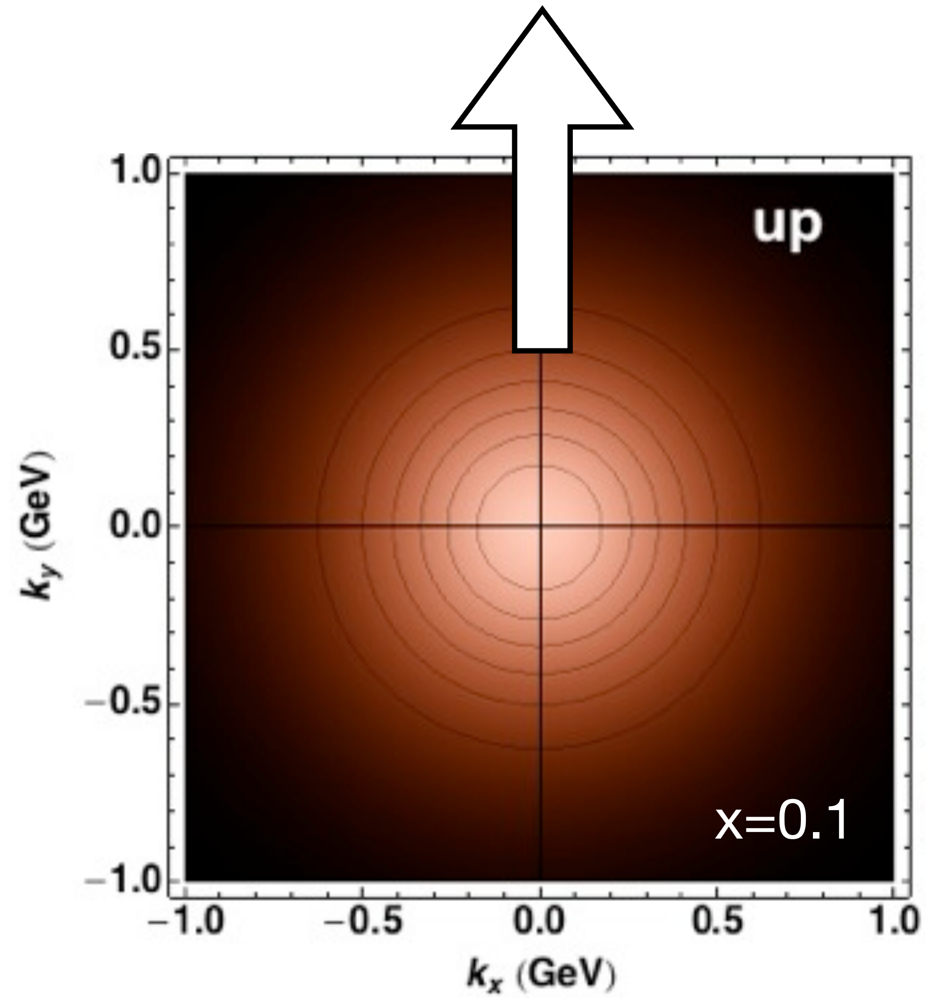


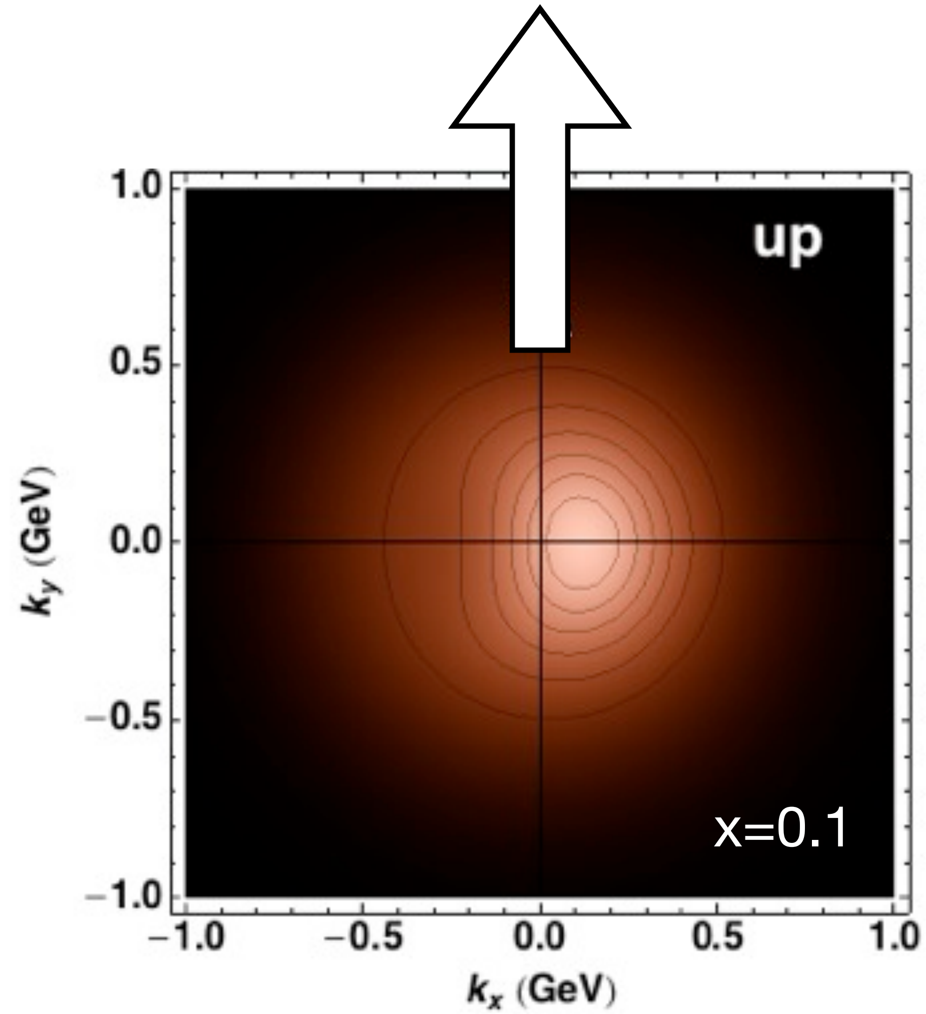
without

orbital angular momentum

Transverse maps and orbital angular momentum

Transverse spin



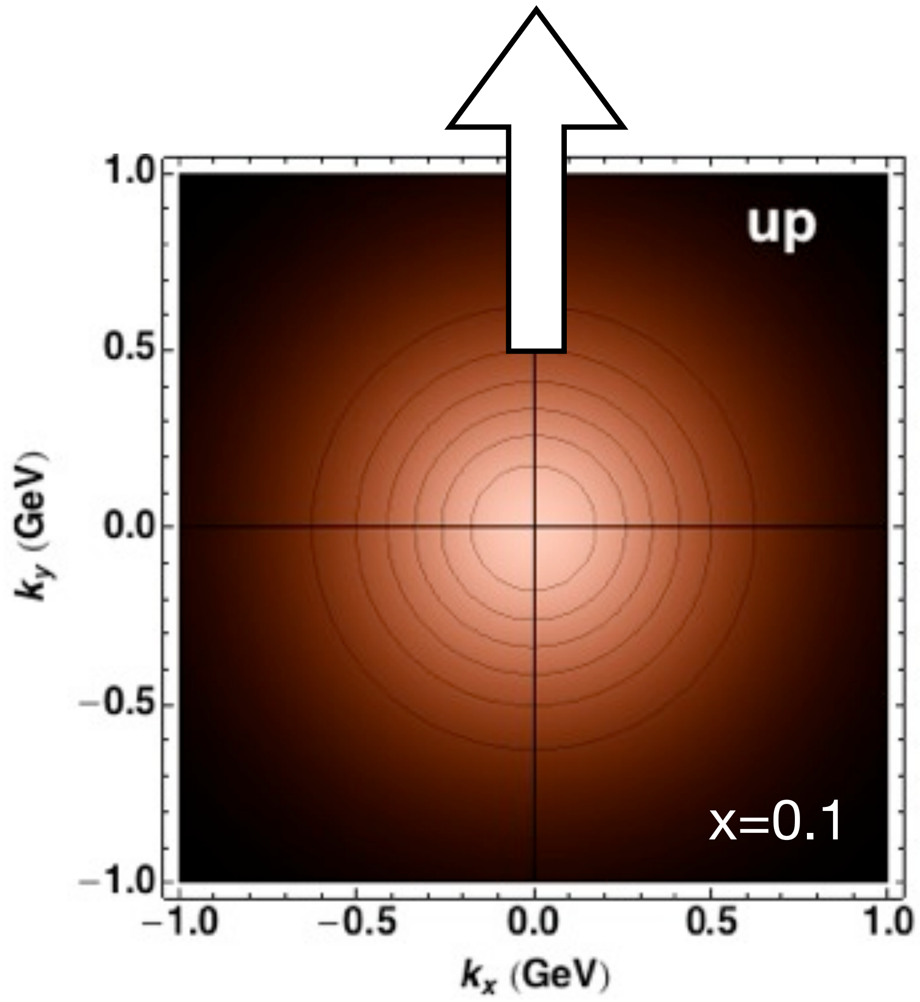


without orbital angular momentum

with orbital angular momentum

Transverse maps and orbital angular momentum

Transverse spin



without

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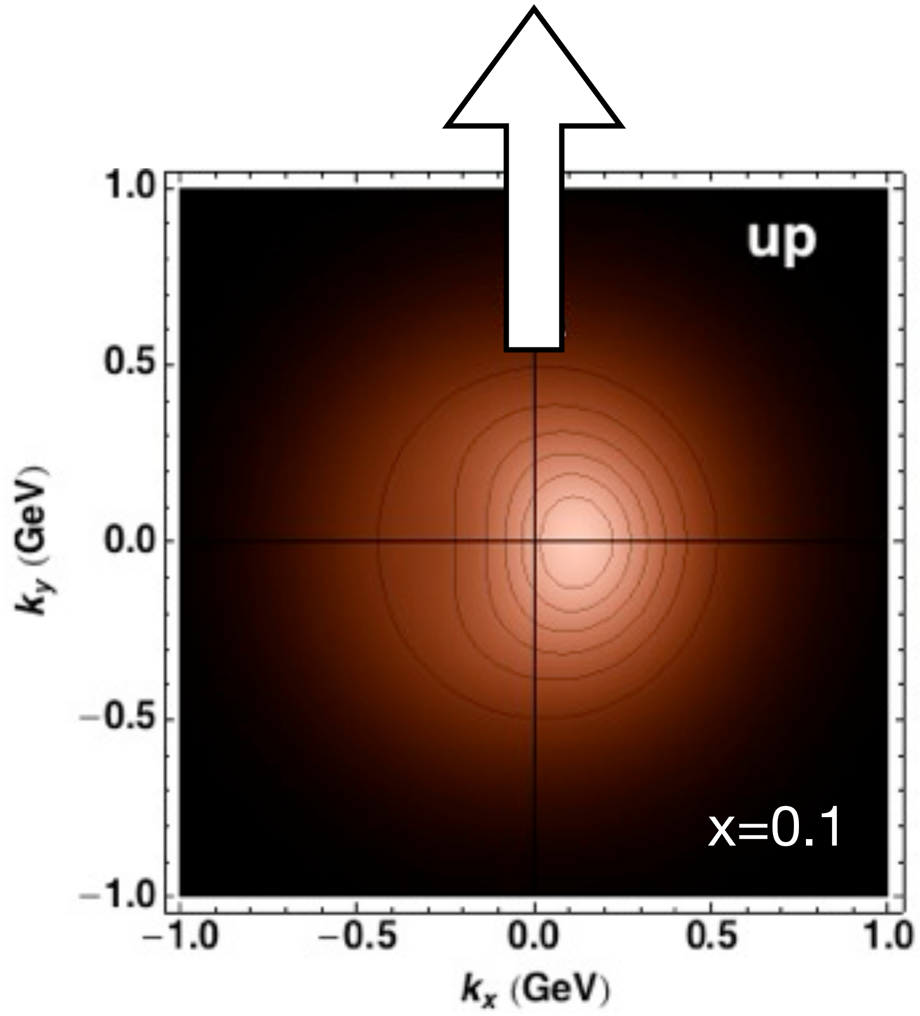


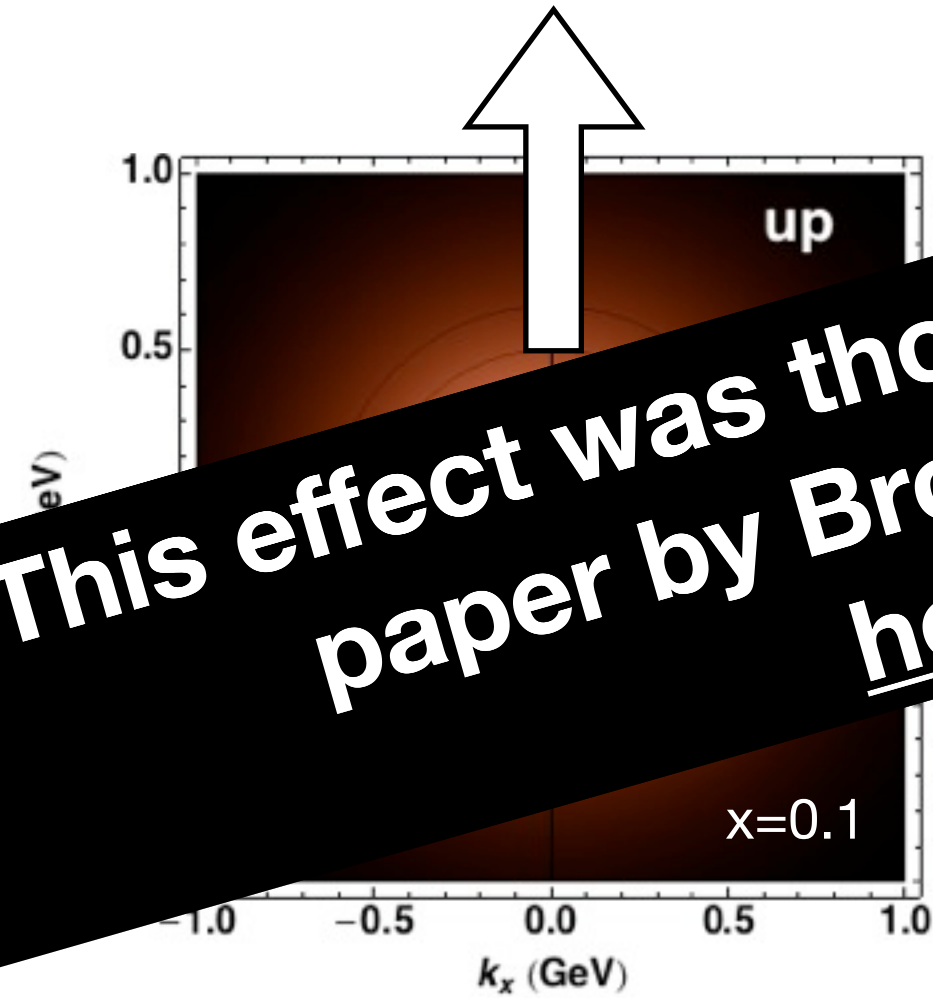
with

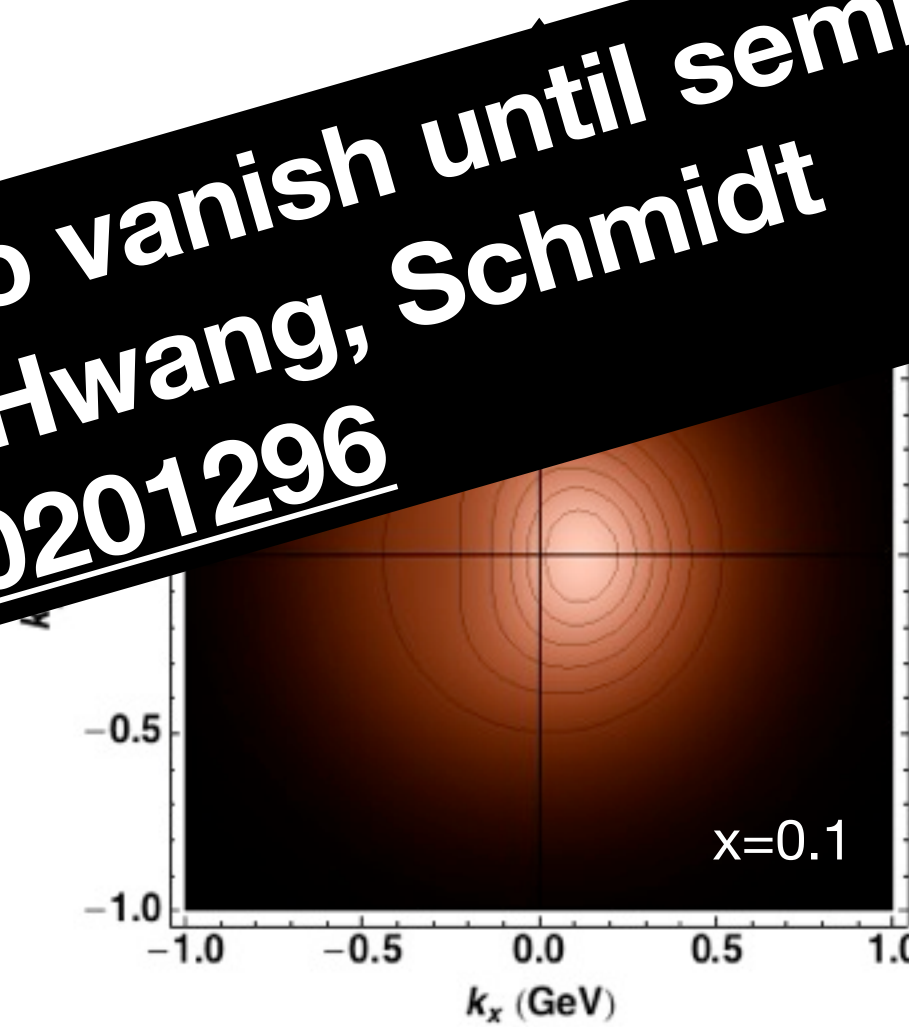
orbital angular momentum

"Sivers effect"

Transverse maps and orbital angular momentum

Transverse spin





This effect was thought to vanish until seminal paper by Brodsky, Hwang, Schmidt
hep-ph/0201296

without

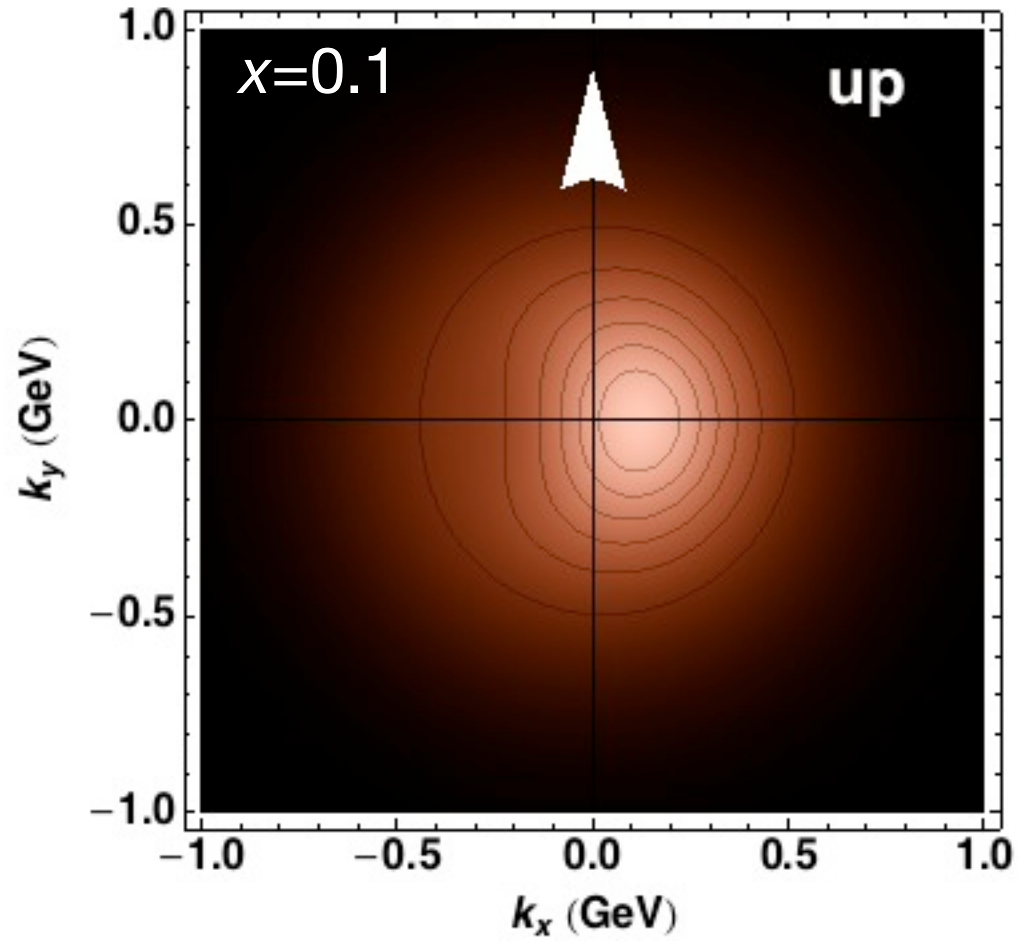
orbital angular momentum

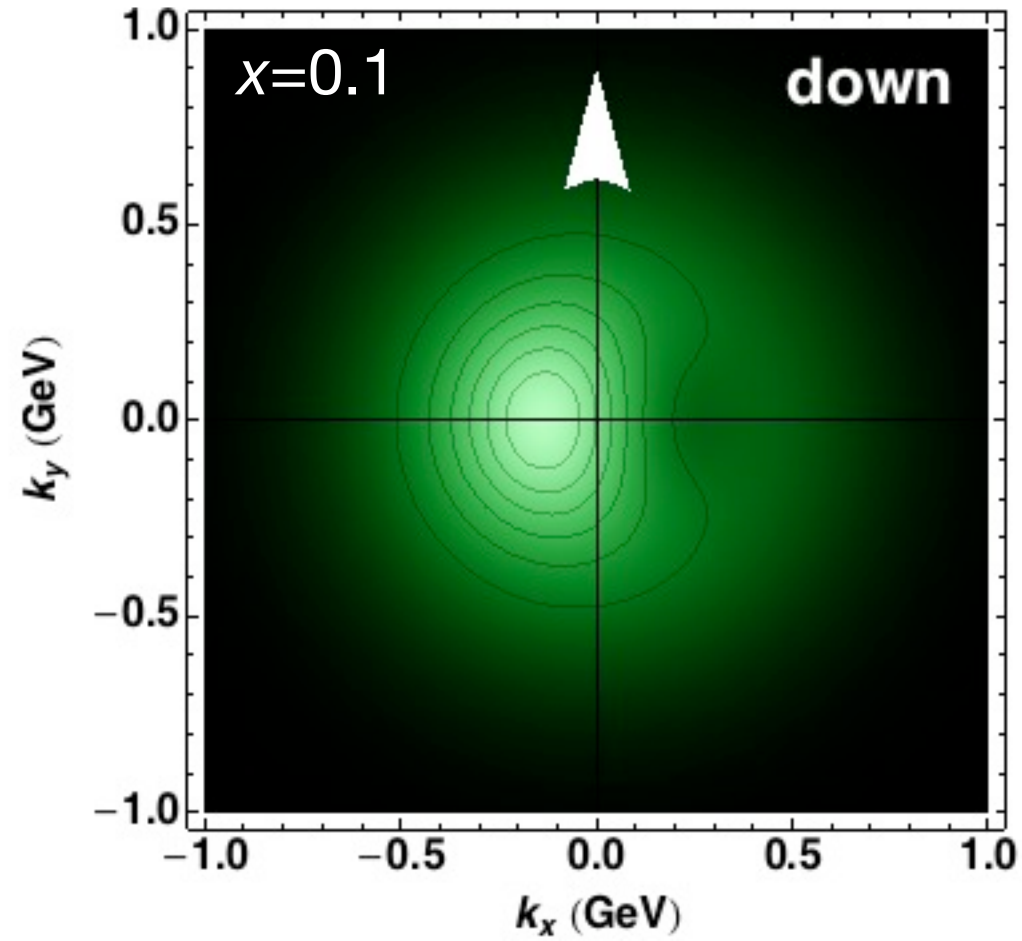
with

orbital angular momentum

"Sivers effect"

Extracted Sivers function





extraction from Bacchetta, Radici, arXiv:1107.5755

picture from A. Bacchetta, M. Contalbrigo, Il Nuovo Saggiatore 2012

see also Anselmino, Boglione, Melis, PRD86 (12)

Change of sign in Drell-Yan

Change of sign in Drell-Yan

Sivers function $_{\text{SIDIS}}$ = − Sivers function $_{\text{Drell-Yan}}$

Collins, PLB 536 (02)

Change of sign in Drell-Yan

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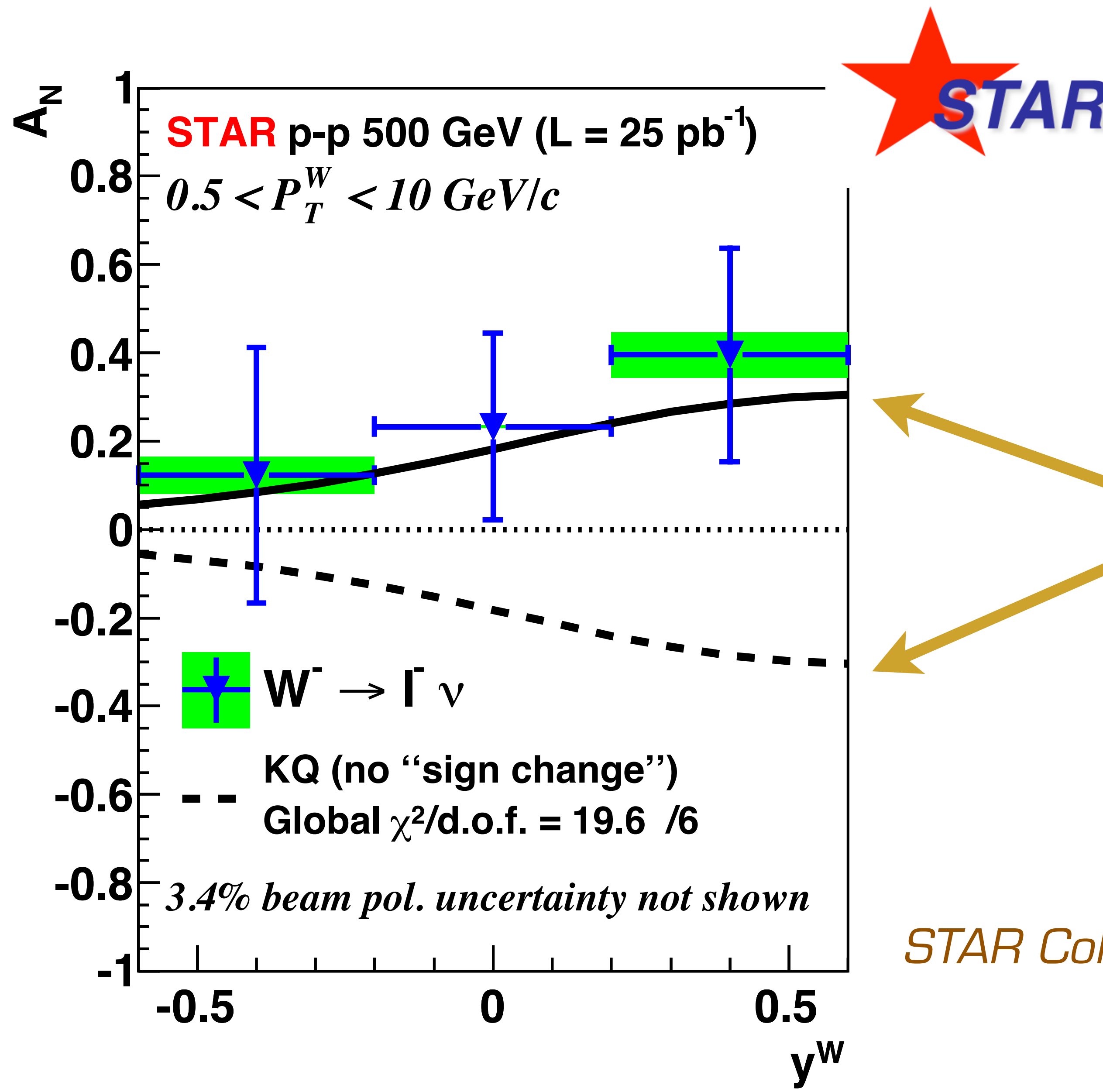
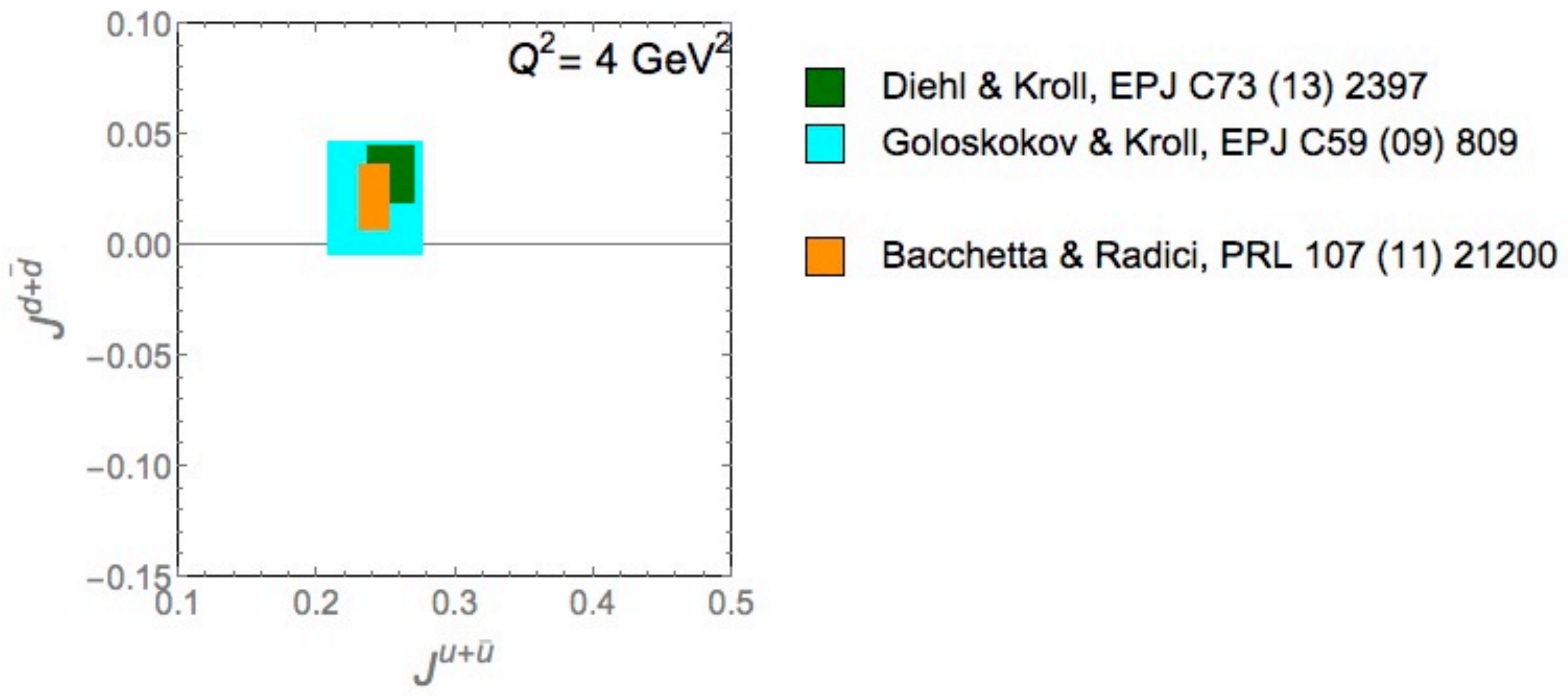
Collins, PLB 536 (02)



first evidence of sign change?

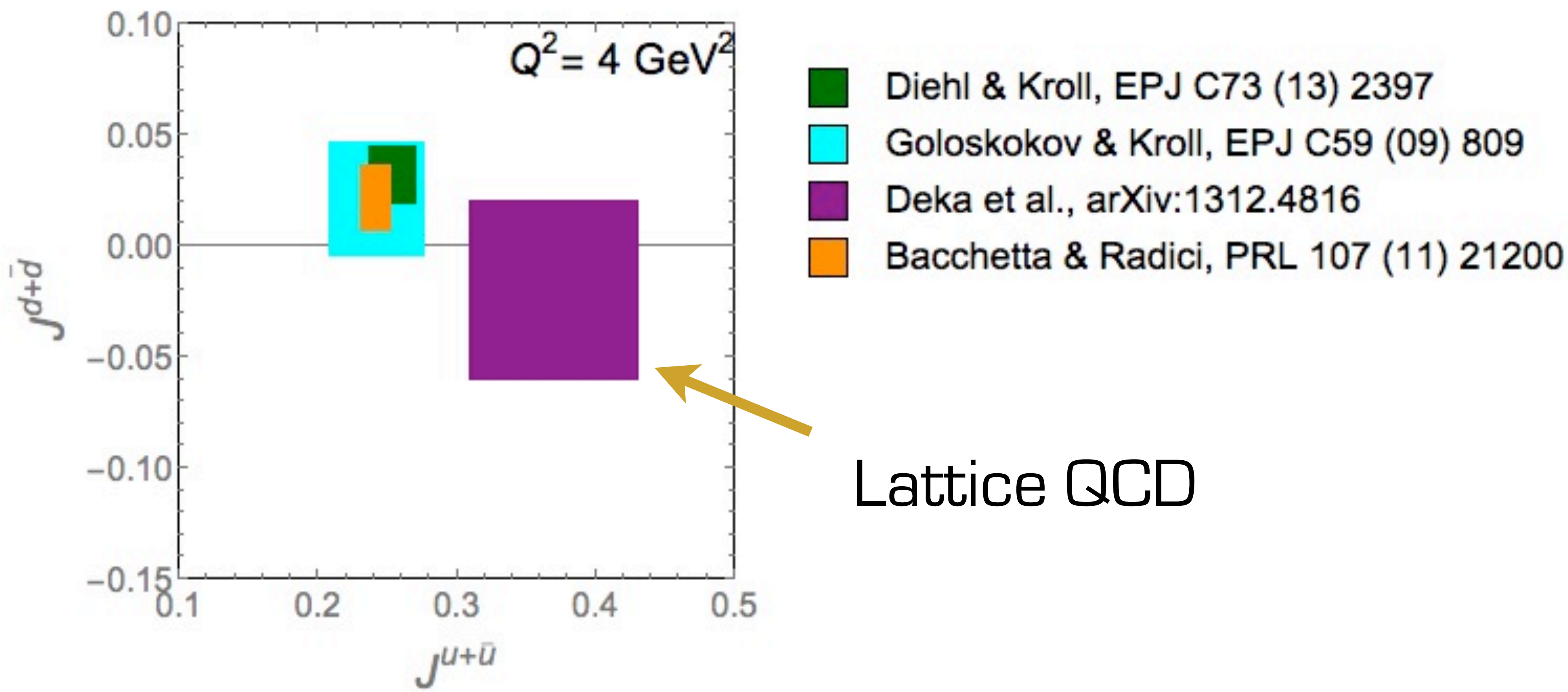
STAR Collab. arXiv:1511.06003

Sivers function and angular momentum



Estimate of angular momentum based on model assumptions + Sivers fit

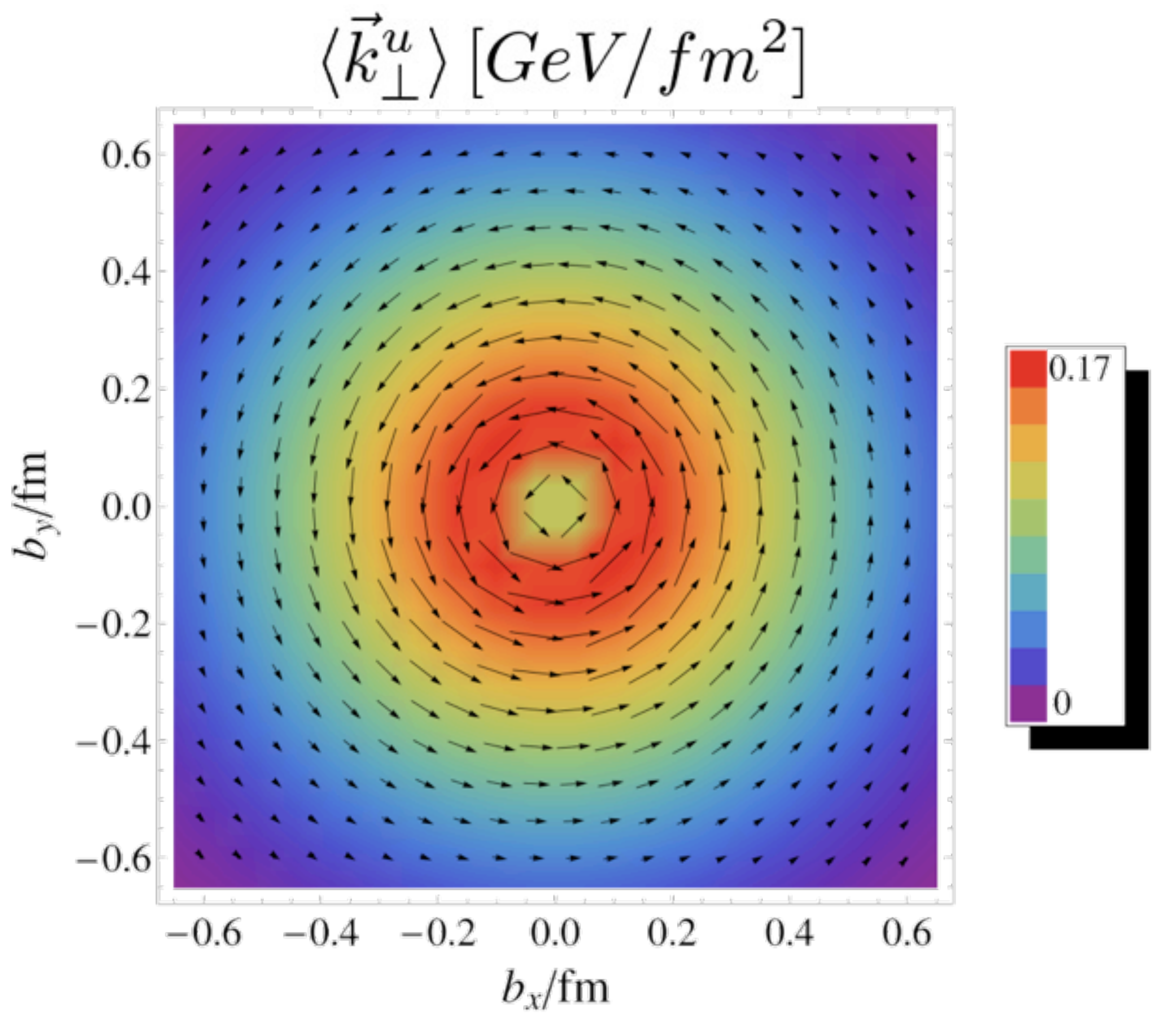
Sivers function and angular momentum

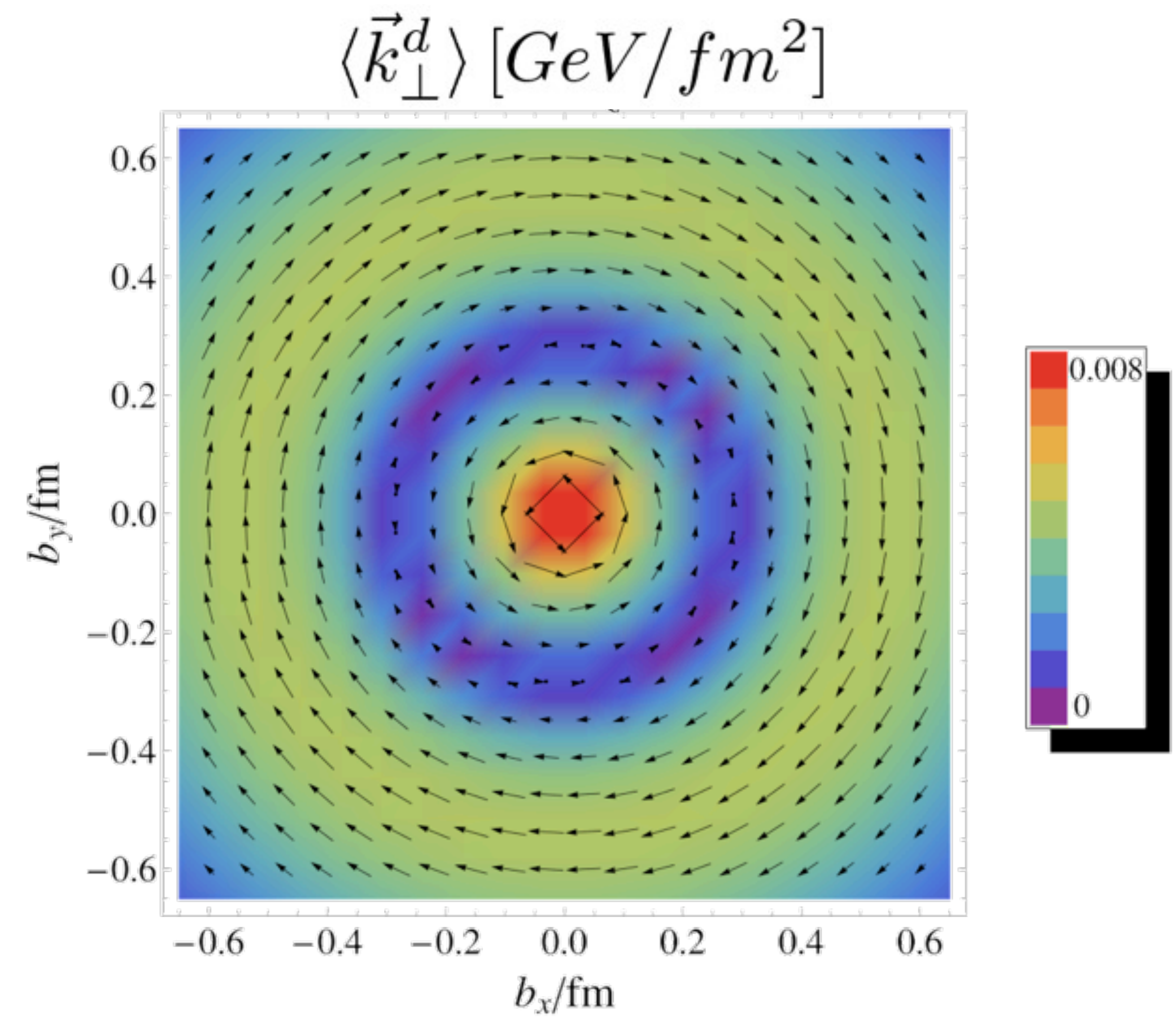


Estimate of angular momentum based on model assumptions + Sivers fit

Angular momentum and Wigner dist.

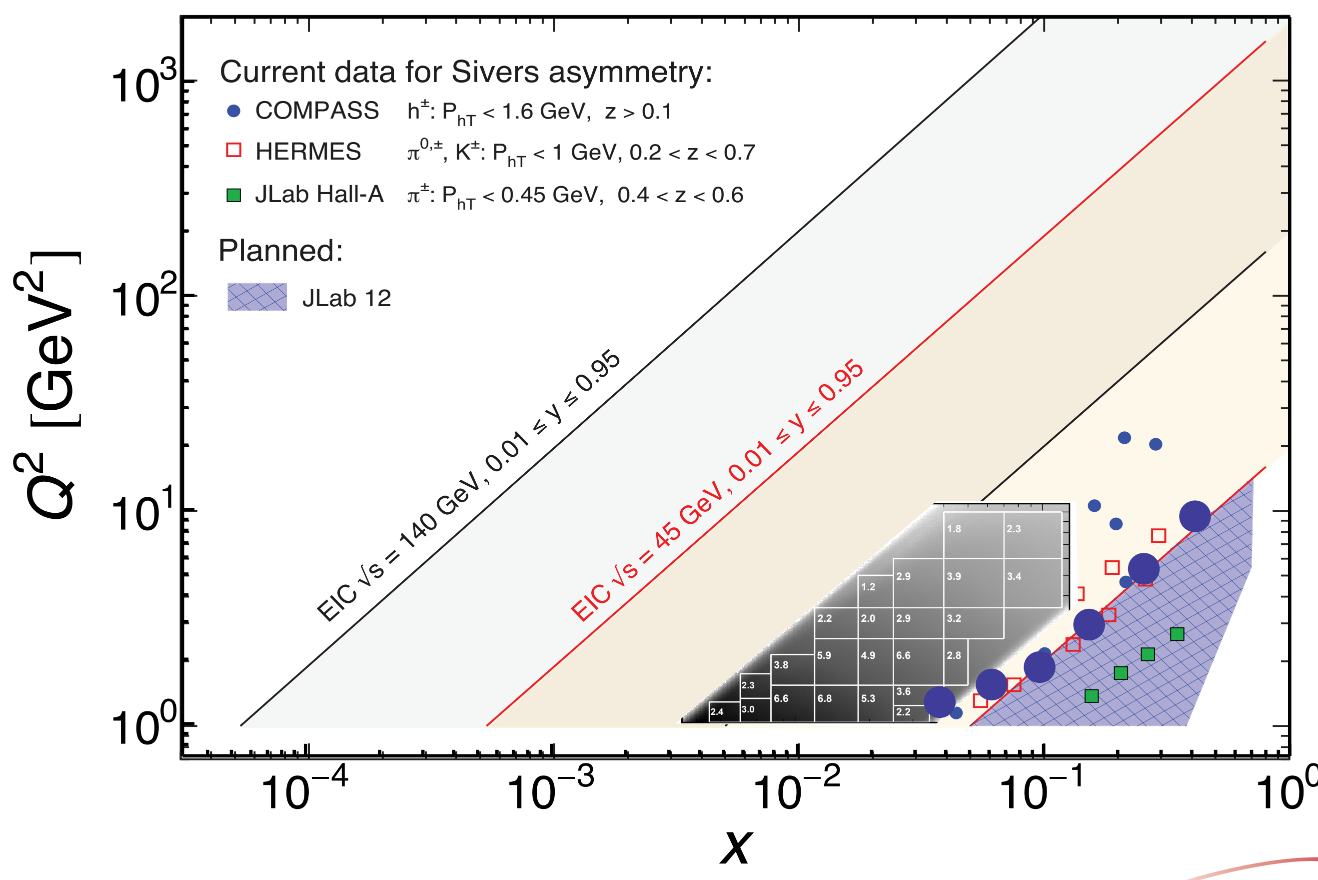
$$\mathcal{L}_z^q = \int \mathrm{d}x \mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp) \rho_{LU}^q(\vec{b}_\perp, \vec{k}_\perp, x)$$





based on Pasquini, Lorcé, Xiong, Yuan, PRD 85 (12)

Future experimental plans

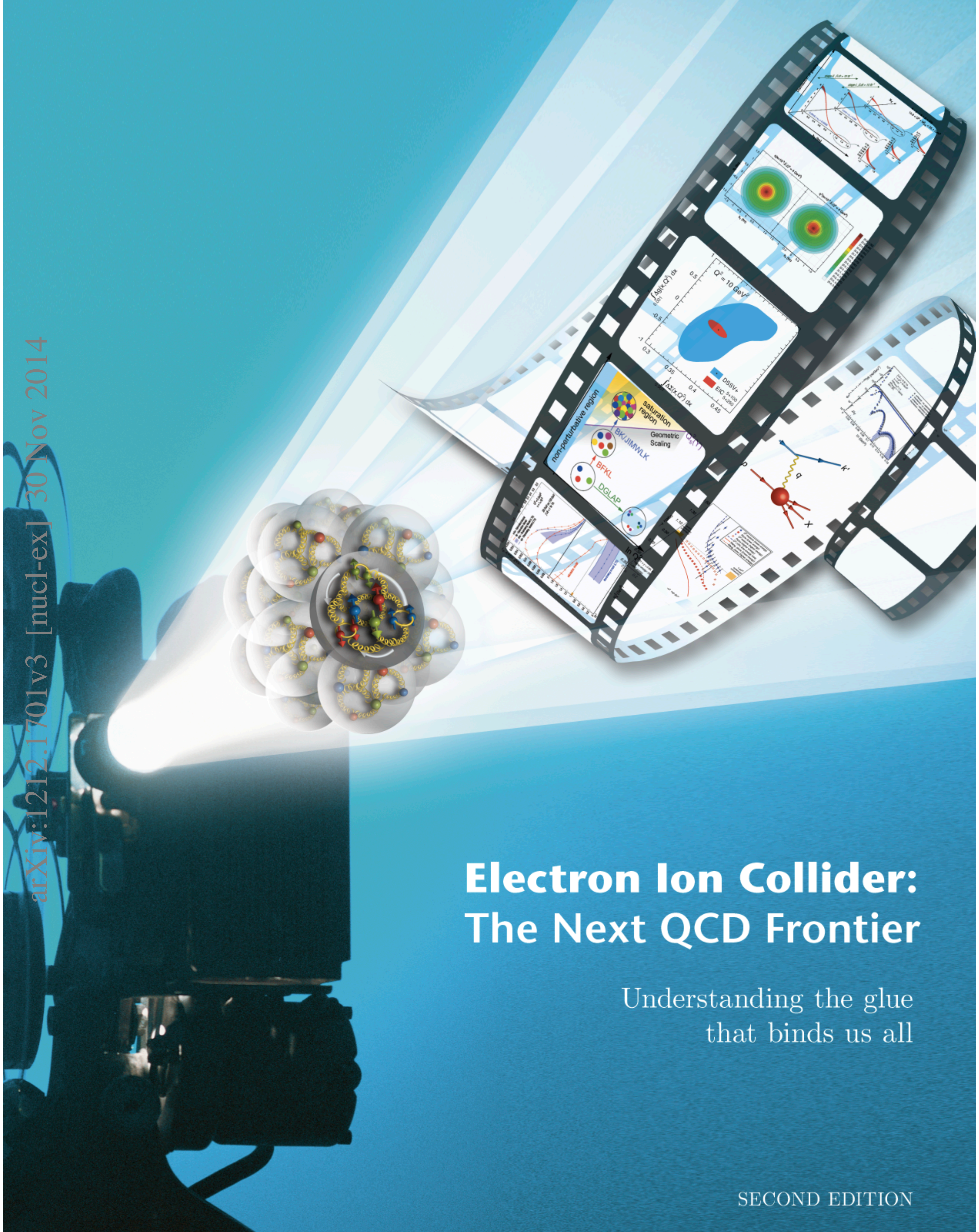


hermes

Jefferson Lab

COMPASS

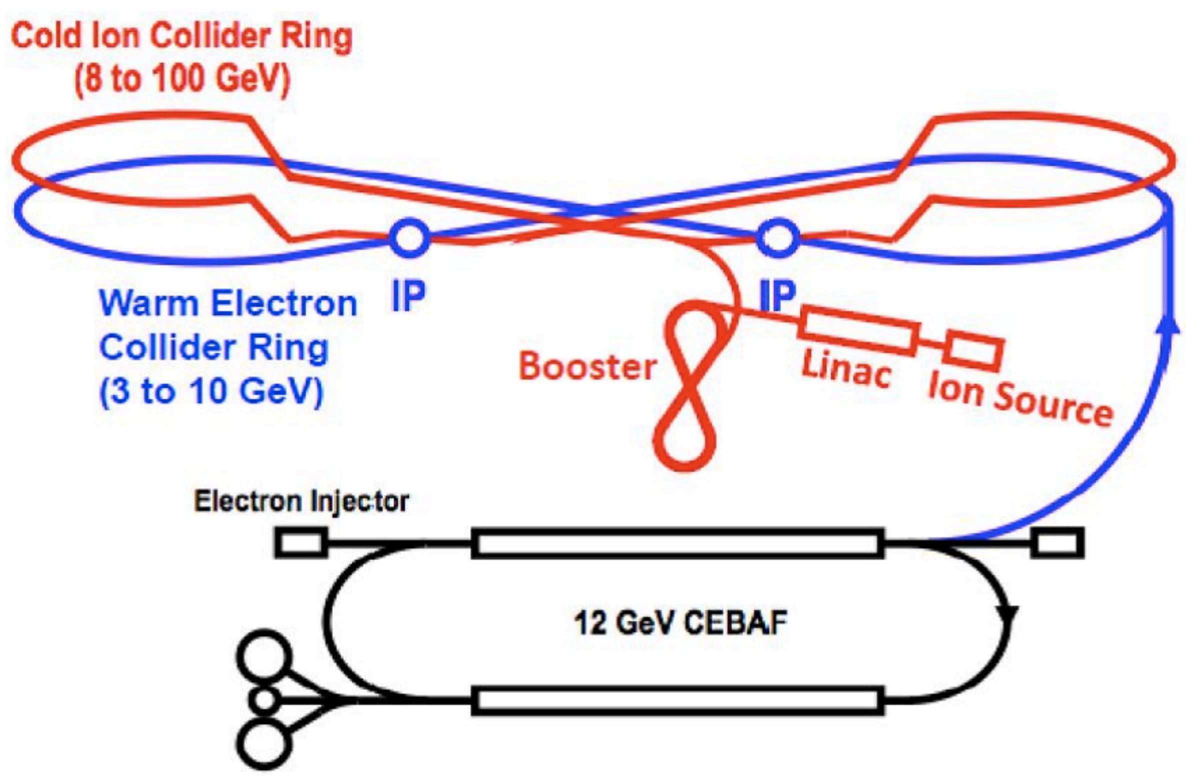
Accardi et al., The Electron Ion Collider: the next QCD Frontier arXiv:1212.1701 http://arxiv.org/abs/arXiv:1212.1701

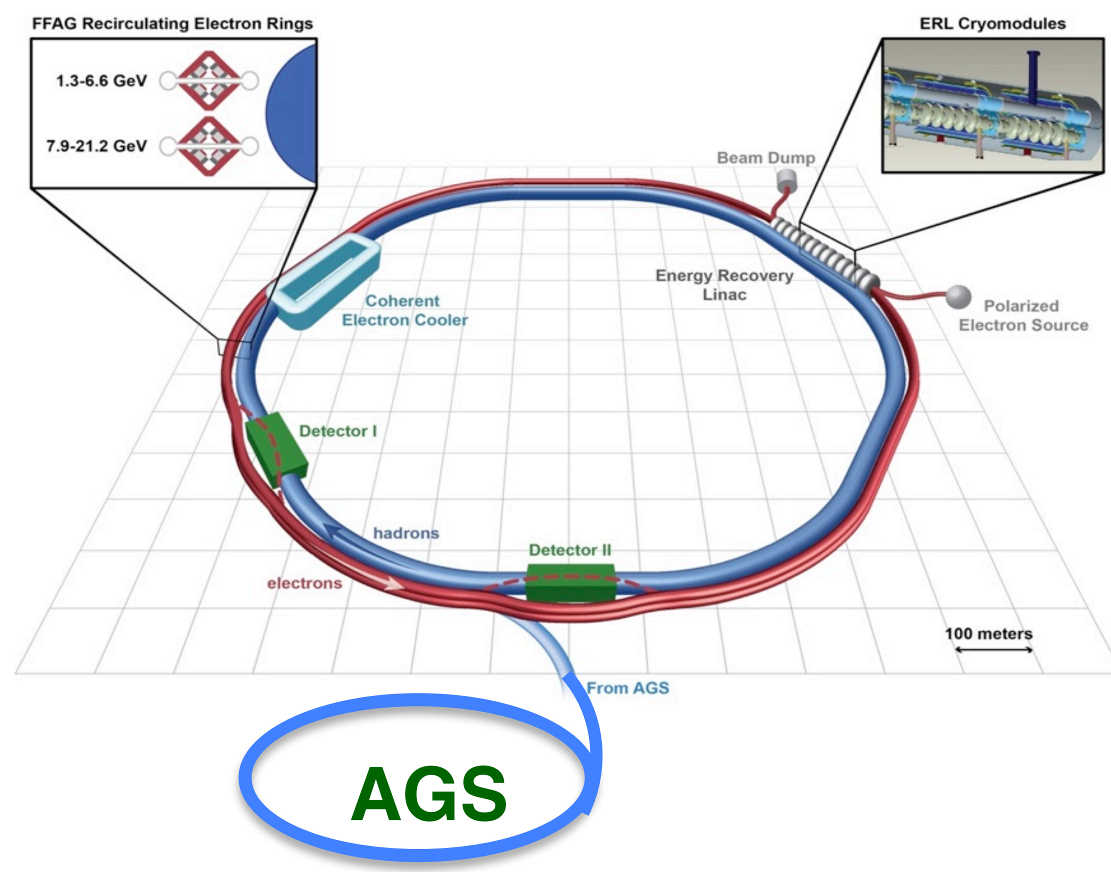


Electron Ion Collider

JLab

BNL





Accardi et al., The Electron Ion Collider: the next QCD Frontier, arXiv:1212.1701

Conclusions

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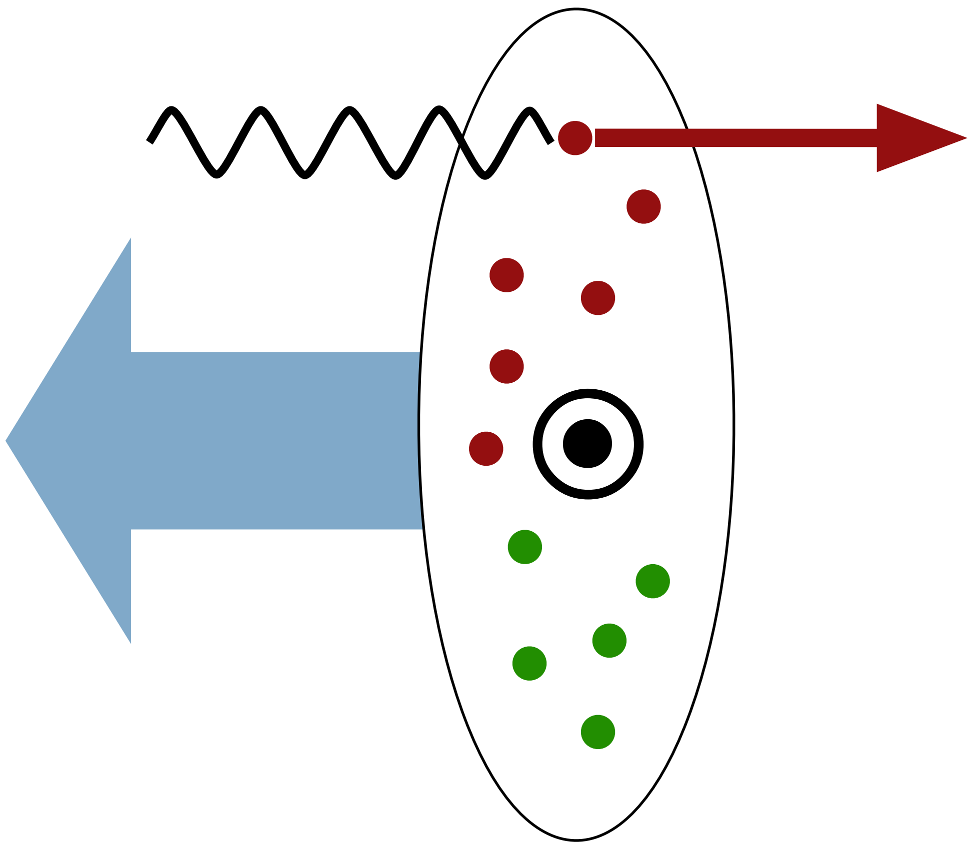
- TMDs allow us to investigates aspects of nucleon structure that are not accessible to standard collinear PDFs

- A lot of data is already available, but we expect more from e^+e^-, SIDIS at higher energies, Drell-Yan…

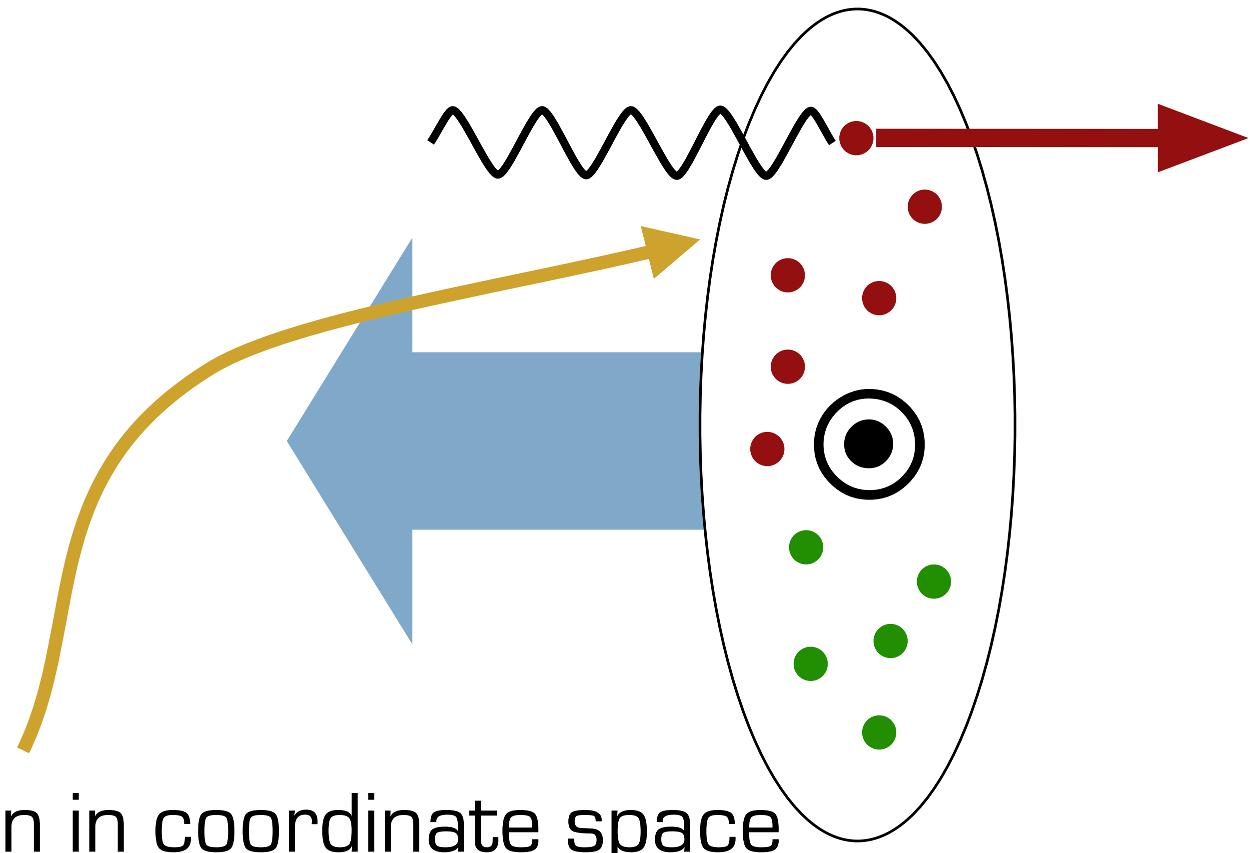
- Some parametrizations of TMDs are available, but we are a long way from anything similar to PDF global fits

Sivers function and angular momentum



based on Burkardt, PRD66 (02)

Sivers function and angular momentum

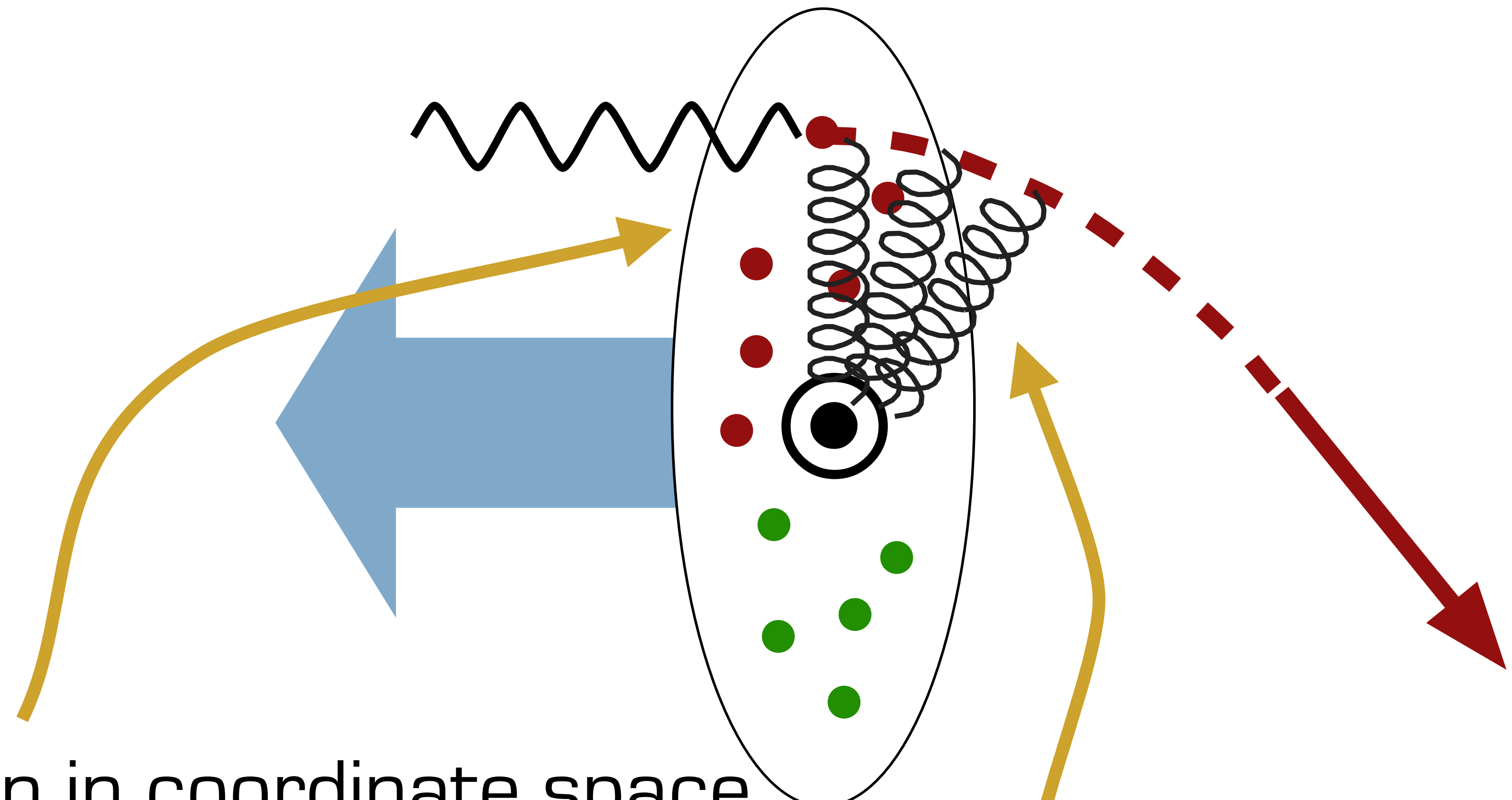


Distortion in coordinate space related to orbital angular momentum

$$E^a(x,0,0;Q_L^2)\ L(x) = f_{1T}^{\perp(0)a}(x;Q_L^2)$$

based on Burkardt, PRD66 (02)

Sivers function and angular momentum



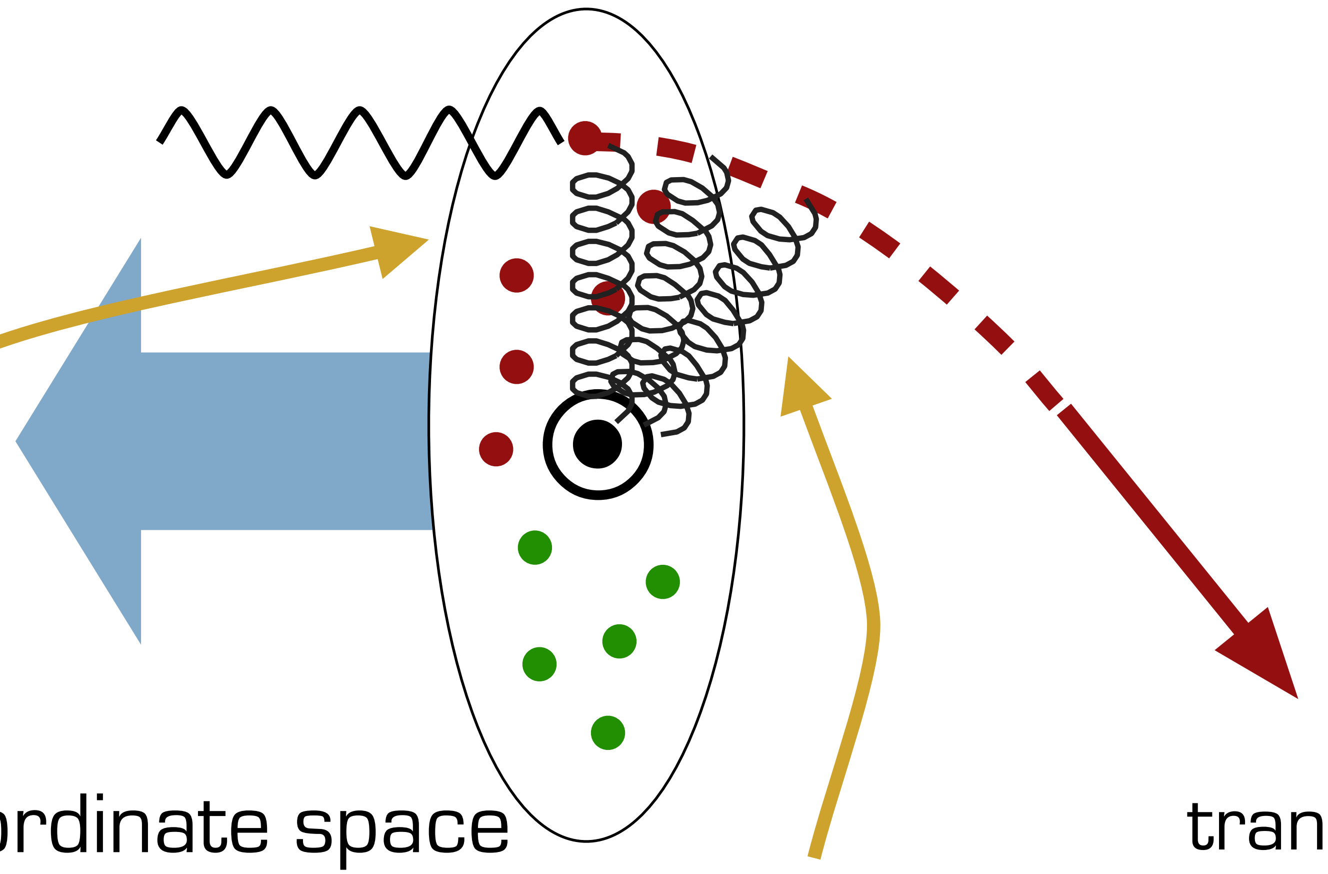
Distortion in coordinate space related to orbital angular momentum

Lensing function (final-state interaction)

$$E^a(x,0,0;Q_L^2)\; L(x) = f_{1T}^{\perp(0)a}(x;Q_L^2)$$

based on Burkardt, PRD66 (02)

Sivers function and angular momentum



Sivers function (distortion in transverse-momentum space)

Distortion in coordinate space related to orbital angular momentum

Lensing function (final-state interaction)

$$E^a(x,0,0;Q_L^2)\ L(x) = f_{1T}^{\perp(0)a}(x;Q_L^2)$$

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