Transverse momentum at work in high-energy scattering experiments

Andrea Signori

APS April meeting
Washington DC
Jan. 29th

Jefferson Lab

About the speaker

Nov. 2016 - present | postdoc
Jefferson Lab (VA, USA)

2012 - 2016 | PhD candidate
Nikhef and Vrije Universiteit
Amsterdam (NL)

2012 | Summer intern
DESY - Hermes collaboration (GE)

2012 | Master student
"Hadron structure and QCD" group
Pavia U. (IT)

Why investigate hadron structure (TMD & collinear) ?

1) **Nucleon tomography**:
to understand how hadrons are built in terms of the elementary degrees of freedom of QCD

2) **High-energy phenomenology**:
to explore the manifestation of hadron structure in high-energy scattering experiments

Some open questions :

1) do we understand the **interplay** and the **matching** between **collinear** and **TMD factorization** ?

2) can we access collinear and TMD distributions ?

3) what's the **impact of hadron structure** on the determination of **Standard Model parameters** ?

4) what is the behavior of gluon TMDs at small-x ?

5) can we quantify factorization breaking effect ?

6) can we attempt a **global fit of TMDs** ?

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Hadron structure in 3D momentum space

TMD correlators

quark content

$$\Phi_{ij}(x, \mathbf{k}_T) \sim \text{F.T. } \langle P|\bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)|P\rangle_{|_{\xi^+=0}}$$

parametrized with → **quark TMD PDFs**

Bacchetta, Mulders
Phys.Rev. D62 (2000) 114004

gluon content

$$\Gamma^{\alpha\beta}(x, \mathbf{k}_T) \sim \text{F.T. } \langle P|F^{+\alpha}(0)\ U_{[0,\xi]}\ F^{+\beta}(\xi)\ U'_{[\xi,0]}|P\rangle_{|_{\xi^+=0}}$$

→ **gluon TMD PDFs**

Boer, Cotogno, van Daal, Mulders, Signori, Zhou
JHEP 1610 (2016) 013

loop correlator

$$\Gamma_0(x, \mathbf{k}_T) \sim \delta(x)\ \text{F.T. } \langle P|U^{[+]}_{[0,\xi]}\ U^{[-]}_{[\xi,0]}|P\rangle_{|_{\xi^+=0}}$$

→ **Wilson loop TMD PDFs**

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link with
small-x physics

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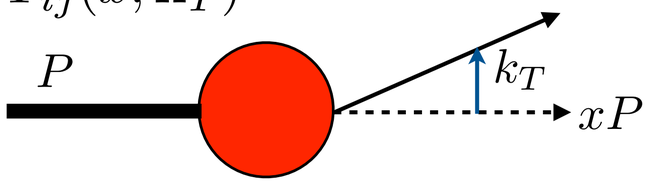
Quark TMD PDFs in a proton

$\Phi_{ij}(x, \mathbf{k}_T)$



extraction of a **quark**
not collinear with the proton

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

$f_1^q(x, k_T^2)$

involve all 3 components:
richer than 1D PDFs

spin-spin and **spin-orbit**
interactions

Contain nonperturbative information,
need (possibly global) fits!

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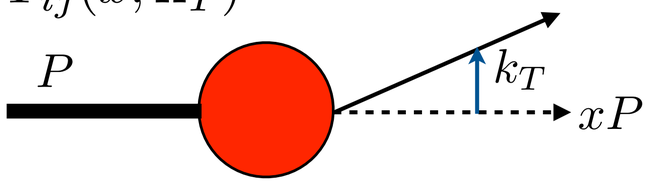

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Twist-2 TMDs

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involve all 3 components:
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Contain nonperturbative information,
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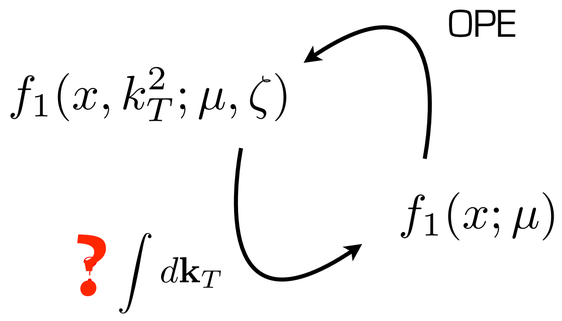
only **three collinear PDFs** survive integration
of the correlator
over the quark transverse momentum

$$\Phi_{ij}(x) \sim f_1(x),\ g_1(x),\ h_1(x)$$

the **relation** between
TMD and collinear distributions
is delicate from the pQCD viewpoint:



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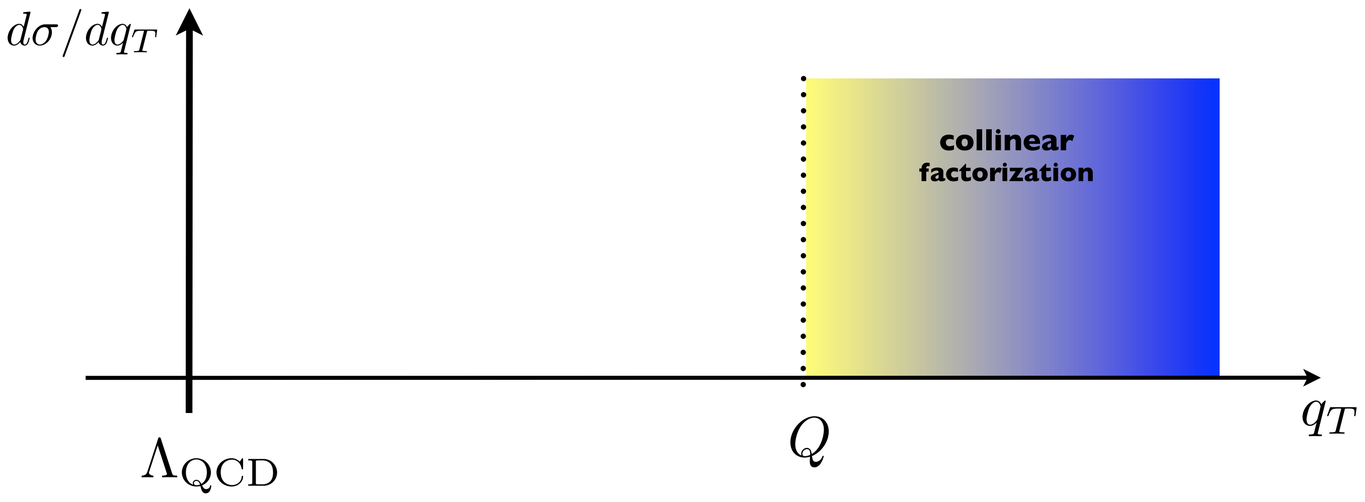
Collinear and TMD factorization

Emergence of TMD and collinear correlators/distributions
from **factorization theorems**



$\sim \Phi_A(x_a)\ \Phi_B(x_b)$

collinear PDFs

$q_T \geq Q$

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Emergence of TMD and collinear correlators/distributions
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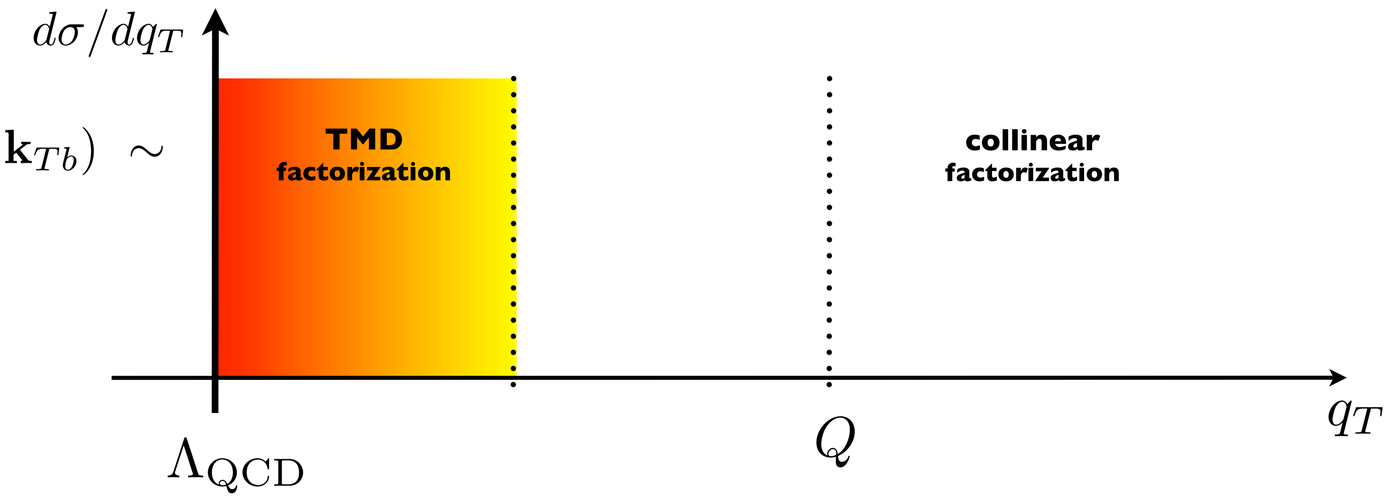
$\Phi_A(x_a, \mathbf{k}_{Ta})\ \Phi_B(x_b, \mathbf{k}_{Tb}) \sim$

TMD PDFs



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collinear PDFs

$$\Lambda_{\rm QCD} \ll q_T \ll Q$$

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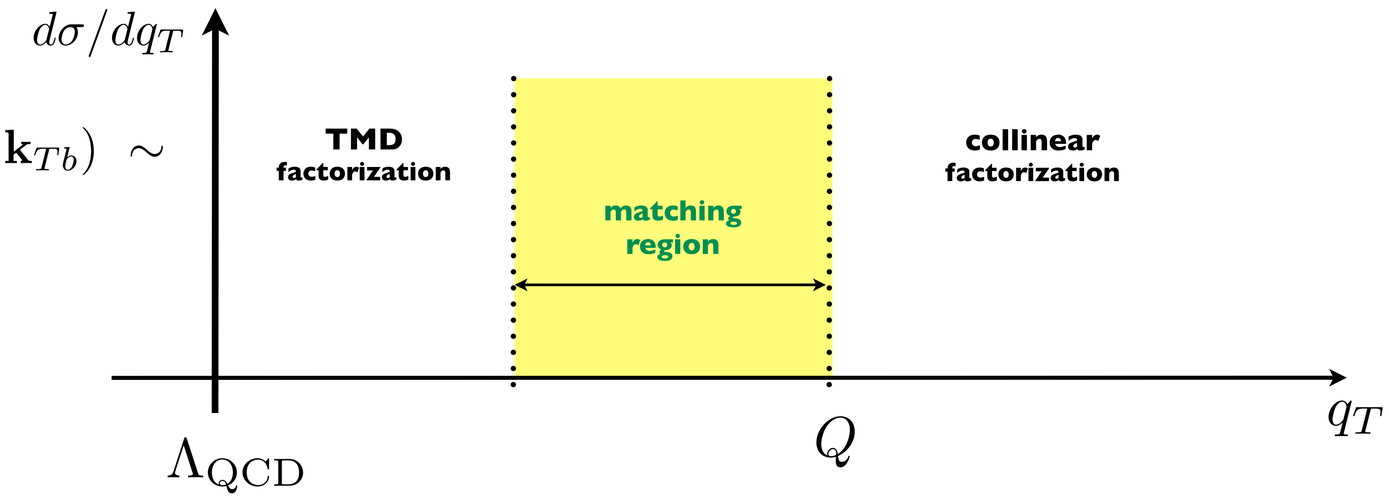

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collinear PDFs

$\Lambda_{\rm QCD} \ll q_T \ll Q$

$q_T \geq Q$

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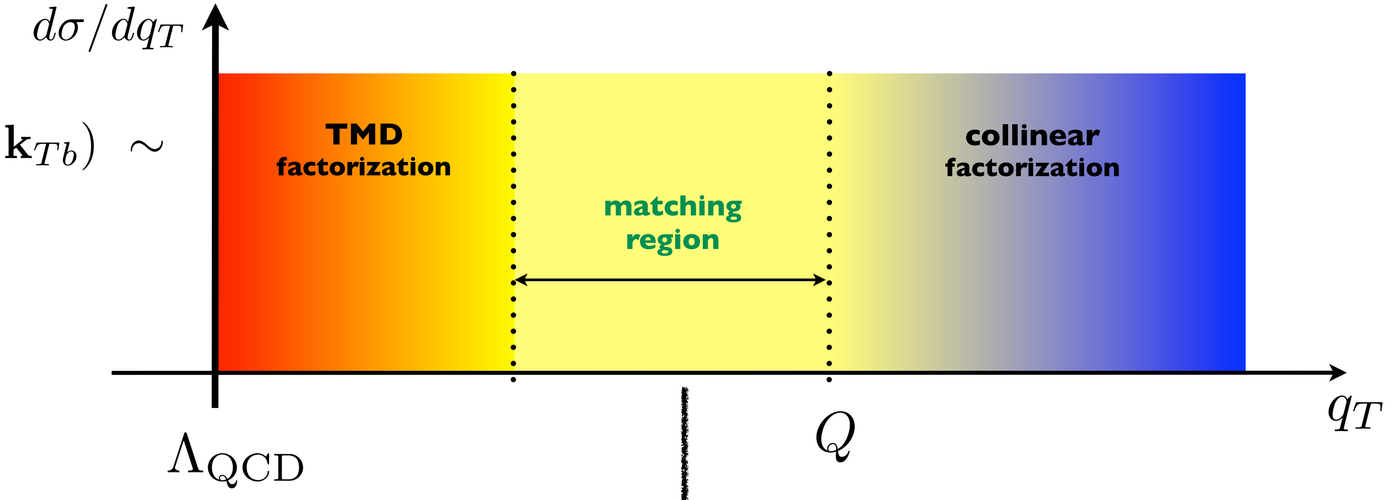
Collinear and TMD factorization

$d\sigma/dq_T$ = **W** (TMD PDFs) + **Y** (collinear PDFs + prescriptions)

$\Phi_A(x_a, \mathbf{k}_{Ta})\ \Phi_B(x_b, \mathbf{k}_{Tb}) \sim$

TMD PDFs



$\sim \Phi_A(x_a)\ \Phi_B(x_b)$

collinear PDFs

The formalism for **Semi-Inclusive DIS** (SIDIS) **at low energy** needs special care:

prescription for matching
Phys.Rev. D94 (2016) no.3, 034014

current fragmentation region ?
Phys.Lett. B766 (2017) 245-253

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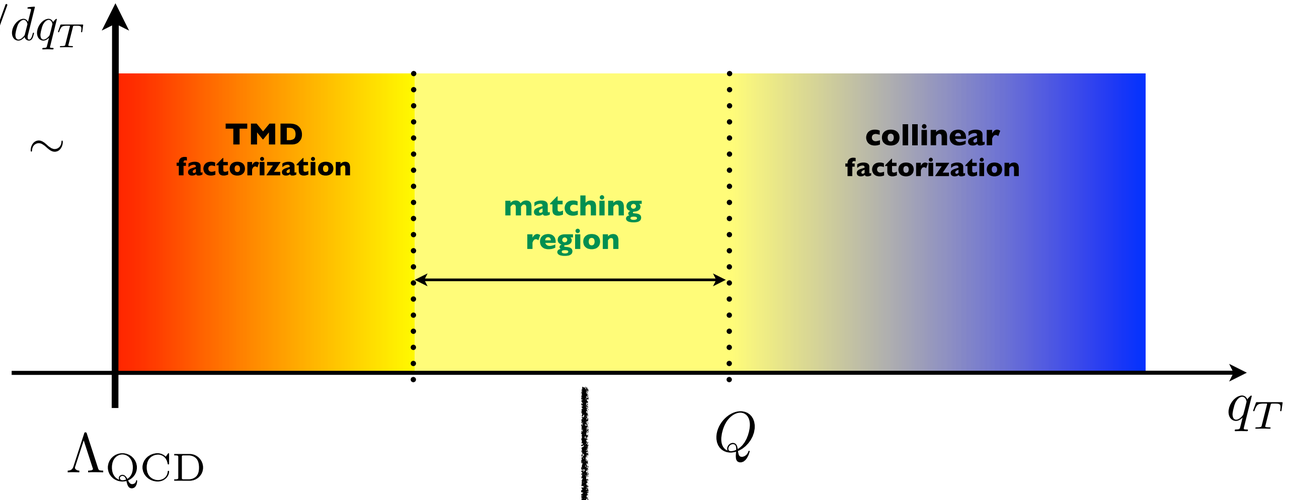

$\sim \Phi_A(x_a)\ \Phi_B(x_b)$

collinear PDFs

A detailed investigation of the **nonperturbative part of TMD PDFs** is affected by the **description of the whole q_T range**

we need to improve the description of both W and Y terms

what about polarized cross sections ..?

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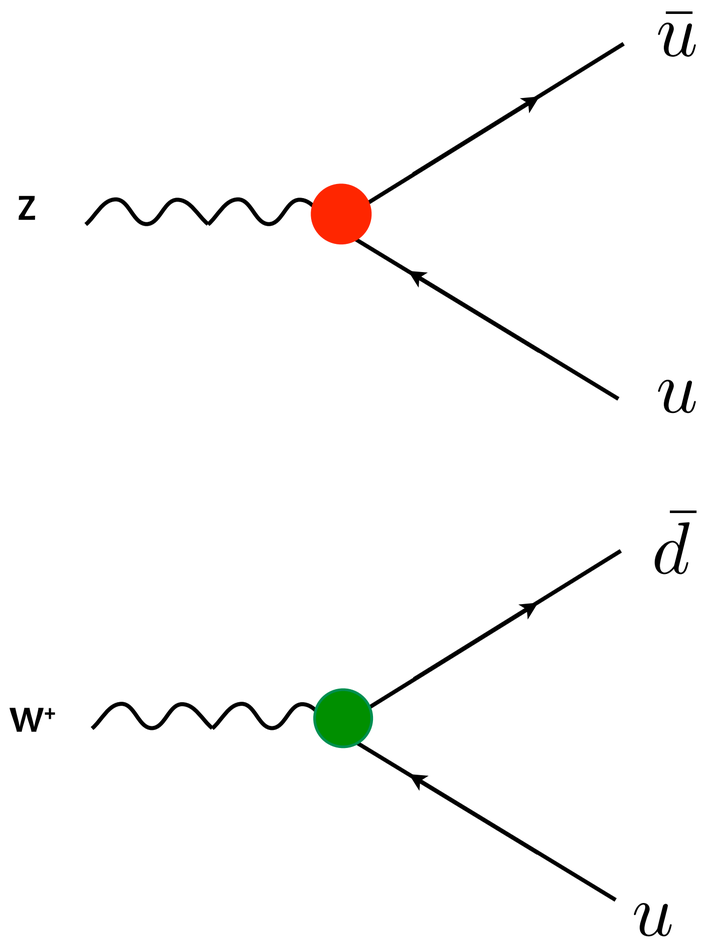
quark TMDs at work : W± at LHC

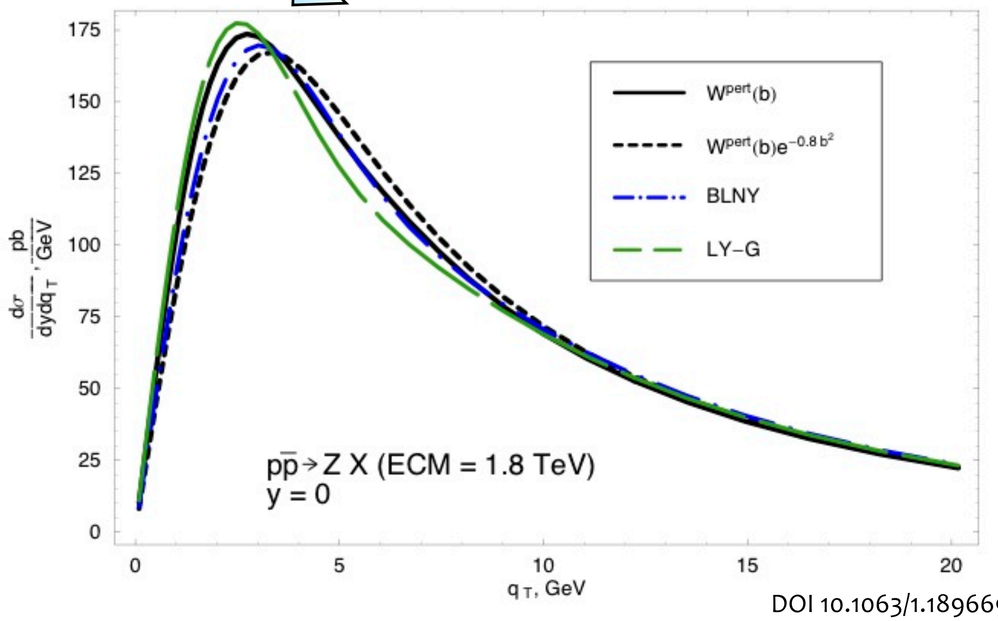
AS - PhD thesis (inspire)



$$\frac{d\sigma^{Z/W^\pm}}{dq_T} \sim \mathrm{FT} \sum_{i,j} \exp\{-g_{ij}\, b_T^2\}$$

g_{ij} comes from 2 TMD PDFs
and ***controls the position of the peak***

$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$



DOI 10.1063/1.1896698

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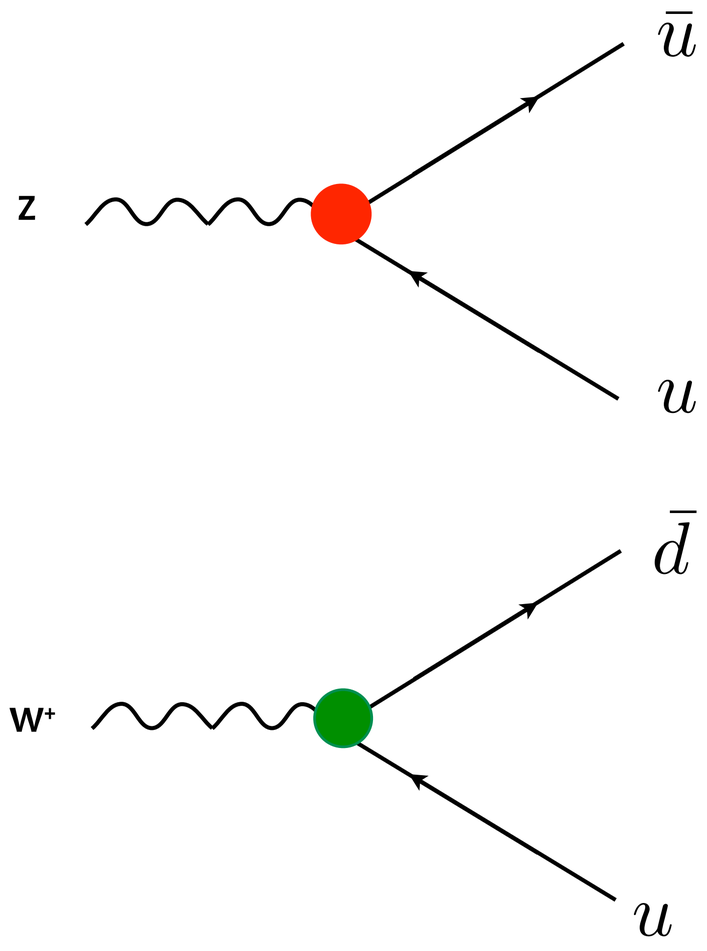

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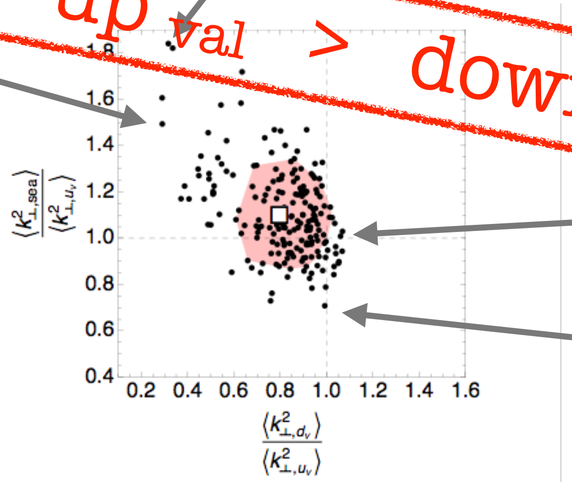
Parton model analysis of HERMES Semi-Inclusive DIS data

sea > up val > down val

replica 149
χ^2/dof = 1.87

replica 73
χ^2/dof = 1.70



replica 130
χ^2/dof = 1.77

replica 186
χ^2/dof = 1.38

sea width > (mostly) u_v width

point of no flavor dep.

d_v width < (mostly) u_v width

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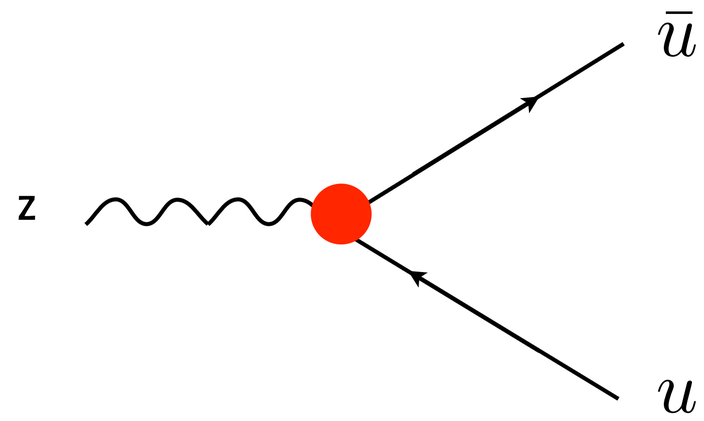

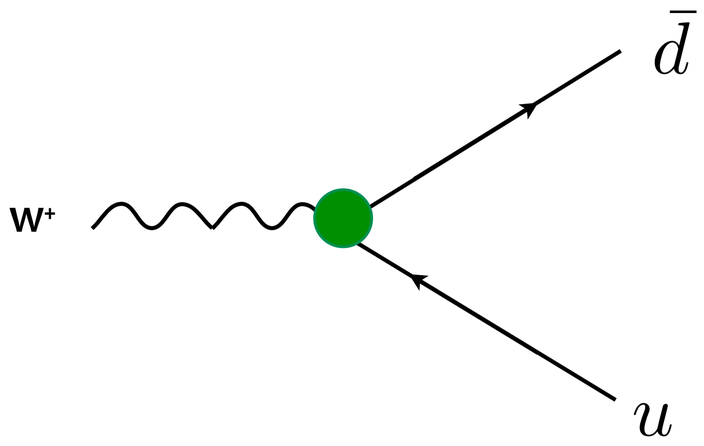

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shifts of peak position in GeV

	W^+		W^-		Z	
$\mu_R = \mu_c/2, 2\mu_c$	$+0.30$	-0.09	$+0.29$	-0.06	$+0.23$	-0.05
pdf (90% cl)	$+0.03$	-0.05	$+0.06$	-0.02	$+0.05$	-0.02
$\alpha_S = 0.121, 0.115$	$+0.14$	-0.12	$+0.14$	-0.14	$+0.15$	-0.15
$\Lambda_{NP} = 0.7, 0.5$ ($\langle \mathbf{k}_\perp^2 \rangle = 1.0, 1.96$)	$+0.16$	-0.16	$+0.16$	-0.14	$+0.16$	-0.15
non-universal $\langle \mathbf{k}_\perp^2 \rangle$ (maximal W^+ effect)	$+0.09$			-0.06	± 0	
non-universal $\langle \mathbf{k}_\perp^2 \rangle$ (maximal W^- effect)		-0.03	$+0.05$		± 0	

MESSAGE:

*the **uncertainty** on the peak position **is not negligible;***

what about the determination of m_W ?

to be published soon

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Conclusions

1) Collinear and TMD factorization **theorems** define the tools to investigate hadron structure in momentum space

2) Collinear and TMD **parton distribution functions** are closely related and provide **complementary information** to the study of high-energy scattering experiments

3) **Detailed knowledge of TMDs** can improve our understanding of important SM parameters

4) We are setting the tools to explore a **precision phase for hadron structure**

Today :

hermes, Jefferson Lab, COMPASS, Belle II, BaBar, BESIII, Fermilab, LHC, RHIC relativistic heavy ion collider, J-PARC, ...

... and **tomorrow** ?

EIC, LHeC, ilc international linear collider, AFTER

...

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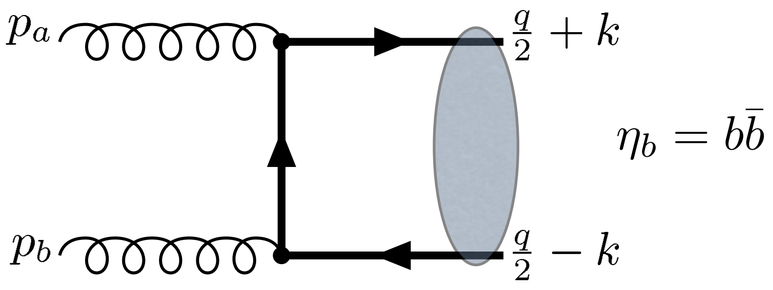
Backup

gluon TMDs at work : η at AFTER@LHC

AS - PhD thesis (inspire)

(heavy) **quarkonium** production



$\eta_b = b\bar{b}$

+ crossed term

$$P_A + P_B \to \eta_b(q_T) + X$$

$$m_{\eta_b} = 9.39 \text{ GeV}$$

collision of (un)polarized protons

$$\frac{d\sigma_{UU}}{dq_T} \sim \{\mathcal{C}[f_1^g f_1^g] - \mathcal{C}[h_1^{\perp g} h_1^{\perp g}]\}$$

unpolarized gluons — **lin. polarized** gluons

$$\frac{d\sigma_{UT}}{dq_T} \sim \{\mathcal{C}[f_1^g f_{1T}^{\perp g}] + \mathcal{C}[h_1^{\perp g} h_{1T}^g] + \mathcal{C}[h_1^{\perp g} h_{1T}^{\perp g}]\}$$

gluon **Sivers** function: link to **orbital angular momentum** of gluons - important for the **proton spin puzzle**

Echevarria, Kasemets, Lansberg, Pisano, Signori - arXiv 17xx.xxxxx

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gluon TMDs at work : η at AFTER@LHC

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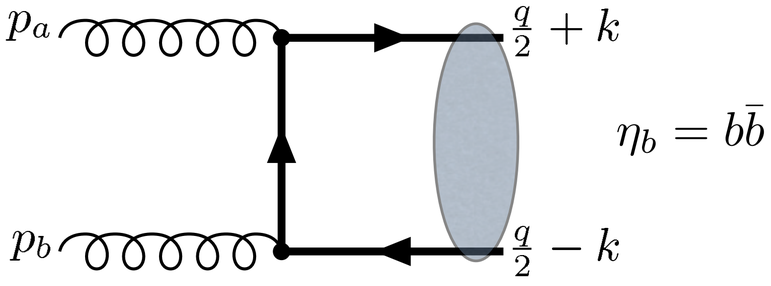

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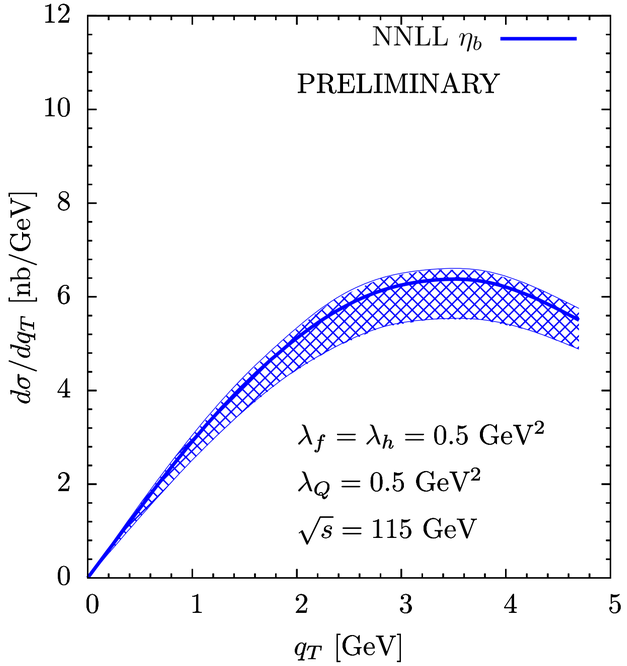

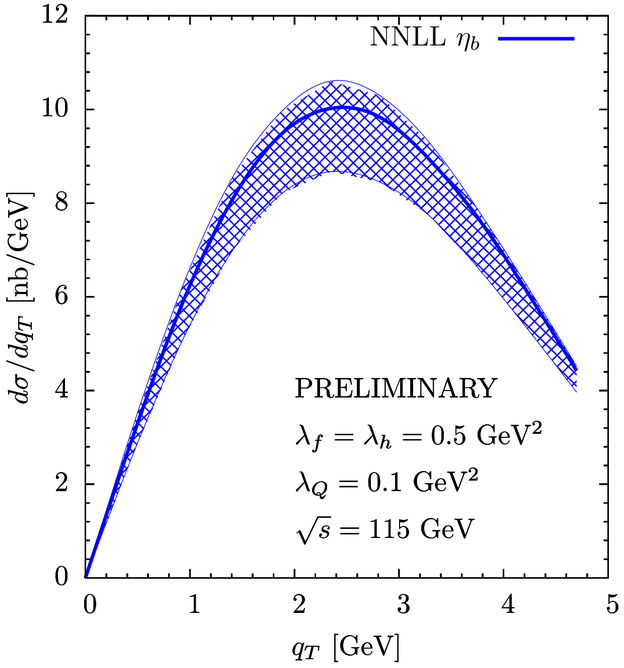

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gluon TMDs at work : η at AFTER@LHC

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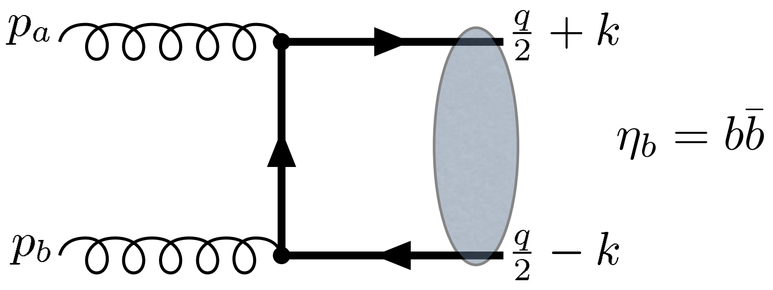

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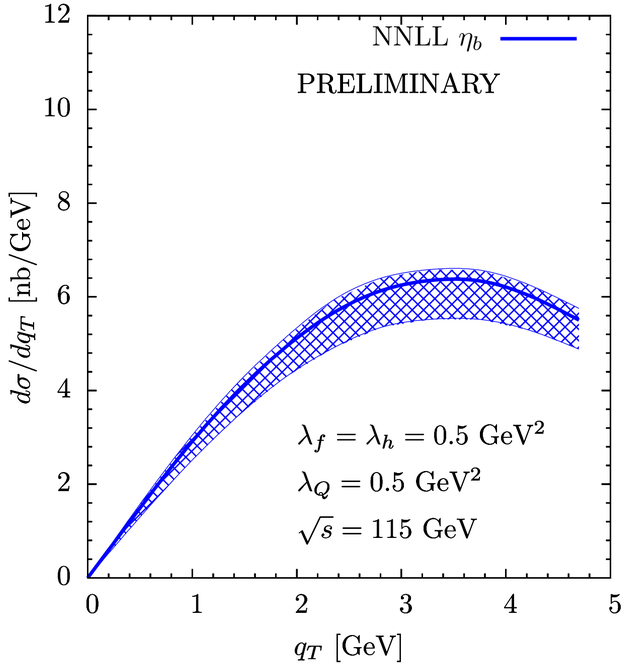

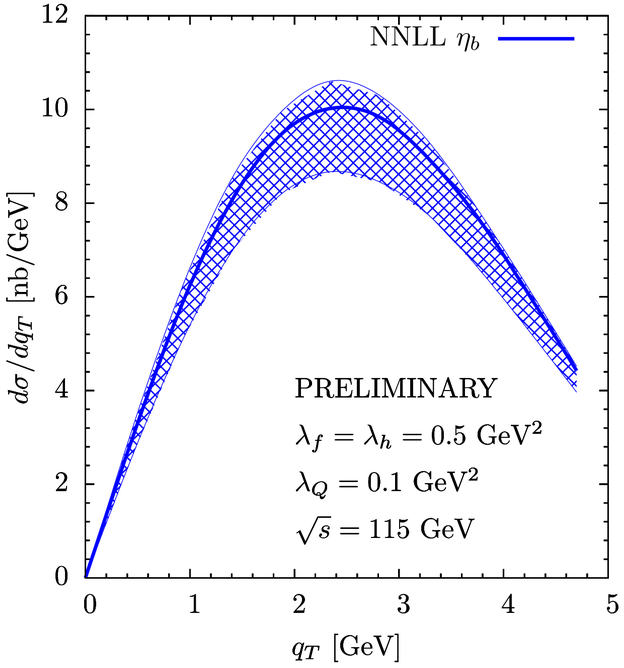

constrain NP information from data and use it to improve other observables

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