

# TMD phenomenology: from JLab to the LHC

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Andrea Signori

Spatial and momentum  
tomography  
of hadrons and nuclei

INT 17-3  
Sept 25 2017



# TMD phenomenology at low and high energy

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# Outline

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I will present some research directions, in collaboration with:

- J. Qiu, LDRD TMD team (JLab)



- M. Grewal, Z. Kang (UCLA)



- A. Bacchetta, G. Bozzi, M. Echevarria, C. Pisano, M. Radici (Pavia)

- T. Kasemets, P. Mulders, M. Ritzmann (Nikhef)



- J. Lansberg (IN2P3)



# Outline

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I will touch different aspects related to phenomenology of TMDs  
**at low and high energy:**

- 1) TMDs and their evolution
- 2) relevance of the nonperturbative part
- 3) extractions from low energy data
- 4) predictions at high energy
- 5) computational tools

# TMDs & their evolution

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References (intro and reviews) :

- “The 3D structure of the nucleon” **EPJ A (2016) 52**
- J.C. Collins “**Foundations of perturbative QCD**”
- material from the TMD collaboration **summer school**, e.g. :
  - \* P.J. Mulders’ **lecture notes**
  - \* A. Bacchetta’s **lecture notes**
  - \* and all the other lecture notes/references on the webpage

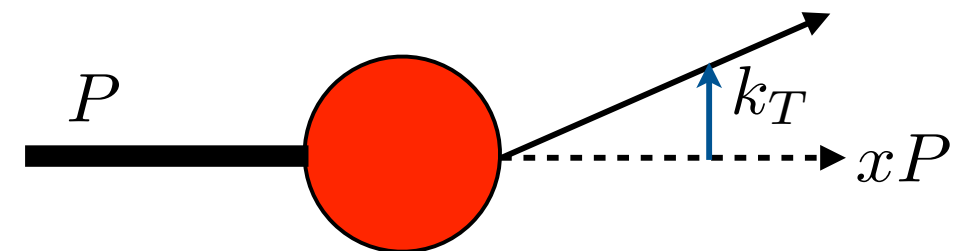
# quark TMD PDFs

$$\Phi_{ij}(k, P; S) \sim \text{F.T.} \langle PS | \bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi) | PS \rangle |_{LF}$$

| Quarks | $\gamma^+$     | $\gamma^+ \gamma^5$ | $i\sigma^{i+} \gamma^5$ |
|--------|----------------|---------------------|-------------------------|
| U      | $f_1$          |                     | $h_1^\perp$             |
| L      |                | $g_1$               | $h_{1L}^\perp$          |
| T      | $f_{1T}^\perp$ | $g_{1T}$            | $h_1, h_{1T}^\perp$     |

Sivers TMD PDF

unpolarized TMD PDF



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

encode all the possible  
**spin-spin** and **spin-orbit**  
**correlation**

between the proton  
and its constituents

**bold** : also collinear

**red** : time-reversal odd (universality properties)

# Status of TMD phenomenology

Theory, data, fits : we are in a position to start validating the formalism

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

quark pol.

nucleon pol.

Twist-2 TMDs

Only first attempts

see, e.g, Bacchetta, Radici, *arXiv:1107.5755*  
 Anselmino, Boglione, Melis, *PRD86* (12)  
 Echevarria, Idilbi, Kang, Vitev, *PRD* 89 (14)  
 Anselmino, Boglione, D'Alesio, Murgia, Prokudin, *arXiv:1612.06413*  
 Anselmino et al., *PRD87* (13)  
 Kang et al. *arXiv:1505.05589*

Lu, Ma, Schmidt, *arXiv:0912.2031*  
 Lefky, Prokudin *arXiv:1411.0580*  
 Barone, Boglione, Gonzalez, Melis,  
*arXiv:1502.04214*

# The frontier

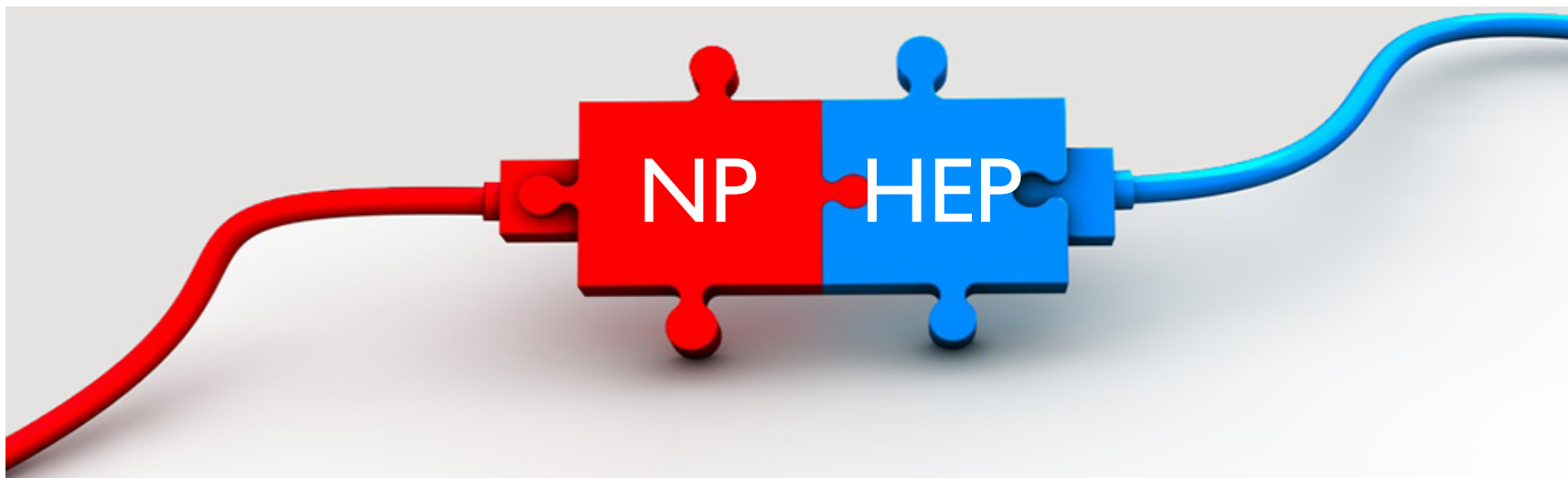
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## Nuclear Physics :

- investigation of nucleon and nuclear structure and associated dynamics
- observables of non-perturbative QCD
- non-perturbative quark-gluon dynamics encoded in (TMD) PDFs and FFs

## High-Energy Physics :

- precision physics, within and beyond the Standard Model
- observables of perturbative QCD
- assuming the knowledge of hadron structure



# W-term & TMDs

**W-term** : transverse momentum resummation in terms of TMDs

$$W(q_T, Q) = \int \frac{d^2 b_T}{(2\pi)^2} e^{i q_T \cdot b_T} \tilde{W}(b_T, Q)$$

$b_T$  is the Fourier-conjugated variable of the [partonic and observed] transverse momenta

$$\tilde{W}(b_T, Q) \sim \tilde{F}_i^{h_1}(x_1, b_T; \mu, \zeta_1) \tilde{F}_j^{h_2}(x_2, b_T; \mu, \zeta_2)$$

Product of Fourier-transformed TMDs

**TMD evolution** is multiplicative in  $b_T$  space

# W-term & TMDs

FT of TMDs :

$$\tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu_{\hat{b}}, \mu_{\hat{b}}^2) \times$$

$$\exp \left\{ \int_{\mu_{\hat{b}}}^Q \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left( \frac{Q^2}{\mu_{\hat{b}}^2} \right)^{-K(\hat{b}_T; \mu_{\hat{b}}) - g_K(\bar{b}_T; \{\lambda\})}$$

Sudakov form factor : perturbative      and      **nonperturbative** contributions

# W-term & TMDs

FT of TMDs :

$$\tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu_{\hat{b}}, \mu_{\hat{b}}^2) \times \exp \left\{ \int_{\mu_{\hat{b}}}^Q \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left( \frac{Q^2}{\mu_{\hat{b}}^2} \right)^{-K(\hat{b}_T; \mu_{\hat{b}}) - g_K(\bar{b}_T; \{\lambda\})}$$

Sudakov form factor : perturbative and **nonperturbative** contributions

(input) TMD distribution : Wilson coefficients and **intrinsic part** Collinear distribution!

$$\tilde{F}_i(x, b_T; \mu_{\hat{b}}, \mu_{\hat{b}}^2) = \sum_{j=q, \bar{q}, g} C_{i/j}(x, \hat{b}_T; \mu_{\hat{b}}, \mu_{\hat{b}}^2) \otimes f_j(x; \mu_{\hat{b}}) \tilde{F}_{i, NP}(x, \bar{b}_T; \{\lambda\})$$

Nonperturbative parts defined in a “negative” way : **observed-calculable**

# Phenomenology



Jefferson Lab



BESIII



RHIC  
relativistic heavy ion collider

LHC ...

consolidate the formalism +  
extractions of TMDs

new data

predictions for  
“unexplored/known” effects  
in  
“unexplored/known” regions

EIC



...



HIEPA

Jefferson Lab

# Phenomenology



Jefferson Lab



LHC ...



BESIII



RHIC  
relativistic heavy ion collider

consolidate the formalism +  
extractions of TMDs

- extraction of unpolarized quark TMDs :  
see talks by A. Bacchetta, A. Vladimirov

- **formalism for unpolarized gluon TMDs** :  
see talks by S. Cotogno, C. Pisano, and next section

new data

predictions for  
“unexplored/known” effects  
in  
“unexplored/known” regions

EIC



...



HIEPA

# Phenomenology



Jefferson Lab



BESIII



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predictions for  
“unexplored/known” effects  
in  
“unexplored/known” regions

examples of predictions for  
“known” effects in “known” regions:  
- **W qT-spectrum at LHC (quark TMDs)**  
- Higgs qT-spectrum at LHC (gluon TMDs)

# Phenomenology

All kinematic regions (namely data) are important:  
some are more suited to **constrain NP part** of TMDs and their evolution,  
others to **test the accuracy needed for TMD evolution**

consolidate the formalism +  
extractions of TMDs

What is the **best kinematic region** to  
**constrain the NP part of TMDs** and what is  
the best **region to be predictive**?

new data

predictions for predictive power & nonperturbative input  
“unexplored/known” effects  
in  
“unexplored/known” regions

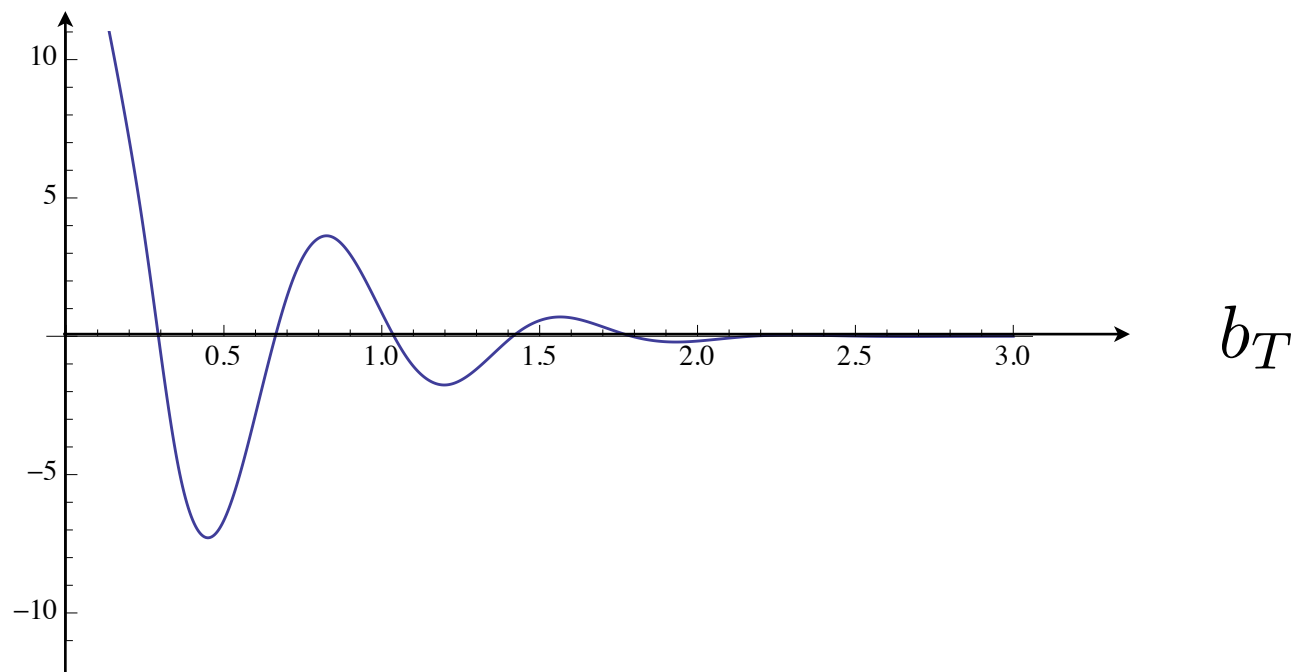
# Saddle point approximation

Qiu-Zhang, Phys. Rev. D 63 114011

$$\begin{aligned} W(x_{1,2}, q_T, Q) &= \int \frac{d^2 b_T}{(2\pi)^2} e^{iq_T \cdot b_T} \tilde{W}(x_{1,2}, b_T, Q) \\ &= \int \frac{db_T}{2\pi} b_T J_0(q_T b_T) \tilde{W}(x_{1,2}, b_T, Q) \end{aligned}$$

Z-boson production

$$b_T J_0(q_T b_T) \tilde{W}(x_{1,2}, b_T, Q)$$



the idea is to calculate **which b-region dominates the integral** as a function of the kinematics

small-b region: computed in pQCD  
high-b region: need nonperturbative model

# Saddle point approximation

Qiu-Zhang, Phys. Rev. D 63 114011

let's look at the integrand at  $q_T=0$  to quantify the importance of the high  $b_T$  region

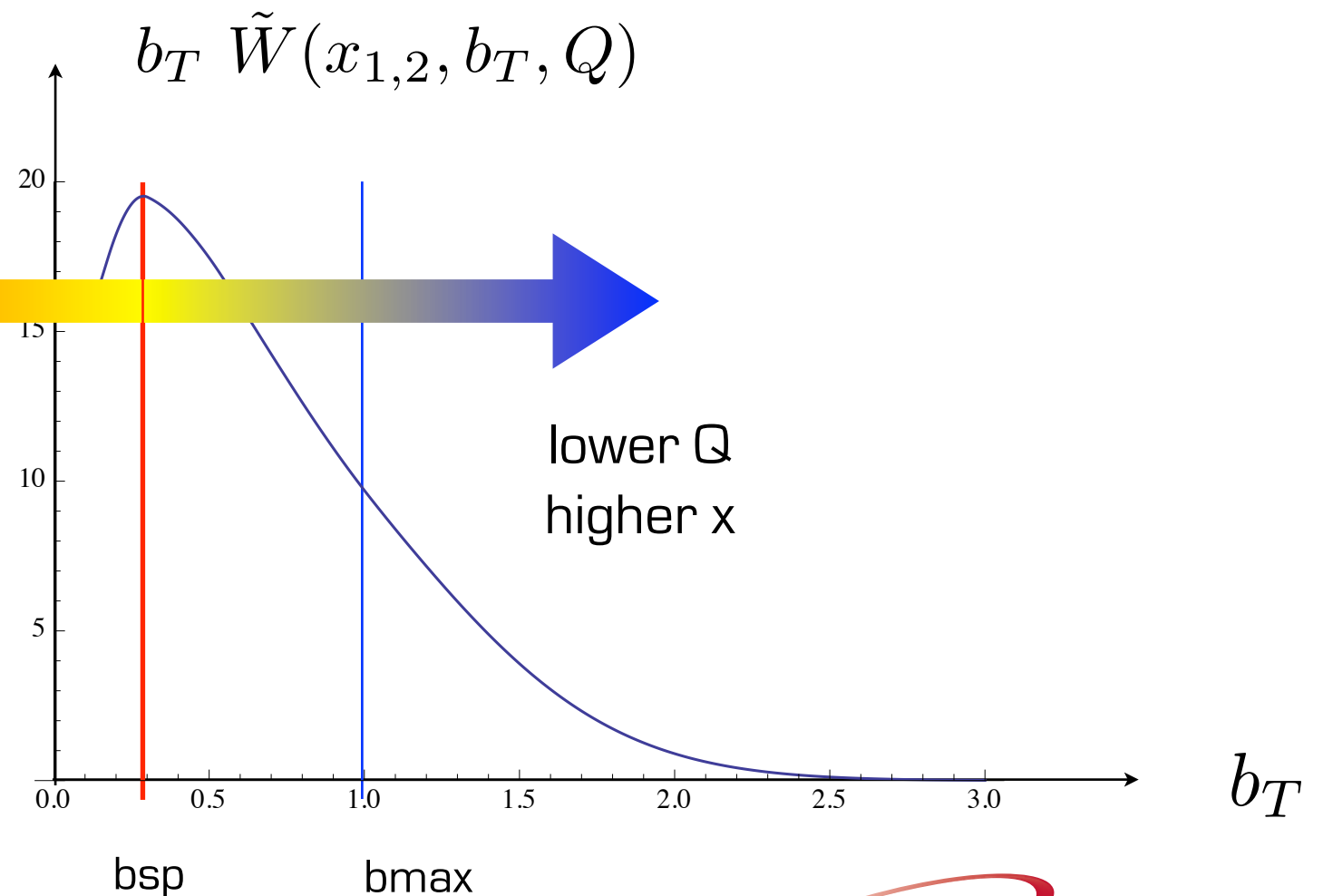
$$W(x_{1,2}, q_T = 0, Q) = \int \frac{db_T}{2\pi} b_T \tilde{W}(x_{1,2}, b_T, Q)$$

$$\left. \frac{d}{db_T} \left[ b_T \tilde{W}(x_{1,2}, b_T, Q) \right] \right|_{b_T=b_{sp}} = 0$$

from the **Sudakov** term

higher  $Q$   
smaller  $x$

from **DGLAP**



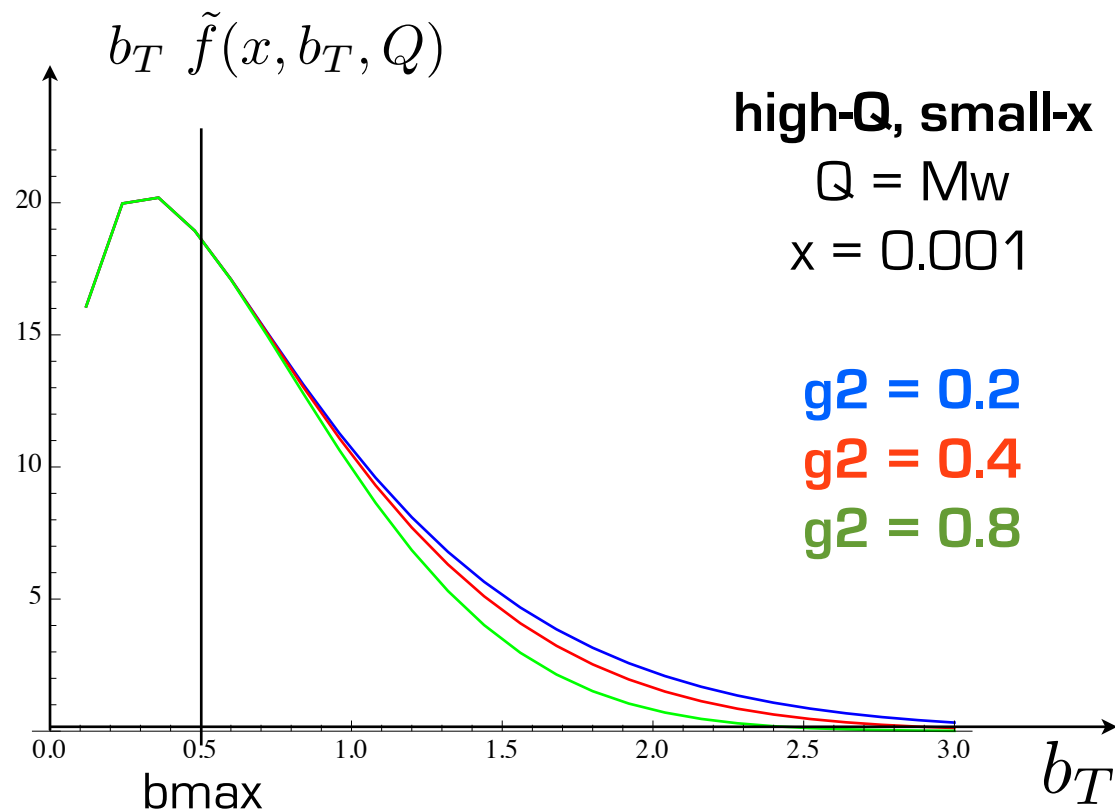
# Quark TMD PDF

preliminary

Grewal, Kang, Qiu, AS - in prep.

We'd like to check if the same statement holds for a single quark TMD PDF

$$f(x, k_T = 0, Q) = \int \frac{db_T}{2\pi} b_T \tilde{f}(x, b_T, Q)$$

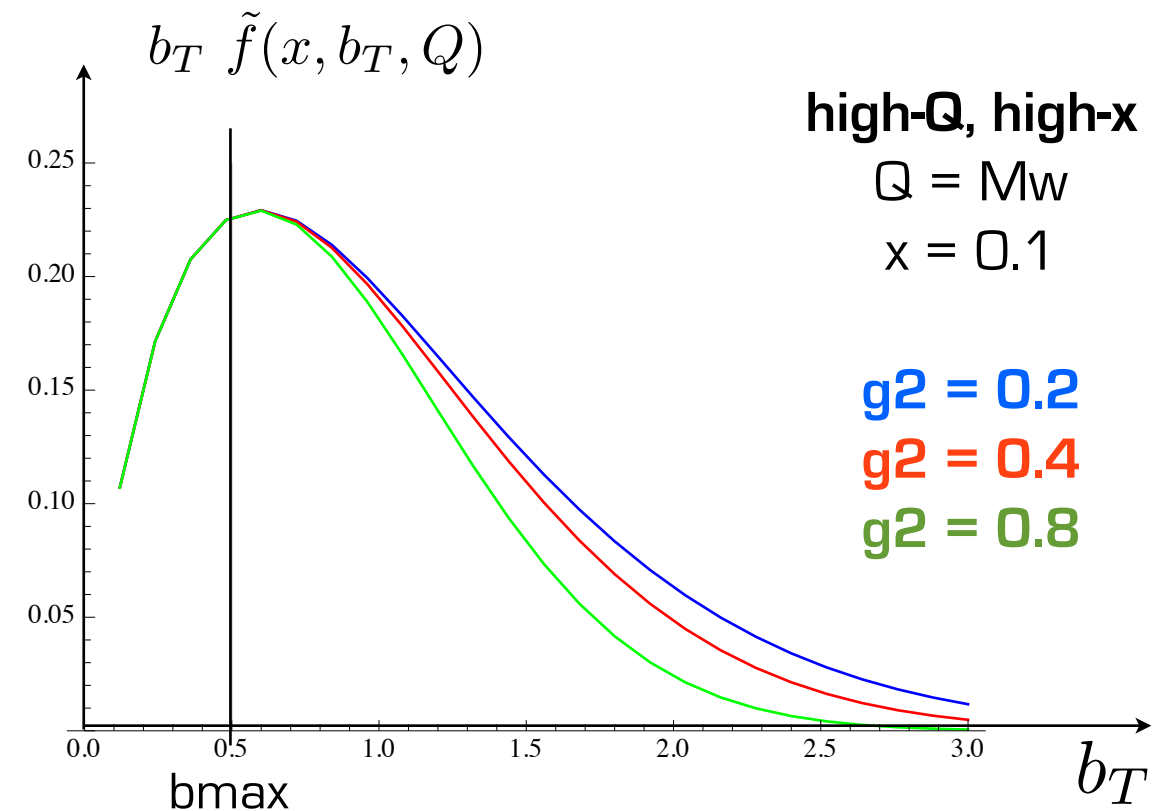


$g2 = 0.4$  integral

|  |  |                |                |
|--|--|----------------|----------------|
|  |  | +5% $g2 = 0.2$ | -7% $g2 = 0.8$ |
|--|--|----------------|----------------|

map the role of the NP contribution as a function of  $x$  and  $Q$

accuracy : NLO and NLL



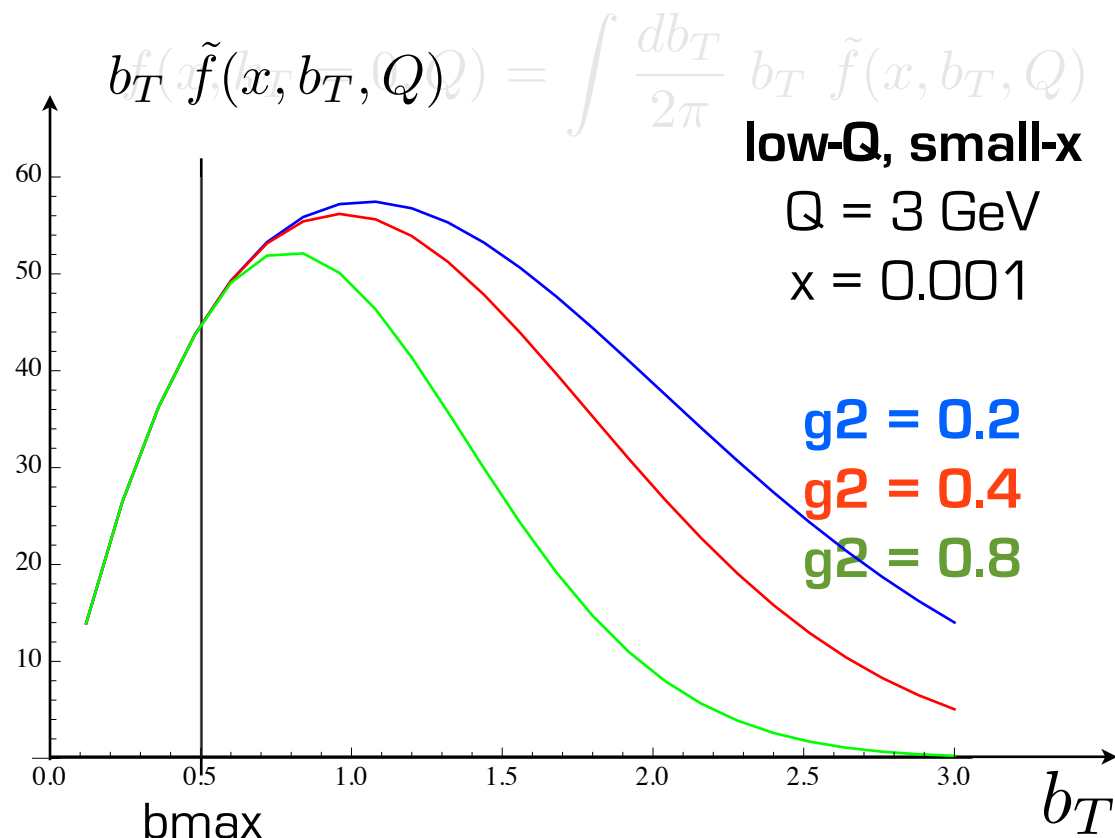
|  |  |                |                 |
|--|--|----------------|-----------------|
|  |  | +8% $g2 = 0.2$ | -13% $g2 = 0.8$ |
|--|--|----------------|-----------------|

# Quark TMD PDF

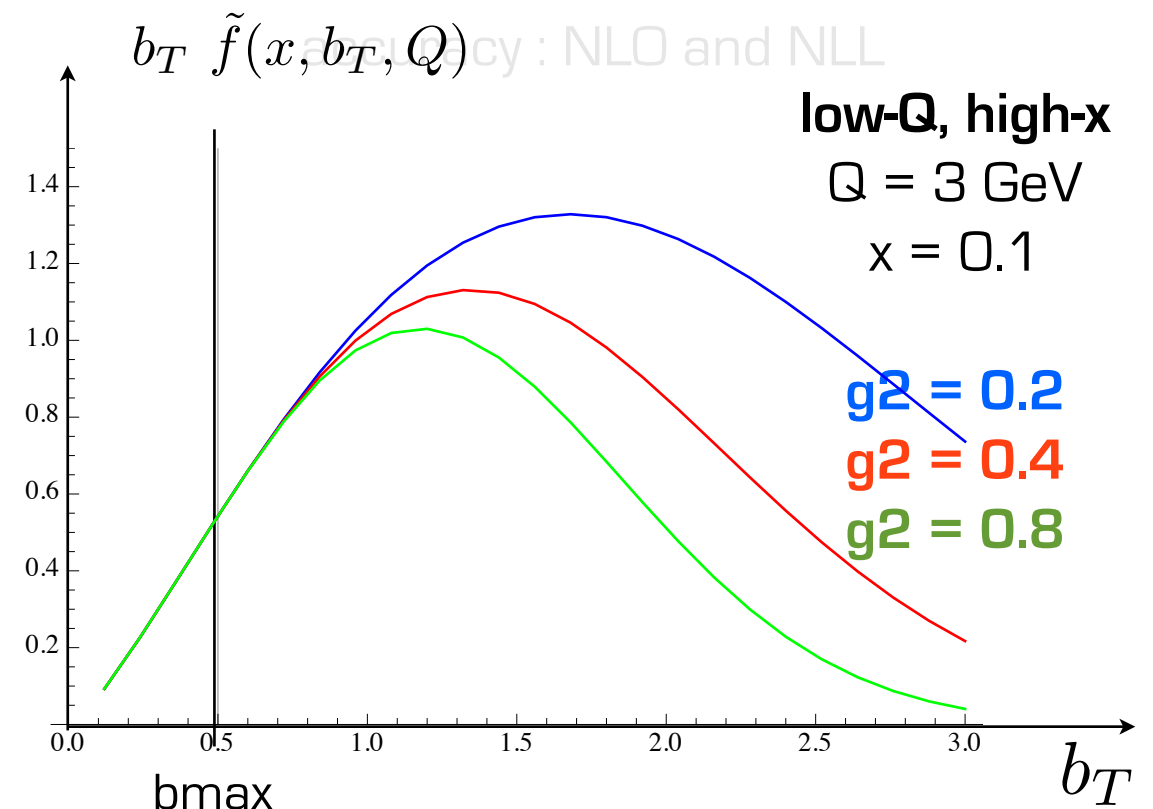
preliminary

Grewal, Kang, Qiu, AS - in prep.

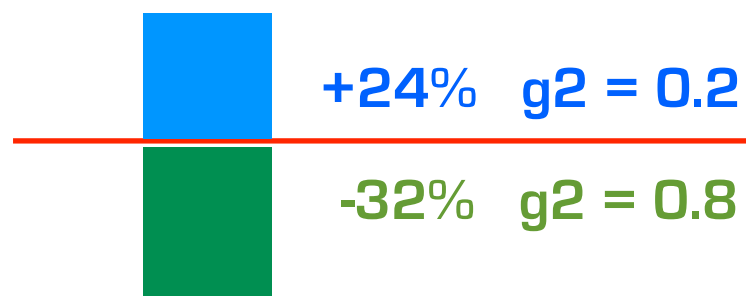
We'd like to check if the same statement holds for a single quark TMD PDF



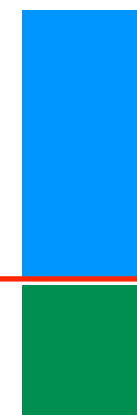
map the role of the NP contribution as a function of  $x$  and  $Q$



$g2 = 0.4$   
integral



+56%  $g2 = 0.2$   
-27%  $g2 = 0.8$



# The message

- **small- $Q$  and high- $x$** : the region where the (quark) TMD PDF is most sensitive to the NP part (but also higher-twists, thresholds, ...); data in this region are precious to constrain the NP part

example: extractions of unpolarized quark TMDs (see Bacchetta, Vladimirov)

**example: formalism for  $\eta_{b,c}$  production at the LHC or AFTER@LHC**

- **high- $Q$  and small- $x$** : the region where the formalism is most predictive and has less sensitivity to the NP corrections; **example  $W$  production at LHC**

**in this case, what is the actual impact of the NP part on physical observables?**

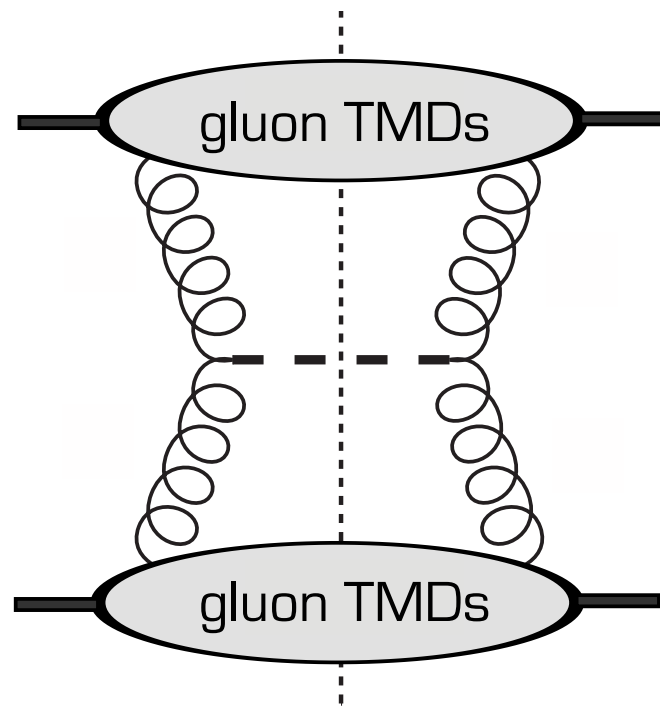
# $\eta_{b,c}$ production at LHC

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(Some) References:

- AS, [PhD thesis](#)
- D. Boer, C. Pisano, [arXiv:1208.3642](#)
- M.G. Echevarria, T. Kasemets, J.P. Lansberg, C. Pisano, AS - in preparation

# gluon TMD PDFs



pseudoscalar quarkonium production:

$$p p \rightarrow \eta_b X \quad M = 9.39 \text{ GeV}$$

$$p p \rightarrow \eta_c X \quad M = 2.98 \text{ GeV}$$

[see also talk by C. Pisano week 4]

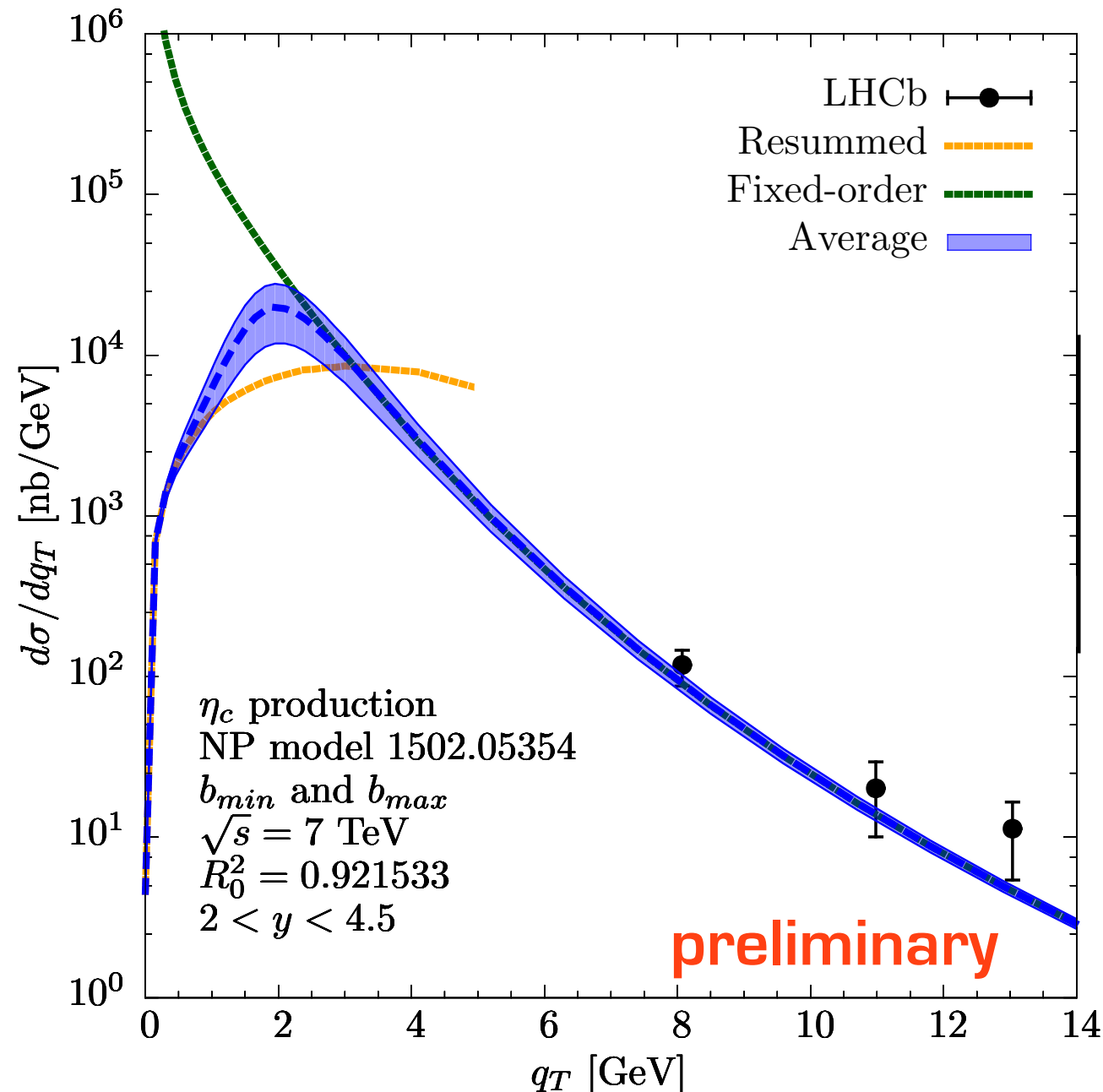
$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \Phi_B^U |\mathcal{M}|^2$$

$$\sim \underbrace{\mathcal{C} \begin{bmatrix} f_1^{g/A} & f_1^{g/B} \end{bmatrix}}_{\text{unpolarized gluons}} \pm \underbrace{\mathcal{C} \begin{bmatrix} h_1^{\perp g/A} & h_1^{\perp g/B} \end{bmatrix}}_{\text{lin. polarized gluons}}$$

unpolarized cross section  
at low transverse momentum  
for (pseudo)scalar state

# $\eta_c$ production at LHC

full transverse momentum spectrum:  
low  $q_T$  matched with high  $q_T$  region



**blue band:** uncertainty from matching

the matching is performed as a  
**weighted average** of the calculations  
at low and high transverse momentum

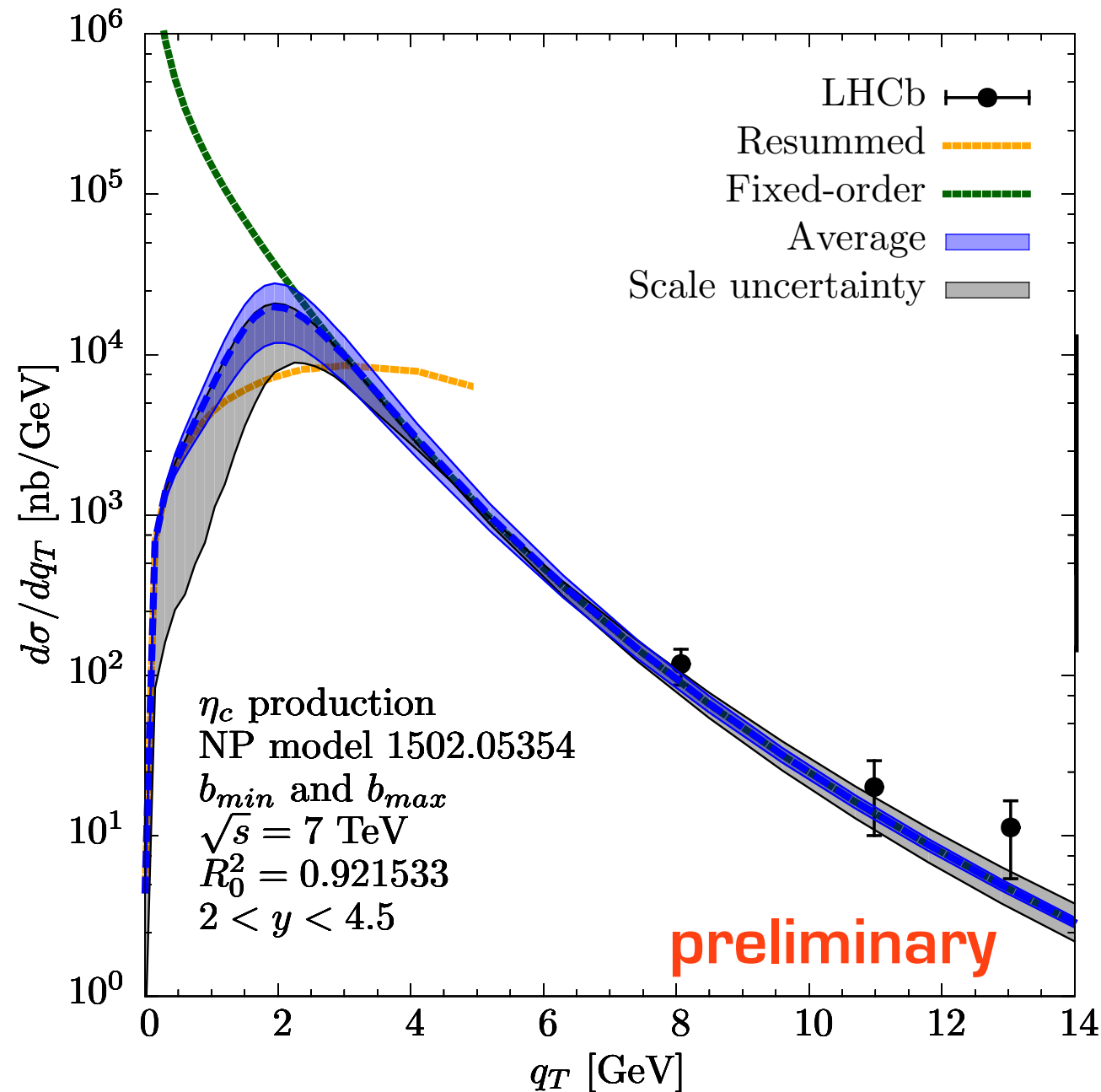
the **weights** are related  
to the **power corrections**  
to TMD and collinear factorization:

$$\frac{d\sigma}{dq_T} = \omega_1 W + \omega_2 Z$$

$$\omega_1 \sim ((q_T + m)/Q)^{-2}, \quad \omega_2 \sim (m/q_T)^{-2}$$

# $\eta_c$ production at LHC

full transverse momentum spectrum:  
low  $q_T$  matched with high  $q_T$  region



blue band: uncertainty from matching

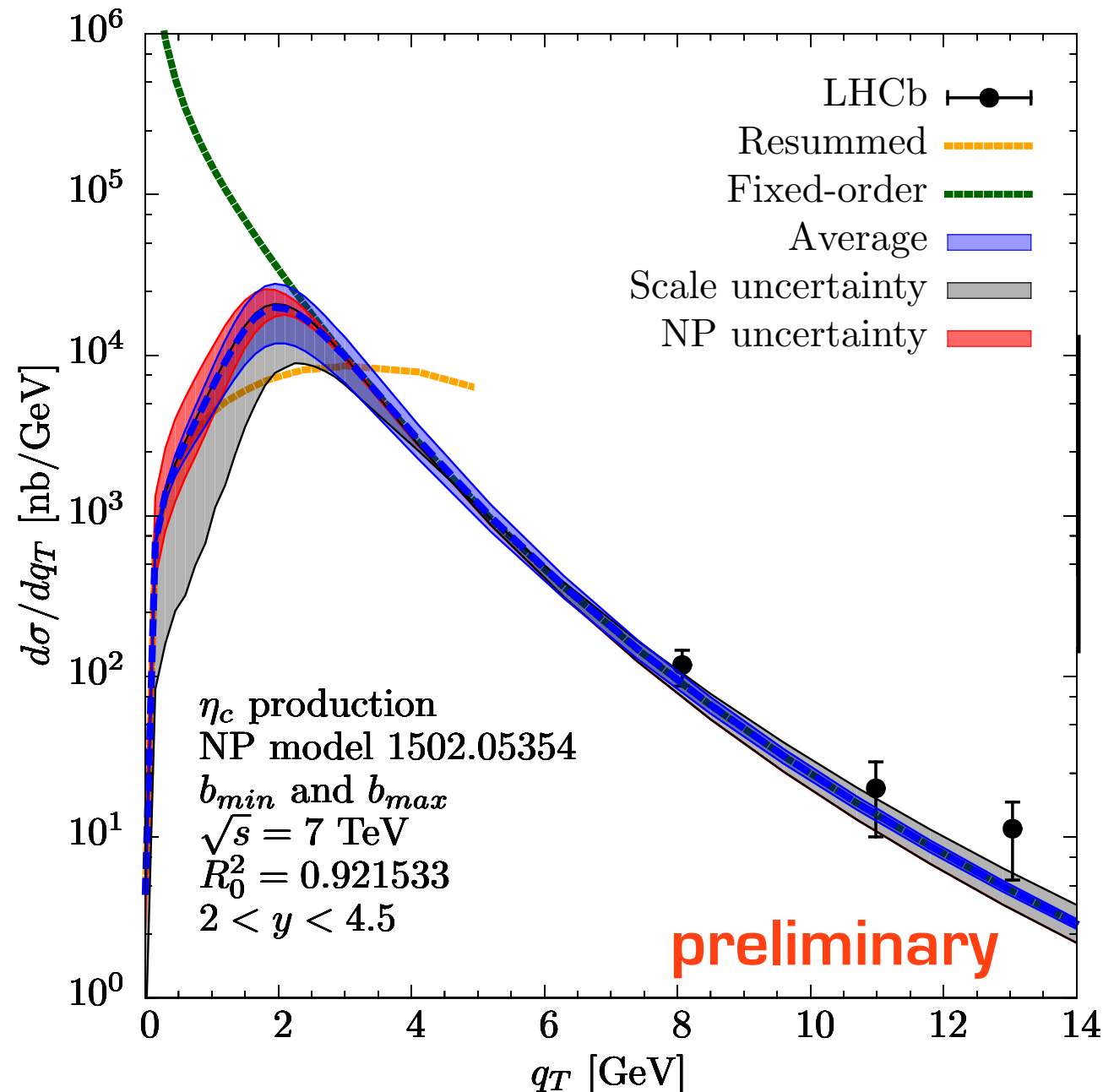
grey band: scale uncertainty

$$\mu_i^2 = \zeta_i = \mu_b^2, \quad \mu_{F.O.} = m_T$$

fact. 2 variation and envelope

# $\eta_c$ production at LHC

full transverse momentum spectrum:  
low  $q_T$  matched with high  $q_T$  region



**blue band:** uncertainty from matching

**grey band:** scale uncertainty

**red band:** nonpert. uncertainty

$$S_{NP}(\bar{b}_T) = - \left[ \frac{a_1}{2} + \frac{a_2}{2} \ln Q^2 \right] \bar{b}_T^2$$

$a_i = 0.5 \text{ GeV}^2$ , var. 50%, envelope

both for unpolarized and  
linearly polarized distributions

**the formalism is in good shape!**  
we need the data at low  $q_T$

# W production at LHC

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References:

- AS, [PhD thesis](#)
- Bacchetta, Bozzi, Radici, Mulders, Ritzmann, AS - in preparation

# Uncertainties - mass

AS - PhD thesis

| Uncertainties on $m_W$ [MeV] from $p_T^\ell$ fit |                        |                      |        |
|--------------------------------------------------|------------------------|----------------------|--------|
| Source                                           | $W \rightarrow \mu\nu$ | $W \rightarrow e\nu$ | Common |
| Lepton energy scale                              | 7                      | 10                   | 5      |
| Lepton energy resolution                         | 1                      | 4                    | 0      |
| Lepton efficiency                                | 1                      | 2                    | 0      |
| Lepton tower removal                             | 0                      | 0                    | 0      |
| Recoil scale                                     | 6                      | 6                    | 6      |
| Recoil resolution                                | 5                      | 5                    | 5      |
| Backgrounds                                      | 5                      | 3                    | 0      |
| PDFs                                             | 9                      | 9                    | 9      |
| $W$ boson $q_T$                                  | 9                      | 9                    | 9      |
| Photon radiation                                 | 4                      | 4                    | 4      |
| Statistical                                      | 18                     | 21                   | 0      |
| Total                                            | 25                     | 28                   | 16     |

sizable uncertainties  
from hadron structure

associated to  $\alpha_s$  and  
NP evolution;  
no intrinsic  
transverse momentum

**Table 7.1.** Uncertainties on  $m_W$  (in MeV) as resulting from charged-lepton transverse-momentum fits in the  $W \rightarrow \mu\nu$  and  $W \rightarrow e\nu$  samples. “ $W$  boson  $q_T$ ” refers to sources discussed before (7.2.1). The last column reports the portion of the uncertainty that is common in the  $\mu\nu$  and  $e\nu$  results. Original version and definitions in [260].

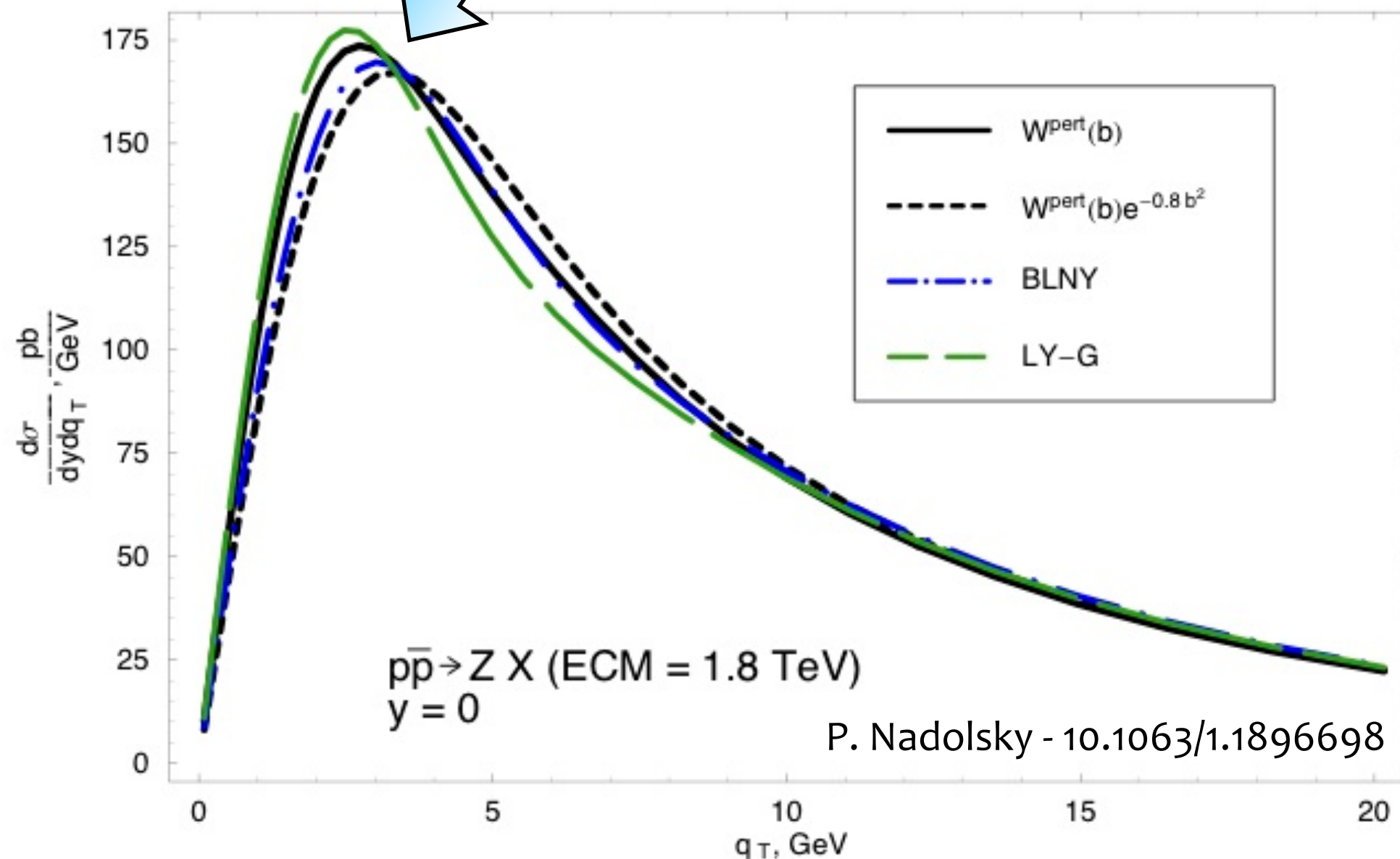
# Nonperturbative effects

[AS - PhD thesis](#)

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

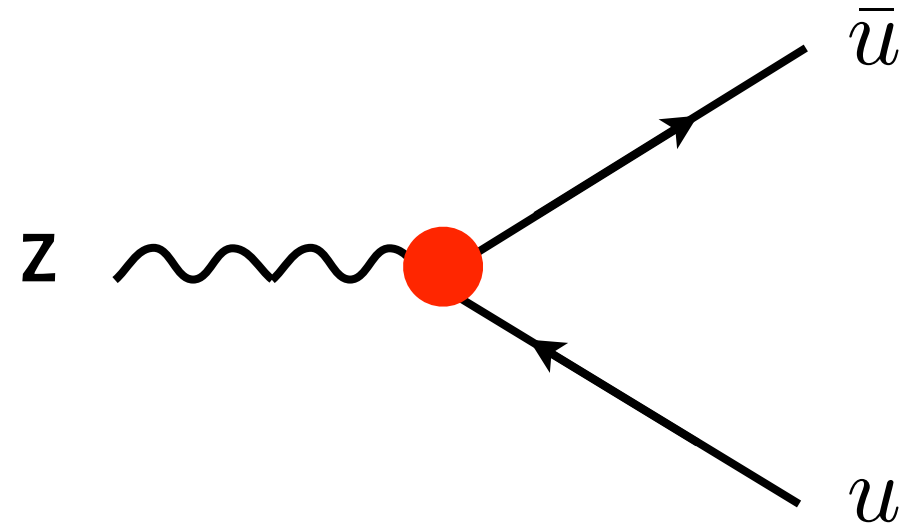
$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$

**g** comes from 2 TMD PDFs  
and **controls the position of the peak**

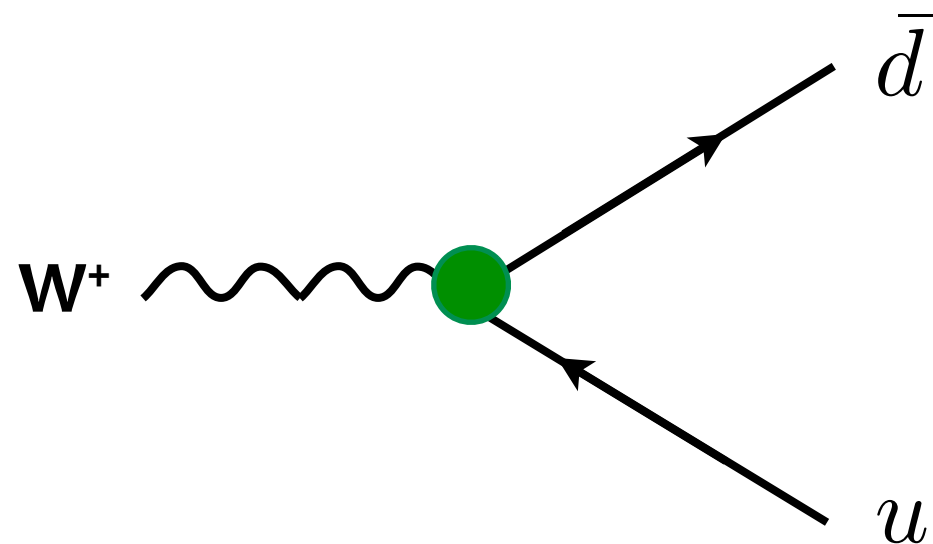


# Z vs W : flavor content

[AS - PhD thesis](#)



Intrinsic kT effects **have been measured on Z data** and used to predict the W distribution, assuming they are the same for Z and W



This reflects a flavor independent approach and might not be optimal because of the **different flavor content:**

the intrinsic contributions are **different in Z and W<sup>±</sup> production**

# Uncertainties - peak

[AS - PhD thesis](#)

|                                                          | $W^+$ |       | $W^-$ |       | $Z$     |       |
|----------------------------------------------------------|-------|-------|-------|-------|---------|-------|
| $\mu_R = \mu_c/2, 2\mu_c$                                | +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 |
| f.i. $\langle \mathbf{k}_T^2 \rangle = 1.0, 1.96$        | +0.16 | -0.16 | +0.16 | -0.14 | +0.16   | -0.15 |
| f.d. $\langle \mathbf{k}_T^2 \rangle$ (max $W^+$ effect) | +0.09 |       |       | -0.06 | $\pm 0$ |       |
| f.d. $\langle \mathbf{k}_T^2 \rangle$ (max $W^-$ effect) |       | -0.03 | +0.05 |       | $\pm 0$ |       |

**Table 7.2.** Summary of the shifts in GeV for the peak position for  $q_T$  spectra of  $W^\pm/Z$  arising from different sources. The colors for the flavor dependent (f.d.) and independent (f.i.) variations match the ones in Sec. 7.4.6.

the uncertainty including intrinsic transverse momentum is comparable in magnitude with the one associated to collinear PDFs!

# Event generators

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References:

- M. Diefenthaler's **talk - week 4**

# Study of Hadronization in **NP** and **HEP**

## **LDRD:**

started in FY17  
at **JLab**

Connection between **NP** and **HEP**

Correlation functions  
of TMD factorization



Pythia MCEG  
LUND string model

## **Urgent requirement**

- MCEG for TMDs
- Understanding of hadronization process

**Unique approach** Connection between hadronization phenomena in **NP** and **HEP**.

## **By doing so:**

- **NP** Improve theoretical framework for TMDs.
- **HEP** Improve hadronization models.

# Work plan

FY17

Publication: DIS in Pythia8

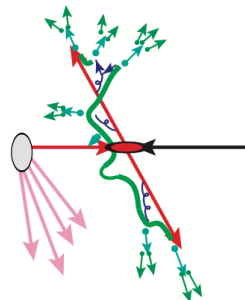
Publication: LUND validation

Publication: Hadronization in NP and HEP

- comparison Pythia8-TMD factorization
- language dictionary
- Pythia8 with spin-independent TMDs

Hadronization plugin

- user model for one phenomenon
- rest from Pythia8



FY18

+ TMD observables

Spin-dependent hadronization

- Incorporate model of transverse spin effects into Pythia8
- Anna Martin and Albi Kerbizi will join project in FY18

FY19

top-bottom approach:  
**incorporate TMD effects**  
in a **fully exclusive event generator (Pythia 8)**



# LDRD personnel (FY17)

JLab

Pythia

Other

PI



Diefenthaler



Joosten

Experimentalists

co-PI



Melnitchouk



Collins

Theorists

co-PI



Rogers



Sato



Lönnblad



Signori



Ethier



Prestel

# Conclusions and future developments

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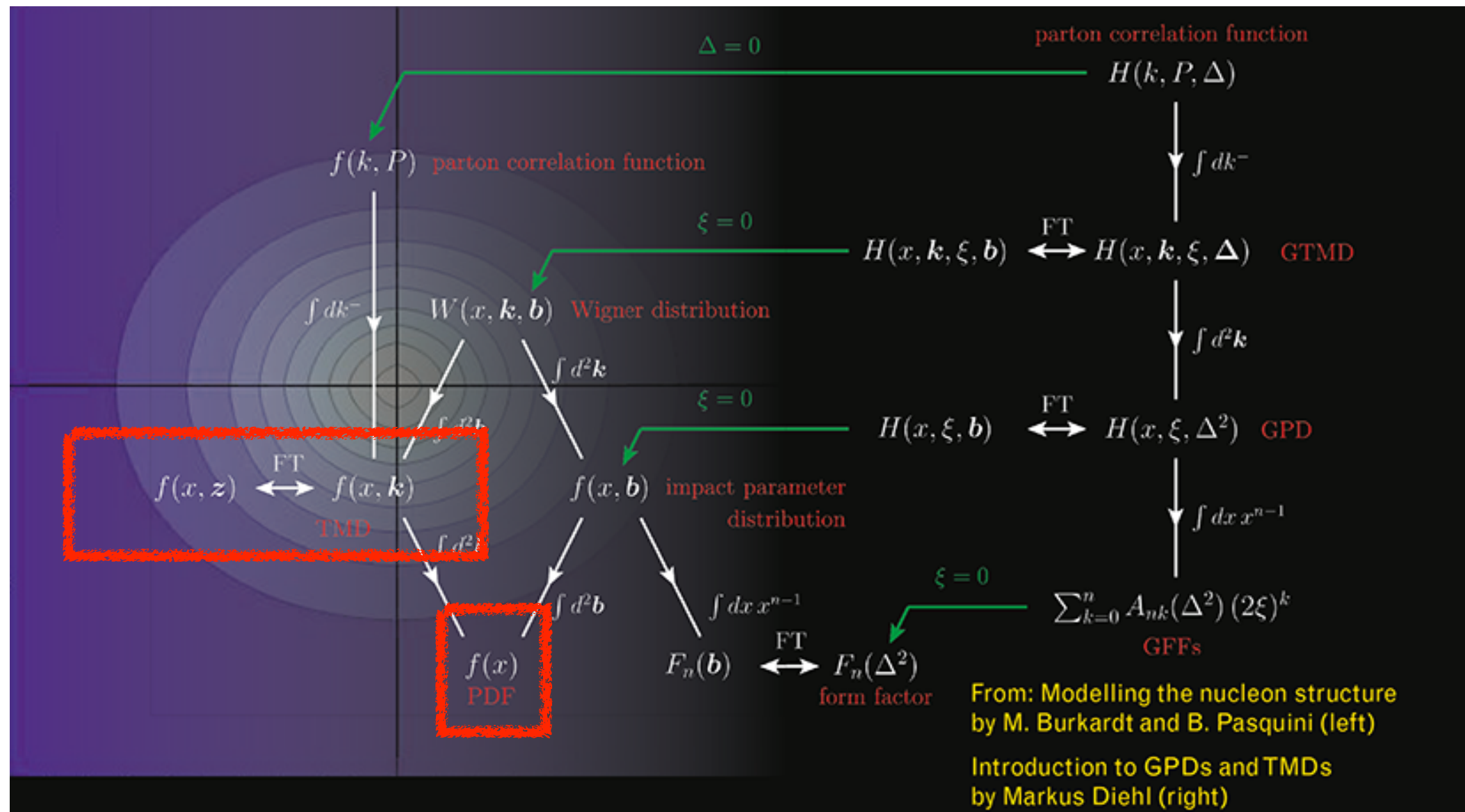
- the **relevance** of the **nonperturbative part of TMDs** changes according to the **kinematic** region explored
- we have extractions of unpolarized quark TMDs ; for gluons we are setting up the formalism (first calculation of full transverse momentum spectrum for  $\eta$  production at the LHC)
- **high- $Q$  & small- $x$**  is the region where the formalism is most **predictive**; even here, though, NP corrections leave **sizable footprints** in observables; see  $W$  production at the LHC
- the **EIC** will be very helpful, since it will be able to provide new data ranging from low to high  $Q$  and from low to high  $x$

# Backup

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# The hadronic landscape

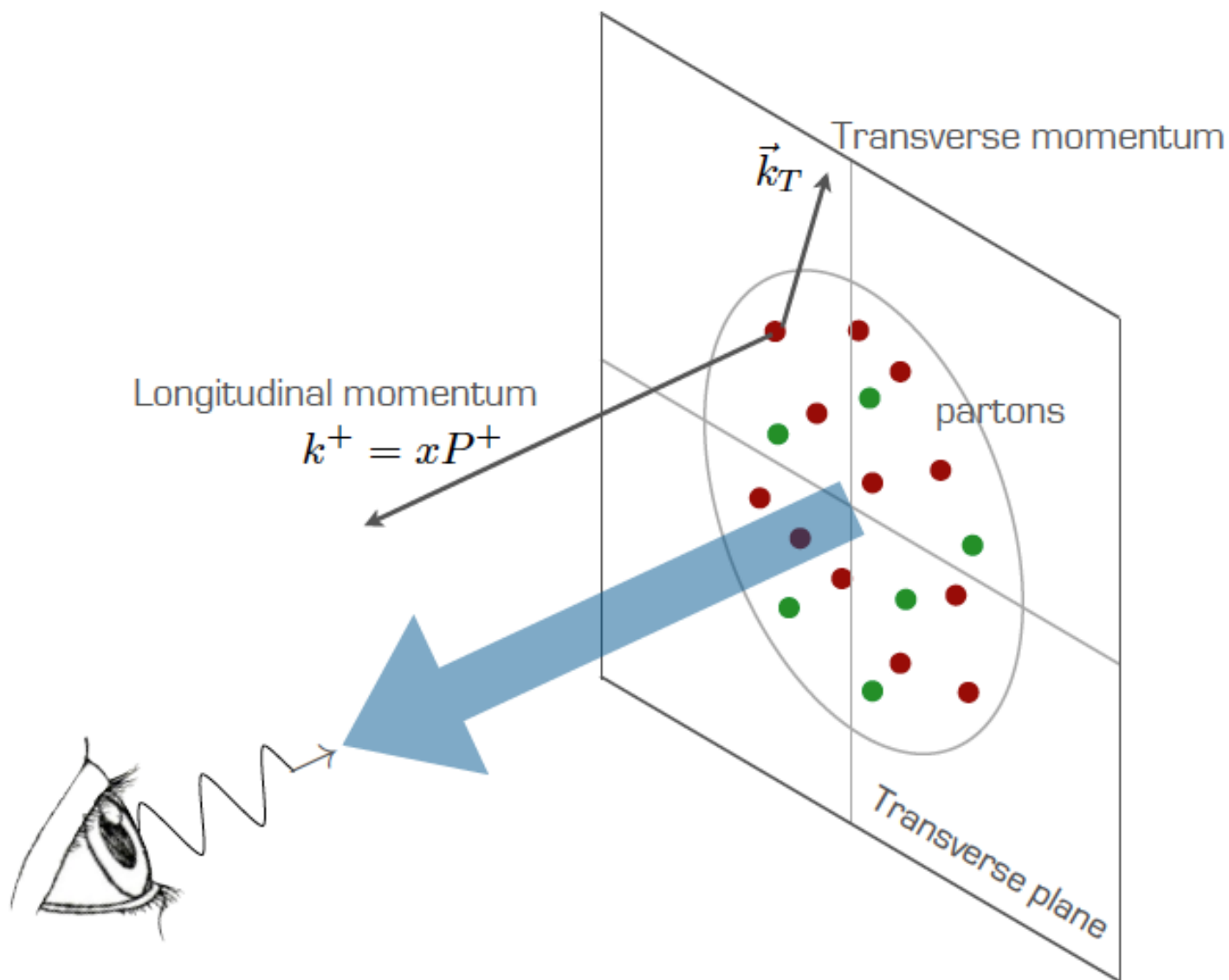
Manifestation of hadron structure in scattering processes



Nature is “**smooth**” : understand the link between TMDs & PDFs

# quark TMD PDFs

$$\Phi_{ij}(k, P; S_{\perp}) \sim \text{F.T.} \langle PS | \bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi) | PS \rangle |_{LF}$$

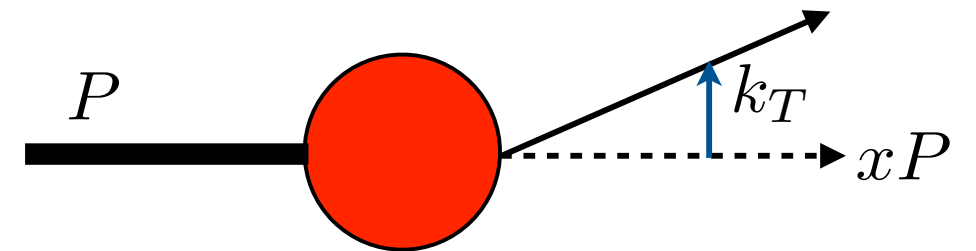


extraction of a **quark**  
**not** collinear with the proton

# quark TMD PDFs

$$\Phi_{ij}(k, P; S) \sim \text{F.T.} \langle PS | \bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi) | PS \rangle |_{LF}$$

| Quarks | $\gamma^+$              | $\gamma^+ \gamma^5$ | $i\sigma^{i+} \gamma^5$      |
|--------|-------------------------|---------------------|------------------------------|
| U      | $\mathbf{f_1}$          |                     | $\mathbf{h_1^\perp}$         |
| L      |                         | $\mathbf{g_1}$      | $\mathbf{h_{1L}^\perp}$      |
| T      | $\mathbf{f_{1T}^\perp}$ | $\mathbf{g_{1T}}$   | $\mathbf{h_1, h_{1T}^\perp}$ |



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

**bold** : also collinear

**red** : time-reversal odd (generalized universality properties)

# The frontier

---

## Nucleon tomography in momentum space:

to understand how hadrons are built in terms of the elementary degrees of freedom of QCD

## High-energy phenomenology:

to improve our understanding of high-energy scattering experiments and their potential to explore BSM physics

## A selection of open questions (formalism) :

1) How well do we understand collinear and TMD **factorization** ?

2) How (well) can we **match** collinear and TMD factorization ?

3) can we quantify **factorization breaking** effects ?

4) how can we investigate gluon TMDs ?

...

# The frontier

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## Nucleon tomography in momentum space:

to understand how hadrons are built in terms of the elementary degrees of freedom of QCD

## High-energy phenomenology:

to improve our understanding of high-energy scattering experiments and their potential to explore BSM physics

## More open questions (phenomenology) :

- 1) what is the **functional form** of TMDs at low transverse momentum ?
- 2) what is its **kinematic** and **flavor** dependence ?
- 3) can we attempt a global fit of TMDs ?
- 4) can we test the generalized **universality** of TMDs ?
- 5) what's the impact of hadron structure on the **high-energy physics** processes ?

# W-term and TMDs

---

Distribution for intrinsic transverse momentum  
(and its FT):

$$\tilde{F}_{i,NP}(x, \bar{b}_T; \{\lambda\})$$

a Gaussian ?

Soft gluon emission

$$g_K(\bar{b}_T; \{\lambda\})$$

# W-term and TMDs

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Separation of  $b_T$  regions

$$\hat{b}_T(b_T; b_{\min}, b_{\max}) \begin{cases} \nearrow b_{\max}, & b_T \rightarrow +\infty \\ \sim b_T, & b_{\min} \ll b_T \ll b_{\max} \\ \searrow b_{\min}, & b_T \rightarrow 0 \end{cases}$$

High  $b_T$  limit : avoid Landau pole

Low  $b_T$  limit : recover fixed order expression

# Collinear and TMD factorization

Let's consider a process with  
**three separate scales:**

(SIDIS, Drell-Yan,  $e^+e^-$  to hadrons,  
pp to quarkonium, ... )

hadronic  
mass scale

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

hard scale

(related to the)  
transverse momentum of the observed particle

The ratios

$$\Lambda_{\text{QCD}}/Q$$

$$\Lambda_{\text{QCD}}/q_T$$

$$q_T/Q$$

**select the factorization theorem** that we rely on.

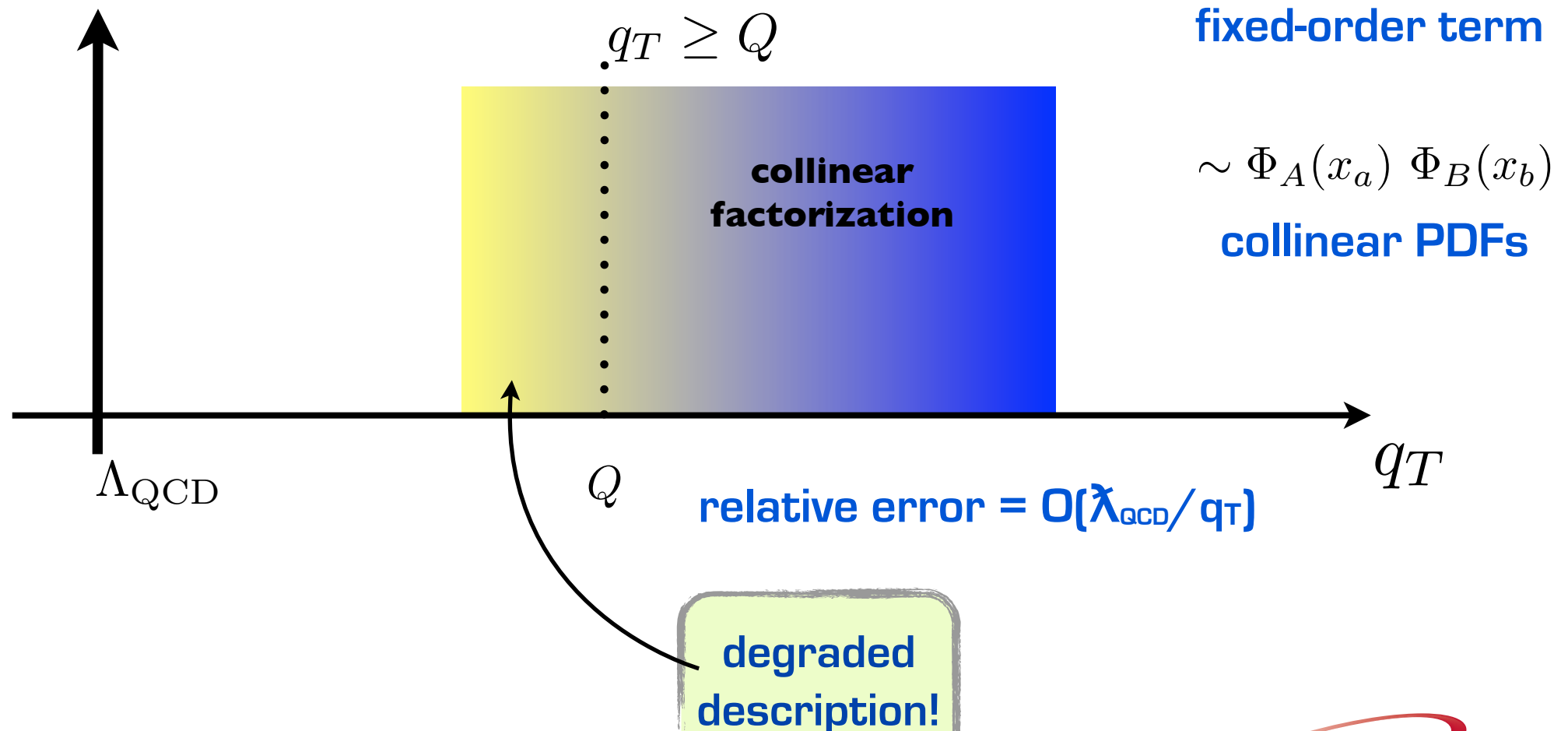
According to their **values** we can access **different**  
“**projections**” of hadron structure

# Collinear and TMD factorization

The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

fixed  $Q$ , variable  $q_T$

$d\sigma/dq_T$

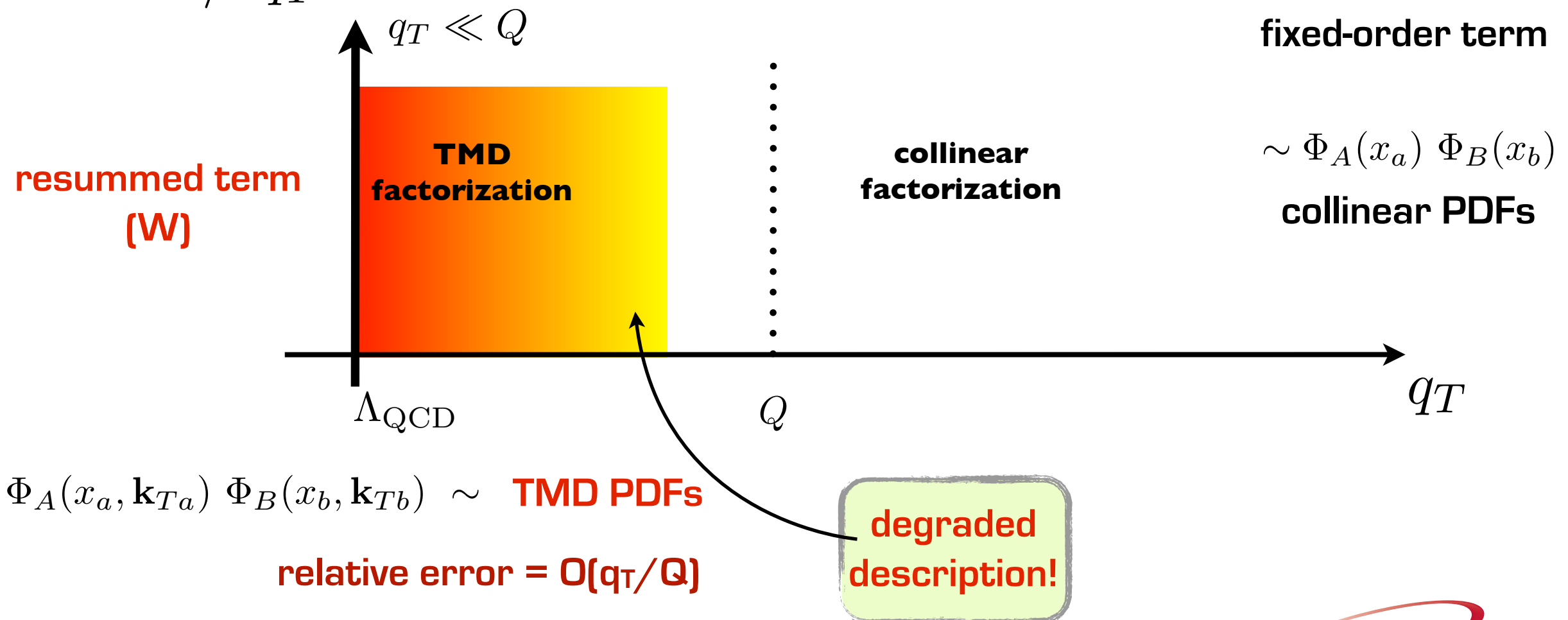


# Collinear and TMD factorization

The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

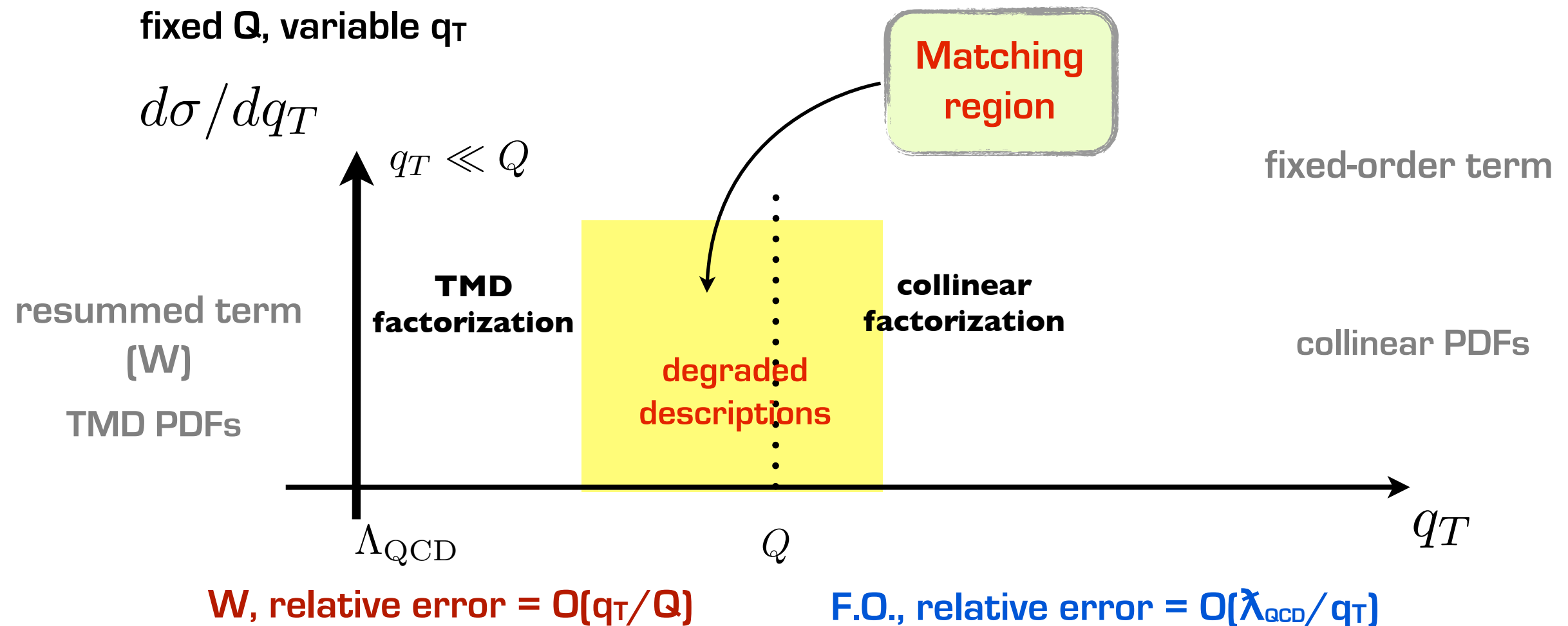
fixed  $Q$ , variable  $q_T$

$d\sigma/dq_T$



# Collinear and TMD factorization

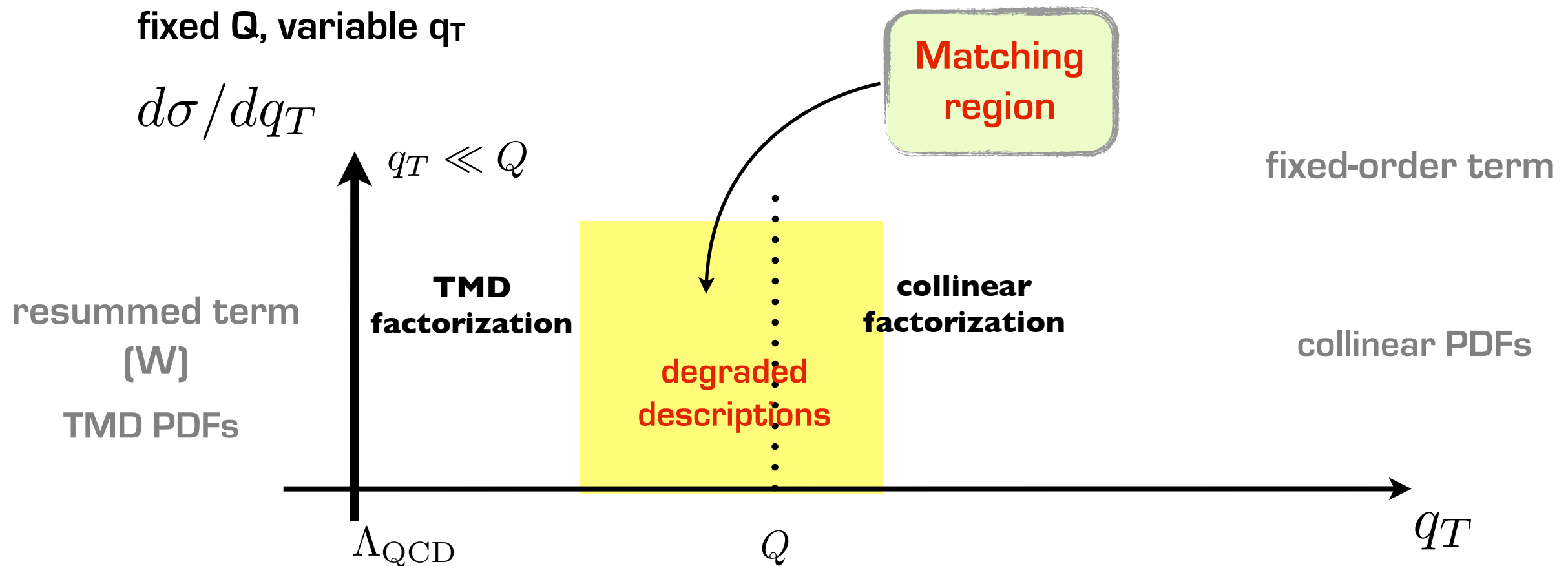
The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**



We need a prescription to deal with the region where both descriptions are not good

# Collinear and TMD factorization

The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**



The extraction of the **nonperturbative (NP) part of TMDs** is affected by the description of the whole  $q_T$  range

Crucial, especially at **low  $Q$**  (e.g. JLab kinematics), where the **regions shrink**

Pheno: we are making progress

polarization ?

# W-term & TMDs

**W-term** : transverse momentum resummation in terms of TMDs

$$W(q_T, Q) = \int \frac{d^2 b_T}{(2\pi)^2} e^{i q_T \cdot b_T} \tilde{W}(b_T, Q)$$

$b_T$  is the Fourier-conjugated variable of the (partonic and observed) transverse momenta

**Need a regularization to recover collinear factorization upon integration over  $q_T$ :**

$$b_T \rightarrow \bar{b}_T \geq b_{\min} \sim 1/Q \implies \int d^2 q_T W(q_T, Q) \sim f_i^{h_1}(x_1; \mu) f_j^{h_2}(x_2; \mu)$$

Collins et al. PRD94 2016

$$\tilde{W}(b_T, Q) \sim \tilde{F}_i^{h_1}(x_1, b_T; \mu, \zeta_1) \tilde{F}_j^{h_2}(x_2, b_T; \mu, \zeta_2)$$

Product of Fourier-transformed TMDs

**TMD evolution** is multiplicative in  $b_T$  space

$$\tilde{W}^{QZ}(b, Q, x_A, x_B) = \begin{cases} \tilde{W}(b, Q, x_A, x_B), & b \leq b_{max} \\ \tilde{W}(b_{max}, Q, x_A, x_B) \tilde{F}_{QZ}^{NP}(b, Q, x_A, x_B; b_{max}), & b > b_{max} \end{cases}$$

$$\tilde{F}_{QZ}^{NP}(b, Q, x_A, x_B; b_{max}) = \exp \left\{ -\ln \left( \frac{Q^2 b_{max}^2}{c^2} \right) \{ g_1 [(b^2)^\alpha - (b_{max}^2)^\alpha] + g_2 (b^2 - b_{max}^2) \} - \bar{g}_2 (b^2 - b_{max}^2) \right\}$$

parameters:  
bmax, g1, g2, α

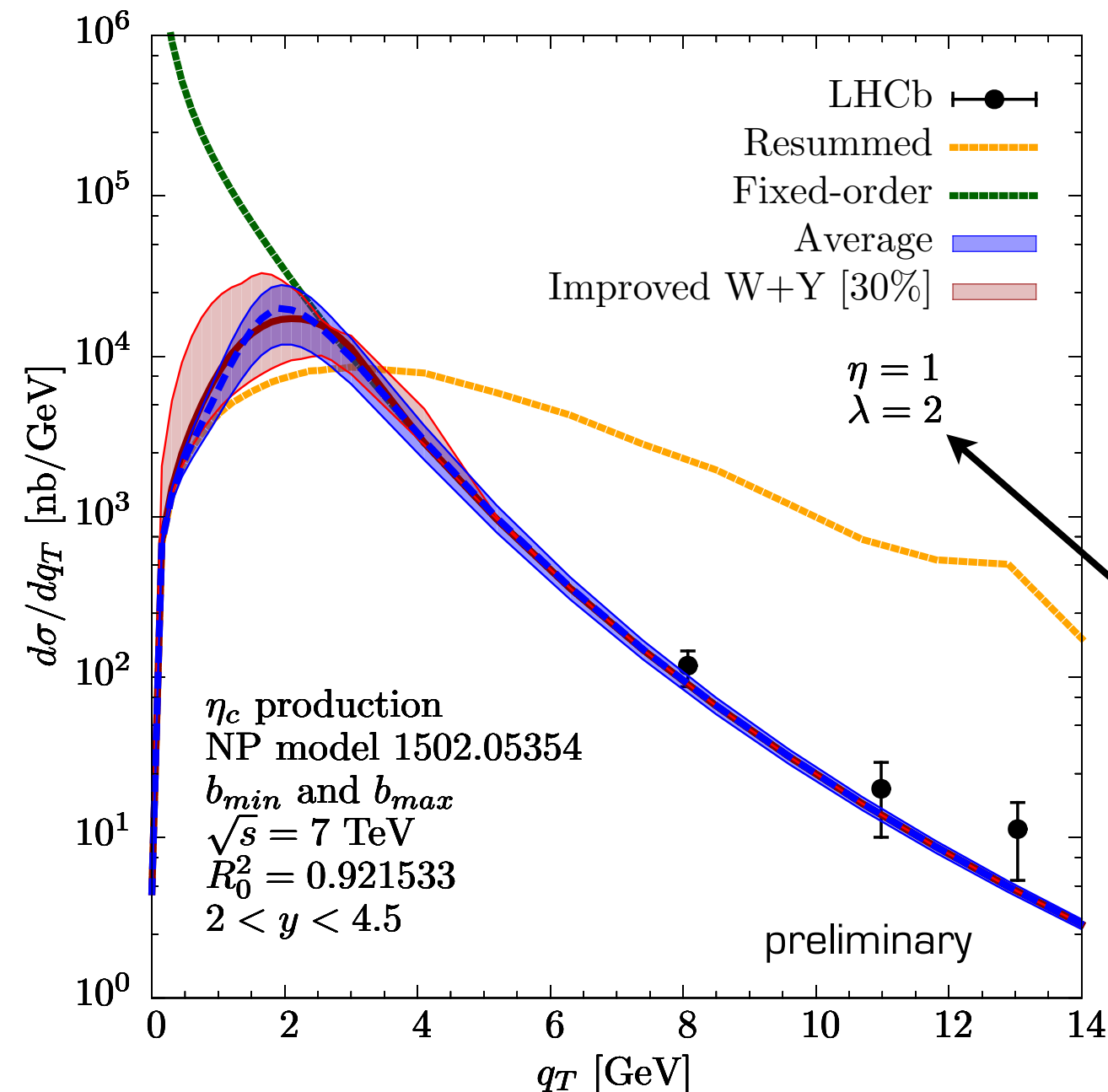
g1 and α are fixed  
as a function of g2, bmax  
requiring continuity in bmax of  
the first and second derivative

# $\eta_c$ production at LHC

log-average vs improved W+Y

low-energy process  
 $Q = M(\eta_c) = 2.98 \text{ GeV}$

$b_{\min}$  and  $b_{\max}$  prescriptions



smooth matching from W to FO

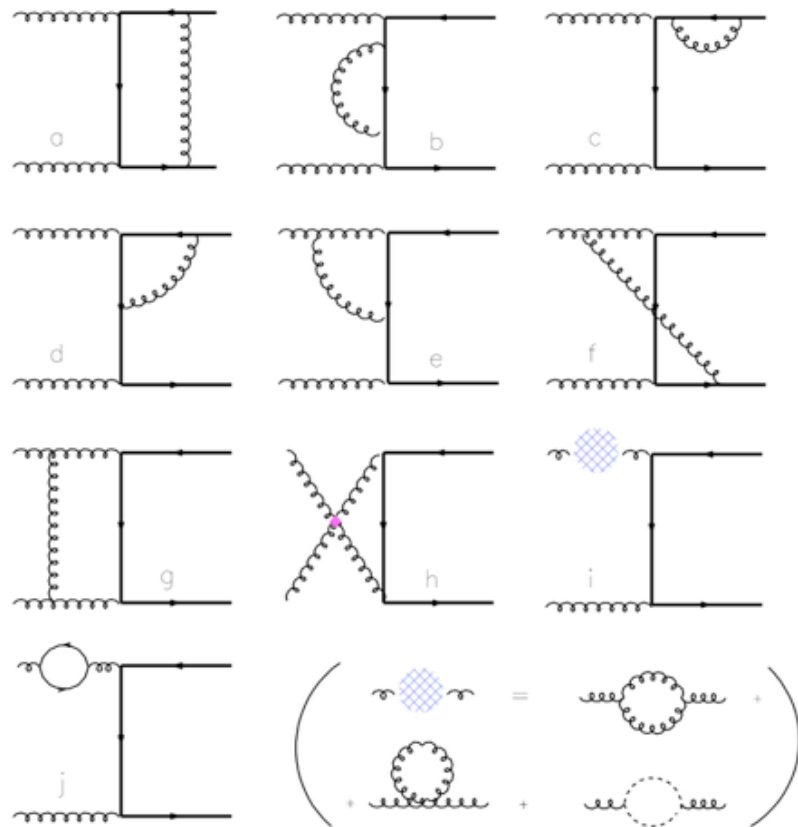
- W dominates for  $q_T < 1 \text{ GeV}$
- FO dominates for  $q_T > 3 \text{ GeV}$

different!

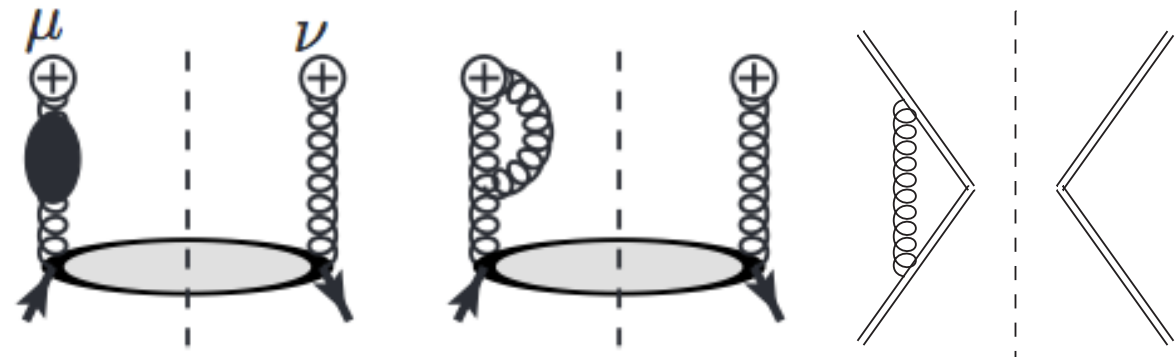
**blue band:** uncertainty from  
log-average matching

**red band:** uncertainty from  
improved W+Y matching  
(larger)

# TMD approach



**Philosophy** : check if the **structure** of the IR divergencies is the same as in ‘full’ QCD.  
If yes, the factorized form works as QCD, namely **factorization is “established”**



$$\sigma^{\text{virt},(1)} \longleftrightarrow \left\{ \mathcal{H} \tilde{f}_1^{g/A} \tilde{f}_1^{g/B} \right\}_{\text{virt}}^{(1)}$$

**? same IR ?**

**no:**

It does not reproduce the physical (=QCD) result

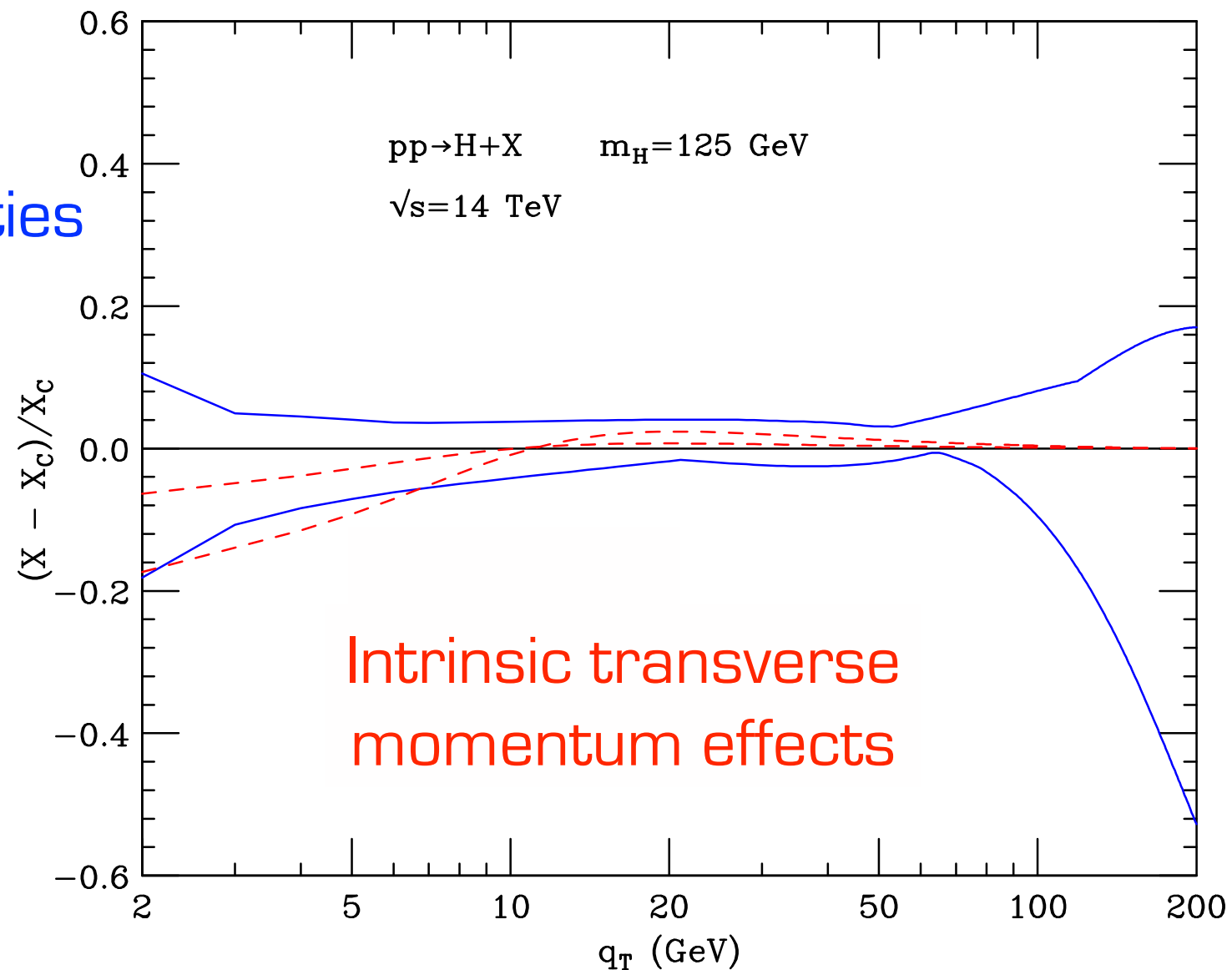
**yes:**

It reproduces the physical result and the hard part can be calculated by subtraction

# Impact on Higgs physics

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

PDF uncertainties



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