TMD phenomenology: from JLab to the LHC

Andrea Signori

Spatial and momentum
tomography
of hadrons and nuclei

INT 17-3
Sept 25 2017

Jefferson Lab

JSA

TMD phenomenology
at low and high energy

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Outline

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

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

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

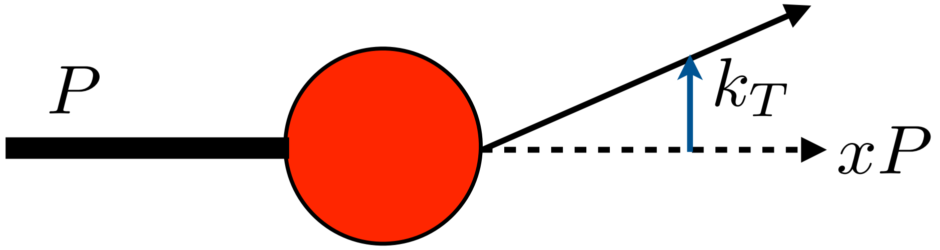
quark TMD PDFs

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

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

Sivers TMD PDF

unpolarized TMD PDF

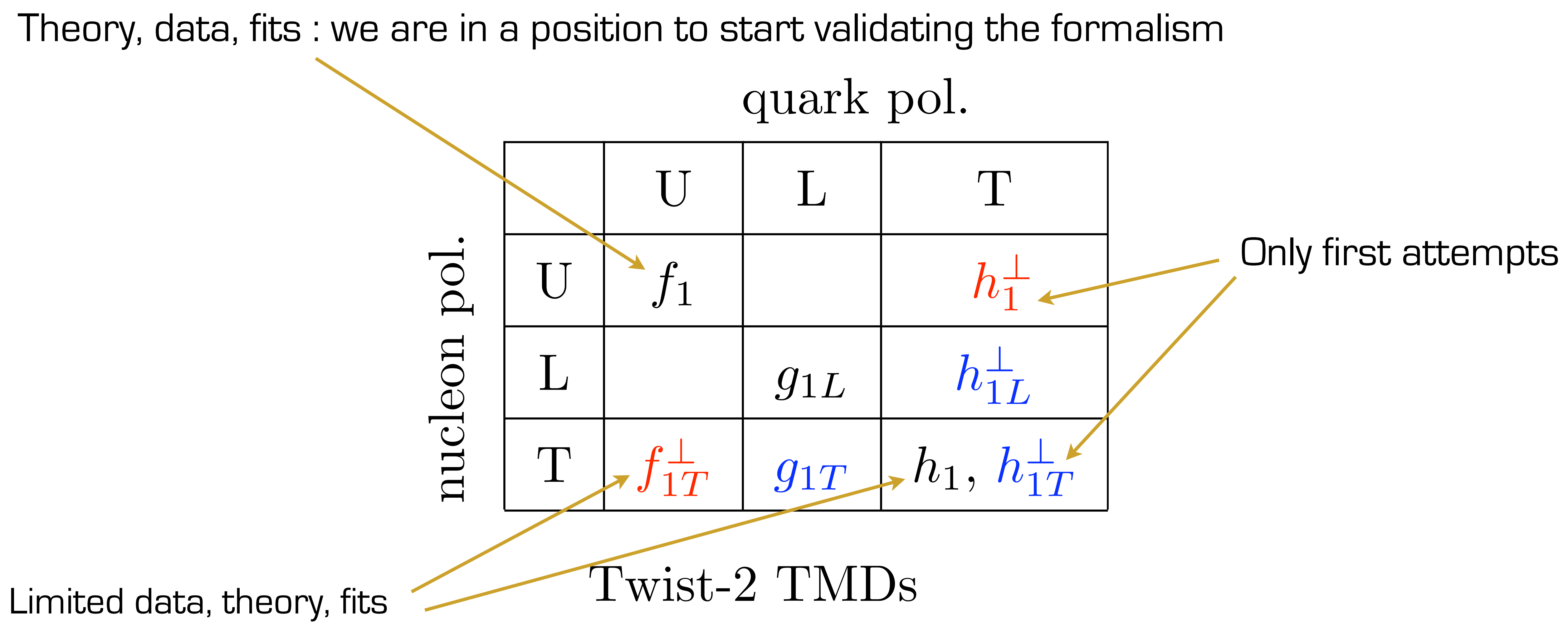


extraction of a **quark**
not collinear with the proton

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

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, $h_{1T}^\perp$

Only first attempts

Limited data, theory, fits

Twist-2 TMDs

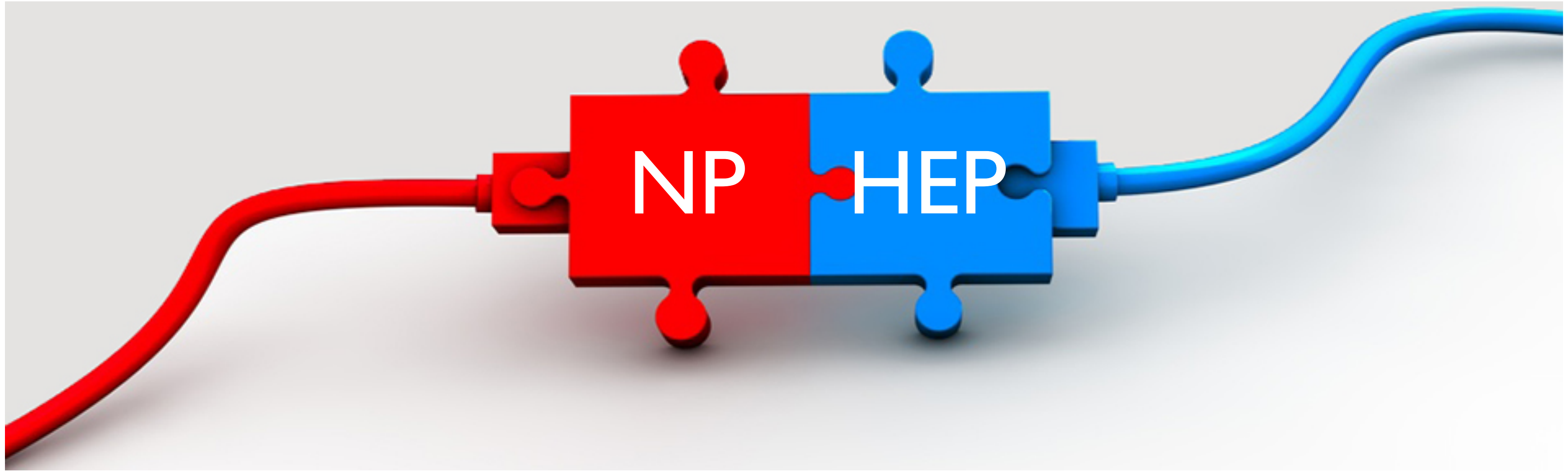
see, e.g, Bacchetta, Radici, arXiv:1107.5755
Anselmino, Boglione, Melis, PRD86 (12)
Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
Anselmino, Boglione, D'Alesio, Murgia, Prokudin, arXiv: 1612.06413
Anselmino et al., PRD87 (13)
Kang et al. arXiv:1505.05589

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

The frontier

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 :

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

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

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

W-term & TMDs

FT of TMDs :

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

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

---

Collinear distribution!

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

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

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

Phenomenology

hermes Jefferson Lab Belle II J-PARC Tevatron 1983-2011

COMPASS BESIII BABAR RHIC relativistic heavy ion collider LHC ...

consolidate the formalism +
extractions of TMDs

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

new data

EIC ilc international linear collider AFTER ...

LHeC HIEPA

Phenomenology

LHC ...

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

LHC ...

consolidate the formalism +
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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**

LHC …

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
"unexplored/known" effects
in
"unexplored/known" regions

predictive power & nonperturbative input

EIC

…

HIEPA

Saddle point approximation

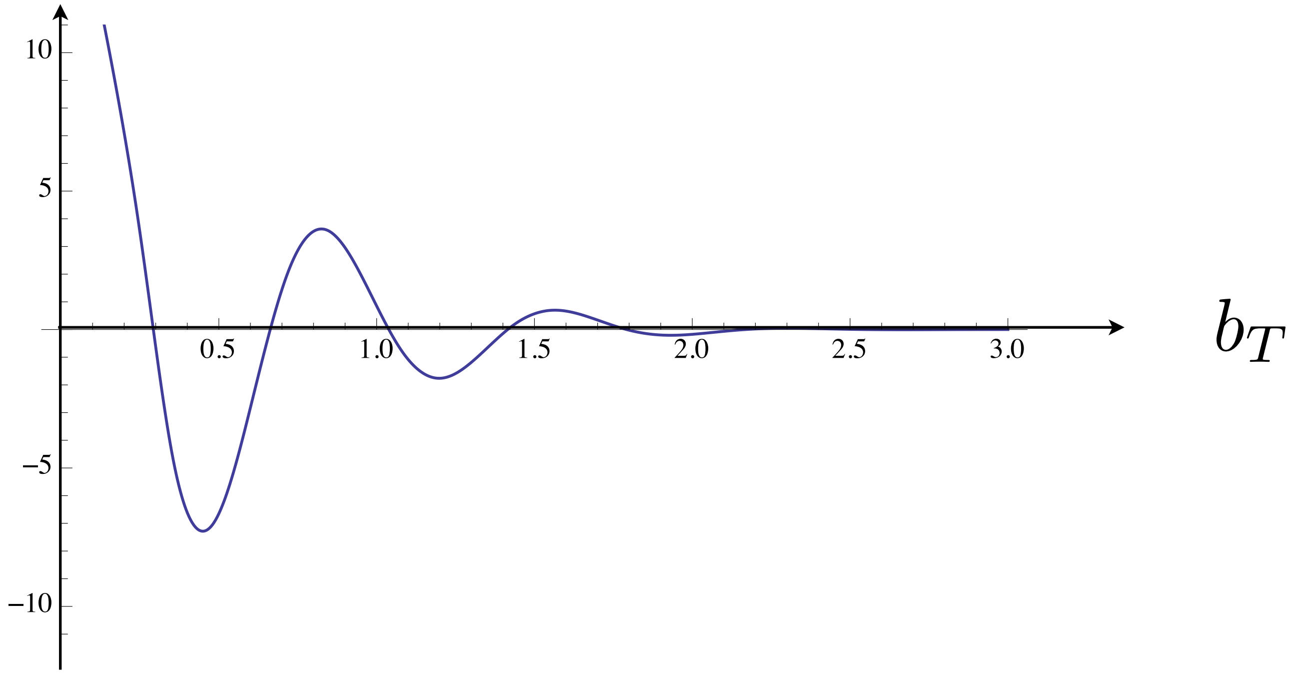
Qiu-Zhang, Phys. Rev. D 63 114011

$$W(x_{1,2}, q_T, Q) = \int \frac{d^2 b_T}{(2\pi)^2}\ e^{i q_T \cdot b_T}\ \tilde{W}(x_{1,2}, b_T, Q)$$

$$= \int \frac{d b_T}{2\pi} b_T\ J_0(q_T b_T)\ \tilde{W}(x_{1,2}, b_T, Q)$$

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

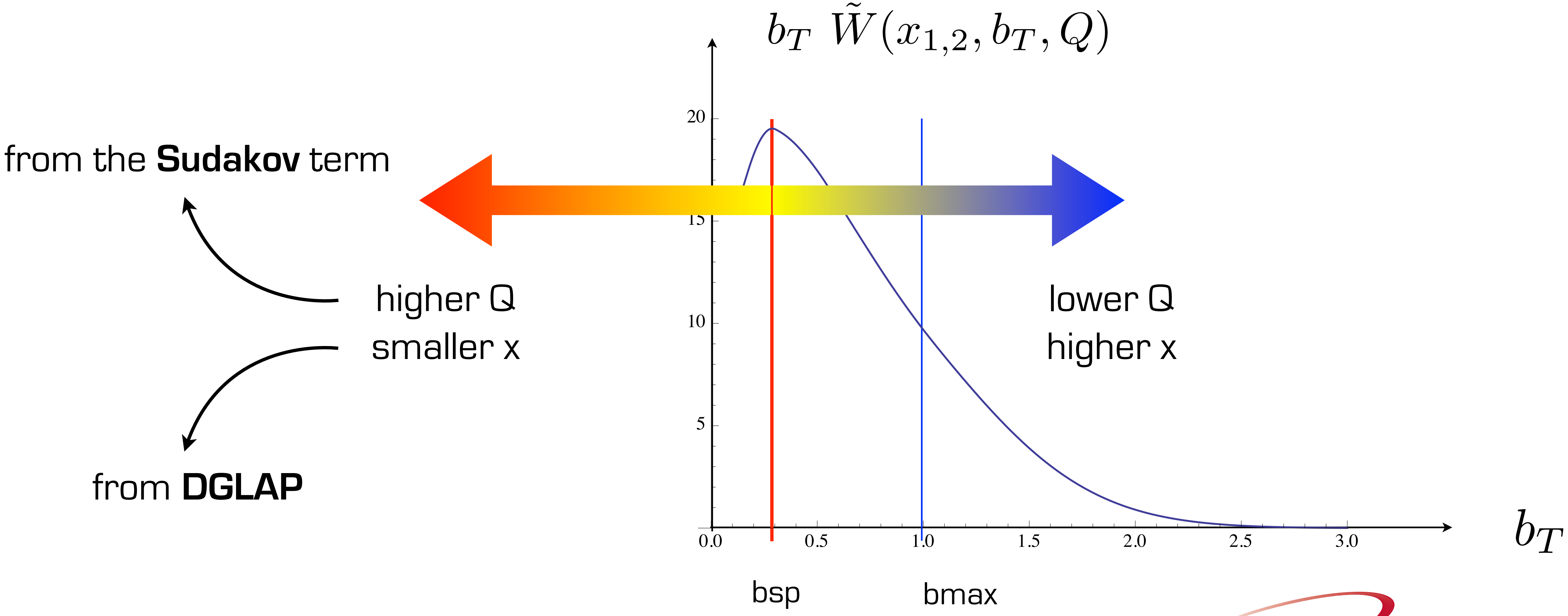
Saddle point approximation

Qiu-Zhang, Phys. Rev. D 63 114011

let's look at the integrand at qT=0 to quantify the importance of the high bT region

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

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



from the **Sudakov** term

higher Q
smaller x

from **DGLAP**

lower Q
higher x

Quark TMD PDF

preliminary

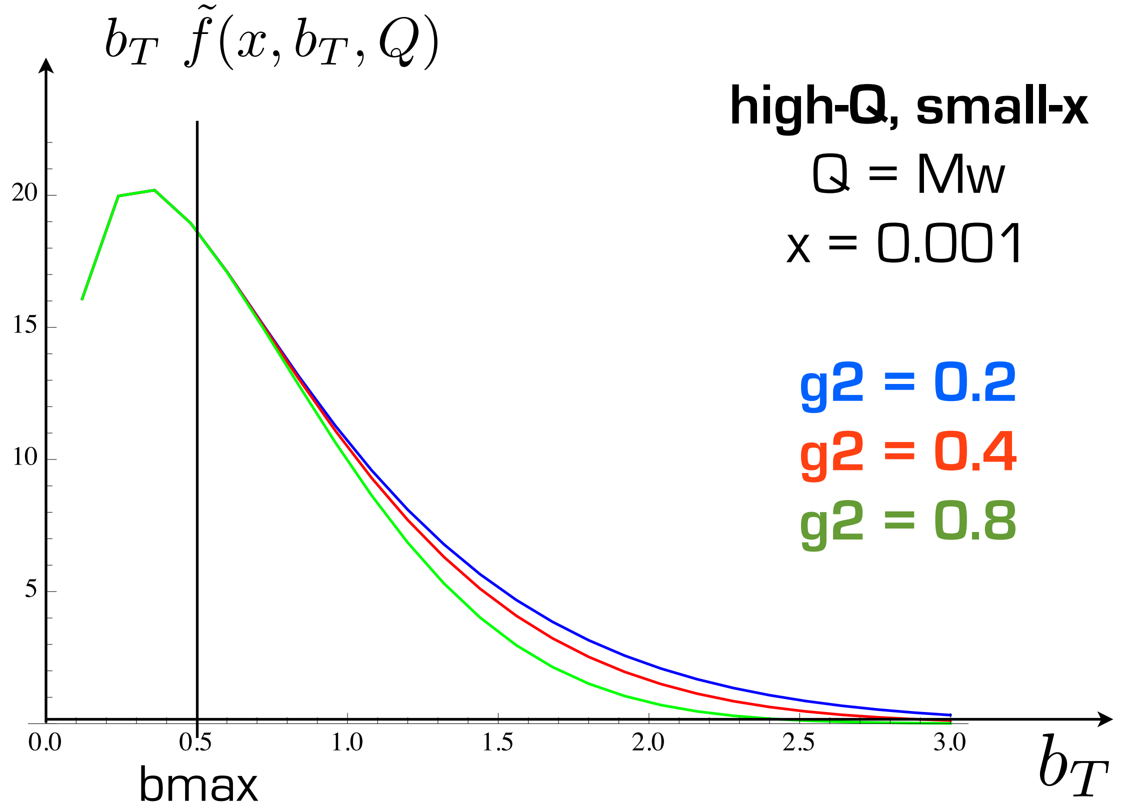
Grewal, Kang, Qiu, AS - in prep.

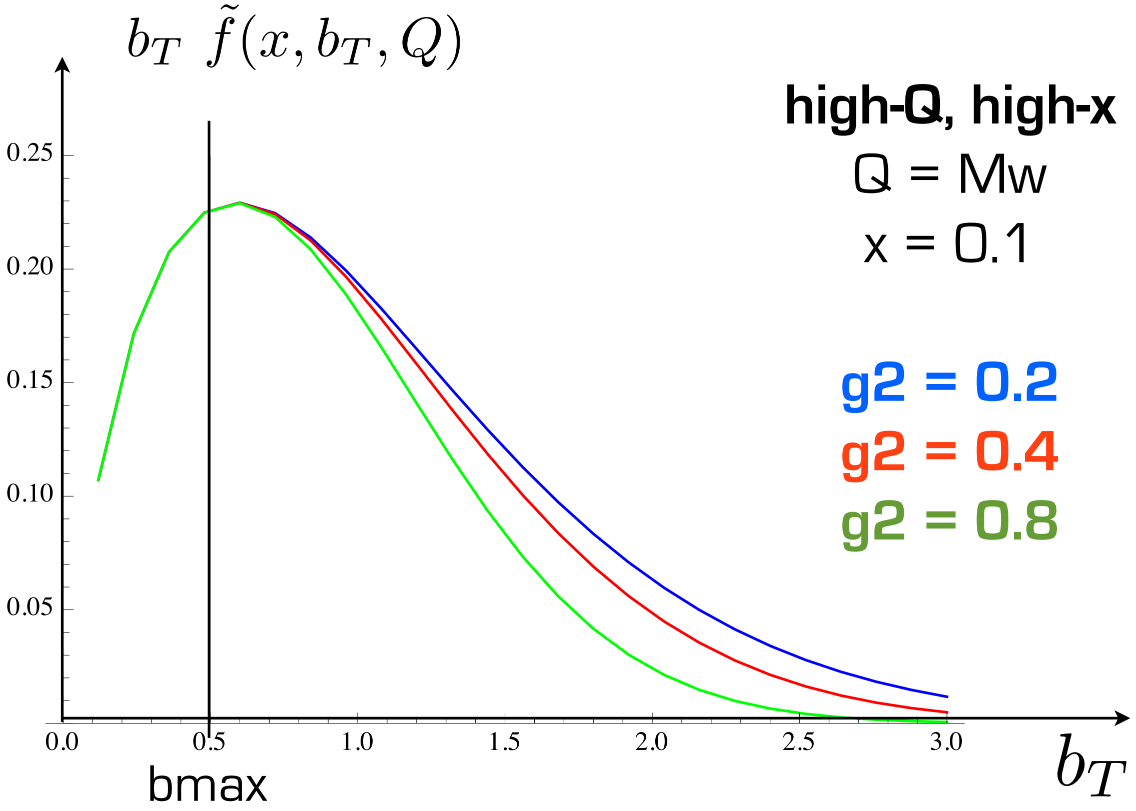
We'd like to check if the same statement holds for a single quark TMD PDF

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

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

accuracy : NLO and NLL





g2 = 0.4

integral

+5% g2 = 0.2

-7% g2 = 0.8

+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

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

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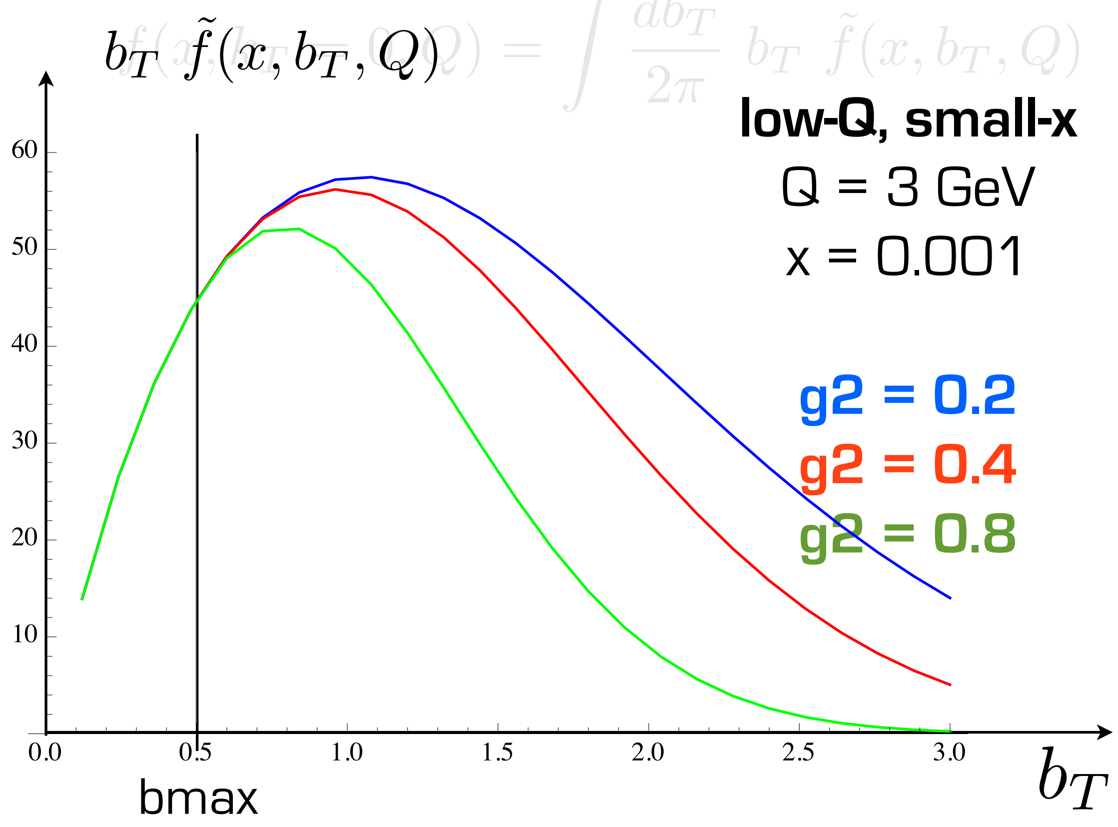
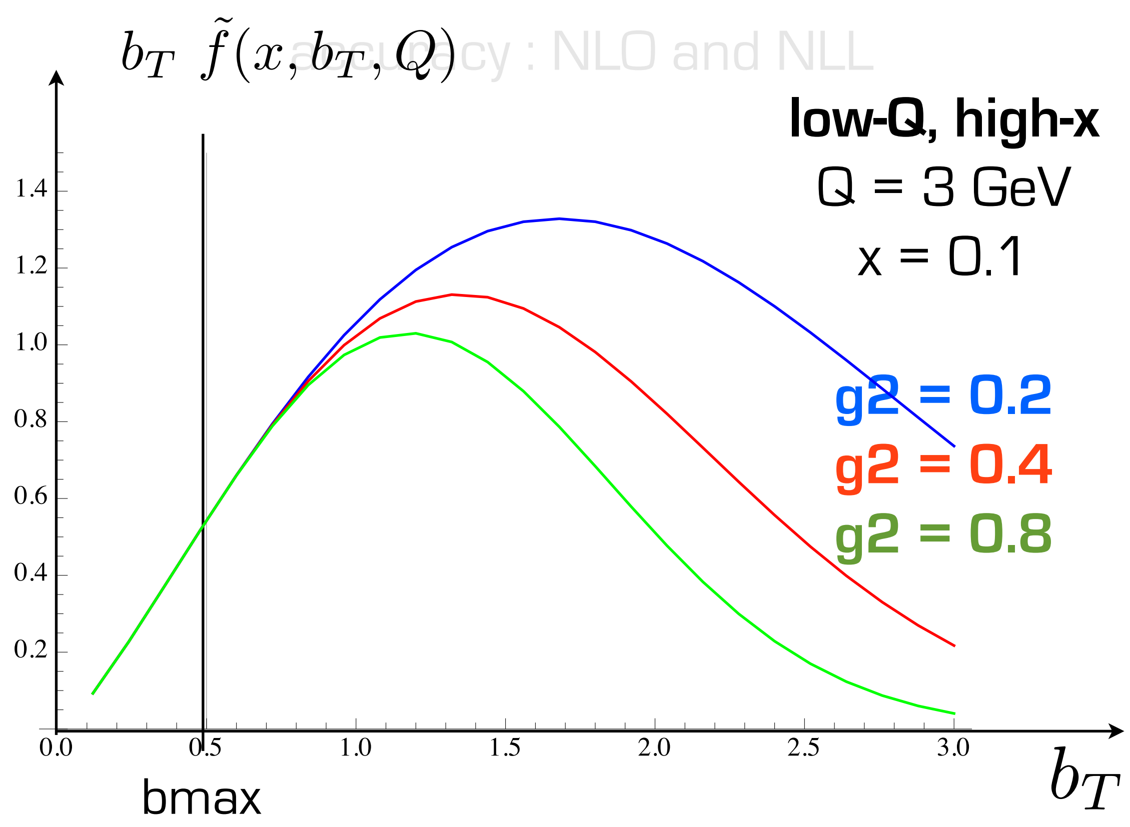
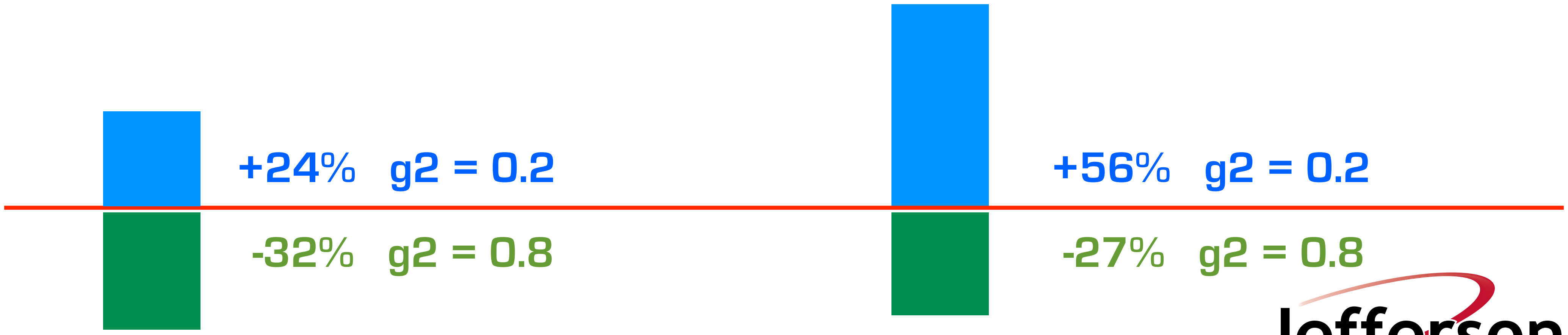


low-Q, small-x
Q = 3 GeV
x = 0.001



low-Q, high-x
Q = 3 GeV
x = 0.1



g2 = 0.4
integral

+24% g2 = 0.2
-32% g2 = 0.8

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

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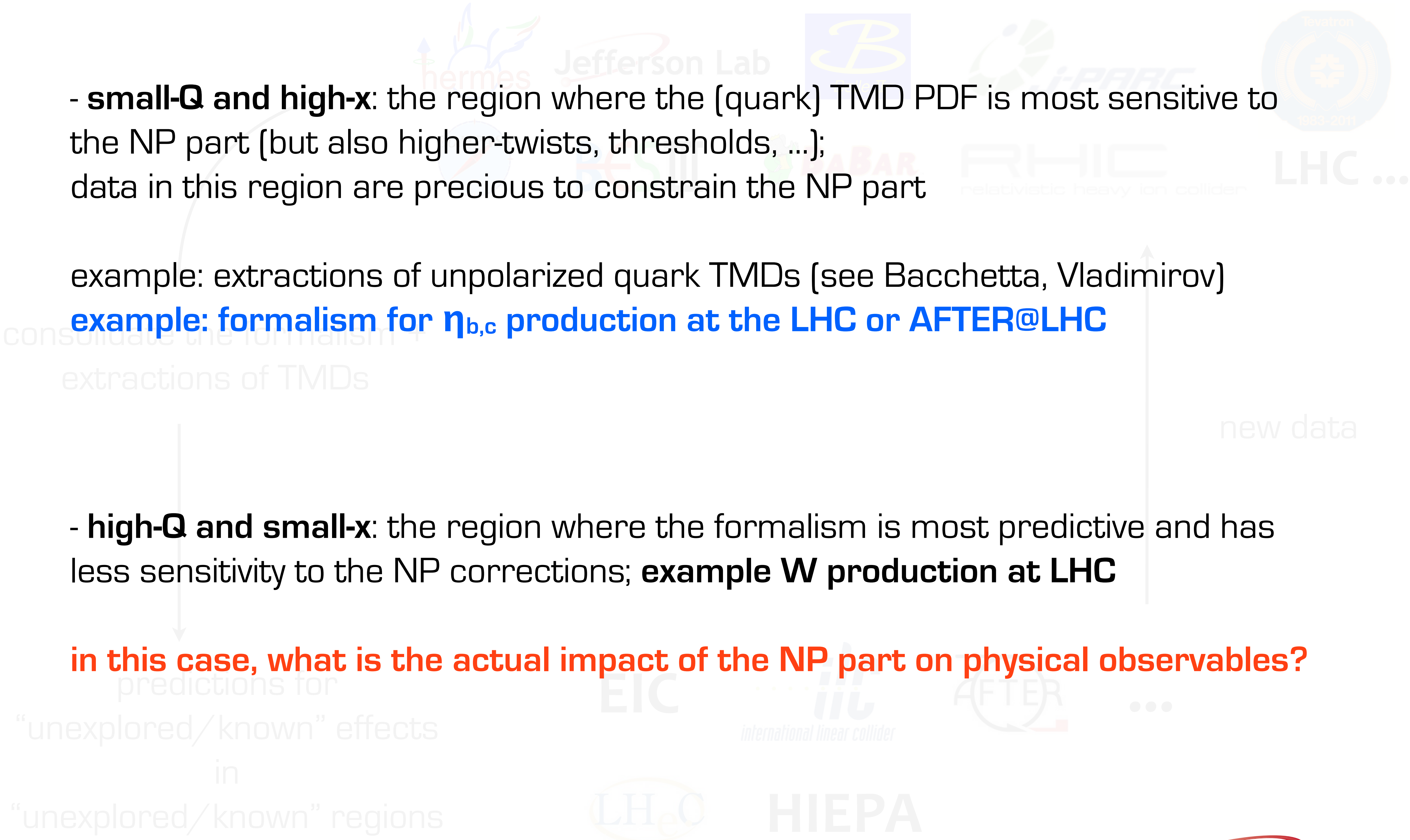
The message



- **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**

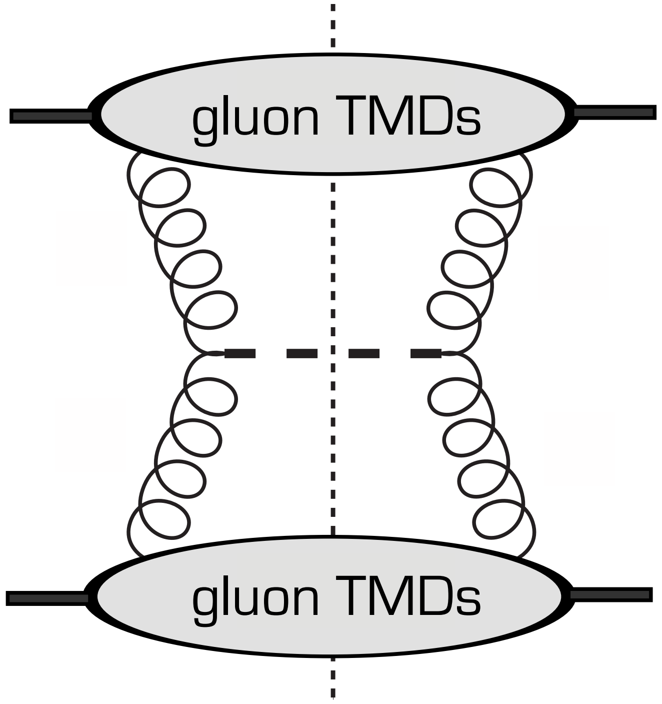
in this case, what is the actual impact of the NP part on physical observables?

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

(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:

$p\ p \rightarrow \eta_b\ X$ M = 9.39 GeV

$p\ p \rightarrow \eta_c\ X$ M = 2.98 GeV

(see also talk by C. Pisano week 4)

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

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

$$\sim \boxed{\mathcal{C}[\ f_1^{g/A}\ \ f_1^{g/B}\ ]} \pm \boxed{\mathcal{C}[\ h_1^{\perp g/A}\ \ h_1^{\perp g/B}\ ]}$$

unpolarized gluons

lin. polarized gluons

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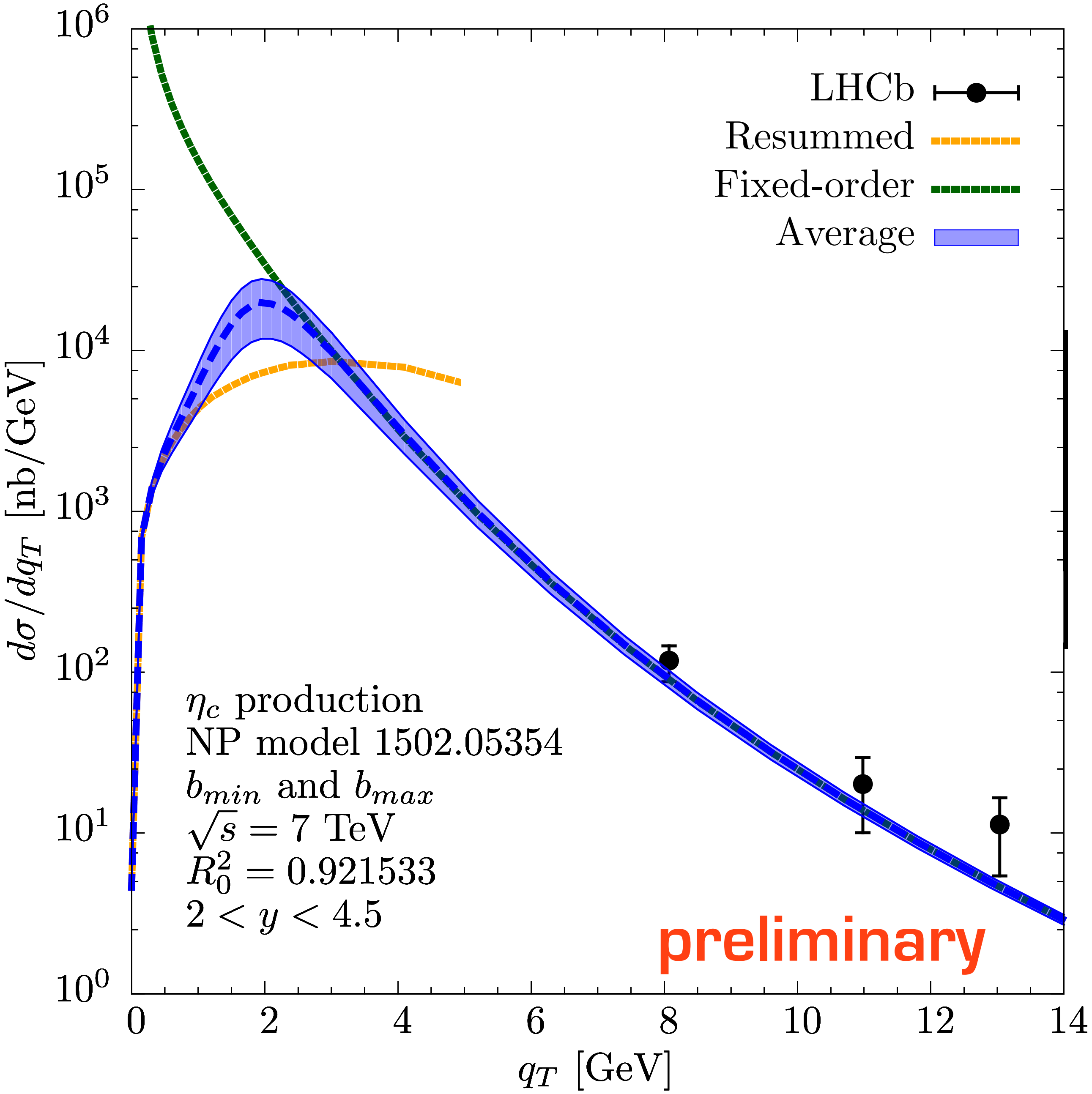
η_c production at LHC

full transverse momentum spectrum:
low qT matched with high qT region



blue band: uncertainty from matching

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

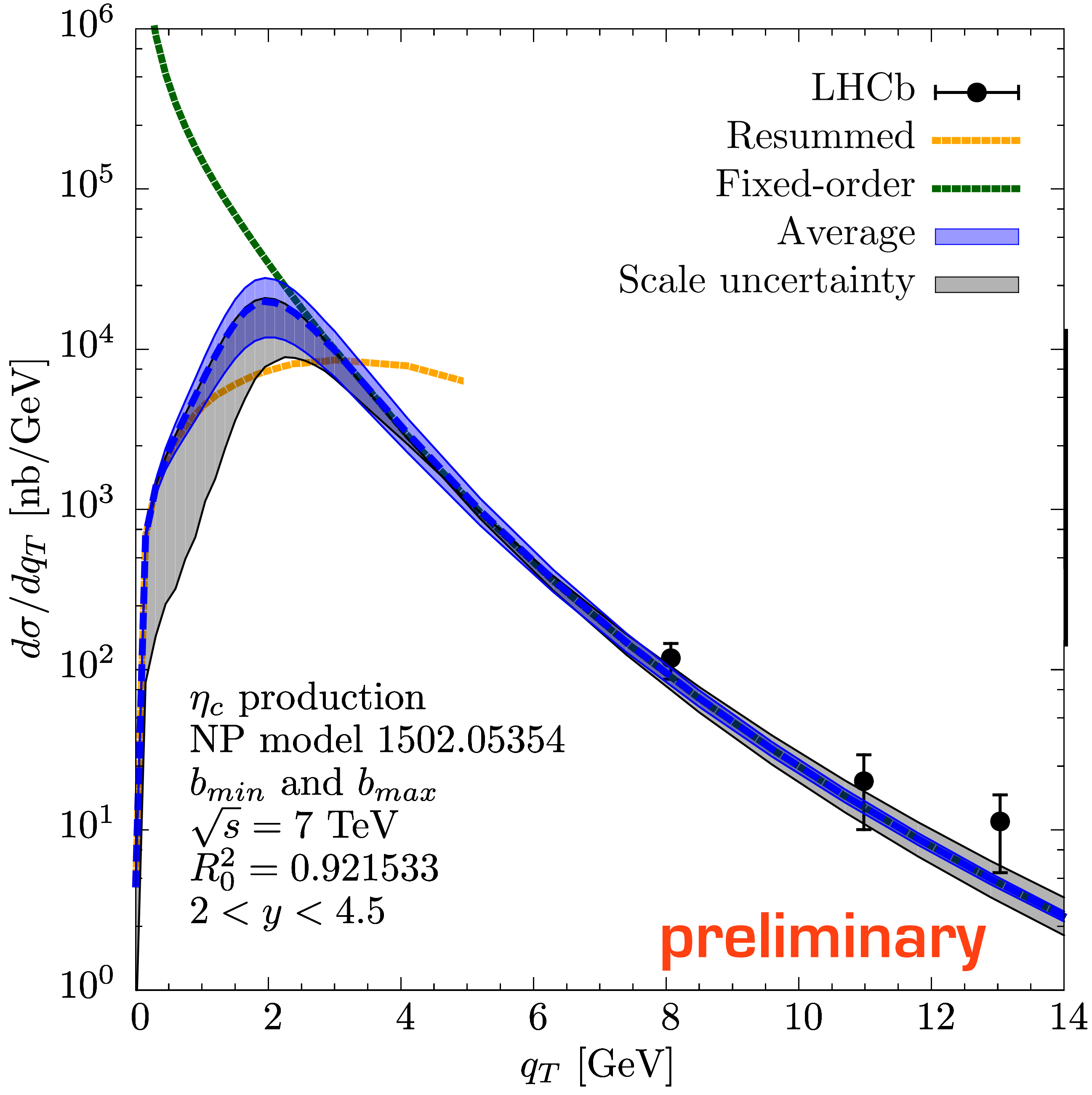
the **weights** are related to the **power corrections** to TMD and collinear factorization:

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

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

η_c production at LHC

full transverse momentum spectrum:
low qT matched with high qT region



blue band: uncertainty from matching

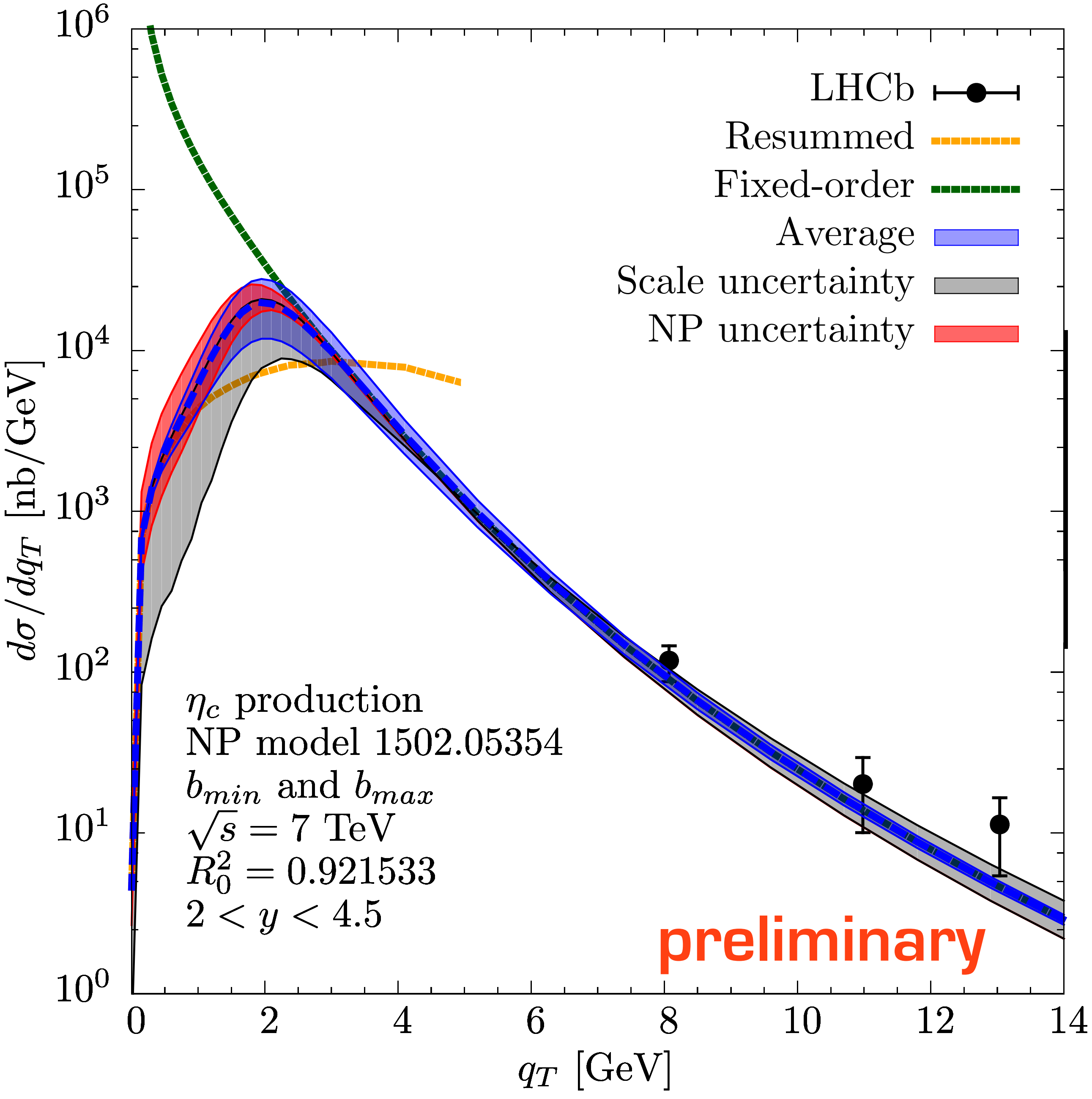
grey band: scale uncertainty

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

fact. 2 variation and envelope

η_c production at LHC

full transverse momentum spectrum:
low qT matched with high qT 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 GeV^2, var. 50%, envelope

both for unpolarized and
linearly polarized distributions

the formalism is in good shape!
we need the data at low qT

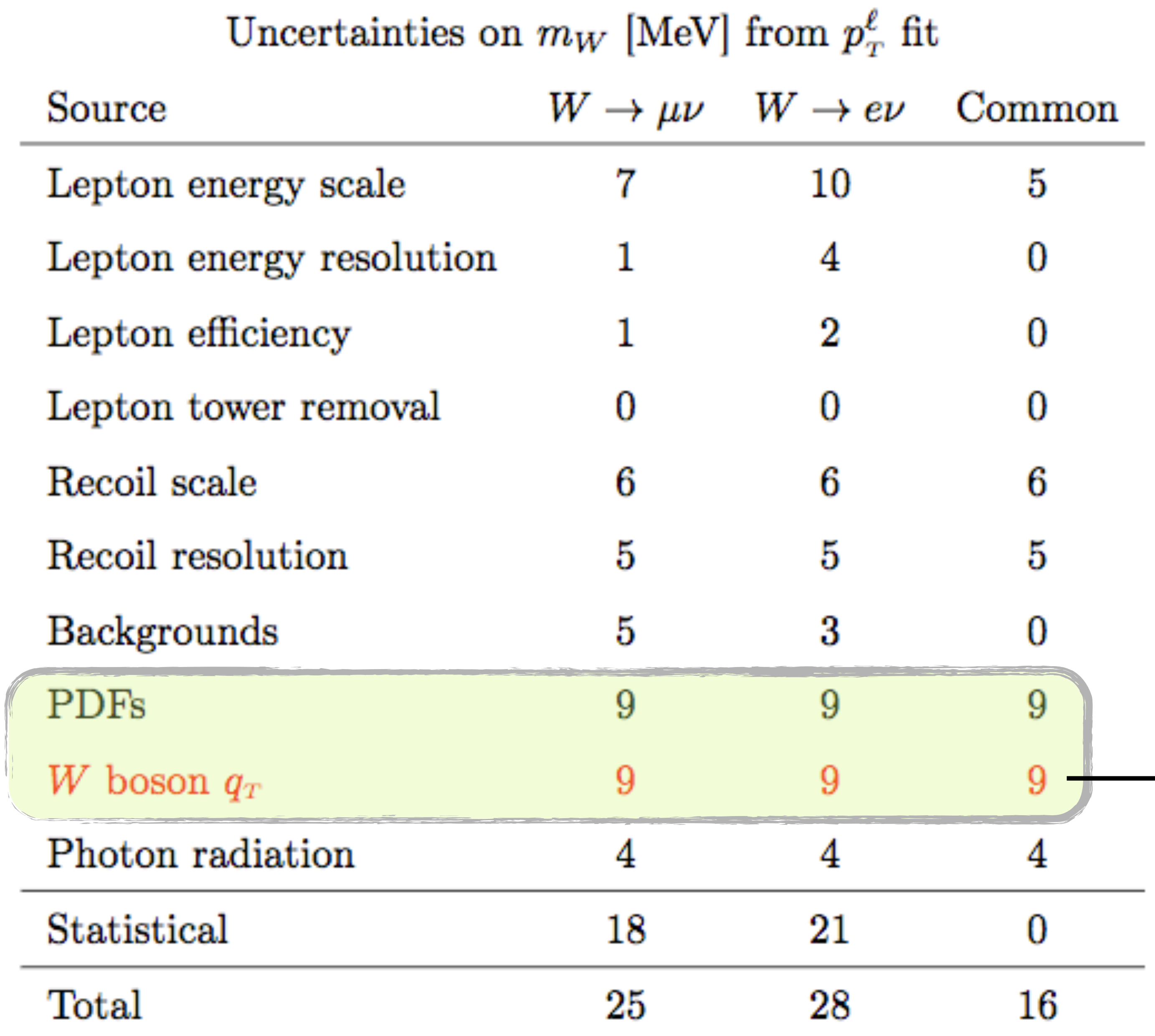
W production at LHC

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^ℓ fit

Source	$W \to \mu\nu$	$W \to e\nu$	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 α_s and NP evolution; no intrinsic transverse momentum

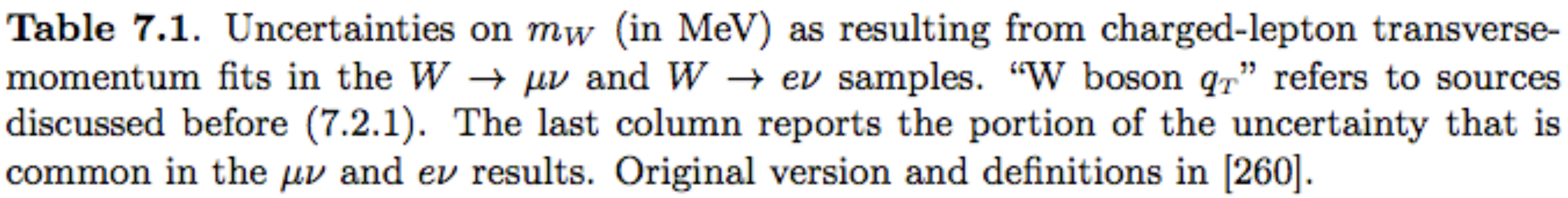


Table 7.1. Uncertainties on m_W (in MeV) as resulting from charged-lepton transverse-momentum fits in the $W \to \mu\nu$ and $W \to e\nu$ samples. "W boson q_T" refers to sources discussed before (7.2.1). The last column reports the portion of the uncertainty that is common in the $\mu\nu$ and $e\nu$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

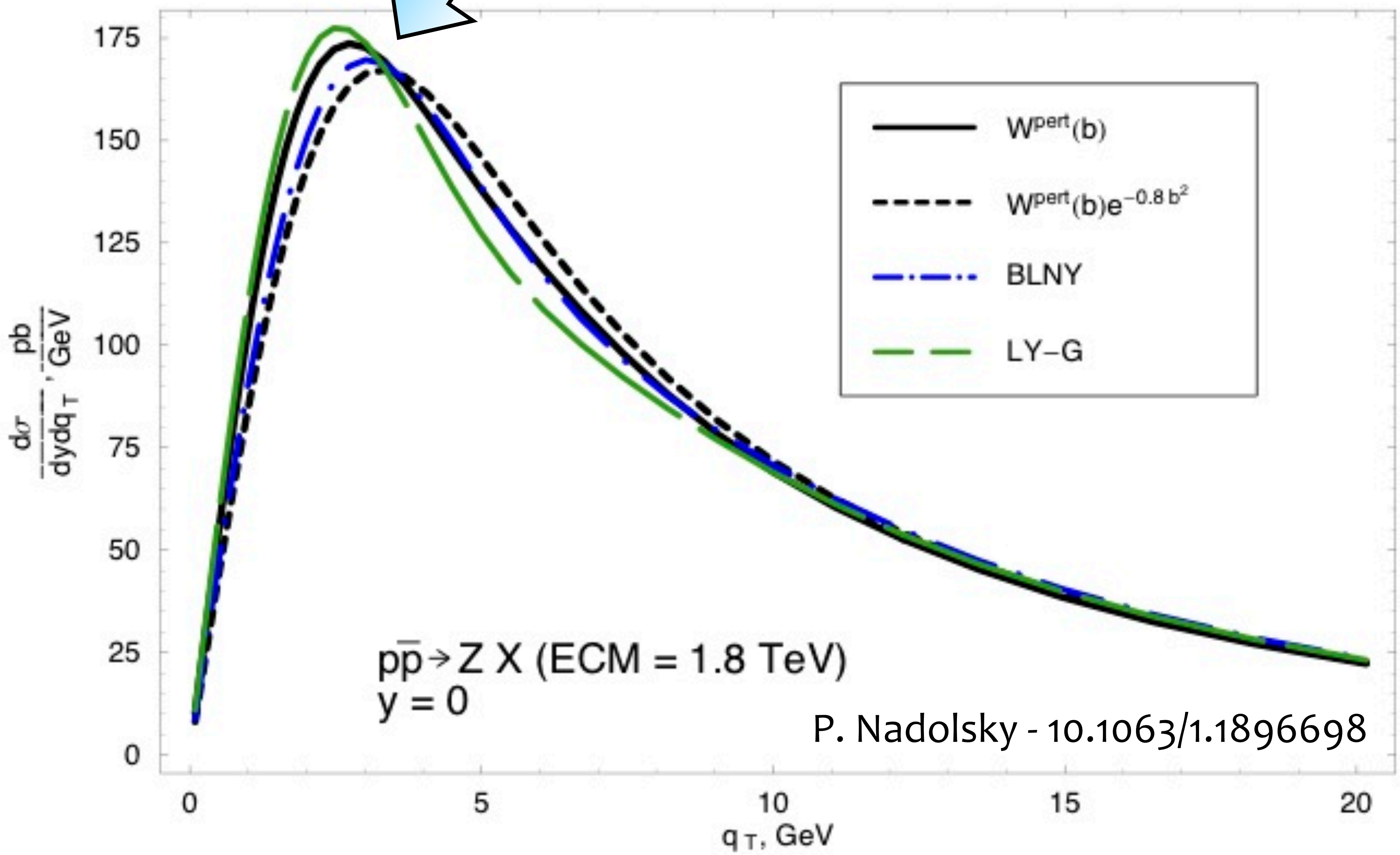
Nonperturbative effects

AS - PhD thesis

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

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

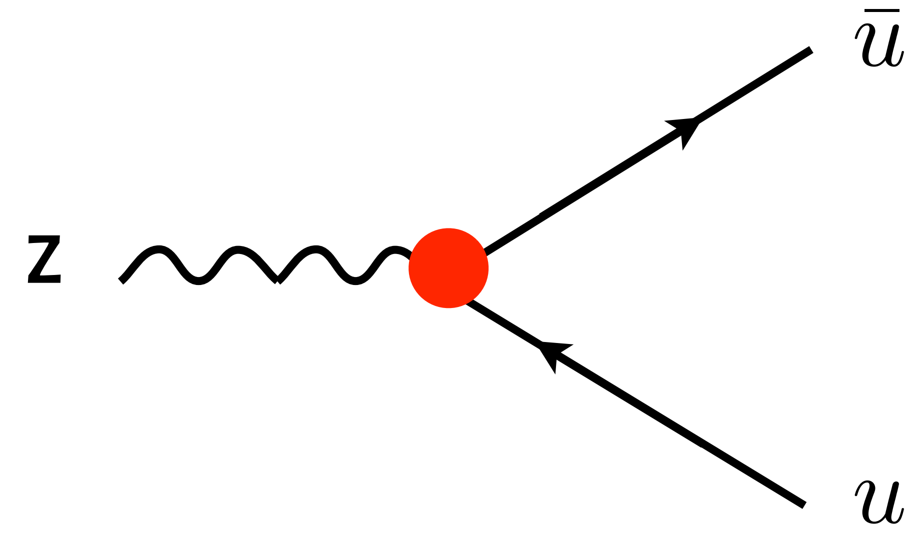
g comes from 2 TMD PDFs
and ***controls the position of the peak***



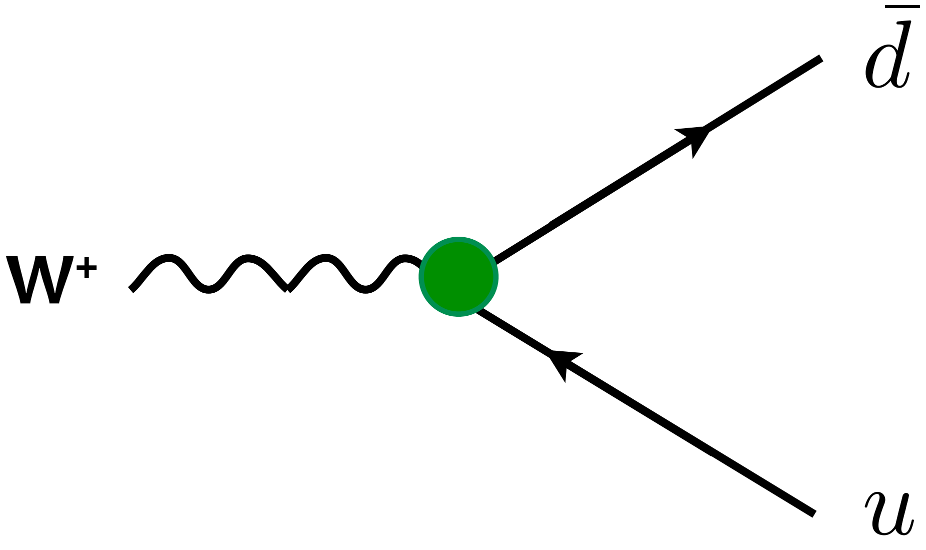
P. Nadolsky - 10.1063/1.1896698

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**

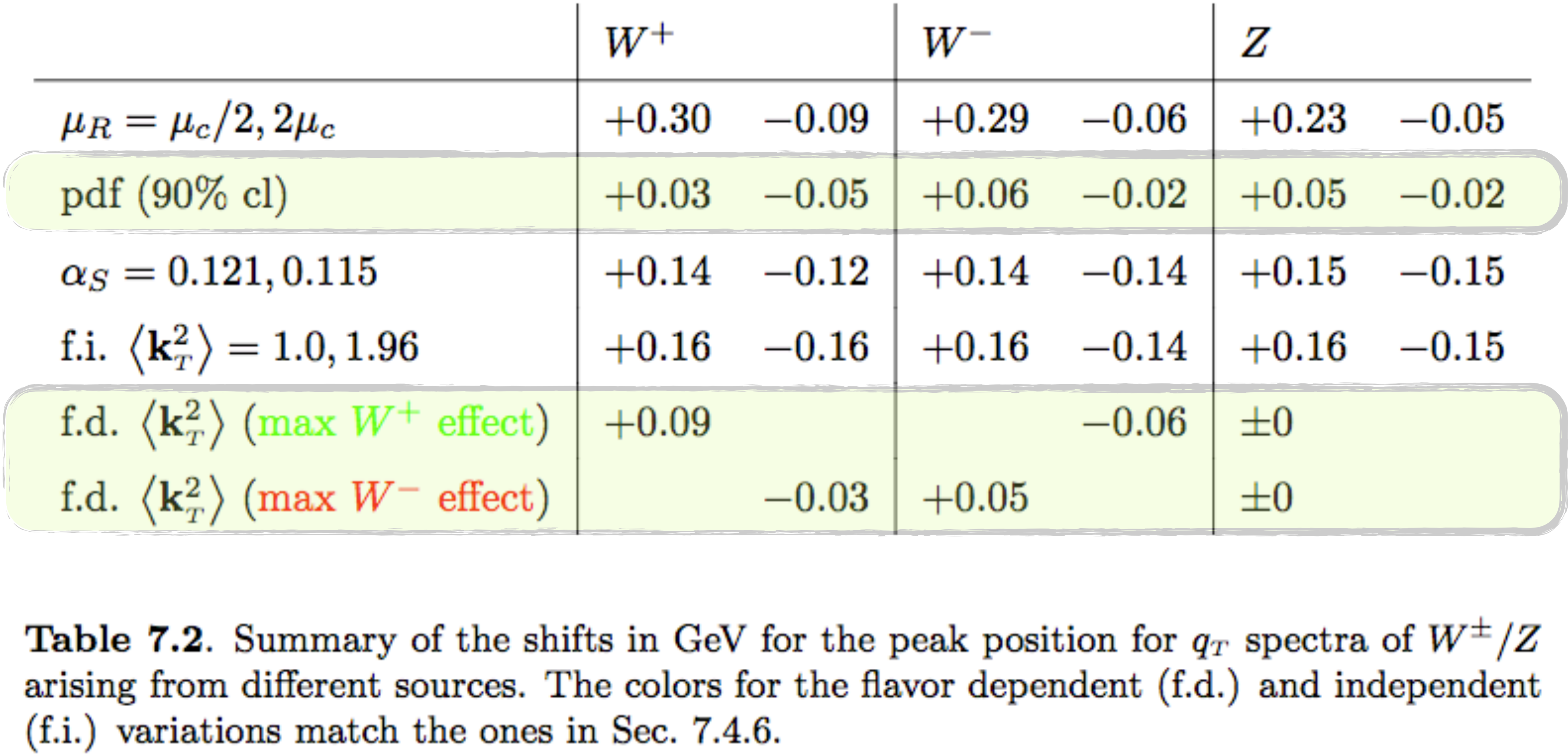


This reflects a flavor independent approach and might not be optimal because of the **different flavor content:**

the intrinsic contributions are ***different in Z and W± 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	± 0	
f.d. $\langle \mathbf{k}_T^2 \rangle$ (max W^- effect)		-0.03	$+0.05$		± 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

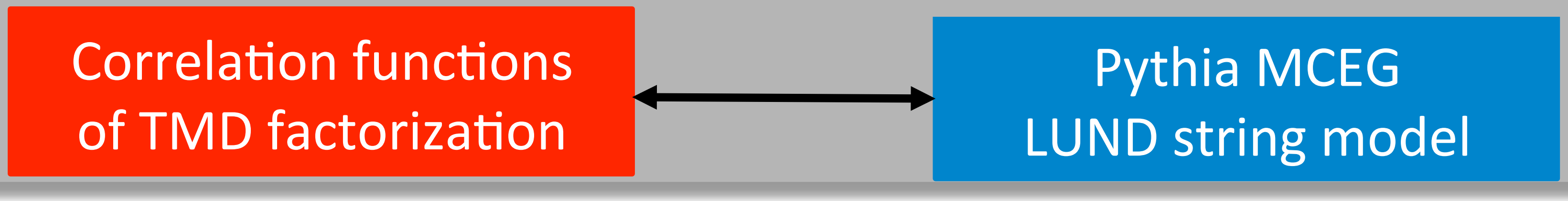
References:

- 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

FY18

FY19

Publication: DIS in Pythia8

Publication: LUND validation

+ TMD observables

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

Publication: Hadronization in NP and HEP

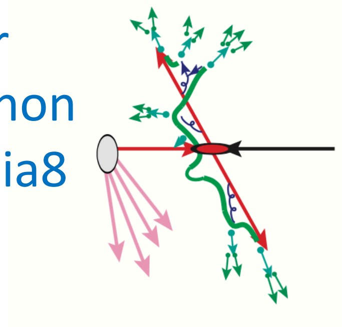
- comparison Pythia8-TMD factorization
- language dictionary
- Pythia8 with spin-independent TMDs

Spin-dependent hadronization

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

Hadronization plugin

- user model for one phenomenon
- rest from Pythia8



LDRD personnel (FY17)

JLab

Pythia

Other


PI
Diefenthaler

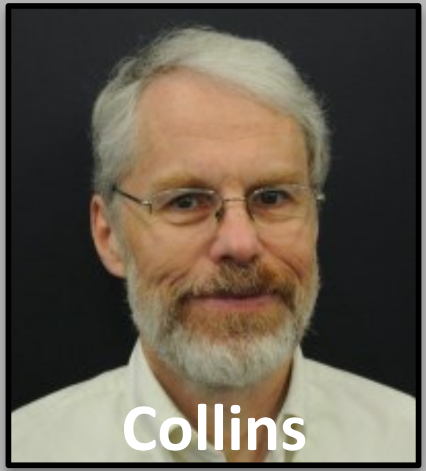

Joosten

Experimentalists


co-PI
Melnitchouk


co-PI
Rogers


Signori


Collins


Sato


Ethier


Lönnblad


Prestel

Theorists

Conclusions and future developments

- 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 η production at the LHC)

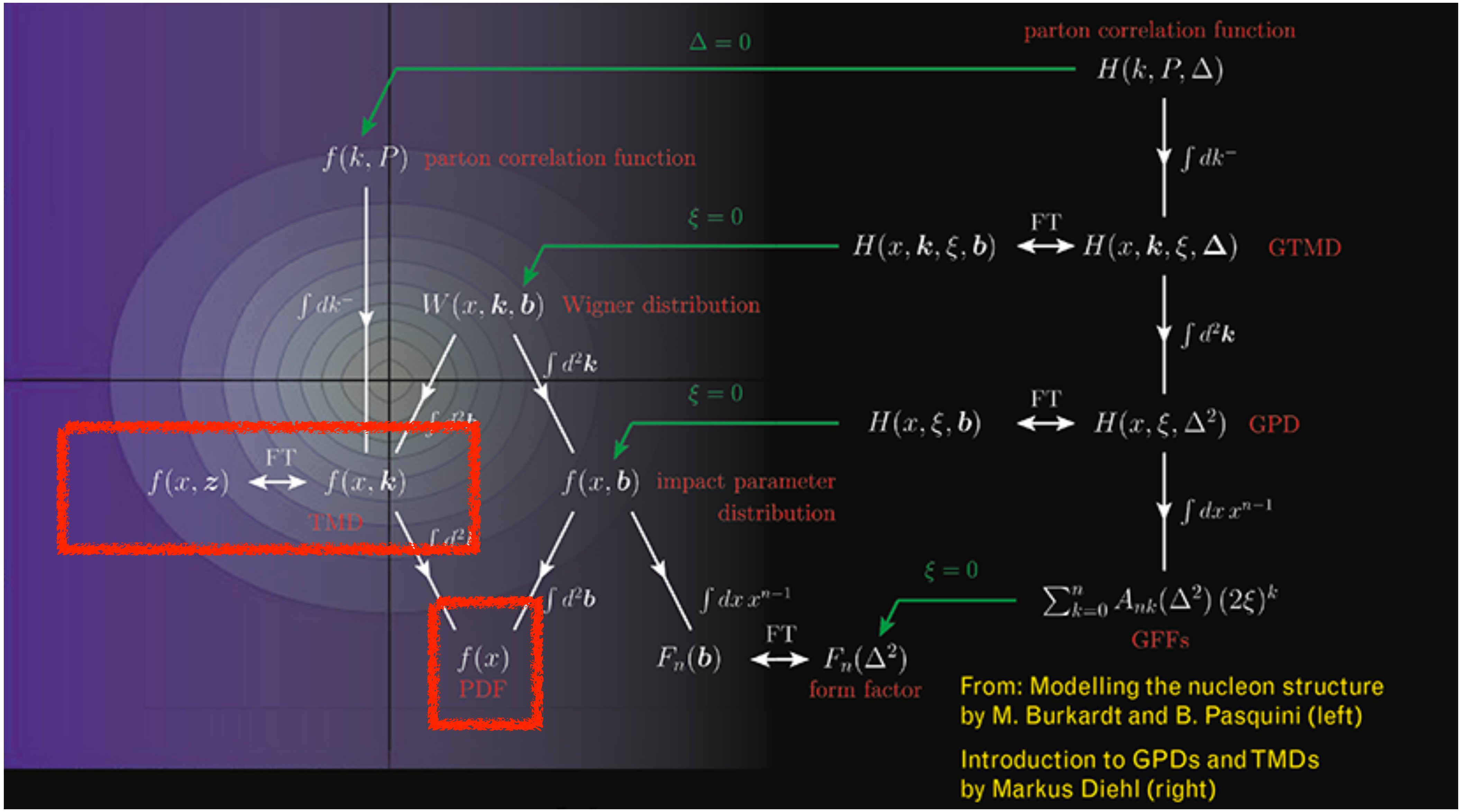
- **high-Q & small-x** is the region where the formalism is most **predictive**; even here, though, NP corrections leave **sizable footprints** in observables; see W production at the LHC

- 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

The hadronic landscape

Manifestation of hadron structure in scattering processes



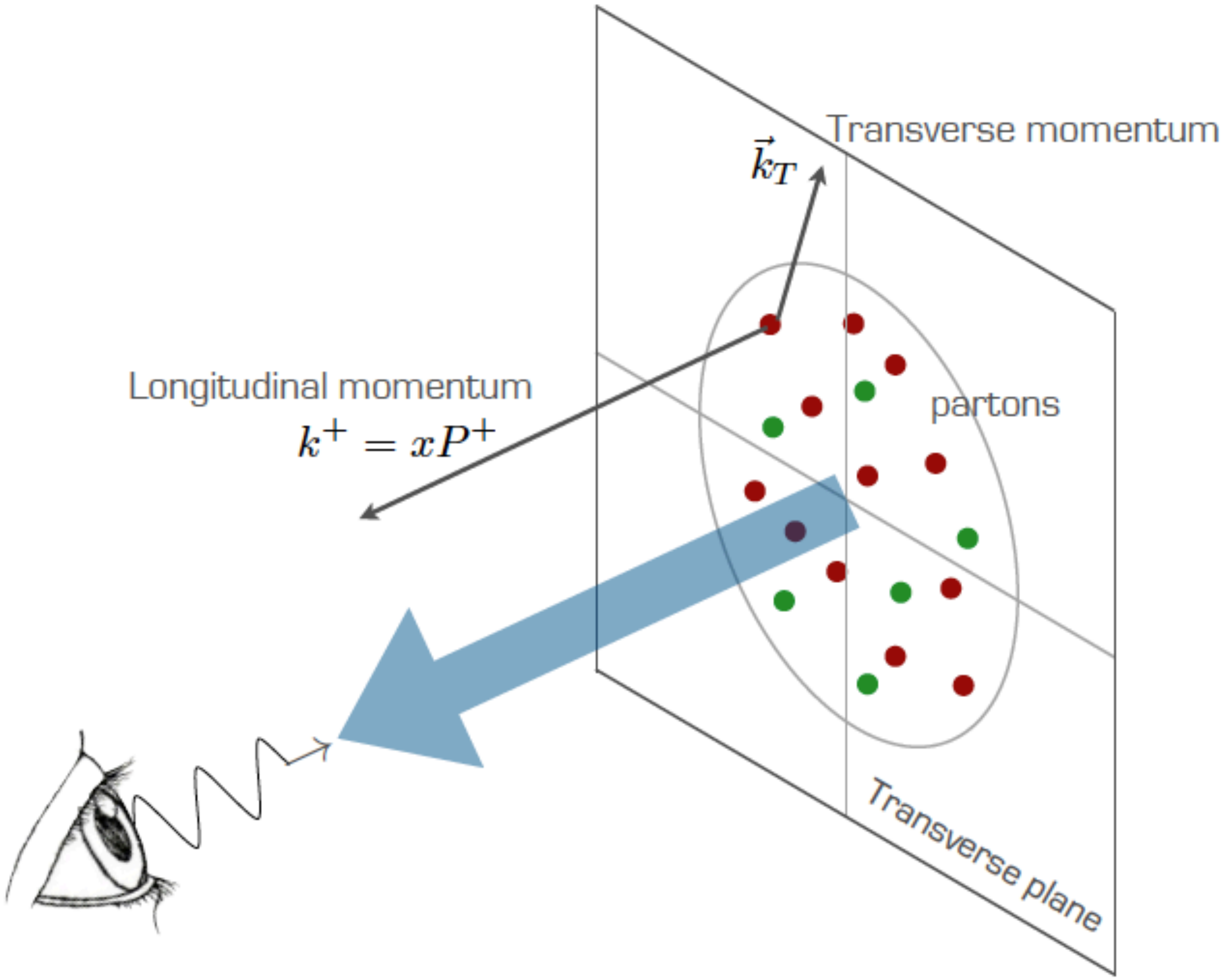
From: Modelling the nucleon structure by M. Burkardt and B. Pasquini (left)

Introduction to GPDs and TMDs by Markus Diehl (right)

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

quark TMD PDFs

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



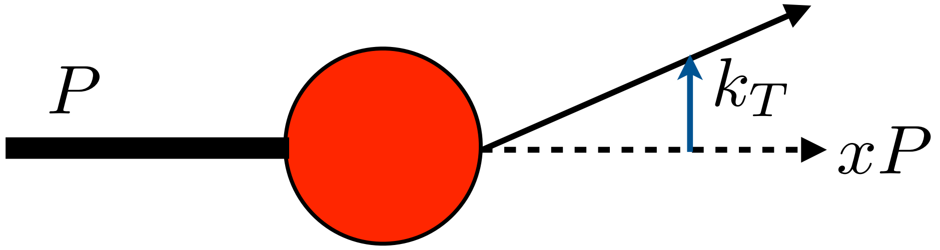
extraction of a **quark**
not collinear with the proton

courtesy A. Bacchetta

quark TMD PDFs

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

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



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

Nucleon tomography in momentum space:
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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

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

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Separation of **b$_T$ regions**

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

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

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

hard scale

(related to the)
transverse momentum of the observed particle

The ratios

$$\Lambda_{\mathrm{QCD}}/Q \qquad \Lambda_{\mathrm{QCD}}/q_T \qquad q_T/Q$$

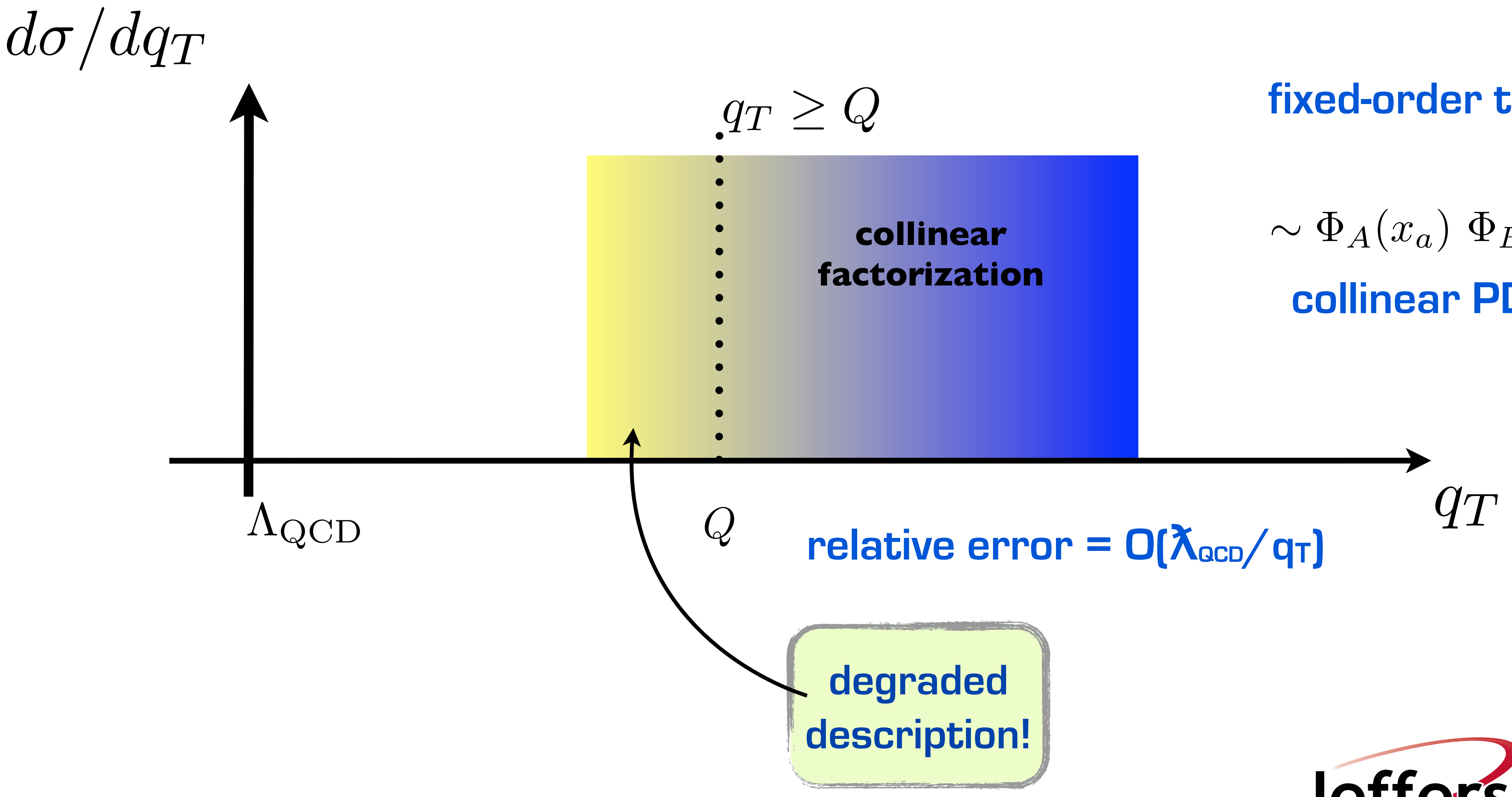
select the factorization theorem that we rely on.

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



fixed-order term

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

collinear PDFs

relative error = $O(\Lambda_{QCD}/q_T)$

Collinear and TMD factorization

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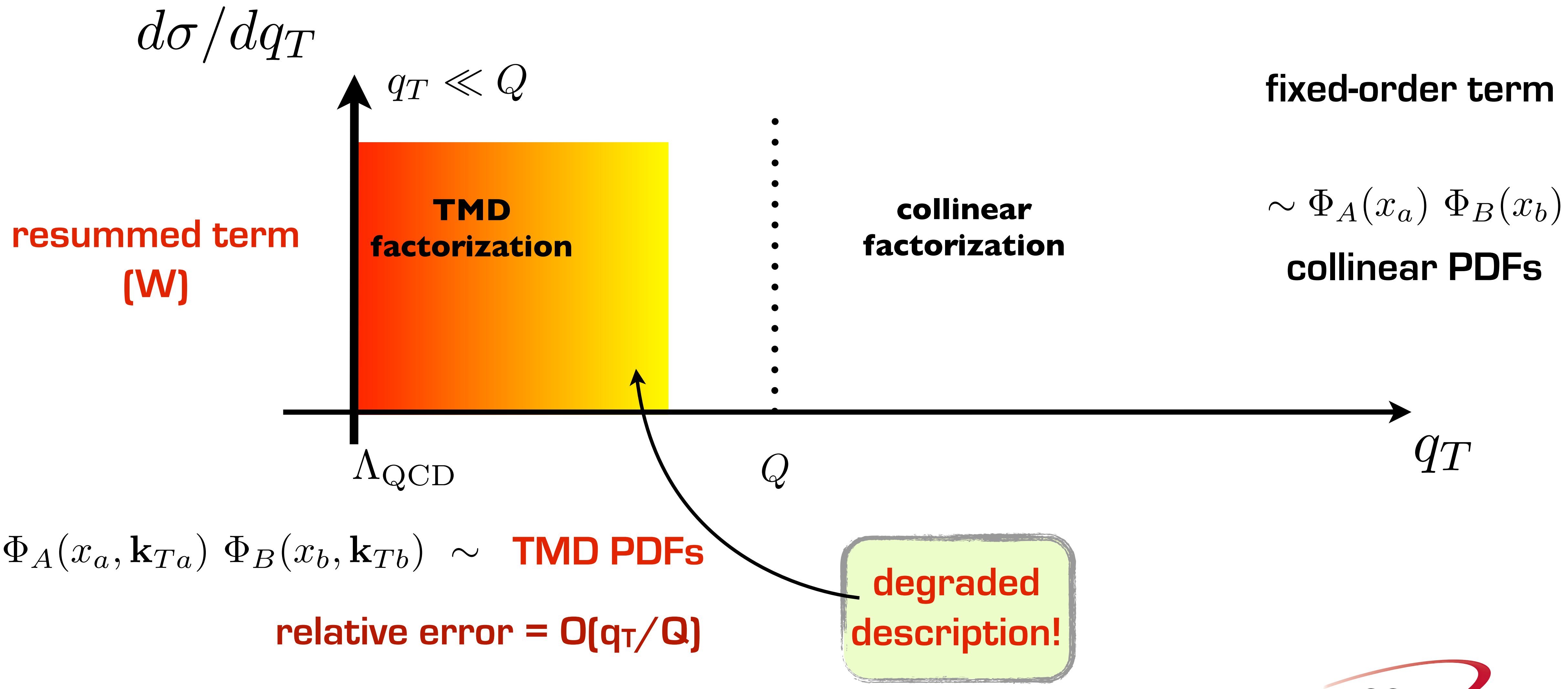

$d\sigma/dq_T$

$q_T \ll Q$

fixed-order term

resummed term (W)

TMD factorization

collinear factorization

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

collinear PDFs

$\Lambda_{\rm QCD}$

Q

q_T

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

relative error = O(q_T/Q)

degraded description!

Collinear and TMD factorization

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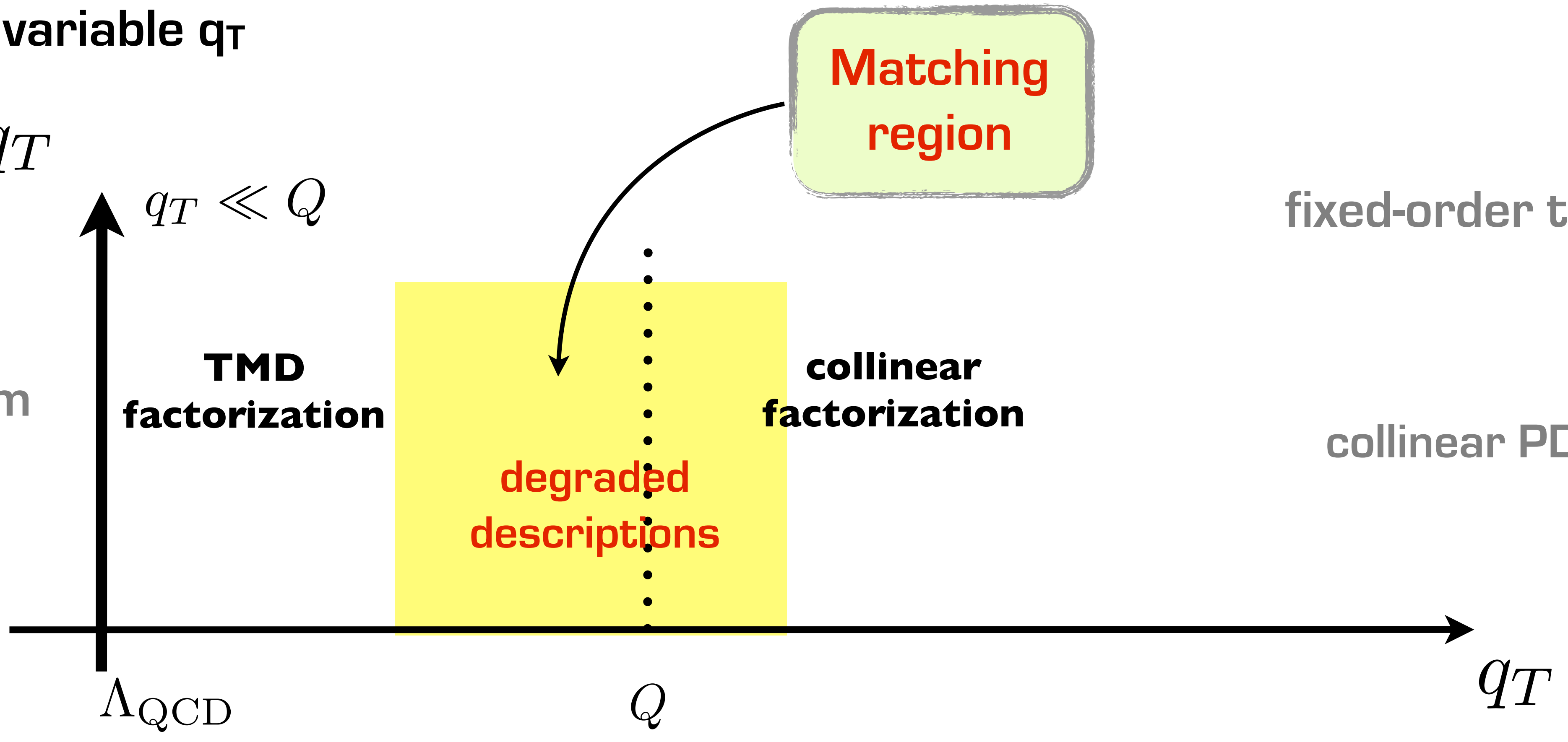
$d\sigma/dq_T$

resummed term (W)

TMD PDFs



TMD factorization

Matching region

degraded descriptions

collinear factorization

fixed-order term

collinear PDFs

W, relative error = O(q_T/Q)

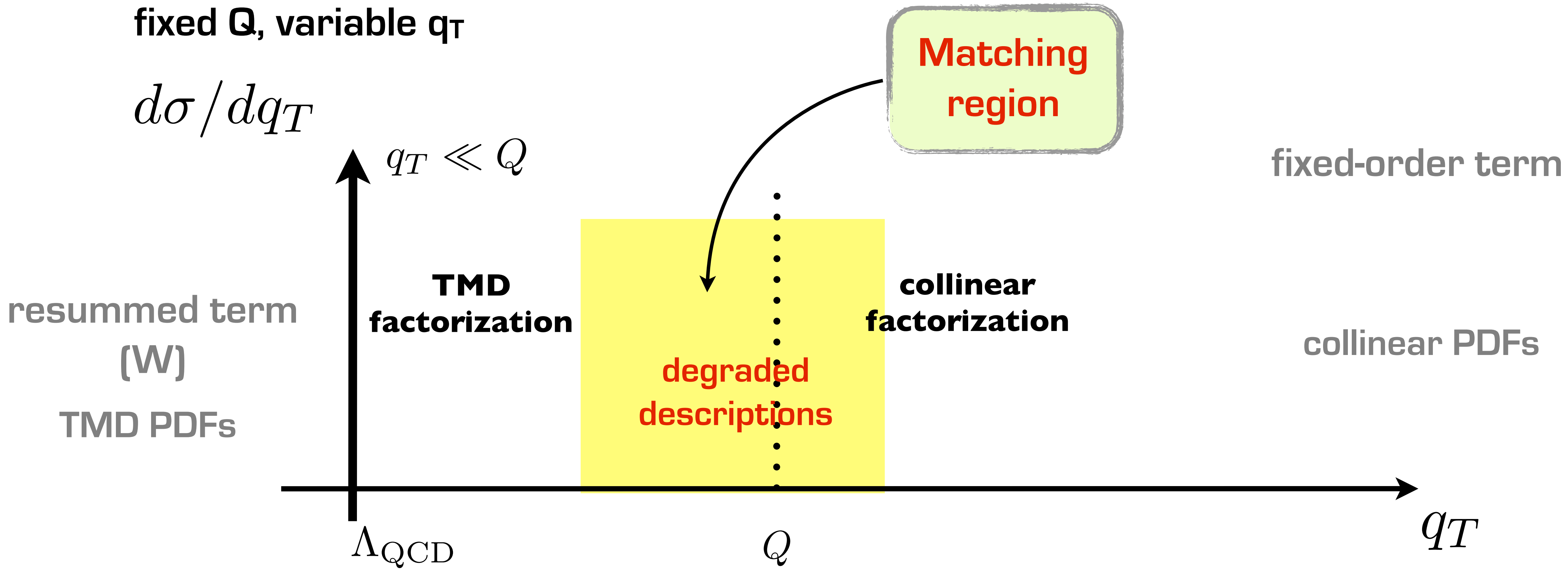
F.O., relative error = O(Λ_{QCD}/q_T)

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**

fixed Q, variable q$_T$



$d\sigma/dq_T$

$q_T \ll Q$

Matching region

fixed-order term

resummed term (W)

TMD PDFs

TMD factorization

degraded descriptions

collinear factorization

collinear PDFs

Λ_{QCD}

Q

q_T

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

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

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

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Need a regularization to recover collinear factorization upon integration over qT:

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

Collins et al. PRD94 2016

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

Product of Fourier-transformed TMDs

TMD evolution is multiplicative in b_T space

Quark TMD PDF

Qiu-Zhang, Phys. Rev. D 63 114011

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

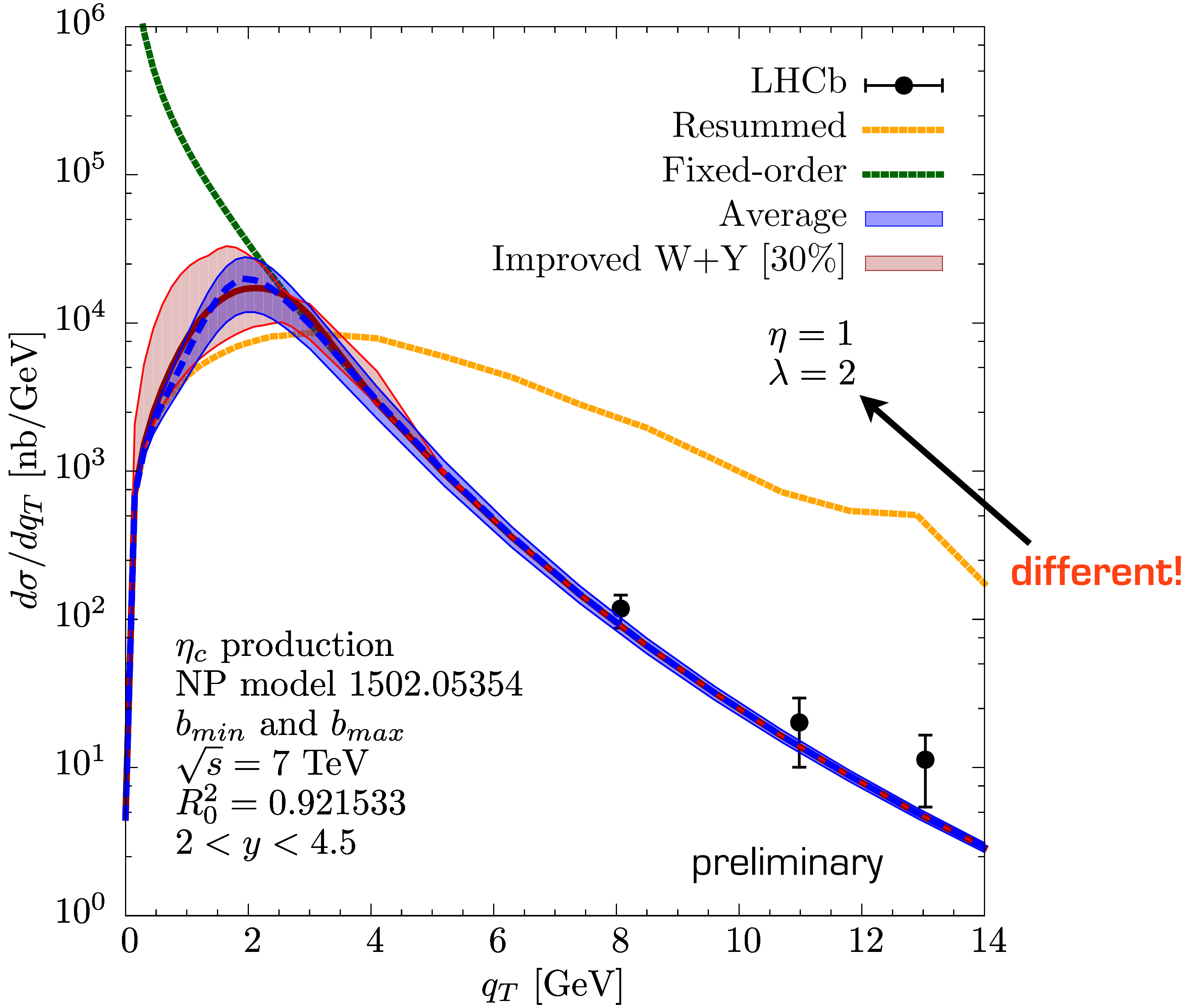
$$F^{NP}_{QZ}(b,Q,x_A,x_B;b_{max})=\exp\left\{-\ln\left(\frac{Q^2b^2_{max}}{c^2}\right)\{g_1[(b^2)^\alpha-(b^2_{max})^\alpha]+g_2(b^2-b^2_{max})\}-\overline{g}_2(b^2-b^2_{max})\right\}$$

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

η_c production at LHC

log-average vs improved W+Y



low-energy process
Q = M(η_c) = 2.98 GeV

b_{min} and b_{max} prescriptions

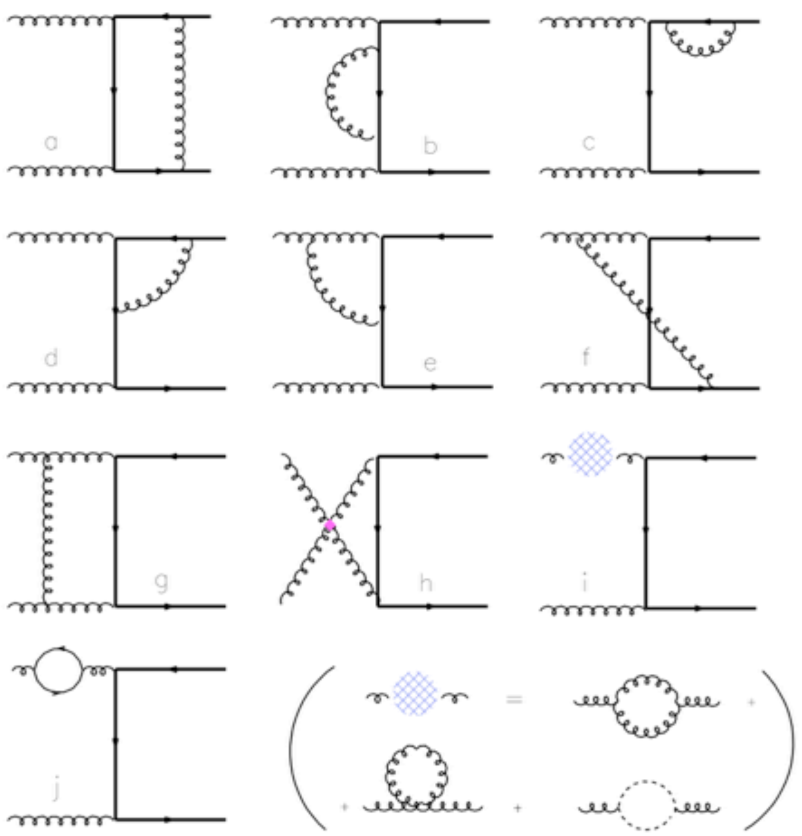
smooth matching from W to FO

- W dominates for $q_T < 1$ GeV
- FO dominates for $q_T > 3$ GeV

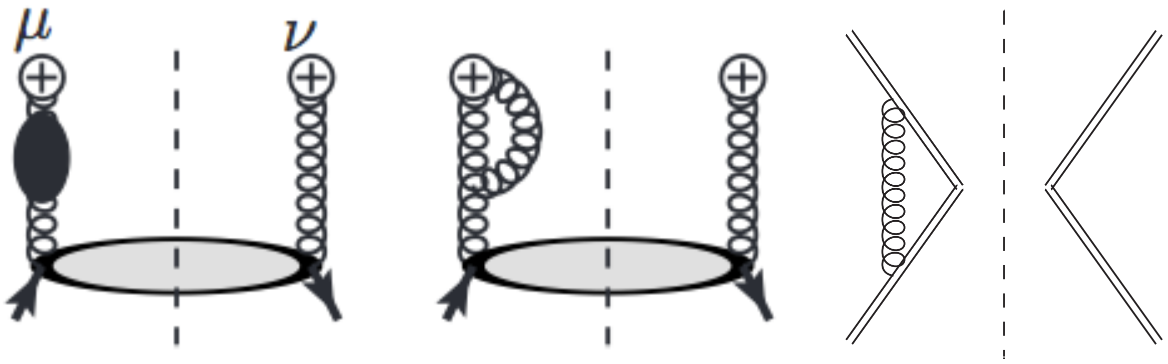
blue band: uncertainty from log-average matching

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”



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

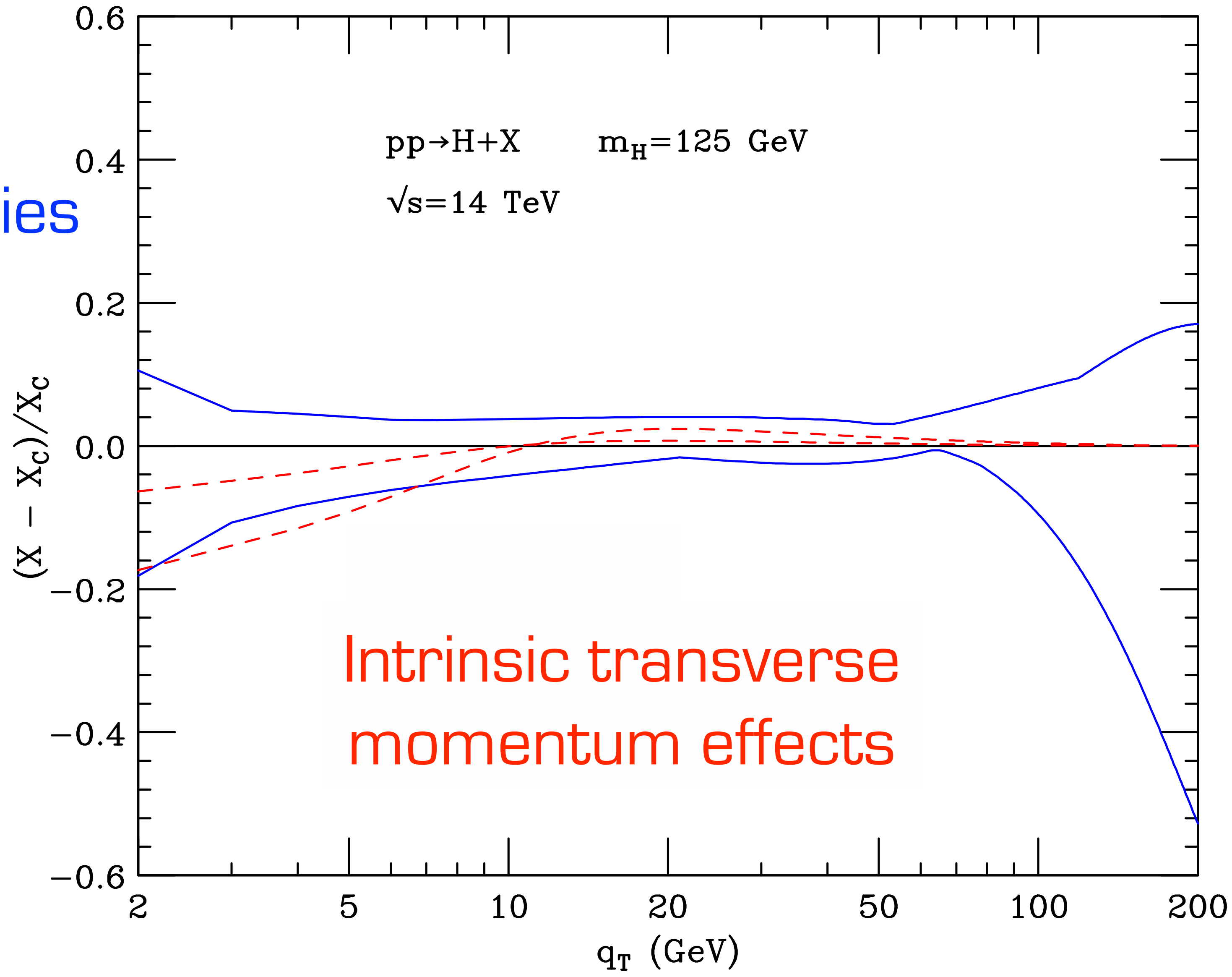
? same IR ?

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

no:
It does not reproduce the physical (=QCD) result

Impact on Higgs physics

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



PDF uncertainties

Intrinsic transverse momentum effects

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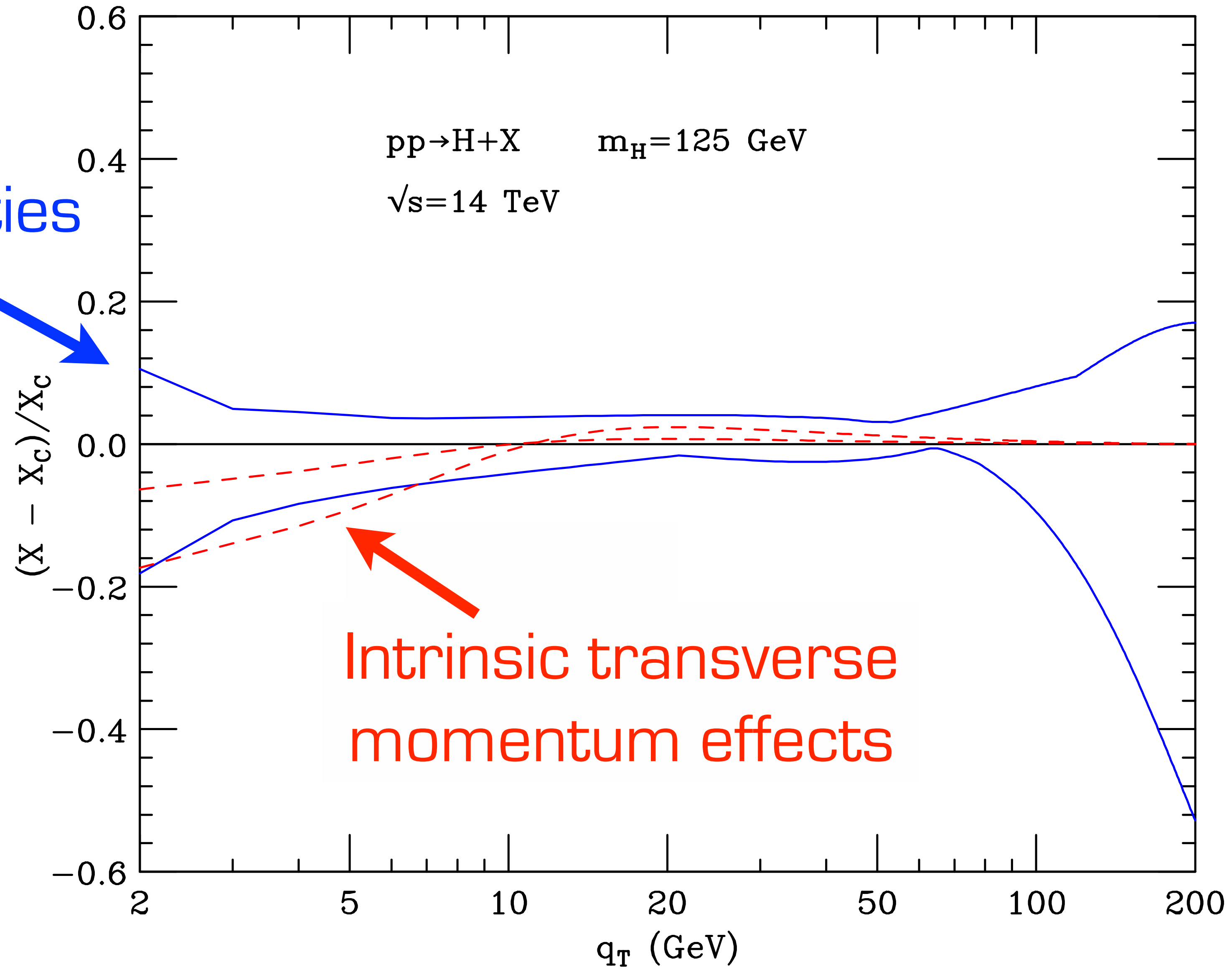

PDF uncertainties

Intrinsic transverse momentum effects