

# Two aspects of TMD phenomenology

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JLab Theory Center

cake seminar  
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# Outline

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I will present two ongoing projects, in collaboration with:

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



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



- J. Lansberg (IN2P3)



# Two aspects

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one more “**motivational**”:

what can we do better once we improve our knowledge of TMD distributions?  
Connection between JLab physics and the LHC

one more “**technical**”:

how do we connect the descriptions at low transverse momentum (TMD factorization) and at high transverse momentum (collinear factorization)?

# TMDs in W production

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## References:

- AS, PhD thesis
- Bacchetta, Bozzi, Radici, Mulders, Ritzmann, AS - in preparation
- experimental literature: Tevatron CDF and D0 - ATLAS and CMS at LHC

# EW precision measurements

Eur.Phys.J. C74 (2014) 3046

After the measurement of the Higgs mass, all the free parameters of the Standard Model are known.

Precise measurements of electroweak quantities allow:

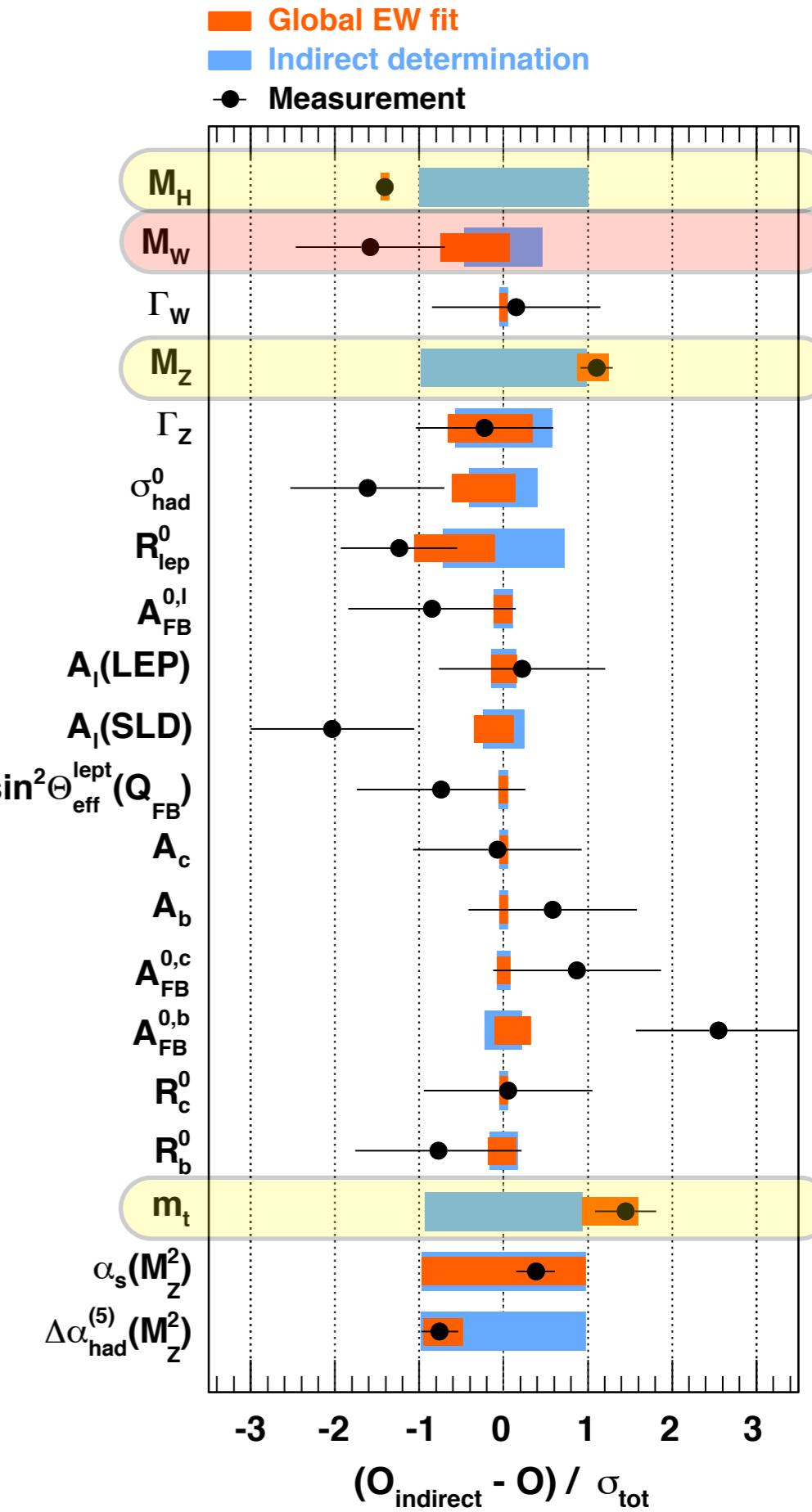
- 1) Stringent **tests** of the self consistency of the SM
- 2) Looking for hints of physics **beyond** the SM

In particular the values of the **masses** of the gauge bosons, the Higgs and the top quark can help in discriminating among different BSM scenarios.

H, Z, t : direct determinations more precise than indirect;  
**not for W !**

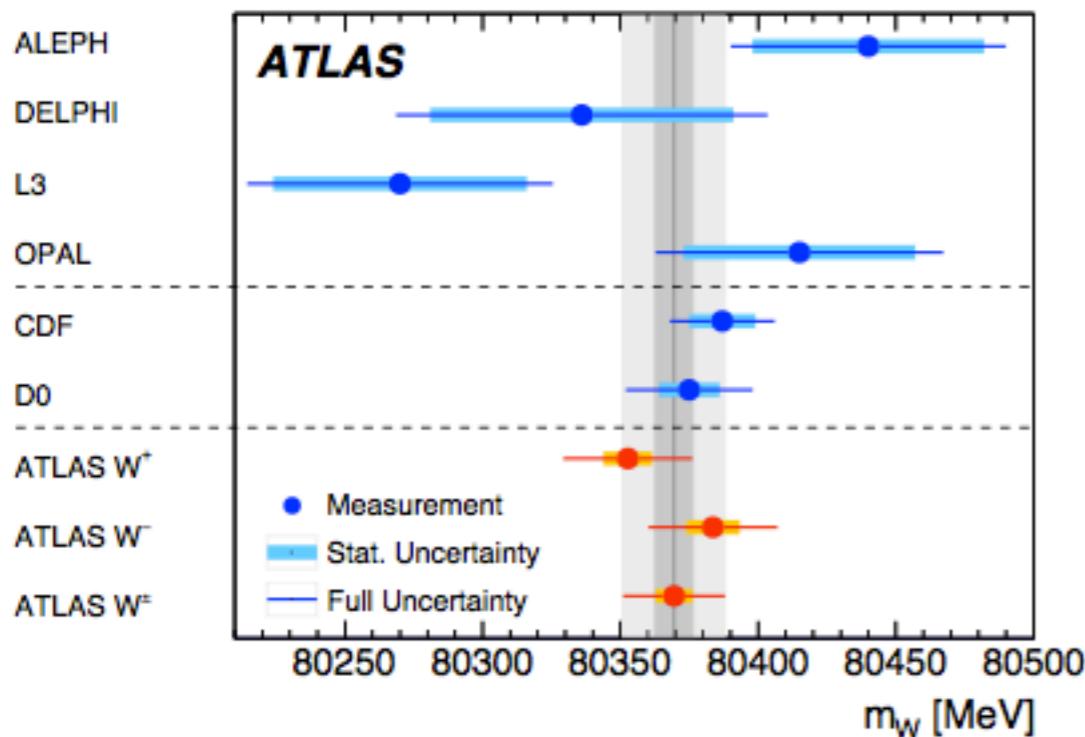
see:

\* S. Camarda - Measurement of the W mass with ATLAS  
 EPS 2017



# W mass

ATLAS, arxiv:1701.07240

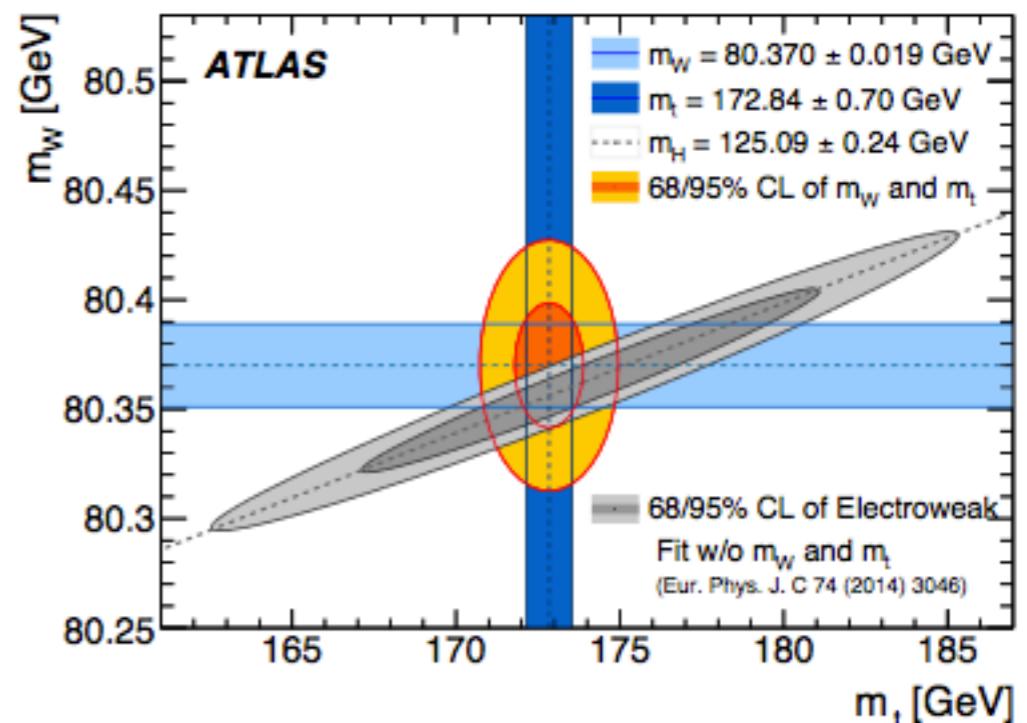


## Experimental measurements

$$m_W = 80370 \pm 19 \text{ MeV}$$

(7 stat, 11 exp, 14 th)

Need to **better control the uncertainties**  
associated to  
**direct** determinations of  $m_W$



## Global EW fit

$$m_W = 80356 \pm 8 \text{ MeV}$$

Is it possible to reduce the uncertainty to less than 10 MeV ?

Are we estimating all the **uncertainties of hadronic nature** in the best way possible?

# W pT & mass

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The **W pT spectrum** is sensitive to:

- \* **perturbative and non-perturbative parts of TMDs**

in particular the **flavor decomposition** of the TMDs in the **transverse momentum** has **not been taken into account yet!**

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Observable sensitive to the **W mass** are:

- \* the **lepton pT distribution** (very sensitive to the treatment of W pT distribution)

- \* the **transverse mass**, defined as  $m_T = \sqrt{2 p_T^\ell p_T^\nu (1 - \cos(\phi_\ell - \phi_\nu))}$

(less sensitive to W pT distribution, due to its high sensitivity to detector effects)

see: S. Camarda - Measurement of the W mass with ATLAS - EPS 2017

G. Bozzi - Flavor dependent effects on the determination of mW (INT 17-68W)

# Uncertainties: mass

[AS - PhD thesis](#)

Source	Uncertainties on $m_W$ [MeV] from $p_T^\ell$ fit		
	$W \rightarrow \mu\nu$	$W \rightarrow e\nu$	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

Tevatron case

sizable uncertainties  
from hadron structure

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

ATLAS (arxiv:1701.07240)

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$m_T$ - $p_T^\ell$ , $W^\pm$ , $e$ - $\mu$	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

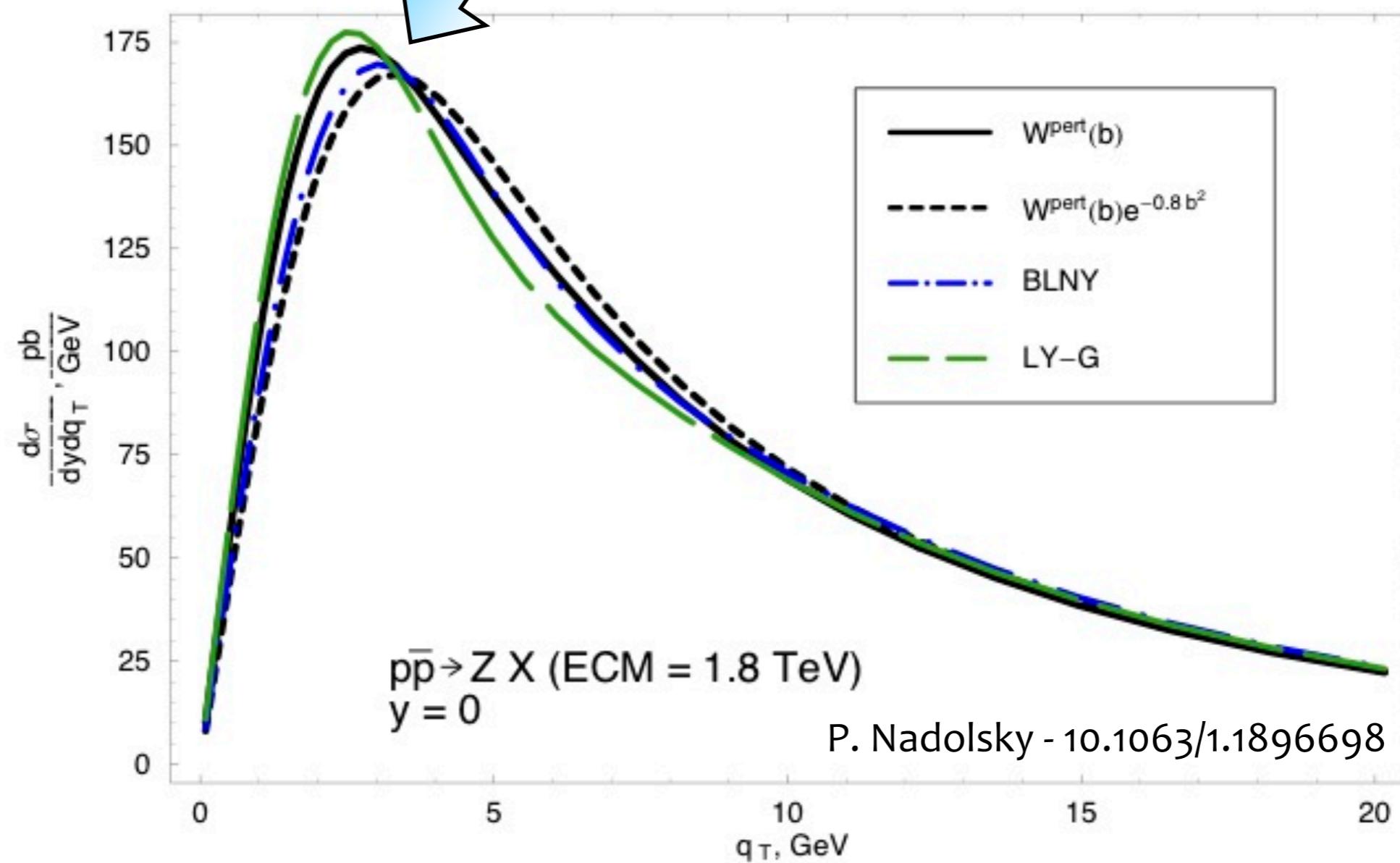
# Nonperturbative effects

[AS - PhD thesis](#)

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

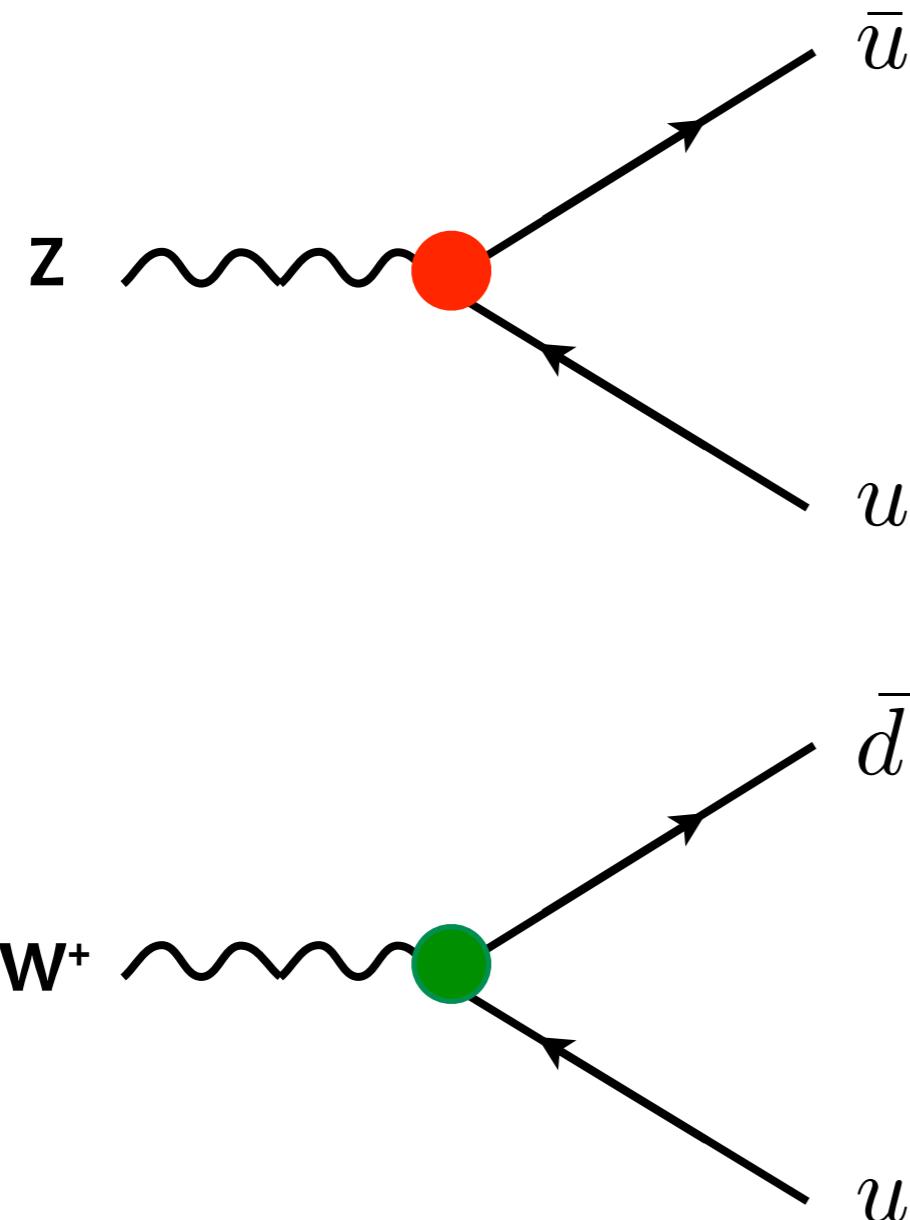
$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$

$g_{ij}$ : determined by 2 TMD PDFs  
*affects the position of the peak*



# Z vs W : flavor content

[AS - PhD thesis](#)



hadronic uncertainties **have been  
estimated 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  $W^\pm$  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		$\pm 0$	

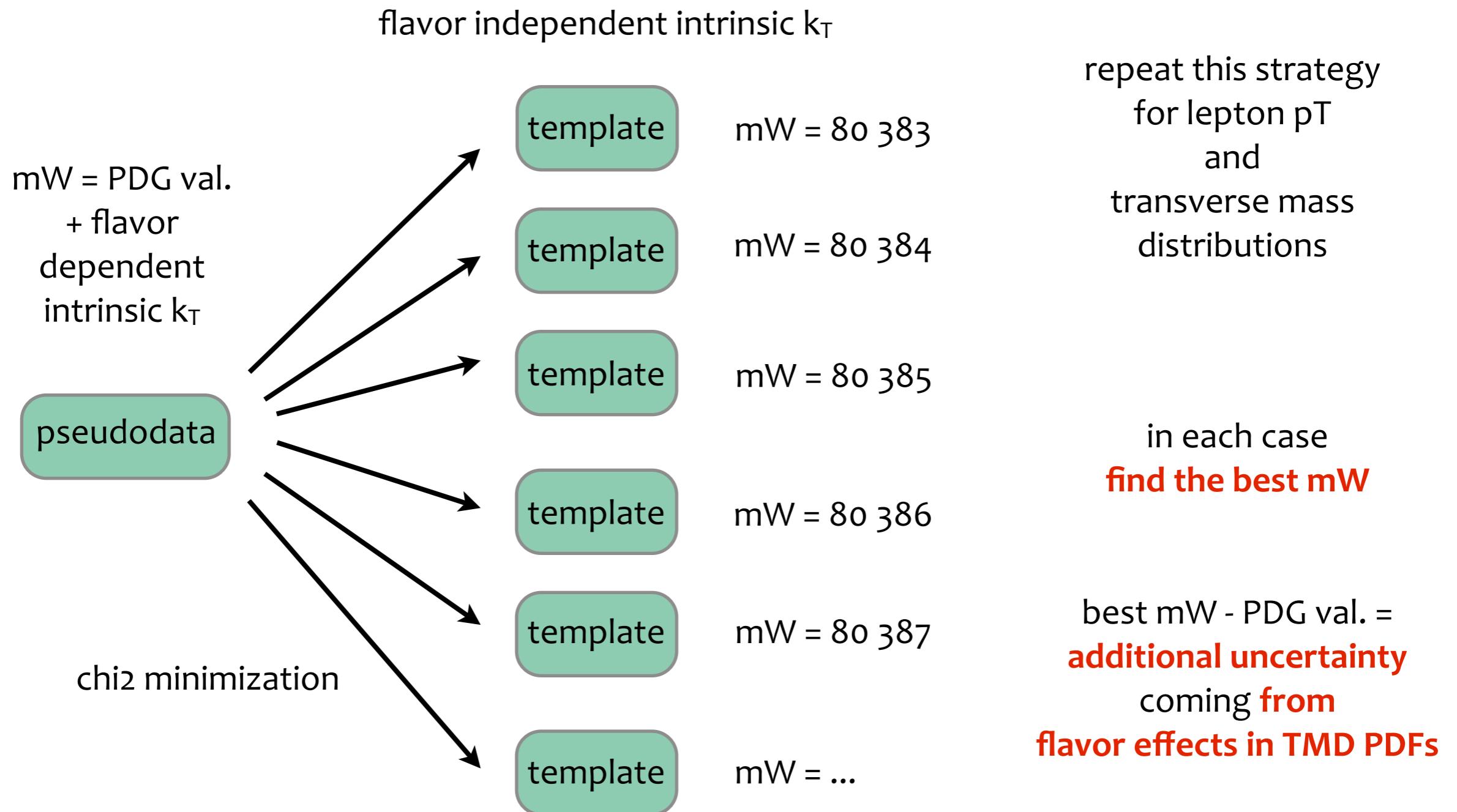
**Table 7.2.** Summary of the shifts in GeV for the peak position for  $q_T$  spectra of  $W^\pm/Z$  arising from different sources. The colors for the flavor dependent (f.d.) and independent (f.i.) variations match the ones in Sec. 7.4.6.

anticorrelated shifts for  $W^\pm$ , which keep the  $Z$  peak unchanged

the flavor dependence of the intrinsic partonic transverse momentum is inspired to the results in [10.1007/JHEP11\(2013\)194](https://doi.org/10.1007/JHEP11(2013)194) (AS et al.)

# Strategy

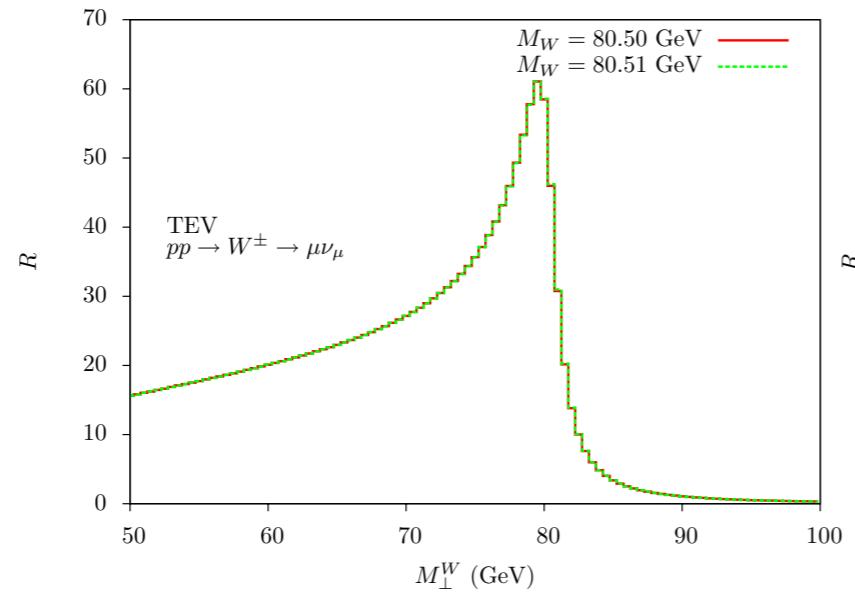
modified version of DYRes 10.1007/JHEP12(2015)047



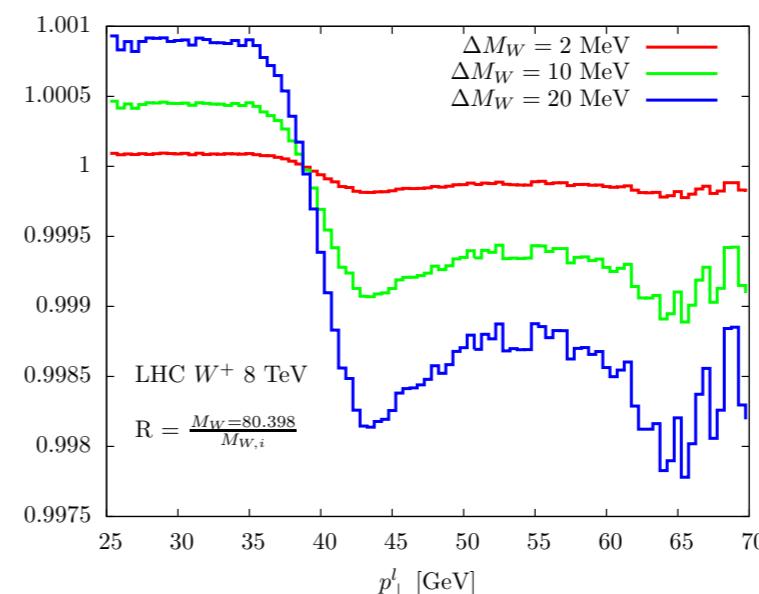
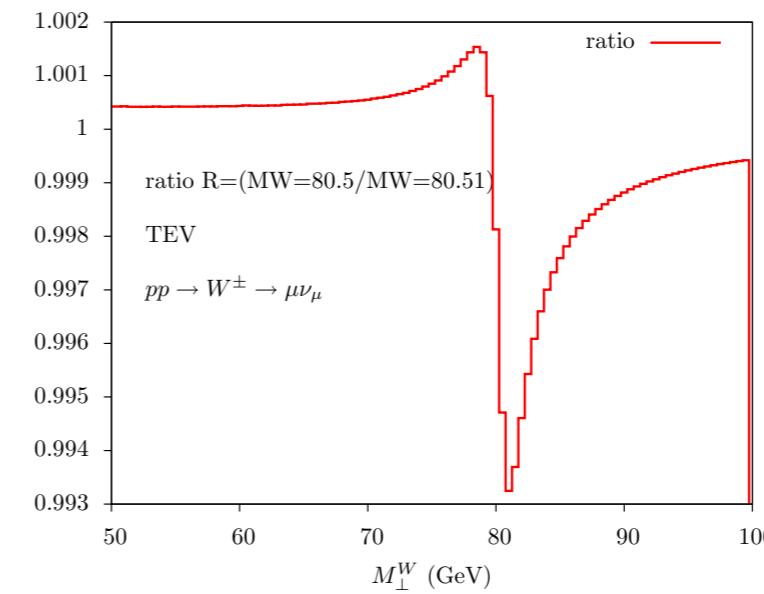
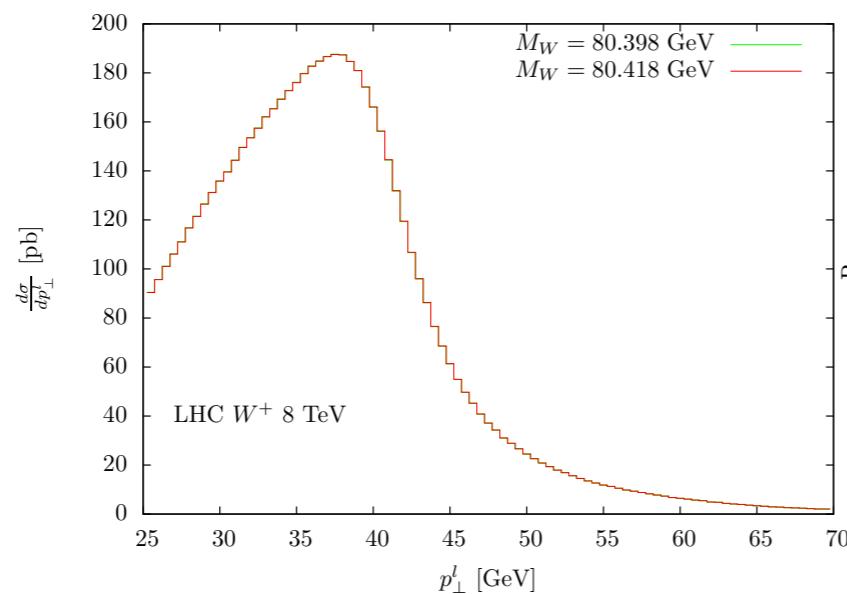
# Strategy

Challenging shape measurement: a distortion at the **few per mille** level of the distributions yields a shift of  $\mathcal{O}(10 \text{ MeV})$  of the  $m_W$  value

$m_T$



$p_{Tl}$



see: G. Bozzi - Flavor dependent effects on the determination of  $m_W$  (INT 17-68W)

# Matching low and high $q_T$

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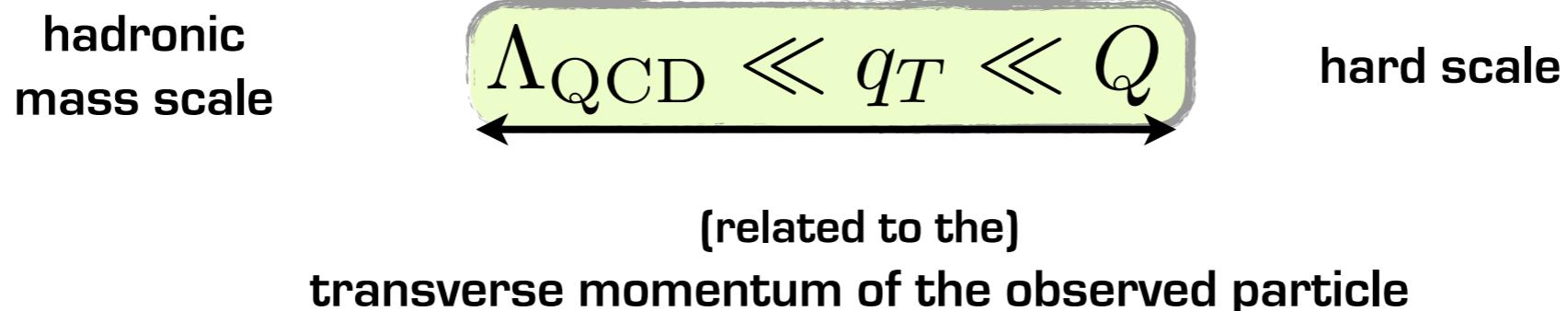
(Some) References:

- Collins, Foundations of pQCD
- Arnold, Kauffmann [10.1016/0550-3213\(91\)90330-Z](https://doi.org/10.1016/0550-3213(91)90330-Z)
- SCET literature
- Collins et al. [10.1103/PhysRevD.94.034014](https://doi.org/10.1103/PhysRevD.94.034014)
- Berger et al. [10.1103/PhysRevD.71.034007](https://doi.org/10.1103/PhysRevD.71.034007)
- Echevarria, Kasemets, Lansberg, Pisano, AS - in preparation

# Collinear and TMD factorization

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

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



The ratios

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

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

$$q_T/Q$$

select the factorization theorem that we rely on.

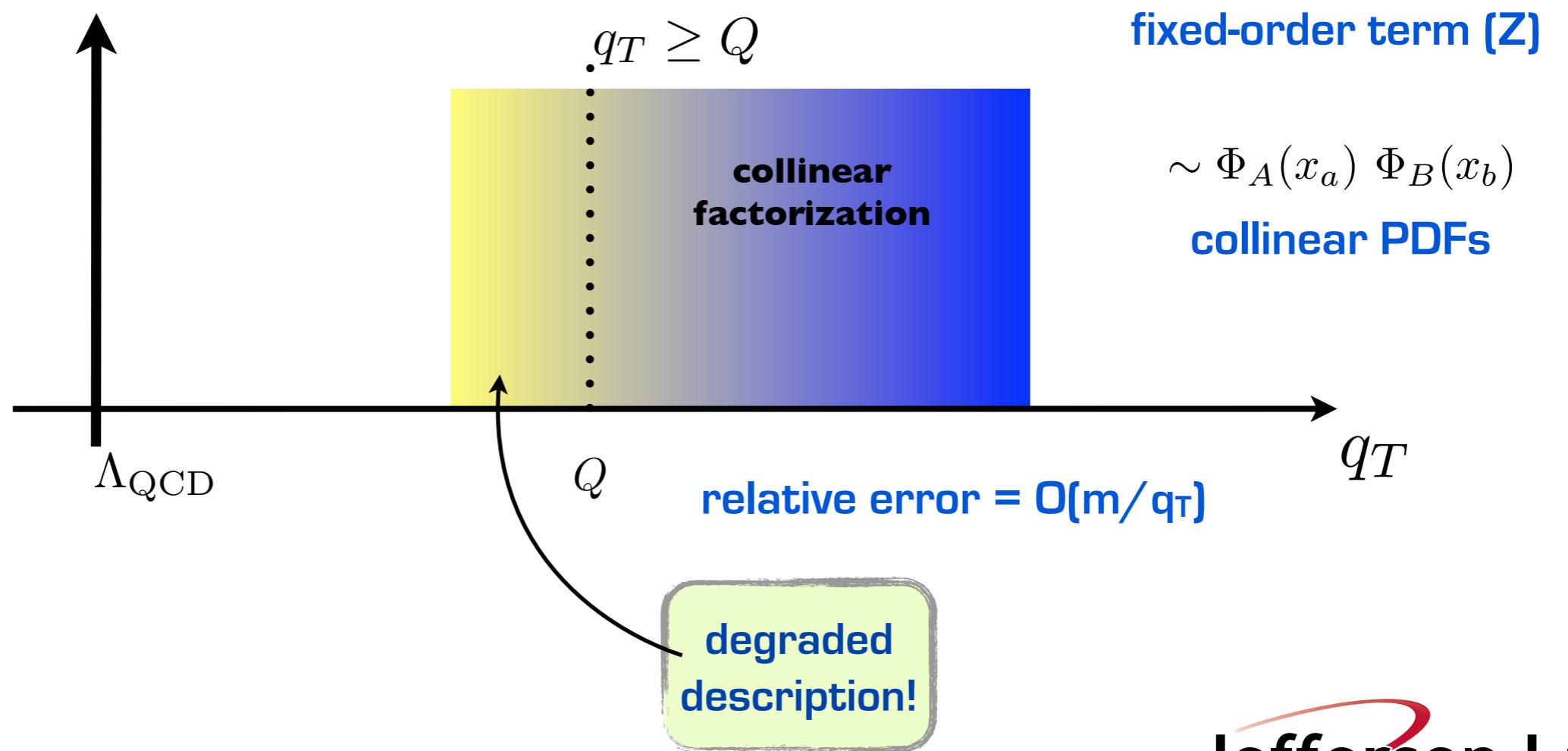
According to their **values** we can access **different**  
“**projections**” of hadron structure

# Collinear and TMD factorization

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

**fixed  $Q$ , variable  $q_T$**

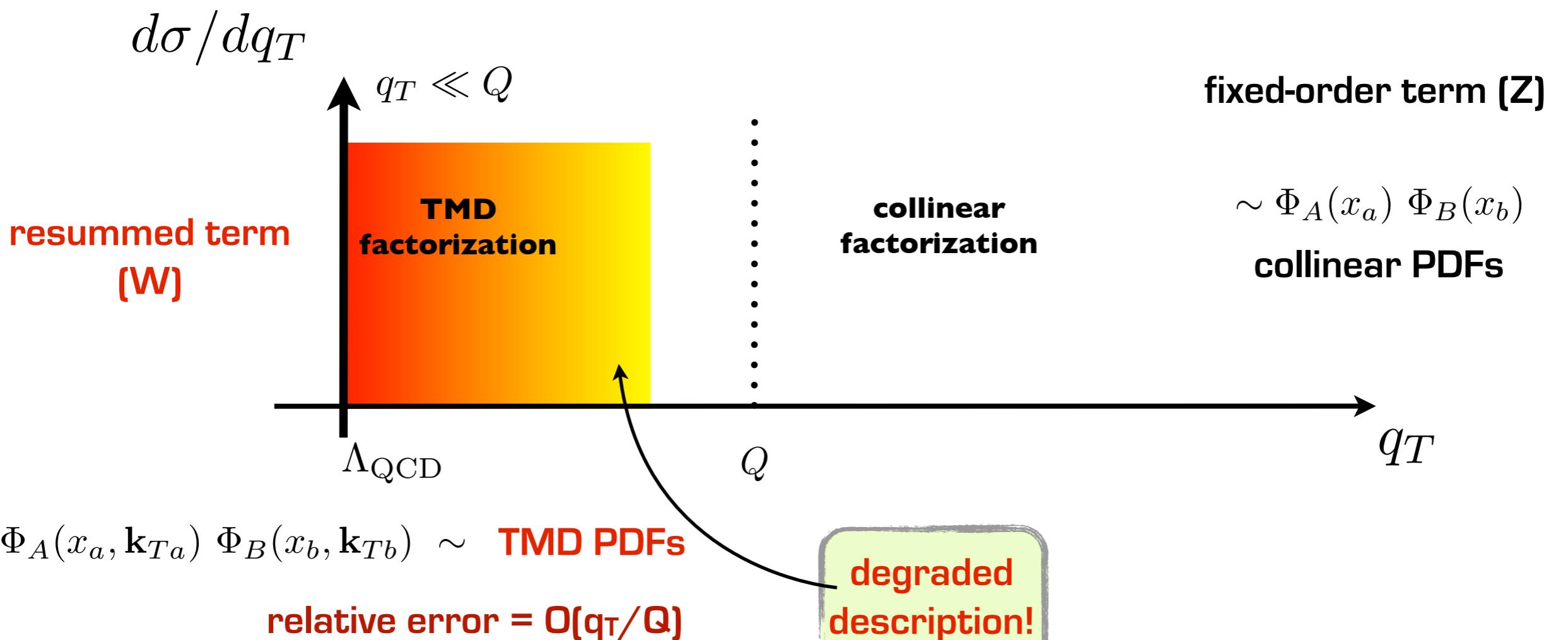
$$d\sigma / dq_T$$



# Collinear and TMD factorization

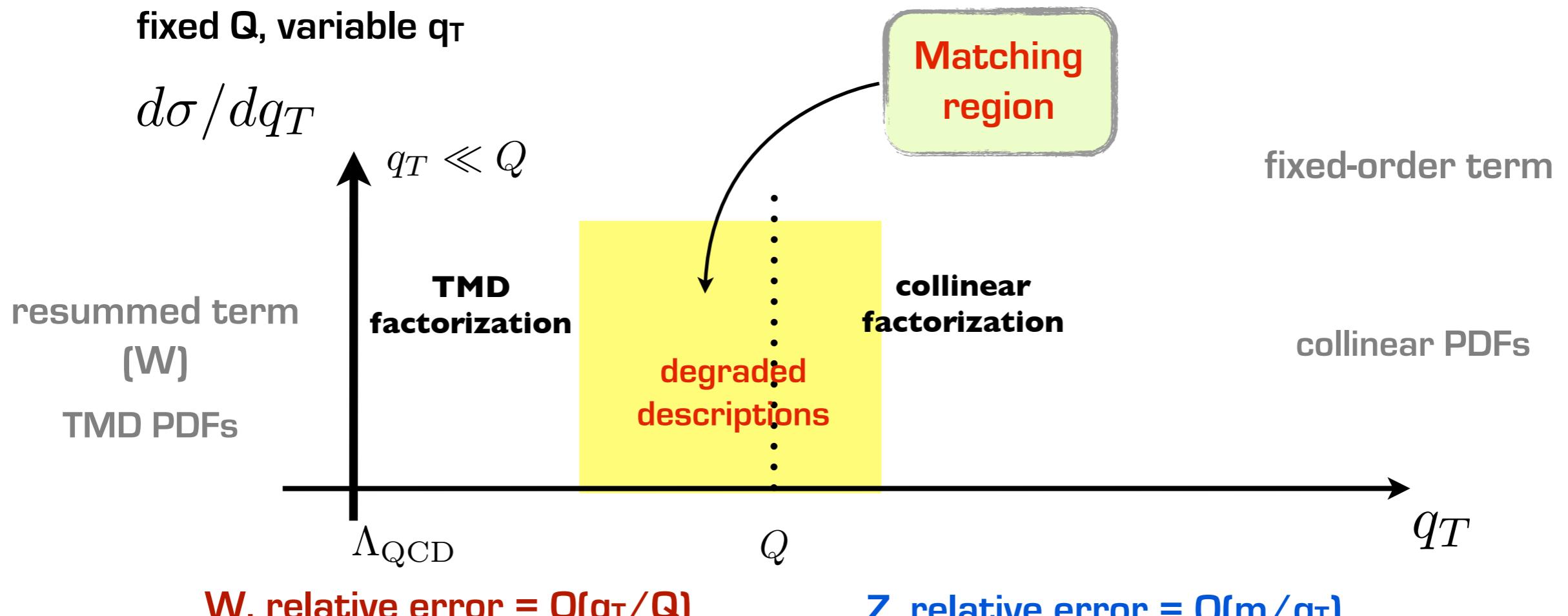
The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

fixed  $Q$ , variable  $q_T$



# Collinear and TMD factorization

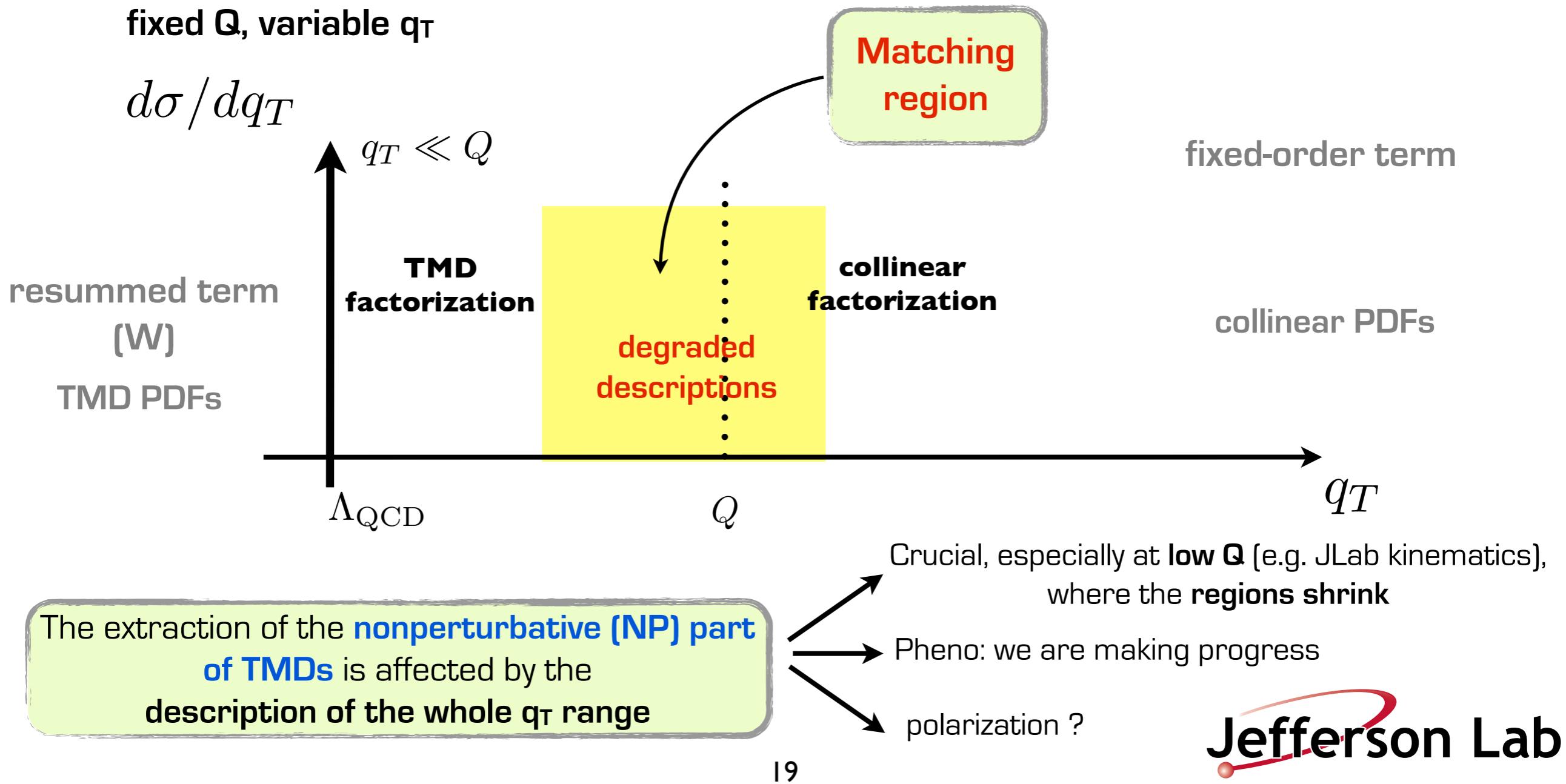
The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**



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**



# W+Y

Cross section → 
$$\Gamma = \mathbf{T}_{\text{TMD}} \Gamma + [\Gamma - \mathbf{T}_{\text{TMD}} \Gamma]$$
  
$$\approx \underbrace{\mathbf{T}_{\text{TMD}} \Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\text{coll}} [\Gamma - \mathbf{T}_{\text{TMD}} \Gamma]}_{\mathbf{Y}}$$

**Y** = Fixed Order (**Z**) -  
F.O. expansion of  
resummed (**ASY**)

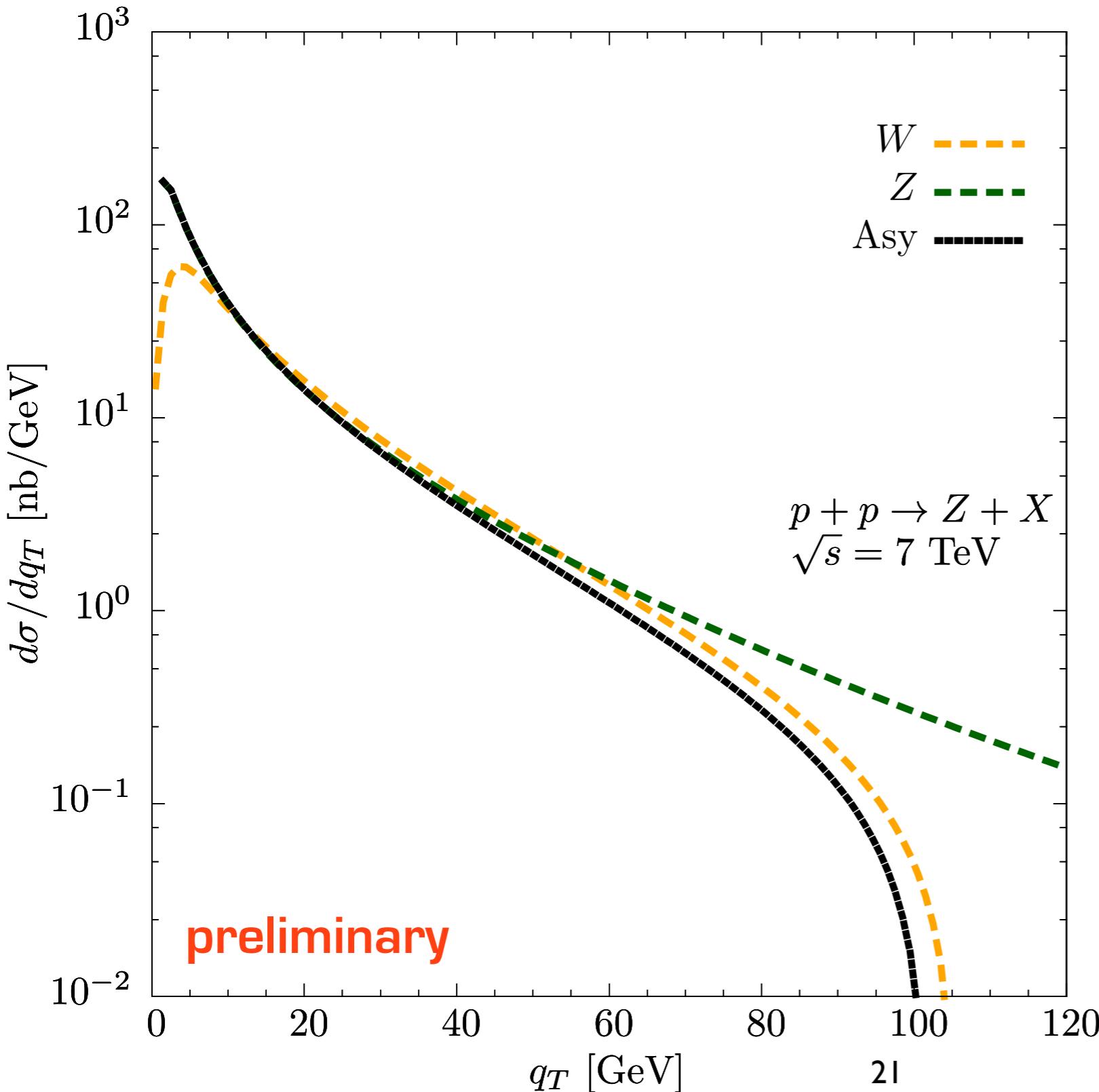
resummed term (**W**) + fixed-order (**Z**) - asymptotic (**Asy**)



the f.o. expansion of the resummed part:  
takes care of canceling the divergent part  
of f.o. at low  $q_T$  and bridges the description  
to the high  $q_T$  region (f.o.)

“improved” version: add **damping functions** at low and high  $q_T$   
- Collins et al. [10.1103/PhysRevD.94.034014](https://doi.org/10.1103/PhysRevD.94.034014)

# W+Y - Z boson

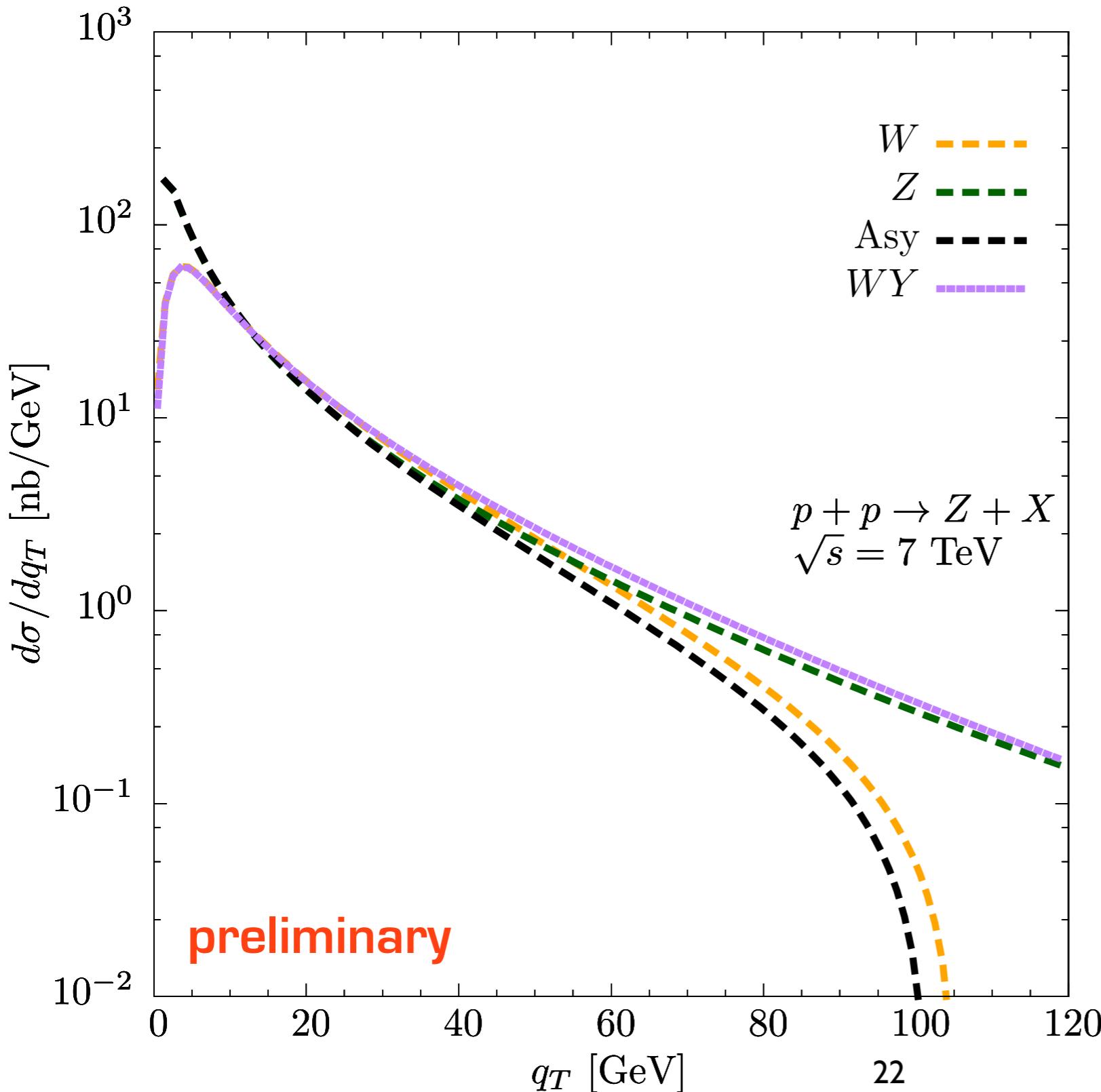


breakdown of W, Z, Asy

the cancellation Z - Asy  
works fine at low  $q_T$

at high  $q_T$  Asy goes  
negative: the matched  
cross section overshoots Z  
(problem)

# W+Y - Z boson

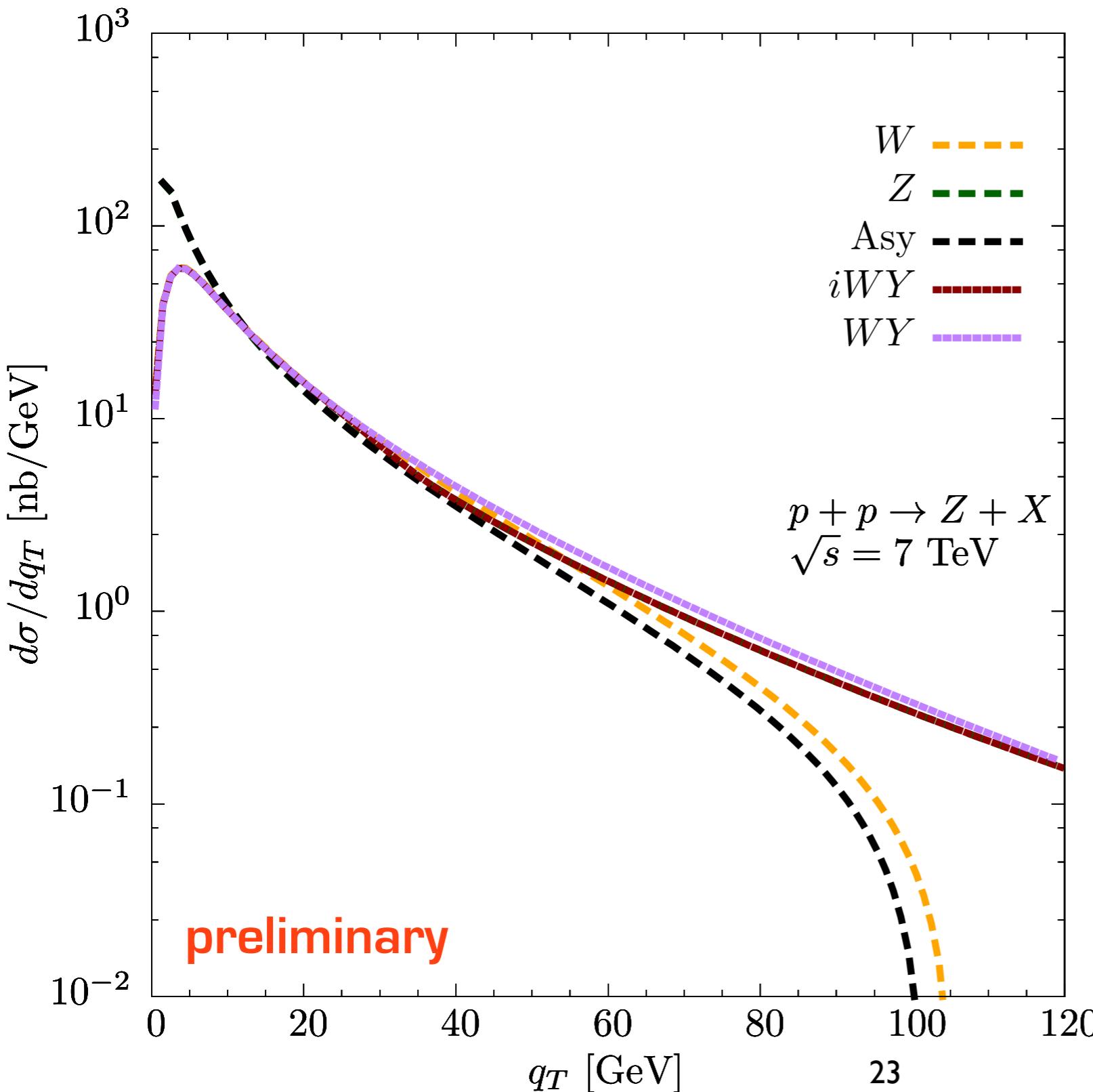


breakdown of W, Z, Asy

the cancellation Z - Asy  
works fine at low  $q_T$

at high  $q_T$  Asy goes  
negative: the matched  
cross section overshoots Z  
(problem)

# iWY - Z boson



breakdown of W, Z, Asy

the cancellation Z - Asy  
works fine at low  $q_T$

at high  $q_T$  Asy goes  
negative: the matched  
cross section overshoots Z  
(problem)

adding damping functions  
for W and Y=Z-Asy, we  
recover the correct limits at  
low  $q_T$  (W) and high  $q_T$  (Z)

(improved W+Y : iWY)

# Averaging W and Z

We propose a **different view on the matching** for the resummed term and the fixed-order calculation, based on a **weighted average of the two contributions**.

The **weights** involve the **power corrections to the factorized expression** at low and high  $q_T$

TMD factorization and TMD PDFs

$$\sigma(q_T, Q) = \underline{W(q_T, Q) + \left[ \mathcal{O}\left(\frac{q_T}{Q}\right)^a + \mathcal{O}\left(\frac{m}{Q}\right)^{a'} \right] \sigma(q_T, Q)}$$

low transverse momentum

$$\sigma(q_T, Q) = \underline{Z(q_T, Q) + \mathcal{O}\left(\frac{m}{q_T}\right)^b \mathcal{O}\left(\frac{Q}{q_T}\right)^{b'} \sigma(q_T, Q)}$$

high transverse momentum

collinear factorization and PDFs

# Averaging W and Z

$$\Delta W = \sigma \Delta_W , \quad \Delta_W = \mathcal{O} \left( \frac{q_T + m}{Q} \right)^a$$

$$\Delta Z = \sigma \Delta_Z , \quad \Delta_Z = \mathcal{O} \left( \frac{m}{q_T} \right)^b \mathcal{O} \left( \frac{Q}{q_T} \right)^{b'}$$

errors

$$\omega_1 = \frac{\Delta W^{-2}}{\Delta W^{-2} + \Delta Z^{-2}} \quad \omega_2 = \frac{\Delta Z^{-2}}{\Delta W^{-2} + \Delta Z^{-2}}$$

weights

$$\bar{\sigma} = \omega_1 W + \omega_2 Z$$

weighted average

$$\Delta \bar{\sigma} = \frac{\Delta_W \Delta_Z}{\sqrt{\Delta_W^2 + \Delta_Z^2}} \sigma \approx \frac{\Delta_W \Delta_Z}{\sqrt{\Delta_W^2 + \Delta_Z^2}} \bar{\sigma}$$

error propagation

# Averaging W and Z

$$\Delta_W = \left( \frac{q_T + c_m m}{c_Q Q} \right)^r$$

cm, cQ = 1  
r,s = {1,2}

$$\Delta_Z = \left( \frac{c_m m}{q_T} \right)^s \left( \frac{c_Q Q}{q_T} \right)^s$$

**practical implementation  
for the errors (choice!)**

$$\omega_1 = \frac{\Delta W^{-2}}{\Delta W^{-2} + \Delta Z^{-2}}$$

$$\omega_2 = \frac{\Delta Z^{-2}}{\Delta W^{-2} + \Delta Z^{-2}}$$

**weights**

$$\bar{\sigma} = \omega_1 W + \omega_2 Z$$

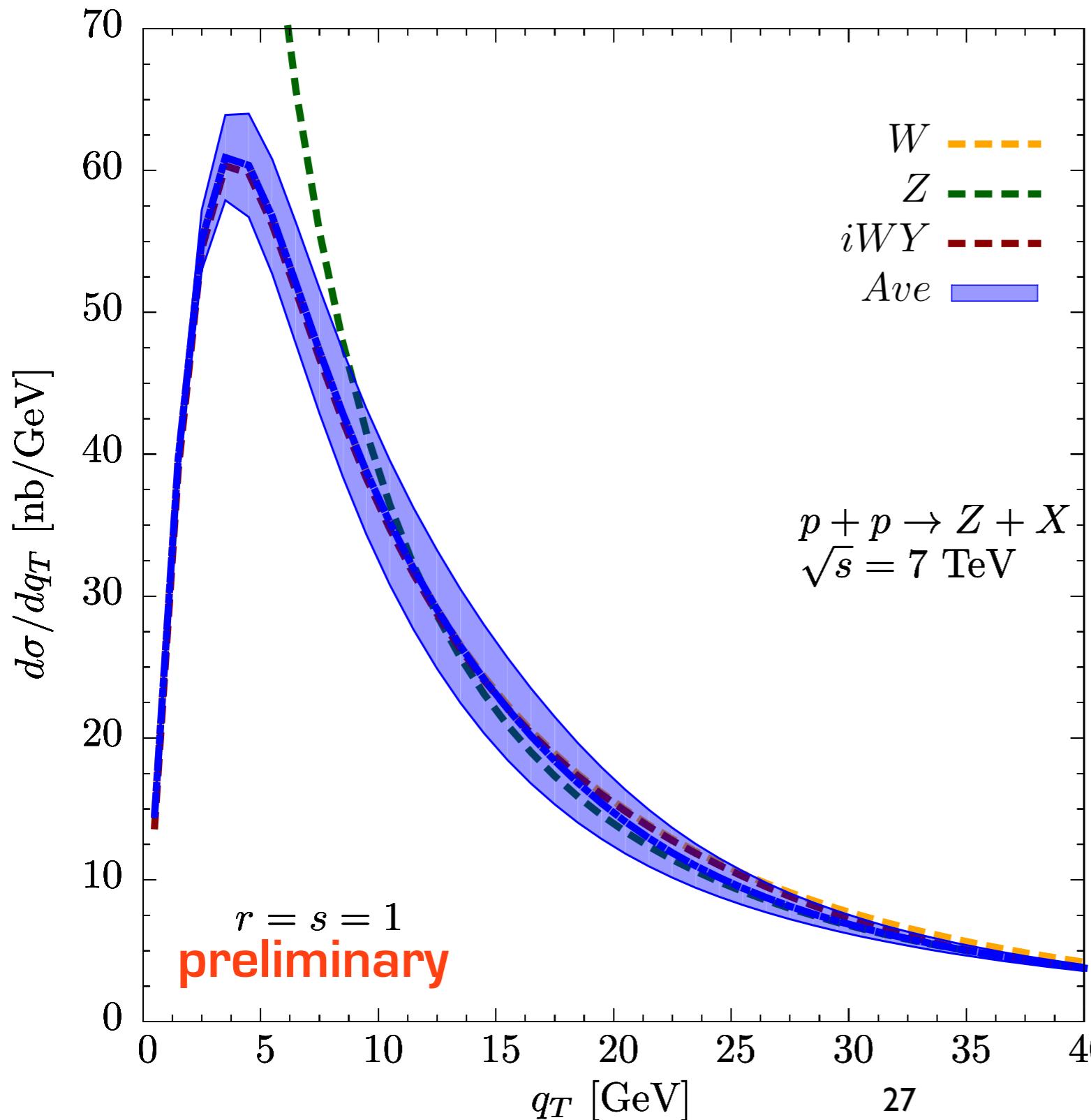
**weighted average**

$$\Delta \bar{\sigma} = \frac{\Delta_W \Delta_Z}{\sqrt{\Delta_W^2 + \Delta_Z^2}} \sigma \approx \frac{\Delta_W \Delta_Z}{\sqrt{\Delta_W^2 + \Delta_Z^2}} \bar{\sigma}$$

**error propagation**

# Z boson production

DYqT [10.1016/j.physletb.2010.12.024](https://doi.org/10.1016/j.physletb.2010.12.024)

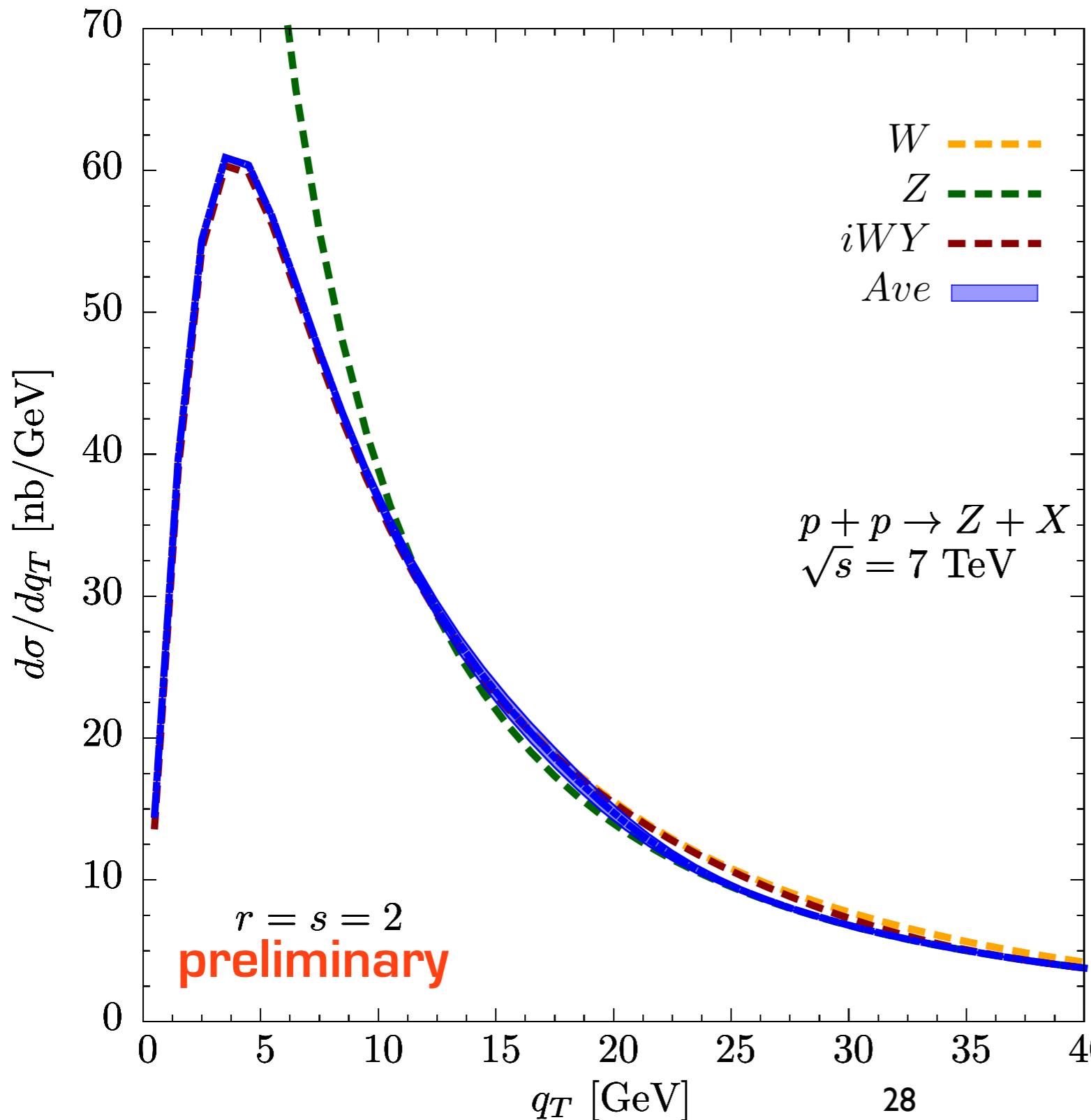


comparison of iWY and  
average matching of W and Z

Jefferson Lab

# Z boson production

DYqT [10.1016/j.physletb.2010.12.024](https://doi.org/10.1016/j.physletb.2010.12.024)

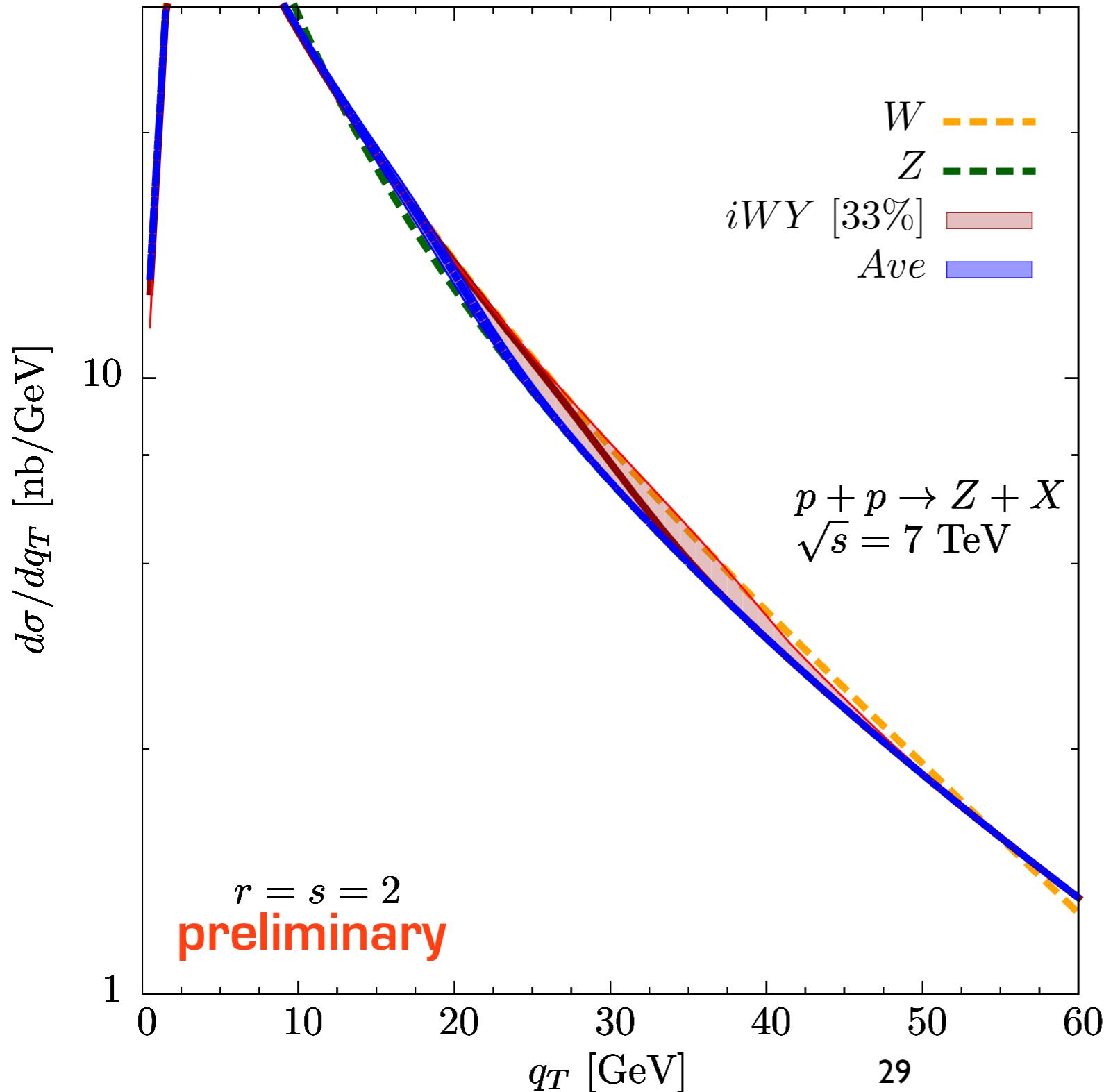


comparison of iWY and  
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# Z boson production

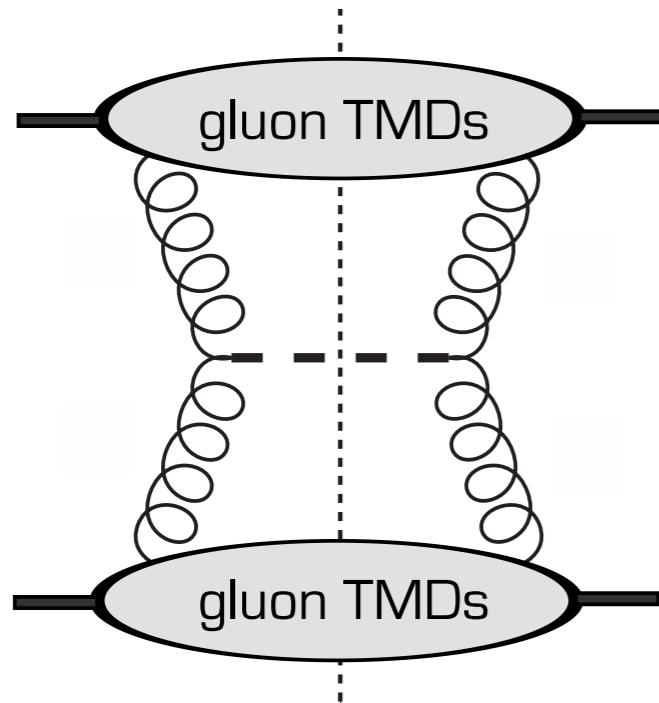
DYqT [10.1016/j.physletb.2010.12.024](https://doi.org/10.1016/j.physletb.2010.12.024)



comparison of iWY and  
average matching of W and Z

Jefferson Lab

# gluon TMD PDFs



pseudoscalar quarkonium/Higgs production:

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

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

$$p \ p \rightarrow H \ X \quad M = 125 \text{ GeV}$$

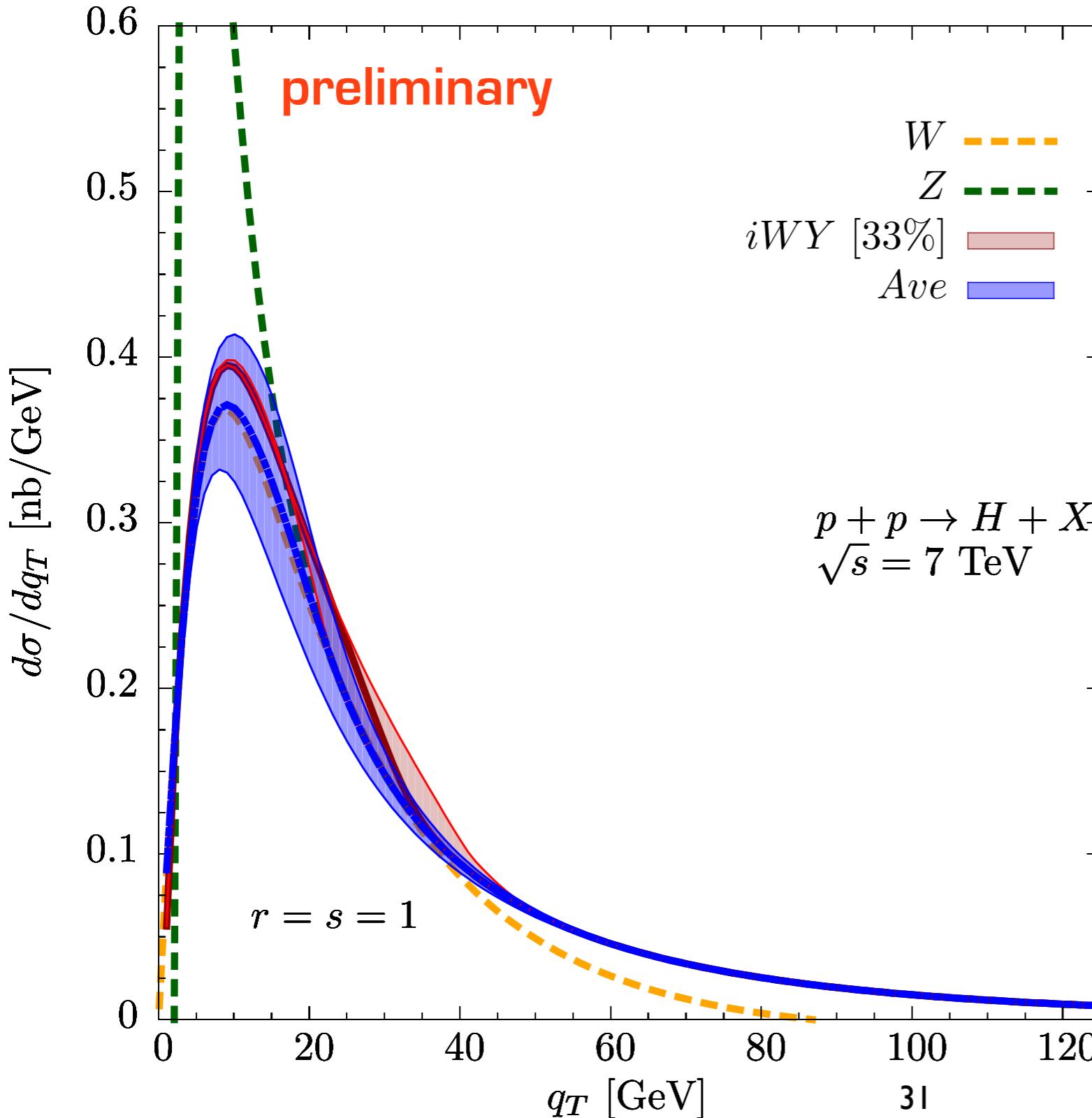
(see also talk by C. Pisano INT 17-3 week 4)

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

$\sim \mathcal{C}[ f_1^{g/A} f_1^{g/B} ]$   
unpolarized gluons

$\pm \mathcal{C}[ h_1^{\perp g/A} h_1^{\perp g/B} ]$   
lin. polarized gluons

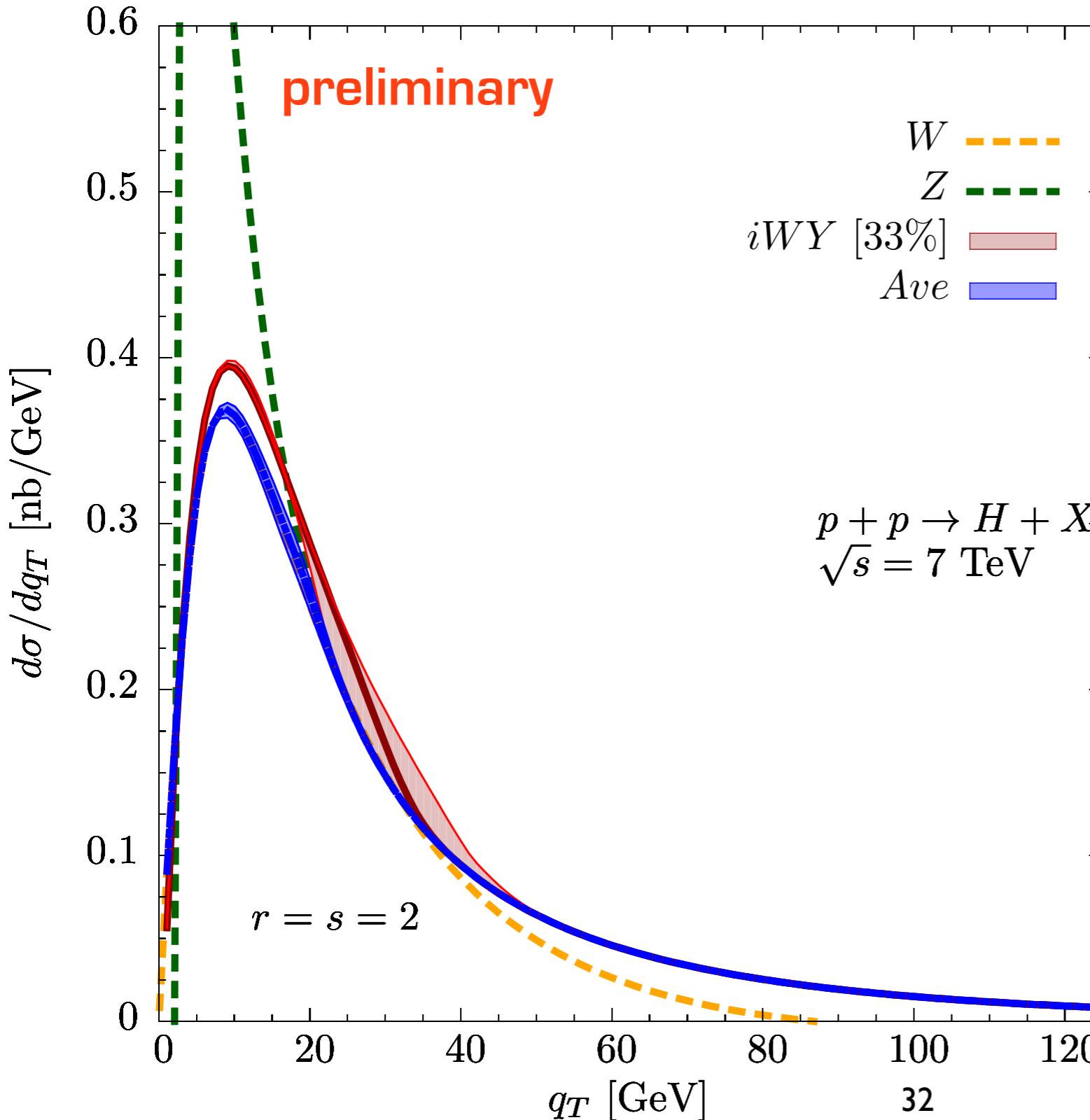
# Higgs boson production



comparison of iWY and  
average matching of W and Z

Jefferson Lab

# Higgs boson production

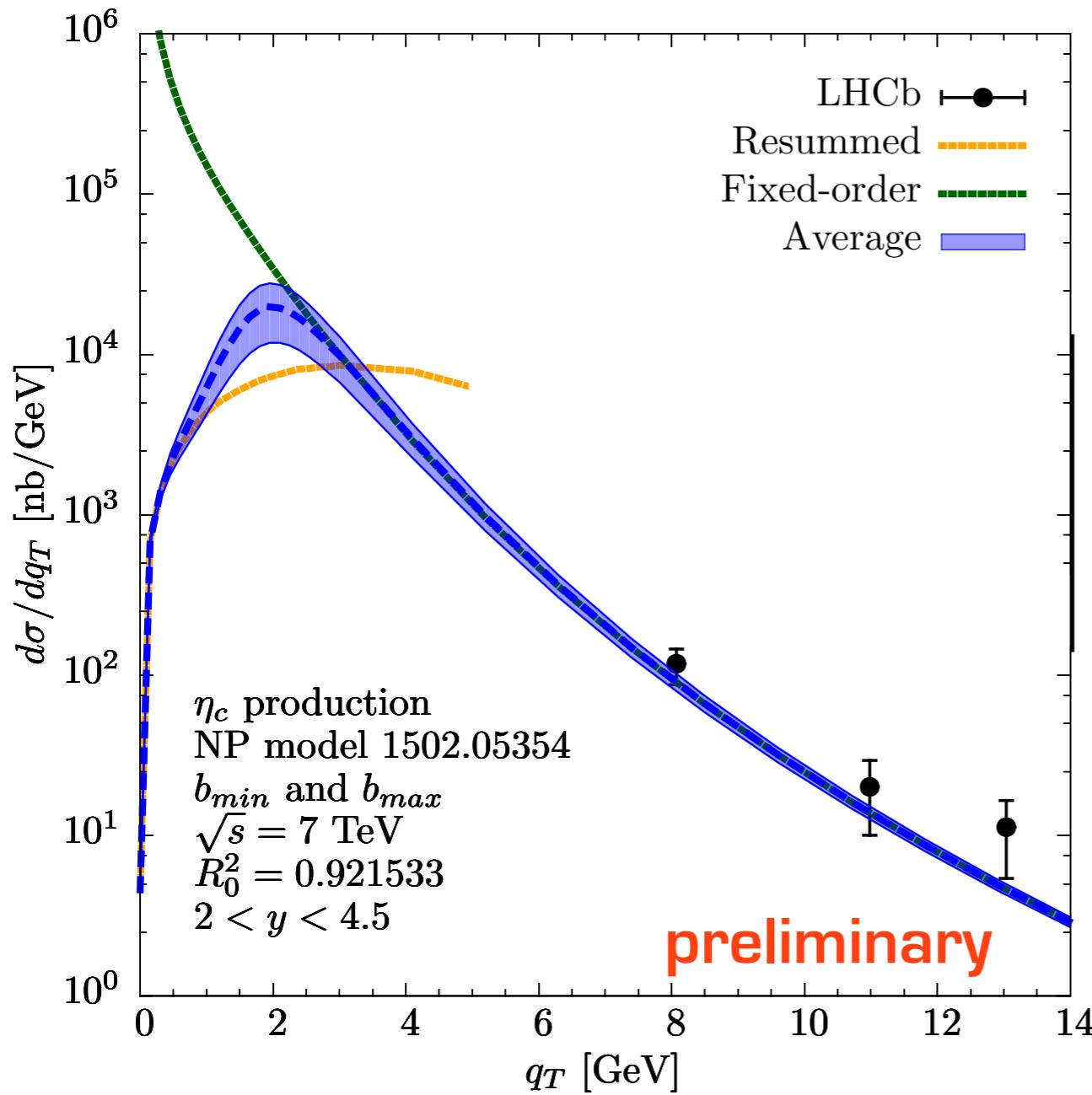


comparison of iWY and  
average matching of W and Z

puzzling feature:  
the central curves do not  
agree in the peak region.

# $\eta_c$ production

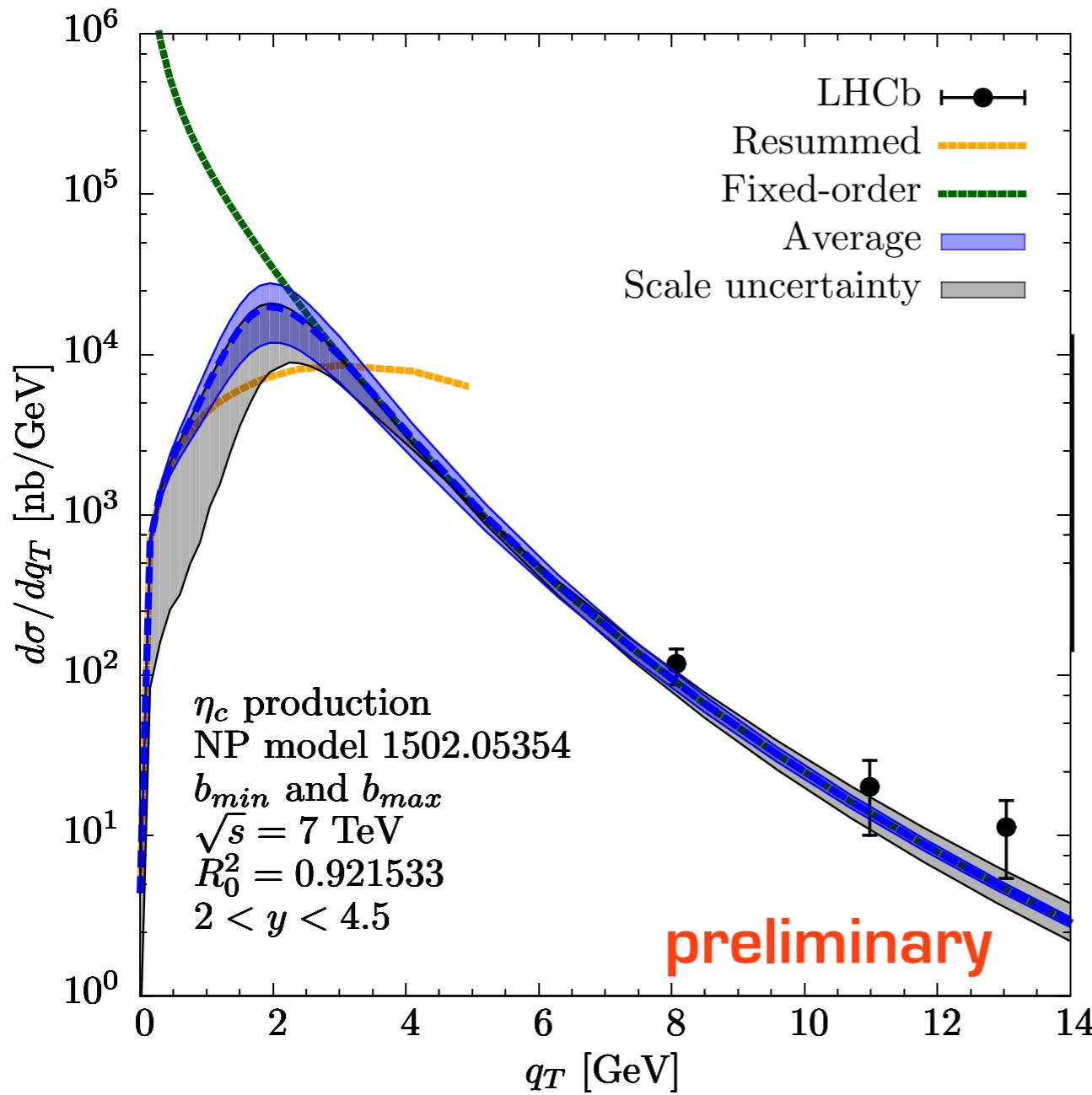
full transverse momentum spectrum:  
low  $q_T$  matched with high  $q_T$  region



blue band: uncertainty from matching

# $\eta_c$ production

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



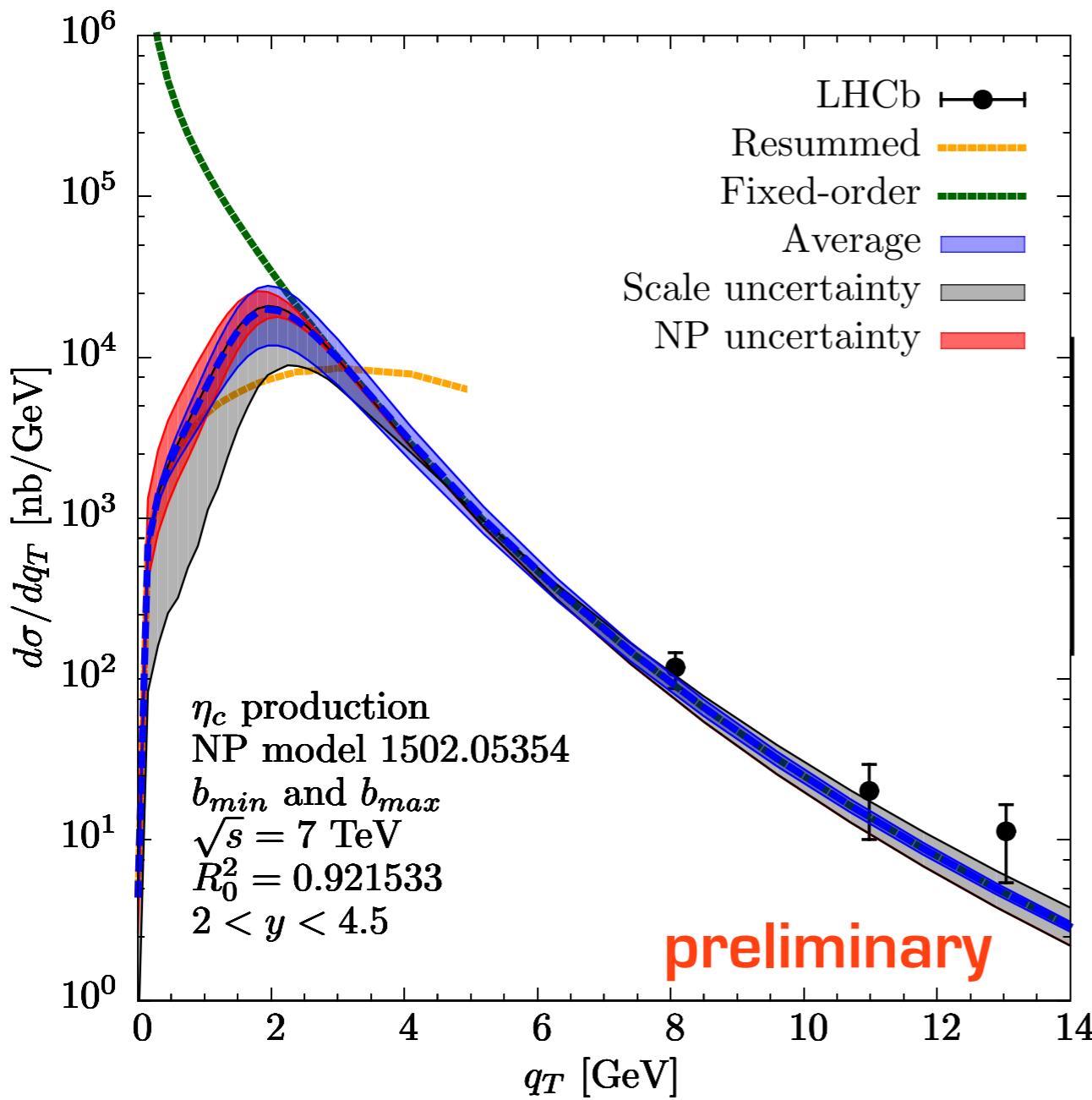
**blue band:** uncertainty from matching

**grey band:** scale uncertainty

$\mu_i^2 = \zeta_i = \mu_b^2$ ,  $\mu_{F.O.} = m_T$   
fact. 2 variation and envelope

# $\eta_c$ production

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

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

$a_i = 0.5$  GeV<sup>2</sup>, var. 50%, envelope

both for unpolarized and  
linearly polarized distributions

we need the data at low  $q_T$   
**to test the formalism**

# Comments & outlook

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## \* \* TMDs & W production

- impact on the peak position of flavor dependent TMDs is assessed: comparable with the impact associated to PDFs in a NN methodology
- the study of the impact on  $m_W$  is underway via a template fit methodology

## \* \* matching high and low transverse momenta

- computationally faster: calculate two terms instead of three
- we can quantify an error associated to the matching procedure as a function of  $q_T$
- lower accuracy compared to iWY ?
- other uncertainties have to be considered too
- no TMD analyses have been performed with matching, let's compare the impact of different prescriptions

# Backup

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# quark TMD PDFs

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

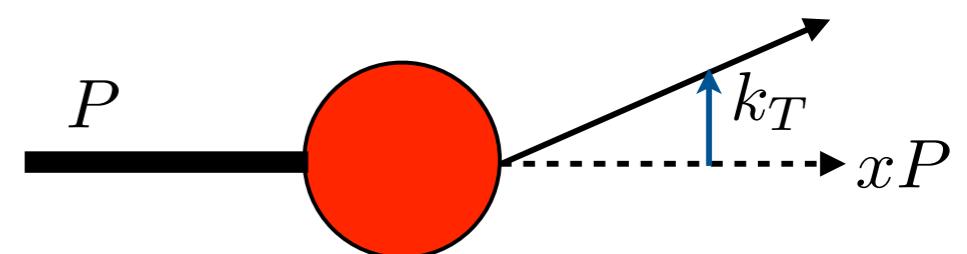
Quarks	$\gamma^+$	$\gamma^+ \gamma^5$	$i\sigma^{i+} \gamma^5$
U	$f_1$		$h_1^\perp$
L		$g_1$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}$	$h_1, h_{1T}^\perp$

Sivers TMD PDF

unpolarized TMD PDF

**bold** : also collinear

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

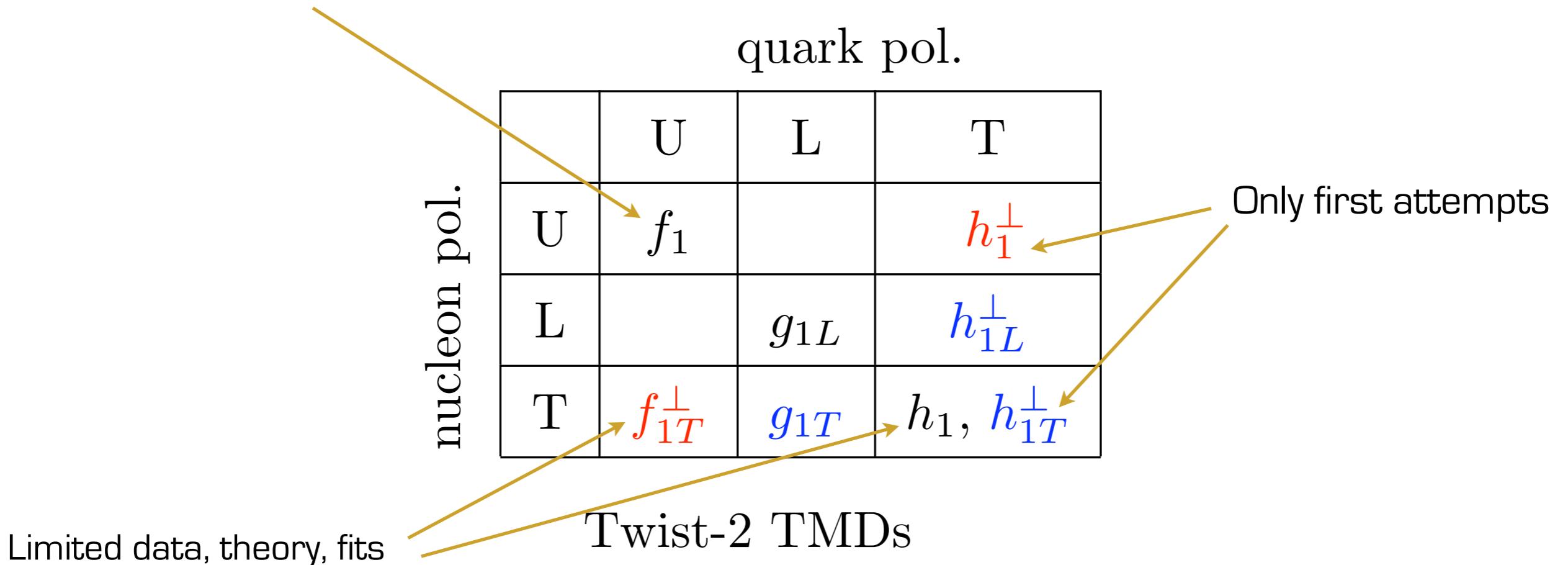


extraction of a **quark**  
**not** collinear with the proton

encode all the possible  
**spin-spin** and **spin-orbit**  
**correlation**  
between the proton  
and its constituents

# Status of TMD phenomenology

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



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

# W-term & TMDs

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

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

$b_T$  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

---

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

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

$b_T$  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  $q_T$ :**

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

Collins et al. PRD94 2016

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

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 :

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

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Sudakov form factor : perturbative and

**nonperturbative** contributions

$$\left( \frac{Q^2}{\mu_{\hat{b}}^2} \right) \rightarrow -K(\hat{b}_T; \mu_{\hat{b}}) - g_K(\bar{b}_T; \{\lambda\})$$

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

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

Collinear distribution!

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

# W+Y

Cross section →  $\Gamma = \mathbf{T}_{\text{TMD}}\Gamma + [\Gamma - \mathbf{T}_{\text{TMD}}\Gamma]$

$$\approx \underbrace{\mathbf{T}_{\text{TMD}}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\text{coll}} [\Gamma - \mathbf{T}_{\text{TMD}}\Gamma]}_{\mathbf{Y}}$$

$\mathbf{Y}$  = Fixed Order (F.O.) - F.O. expansion of resummed (ASY)

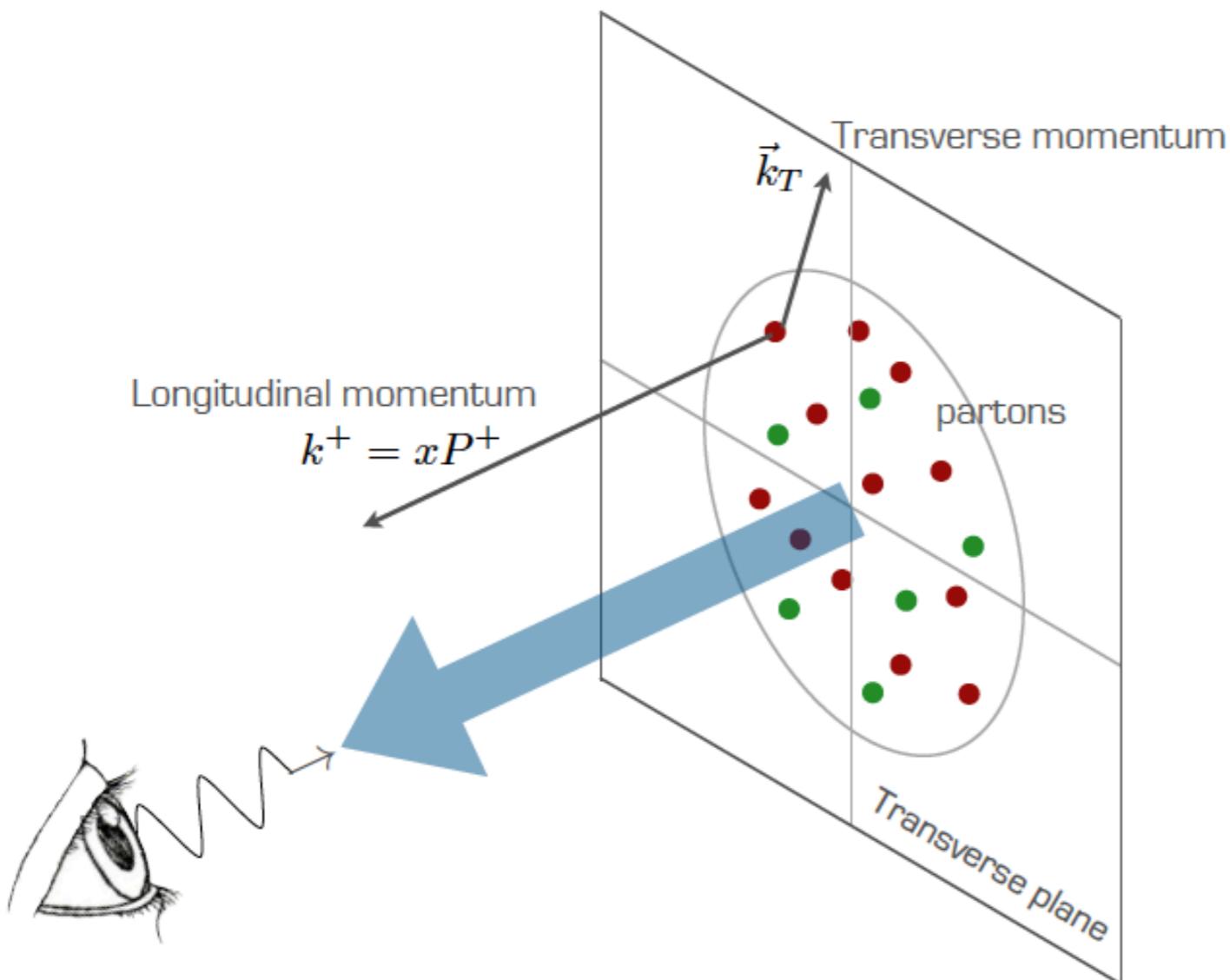
$[\Gamma - \mathbf{T}_{\text{TMD}}\Gamma] = O\left(\frac{q_T}{Q}\right)^a \Gamma$  (error at low  $q_T$ )

$$\begin{aligned} \mathbf{T}_{\text{coll}} [\Gamma - \mathbf{T}_{\text{TMD}}\Gamma] &= [\Gamma - \mathbf{T}_{\text{TMD}}\Gamma] [1 + O\left(\frac{m}{q_T}\right)^b] && \text{(error at higher } q_T) \\ &= [\Gamma - \mathbf{T}_{\text{TMD}}\Gamma] + O\left(\frac{q_T}{Q}\right)^a O\left(\frac{m}{q_T}\right)^b \Gamma \\ &= [\Gamma - \mathbf{T}_{\text{TMD}}\Gamma] + O\left(\frac{m}{Q}\right)^{\min(a,b)} \Gamma && \text{"global" error} \end{aligned}$$

$d\sigma = W + Y + O(\lambda_{\text{QCD}}/Q)^c d\sigma$  error for W+Y

# quark TMD PDFs

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



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

courtesy A. Bacchetta

# 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

## 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

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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

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

High  $b_T$  limit : avoid Landau pole

Low  $b_T$  limit : recover fixed order expression

# Quark TMD PDF

Qiu-Zhang, Phys. Rev. D 63 114011

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

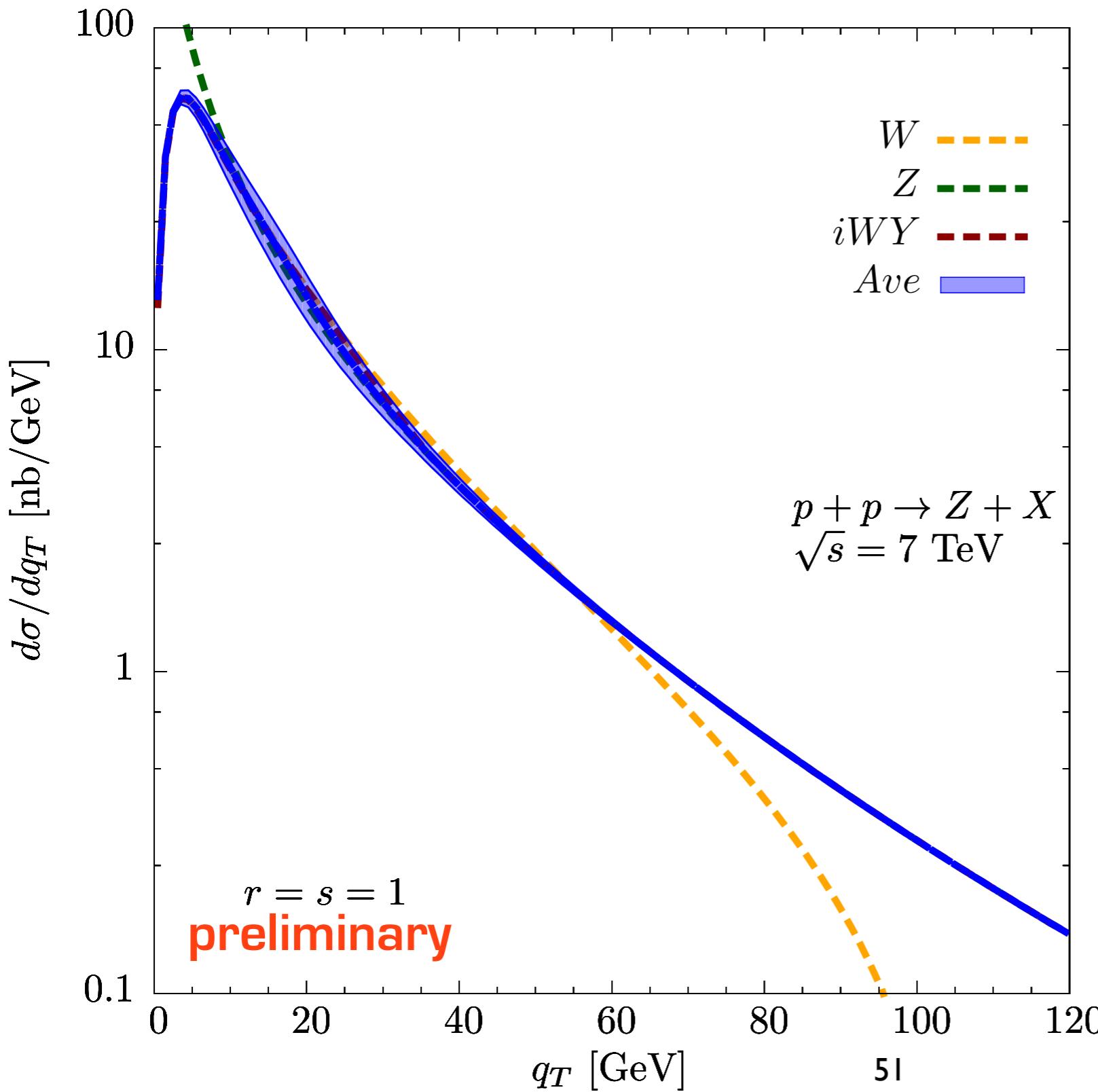
$$F_{QZ}^{NP}(b, Q, x_A, x_B; b_{max}) = \exp \left\{ -\ln \left( \frac{Q^2 b_{max}^2}{c^2} \right) \{g_1[(b^2)^\alpha - (b_{max}^2)^\alpha] + g_2(b^2 - b_{max}^2)\} - \bar{g}_2(b^2 - b_{max}^2) \right\}$$

parameters:  
bmax, g1, g2,  $\alpha$

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

# Z boson production

DYqT [10.1016/j.physletb.2010.12.024](https://doi.org/10.1016/j.physletb.2010.12.024)

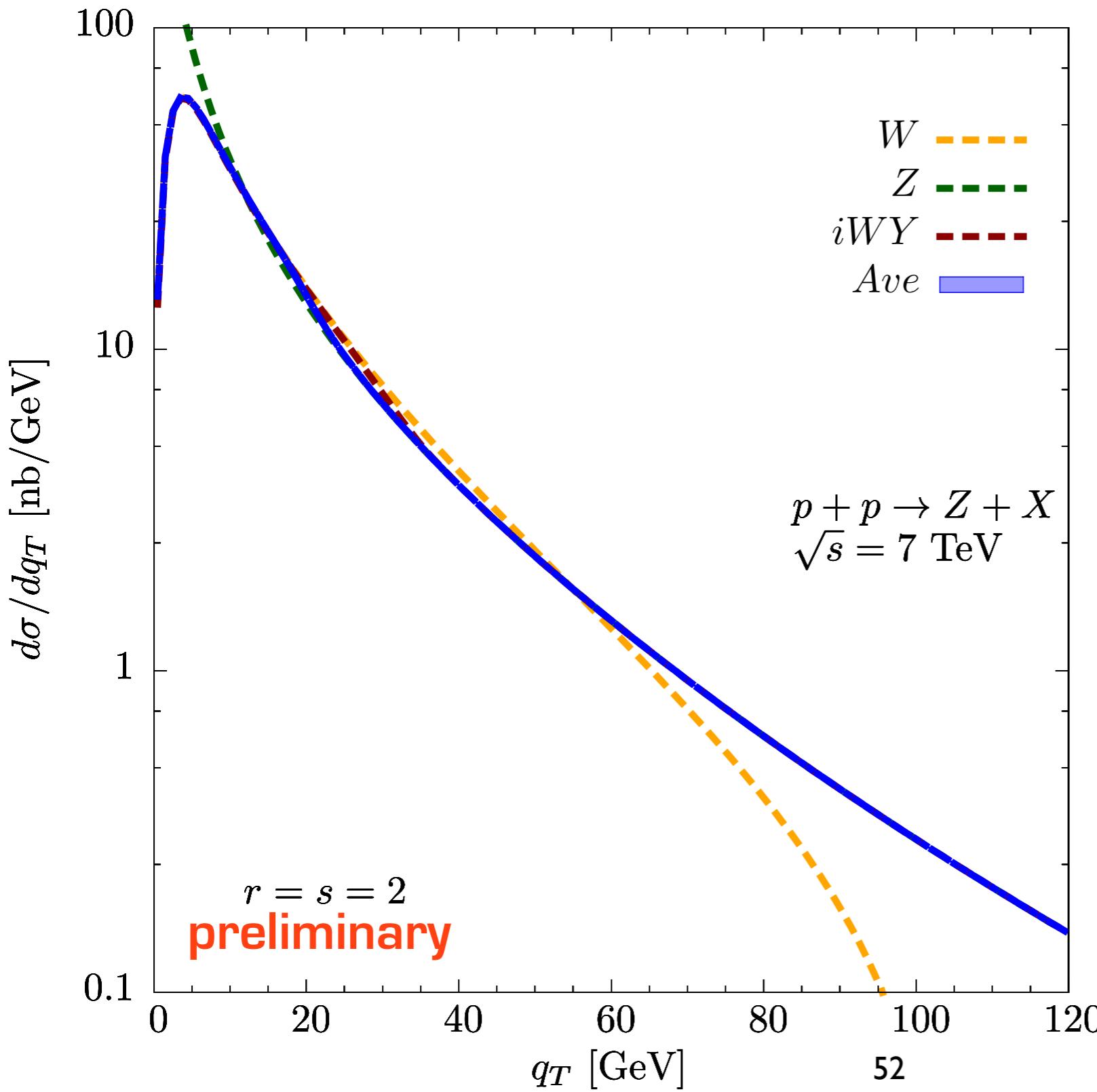


comparison of iWY and  
average matching of W and Z

Jefferson Lab

# Z boson production

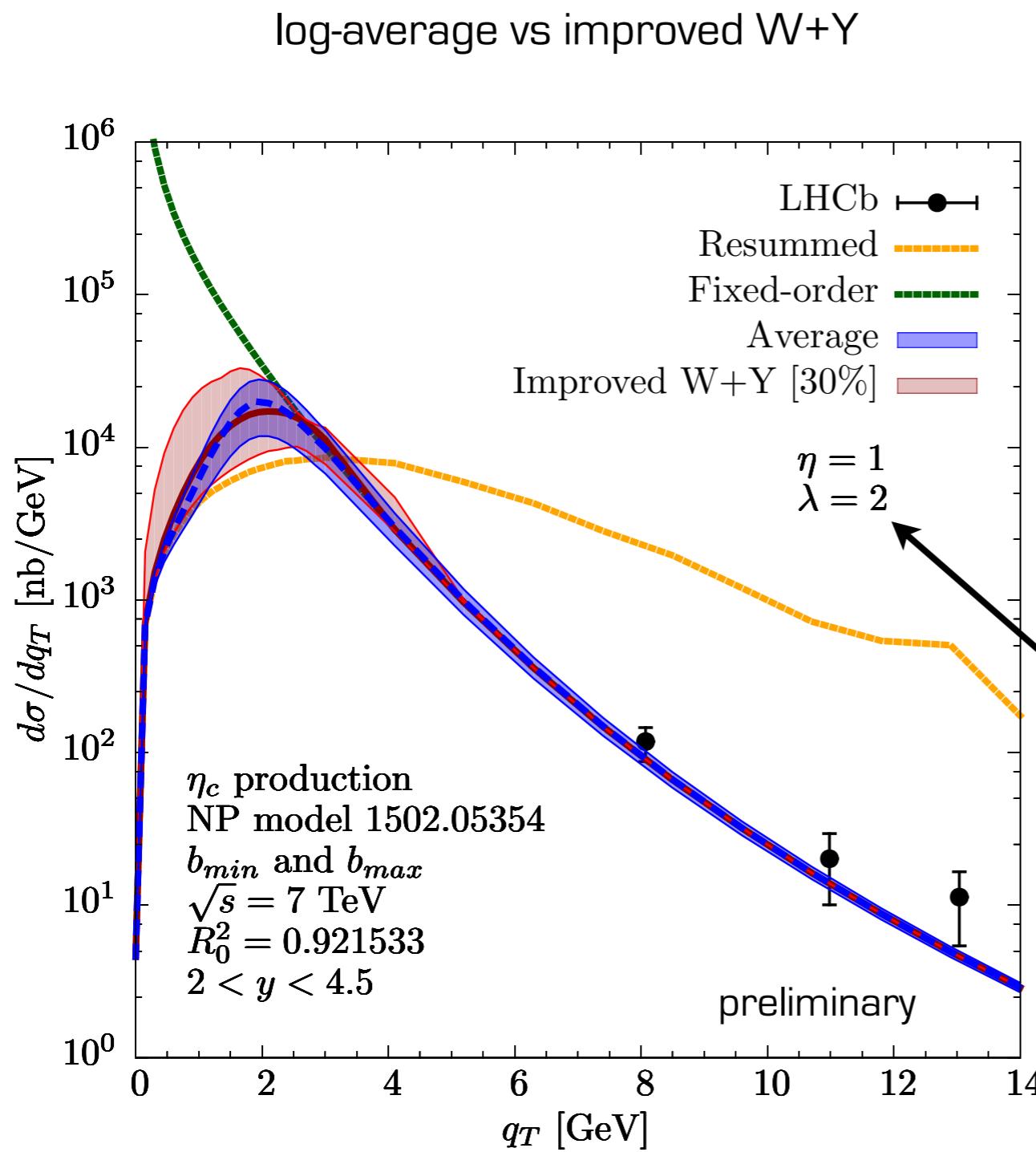
DYqT [10.1016/j.physletb.2010.12.024](https://doi.org/10.1016/j.physletb.2010.12.024)



comparison of iWY and  
average matching of W and Z

Jefferson Lab

# $\eta_c$ production at LHC



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

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

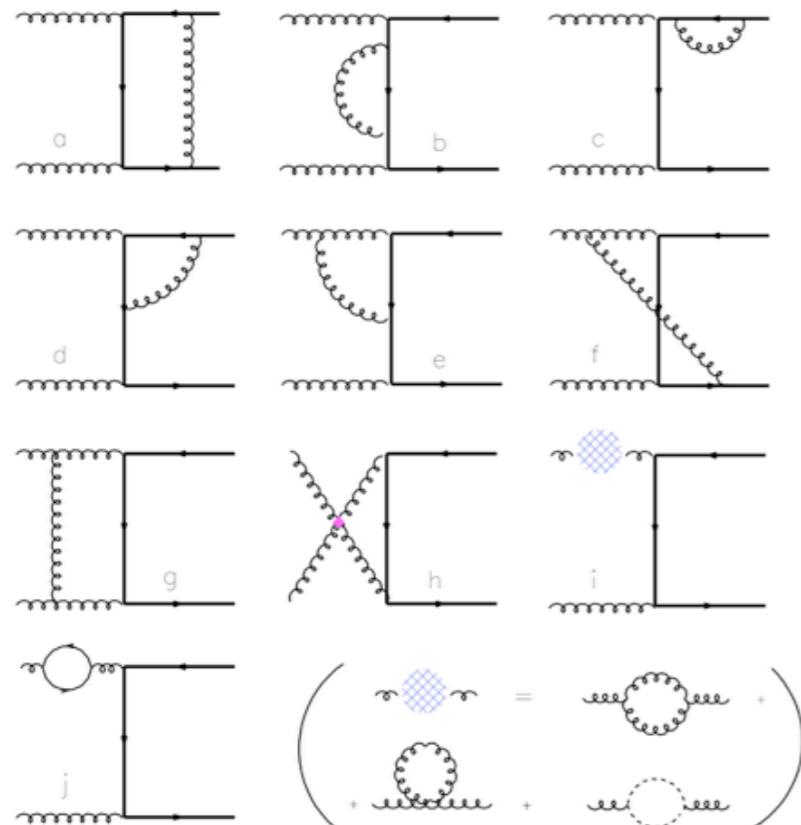
smooth matching from W to FO

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

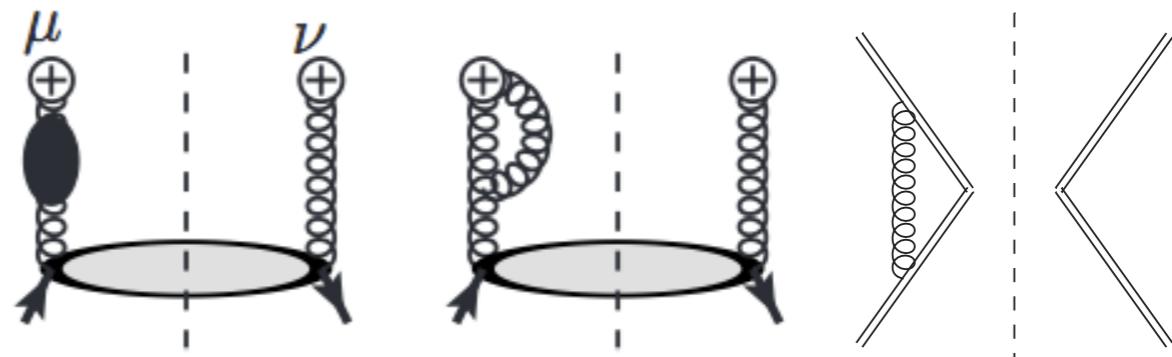
**blue band:** uncertainty from log-average matching

**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”**



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

? same IR ?

**no:**

It does not reproduce the physical (=QCD) result

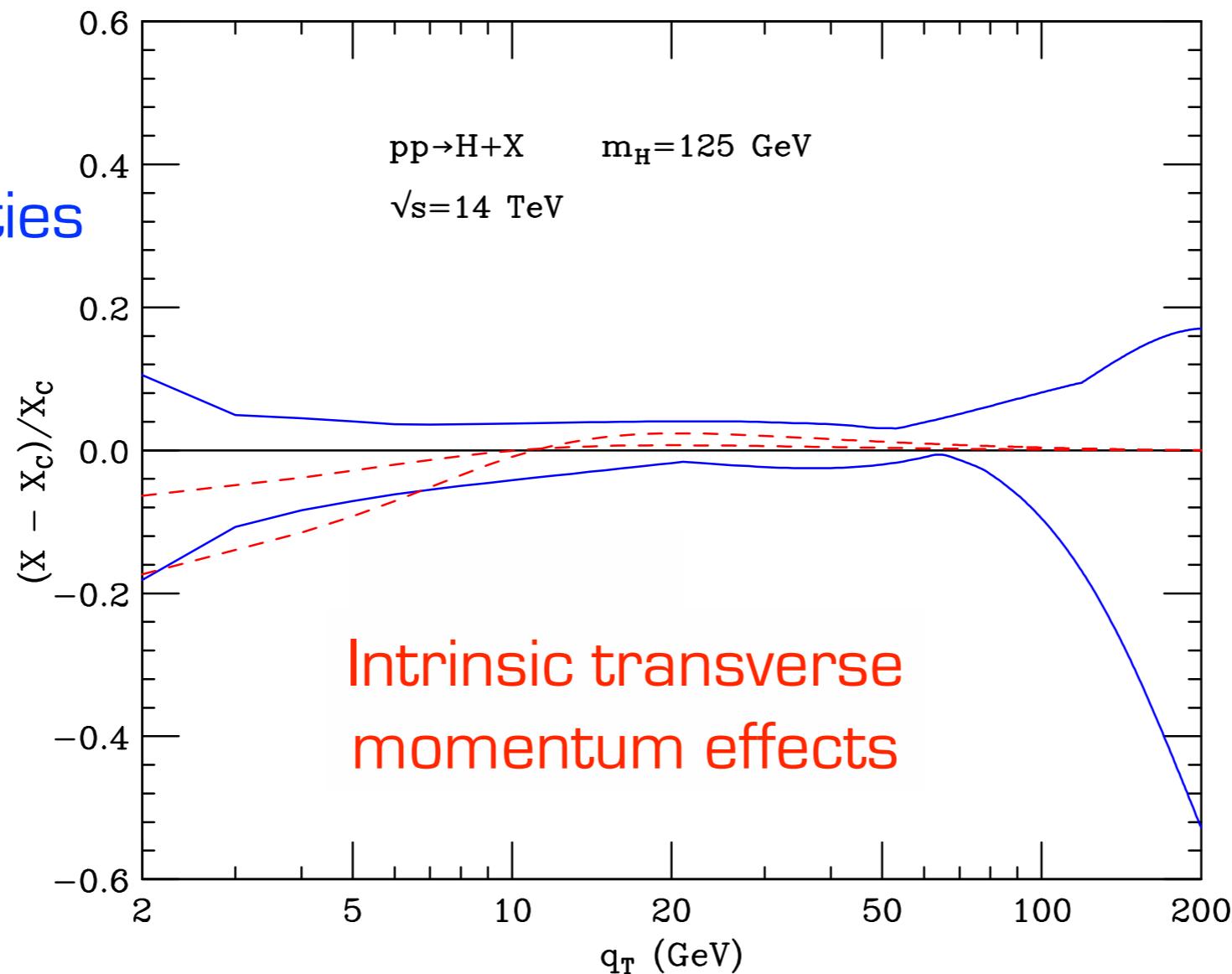
**yes:**

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

PDF uncertainties

