Transverse momentum distributions and the determination of the W mass

Andrea Signori

1st COFI workshop on precision EW physics

Puerto Rico

July 18th, 2019

Outline of the talk

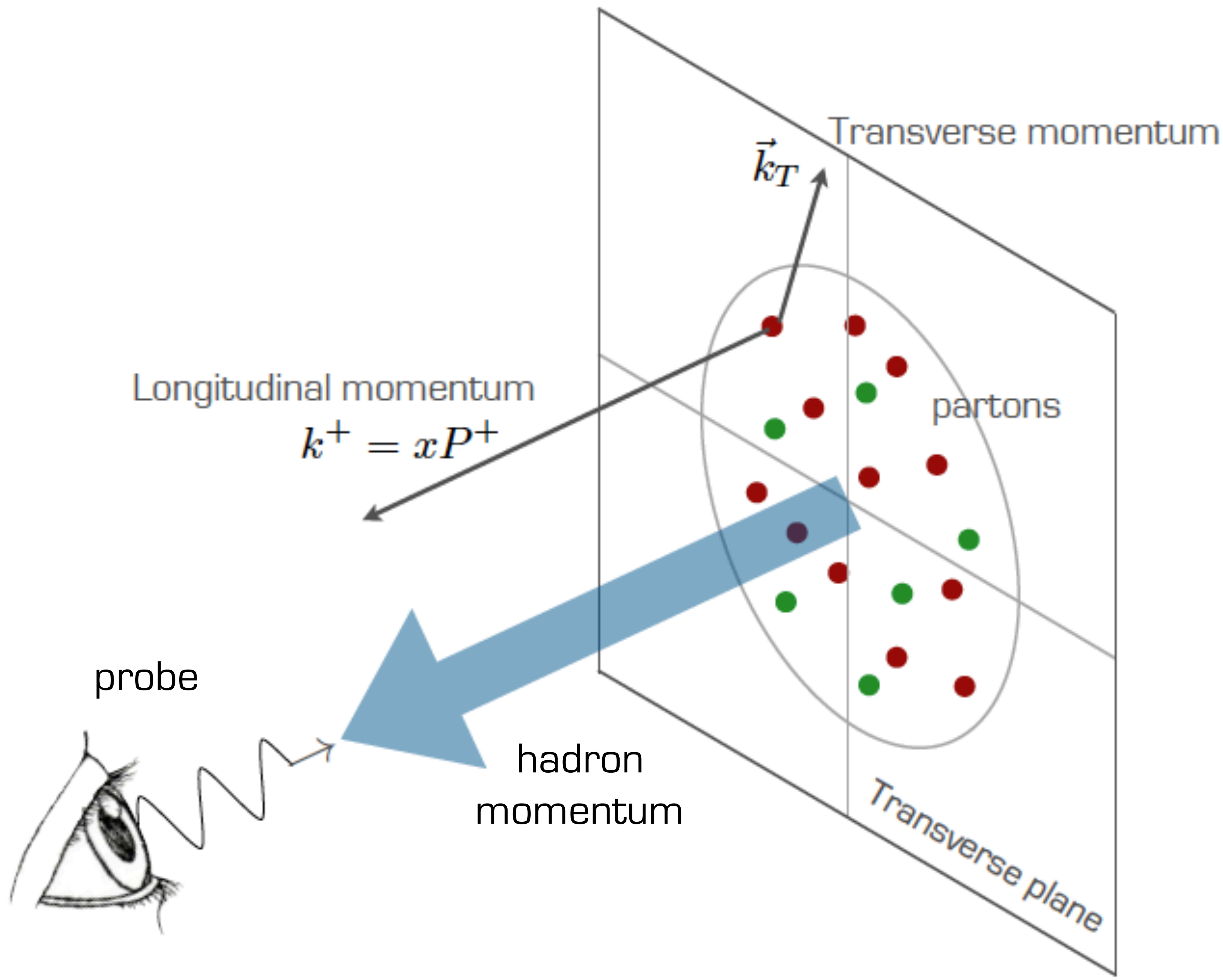
1) hadron structure and TMDs

2) predictive power of TMDs

3) impact on W mass determination

TMDs

TMD PDFs

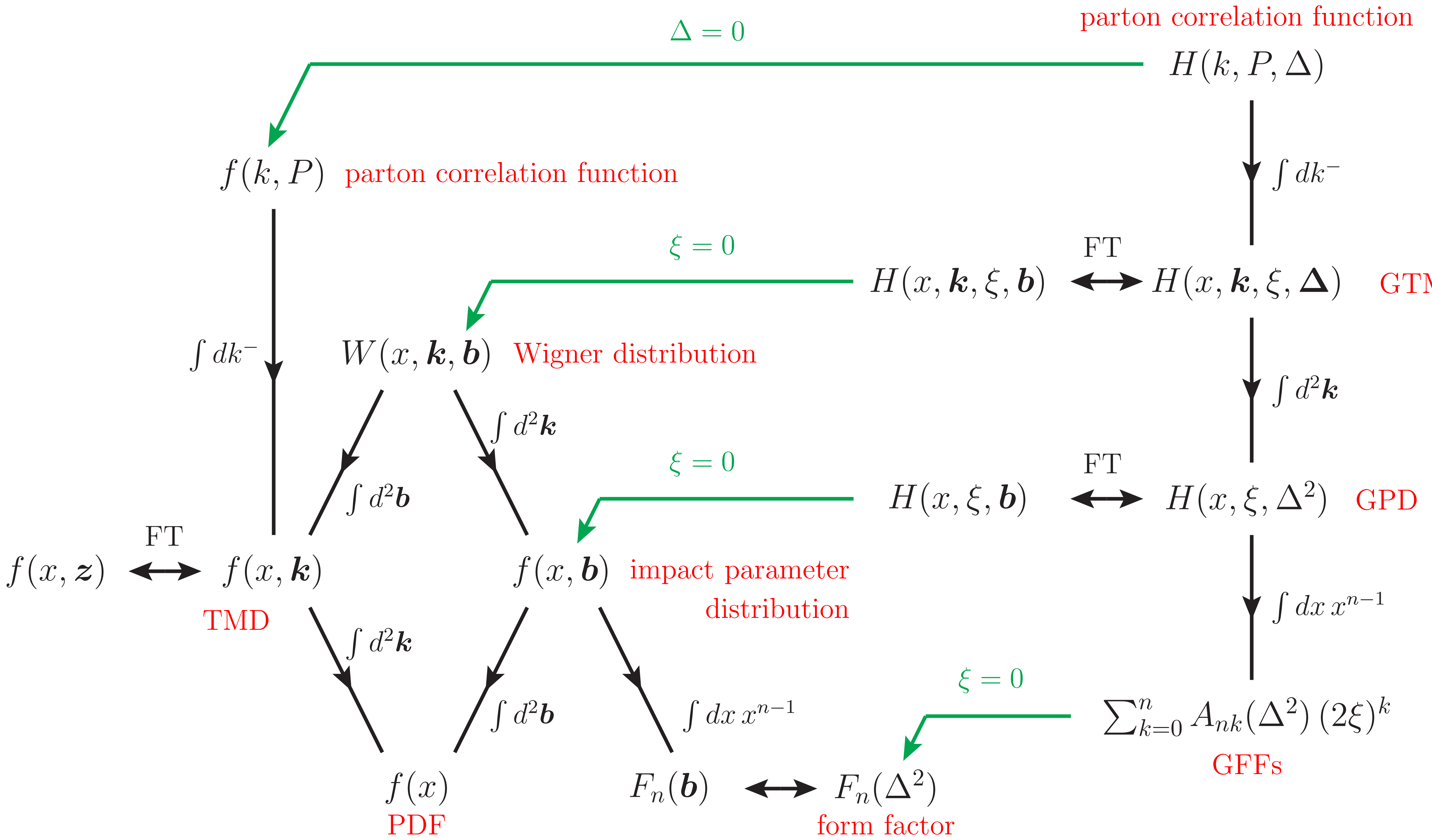


extraction of a **parton** whose momentum has **longitudinal** and **transverse components** with respect to the parent **hadron** momentum

richer structure than collinear PDFs

courtesy A. Bacchetta

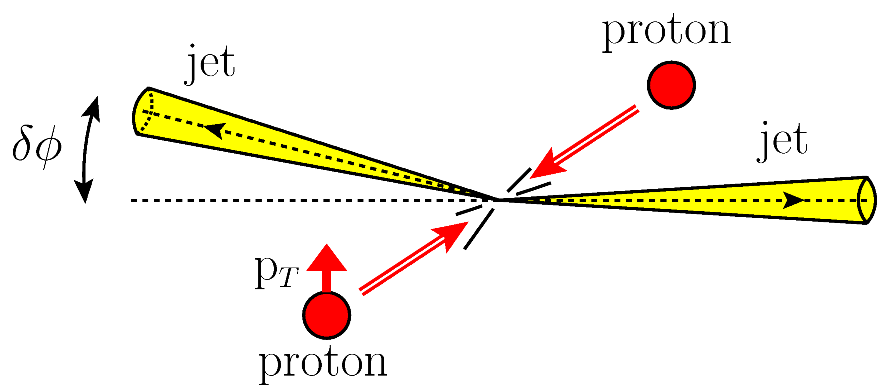
Hadron tomography



M. Diehl - 10.1140/epja/i2016-16149-3

Motivations

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

"The aim of science is not to open the door to infinite wisdom, but to set a limit to infinite error"

B. Brecht, The life of Galileo

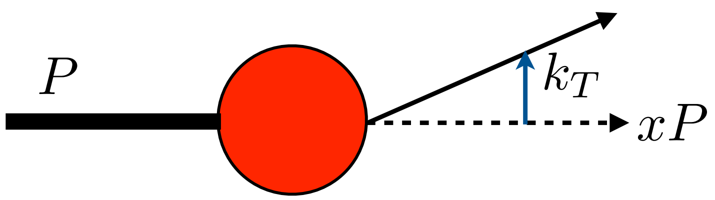
Quark TMD PDFs

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

	U	L	T
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-momentum**
correlations
between the proton
and its constituents

similar table for **gluons** and for **fragmentation functions**

bold : also collinear
red : time-reversal odd (universality properties)

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The transversity PDF

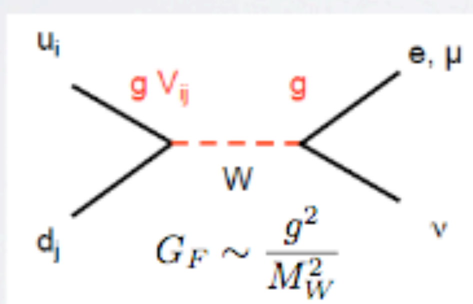
M. Radici - INT 17-3 program

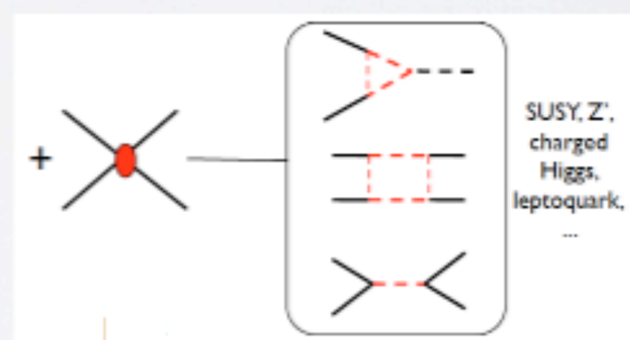
$$P^{[\mu}S^{\nu]}\, g_T^q(Q^2) = P^{[\mu}S^{\nu]} \int_0^1 dx \; [h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)]$$

$$= \langle P,S|\, \bar{q}\, \sigma^{\mu\nu}\, q\, |P,S\rangle$$

tensor operator not directly accessible in $\mathcal{L}_{SM}$
low-energy footprint of new physics (BSM) at higher scales ?

Example: neutron β–decay $n \to p\, e^- \bar{\nu}_e$





$\mathcal{L}_{SM}$ universal V-A

$\mathcal{L}_{BSM}$ new couplings: $\varepsilon_S\, 1,\ \ \varepsilon_{PS}\, \gamma_5,\ \ \varepsilon_T\, \sigma^{\mu\nu}$

$$\varepsilon_T\, g_T \approx M_W^2 / M_{BSM}^2$$

The transversity PDF

M. Radici - INT 17-3 program

Also connected to **CP violation**

Measurements of hadronic EDMs
+ **tensor charge** =
quark EDMs

↓

CKM only accounts for
extremely small EDM
for light quarks

The Sivers function

$$f_{1T}^{a\perp\ [+]}(x, k_T^2) = -f_{1T}^{a\perp\ [-]}(x, k_T^2)$$

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Collins, PLB 536 (02)

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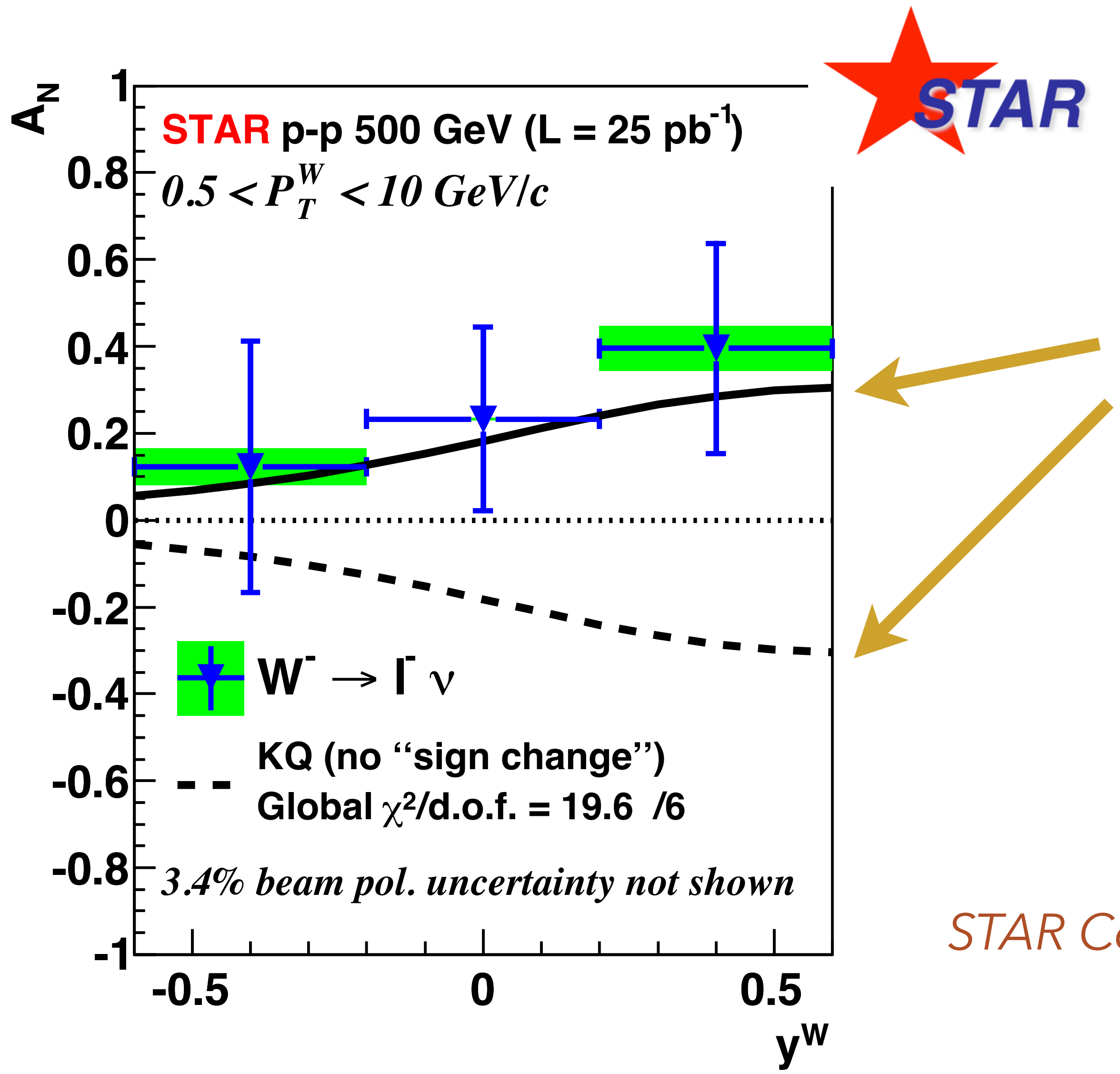

first evidence of sign change?

STAR Collab. arXiv:1511.06003

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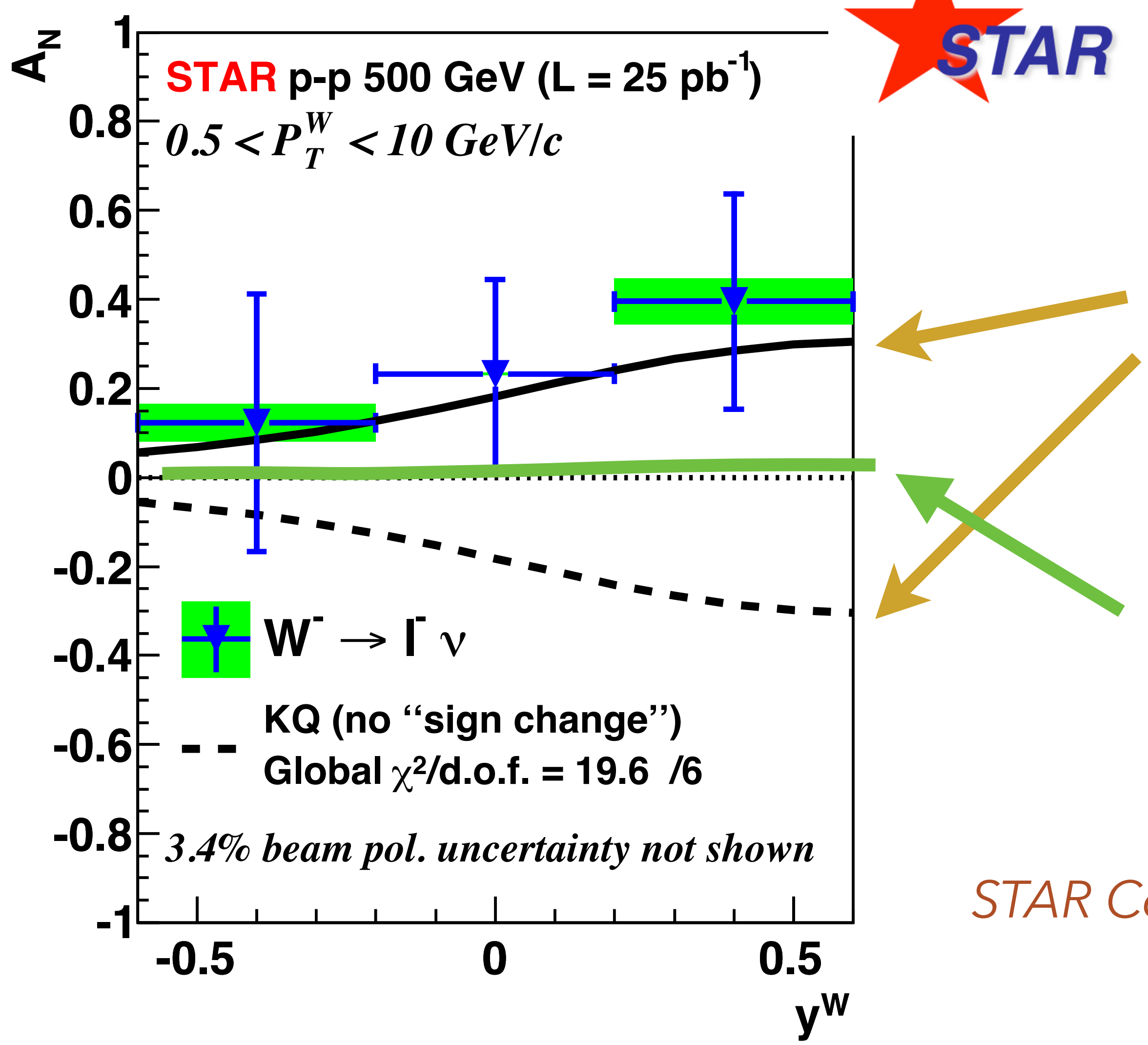


first evidence of sign change?

prediction with TMD evolution equations

STAR Collab. arXiv:1511.06003

TMD factorization

A non-exhaustive list

Quark-induced processes :

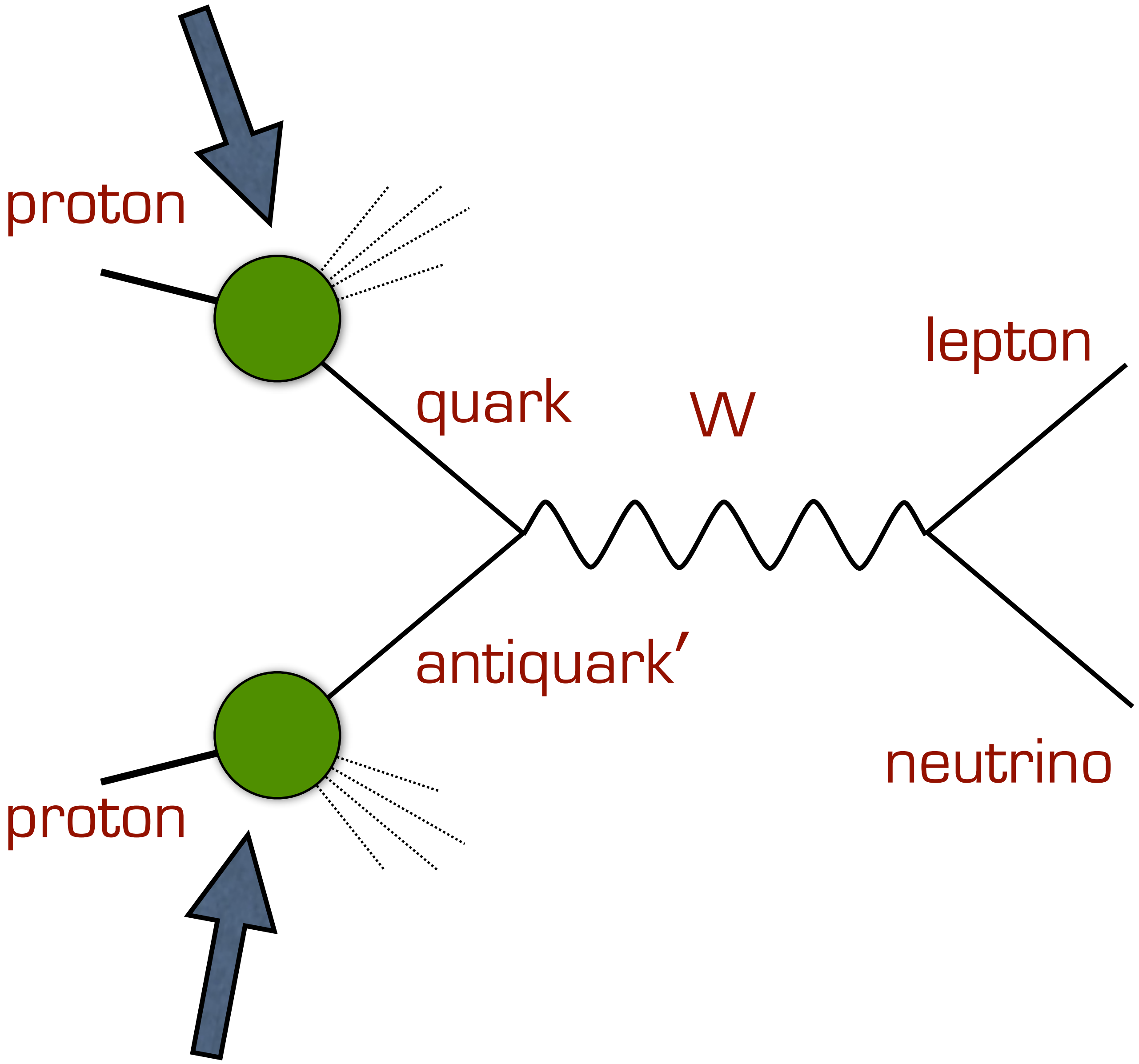
- Collins, Soper (1981) - $e^+e^- \to h_1 h_2 X$ [NPB 193 (1981) 381]
- Collins, Soper, Sterman (1985) - Drell-Yan, W/Z [NPB 250 (1985) 199]
- Ji, Ma, Yuan (2004) - SIDIS [PLB 597 (2004) 299]
- Ji, Ma, Yuan (2005) - Drell-Yan [PRD 71 (2005) 034005]
- Collins (2011) - Foundations of perturbative QCD [Cambridge U. Press]
- Echevarria, Idilbi, Scimemi (2012) - SCET Drell-Yan [JHEP 1207 (2012) 002]
- Echevarria, Idilbi, Scimemi (2014) - SCET SIDIS [PRD 90 (2014) 014003]

Gluon-induced processes :

- Mantry, Petriello (2010) - Higgs boson production [PRD81 (2010) 093007]
- Sun, Xiao, Yuan (2011) - Higgs boson production [PRD 84 (2011) 094005]
- Ma, Wang, Zhao (2012) - \eta_b,c production [PRD 88 (2013) 014027]

W boson production

(TMD) parton distribution functions



(TMD) parton distribution functions

Kinematics (W)

$Q = m_W$ mass

y rapidity

q_T Transverse momentum

Kinematics (partons)

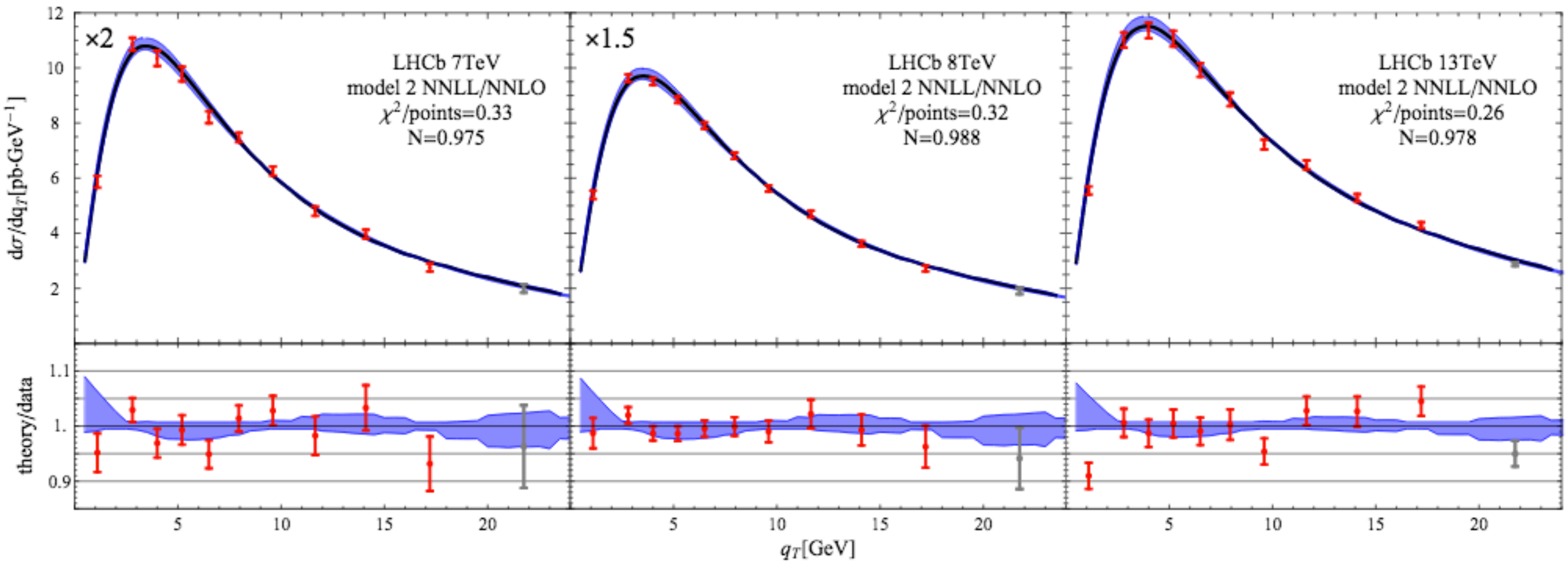
$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

Collinear momentum fractions

$k_{T\,1,2}$ Transverse momenta

TMD factorization at work

Scimemi, Vladimirov [Eur.Phys.J. C78 2018 89] + Scimemi, Vladimirov, Bertone (1902.08474)



Schematically :

$$\frac{d\sigma}{dq_T} \sim \underline{\mathcal{H}\; f_1(x_a, k_{Ta}, Q)\; f_1(x_b, k_{Tb}, Q)\; \delta^{(2)}(q_T - k_{Ta} - k_{Tb})} + \mathcal{O}(q_T/Q) + \mathcal{O}(m/Q)$$

Low transverse momentum (TMD) region

$$q_T \ll Q$$

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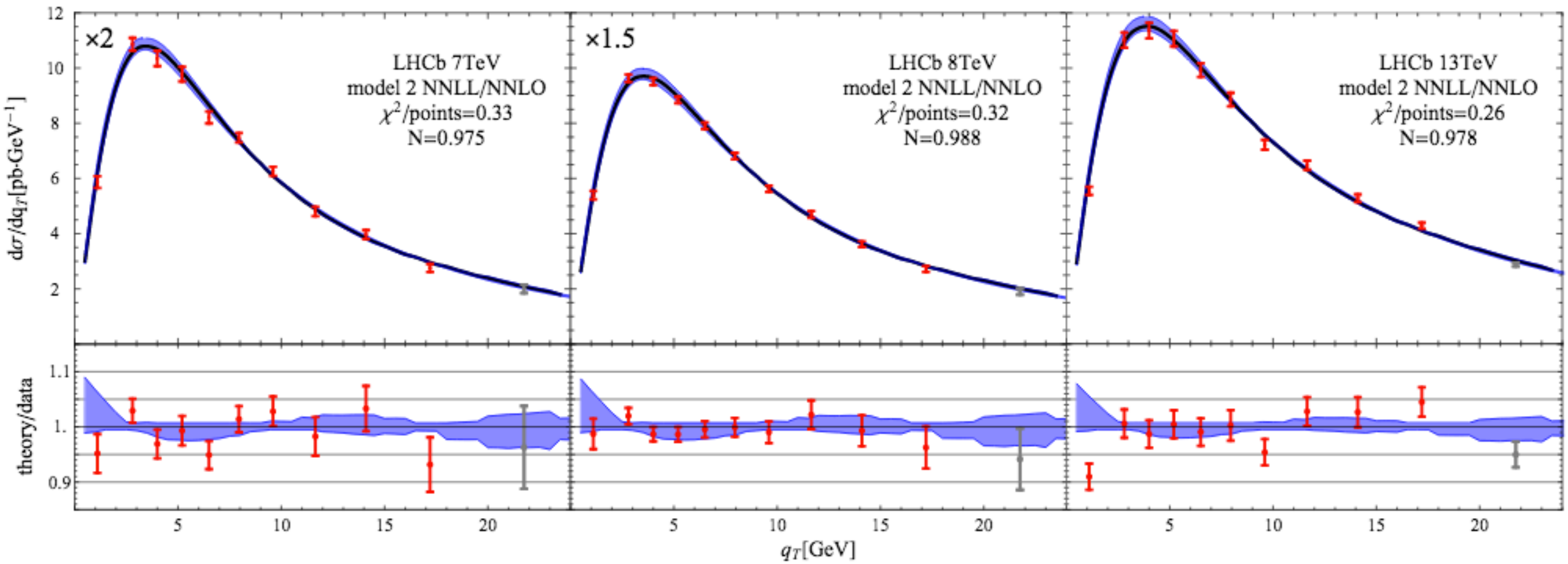

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Matching to fixed-order calculations in coll. factorization

Combining SIDIS, DY, Z production

A fact we have to face: the bulk of the data lies at **low Q**

1) it is possible to perform an **almost global fit** of SIDIS data, fixed-target DY, Z production : 1703.10157

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- Drell-Yan : 1901.06916
- Semi-Inclusive Annihilation : in preparation

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Possible solutions: higher-orders, threshold effects, higher-twist, collinear PDFs and FFs … ?

Definitely a long way to go before achieving NNLO global fits of TMDs!

Predictive power

References :

- Parisi, Petronzio: Nucl. Phys. B154, 427 (1979)
- Collins, Soper, Sterman: Nucl. Phys. B250, 199 (1985)
- Qiu, Berger: Phys. Rev. Lett. 91, 222003 (2003)
- Grewal, Kang, Qiu, **AS**: in preparation

Structure of a TMD PDF

$$f_1^a(x, b_T^2, \mu_f, \zeta_f) = f_1^a(x, b_T^2, \mu_i, \zeta_i)$$

b_T, Fourier conjugate of k_T

two "evolution scales"

$$\times \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2} \right] \right\}$$

evolution in mu
$\mu_i \to \mu_f$

$$\times \left(\frac{\zeta_f}{\zeta_i} \right)^{-K(b_T, \mu_i)}$$

evolution in zeta
$\zeta_i \to \zeta_f$

Input TMD distribution can be **expanded at low b_T** on the collinear distributions

$$f_1^a(x, b_T^2, \mu_i, \zeta_i) = \sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i)$$

A sensible choice is to set the initial and final scale as:

$$\zeta_i = \mu_i^2 = 4e^{-2\gamma_E}/b_T^2 \equiv \mu_b^2$$
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need corrections at large bT

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Non-perturbative structures

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Non-perturbative structures

In which kinematic regimes are they dominant ?

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Predictive power

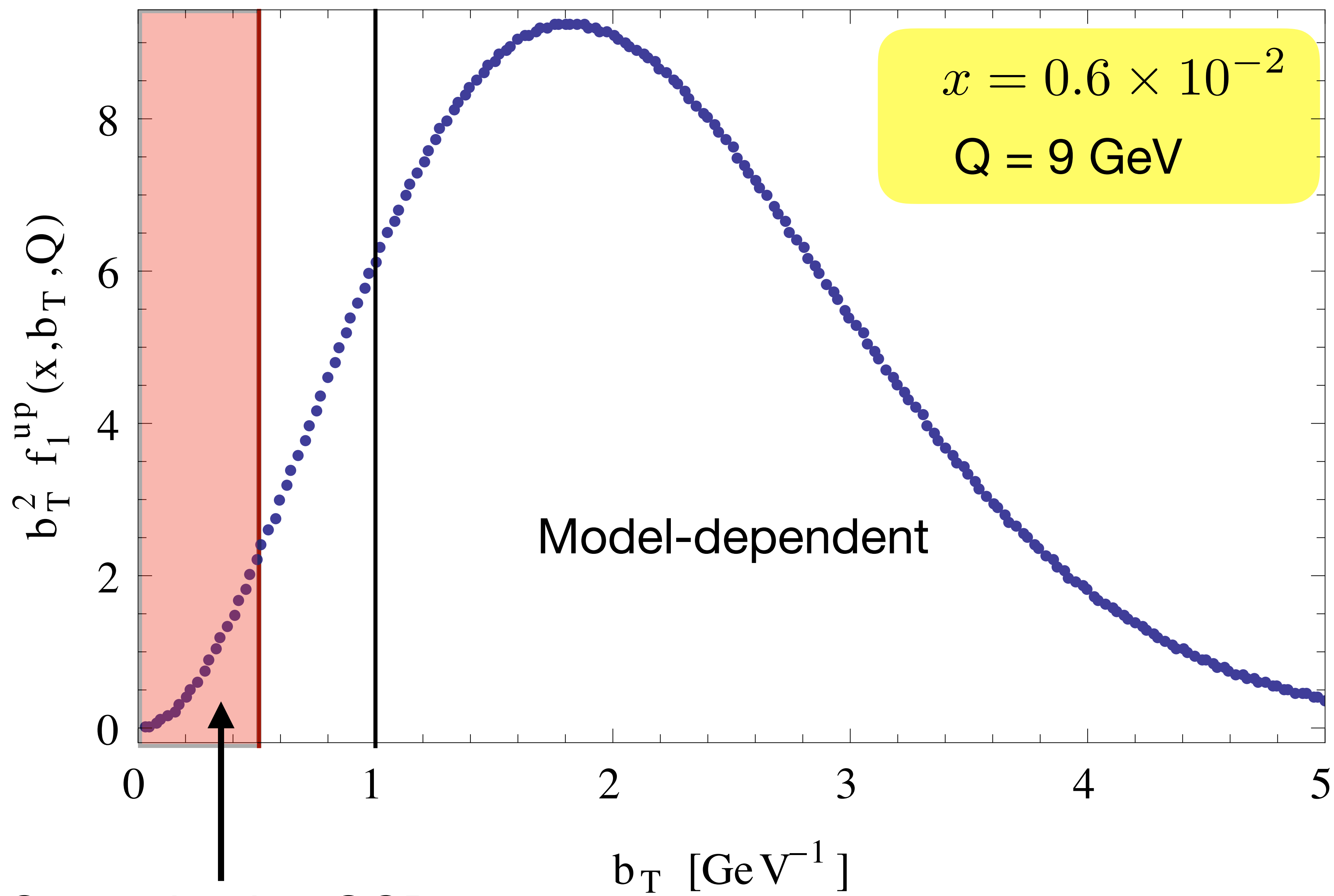
perturbative
region
$b_T \lesssim 1 - 1.5\ \text{GeV}^{-1}$

Fully trusted
perturbative region
$b_T < b_{T\max}$

non-perturbative
region
$b_T > b_{T\max}$

NNLO - NNLL QCD

$b_{T\max} = 0.5\ \text{GeV}^{-1}$



Calculable in pQCD

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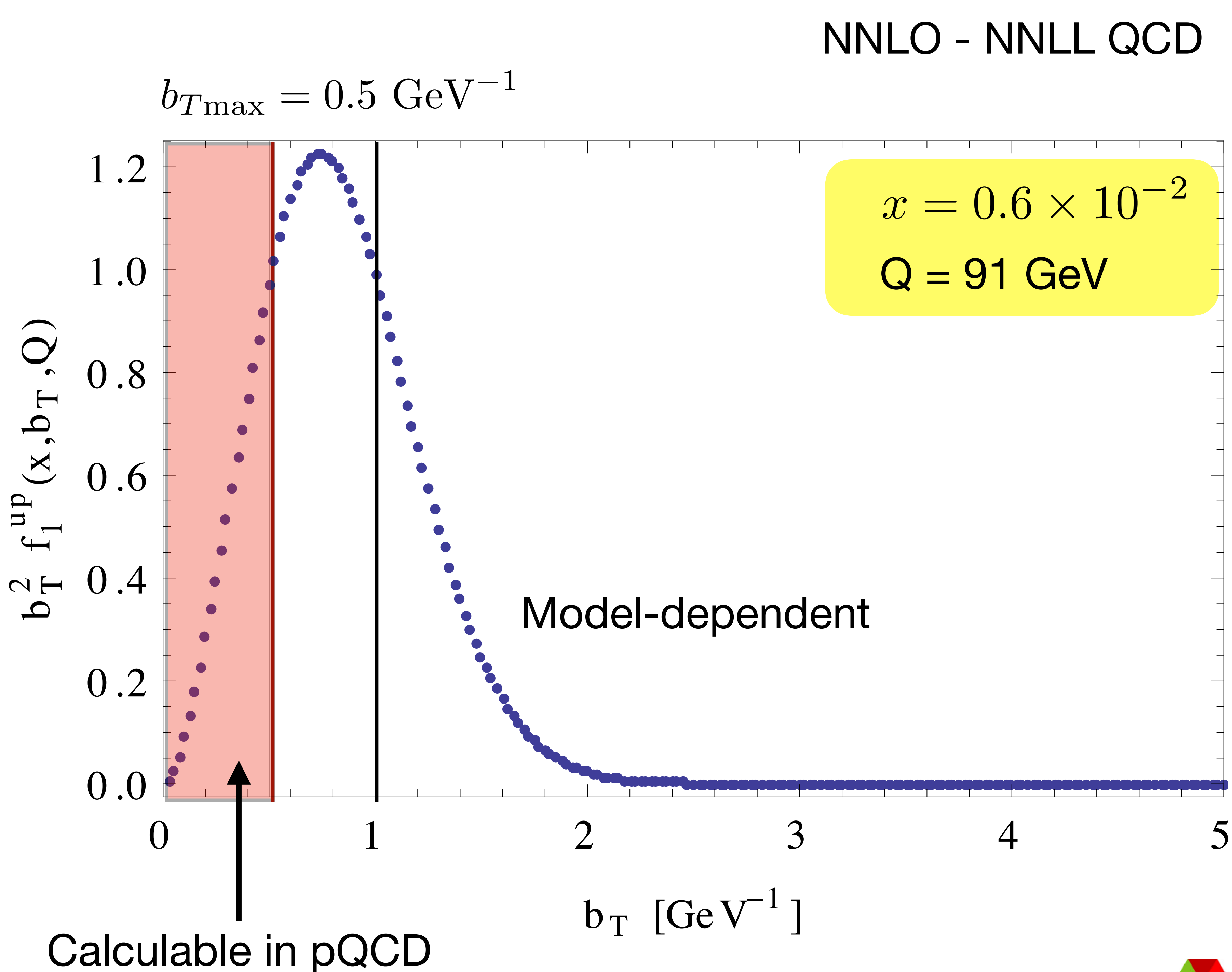

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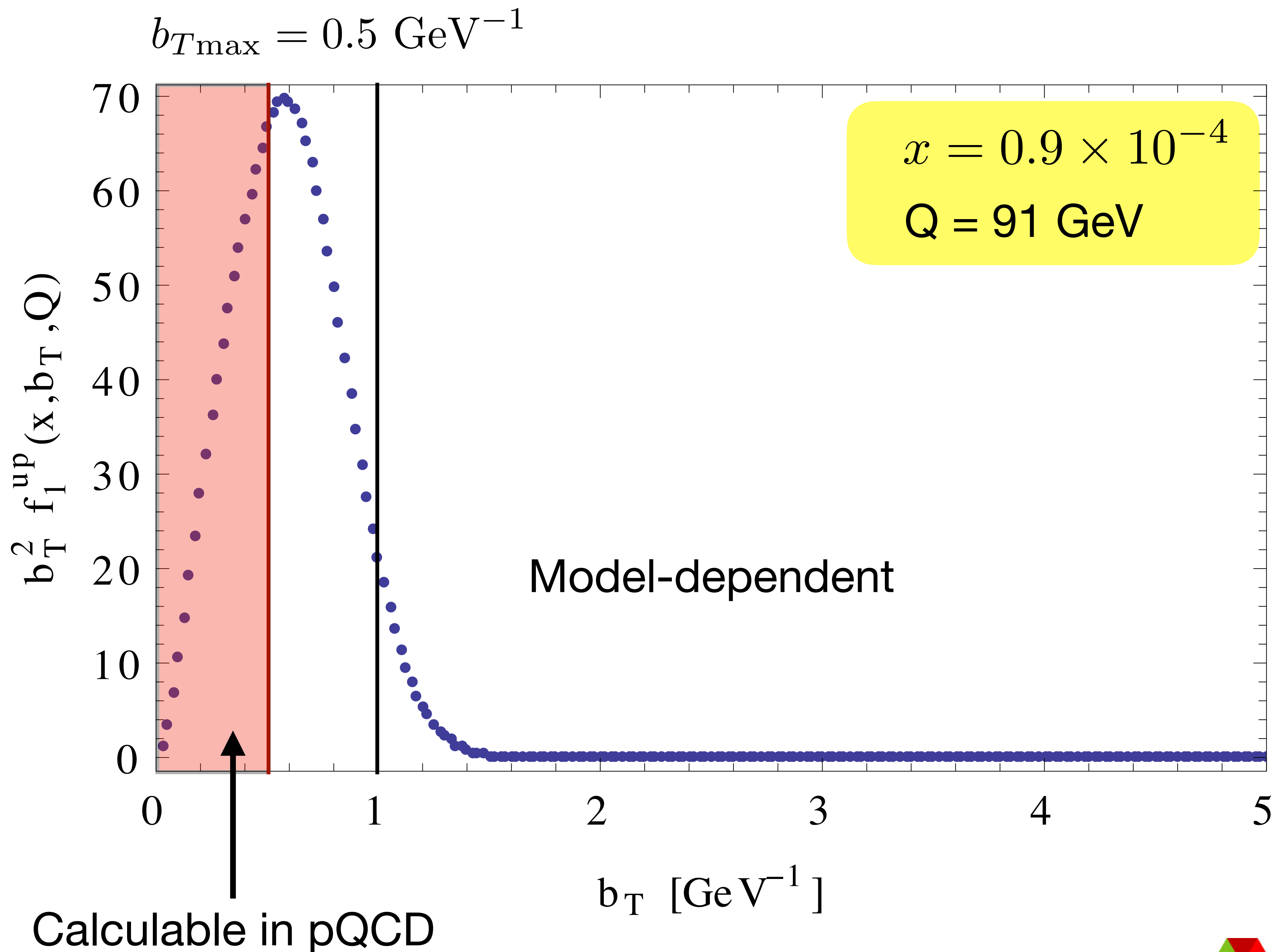

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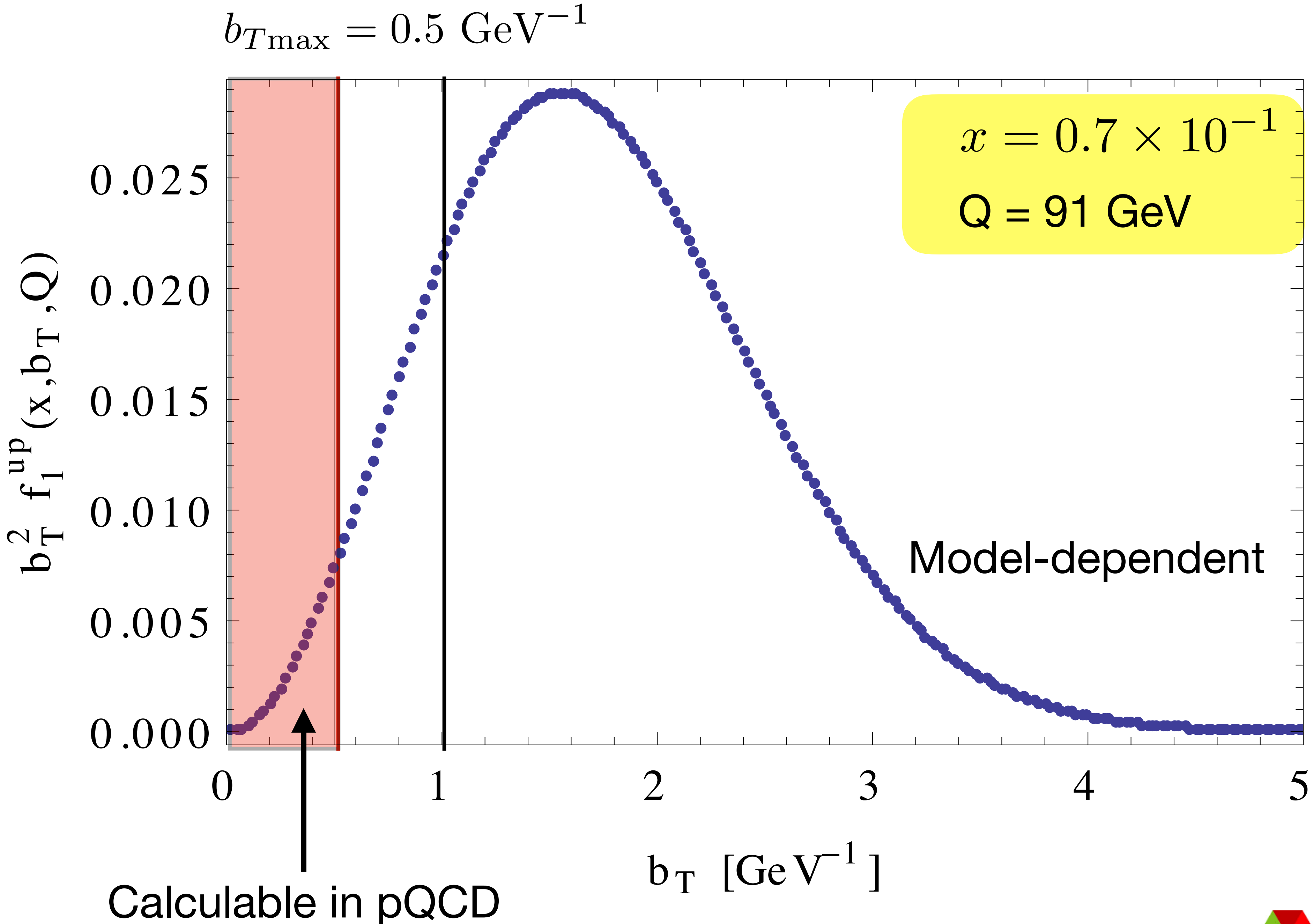

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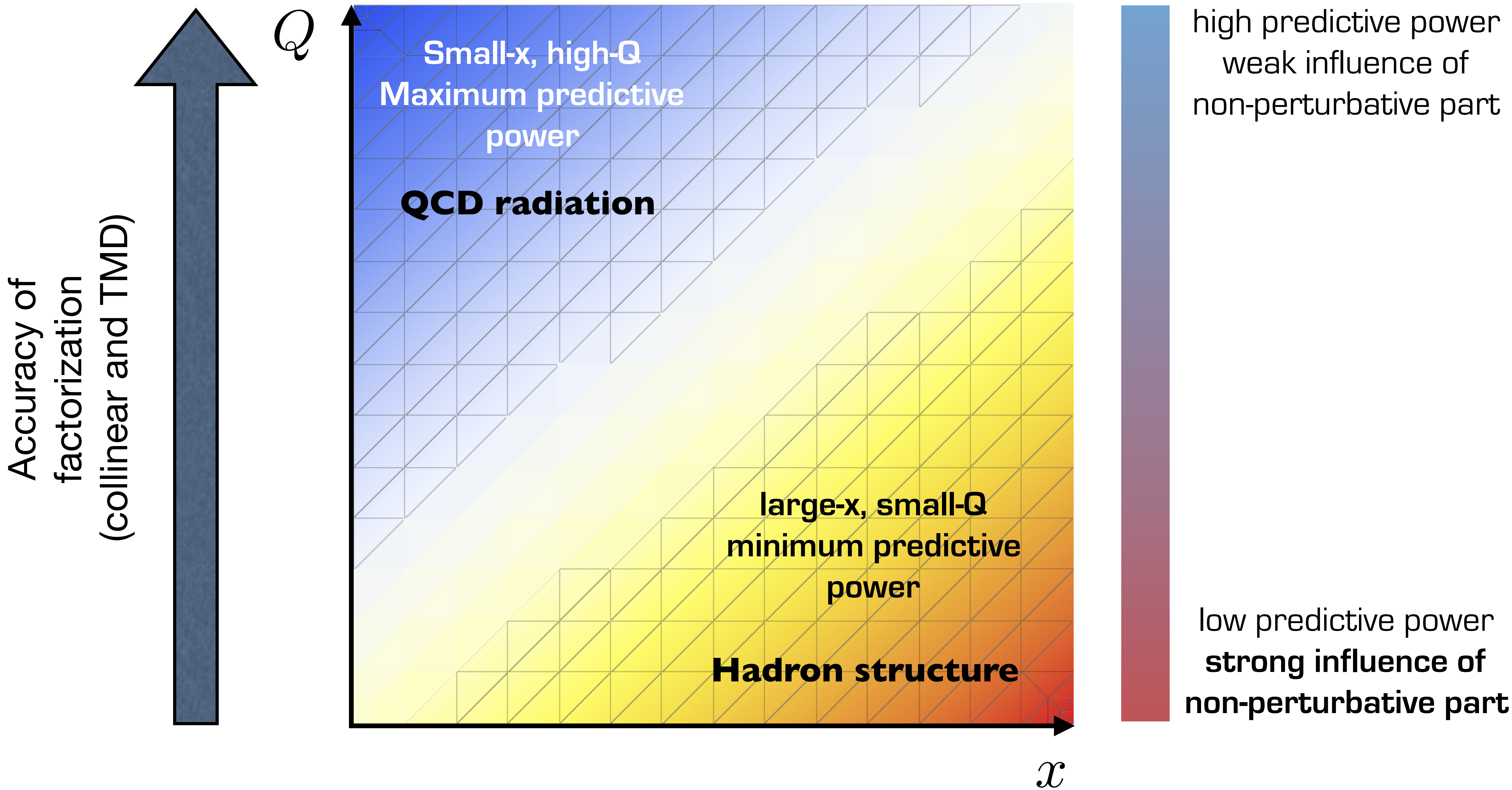
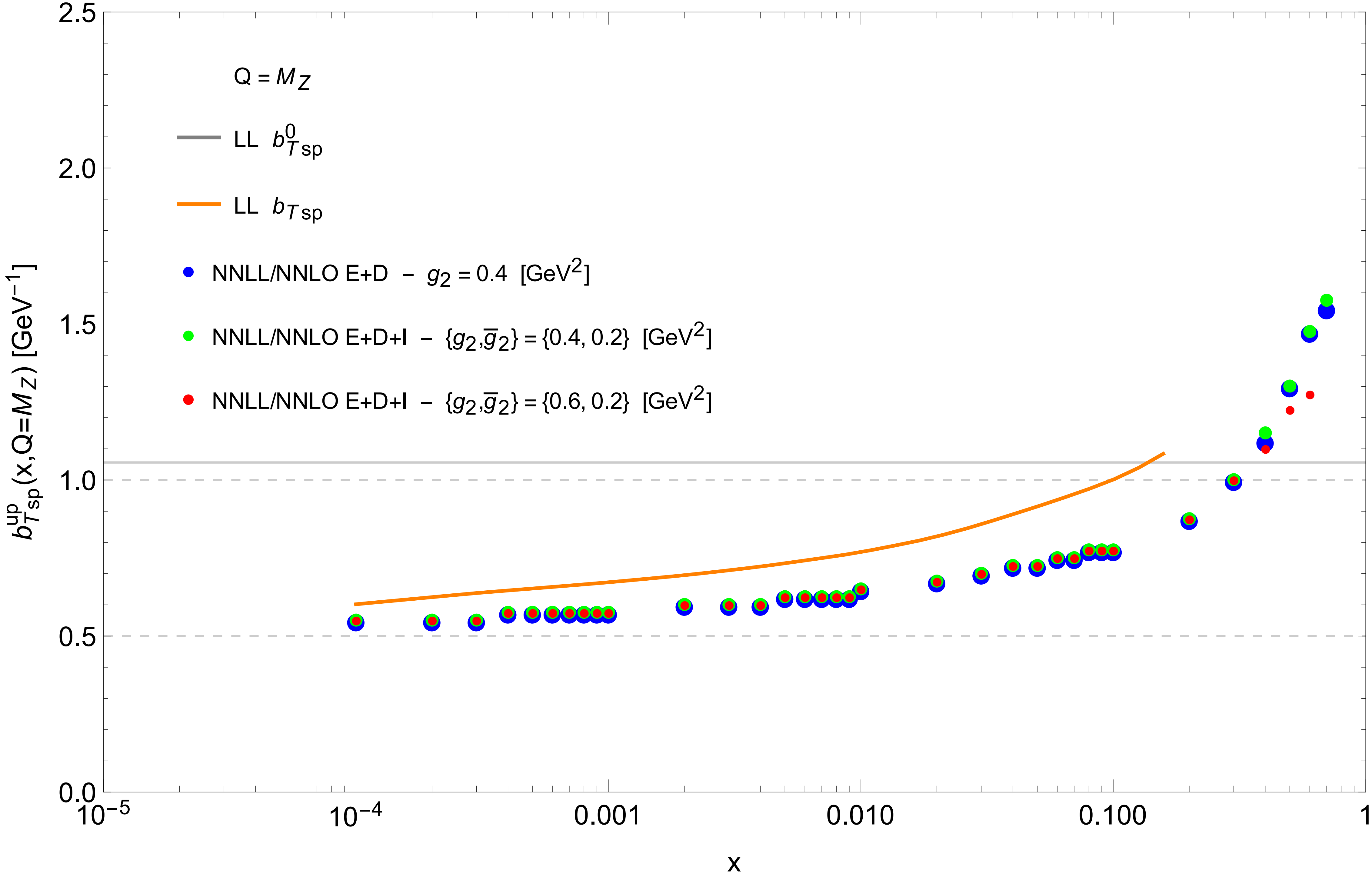
Structure vs radiation



Can we prove this formally? Yes : saddle point approximation

Predictive power

Preliminary



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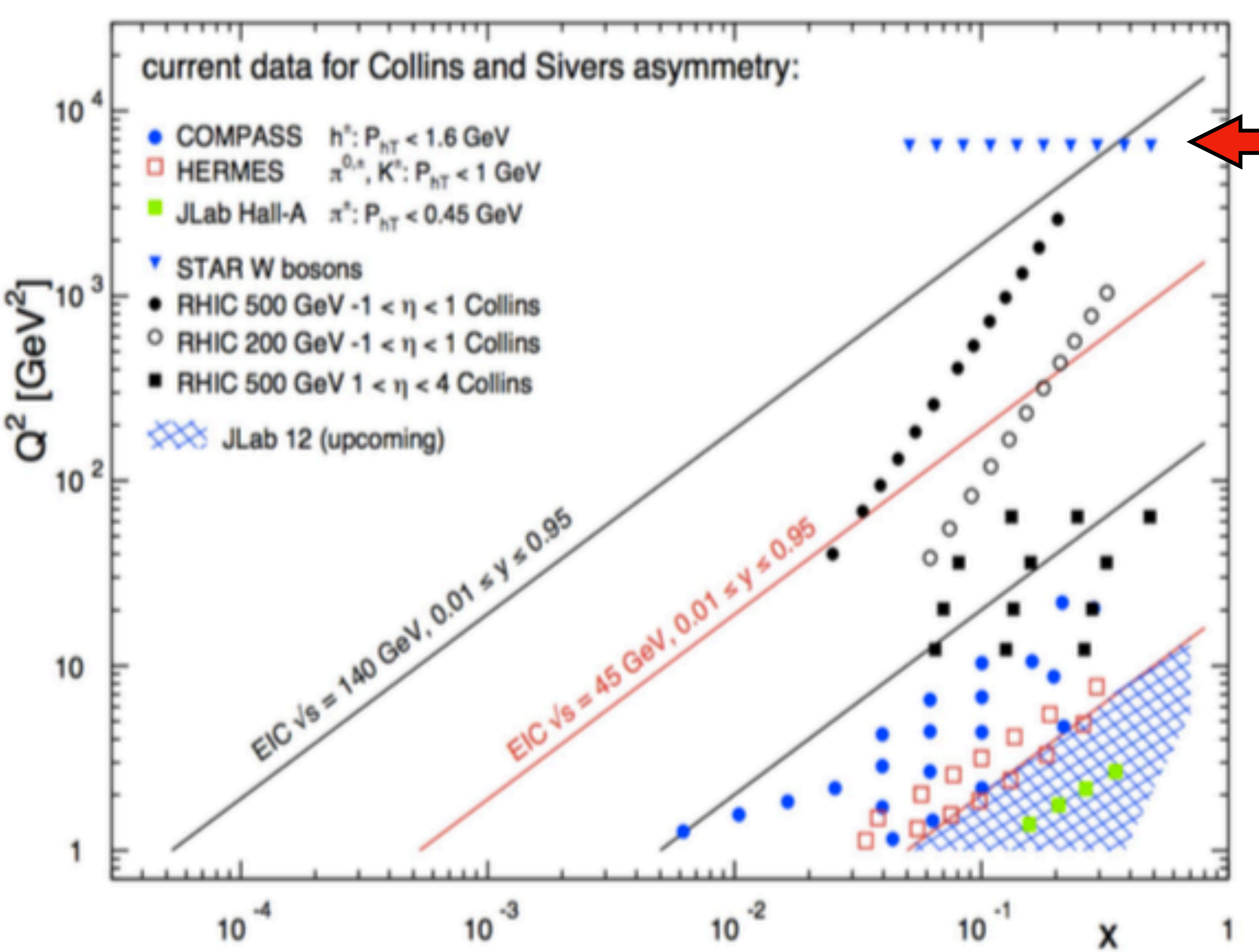
Experimental data



W-boson production at RHIC probes TMDs in the high Q - high x region

High Q : TMD factorization under control

High x : enhanced sensitivity to nonperturbative effects

Interesting combination

Picture from O. Eyser - CIPANP 2018

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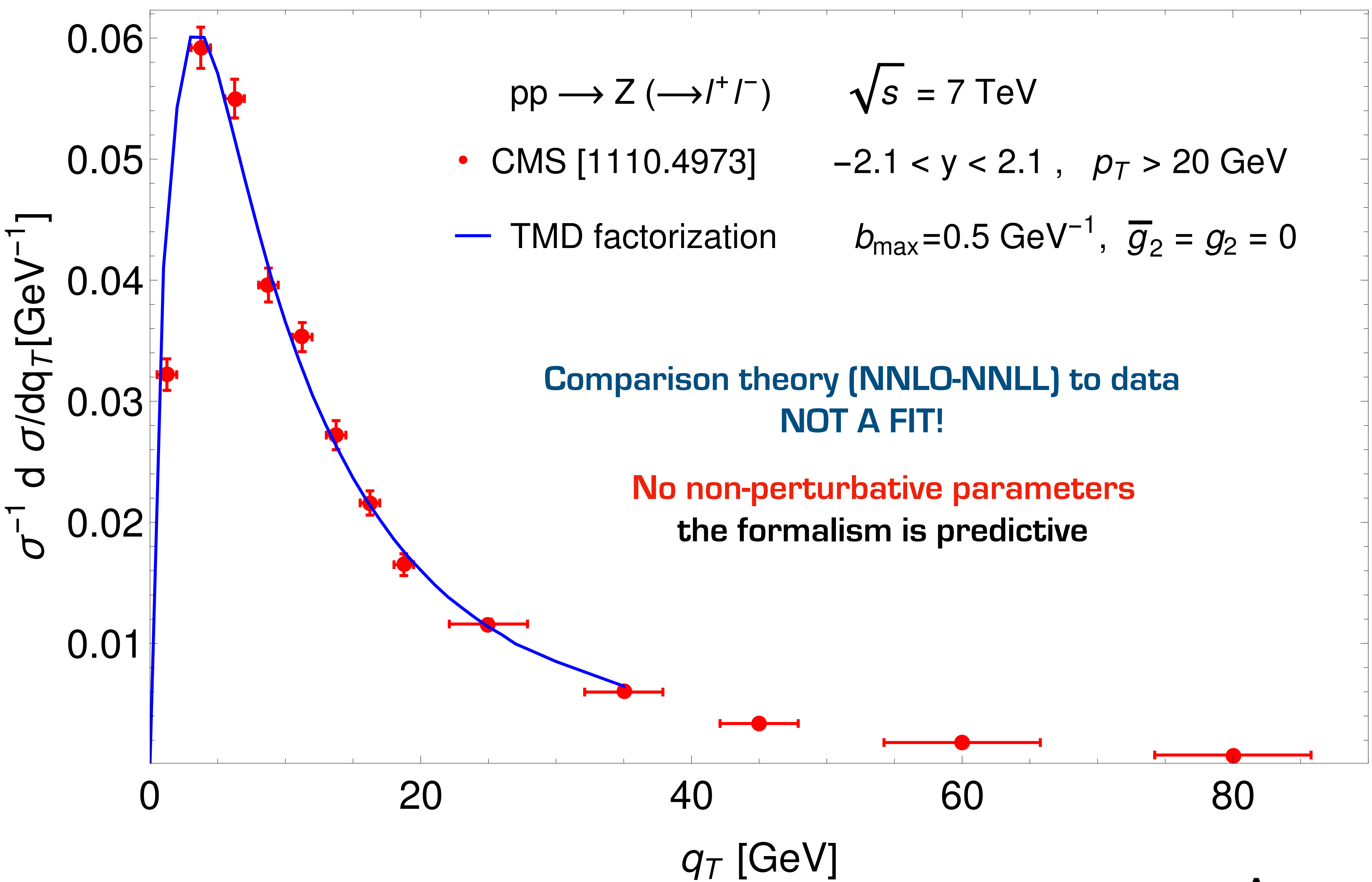
Z production at LHC - CMS

Preliminary



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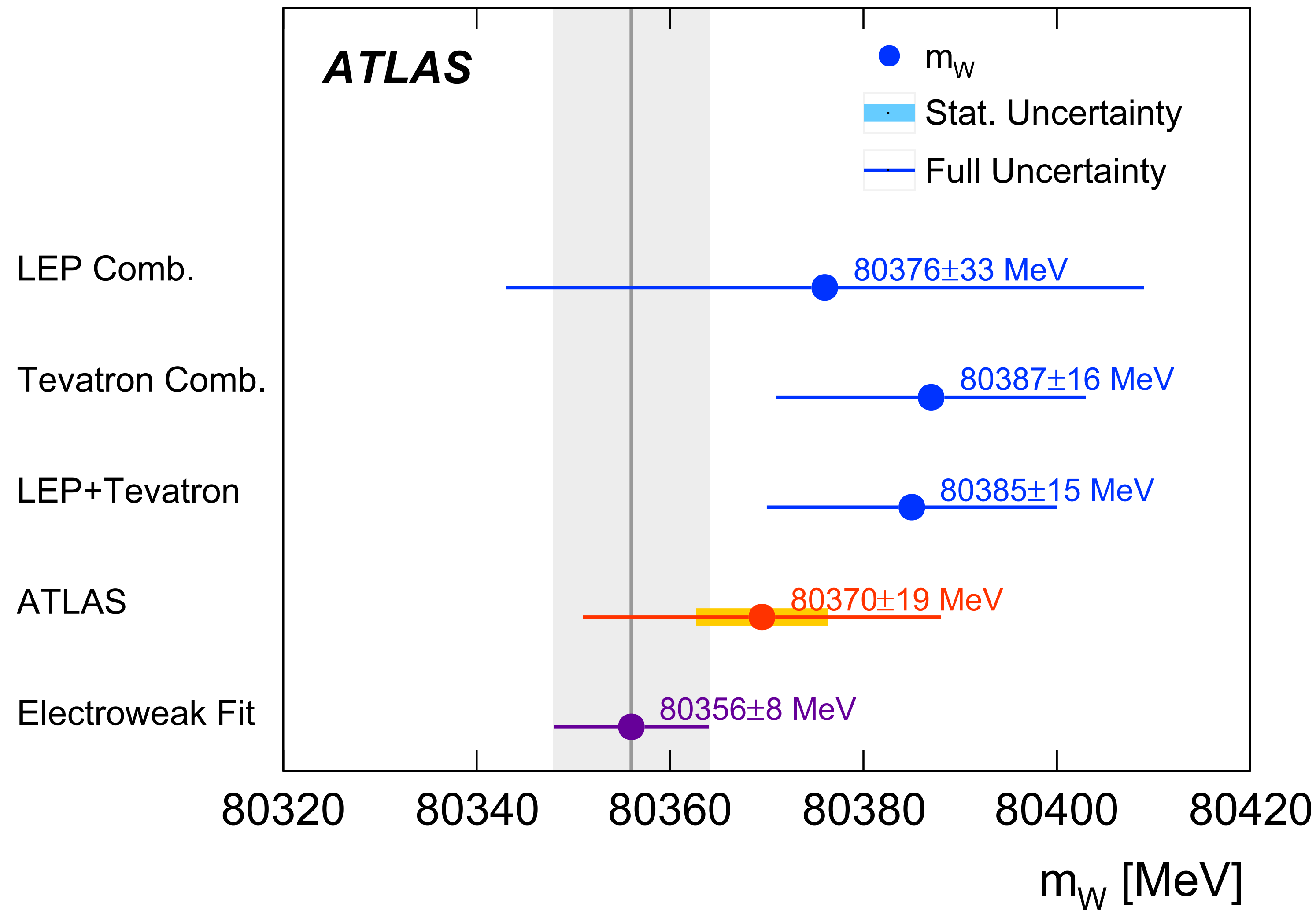
The W mass determination

References :

- Bacchetta, Bozzi, Radici, Ritzmann, **AS**: 1807.02101
- Bozzi, **AS** : 1901.01162
- more work in progress

ATLAS fit

ATLAS Collab. arXiv:1701.07240



$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

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Our findings

The fact that quark intrinsic transverse momentum can be flavor-dependent leads to an additional uncertainty on M_W, not considered so far:

ATLAS - 7 TeV

$$-6 \leq M_{W^+} \leq 9 \text{ MeV}$$

$$-4 \leq M_{W^-} \leq 7 \text{ MeV}$$

- The four-loop QCD corrections generates a shift of -2.2 MeV
- The expectation from missing higher orders is 4 MeV

Eur.Phys.J. C74 (2014) 3046 (“Global EW fit at NNLO”)

Systematic uncertainties @ CDF

CDF Collab. arXiv:1311.0894

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

Uncertainties from q_T modeling determined by fitting to Z data the g2, g3 parameters in the BNLY model in ResBos and $\alpha_S(m_Z)$

Uncertainties from q_T modeling and collinear PDFs are comparable

Systematic uncertainties @ ATLAS

ATLAS Collab. arXiv:1701.07240

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

Pythia tune to Z boson data
7 TeV

assuming no differences in flavor

Systematic uncertainties @ ATLAS

ATLAS Collab. arXiv:1701.07240

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Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

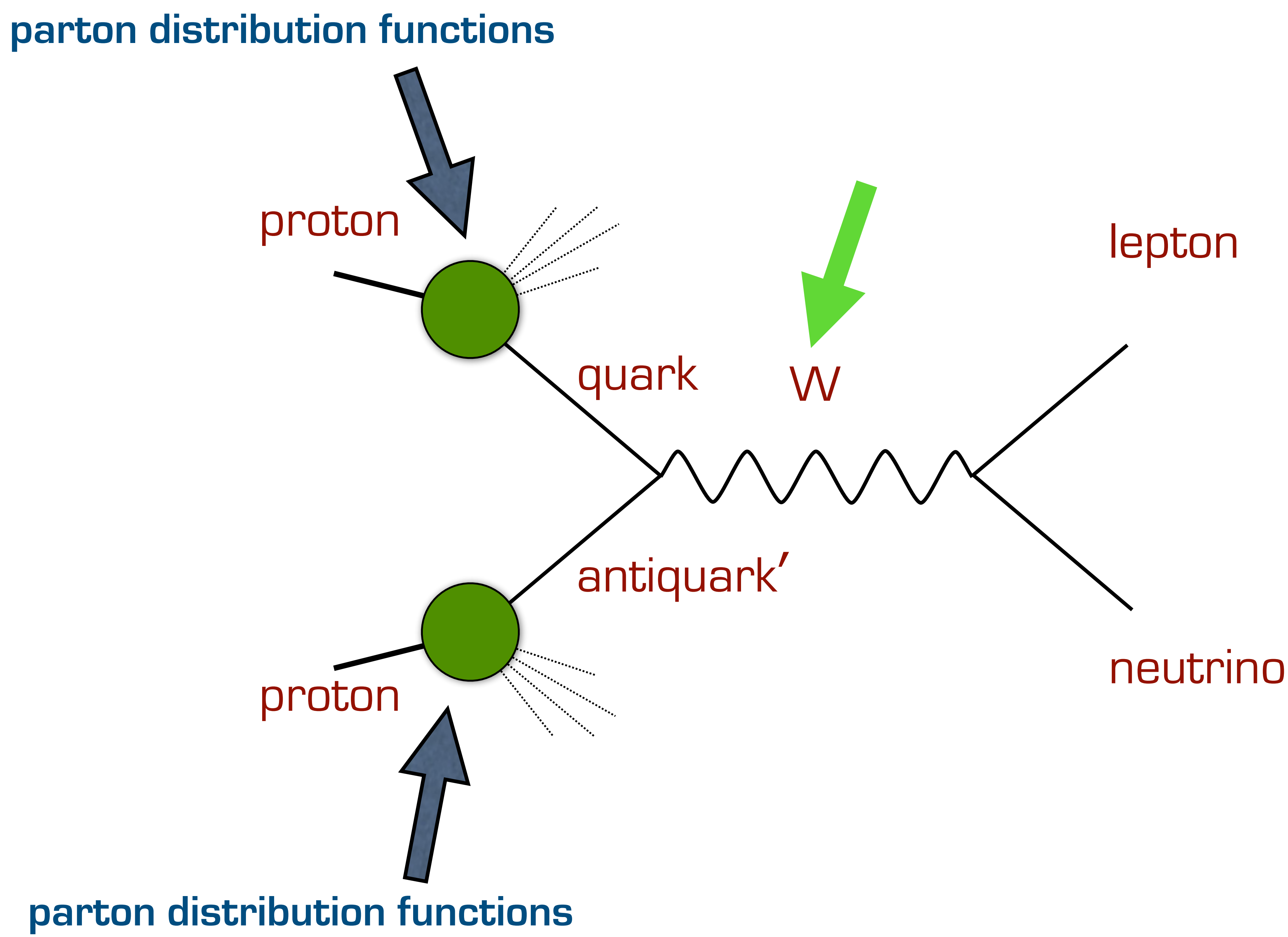
This contribution is determined fitting:

- the intrinsic transverse momentum of partons
- $\alpha_S(m_Z)$
- IR cutoff for ISR

Pythia tune to Z boson data
7 TeV

assuming no differences in flavor

W boson production



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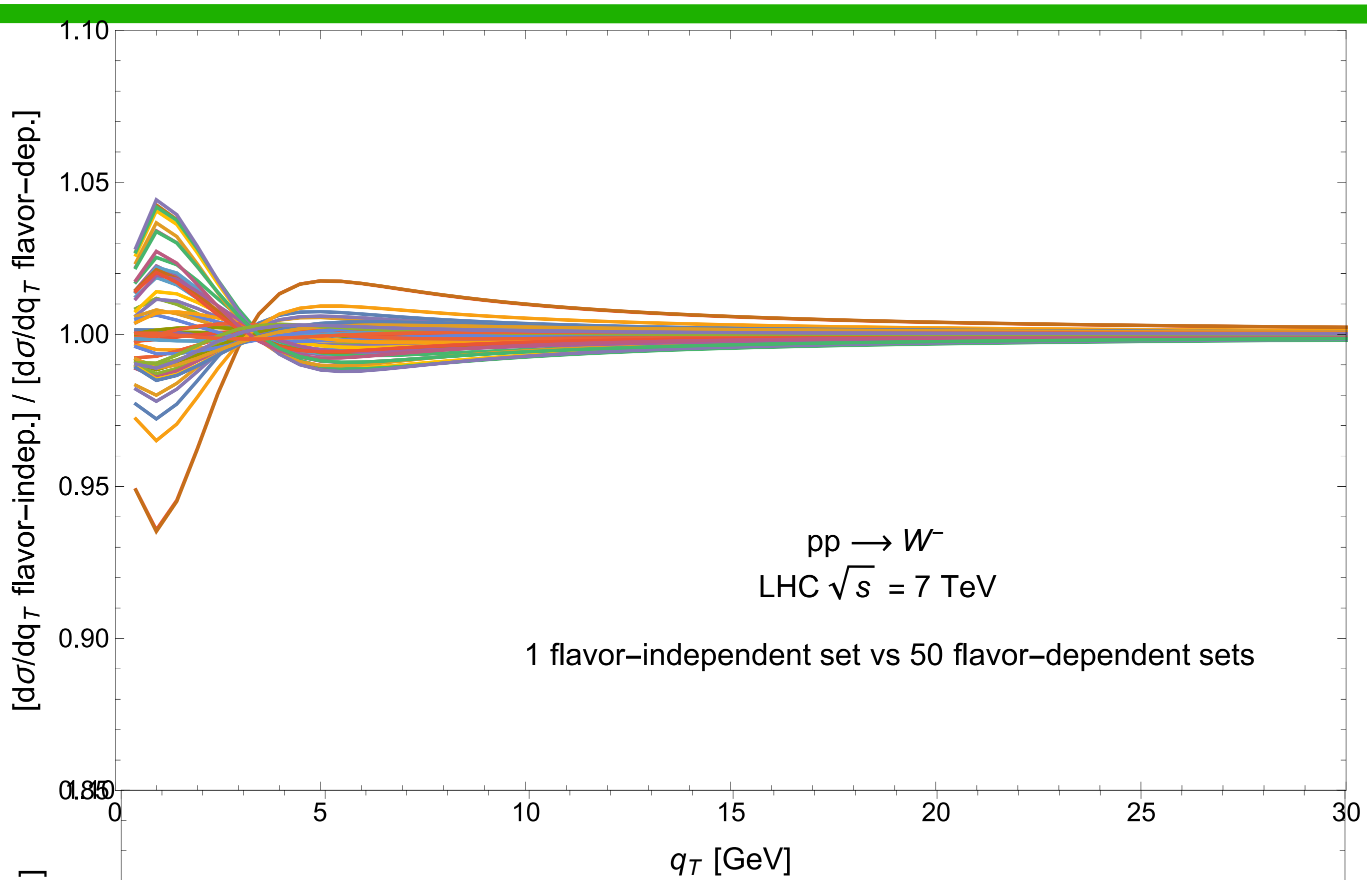
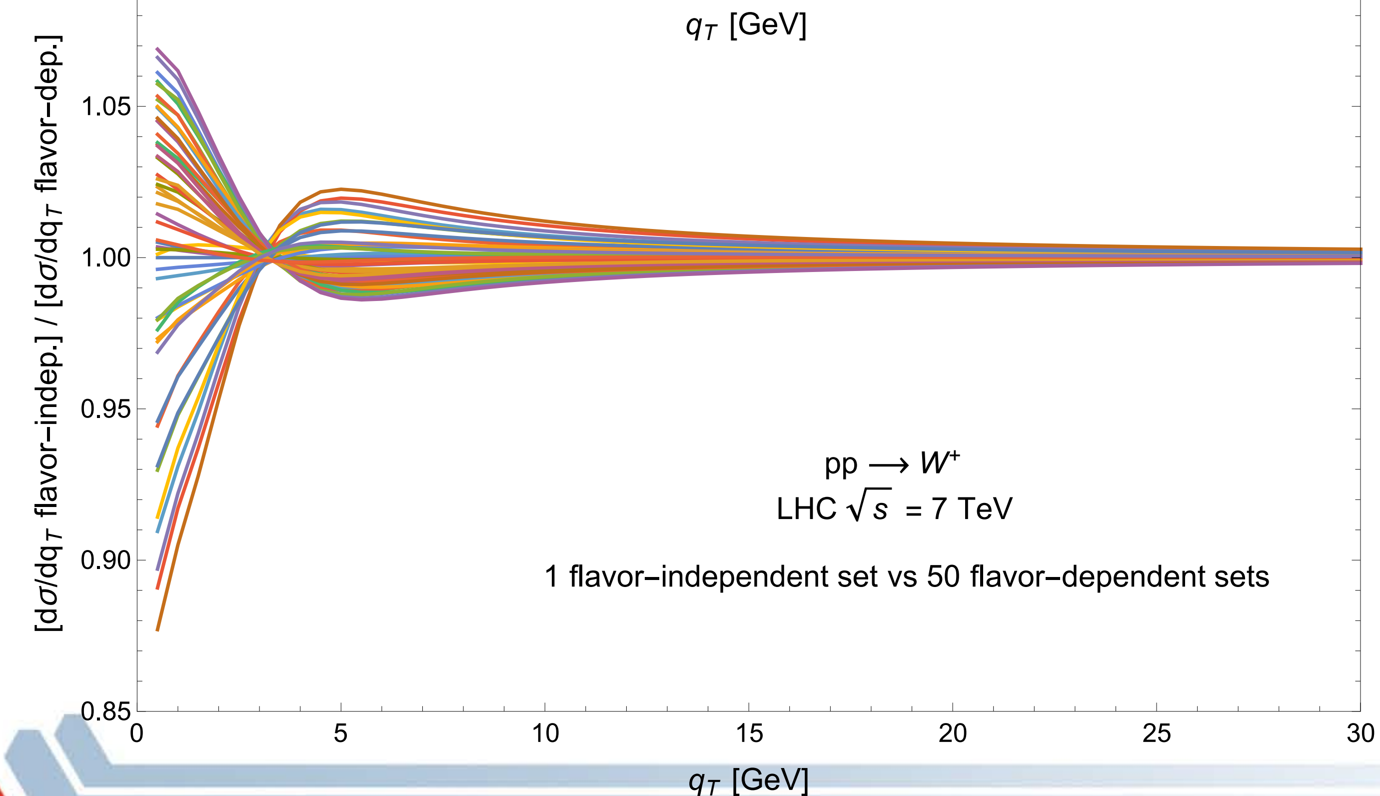
Impact on W q_T spectrum





Flavor-dependent modification of DyqT

The flavor structure of the TMDs can **affect the shape** of the **W qT spectrum** up to 5%-10% at very low qT

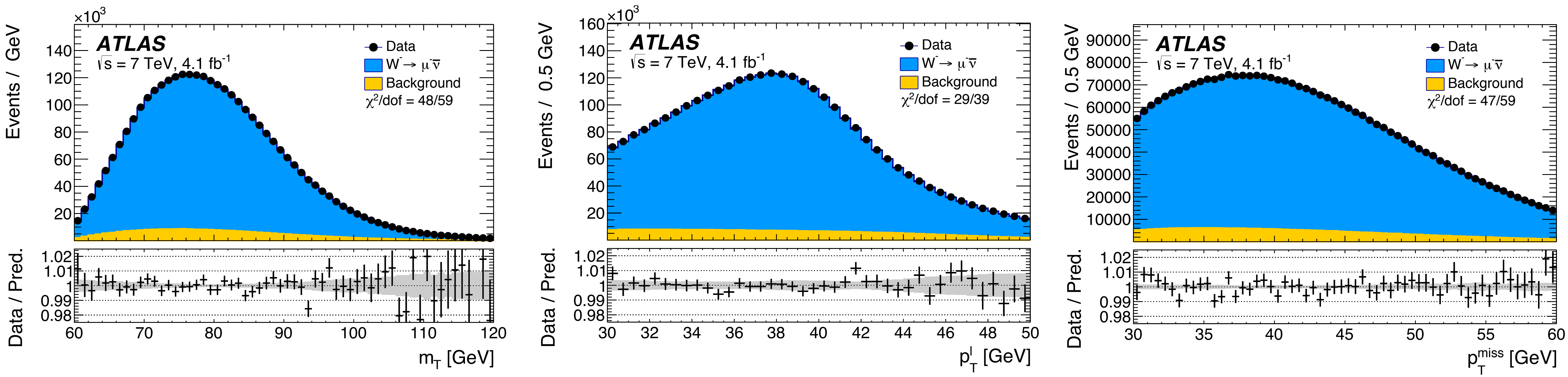
↓

Impact on lepton pT and mT

↓

Impact on mW

How to determine mW



M_W extracted from the study of the shape of m_T, p_{Tl}, p_{Tmiss}

$$M_{\perp}^{W} = \sqrt{2 p_t^l p_t^\nu (1 - \cos(\phi^l - \phi^\nu))},$$

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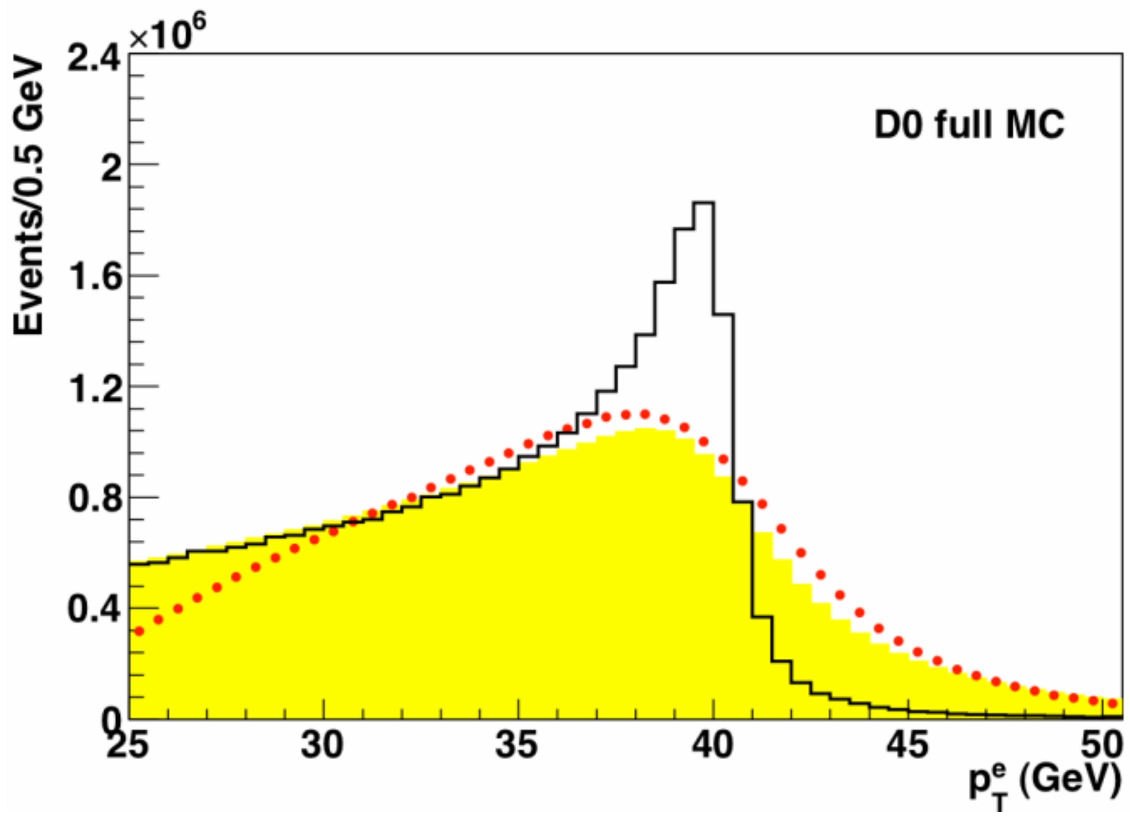
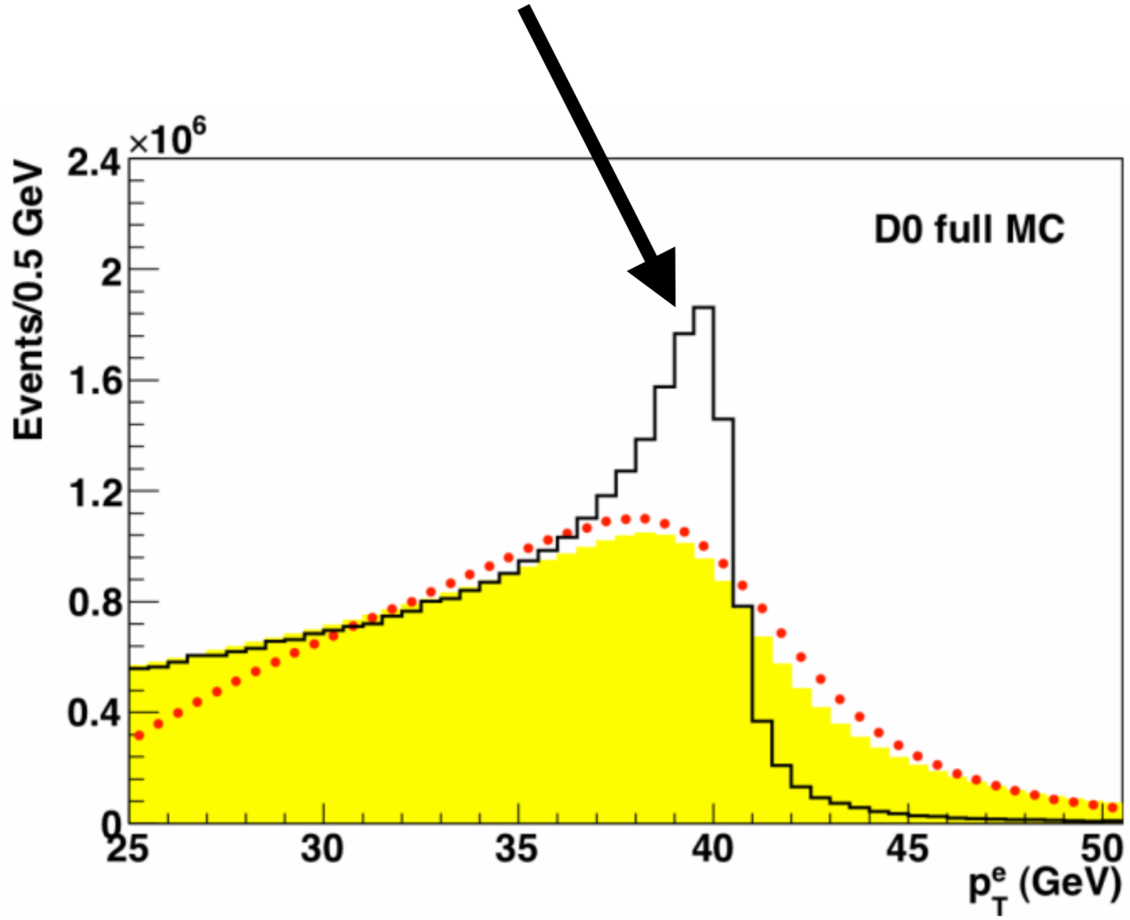
Lepton pT distribution



Lepton pT distribution

If the W were exactly collinear (p_{TW}=0, no TMD effects), the distribution of events would look like this



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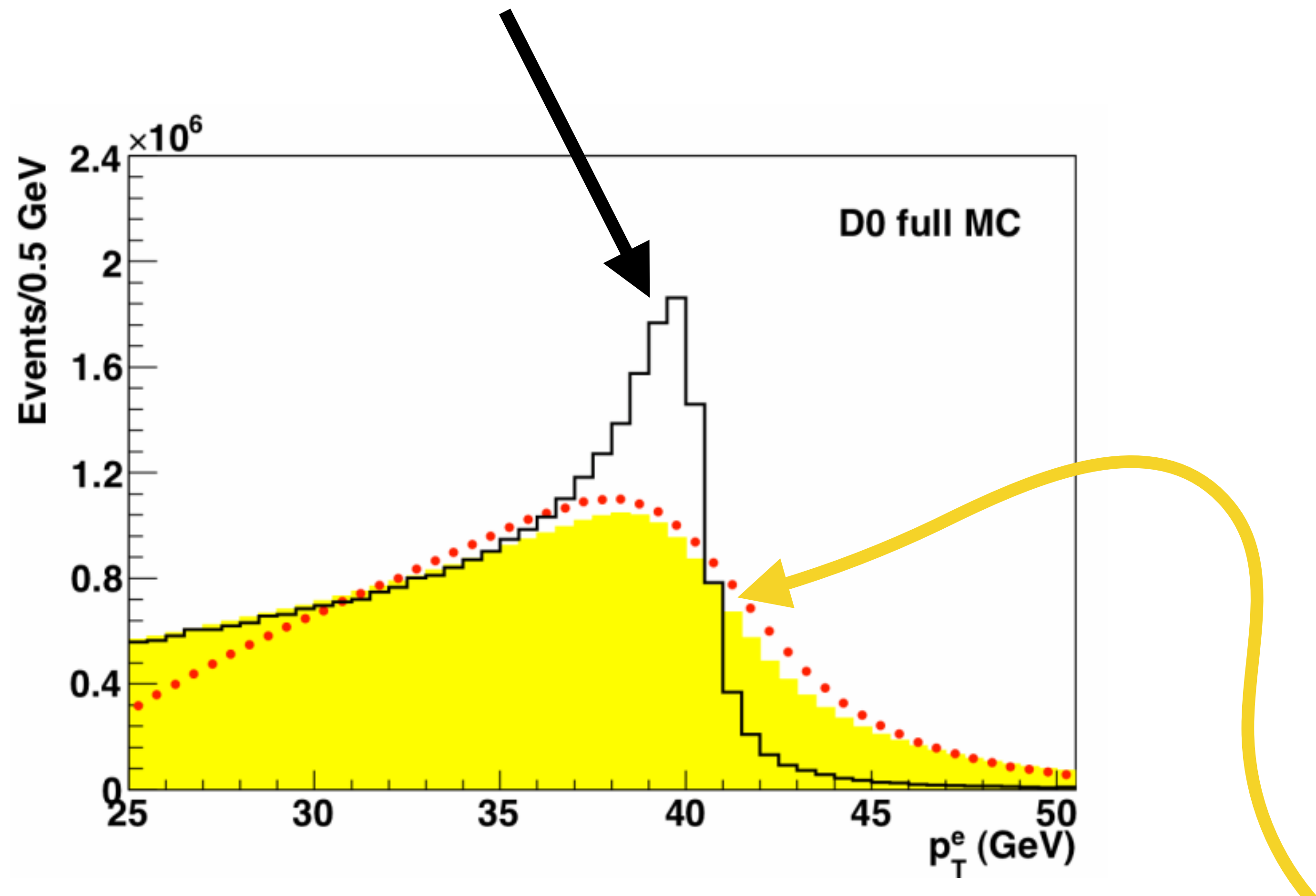

If TMDs are taken into consideration, the distribution gets modified like this

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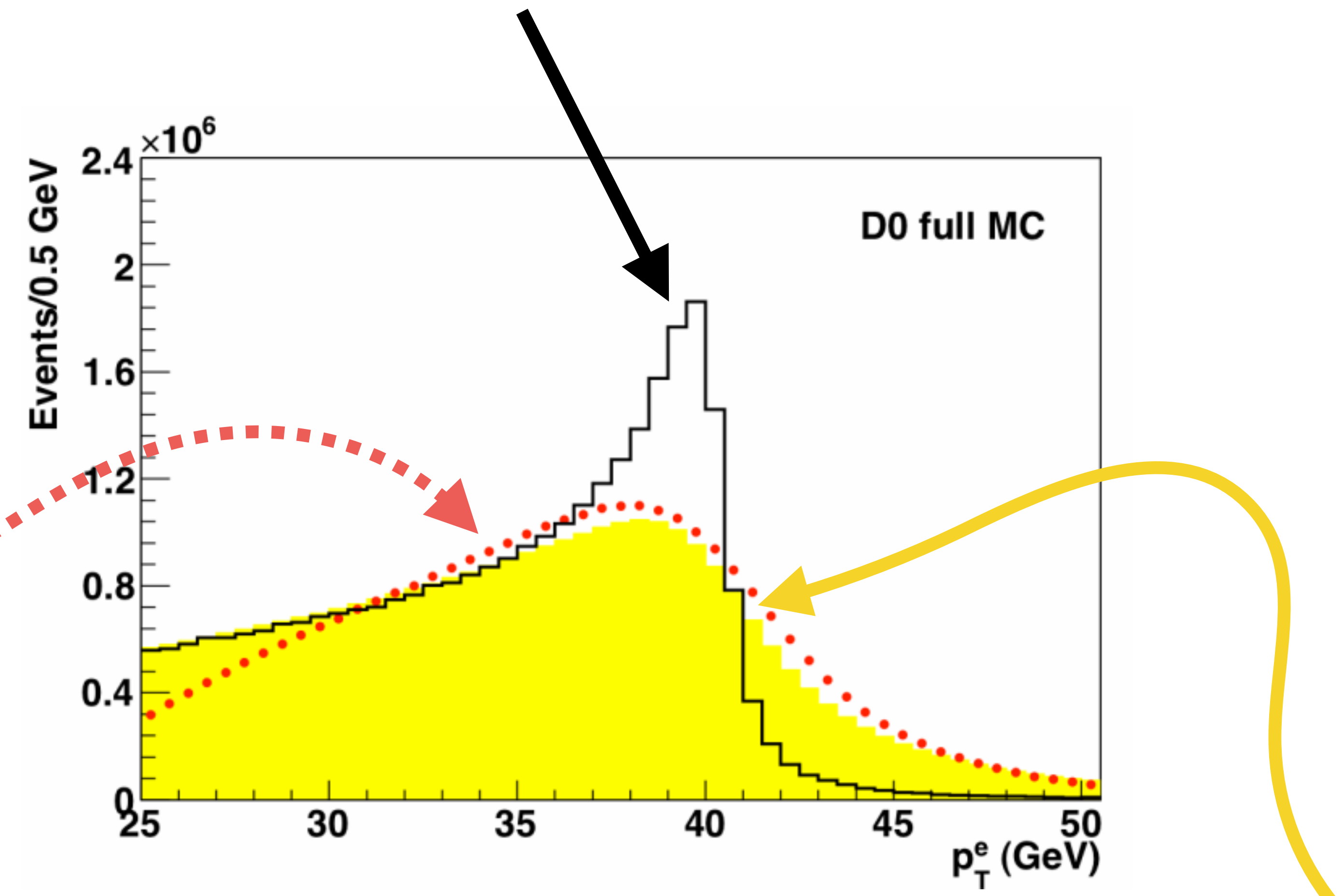
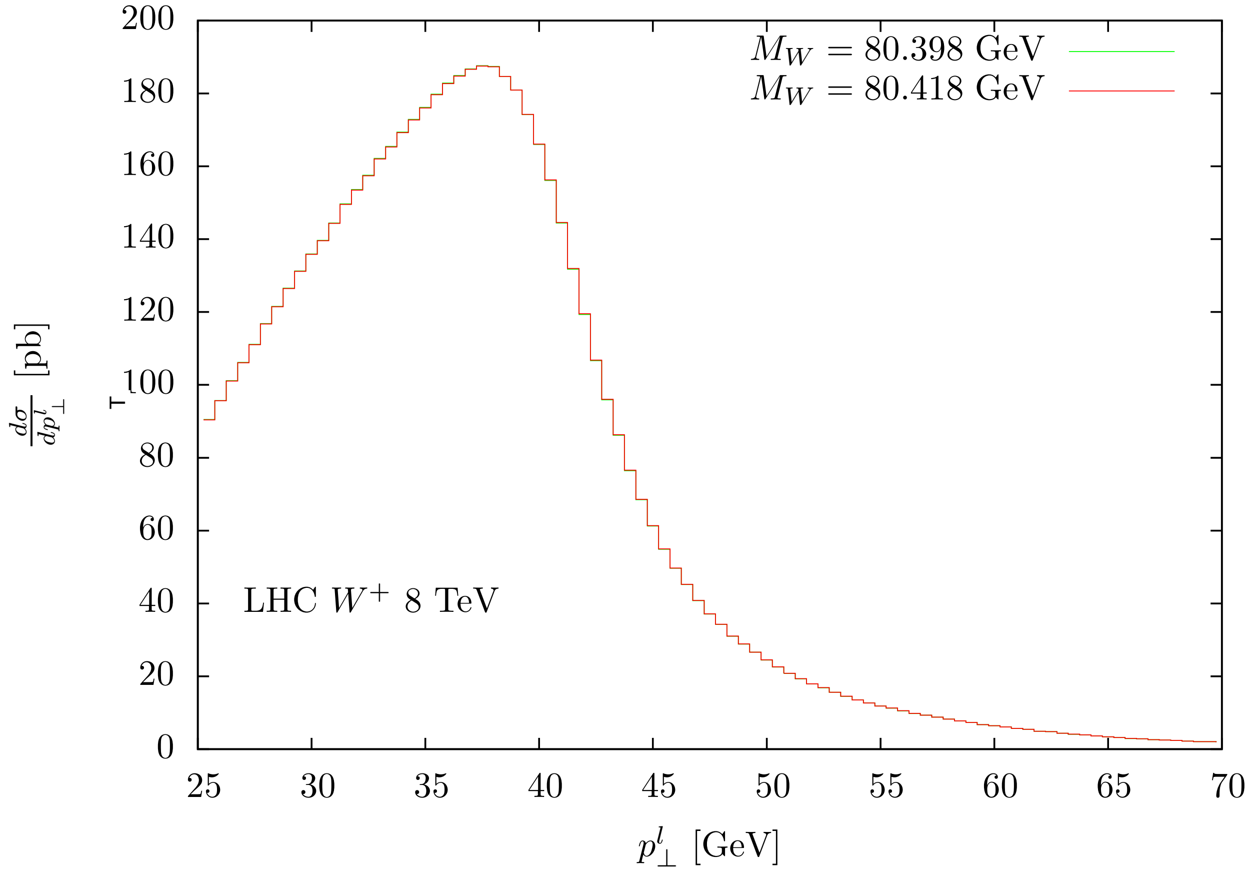


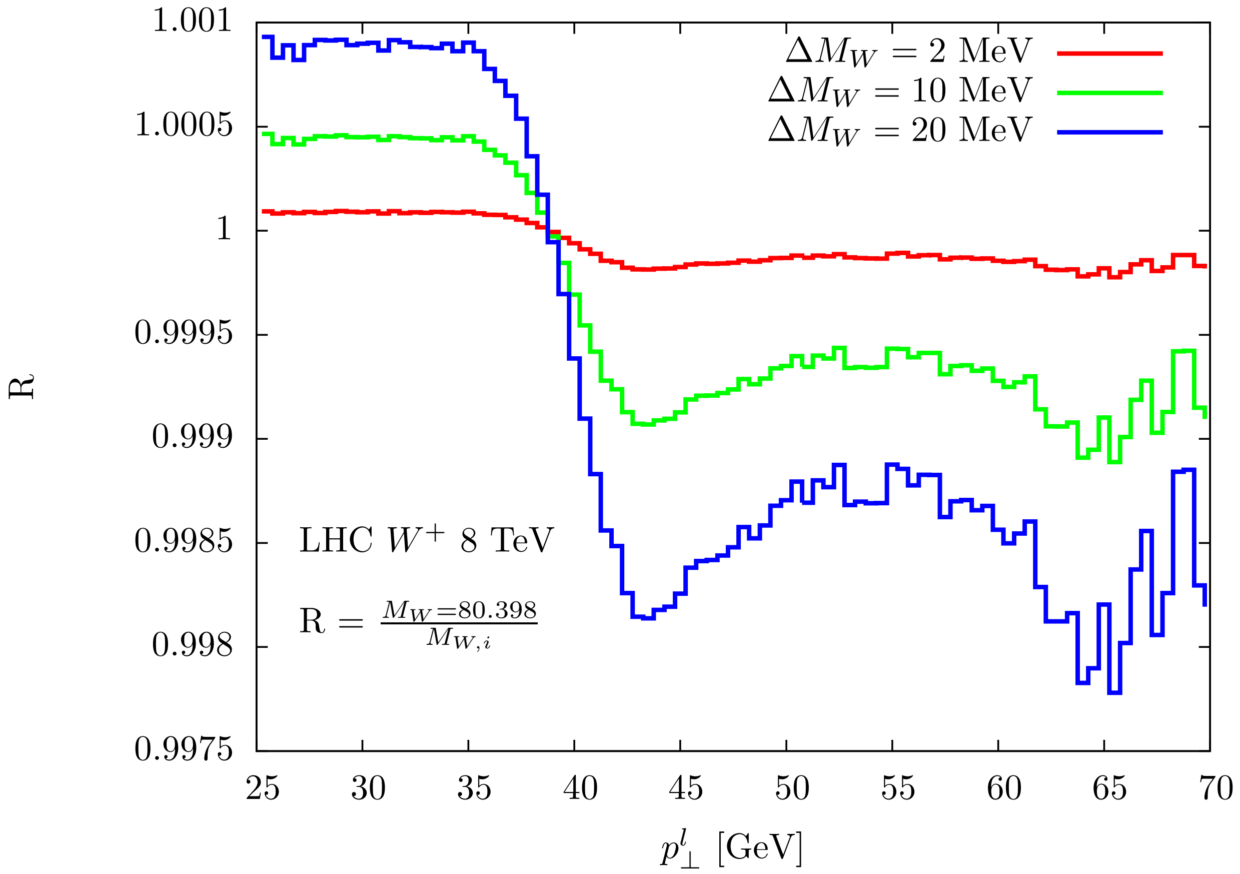
Detector effects cause further changes

If TMDs are taken into consideration, the distribution gets modified like this

Which kind of effect are we after?

see, e.g., Bozzi, Rojo, Vicini, arXiv:1104.2056





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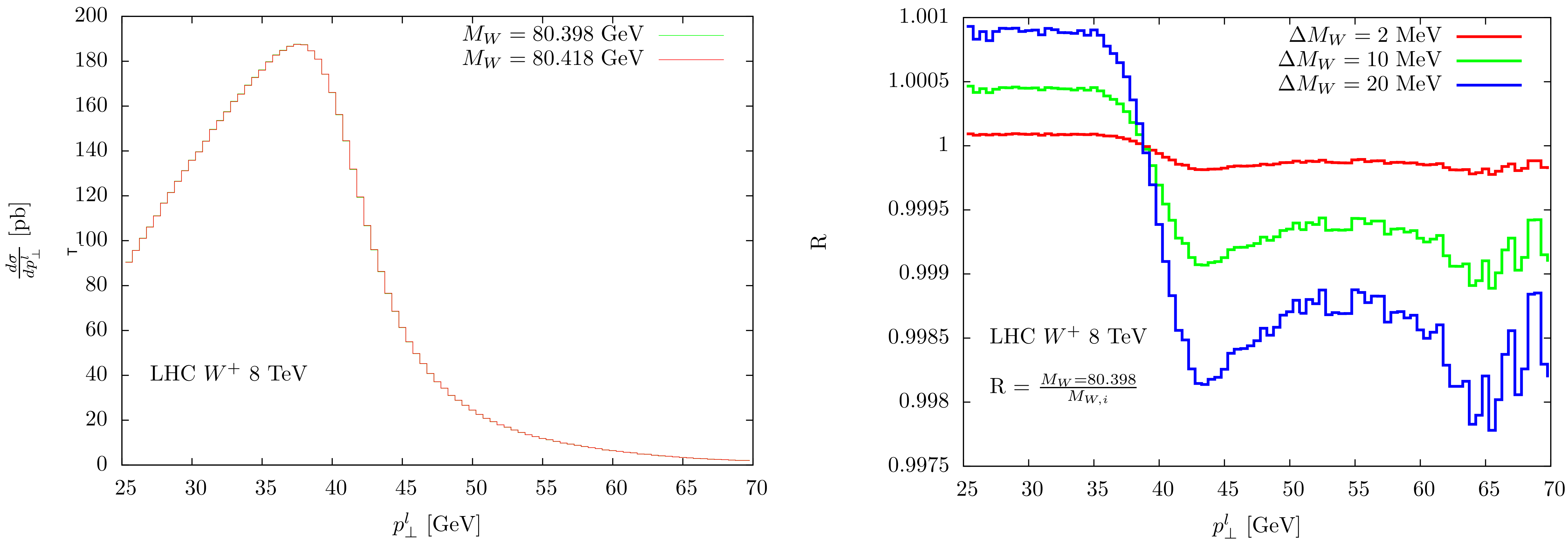

A change of 10 MeV in the W mass induces distortions at the per mille level only: challenging

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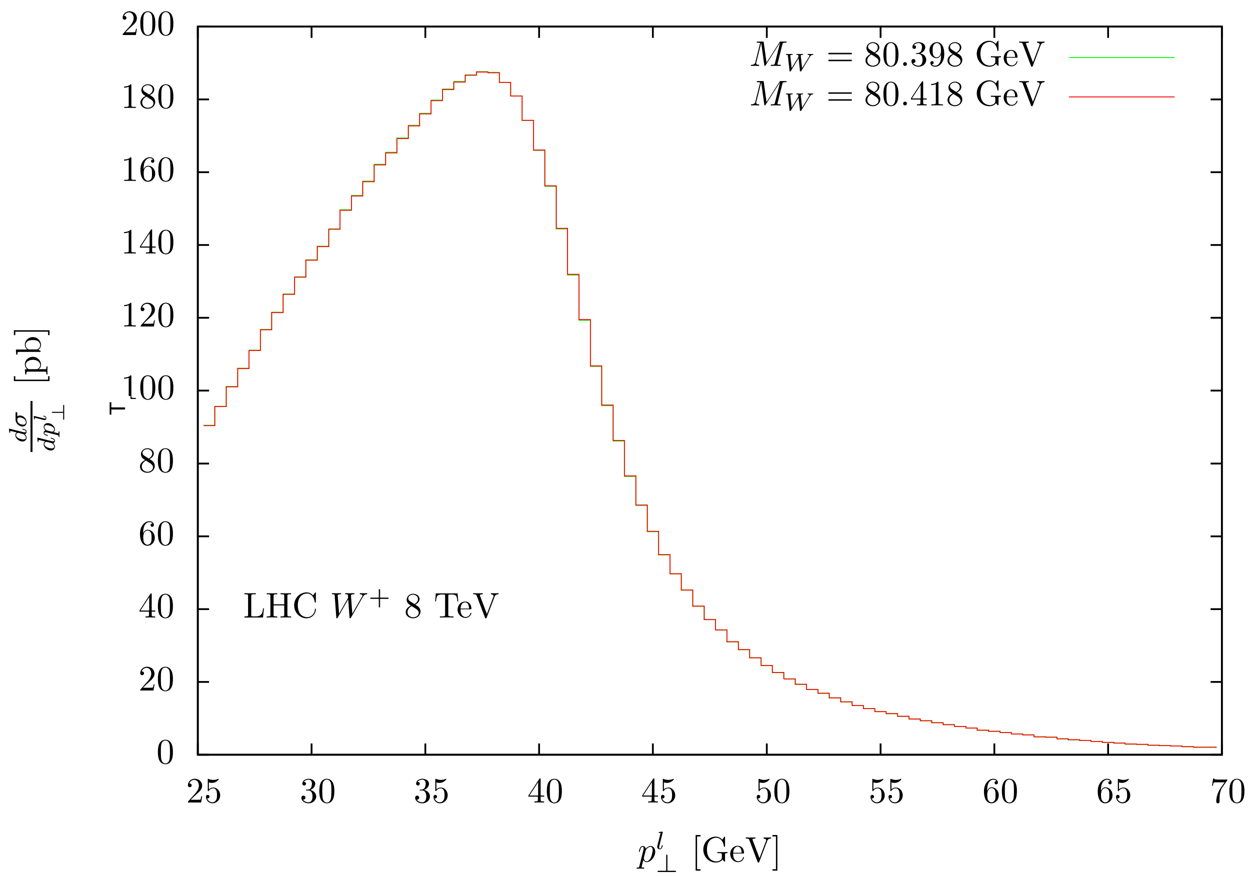

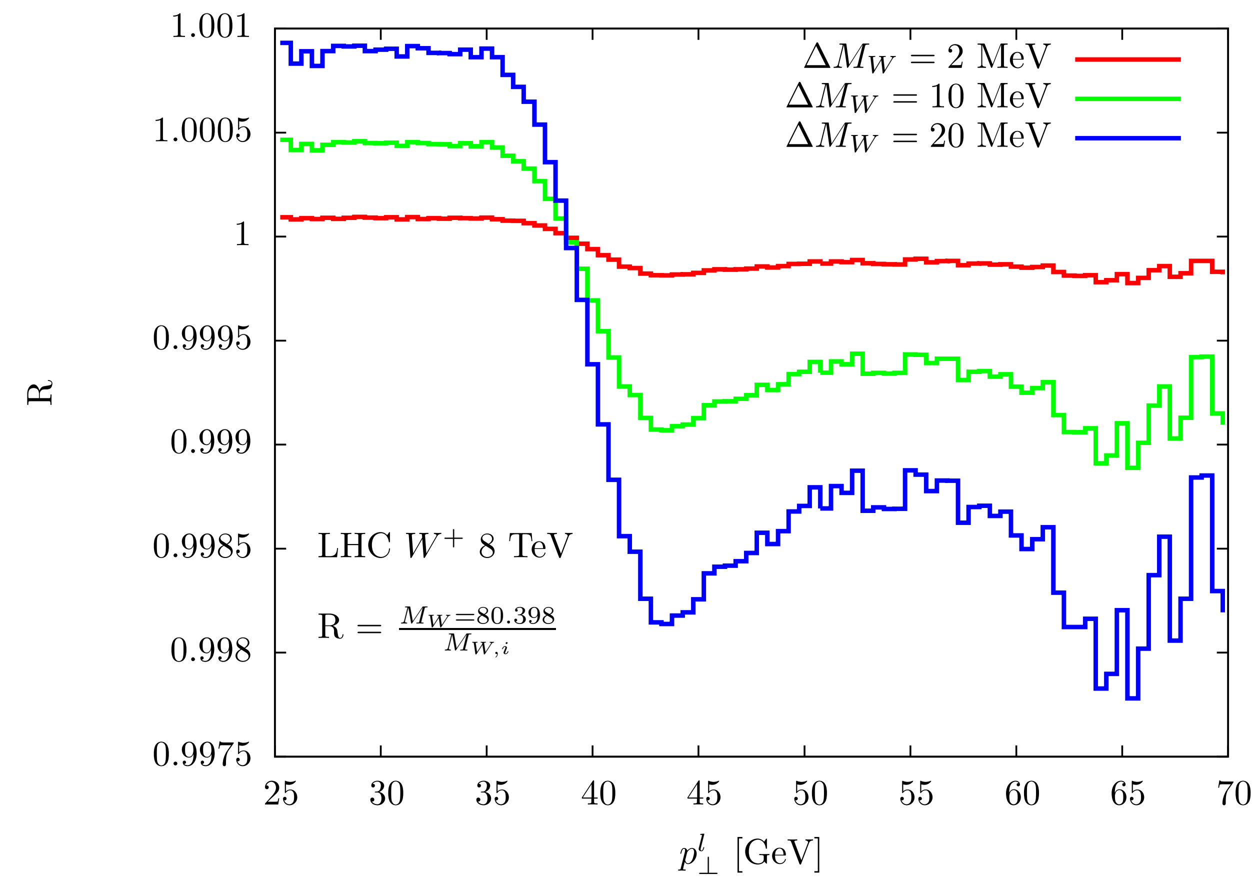

A change of 10 MeV in the W mass induces distortions at the per mille level only: challenging

the key: nonperturbative TMD effects can have an impact at this level of precision

The strategy: template fit

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- Using Monte Carlo generators that include several known corrections, the high-statistics "templates" are produced with different M_W

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- Using Monte Carlo generators that include several known corrections, the high-statistics "templates" are produced with different M_W
- The template that fits data best determines the value of M_W

Estimating uncertainties - coll. PDFs

see, e.g., Bozzi, Rojo, Vicini, arXiv:1104.2056

Estimating uncertainties - coll. PDFs

- The Monte Carlo generator is used to produce **pseudodata** with fixed M_W, but with some other differences (e.g., changing the **PDF set**)

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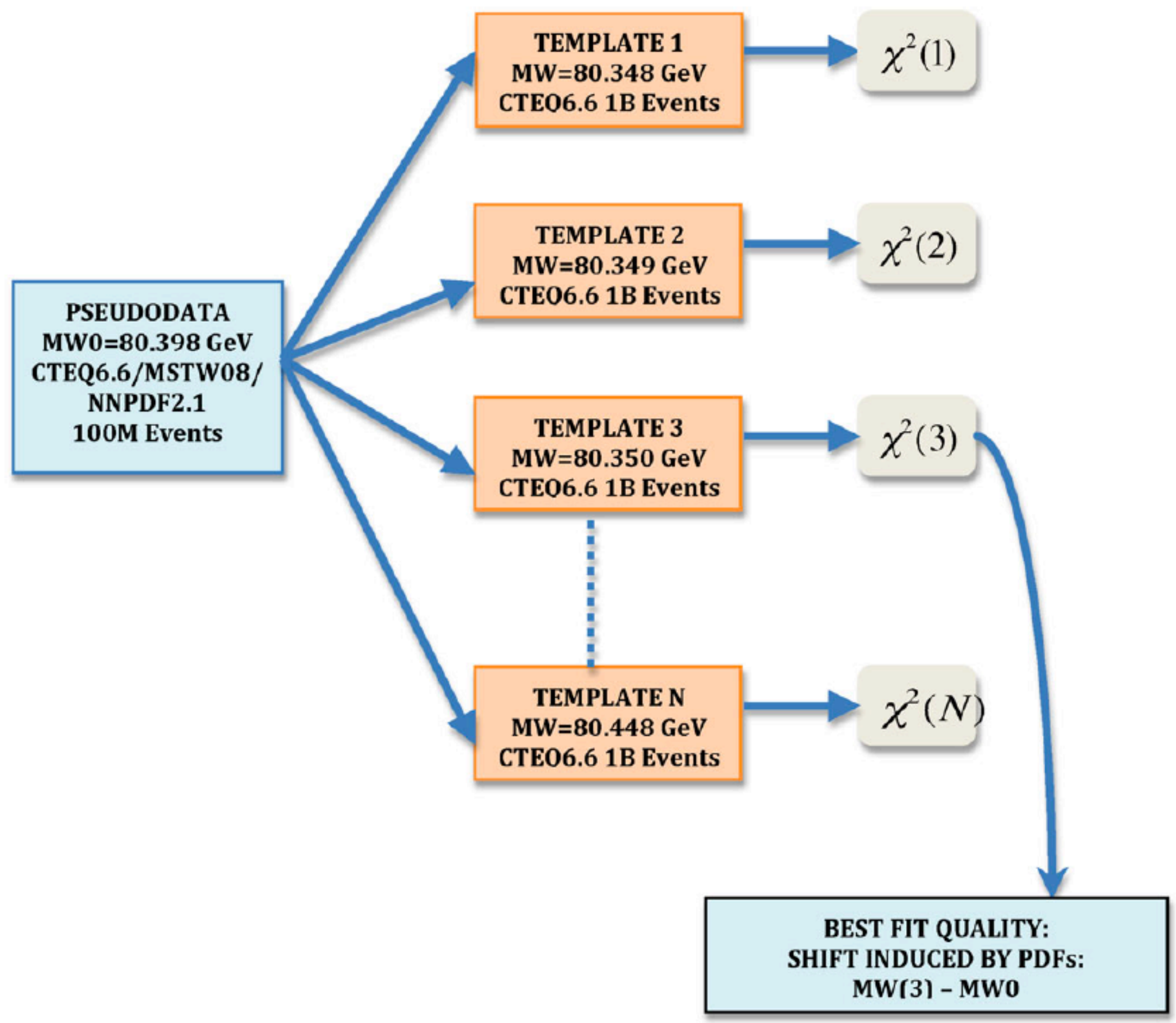

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Event generation

$$f_1^a(x, b_T^2, \mu_i, \zeta_i) = \sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i) \; F_{NP}^a(x, b_T; \{\lambda\})$$

Event generation

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Perturbative parts at order α_S — **NLL**

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Flavor dependent intrinsic transverse momentum F_{NP}

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Matching to collinear factorization at high qT at **$O(\alpha_S)$**

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Perturbative parts at order α_S — **NLL**

Flavor dependent intrinsic transverse momentum F_{NP}

Matching to collinear factorization at high qT at **O(α_S)**

Not using the highest theoretical accuracy available in DYRes :
essentially a matter of computing time

Nonperturbative corrections in TMDs

$$F^a_{NP} \sim e^{-g^a_{NP}\, b_T^2}$$

see, e.g., Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

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$$F^a_{NP} \sim e^{-g^a_{NP}\, b_T^2}$$

$$\exp(-g^a_{NP} b_T^2) \longrightarrow \exp[-[g_{evo} \ln(Q^2/Q_0^2) + g_a]\, b_T^2]$$

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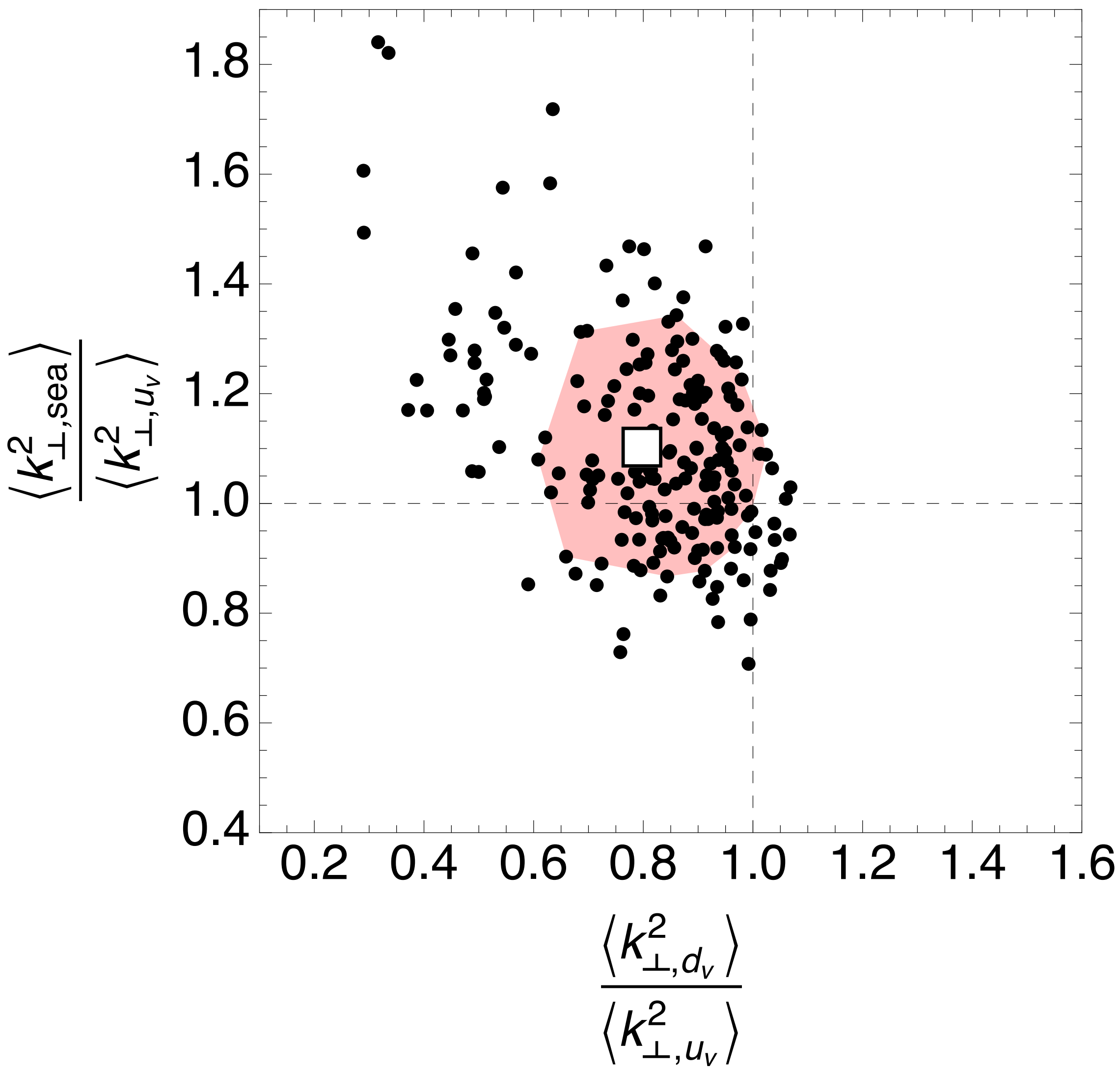
this component can be flavor-dependent

see, e.g., Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

The TMD flavor dependence

Signori, Bacchetta, Radici, Schnell, arXiv: 1309.3507



$$\langle k^2_{\perp,\mathrm{sea}}\rangle > \langle k^2_{\perp,\mathrm{u}_v}\rangle > \langle k^2_{\perp,\mathrm{d}_v}\rangle$$

SIDIS data indicate that there is significant room for flavor dependence.
More flavor-sensitive data needed!

Values for the parameters

Values for the parameters

We considered initially:

- **50 flavour-dependent sets** $\{g_{NP}^{u_v}, g_{NP}^{d_v}, g_{NP}^{u_s}, g_{NP}^{d_s}, g_{NP}^{s}\}$ with $g_{NP}^{a} \in [0.2, 0.6]\ \mathrm{GeV}^2$
- **1 flavour-independent set** with $g_{NP}^{a} = 0.4\ \mathrm{GeV}^2$

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We selected the sets that give a description of Z boson data equivalent to the flavor-independent set ("**Z-equivalent**")

We then chose a few sets with interesting characteristics

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Values for the parameters

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27
6	0.40	0.52	0.46	0.54	0.21
7	0.22	0.21	0.40	0.46	0.49
8	0.53	0.31	0.59	0.54	0.33
9	0.46	0.46	0.58	0.40	0.28

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narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
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Templates vs pseudodata

TEMPLATES

- high statistics (750M events)
- different values of M_W
  ΔM_W = −15 MeV to +15 MeV
- no flavor-dependent intrinsic transverse momentum

Templates vs pseudodata

TEMPLATES

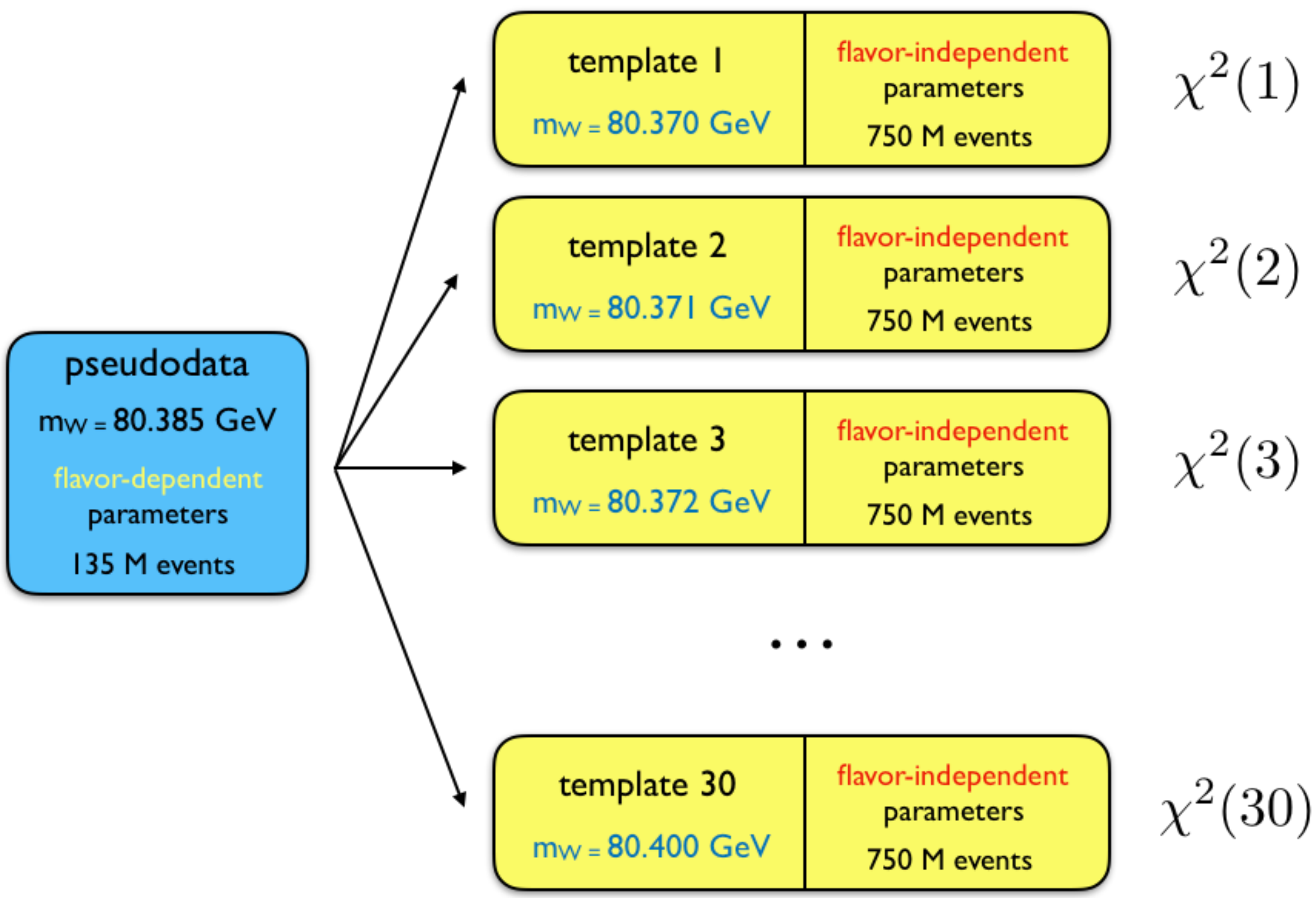
- high statistics (750M events)
- different values of M_W
  $\Delta M_W = -15$ MeV to $+15$ MeV
- no flavor-dependent intrinsic transverse momentum

PSEUDODATA

- "low" statistics (135M events)
- central value
  $M_W = 80.385$ GeV
- flavor-dependent intrinsic transverse momentum

Results

We compute the chi2 between templates and pseudo data, find which template gives the best description, and determine ΔM_W



ATLAS - 7 TeV

	ΔM_{W+}			ΔM_{W-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	0	-1	-2	-2	3	-3
2	0	-6	0	-2	0	-5
3	-1	9	0	-2	-4	-10
4	0	0	-2	-2	-4	-10
5	0	4	1	-1	-3	-6
6	1	0	2	-1	4	-4
7	2	-1	2	-1	0	-8
8	0	2	8	1	7	8
9	0	4	-3	-1	0	7

Statistical uncertainty: ±2.5 MeV

The statistical uncertainty of the template-fit procedure has been estimated by considering statistically equivalent those templates for which $\Delta\chi^2 = \chi^2 - \chi^2_{min} \leq 1$

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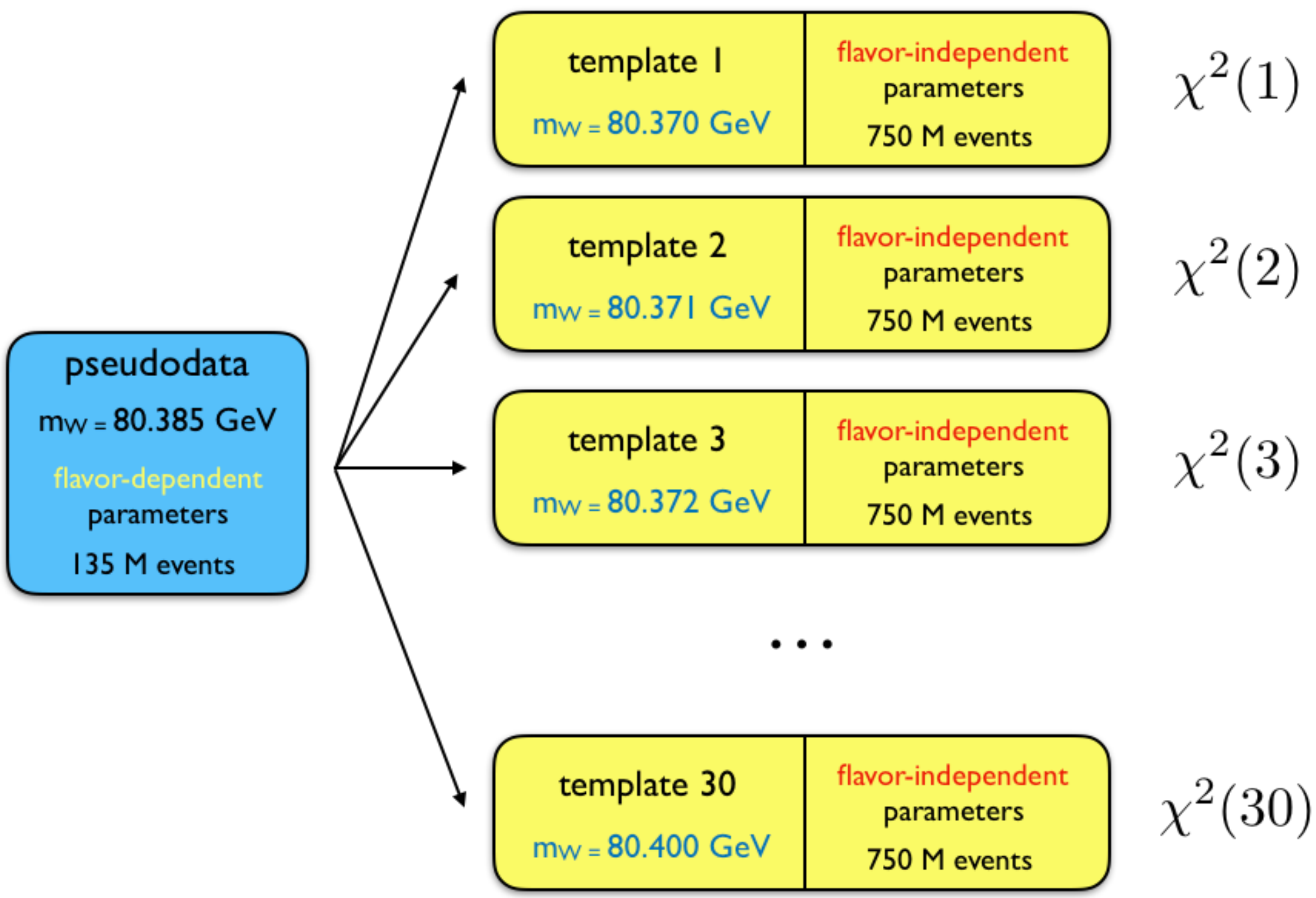

LHCb - 13 TeV

	ΔM_{W+}			ΔM_{W-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	-1	-5	7	-1	-3	8
2	-1	-15	6	0	5	10
3	-1	1	8	-1	-7	5
4	-1	-15	6	0	-4	5
5	-1	-4	6	-1	-7	5
6	-1	-5	7	0	2	9
7	-1	-15	6	-1	-6	5
8	-1	0	8	0	3	10
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W^+ vs W^-

ATLAS finding : $m_{W^+} - m_{W^-} = -29 \pm 28$ MeV.

$m_{W-} > m_{W+}$

ATLAS Collab. arXiv:1701.07240

Part of the discrepancy between the mass of the W+ and the W- can be **artificially induced** by not considering the flavor structure in transverse momentum.

ATLAS - 7 TeV

For example, sets 1 and 2 imply (both ATLAS and LHCb) $\Delta m_{W-} > \Delta m_{W+}$

	ΔM_{W+}			ΔM_{W-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	0	-1	-2	-2	3	-3
2	0	-6	0	-2	0	-5
3	-1	9	0	-2	-4	-10
4	0	0	-2	-2	-4	-10
5	0	4	1	-1	-3	-6
6	1	0	2	-1	4	-4
7	2	-1	2	-1	0	-8
8	0	2	8	1	7	8
9	0	4	-3	-1	0	7

This implies that building templates with sets 1,2, instead of flavor-independent values, the **difference would be reduced**.

Conclusions

The predictive power of TMDs is driven by the kinematics of the process AND by the precision of the observable under consideration.

As for collinear PDFs, also the transverse structure and its flavor-dependence can have an impact on precision studies at high-energies.

It's an example of the **connection** between
hadron structure studies beyond the collinear picture and **HEP**.

The generated mass shifts are **different for W+ and W-** and they are more evident looking at the lepton transverse momentum (rather than the transverse mass)

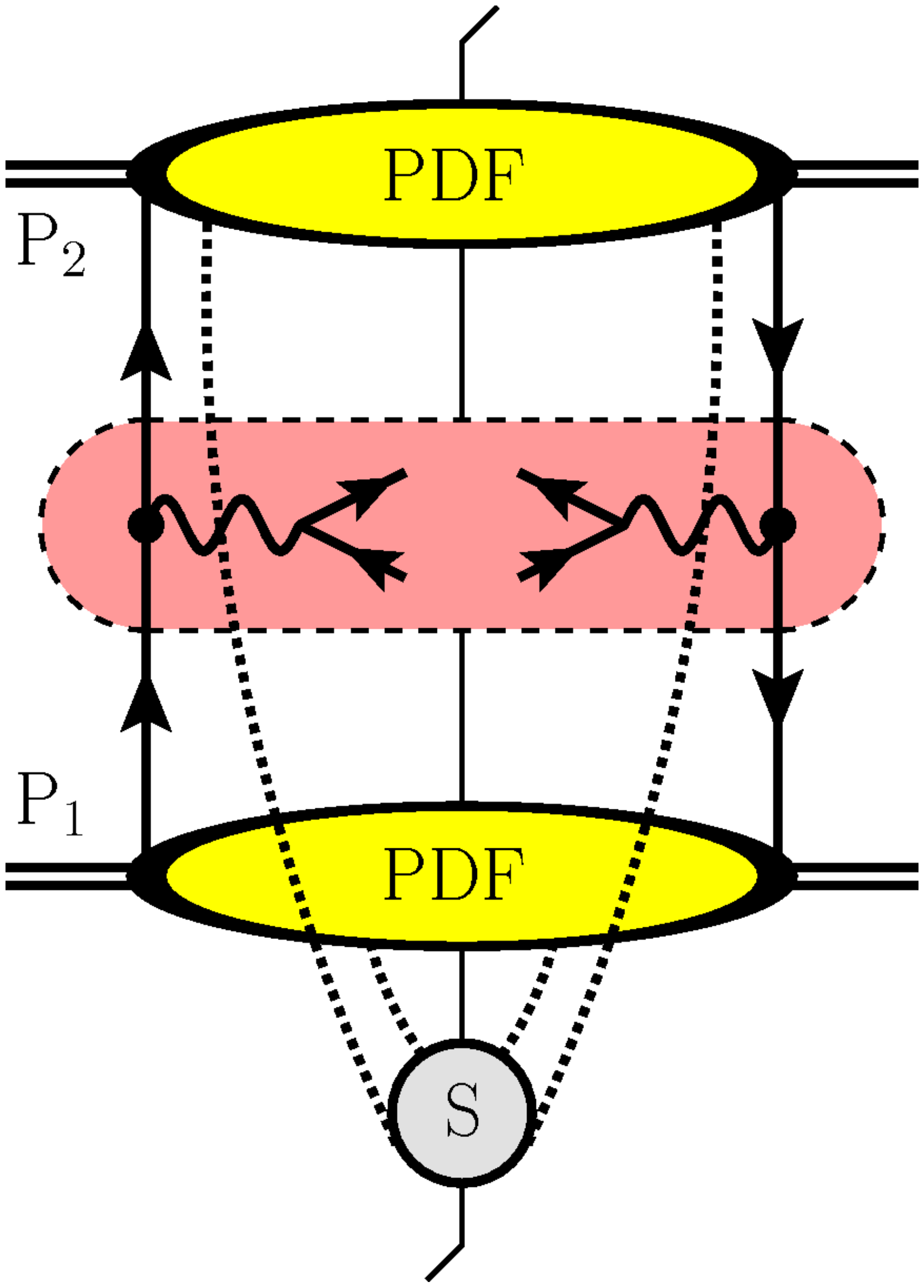
There is a lot of room to improve this exercise:
accuracy, statistics, kinematic regions, model dependence, **other observables**, etc.

We need **more flavor-sensitive data** (e.g. SIDIS) to constrain the flavor-dependence of the unpolarized TMD PDFs (**Electron-Ion Collider**).

Backup

TMD factorization

$p\,p \to \ell\,\bar{\ell}\,X$



credit picture: M. Buffing

In certain processes
the cross section can be **factorized**
in contributions characterized by a specific
scaling of the momenta

$$d\sigma \sim \mathcal{H}\; f_1^{bare}\; f_1^{bare}\; \mathcal{S}$$
$$\sim \mathcal{H}\; f_1\; f_1$$

renormalized TMD PDF :

IR div. : long-distance physics
UV div. and **rapidity div.** cancelled
by UV-renormalization and soft factor S

$$f_1(x, k_T^2; \mu, \zeta)$$

Evolution with respect to two scales

A non-exhaustive list

Transverse momentum dependence

Transverse momentum resummation :

- Qiu, Zhang (2001) - Z production [PRL 86 (2001) 2724-2727]
- Bozzi, Catani, Cieri, Ferrera, de Florian, Grazzini DyqT, DyRes, HqT
- CTEQ collaboration ResBos
- Becher, Neubert CuTe
- Berger, Qiu (2003) - Higgs production [PRL 91 (2003) 222003]
- Berger, Qiu, Wang (2005) - \Upsilon production [PRD 71 (2005) 034007]

One can also consider V+jet(s) ...

- Boughezal et al. : W + 1jet at NNLO [PRL 115 (2015) 062002]
- Boughezal et al. : Z + 1jet at NNLO [PRL 116 (2016) 152001]
- Boughezal et al. : H + 1jet at NNLO [PRL 115 (2015) 082003]

(needed for many LHC applications, including the determination of the gluon PDF)

... and combine QCD and EW effects (photon collinear and TMD PDF) :

- Boughezal, Li, Petriello (2013) - high mass DY @ LHC [JHEP 1707 (2017) 130]
- Gavin, Li, Petriello, Quackenbush FEWZ
- Bacchetta, Echevarria 1810.02297

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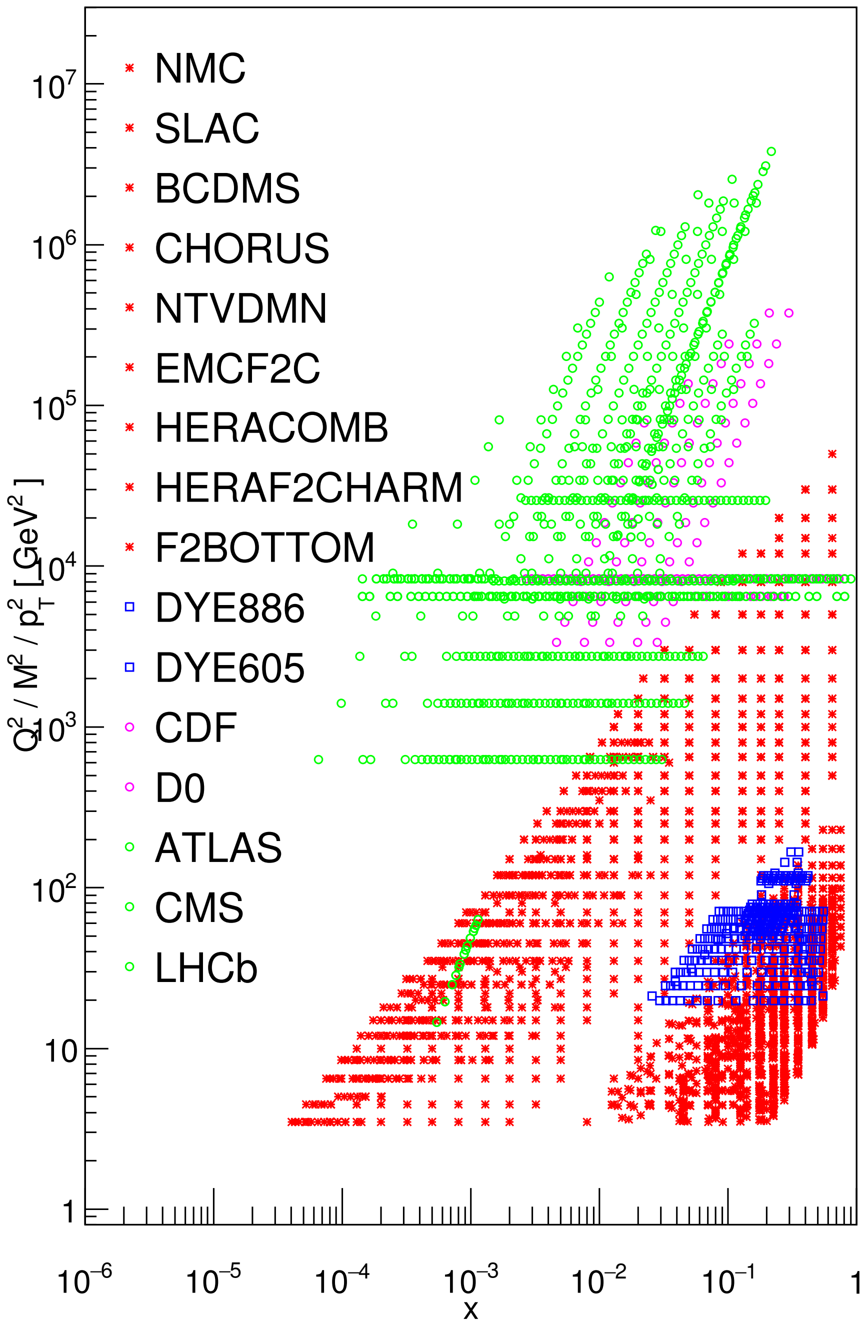
TMD and collinear PDFs

credit: E. Nocera



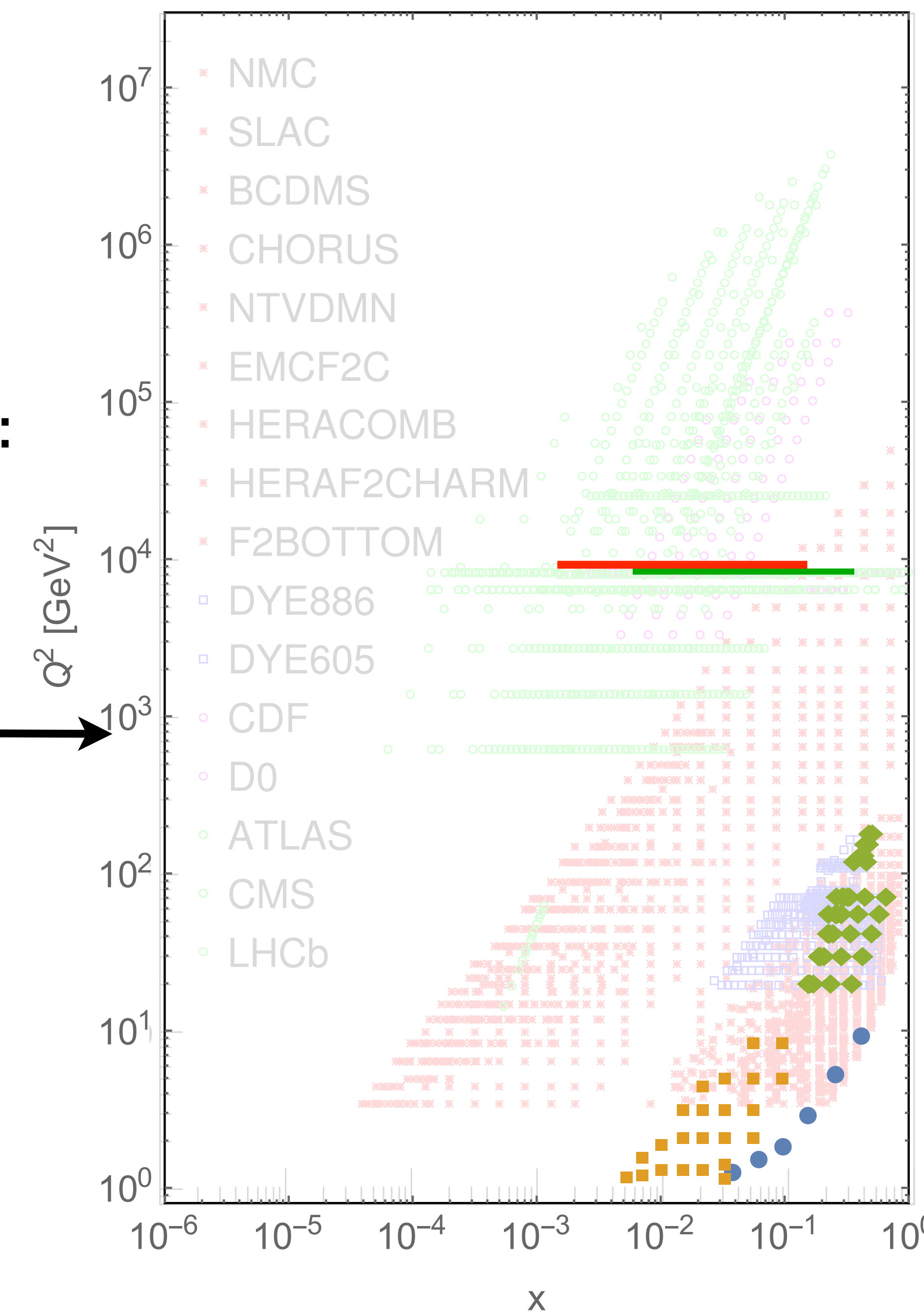
data driven science

data sets available:

← **collinear PDFs**

vs

TMD PDFs →



x : momentum fraction carried by the parton

Q : resolution of the probe

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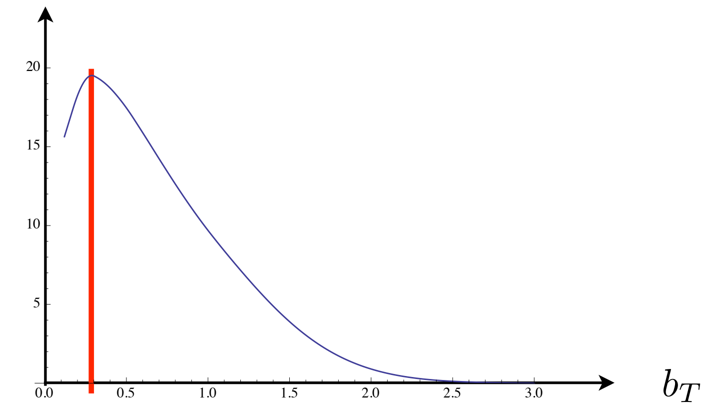
The saddle point approximation

Given a generic function $f \in C^2(a,b)$ and a positive constant A

Given x_0, maximum in (a,b) for f :

$$I(x_0, A) = \int_a^b dx\; e^{Af(x)} = e^{Af(x_0)} \sqrt{\frac{2\pi}{A(-f''(x_0))}} \left(1 + \mathcal{O}\left(\frac{1}{A}\right)\right)$$



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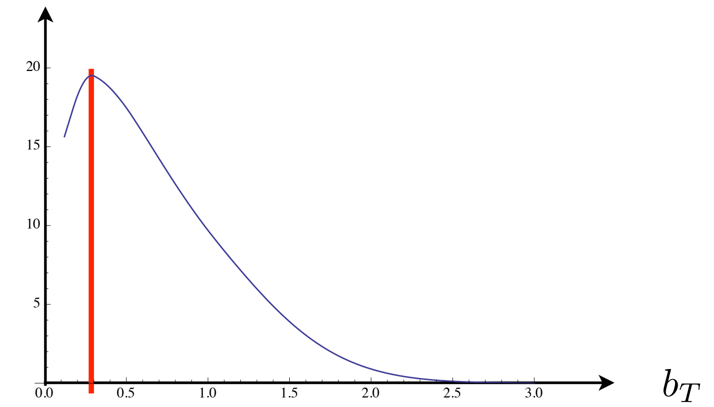


Let's apply this to a TMD PDF evaluated at $k_T = 0$:

$$f_1^a(x, k_T; \mu_f, \zeta_f) = \mathrm{F.T.}\left[f_1^a(x, b_T; \mu_f, \zeta_f)\right]$$

$$f_1^a(x, k_T = 0; \mu_f, \zeta_f) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} d(\ln b_T^2) \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F\left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2}\right] - K(b_T, \mu_i) \ln \frac{\zeta_f}{\zeta_i} + \ln b_T^2 + \ln\left[\sum_b C_{a/b} \otimes f_b\right]\right\}$$

Saddle point of the TMD PDF :
stationary point of the exponent

The saddle point approximation

$$\frac{d}{db_T}\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2}\right] - K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i} + \ln b_T^2 + \ln\left[\sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i)\otimes f_b(x,\mu_i)\right]\right\}_{b_T=b_T^{sp}} = 0$$

Generate the **scale-dependence** of the saddle point

Generates the **x-dependence** of the saddle point

Working at LL the solution is :

$$b_T^{sp} = \frac{c}{\Lambda}\left(\frac{Q}{\Lambda}\right)^{-\Gamma_1^{\rm cusp}/\left[\Gamma_1^{\rm cusp}+8\pi b_0\left(1-\mathcal{X}(x,\mu_b^\star)\right)\right]}$$

$$\mathcal{X}(x,\mu) = \frac{d}{d\ln\mu^2}\ln f_a(x,\mu) \qquad \zeta = \mu^2 = Q^2$$

$$\mu_b^\star = 2e^{-\gamma_E}/b_T^{sp}$$

Requires iterative solution

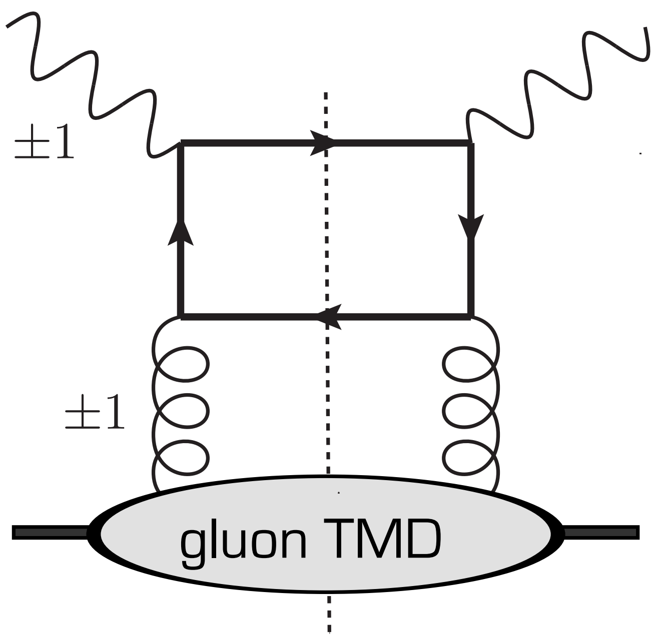
Conclusion : the predictive power is governed by both Q and x

The sign of the derivative of the collinear PDF determines the behavior in x

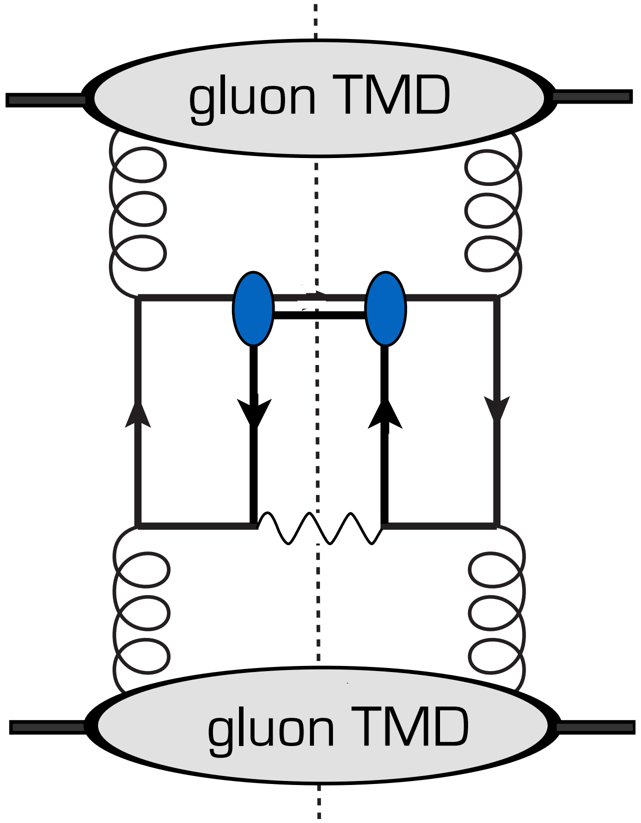
Gluon TMDs

$e\,p \to e$ jet jet X

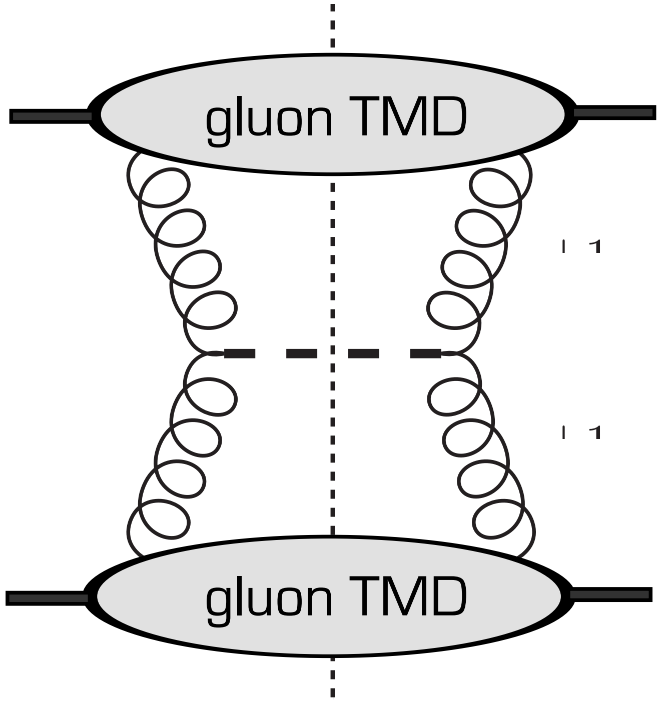
EIC !



$p\,p \to J/\psi\,\gamma\,X$



$p\,p \to \eta_c\,X$



- factorization properties in effective theories
- no extractions beyond parton model yet

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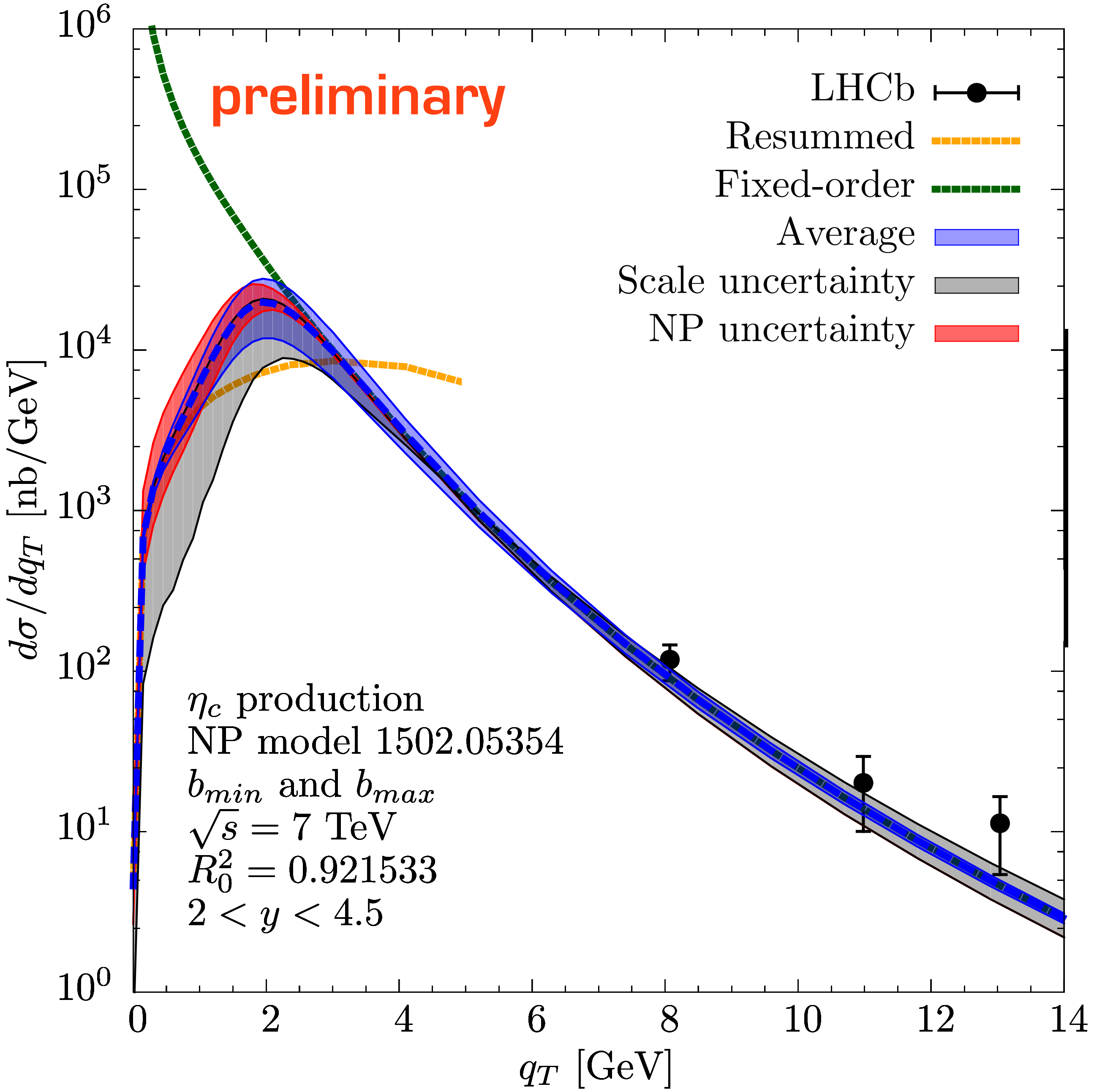
Gluon TMDs

full transverse momentum spectrum: inverse-error weighting :



Echevarria, Kasemets, Lansberg, AS, Pisano
Phys.Lett. B781 (2018) 161-168

blue band: uncertainty from matching

grey band: scale uncertainty

red band: uncertainty associated to the nonperturbative evolution and intrinsic transverse momenta

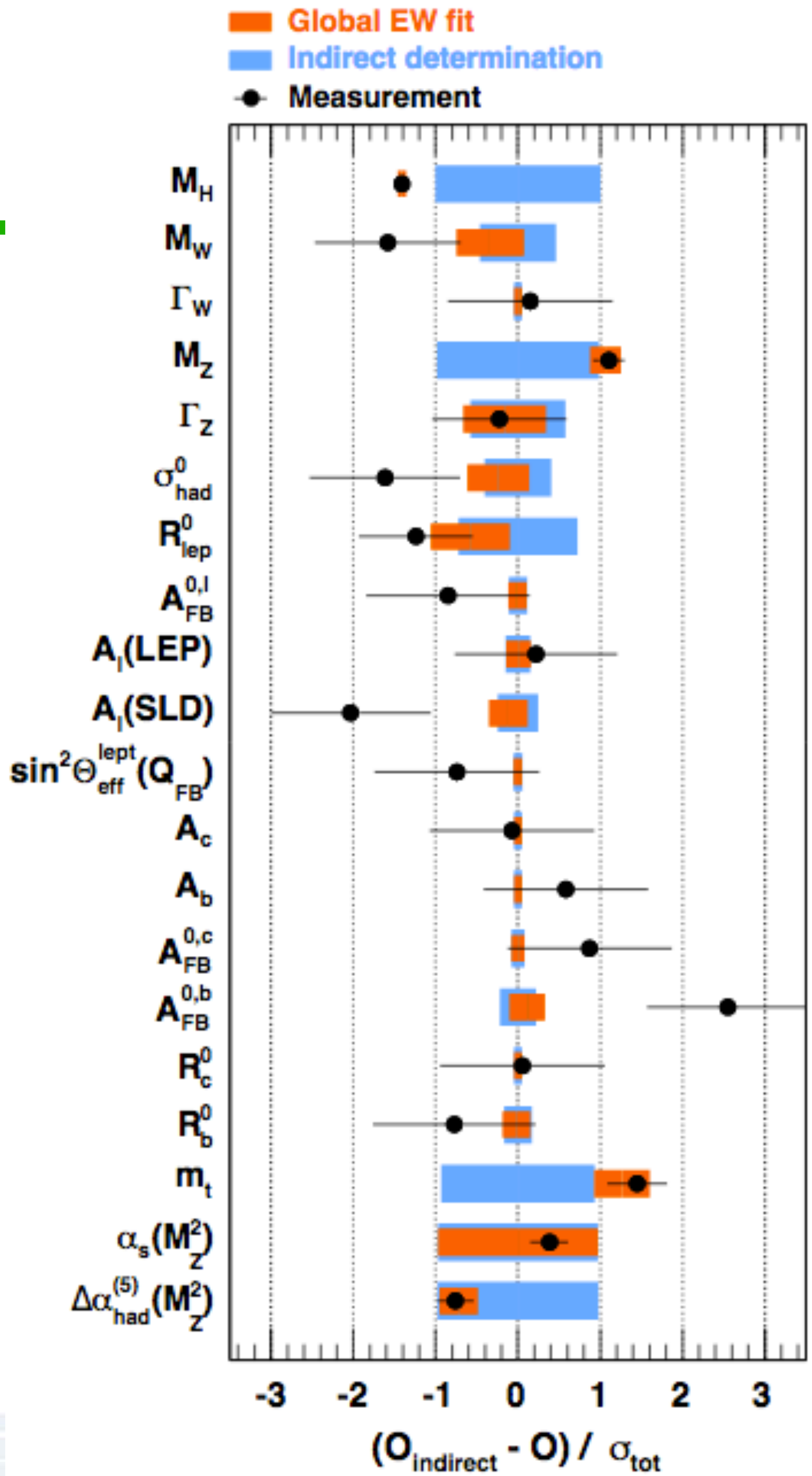
the formalism is in good shape
we need the data at low q_T

EW observables

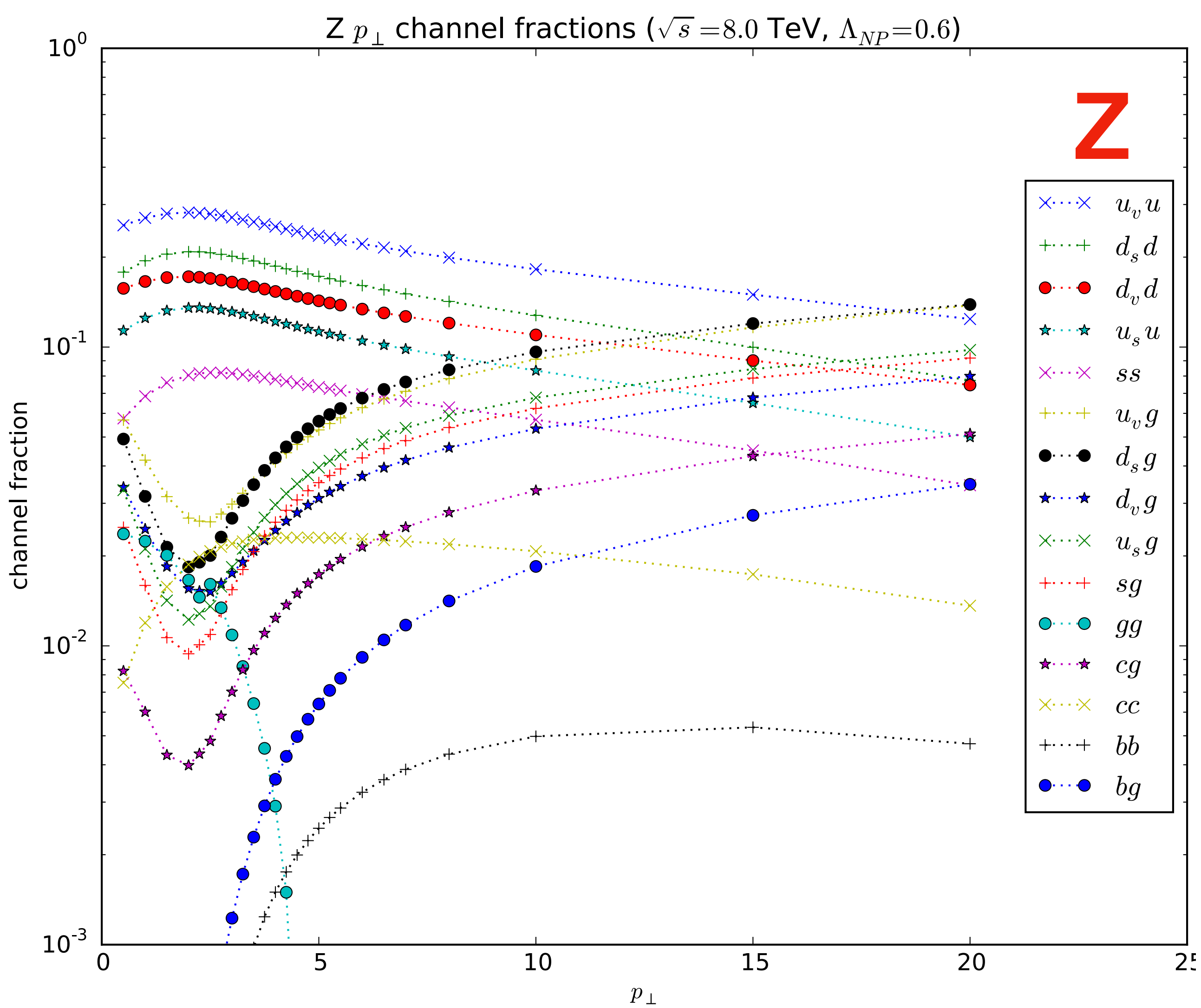
Eur.Phys.J. C74 (2014) 3046

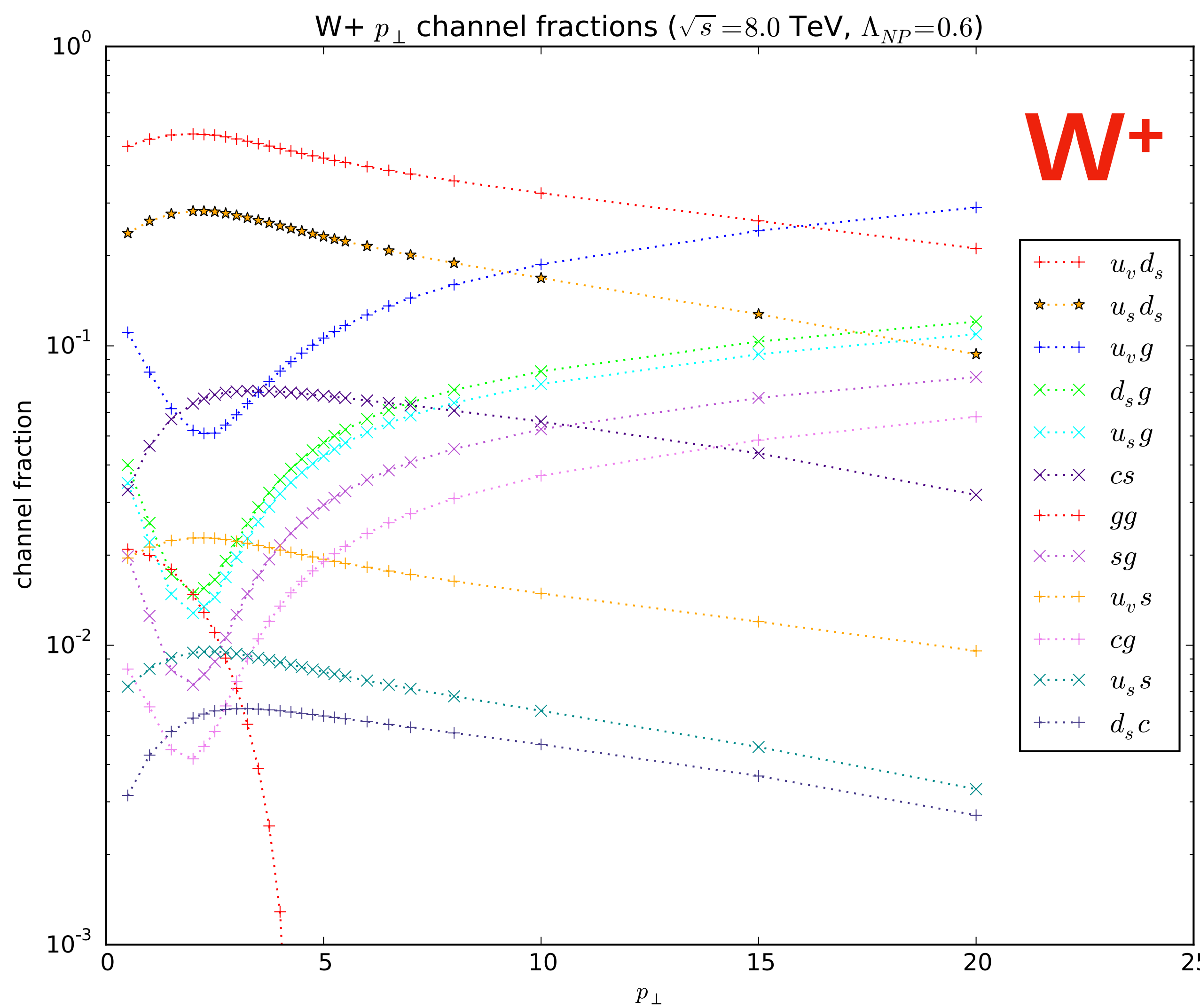
- tension between direct measurements and indirect determinations/global EW fit

- larger uncertainty in direct determinations



Flavor content





uval-ubar and **d-dbar**
are the most important channels

uval-dbar is the most important channel

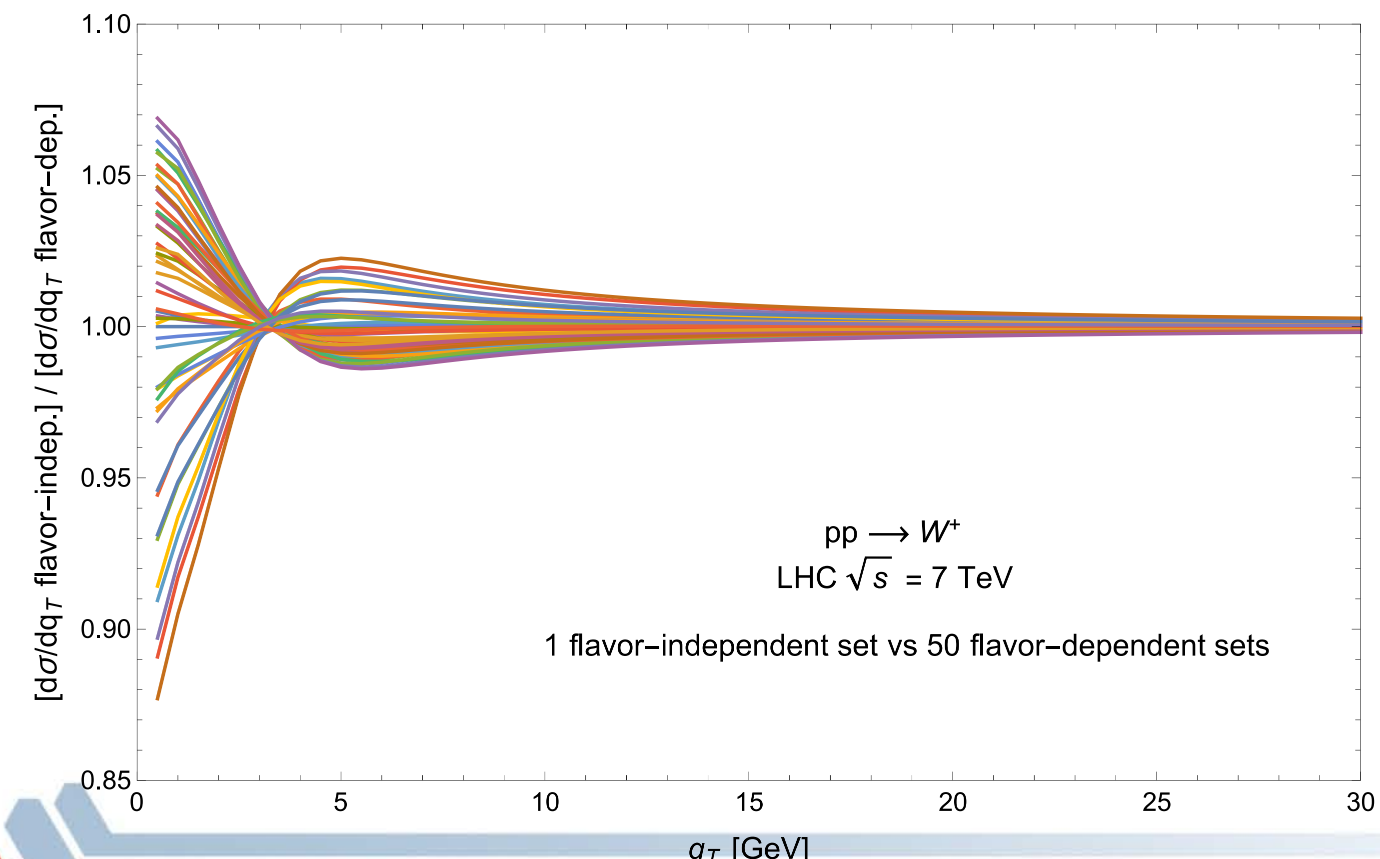
Impact on W q_T spectrum

Shifts in MeV of the peak position for qT spectrum

	W^+		W^-		Z	
$\mu_R = \mu_c/2, 2\mu_c$	$+0.30$	-0.09	$+0.29$	-0.06	$+0.23$	-0.05
pdf (68% cl)	$+0.03$	$+0.03$	$+0.04$	$+0.00$	$+0.03$	-0.02
pdf (90% cl)	$+0.03$	-0.05	$+0.06$	-0.02	$+0.05$	-0.02
$\alpha_s = 0.118 \pm 0.003$	$+0.14$	-0.12	$+0.14$	-0.14	$+0.15$	-0.15
f.i. $\langle \boldsymbol{k}_T^2 \rangle = 1.0, 1.96$	$+0.16$	-0.16	$+0.16$	-0.14	$+0.16$	-0.15
f.d. $\langle \boldsymbol{k}_T^2 \rangle$ (max W^+ effect)	$+0.09$			-0.06	± 0	
f.d. $\langle \boldsymbol{k}_T^2 \rangle$ (max W^- effect)		-0.03	$+0.05$		± 0	

Opposite shifts!

The flavor structure of the TMDs can affect the shape of the W qT spectrum up to 5%-10% at very low qT



Impact on lepton pT and mT

↓

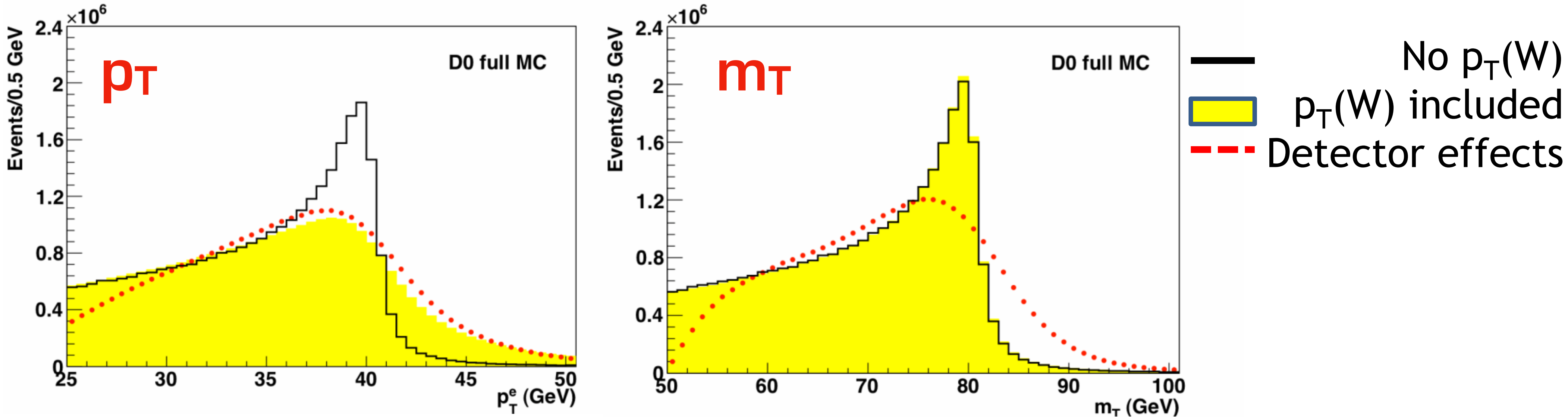
Impact on mW

Transverse mass

p_T

m_T

Transverse mass



Transverse mass: important detector smearing effects, weakly sensitive to p_{TW} modelling

Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

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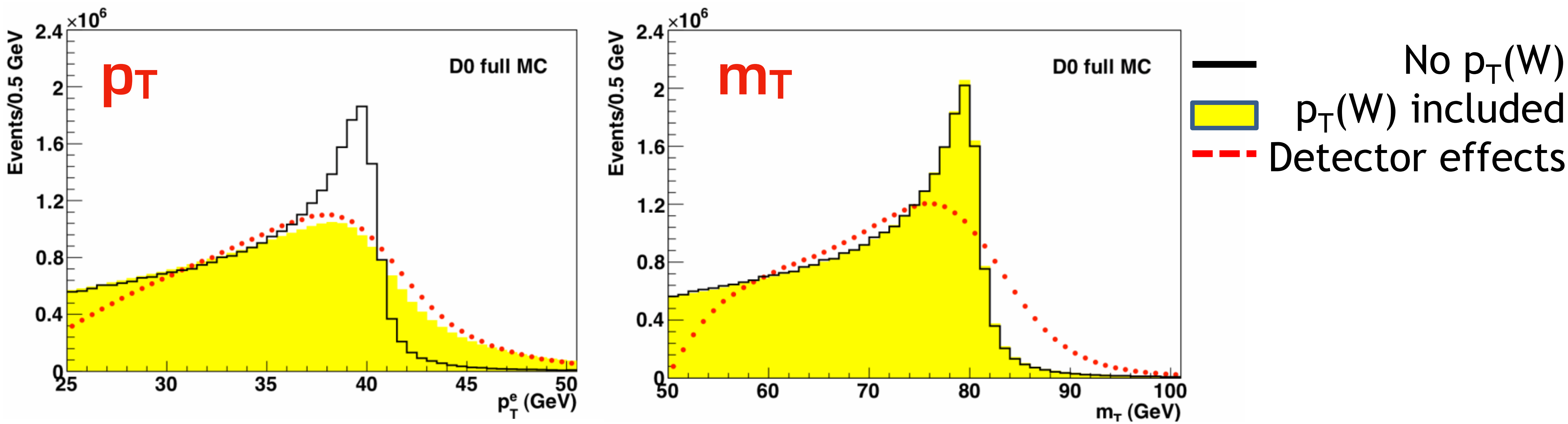
Transverse mass



Transverse mass: important detector smearing effects, weakly sensitive to p_{TW} modelling

Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

p_{TW} modelling depends on flavour and all-order treatment of QCD corrections