Transverse momentum distributions and the determination of the W mass

Andrea Signori

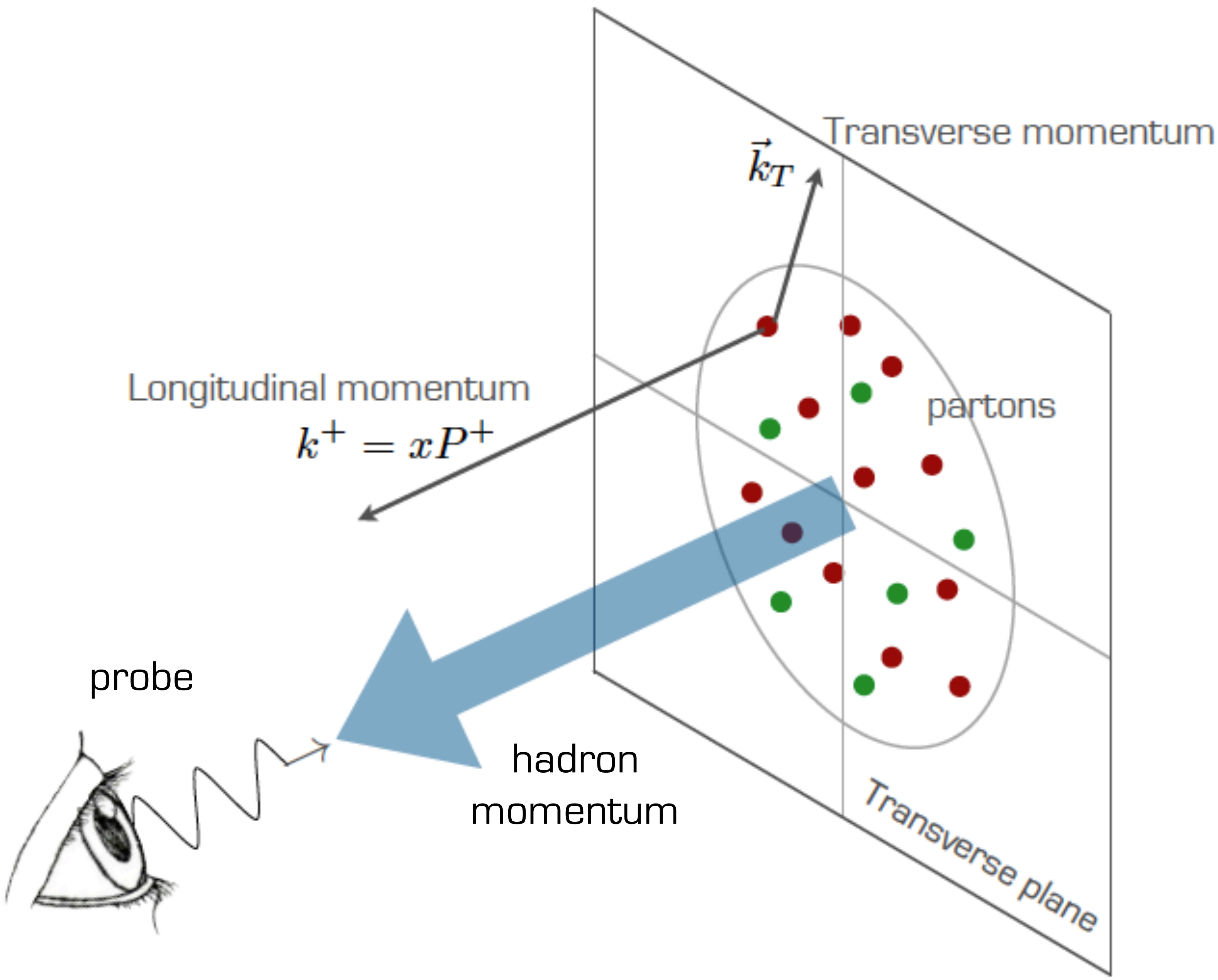
Loop Fest XVIII

Fermilab

August 13th, 2019

TMDs

TMD PDFs



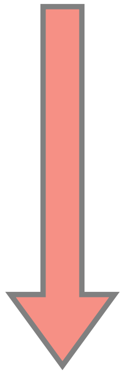
extraction of a **parton** whose momentum has **longitudinal** and **transverse components** with respect to the parent **hadron** momentum

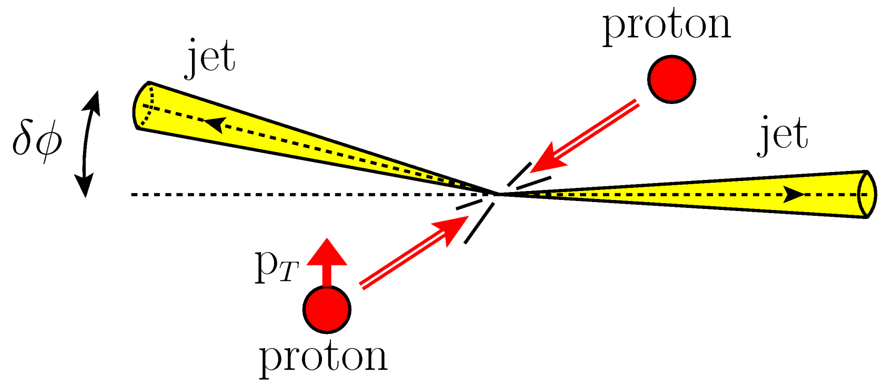
richer structure than collinear PDFs

courtesy A. Bacchetta

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

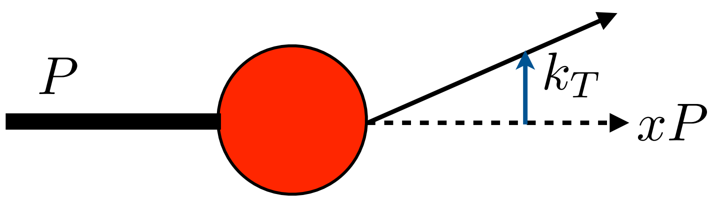
Quark TMD PDFs

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

	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

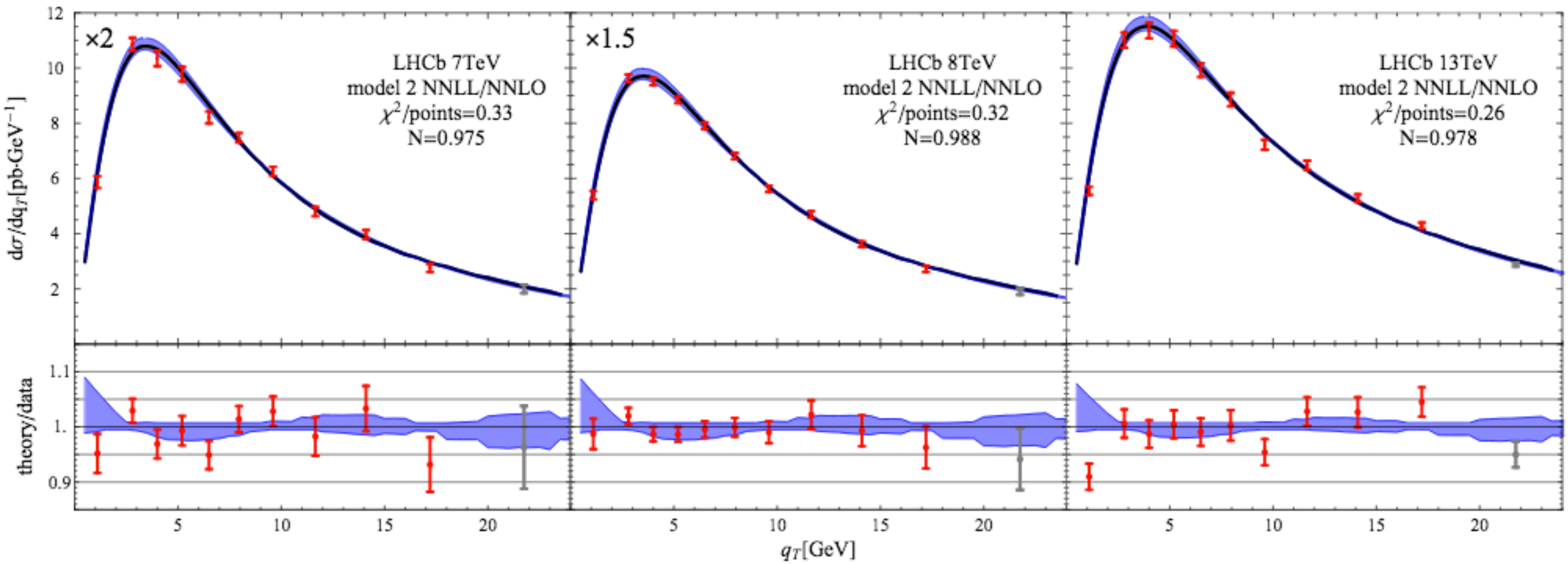
encode all the possible
spin-spin and **spin-momentum**
correlations
between the proton
and its constituents

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

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

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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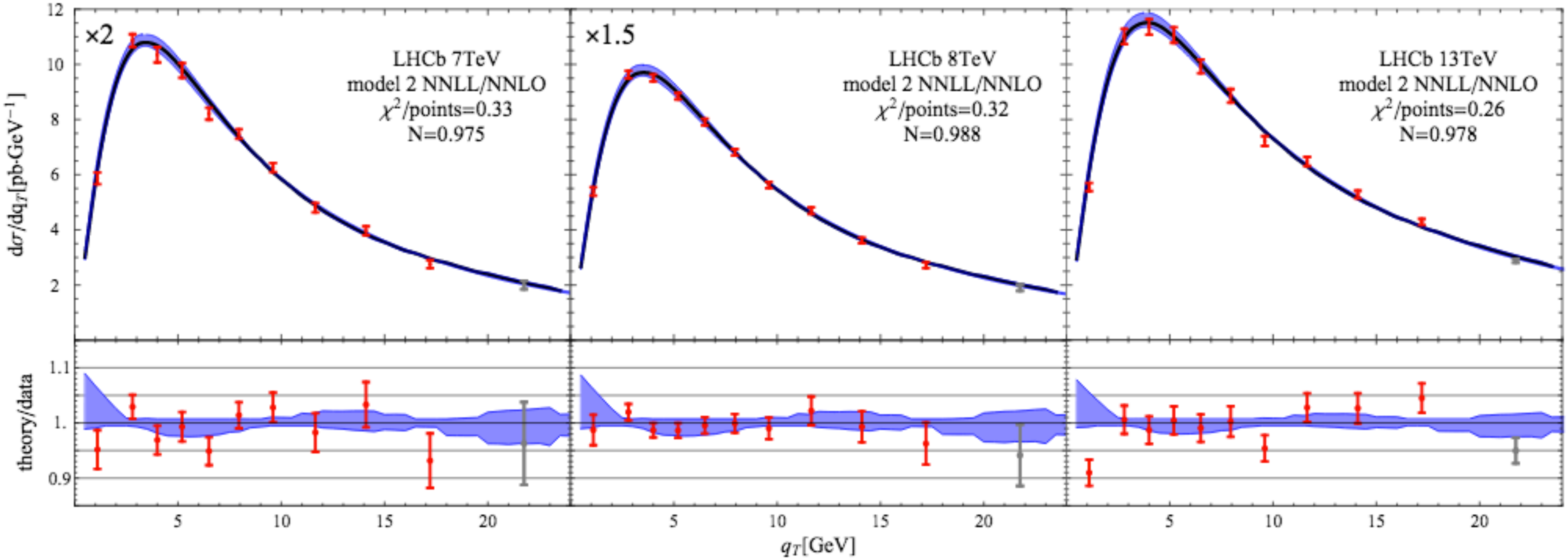

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Matching to fixed-order calculations in coll. factorization

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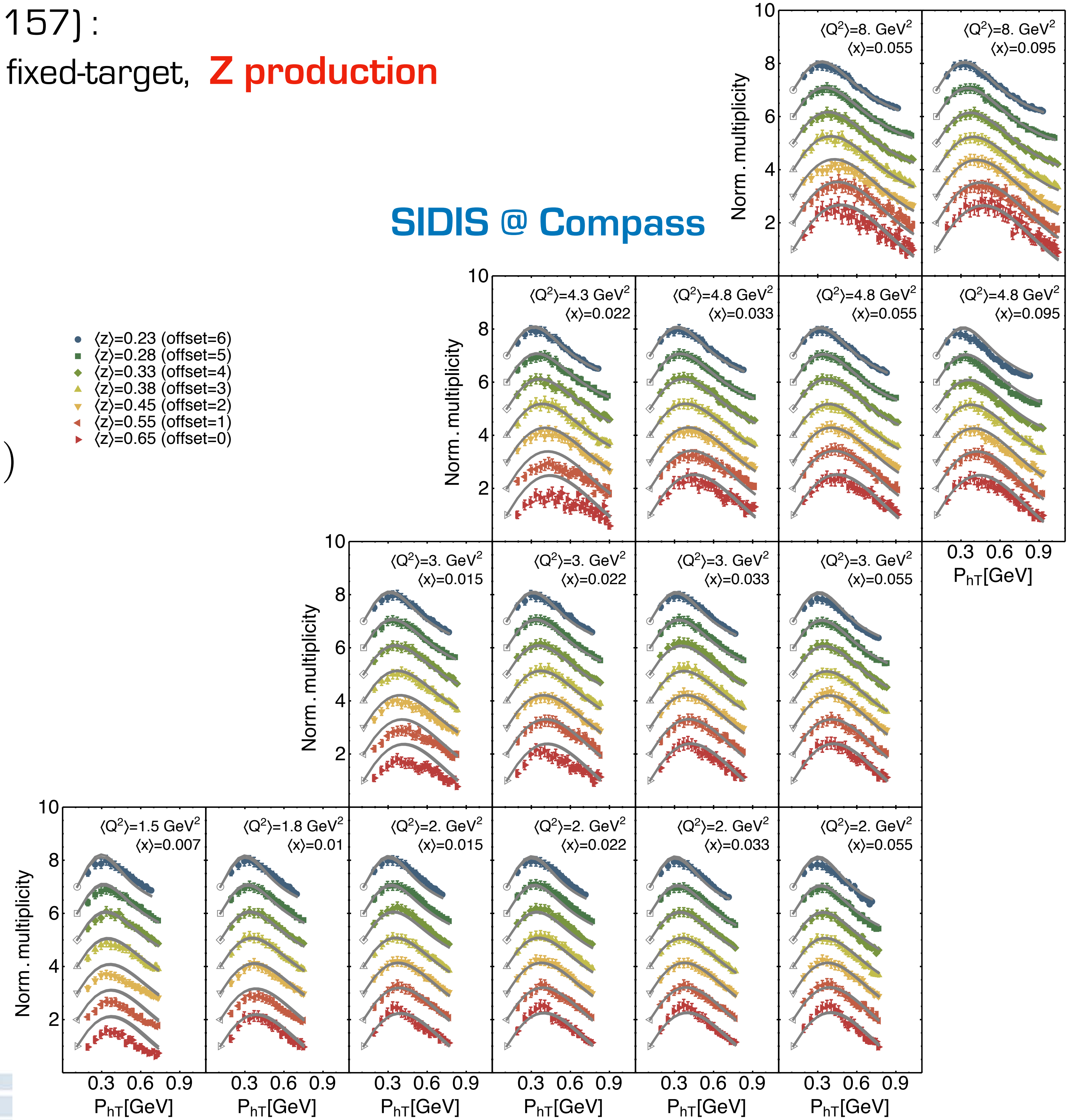
TMD factorization at work

Bacchetta, Delcarro, Pisano, Radici, **AS** (1703.10157) :
unpolarized TMD fit including **SIDIS**, **Drell-Yan** fixed-target, **Z production**

$$pp \quad : \quad f_1^a(x_a, k_{aT}^2, Q^2) \otimes f_1^b(x_b, k_{bT}^2, Q^2)$$

$$ep \quad : \quad f_1^a(x_a, k_{aT}^2, Q^2) \otimes D_1^{a\to h}(z_a, P_T^2, Q^2)$$

SIDIS @ Compass



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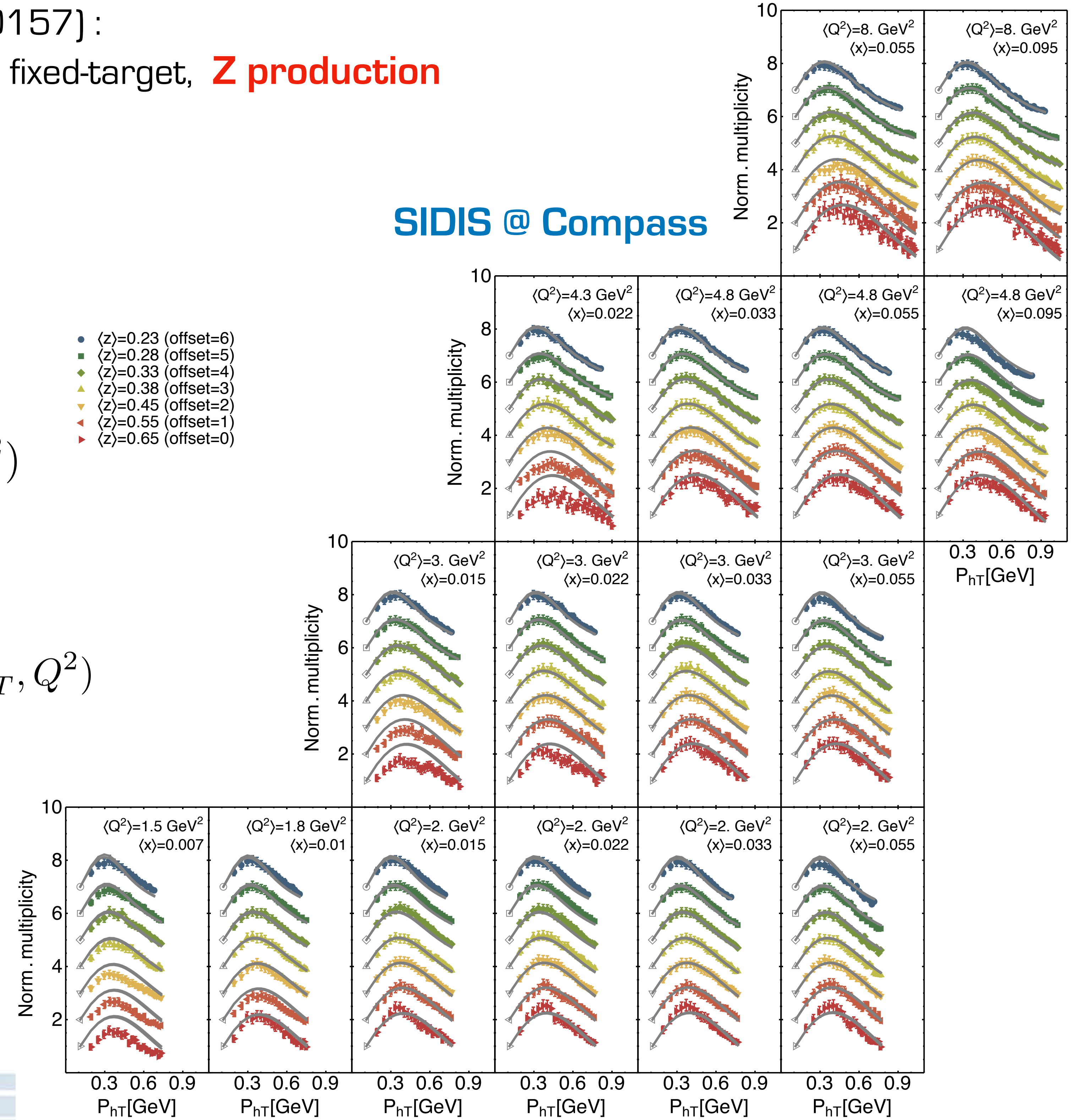
$$e^+e^- \quad : \quad D_1^{a\to h_1}(z_1, P_{1T}^2, Q^2) \otimes D_1^{b\to h_2}(z_2, P_{2T}^2, Q^2)$$

Data not available yet!

Needed for independent analyses of TMD FFs

SIDIS @ Compass



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:

$$\zeta_i = \mu_i^2 = 4e^{-2\gamma_E}/b_T^2 \equiv \mu_b^2$$
$$\zeta_f = \mu_f^2 = Q^2$$

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need corrections
at large bT

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Non-perturbative structures

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evolution in zeta
$\zeta_i \to \zeta_f$

Non-perturbative structures

In which kinematic regimes are they dominant ?

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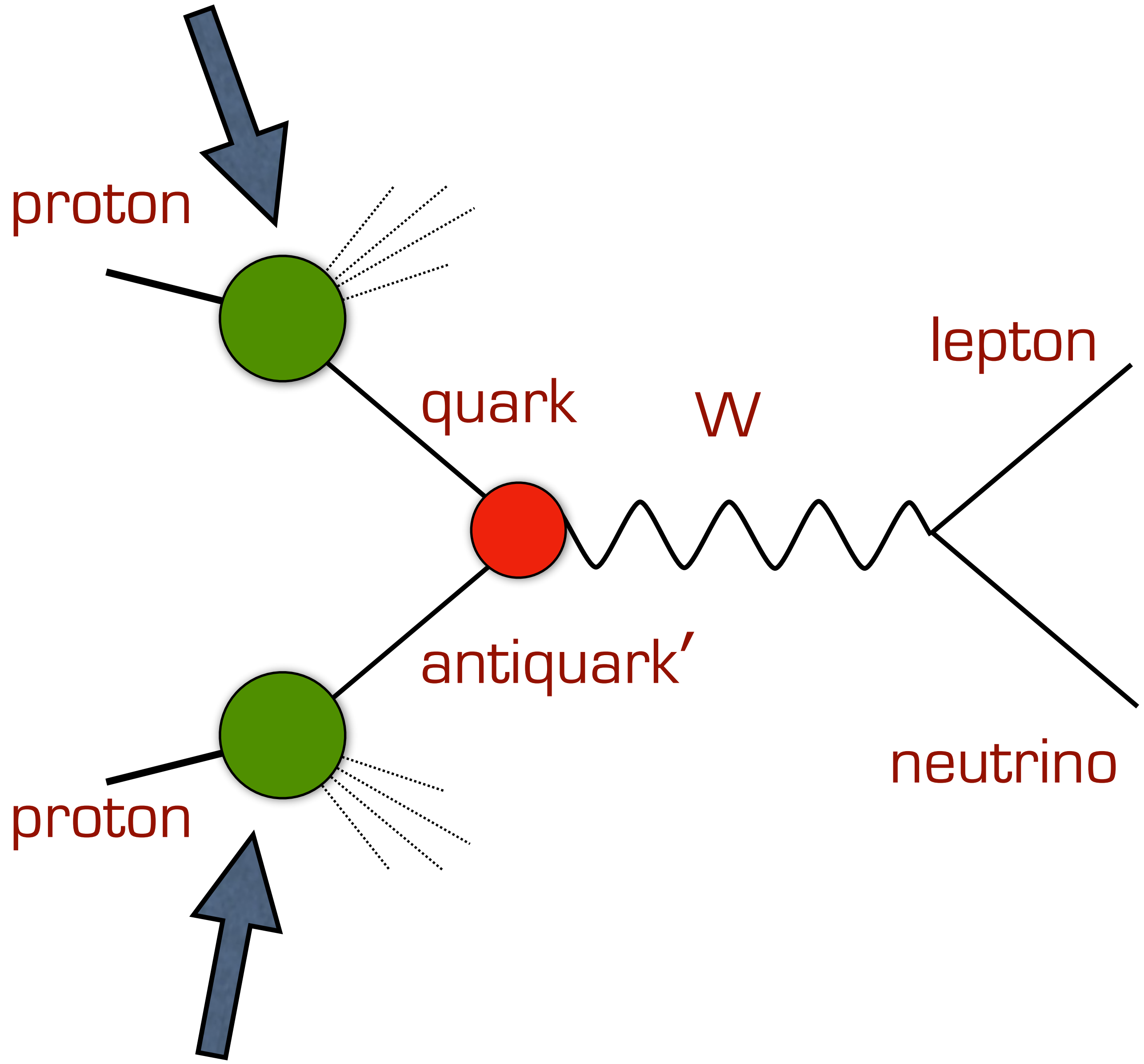
The W mass determination

References :

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

W boson production

(TMD) parton distribution functions : flavor structure



(TMD) parton distribution functions : flavor structure

Kinematics (W)

$Q = m_W$ mass

y rapidity

q_T Transverse momentum

Kinematics (partons)

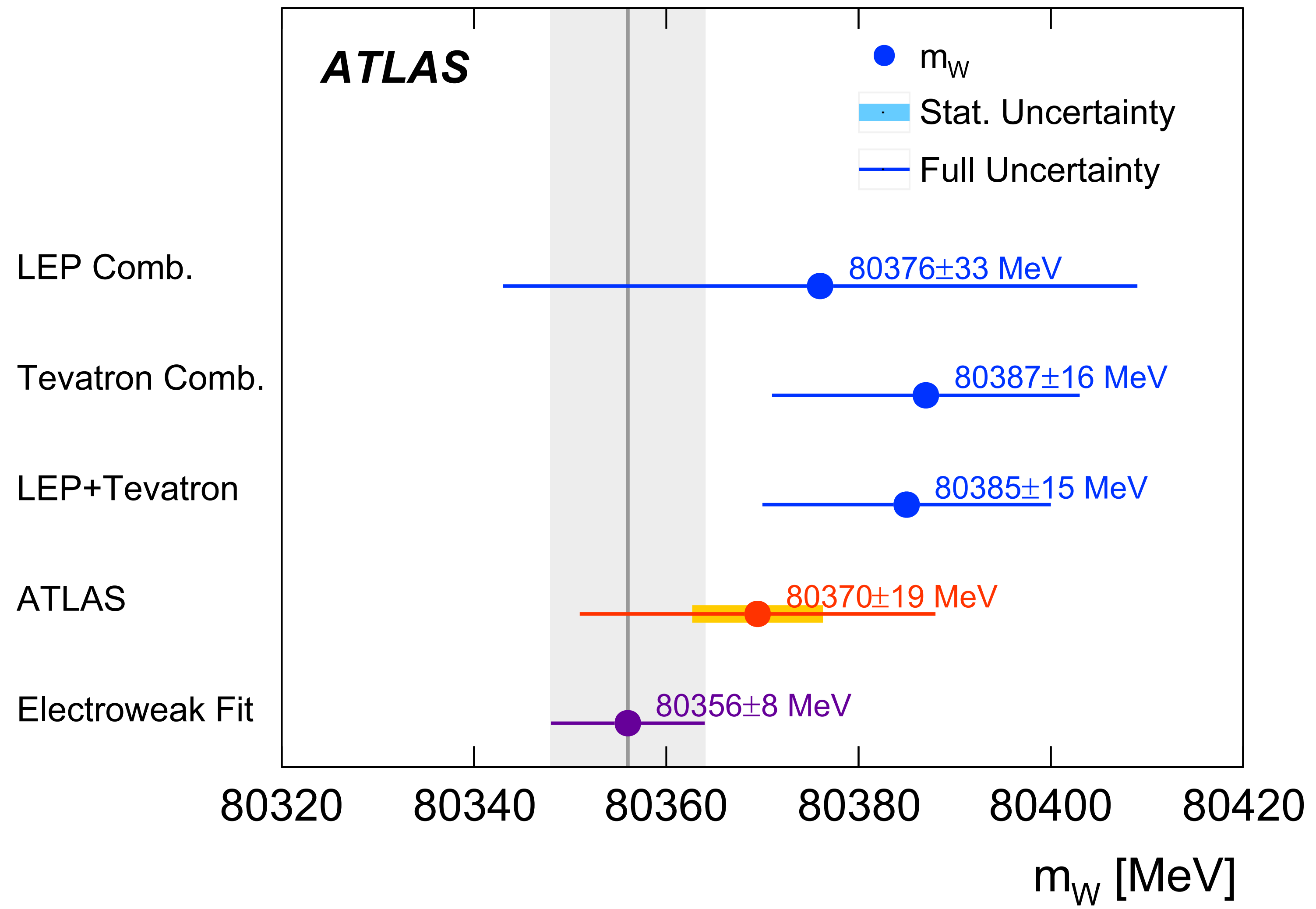
$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

Collinear momentum fractions

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

ATLAS fit

ATLAS Collab. arXiv:1701.07240



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

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

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:

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

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

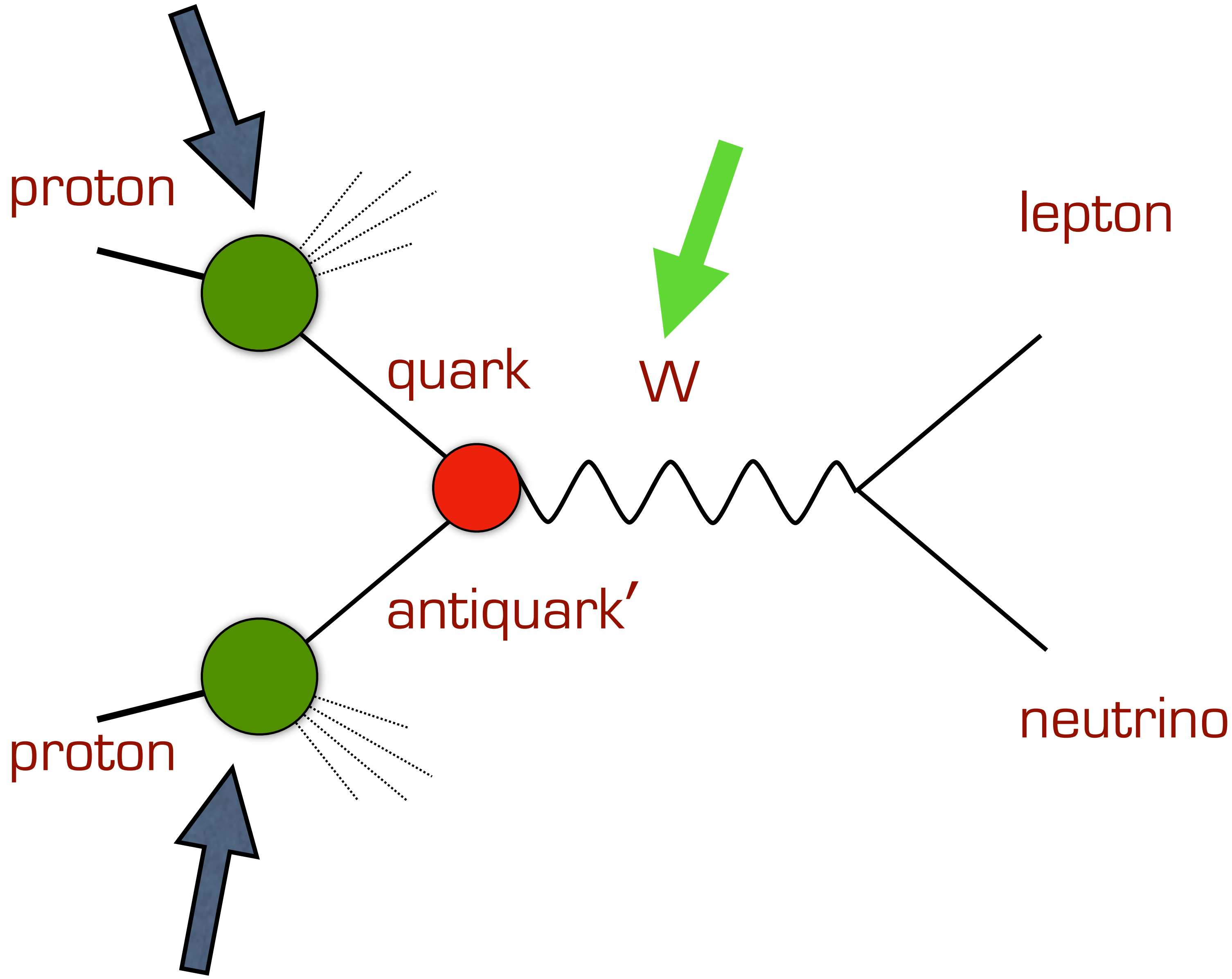
ATLAS - 7 TeV

- The four-loop QCD corrections generate 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”)

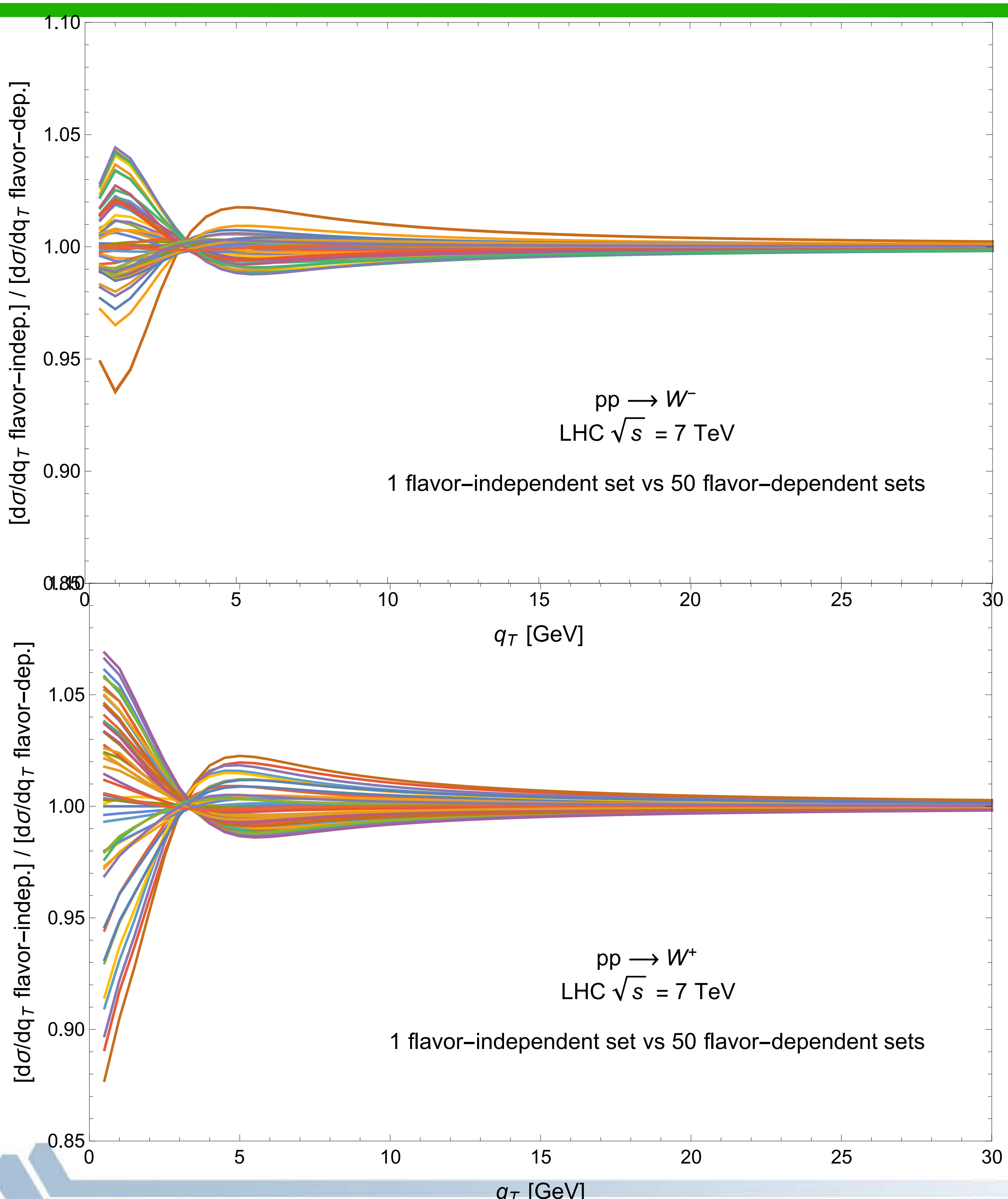
W boson production

(TMD) parton distribution functions : flavor structure



(TMD) parton distribution functions : flavor structure

Impact on W q_T spectrum



Flavor-dependent modification of DyqT

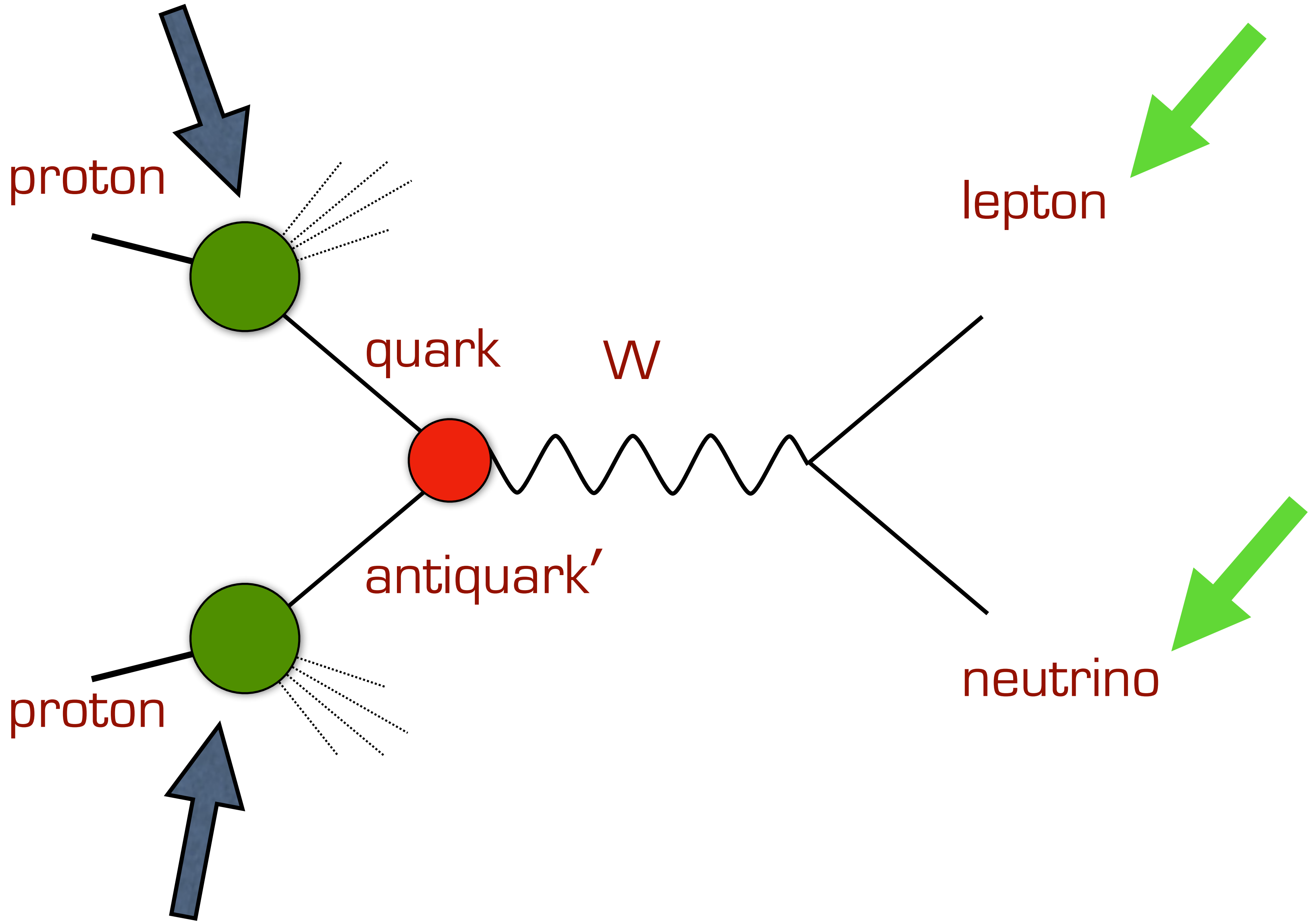
The flavor structure of the TMDs can **affect the shape** of the **W qT spectrum** up to 5%-10% at very low qT

Impact on lepton p_T and m_T

Impact on m_W

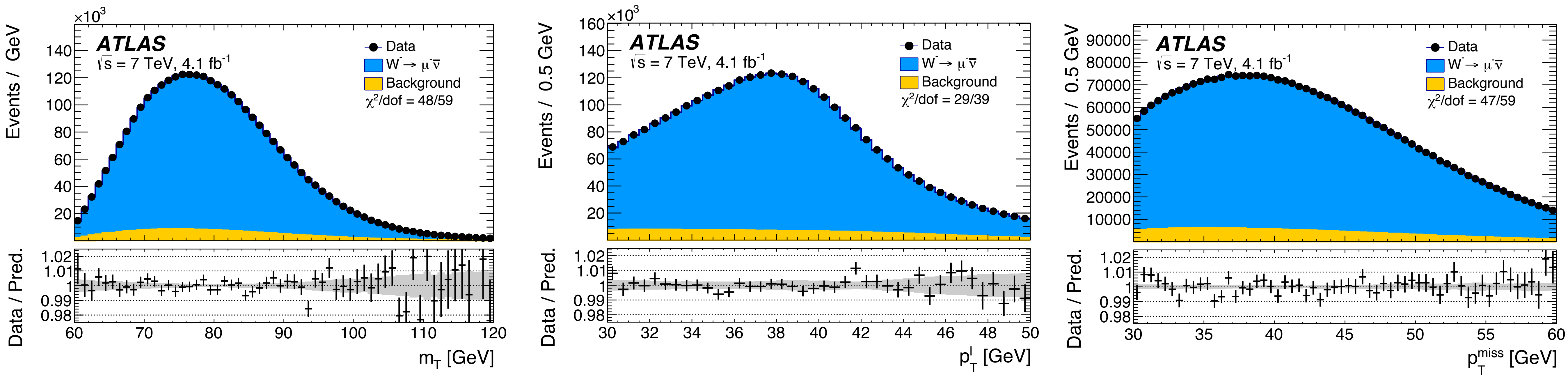
W boson production

(TMD) parton distribution functions : flavor structure



(TMD) parton distribution functions : flavor structure

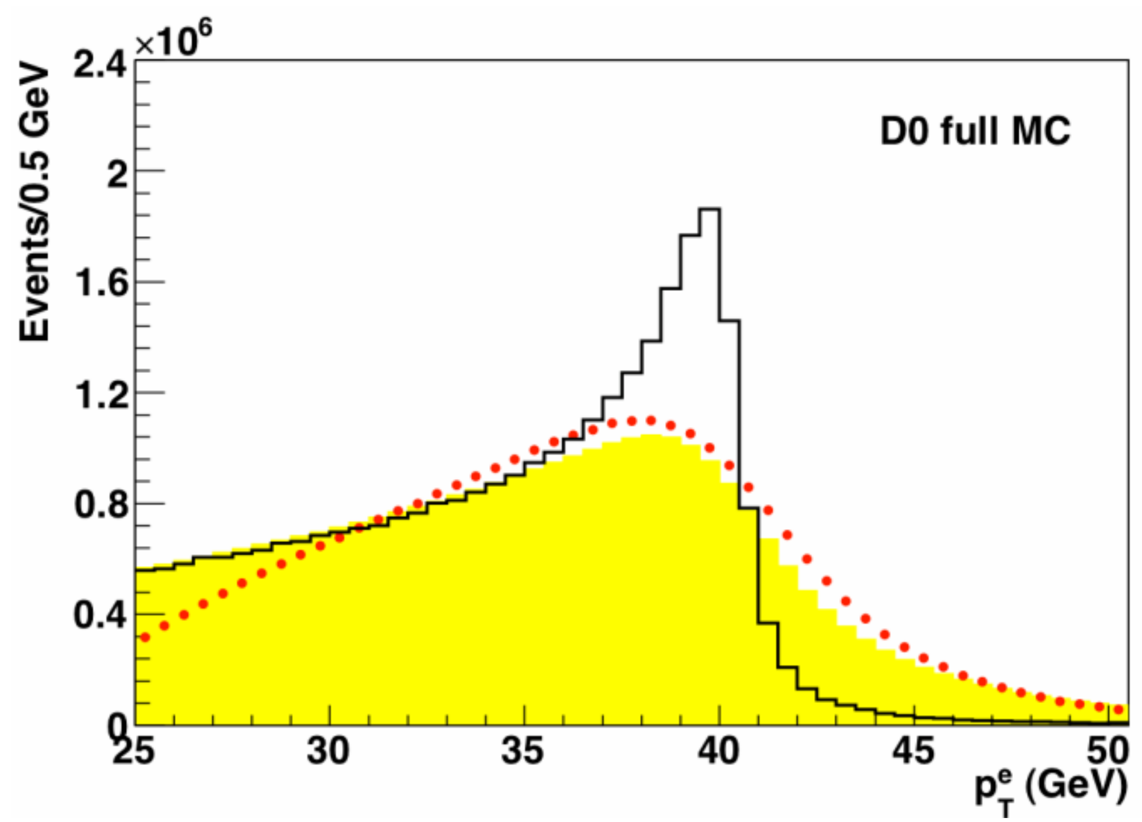
How to determine m_W



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

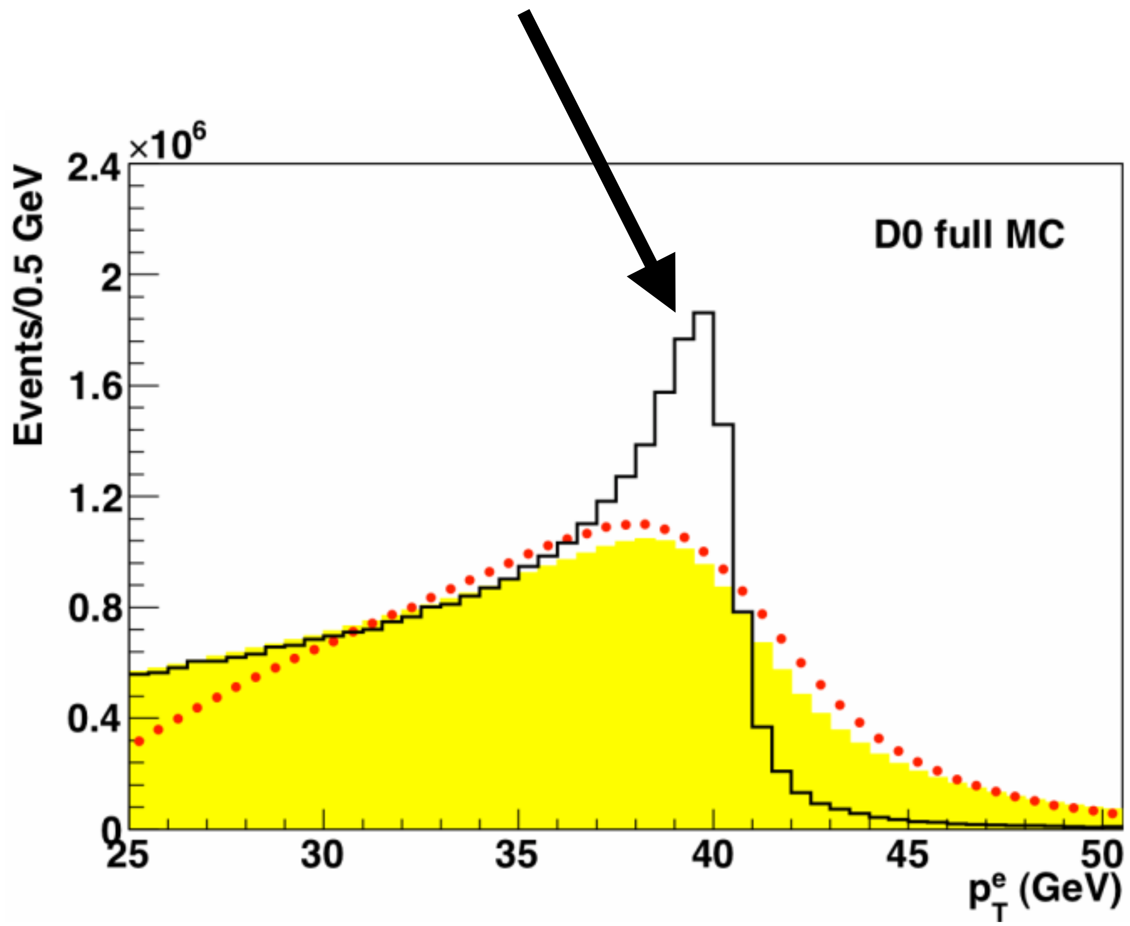
$$M_{\perp}^{W} = \sqrt{2 p_t^l p_t^\nu (1 - \cos(\phi^l - \phi^\nu))},$$

Lepton p_T distribution



Lepton p_T 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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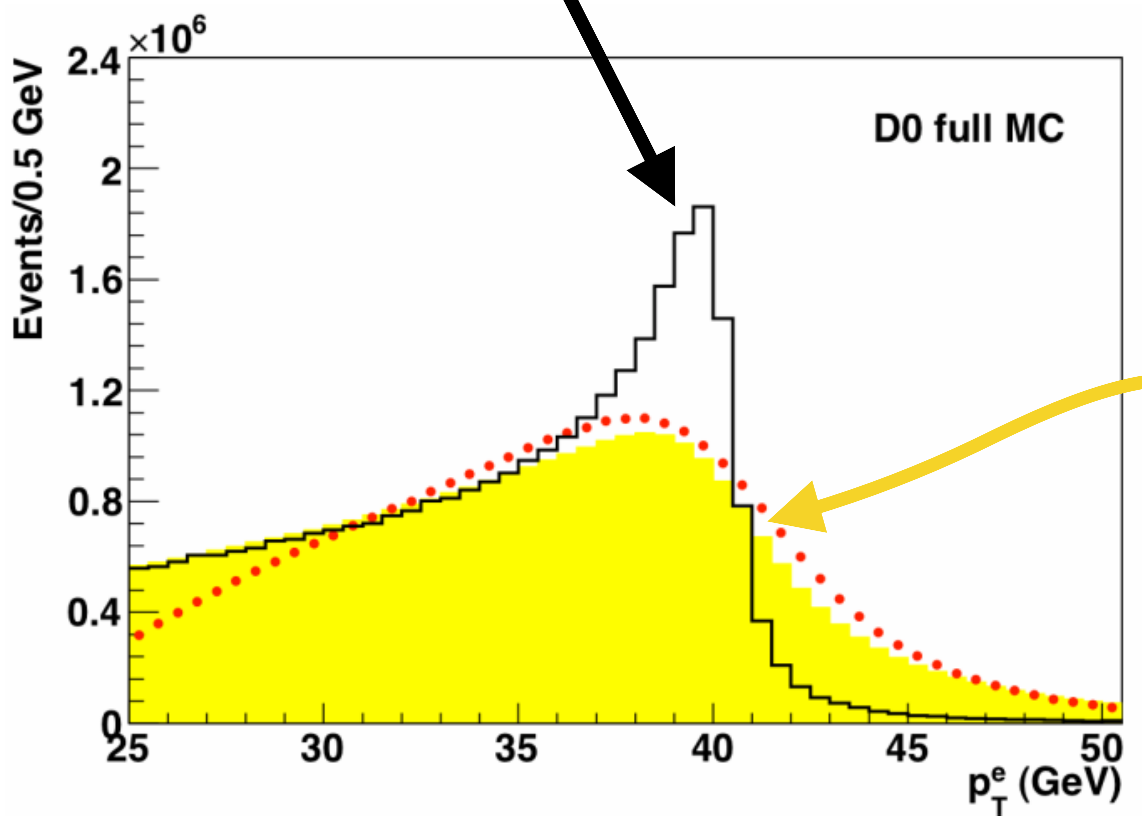

If TMDs are taken into consideration, the distribution gets modified like this

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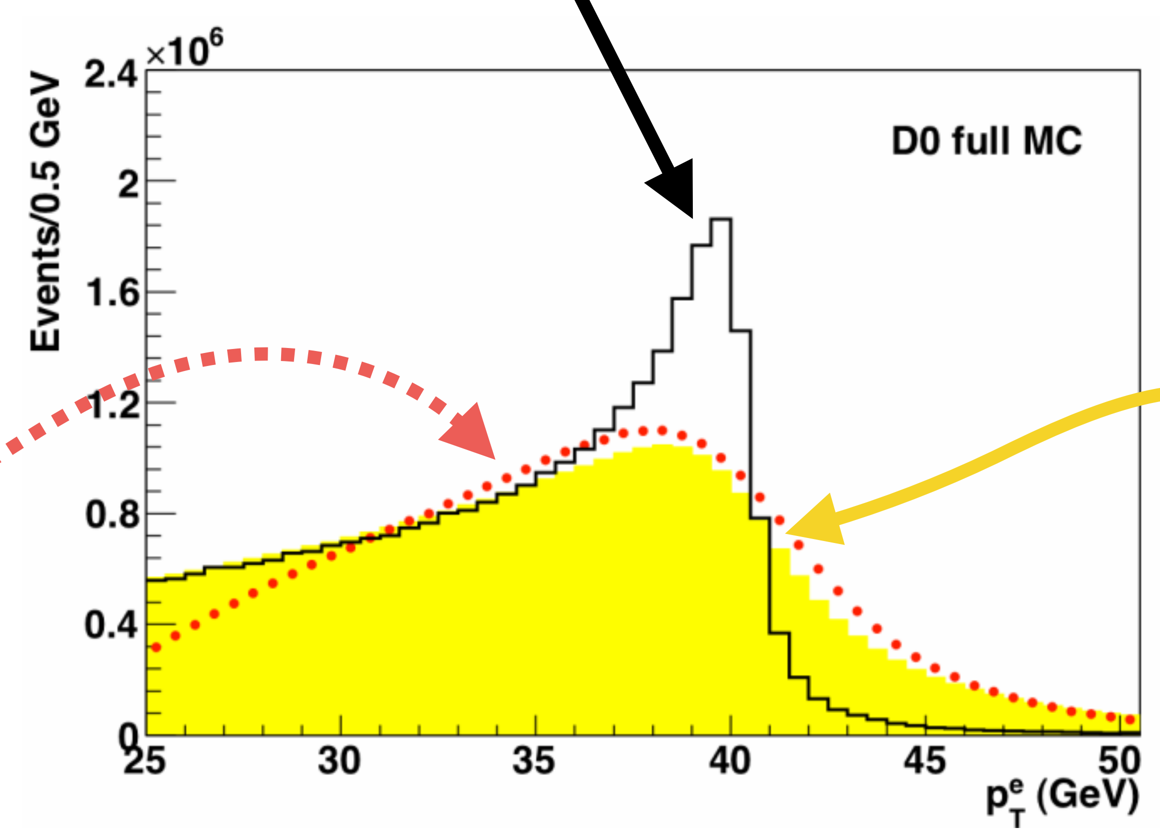
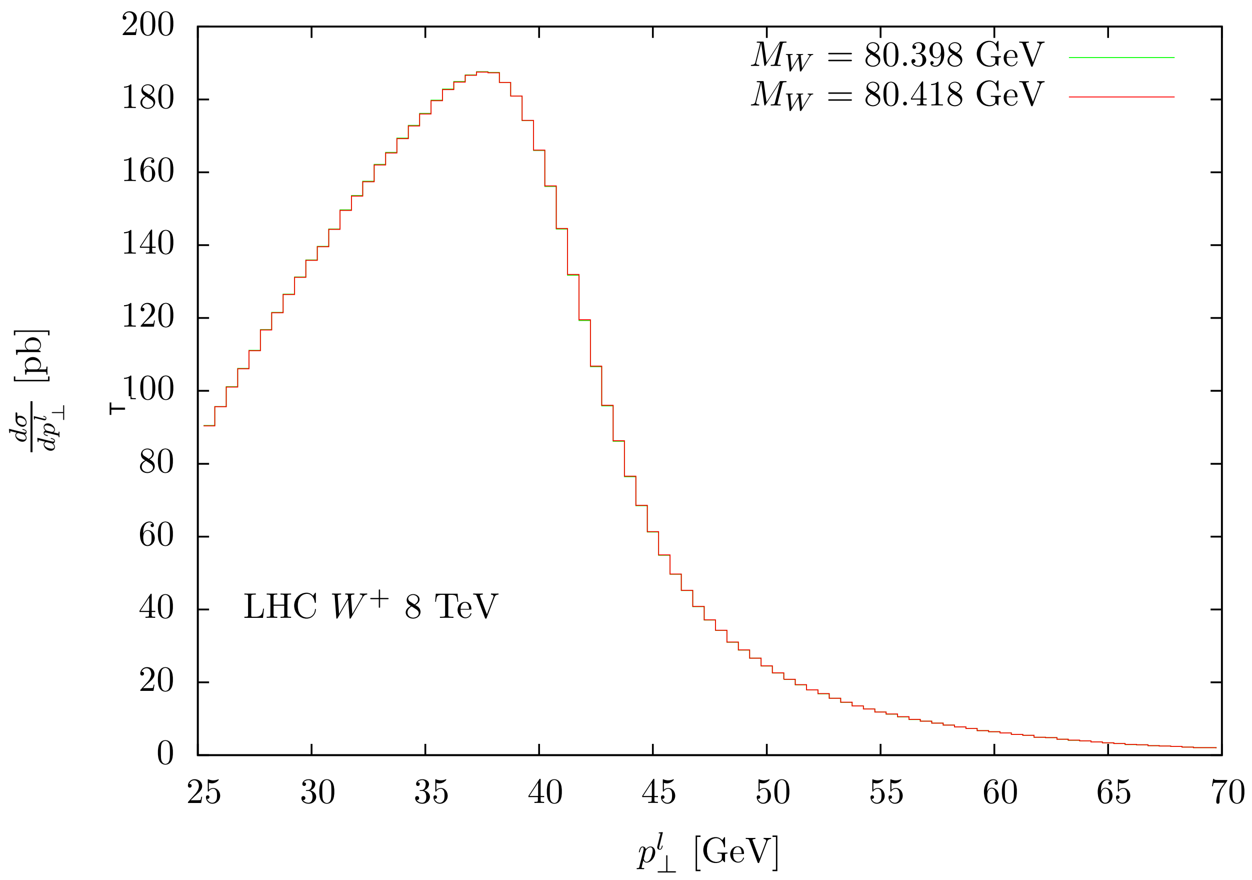


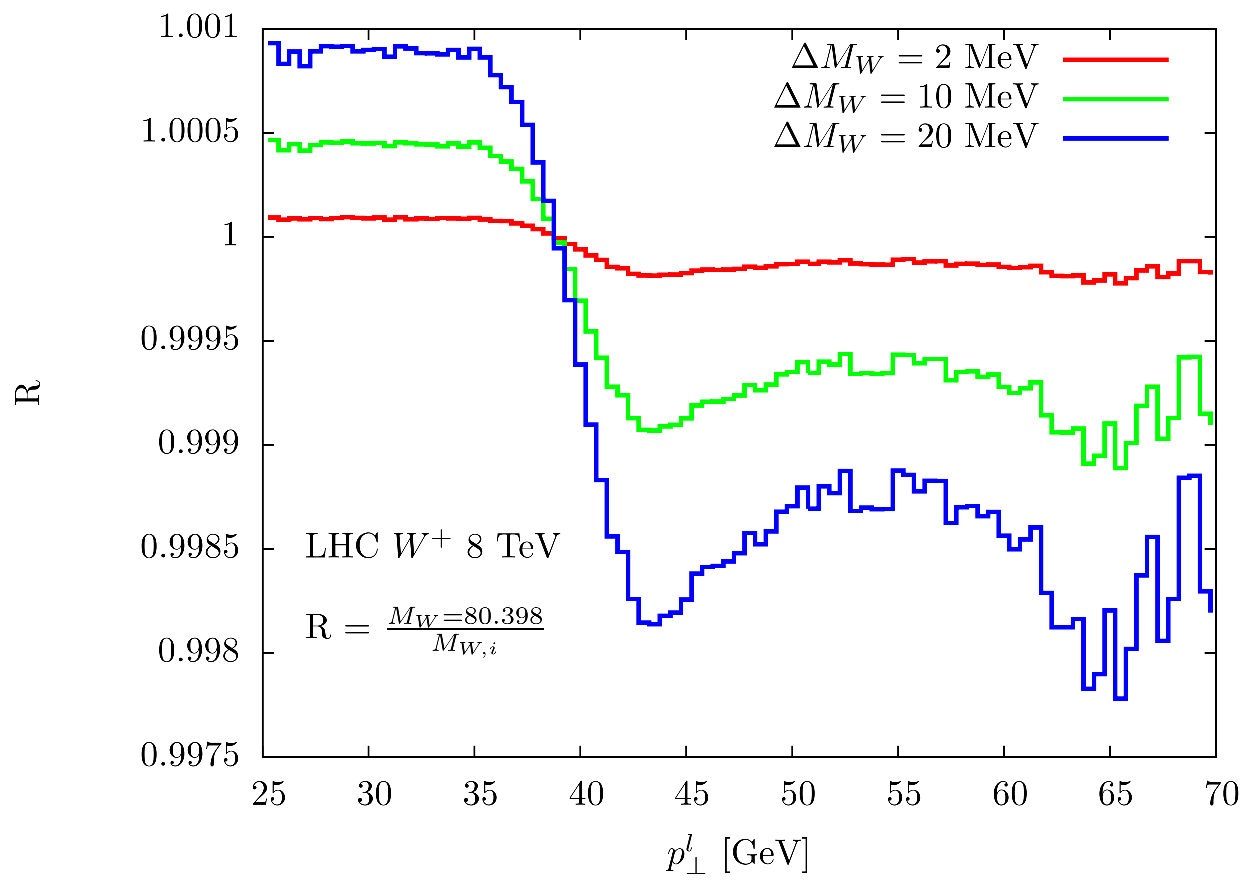
Detector effects cause further changes

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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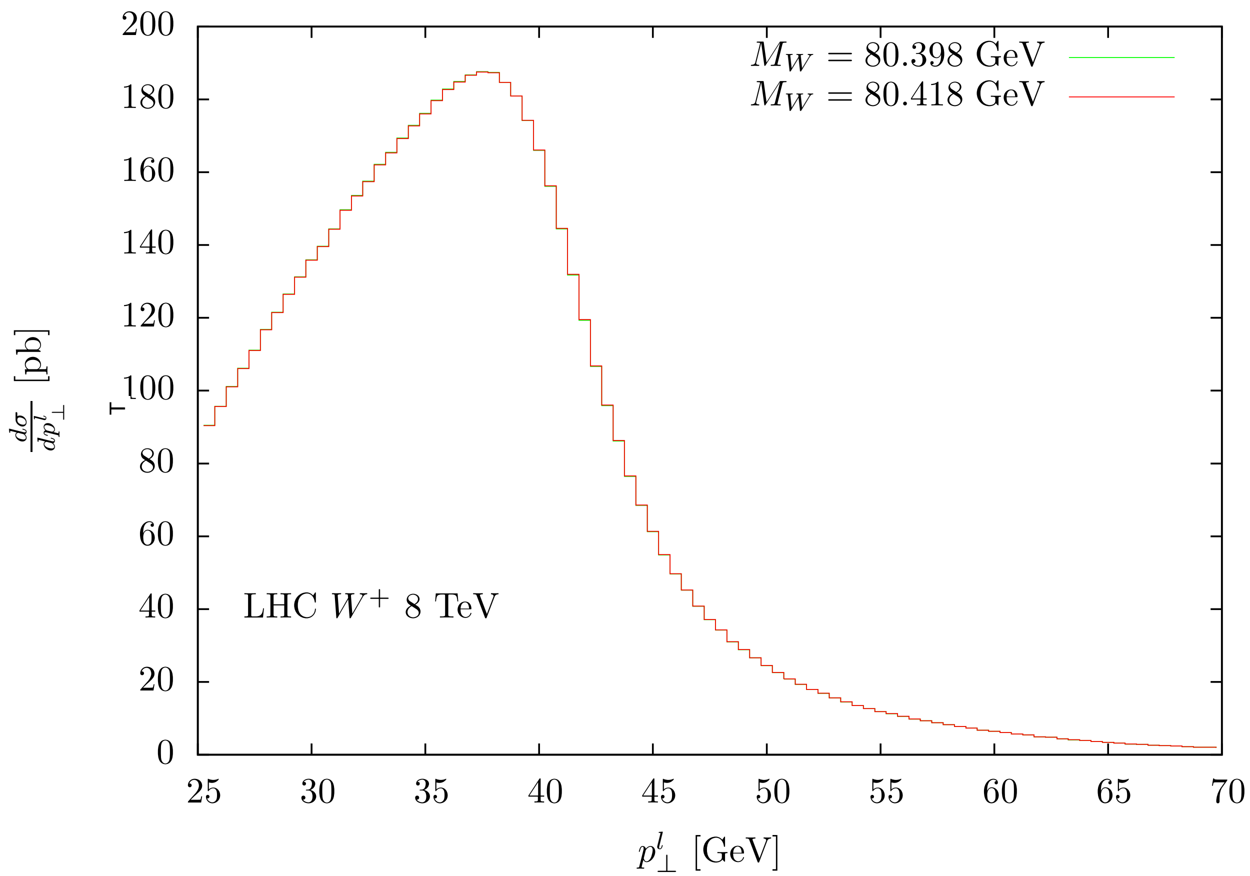

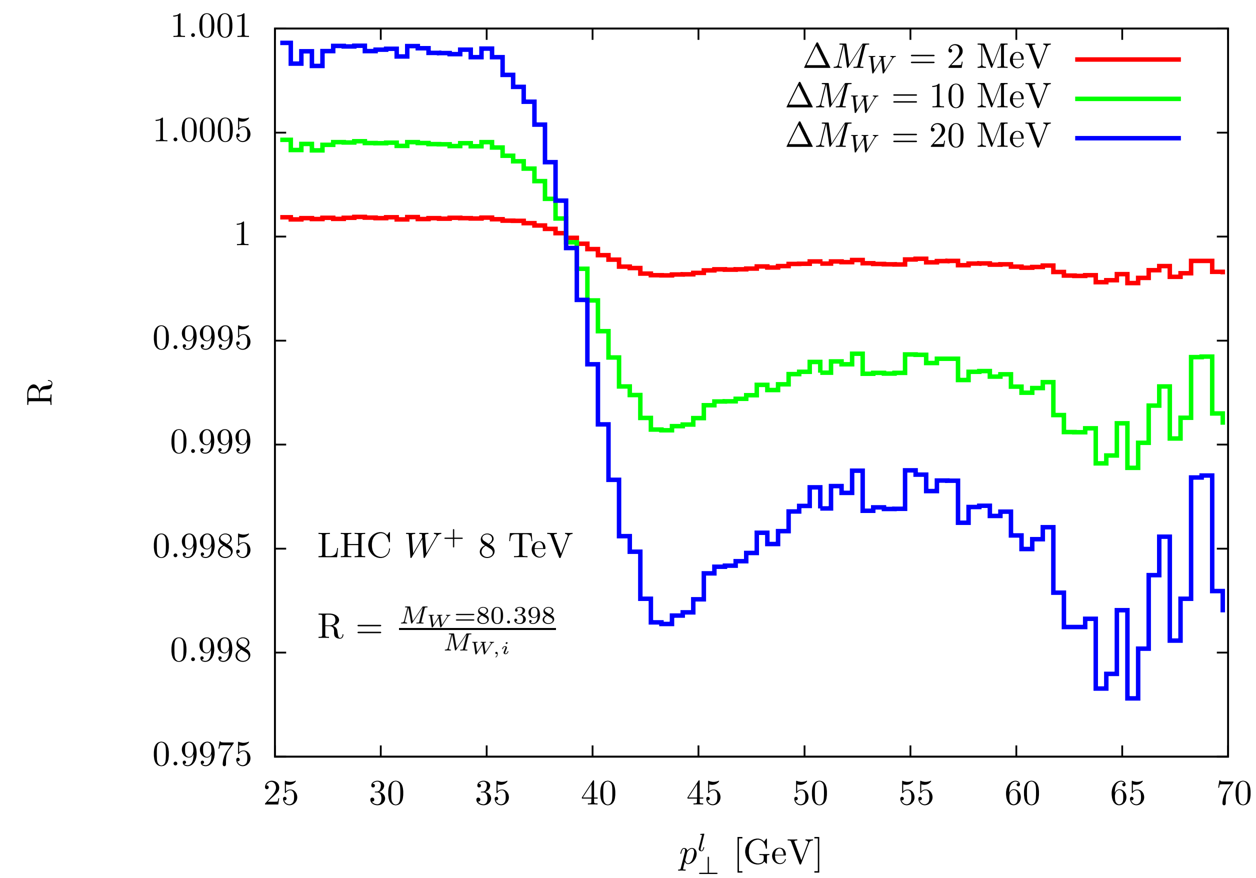

A change of 10 MeV in the W mass induces distortions at the per mille level only: challenging

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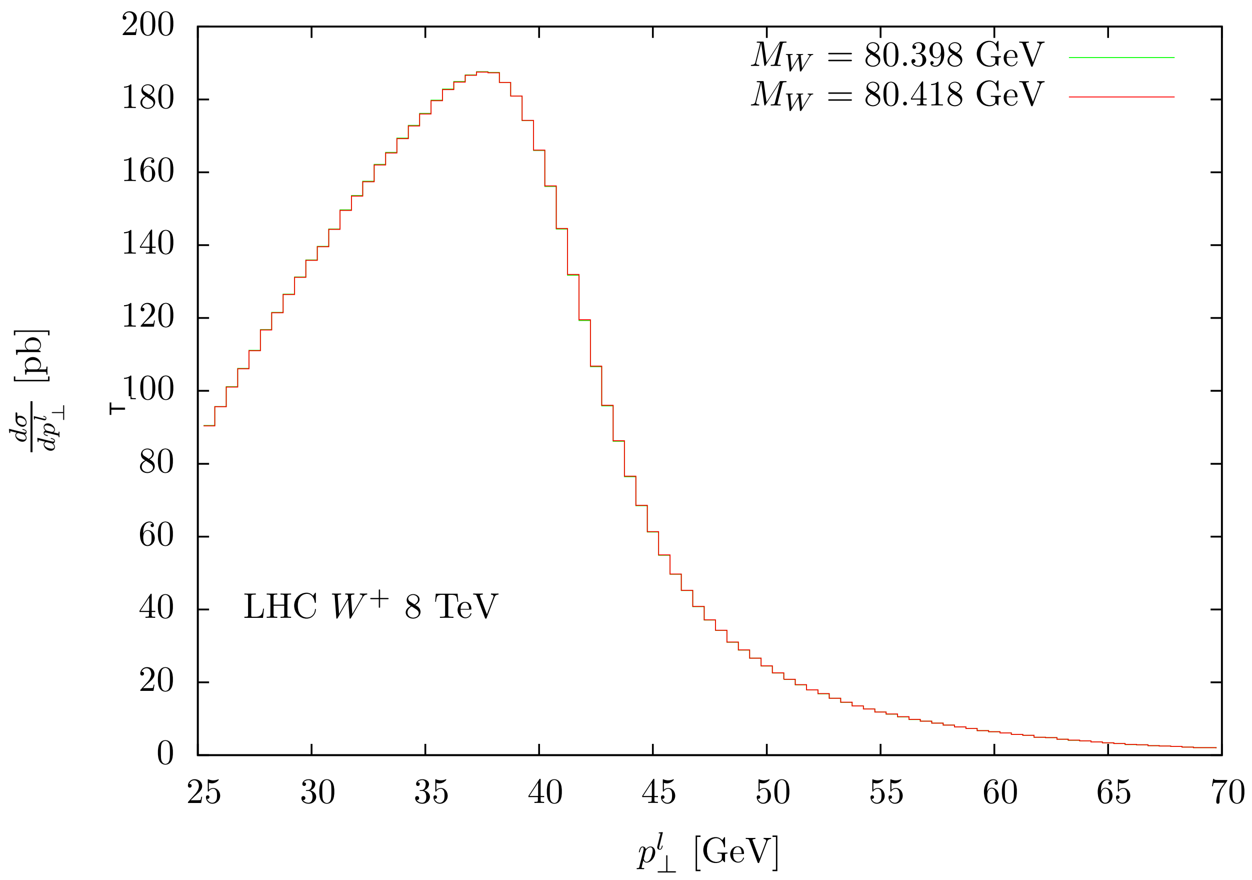

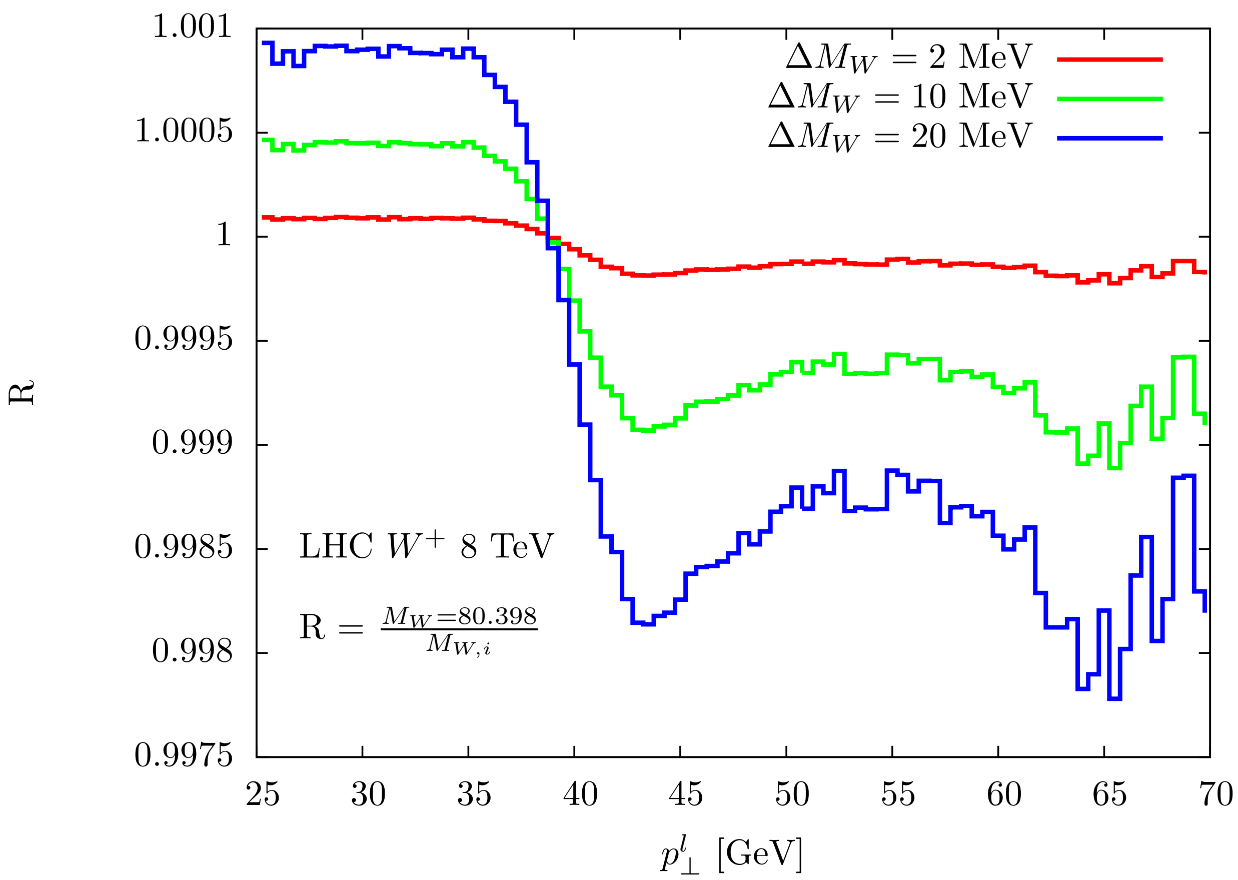

A change of 10 MeV in the W mass induces distortions at the per mille level only: challenging

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

Event generation

- DYRes code (arXiv:1507.06937)

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

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- LHC 7 TeV + ATLAS cuts or 13 TeV + LHCb cuts

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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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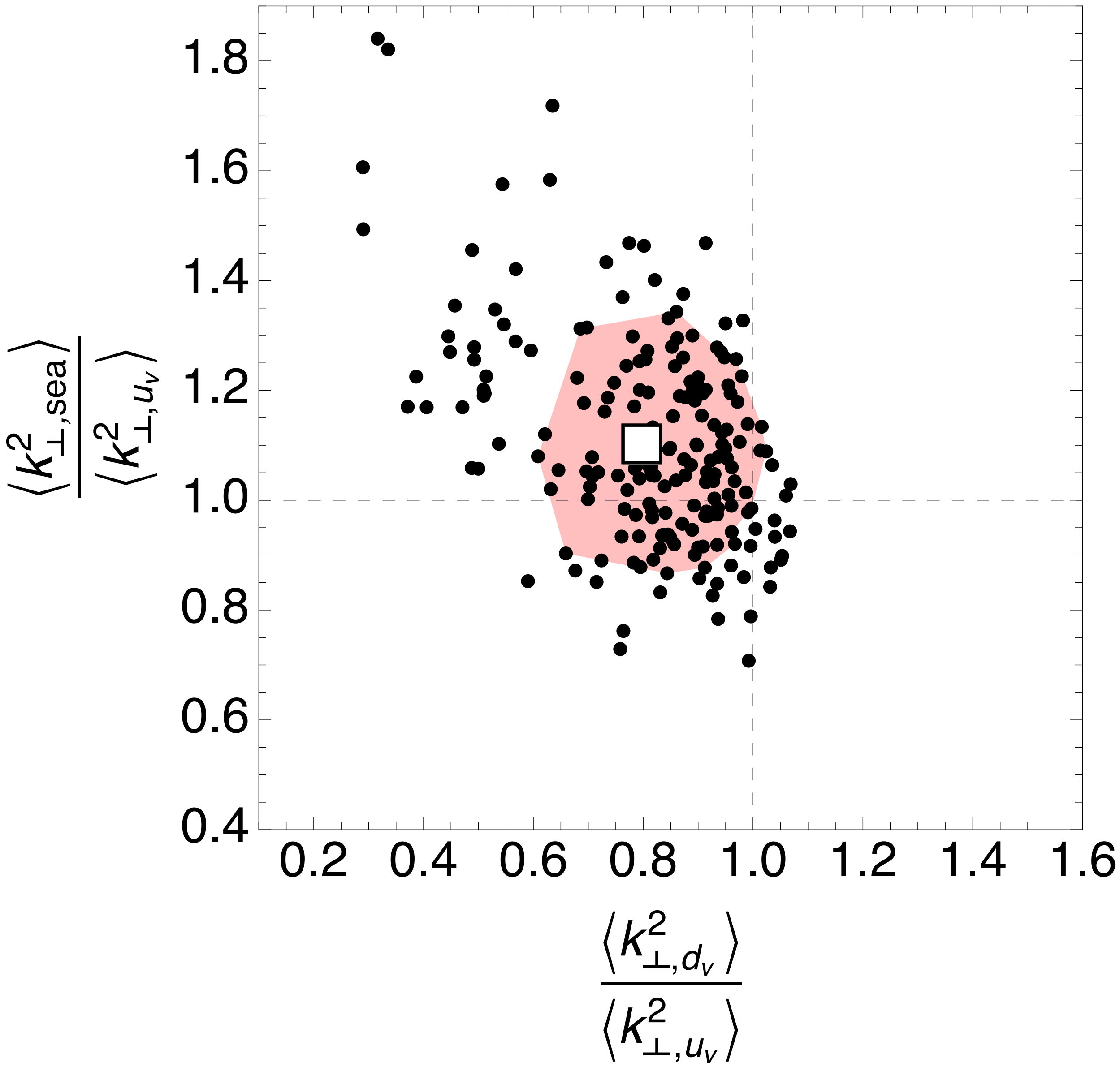
Perturbative parts at order α_S — **NLL**

Flavor dependent intrinsic transverse momentum F_{NP}

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

The TMD flavor dependence

Signori, Bacchetta, Radici, Schnell, arXiv: 1309.3507



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

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

Values for the parameters

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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- **1 flavour-independent set** with $g_{NP}^{a} = 0.4\ \mathrm{GeV}^2$

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

Template fit

TEMPLATES

- high statistics (750M events)
- different values of M_W
  $\Delta M_W = -15$ MeV to $+15$ MeV
- flavor-independent intrinsic transverse momentum

Template fit

TEMPLATES

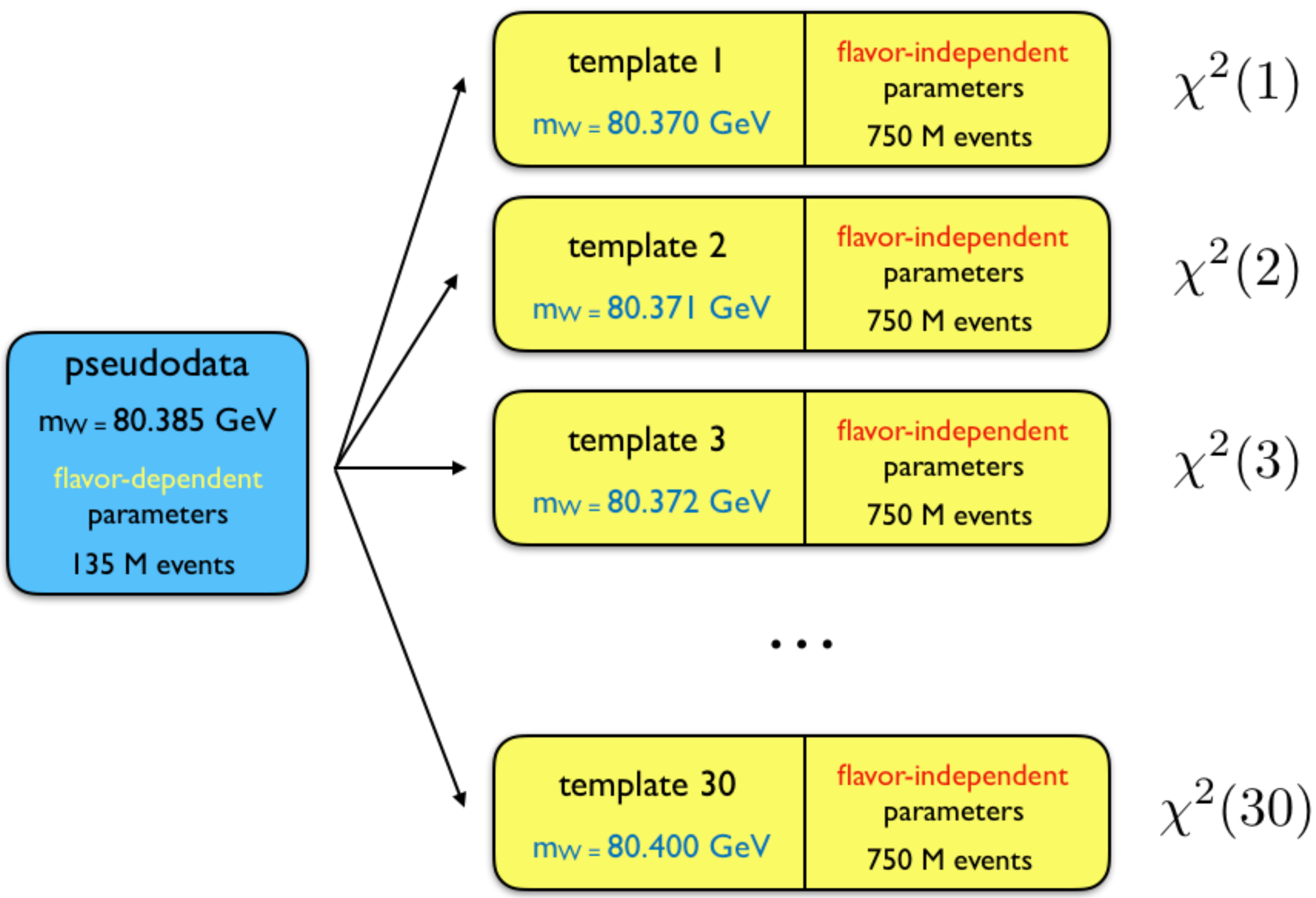
- high statistics (750M events)
- different values of M_W
  $\Delta M_W = -15$ MeV to $+15$ MeV
- flavor-independent intrinsic transverse momentum

PSEUDODATA

- "low" statistics (135M events)
- central value of M_W
- 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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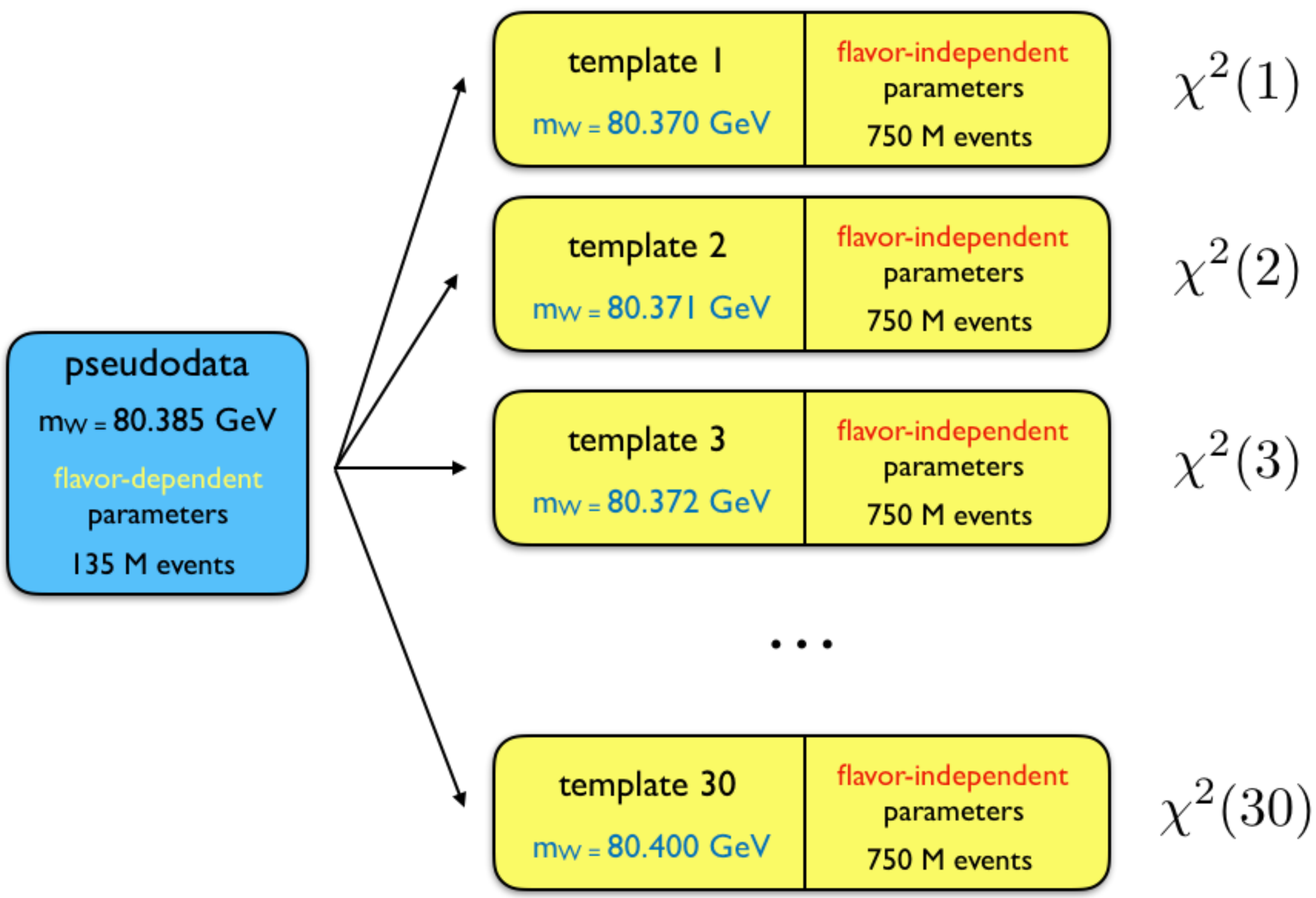
Results

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



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
9	-1	-7	7	0	4	10

Statistical uncertainty: ±2.5 MeV

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

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

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**.

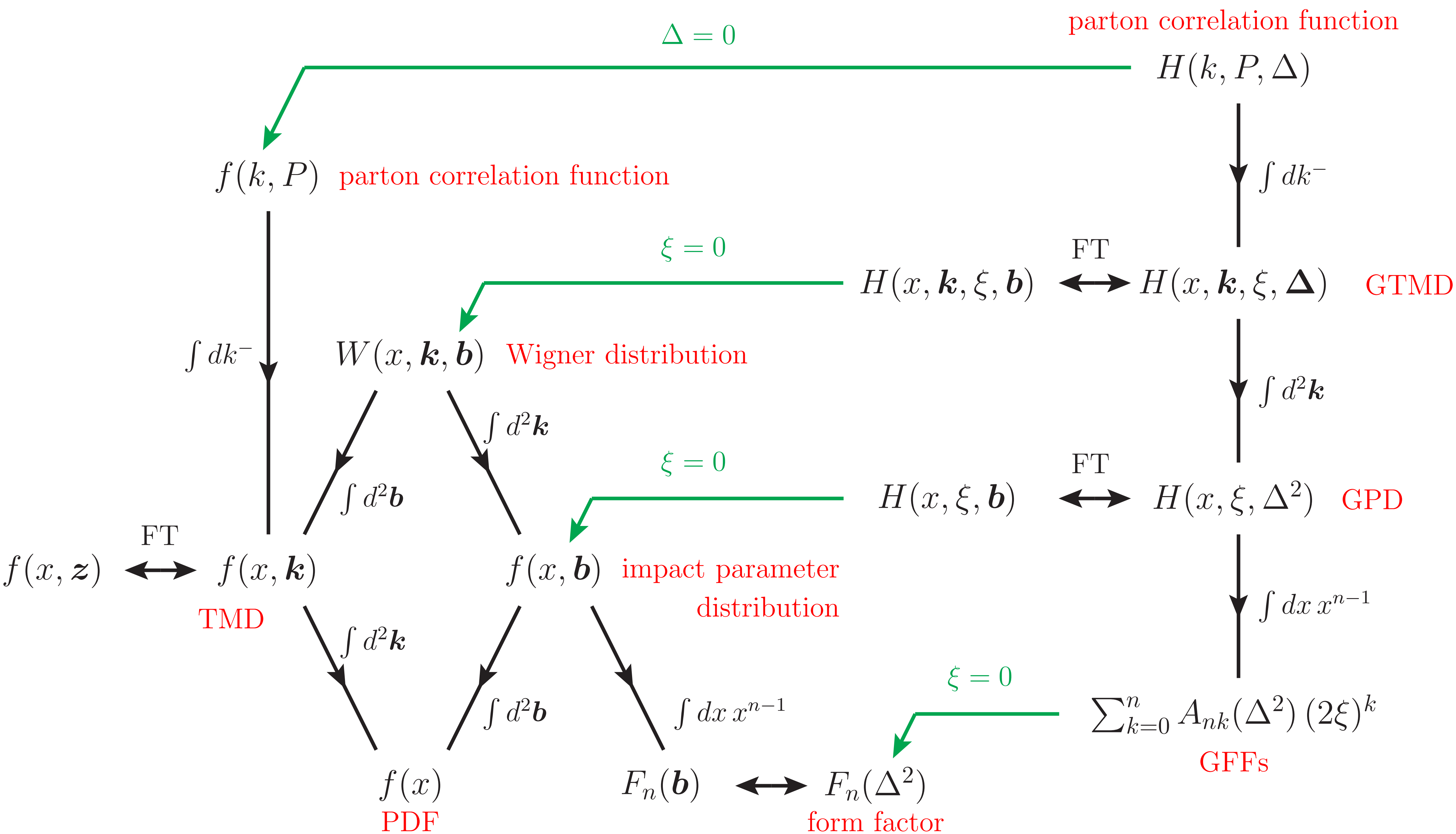
The generated mass shifts are **different for W+ and W-** and they are more evident looking at the lepton transverse momentum (rather than the transverse mass)

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

Hadron tomography



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

TMD factorization

A non-exhaustive list

Quark-induced processes :

- Collins, Soper (1981) - $e^+e^- \longrightarrow h_1h_2X$ [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]

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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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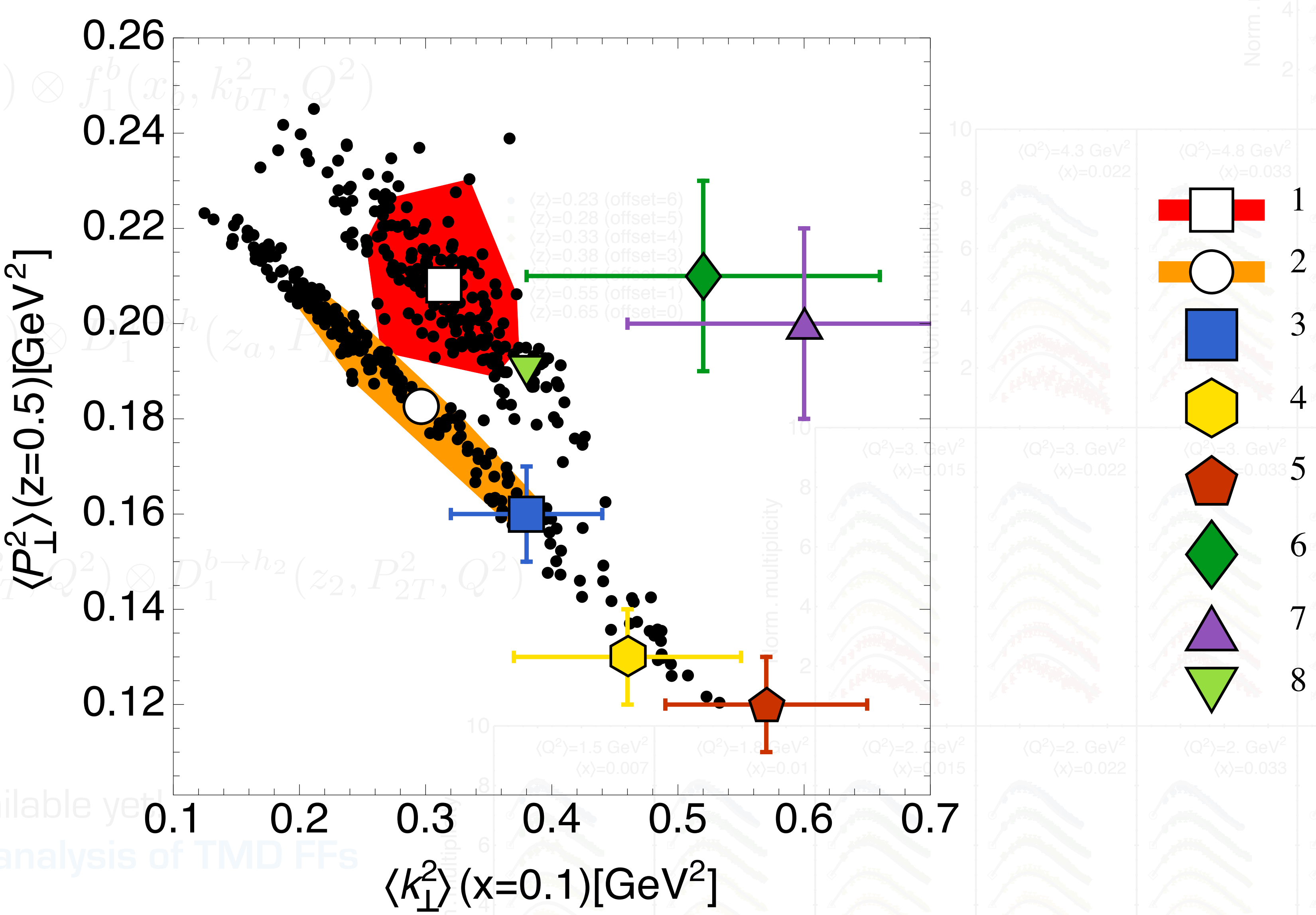
TMD factorization at work

Bacchetta, Delcarro, Pisano, Radici, **AS** (1703.10157) :
unpolarized TMD fit including **SIDIS**, **Drell-Yan** fixed-target, **Z production**



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

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

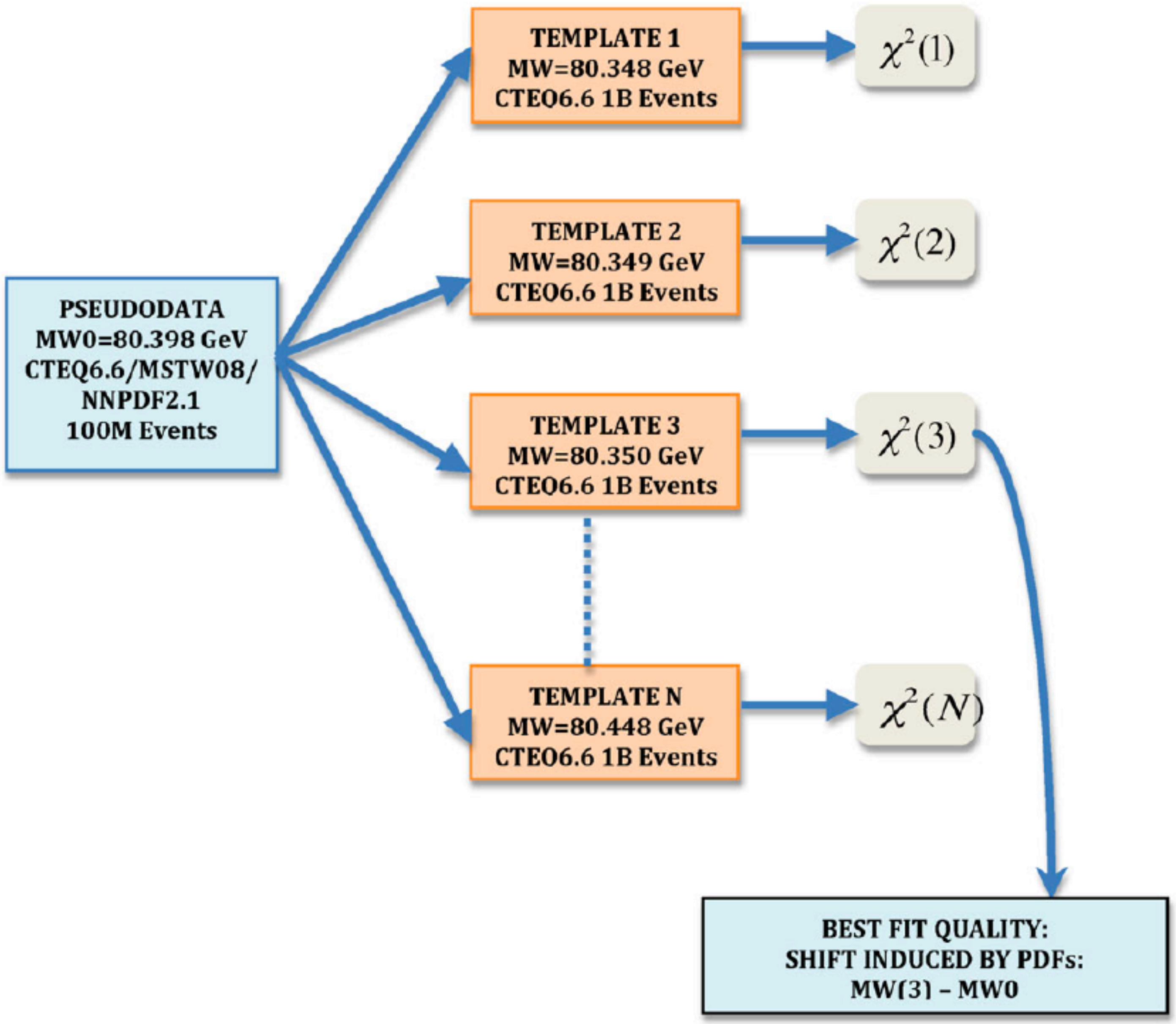
assuming no differences in flavor

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**)

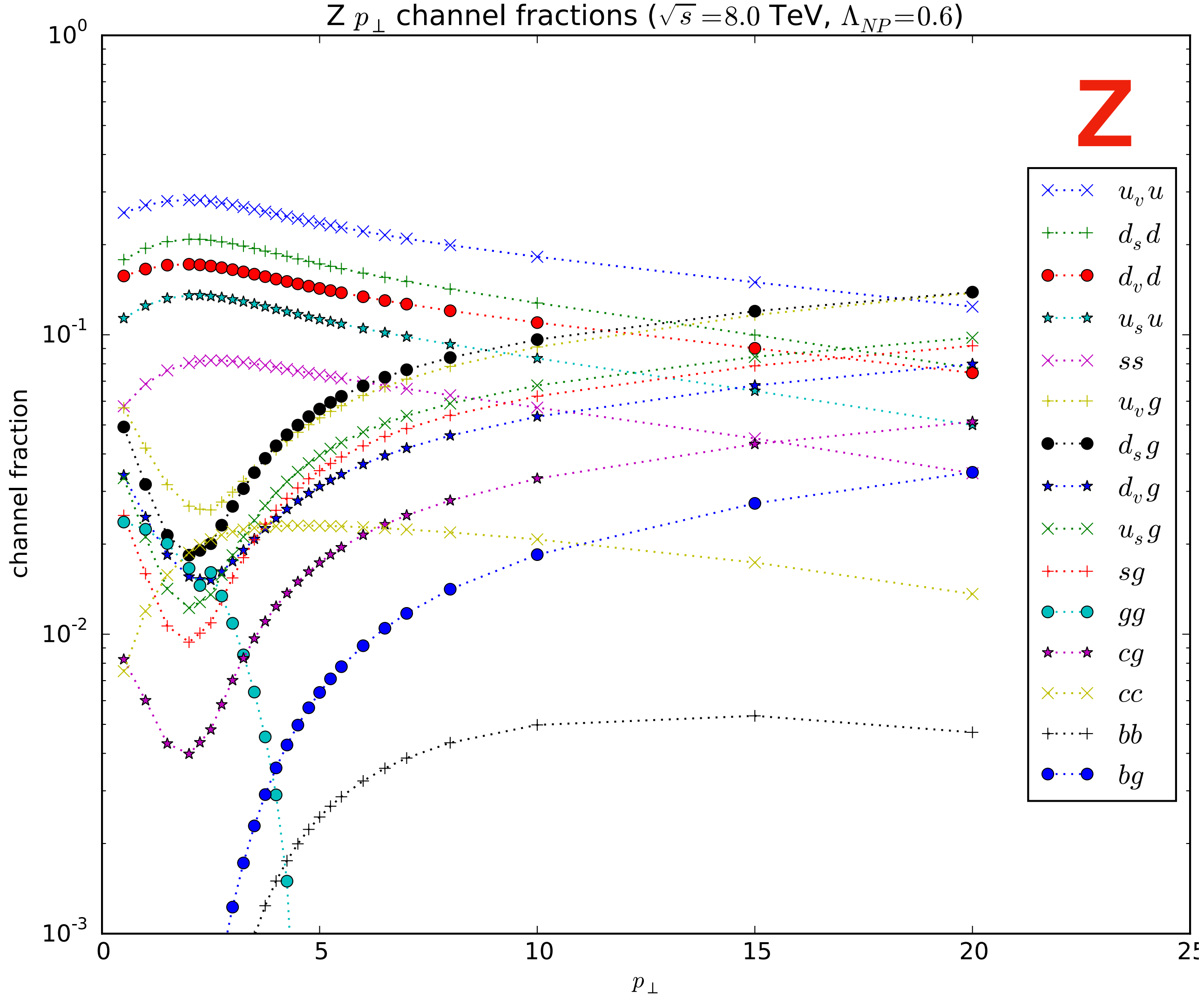
- In the **templates** M_W changes

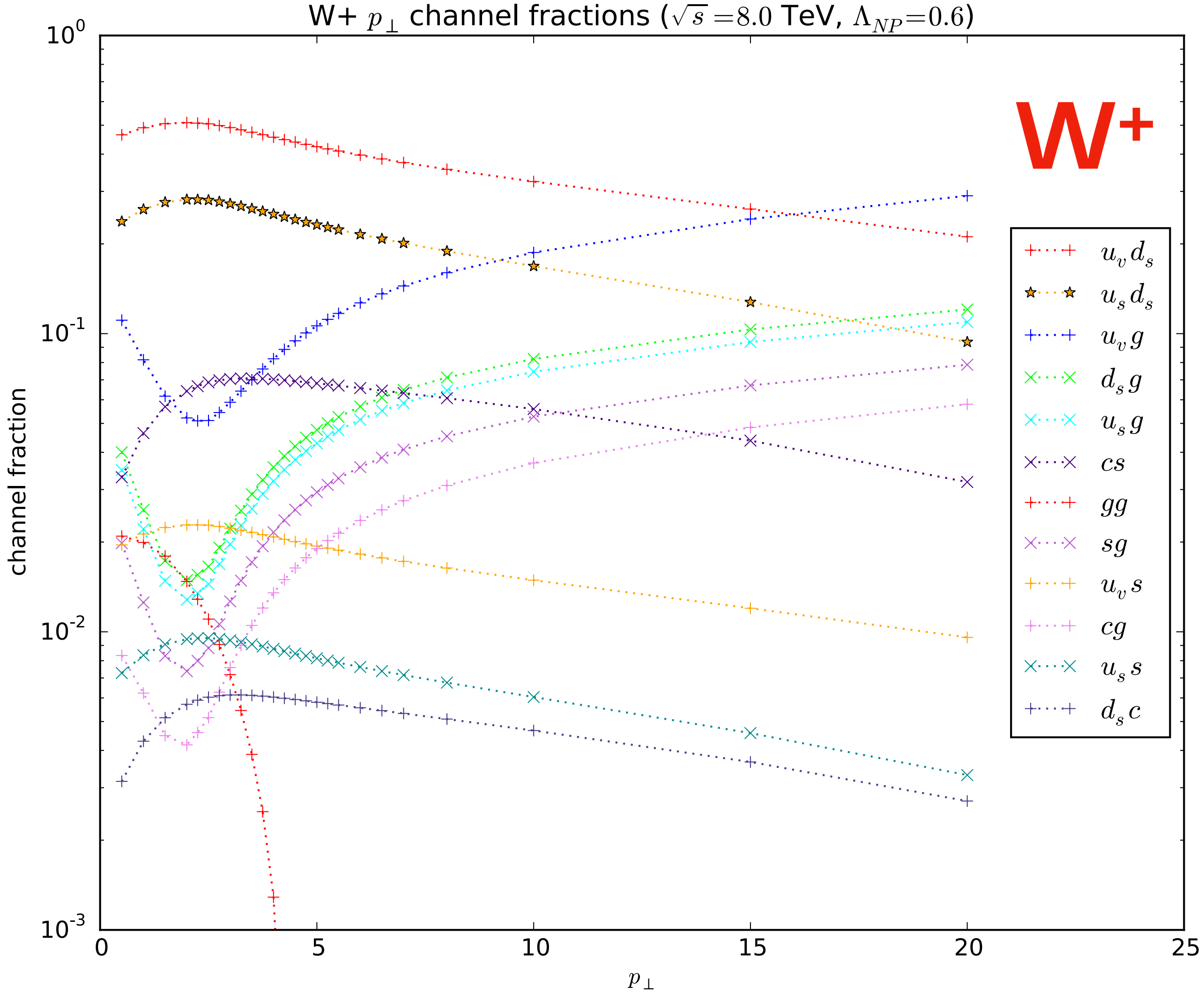
- The template **fit** is applied to the pseudodata and the difference between the extracted M_W and the input one is used to **determine δM_W**



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

Flavor content





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

uval-dbar is the most important channel

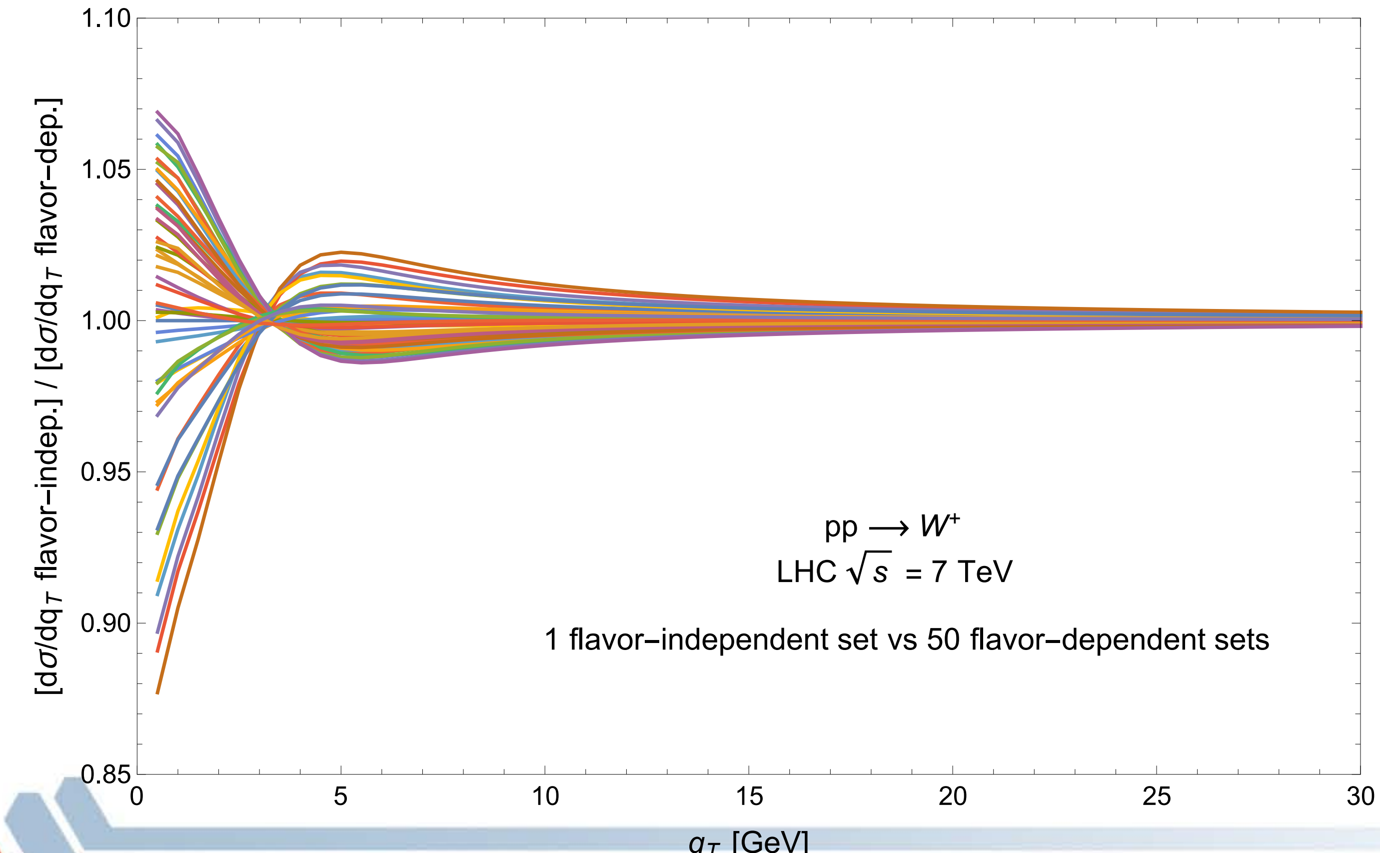
Impact on W q_T spectrum

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!

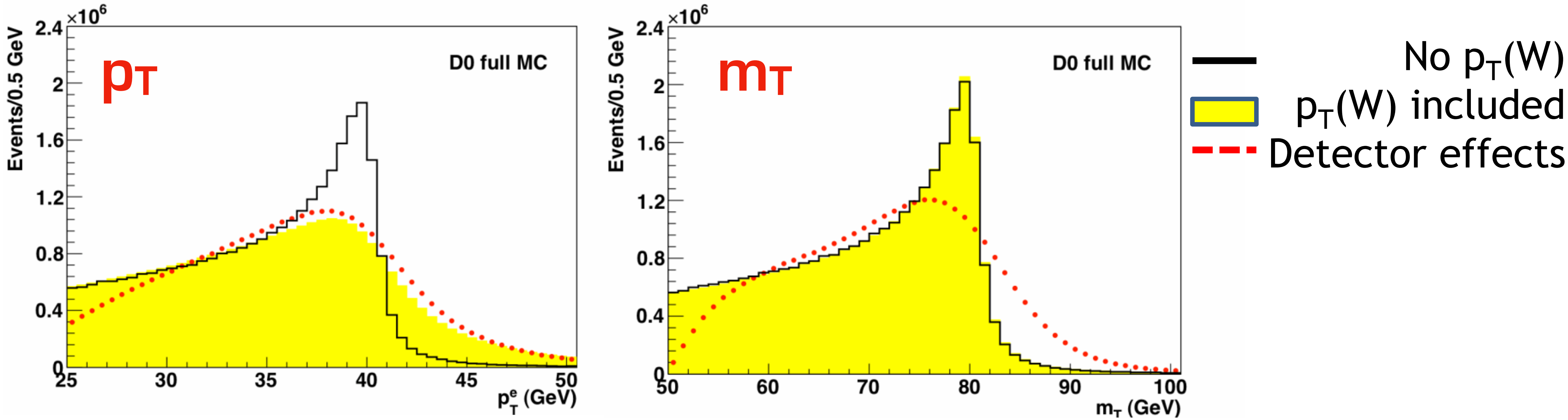
The flavor structure of the TMDs can affect the shape of the W qT spectrum up to 5%-10% at very low qT



Impact on lepton pT and mT

Impact on mW

Transverse mass



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

Values for the parameters

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

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

narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
medium, narrow, large