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Parton distributions as a bridge from low to high energies

CTEQ - Jefferson Lab

Nov. 10th, 2018

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"It has long been an axiom of mine that the little things are infinitely the most important."
— Sir Arthur Conan Doyle, The Memoirs of Sherlock Holmes

F. Olness, yesterday

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Effect of flavor-dependent partonic transverse momentum on the determination of the W boson mass in hadronic collisions

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(Dated: Friday 6th July, 2018)

Within the framework of transverse-momentum-dependent factorization, we investigate for the first time the impact of a flavor-dependent intrinsic transverse momentum of quarks on the production of $W^{\pm}$ bosons in proton-proton collisions at $\sqrt{s} = 7$ TeV. We estimate the shift in the extracted value of the W boson mass M_W induced by different choices of flavor-dependent parameters for the intrinsic quark transverse momentum by means of a template fit to the transverse-mass and the lepton transverse-momentum distributions of the W-decay products. We obtain $-11 \leq \Delta M_{W^+} \leq 4$ MeV and $-6 \leq \Delta M_{W^-} \leq 2$ MeV with a statistical uncertainty of ± 4 MeV. Our findings call for more detailed investigations of flavor-dependent nonperturbative effects linked to the proton structure at hadron colliders.

PACS numbers: 14.70.Fm, 13.85.Qk, 12.38.-t

arXiv:1807.02101v1 [hep-ph] 5 Jul 2018

Introduction and motivation. Nonperturbative effects in transverse-momentum-dependent (TMD) phenomena are a central topic in the hadronic physics community with potentially important applications to high-energy physics. The study of nonperturbative corrections originates from the work of Parisi and Petronzio [1] and Collins, Soper, and Sterman [2], which focused on the role of the hard scale of the process compared to the infrared scale of QCD. TMD factorization and evolution have been extensively studied in the literature [3–6], together with the matching to collinear factorization [2, 7–12]. Despite the limited amount of data available and the many open theoretical questions, in the past years we started gaining phenomenological information about TMD parton distribution functions (TMD PDFs) with increasing level of accuracy. Recently, the unpolarized quark TMD PDF was extracted for the first time from a global fit of data ... deep-inelastic scattering (SIDIS) and ... Z bosons [13].

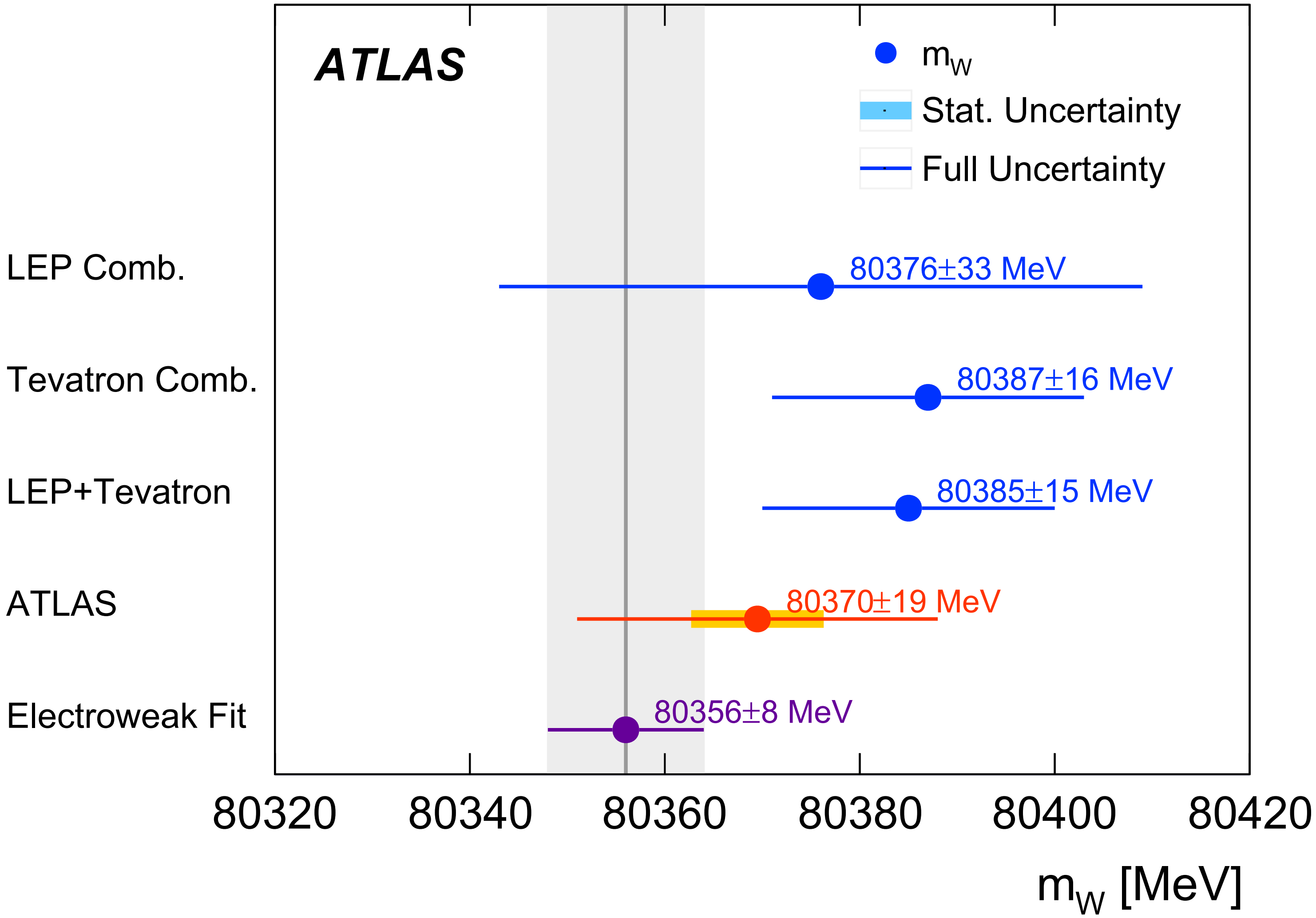
Experimental measurements and uncertainties. The determination of the W boson mass, M_W, from the global electroweak fit (M_W=80.356±8 MeV) [20] features a very small uncertainty that sets a goal for the precision of the experimental measurements at hadron colliders.

Precise determinations of M_W have been extracted from $p\bar{p}$ collisions at D0 [21] and at CDF [22], and from pp collisions at ATLAS [23] with a total uncertainty of 23 MeV, 19 MeV and 19 MeV, respectively. The current world average, based on these measurements and the ones performed at LEP, is M_W=80.379±12 MeV [24]. The experimental analyses are based on a template-fit procedure on the differential distributions of the decay products: in particular, the transverse momentum of the final lepton, $p_{T\ell}$, the transverse momentum of the neutrino $p_{T\nu}$ (only at the Tevatron), and the transverse mass m_T of the lepton pair (where $m_T = \sqrt{2\, p_{T\ell}\, p_{T\nu}\, (1 - \cos(\phi_\ell - \phi_\nu))}$, with $\phi_{\ell,\nu}$ being the azimuthal angles of the lepton and the neutrino, respectively).

... fit procedure, several histograms are gen... ...tical accuracy and

The state of the art

ATLAS Collab. arXiv:1701.07240



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

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

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:

$$-11 \leq M_{W^+} \leq 4 \text{ MeV}$$

$$-6 \leq M_{W^-} \leq 2 \text{ MeV}$$

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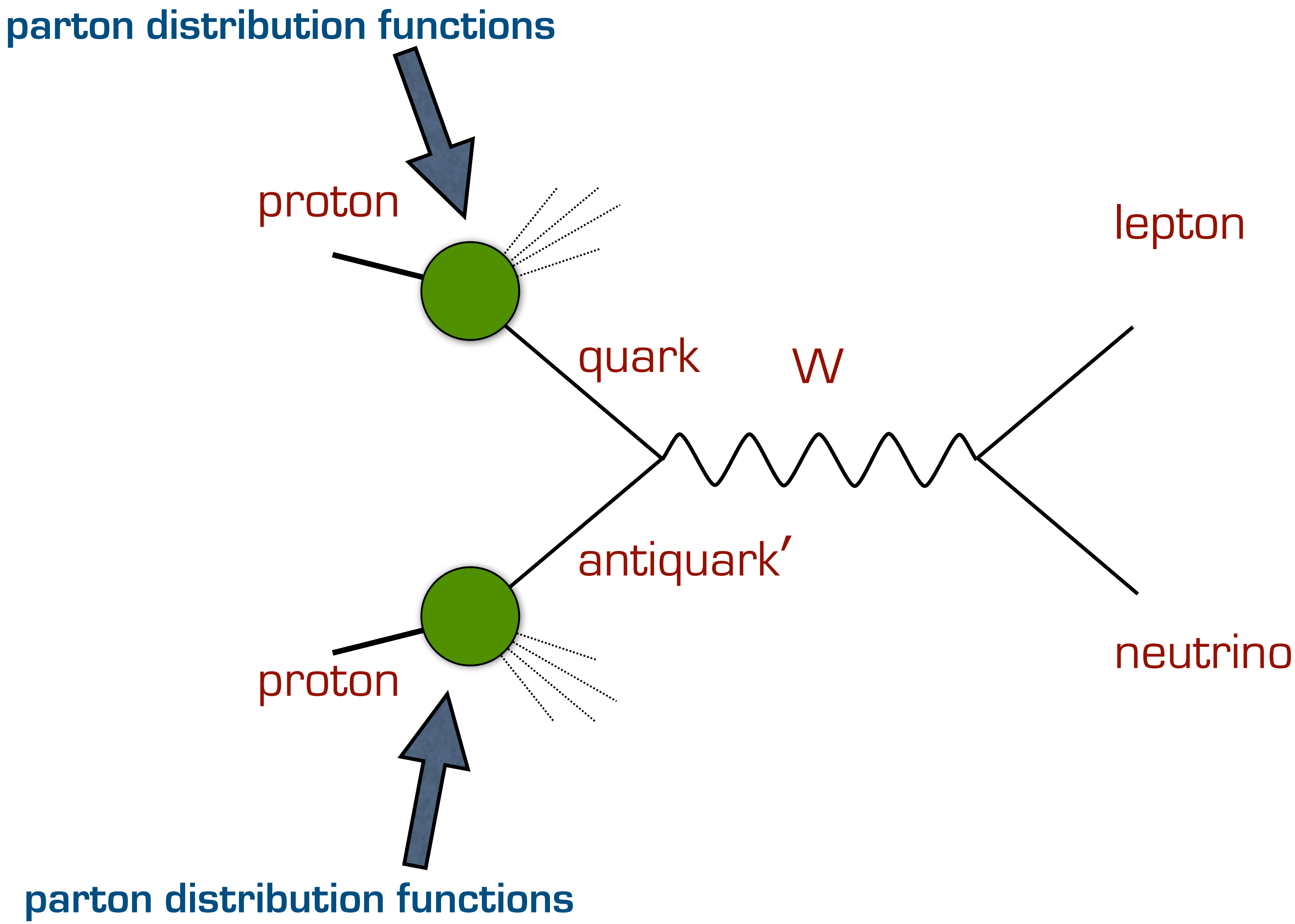
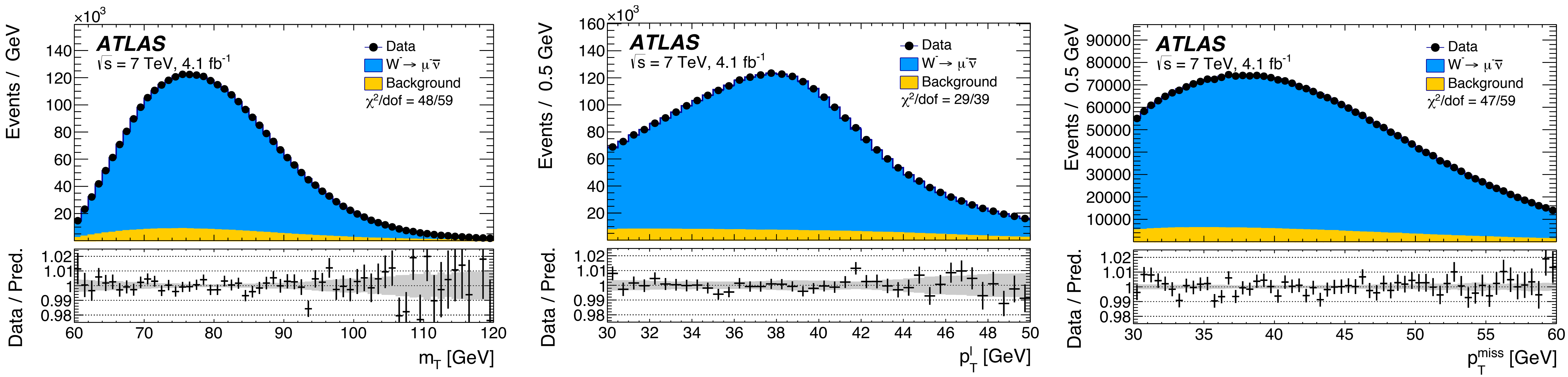
W boson production



How to determine mW

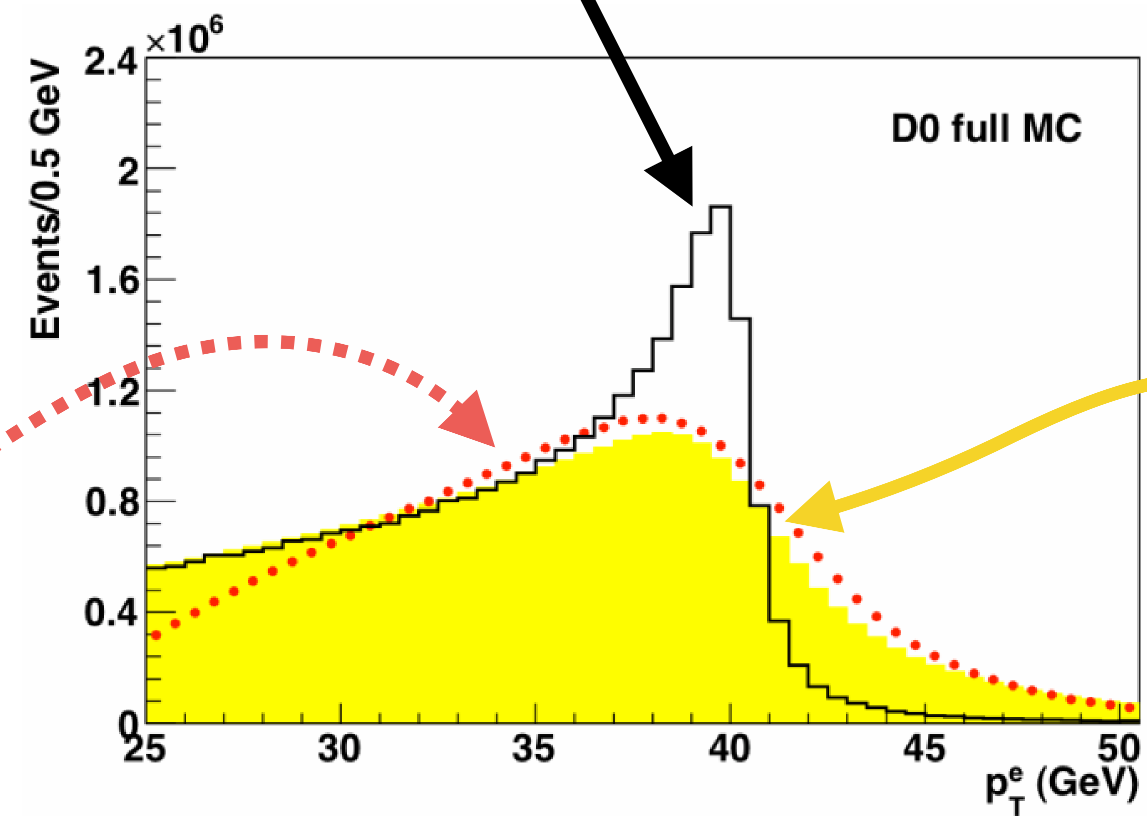


M_W extracted from the study of the shape of m_T, p_{Tl}, p_{Tmiss}

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

Lepton pT distribution

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

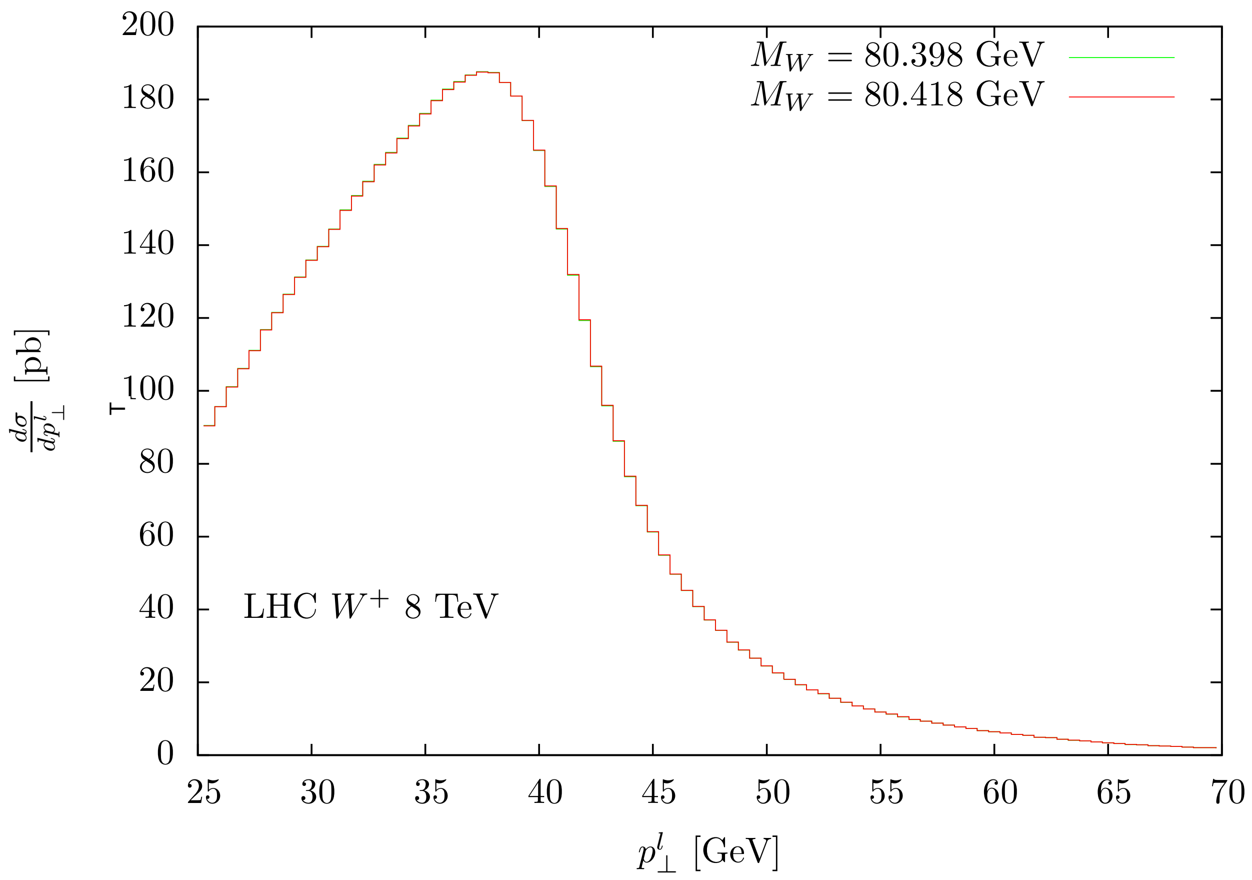


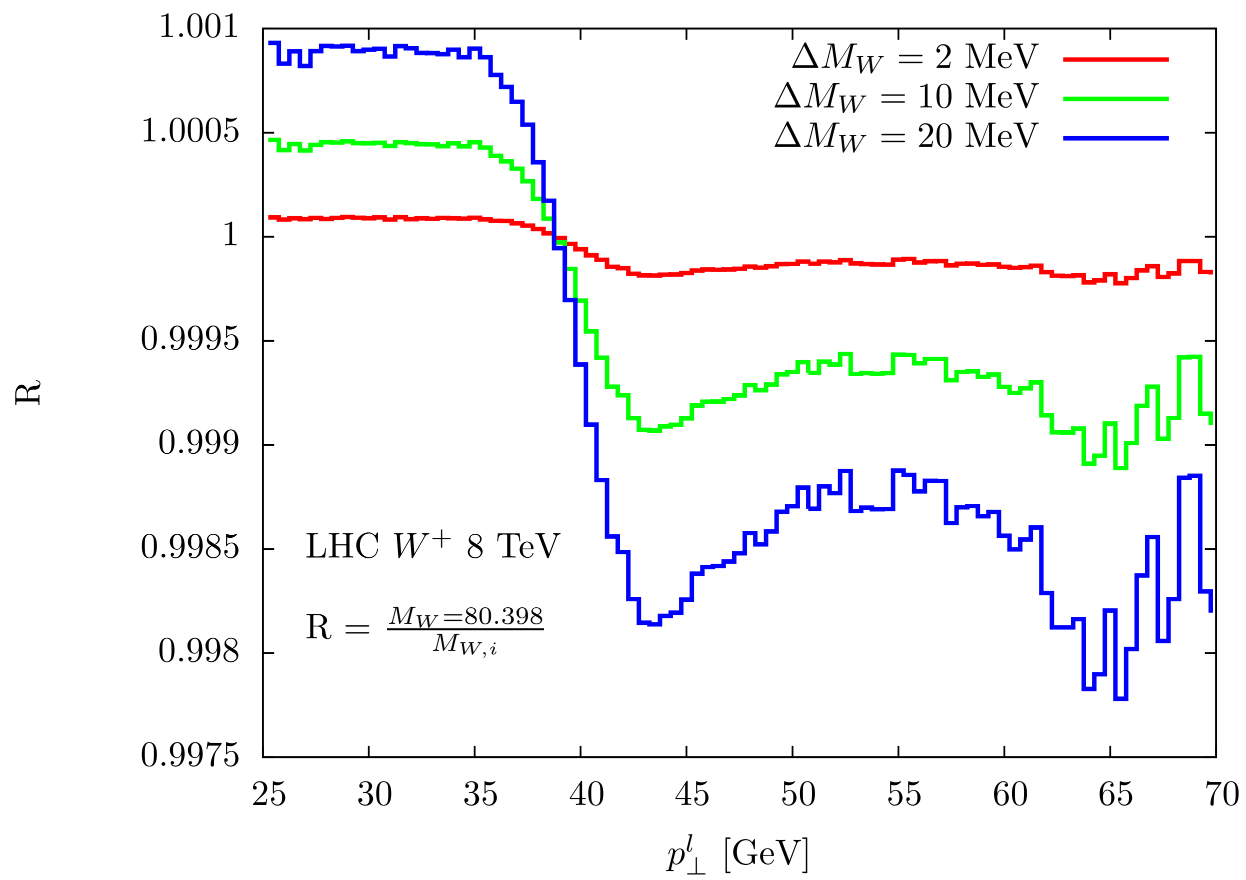
Detector effects cause further changes

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





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

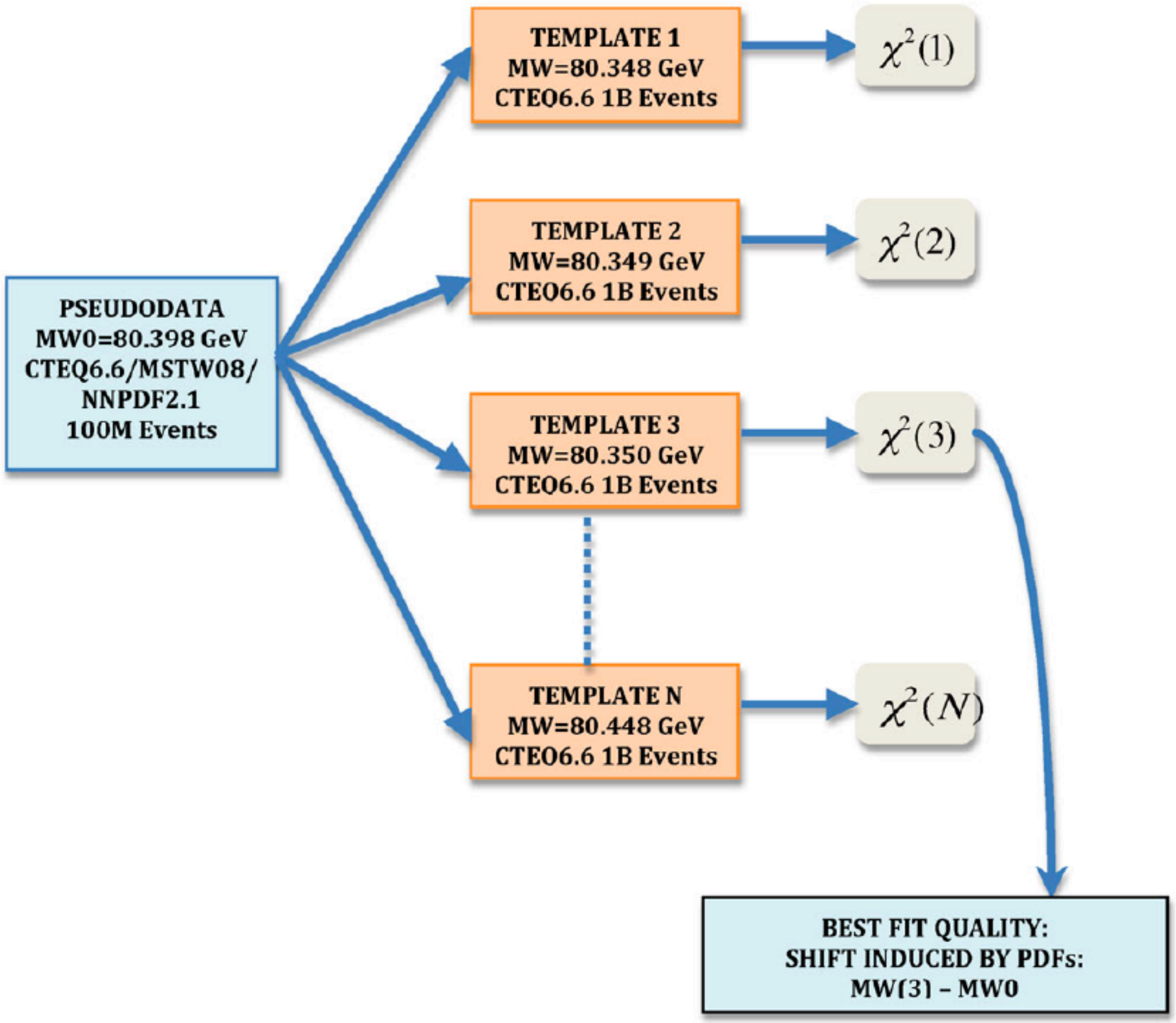
- Using Monte Carlo generators that include all known corrections, several high-statistics “templates” are produced with different M_W.

- The template that fits data best determines the value of M_W.

Estimating uncertainties

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

- 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

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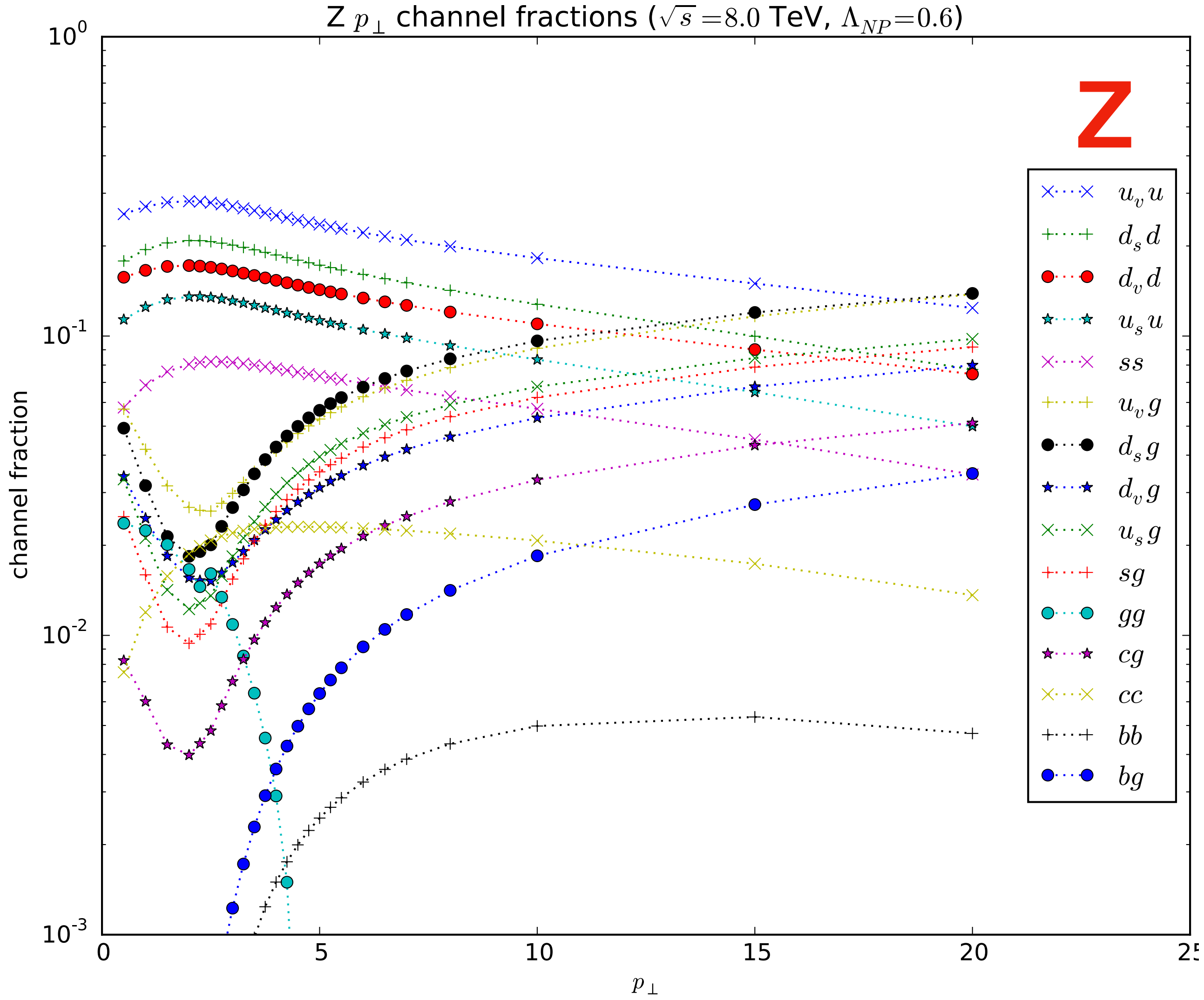
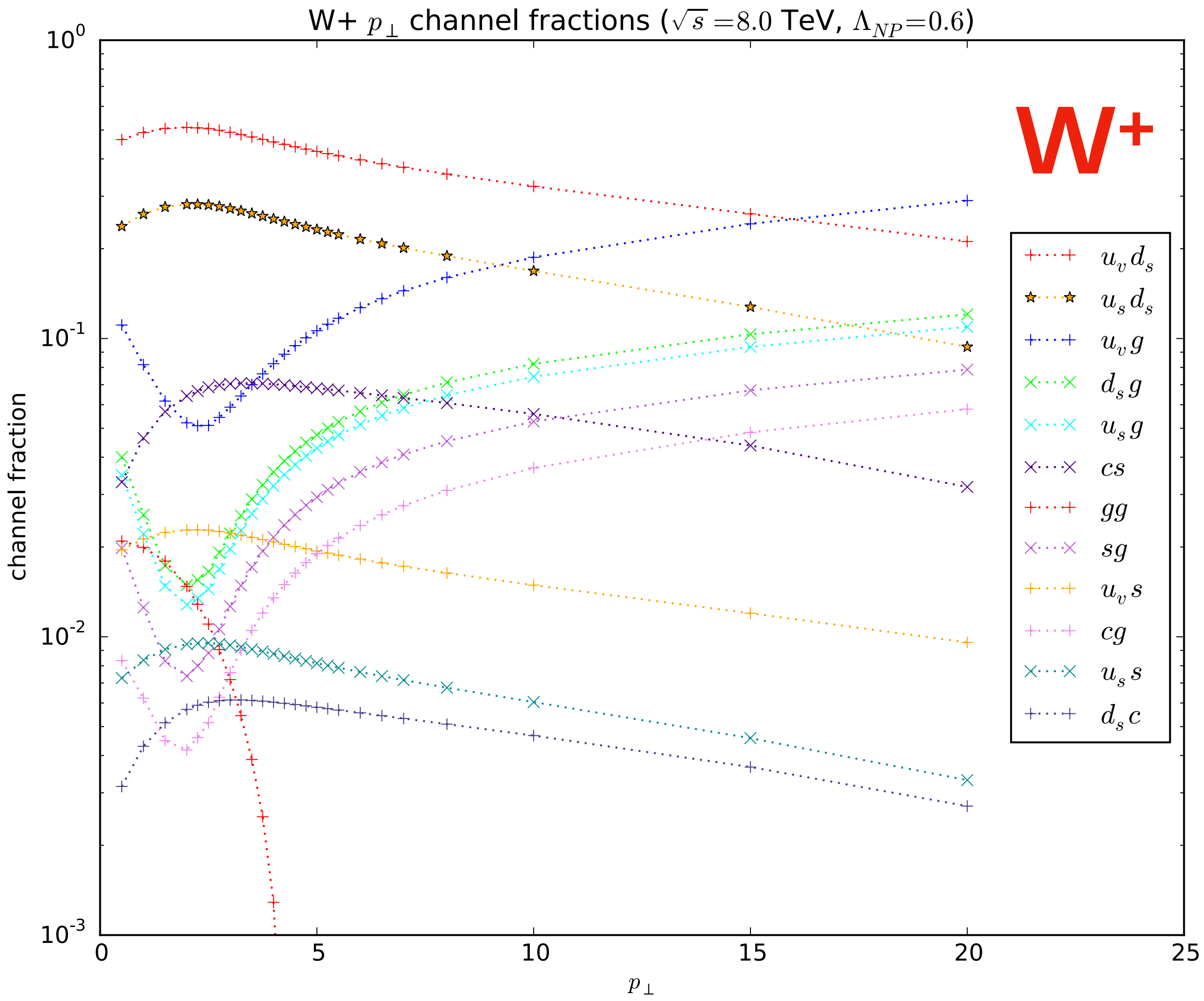
Impact of the transverse structure

Flavor content





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

uval-dbar is the most important channel

Event generation

- DYRes code of Catani, de Florian, Ferrera, Grazzini (2015)
- We assume the conditions of LHC 7 TeV and ATLAS acceptance cuts
- The cross section involves Transverse Momentum Distributions (TMDs)

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-i b_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i \big(\tilde{C}_{a/i} \otimes f_1^i\big)(x, b_*; \mu_b) e^{\tilde{S}(b_*; \mu_b, \mu)} f_1^{a\mathrm{NP}}(x, b_T)$$

Perturbative parts at order α_S — NLL

Nonperturbative corrections in TMDs

$$f_1^{a\,NP}(b_T^2) \propto e^{-g_{NP}^a b_T^2}$$

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

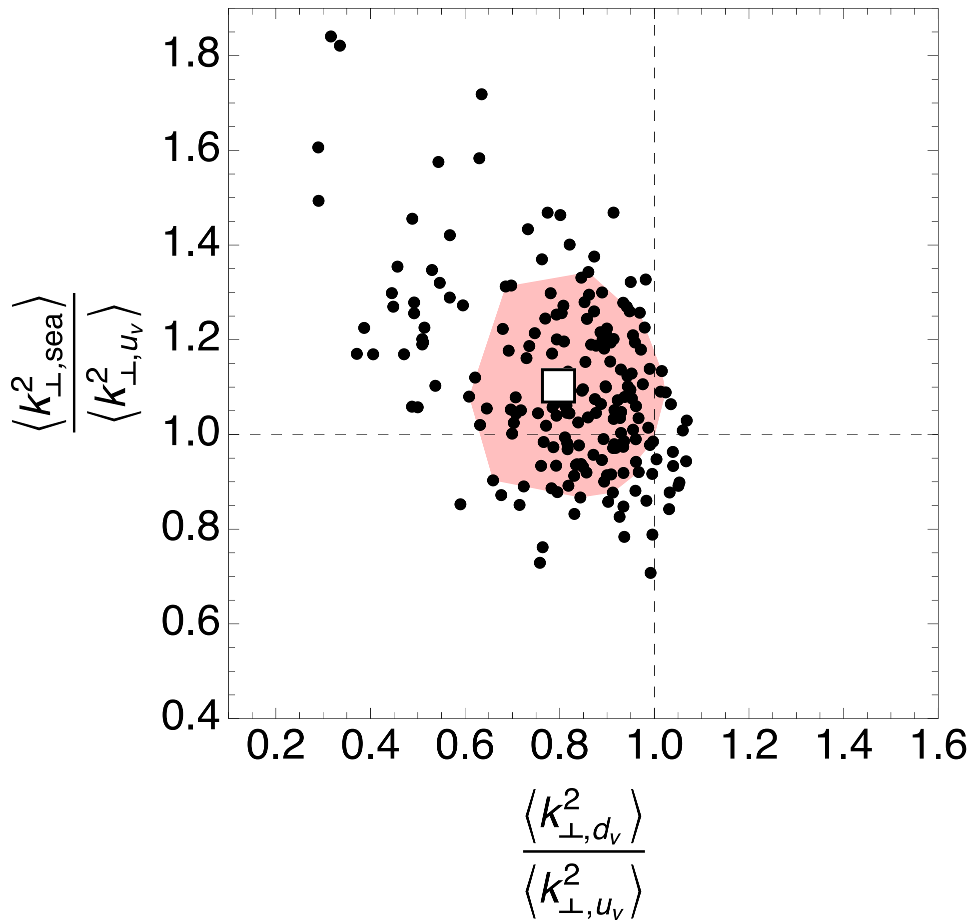
this component is flavor-independent (gluon radiation)

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



Our studies of SIDIS data indicate that there is a lot of room for flavor dependence.
More flavor-sensitive data are 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 $g_{NP}^{a} = 0.4\ \mathrm{GeV}^2$

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

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

this component can be flavor-dependent

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

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

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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 (75M events)
- central value
  $M_W = 80.385$ GeV
- flavor-dependent intrinsic transverse momentum

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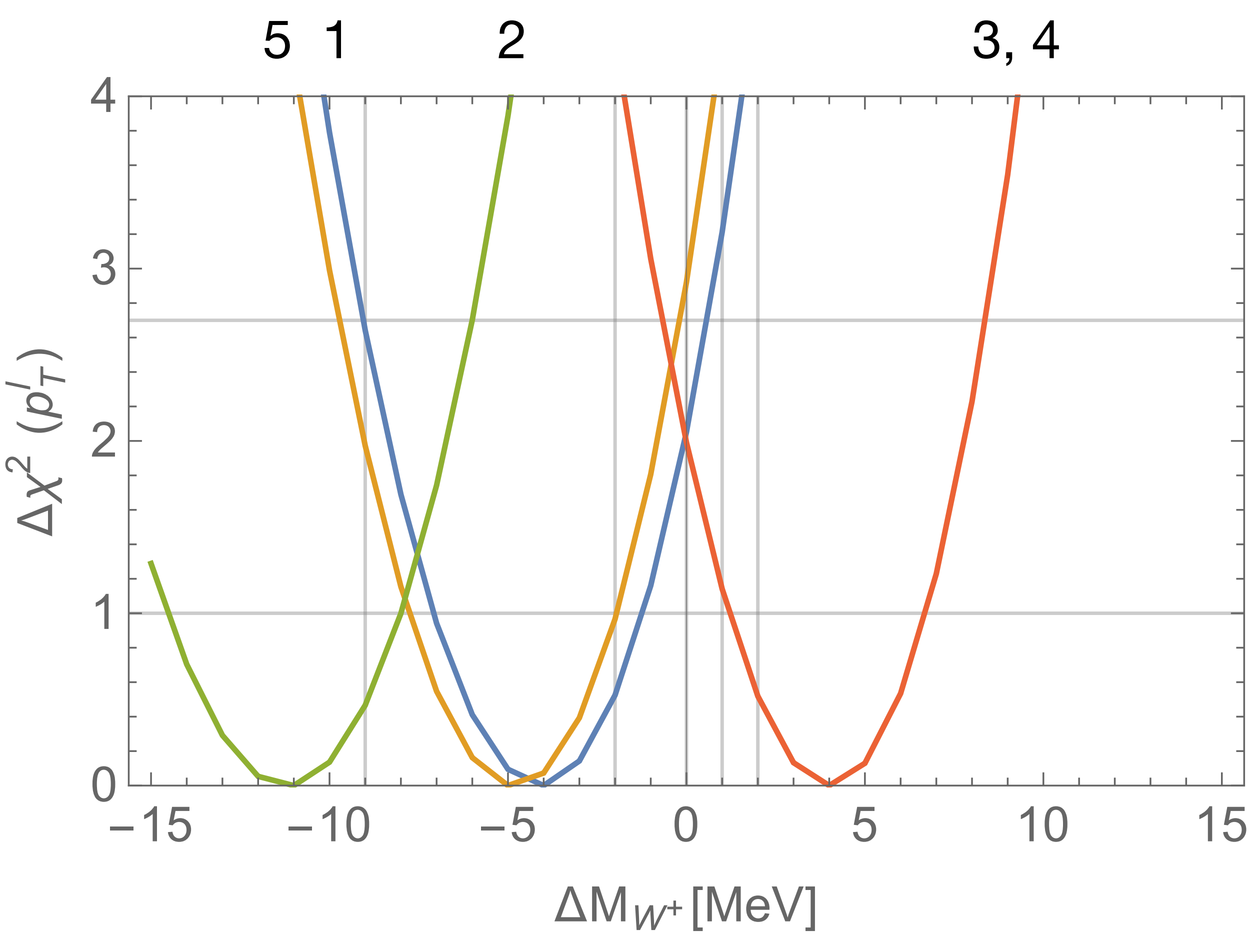
Results

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



	ΔM_{W+}		ΔM_{W-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	2	-4	-2	2
2	1	-11	-1	-3
3	0	4	-3	-6
4	1	4	-2	-5
5	2	-5	0	-5

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.

For example, sets 1 and 2 imply $\Delta m_{W^-} > \Delta m_{W^+}$

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

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	2	-4	-2	2
2	1	-11	-1	-3
3	0	4	-3	-6
4	1	4	-2	-5
5	2	-5	0	-5

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Conclusions

As for collinear PDFs, the transverse structure and its flavor-dependence can have an impact on precision studies at high-energies! It depends on the precision of your observable.

We find that the **uncertainties generated by the flavor structure in the transverse momentum can be non-negligible** in the LHC kinematics

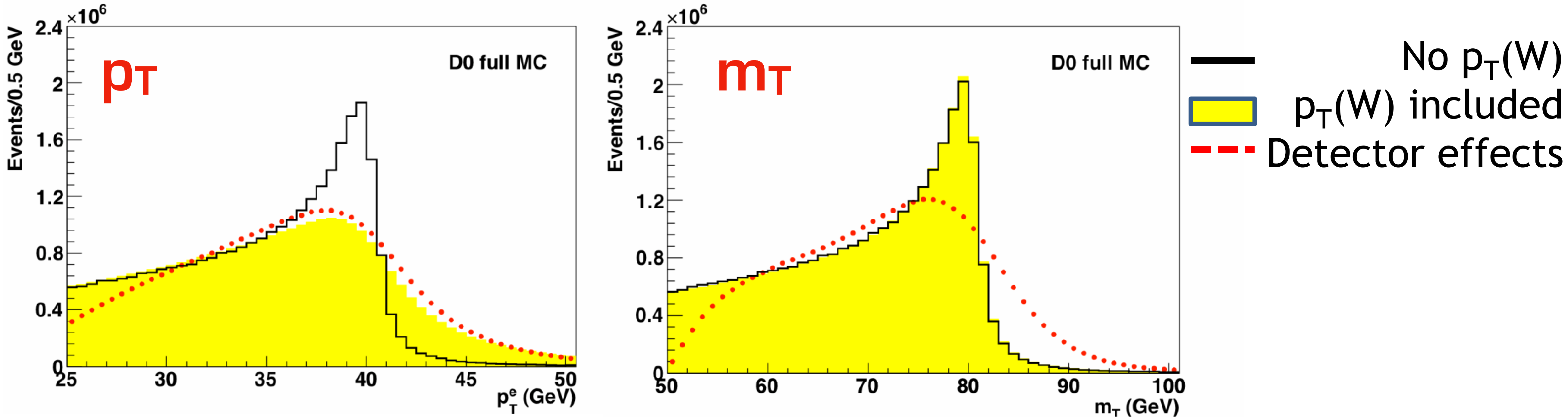
The generated mass shifts are different for W+ and W- and they are more evident looking at the lepton transverse momentum (rather than the transverse mass)

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

In principle a similar analysis can be repeated for the determination of the W mass in e+e- annihilation, looking at the flavor-dependence of the unpolarized TMD FFs.

Backup

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

Systematic uncertainties @ ATLAS

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 contains also intrinsic transverse momentum of partons. The MC has been tuned to describe Z-boson data

ATLAS Collab. arXiv:1701.07240