TMDs and the W boson mass

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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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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.

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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- ... ical accuracy and

This is a slide I presented at MENU 2010 in Williamsburg...

TMDs and determination of W mass

CDF collaboration, PRD77 (08)

TABLE XVI. Systematic uncertainties in units of MeV on the combination of the six fits in the electron and muon channels. Each uncertainty has been estimated by removing its covariance and repeating the sixfold combination.

Source	Uncertainty (MeV)
Lepton scale	23.1
Lepton resolution	4.4
Lepton efficiency	1.7
Lepton tower removal	6.3
Recoil energy scale	8.3
Recoil energy resolution	9.6
Backgrounds	6.4
PDFs	12.6
W boson p_T	3.9
Photon radiation	11.6

$$m_W = 80.398 \pm 0.025 \text{ GeV}. \quad (53)$$

...eight years later we managed to published something about it

Our findings

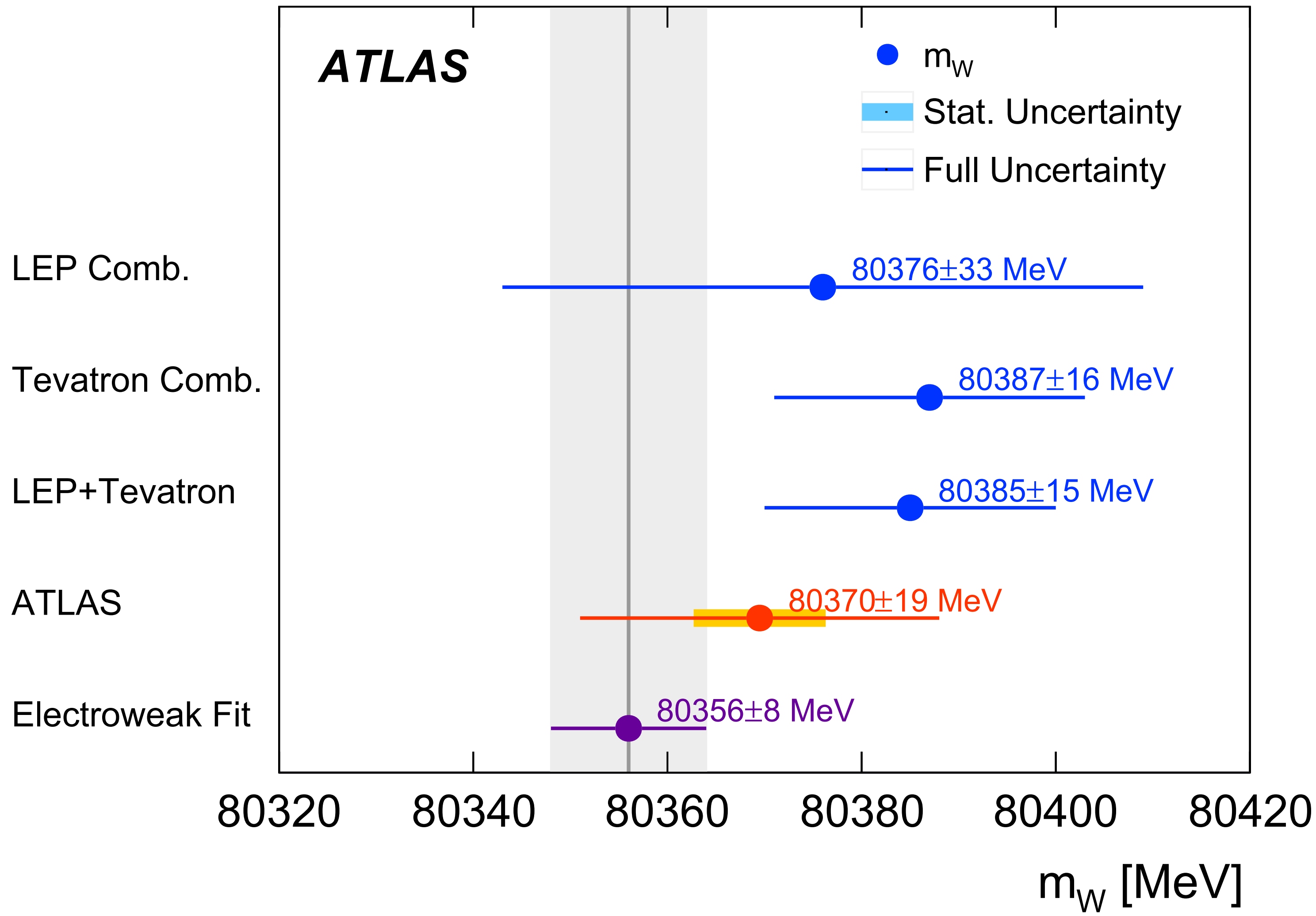
The fact that quark intrinsic transverse momentum can be flavor-dependent leads to an additional uncertainty on M_W, not considered so far.

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

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

The state of the art

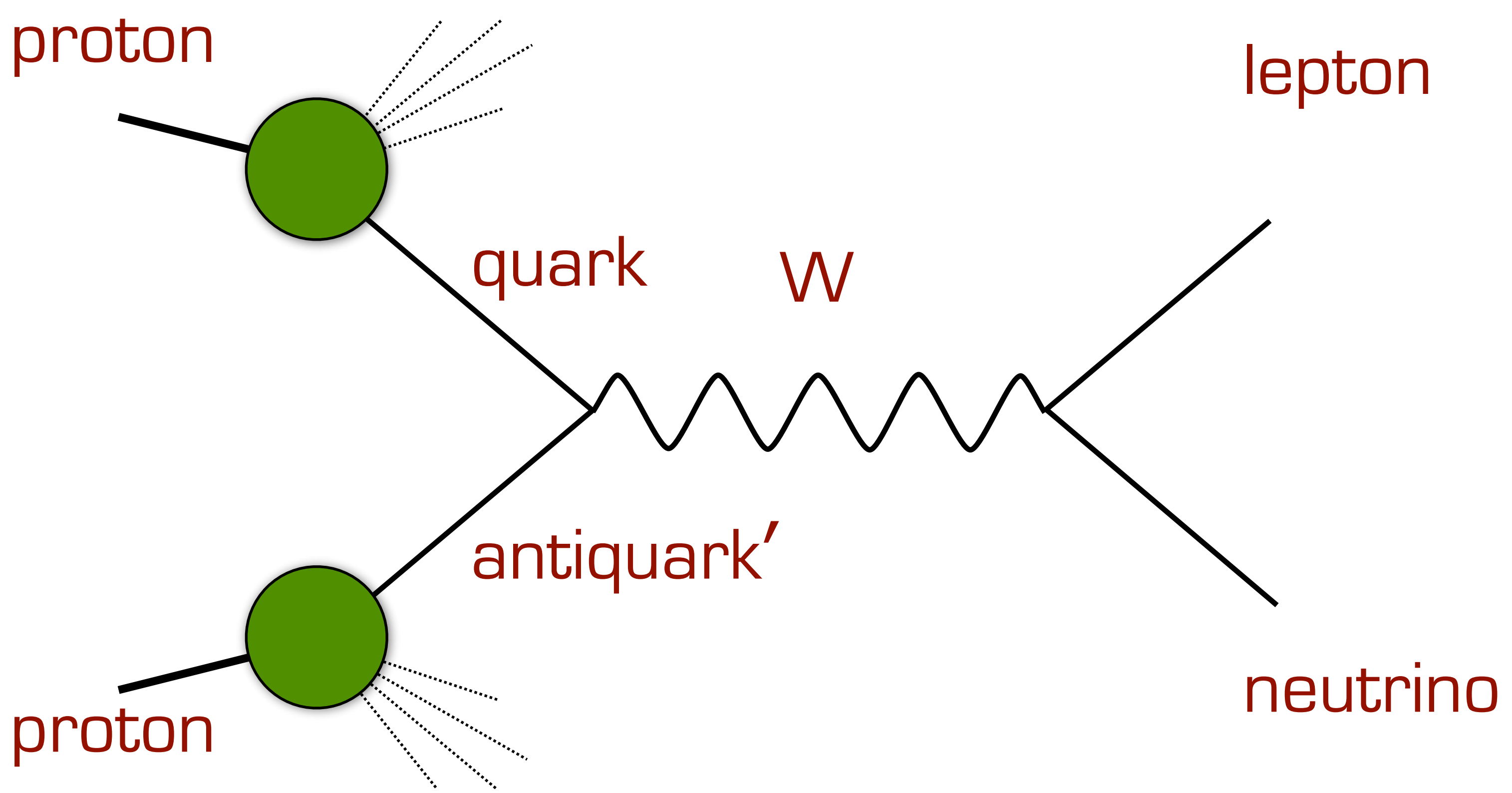
ATLAS Collab. arXiv:1701.07240



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

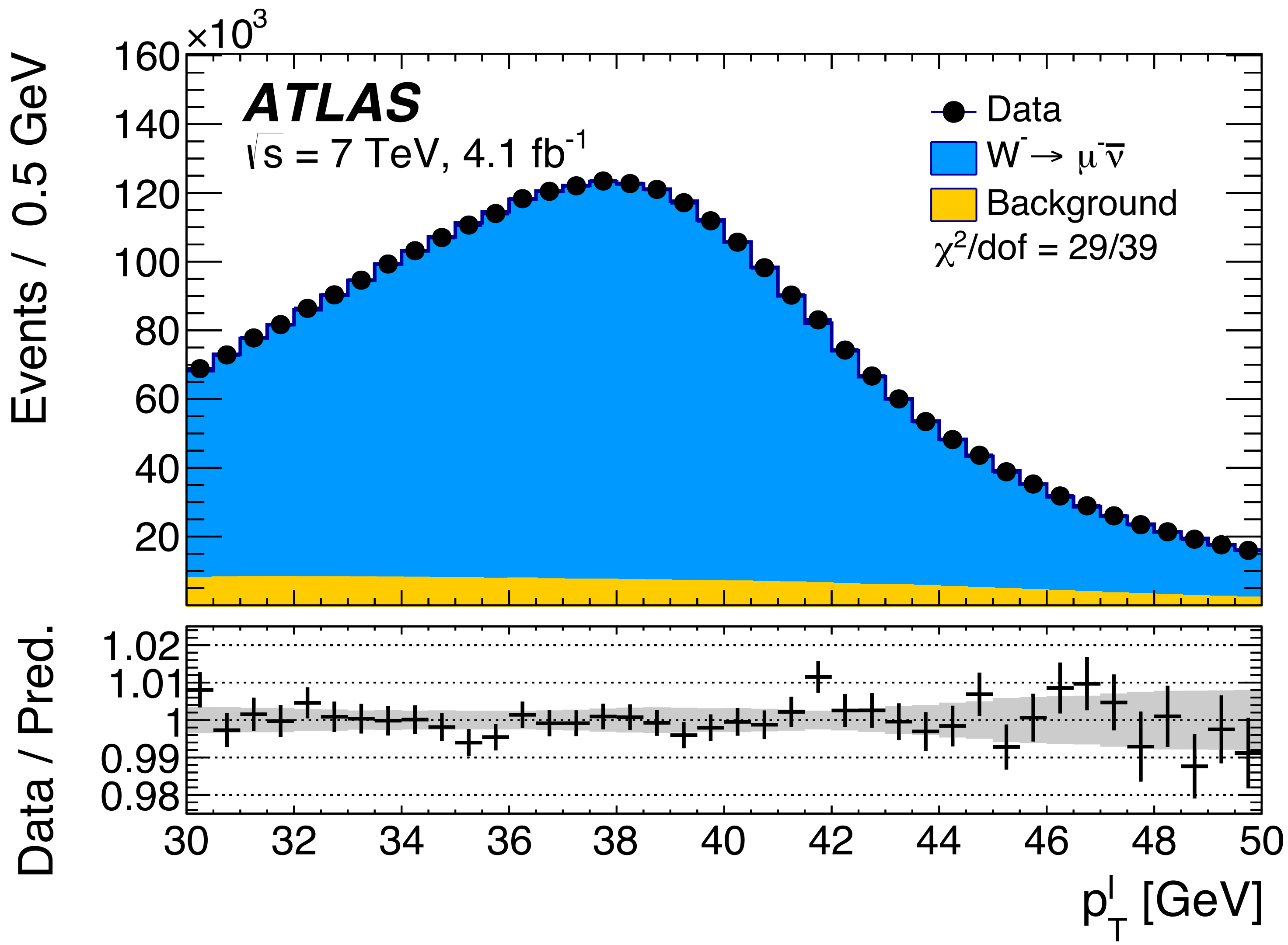
$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

How is the W mass determined?



Lepton transverse momentum

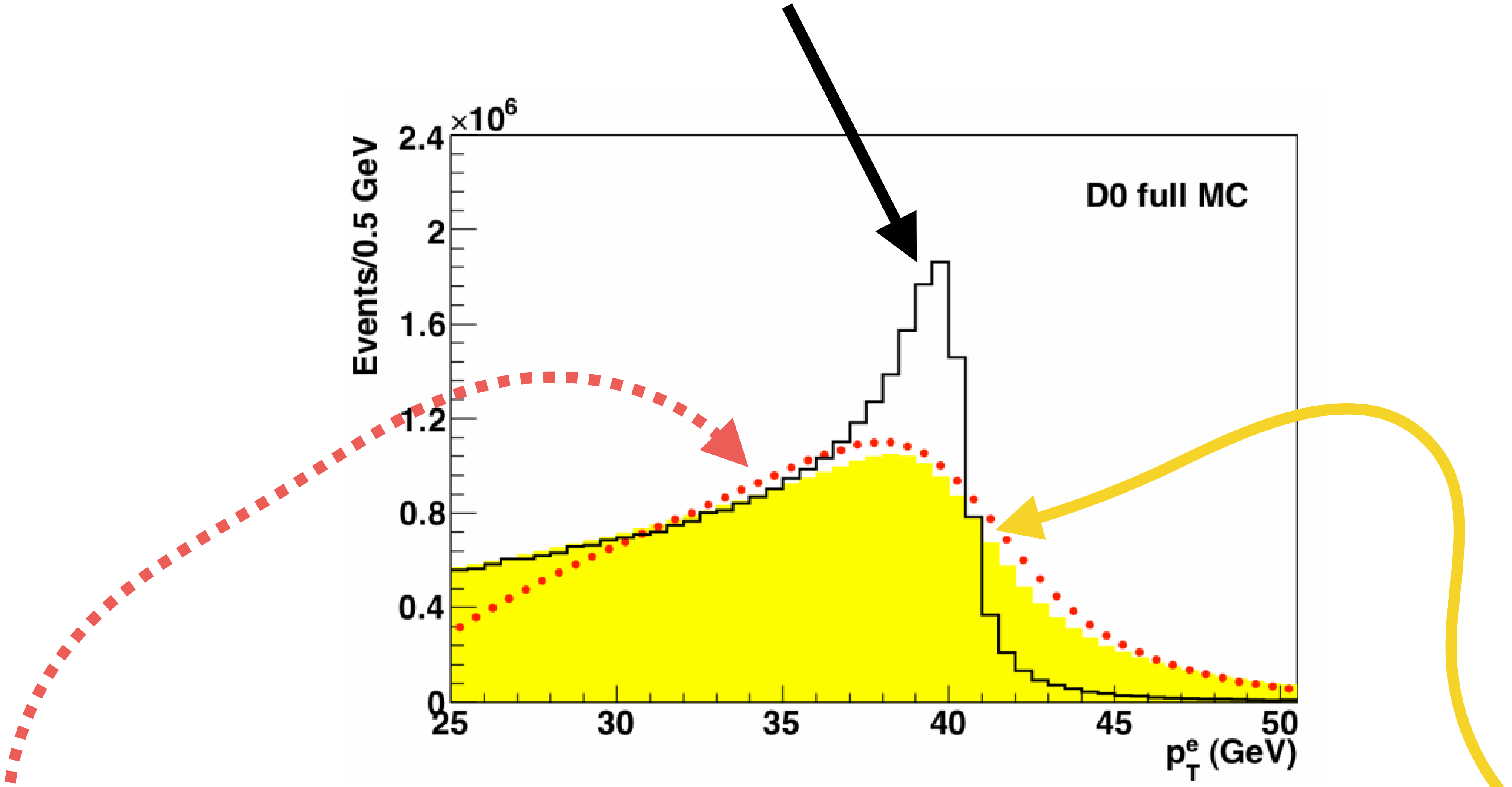
The four-momentum of the neutrino is difficult to determine. Other variables have to be measured, e.g., the lepton p_T



Additional variables are missing p_T and transverse mass m_T

Inclusion of corrections

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

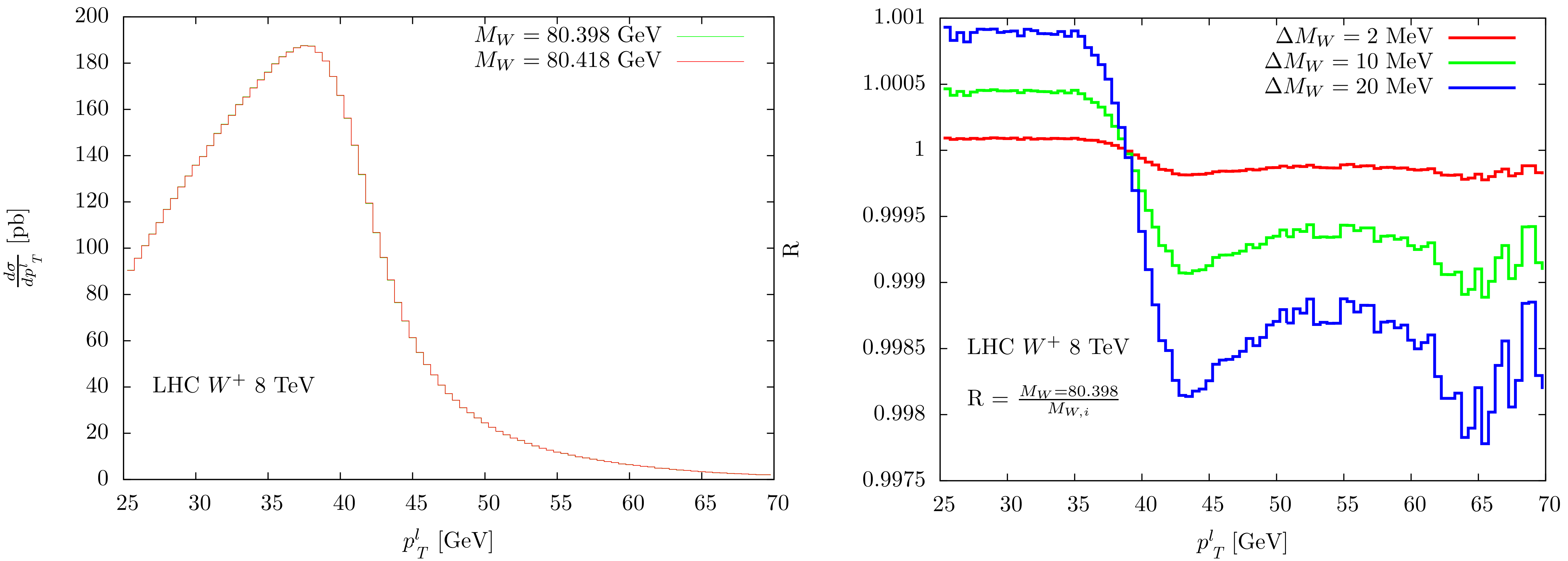


Detector effects cause further changes

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

Effect of changing W mass

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



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

Template fit technique

- 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.

How are sys. uncertainties estimated?

- 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

Uncertainties

W-boson charge	W^+	W^-	Combined
Kinematic distribution	p_T^ℓ	p_T^ℓ	p_T^ℓ
δm_W [MeV]			
Fixed-order PDF uncertainty	13.1	12.0	8.0
AZ tune	3.0	3.0	3.0
Charm-quark mass	1.2	1.2	1.2
Parton shower μ_F with heavy-flavour decorrelation	5.0	5.0	5.0
Parton shower PDF uncertainty	3.6	2.6	1.0
Angular coefficients	5.8	5.8	5.8
Total	15.9	14.8	11.6

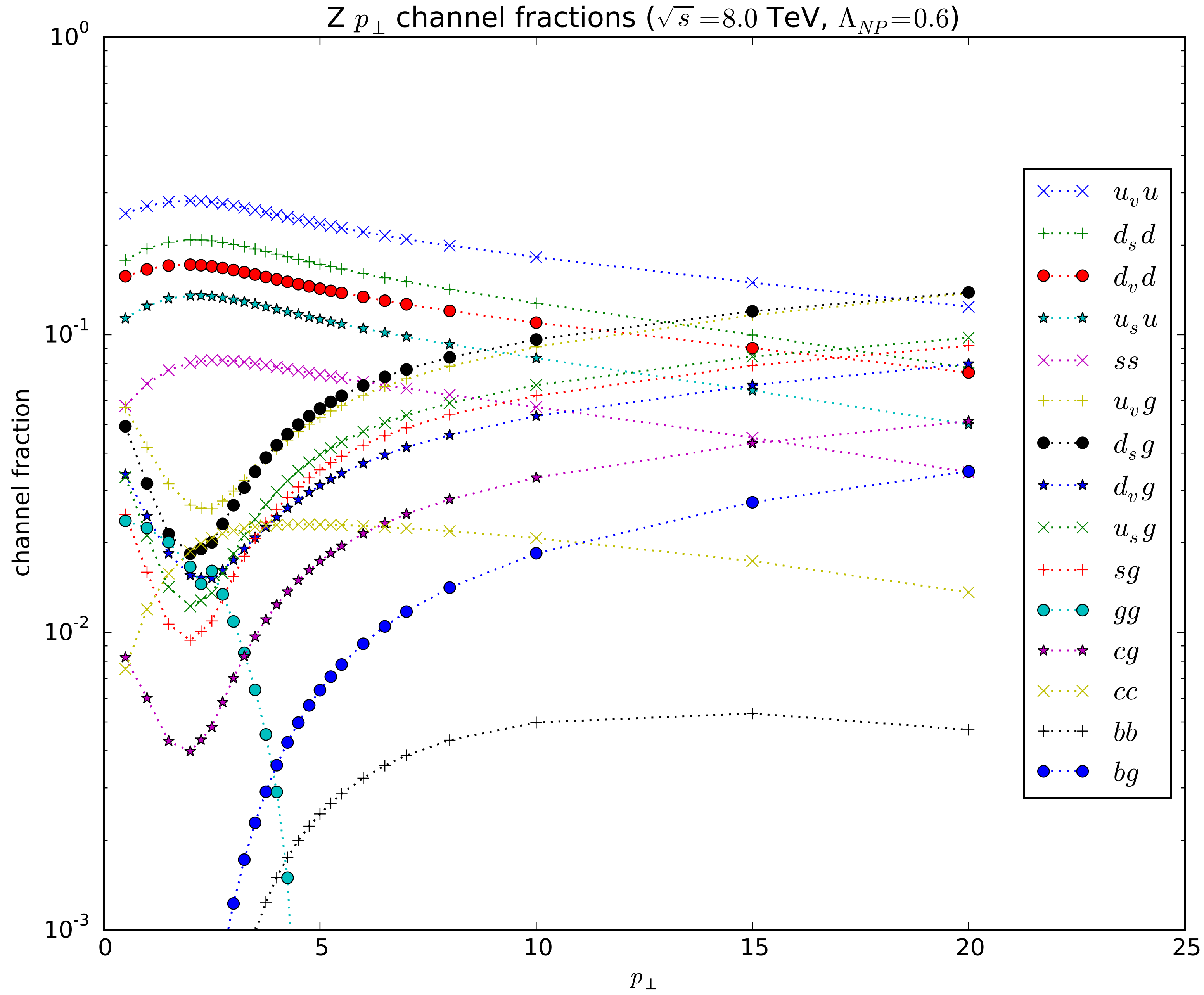
This contribution contains also intrinsic transverse momentum of partons. The MC has been tuned to describe Z-boson data

ATLAS Collab. arXiv:1701.07240


Z and W
production
involve
different flavor
combinations

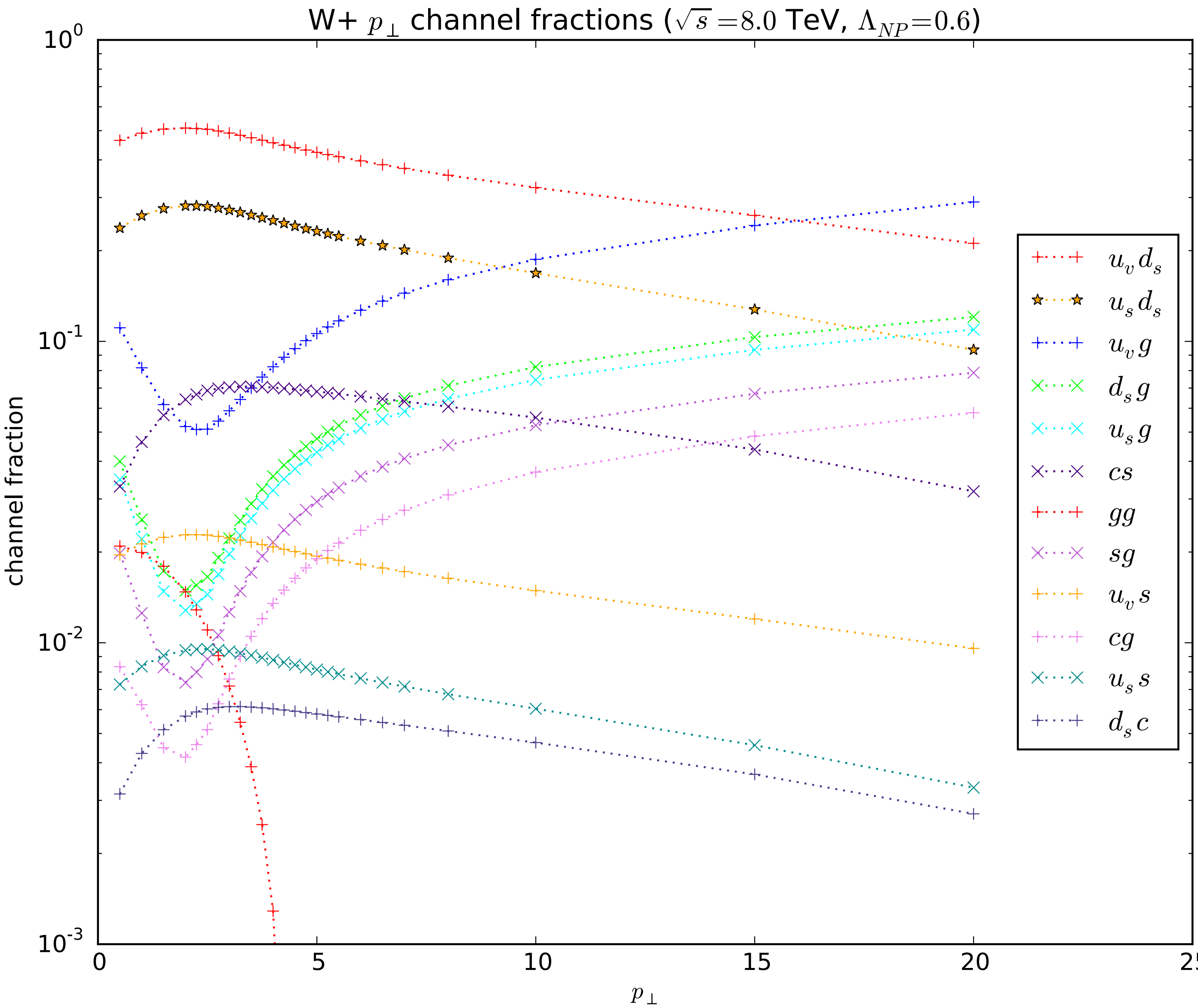
Our work

Flavor contributions: Z boson



u ubar and d dbar are the most important channels

Flavor contributions: W^+ boson



u dbar is the most important channel

Monte Carlo 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)

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

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

Perturbative parts at order α_S — NLL

Nonperturbative parts

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

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

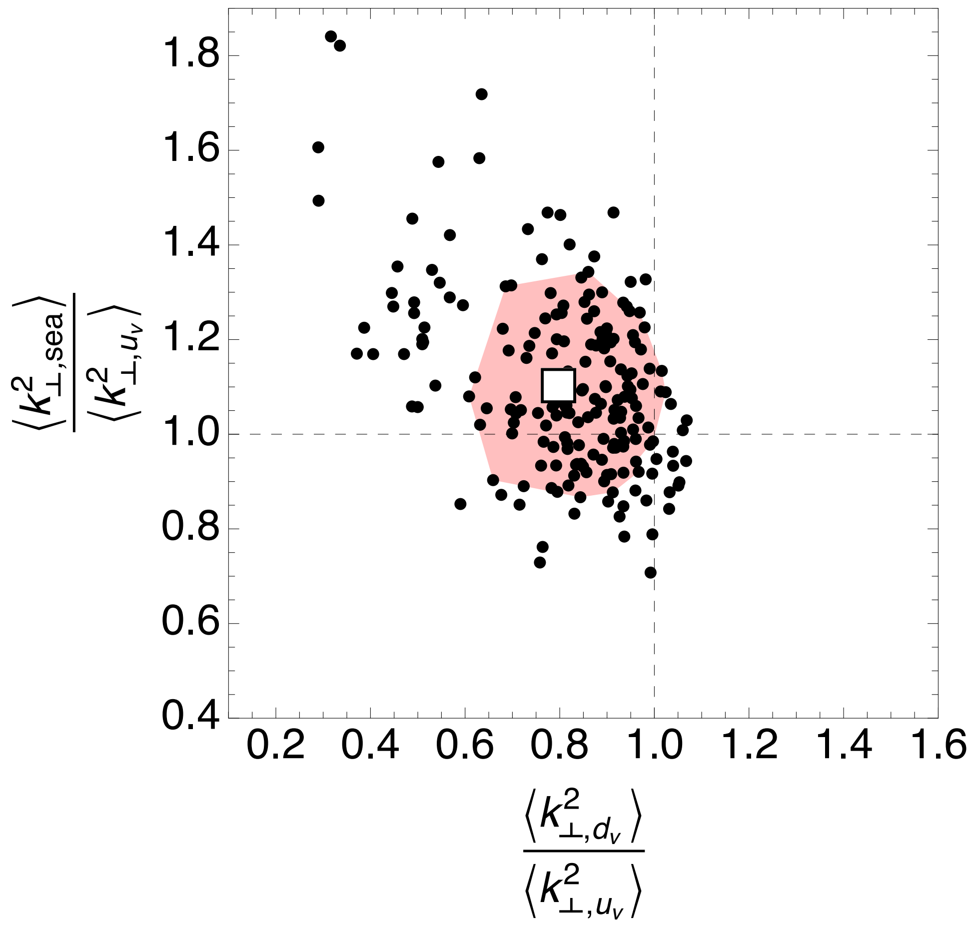
this component is flavor-independent (gluon radiation)

this component can be flavor-dependent

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

Possible flavor dependence

Signori, Bacchetta, Radici, Schnell, arXiv:1409.3507



Our studies of SIDIS data indicate that there is a lot of room for flavor dependence. More flavor-sensitive data are needed!

Choice of nonperturbative 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

Inclusion of flavor dependence

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

Templates and pseudo data

TEMPLATES

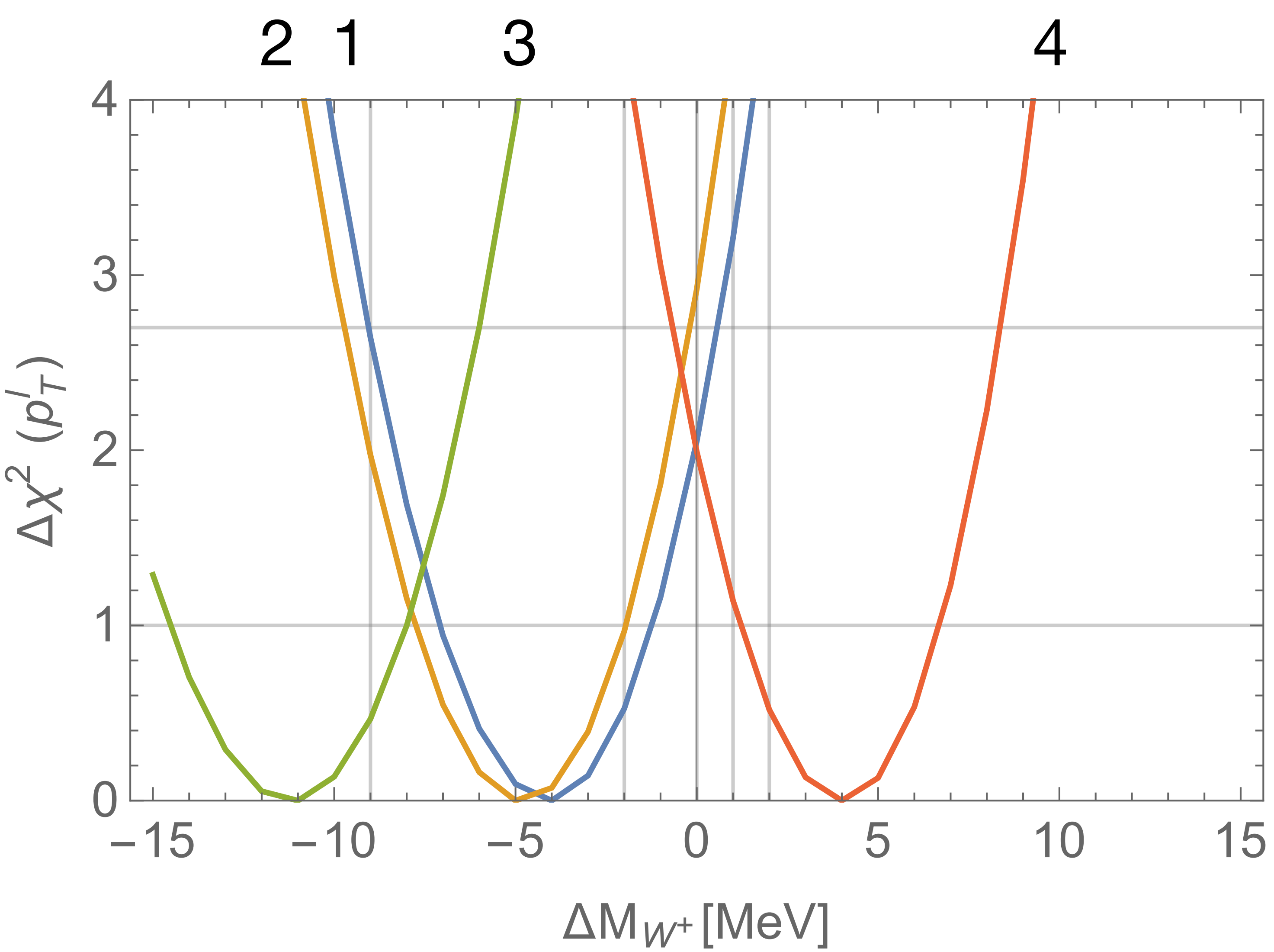
- high statistics (750M events)
- different values of M_W
  $\Delta M_W = -15$ MeV to $+15$ MeV
- no flavor-dependent intrinsic transverse momentum

PSEUDODATA

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

Chi2 profiles

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



Resulting shifts

	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

Conclusions

No flavor-blind analysis of M_W should be allowed

Data sensitive to the flavor dependence of TMDs are needed to reduce this uncertainty