(Towards a quantitative study of) Flavour effects on the determination of M_W

giuseppe bozzi

in collaboration with
Alessandro Bacchetta, Piet Mulders, Marco Radici, Mathias Ritzmann,
Andrea Signori

Istituto Nazionale di Fisica Nucleare

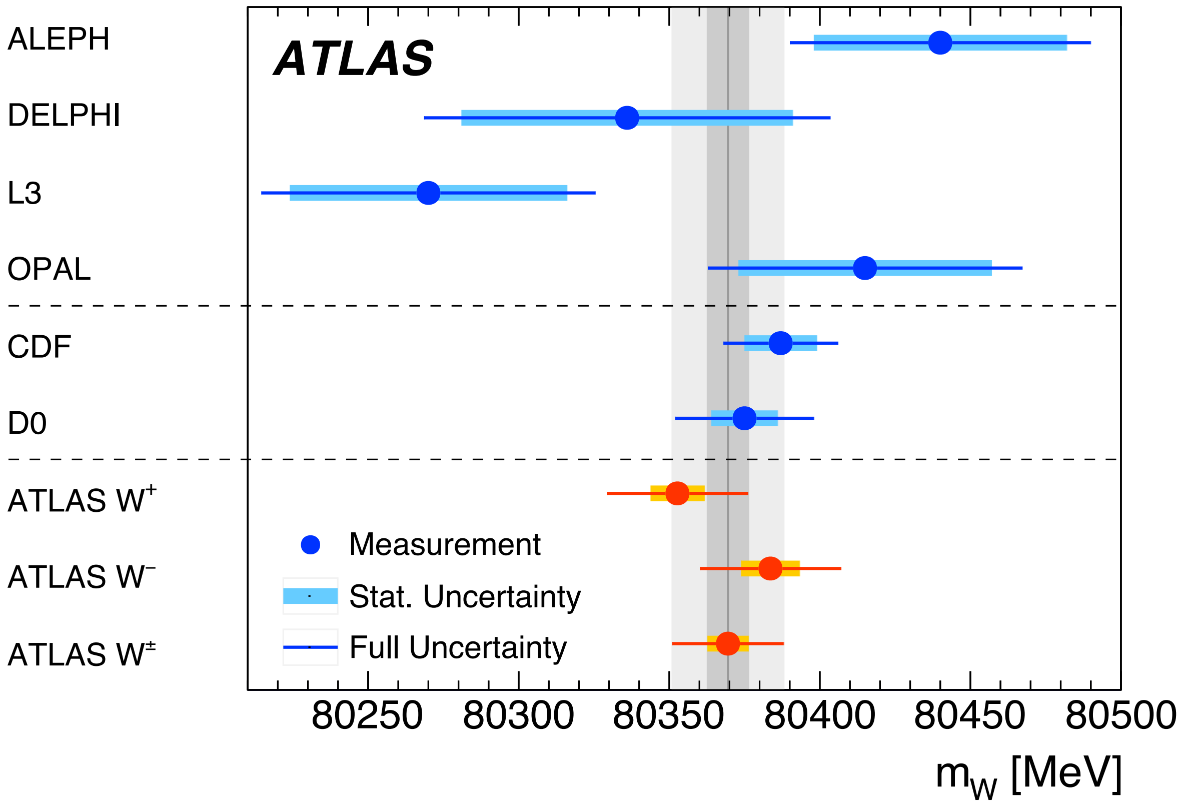
3DSPIN MAPPING THE PROTON IN 3D

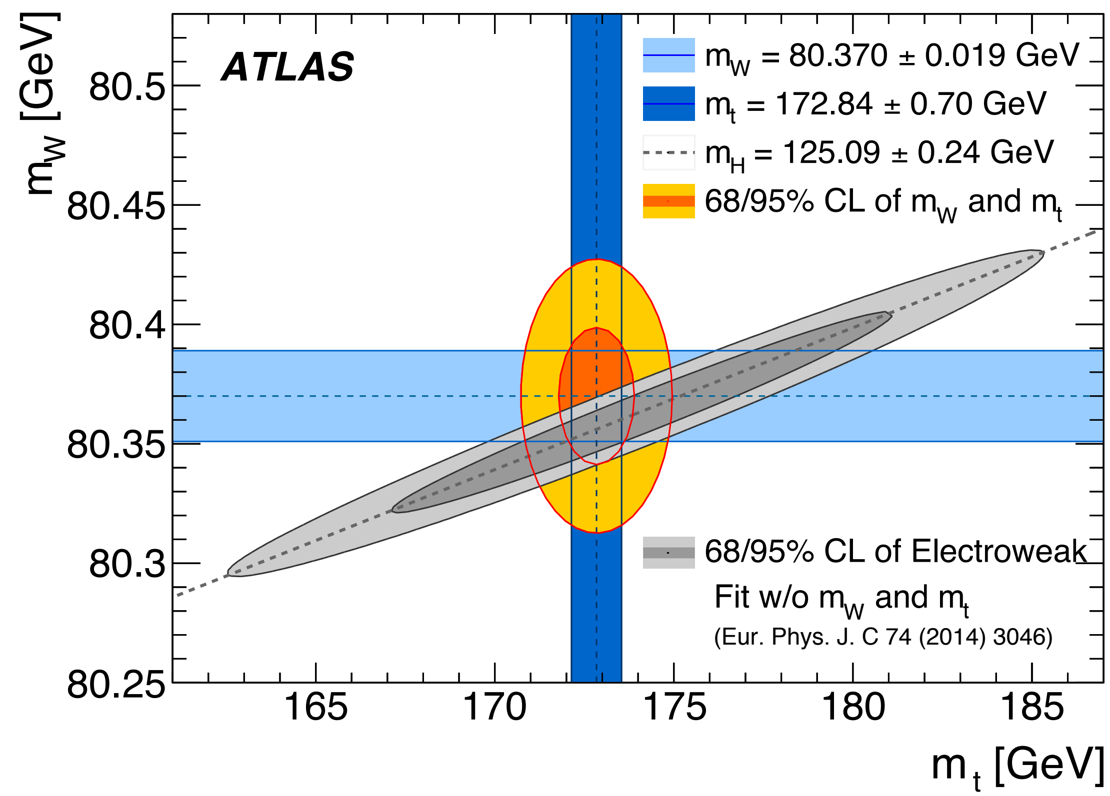
European Research Council

UNIVERSITÀ DI PAVIA

The *W* mass

ATLAS, arXiv:1701.07240





Experimental measurements

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

(7 stat, 11 exp, 14 th)

Global EW fit

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

The determination of the W-boson mass from the global fit of the electroweak parameters has an uncertainty of 8 MeV, which sets a natural target for the precision of the experimental measurement of the mass of the W boson. The modelling uncertainties, which currently dominate the overall uncertainty on the m_W measurement presented in this note, need to be reduced in order to fully exploit the larger data samples available at centre-of-mass energies of 8 and 13 TeV. A better knowledge of the PDFs, as achievable with the inclusion in PDF fits of recent precise measurements of W- and Z-boson rapidity cross sections with the ATLAS detector [41], and improved QCD and electroweak predictions for Drell-Yan production, are therefore crucial for future measurements of the W-boson mass at the LHC.

The extraction of physical quantities

Observables

- accessible via counting experiments: cross sections and asymmetries

Pseudo-Observables

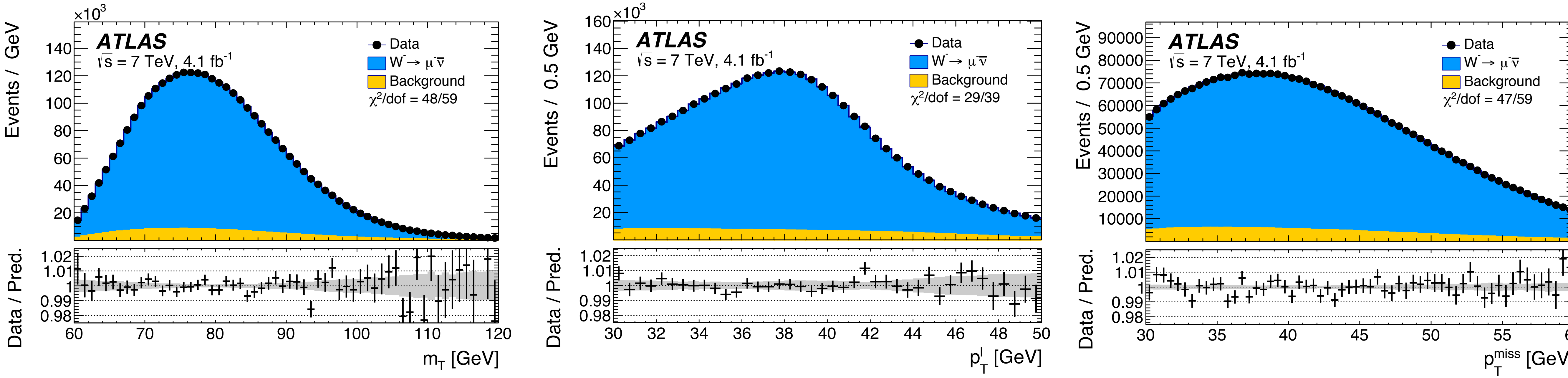
- functions of cross sections and symmetries
- require a model to be properly defined
  - M_Z at LEP as pole of the Breit-Wigner resonance factor
  - M_W at hadron colliders as fitting parameter of a *template fit* procedure

Template fit

1. several histograms describing a differential distribution are computed with the highest available theoretical accuracy and degree of realism in the detector simulation, letting the fit parameter (e.g. M_W) vary in a range
2. the histogram that best describes the data selects the preferred, i.e. measured, M_W

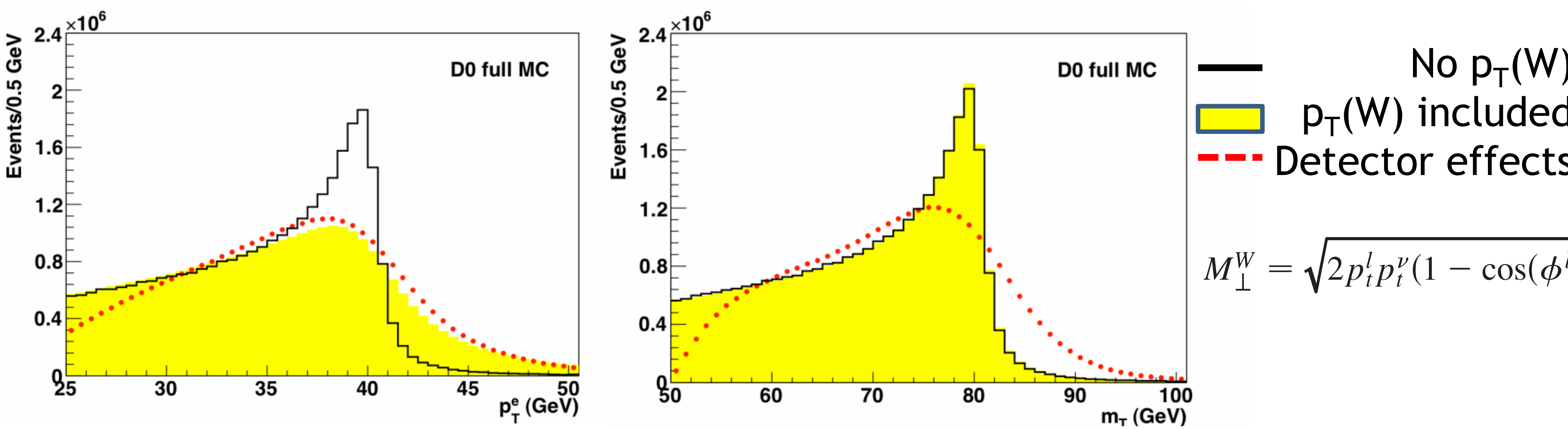
- the result of the fit depends on the hypotheses used to compute the templates (PDFs, scales, non-perturbative, different prescriptions, …)
- these hypotheses should be treated as theoretical systematic errors

Observables and techniques



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

jacobian peak enhances sensitivity to M_W



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

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

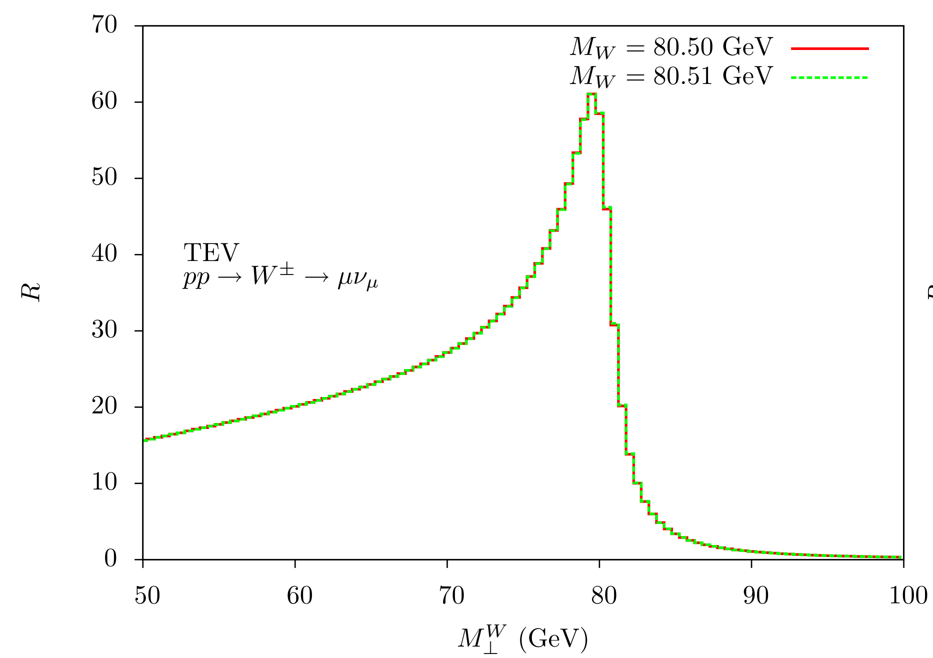
Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

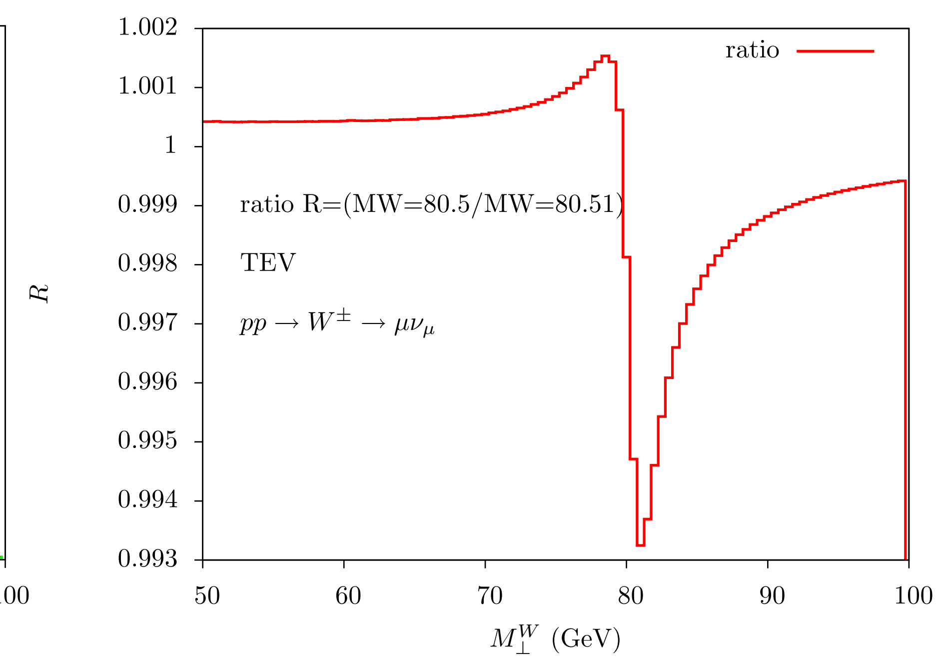
p_{TW} modelling depends on flavour and all-order treatment of QCD corrections

Observables and techniques

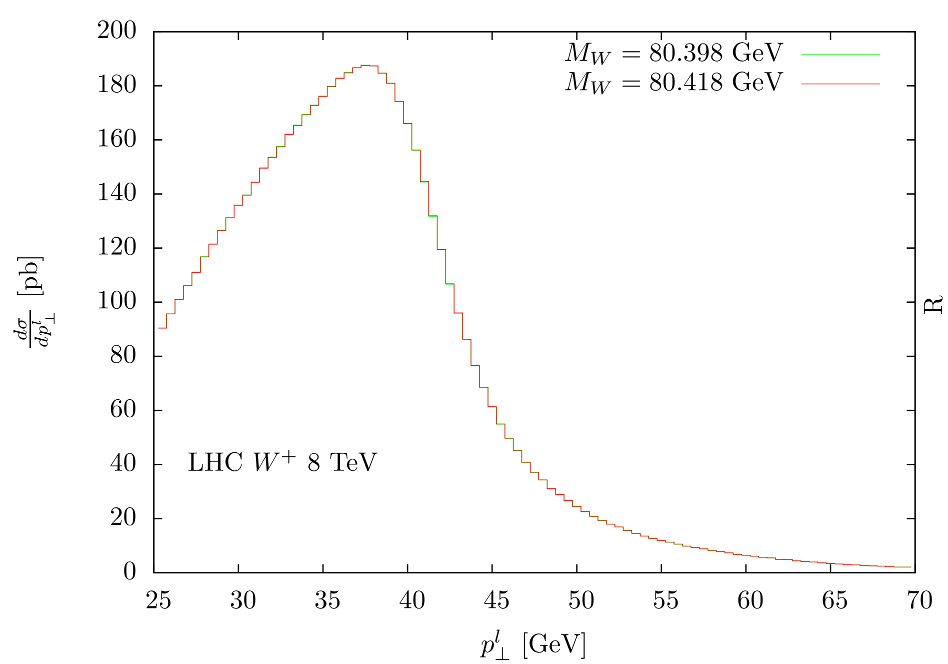
Challenging shape measurement: a distortion at the few per mille level of the distributions yields a shift of O(10 MeV) of the M_W value

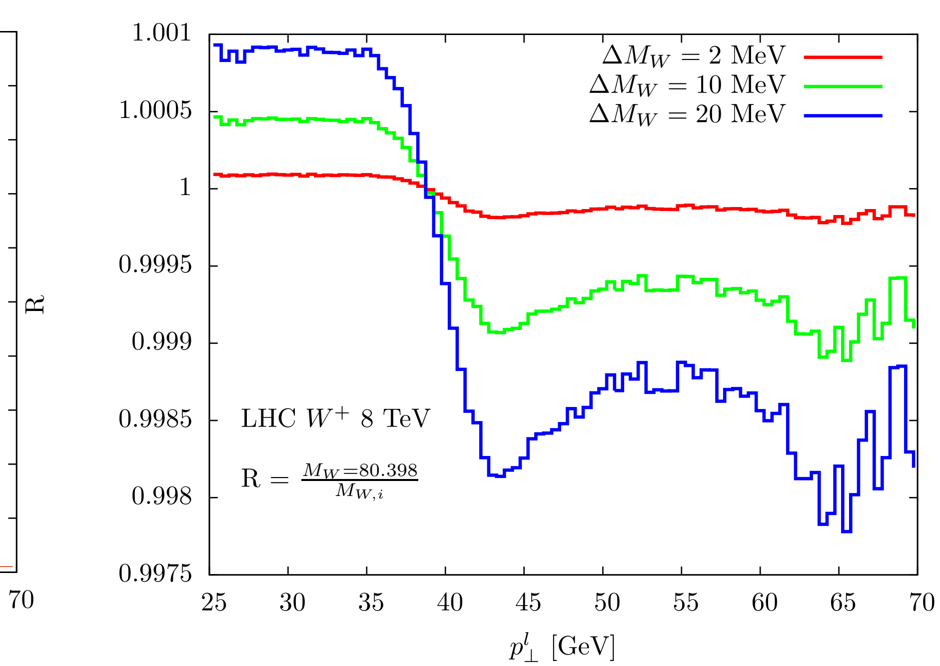
m_T





p_{Tl}





Breakdown of uncertainties

CDF, arXiv:1311.0894

m_T fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

p_T^ℓ fit uncertainties			
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 p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

D0, arXiv:1310.8628

Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

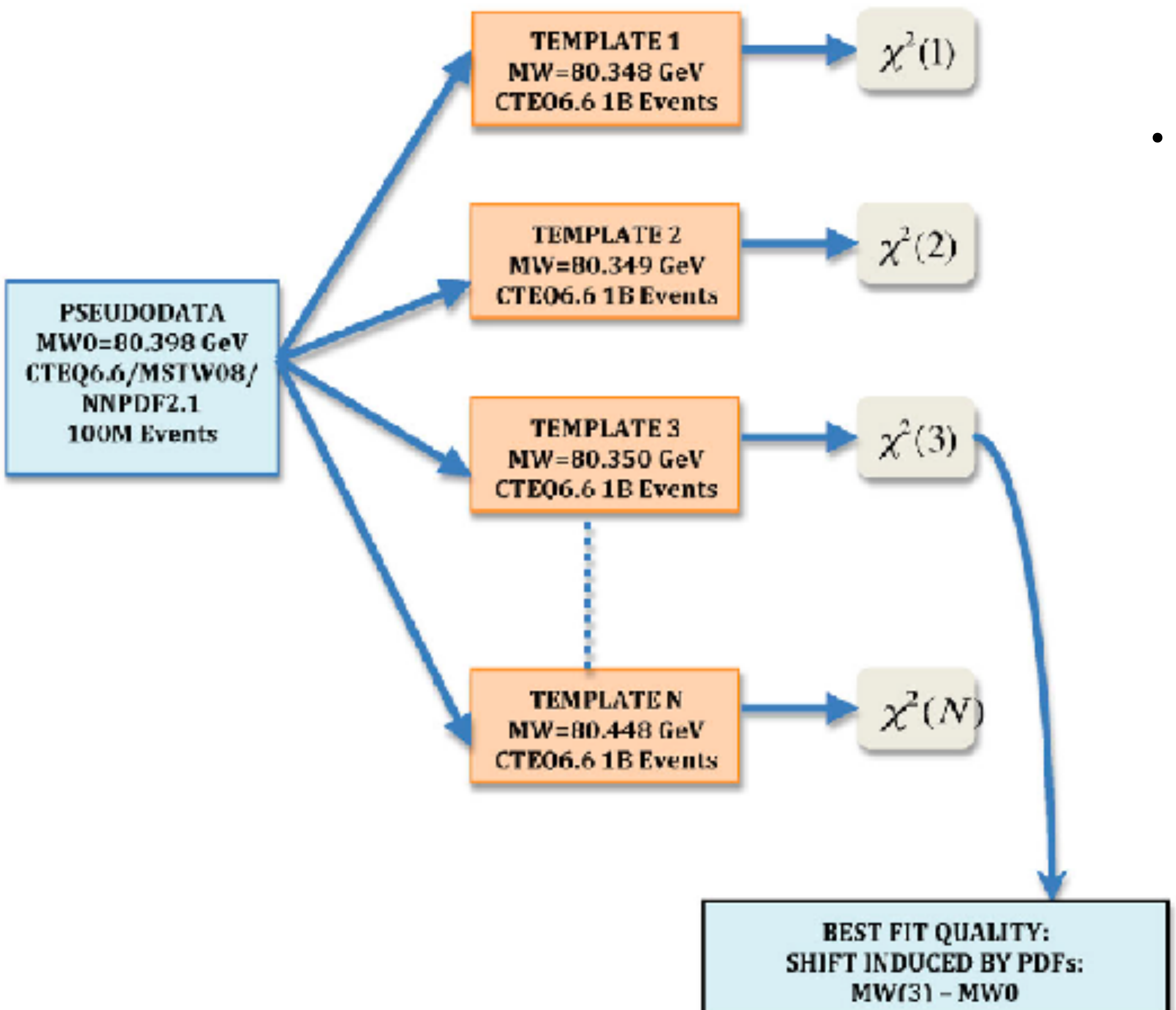
ATLAS, arXiv:1701.07240

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

General fitting strategy

(Bozzi, Rojo, Vicini 1104.2056)

- each PDF replica is used to generate a set of pseudodata (i.e. 100M events) with a fixed value M_{W0}
- a very accurate (i.e. 1B events) set of templates is prepared with a reference (CTEQ6.6) PDF replica
- when pseudodata generated with the reference replica are fitted, the nominal value M_{W0} is found (sanity check)
- same code used to generate both pseudodata and templates → only effect probed is the PDF one



- M_W shift = distance between the PDF replica under study and the reference replica
- PDF error = combination of different M_W results from each replica, according to the formulae recommended by the PDF collaborations

Hessian: CTEQ, MSTW

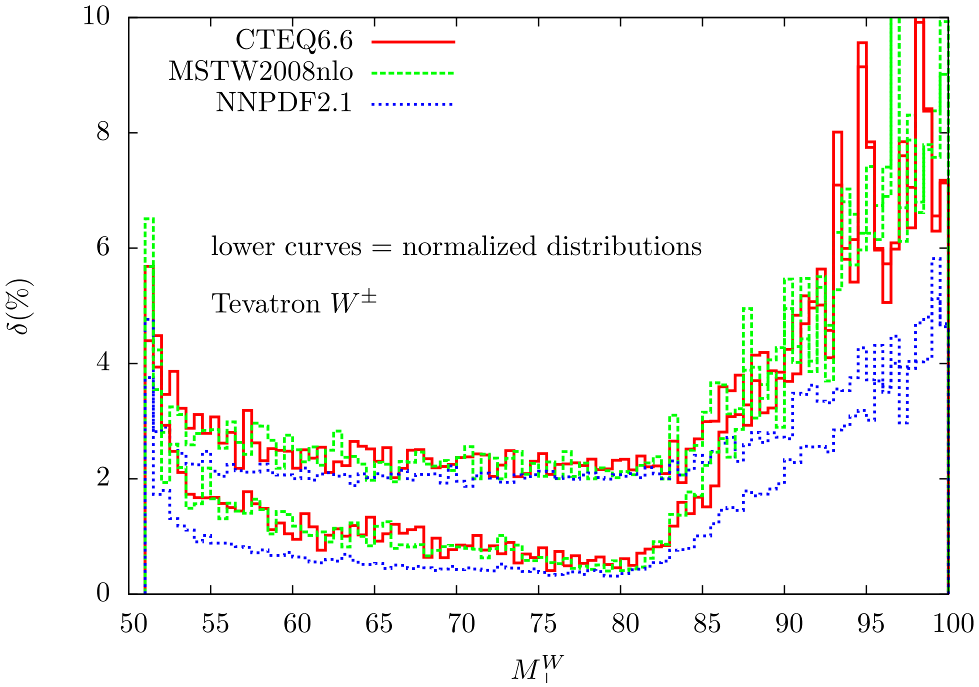
$$\sigma_X^2 = \frac{1}{4}\sum_{k=1}^{N}[X(S_k^+) - X(S_k^-)]^2$$

Montecarlo: NNPDF

$$\sigma_X^2 = \frac{1}{N_{\rm rep}-1}\sum_{i}^{N_{\rm rep}}[X^i - X]^2$$

Effects on transverse mass

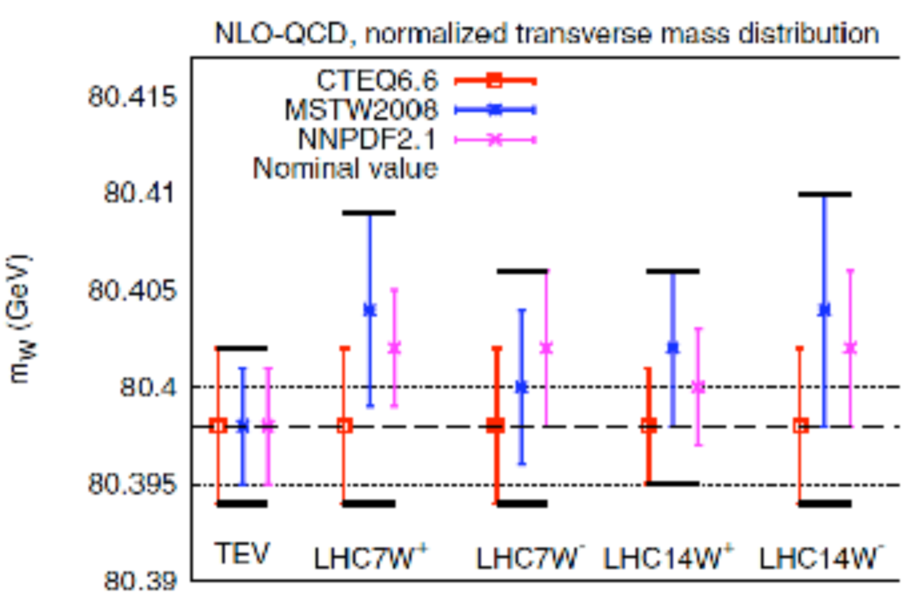
(Bozzi, Rojo, Vicini 1104.2056)



- Normalized distributions: reduced sensitivity to PDFs
- Ratio of (non-)normalised distributions w.r.t. to central PDF set
- Distributions obtained with **DYNNLO**

in first approximation the PDF effects factorise w.r.t. all other theoretical and experimental factors

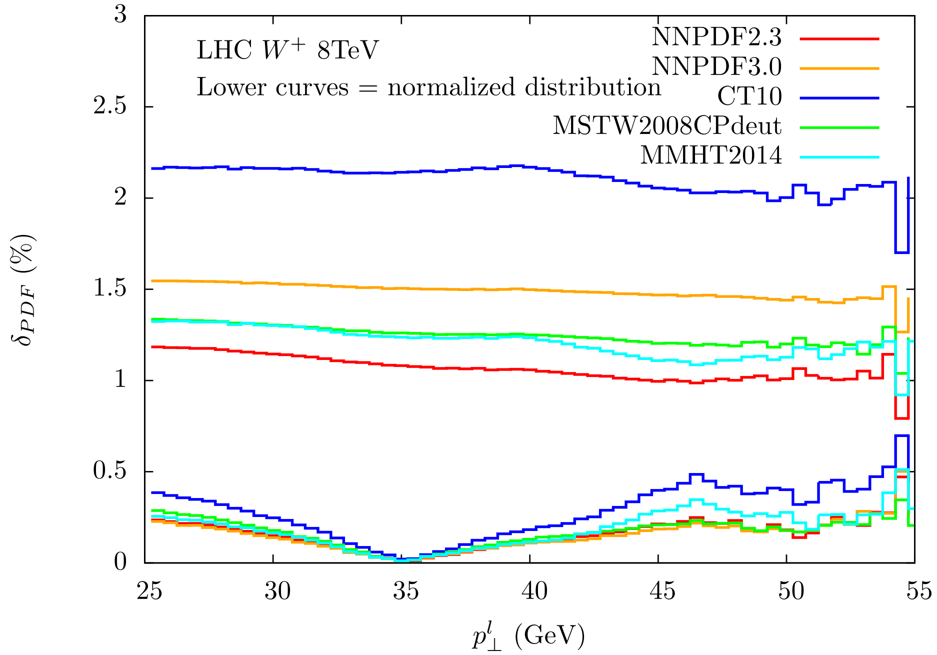
	CTEQ6.6		MSTW2008		NNPDF2.1		
	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$\delta_{\rm pdf}^{\rm tot}$
Tevatron, $W^{\pm}$	80.398 ± 0.004	1.42	80.398 ± 0.003	1.42	80.398 ± 0.003	1.30	4
LHC 7 TeV W^+	80.398 ± 0.004	1.22	80.404 ± 0.005	1.55	80.402 ± 0.003	1.35	8
LHC 7 TeV W^-	80.398 ± 0.004	1.22	80.400 ± 0.004	1.19	80.402 ± 0.004	1.78	6
LHC 14 TeV W^+	80.398 ± 0.003	1.34	80.402 ± 0.004	1.48	80.400 ± 0.003	1.41	6
LHC 14 TeV W^-	80.398 ± 0.004	1.44	80.404 ± 0.006	1.38	80.402 ± 0.004	1.57	8



- Accuracy of templates essential: highly demanding computing task!
- For transverse mass distribution, a fixed-order NLO-QCD analysis is sufficient to assess this PDF uncertainty
- PDF error is moderate at the Tevatron but also at the LHC

Effects on lepton p_T

(Bozzi, Citelli, Vicini 1501.05887)

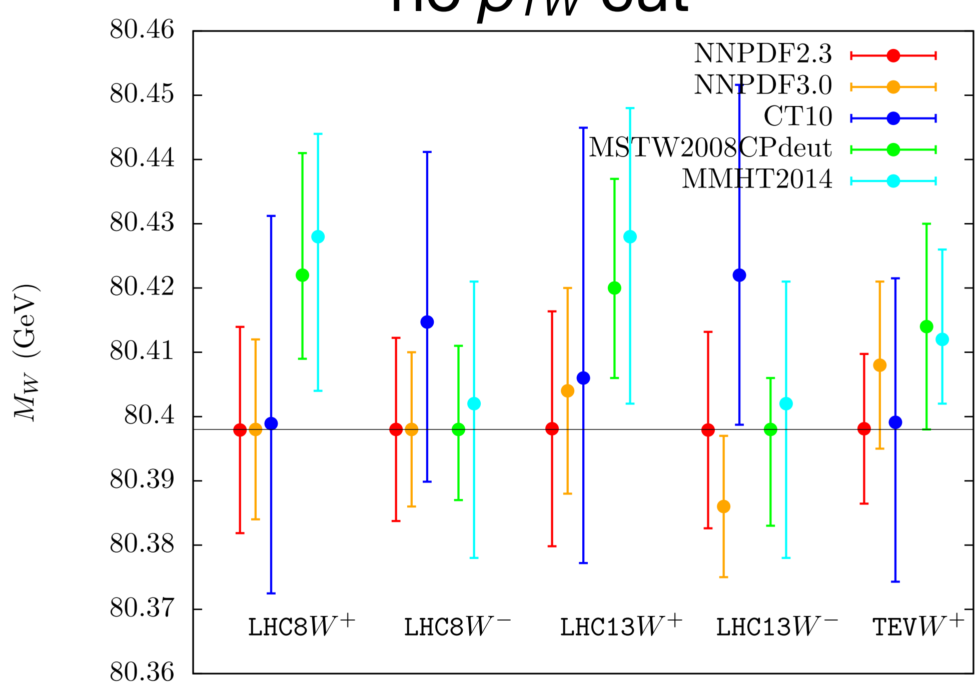


- Conservative estimate of the PDF uncertainty: CC-DY channel alone
- Distributions obtained with **POWHEG+PYTHIA 6.4**
- PDF uncertainty over relevant p_T range almost flat: O(2%)
- Uncertainty of normalized distributions: below the O(0.5%) level (but still sufficient to yield large M_W shifts)

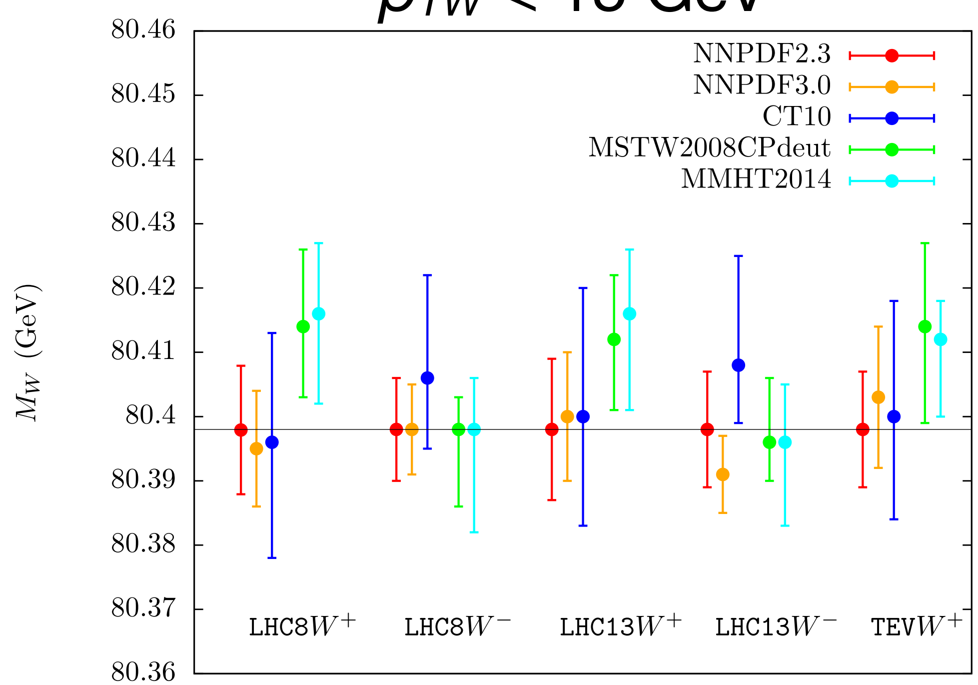
	no $p_\perp^W$ cut		$p_\perp^W < 15$ GeV	
	δ_{PDF} (MeV)	Δ_{sets} (MeV)	δ_{PDF} (MeV)	Δ_{sets} (MeV)
Tevatron 1.96 TeV	27	16	21	15
LHC 8 TeV W^+	33	26	24	18
W^-	29	16	18	8
LHC 13 TeV W^+	34	22	20	14
W^-	34	24	18	12

- Individual PDF sets provide non-pessimistic estimates: $\Delta M_W \sim$ O(10 MeV)
- Global envelope still shows large discrepancies of the central values
- p_{TW} cut is relevant

no p_{TW} cut



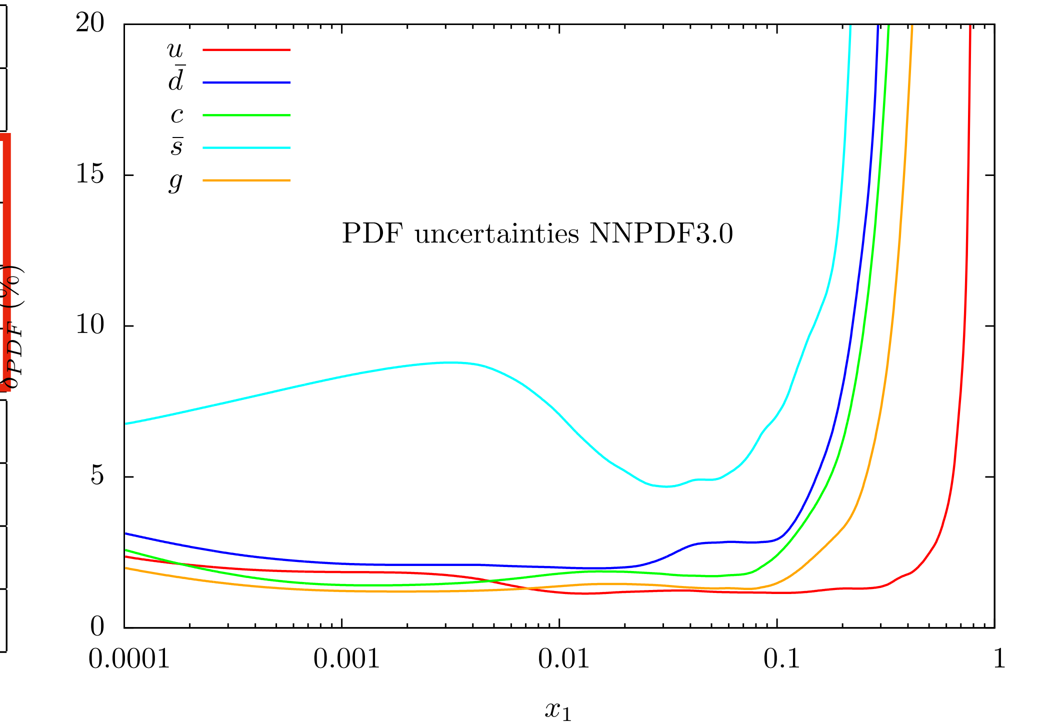
p_{TW} < 15 GeV



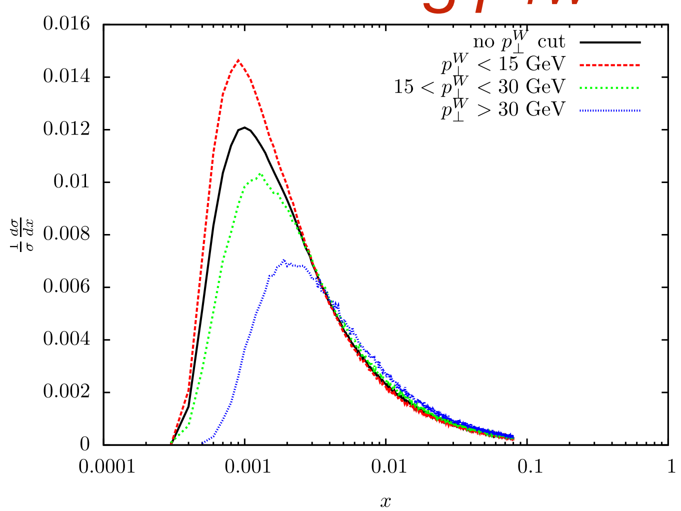
Acceptance cuts: interesting insights

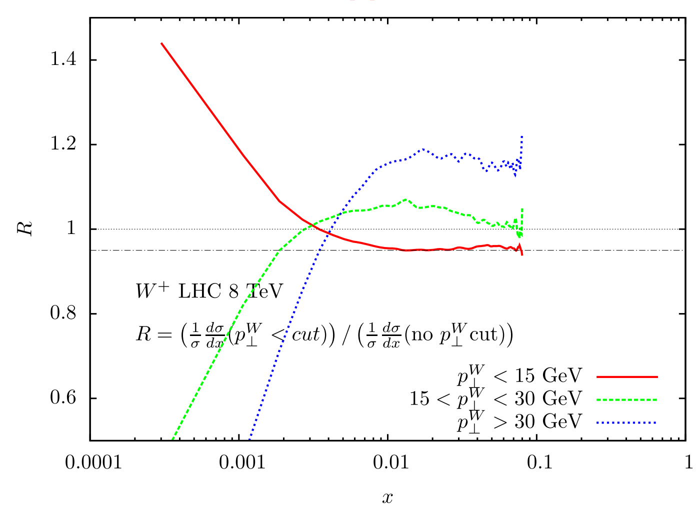
(Bozzi, Citelli, Vicini 1501.05887)

normalized distributions			
cut on $p_\perp^W$	cut on $\lvert\eta_l\rvert$	CT10	NNPDF3.0
inclusive	$\lvert\eta_l\rvert < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 10$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.392 + 0.015 - 0.012$	80.394 ± 0.007
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 1.0$	$80.400 + 0.032 - 0.021$	80.406 ± 0.017
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 4.9$	$80.400 + 0.009 - 0.004$	80.401 ± 0.003
$p_\perp^W < 15$ GeV	$1.0 < \lvert\eta_l\rvert < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012

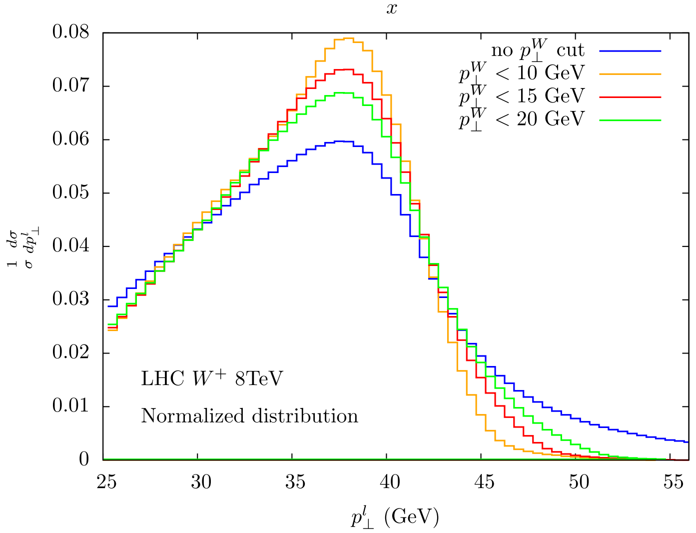


strong p_{TW} cut reduces M_W uncertainty

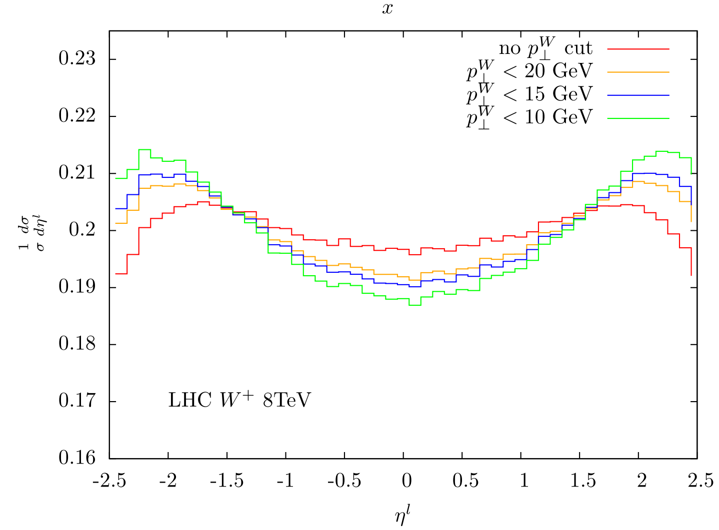




suppression of the large-x region



steeper shape of the p_{Tl} distribution

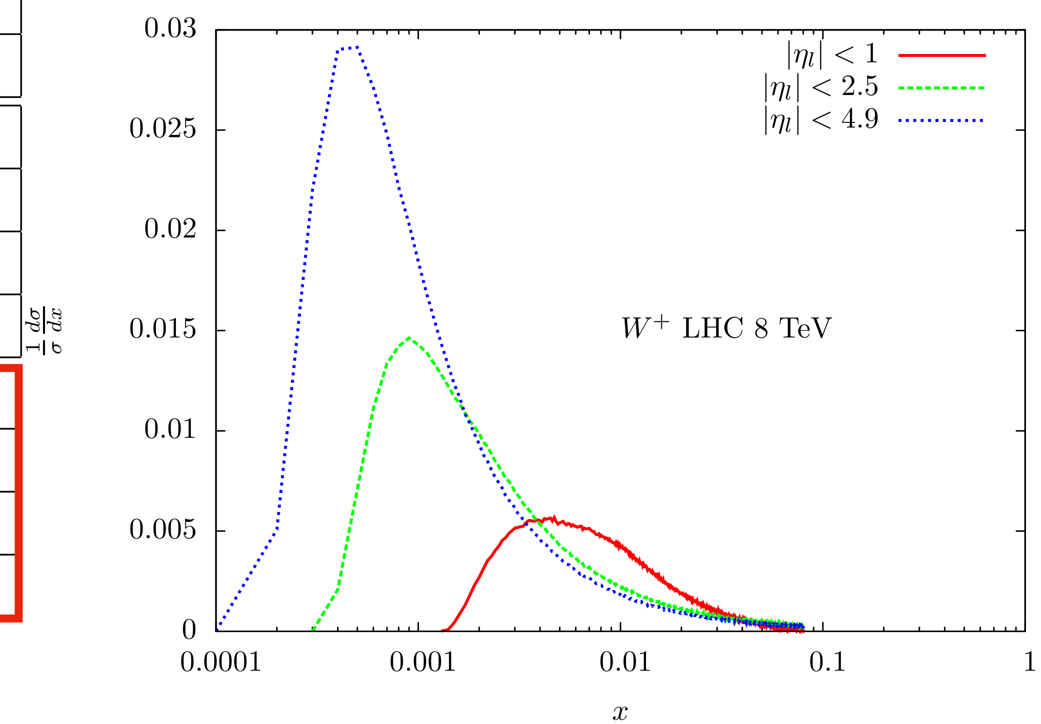


enhancement of high rapidity regions

Acceptance cuts: interesting insights

(Bozzi, Citelli, Vicini 1501.05887)

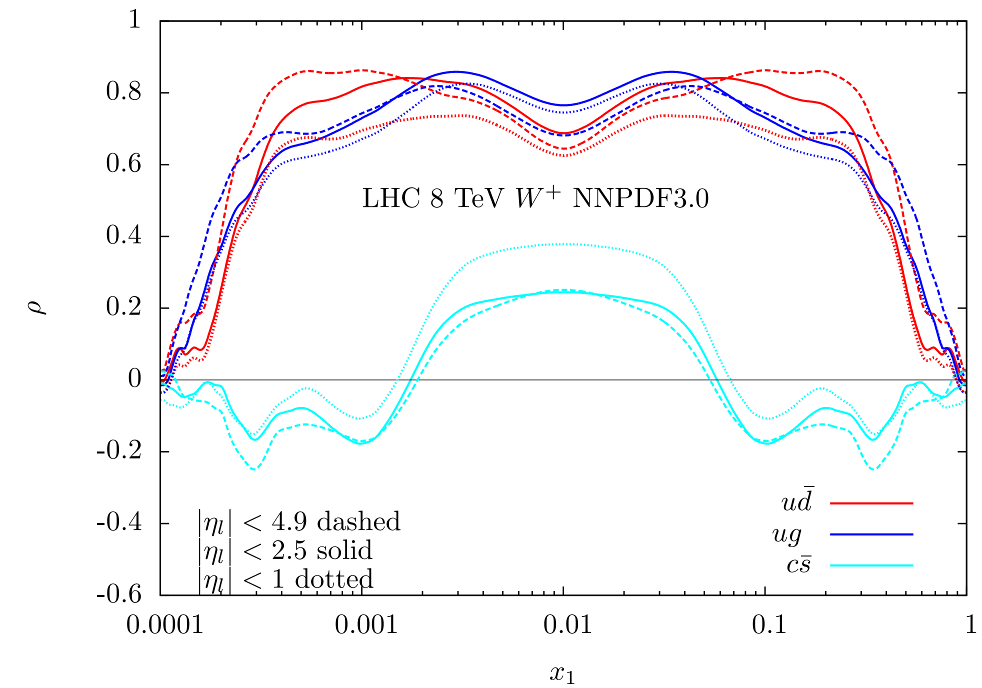
normalized distributions			
cut on $p_\perp^W$	cut on $\|\eta_l\|$	CT10	NNPDF3.0
inclusive	$\|\eta_l\| < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\|\eta_l\| < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 10$ GeV	$\|\eta_l\| < 2.5$	$80.392 + 0.015 - 0.012$	80.394 ± 0.007
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 1.0$	$80.400 + 0.032 - 0.021$	80.406 ± 0.017
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 4.9$	$80.400 + 0.009 - 0.004$	80.401 ± 0.003
$p_\perp^W < 15$ GeV	$1.0 < \|\eta_l\| < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012



loose lepton pseudorapidity cut reduces M_W uncertainty

- uncertainties for (eta<1) and for (1<eta<2.5) are *separately larger* than for (eta<2.5)
- normalized p_{Tl} distribution, integrated over whole rapidity range, does not depend on x
- PDF sum rules → *non trivial compensations between different rapidity intervals among different flavours*

correlation of parton luminosities within the 40.5 GeV p_{Tl} bin



$$\rho(x,\tau) = \frac{\langle \mathcal{P}_{ij}(x,\tau)\,\frac{d\sigma}{dp_\perp^l}\rangle - \langle \mathcal{P}_{ij}(x,\tau)\rangle\langle \frac{d\sigma}{dp_\perp^l}\rangle}{\sigma^{\rm PDF}_{\mathcal{P}_{ij}}\,\sigma^{\rm PDF}_{d\sigma/dp_\perp^l}},$$

p_{TW} and the modelling of intrinsic-k_T

- p_{Tl} <— p_{TW} <— QCD initial state radiation + intrinsic k_T (usually, a Gaussian in k_T)

- PDF uncertainties and k_T-modelling entangled

    —> no universal (flavour-independent) model

- Intrinsic kT effects have been measured on Z data and used to predict the W distribution, assuming they are the same for Z and W (Konychev, Nadolsky, 2006)

- Ratio of CC-DY and NC-DY observables have been proposed to reduce sensitivity to NP effects (Giele, Keller, 1998)

but

different flavour structure

different phase space available

—> different Gaussian factors for different flavours

$$f_1^a(x, k_T) = f_1^a(x)\ \frac{1}{\pi \langle k_T^2 \rangle_a(x)}\ e^{-\frac{k_T^2}{\langle k_T^2 \rangle_a(x)}}$$

$$\langle k^2_{\perp,\mathrm{u_v}} \rangle \neq \langle k^2_{\perp,\mathrm{d_v}} \rangle \neq \langle k^2_{\perp,\mathrm{sea}} \rangle$$

Flavor and kinematic dependent widths

Extraction of parameters from SIDIS

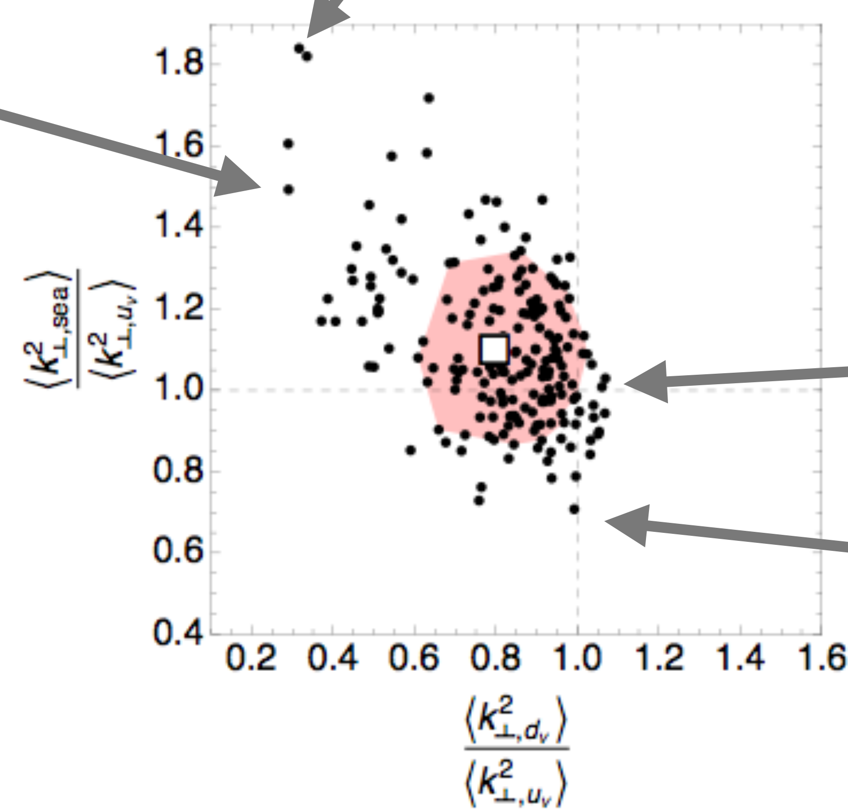
Signori, Bacchetta, Radici, Schnell, 1309.3507

template-fit on HERMES data: distribution of parameters

replica 149
χ^2/dof = 1.87

replica 73
χ^2/dof = 1.70

sea width
> (mostly)
u_v width



replica 130
χ^2/dof = 1.77

replica 186
χ^2/dof = 1.38

point of
no flavor dep.

d_v width < (mostly) u_v width

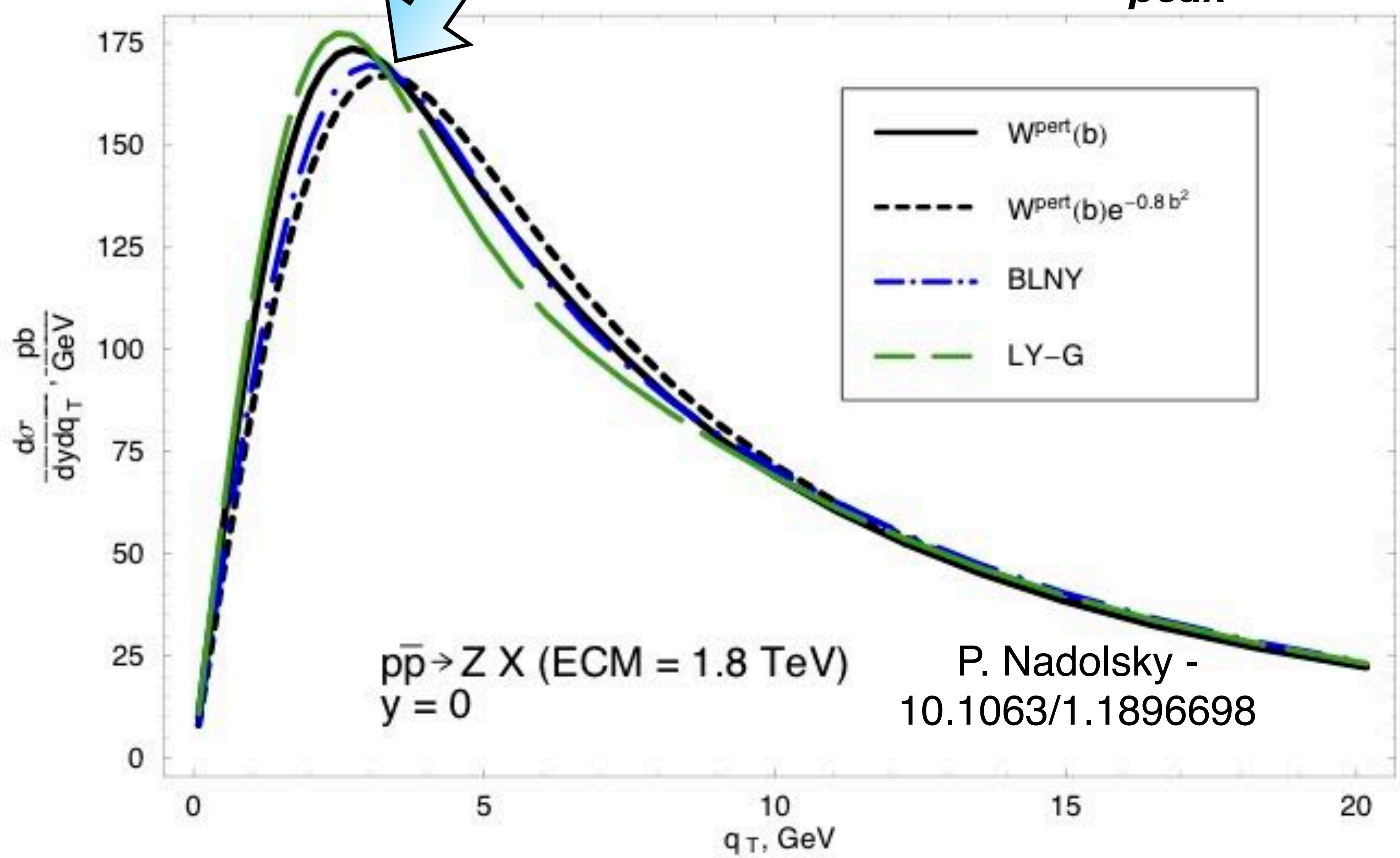
On average, *sea > u_v > d_v*

Application to W/Z p_T spectrum

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

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

g comes from 2 TMD PDFs and ***controls the position of the peak***



Application to *W/Z* p_T spectrum

Use of flavour-dependent configurations that respect the experimental constraint on *Z* producing different distributions for *W*

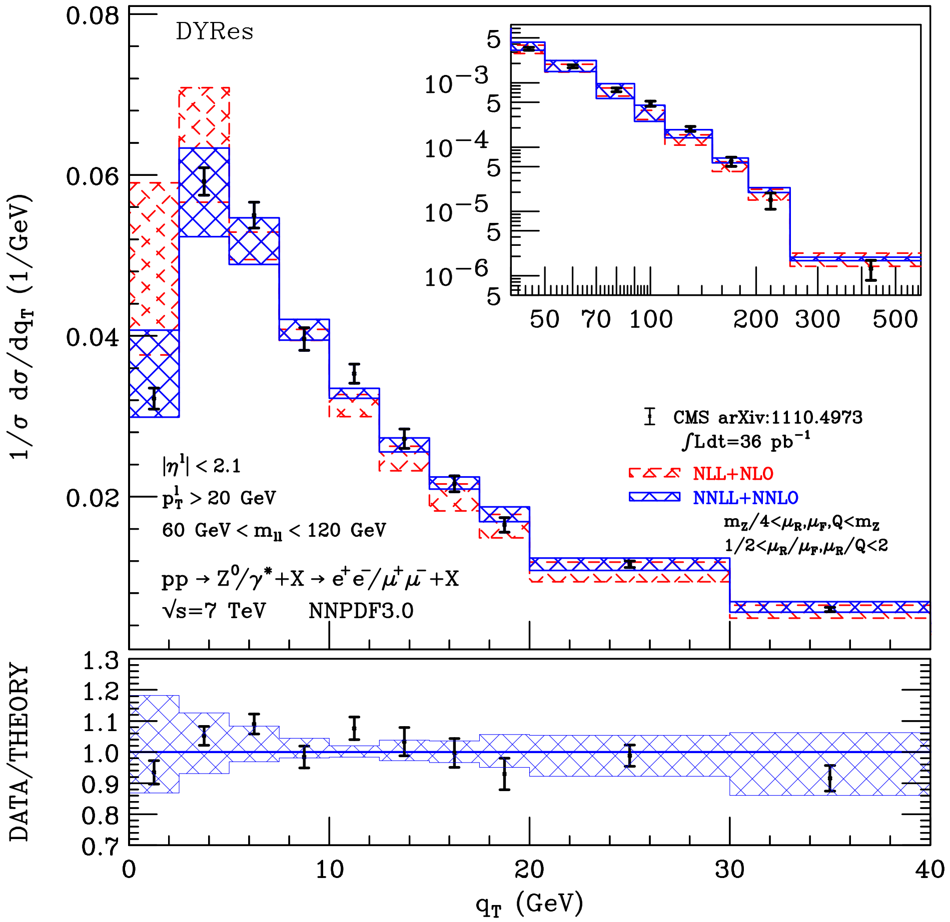
$$g_{ij}(Z) \ : \ [\mathrm{GeV}^2] \ 0.7 = u + \bar{u} = 0.2 + 0.5$$
$$= d + \bar{d} = 0.3 + 0.4$$
$$= \cdots = 0.6 + 0.1 = \ldots$$
$$g_{ij}(W) \ : \ [\mathrm{GeV}^2] \ 0.6 = u + \bar{d} = 0.2 + 0.4 = \ldots$$

	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	± 0	
f.d. $\langle \mathbf{k}_T^2 \rangle$ (max W^- effect)		-0.03	$+0.05$		± 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.

The uncertainty including intrinsic transverse momentum is comparable in magnitude with the one associated to collinear PDFs

Impact on the determination of M_W: in progress!



- DYRes (NNLO-QCD + NNLL) with leptonic decays

  Catani, de Florian, Ferrera, Grazzini, 1507.06937

- NNLO accuracy on the total cross section matched with NNLL accuracy in the description of the low p_{TZ} region

- good description of p_{TZ} data (within uncertainty bands)

- M_T distribution: remarkable stability at jacobian peak

- p_{Tl} distribution: distortion at few % level (NLL—>NNLL)

- flavour dependence coded and consistently-checked: stay tuned for the complete template fit analysis!