W mass: a theory overview

giuseppe bozzi
University and INFN, Cagliari

$$\textbf{Why} \ \frac{\textbf{should we care}}{\textbf{does everyone talk}} \ \textbf{about } m_W\textbf{?}$$

The W boson in the electroweak sector

The W boson in the electroweak sector

- EW sector uniquely determined by fixing 3 parameters (g, g', v) in terms of 3 exp. inputs

➡ other quantities expressed in terms of them, i.e. $m_W = v|g|/2,\ m_Z = v\sqrt{g^2 + g'^2}/2,\ \theta_W = \tan^{-1}(g'/g)$

The W boson in the electroweak sector

- EW sector uniquely determined by fixing 3 parameters (g, g', v) in terms of 3 exp. inputs

➡ other quantities expressed in terms of them, i.e. $m_W = v|g|/2,\ m_Z = v\sqrt{g^2 + g'^2}/2,\ \theta_W = \tan^{-1}(g'/g)$

- Usual choice: $(g, g', v) \leftrightarrow (\alpha, G_\mu, m_Z)$

➡ very precisely measured: $\frac{\Delta\alpha}{\alpha} \sim 3 \times 10^{-10}, \frac{\Delta G_\mu}{G_\mu} \sim 5 \times 10^{-7}, \frac{\Delta M_Z}{M_Z} \sim 2 \times 10^{-5}$

The W boson in the electroweak sector

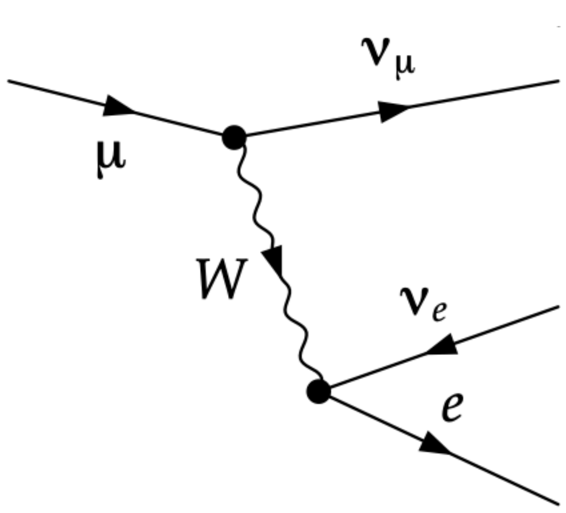
- EW sector uniquely determined by fixing 3 parameters (g, g', v) in terms of 3 exp. inputs

➡ other quantities expressed in terms of them, i.e. $m_W = v|g|/2,\ m_Z = v\sqrt{g^2 + g'^2}/2,\ \theta_W = \tan^{-1}(g'/g)$

- Usual choice: $(g, g', v) \leftrightarrow (\alpha, G_\mu, m_Z)$

➡ very precisely measured: $\frac{\Delta\alpha}{\alpha} \sim 3 \times 10^{-10}, \frac{\Delta G_\mu}{G_\mu} \sim 5 \times 10^{-7}, \frac{\Delta M_Z}{M_Z} \sim 2 \times 10^{-5}$

- Well-known $m_W - m_Z$ interdependence:
  matching of muon decay width within Fermi model and in the full SM



$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{G_\mu\sqrt{2}}$$

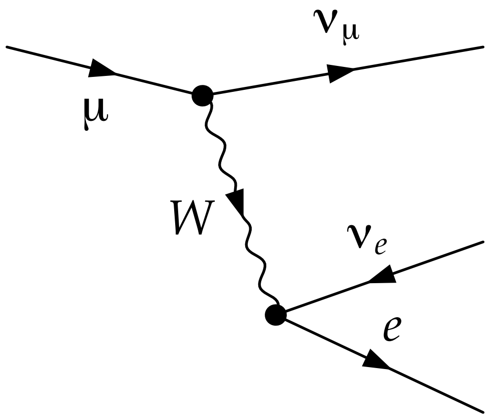
The W boson in the electroweak sector

Radiative corrections: $m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$

The W boson in the electroweak sector

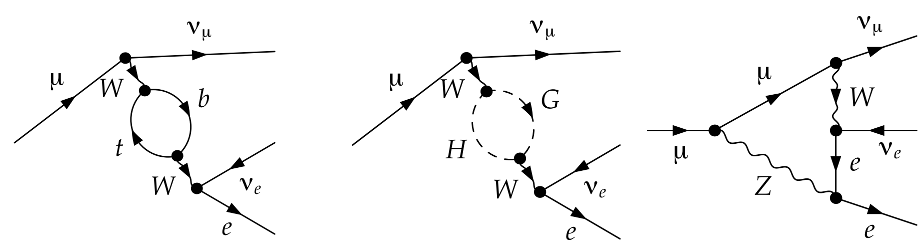
Radiative corrections: $m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$

Tree level



+

1-loop



+ full 2-loop + partial 3- and 4-loop

+ …

$m_W = 80.934$ GeV

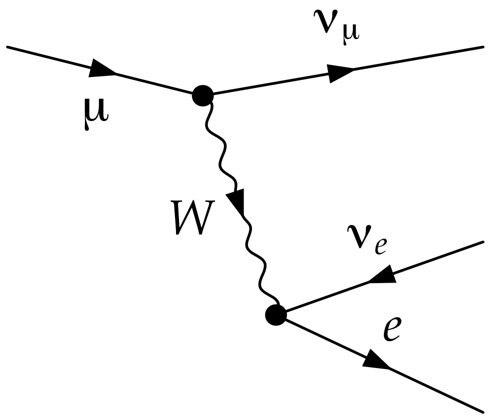
$\Delta m_W = \mathcal{O}(0.5 \text{ GeV})$

$\Delta m_W = \mathcal{O}(50 \text{ MeV})$

The W boson in the electroweak sector

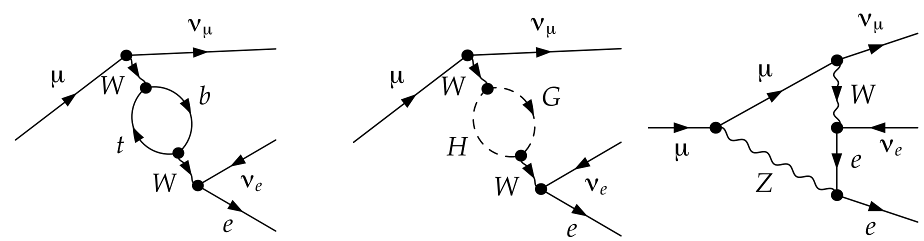
Radiative corrections: $m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$

Tree level



+

1-loop



+ full 2-loop + partial 3- and 4-loop

+ …

$m_W = 80.934$ GeV

$\Delta m_W = \mathcal{O}(0.5 \text{ GeV})$

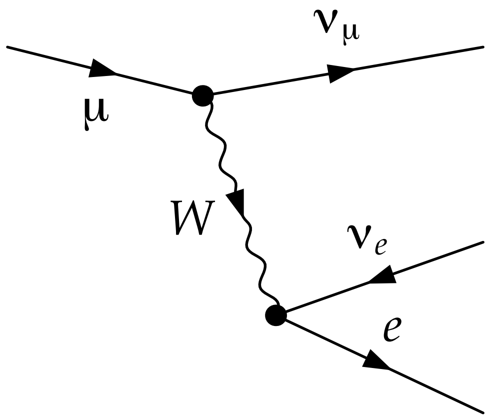
$\Delta m_W = \mathcal{O}(50 \text{ MeV})$

- Missing h.o. uncertainty:
  - $\delta m_W^{OS} = 4$ MeV on-shell scheme [Freitas,Hollik,Walter,Weiglein NPB 632 (2002)]
  - $\delta m_W^{\overline{MS}} = 3$ MeV $\overline{MS}$ scheme [Degrassi,Gambino,Giardino JHEP 05 (2015)]

The W boson in the electroweak sector

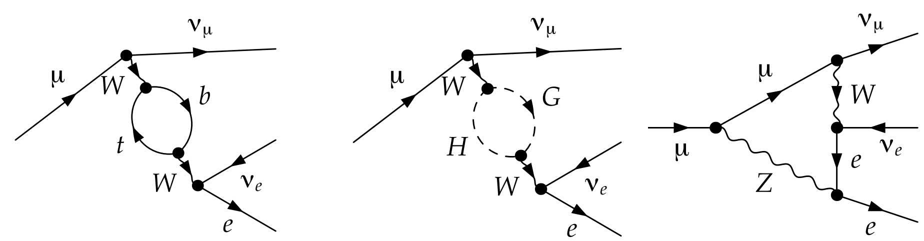
Radiative corrections: $m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$

Tree level



+

1-loop



+ full 2-loop + partial 3- and 4-loop

+ …

$m_W = 80.934$ GeV

$\Delta m_W = \mathcal{O}(0.5\ \mathrm{GeV})$

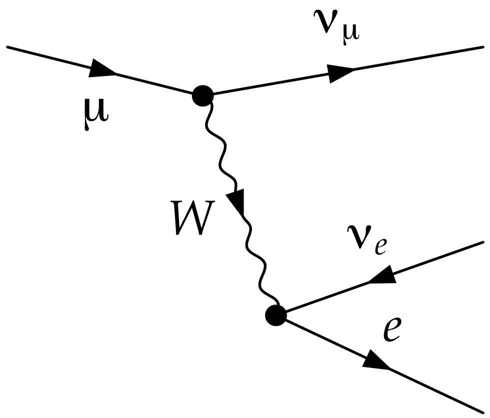
$\Delta m_W = \mathcal{O}(50\ \mathrm{MeV})$

- Missing h.o. uncertainty:
  - $\delta m_W^{OS} = 4$ MeV on-shell scheme [Freitas,Hollik,Walter,Weiglein NPB 632 (2002)]
  - $\delta m_W^{\overline{MS}} = 3$ MeV $\overline{MS}$ scheme [Degrassi,Gambino,Giardino JHEP 05 (2015)]
- Parametric uncertainty: $\delta m_W^{par} = 5$ MeV considering 1σ variation of $(\alpha, \alpha_s, G_\mu, m_Z, m_H, m_t)$

The W boson in the electroweak sector

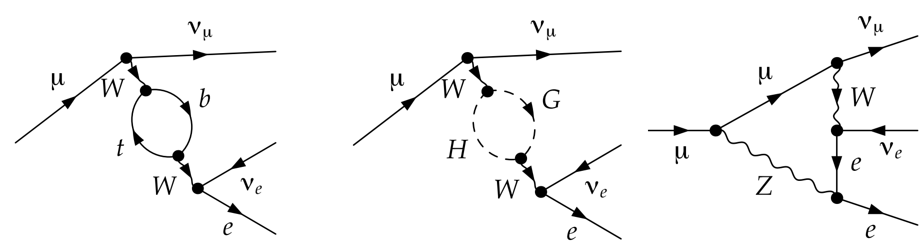
Radiative corrections: $m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$

Tree level



+

1-loop



+ full 2-loop + partial 3- and 4-loop

+ …

$m_W = 80.934$ GeV

$\Delta m_W = \mathcal{O}(0.5 \text{ GeV})$

$\Delta m_W = \mathcal{O}(50 \text{ MeV})$

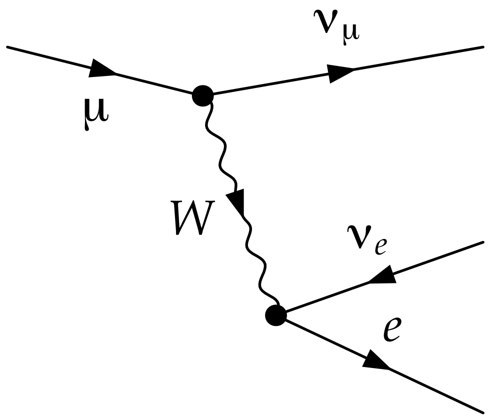
$$\frac{\delta m_W}{m_W} \approx 10^{-4}$$

- Missing h.o. uncertainty:
  - $\delta m_W^{OS} = 4$ MeV on-shell scheme [Freitas,Hollik,Walter,Weiglein NPB 632 (2002)]
  - $\delta m_W^{\overline{MS}} = 3$ MeV $\overline{MS}$ scheme [Degrassi,Gambino,Giardino JHEP 05 (2015)]
- Parametric uncertainty: $\delta m_W^{par} = 5$ MeV considering 1σ variation of $(\alpha, \alpha_s, G_\mu, m_Z, m_H, m_t)$

The W boson in the electroweak sector

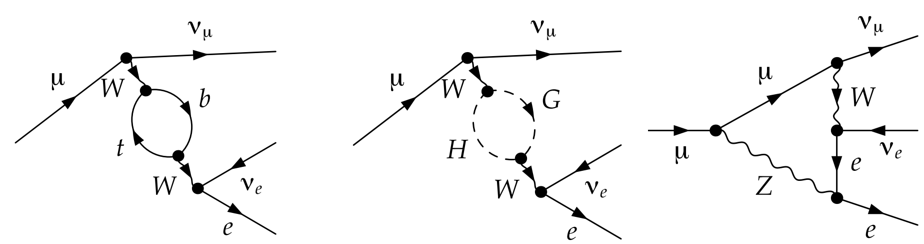
Radiative corrections: $m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$

Tree level



+

1-loop



+ full 2-loop + partial 3- and 4-loop

+ …

$m_W = 80.934$ GeV

$\Delta m_W = \mathcal{O}(0.5\text{ GeV})$

$\Delta m_W = \mathcal{O}(50\text{ MeV})$

$$\frac{\delta m_W}{m_W} \approx 10^{-4}$$

- Missing h.o. uncertainty:
  - $\delta m_W^{OS} = 4$ MeV on-shell scheme [Freitas,Hollik,Walter,Weiglein NPB 632 (2002)]
  - $\delta m_W^{\overline{MS}} = 3$ MeV $\overline{MS}$ scheme [Degrassi,Gambino,Giardino JHEP 05 (2015)]
- Parametric uncertainty: $\delta m_W^{par} = 5$ MeV considering 1σ variation of $(\alpha, \alpha_s, G_\mu, m_Z, m_H, m_t)$

Similar relations available for all other EW observables $\longrightarrow$ Global EW fit

The electroweak fit

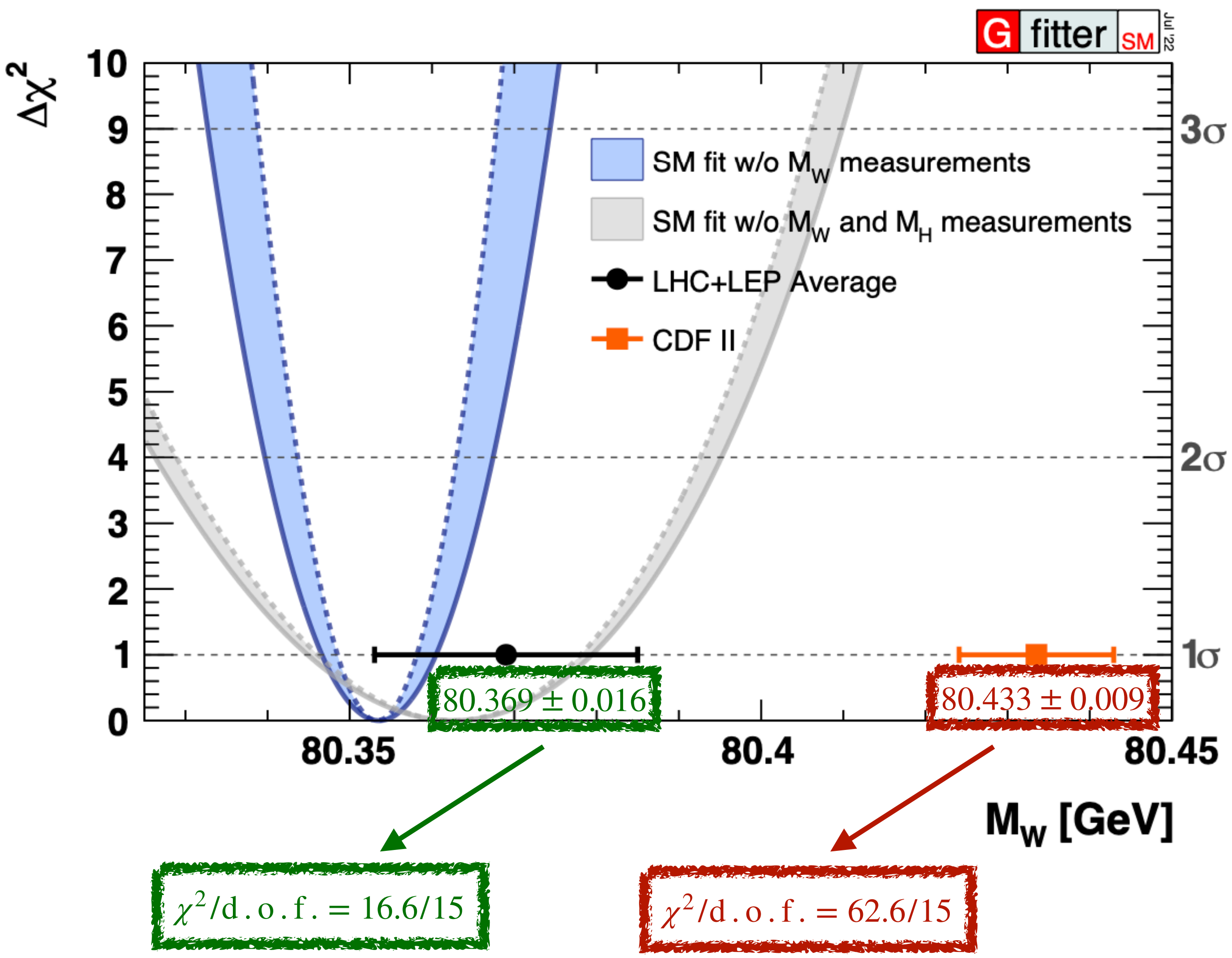
$$\text{Pull} = \frac{\text{Value} - \text{SM}}{\sigma_{\text{value}}}$$

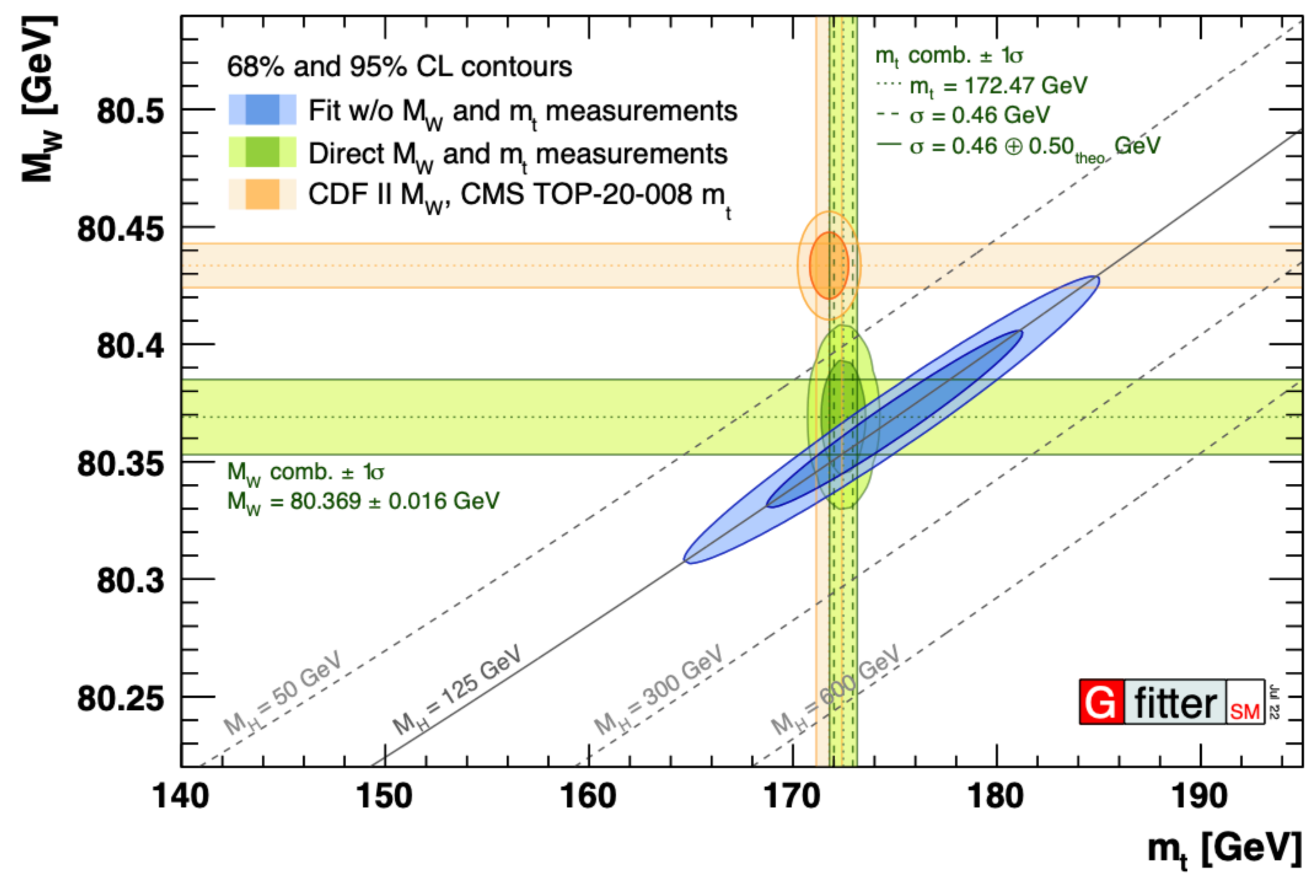
Quantity	Value	Standard Model	Pull
m_t [GeV]	172.83 ± 0.59	173.13 ± 0.56	-0.5
M_H [GeV]	125.30 ± 0.13	125.30 ± 0.13	0.0
Γ_H [MeV]	$3.2^{+2.4}_{-1.7}$	4.12 ± 0.05	-0.4
M_W [GeV]	80.387 ± 0.016 **Tevatron**	80.360 ± 0.006	1.7
	80.376 ± 0.033 **LEP2**		0.5
	80.366 ± 0.017 **LHC**		0.4
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
$\mathcal{B}(W \to \text{hadrons})$	0.6736 ± 0.0018	0.6751 ± 0.0001	-0.8
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0002	1.3
$Q_W(p)$	0.0719 ± 0.0045	0.0709 ± 0.0002	0.2
$Q_W(\text{Cs})$	-72.82 ± 0.42	-73.24 ± 0.01	1.0
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.90 ± 0.02	0.1
$\hat{s}_Z^2(\text{eDIS})$	0.2299 ± 0.0043	0.23122 ± 0.00004	-0.3
τ_τ [fs]	290.75 ± 0.36	288.90 ± 2.24	0.8
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4510.88 \pm 0.60) \times 10^{-9}$	$(4508.61 \pm 0.03) \times 10^{-9}$	3.8

(PDG 2022 **before** CDF II)

See J.Erler's talk

Electroweak fit





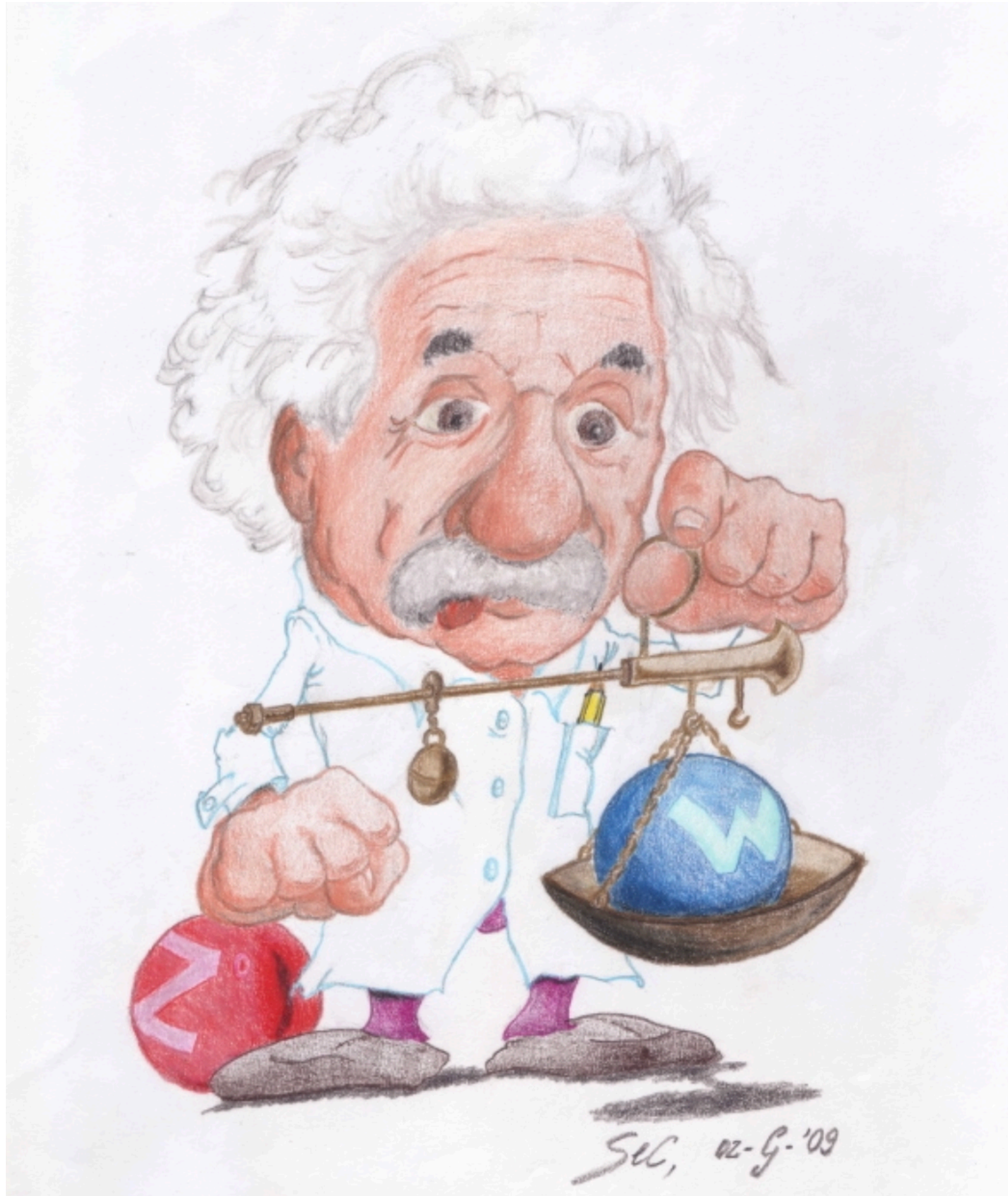
Indirect determination

$m_W = 80.356 \pm 0.006$ GeV (Gfitter) [Haller et al. EPJC 78 (2018)]

$m_W = 80.355 \pm 0.006$ GeV (HEPfit) [De Blas et al. PRD 106 (2022)]

See J.Erler's talk

How do we measure m_W?



The measurement of physical quantities

The measurement of physical quantities

Observables

- accessible via counting experiments: cross sections and asymmetries

The measurement 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

The measurement 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

The measurement 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. generate several histograms with <u>highest available theoretical accuracy</u> and best possible detector simulation, and let the fit parameter (e.g. m_W) vary in a range

The measurement 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. generate several histograms with highest available theoretical accuracy and best possible detector simulation, and let the fit parameter (e.g. m_W) vary in a range
2. the histogram that best describes data selects the preferred (*i.e. measured*) m_W

The measurement 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

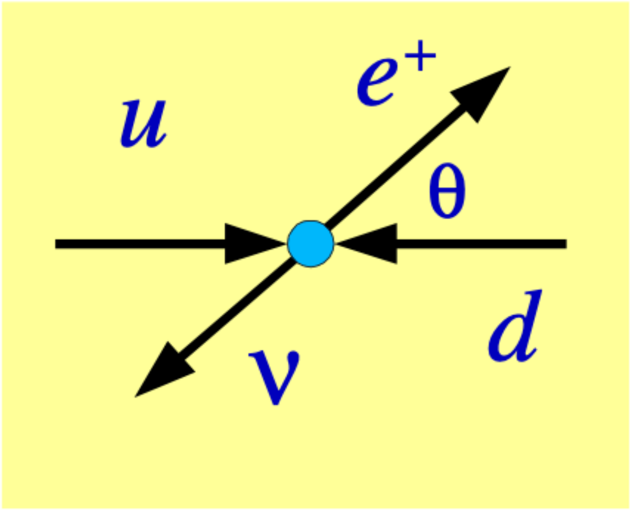
1. generate several histograms with highest available theoretical accuracy and best possible detector simulation, and let the fit parameter (e.g. m_W) vary in a range
2. the histogram that best describes data selects the preferred (*i.e. measured*) m_W

➡ 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

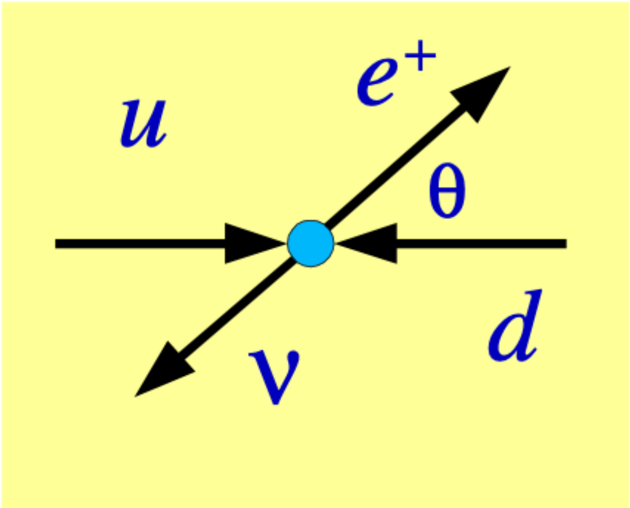
Observables and techniques for m_W

$$u+\overline{d}\rightarrow W^{+}\rightarrow e^{+}\nu$$



Observables and techniques for m_W

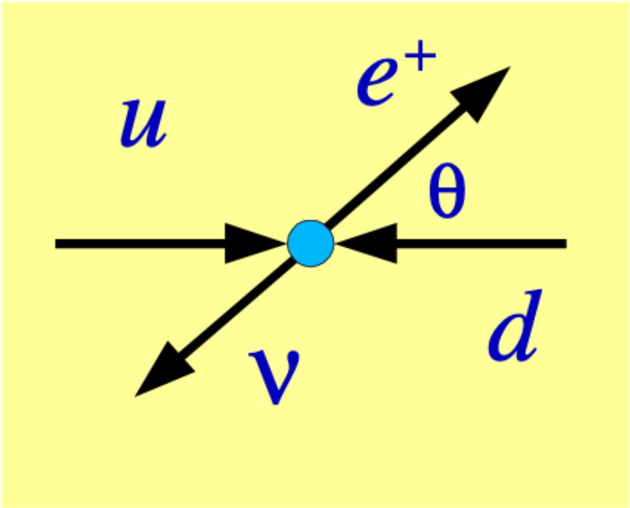
$$u + \overline{d} \rightarrow W^+ \rightarrow e^+ \nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

Observables and techniques for m_W

$$u+\bar{d}\to W^{+}\to e^{+}\nu$$



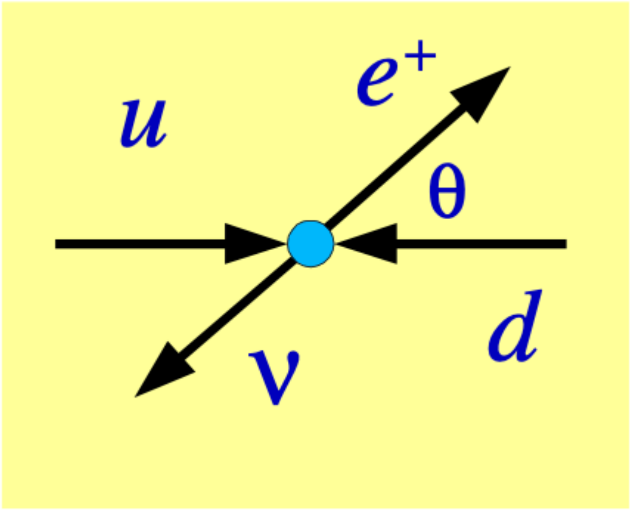
m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

Observables and techniques for m_W

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ \nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

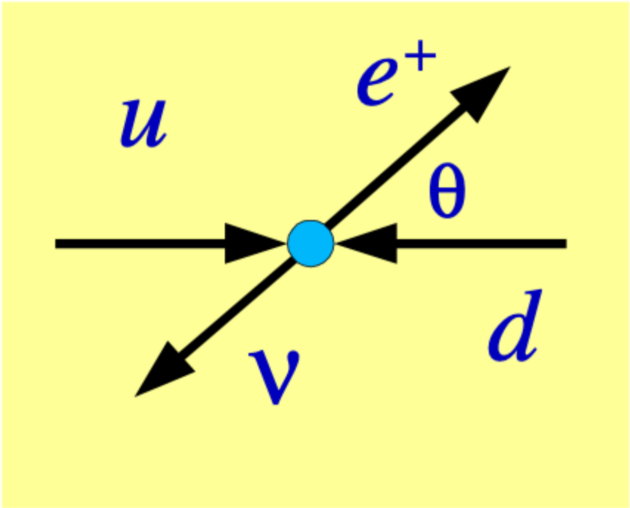
$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

endpoint at $m_T = m$ (invariant mass)

$$m^2 = (|\vec{p}^{\,l}| + |\vec{p}^{\,\nu}|)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$$

Observables and techniques for m_W

$$u + \bar{d} \to W^+ \to e^+ \nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

endpoint at $m_T = m$ (invariant mass)

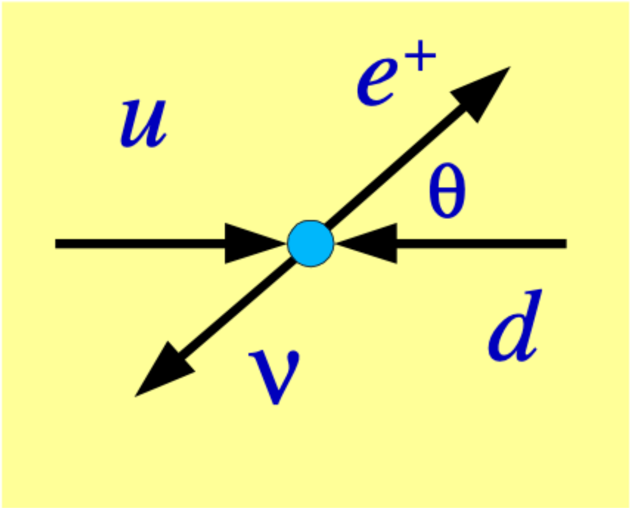
$$m^2 = (|\vec{p}^{\,l}| + |\vec{p}^{\,\nu}|)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$$

also expressed as

$$m_T = \sqrt{2|\vec{p}_T^{\,l}||\vec{p}_T^{\,\nu}|(1 - \cos\Delta\phi)}$$

Observables and techniques for m_W

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ \nu$$

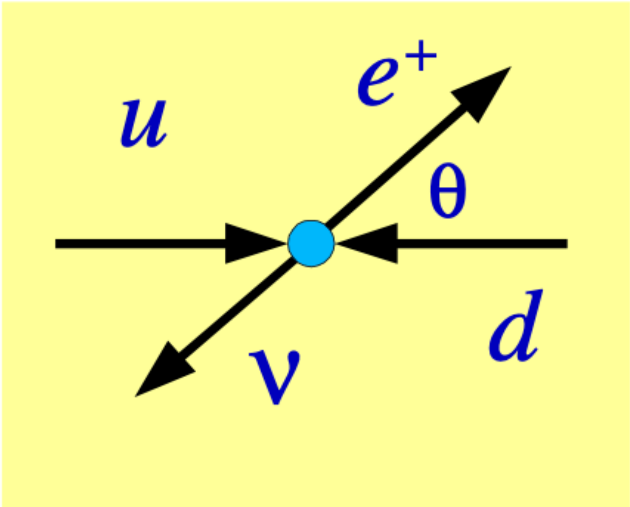


m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass	lepton p_T
$m_T^2 = (\lvert\vec{p}_T^{\,l}\rvert + \lvert\vec{p}_T^{\,\nu}\rvert)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$ **endpoint** at $m_T = m$ (invariant mass) $m^2 = (\lvert\vec{p}^{\,l}\rvert + \lvert\vec{p}^{\,\nu}\rvert)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$ also expressed as $m_T = \sqrt{2\lvert\vec{p}_T^{\,l}\rvert\lvert\vec{p}_T^{\,\nu}\rvert(1 - \cos\Delta\phi)}$	sharp **Jacobian peak** at $p_T^l \sim m_W/2$

Observables and techniques for m_W

$$u+\bar{d}\to W^+\to e^+\nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

endpoint at $m_T = m$ (invariant mass)

$$m^2 = (|\vec{p}^{\,l}| + |\vec{p}^{\,\nu}|)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$$

also expressed as

$$m_T = \sqrt{2|\vec{p}_T^{\,l}||\vec{p}_T^{\,\nu}|(1-\cos\Delta\phi)}$$

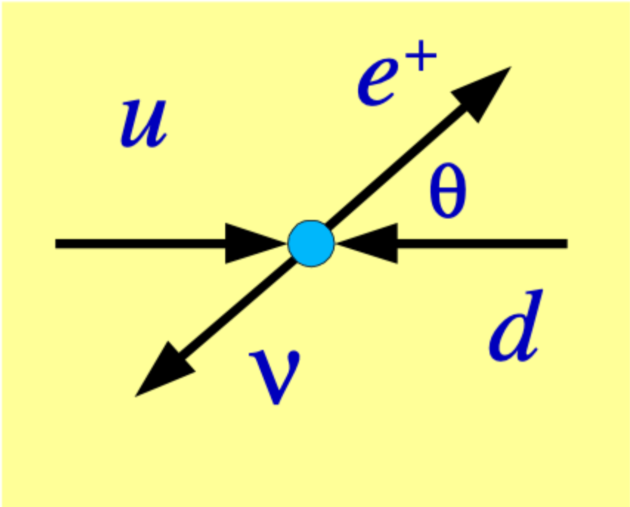
lepton p_T

sharp **Jacobian peak** at $p_T^l \sim m_W/2$

$$p_T^2 = \frac{\hat{s}}{4}\sin^2\theta \longrightarrow \cos\theta = \sqrt{1-\frac{4p_T^2}{\hat{s}}}$$

Observables and techniques for m_W

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ \nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

endpoint at $m_T = m$ (invariant mass)

$$m^2 = (|\vec{p}^{\,l}| + |\vec{p}^{\,\nu}|)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$$

also expressed as

$$m_T = \sqrt{2|\vec{p}_T^{\,l}||\vec{p}_T^{\,\nu}|(1 - \cos\Delta\phi)}$$

lepton p_T

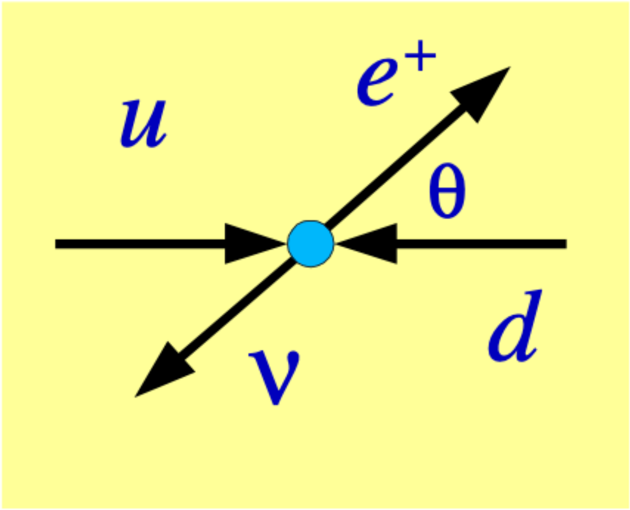
sharp **Jacobian peak** at $p_T^l \sim m_W/2$

$$p_T^2 = \frac{\hat{s}}{4}\sin^2\theta \longrightarrow \cos\theta = \sqrt{1 - \frac{4p_T^2}{\hat{s}}}$$

$$\frac{d\sigma}{dp_T^2} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dp_T^2} \approx \frac{1}{\cos\theta}$$

Observables and techniques for m_W

$$u+\bar{d}\to W^+\to e^+\nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

endpoint at $m_T = m$ (invariant mass)

$$m^2 = (|\vec{p}^{\,l}| + |\vec{p}^{\,\nu}|)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$$

also expressed as

$$m_T = \sqrt{2|\vec{p}_T^{\,l}||\vec{p}_T^{\,\nu}|(1-\cos\Delta\phi)}$$

lepton p_T

sharp **Jacobian peak** at $p_T^l \sim m_W/2$

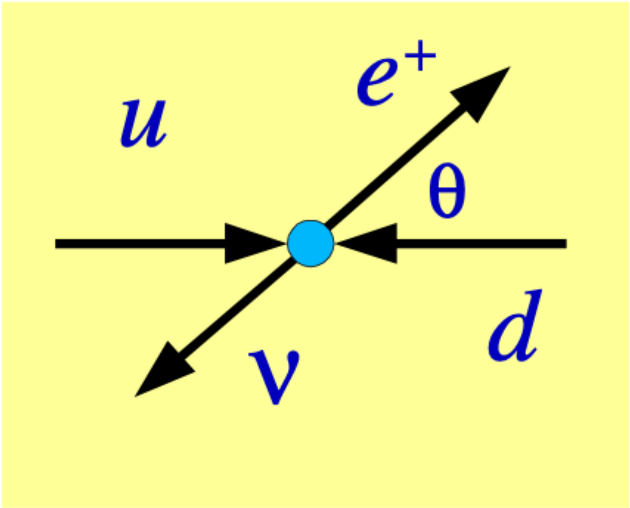
$$p_T^2 = \frac{\hat{s}}{4}\sin^2\theta \longrightarrow \cos\theta = \sqrt{1-\frac{4p_T^2}{\hat{s}}}$$

$$\frac{d\sigma}{dp_T^2} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dp_T^2} \approx \frac{1}{\cos\theta}$$

(enhances sensitivity to m_W)

Observables and techniques for m_W

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ \nu$$



m_W extracted from the study of the shape of m_T, p_T^l, p_T^ν

transverse mass

$$m_T^2 = (|\vec{p}_T^{\,l}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2$$

endpoint at $m_T = m$ (invariant mass)

$$m^2 = (|\vec{p}^{\,l}| + |\vec{p}^{\,\nu}|)^2 - (\vec{p}^{\,l} + \vec{p}^{\,\nu})^2$$

also expressed as

$$m_T = \sqrt{2|\vec{p}_T^{\,l}||\vec{p}_T^{\,\nu}|(1 - \cos\Delta\phi)}$$

lepton p_T

sharp **Jacobian peak** at $p_T^l \sim m_W/2$

$$p_T^2 = \frac{\hat{s}}{4}\sin^2\theta \longrightarrow \cos\theta = \sqrt{1 - \frac{4p_T^2}{\hat{s}}}$$

$$\frac{d\sigma}{dp_T^2} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dp_T^2} \approx \frac{1}{\cos\theta}$$

(enhances sensitivity to m_W)

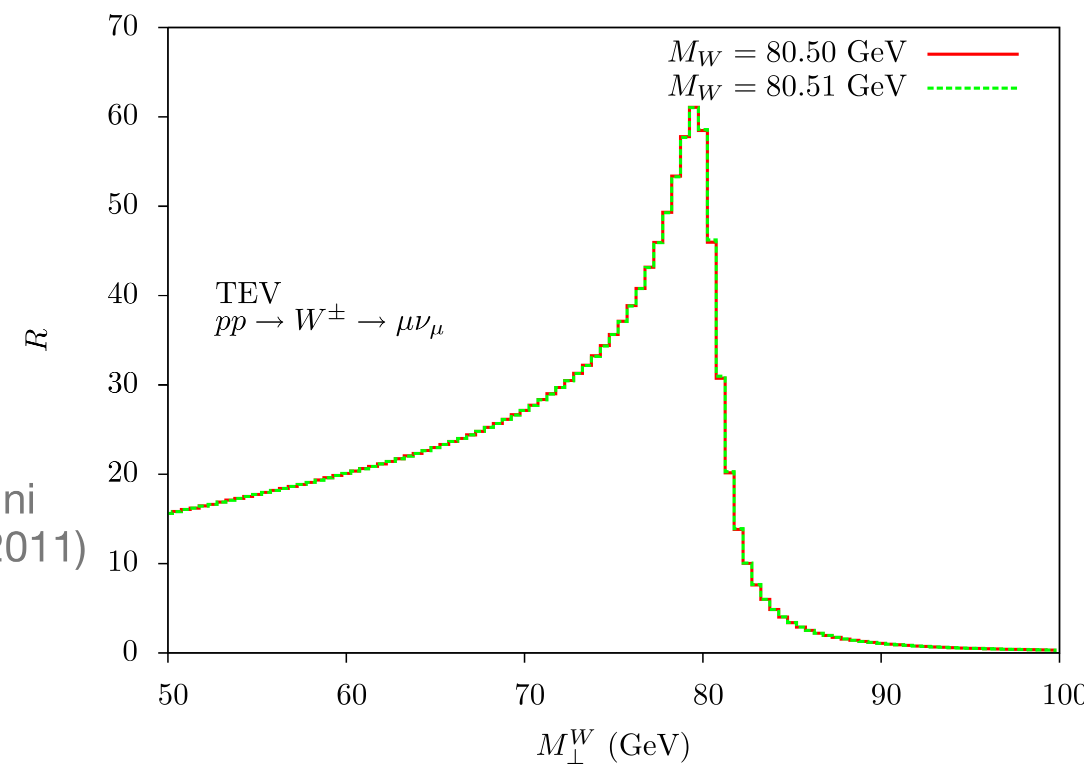
very different dependence on p_T^W and, ultimately, on hadronic uncertainties

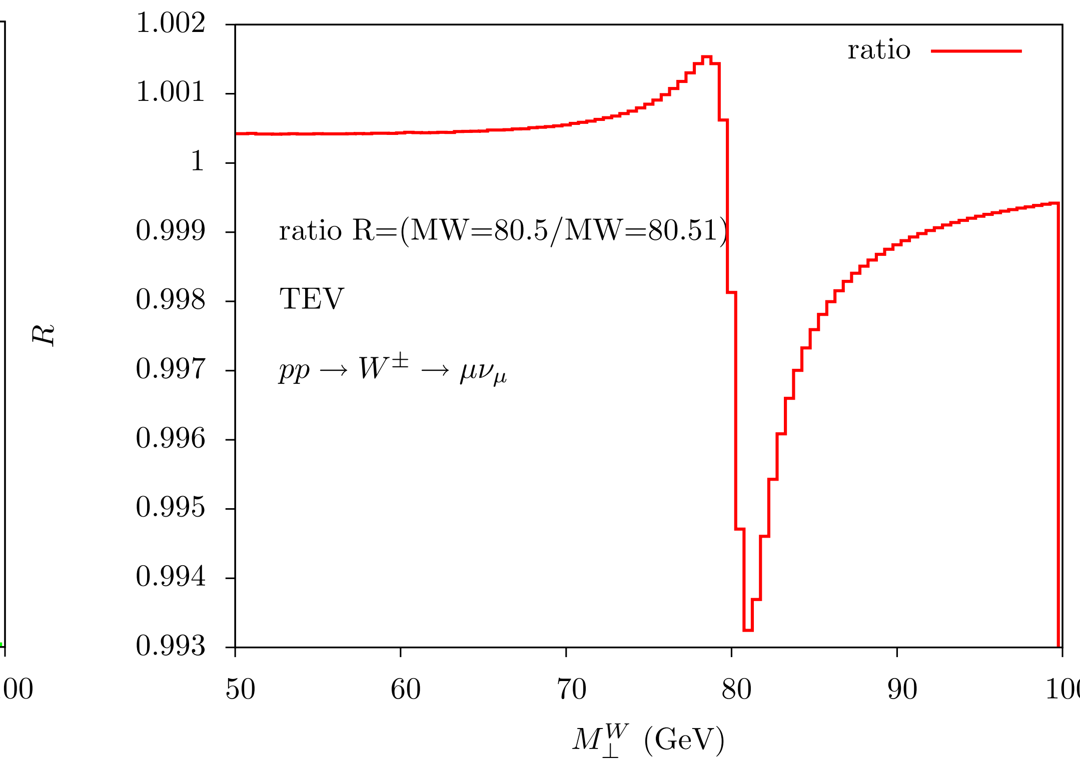
Observables and techniques for m_W

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

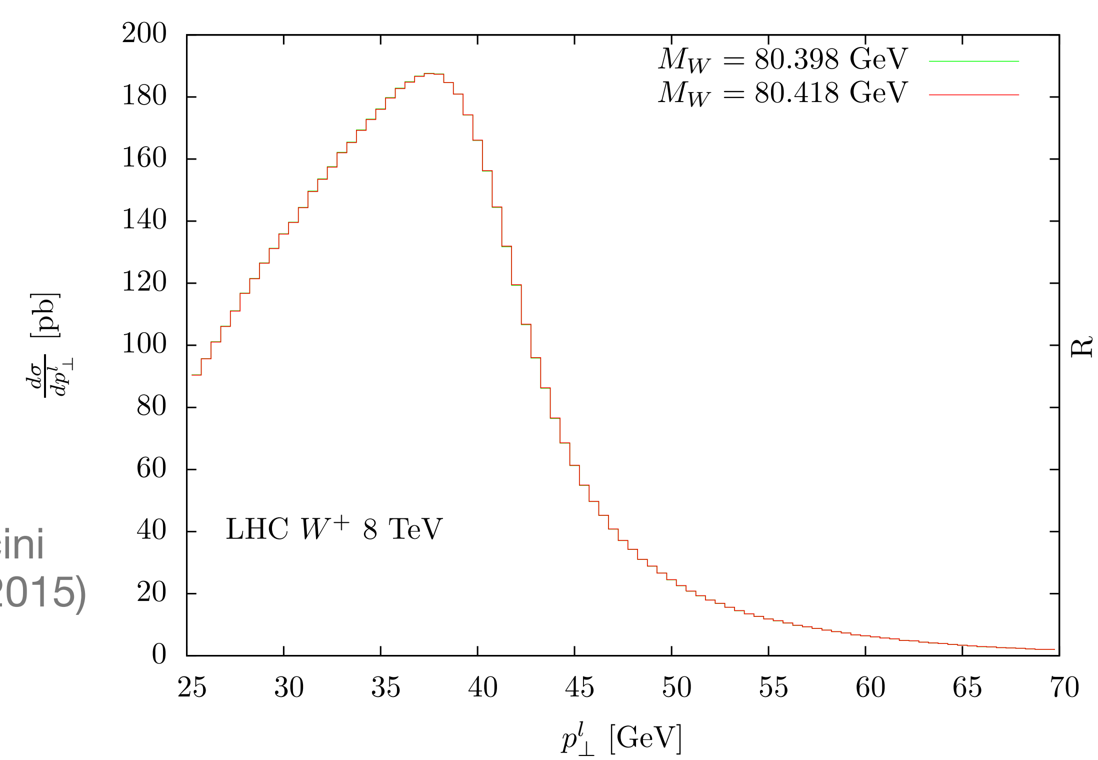
Bozzi, Rojo, Vicini
PRD 83, 113008 (2011)

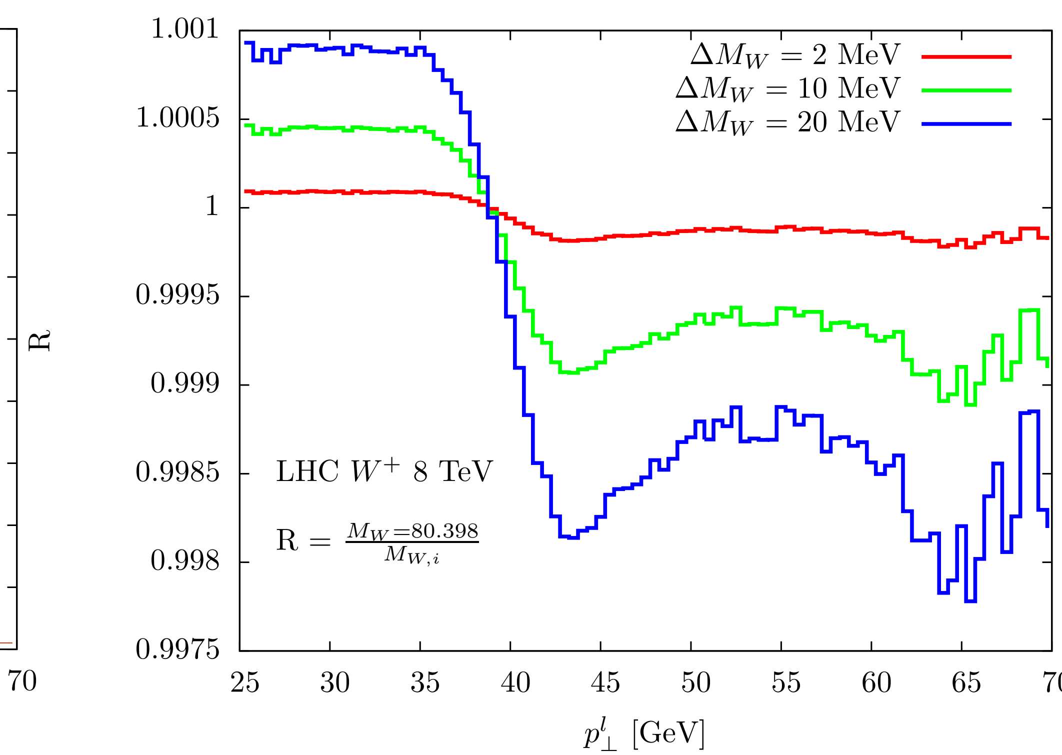




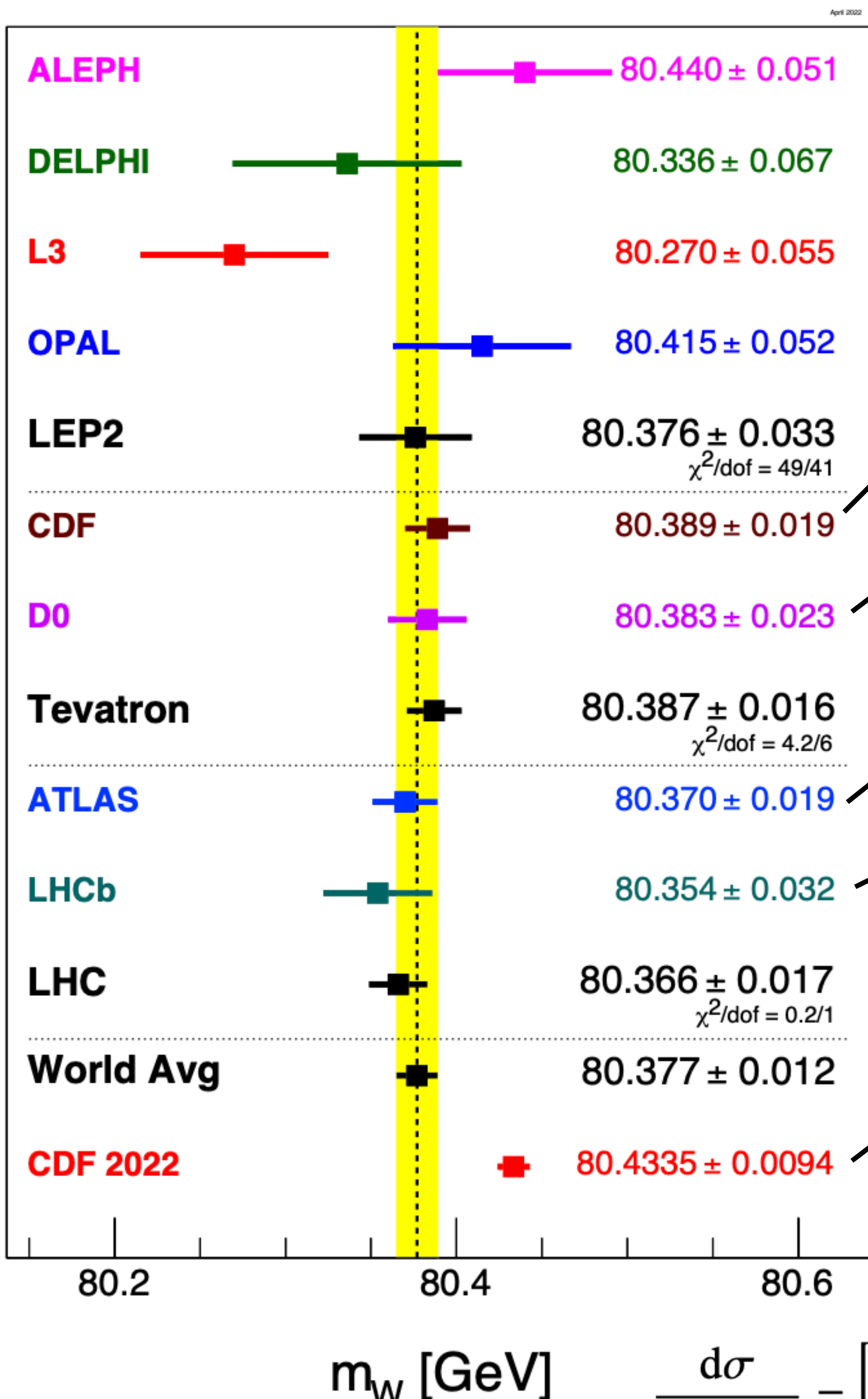
p_{Tl}

Bozzi, Citelli, Vicini
PRD 91, 113005 (2015)





Experimental measurements



CDF I : ±12 (**stat**) ±10 (**exp syst**)
±7 (**model**) ±10 (**PDF**)

D0: ±13 (**stat**) ±18 (**exp syst**)
±9 (**model**) ±11 (**PDF**)

ATLAS: ±7 (**stat**) ±11 (**exp syst**)
±14 (**model**) ±8 (**PDF**)

LHCb: ±23 (**stat**) ±10 (**exp syst**)
±17 (**model**) ±9 (**PDF**)

CDF II : ±6 (**stat**) ±5 (**exp syst**)
±3 (**model**) ±4 (**PDF**)

very different methods to estimate modelling and PDF uncertainties

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

Experimental measurements

D0

	m_T	p_T^e	$\not{E}_T$	
PDF	11	11	14	→ 68% CL template fit CTEQ6.1
QED	7	7	9	→ comparison Wgrad/Zgrad vs. Photos
Boson p_T	2	5	2	→ NP fit on Z data

CDF

	m_T	p_T^e	$\not{E}_T$	
p_T^Z model	0.7	2.3	0.9	→ NP fit on Z data
p_T^W/p_T^Z model	0.8	2.3	0.9	→ propagation of μ_R, μ_F, μ_{res} scale variation
Parton distributions	3.9	3.9	3.9	→ CTEQ6.6 vs. ABMP16, CJ15, CT18, MMHT2014, NNPDF3.1

LHCb

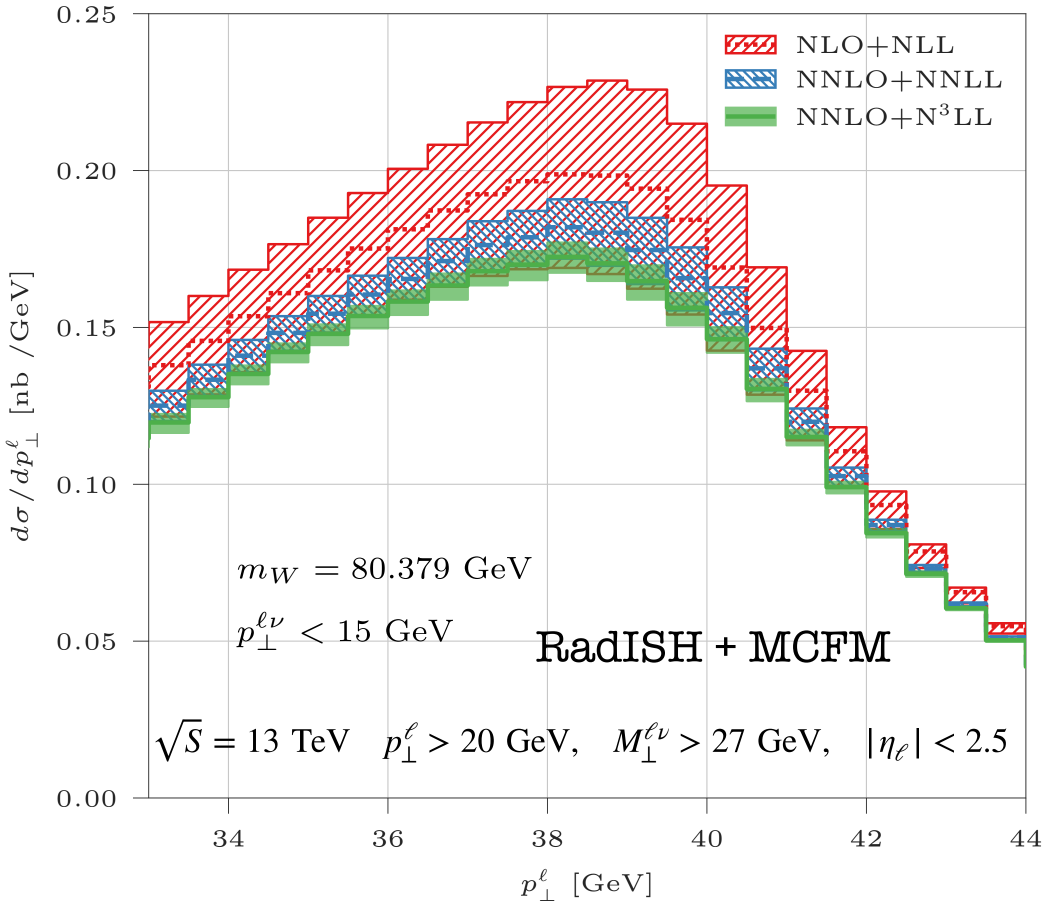
Parton distribution functions	9	→ average of 3 separate fits: CT18, MSHT20, NNPDF3.1
Theory (excl. PDFs) total	17	
Transverse momentum model	11	→ spread of Powheg+Pythia/Herwig, DYTurbo, Pythia/Herwig
Angular coefficients	10	→ μ_R, μ_F scale variation
QED FSR model	7	→ comparison of Herwig, Pythia, Photos

ATLAS

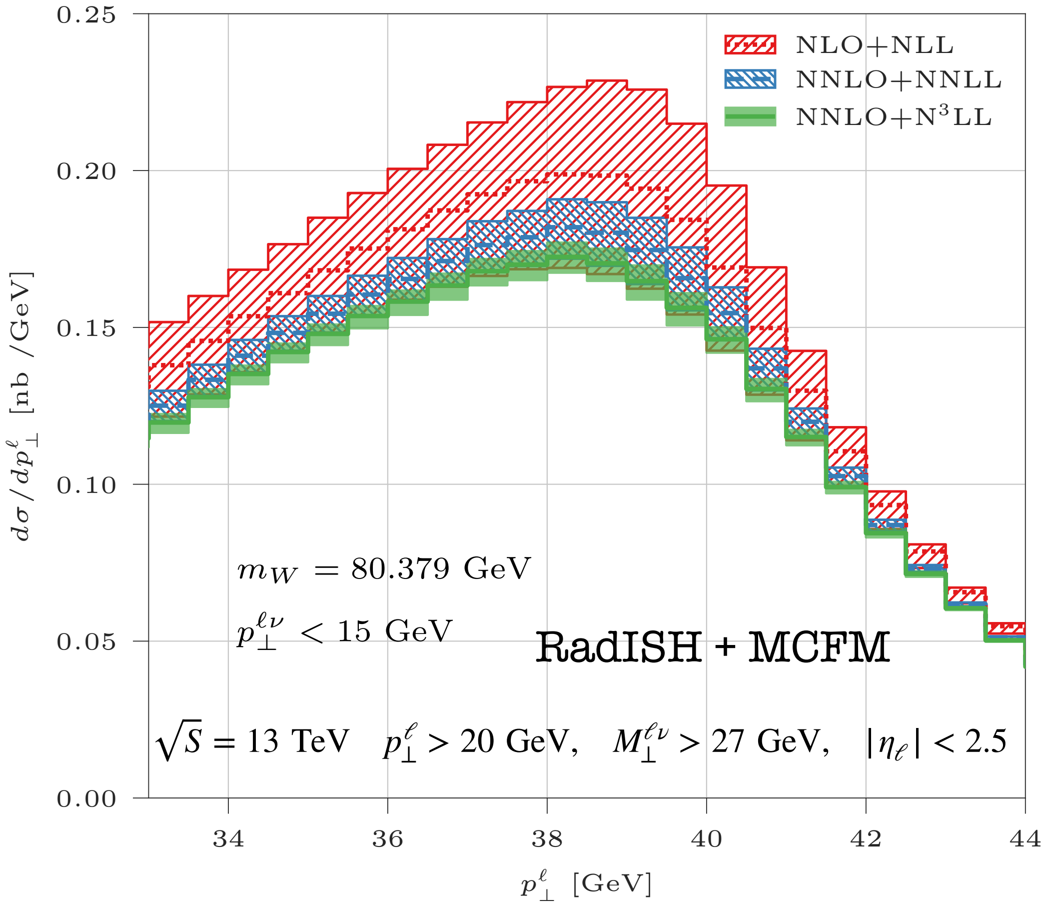
W-boson charge	W^+		W^-		Combined		
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	
δm_W [MeV]							
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7	Hessian on CT10 + quadrature with MMHT2014 and CT14
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4	propagation of Pythia parameter uncertainty
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5	variation of m_c
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9	μ_F variation: simultaneous (independent) for u,d,s (c,b)
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6	variation of LO PDF sets for Parton Shower
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3	propagation of Z data uncertainty
Total	15.9	18.1	14.8	17.2	11.6	12.9	

Perturbative theoretical uncertainties

Perturbative uncertainties

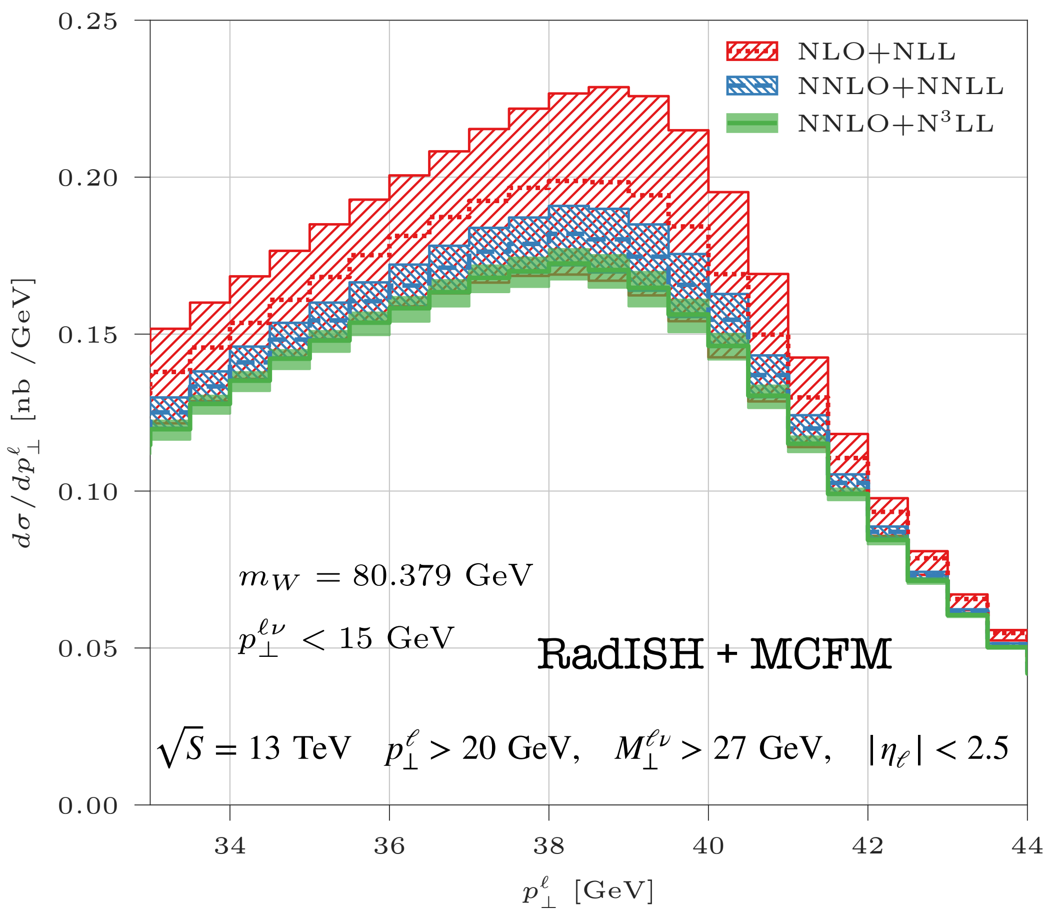


Perturbative uncertainties



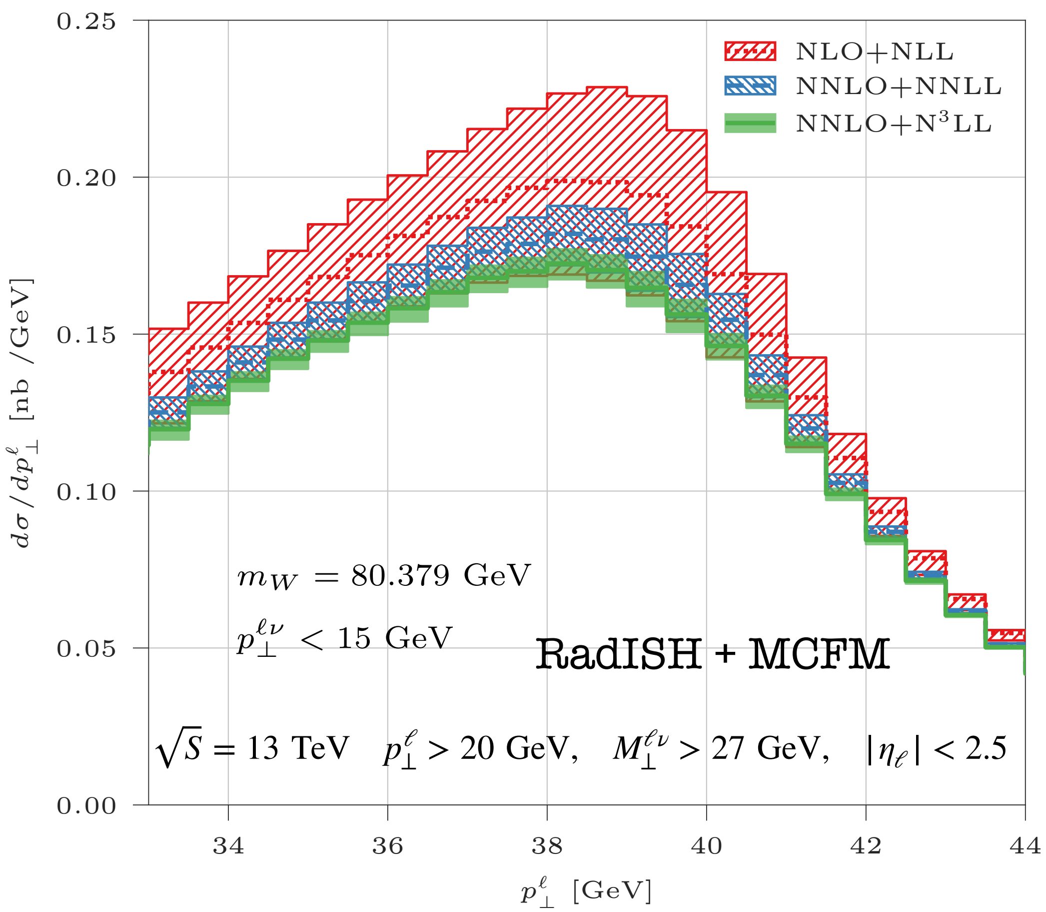
- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!

Perturbative uncertainties



- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure

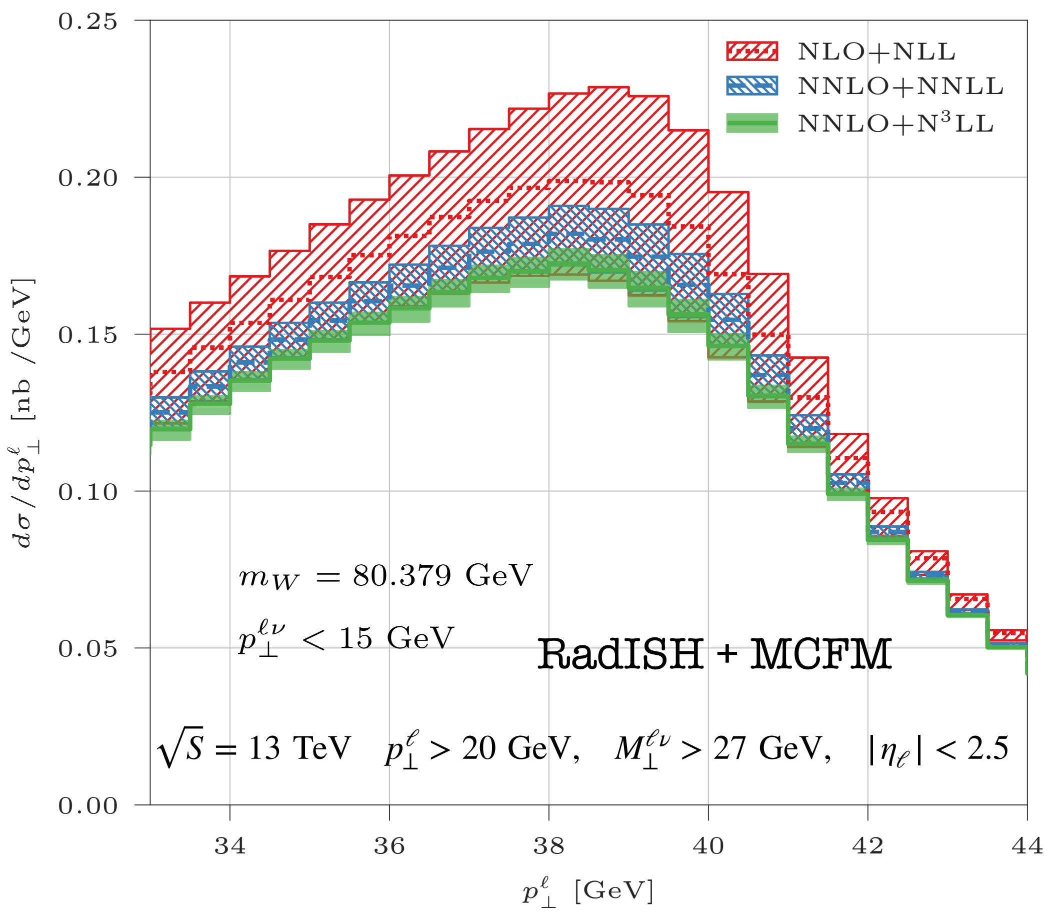
Perturbative uncertainties



- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure

➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

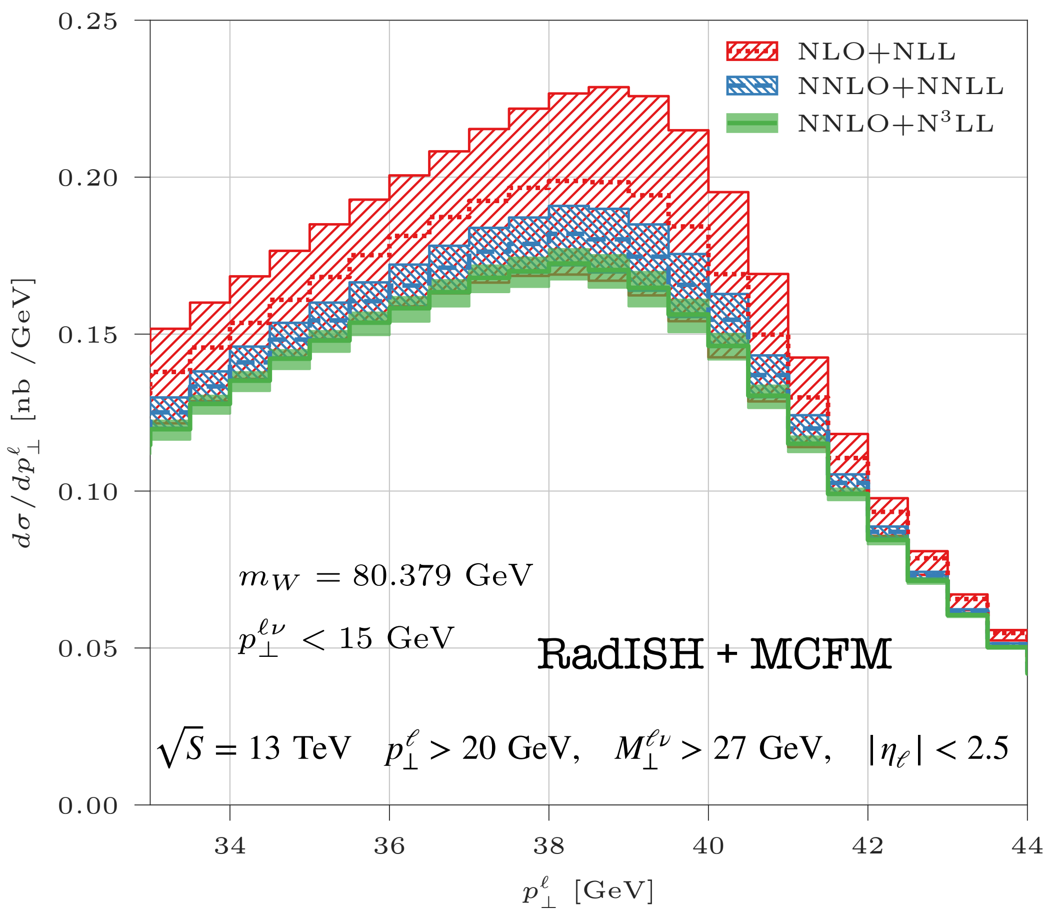
Perturbative uncertainties



- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure
- ➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

- Comments on data-driven approach

Perturbative uncertainties

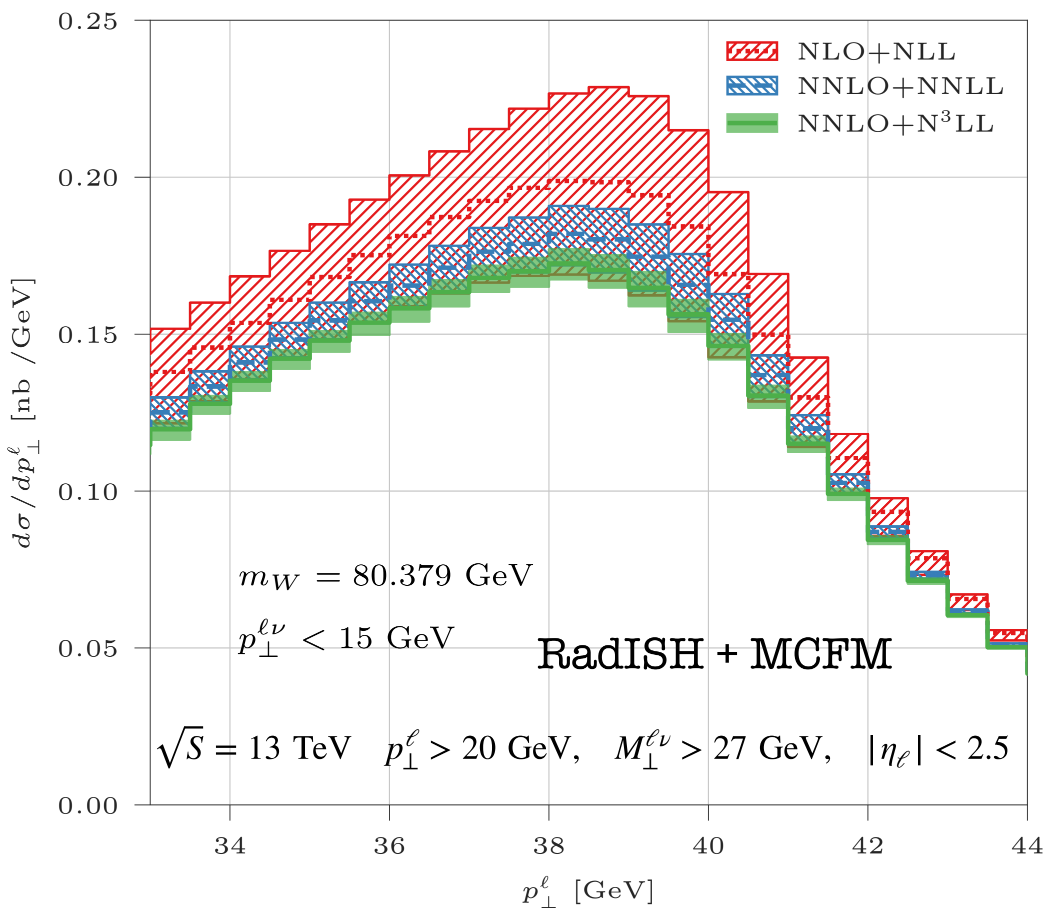


- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure

➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

- Comments on data-driven approach
  - MC usually (N)LL+NLO → large reweighing w.r.t. N3LL+NNLO

Perturbative uncertainties

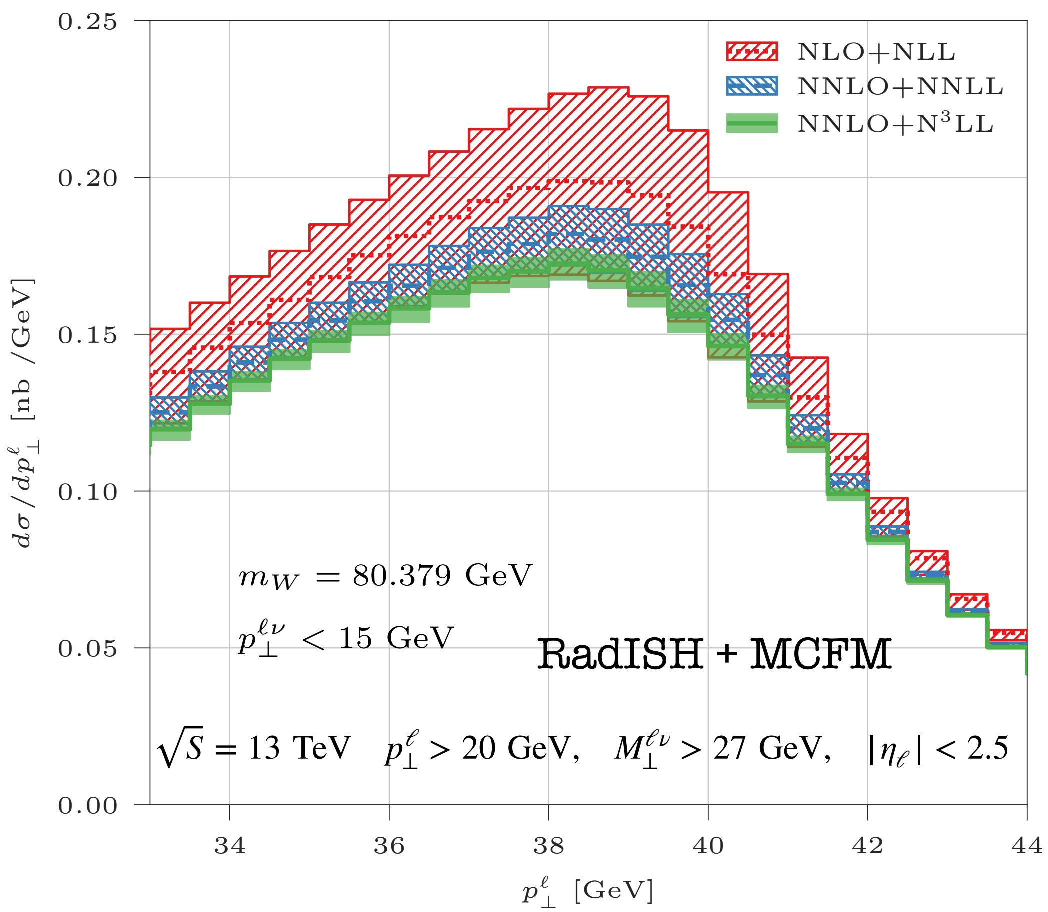


- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure

➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

- Comments on data-driven approach
  - MC usually (N)LL+NLO → large reweighing w.r.t. N3LL+NNLO
  - tuning should be done in association to scale variation (different scales → different reweighing functions → different propagation to CCDY)

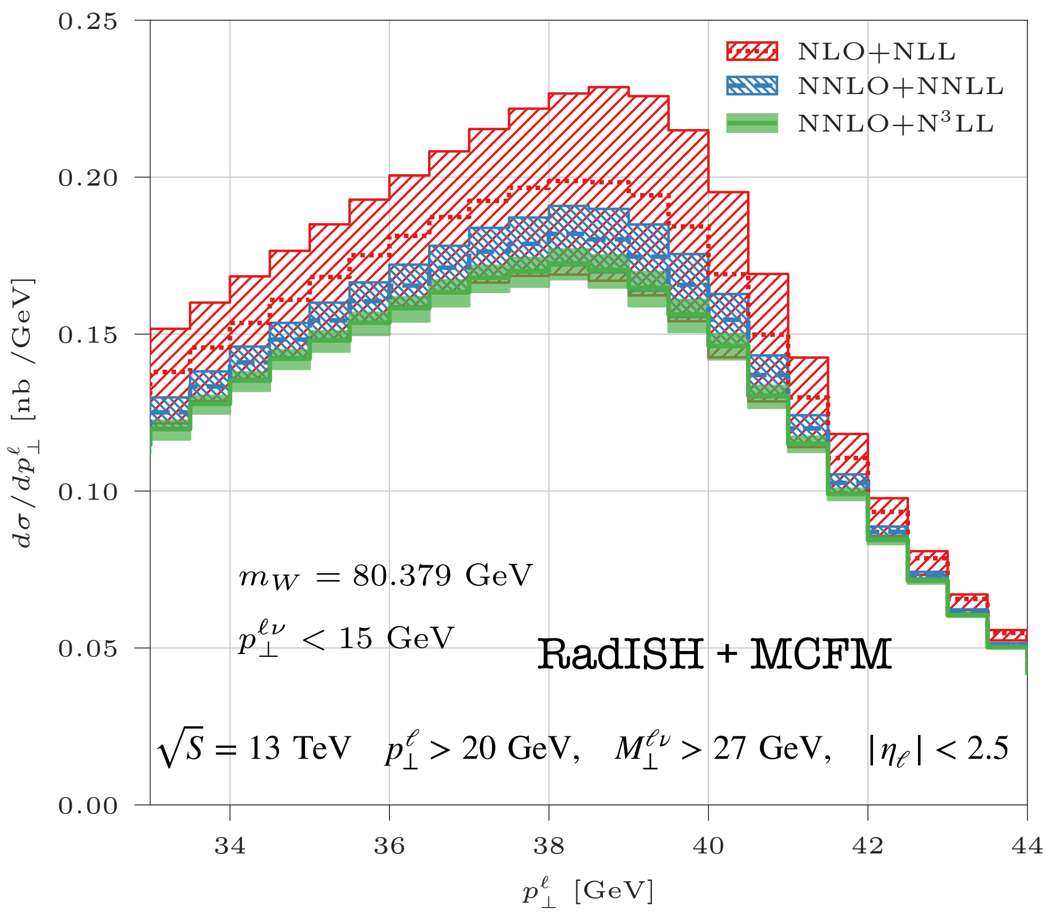
Perturbative uncertainties



- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure
- ➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

- Comments on data-driven approach
  - MC usually (N)LL+NLO → large reweighing w.r.t. N3LL+NNLO
  - tuning should be done in association to scale variation (different scales → different reweighing functions → different propagation to CCDY)
  - underlying differences NCDY-CCDY (masses, charges, acceptances, PDFs, heavy quarks, intrinsic-k_T)

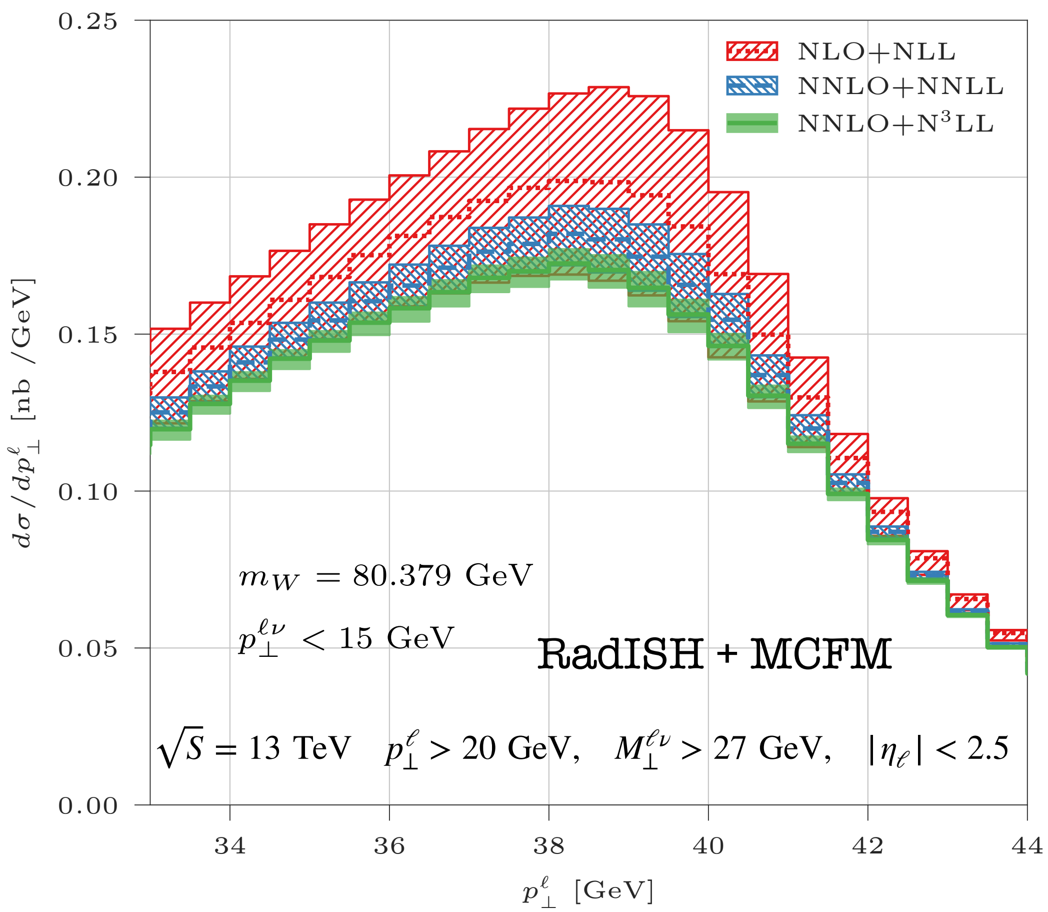
Perturbative uncertainties



- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure
- ➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

- Comments on data-driven approach
  - MC usually (N)LL+NLO → large reweighing w.r.t. N3LL+NNLO
  - tuning should be done in association to scale variation (different scales → different reweighing functions → different propagation to CCDY)
  - underlying differences NCDY-CCDY (masses, charges, acceptances, PDFs, heavy quarks, intrinsic-k_T)
  - BSM physics possibly reabsorbed in tuning

Perturbative uncertainties

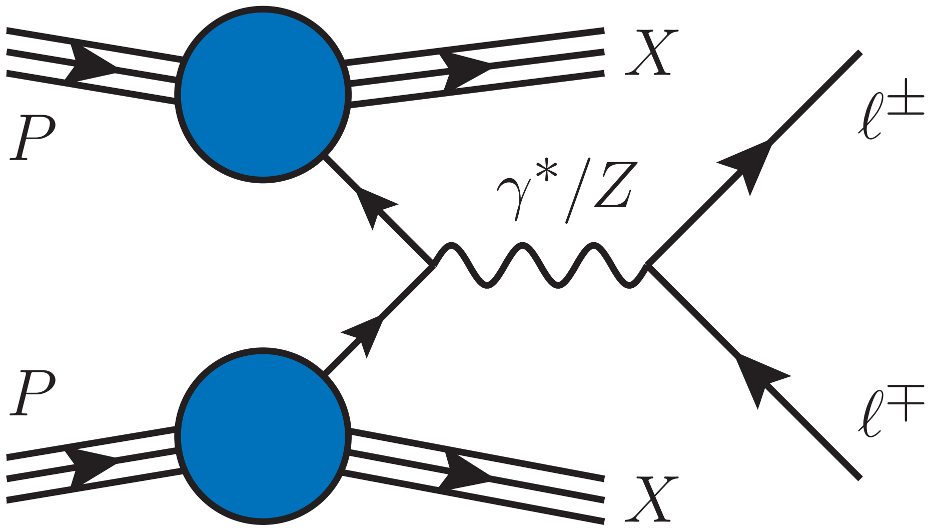


- QCD scale variation
  - set of equally good templates
  - $\mathcal{O}(1\%)$ width → 10x larger than required!
- Non-statistical nature of Th Sys → not included in χ^2 covariance matrix
  - including scale variations in predictions would result in an extremely unstable procedure
- ➡ data-driven approach: MC tuned to NCDY data (typically for single QCD scale choice) and used to prepare CCDY templates

- Comments on data-driven approach
  - MC usually (N)LL+NLO → large reweighing w.r.t. N3LL+NNLO
  - tuning should be done in association to scale variation (different scales → different reweighing functions → different propagation to CCDY)
  - underlying differences NCDY-CCDY (masses, charges, acceptances, PDFs, heavy quarks, intrinsic-k_T)
  - BSM physics possibly reabsorbed in tuning
  - fitted value not necessarily the SM lagrangian parameter

Non-perturbative theoretical uncertainties

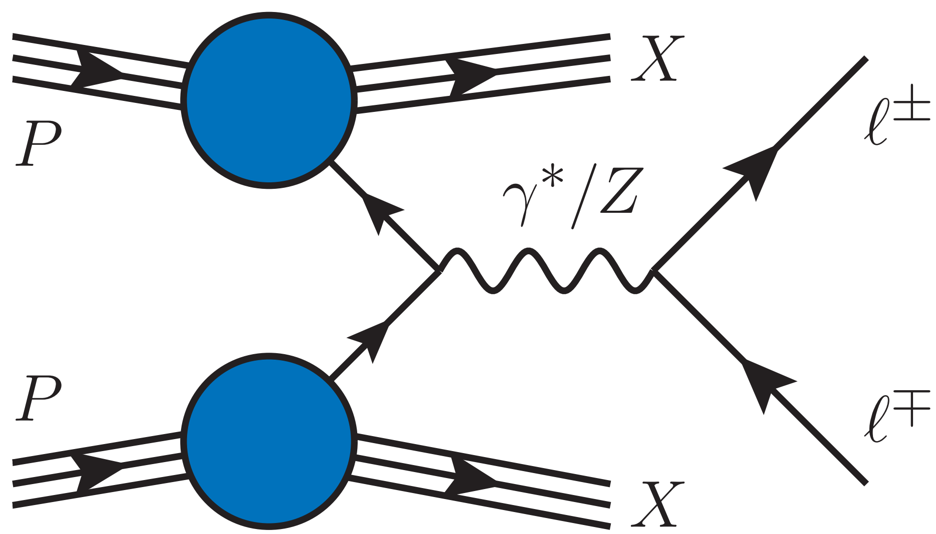
Lepton pair production



$PP \longrightarrow \ell^{\pm}\ell^{\mp}\, X$

$$\sigma(P_1, P_2, Q) = \sum_{a,b} \int_0^1 dx_1 dx_2 \; f_{a,h_1}(x_1, \mu_F)\, f_{b,h_2}(x_2, \mu_F)\; \hat{\sigma}(x_1 P_1, x_2 P_2, \mu_R, \mu_F)$$

Lepton pair production

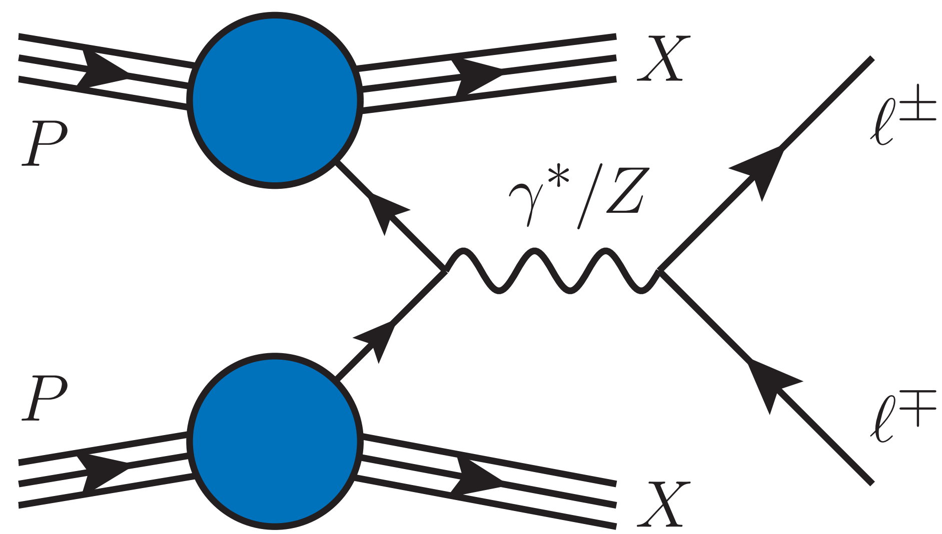


$PP \longrightarrow \ell^{\pm}\ell^{\mp} X$

$$\sigma(P_1, P_2, Q) = \sum_{a,b} \int_0^1 dx_1 dx_2 \; f_{a,h_1}(x_1, \mu_F)\, f_{b,h_2}(x_2, \mu_F)\; \hat{\sigma}(x_1 P_1, x_2 P_2, \mu_R, \mu_F)$$

- PDFs fitted from experimental data $\longrightarrow$ inherit their uncertainties

Lepton pair production

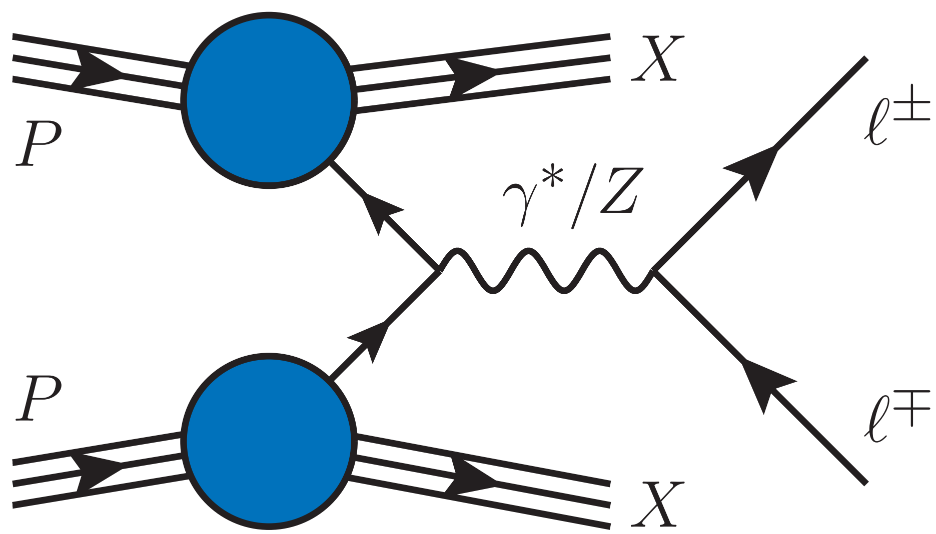


$PP \longrightarrow \ell^{\pm}\ell^{\mp}\, X$

$$\sigma(P_1, P_2, Q) = \sum_{a,b} \int_0^1 dx_1 dx_2\ f_{a,h_1}(x_1, \mu_F)\, f_{b,h_2}(x_2, \mu_F)\ \hat{\sigma}(x_1 P_1, x_2 P_2, \mu_R, \mu_F)$$

- PDFs fitted from experimental data $\longrightarrow$ inherit their uncertainties
- PDF uncertainty represented by different sets (Hessian eigenvectors language: CTEQ, MSHT, …) or different replicas (Monte Carlo language, NNPDF)

Lepton pair production

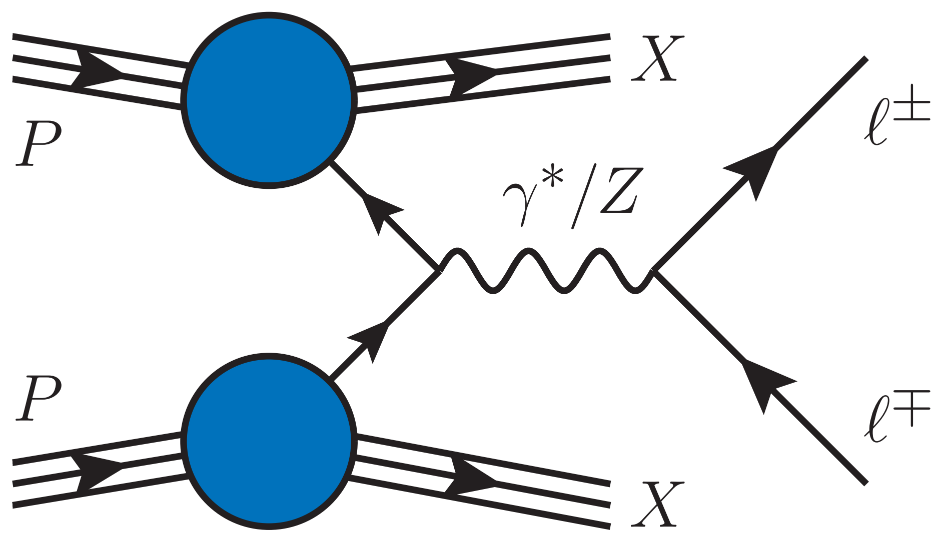


$PP \longrightarrow \ell^{\pm}\ell^{\mp}\, X$

$$\sigma(P_1, P_2, Q) = \sum_{a,b} \int_0^1 dx_1 dx_2\ f_{a,h_1}(x_1, \mu_F)\, f_{b,h_2}(x_2, \mu_F)\ \hat{\sigma}(x_1 P_1, x_2 P_2, \mu_R, \mu_F)$$

- PDFs fitted from experimental data $\longrightarrow$ inherit their uncertainties
- PDF uncertainty represented by different sets (Hessian eigenvectors language: CTEQ, MSHT, …) or different replicas (Monte Carlo language, NNPDF)
- templates used to fit m_W suffer from 2 kind of PDF-related uncertainties

Lepton pair production



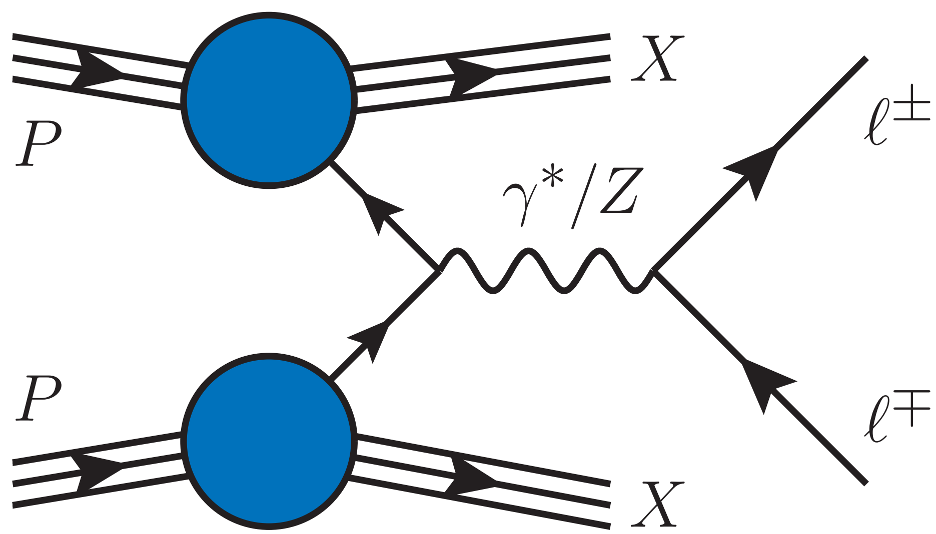
$PP \longrightarrow \ell^{\pm}\ell^{\mp}\, X$

$$\sigma(P_1, P_2, Q) = \sum_{a,b} \int_0^1 dx_1 dx_2\ f_{a,h_1}(x_1, \mu_F)\, f_{b,h_2}(x_2, \mu_F)\ \hat{\sigma}(x_1 P_1, x_2 P_2, \mu_R, \mu_F)$$

- PDFs fitted from experimental data $\longrightarrow$ inherit their uncertainties
- PDF uncertainty represented by different sets (Hessian eigenvectors language: CTEQ, MSHT, …) or different replicas (Monte Carlo language, NNPDF)
- templates used to fit m_W suffer from 2 kind of PDF-related uncertainties

  1. spread of predictions due to different choice of PDFs

Lepton pair production



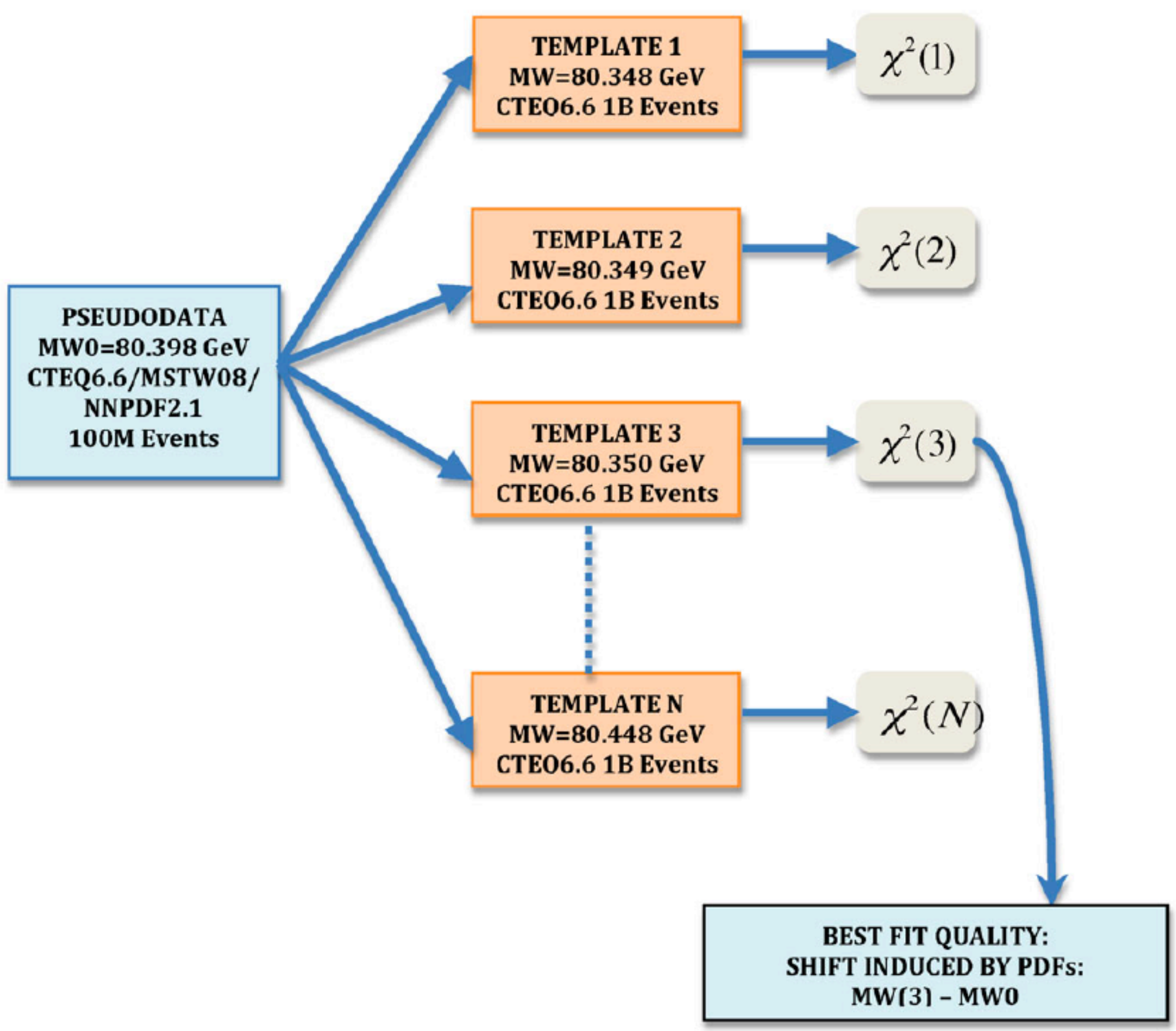
$PP \longrightarrow \ell^{\pm}\ell^{\mp}\,X$

$$\sigma(P_1, P_2, Q) = \sum_{a,b} \int_0^1 dx_1 dx_2 \; f_{a,h_1}(x_1, \mu_F)\, f_{b,h_2}(x_2, \mu_F)\; \hat{\sigma}(x_1 P_1, x_2 P_2, \mu_R, \mu_F)$$

- PDFs fitted from experimental data $\longrightarrow$ inherit their uncertainties
- PDF uncertainty represented by different sets (Hessian eigenvectors language: CTEQ, MSHT, …) or different replicas (Monte Carlo language, NNPDF)
- templates used to fit m_W suffer from 2 kind of PDF-related uncertainties
  1. spread of predictions due to different choice of PDFs
  2. propagation of PDF errors to prediction of observables

Template-fit estimate of PDF uncertainties

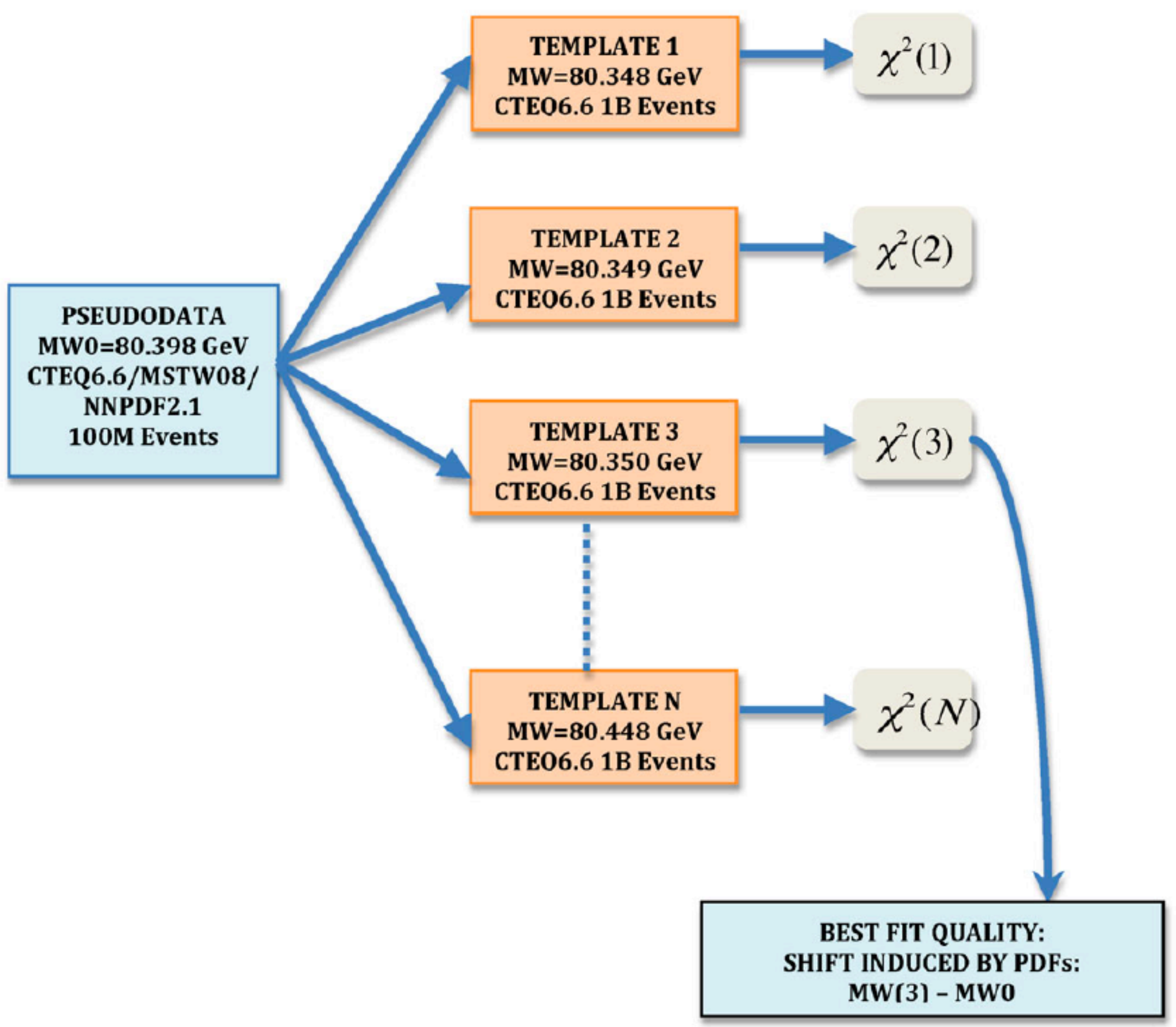
Bozzi, Rojo, Vicini PRD 83 (2011)
Bozzi, Citelli, Vicini PRD 91 (2015)
Bozzi, Citelli, Vesterinen, Vicini EPJC 75 (2015)



Template-fit estimate of PDF uncertainties

Bozzi, Rojo, Vicini PRD 83 (2011)
Bozzi, Citelli, Vicini PRD 91 (2015)
Bozzi, Citelli, Vesterinen, Vicini EPJC 75 (2015)

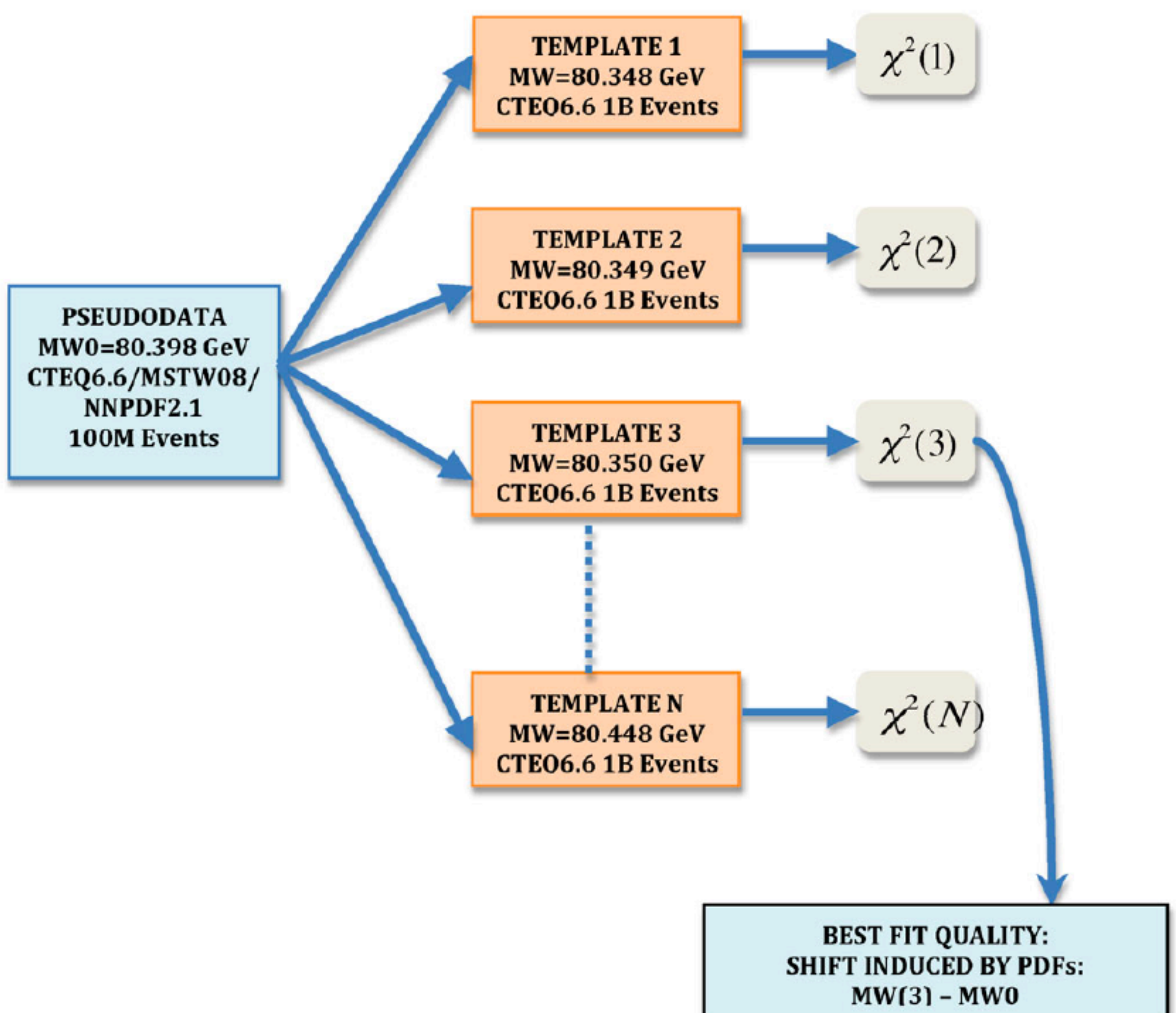
- **pseudodata** with different PDF sets: low-statistics (100M) and fixed m_{W0}



Template-fit estimate of PDF uncertainties

Bozzi, Rojo, Vicini PRD 83 (2011)
Bozzi, Citelli, Vicini PRD 91 (2015)
Bozzi, Citelli, Vesterinen, Vicini EPJC 75 (2015)

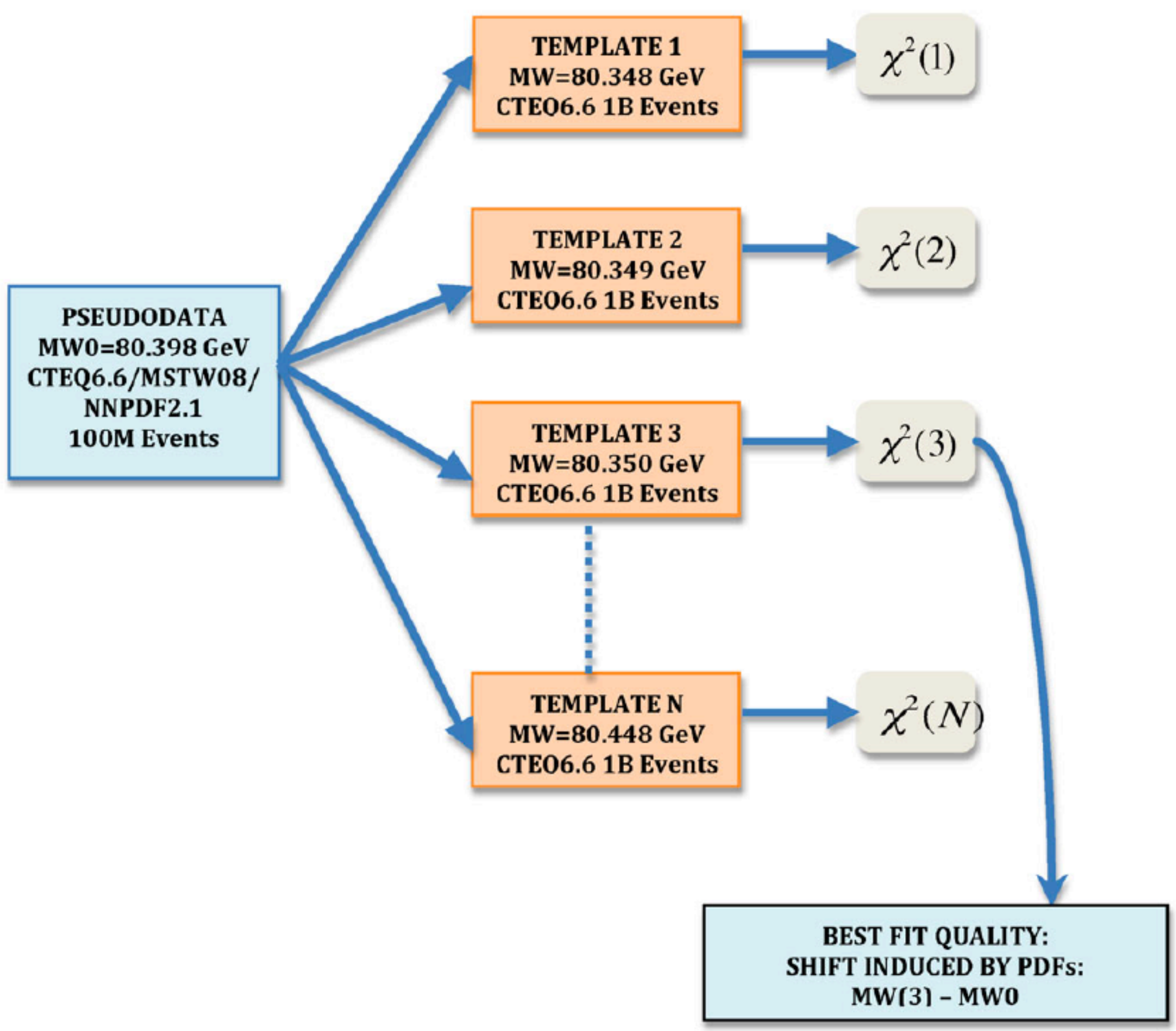
- **pseudodata** with different PDF sets: low-statistics (100M) and fixed m_{W0}
- **templates** with a reference PDF set (CTEQ6.6): high-statistics (1B) and different m_W



Template-fit estimate of PDF uncertainties

Bozzi, Rojo, Vicini PRD 83 (2011)
Bozzi, Citelli, Vicini PRD 91 (2015)
Bozzi, Citelli, Vesterinen, Vicini EPJC 75 (2015)

- **pseudodata** with different PDF sets: low-statistics (100M) and fixed m_{W0}
- **templates** with a reference PDF set (CTEQ6.6): high-statistics (1B) and different m_W
- same code used to generate both pseudodata and templates → only effect probed is the PDF one



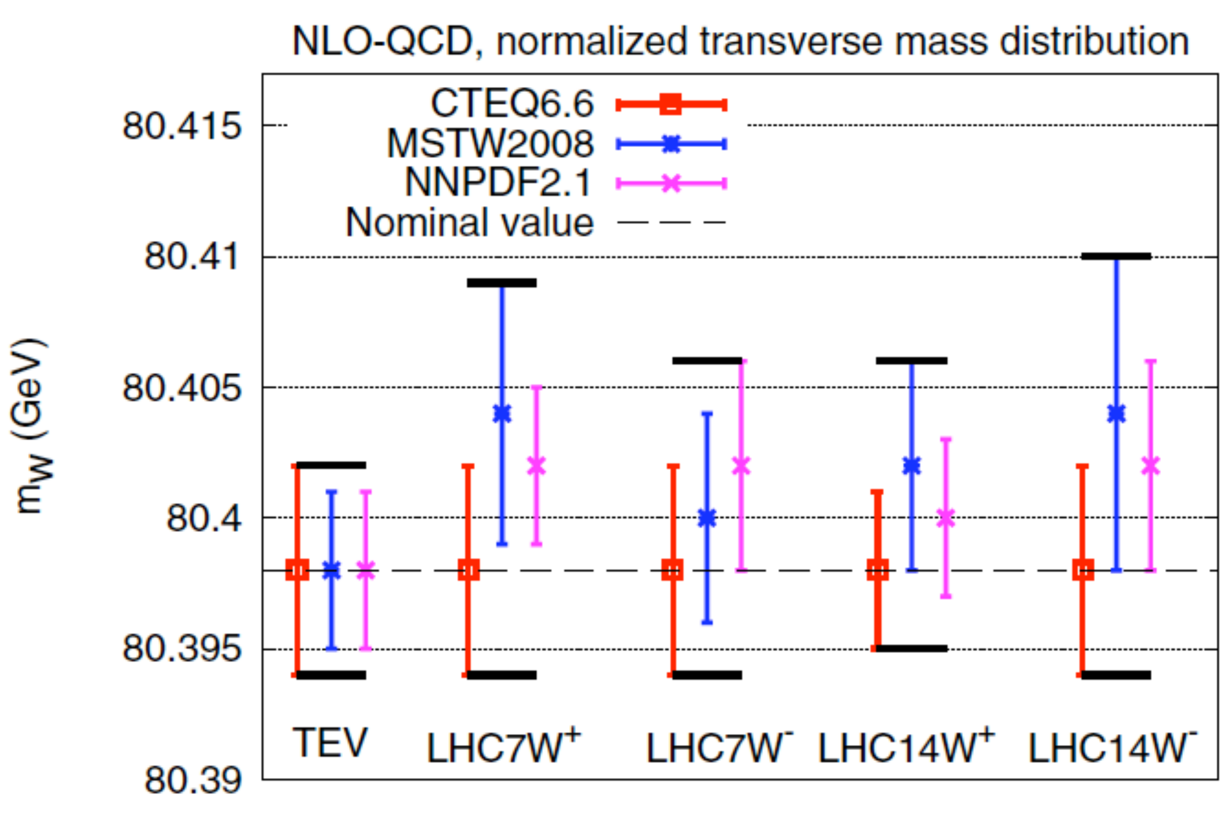
Non-perturbative uncertainties

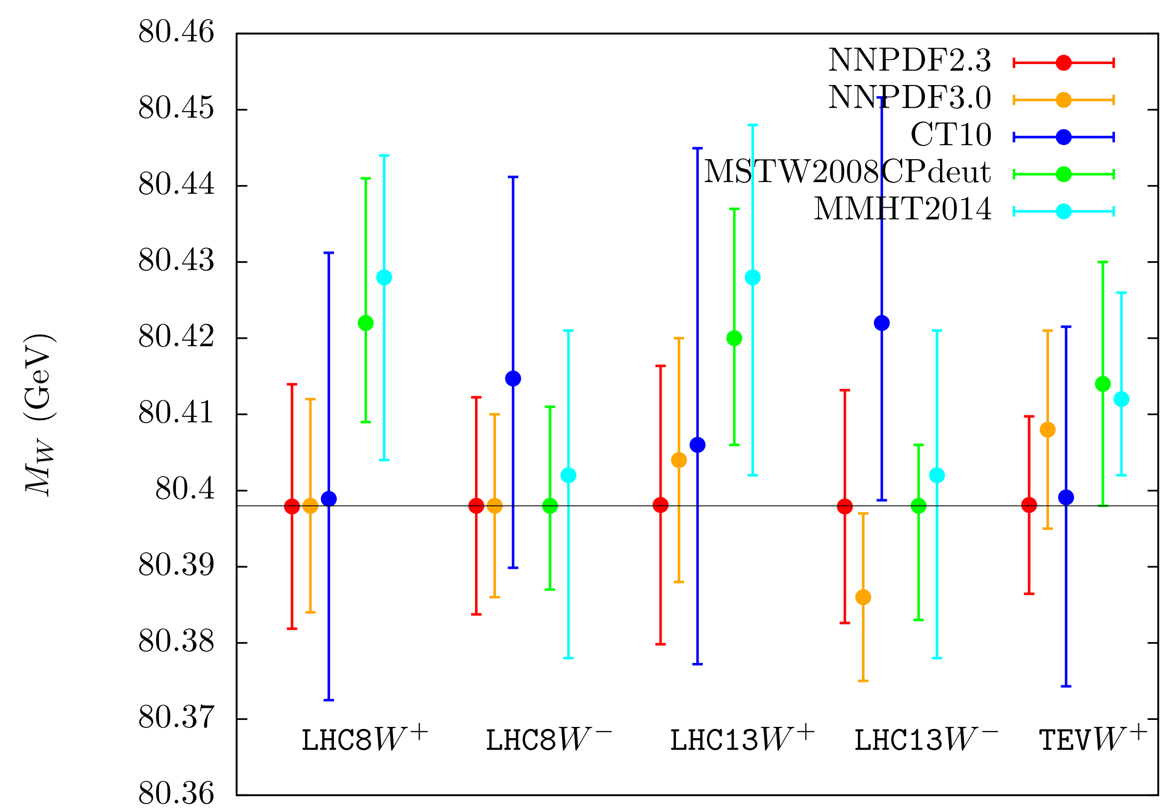
Non-perturbative uncertainties

- PDF: largest uncertainty on m_W, impact on several terms
  - choice of different sets
  - choice of different eigenvectors/replica

Non-perturbative uncertainties

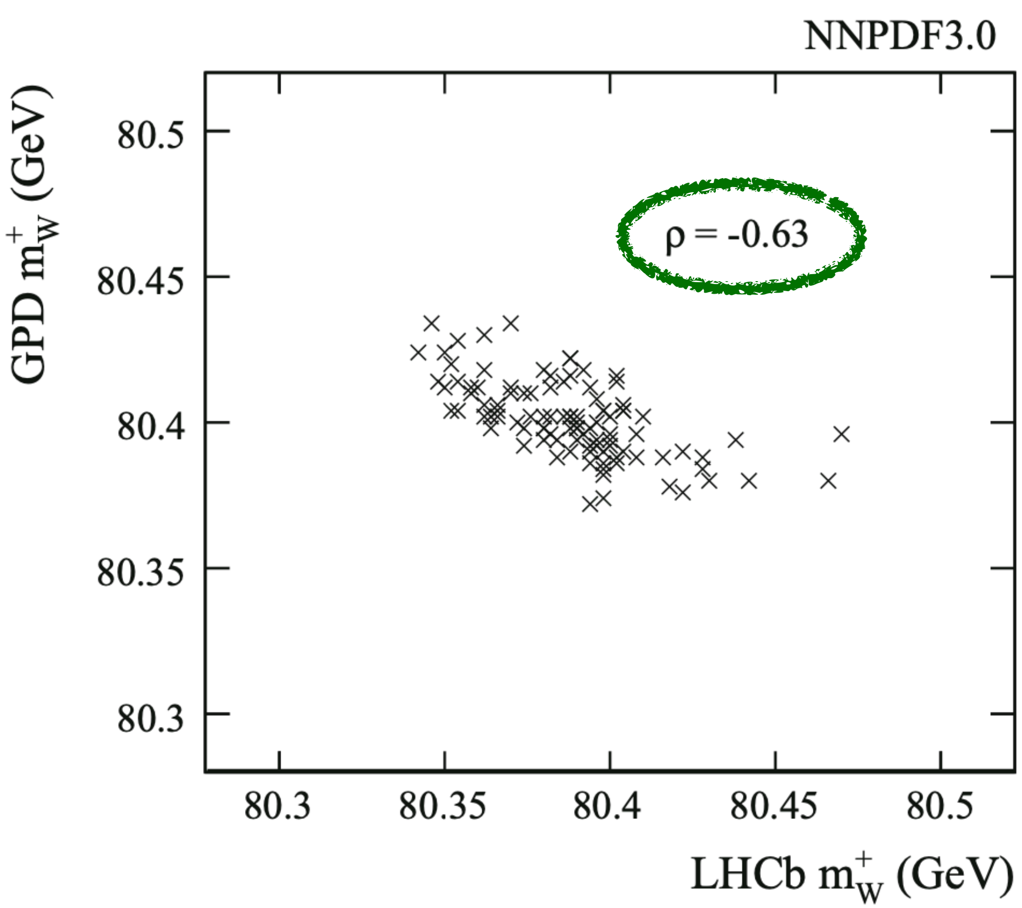
- PDF: largest uncertainty on m_W, impact on several terms
  - choice of different sets
  - choice of different eigenvectors/replica
  - limited impact on m_T [Bozzi,Rojo,Vicini, PRD 83 (2011)], relevant on p_T^ℓ [Bozzi,Citelli,Vicini PRD 91 (2015)]





Non-perturbative uncertainties

- PDF: largest uncertainty on m_W, impact on several terms
  - choice of different sets
  - choice of different eigenvectors/replica
  - limited impact on m_T [Bozzi,Rojo,Vicini, PRD 83 (2011)], relevant on p_T^ℓ [Bozzi,Citelli,Vicini PRD 91 (2015)]
  - reduction 1: anti-correlation forward/central detectors [Bozzi,Citelli,Vesterinen,Vicini EPJC 975 (2015)]



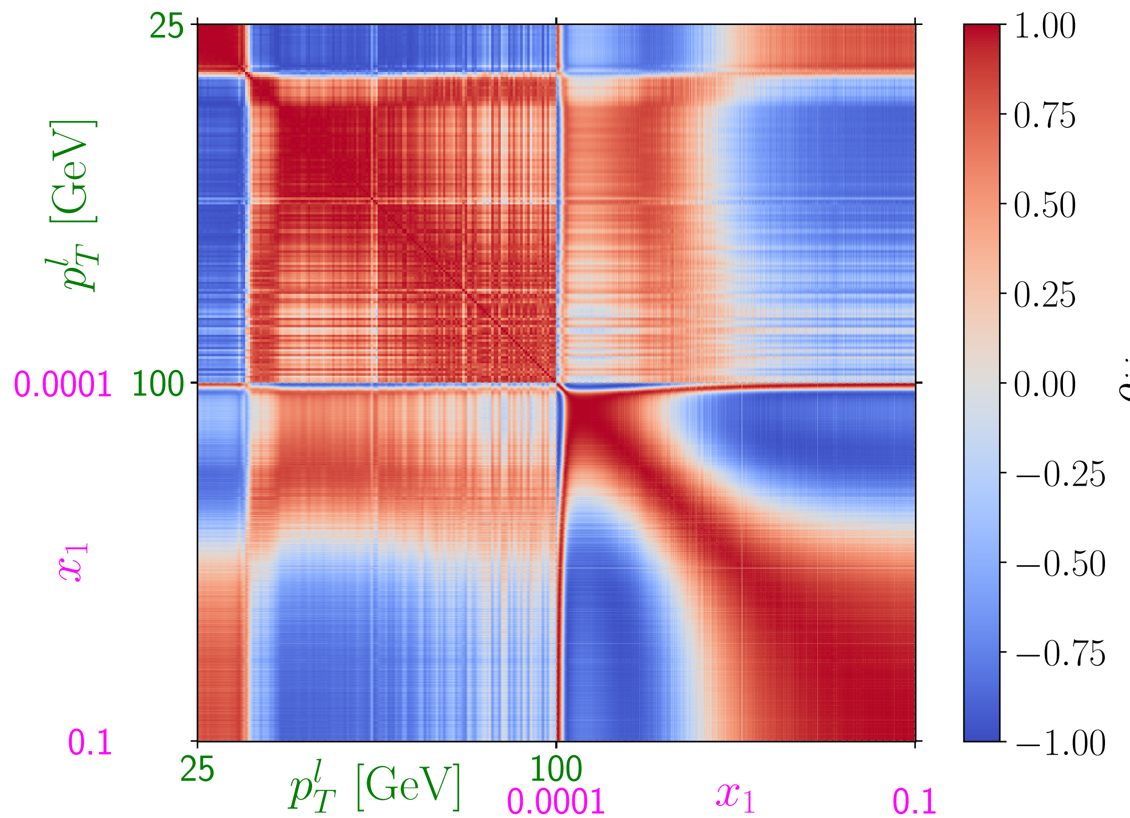
Fitted m_W in ATLAS/CMS vs. LHCb

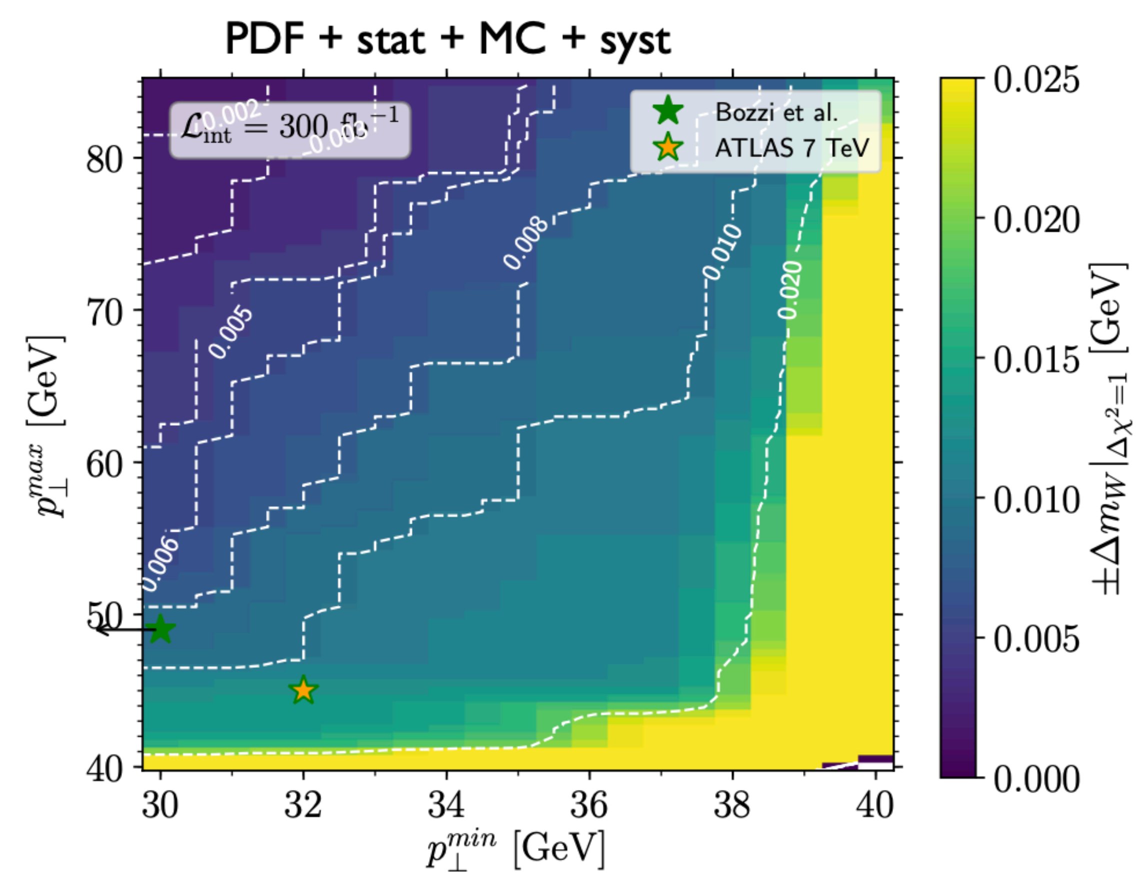
PDFs	Experiments	δ_{PDF}
PDF4LHC(2-sets)	$2\times$ GPD	10.5
PDF4LHC(2-sets)	$2\times$ GPD + LHCb	7.7
PDF4LHC(3-sets)	$2\times$ GPD	16.9
PDF4LHC(3-sets)	$2\times$ GPD + LHCb	12.7
NNPDF30	$2\times$ GPD	5.2
NNPDF30	$2\times$ GPD + LHCb	3.6
MMHT2014	$2\times$ GPD	9.2
MMHT2014	$2\times$ GPD + LHCb	4.6
CT10	$2\times$ GPD	11.6
CT10	$2\times$ GPD + LHCb	6.3

Considerable reduction of PDF uncertainty when combining measurements!

Non-perturbative uncertainties

- PDF: largest uncertainty on m_W, impact on several terms
  - choice of different sets
  - choice of different eigenvectors/replica
  - limited impact on m_T [Bozzi,Rojo,Vicini, PRD 83 (2011)], relevant on p_T^ℓ [Bozzi,Citelli,Vicini PRD 91 (2015)]
  - reduction 1: anti-correlation forward/central detectors [Bozzi,Citelli,Vesterinen,Vicini EPJC 975 (2015)]
  - reduction 2: bin-to-bin correlation with respect to PDF variation [Bagnaschi,Vicini PRL 126 (2021)]

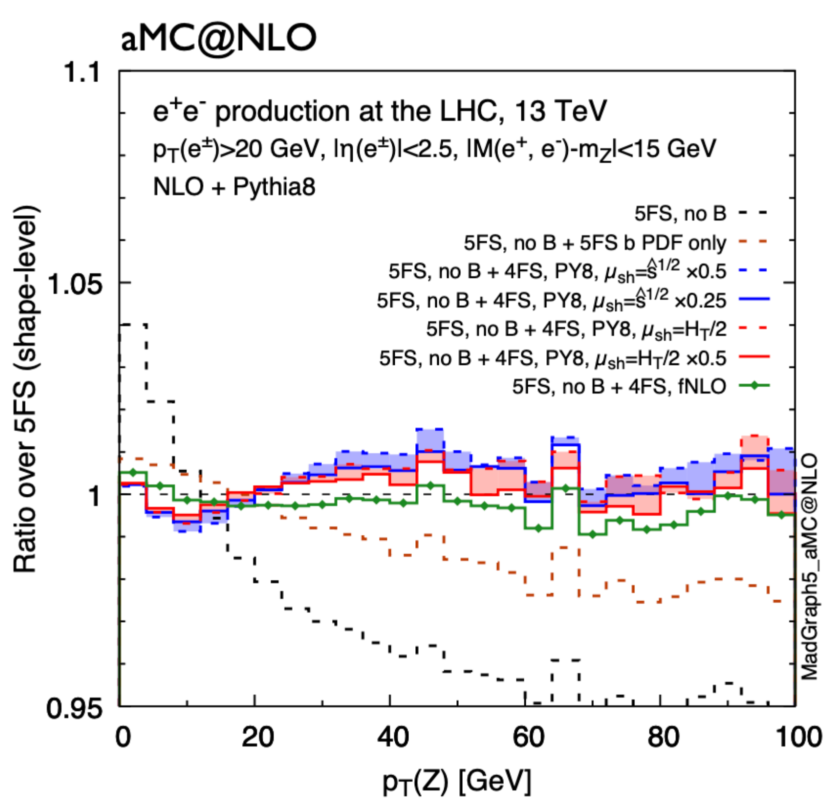


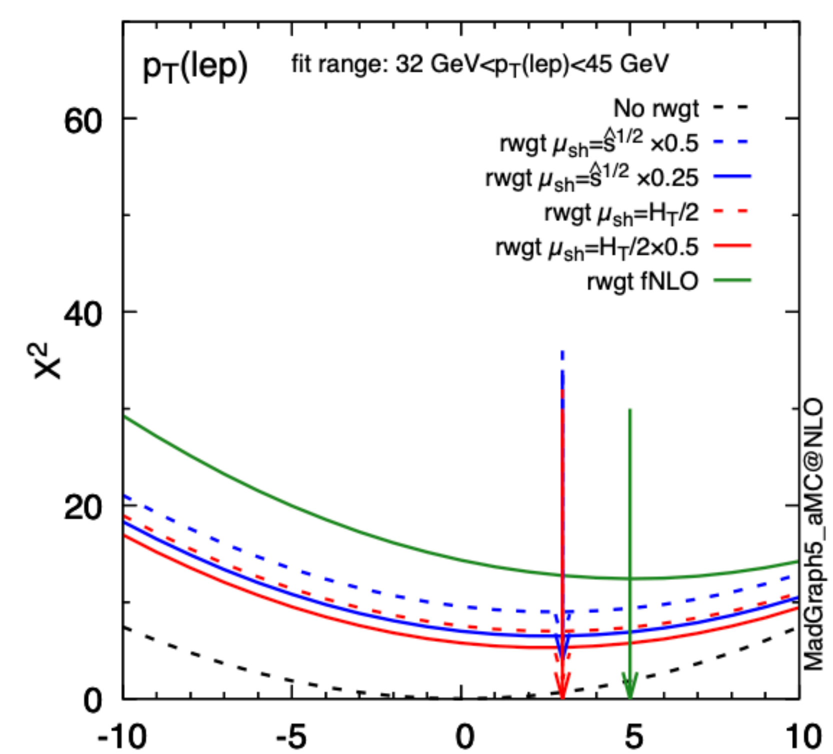


scan over fitting windows

Non-perturbative uncertainties

- PDF: largest uncertainty on m_W, impact on several terms
  - choice of different sets
  - choice of different eigenvectors/replica
  - limited impact on m_T [Bozzi,Rojo,Vicini, PRD 83 (2011)], relevant on p_T^ℓ [Bozzi,Citelli,Vicini PRD 91 (2015)]
  - reduction 1: anti-correlation forward/central detectors [Bozzi,Citelli,Vesterinen,Vicini EPJC 975 (2015)]
  - reduction 2: bin-to-bin correlation with respect to PDF variation [Bagnaschi,Vicini PRL 126 (2021)]
- Heavy quarks: 4FS vs. 5FS
  - distortion on p_T^Z at 1% level (→ 3-5 MeV shift) [Bagnaschi,Maltoni,Vicini,Zaro JHEP 07 (2018)]

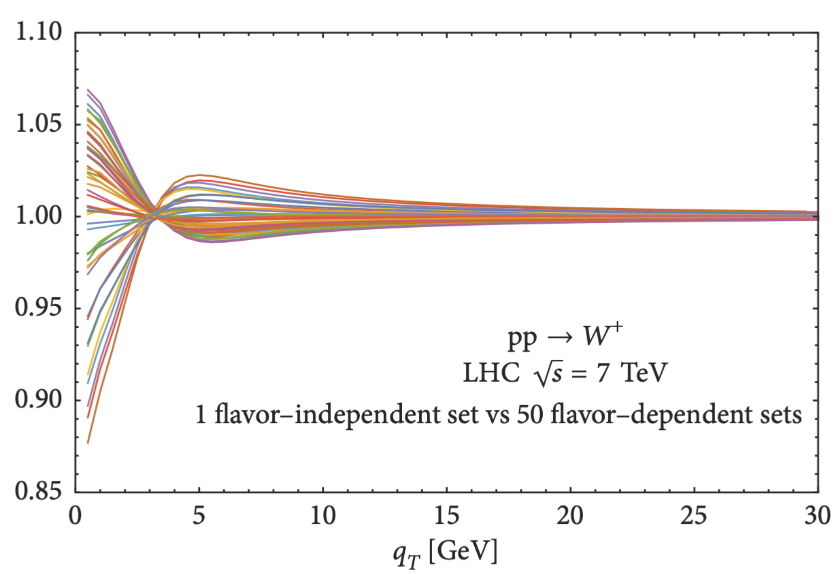


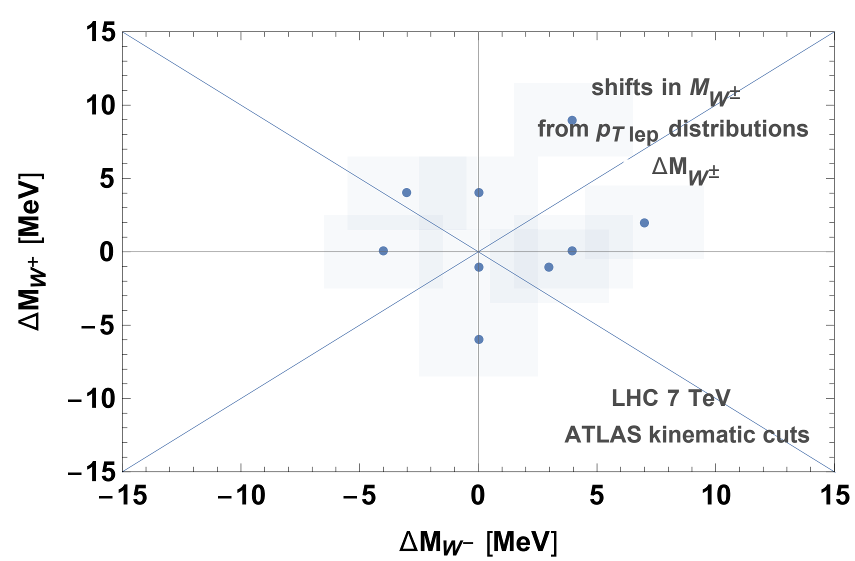


Non-perturbative uncertainties

- PDF: largest uncertainty on m_W, impact on several terms
  - choice of different sets
  - choice of different eigenvectors/replica
  - limited impact on m_T [Bozzi,Rojo,Vicini, PRD 83 (2011)], relevant on p_T^ℓ [Bozzi,Citelli,Vicini PRD 91 (2015)]
  - reduction 1: anti-correlation forward/central detectors [Bozzi,Citelli,Vesterinen,Vicini EPJC 975 (2015)]
  - reduction 2: bin-to-bin correlation with respect to PDF variation [Bagnaschi,Vicini PRL 126 (2021)]
- Heavy quarks: 4FS vs. 5FS
  - distortion on p_T^Z at 1% level ($\rightarrow$ 3-5 MeV shift) [Bagnaschi,Maltoni,Vicini,Zaro JHEP 07 (2018)]
- Intrinsic-k_T
  - impact of flavour-dependence comparable to PDF variations

    [Bacchetta,Bozzi,Radici,Ritzmann,Signori PLB 788 (2019) + Bozzi,Signori AHEP 2526897 (2019)]



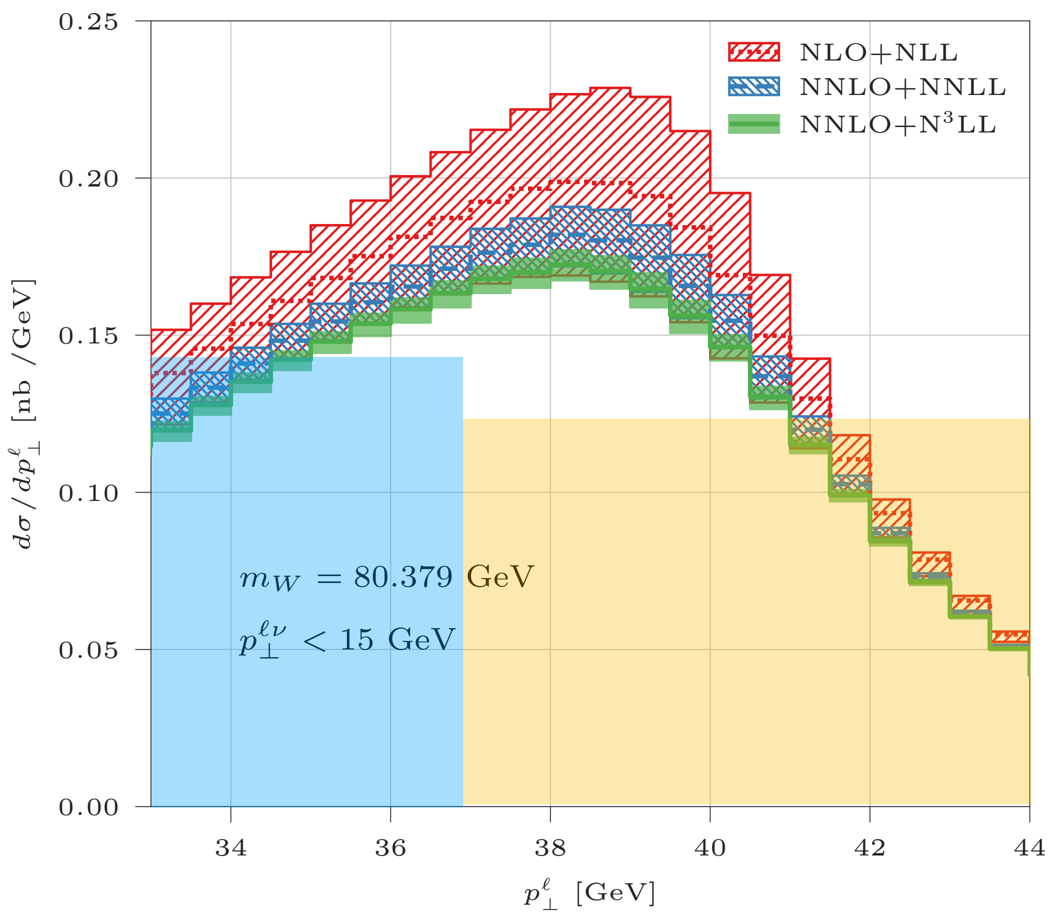


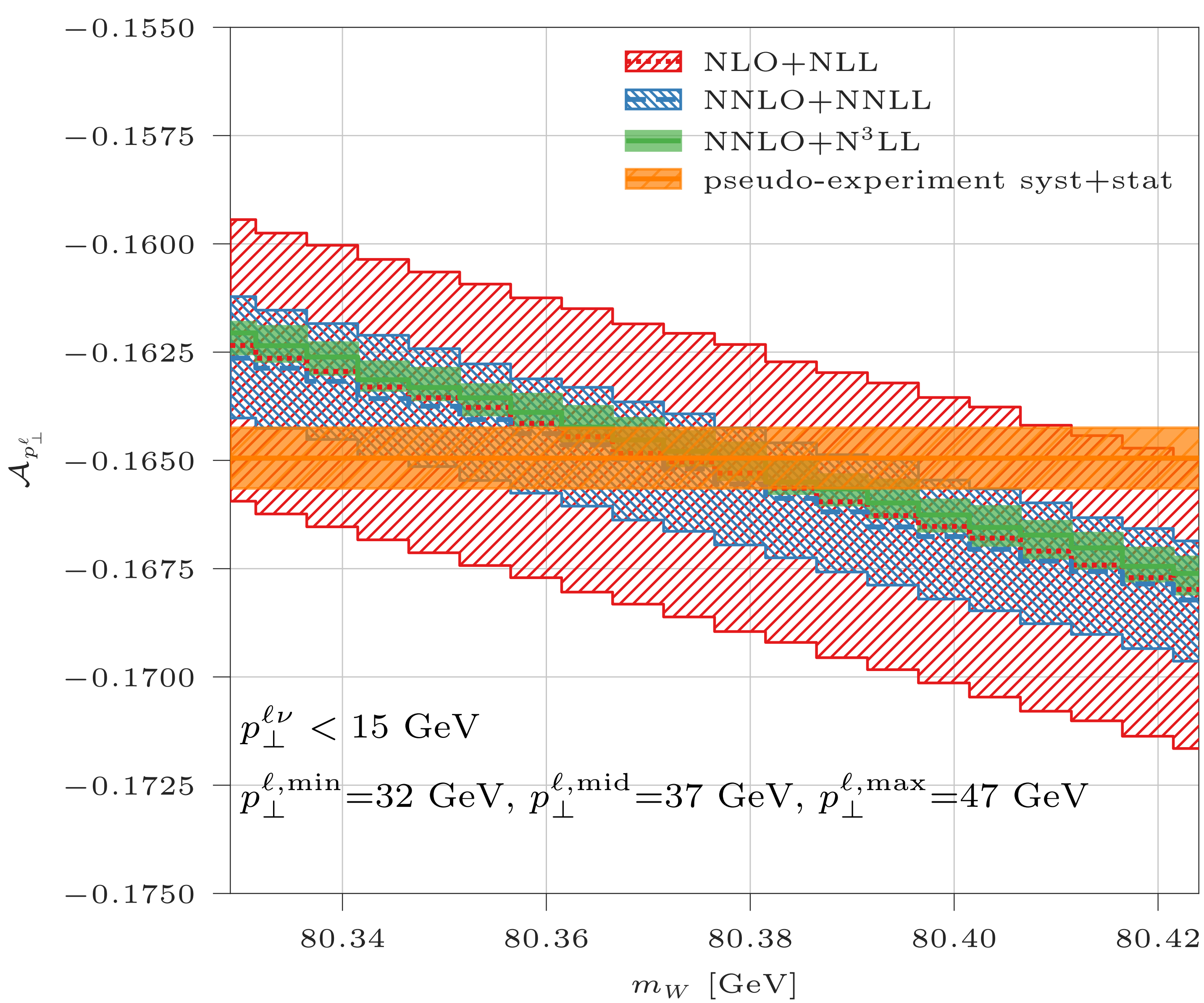
Future prospects

- New Observables: asymmetry around the p_T^ℓ jacobian peak [Rottoli, Torrielli, Vicini - EPJC 83 (2023)]

$$L_{p_\perp^\ell} \equiv \int_{p_\perp^{\ell,\mathrm{min}}}^{p_\perp^{\ell,\mathrm{mid}}} dp_\perp^\ell \frac{d\sigma}{dp_\perp^\ell}, \qquad U_{p_\perp^\ell} \equiv \int_{p_\perp^{\ell,\mathrm{mid}}}^{p_\perp^{\ell,\mathrm{max}}} dp_\perp^\ell \frac{d\sigma}{dp_\perp^\ell}$$

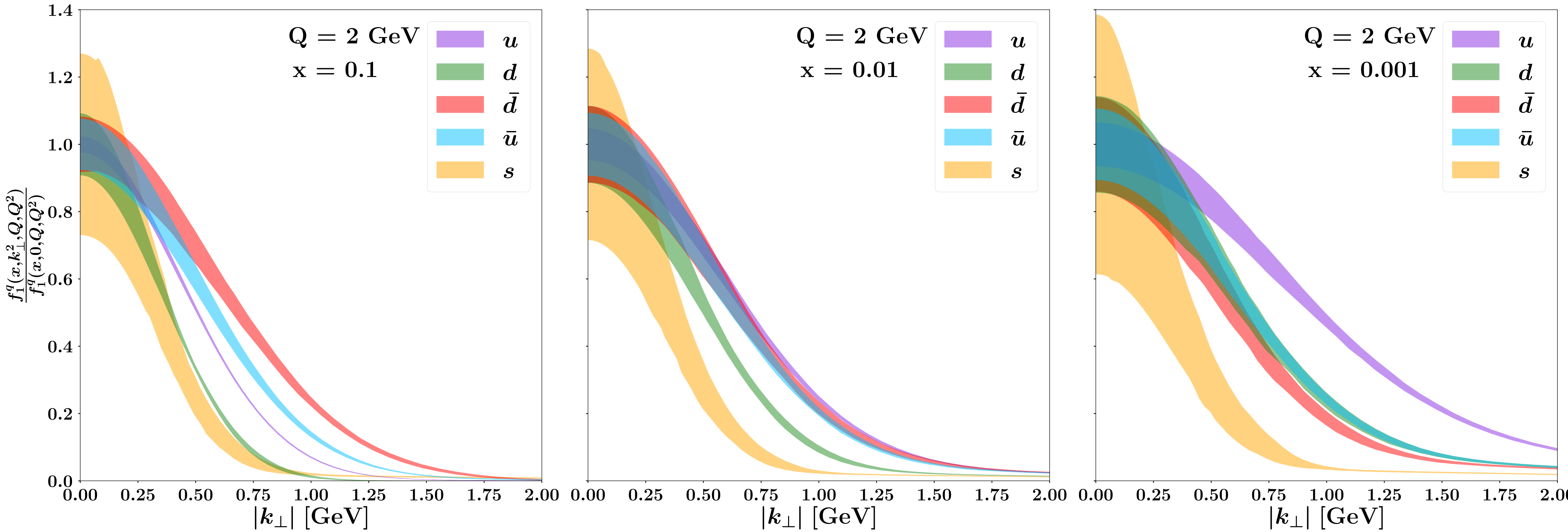
$$\mathcal{A}_{p_\perp^\ell}(p_\perp^{\ell,\mathrm{min}}, p_\perp^{\ell,\mathrm{mid}}, p_\perp^{\ell,\mathrm{max}}) \equiv \frac{L_{p_\perp^\ell} - U_{p_\perp^\ell}}{L_{p_\perp^\ell} + U_{p_\perp^\ell}}$$





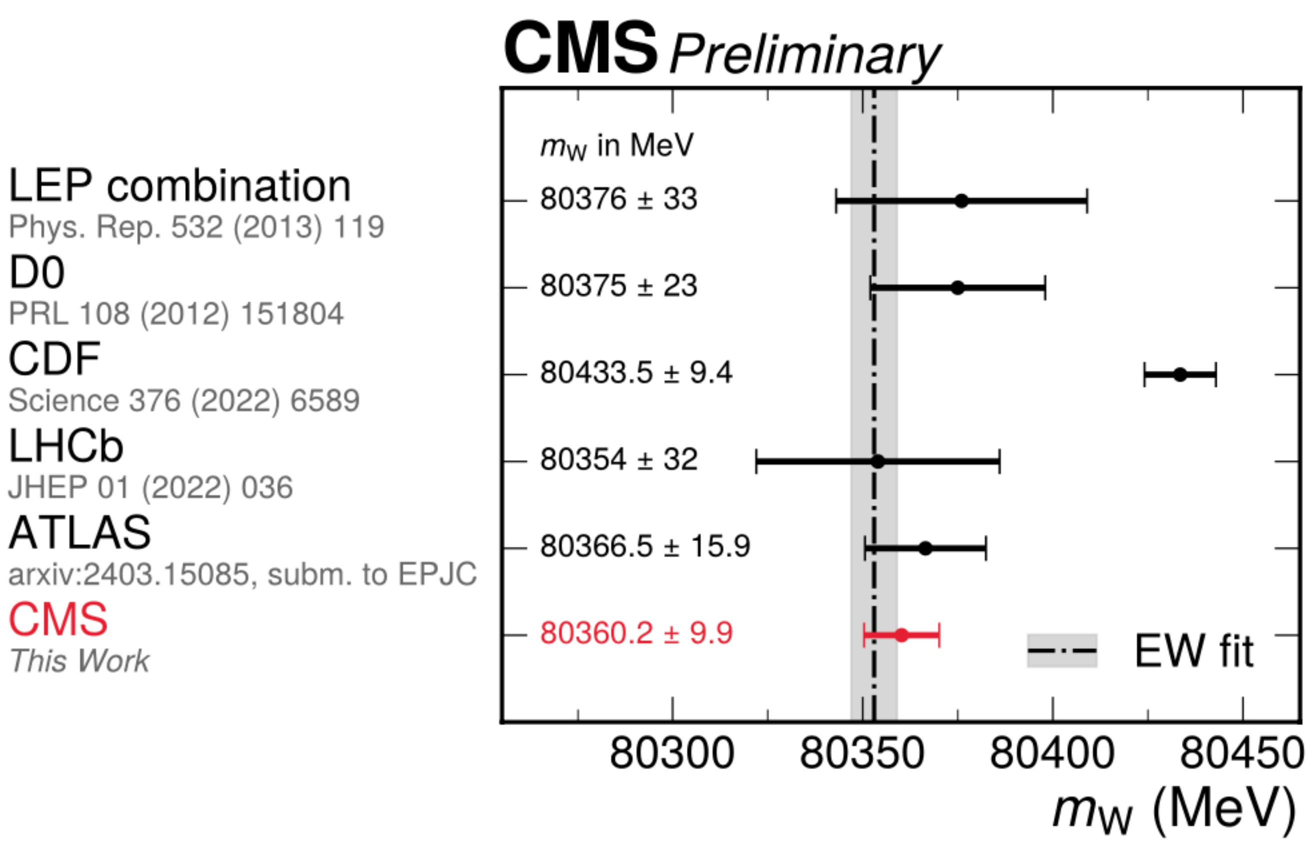
Future prospects

- New Observables: asymmetry around the p_T^ℓ jacobian peak [Rottoli, Torrielli, Vicini - EPJC 83 (2023)]
- Flavour-dependent intrinsic-k_T: preliminary study with arbitrary form factors [Bacchetta et al. - PLB 788 (2019)] → more realistic study thanks to global fit [Bacchetta et al. (MAP Collaboration - 2405.13833]



Future prospects

- New Observables: asymmetry around the p_T^ℓ jacobian peak [Rottoli, Torrielli, Vicini - EPJC 83 (2023)]
- Flavour-dependent intrinsic-k_T: preliminary study with arbitrary form factors [Bacchetta et al. - PLB 788 (2019)] → more realistic study thanks to global fit [Bacchetta et al. (MAP Collaboration - 2405.13833]
- Brand New! CMS measurement: $m_W = 80360.2 \pm 9.9$ MeV



Future prospects

- New Observables: asymmetry around the p_T^ℓ jacobian peak [Rottoli, Torrielli, Vicini - EPJC 83 (2023)]
- Flavour-dependent intrinsic-k_T: preliminary study with arbitrary form factors [Bacchetta et al. - PLB 788 (2019)] → more realistic study thanks to global fit [Bacchetta et al. (MAP Collaboration) - 2405.13833]
- Brand New! CMS measurement: $m_W = 80360.2 \pm 9.9$ MeV
- Dedicated effort: [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/THuncertainties]

Ongoing studies on the assessment of theoretical uncertainties in the precision determination of SM parameters

The following studies are currently ongoing, the active people involved (coordinators) are indicated in each case.

Modelling of non-perturbative corrections in extraction of α_s

Main coordinators
Bacchetta, Bertone, Bozzi, Camarda
Description
Assessment of the impact of the choice of the non-perturbative model in the α_s extraction

State of the art predictions for of ptW/ptZ ratio

Main coordinators
Neumann, Rottoli, Tackmann
Description
Assessment of theoretical uncertainties in the ratio using state-of-the-art predictions for the kinematical distributions

Correlation between α_s and the gluon PDF

Main coordinators
Camarda, D'Enterria, Giuli
Description
Study of the correlation for different proton PDF sets to assess potential biases in the extraction of α_s

PDF profiling in M_W extraction

Main coordinators
Amoroso, Cridge
Description
Assessment of tolerance factor in PDF profiling, and impact on M_W uncertainties and consistency with global PDF sets

Propagation of theory uncertainties through tuning of MC generators

Main coordinators
Torrielli, Vicini
Description
Assessment of the residual uncertainties and impact on M_W extraction

Proposal of future multi-differential measurements

Main coordinators
[TBA]
Description
Feasibility study for future measurements of DY transverse momentum distribution in bins of invariant mass and rapidity

Future prospects

- New Observables: asymmetry around the p_T^ℓ jacobian peak [Rottoli, Torrielli, Vicini - EPJC 83 (2023)]
- Flavour-dependent intrinsic-k_T: preliminary study with arbitrary form factors [Bacchetta et al. - PLB 788 (2019)] → more realistic study thanks to global fit [Bacchetta et al. (MAP Collaboration) - 2405.13833]
- Brand New! CMS measurement: $m_W = 80360.2 \pm 9.9$ MeV
- Dedicated effort: [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/THuncertainties]

Ongoing studies on the assessment of theoretical uncertainties in the precision determination of SM parameters

The following studies are currently ongoing, the active people involved (coordinators) are indicated in each case.

Modelling of non-perturbative corrections in extraction of α_s

Main coordinators
Bacchetta, Bertone, Bozzi, Camarda
Description
Assessment of the impact of the choice of the non-perturbative model in the α_s extraction

State of the art predictions for of ptW/ptZ ratio

Main coordinators
Neumann, Rottoli, Tackmann
Description
Assessment of theoretical uncertainties in the ratio using state-of-the-art predictions for the kinematical distributions

Correlation between α_s and the gluon PDF

Main coordinators
Camarda, D'Enterria, Giuli
Description
Study of the correlation for different proton PDF sets to assess potential biases in the extraction of α_s

PDF profiling in M_W extraction

Main coordinators
Amoroso, Cridge
Description
Assessment of tolerance factor in PDF profiling, and impact on M_W uncertainties and consistency with global PDF sets

Propagation of theory uncertainties through tuning of MC generators

Main coordinators
Torrielli, Vicini
Description
Assessment of the residual uncertainties and impact on M_W extraction

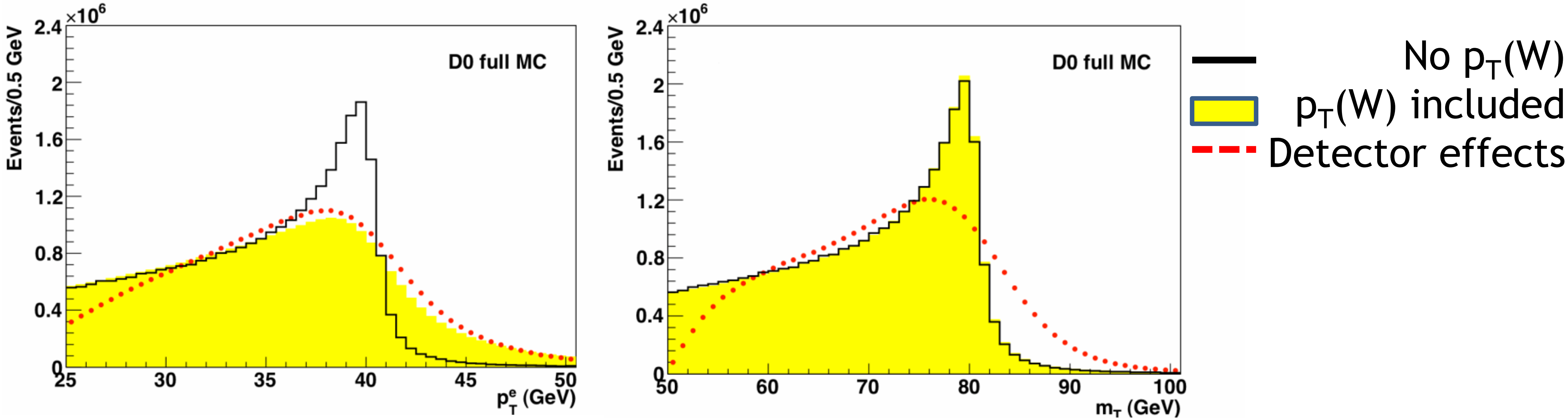
Proposal of future multi-differential measurements

Main coordinators
[TBA]
Description
Feasibility study for future measurements of DY transverse momentum distribution in bins of invariant mass and rapidity

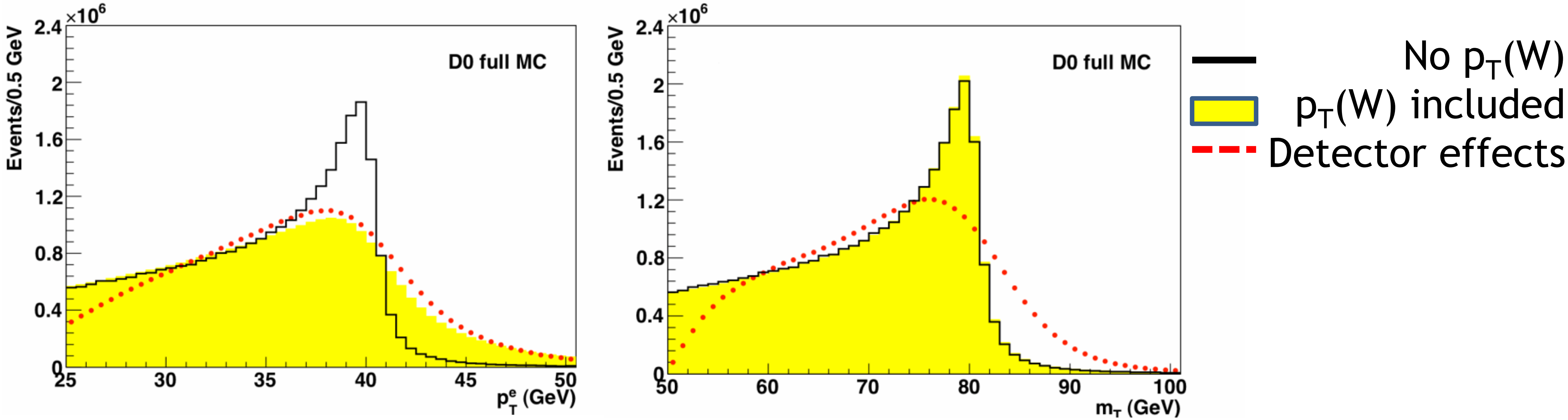
Thank you!

Backup

Observables and techniques for m_W

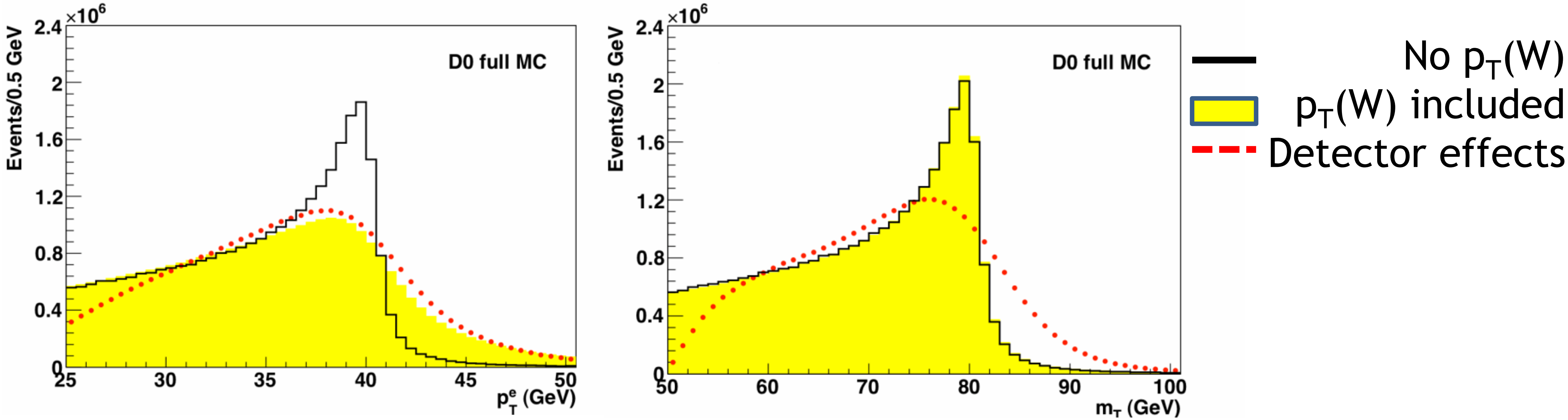


Observables and techniques for m_W



Lepton p_T: **moderate** detector smearing effects, **high** sensitivity to p_{TW} modelling

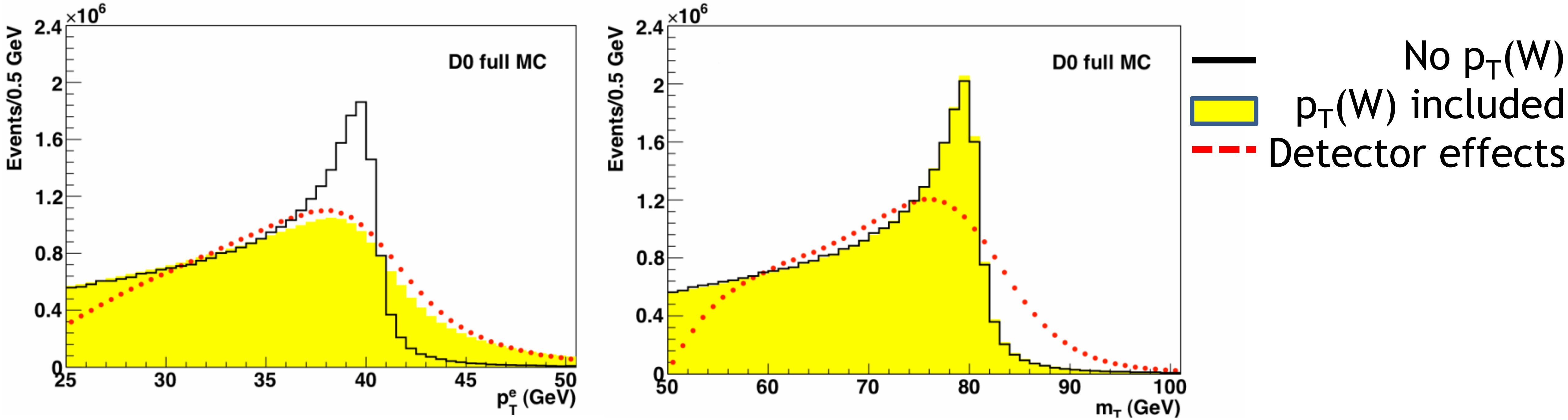
Observables and techniques for m_W



Lepton p_T: **moderate** detector smearing effects, **high** sensitivity to p_{TW} modelling

Transverse mass: **important** detector smearing effects, **low** sensitivity to p_{TW} modelling

Observables and techniques for m_W

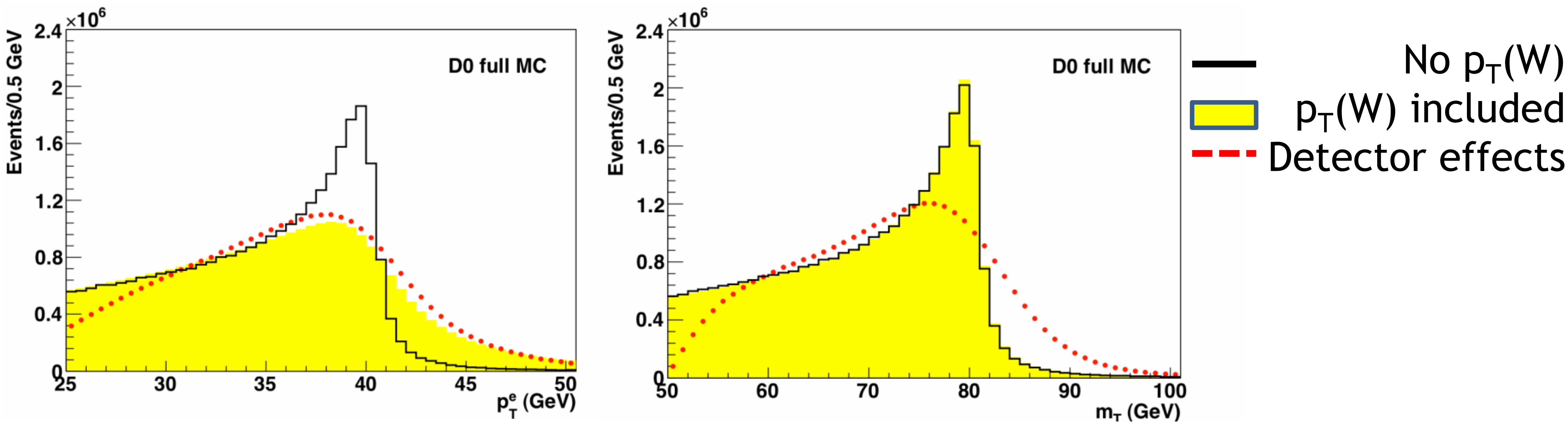


Lepton p_T: **moderate** detector smearing effects, **high** sensitivity to p_{TW} modelling

Transverse mass: **important** detector smearing effects, **low** sensitivity to p_{TW} modelling

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

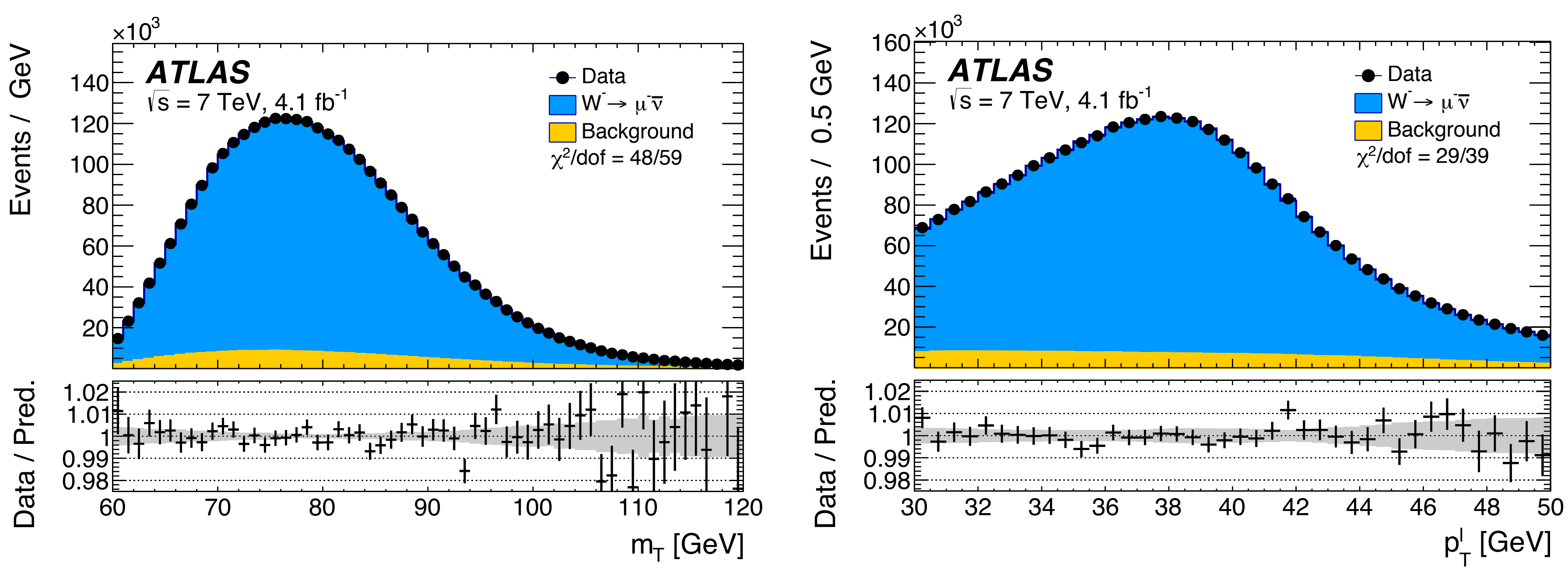
Observables and techniques for m_W



Lepton p_T: **moderate** detector smearing effects, **high** sensitivity to p_{TW} modelling

Transverse mass: **important** detector smearing effects, **low** sensitivity to p_{TW} modelling

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



Measuring m_W at hadron colliders

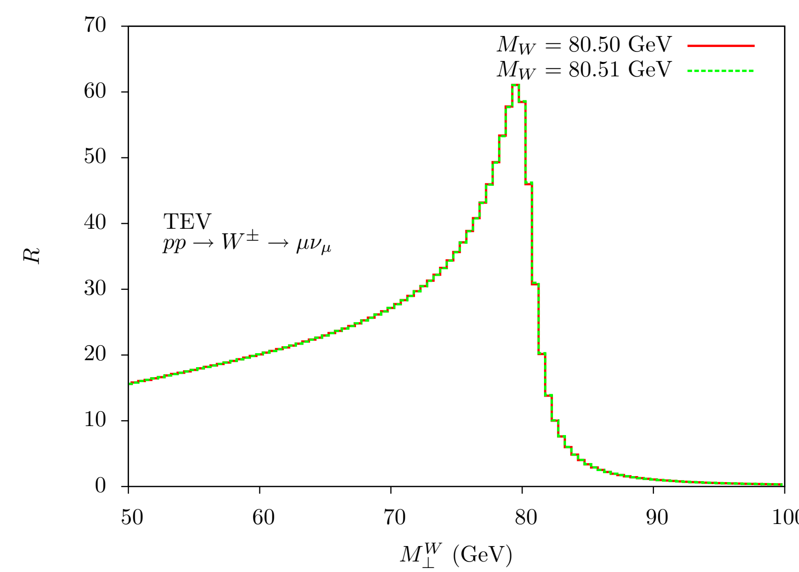
- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

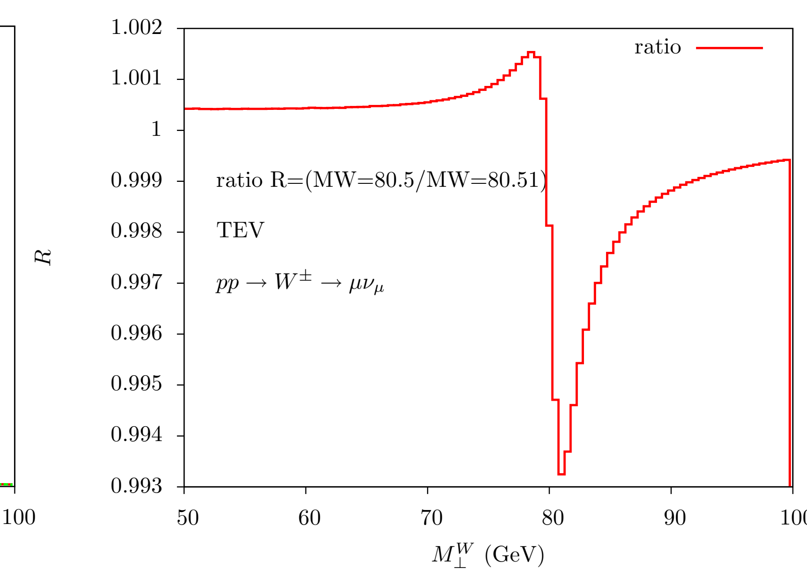
➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1 - \cos\Delta\phi)}$

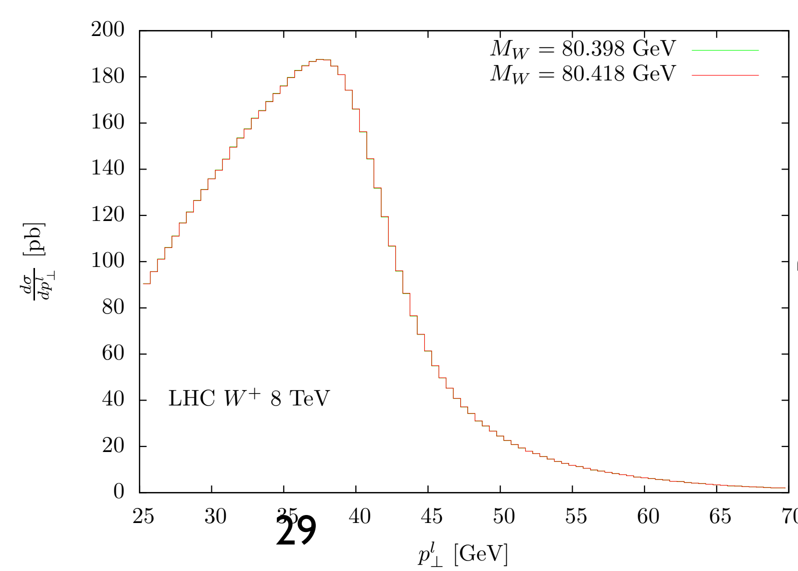
Measuring m_W at hadron colliders

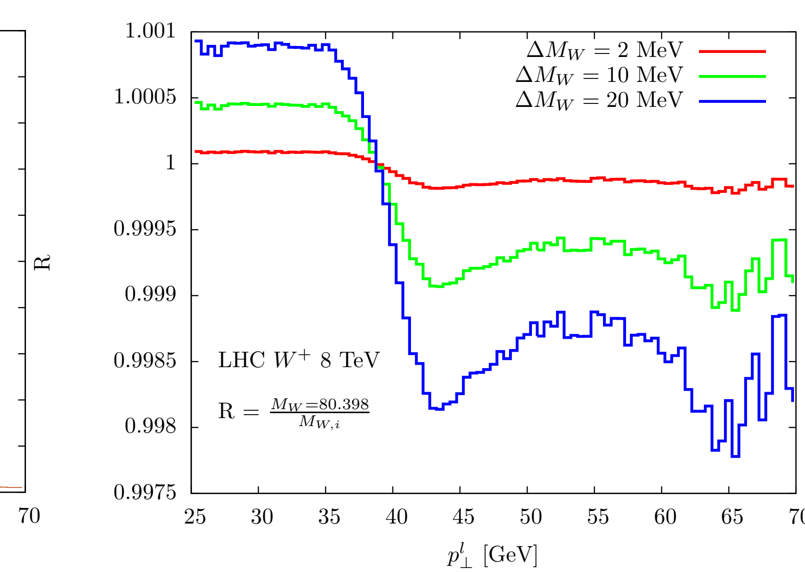
- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1 - \cos\Delta\phi)}$









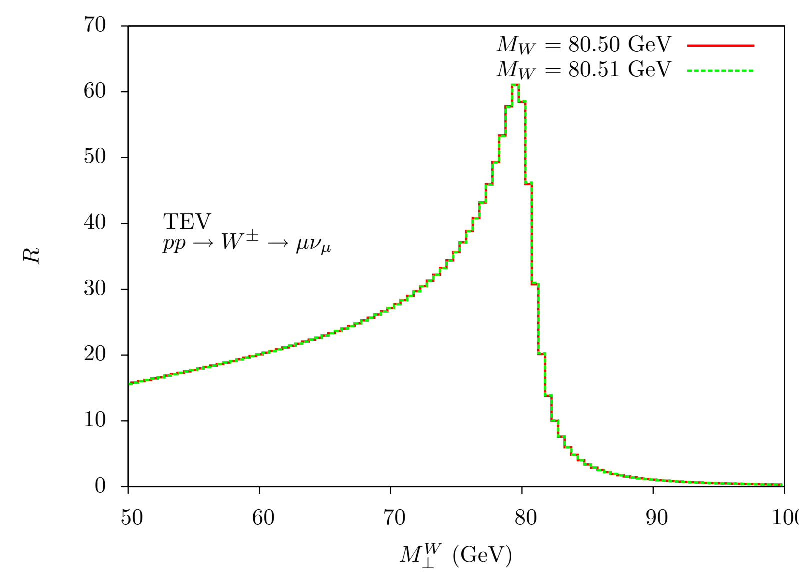
Measuring m_W at hadron colliders

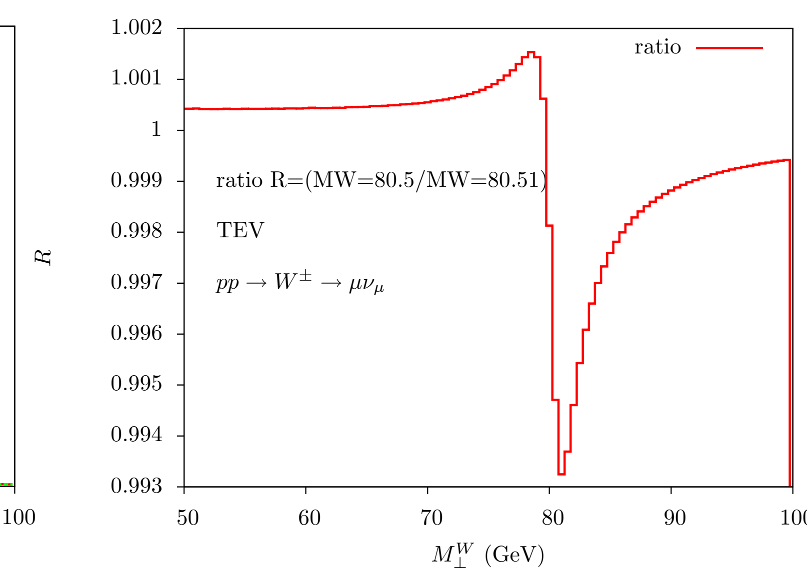
- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

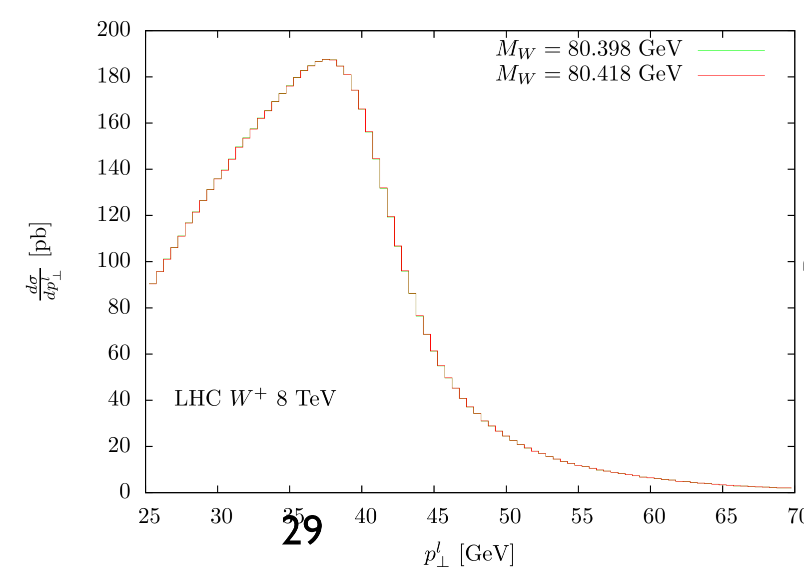
➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1-\cos\Delta\phi)}$

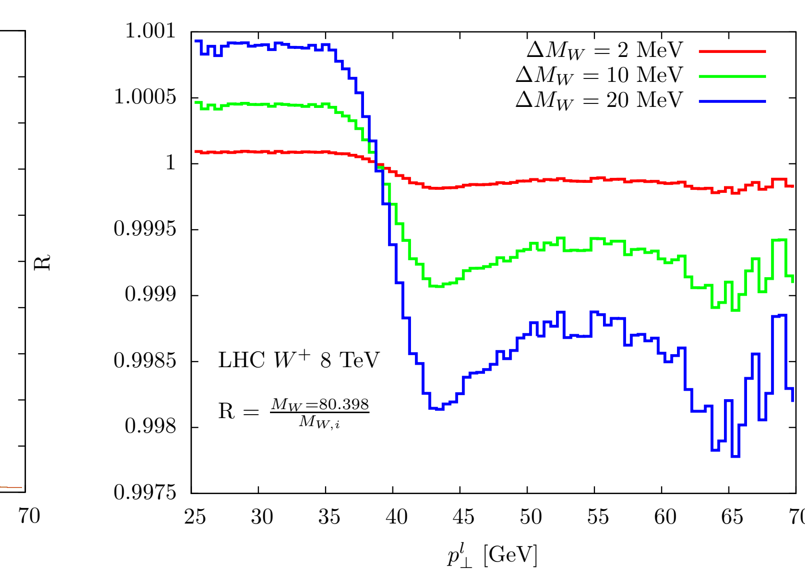
Template fit

Given an experimental distribution:









Measuring m_W at hadron colliders

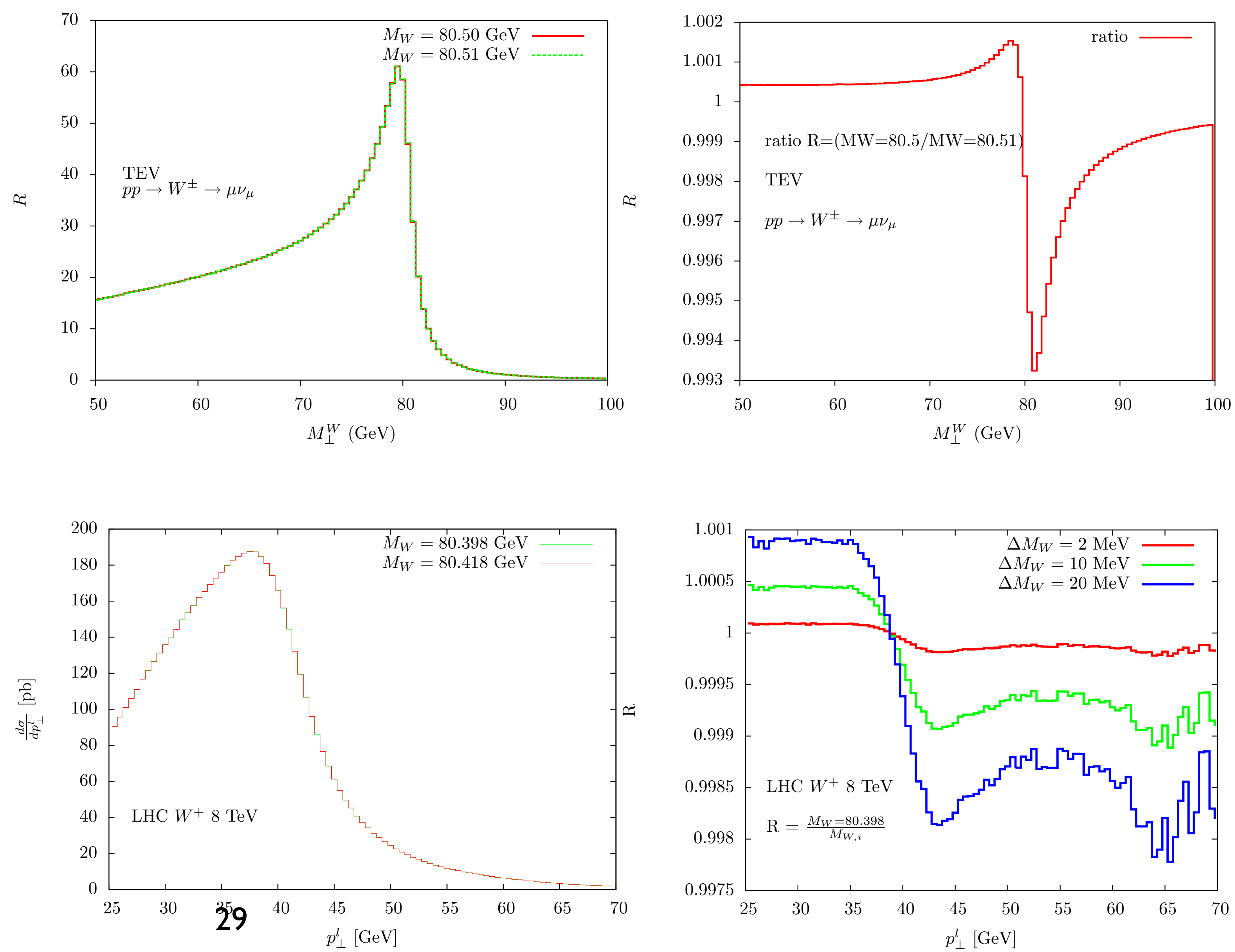
- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1-\cos\Delta\phi)}$

Template fit

Given an experimental distribution:

1. compute corresponding theory distribution at highest available accuracy (QCD N3LL, QCD NNLO, mixed QCD-EW, …) for several $m_W^{(k)}$ values



Measuring m_W at hadron colliders

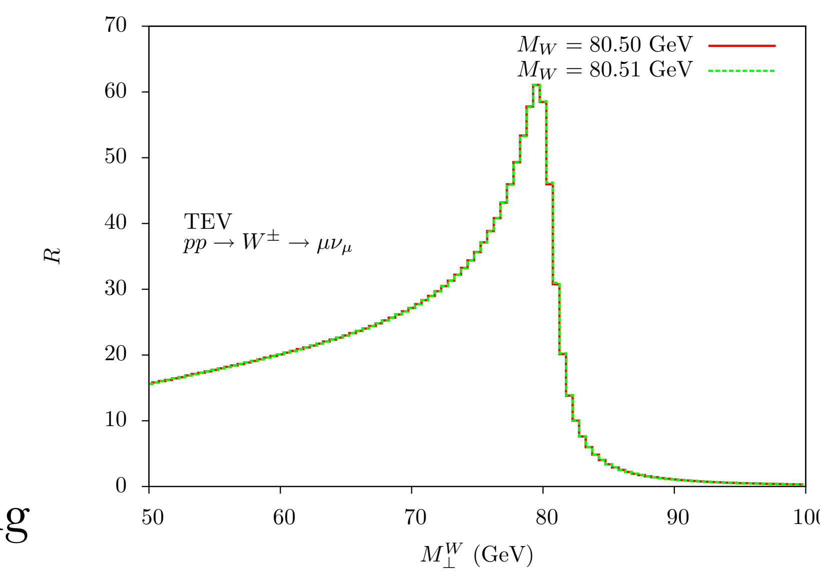
- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

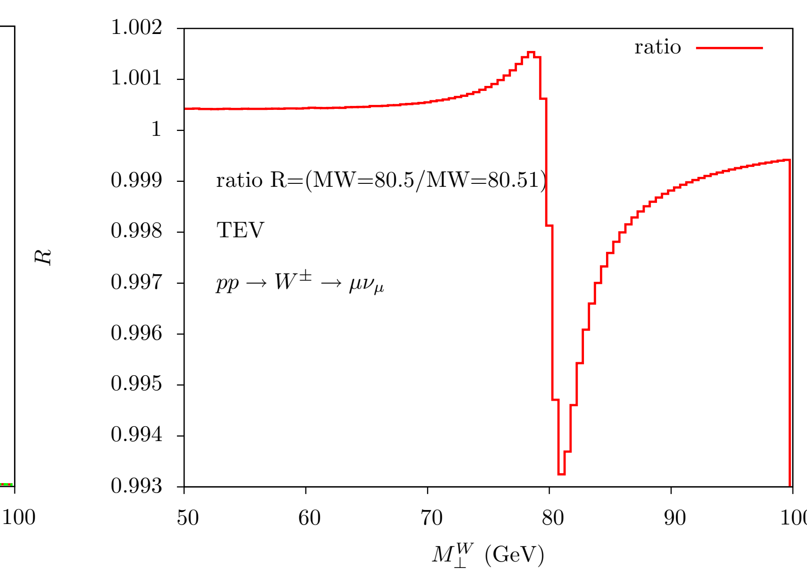
➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1-\cos\Delta\phi)}$

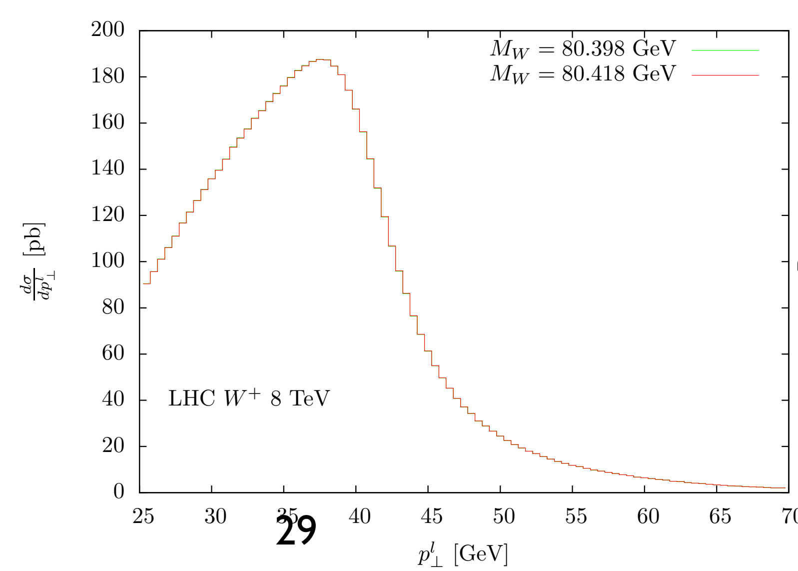
Template fit

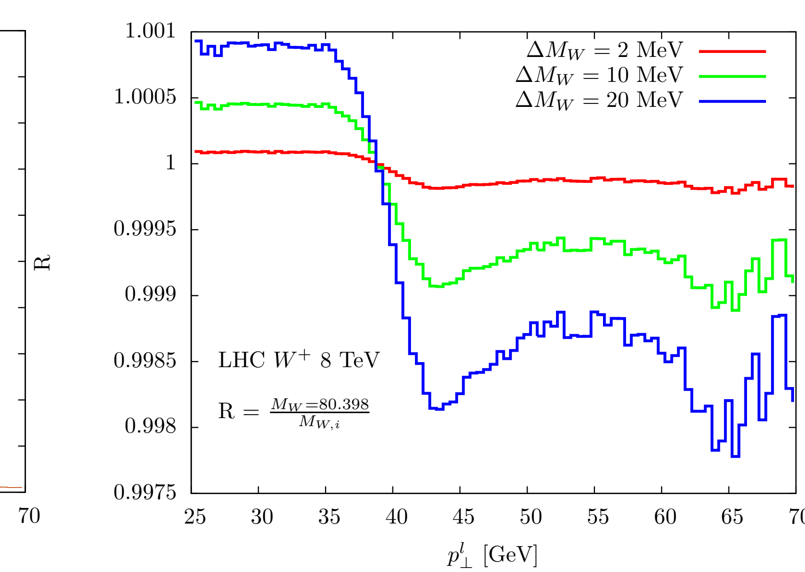
Given an experimental distribution:

1. compute corresponding theory distribution at highest available accuracy (QCD N3LL, QCD NNLO, mixed QCD-EW, …) for several $m_W^{(k)}$ values
2. compute a χ^2_k for each $m_W^{(k)}$ in a certain fitting interval









Measuring m_W at hadron colliders

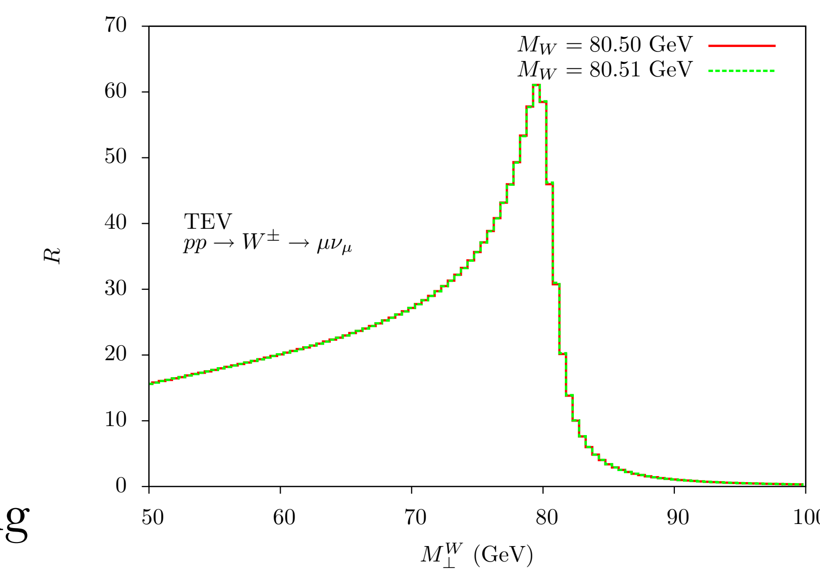
- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

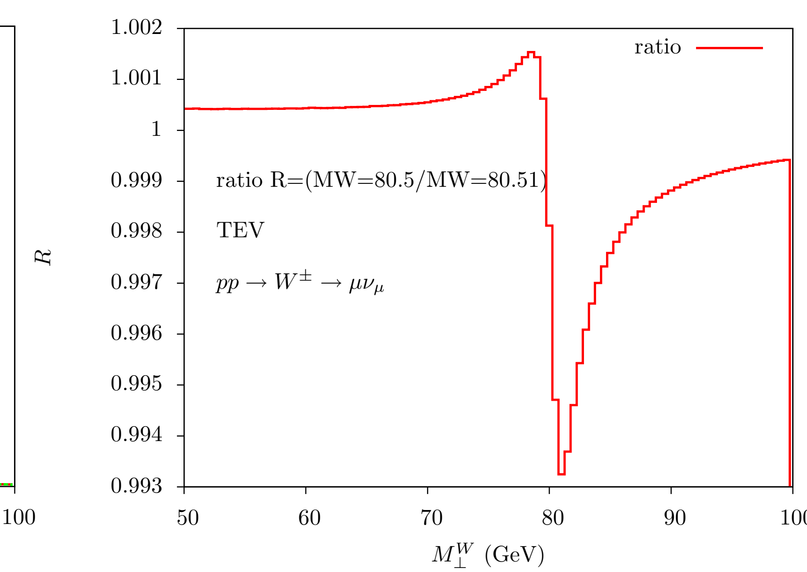
➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1-\cos\Delta\phi)}$

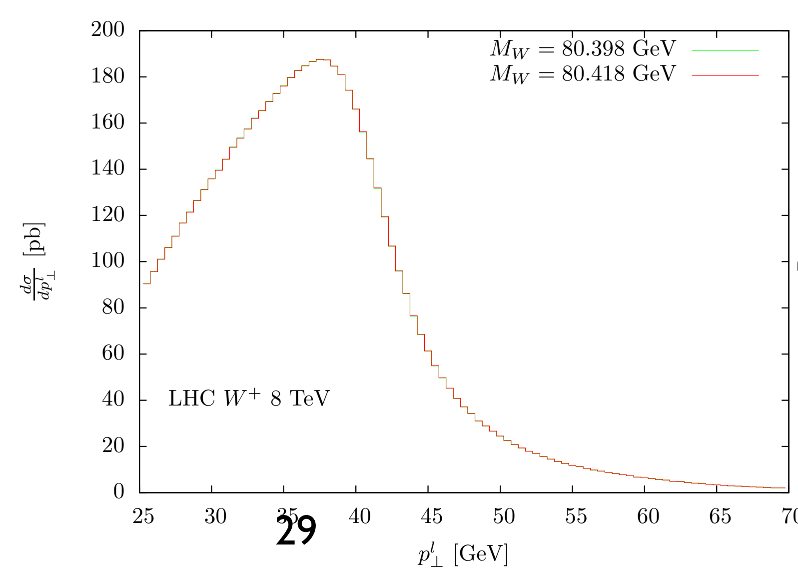
Template fit

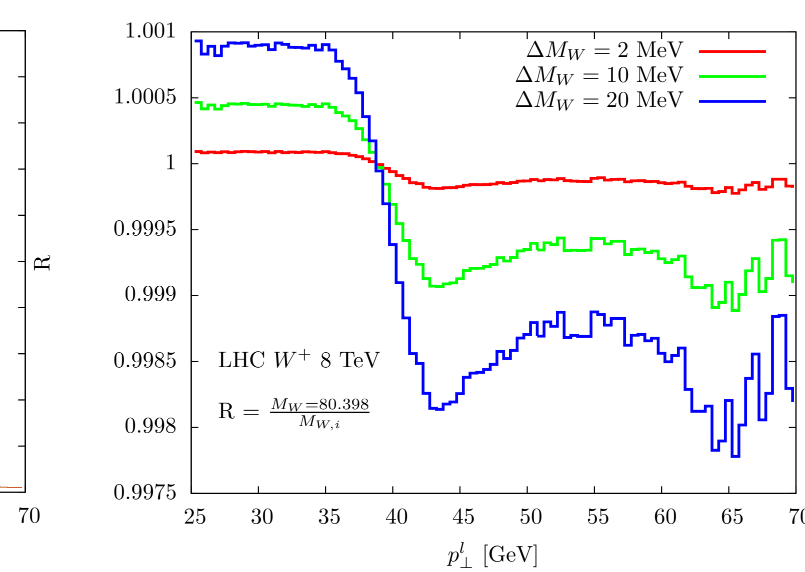
Given an experimental distribution:

1. compute corresponding theory distribution at highest available accuracy (QCD N3LL, QCD NNLO, mixed QCD-EW, …) for several $m_W^{(k)}$ values
2. compute a χ_k^2 for each $m_W^{(k)}$ in a certain fitting interval
3. find the minimum of the χ^2 distribution → measured m_W









Measuring m_W at hadron colliders

- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

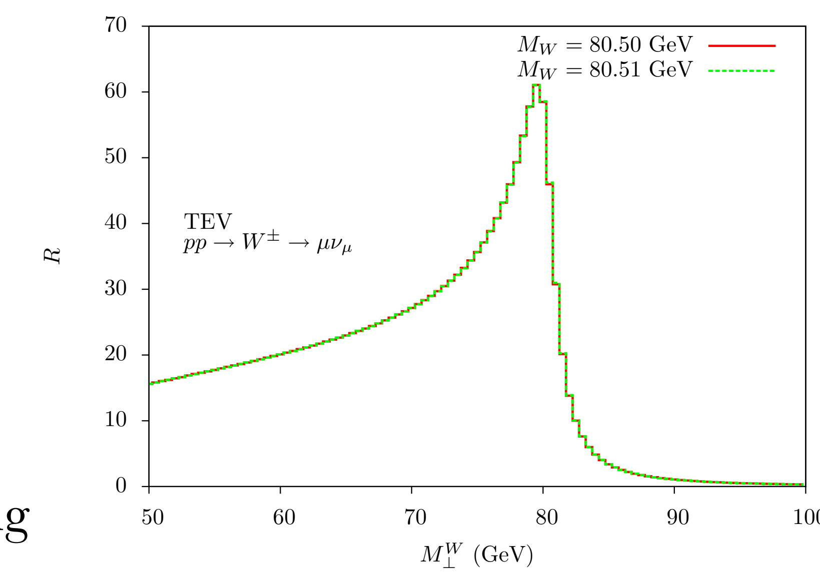
➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1-\cos\Delta\phi)}$

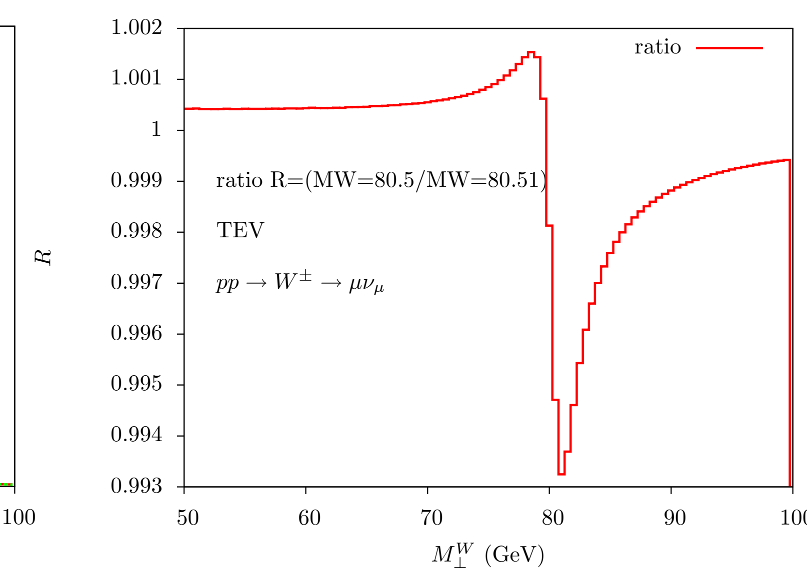
Template fit

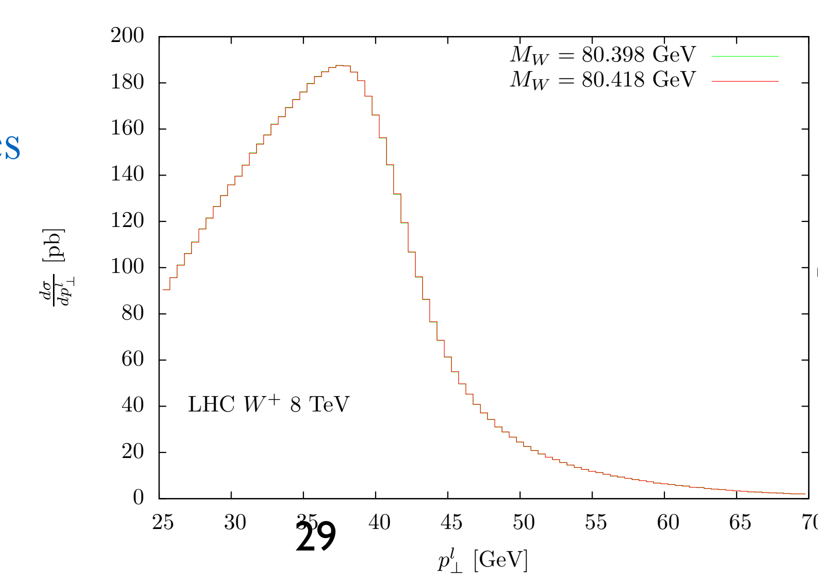
Given an experimental distribution:

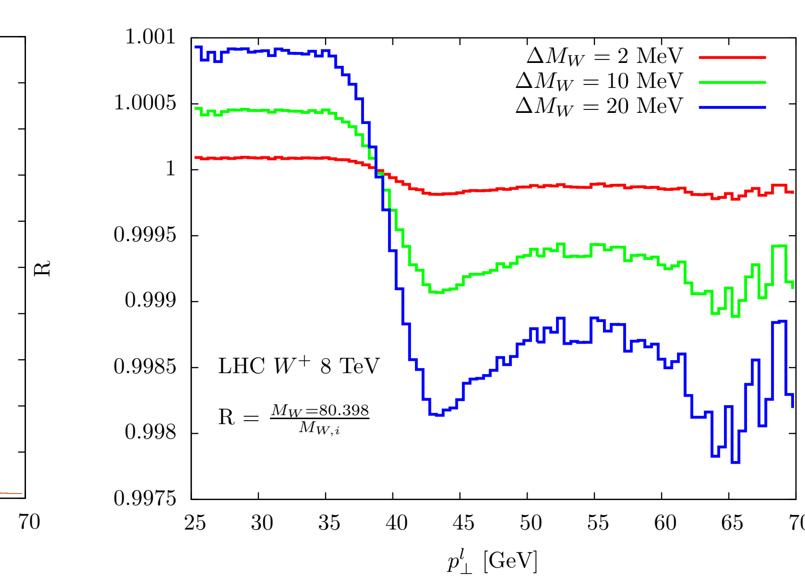
1. compute corresponding theory distribution at highest available accuracy (QCD N3LL, QCD NNLO, mixed QCD-EW, …) for several $m_W^{(k)}$ values
2. compute a χ_k^2 for each $m_W^{(k)}$ in a certain fitting interval
3. find the minimum of the χ^2 distribution → measured m_W

➡ the result of the fit depends on the hypotheses used to compute the templates (perturbative scales, PDFs, non-perturbative, …)









Measuring m_W at hadron colliders

- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1-\cos\Delta\phi)}$

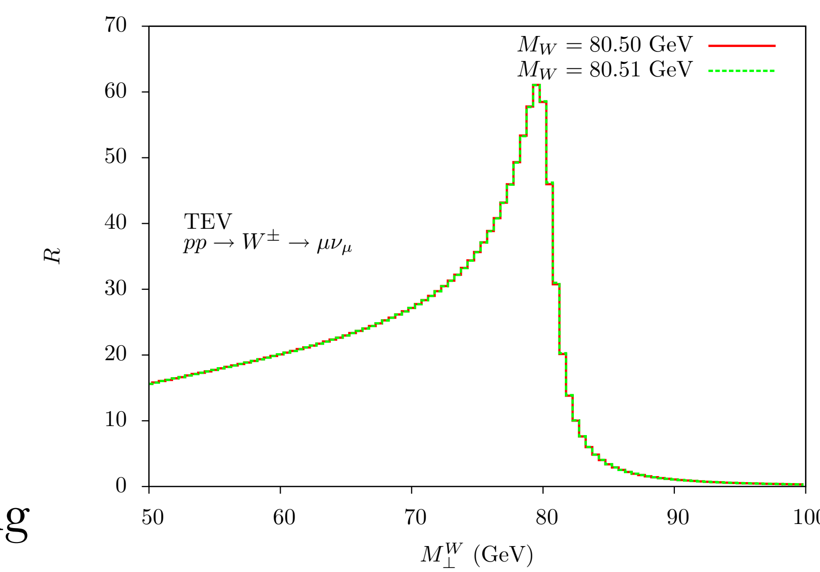
Template fit

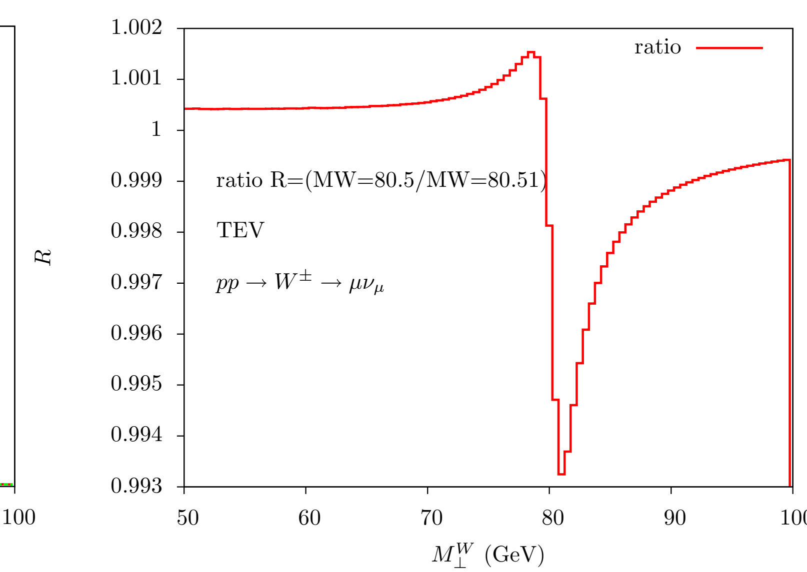
Given an experimental distribution:

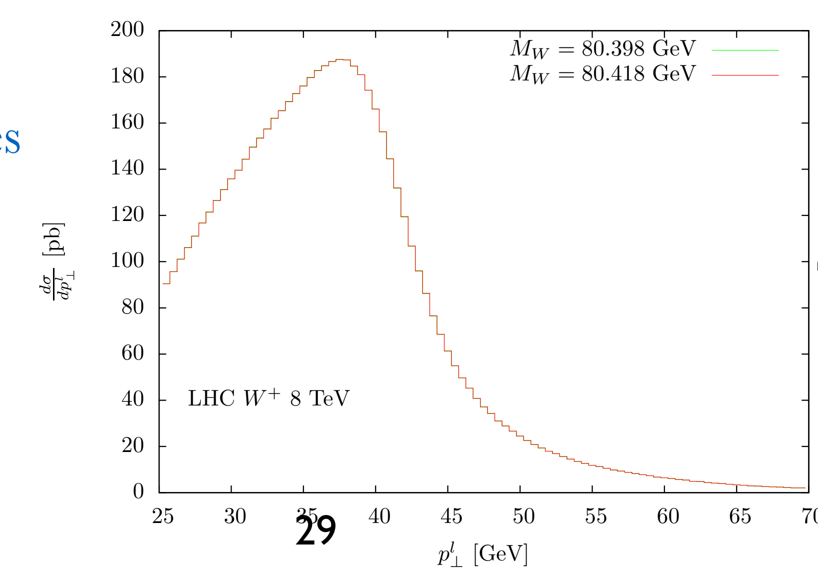
1. compute corresponding theory distribution at highest available accuracy (QCD N3LL, QCD NNLO, mixed QCD-EW, …) for several $m_W^{(k)}$ values
2. compute a χ_k^2 for each $m_W^{(k)}$ in a certain fitting interval
3. find the minimum of the χ^2 distribution → measured m_W

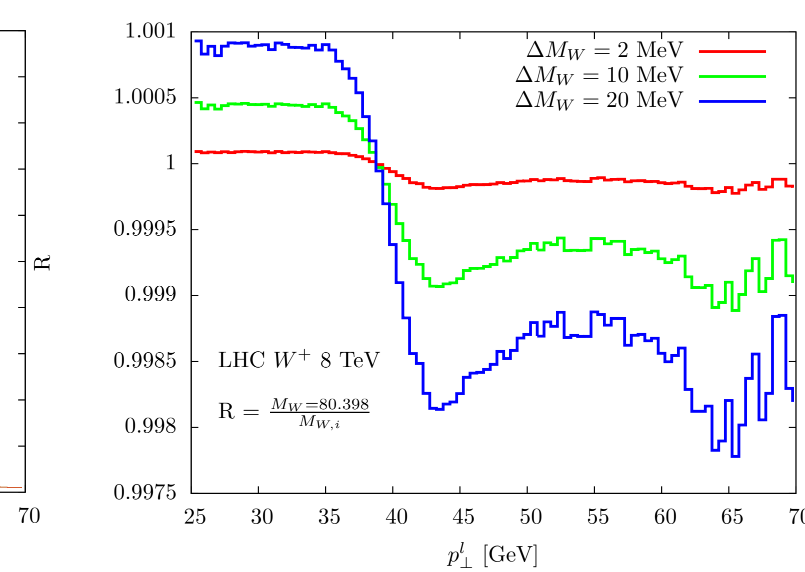
➡ the result of the fit depends on the hypotheses used to compute the templates (perturbative scales, PDFs, non-perturbative, …)

➡ these hypotheses should be treated as theoretical systematic errors









Measuring m_W at hadron colliders

- Measurement performed in leptonic decays only (overwhelming multi-jet bkg)
- Reconstruction of the lepton-neutrino invariant mass is not possible

➡ 2 main observables: p_T^ℓ and $m_T = \sqrt{2|p_T^\ell||p_T^\nu|(1 - \cos\Delta\phi)}$

determination at 10^{-4} level requires control of the shape at permille level

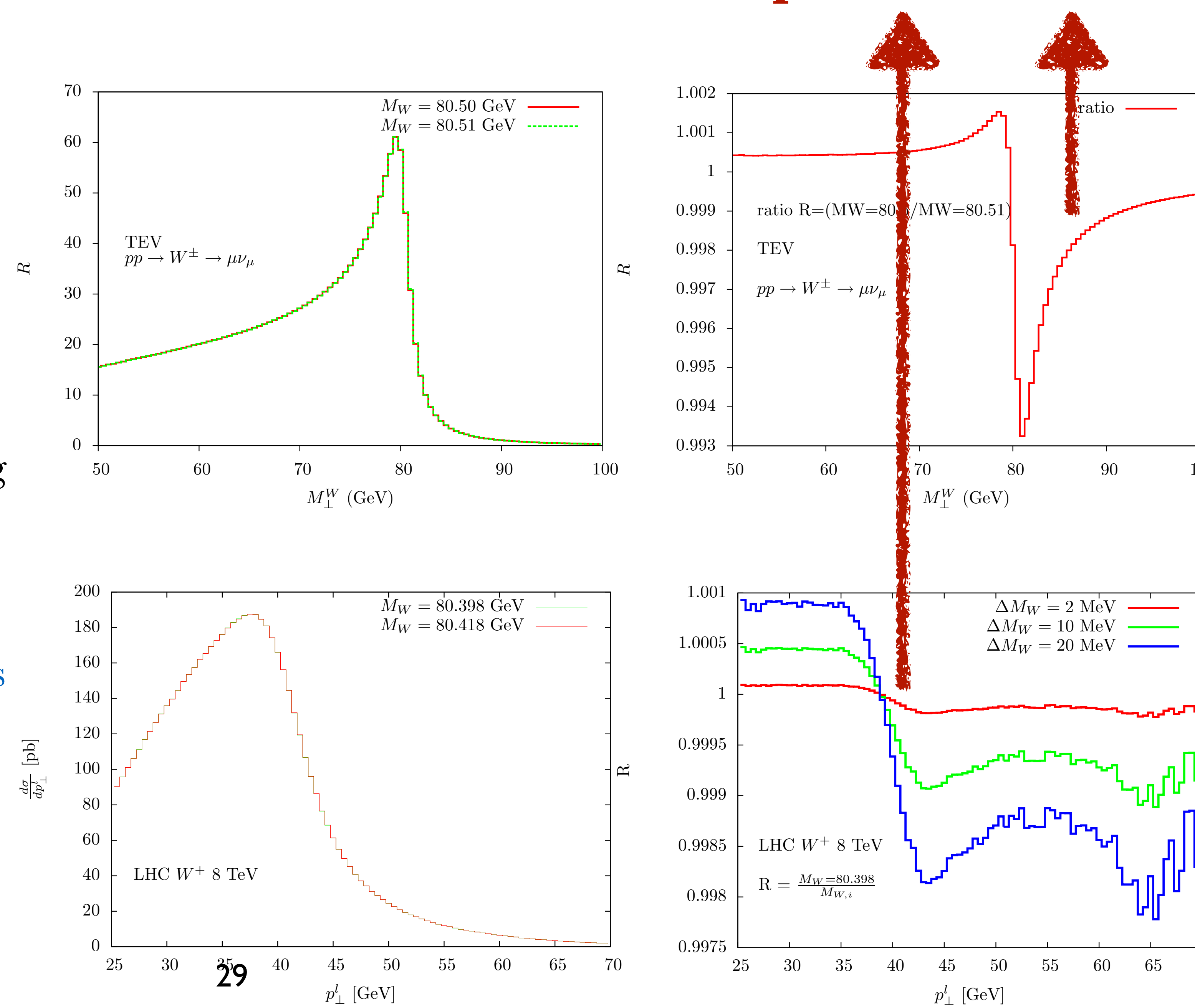
Template fit

Given an experimental distribution:

1. compute corresponding theory distribution at highest available accuracy (QCD N3LL, QCD NNLO, mixed QCD-EW, …) for several $m_W^{(k)}$ values
2. compute a χ^2_k for each $m_W^{(k)}$ in a certain fitting interval
3. find the minimum of the χ^2 distribution → measured m_W

➡ the result of the fit depends on the hypotheses used to compute the templates (perturbative scales, PDFs, non-perturbative, …)

➡ these hypotheses should be treated as theoretical systematic errors



Main sources of theoretical uncertainties

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T
- PDF uncertainties (both different sets and error propagation)

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T
- PDF uncertainties (both different sets and error propagation)
- Heavy-quark-induced processes: collinear-log resummation, mass effects, differences between W and Z production

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T
- PDF uncertainties (both different sets and error propagation)
- Heavy-quark-induced processes: collinear-log resummation, mass effects, differences between W and Z production
- QED radiation and the transverse momentum of the lepton pair

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T
- PDF uncertainties (both different sets and error propagation)
- Heavy-quark-induced processes: collinear-log resummation, mass effects, differences between W and Z production
- QED radiation and the transverse momentum of the lepton pair
- QED DGLAP evolution of the proton PDFs

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T
- PDF uncertainties (both different sets and error propagation)
- Heavy-quark-induced processes: collinear-log resummation, mass effects, differences between W and Z production
- QED radiation and the transverse momentum of the lepton pair
- QED DGLAP evolution of the proton PDFs

ATLAS

δm_W [MeV]	
Fixed-order PDF uncertainty	8.7
AZ tune	3.4
Charm-quark mass	1.5
Parton shower μ_F with heavy-flavour decorrelation	6.9
Parton shower PDF uncertainty	1.6
Angular coefficients	5.3

LHCb

Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

D0

PDF	11
QED	7
Boson p_T	5

Main sources of theoretical uncertainties

- p_T^W-modelling: q_T-resummation / TMD factorisation, matching with fixed order results, (flavour-dependent) intrinsic-k_T
- PDF uncertainties (both different sets and error propagation)
- Heavy-quark-induced processes: collinear-log resummation, mass effects, differences between W and Z production
- QED radiation and the transverse momentum of the lepton pair
- QED DGLAP evolution of the proton PDFs

ATLAS

δm_W [MeV]	
Fixed-order PDF uncertainty	8.7
AZ tune	3.4
Charm-quark mass	1.5
Parton shower μ_F with heavy-flavour decorrelation	6.9
Parton shower PDF uncertainty	1.6
Angular coefficients	5.3

LHCb

Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

CDF II

p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7

D0

PDF	11
QED	7
Boson p_T	5

ATLAS

ATLAS

- default samples for predictions: **POWHEG + PYTHIA 8**
- **reweighing** to include higher-order effects

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_\mathrm{T},y)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_\mathrm{T},y)P_i(\cos\theta,\phi)\right]$$

ATLAS

- default samples for predictions: **POWHEG + PYTHIA 8**
- **reweighing** to include higher-order effects

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_{\mathrm{T}}, y)}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_{\mathrm{T}}, y) P_i(\cos\theta, \phi)\right]$$

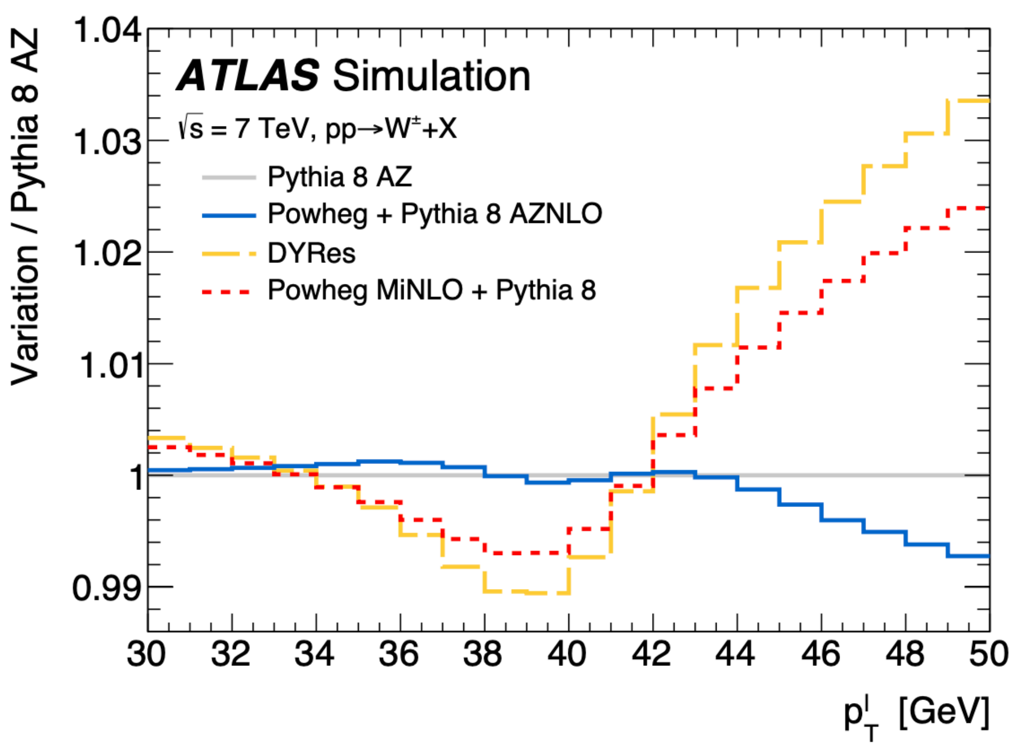
- $d\sigma/dy$ **: DYNNLO** ($\mathcal{O}(\alpha_s^2)$) [comparison with Z data → ***exclusion of PDF sets***]

ATLAS

- default samples for predictions: **POWHEG + PYTHIA 8**
- **reweighing** to include higher-order effects

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

- $d\sigma/dy$ **: DYNNLO** ($\mathcal{O}(\alpha_s^2)$) [comparison with Z data → ***exclusion of PDF sets***]
- $d\sigma/dp_T$ **: (AZ** k_T, α_s, p_{T0}) [comparison with alt. modelling →***reduced*** $p_{T\ell}$ ***fitting range***]

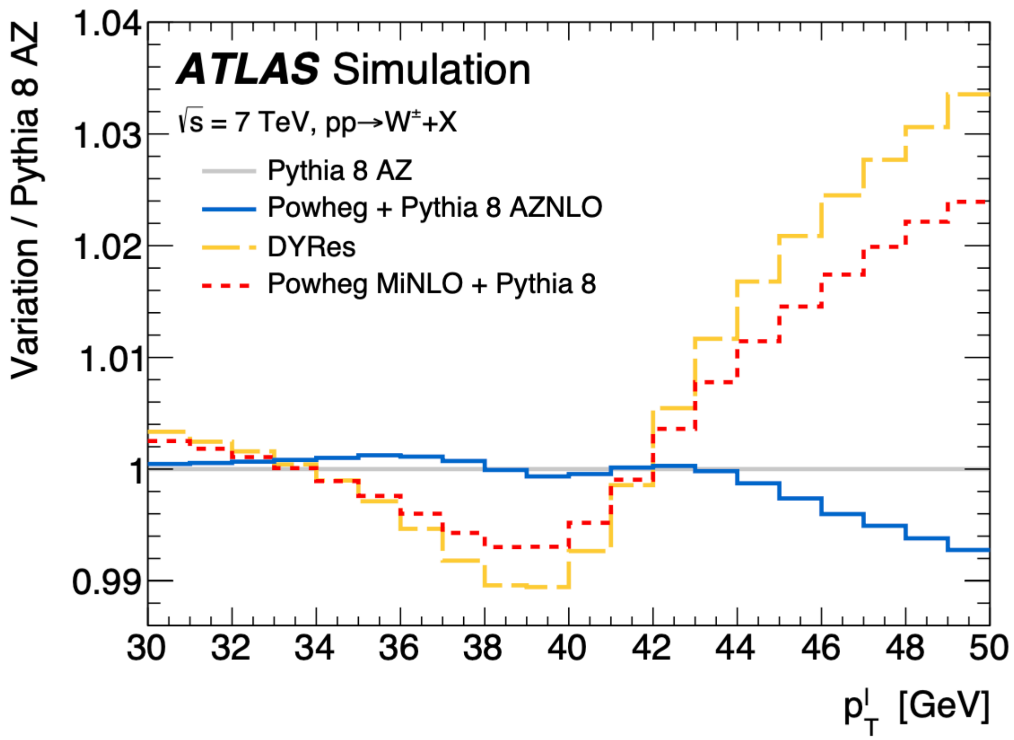


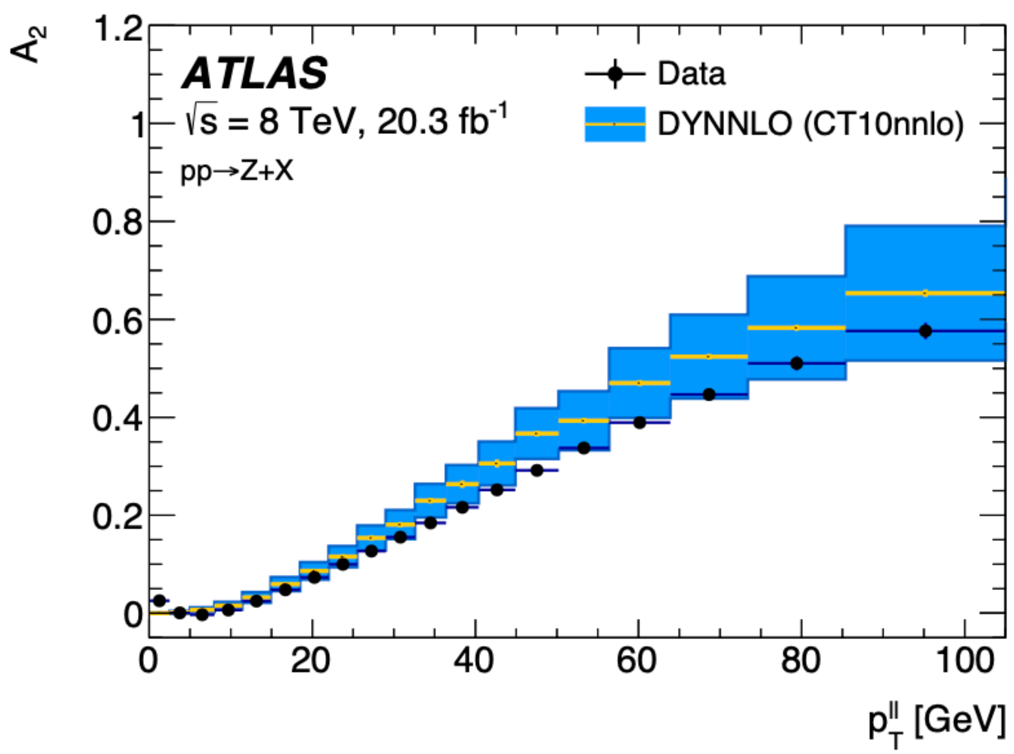
ATLAS

- default samples for predictions: **POWHEG + PYTHIA 8**
- **reweighing** to include higher-order effects

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

- $d\sigma/dy$ **: DYNNLO** ($\mathcal{O}(\alpha_s^2)$) [comparison with Z data → ***exclusion of PDF sets***]
- $d\sigma/dp_T$ **: (AZ** k_T, α_s, p_{T0}) [comparison with alt. modelling →***reduced*** $p_{T\ell}$ ***fitting range***]
- A_i **: DYNNLO** ($\mathcal{O}(\alpha_s^2)$) [large deviations for A_2 → ***additional source of uncertainty***]





ATLAS

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and A_i → 12.0-14.0 MeV
  - + anti-correlation between W^+ and W^- → 7.4 MeV
  - + quadrature with MMHT2014 and CT14 → **(8.0, 8.7) MeV**

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and $A_i \rightarrow$ 12.0-14.0 MeV
  - + anti-correlation between W^+ and W^- $\rightarrow$ 7.4 MeV
  - + quadrature with MMHT2014 and CT14 $\rightarrow$ **(8.0, 8.7) MeV**
- **Scale variation on $d\sigma/dy$ (DYNNLO): negligible (0.1% - 0.3%)**

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and $A_i \rightarrow$ 12.0-14.0 MeV
  - + anti-correlation between W^+ and W^- → 7.4 MeV
  - + quadrature with MMHT2014 and CT14 → **(8.0, 8.7) MeV**
- **Scale variation on** $d\sigma/dy$ **(DYNNLO): negligible (0.1% - 0.3%)**
- **AZ tune:** propagation of k_T, α_s, p_{T0} uncertainties → **(3.0, 3.4) MeV [*flavour blind*]**

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and $A_i \rightarrow$ 12.0-14.0 MeV
  - + anti-correlation between W^+ and W^- $\rightarrow$ 7.4 MeV
  - + quadrature with MMHT2014 and CT14 $\rightarrow$ **(8.0, 8.7) MeV**
- **Scale variation on $d\sigma/dy$ (DYNNLO): negligible (0.1% - 0.3%)**
- **AZ tune:** propagation of k_T, α_s, p_{T0} uncertainties $\rightarrow$ **(3.0, 3.4) MeV [*flavour blind*]**
- **Charm mass:** 1.5 ± 0.5 GeV $\rightarrow$ **(1.2, 1.5) MeV** (m_b variation $\rightarrow$ negligible)

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and A_i → 12.0-14.0 MeV
  - + anti-correlation between W^+ and W^- → 7.4 MeV
  - + quadrature with MMHT2014 and CT14 → **(8.0, 8.7) MeV**
- **Scale variation on $d\sigma/dy$ (DYNNLO): negligible (0.1% - 0.3%)**
- **AZ tune:** propagation of k_T, α_s, p_{T0} uncertainties → **(3.0, 3.4) MeV [*flavour blind*]**
- **Charm mass:** 1.5 ± 0.5 GeV → **(1.2, 1.5) MeV** (m_b variation → negligible)
- **PS μ_F:** variation of $\mu_F^2 = p_{T0}^2 + p_T^2$ simultaneously for $q = u, d, s$, independently for $c\bar{c}, b\bar{b} \to Z$, $c\bar{d}, c\bar{s} \to W$ → **(5.0, 6.9) MeV [*30 MeV if correlated btw flavours but uncorrelated W,Z prod.*]**

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and $A_i \rightarrow$ 12.0-14.0 MeV
  - + anti-correlation between W^+ and $W^- \rightarrow$ 7.4 MeV
  - + quadrature with MMHT2014 and CT14 $\rightarrow$ **(8.0, 8.7) MeV**
- **Scale variation on $d\sigma/dy$ (DYNNLO): negligible (0.1% - 0.3%)**
- **AZ tune:** propagation of k_T, α_s, p_{T0} uncertainties $\rightarrow$ **(3.0, 3.4) MeV [*flavour blind*]**
- **Charm mass:** 1.5 ± 0.5 GeV $\rightarrow$ **(1.2, 1.5) MeV** (m_b variation $\rightarrow$ negligible)
- **PS μ_F:** variation of $\mu_F^2 = p_{T0}^2 + p_T^2$ simultaneously for $q = u, d, s$, independently for $c\bar{c}, b\bar{b} \rightarrow Z$, $c\bar{d}, c\bar{s} \rightarrow W$ $\rightarrow$ **(5.0, 6.9) MeV [*30 MeV if correlated btw flavours but uncorrelated W,Z prod.*]**
- **PS PDF:** variation of LO sets
  - largest spread among CTEQ6L1, CT14LO, NNPDF2.3LO, MMHT2014LO $\rightarrow$ 3.8-2.5 MeV
  - + anti-correlation between W^+ and $W^- \rightarrow$ **(1.0, 1.6) MeV**

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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and A_i → 12.0-14.0 MeV
  - + anti-correlation between W^+ and W^- → 7.4 MeV
  - + quadrature with MMHT2014 and CT14 → **(8.0, 8.7) MeV**
- **Scale variation on $d\sigma/dy$ (DYNNLO): negligible (0.1% - 0.3%)**
- **AZ tune:** propagation of k_T, α_s, p_{T0} uncertainties → **(3.0, 3.4) MeV [*flavour blind*]**
- **Charm mass:** 1.5 ± 0.5 GeV → **(1.2, 1.5) MeV** (m_b variation → negligible)
- **PS μ_F:** variation of $\mu_F^2 = p_{T0}^2 + p_T^2$ simultaneously for $q = u, d, s$, independently for $c\bar{c}, b\bar{b} \to Z$, $c\bar{d}, c\bar{s} \to W$ → **(5.0, 6.9) MeV [*30 MeV if correlated btw flavours but uncorrelated W,Z prod.*]**
- **PS PDF:** variation of LO sets
  - largest spread among CTEQ6L1, CT14LO, NNPDF2.3LO, MMHT2014LO → 3.8-2.5 MeV
  - + anti-correlation between W^+ and W^- → **(1.0, 1.6) MeV**
- **Angular coefficients:**
  - propagation of Z-data uncertainty used to measure A_i
  - + quadrature with propagation of A_2 data-theory mismatch → **(5.8, 5.3) MeV**

ATLAS

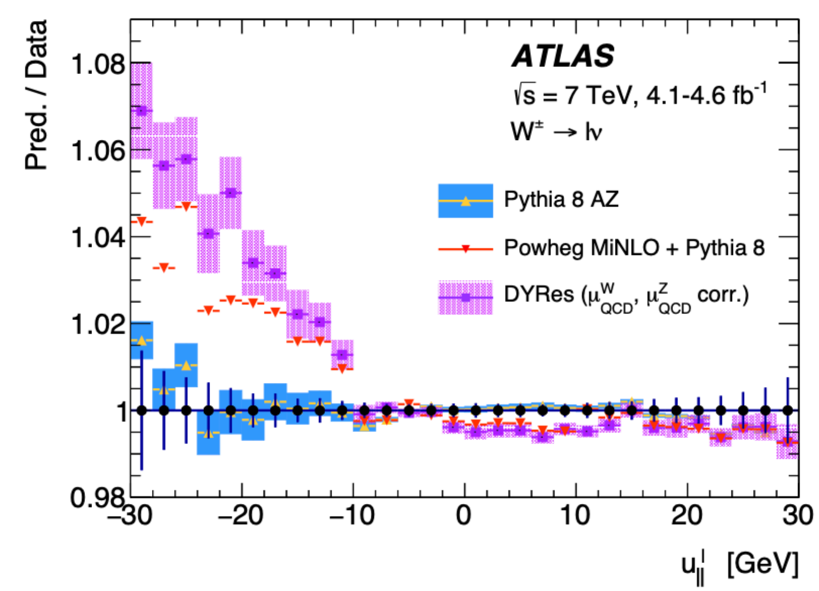
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

ATLAS

- **Fixed-order PDF uncertainty: Hessian method on CT10nnlo**
  - simultaneous variation of $d\sigma/dy$ and $A_i \rightarrow$ 12.0-14.0 MeV
  - + anti-correlation between W^+ and $W^- \rightarrow$ 7.4 MeV
  - + quadrature with MMHT2014 and CT14 → **(8.0, 8.7) MeV**
- **Scale variation on $d\sigma/dy$ (DYNNLO): negligible (0.1% - 0.3%)**
- **AZ tune:** propagation of k_T, α_s, p_{T0} uncertainties → **(3.0, 3.4) MeV [*flavour blind*]**
- **Charm mass:** 1.5 ± 0.5 GeV → **(1.2, 1.5) MeV** (m_b variation → negligible)
- **PS μ_F:** variation of $\mu_F^2 = p_{T0}^2 + p_T^2$ simultaneously for $q = u, d, s$, independently for $c\bar{c}, b\bar{b} \rightarrow Z$, $c\bar{d}, c\bar{s} \rightarrow W$ → **(5.0, 6.9) MeV [*30 MeV if correlated btw flavours but uncorrelated W,Z prod.*]**
- **PS PDF:** variation of LO sets
  - largest spread among CTEQ6L1, CT14LO, NNPDF2.3LO, MMHT2014LO → 3.8-2.5 MeV
  - + anti-correlation between W^+ and $W^- \rightarrow$ **(1.0, 1.6) MeV**
- **Angular coefficients:**
  - propagation of Z-data uncertainty used to measure A_i
  - + quadrature with propagation of A_2 data-theory mismatch → **(5.8, 5.3) MeV**
- **Data-driven check** (based on p_{TW}/p_{TZ}) among Pythia/POWHEG+Pythia/DYRes
  - **DYRes** include $(\mu_{res}, \mu_F, \mu_R)$ variations → would induce $\Delta M_W \sim 60$ MeV → ***not considered***

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



LHCb

LHCb

Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

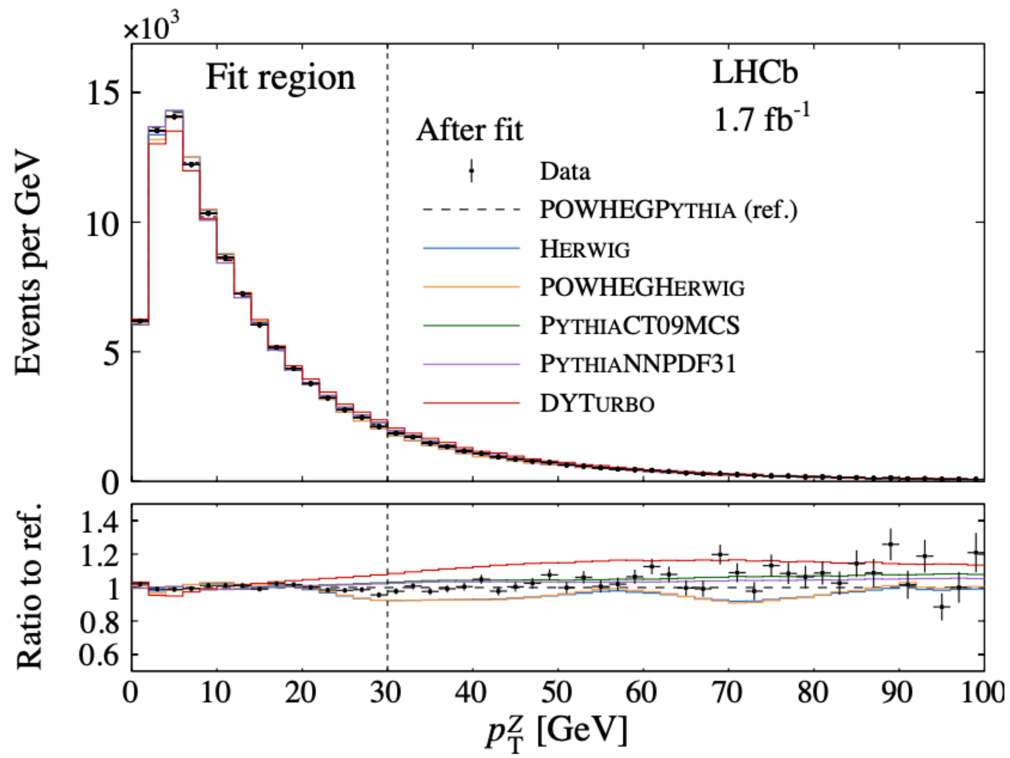
LHCb

- **codes considered for predictions:**
  - Pythia, Herwig, POWHEG+Pythia, POWHEG+Herwig, DYTurbo

LHCb	
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

LHCb

- **codes considered for predictions:**
  - Pythia, Herwig, POWHEG+Pythia, POWHEG+Herwig, DYTurbo
- $d\sigma/dp_T$ **:** tune of NP parameters to p_{TZ} data → best description: POWHEG+Pythia
  - default samples for predictions: **POWHEG+Pythia 8**
  - spread from alternative descriptions → **11 MeV**

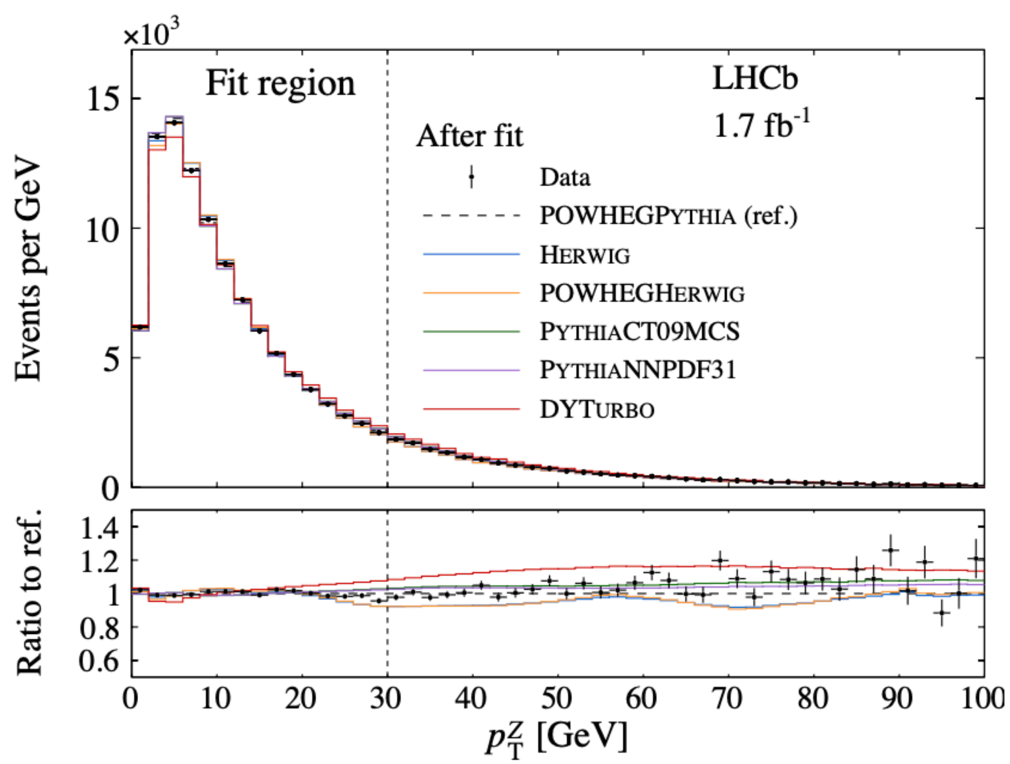


LHCb

Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

LHCb

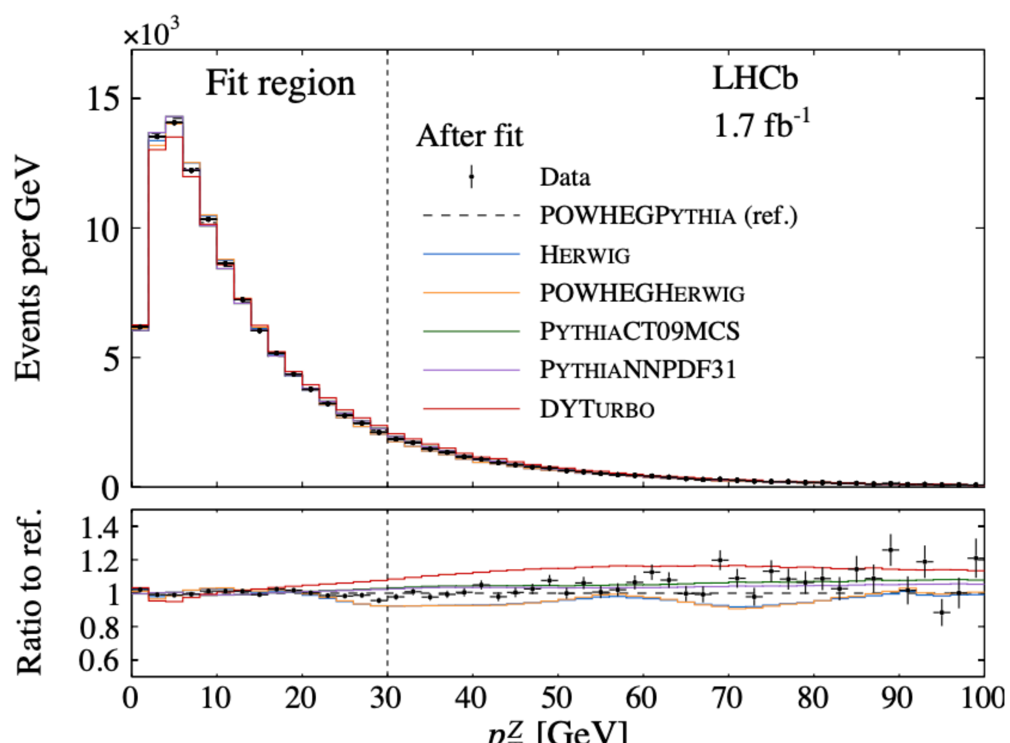
- **codes considered for predictions:**
  - Pythia, Herwig, POWHEG+Pythia, POWHEG+Herwig, DYTurbo
- $d\sigma/dp_T$ **:** tune of NP parameters to p_{TZ} data → best description: POWHEG+Pythia
  - default samples for predictions: **POWHEG+Pythia 8**
  - spread from alternative descriptions → **11 MeV**
- A_i **: DYTurbo** ($\mathcal{O}(\alpha_s^2)$) **scale variation** (instead of DYNNLO, because negligible sensitivity to A_0, A_2)
  - A_3 main source of uncertainty → **10 MeV**



LHCb	
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

LHCb

- **codes considered for predictions:**
  - Pythia, Herwig, POWHEG+Pythia, POWHEG+Herwig, DYTurbo
- $d\sigma/dp_T$ **:** tune of NP parameters to p_{TZ} data → best description: POWHEG+Pythia
  - default samples for predictions: **POWHEG+Pythia 8**
  - spread from alternative descriptions → **11 MeV**
- A_i **: DYTurbo** ($\mathcal{O}(\alpha_s^2)$) **scale variation** (instead of DYNNLO, because negligible sensitivity to A_0, A_2)
  - A_3 main source of uncertainty → **10 MeV**
- **PDF:** separate fits
  - NNPDF3.1 (8.3 MeV replica + 2.4 α_s variation → 8.6 MeV)
  - CT18 (11.5 MeV Hessian + 1.4 α_s variation → 11.6 MeV)
  - MSHT20 (6.5 MeV Hessian + 2.1 α_s variation → 6.8 MeV)
  - assumption: fully correlated uncertainties → **arithmetic average: 9 MeV**



LHCb

Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5

D0

D0

	m_T	p_T^e	$\not{E}_T$
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2

D0

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**

D0

	m_T	p_T^e	$\not{E}_T$
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2

D0

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**
- **Boson p_T : NP modelling** $e^{S_{NP}(b)}$
  - BLNY parameterisation $S_{NP}(b) = \left[-g_1 - g_2 \log\left(\frac{\sqrt{s}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right) \right] b^2$
  - use BLNY fitted values (2003)
  - weak sensitivity to $g_1, g_3 \rightarrow$ propagate g_2 uncertainty $\rightarrow$ **(2,5,2) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$

D0

	m_T	p_T^e	$\not{E}_T$
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2

D0

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**
- **Boson p_T : NP modelling** $e^{S_{NP}(b)}$
  - BLNY parameterisation $S_{NP}(b) = \left[-g_1 - g_2 \log\left(\frac{\sqrt{s}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right)\right] b^2$
  - use BLNY fitted values (2003)
  - weak sensitivity to g_1, g_3 → propagate g_2 uncertainty → **(2,5,2) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$
- **PDF: Pythia with CTEQ6.1 LO (40 error sets)**
  - template fit 68% C.L. → **(11,11,14) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$

D0

	m_T	p_T^e	$\not{E}_T$
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2

CDF II

CDF

	m_T	p_T^e	$\not{E}_T$
p_T^Z model	0.7	2.3	0.9
p_T^W/p_T^Z model	0.8	2.3	0.9
Parton distributions	3.9	3.9	3.9

CDF II

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**

CDF

	m_T	p_T^e	$\not{E}_T$
p_T^Z model	0.7	2.3	0.9
p_T^W/p_T^Z model	0.8	2.3	0.9
Parton distributions	3.9	3.9	3.9

CDF II

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**
- p_T^Z **model : NP modelling** $e^{S_{NP}(b)}$
  - BLNY parameterisation $S_{NP}(b) = \left[-g_1 - g_2 \log\left(\frac{\sqrt{s}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right) \right] b^2$
  - use BLNY fitted values (2003) for g_1, g_3
  - fit g_2 on Z data ($\Delta g_2 = 0.007\,\mathrm{GeV}^2$)
  - $\Delta g_3 = 0.03$ from BLNY fit equivalent to an additional $\Delta g_2 = 0.007\,\mathrm{GeV}^2$ in terms of ΔM_W
  - propagate g_2, g_3 uncertainty → (0.5,2.2,0.5) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - α_s tuning to Z data → (1.0,3.2,1.2) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - anti-correlation between α_s and g_2 uncertainties → **(0.7,2.3,0.9) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$

CDF

	m_T	p_T^e	$\not{E}_T$
p_T^Z model	0.7	2.3	0.9
p_T^W/p_T^Z model	0.8	2.3	0.9
Parton distributions	3.9	3.9	3.9

CDF II

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**
- p_T^Z **model : NP modelling** $e^{S_{NP}(b)}$
  - BLNY parameterisation $S_{NP}(b) = \left[-g_1 - g_2 \log\left(\frac{\sqrt{s}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right)\right] b^2$
  - use BLNY fitted values (2003) for g_1, g_3
  - fit g_2 on Z data ($\Delta g_2 = 0.007\,\mathrm{GeV}^2$)
  - $\Delta g_3 = 0.03$ from BLNY fit equivalent to an additional $\Delta g_2 = 0.007\,\mathrm{GeV}^2$ in terms of ΔM_W
  - propagate g_2, g_3 uncertainty → (0.5,2.2,0.5) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - α_s tuning to Z data → (1.0,3.2,1.2) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - anti-correlation between α_s and g_2 uncertainties → **(0.7,2.3,0.9) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$
- **scale variation in ResBos** (μ_R, μ_F)**:** negligible (0.4 MeV shift)

CDF

	m_T	p_T^e	$\not{E}_T$
p_T^Z model	0.7	2.3	0.9
p_T^W/p_T^Z model	0.8	2.3	0.9
Parton distributions	3.9	3.9	3.9

CDF II

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**
- p_T^Z **model : NP modelling** $e^{S_{NP}(b)}$
  - BLNY parameterisation $S_{NP}(b) = \left[-g_1 - g_2 \log\left(\frac{\sqrt{s}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right) \right] b^2$
  - use BLNY fitted values (2003) for g_1, g_3
  - fit g_2 on Z data ($\Delta g_2 = 0.007\,\mathrm{GeV}^2$)
  - $\Delta g_3 = 0.03$ from BLNY fit equivalent to an additional $\Delta g_2 = 0.007\,\mathrm{GeV}^2$ in terms of ΔM_W
  - propagate g_2, g_3 uncertainty → (0.5,2.2,0.5) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - α_s tuning to Z data → (1.0,3.2,1.2) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - anti-correlation between α_s and g_2 uncertainties → **(0.7,2.3,0.9) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$
- **scale variation in ResBos** (μ_R, μ_F)**:** negligible (0.4 MeV shift)
- p_T^W / p_T^Z **model: use of DYqT**
  - scale variation $(1/4 < (\mu_{res}, \mu_R, \mu_F)/m_{W,Z} < 1)$ central scale $m_Z/2$ → (3.5,10.1,3.9) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - reduction by factor 4.4 when comparing with p_T^W data → **(0.8,2.3,0.9) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$

CDF

	m_T	p_T^e	$\not{E}_T$
p_T^Z model	0.7	2.3	0.9
p_T^W / p_T^Z model	0.8	2.3	0.9
Parton distributions	3.9	3.9	3.9

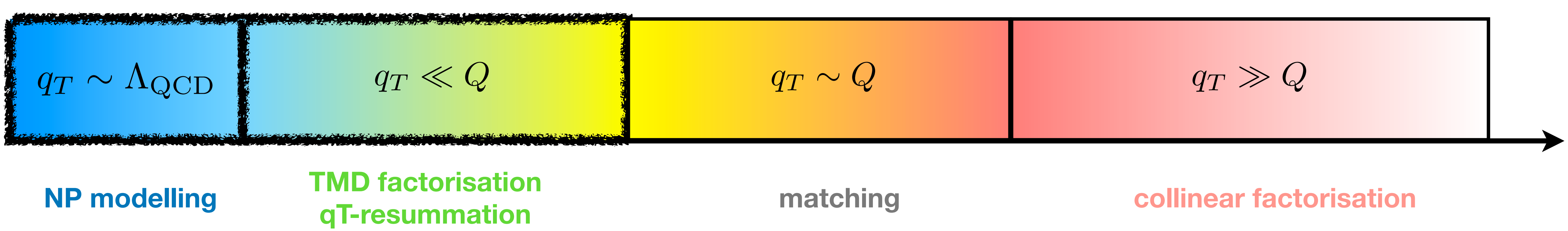
CDF II

- default samples for predictions: **RESBOS(1)@NNLL (CTEQ6Mnlo)**
- p_T^Z **model : NP modelling** $e^{S_{NP}(b)}$
  - BLNY parameterisation $S_{NP}(b) = \left[-g_1 - g_2 \log\left(\frac{\sqrt{s}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right)\right] b^2$
  - use BLNY fitted values (2003) for g_1, g_3
  - fit g_2 on Z data ($\Delta g_2 = 0.007\,\mathrm{GeV}^2$)
  - $\Delta g_3 = 0.03$ from BLNY fit equivalent to an additional $\Delta g_2 = 0.007\,\mathrm{GeV}^2$ in terms of ΔM_W
  - propagate g_2, g_3 uncertainty → (0.5,2.2,0.5) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - α_s tuning to Z data → (1.0,3.2,1.2) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - anti-correlation between α_s and g_2 uncertainties → **(0.7,2.3,0.9) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$
- **scale variation in ResBos** (μ_R, μ_F)**:** negligible (0.4 MeV shift)
- p_T^W/p_T^Z **model: use of DYqT**
  - scale variation $(1/4 < (\mu_{res}, \mu_R, \mu_F)/m_{W,Z} < 1)$ central scale $m_Z/2$ → (3.5,10.1,3.9) MeV for $(m_T, p_{T\ell}, p_{T\nu})$
  - reduction by factor 4.4 when comparing with p_T^W data → **(0.8,2.3,0.9) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$
- **PDF:** pseudodata generated with ABMP16, CJ15, CT18, MMHT2014, NNPDF3.1 (NLO & NNLO)
  - single PDF uncertainty: 25 symmetric NNPDF3.1(NNLO) eigenvectors → **3.9 MeV**
  - all other NNLO sets within uncertainty band of NNPDF3.1
  - shift between NNPDF3.1 and CTEQ6m → **(3.3,3.6,3.0) MeV for** $(m_T, p_{T\ell}, p_{T\nu})$

CDF

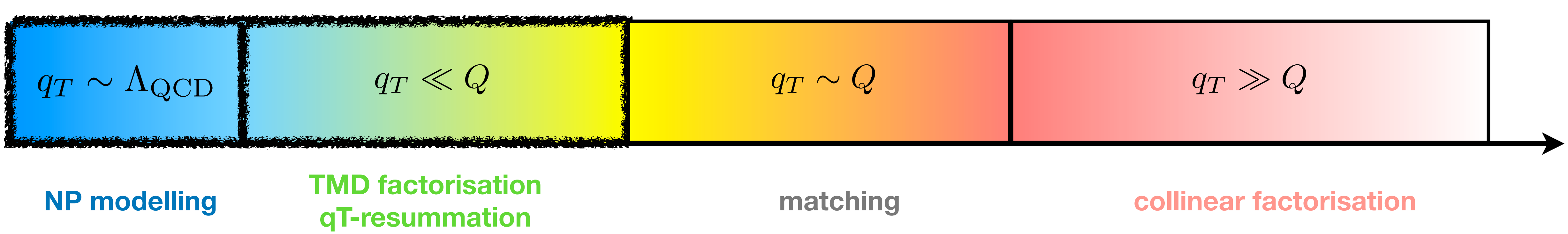
	m_T	p_T^e	$\not{E}_T$
p_T^Z model	0.7	2.3	0.9
p_T^W/p_T^Z model	0.8	2.3	0.9
Parton distributions	3.9	3.9	3.9

The q_T-spectrum of the W boson



The q_T-spectrum of the W boson

- The q_T-distribution of a generic **high-mass** (**Q**) system produced in hadronic collisions has **two** main regimes:

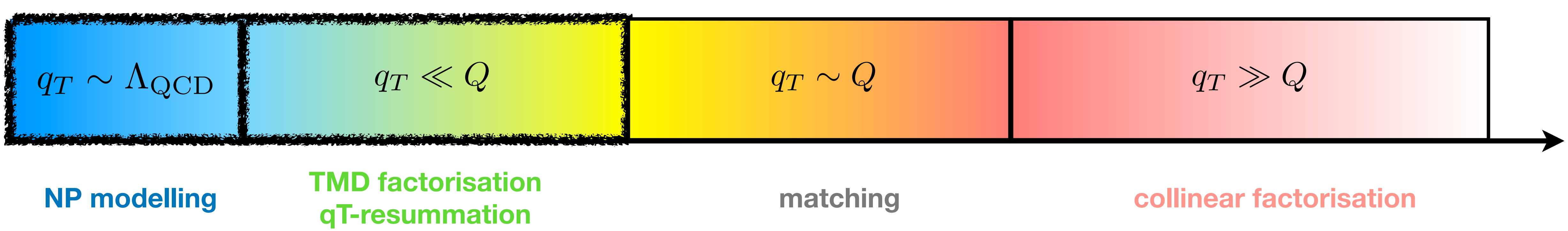


The q_T-spectrum of the W boson

- The q_T-distribution of a generic **high-mass** (**Q**) system produced in hadronic collisions has **two** main regimes:

  - for $q_T \geq Q$ collinear factorisation at fixed perturbative order is appropriate:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{f.o.}} = \int_0^1 dx_1 \int_0^1 dx_2 f_1(x_1, Q) f_2(x_2, Q) \frac{d\hat{\sigma}}{dq_T} + \mathcal{O}\left[\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)^n\right]$$



The q_T-spectrum of the W boson

- The q_T-distribution of a generic **high-mass** (**Q**) system produced in hadronic collisions has **two** main regimes:

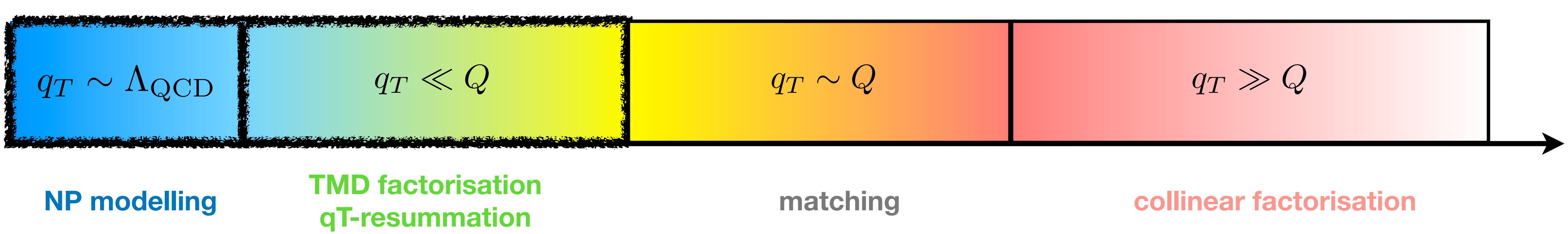
  - for $q_T \geq Q$ collinear factorisation at fixed perturbative order is appropriate:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{f.o.}} = \int_0^1 dx_1 \int_0^1 dx_2 f_1(x_1, Q) f_2(x_2, Q) \frac{d\hat{\sigma}}{dq_T} + \mathcal{O}\left[\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)^n\right]$$

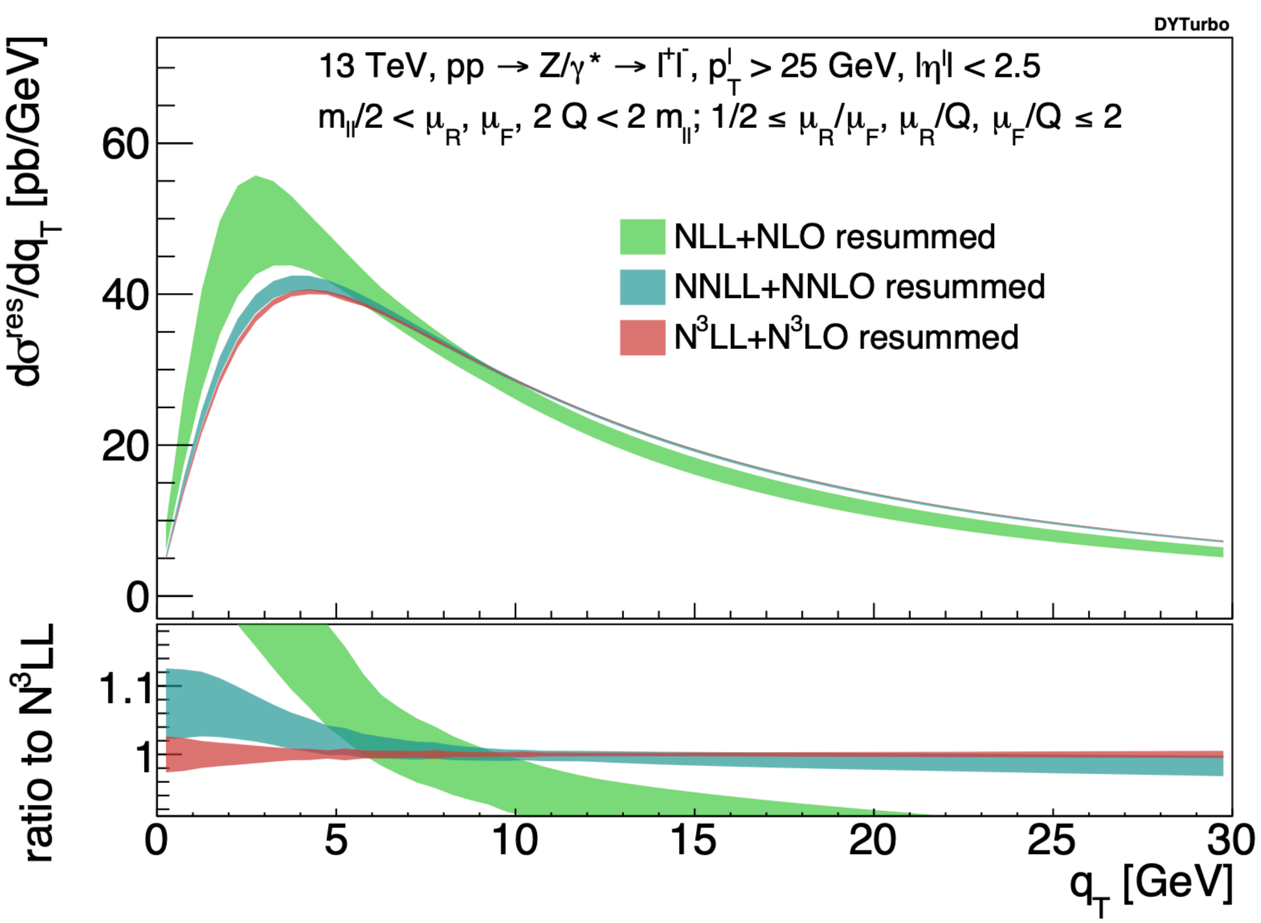
  - for $q_T \ll Q$ TMD factorisation or q_T-resummation are appropriate:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1, \mathbf{b}_T, Q, Q^2) F_2(x_2, \mathbf{b}_T, Q, Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

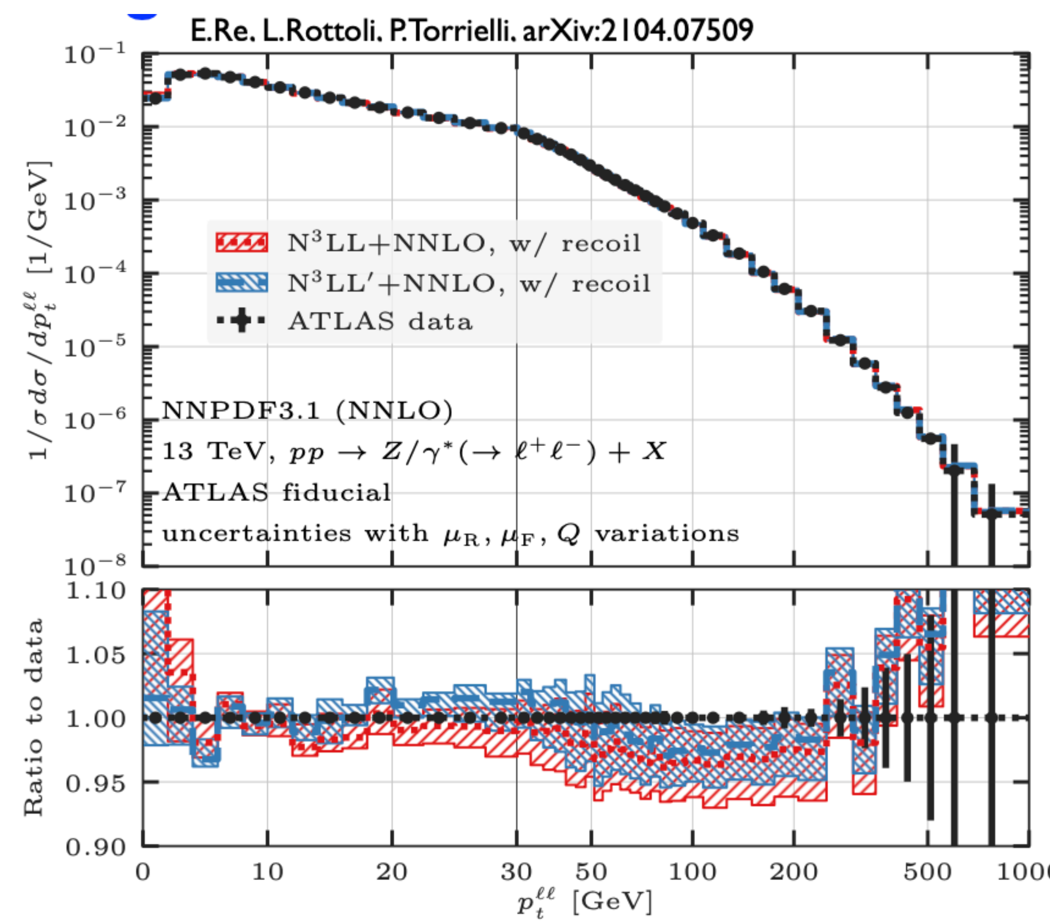
$$\overset{q_T-\text{res.}}{=} \sigma_0 \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} e^{-S(\mathbf{b}_T, Q)} \left[\mathcal{C} \otimes f_1\right](x_1, \mathbf{b}_T, Q) \left[\mathcal{C} \otimes f_2\right](x_2, \mathbf{b}_T, Q) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$



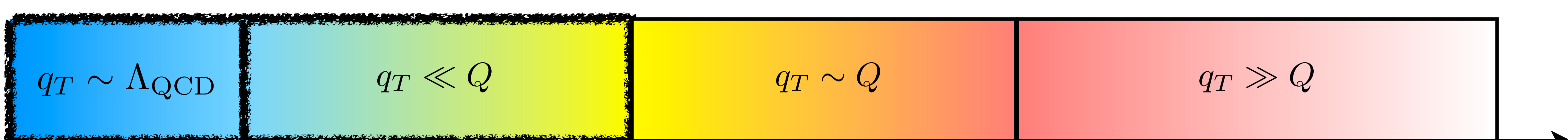
The q_T-spectrum of the W boson



HqT, HRes, DYqT, DYRes, DYTurbo codes
[Bozzi, Catani, deFlorian, Ferrera, Grazzini]

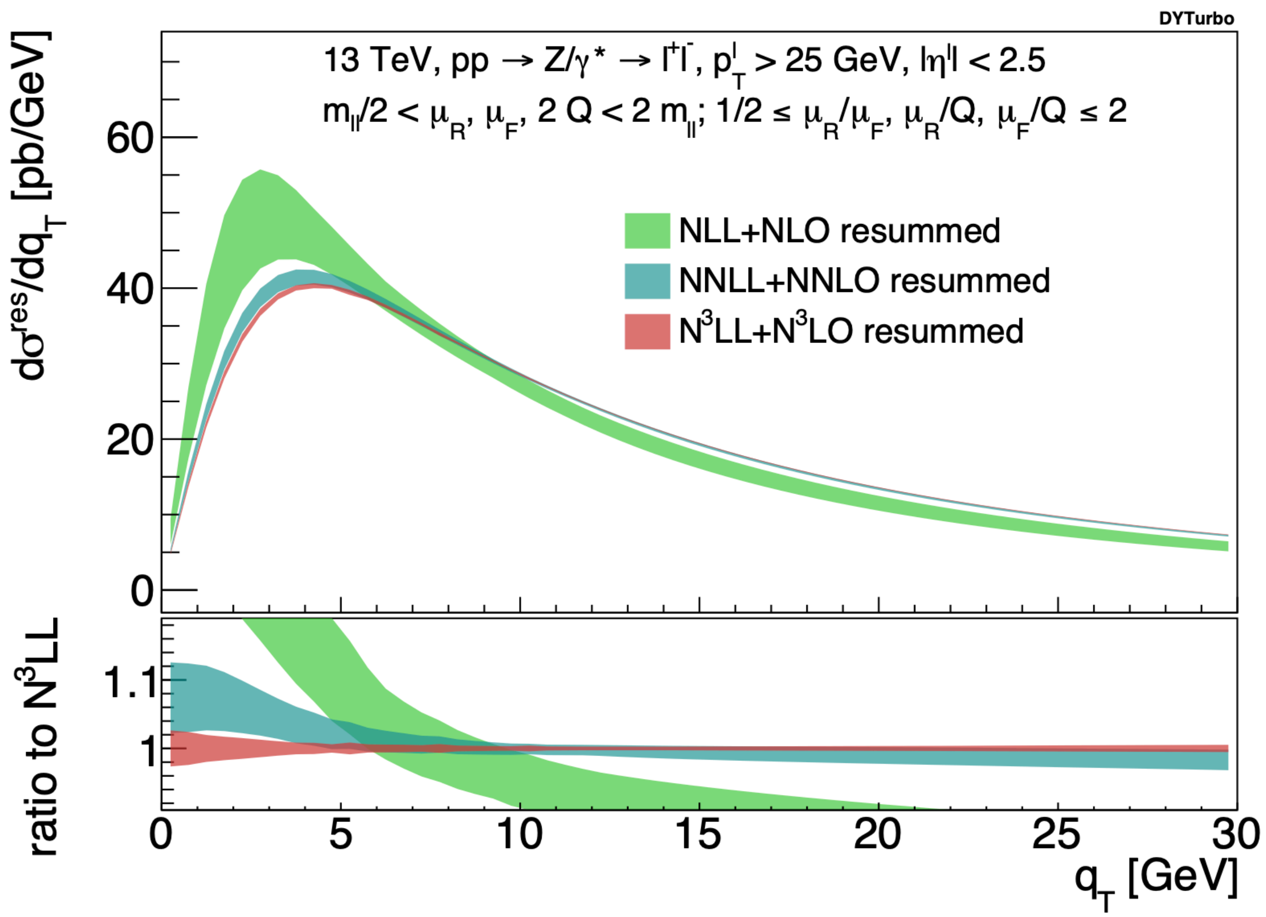


RadISH code [Monni et al.]

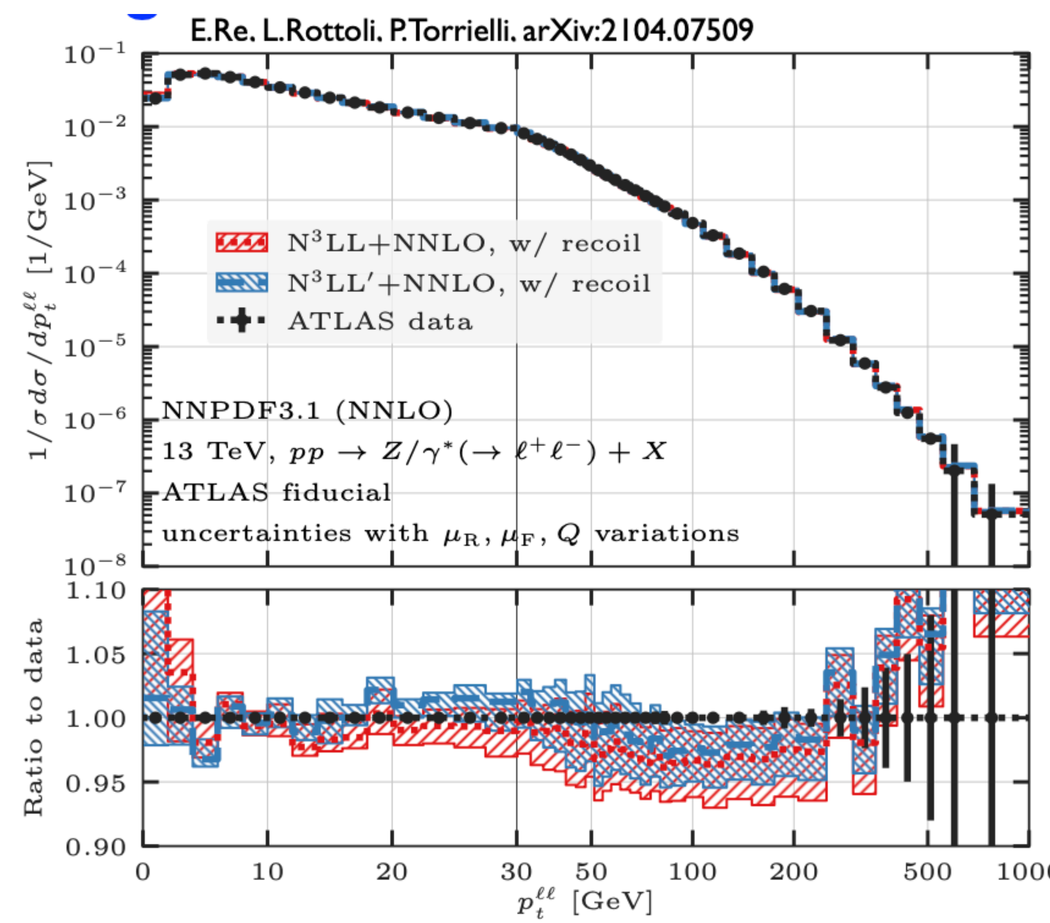


NP modelling | **TMD factorisation qT-resummation** | **matching** | **collinear factorisation**

The q_T-spectrum of the W boson

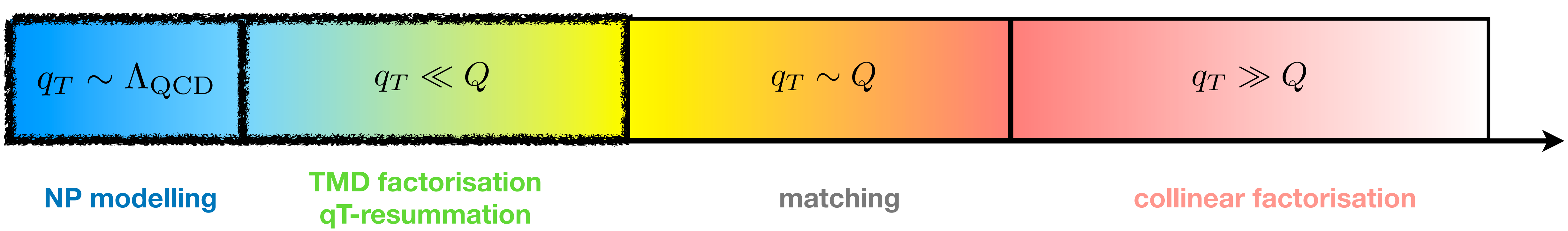


HqT, HRes, DYqT, DYRes, DYTurbo codes
[Bozzi, Catani, deFlorian, Ferrera, Grazzini]

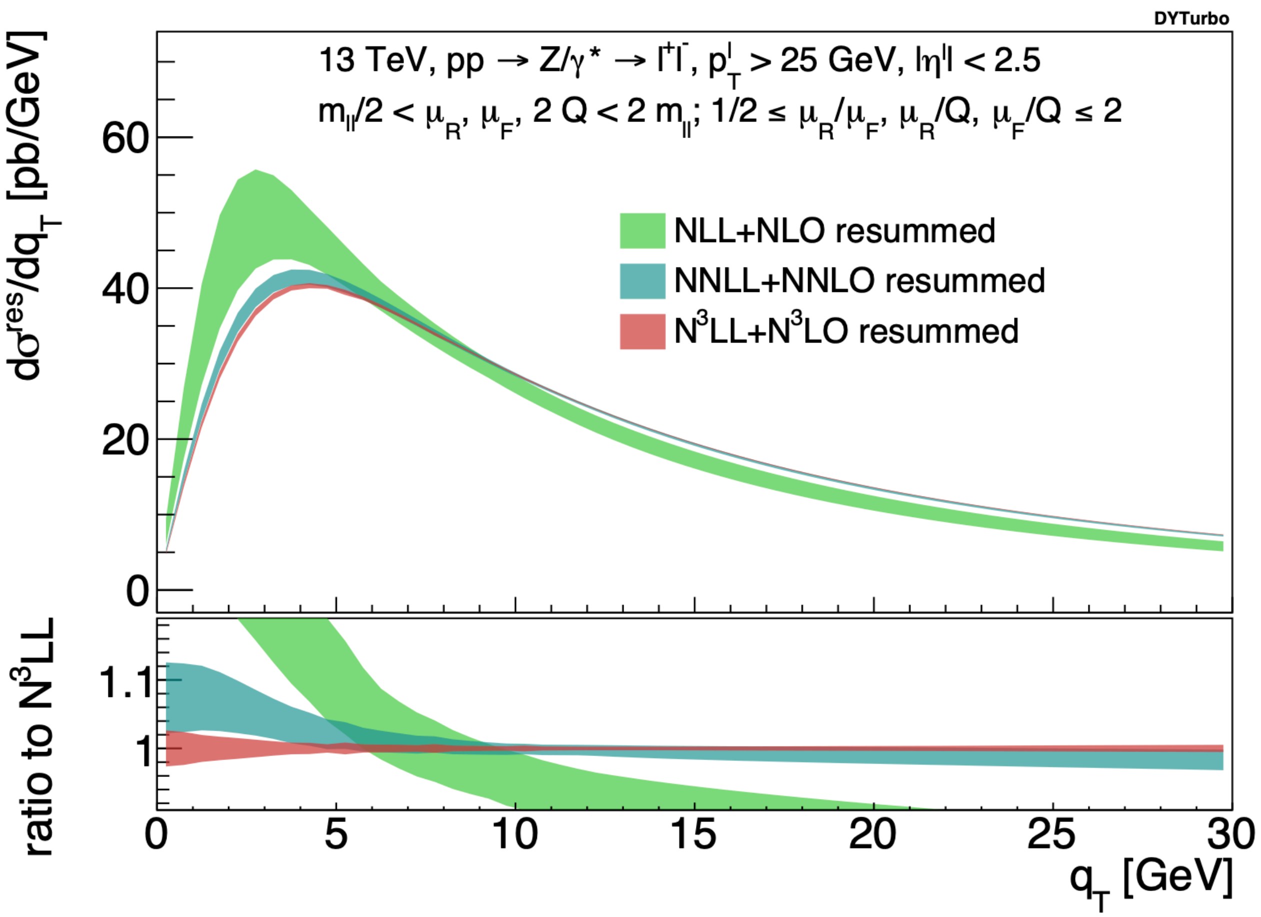


RadISH code [Monni et al.]

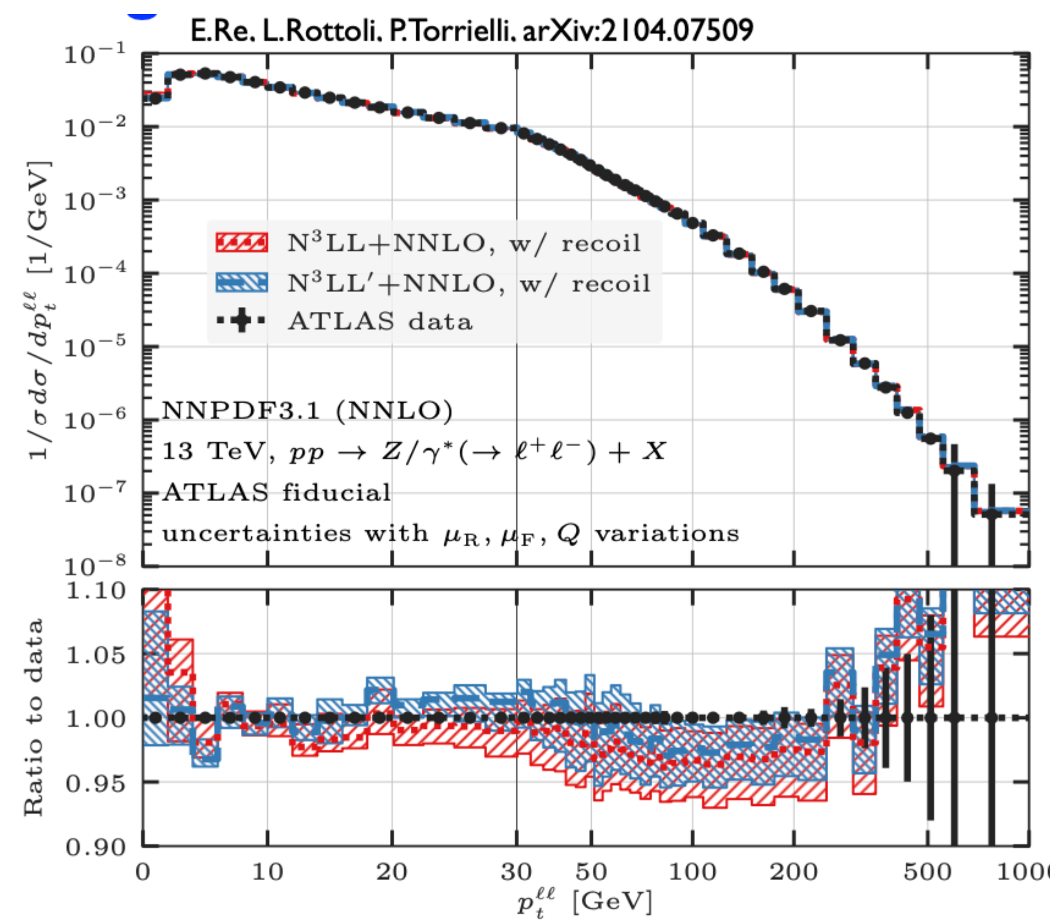
- Precise p_T^W measurement not available: rely on p_T^Z and extrapolate



The q_T-spectrum of the W boson

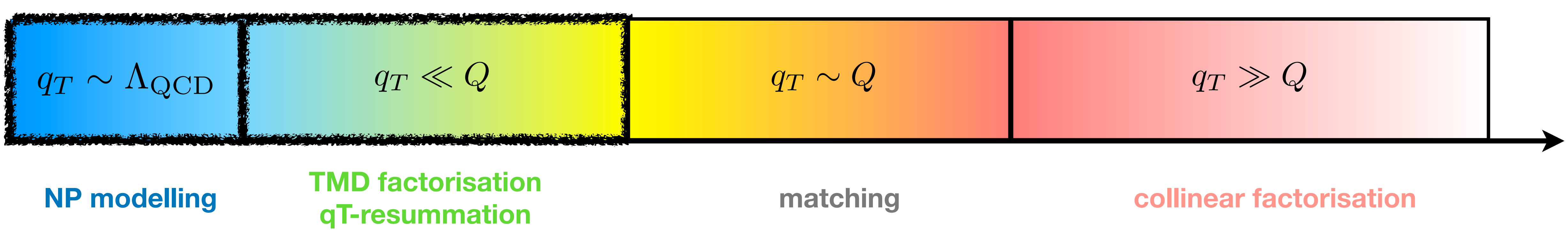


HqT, HRes, DYqT, DYRes, DYTurbo codes
[Bozzi, Catani, deFlorian, Ferrera, Grazzini]

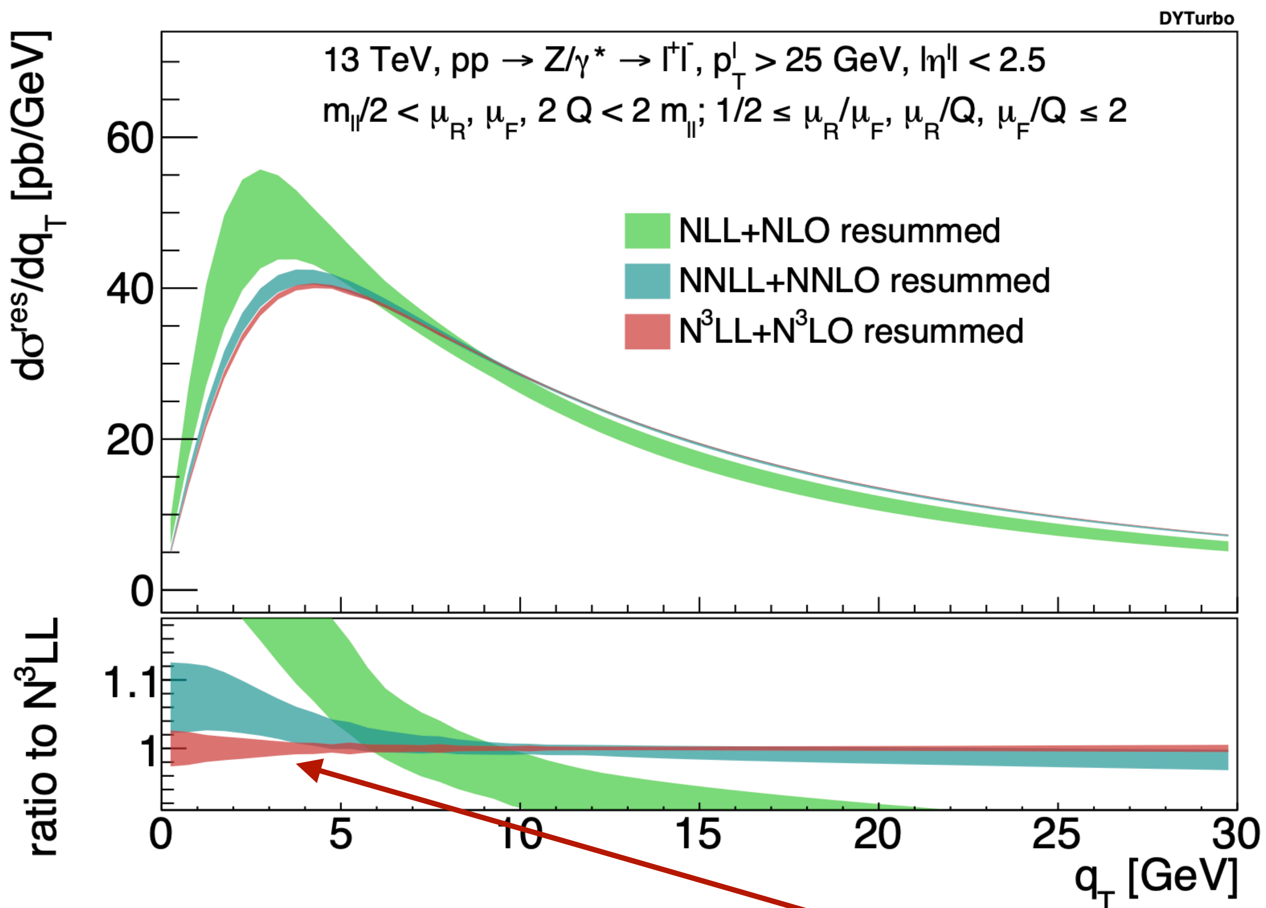


RadISH code [Monni et al.]

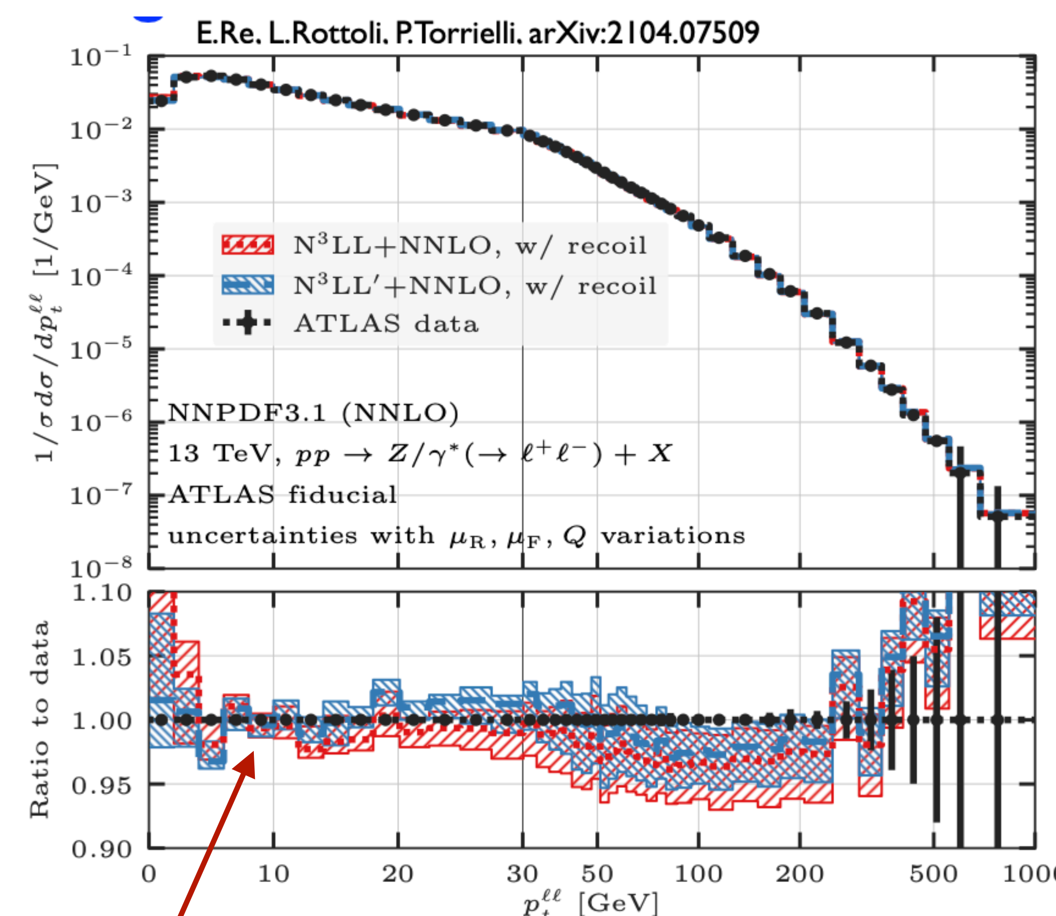
- Precise p_T^W measurement not available: rely on p_T^Z and extrapolate
- p_T^Z also used to tune non-perturbative modelling



The q_T-spectrum of the W boson



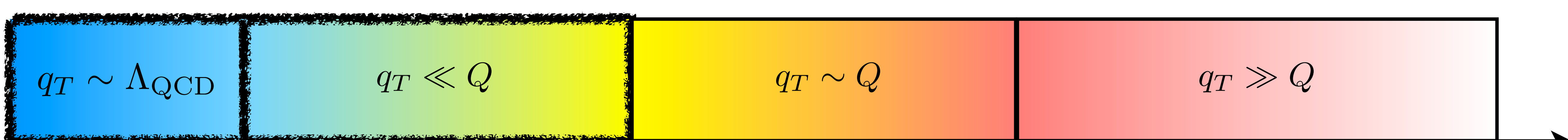
HqT, HRes, DYqT, DYRes, DYTurbo codes
[Bozzi, Catani, deFlorian, Ferrera, Grazzini]



RadISH code [Monni et al.]

at best ± 1 %

- Precise p_T^W measurement not available: rely on p_T^Z and extrapolate
- p_T^Z also used to tune non-perturbative modelling

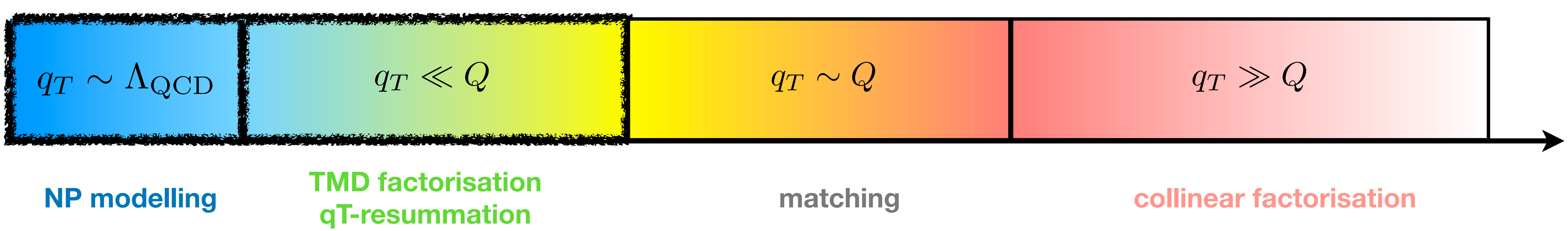


NP modelling | TMD factorisation qT-resummation | matching | collinear factorisation

NP modelling of intrinsic-k_T

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \stackrel{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1,\mathbf{b}_T,Q,Q^2) F_2(x_2,\mathbf{b}_T,Q,Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\stackrel{q_T-\text{res.}}{=} \sigma_0 \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} e^{-S(\mathbf{b}_T,Q)} \left[\mathcal{C}\otimes f_1\right](x_1,\mathbf{b}_T,Q) \left[\mathcal{C}\otimes f_2\right](x_2,\mathbf{b}_T,Q) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

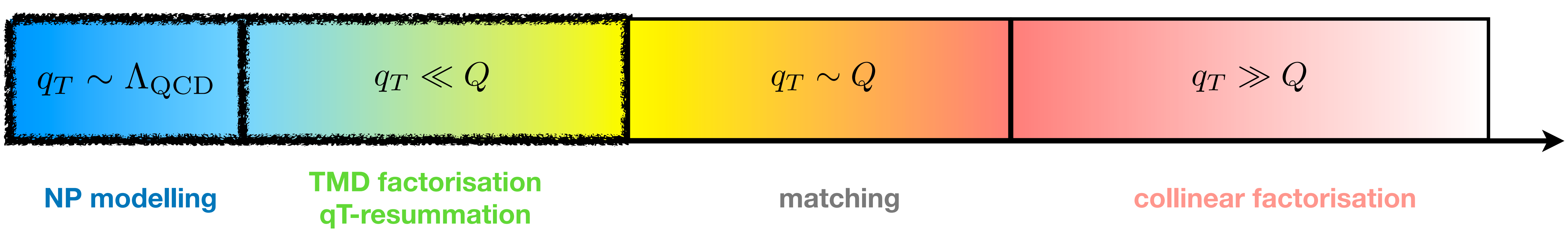


NP modelling of intrinsic-k_T

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1,\mathbf{b}_T,Q,Q^2) F_2(x_2,\mathbf{b}_T,Q,Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\overset{q_T-\text{res.}}{=} \sigma_0 \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} e^{-S(\mathbf{b}_T,Q)} \left[\mathcal{C}\otimes f_1\right](x_1,\mathbf{b}_T,Q) \left[\mathcal{C}\otimes f_2\right](x_2,\mathbf{b}_T,Q) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

Intrinsic-k_T effects parametrised with additional Gaussian factors: $e^{-g b_T^2}$



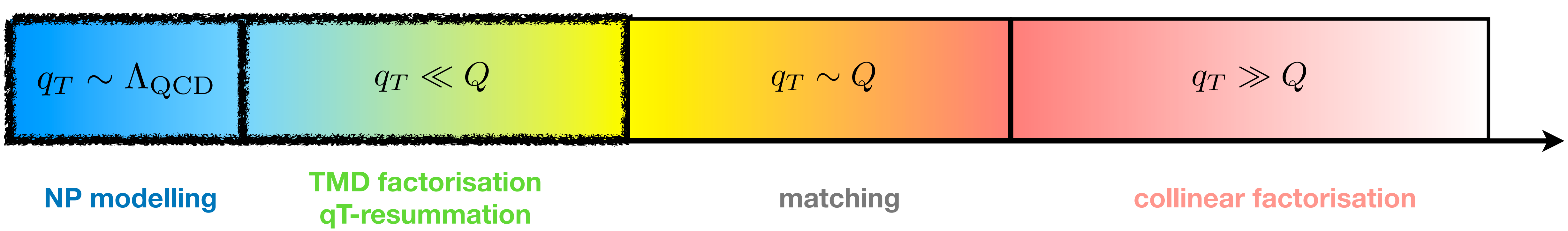
NP modelling of intrinsic-k_T

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1,\mathbf{b}_T,Q,Q^2) F_2(x_2,\mathbf{b}_T,Q,Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\overset{q_T-\text{res.}}{=} \sigma_0 \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} e^{-S(\mathbf{b}_T,Q)} \left[\mathcal{C}\otimes f_1\right](x_1,\mathbf{b}_T,Q) \left[\mathcal{C}\otimes f_2\right](x_2,\mathbf{b}_T,Q) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

Intrinsic-k_T effects parametrised with additional Gaussian factors: $e^{-gb_T^2}$

g **measured on *Z* data** and used to **predict *W* distributions**, *assuming universality*



NP modelling of intrinsic-k_T

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1, \mathbf{b}_T, Q, Q^2) F_2(x_2, \mathbf{b}_T, Q, Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

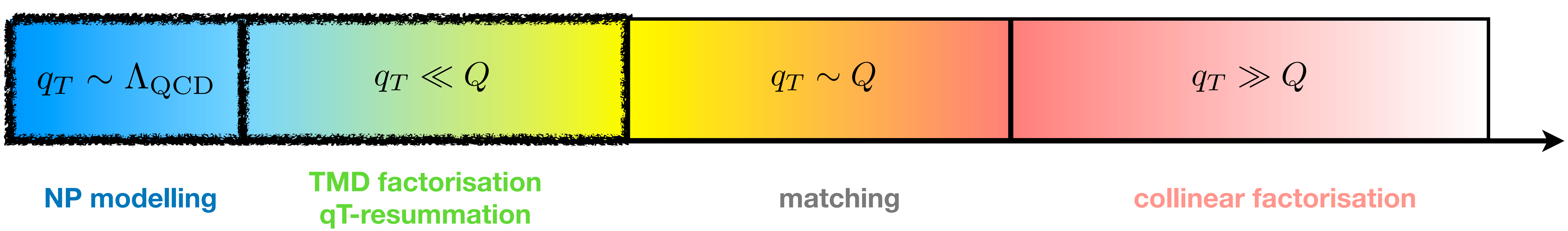
$$\overset{q_T-\text{res.}}{=} \sigma_0 \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} e^{-S(\mathbf{b}_T,Q)} \left[\mathcal{C}\otimes f_1\right](x_1, \mathbf{b}_T, Q) \left[\mathcal{C}\otimes f_2\right](x_2, \mathbf{b}_T, Q) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

Intrinsic-k_T effects parametrised with additional Gaussian factors: $e^{-g b_T^2}$

g **measured on *Z* data** and used to **predict *W* distributions**, *assuming universality*

but

different flavour structure & different phase space available



NP modelling of intrinsic-k_T

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1,\mathbf{b}_T,Q,Q^2) F_2(x_2,\mathbf{b}_T,Q,Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\overset{q_T-\text{res.}}{=} \sigma_0 \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} e^{-S(\mathbf{b}_T,Q)} \left[\mathcal{C}\otimes f_1\right](x_1,\mathbf{b}_T,Q) \left[\mathcal{C}\otimes f_2\right](x_2,\mathbf{b}_T,Q) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

Intrinsic-k_T effects parametrised with additional Gaussian factors: $e^{-g b_T^2}$

g **measured on *Z* data** and used to **predict *W* distributions**, *assuming universality*

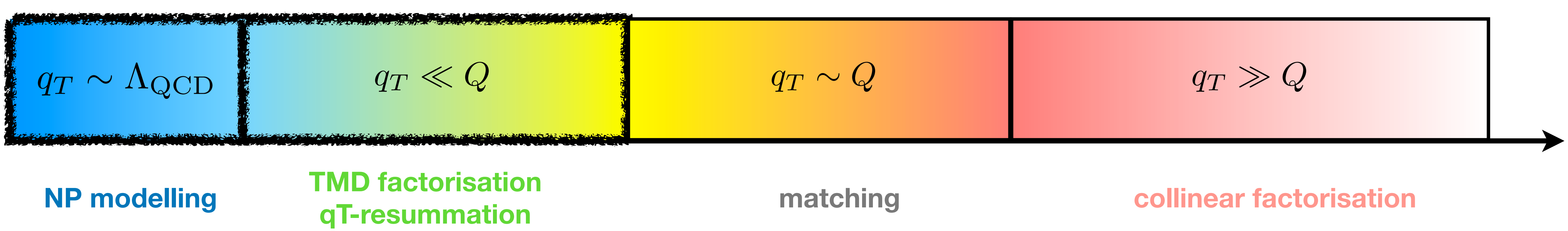
but

different flavour structure & different phase space available

⟶ *different Gaussian factors for different flavours*

$$e^{-g_a b_T^2}$$

Flavor and ~~kinematic~~ dependent widths



Flavour-dependent intrinsic-k_T

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Flavour-dependent intrinsic-k_T

$$\frac{d\sigma}{dq_T} \sim \text{FT}\ \exp\{-g b_T^2\}$$

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Flavour-dependent intrinsic-k_T

$$\frac{d\sigma}{dq_T} \sim \text{FT} \exp\{-g b_T^2\}$$

→ Fit to Z/γ* Tevatron data: $g \sim 0.8 \text{ GeV}^2$

[Guzzi, Nadolsky, Wang (2014)]

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Flavour-dependent intrinsic-k_T

$$\frac{d\sigma}{dq_T} \sim \text{FT}\,\exp\{-g b_T^2\}$$ $\longrightarrow$ Fit to Z/γ^* Tevatron data: $g \sim 0.8\ \text{GeV}^2$

[Guzzi, Nadolsky, Wang (2014)]

For each TMD: $0.4\ \text{GeV}^2 \sim g \longrightarrow g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) + g_a$

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Flavour-dependent intrinsic-k_T

$$\frac{d\sigma}{dq_T} \sim \text{FT} \exp\{-g b_T^2\} \longrightarrow$$ Fit to Z/γ^* Tevatron data: $g \sim 0.8\ \text{GeV}^2$

[Guzzi, Nadolsky, Wang (2014)]

For each TMD: $0.4\ \text{GeV}^2 \sim g \longrightarrow g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) + g_a$

Fit to SIDIS/DY/Z data: $g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) \in [0.17, 0.39]\ \text{GeV}^2$

[Bacchetta, Delcarro, Pisano, Radici, Signori (2017)]

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Flavour-dependent intrinsic-k_T

$$\frac{d\sigma}{dq_T} \sim \text{FT} \exp\{-g b_T^2\}$$ → Fit to Z/γ^* Tevatron data: $g \sim 0.8 \text{ GeV}^2$

[Guzzi, Nadolsky, Wang (2014)]

For each TMD: $0.4 \text{ GeV}^2 \sim g \longrightarrow g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) + g_a$ → *variation range for g_a*

Fit to SIDIS/DY/Z data: $g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) \in [0.17, 0.39] \text{ GeV}^2$

[Bacchetta, Delcarro, Pisano, Radici, Signori (2017)]

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Flavour-dependent intrinsic-k_T

$$\frac{d\sigma}{dq_T} \sim \text{FT} \exp\{-g b_T^2\}$$ ⟶ Fit to Z/γ^* Tevatron data: $g \sim 0.8$ GeV^2

[Guzzi, Nadolsky, Wang (2014)]

For each TMD: $0.4\ \text{GeV}^2 \sim g \longrightarrow g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) + g_a$ ⟶ *variation range for* g_a

Fit to SIDIS/DY/Z data: $g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) \in [0.17, 0.39]$ GeV^2

[Bacchetta, Delcarro, Pisano, Radici, Signori (2017)]

We consider :

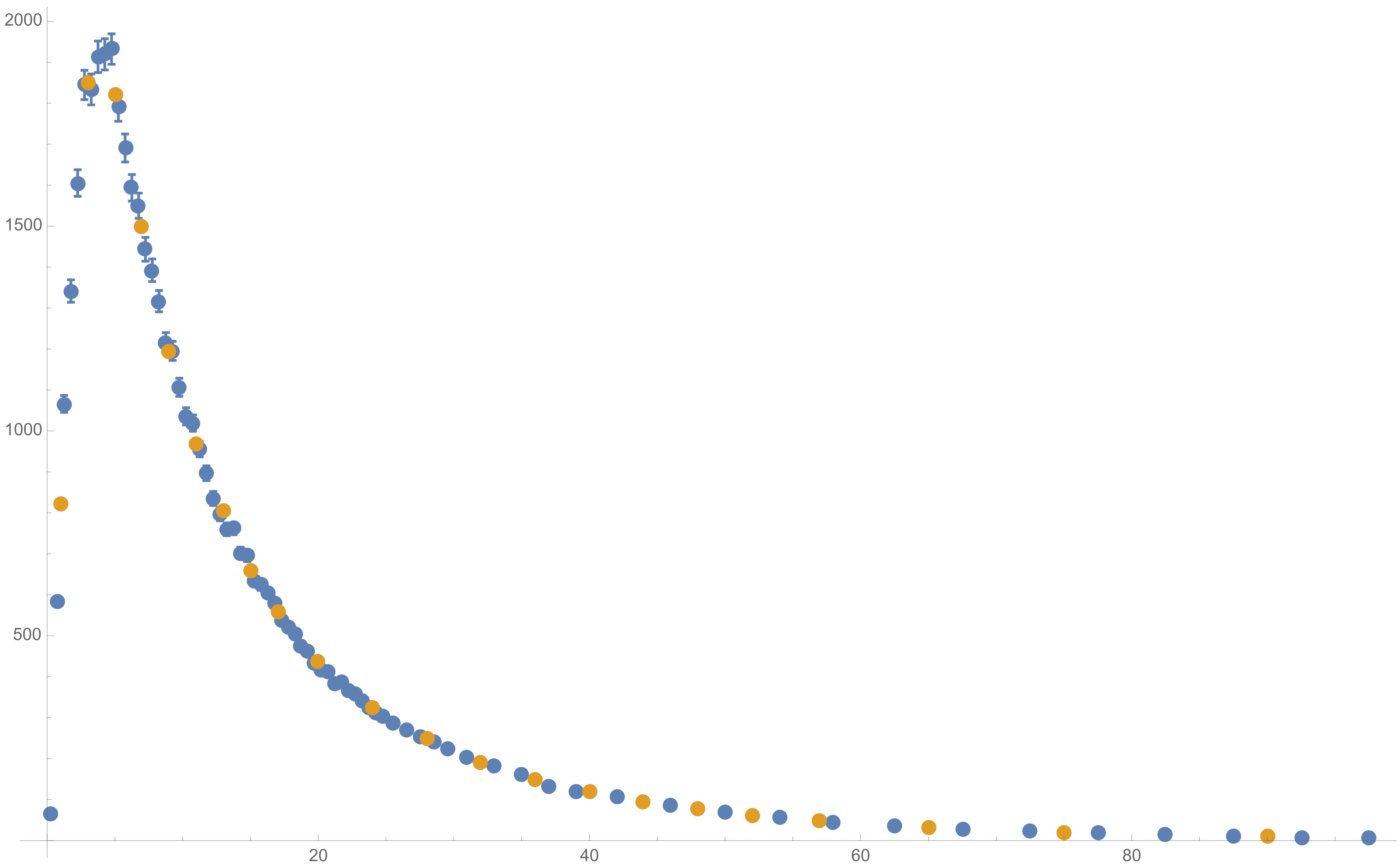
- **50 flavour-dependent sets** $\{g_{NP}^{u_v}, g_{NP}^{d_v}, g_{NP}^{u_s}, g_{NP}^{d_s}, g_{NP}^{s}\}$ with $g_{NP}^{a} \in [0.2, 0.6]$ GeV^2
- **1 flavour-independent set** with $g_{NP}^{a} = 0.4$ GeV^2

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

“Z-equivalent” sets

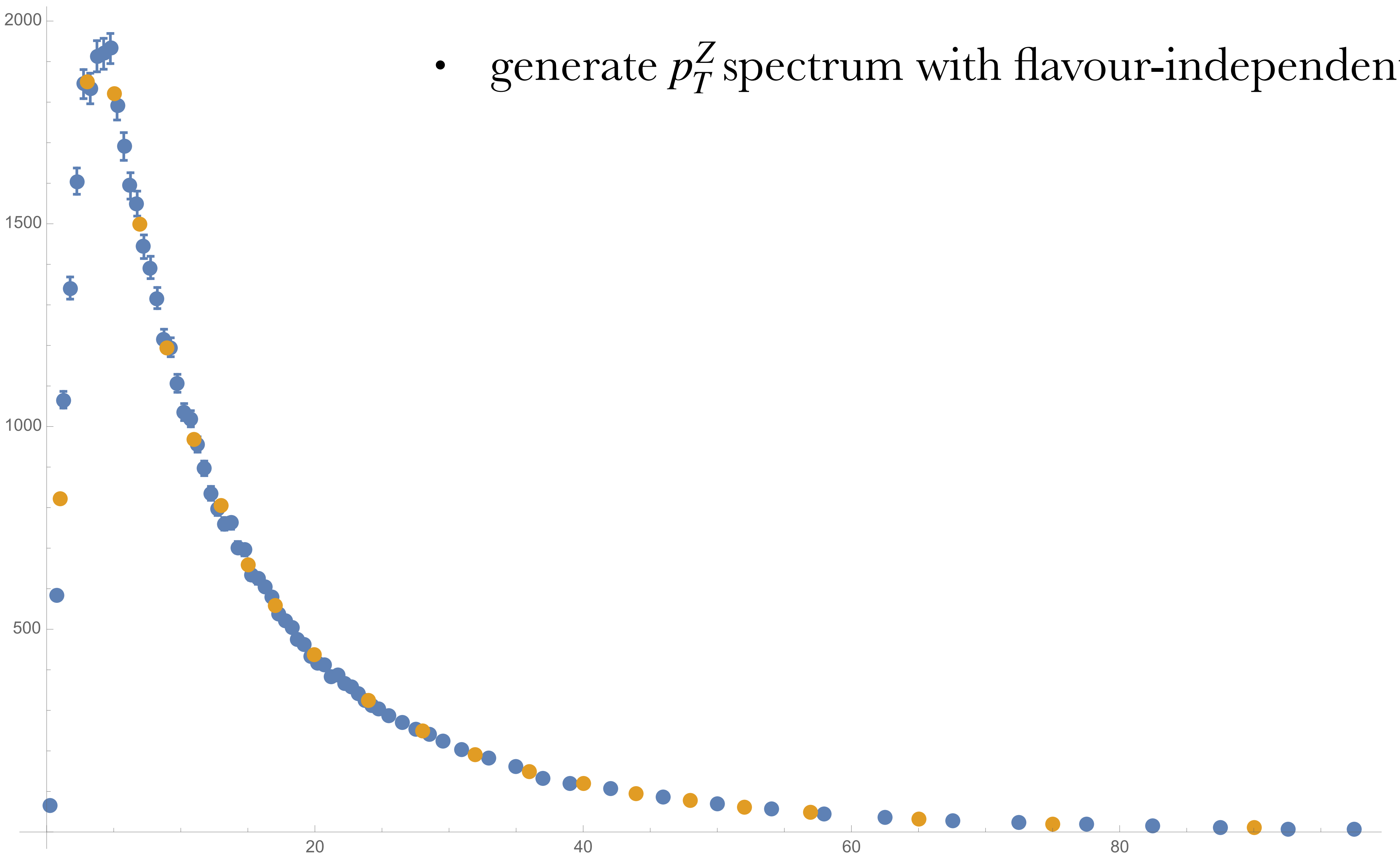
Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

“Z-equivalent” sets



Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

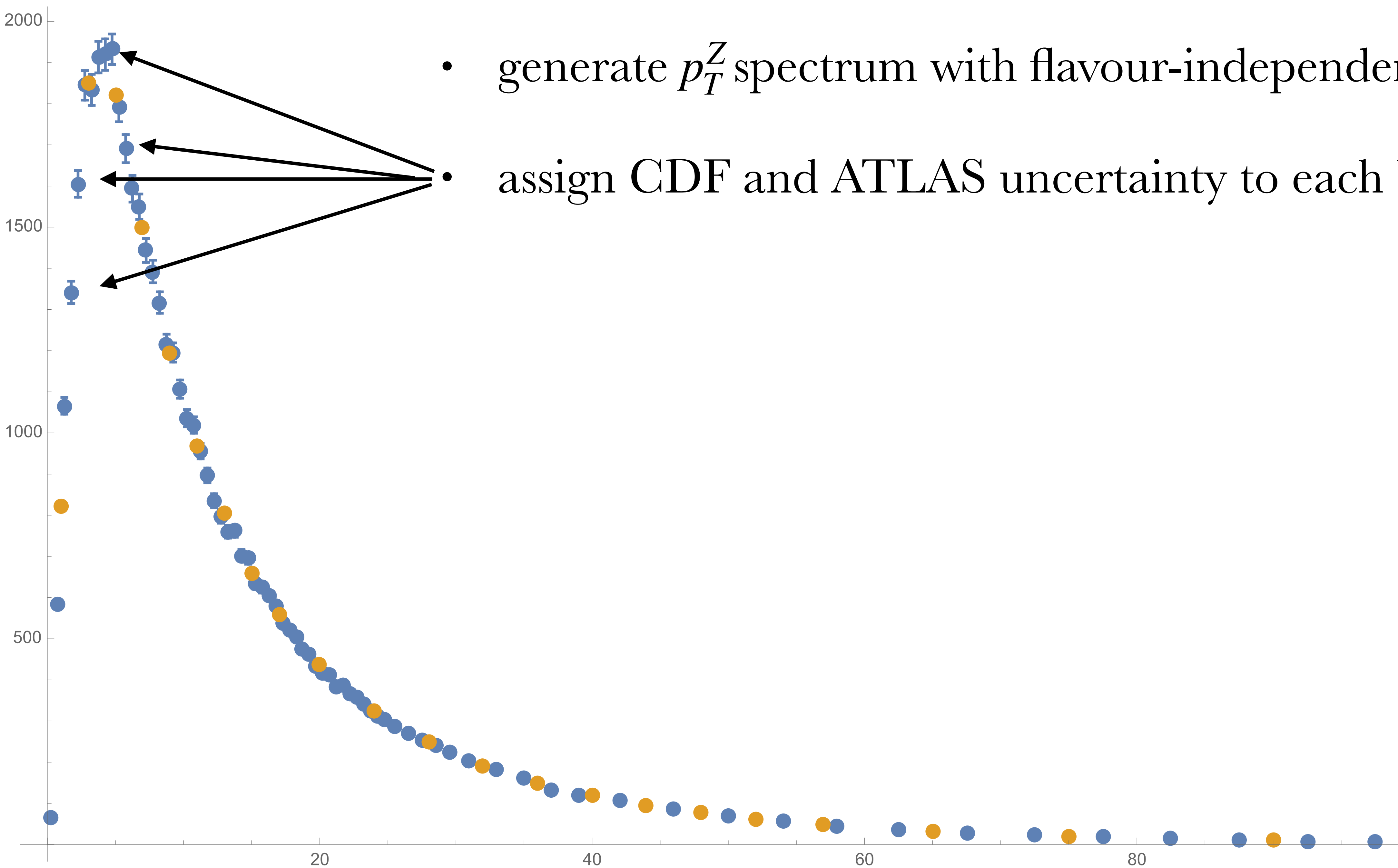
“Z-equivalent” sets



- generate p_T^Z spectrum with flavour-independent set

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

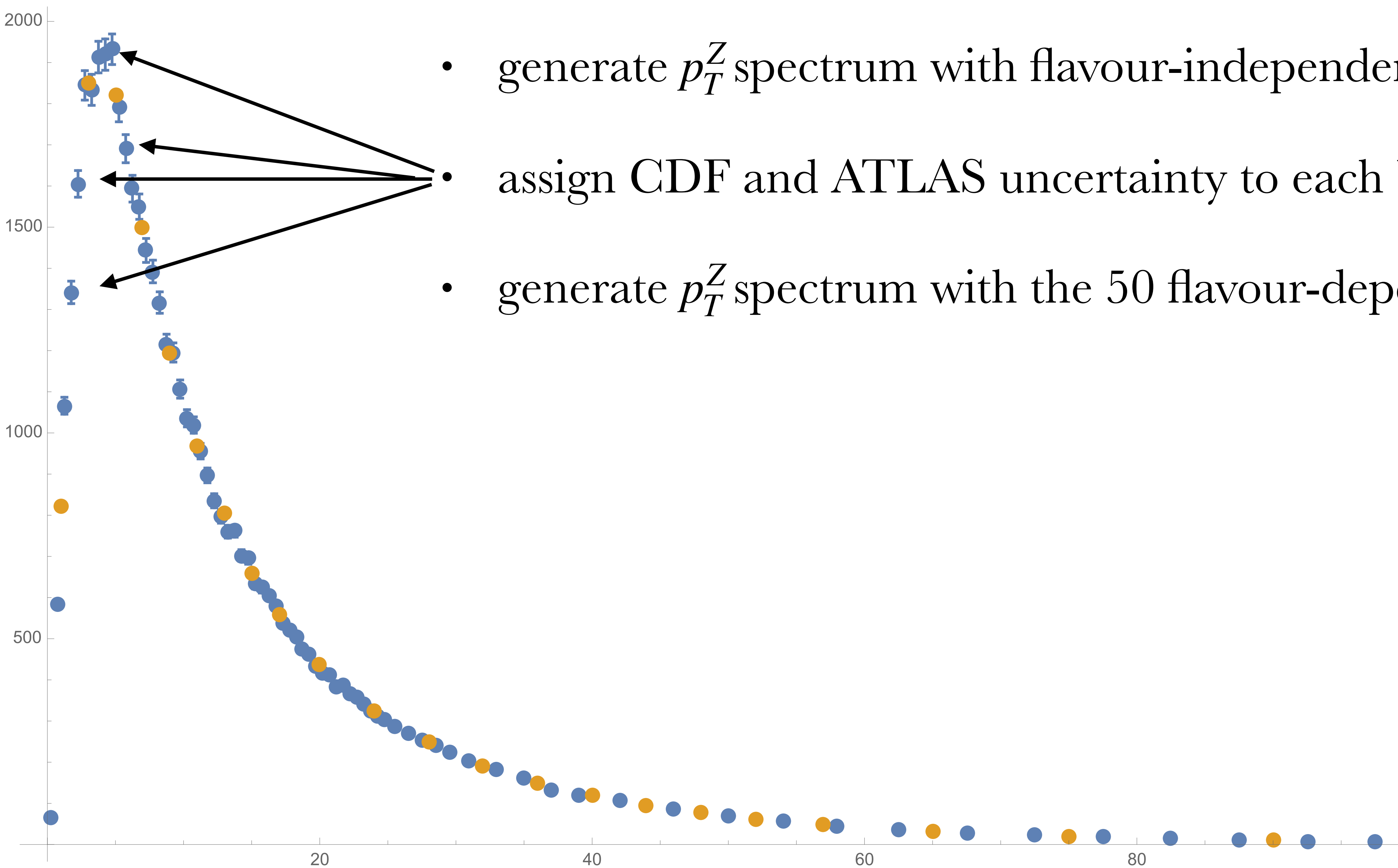
“Z-equivalent” sets



- generate p_T^Z spectrum with flavour-independent set
- assign CDF and ATLAS uncertainty to each bin

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

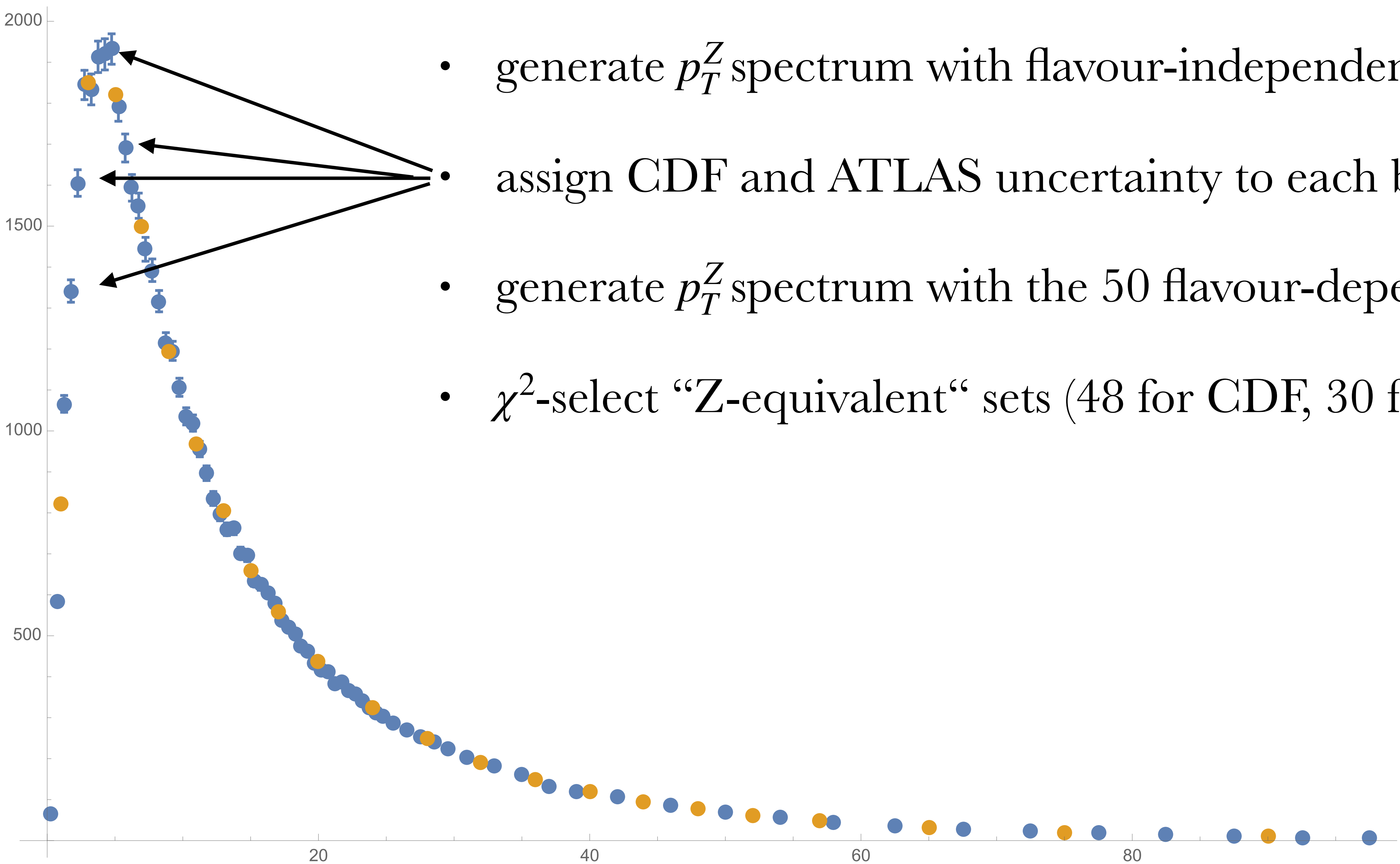
“Z-equivalent” sets



- generate p_T^Z spectrum with flavour-independent set
- assign CDF and ATLAS uncertainty to each bin
- generate p_T^Z spectrum with the 50 flavour-dependent sets

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

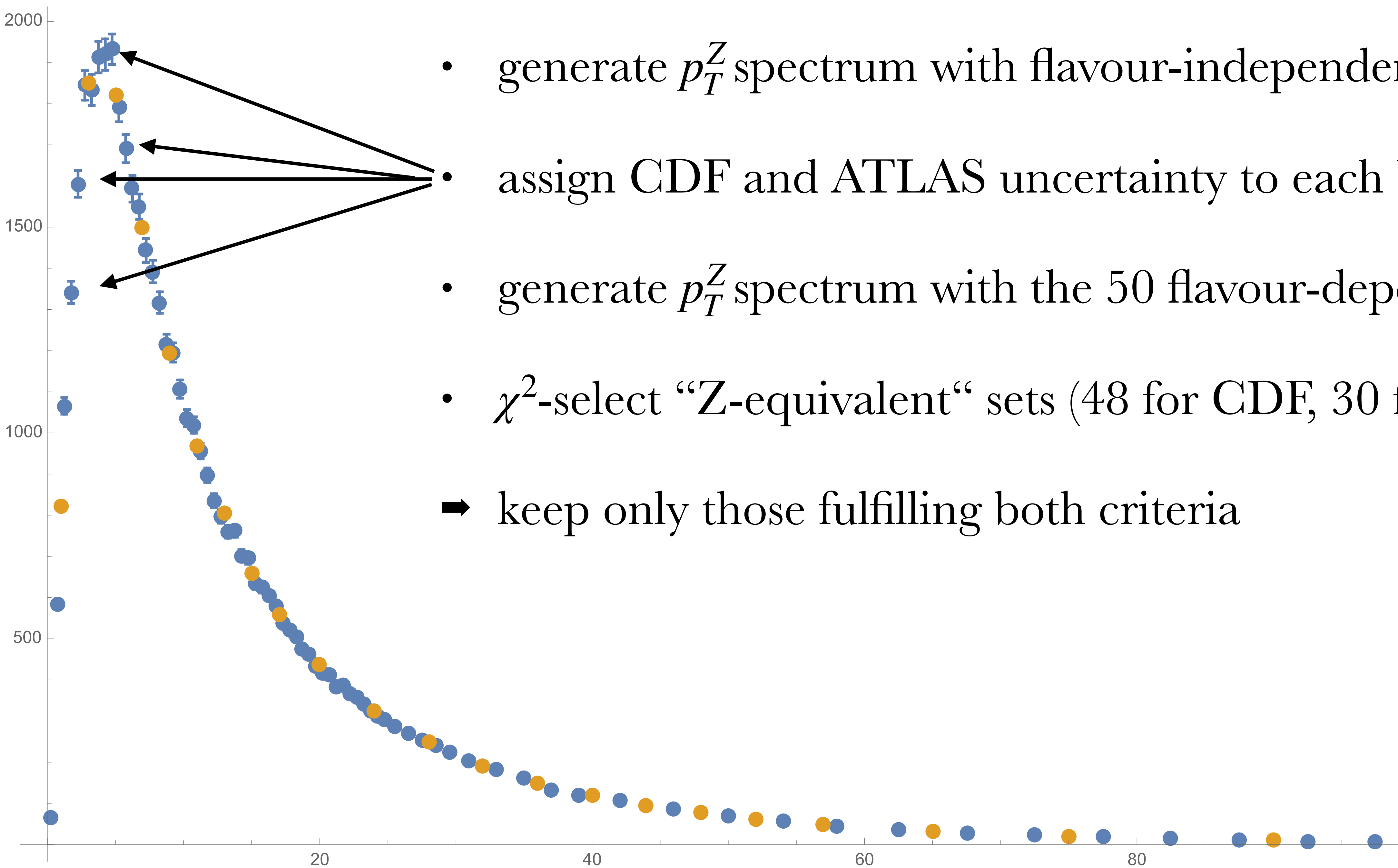
"Z-equivalent" sets



- generate p_T^Z spectrum with flavour-independent set
- assign CDF and ATLAS uncertainty to each bin
- generate p_T^Z spectrum with the 50 flavour-dependent sets
- χ^2-select "Z-equivalent" sets (48 for CDF, 30 for ATLAS)

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

“Z-equivalent” sets



- generate p_T^Z spectrum with flavour-independent set
- assign CDF and ATLAS uncertainty to each bin
- generate p_T^Z spectrum with the 50 flavour-dependent sets
- χ^2-select “Z-equivalent“ sets (48 for CDF, 30 for ATLAS)

➡ keep only those fulfilling both criteria

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

➡ **pseudodata**

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

  ➡ **templates**

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the “Z-equivalent” *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

  ➡ **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

  ➡ **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

	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

TABLE I: 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	-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

TABLE II: LHCb 13 TeV

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

Statistical uncertainty: 2.5 MeV

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

  ➡ **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

- transverse mass: zero or few MeV shifts, generally favouring lower values for W- (preferred by EW fit)

	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

TABLE I: 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	-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

TABLE II: LHCb 13 TeV

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

Statistical uncertainty: 2.5 MeV

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

  ➡ **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

- transverse mass: zero or few MeV shifts, generally favouring lower values for W- (preferred by EW fit)

- lepton pt: quite important shifts (envelope **up to 15 MeV**)

	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

TABLE I: 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	-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

TABLE II: LHCb 13 TeV

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

Statistical uncertainty: 2.5 MeV

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Impact on m_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T, p_T^l, p_T^ν distributions

  ➡ **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T, p_T^l, p_T^ν distributions for 30 different values of M_W

  ➡ **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

- transverse mass: zero or few MeV shifts, generally favouring lower values for W- (preferred by EW fit)

- lepton pt: quite important shifts (envelope **up to 15 MeV**)

- neutrino pt: same order of magnitude (or bigger) as lepton pt

	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

TABLE I: ATLAS 7 TeV

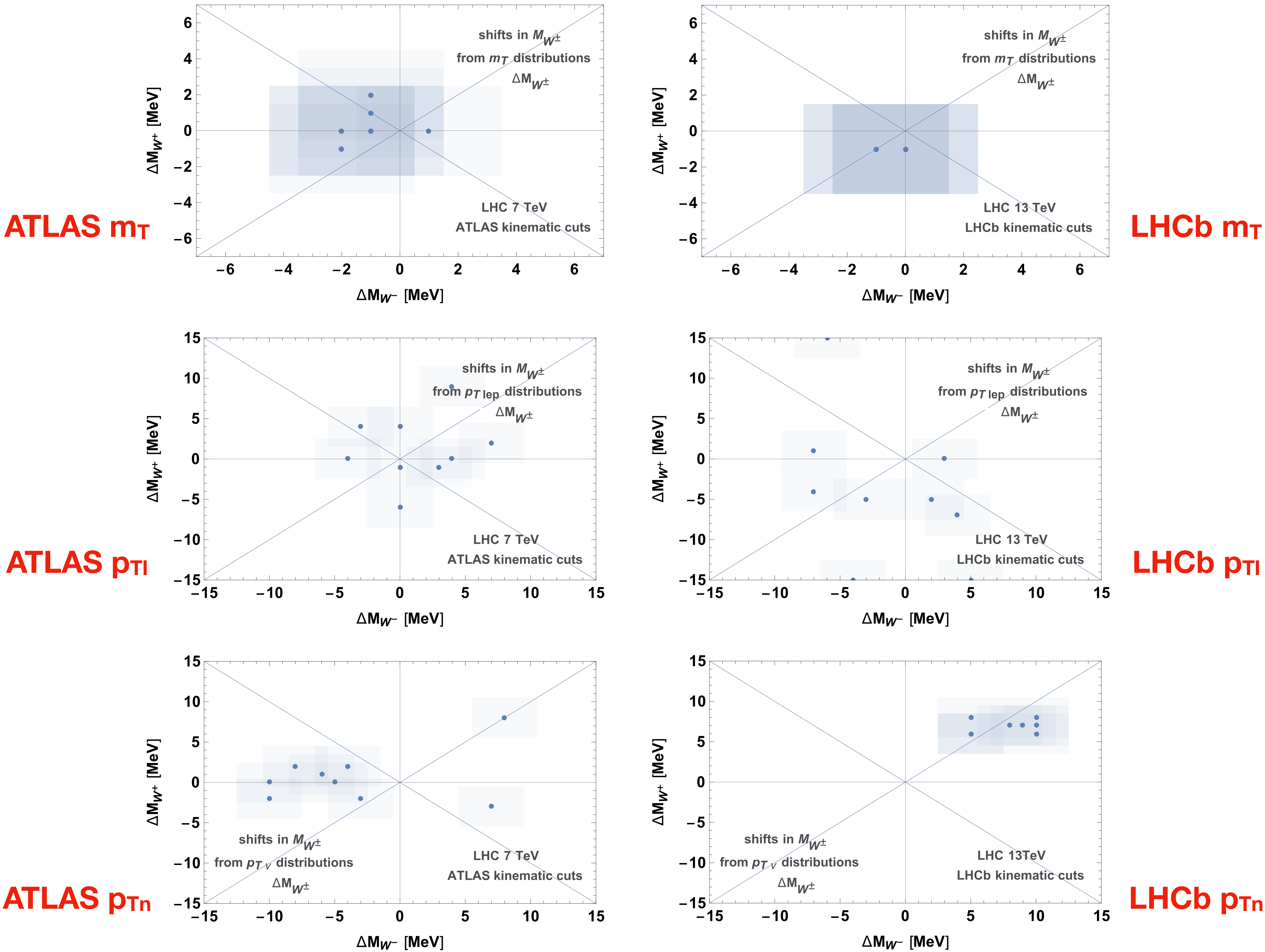
	ΔM_{W+}			ΔM_{W-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	-1	-5	7	-1	-3	8
2	-1	-15	6	0	5	10
3	-1	1	8	-1	-7	5
4	-1	-15	6	0	-4	5
5	-1	-4	6	-1	-7	5
6	-1	-5	7	0	2	9
7	-1	-15	6	-1	-6	5
8	-1	0	8	0	3	10
9	-1	-7	7	0	4	10

TABLE II: LHCb 13 TeV

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

Statistical uncertainty: 2.5 MeV

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)



ATLAS mT
shifts in $M_{W^\pm}$ from m_T distributions $\Delta M_{W^\pm}$
LHC 7 TeV
ATLAS kinematic cuts
LHCb mT
shifts in $M_{W^\pm}$ from m_T distributions $\Delta M_{W^\pm}$
LHC 13 TeV
LHCb kinematic cuts
ATLAS pTl
shifts in $M_{W^\pm}$ from $p_{T\,lep}$ distributions $\Delta M_{W^\pm}$
LHC 7 TeV
ATLAS kinematic cuts
LHCb pTl
shifts in $M_{W^\pm}$ from $p_{T\,lep}$ distributions $\Delta M_{W^\pm}$
LHC 13 TeV
LHCb kinematic cuts
ATLAS pTn
shifts in $M_{W^\pm}$ from $p_{T\,\nu}$ distributions $\Delta M_{W^\pm}$
LHC 7 TeV
ATLAS kinematic cuts
LHCb pTn
shifts in $M_{W^\pm}$ from $p_{T\,\nu}$ distributions $\Delta M_{W^\pm}$
LHC 13TeV
LHCb kinematic cuts
ΔM_{W^-} [MeV]
ΔM_{W^+} [MeV]