A new observable for W-mass determination

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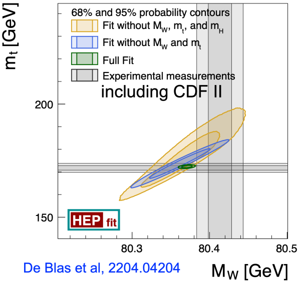
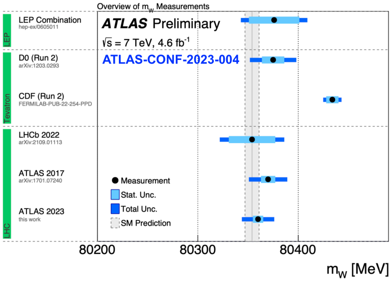
Based on: Rottoli, PT, Vicini, hep-ph/2301.04059

Role of M_W



De Blas et al, 2204.04204



- M_W fundamental SM parameter, input to global EW fits.
- Quantum corrections to M_W are sensitive to $M_{\rm top}$, M_H, allowing stringent SM tests.
- Aiming at 10^{-4} relative accuracy on its determination.
- Also in view of recent CDF result, need to assess accuracy of methodologies employed for M_W determination.

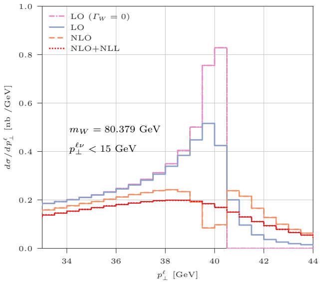
M_W determination at hadron colliders

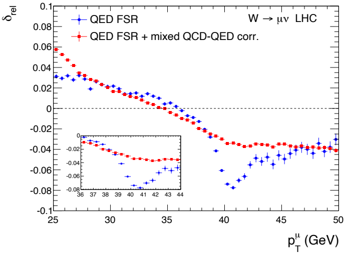
- M_W extracted from $pp \to \ell\nu$, charged-current DY (CCDY) at hadron colliders.
- In CCDY neutrino reconstruction possible in the transverse plane: p_t^ν inferred from $\not{E}_t$.
- Define relevant transverse observables: p_t^ℓ, and $M_t^{\ell\nu} = \sqrt{2\, p_t^\ell\, p_t^\nu (1 - \cos\Delta\phi^{\ell\nu})}$.
- p_t^ℓ and $M_t^{\ell\nu}$ spectra display a kinematical jacobian peak with position related to M_W:

$$\frac{d\sigma}{dp_t^\ell} \propto \frac{1}{\sqrt{1-(2\,p_t^\ell/\hat{s})^2}} \sim \frac{1}{\sqrt{1-(2\,p_t^\ell/M_W)^2}}$$

Jacobian-peak description

- Jacobian peak sensitive to a variety of effects.
- Soft radiation causes integrable singularity [Catani,Webber '97] at fixed order beyond LO at $p_t^\ell = M_W/2$.
- QCD resummation required. Significant progress [Chen et al., 2203.01565; Chen et al., 2205.11426; Campbell, Neumann 2207.07056; Camarda, Cieri, Ferrera, 2303.12781].

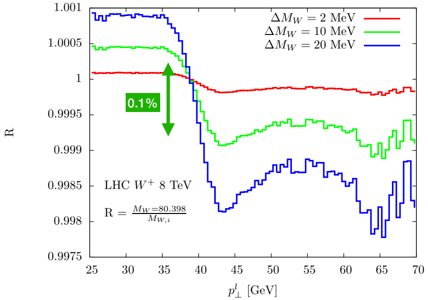




- Importance of QED FSR and mixed QCD-EW corrections at the jacobian peak (see e.g. [Carloni et al., 1612.02841]).
- Significant progress in mixed QCD-EW corrections at fixed order [Behring, et al. 2009.10386, 2103.02671; Buonocore et al. 2102.12539; Bonciani et al., 2106.11953; Armadillo et al. 2201.01754; Buccioni et al. 2203.11237], and with resummation [Cieri et al. 1805.11948; Autieri et al. 2302.05403].

Standard extraction of M_W from jacobian peak: template fitting

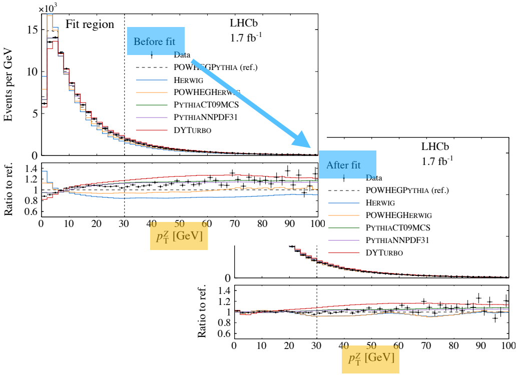
- Compute theoretical distributions for p_t^ℓ (or $M_t^{\ell\nu}$) with different hypotheses $M_{W,i}$ for the W mass (template distributions).
- Compare templates with exp. data in a fit window; calculate χ_i^2 for each $M_{W,i}$ hypothesis.
- Extract M_W as the $M_{W,i}$ hypothesis associated to the smallest χ_i^2.



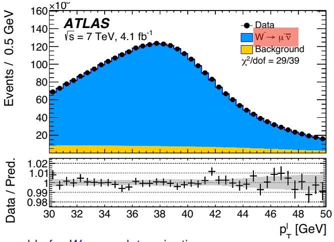
- Theory prediction must be close to data to get reasonable minimum χ^2.
- Need to control shapes at the permille level to resolve $\Delta M_W / M_W \sim 10^{-4}$.
- But: even most accurate QCD predictions for p_t^ℓ or $M_t^{\ell\nu}$ have uncertainties at the percent level (see e.g. [Chen et al., 2203.01565, Chen et al., 2205.11426; Neumann, Campbell 2207.07056]).

The role of tuning in template fits

- Procedure restored leveraging high-precision p_t^Z data in neutral-current Drell Yan (NCDY).
- (Low accuracy) event generators are calibrated to describe NCDY data.
- Tuning performed on parameters of a non-perturbative (NP) model, typically intrinsic k_t and shower NP scale p_{t0}.



- Same tuning parameters are used to prepare CCDY templates.
- After tuning, χ^2 of p_t^ℓ templates in CCDY is under control.



Concerns about template fitting

- Heavily reliant on tuning of parton showers. Dominated by NP physics, the least known.
- Assumes universality of NP model: should carefully assess uncertainty on information transfer from p_t^Z to CCDY p_t^ℓ.
- Higher-orders partly included via reweighing and partly mimicked by tuning. Significant progress in perturbative understanding of DY not fully exploited.
- χ^2 definition does not include scale uncertainties (non-statistical).

Robust assessment of theoretical uncertainties given up in template fitting.

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Robust assessment of theoretical uncertainties given up in template fitting.

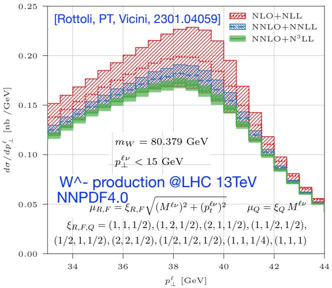
Aim: define a procedure allowing for a transparent discussion of M_W uncertainties.

Aim: minimise reliance on Z calibration when extracting M_W.

A new observable for M_W determination

p_t^ℓ distribution in CCDY

- p_t^ℓ spectrum at $\pm 2\%$ accuracy using accurate QCD predictions. N^{3}LL from RadISH [Bizon, Monni, Re, Rottoli, PT, '17,'18,'19,'21], NNLO from MCFM [Campbell, Ellis, Neumann].
- Including resummation cures integrable singularity: physical description of the jacobian peak.



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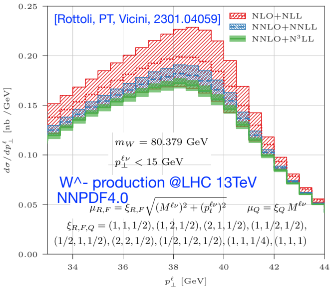
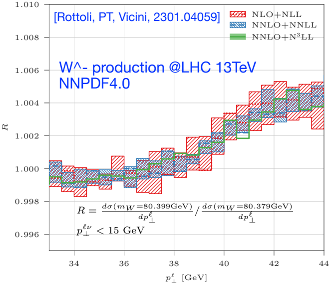


- Ratio of p_t^ℓ spectra with different M_W largely independent of QCD (resummed) approximation. Mild dependence only in uncertainty band.
- Sensitivity to M_W variations stems from W propagation and decay, factorised from QCD ISR.
- Which p_t^ℓ bins carry most of the sensitivity to M_W?



Covariance matrix w.r.t. M_W variations (I)

- Given N bins σ_i around the p_t^ℓ jacobian peak, their sensitivity to M_W can be quantified by constructing a covariance matrix

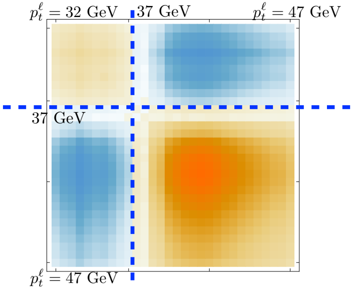
$$\mathcal{C}_{ij}^{(M_W)} = \langle \sigma_i \, \sigma_j \rangle - \langle \sigma_i \rangle \langle \sigma_j \rangle \, , \qquad \langle x \rangle = \frac{1}{p} \sum_{k=1}^{p} x_{(k)} \, ,$$

  where p is the number of M_W hypotheses considered.

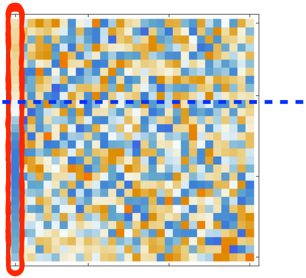
- Diagonalisation of $\mathcal{C}^{(M_W)}$ gives N orthogonal p_t^ℓ-bin combinations (eigenvectors).

- Corresponding eigenvalues represent the sensitivity of eigenvectors to M_W variations.

Covariance matrix w.r.t. M_W variations (II)



Covariance @ NNLO+N3LL central scales



Covariance eigenvectors

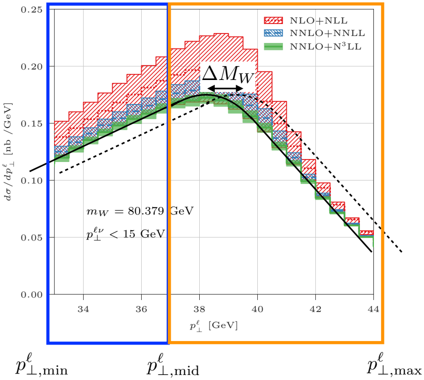
- First eigenvalue dominates (Eigen[1]/Tr[COV] $\sim$ 99%): bulk of M_W sensitivity captured by a single bin combination.
- Indeed the dominant effect of ΔM_W is just to rigidly shift the spectrum by $\Delta M_W/2$.
- Define a simple observable as a proxy for the dominant eigenvector (i.e. positive coeffs. below $\sim$ 37 GeV, negative above): jacobian asymmetry.

The jacobian asymmetrty $\mathcal{A}_{p_t^\ell}$

$$\mathcal{A}_{p_t^\ell}(p^\ell_{\perp,\mathrm{min}}, p^\ell_{\perp,\mathrm{mid}}, p^\ell_{\perp,\mathrm{max}}) \equiv \frac{L-U}{L+U}$$

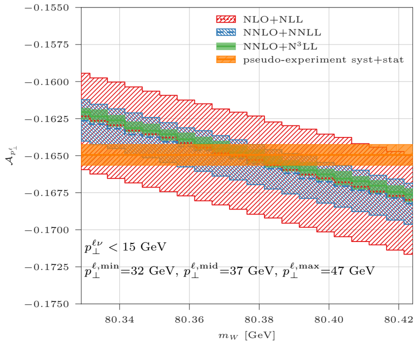
$$L \equiv \int_{p^\ell_{\perp,\mathrm{min}}}^{p^\ell_{\perp,\mathrm{mid}}} dp_t^\ell \, \frac{d\sigma}{dp_t^\ell}$$

$$U \equiv \int_{p^\ell_{\perp,\mathrm{mid}}}^{p^\ell_{\perp,\mathrm{max}}} dp_t^\ell \, \frac{d\sigma}{dp_t^\ell}$$



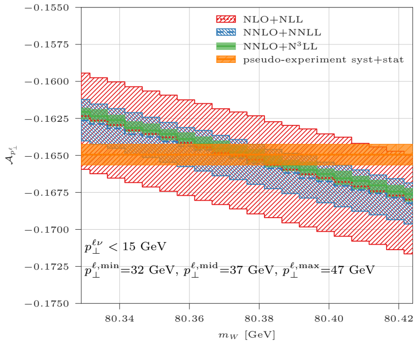
- L = sum of bins below $\sim$ 37 GeV, with $+1$ coeff; $-U$ = sum of bins above, with -1 coeff. Mimicking the dominant covariance eigenvector.
- Simple observable constructed as combination of fiducial rates in relatively wide p_t^ℓ bins.
- A single scalar number depending only on the bin edges, measurable via counting.

$\mathcal{A}_{p_t^\ell}$ sensitivity to M_W (I)



- $+\Delta M_W$ shifts jacobian peak by $+\Delta M_W/2$, depleting L and populating U: asymmetry decreases linearly if $p^\ell_{\perp,\mathrm{mid}}$ at the left of the peak.
- Slope independent of QCD approx./scale: reflecting factorisation of QCD production from M_W-sensitive propagation/decay.
- Expected to carry over to NP QCD.
- Slope related to the magnitude of the first covariance eigenvalue.
- Slope depends on the value of the bin edges [$p^\ell_{\perp,\min}$, $p^\ell_{\perp,\mathrm{mid}}$, $p^\ell_{\perp,\max}$].

$\mathcal{A}_{p_t^\ell}$ sensitivity to M_W (II)



$\mathcal{A}_{p_t^\ell}$ = combination of fiducial rates.

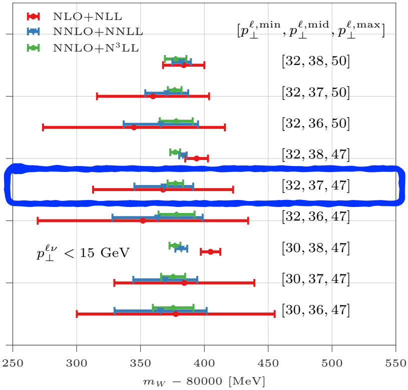
- Excellent perturbative QCD convergence.
- Importance of higher-order results for high-accuracy prediction.

$\mathcal{A}_{p_t^\ell}$ = based on wide p_t^ℓ bins $\mathcal{O}$(5-10 GeV).

- Small stat./syst. experimental errors.
- Viability to unfold detector effects: combination of different experimental M_W determinations.

- M_W simply extracted as the intersection of theoretical and experimental lines.
- $\Delta M_W \sim \pm 15$ MeV from asymmetry measurement seems feasible experimentally. (Estimated assuming 0.1% error on the measurement of L and U and no correlation. Statistical error $\sim$ 10 times smaller already with $\mathcal{L} = 140$ fb^{-1})

$\mathcal{A}_{p_t^\ell}$ dependence on p_t^ℓ bin edges



- Perturbative convergence generally very well behaved.
- Importance of including N^{3}LL to assess quality of perturbative convergence. Perturbative stability checked beyond mere scale variation.
- Some trade-off between sensitivity (improving at higher $p^\ell_{\perp,\mathrm{mid}}$) and perturbative convergence (improving at lower $p^\ell_{\perp,\mathrm{mid}}$).
- $\Delta M_W \sim \pm 5$ MeV from perturbative QCD achievable based on CCDY alone.

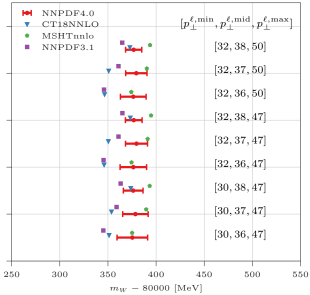
Including further effects

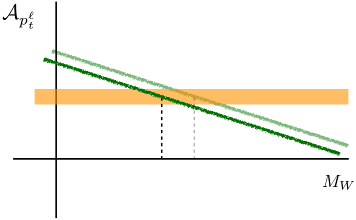
Preliminary study only dealt with perturbative QCD.

Starting point for a complete quantitative assessment of contributions sensitive to M_W and their theoretical uncertainty.

- Impact of PDFs.
- Impact of NP QCD modelling.
- QED and mixed QCD-EW perturbative corrections.
- Systematic covariance studies to include effects beyond asymmetry.
- ...

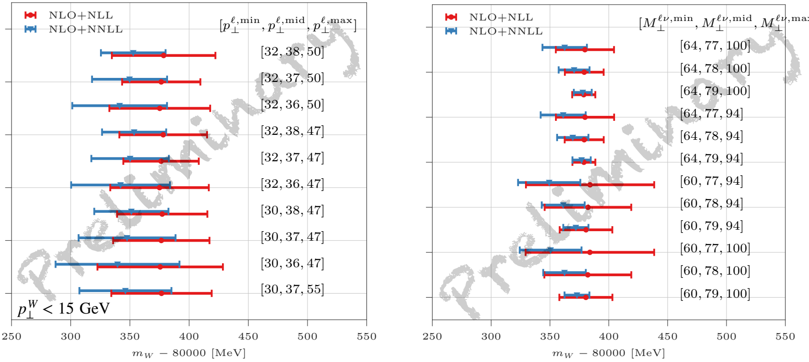
Impact of PDF choice on jacobian asymmetry





- Variations from 100 NNPDF4.0 NNLO replicas on NLO+NLL result: $\Delta M_W \sim \pm 12$ MeV.
- Spread from 3 other PDF sets (central replica) on N3LL+NNLO result: $\Delta M_W \sim 30$ MeV.
- Asymmetry slope unaffected: factorisation of initial-state effects from W propagation/decay.
- PDF spread can be reduced to few MeV using additional p_t^ℓ bins, anti-correlation of different rapidity windows [Bozzi, Citelli, Vesterinen, Vicini, '15; Bagnaschi, Vicini, '19], combination of W^+ and W^-.

Tevatron check



- $\Delta M_W \gtrsim \pm 30$ MeV (± 10 MeV) at the Tevatron using p_t^ℓ ($M_t^{\ell\nu}$) NLO+(N)NLL QCD (the ResBos accuracy [Balazs, Yuan, '97; Landry, Brock, Nadolsky, Yuan, '03]).
- To be compared with $\mathcal{O}(\pm 2$ MeV) perturbative-model uncertainties quoted by CDF II, see also [Isaacson, Fu, Yuan, 2205.02788].

Outlook

Study of theoretical uncertainties problematic with a template-fit procedure to M_W extraction.

Calibration on data improves the accuracy of data description, not the precision of the model.

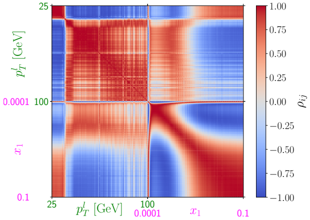
Jacobian asymmetries $\mathcal{A}_{p_t^\ell}$ and $\mathcal{A}_{M_t^{\ell\nu}}$ can help discussion of uncertainties.

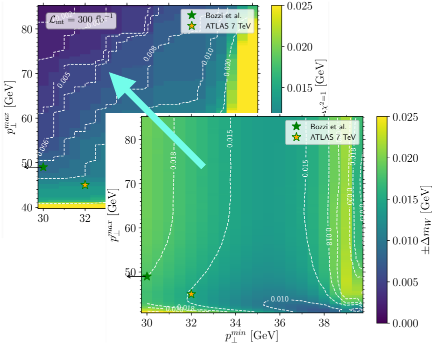
- Capturing most of the sensitivity to M_W (covariance): visible linear dependence on M_W.
- Excellent perturbative QCD stability and accuracy.
- Experimental statistical and systematic errors under control $\rightarrow$ precision measurement.
- Viability to unfold data to particle level $\rightarrow$ global experimental combination.
- Systematic assessment of all sources of sensitivity to M_W: PDF, NP, EW, ...

Thank you for your attention

Backup

Taming PDF uncertainties with additional p_t^ℓ bins [Bagnaschi, Vicini, 1910.04726]





- Strong anti-correlation under PDF variations between p_t^ℓ regions below/above jacobian peak.
- Take PDF correlations into account directly in the definition of χ^2:

$$\chi_i^2 = \sum_{r,s\,\in \mathrm{bins}} \left(\mathcal{T}^i - \mathcal{D}^{\rm exp}\right)_r \left(C^{-1}\right)_{rs} \left(\mathcal{T}^i - \mathcal{D}^{\rm exp}\right)_s$$

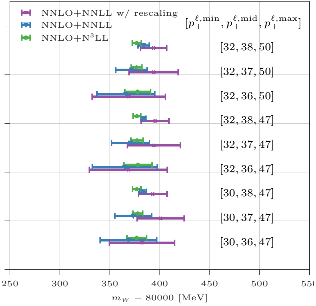
$$C = \Sigma_{\rm pdf} + \Sigma_{\rm stat} + \Sigma_{\rm mc} + \Sigma_{\rm exp}^{\rm syst}$$

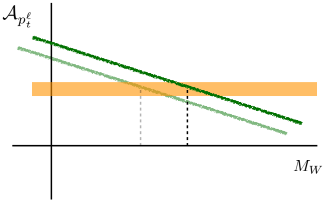
$$(\Sigma_{\rm pdf})_{rs} = \langle \mathcal{T}_r^i\, \mathcal{T}_s^i \rangle_{\rm pdf} - \langle \mathcal{T}_r^i \rangle_{\rm pdf}\, \langle \mathcal{T}_s^i \rangle_{\rm pdf}$$

- Correlation leads to profiling of PDF replicas $\rightarrow$ significant reduction of PDF uncertainty w.r.t. the case with no PDF covariance, at the few-MeV level.

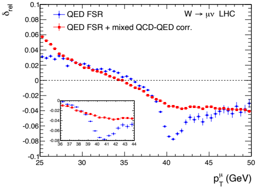
Toy study on the effect of calibration to Z production

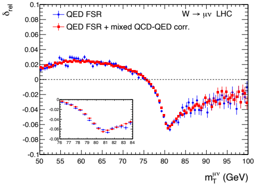
- Compute NNLO+NNLL NCDY p_t^Z reweighing factors to match NCDY 'data' (NNLO+N^{3}LL central), mimicking tuning.
- One reweighing factor per scale choice to estimate how perturbative QCD uncertainty propagates in the tuning procedure.
- Apply rwg factors to NNLO+NNLL CCDY $p_t^{\ell\nu}$ spectrum; compare with CCDY 'data' (NNLO+N^{3}LL central).
- p_t^ℓ after reweighing agrees better with CCDY 'data', but maintain some shape difference: delicate to assume that $p_t^{\ell\nu}$ rescaling applies equally well to p_t^ℓ.
- ΔM_W similar with and without reweighing: starting point for tuning should be the highest available perturbative order to minimise systematics in the Z to W transfer.
- NP = additional effect to asymmetry calculation (slope unaffected), not the central ingredient of M_W extraction, as for template fitting.

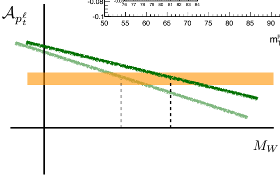




Importance of EW effects







- Significant effects from QED FSR and from mixed QCD-EW corrections at the jacobian peak for p_t^ℓ (see e.g. [Carloni, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, Vicini, 1612.02841]).
- Effects only from QED FSR at the jacobian peak for $M_t^{\ell\nu}$.
- QED FSR affect both asymmetry value and slope.
- Smearing of p_t^ℓ distribution expected, leading to slight M_W-sensitivity loss.

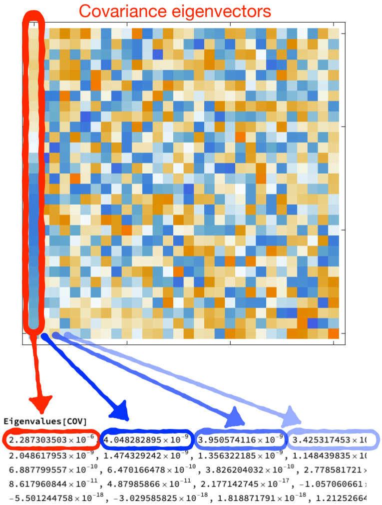
EW effects at the jacobian peak [Carloni, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, Vicini, 1612.02841]

$p\bar{p} \to W^+$, $\sqrt{s} = 1.96$ TeV Templates accuracy: NLO-QCD+QCD$_{PS}$ Pseudodata accuracy	QED FSR	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$(dres) M_T	 p_T^ℓ
1 NLO-QCD+(QCD+QED)$_{PS}$	PYTHIA	-91±1	-308±4	-37±1	-116±4
2 NLO-QCD+(QCD+QED)$_{PS}$	PHOTOS	-83±1	-282±4	-36±1	-114±3
3 NLO-(QCD+EW)-two-rad+(QCD+QED)$_{PS}$	PYTHIA	-86±1	-291±3	-38±1	-115±3
4 NLO-(QCD+EW)-two-rad+(QCD+QED)$_{PS}$	PHOTOS	-85±1	-290±4	-37±2	-113±3

$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$ M_T	 p_T^ℓ
1 HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2 HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3 HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4 HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5 PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

- EW effects induce a smearing of the jacobian peak, shifting the extracted M_W.
- Leading effect from QED FSR, extra few-MeV shifts from subleading EW effects.
- Quantitatively, EW impact depends on the underlying QCD model: importance to include EW effects on top of an accurate QCD prediction.
- Significant progress in calculation of QCD-EW corrections at fixed order [Behring, et al. 2009.10386, 2103.02671; Buonocore et al. 2102.12539; Bonciani et al., 2106.11953; Armadillo et al. 2201.01754; Buccioni et al. 2203.11237], and in resummation [Cieri et al. 1805.11948; Autieri et al. 2302.05403].

Covariance studies beyond jacobian asymmetry



- Effect of ΔM_W on p_t^ℓ is a shift: sensitivity to M_W mainly encoded in primary eigenvector ($\sim$ asymmetry) representing translations (Eigen[1]/Tr[COV] $\sim$ 0.99).
- Secondary eigenvalues extremely suppressed
- Covariance allows systematic classification of eigenvectors according to M_W sensitivity.
- Secondary eigenvectors can be separately analysed (if need be) and included once their perturbative stability is established.
- Not possible with template fitting, all secondary eigenvectors lumped with the first: very little gain in sensitivity at the price of much more noisy analysis.