Electroweak corrections to Drell-Yan processes and M_W determination

Mauro Chiesa

INFN Pavia

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M_W at hadron colliders

Template fit procedure:

1. measure a relevant distribution (P_{T}^{l}, $M_T^{l\nu}$)
2. generate several Monte Carlo samples with different M_W (templates)
3. the measured M_W corresponds to the sample that best fits to the data

Monte Carlo simulations are affected by perturbative (radiative corrections) and non-perturbative (i.e. PDFs, p_{T}^{W} modelling) theoretical uncertainties

$$\Downarrow$$

these theory uncertainties propagate to M_W measurement

Theoretical uncertainties in M_W measurement: strategy

Theory uncertainties from weak and mixed QCD-EW corrs studied in Carloni Calame et al. arXiv:1612.02841

1. pseudodata
   - Monte Carlo samples with a given theoretical accuracy
   - play the role of experimental data
2. templates
   - MC samples at NLO QCD+QCD-PS (or LO) generated for different values of M_W
   - will be fitted to the pseudodata
3. $\Delta M_W = M_W(\text{pseudodata}) - M_W(\text{fit output})$

Theory uncertainties in M_W measurement: event generators

- HORACE (Carloni Calame et al. hep-ph/0303102, hep-ph/050626)
  - MC event generator for DY
  - can generate events at NLO EW+QED-PS, and NLO EW+QED-PS+unresolved l^+l^- radiation

- POWHEG-BOX-V2/W_ew-BMNNP (Barze et al. arXiv:1202.0465)
  - MC event generator for charged DY
  - can generate events at NLO QCD+QCD-PS and NLO (QCD+EW)+(QCD+QED)-PS
  - relies on external shower MC programs (i.e. PYTHIA, PYTHIA+PHOTOS)

Theory unc. in M_W measurement: shower MC tools)

- PYTHIA (Sjostrand et al. hep-ph/0603175; arXiv:0710.3820)
  - general purpose shower MC generator
  - can generate multiple QCD and QED radiation
  - used for ISR multiple QCD (and QED) radiation AND non-perturbative QCD effects
  - in some runs used for QED FSR (see later)
- PHOTOS (Barberio et al. CPC 66 (1991), CPC 79 (1994), Golonka et al. hep-ph/0506026)
  - general purpose shower MC generator
  - can generate multiple QED radiation off fermions (from W decay)
  - in some runs used for QED FSR (see later)
- HORACE (has its own implementation of QED PS algorithm)

Theoretical uncertainties in M_W measurement: notation

- NLO EW corrections: $d\sigma = d\sigma_0 \left[1 + \delta_\alpha\right]$

- QED-PS: all order γ radiation in leading log approx.

  $$d\sigma = d\sigma_0 \left[1 + \sum_{n=1}^{\infty} \delta'_{\alpha^n}\right]$$

- NLO EW+QED-PS: $d\sigma = d\sigma_0 \left[1 + \delta_\alpha + \sum_{n=2}^{\infty} \delta'_{\alpha^n}\right]$

  matching replaces first PS radiation with NLO real radiation

- HORACE NLO EW+QED-PS: $d\sigma = d\sigma_0 \left[1 + \delta_\alpha + \sum_{n=2}^{\infty} \delta'_{\alpha^n}\right]$

- POWHEG NLO (QCD+EW)+(QCD+QED)-PS:

  $$d\sigma = d\sigma_0 \left[1 \ + \ \delta_{\alpha_s} + \delta_\alpha + \sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n}\right]$$

Mixed QCD-EW corrections (1)

$pp \to \mu^+\nu_\mu$, fit to $M_\mathrm{T}(\mu^+\nu_\mu)$

	Templates	Pseudodata	M_W shifts (MeV)
1	LO	POWHEG(QCD) NLO	56.0 $\pm$ 1.0
2	LO	POWHEG(QCD)+PYTHIA(QCD)	74.4 $\pm$ 2.0
3	LO	HORACE(EW) NLO	-94.0 $\pm$ 1.0
4	LO	HORACE (EW,QEDPS)	-88.0 $\pm$ 1.0
5	LO	POWHEG(QCD,EW) NLO	-14.0 $\pm$ 1.0
6	LO	POWHEG(QCD,EW) `two-rad`+PYTHIA(QCD)+PHOTOS	-5.6 $\pm$ 1.0

	samples	M_W shift (MeV)
$\sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n}$	[6]-[5]	8.4 ± 1.4 MeV
$\sum_{m=2}^{\infty} \delta'_{\alpha_s^m}$	[2]-[1]	18.4 ± 2.2 MeV
$\sum_{n=2}^{\infty} \delta'_{\alpha^n}$	[4]-[3]	6.0 ± 1.4 MeV

$\sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n}$=([6]-[5])-([2]-[1])-([4]-[3])=-16.0$\pm$3.0 MeV

in agreement with the results of Dittmaier et al. 1511.08016 for the full $\mathcal{O}(\alpha\alpha_\mathcal{S})$ corrections in pole approx. (-14 MeV)

Mixed QCD-EW corrections (2)

see also next talk

- mixed QCD-EW corrections from POWHEG $\sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n}$
  - factorized approx
  - spurious H.O. effects $(\mathrm{PS} \times \Delta \times \overline{B})$
- another estimate including exact $\mathcal{O}(\alpha\alpha_S)$ IS corrections in Behring et al. arXiv:2103.02671

$$m_W^{\mathrm{meas}} = \frac{\langle p_\perp^{l,W} \rangle^{\mathrm{meas}}}{\langle p_\perp^{l,Z} \rangle^{\mathrm{meas}}} \, m_Z \, C_{\mathrm{th}}, \qquad C_{\mathrm{th}} = \frac{m_W}{m_Z} \frac{\langle p_\perp^{l,Z} \rangle^{\mathrm{th}}}{\langle p_\perp^{l,W} \rangle^{\mathrm{th}}}, \qquad \frac{\delta m_W^{\mathrm{meas}}}{m_W^{\mathrm{meas}}} = \frac{\delta C_{\mathrm{th}}}{C_{\mathrm{th}}}$$

- Full $\mathcal{O}(\alpha\alpha_S)$ (arXiv:2102.12539,arXiv:2201.01754): it would be nice to study their impact on M_W extraction
  - per se
  - to asses the uncertainties coming from the factorized approach in MC generator at NLO QCD+NLO EW with PS matching (e.g. W_ew-BMNNP in POWHEG)

$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{\mathrm{PS}}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Photos	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$two-rad	Pythia	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$two-rad	Photos	-88.6±0.6	-370±3	-39.2±0.6	-159±2

- dressed e: recombine γ with e if $\Delta R(\gamma e) < 0.1$
- bare μ: corrections enhanced by logs $\alpha \log(\frac{m_\mu^2}{Q^2})$

Theory uncertainties from QED PS (1)

	$pp \to W^+$, $\sqrt{s} = 14$ TeV		M_W shifts (MeV)			
	Templates accuracy: NLO-QCD+QCD$_{\rm PS}$		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
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- difference between QED-PS in PHOTOS and PYTHIA at $\mathcal{O}(\alpha)$
- PHOTOS $\propto \frac{1}{1-\beta\cos\theta_{l\gamma}}$
- PYTHIA -QED $\propto \frac{1}{p_{\rm T}^{\gamma}}$
- 32 MeV ($p_{\rm T}$)/ 7 MeV ($M_{\rm T}$) effect for bare μ

Theory uncertainties from QED PS (2)

	$pp \to W^+$, $\sqrt{s} = 14$ TeV		M_W shifts (MeV)			
	Templates accuracy: NLO-QCD+QCD$_{\rm PS}$		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
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- first QED radiation generated by Powheg
- difference between QED-PS in Photos and Pythia at $\mathcal{O}(\alpha^2)$

Theory uncertainties from QED PS (3)

Theory uncertainties from QED PS estimated from the difference in the shifts from PYTHIA and PHOTOS

- might be an overestimate (photon spectrum suggests that PHOTOS is more accurate)
- comparison should be extended to other QED PS: HERWIG, SHERPA, ...
- how would the shifts charge if a QED PS beyond LL accuracy was used?

non-log QED, weak and mixed EW-QCD contributions (1)

$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{\mathrm{PS}}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
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- impact of non-log QED, weak and mixed EW-QCD contributions
- different effects for PHOTOS or PYTHIA (different non-log QED terms)
- more stable results for M_{T} (less sensitive to mixed EW-QCD corrections)

non-log QED, weak and mixed EW-QCD contributions (2)

$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{\mathrm{PS}}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-95.2±0.6	-400±3	-38.0±0.6	-149±2
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ATLAS collaboration at LHC use as templates
Powheg-QCD+Pythia-QCD+Photos

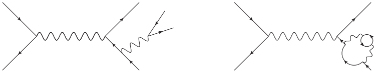
uncertainties from
non-log QED,
weak,
mixed QCD-EW corr.

		ΔM_W (MeV) bare muons	
	QED FSR model	M_T	p_T^ℓ
LHC	Pythia	+6.2 ± 0.8	+29 ± 4
	Photos	-0.6 ± 0.8	-2 ± 4

non-log QED, weak and mixed EW-QCD contributions (3)

- QED, WEAK, and mixed effects inevitably have an interplay with IS QCD effects (e.g. $\mathrm{PS} \times \overline{B}$)
- in our simulation we only used PYTHIA8 for ISR QED and QCD shower and non-perturbative effects with a default PYTHIA tuning
- how do the shifts change if we use another shower MC, say HERWIG?
- how do the estimates change when changing the PYTHIA tune? (having in mind the ATLAS procedure of tuning PYTHIA to reproduce the Z p_T data)
- how do the shifts change if we use another description of IS effects, say for instance RESBOS like in TEVATRON analyses?

Higher order effects: pair radiation (1)



same order as 2 γ radiation

Unresolved pair radiation can be included in the Sudakov through the running [1] of α

$$\alpha \Longrightarrow \alpha(s) = \begin{cases} \alpha / \left(1 - \frac{\alpha}{3\pi} \ln \frac{s}{m_e^2}\right) & \text{electrons only} \\ \alpha / \left(1 - \frac{\alpha}{3\pi} \ln \frac{s}{m_e^2} - \theta(s - m_\mu^2) \frac{\alpha}{3\pi} \ln \frac{s}{m_\mu^2}\right) & \text{electrons + muons} \end{cases}$$

$pp \to W^+$, $\sqrt{s} = 14$ 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 FSR-LL	-89±1	-97±1	-179±1	-195±1
2	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1

$\Delta M_W(\mu^+\nu) \sim 5 \pm 1$ MeV (from μ) and $\sim 3 \pm 2$ MeV (from e)

[1] alternative implementation: N. Davidson et al arXiv:1011.0937

Higher order effects: pair radiation (2)

$pp \to W^+$, $\sqrt{s} = 14$ 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
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2	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1

- pair corrections estimated using HORACE: no interplay with QCD effects possible

- similar strategy can be implemented in POWHEG (actually is already there...)

  $\Longrightarrow$ one could repeat the study within POWHEG-BOX-V2/W_ew-BMNNP to see what are the changes in the shifts due to the presence of QCD pert and non-pert effects

NNLO uncertainty: input parameter schemes (1)

scheme choice = choice of the 3 independent EW params

- all choices formally equivalent at a given order in P.T.
- numerical differences in predictions from missing H.O. terms

$\Longrightarrow$ difference in predictions from different schemes at a given order can be taken as an estimate of the theory uncertainty from missing H.O.

However....

- not conclusive: basically impossible to consider all possible choices of IPS
- might be over-estimate: we might consider some schemes as "more precise" than others
  - parametric uncertainties
  - perturbative convergence
  - ...

NNLO uncertainty: input parameter schemes (2)

- $\alpha(0)$, M_W and M_Z
- G_μ, M_W and M_Z to be preferred in the CC DY
- we can define

$$\alpha_\mu^{tree} \equiv \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2\vartheta$$
$$\alpha_\mu^{1l} \equiv \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2\vartheta \,(1-\Delta r)$$

The expressions for the cross section differ at $\mathcal{O}(\alpha^2)$

$$\alpha_0 \;:\quad \sigma = \alpha_0^2\sigma_0 + \alpha_0^3(\sigma_{SV}+\sigma_H)\,,$$
$$G_\mu\; I \;:\quad \sigma = (\alpha_\mu^{tree})^2\sigma_0 + (\alpha_\mu^{tree})^2\alpha_0(\sigma_{SV}+\sigma_H) - 2\Delta r(\alpha_\mu^{tree})^2\sigma_0\,,$$
$$G_\mu\; II \;:\quad \sigma = (\alpha_\mu^{1l})^2\sigma_0 + (\alpha_\mu^{1l})^2\alpha_0(\sigma_{SV}+\sigma_H)$$

NNLO uncertainty: input parameter schemes (3)

- potentially effects on M_W because of the different sharing among different photon multiplicities

	$p\bar{p} \to W^+$, $\sqrt{s} = 1.96$ TeV Templates accuracy: LO Pseudodata accuracy	Input scheme	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ
1	HORACE NLO-EW	α_0	-101±1	-117±2
2		$G_\mu - I$	-112±1	-130±1
3		$G_\mu - II$	-101±1	-117±1
4	HORACE NLO-EW+QED-PS	α_0	-70±1	-81±1
5		$G_\mu - I$	-72±2	-83±1
6		$G_\mu - II$	-72±1	-82±2

- differences present at NLO, after matching with higher orders, become much smaller

$$\Delta M_W \sim 2 \text{ MeV} \pm 1 - 2 \text{ MeV}$$

NNLO uncertainty: input parameter schemes (4)

- uncertainties from IPS choice evaluated with HORACE: no interplay with QCD

- how do the shifts from different IPS change in the presence of QCD effects?

order	G_μ	$\alpha(0)$	$\delta(G_\mu\text{-}\alpha(0))$ (%)
NNLO-QCD	55787	53884	3.53
NNLO-QCD+NLO-EW	55501	55015	0.88
NNLO-QCD+NLO-EW+ NNLO QCD-EW	55469	55340	0.23

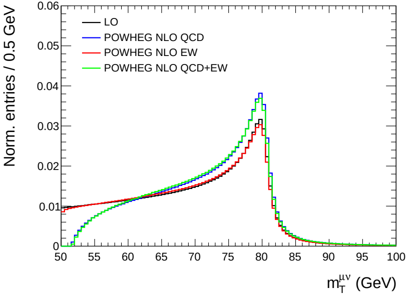
the LO + NLO-EW result would suffer of only 0.55% spread;
the NLO-QCD and NNLO-QCD corrections are only LO-EW and reintroduce a dependence (→0.88%)

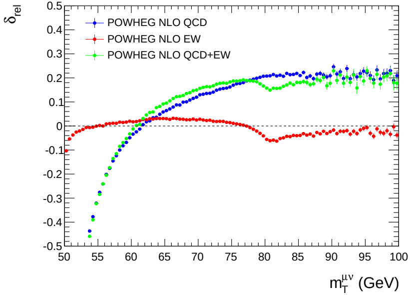
- one could estimate the H.O. corrections including the universal fermionic corrections connected to $\Delta\alpha$ and $\Delta\rho$

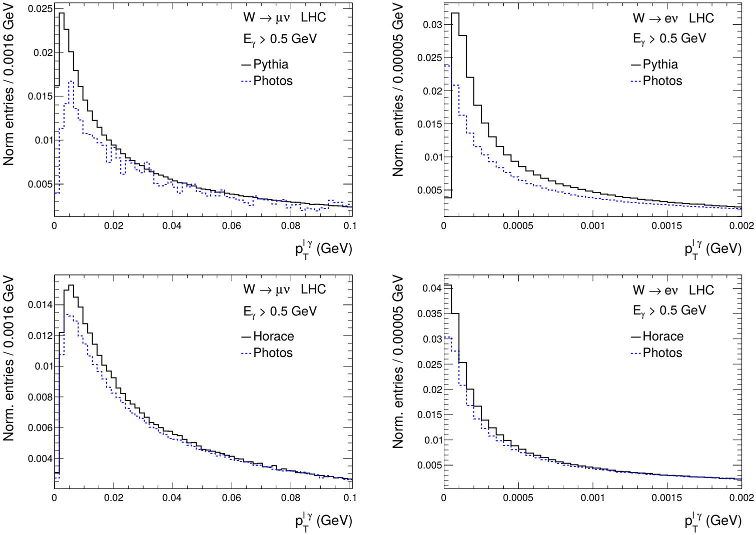
Possible points to discuss

- approximated factorized mixed QCD-EW corrections VS $\alpha\alpha_S$ corrections: theory uncertainties in MC generators at NLO QCD+NLO EW matched to QED and QCD PS
- estimate of QED, weak, and mixed corrections: how do they change when changing the IS QCD modeling? (use different shower MCs, different tunes,...)
- uncertainties from QED PS (H.O. qed): comparing other QED showers
- impact of pair radiation: possible interplay with IS QCD modeling
- estimate of missing NNLO EW corrections: input parameter scheme variations? Interplay with QCD? Other possible estimates?

Backup Slides


Norm. entries / 0.5 GeV
LO
POWHEG NLO QCD
POWHEG NLO EW
POWHEG NLO QCD+EW
$m_T^{\mu\nu}$ (GeV)


δ_{rel}
POWHEG NLO QCD
POWHEG NLO EW
POWHEG NLO QCD+EW
$m_T^{\mu\nu}$ (GeV)


W → μν LHC
E_γ > 0.5 GeV
Pythia
Photos
Norm entries / 0.0016 GeV
p_T^{lγ} (GeV)
W → eν LHC
E_γ > 0.5 GeV
Pythia
Photos
Norm. entries / 0.00005 GeV
p_T^{lγ} (GeV)
W → μν LHC
E_γ > 0.5 GeV
Horace
Photos
Norm. entries / 0.0016 GeV
p_T^{lγ} (GeV)
W → eν LHC
E_γ > 0.5 GeV
Horace
Photos
Norm. entries / 0.00005 GeV
p_T^{lγ} (GeV)

HORACE

$$d\sigma^{\infty} = F_{SV}\;\Pi(Q^2,\varepsilon)\sum_{n=0}^{\infty}\frac{1}{n!}\left(\prod_{i=0}^{n}F_{H,i}\right)|\mathcal{M}_{n,LL}|^2 d\Phi_n$$

POWHEG

$$d\sigma = \sum_{f_b}\bar{B}^{f_b}(\mathbf{\Phi}_n)\,d\mathbf{\Phi}_n\Bigg\{\Delta^{f_b}(\mathbf{\Phi}_n,p_T^{min}) + \sum_{\alpha_r\in\{\alpha_r|f_b\}}\frac{\left[d\Phi_{rad}\,\theta(k_T-p_T^{min})\,\Delta^{f_b}(\mathbf{\Phi}_n,k_T)\,R(\mathbf{\Phi}_{n+1})\right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r}=\mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)}\Bigg\}$$

taken from 1701.07240

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

Table 3: Systematic uncertainties in the m_W measurement due to QCD modelling, for the different kinematic distributions and W-boson charges. Except for the case of PDFs, the same uncertainties apply to W^+ and W^-. The fixed-order PDF uncertainty given for the separate W^+ and W^- final states corresponds to the quadrature sum of the CT10nnlo uncertainty variations; the charge-combined uncertainty also contains a 3.8 MeV contribution from comparing CT10nnlo to CT14 and MMHT2014.