Electroweak and QCD effects in the W boson mass determination

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Electroweak precision measurements at hadron colliders

- M_W

- $\sin^2 \vartheta^\ell_{eff}$

measured through C.C. and N.C. Drell-Yan

previous talk by S. Camarda for experimental status

- we have to remind that their most precise values come from EWPO @LEP1

talk by A. Freitas

M_W calculated in the Standard Model

$$M_W^2 = \frac{M_Z^2}{2}\left\{1+\left[1-\frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}\,(1+\Delta r)\right]^{1/2}\right\}$$

$$M_W^2 = 80.357 \pm 0.009 \pm 0.003\mathrm{GeV}$$

- one loop $\mathcal{O}(\alpha)$ calculation

  A. Sirlin, PRD22 (1980) 971

- two loop $\mathcal{O}(\alpha\alpha_s)$

  A. Djouadi, C. Verzegnassi, PLB195 (1987) 265

- three loop $\mathcal{O}(\alpha\alpha_s^2)$

  L. Avdeev et al., PLB336 (1994) 560;

  K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394

- $\mathcal{O}(\alpha^2)$ for large top / Higgs mass

  R. Barbieri et al., PLB288 (1992) 95; NPB409 (1993) 105

  G. Degrassi, P. Gambino, A. Vicini, PLB383 (1996) 219

- exact $\mathcal{O}(\alpha^2)$

  A. Freitas et al., PLB495 (2000) 338; NPB632 (2002) 189
  M. Awramik, M. Czakon, PLB568 (2003) 48; PRL89 (2002) 241801
  A. Onishchenko, O. Veretin, PLB551 (2003) 111; M. Awramik et al., PRD68 (2003) 053004

  G. Degrassi, P. Gambino, P.P. Giardino, JHEP 1505 (2015) 154; I. Dubovik et al., arXiv:1906.08815

$$\sin^2\vartheta^l_{eff} = \frac{1}{4}\left(1 - \mathrm{Re}\frac{g_v}{g_a}\right), \qquad \mathrm{Z l\bar{l}\,vertex} \sim \bar{l}\gamma^\mu(g_v - g_a\gamma_5)lZ_\mu$$

- measured at Z peak: 0.23153 ± 0.00016
- uncertainty in the Standard Model calculations: $\sim 0.00005 \oplus 0.00004$
  - at one loop $\mathcal{O}(\alpha)$

    A. Sirlin, PRD22, (1980) 971, W.J. Marciano, A. Sirlin, PRD22 (1980) 2695

    G. Degrassi, A. Sirlin, NPB352 (1991) 352, P. Gambino and A. Sirlin, PRD49 (1994) 1160
  - at higher orders:
    - ★ $\mathcal{O}(\alpha\alpha_s)$

      A. Djouadi, C. Verzegnassi, PLB195 (1987) 265
      B. Kiehl, NPB353 (1991) 567; B. Kniehl, A. Sirlin, NPB371 (1992) 141, PRD47 (1993) 883

      A. Djouadi, P. Gambino, PRD49 (1994) 3499
    - ★ $\mathcal{O}(\alpha\alpha_s^2)$

      L. Avdeev et al., PLB336 (1994) 560;

      Chetyrkin, Kühn, Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394; NPB482 (1996) 213
    - ★ $\mathcal{O}(\alpha\alpha_s^3)$

      Y. Schröder, M. Steinhauser, PLB622 (2005) 124;

      K.G. Chetyrkin et al., hep=ph/0605201; R. Boughezal, M. Czakon, hep-ph/0606232
    - ★ $\mathcal{O}(\alpha^2)$ for large Higgs / top mass

      G. Degrassi, P. Gambino, A. Sirlin, PLB394 (1997) 188
    - ★ exact $\mathcal{O}(\alpha^2)$ M. Awramik, M. Czakon, A. Freitas, JHEP0611 (2006) 048

      W. Hollik, U. Meier, S. Uccirati, NPB731 (2005) 213; I. Dubovik et al., arXiv:1906.08815

direct M_W measurements at LEP2: 80.376 ± 0.033 MeV

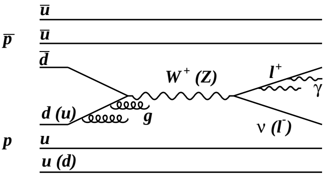
ADLO and LEP EWWG arXiv:1302.3415

- cross section dependence on M_W at threshold $\sim \beta = \sqrt{1 - \frac{4M_W^2}{s}}$
  - $M_W = 80.42 \pm 0.20 \pm 0.03(E_{\rm LEP})$ GeV

- direct reconstruction of decay products in $e^+e^- \to 4$ fermions
  - $q\bar{q}'q\bar{q}'$
  - $q\bar{q}'\ell\nu_\ell$

  - $M_W = 80.375 \pm 0.025({\rm stat}) \pm 0.022({\rm syst})$ GeV

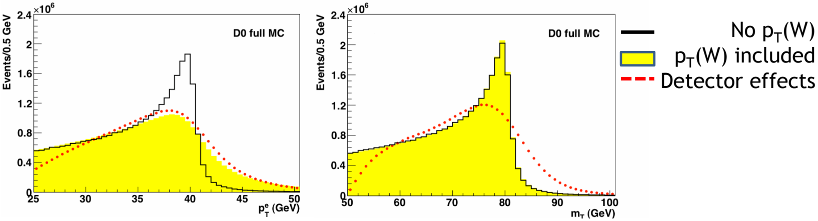
direct M_W measurement at hadron colliders



$$\sigma^{\text{theory}} = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times$$
$$\times \int_\Phi d\hat{\sigma}_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2) + \mathcal{O}\left(\frac{\Lambda^n_{QCD}}{Q^n}\right)$$

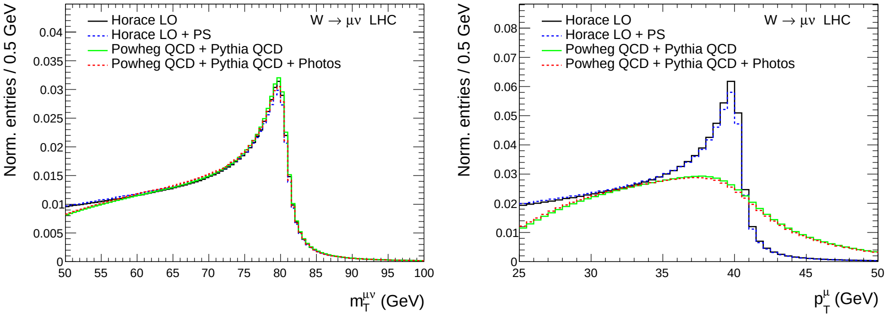
- extremely important that the direct determinations of M_W and $\sin^2\vartheta^\ell_{eff}$ is be as much as possible independent of each other, also from a theoretical point of view
- M_W and $\sin^2\vartheta^\ell_{eff}$ are tightly intertwined by with other electroweak parameters in the gauge sector (quite different w.r.t. m_{top} and m_H)

Main relevant observables for M_W



- $M_\perp$
  - theoretically stable vs radiative corrections
  - determination of neutrino momentum exp. challenging
- $p_\perp^\ell$
  - experimentally clean
  - theoretically very sensitive to ISR

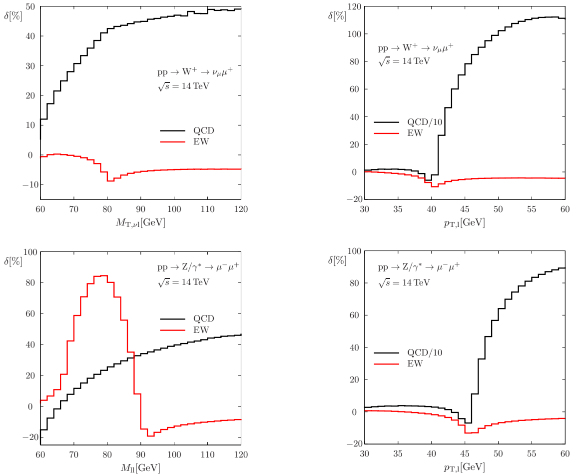
sensitivity to radiative corrections



C.M. Carloni Calame et al., arXiv:1612.02841

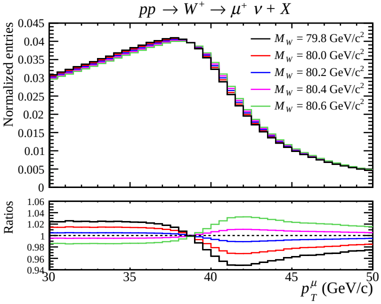
- crucial a good control of $p_\perp^W$ (which affects directly $p_\perp^\ell$)

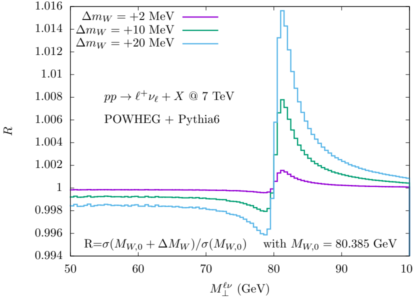
NLO QCD and NLO EW



S. Dittmaier, A. Huss, C. Schwinn, arXiv:1403.3216

sensitivity to M_W





Farry, Lupton, Pili, Vesterinen, arXiv:1902.04323

by A. Vicini

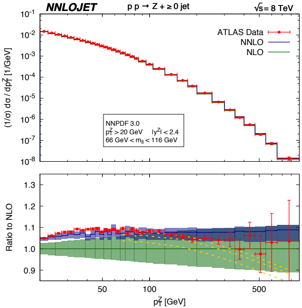
- control of shapes below 1% scale for $\Delta M_W \sim 10 - 20$ MeV

lepton pair (Z/W) $p_\perp$: two regimes

- large $p_\perp$ ($\gtrsim 20$ GeV), where pert. th. is reliable
  - state of the art is NNLO QCD

- small $p_\perp$ ($\lesssim 20$ GeV): $\sim$90% of the cross section
  - resummation of $\log\left(\frac{M_V}{q_\perp}\right)$ is needed
  - sensitivity to the non-perturbative model of the MC Evt Gen

Large $p_\perp$ region



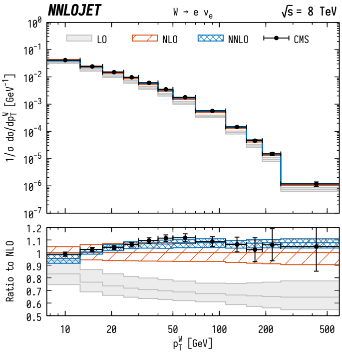
A. Gehrmann-De Ridder et al., arXiv:1605.04295

A. Huss, p_T^Z and p_T^W theory meeting, CERN 2018

R. Boughezal et al., 1512.01291, 1602.05612, 1602.08140

- yellow dash: ew corrections

A. Denner et al., arXiv:1103.0914

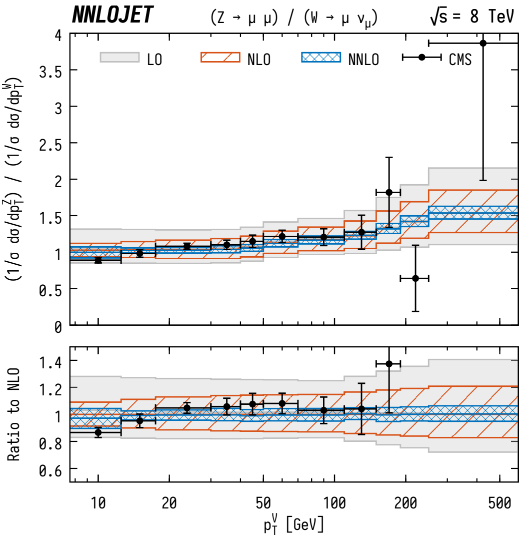


A. Gehrmann-De Ridder et al., arXiv:1712.07543

A. Huss at p_T^Z and p_T^W theory meeting, CERN 2018

R. Boughezal et al., arXiv:1602.06965

and on the ratio W/Z



A. Gehrmann-De Ridder et al., arXiv:1712.07543

Small $p_\perp$ region: resummation techniques

- recent progress by different groups on resummation
  - $q_\perp$ resummation in impact parameter space
    - ⋆ DYRES, DYTURBO S. Catani et al., arXiv:1507.06937; G. Ferrera, S. Camarda
    - ⋆ ReSolve T. Cridge and F. Coradeschi
    - ⋆ Resbos2, CSS formalism J. Isaacson
  - SCET based resummation
    - ⋆ GENEVA, SCETlib S. Alioli et al., arXiv:1211.7049, arXiv:1508.01475; F. Tackmann et al
    - ⋆ CuTe T. Becher et al., arXiv:1109.6027, arXiv:1212.2621

      T. Becher, Hager, arXiv:1904.08325
  - resummation in direct space (RadISH) W. Bizon et al., arXiv:1705.09127; 1604.02191
  - resummation throuh TMD factorisation (NangaParbat) V. Bertone and G. Bozzi
- recent progress in Monte Carlo generators
  - inclusion of NLO splitting kernels (DIRE)

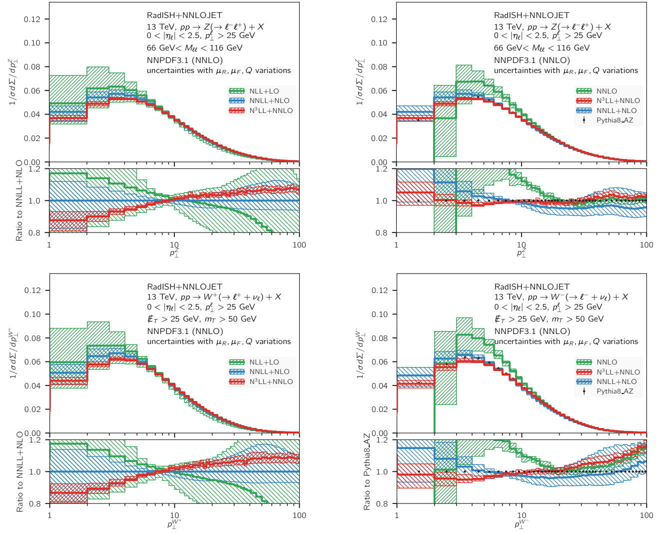
    S. Höche, F. Krauss, S. Prestel, 1705.00982

    S. Höche, S. Prestel, arXiv:1705.00742
  - DY at NNLOPS accuracy with different methods
    - ⋆ MiNLO with POWHEG Karlberg, Re, Zanderighi, arXiv:1407.2940
    - ⋆ UNNLOPS with SHERPA Höche, Li, Prestel, arXiv:1405.3607
    - ⋆ GENEVA Alioli, Bauer, Berggren, Guns, Tackmann, Walsh, '15-'16
- first investigations of possible flavour dependence of non-perturb partonic intrinsic $k_\perp$ talk by A. Signori

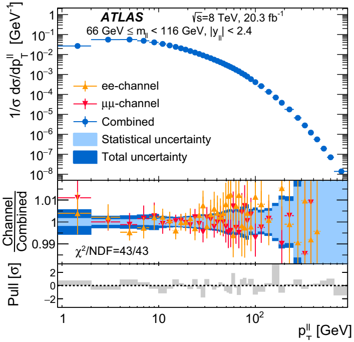
- different approaches, even if with the same nominal accuracy, can differ
  - subleading terms
  - different matching effects in the transition region
  - matching schemes (additive vs multiplicative)
  - non-perturbative corrections/MC tune
  - order of PDF evolution
  - thresholds and treatment of heavy quarks
- within the LHC EWWG, important benchmarking activity among different codes
  - this is the first time such an exercise is beeing performed, after the studies of S. Alioli, arXiv:1606.02330

latest results from RadISH+NNLOjet: $N^3LL+NNLO$

W. Bizon et al., arXiv:1905.05171



measured $p_\perp^Z$

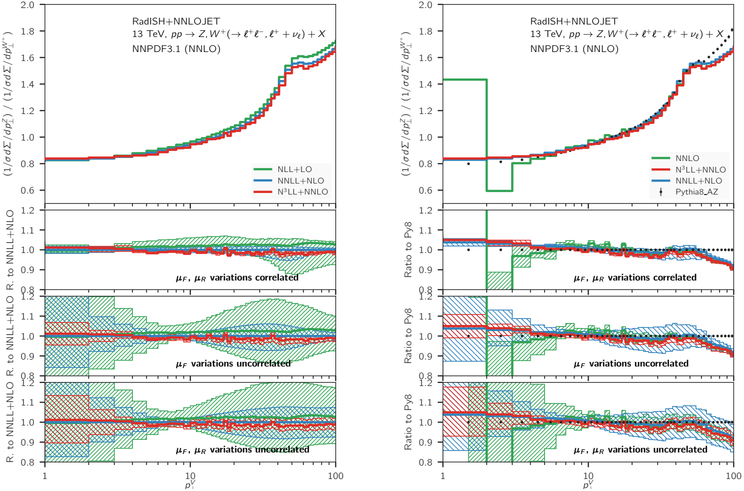


ATLAS coll., arXiv:1512.02192

$\Longrightarrow$

$$p_\perp^W = (p_\perp^Z)_{\text{measured}} \left(\frac{p_\perp^W}{p_\perp^Z}\right)_{\text{th}}$$

- How to treat th uncertainties in numerator and denominator?



W. Bizon et al., arXiv:1905.05171

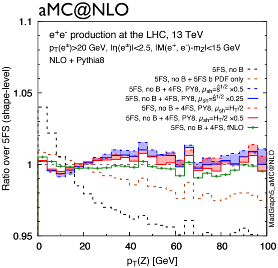
- stability of the best predictions vs (un)correlation of scales
- remaining $\mathcal{O}(\%)$ th. uncertainty

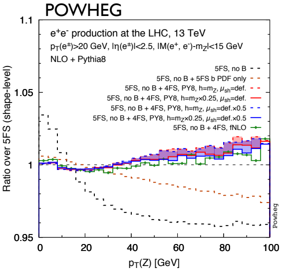
$b\bar{b}$ contribution to $p_\perp^Z$

E. Bagnaschi, F. Maltoni, A. Vicini and M. Zaro, arXiv:1803.04336

- two schemes
  - 5 flavour scheme (massless b, resummation of $\log(p_\perp^b/m_b)$)
  - 4 flavour scheme (finite m_b with exact kinematics of $\ell^+\ell^- b\bar{b}$)
- improvement from a combination of the two schemes
  - $p_\perp^Z$ distribution split into 2 contributions: with and without B hadrons in final state

$$\frac{d\sigma^{best}}{dp_\perp^{\ell^+\ell^-}} = \frac{d\sigma^{5FS-Bveto}}{dp_\perp^{\ell^+\ell^-}} + \frac{d\sigma^{4FS}}{dp_\perp^{\ell^+\ell^-}}$$





- $\Delta M_W < 5$ MeV from $p_\perp^\ell$ (with sensitivity to the fit window)

Higher-order corrections (for M_W fit)

$$
\begin{aligned}
d\sigma &= d\sigma_0 \\
&+ d\sigma_{\alpha_s} + d\sigma_\alpha \\
&+ d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \dots
\end{aligned}
$$

- multi-photon emission from the final state $\rightarrow \delta M_W \simeq 10$ MeV for $\mu\nu_\mu$ final state

Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0710 (2007)

- mixed QCD-EWK corrections

Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216

- NNLO EWK effects

C.M. Carloni Calame et al., Phys.Rev. D96 (2017) 093005

  - EWK input scheme
  - lepton pair emission

QCD-EWK interference

- the $\mathcal{O}(\alpha\alpha_s)$ calculation involves as building blocks
  - NNLO virtual corrections at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
    - ★ necessary two-loop master integrals (with $m = 0$ external particles and $M_W = M_Z$, or with one massive internal line)

      R. Bonciani et al., arXiv:1604.08581; A. von Manteuffel and R.M. Schabinger, arXiv:1701.06583
  - NLO EW corrections to $l\bar{l}^{(\prime)}+$ jet
  - NLO QCD corrections to $l\bar{l}^{(\prime)} + \gamma$
  - double real contributions $l\bar{l}^{(\prime)} + \gamma +$ jet
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
    - ★ very recent progress on NNLO mixed QCD-QED ISR corrections

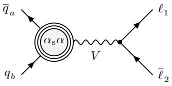
      talk by D. De Florian
- what is available:
  - fixed order dominant $\mathcal{O}(\alpha_s\alpha)$ corrections to DY in pole approximation

    Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216
  - Monte Carlo estimates through NLO QCD $\otimes$ NLO EW (with higher orders)

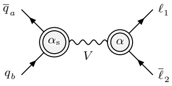
    L. Barzè et al., JHEP 1204 (2012) 037, Eur. Phys. J. C73 (2013) 2474

fixed order $\mathcal{O}(\alpha_s\alpha)$ in pole approximation

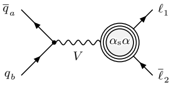
- two main classes of contributions:
  - factorizable
  - non-factorizable



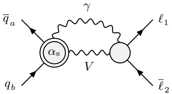
(a) Factorizable initial–initial corrections



(b) Factorizable initial–final corrections



(c) Factorizable final–final corrections



(d) Non-factorizable corrections

S. Dittmaier, A. Huss and C. Schwinn, arXiv:1601.02027

a) not known but expected to be small

recent progress covered by D. De Florian

($\mathcal{O}(\alpha)$ corrections in PA $\Longrightarrow$ $M_\perp$ and $M(l^+l^-)$ insensitive to QED ISR
in addition $M_\perp$ and $M(l^+l^-)$ mildly affected by NLO QCD corrections)

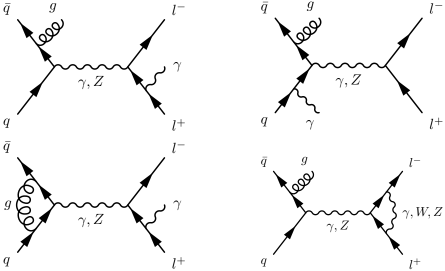
b) this gives the bulk of the contribution

c) no real contributions $\Longrightarrow$ no impact on shape of $M_\perp$ and $M(l^+l^-)$

d) numerical impact below 0.1%

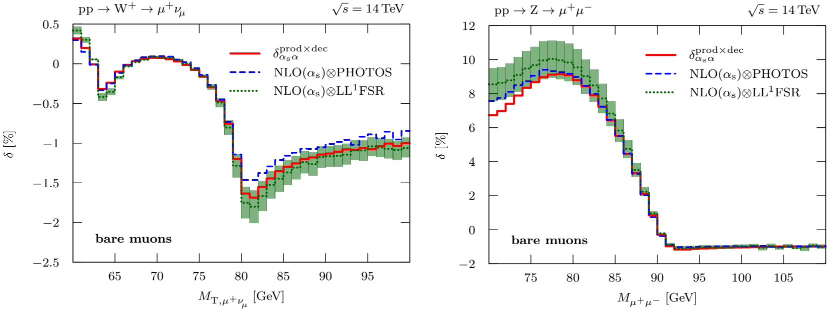
$\mathcal{O}(\alpha_s \alpha)$ corrections through Monte Carlo

- The POWHEG-BOX includes NLO QCD & EW corrections interfaced to QCD/QED shower, i.e. NLOPS EW $\oplus$ QCD accuracy
  1. POWHEG_W_ew_BMNNP, CC DY — Barzè et al, JHEP 1204 (2012) 037
  2. POWHEG_W_ew_BW, CC DY — Bernaciak and Wackeroth, PRD 85 (2012) 093003
  3. POWHEG_Z_ew_BMNNPV, NC DY — Barzè et al, EPJC 73 (2013) 6, 2474
  4. independent implementation — Mück and Oymanns, JHEP 1705 (2017) 090
- correctly taken into account the NLO contribution with one additional radiation in the soft/collinear limit



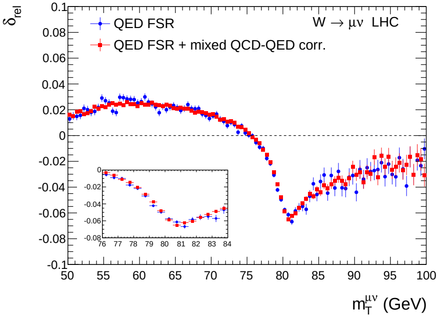
$\mathcal{O}(\alpha\alpha_s)$ with other factorized approaches

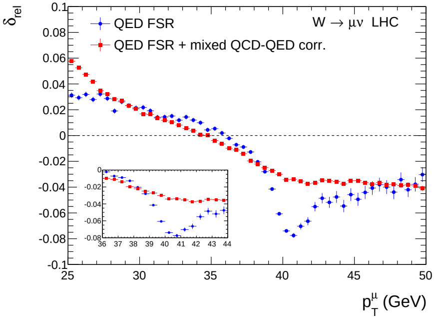
- since the bulk of the $\mathcal{O}(\alpha_s\alpha)$ corrections come from initial-final factorized contributions, it is interesting to compare the PA prediction for $\mathcal{O}(\alpha\alpha_s)$ corrections with the factorized approximation NLO QCD $\otimes$ FSR QED
- FSR QED treated with collinear structure functions or with PHOTOS



Dittmaier, Huss, Schwinn, NPB 904 (2016) 216

from Monte Carlo





C.M. Carloni Calame et al., arXiv:1612.02841

- comparison POWHEG-BOX-V2 vs NNLO in pole approx

C.M. Carloni Calame et al., Phys.Rev. D96 (2017) 093005

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

$$\Delta M_W{}^{\alpha_s\alpha}(\mu^+\nu_\mu) = -16.0 \pm 3.0 \text{ MeV} \qquad \text{vs} \qquad \delta_{\rm NNLO} = -14 \text{ MeV}$$

Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216

- summary of residual effects present in $(\text{QCD}\oplus\text{EW})_{\rm NLOPS}$ but missing in $\text{QCD}_{\rm NLOPS} \otimes$ QEDPS

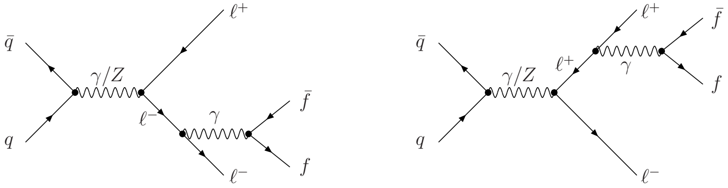
		ΔM_W (MeV)	
	QED FSR model	M_T	p_T^ℓ
Tevatron	Pythia	+5 ± 2	+17 ± 5
	Photos	-2 ± 1	-8 ± 5
LHC	Pythia	+6.2 ± 0.8	+29 ± 4
	Photos	-0.6 ± 0.8	-2 ± 4

- differences in shifts induced by PYTHIA QEDPS and PHOTOS disappear when used on top of QCD⊕EW NLO

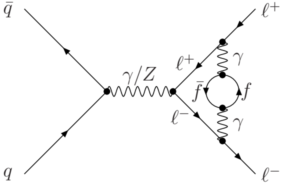
Lepton pair corrections: virtual and real contributions

- emission of a photon converting to a lepton pair
  $\sim \mathcal{O}(\alpha^2 L^2) \sim$ two-photon contribution

Real pair emission



Virtual pair correction



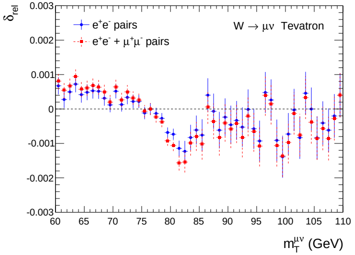
S. Antropov, A. Arbuzov, R. Sadykov, Z. Was, arXiv:1706.0557

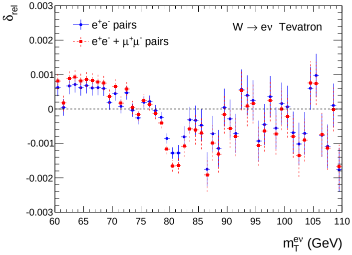
Lepton pair corrections: implementation in HORACE v3.1

C.M. Carloni Calame et al., arXiv:1612.02841

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

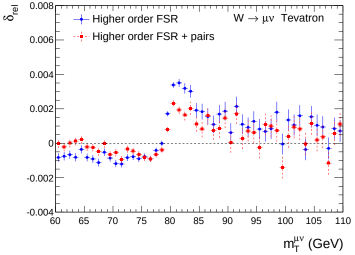
- running of α included in the Sudakov form factor

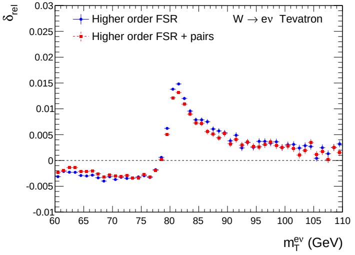




- Normalization: multiphoton radiation

- Normalization: one-photon radiation from HORACE





$pp \to W^+$, $\sqrt{s} = 14$ 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

$\Delta M_W(\mu^+\nu) \sim 5 \pm 1$ MeV (from $M_\perp$) and $\sim 3 \pm 2$ MeV (from $p_\perp^\ell$)

NNLO uncertainty: input parameter scheme

- pert. EW calculations require a coherent set of input param. in the gauge sector, e.g.
  - $\alpha(0)$, M_W and M_Z
  - G_μ, M_W and M_Z to be preferred in the CC DY
  - we can define

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

  - three possible different expression for the cross section, starting to differ at $\mathcal{O}(\alpha^2)$

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

- 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

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

Summary

- aiming at a precision $\delta M_W \leq 10$ MeV, the details of simulating radiation in MC's become relevant
- QCD: **impressive recent progress** in resummation matched to full fixed order results calculation
  - benchmarking activity started within LHCEEWG at Cern
- mixed QCD$\times$ EW: comparison with fixed order in pole approximation nicely compatible, at the MeV scale
- the pragmatic recipe QCD NLOPS$\otimes$ QEDLL (with PHOTOS) agrees at the MeV level with the factorized prescription QCD NLOPS$\otimes$ EWNLOPS
  - the above prescription inherits an uncertainty of $\sim$ 5 MeV if QED FSR is simulated with PYTHIA $(M_\perp)$ and of ~ 29 MeV $(p_\perp^\ell)$
- the differences between PYTHIA and PHOTOS disappear if used on top of EW NLO precision
- leptonic pair corrections at the level of 5 MeV
- $\mathcal{O}(\alpha^2)$ uncertainties by exploring different input param schemes at the level of $1-2$ MeV (with the available statistics)