Theory aspects of precision physics at the LHC: M_W and $\sin^2 \vartheta^{\ell}_{eff}$

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Matter To The Deepest

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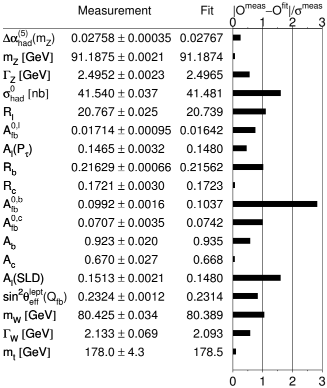
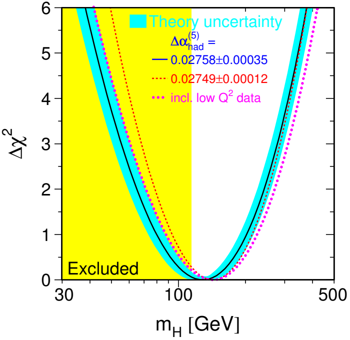
precision physics $\Longrightarrow$ LEP/SLC legacy at the $\mathbf{Z}$ pole





LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

- given precisely measured parameters, e.g. α, G_μ, M_Z, m_f, $(\Delta\alpha_h)$, $\alpha_s(M_Z)$ and, after LHC run I, m_H, all other quantities can be computed with high precision through perturbative calculations
- in particular, two **SM parameters**: M_W and $\sin^2\vartheta^\ell_{eff}$

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

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

- 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
    - ⋆ $\mathcal{O}(\alpha\alpha_s^3)$

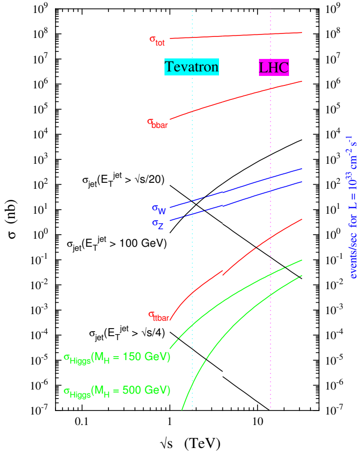
      Y. Schröder, M. Steinhauser, PLB622 (2005) 124;

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

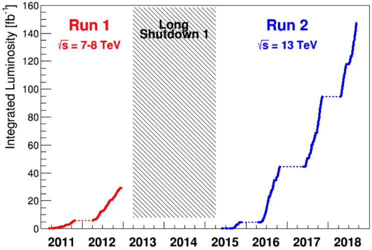
      G. Degrassi, P. Gambino, A. Sirlin, PLB394 (1997) 188
    - ⋆ exact $\mathcal{O}(\alpha^2)$ M. Awramik, M. Czakon, A. Freitas, JHEP0611 (2006) 048

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

At hadron colliders



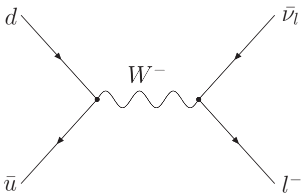
LHC luminosity



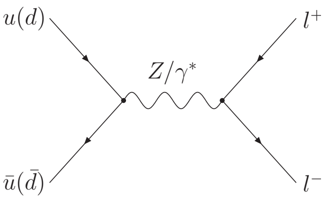
- with $L \sim 100$ fb^{-1} $\sim 10^{10} W$!!
- statistics is not an issue

- at hadronic colliders we have the opportunity to perform direct determination of both M_W and $\sin^2\vartheta^\ell_{eff}$ through **Drell-Yan** processes, to compare with the calculated values for a stress test of the SM internal consistency

CC

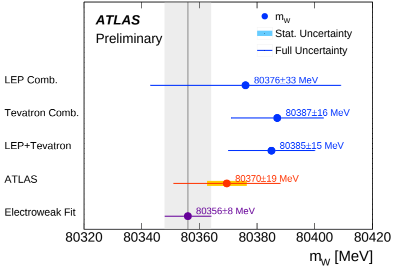


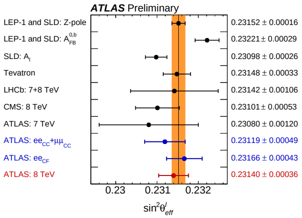
NC



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

on the experimental side



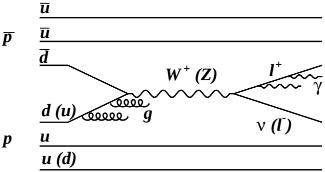


ATLAS 2017

ATLAS 2016

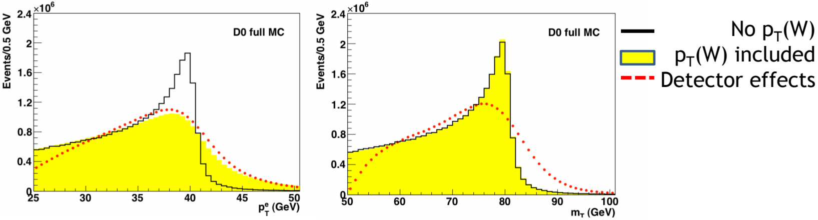
- largest th. systematics: PDF's, QCD scale uncertainties

- **main difficulty: protons are composite objects**



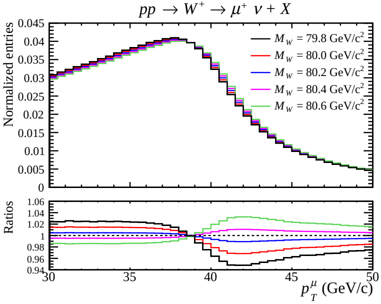
$$\sigma^{\text{theory}} \equiv \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times$$
$$\times \int_\Phi d\hat{\sigma}_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}^n}{Q^n}\right)$$

Main relevant observables for M_W

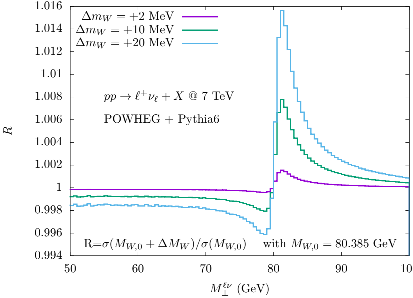


- $M_\perp$
  - theoretically stable vs radiative corrections
  - determination of neutrino momentum exp. challenging
- $p_\perp^\ell$
  - experimentally clean
  - theoretically very sensitive to ISR

sensitivity to M_W



Farry, Lupton, Pili, Vesterinen, arXiv:1902.04323



by A. Vicini

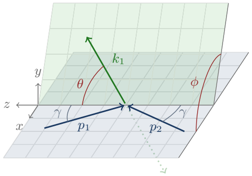
- control of shapes below 1% scale for $\Delta M_W \sim 10 - 20$ MeV

Main relevant observable for $\sin^2 \vartheta^{\ell}_{eff}$

- the matrix element for the production and decay of a spin one vector boson can be parameterized by an expansion on second order polinomials with nine coefficients (corresponding to nine polarization terms)

$$\begin{aligned}
\frac{d\sigma}{dq_T^2\, dy\ \ d\cos\vartheta\ \ d\phi} &= \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{dq_T^2\ \ dy\ \ d\cos\vartheta\ \ d\phi} \Big\{ 1 + \cos^2\vartheta \frac{1}{2} A_0 (1 - 3\cos^2\vartheta) + A_1 \sin 2\vartheta \cos\phi \\
&+ \frac{1}{2} A_2 \sin^2\vartheta \cos 2\phi + A_3 \sin\vartheta \cos\phi + A_4 \cos\vartheta + A_5 \sin^2\vartheta \sin 2\phi \\
&+ A_6 \sin 2\vartheta \sin\phi + A_7 \sin\vartheta \sin\phi \Big\}
\end{aligned}$$

- ϑ and ϕ refer to a $\ell\bar{\ell}$ rest frame
- orientation given by the Collin-Soper frame

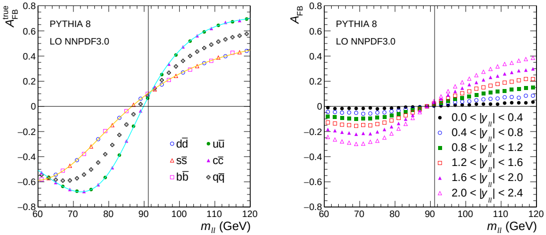


- integrating over the azimuthal angle the general parameterization of production and decay of a spin-one vector in terms of angular coefficients,

$$\frac{d\sigma}{dq_T^2\, dy\;\, d\cos\vartheta} = \frac{3}{8}\frac{d\sigma^{\text{unpol.}}}{dq_T^2\;\, dy\;\, d\cos\vartheta}\left\{1+\cos^2\vartheta+\frac{1}{2}A_0(1-3\cos^2\vartheta)+A_4\cos\vartheta\right\}$$

$$\Downarrow$$

$$A_{FB}(M,y) = \frac{\sigma^+(M,y)-\sigma^-(M,y)}{\sigma^+(M,y)+\sigma^-(M,y)} = \frac{3}{8}A_4(M,y)$$



ATLAS 2017

- $\Delta A_{FB} \sim 10^{-4} \Longrightarrow \Delta \sin^2 \vartheta^{\ell}_{eff} \sim 2 \cdot 10^{-4}$

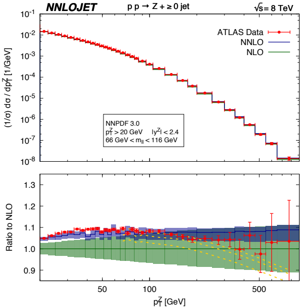
- **crucial common ingredients to $\mathbf{W}$ and $\mathbf{Z}$**
  - $p_{\perp}^{Z}$, $p_{\perp}^{W}$ (and their ratio), mainly sensitive to ISR QCD and different parton luminositites
  - reliable PDF's determinations

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): ∼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

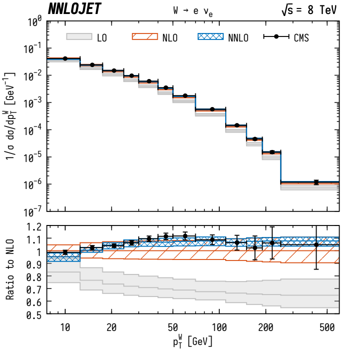
Large $p_\perp$ region



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



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

- yellow dash: ew corrections

A. Denner et al., arXiv:1103.0914

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)

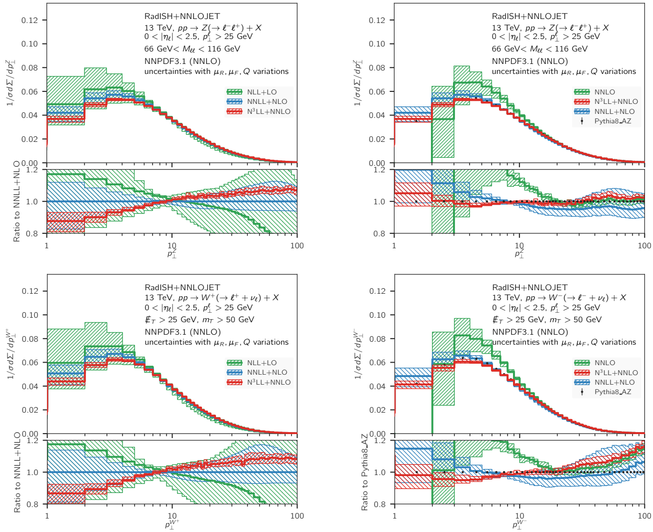
    S. Höche, F. Krauss, S. Prestel, 1705.00982

    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 $k_\perp$ A. Bacchetta et al., arXiv:1807.02101; G. Bozzi, A. Signori, arXiv:1901.01162

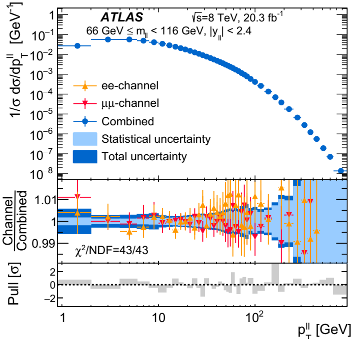
- different approaches, even if with the same nominal accuracy, can differ
  - subleading terms
  - different matching effects in the transition region
  - matching schemes (additive vs multiplicative)
  - non-perturbative corrections/MC tune
  - order of PDF evolution
  - thresholds and treatment of 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^{3}LL+NNLO

W. Bizon et al., arXiv:1905.05171



measured $p_\perp^Z$

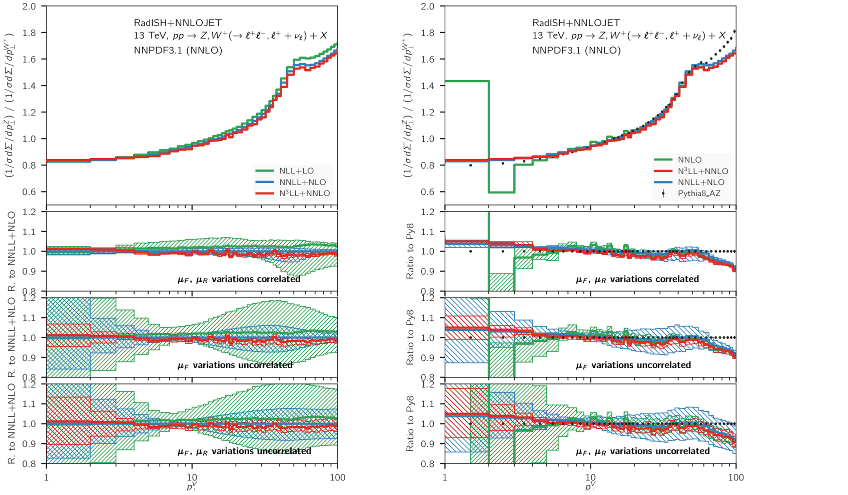


ATLAS coll., arXiv:1512.02192

$\Longrightarrow$

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

- 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

Higher-order corrections (for M_W fit)

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

- multi-photon emission from the final state $\to \delta M_W \simeq 10$ 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

    Cieri, Ferrera, Sborlini arXiv:1805.11948; De Florian, Der, Fabre, arXiv:1805.12214
- what is available:
  - fixed order dominant $\mathcal{O}(\alpha_s\alpha)$ corrections to DY in pole approximation

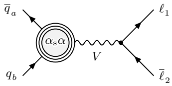
    Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216
  - Monte Carlo estimates through NLO QCD $\otimes$ NLO EW (with higher orders)

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

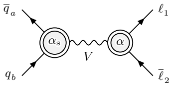
    C.M. Carloni Calame et al., arXiv:1612.02841

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

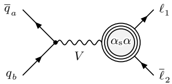
- two main classes of contributions:
  - factorizable
  - non-factorizable



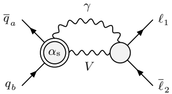
(a) Factorizable initial–initial corrections



(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) small contribution ($\sim 0.1\%$ level) (for on-shell Z) De Florian, Der, Fabre, arXiv:1805.12214
($\mathcal{O}(\alpha)$ 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)

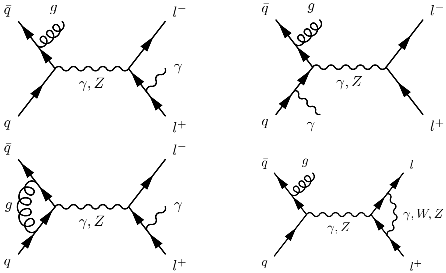
b) this gives the bulk of the contribution

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

- (e.g.) 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



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

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

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

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

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

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

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

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

$\Delta M_W(\mu^+\nu) \sim 5 \pm 1$ 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

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

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

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

- 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

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

Considerations on input parameter schemes

- **independent quantities in the SM:**
  - 3 in the electroweak gauge sector (to be specified)
  - $\alpha_s(Q^2)$, for a given Q^2, e.g. $Q^2 = M_Z^2$
  - lepton masses, m_t, m_H
  - light quark masses (including c and b) crucial for the running of $\alpha \Longrightarrow$ circumvented by using low-energy data and dispersion relations
- possible triplets of input (Lagrangian) parameters (in the gauge sector)
  - (e, M_W, M_Z), (g, M_W, M_Z), $(g, \sin\vartheta, M_Z)$, ...
- **renormalization scheme**: input parameters need to be defined with reference to three data points
- $\Longrightarrow$ everything else is calculated in terms of input parameters
- conceptually, independently of any simplified assumption (e.g. factorization properties at the Z peak), every parameter can be directly determined through a template fit procedure to any observable, provided our theoretical prediction of the observable allows us to freely move the measured parameter without spoiling the accuracy of the calculation (e.g. M_W with G_μ, M_W, M_Z)

requirement for an input/renormal. scheme

- **minimize the parametric uncertainty of the reference observables** defining the scheme
  - e.g. the LEP (G_μ, α, M_Z) scheme
- **minimize the effects of higher order corrections**, in order to have stable predictions in perturb. theory
  - e.g. the (G_μ, M_W, M_Z) scheme used for DY at Tevatron/LHC
- **minimize the parametric uncertainty** due to imperfect knowledge of other Lagrangian parameters (e.g. m_t, $\Delta\alpha_h$)

- for a direct determination of $\sin^2\vartheta^\ell_{eff}$ at the LHC, based on simulations includig higher order EW corrections, investigation of a scheme with $\sin^2\vartheta^\ell_{eff}$ as an input parameter

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α/G_μ, M_Z, $\sin^2\vartheta^\ell_{eff}$ as reference data

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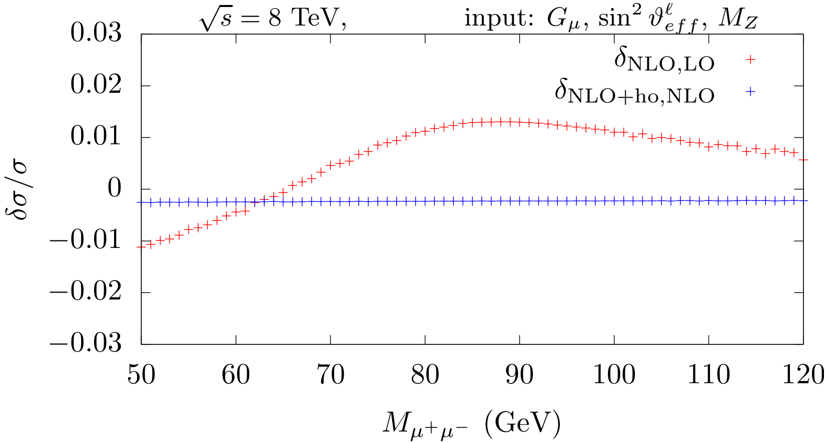
- our Lagrangian parameters: e, $\sin^2\vartheta$, M_Z
- e and M_Z renormalized parameters fixed as usual through α/G_μ and M_Z value measured at LEP
- $\sin^2\vartheta$ renormalized parameter fixed at $\sin^2\vartheta^\ell_{eff}$
  - this can be achieved by requiring that the ratio $\frac{g^\ell_V}{g^\ell_A}$ does not get radiative corrections
  - procedure independent of QED corrections because g_L and g_R receive the same corrections
  - Δr has to be changed accordingly w.r.t. to the usual expression
- the scheme can be used for making predictions
  - "drawback": parametric uncertainty inherited by the LEP measurement of $\sin^2\vartheta^\ell_{eff}$
- most important: the scheme can be used in a fitting procedure to measure $\sin^2\vartheta^\ell_{eff}$ with a template fit

convergence of pert. th. on $d\sigma/dM_{\ell\ell}$



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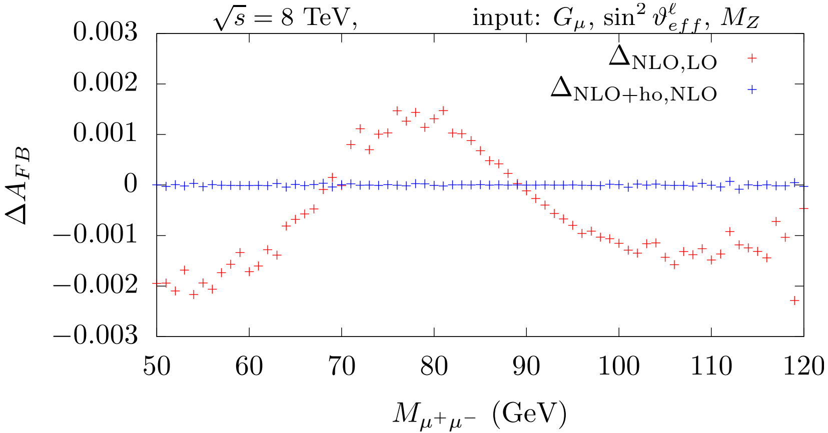

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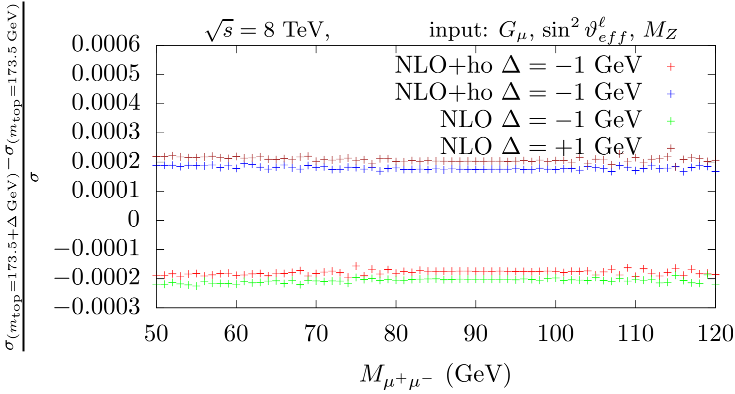
parametric dependence on m_{top}



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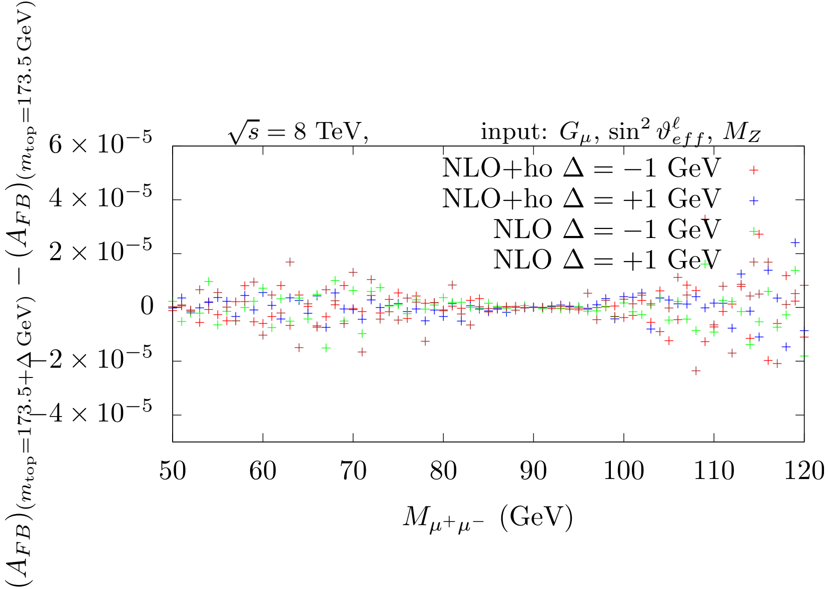
parametric dependence on $m_{\rm top}$



Summary

- aiming at a precision $\Delta M_W \leq 10$ MeV as well as $\Delta \sin^2 \vartheta^{\ell}_{eff} \leq 30 \cdot 10^{-5}$, the details of simulating radiation in MC's become relevant
- QCD for p_T^Z, p_T^W: **impressive recent progress** in resummation matched to full fixed order results calculation
  - benchmarking activity started within LHC EWWG at Cern
- M_W
  - 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 $\sim$ 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 through input param schemes of $\mathcal{O}(1-2)$ MeV
- $\sin^2 \vartheta^{\ell}_{eff}$
  - proposal of a new input param. scheme with $\sin^2 \vartheta^{\ell}_{eff}$ as input
  - (not discussed) ongoing studies and estimates of QED radiative effects which break factorization
  - (not discussed) ongoing studies of the effects of γ induced processes and their dependence on PDF set