Electro-Weak corrections to Drell-Yan processes

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in collaboration with

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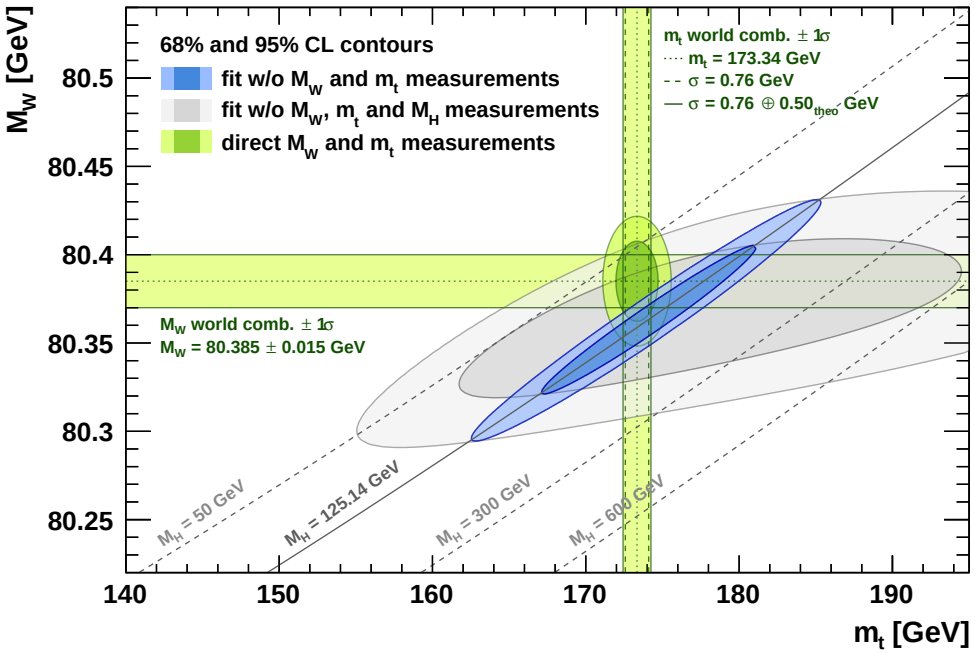
Outline

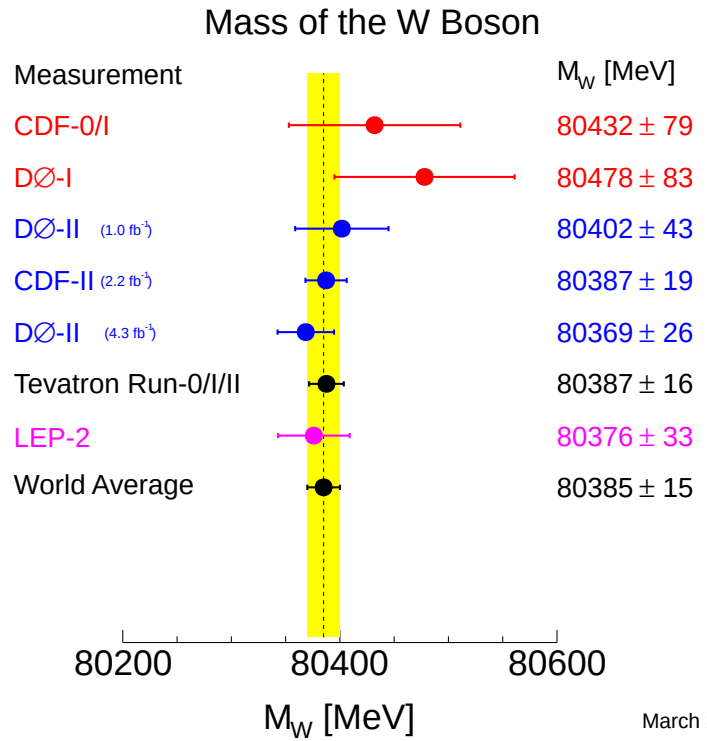
- Intro and motivations
- Overview of the literature (with available codes)
- Effects of EW RC on DY observables
- Combination of NLO EW$\oplus$QCD into a NLOPS framework
- Fixed order NNLO EW$\otimes$QCD $\mathcal{O}(\alpha_s\alpha)$
- Work in progress
- Conclusions and outlook

Motivations: M_W measurement

- A precise measurement of M_W provides a crucial test of the SM



Gfitter, EPJC 74 (2014) 3046



TeVatron EWWG, arXiv:1204.0042

M_W measurement at LHC

M. D'Alfonso, Moriond EWK 2016

- TeVatron-competitive measure feasible at LHC:
  - 7/8 TeV: 4.5/20 fb^{-1} $\rightarrow$ stat uncertainty $\mathcal{O}(10/5)$ MeV
  - 13 TeV much higher stats
- ⋆ e.g. "W-like" M_Z measurement at CMS with 4.7 fb^{-1} at 7 TeV

$$M_Z^{\text{W-like}} = 91206 \pm 30\ (\text{stat.}) \pm 36\ (\text{syst.})\ \text{MeV}$$

CMS, CMS-PAS-SMP-14-007

"W-like" mass milestone

First step: use the Z→ll events as test sample to measure the Z mass as if it was a W-like system.

i.e. we build a W-like system removing one lepton and recalculating MET and M_T.

Statistical erros		
Systematic source	W-like	W
PDF	skip	✓ YES
Boson PT	skip	✓ YES
Boson PT W/Z extrapolation	**NO**	✓ YES
EWK correction	skip	✓ YES
Polarization	skip	✓ YES
[] momentum scale	✓ YES	✓ YES
[] tr-iso-id efficiency	✓ YES	✓ YES
Missing et scale/resolution DATA/MC agreement	✓ YES	✓ YES
MET W/Z extrapolation	**NO**	✓ YES
Background to 1-l	**NO**	✓ YES

Advantages:

- low background
- can use the dilepton system to anchor the theory part

  Zmass, Z momentum, Zrapidity and angular distribution

  → Adopted a temporary re-weighting of the distributions

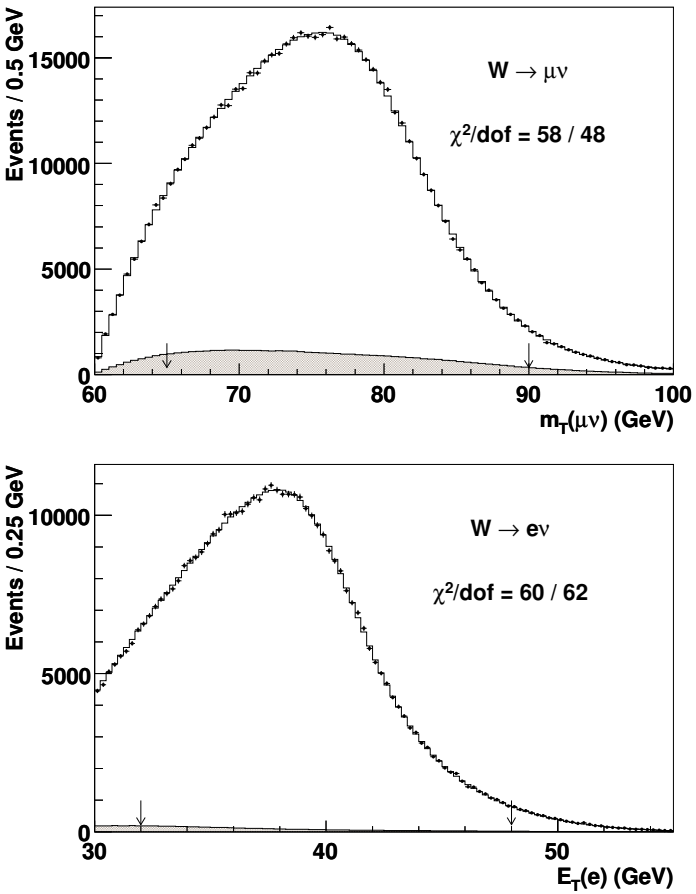
→ *For W-like measurement used half of the sample for the calibration and the other half for the measurement*

Convince:

- *The HEP community that we are on track on the experimental calibration.*
- *the theory community to invest more efforts on the M_T variable*

Motivations: M_W measurement

- M_W is extracted from the $p_\perp^\ell$ distribution, showing a (Jacobian) peak at $M_W/2$
- more reliable is $M_T^W = \sqrt{2p_\perp^\ell p_\perp^\nu (1-\cos\phi_{\ell\nu})}$ (less sensitive to QCD RC)



2.2/fb, CDF, PRL 108 (2012) 151803

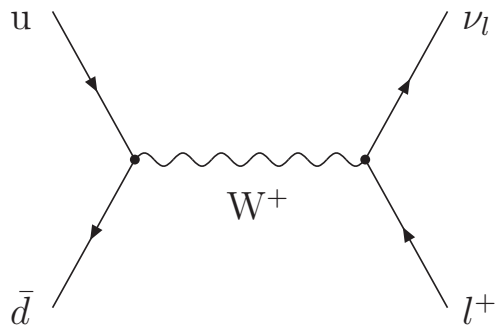
- M_W is extracted with a template fit technique to M_T and/or $p_\perp^\ell$ distributions
- The theoretical description of the distributions has to match the aimed experimental accuracy, both for NC and CC DY

⋆ EW corrections (mainly QED FSR) can distort the shape → the extracted M_W is affected

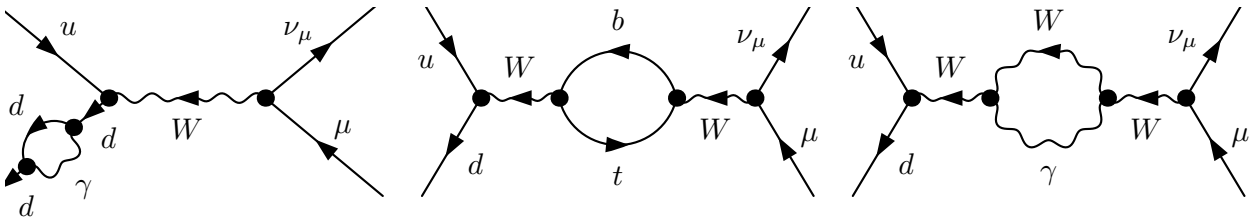
⋆ EW RC get large at high energy (Sudakov logs), where DY is a background to New Physics searches

Virtual corrections (for W production)

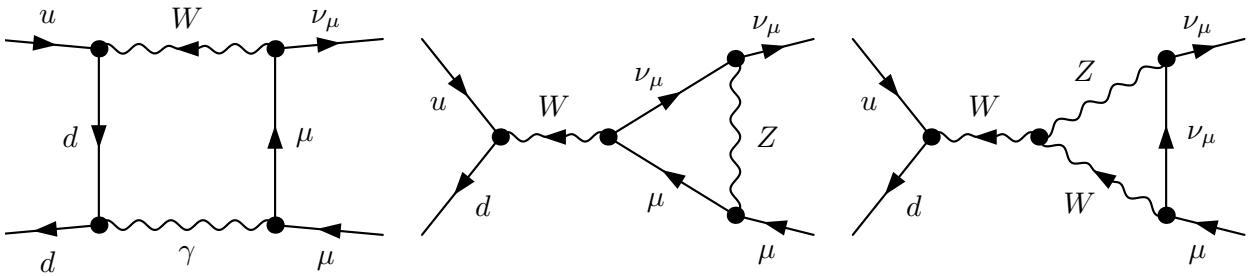
- LO diagram



- some virtual-correction diagrams (require careful treatment of W decay width)

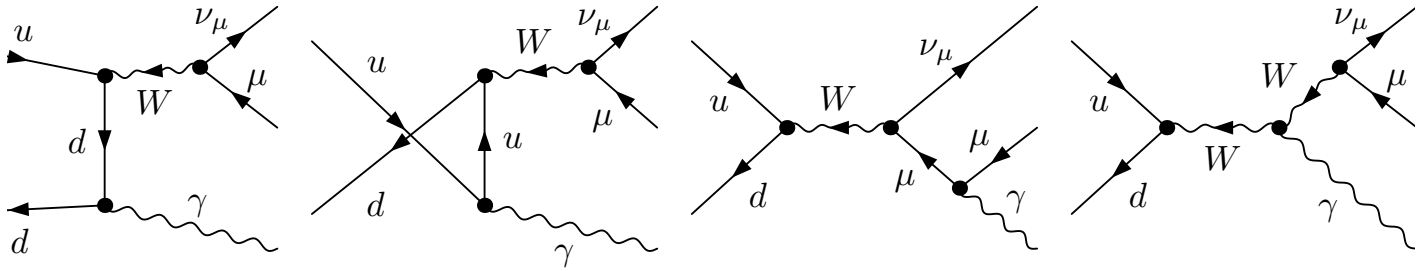


(a) (b) (c)

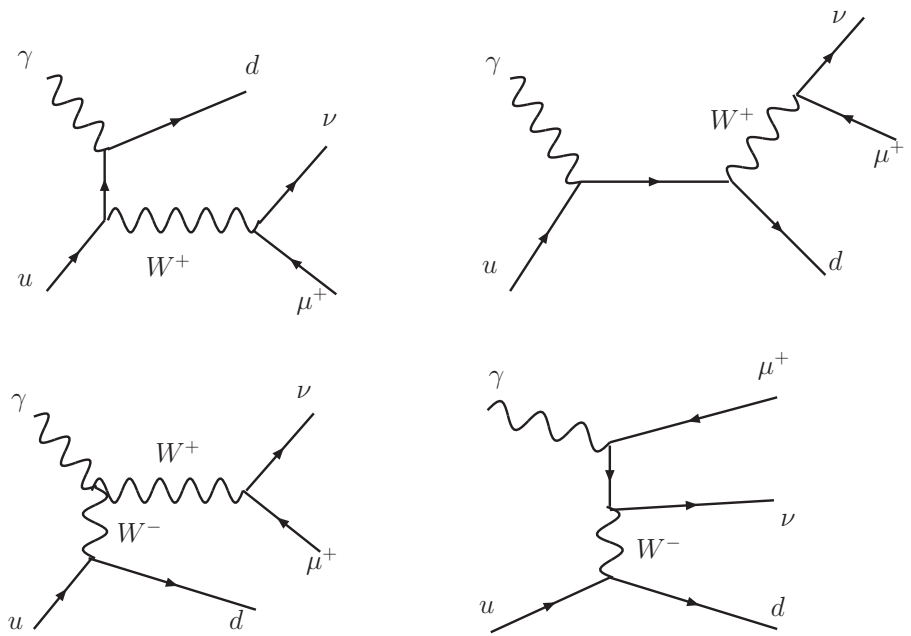


Real corrections (for W production)

- + real radiation



- + photon-induced processes diagrams (γ-PDF $\rightarrow$ `MRST2004QED`, `NNPDF2.3QED`)



⋆ Similarly for NC DY

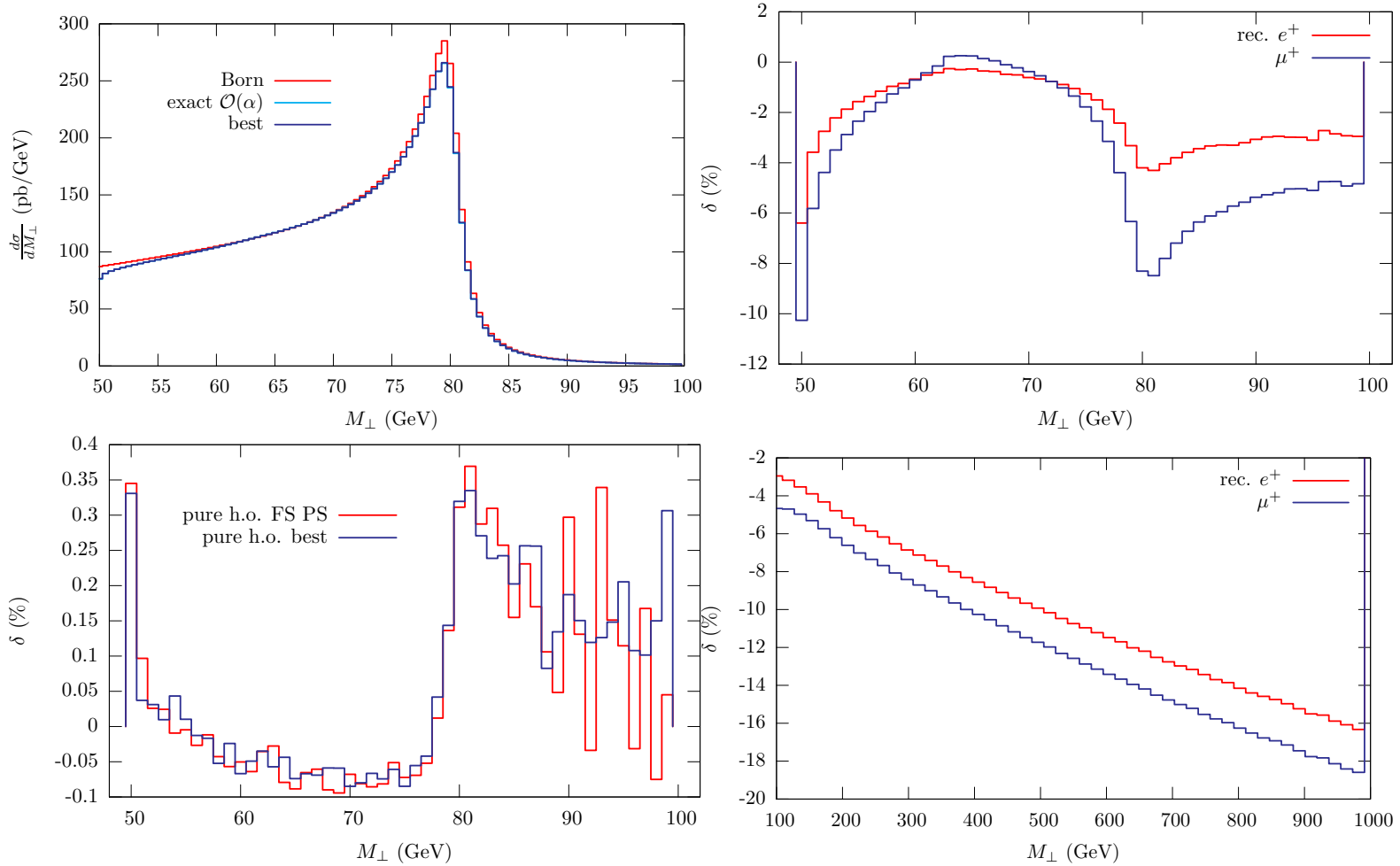
EW RC calculations and MC tools

- Relevant literature
  1. Baur, Wackeroth, et al., PRD 65 (2002) 033007, PRD 70 (2004) 073015
  2. Dittmaier, Krämer, PRD 65 (2002) 073007
  3. Jadach, Płaczek, EPJC 29 325 (2003), D. Bardin et al., Acta Phys. Polon. B40 (2009) 75
  4. Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0612 (2006) 016, JHEP 0710 (2007) 109
  5. Arbuzov et al., EPJC 46, 407 (2006), EPJC 54 (2008) 451
  6. Dittmaier, Huber, JHEP 1001 (2010) 060
- Tools
  1. **Z/WGRAD**, NLO EW to CC and NC DY
  2. **DK**, NLO EW to CC DY
  3. **WINHAC**, NLO EW + multiple photon to CC DY
  4. **HORACE**, NLO EW + matched multiple photon emission to CC and NC DY
  5. **SANC**, NLO EW to CC and NC DY
  6. **RADY**, NLO EW + MSSM to NC DY

→ Sudakov logs in the high-energy regime:
Denner et al., JHEP 0811 (2008) 062, NPB 761 (2007), Jantzen et al. NPB 731 (2005) 188, Brensing et al., PRD 77 (2008) 073006, Chiesa et al., work in progress (on **ALPGEN**)

Effects of EW corrections: W production

HORACE



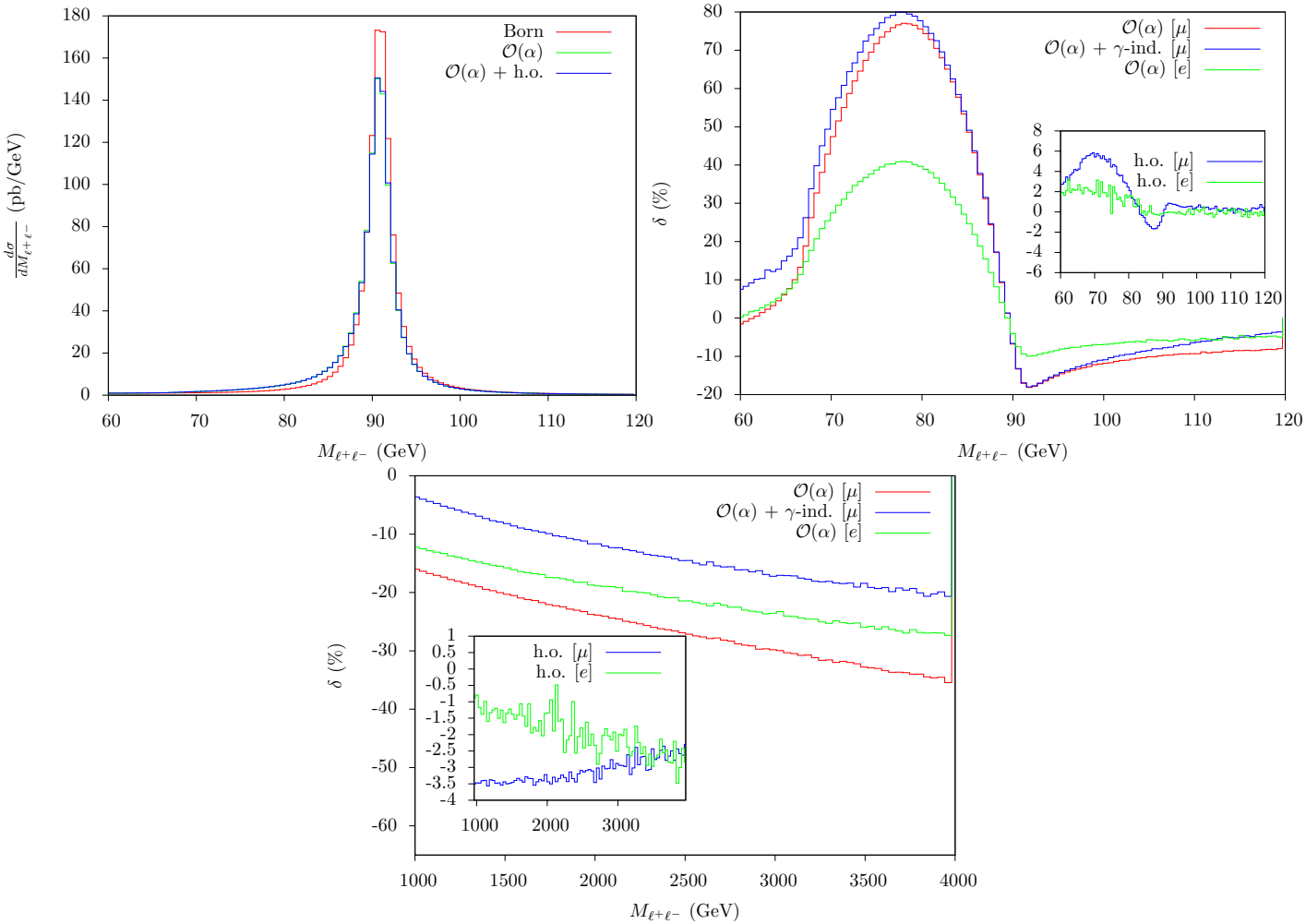
- EW $\mathcal{O}(\alpha)$ change the shape at $\mathcal{O}(10)\%$ level $\rightarrow \delta M_W \simeq 100$ MeV
- also multi-photon emission is important $\rightarrow \delta M_W \simeq -10$ MeV

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

- weak RC growing larger at high $M_T \rightarrow$ Sudakov logs

Effects of EW corrections: Z production

HORACE



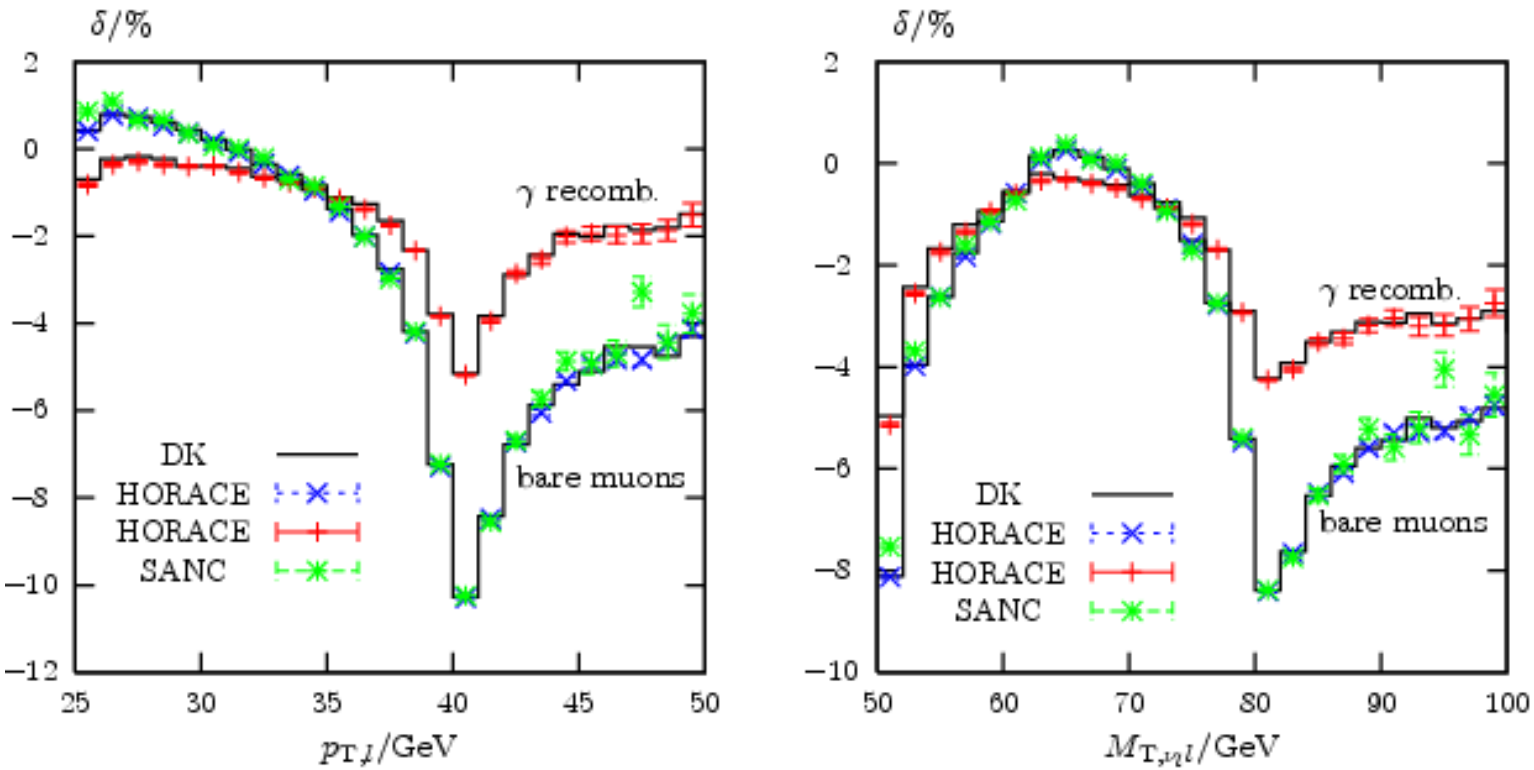
- γ-induced processes are important

  (although with large errors due to present γ-PDF uncertainty)

- weak RC growing larger at high $M_{\ell+\ell-}$

Effects of EW corrections: tuned comparisons

- During LH2005/7, TeV4LHC, successful tuned comparison among codes and predictions



Les Houches 2005, SM and Higgs WG Report, **hep-ph/0604120**

Budget of EW corrections (W)

from Brensing et al, PRD 77 (2008) 073006

$\mathrm{pp} \to l^+\nu_l X$ at $\sqrt{s} = 14\,\mathrm{TeV}$

$M_{\mathrm{T},\nu_l l}$/GeV	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
σ_0/pb	4495.7(2)	27.589(2)	1.7906(1)	0.084697(4)	0.0065222(4)	0.00027322(1)
$\delta_{q\bar{q}}^{\mu^+\nu_\mu}$/%	−2.9(1)	−5.2(1)	−8.1(1)	−14.8(1)	−22.6(1)	−33.2(1)
$\delta_{q\bar{q}}^{\mathrm{rec}}$/%	−1.8(1)	−3.5(1)	−6.5(1)	−12.7(1)	−20.0(1)	−29.6(1)
$\delta_{q\gamma}$/%	0.052(1)	0.12(1)	0.25(1)	0.37(1)	0.39(1)	0.36(1)
$\delta_{\mathrm{Sudakov}}^{(2)}$/%	−0.0002	−0.023	−0.082	0.21	1.3	3.8
$\delta_{\mathrm{multi}-\gamma}$/%	$0.12^{+0.03}_{-0.02}$	$0.20^{+0.05}_{-0.04}$	$0.16^{+0.03}_{-0.03}$	$0.19^{+0.04}_{-0.03}$	$0.24^{+0.04}_{-0.04}$	$0.34^{+0.06}_{-0.05}$
$\delta_{\mathrm{EW}}^{\mu^+\nu_\mu}$/%	−2.7(1)	−4.9(1)	−7.7(1)	−14.2(1)	−22.0(1)	−32.5(1)
$\delta_{\mathrm{EW}}^{\mathrm{rec}}$/%	−1.7(1)	−3.4(1)	−6.3(1)	−12.3(1)	−19.6(1)	−29.3(1)
$\delta_{\mathrm{QCD}}^{\mu=M_{\mathrm{W}}}$/%	−4.2(1)	23.2(1)	26.6(1)	19.1(1)	4.7(1)	−18.5(1)
$\delta_{\mathrm{QCD}}^{\mu=M_{\mathrm{T,W}}}$/%	−4.4(1)	22.5(1)	24.0(1)	12.6(1)	−6.2(1)	−34.6(1)

Table 2: Integrated LO cross sections σ_0 for W^+ production at the LHC for different ranges in $M_{\mathrm{T},\nu_l l}$ and corresponding relative corrections δ in the SM.

Photon induced processes (Z)

- **MCSANC** (Arbuzov et al., JETP Lett. 103 (2016) 2, 131) compared to Dittmaier, Huber, JHEP 1001 (2010) 060

M_{ll}/GeV	σ_0/pb	$\delta_{q/\bar{q}\gamma}/\%$	$\delta_{\gamma\gamma,0}/\%$	$\delta_{h.o.weak}/\%$
50-∞	738.813(5)	-0.105(1)	0.17(1)	0.030(1)
	738.773(6)	-0.11	0.17	0.030
100-∞	32.7293(2)	-0.207(1)	1.16(1)	0.013(1)
	32.7268(3)	-0.21	1.15	0.012
200-∞	1.48488(1)	0.381(1)	4.30(1)	-0.23(1)
	1.48492(1)	0.38	4.30	-0.23
500-∞	0.080942(3)	1.522(1)	4.92(1)	-0.29(1)
	0.0809489(6)	1.53	4.92	-0.29
1000-∞	0.0067998(1)	1.901(1)	5.21(1)	-0.31(1)
	0.00680008(3)	1.91	5.21	-0.31
2000-∞	0.00030375(1)	2.343(1)	6.18(1)	-0.31(1)
	0.000303767(1)	2.34	6.17	-0.32

Table 5: The LO cross section σ_0 of $pp \to e^+e^-X$ in pb, the contributions of $(q\gamma)$ and $(\gamma\gamma)$ configurations in the initial pp state: $\delta_{q/\bar{q}\gamma}$ and $\delta_{\gamma\gamma,0}$, and higher order corrections $\delta_{h.o.weak}$ (`iho=2`). Results of MCSANC (first rows) are compared to numbers from Ref.[7] (second rows).

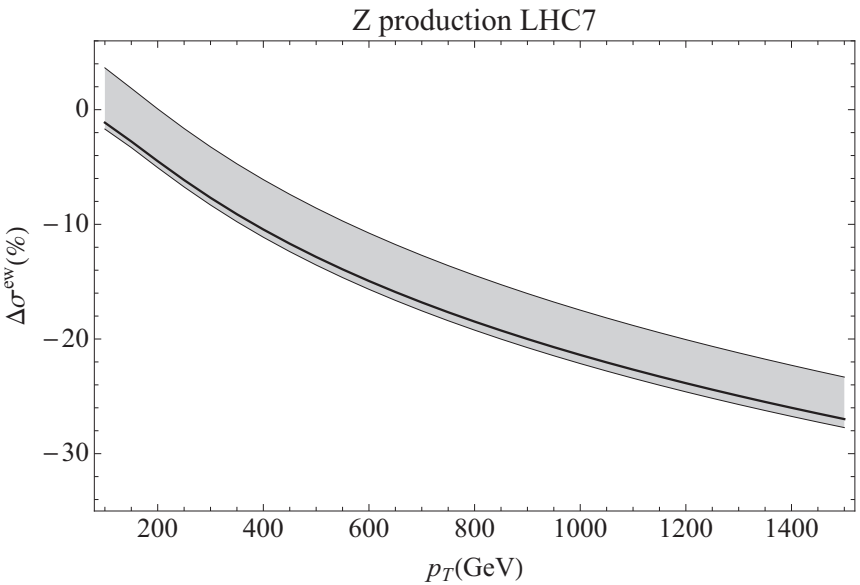
EW Sudakov resummation with SCET

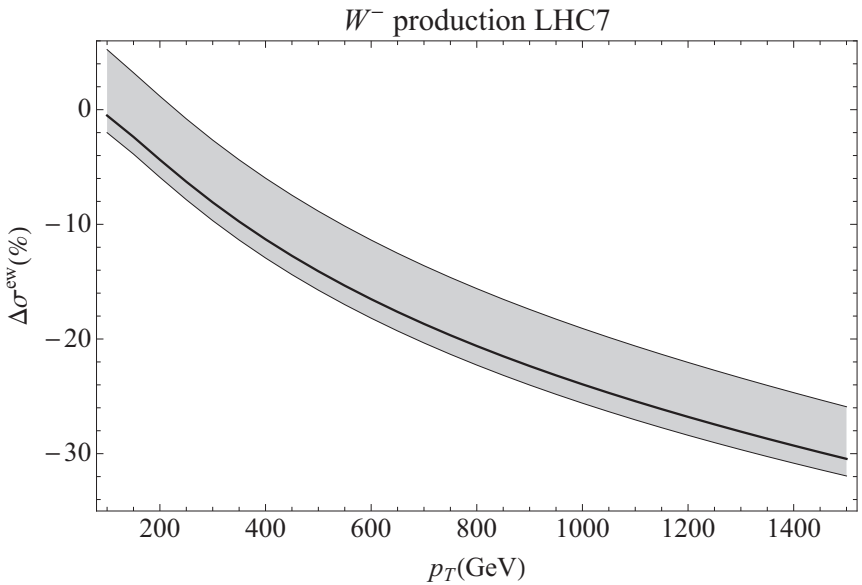
- To control $p_\perp^W$ systematics in M_W measurement, there is a proposal of directly measuring it over a wider range (up to some 100s GeV)

M. Boonekamp, Moriond 2015

- This region is sensitive to EW Sudakov logs and their resummation $\rightarrow$ SCET approach

Becher, Garcia i Tormo, PRD 88 (2013) 1, 013009





Combining EW & QCD corrections

see next talk by Ye Li for QCD summary

A complete and precise description of the observables demands for the combination of EW and QCD effects (both QCD shower and NLO QCD)

- **PYTHIA/HERWIG/SHERPA** + **PHOTOS** (or own QED shower)
- **HORACE**, **Z/WGRAD**, **WINHAC**, . . . , + QCD shower

  e.g. Balossini et al., JHEP 1001 (2010) 013
- inclusion of EW RC into **POWHEG-BOX** for 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
- NNLO QCD + NLO EW: **FEWZ**

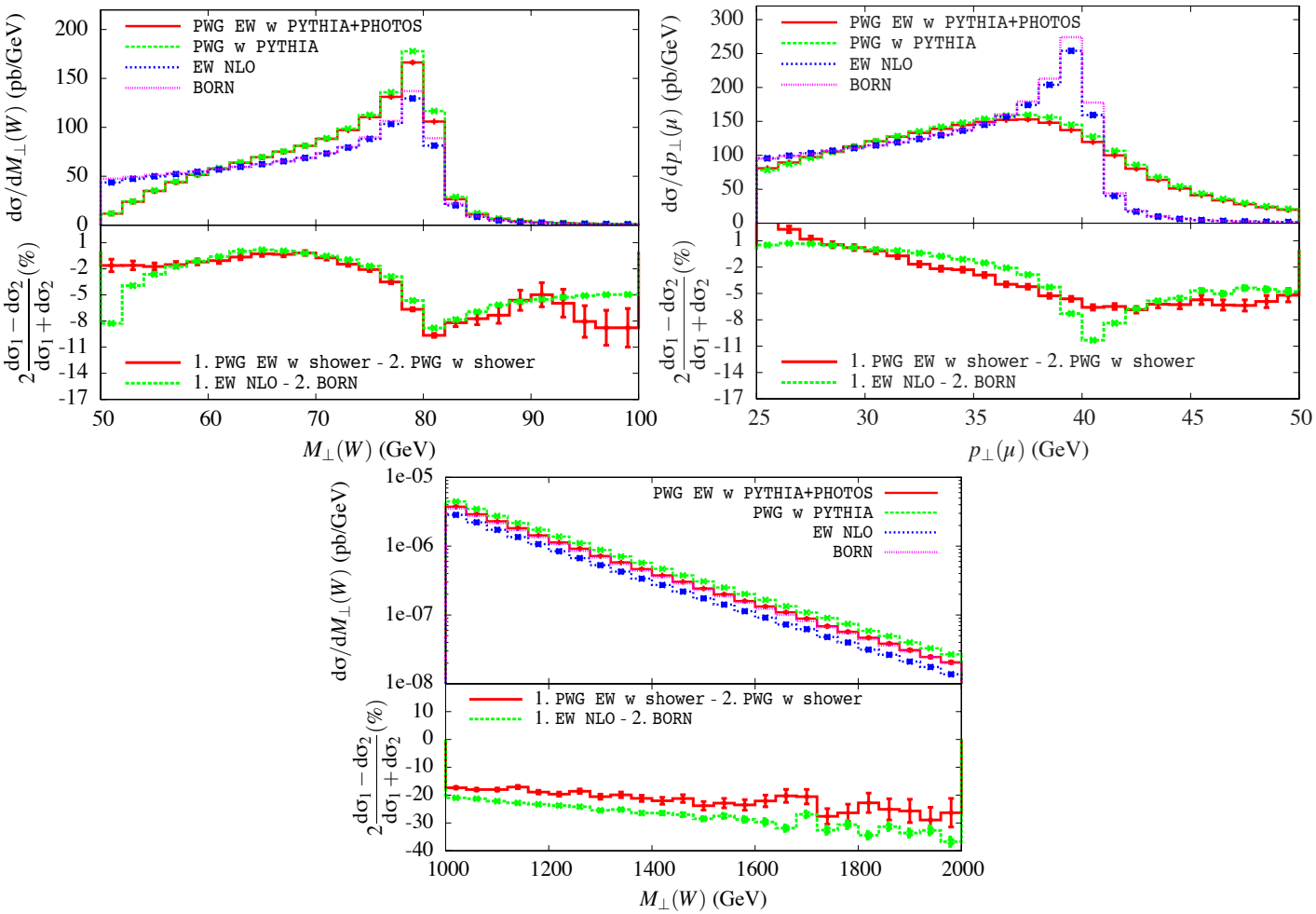
  Li and Petriello, PRD 86 (2012) 094034
- Fixed order mixed NNLO EW $\otimes$ QCD $\mathcal{O}(\alpha_s\alpha)$, in pole approximation, NC and CC DY

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

Combining EW & QCD corrections: W

Barzè et al, JHEP 1204 (2012) 037

POWHEG_W_ew_BMNNP



- EW effect not changed by QCD for M_T at peak, flattened for $p_\perp^\ell$
- Mixed EW⊗QCD at few % level, larger in the tail

Effect of dominant $\mathcal{O}(\alpha\alpha_s)$ correction in pole approximation

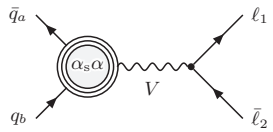
Dittmaier et al., NPB 885 (2014) 318, NPB 904 (2016) 216

- The NNLO $\mathcal{O}(\alpha\alpha_s)$ correction was the largest unknown fixed order term
- The calculation by Dittmaier et al. is performed in pole approximation allowing for the factorization "production $\times$ decay"

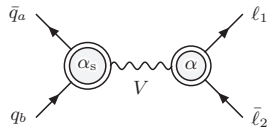
EW/QCD corrections in pole approximation (Dittmaier/Huss/CS)

(+ corresponding real-virtual and double real)

- Factorizable initial (partial results: Kotikov/Kühn/Veretin 07; Bonciani 11)

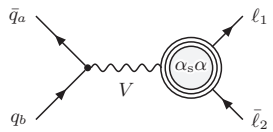


- Factorizable initial$\times$final (expected to be dominant, preliminary results)

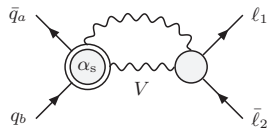


- Factorizable final$\times$final

(from counterterm, can be obtained from Djouadi/Gambino 93)



- Non-factorizable corrections (completed, numerically negligible)

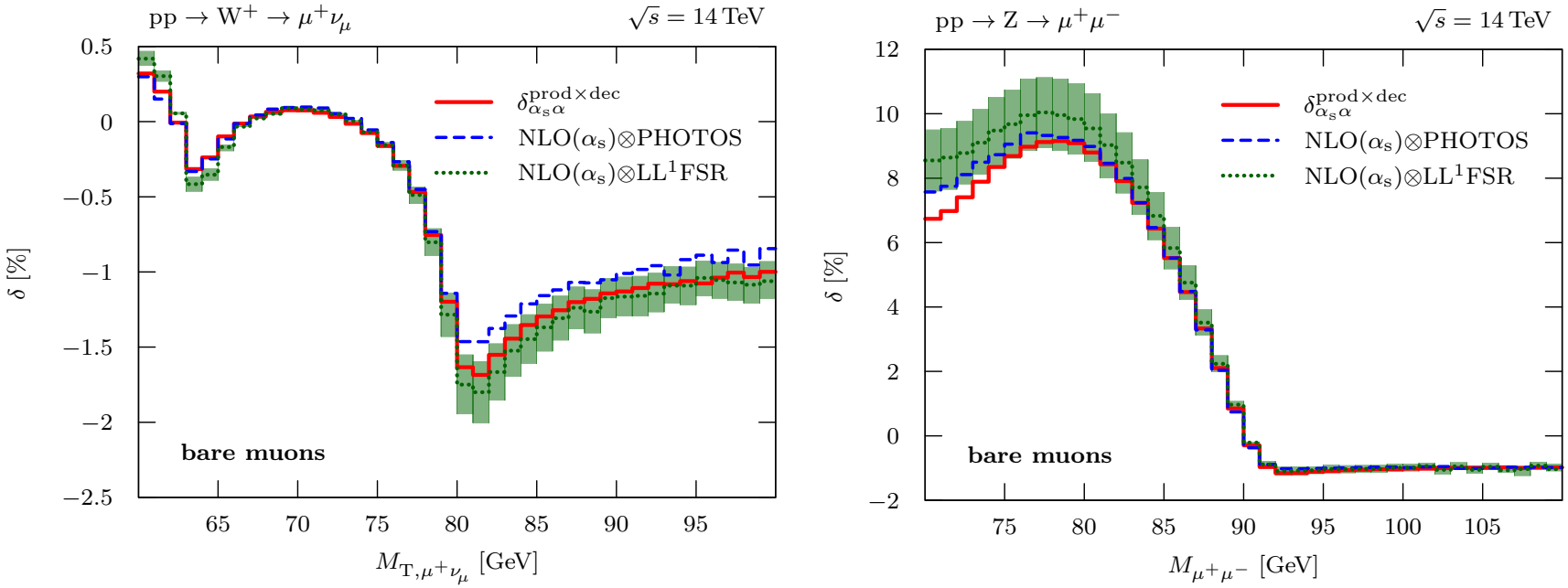


from C. Schwinn, SM@LHC 2015

Effect of dominant $\mathcal{O}(\alpha\alpha_s)$ correction in pole approximantion

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

- *In principle* NLOPS QCD⊕EW approach catches only part of this correction



- *A posteriori* the dominant correction is quite well reproduced by a **POWHEG**-like QCD⊕EW NLOPS approach, both in CC and NC DY
- Estimate of the M_W shift induced by NNLO $\mathcal{O}(\alpha\alpha_s) \rightarrow \delta M_W = \mathcal{O}(10)$ MeV

Work in progress

PRELIMINARY

Precisions Studies of Observables in $pp \to W \to l\nu_l$ and $pp \to \gamma, Z \to l^+l^-$ processes at the LHC

coordinated by A.Vicini, D. Wackeroth

Within the LPCC EW WG activities, a report is being finalized aiming at

- ⋆ providing a benchmark framework for precise studies of DY observables, with tuned setup, reproducible results from several MC tools/calculations and comparisons among them
- ⋆ mantainining a repository of codes "blessed" by the authors to calculate QCD NNLO, QCD NLO, EW NLO, mixed EW⊗QCD, multi-photon corrections

Theoretical contributions and systematics to the M_W measurement

Carloni Calame, Martinez, Montagna, Nicrosini, Piccinini, Vicini, *in preparation*

- We study, from a theory point of view, the interplay of EW and QCD RC on M_W extraction, aiming at a sound estimate of the theoretical error & systematics
- We make use of **POWHEG_ew** / **HORACE** / **PHOTOS** / **PYTHIA** to quantify in a consistent way the effect of NLO QCD, NLO EW, multi-photon radiation, light-pair corrections, mixed $\mathcal{O}(\alpha\alpha_s)$ corrections, with and w/o detector effects (using **DELPHES**)

  Delphes collaboration, JHEP 02 (2014) 057
- A template fitting procedure is performed: we produce pseudo data at a given accuracy with "nominal" M_W and we extract the relative δM_W by fitting distributions which include the effect under study

⋆ A non-trivial tuning of the codes has to be done, high MC statistics is needed to disentangle small effects (at the MeV level)

⋆ Work in progress

Conclusions and Outlook

- In the last decade and a ½, EW corrections to charged and neutral current Drell-Yan have been scrutinized in detail
  - ⋆ full EW NLO
  - ⋆ higher order QED effects matched with EW NLO
  - ⋆ matching with QCD NLOPS generators
  - ⋆ NNLO fixed order $\mathcal{O}(\alpha\alpha_s)$ corrections
- Generally available into MC, they play an important role in precision physics at LHC for SM tests (M_W), New Physics searches at high energy, detector calibration (Z), PDF constraint and measurement
- On-going effort by the theory community to setup a common framework for simulation of DY with (almost) all publicly availables codes, to provide benchmark numbers and to mantain a repository
- Work in progress to systematically evaluate the effect of various RC on M_W extraction from experiments, for a sound estimate of the residual theoretical error in view of the LHC measurement