W/Z production at the LHC: state of the art of radiative corrections

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Mainly based on work in coll. with L. Barzè, C.M. Carloni Calame, P. Nason, O. Nicrosini, F. Piccinini, A. Vicini

The quest for precision

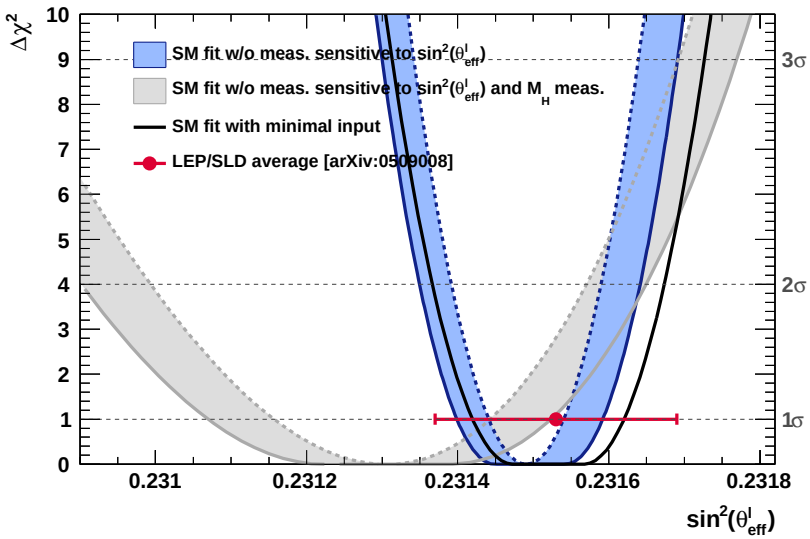
Several millions / year of $p\,p \to W, Z \to \ell\nu_\ell, \ell^+\ell^-$, $l = e, \mu$ events at the LHC

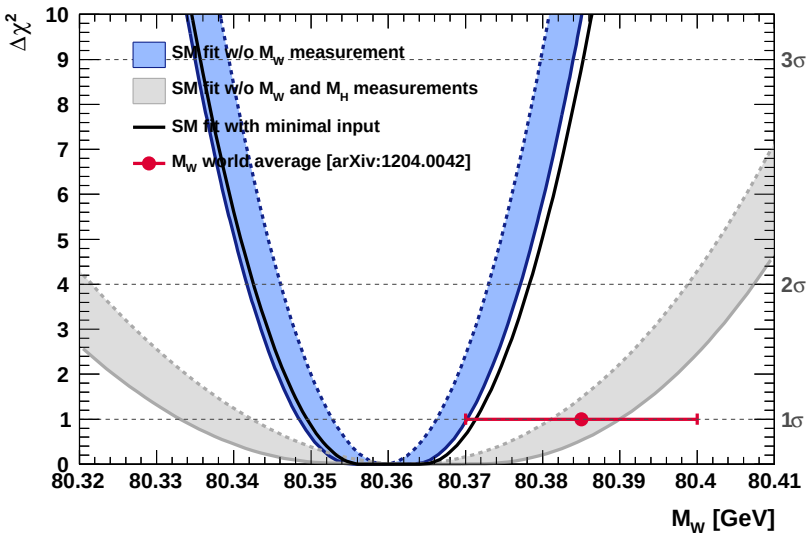
$$\hookrightarrow \quad \sigma_{W/Z} = \sigma_{\rm LO} + \sigma_{\alpha_{\rm s}} + \sigma_{\alpha_{\rm s}^2} + \text{higher orders} \qquad \text{QCD}$$
$$+ \quad \sigma_{\alpha} + \text{higher orders} \qquad \text{EW}$$
$$+ \quad \sigma_{\alpha\alpha_{\rm s}} + \sigma_{\alpha^n\alpha_{\rm s}^m} + \cdots \qquad \text{QCD} - \text{EW}$$

1. standard candles to calibrate detectors, constrain the PDFs, tune Monte Carlo ...
2. backgrounds to new physics searches
3. handles to measure precisely electroweak parameters: $M_W, \Gamma_W, \sin^2\theta^\ell_{\rm eff}$

Quantum consistency of the SM after the discovery of the Higgs

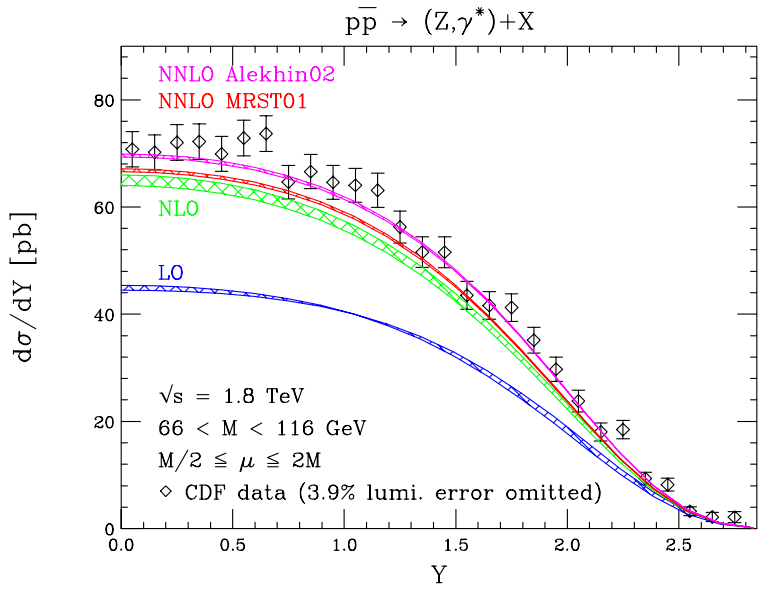
M. Baak *et al.*, the Gfitter group 2012





High–precision QCD

- Total production rates and rapidity distributions at NNLO (R. Hamberg, W.L. van Neerven and T. Matsuura 1991 / W.L. van Neerven and E.B. Zijlstra 1992 / R.V. Harlander and W.B. Kilgore 2002 / C. Anastasiou *et al.* 2003, 2004)



- Fully differential cross sections at NNLO in FEWZ (K. Melnikov and F. Petriello 2006 / R. Gavin *et al.* 2010, 2012) and DYNNLO (S. Catani *et al.* 2009)

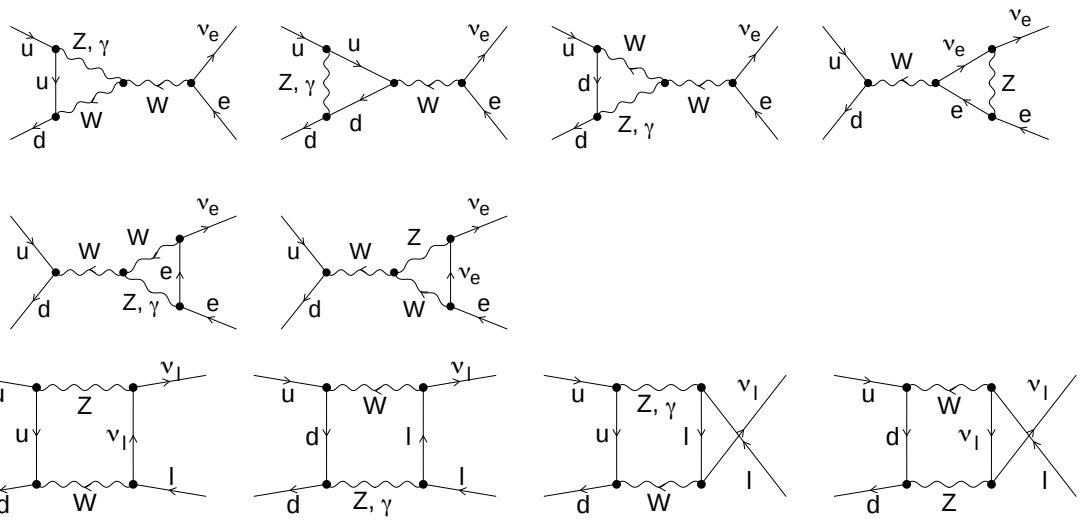
- Large logs resummation in ResBos (C. Balazs and C.P. Yuan 1997 / F. Landry *et al.* 2002) and in DYqT (G. Bozzi *et al.* 2009, 2011)

- NLO Parton Showers: MC@NLO (S. Frixione and B. Webber 2002) / POWHEG (P. Nason 2004) / SHERPA (S. Hoeche *et al.* 2011)

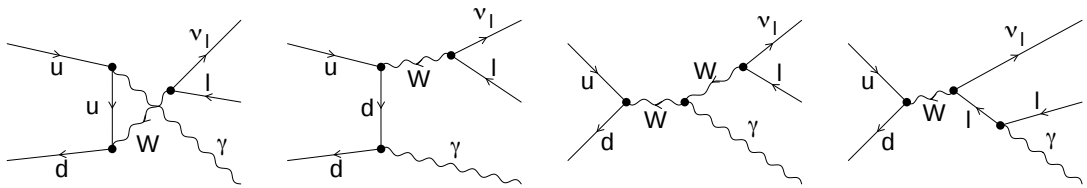
Electroweak corrections: main features

- **Loop corrections** $\longrightarrow$ 1. running of the couplings 2. electroweak Sudakov logs

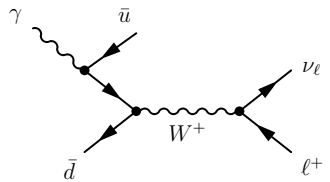
  $\alpha_{\rm ew} \log^n(\hat{s}/M_V^2)$, $n = 2, 1$, relevant for $\hat{s} \gg M^2_{V=W,Z}$

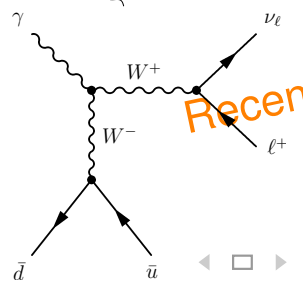


- **Bremsstrahlung corrections** $\longrightarrow$ mass singularities $\alpha_{\rm em} \log(\hat{s}/m_f^2)$, dominant at $\sqrt{\hat{s}} \simeq M_V$ [initial-state divergences reabsorbed into PDFs]



- **Photon-induced processes**





Recent work by NNPDF & CTEQ

Electroweak calculations & tools

- Complete NLO calculations
  - W production

    Pole approximation / NLO — U. Baur, S. Keller and D. Wackeroth 1999 / U. Baur and D. Wackeroth 2004 — WGRAD/WGRAD2

    NLO — S. Dittmaier and M. Krämer 2002 — DK → RADY

    + γ-induced/$\mathcal{O}(\alpha^2)$ Sudakov logs / multi-photon FSR — S. Brensing *et al.* 2007

    NLO + γ-induced + multi-photon PS — C.M. Carloni Calame *et al.* 2006 — HORACE

    NLO + γ-induced — A. Arbuzov *et al.* 2006, 2008 — SANC

  - γ^*, Z production

    $\mathrm{NLO_{QED}}$ / $\mathrm{NLO_{EW}}$ — U. Baur, S. Keller and W.K. Sakumoto 1998 / U. Baur *et al.* 2002 — ZGRAD/ZGRAD2

    NLO + γ-induced + multi-photon PS — C.M. Carloni Calame *et al.* 2007 — HORACE

    NLO + γ-induced — A. Arbuzov *et al.* 2008 — SANC

    NLO + γ-induced/$\mathcal{O}(\alpha^2)$ Sudakov logs / multi-photon FSR — S. Dittmaier and M. Huber 2010 — RADY

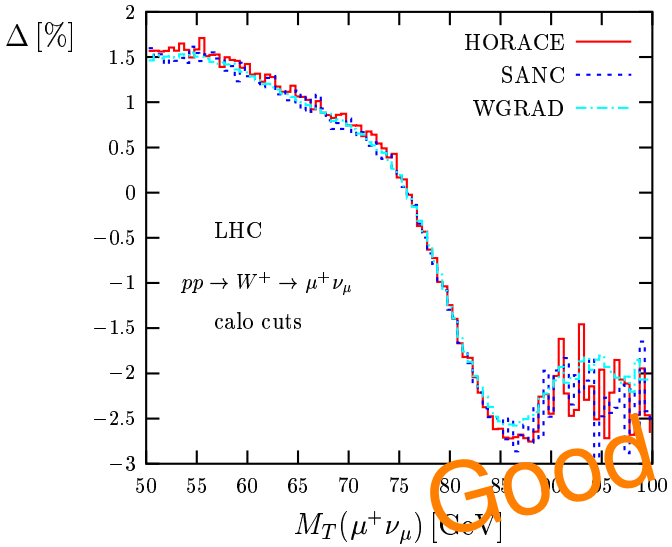
- Tools for exclusive multiple photon radiation PHOTOS (P. Golonka and Z. Was 2006) / WINHAC (W. Placzek and S. Jadach 2003) / HORACE (C.M. Carloni Calame *et al.* 2004, 2005) ...

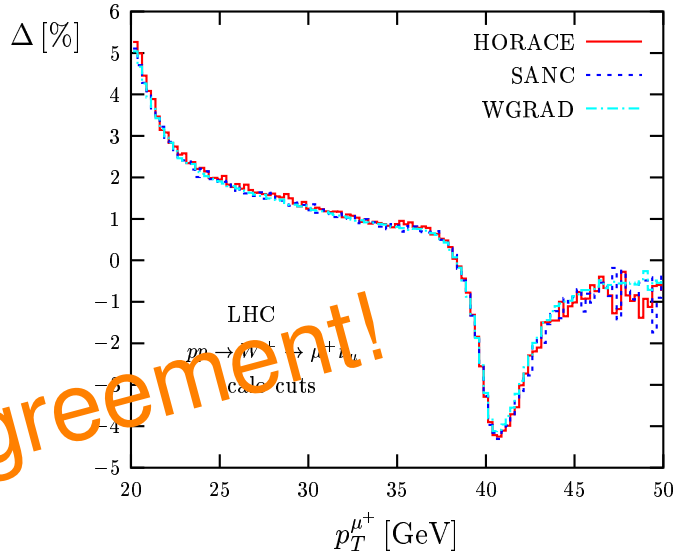
Tuned comparisons: examples

Ongoing work @ CERN coordinated by
D. Wackeroth and A. Vicini

Les Houches 2005, 2007 / TeV4LHC 2007

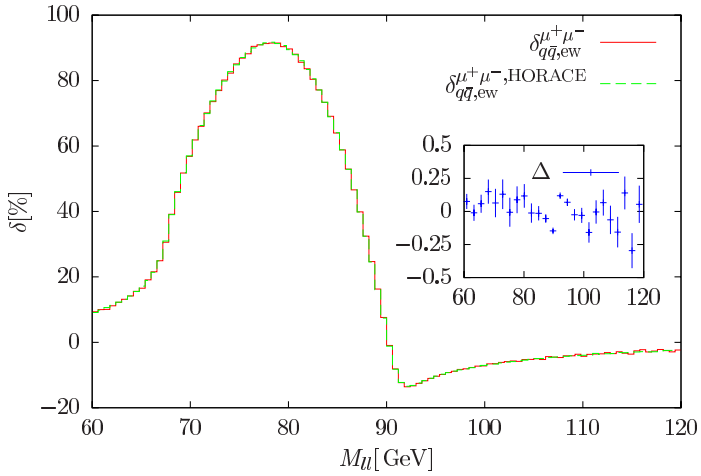
- W production

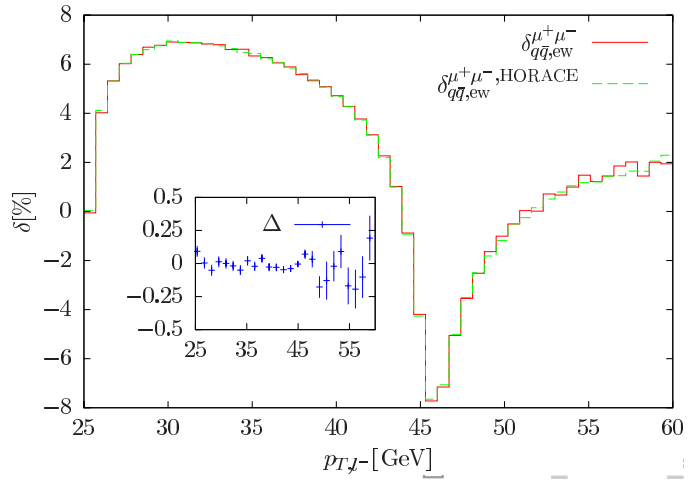




Good agreement!

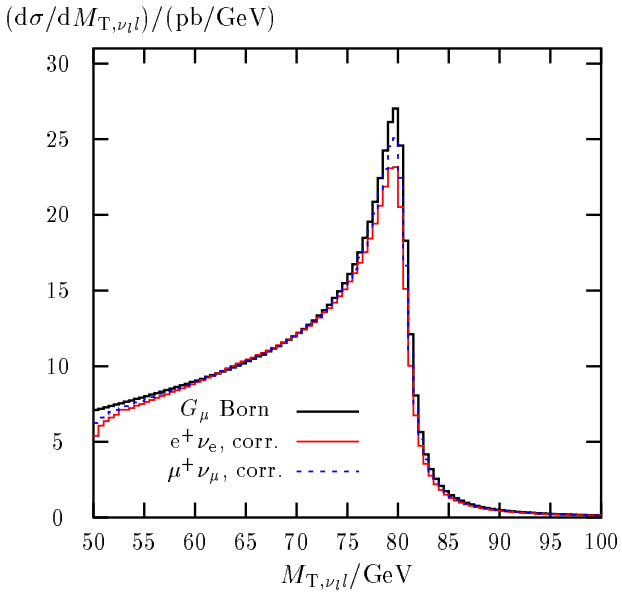
- Z production

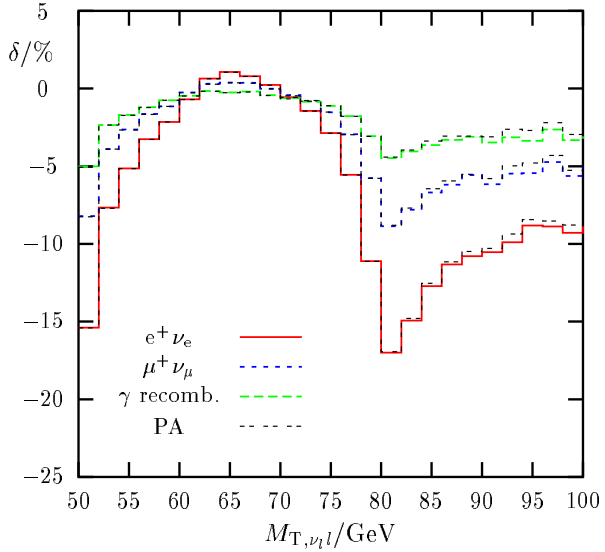




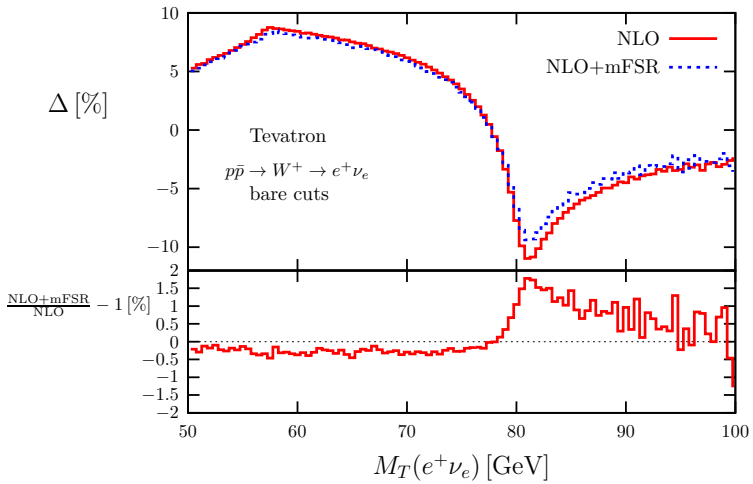
$\mathrm{NLO_{EW}}$ and multi–photon corrections at the pole

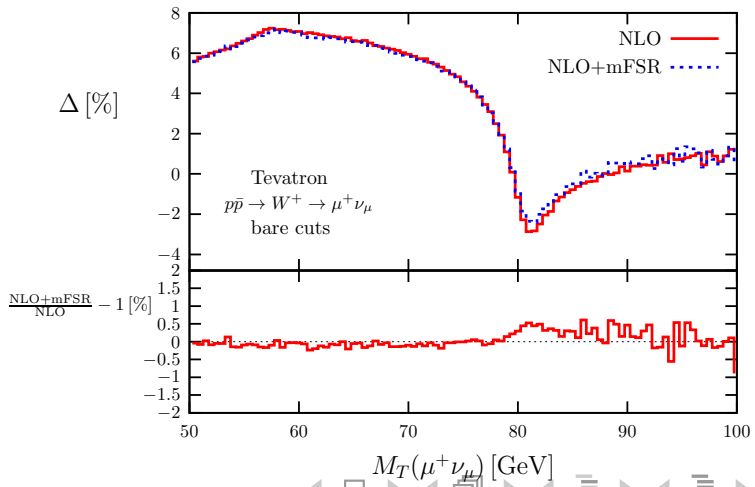
- $\mathrm{NLO_{EW}}$ dominated by FSR, that strongly depends on lepton id. criteria





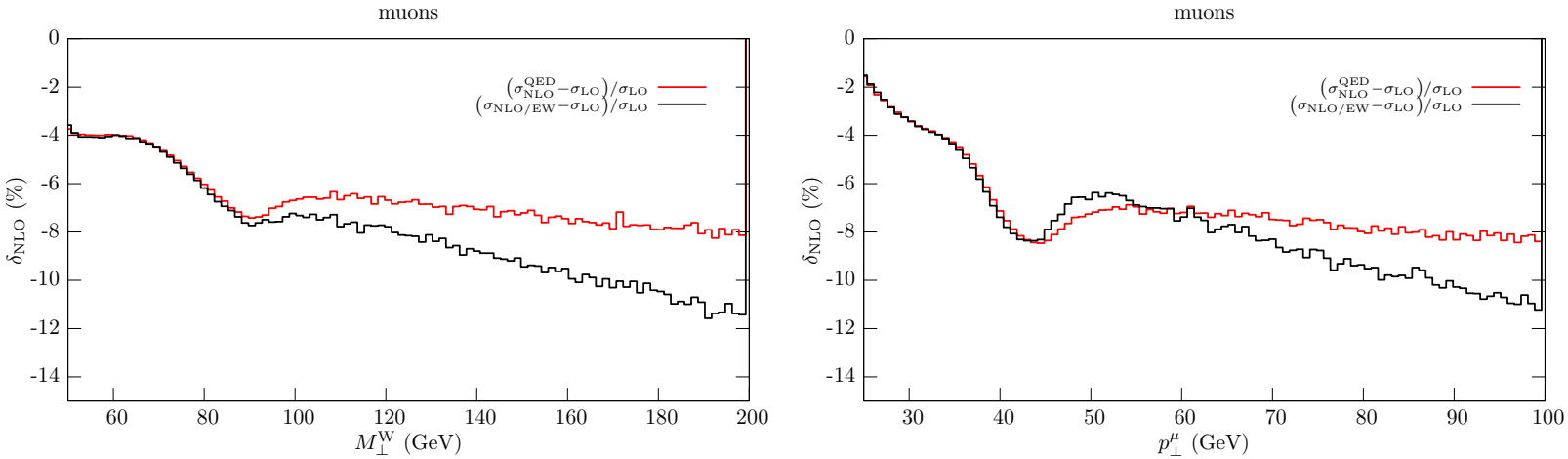
- Multiple γ at the (sub-)percent level $\longrightarrow \Delta M_W^{\mathrm{QED}^\infty} \sim 10\%\, \Delta M_W^{\mathrm{QED}^\alpha}$





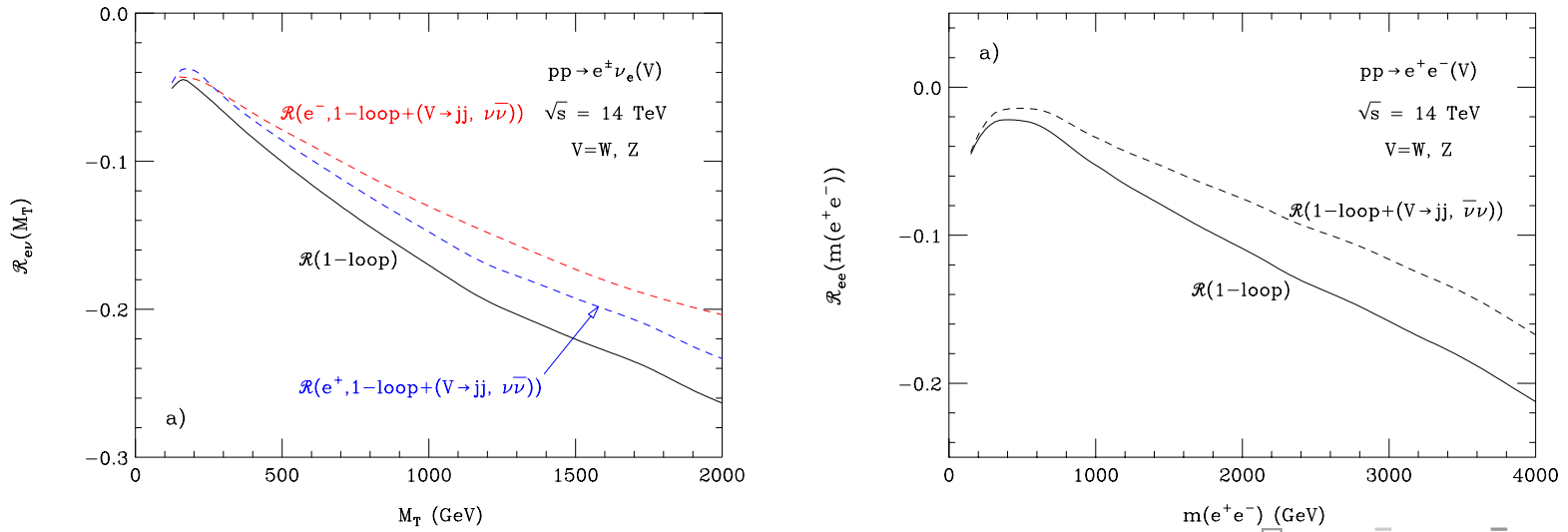
Electroweak Sudakov logs in the high tails

- FSR (red) insufficient w.r.t. $\mathrm{NLO_{EW}}$ (black) in the tails



- Two-loop Sudakov logs and (inclusive) radiation of real vector bosons partially cancel the large negative one-loop Sudakov logs

U. Baur 2007



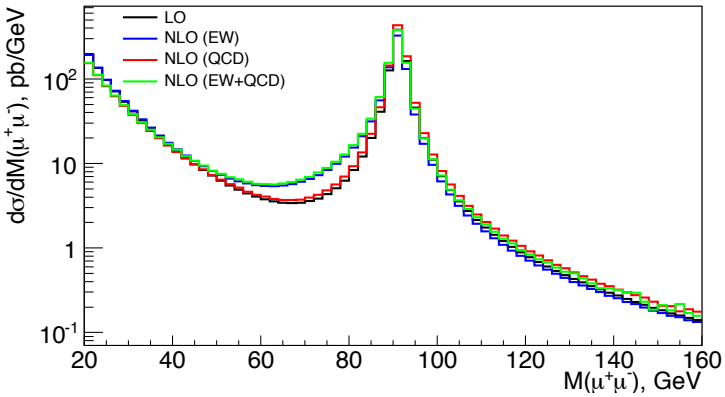
Combining QCD and electroweak corrections

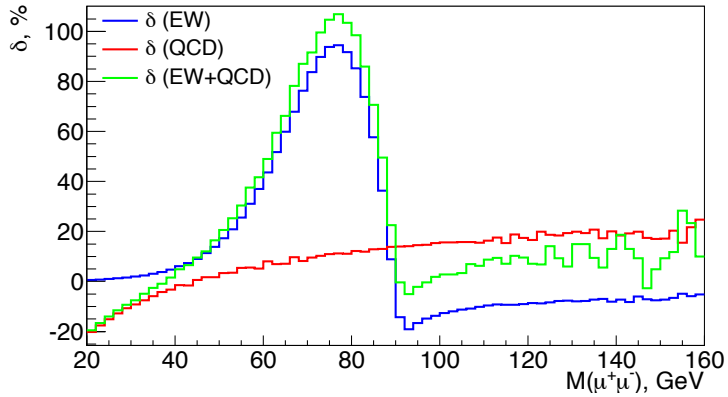
Issue fixed by the calculation of the full 2-loop $\mathcal{O}(\alpha\alpha_s)$ corrections, unavailable yet.
Alternatives:

Additive $1 + \delta_{\rm QCD} + \delta_{\rm EW}$ vs. **Factorized** $(1 + \delta_{\rm QCD}) \times (1 + \delta_{\rm EW})$

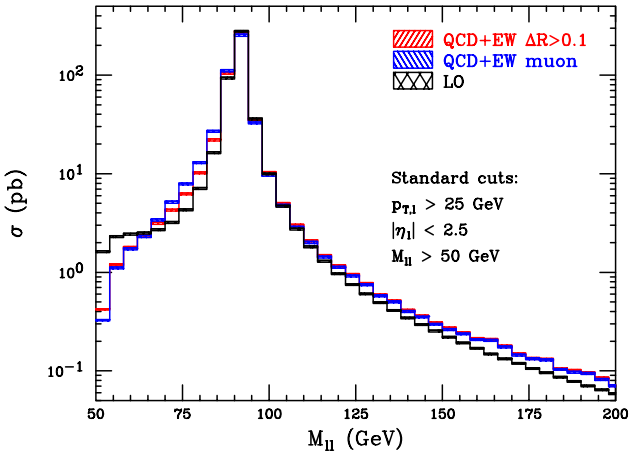
- $\text{NLO}_{\rm QCD} \oplus \text{NLO}_{\rm EW}$: RADY and SANC/mcsanc for W & Z production

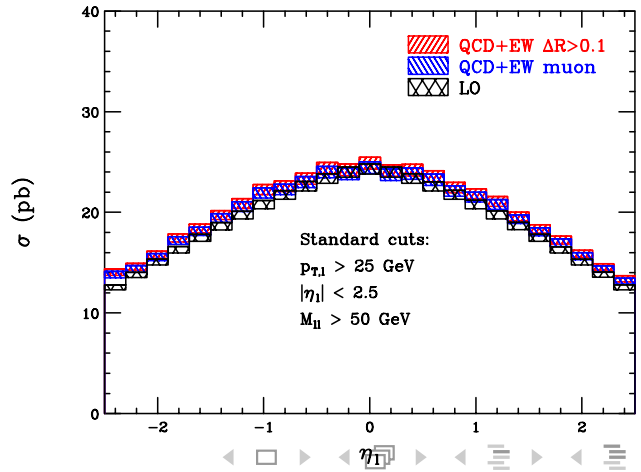
S. Bondarenko and A. Sapronov 2013





- $\text{NNLO}_{\rm QCD} \oplus \text{NLO}_{\rm EW}$: recent FEWZ version (Y. Li and F. Petriello 2012) [Z only]





QCD⊗EW combination in POWHEG: the method

P. Nason 2004 / S. Frixione, P. Nason and C. Oleari 2007

POWHEG idea: **hardest radiation at NLO followed by $p_{\rm T}$-ordered shower**

$$d\sigma = \sum_f \bar{B}^f(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^f\left(\mathbf{\Phi}_n, p_{\rm T}^{\rm min}\right) + \sum_{\alpha_{\rm r}} \frac{d\Phi_{\rm rad}\ \theta\left(k_{\rm T} - p_{\rm T}^{\rm min}\right) \Delta^f(\mathbf{\Phi}_n, k_{\rm T})\ R(\mathbf{\Phi}_{n+1})}{B^f(\mathbf{\Phi}_n)} \right\}$$

- $\bar{B}^f(\mathbf{\Phi}_n)$: **NLO normalization**

$$\bar{B}^f(\mathbf{\Phi}_n) = \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)\right]_f + \sum_{\alpha_{\rm r}} \int d\Phi_{\rm rad} \left[R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1})\right]$$
$$+ \sum_{\alpha_\oplus} \int \frac{dz}{z} G_\oplus^{\alpha_\oplus}(\mathbf{\Phi}_{n,\oplus}) + \sum_{\alpha_\ominus} \int \frac{dz}{z} G_\ominus^{\alpha_\ominus}(\mathbf{\Phi}_{n,\ominus})$$

- $\Delta^f(\mathbf{\Phi}_n, p_{\rm T})$: **(modified) Sudakov form factor**

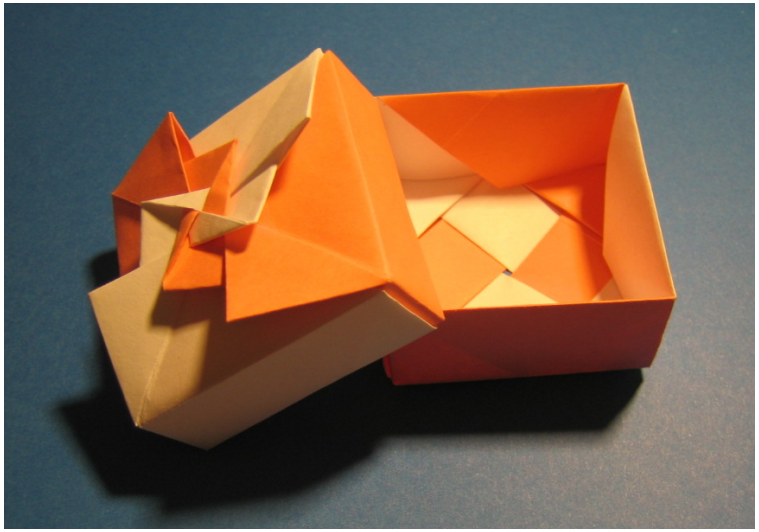
$$\Delta^f(\mathbf{\Phi}_n, p_{\rm T}) = \exp\left\{ -\sum_{\alpha_{\rm r}} \int \frac{d\Phi_{\rm rad}\, R(\mathbf{\Phi}_{n+1})\ \theta(k_{\rm T}(\mathbf{\Phi}_{n+1}) - p_{\rm T})}{B^f(\mathbf{\Phi}_n)} \right\} .$$

- **QCD $\longrightarrow$ QCD⊗EW combination**

C. Bernaciak and D. Wackeroth 2012
L. Barzè *et al.* 2012, 2013

V = virtual + soft/coll. = $V_{\rm QCD} + V_{\rm EW}$
R = real radiation m.e. = $R_{\rm QCD} + R_{\rm EW}$
C = coll. counterterms = $C_{\rm QCD} + C_{\rm QED}$
$G_{\oplus/\ominus}$ = coll. remnants = $G_{\rm QCD} + G_{\rm QED}$
$\alpha_{\rm r}$ = singular regions of R = ${\alpha_{\rm r}}^{\rm QCD} + {\alpha_{\rm r}}^{\rm QED}$

QCD⊗EW combinations in the POWHEG BOX



Two independent realizations, both available in the POWHEG BOX repository (S. Alioli *et al.* 2010) at `http://powhegbox.mib.infn.it`

1. W production – `POWHEG-BOX/W_ew-BW` (C. Bernaciak and D. Wackeroth 2012)
2. W/Z production
   `POWHEG-BOX/W_ew-BMNNP`
   `POWHEG-BOX/Z_ew-BMNNPV`
   (L. Barzè *et al.* 2012, 2013)

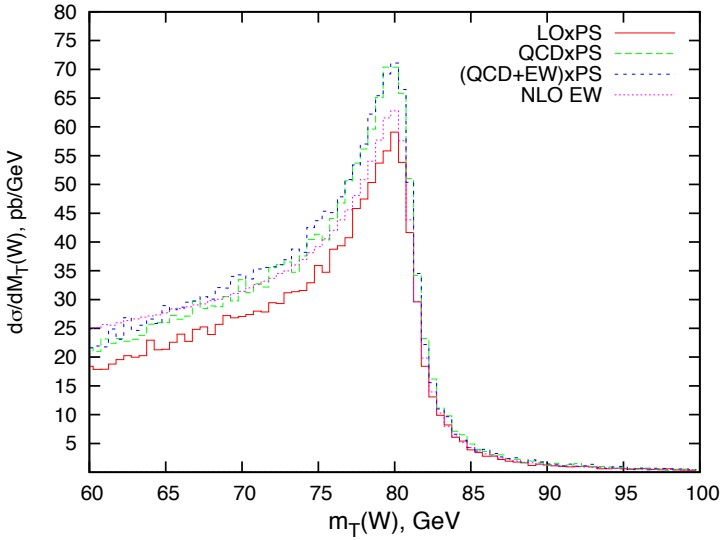
Main differences

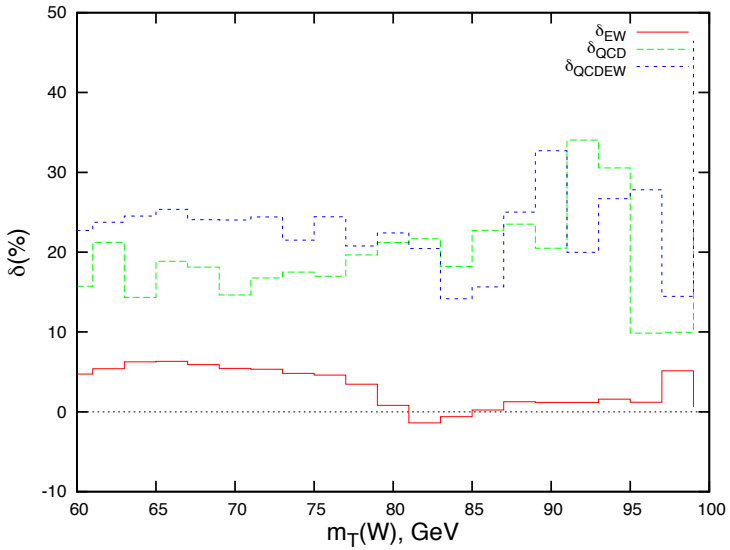
- L. Barzè *et al.* 2012, 2013
  - $V_{\rm EW}$ with hybrid regularization scheme: DR + mass scheme ($m_{q/g} = m_\gamma$ = 0, $m_\ell \neq 0$). FKS subtraction for IR divergences.
  - QCD shower and multiple FSR with `PHOTOS`. Choice of $p_{\rm T}^{\rm min}$: $\sim \Lambda_{\rm QCD}$ for QCD/QED radiation from partons / m_ℓ for QED radiation off leptons.
- C. Bernaciak and D. Wackeroth 2012
  - $V_{\rm EW}$, $R_{\rm EW}$ from `WGRAD2` library. Phase space slicing for IR divergences.
  - QCD shower but no multi-γ radiation.

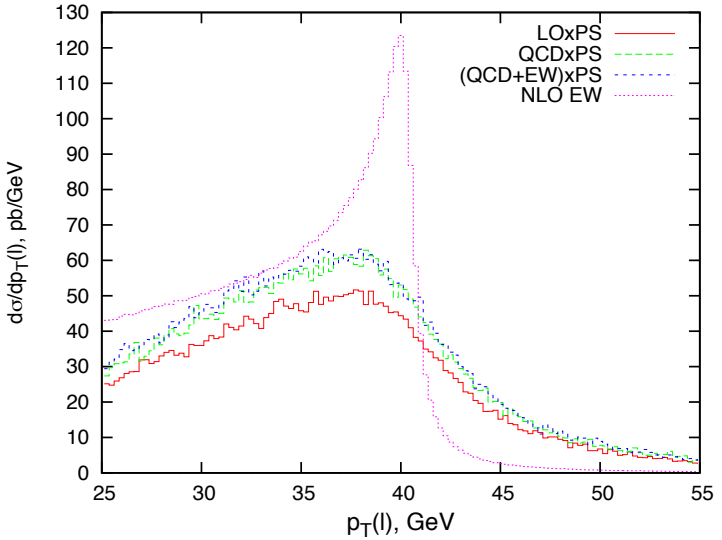
Combined QCD⊗EW corrections with POWHEG

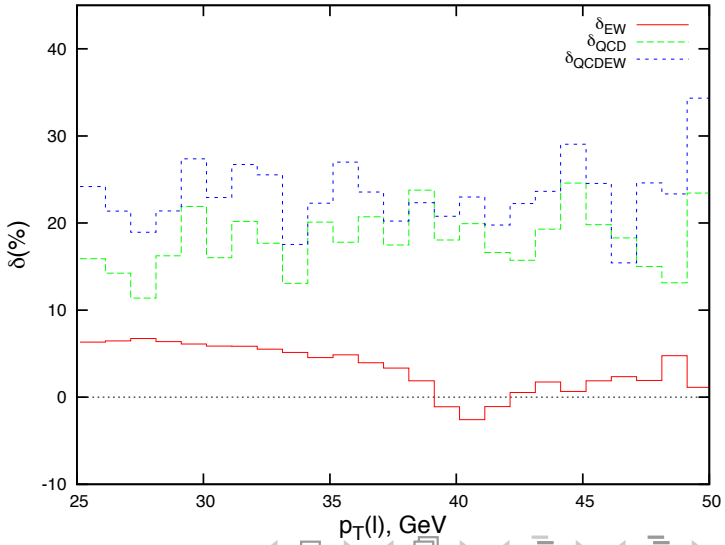
C. Bernaciak and D. Wackeroth 2012

- W production





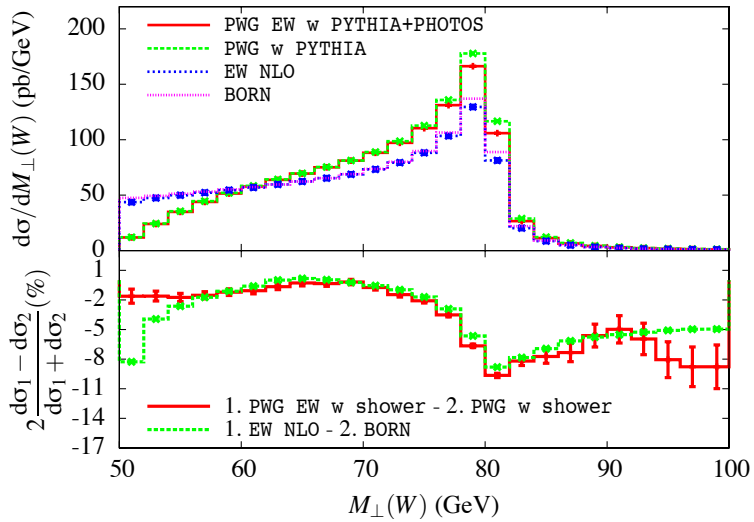


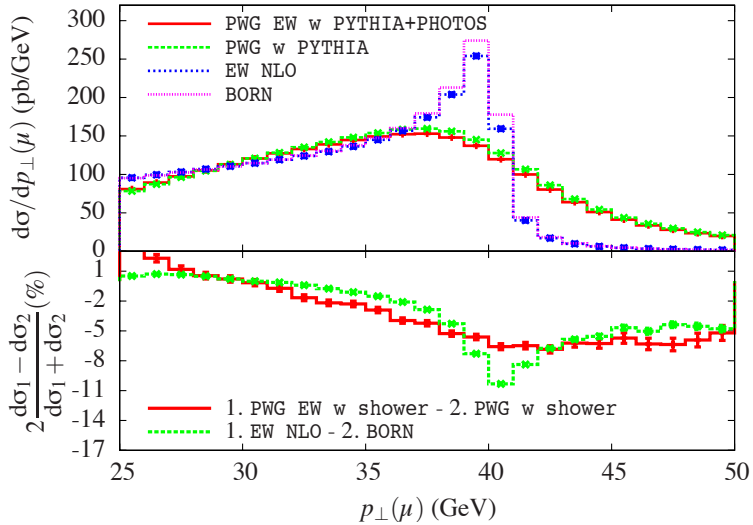


Combined QCD⊗EW corrections with POWHEG

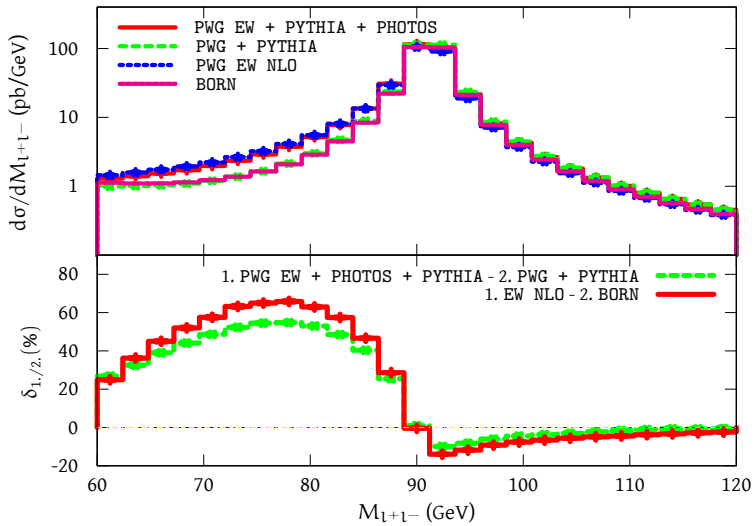
L. Barzè *et al.* 2012, 2013

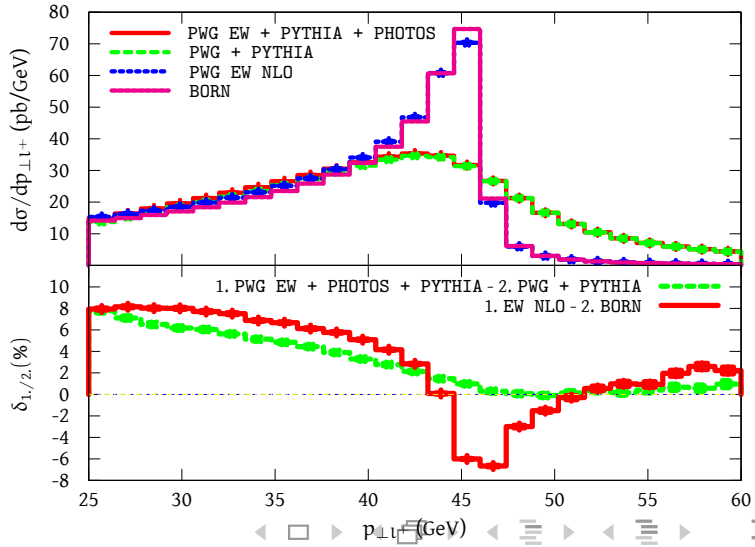
- W production





- Z production

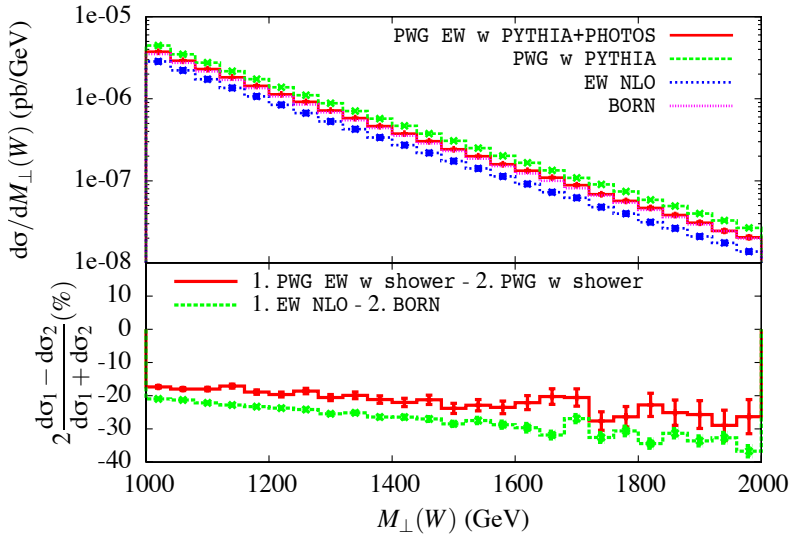


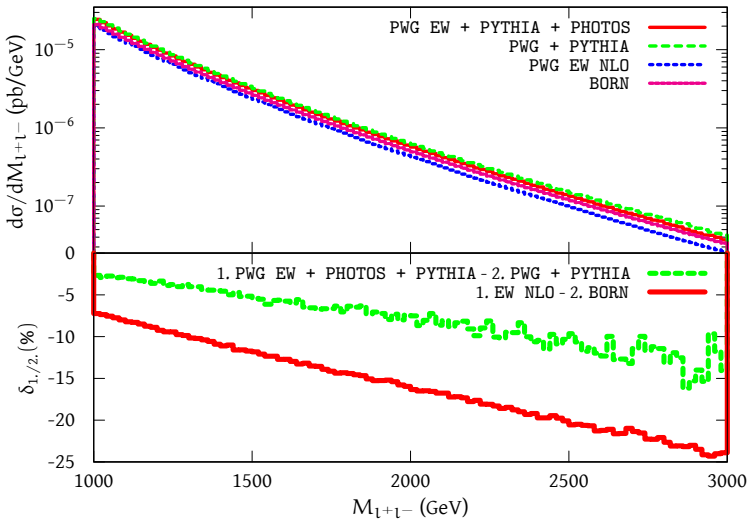


Combined QCD⊗EW corrections with POWHEG

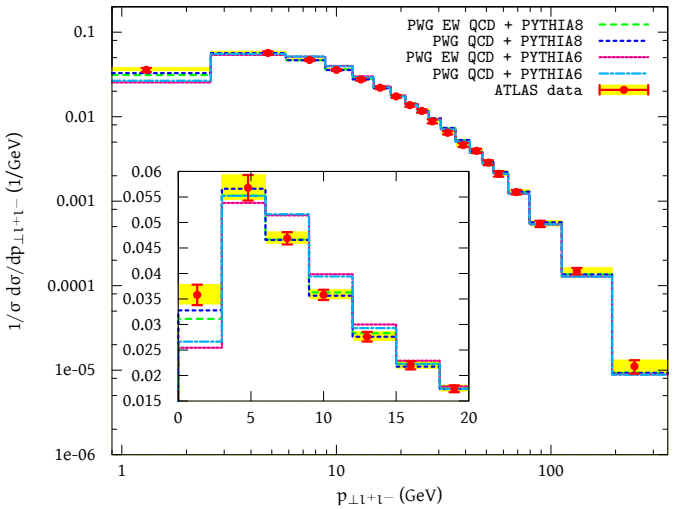
L. Barzè *et al.* 2012, 2013

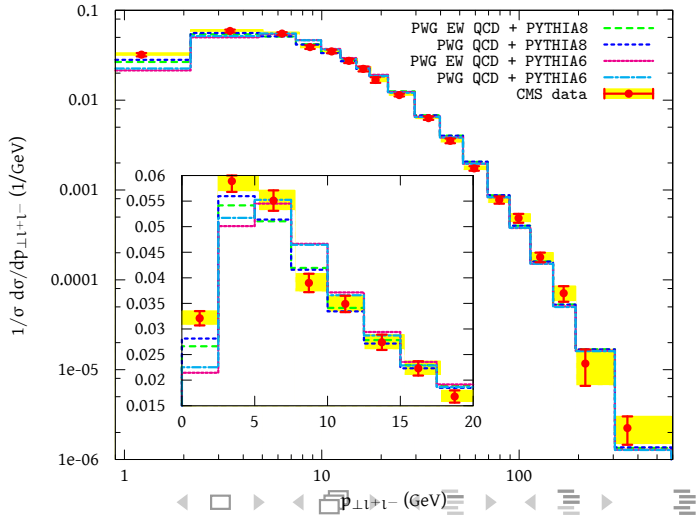
- W/Z production off the resonance





- Z-boson p_T vs. ATLAS/CMS data (w/o tuning)





Conclusions

What is available

QCD

- $\surd$ NNLO QCD corrections to total and differential cross sections
- $\surd$ NLO PS generators / Calculations including resummation

EW

- $\surd$ NLO + multiple photon corrections + two-loop Sudakov logs

QCD$\oplus/\otimes$EW

- $\surd\,\surd$ Partial $\mathcal{O}(\alpha_s\alpha)$ calculations (A. Denner *et al.* 2009, 2011 / W.B. Kilgore & C. Sturm 2011)
- $\surd\,\surd$ Additive (N)NLO$_{\rm QCD}\oplus$NLO$_{\rm EW}$ combinations
- $\surd\,\surd$ Factorized NLO$_{\rm QCD}\oplus$NLO$_{\rm EW}\otimes$ QCD/QED PS combinations

What is needed

- $\ominus$ Full $\mathcal{O}(\alpha_s\alpha)$ calculation(s)
- $\ominus$ New PDF set(s) with QED contributions $\hookrightarrow$ Ongoing work by CTEQ & NNPDF Coll.
- $\ominus$ Deeper understanding of th. uncertainty due to EW (e.g. pair radiation, γ-induced processes ...) and mixed QCD-EW contributions to precision measurements

GGI Workshop

Prospects and Precision at the Large Hadron Collider at 14 TeV

Period: From 01–09–2014 to 24–10-2014 / With 5^{th} HP2 workshop, 3–5 September

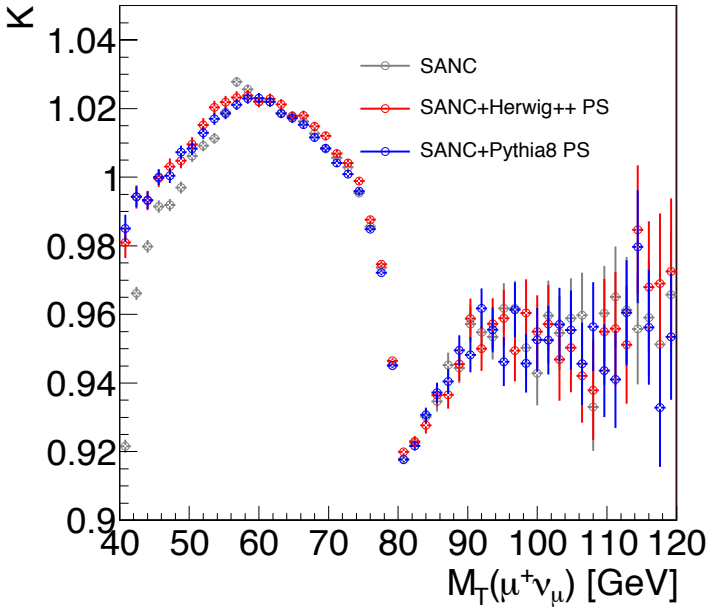
Organizers: Daniel de Florian, Sven Moch, Guido Montagna and Fulvio Piccinini

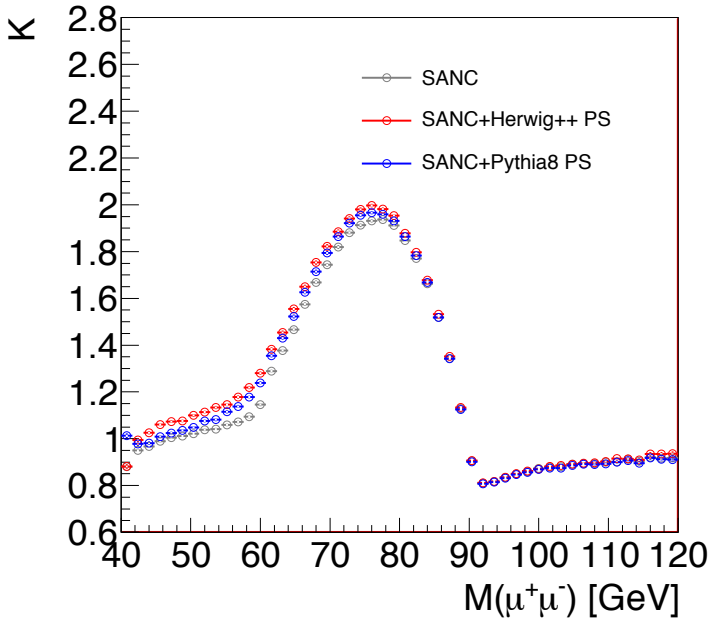
Topics:

- Particle physics in view of the next generation of LHC data
- Precision QCD and electroweak calculations
- New developments in Quantum Field Theory at higher orders and Monte Carlo generators
- Higgs physics, electroweak measurements and new physics searches
- Jet dynamics, parton distribution functions and multiple parton interactions

Independent studies of QCD⊗EW combination

- SANC interfaced to PYTHIA8 and HERWIG++ (P. Richardson *et al.* 2012)

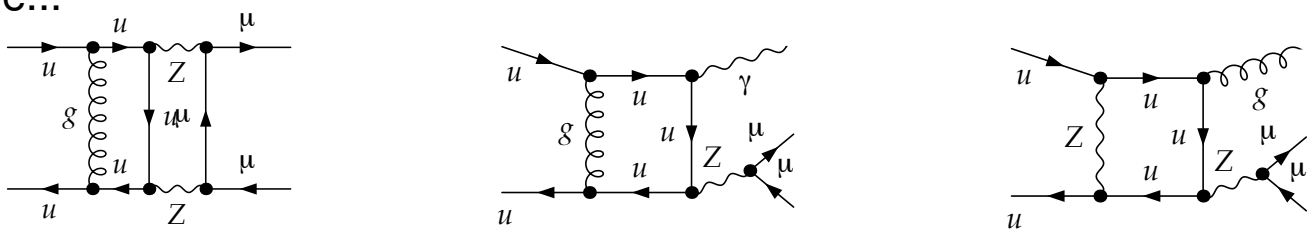




- NLO EW corrections and YFS QED⊗QCD exponentiation in HERWIRI2 (S. Yost *et al.* 2011)
- Additive/Factorized combination using MC@NLO and HORACE (G. Balossini *et al.* 2010)
- PHOTOS interfaced to MC@NLO (N.E. Adam *et al.* 2008, 2010)
- QCD resummation & NLO QED FSR in ResBos-A (Q.-H. Cao & C.P. Yuan 2004)

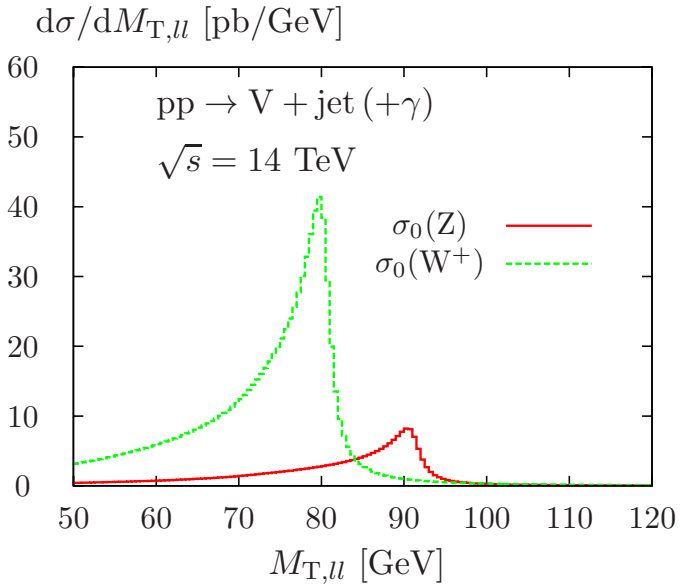
Available $\mathcal{O}(\alpha\alpha_s)$ calculations

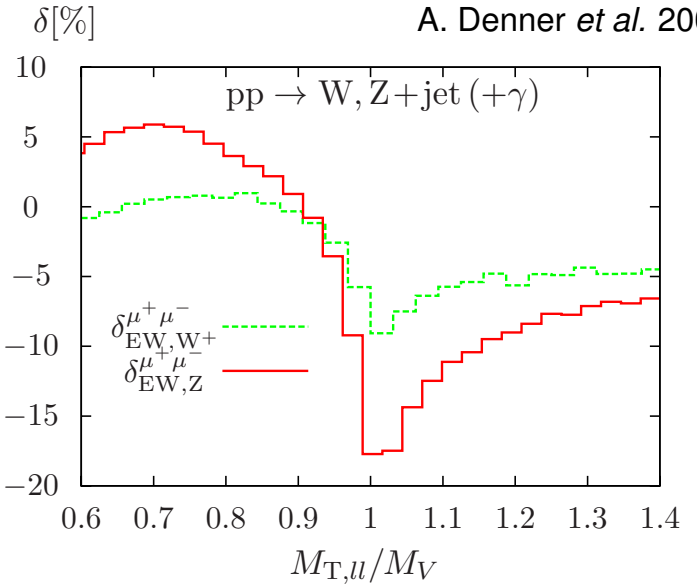
In principle...



1. NLO_{QCD} corrections to V + visible γ production, including leptonic V decays (J.M. Campbell, R.K. Ellis and C. Williams 2011 / D. de Florian and A. Signer 2000)
2. NLO_{EW} corrections to V + visible jet production, w/o (J.H. Kühn *et al.* 2005, 2007) and with leptonic V decays (A. Denner *et al.* 2009, 2011)
3. Mixed QCD⊗QED virtual corrections to NC DY (W.B. Kilgore and C. Sturm 2011)

A. Denner *et al.* 2009, 2011



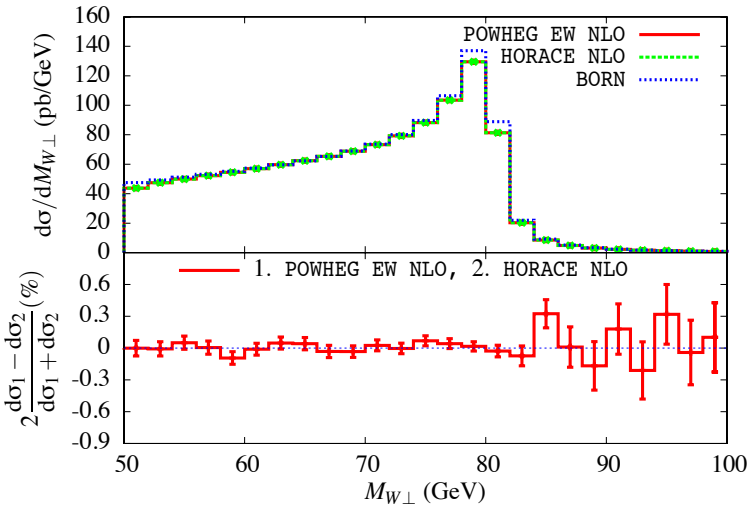


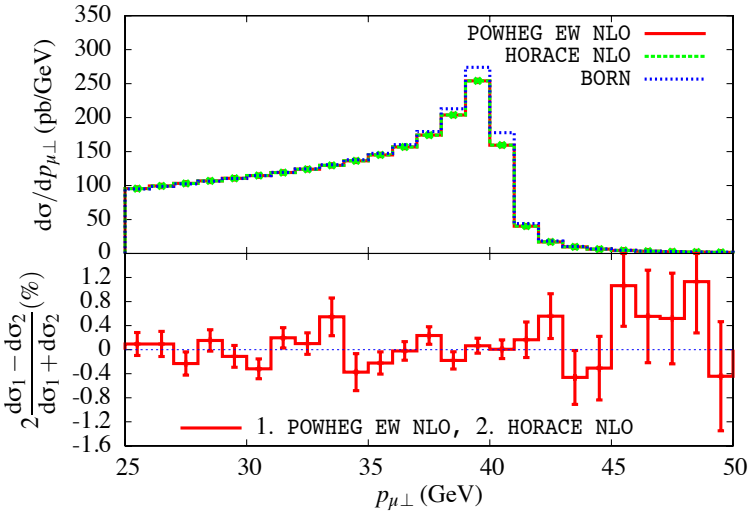
↪ $\delta_{\text{EW}}^{\text{NLO}}$ to V + jet "identical" to V production ⟶ supports QCD⊗EW factorization

$\mathrm{NLO_{EW}}$ corrections in POWHEG: validation

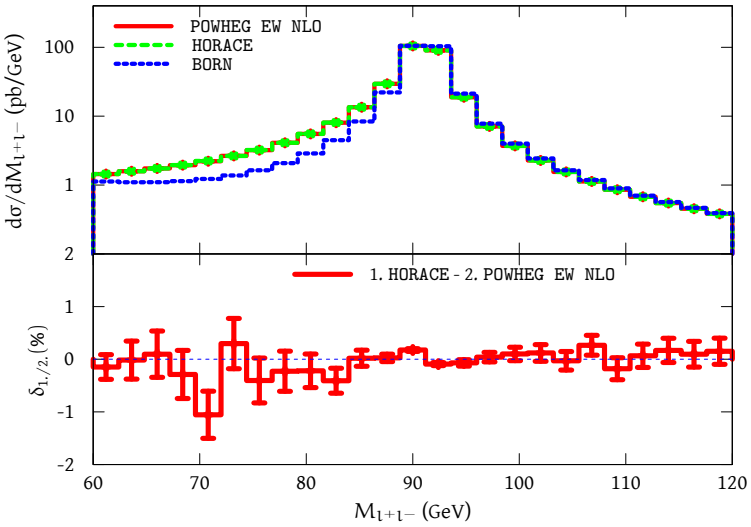
L. Barzè *et al.* 2012, 2013

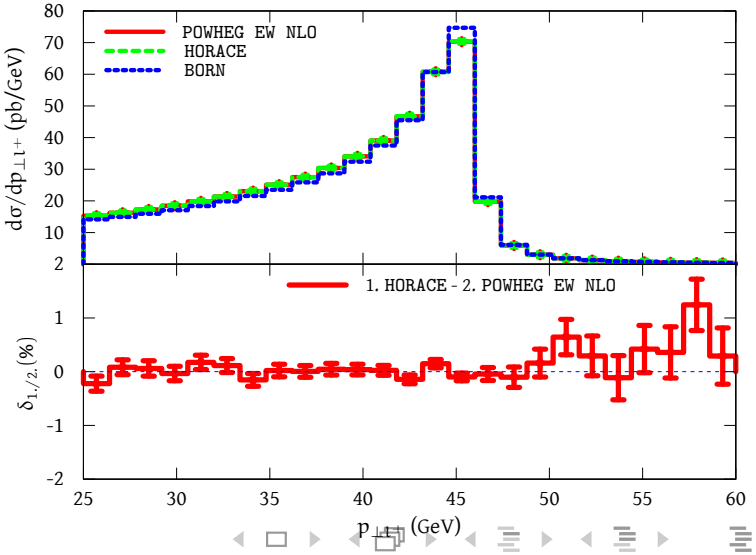
- W production



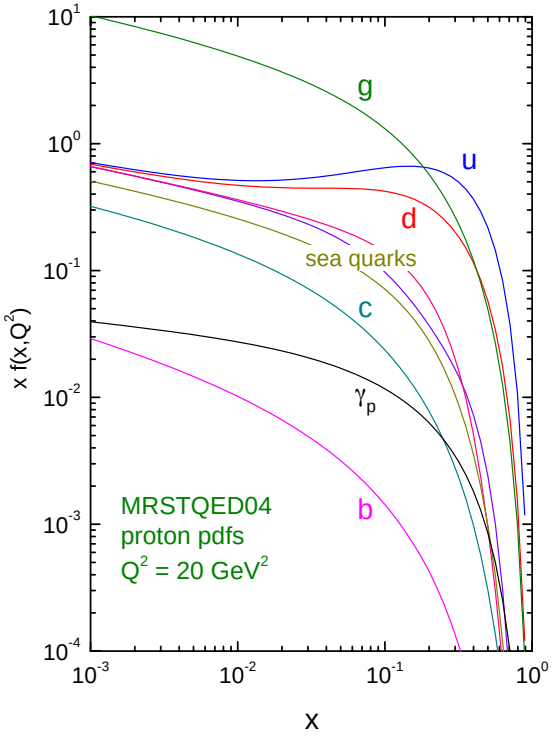
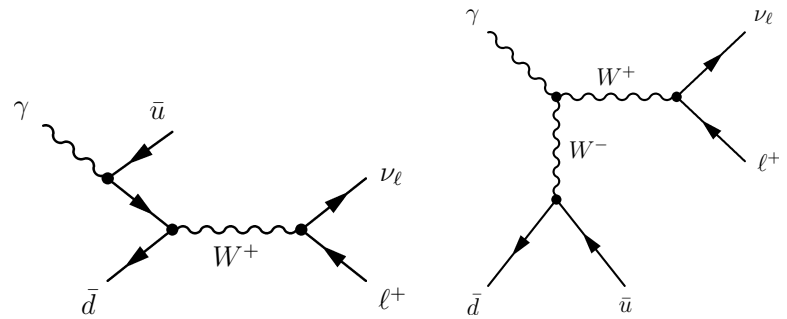
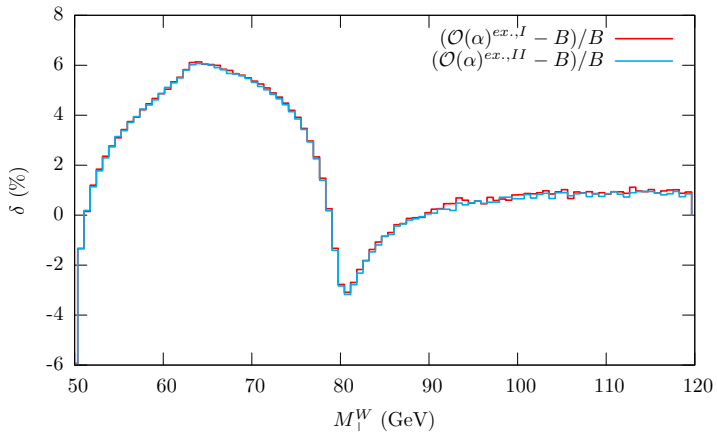
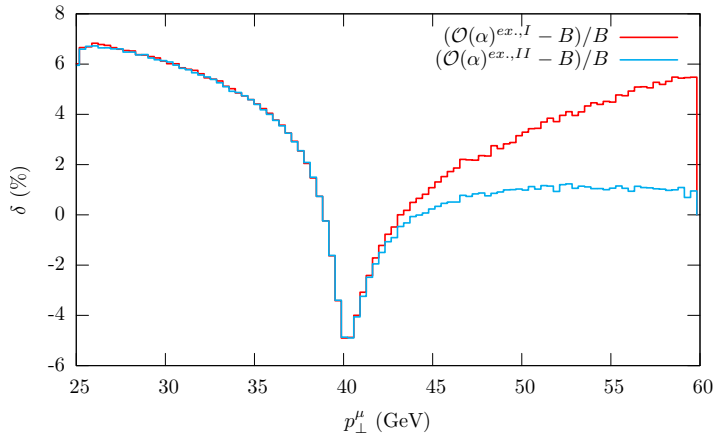


- Z production





QED effects in PDFs & γ–induced processes



- QED contribution to PDF evolution via $\alpha_{\rm em}$ modification of DGLAP equation (H. Spiesberger 1995 / M. Roth and S. Weinzierl 2004 / A.D. Martin *et al.* 2005)
  ↪ NEW: work by NNPDF and CTEQ Coll.
- dynamic generation of photon PDF
  ⟶ photon induced processes