Electroweak NLOPS for the Higgs decay into four charged leptons

C.M. Carloni Calame
Pavia University

HP2^5 workshop, Galileo Galilei Institute, Florence

in collaboration with S. Boselli, G. Montagna, O. Nicrosini, F. Piccinini

Summary

- ⋆ Motivations for a detailed simulation of $H \to ZZ \to 2\ell 2\ell^{(\prime)}$
- ⋆ Outline of the EW NLO calculation (in the SM)
- ⋆ Matching EW NLO with a QED Parton Shower
- ⋆ Comparison to independent calculations
- ⋆ Results
- ⋆ Conclusions and outlook

Motivations

- after the Higgs discovery, its nature is studied with high precision
- H mass already measured at the few 0.1% level

$$
\begin{aligned}
m_H \;=\; & 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys})\ \text{GeV} \quad [\text{ATLAS}] \\
& 125.6 \pm 0.4\,(\text{stat}) \pm 0.2\,(\text{sys})\ \text{GeV} \quad [\text{CMS}]
\end{aligned}
$$

arXiv:1406.3827 (submitted to PRD); PRD 89, 092007

- spin/parity consistent with the SM
- next run will require high accuracy SM predictions, to test SM itself or disentagle any deviation, firstly in the cleanest decay channels
  - ⋆ $H \to \gamma\gamma$
  - ⋆ $H \to ZZ \to 4$ charged leptons
- EW NLO and higher order corrections to H decay into 4ℓ have to be considered

Previous and independent work

- (gauge invariant) QED corrections to $H \to ZZ \to 4\ell$ in leading-log (LL) approximation, QED Parton Shower approach

  CMCC et al., NPB Proc. Suppl. **157**, 73 (2006)

  PoS HEP **2005**, 307 (2006)

  - ⋆ estimated impact of $\mathcal{O}(\alpha)$ RC on extracted m_H: $\mathcal{O}$(100 MeV)
  - ⋆ estimated impact of higher-order RC: $\mathcal{O}$(few 10 MeV)

- full one-loop EW (& QCD) corrections to $H \to ZZ/WW \to 4f$, implemented in the publicly available **`Prophecy4f`**

  A. Bredenstein et al., PRD 74 (2006) 013004

  NPB Proc. Suppl. **160** (2006) 131

  JHEP 0702 (2007)

⋆ combination of 1-loop EW RC and QED exponentiation is a desirable feature

NLO RC: calculation approach

As usual, the partial width is split into two parts, $\Gamma^{NLO} = \Gamma_{1\to4} + \Gamma_{1\to5}$

IR singularities are regularized with a vanishingly small photon mass λ

- $H \to 4\ell$

$$\Gamma_{1\to4} = \frac{1}{2m_H}\int d\Phi_4(|M_0|^2 + 2\Re[M_0^* \times M_\alpha^{1L}(\lambda)])$$

- $H \to 4\ell + \gamma$

$$\Gamma_{1\to5} = \frac{1}{2m_H}\int_{\omega>\lambda} d\Phi_5|M_\alpha^{1\gamma}|^2 = \delta(\lambda, k_0)\,\Gamma_0 + \frac{1}{2m_H}\int_{\omega>k_0} d\Phi_5|M_\alpha^{1\gamma}|^2$$

- matrix elements consistently evaluated including Z (and W, top) decay widths
- the integration over the 4/5-particles phase space is done with MC techniques and fully-exclusive events are generated

NLO RC: 1-loop corrections

- the full set (vertex, box, pentagon, self-energy corrections) of 1-loop EW diagrams are evaluated in the Feynman-'t Hooft gauge, in the on-shell renormalization scheme

  Omitted only the (negligible) diagrams where H is coupled to external fermions

- the on-shell ren. is "translated" to the *complex mass scheme* to consistently treat the Z (+ W, top) widths in the loop diagrams preserving IR cancellation and gauge invariance

  A. Denner et al., PLB **612**, 223 (2005), ibid. **704**, 667 (2011)

  A. Denner et al., NPB **724**, 247 (2005), ibid. **854**, 504 (2012)

- the 1-loop A, B, C, D, E functions and tensor coefficients are evalutated with the help of **`LoopTools v2.10`**, with complex Z, W, top masses

  T. Hahn, `www.feynarts.de/looptools/`

- *independence of UV & IR regulators checked with high numerical accuracy*

NLO cross-checks, comparison to **Prophecy4f**

- the calculation is implemented in the new MC EG **Hto4l**
- numerics done in the G_μ scheme with the inputs

$$\begin{aligned} M_{\mathrm{W}}^{\mathrm{LEP}} &= 80.398\,\mathrm{GeV} & \Gamma_{\mathrm{W}}^{\mathrm{LEP}} &= 2.141\,\mathrm{GeV} \\ M_{\mathrm{Z}}^{\mathrm{LEP}} &= 91.1876\,\mathrm{GeV} & \Gamma_{\mathrm{Z}}^{\mathrm{LEP}} &= 2.4952\,\mathrm{GeV} \\ m_{\mathrm{t}} &= 172.5\,\mathrm{GeV} \end{aligned}$$

the "on-shell" LEP M_V and Γ_V are converted to the "pole" (fixed-width) ones by means of

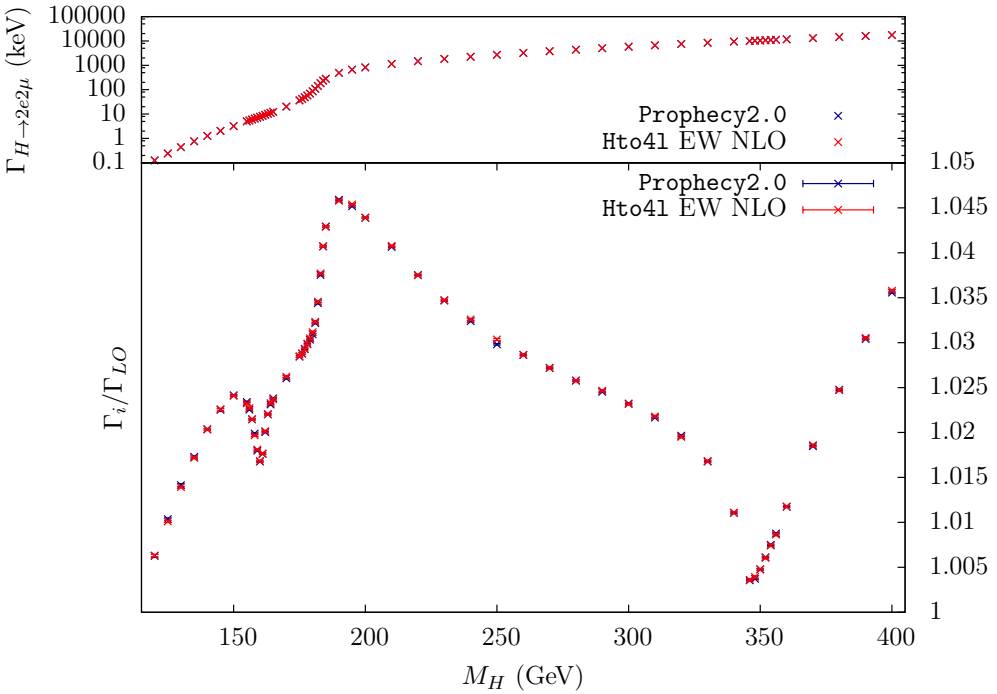
$$M_V = M_V^{\mathrm{LEP}}/\sqrt{1+(\Gamma_V^{\mathrm{LEP}}/M_V^{\mathrm{LEP}})^2} \qquad \Gamma_V = \Gamma_V^{\mathrm{LEP}}/\sqrt{1+(\Gamma_V^{\mathrm{LEP}}/M_V^{\mathrm{LEP}})^2}$$

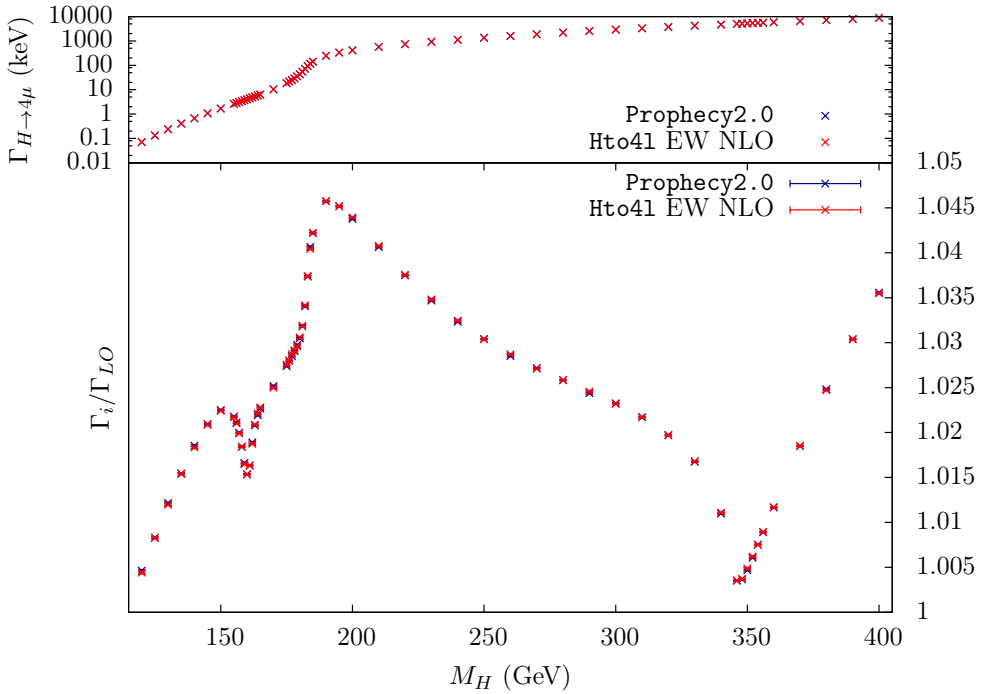
- various lepton pairs invariant masses and the angle between the Z decay planes are considered

$$\cos\phi \equiv \frac{[(\mathbf{p}_1+\mathbf{p}_2)\times\mathbf{p}_1]\cdot[-(\mathbf{p}_3+\mathbf{p}_4)\times\mathbf{p}_3]}{|(\mathbf{p}_1+\mathbf{p}_2)\times\mathbf{p}_1||(\mathbf{p}_3+\mathbf{p}_4)\times\mathbf{p}_3|}$$

⋆ $\cos\phi$ is sensitive to H spin

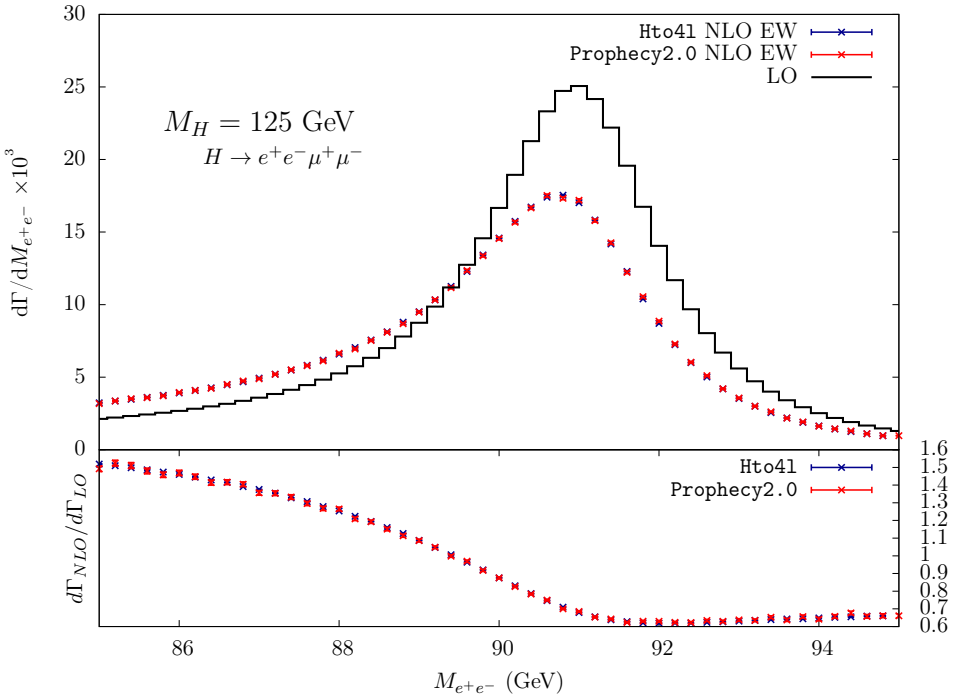
NLO cross-checks, comparison to **Prophecy4f**

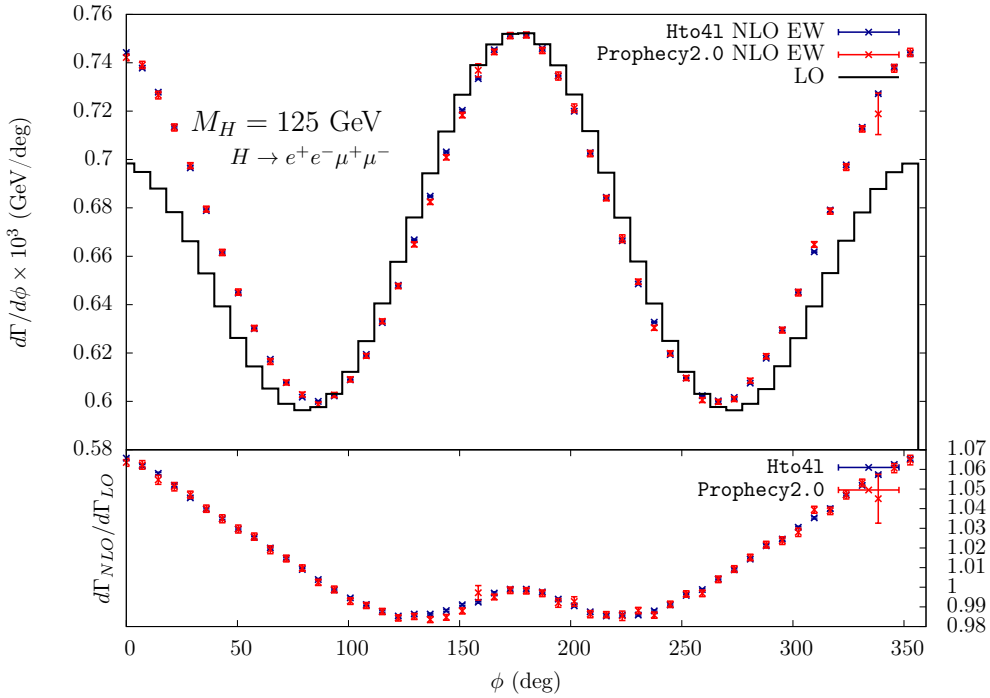




- perfect agreement for EW NLO partial decay widths between **Hto4l** and **Prophecy4f**
- for $m_H = 125$ GeV, EW NLO corrected decay width is $\simeq 1\%$ larger than LO

NLO cross-checks, comparison to **Prophecy4f**





- perfect agreement also on distributions

Beyond NLO: matching with multiple photon emission

- the LL QED (PS) exponentiated width can be cast as

$$d\Gamma^{\infty}_{PS} = \frac{1}{2m_H}\,\Pi(Q^2,k_0)\,\sum_{n=0}^{\infty}\frac{1}{n!}|M_{LL,n}|^2 d\Phi_{4+n}^{[\omega_n>k_0]}$$

- which can be improved to include exact NLO EW corrections by the master formula

$$d\Gamma^{\infty}_{matched} = \frac{1}{2m_H}\,\Pi(Q^2,k_0)\,C_{SV}\,\sum_{n=0}^{\infty}\frac{1}{n!}\prod_{i=1}^{n}C_{H,i}|M_n^{LL}|^2 d\Phi_{4+n}$$

with $\quad C_{SV} = 1 + \frac{d\Gamma^{NLO}_{SV} - d\Gamma^{PS}_{SV}}{d\Gamma_0} \qquad C_{H,i} = 1 + \frac{|M^{ex}_{[i]}|^2 - |M^{LL}_{[i]}|^2}{|M^{LL}_{[i]}|^2}$

CMCC et al., NPB **758**, 227 (2006)

CMCC et al., JHEP **0710**, 109 (2007), JHEP **0612**, 016 (2006)

Beyond NLO: matching properties

C_{SV} and $C_{H,i}$:

- are built with up-to-1-loop "ingredients" and infrared/collinear safe
- account for $\mathcal{O}(\alpha)$ QED non-log & weak RC missing in the PS, avoiding LL double counting, so that

⋆ $[\Gamma^{\infty}_{matched}]_{\mathcal{O}(\alpha)} = \Gamma_{NLO}$

⋆ the resummation of QED LL higher orders is preserved

- the master formula allows for a fully exclusive generation of all f.s. momenta (leptons and photons)
- the integral over the phase space $d\Phi_{4+n}$ is exact

- the closer $|M^{LL}_{[i]}|^2$ to $|M^{ex}_{[i]}|^2$ the closer $C_{H,i}$ to 1.
  A "good" LL approximation for photon emission is required.

Radiation LL approximation

- the peaking structure is driven by
  soft/collinear radiation $\otimes$ Z resonances
  E.g. $H \to 2e2\mu + n\gamma$ amplitude

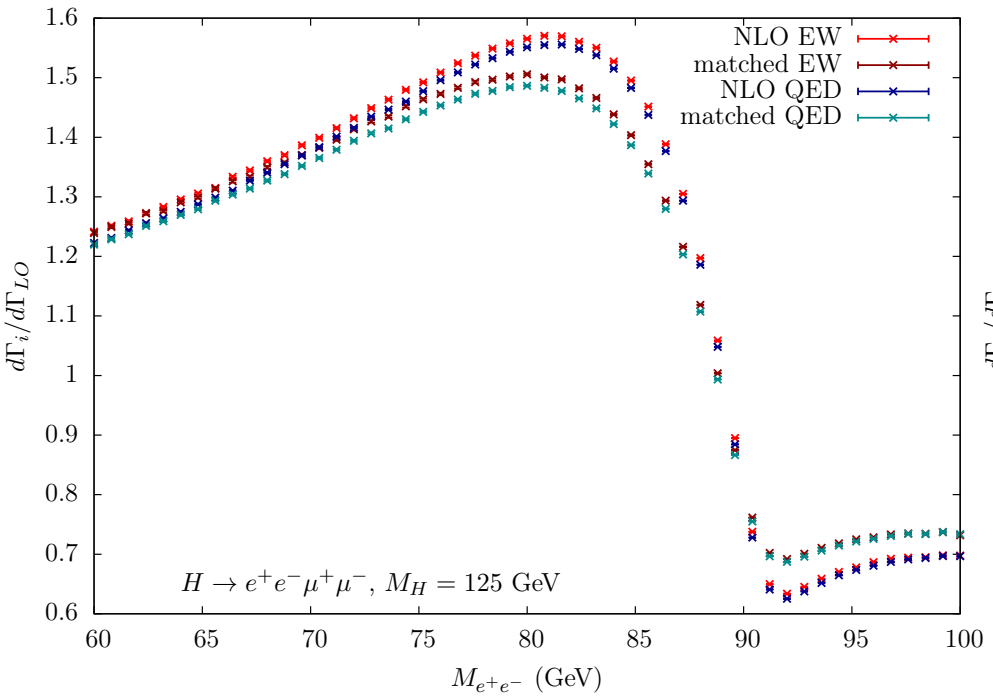
$$M_n^{\text{peak}} = \frac{C}{n!} \sum_{\mathcal{P}} \sum_{i=1}^{n} \frac{J_{12}^{\mu}}{(P_{12} + Q_{\mathcal{P}})^2 - m_z^2} \frac{J_{\mu,34}}{(P_{34} + Q_{\mathcal{P}'})^2 - m_z^2} \prod_{j=1}^{4} \frac{\eta_j p_j \cdot \varepsilon(q_i)}{p_j \cdot q_i}$$

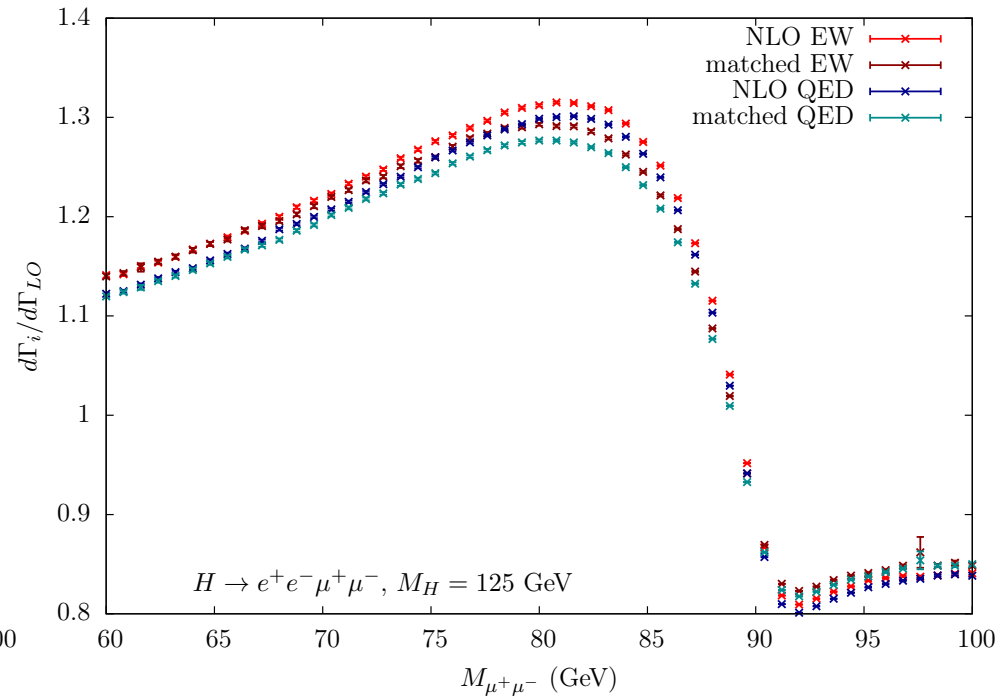
$$J_{ij}^{\mu} \equiv \bar{u}(p_i)\gamma^{\mu}(g_V - g_A\gamma_5)v(p_j), \quad P_{ij} = p_i + p_j, \quad Q_{\mathcal{P}} = \sum_{i \in \mathcal{P}} q_i, \quad m_z^2 = M_Z^2 - i\Gamma_Z M_Z$$

- although approximately, radiation interferences are accounted for
- $|M_n^{LL}|^2 = |M_n^{\text{peak}}|^2 \oplus$ AP enhancement for hard-collinear radiation
  (i.e. photons' energy spectrum according to AP vertex)
- e.g., with $C_{H,i}$ switched on and $n = 2$ ($H \to 4\ell + 2\gamma$ at LO), checks vs **MadGraph** and **GoSam** show very good agreement

thanks to F. Tramontano

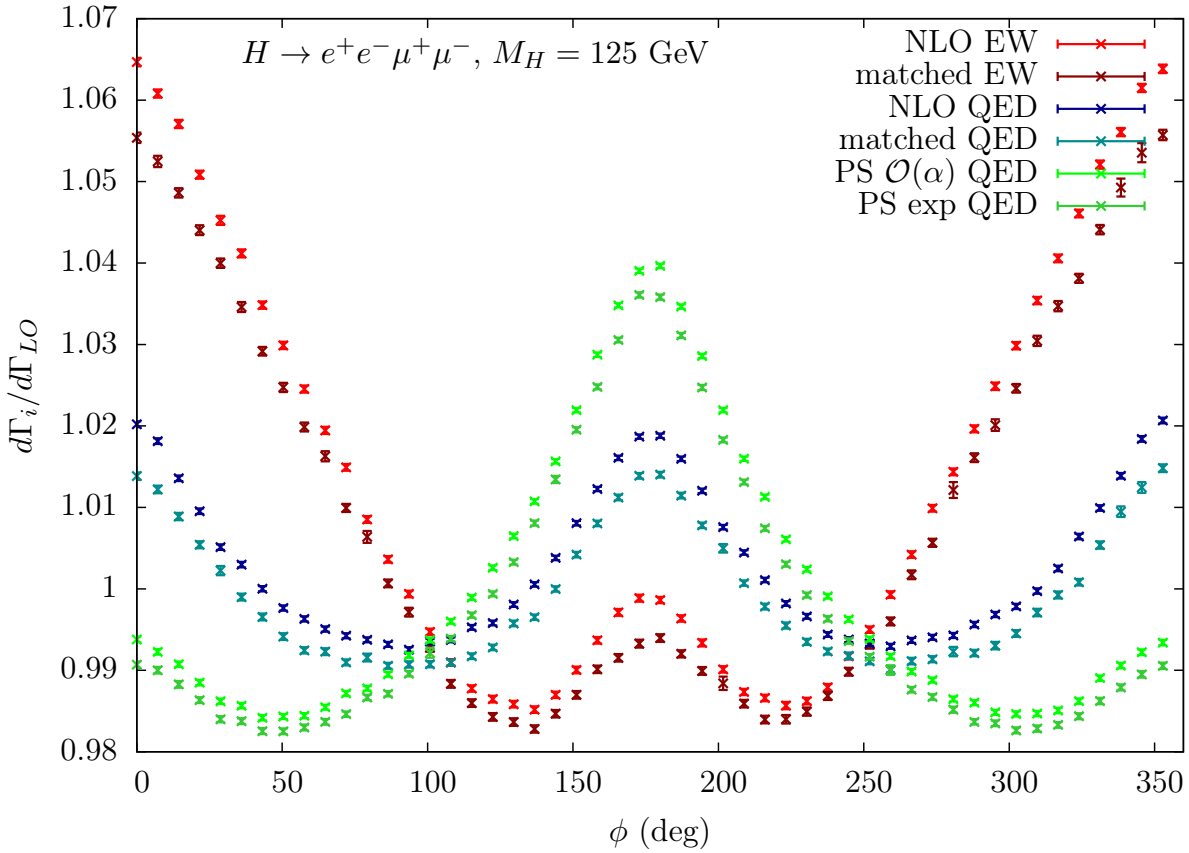
Results: relative corrections





- large corrections on lepton invariant masses (mainly) due to QED
  - ⋆ up to 50% NLO correction on (bare) $M_{e^+e^-}$
  - ⋆ $\mathcal{O}(10\%)$ due to exponentiation, multiple-photon emissions

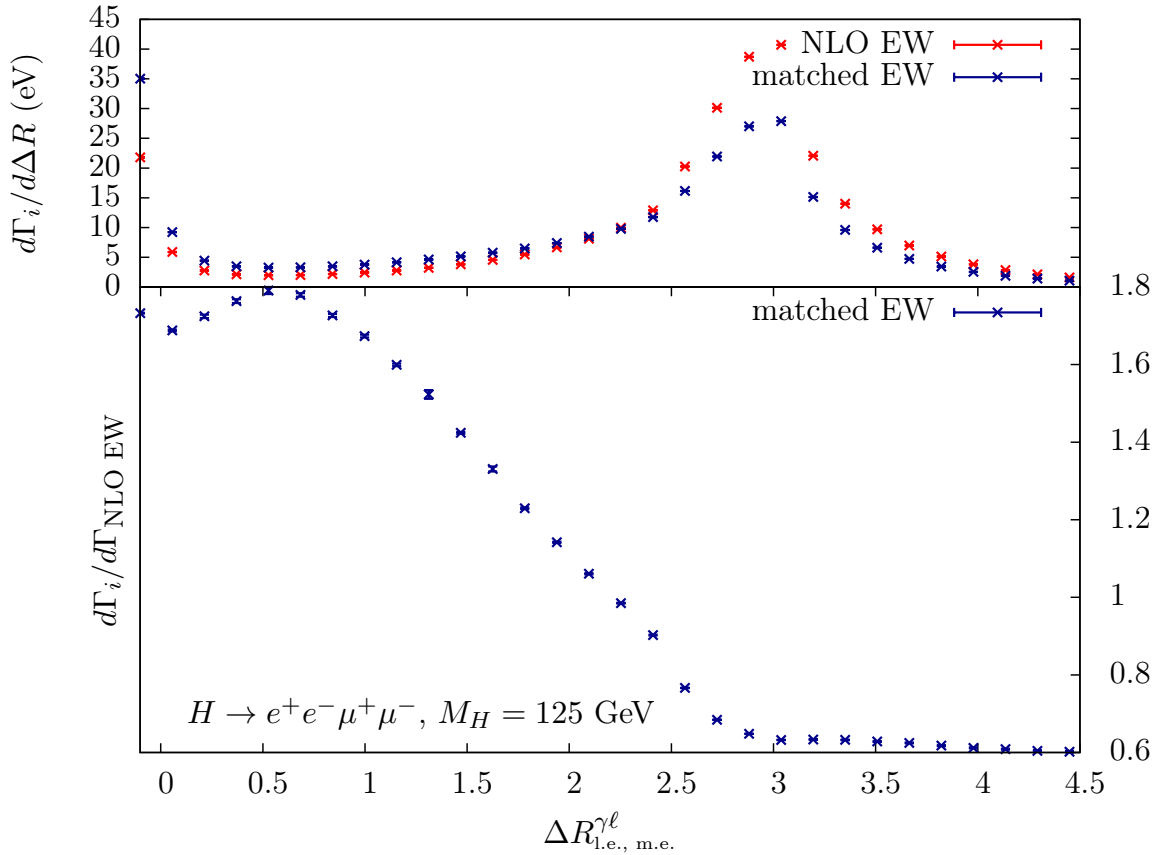
Results: relative corrections



- interplay between non-log QED and pure weak corrections
- moderate effect of exponentiation

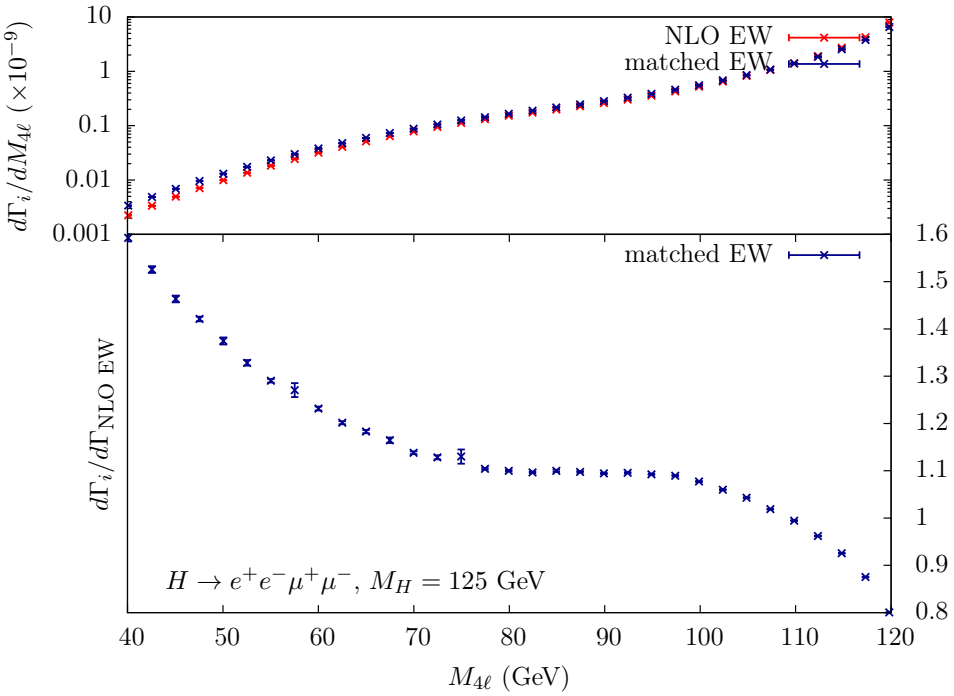
Radiation exclusive observables

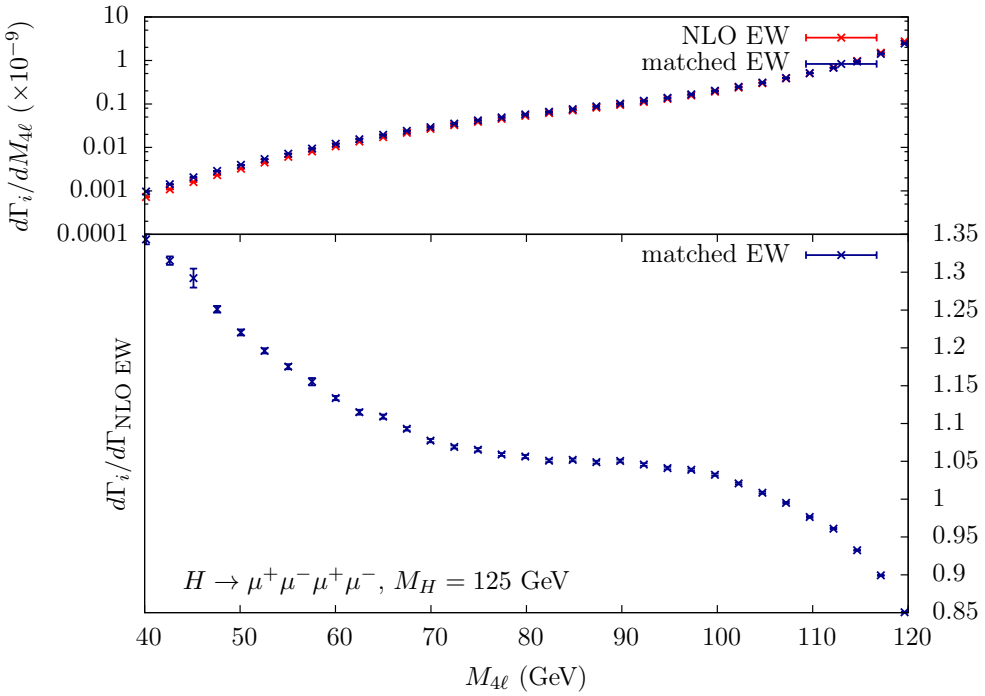
- the events are fully exclusive over emitted photons
  e.g. ΔR between softest γ (with $E_\gamma > 4$ GeV) and hardest ℓ



⋆ remarkable effect due to multiple photon emissions

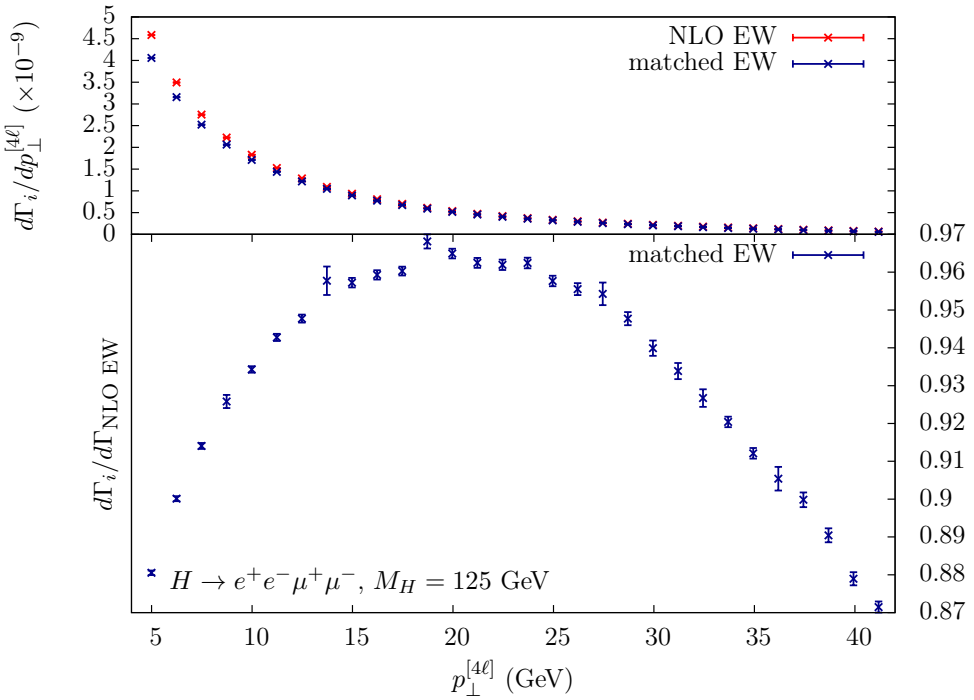
Radiation exclusive observables

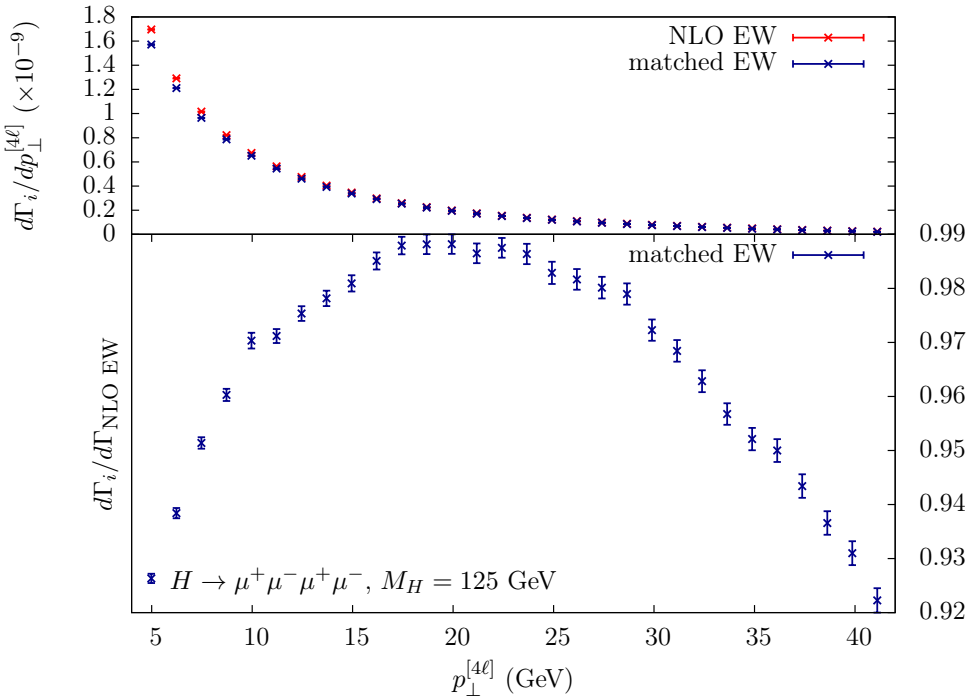




- 4-lepton invariant mass: large effect due to multiple-photon emission

Radiation exclusive observables





- 4-lepton $p_\perp$ (i.e. $p_\perp^H$): large effect due to multiple-photon emission

Conclusion and outlook

- the Higgs boson will be studied with high precision, to unveil its nature
- the new MC **`Hto4l`** has been developed for the precise simulation of the decay $H \to ZZ \to 4\ell$, including
  - ⋆ full one-loop EW corrections in the SM, in the complex-mass scheme
  - ⋆ consistent matching with multiple photon emission
  - ⋆ fully exclusive event generation
  - ⋆ LHE compliant for interfacing to any EG for H production
- preliminary studies in the H rest frame show the effects are important in view of precise mass and spin/parity measurements
- work is in progress to study the realistic impact of the corrections including H production and detector effects