Presicion Higgs-boson decays in the SM

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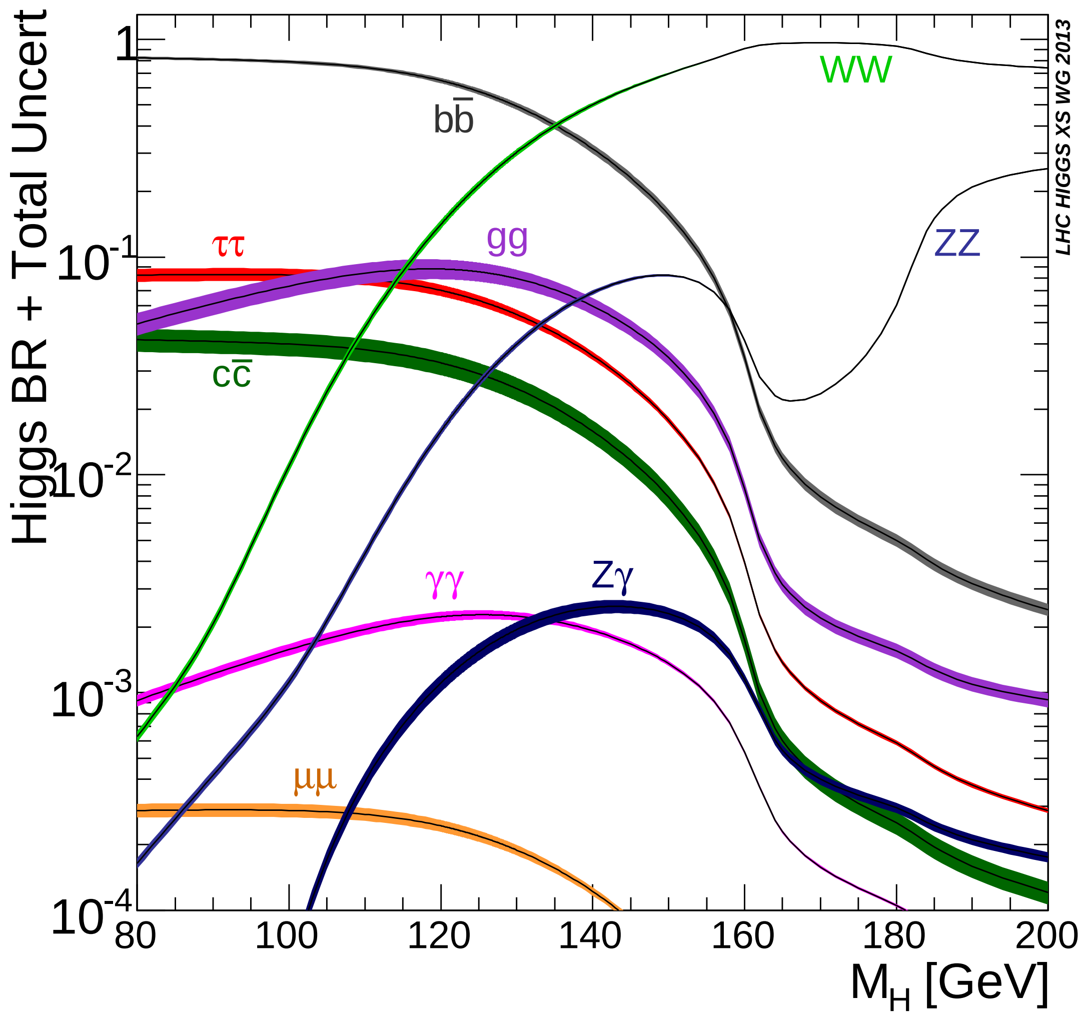
Outline

- Standard Model Branching Ratios
  - status and perspectives
  - theory updates and input parameters
  - rare exclusive decays
- Differential predictions for Higgs decays
  - $H \to b\bar{b}$
  - $H \to 4$ leptons at NLO electroweak and beyond

SM BRs

Branching ratios including error estimates:



to be updated for YR4 of HXSWG

Theory status

Theory uncertainties for $H \to b\bar{b}$ partial width:

QCD: $\sim 0.2\%$ uncertainty at NNNNLO (from usual scale variation)

EW: $\sim 2\% \;\to\; \sim 0.5\%$ in YR4 at full NLO

(now included in latest HDECAY)

New result: full $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections

Mihaila, Schmidt, Steinhauser [arXiv:1509.02294]

- $\Delta^{(\mathrm{weak},\alpha_s)} = -0.29\%$ ($\mu = M_H$) ($\Delta^{(\mathrm{QED},\alpha_s)} = 0.01\%$ is negligible)
- compared to $\Delta^{(\alpha_s^3)} = 0.2\%$ ($\mu = M_H$)
- factorization of QCD and EW corrections holds at $\mathcal{O}(30\%)$
  ($\Delta^{(\mathrm{weak})}\Delta^{(\alpha_s)} = -0.2\%$)

Theory status

Theory uncertainties:

- $H \to \tau^+\tau^-/\mu^+\mu^-$: $\sim 0.5\%$ at full NLO EW

(and unchanged with respect to YR3)

- $H \to t\bar{t}$: $\sim 5\%$ at (NNN)NLO QCD
- $H \to gg$: $\sim 3\%$ at NNNLO approx. QCD/NLO EW
- $H \to \gamma\gamma$: $\sim 1\%$ at NLO QCD/NLO EW
- $H \to Z\gamma$: $\sim 5\%$ at LO QCD/LO EW

(all included in HDECAY)

Theory status

Theory uncertainties for $H \to WW/ZZ \to 4f$ partial width:

QCD: < 0.5% uncertainty at NLO

EW: $\sim 0.5\%$ at NLO

(using Prophecy4f)

New result: recalculation for $H \to WW/ZZ \to 4l$

Boselli et al. [arXiv:1503.07394]

- $H \to WW/ZZ \to 4l$ at NLOPS EW accuracy

  (for differential decays $\to$ more later)

- perfect agreement with Prophecy4f for partial widths

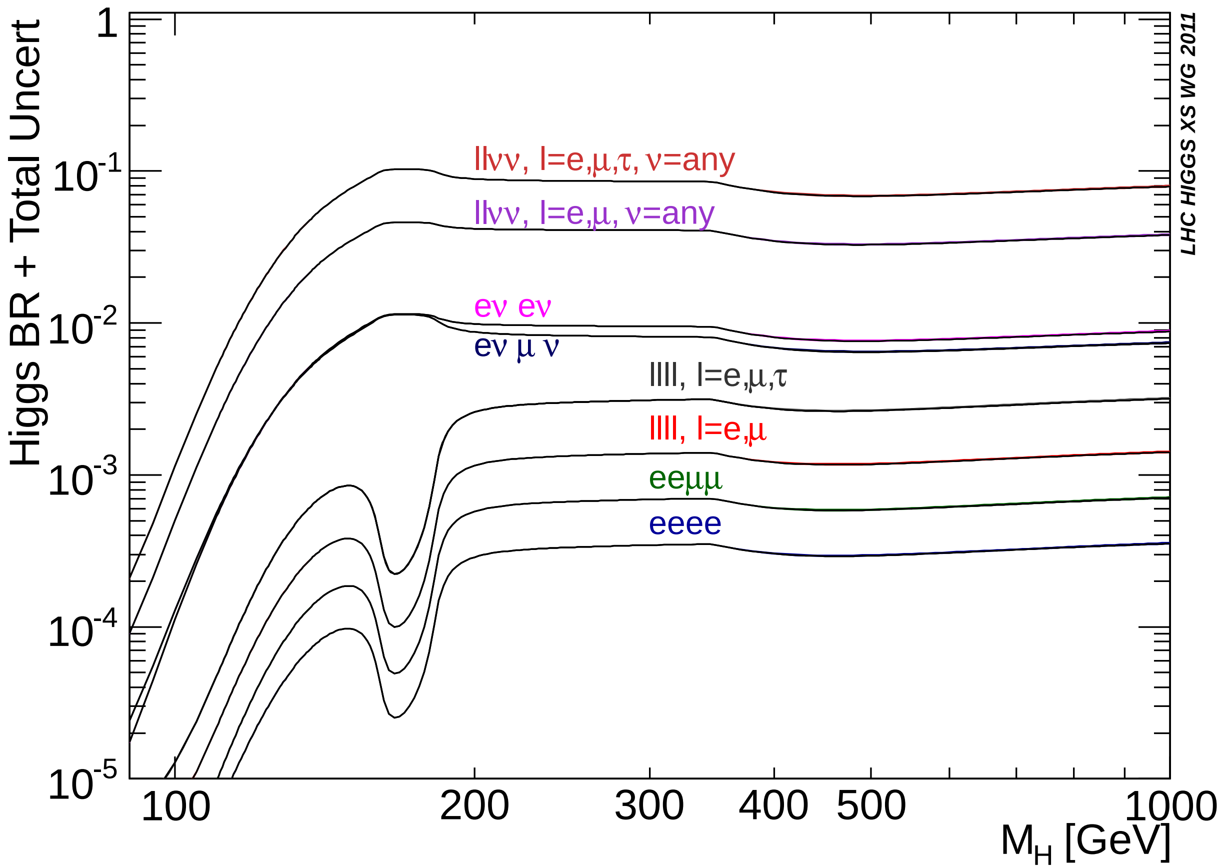
  $H \to ee\mu\mu$: 0.24151(8) vs. 0.24165(2) keV

  $H \to 4\mu$: 0.13324(2) vs. 0.13325(2) keV

  for $M_H = 125 GeV$

Theory status

Branching ratios for $4f$ final states:



Partial widths → BRs

- errors on partial widths induced by theory and parametric uncertainties :

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to bb$	122	2.30	-2.3% $+2.3\%$	$+3.2\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
	126	2.36	-2.3% $+2.3\%$	$+3.3\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
	130	2.42	-2.4% $+2.3\%$	$+3.2\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
$H \to \tau^+\tau^-$	122	$2.51\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	126	$2.59\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
	130	$2.67\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%

⋮

YR3 [1307.1347]

- starting point to include error correlations for BRs
- HXSWG theory uncertainties based on existing tools (HDECAY, PROPHECY4F)
- new release of HDECAY → reduced THU errors
- parametric uncertainties crucial
- updated BRs in YR4

Parametric uncertainties

Recommendation by HXSWG:

- YR3 [1307.1347]: conservative assumptions

  $m_t = 172.5 \pm 2.5$ GeV

  $\alpha_s(M_Z) = 0.119 \pm 0.002$

  $m_b(m_b) = 4.16 \pm 0.06$ GeV

  $m_c(m_c) = 1.28 \pm 0.03$ GeV

- new recommendation

  Denner, Dittmaier, Grazzini, Harlander, Thorne, Spira, Steinhauser [LHCHXSWG-INT-2015-00

  $m_t = 172.5 \pm 1.0$ GeV

  $\alpha_s(M_Z) = 0.118 \pm 0.0015$ (use PDF4LHC recommendation in general)

  $m_b(m_b) = 4.18 \pm 0.03$ GeV

  $m_c(3\mathrm{GeV}) = 0.986 \pm 0.026$ GeV

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more BR calculations

Almeida, Lee, Pokorski, Wells [arXiv:1311.6721]

- recalculation of partial width for $m_H = 125.7$ GeV
- using predictions from the literature
- parametric dependence in terms of Taylor coefficients

$$\Gamma_{H\to X} = \Gamma_X^{(\mathrm{ref})}\left(1 + \sum_i a_{\tau_i,X}\overline{\delta\tau_i}\right) \quad \text{with} \quad \overline{\delta\tau_i} = \frac{\tau_i - \tau_{i,ref}}{\tau_{i,ref}}$$

	$\Gamma_X^{(\mathrm{Ref})}$/GeV	$a_{m_t,X}$	$a_{m_H,X}$	$a_{\alpha(M_Z),X}$	$a_{\alpha_S(M_Z),X}$	$a_{m_b,X}$	$a_{M_Z,X}$	$a_{m_c,X}$	$a_{m_\tau,X}$	$a_{G_F,X}$
total	3.96×10^{-3}	-3.48×10^{-2}	4.53	8.77×10^{-1}	-1.35	1.4	-3.49	9.05×10^{-2}	1.3×10^{-1}	8.43×10^{-1}
gg	3.57×10^{-4}	-1.62×10^{-1}	2.89	0.	2.49	-7.1×10^{-2}	3.77×10^{-1}	0.	0.	1.
$\gamma\gamma$	1.08×10^{-5}	-2.73×10^{-2}	4.32	2.56	1.8×10^{-2}	9.01×10^{-3}	-1.85	0.	0.	7.24×10^{-1}
$b\bar{b}$	2.17×10^{-3}	8.11×10^{-3}	8.09×10^{-1}	3.76×10^{-2}	-2.46	2.57	-4.75×10^{-1}	0.	0.	9.53×10^{-1}
$c\bar{c}$	9.99×10^{-5}	-4.55×10^{-2}	7.99×10^{-1}	1.02×10^{-2}	-9.17	0.	-1.41	3.59	0.	9.7×10^{-1}
$\tau^+\tau^-$	2.58×10^{-4}	4.74×10^{-2}	9.95×10^{-1}	-2.09×10^{-2}	-2.15×10^{-3}	0.	-1.61×10^{-2}	0.	2.01	1.02
WW^*	9.43×10^{-4}	-1.13×10^{-1}	1.37×10^{1}	3.66	9.04×10^{-3}	0.	-1.21×10^{1}	0.	0.	2.49×10^{-1}
ZZ^*	1.17×10^{-4}	2.28×10^{-2}	1.53×10^{1}	-7.37×10^{-1}	-1.82×10^{-3}	0.	-1.12×10^{1}	0.	0.	2.53
$Z\gamma$	6.88×10^{-6}	-1.54×10^{-2}	1.11×10^{1}	8.46×10^{-1}	0.	-9.76×10^{-3}	-4.82	0.	0.	2.62
$\mu^+\mu^-$	8.93×10^{-7}	4.84×10^{-2}	9.92×10^{-1}	-4.31×10^{-2}	-2.2×10^{-3}	0.	-1.62×10^{-2}	0.	0.	1.02

different way to give complete information
m_H treated as input parameter

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more BR calculations

Almeida, Lee, Pokorski, Wells [arXiv:1311.6721]

- BRs and their ratios derived from partial width

  (as in HXSWG)

- assumptions on parametric errors differ

  (0.7% for α_s; 0.7% for m_b ($\overline{\mathrm{MS}}$ mass))

  (more optimistic estimates than HXSWG)

- theory uncertainty from scale variation only

- pole or $\overline{\mathrm{MS}}$ masses can be used as input for m_b and m_c

  (HXSWG uses $\overline{\mathrm{MS}}$ masses internally, pole mass input only as bookkeeping device to minimize correlation with α_s)

- complete comparison with HXSWG results not done

Parametric uncertainties

Different approach to input parameters:

Petrov, Pokorski, Wells, Zhang [arXiv:1501.02803]
[arXiv:1509.04173]

- use low-energy observables in global fit

$$\left\{\begin{matrix} \widehat{O}_1^{\mathrm{low}}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_2^{\mathrm{low}}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_3^{\mathrm{low}}(m_c, m_b, \alpha_s, \dots) \\ \vdots \end{matrix}\right\} \Leftarrow \left\{\begin{matrix} \underline{\text{Inputs}} \\ m_c \\ m_b \\ \alpha_s \\ \vdots \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} \widehat{O}_1^{\mathrm{Higgs}}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_2^{\mathrm{Higgs}}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_3^{\mathrm{Higgs}}(m_c, m_b, \alpha_s, \dots) \\ \vdots \end{matrix}\right\}$$

- better understanding of uncertainties
- exemplaric calculation performed

(using moments of $e^+e^- \to Q\overline{Q}$ inclusive cross sections)

- long-time goal for precision Higgs physics

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Parametric uncertainties

Lepage, Mackenzie, Peskin [arXiv:1404.0319]

- How well can the Higgs BRs be predicted in the far future?
- use lattice gauge theory to improve α_s, m_b, and m_c
  (e.g. using current-current correlators)
  (stated errors already now quite small)
- optimistic projection for lattice improvements:

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

(errors in %)

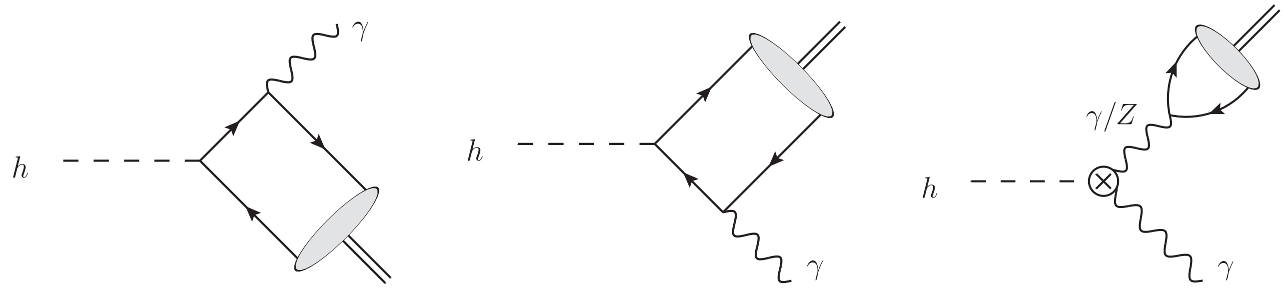
time-scale: 10-15 years

Rare decays

Exclusive decays: $H \to J/\Psi\,\gamma$ and $H \to \Upsilon\gamma$

Bodwin, Petriello, Stoynev, Velasco [arXiv:1306.5770]
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan [arXiv:1406.1722]
Bodwin, Chung, Ee, Lee, Petriello [arXiv:1407.6695]
König, Neubert [arXiv:1505.03870]

- Use rare decays to measure $Hc\bar{c}$ and $Hb\bar{b}$ couplings
- destructive interference of direct and indirect contributions



(calculated using QCD factorization)

Rare decays

Exclusive decays: $H \to J/\Psi\,\gamma$ and $H \to \Upsilon\gamma$

- SM results: König et al. (arXiv:1505.03870)

$$\text{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\text{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

$$\text{Br}(h \to \Upsilon(1S)\,\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\,{}^{+\,1.75}_{-\,1.21}{}_{\text{direct}} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

$$\text{Br}(h \to \Upsilon(2S)\,\gamma) = (2.34 \pm 0.04_{f_{\Upsilon(2S)}}\,{}^{+\,0.75}_{-\,0.99}{}_{\text{direct}} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

$$\text{Br}(h \to \Upsilon(3S)\,\gamma) = (2.13 \pm 0.04_{f_{\Upsilon(3S)}}\,{}^{+\,0.75}_{-\,1.12}{}_{\text{direct}} \pm 0.10_{h\to\gamma\gamma}) \cdot 10^{-9}\,.$$

- SM results: Bodwin et al. (arXiv:1407.6695)

$$\text{Br}(h \to J/\psi\,\gamma) = (2.79\,{}^{+\,0.15}_{-\,0.16}) \cdot 10^{-6}$$

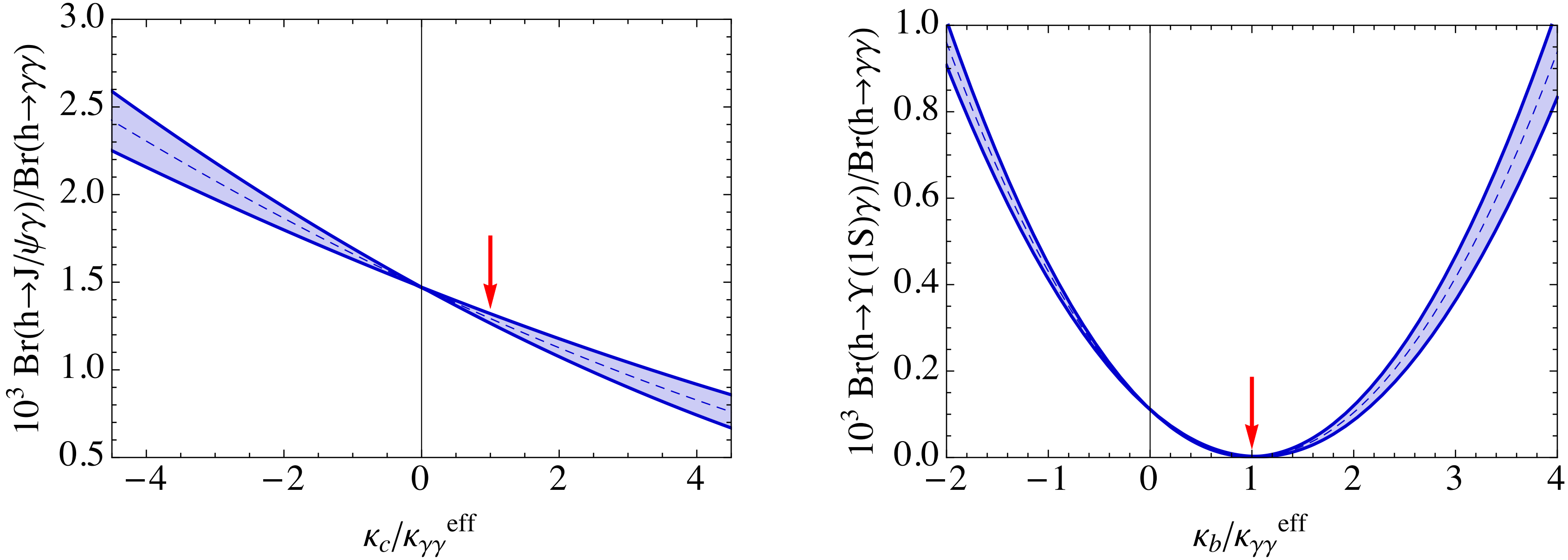
$$\text{Br}(h \to \Upsilon(1S)\,\gamma) = (0.61\,{}^{+\,1.74}_{-\,0.61}) \cdot 10^{-9}$$

$$\text{Br}(h \to \Upsilon(2S)\,\gamma) = (2.02\,{}^{+\,1.86}_{-\,1.28}) \cdot 10^{-9}$$

$$\text{Br}(h \to \Upsilon(3S)\,\gamma) = (2.44\,{}^{+\,1.75}_{-\,1.30}) \cdot 10^{-9}$$

Rare decays

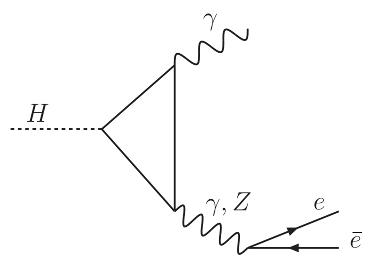
Exclusive decays: $H \to J/\Psi\,\gamma$ and $H \to \Upsilon\gamma$

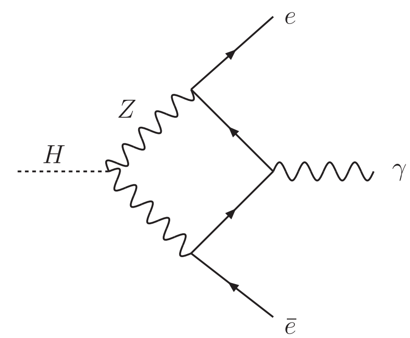


König, Neubert [arXiv:1505.03870]

Dalitz Decay

- $H \to e^+e^-\gamma$ not Yukawa suppressed at 1-loop





- $H \to e^+e^-\gamma$ to be defined by suitable cuts

Abbasabadi, Bowser-Chao, Dicus, Repko [hep-ph/9611209]
Chen, Qiao, Zhu [arXiv:1211.6058]
Dicus, Repko [arXiv:1302.2159]
Passarino [arXiv:1308.0422]

- use invariant masses $m_{e^+e^-}$, $m_{e^\pm\gamma}$ as identification cuts

Dicus, Repko [arXiv:1302.2159]
Passarino [arXiv:1308.0422]

- use proper definition of pseudo-observable $H \to Z\gamma$

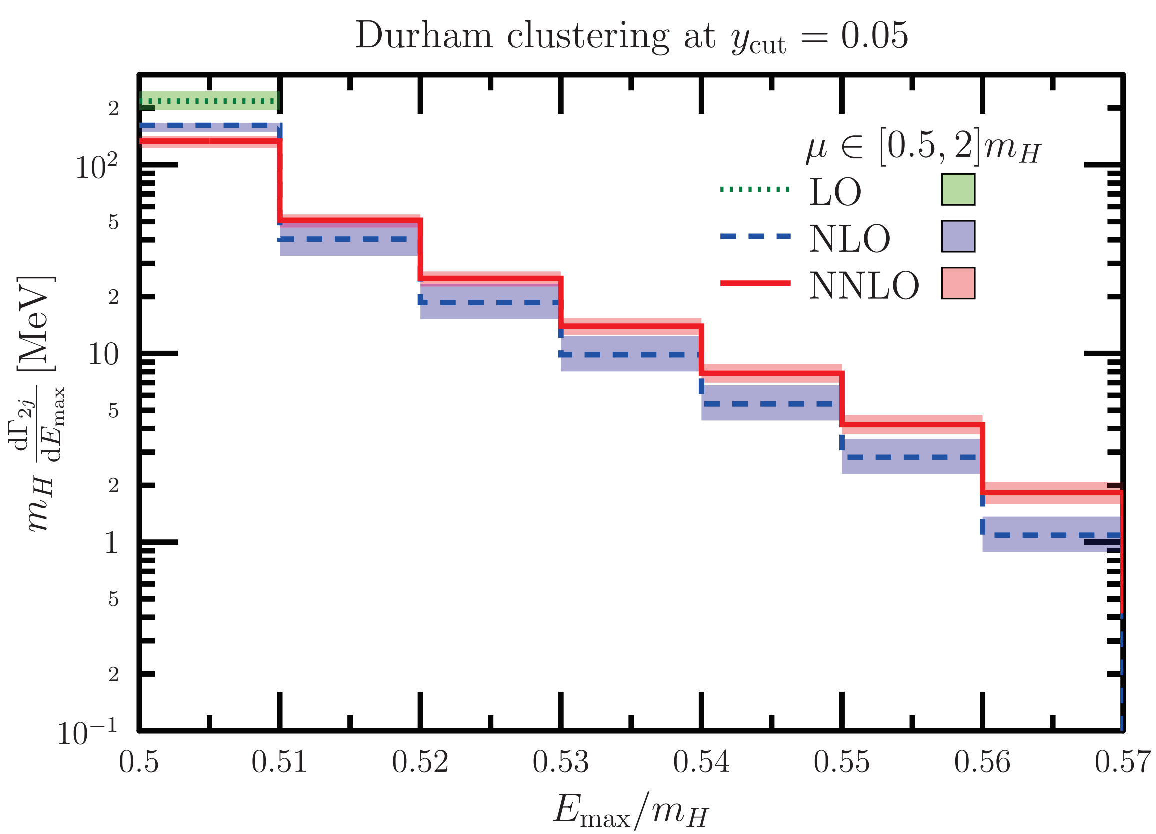
Passarino [arXiv:1308.0422]

$H \to b\bar{b}$ at NNLO

- now two calculations available

Anastasiou, Herzog, Lazopoulos [arXiv:1110.2368]

Del Duca, Duhr, Somogyi, Tramontanoe, Trocsany [arXiv:1501.07226]



[1501.07226]

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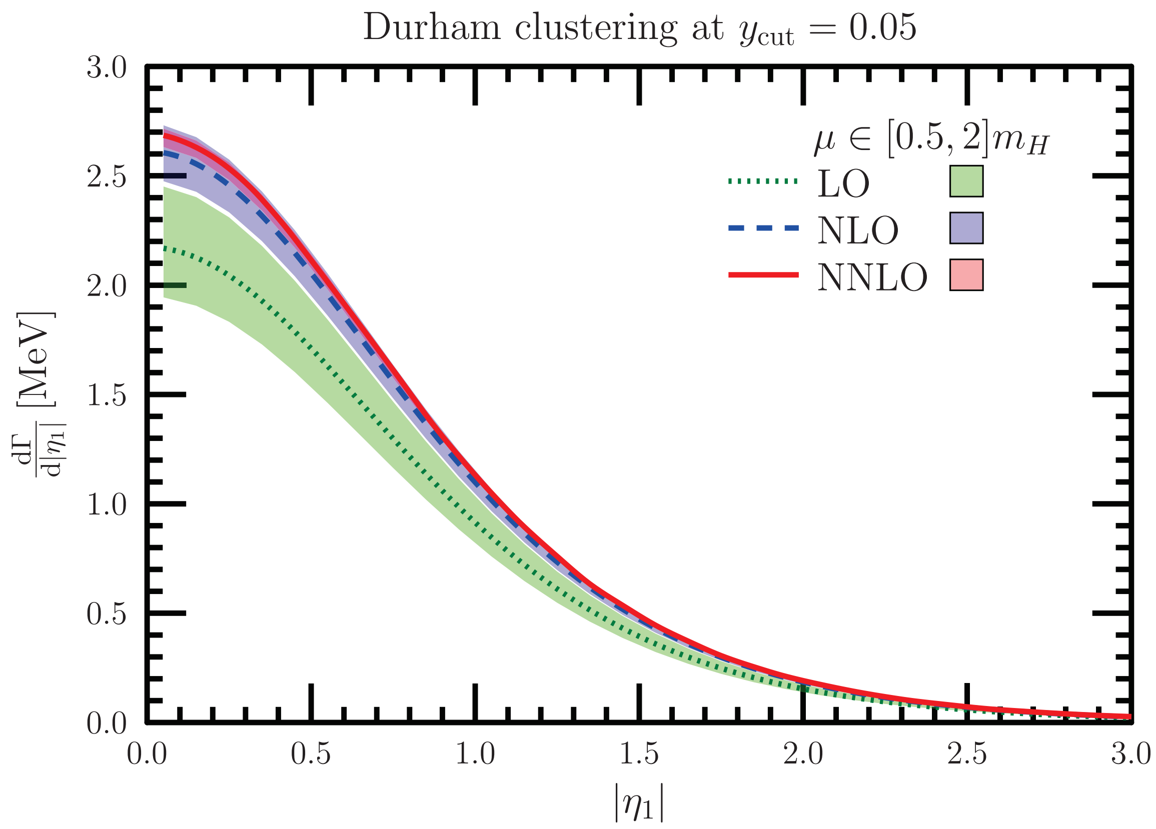


[1501.07226]

Fully differential $H \to 4l$

- Now two event generators available:
  - Prophecy4f at NLO EW for all 4l final states

    Bredenstein, Denner, Dittmaier, Weber [0708.4123]

    Denner, Dittmaier, AM

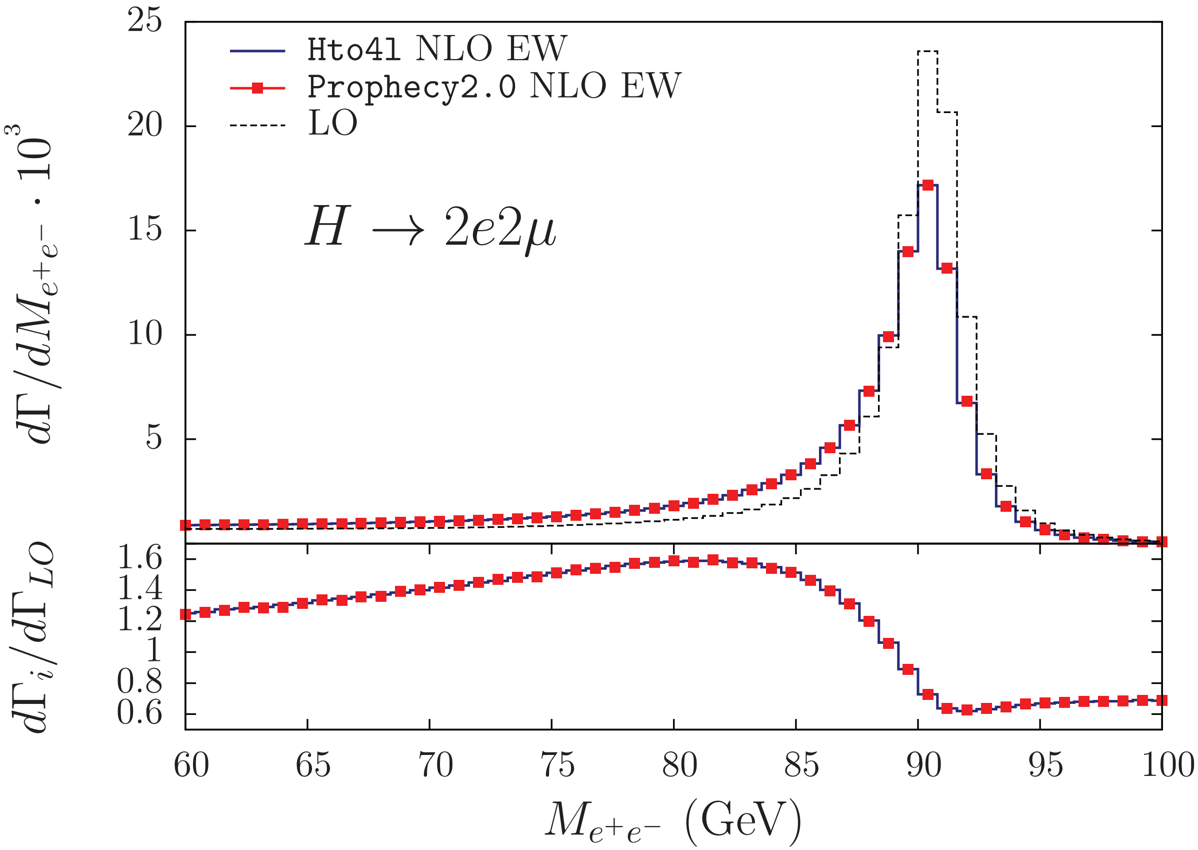
    `http://omnibus.uni-freiburg.de/~sd565/programs/prophecy4f/prophecy4f.html`
  - Hto4l at NLOPS EW for 4 charged leptons

    Boselli, Carloni Calame, Montagna, Nicrosini, Piccinini [1503.07394]

    `http://www.pv.infn.it/hepcomplex/hto4l.html`
- interface using LHE format
- complete agreement at NLO EW

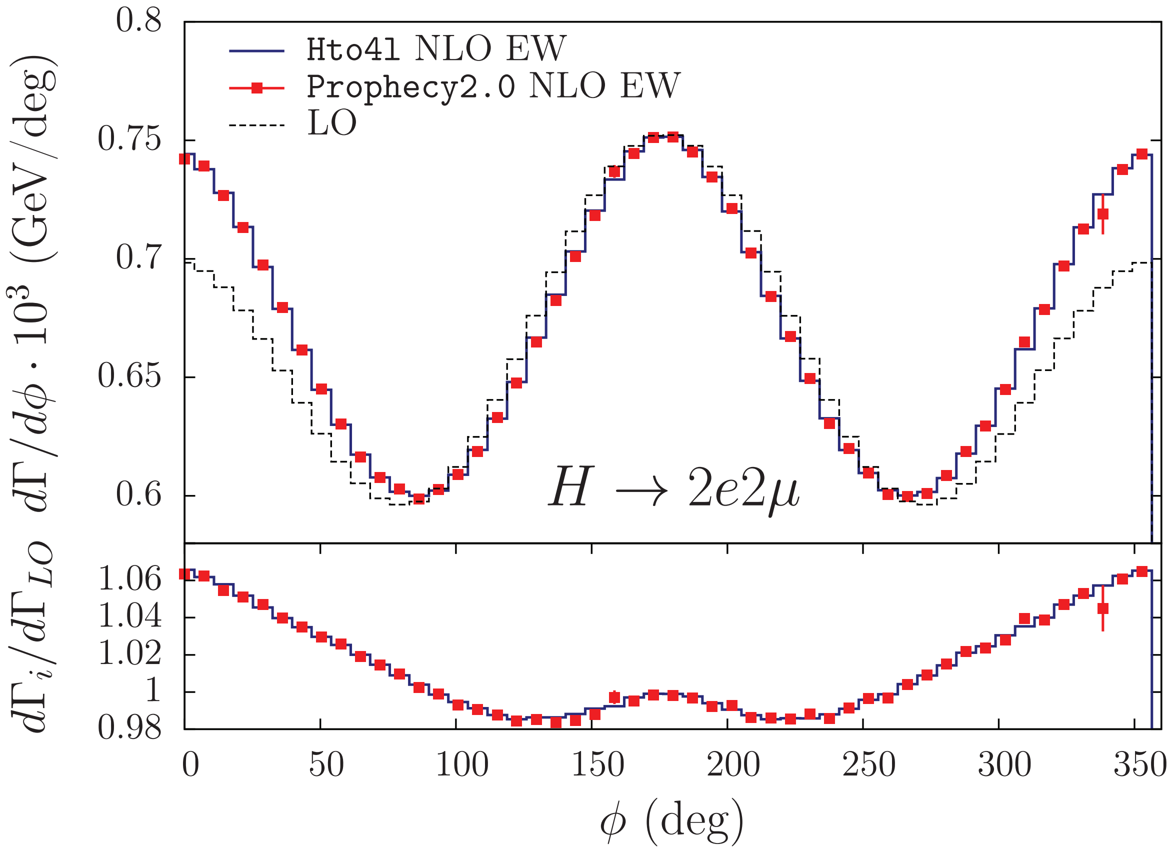
Fully differential $H \to 4l$

- complete agreement at NLO EW



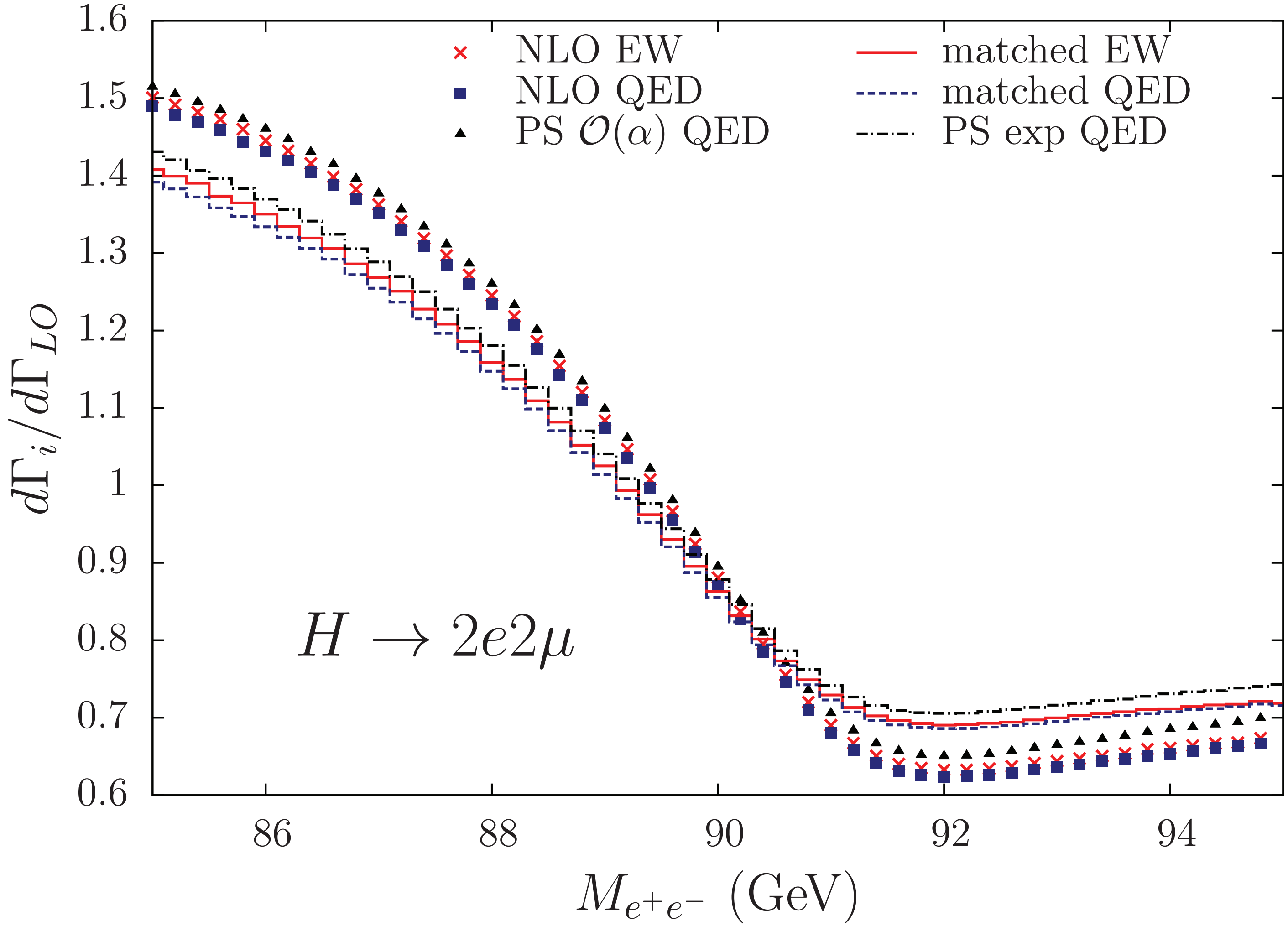
Fully differential $H \to 4l$

- complete agreement at NLO EW



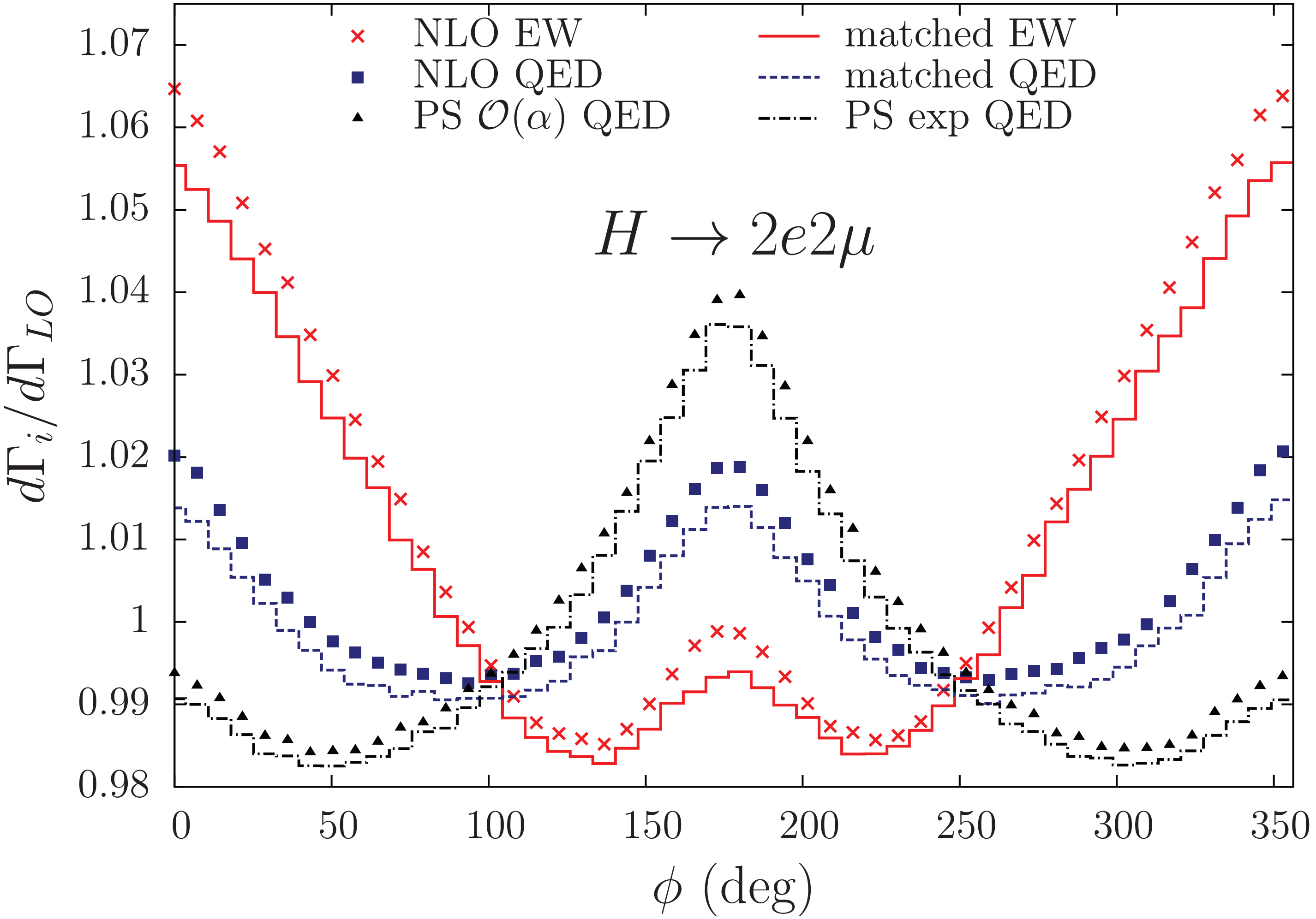
Fully differential $H \to 4l$

- beyond NLO EW



Fully differential $H \to 4l$

- beyond NLO EW



Conclusions

Branching ratios

- no big news
- HXSWG update due to improved TUs and PUs
- quest for precise input ongoing
- rare exclusive decays for high-luminosity LHC

Differential Higgs decays

- Hto4l as new tool at NLOPS EW