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Production and decay of the Higgs boson in association with top quarks

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Institute for Theoretical Particle Physics and Cosmology
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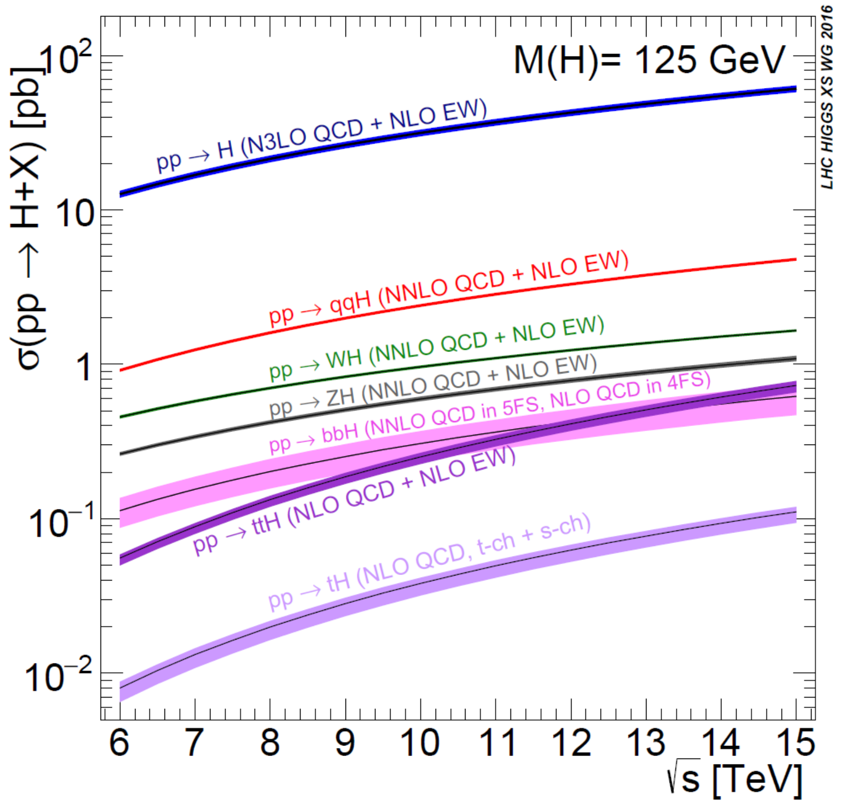
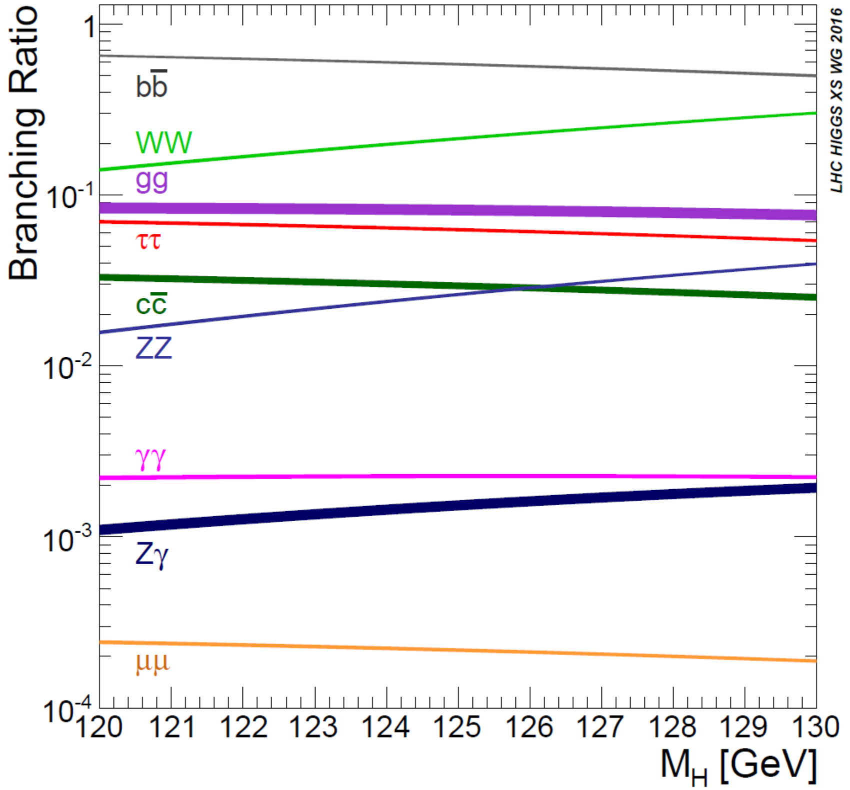
Motivation

- Observation of $t\bar{t}H$ in 2018 by ATLAS and CMS using a combination of decay channels
- Direct probe of Y_t at tree level
- Only 1% of total Higgs production $pp \to H$



- $H \to b\bar{b}$ has largest BR ~58%, but large irreducible background $t\bar{t}b\bar{b}$
- $H \to \gamma\gamma$ has clean signature, but small BR

⇨ Precise predictions for fully realistic final states are required



Theory status (tt̄H)

State of the art: **NLO (QCD + EW) + NNLL**

- **Parton level**
  - $pp \to t\bar{t}H$

    Beenakker et al. '01'03
    Reina, Dawson '01
    Dawson et al. '02'03
    Martin, Moch, Saibel '21

    Frixione et al. '14'15
    Zhang et al. '14
    Frederix et al. '18

    Kulesza et al. '16'18'20
    Broggio et al. '16'17'19

  - $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H$

    Denner, Feger '15
    Denner, Lang, Pellen, Uccirati '17

- **Parton Shower**
  - **POWHEG matching**

    Garzelli, Kardos, Papadopoulos, Trocsanyi '11
    Hartanto, Jäger, Reina, Wackeroth '15

  - **MC@NLO matching**

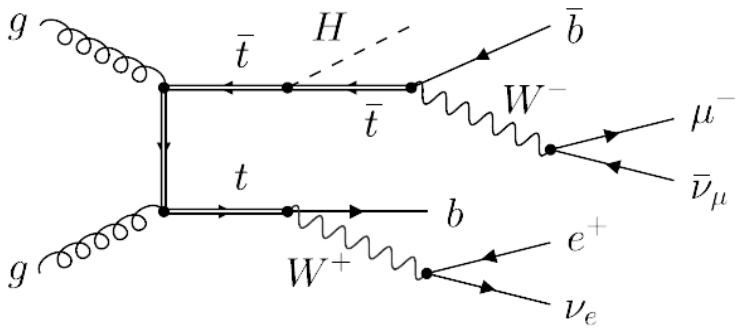
    Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli '11
    Maltoni, Pagani, Tsinikos '16

Setup

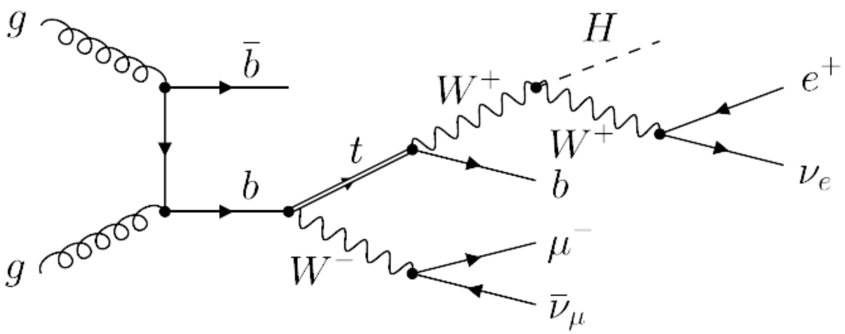
$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H \text{ at the LHC with } \sqrt{s} = 13 \text{ TeV}$$

- NLO QCD corrections
- Breit Wigner propagators for the top quark and gauge bosons in the complex-mass scheme
- Diagonal CKM matrix
- 5 flavour scheme ($m_b = 0, Y_b = 0$)
- Top-quark width treated as fixed parameter

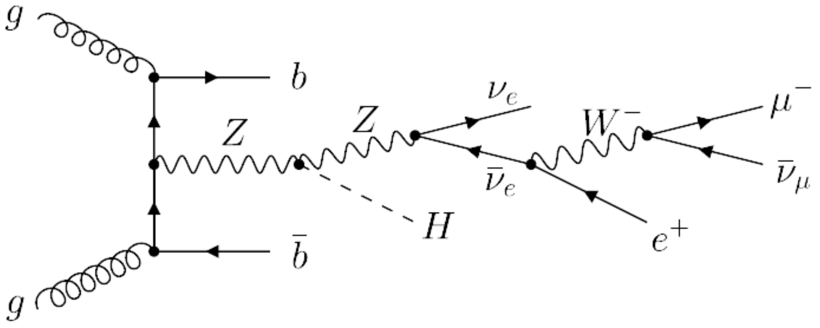
Double resonant



Single resonant



Non resonant



Narrow-width approximation (NWA)

- Unstable particles in the limit $\Gamma/m \to 0$

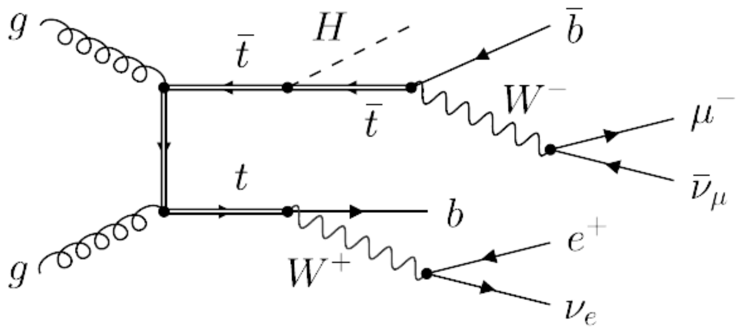
$$\frac{1}{\left(p^2 - m^2\right)^2 + m^2\Gamma^2} \to \frac{\pi}{m\Gamma}\delta\left(p^2 - m^2\right)$$

- Neglect all single and non-resonant diagrams

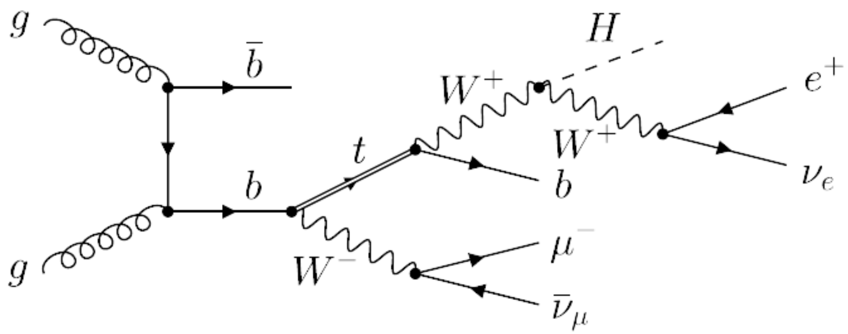
⇨ Assess impact of off-shell effects for $pp \to t\bar{t}H$

⇨ Model Higgs boson decays in NWA

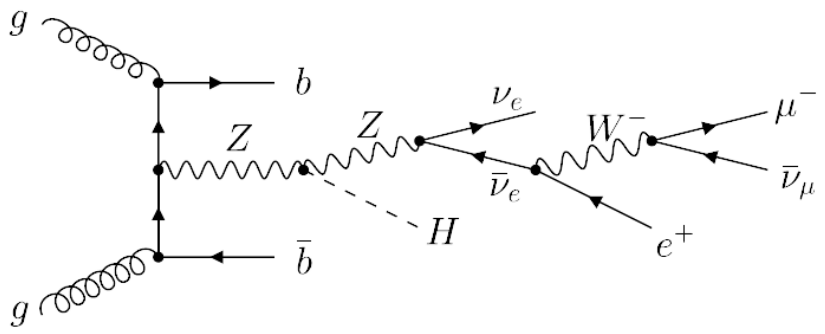
Double resonant



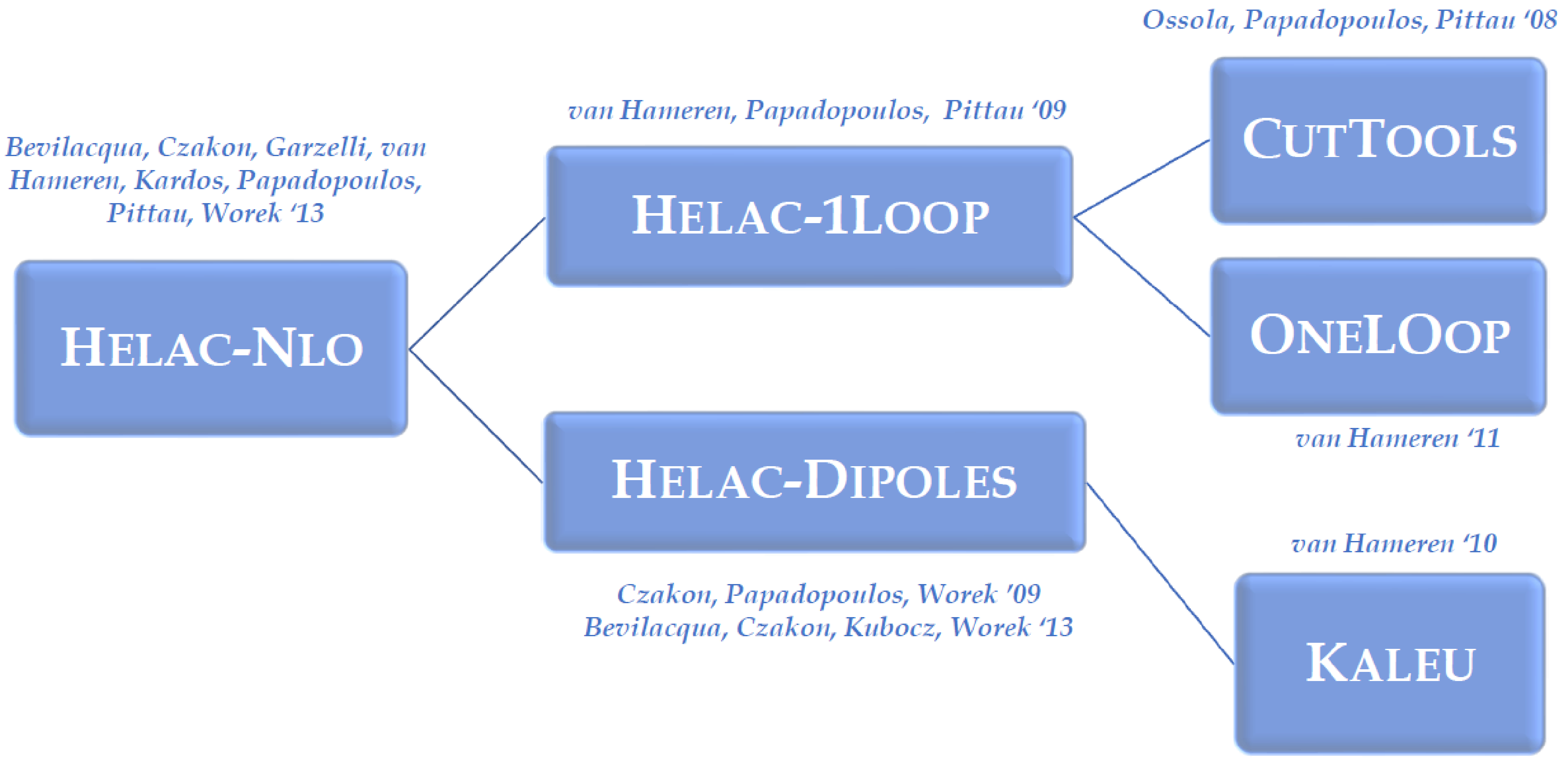
Single resonant



Non resonant



HELAC-NLO



- Theoretical prediction are stored in modified Les Houches Event Files (LHEFs)

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre '14

- Events can be reweighted to different renormalisation/factorisation scales and PDF sets
- Model Higgs decays in the NWA with LHEFs

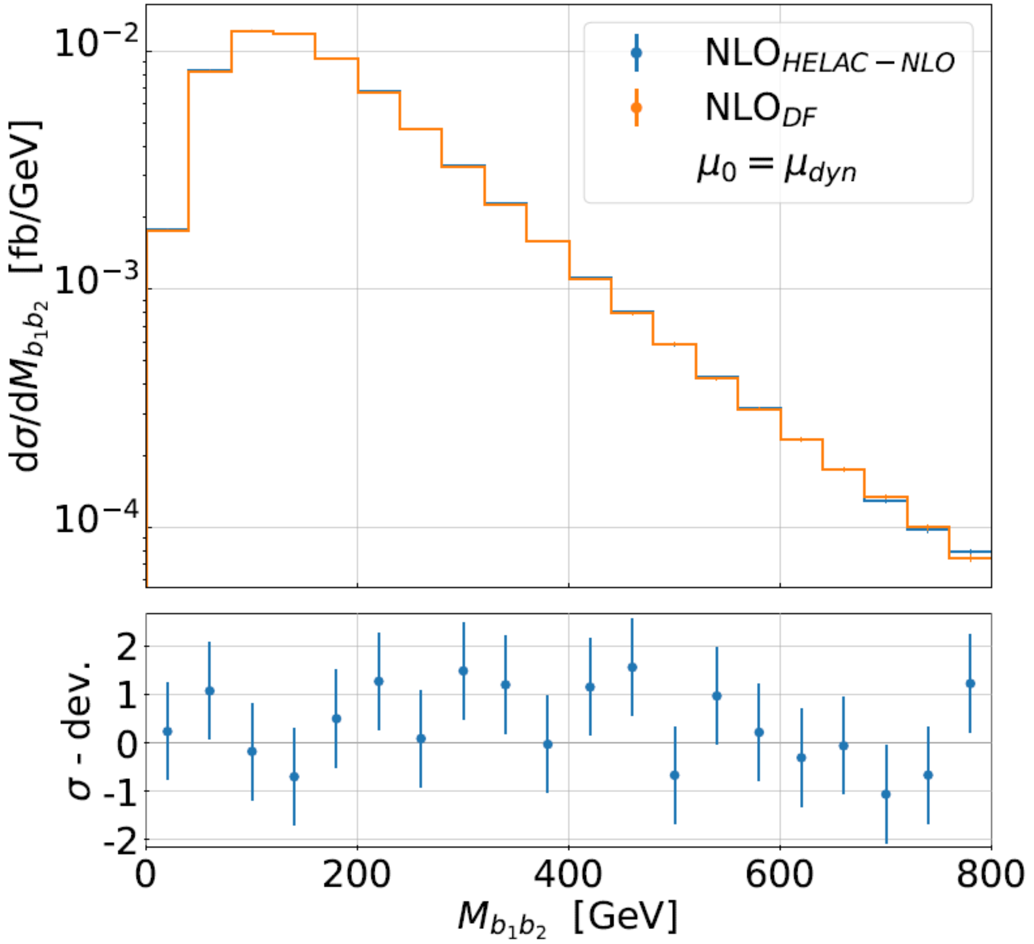
Numerical Checks

- Comparison with results from Denner, Feger '15

μ_0		HELAC-NLO	DF
μ_{dyn}	σ_{LO} [fb]	$2.2659(2)^{+30.8\%}_{-22.0\%}$	$2.2656(1)^{+30.8\%}_{-22.0\%}$
	σ_{NLO} [fb]	$2.654(2)^{+0.9\%}_{-4.7\%}$	$2.656(3)^{+0.9\%}_{-4.6\%}$
	$\mathcal{K}$	$1.171(1)$	$1.172(1)$
μ_{fix}	σ_{LO} [fb]	$2.2402(2)^{+31.0\%}_{-22.0\%}$	$2.2401(1)^{+31.0\%}_{-22.0\%}$
	σ_{NLO} [fb]	$2.633(2)^{+0.6\%}_{-5.0\%}$	$2.633(3)^{+0.6\%}_{-5.0\%}$
	$\mathcal{K}$	$1.175(1)$	$1.176(1)$

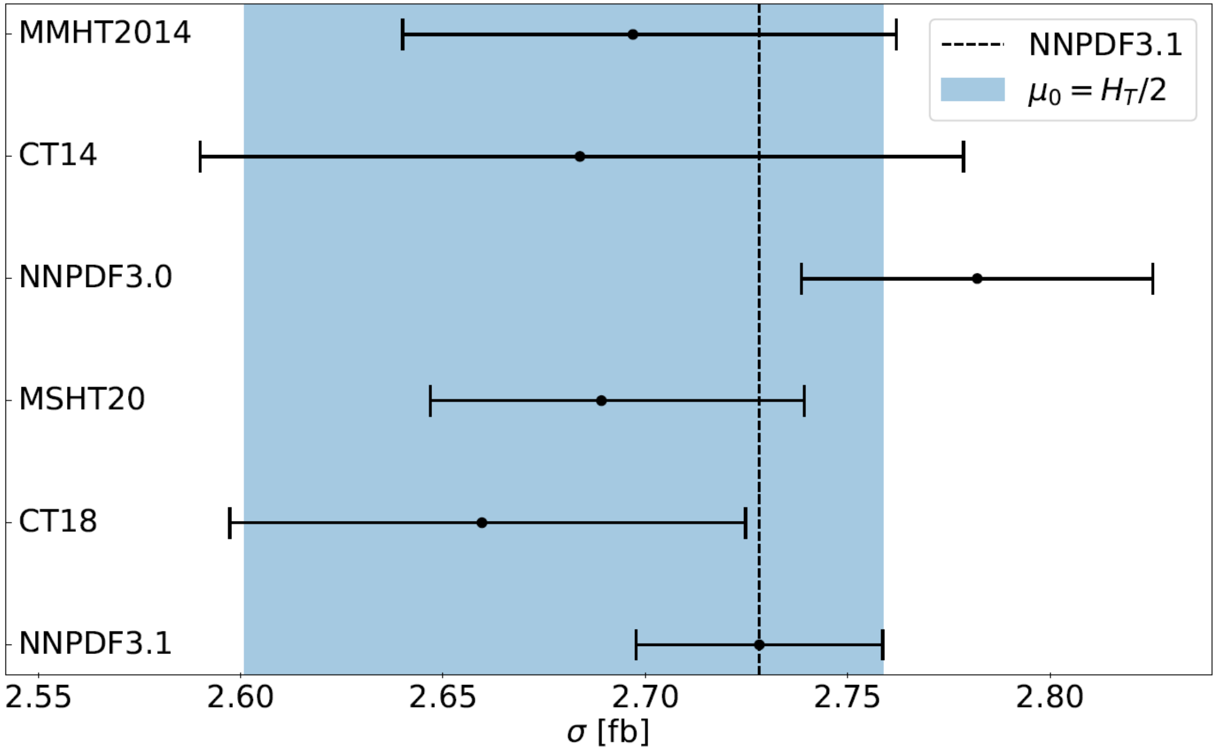
$$\mu_{fix} = \frac{1}{2}(2m_t + M_H) = 236 \text{ GeV}$$

$$\mu_{dyn} = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \qquad \text{with} \quad m_T = \sqrt{m^2 + p_T^2}$$



Fiducial cross sections

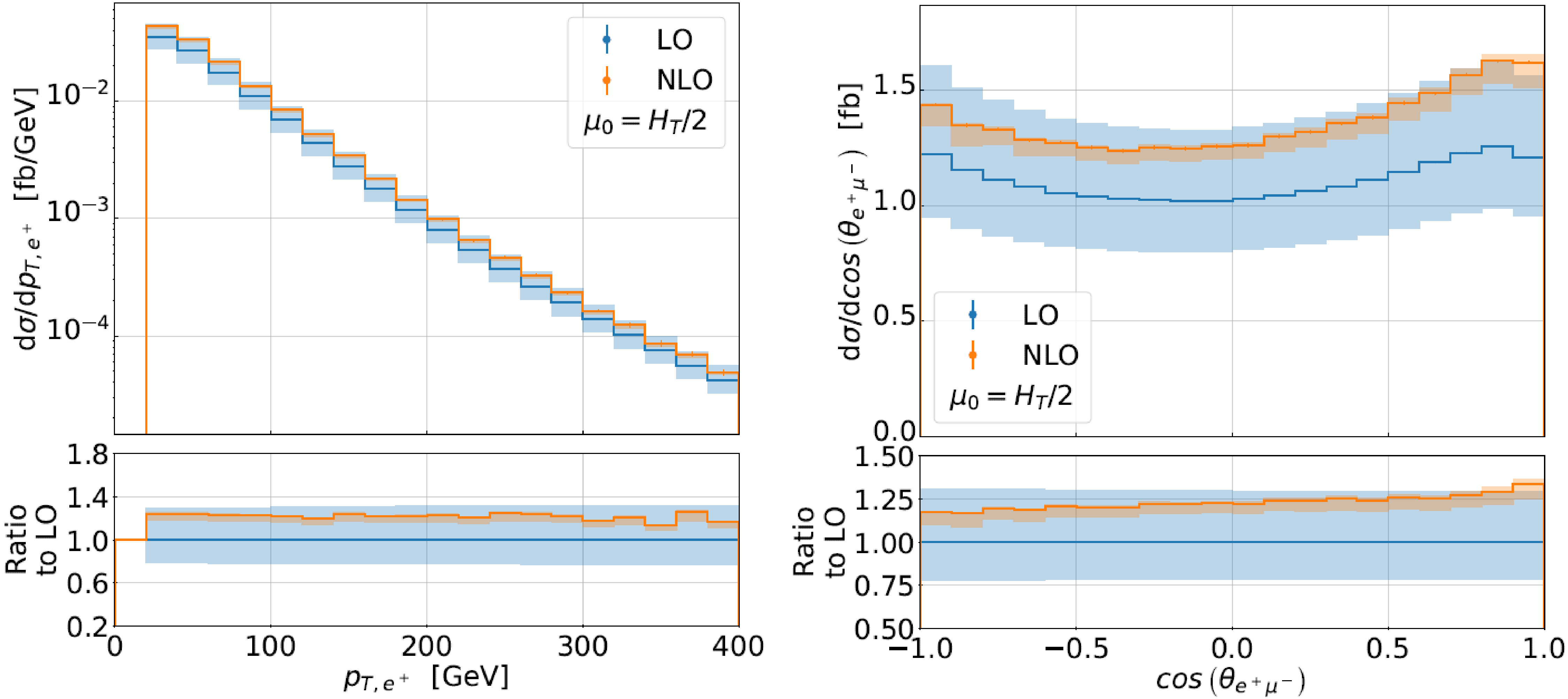
PDF set	$\sigma_{\rm NLO}$ [fb]	δ_{scale}	$\delta_{\rm PDF}$
NNPDF3.1	2.728(2)	$+0.030\,(1.1\%)$ $-0.127\,(4.7\%)$	$+0.030\,(1.1\%)$ $-0.030\,(1.1\%)$
CT18	2.660(2)	$+0.029\,(1.1\%)$ $-0.121\,(4.6\%)$	$+0.065\,(2.4\%)$ $-0.062\,(2.3\%)$
MSHT20	2.689(2)	$+0.030\,(1.1\%)$ $-0.123\,(4.6\%)$	$+0.050\,(1.9\%)$ $-0.042\,(1.6\%)$



- $\sigma_{\rm LO,NNPDF31} = 2.2130(2)^{+30.1\%}_{-21.6\%}$
- NLO QCD corrections ~20%
- 5% scale uncertainties
- 1% – 2% PDF uncertainties
- All PDF sets are consistent

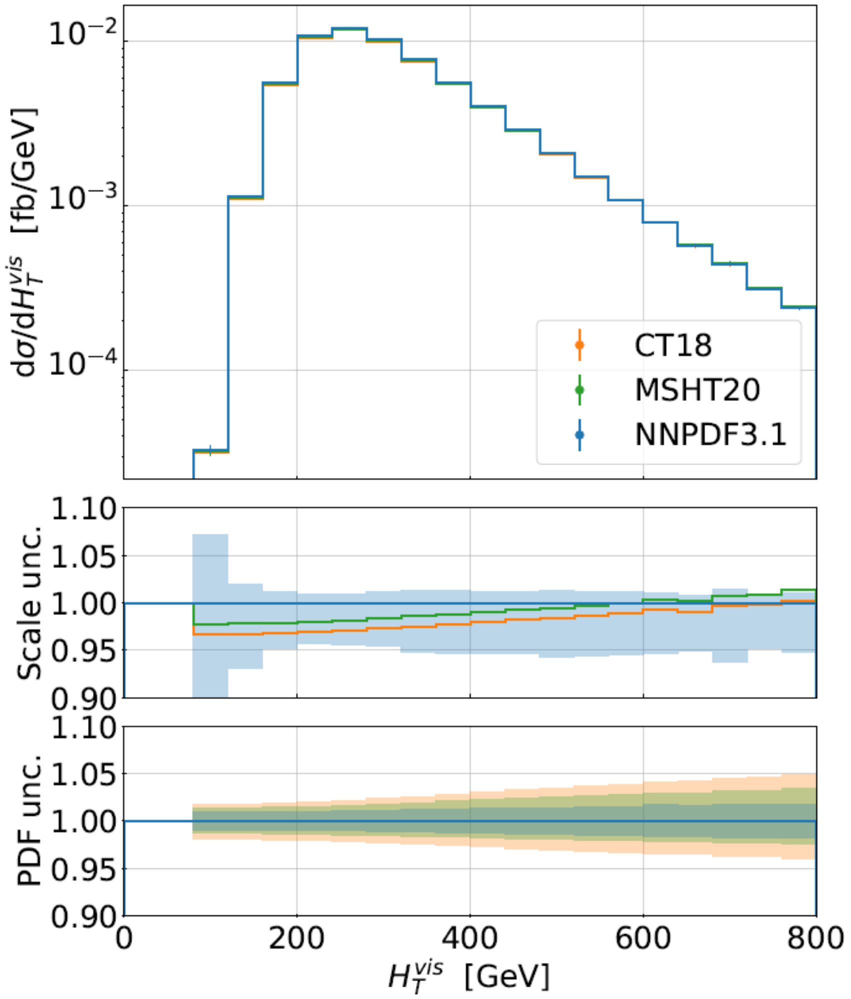
$$H_T = p_{T,b_1} + p_{T,b_2} + p_{T,e^+} + p_{T,\mu^-} + p_{T,miss} + p_{T,H}$$

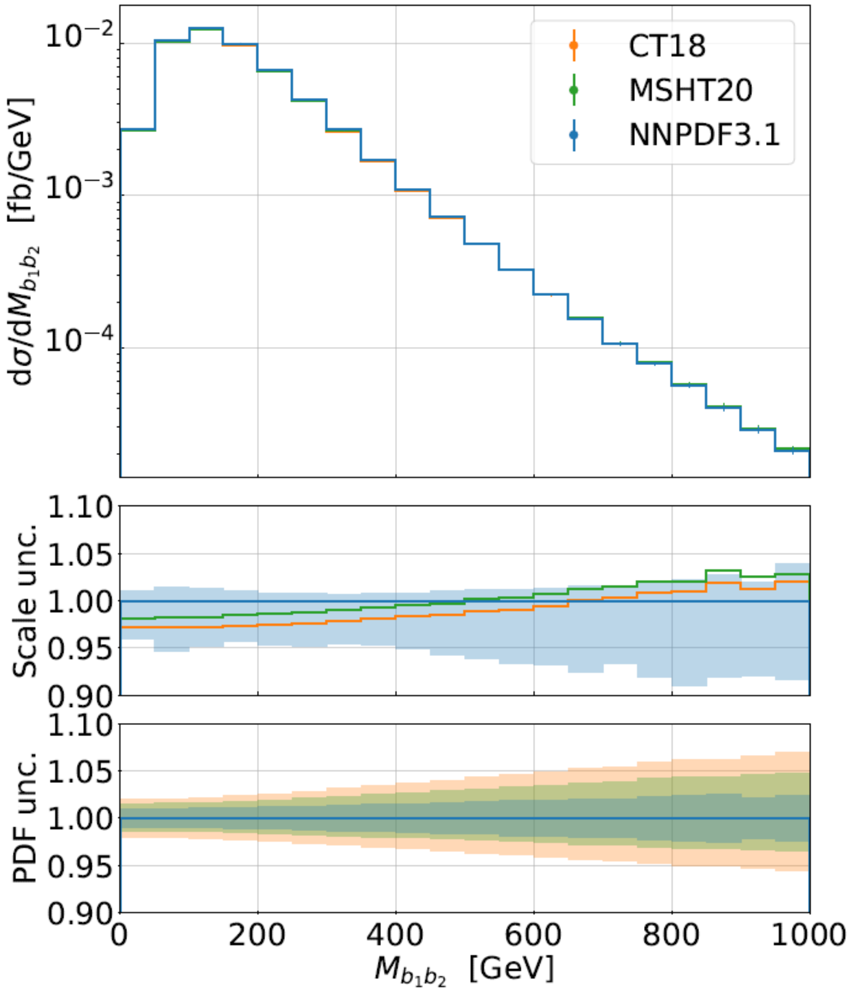
Differential distributions



- NLO QCD corrections $\sim 20\% - 35\%$
- Scale uncertainties reduced from $\sim 30\%$ at LO to $5\% - 10\%$ at NLO

Differential distributions



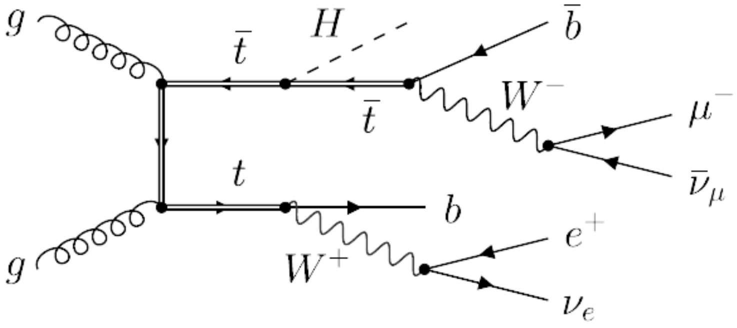


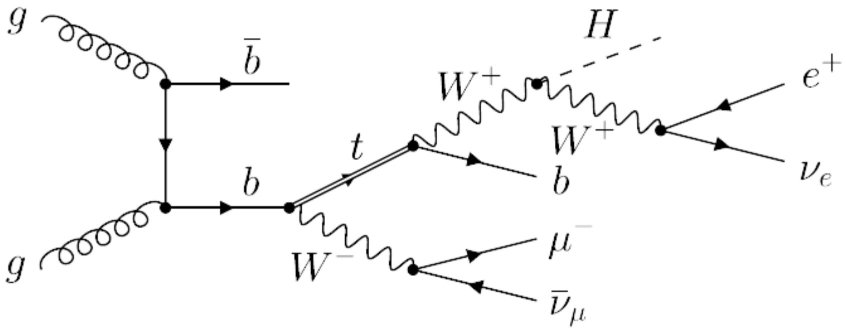
- PDF uncertainties increases towards the tails
- Comparable in size to scale uncertainties in tails

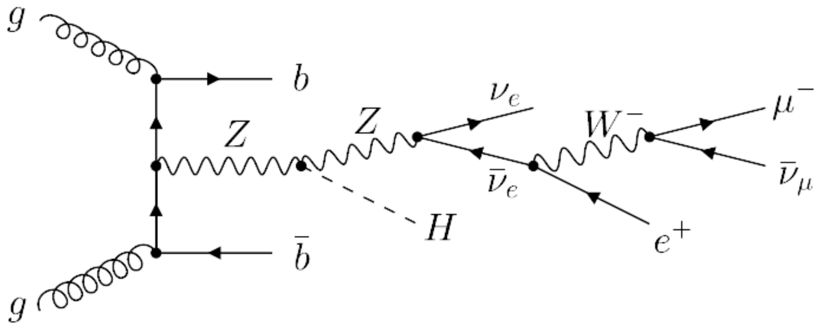
Top quark modeling

	μ_0	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]
full off-shell	$H_T/2$	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.728(2)^{+1.1\%}_{-4.7\%}$
	μ_{fix}	$2.3005(2)^{+30.8\%}_{-21.9\%}$	$2.731(2)^{+0.6\%}_{-5.4\%}$
NWA	$H_T/2$	$2.2235(2)^{+30.1\%}_{-21.6\%}$	$2.738(1)^{-3.0\%}_{-4.7\%}$
	μ_{fix}	$2.3074(2)^{+30.7\%}_{-21.9\%}$	$2.742(1)^{-3.8\%}_{-5.3\%}$
$\rm NWA_{LOdec}$	$H_T/2$	-	$2.862(1)^{+6.3\%}_{-9.4\%}$
	μ_{fix}	-	$2.897(1)^{+5.1\%}_{-9.0\%}$

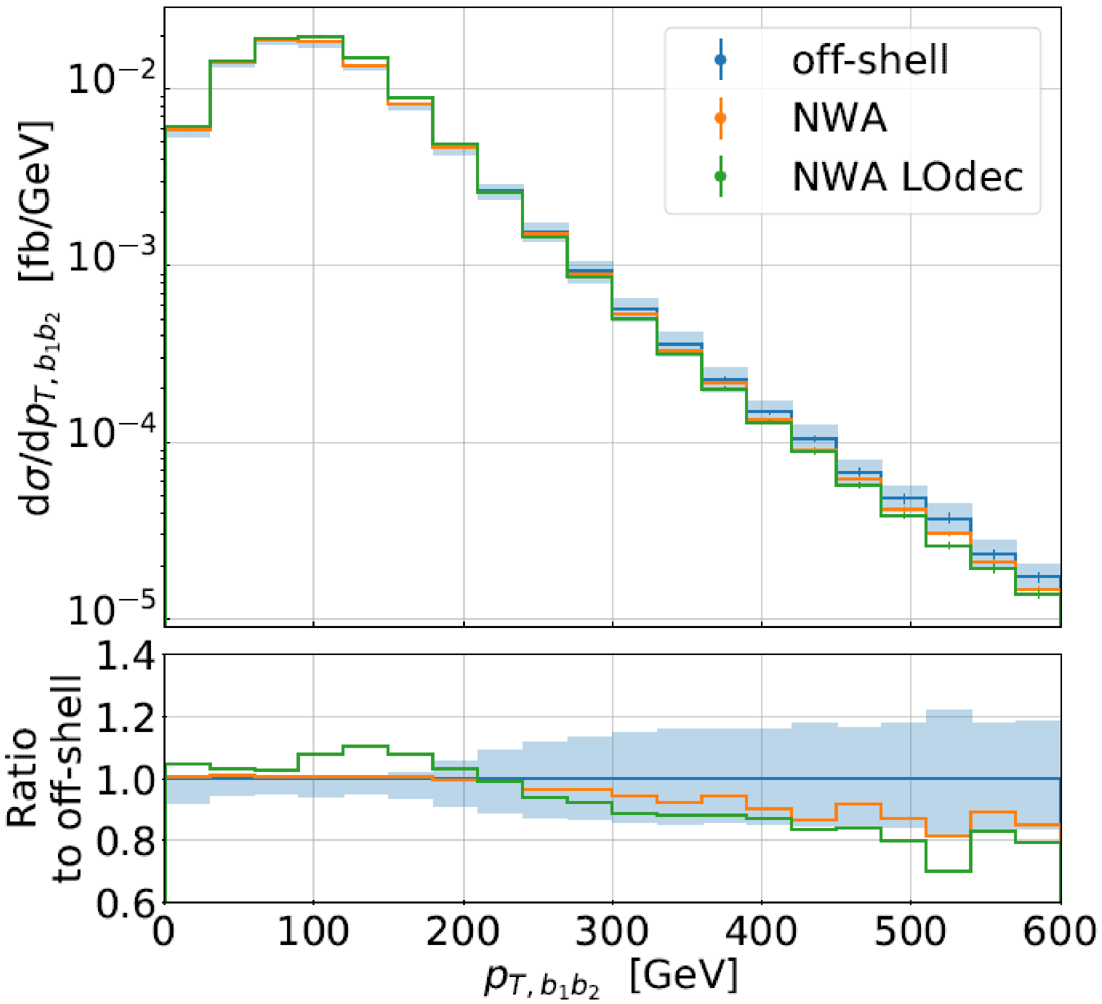
- Off-shell effects: ~ 0.3% – 0.5%
- $\rm NWA_{LOdec}$ about ~ 4% – 5% larger than NWA
- $\rm NWA_{LOdec}$ about 5% larger scale uncertainties

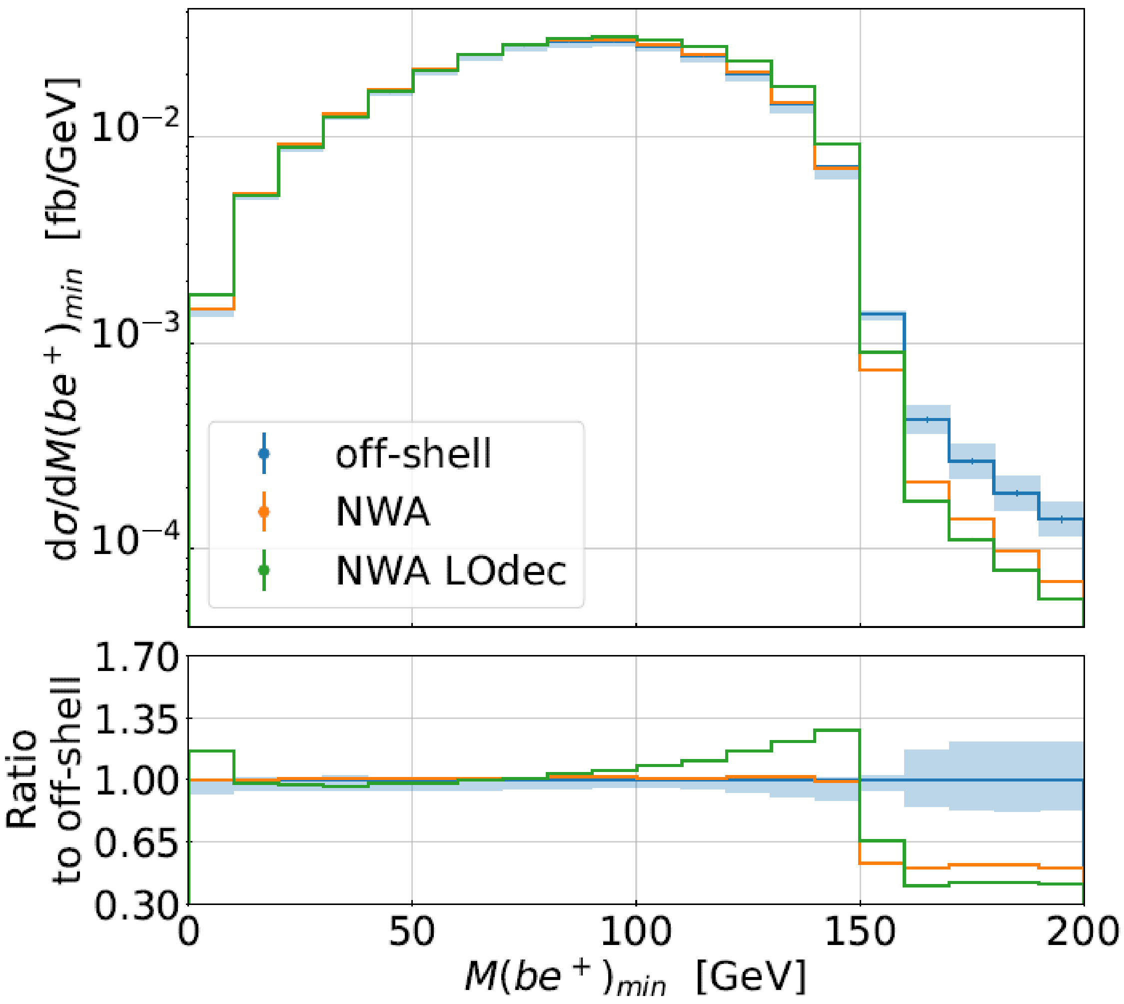






Top quark modeling





- Off-shell effects ~ 15% – 20% in the tails
- $\mathrm{NWA}_{\mathrm{LOdec}}$ further shape distortions
- $\mathrm{LO}_{\mathrm{NWA}} \rightarrow M(be^+)_{min} \leq \sqrt{m_t^2 - m_W^2} \approx 153$ GeV

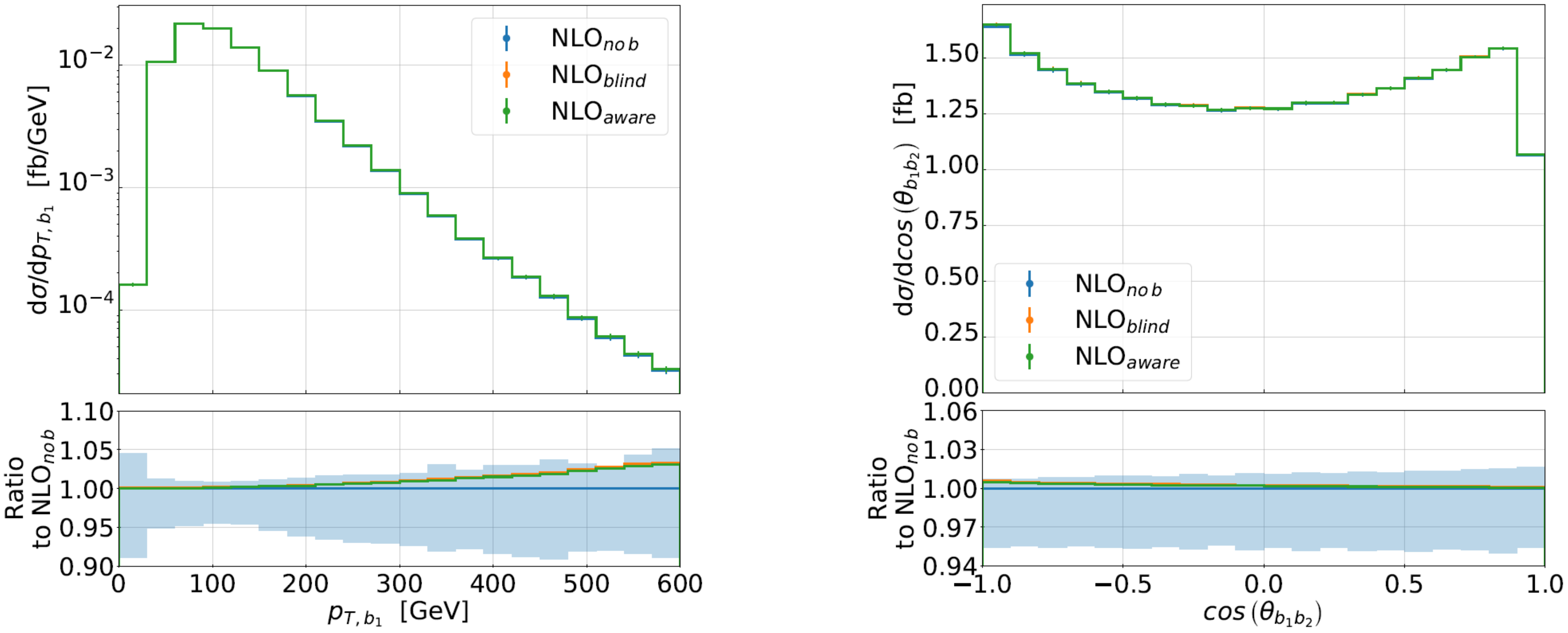
Initial-state b quark contribution

- Charge-blind: b and $\bar{b}$ cannot be distinguished $\quad b\bar{b} \to g \qquad bb \to g,\ \bar{b}\bar{b} \to g$
- Charge-aware: b and $\bar{b}$ can be distinguished $\quad b\bar{b} \to g \qquad bb \to b,\ \bar{b}\bar{b} \to \bar{b}$

	μ_0	$\sigma_{\text{no b}}$ [fb]	σ_{aware} [fb]	σ_{blind} [fb]	δ_{aware}	δ_{blind}
LO	$H_T/2$	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.2169(2)^{+30.0\%}_{-21.5\%}$	$2.2170(2)^{+30.0\%}_{-21.5\%}$	0.18%	0.18%
NLO	$H_T/2$	$2.728(2)^{+1.1\%}_{-4.7\%}$	$2.734(2)^{+1.3\%}_{-4.8\%}$	$2.736(2)^{+1.3\%}_{-4.8\%}$	0.22%	0.29%
LO	μ_{fix}	$2.3005(2)^{+30.8\%}_{-21.9\%}$	$2.3044(2)^{+30.7\%}_{-21.9\%}$	$2.3045(2)^{+30.7\%}_{-21.9\%}$	0.17%	0.17%
NLO	μ_{fix}	$2.731(2)^{+0.6\%}_{-5.4\%}$	$2.738(2)^{+0.7\%}_{-5.1\%}$	$2.740(2)^{+0.7\%}_{-5.1\%}$	0.26%	0.33%

- Bottom quark contribution negligible $\sim 0.2\% - 0.3\%$

Initial-state b quark contribution



- Bottom quark contributions enhanced in the tails of hadronic observables (3%)
- Only minor effects in angular distributions and non-hadronic observables

Production and decay of the Higgs boson

$$pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu \, b\bar{b} \, H \, (H \to X)$$

- Model Higgs decay in the NWA using the LHEFs
- Generate unweighted events of the decay process in the rest frame of the Higgs boson

$$\begin{aligned} d\sigma &= d\sigma_{t\bar{t}H} \frac{d\Gamma_{H\to X}}{\Gamma_H} \\ &= d\sigma^0_{t\bar{t}H} \frac{d\Gamma^0_{H\to X}}{\Gamma_H} + d\sigma^1_{t\bar{t}H} \frac{d\Gamma^0_{H\to X}}{\Gamma_H} + d\sigma^0_{t\bar{t}H} \frac{d\Gamma^1_{H\to X}}{\Gamma_H} \end{aligned}$$

(i) $H \to b\bar{b}$

(ii) $H \to \tau^+\tau^-$

(iii) $H \to \gamma\gamma$

(iv) $H \to Z^* Z^* \to e^+ e^- e^+ e^-$

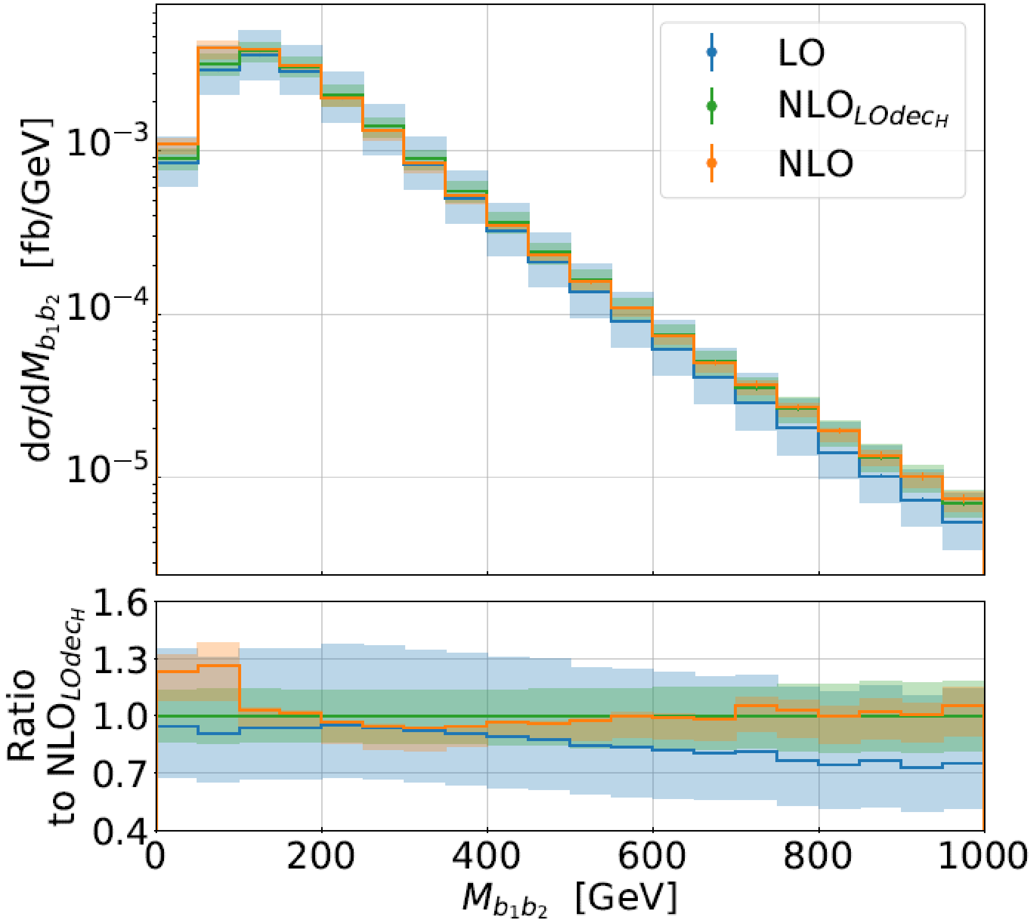
Production and decay of the Higgs boson

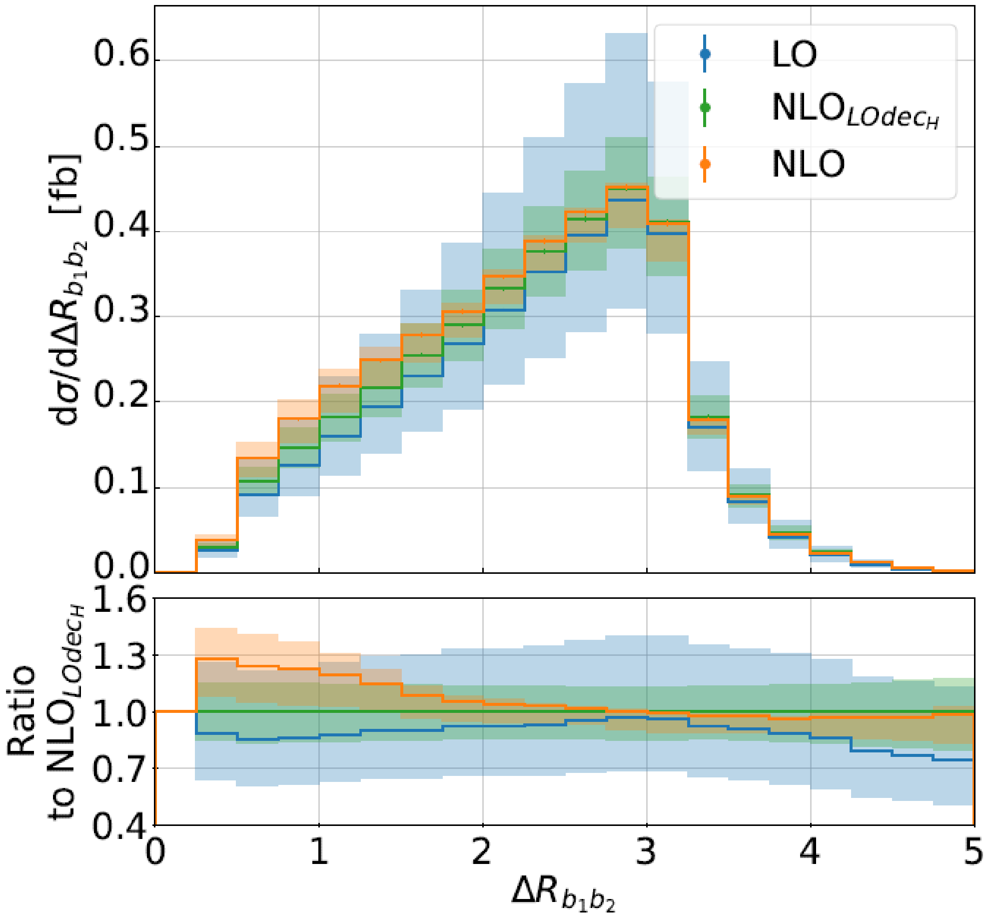
	σ_{LO} [fb]	σ_{NLO} [fb]	$\mathcal{K}$
Stable Higgs	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.728(2)^{+1.1\%}_{-4.7\%}$	1.23
$H \to b\bar{b}$	$0.8304(2)^{+44.4\%}_{-28.7\%}$	$0.9456(8)^{+2.5\%}_{-9.5\%}$	1.14
$H \to \tau^+\tau^-$	$0.11426(2)^{+30.0\%}_{-21.6\%}$	$0.1418(1)^{+1.2\%}_{-4.8\%}$	1.24
$H \to \gamma\gamma$	$0.0037754(8)^{+30.0\%}_{-21.6\%}$	$0.004552(4)^{+0.9\%}_{-4.1\%}$	1.21
$H \to e^+e^-e^+e^-$	$1.0083(7) \cdot 10^{-5}{}^{+30.2\%}_{-21.6\%}$	$1.313(4) \cdot 10^{-5}{}^{+1.8\%}_{-6.2\%}$	1.30

$$\sigma_{\mathrm{NLO}_{LOdec_H}}(H \to b\bar{b}) = 0.8956(8)^{+13.8\%}_{-14.2\%}\ \mathrm{fb}$$

- $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$: Y_b renormalised in $\overline{MS}$ scheme with scale $\mu_{R,dec} = m_H$
- Similar scale uncertainties except for ($\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$)
- Corrections in the decay about 5% and scale uncertainties reduced by 5%
- Only 15% of stored events pass the event selection for $\mathrm{H} \to e^+e^-\,e^+\,e^-$ (70% – 80% for other decay channels)

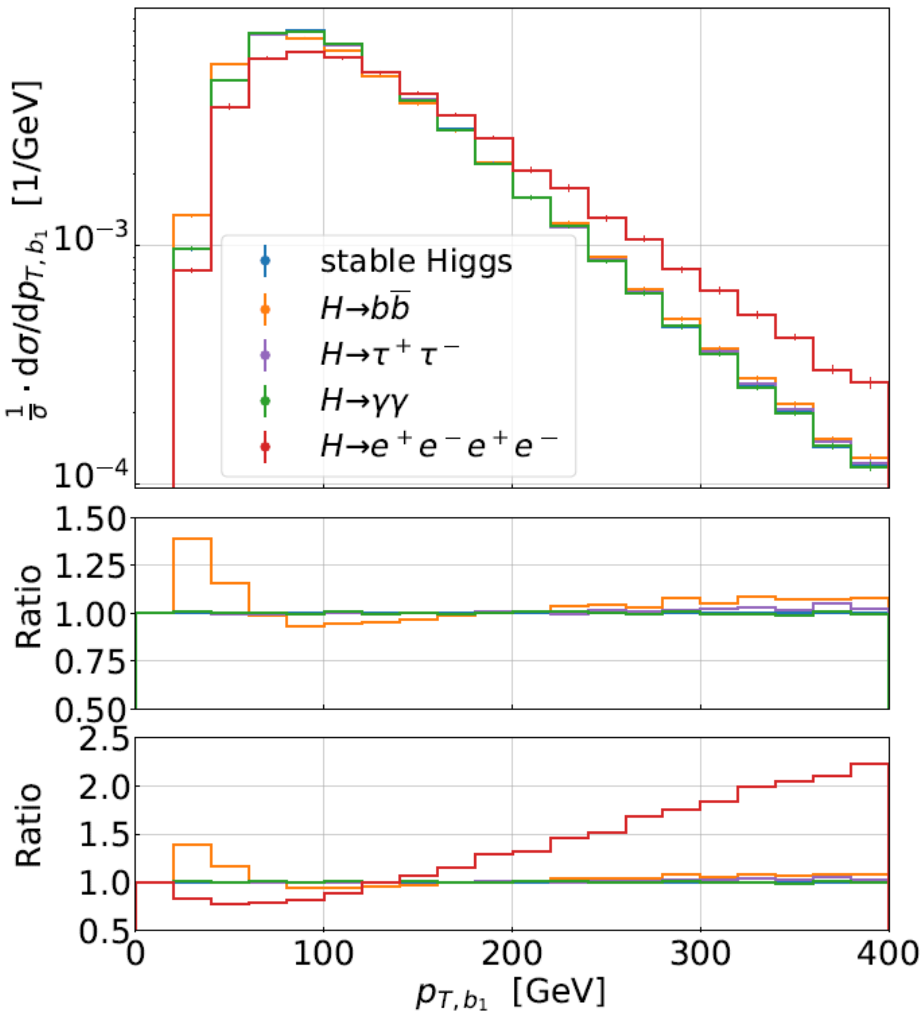
Production and decay of the Higgs boson ($H \to b\bar{b}$)

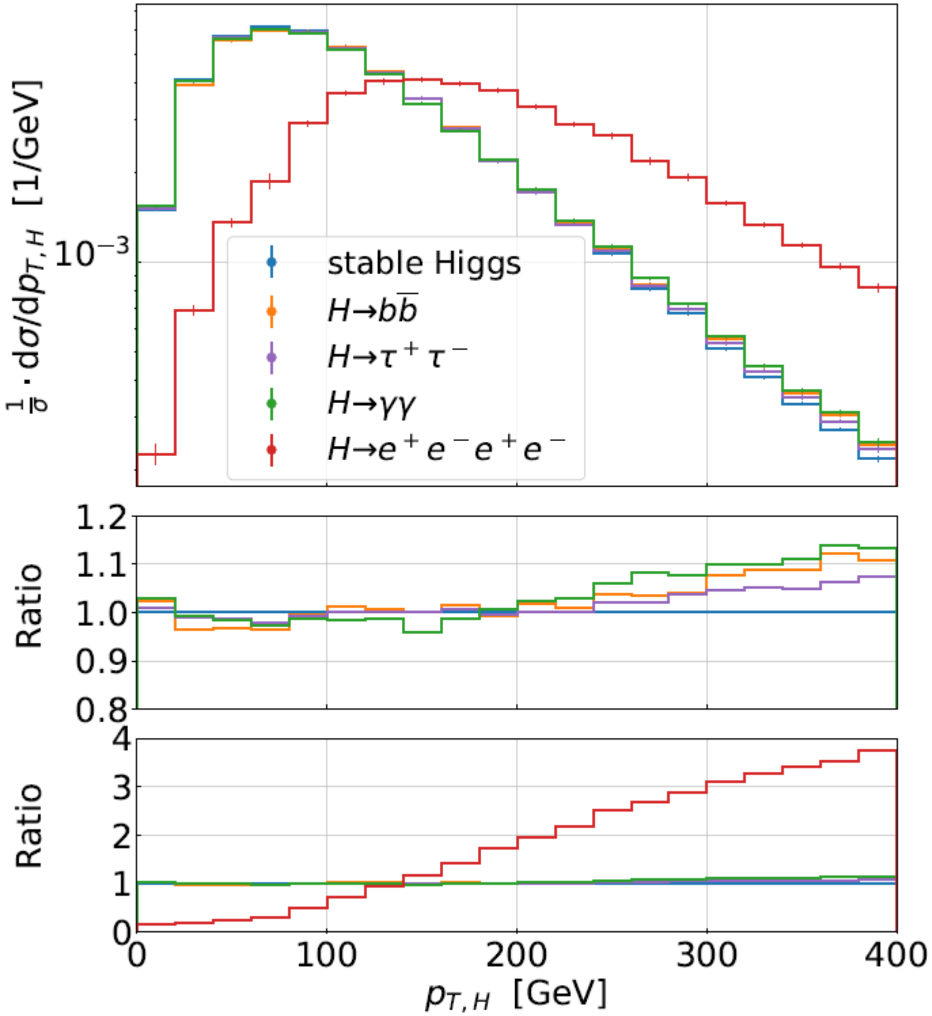




- Reduction of scale uncertainties by 30% from LO to NLO_{LOdec_H}
- Additional reduction of scale uncertainties by 5% from NLO_{LOdec_H} to NLO

Production and decay of the Higgs boson





- Harder distributions for $\mathrm{H} \to e^+e^-\, e^+\, e^-$
- Hadronic observables enhanced for small energies for $\mathrm{H} \to \mathrm{b\bar{b}}$

Conclusion

- NLO QCD corrections to $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}\, H\,(H \to X)$
- Theoretical uncertainties dominated by scale uncertainties
- NWA sufficient for most distributions,
  Still sizeable off-shell effects around kinematical edges and in high energy regions
- Initial-state bottom quark contribution negligible for most distributions
- Inclusion of different Higgs decay channels

  (i) $H \to b\bar{b}$

  (ii) $H \to \tau^+\tau^-$

  (iii) $H \to \gamma\gamma$

  (iv) $H \to Z^*Z^* \to e^+e^-e^+e^-$

Backup

Input Parameters

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) \qquad G_\mu = 1.16637 \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$

$$m_t = 173\ \mathrm{GeV} \qquad M_H = 126\ \mathrm{GeV}$$

$$M_W^{\mathrm{OS}} = 80.385\ \mathrm{GeV} \qquad \Gamma_W^{\mathrm{OS}} = 2.0850\ \mathrm{GeV}$$

$$m_Z^{\mathrm{OS}} = 91.1876\ \mathrm{GeV} \qquad \Gamma_Z^{\mathrm{OS}} = 2.4952\ \mathrm{GeV}$$

$$M_V = \frac{M_V^{\mathrm{OS}}}{\sqrt{1 + \left(\Gamma_V^{\mathrm{OS}}/M_V^{\mathrm{OS}}\right)^2}} \qquad \Gamma_V = \frac{\Gamma_V^{\mathrm{OS}}}{\sqrt{1 + \left(\Gamma_V^{\mathrm{OS}}/M_V^{\mathrm{OS}}\right)^2}}$$

Complex-mass scheme

$$\mu_X^2 = m_X^2 - i m_X \Gamma_X \qquad s_w^2 = 1 - \mu_W^2/\mu_Z^2$$

Event selection

- Jets clustered using the anti-k_T algorithm with $R = 0.4$

$$p_{T,b} > 25 \text{ GeV} \qquad |\eta_b| < 2.5 \qquad p_{T,miss} > 20 \text{ GeV}$$

$$p_{T,l} > 20 \text{ GeV} \qquad |\eta_l| < 2.5$$

Scale Uncertainties

$$\frac{1}{2}\,\mu_0 \le \mu_R\,,\mu_F \le 2\,\mu_0 \qquad\qquad \frac{1}{2} \le \frac{\mu_R}{\mu_F} \le 2$$

$$\left(\frac{\mu_R}{\mu_0}\,,\frac{\mu_F}{\mu_0}\right) = \Big\{\,(2,1)\,,(0.5,1)\,,(1,2)\,,(1,1),(1,0.5),(2,2),(0.5,0.5)\Big\}$$

In addition for $H \to b\bar{b}$

$$\frac{1}{2}\,M_H \le \mu_{R,dec} \le 2\,M_H$$

$$\left(\frac{\mu_{R,dec}}{M_H}\right) = \Big\{0.5, 1, 2.0\Big\}$$

Fiducial cross section

μ_0	PDF	σ_{LO} [fb]	σ_{NLO} [fb]	$\mathcal{K}$
$H_T/2$	NNPDF3.1	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.728(2)^{+1.1\%}_{-4.7\%}$	1.23
μ_{fix}	NNPDF3.1	$2.3005(2)^{+30.8\%}_{-21.9\%}$	$2.731(2)^{+0.6\%}_{-5.4\%}$	1.19
μ_{dyn}	NNPDF3.1	$2.3320(2)^{+30.7\%}_{-21.9\%}$	$2.754(2)^{+0.9\%}_{-5.1\%}$	1.18

$$\mu_{fix} = \frac{1}{2}(2m_t + M_H) = 236 \text{ GeV}$$

$$\mu_{dyn} = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \qquad \text{with} \quad m_T = \sqrt{m^2 + p_T^2}$$

$$H_T = p_{T,b_1} + p_{T,b_2} + p_{T,e^+} + p_{T,\mu^-} + p_{T,miss} + p_{T,H}$$

Higgs decays - Parameters

$$m_\tau = 1.77682 \text{ GeV}, \qquad m_b^{OS} = 4.92 \text{ GeV}, \qquad \overline{m}_b(\overline{m}_b) = 4.18 \text{ GeV}.$$

$$\Gamma_H = 4.226 \cdot 10^{-3} \text{ GeV}$$

$$R(\gamma,\gamma) > 0.3 \qquad R(\gamma,l) > 0.3 \qquad R(\gamma,b) > 0.3$$

$$p_{T,\gamma} > 25 \text{ GeV} \qquad |\eta_\gamma| < 2.5$$

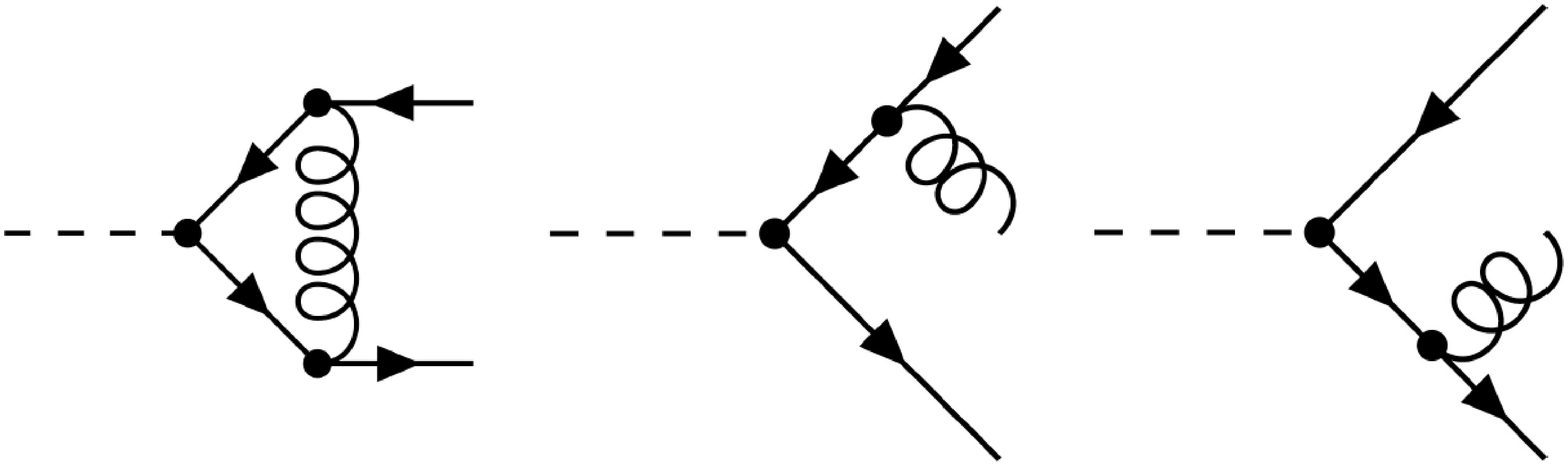
Frixione photon isoloation

- Partonic event has to satisfy following condition for both photons
- $\epsilon_\gamma = 1,\ n = 1,\ R(\gamma j) = 0.3$
- Sum runs over all finale state partons

$$\sum_i E_T(i)\Theta(R - R(\gamma i)) \leq \epsilon_\gamma E_T(\gamma)\left(\frac{1-\cos(R)}{1-\cos(R(\gamma j))}\right)^n \qquad \forall R \leq R(\gamma j)$$

Production and decay of the Higgs boson ($H \to b\bar{b}$)

- Bottom quark mass neglected in complete calculation
- Y_b neglected in Higgs production
- Y_b renormalised in $\overline{MS}$ scheme with scale $\mu_{R,dec} = m_H$
- Virtual corrections and integrated dipoles calculated with LHEFs
- Subtracted Real emission calculated with HELAC-DIPOLES



$\overline{MS}$ mass running

$$\overline{m}_b(\mu) = \overline{m}_b(\mu_0)\frac{c(a_s(\mu))}{c(a_s(\mu_0))}$$

with $a_s = \alpha_s/\pi$ and $c(a_s) = a_s^{c_0}\left[1 + (c_1 - b_1 c_0)a_s\right]$

$$c_i = \frac{\gamma_i^m}{\beta_0} \quad \text{and} \quad b_i = \frac{\beta_i}{\beta_0}.$$

$$\beta_0 = \frac{11}{4} - \frac{1}{6}N_f \qquad \gamma_0^m = 1$$

$$\beta_1 = \frac{51}{8} - \frac{19}{24}N_f \qquad \gamma_1^m = \frac{101}{24} - \frac{5}{36}N_f$$

Input Parameters ($H \to b\bar{b}$)

- Factorization and renormalization scale set to $\mu_0 = H_T/2$

$$H_T = p_{T,b_1} + p_{T,b_2} + p_{T,e^+} + p_{T,\mu^-} + p_{T,miss} + p_{T,H}$$

- Higgs boson reconstructed by minimizing Q_{ij}
- p_{T,b_1}, p_{T,b_2} b-jets from top quarks

$$Q_{ij} = \left| M_{b_i b_j} - M_H \right|$$

LO

$$\overline{m}_b(M_H/2) = 3.160804 \text{ GeV}, \quad \overline{m}_b(M_H) = 2.999774 \text{ GeV}, \quad \overline{m}_b(2M_H) = 2.860548 \text{ GeV}$$

NLO

$$\overline{m}_b(M_H/2) = 2.977119 \text{ GeV}, \quad \overline{m}_b(M_H) = 2.805836 \text{ GeV}, \quad \overline{m}_b(2M_H) = 2.660844 \text{ GeV}$$