CP structure of the top-quark Yukawa interaction: NLO QCD corrections and off-shell effects

Based on *arXiv:2205.09983* (accepted for publication in JHEP)

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International Workshop on Top-Quark Physics • 06.09.2022 • Durham

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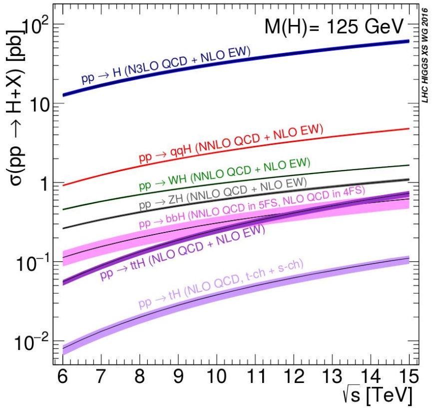
Introduction

ttH production:

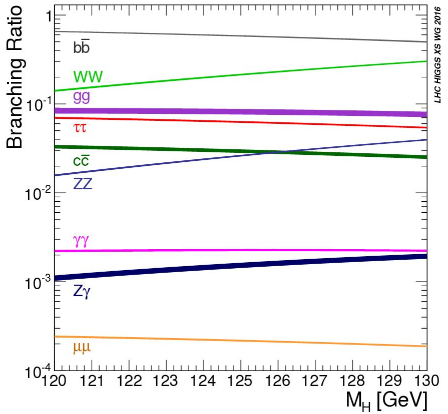
- Observed for the first time in 2018, ATLAS '18, CMS'18
- Allows for direct probe of Yukawa interaction and it's CP nature at tree level
- Top is heaviest SM particle
  → strongest Yukawa coupling
- Measurement of CP-odd component would indicate new physics

Higgs production:



ttH only 1% of total

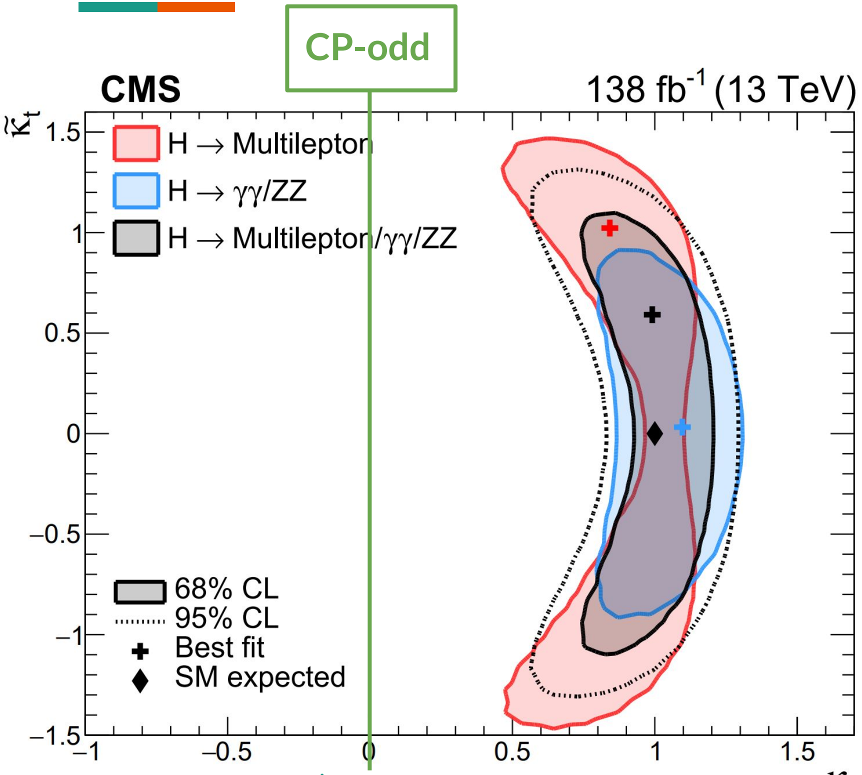
Higgs decay:



Main decay channel:
$\mathcal{BR}(H \rightarrow bb) \sim 58\%$

LHC Higgs XS WG '16

Introduction



CMS '22

SM-like interpretation:

- Still freedom in the CP-state of the Higgs boson
- SM prediction: Higgs is CP-even
- CP-odd state excluded with 3.9 σ (*ATLAS '20*) and 3.7 σ (*CMS '22*)
- $\alpha_{CP} > 43^\circ$ excluded at 95% CL if CP-even and CP-odd couplings are equal (*ATLAS '20*), $|f_{CP}^{\mathrm{Htt}}| < 0.55$ at 68 % (*CMS '22*)

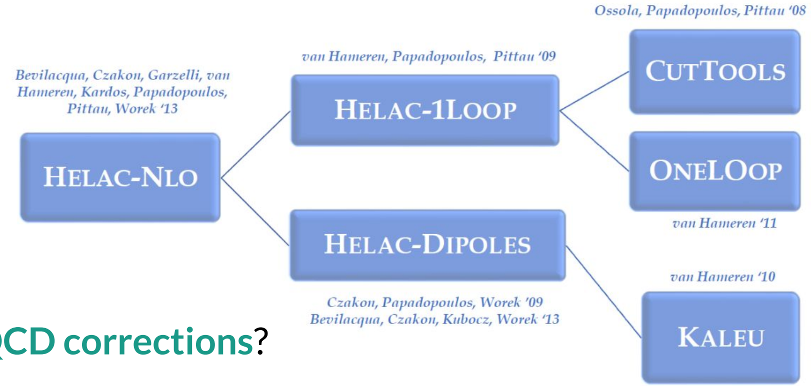
BSM interpretations:

- Extended Higgs sector
- 2HDM
- …

Introduction

Main Goal: $pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu \, b\bar{b} \, H + X \text{ at } \mathcal{O}(\alpha_S^3 \alpha^5)$

Provide state-of-the-art predictions for ttH production with possible **CP-mixing** between CP-even (SM) and CP-odd Higgs states at **NLO in QCD** including **full off-shell effects** using **HELAC-NLO**



Questions:

- Which **observables** are sensitive to the CP-state?
- How are the different CP-states affected by **NLO QCD corrections**?
- How are the different CP-states affected by **off-shell effects**?

Theory status

SM Higgs boson (stable tops):

- ttH @ NLO in QCD+EW with NNLL soft gluon resummation Broggio et al. '16, '17, '19, Kulesza, et al. '16, '18, '20

SM Higgs boson (with top quark decays):

- ttH @ NLO in QCD with full off-shell effects Denner, Feger '15
- ttH @ NLO in QCD+EW with full off-shell effects Denner, Lang, Pellen, Uccirati '17
- ttH @ NLO in QCD with full off-shell effects + Higgs decays in NWA Stremmer, Worek '22

Higgs boson with CP-odd admixture:

- ttX @ NLO in QCD with LO top decays matched to Parton Shower Demartin et al. '14
  - HC_NLO_X0 model Artoisenet et al. '13, Maltoni et al. '14, Demartin et al. '14, Demartin et al. '15
- ttX @ NLO in QCD with full off-shell effects JH, Stremmer, Worek '22

The Higgs characterisation framework (HCF)

SM:

$$\mathcal{L}_{t\bar{t}H} = -\frac{Y_t}{\sqrt{2}}\bar{\psi}_t\psi_t H$$

HCF:

Mixing angle

$$\mathcal{L}_{t\bar{t}H} = -\frac{Y_t}{\sqrt{2}}\bar{\psi}_t\left(\kappa_{Ht\bar{t}}\cos(\alpha_{CP}) + i\kappa_{At\bar{t}}\sin(\alpha_{CP})\gamma_5\right)\psi_t H$$

CP-even CP-odd

$$\mathcal{L}_{HVV} = \kappa_{HVV}\left(\frac{g_{HZZ}}{2}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right)H$$

Additional coupling

Coupling choices:

Ensure consistency with current experimental bounds (ggF, VBF)

$\boxed{\kappa_{Ht\bar{t}} = 1}$

$\boxed{\kappa_{At\bar{t}} = 2/3}$

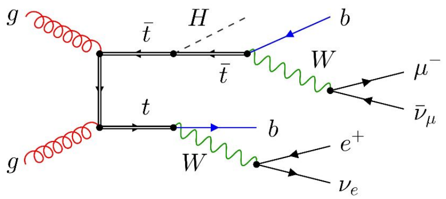
$\boxed{\kappa_{HVV} = 1}$

Artoisenet et al. '13
Maltoni et al. '14
Demartin et al. '14
Demartin et al. '15

Full off-shell effects

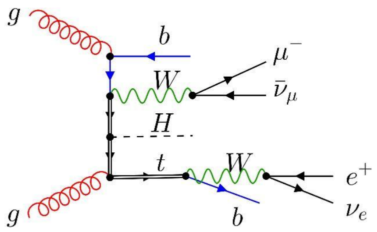
Process: $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H$ at $\mathcal{O}(\alpha_S^2\alpha^5)$

Double resonant

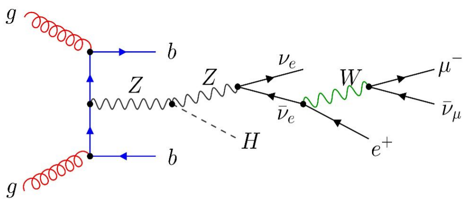


NWA

Single resonant



Non resonant



Off-shell

Full off-shell = DR + SR + NR + interference + Breit-Wigner

NWA = DR with on-shell masses $\quad \dfrac{\Gamma}{m} \to 0$

$$\mathcal{O}(\Gamma_t/m_t) \sim 0.8\%$$

Integrated fiducial cross-sections (NLO)

α_{CP}		Off-shell	NWA	Off-shell effects
CP-even	σ_{LO} [fb]	$2.0313(2)^{+0.6275\,(31\%)}_{-0.4471\,(22\%)}$	$2.0388(2)^{+0.6290\,(31\%)}_{-0.4483\,(22\%)}$	-0.37%
0 (SM)	σ_{NLO} [fb]	$2.466(2)^{+0.027\,(1.1\%)}_{-0.112\,(4.5\%)}$	$2.475(1)^{+0.027\,(1.1\%)}_{-0.113\,(4.6\%)}$	-0.36%
	$\sigma_{\mathrm{NLO}_{\mathrm{LOdec}}}$ [fb]	–	$2.592(1)^{+0.161\,(6.2\%)}_{-0.242\,(9.3\%)}$	
	$\mathcal{K} = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.21	1.21 (LOdec: 1.27)	
CP-mixed	σ_{LO} [fb]	$1.1930(2)^{+0.3742\,(31\%)}_{-0.2656\,(22\%)}$	$1.1851(1)^{+0.3707\,(31\%)}_{-0.2633\,(22\%)}$	0.66%
$\pi/4$	σ_{NLO} [fb]	$1.465(2)^{+0.016\,(1.1\%)}_{-0.071\,(4.8\%)}$	$1.452(1)^{+0.015\,(1.0\%)}_{-0.069\,(4.8\%)}$	0.89%
	$\sigma_{\mathrm{NLO}_{\mathrm{LOdec}}}$ [fb]	–	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
	$\mathcal{K} = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.23	1.23 (LOdec: 1.28)	
CP-odd	σ_{LO} [fb]	$0.38277(6)^{+0.13123\,(34\%)}_{-0.09121\,(24\%)}$	$0.33148(3)^{+0.11240\,(34\%)}_{-0.07835\,(24\%)}$	13.4%
$\pi/2$	σ_{NLO} [fb]	$0.5018(3)^{+0.0083\,(1.2\%)}_{-0.0337\,(6.7\%)}$	$0.4301(2)^{+0.0035\,(0.8\%)}_{-0.0264\,(6.1\%)}$	14.3%
	$\sigma_{\mathrm{NLO}_{\mathrm{LOdec}}}$ [fb]	–	$0.4433(2)^{+0.0323\,(7.3\%)}_{-0.0470\,(11\%)}$	
	$\mathcal{K} = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.31	1.30 (LOdec: 1.34)	

NLO corrections:

- **21% - 31%** corrections
- Increase with the mixing angle
- Reduced scale uncertainties
- NLO with LO decays overestimates NLO results by a few percent

Off-shell effects:

- Small for CP-even and CP-mixed Higgs boson
- Large effects for CP-odd Higgs boson

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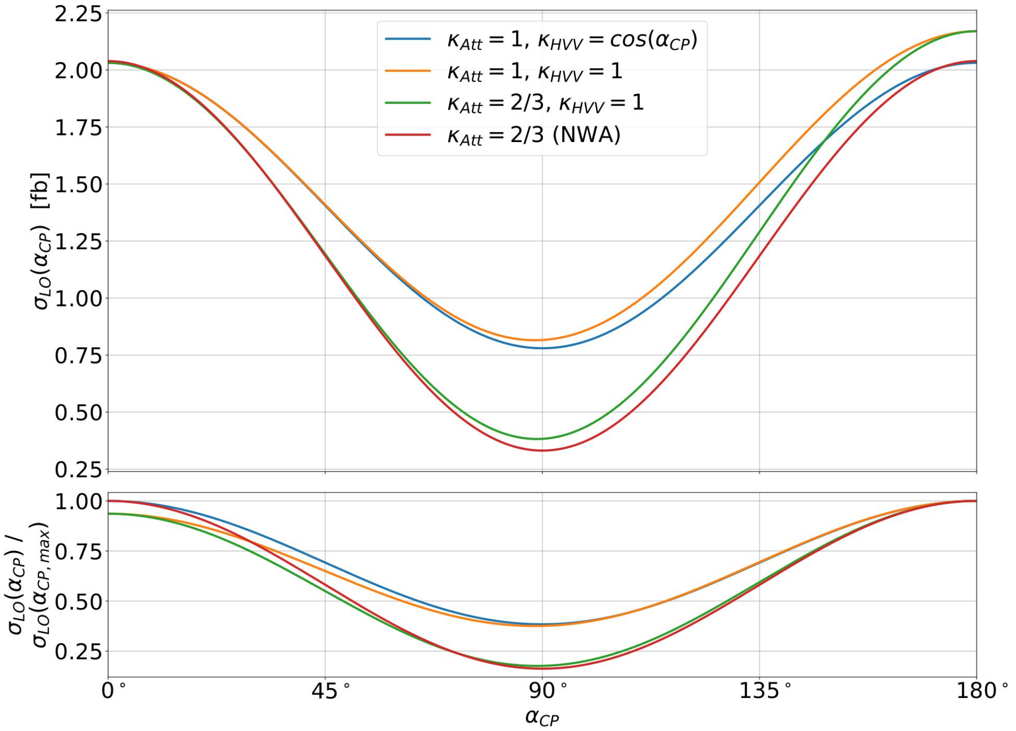
Integrated fiducial cross-sections (LO)



- **NWA is symmetric**
- Full result is only symmetric for $\kappa_{HVV} = \cos(\alpha_{\mathrm{CP}})$
- $\kappa_{At\bar{t}}$ only influences the size of the CP-odd contribution

Off-shell contributions break symmetry

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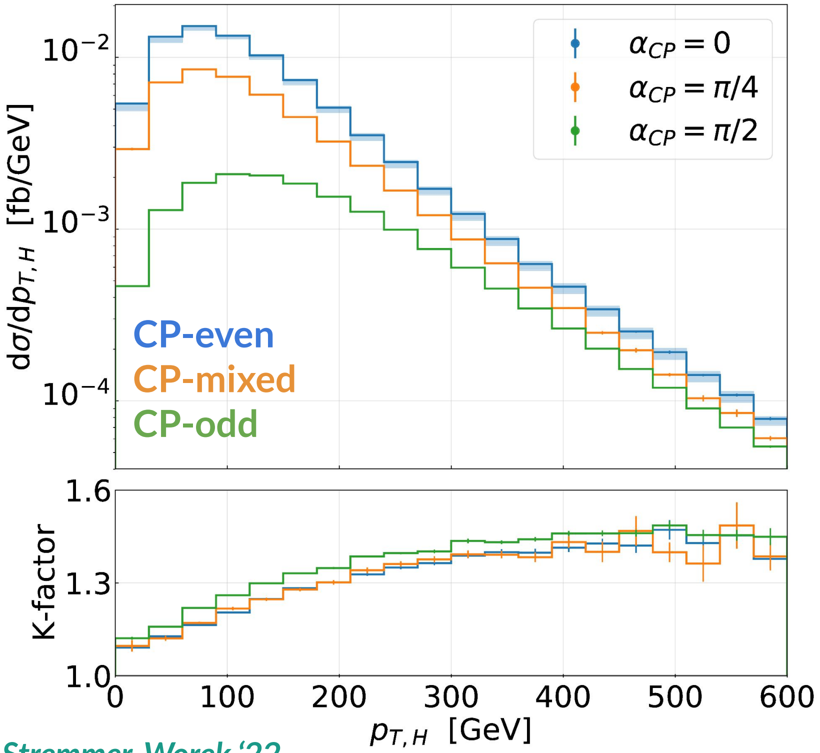
Differential distributions - NLO corrections



General behaviour:

- Larger corrections in distribution tails
- Corrections largest for CP-odd case
- Shape of K-factor similar between different CP-states
- Harder Higgs radiation in CP-odd case

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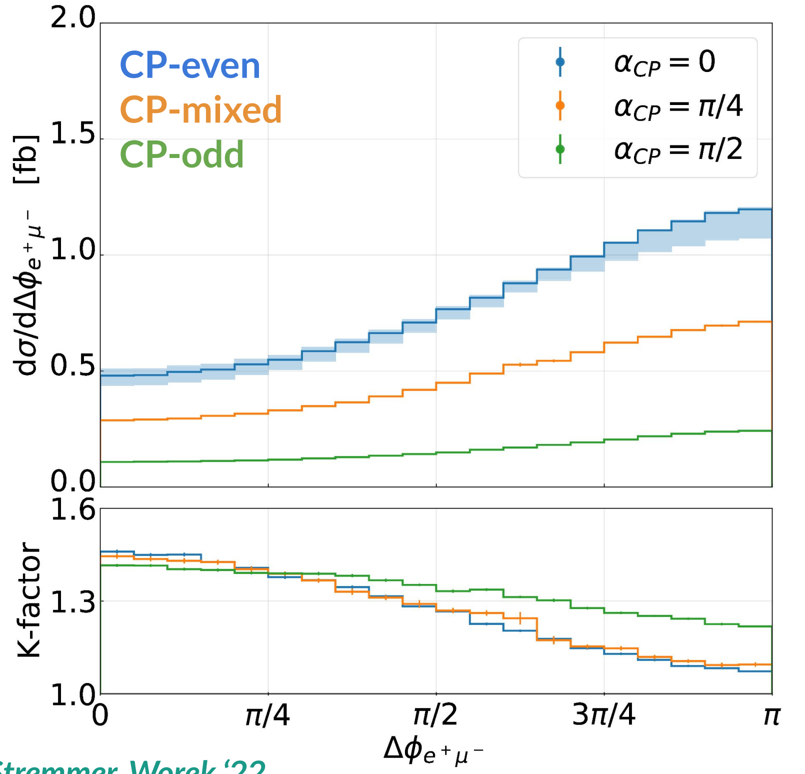
Differential distributions - NLO corrections



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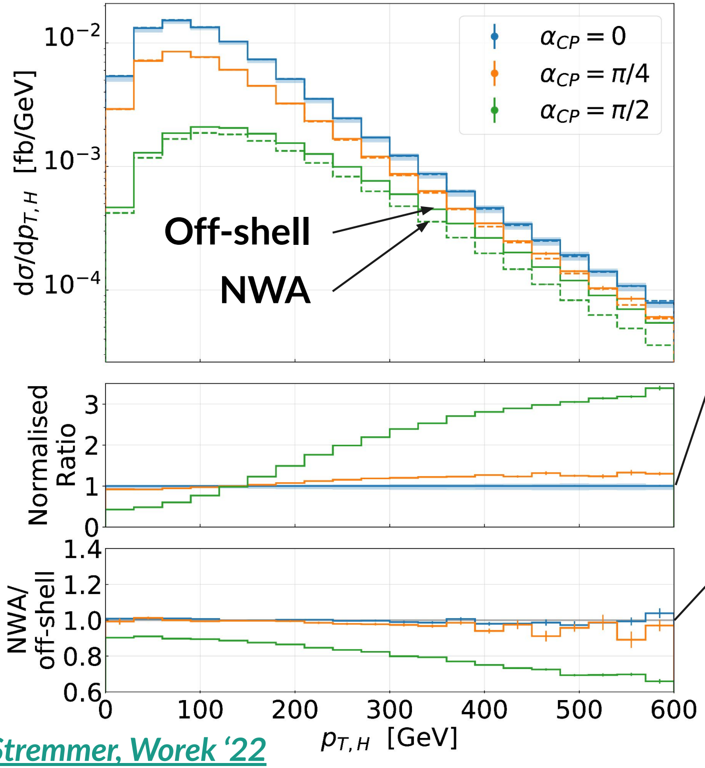
Observables with top-quark decay products:

- Corrections largest for CP-odd case only for large opening angles
- For small opening angles, CP-odd case receives smallest corrections -> smaller shape distortions
- Harder Higgs radiation in CP-odd case suppresses K-factor
- CP-even and CP-mixed very similar

Differential distributions - Off-shell effects



Shape comparison:

- CP-even and CP-mixed similar, small difference in tails
- Tails much more pronounced in CP-odd case

Off-shell effects:

- Large effects on size and shape for CP-odd Higgs boson
- Only small effects for CP-even and CP-mixed

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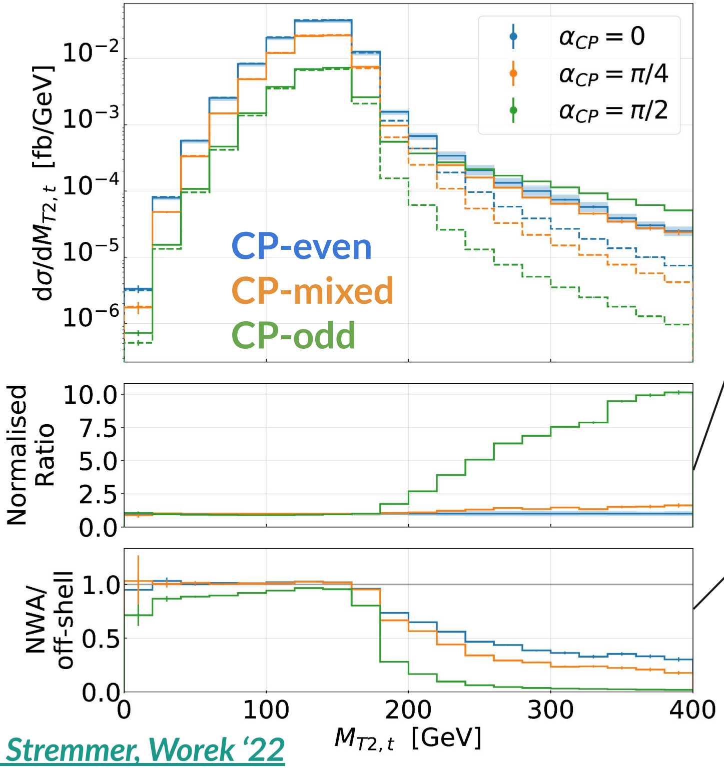
Differential distributions - Off-shell effects



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Shape comparison:

- CP-even and CP-mixed similar, large difference in tails
- In the tails, the CP-odd cross-section is actually the largest

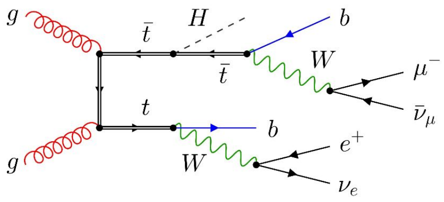
Off-shell effects:

- Large effects for all CP-states above kinematic edge, largest for CP-odd

What is causing the large off-shell effects?

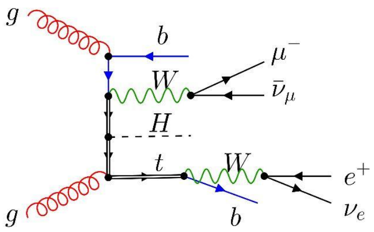
Process: $pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu \, b\bar{b} \, H$ at $\mathcal{O}(\alpha_S^2 \alpha^5)$

Double resonant

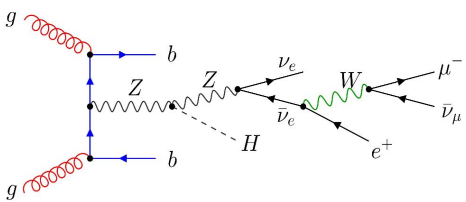


NWA

Single resonant



Non resonant



Off-shell

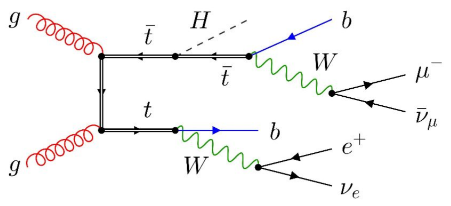
Additional contributions in off-shell calculation

Try to extract the different contributions from the full result

What is causing the large off-shell effects?

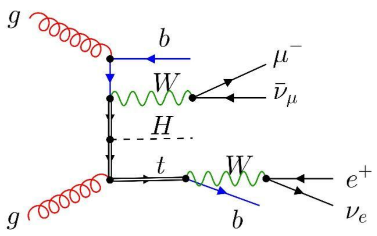
Investigate different resonance regions:

Double resonant

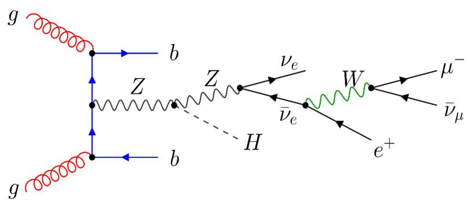


NWA

Single resonant



Non resonant



Off-shell

$$|M(b\mu\bar{\nu}_\mu(+j)) - m_t| < n \cdot \Gamma_t$$

and

$$|M(\bar{b}e\nu_e(+j)) - m_t| < n \cdot \Gamma_t$$

One ">", one "<"

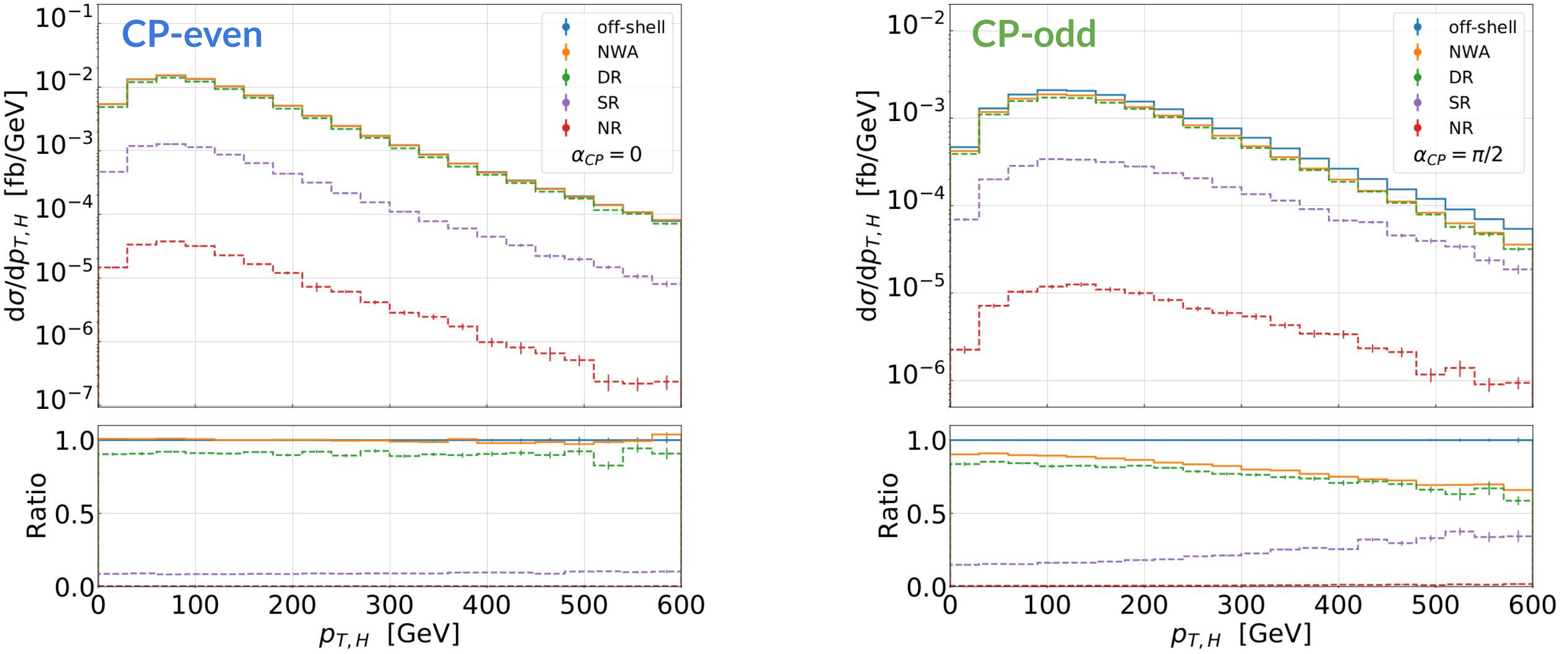
$$|M(b\mu\bar{\nu}_\mu(+j)) - m_t| > n \cdot \Gamma_t$$

and

$$|M(\bar{b}e\nu_e(+j)) - m_t| > n \cdot \Gamma_t$$

What is causing the large off-shell effects?

JH, Stremmer, Worek '22



SR contributions (~ tWHb) lead to larger off-shell effects in CP-odd case (also at integrated level)

Conclusions

- Provided predictions for **ttH** production at **NLO in QCD** with **full off-shell effects** including CP-mixing in the Yukawa coupling
- **NLO corrections**
  - Around **20 % - 30 %** at integrated level, larger in distribution tails
  - Overall larger effects for CP-odd Higgs but smaller impact on distribution shapes
- **Off-shell effects** important
  - Large effects in distribution tails and around kinematic edges
  - Large effects already at integrated level for CP-odd Higgs
  - Break symmetry in mixing angle
  - Enhancement of single resonant contributions for CP-odd Higgs
- Many observables affected by CP-mixing, e.g. $\sigma, M_{T2,t}, M_{e^+b}, \cos\theta^*_{ll}, \ldots$

Thank you for your attention!

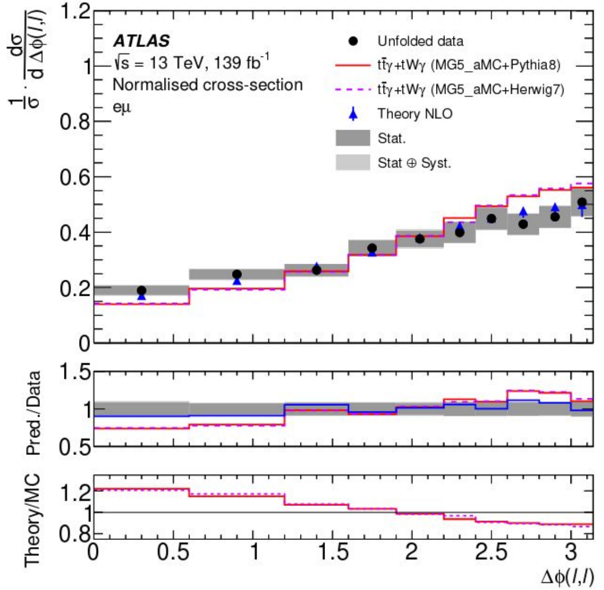
Backup

Outlook

How can these predictions be used?

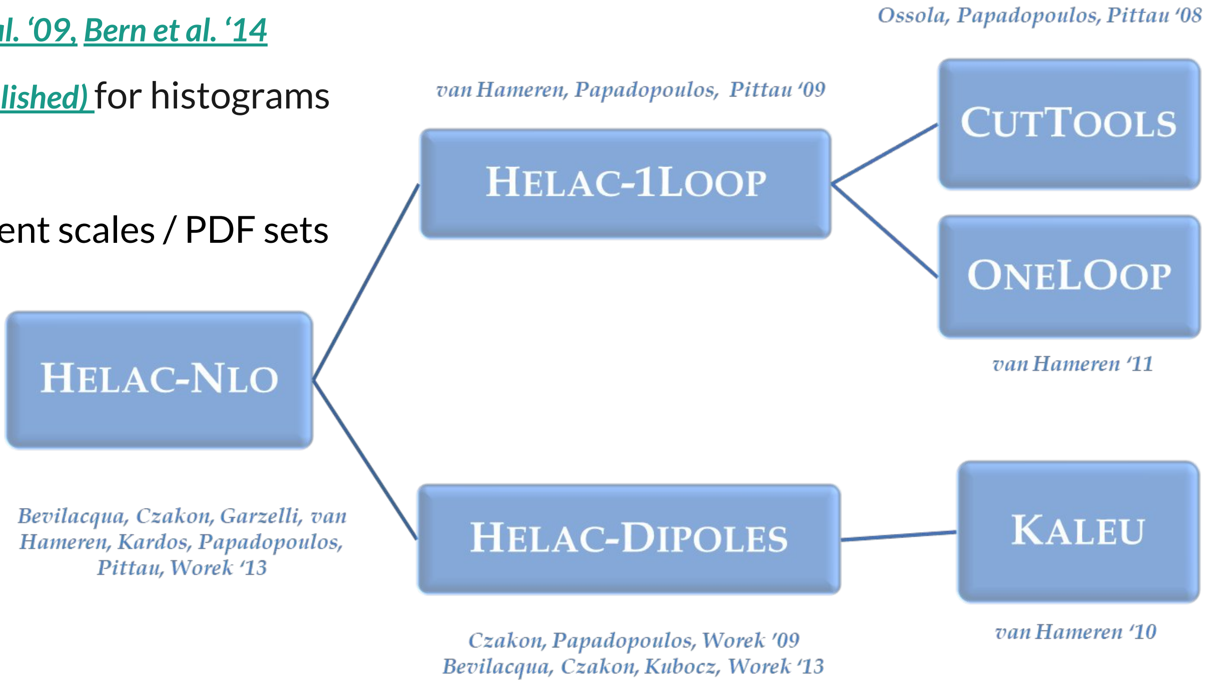
- Comparison to data (with parton level unfolding) in fiducial phase-space regions
  - Has been done for tt Czakon et al. ‘20 , CMS ‘22 and ttγ Bevilacqua et al. ‘18 ‘19 ‘20, ATLAS ‘20
- Combine with tt+X predictions matched to Parton showers to approximately take into account off-shell effects
  - Has been done for ttW Bevilacqua et al. ‘22
- Resonance-aware matching to Parton showers
  - Has been done for tt Jezo et al. ‘16

ATLAS ‘20



HELAC-NLO

- Store events in Les Houches Event files Alwall et al. '06 or Root Ntuples Antcheva et al. '09, Bern et al. '14
- Use **HEPlot** Bevilacqua (unpublished) for histograms
  - Flexible cuts
  - Reweighting to different scales / PDF sets



Inputs

PDF: `NNPDF31-nlo-as-0118`

Parameters:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right), \qquad G_\mu = 1.166378 \cdot 10^{-5}\ \text{GeV}^{-2}$$

$$m_t = 172.5\ \text{GeV}, \qquad m_H = 125\ \text{GeV},$$

$$m_W = 80.385\ \text{GeV}, \qquad \Gamma_W = 2.09767\ \text{GeV},$$

$$m_Z = 91.1876\ \text{GeV}, \qquad \Gamma_Z = 2.50775\ \text{GeV},$$

$$\Gamma_t^{\text{LO}} = 1.45759\ \text{GeV}, \qquad \Gamma_t^{\text{NLO}} = 1.33247\ \text{GeV}$$

$$\Gamma_{t,\text{NWA}}^{\text{LO}} = 1.48063\ \text{GeV}, \qquad \Gamma_{t,\text{NWA}}^{\text{NLO}} = 1.35355\ \text{GeV}$$

Inputs

Cuts:

$$p_{T,\ell} > 25 \text{ GeV}\,, \qquad p_{T,b} > 25 \text{ GeV}\,,$$

$$|y_\ell| < 2.5\,, \qquad |y_b| < 2.5\,,$$

Jet-clustering: *anti-k_T* jet algorithm $\quad R = 0.4$

Scale choice:

$$\mu_0 = \mu_R = \mu_F = H_T/2$$

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

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

Parameter choices

$\kappa_{Ht\bar{t}}$

- Choose $\kappa_{Ht\bar{t}} = 1$ to **recover SM** results for $\alpha_{CP} = 0$

$\kappa_{At\bar{t}}$

- Choose $\kappa_{At\bar{t}} = 1$ to have the same coupling as for CP-even part
- Choose $\kappa_{At\bar{t}} = 2/3$ to be consistent with **gluon-gluon fusion (ggF) measurements** *(ATLAS '21)*

κ_{HVV}

$$\mathcal{L}_{HVV} = \kappa_{HVV} \left(\frac{g_{HZZ}}{2} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right) H$$

Additional coupling

Parameter choices

$\kappa_{Ht\bar{t}}$

- Choose $\kappa_{Ht\bar{t}} = 1$ to recover SM results for $\alpha_{CP} = 0$

$\kappa_{At\bar{t}}$

- Choose $\kappa_{At\bar{t}} = 1$ to have the same coupling as for CP-even part
- Choose $\kappa_{At\bar{t}} = 2/3$ to be consistent with gluon-gluon fusion (ggF) measurements *(ATLAS '21)*

κ_{HVV}

- Choose $\kappa_{HVV} = 1$ to be consistent with vector-boson fusion (VBF) measurements *(CMS '19)*
- Choose $\kappa_{HVV} = \cos(\alpha_{\mathrm{CP}})$ to avoid coupling of pseudoscalar particle to vector bosons (e.g. 2HDM)

Integrated fiducial cross-sections (LO)

Interpolation formula:

$$\sigma\left(\alpha_{CP}\right) = \cos^2\left(\alpha_{CP}\right)\kappa^2_{Ht\bar{t}}\,\sigma_1 + \sin^2\left(\alpha_{CP}\right)\kappa^2_{At\bar{t}}\,\sigma_2 + \cancel{\cos\left(\alpha_{CP}\right)\sin\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}\,\kappa_{At\bar{t}}\,\sigma_3}$$
$$\cancel{+\cos\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}\,\kappa_{HVV}\left(\alpha_{CP}\right)\sigma_4} \cancel{+\sin\left(\alpha_{CP}\right)\kappa_{At\bar{t}}\,\kappa_{HVV}\left(\alpha_{CP}\right)\sigma_5} \cancel{+\kappa^2_{HVV}\left(\alpha_{CP}\right)\sigma_6}$$

- No interference between diagrams with CP-even and CP-odd Yukawa interactions
- No interference between diagrams with HVV and CP-odd Yukawa interactions
- No HVV couplings in **NWA**

	Off-shell	NWA
σ_1 [fb]	2.0643(4)	2.0388(2)
σ_2 [fb]	0.7800(1)	0.74583(7)
σ_3 [fb]	−0.0002(8)	−0.0001(3)
σ_4 [fb]	−0.0693(8)	–
σ_5 [fb]	−0.0001(9)	–
σ_6 [fb]	0.0363(9)	–

Integrated fiducial cross-sections (LO)

Interpolation formula (without vanishing terms):

$$\sigma\left(\alpha_{CP}\right) = \cos^2\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}^2\,\sigma_1 + \sin^2\left(\alpha_{CP}\right)\kappa_{At\bar{t}}^2\,\sigma_2 + \boxed{\cos\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}\,\kappa_{HVV}\left(\alpha_{CP}\right)\,\sigma_4} + \kappa_{HVV}^2\left(\alpha_{CP}\right)\sigma_6$$

- First two terms are symmetric in α_{CP}
- Last term is either constant ($\kappa_{HVV} = 1$) or symmetric ($\kappa_{HVV} = \cos(\alpha_{\mathrm{CP}})$) with respect to α_{CP}

Interference between diagrams with HVV and CP-even Yukawa interactions breaks the symmetry

	Off-shell	NWA
σ_1 [fb]	2.0643(4)	2.0388(2)
σ_2 [fb]	0.7800(1)	0.74583(7)
σ_3 [fb]	−0.0002(8)	−0.0001(3)
σ_4 [fb]	−0.0693(8)	–
σ_5 [fb]	−0.0001(9)	–
σ_6 [fb]	0.0363(9)	–

Integrated fiducial cross-sections (NLO)

Interpolation formula (without vanishing terms):

$$\sigma\left(\alpha_{CP}\right) = \cos^2\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}^2\,\sigma_1 + \sin^2\left(\alpha_{CP}\right)\kappa_{At\bar{t}}^2\,\sigma_2 \\ + \cos\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}\,\kappa_{HVV}\left(\alpha_{CP}\right)\,\sigma_4 + \kappa_{HVV}^2\left(\alpha_{CP}\right)\,\sigma_6$$

Problem: The virtual contributions do not factorise in this manner
→ Interpolation much more complicated

Integrated fiducial cross-sections (NLO)

$$\sigma_{NLO,expanded} = (\frac{\Gamma_{NLO}}{\Gamma_{LO}})^2 \cdot \sigma_{NLO} - 2\frac{\Gamma_{NLO} - \Gamma_{LO}}{\Gamma_{LO}} \cdot \sigma_{LO}$$

α_{CP}		Off-shell	NWA	Off-shell effects
0 (SM)	$\sigma_{\rm LO}$ [fb]	$2.0313(2)^{+0.6275\,(31\%)}_{-0.4471\,(22\%)}$	$2.0388(2)^{+0.6290\,(31\%)}_{-0.4483\,(22\%)}$	-0.37%
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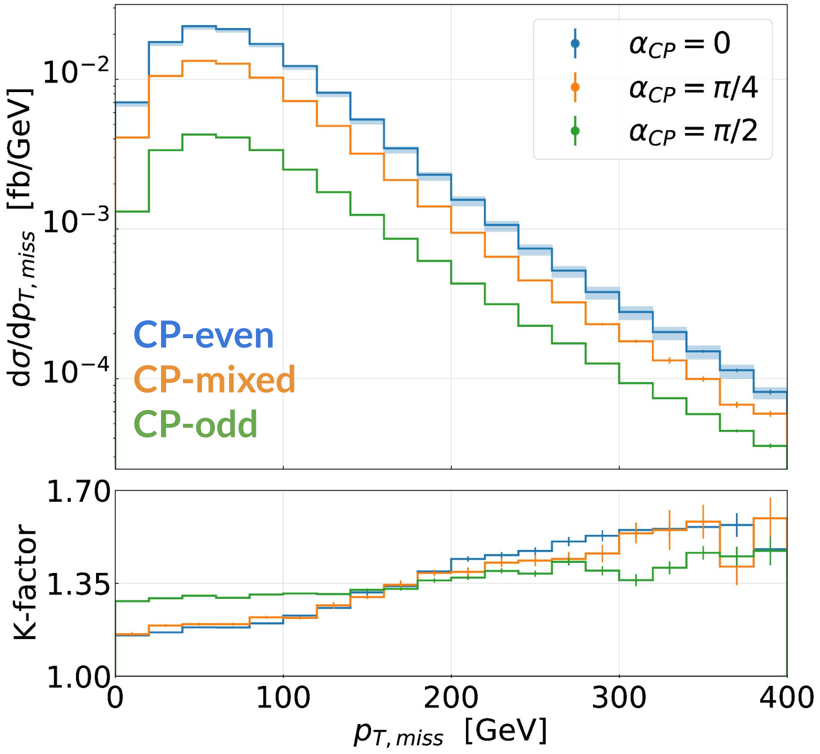
	$\sigma_{\rm NLO_{LOdec}}$ [fb]	–	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$	1.23	1.23 (LOdec: 1.28)	
$\pi/2$	$\sigma_{\rm LO}$ [fb]	$0.38277(6)^{+0.13123\,(34\%)}_{-0.09121\,(24\%)}$	$0.33148(3)^{+0.11240\,(34\%)}_{-0.07835\,(24\%)}$	13.4%
	$\sigma_{\rm NLO}$ [fb]	$0.5018(3)^{+0.0083\,(1.2\%)}_{-0.0337\,(6.7\%)}$	$0.4301(2)^{+0.0035\,(0.8\%)}_{-0.0264\,(6.1\%)}$	14.3%
	$\sigma_{\rm NLO_{LOdec}}$ [fb]	–	$0.4433(2)^{+0.0323\,(7.3\%)}_{-0.0470\,(11\%)}$	
	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$	1.31	1.30 (LOdec: 1.34)	

Expanded NWA:

- CP-even: 2.418 fb (-2.3 %)
- CP-mixed: 1.417 fb (-2.4 %)
- CP-odd: 0.416 fb (-3.2 %)

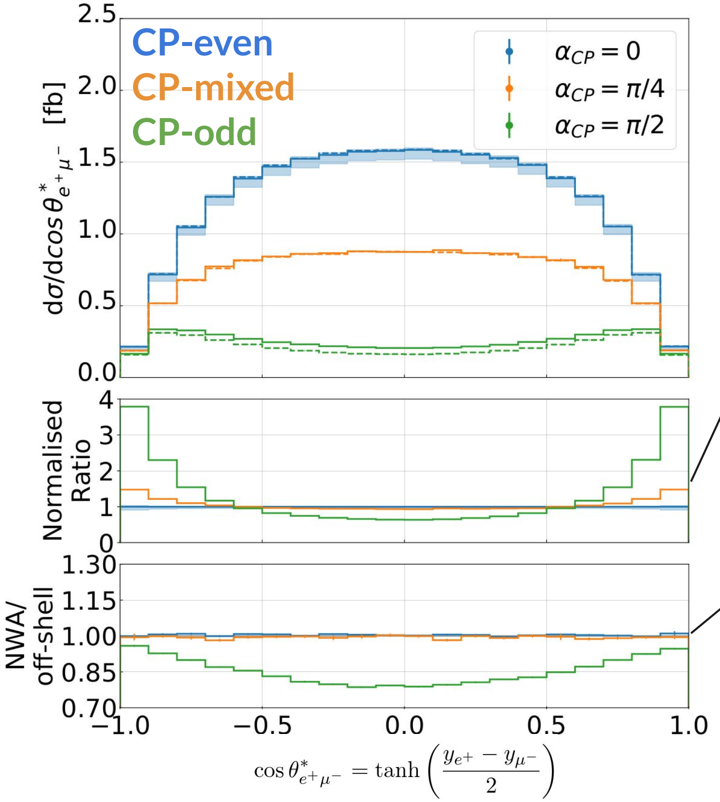
Differential distributions - NLO corrections



Observables with top-quark decay products:

- Corrections largest for CP-odd case only for small transverse momenta
- For large momenta, CP-odd case receives smallest corrections -> smaller shape distortions
- Harder Higgs radiation in CP-odd case suppresses K-factor
- CP-even and CP-mixed very similar

Differential distributions



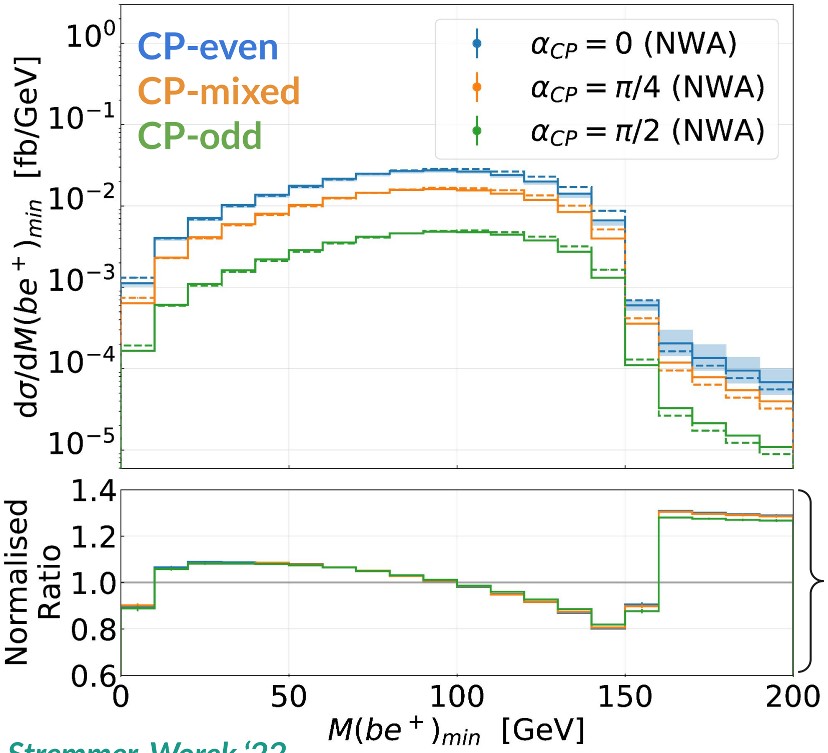
Shape comparison:

- CP-even and CP-mixed similar, small differences around 1 and -1
- Significant differences for CP-odd case

Off-shell effects:

- Significant effects on size and shape for CP-odd Higgs boson
- Only small effects for CP-even and CP-mixed

Differential distributions - NLO corrections



$$\frac{\text{NLO}}{\text{NLO}_{\text{LOdec}}}$$ (both normalised)

NLO corrections to top-quark decays:

- Almost no difference between the CP-states
- Significant shape distortions

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SM Higgs boson decays

- Include SM Higgs boson decays in NWA (only Higgs on-shell)
- Decay events generated from LHEF in Higgs boson rest frame
- NLO QCD corrections to Higgs decays included

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

- Four decay channels

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

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

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

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

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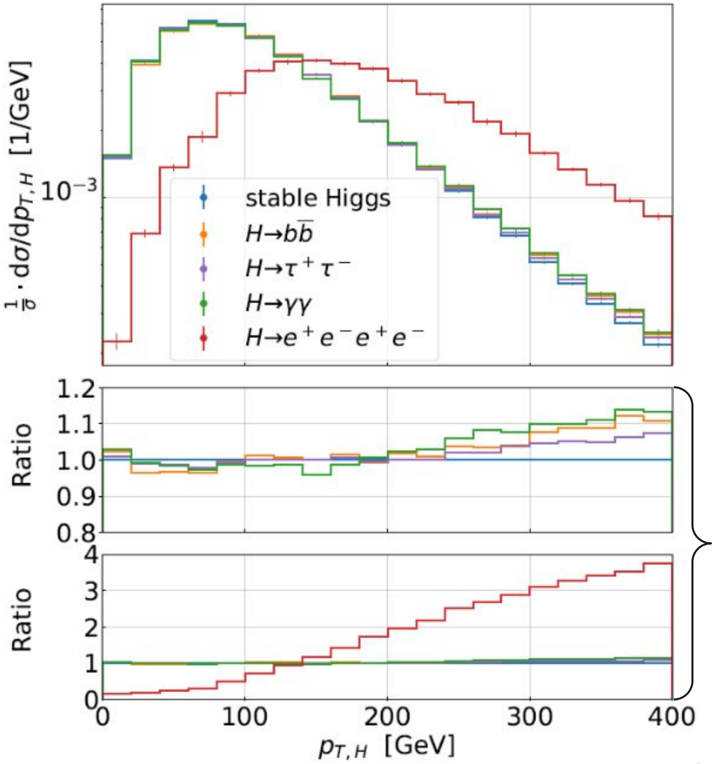
SM Higgs boson decays

	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

- Integrated cross-sections ordered according to branching ratio
- Most distribution shapes similar to stable Higgs case
- Cuts on leptons reduce cross-section and affect distribution shapes for $H \to e^+e^-e^+e^-$

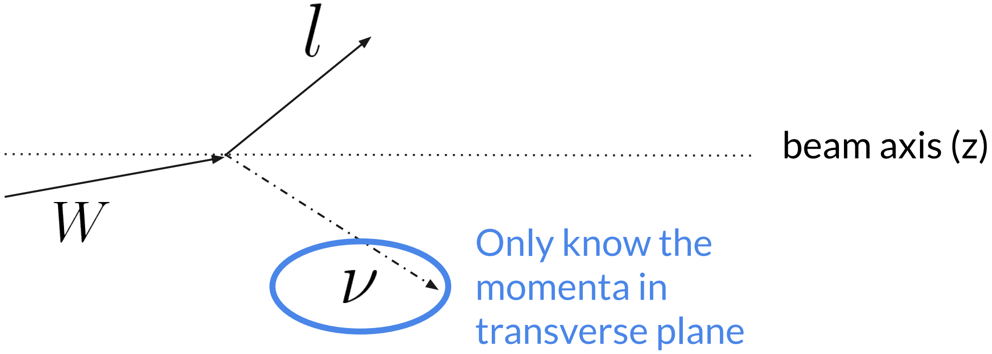


Ratio to stable Higgs

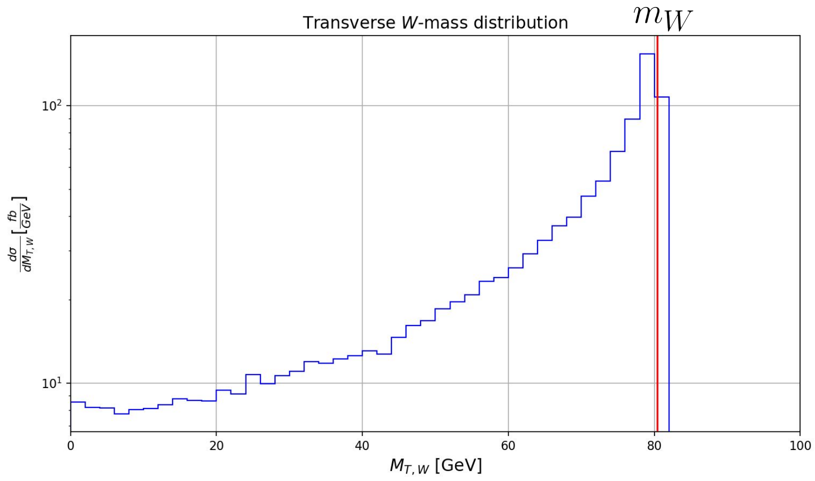
Stremmer, Worek '22

The ‘stransverse’ mass - idea

Transverse mass: reconstruct mass of particle with partly invisible final state



Reconstruct the W mass:



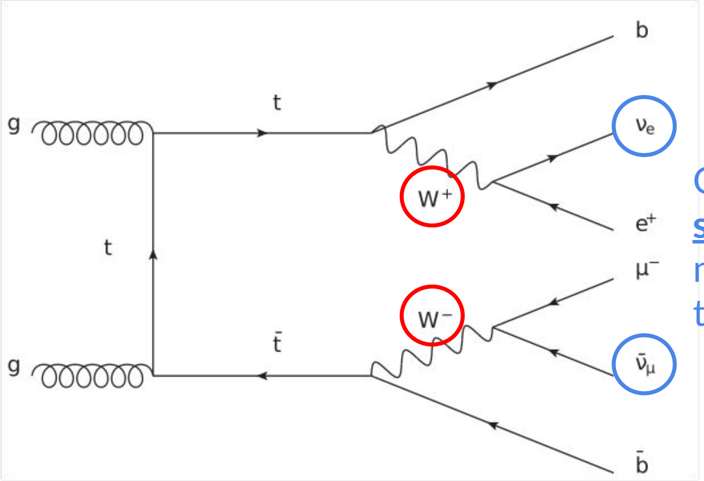
⇨ Define mass & momenta in transverse plane

$p_T = (E_T, p_x, p_y, 0)$ where $E_T = \sqrt{p_{T,x}^2 + p_{T,y}^2}$ ⇨ $M_T^2 = (p_T^l + p_T^\nu)^2 \leq m_W^2$

The ‘stransverse’ mass - idea & definition

‘Stransverse’ mass:
generalization for **two** particles with partly invisible final state

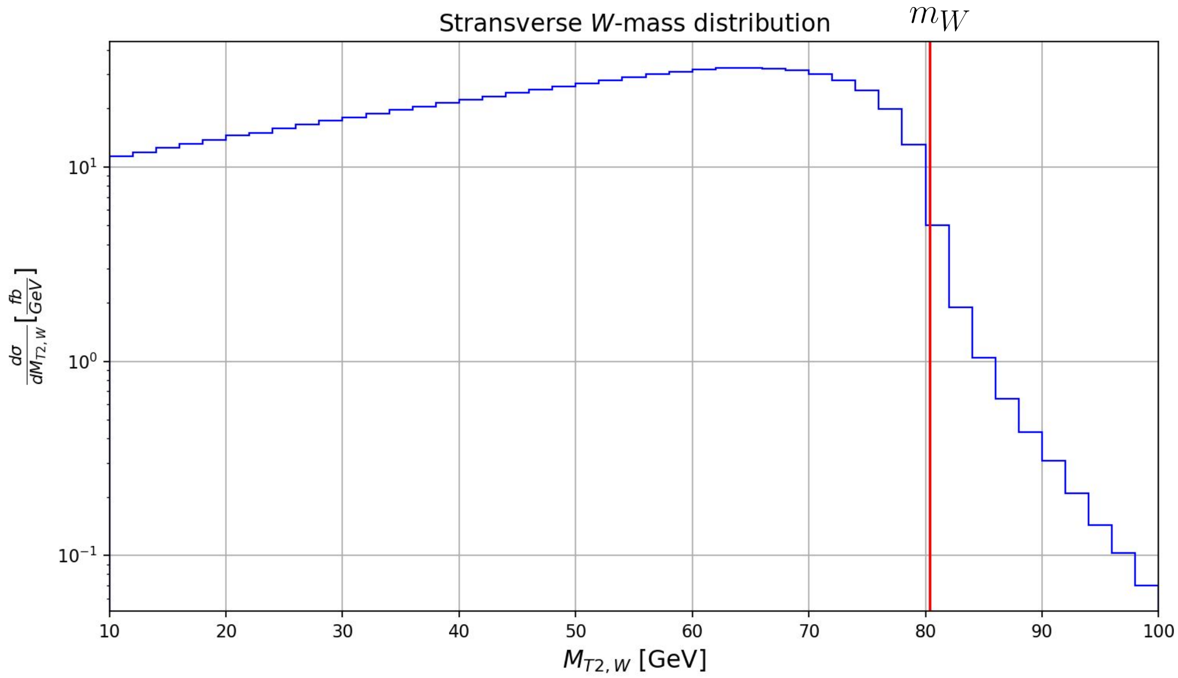
$$M_{T2,W}^2 = \min_{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2}=\mathbf{p}_{T,\mathrm{miss}}} \left[\max\{ M_T^2\left(\mathbf{p}_T^{l_1},\mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{l_2},\mathbf{p}_T^{\nu_2}\right)\} \right]$$



Only know the <u>sum</u> of the momenta in transverse plane

Minimize over all missing momentum combinations

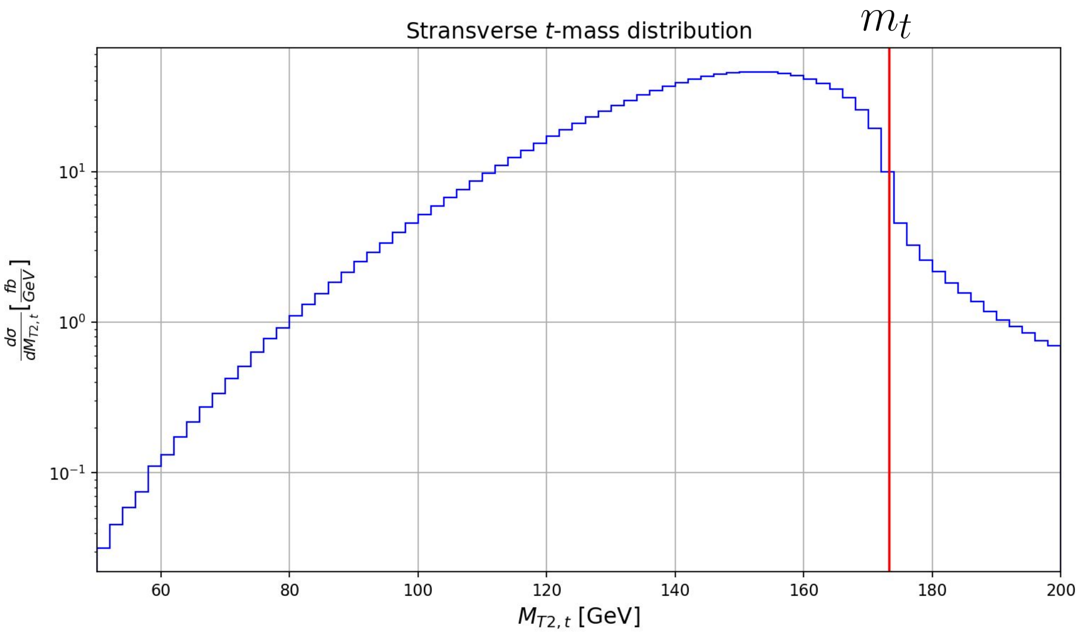
The ‘stransverse’ mass - distribution



- Not a ‘hard’ cut-off but drop-off is clearly visible

The ‘stransverse’ mass - distribution

We can do the same for the top quarks:



- Use b-jet + lepton instead of lepton as visible, massive ‘particle’
- Problem: which jet is associated with which lepton?
  - take minimum of invariant b-jet + lepton mass combinations
  - minimize the sum of the two invariant masses to avoid combining one lepton with both b-jets

The ‘stransverse’ mass - definition

$$M_{T2}^2 = \min_{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2}=\mathbf{p}_{T,\text{miss}}} \left[\max\{M_T^2\left(\mathbf{p}_T^{(lb)_1}, \mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{(lb)_2}, \mathbf{p}_T^{\nu_2}\right)\}\right]$$

where $$M_T^2\left(\mathbf{p}_T^{(lb)_i}, \mathbf{p}_T^{\nu_i}\right) = M_{(lb)_i}^2 + 2\left(E_T^{(lb)_i} E_T^{\nu_i} - \mathbf{p}_T^{(lb)_i}\mathbf{p}_T^{\nu_i}\right)$$

Lepton + b-jet combinations chosen such that $M_{(lb)_1} + M_{(lb)_2}$ is minimal