ttH production in the Higgs characterisation model at NLO in QCD with full off-shell effects

Based on [*arXiv:2205.09983*]

Jonathan Hermann, RWTH Aachen University
In collaboration with **Daniel Stremmer**, RWTH Aachen University
and **Małgorzata Worek**, RWTH Aachen University

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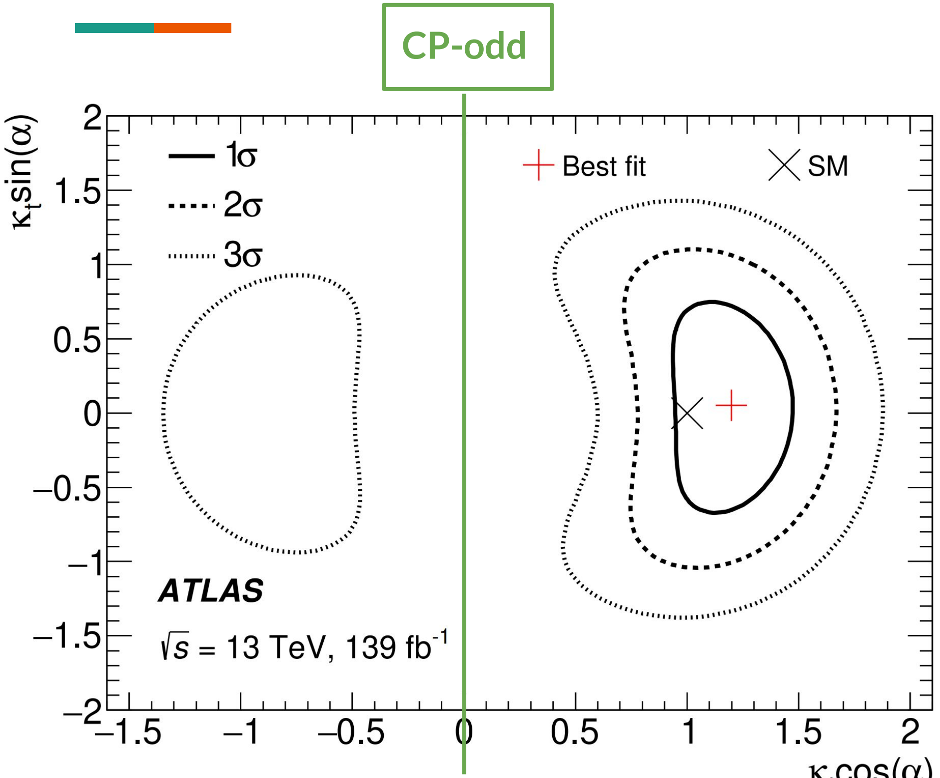
Introduction

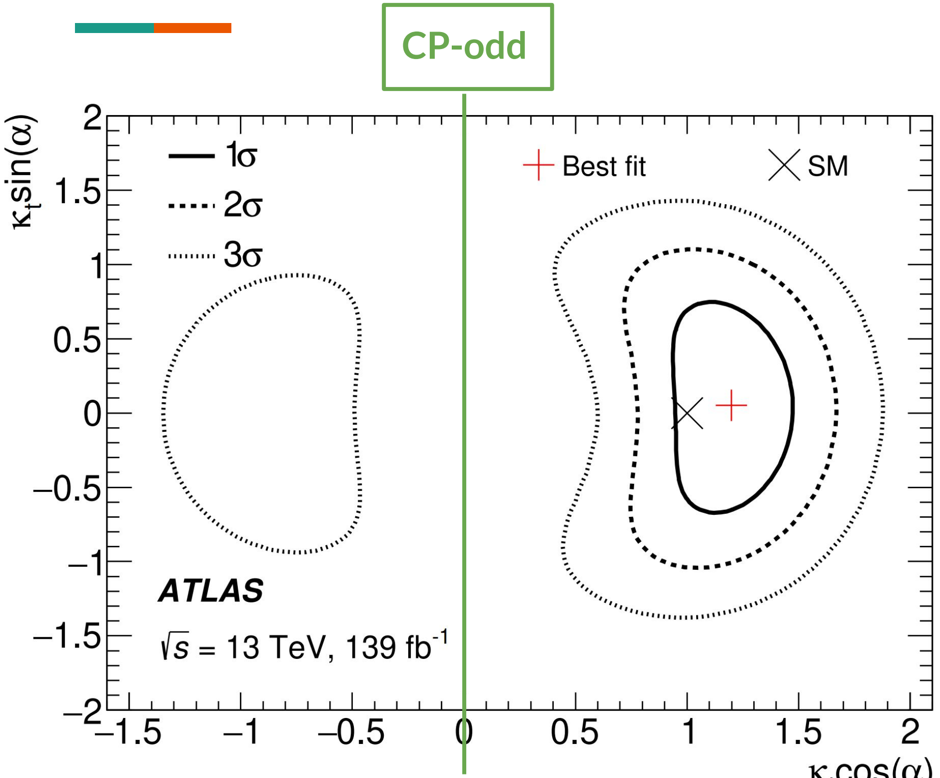


ATLAS '20

ttH production:

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

Introduction



ATLAS '20

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
- $\alpha_{CP} > 43^{\circ}$ excluded at 95% CL if CP-even and CP-odd couplings are equal

ATLAS '20

BSM interpretations:

- Extended Higgs sector
- 2HDM
- ...

Introduction

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

Provide state-of-the-art predictions for ttH production with possible 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. '19, Kulesza, et al. '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*

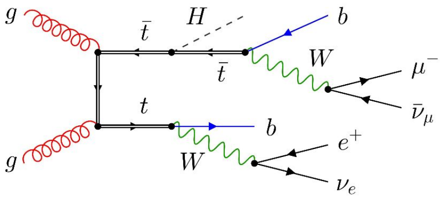
Higgs boson with CP-odd admixture:

- ttX @ NLO in QCD with LO decays *Artoisenet et al. '13*, *Demartin et al. '14*
  - HC_NLO_X0 model *Artoisenet et al. '13*, *Maltoni et al. '14*, *Demartin et al. '14*

Off-shell effects

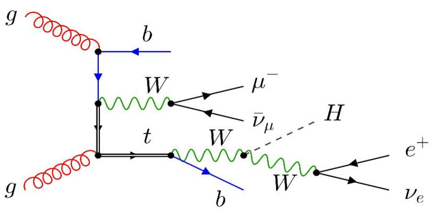
Process: $pp \to e^+ \nu_e \, \mu^- \bar{\nu}_\mu \, b\bar{b} \, H$ at $\mathcal{O}(\alpha_S^2 \alpha^5)$

Double resonant

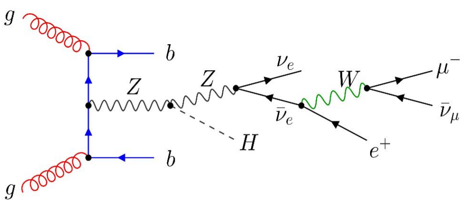


NWA

Single resonant



Non resonant



Off-shell

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

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

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

The Higgs characterisation framework (HCF)

Top-Yukawa coupling

Top-quark fields

SM:

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

Higgs boson field

Mixing angle

HCF:

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

Additional couplings

Recover SM for $\kappa_{Ht\bar{t}} = 1$ and $\alpha_{CP} = 0$

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

The Higgs characterisation framework (HCF)

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

Three reference points:

- **CP-even:** $\alpha_{\mathrm{CP}} = 0 \longrightarrow \cos(\alpha_{\mathrm{CP}}) = 1,\ \sin(\alpha_{\mathrm{CP}}) = 0$
- **CP-odd:** $\alpha_{\mathrm{CP}} = \frac{\pi}{2} \longrightarrow \cos(\alpha_{\mathrm{CP}}) = 0,\ \sin(\alpha_{\mathrm{CP}}) = 1$
- **CP-mixed:** $\alpha_{\mathrm{CP}} = \frac{\pi}{4} \longrightarrow \cos(\alpha_{\mathrm{CP}}) = \sin(\alpha_{\mathrm{CP}}) = \frac{1}{\sqrt{2}}$

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

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

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- 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 (NLO)

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%
	$\sigma_{\rm NLO}$ [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%
	$\sigma_{\rm NLO_{LOdec}}$ [fb]	–	$2.592(1)^{+0.161\,(6.2\%)}_{-0.242\,(9.3\%)}$	
	$\mathcal{K} = \sigma_{\rm NLO}/\sigma_{\rm LO}$	1.21	1.21 (LOdec: 1.27)	
$\pi/4$	$\sigma_{\rm LO}$ [fb]	$1.1930(2)^{+0.3742\,(31\%)}_{-0.2656\,(22\%)}$	$1.1851(1)^{+0.3707\,(31\%)}_{-0.2633\,(22\%)}$	0.66%
	$\sigma_{\rm NLO}$ [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%
	$\sigma_{\rm NLO_{LOdec}}$ [fb]	–	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
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$\pi/2$	$\sigma_{\rm LO}$ [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)	

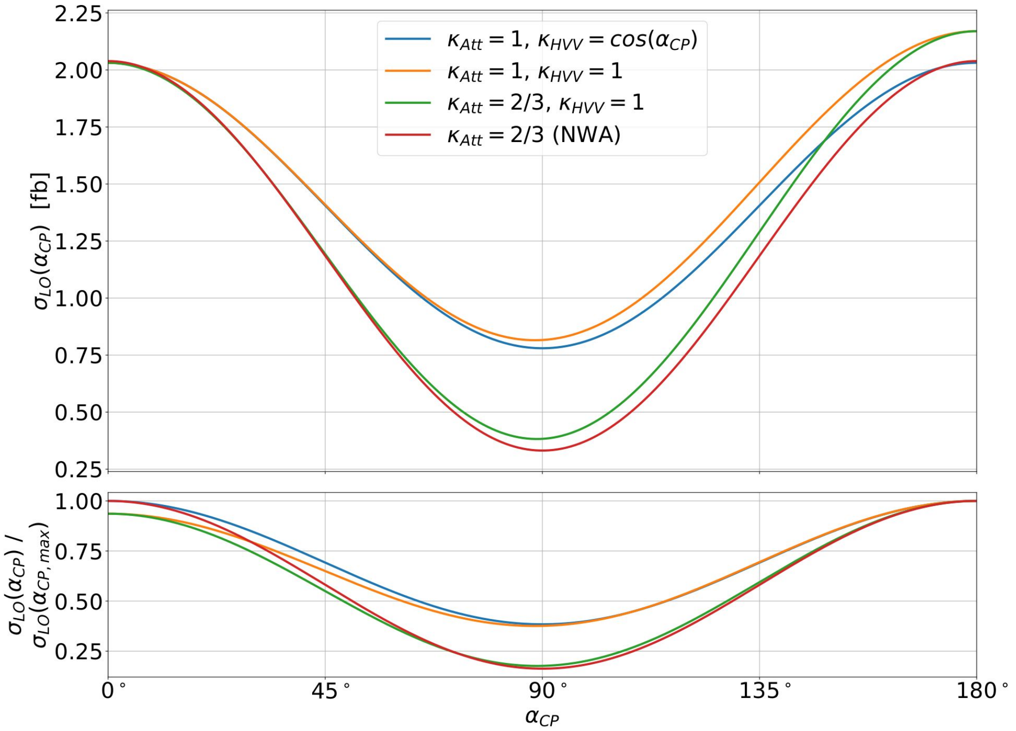
NLO corrections:

- 21% - 31%
- Increase with the mixing angle
- 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

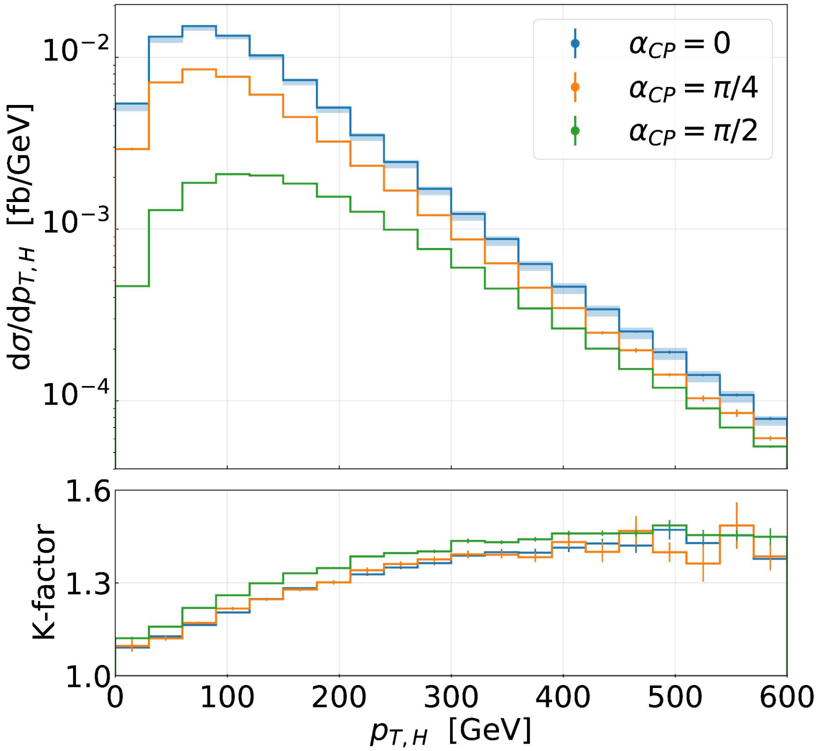
Integrated fiducial cross-sections (LO)



- **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**

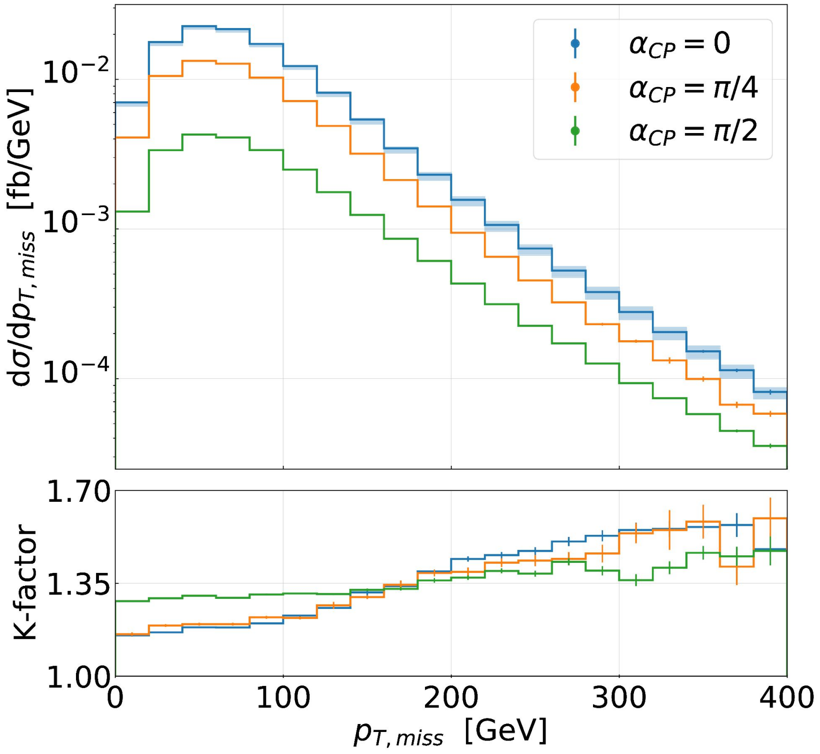
Differential distributions - NLO corrections



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

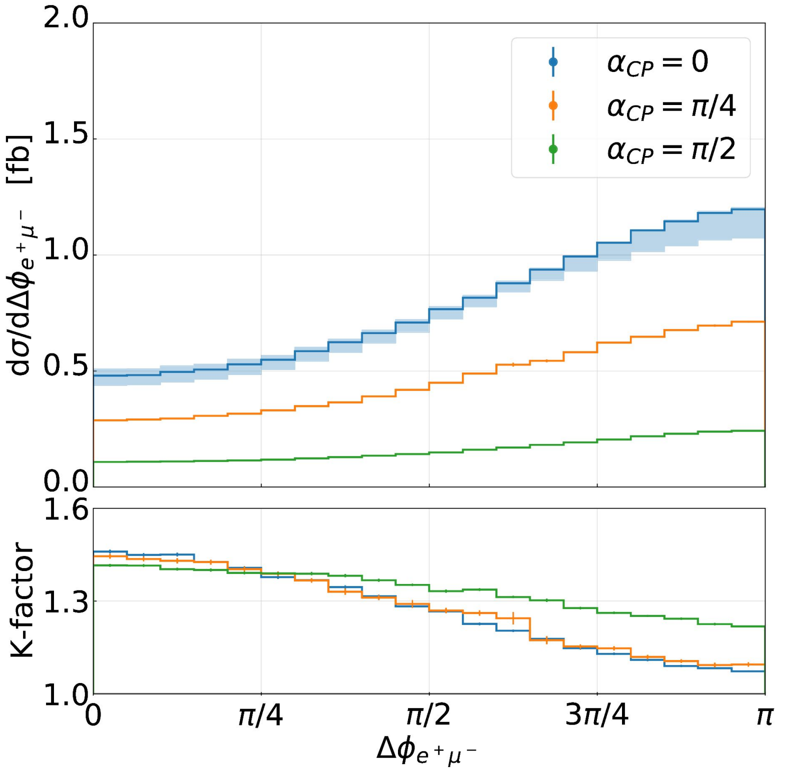
Differential distributions - NLO corrections



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

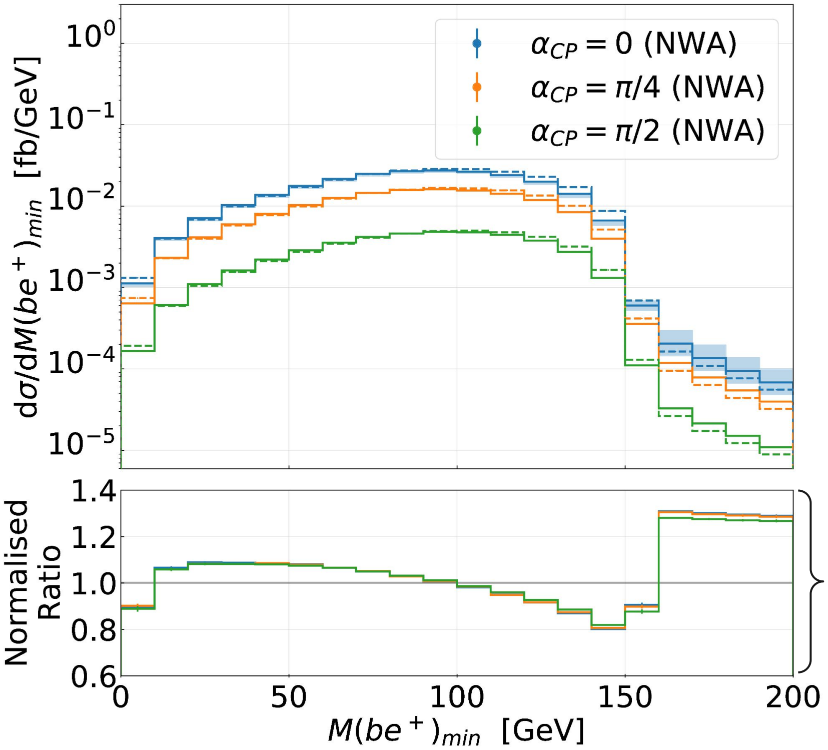
Differential distributions - NLO corrections



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 - NLO corrections

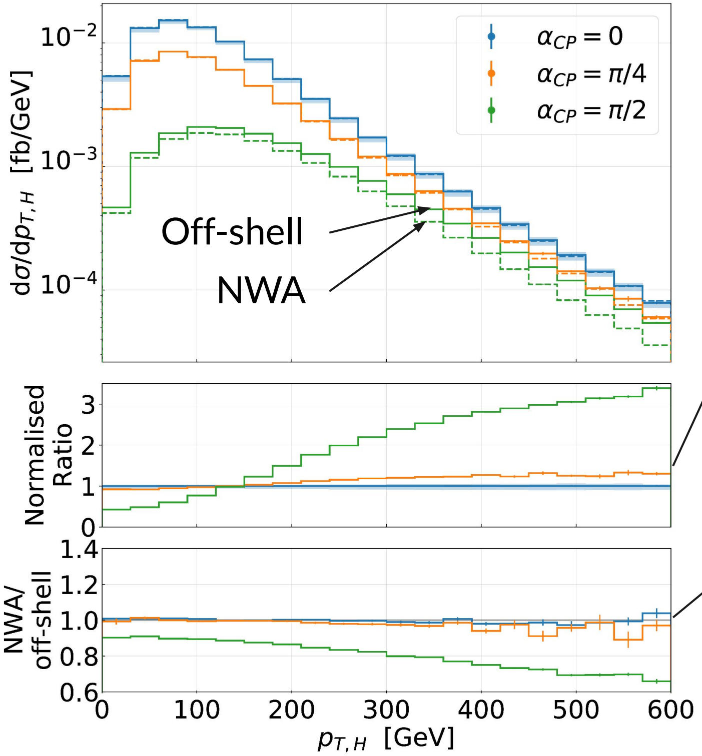


$$\frac{\text{NLO}}{\text{NLO}_{\text{LOdec}}}$$ (both normalised)

NLO corrections to top-quark decays:

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

Differential distributions



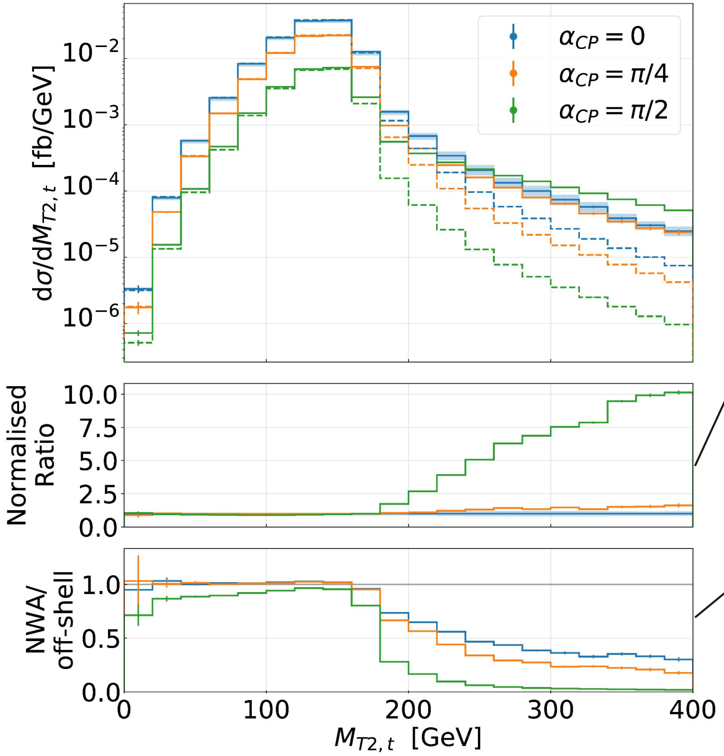
Shape comparison:

- 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

Differential distributions



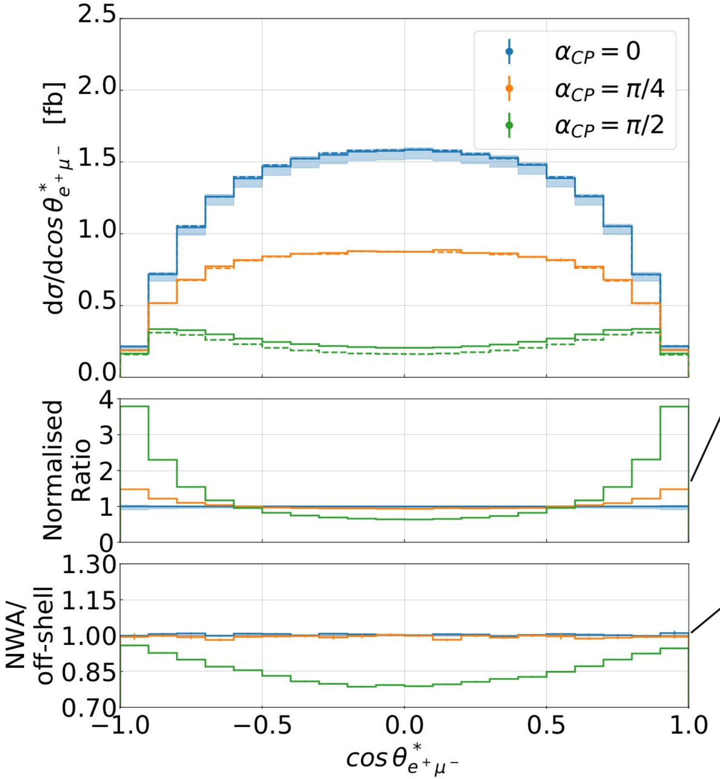
Shape comparison:

- 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

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

Conclusions

- Which **observables** are sensitive to the CP-state?
  - Integrated fiducial cross-section (total rate)
  - Observables with kinematic edges ($M_{T2,t}$, M_{e^+b})
  - Observables involving decay products of both top quarks ($p_{T,miss}$, $p_{T,b\bar{b}}$, $\cos\theta^*_{ll}$, ...)
- How are the different CP-states affected by **NLO QCD corrections**?
  - Larger overall corrections for CP-odd Higgs boson but smaller shape distortions
  - CP-mixed very similar to CP-even (SM) case
- How are the different CP-states affected by **off-shell effects**?
  - Large corrections in CP-odd case even for integrated cross-section
  - Off-shell effects break symmetry of integrated cross-section
  - Particularly large effects in distribution tails and above kinematic edges

Thank you for your attention!

Backup

Outline

- Introduction
- The Higgs characterisation framework
- Off-shell effects
- Integrated fiducial cross-sections
- Differential fiducial cross-section distributions
- Conclusions

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: $anti\text{-}k_T$ jet algorithm $\qquad R = 0.4$

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

Integrated fiducial cross-sections (NLO)

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

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	$\sigma_{\mathrm{NLO_{LOdec}}}$ [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)	

Expanded NWA:

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

Integrated fiducial cross-sections (LO)

Interpolation formula:

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

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

- 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):

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

- 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)
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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):

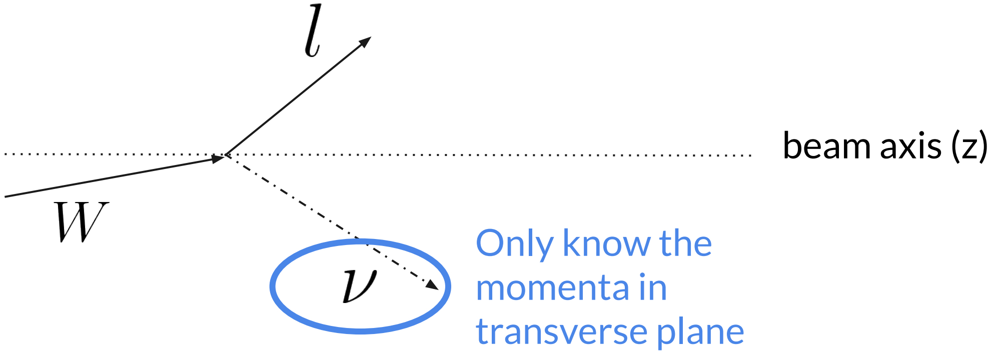
$$\sigma\left(\alpha_{CP}\right) = \cos^2\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}^2\,\sigma_1 + \sin^2\left(\alpha_{CP}\right)\kappa_{At\bar{t}}^2\,\sigma_2 + \cos\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}\,\kappa_{HVV}\left(\alpha_{CP}\right)\,\sigma_4 + \kappa_{HVV}^2\left(\alpha_{CP}\right)\,\sigma_6$$

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

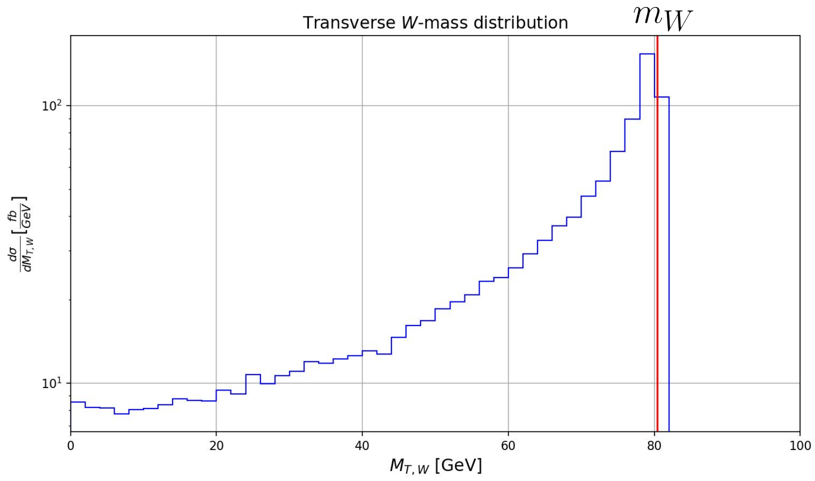
Example diagram?

The 'stransverse' mass - idea

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



Reconstruct the W mass:



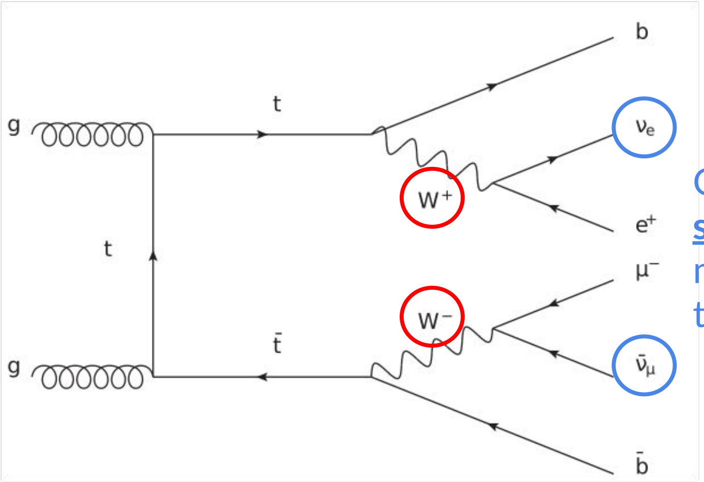
Define mass & momenta in transverse plane

$$p_T = (E_T, p_x, p_y, 0) \quad \text{where} \quad E_T = \sqrt{p_{T,x}^2 + p_{T,y}^2}$$

$$M_T^2 = (p_T^l + p_T^\nu)^2 \leq m_W^2$$

The ‘stransverse’ mass - idea & definition

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

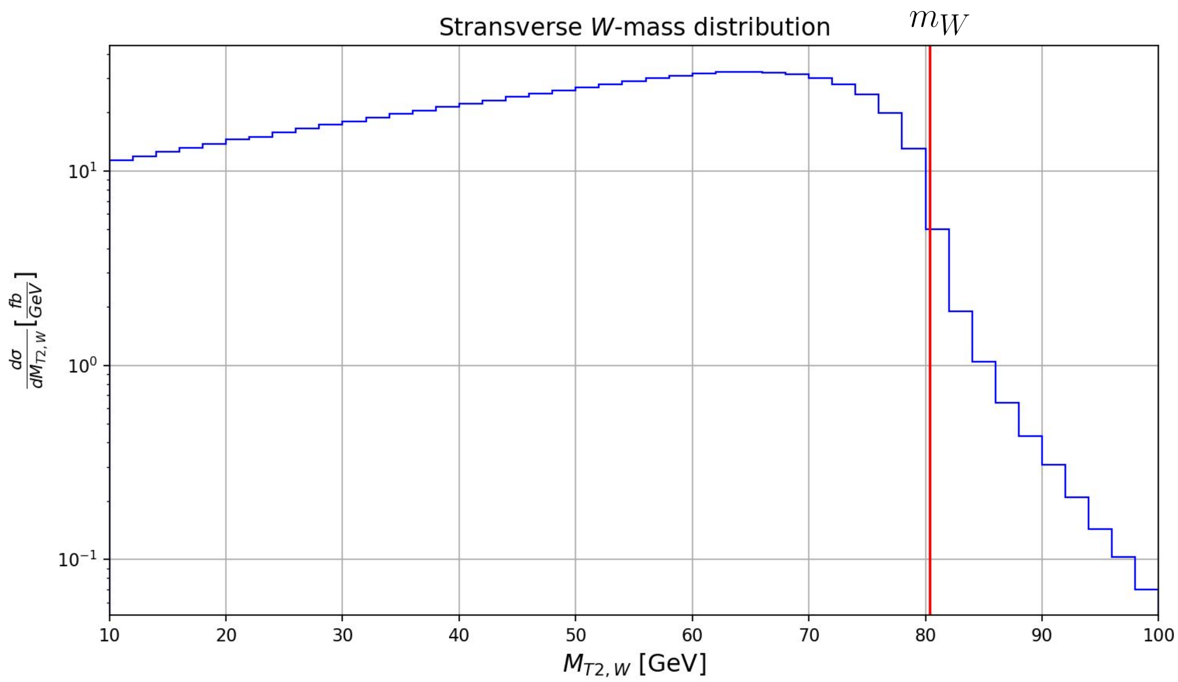


$$M_{T2,W}^2 = \min_{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2}=\mathbf{p}_{T,\mathrm{miss}}} \left[\max\{M_T^2\left(\mathbf{p}_T^{l_1},\mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{l_2},\mathbf{p}_T^{\nu_2}\right)\}\right]$$

Only know the sum of the momenta in transverse plane

→ Minimize over all missing momentum combinations

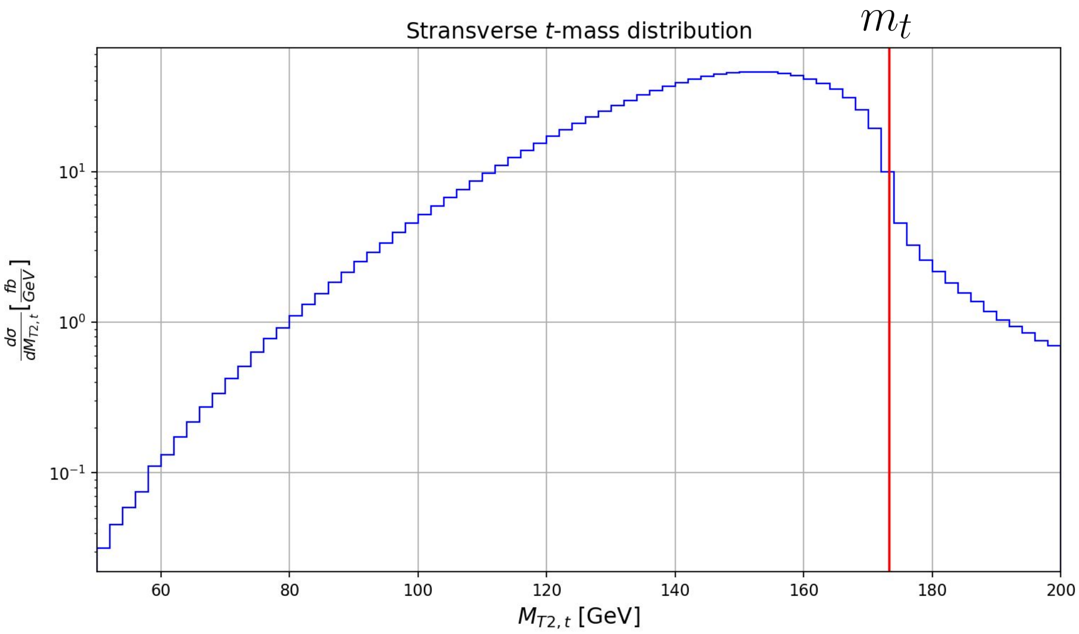
The ‘stransverse’ mass - distribution



- 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

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

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