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

Based on *JHEP 02 (2022)*, *arXiv:2205.09983*

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

International Conference on High Energy Physics • 08.07.2022 • Bologna

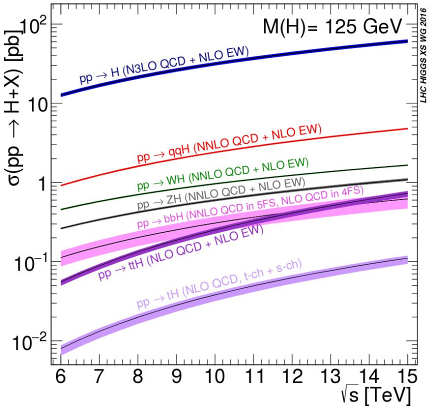
SPONSORED BY THE
Federal Ministry
of Education
and Research

Introduction

ttH production:

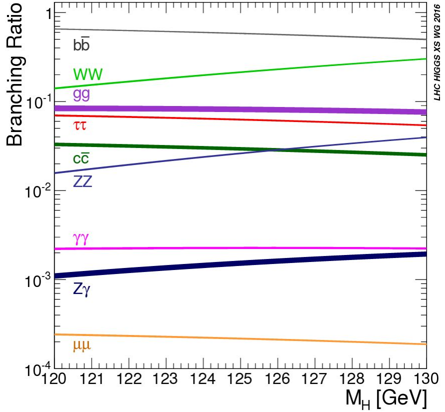
- Observed for the first time in 2018, ATLAS '18, CMS'18
- Allows for direct probe of Yukawa interaction and it's CP nature at tree level
- Top is heaviest SM particle
  → strongest Yukawa coupling
- Measurement of CP-odd component would indicate new physics

Higgs production:



ttH only 1% of total

Higgs decay:

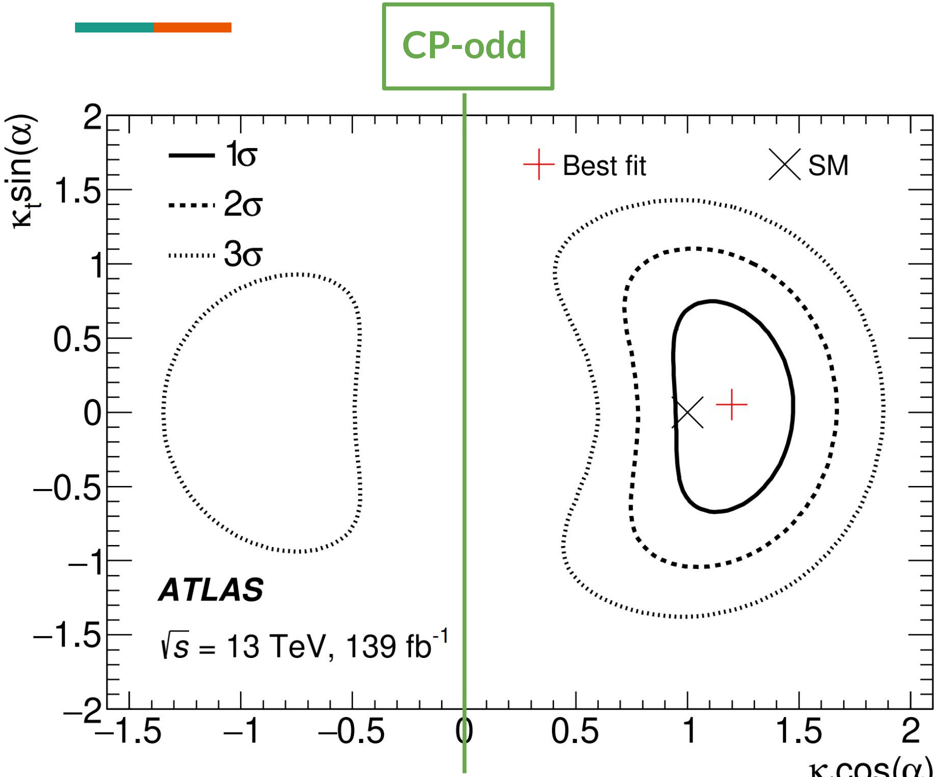


Main decay channel:

$\mathcal{BR}(H \to bb) \sim 58\%$

LHC Higgs XS WG '16

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

- Provide state-of-the-art predictions for **ttH** production at **NLO in QCD** including **full off-shell effects** for top quarks and gauge bosons with **Higgs decays** in the NWA

  ⇨ *JHEP 02 (2022)*

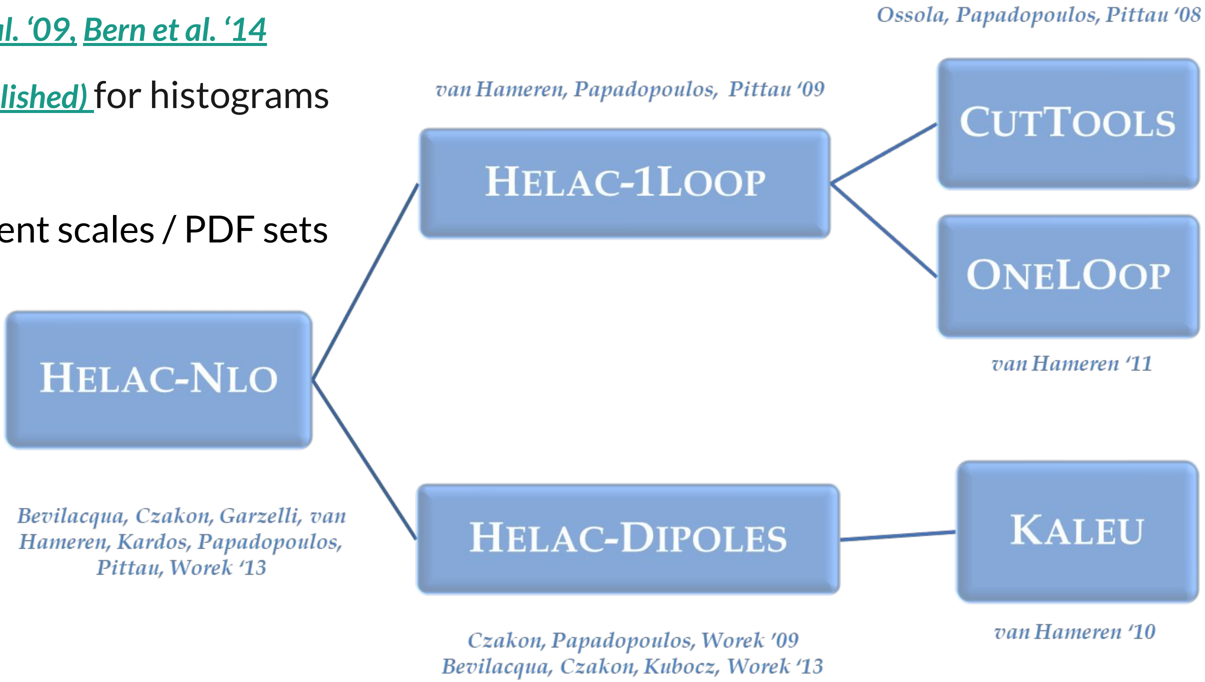
- Provide state-of-the-art predictions for **ttH** production at **NLO in QCD** including **full off-shell effects** for top quarks and gauge bosons and allowing for **CP-mixing** in the Higgs-Yukawa interaction

  ⇨ *arXiv:2205.09983*

  - ❖ Focus on second paper since CP-even case corresponds to SM
  - ❖ Discuss SM Higgs decays separately at the end

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



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)

HCF:

Mixing angle

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

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

Coupling choices:

$$\boxed{\kappa_{Ht\bar{t}} = 1} \qquad \boxed{\kappa_{At\bar{t}} = 2/3} \qquad \boxed{\kappa_{HVV} = 1}$$

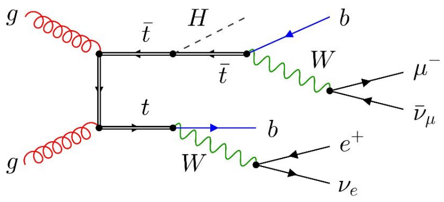
Artoisenet et al. ‘13
Maltoni et al. ‘14
Demartin et al. ‘14
Demartin et al. ‘15

⇨ Ensure consistency with current experimental bounds (ggF, VBF)

Full off-shell effects

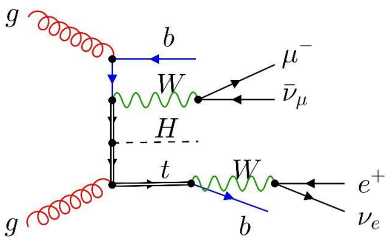
Process: $pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,H$ at $\mathcal{O}(\alpha_s^2\alpha^5)$

Double resonant

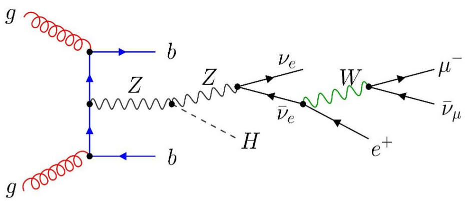


NWA

Single resonant



Non resonant



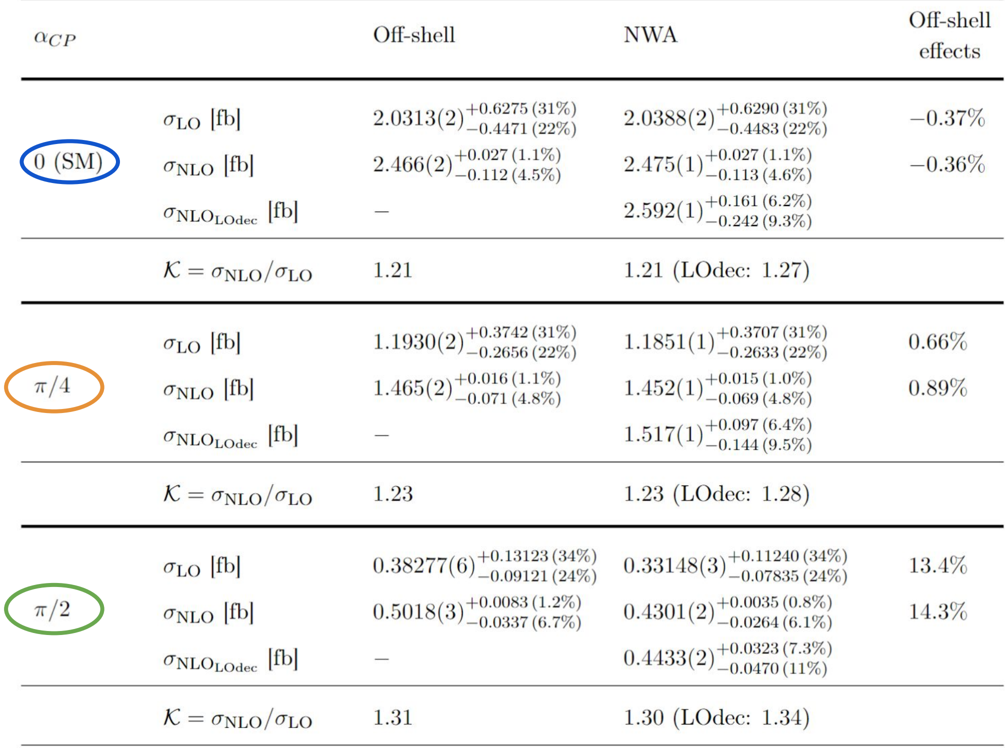
Off-shell

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

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

$$\left.\begin{array}{l} \text{Full off-shell} \\ \text{NWA} \end{array}\right\} \mathcal{O}(\Gamma_t/m_t) \sim 0.8\%$$

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]	–	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
	$\mathcal{K}=\sigma_{\rm NLO}/\sigma_{\rm LO}$	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)	

JH, Stremmer, Worek '22

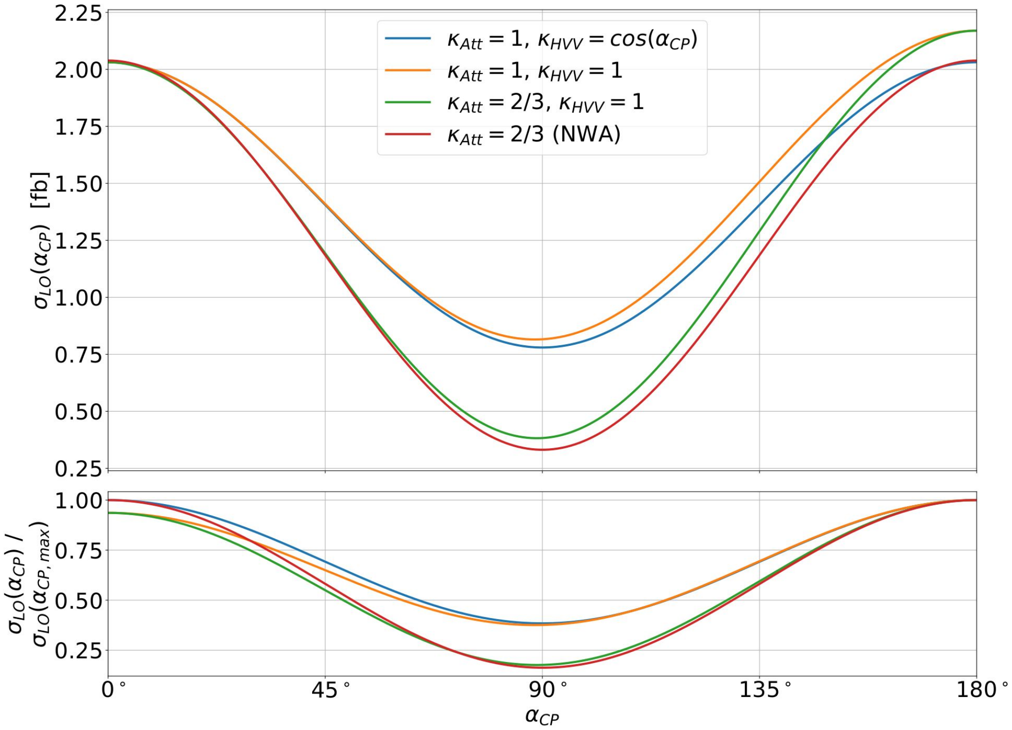
NLO corrections:

- **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

Integrated fiducial cross-sections (LO)

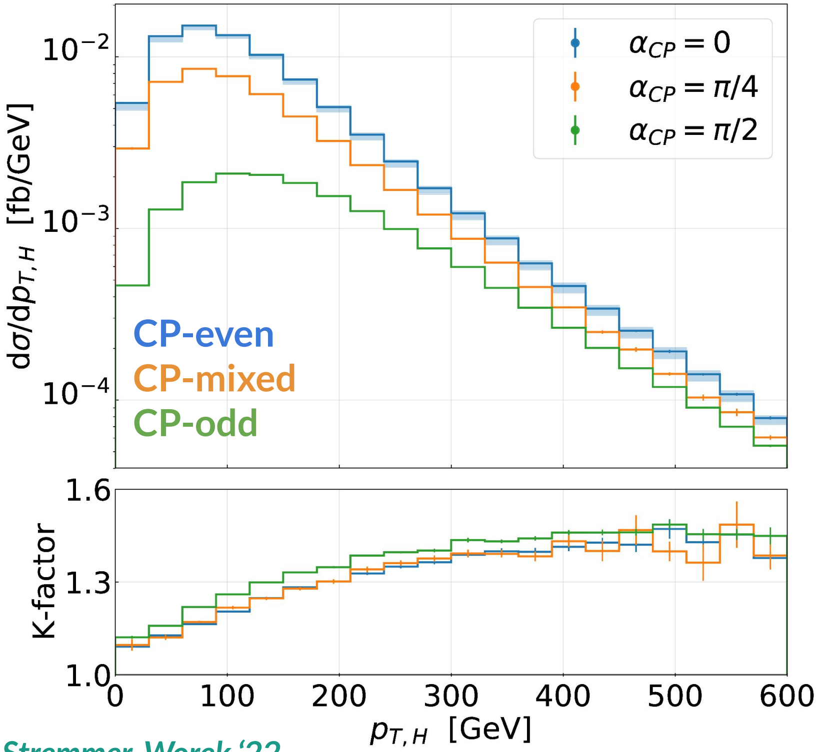


JH, Stremmer, Worek '22

- **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

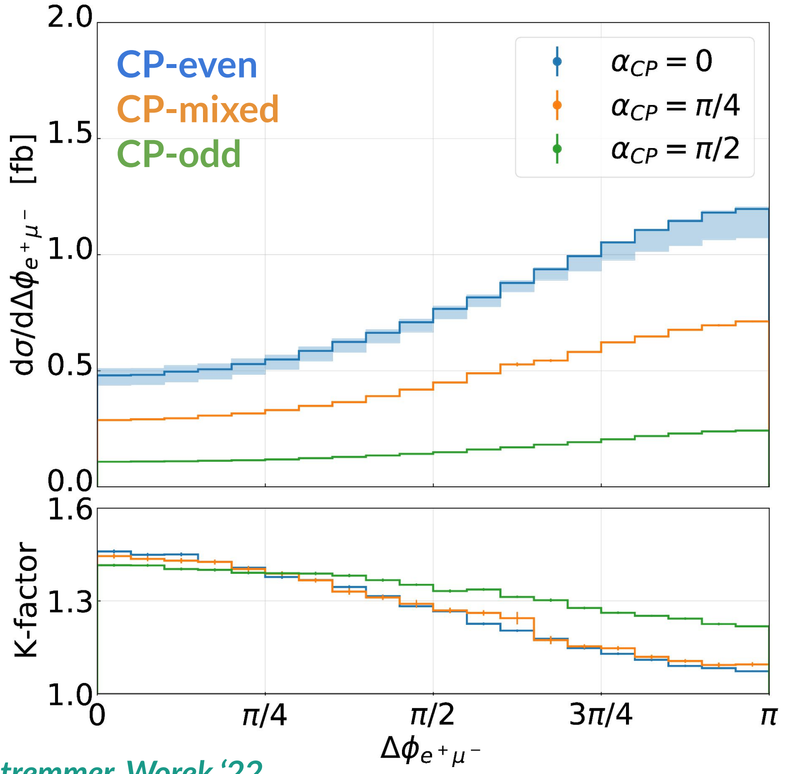


JH, Stremmer, Worek '22

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

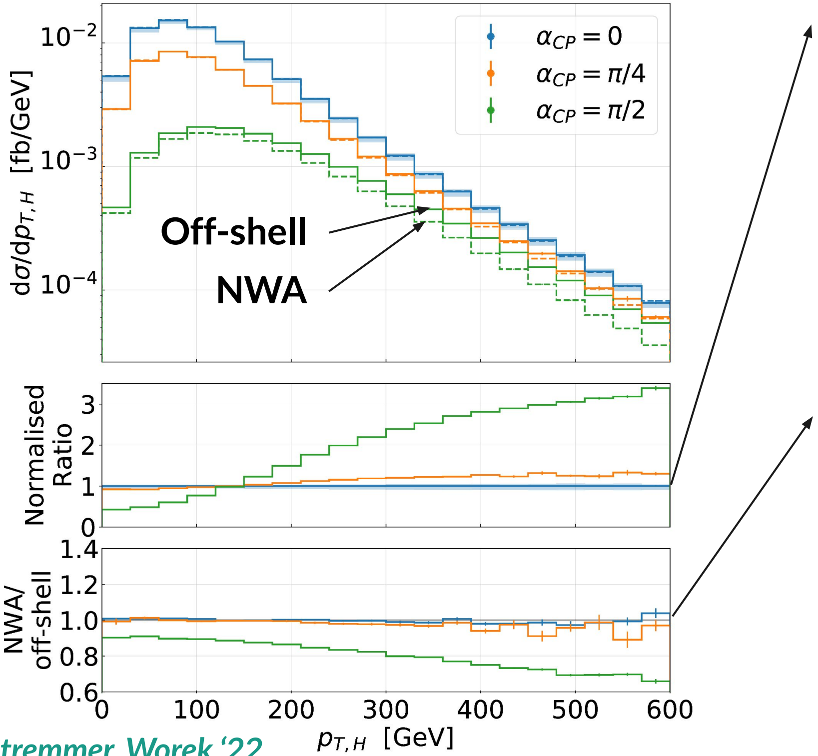


JH, Stremmer, Worek '22

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
- Larger effects around kinematic edges ($M_{T2,t}$, M_{e^+b})

JH, Stremmer, Worek ‘22

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) $H \to \gamma\gamma$

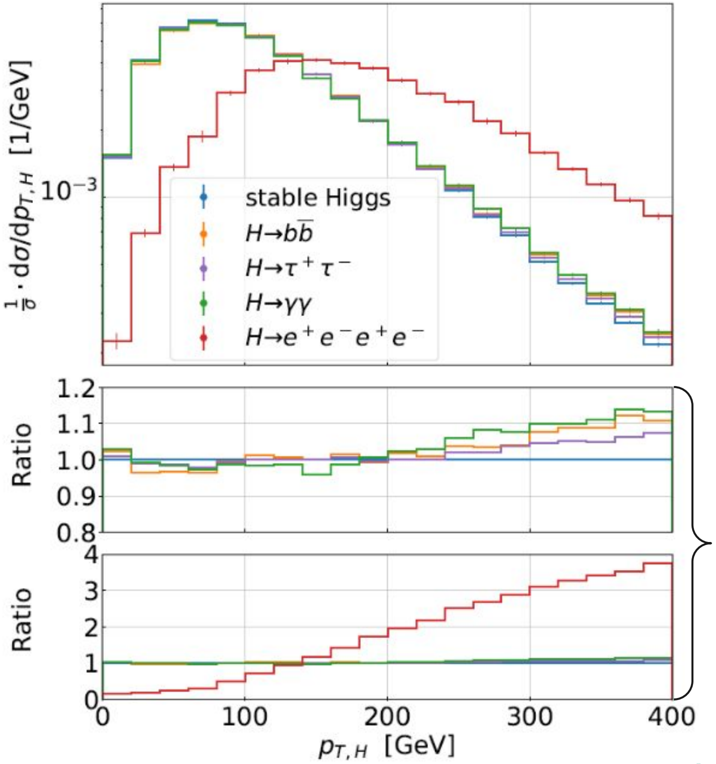
(iv) $H \to Z^* Z^* \to e^+e^-e^+e^-$

Stremmer, Worek ‘22

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

Conclusions

- Provided predictions for **ttH** production at **NLO in QCD** with **full off-shell effects** …
    - … including **SM Higgs decays** in NWA
    - … with **CP-mixing** in Yukawa coupling
- **NLO corrections**
    - Around **14 % - 30 %** with Higgs decays included, **20 % - 30 %** without
    - 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
    - Break symmetry in mixing angle
    - Large effects at integrated level 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!

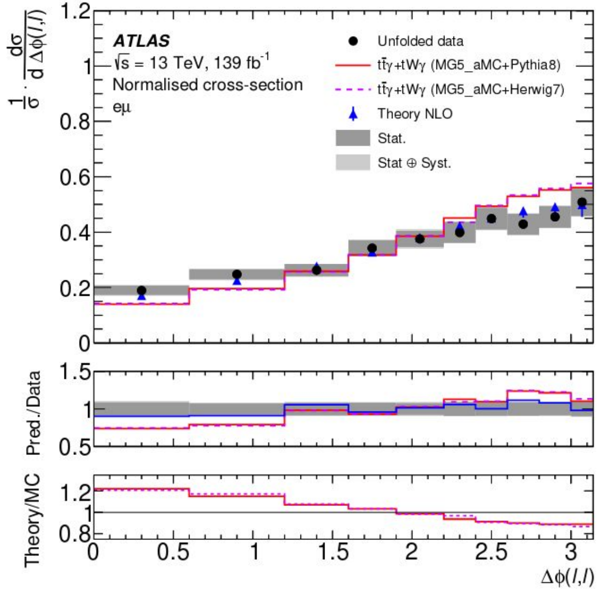
Backup

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 tty 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



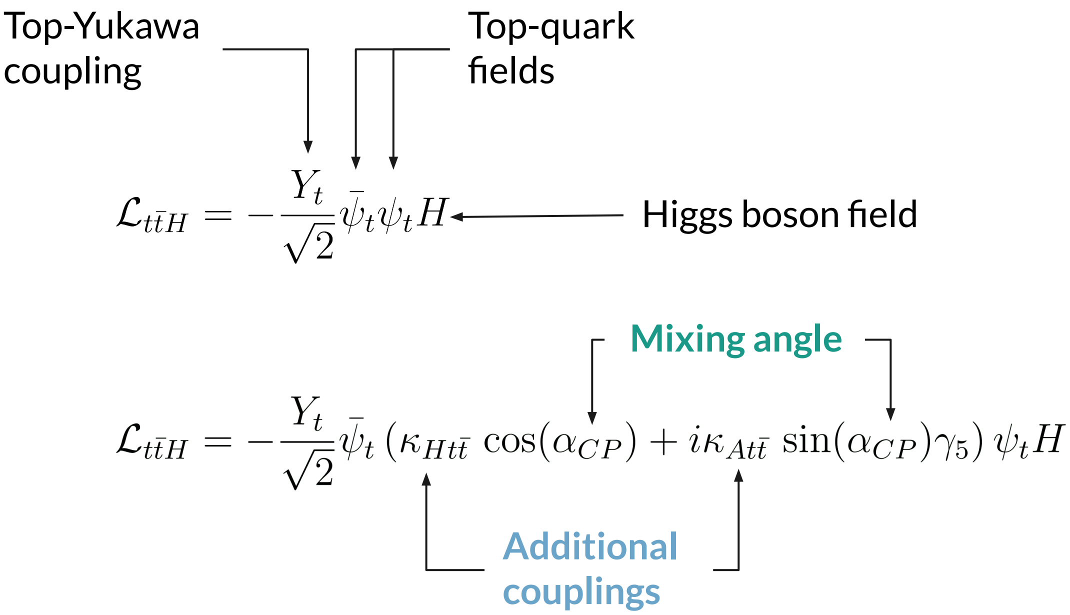
Conclusions

- 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 ($\cos\theta^*_{ll}, \ldots$)

- 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

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

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

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}

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

Additional coupling

Parameter choices

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

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

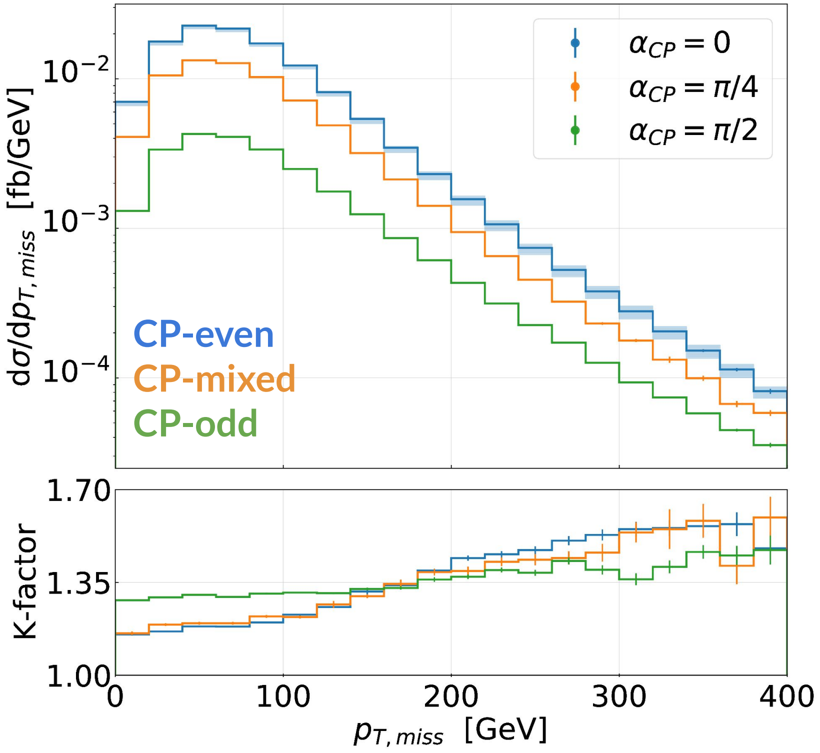
$\kappa_{At\bar{t}}$

- 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)

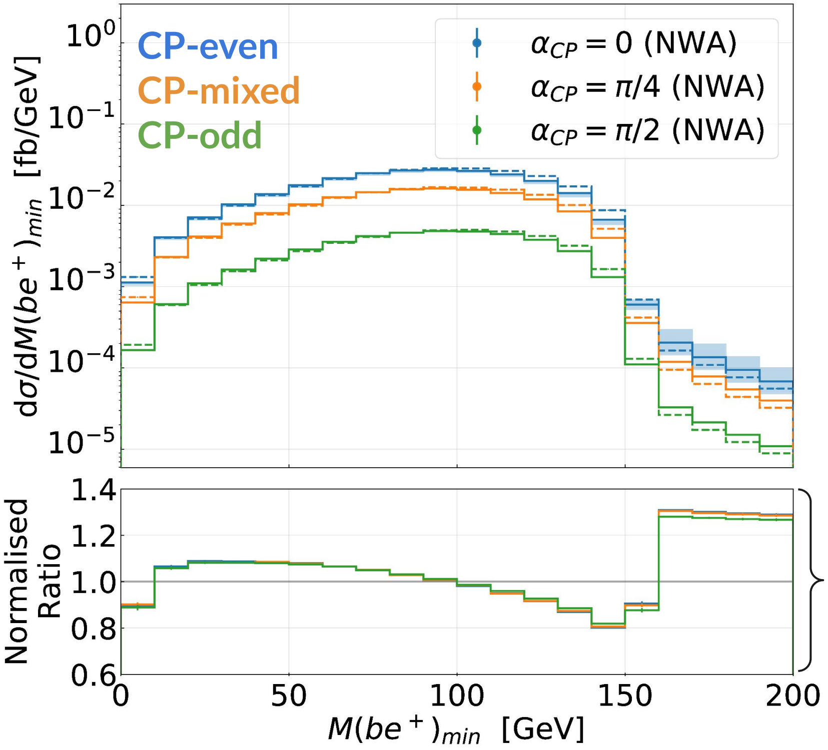
Differential distributions - NLO corrections



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

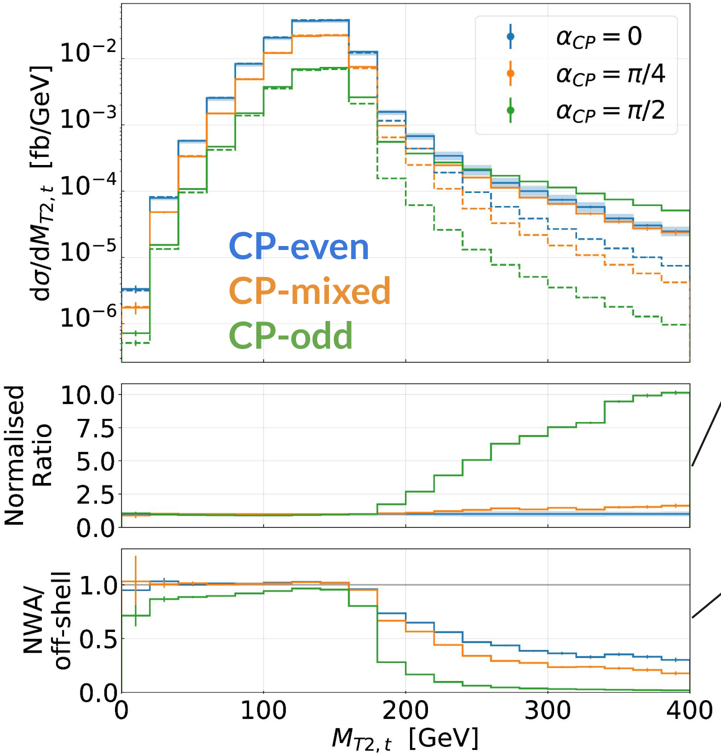


$$\frac{\mathrm{NLO}}{\mathrm{NLO}_{\mathrm{LOdec}}}$$ (both normalised)

NLO corrections to top-quark decays:

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

Differential distributions - Off-shell effects



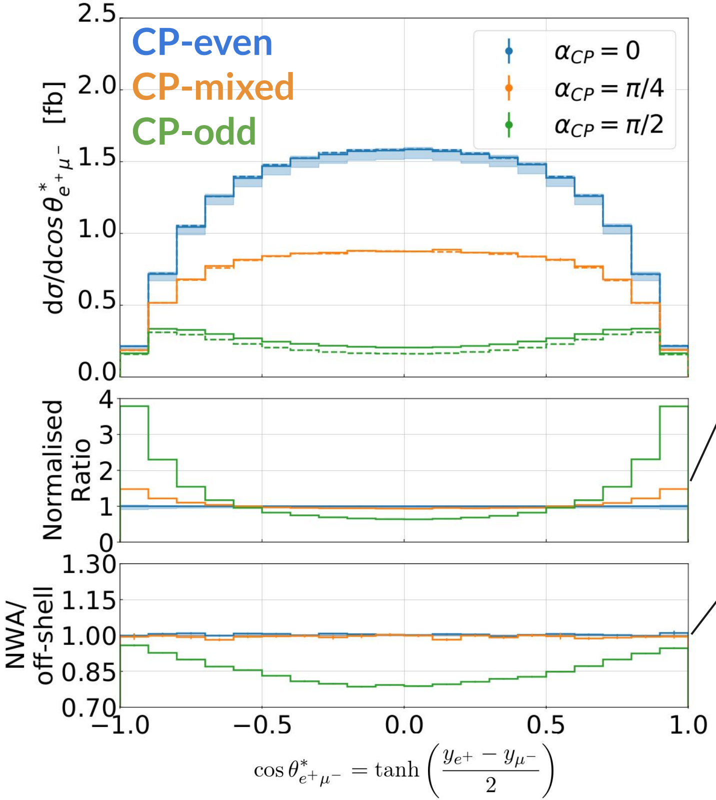
Shape comparison:

- 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

Inputs Paper 1

PDF: `NNPDF31-lo-as-0118` `NNPDF31-nlo-as-0118`

Parameters:

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

$$m_t = 173 \ \text{GeV} , \qquad m_H = 126 \ \text{GeV} ,$$

$$m_W^{\text{OS}} = 80.385 \ \text{GeV} , \qquad \Gamma_W^{\text{OS}} = 2.0850 \ \text{GeV} ,$$

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

$$m_V = \frac{M_V^{\text{OS}}}{\sqrt{1 + (\Gamma_V^{\text{OS}}/m_V^{\text{OS}})^2}} , \qquad \Gamma_V = \frac{\Gamma_V^{\text{OS}}}{\sqrt{1 + (\Gamma_V^{\text{OS}}/m_V^{\text{OS}})^2}}$$

$$\Gamma_t^{\text{LO}} = 1.472886 \ \text{GeV} , \qquad \Gamma_t^{\text{NLO}} = 1.346449 \ \text{GeV}$$

$$\Gamma_{t,\,\text{NWA}}^{\text{LO}} = 1.495948 \ \text{GeV} , \qquad \Gamma_{t,\,\text{NWA}}^{\text{NLO}} = 1.367547 \ \text{GeV}$$

Inputs Paper 1

Cuts:

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

$$p_{T,\ell} > 20\text{ GeV}\,,\qquad |y_\ell| < 2.5\,,$$

Jet-clustering: $\textit{anti-}k_T$ 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: $\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \Big\{ (2,1)\,,(0.5,1)\,,(1,2)\,,(1,1),(1,0.5),(2,2),(0.5,0.5)\Big\}$

Inputs Paper 1

Masses for decays: $m_\tau = 1.77682$ GeV, $m_b^{OS} = 4.92$ GeV, $\overline{m}_b(\overline{m}_b) = 4.18$ GeV

(Bottom mass set to zero, but non-zero Yukawa coupling)

Higgs width: $\Gamma_H = 4.226 \cdot 10^{-3}$ GeV

Mass variation for Yukawa renormalization:

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

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

Photon cuts:

$$R_{\gamma\gamma} > 0.3\,, \qquad R_{\gamma\ell} > 0.3\,, \qquad R_{\gamma b} > 0.3\,,$$

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

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

$$\epsilon_\gamma = 1,\; n = 1 \text{ and } R_{\gamma,j} = 0.3$$

Inputs Paper 2

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 Paper 2

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: $\textit{anti-}k_T$ jet algorithm $\quad R = 0.4$

Scale choice:

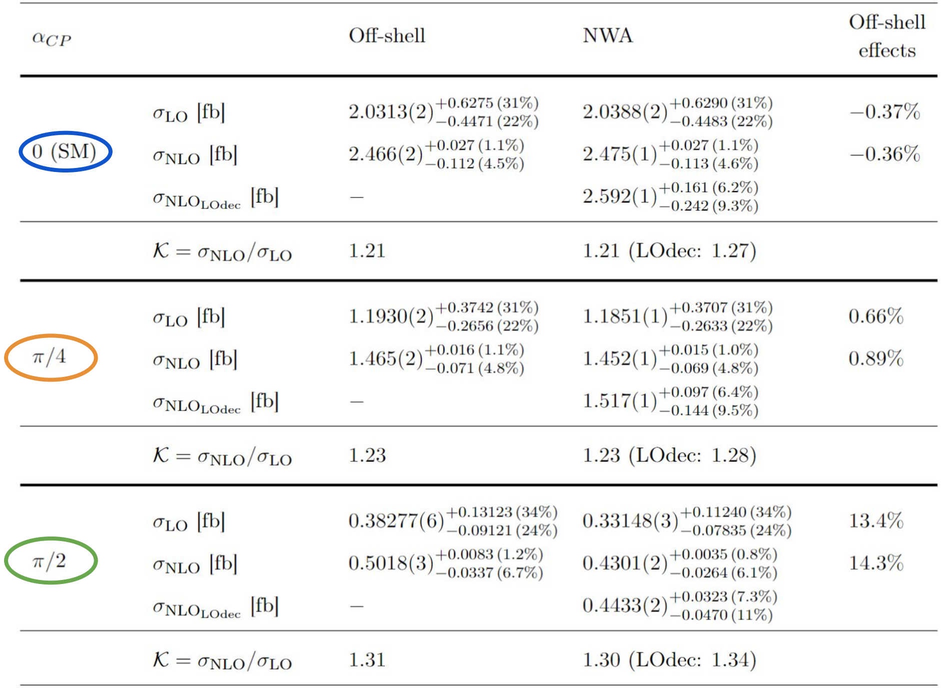
$$\mu_0 = \mu_R = \mu_F = H_T/2$$

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

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

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)	σ_{LO} [fb]	$2.0313(2)^{+0.6275\,(31\%)}_{-0.4471\,(22\%)}$	$2.0388(2)^{+0.6290\,(31\%)}_{-0.4483\,(22\%)}$	-0.37%
	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%
	$\sigma_{\text{NLO}_{\text{LOdec}}}$ [fb]	–	$2.592(1)^{+0.161\,(6.2\%)}_{-0.242\,(9.3\%)}$	
	$\mathcal{K} = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$	1.21	1.21 (LOdec: 1.27)	
$\pi/4$	σ_{LO} [fb]	$1.1930(2)^{+0.3742\,(31\%)}_{-0.2656\,(22\%)}$	$1.1851(1)^{+0.3707\,(31\%)}_{-0.2633\,(22\%)}$	0.66%
	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%
	$\sigma_{\text{NLO}_{\text{LOdec}}}$ [fb]	–	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
	$\mathcal{K} = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$	1.23	1.23 (LOdec: 1.28)	
$\pi/2$	σ_{LO} [fb]	$0.38277(6)^{+0.13123\,(34\%)}_{-0.09121\,(24\%)}$	$0.33148(3)^{+0.11240\,(34\%)}_{-0.07835\,(24\%)}$	13.4%
	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%
	$\sigma_{\text{NLO}_{\text{LOdec}}}$ [fb]	–	$0.4433(2)^{+0.0323\,(7.3\%)}_{-0.0470\,(11\%)}$	
	$\mathcal{K} = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$	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:

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

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

- **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):

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

- First two terms are symmetric in α_{CP}
- Last term is either **constant** ($\kappa_{HVV} = 1$) **or** **symmetric** ($\kappa_{HVV} = \cos(\alpha_{\text{CP}})$) 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):

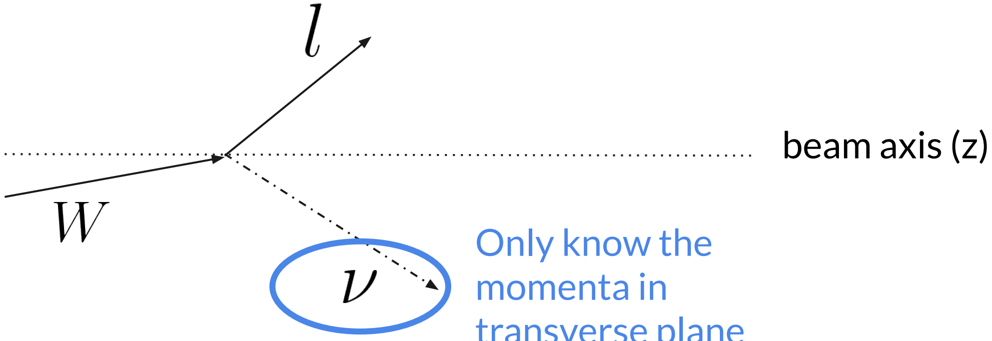
$$\begin{aligned}\sigma\left(\alpha_{CP}\right) = \cos^2\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}^2\,\sigma_1 + \sin^2\left(\alpha_{CP}\right)\kappa_{At\bar{t}}^2\,\sigma_2 \\ + \cos\left(\alpha_{CP}\right)\kappa_{Ht\bar{t}}\,\kappa_{HVV}\left(\alpha_{CP}\right)\,\sigma_4 + \kappa_{HVV}^2\left(\alpha_{CP}\right)\,\sigma_6\end{aligned}$$

Problem: The virtual contributions do not factorise in this manner

→ Interpolation much more complicated

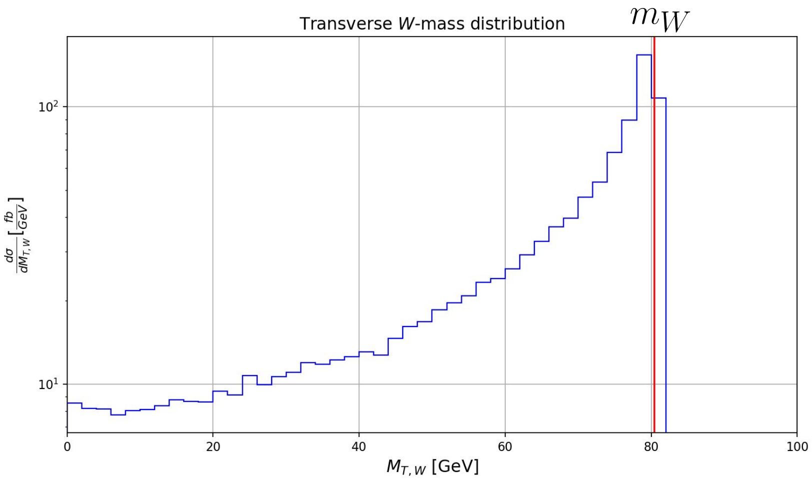
The ‘stransverse’ mass - idea

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



Only know the momenta in transverse plane

Reconstruct the W mass:



Define mass & momenta in transverse plane

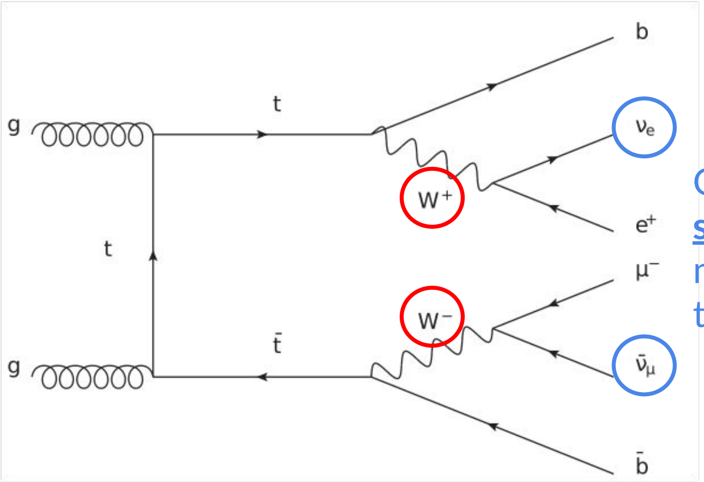
$$p_T = (E_T, p_x, p_y, 0) \quad \text{where} \quad E_T = \sqrt{p_{T,x}^2 + p_{T,y}^2}$$

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

The ‘stransverse’ mass - idea & definition

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

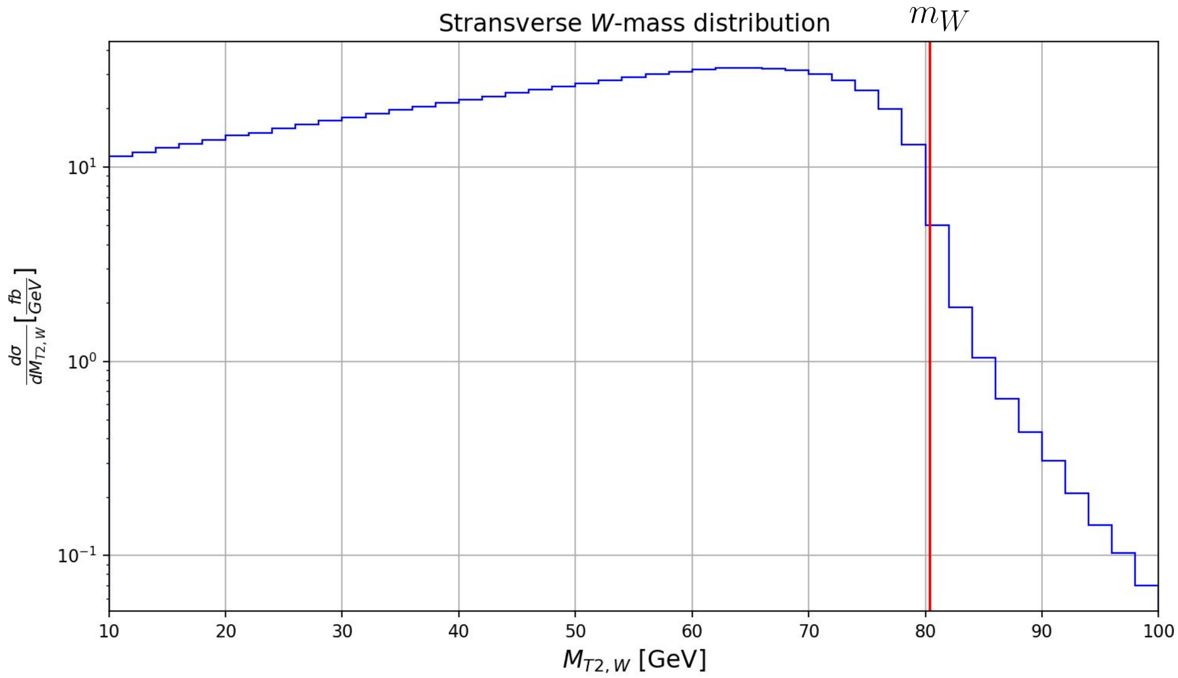
$$M^2_{T2,W} = \min_{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2}=\mathbf{p}_{T,\text{miss}}} \left[\max\{M_T^2\left(\mathbf{p}_T^{l_1},\mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{l_2},\mathbf{p}_T^{\nu_2}\right)\}\right]$$



Only know the sum of the momenta in transverse plane

Minimize over all missing momentum combinations

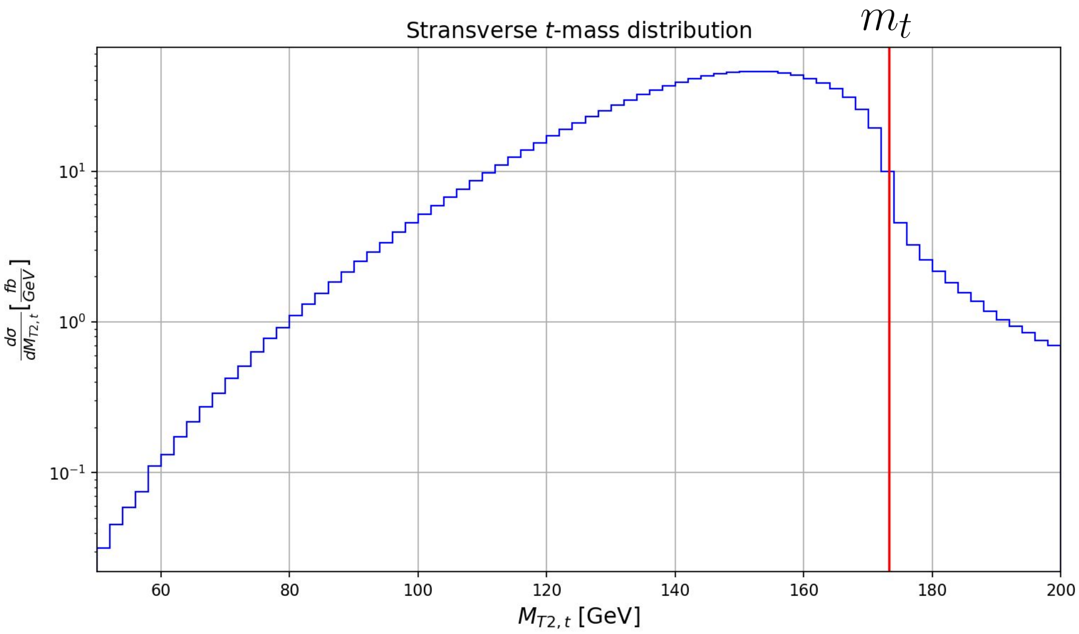
The ‘stransverse’ mass - distribution



- 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

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

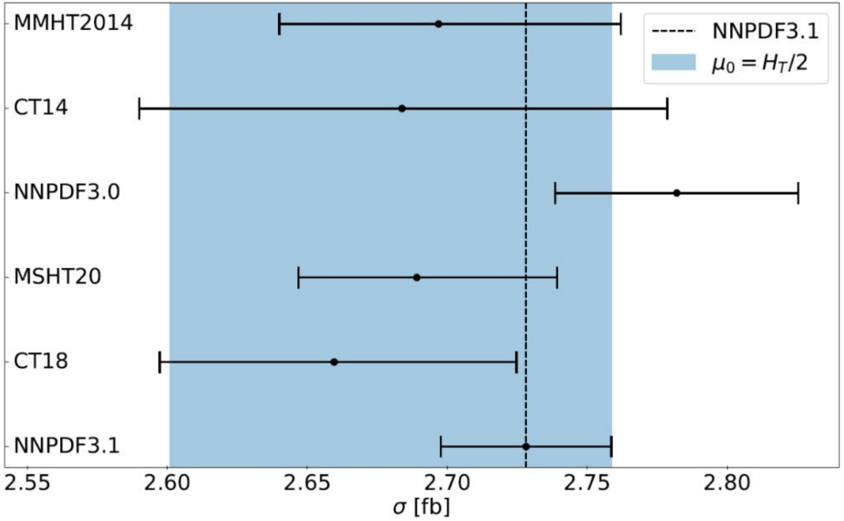
where $$M_T^2\left(\mathbf{p}_T^{(lb)_i}, \mathbf{p}_T^{\nu_i}\right) = M_{(lb)_i}^2 + 2\left(E_T^{(lb)_i} E_T^{\nu_i} - \mathbf{p}_T^{(lb)_i} \mathbf{p}_T^{\nu_i}\right)$$

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

Fiducial cross sections

Slide by Daniel Stremmer

PDF set	σ_{NLO} [fb]	δ_{scale}	δ_{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)	$+0.030\,(1.1\%)$ $-0.123\,(4.6\%)$	$+0.050\,(1.9\%)$ $-0.042\,(1.6\%)$

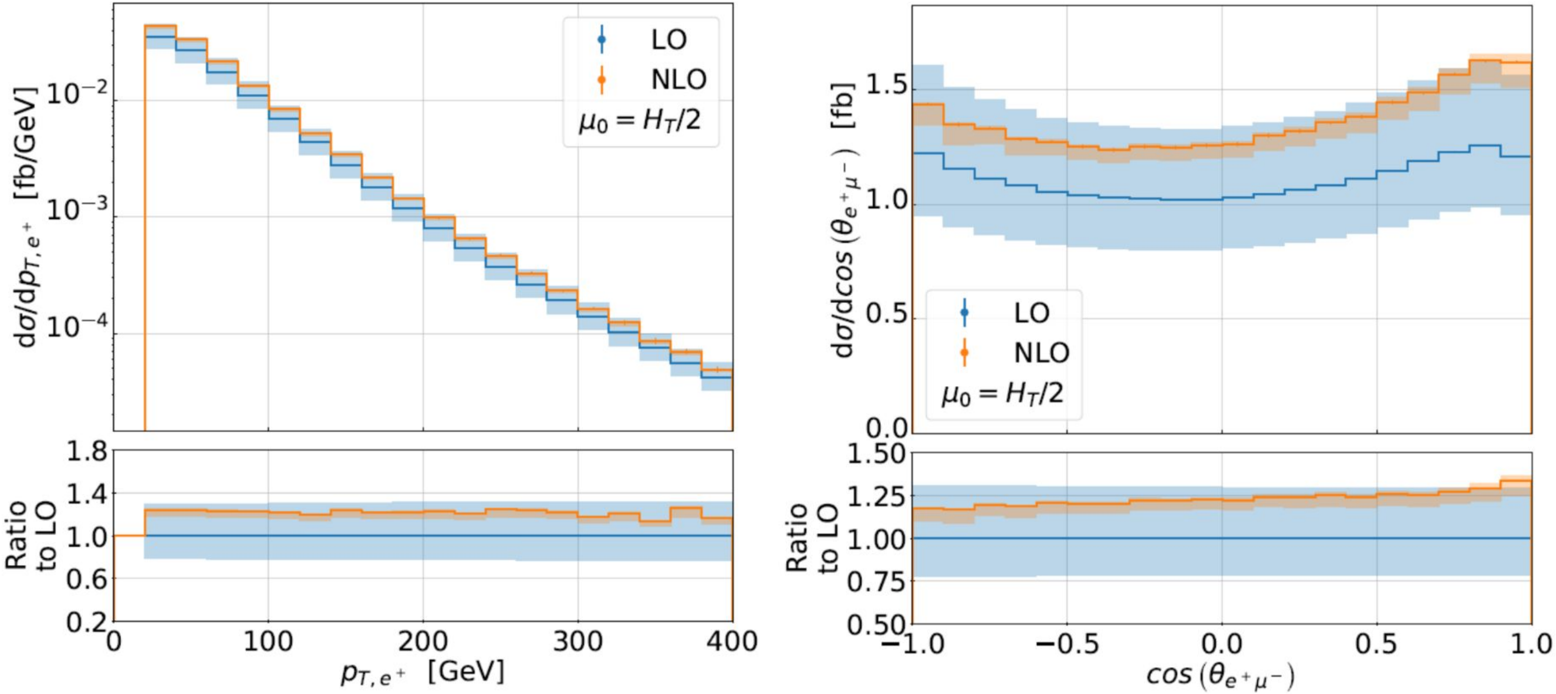


- $\sigma_{\mathrm{LO,NNPDF31}} = 2.2130(2)^{+30.1\%}_{-21.6\%}$
- NLO QCD corrections ~20%
- 5% scale uncertainties
- 1% – 2% PDF uncertainties
- All PDF sets are consistent

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

Slide by Daniel Stremmer

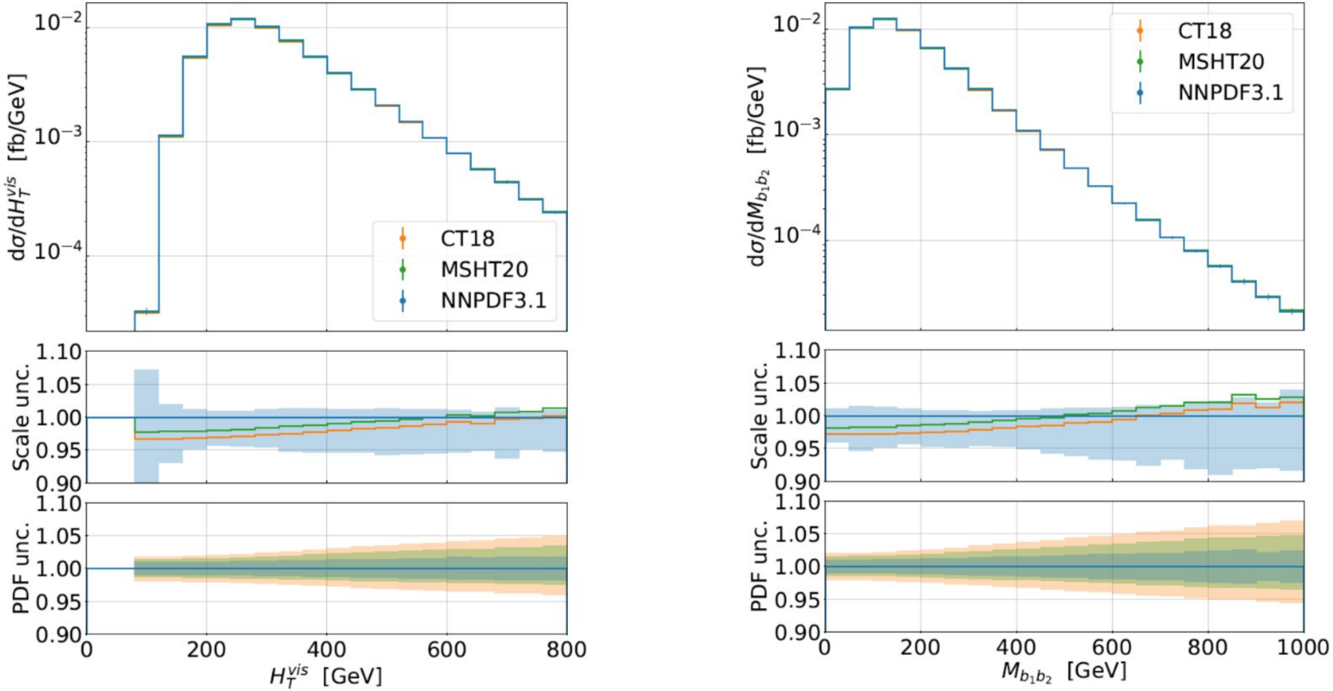
Differential distributions



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

Slide by Daniel Stremmer

Differential distributions



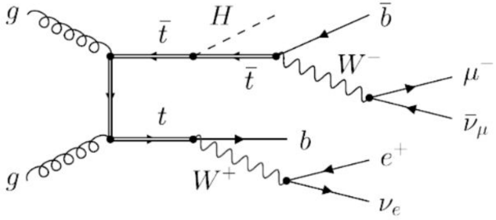
- PDF uncertainties increases towards the tails
- Comparable in size to scale uncertainties in tails

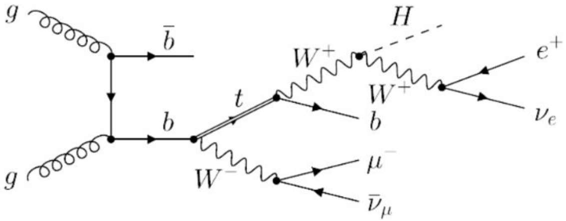
Slide by Daniel Stremmer

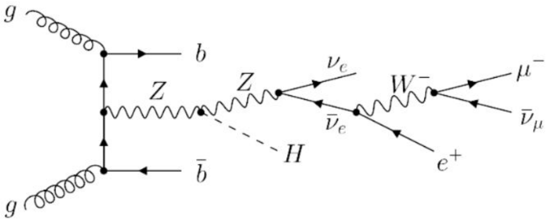
Top quark modeling

	μ_0	σ_{LO} [fb]	σ_{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}	$2.3074(2)^{+30.7\%}_{-21.9\%}$	$2.742(1)^{-3.8\%}_{-5.3\%}$
$\mathrm{NWA}_{\mathrm{LOdec}}$	$H_T/2$	-	$2.862(1)^{+6.3\%}_{-9.4\%}$
	μ_{fix}	-	$2.897(1)^{+5.1\%}_{-9.0\%}$

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

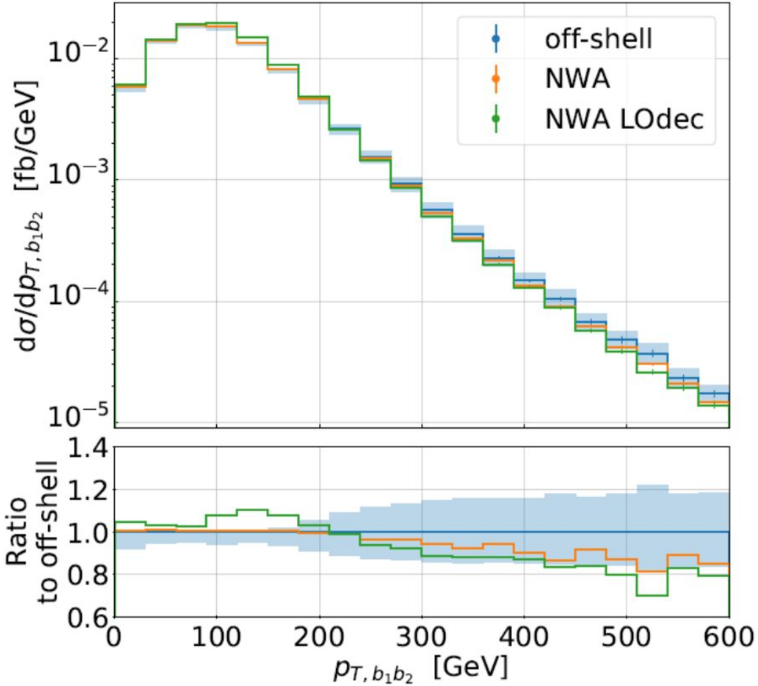




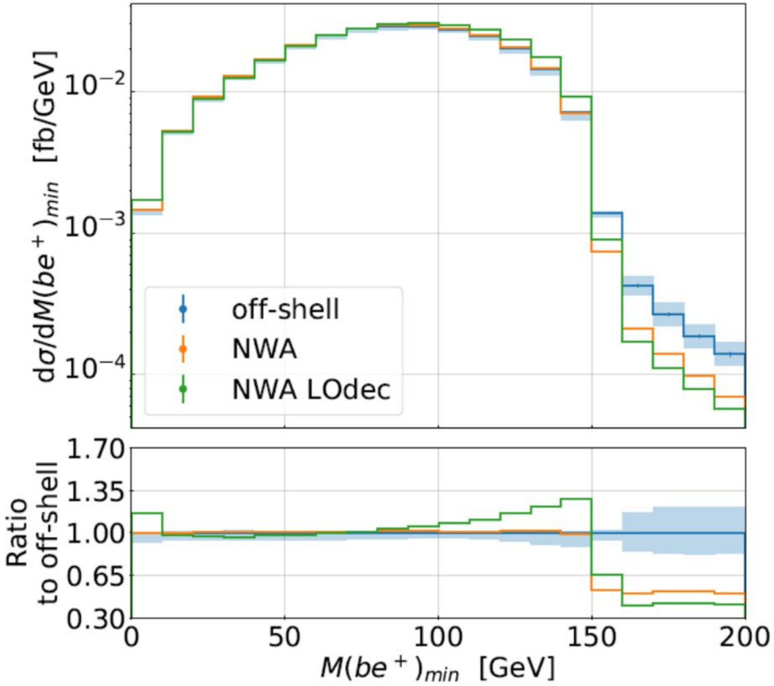


Top quark modeling

Slide by Daniel Stremmer



- Off-shell effects ~ 15% – 20% in the tails
- $\text{NWA}_{\text{LOdec}}$ further shape distortions

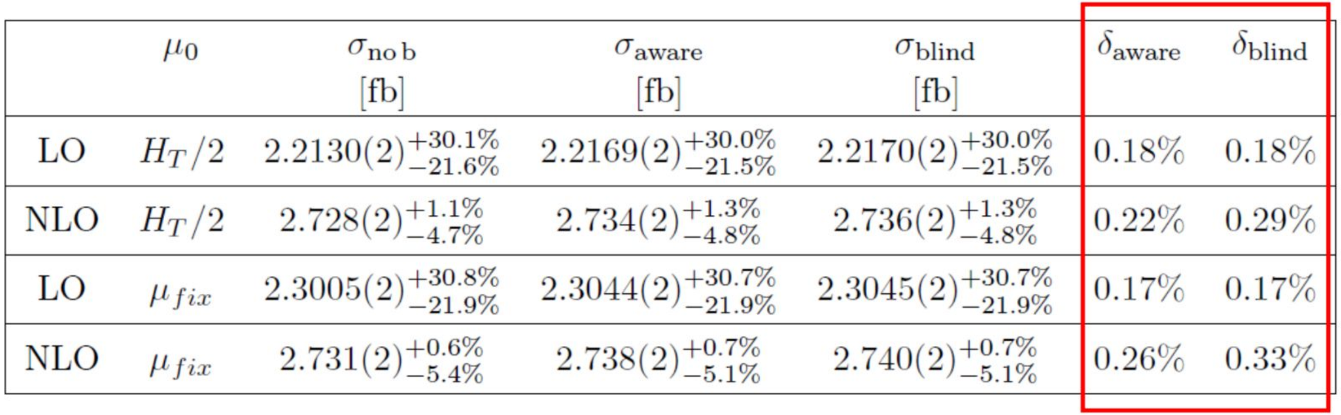


- $\text{LO}_{\text{NWA}} \rightarrow M(be^+)_{min} \leq \sqrt{m_t^2 - m_W^2} \approx 153\ \text{GeV}$

Initial-state b quark contribution

Slide by Daniel Stremmer

- 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 $\quad b\bar{b} \to g \qquad bb \to b,\ \bar{b}\bar{b} \to \bar{b}$

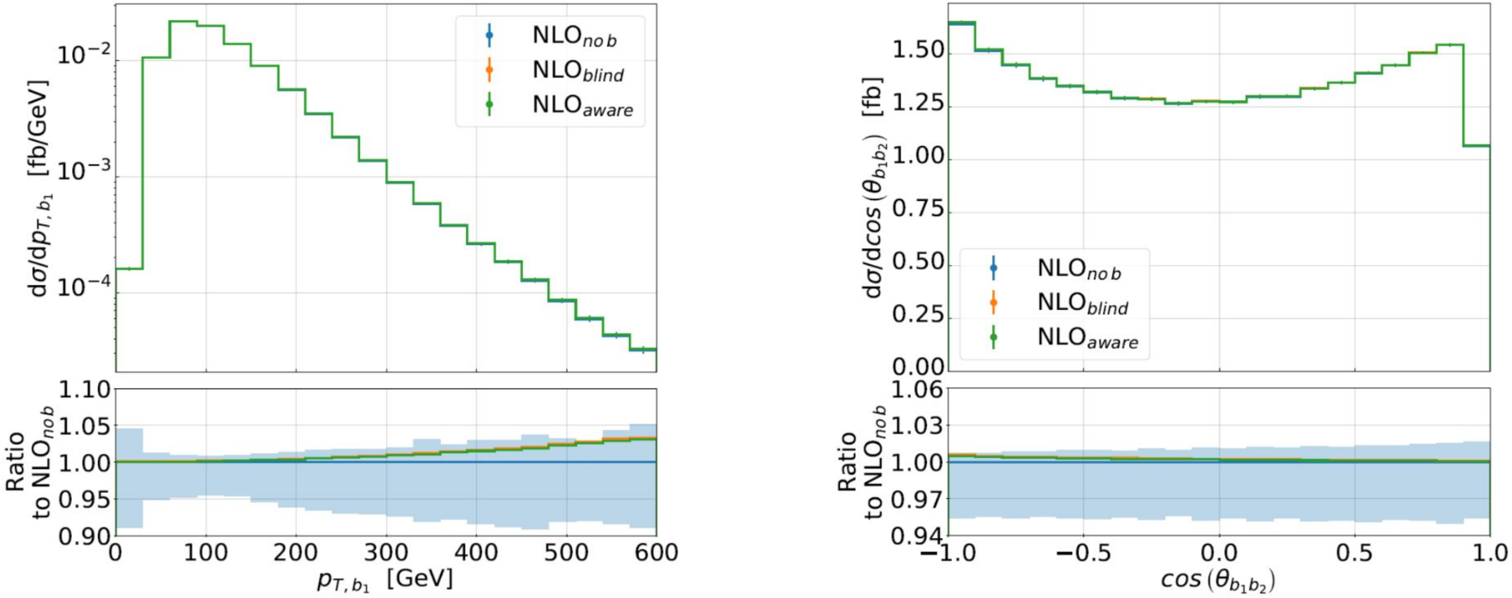


	μ_0	$\sigma_{\text{no b}}$ [fb]	σ_{aware} [fb]	σ_{blind} [fb]	δ_{aware}	δ_{blind}
LO	$H_T/2$	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.2169(2)^{+30.0\%}_{-21.5\%}$	$2.2170(2)^{+30.0\%}_{-21.5\%}$	0.18%	0.18%
NLO	$H_T/2$	$2.728(2)^{+1.1\%}_{-4.7\%}$	$2.734(2)^{+1.3\%}_{-4.8\%}$	$2.736(2)^{+1.3\%}_{-4.8\%}$	0.22%	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 ~ 0.2% – 0.3%

Slide by Daniel Stremmer

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