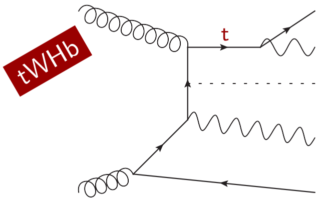
Single top + Higgs

Interference in tHW and $t\bar{t}H$

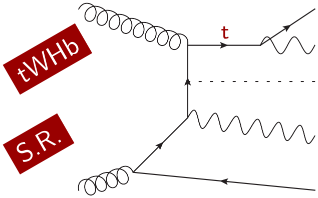
April 22, 2015

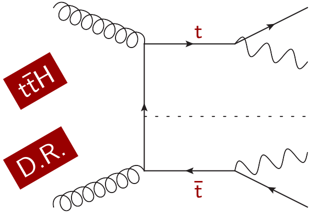
Benedikt Maier

Introduction to tHW

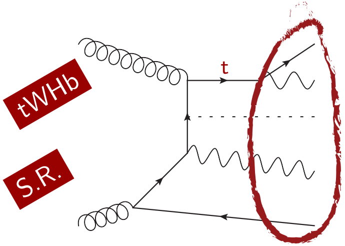


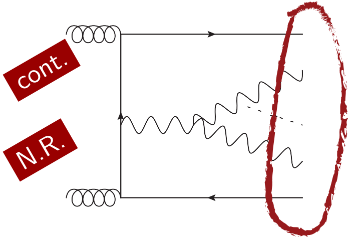
Introduction to tHW





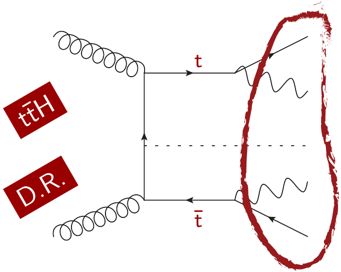
Introduction to tHW



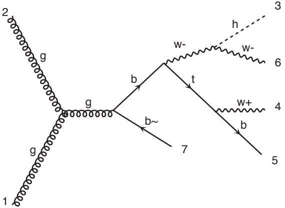


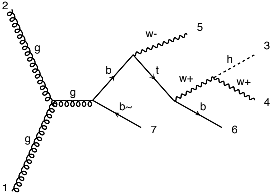
→ same HWWbb final state

→ interference

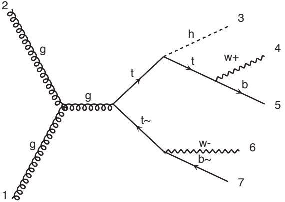


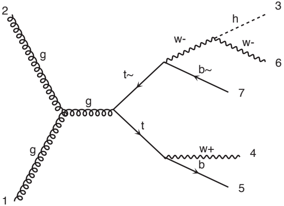
Modelling at LO





p p > h w+ w- b b~





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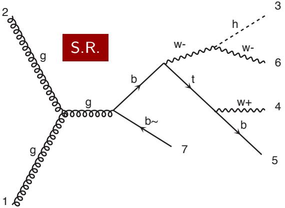

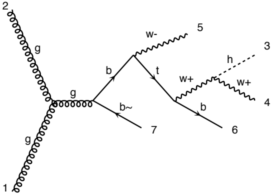

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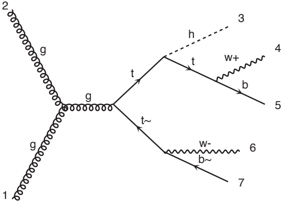

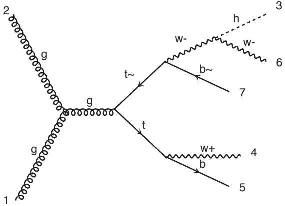

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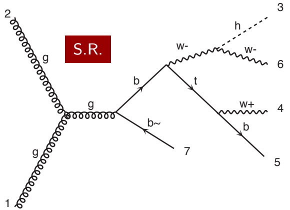
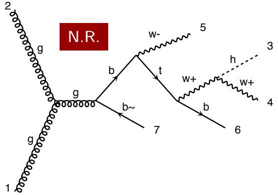
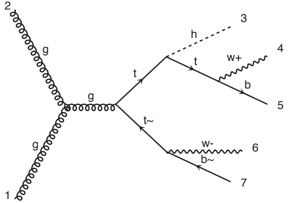
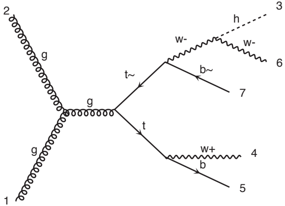


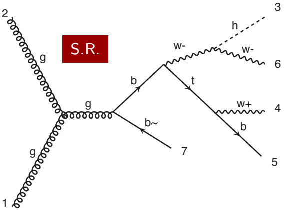


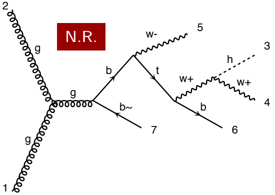
p p > h w+ w- b b~



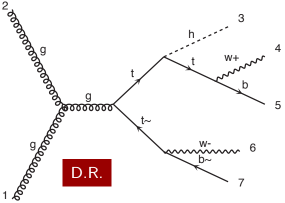


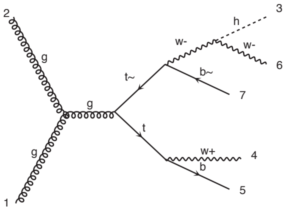
Modelling at LO





p p > h w+ w- b b~





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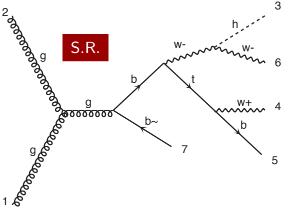
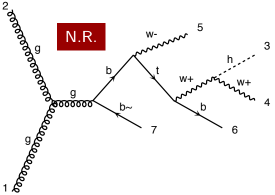
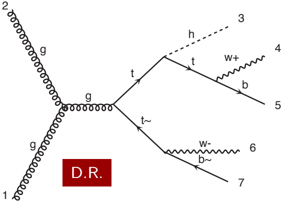
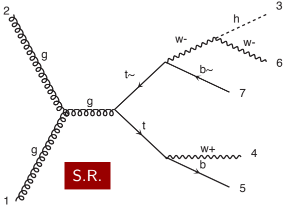




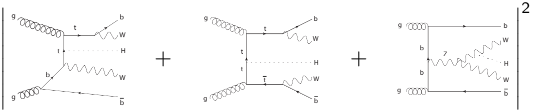
`p p > h w+ w- b b~`





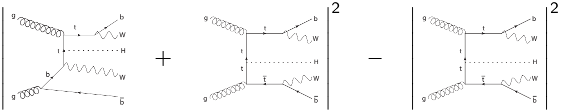
HWWbb – approximations

`p p > h w+ w- b b~` $\rightarrow$



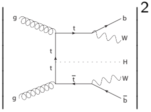
=

`p p > h t w- b~` $\rightarrow$



+

`p p > h t t~` $\rightarrow$



+ non-resonant part

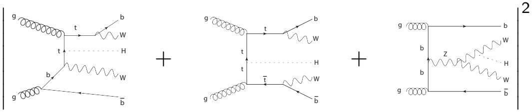
?

diagram subtraction

taking into account interference

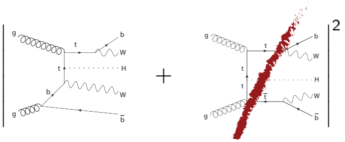
HWWbb – approximations

`p p > h w+ w- b b~`



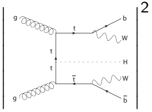
=

`p p > h t w- b~`



+

`p p > h t t~`



+ non-resonant part

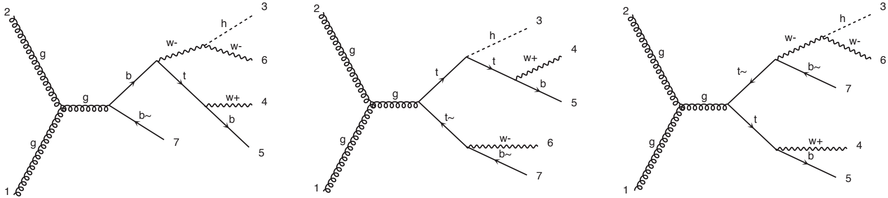
?

diagram removal

not taking into account interference

tHWb generation – diagram removal

Generating `p p > h t w- b~, t > w+ b` out-of-the-box will include the following types of diagrams:



We don't want the contribution of the middle diagram. The right one is not double-resonant, but contributes to tHWb as we understand and want it.

Comparison in 4fs

`p p > h w+ w- b b~` $\rightarrow \sigma = 0.3878\,\text{pb}$

benchmark!

`double-resonant` $\rightarrow \sigma = 0.378\,\text{pb}$

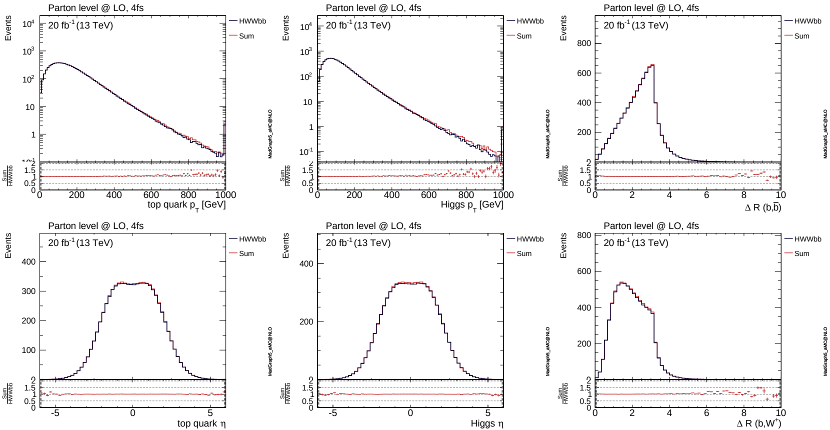
`single-resonant` $\rightarrow \sigma = 0.0125\,\text{pb}$

`non-resonant` $\rightarrow \sigma = 0.0008\,\text{pb}$

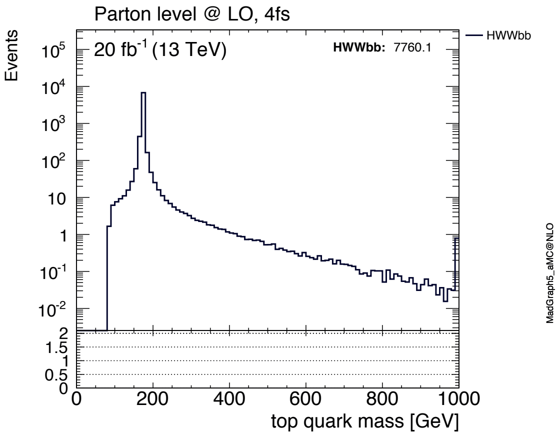
`SUM` $\rightarrow \sigma = 0.3913\,\text{pb}$

0.9% difference (generated sample size was 1M each ... $\rightarrow$1‰ stat. unc.)

Comparison in 4fs



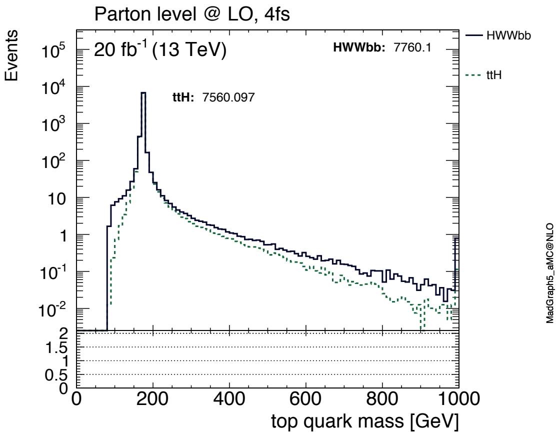
Comparison in 4fs



`p p > h w+ w- b b~`

- benchmark
- full interference

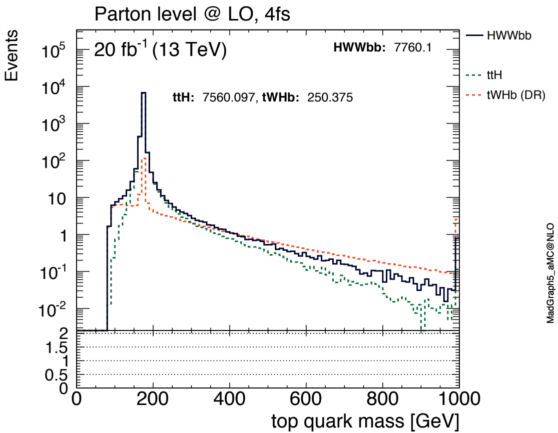
Comparison in 4fs



`p p > h t t~`

- double-resonant
- `bwcutoff=1000`

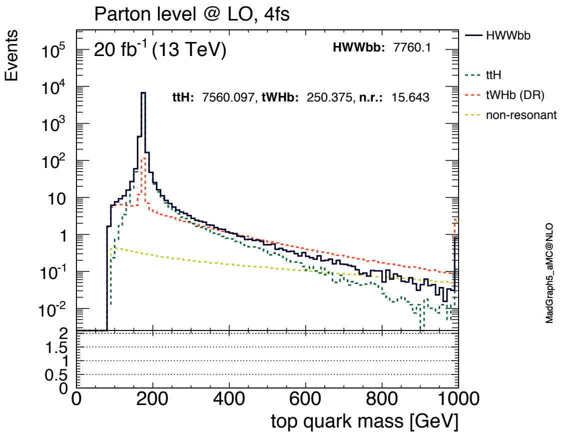
Comparison in 4fs



`p p > h tt bb ww`

- single-resonant
- remove double-res. diagrams
- `bwcutoff=1000`

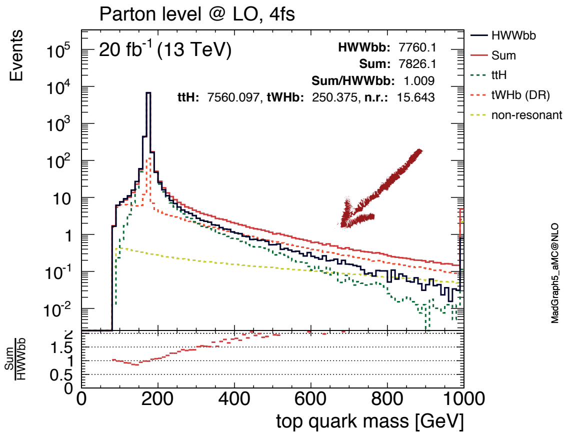
Comparison in 4fs



`p p > h w+ w- b b~`

- non-resonant
- remove double- and single-res. diagrams

Comparison in 4fs



Sum

- ttH
- tWHb (DR)
- non-resonant

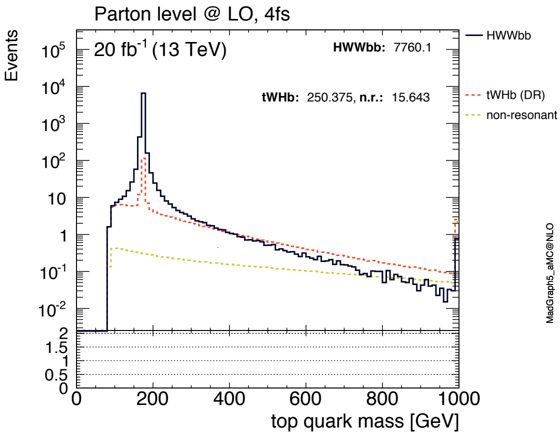
- Exceeds the benchmark in the tail! (from $\sim 250\,\mathrm{GeV}$ on)
- Suspect: neglected interference in tWHb

Neglected interferences

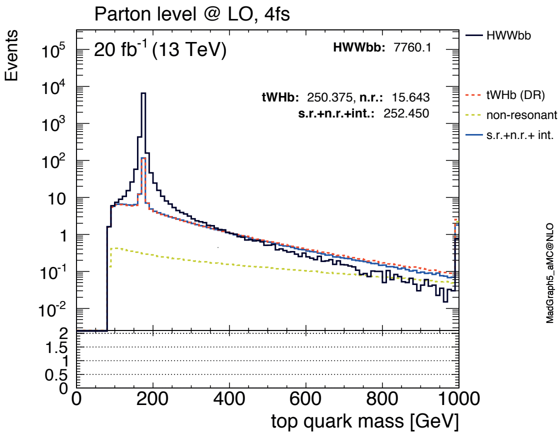
- With the diagram removal in `p p > h tt bb ww`, we do not take interference with `p p > h t t~` into account.
- But we are also neglecting inteferences between the single- and non-resonant part! $\rightarrow$ Is this the reason for the observed behaviour?

- Checking it with `p p > h w+ w- b b~`, where double-resonant diagrams have been removed (i.e. preserving interferences between single- and non-resonant parts)

Comparison in 4fs



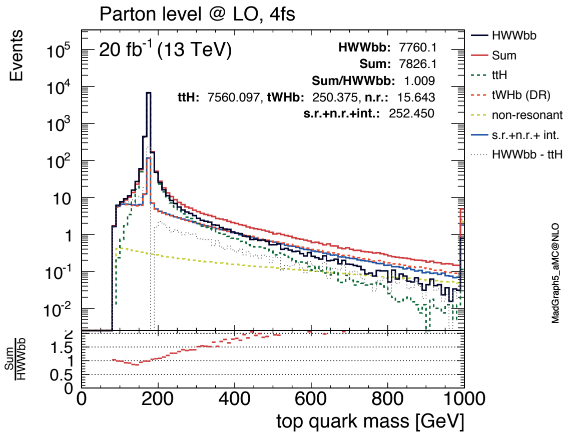
Comparison in 4fs



`p p > h w+ w- b b~`

- removing double-resonant diagrams
- obviously, there is destructive interference
- but not enough!

Comparison in 4fs

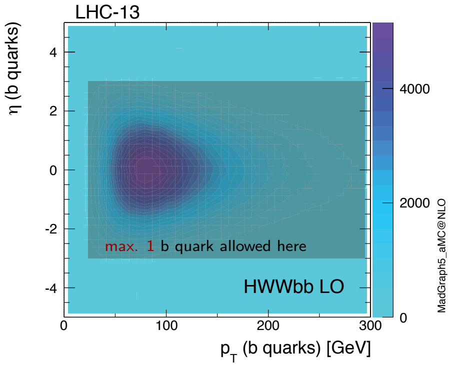


Full picture

- shows also HWWbb-ttH

Try to isolate possible effect of missing interference

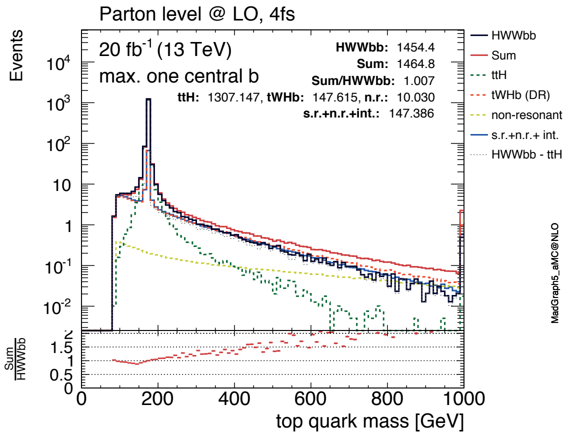
Those were inclusive distributions / numbers.
Let's have a look at the scenario where we allow only up to 1 b quark (with $p_T > 20\,\text{GeV}$) in the central region ($|\eta| < 2.5$).



Idea:

- Only one central b quark
- More likely to be a tWHb event (as opposed to ttH)
- Effect of (missing) interference should be more visible

Comparison in 4fs

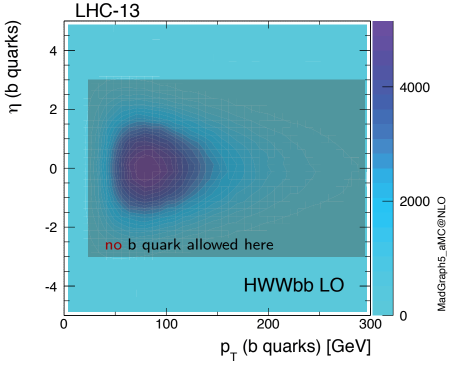


Max. one central b

- enhanced tWHb contribution
- ratio improved, but still too large in tail
- dip in HWWbb-ttH is gone

Try to isolate possible effect of missing interference

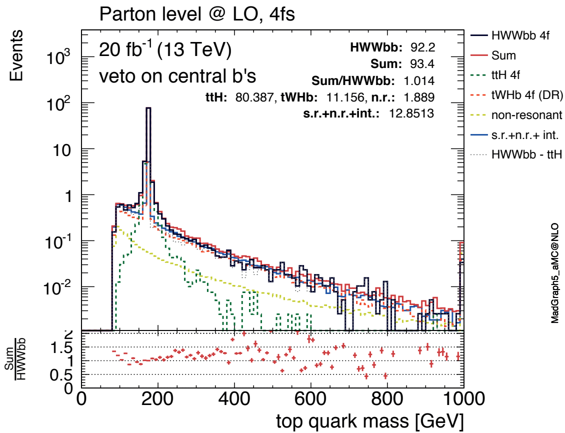
Let's have a look at the scenario where no b quark (with $p_T > 20\,\text{GeV}$) in the central region ($|\eta| < 2.5$) is allowed.



Idea:

- No central b quark
- Most likely to NOT be a ttH event
- Effect of (missing) interference should be more visible

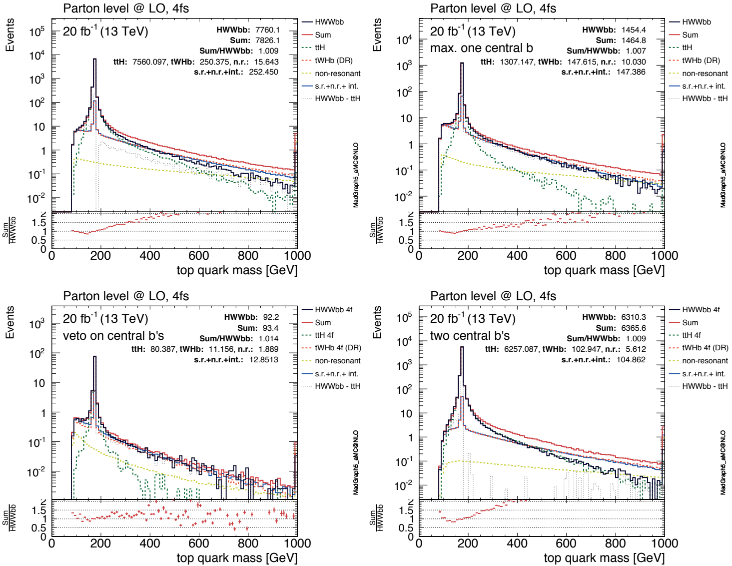
Comparison in 4fs



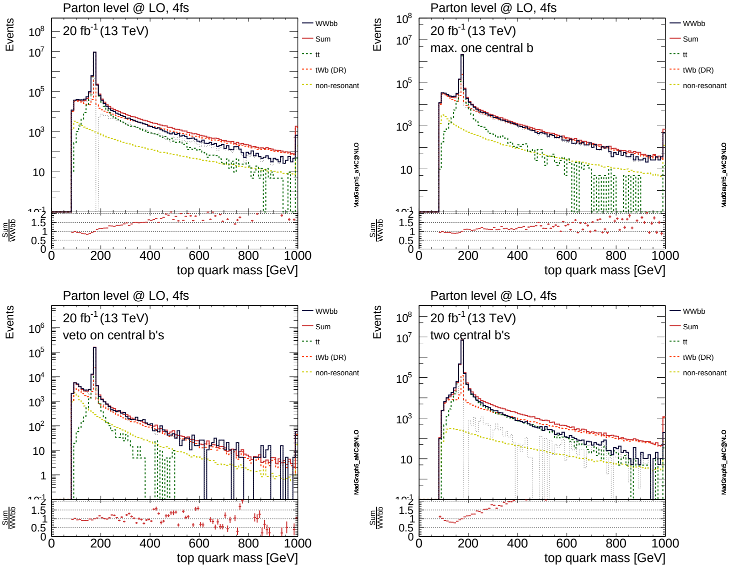
Veto on central b's

- enhanced tWHb contribution
- ratio improved almost flat

Comparison in 4fs



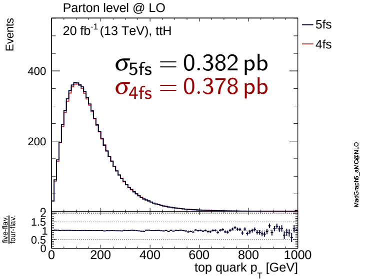
Comparison in 4fs – WWbb cross check

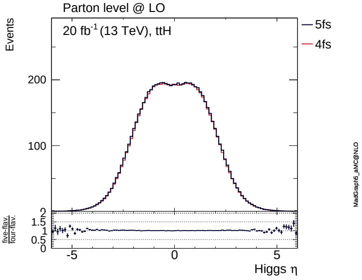


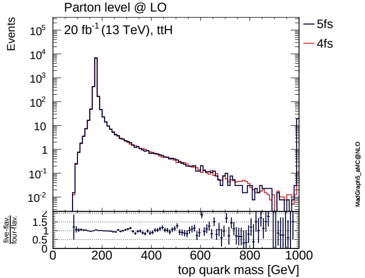
Comparison in 5fs

- Naturally, no overlap between ttH and tWH $\rightarrow$ no diagram removal necessary
- However, in the 5fs one must take additional b quarks from the (backwards evolution of the) shower for tWH
- One thing one can still look at very easily is ttH
  $\rightarrow$ straightforward fs comparison possible

4fs vs. 5fs – ttH







Comparison in 5fs

`p p > h w+ w- b b~ (4fs)` $\rightarrow \sigma = 0.3878\,\mathrm{pb}$

benchmark!

`p p > h t t~ (5fs)` $\rightarrow \sigma = 0.382054\,\mathrm{pb}$

`p p > h tt ww (5fs)` $\rightarrow \sigma = 0.01598\,\mathrm{pb}$

`b b~ > h w+ w- (5fs)` $\rightarrow \sigma = 8.950849\text{e-}05\,\mathrm{pb}$

`SUM` $\rightarrow \sigma = 0.3981\,\mathrm{pb}$

2.7% difference (generated sample size was 1M each ... $\rightarrow$1‰ stat. unc.)

Open points & next steps

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- Check LO parton behaviour for case without Higgs

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- Compare showered distributions for 4fs and 5fs

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- Compare showered distributions for 4fs and 5fs

- Study on-shell subtraction method(s)

Open points & next steps

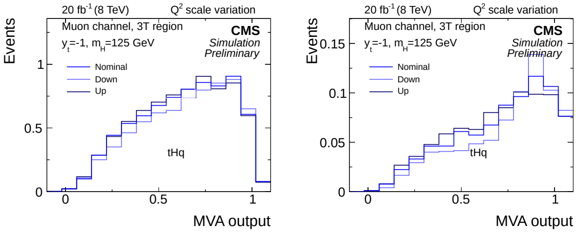
- Check LO parton behaviour for case without Higgs
- Compare showered distributions for 4fs and 5fs

- Study on-shell subtraction method(s)
- Go NLO

Backup

CMS Monte Carlo strategy in Run-I

- Using LO MadGraph + Pythia6 TuneZ2star for tHq generation
  - 4-and 5-flavour-scheme (depending on channel)
    - 4fs for $H \to b\bar{b}$
    - 5fs for $H \to W\bar{W}, \tau\tau, \gamma\gamma$ (historical reasons) ... 4fs taken into account as syst. unc. ($\mathcal{O}(5.5\,\%)$)
  - cteq6l1 PDF
  - Fixed fact./ren. scale: $\mu = 100\,\mathrm{GeV}$
  - $y_t = -1$
- Q^2 uncertainty via rate/shape uncertainties → dedicated samples



CMS Monte Carlo strategy in Run-I

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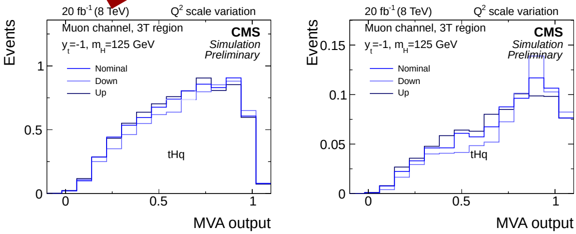
  - cteq6l1 PDF
  - Fixed fact./ren. scale ... 00 GeV
  - $y_t = -1$
- Q^2 uncertainty ... /shape uncertainties → dedicated samples

Did not consider tWH in Run-I



Reweighting at LO

- Concept: associate a weight to a set of events corresponding to a new theoretical hypothesis:

$$W_{\text{new}} = \frac{|M_{\text{new}}|^2}{|M_{\text{old}}|^2} \cdot W_{\text{old}}$$

- Limitations to this method:
  - The two hypotheses must have the same process, the same model and the same PDF
  - The same scale is used for both hypotheses – can lead to biases for dynamical scales
  - Statistical limitations where the hypotheses are not populating phase space enough
- Further information: see here

Reweighting at LO

```
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<weight id='mg_reweight_3'>set param_card yukawa 6 69.0 # orig: 172.5
</weight>
<weight id='mg_reweight_4'>set param_card yukawa 6 34.5 # orig: 172.5
</weight>
<weight id='mg_reweight_5'>set param_card yukawa 6 0.0001 # orig: 172.5
</weight>
<weight id='mg_reweight_6'>set param_card yukawa 6 -34.5 # orig: 172.5
</weight>
<weight id='mg_reweight_7'>set param_card yukawa 6 -69.0 # orig: 172.5
</weight>
<weight id='mg_reweight_8'>set param_card yukawa 6 -103.5 # orig: 172.5
</weight>
<weight id='mg_reweight_9'>set param_card yukawa 6 -138.0 # orig: 172.5
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<weight id='mg_reweight_10'>set param_card yukawa 6 -172.5 # orig: 172.5
</weight>
</weightgroup>
</initrwgt>
```

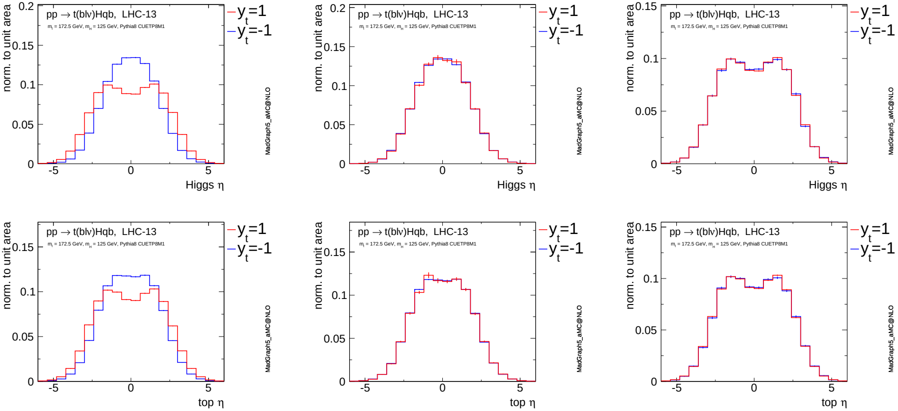
- Weights vector is put through until the final AODSIM file and readable in CMSSW
- Do not wonder: y_t parametrized in terms of the top mass value

Study performed on ...

- 300k events for both $y_t = +1$ and -1
- MadGraph5_aMC@NLO 2.2.1
- LO mode
- NNPDF3.0_nlo_nf4 (LO PDF not yet available at that time, but doesn't make a difference!)
- Fixed scale at 100 GeV (this will become dynamical in Run-II)
- Showered with Pythia8, CMS Tune CUETP8M1 (Run-II default)
- Reweighting in 9 steps between $+1 \leftrightarrow -1$
- Now looking at the most extrem cases of ± 1

Resulting distributions – I

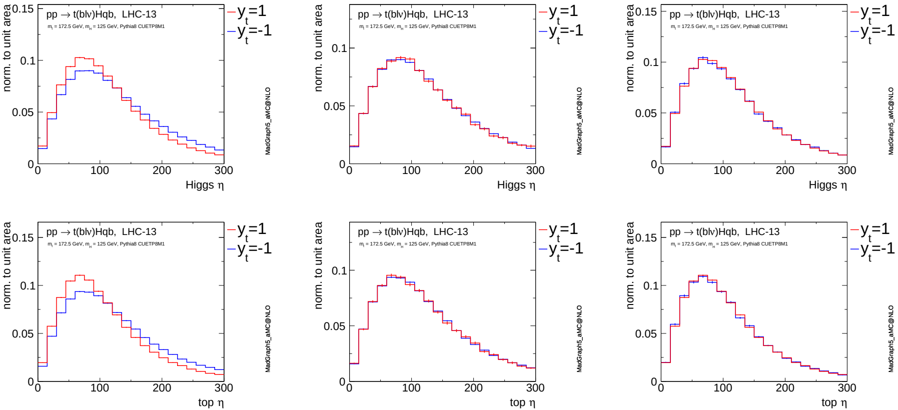
without reweighting | $y_t = +1 \rightarrow y_t = -1$ | $y_t = -1 \rightarrow y_t = +1$



- Error bars indicate statistical errors
- Even for most extreme cases, the reweighting gives reliable shape predictions!

Resulting distributions – II

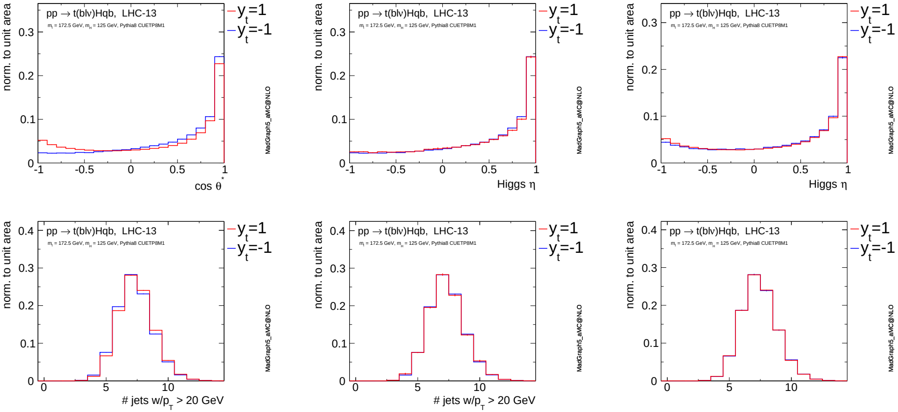
without reweighting | $y_t = +1 \rightarrow y_t = -1$ | $y_t = -1 \rightarrow y_t = +1$



- Error bars indicate statistical errors
- Even for most extreme cases, the reweighting gives reliable shape predictions!

Resulting distributions – III

without reweighting | $y_t = +1 \rightarrow y_t = -1$ | $y_t = -1 \rightarrow y_t = +1$



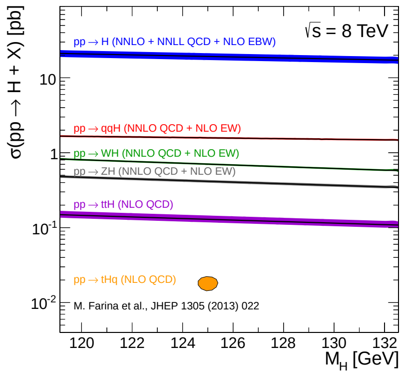
- Error bars indicate statistical errors
- In this case: $\cos\theta^*$ built from lepton and most forward jet with $p_T > 30\,\text{GeV}$

CMS strategy in Run-II

- Model tHq and tHW with MadGraph5_aMCatNLO
  - LO mode for Run-II startup
  - In the mid-term: switch to NLO
- Switch from Pythia6 to Pythia8
- Not only focus on $y_\mathrm{t} = -1$
  - Use Higgs characterization model
  - Scan in κ_f-κ_V plane
- Scale: $\mu = \sum p_\mathrm{T}(\mathrm{H,t,b})/6 \leftarrow$ new!
- Systematics:
  - Access Q^2 uncertainty via event weights in LHE_v2 format (same holds for PDF uncertainty)
  - Include parton shower uncertainty: e.g. Pythia8 vs. Herwig++

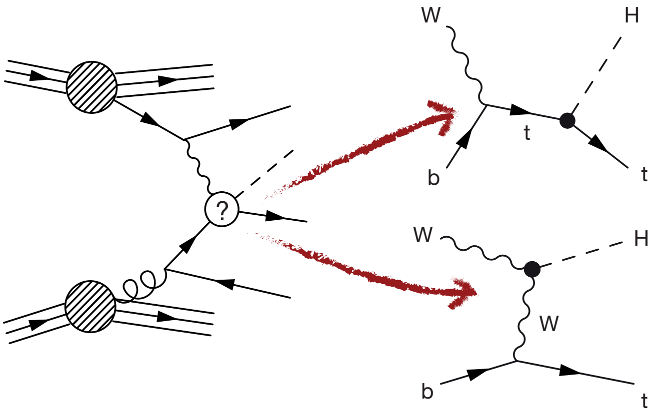
Introduction

- Search for associated production of single top quarks with a Higgs boson
- Very small production cross section



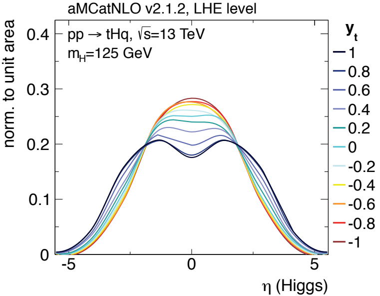
Why even bother searching?

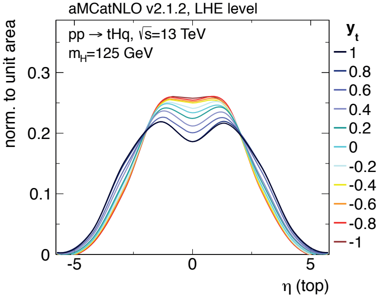
Interference in the *t*-channel

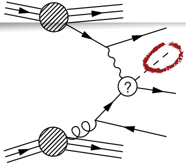


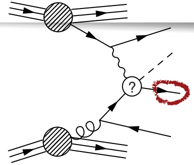
- Destructive interference for SM, constructive for flipped top-Yukawa coupling
- Flipped top-Yukawa coupling increases production rate by a factor ~ 13

Effect of y_t on η distributions (LHE level)

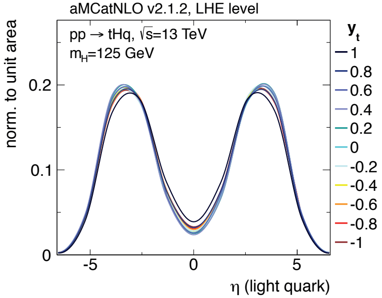


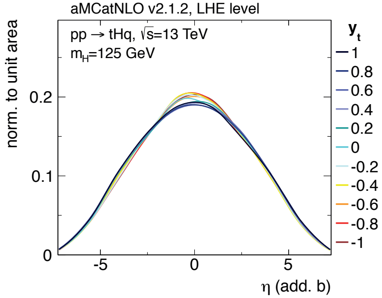


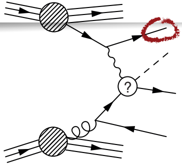


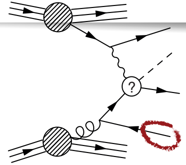


Effect of y_t on η distributions (LHE level)

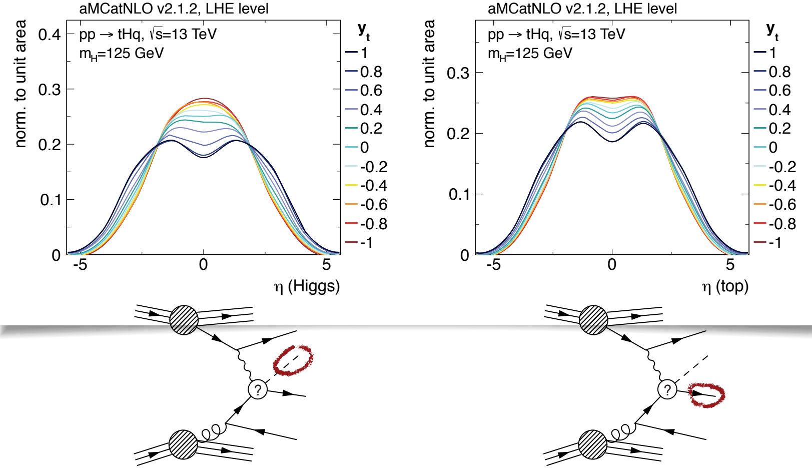




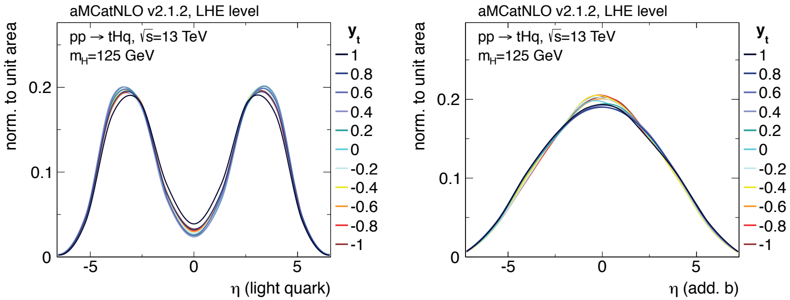




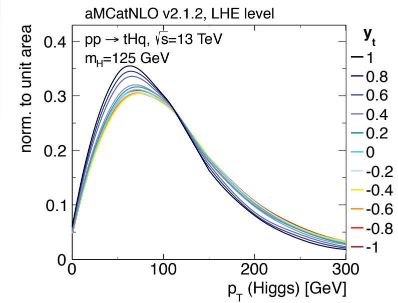
Effect of y_t on η distributions (LHE level)

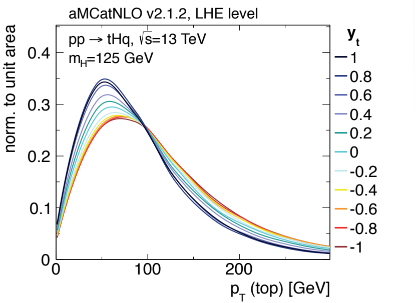


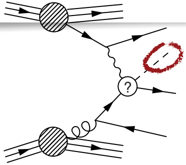
Effect of y_t on η distributions (LHE level)

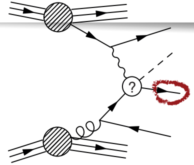


Effect of y_t on p_T distributions (LHE level)

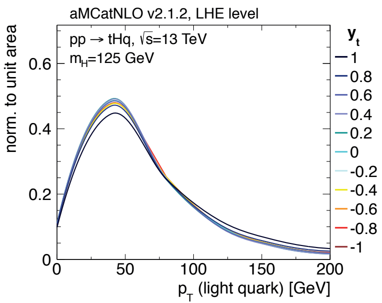


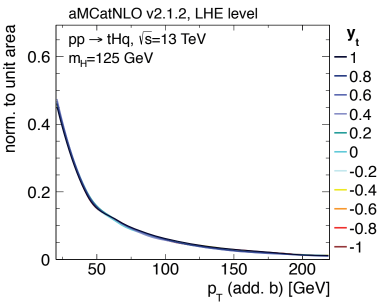


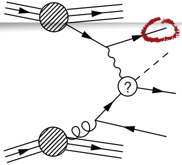


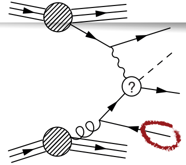


Effect of y_t on p_T distributions (LHE level)

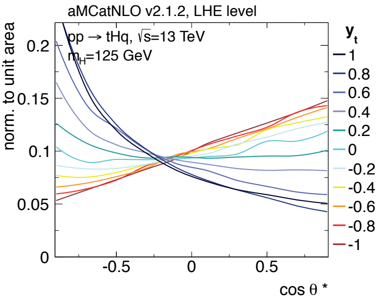


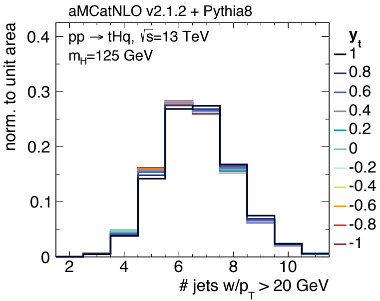


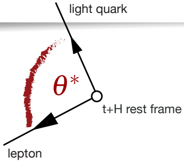


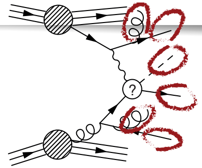


Effect of y_t on other distributions

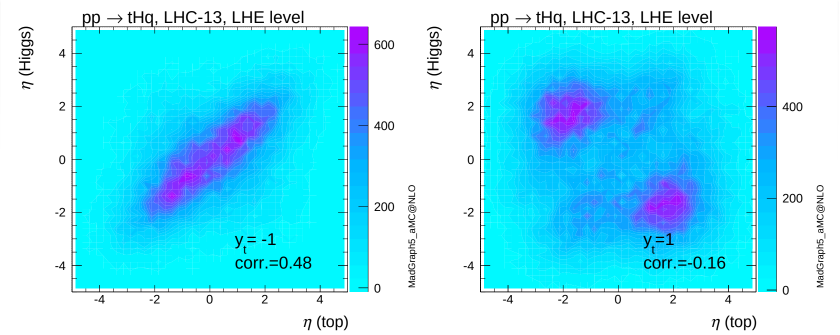








Effect of y_t on other distributions



$y_t = -1$ $y_t = +1$