Report from the ttH/tH Subgroup

Preparatory Meeting of the
LHC Higgs Cross Section Working Group
7 July 2016

Stefan Guindon,
Chris Neu,
Stefano Pozzorini,
Laura Reina

Recap: ttH/tH Section of YR4

- Significant amount of work went into the results of the ttH/tH section of YR4
  - 80+ pages
  - 40+ authors
- Focus was on:
  - state-of-the-art calculations of ttH and tH signal xsecs, including systematic uncertainties
  - SOTA xsecs for particularly troublesome backgrounds
  - comparison of various fixed-order QCD+PS event generators
- This work is essential for the current ttH and tH campaigns at the LHC

Thorough review of the many contributions in
Stefano Pozzorini's talk
from the January General Meeting.

A few highlights….
impossible to recap everything

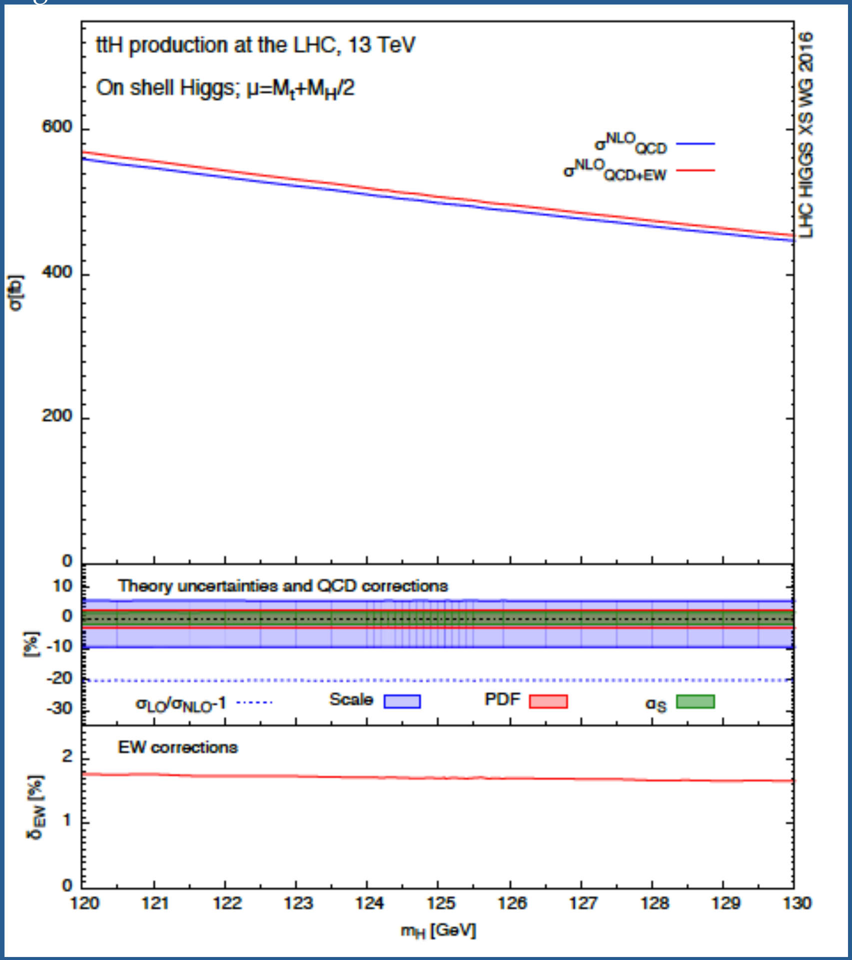
State of the Art Signal Modeling – ttH

- ttH signal xsec calculated at NLO in both QCD and EW
- In an inclusive sense, NLO EW effect small but:
  - EW corrections play an important role and ruin the simple view of the xsec being proportional to y_t^2
  - Impact of EW corrections more important in boosted regime – which experiments seek to use to help suppress backgrounds
- Recommendation, 13 TeV, M_H=125:

$$\sigma(ttH) = 507.2\ ^{+5.8\%}_{-9.2\%}\ (\text{scale})\ \pm 3.6\%\ (\text{pdf},\alpha_s)\ \text{fb}$$

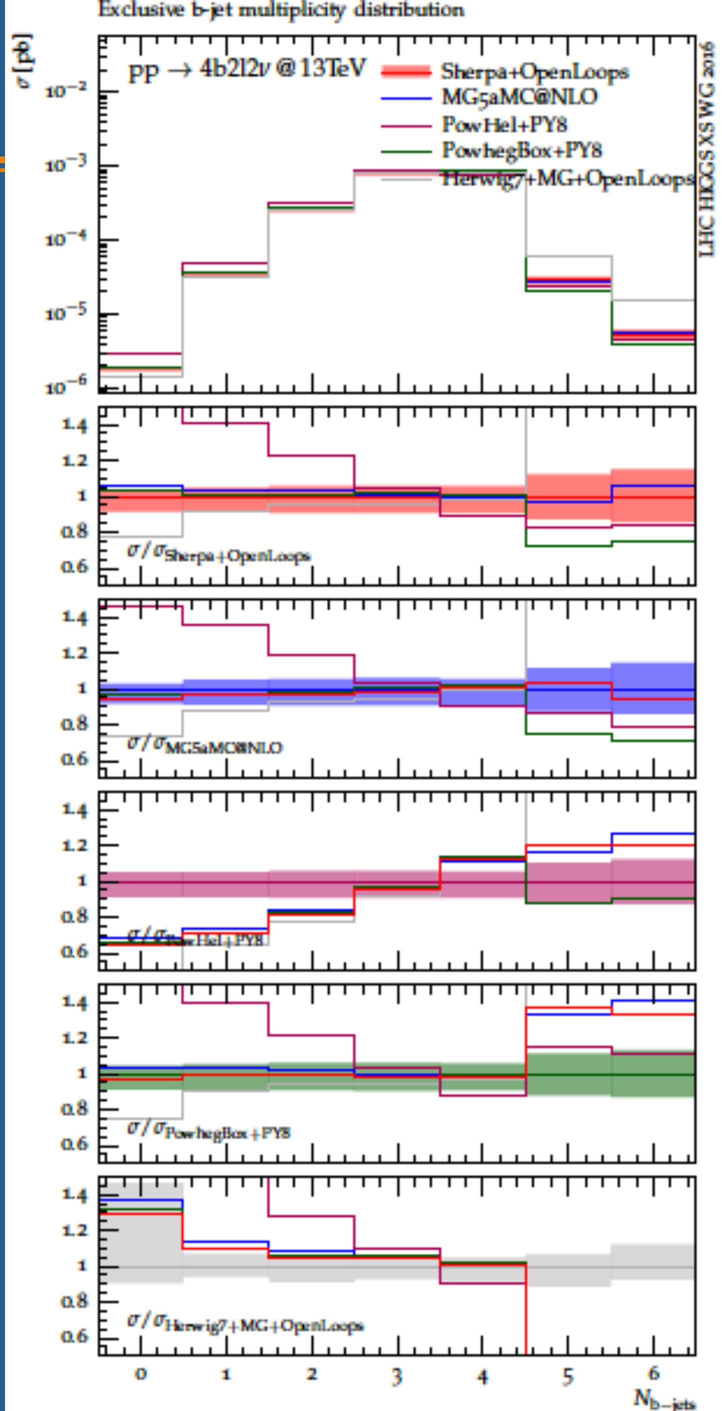
  - $K_{QCD} = (\sigma(NLO)/\sigma(LO))_{QCD} = 1.25$
  - $\sigma(NLO)_{EW} / \sigma(NLO)_{QCD} = 1.7\%$
- Details of the conditions under which the calculation was executed can be found in YR4

Fig 6.1



SOTA ttH, cont'd

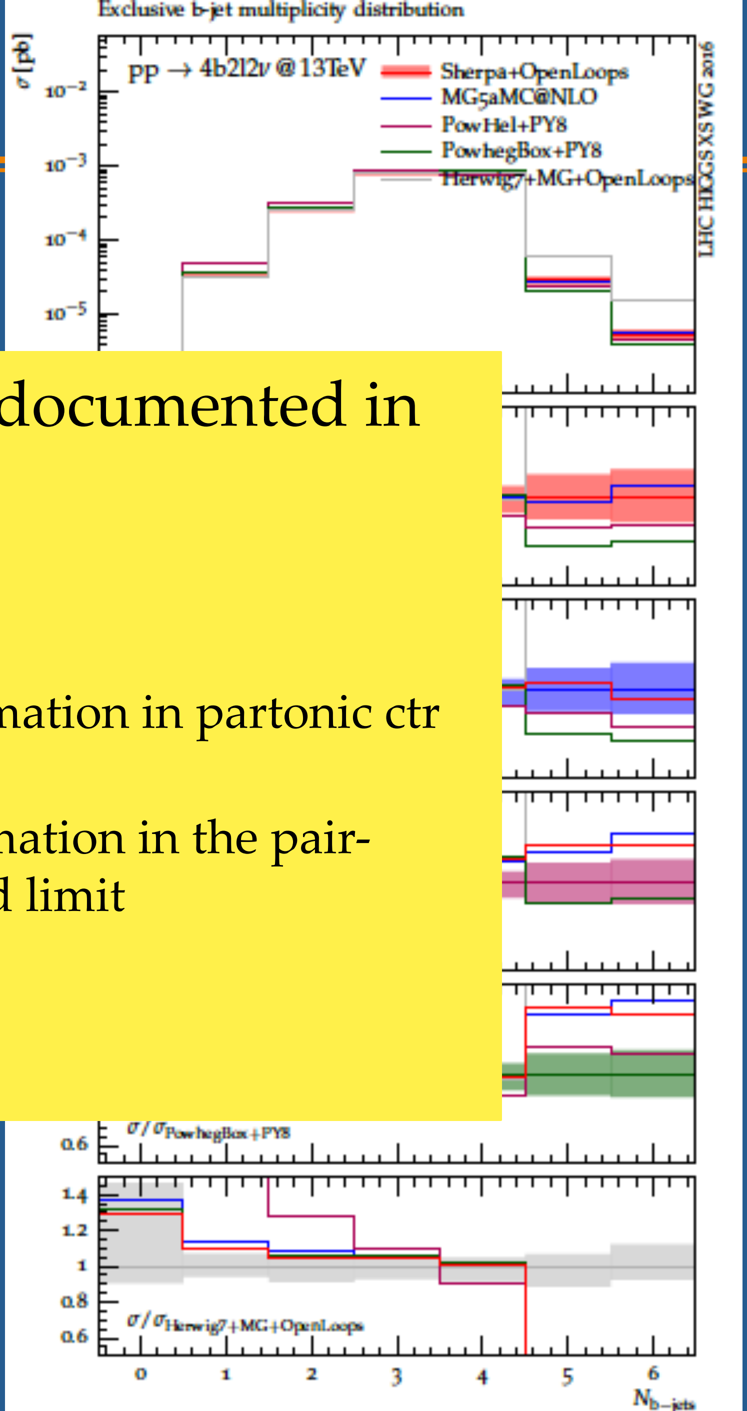
- Thorough comparison of NLO QCD + PS event generators for ttH
- Look at the mutual compatibility of the available tools
  - Identify and understand differences
  - Improve generally all tools looking at the these processes
- Compare:
  - S-MC@NLO using OpenLoops 1.2.3 + Sherpa 2.2.0,
  - MadGraph5_aMC@NLO 2.3.2 + Pythia8 2.1.0,
  - PowHel + Pythia8 2.1.0,
  - Powheg Box + Pythia8 2.1.0,
  - Herwig7 using OpenLoops 1.2.4+ MadGraph5_aMC@NLO 2.3.0+ Herwig7.
- Examine two cases
  - On-shell case (no t,tbar, or H decays)
  - With decays: ttH → eνbμνbbb
- General good agreement, save for $N_{b\text{-jet}}$ dist for POWHEL + P8
  - artifact of massless b convention in top decays v. massive b in PS



SOTA ttH, cont'd

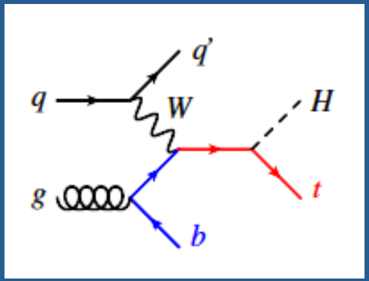
- Thorough comparison of NLO QCD + PS event generators for ttH
- Loo
  of th
  - I
  - I
    t
- Con
  - S-MC@
  - MADGR
  - POWHE
  - POWHE
  - HERWIG
- Exa
  - C
  - With decays: ttH → eνbμνbbb
- General good agreement, save for N $_{b\text{-jet}}$ dist for POWHEL + P8
  - artifact of massless b convention in top decays v. massive b in PS

- Other important ttH studies documented in YR4 as well:
  - off-shell effects in ttH
  - ttH beyond NLO
    - NLO + NLL soft-gluon resummation in partonic ctr of mass limit
    - aNNLO via soft-gluon resummation in the pair-invariant mass (PIM) threshold limit

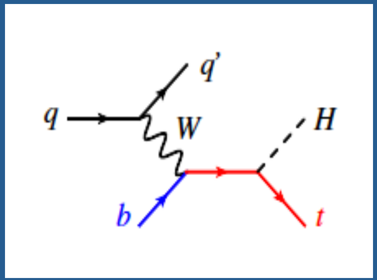


State of the Art Signal Modeling – tH

t-channel:



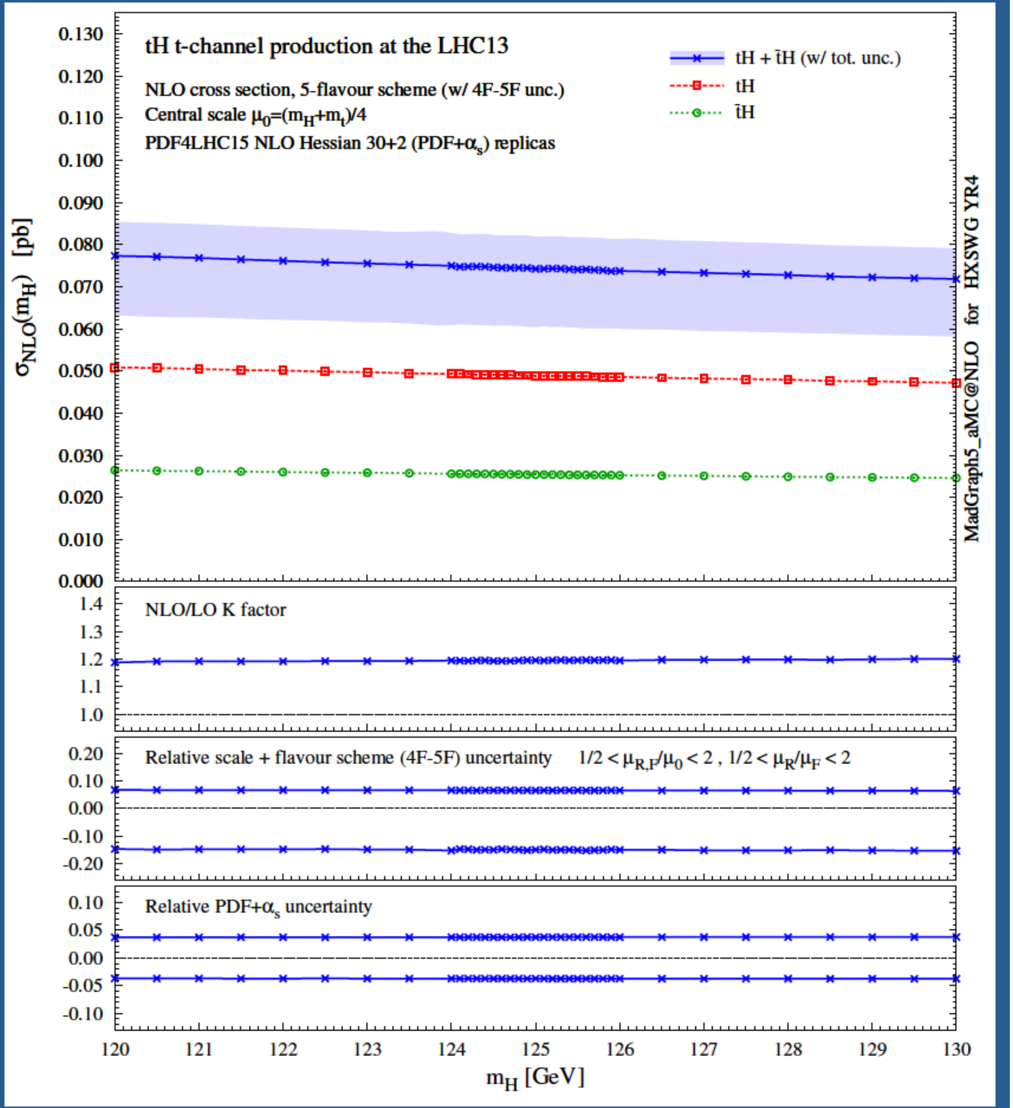
v.



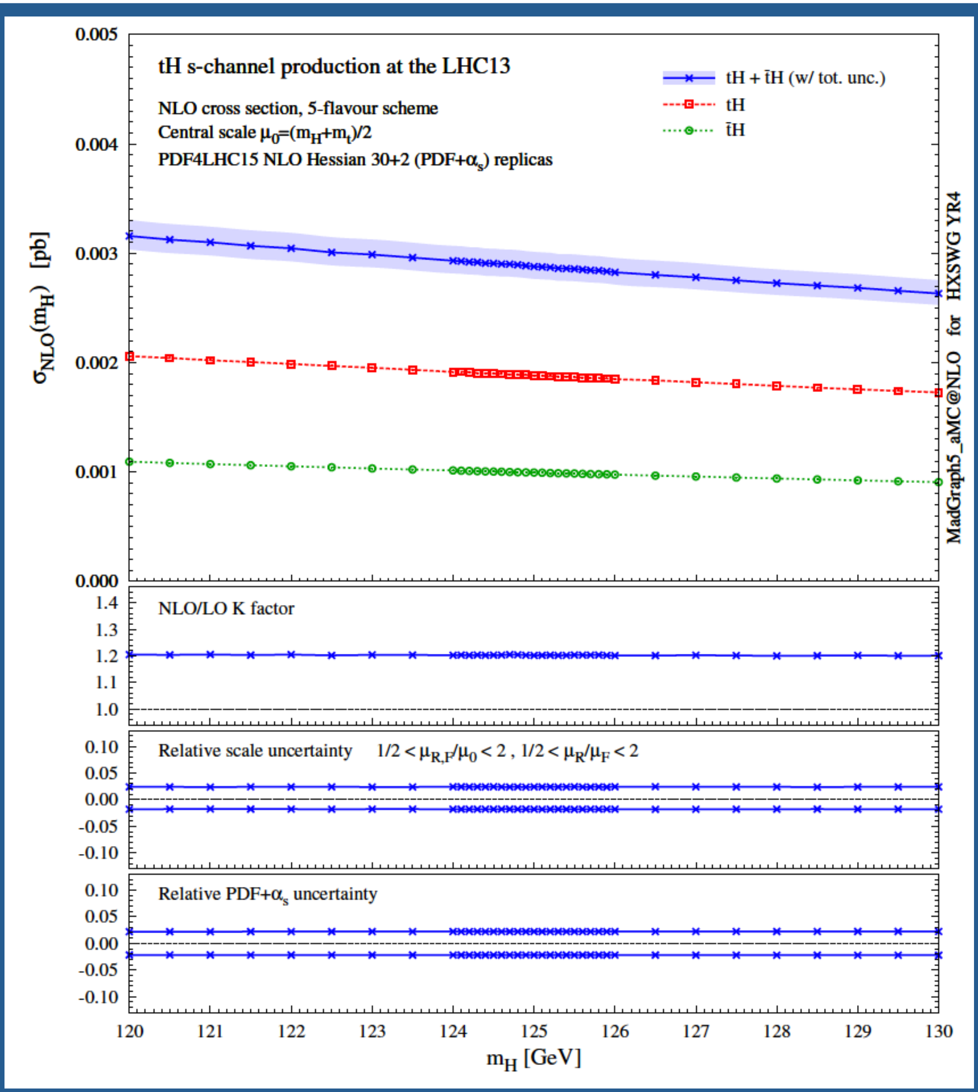
- Initiated by b quarks, so need to consider 4FS v. 5FS
- Kinematics similar, choose 5FS as default and express choice as flavor-scheme-choice syst
- Recommendation, 13 TeV, M_H=125:

$$\sigma(tH)^{t\text{-}ch}_{TOT} = 74.25\ ^{+6.5\%}_{-14.9\%}\ (\text{scale,FS})\ \pm 3.7\%(\text{pdf},\alpha_S)\ \text{fb}$$

- See YR4 for details



State of the Art Signal Modeling – tH



s-channel:

– No complications from flavor numbering scheme

$\sigma(tH)^{s\text{-}ch}_{TOT} = 2.879\ ^{+2.4\%}_{-1.8\%}$ (scale) $\pm 2.2\%$(pdf,α_S) fb

tW-channel:

– large interference with ttH

– NLO simulation complicated

– not treated in YR4 (more later)

State of the Art Background Modeling – ttV, ttVV’

- tt+V(V) is an important background, esp for ttH,H→WW signatures
- YR4 contains NLO QCD+EW predictions for the relevant ttVand ttVV processes:

Process	$\sqrt{s}$	$\sigma^{\rm NLO}_{\rm QCD}$	$\sigma^{\rm NLO}_{\rm QCD+EW}$	$K_{\rm QCD}$	$\delta_{\rm EW}[\%]$	Scale[%]		PDF[%]	
$t\bar{t}Z$	13	841.3(1.6)	839.3(1.6)	1.39	−0.2	+9.6%	− 11.3%	+2.8%	− 2.8%
$t\bar{t}W^+$	13	412.0(0.32)	397.6(0.32)	1.49	−3.5	+12.7%	− 11.4%	+2.0%	− 2.0%
$t\bar{t}W^-$	13	208.6(0.16)	203.2(0.16)	1.51	−2.6	+13.3%	− 11.7%	+2.1%	− 2.1%

13 TeV σ [ab]	$t\bar{t}W^+Z$	$t\bar{t}W^-Z$	$t\bar{t}ZZ$
NLO QCD	$2705(3)^{+9.9\%}_{-10.6\%}{}^{+2.7\%}_{-2.7\%}$	$1179(2)^{+11.2\%}_{-11.2\%}{}^{+3.7\%}_{-3.7\%}$	$1982(2)^{+5.2\%}_{-9.0\%}{}^{+2.6\%}_{-2.6\%}$
LO	$1982(2)^{+28.4\%}_{-20.6\%}{}^{+3.3\%}_{-3.3\%}$	$839.4(6)^{+28.2\%}_{-20.5\%}{}^{+4.2\%}_{-4.2\%}$	$1611(1)^{+31.4\%}_{-22.1\%}{}^{+2.7\%}_{-2.7\%}$
K-factor	1.36	1.40	1.23
13 TeV σ [ab]	**$t\bar{t}W^+H$**	**$t\bar{t}W^-H$**	**$t\bar{t}ZH$**
NLO QCD	$1089(1)^{+1.8\%}_{-5.9\%}{}^{+2.6\%}_{-2.6\%}$	$493.0(5)^{+2.6\%}_{-6.4\%}{}^{+3.4\%}_{-3.4\%}$	$1535(2)^{+1.9\%}_{-6.8\%}{}^{+3.0\%}_{-3.0\%}$
LO	$997.0(9)^{+26.9\%}_{-19.8\%}{}^{+3.0\%}_{-3.0\%}$	$440.0(4)^{+26.9\%}_{-19.8\%}{}^{+3.8\%}_{-3.8\%}$	$1391(1)^{+32.2\%}_{-22.6\%}{}^{+2.8\%}_{-2.8\%}$
K-factor	1.09	1.12	1.10
13 TeV σ [ab]	**$t\bar{t}W^+W^-$**	**$t\bar{t}W^+W^-$ (4f)**	**$t\bar{t}HH$**
NLO QCD	–	$11500(10)^{+8.1\%}_{-10.9\%}{}^{+3.0\%}_{-3.0\%}$	$756.5(7)^{+1.1\%}_{-4.4\%}{}^{+3.3\%}_{-3.3\%}$
LO	$8380(5)^{+33.2\%}_{-23.1\%}{}^{+3.0\%}_{-3.0\%}$	$8357(5)^{+33.3\%}_{-23.1\%}{}^{+3.0\%}_{-3.0\%}$	$765.4(5)^{+31.8\%}_{-22.4\%}{}^{+2.9\%}_{-2.9\%}$
K-factor	–	1.38	0.99

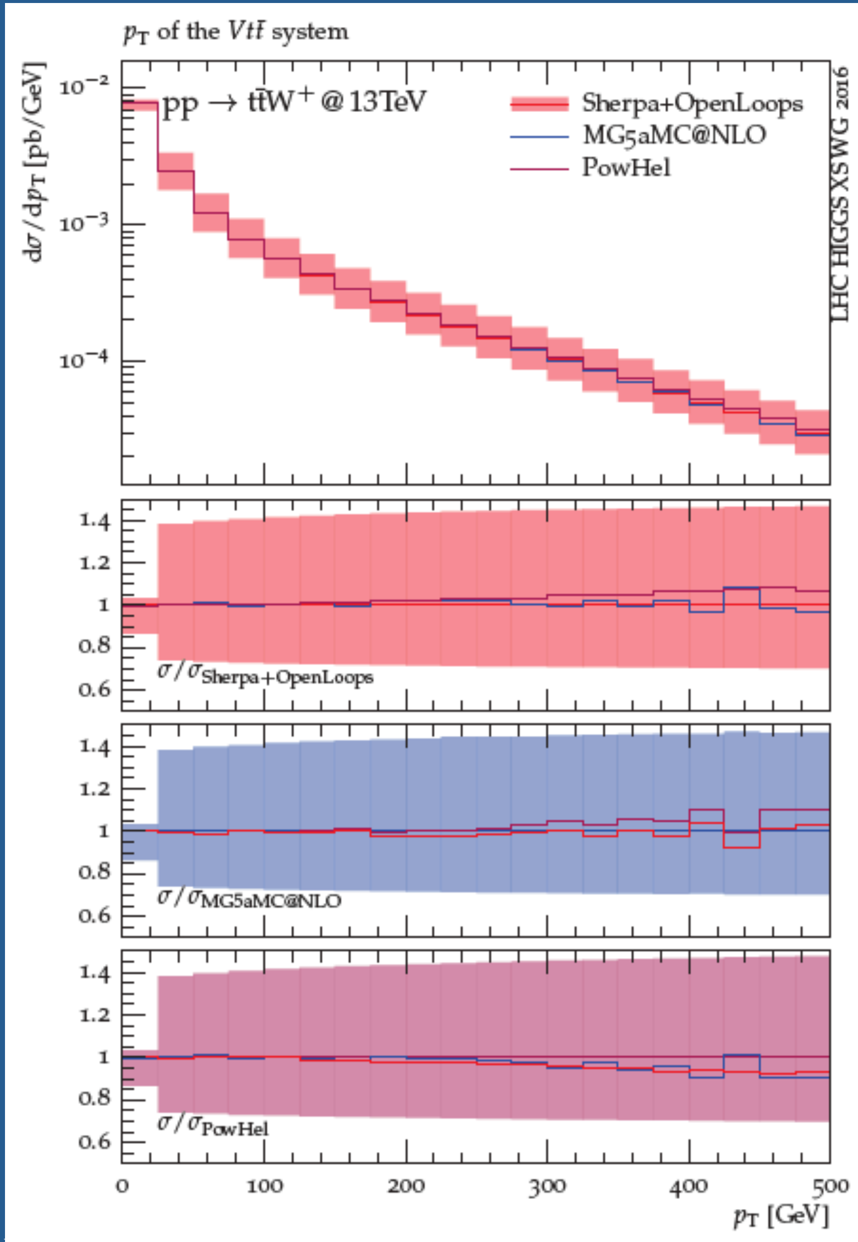
State of the Art Background Modeling – ttV, ttVV’

- Similar as in the study of signal ttH production, a comparison of NLO QCD + PS event generators for ttV was performed as well

- Comparing:
  - SHERPA 2.2.0 + OPENLOOPS 1.2.3,
  - MADGRAPH5_AMC@NLO 2.3.2,
  - POWHEL.

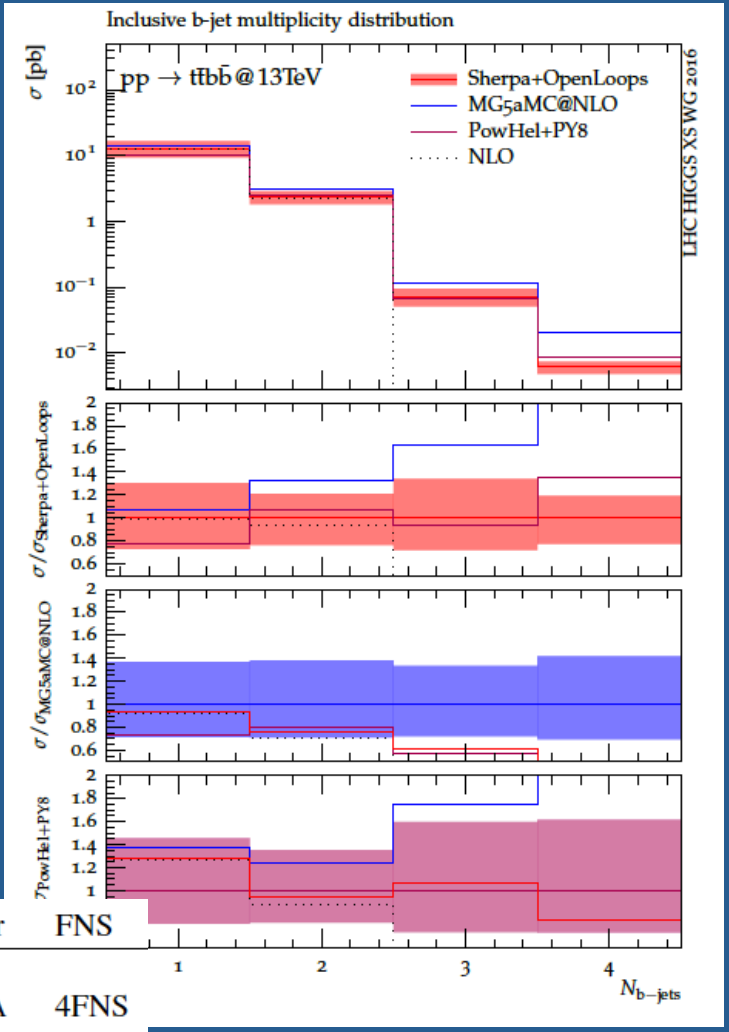
- As in other such studies, great care was taken to define the conditions under which the comparisons would be done

- Specifics of the conditions are given in Section 6.7 of YR4



State of the Art Background Modeling – tt+bb

- tt+HF is the biggest obstacle for ttH observation at the LHC
  - Large irreducible bkgd to ttH,Hbb
- Modeling challenges
  - Complicated process
  - Large higher order contributions, hence NLO is essential:
    - Scale uncertainty improves from 70-80% at LO to 20-30% at NLO
  - 4FS v. 5FS
- Several NLO+PS simulations of tt+bb available



Tools	Matching method	Shower	FNS
SHERPA 2.2.1+OPENLOOPS 1.2.3	S-MC@NLO	SHERPA	4FNS
MADGRAPH5_AMC@NLO 2.3.2+PYTHIA8 2.1.0	MC@NLO	PYTHIA8	4FNS
POWHEL+PYTHIA8 2.1.0	POWHEG	PYTHIA8	5FNS

More on these critical studies in a few slides

Next Phase of Our Work

- ttH/tHq is a bit unique compared to other WG1 subgroups:
  - ttH production has not yet been observed

- So what?
  - Direct measurement of top-Higgs coupling is essential for full characterization of the Higgs boson
    - Best avenue is through observation of ttH production
      - Need to do everything we can to enable the observation of this process
      - A single-channel observation of ttH will need corroboration in other decay modes
        - » ttH,H→bb and ttH,multileptons and ttH,H→$\tau\tau$ all important
        - » ttH,H→$\gamma\gamma$ essential as well – especially for precision studies post-measurement

  - Window to new physics:
    - Non-standard top-Higgs coupling could point to BSM contributions to ggF Higgs production and/or H→$\gamma\gamma$ decay
    - tHq production has sensitivity to negative Yukawa coupling – until this possibility is excluded, need to consider this possibility

Next Phase of Our Work

- Several needs still exist
- Followup studies in mind to be undertaken building on the contents of YR4:
  - PS effects in ttH production
  - NLO ttH+jets
  - study reliability of aNNLO for ttH based on NNLL-SCET resummation
  - t,W,H decays in tH simulations
  - ttV+multijet merging
  - off-shell ttZ/γ^* , $Z/\gamma^* \rightarrow ll$
  - others…

Taken from Stefano's talk in January!

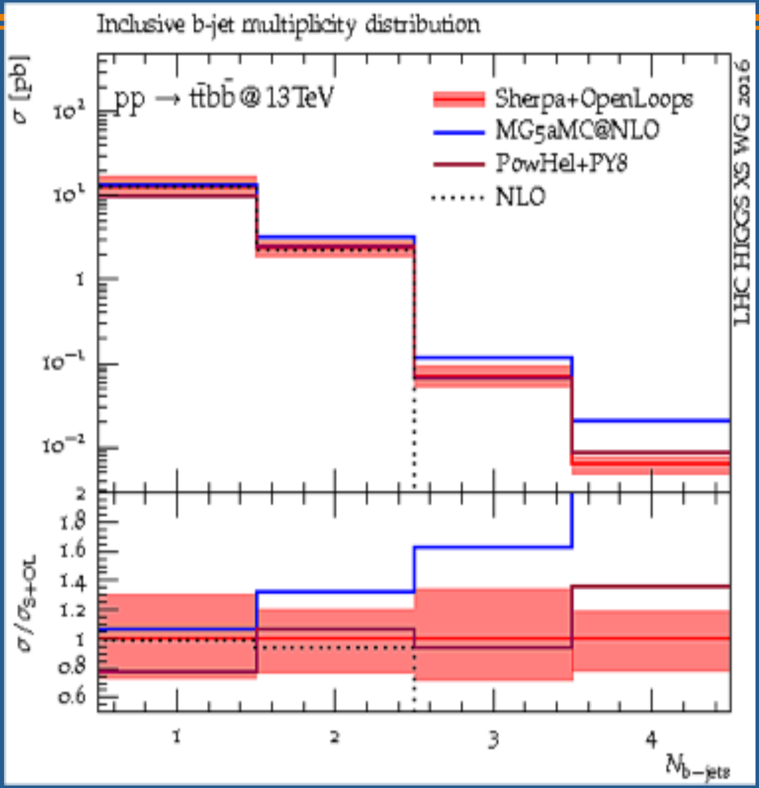
Next Phase of Our Work

- Several needs still exist:

1. **Finalize tt+HF background recommendations for ttH,H→bb**
    - Namely, define recommendation for tt+b-jets treatment to be used at both experiments, including systematic uncertainties. Needs to go beyond YR4 studies to include validation from experimental observations.
    - Understand 4FS tt+bb mismatch from YR4 (see next slide)

NLO tt+bb in 4FS

- **Comparisons of two 4FS tt+bb NLO generators**
  - MG5_aMC@NLO and Sherpa+OpenLoops
  - Same settings are used for the generation of events
- Truth level comparison shows:
  - ~ same inclusive tt+bb cross-section as SherpaOL
  - Larger XS in nb >= 2 regions
- Systematics from scale variations
  - mainly renormalisation, on aMC@NLO+Py8 are large: +50% / -30%



Counting non-top-decay b-jets w/ p_T >25, |η|<2.5:

Selection	Tool	σ_{NLO} [fb]	σ_{NLO+PS} [fb]	$\sigma_{NLO+PS}/\sigma_{NLO}$
$n_b \geq 1$	Sherpa+OpenLoops	$12820^{+35\%}_{-28\%}$	$12939^{+30\%}_{-27\%}$	1.01
	MadGraph5_aMC@NLO		$13833^{+37\%}_{-29\%}$	1.08
	PowHel		$10073^{+45\%}_{-29\%}$	0.79
$n_b \geq 2$	Sherpa+OpenLoops	$2268^{+30\%}_{-27\%}$	$2413^{+21\%}_{-24\%}$	1.06
	MadGraph5_aMC@NLO		$3192^{+38\%}_{-29\%}$	1.41
	PowHel		$2570^{+35\%}_{-28\%}$	1.13

parton shower	on
hadronisation	off
UE	off
top decays	off

Current work: Checks of samples including top decays to compare ttbar kinematics and determine if variations are possibly larger in analysis phase-space.

Next Phase of Our Work

- Several needs still exist:

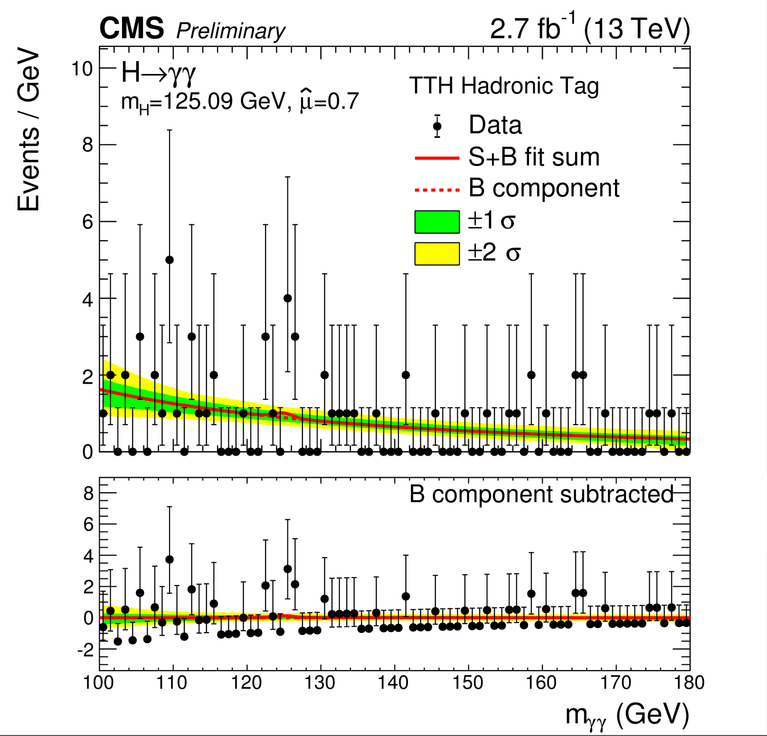
1. **Finalize tt+HF background recommendations for ttH,H→bb**
    - Namely, define recommendation for tt+b-jets treatment to be used at both experiments, including systematic uncertainties. Needs to go beyond YR4 studies to include validation from experimental observations.
    - Understand 4FS tt+bb mismatch from YR4 (see next slide)
    - Define matching procedure for NLO 4FS tt+bb with NLO 5FS tt+inclusive jets; experimental studies to validate such a procedure.
    - No attention yet paid to tt+charm-jets despite the large contribution the process plays to signal-rich regimes in the ttH,H→bb analysis

Next Phase of Our Work, cont'd

2. tt+γγ at (N)NLO:

- ttH,H→γγ signal is clear, yet very rare
  - Searches for ttH,H→γγ currently rely on data-driven background models
  - Parametrized into signal region based on a falling exponential model
- But ttH,H→γγ will provide <u>the most-clear and satisfying signature:</u>
  - a diphoton bump at 125
  - in events with a well-identified ttbar system with b-tagged jets, leptons, MET, reconstructed top candidates

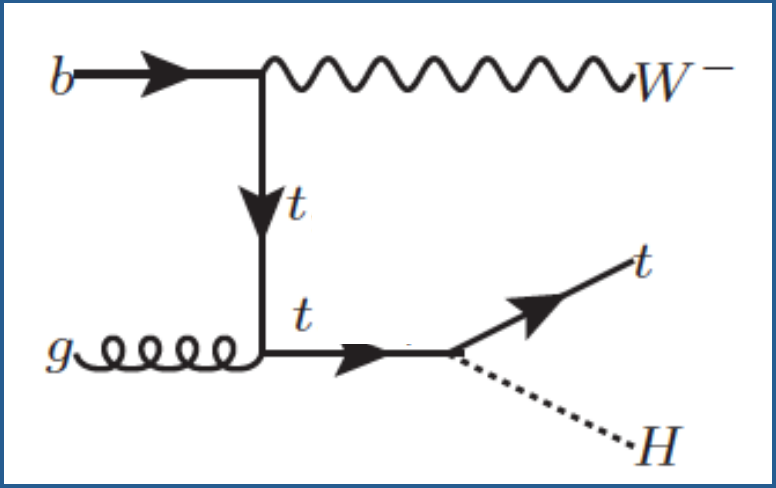
CMS-PAS-HIG-15-005



- Hence, ttH,H→γγ will be a very important process for precision differential ttH production studies
- Ideal to have high-precision simulated samples of tt+γγ as part of such characterization studies

Next Phase of Our Work, cont'd

http://iopscience.iop.org/article/10.1209/0295-5075/110/21001/pdf



3. Additional signal: tHW
   - Not much attention paid to this SM process
   - Enhancement predicted in some BSM models (eg, LHT model as described here)
   - Would like to have high-precision cross section predictions for this process