# $t\bar{t}H$ and $tH$ production at the LHC: theory overview

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Linear Collider Workshop 2015 (LCWS 15)

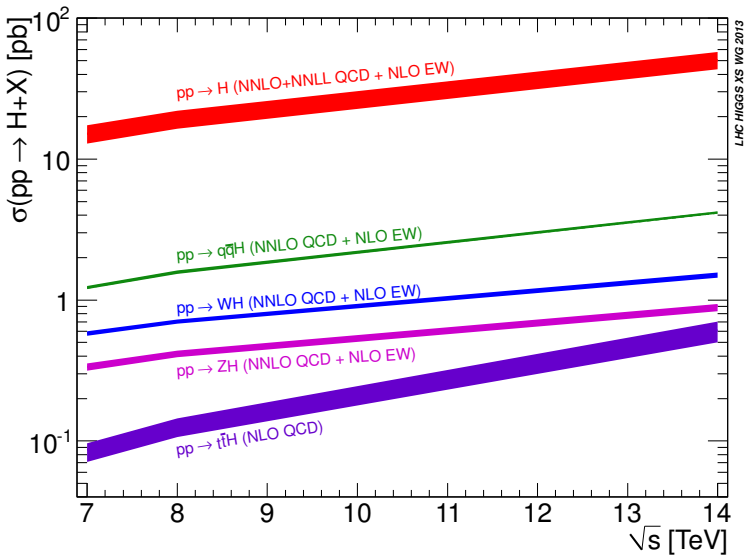
Whistler, CA - November, 3rd 2015

# Outline

- Motivation: $t\bar{t}H$ and $tH$ crucial for Higgs Physics at Run II.
- Difficult channels: Run I results are encouraging and show how theoretical accuracy could become a limitation in Run II.
- Dedicated theoretical effort now converging in providing more accurate theoretical results for both signal and background.
- Review of recent theoretical progress and ongoing studies of both signal and background.
- Outlook and conclusions.

# Motivations

Small cross section that grows substantially from 7(8) to 14 TeV.
The last main production mode still to be observed!




Ex.: $M_H = 125$ GeV (NLO QCD):

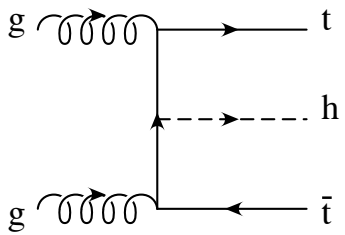
$\rightarrow$ $\sqrt{s} = 7$ TeV: $\sigma(t\bar{t}H) \simeq 86$ fb

$\rightarrow$ $\sqrt{s} = 8$ TeV: $\sigma(t\bar{t}H) \simeq 130$ fb

$\rightarrow$ $\sqrt{s} = 14$ TeV: $\sigma(t\bar{t}H) \simeq 611$ fb

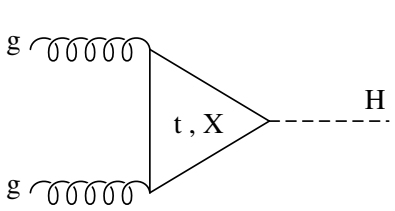
In the era of Higgs-boson precision physics: $t\bar{t}H$ and $tH$ give direct access to the top-Higgs Yukawa coupling: crucial to disentangle new physics from measurements of the $ggH$ and $\gamma\gamma H$ couplings.

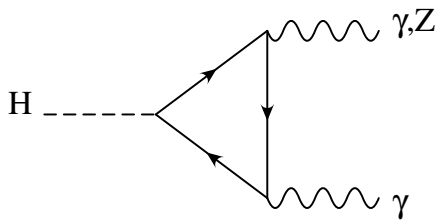
Namely:

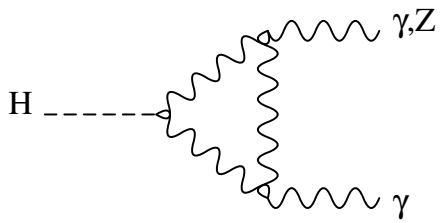



$$\longrightarrow \quad \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

versus

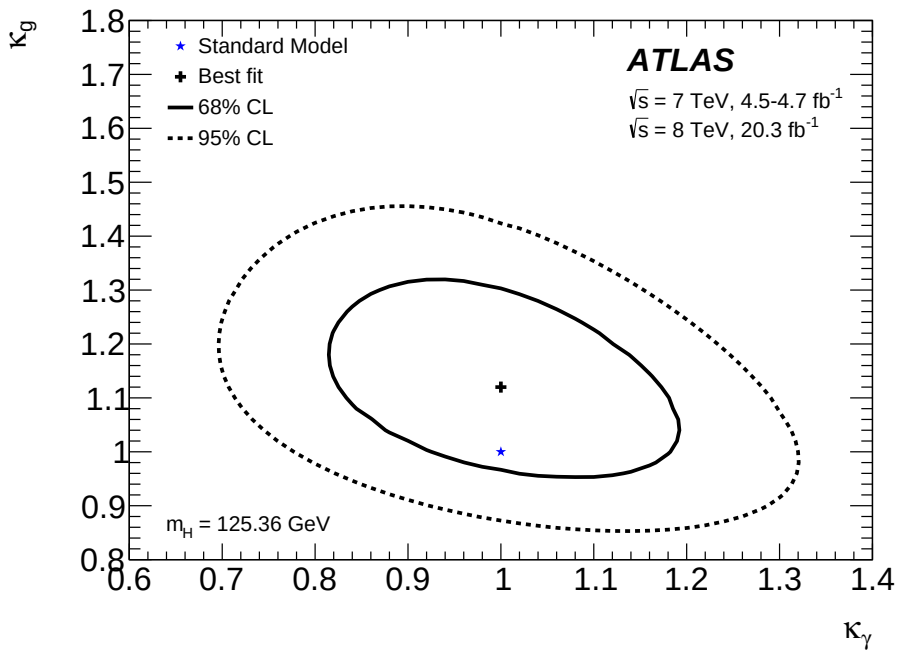


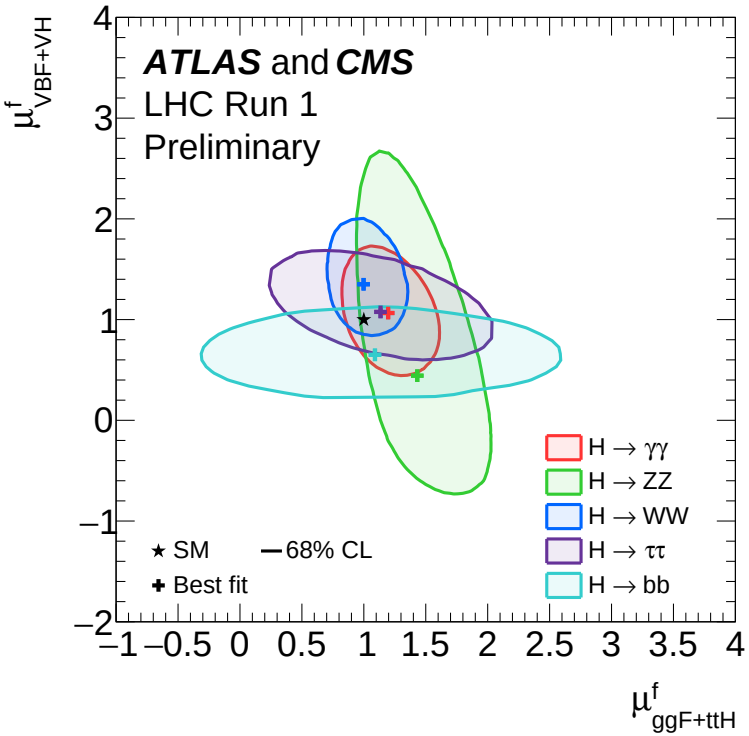




$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \kappa_g^2(\kappa_t, \kappa_b, m_H, X)$$

$$\frac{\Gamma_{\gamma\gamma H}}{\Gamma^{SM}_{\gamma\gamma H}} = \kappa_\gamma^2(\kappa_t, \kappa_b, \kappa_W, m_H, X)$$




See studies in:

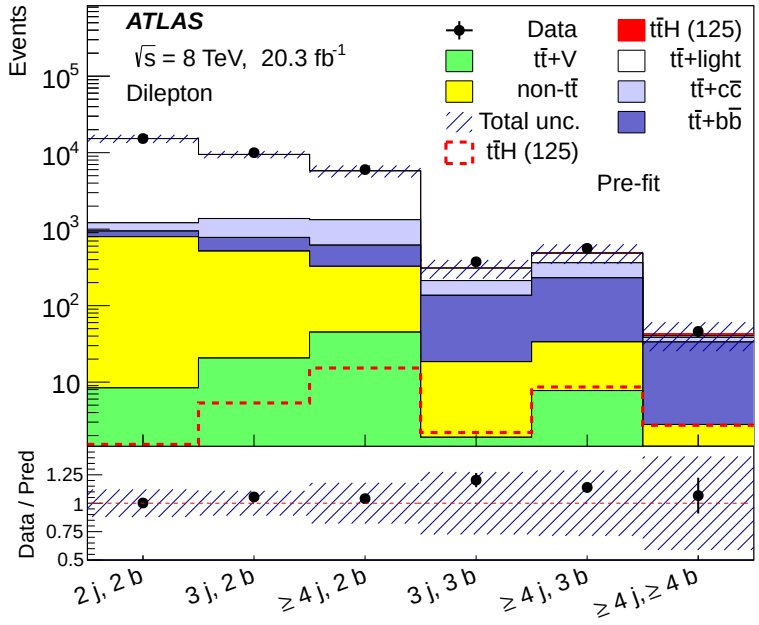
ATLAS-CONF-2015-144, and arXiv:1507.04548

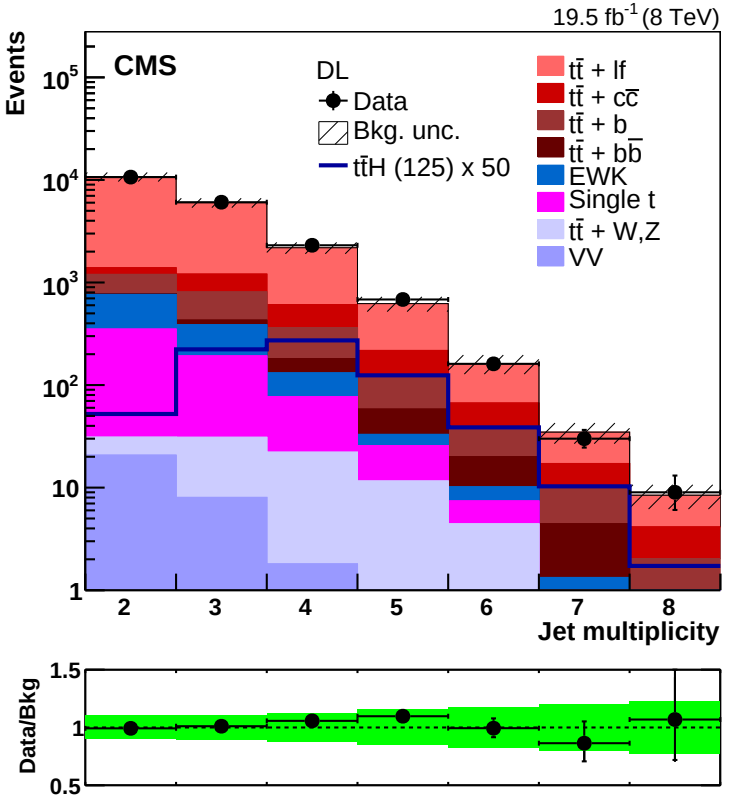
CMS-PAS-HIG-15-002, and CMS-PAS-HIG-14-009

Notice:

- hard to constrain $\kappa_t$ from $(\kappa_g, \kappa_\gamma)$ fit, direct $\kappa_t$ measurement is crucial
- sign of $\kappa_t$ cannot come from $t\bar{t}H \longrightarrow$ need $pp \to Ht + q$ production
- expected experimental precision on $\kappa_t$: 10-15%: need same or better level of theoretical accuracy: not trivial for these modes!

Small signal on the shoulder of a very large background ...




requires very accurate theoretical modeling of both signal AND background, in particular $t\bar{t}+b$ jets, $t\bar{t}$+light jets, $t\bar{t}V$.

# Main theoretical issues and priorities

- Accurate prediction of total and differential cross sections for both signal and background
  - ▷ NLO QCD and EW corrections
  - ▷ resummation of kinematically enhanced corrections
  - ▷ off-shell final states, account for spin correlations in decay products
  - ▷ account for signal-background interference
- Improved systematic description of multijet processes
  - ▷ match with parton-shower (PS) generators at NLO QCD
  - ▷ NLO jet-merging (ex.: $t\bar{t}$, $t\bar{t}+j$, $t\bar{t}+2j$, etc.)
- systematic assessment of theoretical uncertainty/accuracy
  - ▷ dependence on perturbative scales ($\mu_R$, $\mu_F$)
  - ▷ dependence on other scales (showering scale, merging scale, ...)
  - ▷ treatment of $b$-jet processes (ex: $t\bar{t}b\bar{b}$, 4F vs 5F, $b$ jets from hard process vs $b$ jets from PS, ...)

# Signal: theoretical progress

- $\underline{t\bar{t}H}$
  - → NLO QCD corrections
    - Beenakker et al. hep-ph/0107081 & hep-ph/0211352
    - Dawson et al. hep-ph/0211438 & hep-ph/0305087
  - → Matching to PS
    - aMC@NLO: Frederix et al., arXiv:1104.5613
    - PowHel: Garzelli et al., arXiv:1108.0387
    - Powheg Box: Hartanto et al., arXiv:1501.04498
  - → Off-shell effects: NLO QCD corrections to $b\bar{b}l^+l^-\nu\bar{\nu}H$
    - Denner et al., arXiv:1506.07448
  - → EW corrections
    - Frixione et al.: arXiv:1407.0823 & arXiv:1504.03447
    - Zhang et al.: arXiv:1407.1110
  - → Soft gluon resummation
    - Kulesza et al.: arXiv:1509.02780
    - Broggio et al.:arXiv:1510.01914

- $\underline{tH}$
  - → NLO QCD corrections
    - Farina et al.: (5FS) arXiv:1211.3737
    - Campbell et al.: (5FS) 1302.3856
  - → Matching to PS,
    - Demartin et al (4FS and 5FS) arXiv:1504.00611

# $t\bar{t}H$: NLO QCD corrections to $pp \to t\bar{t}H$

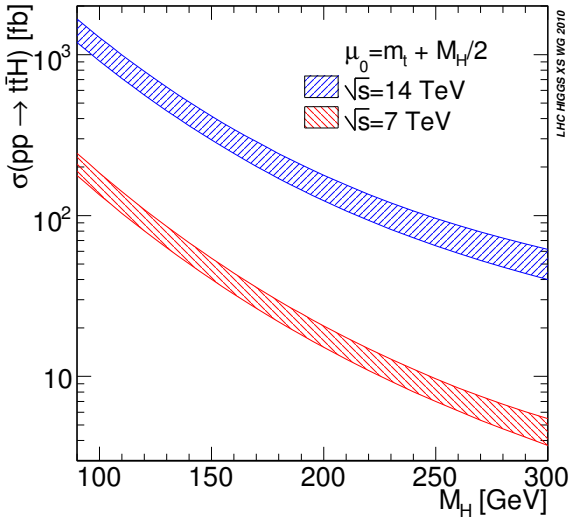
[Beenakker et al., arXiv:hep-ph/0107081, arXiv:hep-ph/0211352]

[Dawson et al., arXiv:hep-ph/0107101, arXiv:hep-ph/0211438]

used to estimate the theoretical uncertainties currently used in Higgs searches

↪ Higgs Cross Section Working Group (HXSWG-$t\bar{t}H$)

(First Yellow Report, arXiv:1101.059)




$m_H \simeq 125$ GeV, $\sqrt{s} = 14$ TeV

$\delta\sigma^{NLO}|_{scale}(\%) \simeq [+5.9, -3.3]$

$\delta\sigma^{NLO}|_{PDF+\alpha_s} \simeq \pm 8.9$

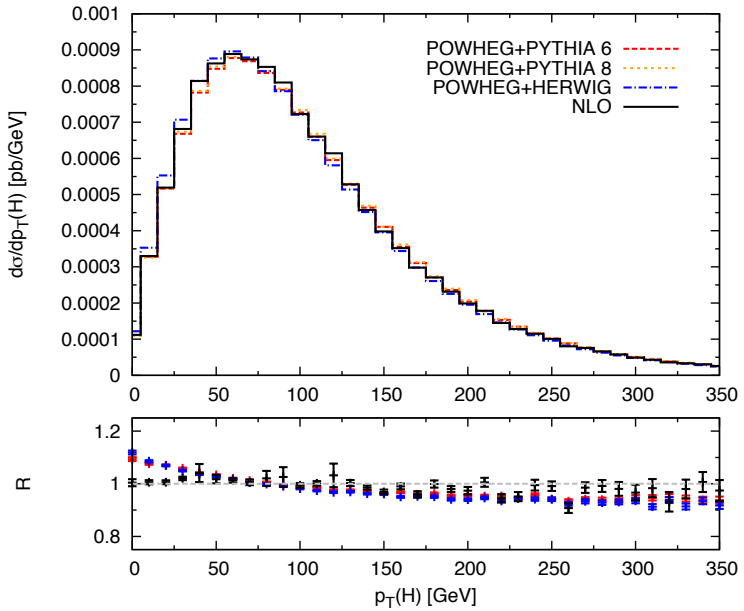
where

scale: $\mu_0/2 < \mu < 2\mu_0$

PDF:MSTW08, CTEQ6.6, NNPDF2.0

↪ Now being updated for Run II ⟶ Fourth Yellow Report (early 2016).

# $t\bar{t}H$ NLO+PS publicly available




`MG5_aMC@NLO` (Frederix et al.)

`POWHEG BOX` (Hartanto et al.)

`PowHel` (Garzelli et al.)

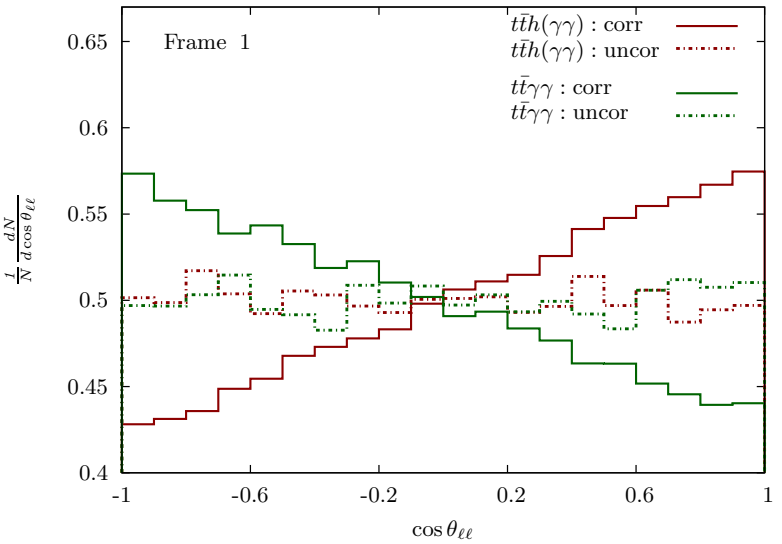
`SHERPA+OpenLoops`

`SHERPA+GoSam`

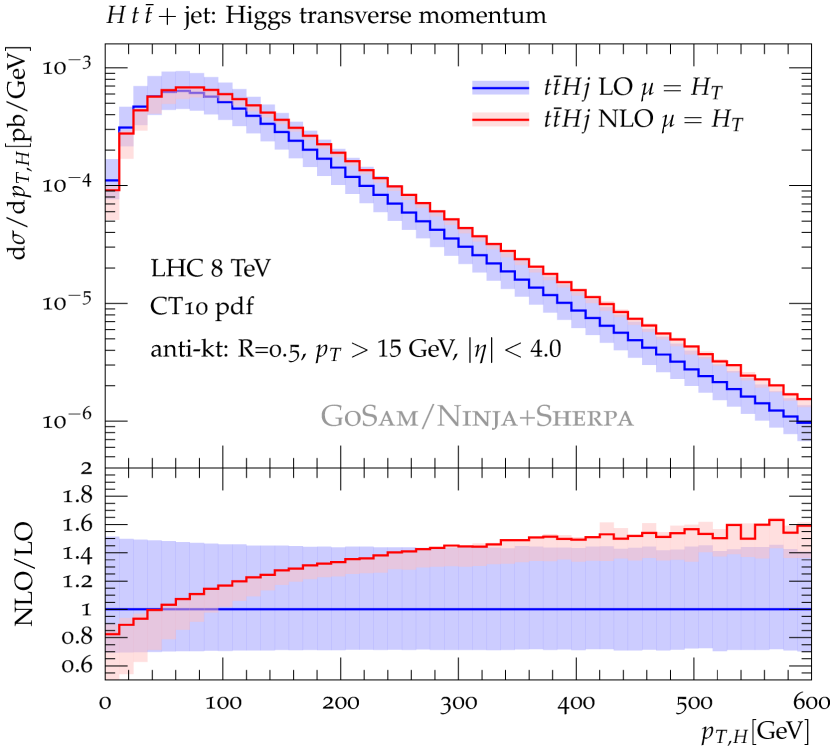
moderate PS effects in non-jet observables

Including top-quark spin correlations (Biswas et al., arXiv:1403.1790)

Mandatory for Higgs-boson studies at Run II



# $t\bar{t}H + j$: NLO QCD+PS




NNLO contribution from hard radiation

Important to reduce uncertainty from extra jet activity

Moving towards analysis with NLO merging of $t\bar{t}H$+0j and $t\bar{t}H$+1j

MEPS@NLO merging [Höche et al.]

FxFx merging [Frederix, Frixione]

# Soft-gluon resummations: towards $t\bar{t}H$ at NNLO QCD

→ (Kulesza et al., arXiv:1509.02780): NLL (threshold logs)

→ (Broggio et al., arXiv:1510.01914): NNLL (threshold logs) SCET methods

↪ 5-8% correction, reduced scale uncertainty

# NLO QCD+EW corrections for $t\bar{t} + H/Z/W$ production

[Frixione, Hirschi, Pagani,Shao, Zaro, arXiv:1504.03446]

[Zhang et al., arXiv:1407.1110]

| $\sqrt{s} = 13$ TeV | $t\bar{t}H$ | $t\bar{t}Z$ | $t\bar{t}W^+$ | $t\bar{t}W^-$ |
|---|---|---|---|---|
| NLO scale uncertainty | [+7,-11]% | [+13,-16]% | [+14,-14]% | [+15,-14]% |
| LO QCD-EW interference | +1.2% | 0% | 0% | 0% |
| NLO EW corrections | -1.2% | -3.8% | -7.7% | -6.7% |

- inclusive cross section: NLO EW corrections $\ll$ NLO QCD uncertainty
- Boosted regime: $p_t, p_{\bar{t}}, p_H \geq 200$ GeV $\Rightarrow$ 8 (11-20)% negative corrections for $t\bar{t}H$ ($t\bar{t}V$)
- calculation automated in `MG5_aMC@NLO`

# Off-shell $t\bar{t}H$ production and decay

[Denner, Feger, Scharf, arXiv:1412.5290, Denner and Feger, arXiv:1506.07448]

Full $2 \to 7$ process $pp \to t(be^+\nu_e)\bar{t}(\bar{b}\mu^-\nu_\mu)H$ at NLO in QCD

- include all non-resonant effects, off-shell effects, and interferences
- effects of only 1% on total cross section

Full $2 \to 8$ process $pp \to t(bl^+\nu)\bar{t}(\bar{b}jj)H(b\bar{b})$ at LO

- include all possible channels with/without top and Higgs resonances
- include all QCD and EW contributions to matrix elements and interferences

| matrix-element order | $O(\alpha_s^3\alpha)$ | $O(\alpha_s^2\alpha^2)$ | $O(\alpha_s\alpha^3)$ | $O(\alpha^4)$ |
|---|---|---|---|---|
| $t\bar{t}H(b\bar{b})$ signal | | | $\times$ | $\times$ |
| $t\bar{t}b\bar{b}$ background | | $\times$ | $\times$ | $\times$ |
| full process $(l^+\nu + 2j + 4b)$ | $\times$ | $\times$ | $\times$ | $\times$ |

- Results for 13 TeV LHC:
  - → negligible $t\bar{t}H$ signal-background interference
  - → significant -8% interference between QCD and EW contributions to $t\bar{t}b\bar{b}$ background (from $W$ exchange in $t$-channel)
  - → significant +11% enhancement in $t\bar{t}b\bar{b}$ background from diagrams without top resonances

# NLO QCD+PS predictions for $pp \to tHj$ at 13 TeV

[Demartin, Maltoni, Mawatari, Zaro, arXiv:1504.00611]

## Ingredient of the calculation

- NLO and MC@NLO predictions
- $t$-channel and $s$-channel contributions
- comparison of 4F and 5F schemes
- uncertainties from scale variations, PDFs, $\alpha_s$, $m_t$, $m_b$

## NLO cross sections and uncertainties at 13 TeV

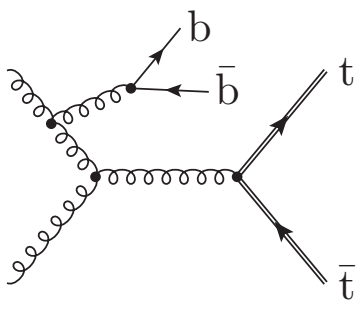
- low scale $\mu = (m_H + m_t)/4$ in order to obtain satisfactory 5F-4F agreement ( within 5% at NLO)
- NLO corrections reduce scale dependence from 25% (4F scheme) to 5% (both schemes)

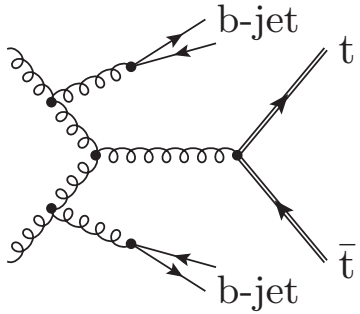
# Background: theoretical progress

- $t\bar{t}b\bar{b}$
  - → NLO QCD corrections
    - Bredenstein et al., arXiv:0905.0110 & arXiv:1001.4006
    - Bevilacqua et al., arXiv:0907.4723
  - → Matching to PS
    - PowHel: Kardos et al., arXiv:1303.6201
    - Sherpa+Openloops: Cascioli et al., arXiv:1309.5912
- $t\bar{t}V$
  - → NLO QCD corrections
    - Melnikov et al., arXiv:1102.1967 ($t\bar{t}\gamma$)
    - Hirschi et al., arXiv:1103.0621 ($t\bar{t}Z/W/\gamma^*$ and $t\bar{t}\gamma$)
    - Lazopoulos et al., arXiv:0804.2220 ($t\bar{t}Z$)
    - Kardos et al., arXiv:1111.0610 ($t\bar{t}Z$)
    - Campbell et al., arXiv:1204.5678 ($t\bar{t}W$)
  - → Matching to PS,
    - Garzelli et al., arXiv:1111.1444 ($t\bar{t}Z$) & arXiv:1208.2665 ($t\bar{t}Z/W$)
  - → EW corrections
    - Frixione et al., arXiv:1504.03446
- $t\bar{t}VV$
  - → NLO QCD corrections+PS
    - Kardos et al., arXiv:1408.0278 ($t\bar{t}\gamma\gamma$)
    - Maltoni et al., arXiv:1507.05640 ($t\bar{t}VV$)
    - van Deurzen et al., arXiv:1509.02077 ($t\bar{t}\gamma\gamma$)

# Irreducible $t\bar{t}b\bar{b}$ QCD background at NLO+PS

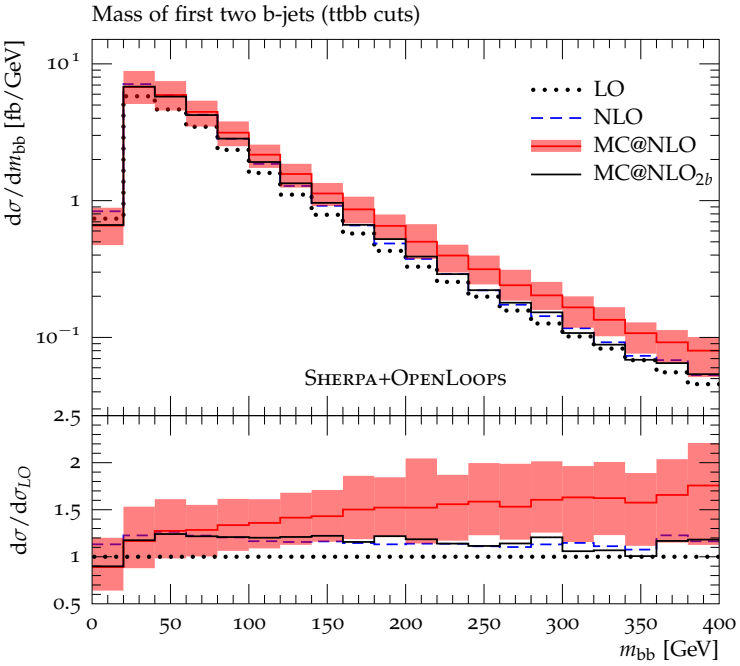
- NLO QCD: good perturbative stability
  (Bredenstein et al. arXiv:0905.0110 & arXiv:1001.4006,
  Bevilacqua et al. arXiv:0907.4723)
- NLO+PS in 5F scheme ($m_b = 0$) with `PowHel`
  (Garzelli et al. arXiv:0905.0110 & arXiv:1001.40060)




Difficult to evaluate effect of $b$ jet from showering: NLO QCD+PS can have large effects $\rightarrow$ need $m_b \neq 0$

- NLO+PS in 4F scheme ($m_b \neq 0$) with `SHERPA+OpenLoops`
  (Cascioli et al. arXiv:0907.4723)
  now also available in `MG5_aMC@NLO`.




matching, shower, and 4F/5F systematics needs to be studied

- Systematic comparison between different tools: work in progress through $t\bar{t}H$ HXSWG → YR4. ↪
  `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGTTH`
- Boosted regime: new recent study (Moretti et al. arXiv:1510.08468)

# Outlook and Conclusions

- $t\bar{t}H$ and $tH$ crucial players in precision measurement of Higgs couplings:
  - last main Higgs-boson production mode to be observed ($t\bar{t}H$)
  - only direct measurement of top-quark Yukawa coupling
  - Run I studies are very promising. Awaiting results from Run II larger statistics.
- Recent theory progress
  - NLO QCD implemented in automated NLO MC tools
  - lots of development for $t\bar{t}H$ (NLO QCD+EW, soft QCD resummation, off-shell effects)
  - all backgrounds available in NLO QCD MC tools, and under study.
- Theoretical priority on understanding sophisticated MC simulation issues
  - matching/merging/shower uncertainties
  - $b$-jet treatment in NLO parton-shower MC
- Updates and Development through the $t\bar{t}H/tH$ HXSWG

  → `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGTTH`

  → e-group mailing list lhc-higgs-xsbr-tth