$t\bar{t}H$ production at the LHC

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Spring Institute 2014: High-energy physics after LHC Run I

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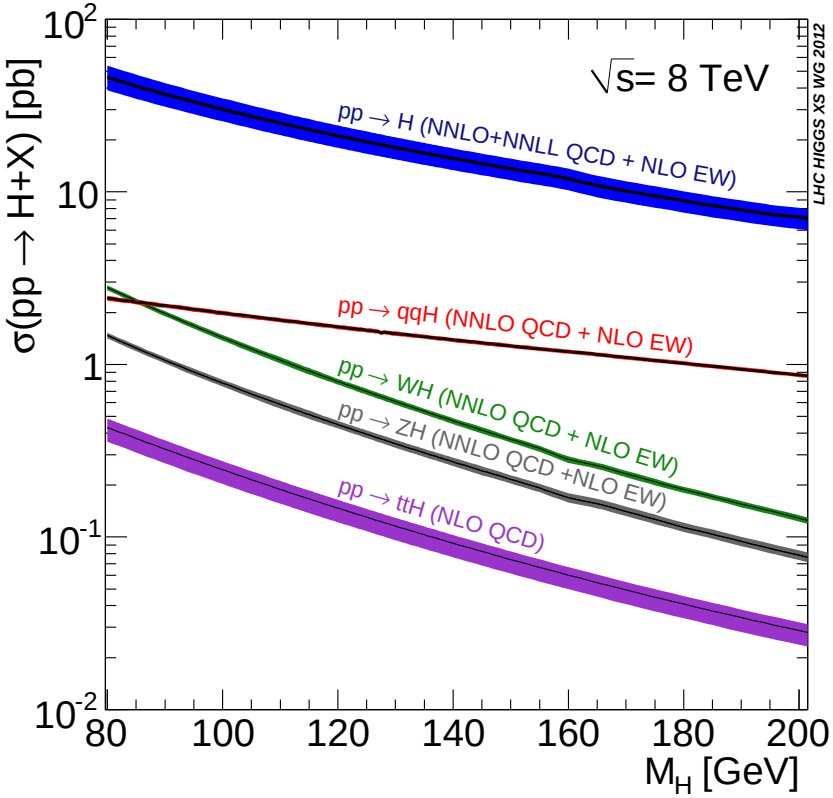
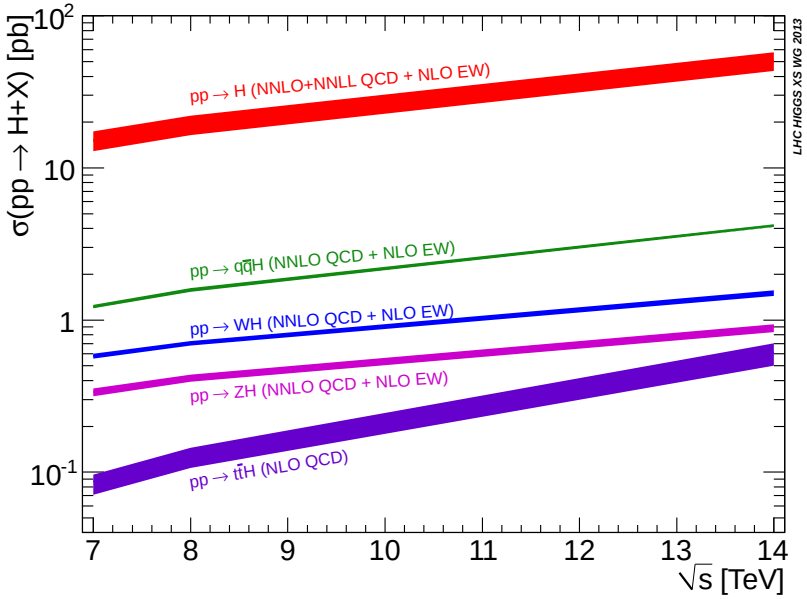
Outline

- Motivations for $t\bar{t}H$ studies.
- First results coming from LHC's Run I data, most expected from Run II data.
- Difficult channel: Run I results are encouraging and show how theoretical systematic uncertainty could become a limitation.
- Review of recent theoretical progress and ongoing studies.
- Outlook and conclusions.

Motivations





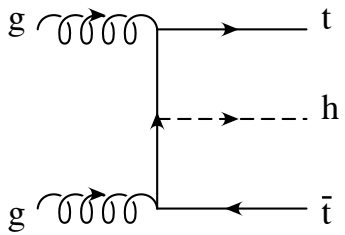
Small cross section that grows substantially from $7-8$ to 14 TeV.

For $M_H = 125$ GeV (and including NLO corrections):

- $\rightarrow$ $\sqrt{s} = 7$ 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

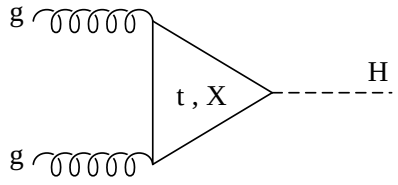
Motivations

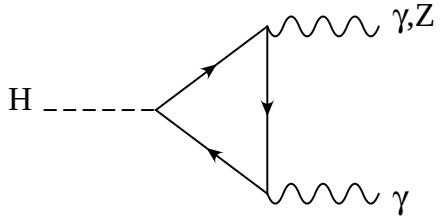
After the discovery of a Higgs-boson at 125 GeV, the focus is on precision measurements of its couplings.

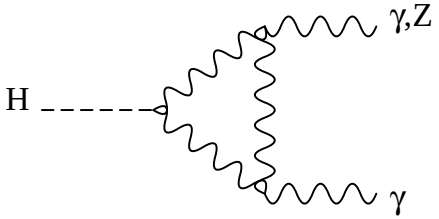


$$\longrightarrow \quad \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

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

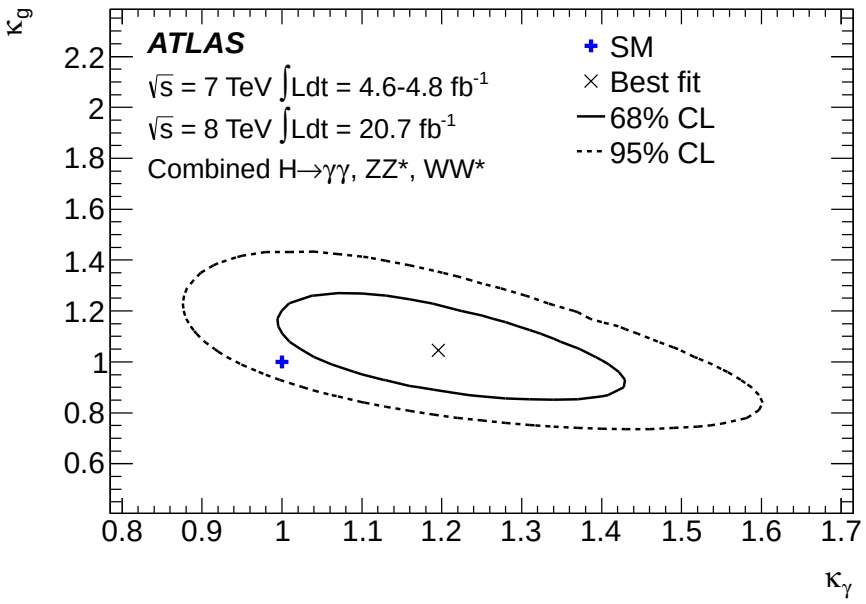


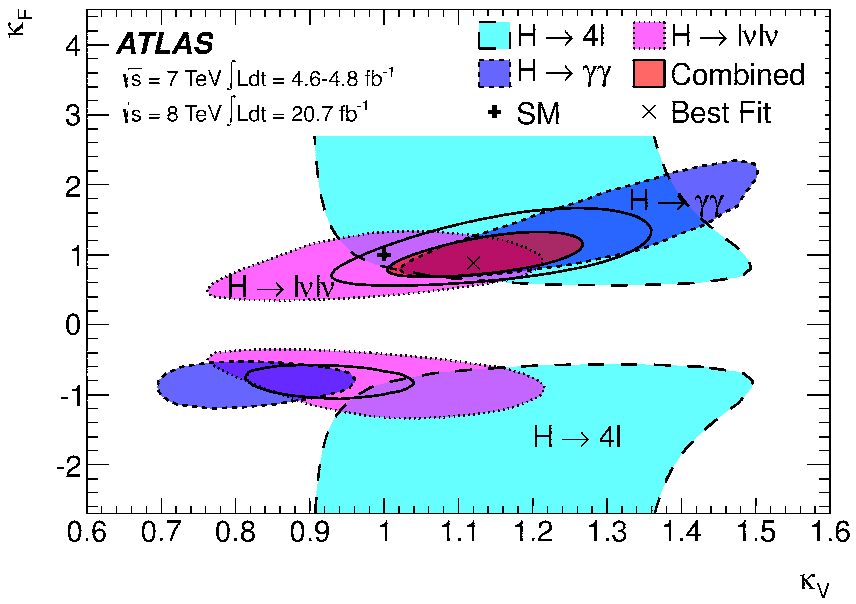




$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \kappa_g^2(\kappa_t, \kappa_b, m_H, X)$$

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





See studies in:

ATLAS-CONF-2012-127, and arXiv:1307.1427

CMS-PAS-HIG-12-020

Notice:

- ▷ hard to constrain κ_t from $(\kappa_g, \kappa_\gamma)$ fit, direct κ_t measurement is crucial
- ▷ sign of κ_t cannot come from $t\bar{t}H \longrightarrow H + t$ production

  (see Biswah, Gabrielli, Mele, arXiv:1211.0499, $pp \to tq + H \to tq + \gamma\gamma$)

New: study of spin correlation in $t\bar{t}H$

Spin-correlation effects can be used to distinguish scalar vs pseudoscalar associated production, i.e. SM from non-SM effects

$\hookrightarrow$ Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

and can be very visible in decay product's kinematic distributions,

$\hookrightarrow$ Ellis, Hwang, Sakurai, Takeuchi, arXiv:1312.5736

and even more can be used to improve the separation of signal ($t\bar{t}H$) and some irreducible backgrounds (e.g. $t\bar{t}\gamma\gamma$)

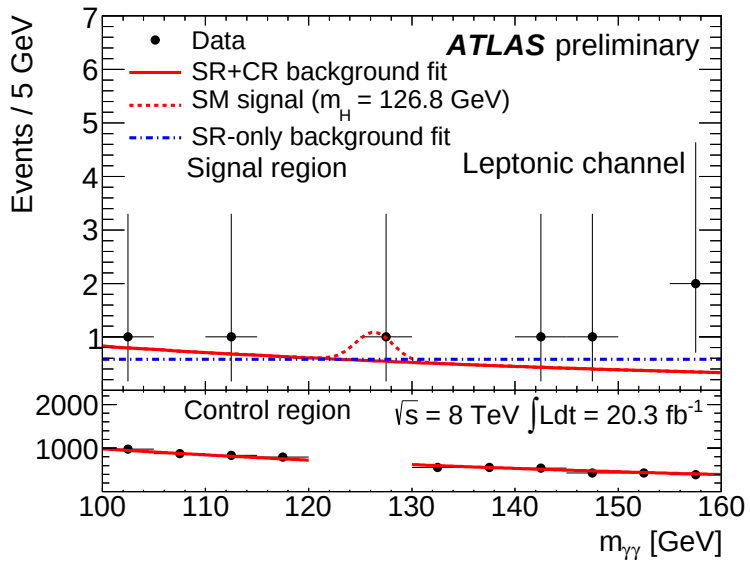
$\hookrightarrow$ (Biswah,Frederix, Gabrielli, Mele, arXiv:1403.1790) $\rightarrow$ See B. Mele's talk

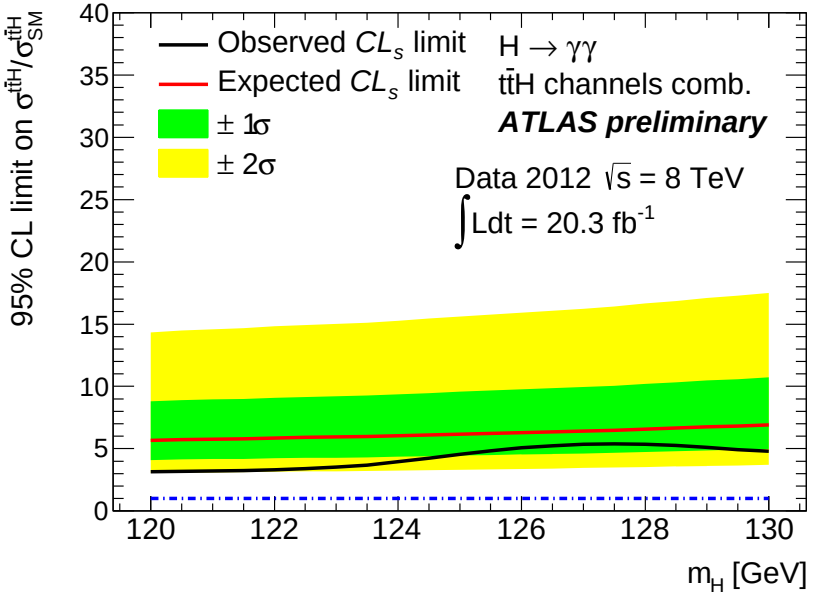
Results for $t\bar{t}H$ from LHC Run I

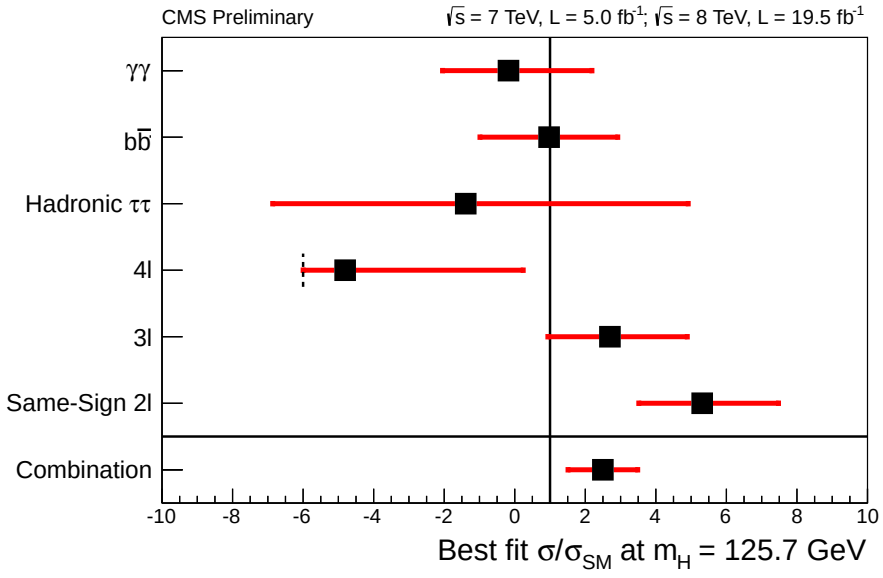
- ATLAS
  - $t\bar{t}H, H \to b\bar{b}$: ATLAS-CONF-2012-135
  - $t\bar{t}H, H \to \gamma\gamma$: ATLAS-CONF-2013-080
- CMS
  - $t\bar{t}H, H \to b\bar{b}, \tau^+\tau^-$: CMS-PAS HIG-13-019
  - $t\bar{t}H, H \to \gamma\gamma$: CMS-PAS HIG-13-015

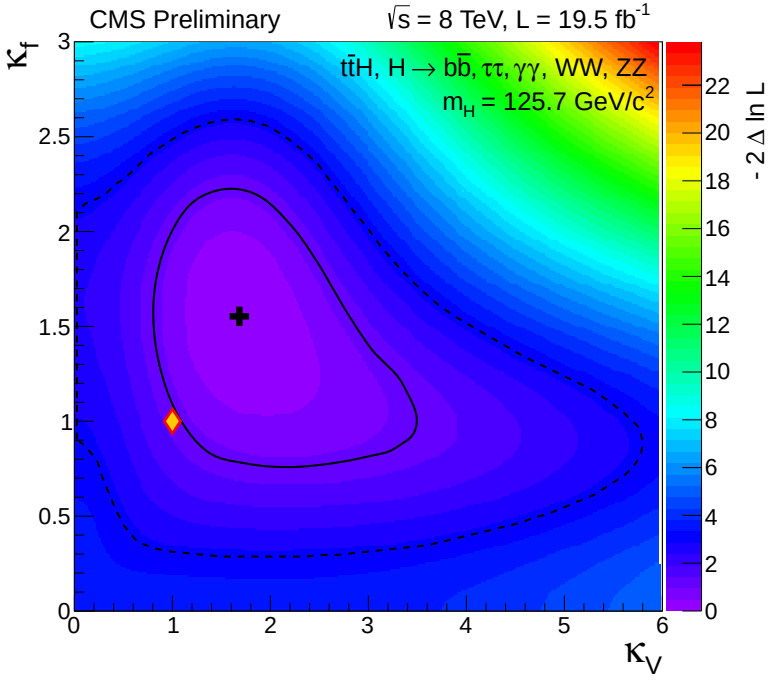
With a data set of about $5\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and $20\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV, they observe:

- a 95% C.L. upper limit of 5.4 (CMS) and 5.3 (ATLAS) times σ_{SM} in the $H \to \gamma\gamma$ channel;
- 95% C.L. upper limit of 5.2 (CMS) times σ_{SM} in the $H \to b\bar{b}$ channel;
- first measurement of signal strength: $\sigma/\sigma_{SM} = 2.5^{+1.1}_{-1.0}$ (combining $H \to b\bar{b}, \gamma\gamma, \tau^+\tau^-$, and assuming SM Br).


Events / 5 GeV
Data
SR+CR background fit
SM signal (m_H = 126.8 GeV)
SR-only background fit
Signal region
ATLAS preliminary
Leptonic channel
Control region
√s = 8 TeV ∫Ldt = 20.3 fb^-1
m_γγ [GeV]

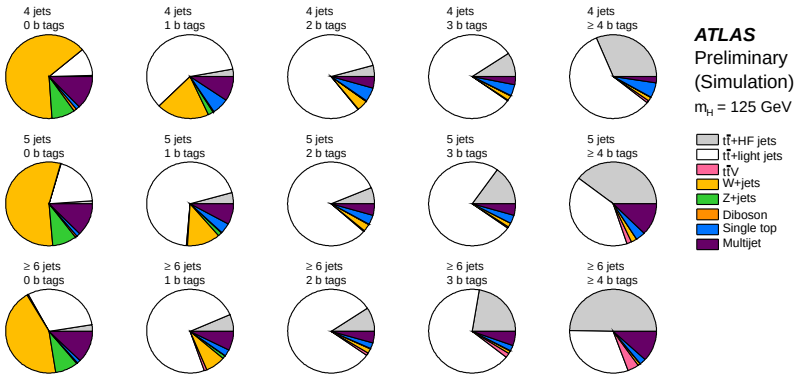

95% CL limit on σ^ttH/σ^ttH_SM
Observed CL_s limit
Expected CL_s limit
± 1σ
± 2σ
H → γγ
ttH channels comb.
ATLAS preliminary
Data 2012 √s = 8 TeV
∫Ldt = 20.3 fb^-1
m_H [GeV]

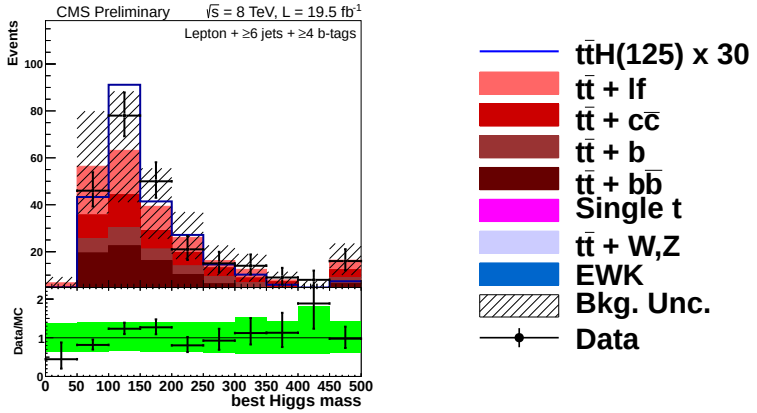

CMS Preliminary
√s = 7 TeV, L = 5.0 fb^-1; √s = 8 TeV, L = 19.5 fb^-1
γγ
bb̄
Hadronic ττ
4l
3l
Same-Sign 2l
Combination
Best fit σ/σ_SM at m_H = 125.7 GeV


CMS Preliminary
√s = 8 TeV, L = 19.5 fb^-1
ttH, H → bb̄, ττ, γγ, WW, ZZ
m_H = 125.7 GeV/c^2
κ_f
κ_V
- 2 Δ ln L

Main limitations

- All signal and background samples used in experimental analyses still do not include NLO QCD corrections;
- Irreducible backgrounds introduce large uncertainty (e.g. $t\bar{t}b\bar{b}$, $t\bar{t}jj$ for $H \to b\bar{b}$)





$t\bar{t}H$: PYTHIA

$t\bar{t}$+jets: ALPGEN+HERWIG (ATLAS), MADGRAPH+PYTHIA (CMS)

$t\bar{t}W/Z$: MADGRAPH+PYTHIA

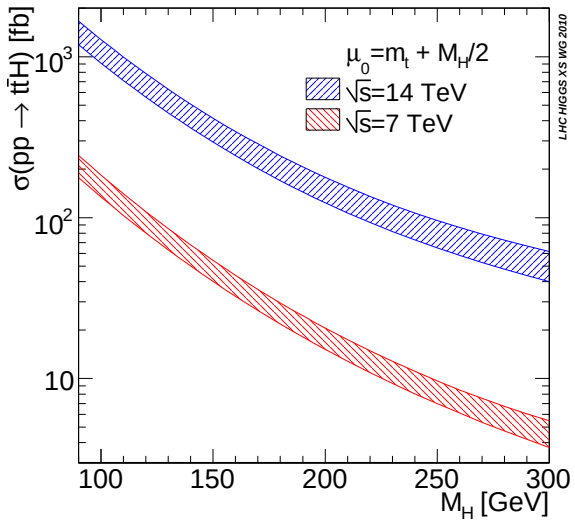
$t\bar{t}H$: towards more accurate theoretical predictions

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

→ 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

Matched at NLO to Parton Shower Monte Carlo generators

NLO calculation (by Dawson et al.) interfaced with Parton Shower Monte Carlo generators (PYTHIA/HERWIG) within

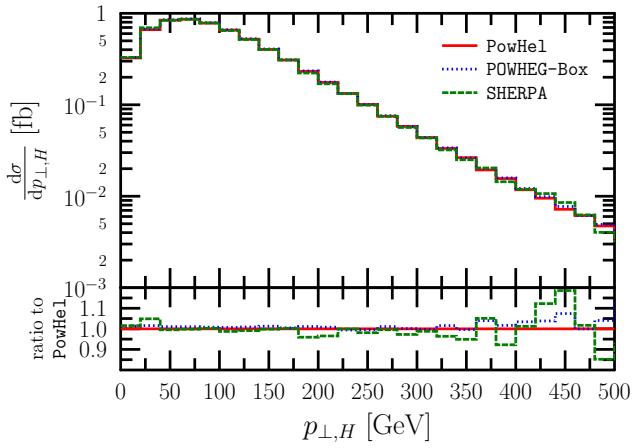
- ▷ POWHEG-BOX
- ▷ Sherpa

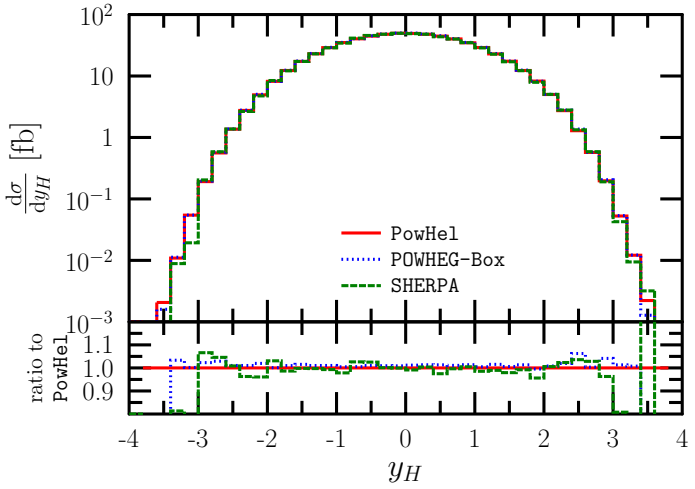
and successfully compared to PowHel (HELAC-NLO+POWHEG-BOX)

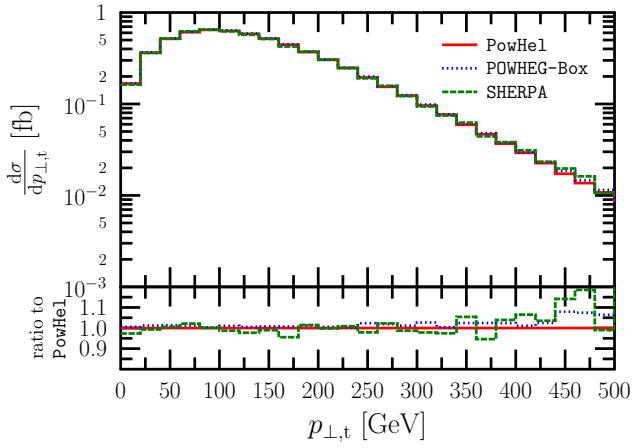
↪ Garzelli, Kardos, Trócsányi ; Jäger, Hartanto, Reina, Wackeroth
Les Houches Higgs Working Group (2013)

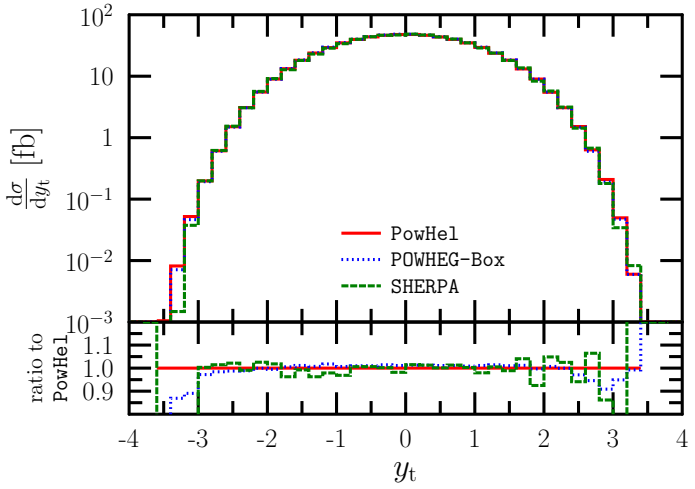
for a standard choice of selection cuts, and assuming $H \to \gamma\gamma$ (all decays implemented through the PS MC),

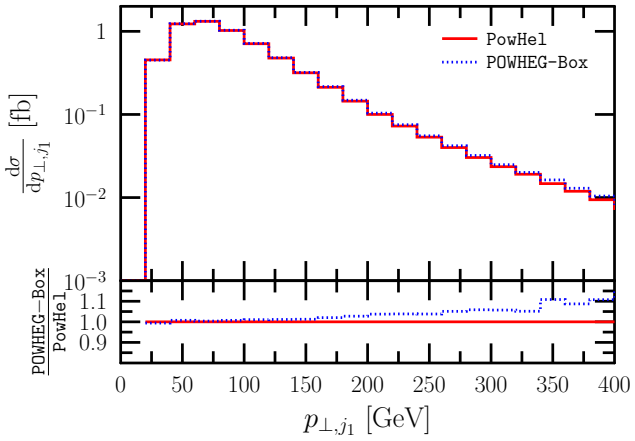
- $p_T^{jet} > 20$ GeV, $|y^{jet}| < 4.5$
- $p_T^{l} > 20$ GeV, $|y^{l}| < 2.5$
- $\Delta R_{l,jet} > 0.4$

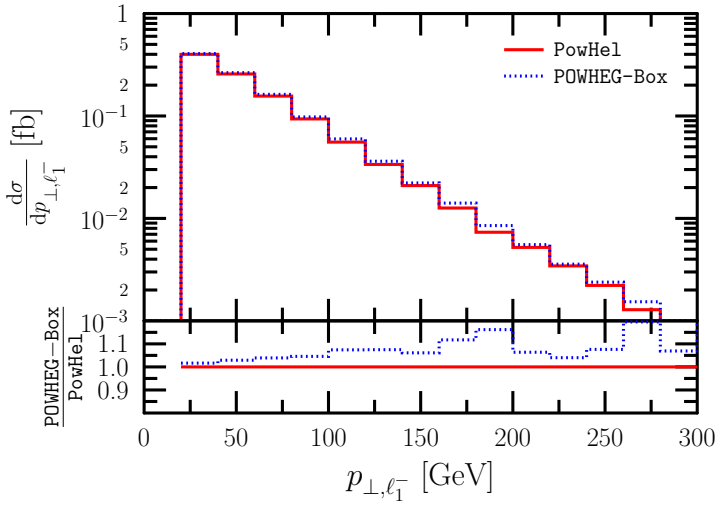

PowHel
POWHEG-Box
SHERPA
$\frac{d\sigma}{dp_{\perp,H}}$ [fb]
ratio to PowHel
$p_{\perp,H}$ [GeV]

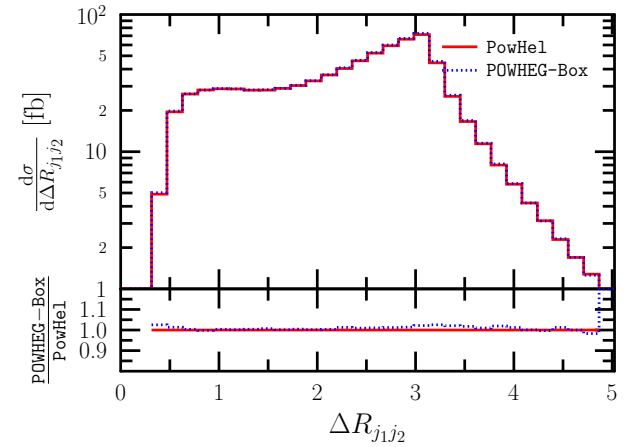

PowHel
POWHEG-Box
SHERPA
$\frac{d\sigma}{dy_H}$ [fb]
ratio to PowHel
y_H

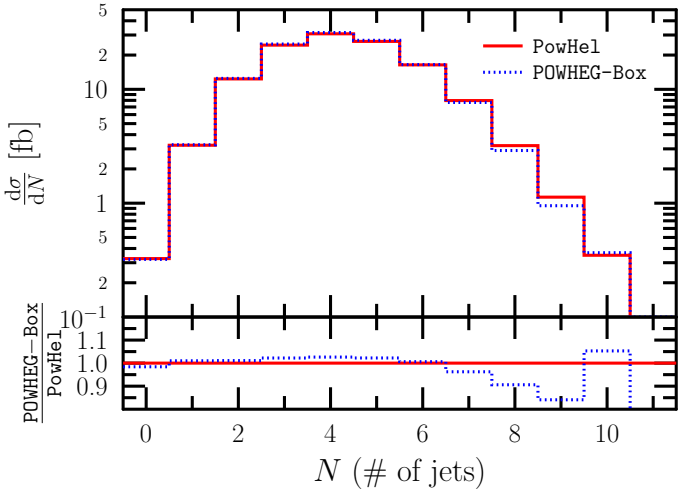

PowHel
POWHEG-Box
SHERPA
$\frac{d\sigma}{dp_{\perp,t}}$ [fb]
ratio to PowHel
$p_{\perp,t}$ [GeV]


PowHel
POWHEG-Box
SHERPA
$\frac{d\sigma}{dy_t}$ [fb]
ratio to PowHel
y_t


PowHel
POWHEG-Box
$\frac{d\sigma}{dp_{\perp,j_1}}$ [fb]
$\frac{\text{POWHEG-Box}}{\text{PowHel}}$
$p_{\perp,j_1}$ [GeV]


PowHel
POWHEG-Box
$\frac{d\sigma}{dp_{\perp,\ell_1^-}}$ [fb]
$\frac{\text{POWHEG-Box}}{\text{PowHel}}$
$p_{\perp,\ell_1^-}$ [GeV]

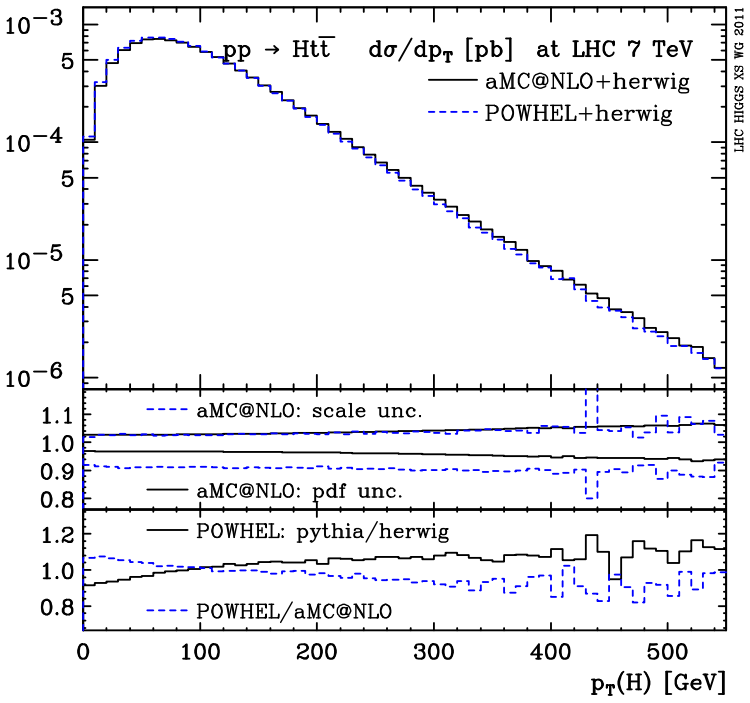

PowHel
POWHEG-Box
$\frac{d\sigma}{d\Delta R_{j_1 j_2}}$ [fb]
$\frac{\text{POWHEG-Box}}{\text{PowHel}}$
$\Delta R_{j_1 j_2}$

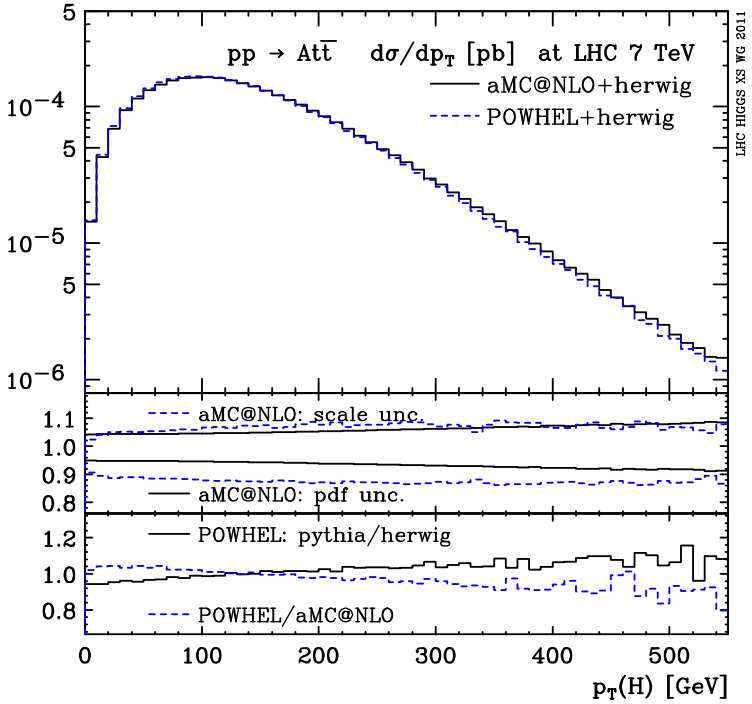

PowHel
POWHEG-Box
$\frac{d\sigma}{dN}$ [fb]
$\frac{\text{POWHEG-Box}}{\text{PowHel}}$
N (# of jets)

Independent calculation from aMC@NLO, also successfully compared with PowHel (both $t\bar{t}H$ and $t\bar{t}A$)

↪ Garzelli, Kardos, Trócsányi ; Frederix

(HXSWG-$t\bar{t}H$, Yellow Report II, arXiv:1201.3084)



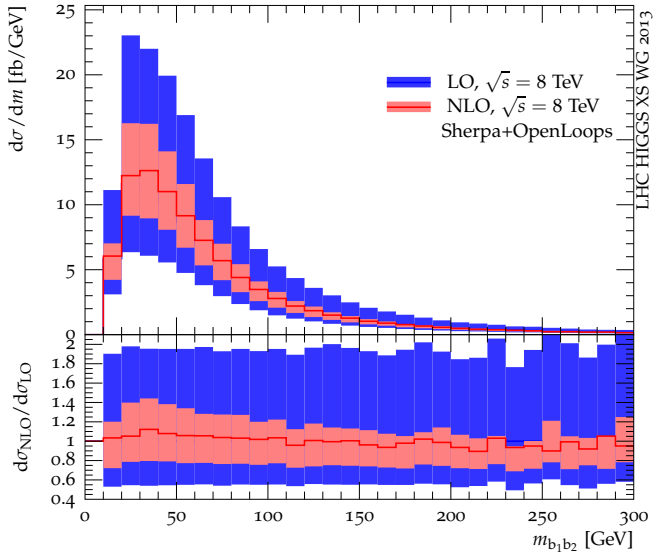


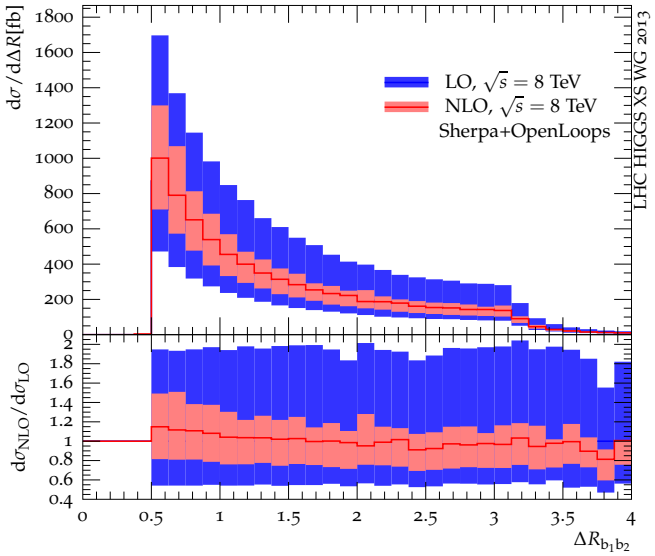
Background: $t\bar{t}b\bar{b}$

NLO QCD corrections to $pp \to t\bar{t}b\bar{b}$ calculated in:

- → Bredenstein et al. (arXiv:0807.1248, arXiv:0905.0110, arXiv:1001.4006)
- → Bevilacqua et al. (arXiv:0907.4723)
- → Bevilacqua et al. (arXiv:1403.2046): ratio $t\bar{t}b\bar{b}/t\bar{t}jj$ See Bevilacqua's talk

updated in the context of HXSWG-$t\bar{t}H$ ($\sqrt{s} = 7, 8$ GeV) (Yellow Report 3, arXiv:1307.1347)





Now interfaced with PS Monte Carlo (Sherpa) in the context of OPENLOOP+Sherpa

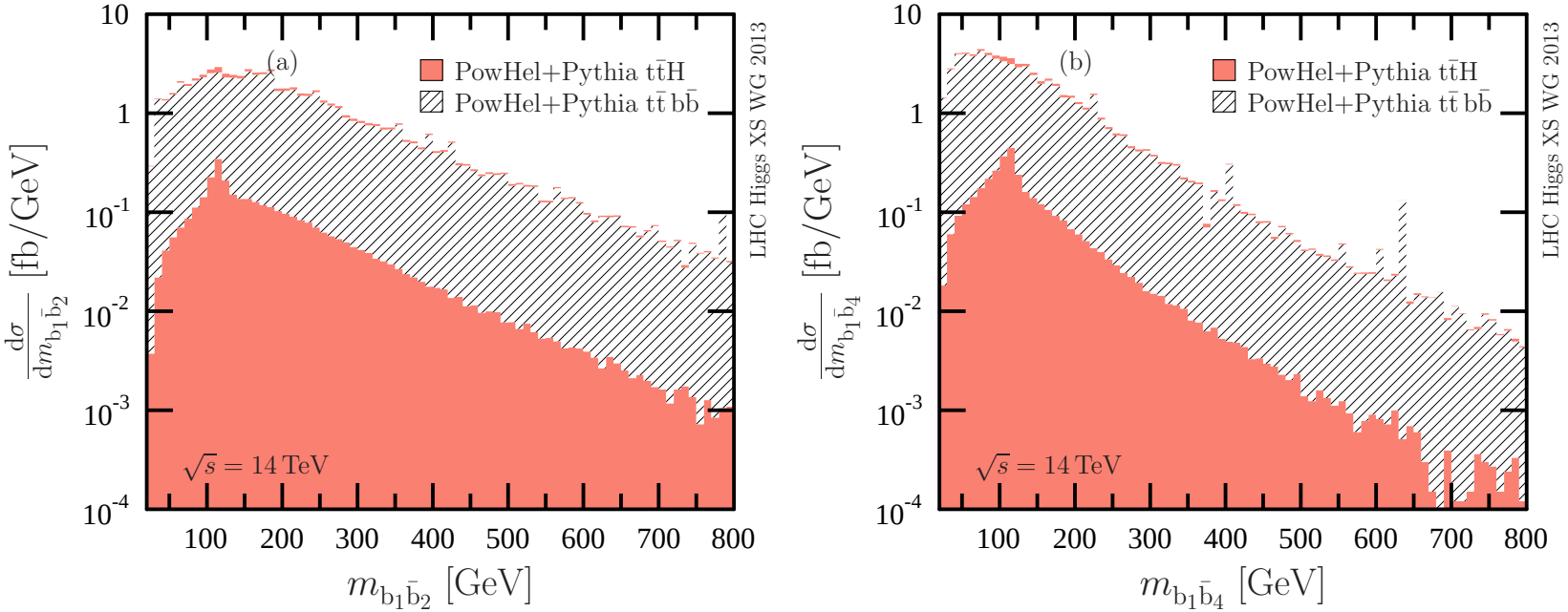
- ↪ Cascioli, et al (arXiv:1309.5912)

Powhel: $t\bar{t}H$ vs $t\bar{t}b\bar{b}$

HELAC-NLO calculation (Bevilacqua et al.) interfaced with PS Monte Carlo using POWHEG

↪ Kardos, et al.(arXix:1303.6291)

↪ Garzelli, et al. (HXSWG, Yellow Report 3, arXix:1307.1347)



Outlook and Conclusions

- $t\bar{t}H$ crucial player in precision measurement of Higgs couplings: rich potential when all properties are considered

  ↪ See B. Mele's talk today

- First measurements from Run I of the LHC very promising. Awaiting Run II for much larger statistics.
- Great progress in implementing existing NLO QCD calculations into PS Monte Carlos, available to the experiments for future analyses.
- Complex backgrounds like $t\bar{t}b\bar{b}$ now thoroughly under examination as benchmark process for several cutting-edge multijet automated NLO calculators.

  ↪ See G. Bevilacqua's talk on Friday