Higgs-boson phenomenology:
from discovery to precision studies

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Outline

- Higgs-boson physics, from discovery to precision studies: an overview.
- Nature of current and future theoretical studies, with emphasis on:
  - ↪ accurate description of signal (new physics) and background (SM): theory cannot be the limiting factor;
  - ↪ new ideas to enhance signal vs background (ex: boosted regimes, spin correlations);
  - ↪ systematic parametrization of BSM effects: looking for indirect effects.
- Looking forward and getting ready for more LHC physics.

Overview

If Run I of the LHC has brought us one of the most exciting times of the last several decades with

↪ the Higgs-boson discovery

. . . an equally exciting time may await us in Run II, looking for

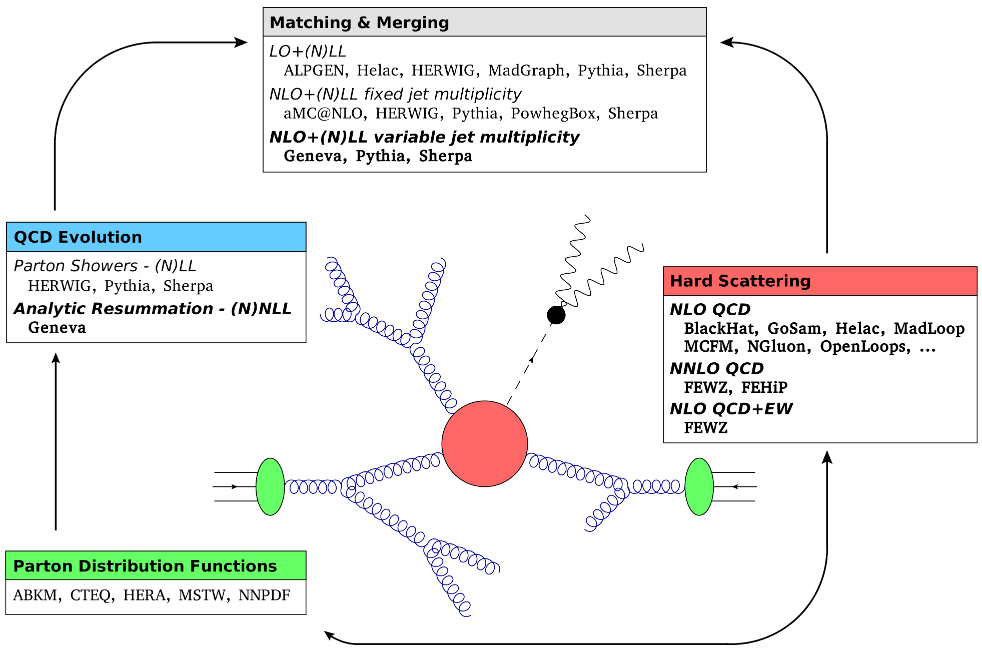
↪ anomalies w.r.t. SM-Higgs couplings
↪ direct signals of new physics

Unprecedented experimental means and expertise matched by the results of decades of theoretical efforts to provide the most accurate description of collider data

↪ has been a winning synergy in Higgs-boson discovery
↪ will be essential for Higgs-boson precision studies

as shown by LHC-Run I results.

Theoretical predictions for the LHC



- ▷ interpreting LHC data requires accurate theoretical predictions
- ▷ complex SM backgrounds call for sophisticated calculational tools
- ▷ higher order QCD(+EW) corrections mandatory at all levels

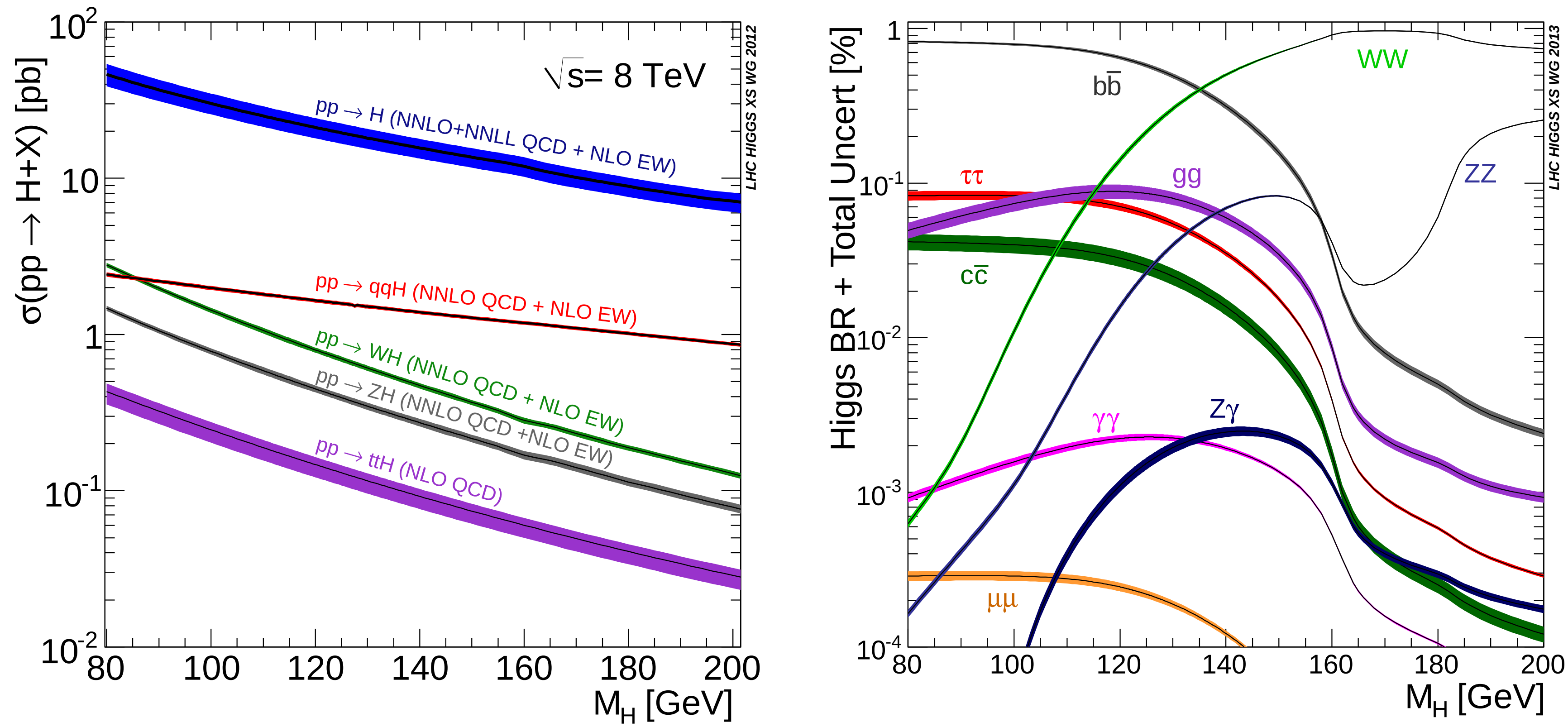
Higher-order terms in QCD/EW essential to:

- ▷ stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales;
- ▷ more realistic modelling of parton level since higher parton multiplicity (distributions, jets, ...);
- ▷ first step towards matching with resummed calculations and parton shower Monte Carlo programs.

- NLO QCD, challenges have largely been met:
  - → traditional approach (FD's) made more efficient to handle high multiplicity;
  - → new techniques based on unitarity methods and recursion relations offers a powerful alternative, particularly suited for automation;
  - → interface with parton shower MC well advanced (MC@NLO, POWHEG, Sherpa);
  - → automation mostly achieved (aMC@NLO, BlackHat, GoSam, ...).
- NLO EW and EW+QCD: corrections known for most processes relevant for Run I of the LHC.
- NNLO QCD: conquered or under way for a variety of $2 \to 2$ processes (e.g. $pp \to Q\bar{Q}$, and $pp \to H + j$). Essential when:
  - → processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
  - → new parton level subprocesses first appear at NLO;
  - → new dynamics first appear at NLO.

- N^{3}LO results for $2 \rightarrow 1$ processes ($gg \rightarrow H$ in $m_t \rightarrow \infty$ limit)
- Developed systematic resummation techniques for multiscale processes to account for:
  - $\rightarrow$ large corrections from dominant kinematic regions (soft/collinear);
  - $\rightarrow$ large corrections induced by exclusive cuts/vetos.
- PDF: constant development, NNLO is now the state of the art. Enormous effort to optimize PDF sets for LHC physics.

More than a proof of concept: Higgs discovery and beyond

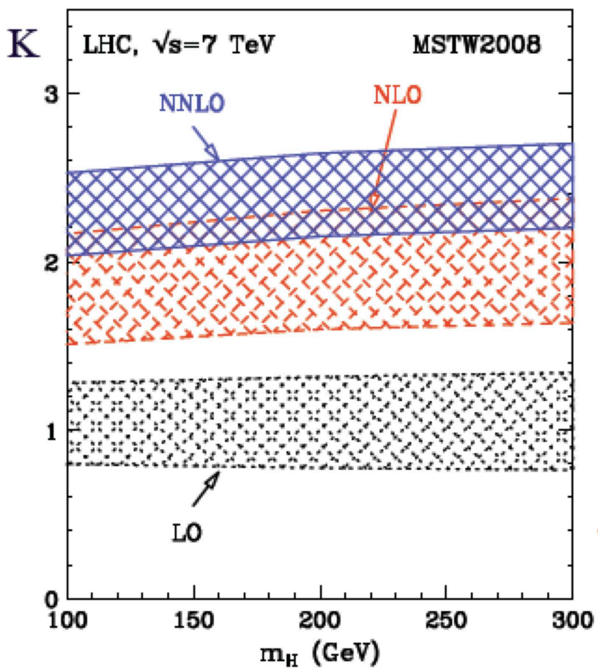


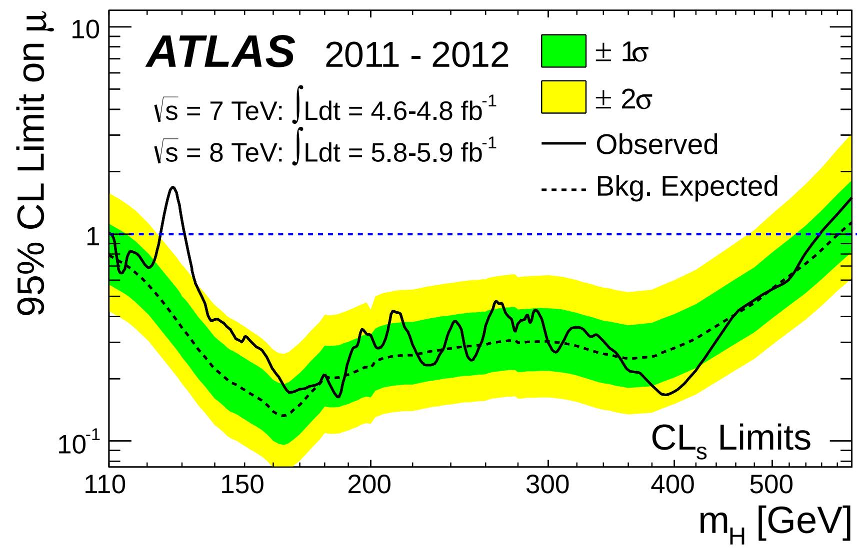
(LHC Higgs Cross Sections Working Group, arXiv:1101.0593,1201.3084 and 1307.1347)

- ▷ all channels combined in a a coherent way;
- ▷ all orders of calculated higher orders corrections included consistently (tested with all existing calculations);
- ▷ theory errors (scales, PDF, α_s, ...) combined according to a common recipe.

The exclusion/discovery process would have been different, if at all possible, had we not had the most important inclusive corrections under control.

Ex.: large impact of QCD corrections on $gg \to H$ (determine expected SM signal).

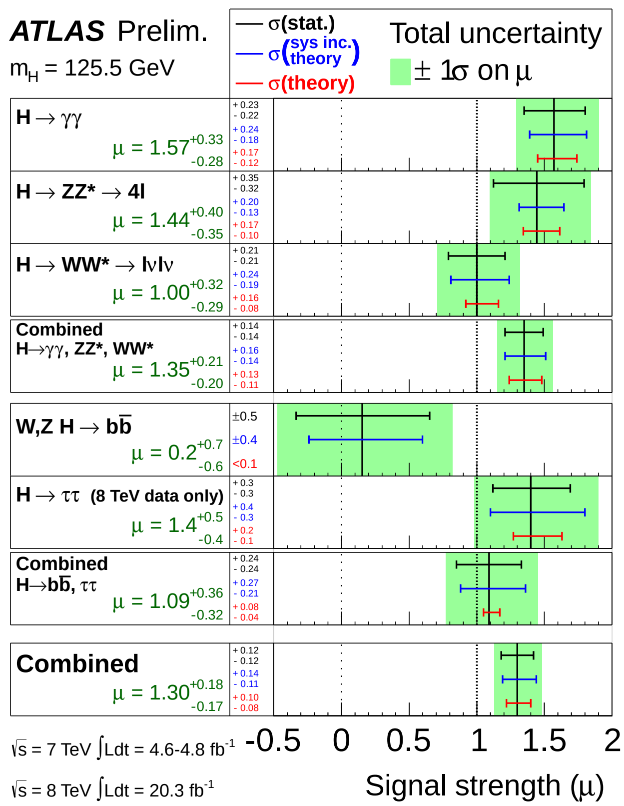


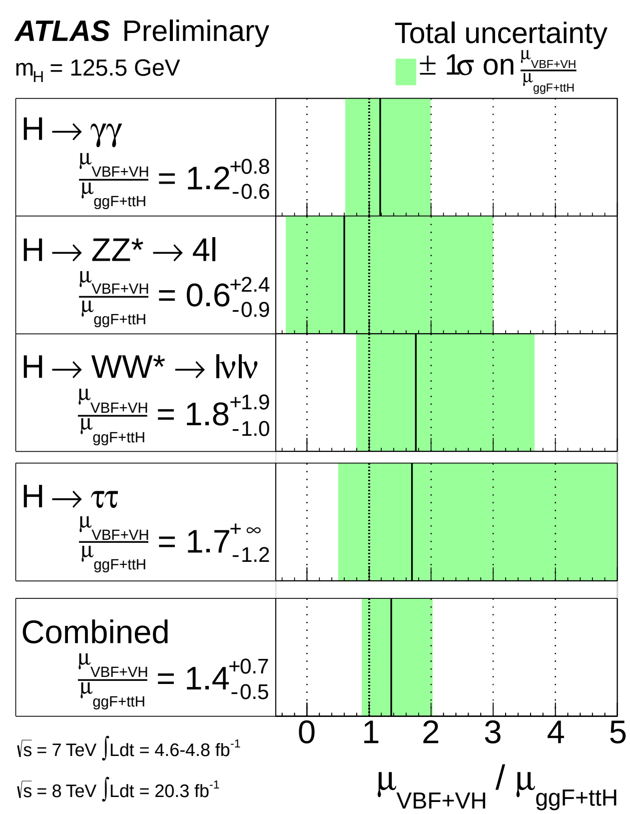


Harlander,Kilgore,Anastasiou,Melnikov,

Ravindran, Smith, van Neerven, 2002-2003

Signal strength now measured in several channels:





(ATLAS-CONF-2014-009)

- ▷ Observed both bosonic and fermionic decays (both ATLAS and CMS)
- ▷ Each measurement is the result of several analyses, where specific kinematics cuts/vetos have been applied.
- ▷ Notice how the theoretical errors are about to become the limiting uncertainty.

From signal strength to couplings

The experiments measure signal strengths and can only fit the product:

$$\mu_p^i = \mu_p \cdot \mu_{BR}^i$$

where $\mu_p = \sigma_p/\sigma_p^{SM}$ (production) and $\mu_{BR}^i = BR_i/BR_i^{SM}$ (decay) (n.w.a.)

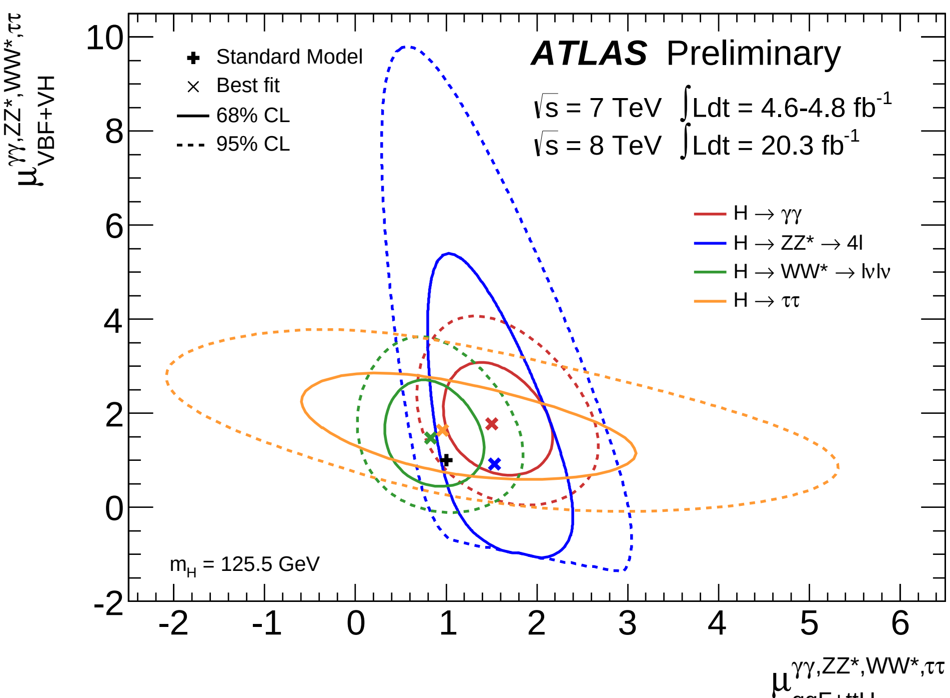
Taking one decay mode at a time one can go one step further and fit the ratio per channel:

$$\frac{\mu_{VBF+VH}^i}{\mu_{ggF+ttH}^i} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

under the assumption

$$\mu_{VBF+VH} \simeq g_{VVH}^2$$

$$\mu_{ggF+ttH} \simeq g_{ttH}^2$$



Relation to couplings only under specific assumptions

Define the normalized couplings κ such that:

$$\mu_p^i = \sigma_p \cdot BR_i = \sigma_p^{SM} \cdot BR_i^{SM} \cdot \frac{\kappa_p \cdot \kappa_i}{\kappa_H}$$

where $\kappa_H = \Gamma_H / \Gamma_H^{SM}$.

One can then consider different scenarios of increasing complexity:

- $\kappa_V = \kappa_W = \kappa_Z$ and $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau$
- κ_Z, $\lambda_{WZ} = \kappa_W / \kappa_Z$, and κ_f
- κ_t, $\lambda_{du} = \kappa_d / \kappa_u$, and κ_V
- $\ldots$

with $\kappa_{g,\gamma,H} = \kappa_{g,\gamma,H}(\kappa_f, \kappa_V, \ldots)$, or just independent effective parameters.

Ultimately to be rephrased in terms of effective BSM interactions:

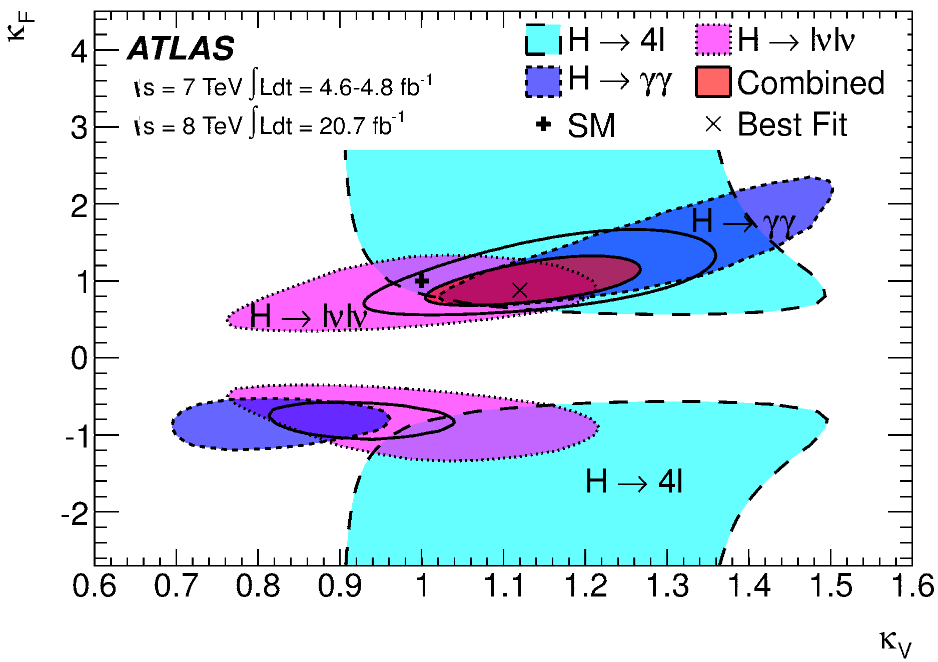
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda^{d_i - 4}} c_i \mathcal{O}_i$$

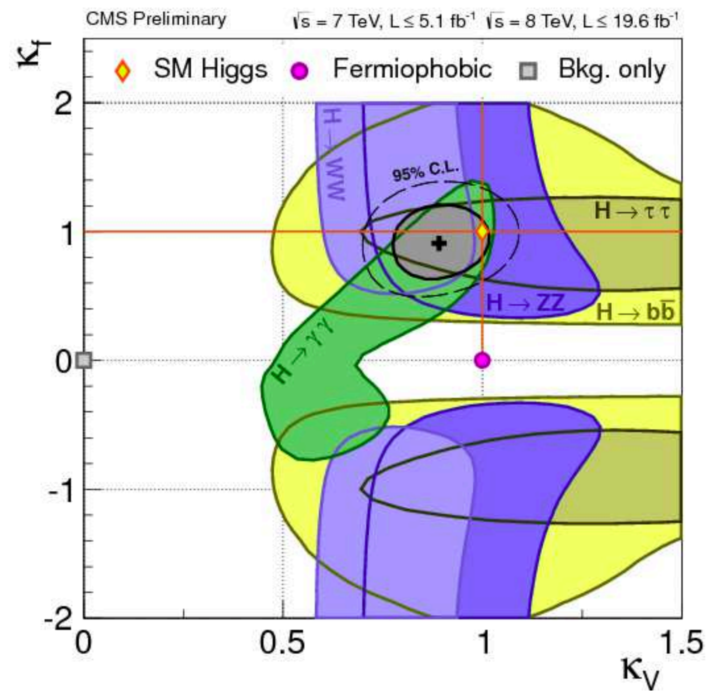
already implemented in public codes:

eHDECAY $\rightarrow$ Contino et al. $\rightarrow$ for H decays

SUSYFit $\rightarrow$ Ciuchini et al. $\rightarrow$ as part of global EW fit.

Example: (κ_V, κ_f) fit



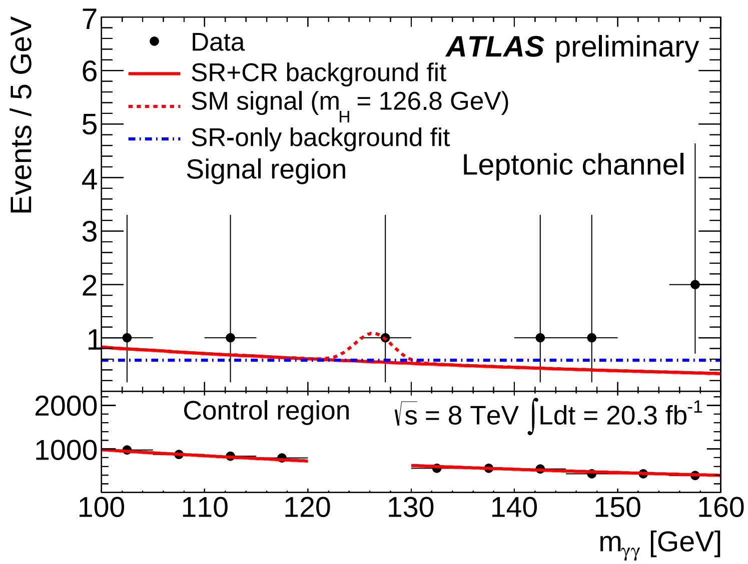


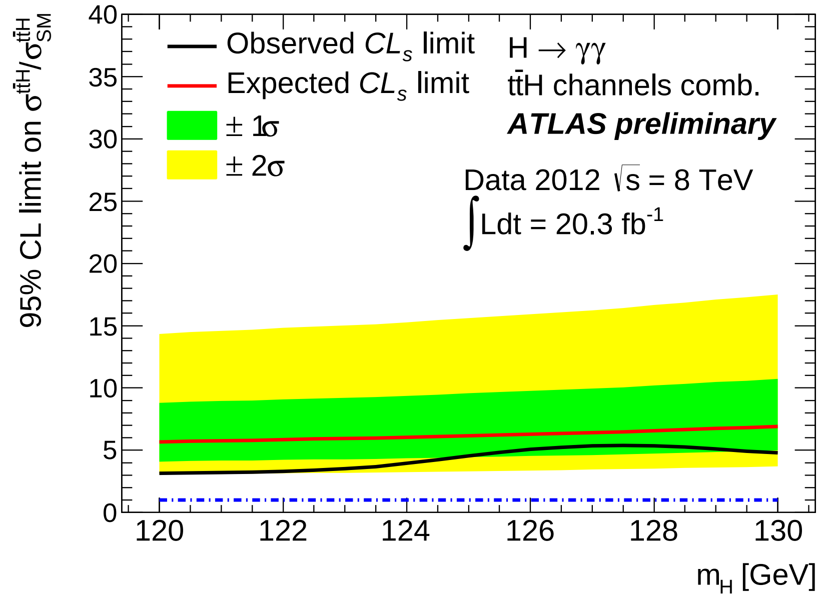
$$\kappa_V = 1.15 \pm 0.08$$
$$\kappa_f = 0.99^{+0.17}_{-0.15}$$

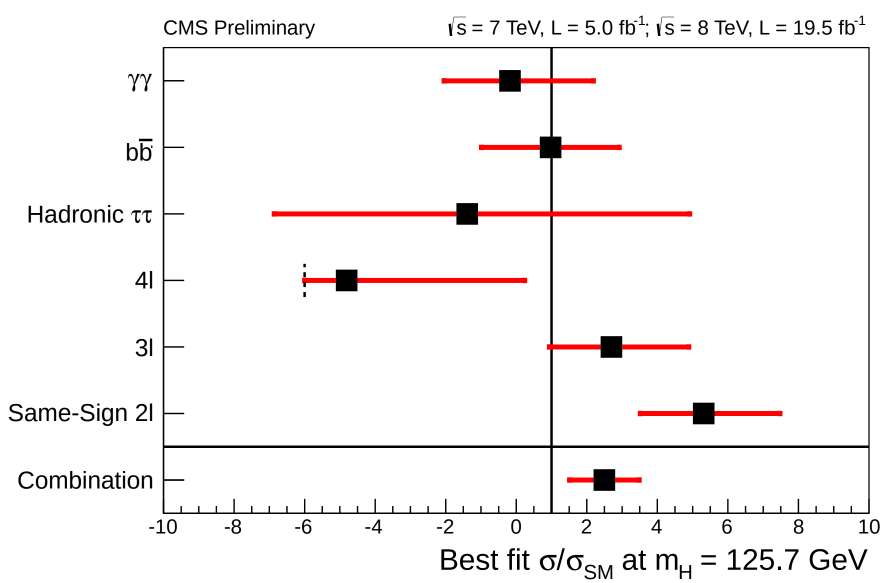
$$\kappa_V = [0.81, 0.97]$$
$$\kappa_f = [0.71, 1.11]$$

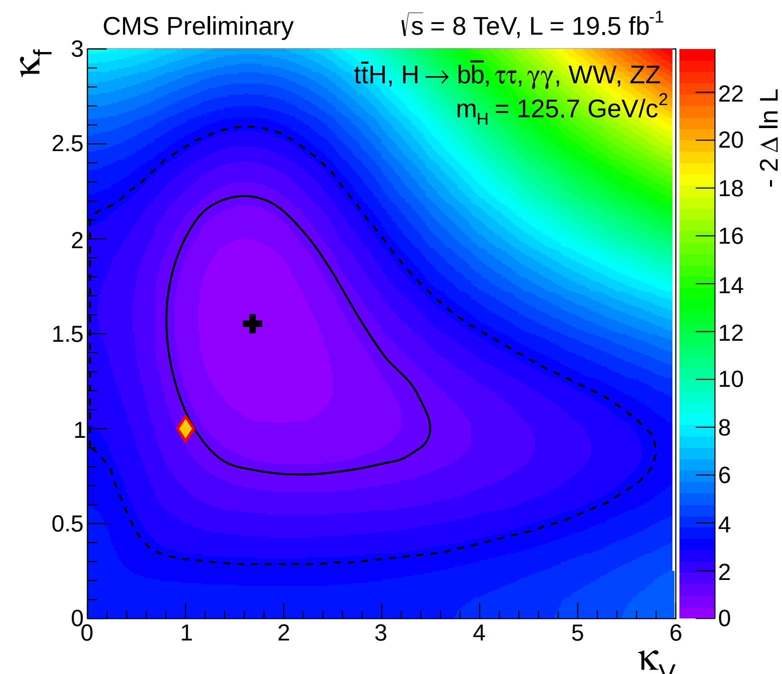
with less constraining bounds obtained in other scenarios.

First measurement of $t\bar{t}H$ production









How can we still improve theoretical predictions?

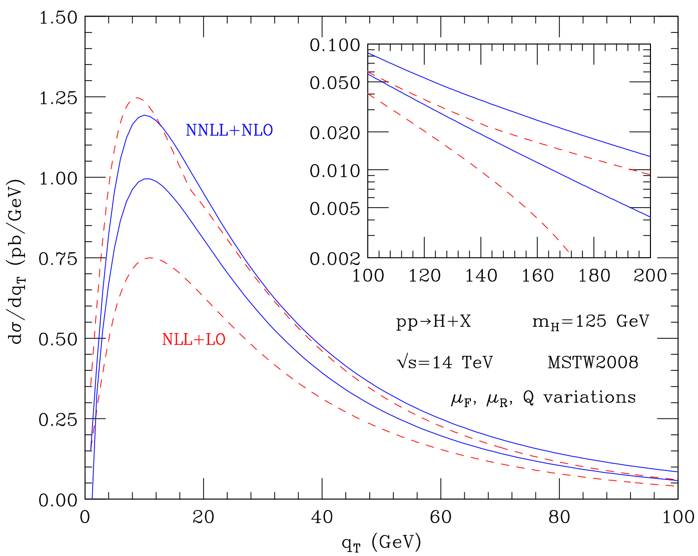
The main outstanding issue is now the measurement of couplings, looking for deviations from the SM-Higgs paradigm:

- different production channels need to be disentangled (via cuts/vetos)
  ↪ from each other
  ↪ from background
- exclusive modes need to be calculable with sufficient accuracy and flexibility:
  - ▷ provide accurate interface to specific decay channels;
  - ▷ investigate need for resummation of induced large logarithmic effects in selection process (via cuts/vetos);
  - ▷ investigate accurate matching between various selection channels (e.g.: $H + N$ jets, $N = 0, 1, 2, \ldots$);
- large fixed-order corrections still need to be investigated;
- assumptions need to be revisited (e.g. $m_t \to \infty$ in $gg \to H$)

Some important developments presented in the following

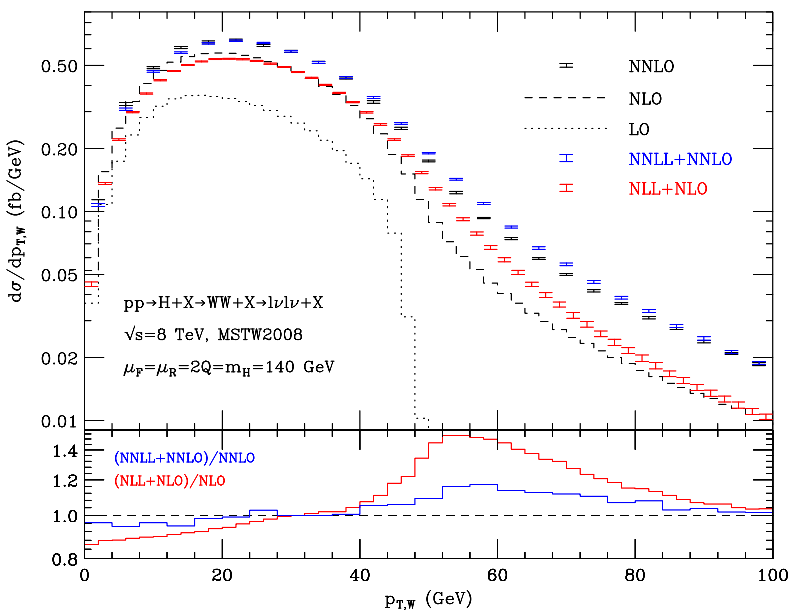
$gg \to H$ beyond NNLO, including Higgs decays

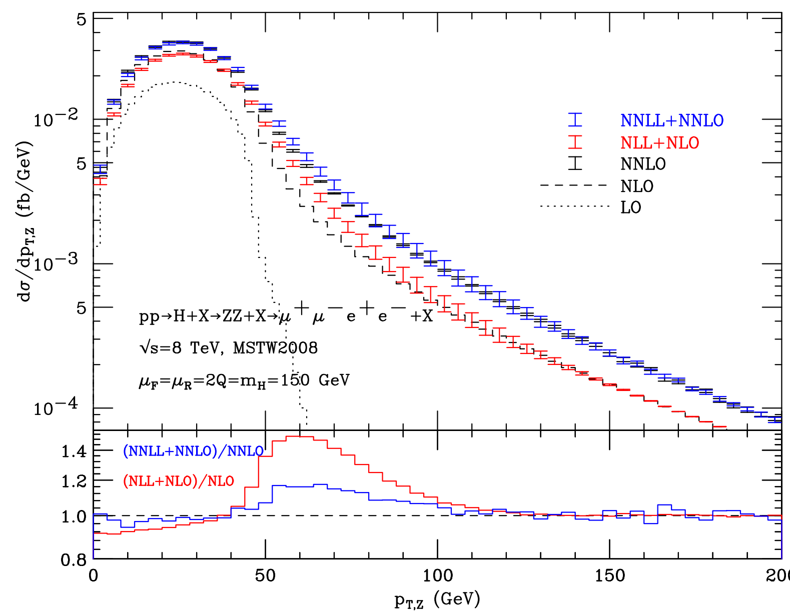
Resummation of multiple soft-gluon emission at small transverse momentum



HqT $\to$ no decay

HRes$\to$ includes $H \to WW, ZZ, \gamma\gamma$

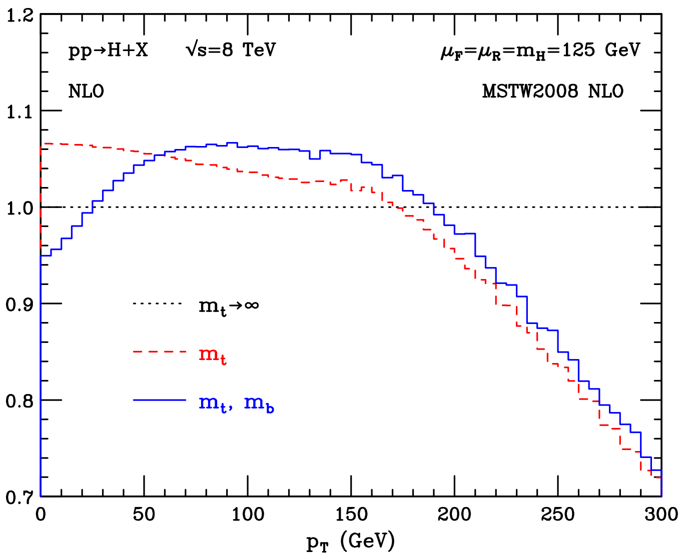


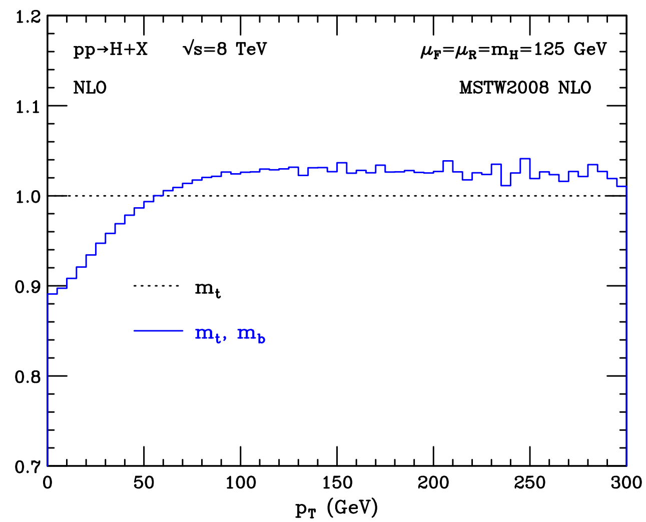


(de Florian, Ferrera, Grazzini, Tommasini, 2012-13)

$gg \to H$ beyond existing NNLO calculation

- Studied impact of HQ mass in $gg \to H$ (going beyond $m_t \to \infty$)



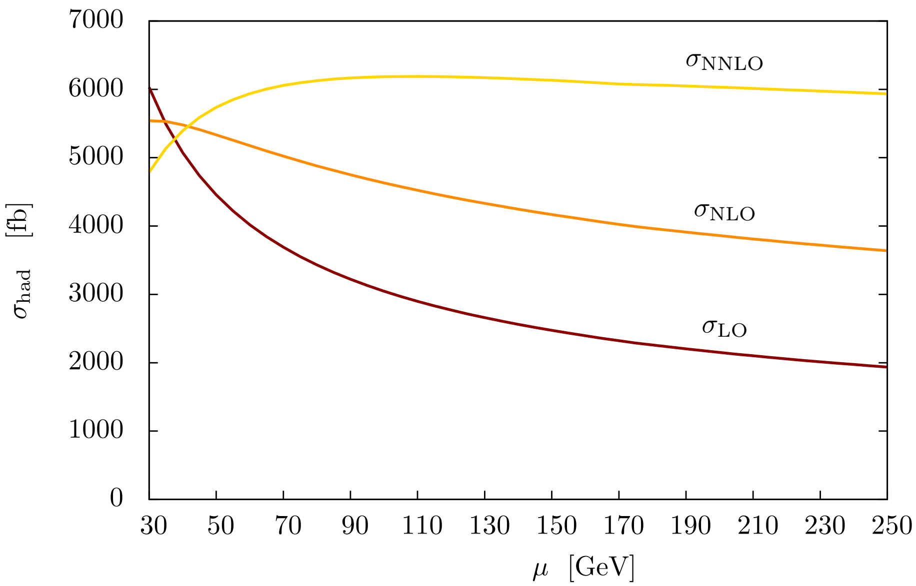


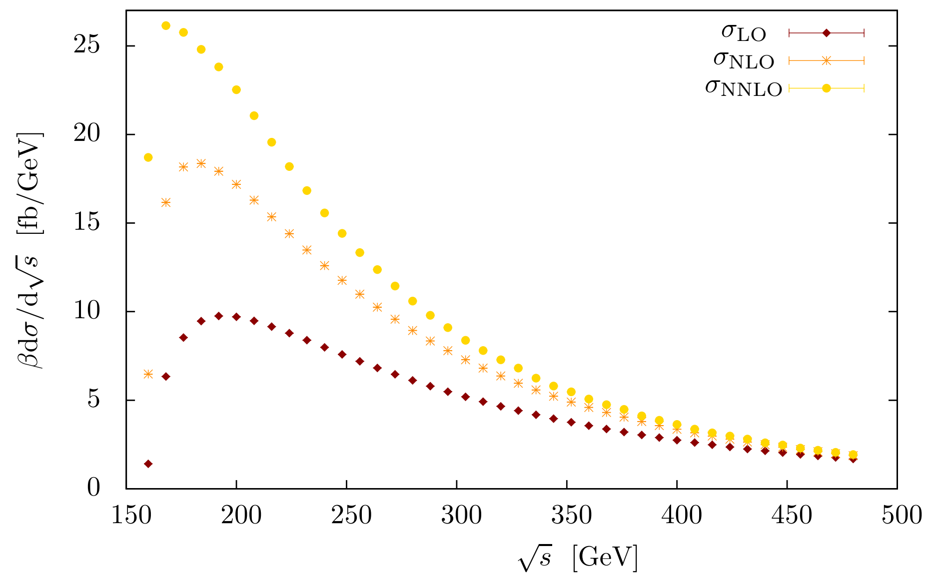
(Grazzini, Sargsyan, arXiv:1306.4581)

- N^{3}LO inclusive cross section computed in soft limit $\to$ threshold production

(Anastasiou, Duhr, Dulat, Furlan, Gerhmann, Herzog, Mistlberger, arXiv:1403.4616)

$H + j$, including NNLO QCD corrections





(Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1302.6216)

- large K factors: $\sigma_{NLO}/\sigma_{LO} = 1.6$ and $\sigma_{NN:P}/\sigma_{NLO} = 1.3$
- scale dependence significantly reduced to $\simeq 4\%$

New: matching of resummed results in different jet bins: $H + 0$ jet (NNLO) and $H + 1$ jet (NLO

(Boughezal, Liu, Petriello, Tackmann, Walsh, arXiv:1312.4535)

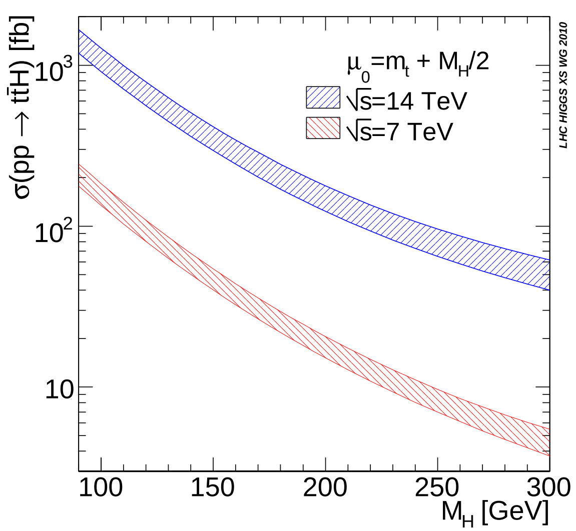
$t\bar{t}H$: towards more accurate theoretical predictions

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

$\to$ Beenakker et al. (arXiv:hep-ph/0107081, arXiv:hep-ph/0211352)
$\to$ Dawson et al. (arXiv:hep-ph/0107101, arXiv:hep-ph/0211438)

used to estimate the theoretical uncertainties currently used in Higgs searches

$\hookrightarrow$ 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

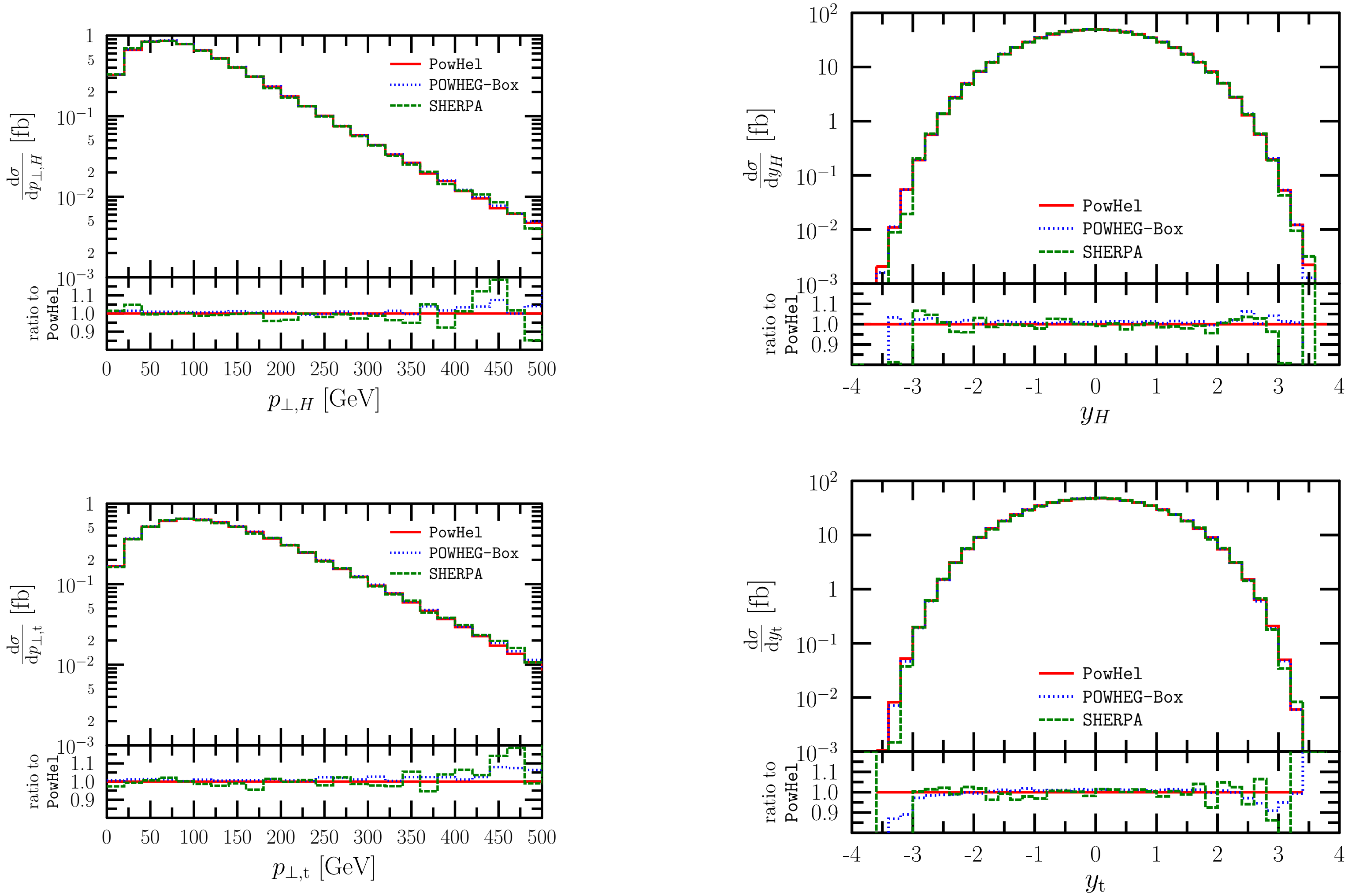
- ▷ POWHEG-BOX
- ▷ Sherpa

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

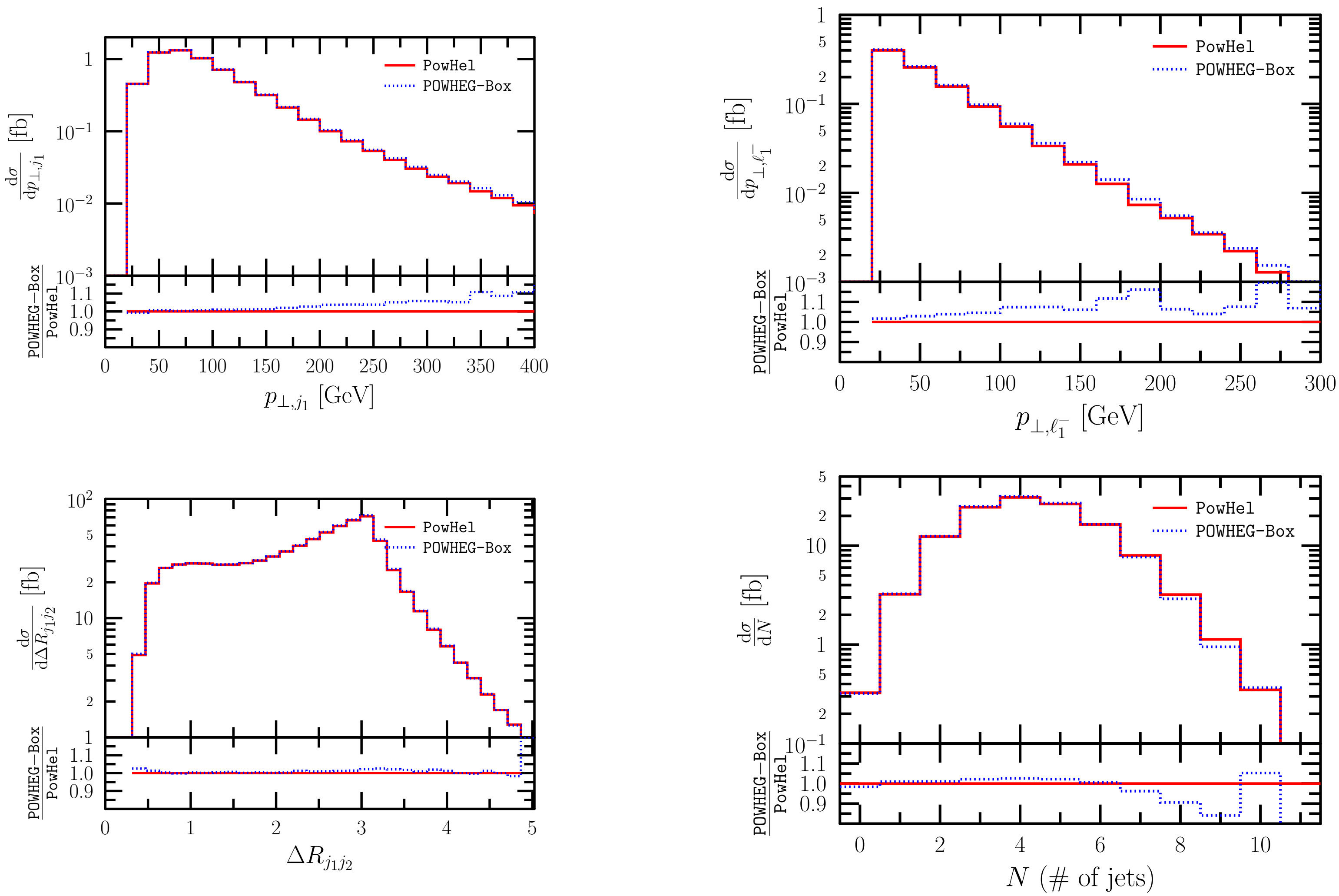
↪ Garzelli,Kardos, Trócsányi ; Jäger, Hartanto, Reina, Wackeroth
Les Houches Higgs Working Group (2013) (arXiv:1405.1067)

for a standard choice of selection cuts, and assuming $H \to \gamma\gamma$ (all decays implemented through the PS MC, e.g. Pythia in following plots),

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



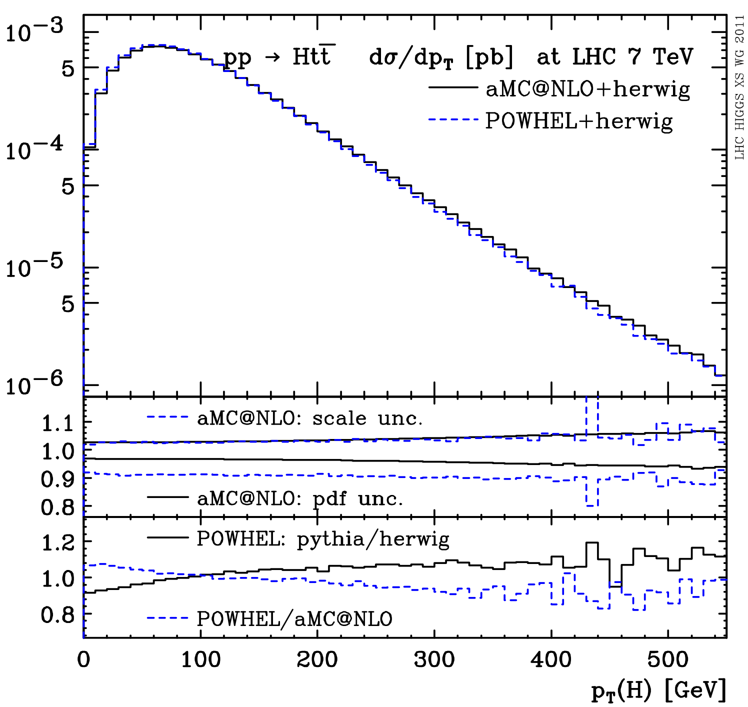
(Garzelli, et al., arXiv:1405.1067)

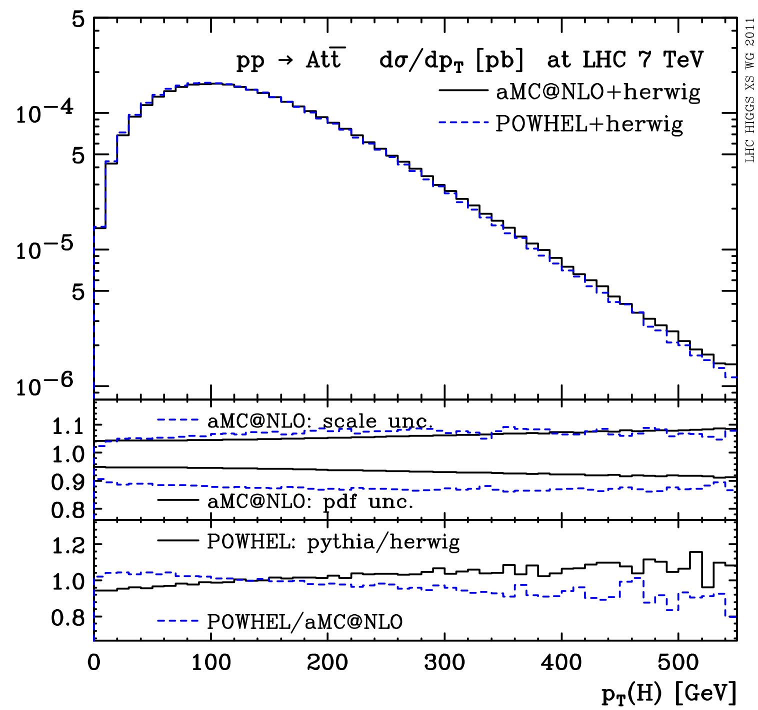


(Garzelli, et al., arXiv:1405.1067)

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)



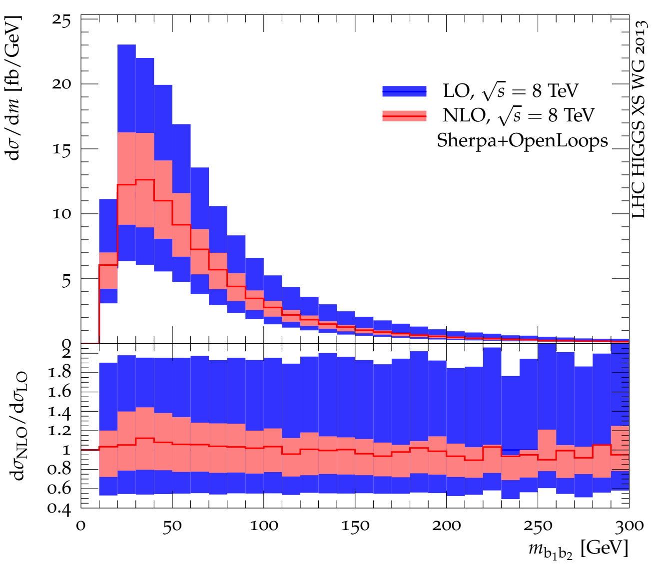


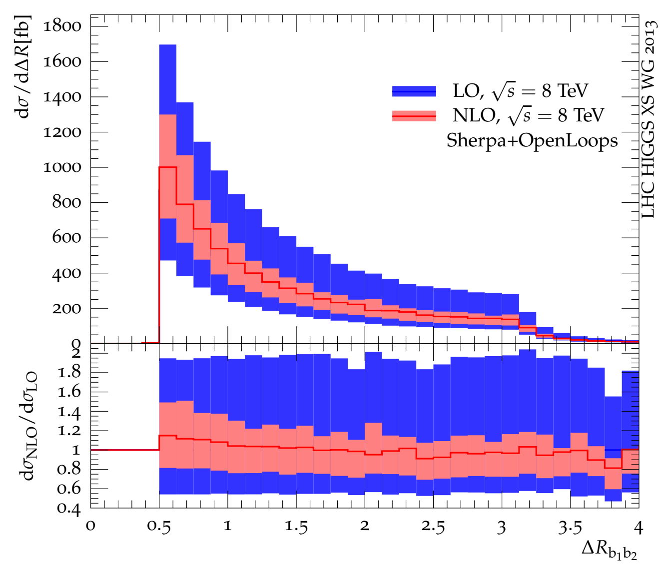
Background: $t\bar{t}b\bar{b}$

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

- $\to$ Bredenstein et al. (arXiv:0807.1248, arXiv:0905.0110, arXiv:1001.4006)
- $\to$ Bevilacqua et al. (arXiv:0907.4723)
- $\to$ Bevilacqua et al. (arXiv:1403.2046): ratio $t\bar{t}b\bar{b}/t\bar{t}jj$

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





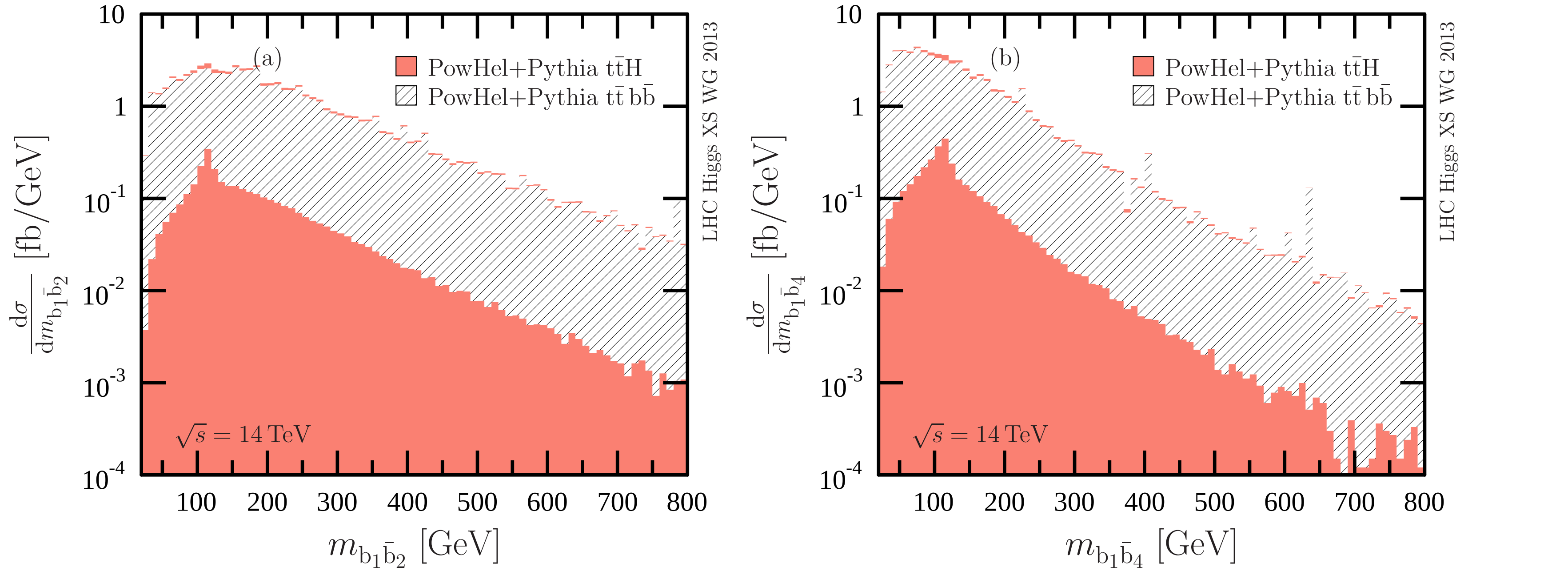
Now interfaced with PS Monte Carlo (Sherpa) in the context of OPENLOOP+Sherpa

$\hookrightarrow$ 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)



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

Summary and Outlook

- After the discovery of a SM-like Higgs boson during Run I of the LHC, precision studies of its couplings could bring very important indirect evidence of non SM physics. It's a unique time!
- The close interaction between theory and experiment and the comparable level of accuracy reached on both sides has been instrumental to the discovery.
- Precision studies needs this process to continue and to be broadened to include new techniques and ideas.
- The field is moving fast and this will have positive repercussions on a broad spectrum of LHC-Run II physics.