INFN
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NLO simulation of gg → HH using POWHEG

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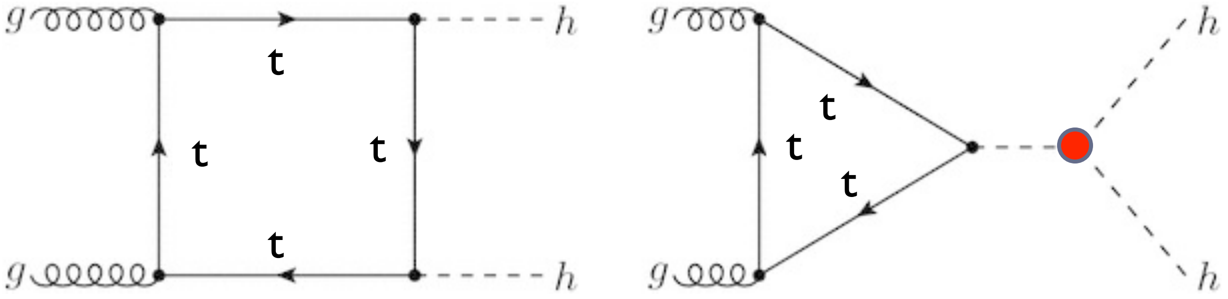
gg → HH: generalities

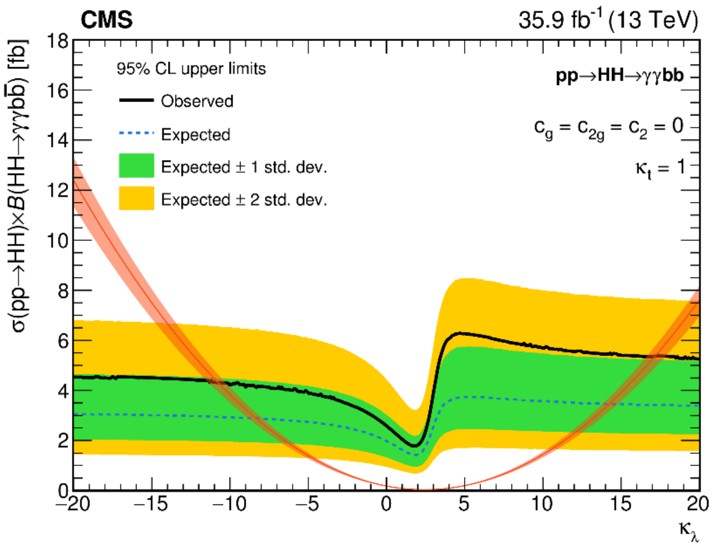
- Crucial search channel for EW precision
  - Measure λ_{HHH} (just λ in the following)
- Non-trivial phenomenology → in the SM, large destructive interference of «triangle» diagram (containing λ-vertex) and «box» diagram



- SM evidence expected only at the HL-LHC
  - For Run2 and 3, it is essential to be able to model (and exclude) large BSM effects → $|\kappa_\lambda| >> 1$

gg → HH: current MC status (2)

- How to generate arbitrary κ_λ for BSM scans?
- Generate a limited number of scenarios («nodes»), with scalings κ_λ = 0, 1 (SM) and k, for for example
- Use:

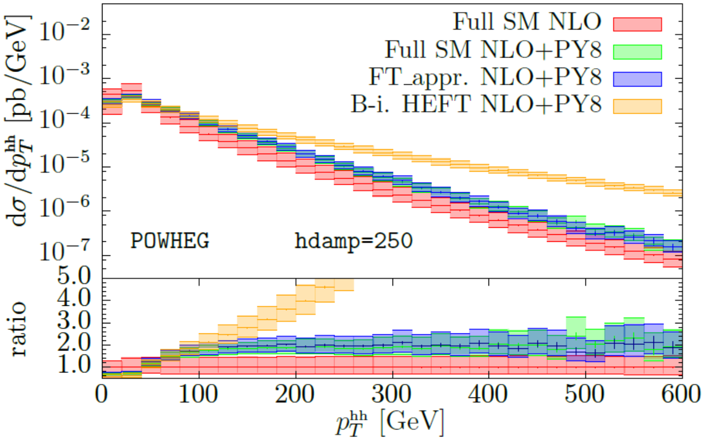


$$\begin{cases} \sigma_0 = b \\ \sigma_1 = t + b + i \\ \sigma_k = k^2 t + b + ki \end{cases} \quad\Longrightarrow\quad \begin{cases} b = \sigma_0 \\ i = \dfrac{k(\sigma_1 - \sigma_0)}{k-1} - \dfrac{\sigma_k - \sigma_0}{k(k-1)} \\ t = \dfrac{\sigma_k - \sigma_0}{k(k-1)} - \dfrac{\sigma_1 - \sigma_0}{k-1} \end{cases}$$

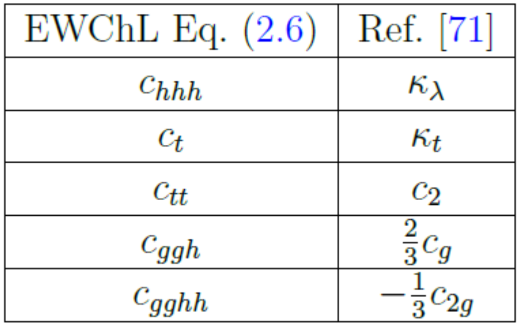
- Therefore, for generic k' : $\sigma_{k'} = k'^2 t(k) + b(k) + k' i(k)$

POWHEG implementation

- https://arxiv.org/pdf/1703.09252.pdf
  - NLO+PS calculation with a few options to obtain a more/less approximated finite t-mass dependence
    - Born-improved EFT
    - FT-approximated top mass
    - Full SM
  - Code available in POWHEG-BOX



- https://arxiv.org/pdf/1806.05162.pdf
  - BSM implementation in the EWChL model (paper provides «translation» to SMEFT parameters)



EWChL Eq. (2.6)	Ref. [71]
c_{hhh}	κ_λ
c_t	κ_t
c_{tt}	c_2
c_{ggh}	$\frac{2}{3}c_g$
c_{gghh}	$-\frac{1}{3}c_{2g}$

Our POWHEG validation

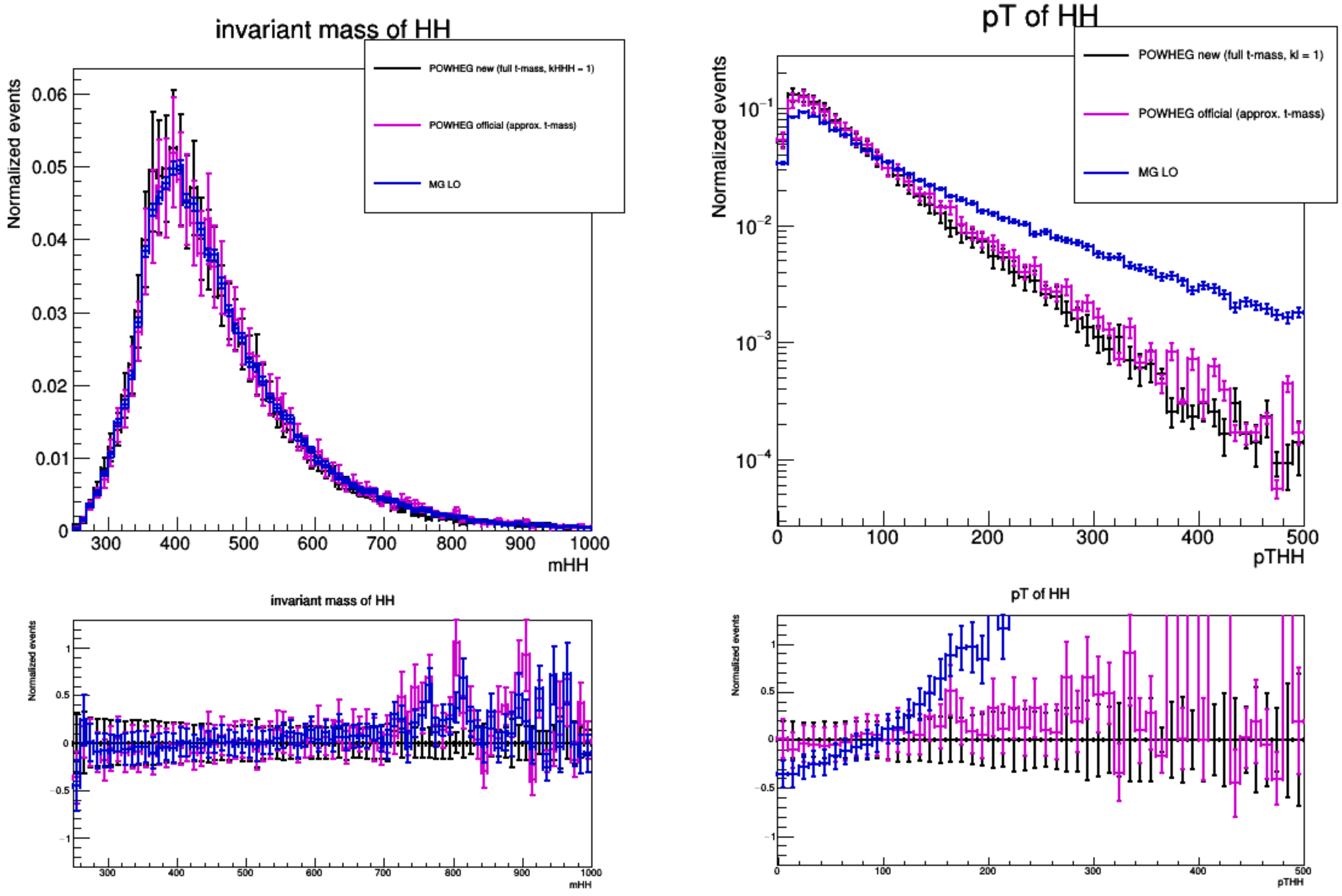
- Validate NLO model with two options:
  1. FT-approximated t-mass
  2. Full t-mass → Technical aspects:
     - Only compiles with gcc7.0, **not gcc6.3**
     - Grids for virtual contributions provided (not computed by POWHEG itself) and read through a custom Fortran/C++/Python interface…
- Validate k'-extrapolation method at the NLO
  - Since triangle and box diagrams can in principle receive different QCD corrections, the method needs to be validated
- To avoid final-state bias, use just HH → bb2l2ν

Running parameters

Sample	Time/event (POWHEG+ Pythia) [s]	Negative weight fraction	σ (NLO) [fb]	σ (LO) [fb]
SM (approx.)	217	4.8%	27.4	14.5
SM (full)	21	6.3%	26.8	
κ_λ = 0	16	3.2%	60.0	30.5
κ_λ = 5	13	0.6%	79.0	34.4
κ_λ = 20	9.5	0.1%	2920	1310

- Time/event computed with scale and NNPDF3.1 NNLO PDF weights only (9+101)
  - Change in first column expected → code become much faster recently, as advertised by the authors

Basic variables: m(HH), p_T(HH)

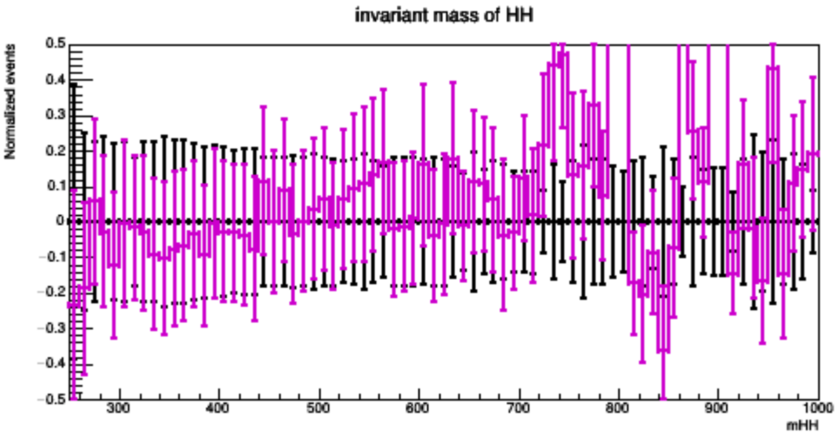


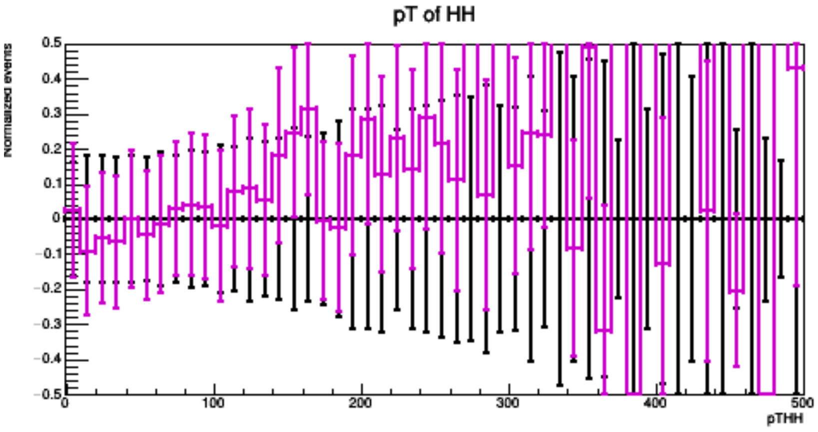
Error bars:
- MC stats for LO
- Actual scale uncertainties for NLO

- Spectrum significantly softer than LO+EFT modeling

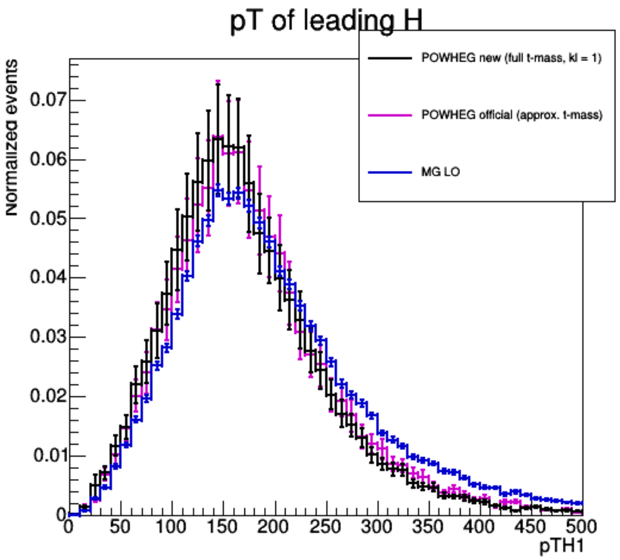
Basic variables: m(HH), p_T(HH)

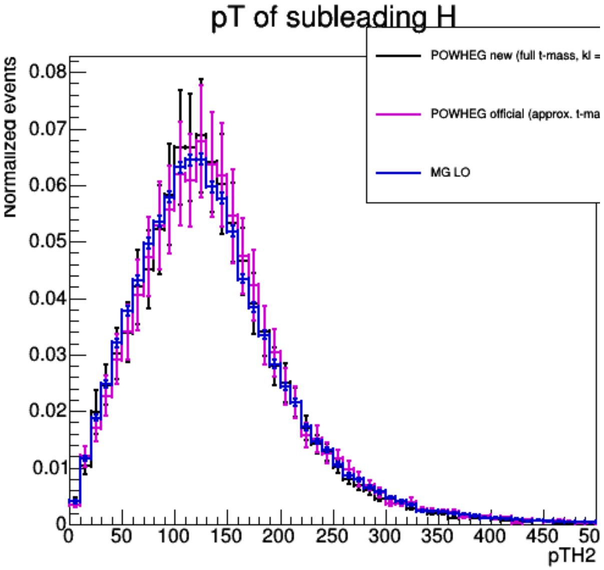
- A closer look to POWHEG (approximated) vs. POWHEG (full) shows discepancies of -10% to 15-20%
  - Contained in the quite large scale uncertainties for pT < 300 GeV, after that statistics is insufficient
- Consistent with paper results

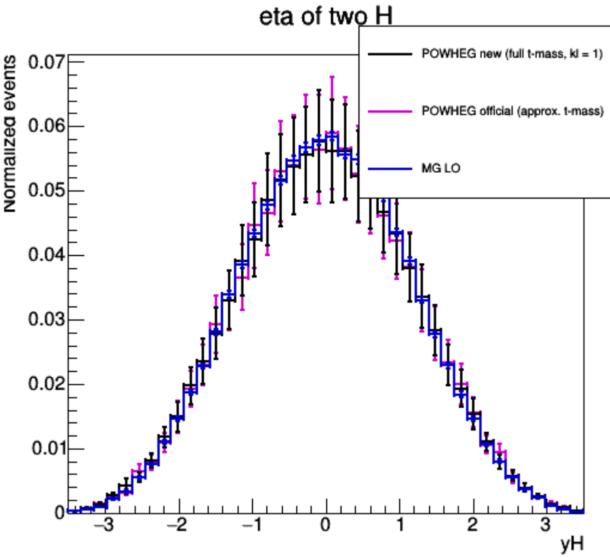


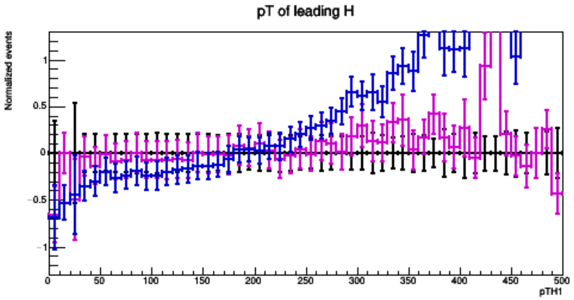


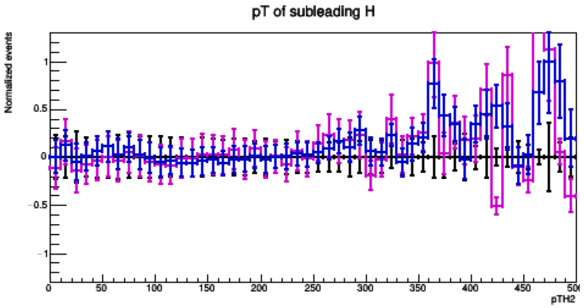
Basic variables: $p_T(H_1)$, $p_T(H_2)$, $y(H)$

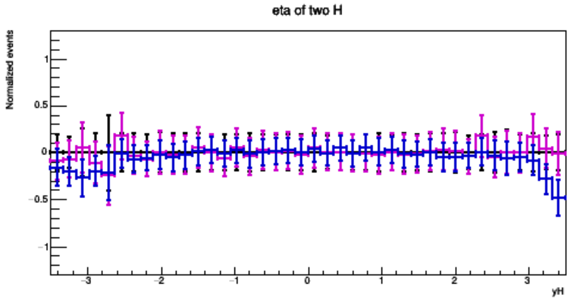




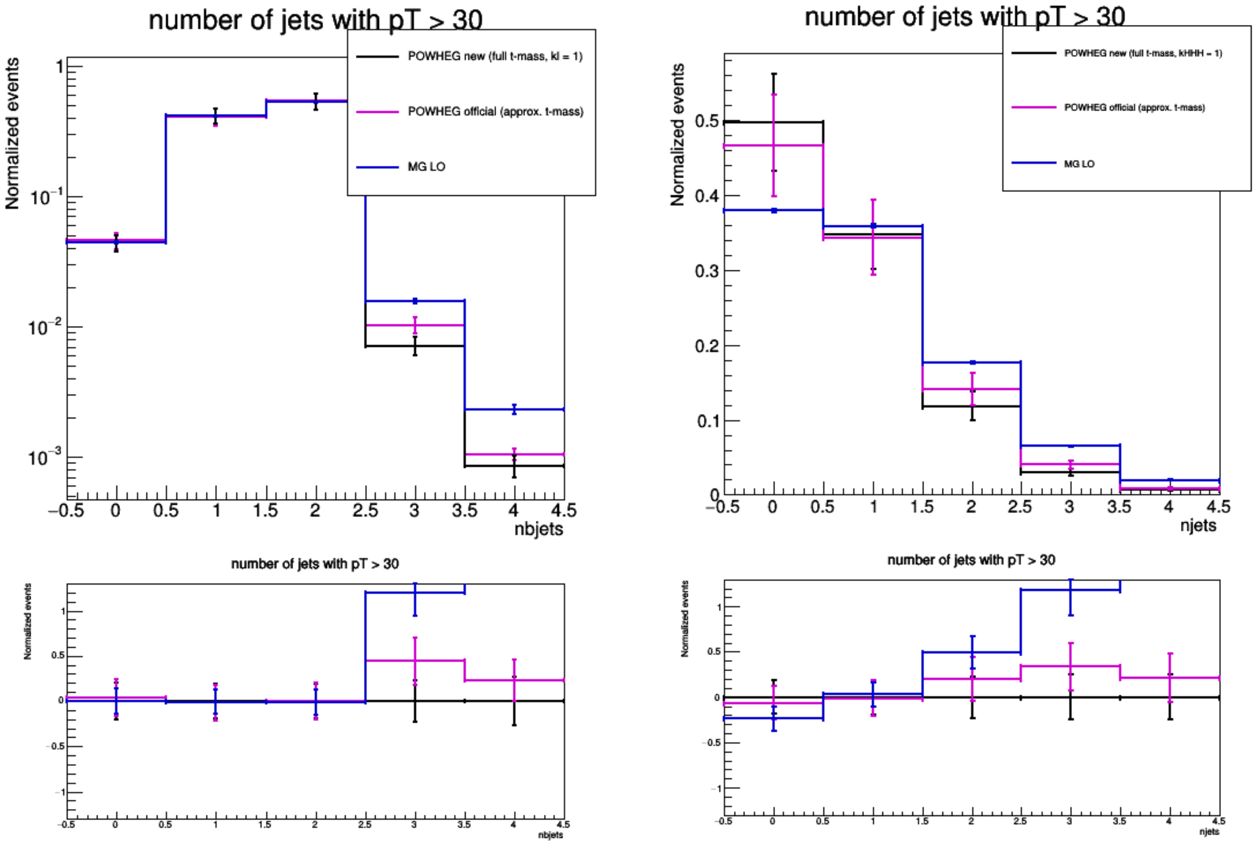








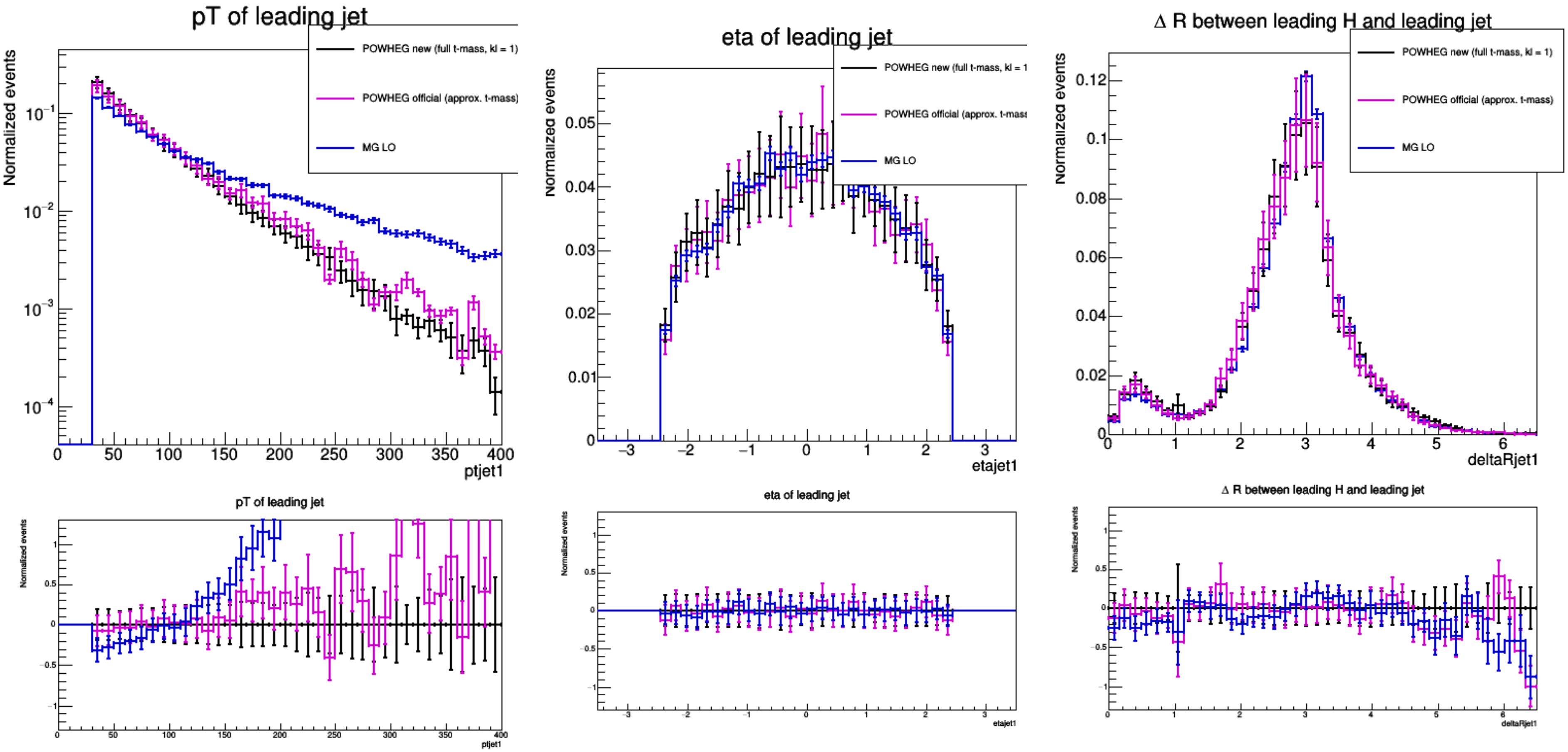
N(b jets) and N(extra light jets)



«GEN-level b-tagging»: Require a B-hadron inside the jet with pT > 10 GeV

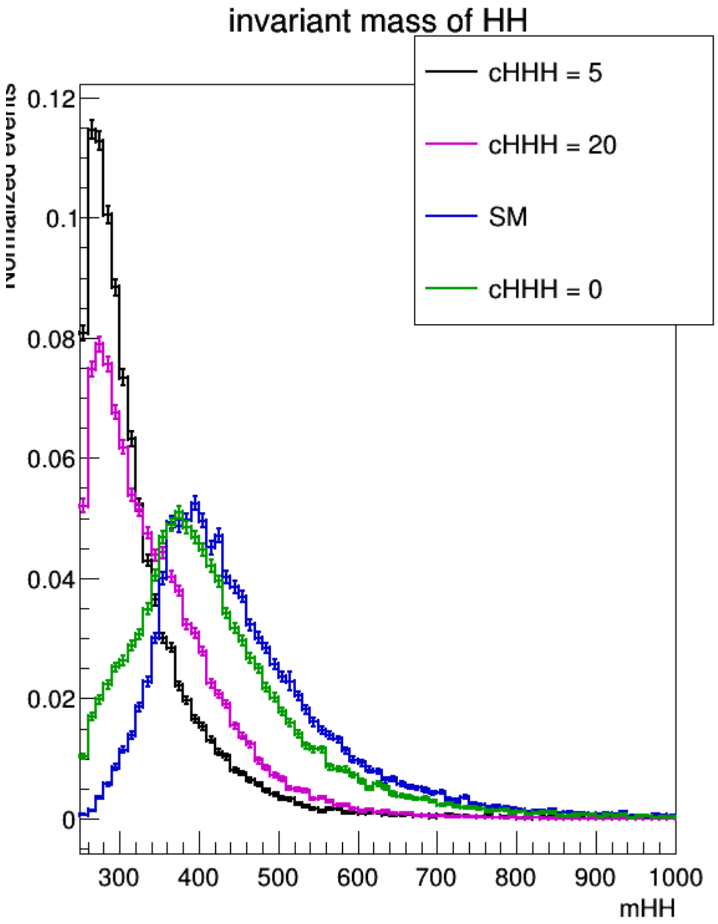
- Unmatched PS producing more jets and (a few) more extra b-jets

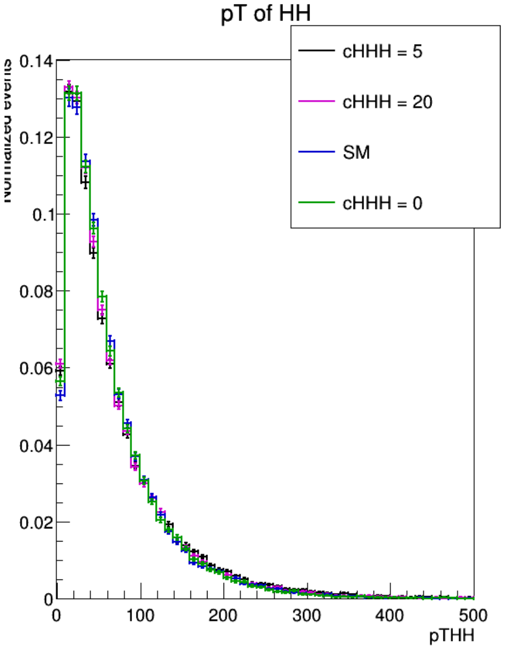
Leading jet: p_T, η, $\Delta R(H_1)$



k’ extrapolation method

- Test SM + 3 BSM predictions (κ_λ = 0, 5, 20)
  - Large change in m(HH), almost no changes in p_T(HH) or cosθ^*





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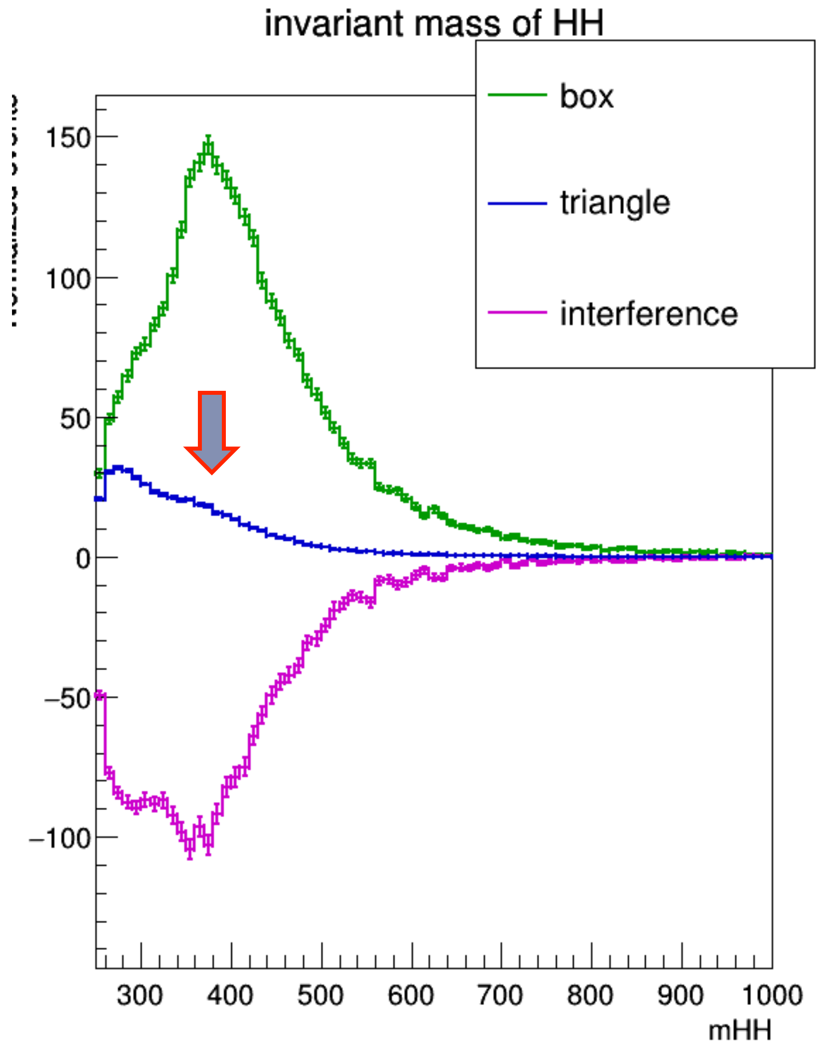
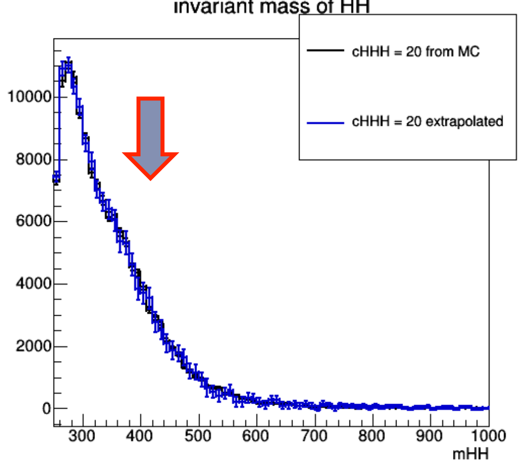
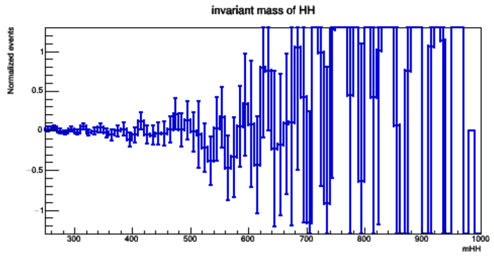
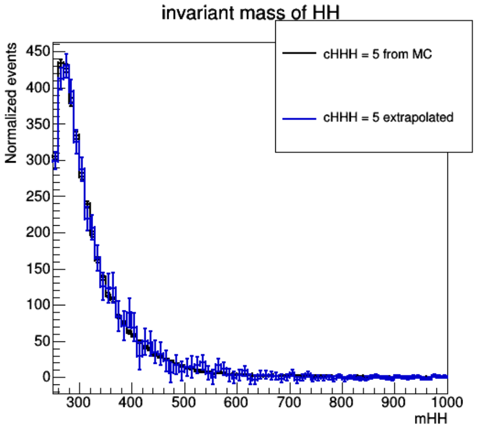


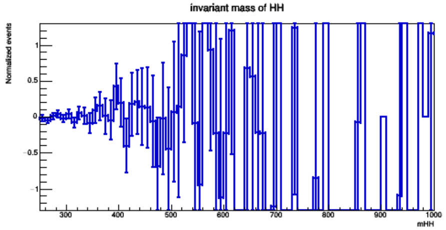
- k’ = 20
  from 0, 1, 5

- k’ = 5
  from 0, 1, 20





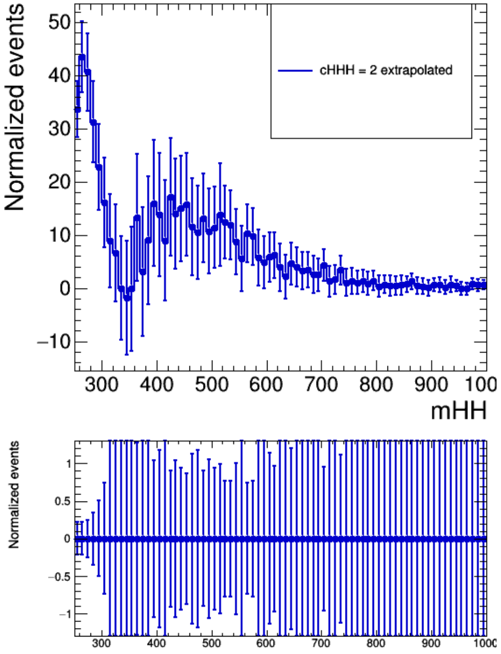




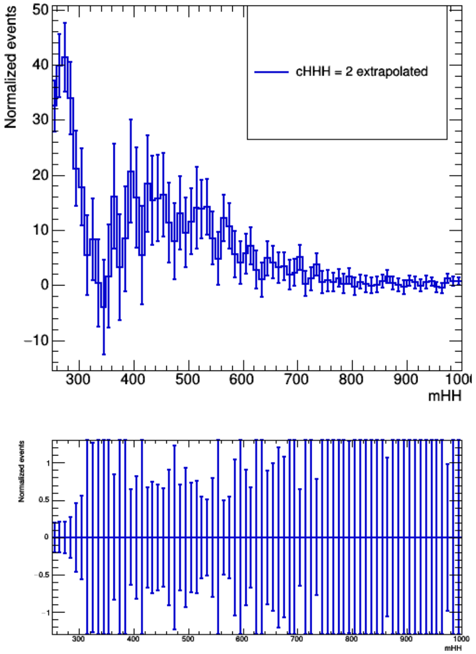
Statistical power

- Tricky effects of the destructive interference:
  - the choice of k giving the maximal statistical power in modeling arbitrary k' is not the most signal-like ($\kappa_\lambda = 20$) but the one with the most different, i.e. softest, m(HH) spectrum ($\kappa_\lambda = 5$)
- Not true in all cases:
  - e.g. maximal interference case ($\kappa_\lambda = 2.45$)

- k' = 2.45 from 0, 1, 5



- k' = 2.45 from 0, 1, 20



Conclusions

- NLO POWHEG implementation of the gg → HH process is validated in the CMS generator framework
  - Technical issues solved, but compilation requires gcc7.0
  - Time/event and negative weight fractions OK for official production and general use
- Comparisons:
  - With LO+EFT model: significantly softer p_T(HH) and N_{jets} spectra
  - Full vs. approximated t-mass: discrepancies within scale uncertainties
- k' extrapolation method
  - Fully validated, no conclusive answer on the best choice of the «nodes»