Off-shell Higgs and Interference: Theory update

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LHC HIGGS CROSS SECTION WORKING GROUP
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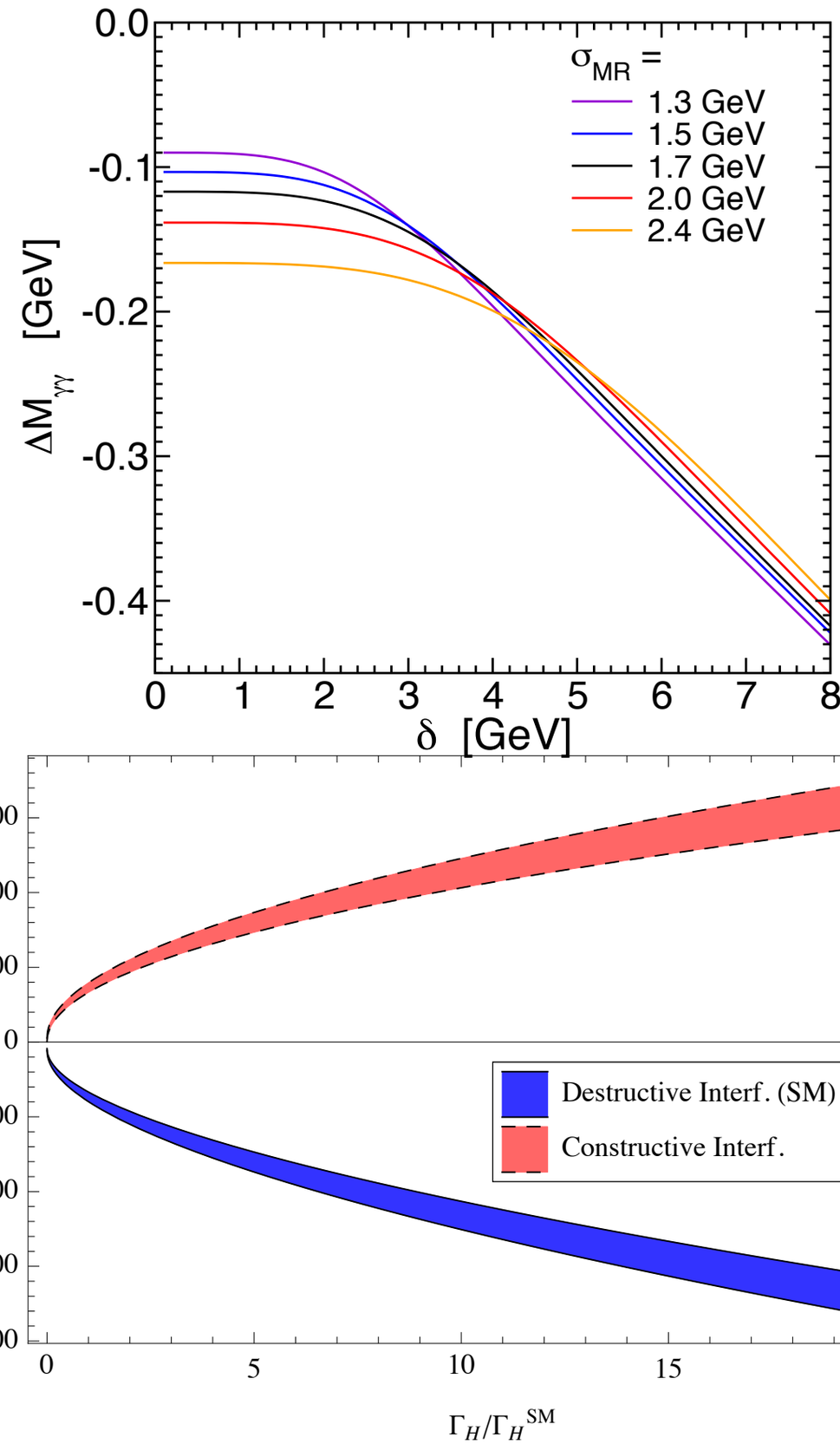
H→γγ: interference and mass shift

[Martin (2012), Dixon and Li; de Florian et al (2013)]

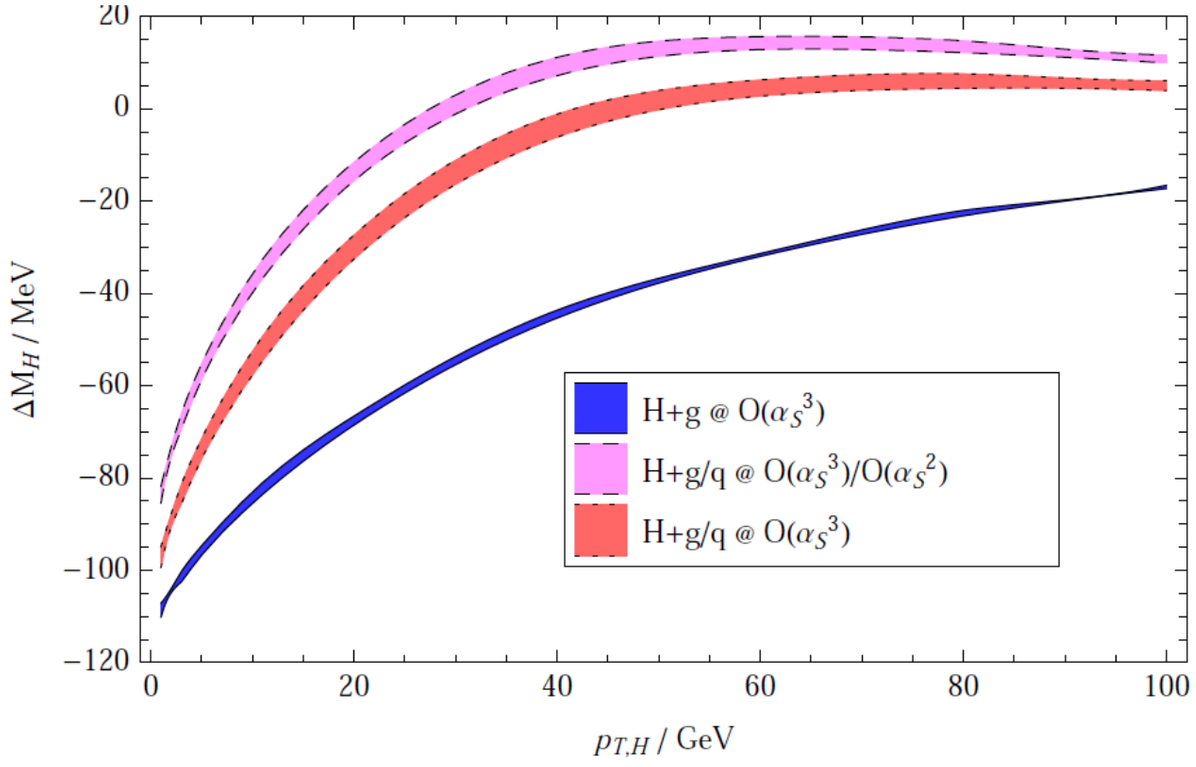


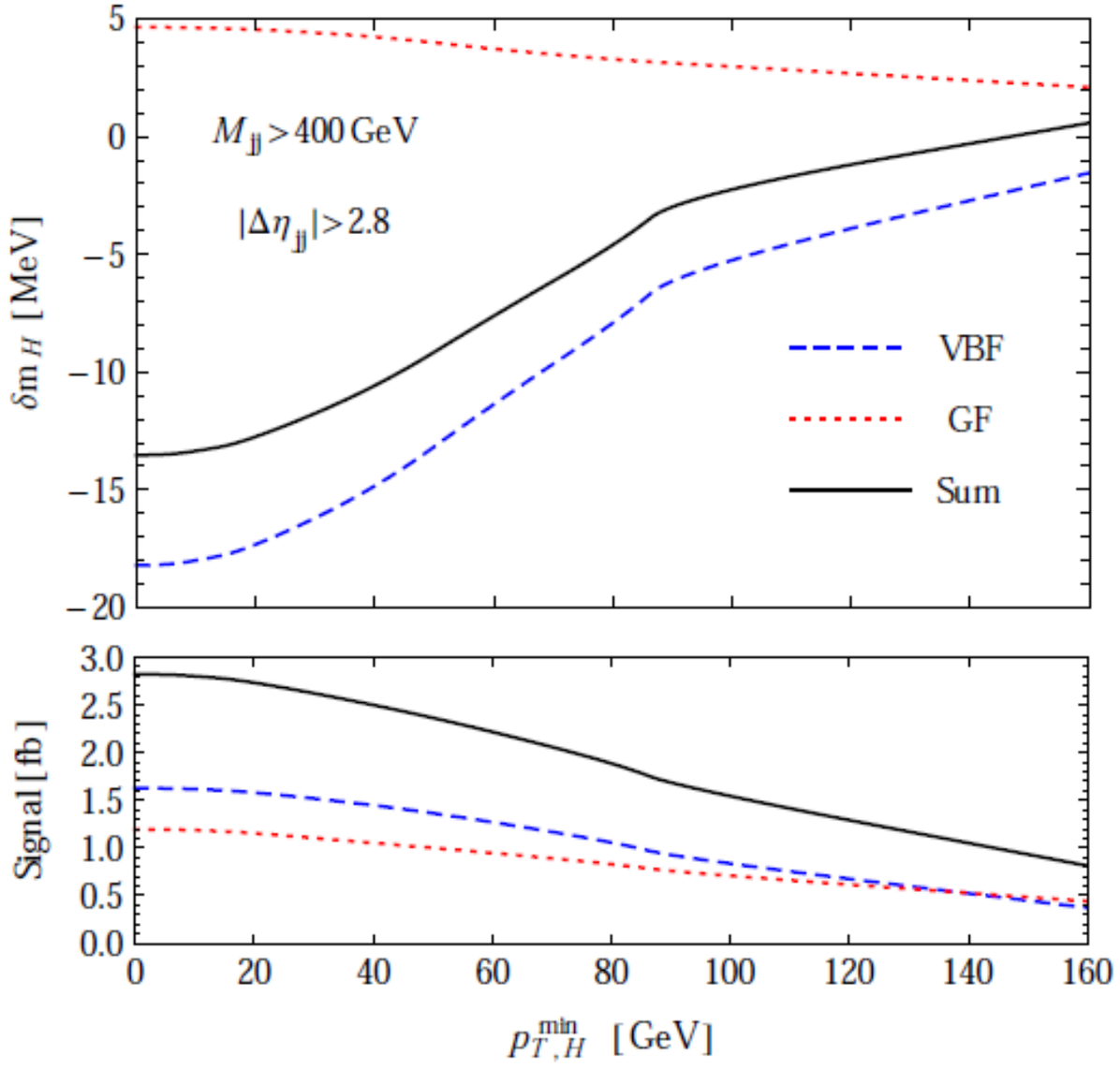
- Real part of signal gg → H → γγ and continuum gg → γγ production leads to *distortion in $m_{\gamma\gamma}$ shape*
- Peak shift ~ *independent* on the Higgs width, dependent on *environmental parameters* (detector resolution) and *interference strength*, ~ $g_i\, g_f$
- Combined with signal yield $\sigma \sim g_i^2\, g_f^2 / \Gamma_H$, can give *constraints on the Higgs width*
- Largely model-independent
- Small effect (~50 MeV, see Yanyan talk for thorough estimates)
- Need to minimize systematic uncertainties

Using γγ as control sample

[Martin (2012); Dixon and Li; de Florian et al (2013), Coradeschi et al (2015)]

- Mass shift *strongly sensitive* on selection cuts → can use γγ both as signal and as control regions, reduce systematic error w.r.t. e.g. ZZ
- Largest mass shift at low p_t → 2-bin analysis
- Particularly useful: γγ + 2j samples: opposite effect in GF and VBF, very small mass shift
- Good control region: $m_{jj} > 400$ GeV, standard photon cuts (small shift, non negligible rates)

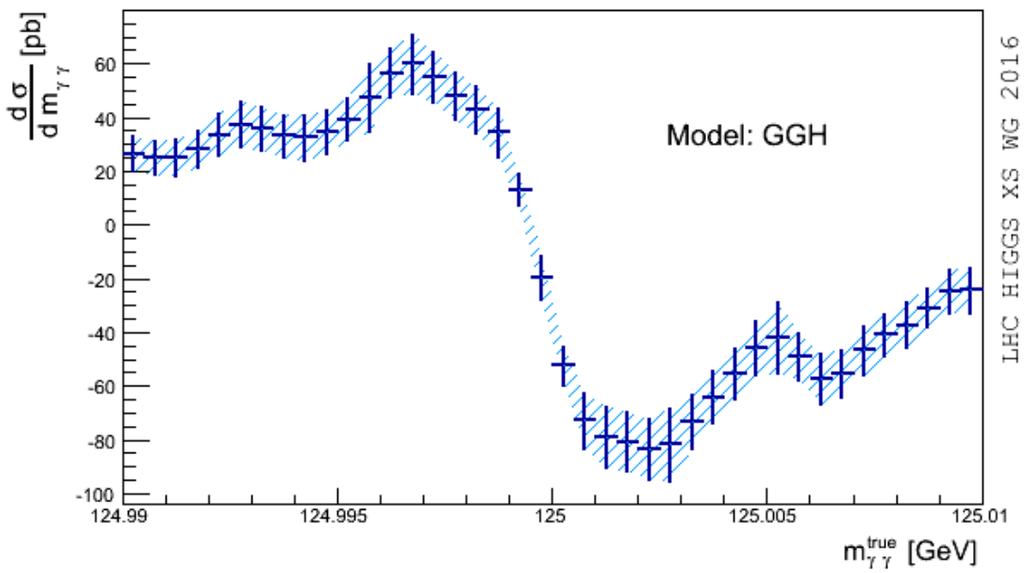




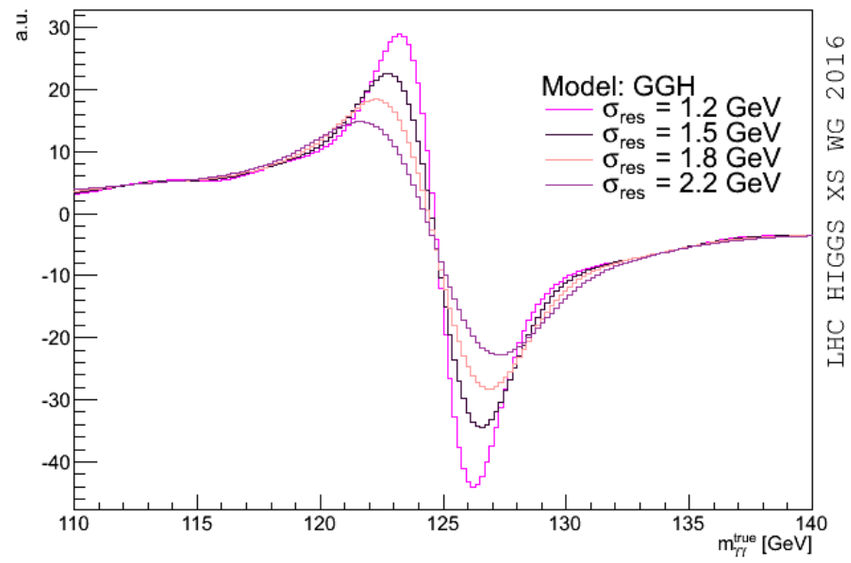
Available tools and K-factors

- Parton shower implementation available, Sherpa+DIRE (Höche et al.)

Interference



Interference, w. energy smearing

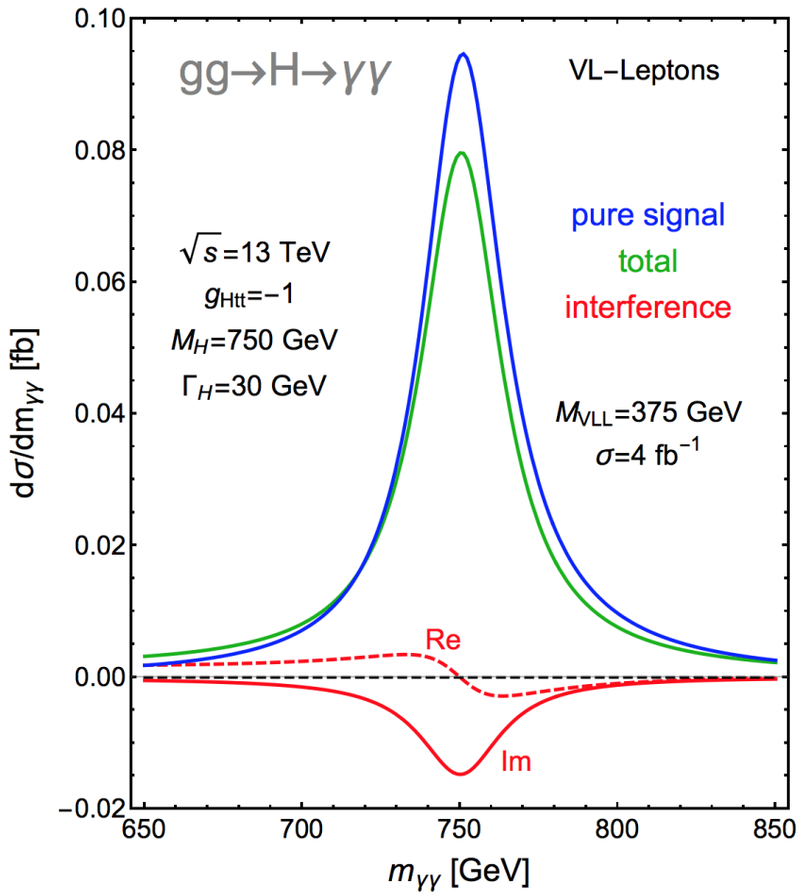


- ATLAS analysis: → see Yanyan's talk
- Signal: NNLO. Background/interference: NLO
- NNLO background: 3-loop, mass effects…
- Reasonable assumption: $K_B \in [1, K_S]$. Motivated by NLO K-factor

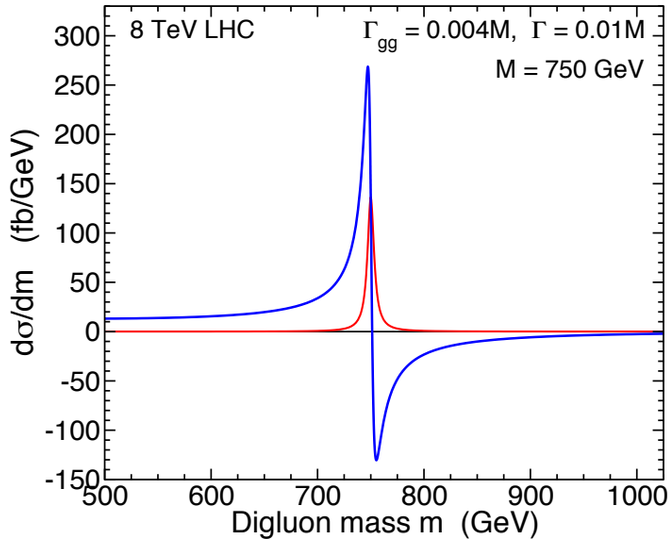
Interference for BSM resonances

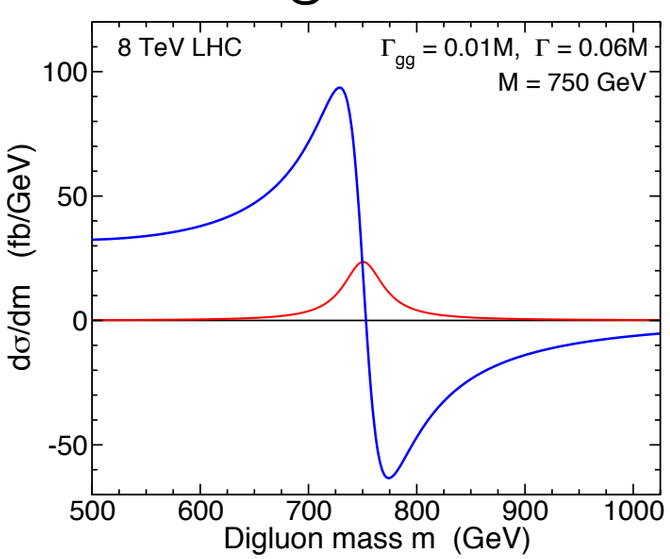
[Djouadi et al; Hespel et al; Dawson, Lewis; Martin (2016)]

Photons

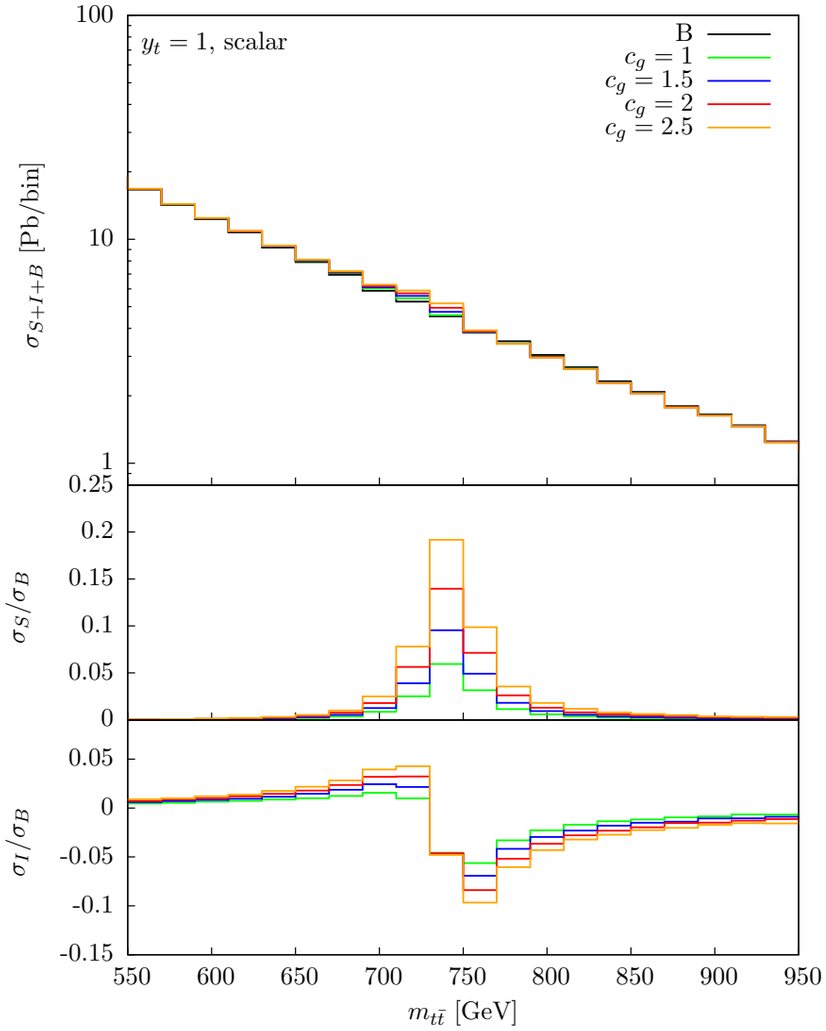


gluons





Tops

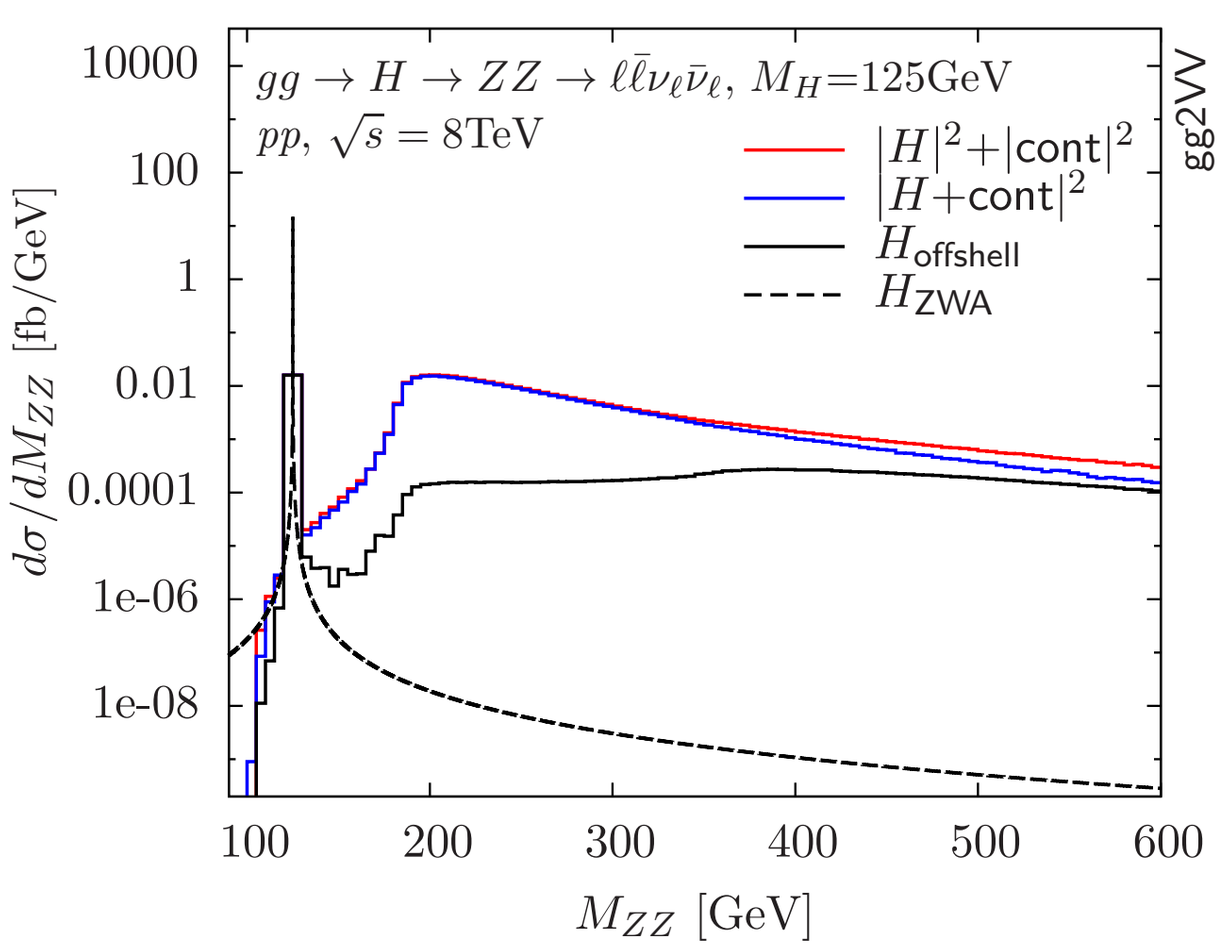


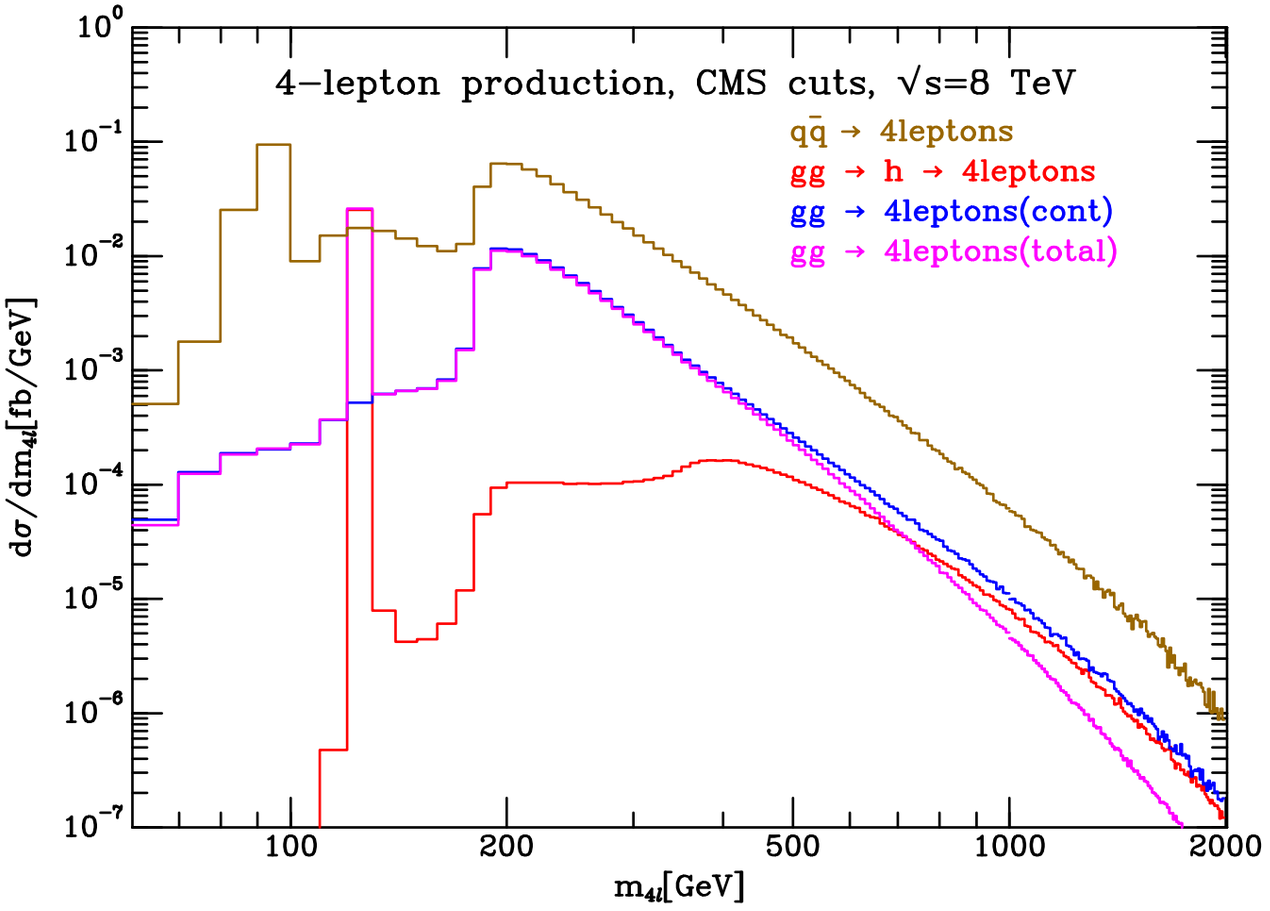
- Interference effects likely to play a role for (high mass) resonances
- Same spirit, but situation can be *qualitatively different* (top, thresholds…)
- Cannot just rescale Higgs results

Off-shell Higgs

[NK, Passarino (2012); FC, Melnikov (2013); Campbell, Ellis, Williams (2013)]

- Despite being a *narrow resonance*, in the SM the Higgs develops a sizable *high invariant mass tail* (enhanced decay to real longitudinal W/Z)
- The tail is *width independent* → direct extraction of off-shell couplings
- Under assumptions on on/off-shell coupling correlations → strong bounds on Higgs width by combining off-shell tail and signal yield





Relevance for σ_{tot} and available tools

At the inclusive level, σ_{off} ~ 10% enhancement of BW result. *However*

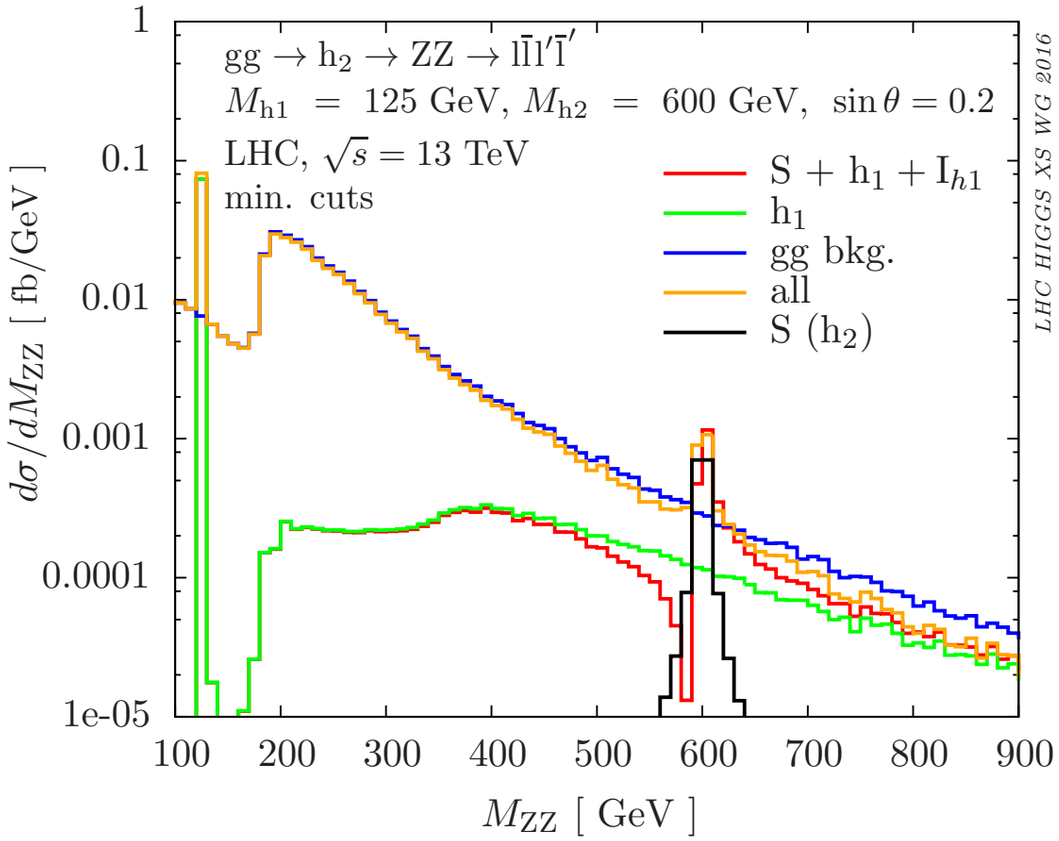
- Off-shell effects completely killed by m_{4l} cuts for ZZ analysis
- WW analysis require a m_T cut to avoid large off-shell contamination

Status of theoretical predictions

- Many available tools for LO background and interference: gg2VV, MCFM, MadGraph5_aMC@NLO, OpenLoops+Sherpa, GoSam, JHUGen/MELA+MCFM… Benchmark results in YR4
- Signal: NNLO. Benchmark K-factors in the off-shell region in YR4
- Background/interference: LO/LO+PS (→see Yanyan)/Merged LO+PS
- After YR4: first exact results for NLO background/interference in the intermediate off-shell region $m_{4l} < 350$ GeV

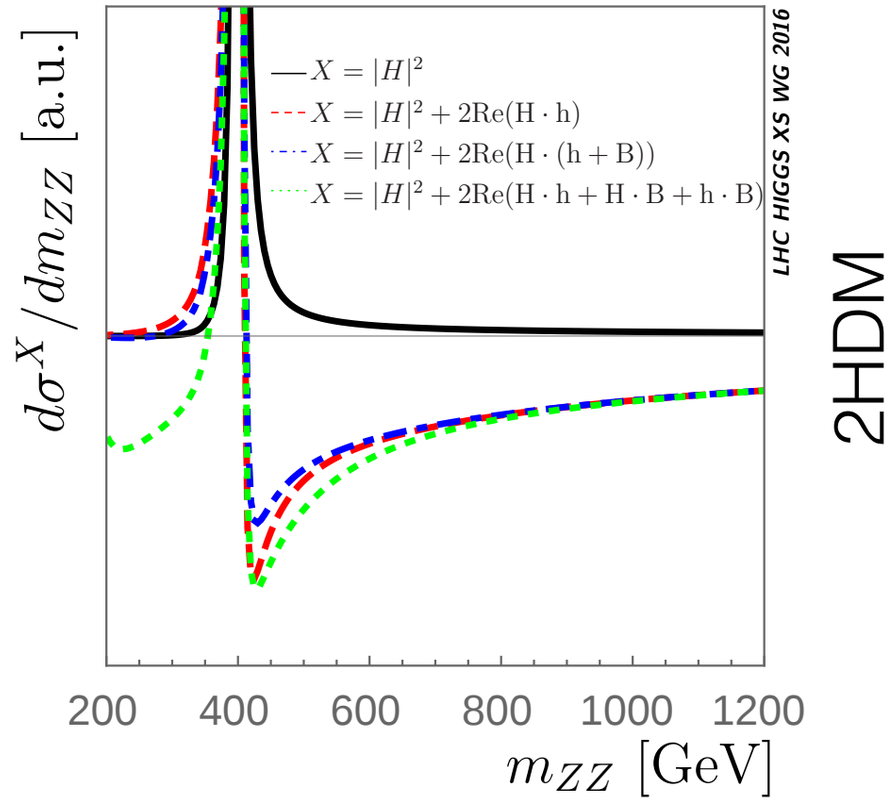
Studies for benchmark BSM models

Singlet extension

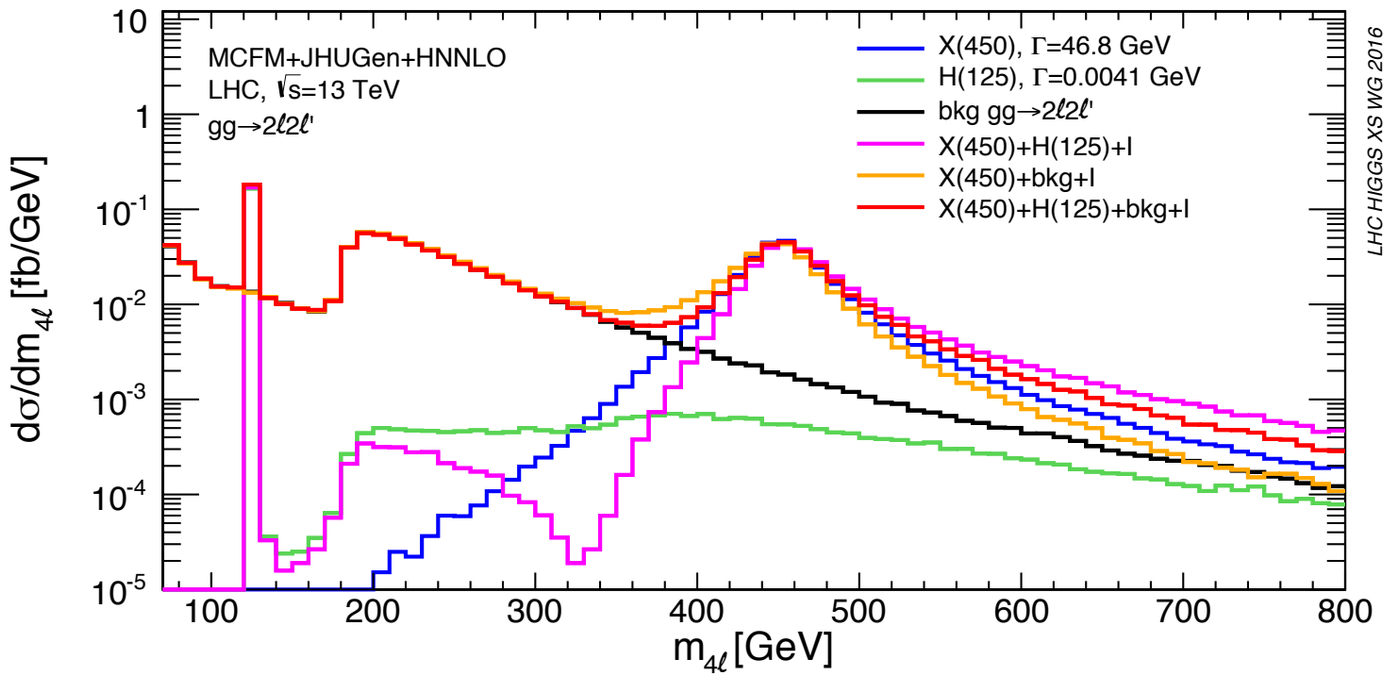


- Non trivial interference patterns
- Signal/background interference
- Light/heavy interference

2HDM

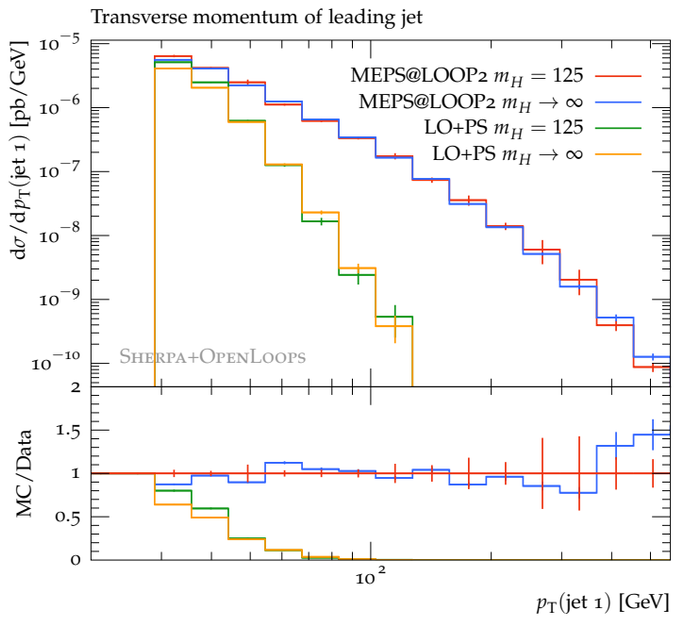


Generic couplings



Beyond LO

PS merging: gg→(H)→WW [OpenLoops+Sherpa]

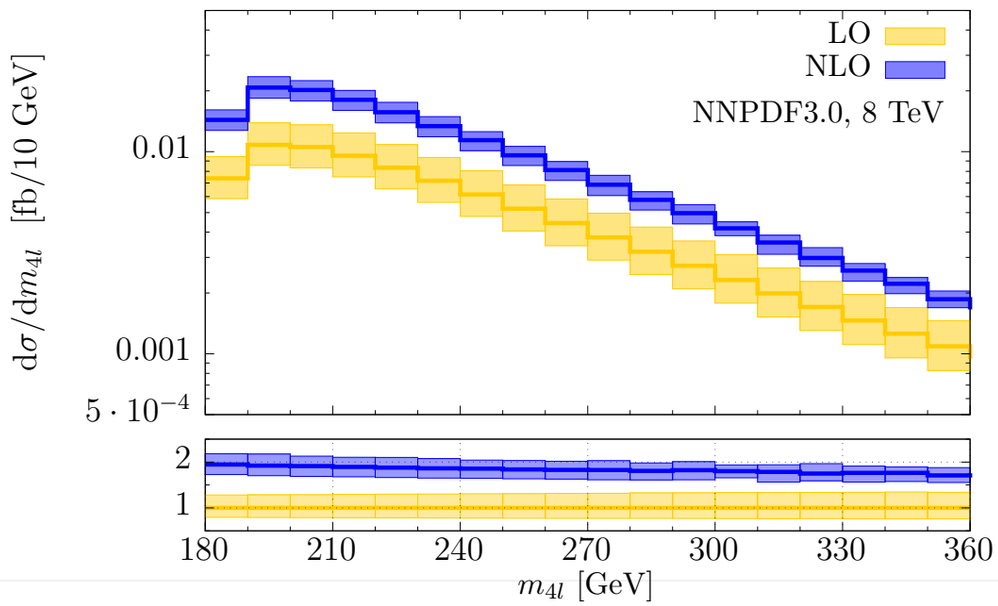


Results as expected

- Harder p_t spectrum
- More jet activity

NLO for the background, $m_{4l} \sim 2\, m_V$

[FC, Melnikov, Röntsch, Tancredi (2015)]

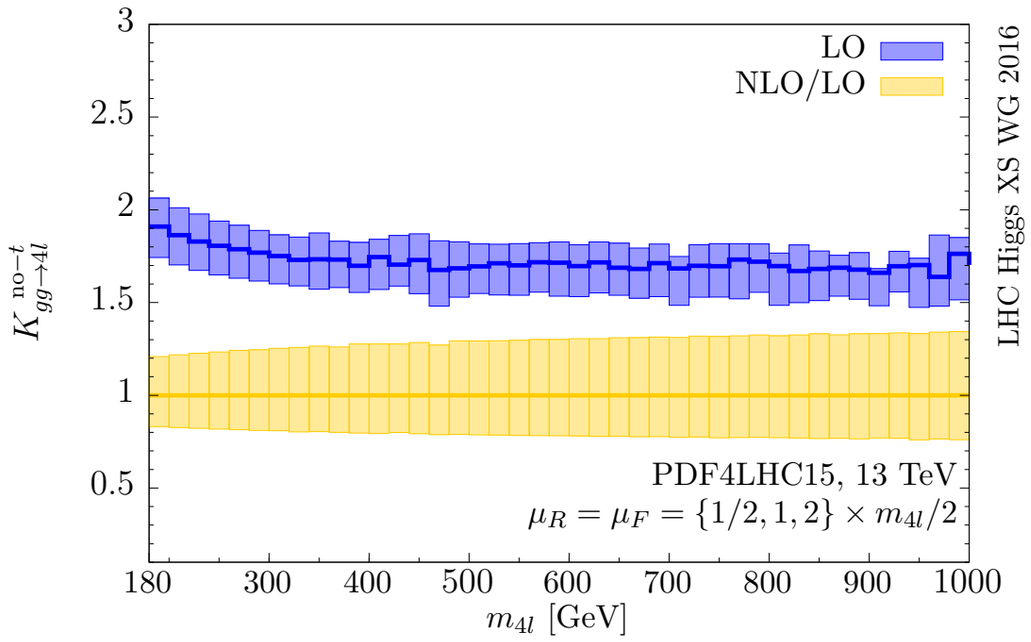


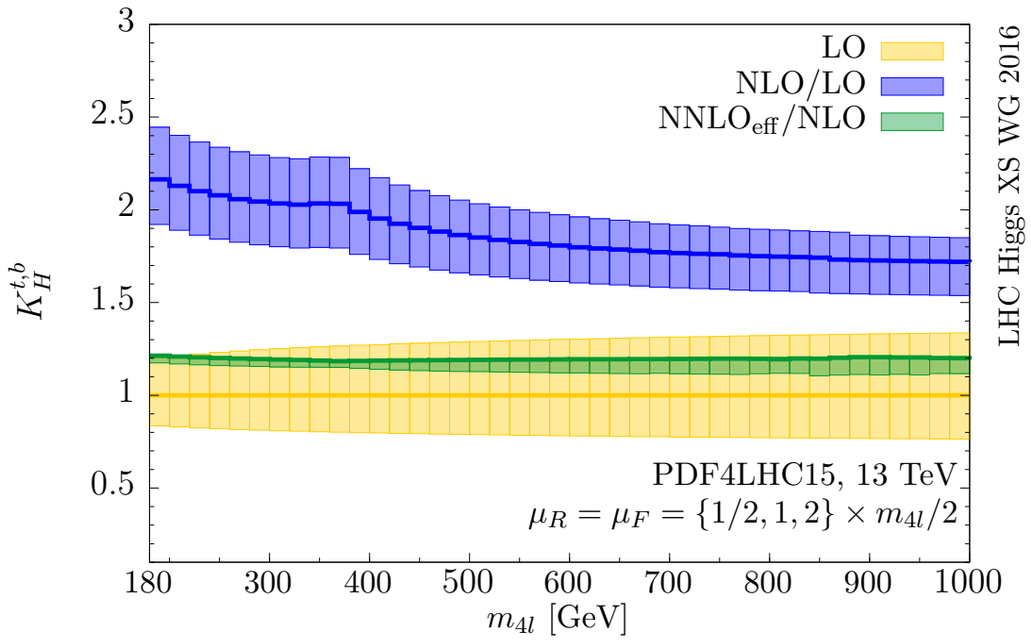
No surprises

- K-factor ~ Higgs
- K-factor rather flat

The NLO K-factor: YR4 suggestions

- Large corrections, K-factor is important
- All information available support $K_S \sim K_B$. Natural scale: $m_{4l}/2$
- Large residual scale variation → fine details not so relevant



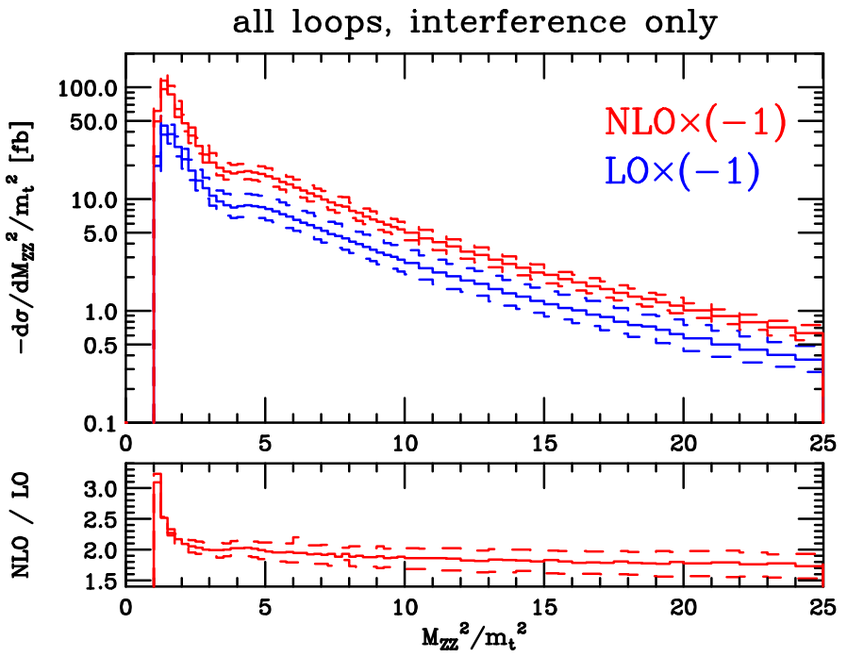


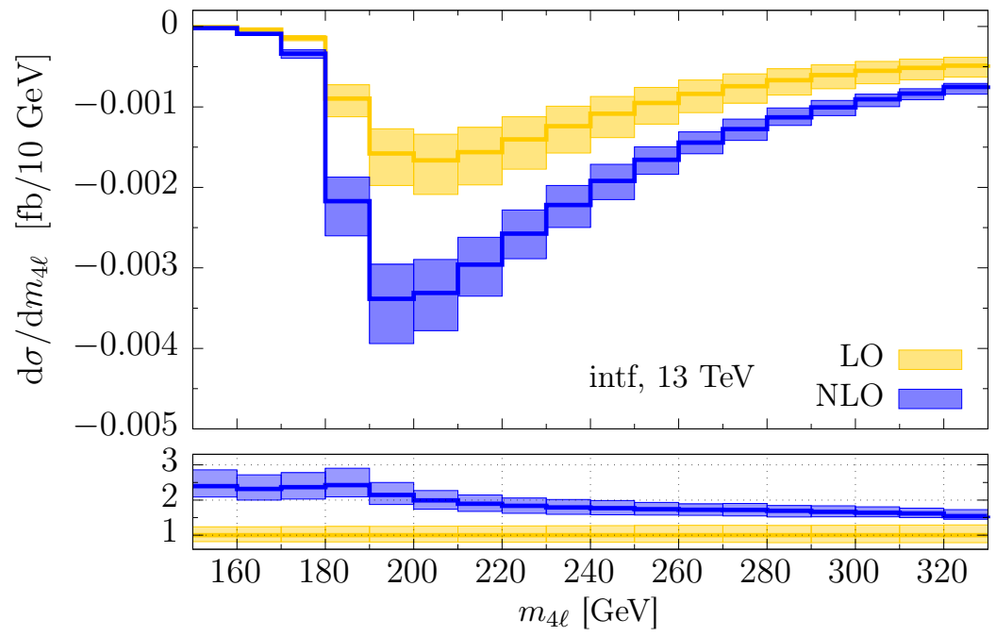
- Reasonable to expect similar pattern at NNLO
- One option for K_B: use exact (massless) NLO K-factor, with related uncertainty
- Another option: use $K_S \sim K_B$, at NNLO
- Difference gives an estimate of uncertainties
- Interference: geometric mean of K_S and K_B

Post YR4 developments

Recently, first exact results for signal/background/interference at NLO in the mild off-shell region $m_{4l} < 350$ GeV available

[Cambpell, Czakon, Ellis, Kirschner; FC, Dowling, Melnikov, Röntsch, Tancredi (2016)]



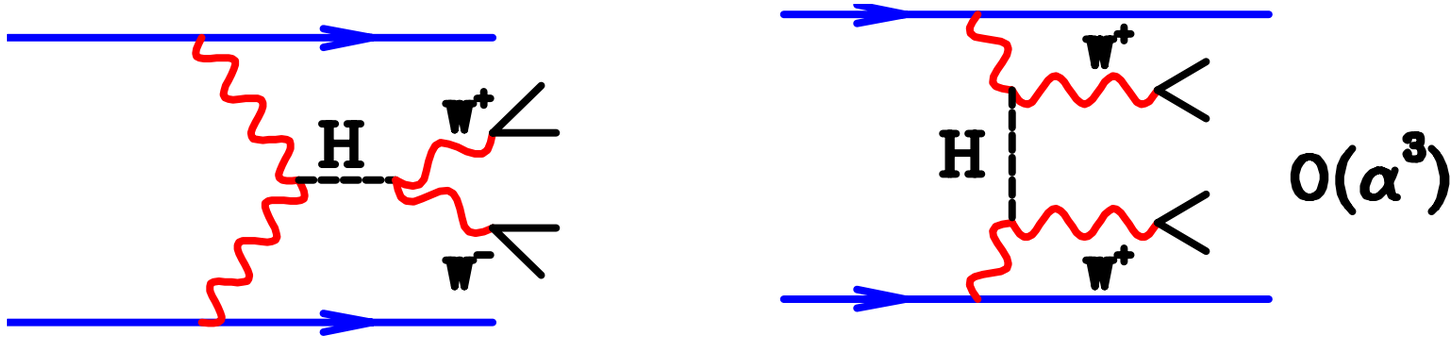


- YR4 suggestions confirmed: $K_S \sim K_B \sim K_{int}$
- $K_{int} \sim \sqrt{K_s}\, K_b$ badly violated only for $m_{4l} < 2m_V$, where interference effects negligible
- Suggestions that results should hold also in the very high mass $m_{4l} > 350$ GeV region

An alternative approach: VBF

[Campbell, Ellis (2015)]

- No K-factor problem
- Theory systematics (interpretation issues…) somewhat different
- Complementary approach w.r.t. ggF



- Smaller rates → less significance. Rough estimate: at the end of Run II similar bound to ggF now (but different theory systematics)
- Dedicated generators available (e.g. VBFNLO, MCFM, PHANTOM, JHUGen/MELA, MadGraph5_aMC@NLO…)

Summary

- Interesting developments for interference/off-shell studies
- Many available results, a lot of theoretical studies
- gg → VV: lot of progress, but high-mass NLO still unknown. Future developments
  - Merge NLO in the intermediate off-shell region with PS → generators available to experiments
  - NLO at high mass: recent progress in fully numerical multi-loop computations suggests this could be done, at least with some reasonable approximations

- Not a lot of discussion in the WG about interpretation issues / BSM studies beyond benchmark models
- *Proposal*: add a new theory convener with more BSM expertise