HXSWG-WG1: Off-shell task force, first open meeting (theory)

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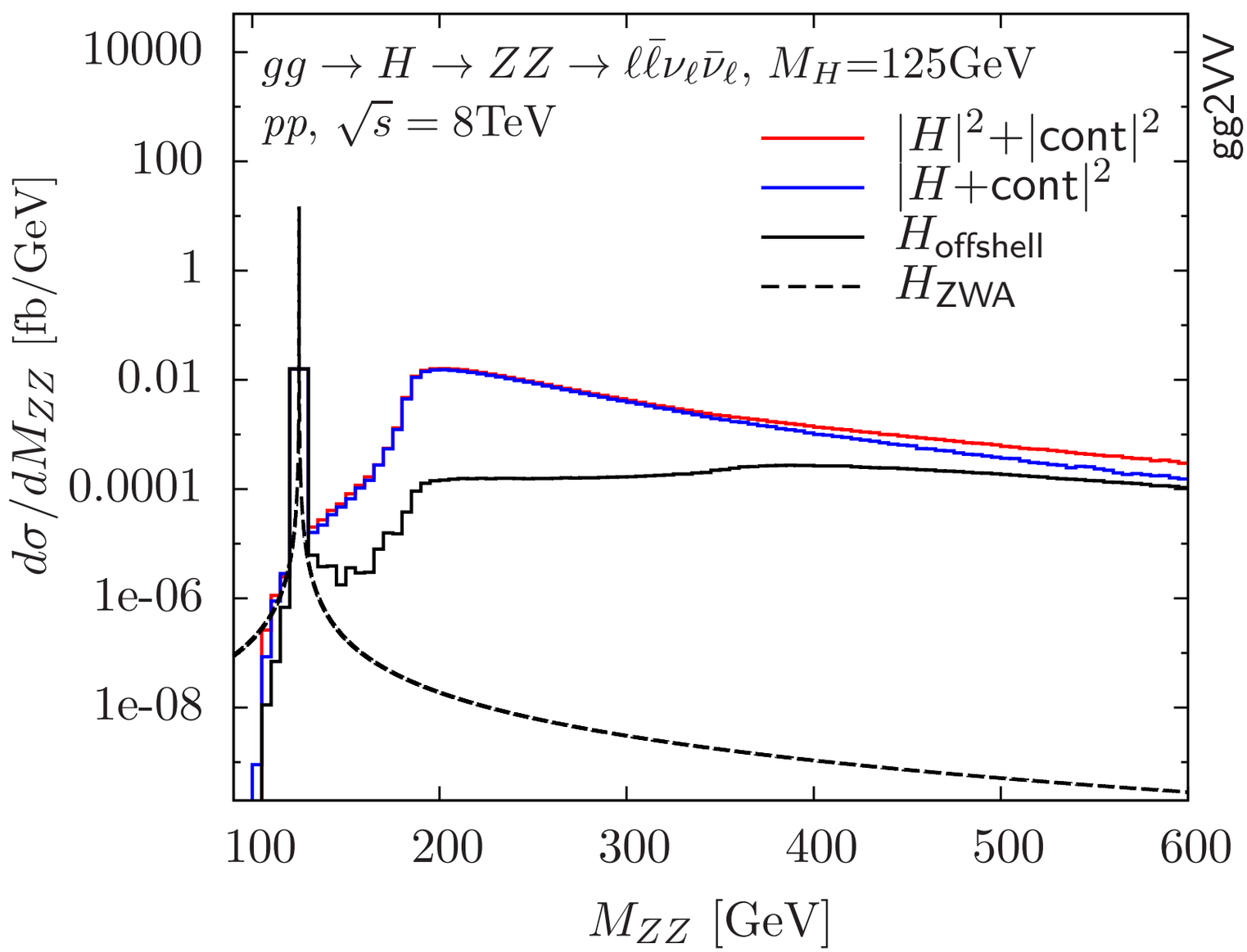
H->VV and the off-shell cross-section

[NK, Passarino (2012)]

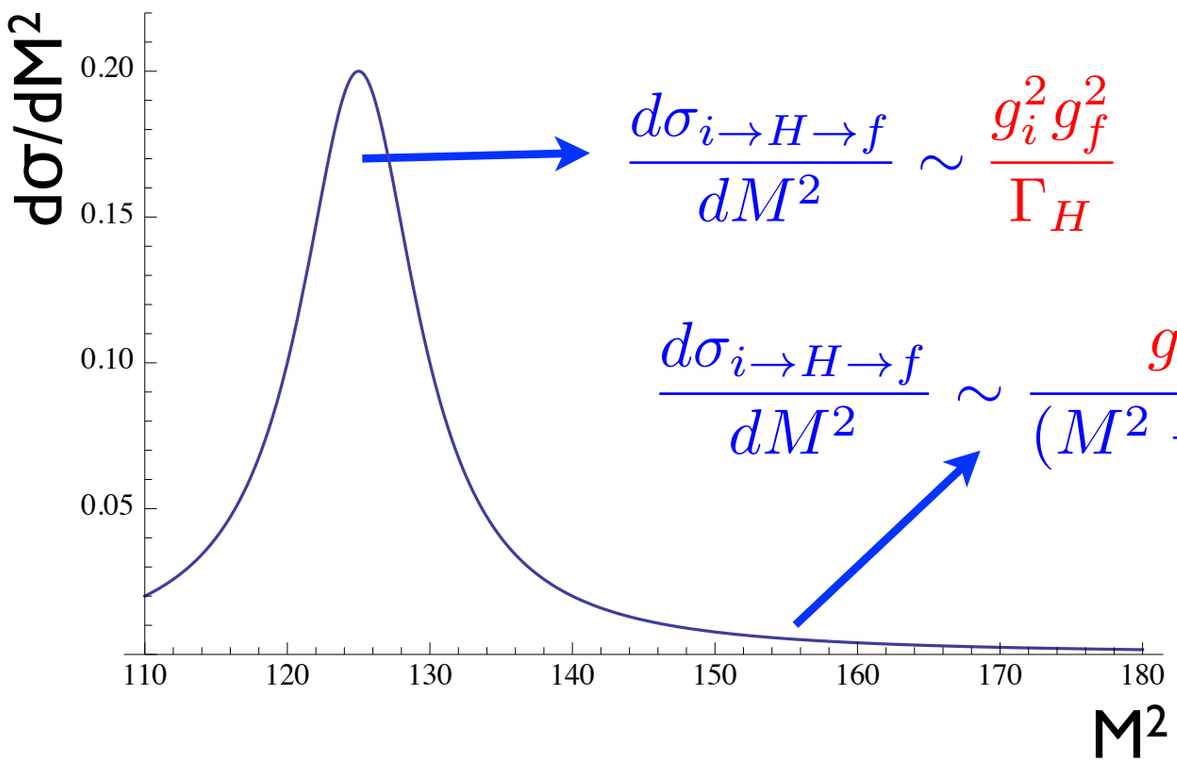


- Past the VV threshold: enhanced decays in $V_L V_L$ which compensate the rapid fall of the Higgs propagator (BW fails)
- Small but persistent effect, up to ~ 1 TeV (then washed away by PDF)
- Sensitive to (top) thresholds
- Width-independent effect

- Irrelevant for standard analysis because of selection cuts
- Can provide complementary information about the Higgs sector

Example: bounding the Higgs width

[FC, Melnikov (2013)]



$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2 - m_H^2)^2}$$

- On the peak, only access to production cross-section times BR
- Off-shell, Γ_H independent
- Because of this, combine peak and off-shell and obtain Γ_H

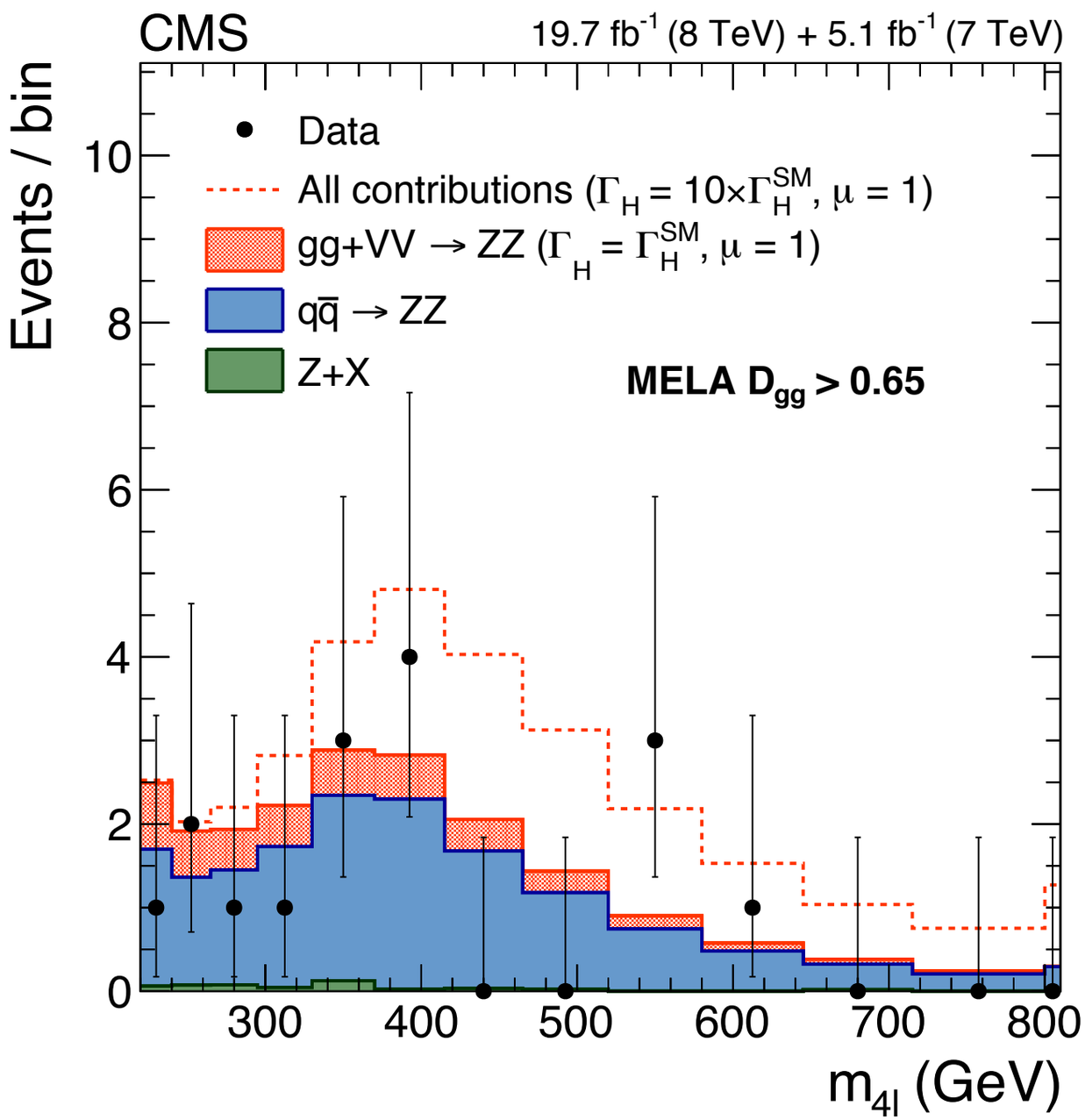
- Peak looks SM-like -> $\frac{g_i^2 g_f^2}{\Gamma_H} = \frac{g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2}{\Gamma_{H,\mathrm{SM}}} \longrightarrow g = \xi g_{\mathrm{SM}},\ \Gamma_H = \xi^4 \Gamma_{H,\mathrm{SM}}$
- Off-shell -> $N_{obs}^{off} \propto g_i^2 g_f^2 = \xi^4 g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2 \propto \xi^4 N_{\mathrm{SM}}^{off} = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} N_{\mathrm{SM}}^{off}$

Pheno studies: bounds of the order ~ 10-20 $\Gamma_{H,\mathrm{SM}}$ can be achieved

[Ellis,Campbell,Williams (2013)]

CMS analysis

[CMS-HIG-14-002]

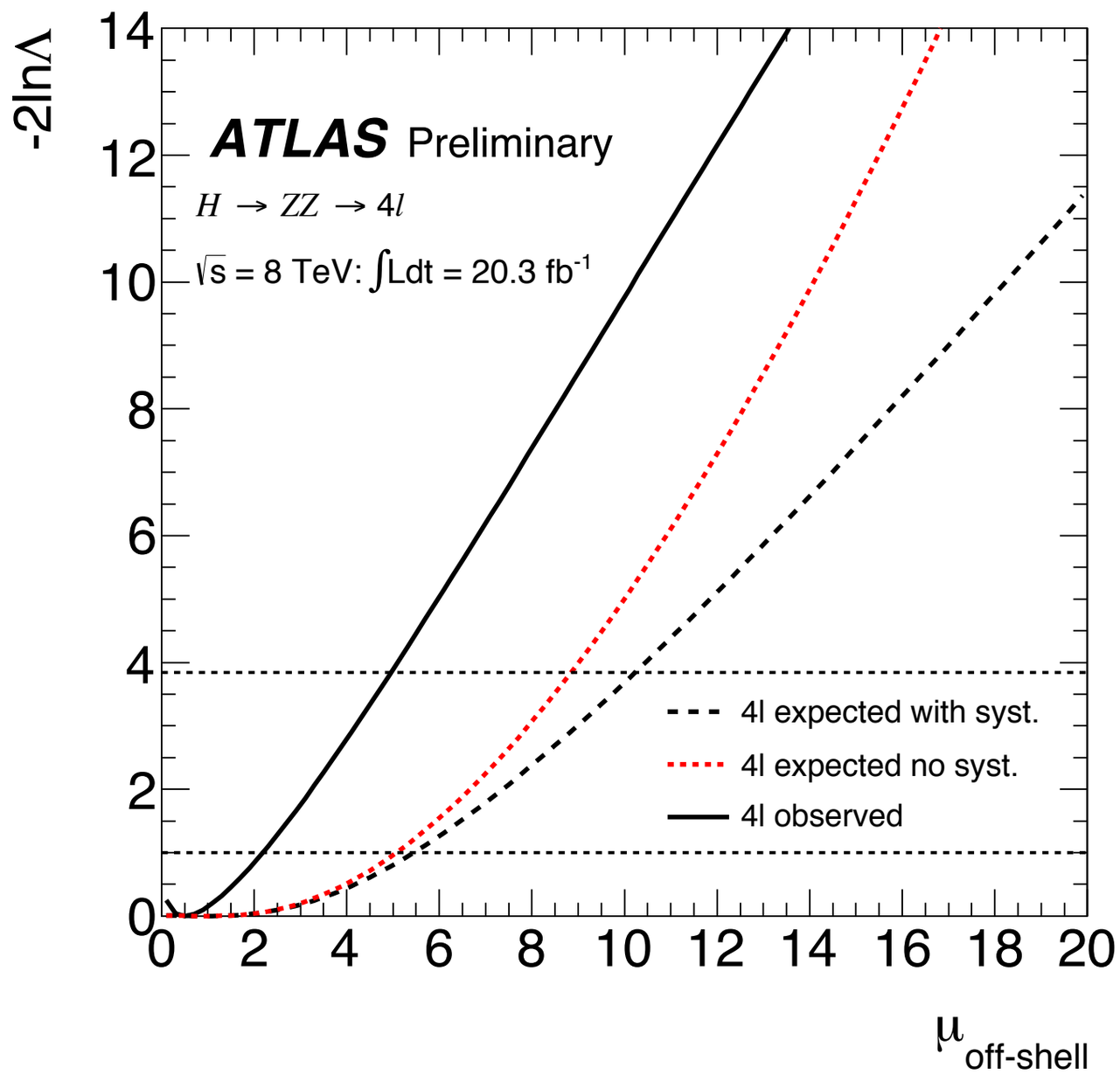


- Include 2l2v final state
- Include VBF channel (~7% on peak, O(10%) above 2 M_Z)
- Include (known and estimated) QCD and EW corrections
  [FC, Kasprzik, Passarino, Zaro et al]
- Use kinematic discriminant (similar to the one proposed in MCFM analysis) to boost signal and reject background/signal-background interferences

$\Gamma_H < 5.4\ \Gamma_{H,SM} = 22$ MeV @ 95CL

ATLAS analysis

[ATLAS-CONF-2014-042]



- Similar to CMS analysis
- ME discriminant as in MCFM
- Thorough consideration of systematic uncertainties
- Provide result as function of the unknown gg->ZZ K-factor ([0.5-2] x signal K-factor)

$\Gamma_H < 4.8\text{-}7.7\ \Gamma_{H,SM} = 20\text{-}32$ MeV @ 95CL

Off-shell cross-section: interpretation issues

- Bounds on the width from off-shell cross-section based in relating coupling on and off-peak, assuming they do not change
- In QFT, couplings run
- For small (i.e. logarithmic) modifications, negligible effect
- Big effects if strong modifications occurs, like for instance
  - higher dimensional HVV operators
  - light d.o.f. running in the loops

In principle, such modifications are problematic for the interpretation of off-shell measurements

- To what extent can they be constrained by other measurements? (boosted Higgs?, [Buschmann et al (2014)])
- What is their impact on off-shell measurements?
- How to parametrize / quantify these effects? (BSM classification, [Englert, Soreq, Spannowsky (2014)])

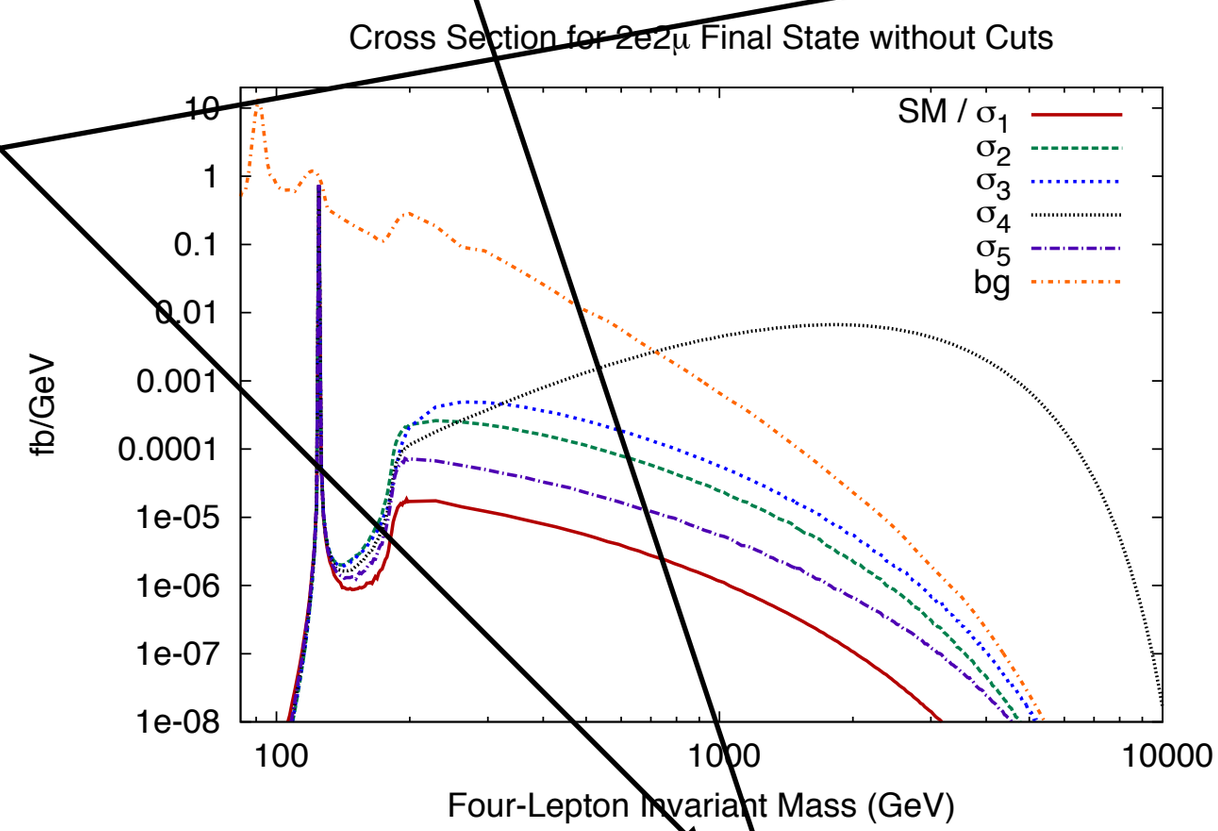
Example: anomalous HZZ couplings

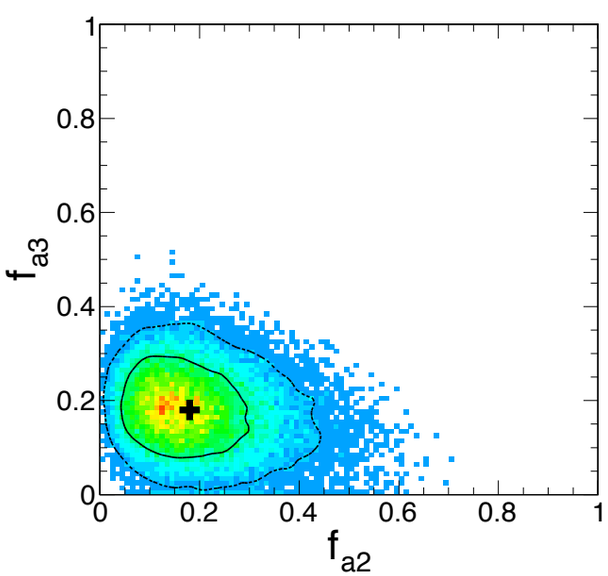
EFT language, basis of (low dim) HZZ operators [Gainer et al (2013)]

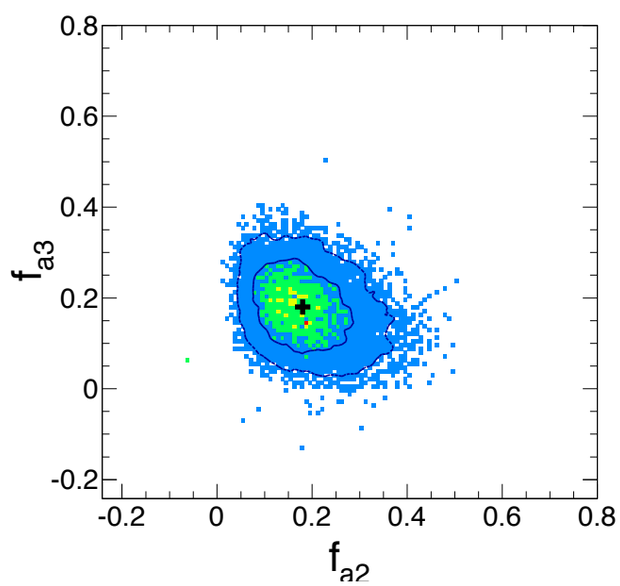
$$\mathcal{O}_1 = -\frac{M_Z^2}{v} H Z_\mu Z^\mu, \quad \mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu} \quad \mathcal{O}_3 = -\frac{1}{2v} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}, \quad \mathcal{O}_4 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$$

$$\mathcal{O}_6 = -\frac{M_Z^2}{M_H^2 v} Z_\mu Z^\mu \partial^2 H$$

Modification of the m_{4l} shape







Good control at the HL-LHC

[Anderson et al (2013)]

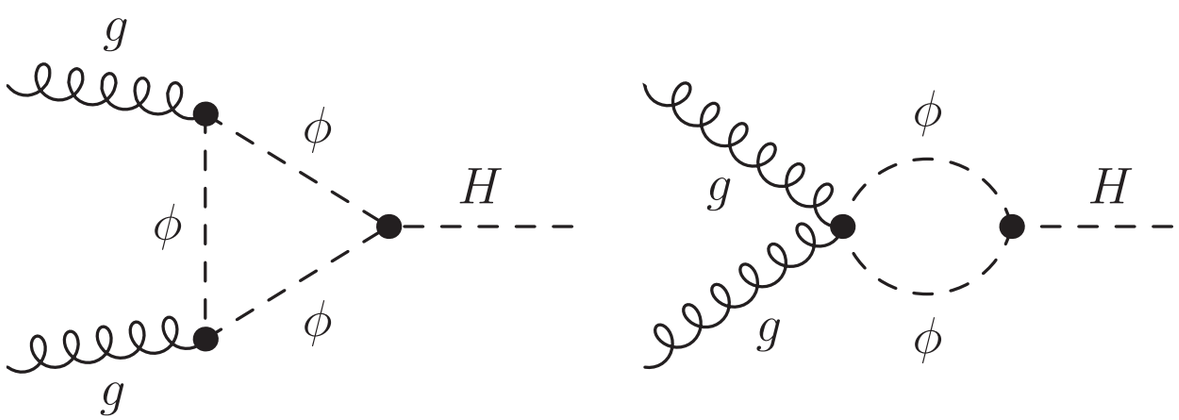
Modification of lepton angular distributions

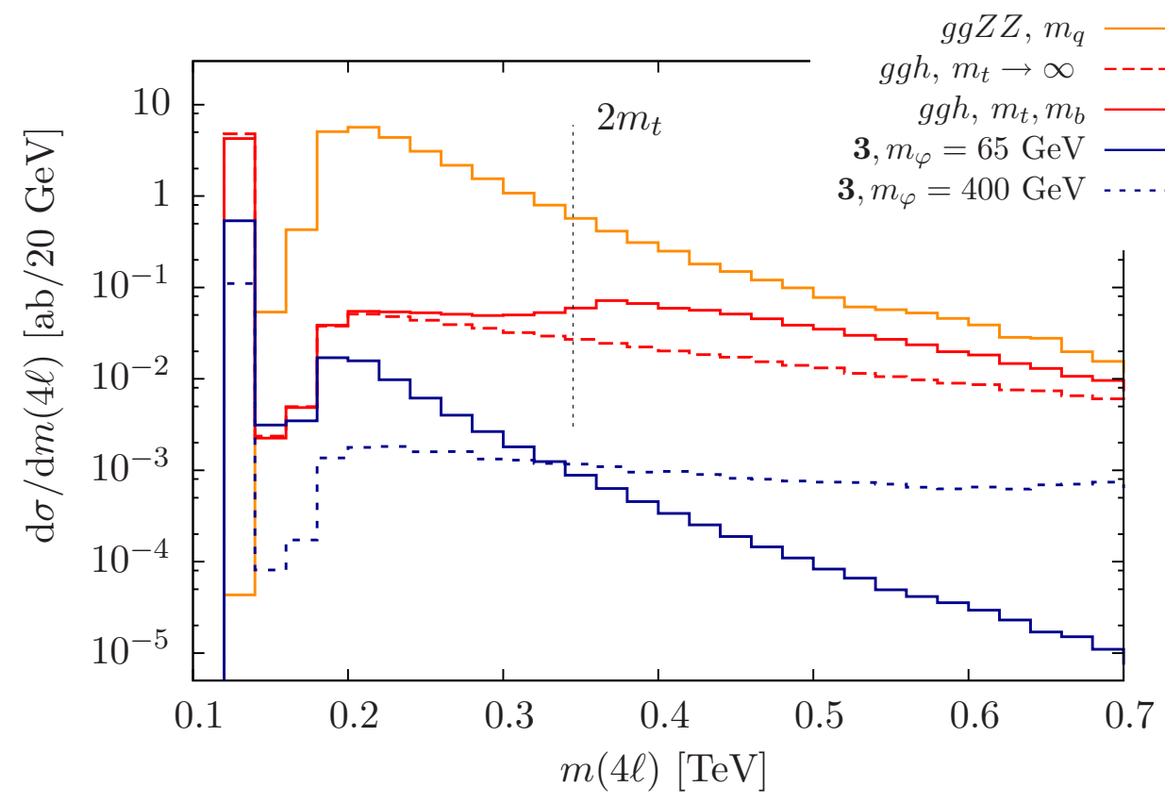
What is the constraining power for off-shell analysis?

Example: light d.o.f. in the Hgg coupling

[Englert, Spannowski (2014)]

Light d.o.f. qualitatively change the picture





Complementary constraints from other measurements?

- Will also affect other observables e.g. Higgs pT (Arnesen et al (2008)])
- Information from boosted Higgs regime? ([Buschmann et al (2014)])
- finite m_t effects crucial -> need theoretical improvement
- Can (very large) S/B interference in the γγ channel give constraints? (along the lines of [Dixon, Siu (2003)])

Beyond the width: BSM constraints from off-shell

Which extra information can
we gain from off-shell measurements?

EFT studies:

- constraint on higher dim operator: → A. Azatov's talk
- limitations of model dependence (HL-LHC?)
- disentangling new physics with off-shell Higgs

Are EFT analysis generic enough? [Englert, Soreq, Spannowsky (2014)]

(I) light d.o.f.

(II) new d.o.f. in the sub-TeV -> thresholds

(III) resonant TeV d.o.f. with parametrically suppressed cross-section

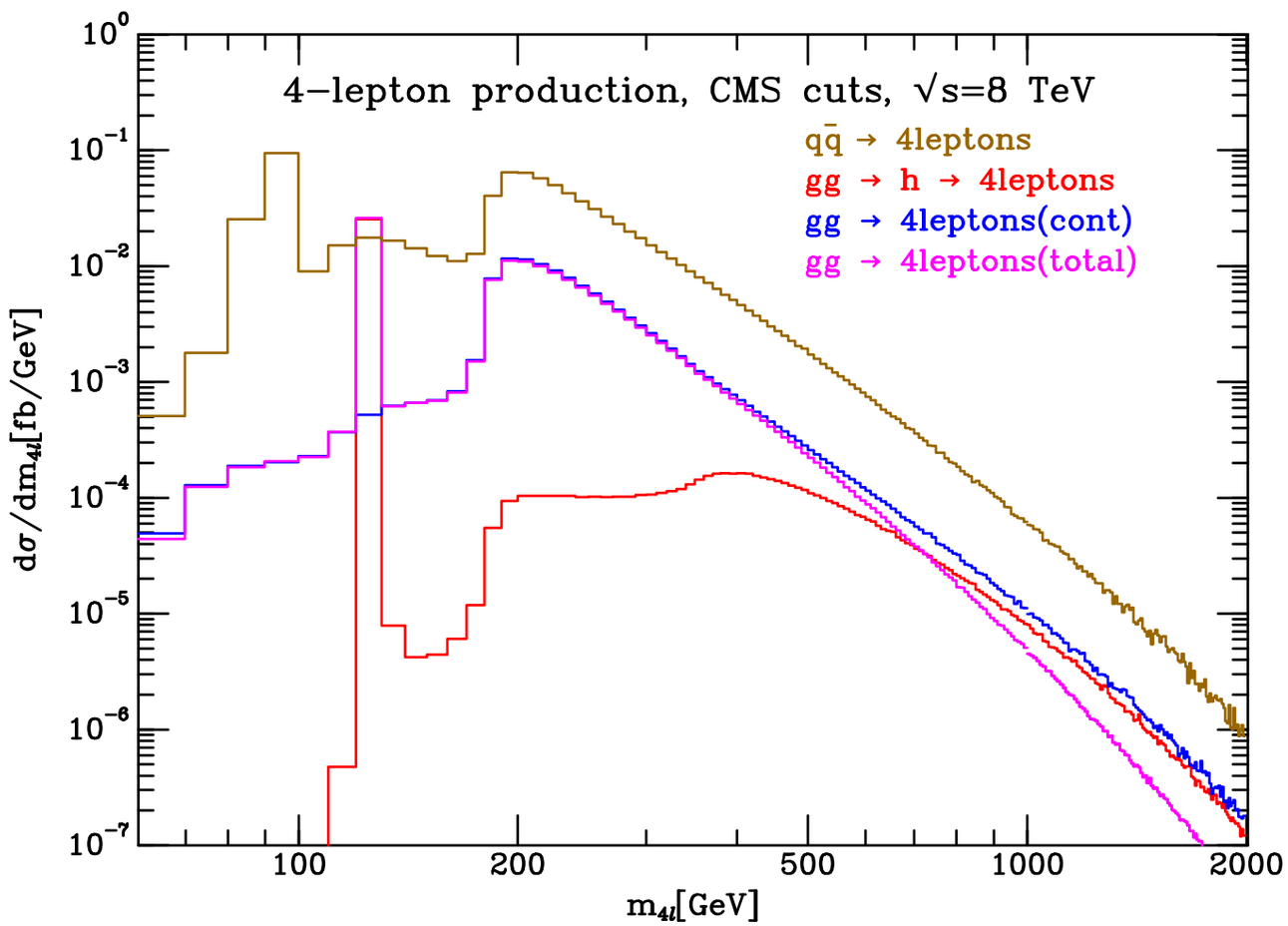
(IV) new heavy d.o.f. -> EFT

Well-motivated benchmark models for (i-iii)?

SM tools for off-shell analysis

Method based on counting VV events in the high invariant-mass tail ->

good predictions for 4l final state required



$$N_{qq\to ZZ} \approx N_{\rm tot}$$

$$N_{gg} \sim 10^{-1} \times N_{\rm tot}$$

$$N_H \sim 5 \times 10^{-2} \times N_{\rm tot}$$

$$N_{\rm off} \sim 10^{-2} N_{\rm tot}$$

$$N_{\rm int} \sim -2 \times 10^{-2} N_{\rm tot}$$

Large (uninteresting) qqb background

Delicate signal/background interference patterns

(Possible) BSM effects

SM tools for off-shell analysis

good predictions for 4l final state required

Precision tools for signal / background interference within the SM

- MEM techniques → R. Rontsch's talk
- analysis also in other VV channels
- effects of extra jet radiation

Realistic simulation for the LHC

- BSM scenarios
- multi-jet merging -> easier handle on sensitive variables
- event generators for the off-shell Higgs

→ F. Maltoni and F. Krauss' reports

SM tools for off-shell analysis

- First NNLO results for the inclusive qqb -> VV background

(qT subtraction + OpenLoops + Gehrmann et al [Cascioli et al, Gehrmann et al (2014)])

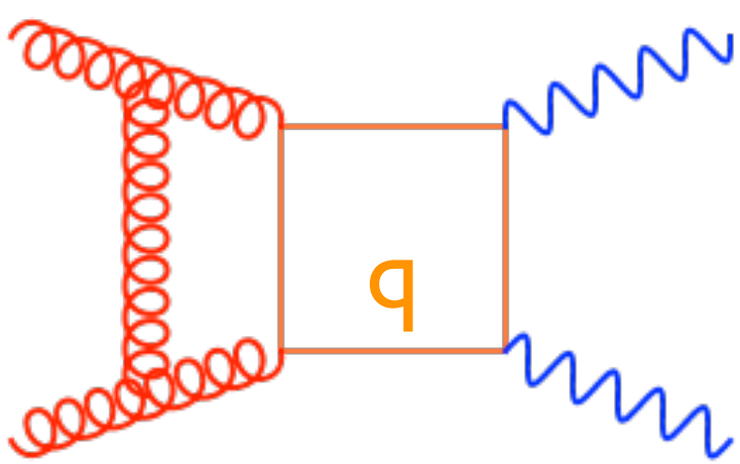
thorough phenomenological analysis in the near future?

- In the off-shell region (or at high p_t): go beyond the infinite m_t approximation

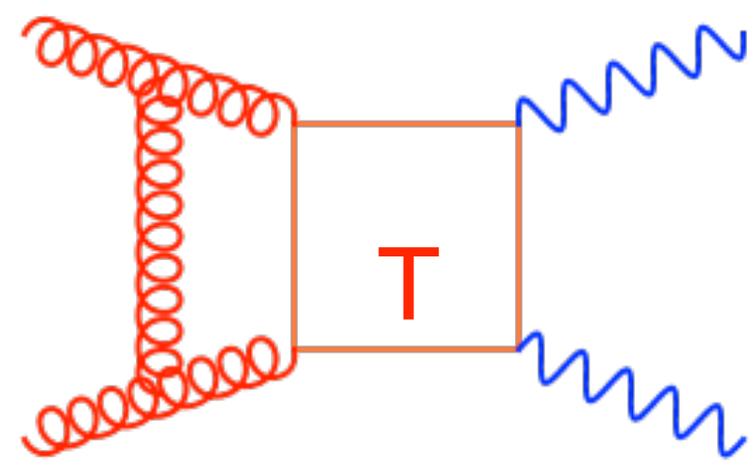
(complicated, but remarkable progress in related problems in the recent past)

- Major drawback for these studies: gg->VV only known at LO

(large K-factor is expected, very important for delicate signal/background patterns)



All ingredients
recently computed



Complicated

Non-negligible/dominant in
the off-shell tail

estimates based on (improved) soft-gluon approximation?

Other very interesting Higgs interference analysis

Γ_H from S/B interference in the $\gamma\gamma$ channel

- mass shifts from interferences
- results from the VBF category
- (bounds on light d.o.f.?)

$\longrightarrow$ N. Fidanza's talk

Hcc coupling from J/Ψ interference

- direct vs fragmentation interference
- interference boosts the signal
- apply to 1st and 2nd generations

$\longrightarrow$ S. Stoynev's talk