Interference effects and precision LHC physics

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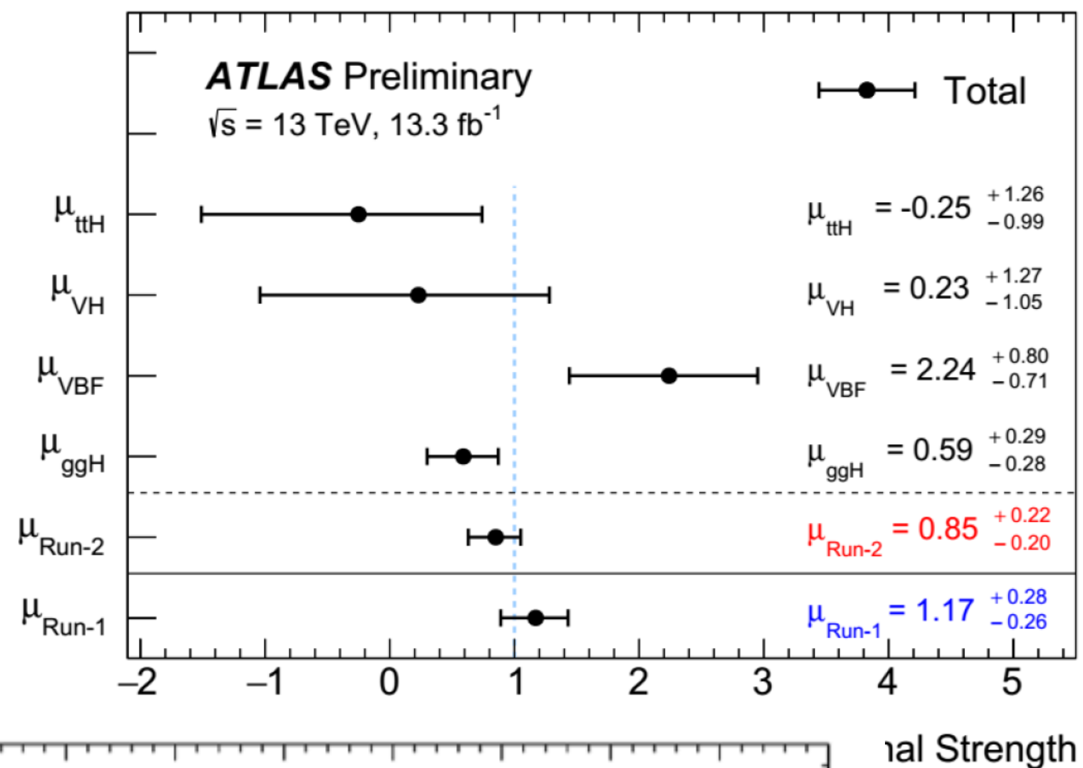
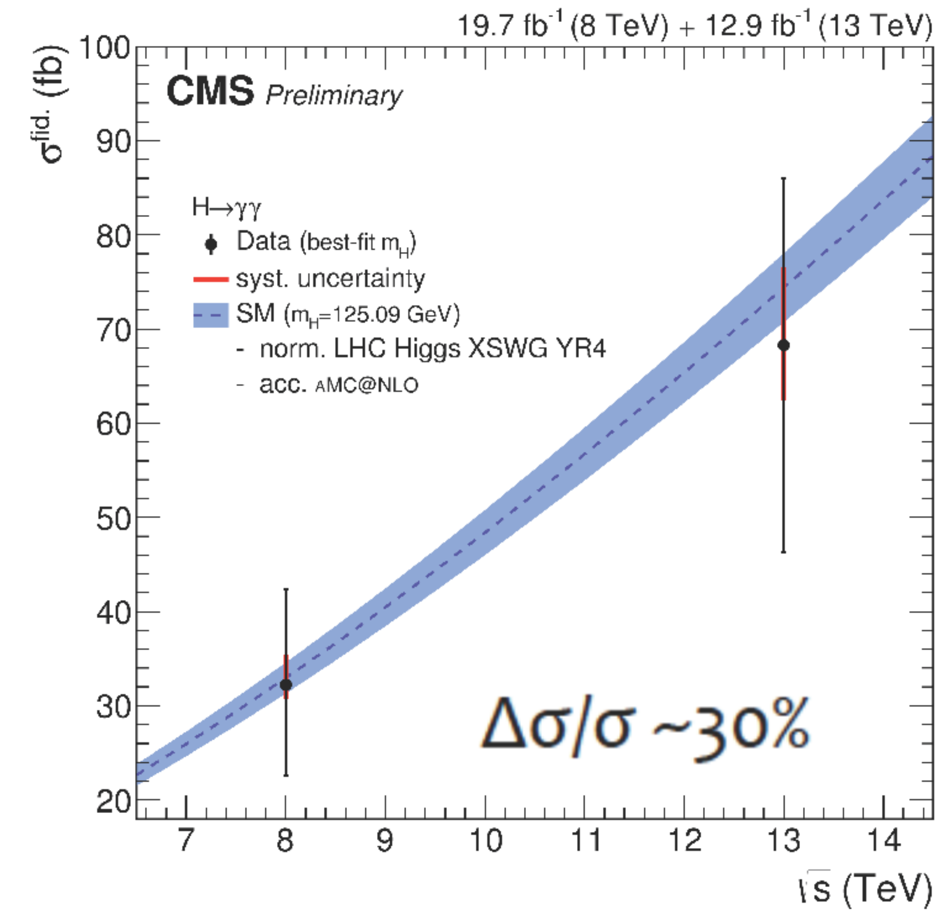
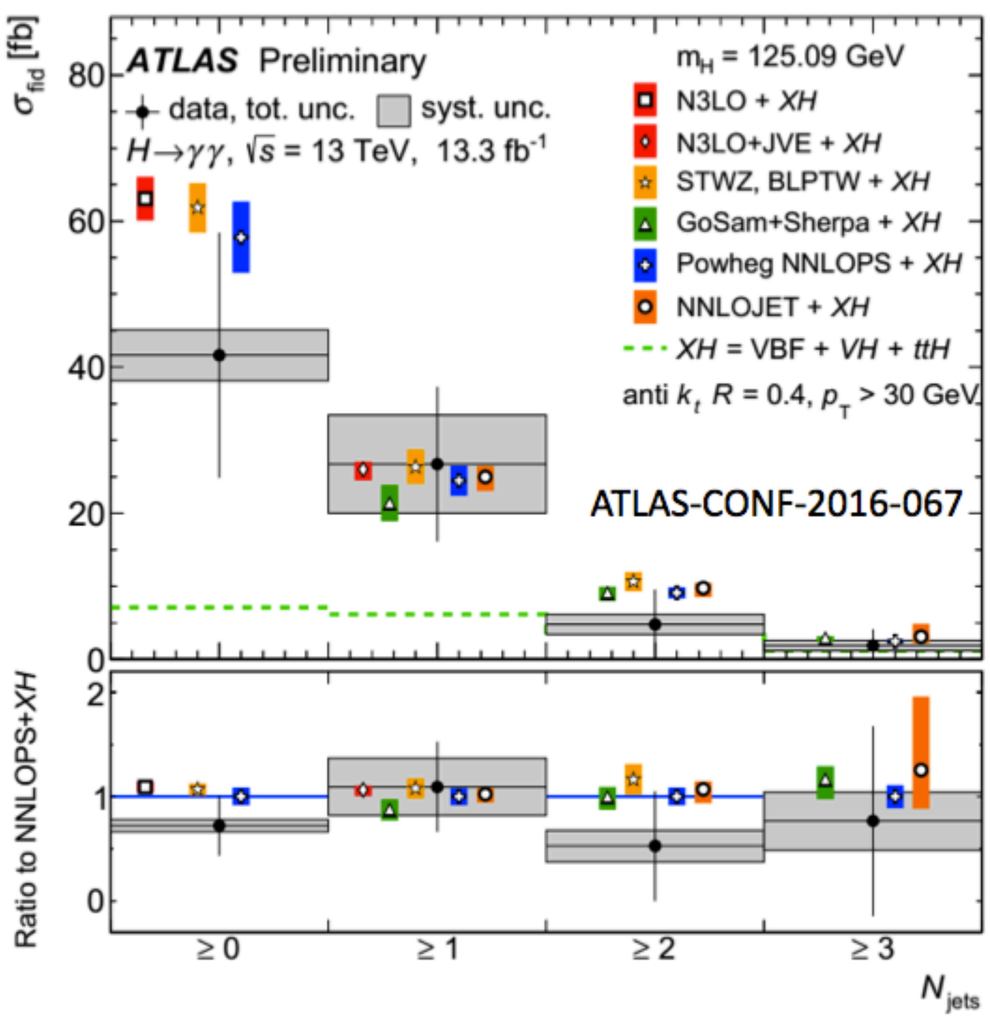
UK HEP Forum: *Into the Unknown with LHC13*

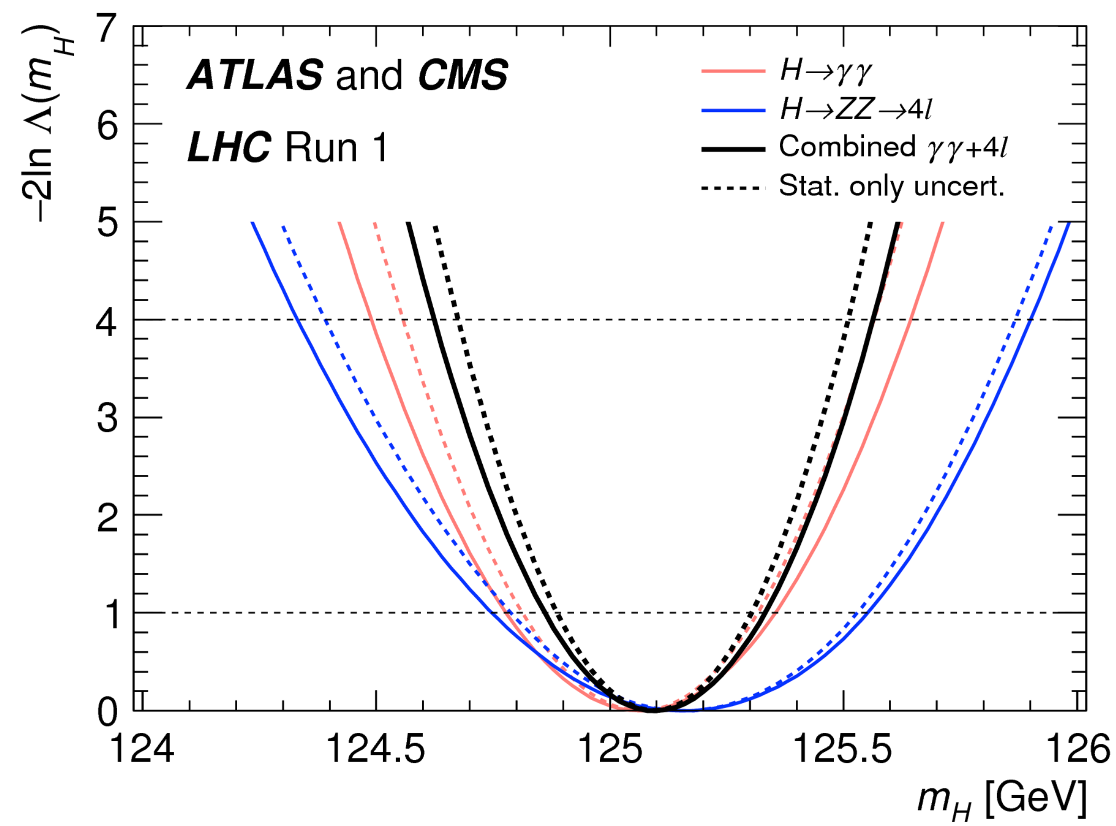
The Cosener's House, Abingdon, Nov. 4th 2016

Higgs at the LHC: a success story







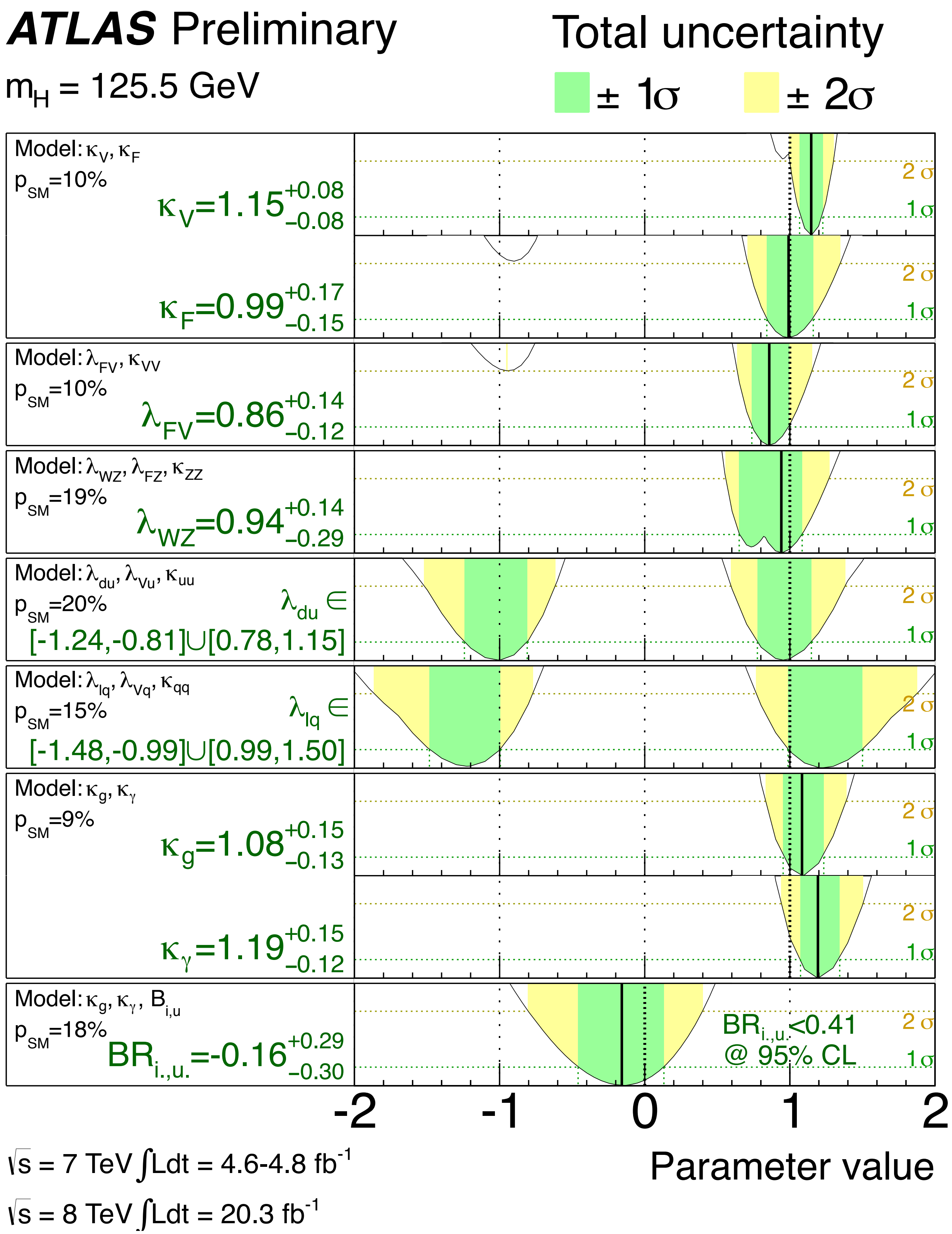


The Higgs: what we already know

- A narrow resonance, most likely 0^+
- Mass known to 0.2% accuracy, $m_H = 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$ GeV
- It decays into vector bosons (γ,Z,W)
- It decays into fermions (τ,b)
- It is produced both in gluon fusion and in VBF
- Its couplings agree with SM predictions, within ~ 10%, $\mu = 1.09^{+0.11}_{-0.10}$
- Coherent picture emerging at 13 TeV

A SM-LIKE HIGGS BOSON

Higgs couplings: a closer look



$$\sigma_{i\to H\to f} \approx \frac{\sigma_{i\to H}\Gamma_{H\to f}}{\Gamma_H} \approx \frac{g_i^2 g_f^2}{\Gamma_H}$$

Naively, we only have access to coupling ratios

A pragmatic approach:

1. take cross-section ratios to isolate desired production / decay mode
2. fit assuming (rescaled) SM-like behavior

[see e.g. LHC XS WG, arXiv:1209.0040]

Can we Obtain Extra Information?

Higgs couplings: a closer look

$$\sigma_{i\to H\to f} \approx \frac{\sigma_{i\to H}\Gamma_{H\to f}}{\Gamma_H} \approx \frac{g_i^2 g_f^2}{\Gamma_H}$$

Formally, the Higgs cross-section is invariant under the rescaling

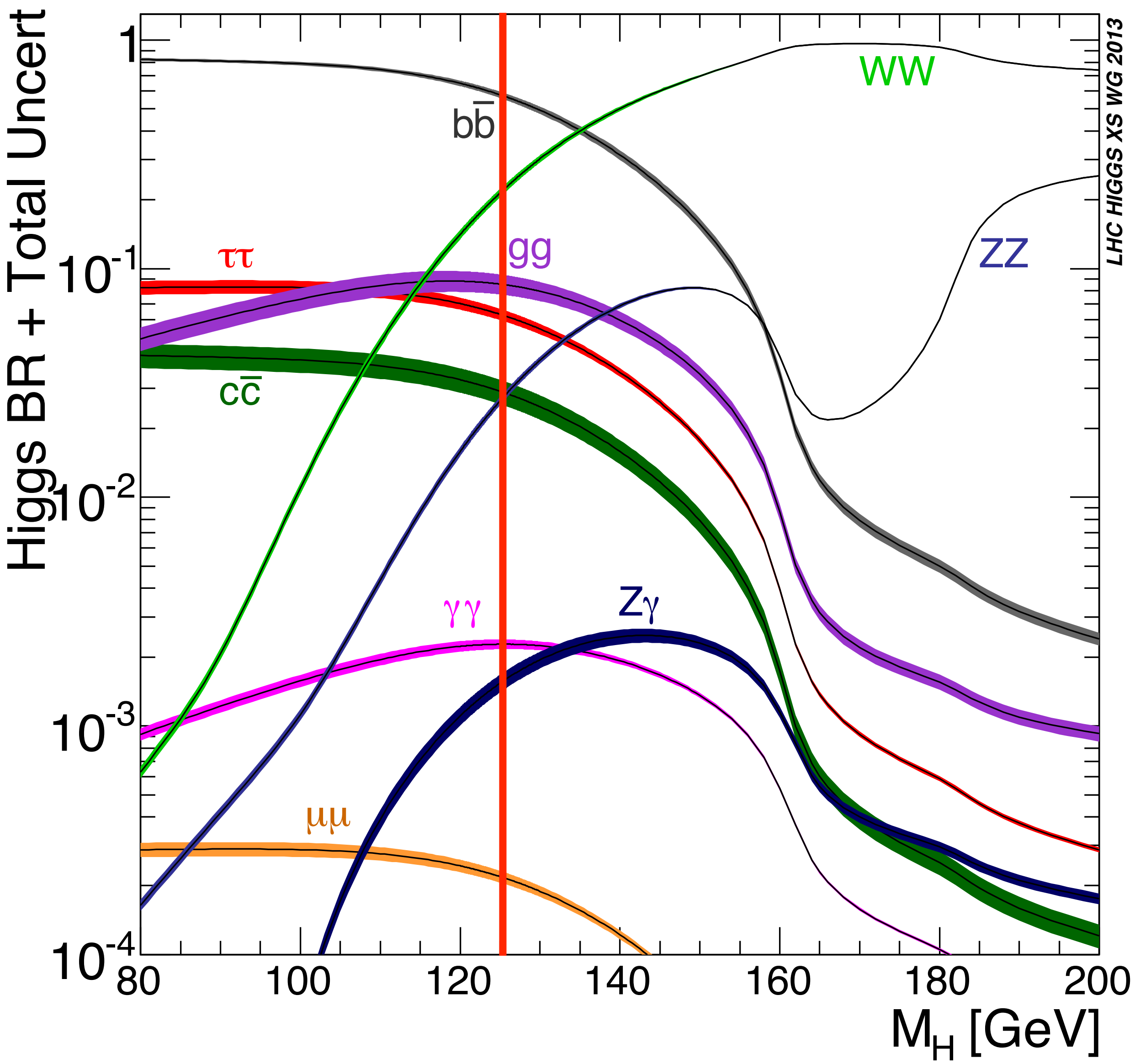
$$g \to \xi g, \quad \Gamma_H \to \xi^4 \Gamma_H \quad \Longrightarrow \quad \sigma_{i\to H\to f} \to \sigma_{i\to H\to f}$$

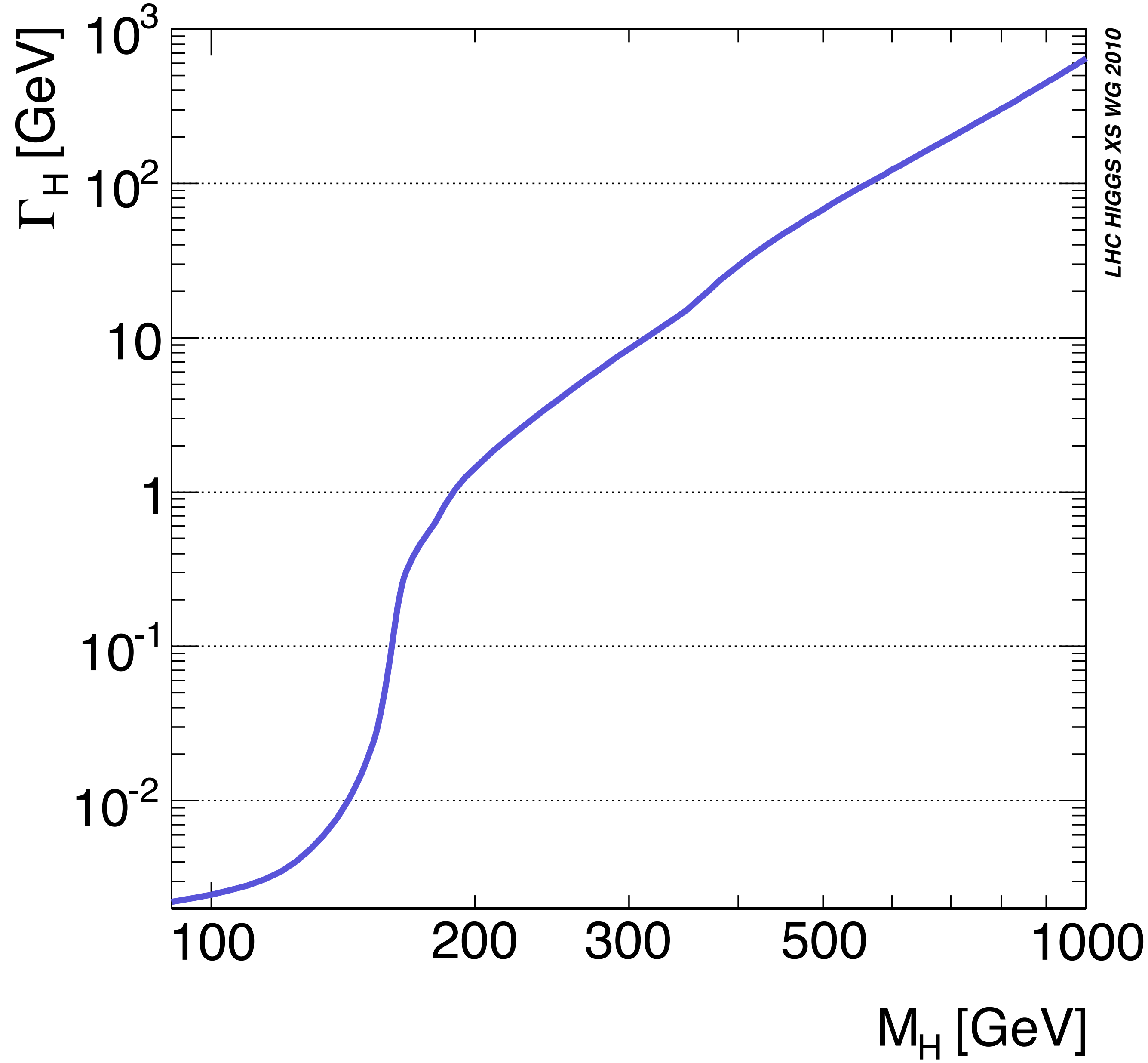
Any measurement on the mass peak only determines a family of ∞ degenerate solutions for g, Γ_{H}

To uniquely determine Higgs boson properties, the width/couplings need to be measured independently from each other

The SM width: a blessing and a curse

In the SM for m_H ~ 125 GeV, Γ_H ~ 4 MeV

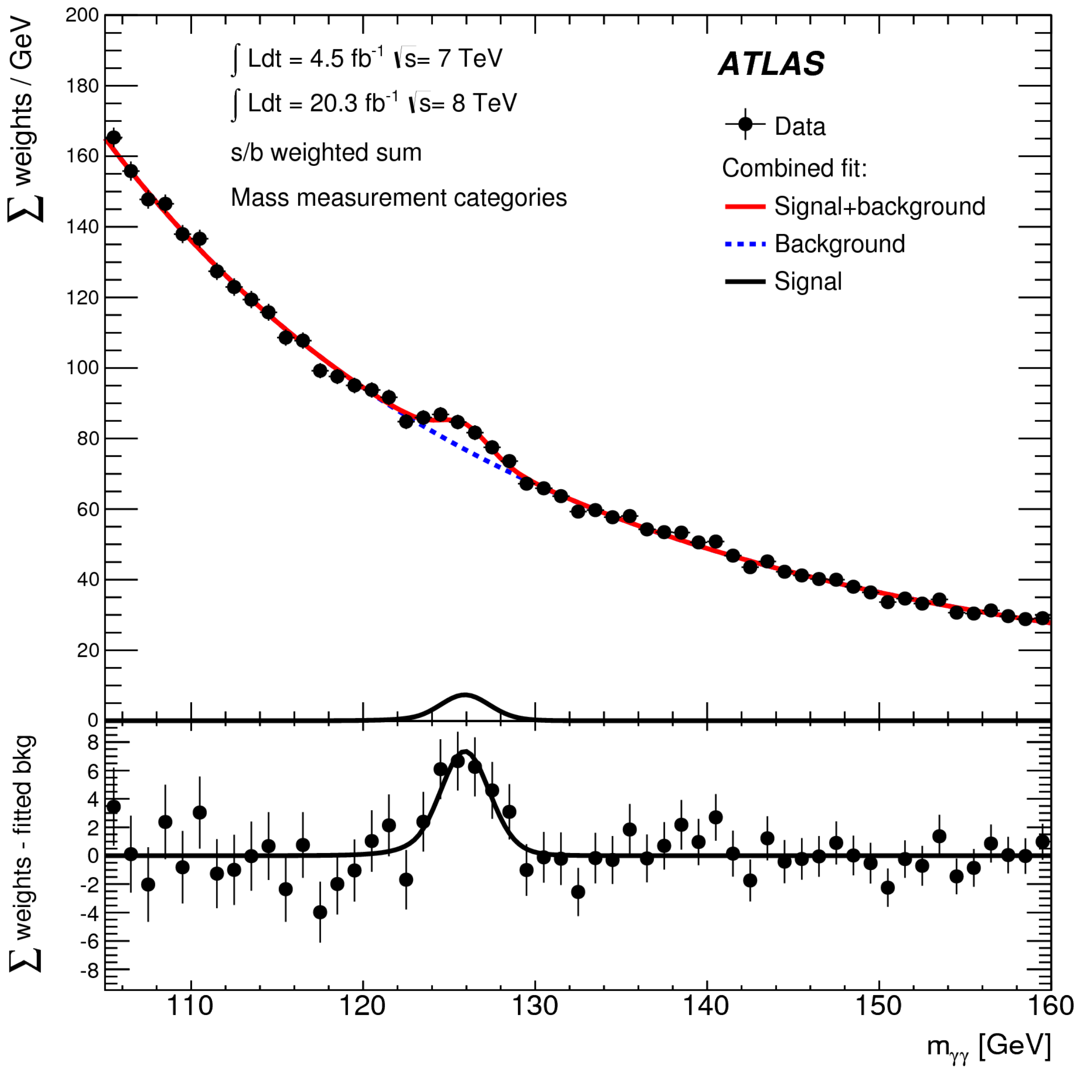


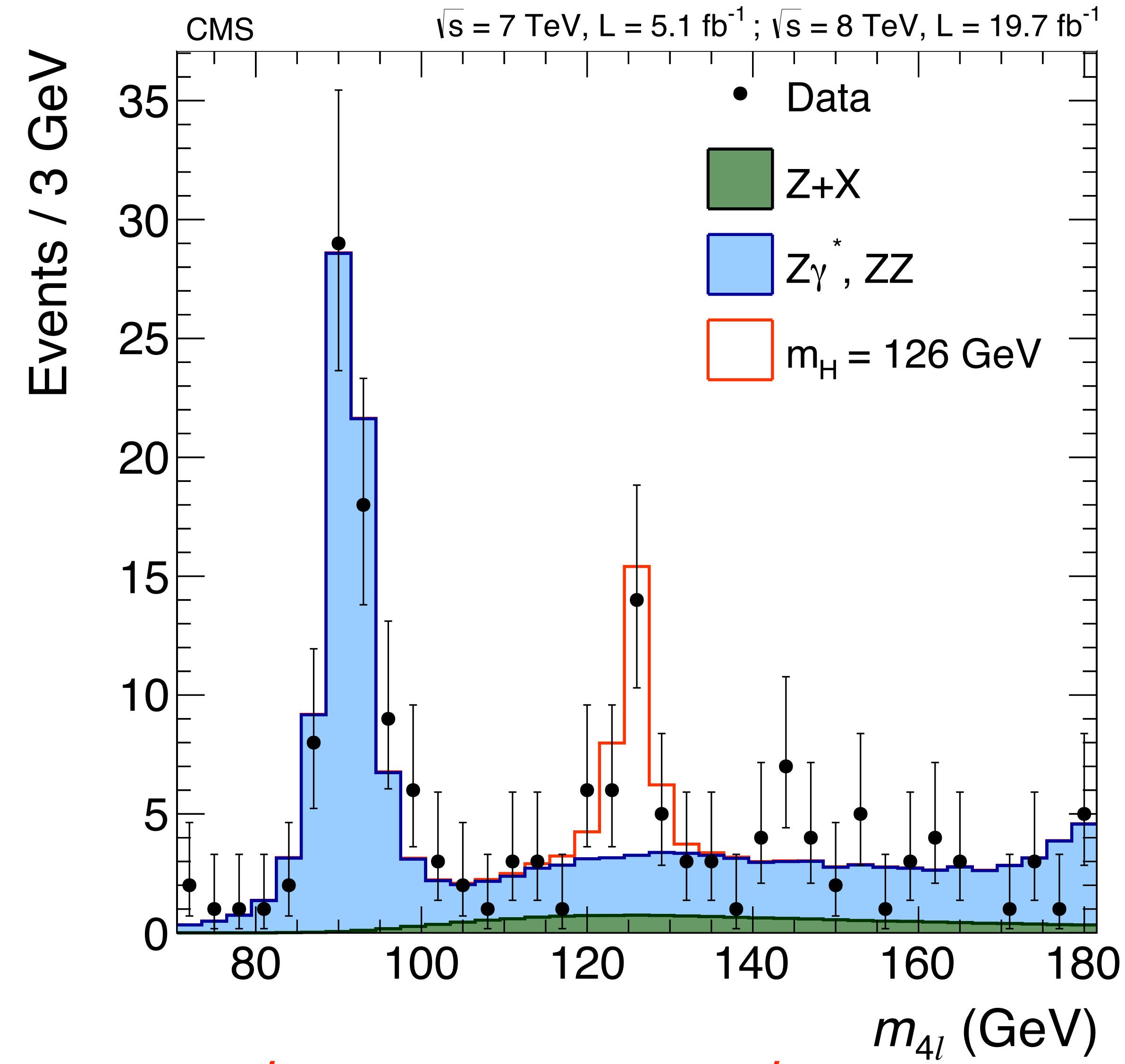


Almost impossible to measure directly
(with possible exception of muon collider)

Γ_H: direct constraints at the LHC

Profiling the resonance limited by detector resolution





Current direct bound: $\Gamma_H \leq \sim 5_{\text{ATLAS},\gamma\gamma}$ / $2.6_{\text{ATLAS,ZZ}}$ / 1.7_{CMS} GeV

LHC estimated reach: ~ 1 GeV

TO BE SENSITIVE TO SM WIDTH, WOULD NEED X1000 IMPROVEMENT

Γ_H: direct constraints at the LHC

We know the Higgs decays → $\Gamma_H > 0$

More in general, the Higgs cannot be too narrow → long lived particle → displaced vertex

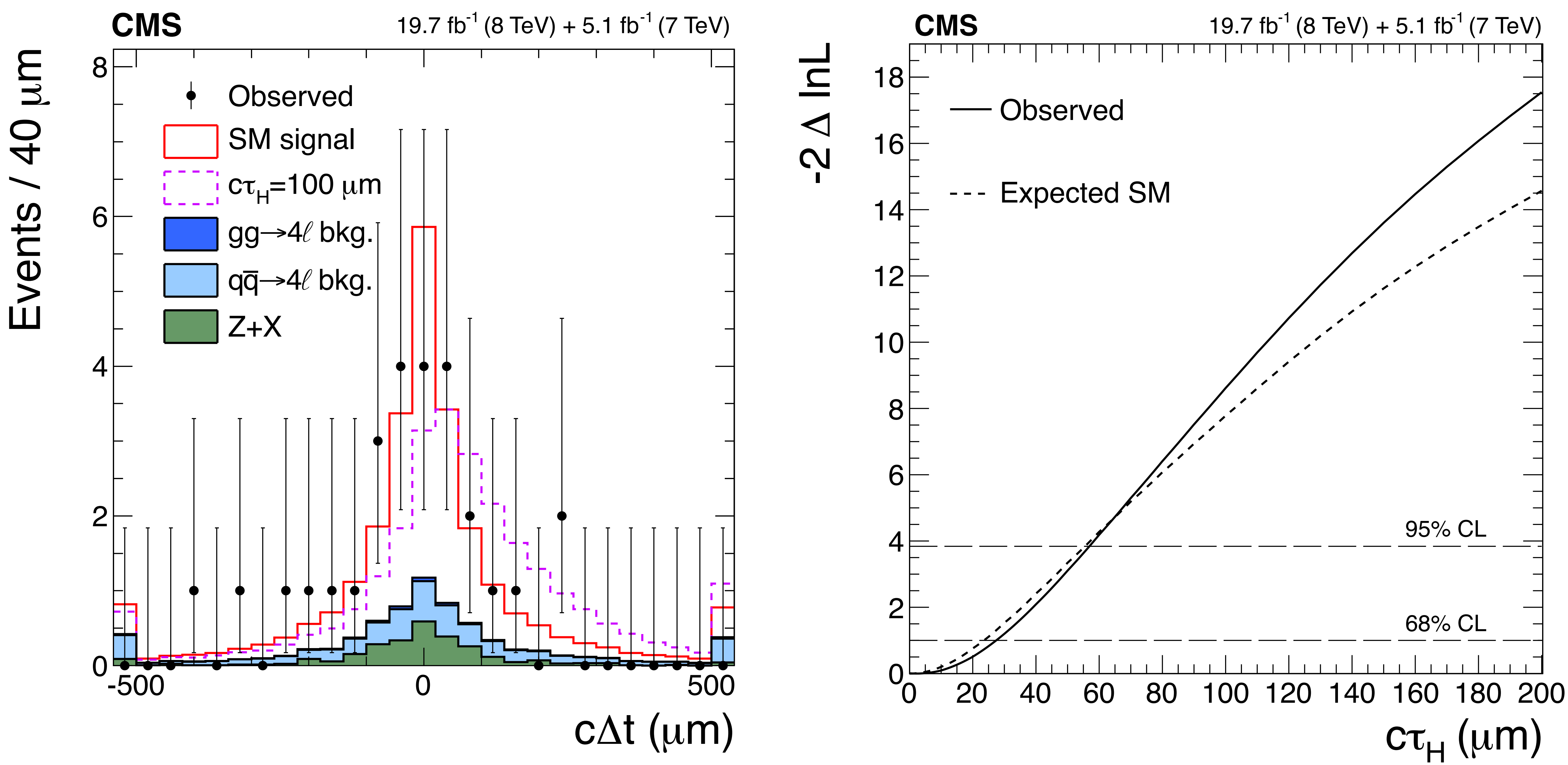
Lower bound can be obtained by
LIFETIME MEASUREMENTS

In the Higgs rest frame:

$$\Delta t = \frac{m}{p_\perp} (\Delta \vec{r}_\perp \cdot \hat{p}_\perp) \qquad \langle \Delta t \rangle = \tau_H = \frac{1}{\Gamma_H}$$

In the SM: $\tau_H \sim 4.8\ 10^{-8}\ \mu m/c$, well below experimental sensitivity

CMS bounds on the Higgs lifetime



H→4l: $c\tau_H < 57$ μm → $\Gamma_H > 3.5\ 10^{-9}$ MeV @ 95cl

(SM: $c\tau_H \sim 4.8\ 10^{-8}$ μm, $\Gamma_H \sim 4.2$ MeV)

Higgs couplings: a closer look

$$\sigma_{i\to H\to f} \approx \frac{\sigma_{i\to H}\Gamma_{H\to f}}{\Gamma_H} \approx \frac{g_i^2 g_f^2}{\Gamma_H}$$

σ is invariant under

$$g \to \xi g, \quad \Gamma_H \to \xi^4 \Gamma_H$$

To avoid imposing SM behavior, we must break this degeneracy

A direct measurement of the Higgs width is not feasible

- LHC sensitivity ~ 10^{-9} MeV < Γ_H < 1 GeV
- SM width ~ 4 MeV

MUST OBTAIN INDIRECT CONSTRAINTS

Key point: search for observables which are width-independent, or with different coupling/width dependence

A first example:

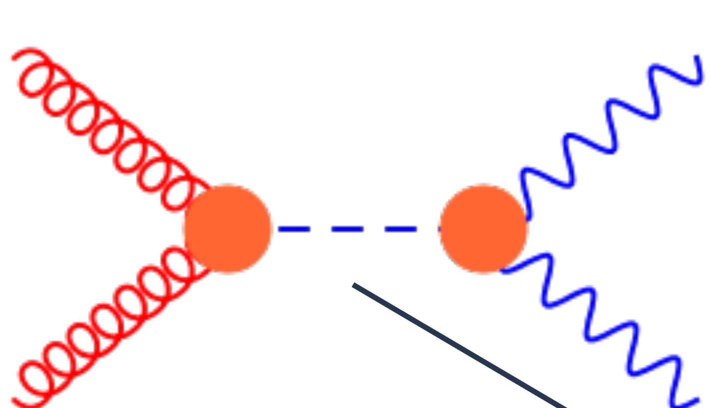
$H \to \gamma\gamma$ interference

[Martin; Dixon, Li (2013)]

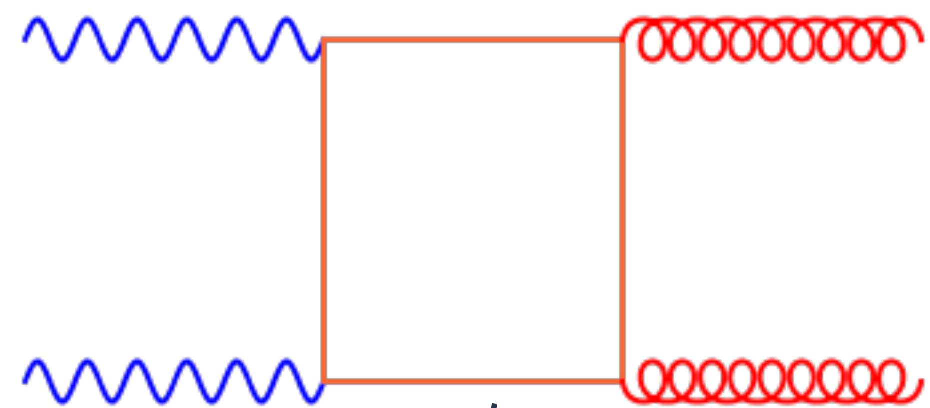
Typical interference scaling: g vs g^2

Consider the full pp →γγ process:

SIGNAL ~ $g_i\, g_f$



BACKGROUND



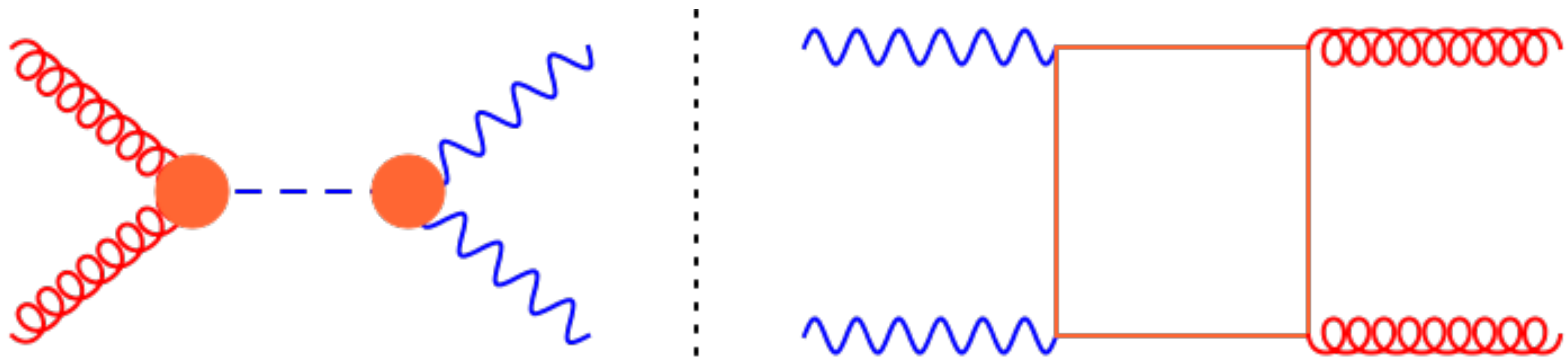
$$A_{i\to f} = \frac{S m_H^2}{s - m_H^2 + i m_H \Gamma_H} + B$$

$$|A_{i\to f}|^2 = \frac{|S|^2 m_H^2}{(s-m_H^2)^2 + \Gamma_H^2 m_H^2}\left[1 + \frac{2(s-m_H^2)}{m_H^2}\Re\left(\frac{B^*}{S}\right) + 2\frac{\Gamma_H}{m_H}\Im\left(\frac{B^*}{S}\right)\right] + |B|^2$$

$$\frac{g_i^2 g_f^2}{\Gamma_H}$$

$$g_i g_f$$

Interference: the imaginary part



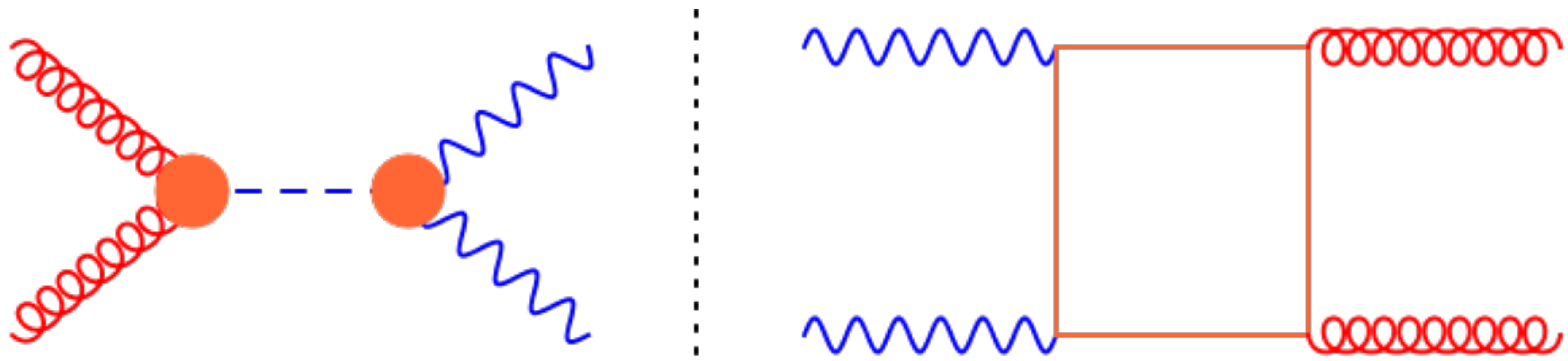
$$|A_{i\to f}|^2 = \frac{|S|^2 m_H^2}{(s-m_H^2)^2+\Gamma_H^2 m_H^2}\left[1+\frac{2(s-m_H^2)}{m_H^2}\Re\left(\frac{B^*}{S}\right)+\boxed{2\frac{\Gamma_H}{m_H}\Im\left(\frac{B^*}{S}\right)}\right]+|B|^2$$

- Symmetric around the peak → contribute to σ
- Naively: loop enhanced (S→2 loop,B→ 1 loop)

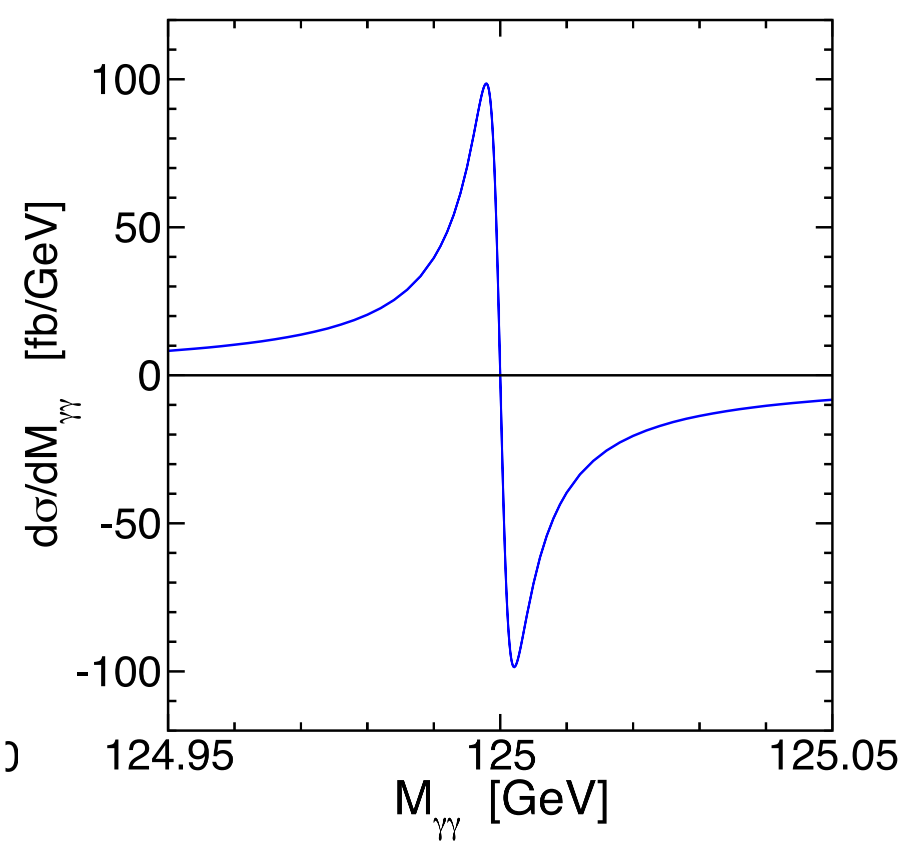
$$S\sim\frac{g_s^2e^2}{(16\pi^2)^2}\frac{m_H^2}{v^2}\qquad B\sim\frac{g_s^2e^2}{16\pi^2}\qquad\left[\frac{\sigma_{\rm int}}{\sigma_H}\right]_{\rm naive}\approx c\frac{2\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_H^2}\approx 0.1$$

- In reality: interference starts at two=loop (optical theorem, no ±± cut for the background amplitude)
- Small effect in the SM (different for BSM)

Interference: the real part



$$|A_{i\to f}|^2 = \frac{|S|^2 m_H^2}{(s-m_H^2)^2+\Gamma_H^2 m_H^2}\left[1+\boxed{\frac{2(s-m_H^2)}{m_H^2}\Re\left(\frac{B^*}{S}\right)}+2\frac{\Gamma_H}{m_H}\Im\left(\frac{B^*}{S}\right)\right]+|B|^2$$



$$\sigma_{\rm off} \sim \frac{2\Re(SB^*)}{s-m_H^2}, \qquad (s-m_H^2)\gg m_H\Gamma_H$$

Asymmetric in $m_{\gamma\gamma}$ distribution

- no net effect on the total rate
- width independent
- more events below the peak
- interesting observable consequences

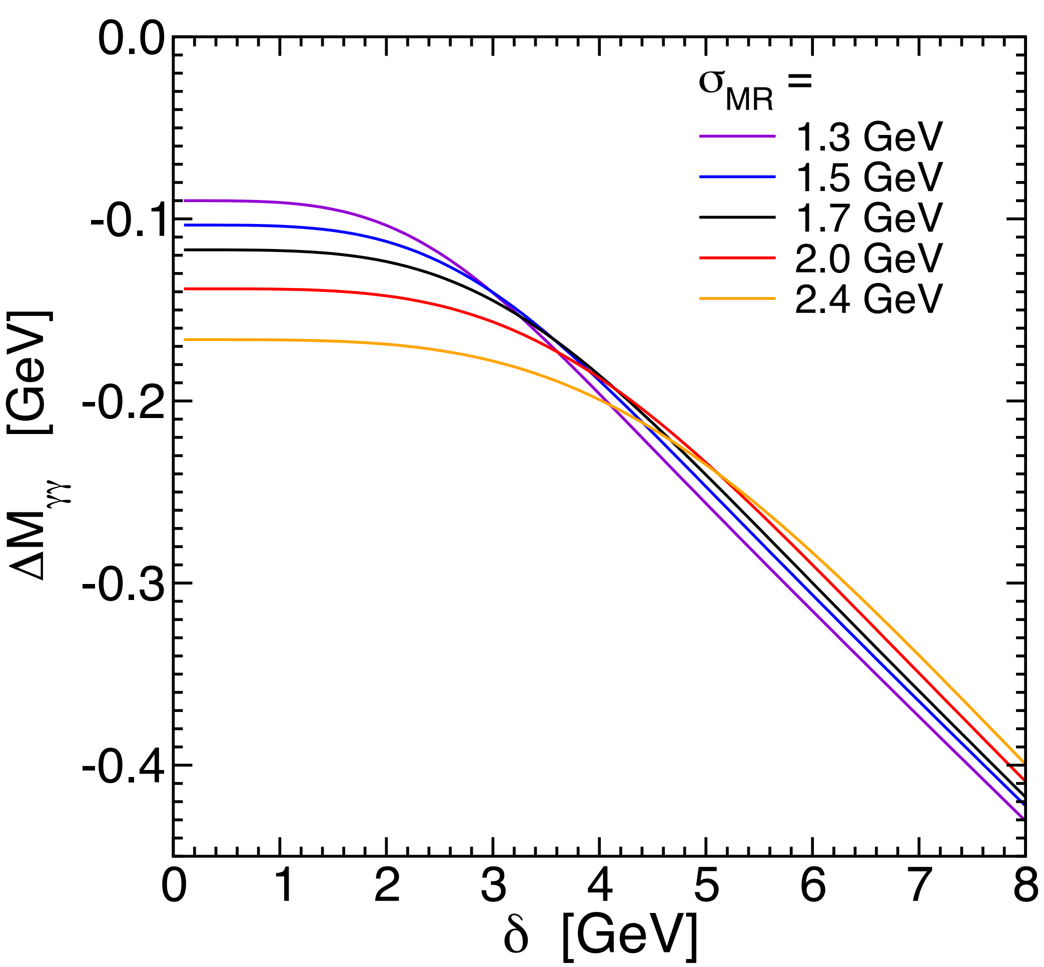
[Martin (2012)]

Interference: the real part and the mass shift

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

Higgs mass:

- ~ first moment of the invariant mass distribution
- extraction affected by real part of interference
- independent on Γ_H, dependent on environmental parameters (energy resolution)



$$\frac{d\sigma}{ds} = \frac{A}{(s-m_H^2)^2 + m_H^2\Gamma_H^2} + \frac{(s-m_H^2)I}{(s-m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\langle M^2 \rangle = \frac{1}{\sigma_0}\int ds\, s\frac{d\sigma}{ds} = m_H^2 + \frac{I}{\sigma_0}\int_{s_-}^{s^+} ds$$

$$\delta m_H = \frac{2I\delta}{\sigma_0}, \qquad s_\pm = (m_H \pm \delta)^2$$

Simple analysis: shift ~ 50-100 MeV

Shift proportional to $I \sim g_i\, g_f$

Interference: the real part and the mass shift

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

- compare measurement in H→$\gamma\gamma$ with control mass
- shift gives access to real part of interference

$\delta m_H = 2I\delta/\sigma_H \sim g_i g_f$

- LHC: Higgs peak cross-section is SM-like

$$\sigma_H \sim \sigma_{H,\mathrm{SM}} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \to \frac{g_i g_f}{(g_i g_f)_{\mathrm{SM}}} = \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}}$$

- This implies

$$\delta m_H = (\delta m_H)_{\mathrm{SM}} \times \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} \approx -[50:100]\ \mathrm{MeV} \times \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}}$$

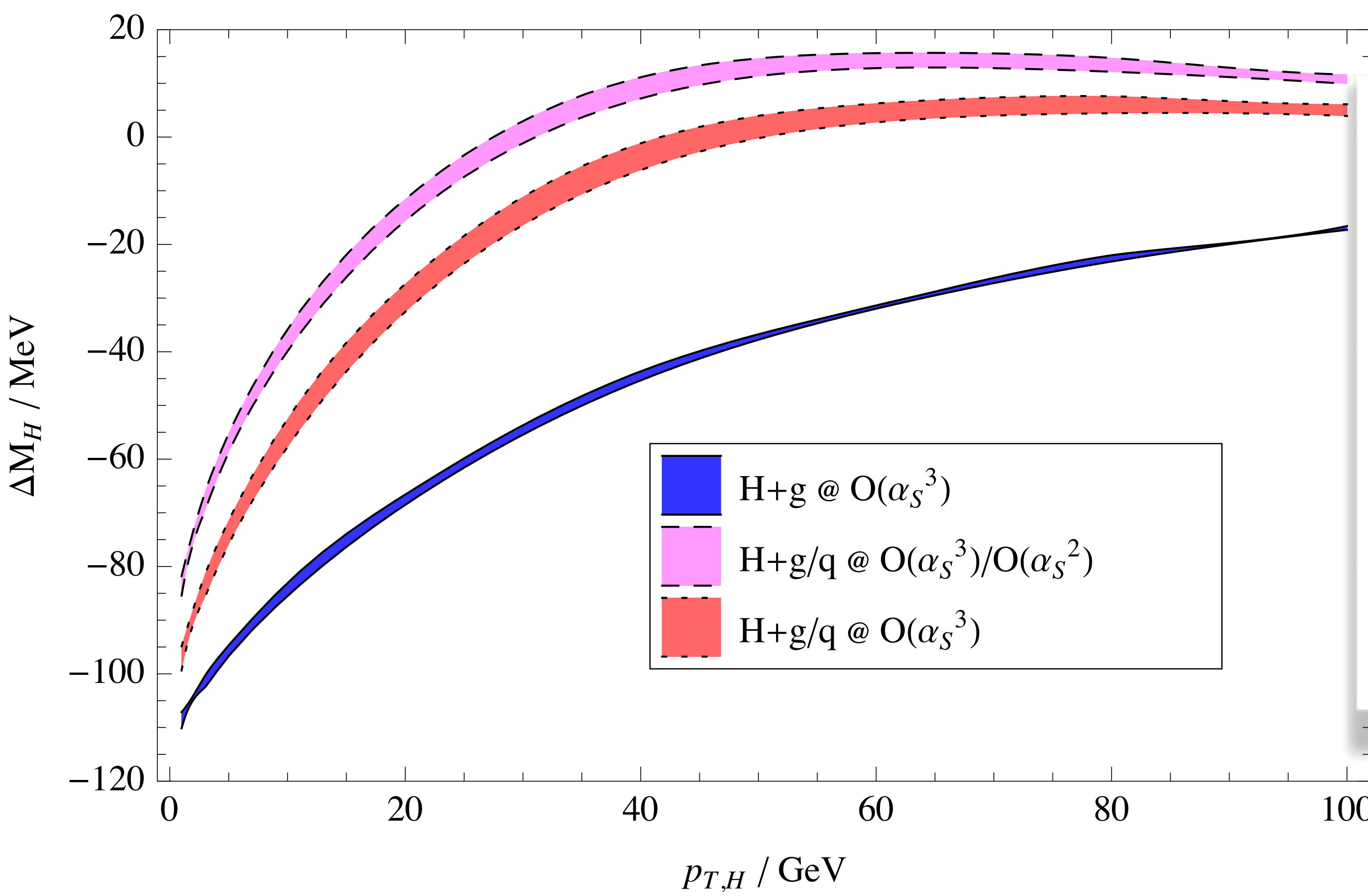
Mass shift measurement gives access to Γ_H →

BREAK WIDTH / COUPLING DEGENERACY

From the mass shift to the Higgs width

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

- interference theoretically under control (NLO+PS)
- several options for the control mass, i.e. H→ZZ or VBF (where interference small)
- the interference is strongly p_t-dependent → control mass in the $\gamma\gamma$ channel to reduce systematics



REALISTIC ATLAS ESTIMATE FOR THE MASS SHIFT:

-35 ± 9 MeV

[ATL-PHYS-PUB-2016-009]

Experimentally tough

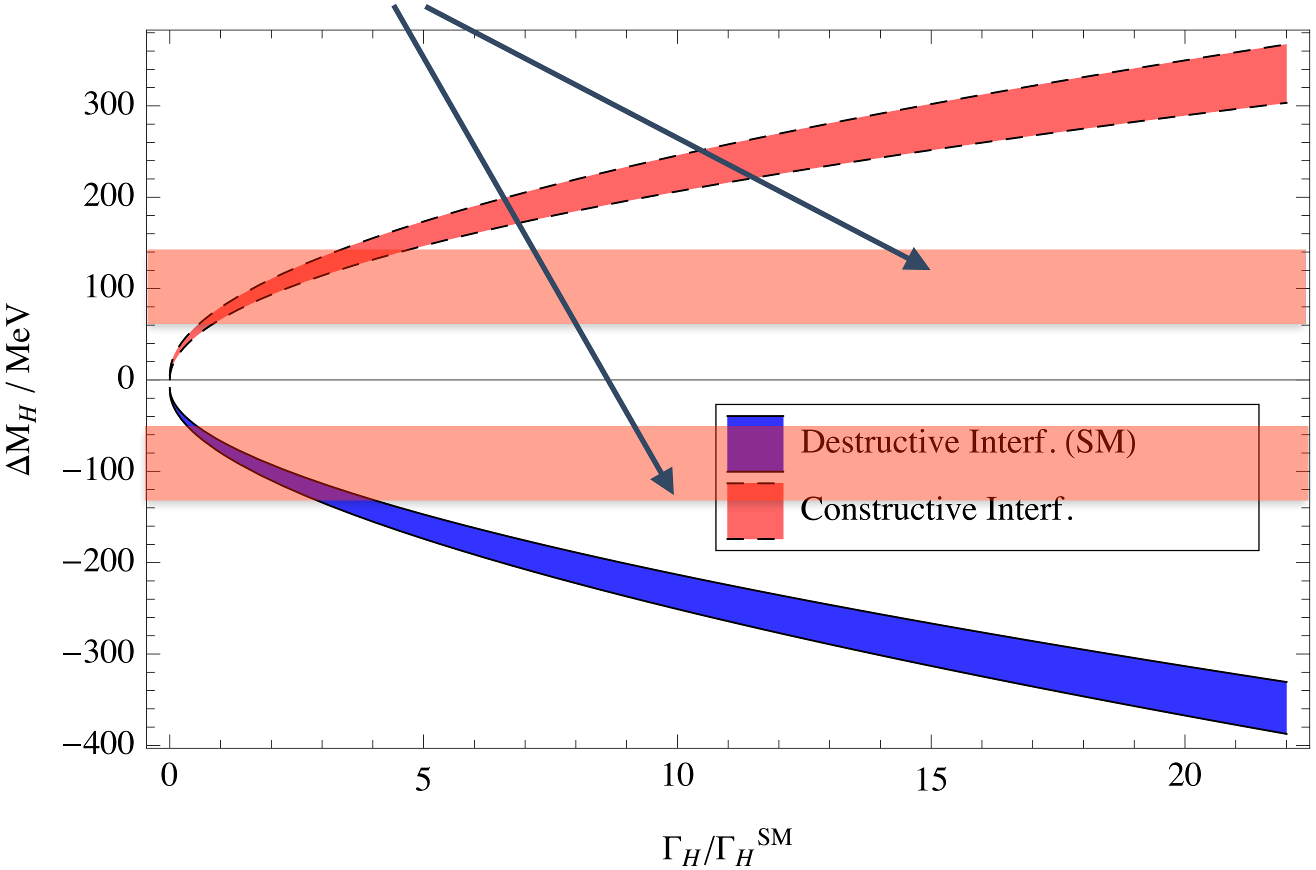
Γ_H from the mass-shift: prospects

$$\delta m_H \approx -35 \pm 9 \text{ MeV} \times \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}}$$

The mass sensitivity right now:

$m_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$

ultimate LHC reach



ATLAS projections @95 cl
[ATL-PHYS-PUB-2013-014]

- LHC [300 fb^{-1}] → $\Gamma_H < 200\ \Gamma_{H,SM} \approx 880$ MeV
- LHC [3000 fb^{-1}] → $\Gamma_H < 40\ \Gamma_{H,SM} \approx 160$ MeV

SENSITIVITY TO $\Gamma_H < [10\text{-}40]\ \Gamma_{H,SM}$ ACHIEVABLE

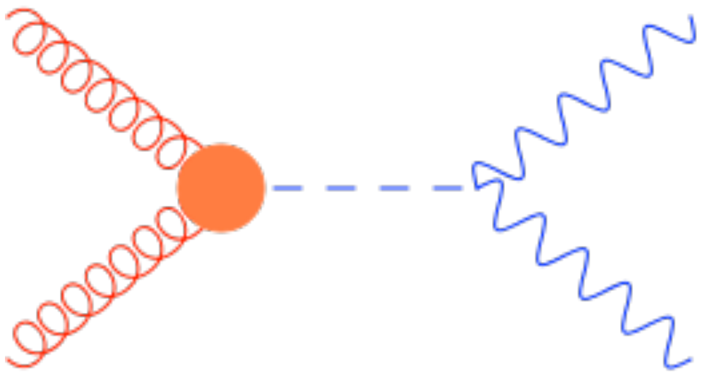
(direct sensitivity: $\Gamma_H < 1$ GeV)

A second example:

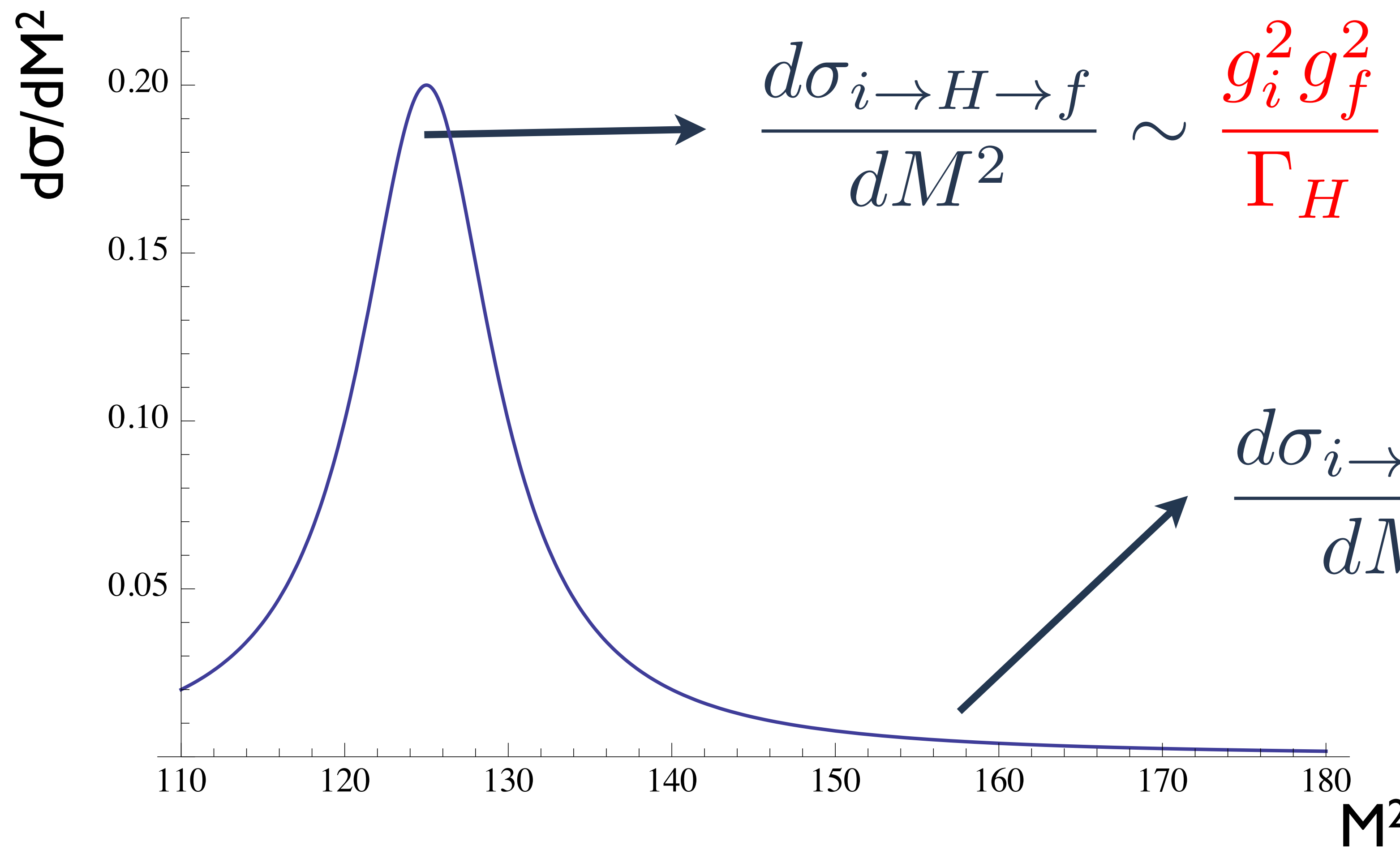
off-shell Higgs measurements

Decoupling Γ_H/g: the off-shell region

THE GOAL: break the $g \to \xi g, \quad \Gamma_H \to \xi^4 \Gamma_H$ degeneracy



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



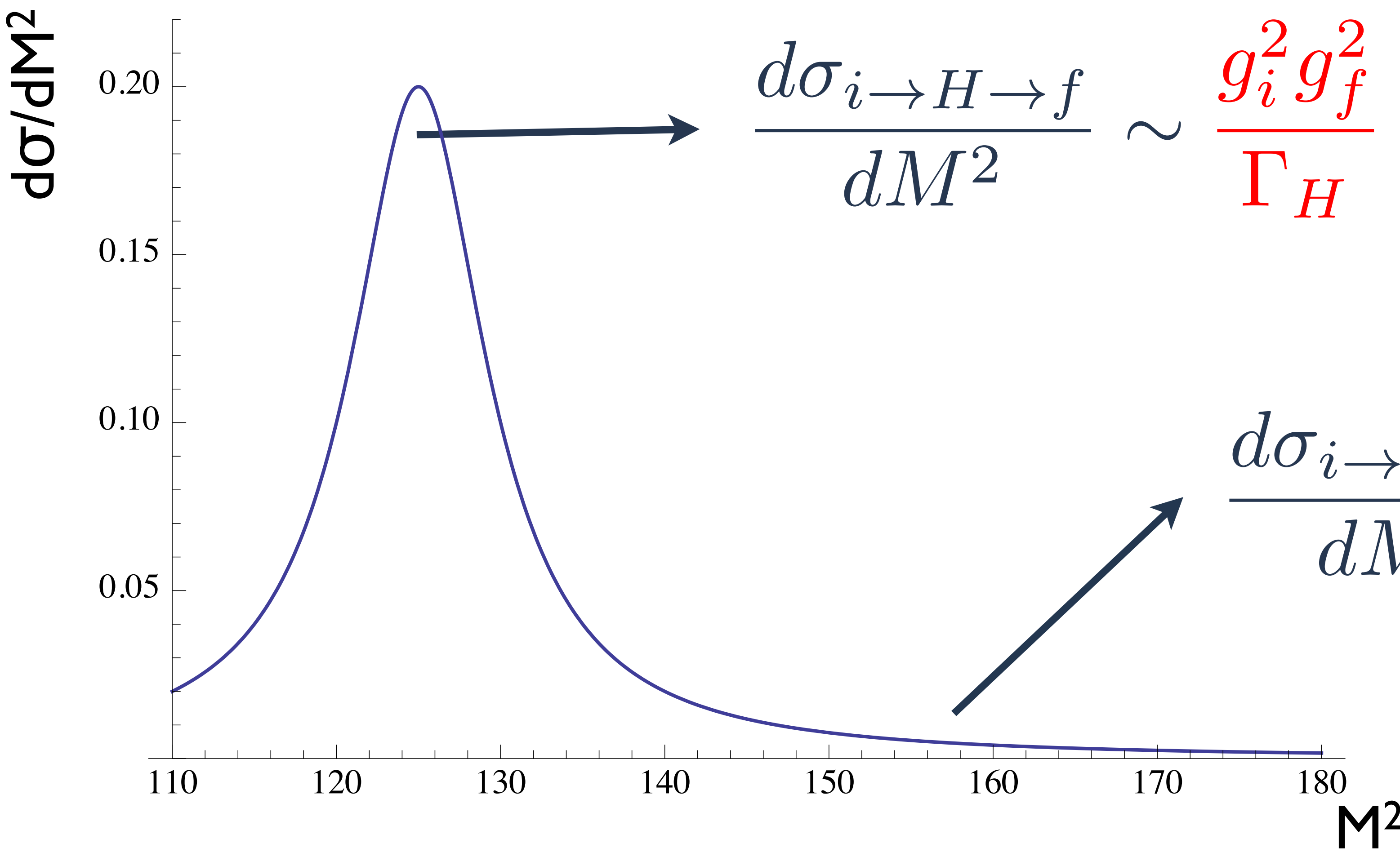
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

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

OFF THE MASS SHELL, σ DOES NOT DEPEND ON Γ_H

The off-shell region for narrow resonances

The Higgs is a very narrow resonance



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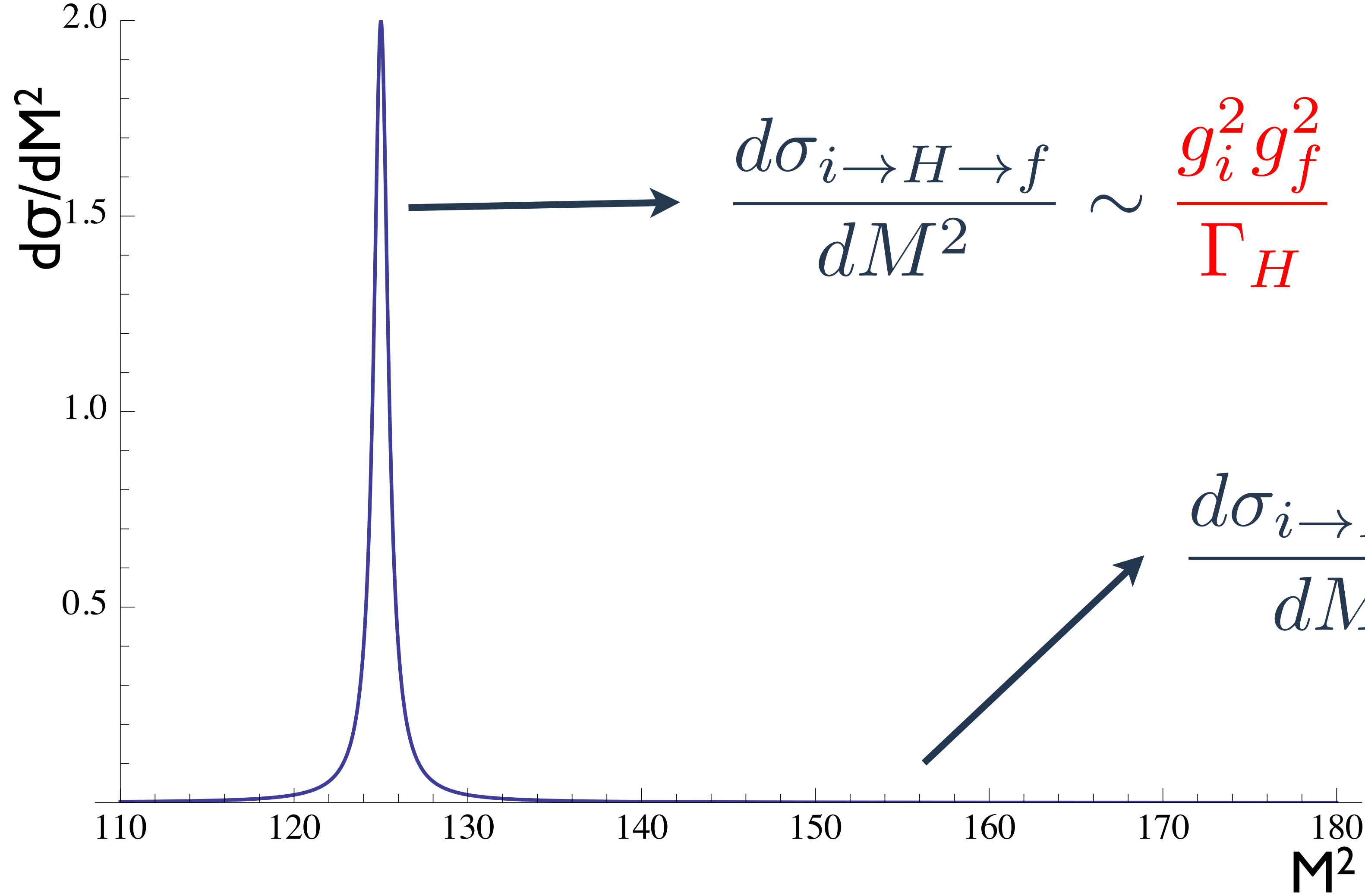


$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

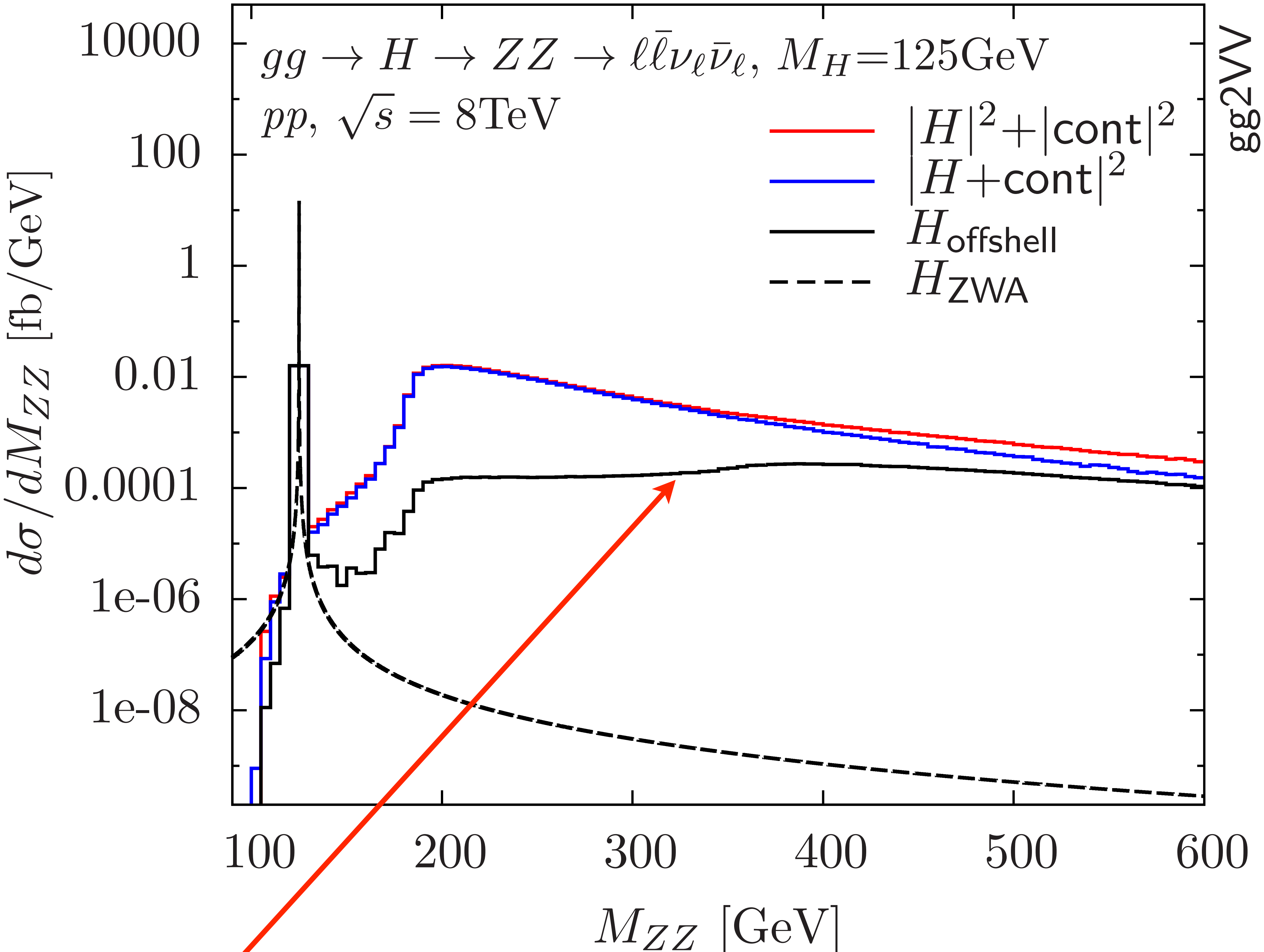
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2 - m_H^2)^2}$$

In general, ~no cross-section in the off-shell region

IS THERE A MECHANISM TO COMPENSATE THE SHARP FALL?

Yes, look at VV decay modes

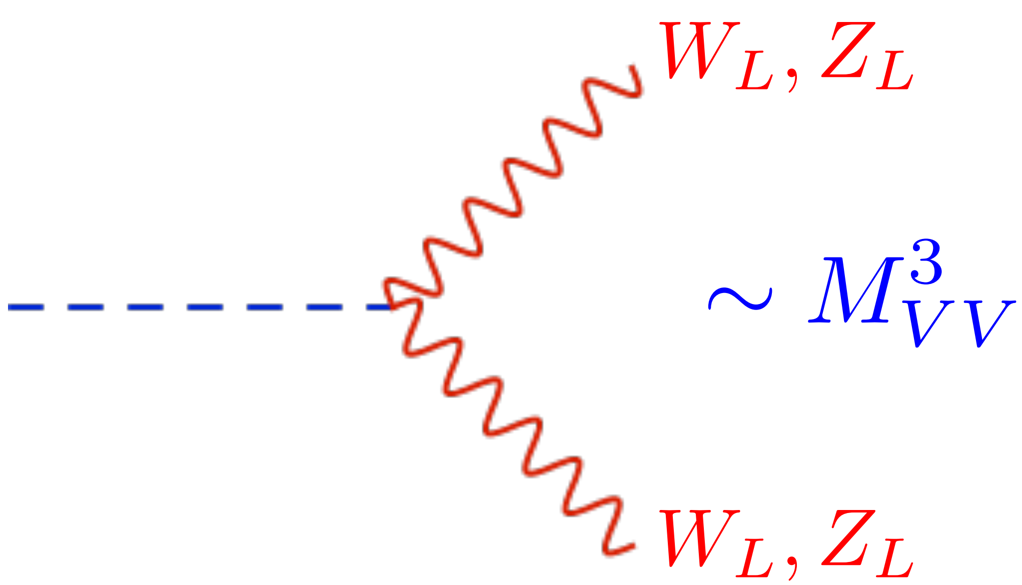
[Kauer, Passarino (2012)]



Large off-shell tail (O(10%) of the total cross section)

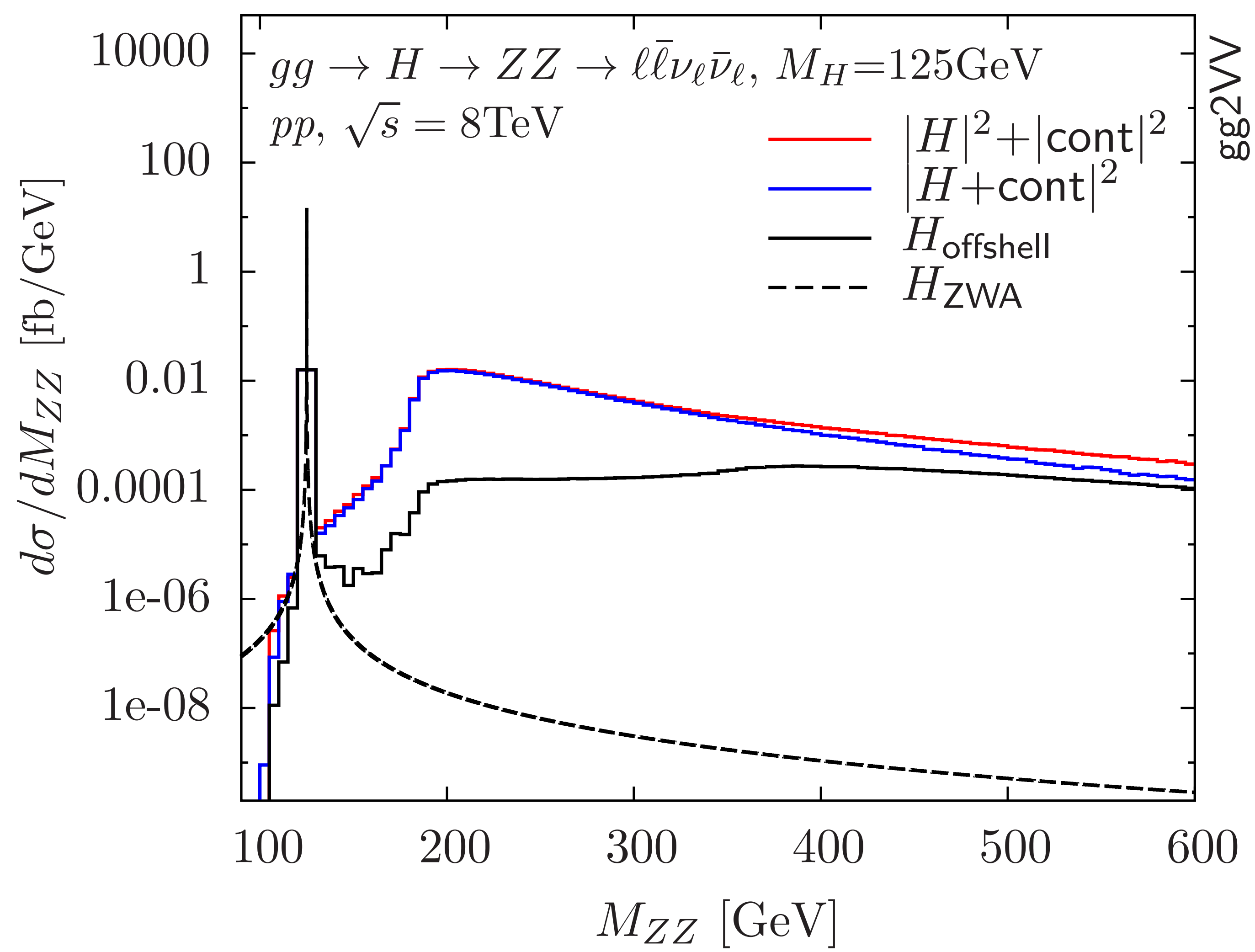
Yes, look at VV decay modes

[Kauer, Passarino (2012)]



Above the VV threshold:
enhanced decay into
longitudinal gauge bosons

Large plateau, eventually washed away by parton luminosities



Constraining Γ_H from $\sigma_{\text{off-shell}}$

[FC, Melnikov (2013)]

LHC on-peak results: SM-like Higgs boson

$$\frac{g_i^2 g_f^2}{\Gamma_H} = \frac{g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2}{\Gamma_{H,\mathrm{SM}}} \longrightarrow g = \xi g_{\mathrm{SM}}, \;\; \Gamma_H = \xi^4 \Gamma_{H,\mathrm{SM}}$$

Off-shell cross section Γ_H- independent: $\sigma_{\mathrm{off}} \sim g_i^2 g_f^2$

Assuming $g_{peak} = g_{\text{off-shell}}$:

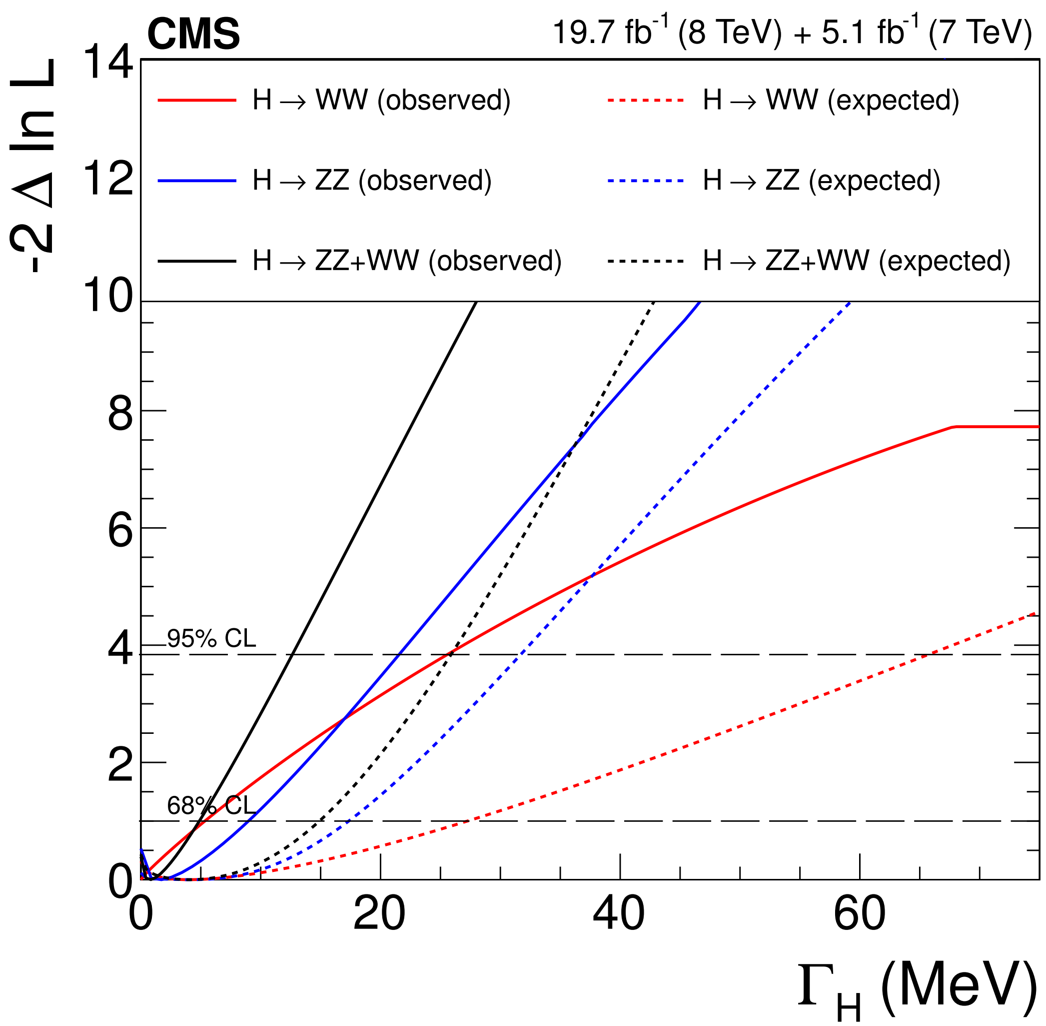
$$N_{obs}^{\mathrm{off}} \propto g_i^2 g_f^2 = \xi^4 g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2 \propto \xi^4 N_{\mathrm{SM}}^{\mathrm{off}} = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} N_{\mathrm{SM}}^{\mathrm{off}}$$

$$\Gamma_H = \frac{N_{obs}^{\mathrm{off}}}{N_{\mathrm{SM}}^{\mathrm{off}}} \Gamma_{H,\mathrm{SM}}$$

DIRECT ACCESS TO Γ_H, linear sensitivity

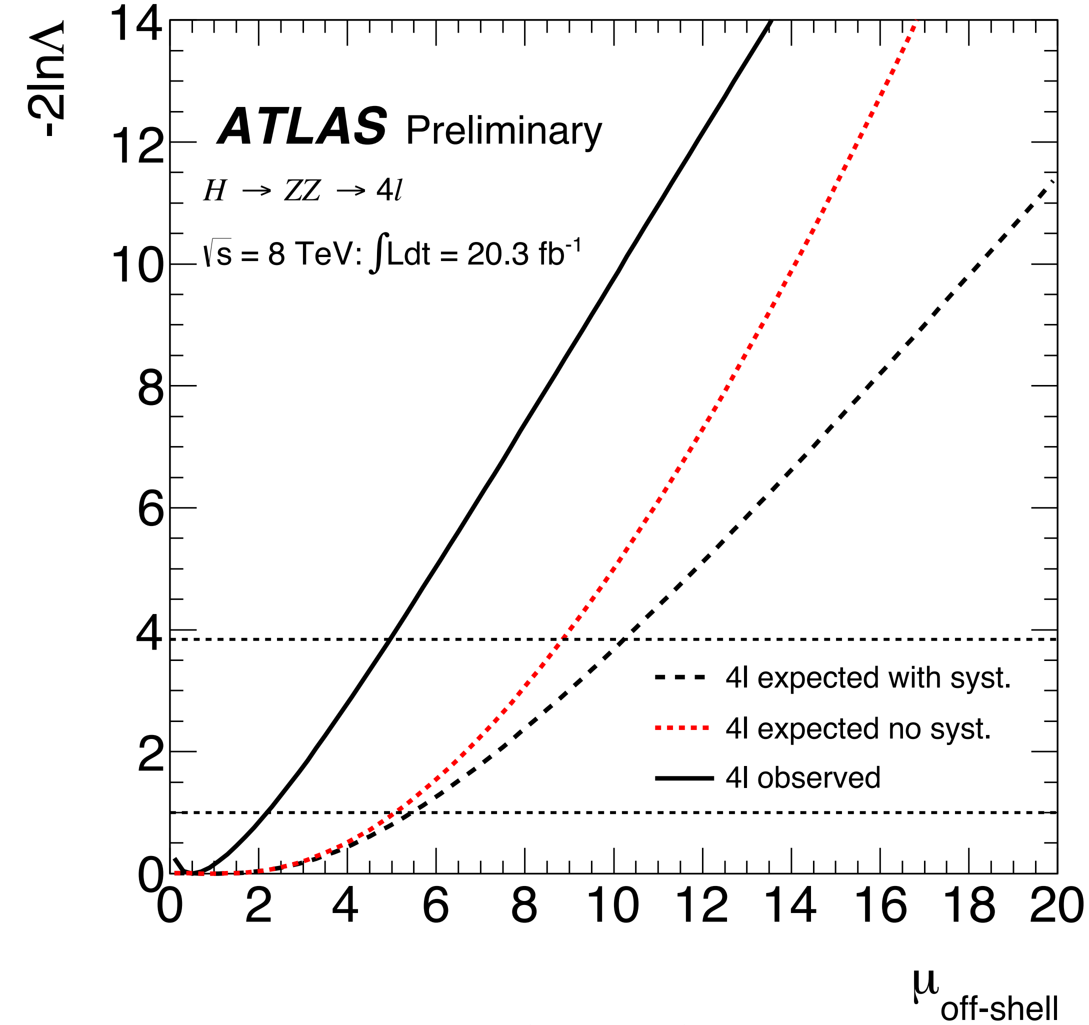
Γ_H from $\sigma_{\text{off-shell}}$: LHC results

CMS $H \to 4l, 2l2\nu$



[JHEP 09 (2016) 051]

ATLAS $H \to 4l, 2l2\nu$



[EPJC (2015) 75:335]

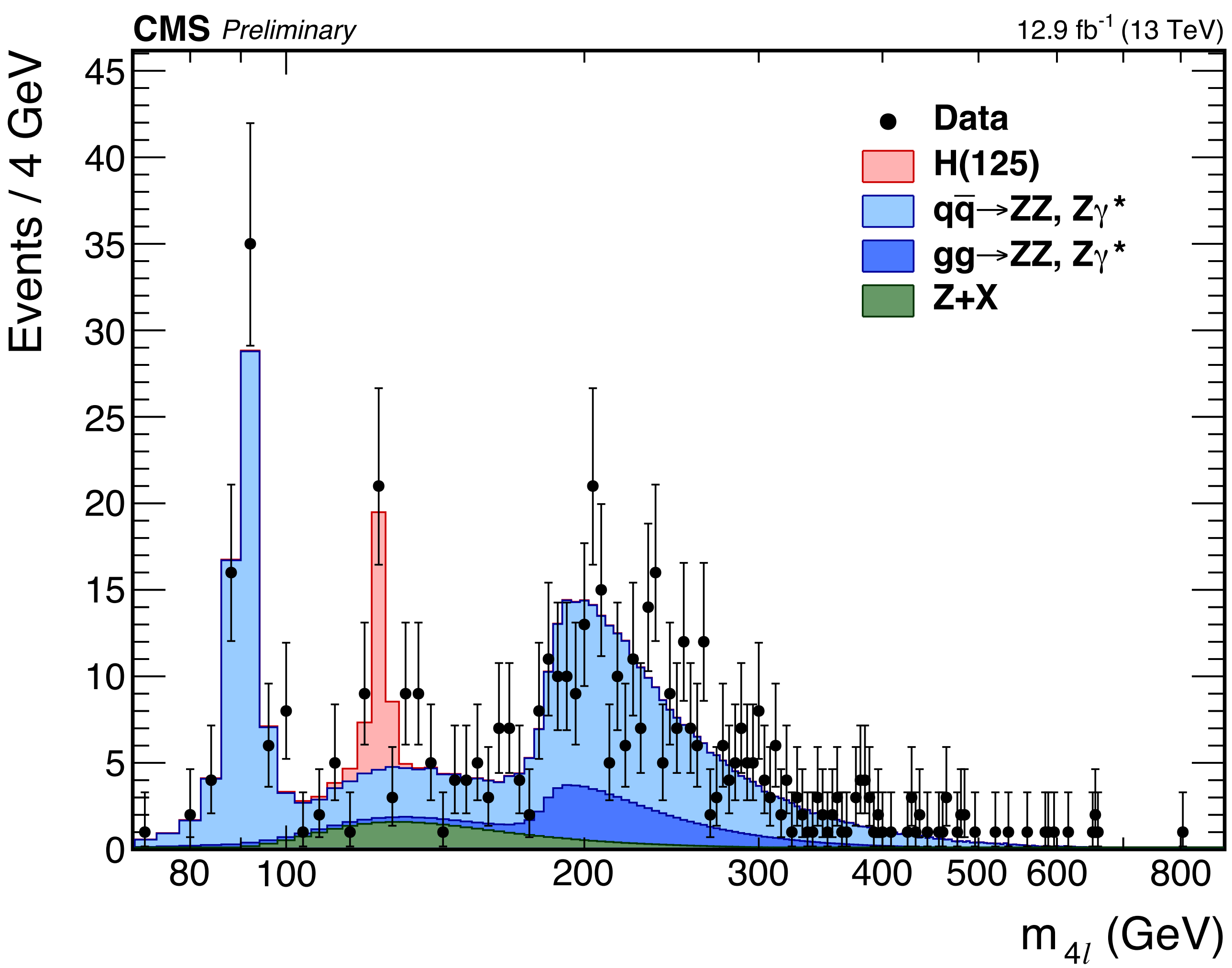
$\Gamma_H < 13$ (26) MeV obs(exp)

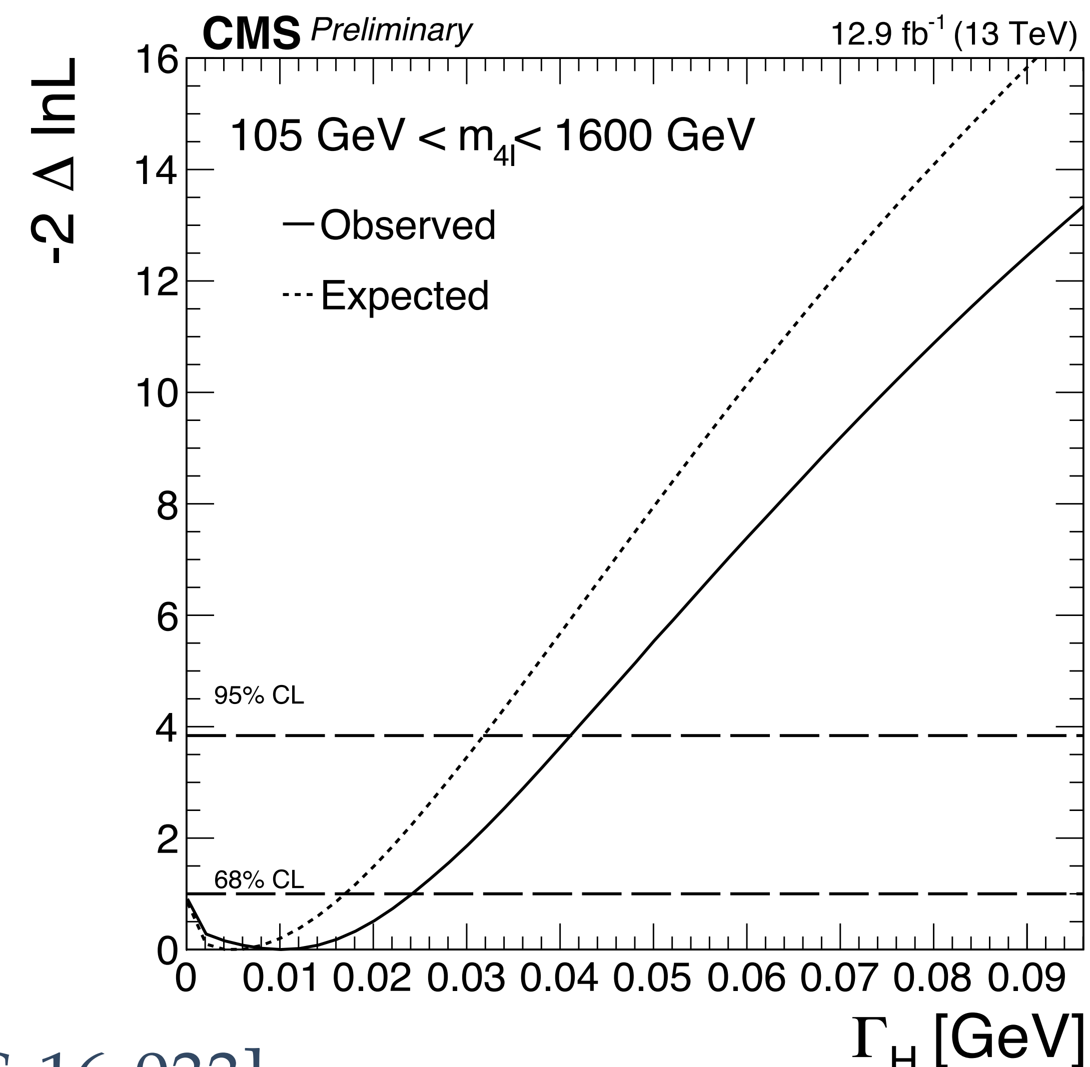
$\Gamma_H < 23$ (33) MeV obs(exp)

(direct sensitivity: $\Gamma_H < 1$ GeV)

Γ_H from $\sigma_{\text{off-shell}}$: Run II

CMS H→4l, MCFM + JHUGEN + HNNLO with MELA





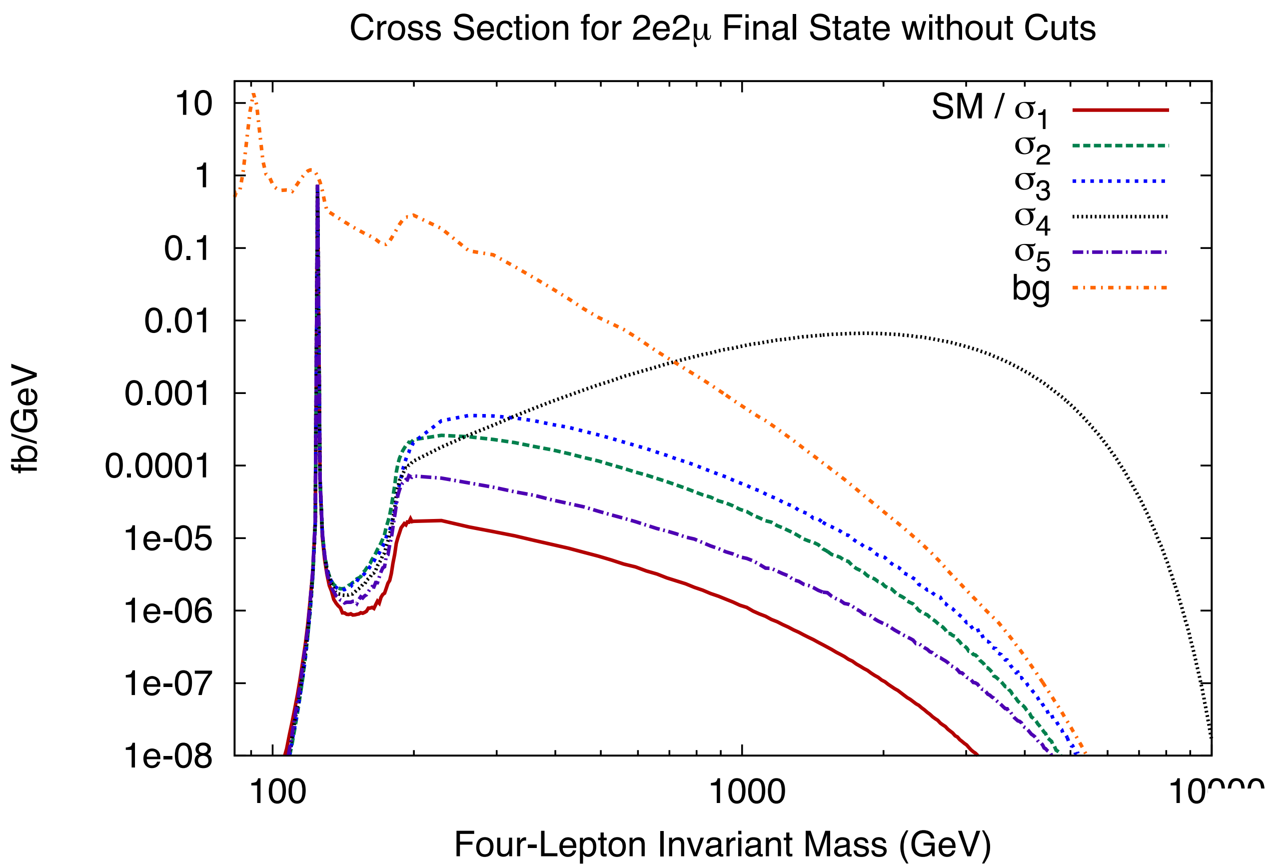
[CMS-HIG-16-033]

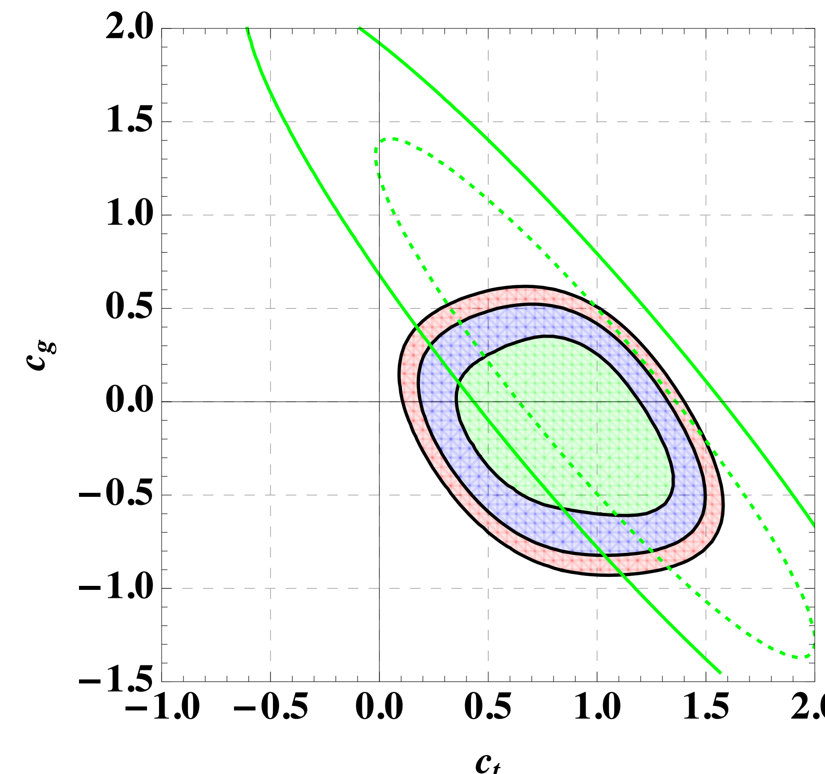
$\Gamma_H < 41$ MeV

(already better than RI 4l alone)

$\sigma_{\text{off-shell}}$ analysis: opportunities

Allow to study energy dependence of Higgs couplings

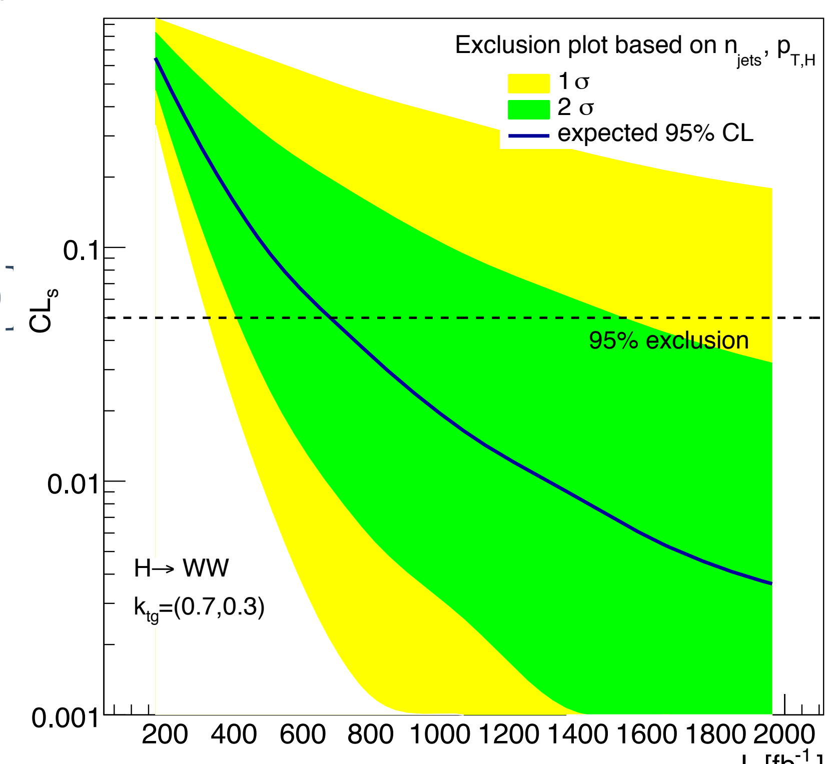




c_g, c_t [Azatov et al (2014)]

Anomalous HZZ couplings

[Gainer et al, Anderson et al (2013)]



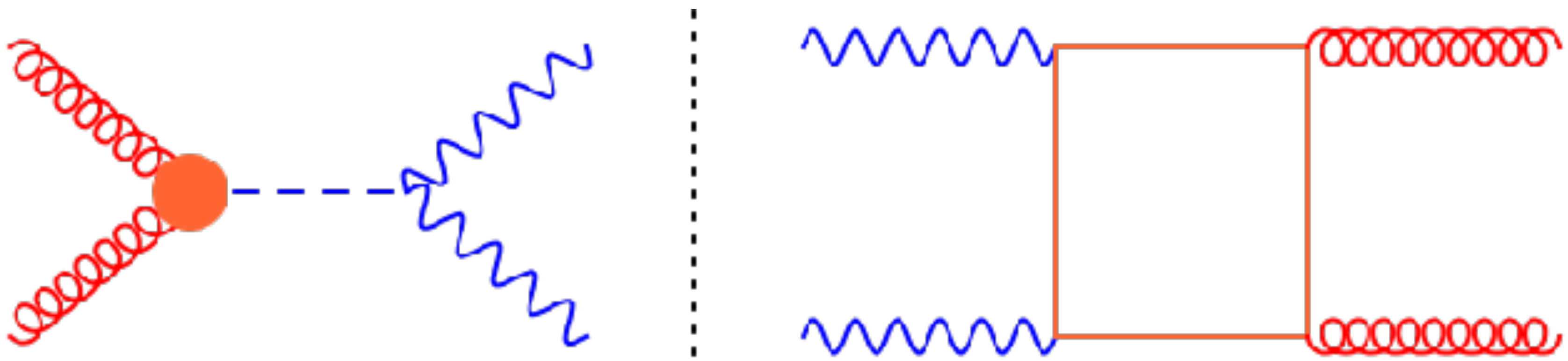
Relation to boosted regime

[Buschmann et al (2014)]

$\sigma_{\text{off-shell}}$ analysis: challenges

Off-shell analysis require GOOD CONTROL OF 4L PROCESSES

In particular: SIGNAL / BACKGROUND INTERFERENCE which makes SIGNAL DISENTANGLING HIGHLY NON TRIVIAL



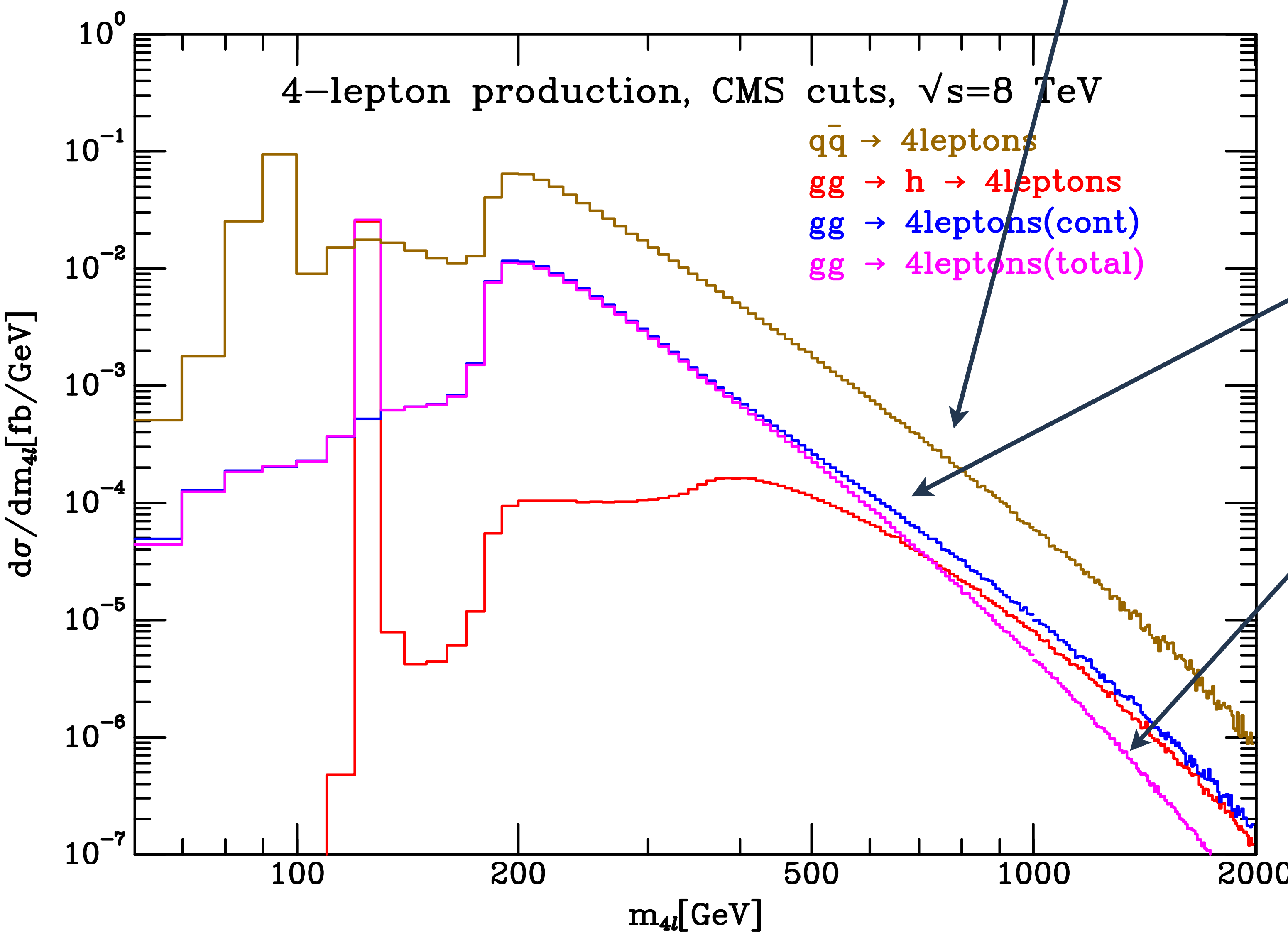
[Kauer, Passarino (2012); Campbell, Ellis, Williams (2013)]

In the SM: large O(50-100%) destructive interference → UNITARITY RESTORATION

4-lepton spectrum at the LHC

Dominated by qq background (known at NNLO)

Can be efficiently separated with MEM (angular correlations…)



[Campbell, Ellis, Williams (2013)]

Very tricky gg background and interference

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

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

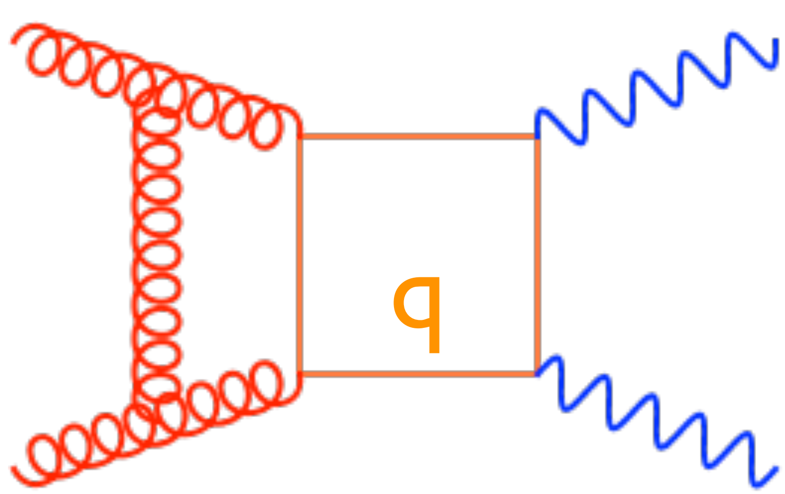
$N_H \sim 5 \times 10^{-2} \times N_{\rm tot}$

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

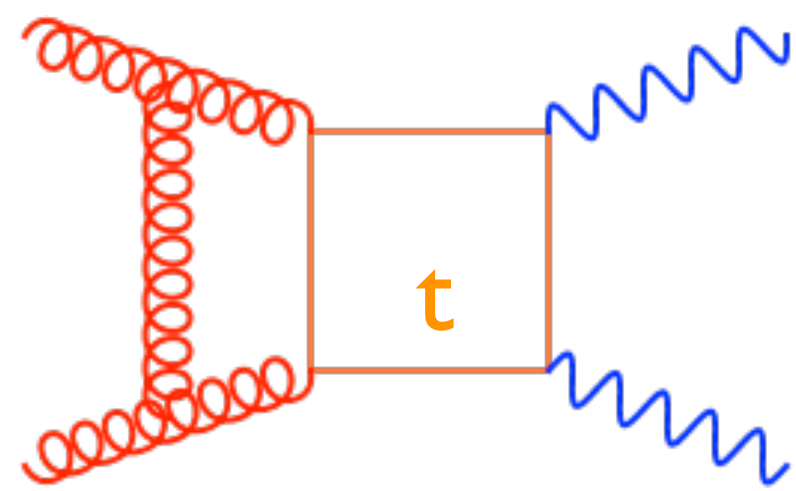
$N_{\rm int} \sim -2 \times 10^{-2} N_{\rm tot}$

The gg→VV background/interference

- right now, we have NNLO for the qq channel and ~ N^{3}LO for the signal, but LO only for the full GG→VV BACKGROUND AND INTERFERENCE
- gluon initiated process → expect large QCD corrections
- the problem: loop-induced process, NLO INVOLVES (VERY) COMPLICATED 2-LOOP AMPLITUDES



Recently computed

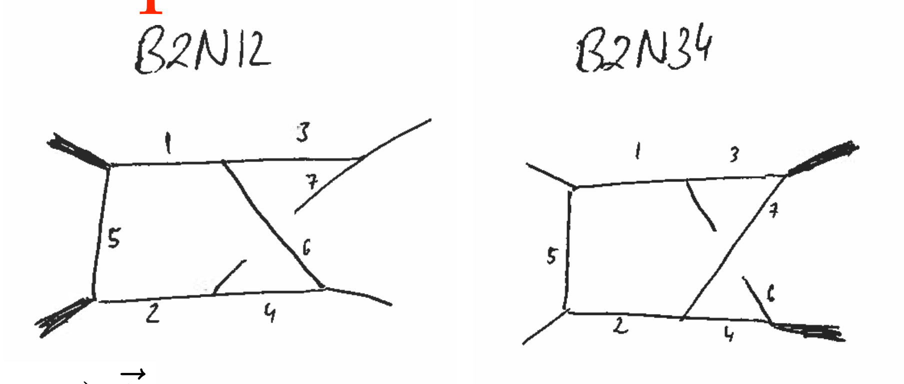


VERY HARD
[important in the off-shell region]

gg→VV@NLO: massless quark

2-loop amplitude for VV*

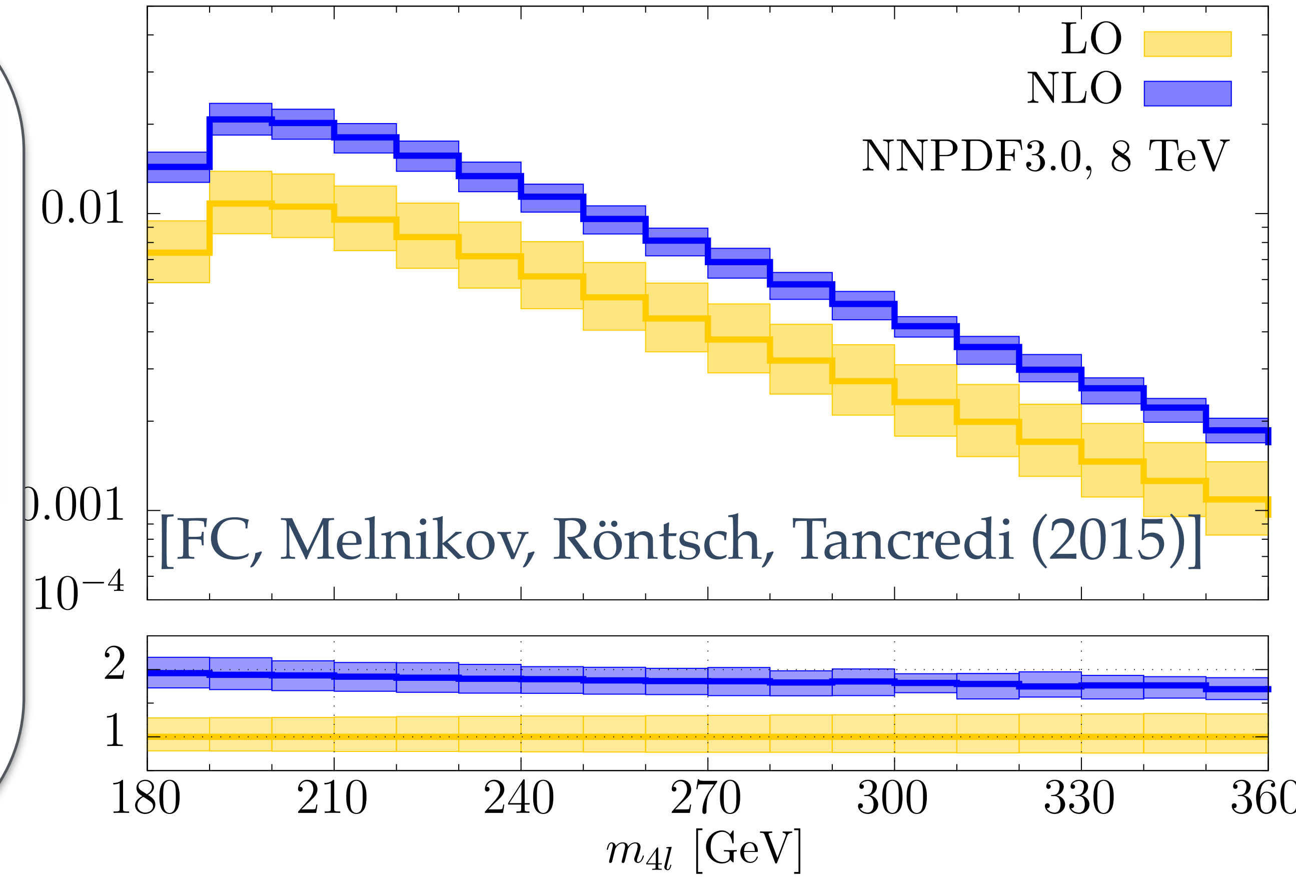
new ideas for FI at work



$$\partial_x \vec{f} = \epsilon \hat{A}_x(x,y,z\ldots)\vec{f}$$

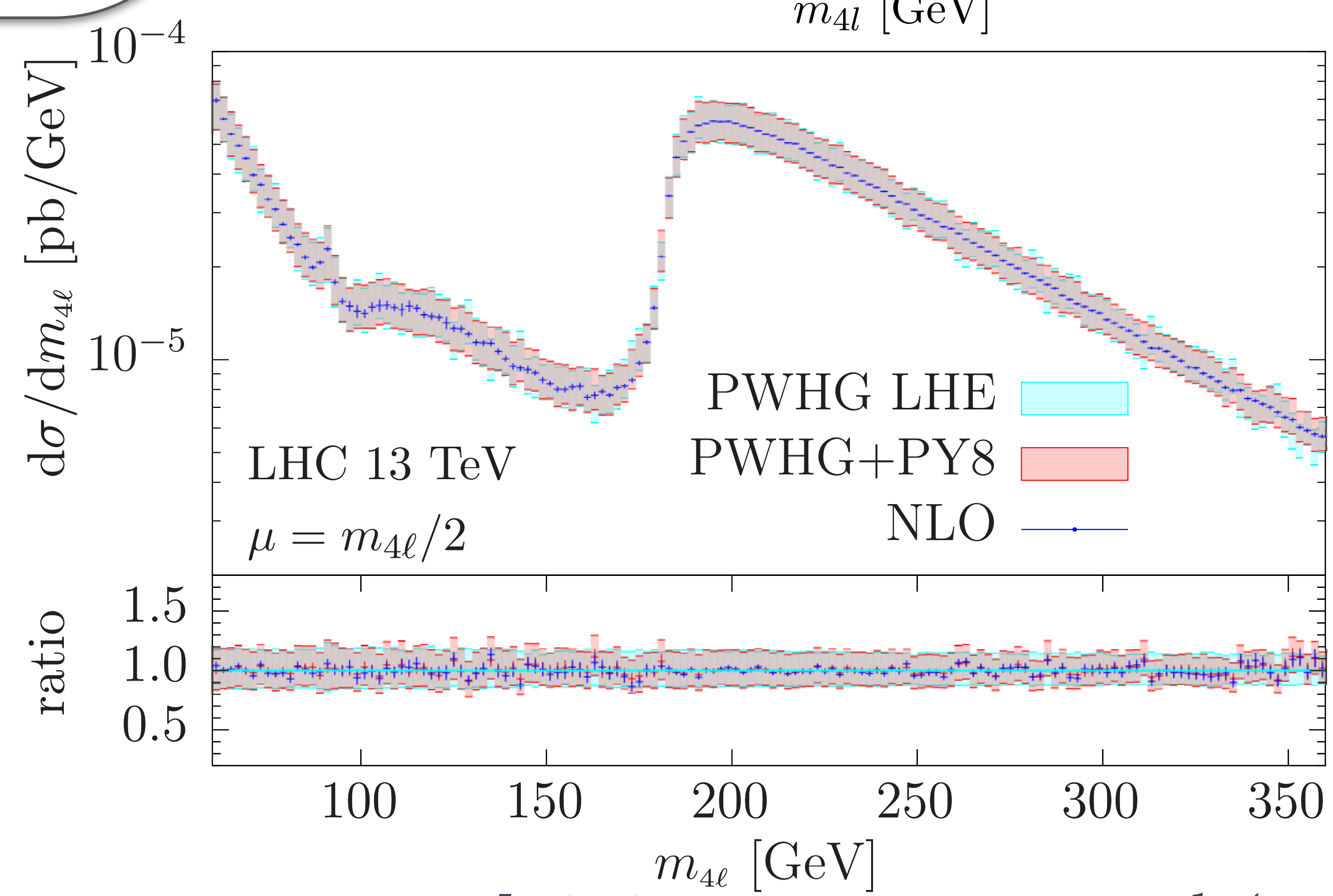
$$G(a_n, a_{n-1}, \ldots, a_1, t) = \int_0^t \frac{dt_n}{t_n - a_n} G(a_{n-1}, \ldots a_1, t_n)$$

[FC, Henn, Melnikov, Smirnov, Smirnov (2014-15); Gehrmann, Manteuffel, Tancredi (2014-15)]



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

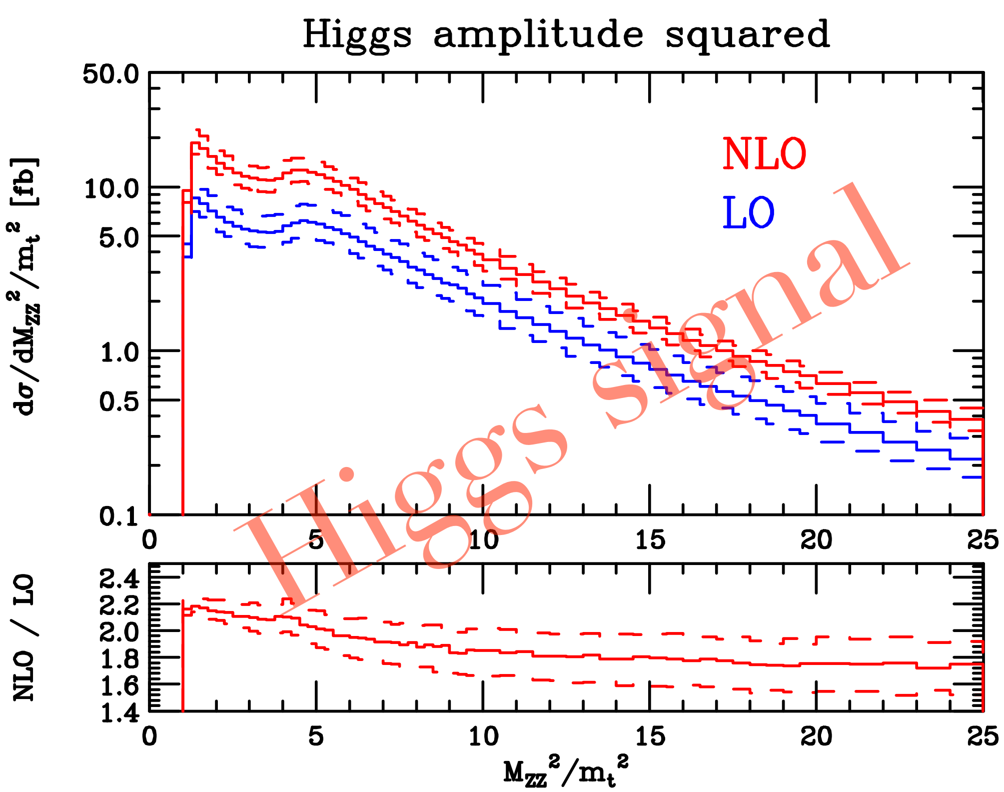
- large corrections (as expected)
- behavior very similar to gg→H signal (expected)
- confirms previous estimates based on soft-gluon approximation

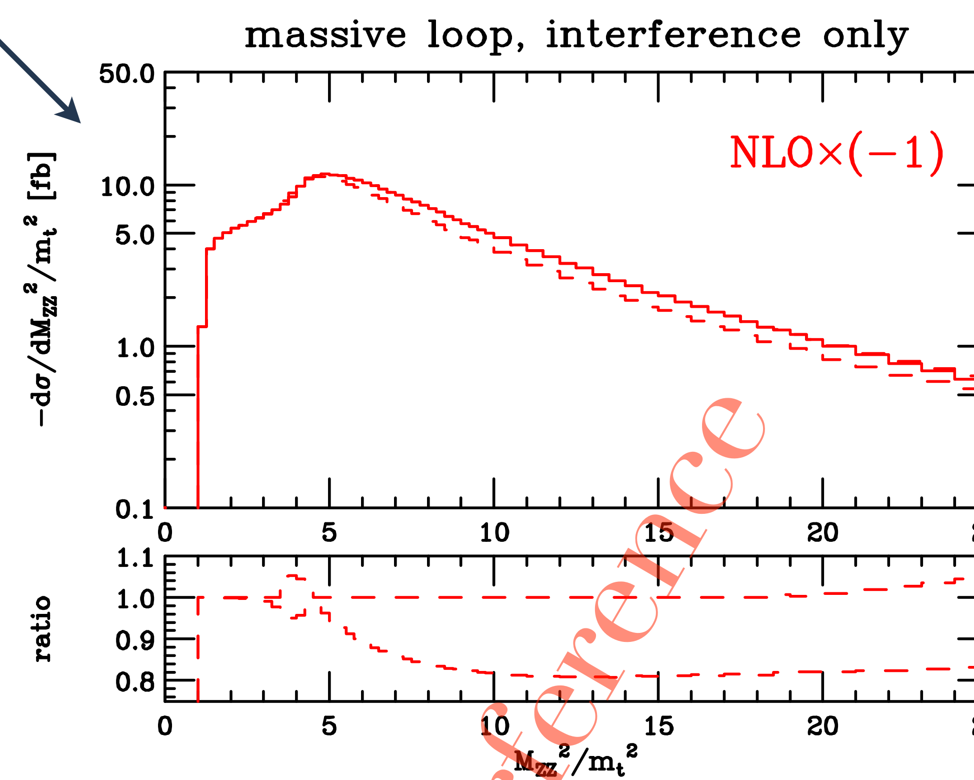


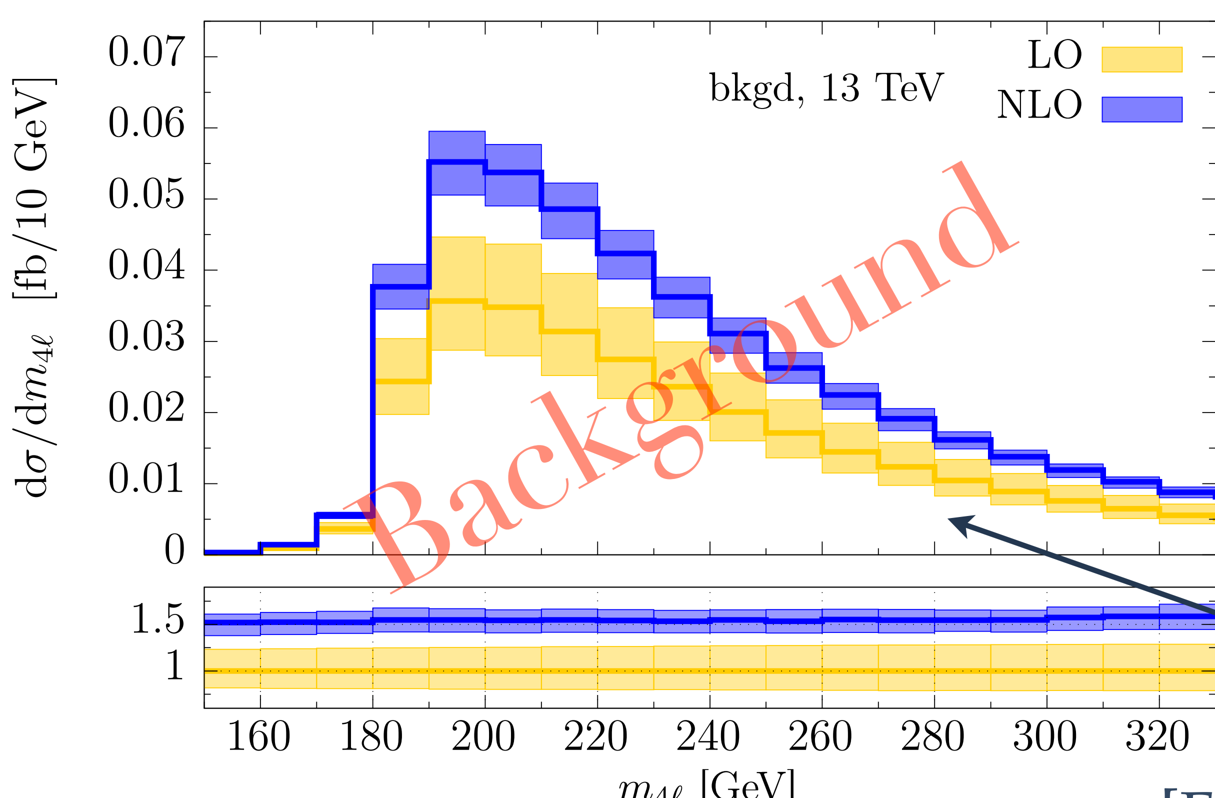
[Alioli, FC, Luisoni, Röntsch (2016)]

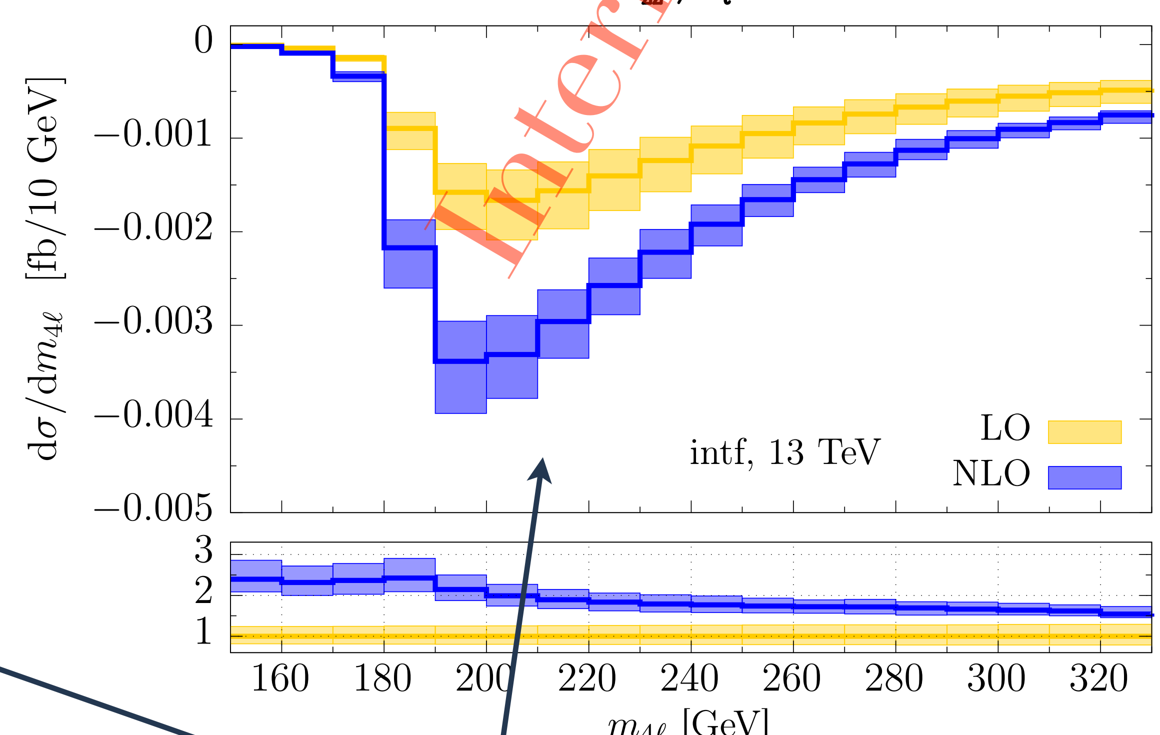
gg→VV@NLO: approximate top

[Campbell, Czakon, Ellis, Kirchner (2016)]









[FC, Dowling, Melnikov, Röntsch, Tancredi (2016)]

Conclusion

- the LHC is pointing towards a SM-like Higgs
- standard analysis can only constrain σ x BR
- interesting observables / regime can give further constraints

- $H \rightarrow \gamma\gamma$:
  - signal/background interference gives access to Γ_H
  - largely model-independent, but exp. tough

- off-shell Higgs:
  - under certain assumptions, strong bounds on Γ_H
  - more in general, allows to study kinematics dependence of Higgs couplings
  - very delicate signal/background interference effects, quite complicated to properly model

Outlook

A lot of work still needs to be done

- for experimentalists (better handle on $\gamma\gamma$ interference, qq/gg $\rightarrow$ 4l separation, discriminants…)
- for BSM phenomenologists (BSM constraints for the off-shell width analysis, anomalous couplings, interplay off-shell vs boosted…)
- for SM theorists/phenomenologists (massive loops for the gg$\rightarrow$VV signal/background interference: new insight, numerical methods…)

INTERESTING TIMES AHEAD!

Thank you for your attention!