Constraining the Higgs width at the LHC

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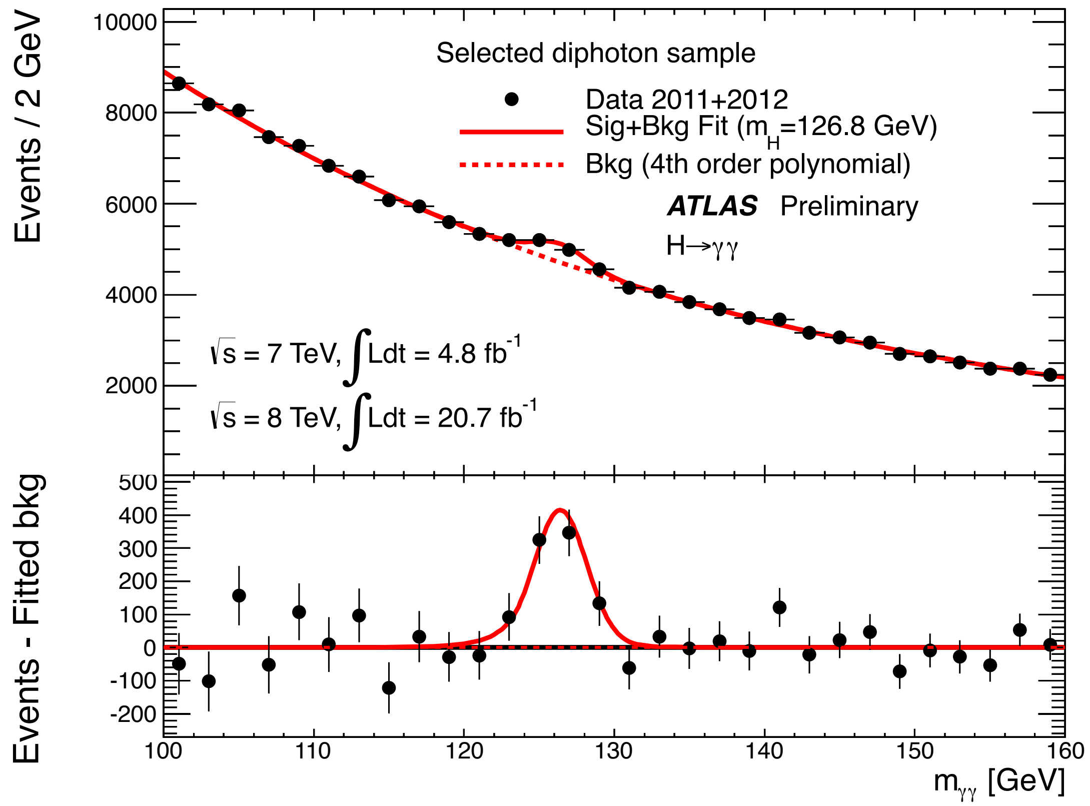
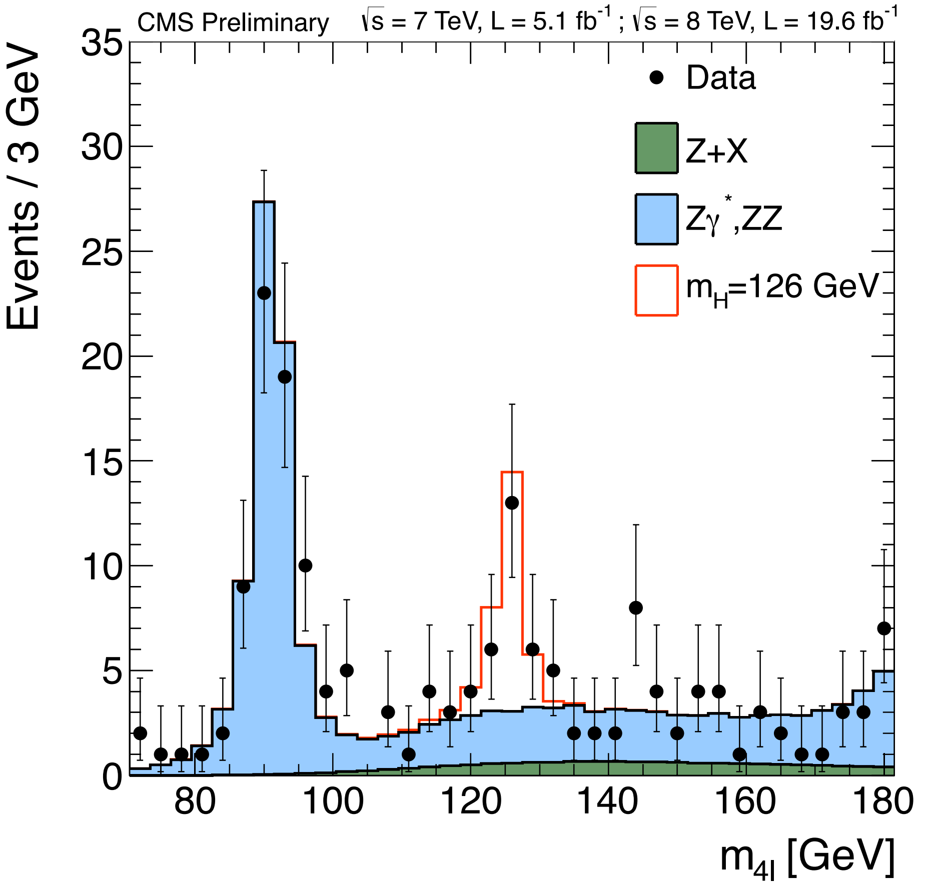
GRADUIERTENKOLLEG GRK 2044
MASS AND SYMMETRIES AFTER THE DISCOVERY OF THE HIGGS PARTICLE AT THE LHC

FREIBURG, DECEMBER 16TH 2015

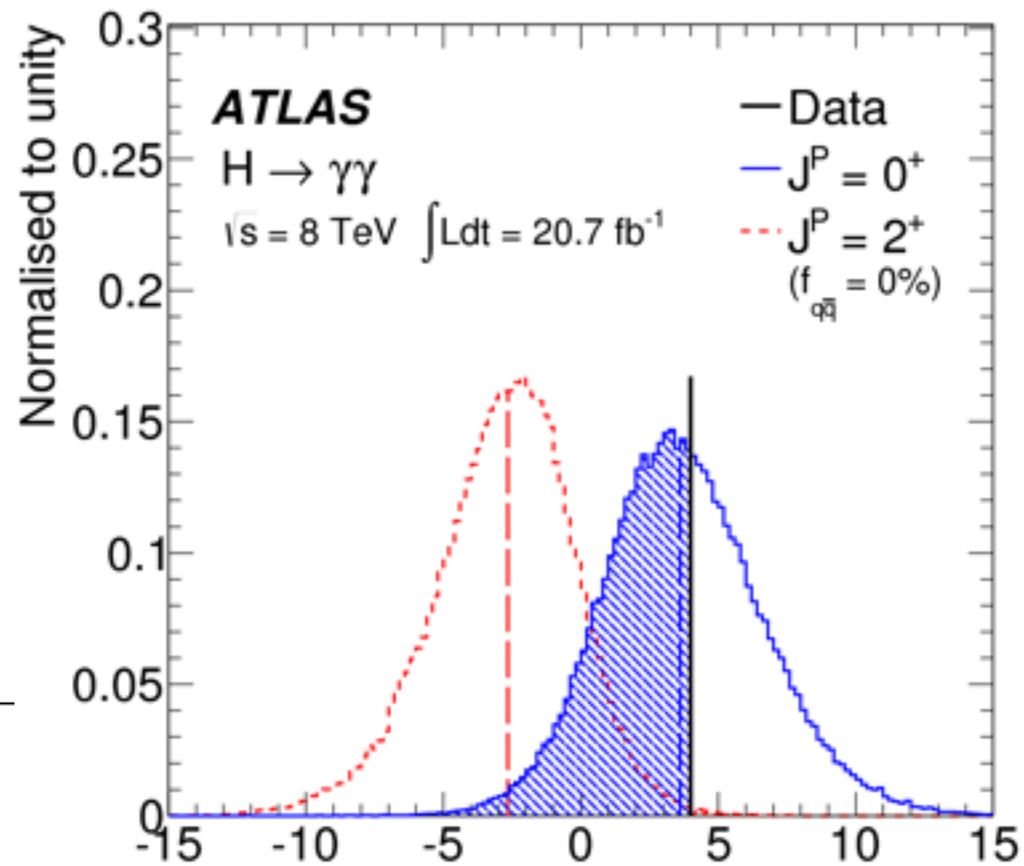
The Higgs: a remarkable achievement

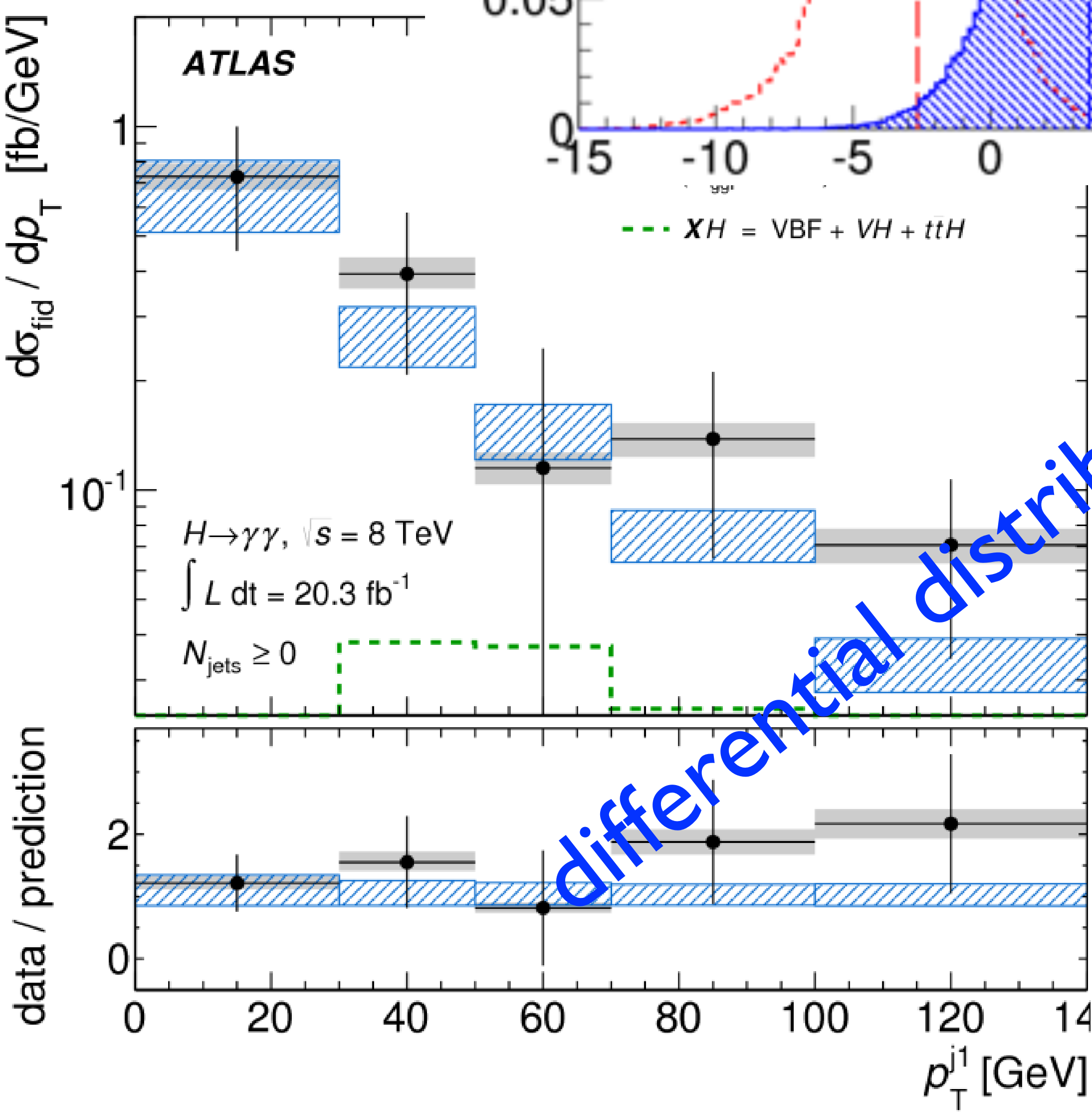




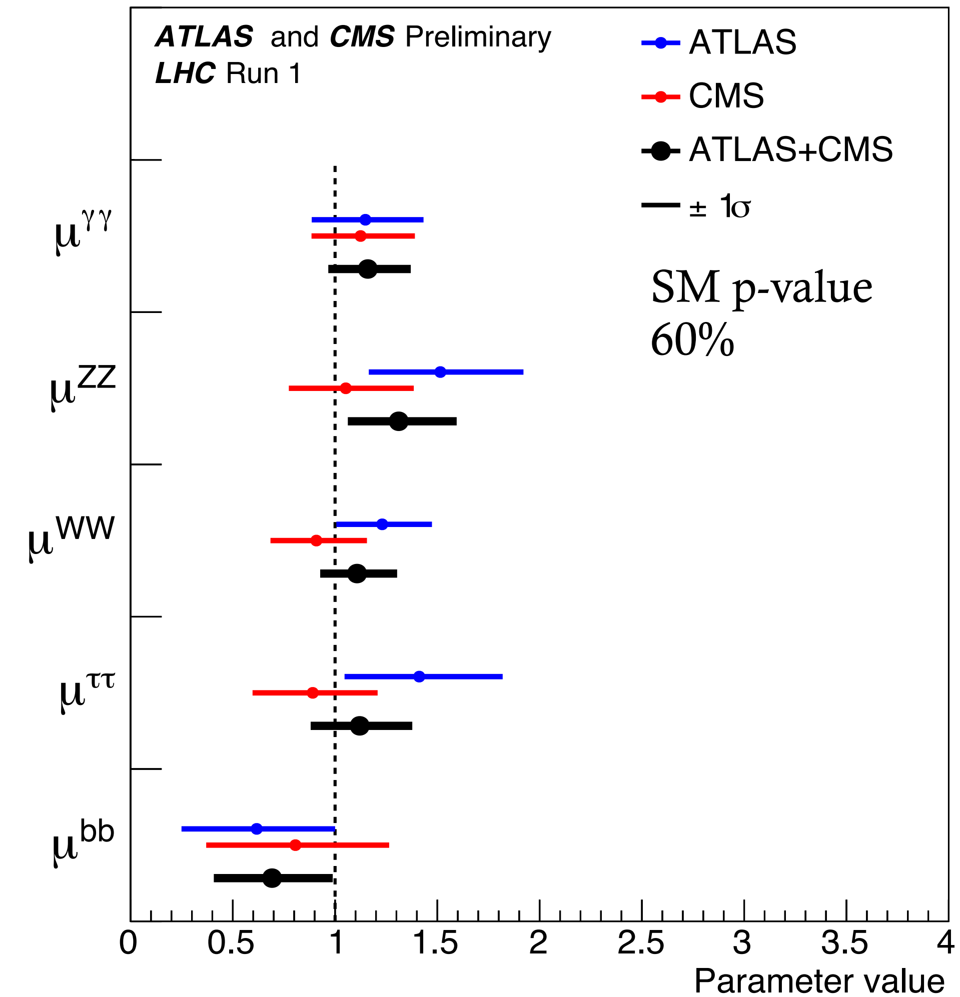
Many properties already constrained

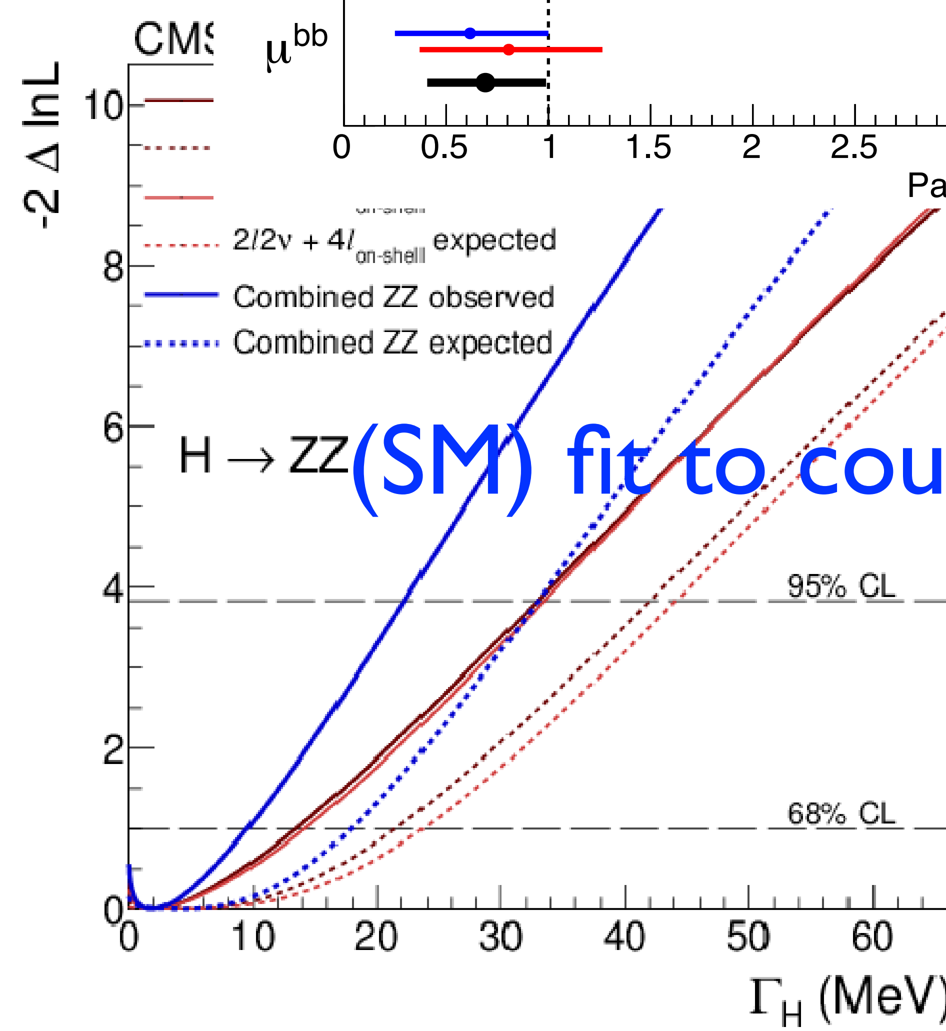
Spin-parity





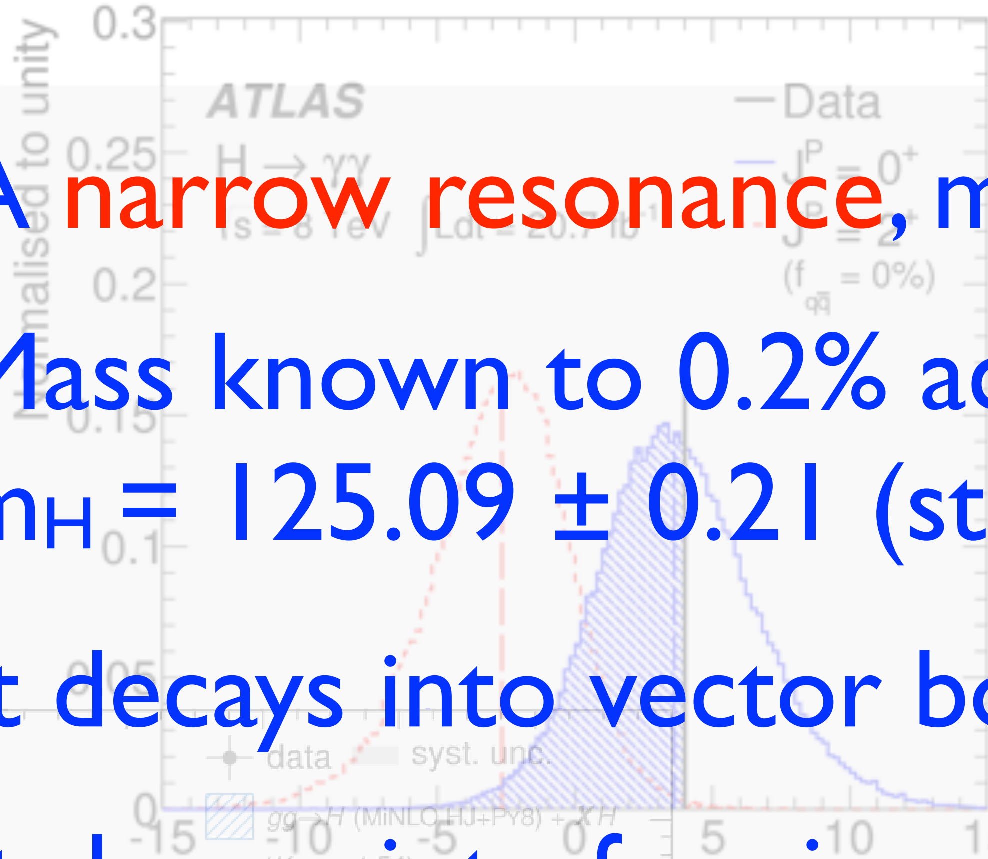
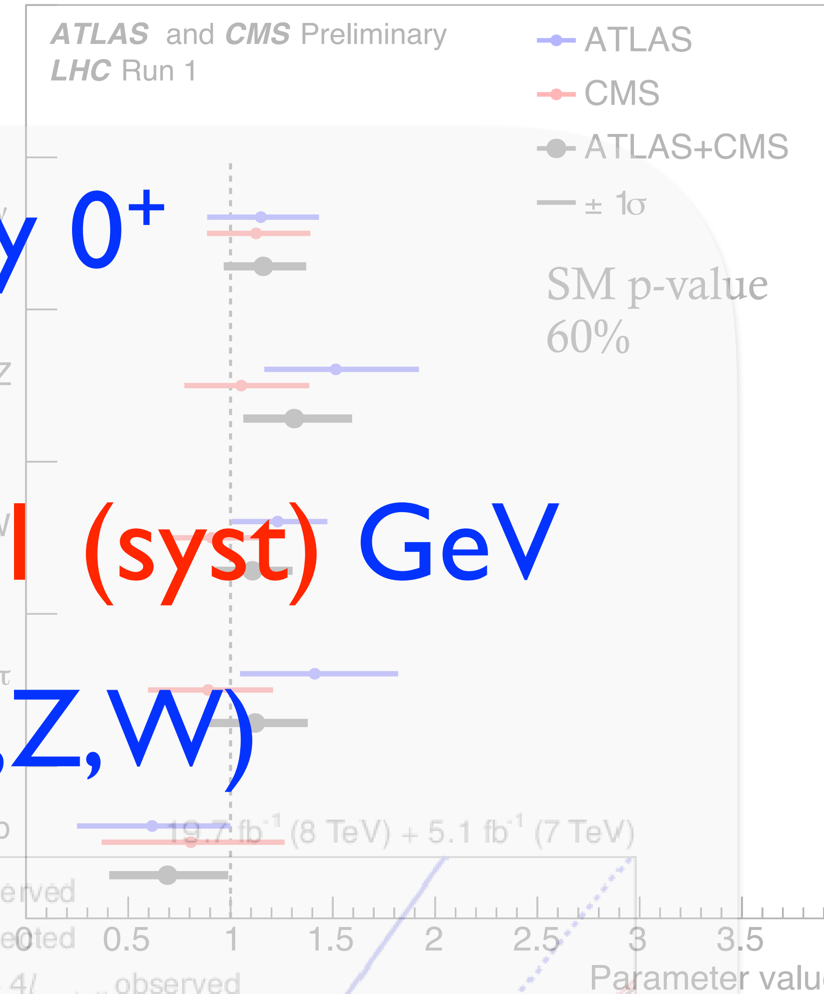
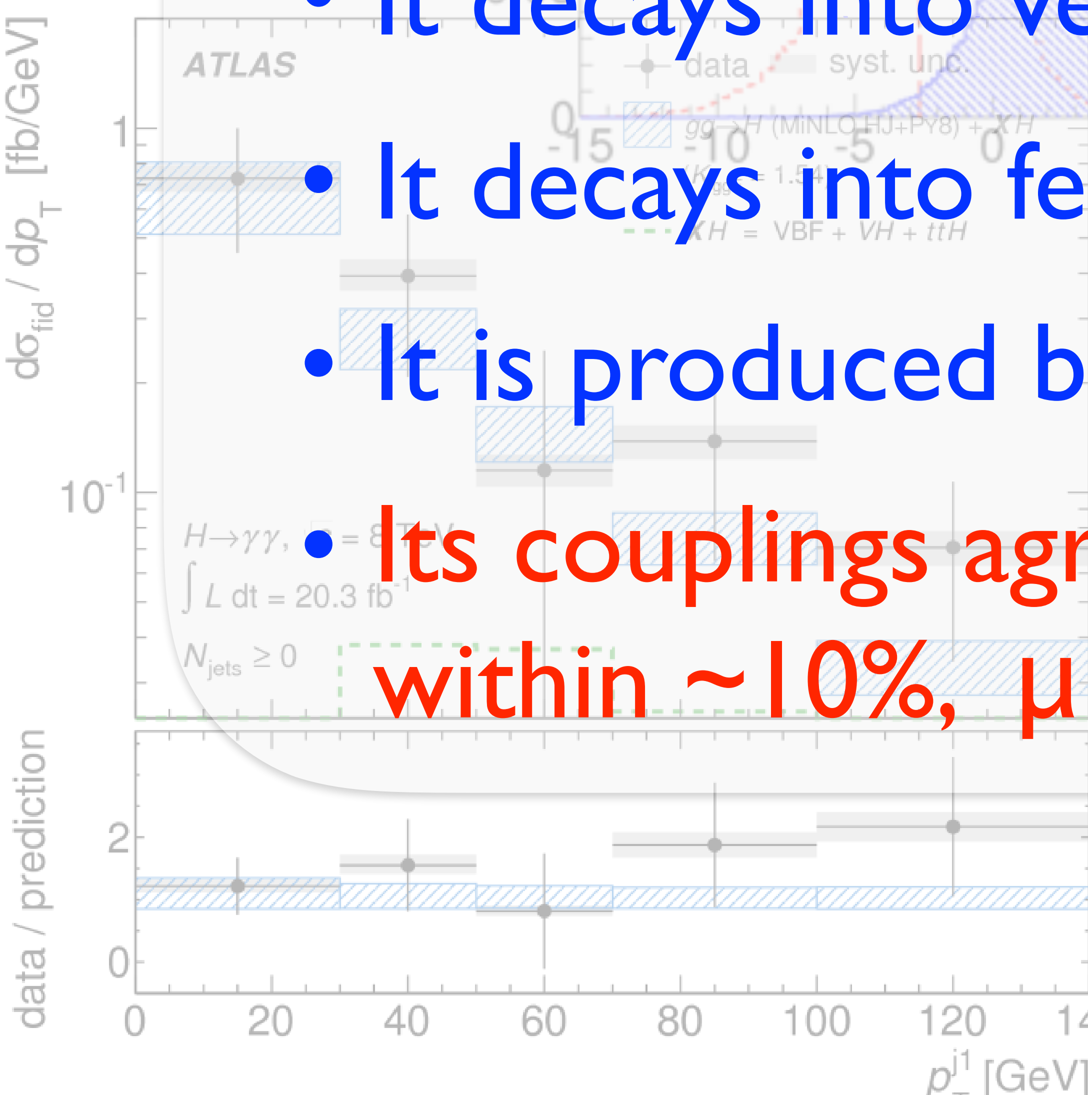
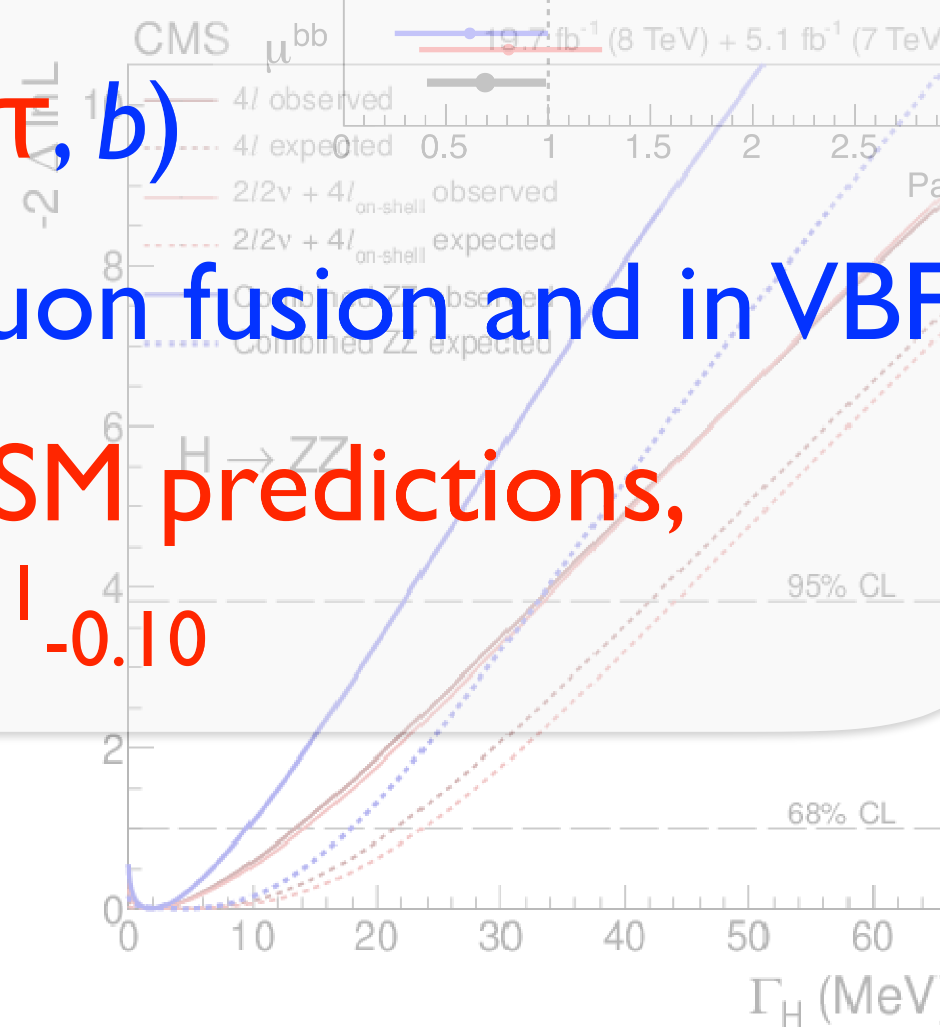
differential distributions





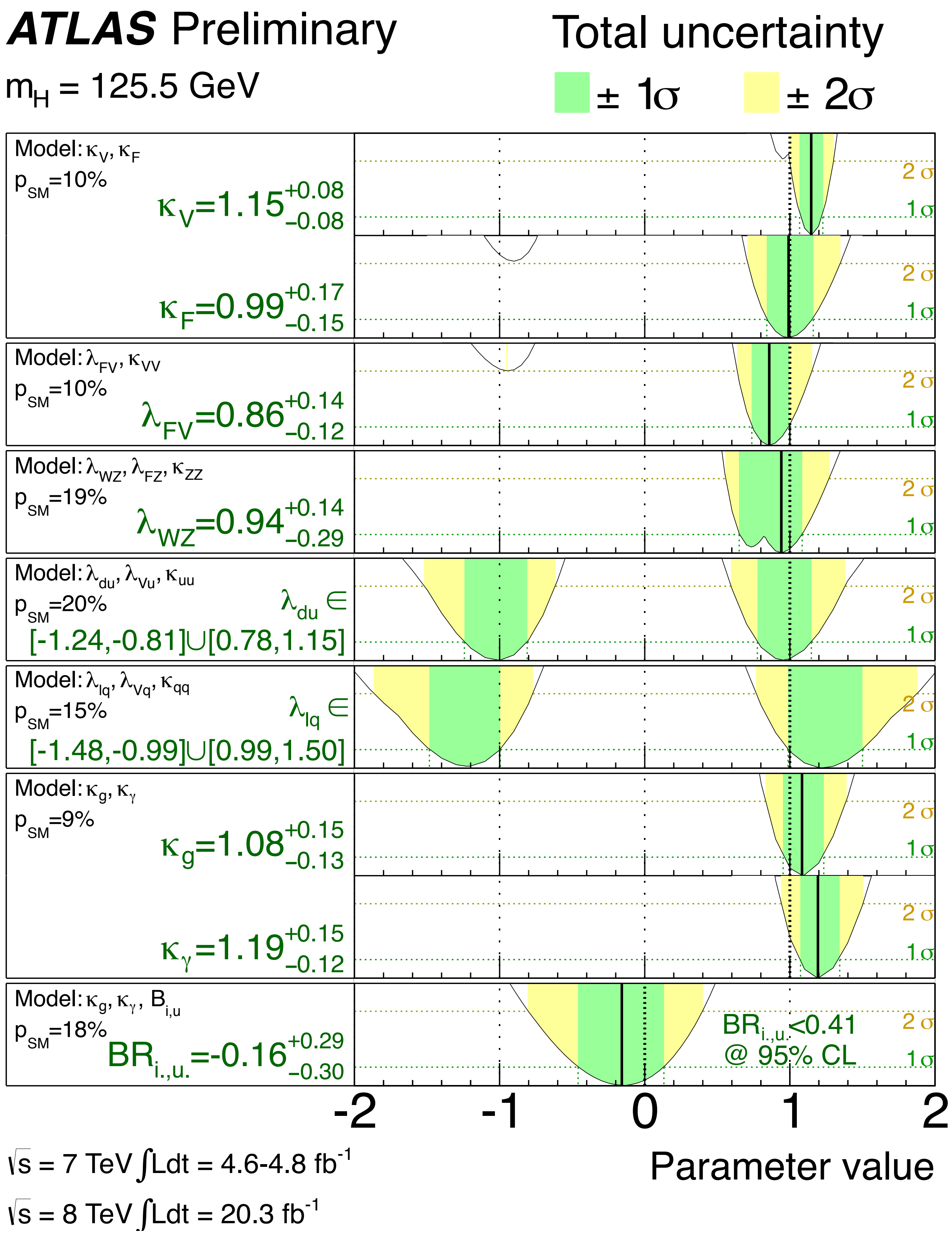
(SM) fit to couplings

The Higgs: what to 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%, $\mu=1.09^{+0.11}_{-0.10}$

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 rations 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

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

The Higgs cross section x BR is invariant under the rescaling

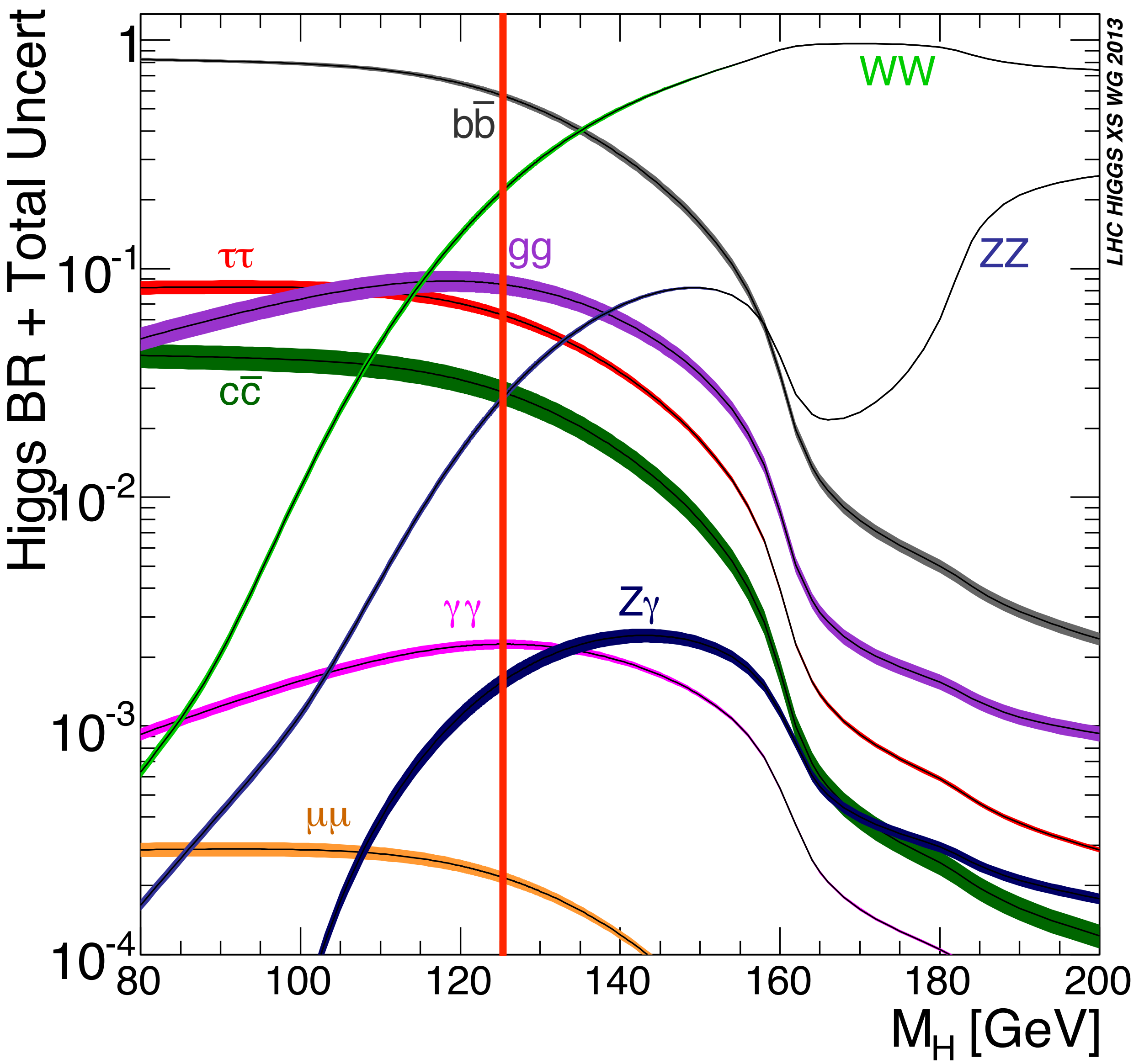
$$g \to \xi g,\ \Gamma_H \to \xi^4 \Gamma_H \implies \sigma_{i\to H\to f} \to \sigma_{i\to H\to f}$$

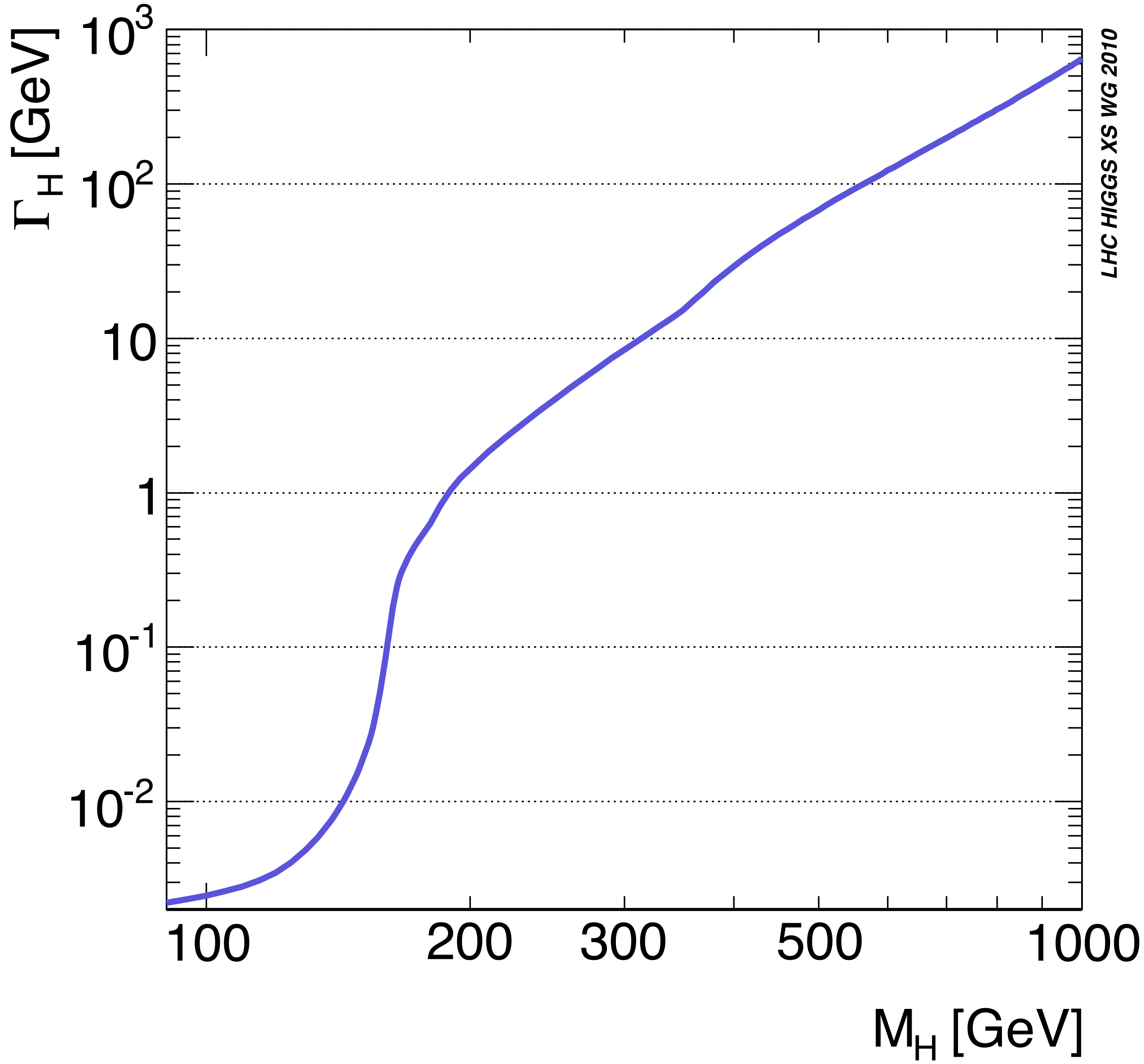
Any measurement on the Higgs peak, only determines a family of ∞ degenerate solutions for g, Γ_H

To resolve this ambiguity, the width/couplings need to be measured independently from each other

The SM width: extremely small

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

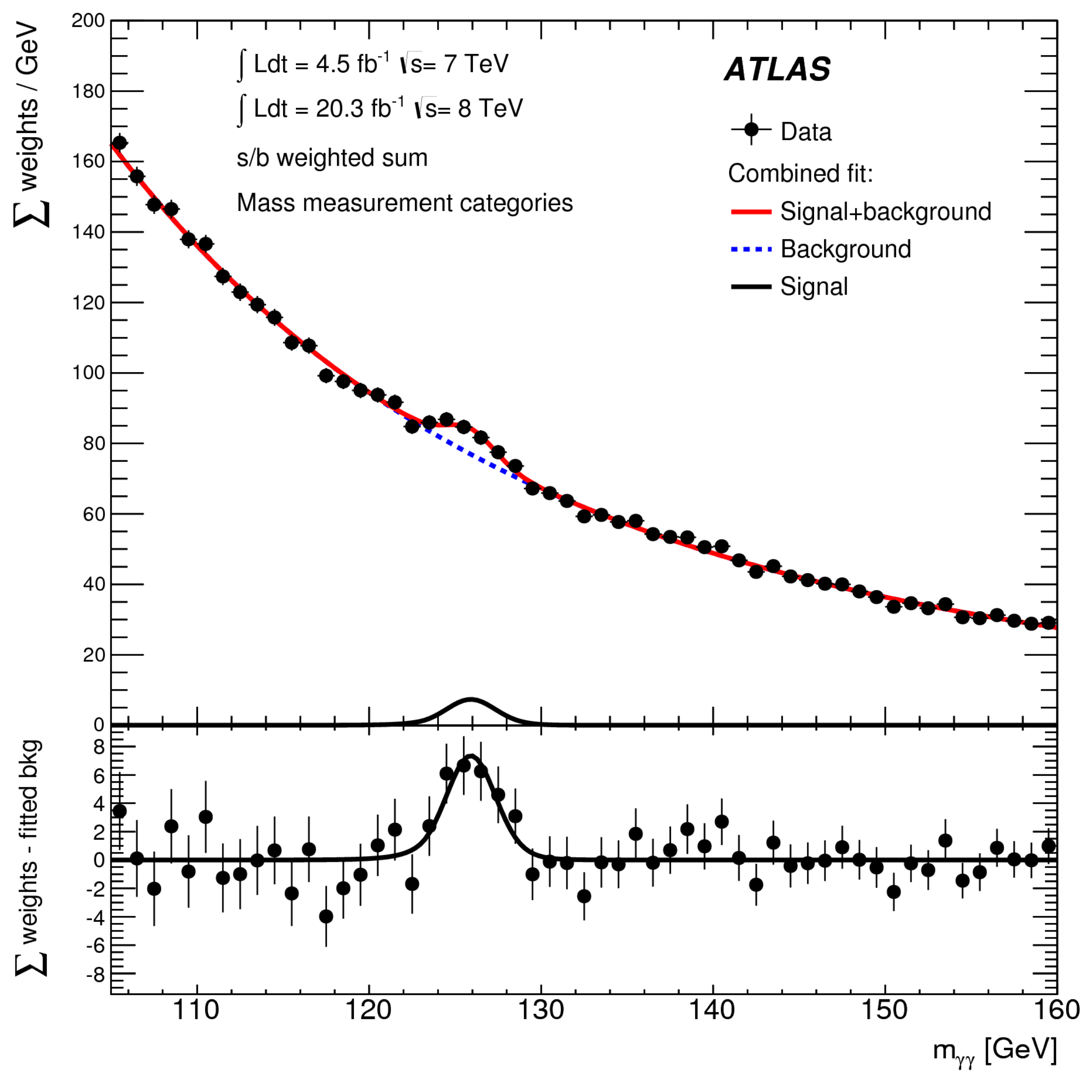


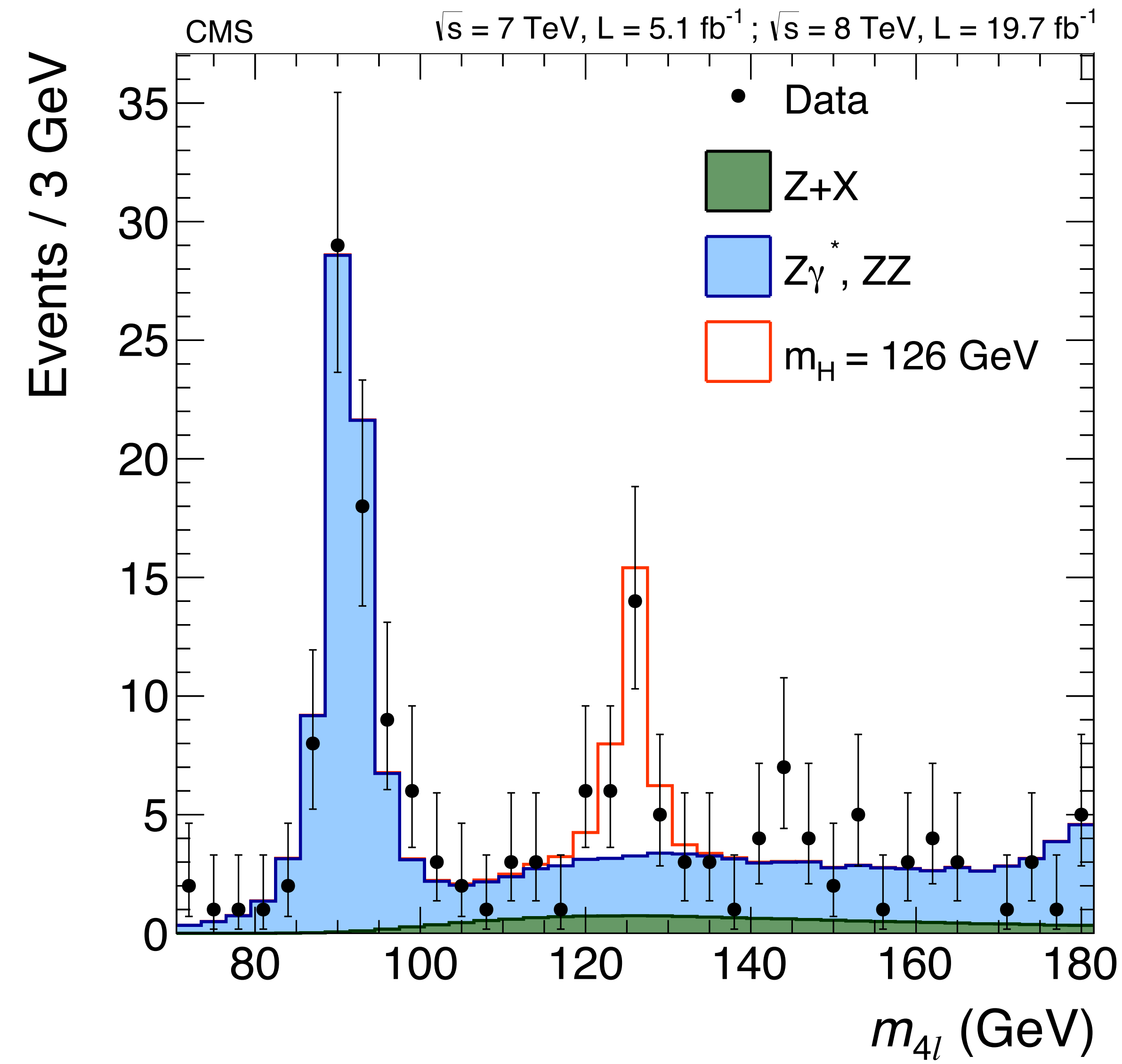


Almost impossible to measure directly
(with possible exception of muon collider)

Direct measurement at the LHC

Profiling the Higgs 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 (~4 MeV), must be improved by factor 1000

The Higgs width: 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

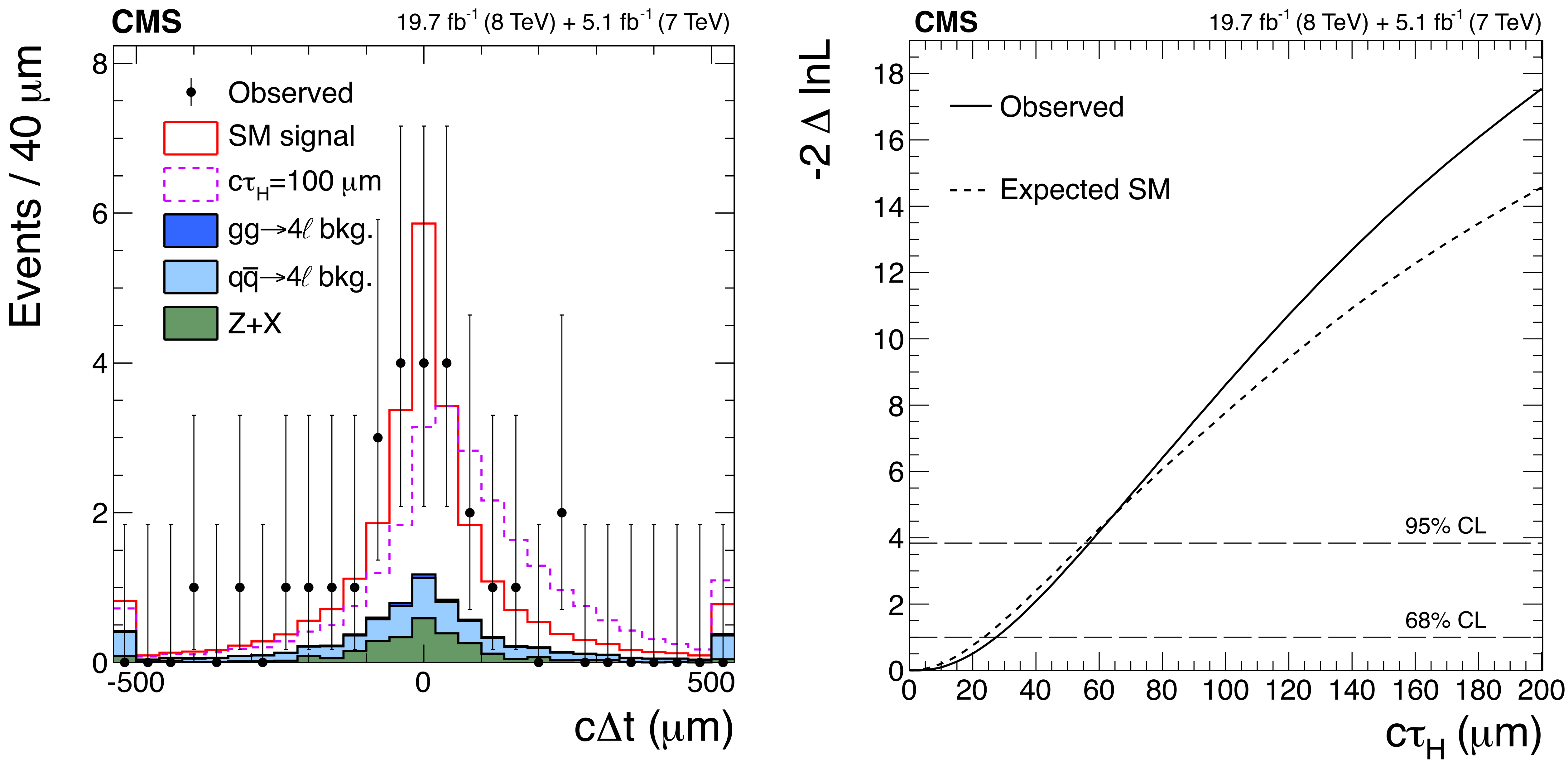
Lower bound can be obtained by
LIFETIME MEASUREMENTS

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: $\tau_H \sim 4.8 \ 10^{-8}$ μm/c, well below exp. sensitivity

CMS: bounds on the Higgs lifetime



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

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

Higgs couplings and width: 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

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

To avoid imposing SM-like behavior:

we must break this degeneracy

A direct measurement of the Higgs width:

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

WE NEED AN INDIRECT WAY OF MEASURING Γ_H

Key point: search for an observable with different dependence on $g_{i,f}$ and Γ_H

An example:

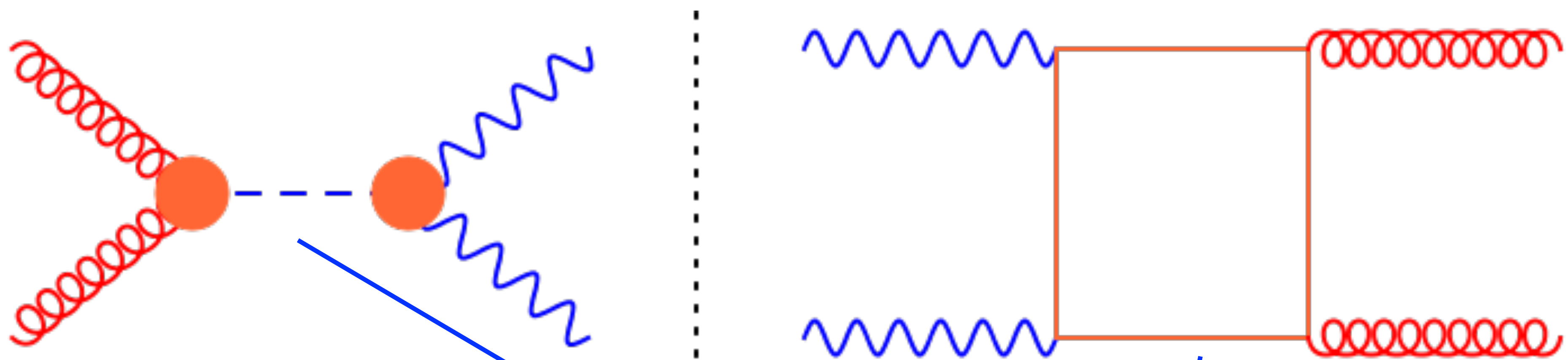
H-> $\gamma\gamma$ interference

[Martin; Dixon, Li (2013)]

Typical interference scaling: g vs g^2

Consider the full pp->γγ process:

SIGNAL ~ $g_i\, g_f$ BACKGROUND

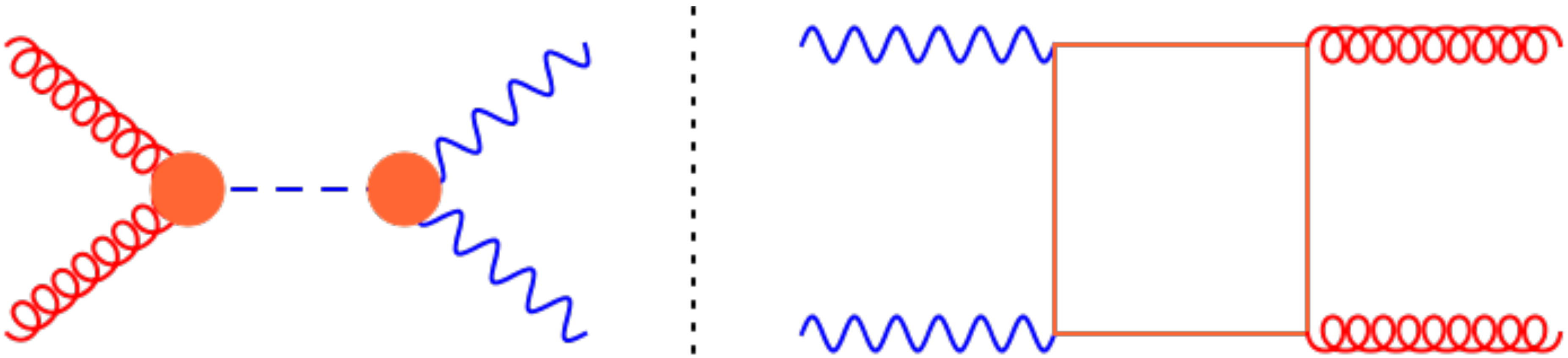


$$A_{i\to f} = \frac{S m_h^2}{s - m_h^2 + i m_h \Gamma_h} + B$$

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

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

Interference: the imaginary part



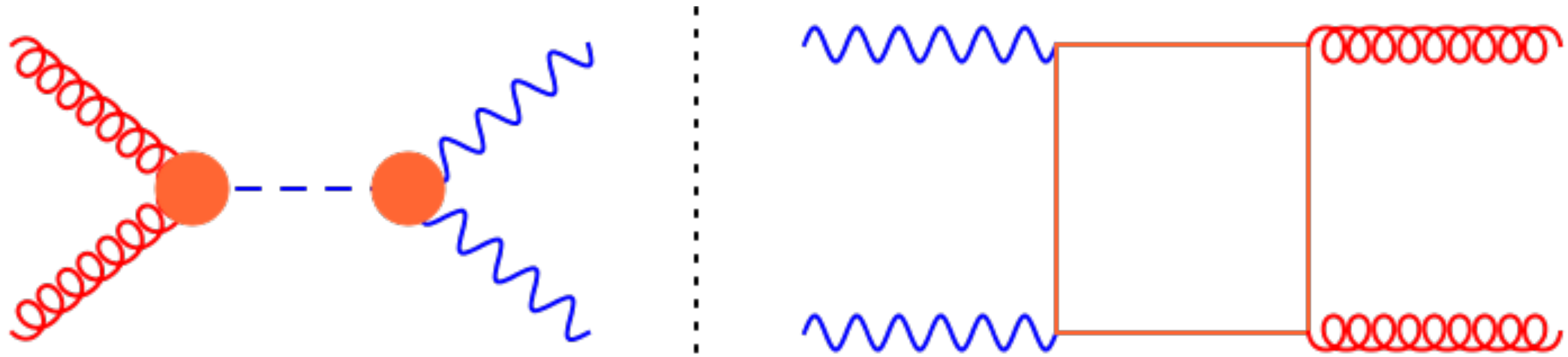
$$|A_{i\to f}|^2 = \frac{|S|^2 m_h^2}{(s-m_h^2)^2+\Gamma_h^2 m_h^2}\left[1+\frac{2(s-m_h^2)}{m_h^2}\mathrm{Re}\left(\frac{B^*}{S}\right)+\boxed{\frac{2\Gamma_h}{m_h}\mathrm{Im}\left(\frac{B^*}{S}\right)}\right]+|B|^2$$

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

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

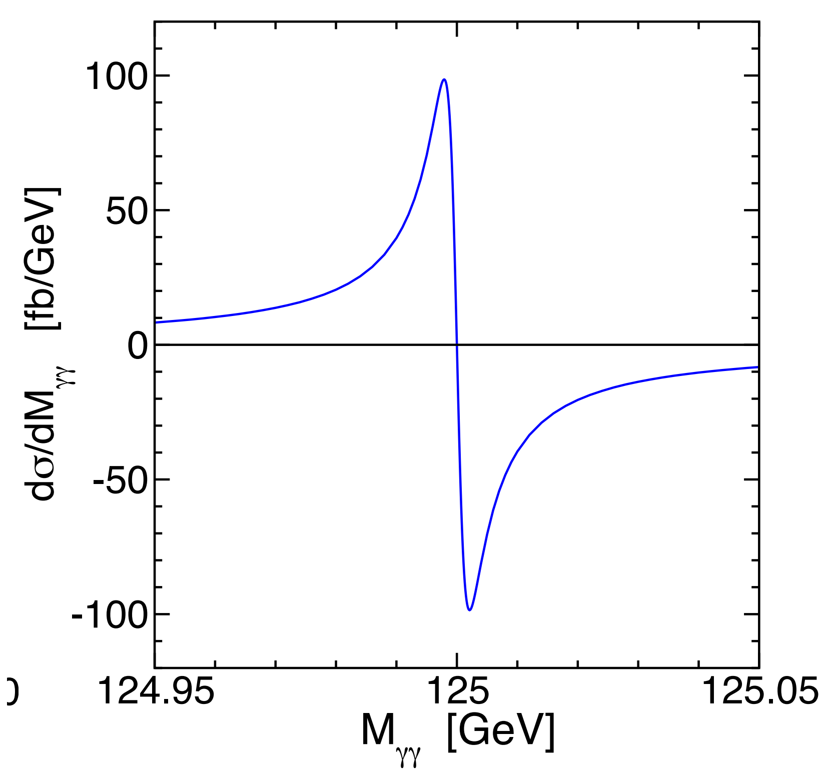
- In reality: interference starts at two-loop (no ±± cut for the background amplitude)
- Small effect (~ few percent) in the SM

Interference: the real part



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

$$\sigma_{off} \sim \frac{2\mathrm{Re}(SB^*)}{s-m_h^2}, \qquad (s-m_h^2) \gg m_h\Gamma_h$$



Asymmetry in the $m_{\gamma\gamma}$ distribution

- more events below the peak
- asymmetric -> irrelevant for σ
- however, interesting physical effects

[Martin (2012)]

Interference: the real part and the mass-shift

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

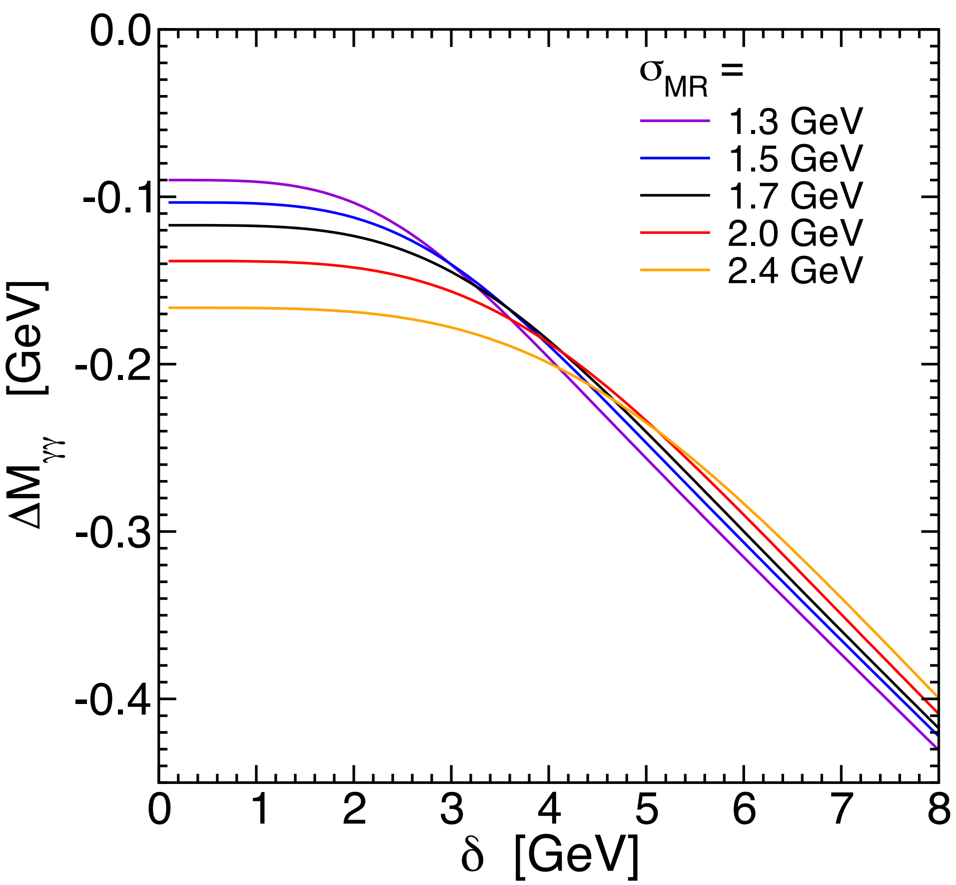
Higgs mass:

- ~ first moment of the invariant mass distribution
- extraction affected by real part of interference
- independent on Γ, 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 ~ 80-100 MeV

Shift proportional to *I* ~ $g_i\, g_f$

From the mass shift to the Higgs width

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

- compare mass measurement in H->γγ with control mass
- mass shift gives access to the real part of the interference, $\delta m_h = 2I\delta/\sigma_h \sim g_i g_f$
- LHC: Higgs peak cross section is SM-like

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

- This implies

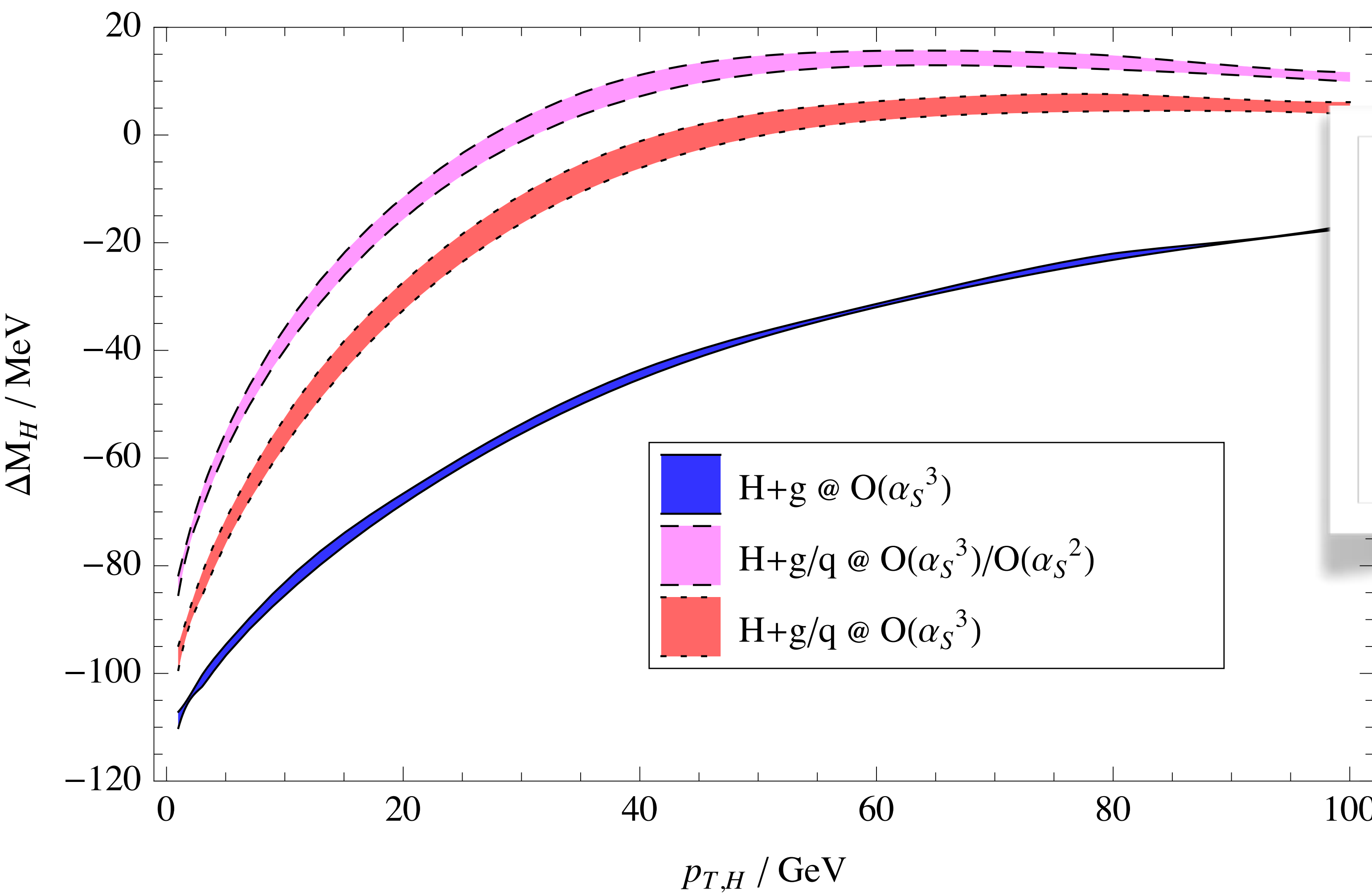
$$\delta m_H = (\delta m_H)_{\mathrm{SM}} \times \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} \approx -100\mathrm{MeV} \times \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}}$$

- Mass shift measurement gives access to the Higgs width

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 $\gamma\gamma$ system to reduce systematics



Realistic ATLAS estimates for the shift: ~ 50 MeV

EXPERIMENTALLY TOUGH

$\Delta M_{\gamma\gamma}$: indirect determination of Γ_H

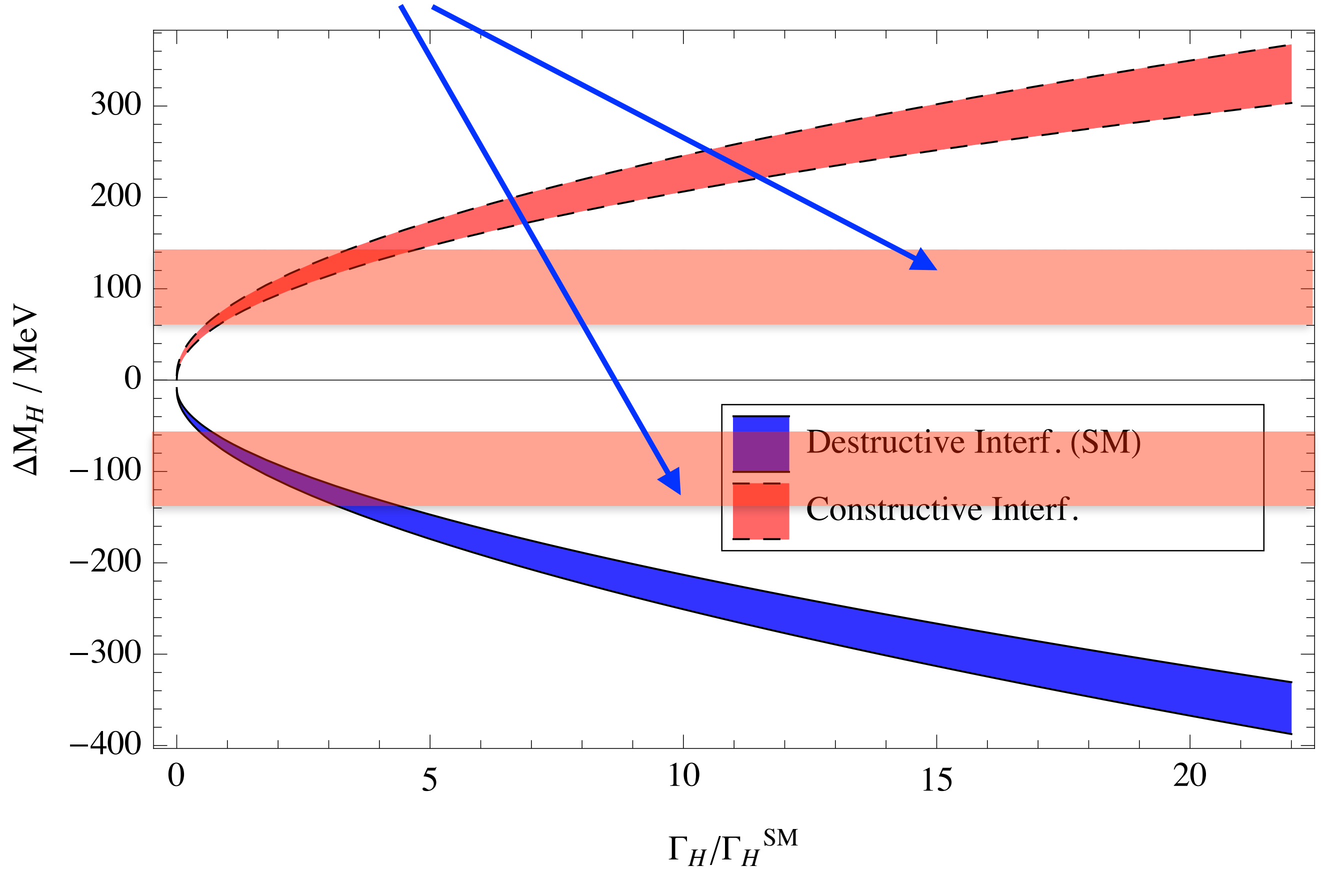
[Dixon and Li (2013)]

$$\delta m_H \approx -[50:80]\ \text{MeV} \times \sqrt{\Gamma_H/\Gamma_{H,\text{SM}}}$$

The mass-sensitivity right now:

$m_H = 125.09 \pm 0.21$ (stat) $\pm$ 0.11 (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

Much better than ultimate direct limit ~ Γ_H < 1 GeV

From the mass shift to the Higgs width: recap

- in the di-photon channel, observable effect of the signal/background interference -> mass shift
- the mass shift ~ $g_i\, g_f$ does not depend on the width -> break the width/coupling degeneracy.
- combining the peak measurement, $\sigma \sim g_i^2\, g_f^2/\Gamma_H \approx g_{i,SM}^2\, g_{f,SN}^2/\Gamma_{H,SM}$ -> $\delta m \sim g_i\, g_f \approx g_{i,SM}\, g_{f,SM} \sqrt{\Gamma_H/\Gamma_{H,SM}}$ -> ACCESS TO THE WIDTH [UNFORTUNATELY: MILD ~ SQUARE-ROOT DEPENDENCE]

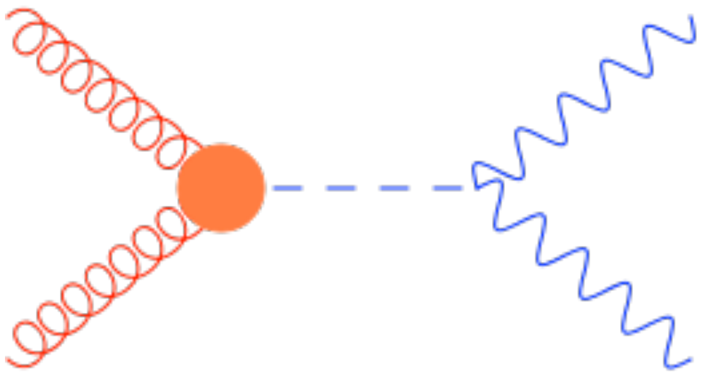
- theoretically very clean. Signal / background well-known
- experimentally challenging. Systematic-dominated
- current projections for the HL-LHC: $\Gamma_H < 40\, \Gamma_{H,SM} \approx 160$ MeV
- ~ 1 order of magnitude better than direct limit
- new ideas for analysis, theory may lead to better constraints

Another example: bounds from off-shell measurements

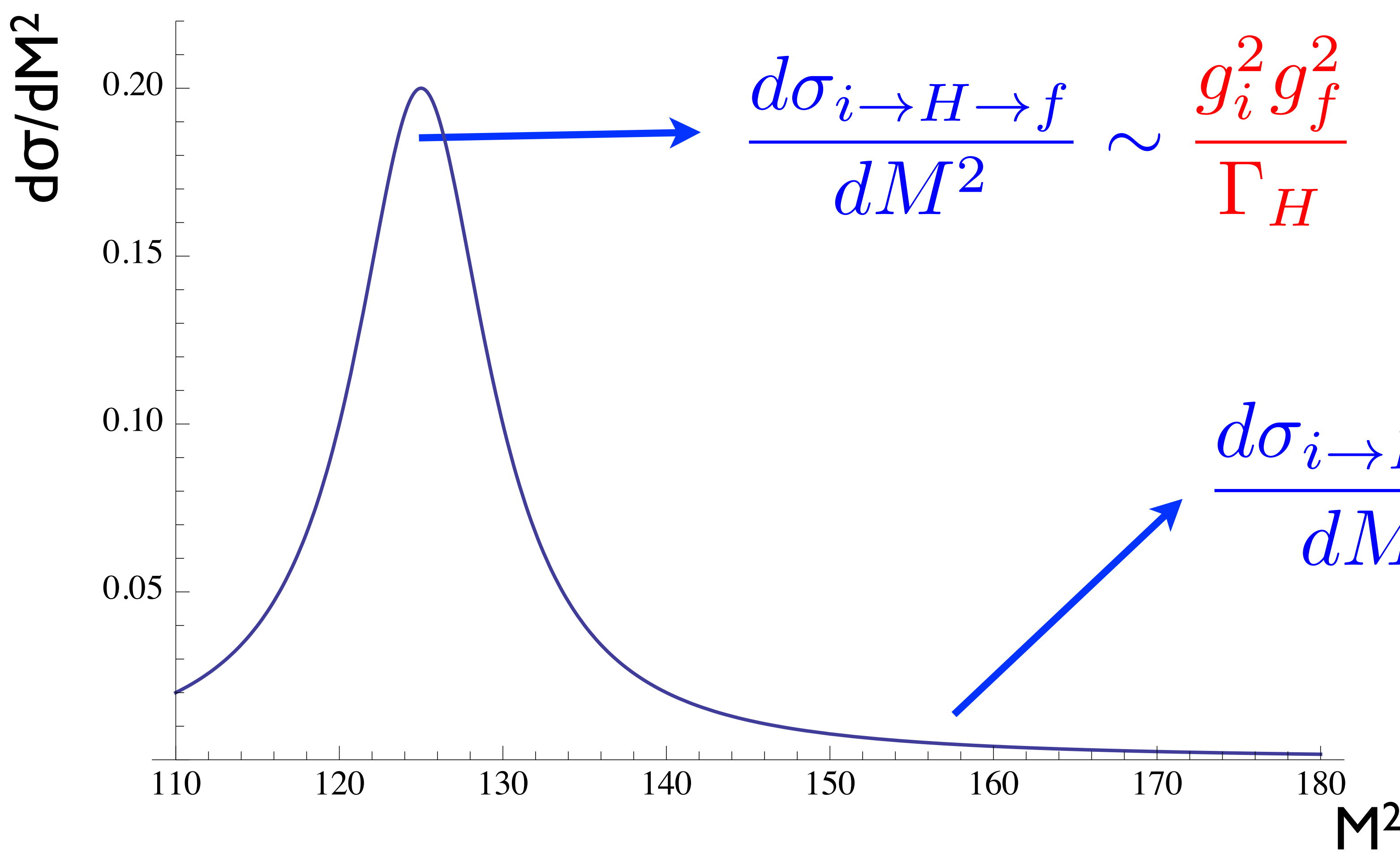
[FC, Melnikov (2013)]

Another option: use the cross-section itself

To break the $g \to \xi g,\ \Gamma_H \to \xi^4 \Gamma_H$ 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

Using the off-shell cross-section to bound Γ_H

LHC results: on the Higgs peak, the number of events is compatible with the SM expectation

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

Look for off-peak events: $\sigma_{off} \sim g_i^2 g_f^2$

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

DIRECT ACCESS TO THE WIDTH

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

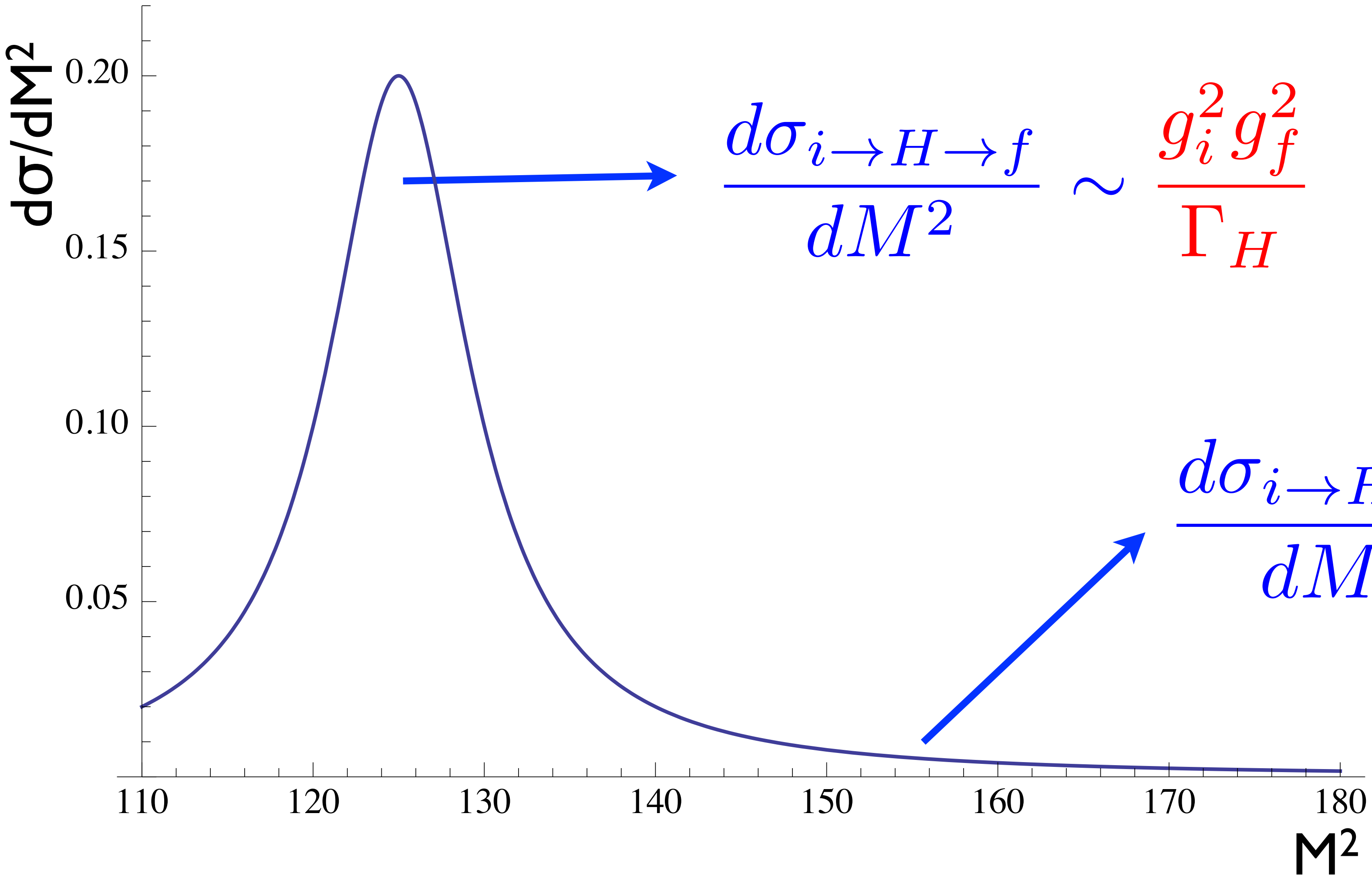
LINEAR DEPENDENCE

ASSUMPTION:

$[g_i^2 g_f^2]_{[\mathrm{off}]} = [g_i^2 g_f^2]_{[125\ \mathrm{GeV}]}$

Off-shell measurement: feasibility

The Higgs is a very narrow resonance

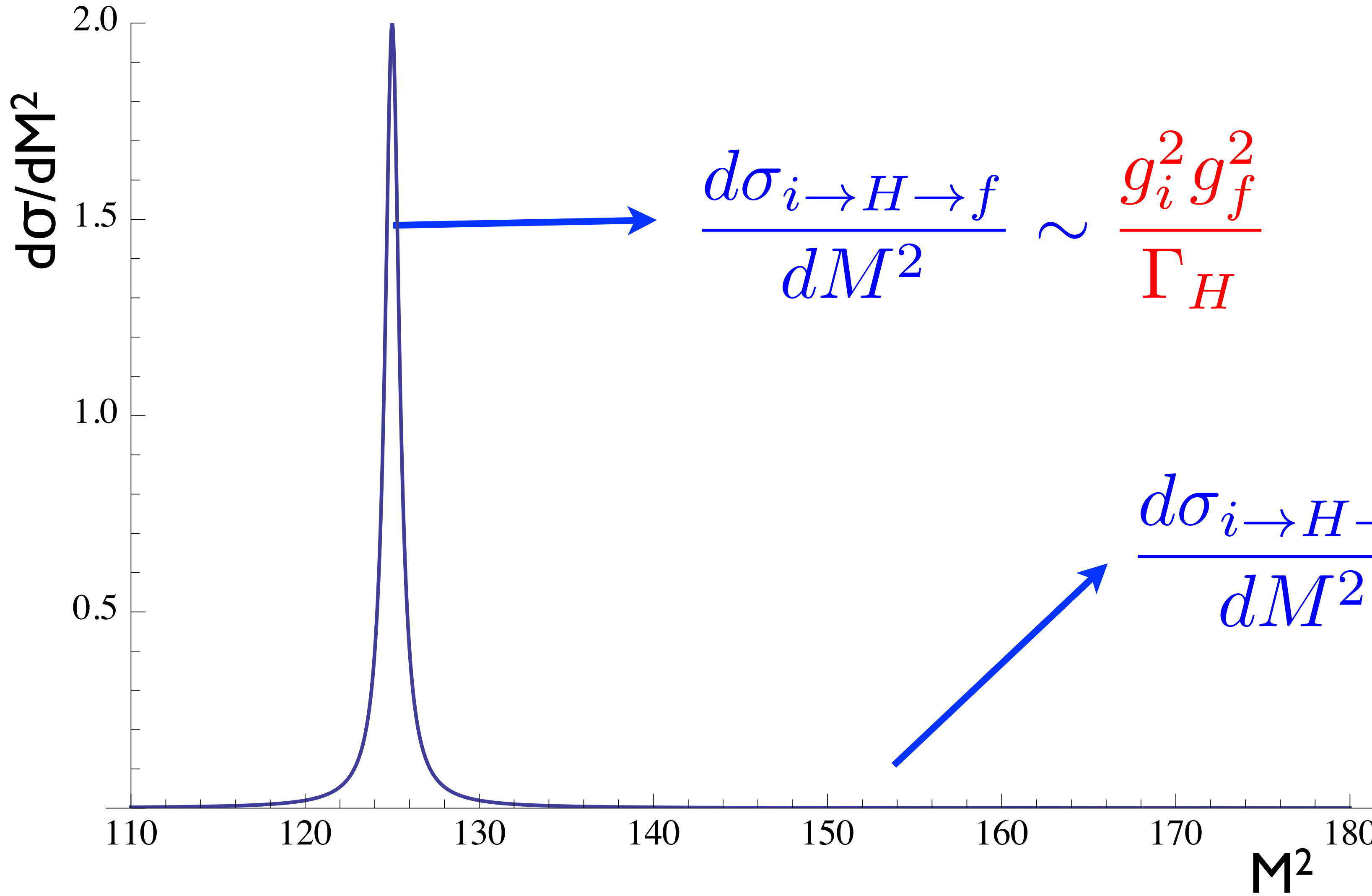


$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

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

Our proposal: feasibility

The Higgs is a very narrow resonance



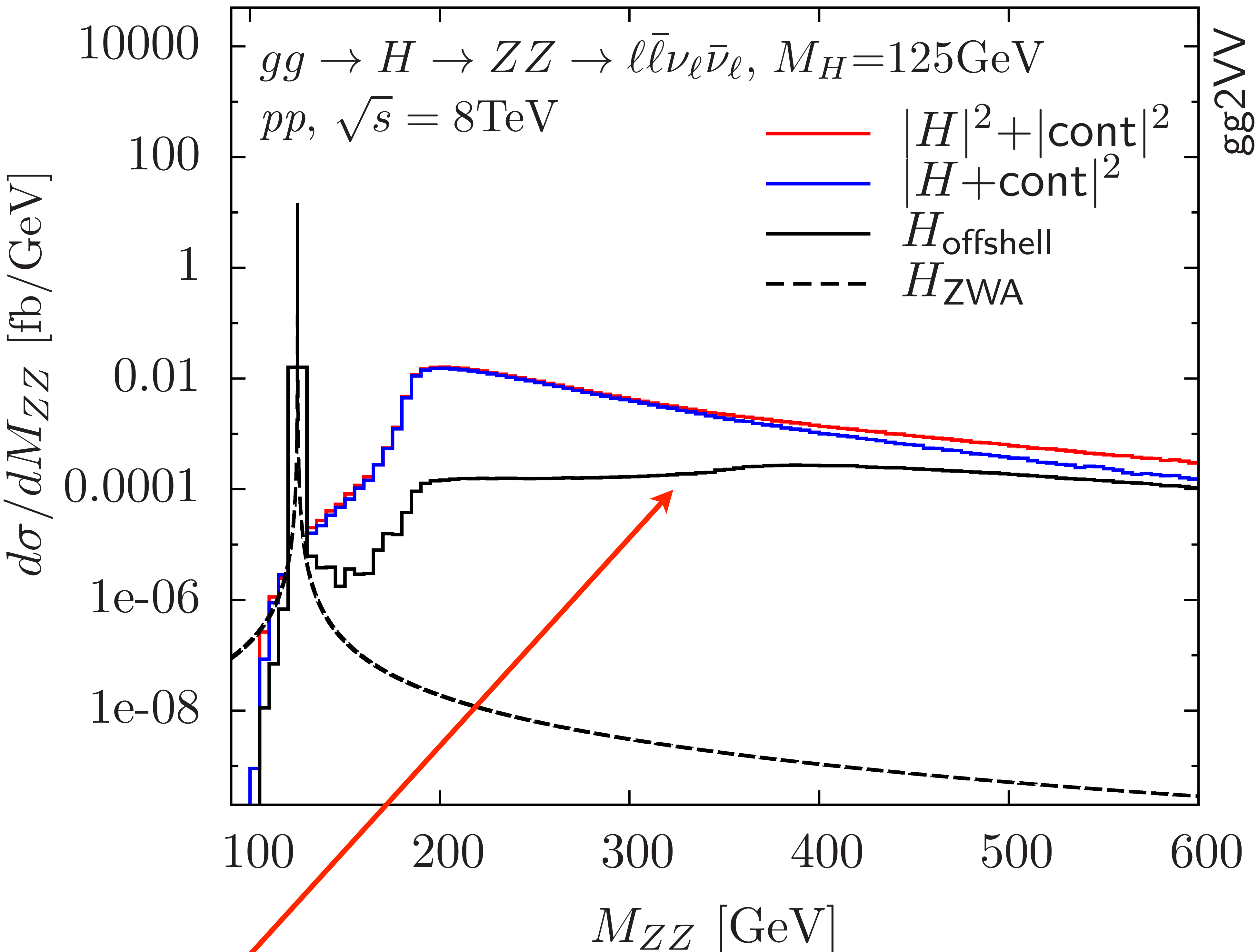
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

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

In general, $N_{SM} \sim N_{obs} \sim 0$

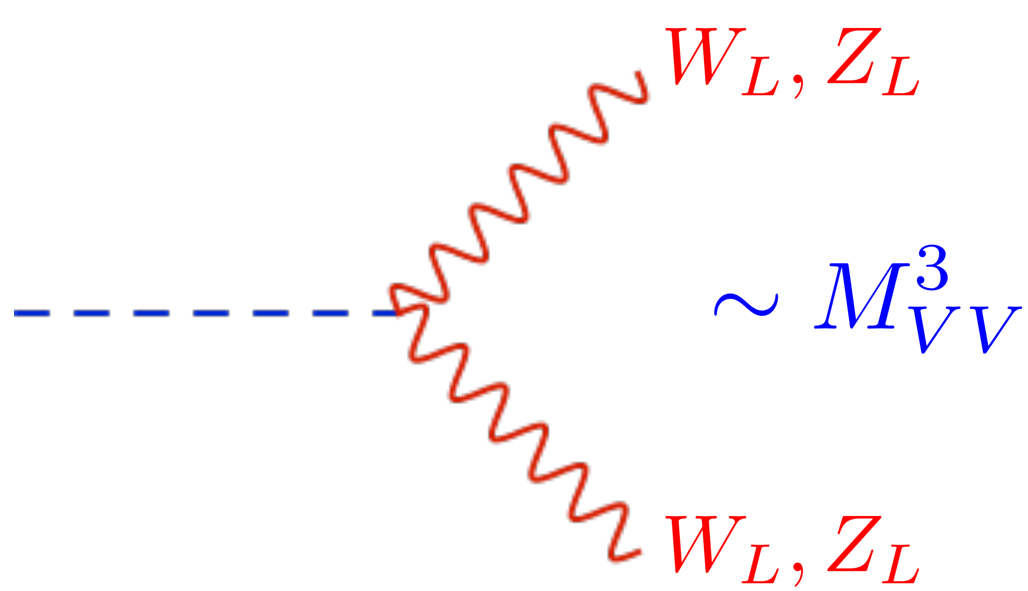
Is there a mechanism to compensate this rapid fall?

Yes: look at VV decay modes [Kauer, Passarino (2012)]



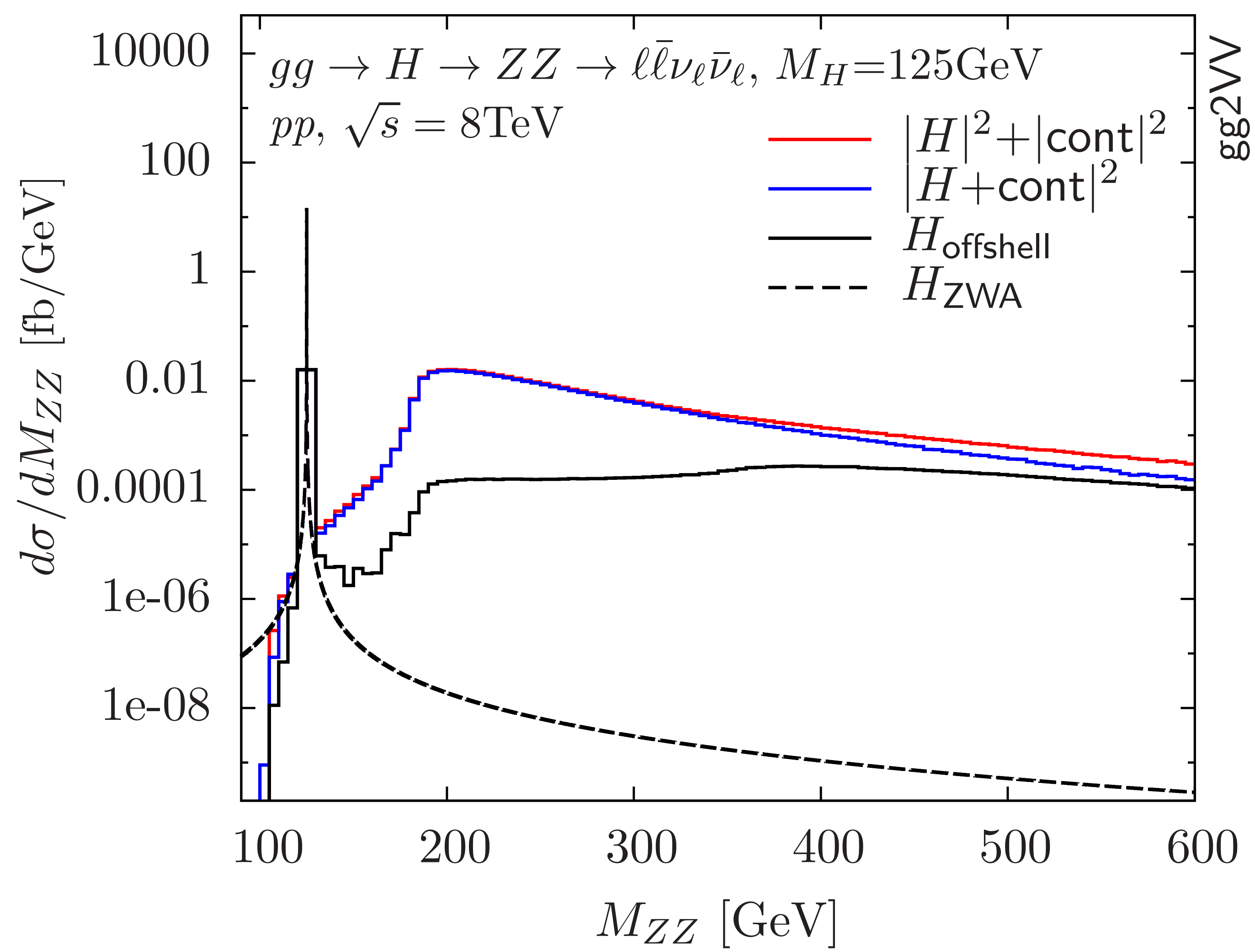
Large off-shell tail (O(10%) of the total cross section)

Yes: look at VV decay modes [Kauer, Passarino (2012)]



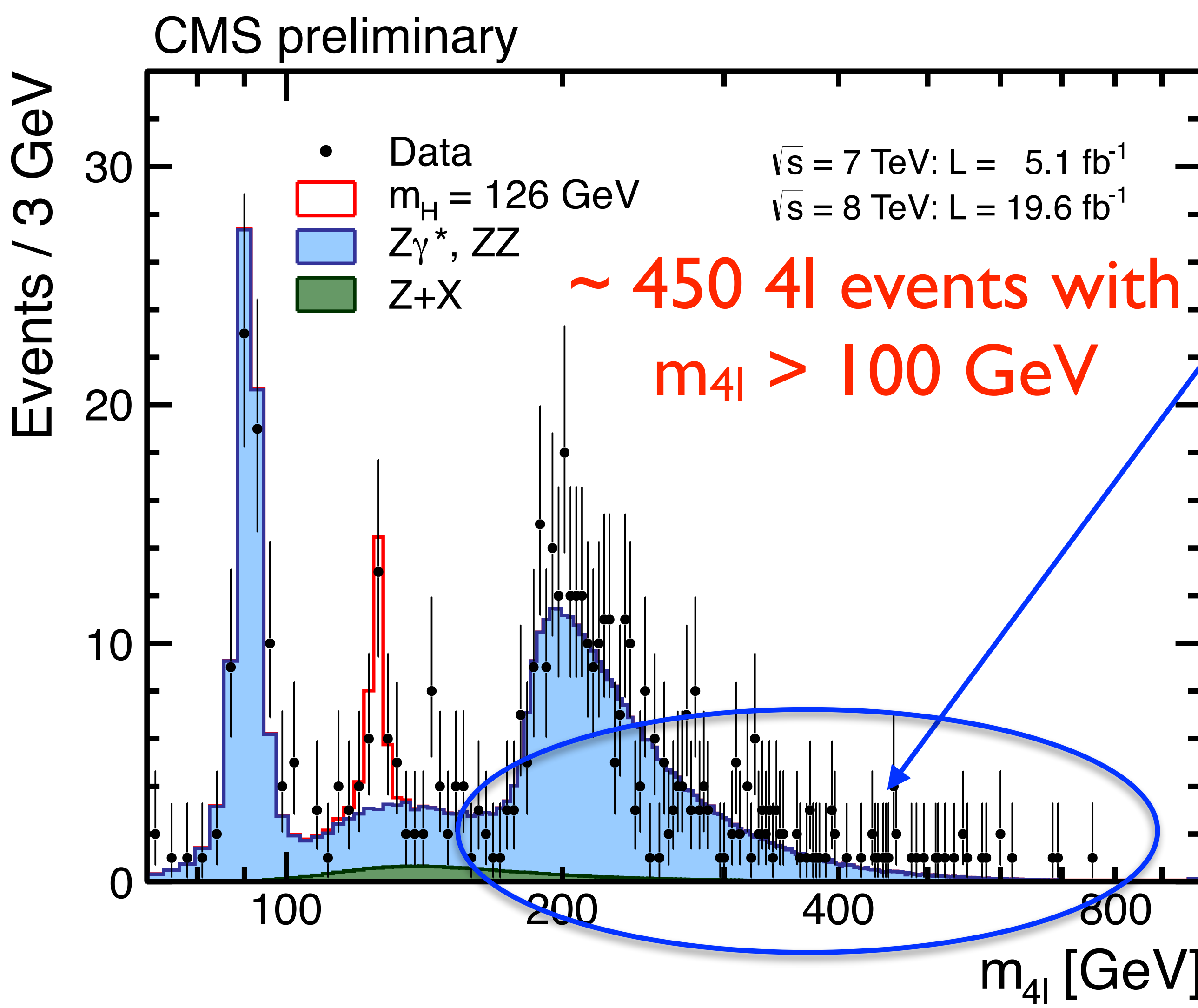
Above the VV threshold:
enhanced decay into
longitudinal gauge bosons

Large plateau,
eventually washed away
by parton luminosities



A back-of-the envelope estimate

$$\sigma_{off} \sim g_i^2 g_f^2 \Longrightarrow \sigma_{off} = \sigma_{off,\mathrm{SM}} \times \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}$$

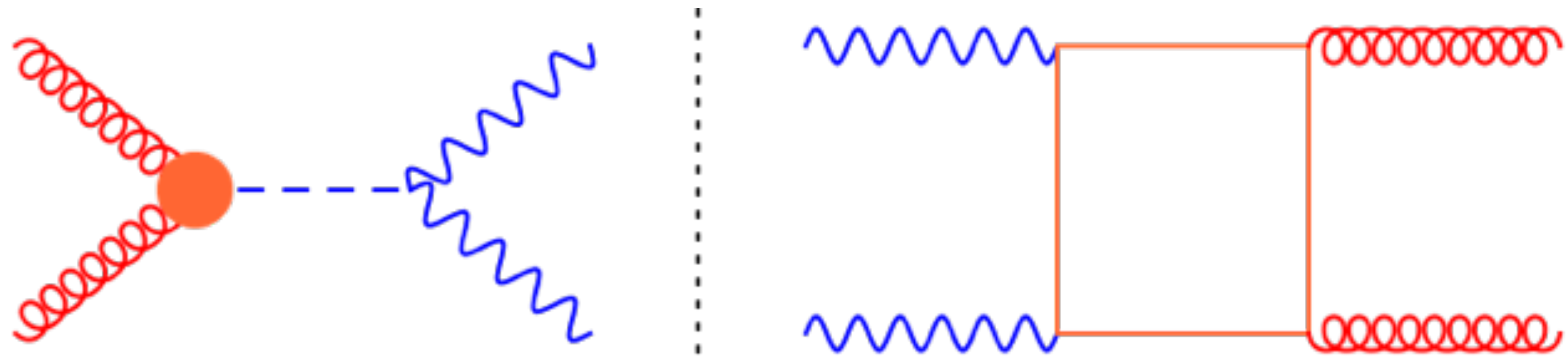


- Look at the high-tail of the M_{ZZ} distribution
- A SM-like peak cross-section + deviation in Γ_H lead to excess/ deficit of ZZ events
- If Γ_H = 1.7 GeV (direct bound), then $\Gamma_H/\Gamma_{H,SM} \sim 400$ and

$N_{off} \approx [0.1\text{x } N_{peak}] \text{ x } 400 \approx 800 \gg N_{4l,total}$

THE OFF-SHELL CROSS-SECTION IS VERY SENSITIVE TO Γ_H

A more careful analysis: large interference



In the SM: large destructive interference at high invariant mass σ^{int} ~ - 50% off peak (unitarity) [on-peak: negligible]

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

$$\sigma^{int} \sim g_{Hgg} g_{HVV} = [e^{i\theta}] \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} \sigma^{int}_{\mathrm{SM}}$$

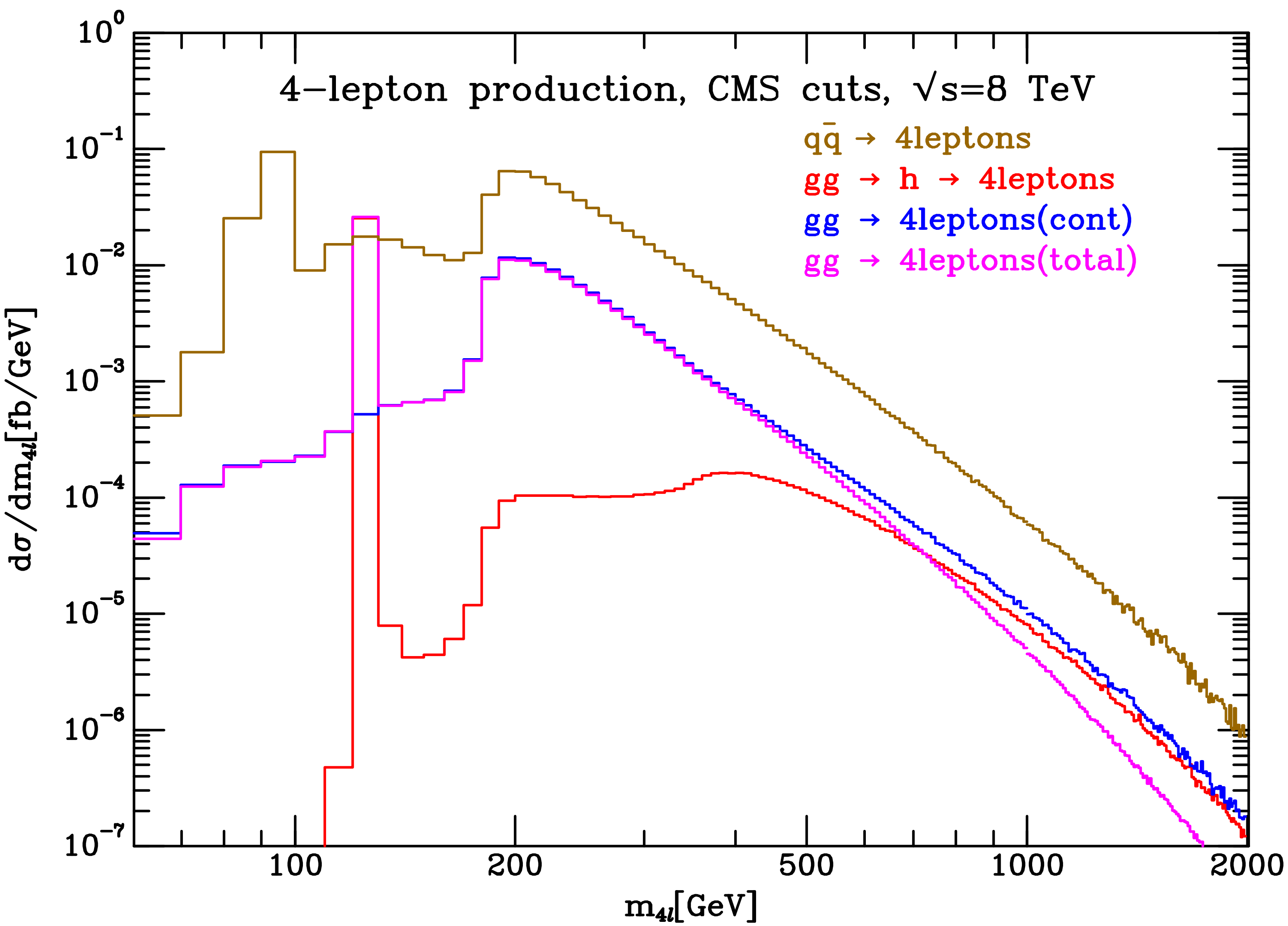
PUTTING EVERYTHING TOGETHER:

$$N^{off} = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} N^{off}_{\mathrm{SM}} - [e^{i\theta}] \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} N^{int}_{\mathrm{SM}}$$

Negative interference -> less off-shell events -> decrease sensitivity

The 4l spectrum at high invariant mass

- In Run I, CMS observed 451 m_{4l} > 100 GeV events
- SM prediction: 429 ± 31 events
- Dominated by pp->ZZ background (mostly qq)
- Off-shell tail negligible if not looked for



[Campbell, Ellis, Williams (2013)]

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

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

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

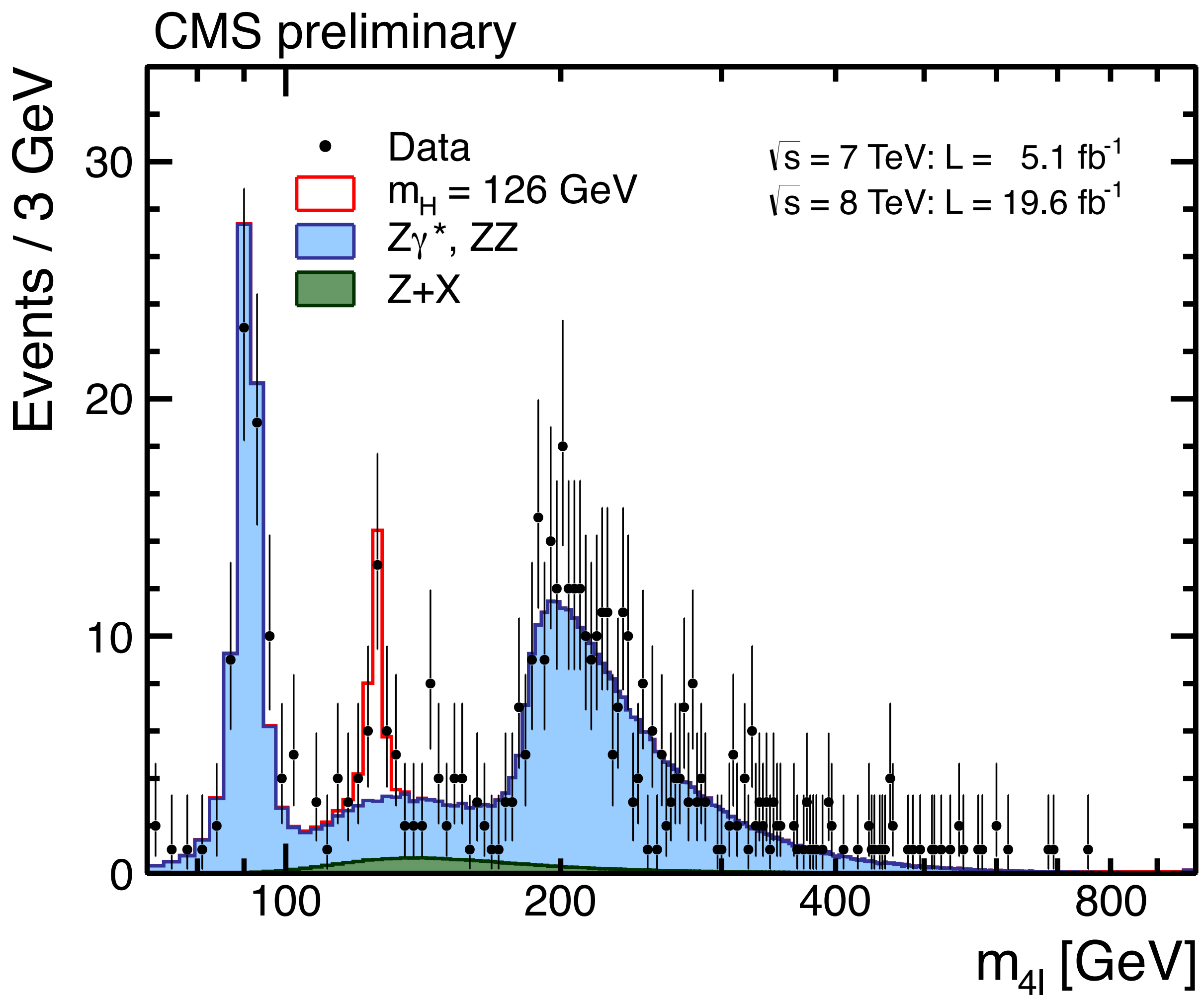
$$N_{\rm off} \sim 10^{-2} N_{\rm tot}$$

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

How does the picture change if $\Gamma_H \neq \Gamma_{H,SM}$?

The idea @ work: the CMS dataset

$$N_{exp} = 432 + 2.78\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} \pm 31$$



$$N_{obs}^{\mathrm{CMS}} = 451$$

At 95% CL:

$$|N_{exp} - N_{obs}| < 2\sigma$$

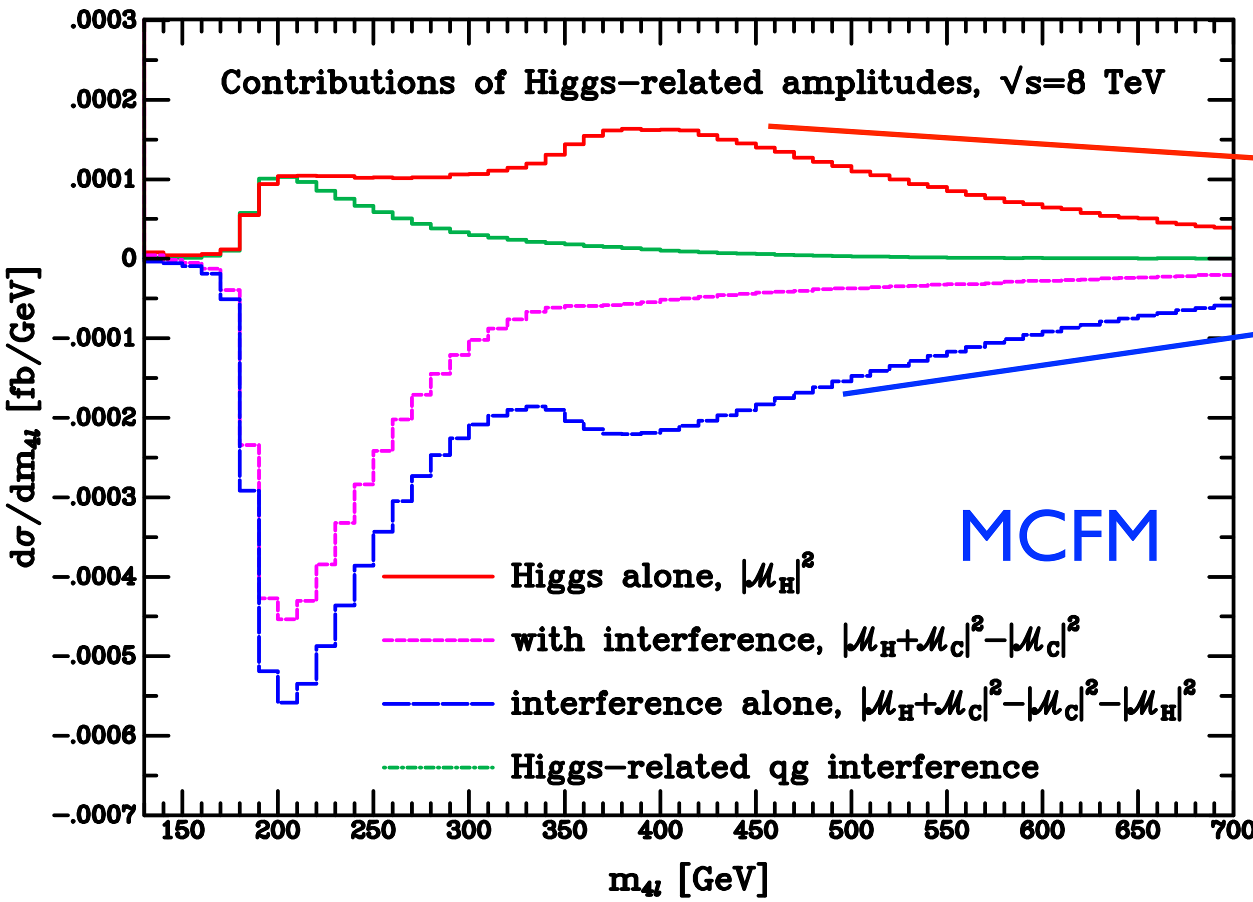
EXISTING DATASET, 'OUT-OF-THE-BOX' ANALYSIS:

$$\Gamma_H \leq 43\ \Gamma_{H,\mathrm{SM}} \approx 163\ \mathrm{MeV}\ @\ 95\%\ \mathrm{CL}$$

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

The idea @ work: look at CMS data

Simple improvement: reduce the interference



Signal and interference: very different shape

EXISTING DATASET, SIMPLE M_{4l} CUT:

$$\Gamma_H \leq 25.2\ \Gamma_{H,\mathrm{SM}} \approx 105\ \mathrm{MeV}\ @\ 95\%\ \mathrm{CL}$$

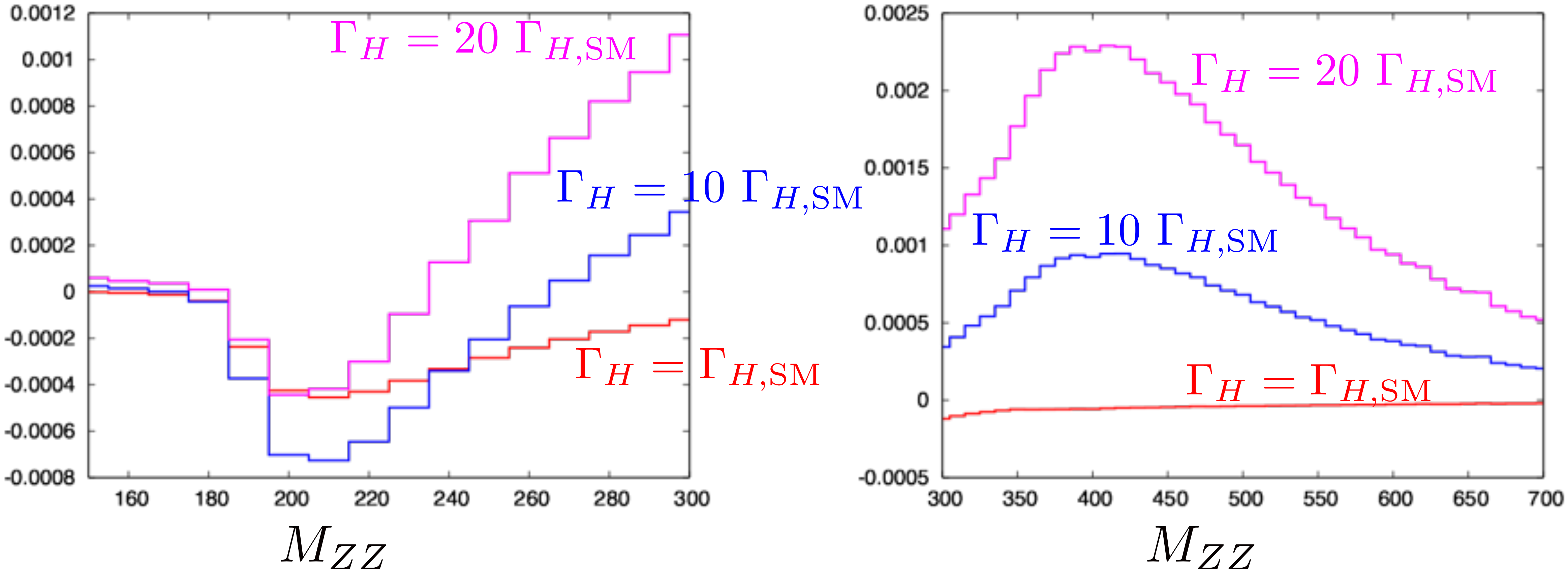
[FC, Melnikov; Campbell, Ellis, Williams (2013)]

p.s.: if the interference would have the opposite sign wrt SM:

$$\Gamma_H \leq 7 - 13\ \mathrm{MeV}$$

Other possible improvements

Profit even more from different shape of signal and interference, and shape dependence on Γ_H



To reduce qq contamination:

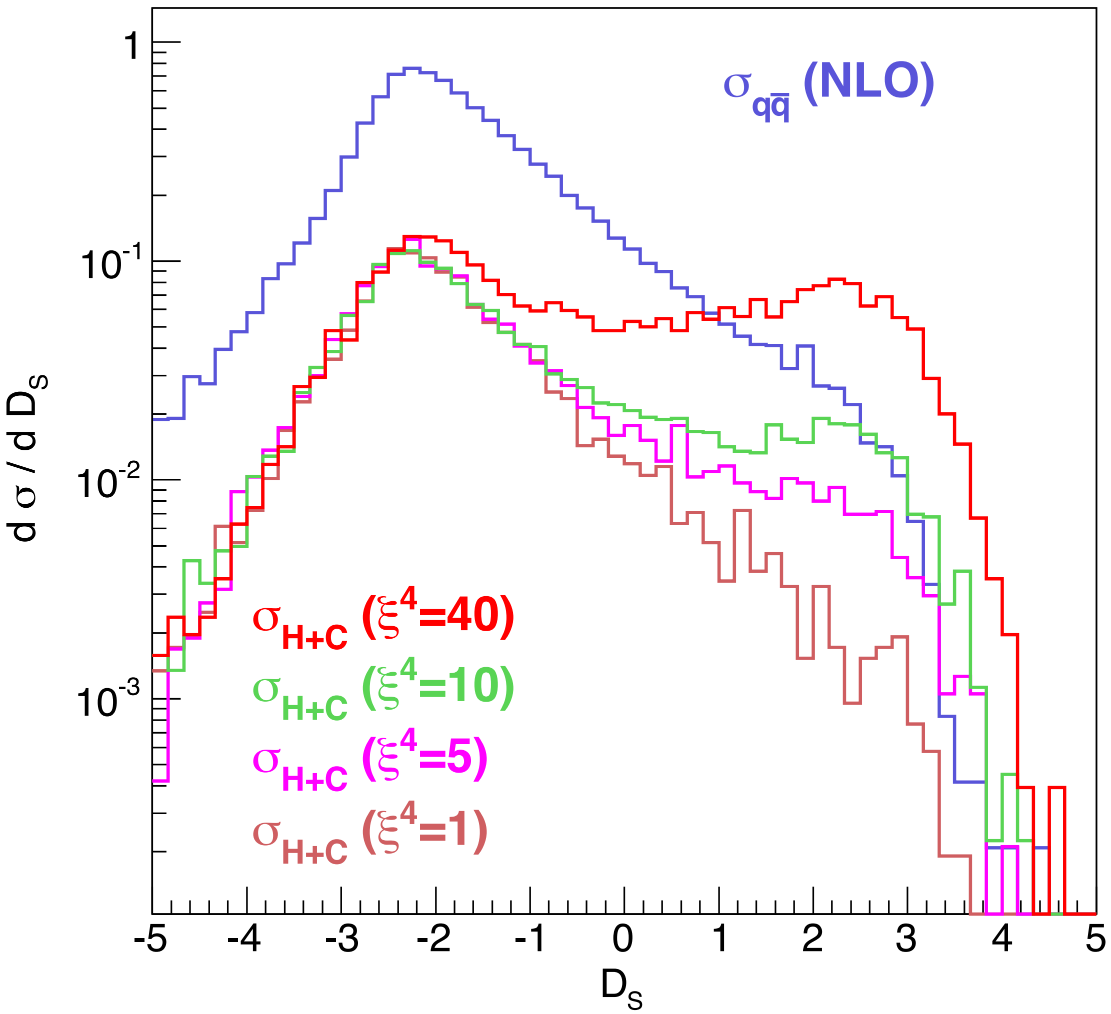
select longitudinal polarizations ->

study angular correlations of the leptons.

Other possible improvements

Apply a kinematic discriminant (ME method)

[Campbell, Ellis, Williams (2013)]



$$D_S = \log\left[\frac{P_{gg\to H\to ZZ}}{P_{gg\to ZZ} + P_{q\bar{q}\to ZZ}}\right]$$

$$P_i \sim |M_i|^2$$

'Interesting' events: large D_S

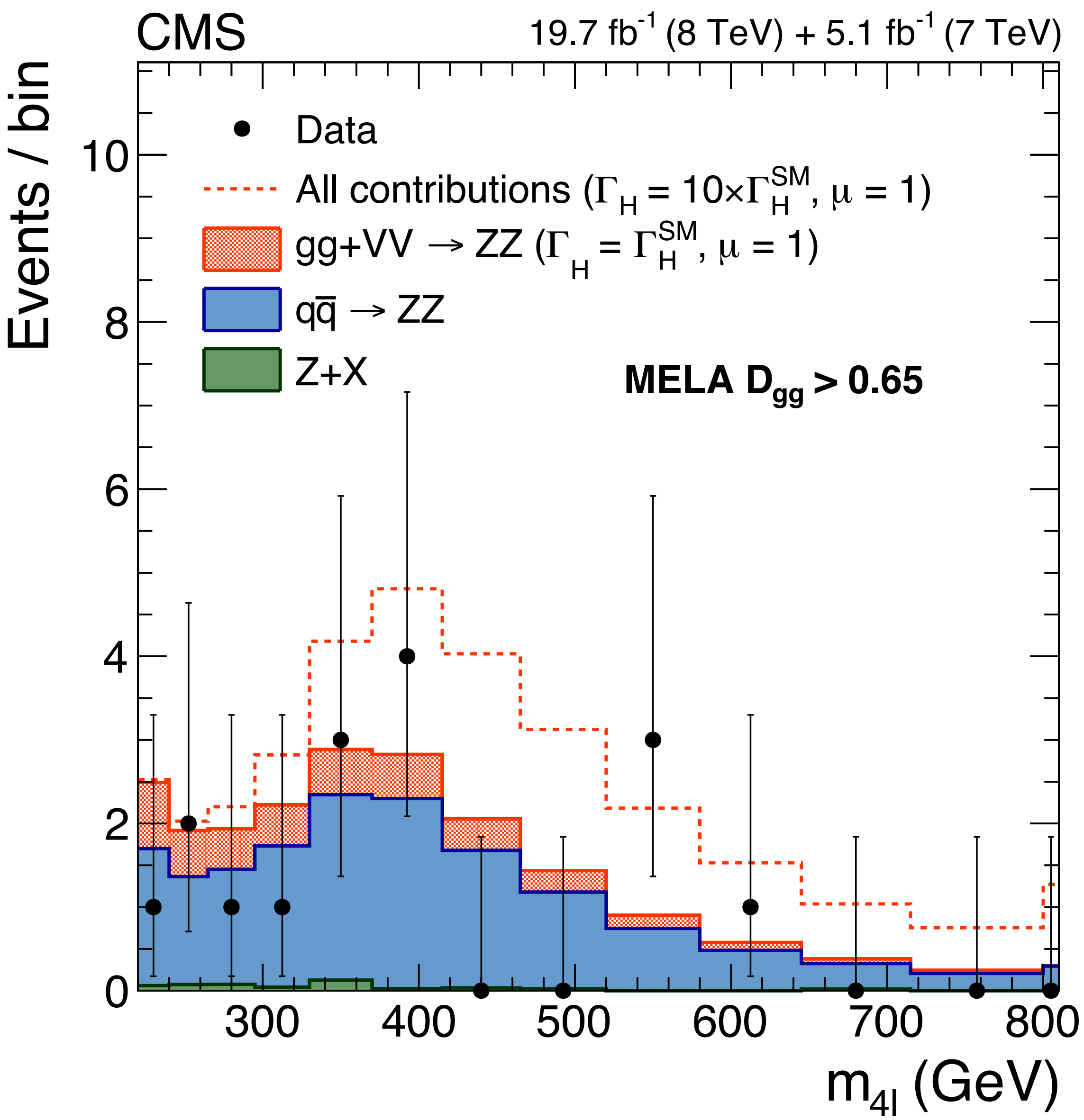
JUST BY CUTTING D_S > 1:

$$\Gamma_H \leq 15.7\ \Gamma_{H,\mathrm{SM}} \approx 66\ \mathrm{MeV}\ @\ 95\%\ \mathrm{CL}$$

Recall direct bound ~ 1 GeV

Experimental results: CMS

[PLB 736 (2014) 64]



Analysis in the 4l and 2l2ν channels combined

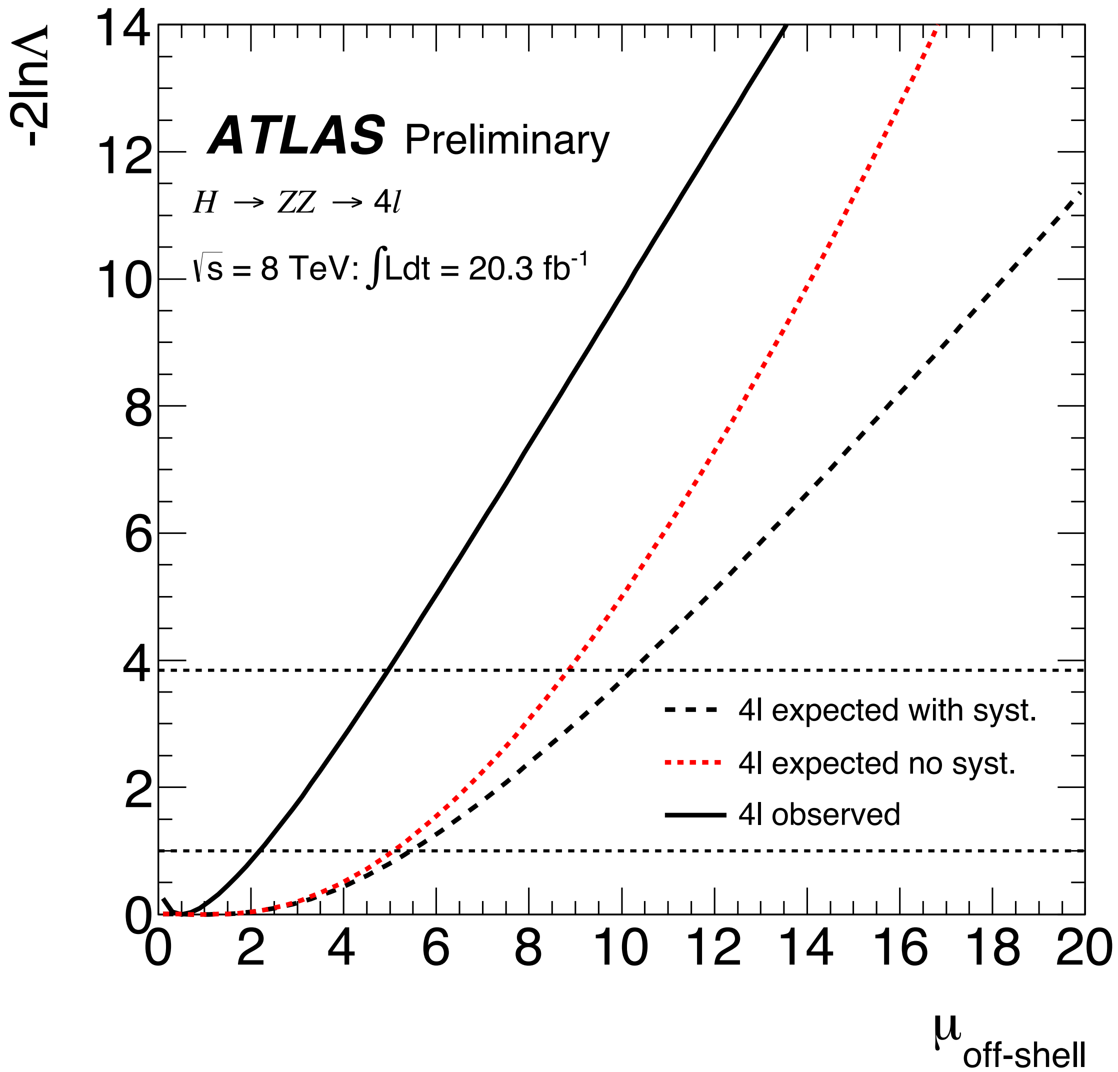
		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2	39.8 ±5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ±0.01	0.90 ±0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ±0.01	0.32 ±0.02
	VBF background component	0.35±0.02	1.22 ±0.07
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	0.77 ±0.04	2.40 ±0.14
(e)	$q\bar{q}$ background	9.3 ±0.7	47.6 ±4.0
(f)	other backgrounds	0.05 ±0.02	35.1 ±4.2
(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8	93.2 ±6.0
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4	124.9 ±7.8
	observed	11	91

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

(Even better than anticipated)

Experimental results: ATLAS

[EPJ (2015) 75:335]



Analysis in the 4l and 2l2ν channels combined

Process	220 GeV $< m_{4\ell} <$ 1000 GeV	400 GeV $< m_{4\ell} <$ 1000 GeV
$gg \to H^* \to ZZ$ (S)	2.2 ± 0.5	1.1 ± 0.3
$gg \to ZZ$ (B)	30.7 ± 7.0	2.7 ± 0.7
$gg \to (H^* \to)ZZ$	29.2 ± 6.7	2.3 ± 0.6
$gg \to (H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 10$)	40.2 ± 9.2	9.0 ± 2.5
VBF $H^* \to ZZ$ (S)	0.2 ± 0.0	0.1 ± 0.0
VBF ZZ (B)	2.2 ± 0.1	0.7 ± 0.0
VBF $(H^* \to)ZZ$	2.0 ± 0.1	0.6 ± 0.0
VBF $(H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 10$)	3.0 ± 0.2	1.4 ± 0.1
$q\bar{q} \to ZZ$	168 ± 13	21.3 ± 2.1
Reducible backgrounds	1.4 ± 0.1	0.1 ± 0.0
Total Expected (SM)	200 ± 15	24.3 ± 2.2
Observed	182	18

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

(depending on the gg->ZZ background K-factor)

Γ_H from the off-shell tail: issues

- the technique is very promising, bounds 2 order of magnitude better than direct measurements accessible. Eventually, values as low as the SM width within reach.

- However, there are TWO BIG ISSUES to be addressed
  - the method assumes $[g_i^2 g_f^2]_{[\mathrm{off}]} \approx [g_i^2 g_f^2]_{[\mathrm{peak}]}$.
    This is true in the SM, but it may be violated by BSM physics. If a violations do indeed occur, off-shell measurement still very solid but interpretation in terms of Γ_H problematic
  - even with all MEM improvements, the method boils down to count events in the high-mass tail and compare with SM predictions -> very good theoretical control on pp->4l processes is needed

Interpretation issues

- Large de-correlation of on-shell and off-shell couplings make the width interpretation problematic
- In the SM: logarithmic running, negligible effect (taken into account in all the analysis)
- De-correlation however possible if strong (energy-dependent) modifications of the Hgg / HVV couplings.
  - large anomalous HZZ couplings
  - light colored d.o.f. in the Hgg vertex [Englert, Spannowksy (2014)]
  - extra Higgses to restore unitarity [Logan (2014)]

TO WHICH EXTENT THESE EFFECTS CAN BE CLASSIFIED AND CONSTRAINED BY OTHER MEASUREMENTS IS A THEN AN INTERESTING BSM PHENOMENOLOGY OPEN PROBLEM

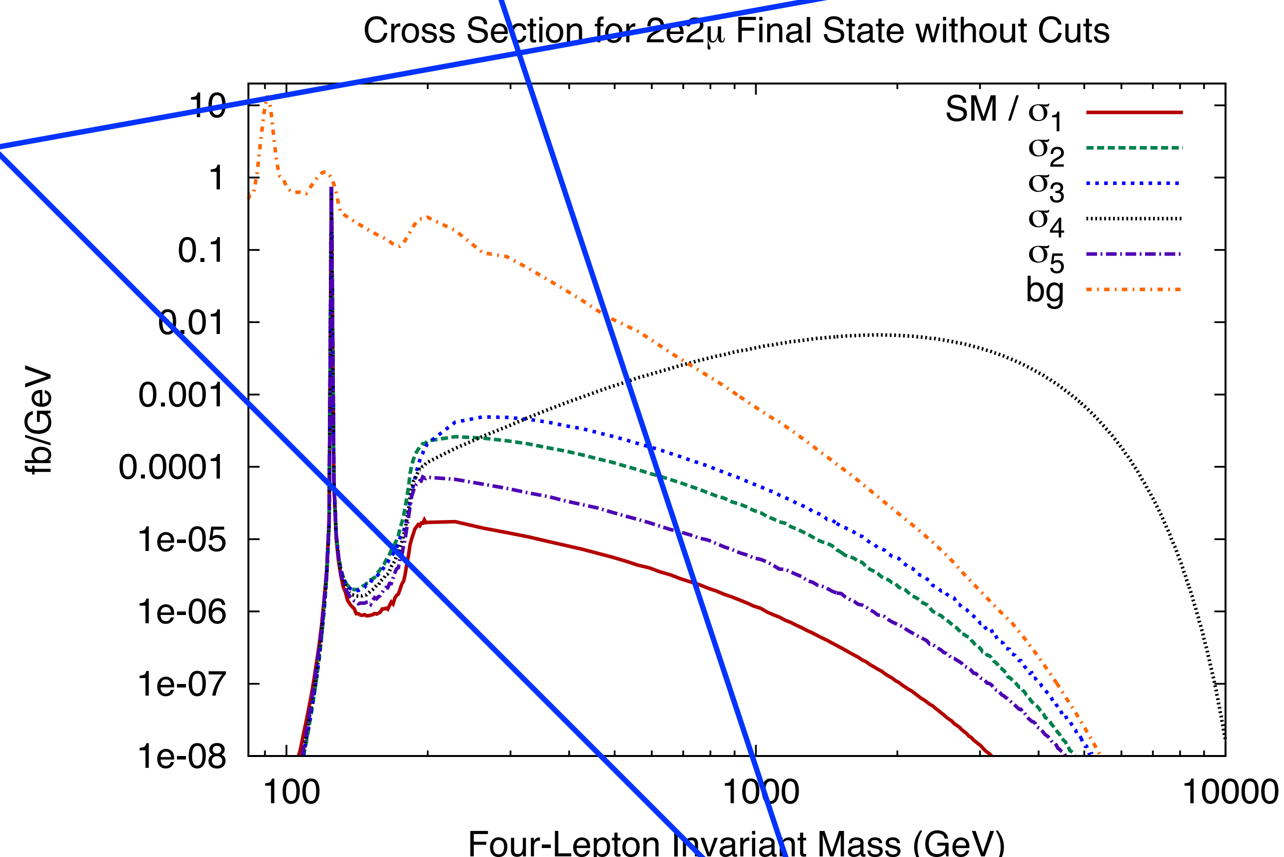
Example: anomalous HZZ couplings

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

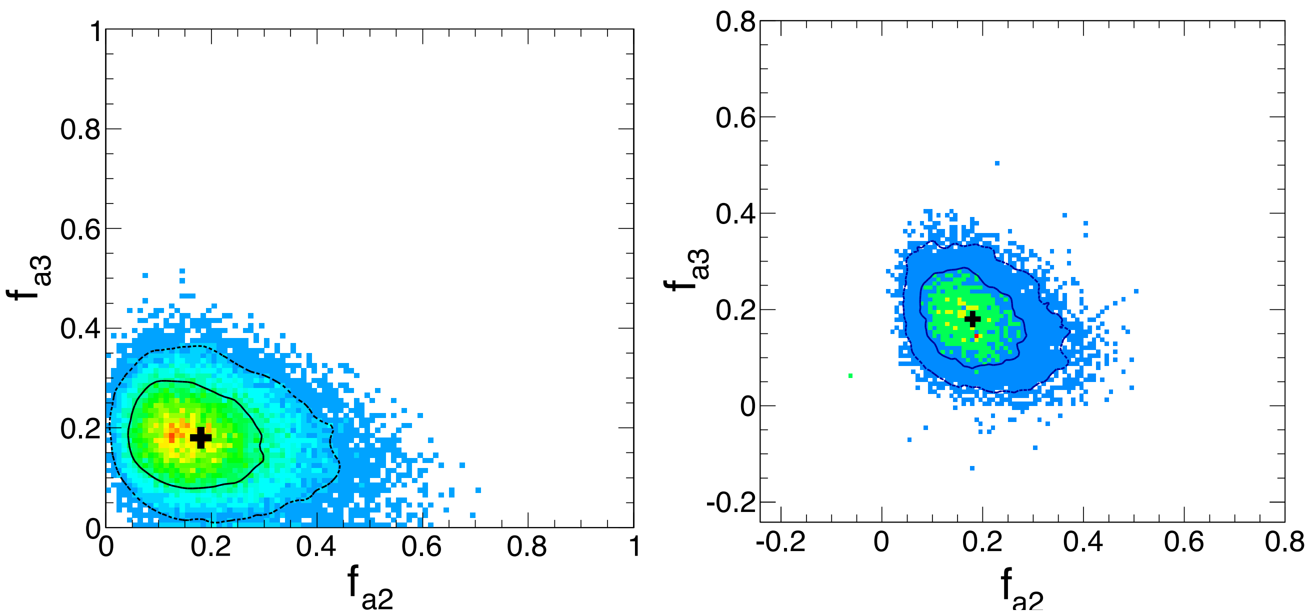
$$\mathcal{O}_1 = -\frac{M_Z^2}{v} H Z_\mu Z^\mu, \quad \mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu} \qquad \mathcal{O}_3 = -\frac{1}{2v} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}, \quad \mathcal{O}_4 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$$

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

Modification of the m_{4l} shape



Modification of lepton angular distributions



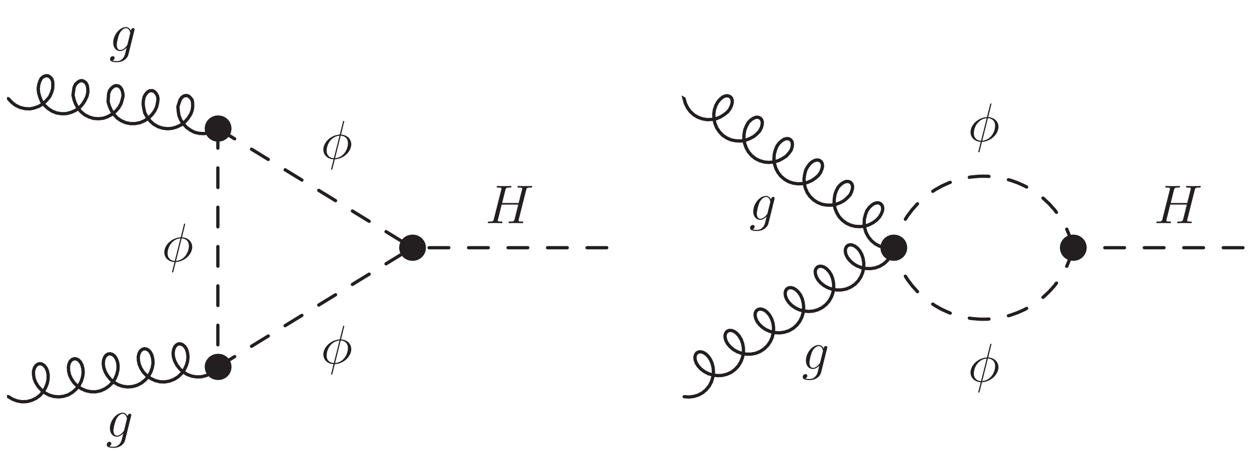
Good control at the HL-LHC [Anderson et al (2013)]

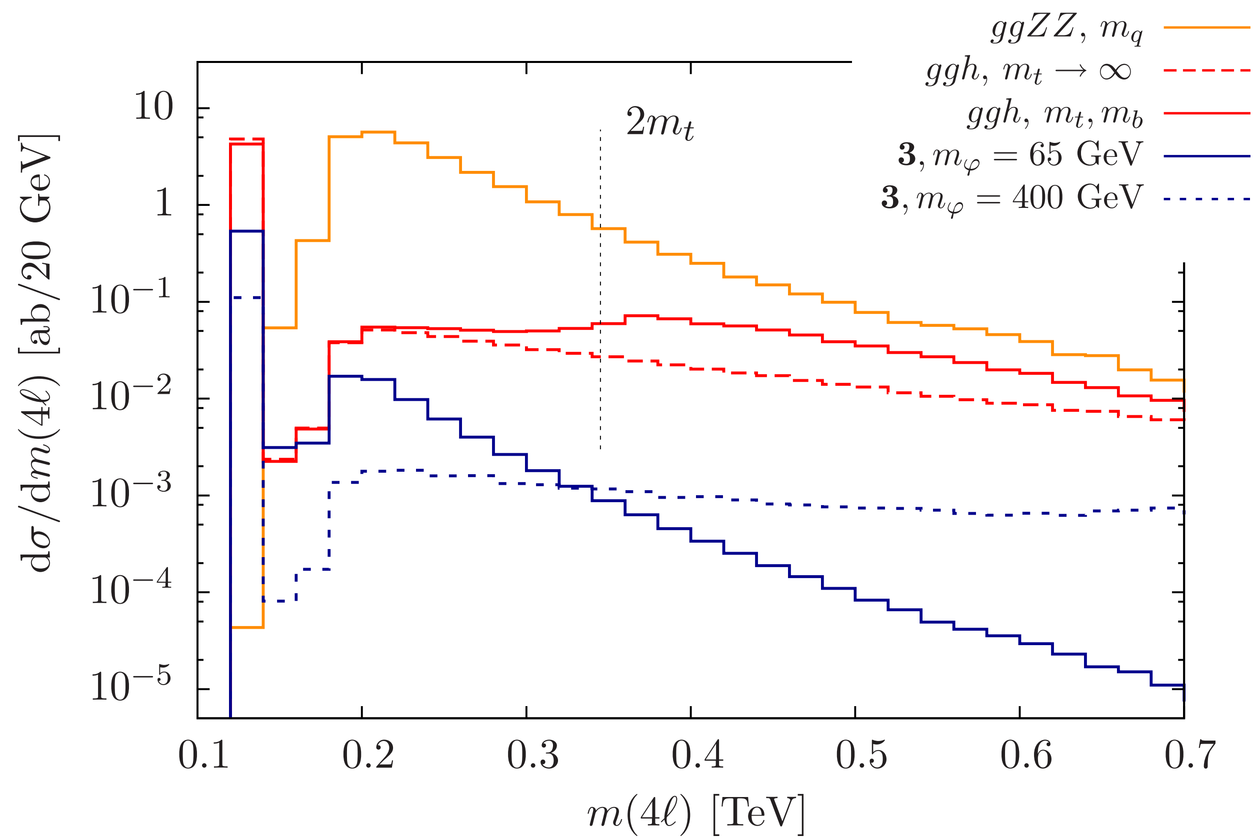
What is the constraining power for off-shell analysis?

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

[Englert, Spannowski (2014)]

Light d.o.f. qualitatively change the picture





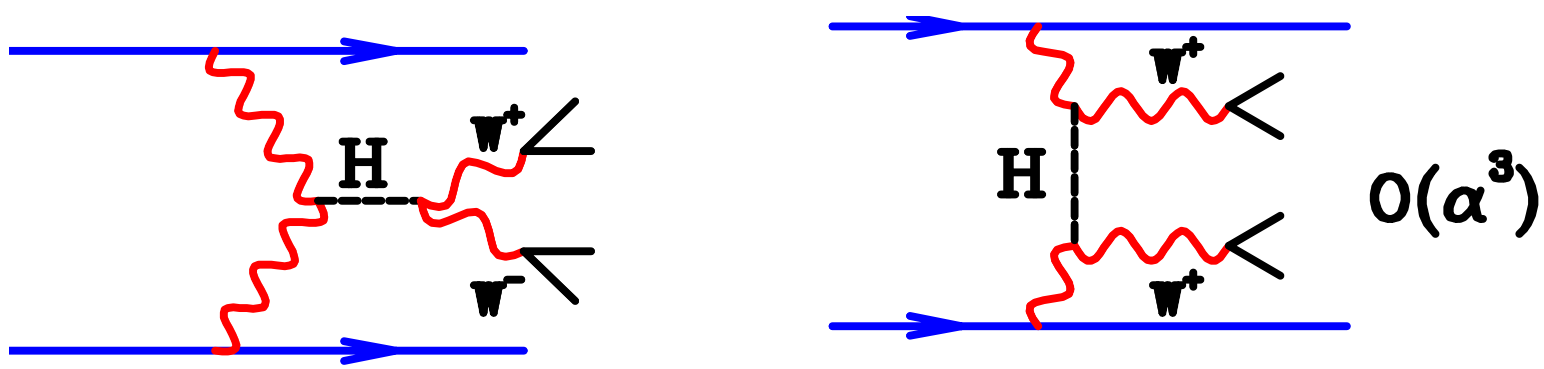
Complementary constraints from other measurements?

- Will also affect other observables e.g. Higgs p_T ([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)])

A complementary approach: VBF

[Campbell, Ellis (2014)]

- Different theory systematics w.r.t. gluon fusion
- At least in the SM, good theoretical control
- The most promising channel: W^+W^+ (small background)



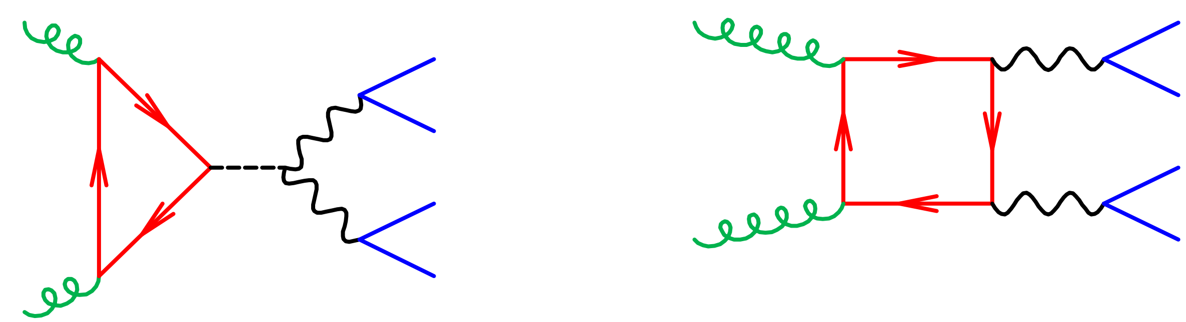
- Although much smaller rates, at the end of Run II: sensitivity ~ to gluon fusion right now

VERY INTERESTING COMPLEMENTARY PROCESS

The second issue: SM theoretical predictions

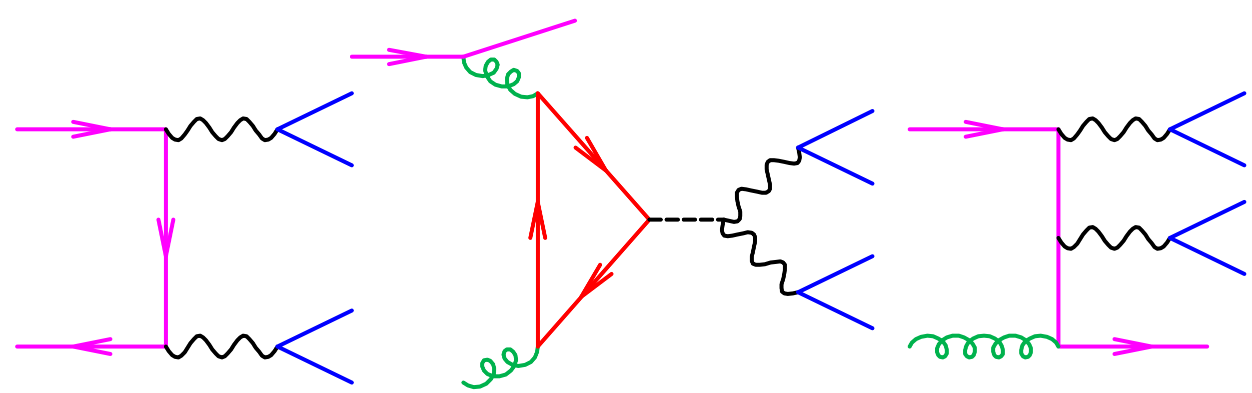
Method based on counting ZZ events in the high invariant-mass tail -> good predictions for 4l final state required

- qq -> ZZ (NNLO QCD)
- gg -> ZZ



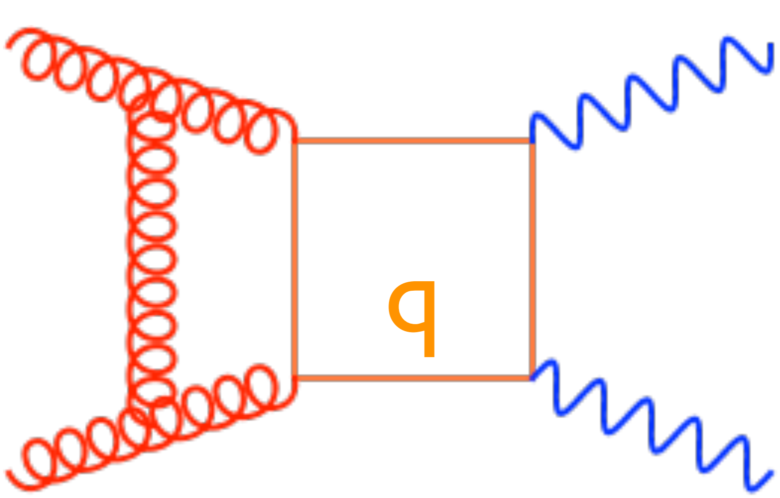
(a) (b)

- qg -> ZZq

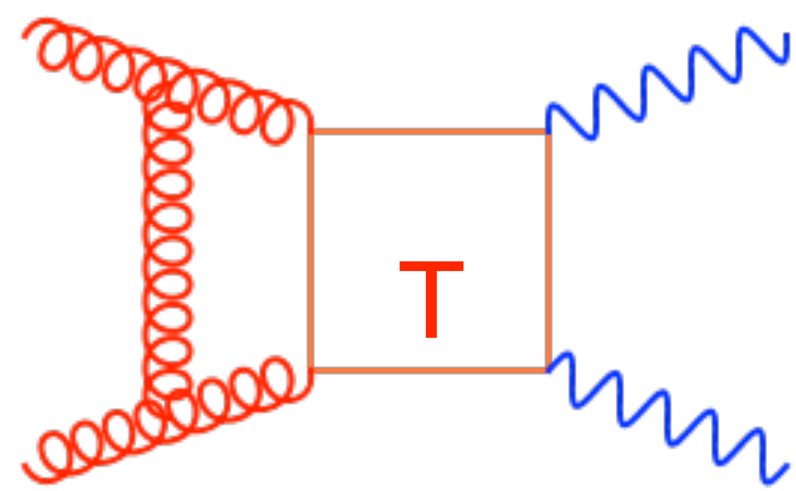


The second issue: SM theoretical predictions

- right now, we have NNLO for the qq channel and N^{3}LO (inclusive) for the signal, but LO ONLY FOR THE FULL GG->ZZ BACKGROUND AND INTERFERENCE
- gluon-initiated process -> expect large corrections
- the problem: loop induced process, NLO involves (very complicated) 2-loop amplitudes



Recently computed

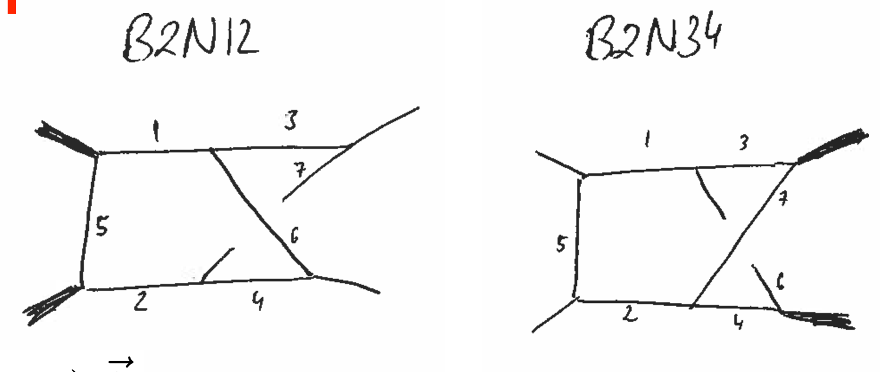


VERY HARD
[important in the off-shell region]

gg->VV@NLO: massless quarks

2-loop amplitude for VV*

new ideas
for FI
at work

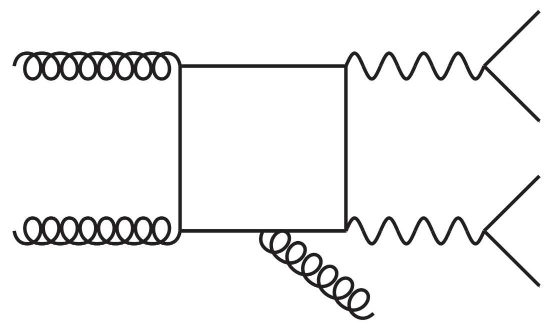


$$\partial_x \vec{f} = \epsilon \hat{A}_x(x, y, z \ldots) \vec{f}$$

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

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

Real emission

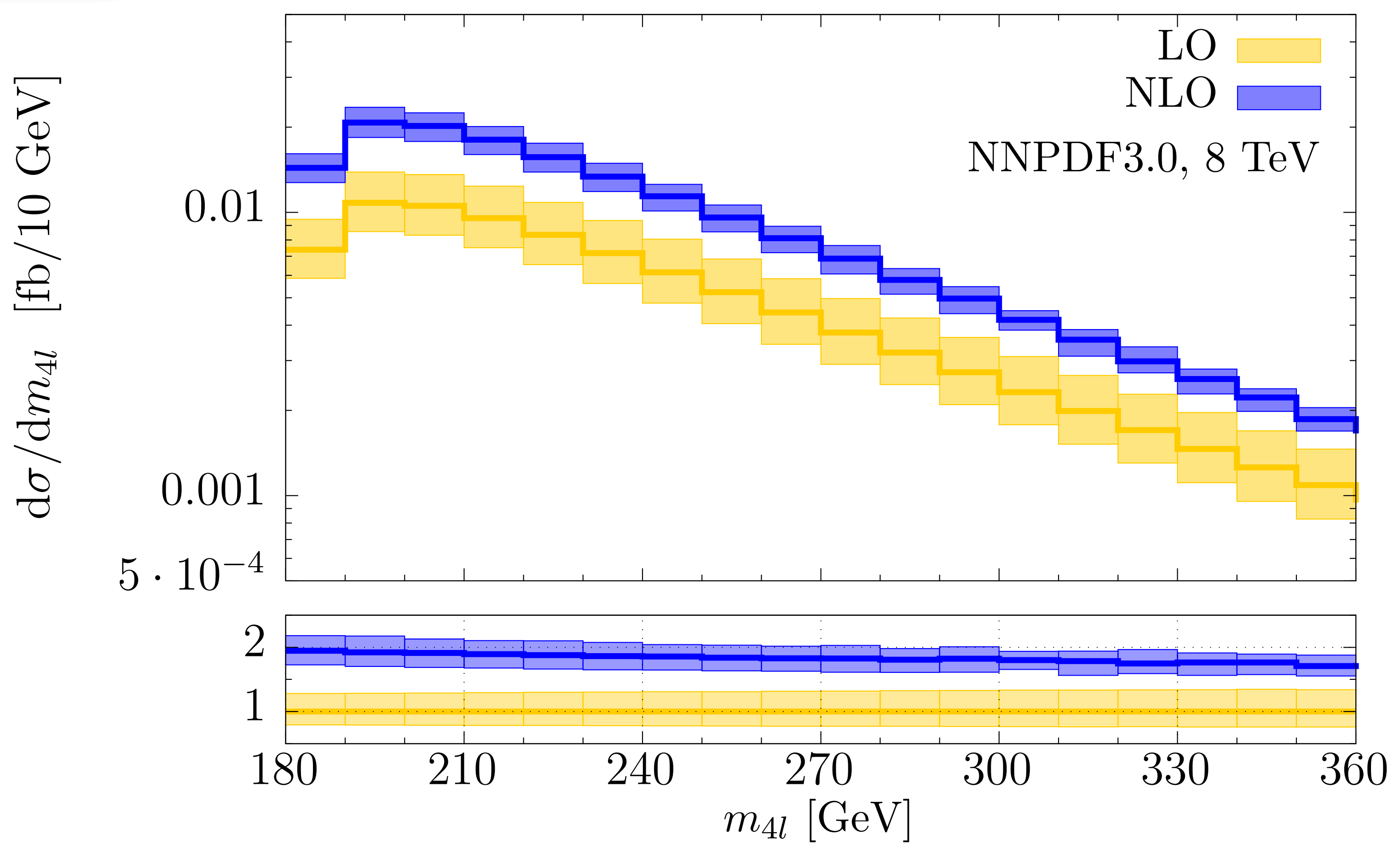


fast and stable
in soft/colliner
configurations

mixed analytical
+numerical unitarity

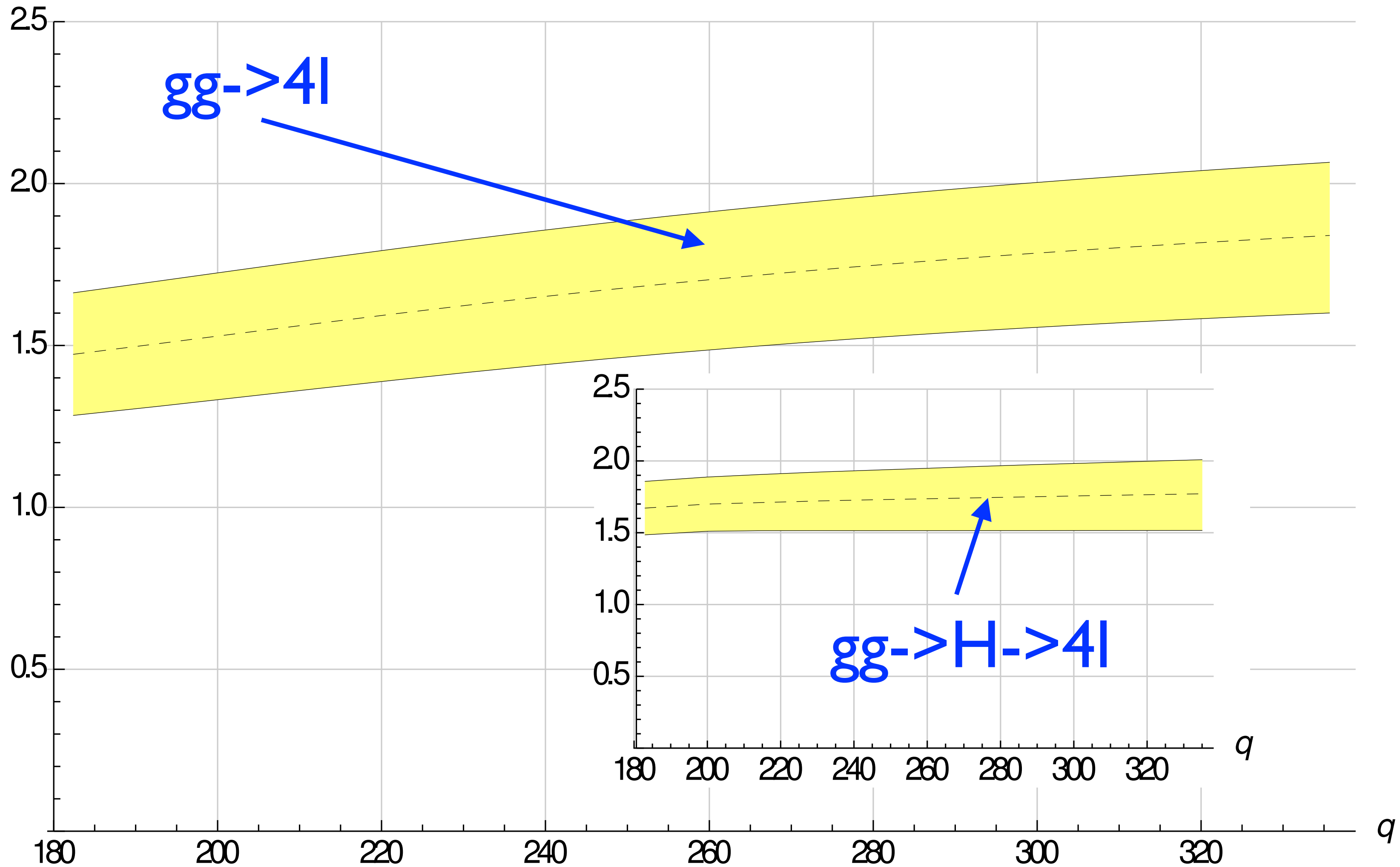
[FC, Melnikov, Röntsch, Tancredi (2015)]

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



gg->VV@NLO: top loops

- exact result beyond reach right now
- estimates: $1/m_t$ expansions [Dowling, Melnikov (2015)]

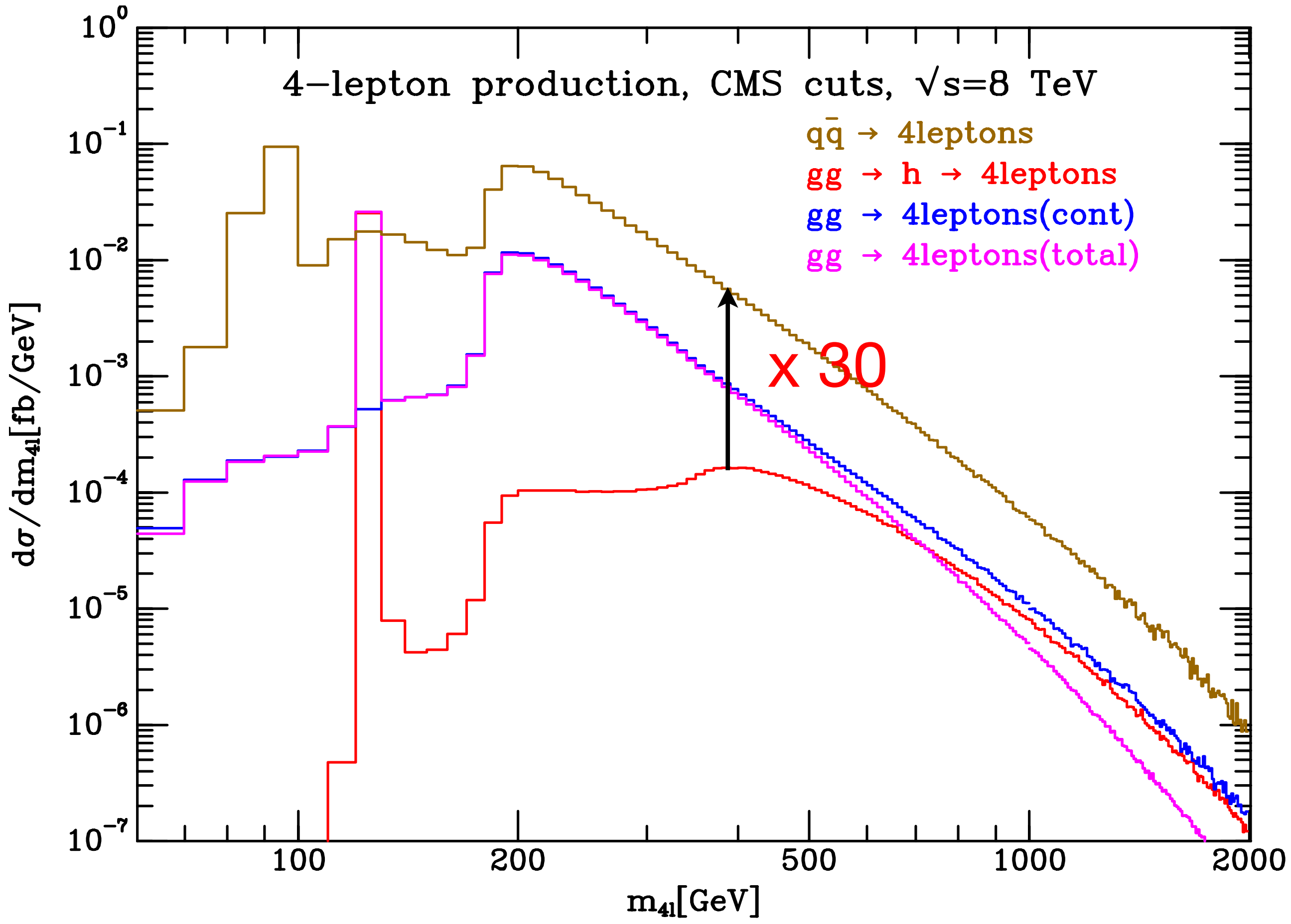


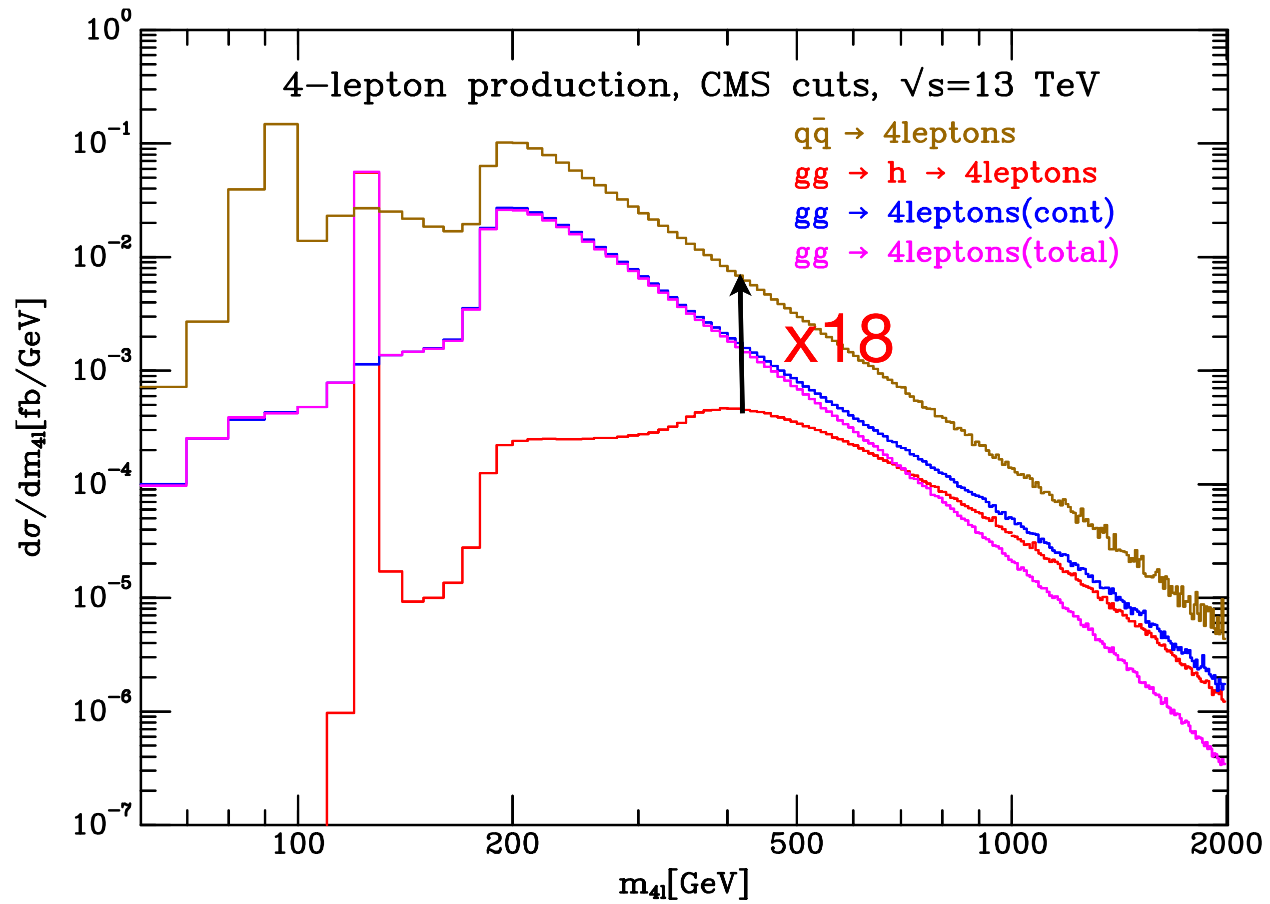
again, behavior similar to Higgs signal

Both for NLO (massless) prediction and for massive $1/m_t$ expansion, off-shell phenomenology not known yet (ongoing)

Off-shell measurements: Run II

Gluon PDF grows faster with energy than quark PDF





[Ellis, MCFM (2015)]

S/B enhancement, interesting off-shell phenomenology ahead

Conclusions

- the Higgs is a very narrow resonance -> direct measurement of its width is not possible at hadron colliders
- still, under some assumptions it is possible to obtain indirect constraints for it
  - in the $\gamma\gamma$ channel, by looking at mass shift from signal/background interference. Theoretically clean, but experimentally challenging
  - in the ZZ channel, by measuring couplings away from the resonant peak. Big potential, but delicate theoretical issues
- if theoretical control improves, bounds as low as the SM width $\Gamma_H \sim 4.2$ MeV may be possible at the LHC

Outlook

Many work still needs to be done:

- for experimentalists (better handle on the $\gamma\gamma$ interference, qq/gg->4l separation, discriminants…)
- for BSM phenomenologists (interpretation of the off-shell signal, anomalous couplings, interplay off-shell vs boosted…)
- for SM theorists/phenomenologists (massive loop amplitudes, gg->m_{4l}, Higgs p_T spectrum…)

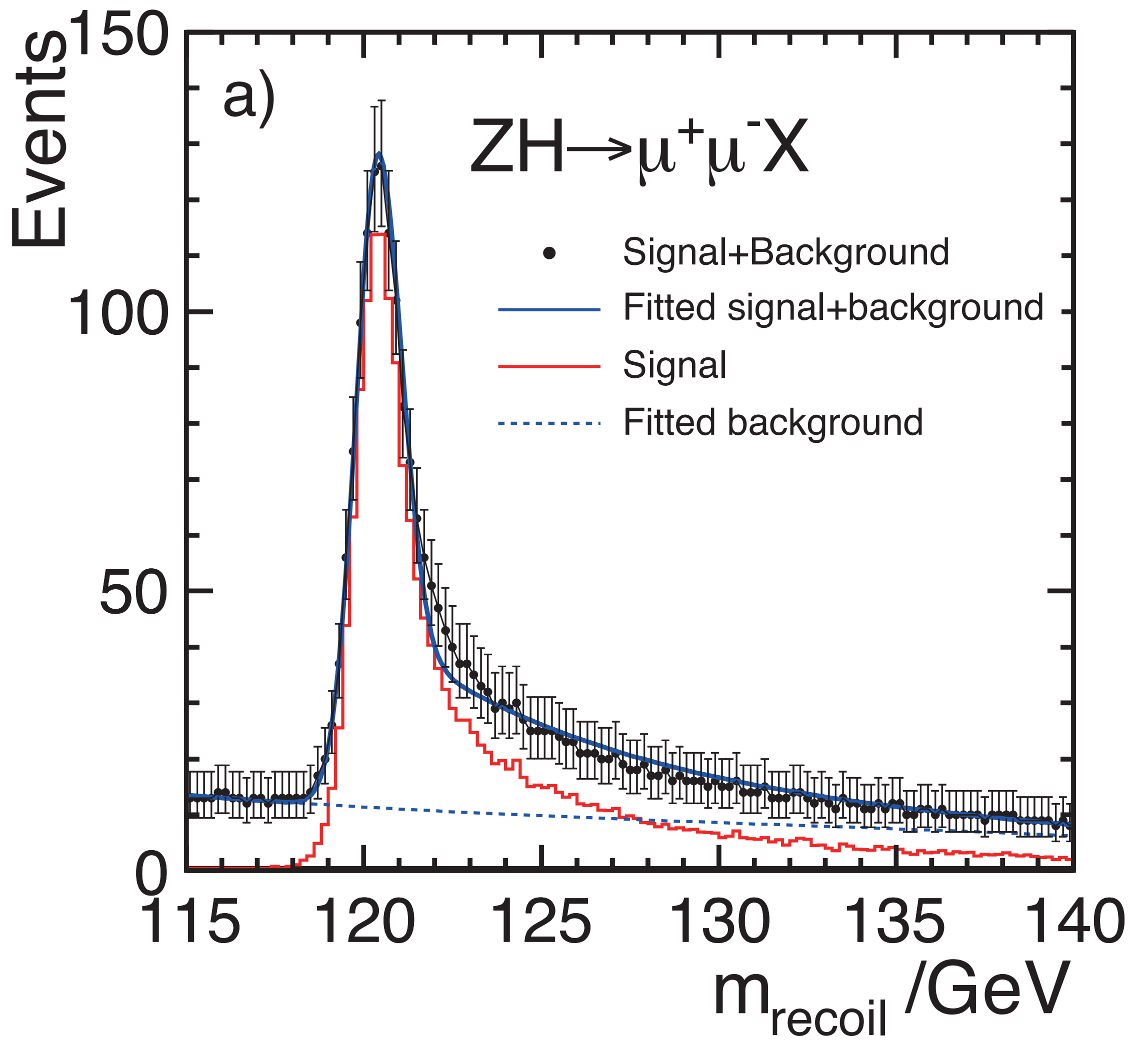
IMPACT OF THESE STUDIES WELL BEYOND THE WIDTH MEASUREMENT

Thank you!

Back-up

The Bjorken process at e^+e^- colliders

Consider the process $e^+e^- \to Z^* \to HZ$



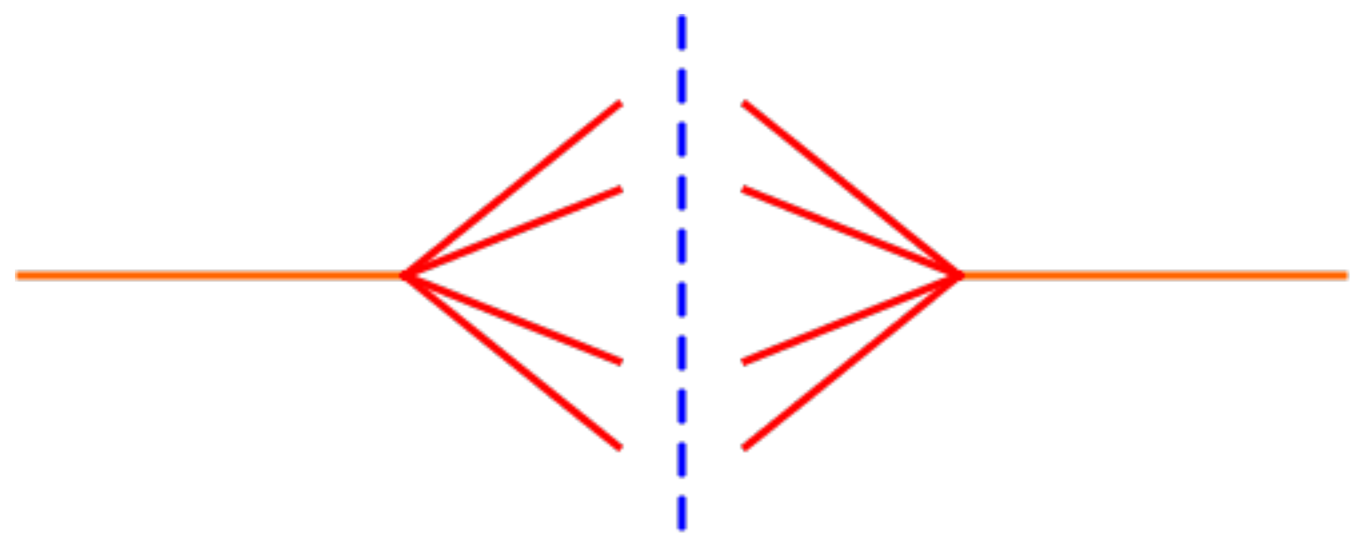
- From the decay leptons of the Z, construct recoil mass -> access to the Higgs cross section
- Insensitive to Higgs decay -> Higgs to invisible is accounted for
- At the end:
  $$\sigma \approx g_i^2 \sum_f g_f^2 / \Gamma_H \approx g_i^2$$
- Degeneracy is broken -> combine with H->ZZ and get Γ_H

Measurement with few percent precision may be possible

Lifetime and width

$$\psi(t) = \psi(0)e^{-iEt} = \psi(0)e^{-iE_0 t - \frac{\Gamma}{2}t}$$

$$\psi(E) = \int dt\ e^{iEt}\psi(t) = \frac{i\psi(0)}{E - E_0 + i\Gamma/2}$$



$$|\psi(E)|^2 \sim \frac{1}{(E - E_0)^2 + \Gamma^2/4}$$

$$|\psi(t)|^2 = |\psi(0)|^2 e^{-t/\tau} \qquad \Gamma = -\frac{1}{|\psi(t)|^2}\frac{d|\psi(t)|^2}{dt} = \frac{1}{\tau}$$

VBF rates [Ellis, talk given at MITP 2015]

Rates for signal and background

Signal, $O(\alpha^6)$

W+W+

Process	Nominal process	Cut	σ [fb] $O(\alpha^6)$	Factor	Events in 100 fb^{-1}
$pp \to e^- \mu^+ \nu_\mu \bar{\nu}_e jj$	W^-W^+	$m_T^{WW} > 300$ GeV	0.2378	x4	95
$pp \to \nu_e e^+ \nu_\mu \mu^+ jj$	W^+W^+	$m_T^{WW} > 300$ GeV	0.1358	x2	27
$pp \to e^- \bar{\nu}_e \mu^- \bar{\nu}_\mu jj$	W^-W^-	$m_T^{WW} > 300$ GeV	0.0440	x2	9
$pp \to \nu_e e^+ \mu^- \mu^+ \mu^+ jj$	W^+Z	$m_T^{WZ} > 300$ GeV	0.0492	x4	20
$pp \to e^- \bar{\nu}_e \mu^- \mu^+ jj$	W^-Z	$m_T^{WZ} > 300$ GeV	0.0242	x4	10
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{ZZ} > 300$ GeV	0.0225	x6	14
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{WW} > 300$ GeV	0.0181	x6	11
$pp \to e^- e^+ \mu^- \mu^+ jj$	ZZ	$m_{4l} > 300$ GeV	0.0218	x2	4

Table 3. Electroweak ($\mathcal{O}(\alpha^6)$) cross sections at $\sqrt{s} = 13$ TeV, under the cuts given in Eqs. (2.2)–(2.6) and the off-shell definition specified in the table. The factor gives the approximate number by which the result shown for specific lepton flavours must be multiplied to account for two flavours of charged leptons, e, μ and three flavours of neutral leptons, ν_e, ν_μ, ν_τ.

Factor takes into account sum over e, μ and ν_e, ν_μ, ν_τ

c.f. ttbar 254 events

Background, $O(\alpha^4 \alpha_s^2)$

Process	Nominal process	Cut	σ [fb] $O(\alpha^4 \alpha_s^2)$	Factor	Events in 100 fb^{-1}
$pp \to e^- \mu^+ \nu_\mu \bar{\nu}_e jj$	W^-W^+	$m_T^{WW} > 300$ GeV	0.2227	x4	89
$pp \to \nu_e e^+ \nu_\mu \mu^+ jj$	W^+W^+	$m_T^{WW} > 300$ GeV	0.0079	x2	2
$pp \to e^- \bar{\nu}_e \mu^- \bar{\nu}_\mu jj$	W^-W^-	$m_T^{WW} > 300$ GeV	0.0025	x2	0
$pp \to \nu_e e^+ \mu^- \mu^+ \mu^+ jj$	W^+Z	$m_T^{WZ} > 300$ GeV	0.0916	x4	37
$pp \to e^- \bar{\nu}_e \mu^- \mu^+ jj$	W^-Z	$m_T^{WZ} > 300$ GeV	0.0454	x4	18
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{ZZ} > 300$ GeV	0.0143	x6	9
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{WW} > 300$ GeV	0.0118	x6	7
$pp \to e^- e^+ \mu^- \mu^+ jj$	ZZ	$m_{4l} > 300$ GeV	0.0147	x2	3

Table 4. Mixed QCD-electroweak ($\mathcal{O}(\alpha^4 \alpha_s^2)$) cross sections at $\sqrt{s} = 13$ TeV, under the cuts given in Eqs. (2.2)–(2.6) and the off-shell definition specified in the table.

W+W+

Ignore other sources of background, W+jet, QCD…..