The off-shell Higgs boson at the LHC

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Physics Challenges at the LHC Workshop

Outline

- Motivation, and methodology
- Off shell predictions in the SM
- Experimental Results
- BSM considerations
- Recent developments and future directions.

Motivation + Methodology

Decays of the Higgs at Colliders : Notation

The Higgs is unstable, and we observe its decay products in the detector.

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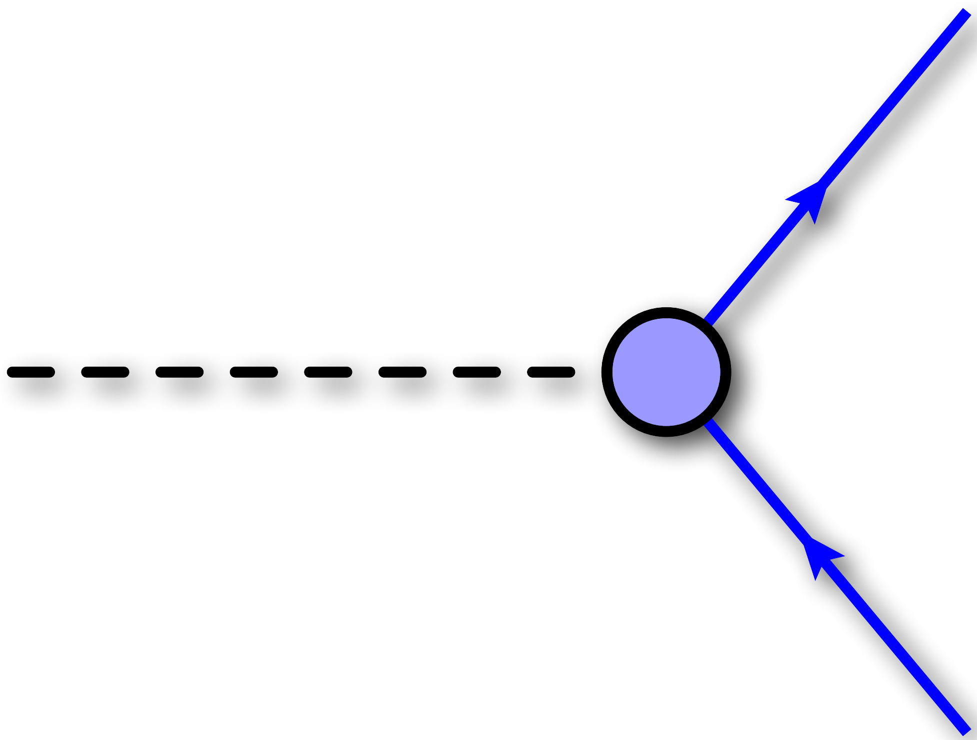
Partial widths define the rate for each open decay

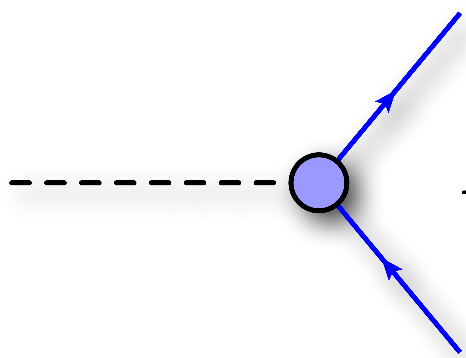
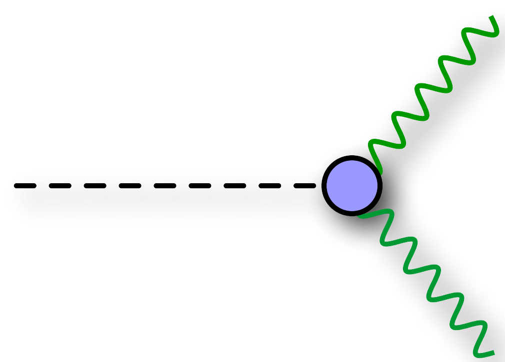
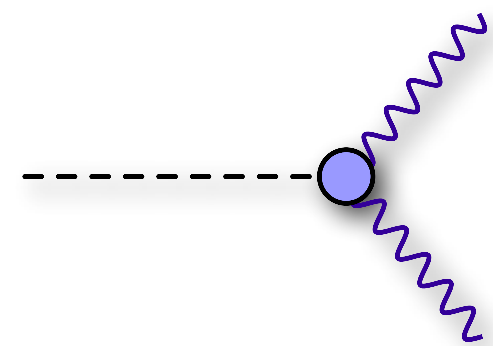


$$\sim \Gamma_{b\bar{b}}\ [\mathrm{GeV}]$$

Decays of the Higgs at Colliders : Notation

The Higgs is unstable, and we observe its decay products in the detector.

Summing over all the partial widths yields the total width.

$\Gamma_{tot} =$  $+$  $+$  $+ \cdots$

Decays of the Higgs at Colliders : Notation

The Higgs is unstable, and we observe its decay products in the detector.

Finally, the branching ratio defines the relative fraction for a particular decay.

$$BR(H \to X) = \frac{\Gamma_X}{\Gamma_{tot}}$$

Relationship between the total width and couplings

In the narrow width approximation the total Higgs cross section can be written as follows,

$$\sigma_{i\to H\to f} = \sigma_{i\to H} \times BR_{H\to f} \propto \frac{\sigma_{i\to H}\sigma_{H\to f}}{\Gamma_H}$$

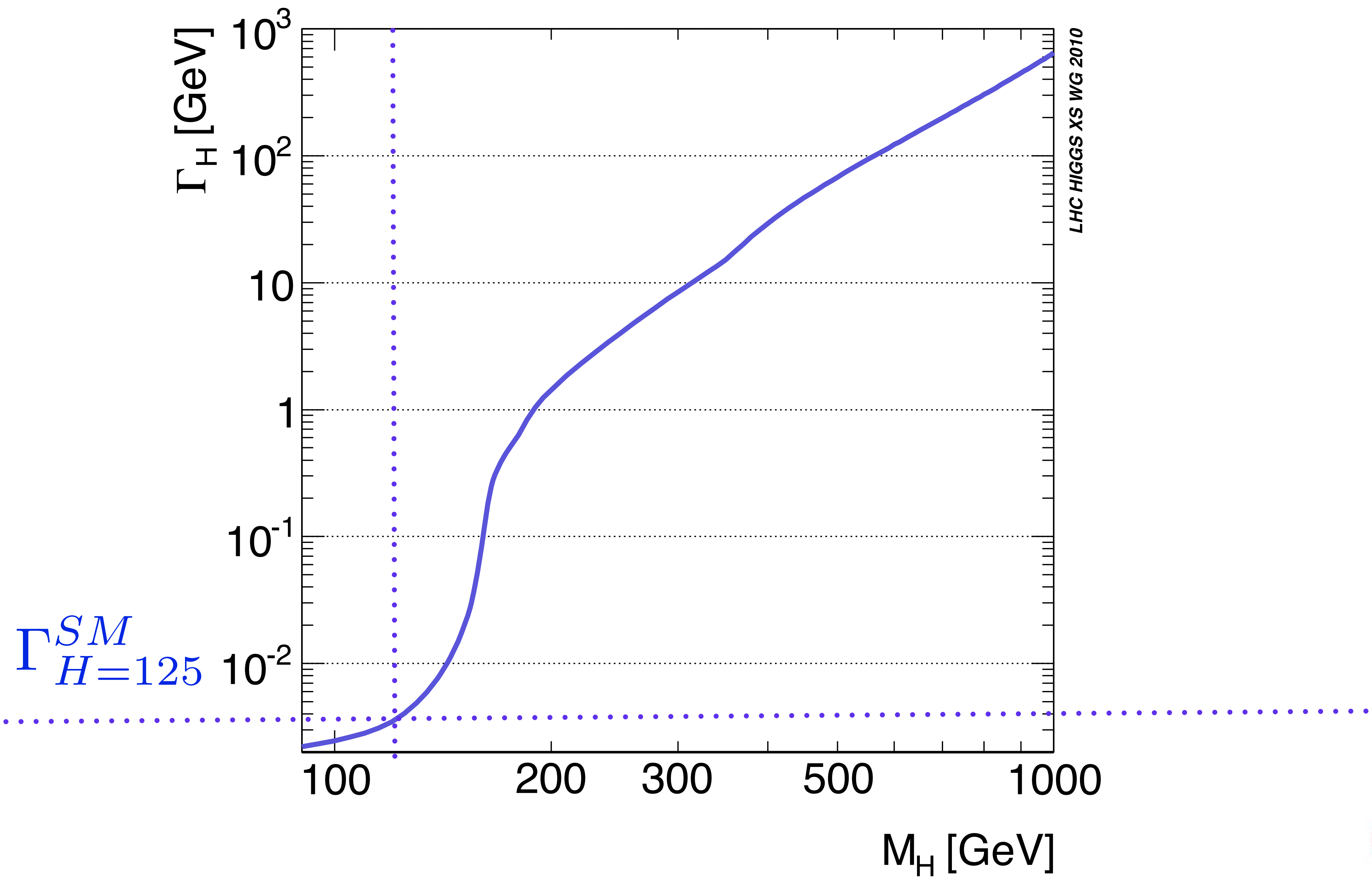
Ultimately we want to extract information regarding the Higgs coupling to SM particles, i.e.

$$\sigma_{i\to H\to f} \propto \frac{g_i^2 g_f^2}{\Gamma_H} \sim \frac{g_i^2 g_f^2}{\sum_j g_j^2}$$

Measurements in individual channels are thus complicated by a dependence on the global Higgs properties, through the width.

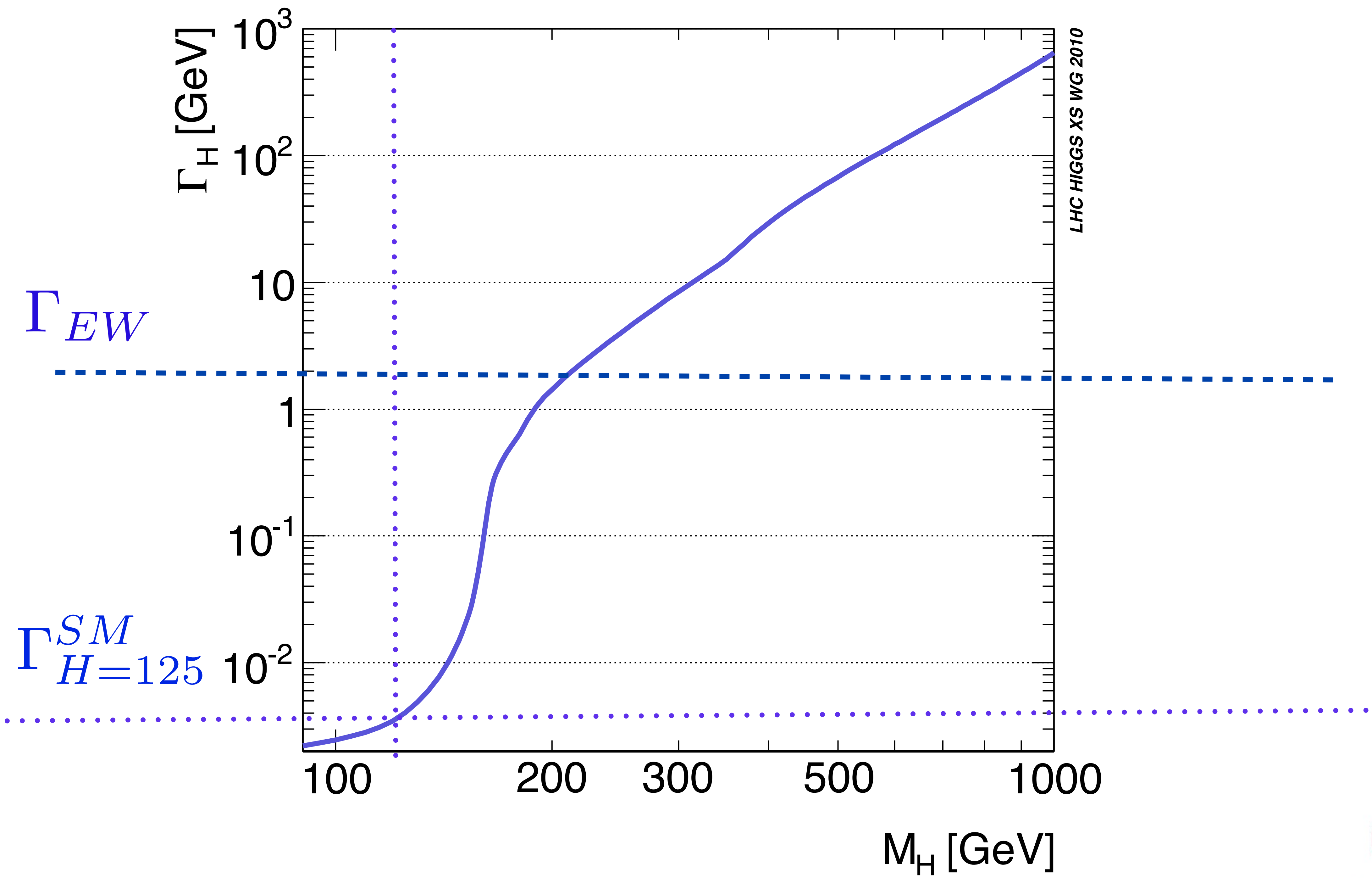
The Higgs Width

The width of the Higgs at 125 GeV is very small ~ 4 MeV



The Higgs Width

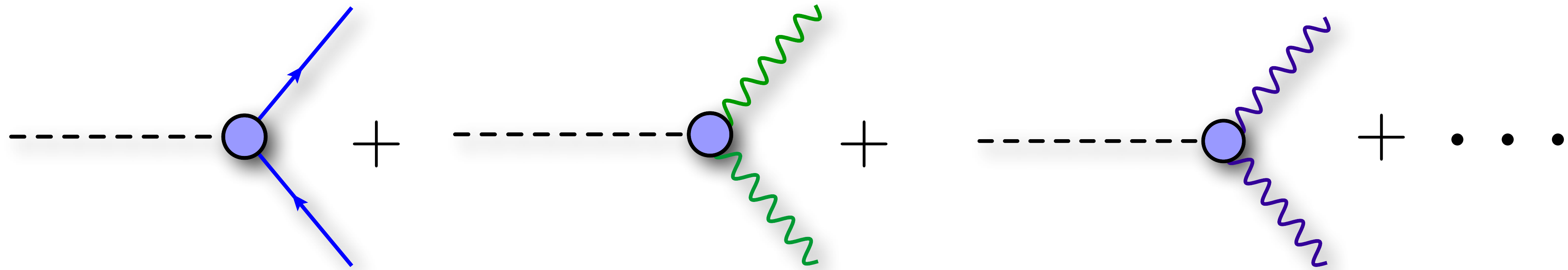
The widths of the other heavy EW particles (W,Z and top) are around 2 GeV



Why is the Higgs Width so Small?

Recall that the width is calculated by summing over the decays

$$\Gamma_{tot} =$$



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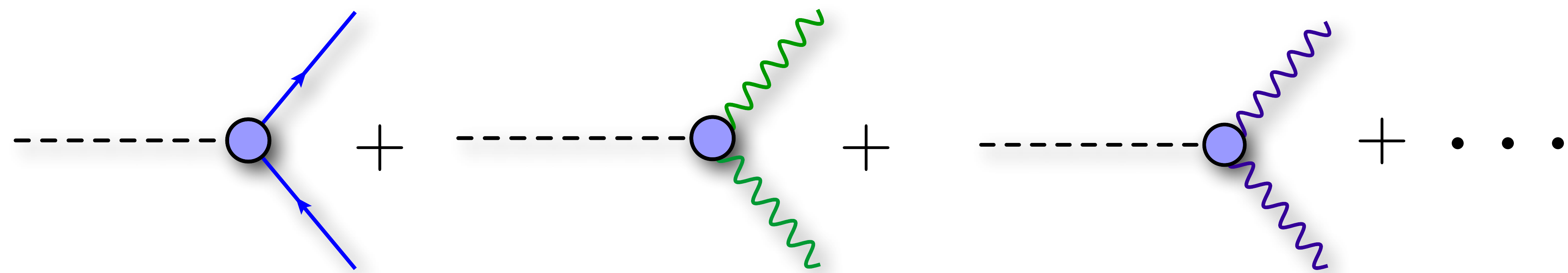
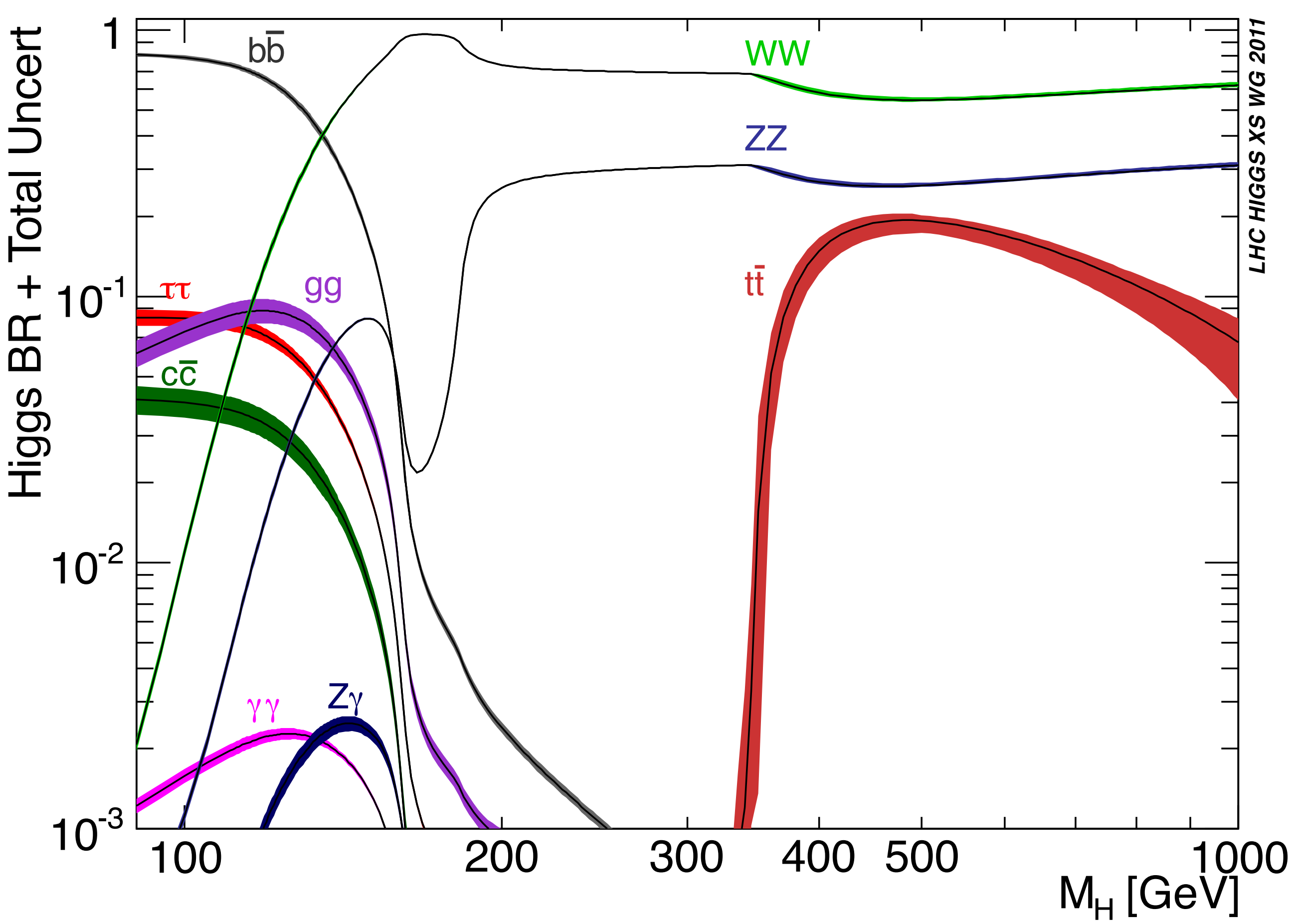


And that the light Higgs decays mostly to bottom quarks



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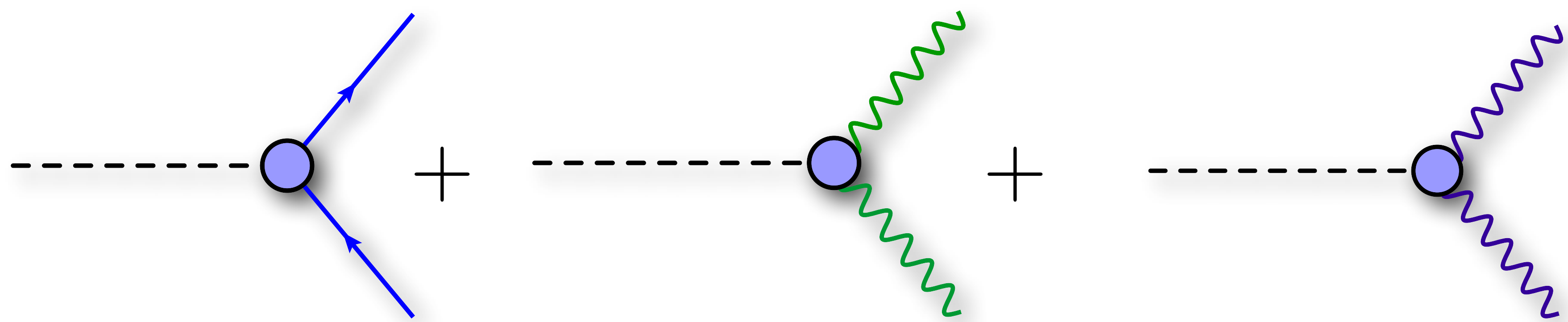

$+ \cdots$

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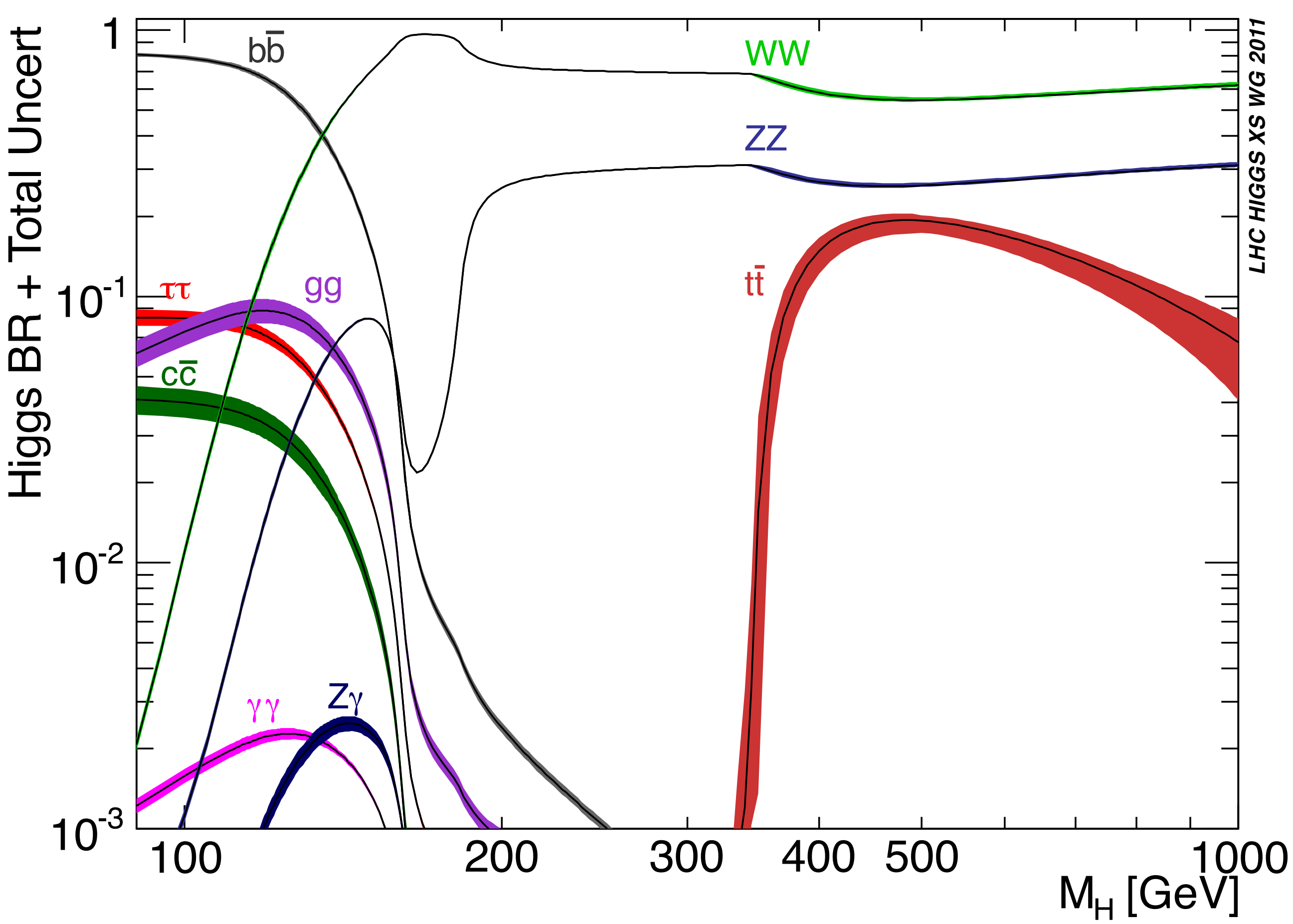
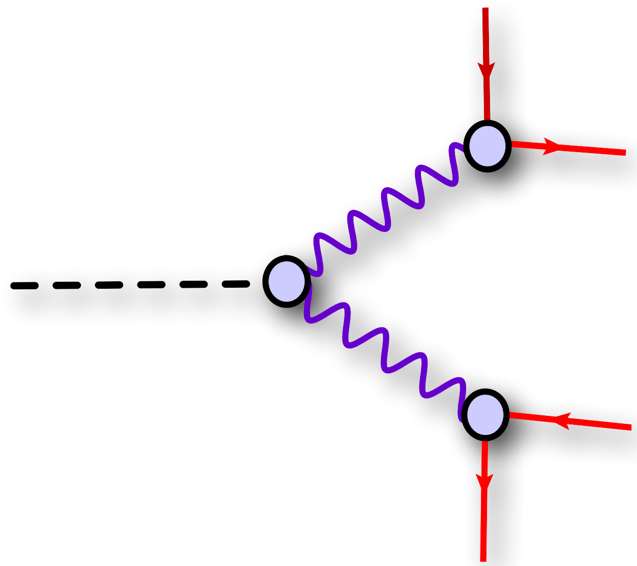
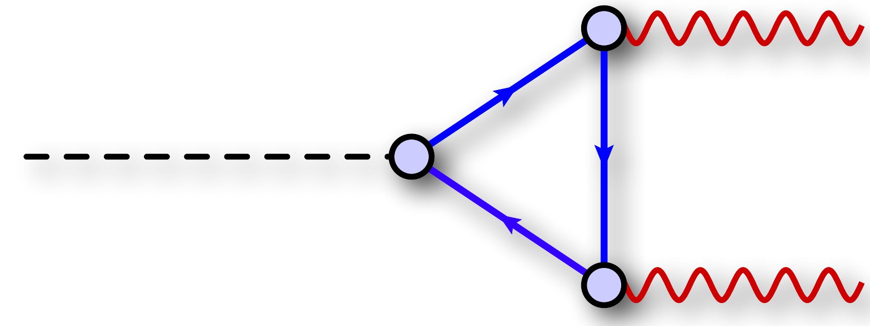


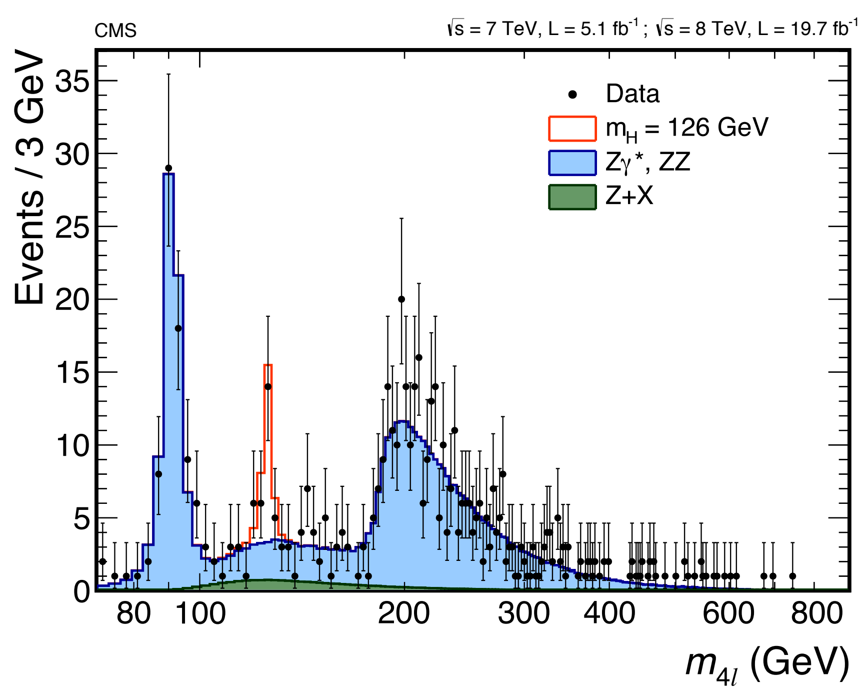
But the bottom is light compared to the EW scale, so that

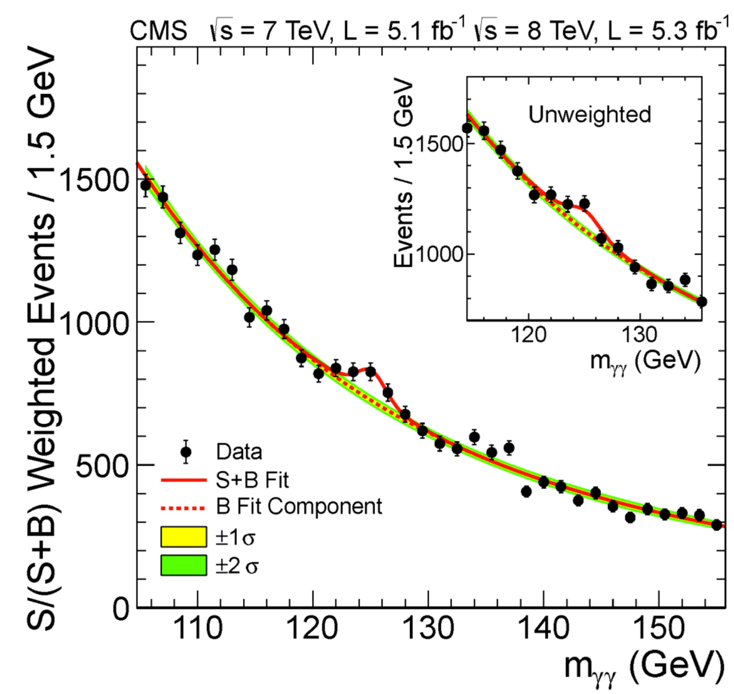
$$\Gamma_H \sim \left(\frac{m_b^2}{m_{EW}^2}\right)\Gamma_{EW}$$

Examples of direct bounds on the width at the LHC









$$\Gamma_H < 3.4\ \mathrm{GeV} \sim 820\ \Gamma_H^{SM}$$

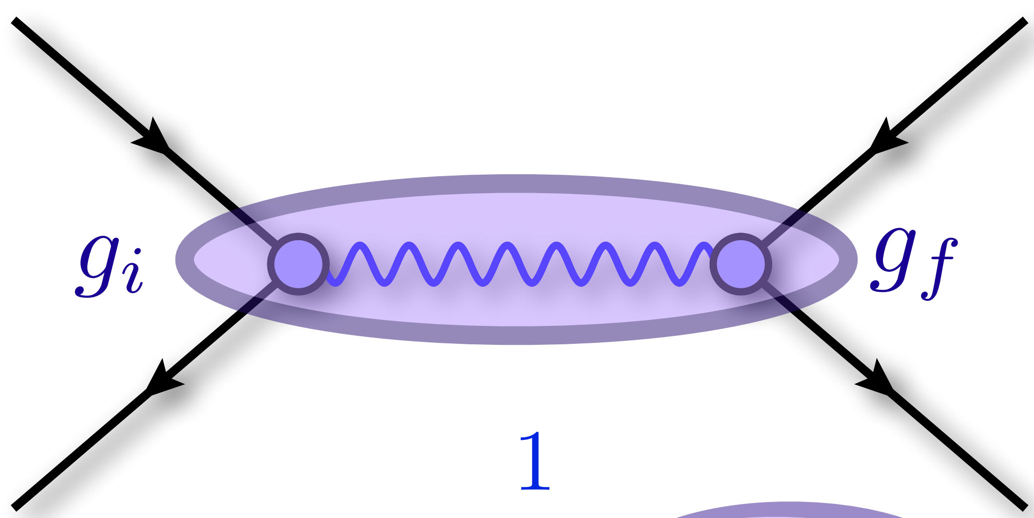
$$\Gamma_H < 6.9\ \mathrm{GeV} \sim 1650\ \Gamma_H^{SM}$$

1312.5353

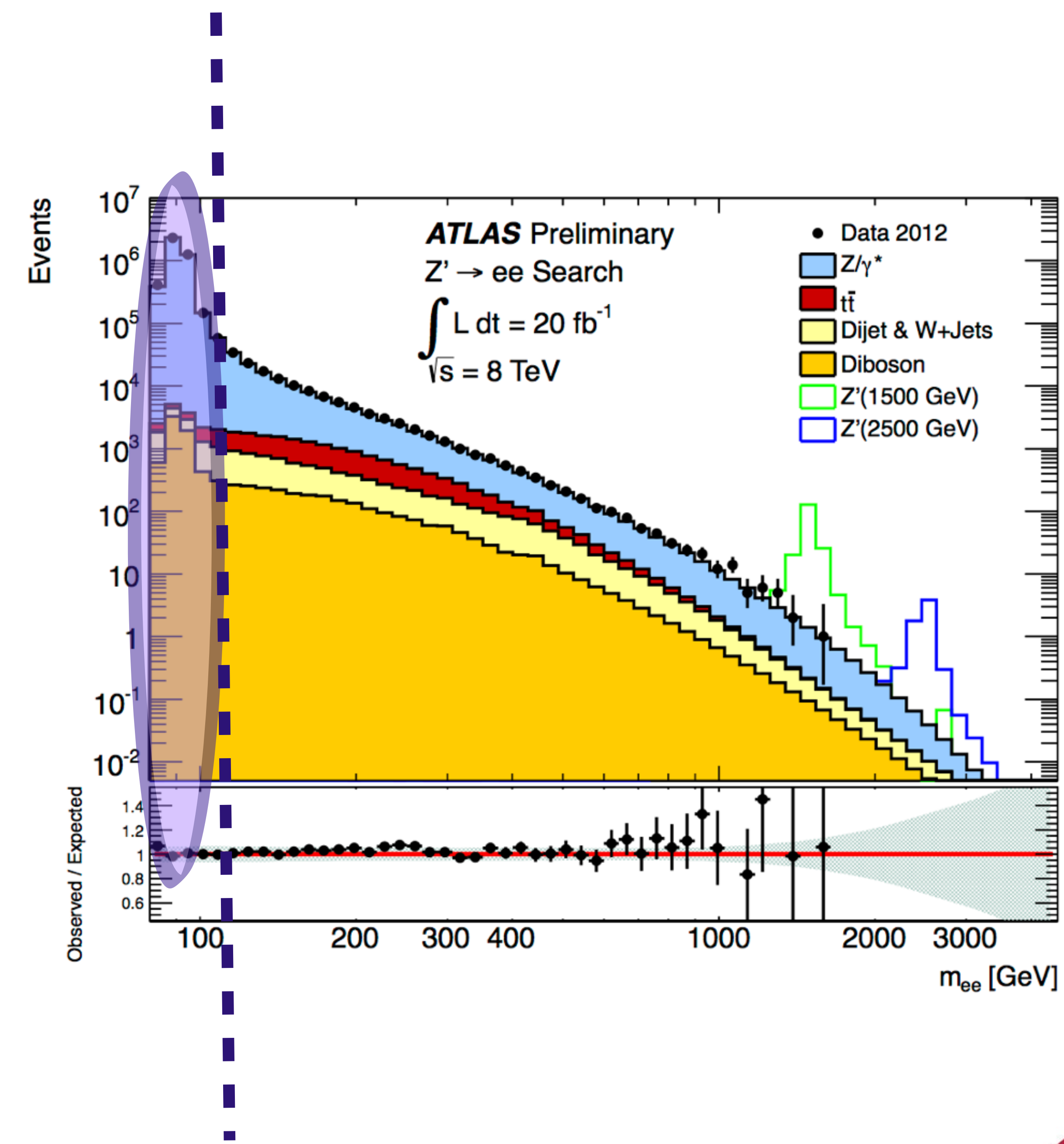
CMS-PAS-HIG-013-016

Properties of the Off-shell Cross Section

(Kauer, Passarino 12)
(Caola, Melinikov 13)
(Campbell, Ellis, CW 13)



$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$



In the resonance region the "on-shell" cross section is dominated by the width.

$$\sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$

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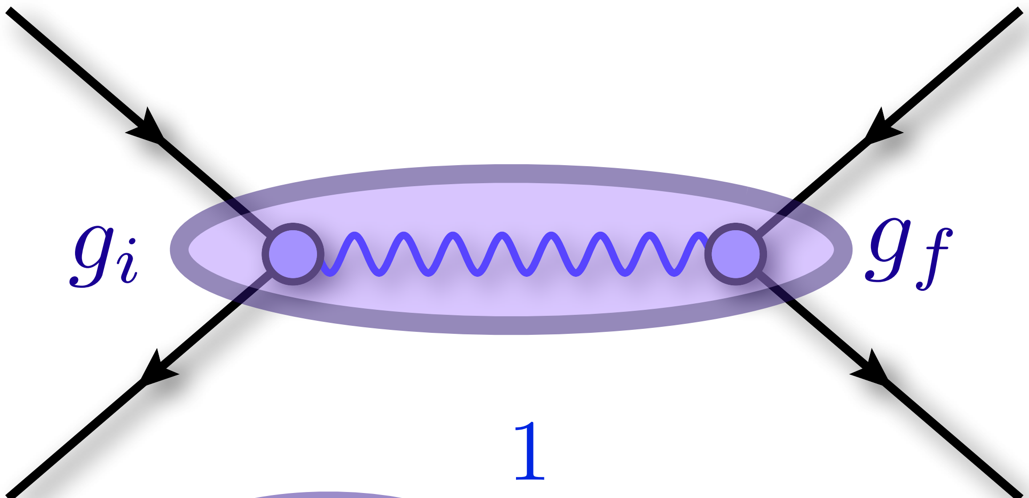
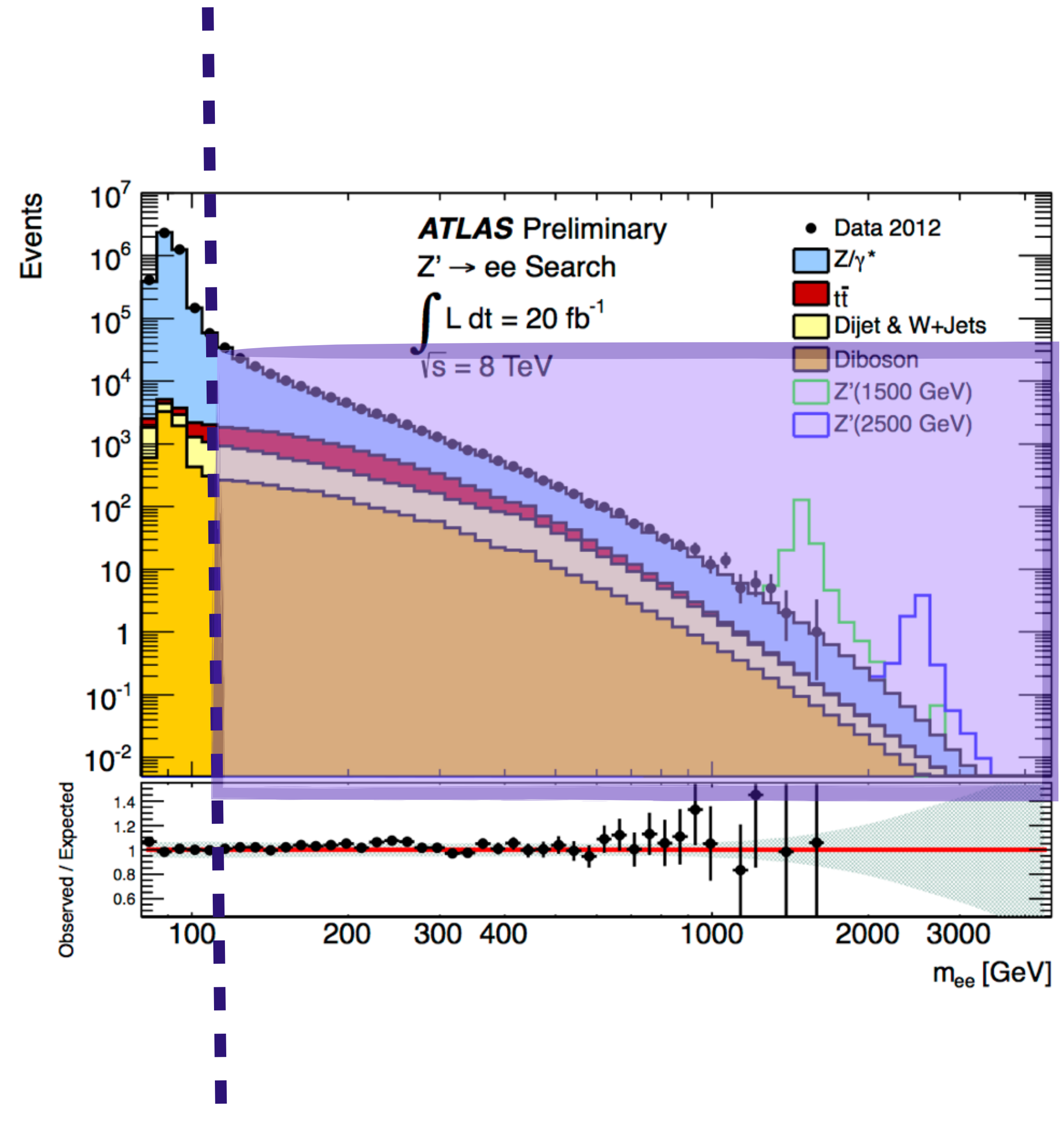


$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$

Away from the resonance region, the “off-shell” cross section does not depend on the width.

$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$



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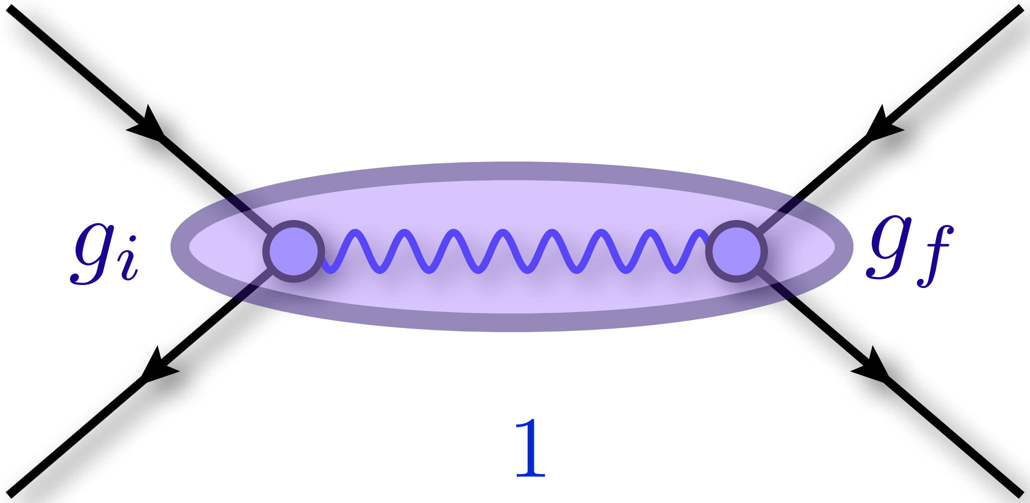
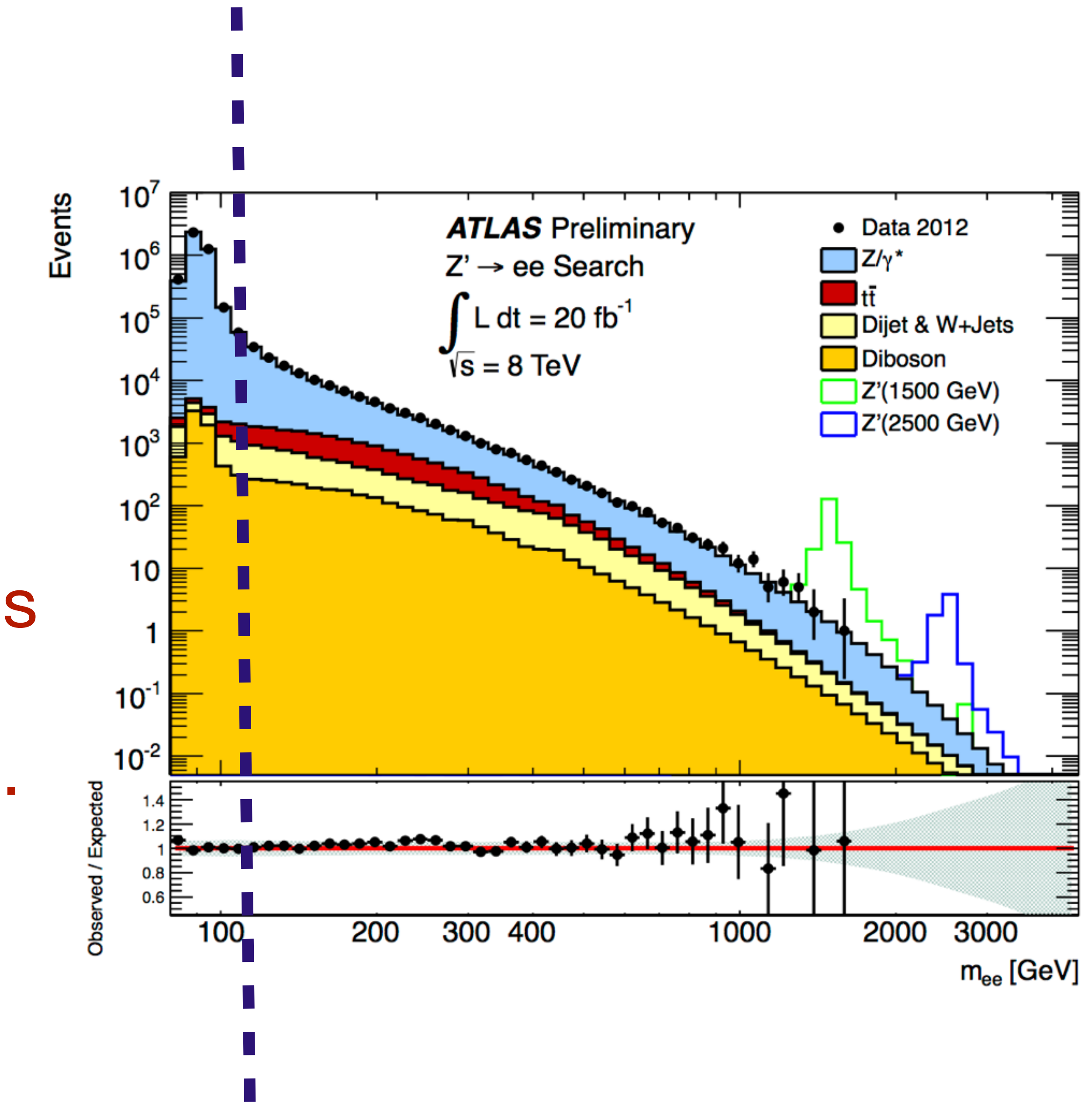


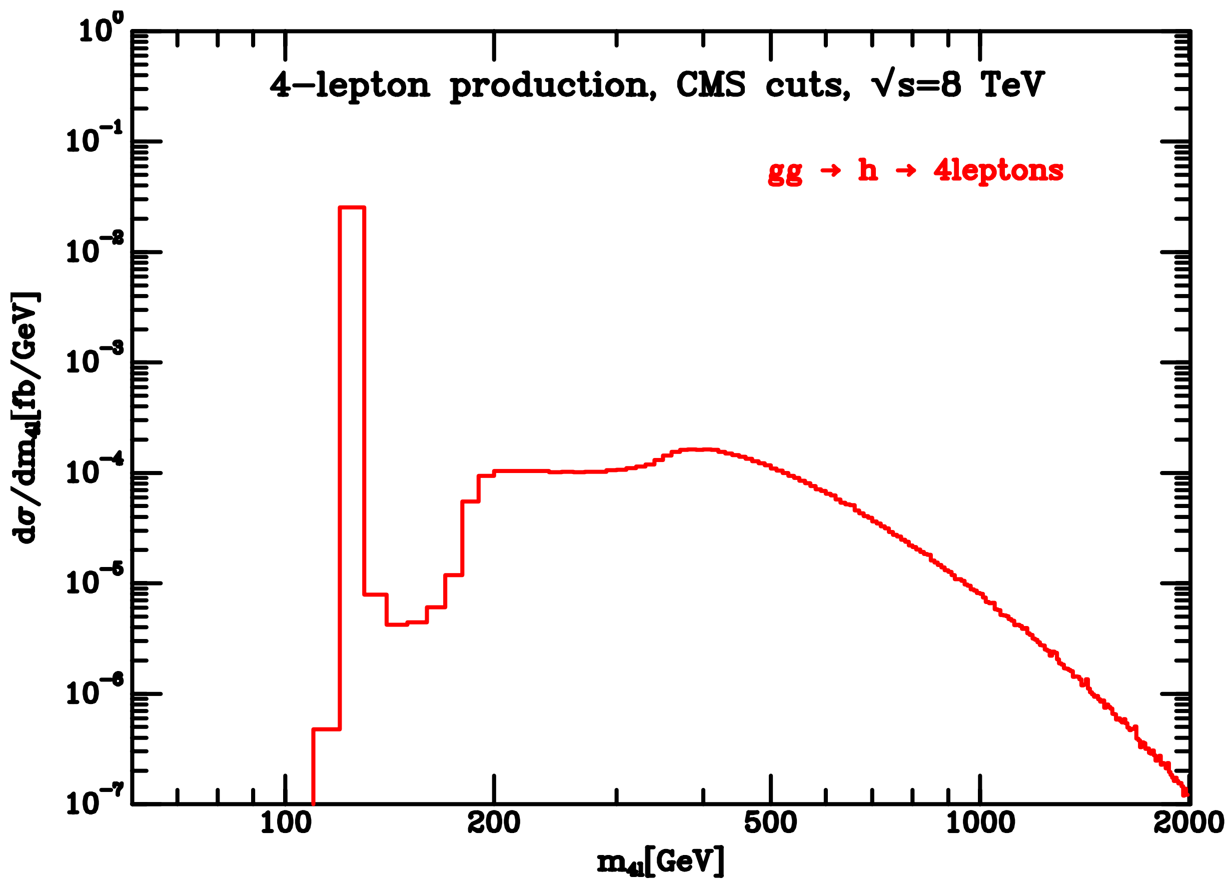
$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$



The ratio of these cross sections is therefore dependent on the width and *independent* of the couplings.

$$\frac{\left(\frac{\sigma_{off}}{\sigma_{on}}\right)_{exp}}{\left(\frac{\sigma_{off}}{\sigma_{on}}\right)_{SM}} \propto \frac{\Gamma_X}{\Gamma_X^{SM}}$$

Off Shell Higgs cross sections.

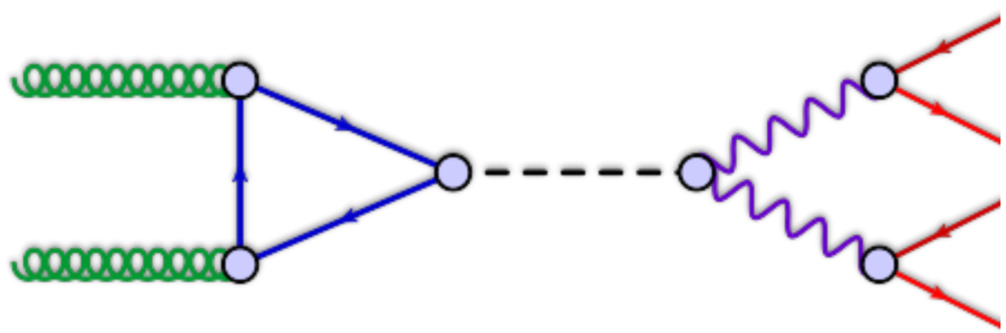


Energy	σ^H_{peak}	σ^H_{off}
7 TeV	0.203	0.044
8 TeV	0.255	0.061

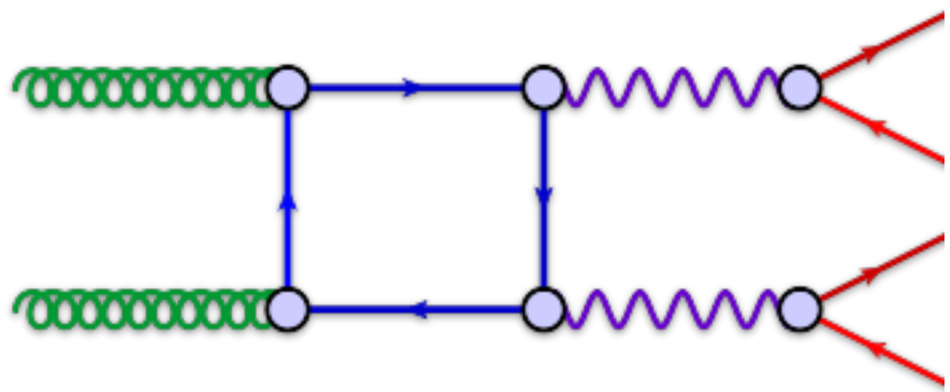
- Since Γ_H / M_H=1/30,000 one might expect off-shell corrections to be very small.
- However this is not the case, there is a sizable contribution to the total cross section away from the peak.
- This arises from the proximity of the two Z threshold, and is further enhanced by the threshold at twice the top mass.

Off shell predictions in the SM

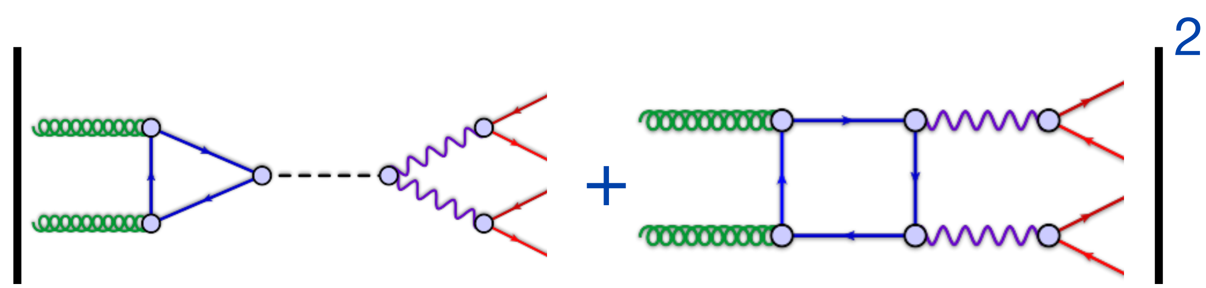
Production of four leptons at the LHC



In order to bound the width we are interested in off-shell Higgs events.

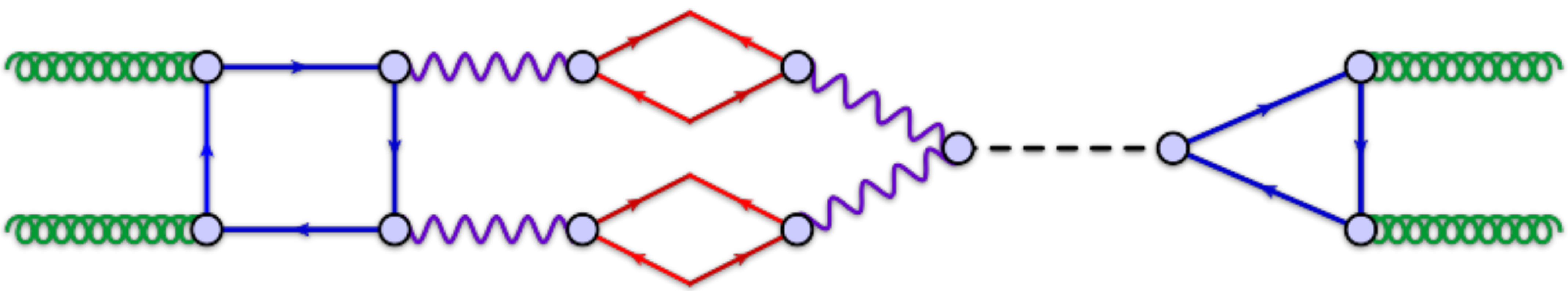


However the same final state can occur via a loop of fermions.



The Matrix element is thus given by the coherent sum.

Interference effects in four lepton final states.



The structure of the interference can be examined by writing it in the following way

$$\delta\sigma_i = \frac{s - m_H^2}{(s - m_H^2)^2 + m_H^2\Gamma_H^2}\mathrm{Re}\,(2A_{Higgs}A^*_{box}) + \frac{m_H\Gamma_H}{(s - m_H^2)^2 + m_H^2\Gamma_H^2}\mathrm{Im}\,(2A_{Higgs}A^*_{box})$$

An odd function about the Higgs mass, which therefore effectively cancels near the resonance.

A piece proportional to the width of the Higgs, very small for 125 GeV Higgs.

Impact on the off-shell cross section,

As a result of the interference, our previous assumption,

$$\frac{\sigma_{off}}{\sigma_{on}} \propto \Gamma_H$$

is invalid. The interference modifies the above equation, introducing a term which scales as the root of the width.

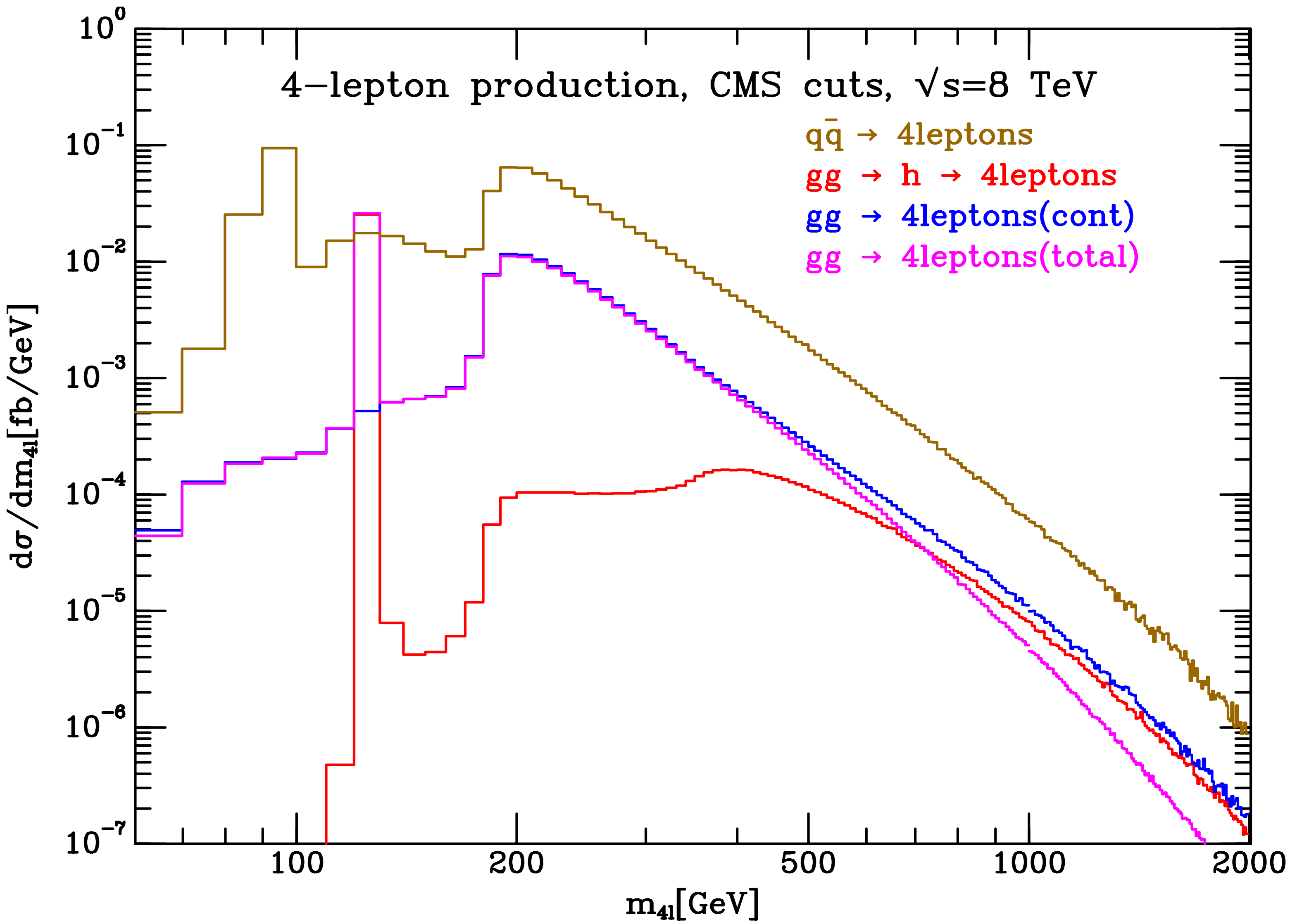
$$\frac{\sigma_{off}}{\sigma_{on}} \propto a\Gamma_H + b\sqrt{\Gamma_H}$$

For now we assume that the on-shell cross section is the SM, and re-write the off-shell cross section as,

$$\sigma_{off}^{gg\to 4\ell} = a\frac{\Gamma_H}{\Gamma_H^{SM}} + b\sqrt{\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right)} + c$$

Need the gg=>ZZ box to calculate b and c!

Putting it all together : the big picture

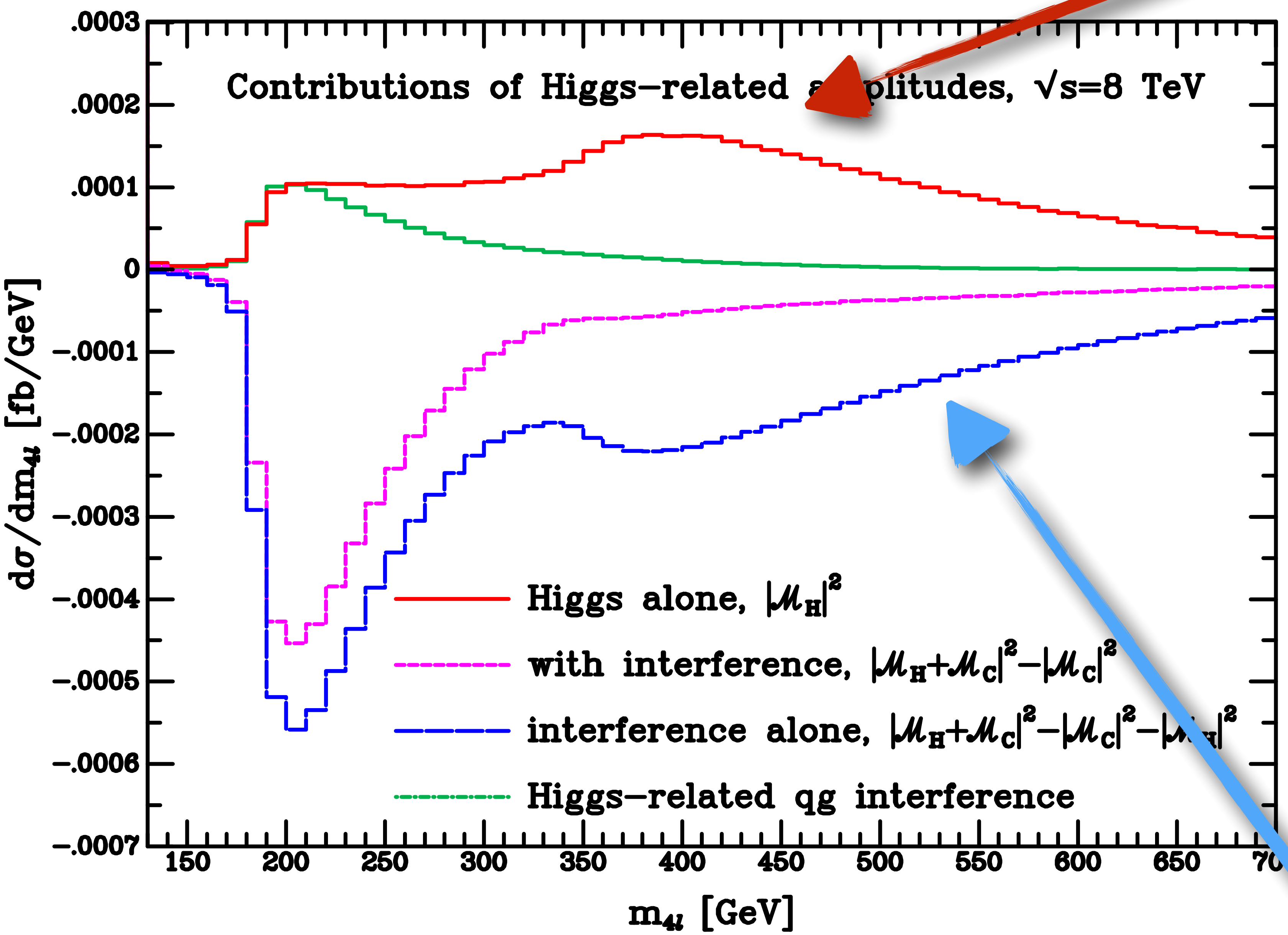


Putting it all together we confirm that the signal only hypothesis, is a very poor approximation away from the peak.

The unitarizing nature of the Higgs is apparent from the destructive tail.

Interference effects

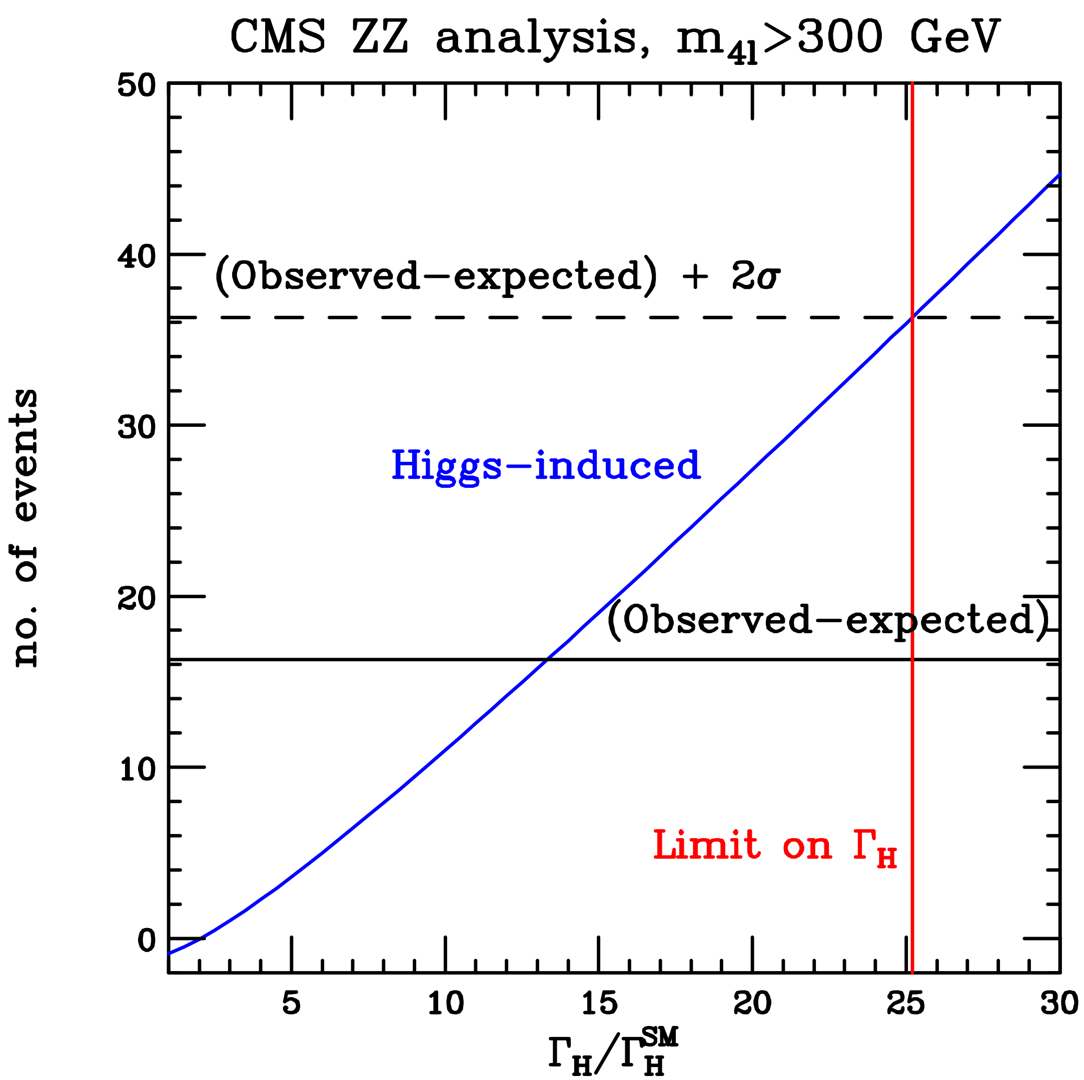
Scales like $g_t^2 g_Z^2$ i.e. $\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right)$



The interference shares similar features to the signal (in particular the thresholds), washing out many of the features associated with the top quark.

Scales like $g_t g_Z$ i.e. $\sqrt{\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right)}$

Bounding the Higgs width using LHC data : high masses

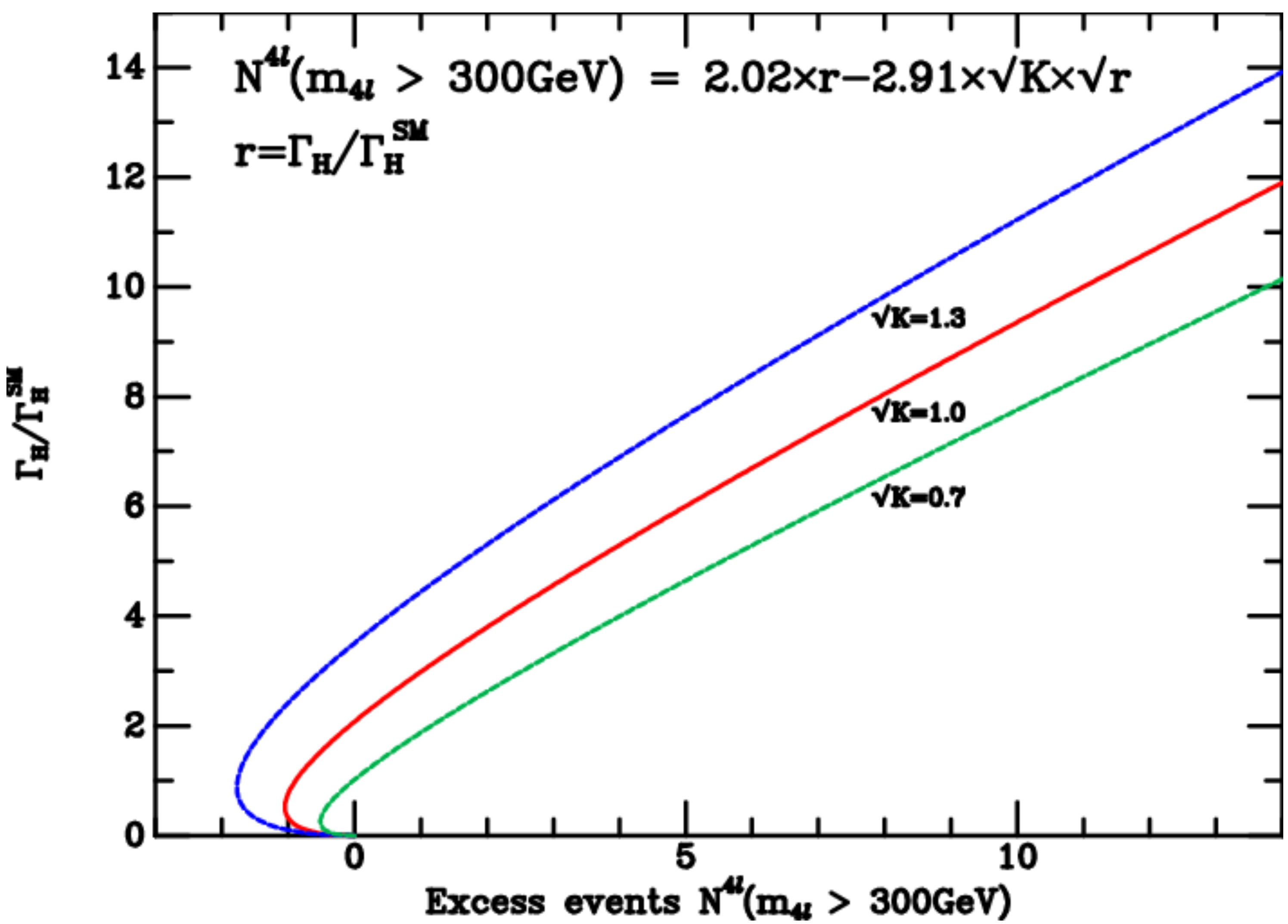


Performing the analysis in the higher invariant mass range produces better results (since the background is reduced but the mt threshold is maintained). At > 300 GeV we find.

$$N^{4\ell}_{off}(m_{4\ell} > 300\ \text{GeV}) \;=\; 2.02\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

$$\Gamma_H < 25.2\,\Gamma_H^{SM} \text{ at } 95\%\text{ c.l.},\quad (m_{4\ell} > 300\text{ GeV analysis})$$

Theoretical issues….



Currently the gg=>ZZ process is only known at LO.

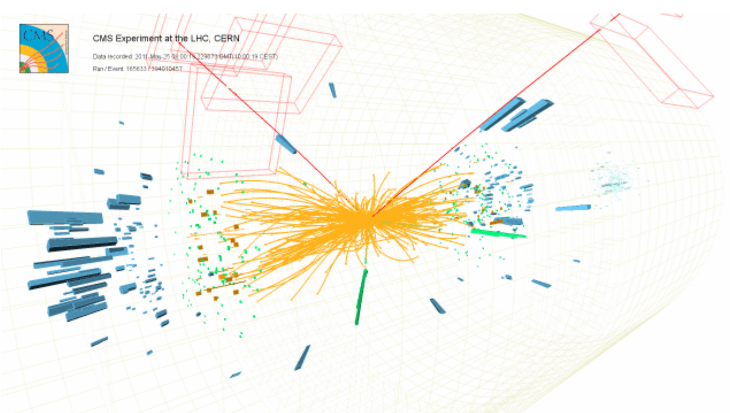
Variation of potential K-factors reveal the dependence of the off-shell cross section on potential higher order corrections.

Experimental Results

Matrix Element Methods

See Michael's Talk!

Start with an event



Matrix Element Methods

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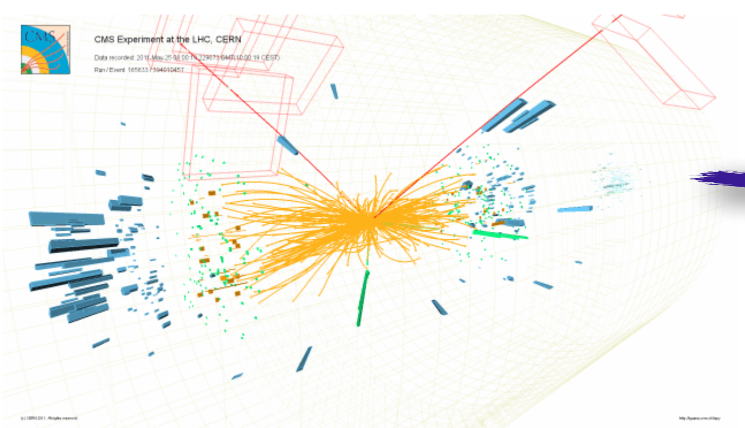
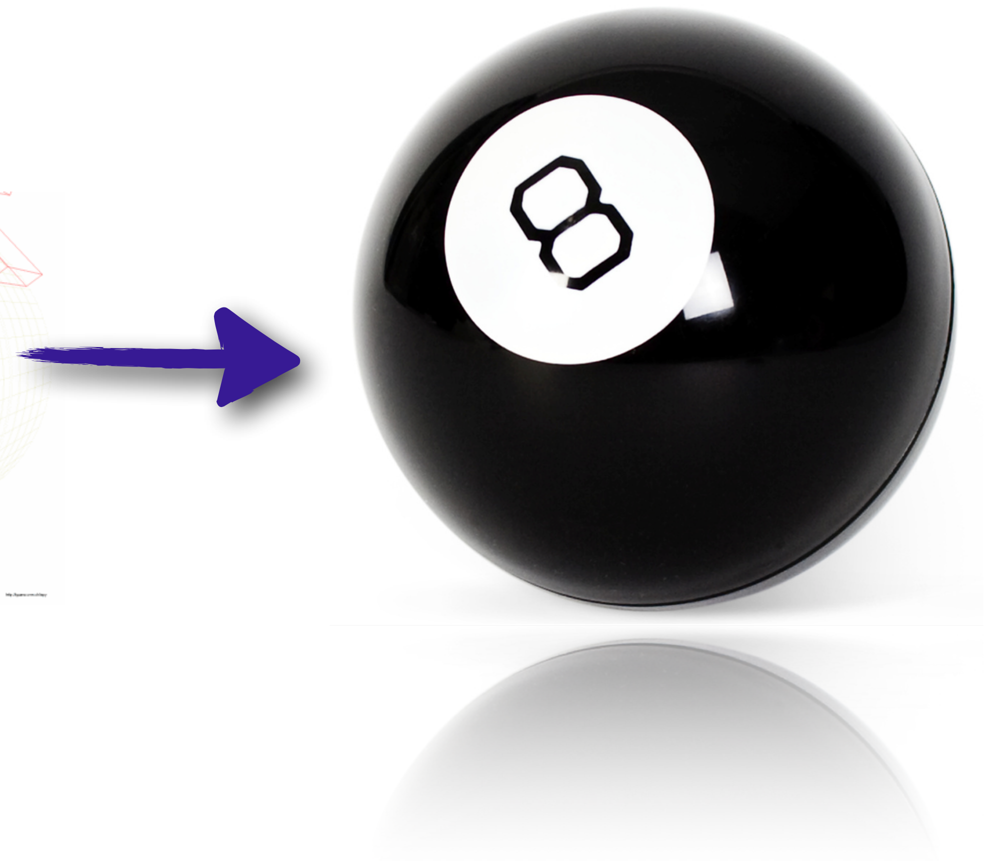
Start with an event

Pass it to the MEM algorithm





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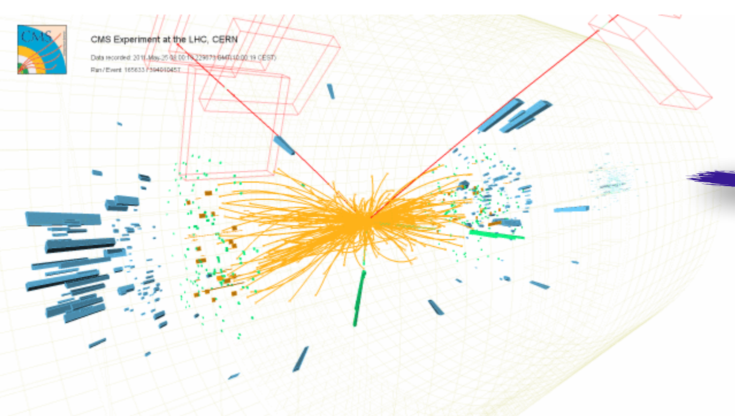
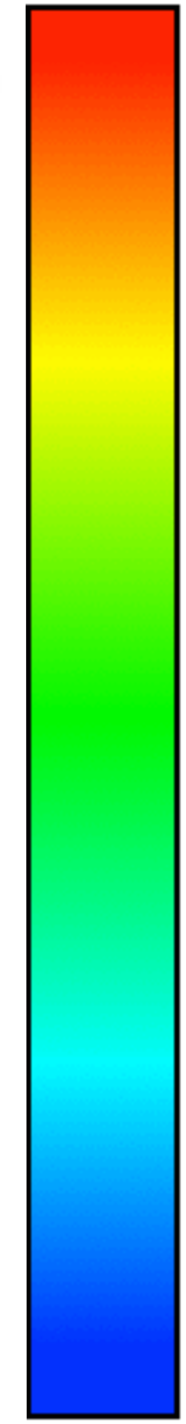
Decide whether it looks like signal....





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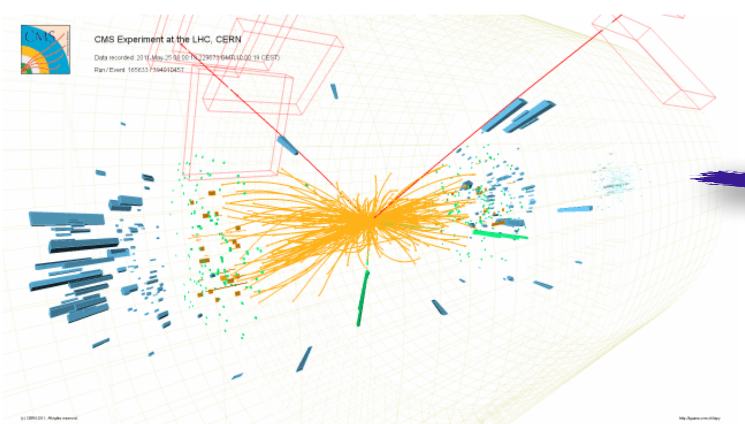
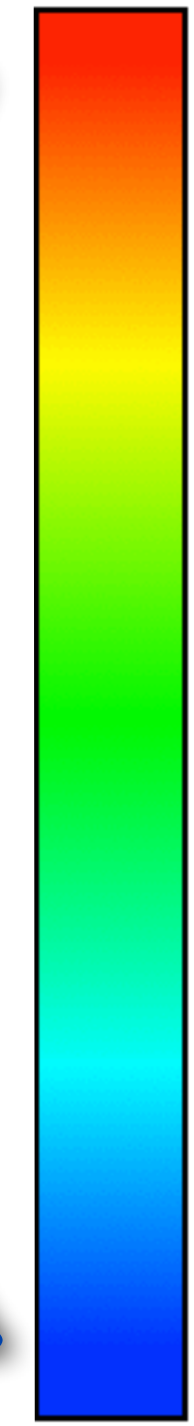
or background



Signal

1



0

Background

Matrix Element Methods

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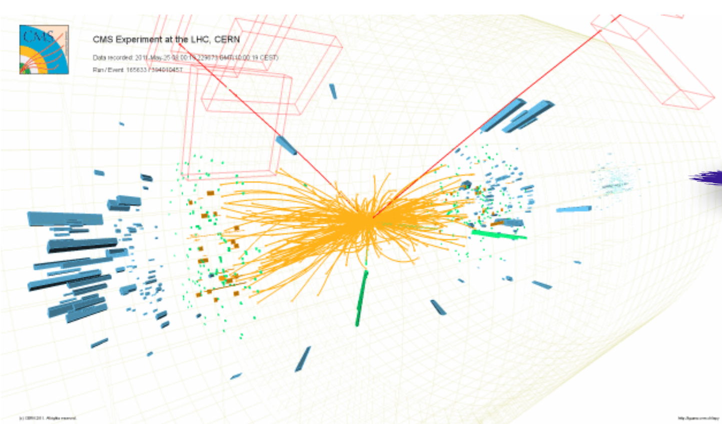
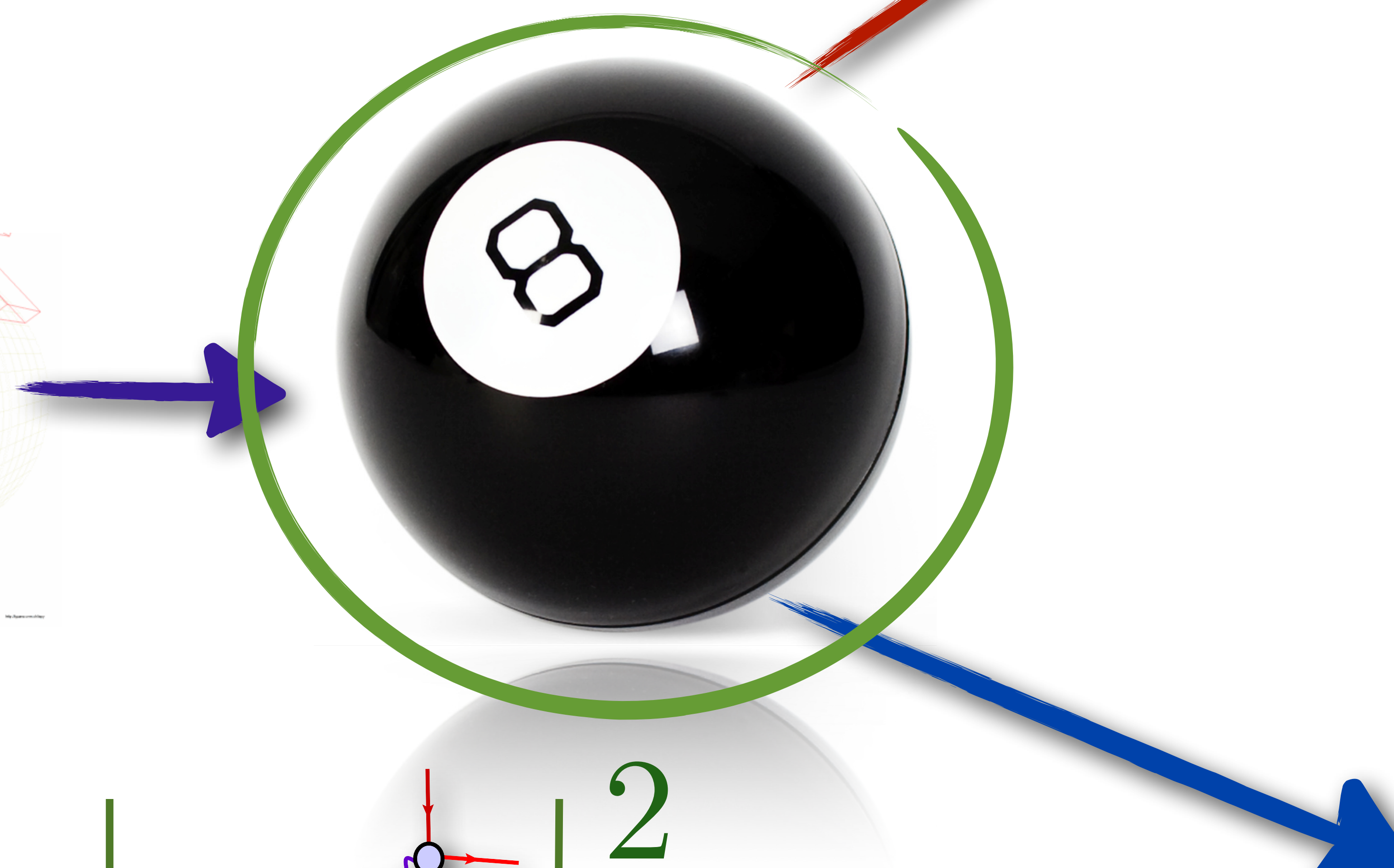
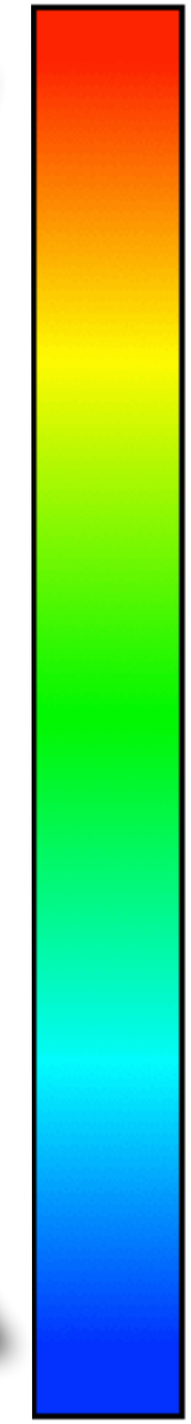




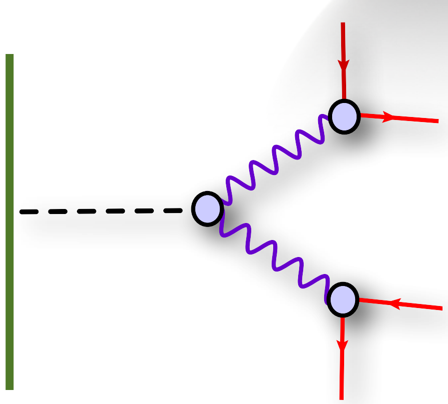
Signal

1

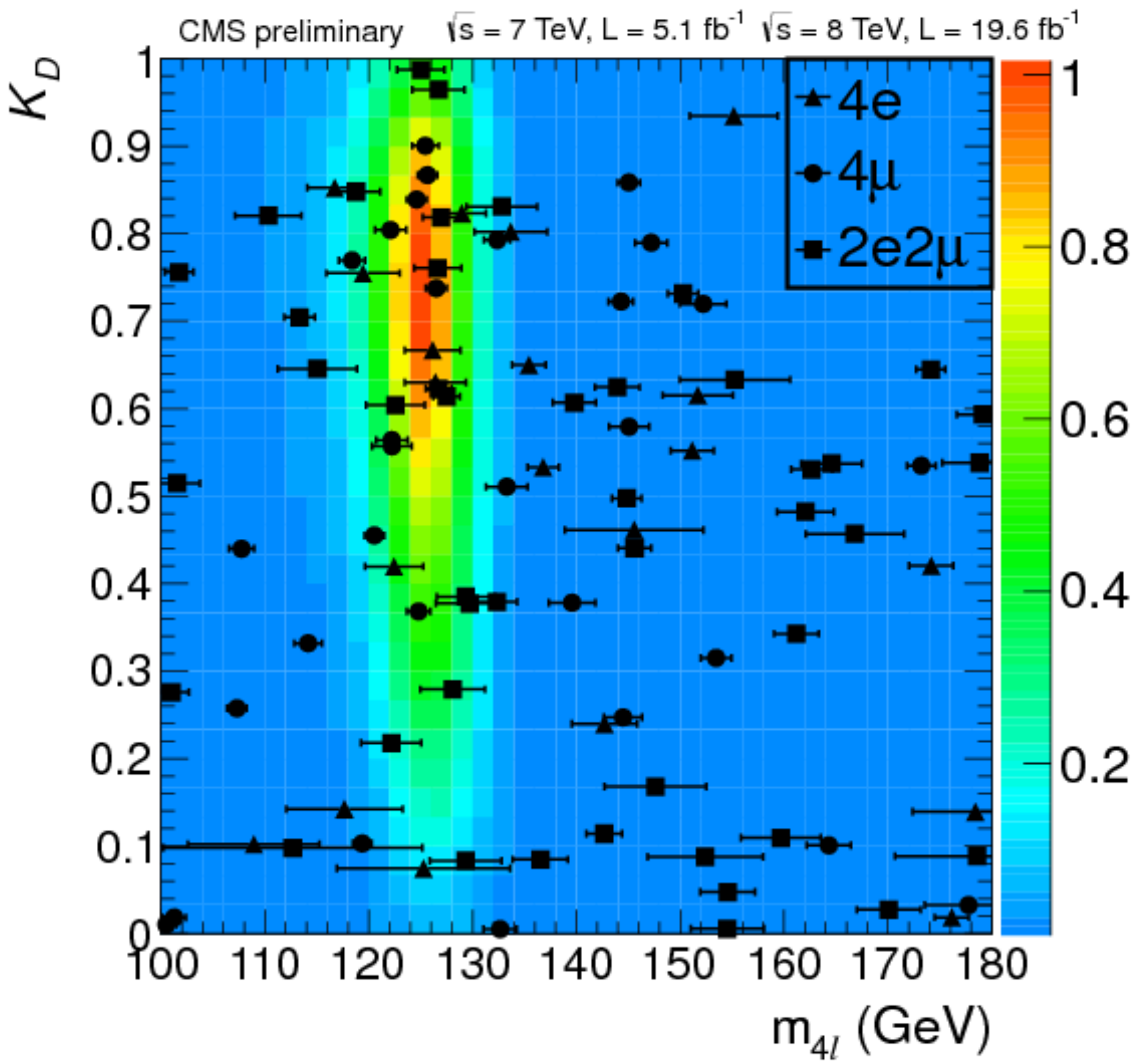


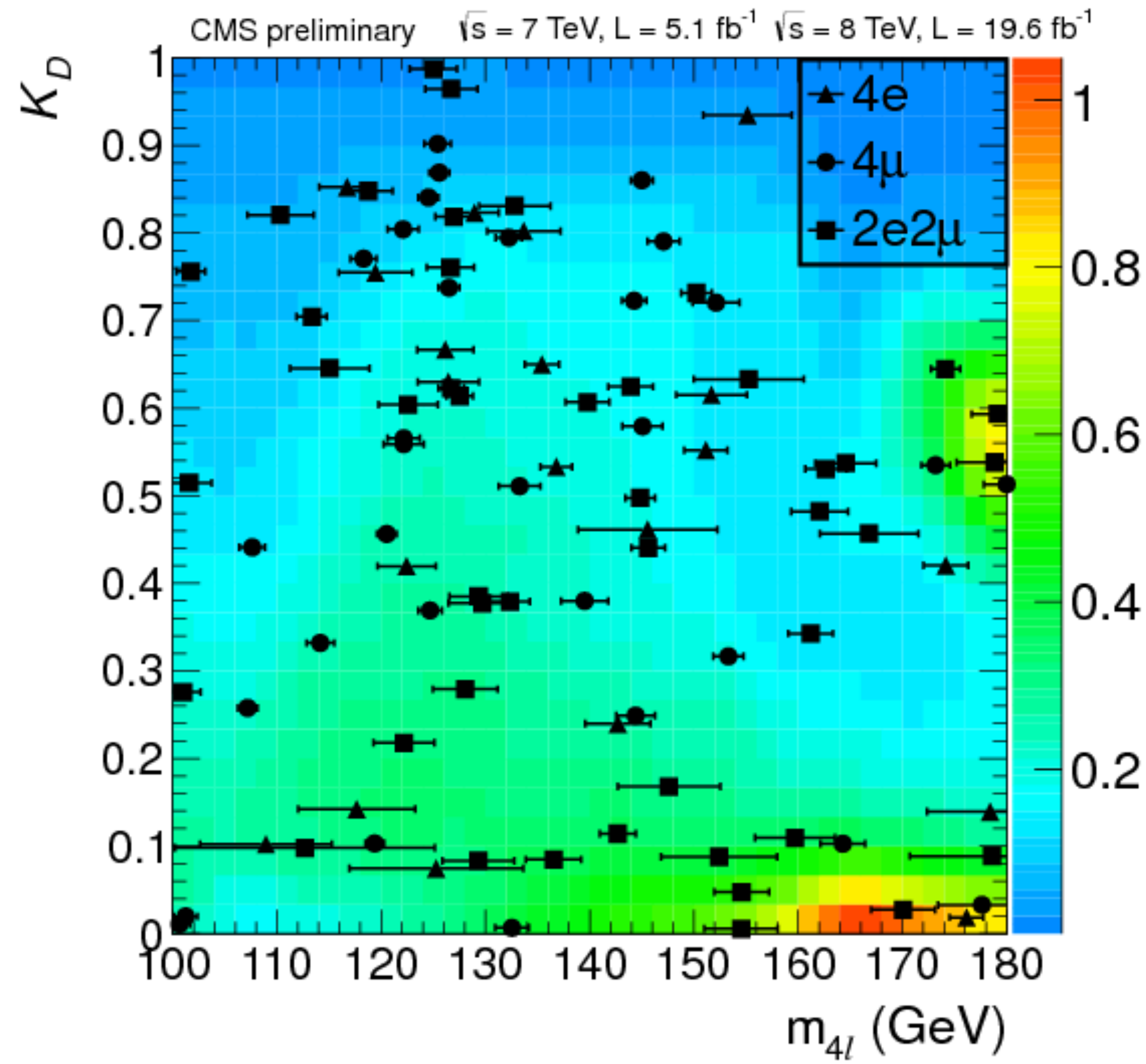
0

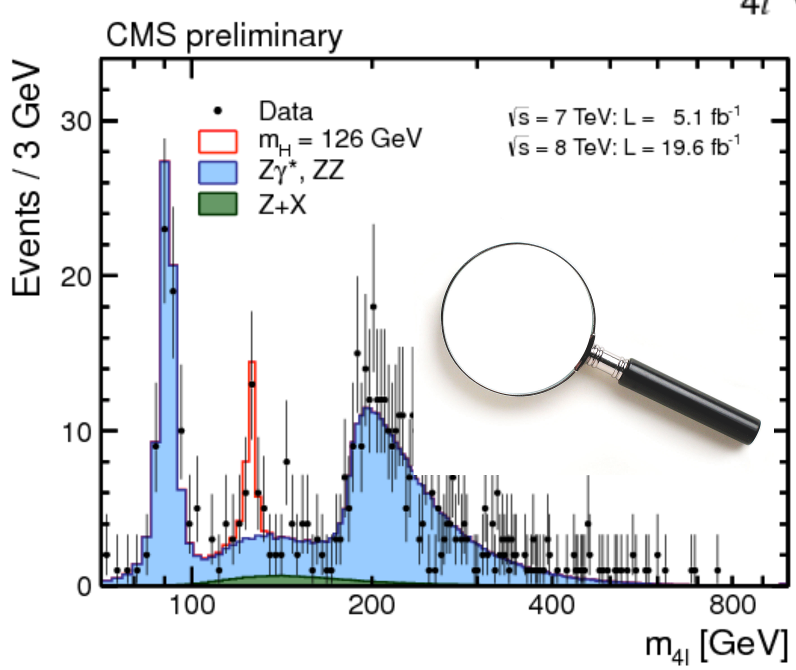
Background

$$|\mathcal{M}|^2 = \Bigg|$$  $$\Bigg|^2$$

MEMs in Action







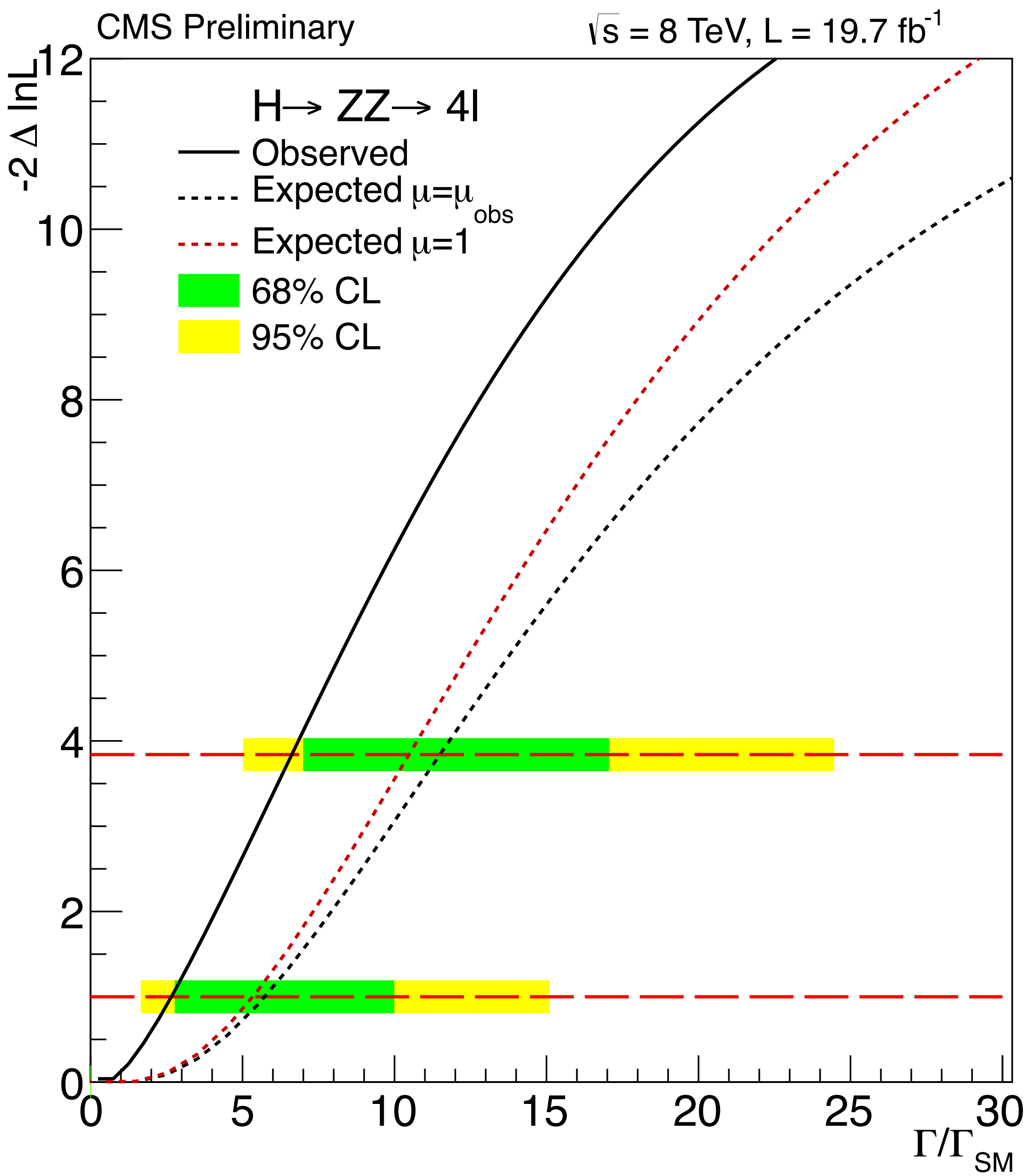
MEM's are powerful tools, we can gain more information than simply looking at a one dimensional distribution.

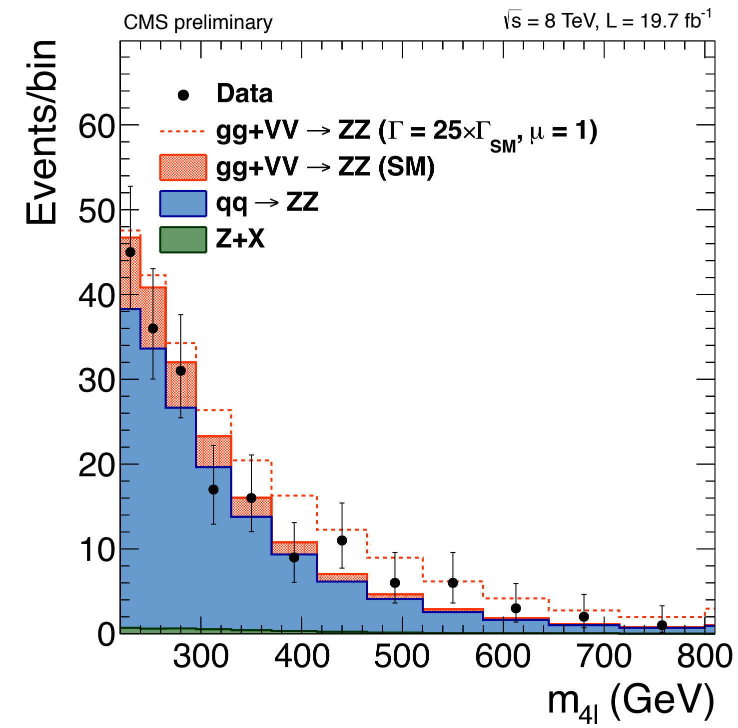
The same principles work in the off-shell region, and allow us to search for "Higgs like" events.

CMS Analysis

1405.3455 & CMS-PAS-HIG-014-002

CMS have recently performed the analysis discussed here.





Using the high mass region they find.

$$\Gamma_H \leq 26.3 \times \Gamma_H^{SM}$$

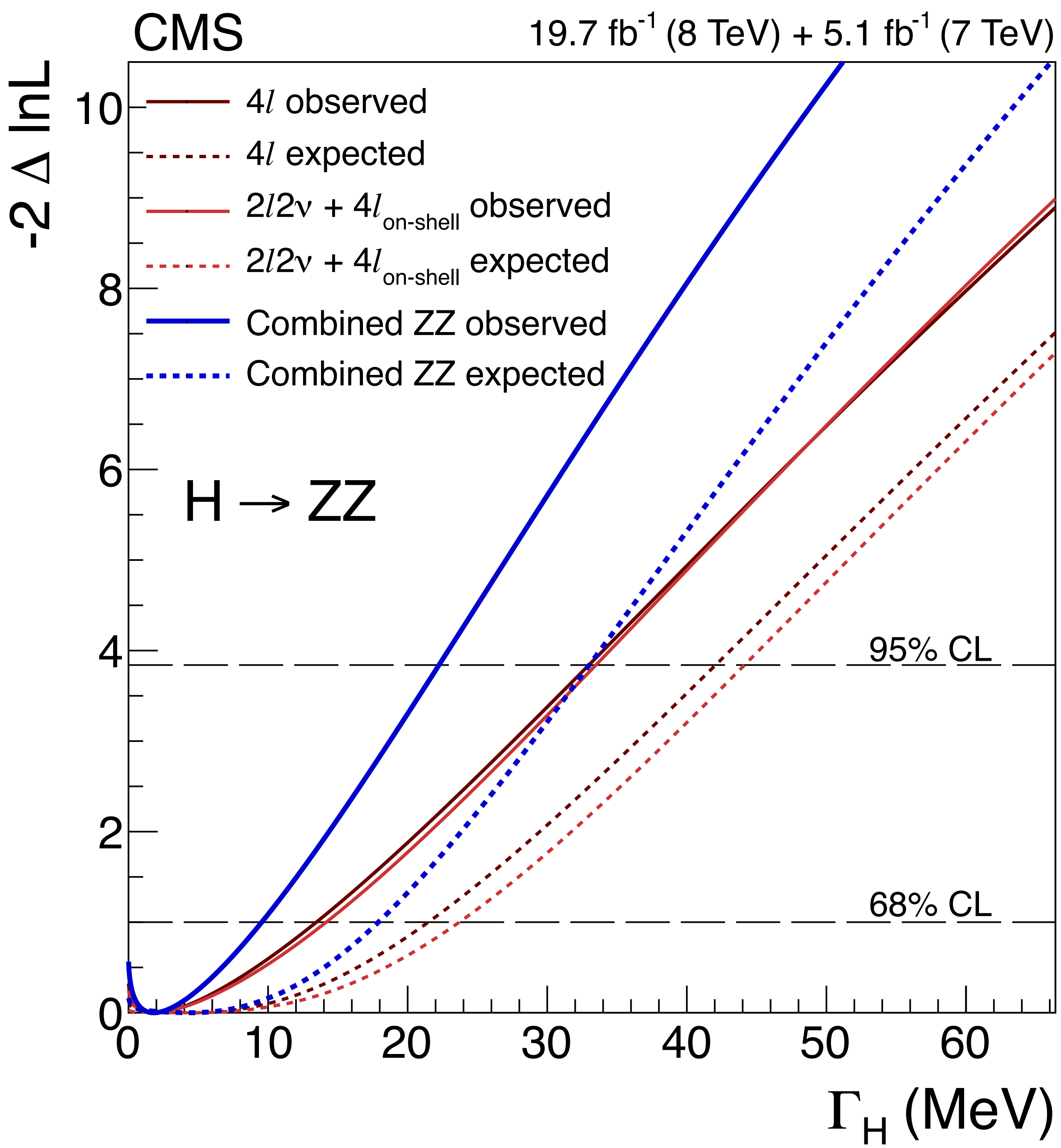
Using MCFM and a MEM kinematic discriminant they quote

$$\Gamma_H \leq 7.1 \times \Gamma_H^{SM}$$

(~ 30 MeV)

CMS Analysis inc. ll + MET

1405.3455 & CMS-PAS-HIG-014-002



CMS gain additional discriminating power by including the 2l + MET channel

They report

$$\Gamma_H \leq 5.4\, \Gamma_H^{SM}$$

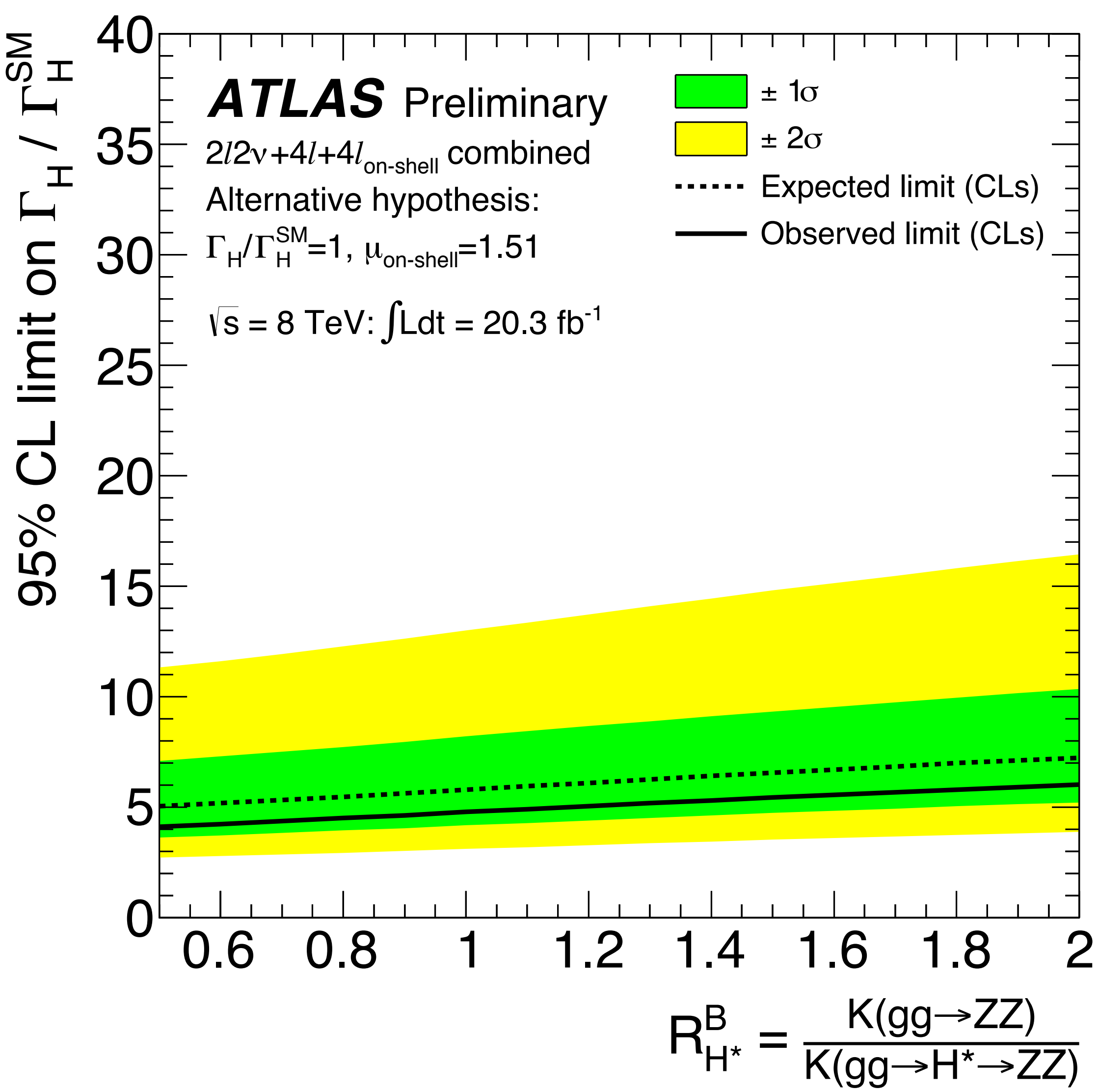
or

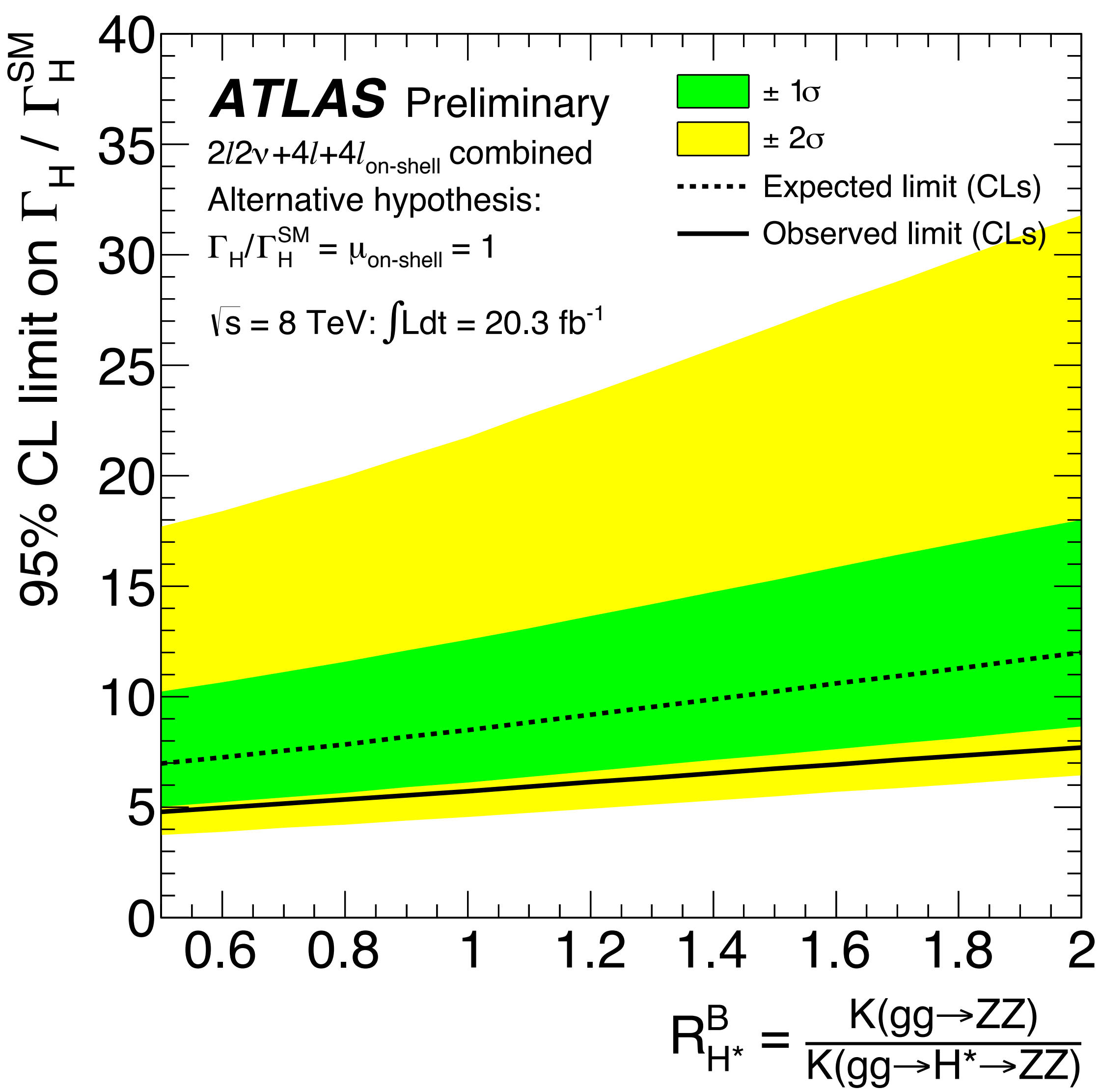
$$\Gamma_H \leq 22 \text{ MeV}$$

ATLAS have performed a similar analysis, finding

$$\Gamma_H \leq (4.8 - 7.7)\Gamma_H^{SM}$$

where the spread allows for variation in the background K factor.





BSM Scenarios

Model independence

(see discussion in Englert, Spannowsky 14')

In our initial assumptions we wrote

$$\sigma_{on} \propto \frac{g_i^2 g_f^2}{\Gamma_H} \quad \text{and} \quad \sigma_{off} \propto g_i^2 g_f^2$$

Assuming identical couplings on and off-shell, a more general statement is,

$$\sigma_{on} \propto \frac{g_i^2(m_H^2) g_f^2(m_H^2)}{\Gamma_H} \quad \text{and} \quad \sigma_{off} \propto g_i^2(s) g_f^2(s)$$

So our bound on the width, using the ratio of on-shell to off-shell cross sections is only valid in theories in which,

$$\frac{g_X(m_H^2)}{g_X(s)} \sim 1 + \Delta \quad (\Delta << \text{QCD th. err})$$

BSM scenarios :

Although not model independent, the off-shell cross section bound can still be utilized to gleam insights into potential new physics effects.

BSM effects could manifest themselves through an EFT made from 6 (and higher) dimension operators.

In these instances momentum dependent couplings can render the width analysis invalid, instead the aim is to use the off-shell cross section to bound the coefficients of the various EFT operators

See discussion in the following (and refs therin) for more details and prospects..

(Englert, Spannowsky 14')

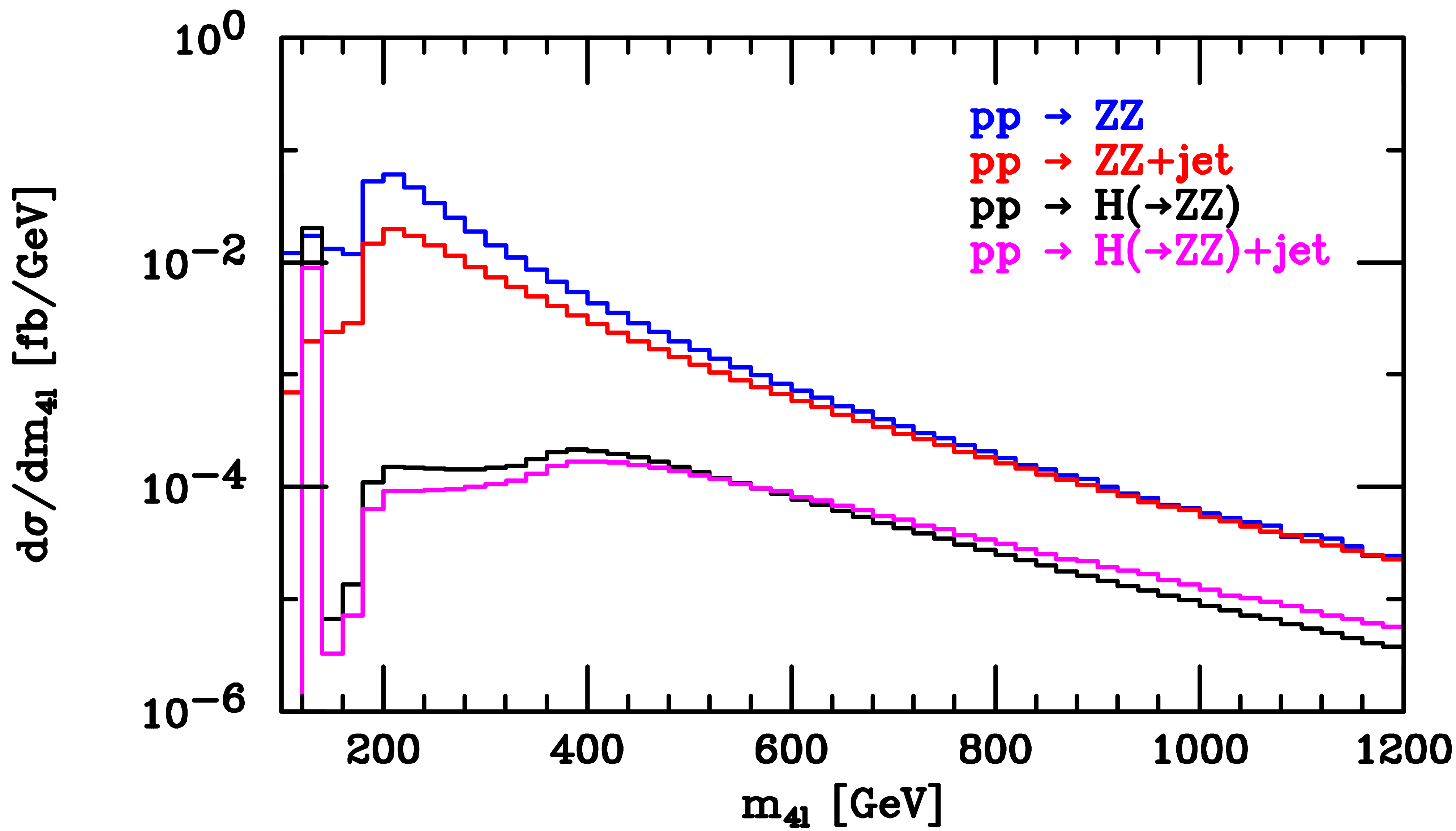
(Azatov, Grojean, Paul, Salvioni 14')

(Ghezzi, Passarino, Uccriati 14')

(Cacciapaglia, Deandrea, La Rochelle, Flamment 14')   (…..)

Recent developments and Future directions

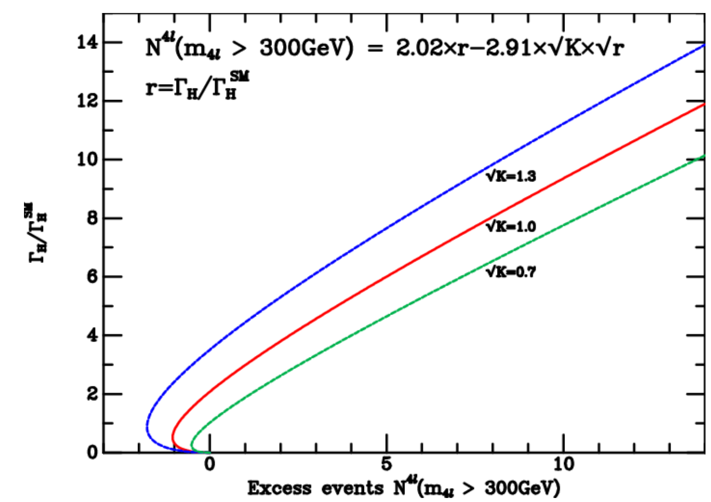
ZZ+jet (Campbell, Ellis, Furlan, Ronstch 14')



There is a slight improvement in the signal to background in the one-jet bin, therefore a dedicated analysis in this channel may help improve the analysis.

ZZ@NNLO

Clearly theory errors are serious obstacle to further improvements in off-shell measurements. (c.f.)



The interference is known only at LO, to go to NLO, requires the two-loop gg=>ZZ process (inc. top loops) and the ZZ+jet process.

A further necessary improvement is the calculation of the qqb background at NNLO.

Recently, there has been significant progress in these directions

(Caola, Henn, Melnikov, Smirnov, Smirnov 14')

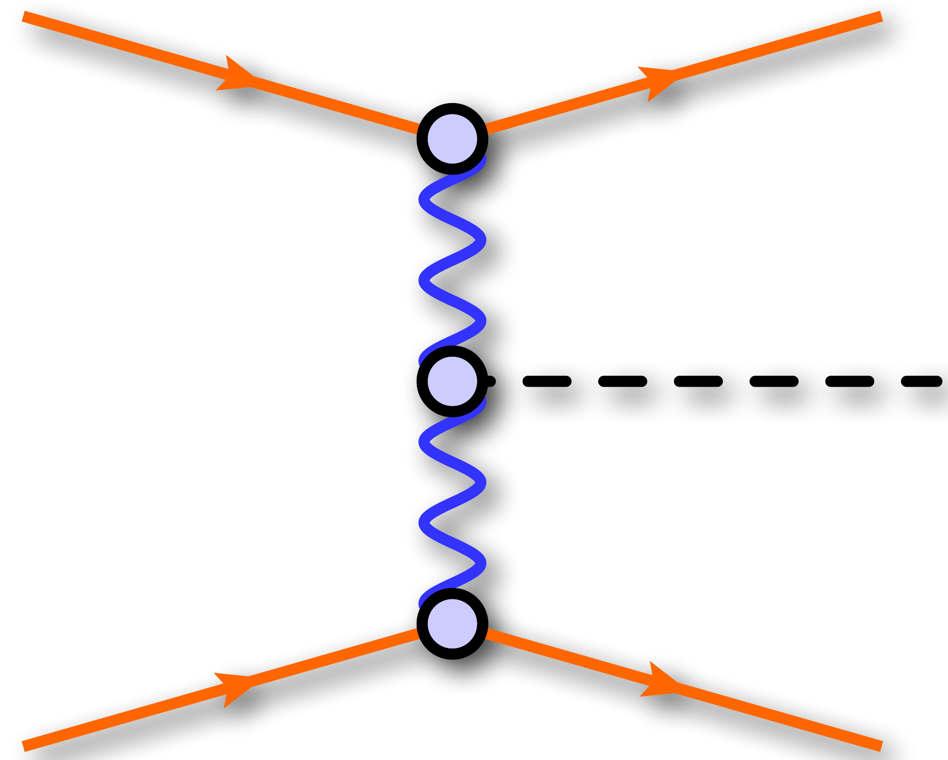
(Henn, Melnikov, Smirnov 14')

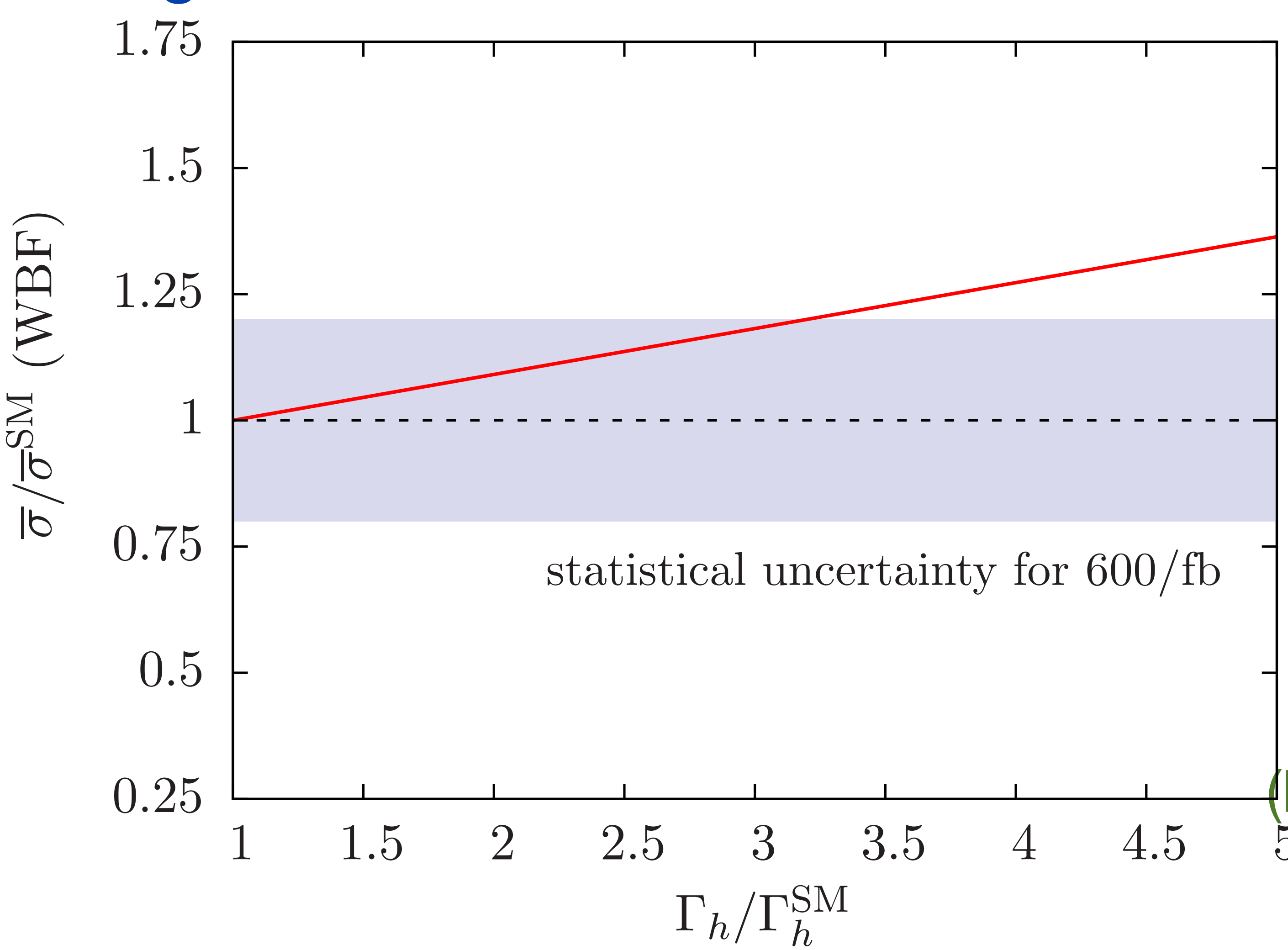
(Gehrmann, Grazzini, Kallweit, Maierhöfer, Manteuffel, Pozzorini, Rathlev, Tancredi 14')

Other channels

VBF provides a very promising channel to use since,

- Theoretically under better control
- Less sensitive to model dependencies, better from a BSM point of view.
- Lower rate, but could be studied with the larger Run II data set.





(Englert, Spannowsky 14')

Conclusions

- The off-shell Higgs boson has gone from being a nuisance, to the forefront of Higgs studies at the LHC.
- The off-shell cross section can be used constrain the couplings, without a dependence on the width.
- Or, conversely bounding the off-shell cross section can be used to bound the width.
- Current bounds ~ 5 x SM, are dominated by theory errors related to the overall normalization (LO).
- By increasing the precision of the predictions, and investigating other channels, further improvements in Run II can be expected…..