Bounding the Higgs width with the MEM

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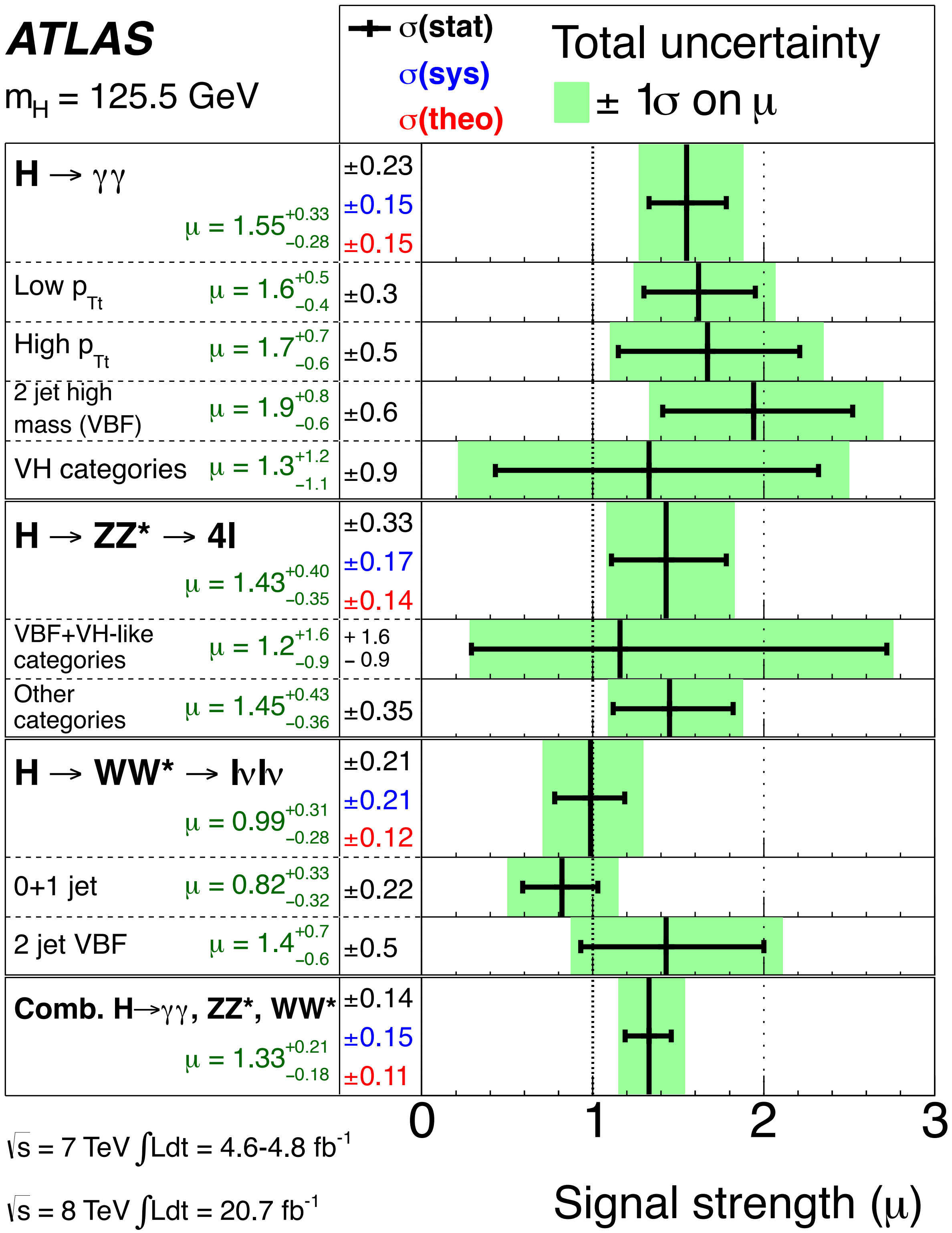
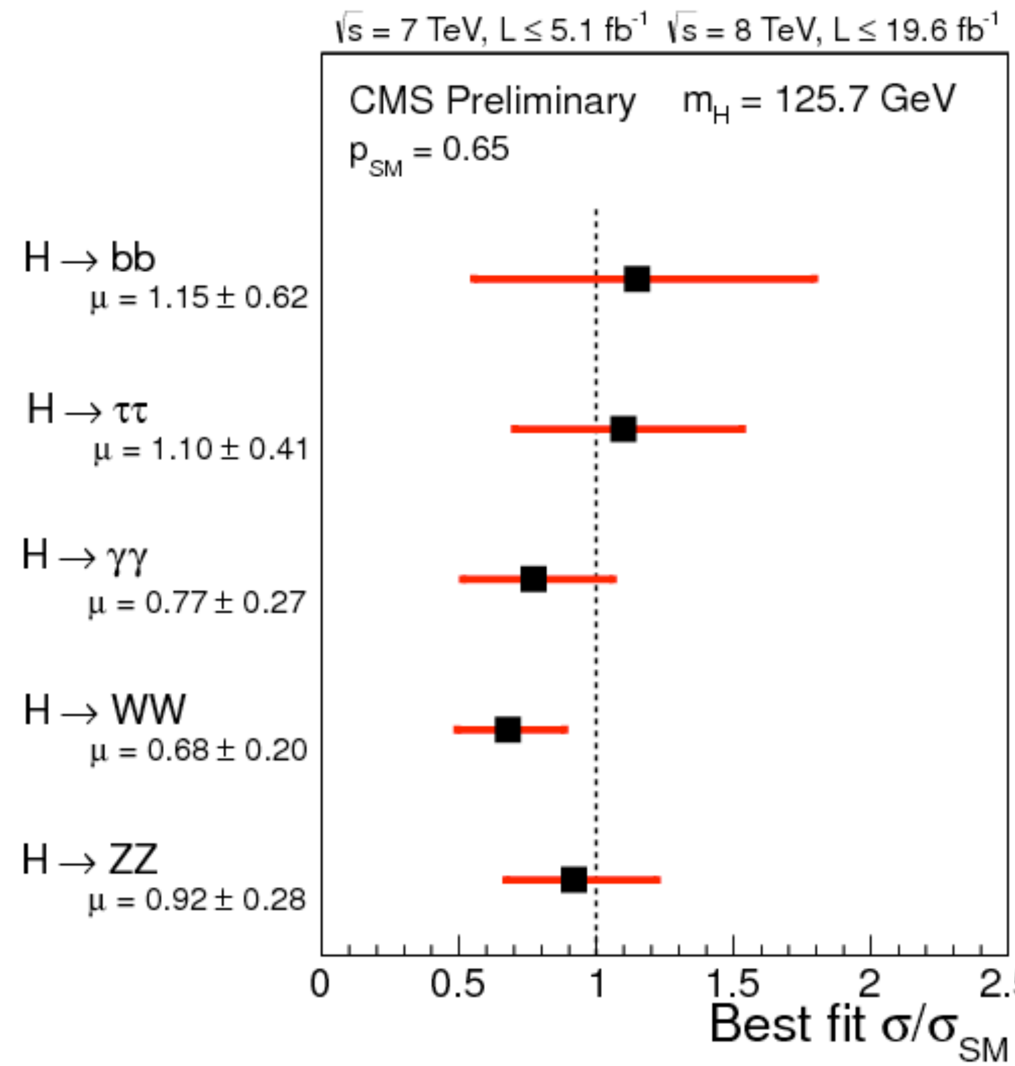
see 1311.3589 with John Campbell and Keith Ellis
and 1311.5811, 1204.4424 with John Campbell and Walter Giele

Outline

* Motivation, constraining the Higgs width at the LHC
* Reminder of the MEM algorithm
* Application of the MEM to Higgs width studies.

Higgs Couplings at the LHC





LHC measurements look at the Higgs in different channels, reporting results for cross section x BR for each channel, with the aim of comparing this to the SM predictions.

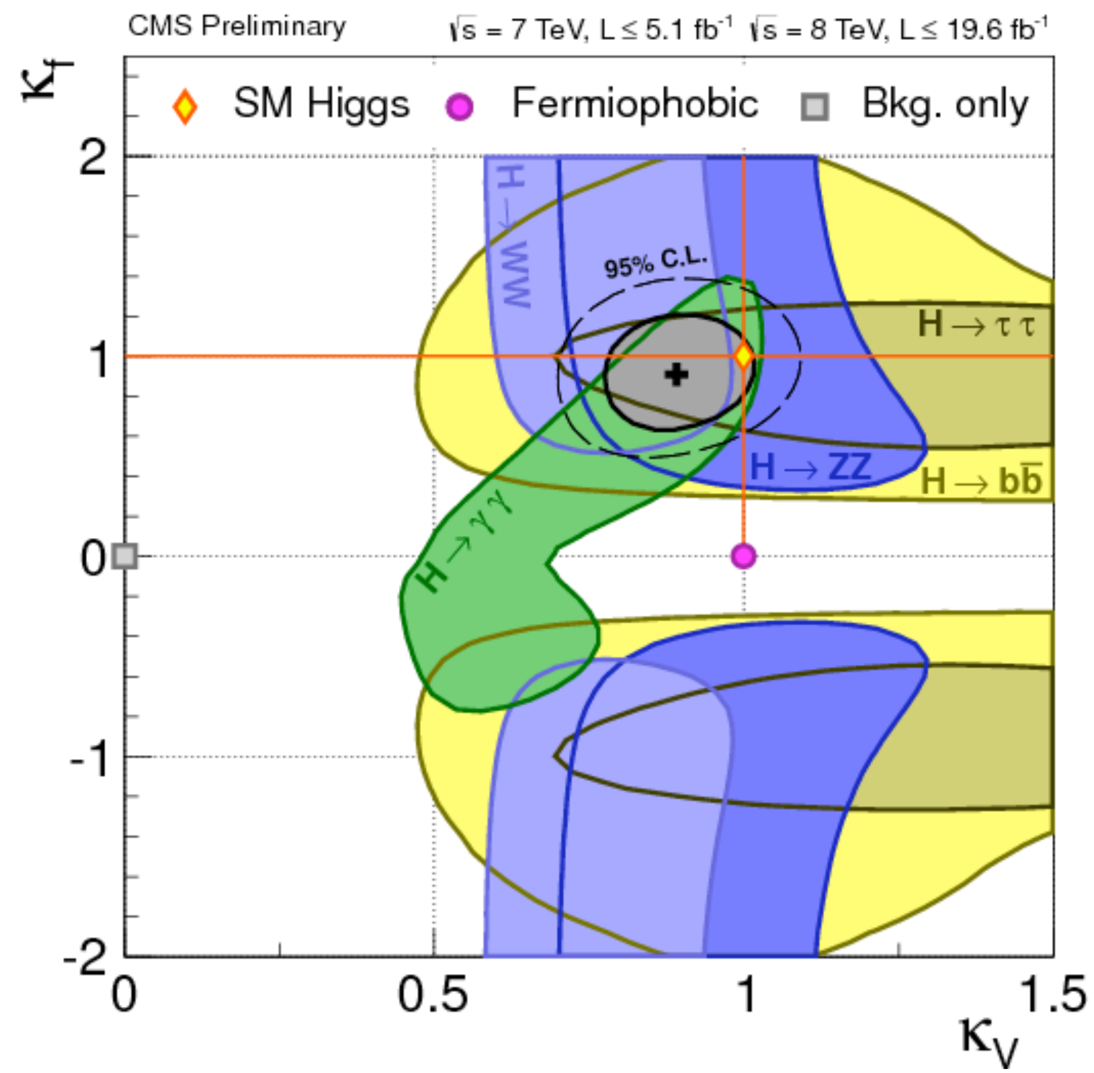
Turning this into coupling constraints.

* For on-shell Higgs bosons the cross section and the couplings are related as follows.

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

* Therefore, a measurement of an individual channel is exposed to a degeneracy in coupling/width rescaling. Knowledge of the Higgs width would eliminate this problem.

* Couplings can of course still be constrained by pooling information across multiple channels....



Higgs width at the LHC.

- The SM Higgs width is tiny,

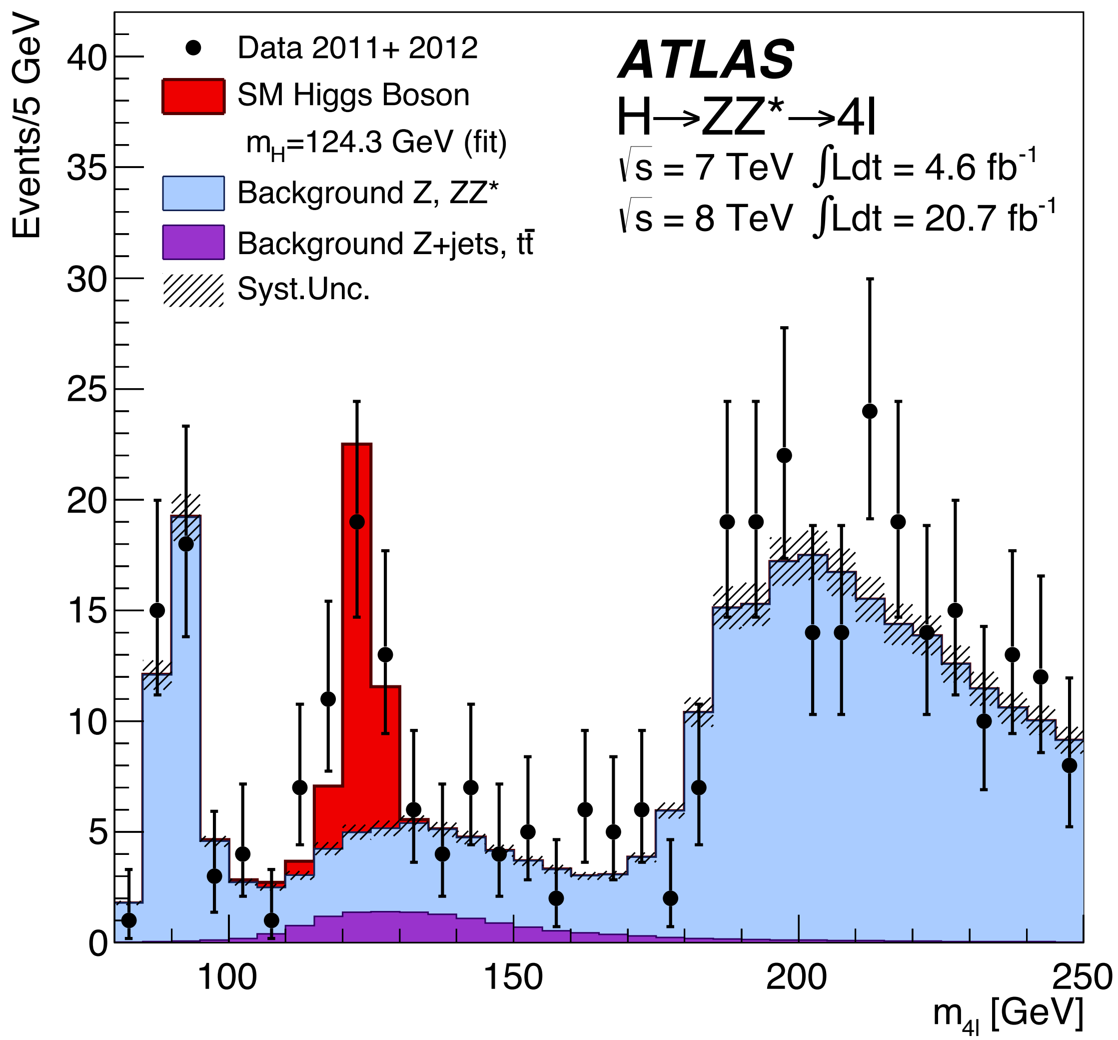
$$\Gamma_H^{SM} \sim 4 \text{ MeV}$$

- Thus the lineshape is completely dominated by experimental resolution, which for the cleanest channels is several GeV.

- Direct constraints are therefore rather weak, i.e. CMS-PAS-HIG-13-016 report,

$$\Gamma_H < 6.9 \text{ GeV} = 1600 \, \Gamma_{\rm H}^{\rm SM}$$

- So one might expect us to have to wait for a lepton collider to get more stringent bounds or a measurement of the width....



An alternate approach.....

Caola, Melnikov 1307.4935

- The Higgs propagator, has two distinct regions, an on-shell region, in which the cross section depends on the width, and the off-shell region, where the width can be completely neglected.

$$\mathcal{P}_H(s) = \frac{1}{(s - m_H^2) + i\Gamma_H m_H}$$

- The two cross sections depend on the width/couplings as follows

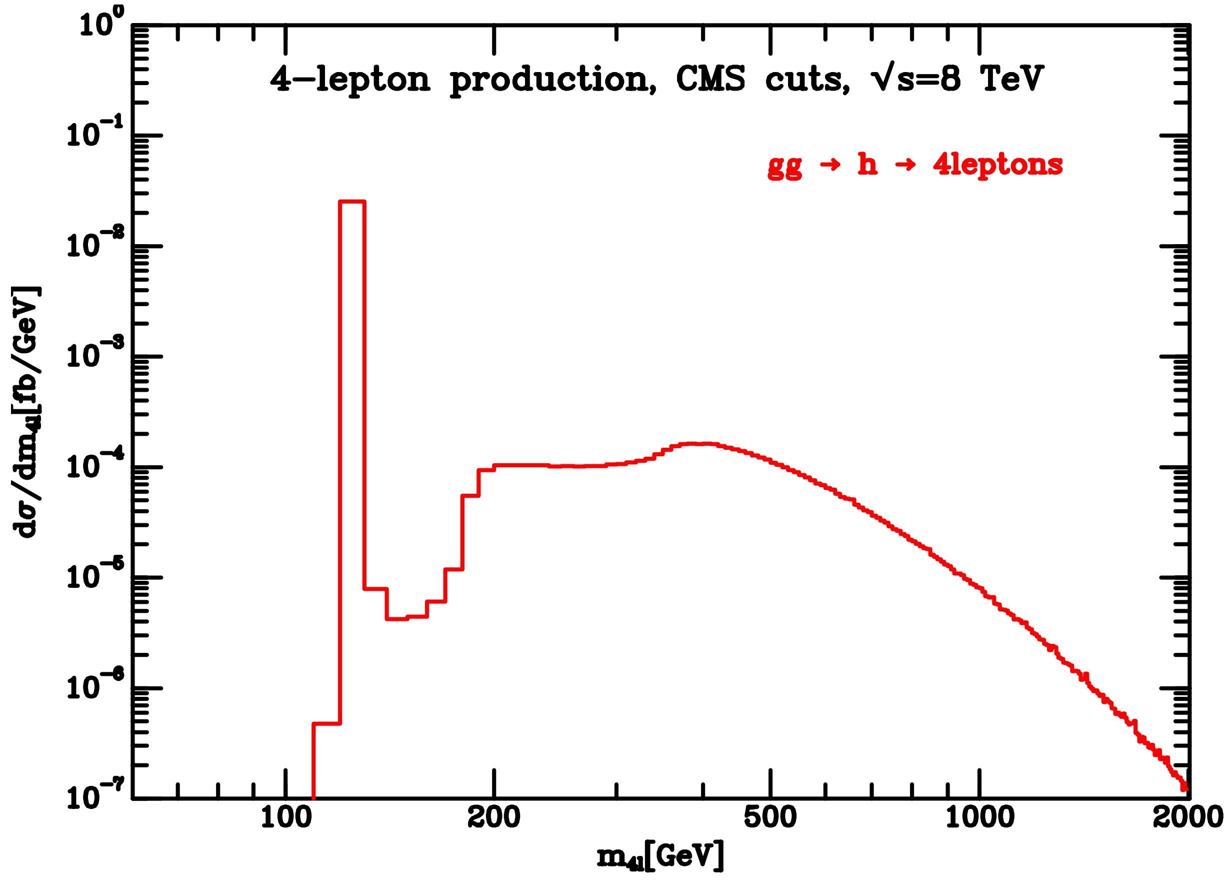
$$\sigma_{on} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \quad \sigma_{off} \sim g_i^2 g_f^2$$

- Thus by defining the ratio, one obtains the following relation,

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

Is there any off-shell cross section?

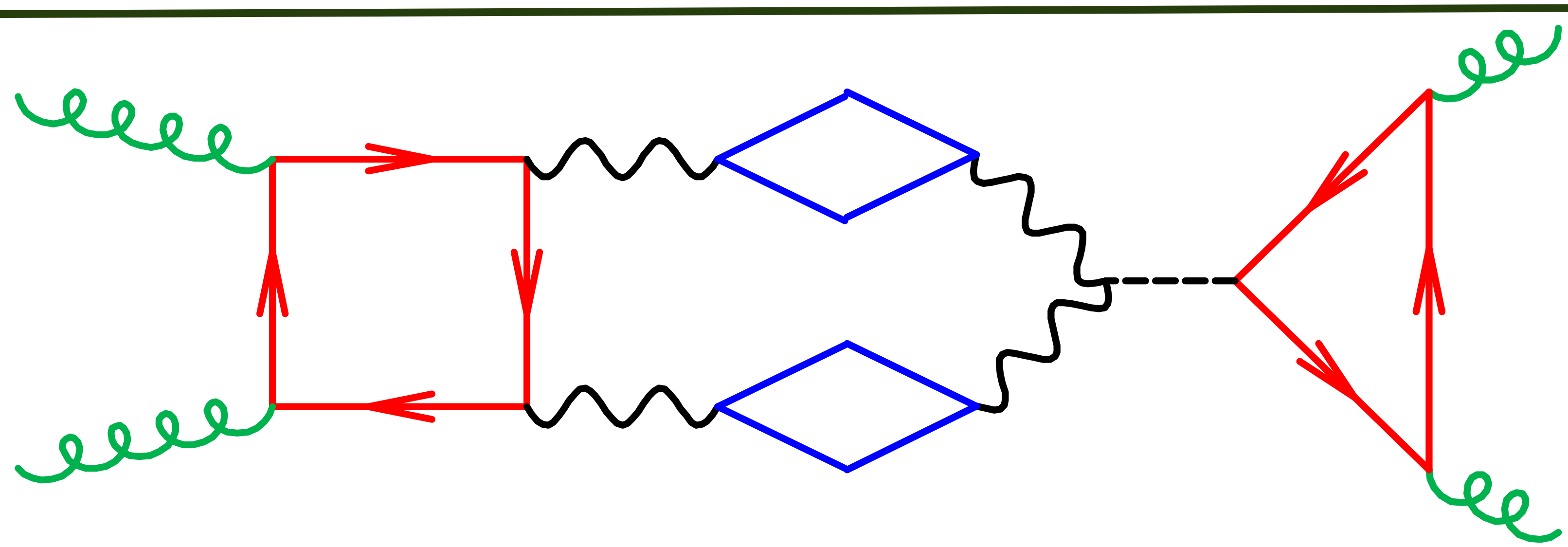
Kauer, Passarino,arXiv:1206.4803



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.

Interferences in ZZ,



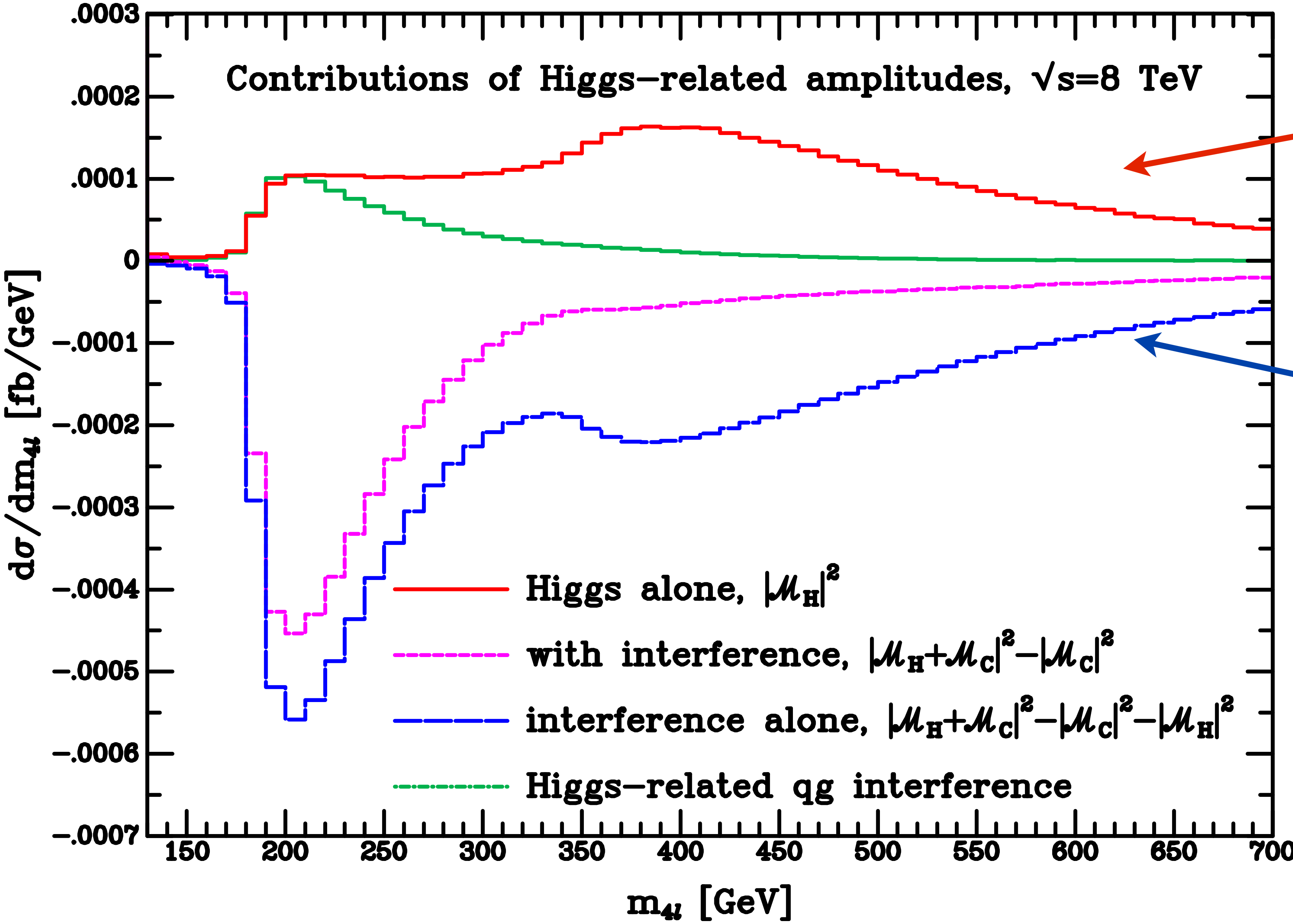
* The Higgs mediated diagrams interfere with the gg initiated quark loops.

* For our purposes these terms introduce a piece which depends linearly on the Higgs coupling, so the total cross section depends on the Higgs width as follows,

$$\sigma_{off} = \sigma_H \left(\frac{\Gamma_H}{\Gamma_H^{SM}} \right) + \sigma_{int} \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

* Note that for $\Gamma_H \geq 10\, \Gamma_H^{SM}$ the interference piece is quite small.

Off shell Higgs events at 8 TeV



Scales like $\frac{\Gamma_H}{\Gamma_H^{SM}}$

Scales like $\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$

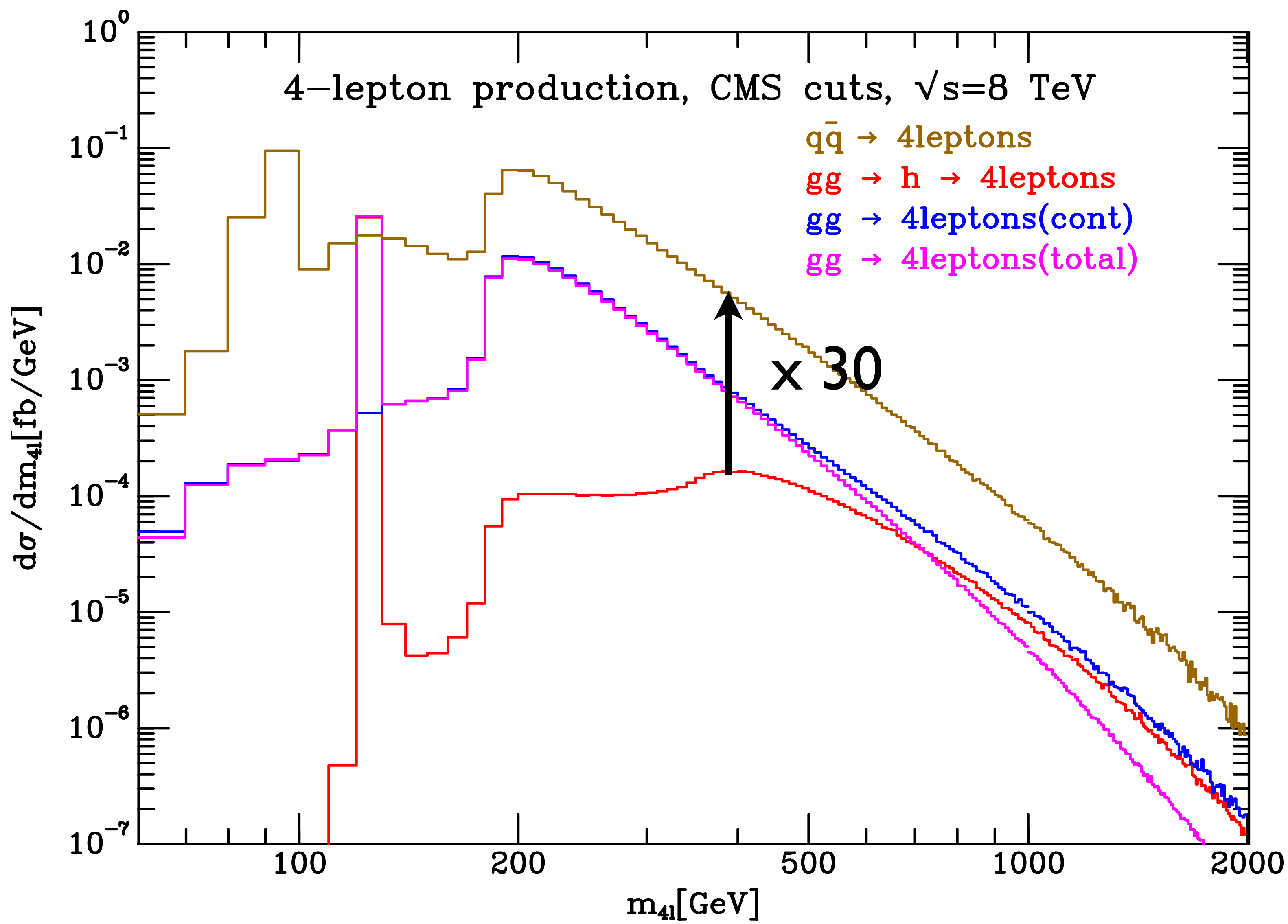
$$\sigma_{off} = \sigma_H \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) + \sigma_{int} \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

The big picture @ 8TeV

- Peak at Z mass due to singly resonant diagrams.
- With the standard model width, Γ_H , challenging to see enhancement/ deficit due to Higgs channel (in the tail).
- However, a rescaling of the off-shell cross section by ~ 30 should easily be visible at high invariant mass.

$$p_{T,\mu} > 5 \text{ GeV}\,, \quad |\eta_\mu| < 2.4\,,$$
$$p_{T,e} > 7 \text{ GeV}\,, \quad |\eta_e| < 2.5\,,$$
$$m_{ll} > 4 \text{ GeV}\,, \quad m_{4\ell} > 100 \text{ GeV}\,.$$

CMS cuts
CMS PAS HIG-13-002



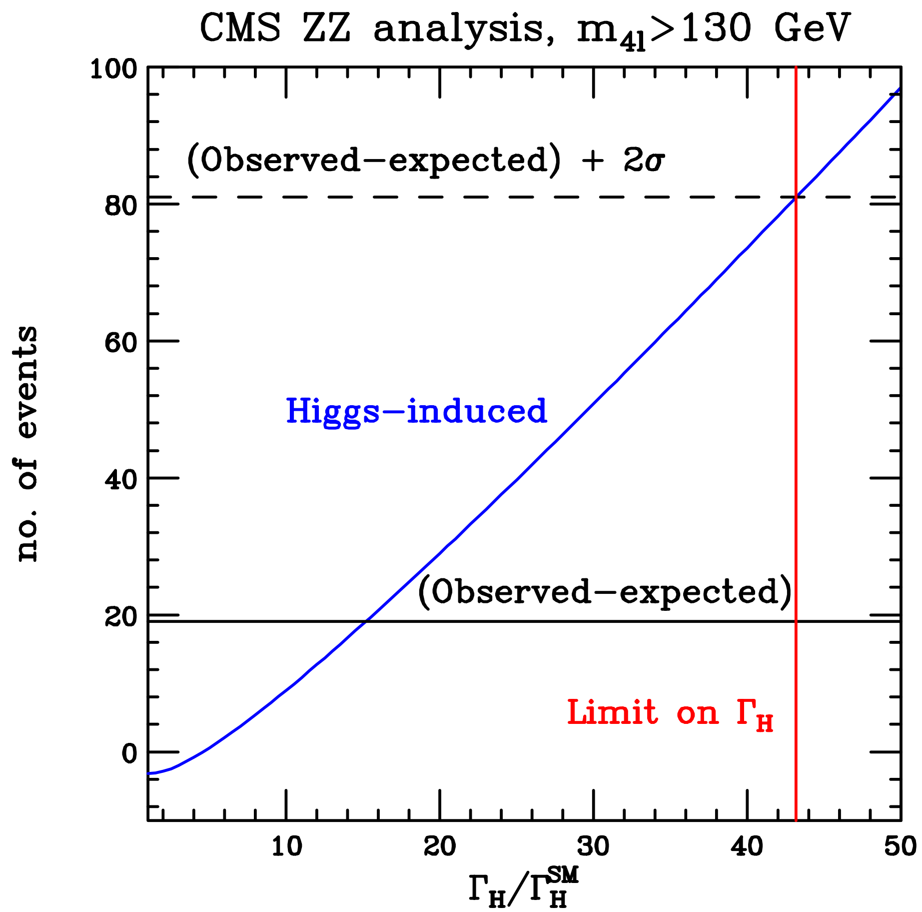
Bounding the Higgs width, a basic cut and count

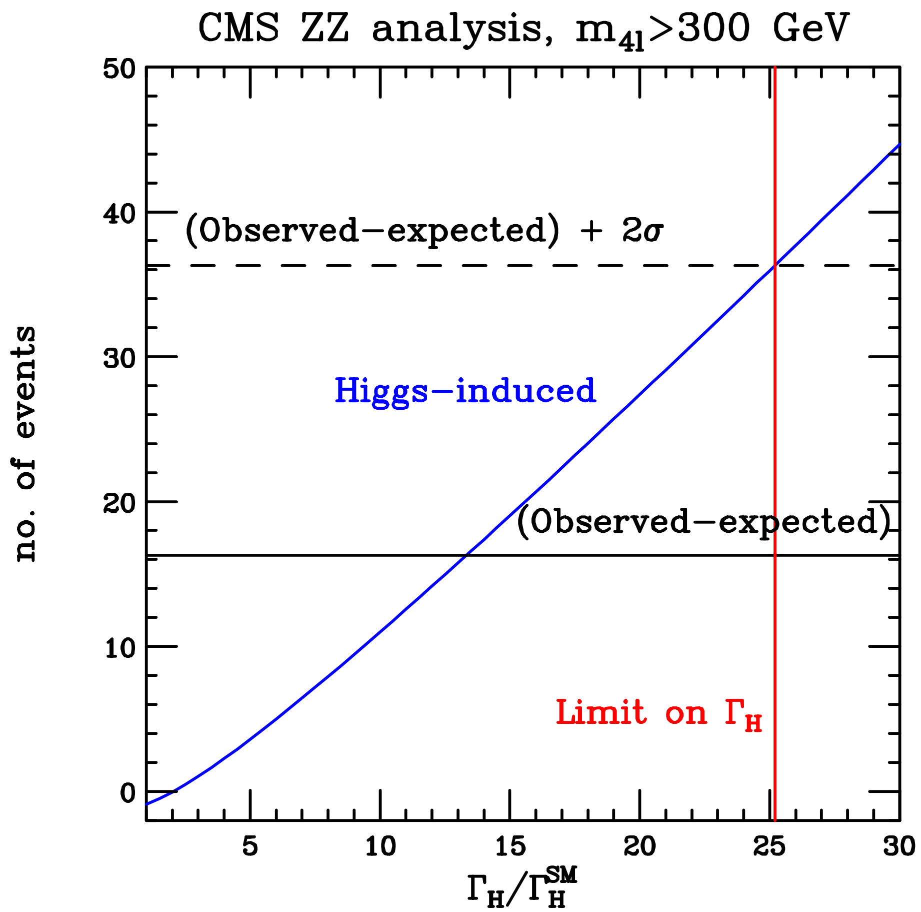
- Use the number of events observed in the off-peak region (451) and number expected on the basis of continuum alone (431±31)

couplings have been rescaled by

$$g_x \rightarrow \xi g_x$$

in the off-shell region.





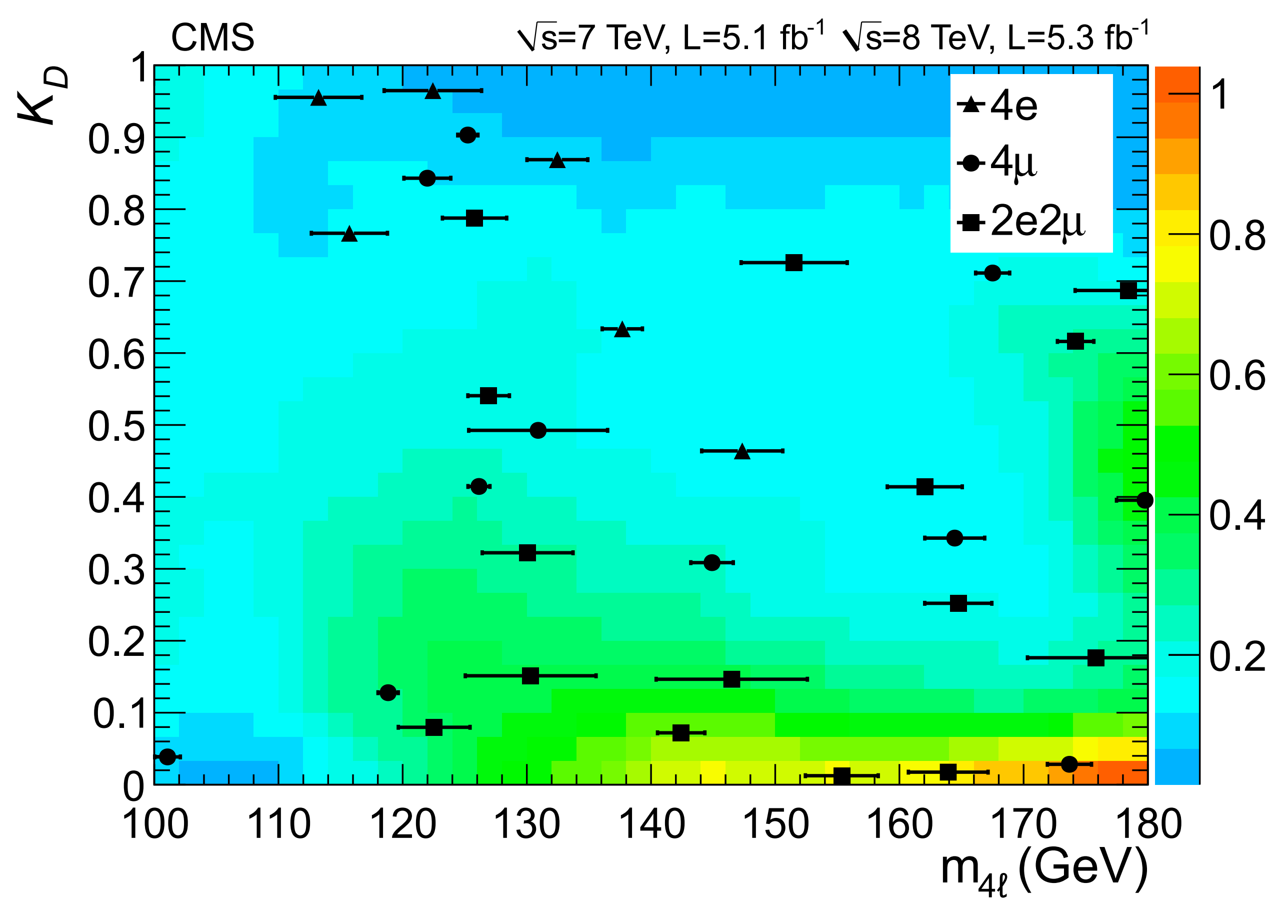
$$\Gamma_H < 43.2\,\Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}, \quad (m_{4\ell} > 130 \text{ GeV analysis})$$
$$\Gamma_H < 25.2\,\Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}, \quad (m_{4\ell} > 300 \text{ GeV analysis})$$

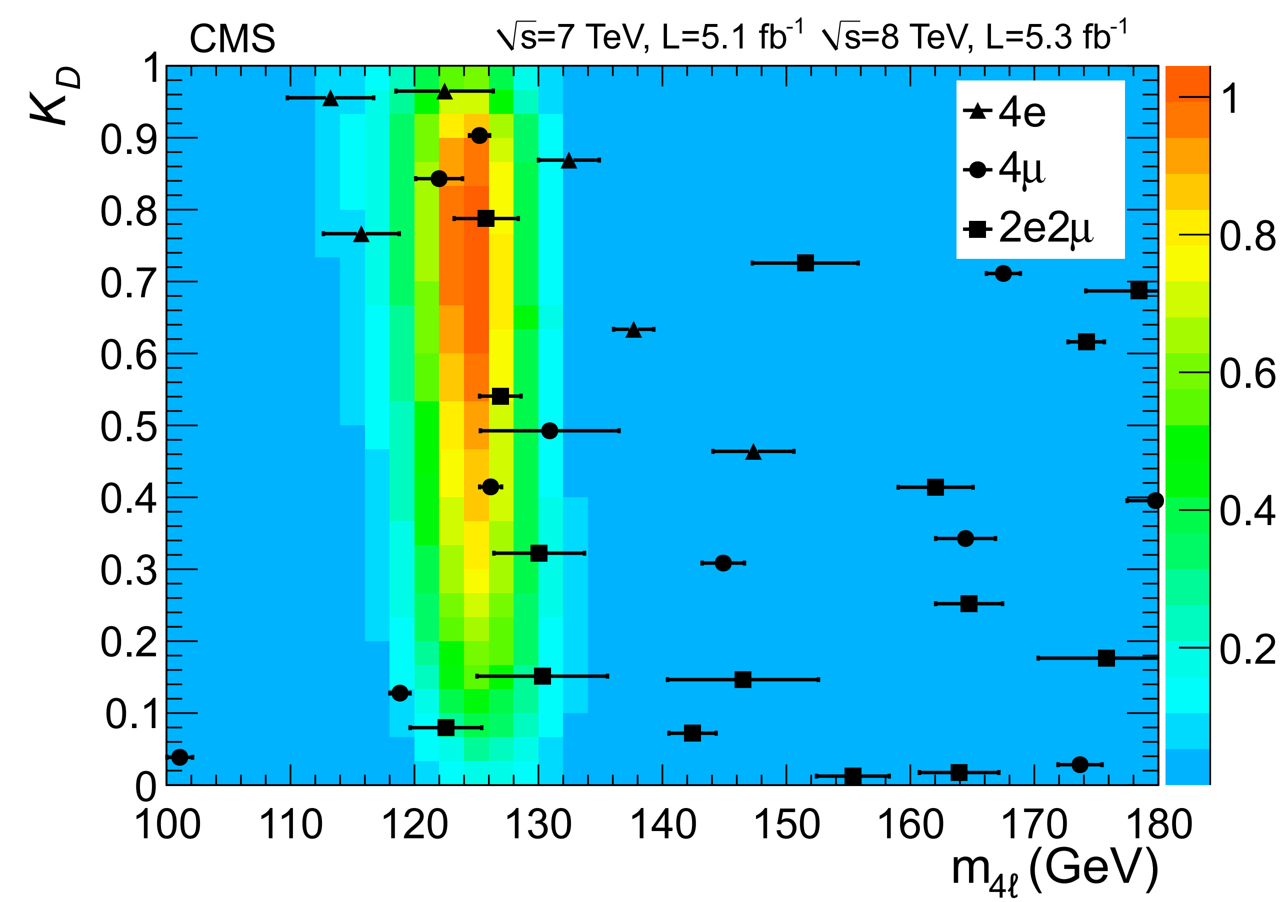
- Can the MEM do better?

The MEM and ZZ

See Jamie's talk for more details.

- It may be possible to significantly improve upon the basic cut and count analysis using the MEM
- This is motivated by the extensive and successful application of the MEM family to on-shell H=>ZZ studies.



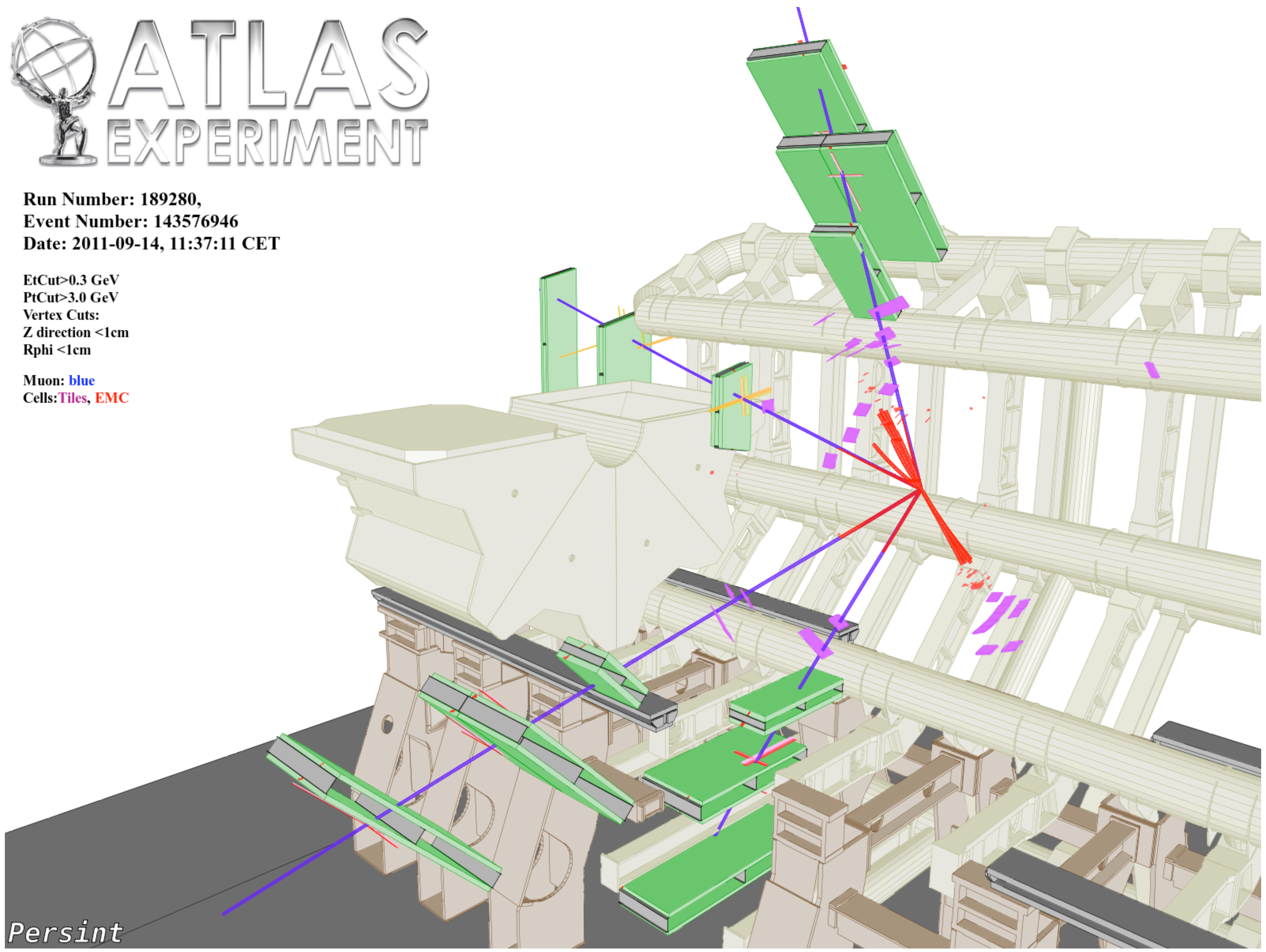


The MEM algorithm

- The MEM algorithm must be unique and well defined.
- Ideally, it should be possible to extend the algorithm to include the effect of higher order corrections.

In order to include the effects of parton distribution functions in the weights the first point is non-trivial.

MEM



Starting from a four-lepton event, we want to ensure a well-defined weight, using the four-lepton LO ME.

We also want to keep the beams along the z-axis, so to ensure momentum conservation we should perform a transverse boost.

Weights of the form, $P(\Phi_{4\ell}) \propto |\mathcal{M}(\Phi_{4\ell}, x_1, x_2)|^2$

Are now unique and well defined, since the ME is a Lorentz scalar, one can thus choose any boost which results in no net 4 lepton transverse momentum.

Including the PDFs

- The weights can be extended, incorporating the PDF's.
- However, now the dependence on x in the PDFs requires the integration over all equivalent boosts, or the resulting weight will not be unique.

$$P(\Phi_{4\ell}) = \frac{1}{\sigma_{LO}} \int_{x_l}^{x_u} dx_1 dx_2 f_i(x_1) f_j(x_2) |\mathcal{M}^{ij}(\Phi_{4\ell}, x_1, x_2)|^2 \delta(x_1 x_2 s - s_\Phi)$$

  - The upper and lower bounds are calculated in order to ensure the correct overall normalization,

$$\eta_i = \frac{1}{2} \log\left(\frac{x_1 s_{2i}}{x_2 s_{1i}}\right)$$

  - This method can be extended to higher orders. But for the Higgs width study we are interested in today the full NLO is not known

Building the weights

We are now ready to use our MEM weights to build kinematic discriminants.

$$P_{LO}(\phi) = \frac{1}{\sigma_{LO}} \sum_{i,j} \int dx_1 dx_2\, \delta(x_1 x_2 s - Q^2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2, \phi)$$

We will need the following hypotheses

$P_{q\bar{q}}$: $q\bar{q}$ initiated background.

P_{gg} : gg initiated pieces, including Higgs signal, box diagrams and interference.

P_H : gg initiated Higgs signal squared.

Using these we construct the following, to be evaluated for each event.

$$D_S = \log\left(\frac{P_H}{P_{gg} + P_{q\bar{q}}}\right)$$

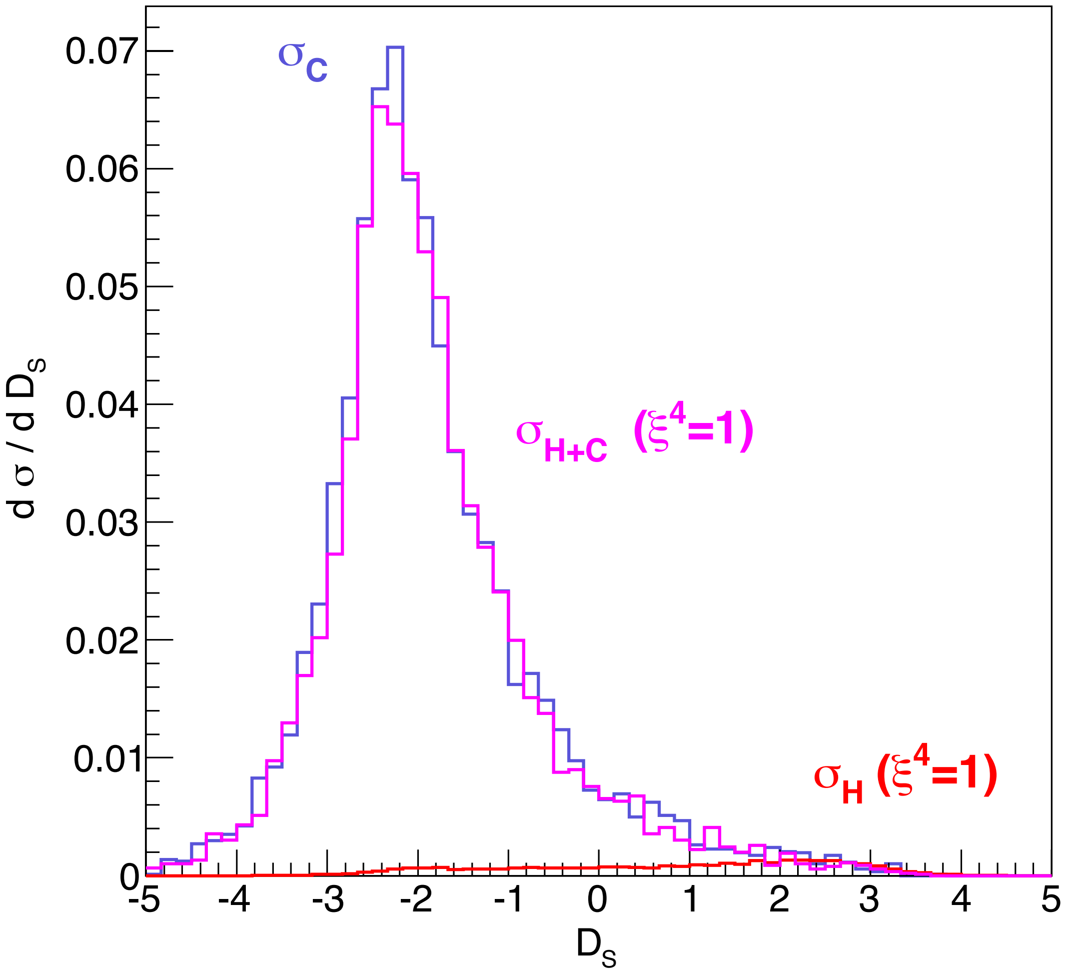
Events with large D, should be associated with Higgs like events.

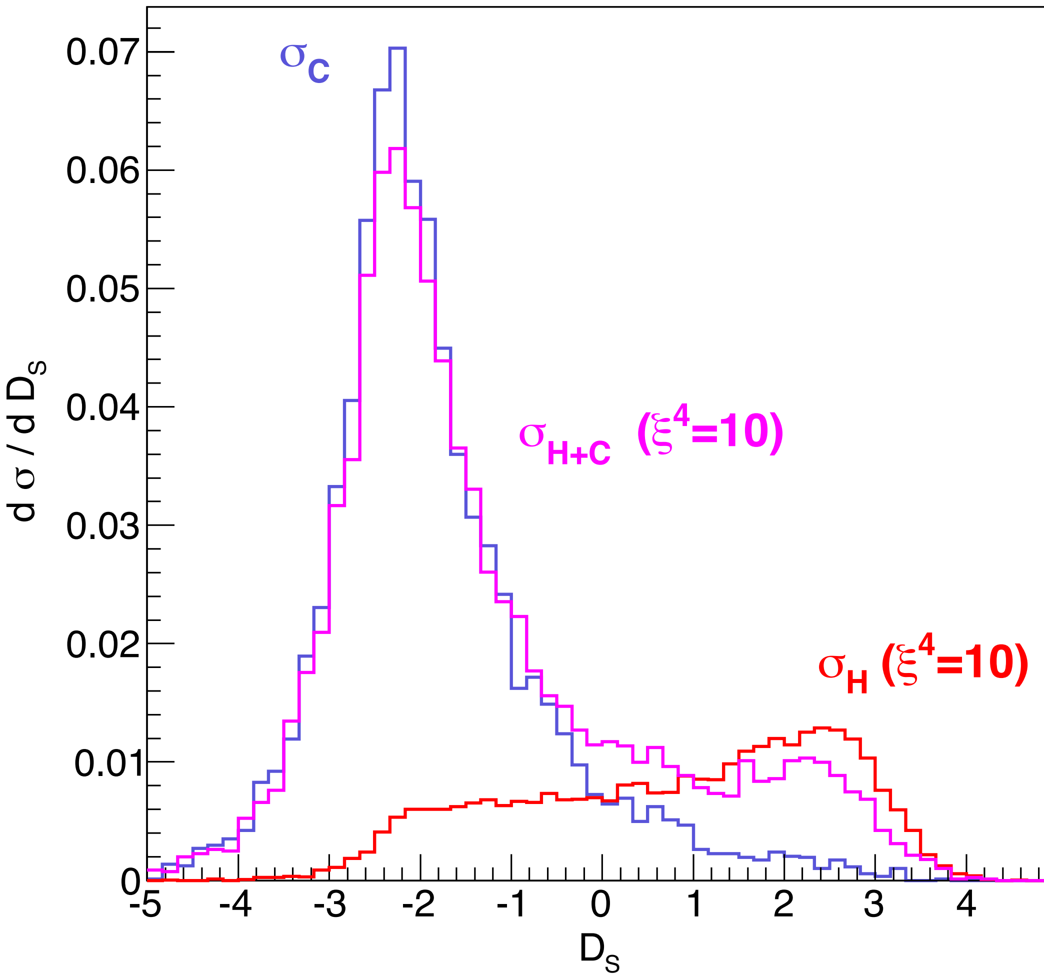
Generating the samples.

- In order to test our weights we generate sample events from MC.
- We use POWHEG + PYTHIA to generate the background “qqb” sample.
- We use MCFM 6.7 interfaced to PYTHIA to generate 3 gg samples, 1) Only Higgs, 2) Only continuum and 3) the full Higgs plus continuum (including intf).
- Finally, we apply basic detector effects by smearing the leptonic pT using a Gaussian function.
- We focus on the off-shell regime, requiring the CMS cuts plus and that the invariant mass of the four lepton system > 130 GeV.

MEM results : gg pieces

$g_x \to \xi g_x \quad \Gamma_H \to \xi^4 \Gamma_H^{SM}$

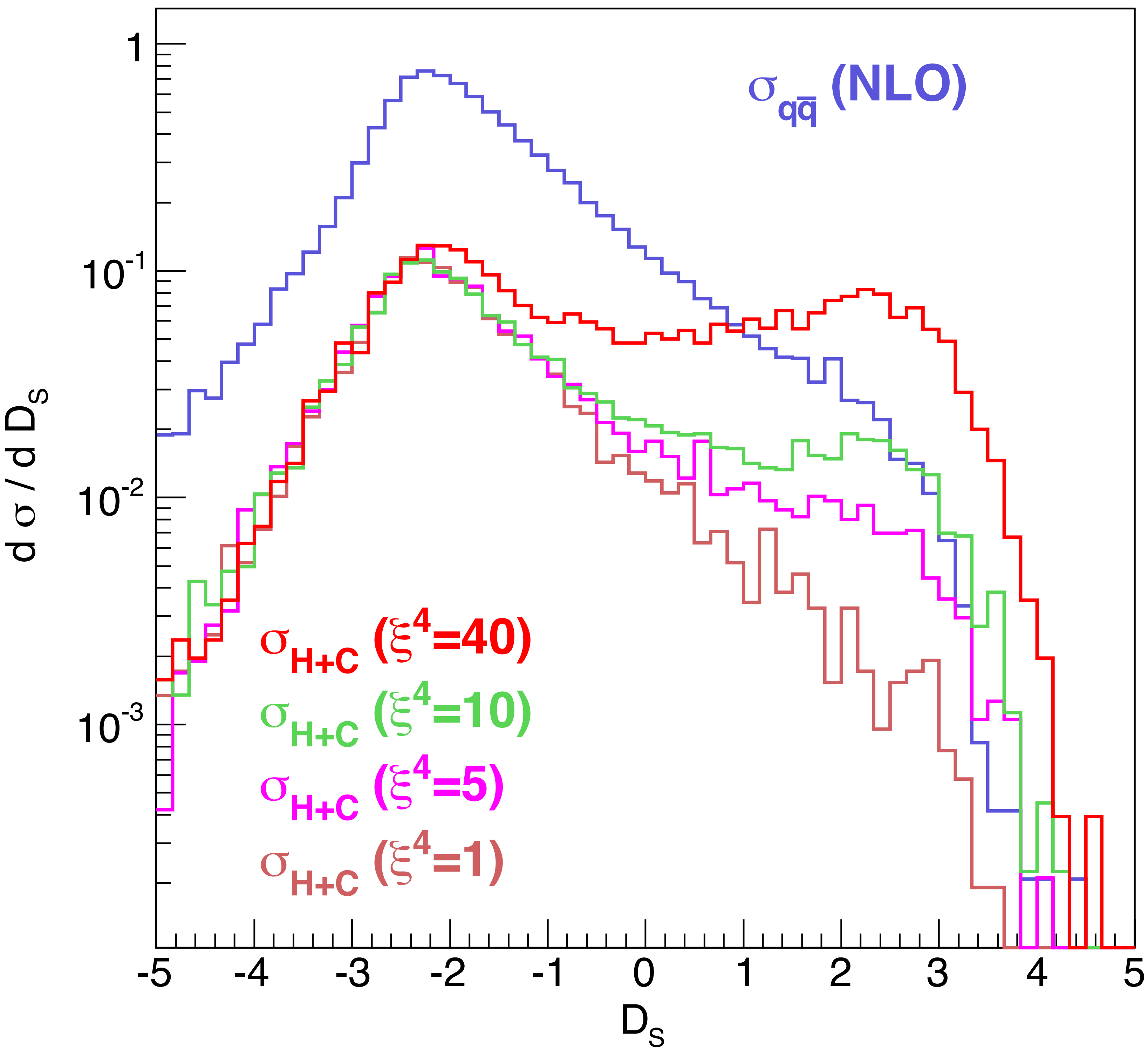




We begin by validating our sample on the gg initiated samples only, for the SM and for the case where the off-shell cross section is a factor of ten larger.

The number of events at large D is dependent on the off-shell Higgs cross section, as desired!

MEM results

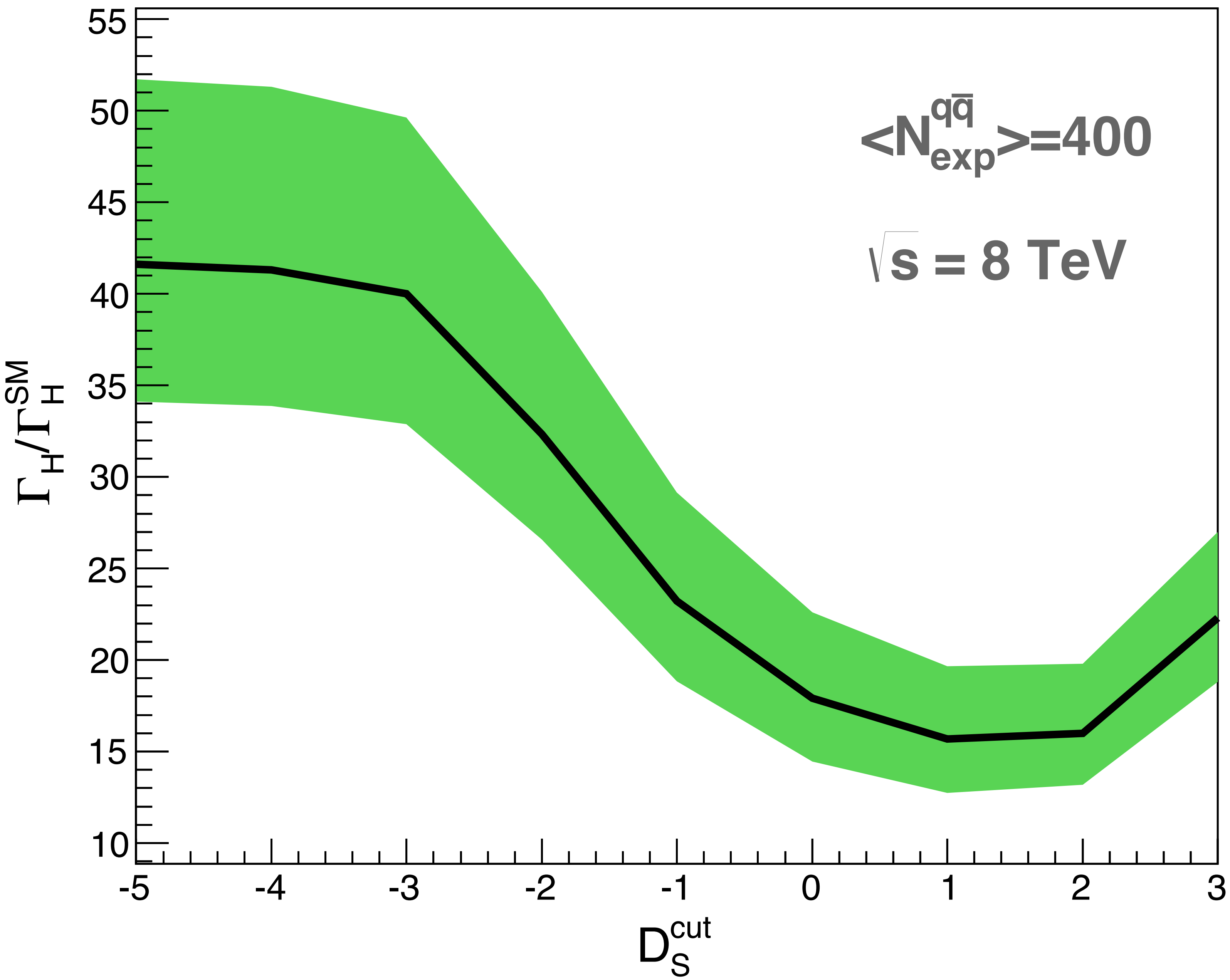


Next, we compare our gg samples to the full NLO(+PS) sample.

The qqb and gg continuum have similar shapes, the tail is still sensitive to the rescaling parameter.

To compare to cut and count results, we simply treat D as an additional variable which can be cut on.

MEM bounds



We present the expected limit, (shading represents theory uncertainty) where the expected no. of events is around the CMS observation (8 TeV data).

The most stringent limits occur around D > 1, (run out of statistics beyond that).

$$\Gamma_H < \left(15.7\ {}^{-2.9}_{+3.9}\right)\ \Gamma_H^{SM} \text{ at } 95\% \text{ c.l. .}$$ (Ds > 1)

Note that a real experimental analysis could be *much* smarter.

Conclusions

- I’ve presented results for the bounding of the Higgs width using the MEM.
- Using off-shell ZZ events one can constrain the Higgs width to levels well below the detector resolution.
- MEM discriminants provide a powerful tool for finding off-shell Higgs events, and should significantly improve the basic cut and count analysis.
- In the future it should be possible to do MEM@NLO (once the full gg=>4l is known at NLO). Over the lifetime of the LHC this may result in limits < 10 * SM, a fantastic (and surprising) achievement for the LHC.