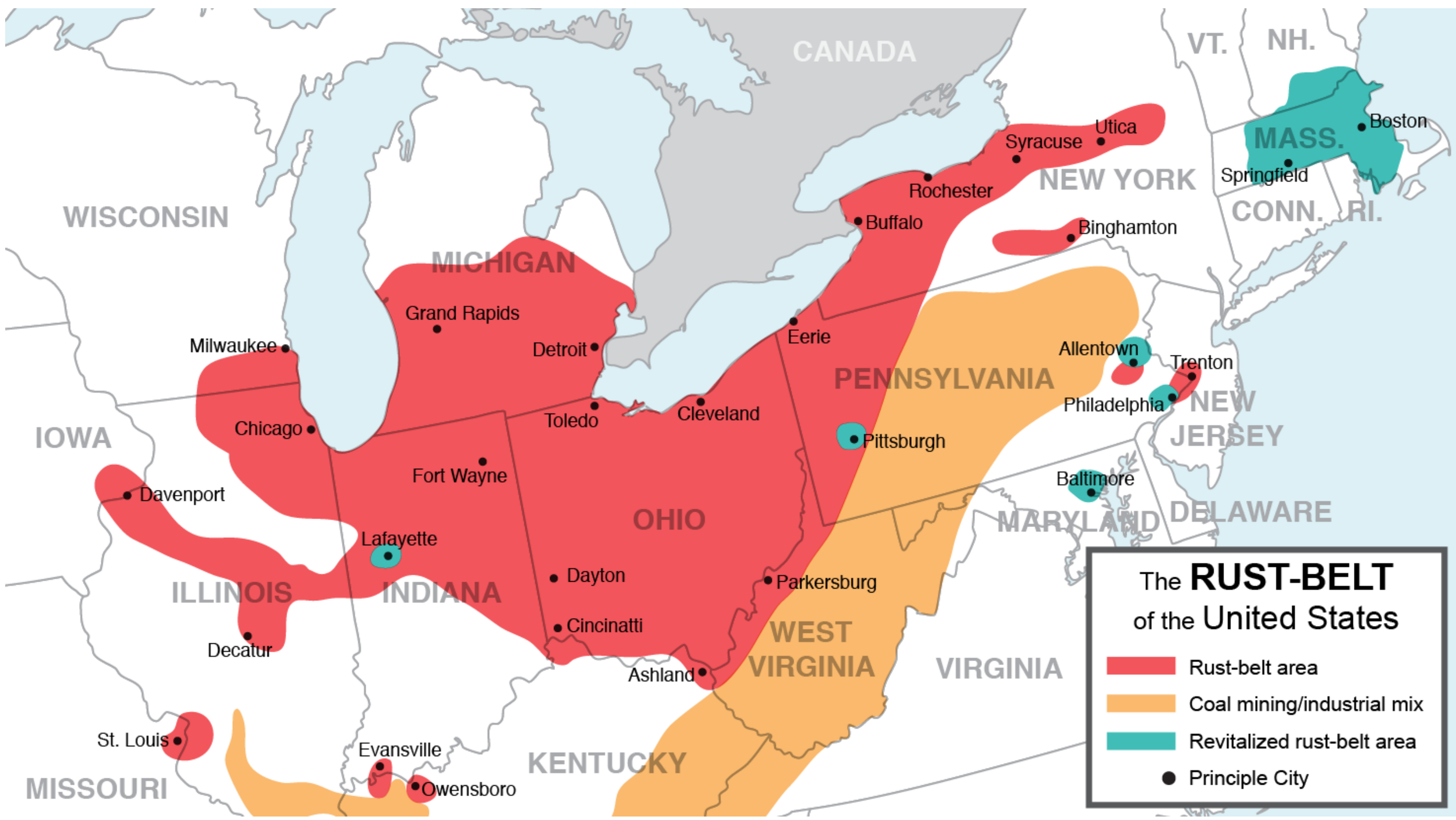
Off-shell Higgs bosons at the LHC

Ciaran Williams (SUNY Buffalo)



Higgs and Beyond, Pittsburgh 2015

The Higgs Boson

The Higgs Boson

The New York Times

Scientists at the Fermilab in Batavia, Ill., on Wednesday watched the presentation about the discovery of the Higgs boson, which was shown from Geneva.

The Higgs Boson

The New York Times

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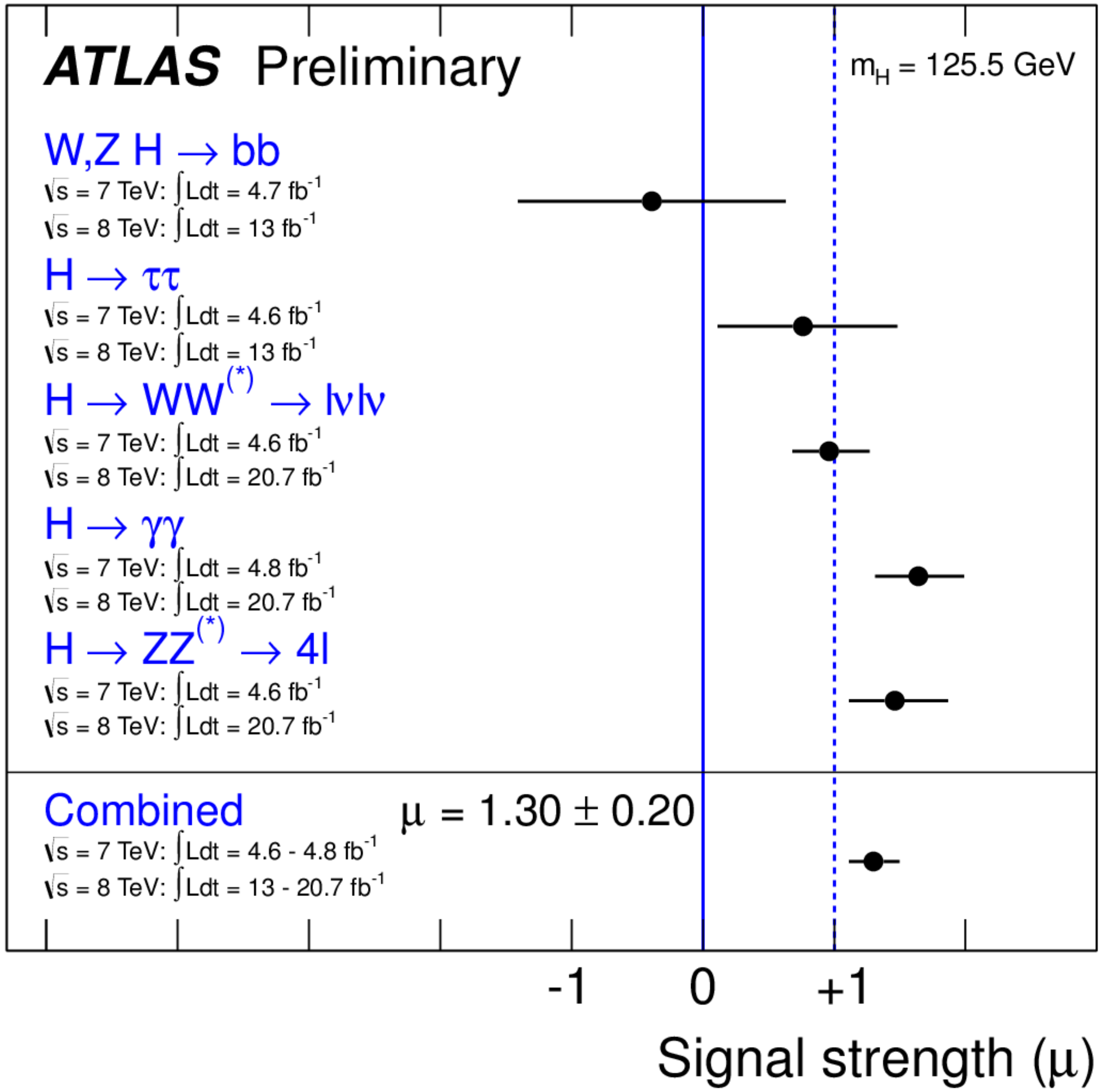
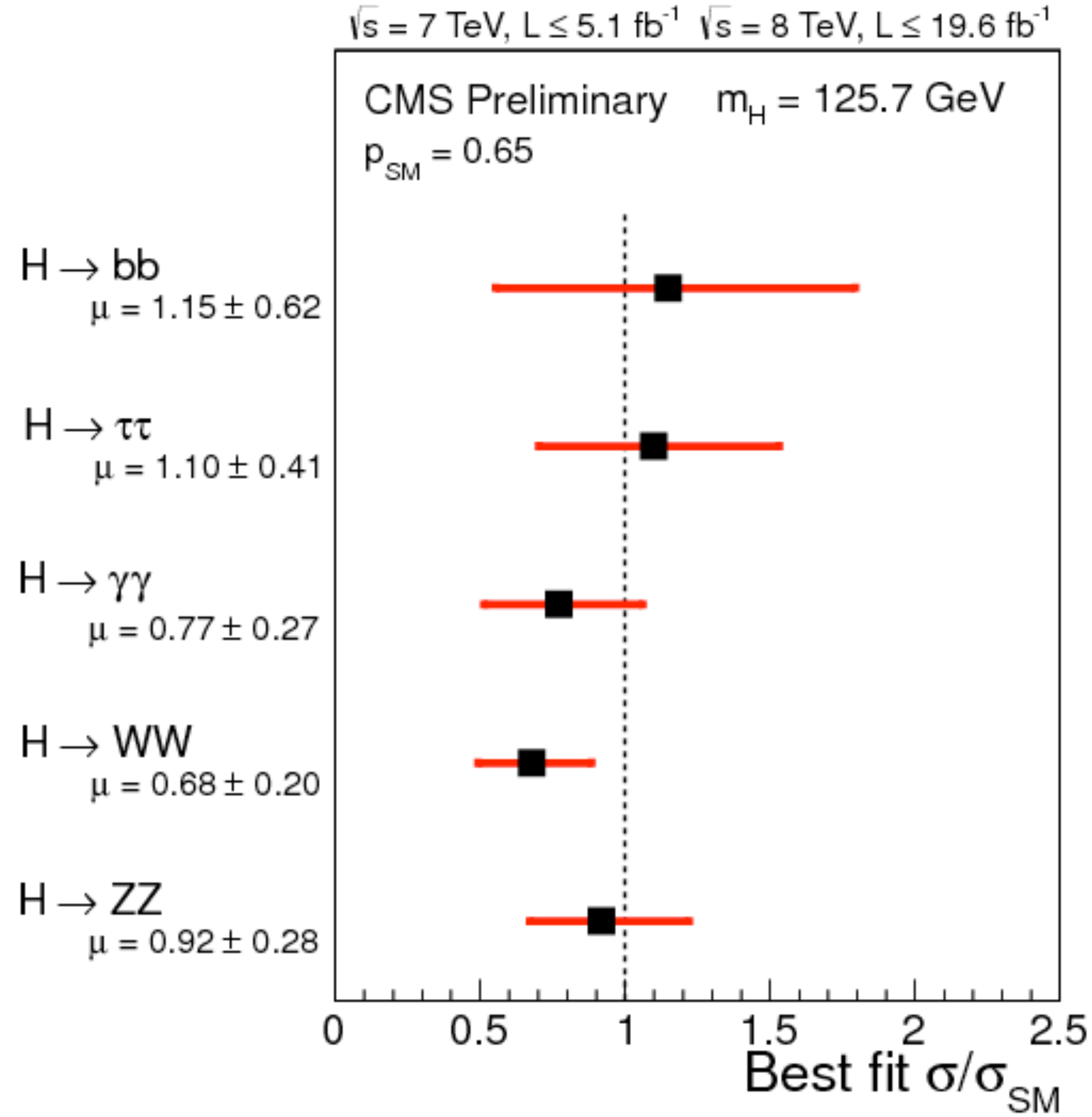
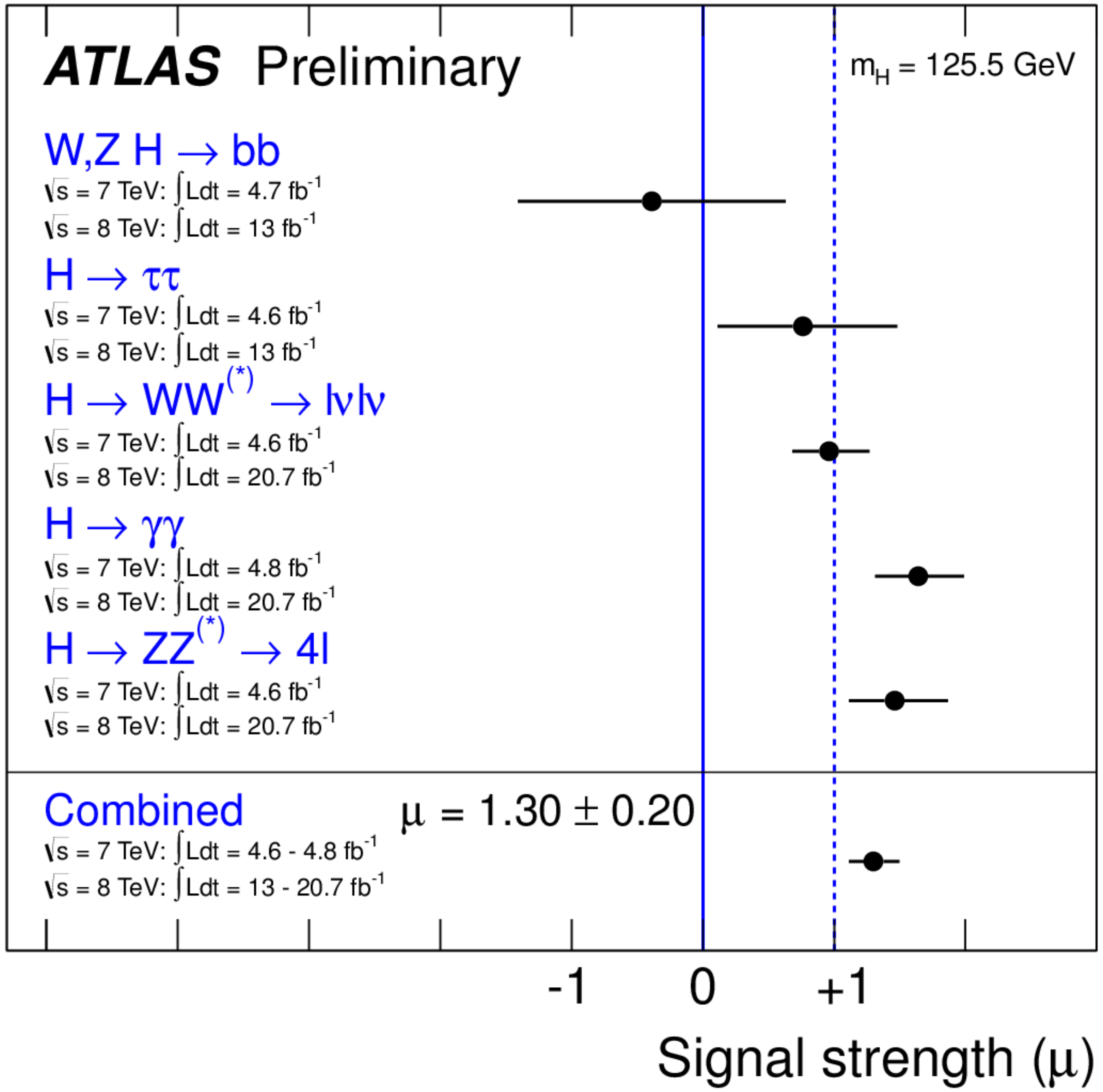
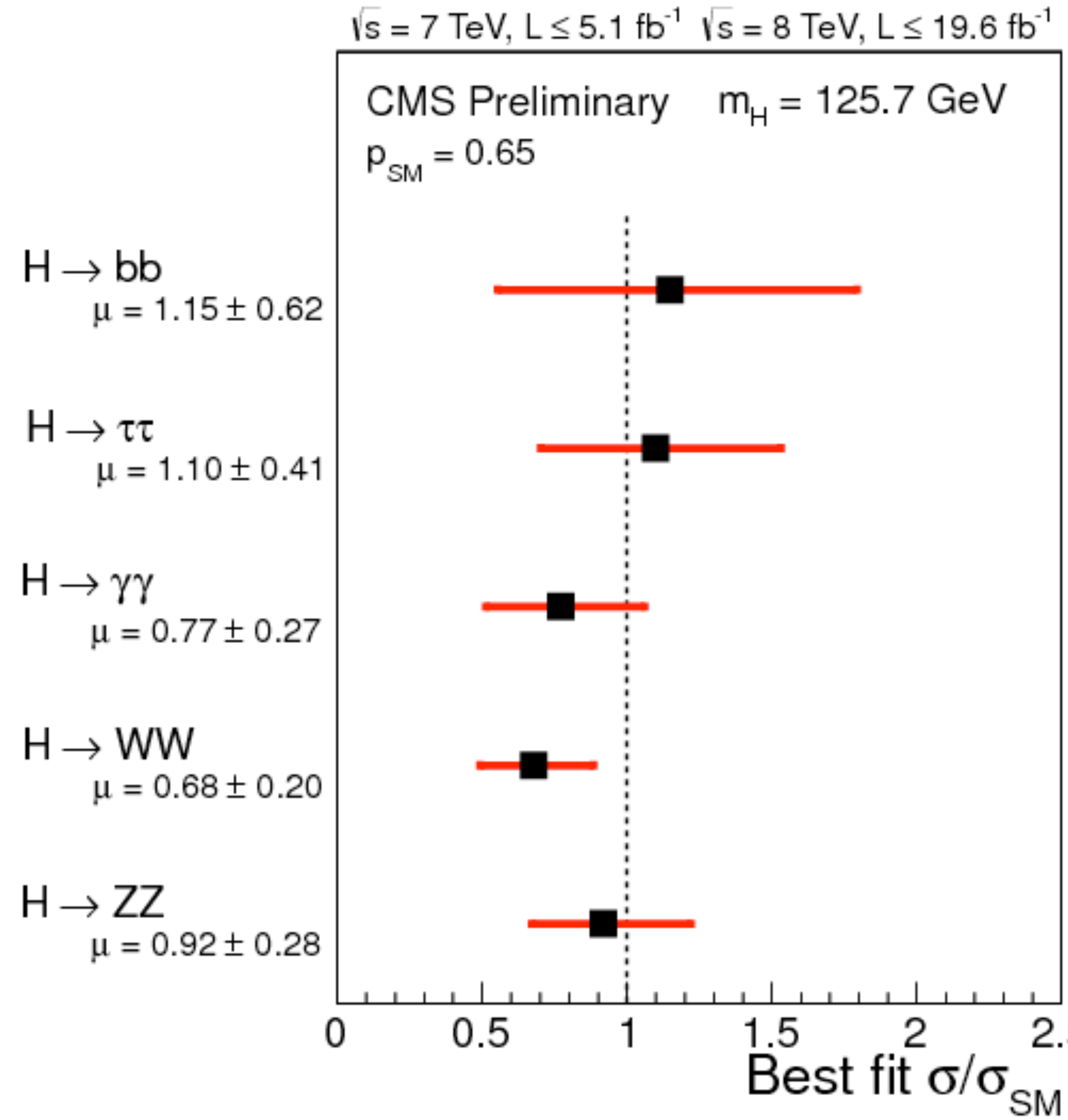




Each decay mode is measured and cross sections are determined using the Narrow width approximation,

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



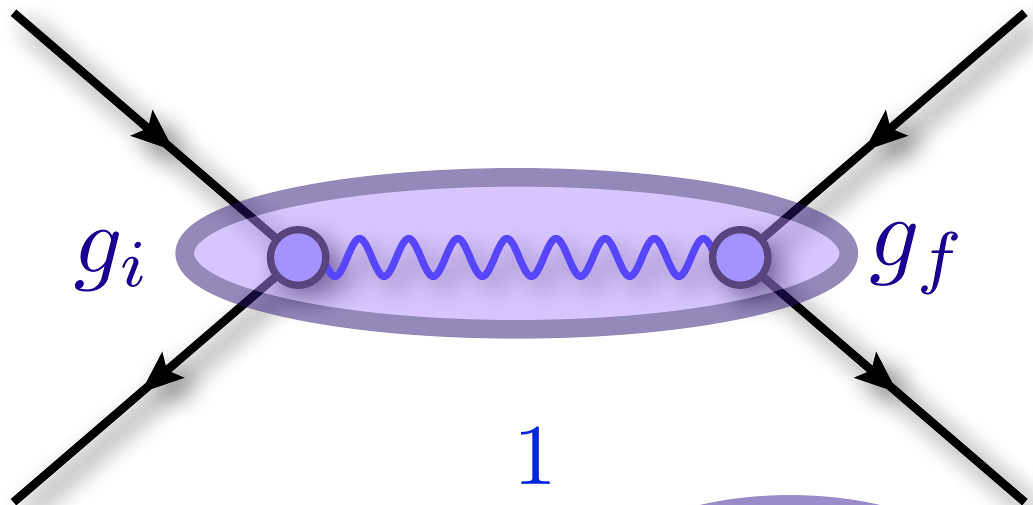


Ultimately we want to extract information regarding the Higgs coupling to SM particles, which is a difficult task since.

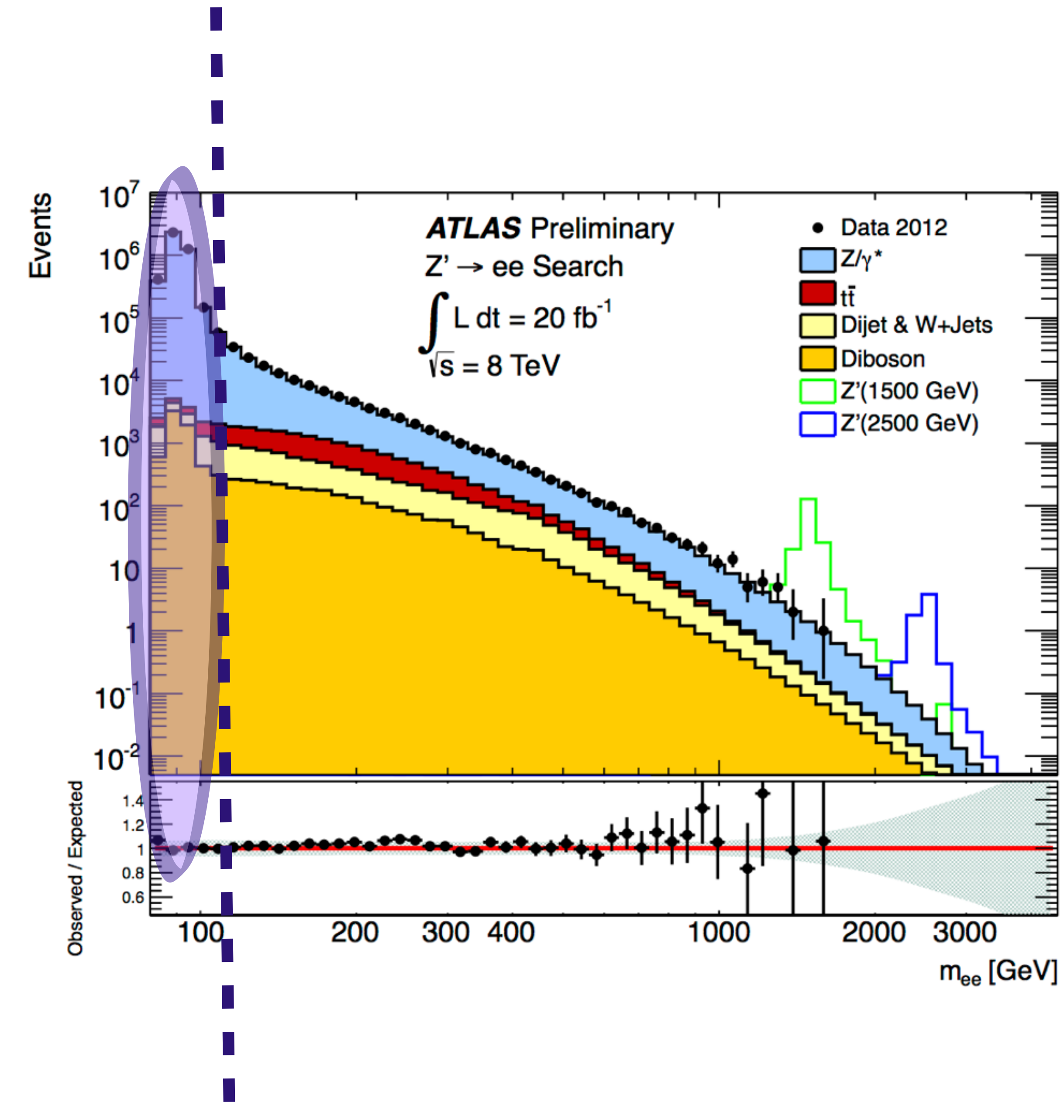
$$\sigma_{i\to H\to f} \propto \frac{g_i^2 g_f^2}{\Gamma_H} \sim \frac{g_i^2 g_f^2}{\sum_j g_j^2}$$

such that global fits are required to determine the couplings.

Properties of On- and Off-shell Cross Sections



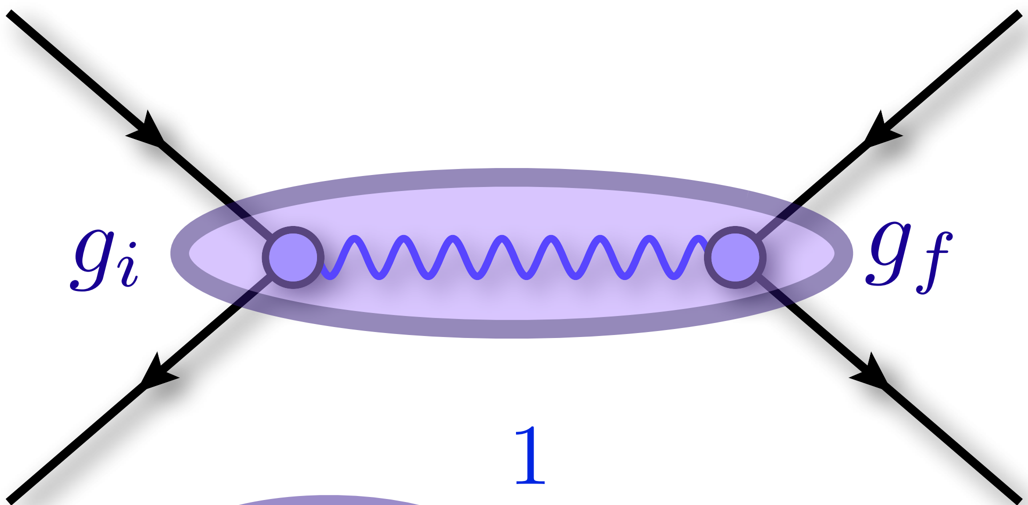
$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$



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

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

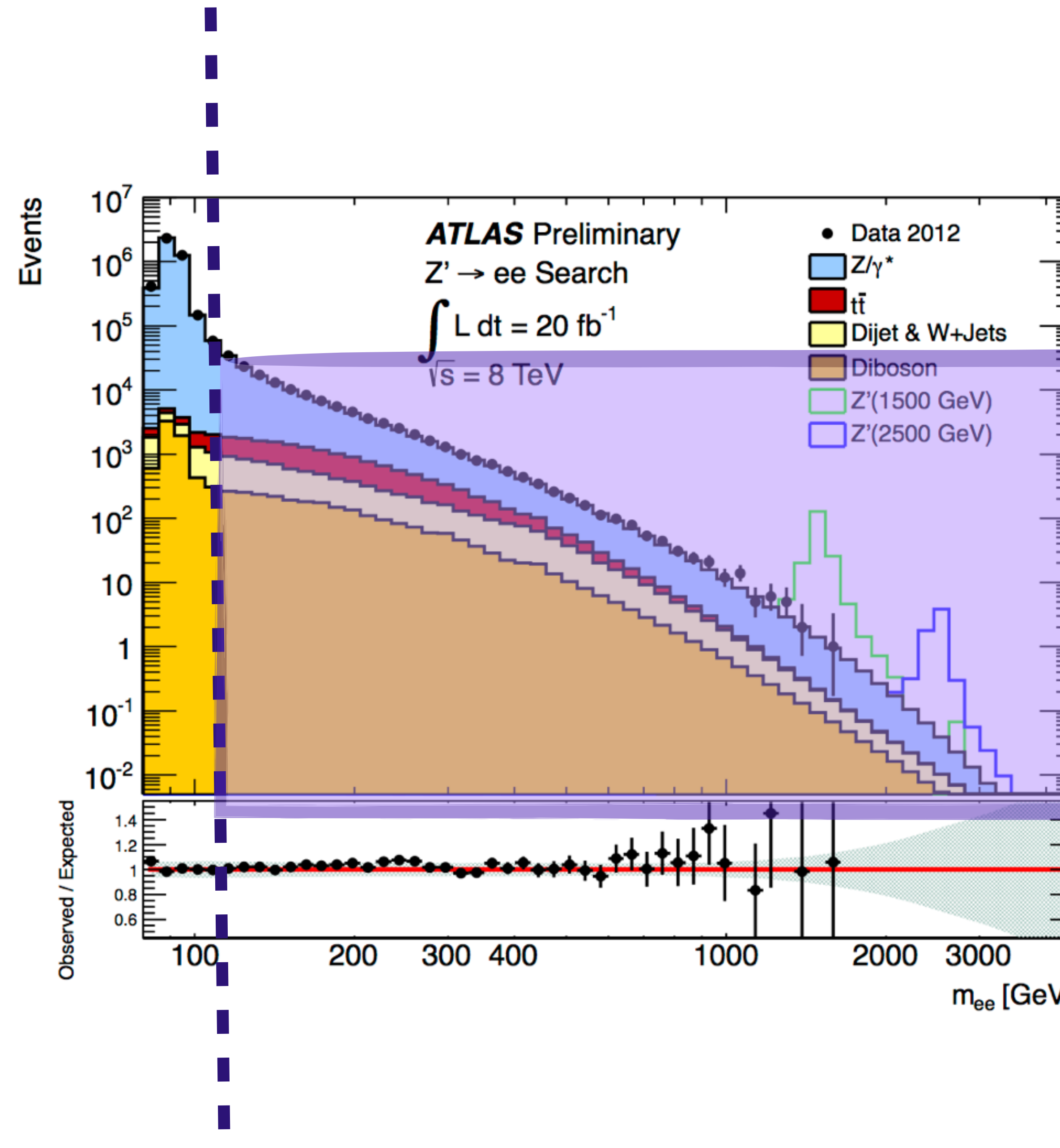
Properties of On- and Off-shell Cross Sections



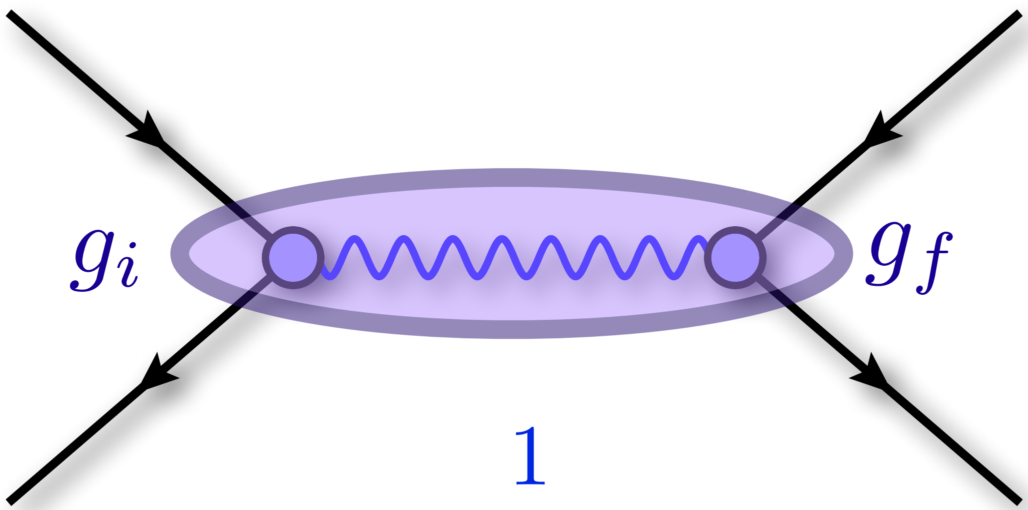
$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$

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

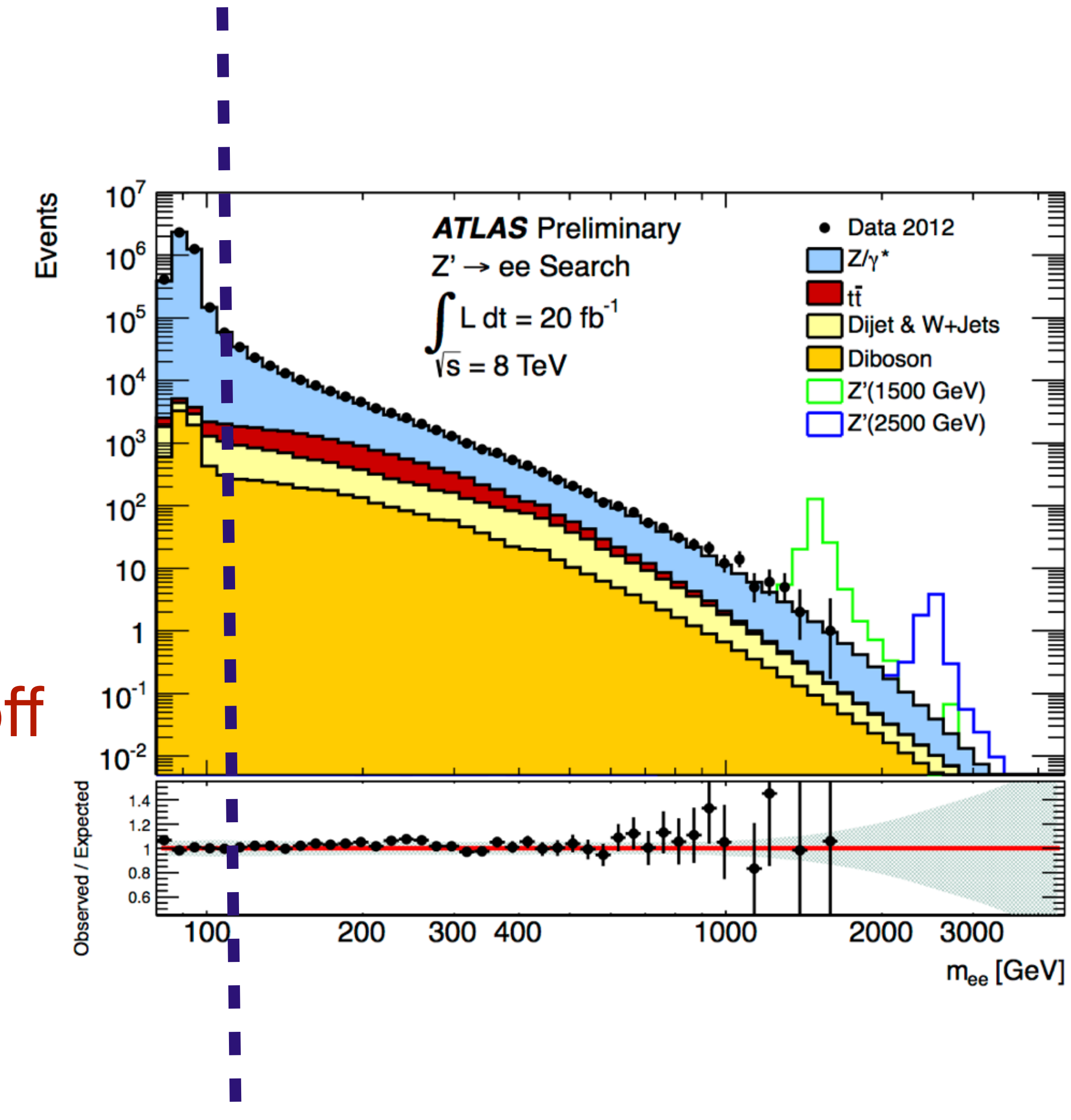
$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$



Properties of On- and Off-shell Cross Sections



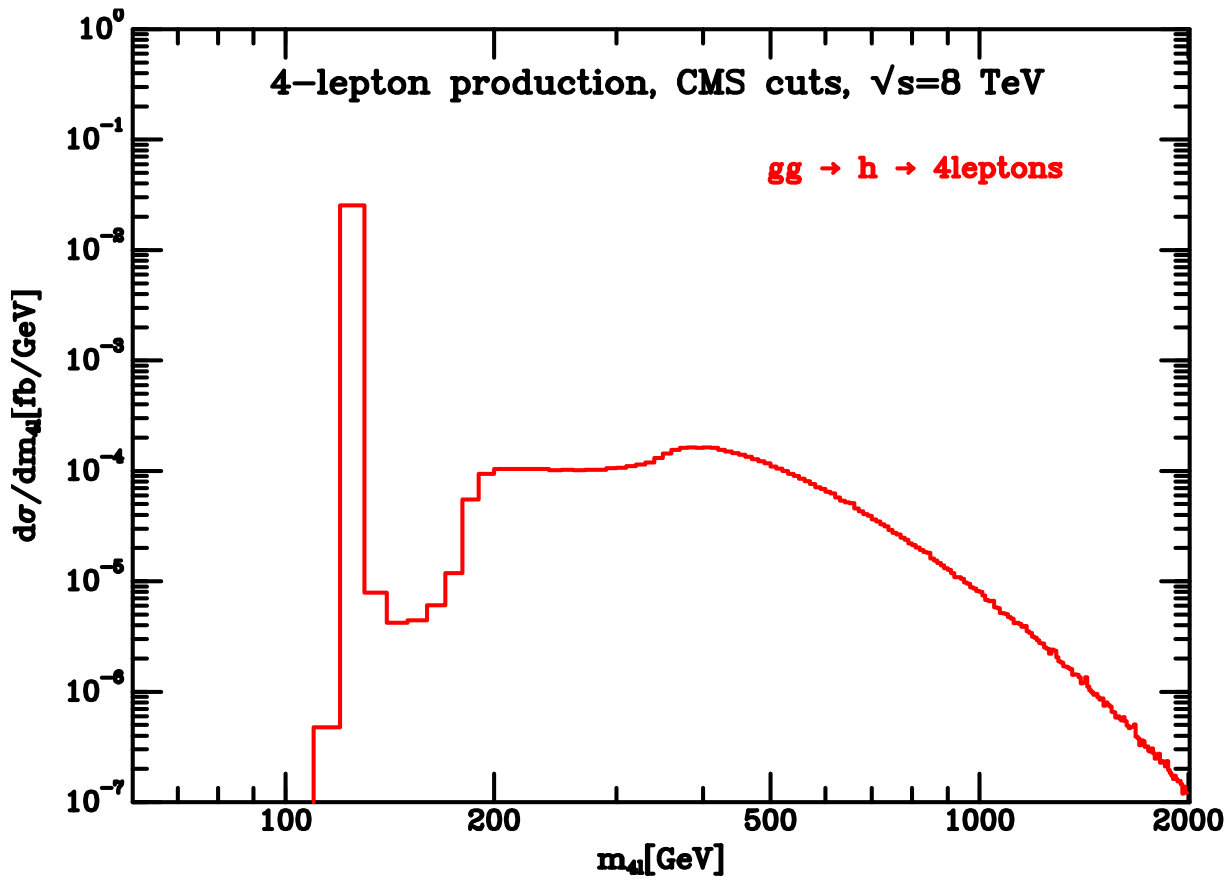
$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$



So if we are able to measure the off shell cross section, we can isolate process specific couplings.

Off Shell Higgs cross sections.

(Kauer, Passarino 12)
(Caola, Melinikov 13)
(Campbell, Ellis, CW 11,13)

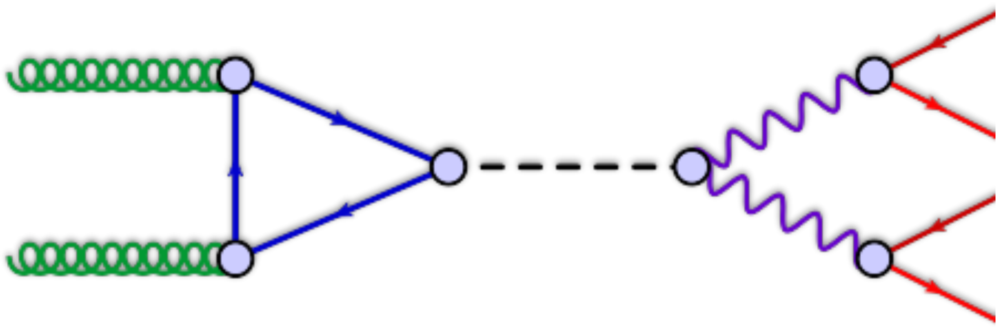


Energy	σ^H_{peak}	σ^H_{off}
7 TeV	0.203	0.044
8 TeV	0.255	0.061

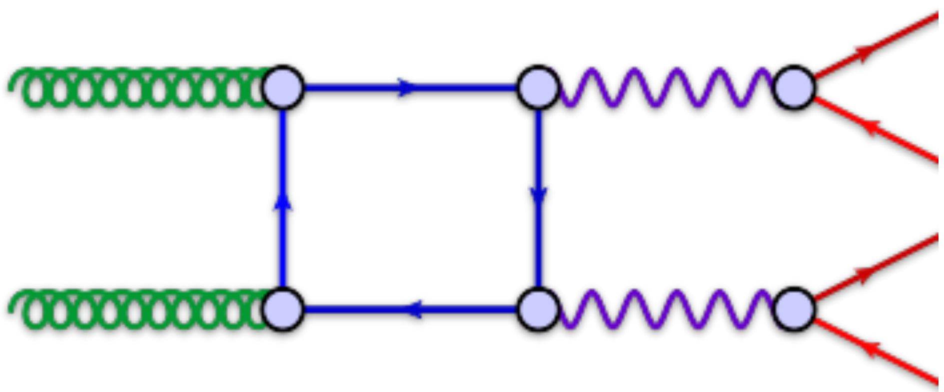
- Since Γ_H / M_H=1/30,000 one might expect off-shell corrections to be very small.
- However this is not the case in decays to VV, there is a sizable contribution to the total cross section away from the peak.
- This arises from the proximity of the two VV threshold, and is further enhanced by the threshold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

Off shell predictions for H=>4 leptons

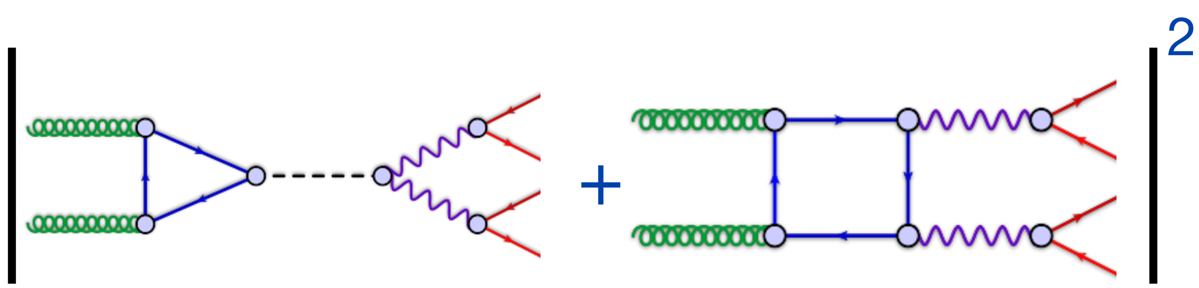
gg initiated production of four leptons at the LHC



We are mostly interested in off-shell Higgs events which proceed through a top quark loop, with subsequent ZZ decays.

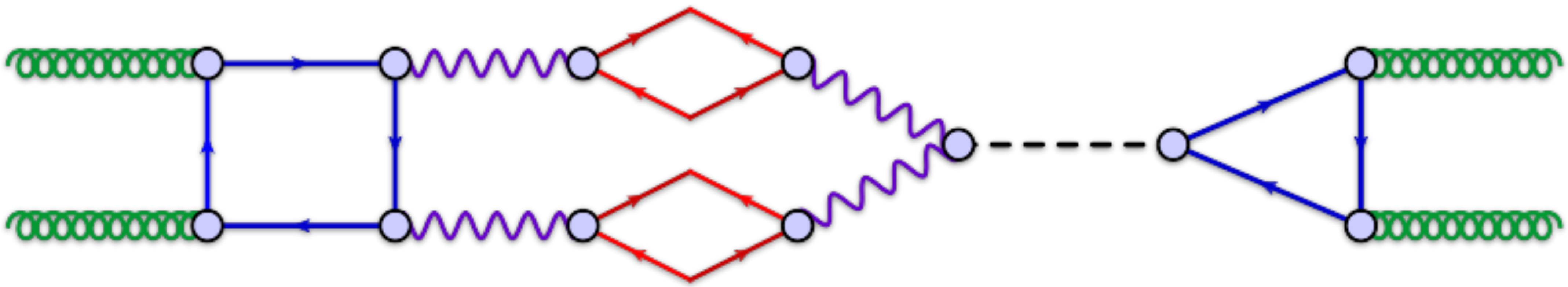


However the same final state can occur via a loop of fermions.



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 (Dixon, Siu 03)

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

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,

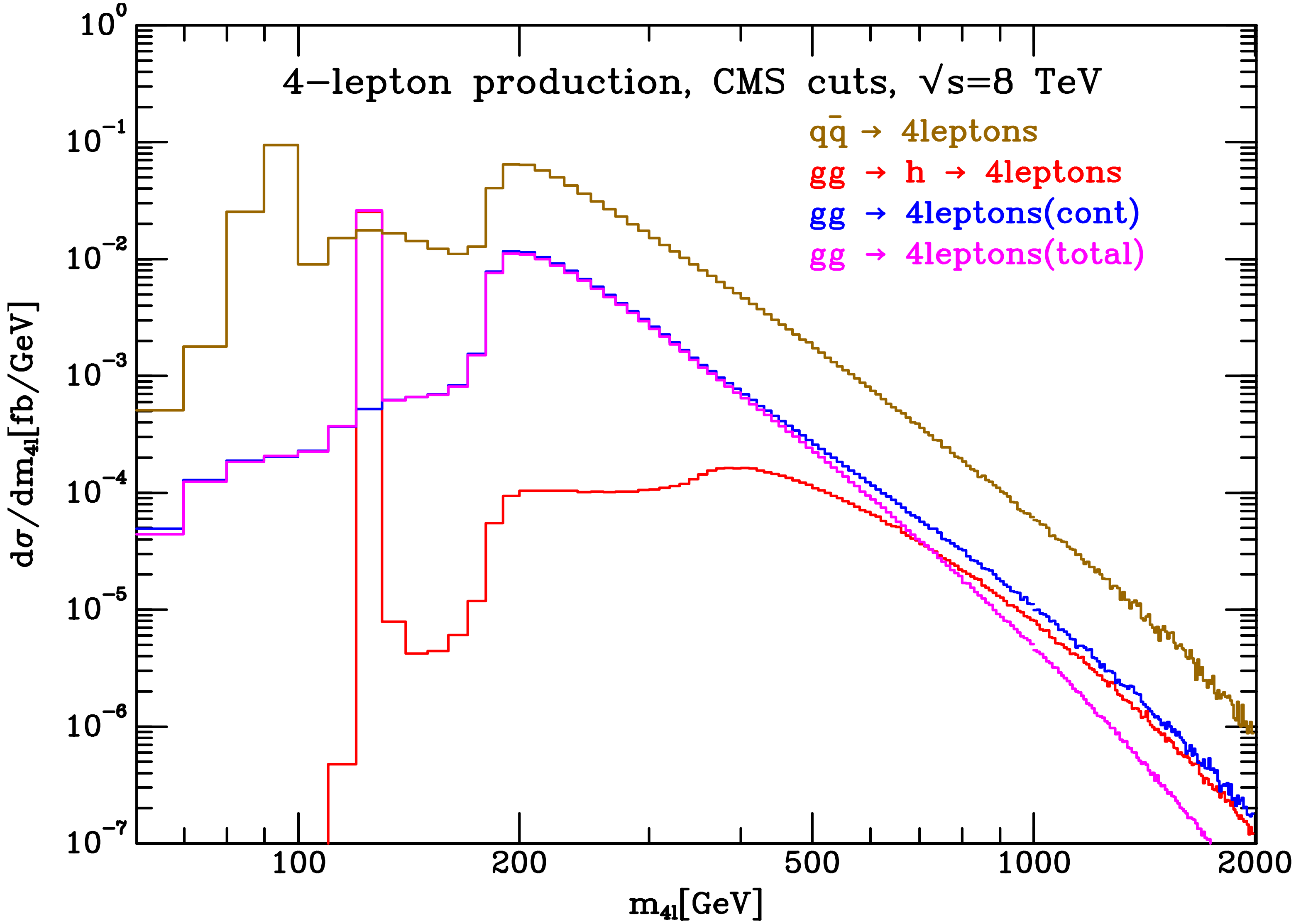
$$\sigma_{off} \propto g_T^2 g_Z^2$$

is invalid. The interference modifies the above equation, introducing a term which scales as linearly with the couplings.

$$\sigma_{off} \propto g_T^2 g_Z^2 |A_H^* A_H| \; + 2 g_T g_Z |A_H^* A_B| + |A_B^* A_B|$$

As we will see, the second term is crucial to ensure the validity of the SM

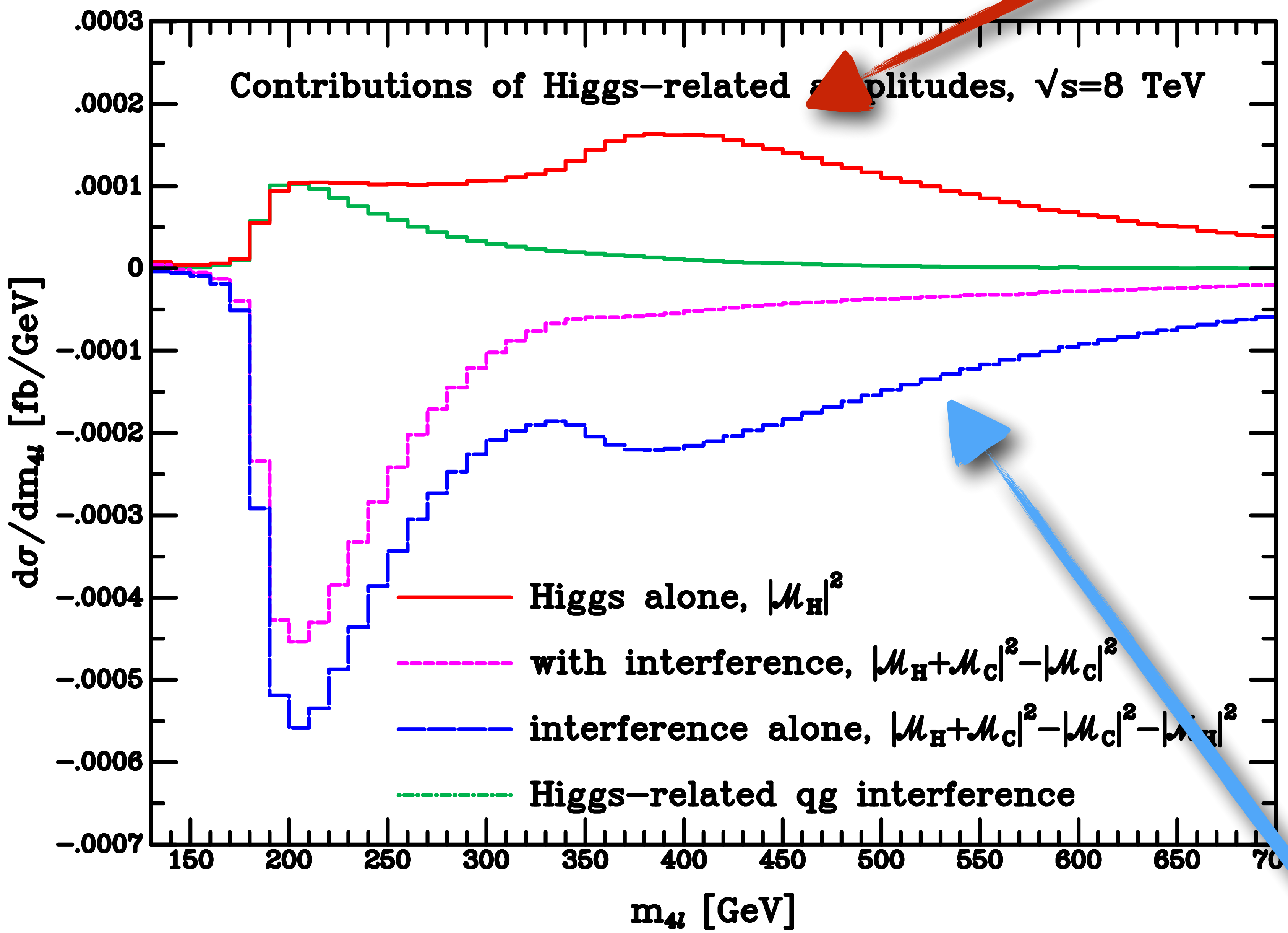
Putting it all together : the big picture



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.

Scales like $g_t^2 g_Z^2$

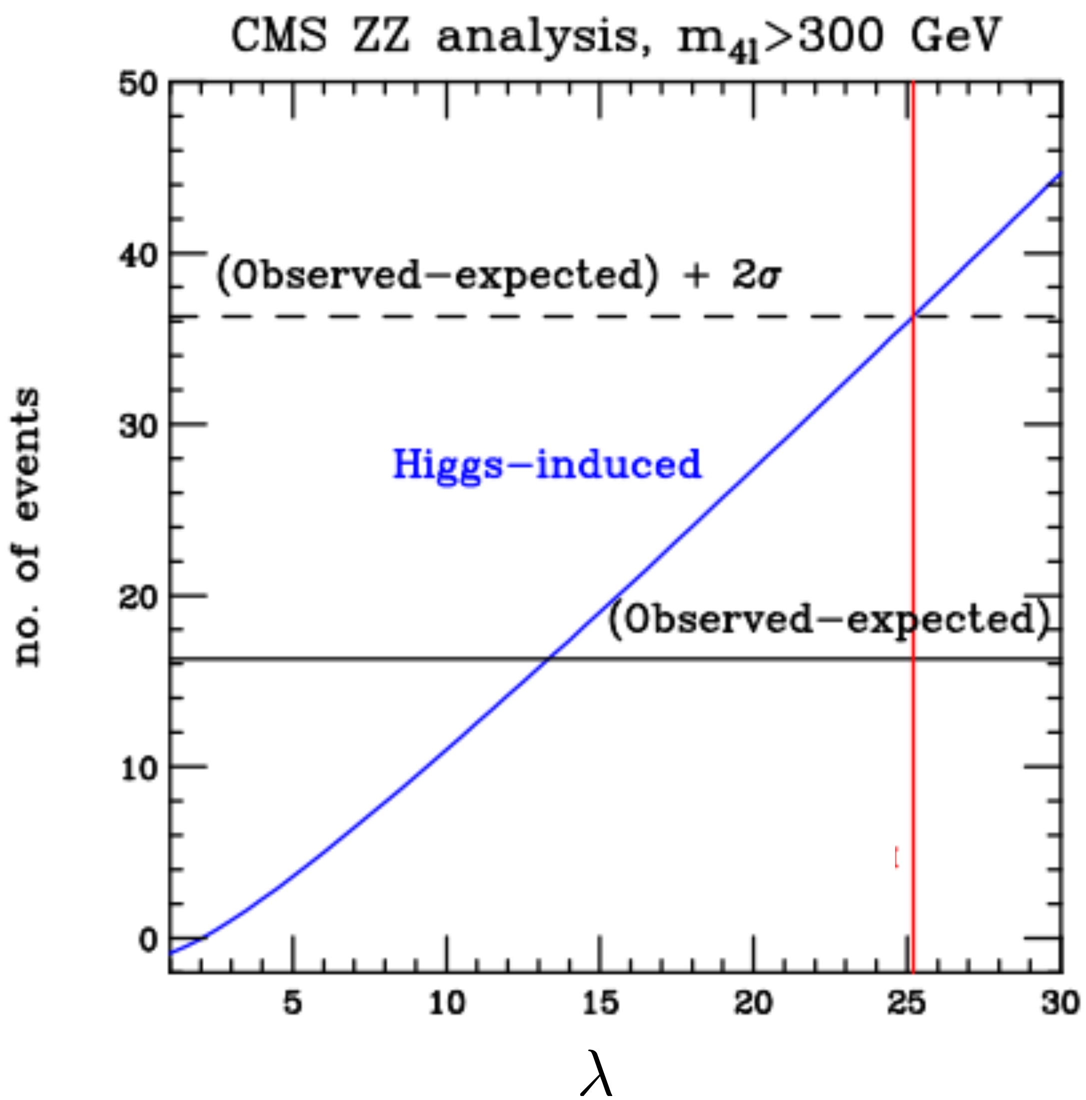


The interference shares similar features to the signal (in particular the thresholds), washing out many of the features associated with the top quark.

Scales like $g_t g_Z$

Bounding the Higgs couplings off shell using LHC data

(Caola, Melinikov 13)
(Campbell, Ellis, CW 13)



One can calculate the number of expected off-shell Higgs events as a function of the rescaling parameter,

$$g_T^2 g_Z^2 \to \lambda g_T^2 g_Z^2$$

For example, with CMS cuts one finds,

$$N_{off}^{4\ell}(m_{4\ell} > 300 \text{ GeV}) = 2.02\lambda - 2.91\sqrt{\lambda}$$

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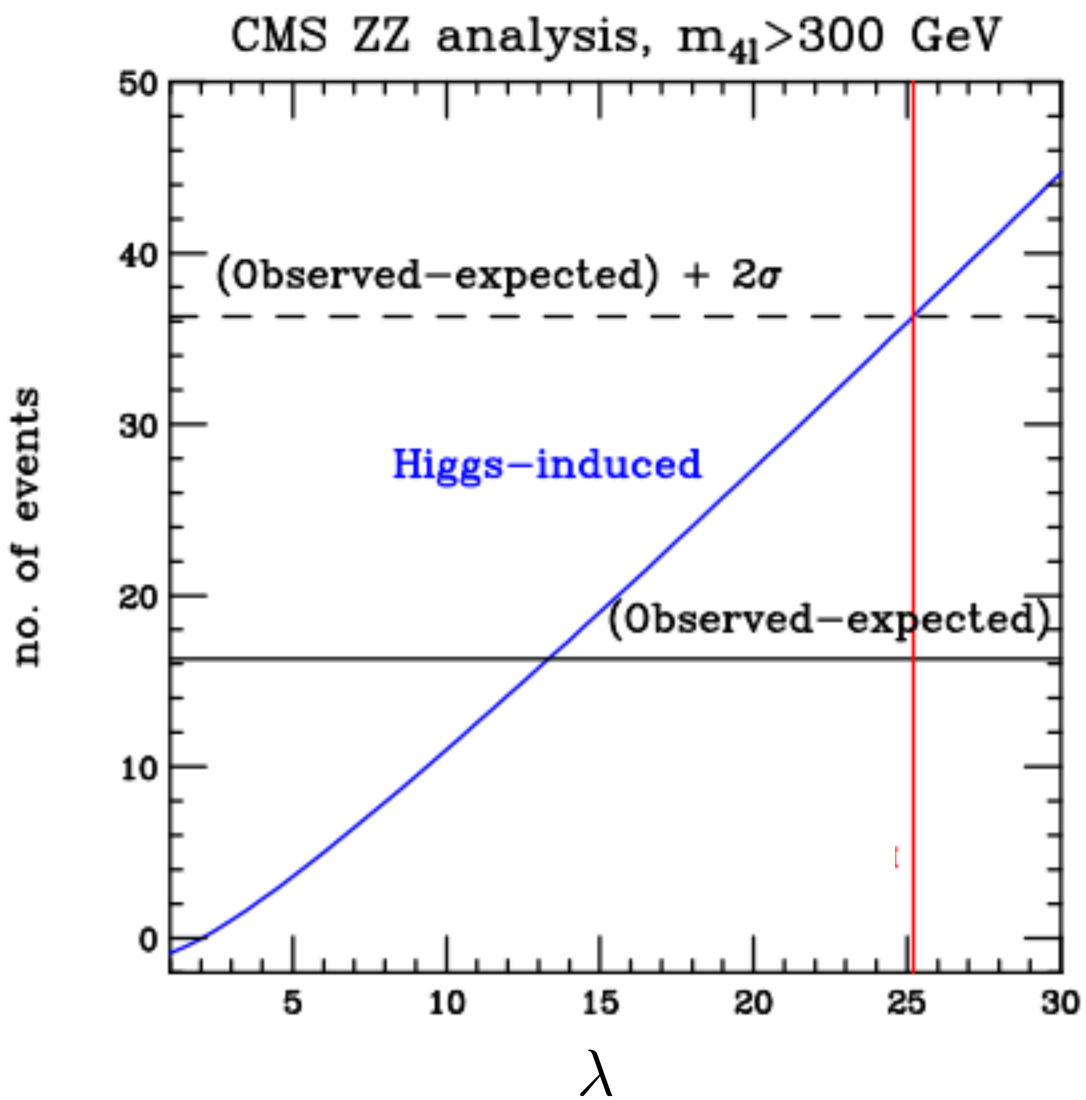

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Using public CMS data and MCFM we find

$$g_T^2 g_Z^2 < 25.2 \ \left(g_Z^2 g_T^2\right)_{SM}$$

Bounding the Higgs couplings off shell using LHC data

(Caola, Melinikov 13)
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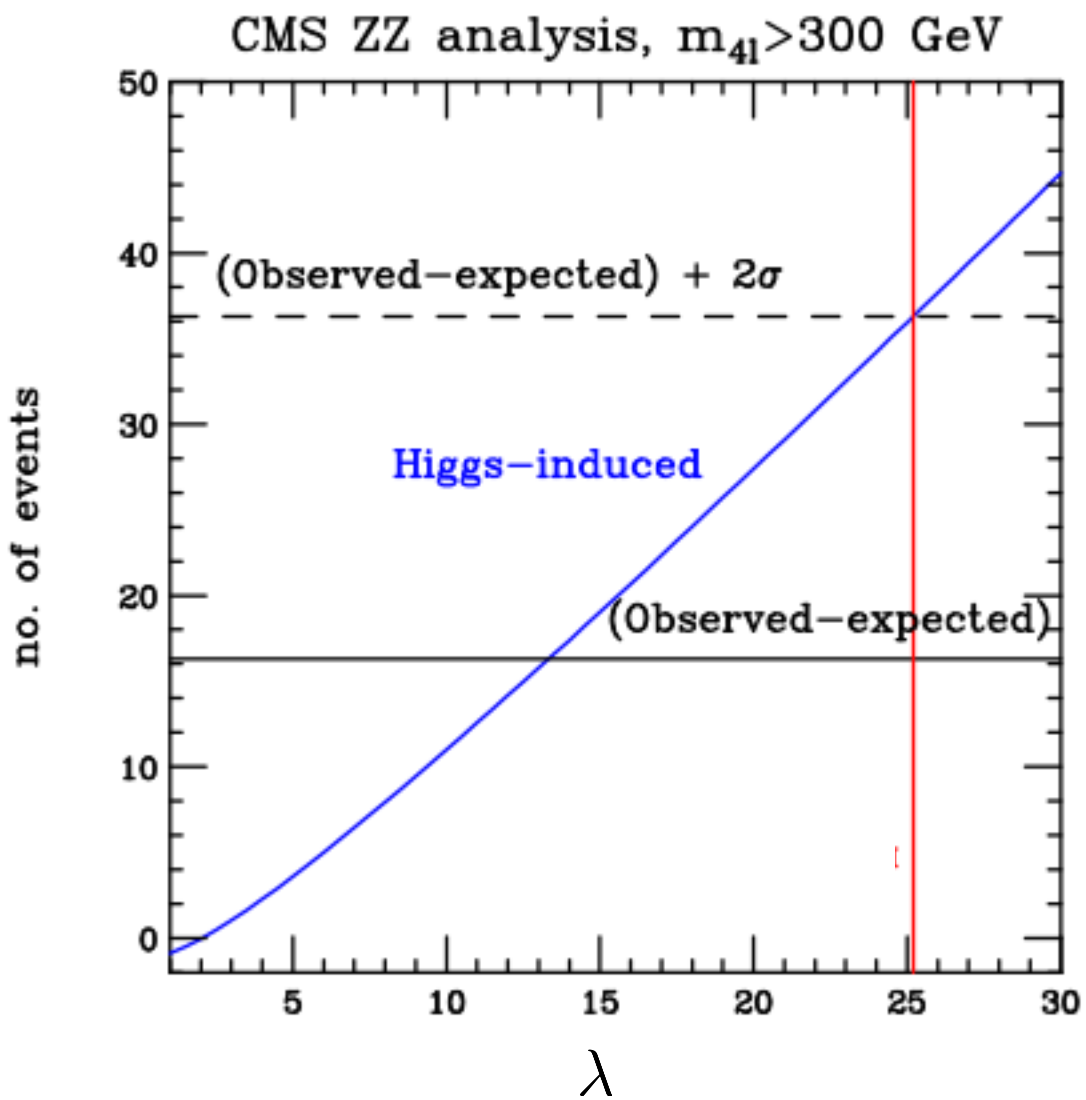

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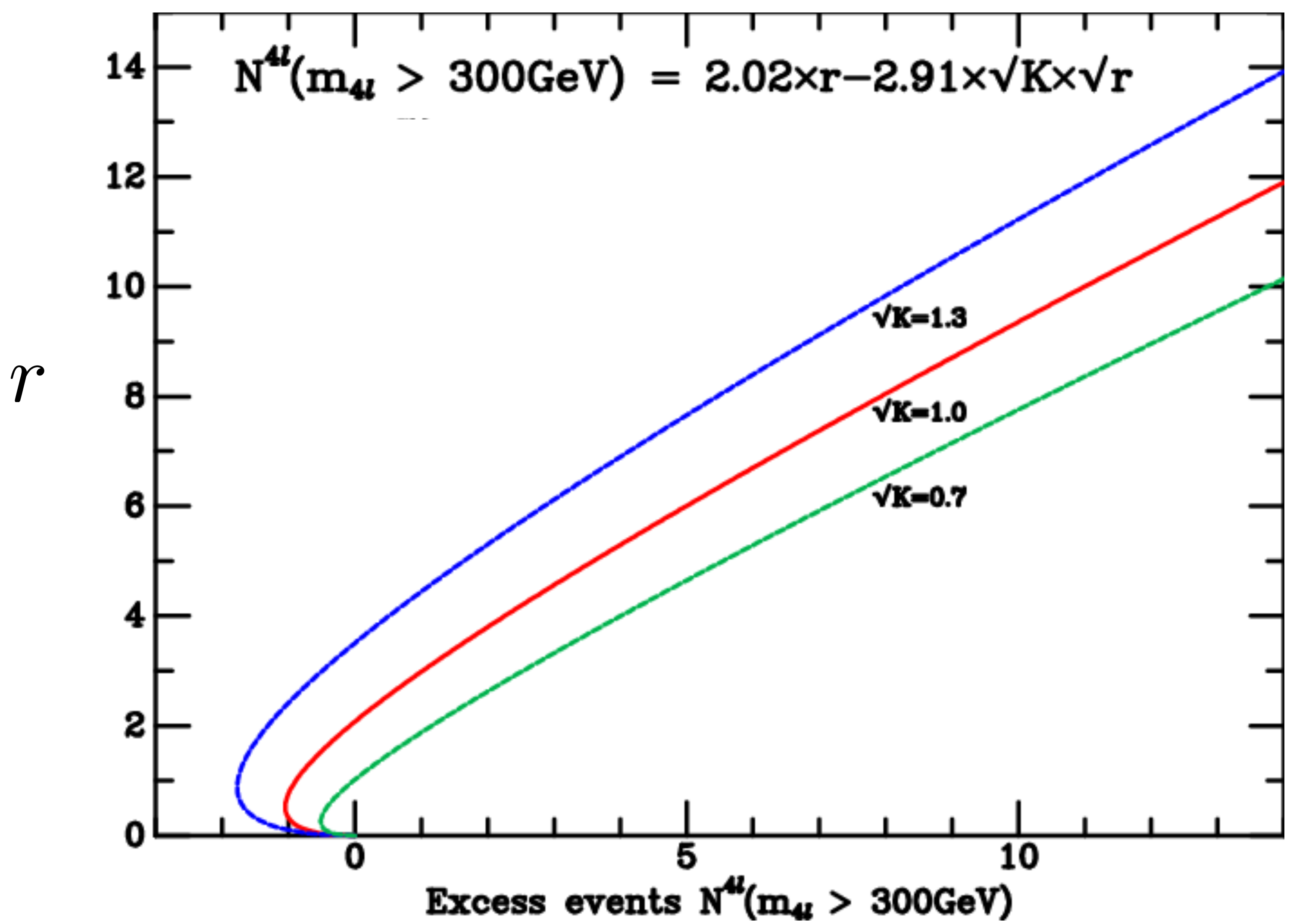
$$N_{off}^{4\ell}(m_{4\ell} > 300 \text{ GeV}) = 2.02\lambda - 2.91\sqrt{\lambda}$$

CMS have repeated the analysis, finding

$$g_T^2 g_Z^2 < 26.3 \ \left(g_Z^2 g_T^2\right)_{SM}$$

1405.3455 & CMS-PAS-HIG-014-002

Theoretical issues….

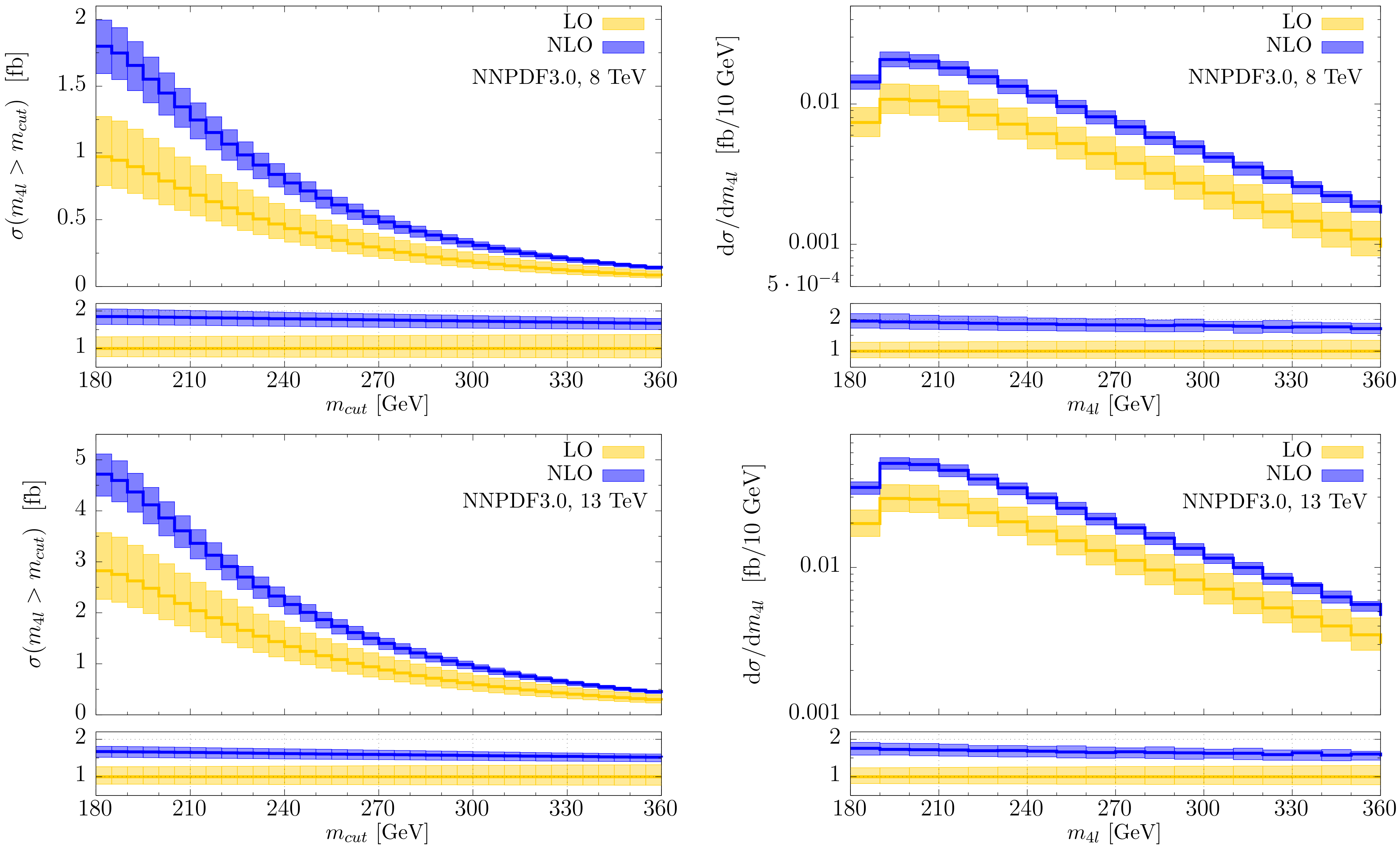


The discussion on the previous slides as based on LO calculations.

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

gg=>ZZ @ NLO

(Caola, Melnikov, Ronstch, Tancredi 15')



Recently, a big step was taken towards performing this analysis at NLO, with the computation of the gg=>ZZ for massless loop particles.

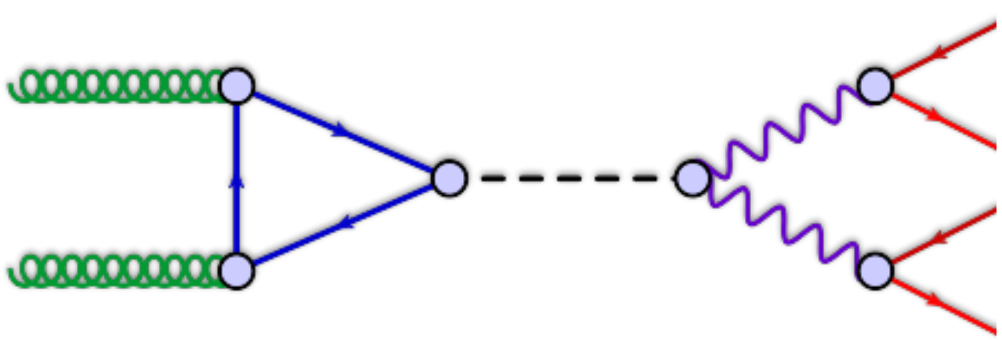
Model independence.

(see discussion in Englert, Spannowsky 14')

Our previous results were based on the bounds derived from the number of events observed off-shell, and are model independent (for couplings evaluated above a scale of the "off-shell" threshold) i.e.

$$g_T^2(s > 300)g_Z^2(s > 300) < 26.3\left(g_T^2 g_Z^2\right)_{SM}$$

From now on we will discuss results obtained using the MEM, and require that the event look like a SM decay. This imposes model dependence. The model dependence is strongest for g_Z since we look for SM decays.



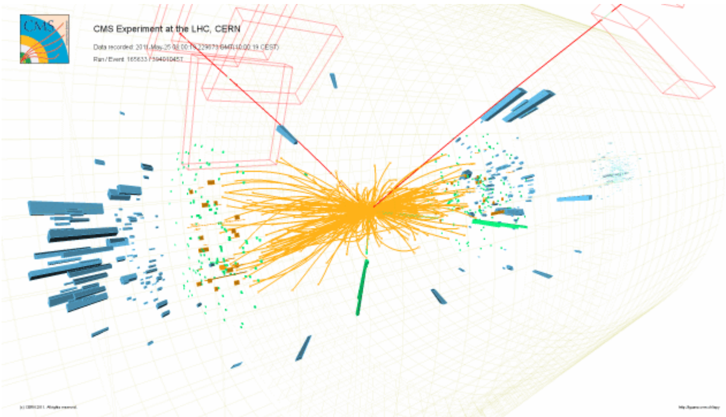
Model dependence on g_T is weaker since it enters either as an overall normalization (non-threshold), or localization in mass (threshold).

MEM improvements.

Matrix Element Methods

See Michael's Talk!

Start with an event

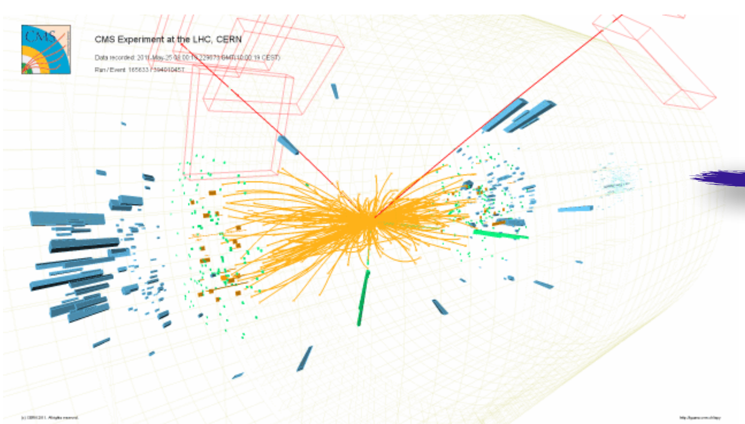


Matrix Element Methods

See Michael's Talk!

Start with an event

Pass it to the MEM algorithm



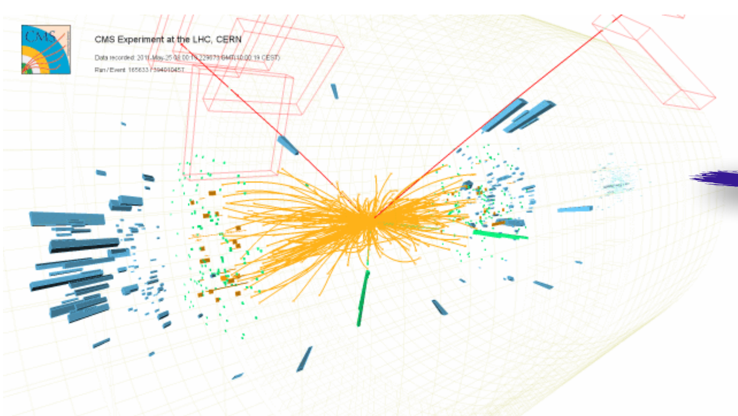
Matrix Element Methods

See Michael's Talk!

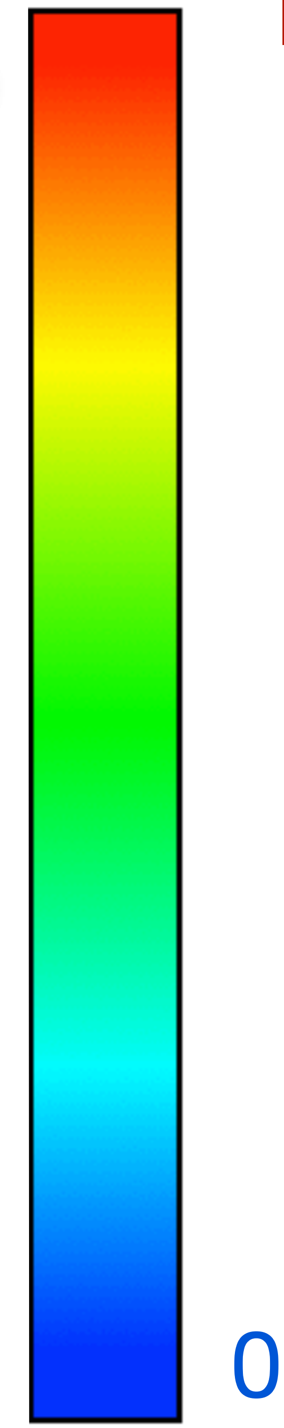
Start with an event

Pass it to the MEM algorithm

Decide whether it looks like signal....



Signal



Background

Matrix Element Methods

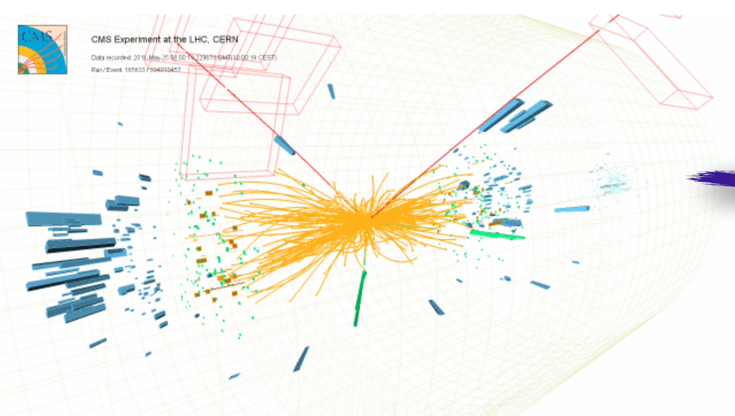
See Michael's Talk!

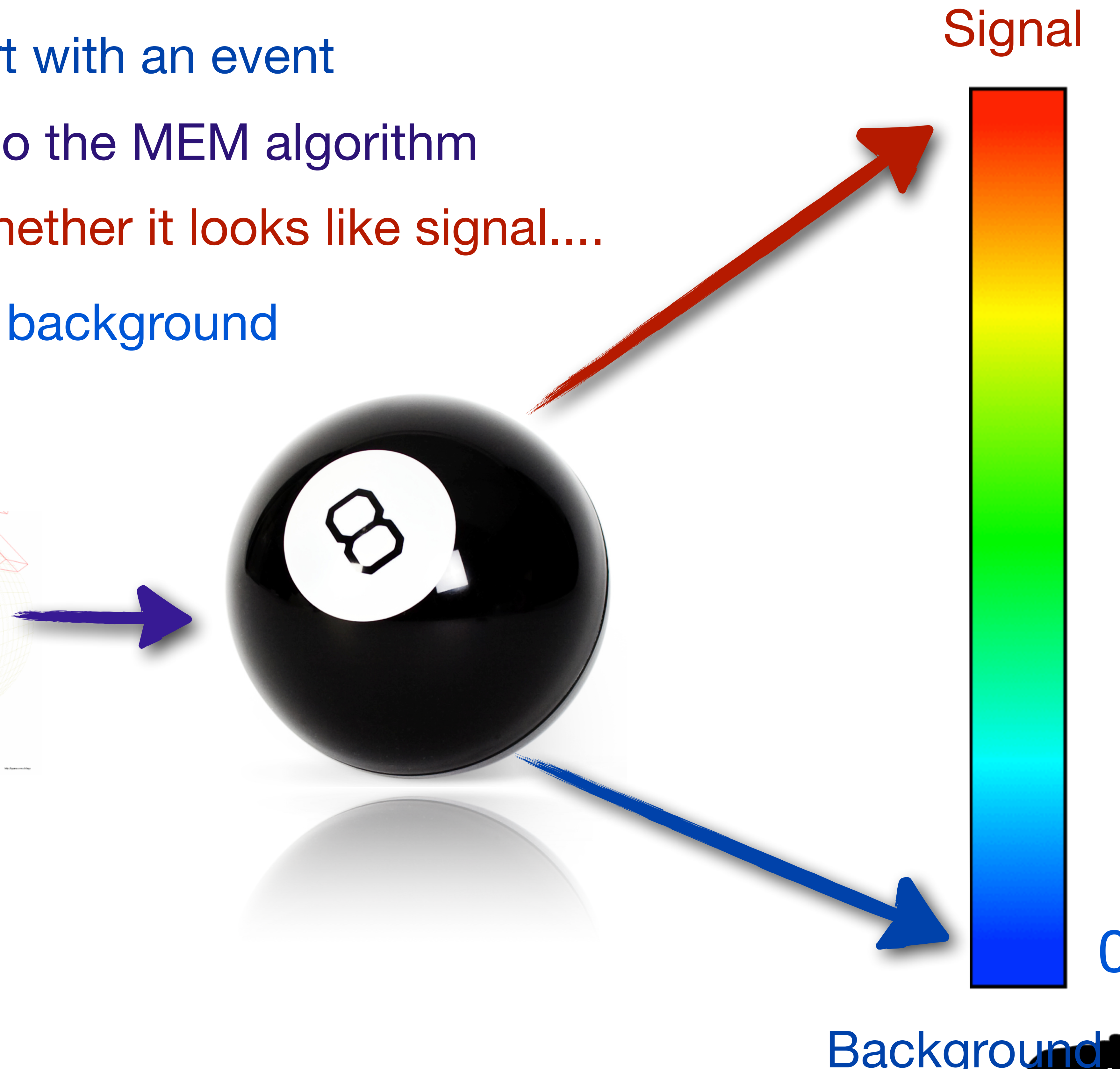
Start with an event

Pass it to the MEM algorithm

Decide whether it looks like signal....

or background





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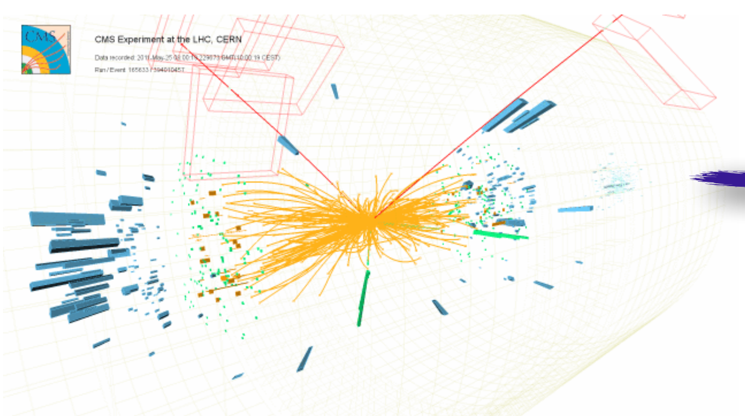
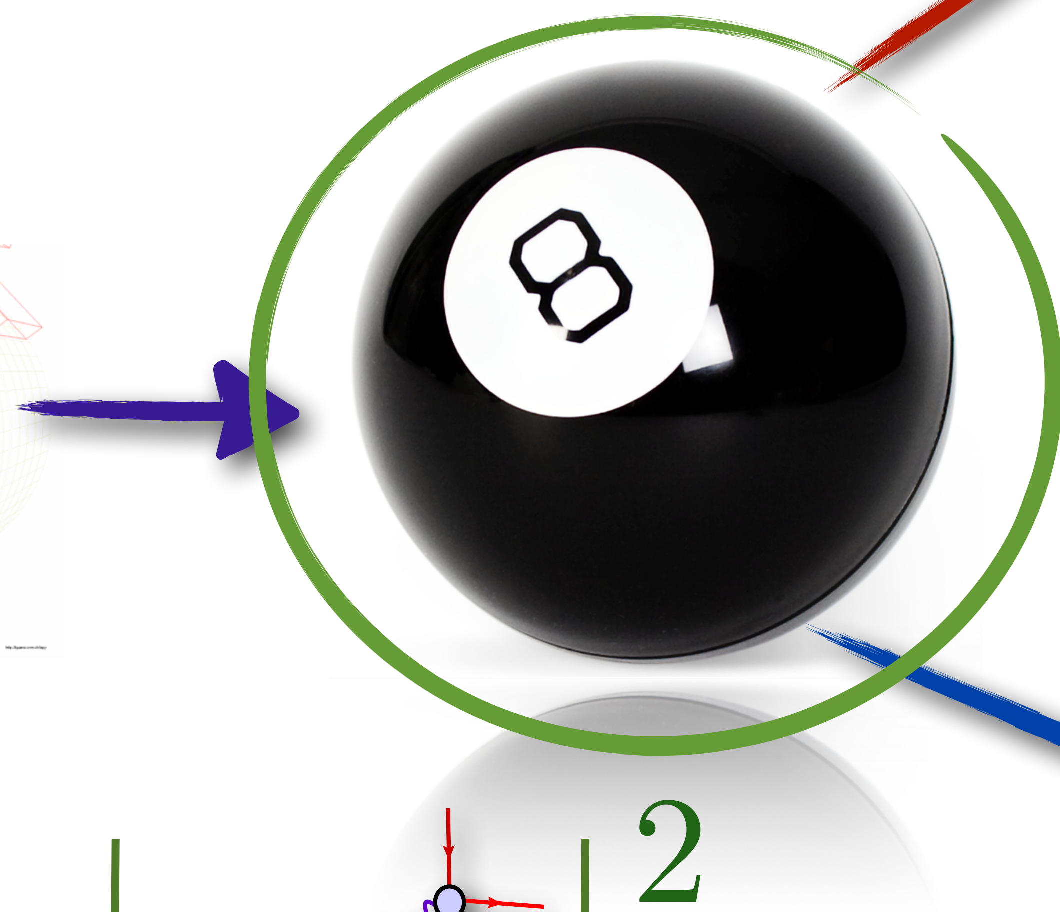
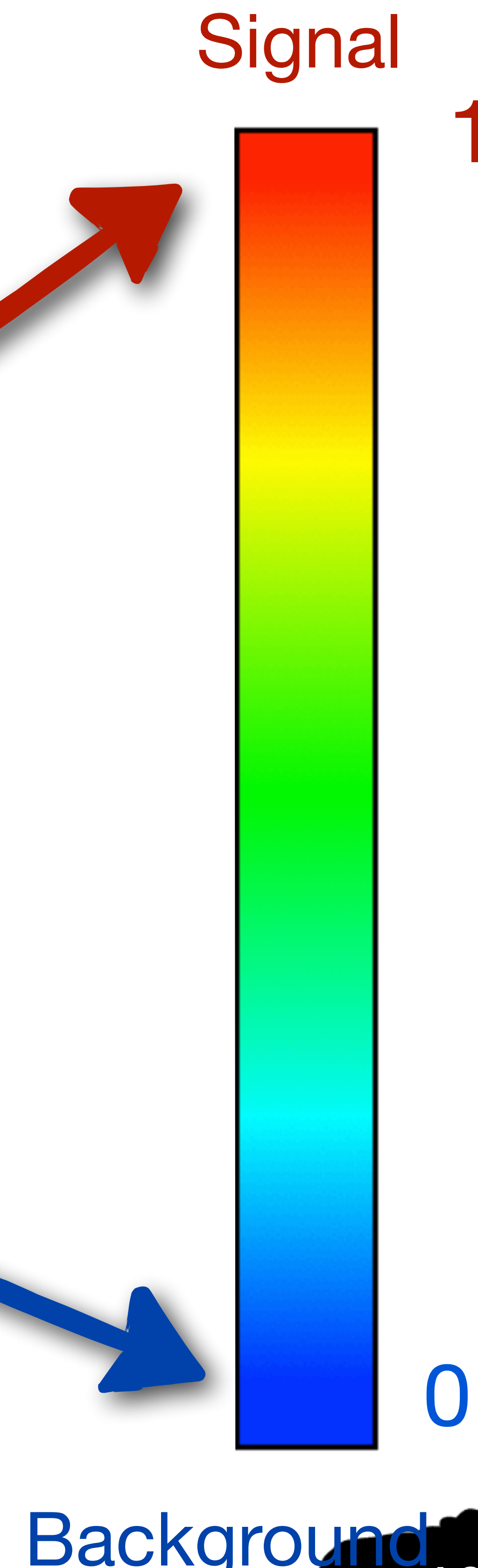
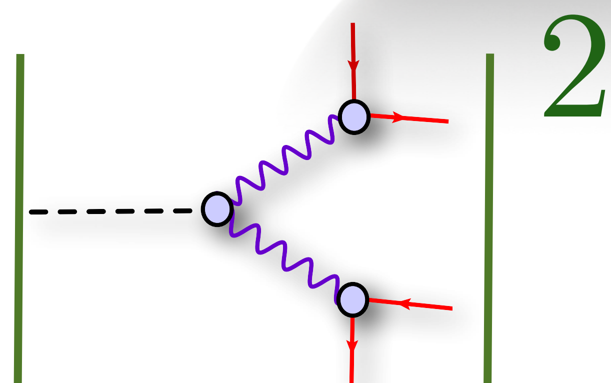


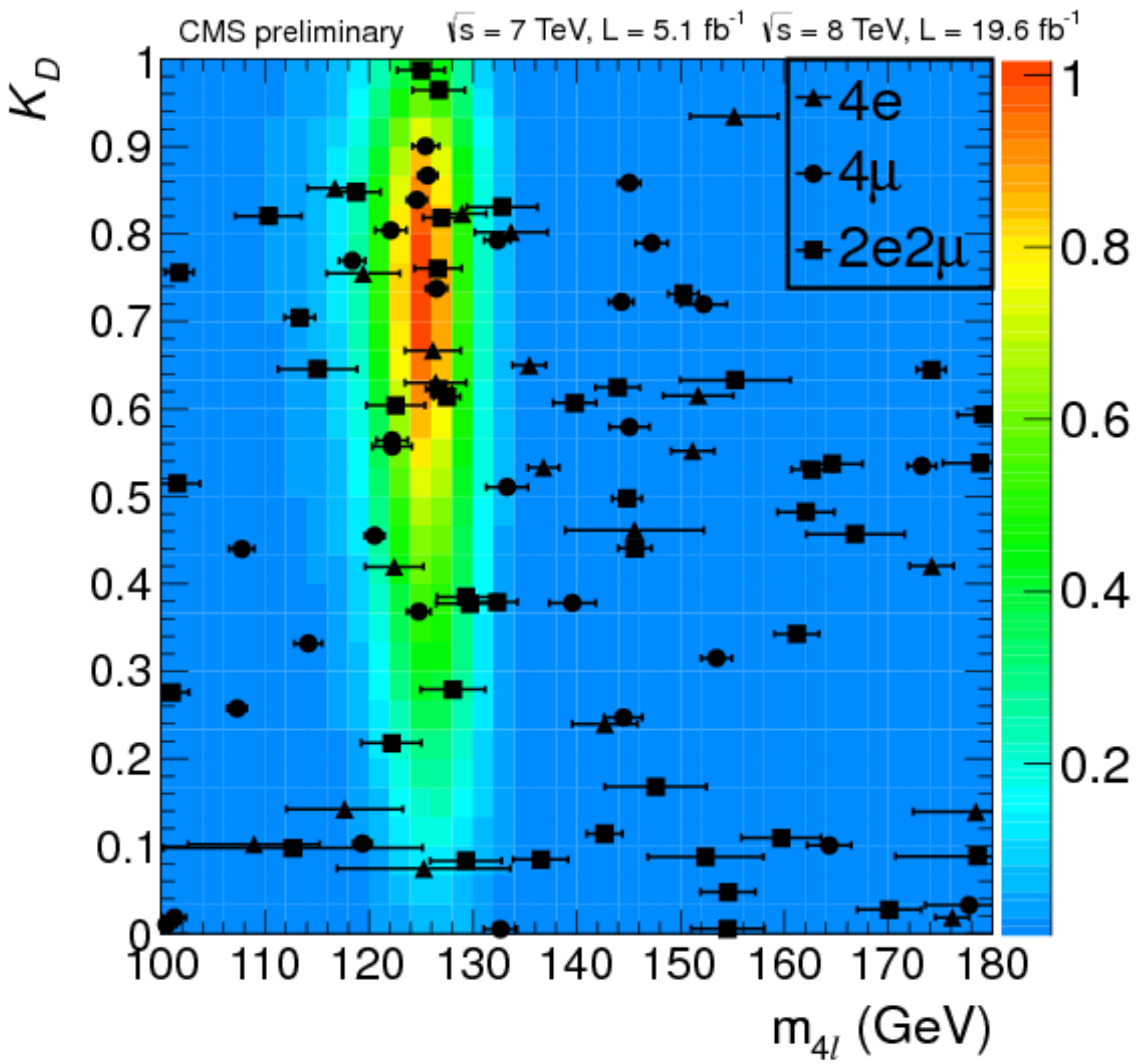


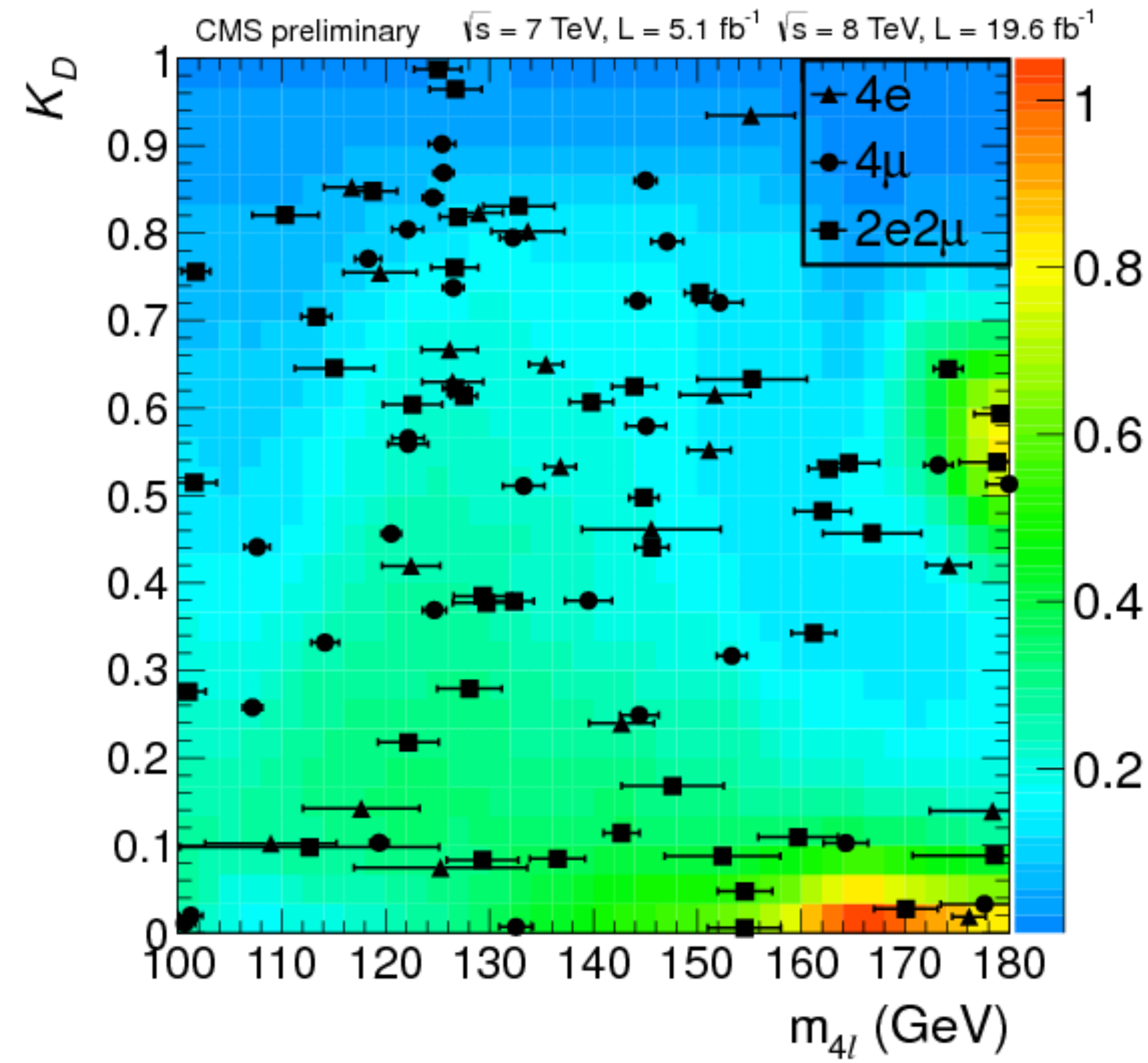


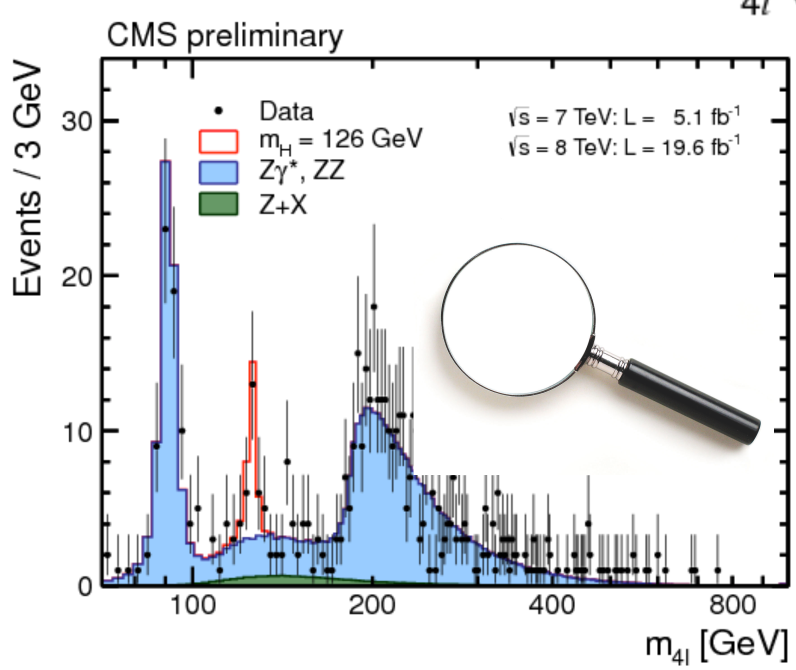
$$|\mathcal{M}|^2 =$$



MEMs in Action



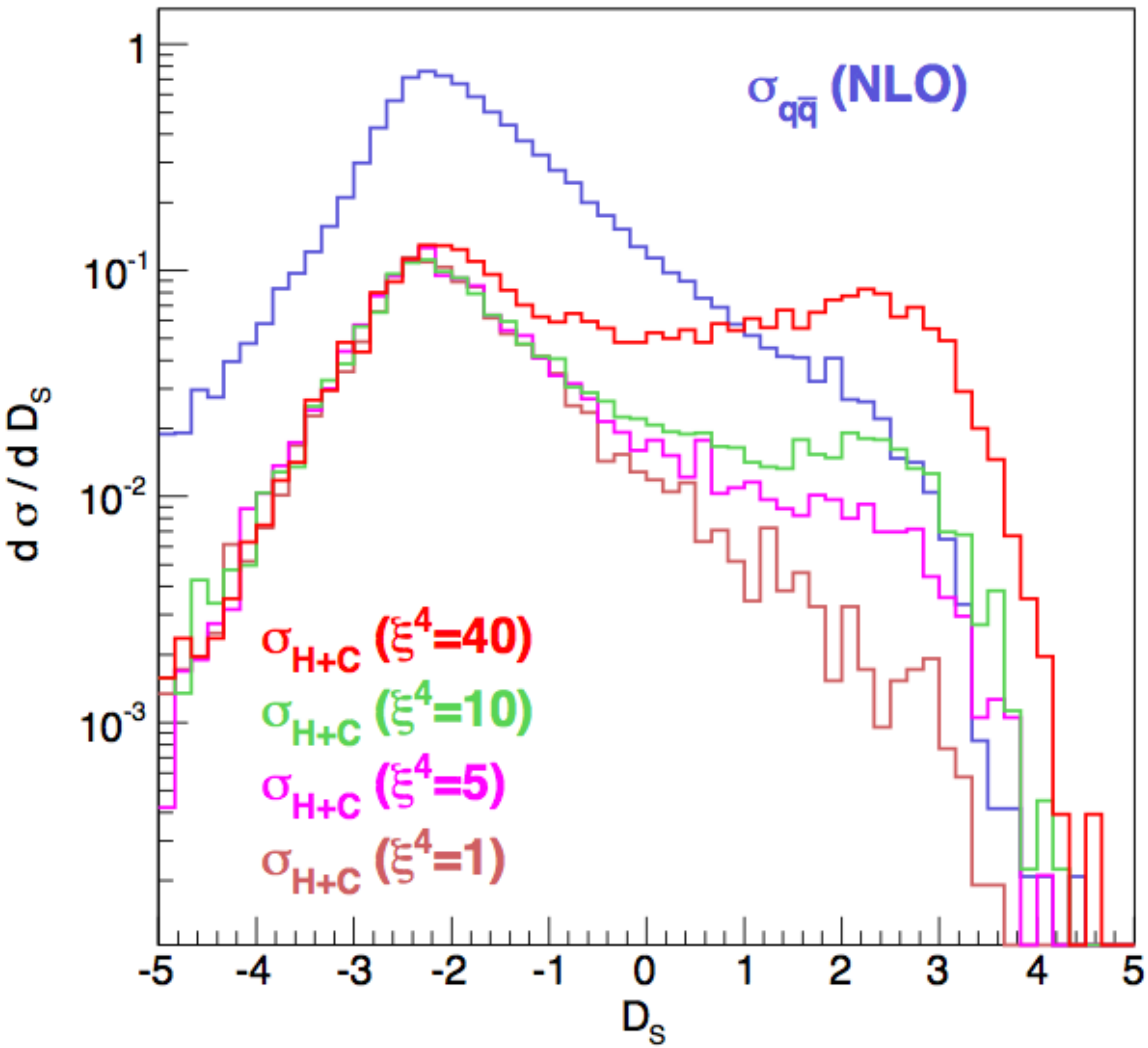




MEM's are powerful tools, we can gain more information than simply looking at a one dimensional distribution.

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

A MEM example.



By studying the most "Higgs like" of events, it appears that couplings rescalings of order 5-10 x SM are accessible.

Similar results should hold in other models, provided they induce kinematic differences w.r.t to the continuum background.

Experimental results and Higgs width interpretation

Interpretation as a bound on the width.

Until now we have only discussed the off-shell cross section.
However opportunities arise when we look at both on and off together,
recall (to leading powers in the coupling)

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

So that

$$\frac{\sigma_{off}}{\sigma_{on}} \propto \Gamma_H \left(\frac{g_T^2(s)g_Z^2(s)}{g_T^2(m_H^2)g_Z^2(m_H^2)} \mathcal{K}(s) + \ldots \right)$$

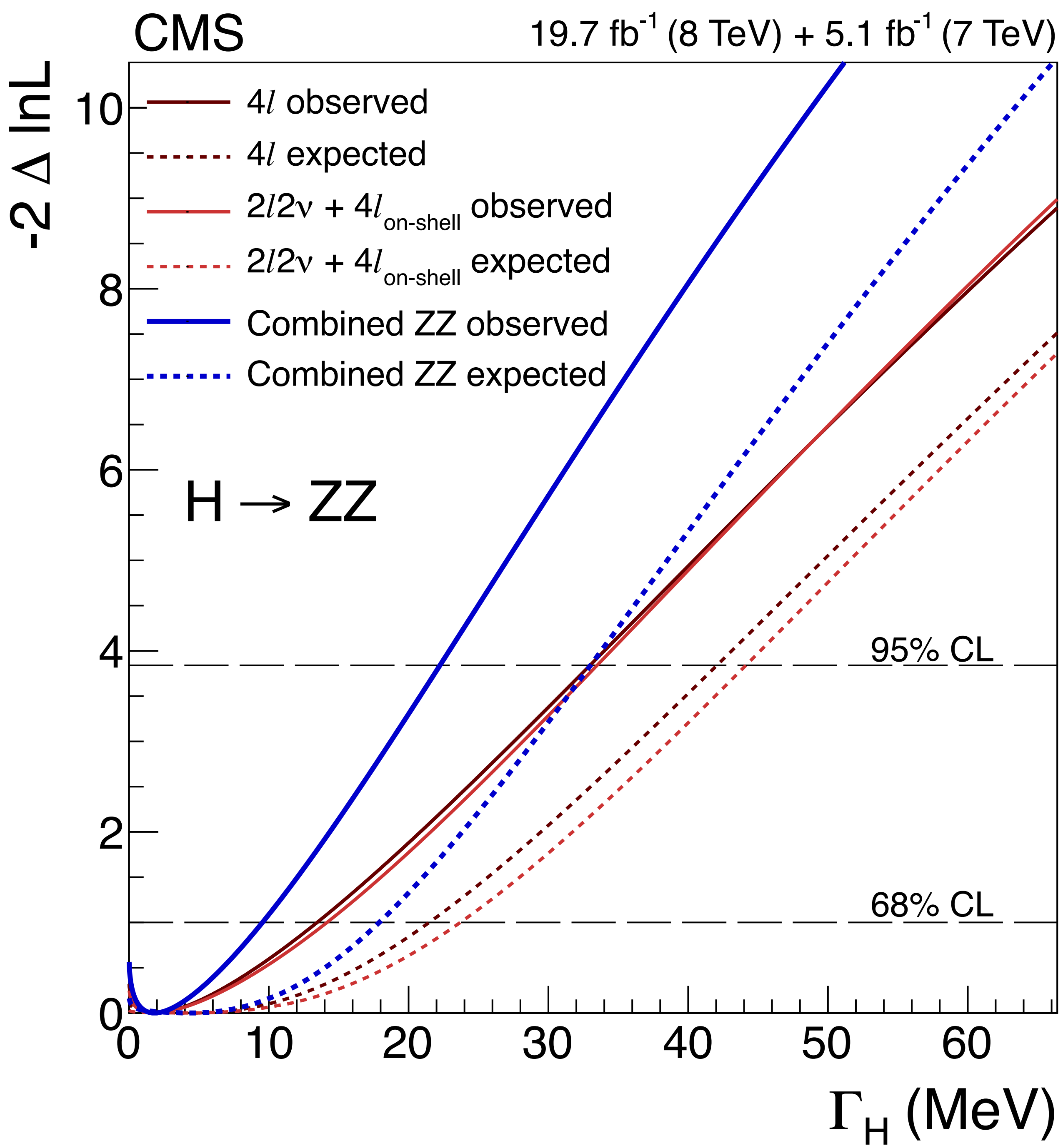
i.e.

$$\frac{\left(\frac{\sigma_{off}}{\sigma_{on}}\right)_{EXP}}{\left(\frac{\sigma_{off}}{\sigma_{on}}\right)_{TH}} \leq \frac{\Gamma_H}{\Gamma_{TH}} \tilde{K}_{TH}^{1} + \sqrt{\frac{\Gamma_H}{\Gamma_{TH}}} \tilde{K}_{TH}^{1/2}$$

where the model dependence is encoded in the theoretical yields in a given model.

CMS Analysis inc. ll + MET

1405.3455 & CMS-PAS-HIG-014-002



CMS work in the model in which the off-shell cross section is a rescaled SM signature

Using a MEM method to construct a kinematic discriminant they find.

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

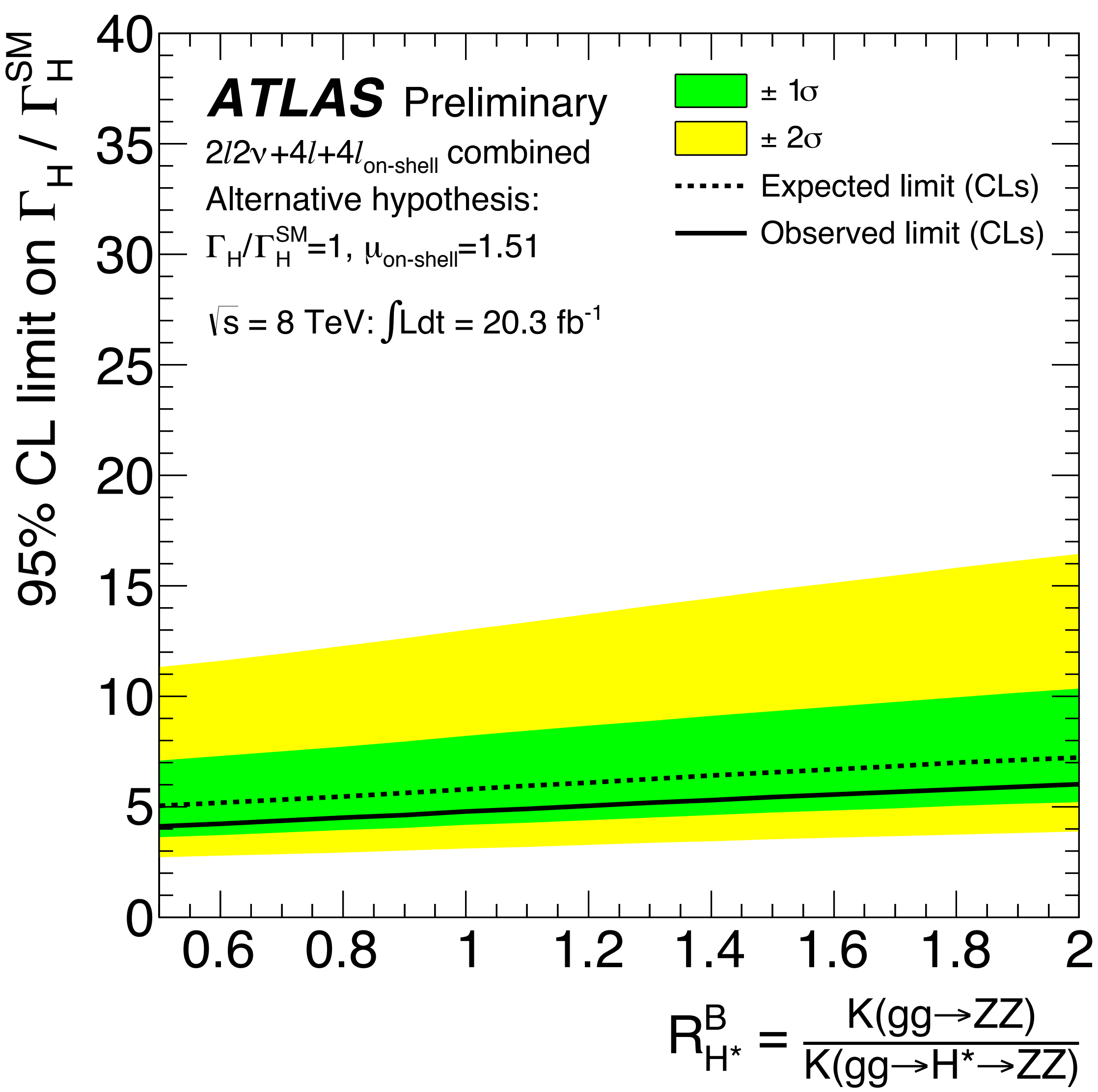
or

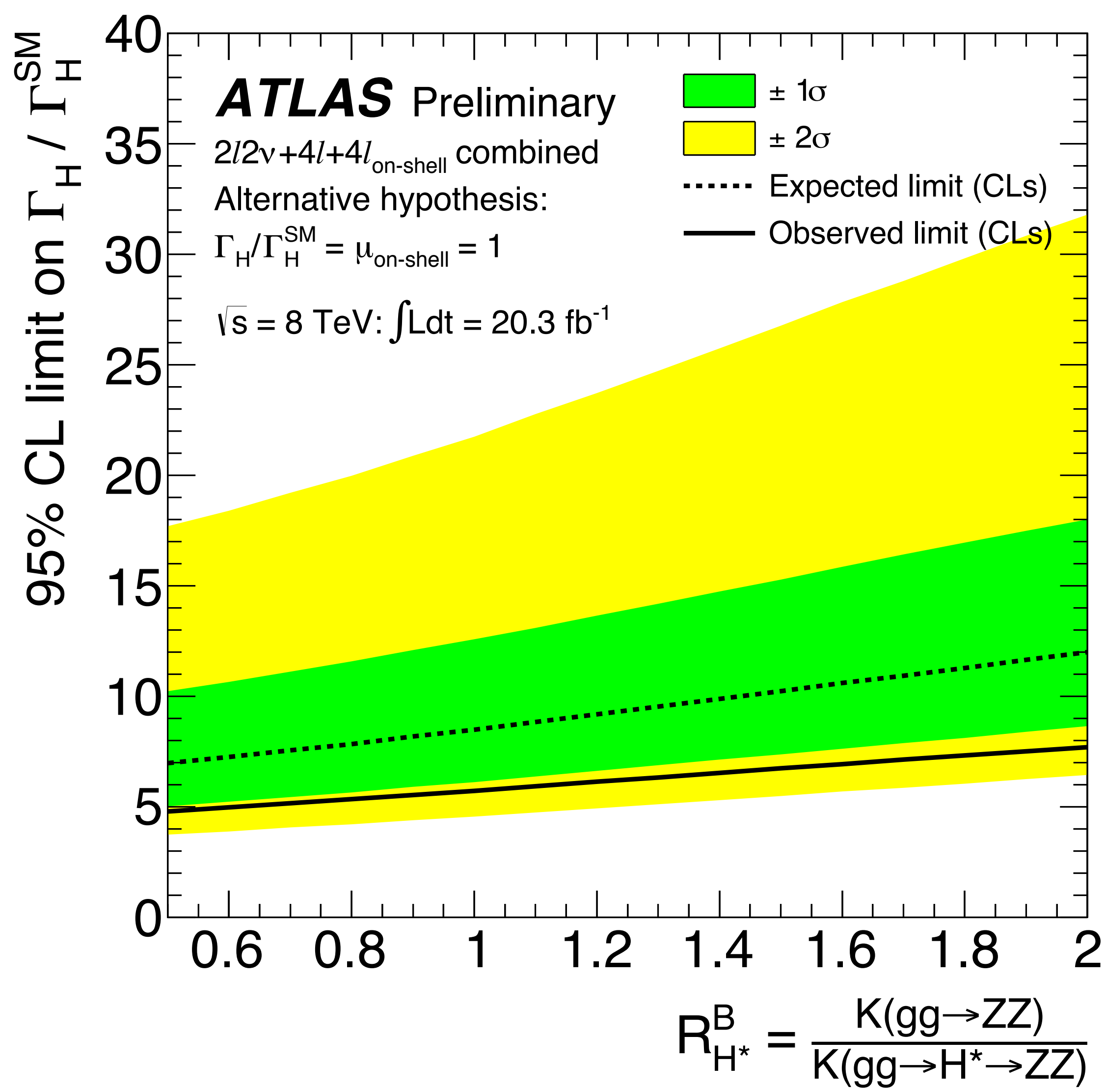
$$\Gamma_H \leq 22\ \mathrm{MeV}$$

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.





Recent developments and Future directions

BSM scenarios :

The off-shell cross section bound can 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 change the off-shell analysis, the aim is to use the off-shell cross section to bound the coefficients of the various EFT operators at high inv. mass.

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

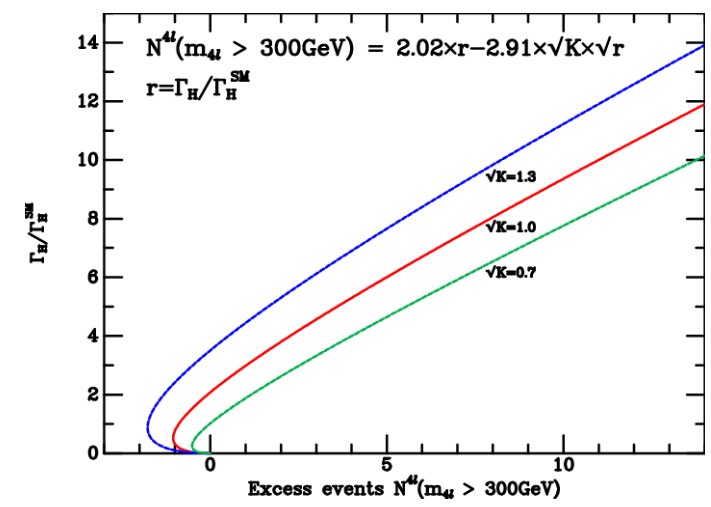
(Englert, Spannowsky 14')

(Ghezzi, Passarino, Uccriati 14')

(Azatov, Grojean, Paul, Salvioni 14')

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

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 in full)

A further necessary improvement on the discussions herein 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')

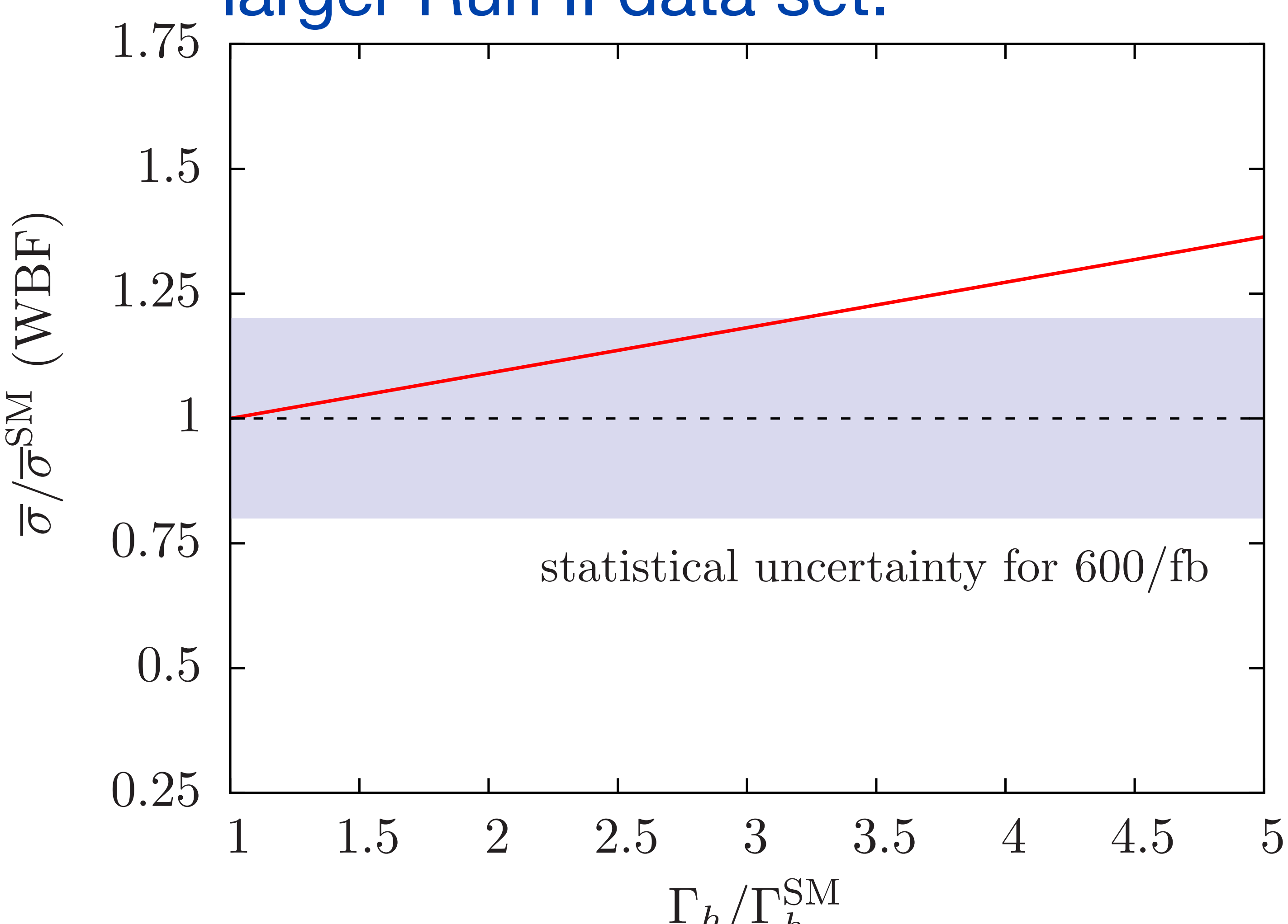
(Gehrmann, Grazzini, Kallweit, Maierhöfer, Manteuffel, Pozzorini, Rathlev, Tancredi 14')

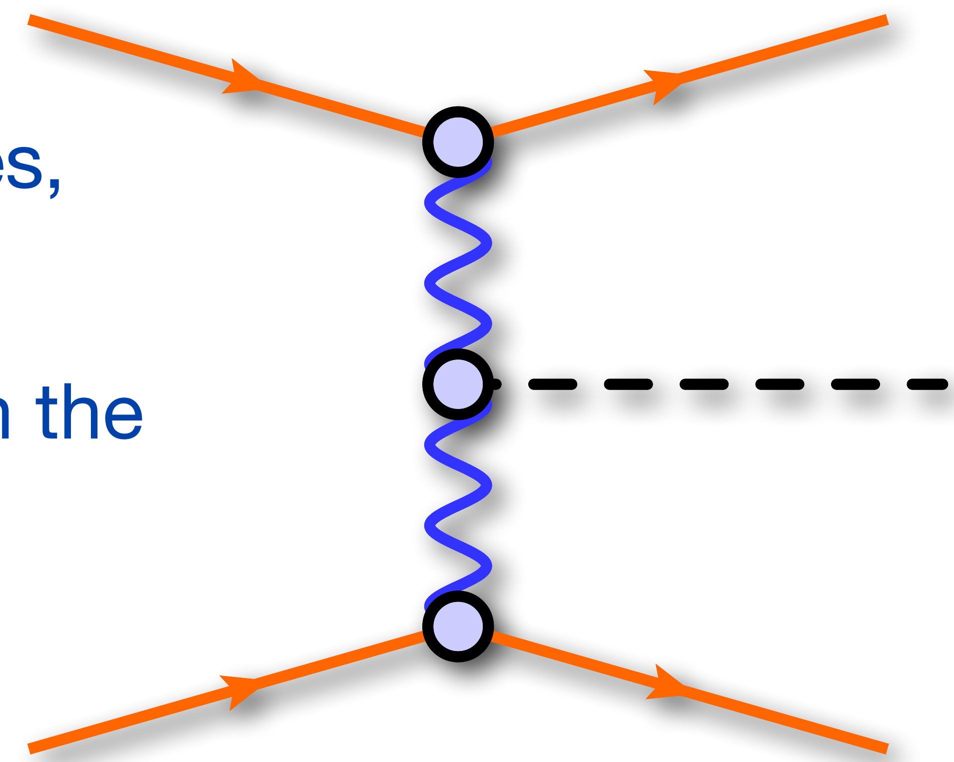
(Caola, Melnikov, Ronstch, Tancredi 15')

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 are obtained using rescalings of the SM, finding sensitivity to values of around 5-7 * SM parameters.
- Theory errors are dominated by LO predictions off-shell.
- By increasing the precision of the predictions, and investigating other channels, further improvements in Run II can be expected…..