Higgs II : Higgs at the LHC

CTEQ Summer School 2017

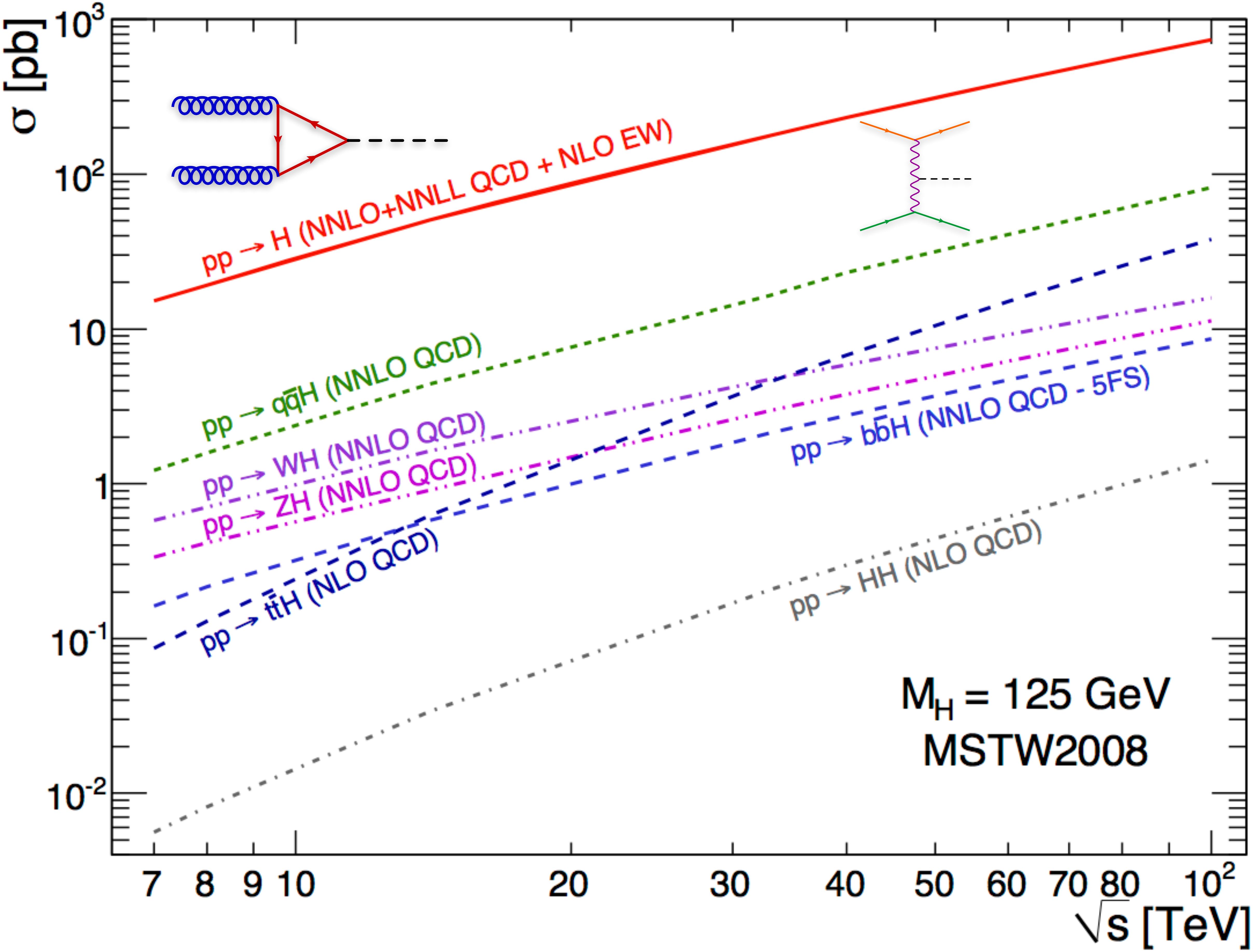
Ciaran Williams

This Lecture

- **Life of the Higgs :** Production mechanisms at the LHC, Heavy top EFT.
- **Death of the Higgs:** Decays of the Higgs boson.
- **Future of the Higgs:** Outstanding issues, future measurements and prospects.

Life of the Higgs boson.

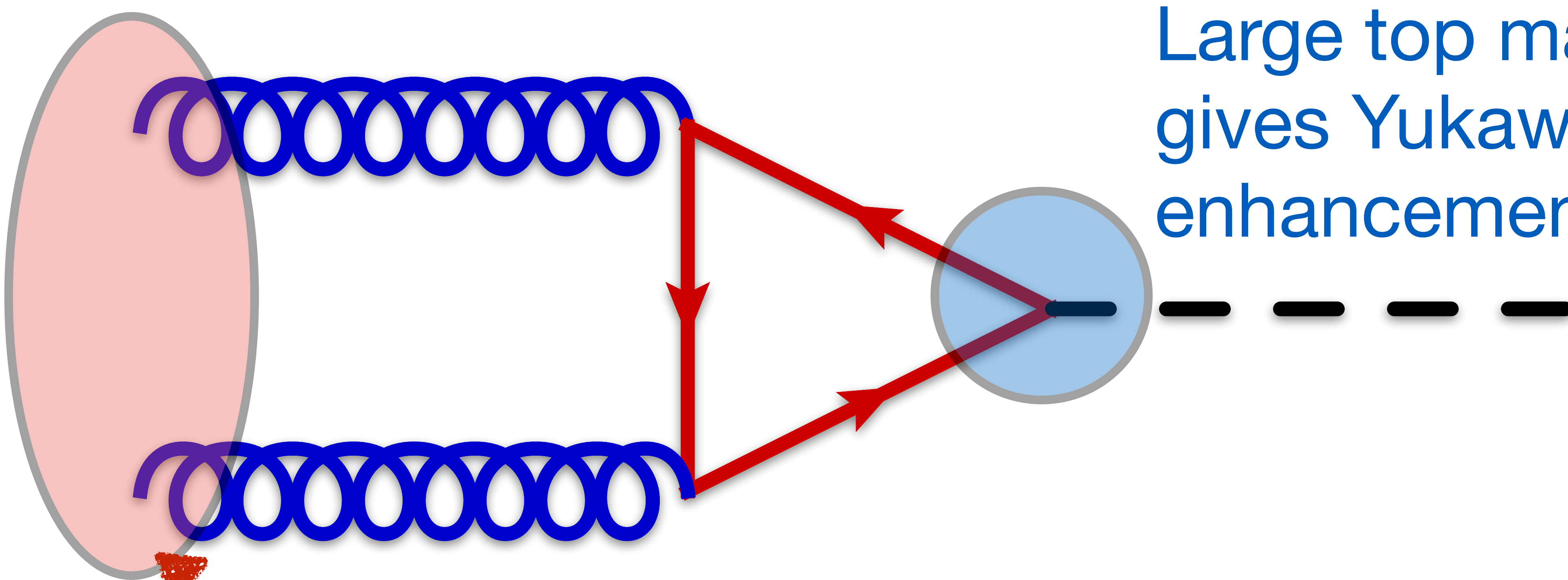
Higgs production XS



Gluon Fusion

At pp colliders gluon fusion is the dominant Higgs production mechanism

Since the gluon is a massless particle, the Higgs couples to it via a virtual top quark loop.



Large top mass gives Yukawa enhancement.

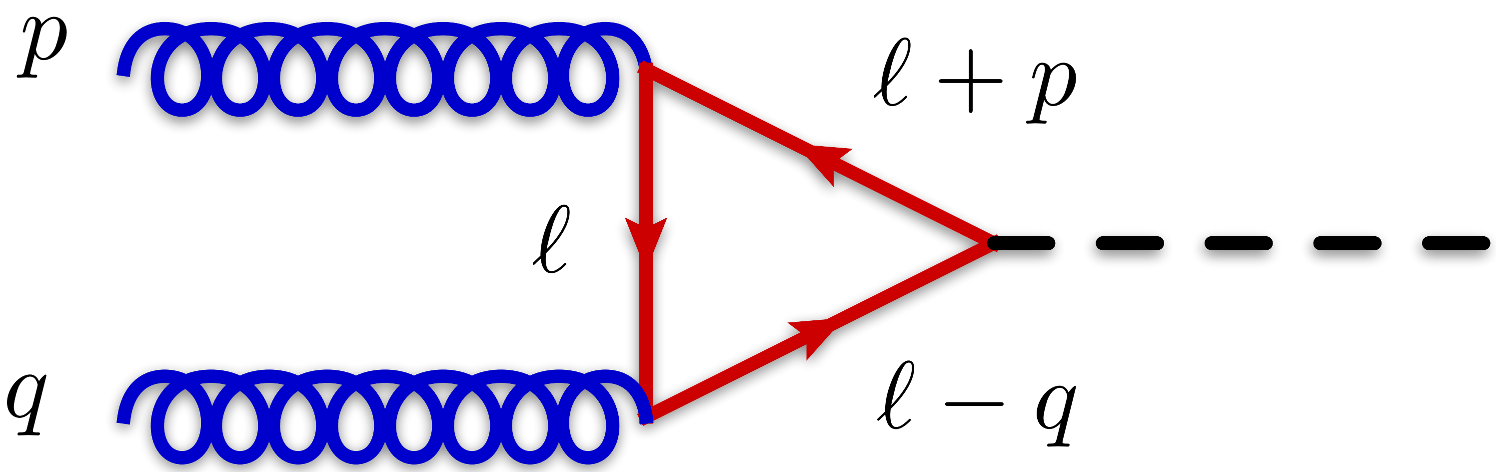
Gluon PDFs dominate $m_H/\sqrt{s}$

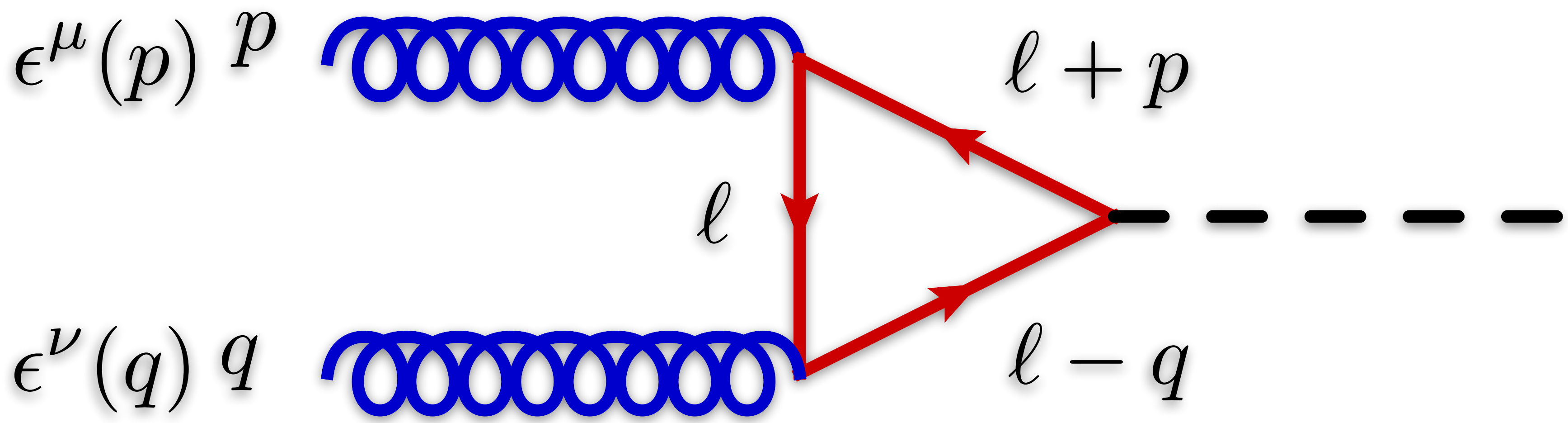
Calculating Gluon Fusion

The task is considerably more complicated due to the presence of the top quark loop.

You've probably seen that loop diagrams often generate infinities. Do we expect this process to have these issues? Why?

Lets see how we go about calculating this amplitude.





We can write the amplitude as the following tensor combination.

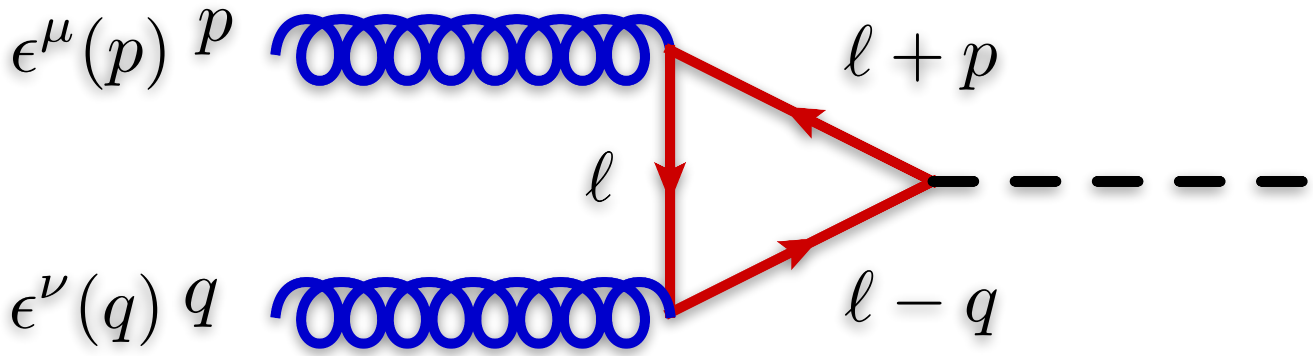
$$\mathcal{A} \sim A_{\mu\nu}\epsilon^\mu(p)\epsilon^\nu(q)$$

If we were being smart then we would realize that the form of A is constrained since

$$q_\nu \epsilon^\nu(q) = 0$$

So we should find,

$$A^{\mu\nu} = Bg^{\mu\nu} + Cp^\nu q^\mu$$



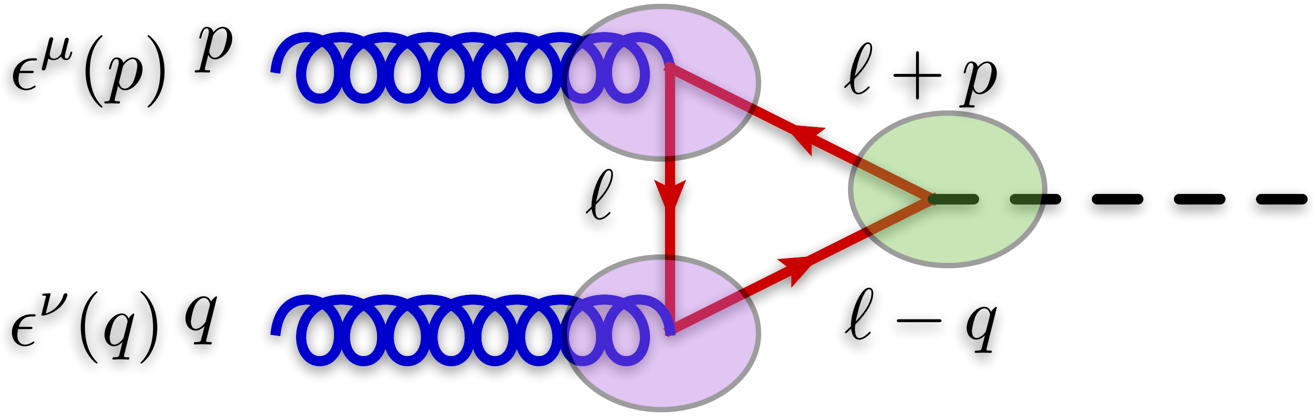
In fact, the Ward identity completely fixes the tensor structure.

$$A^{\mu\nu} = B\left(g^{\mu\nu}\frac{m_H^2}{2} - p^\nu q^\mu\right)$$

Note that as required,

$$A^{\mu\nu}p_\mu = A^{\mu\nu}q_\nu = 0$$

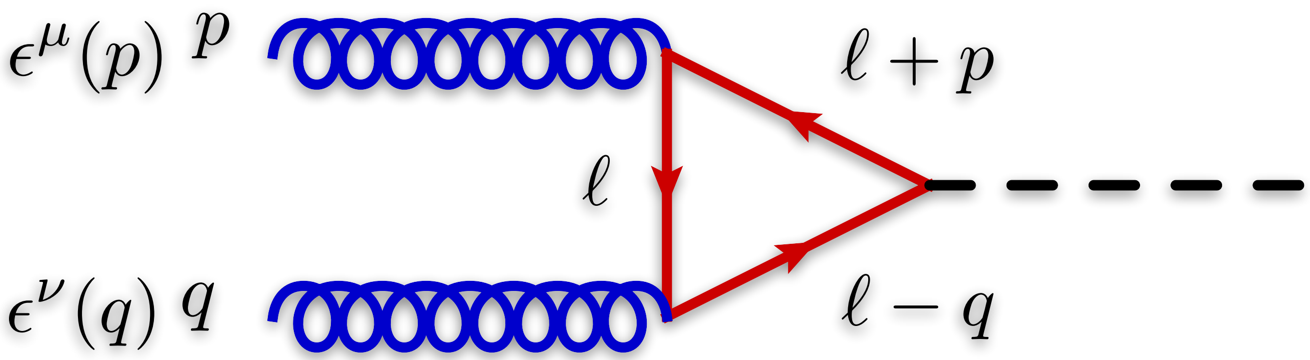
We can use this to drop the more complicated structure from our calculation (i.e. we calculate B as simply as possible!)



Using the Feynman rules we find that this diagram gives us the following contribution

$$i\mathcal{A} = -(-ig_s)^2 \mathrm{Tr}(t^a t^b) \left(\frac{-im_t}{v}\right) \int \frac{d^d\ell}{(2\pi)^d} \frac{N_{\mu\nu}}{\mathcal{D}} i^3 \epsilon^\mu(p) \epsilon^\nu(q)$$

QCD Vertices | Higgs Vertex | Propagators



$$iA = -(-ig_s)^2 \mathrm{Tr}(t^a t^b) \left(\frac{-im_t}{v}\right) \int \frac{d^d\ell}{(2\pi)^d} \frac{\mathcal{N}_{\mu\nu}}{\mathcal{D}} i^3 \epsilon^\mu(p)\epsilon^\nu(q)$$

We define the numerator as follows

$$\mathcal{N}_{\mu\nu} = \mathrm{Tr}\left((\ell + p) - m_t)\gamma_\mu(\ell - m_t)\gamma_\nu((\ell - q) - m_t)\right)$$

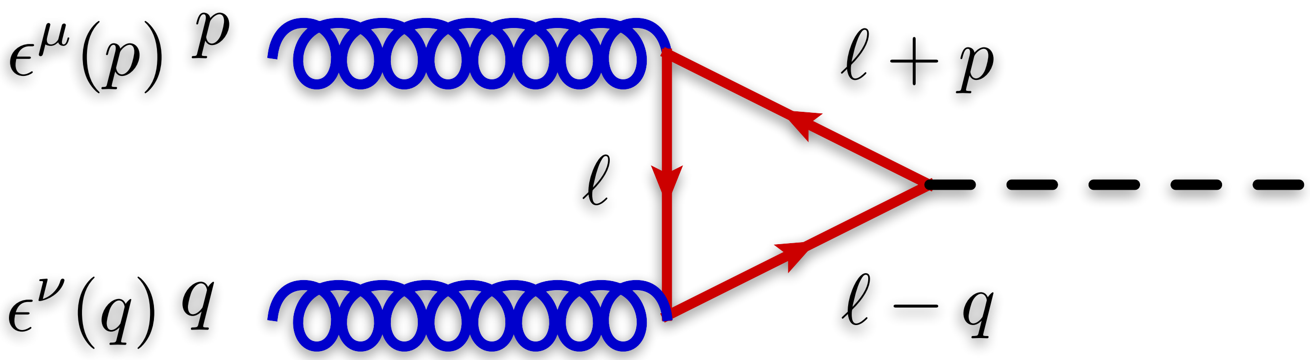
(implicitly defining the momenta as slashed momenta, but dropping the slashes for readability)

And the denominator as follows,

$$\mathcal{D} = ((\ell + p)^2 - m_t^2)(\ell^2 - m_t^2)((\ell - q)^2 - m_t^2)$$

Lets first look at the denominator, we can use the usual Feynman parameter decomposition

$$\frac{1}{D_1 D_2 D_3} = 2\int_0^1 dx \int_0^{1-x} dy \frac{1}{(xD_1 + yD_2 + (1-x-y)D_3)^3}$$



$$i\mathcal{A} = -(-ig_s)^2 \mathrm{Tr}(t^a t^b) \left(\frac{-im_t}{v}\right) \int \frac{d^d\ell}{(2\pi)^d} \frac{\mathcal{N}_{\mu\nu}}{\mathcal{D}} i^3 \epsilon^{\mu}(p)\epsilon^{\nu}(q)$$

$$\frac{1}{D_1 D_2 D_3} = 2\int_0^1 dx \int_0^{1-x} dy \frac{1}{(xD_1 + yD_2 + (1-x-y)D_3)^3}$$

So we can use this trick to group all of the loop momenta dependence into one term (at the cost of additional integrals).

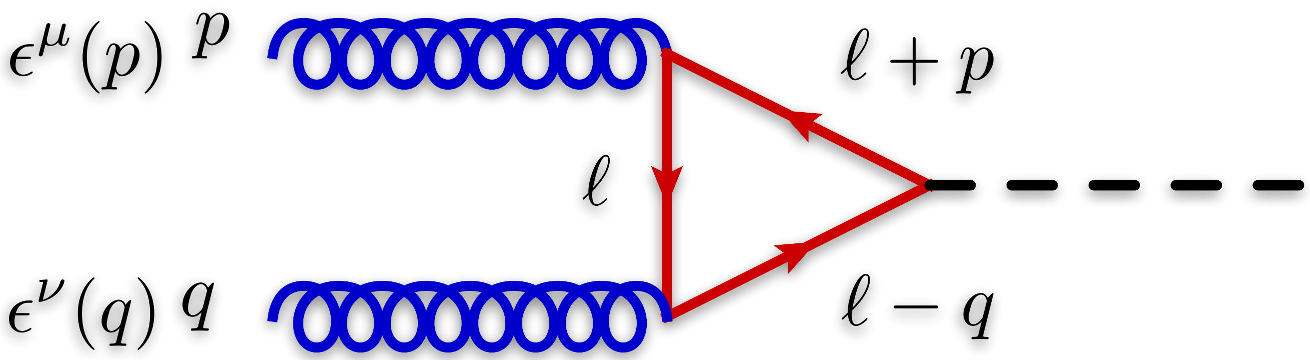
$$\frac{1}{\mathcal{D}} = 2\int dx dy \frac{1}{[\ell^2 - m_t^2 + 2\ell\cdot(px - qy)]^3}$$

This doesnt look like much of an improvement, however if we make the following shift

$$\ell \to \ell - px + qy = \ell'$$

Then

$$\frac{1}{\mathcal{D}} = 2\int dx dy \frac{1}{[(\ell')^2 - m_t^2 + 2p\cdot qxy]^3}$$



$$\frac{1}{\mathcal{D}} = 2\int dxdy \frac{1}{[(\ell')^2 - m_t^2 + 2p\cdot qxy]^3}$$

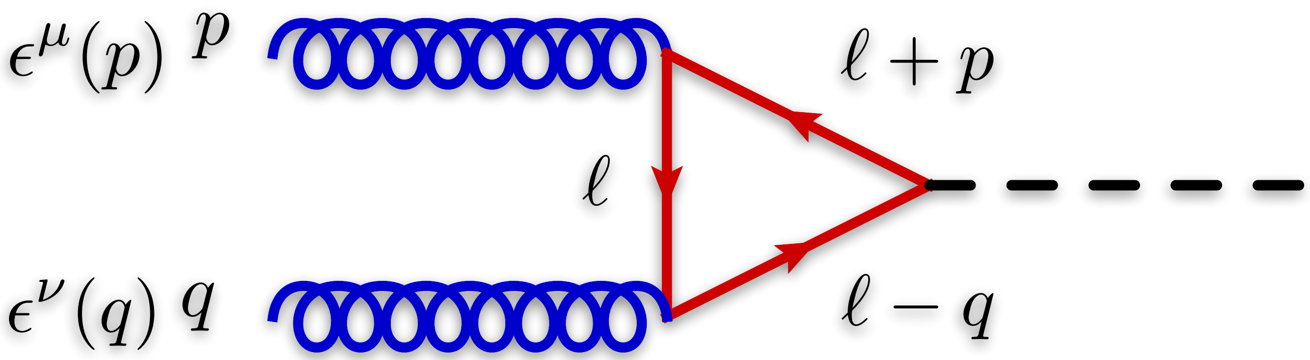
We can simplify this even more since $2p\cdot q = m_H^2$

So $$\frac{1}{\mathcal{D}} = 2\int dxdy \frac{1}{[(\ell')^2 - m_t^2 + m_H^2 xy]^3}$$

Next we have to express the numerator in terms of the shifted momentum

I'll leave the entire calculation as an exercise and instead use our result that we can get everything from the $p^\mu q^\nu$ term

$$N_{\mu\nu}(\ell', p_\nu q_\mu) = 4(1-4xy)m_t p_\nu q_\mu$$



$$\frac{1}{\mathcal{D}} = 2\int dxdy \frac{1}{[(\ell')^2 - m_t^2 + 2p\cdot qxy]^3}$$

$$N_{\mu\nu}(\ell', p_\nu q_\mu) = 4(1-4xy)m_t p_\nu q_\mu$$

Putting this all together we see that our (partial) diagram can be written as follows

$$i\mathcal{A}_{pq} = -\delta^{ab}\frac{2g_s^2 m_t^2}{v}\int \frac{d^d\ell'}{(2\pi)^d}\int dxdy \frac{2p^\nu q^\mu (1-4xy)}{[(\ell')^2 - m_t^2 + m_H^2 xy]^3}\epsilon^\mu(p)\epsilon^\nu(q)$$

Great! Now we want to do the loop momenta integral

You can look this up in your favorite QFT textbook,

$$\int \frac{d^d\ell}{(2\pi)^d}\frac{1}{(\ell^2-\Delta)^3} = -\frac{i(4\pi)^\epsilon}{32\pi^2}\Gamma(1+\epsilon)\Delta^{-1-\epsilon}$$

Note that this is finite. (The pole cancellation for the other tensor structure is more intricate).

Finally we can write the whole tensor structure as a finite integral

$$\mathcal{A}_{pq} = \frac{\alpha_s m_t^2}{\pi v} \delta^{ab} p_\nu q_\mu \int dx dy \left(\frac{1 - 4xy}{m_t^2 - m_H^2 xy} \right) \epsilon^\mu(p) \epsilon^\nu(q)$$

Note that we are still some way away from a physical cross section (we need to restore the full tensor structure, include the second diagram (factor of 2), square the amplitude, convolve with PDFs…)

However, we can actually learn a lot from the above expression

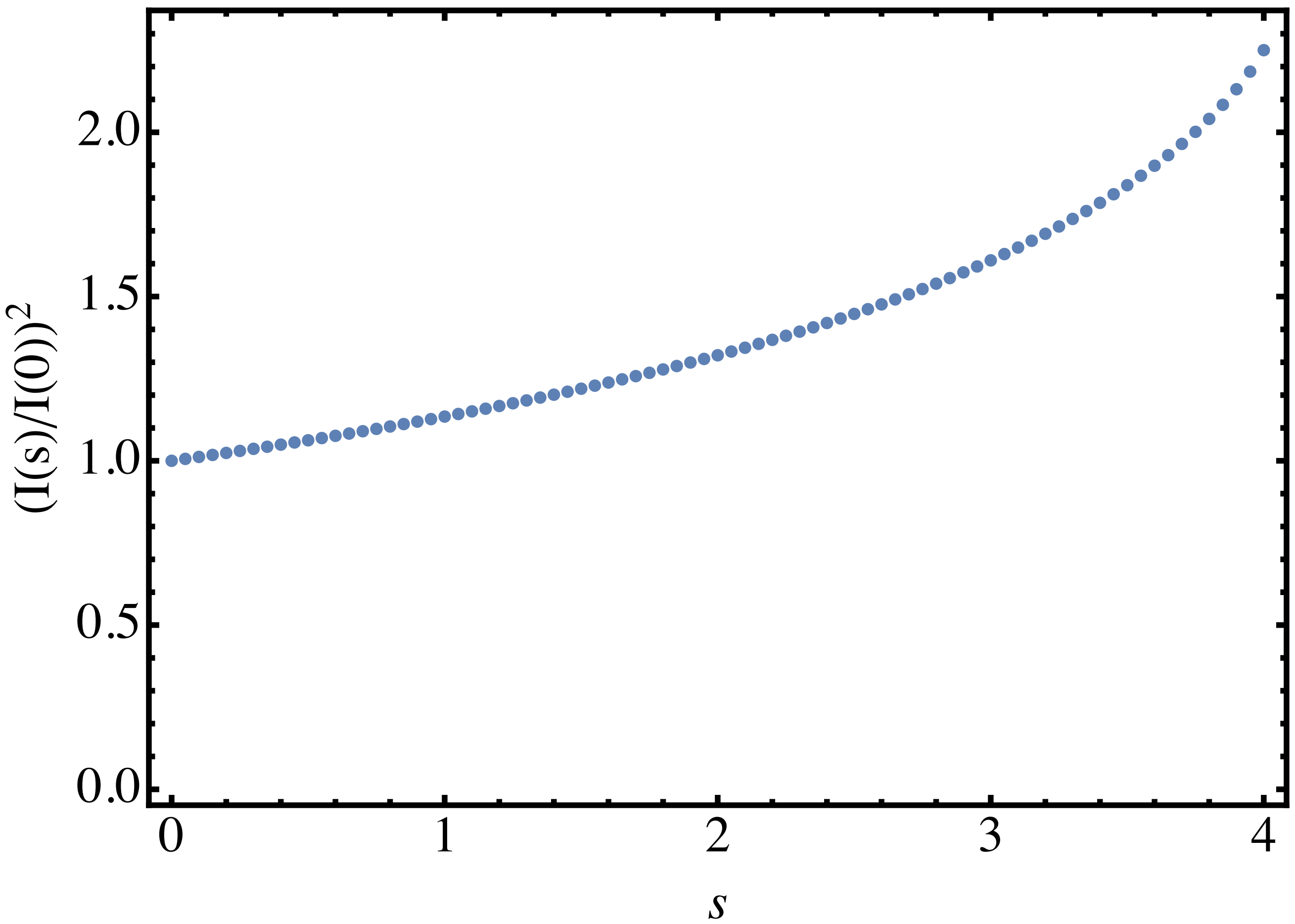
If we define

$$I(s) = \int dx dy \left(\frac{1 - 4xy}{1 - sxy} \right)$$

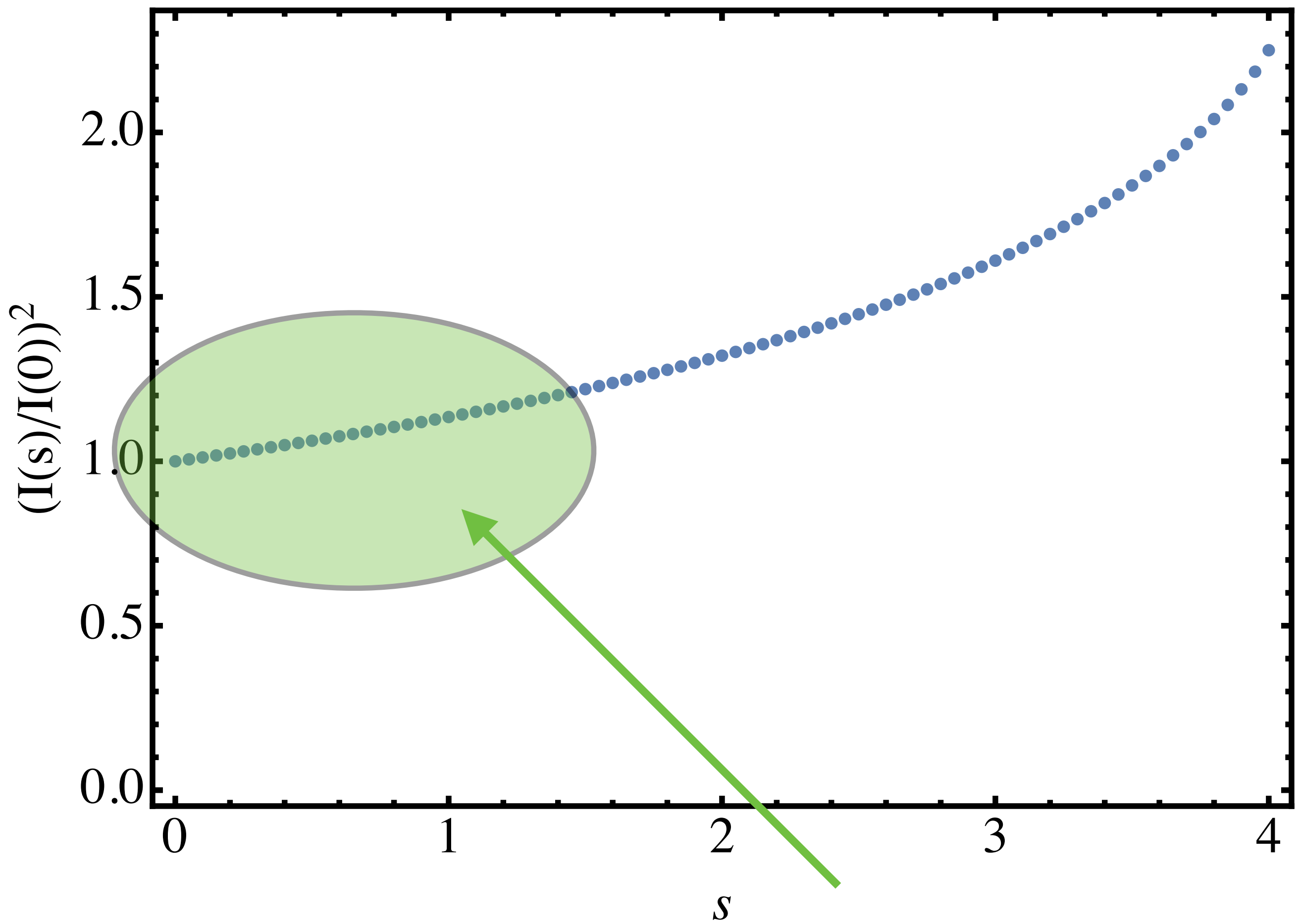
Then

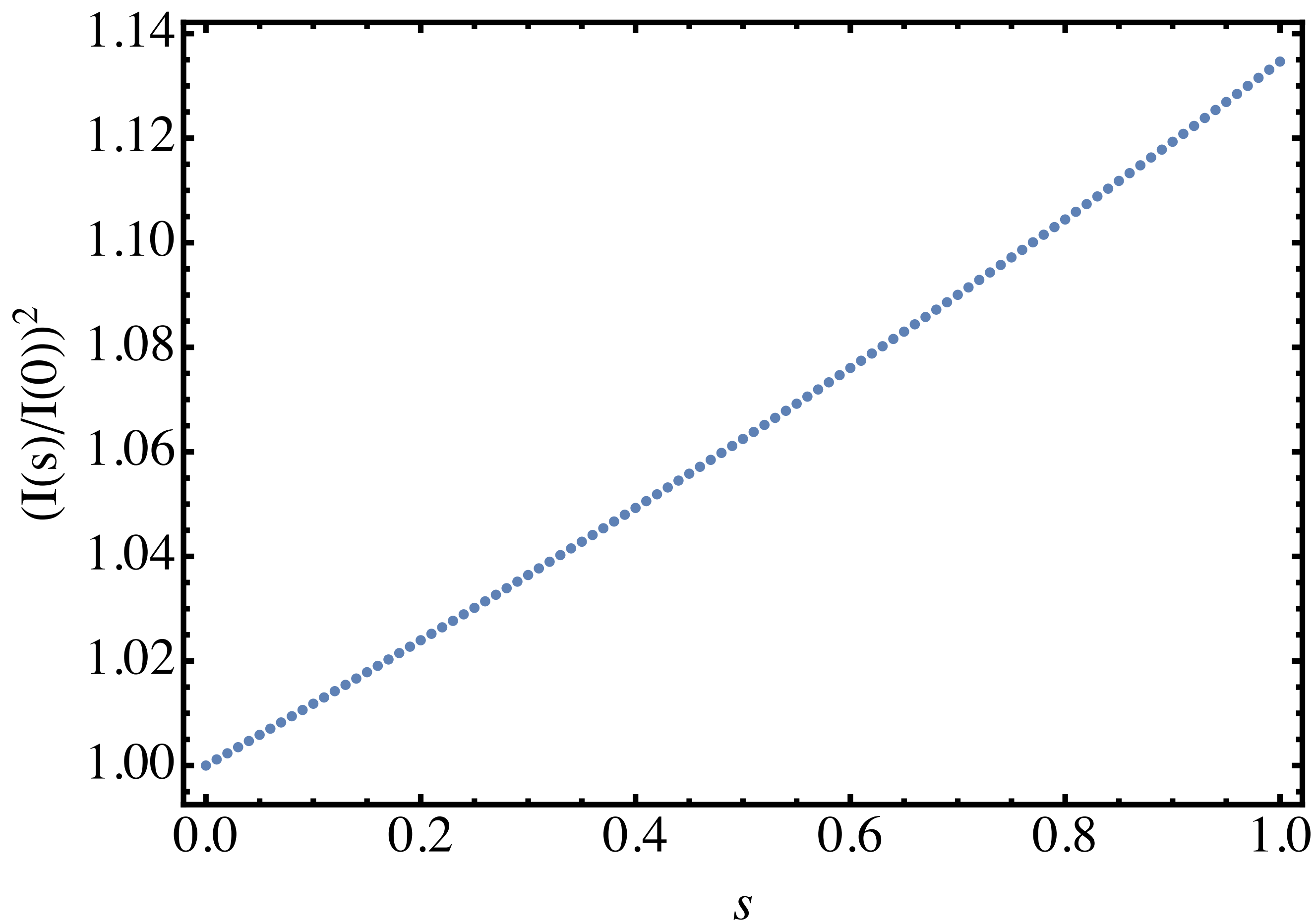
$$\mathcal{A}_{pq} = \frac{\alpha_s}{\pi v} \delta^{ab} (\epsilon(p) \cdot q)(\epsilon(q) \cdot p) I(m_H^2/m_t^2)$$

Lets look at the ratio of (I(s)/I(0))^2 as a function of s



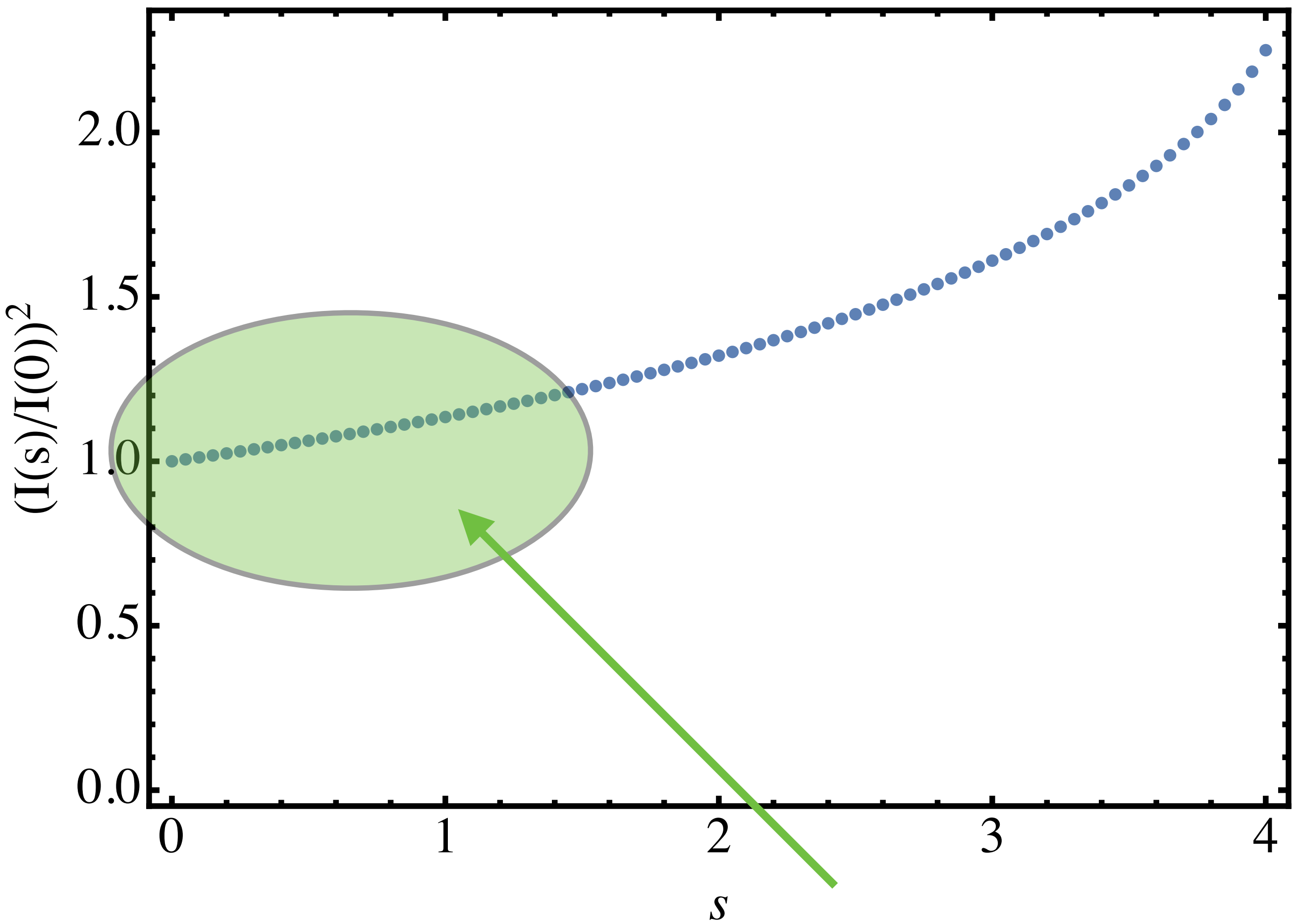
Lets look at the ratio of (I(s)/I(0))^2 as a function of s

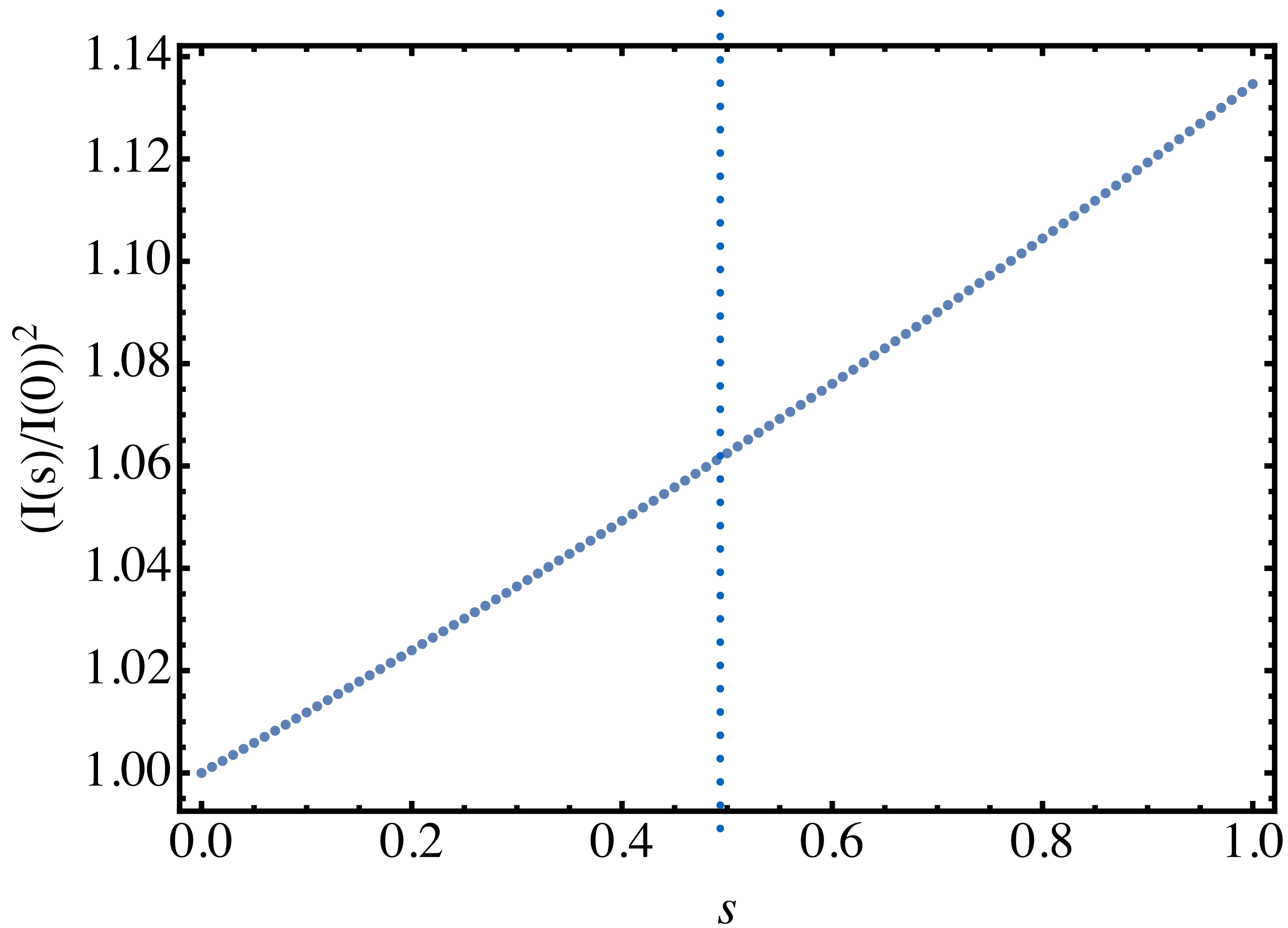




Slowly growing function as a function of s

Lets look at the ratio of (I(s)/I(0))^2 as a function of s





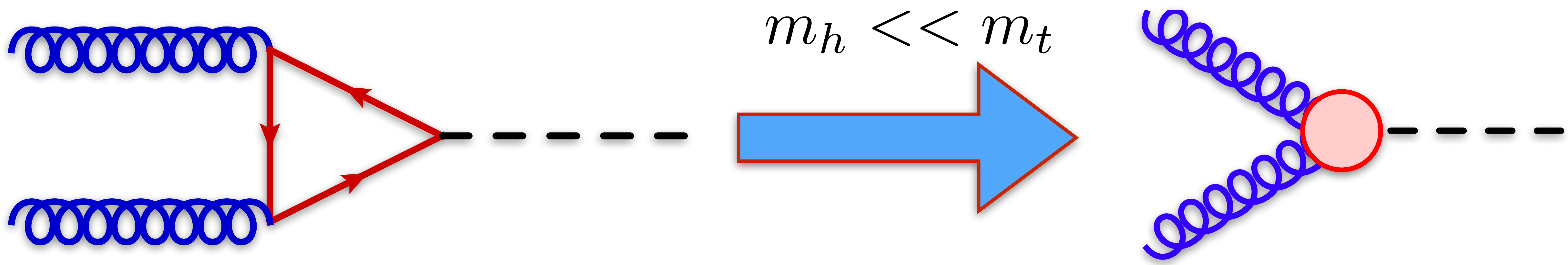
Slowly growing function as a function of s

We see that for the 125 GeV Higgs, the ratio is around 1.05

We see that the effect of the top quark is a small correction to the full result, motivating us to write the amplitude in terms of the s->0 limit.

$$\mathcal{A} = -\frac{\alpha_s}{3\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{m_H^2}{2} - p^\nu q^\mu\right)\epsilon_\mu(p)\epsilon_\nu(q)$$

- The amplitude is independent of the top quark mass
- If heavier fermions were present, they would scale linearly with the amplitude



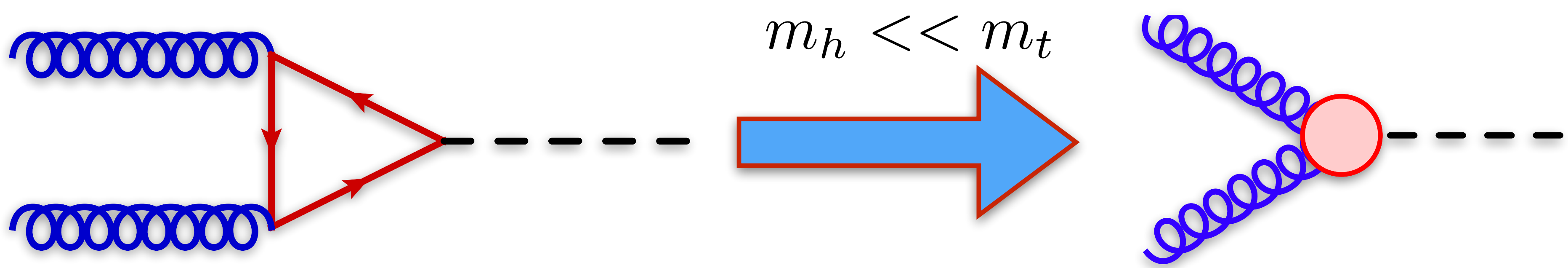
When we take the heavy top limit, we decouple the top quark from the calculation.

This is equivalent to working in an **Effective Field Theory** in which the top quark is integrated out.

I.e. we could have calculated our amplitude by adding the follow term to our QCD Lagrangian

$$\mathcal{L}_{\text{eff}} = -\frac{A}{4} H G_a^{\mu\nu} G^a_{\mu\nu}$$

Lets look at this a little more.



This term has mass dimension 5

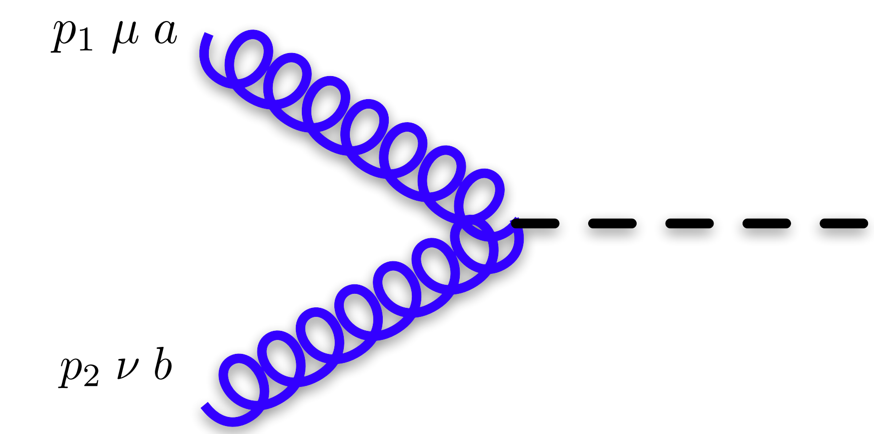
$$\mathcal{L}_{\text{eff}} = -\frac{A}{4} H G_a^{\mu\nu} G^a_{\mu\nu}$$

So A has to have an inverse mass dimension, we can get A from our calculation.

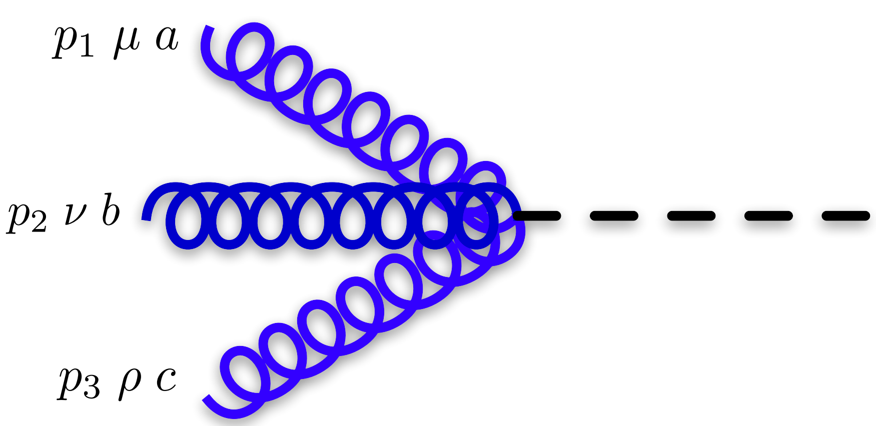
$$A = \frac{\alpha_s}{3\pi v}\left(1 + \mathcal{O}(\alpha_s)\right)$$

We have matched our EFT operator to the full theory calculation. We can now use this Lagrangian to calculate other quantities.

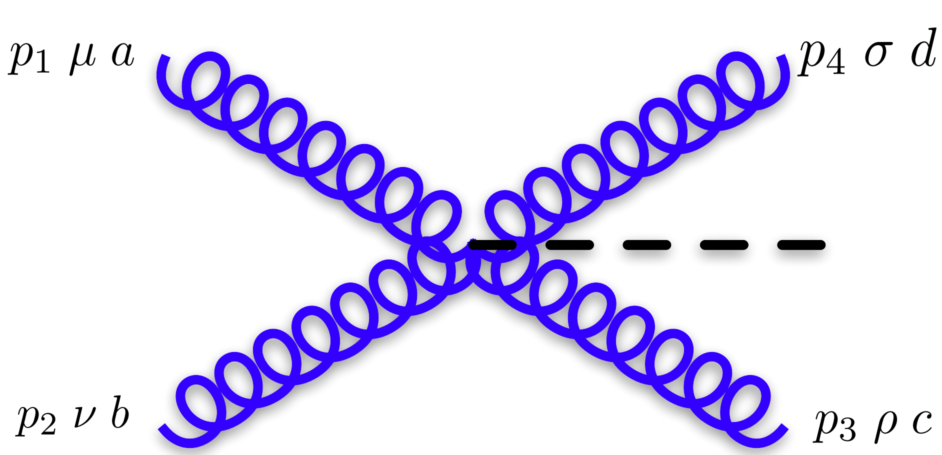
We can expand the field strength contributions to get the Feynman rules for the coupling of the Higgs to two, three and four gluons.



$$iA\delta^{ab}(g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$$



$$-Af^{abc}g_s\Big(g^{\mu\nu}(p_1^\rho - p_2^\rho) + g^{\mu\rho}(p_3^\nu - p_1^\nu) + g^{\nu\rho}(p_2^\mu - p_3^\mu)\Big)$$



$$Ag_s^2\Big(f_{abe}f_{cde}(g^{\mu\sigma}g^{\nu\rho} - g^{\mu\sigma}g^{\nu\rho}) + f_{ace}f_{bde}(g^{\mu\nu}g^{\sigma\rho} - g^{\mu\sigma}g^{\nu\rho}) + f_{ade}f_{bce}(g^{\mu\nu}g^{\sigma\rho} - g^{\mu\rho}g^{\nu\sigma})\Big)$$

The benefit of the EFT is that it allows us to extend the reach of perturbation to higher orders.

For Higgs production this is essential, e.g. expanding the cross section to NNLO we see that

$$\sigma^{NNLO}(gg \to H) = 12.937 \times (1 + 1.28 + 0.77)\ \mathrm{pb}$$

The benefit of the EFT is that it allows us to extend the reach of perturbation to higher orders.

For Higgs production this is essential, e.g. expanding the cross section to NNLO we see that

$$\sigma^{NNLO}(gg \to H) = 12.937 \times (1 + 1.28 + 0.77)\ \text{pb}$$

LO cross section (we just looked at this (almost))

The benefit of the EFT is that it allows us to extend the reach of perturbation to higher orders.

For Higgs production this is essential, e.g. expanding the cross section to NNLO we see that

$$\sigma^{NNLO}(gg \to H) = 12.937 \times (1 + 1.28 + 0.77)\ \mathrm{pb}$$

LO cross section (we just looked at this (almost))

NLO corrections are more than 100%!

The benefit of the EFT is that it allows us to extend the reach of perturbation to higher orders.

For Higgs production this is essential, e.g. expanding the cross section to NNLO we see that

$$\sigma^{NNLO}(gg \to H) = 12.937 \times (1 + 1.28 + 0.77)\,\mathrm{pb}$$

LO cross section (we just looked at this (almost))

NLO corrections are more than 100%!

NNLO Corrections are also huge!

The benefit of the EFT is that it allows us to extend the reach of perturbation to higher orders.

For Higgs production this is essential, e.g. expanding the cross section to NNLO we see that

$$\sigma^{NNLO}(gg \to H) = 12.937 \times (1 + 1.28 + 0.77)\,\text{pb}$$

LO cross section (we just looked at this (almost))

NLO corrections are more than 100%!

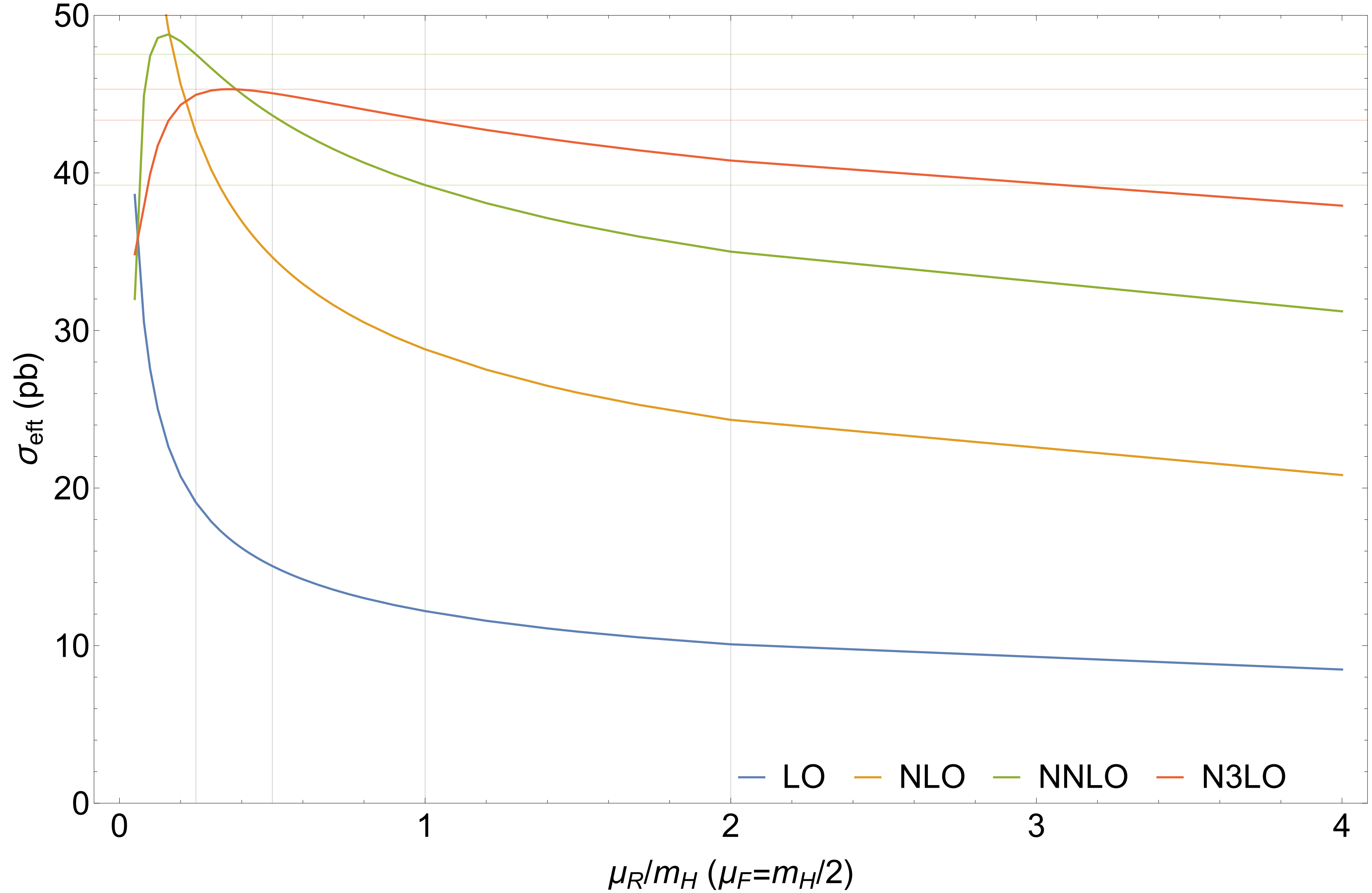
NNLO Corrections are also huge!

Can you imagine what would have happened without higher order QCD corrections?…..

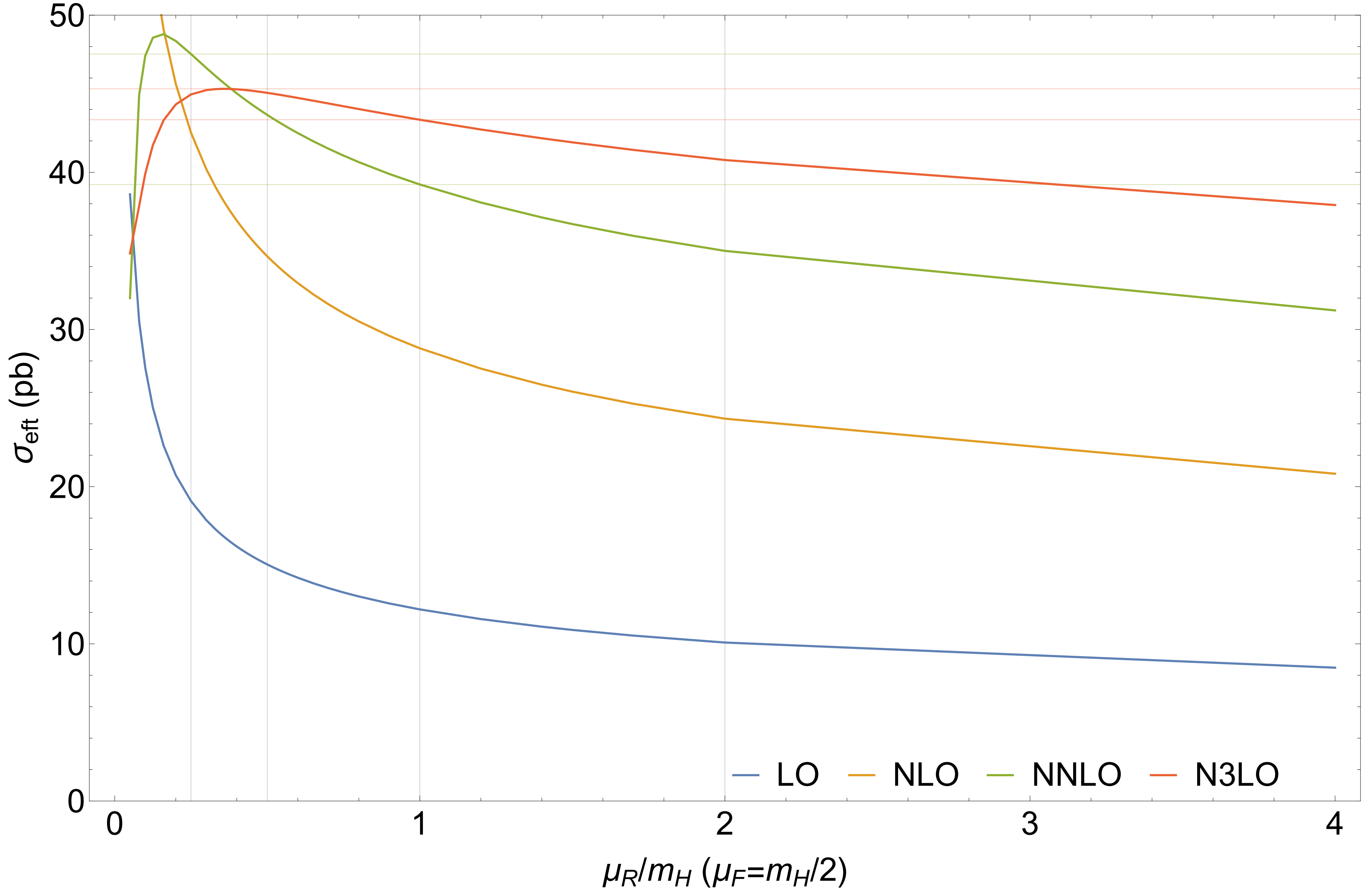
Impressively we now have predictions for Higgs production accurate to N3LO.

Given how large the NNLO coefficient is, this correction was critical to understand for the LHC program.

Anastasiou *et al.* 1602.00695



Anastasiou *et al.* 1602.00695

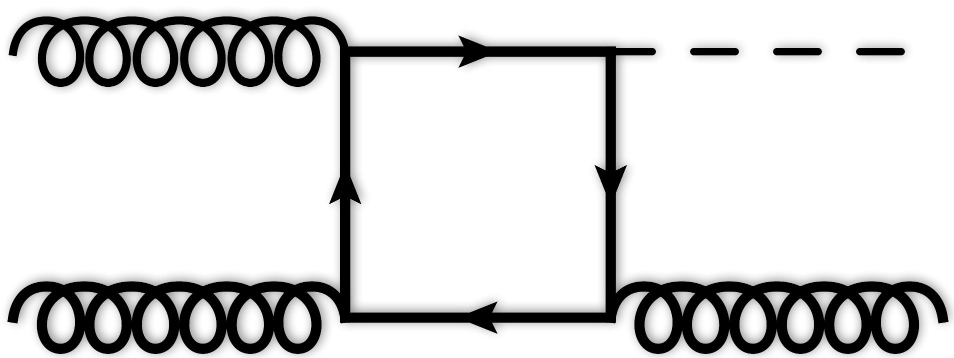


We see that finally the perturbative expansion is under control, and that the previous order lies within the uncertainty band of the NNLO one.

We saw that we could derive an EFT in which we made the top mass infinitely heavy. Is this always a good approximation?

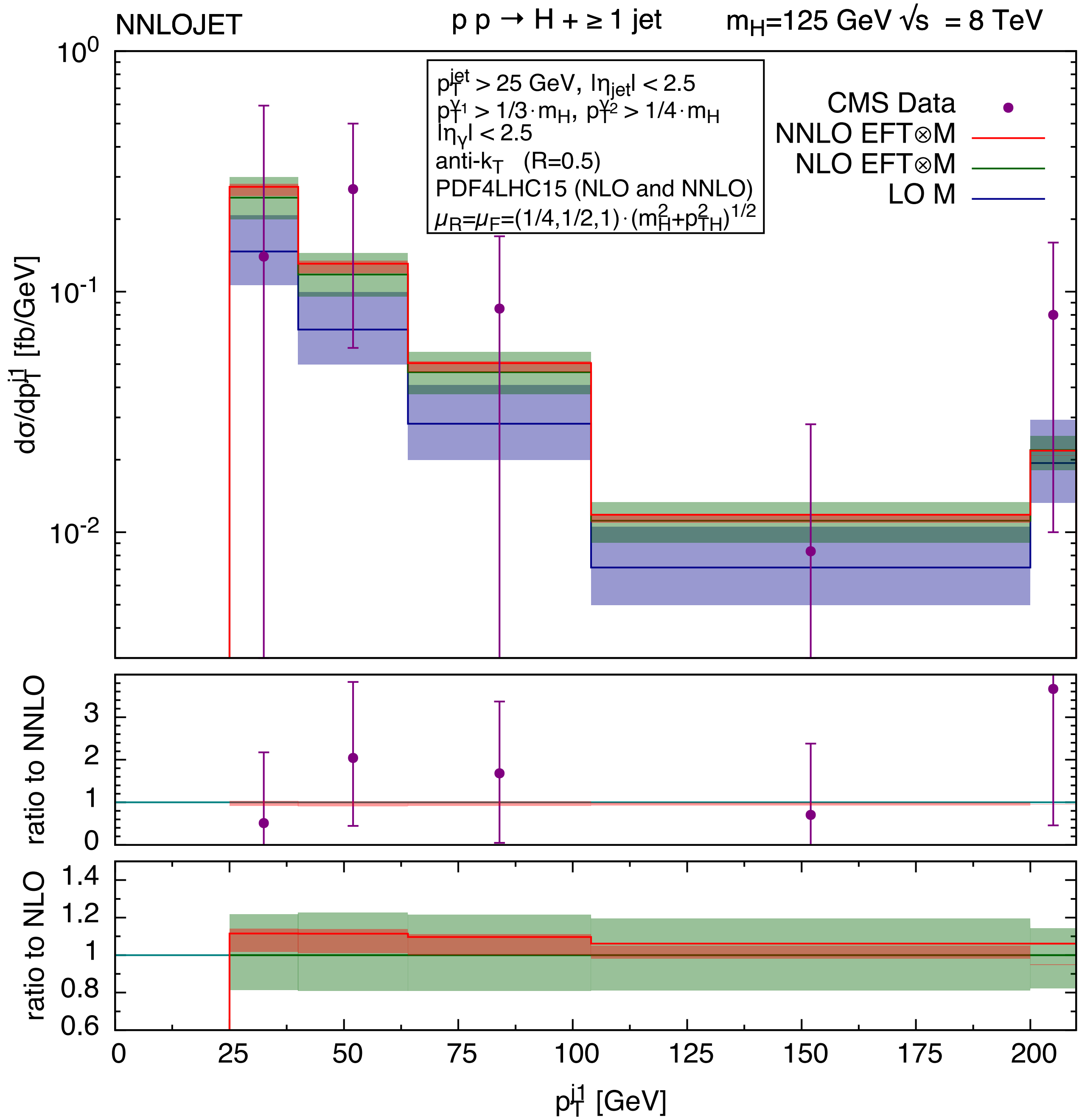
No! If we probe scales near the top mass we see deviations from the EFT result.

We can achieve this by looking at the Higgs at high transverse momentum



$$p_T \sim m_t \implies \hat{s} \sim 2m_t^2$$

So we have to be a little more careful when we study the Higgs at finite momentum (e.g. in differential distributions)



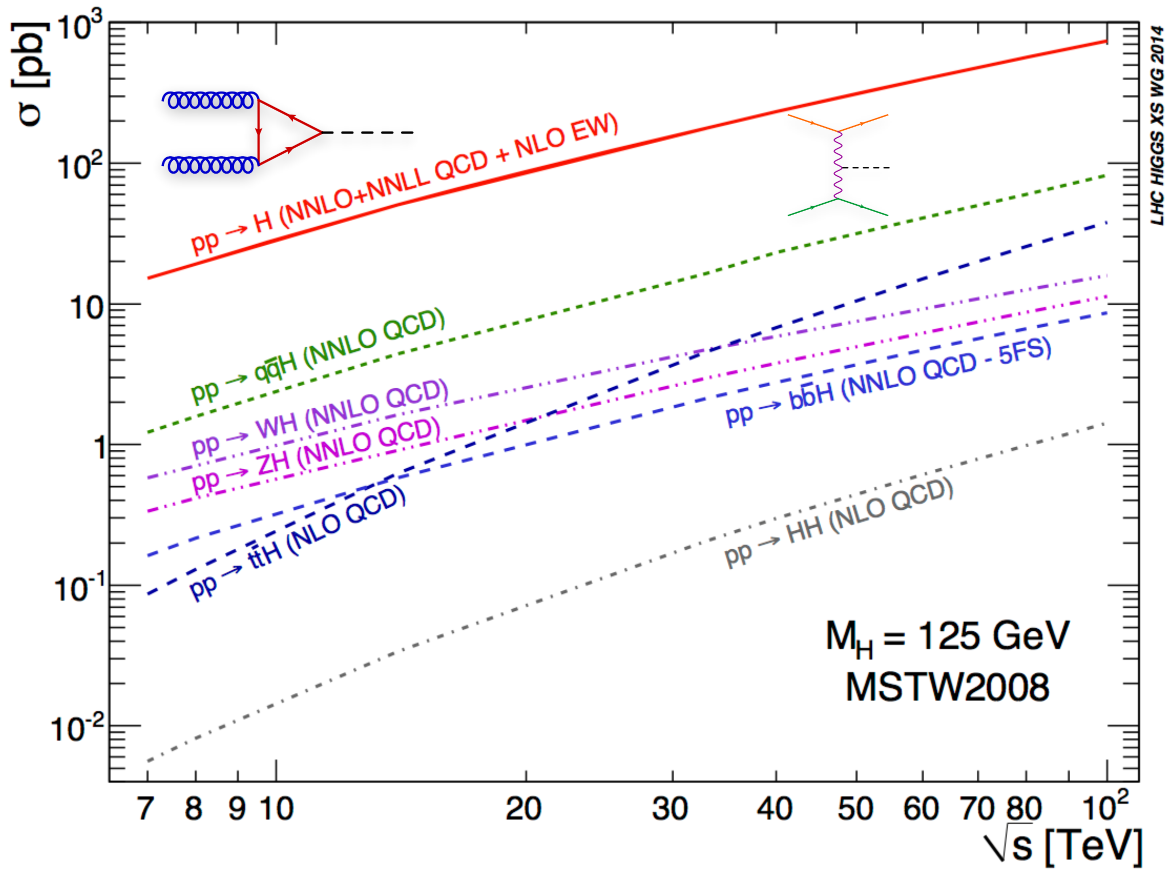
Chen *et al.* 1607.08817

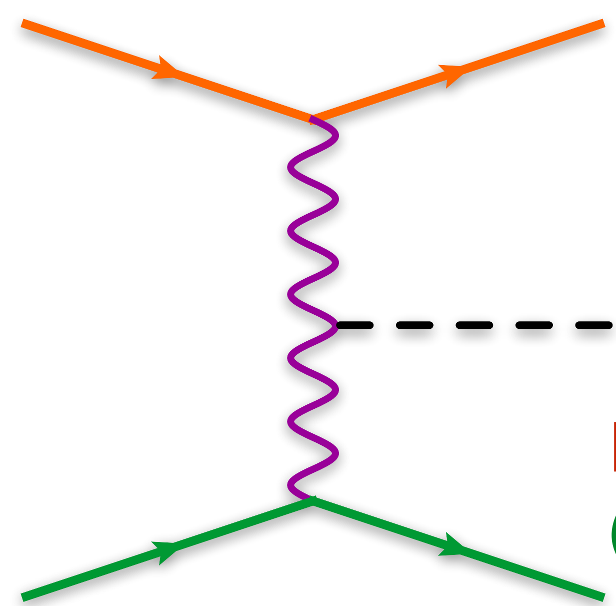
The state of the art for a differential Higgs is to have H+j at NNLO in the EFT, reweighed by the LO Full theory ratio.

Some progress towards NLO in the full theory

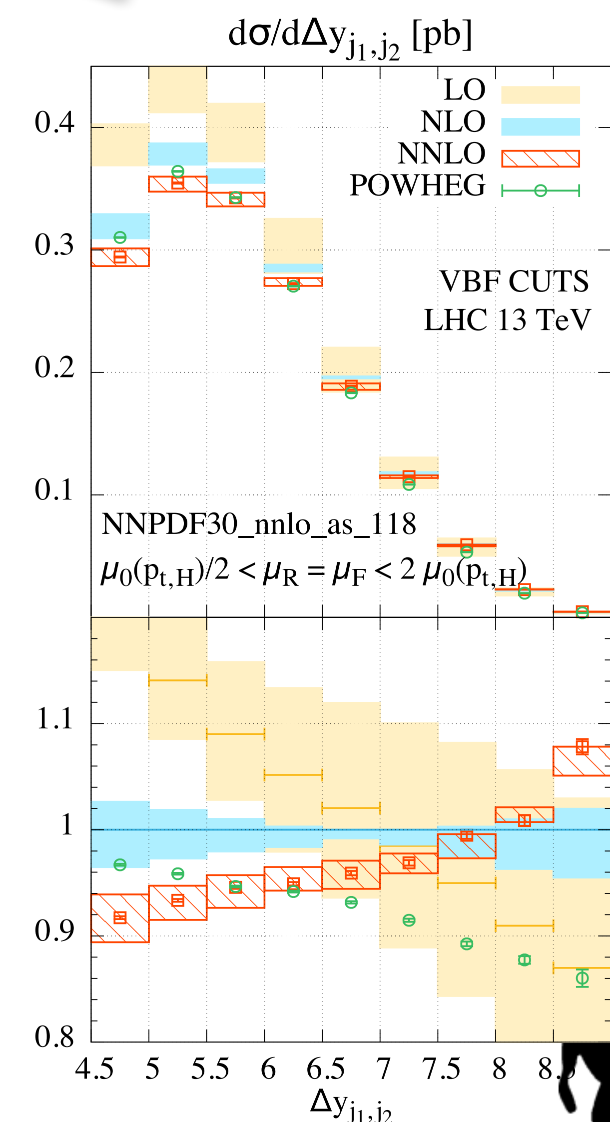
(Neumann, CW 1609.00367)

Subleading production





Know to NNLO in QCD
(Cacciari *et al* 1506.02660)



The second largest Higgs production mechanism corresponds to Vector Boson Fusion.

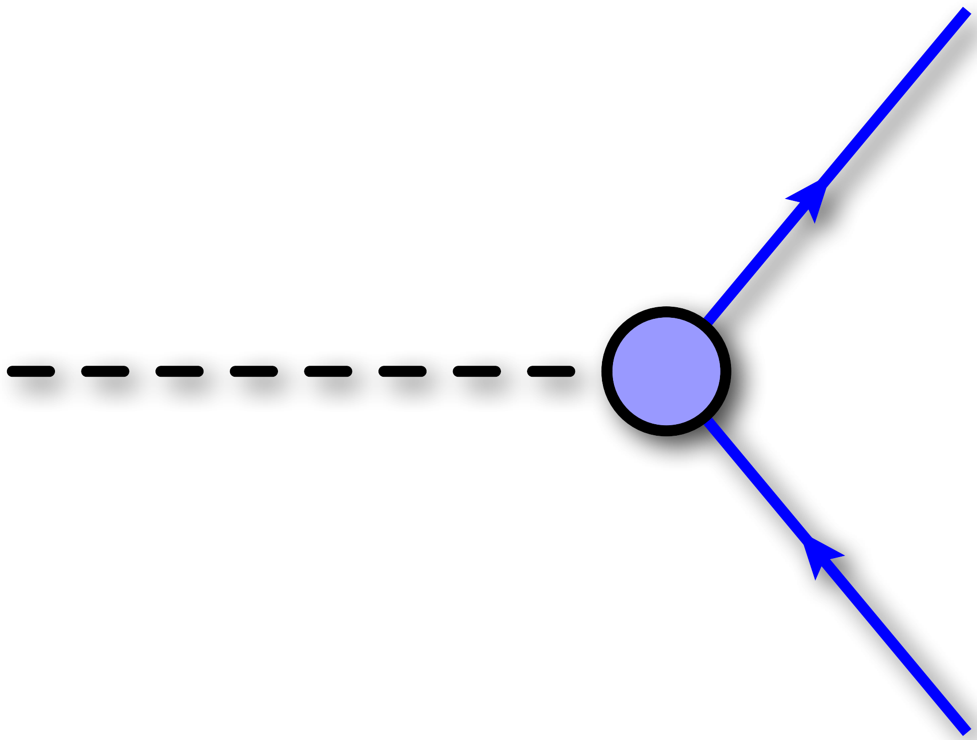
Complementary to gg fusion, since VBF probes couplings to vector bosons (versus top quark)

Death of the Higgs boson.

Firstly, lets recall the notation used for unstable particles in QFT.

Firstly, lets recall the notation used for unstable particles in QFT.

The rate for each decay is called a partial width.



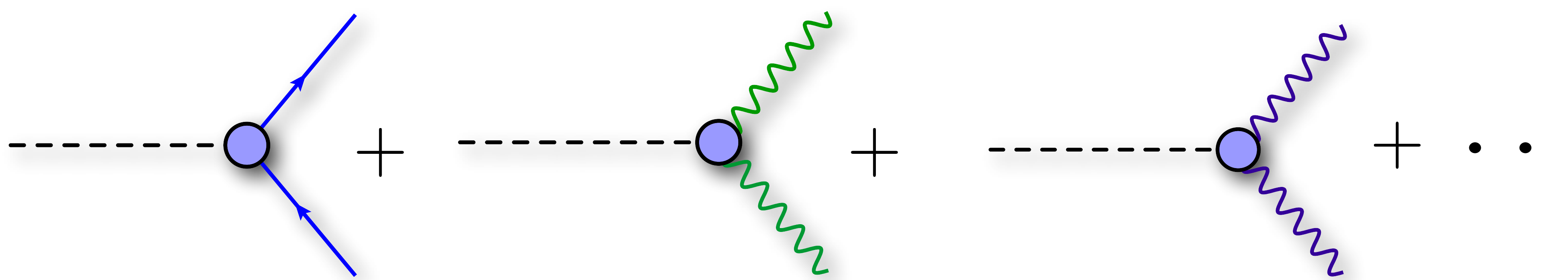
$$\sim \Gamma_{b\bar{b}} \ [\text{GeV}]$$

Widths of particles

Firstly, lets recall the notation used for unstable particles in QFT.

Summing over all the partial widths yields the total width.

$\Gamma_{tot} =$

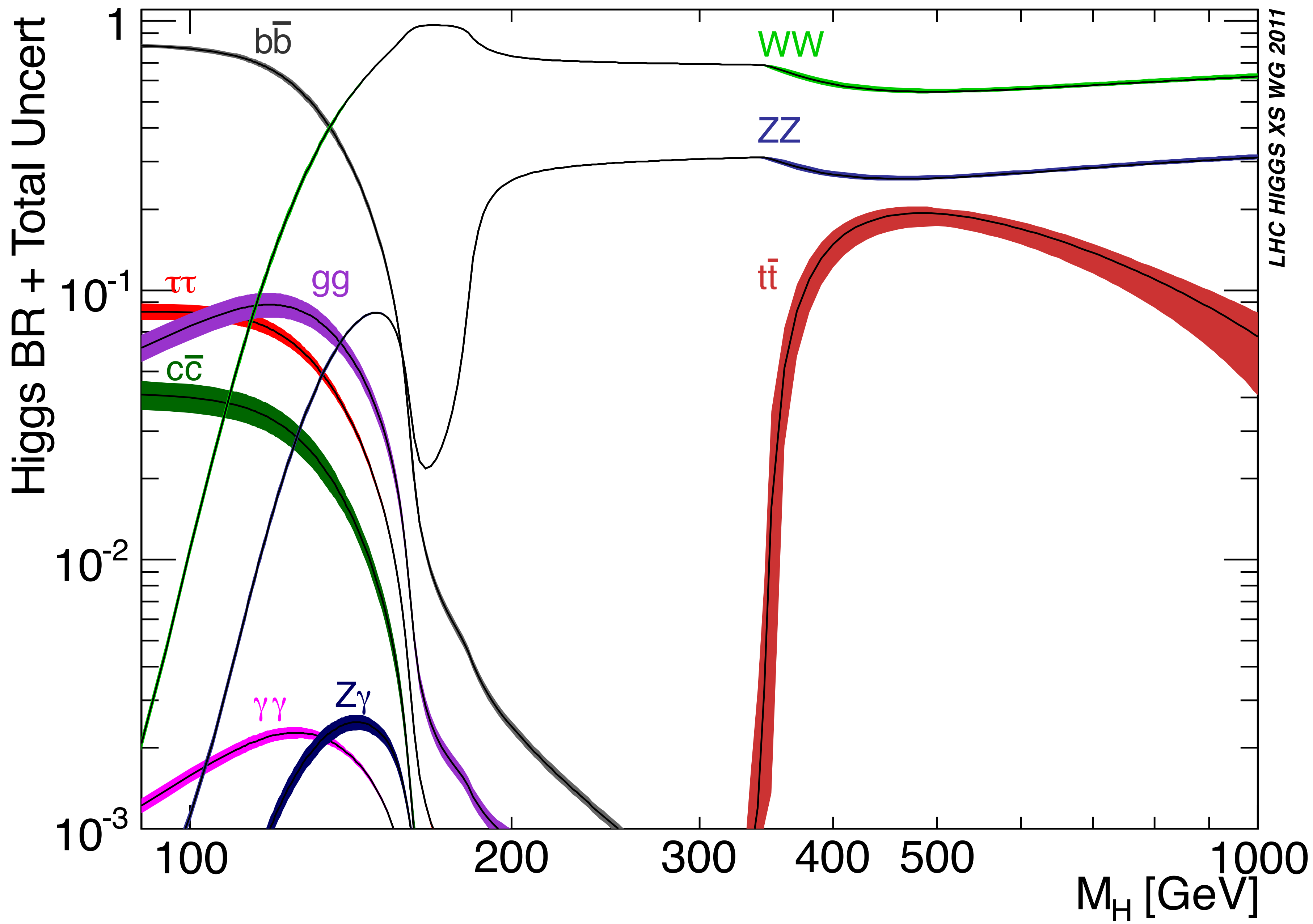


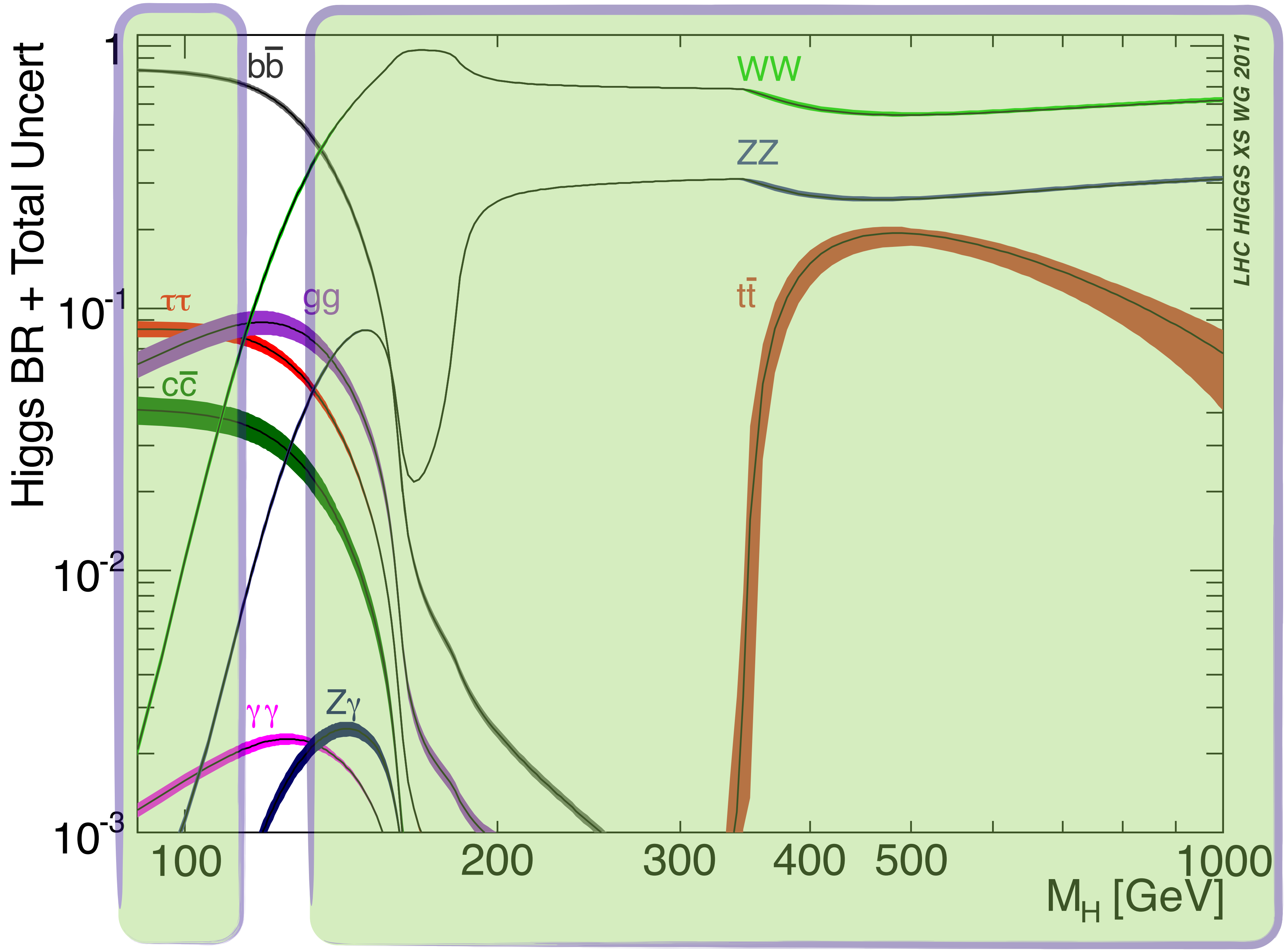
Widths of particles

Firstly, lets recall the notation used for unstable particles in QFT.

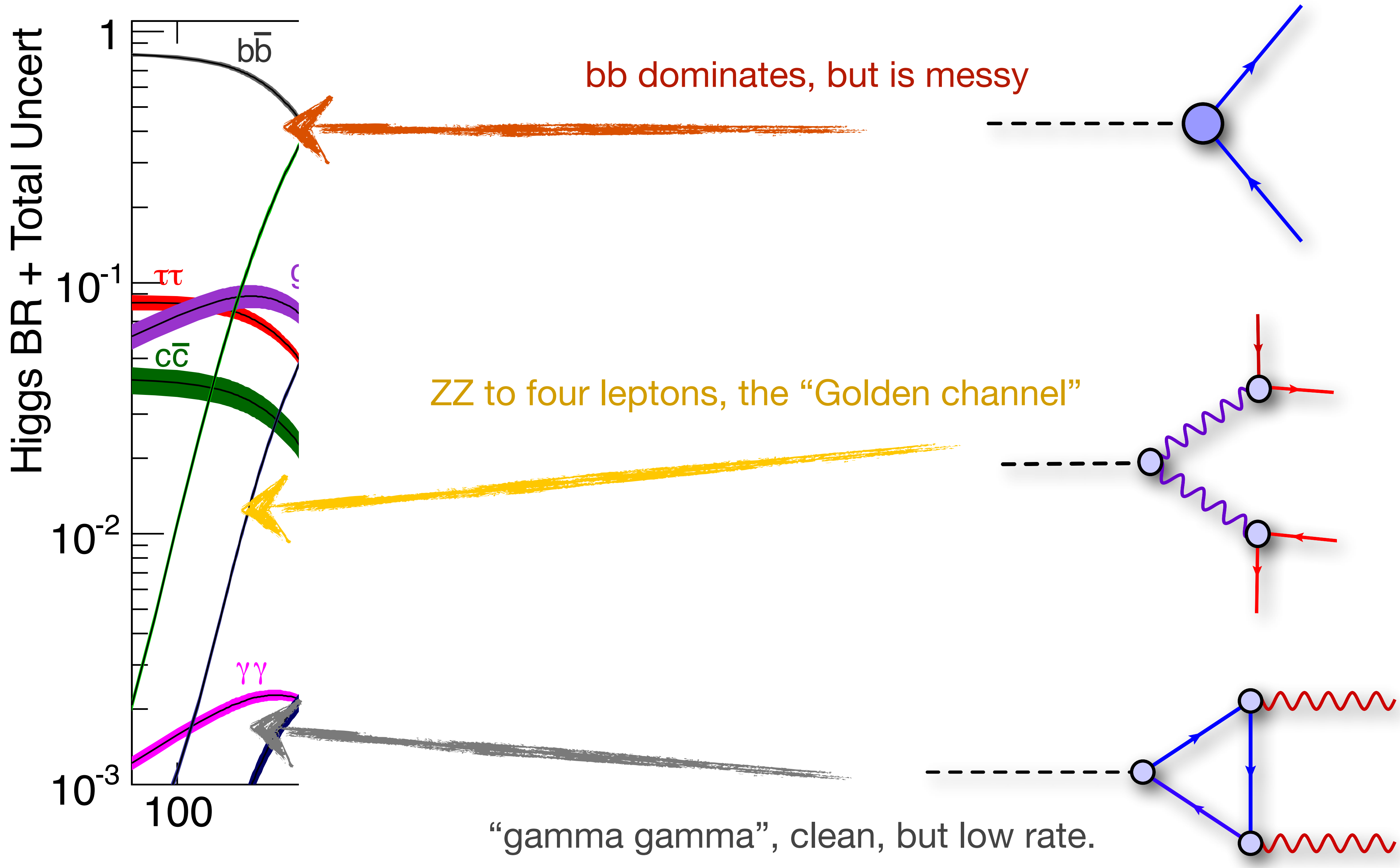
Finally, the branching ratio defines the relative fraction for a particular decay.

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


Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
100
200
300
400
500
1000
M_H [GeV]
$b\bar{b}$
WW
ZZ
$t\bar{t}$
ττ
gg
$c\bar{c}$
γγ
Zγ
LHC HIGGS XS WG 2011

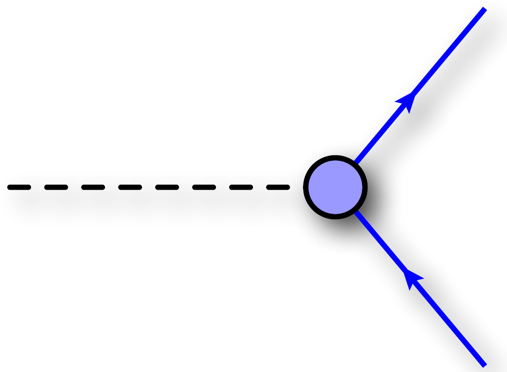


The 125 GeV Higgs is one of the most interesting to study



Phenomenologically the diboson and bb decays are most relevant

We can jump straight to the matrix element squared here,



$$|\mathcal{M}_{H\to b(p_1)\bar{b}(p_2)}|^2 = \frac{N_c g_W^2 m_b^2}{4m_W^2}\left(4p_1p_2 - 4m_b^2\right)$$

The partial width is obtained from Fermi's Golden Rule $\Gamma = \frac{|\mathbf{p_2}|}{8\pi m_H^2}|\mathcal{M}|^2$

So that

$$\Gamma_{H\to b\bar{b}} = g_W^2 N_c \frac{m_b^2 m_H}{32\pi m_W^2}\left(1 - \frac{4m_b^2}{m_H^2}\right)^{3/2}$$

Here the matrix element is given by (on-shell W's)

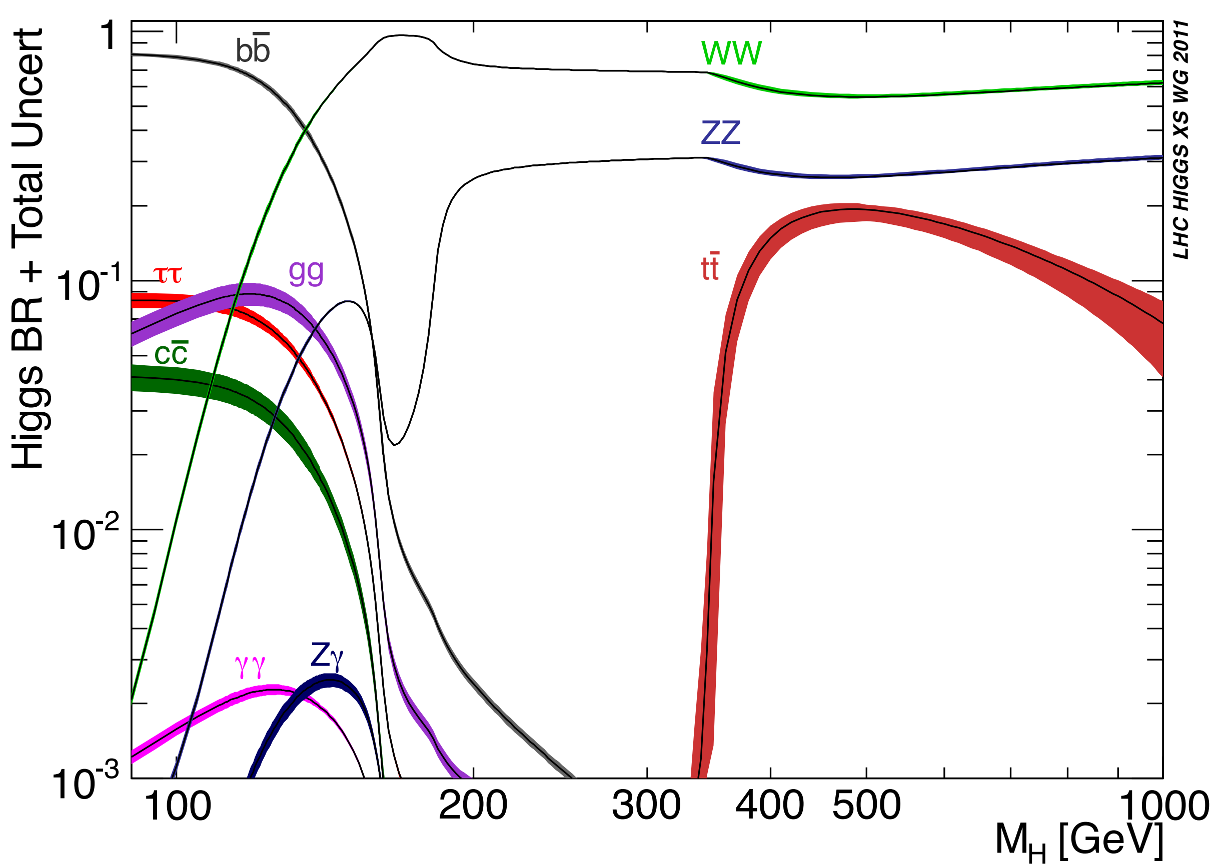
$$|\mathcal{M}_{H\to W^+(p_1)W^-(p_2)}|^2 = g_W^2 m_W^2 \left(2 + \frac{(p_1 p_2)^2}{m_W^4}\right)$$

With a partial width given by

$$\Gamma_{H\to WW} = g_W^2 \frac{m_H^3}{64\pi m_W^2}\left(1 - \frac{4m_W^2}{m_H^2}\right)^{1/2}\left(1 - 4\frac{m_W^2}{m_H^2} + 12\frac{m_W^4}{m_H^4}\right)$$

We see that approximately the widths scale like

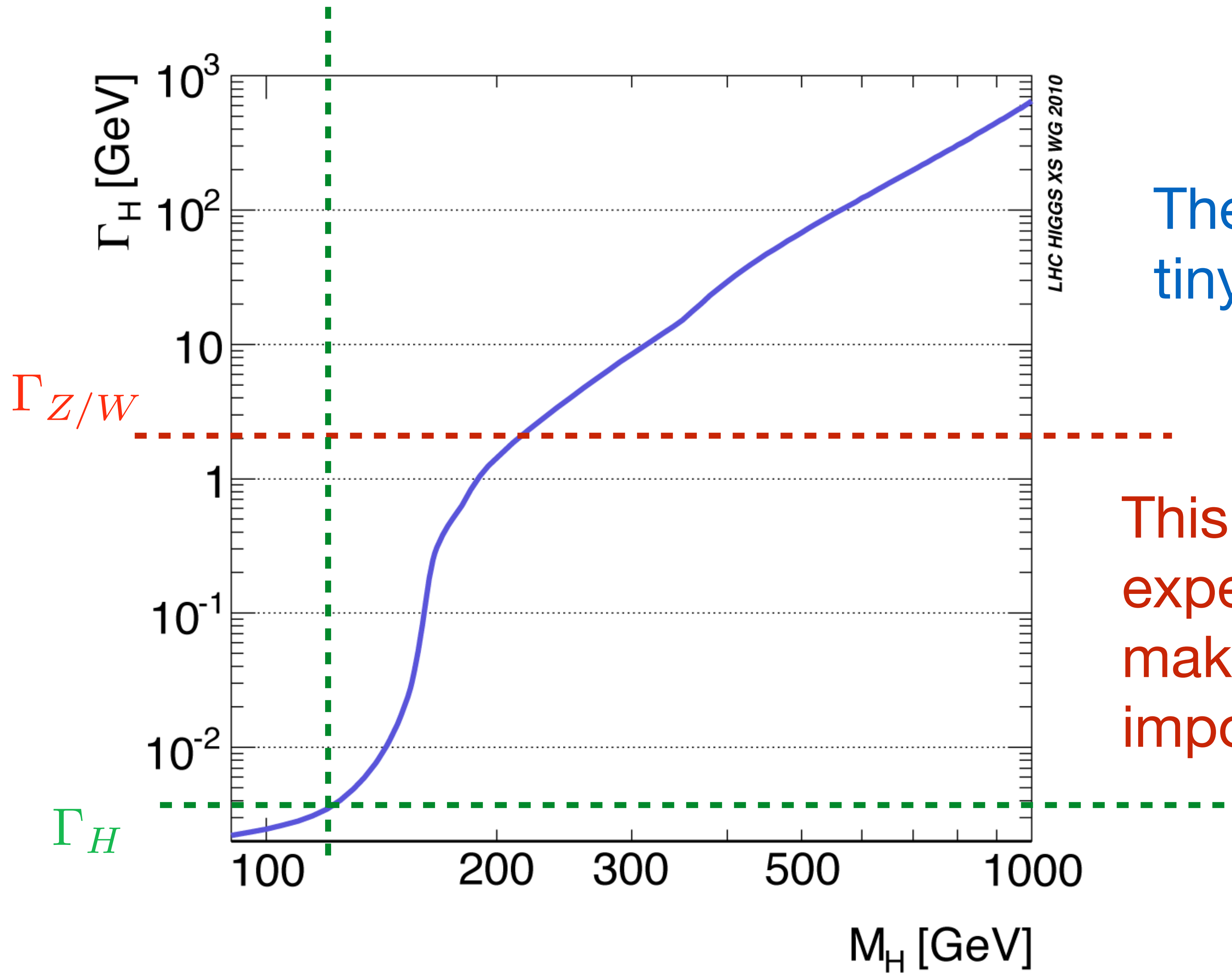
$$\Gamma_{H\to b\bar{b}} \sim \left(\frac{m_b^2}{m_W^2}\right)\Gamma_{H\to WW}$$



So in the regime where bb dominates (before WW becomes on-shell) the Higgs width is suppressed by the lightness of the b quark.

In the region in which WW dominates the Higgs width is much larger (and more like the W/Z bosons)

Calculating the Higgs width

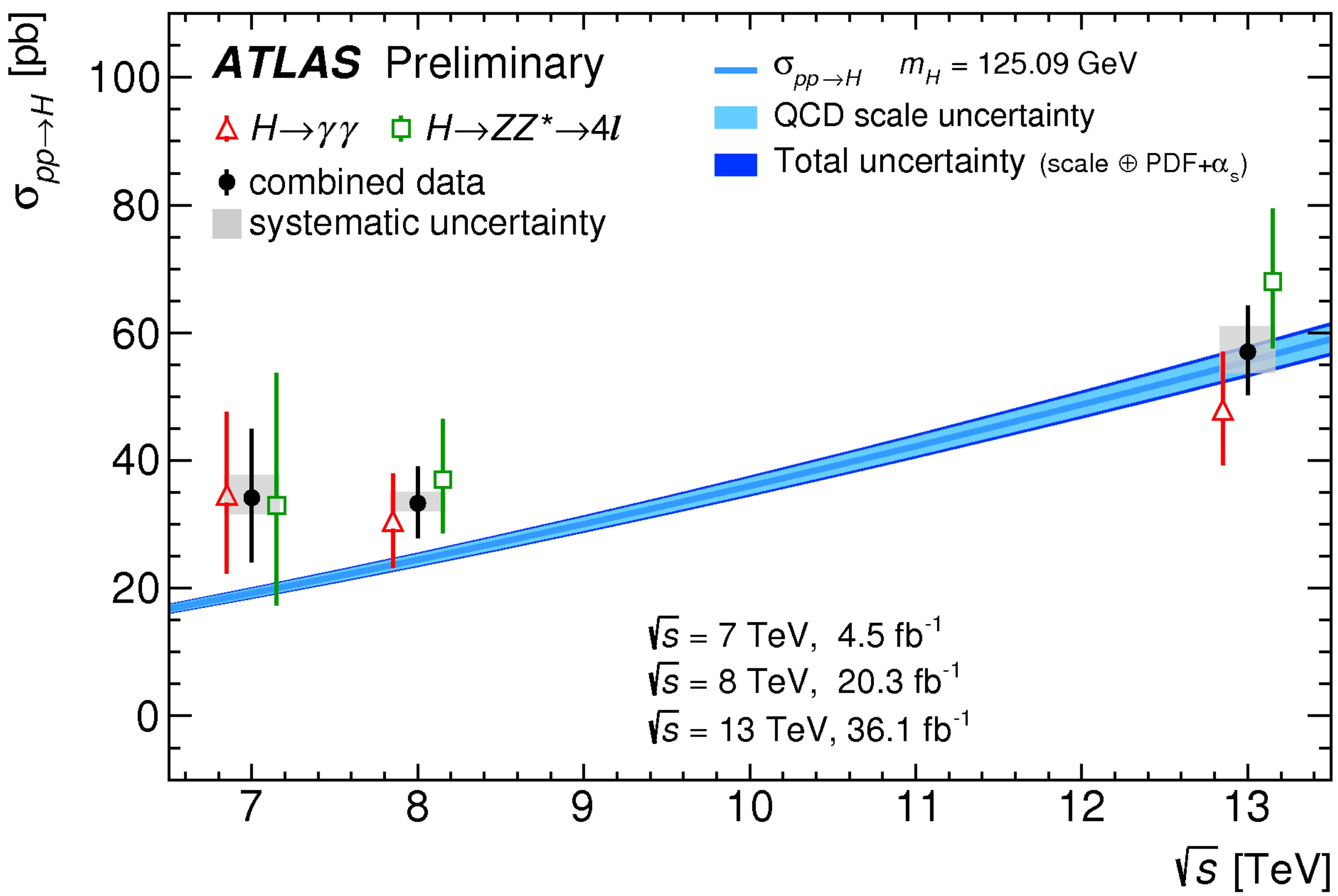


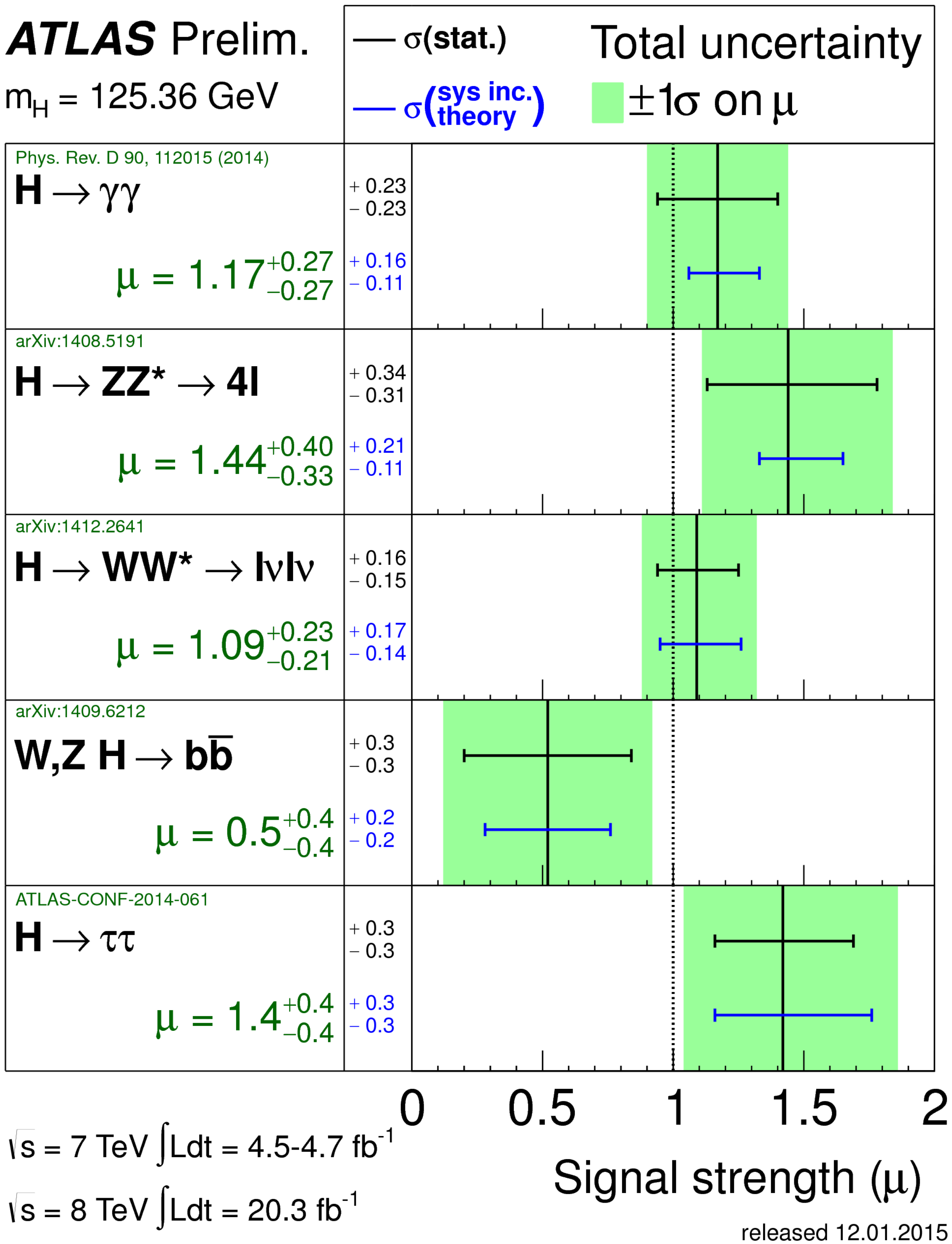
The Higgs width in the SM is tiny!

This much smaller than the experimental resolution, making direct measurement impossible. (more later).

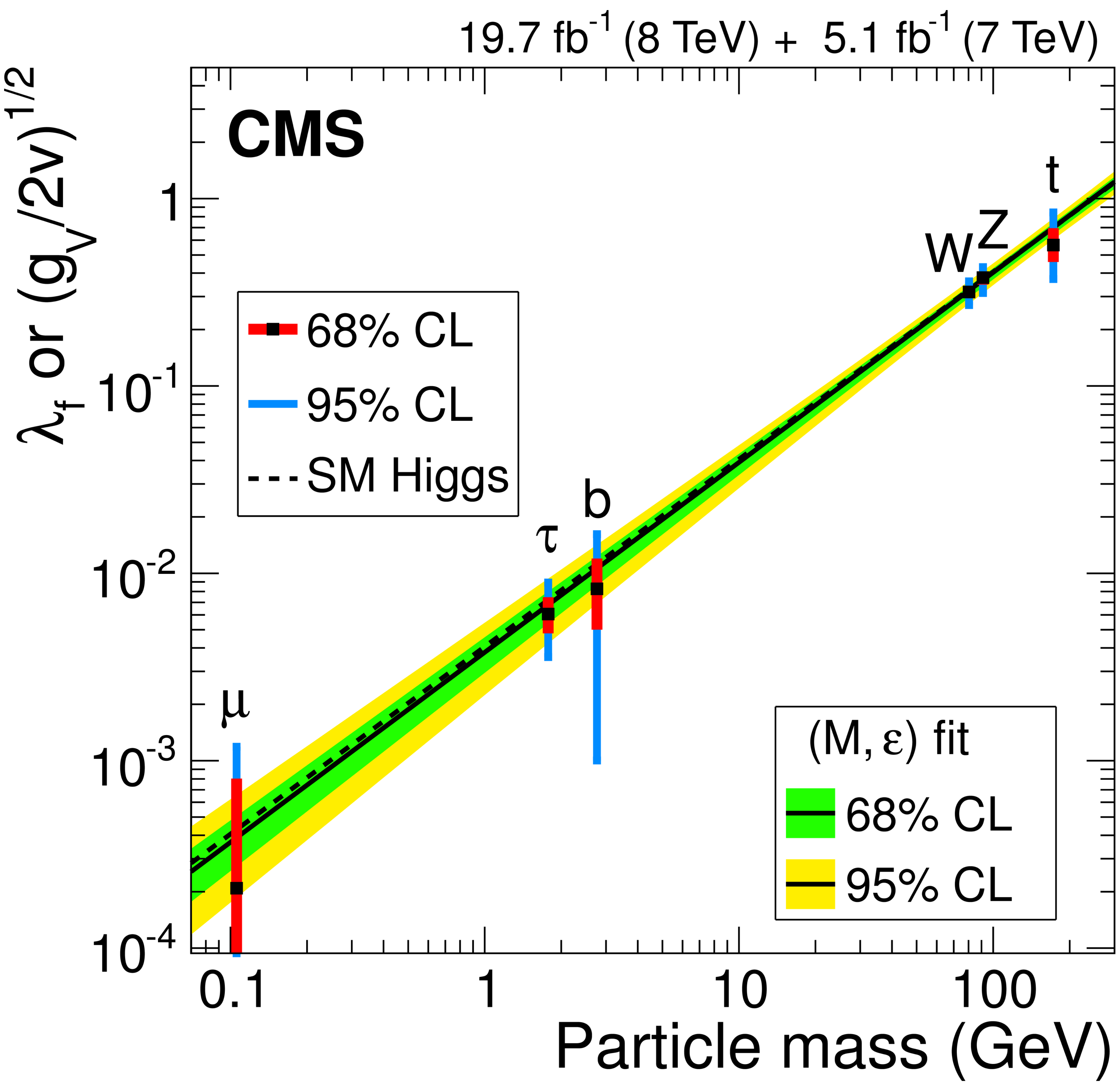
Future of the Higgs boson

Where are we now?

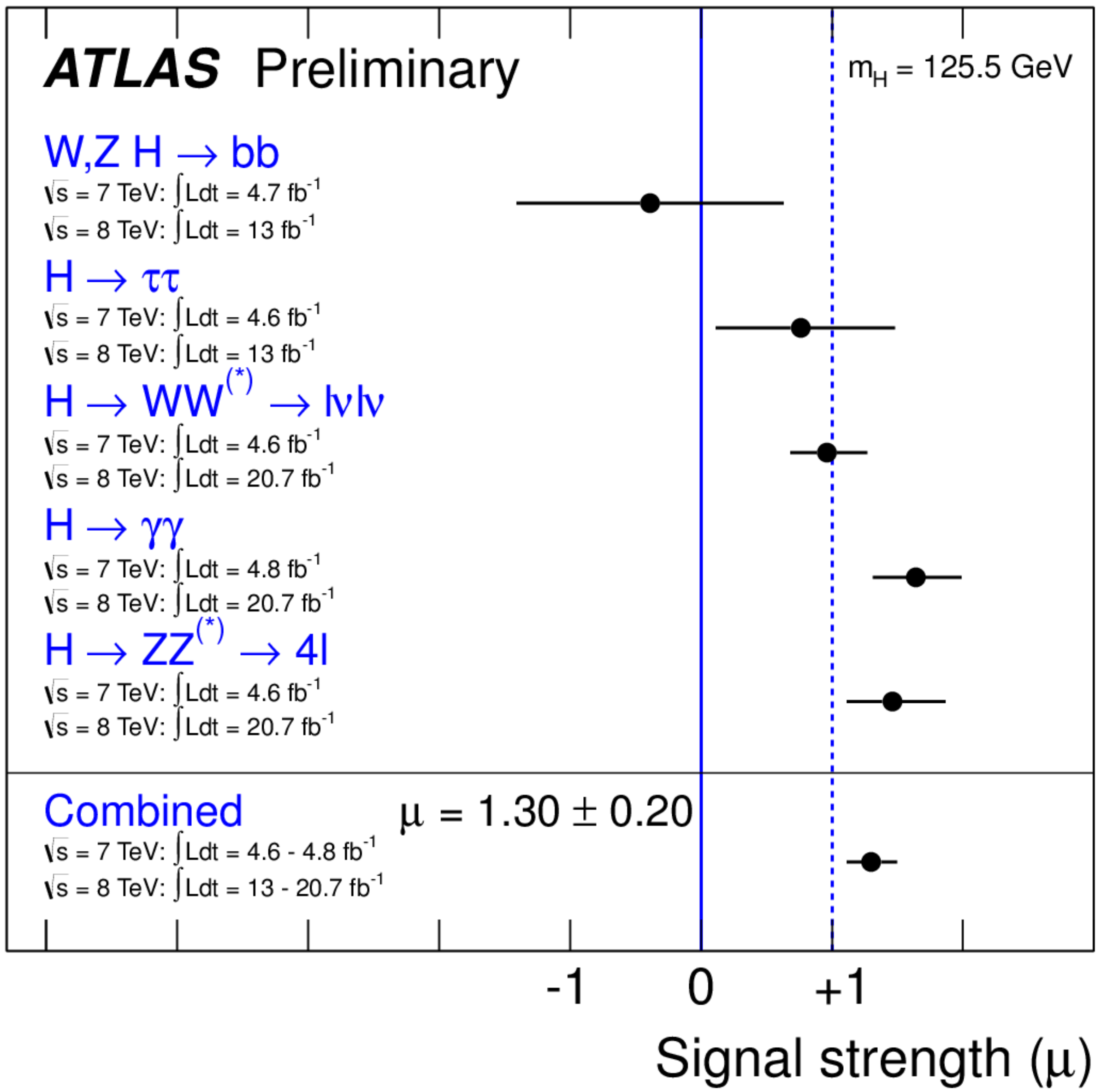


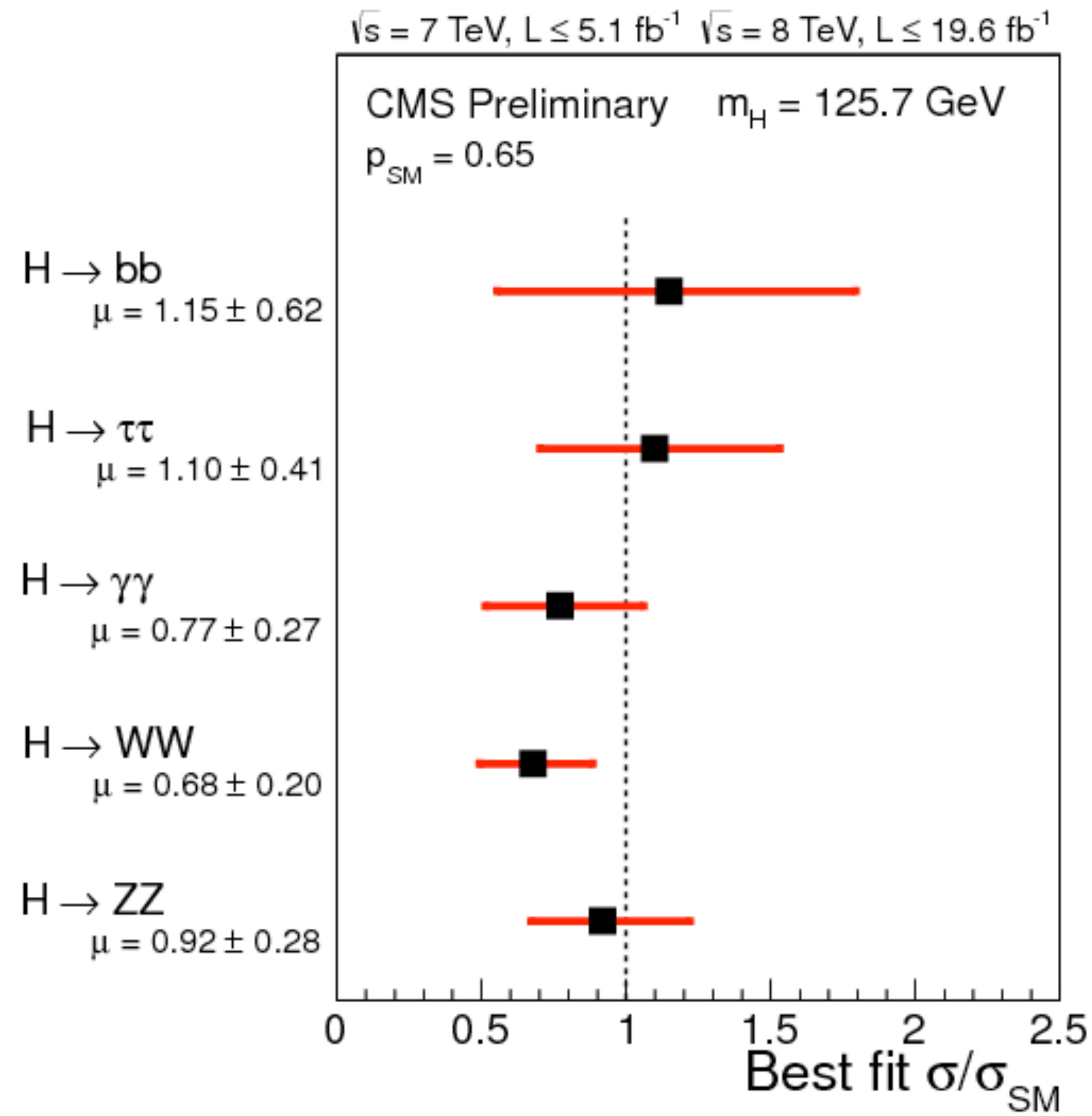


We are beginning to get to know the Higgs quite well (see Bruce's talks)



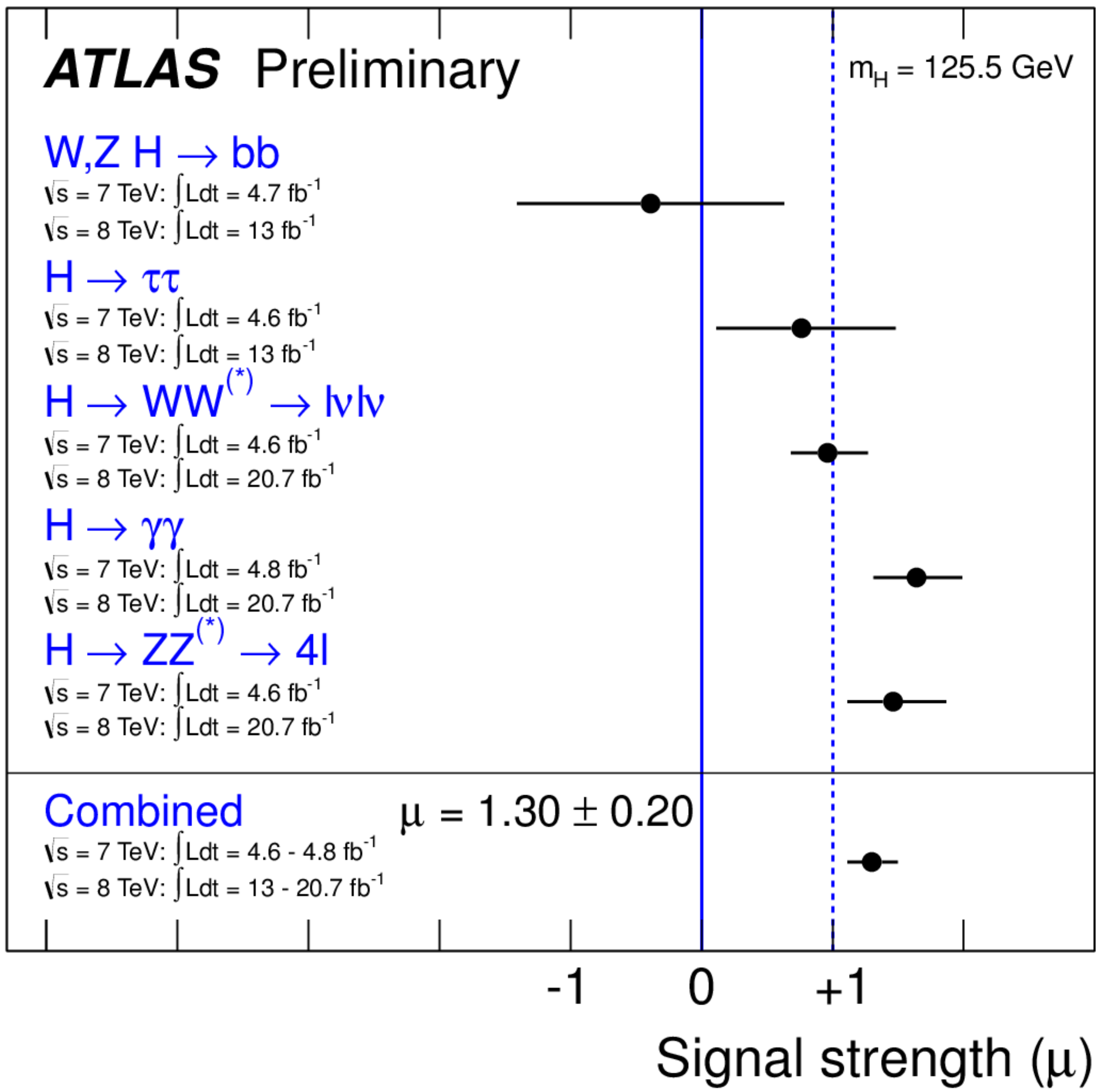
In order to test the Higgs mechanism we want to see the coupling promotional to the mass of the particles

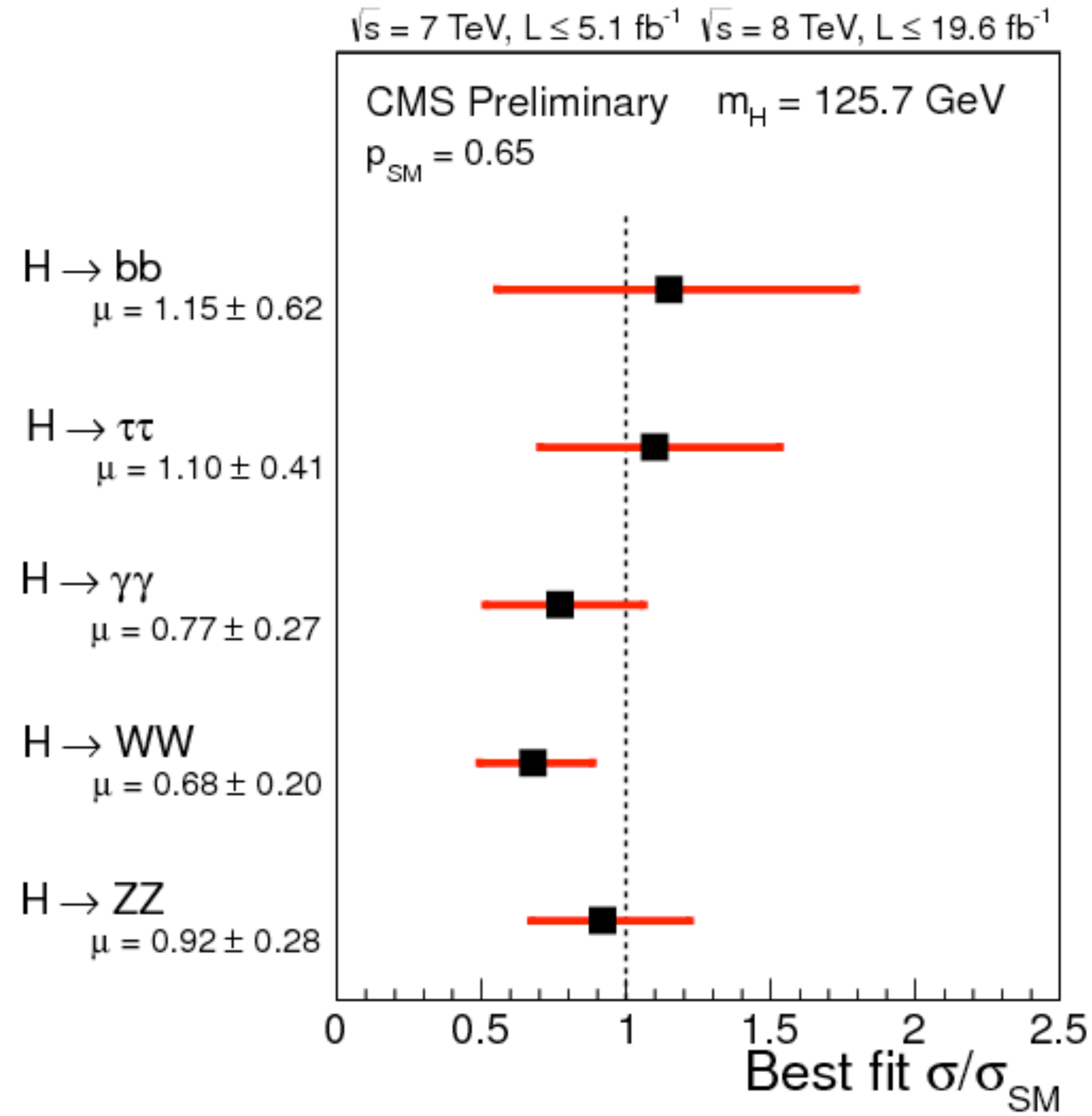




Each decay mode is measured and cross sections are determined using the Narrow width approximation,

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

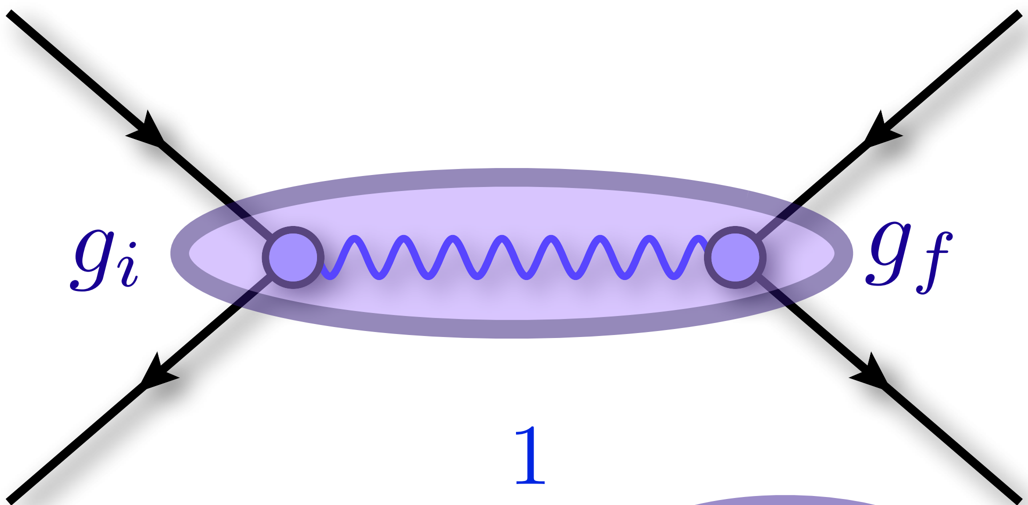




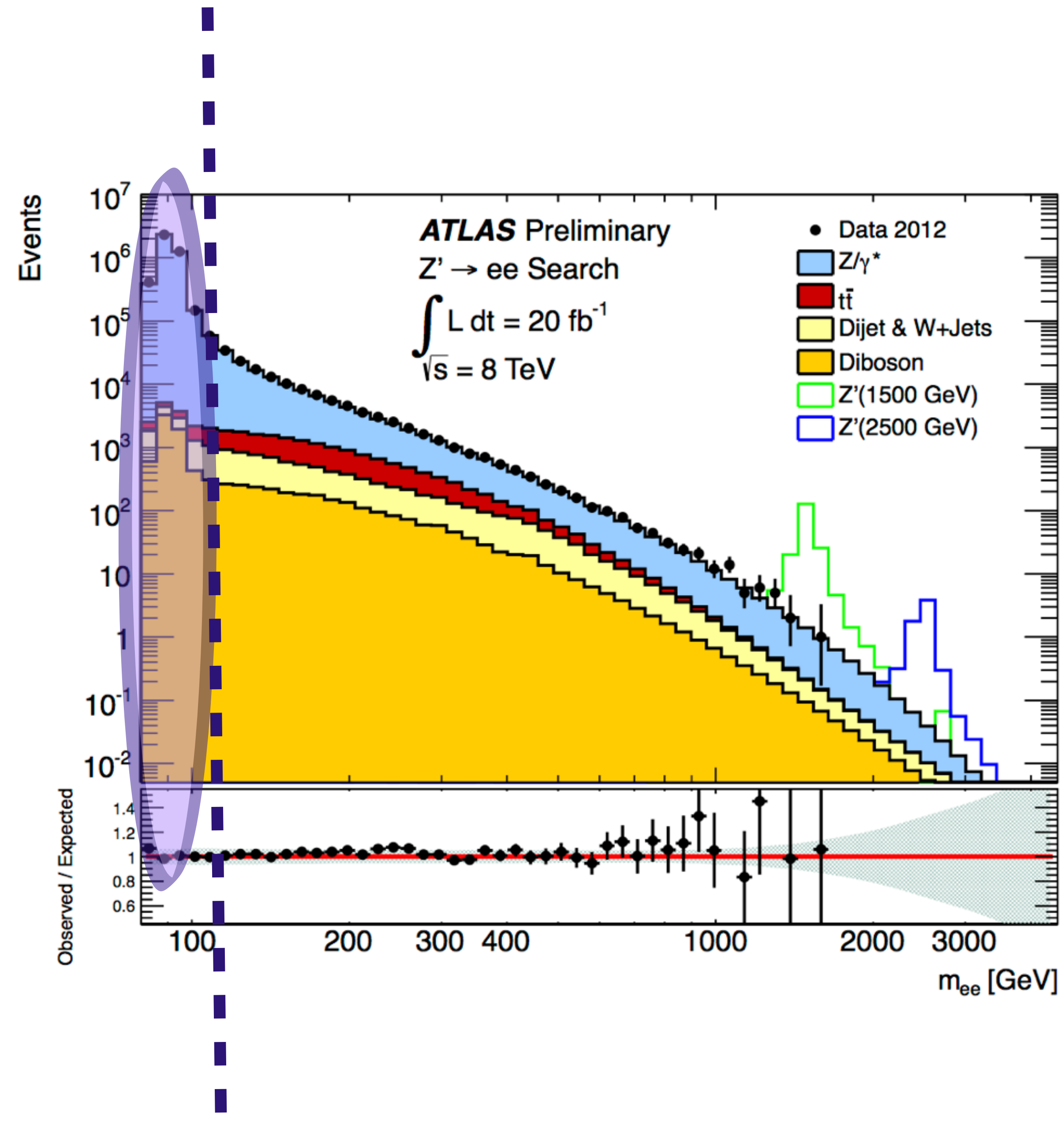
Ultimately we want to extract information regarding the Higgs coupling to SM particles, which is a difficult task since.

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

such that global fits are required to determine the couplings.

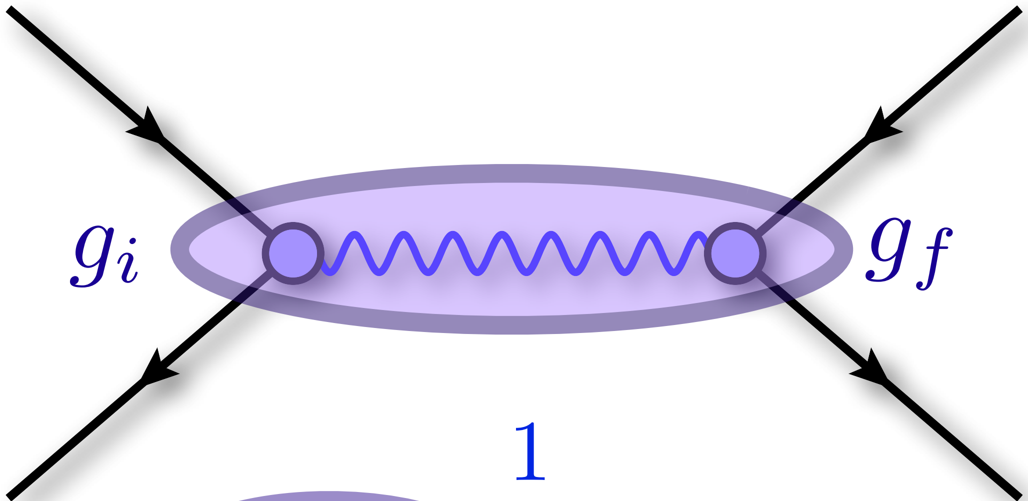


$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$

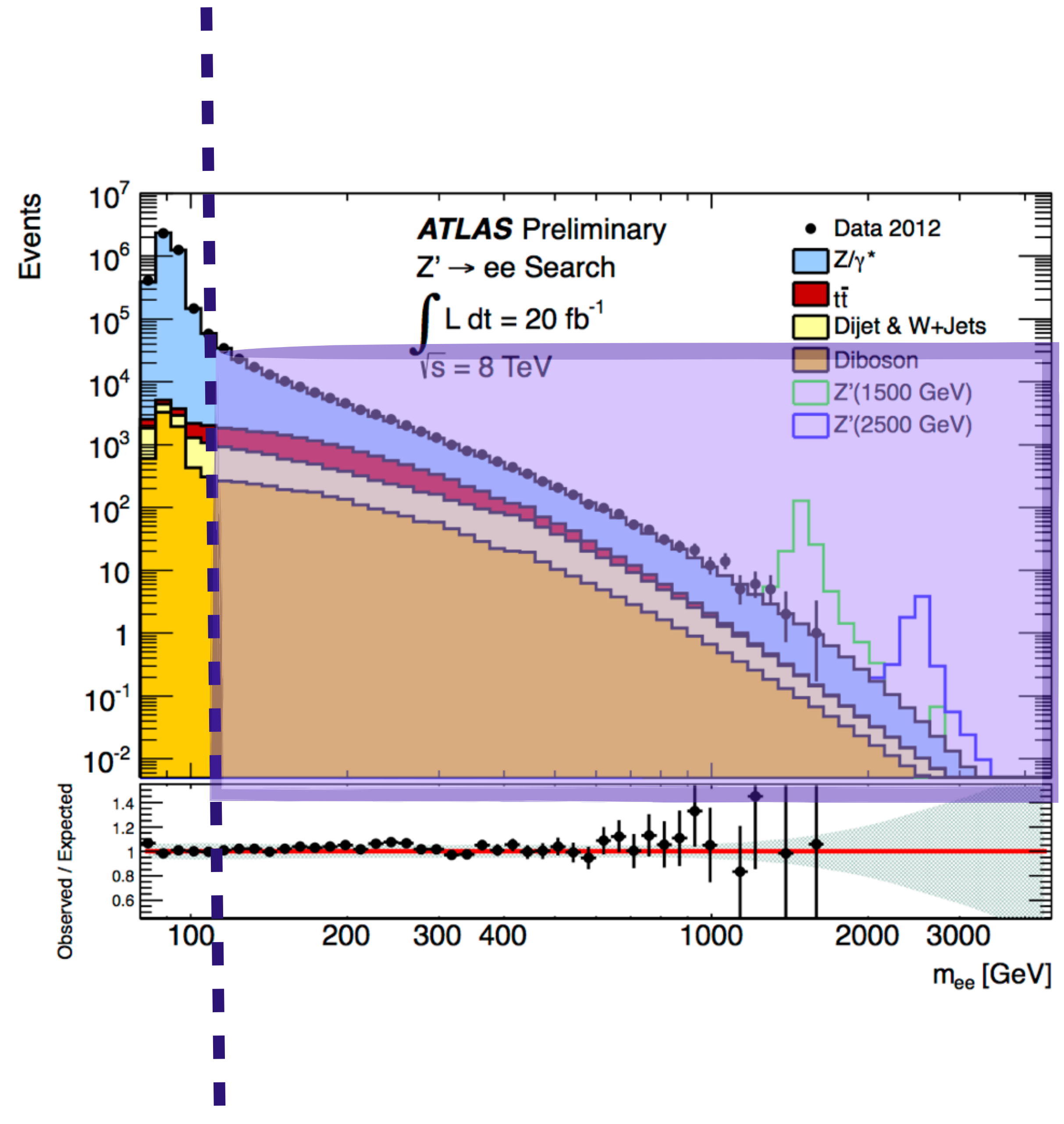


In the resonance region the "on-shell" cross section is dominated by the width.

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

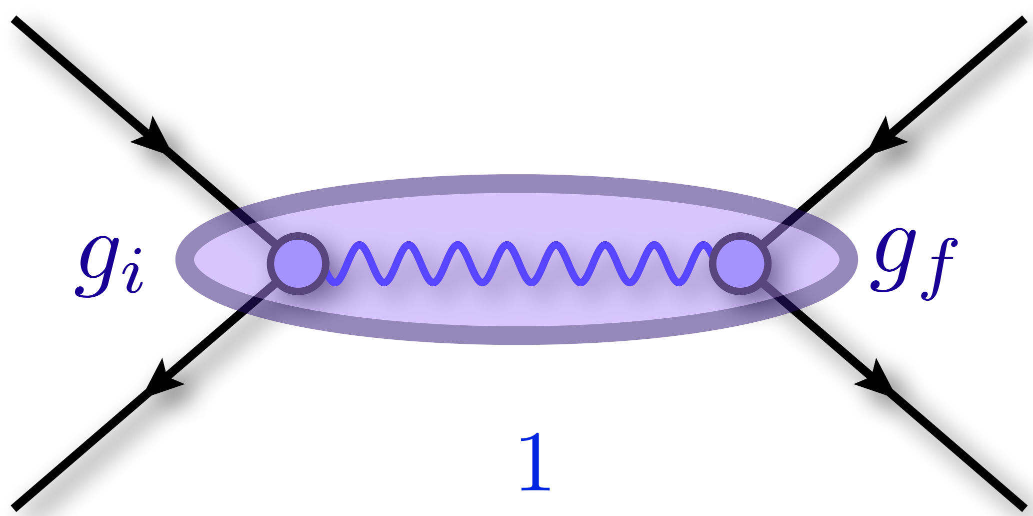


$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$



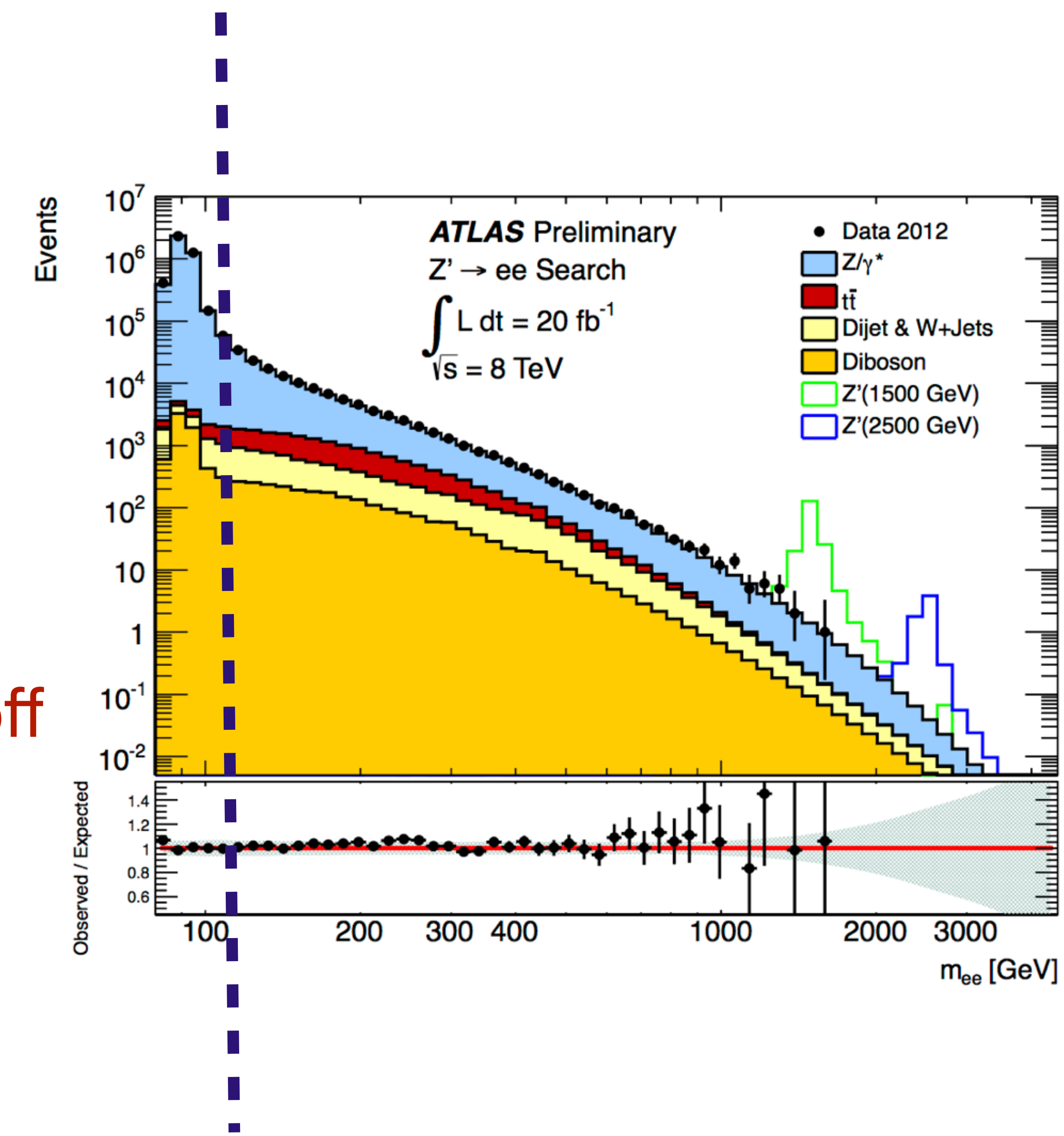
Away from the resonance region, the "off-shell" cross section does not depend on the width.

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



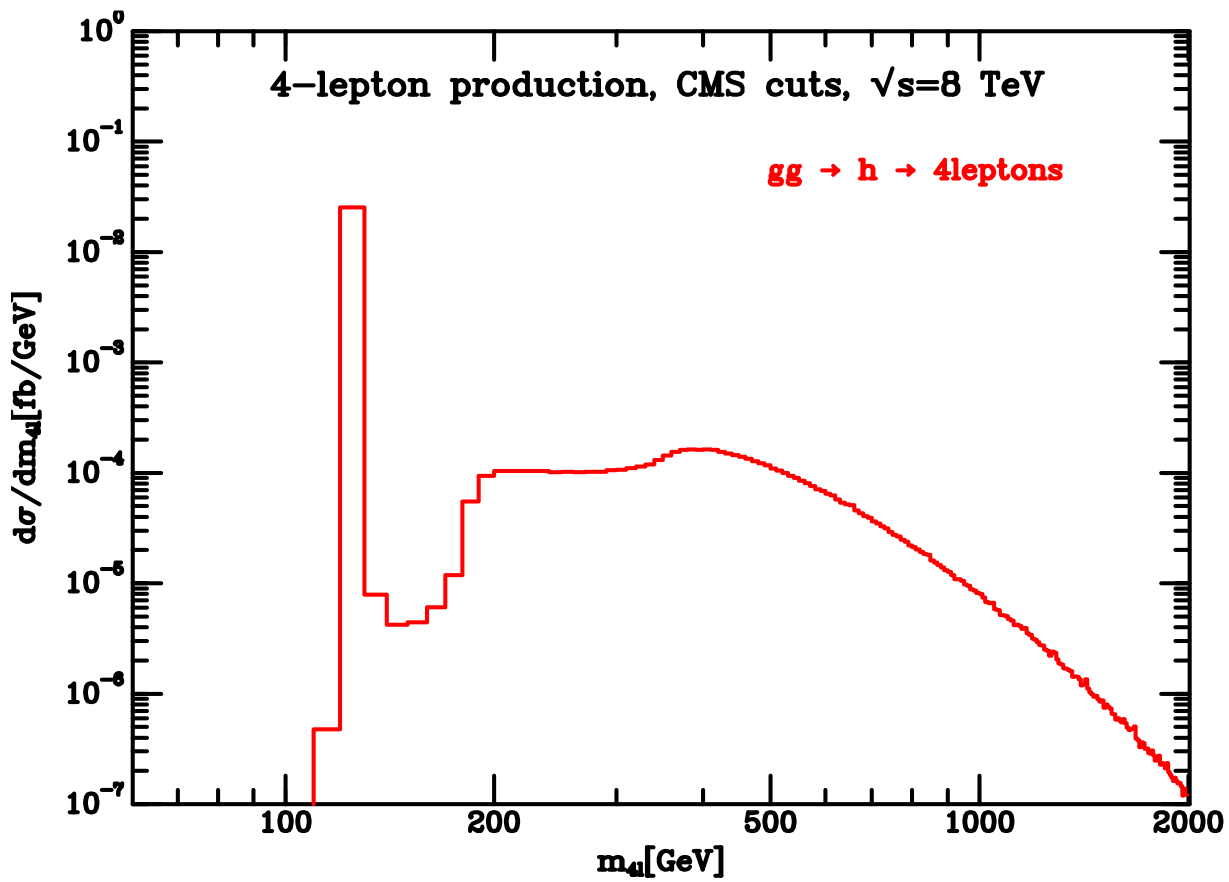
$$\frac{1}{(s - M_X^2) + i\Gamma_X M_X}$$

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



Off Shell Higgs cross sections.

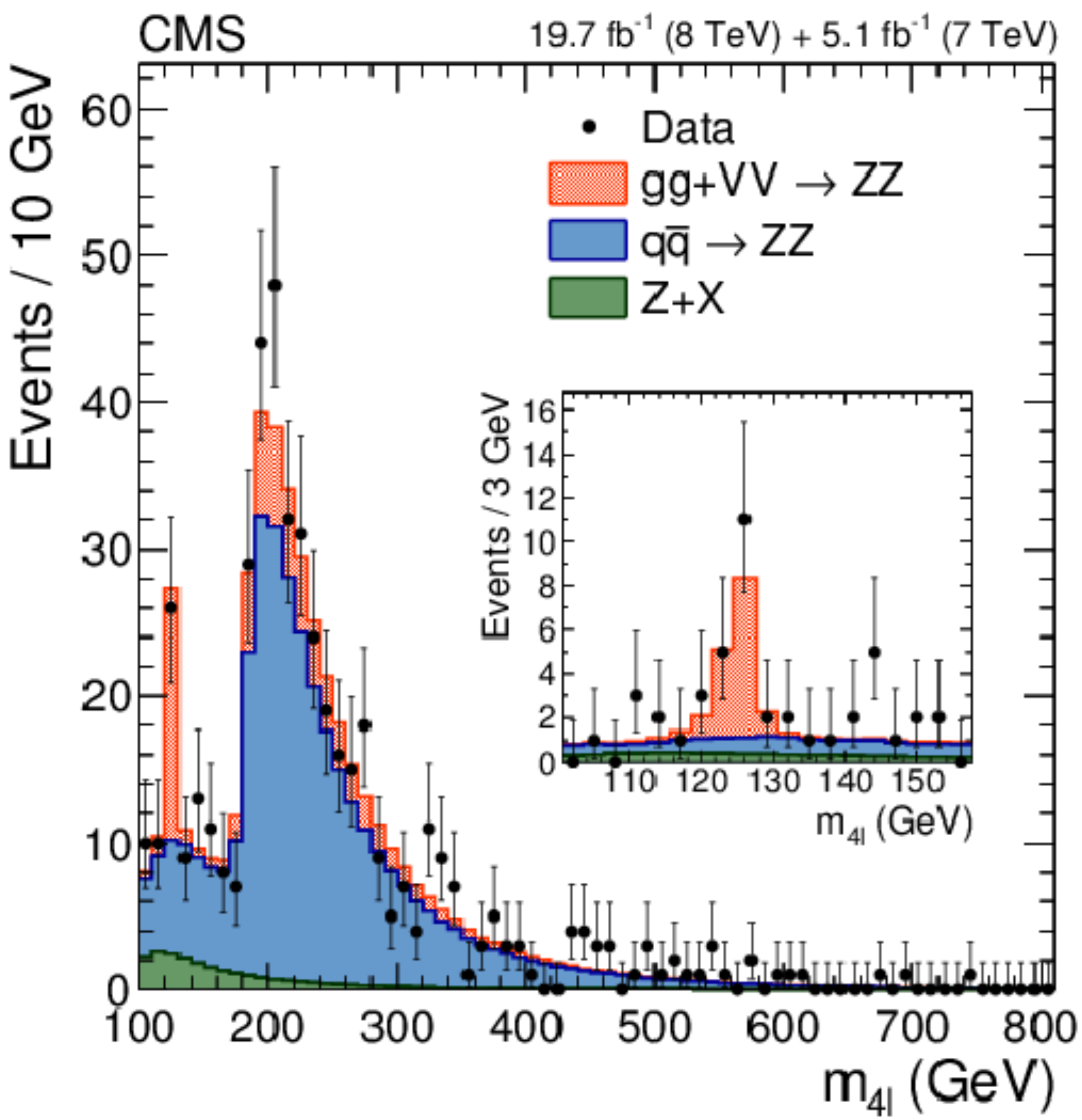
(Kauer, Passarino 12)
(Caola, Melinikov 13)
(Campbell, Ellis, CW 11,13)

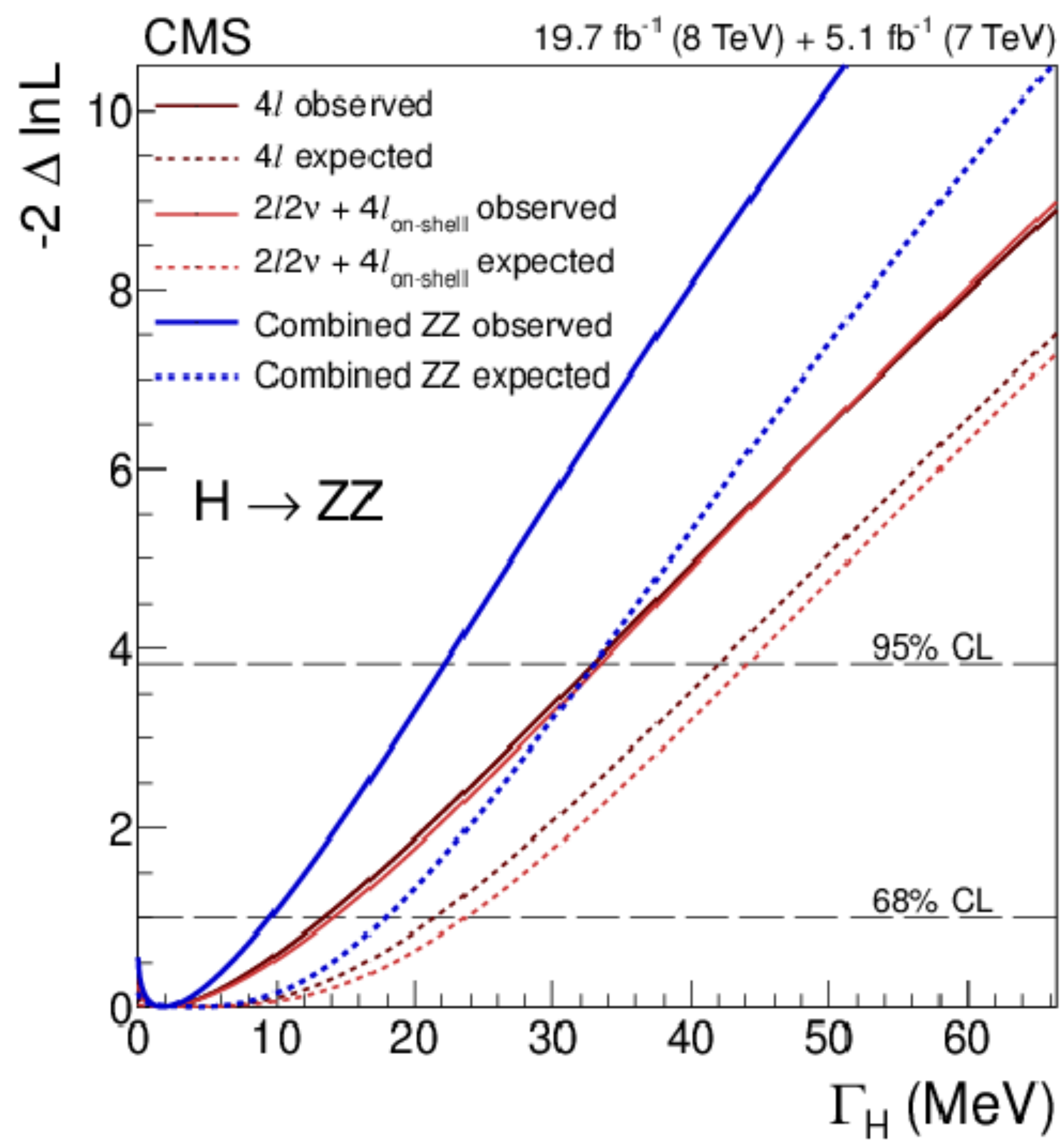


Energy	σ^H_{peak}	σ^H_{off}
7 TeV	0.203	0.044
8 TeV	0.255	0.061

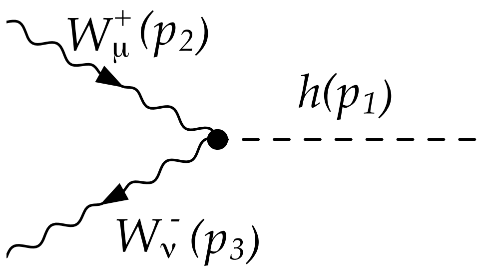
* Since Γ_H / M_H=1/30,000 one might expect off-shell corrections to be very small.
* However this is not the case in decays to VV, there is a sizable contribution to the total cross section away from the peak.
* This arises from the proximity of the two VV threshold, and is further enhanced by the threshold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

Off-shell Higgs bosons

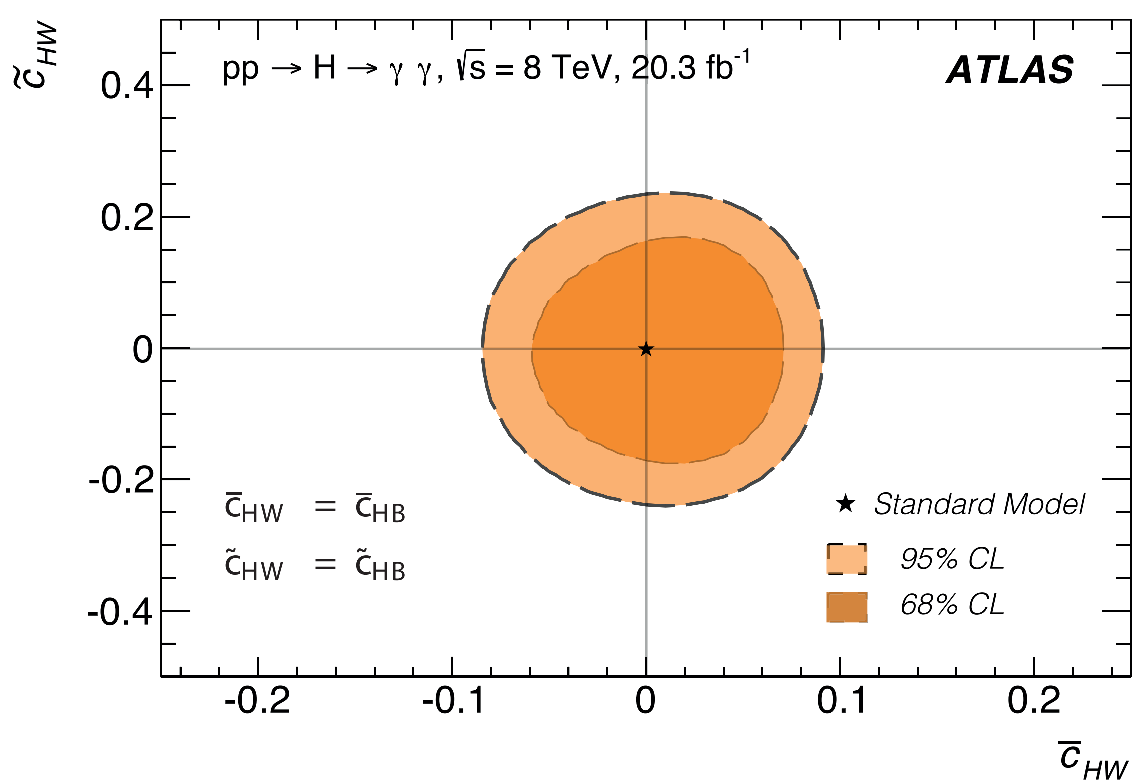


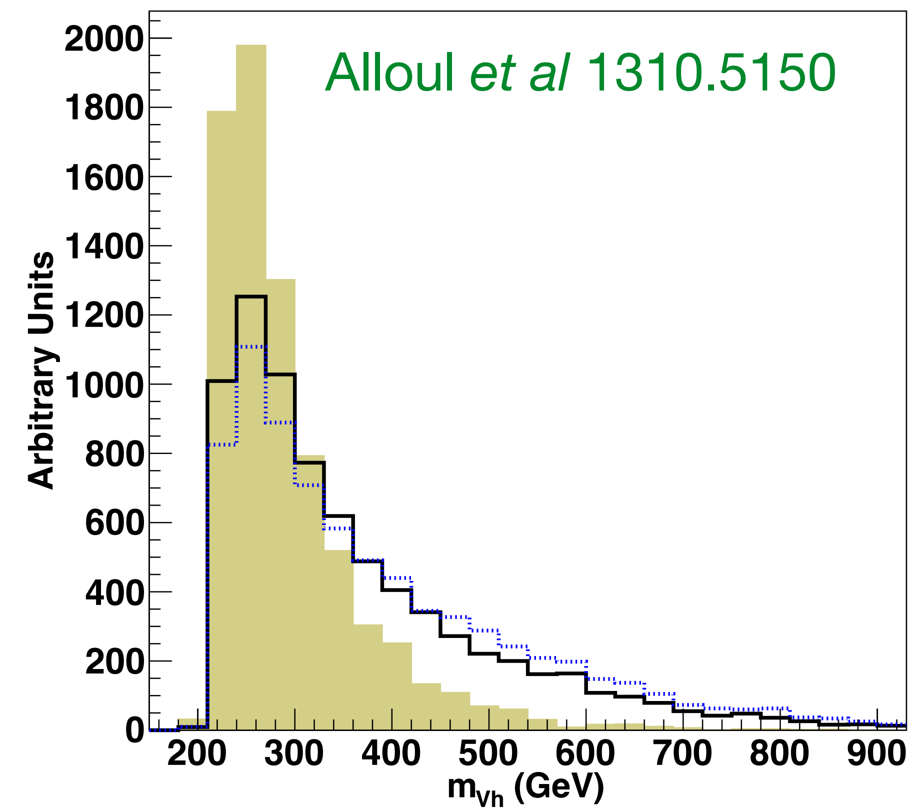


Anomalous Higgs



$$i\Big[\eta^{\mu\nu}\big(g m_W + g^{(1)}_{hww} p_2\cdot p_3 + g^{(2)}_{hww}(p_2^2+p_3^2)\big) - g^{(1)}_{hww} p_2^\nu p_3^\mu - g^{(2)}_{hww}\big(p_2^\nu p_2^\mu + p_3^\nu p_3^\mu\big) - \epsilon^{\mu\nu\rho\sigma}\tilde{g}_{hww} p_{2\rho} p_{3\sigma}\Big],$$

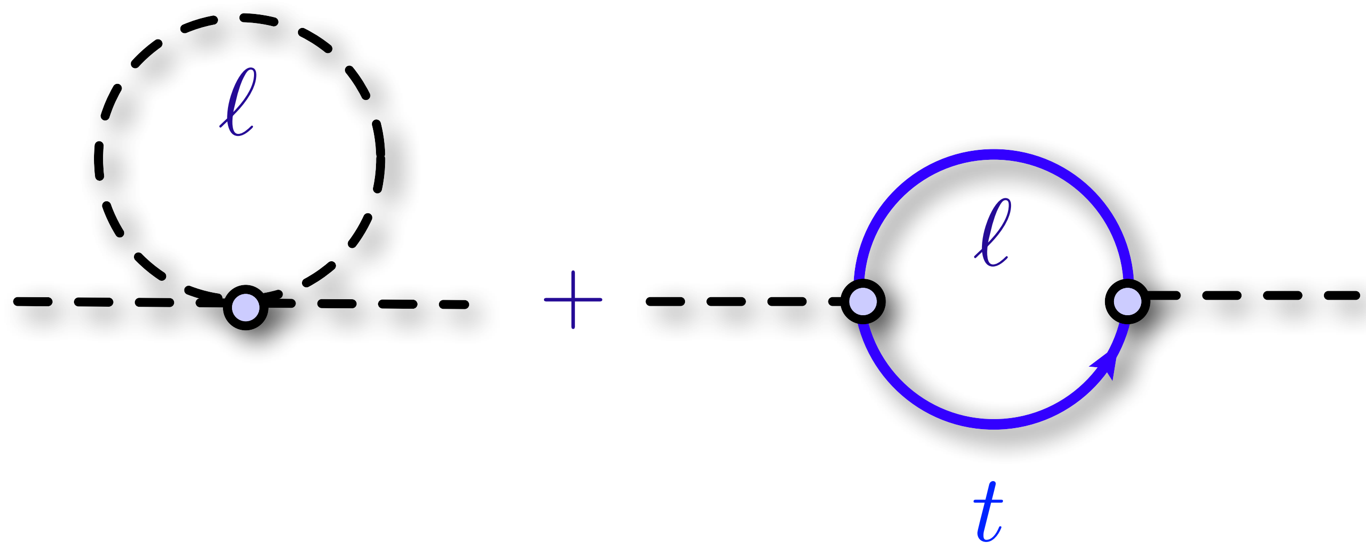




Hierarchy problem.

The SM has some problems, its not natural!

$$\int_0^\Lambda d^4\ell$$

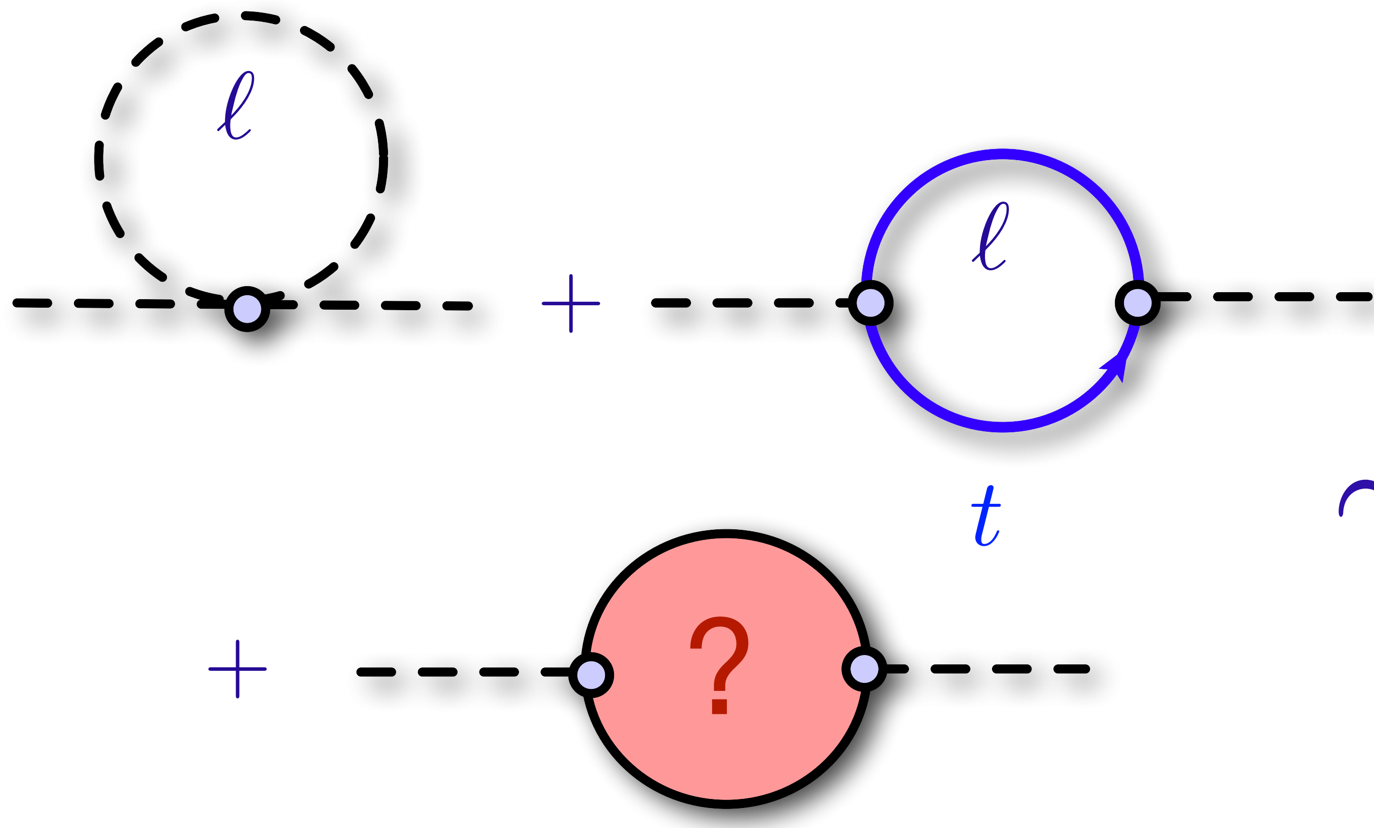


$$\sim \Lambda^2$$

A natural theory would thus predict a (very) heavy Higgs.

Naturalness can be restored if we add in some new contributions!

$$\int_0^\Lambda d^4\ell$$



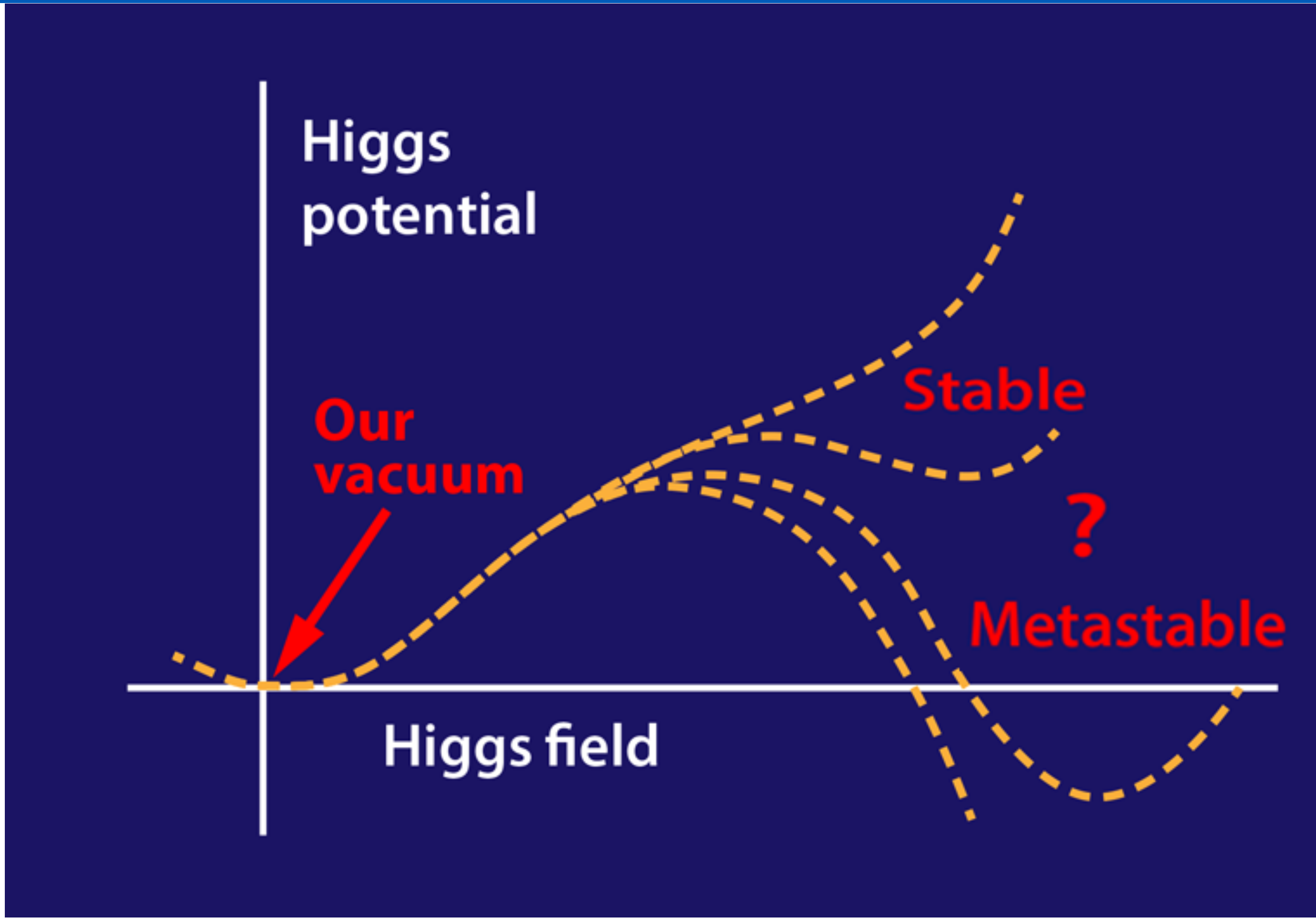
$$\sim M_{EW}^2$$

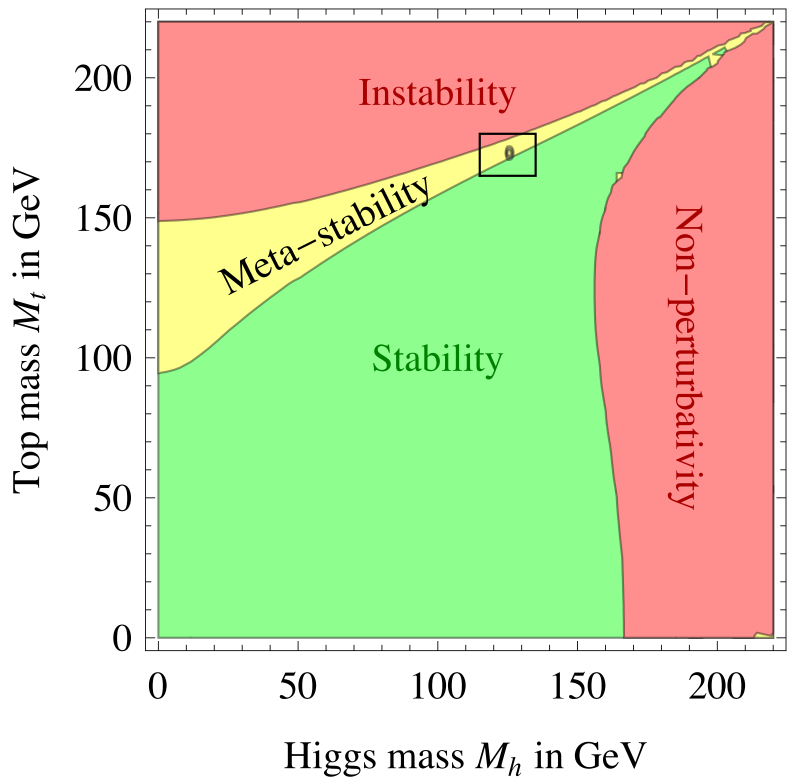
BSM contribution.

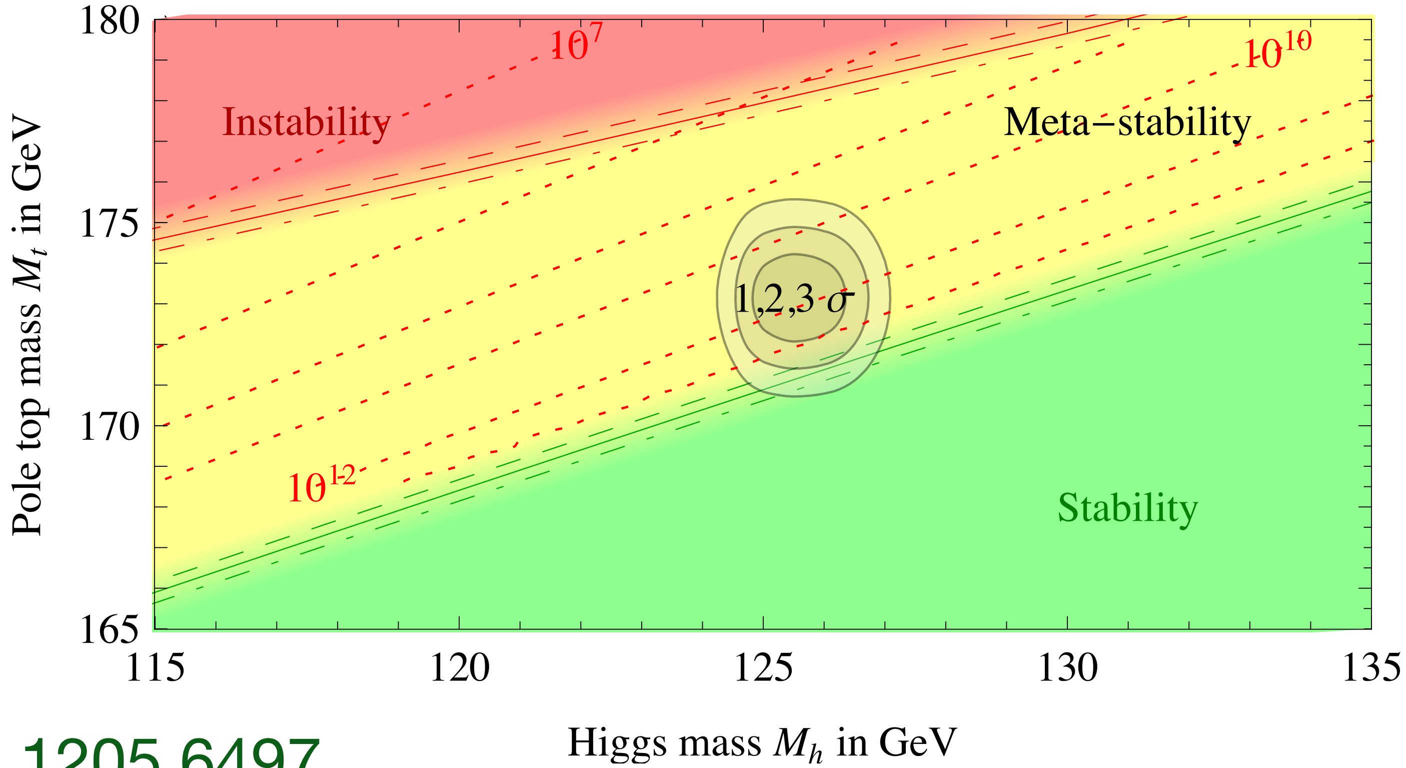
The search for the question of whether we live in a natural world is one of the driving questions of particle physics.

Theoretical issues

$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \,,$$







1205.6497

We recall the form of the Higgs potential

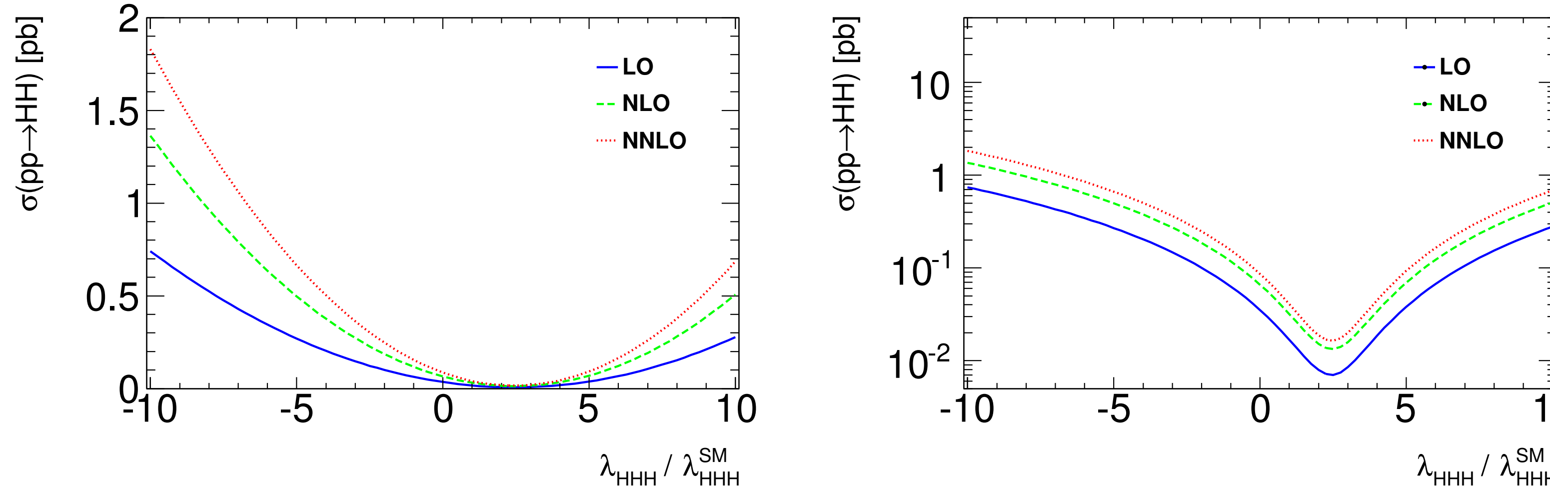
$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4,$$

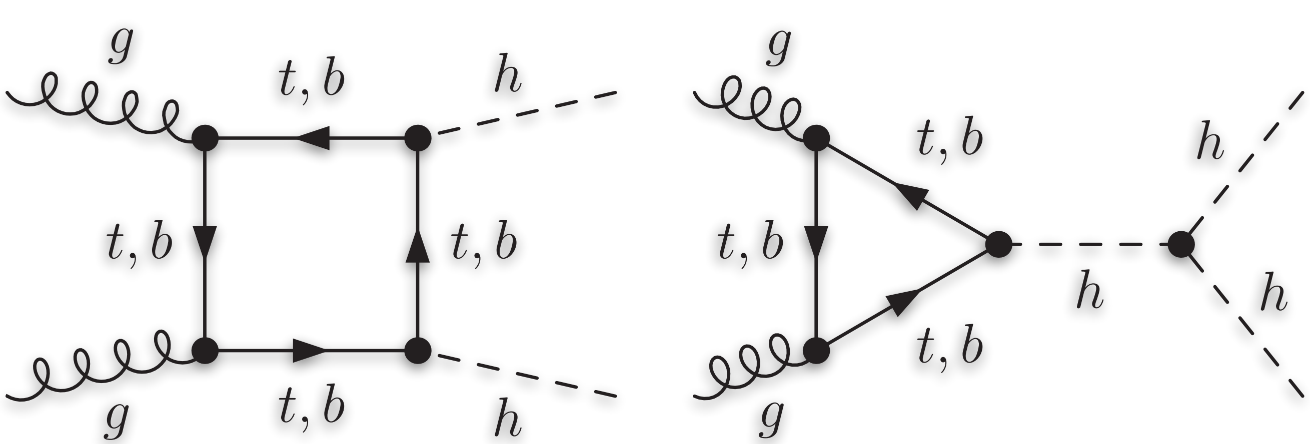
And in the SM we completely fix the couplings once we know the mass

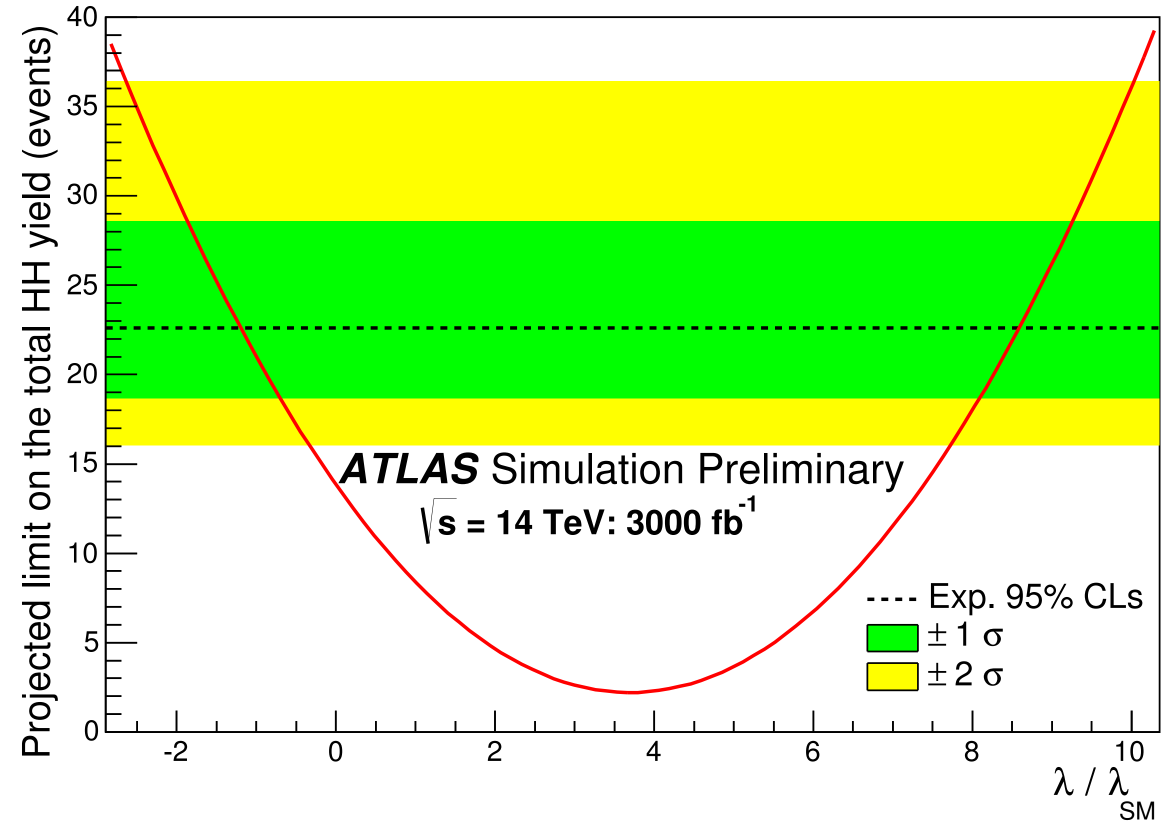
$$\lambda_3 = \lambda_4 = m_h^2/(2v^2)$$

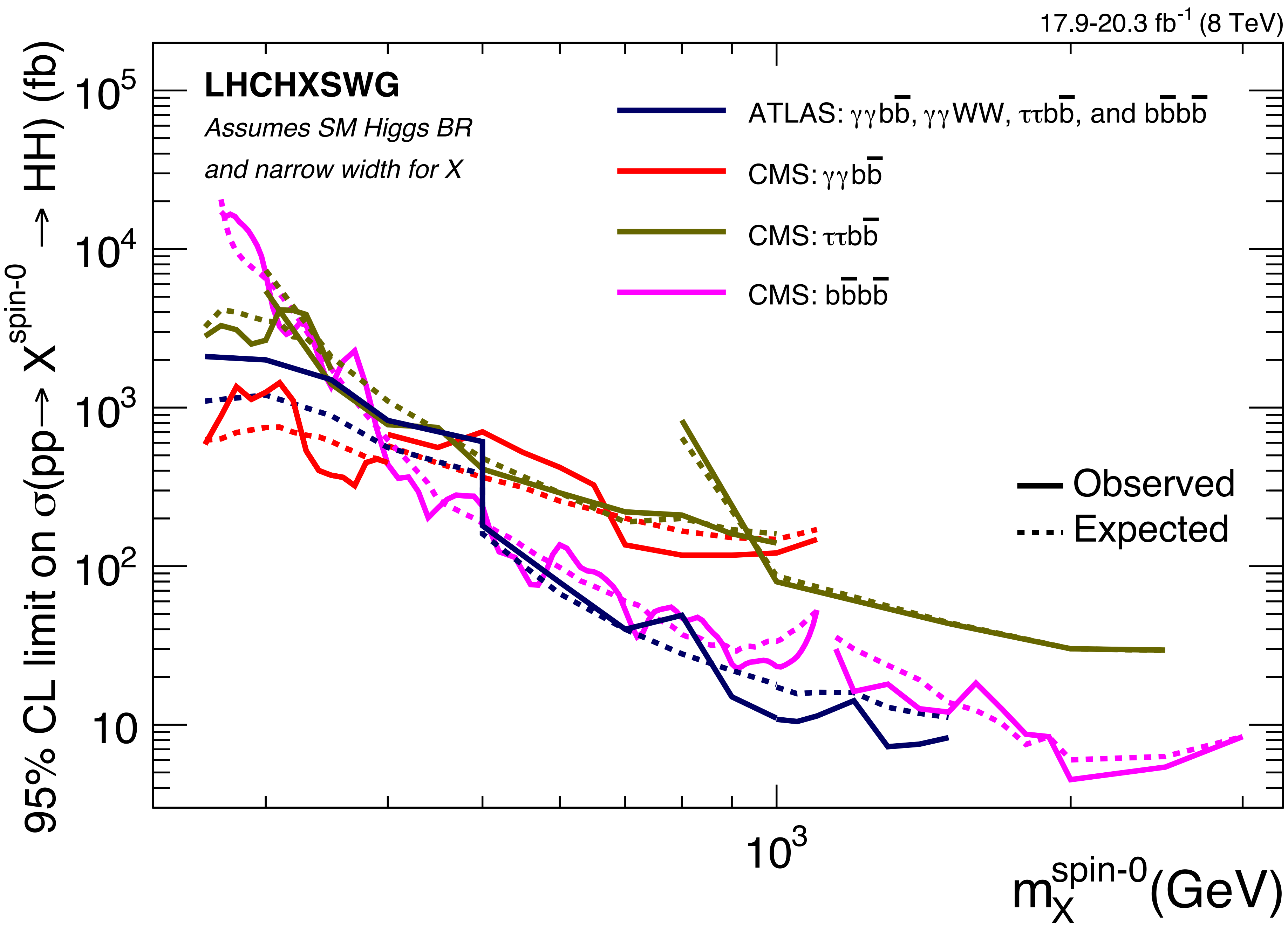
Deviations from this would thus imply new physics.

Higgs self coupling





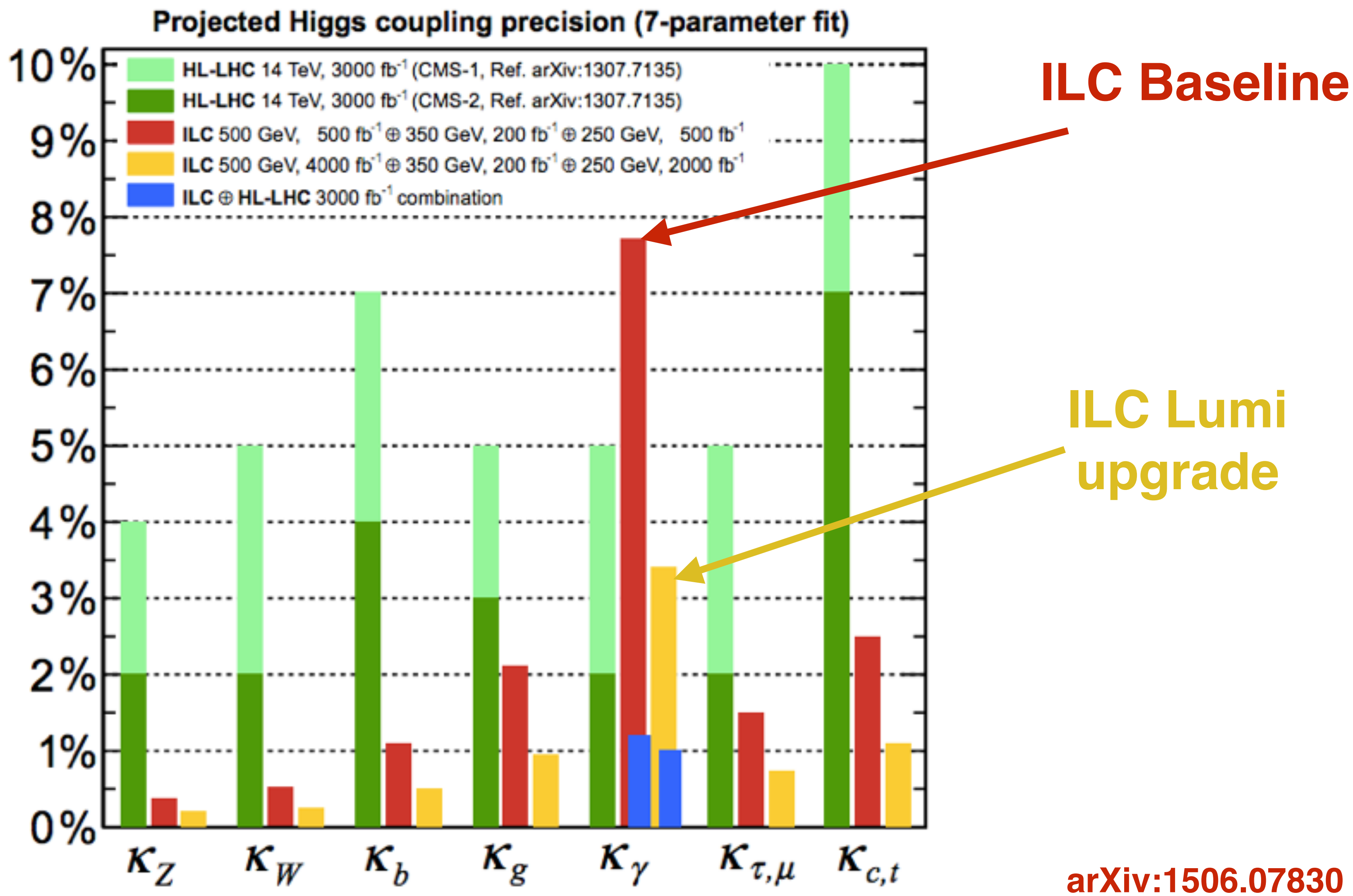




17.9-20.3 fb^{-1} (8 TeV)
LHCHXSWG
Assumes SM Higgs BR
and narrow width for X
ATLAS: γγbb̄, γγWW, ττbb̄, and bb̄bb̄
CMS: γγbb̄
CMS: ττbb̄
CMS: bb̄bb̄
Observed
Expected
95% CL limit on σ(pp→ X^{spin-0} → HH) (fb)
m_X^{spin-0} (GeV)

Precision Higgs Couplings

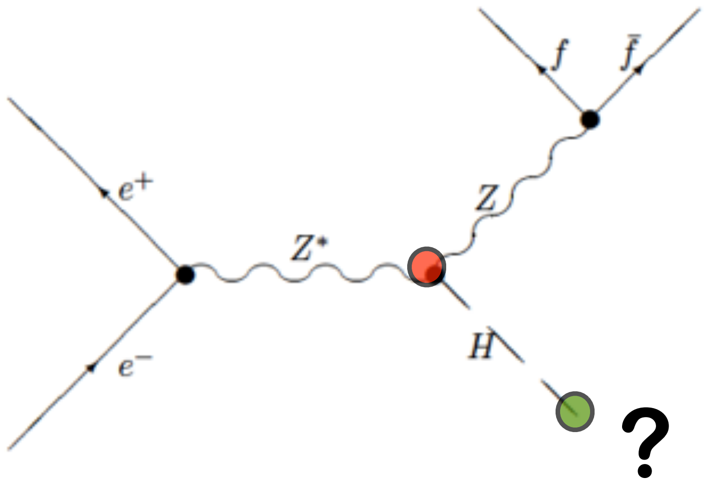
➡ Measurements will built on, complement, and supersede LHC results



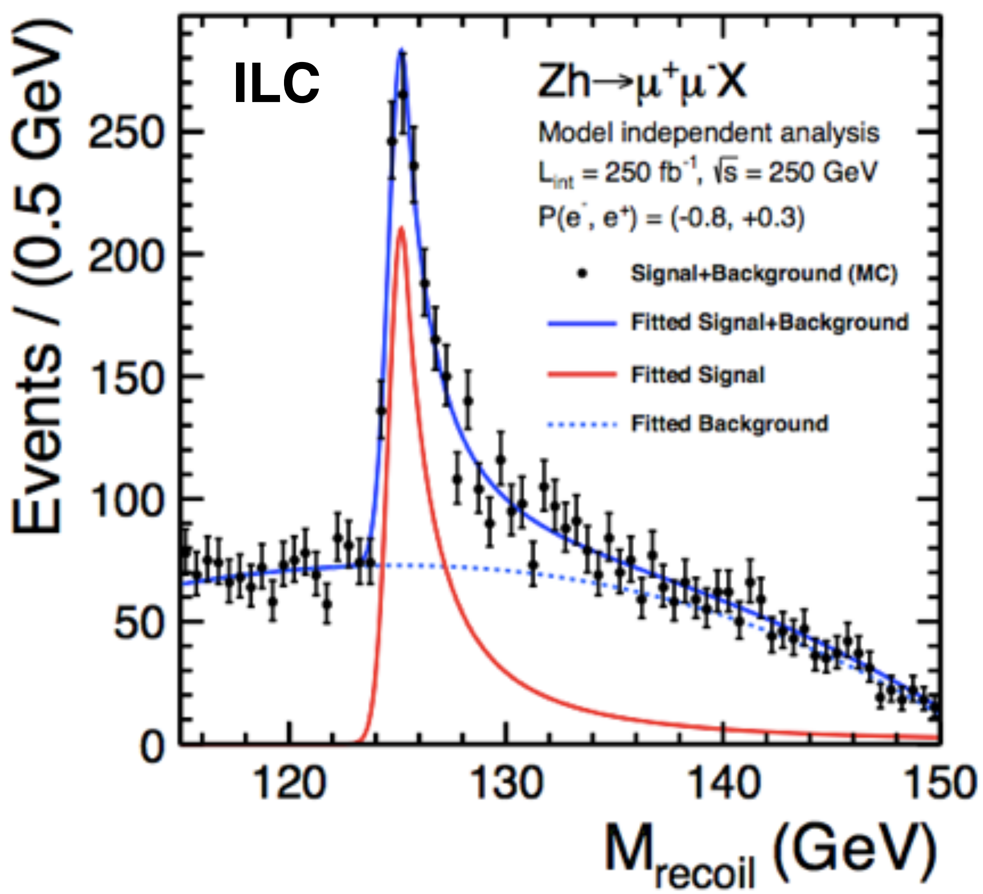
arXiv:1506.07830
arXiv:1506.05992

Higgs Precision Measurements

- ➡ Recoil method unique to lepton collider
- ➡ Tag Higgs event independent of decay mode
- ➡ Provides precision and model independent measurements of
  - ◉ $\sigma(ee\rightarrow ZH) \propto g_{HZZ}^2$
  - ◉ m_H
- ➡ Key input to Γ_H



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



Michelangelo Mangano

Why Higgs at 100 TeV?

- W/Z discovered in '83. Still discussing today how to improve the measurement of their properties! Hadron colliders played, are playing and will continue playing a key role in this game
  - reasonable to expect the same will be true for the Higgs 30-40 yrs after 2012, with the measurement of Higgs properties intertwined with the testing for SM anomalies
- Great improvement in precision will arise from e^+e^- colliders *[see later talks by D'Enterria (FCC-ee), Ruan (CEPC), Lukic (CLIC), Strube (ILC)].*
- Depending on the configuration (linear vs circular) and energy (ILC vs CLIC), there will nevertheless still remain a need for complementary input, which could be provided by a 100 TeV pp collider:
  - direct probe of EW interactions and EWSB at scales > 1 TeV
  - exploration of extended Higgs sectors
  - precise measurement of rare Higgs decays and tests of rare production mechanisms
  - precise determination of top-Higgs coupling and Higgs self-couplings (if ECM of e^+e^- colliders will stay below the TeV)
- At the LHC, the Higgs is already an analysis tool, if not a background, in searches of new particles (like W/Z and like the top quark). This will be even more true at 100 TeV!!