LHC physics

DESY summer student lecture
August 2019

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Overview of these lectures

Intro

Electroweak physics, top quark

Higgs boson << my favorite topic :)

Searches for physics beyond the Standard Model

The Higgs boson - very brief theory reminder

Higgs mechanism:

- makes use of one Higgs doublet of complex scalar fields
- to spontaneously break the $SU(2)_L \times U(1)_Y$ symmetry
- to generate in a gauge invariant way
- the masses of the $W^{\pm}$, Z gauge bosons and the fermions

Basically:
In order to give the gauge bosons mass and keep gauge invariance
-> introduce a Higgs field, with a scalar potential
-> find ground state -> express in terms of ground state

-> Higgs boson
-> Gauge bosons with mass
-> Higgs-particle couplings terms ——> Higgs couplings ~ boson mass^2
Higgs couplings ~ fermion mass

The Higgs boson - very brief theory reminder

$$
\begin{aligned}
\mathcal{L} = & -{}^{1}/_{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \Psi + h.c. \\
& + \Psi_i y_{ij} \Psi_j \Phi + h.c. \\
& + \left| D_\mu \Phi \right|^2 - V(\Phi)
\end{aligned}
$$

Higgs-fermion interactions

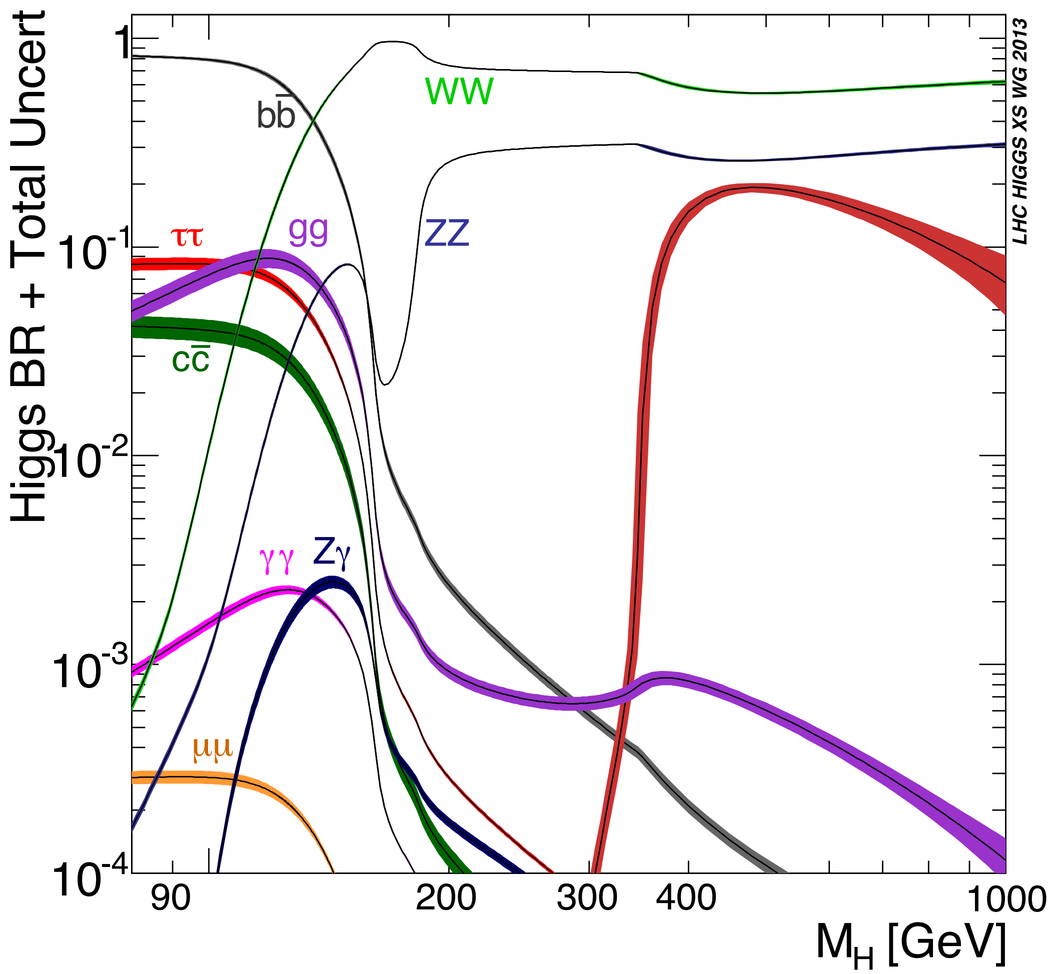
Higgs-self interactions/potential

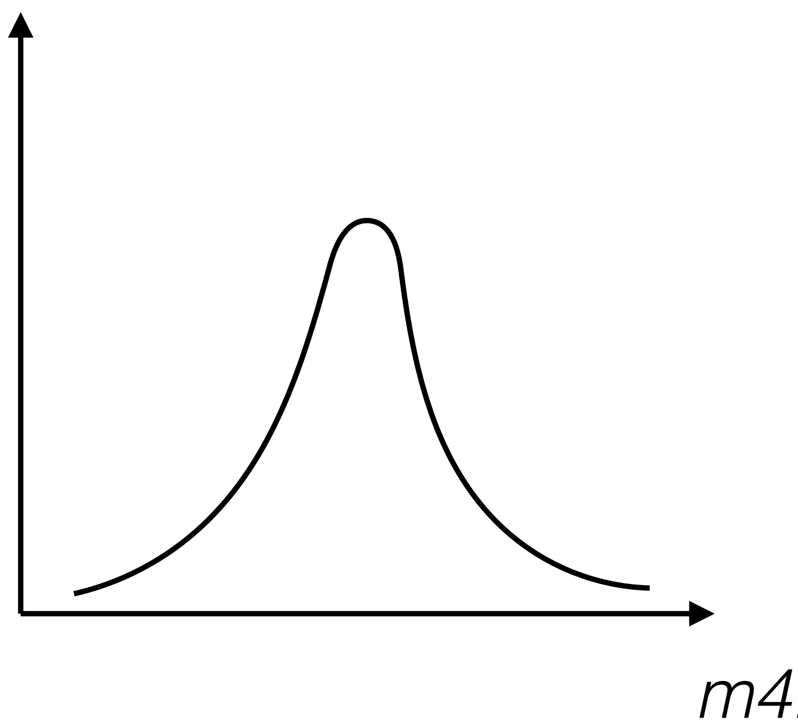
Higgs-gauge boson interactions

The Higgs - what do we expect at the LHC?

The Higgs is predicted to be very short-lived
=> we have to look at its decay products

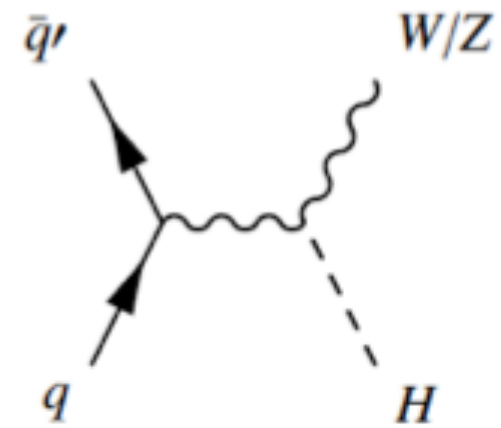
Standard Model predicts the branching ratios, but they depend on the Higgs mass (which was unknown before 2012)

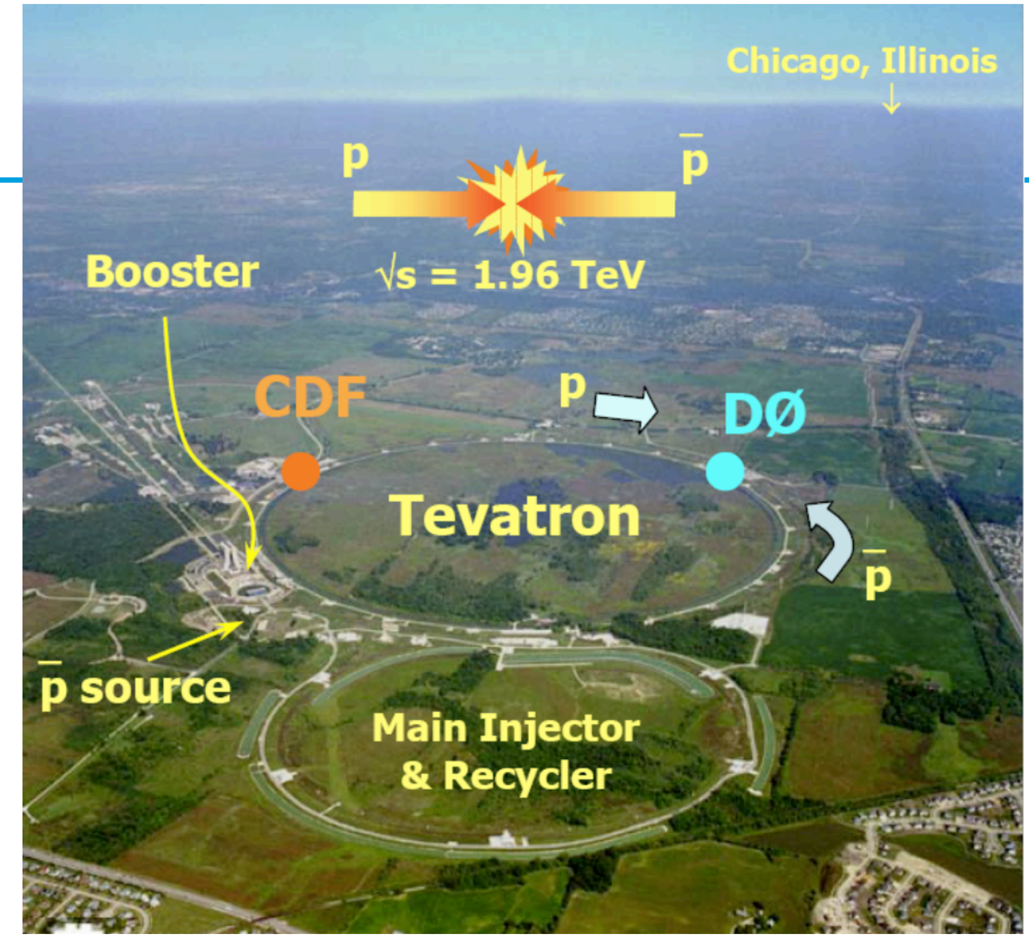




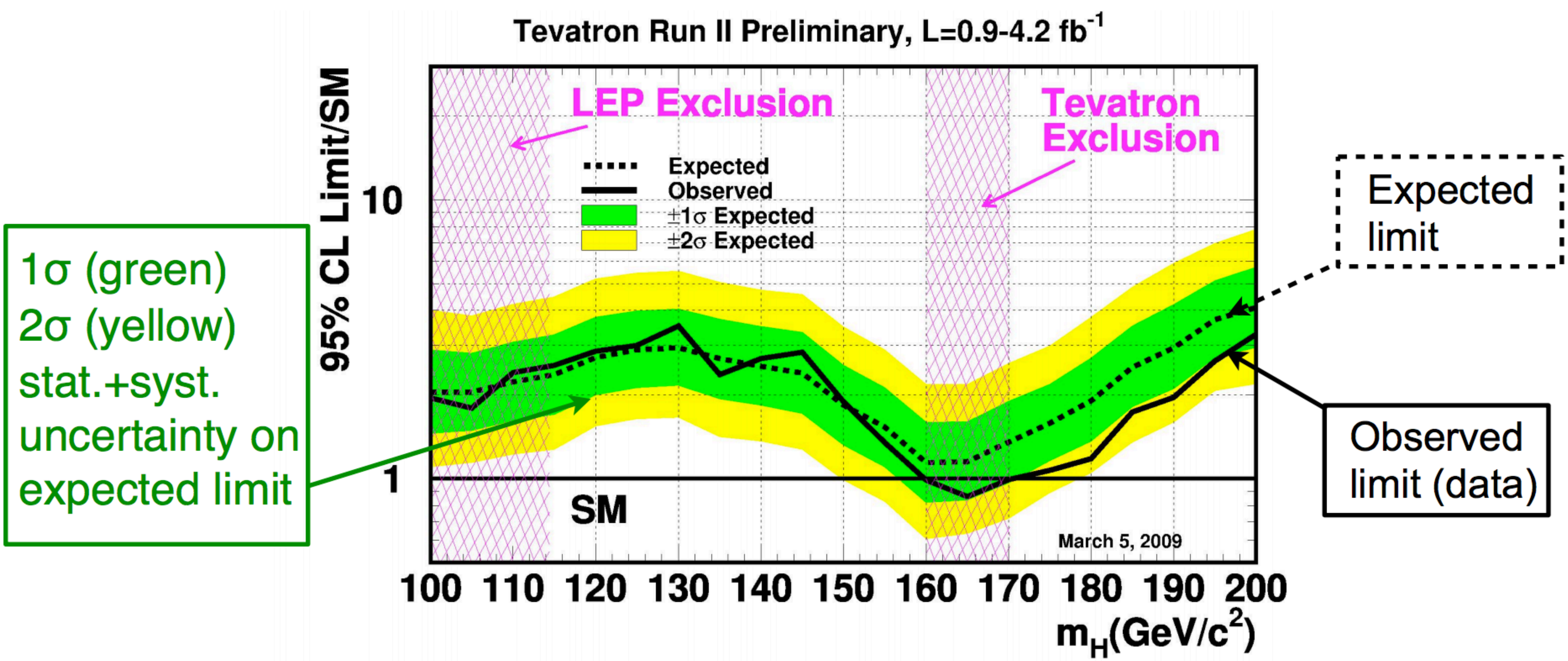
=> we are looking for peaks in the invariant mass of the decay particles
=> combine results of the searches in the different final states

Situation before the LHC

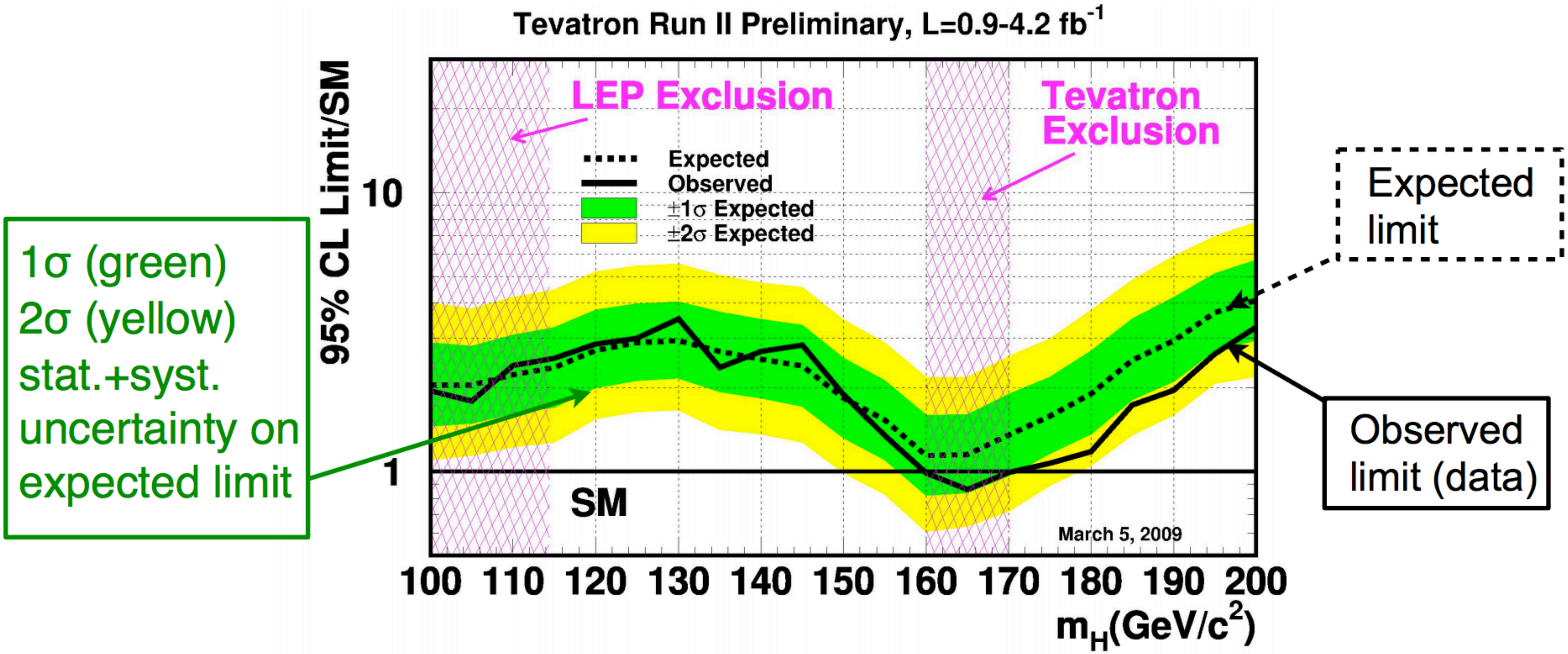




Status 2009: SM Higgs mass above 114 GeV, and NOT in the range 160-170 GeV



Limit plots



Limit plots are used if no signal is seen

95% CL upper limit on "signal strength":

- signal strength μ = XS_meas/XS_SM
- **With 95% confidence level, we can say that the real signal strength is smaller than the indicated value**
- done for each mass point separately

95% CL limit

We have an observation and try to make a statement of the underlying physics model (is it the SM? or something else?)

=> Find the signal strength, for which we can be sure that it is excluded, even if the data has a downward fluctuation

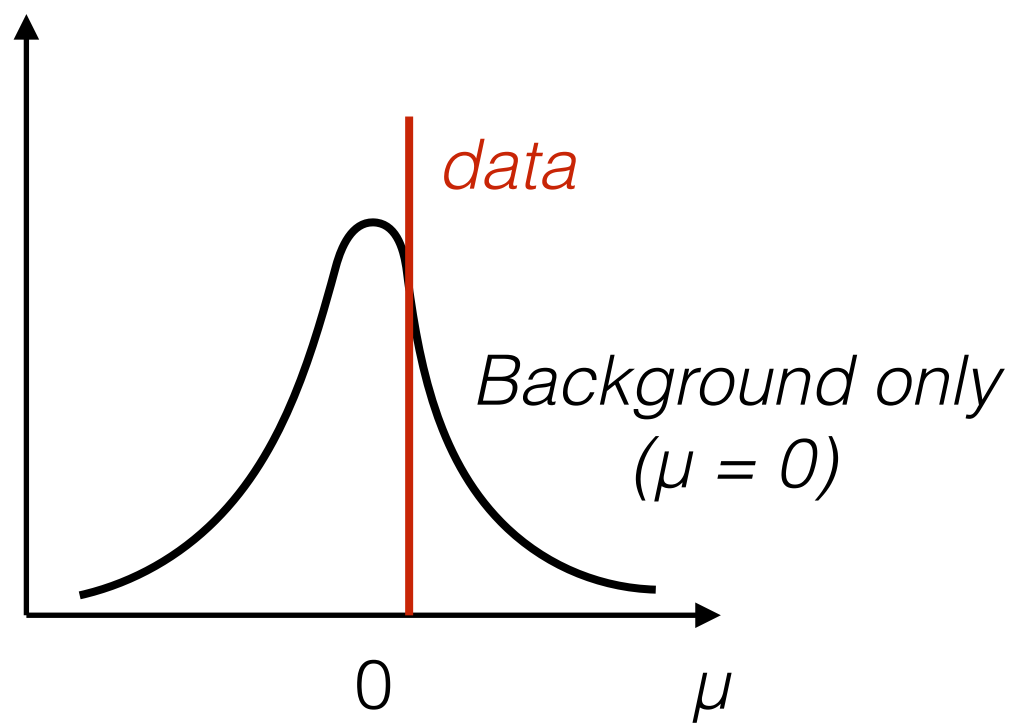
Here:
>> Frequentist method, with toys (alternatives: asymptotic approximations, Bayesian)
>> simplified test statistics (μ)

More details on asymptotic approximations:
https://arxiv.org/pdf/1007.1727.pdf

95% CL limit

Start with a background-only prediction

=> sample this prediction to create “pseudo-data sets” with the same statistics as the data => O(1000-10000) pseudo-data sets
=> perform the background+signal fit, extract the signal
=> plot the distribution of fitted signal events, compare to the data

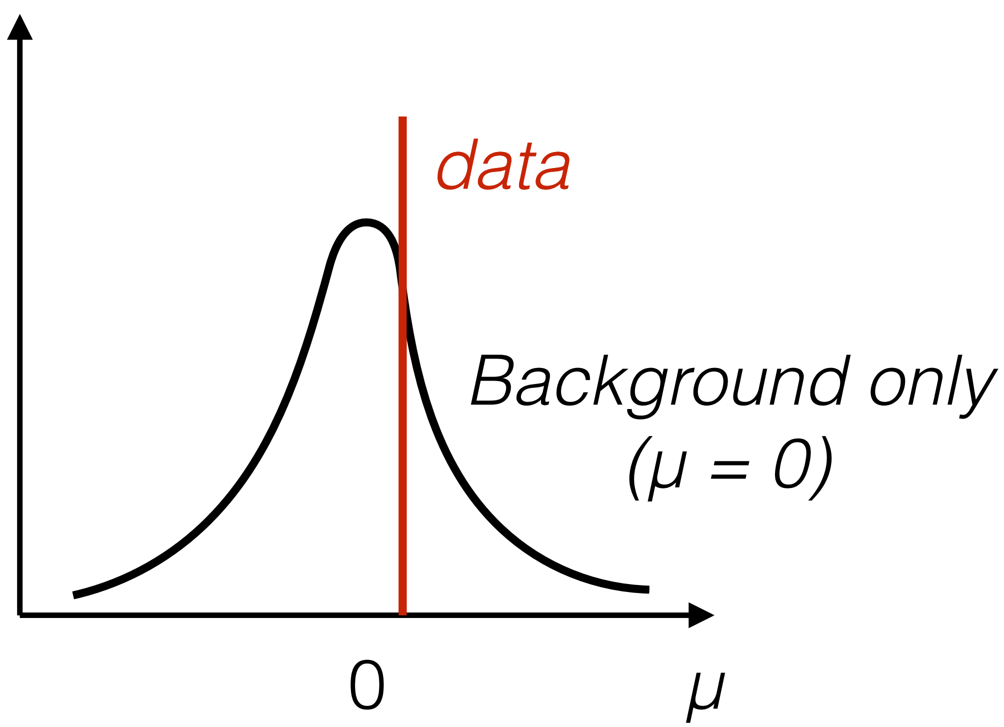


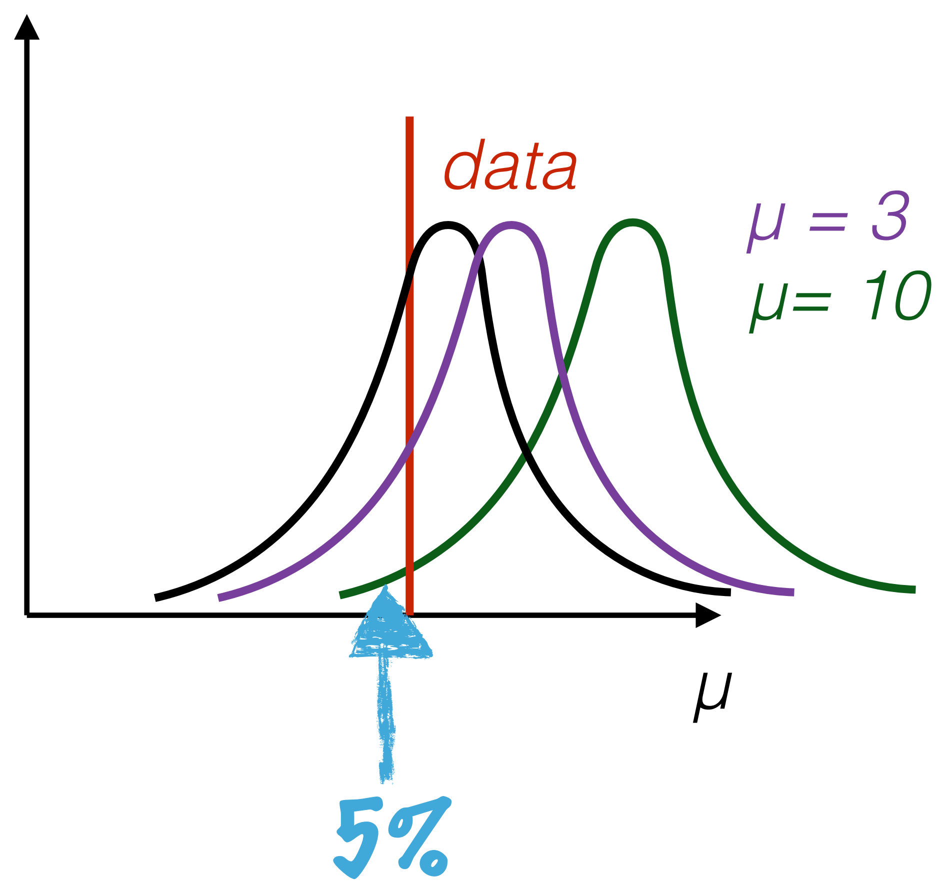
95% CL limit

Add signal to your pseudo-datasets

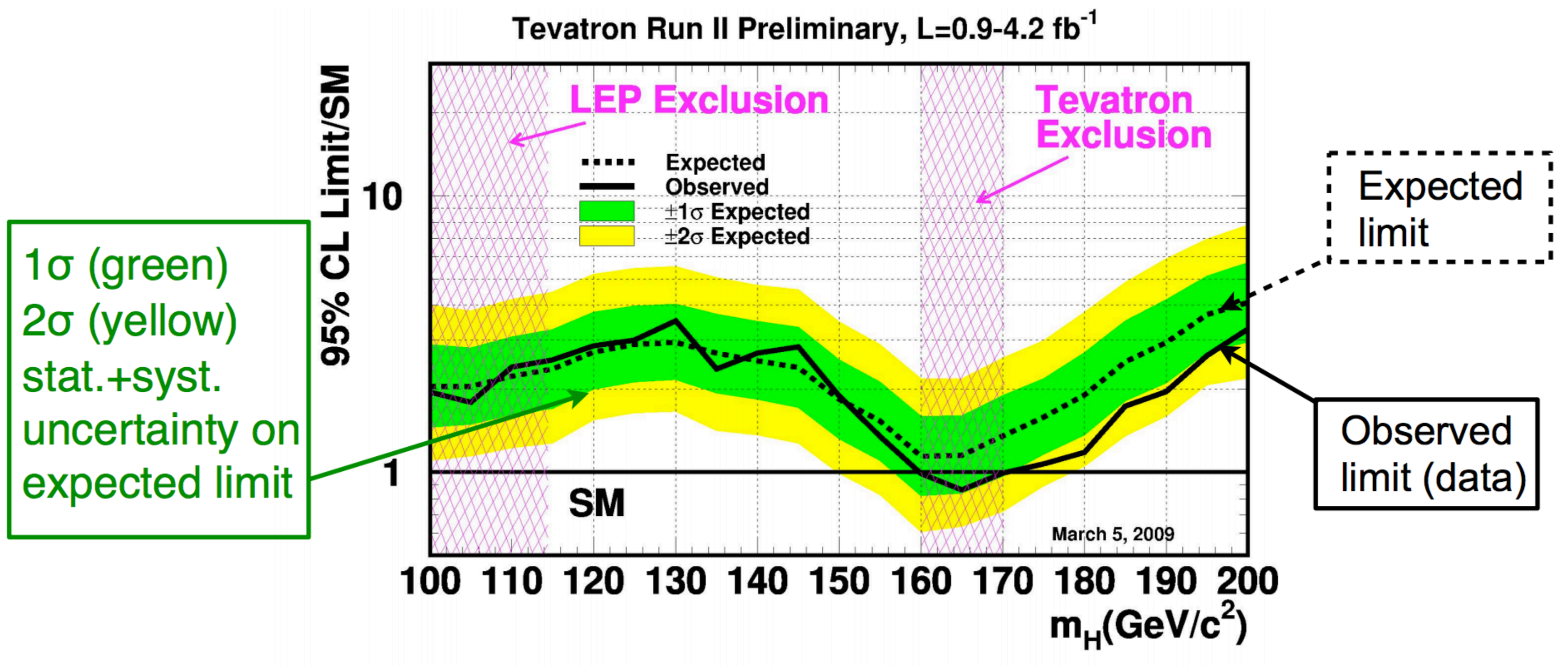
=> perform the background+signal fit, extract the signal
=> find the signal strength, which has 5% to the left of the data line

=> This the signal strength, for which we can be sure (with 95% CL) that it is excluded, even if it has a downward fluctuation



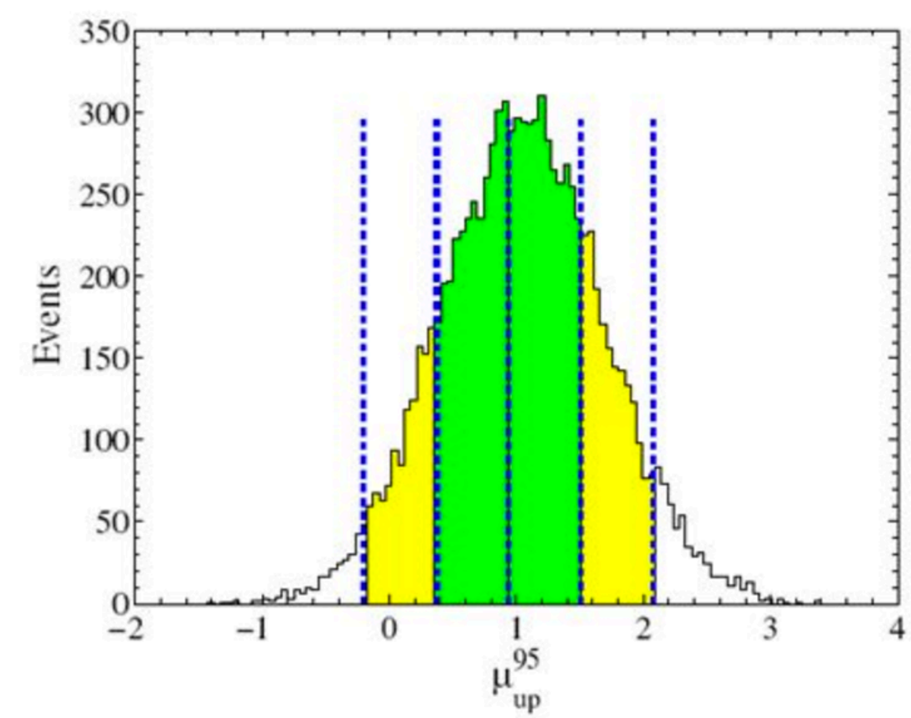


What is the green and yellow?



- **background-only** expectation (with no signal, what limit would we expect?)

- repeat procedure with pseudo-data for μ = 0, do this many times
- plot the extracted limit μs
- find mean, 68% (1 sigma), 95% (2 sigma) ranges



=> in absence of signal, observed and expected limit should be very similar

=> pseudo-experiments are very time-intensive, preferable to do this analytically where possible

One word about likelihoods

We usually form likelihood functions based on the Poisson probability

$$\mathcal{L}(\mathrm{data}|\mu,\theta) = \mathrm{Poisson}(\mathrm{data}|\mu\cdot \mathrm{s}(\theta) + \mathrm{b}(\theta)) \cdot \mathrm{p}(\tilde{\theta}|\theta)$$

Test statistics: Likelihood ratio

(For illustration, I chose the signal strength μ instead of the more commonly used likelihood ratio)

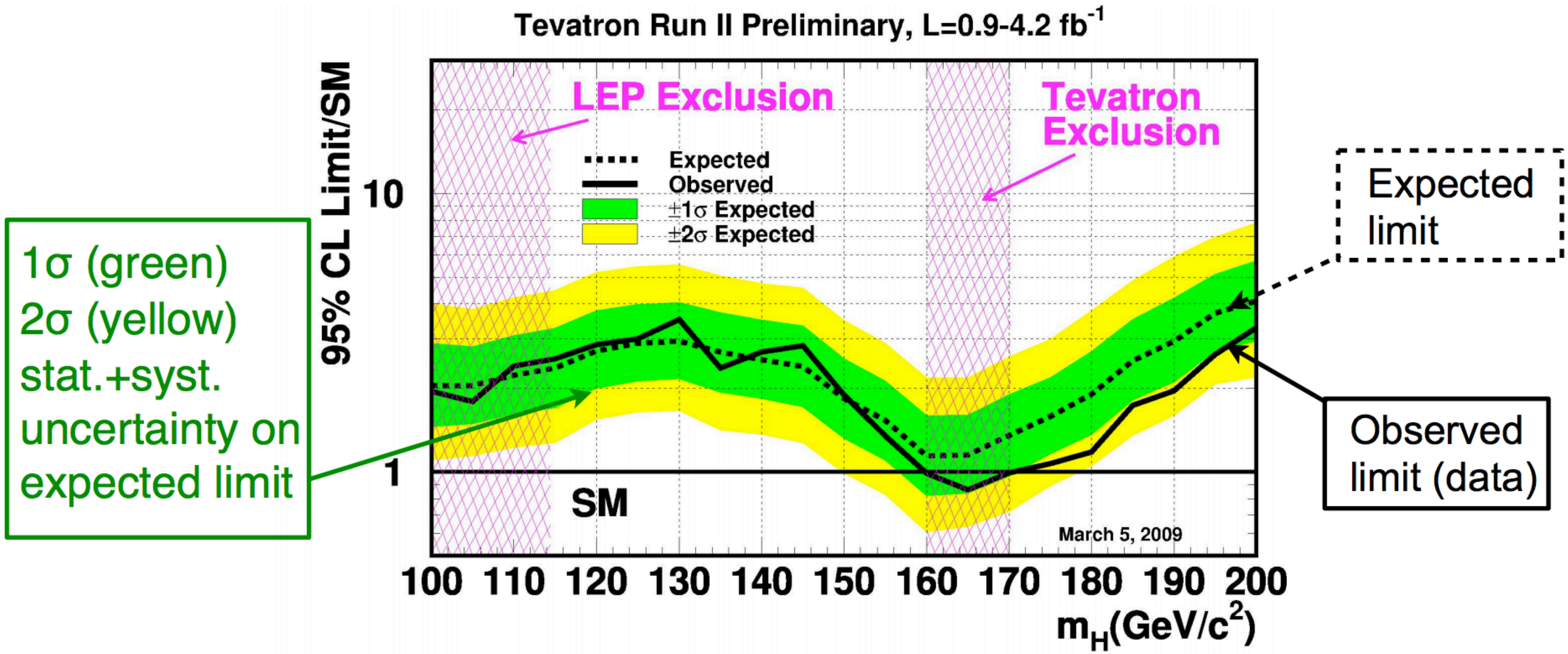
$$\frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu},\hat{\boldsymbol{\theta}})}$$

Advantage of likelihood functions

>> can use asymptotic approximations instead of toys (toys are very CPU intensive)

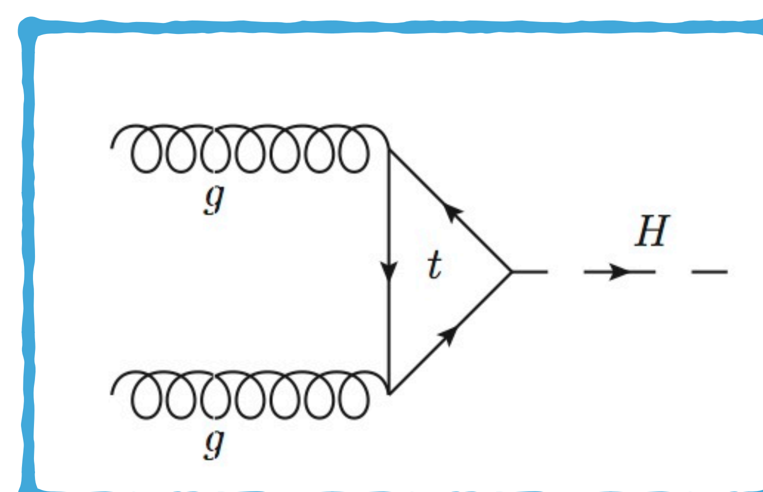
>> allows for straightforward combinations

Tevatron => LHC



- LHC: Higher CM energy (8 - 13 TeV so far)
=> higher Higgs production cross section

- it was clear that the time to discovery (if any) would depend on the Higgs mass

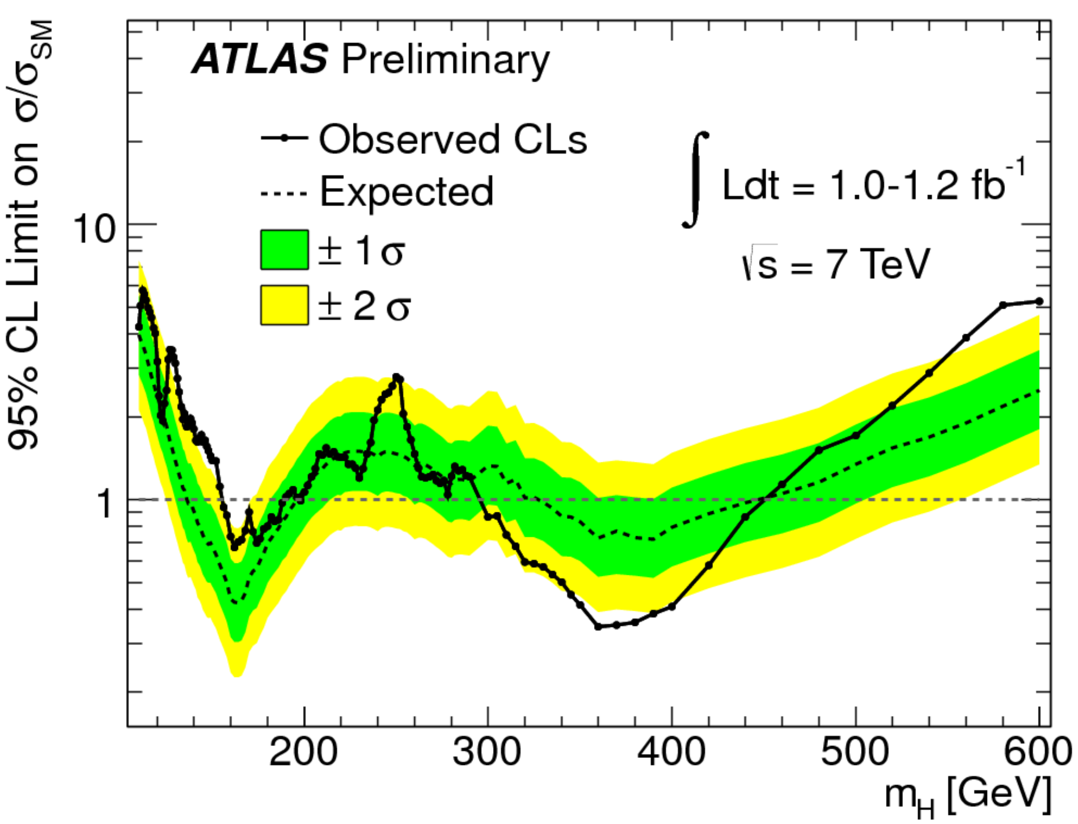


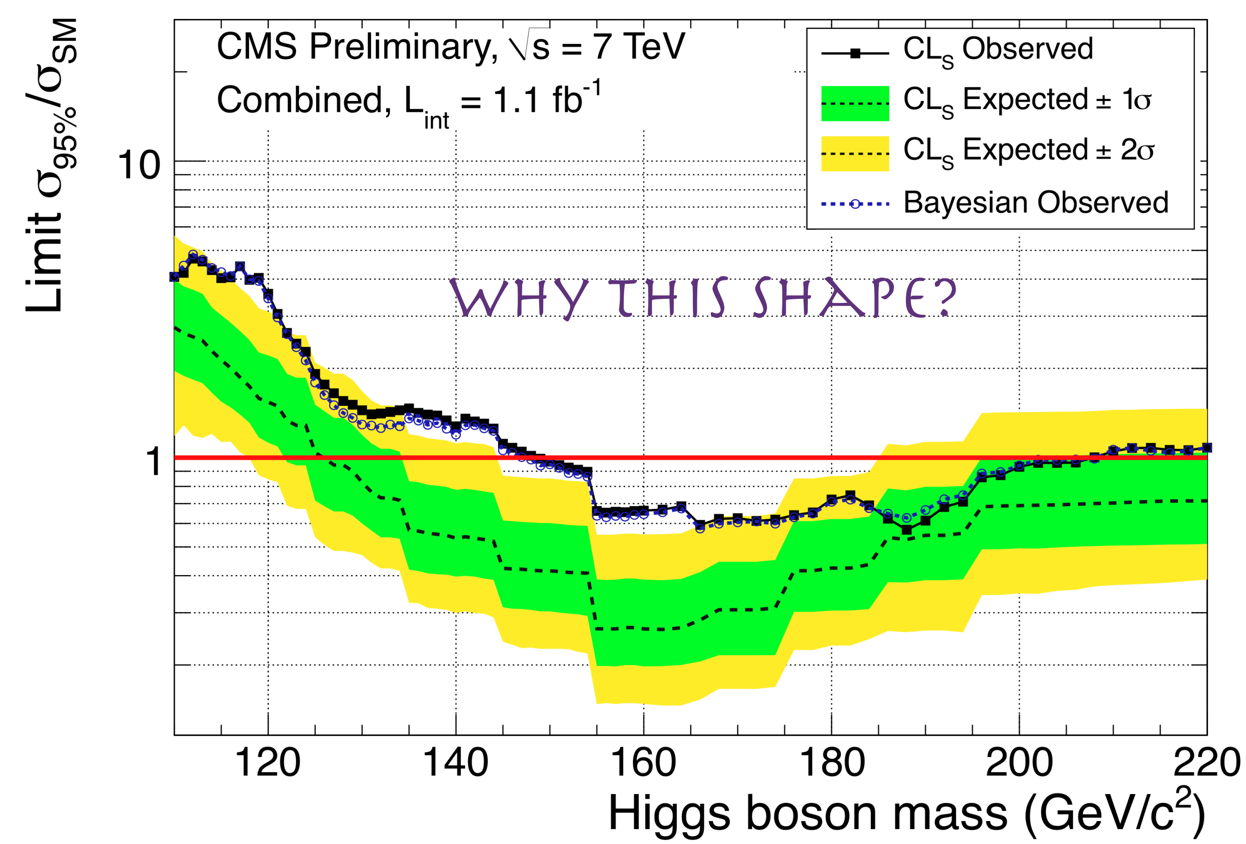
2011

First big dataset of LHC

- looking for an excess in the different decay channels

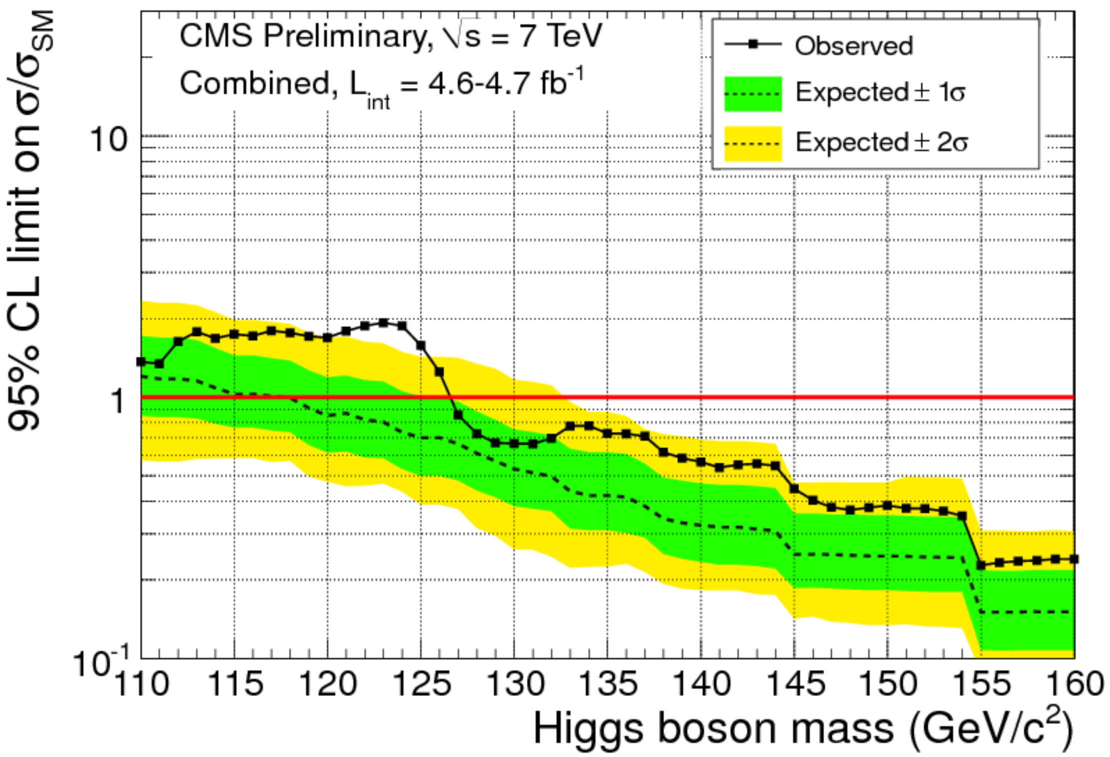
1 fb-1

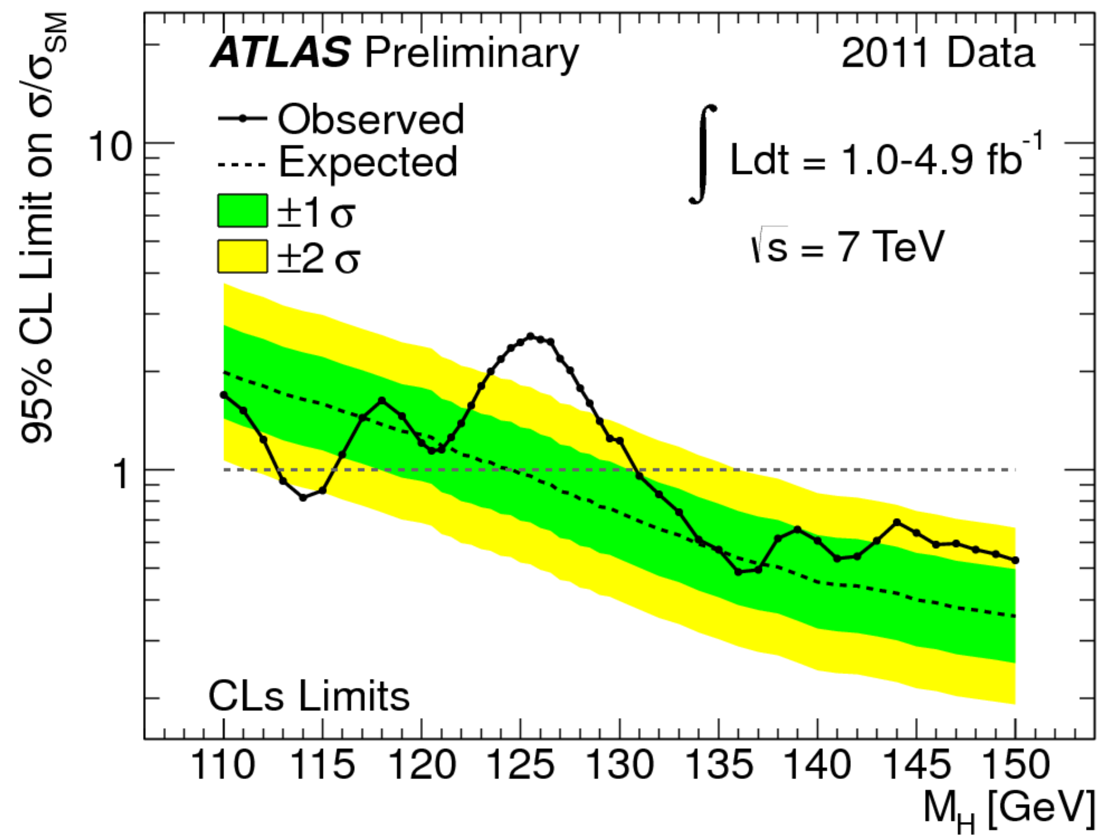




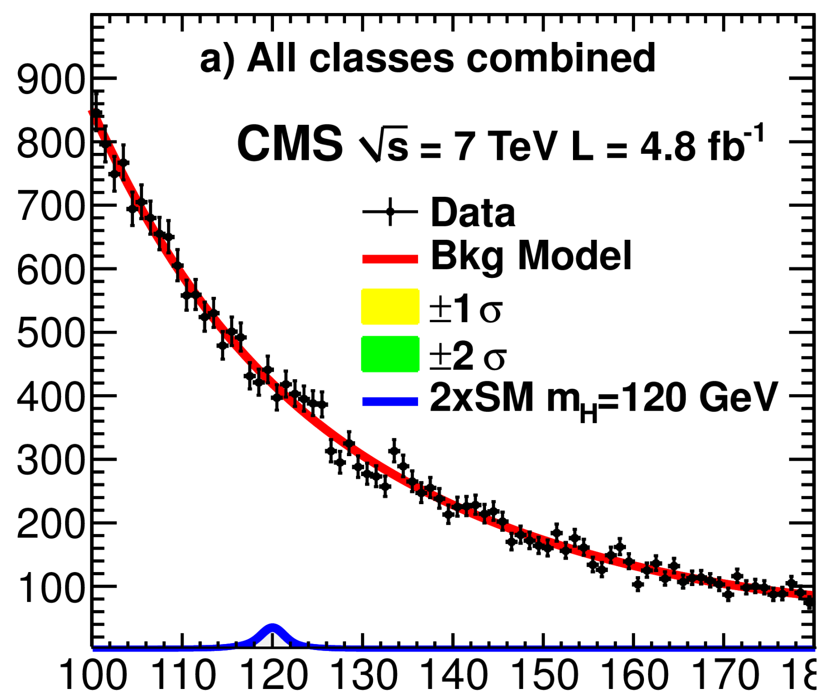
Christmas 2011

5 fb^{-1}

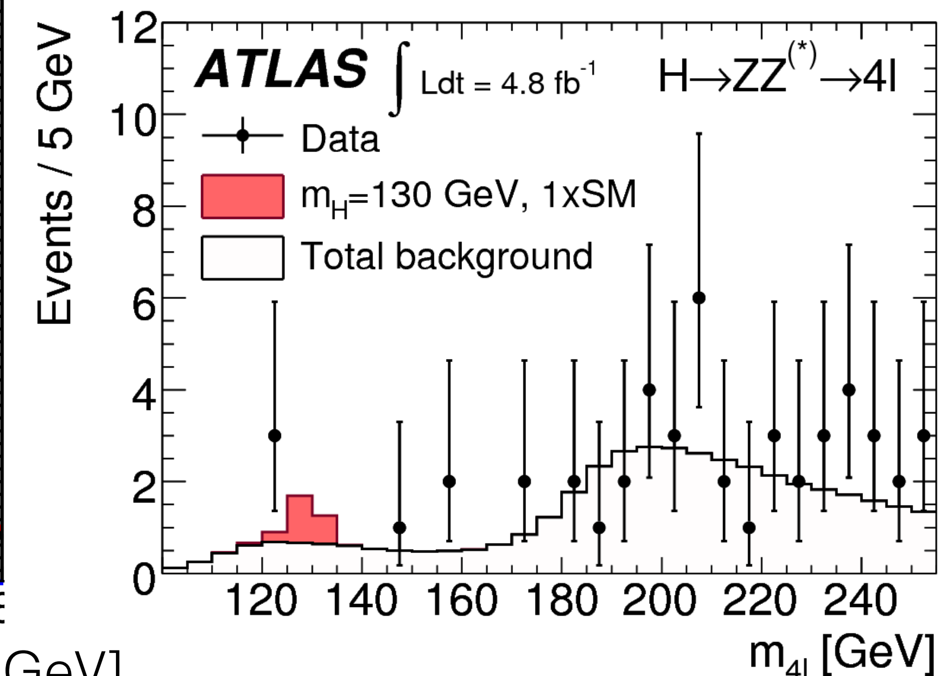




Example inv. mass plots

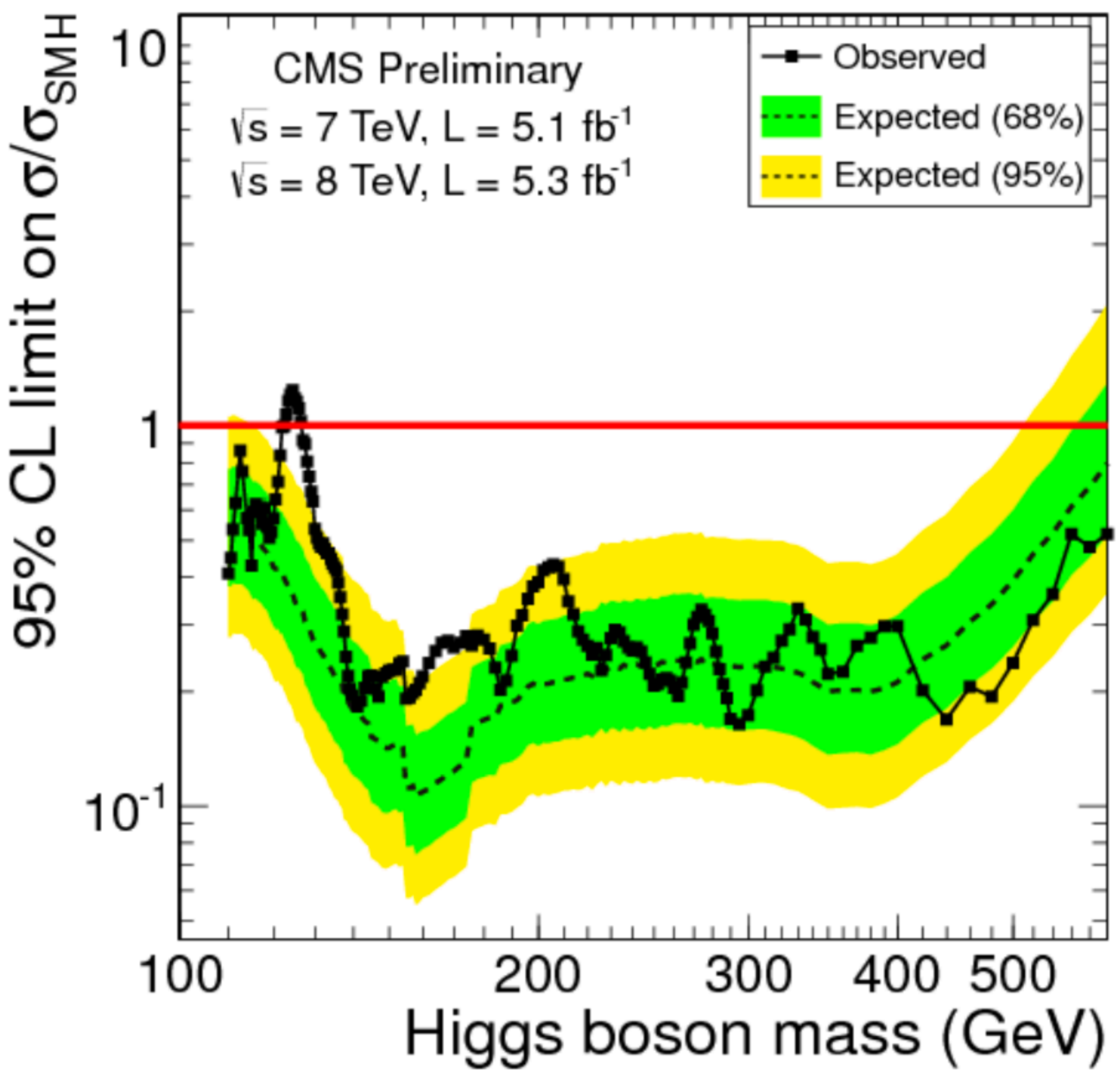


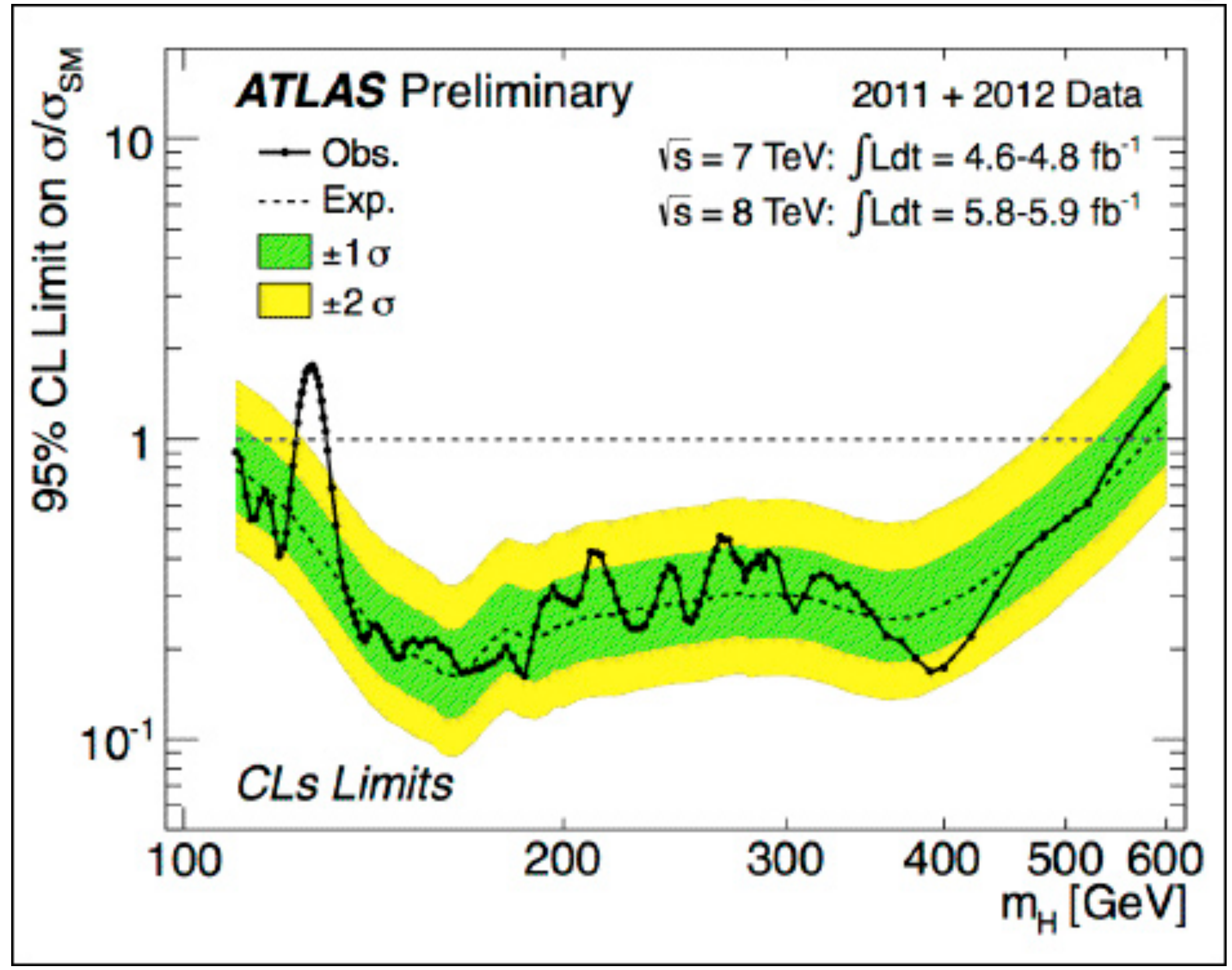
myy [GeV]



July 2012

10 fb-1



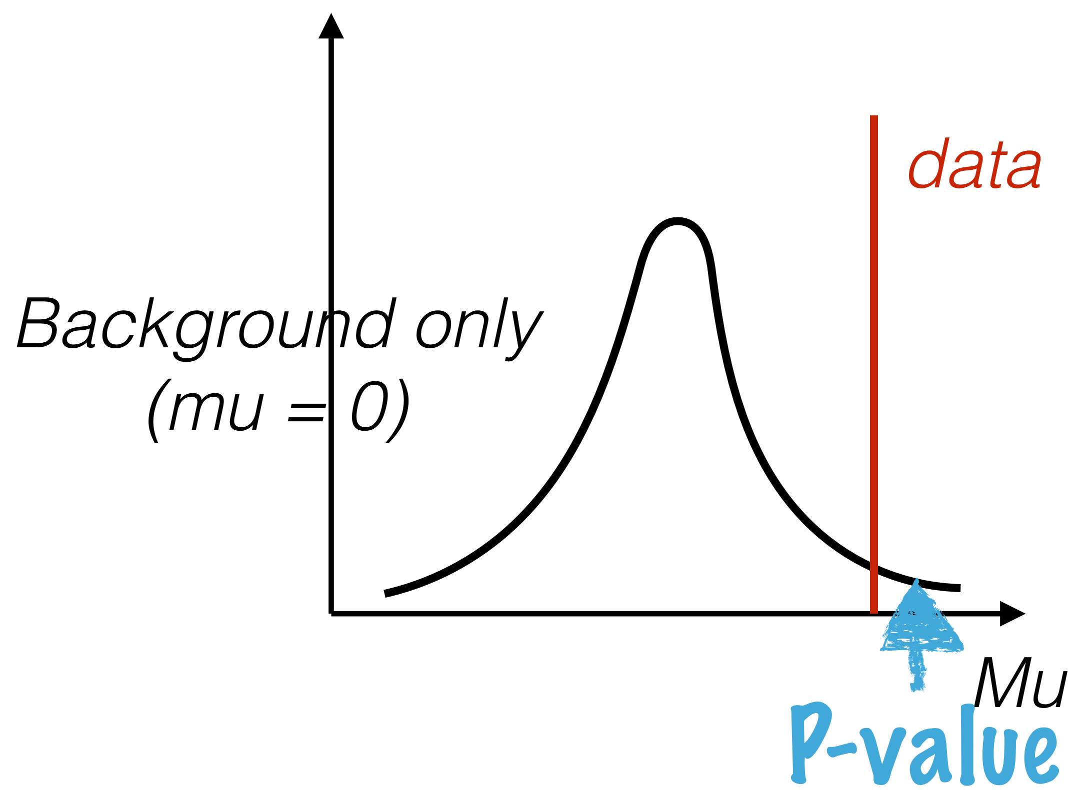


Limit plots not appropriate anymore!

p-value:
Probability that the background alone fluctuates as high as the observed signal

<u>Estimation done similar to limit plots (here again based on pseudo-experiments):</u>

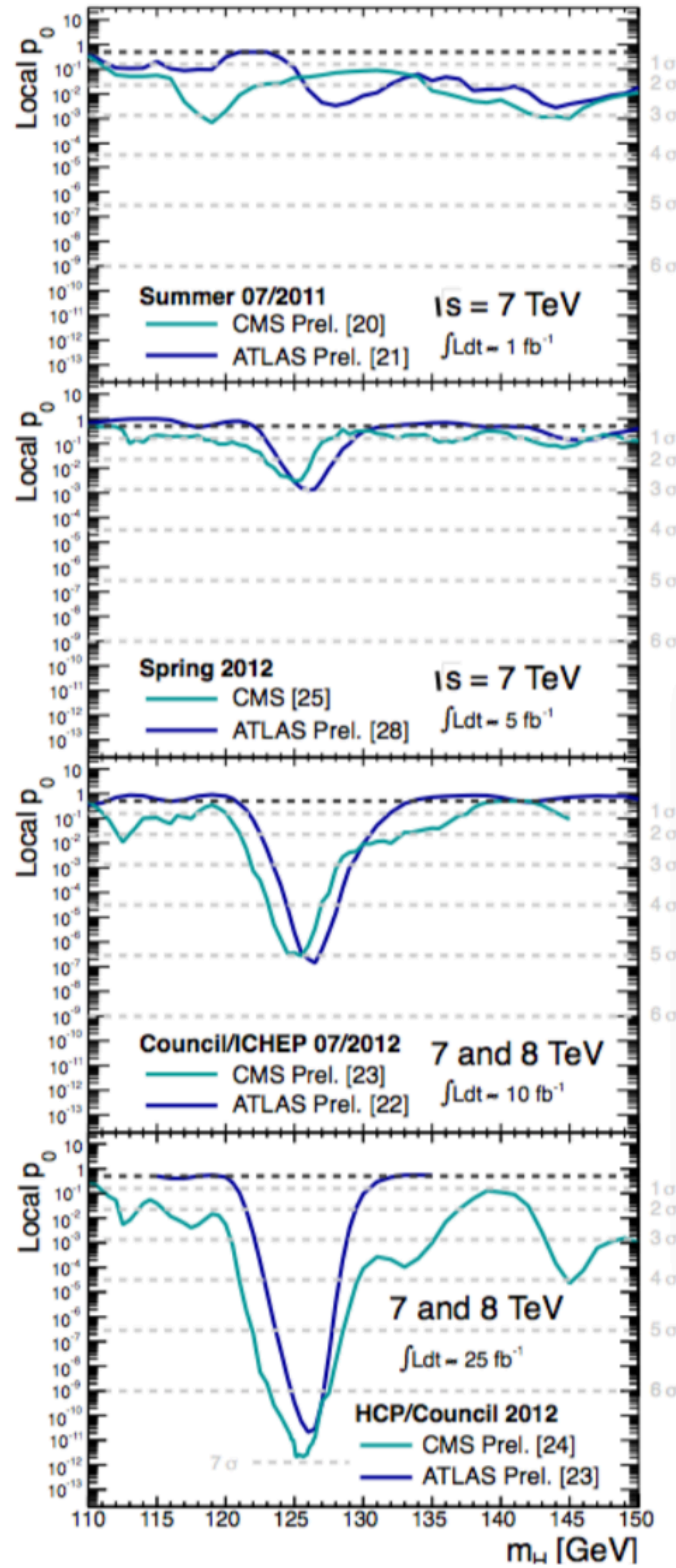
- assume background only (p.ex. from simulation)
- plot test statistics for this pseudo-data (>1000 times)
- put data on this plot, check where it lies



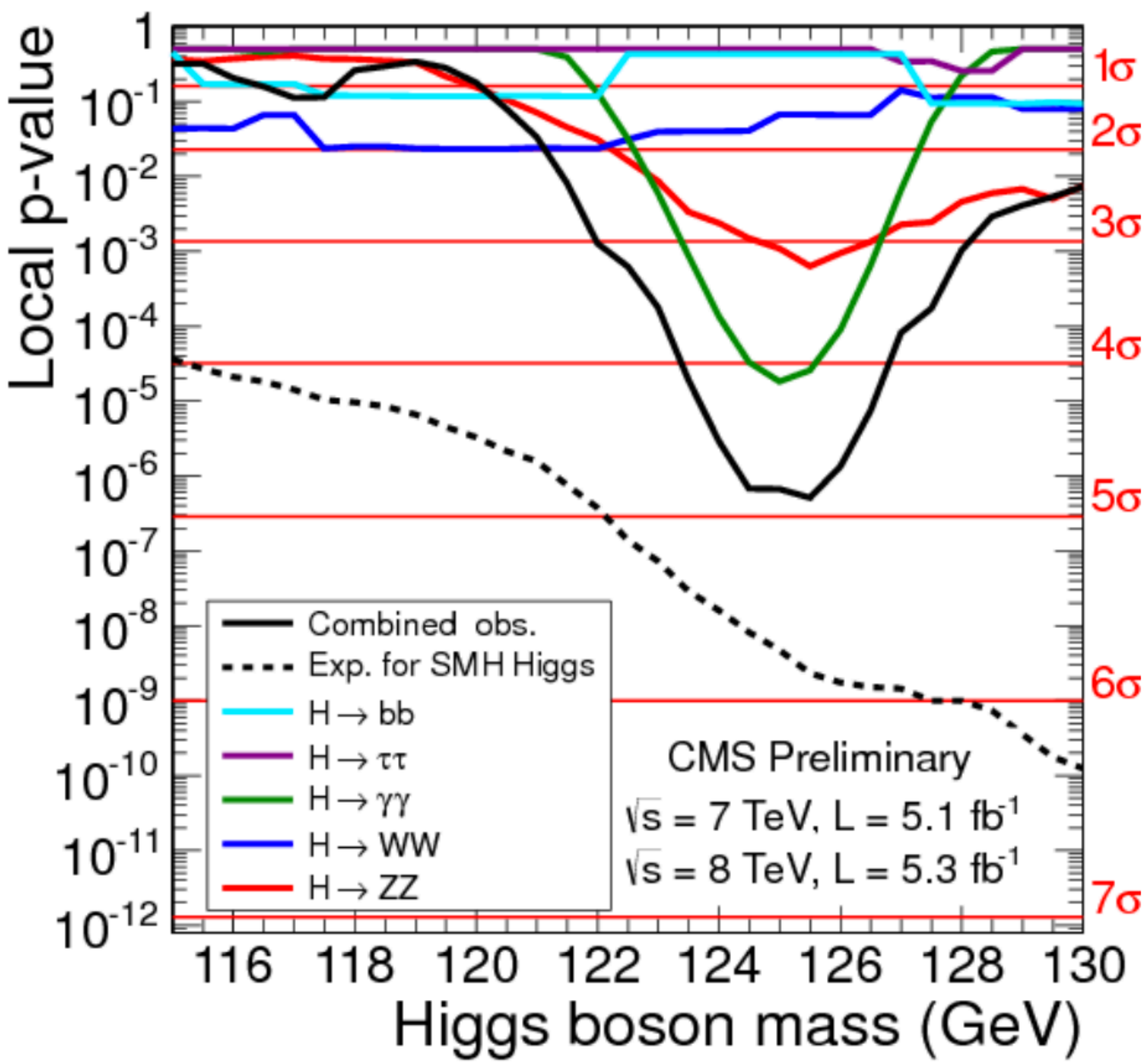
<u>Conversion to sigma</u>

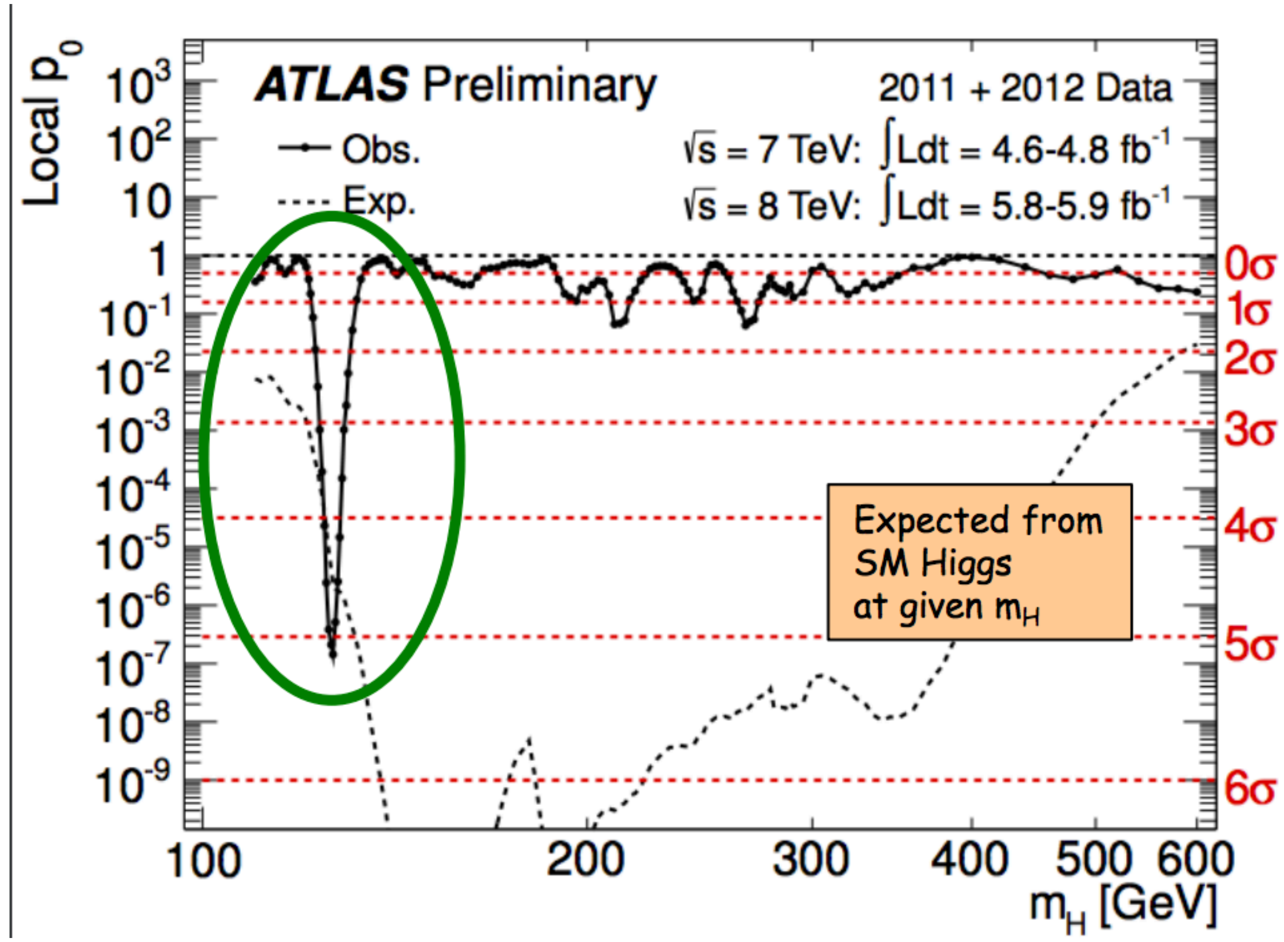
0.05 -> 2 sigma
0.003 -> 3 sigma (evidence)
0.0000003 -> 5 sigma (discovery)

P-values (over time)

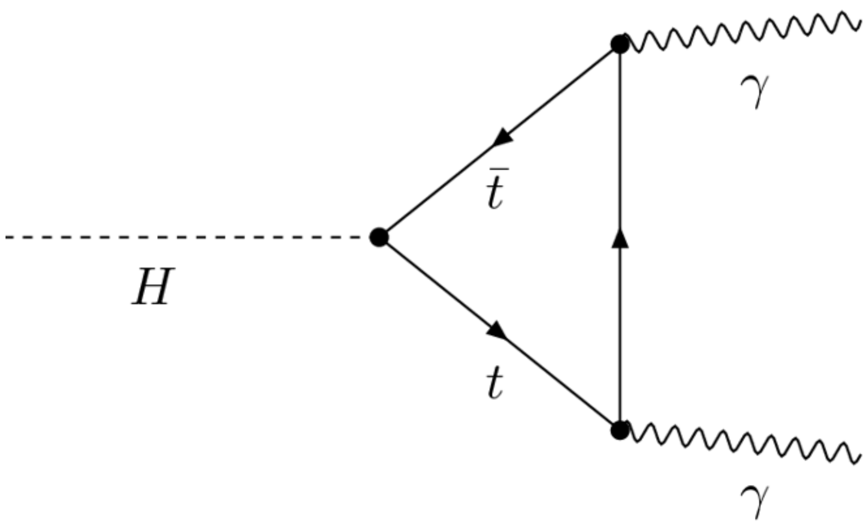


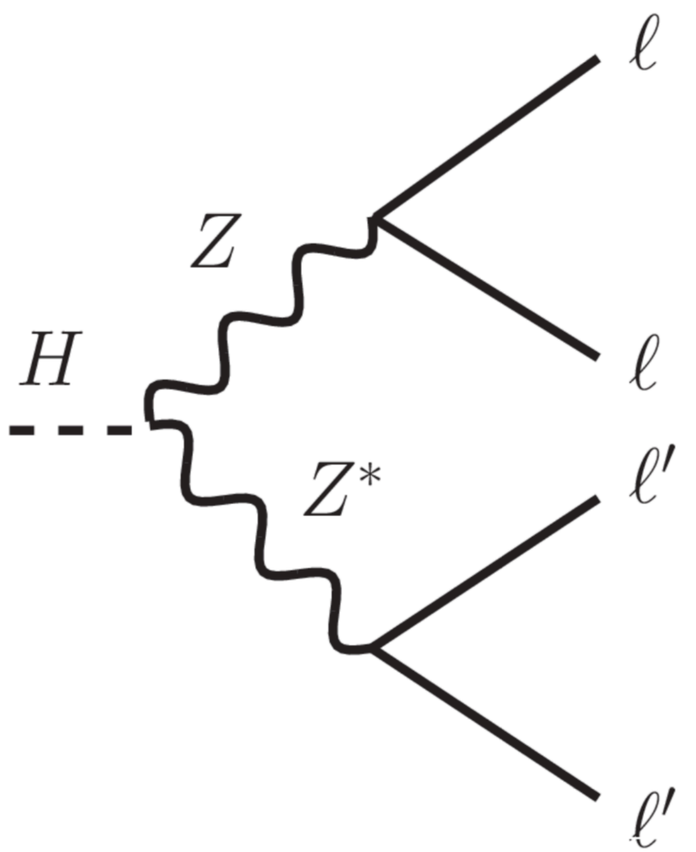
P-values

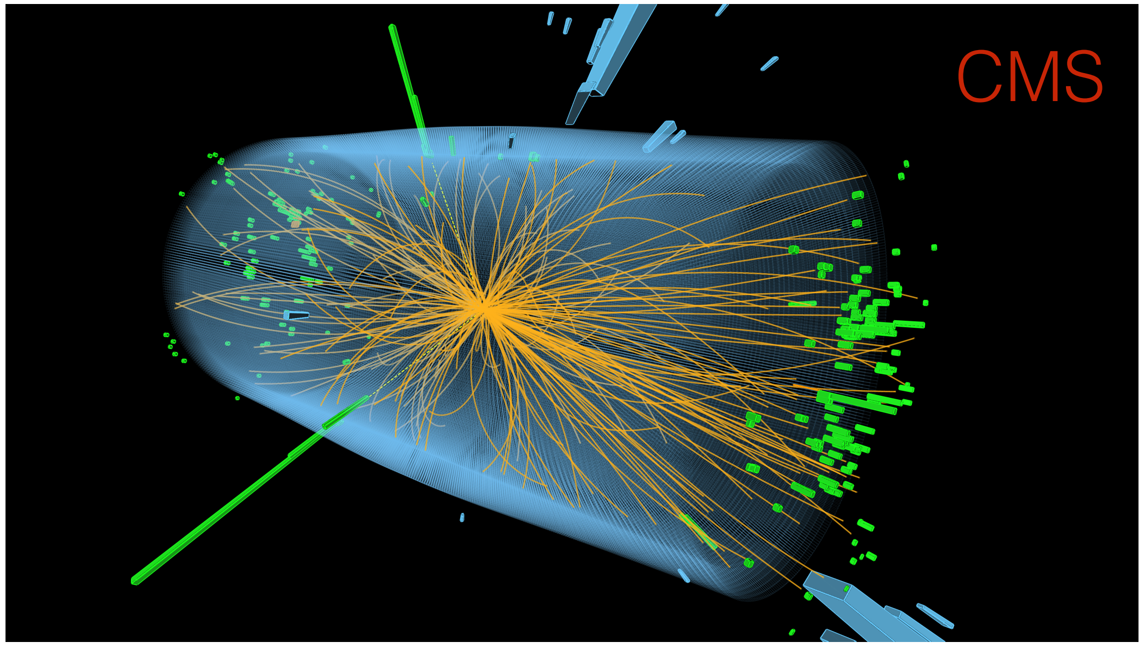

Local p-value
Higgs boson mass (GeV)
Combined obs.
Exp. for SMH Higgs
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
1σ
2σ
3σ
4σ
5σ
6σ
7σ

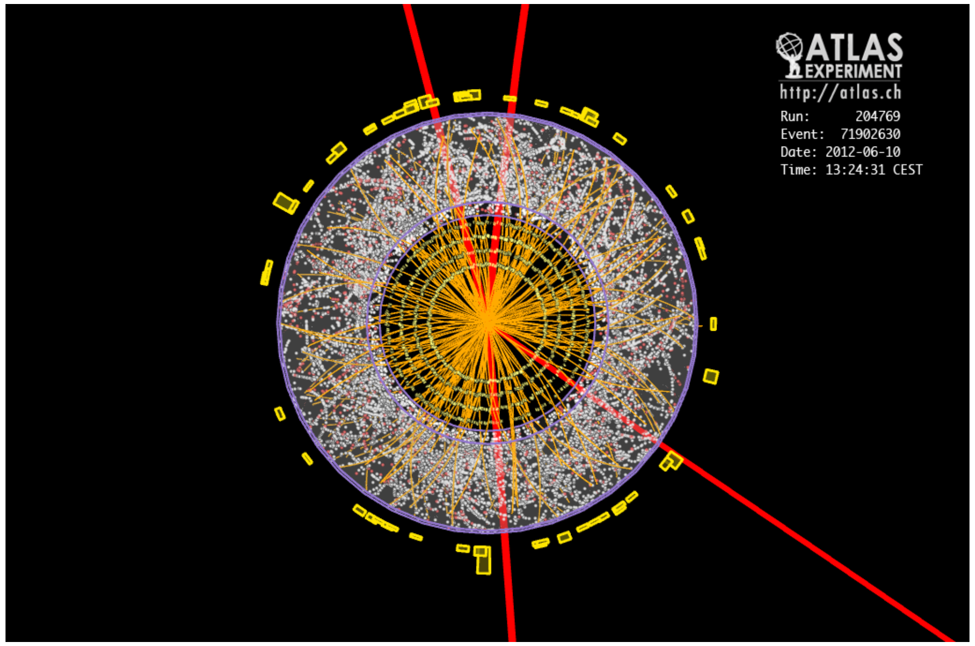

ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Local p0
mH [GeV]
0σ
1σ
2σ
3σ
4σ
5σ
6σ
Expected from
SM Higgs
at given mH

The main discovery channels

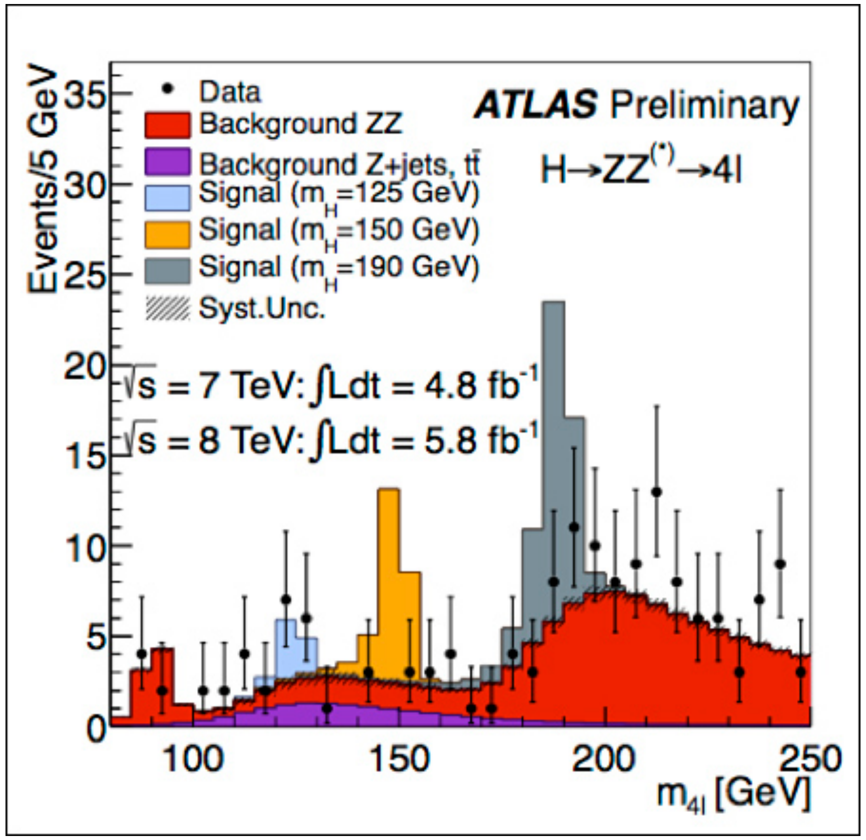




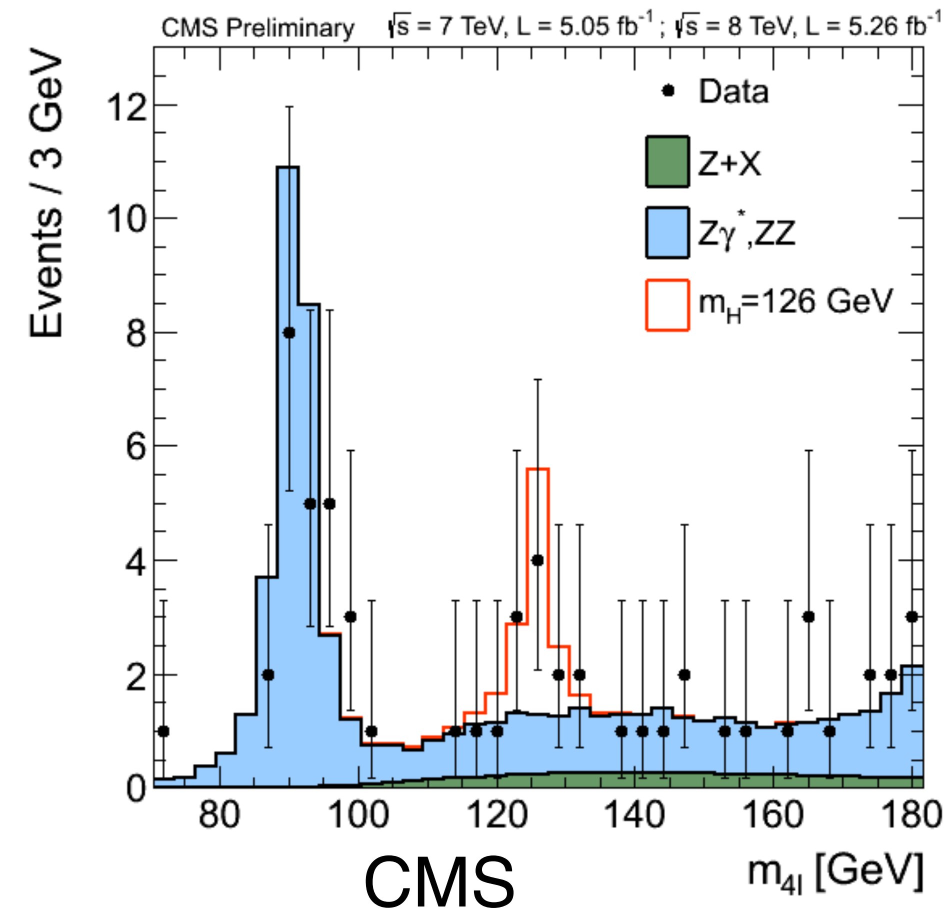




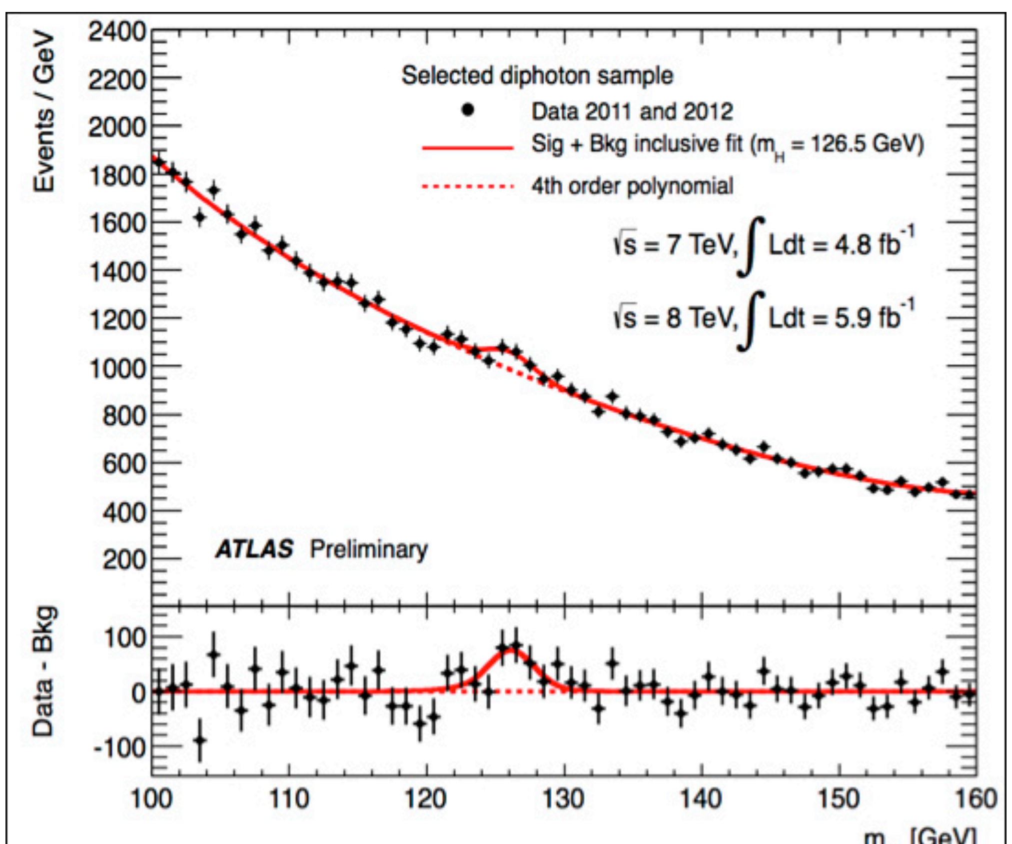
The discovery peaks

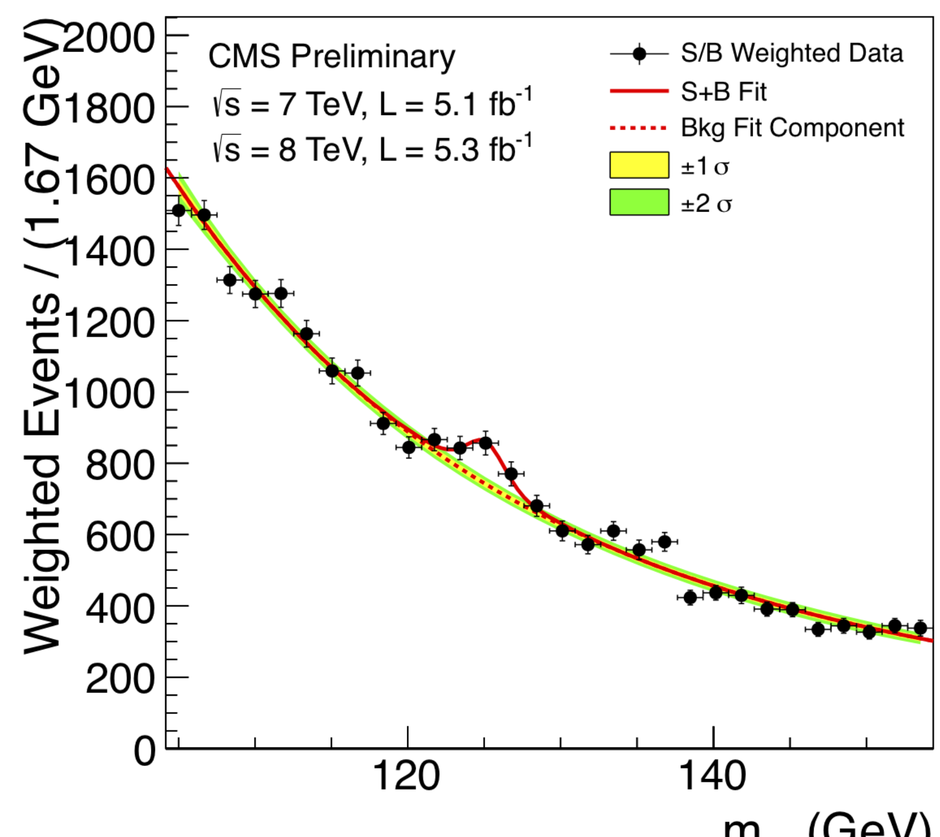


ATLAS



CMS



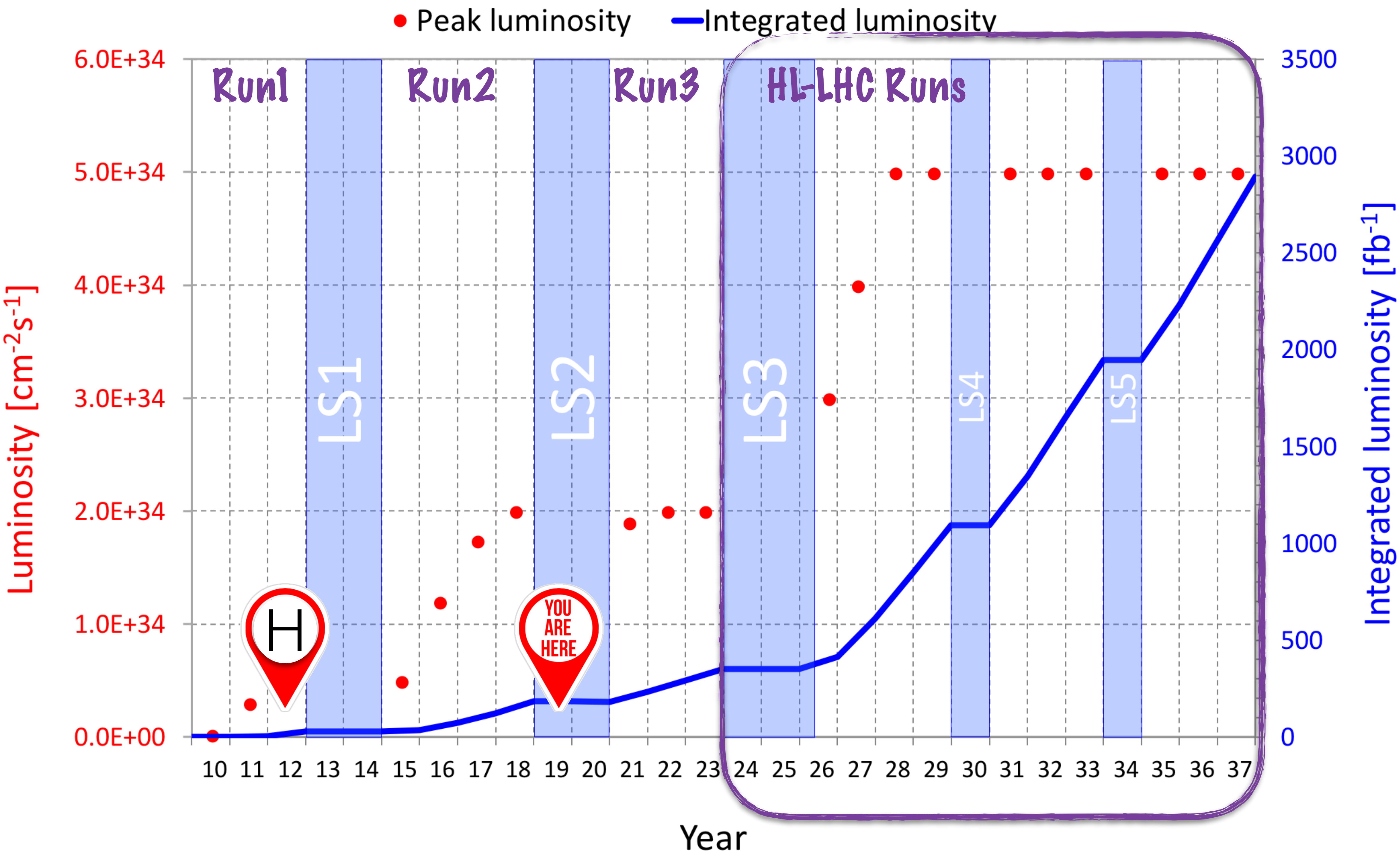


Higgs boson discovery (5 sigma)

Announced on July 4th, 2012 in CERN special seminar

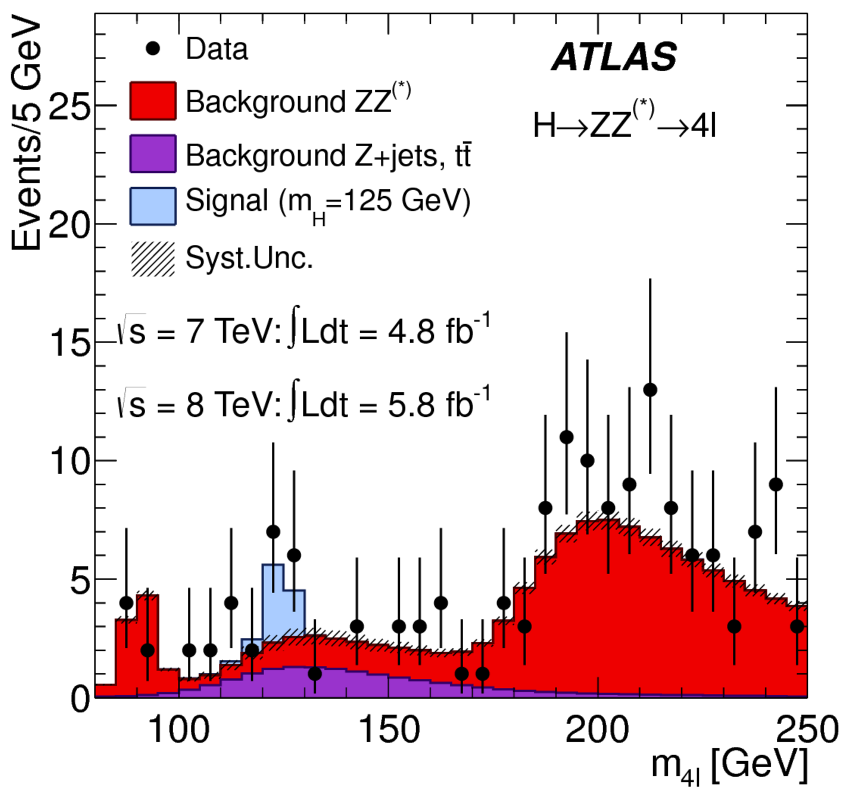
(A year later: Nobel prize awarded to Peter Higgs and Francois Englert)

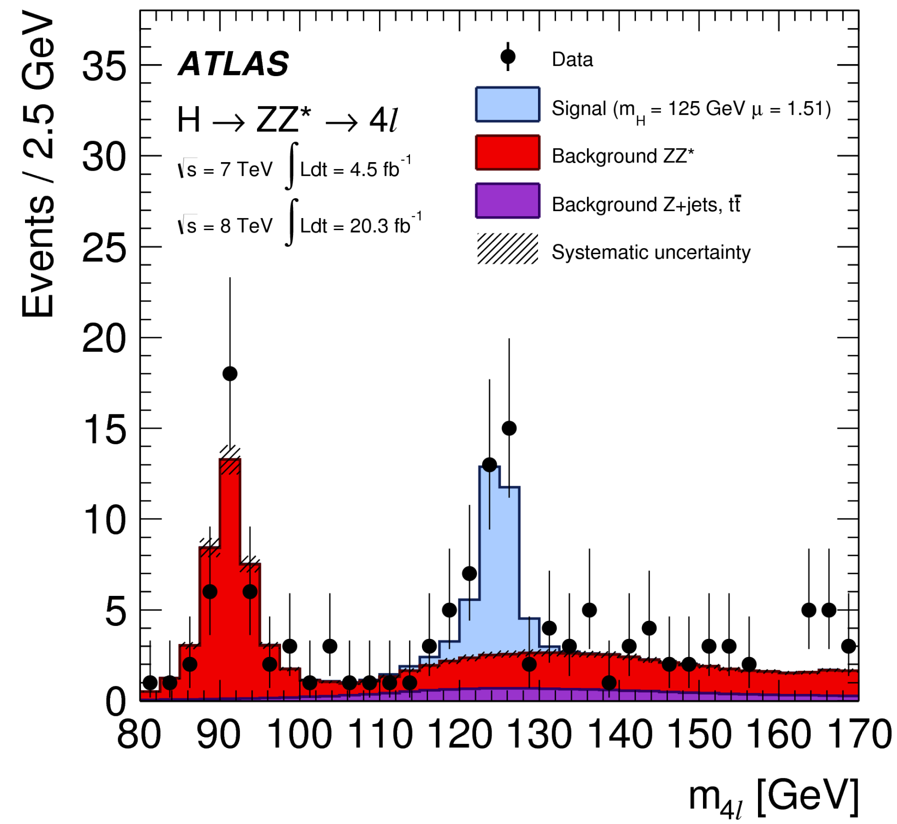
LHC program


Peak luminosity
Integrated luminosity
Run1
Run2
Run3
HL-LHC Runs
LS1
LS2
LS3
LS4
LS5
H
YOU ARE HERE
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
1500
1000
500
0
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Luminosity [cm^{-2}s^{-1}]
Integrated luminosity [fb^{-1}]
Year

From discovery to property measurements

2012

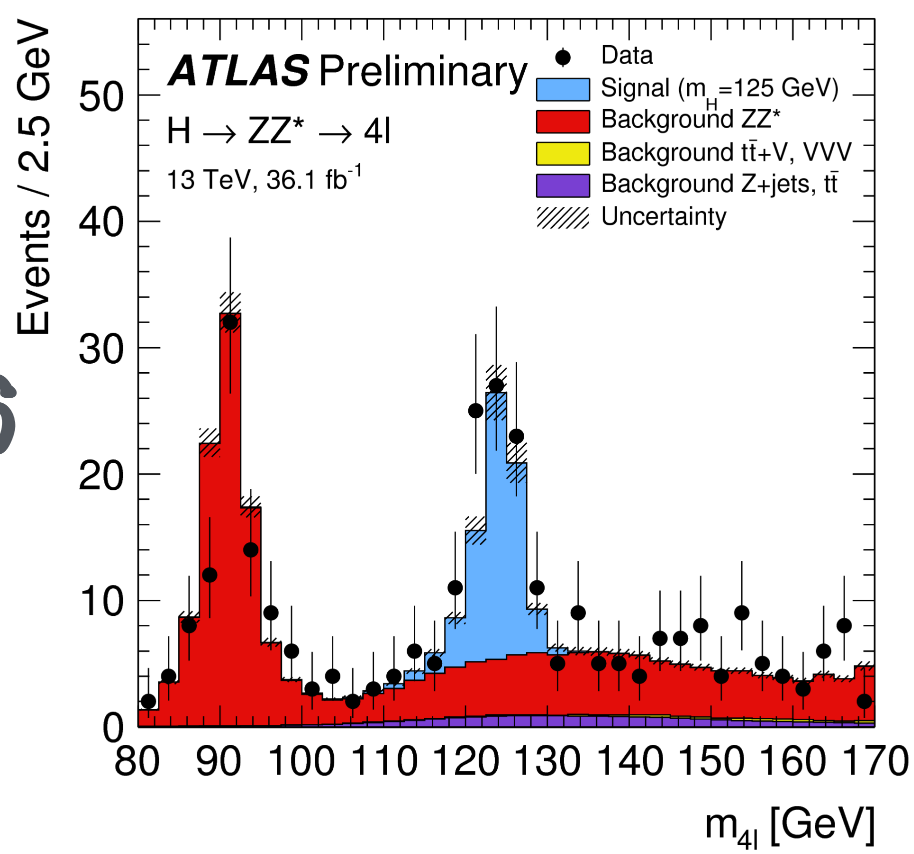


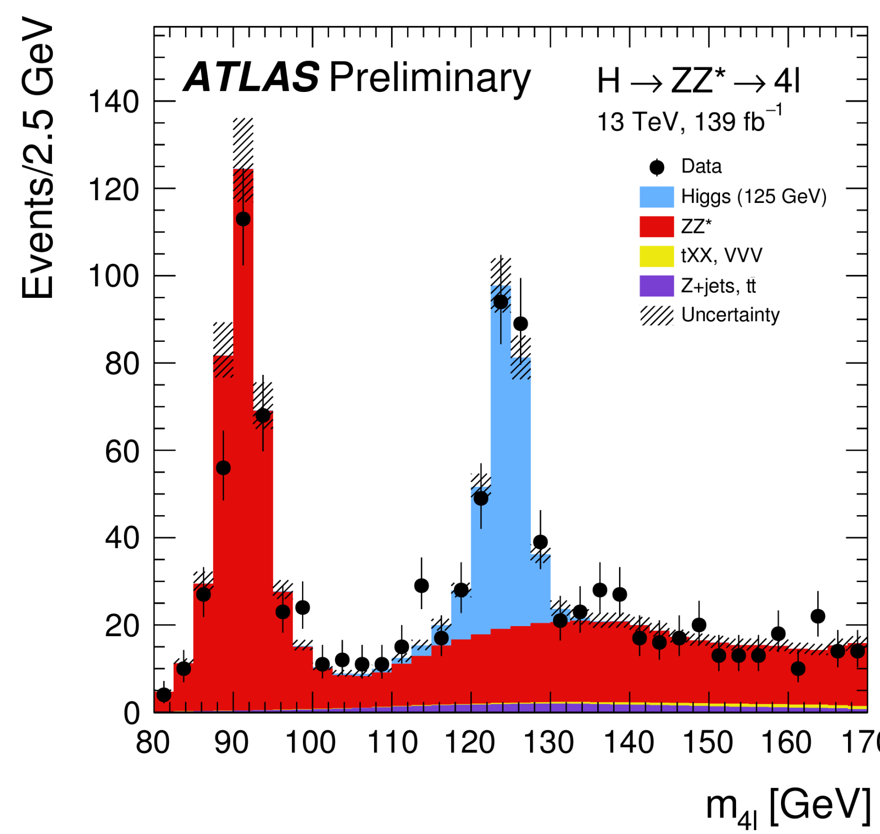


2012

Run 1

2016





2018

Run 2

What does the SM predict for the Higgs boson?

Spin and CP

scalar: spin 0, CP even

Yukawa couplings

Width

Depends on the mass

Couplings

Higgs-fermion couplings ~ fermion mass

Higgs-boson couplings ~ boson mass^2

=> SM Higgs sector is overall very predictive:

Knowing the fermion masses, only free parameter is m_H

Let's test it

Why?

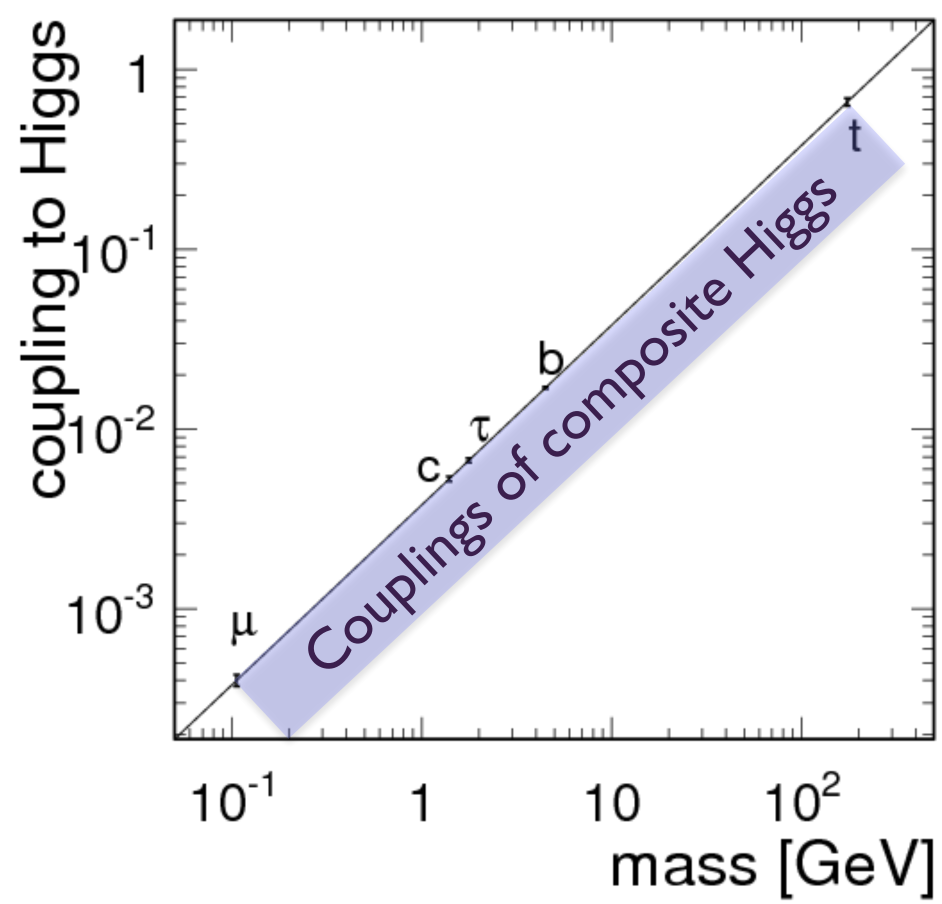
>> deviations could point to physics beyond the SM

>> this is a "new" particle, a new chance to find deviations

>> since the Higgs is responsible for giving particles mass, it plays a very special role, could be the gateway to new physics

Examples of non-Standard Model Higgs mechanisms

- SUSY Higgs sector (h, H, H+/-, A)
  -> see later lecture
- Composite Higgs
- Higgs coupling to unknown particles, like dark matter

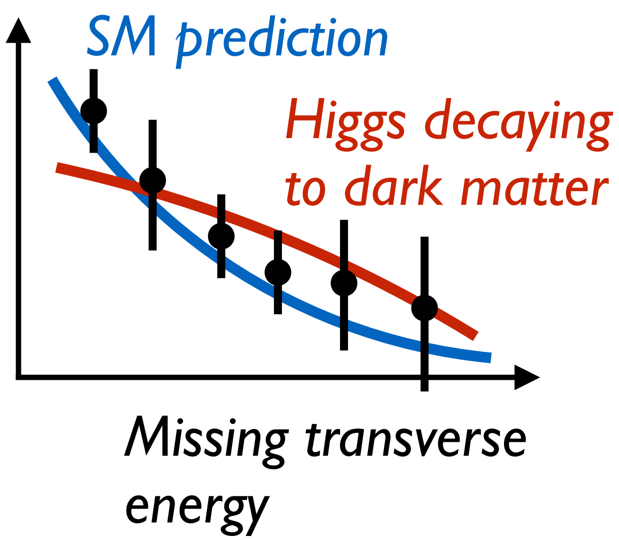


Is it the Higgs boson the SM predicts?

Two ways of searching:

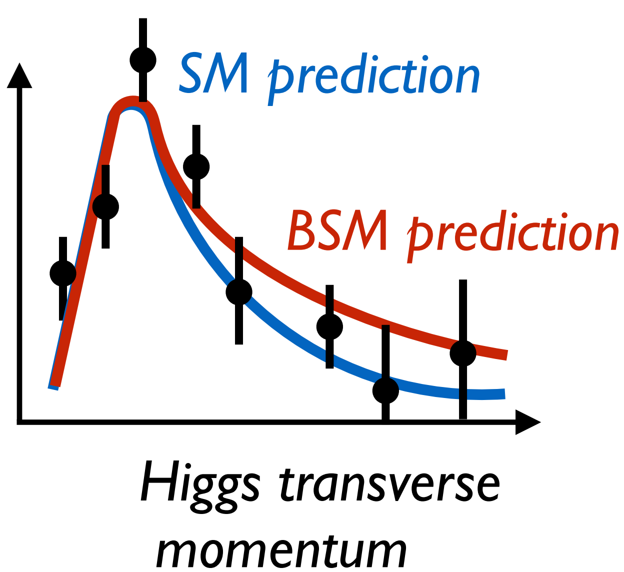
1. Direct search:

   Search for new phenomena directly, like additional Higgs bosons or dark matter decays of the Higgs boson



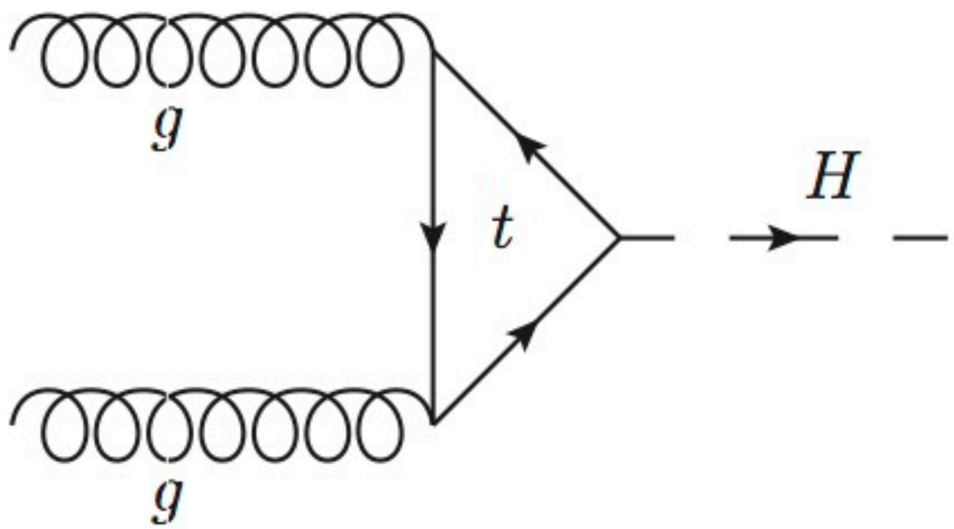
2. Indirect search:

   Measure Higgs boson properties, compare to predictions of the Standard Model

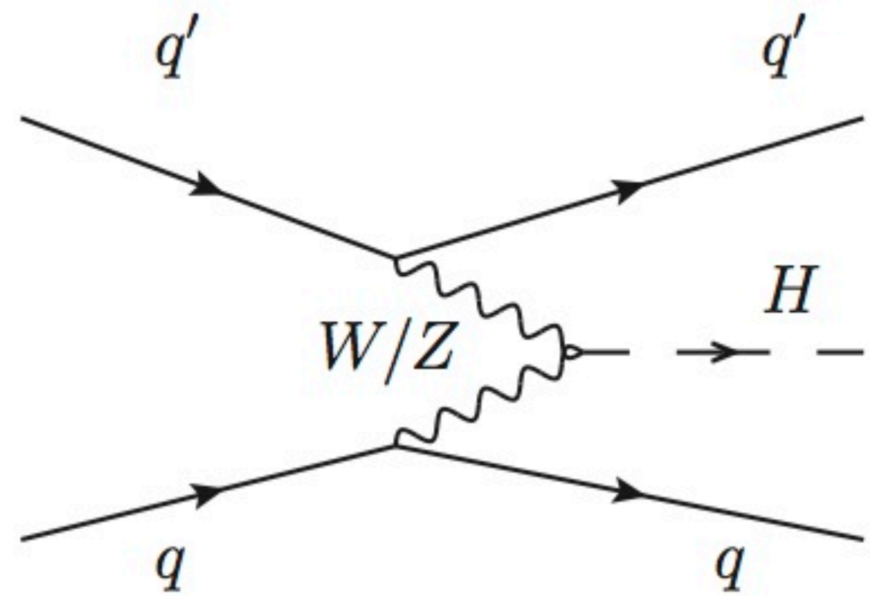


Higgs production

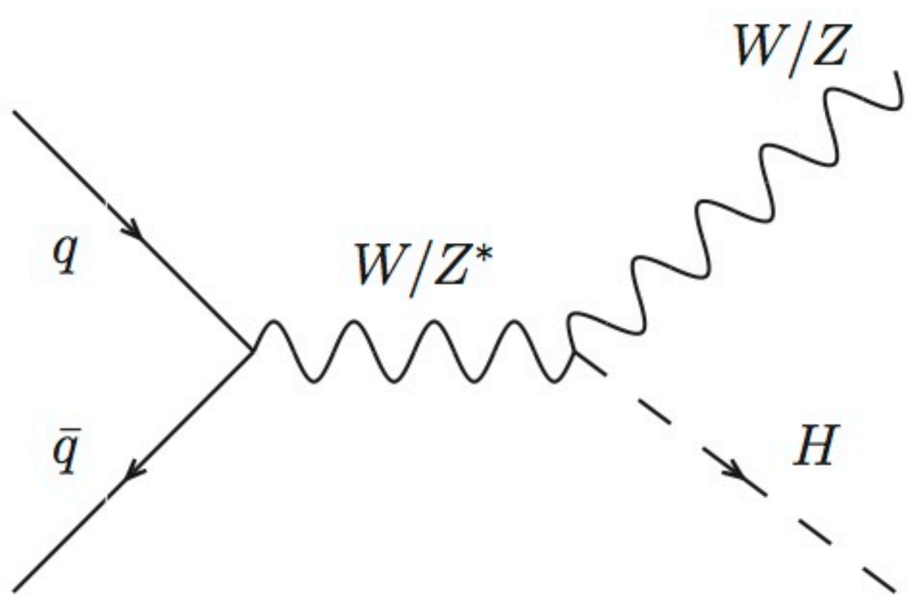
…as predicted by the Standard Model at 13 TeV



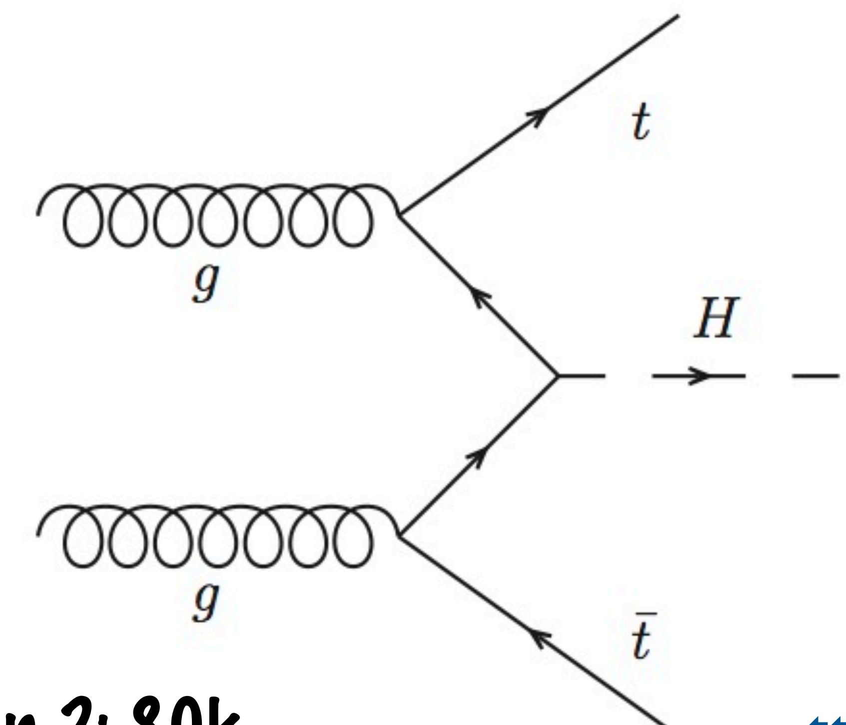
Run 2: 8 Mio ggF: 87.2%



Run 2: 600k VBF: 6.8%



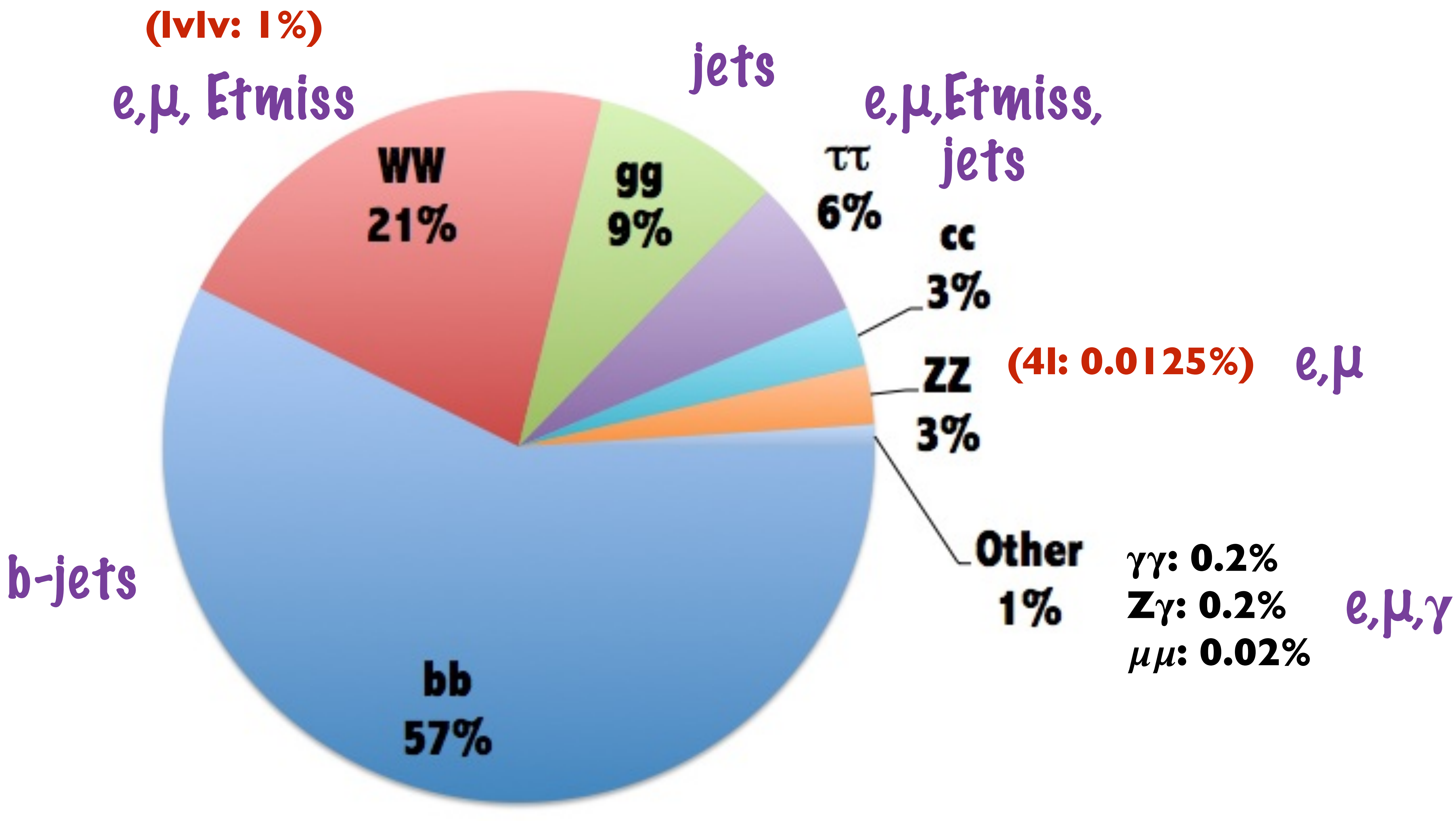
Run 2: 400k VH: 4.1%



Run 2: 80k ttH: 1.9%

Higgs decays

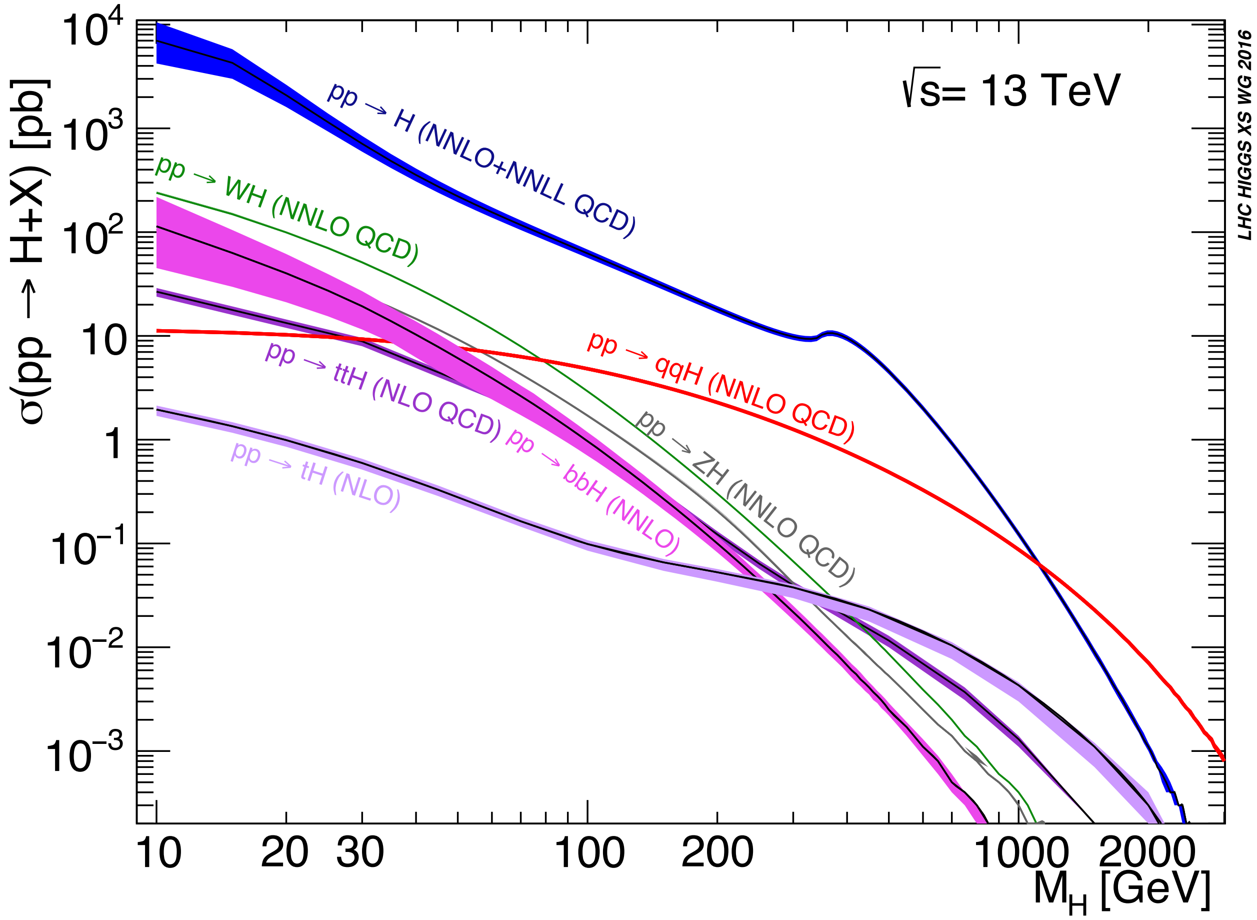
…as predicted by the Standard Model

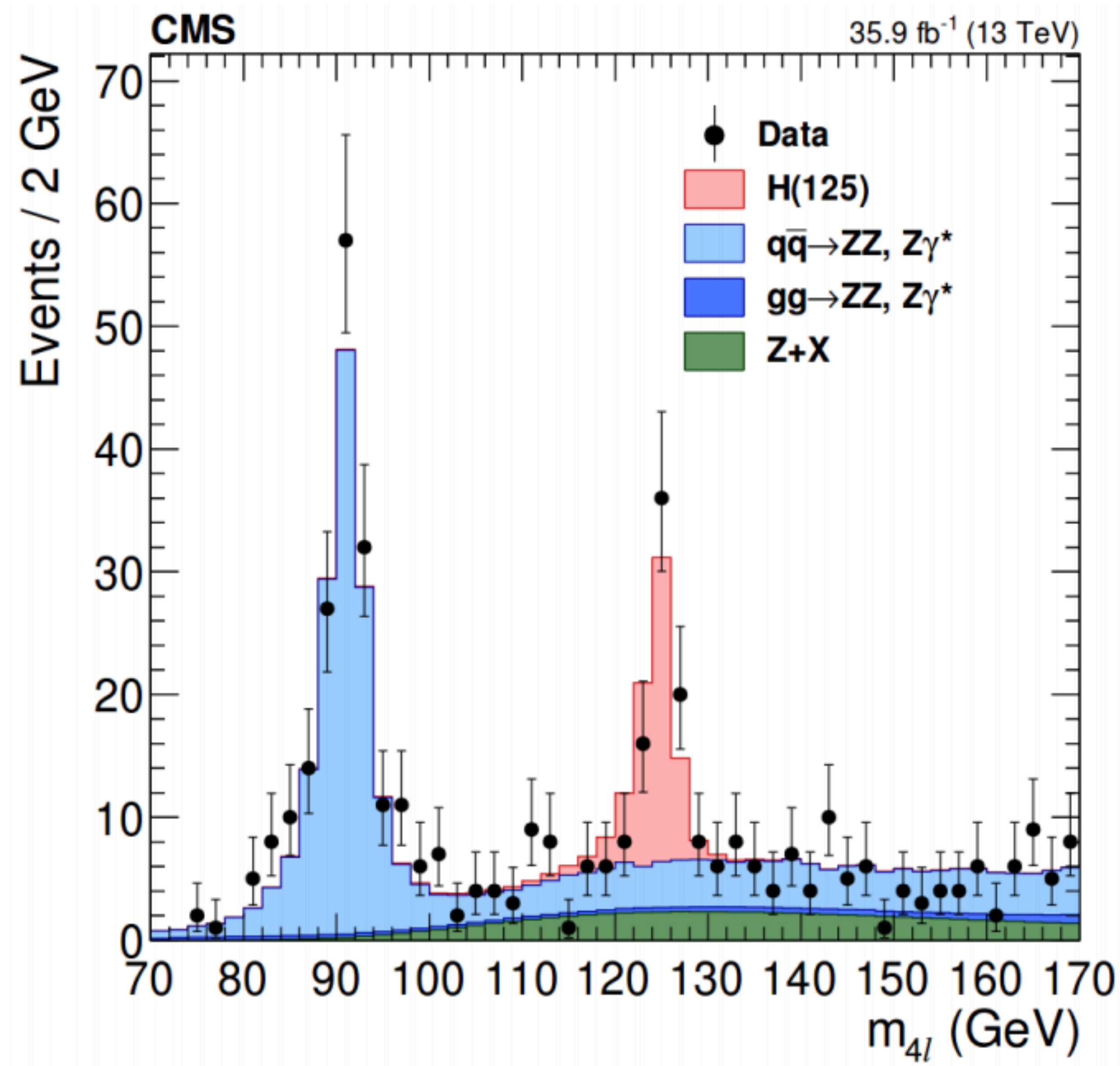


+ jets in VBF, b-jets in top quarks…

Higgs mass

- NOT predicted by the SM
- Important input to determine cross sections and branching ratios
- measured in the channel with the most precise peaks: $\gamma\gamma$ and 4l



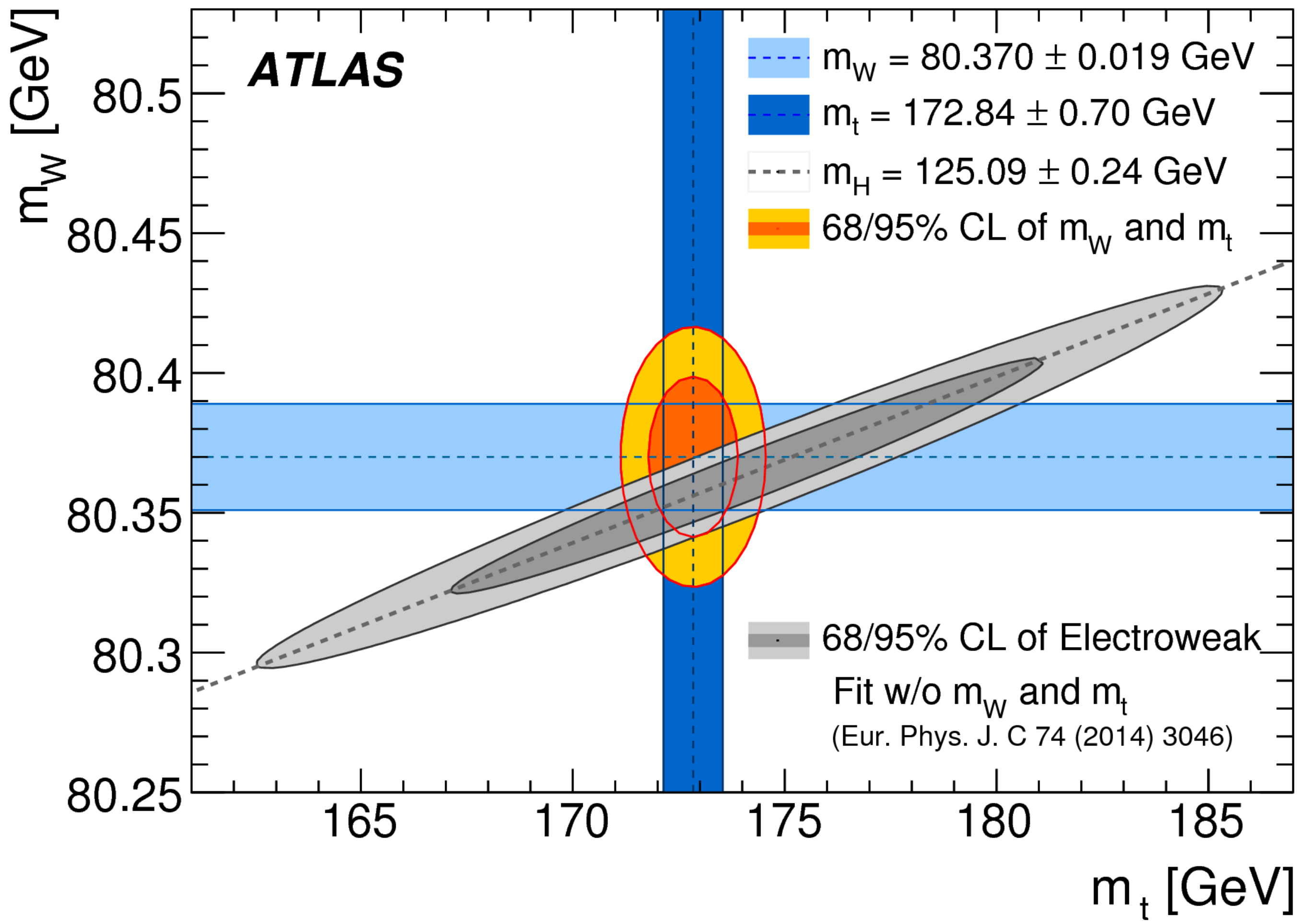


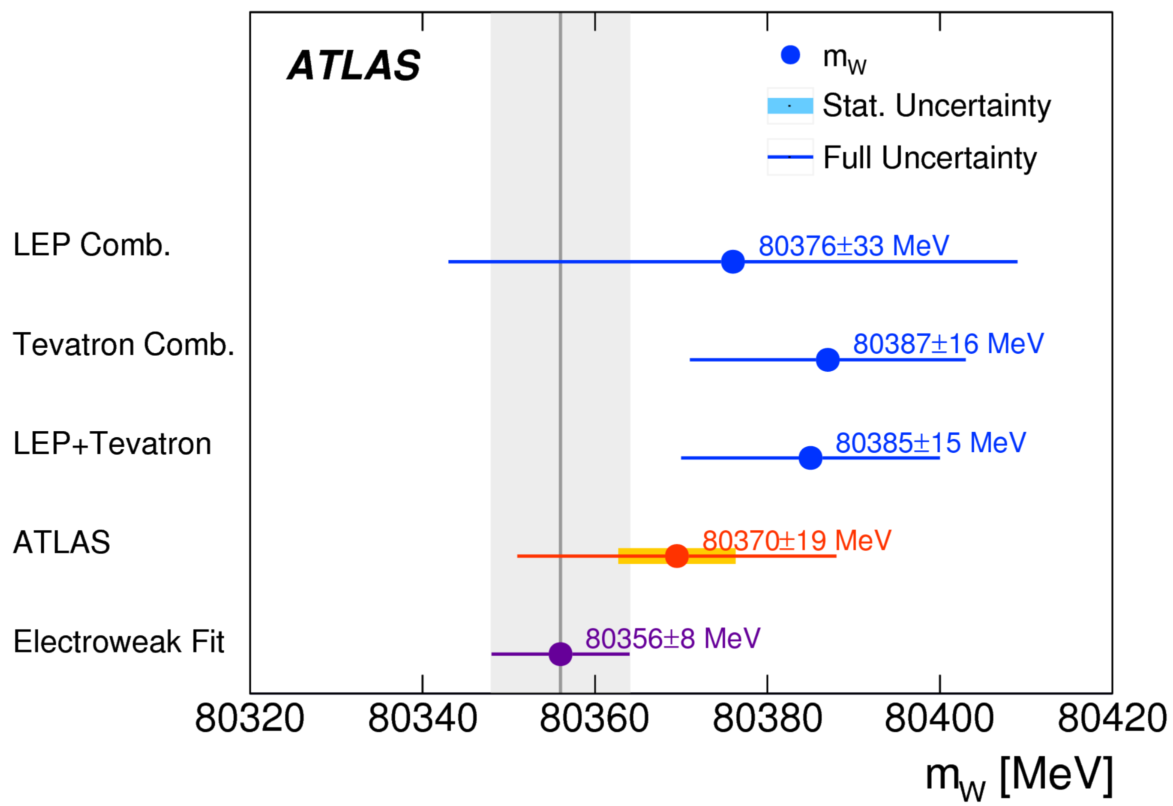
$$125.26 \pm 0.21 \ (\pm 0.20) \ \text{GeV}$$

2 permille accuracy!

Implications of the Higgs (mass) for global fits

Everything seems consistent





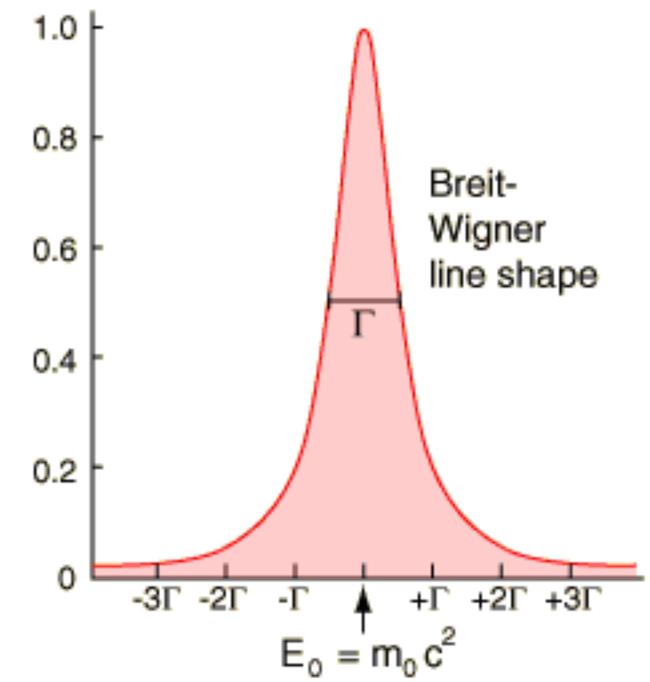
Higgs width

What is the width?

Probability of a decay process occurring within a given amount of time in the parent particle's rest frame.

The larger the width, the shorter the particle's life time

$$\tau \times \Gamma = \hbar$$



Why is the width interesting?

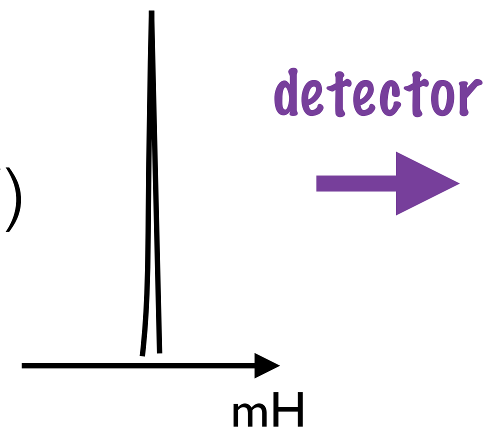
- SM prediction of Higgs width: 4 MeV (Z boson: 2.5 GeV)
- gives life time of the Higgs boson (SM: 10^{-22} s)
- if width larger than SM prediction: new (invisible?) decay modes?

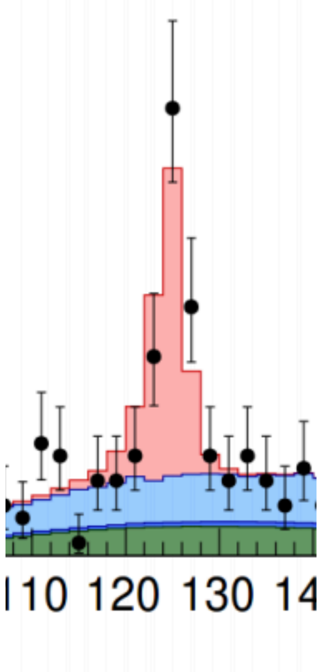
$$\Gamma_{\text{tot}} = \sum_f \Gamma_f$$

Higgs width measurements

Predicted to be extremely small: 4 MeV!

- Direct: limited by experimental resolution (1-2 GeV)





- Indirect methods exist, p.ex. using offshell signal strength
  - offshell: away from the peak
  - on-shell cross section depends on width, off-shell does not

  => ratio is sensitive to width!

Latest CMS results, with SM-like couplings, using 7, 8, 13 TeV data:
95% CL upper limit: 9.16 MeV (expected limit 13.7 MeV)

Higgs spin/CP

Spin (SM: 0)
Spin 1 excluded using ZZ, WW decays (and by the fact that Higgs decays into photons)
Spin 2 excluded for a number of different tensor structures (~ 99.9%)
=> ~spin 0 as predicted for the SM Higgs

Parity (SM: even)
Parity odd excluded at > 99.9% (ATLAS, CMS)
Admixtures (CP even and CP odd couplings) still possible
(fermion channels play important role in these studies!)

=> CP and coupling structures need be tested together
=> turns into Lagrangian checks

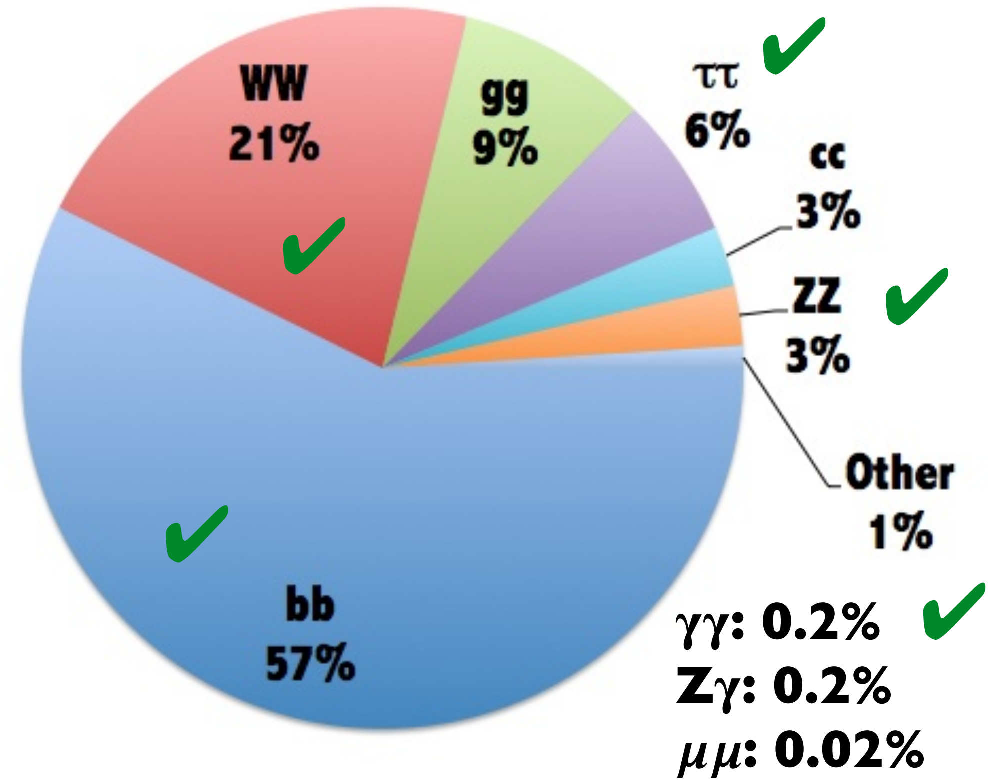
$$\mathcal{L} = g_{\tau\tau}(\cos(\phi_\tau)\bar{\tau}\tau + \sin(\phi_\tau)\bar{\tau}i\gamma_5\tau)h \longrightarrow \text{SM: } \boldsymbol{\phi_\tau} = 0$$

Higgs decays

Latest discovery: H -> bb

>> the one with the largest BR!

>> important because it probes second generation fermion couplings, down type



Why did it take so long?

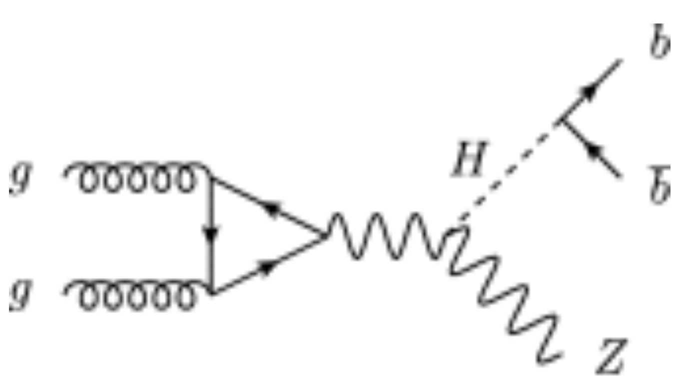
H -> bb

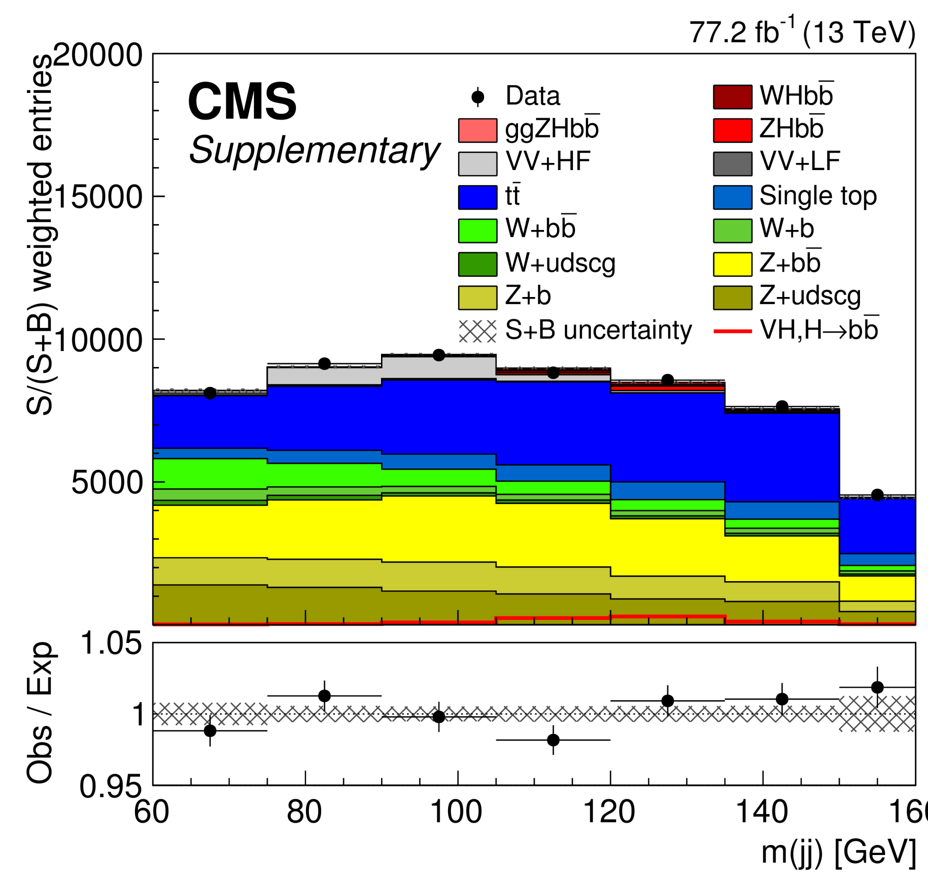
=> two b-jets in the final state

LHC is a pp collider: produces tons of jets

-> use VHbb (ZH, WH)

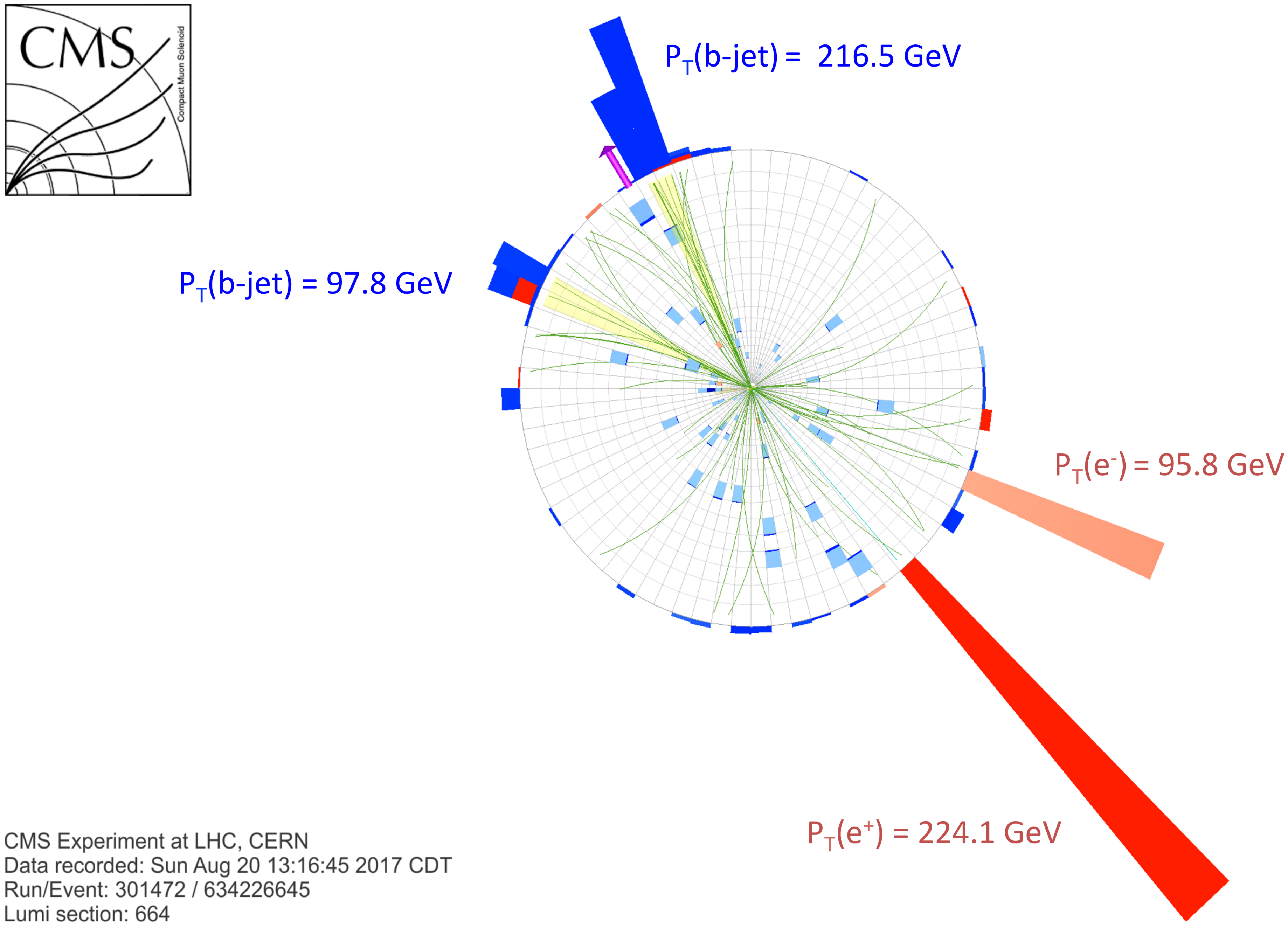
=> 2 b jets + 2l or 1l + MET or MET





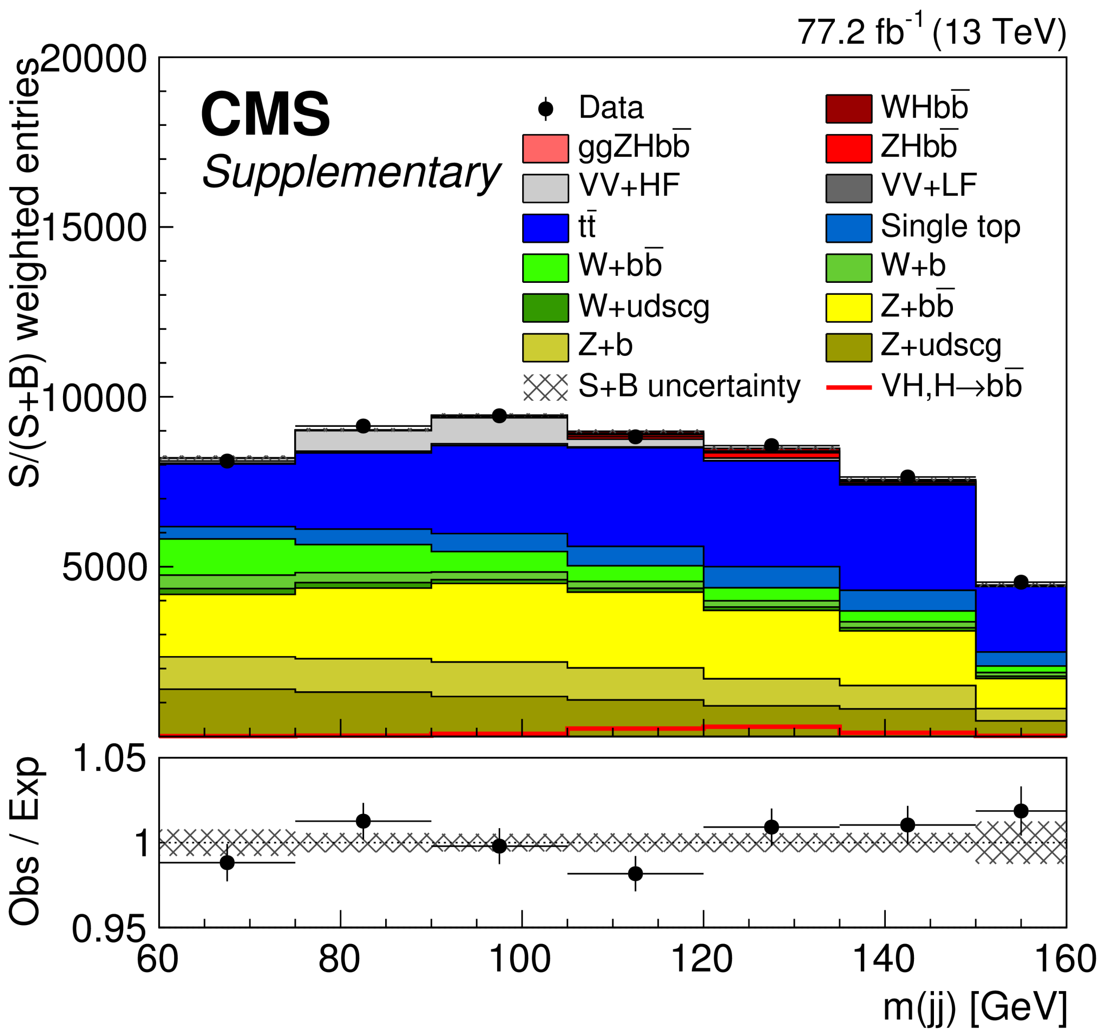
-> still dominated by background!

Higgs decays - bb

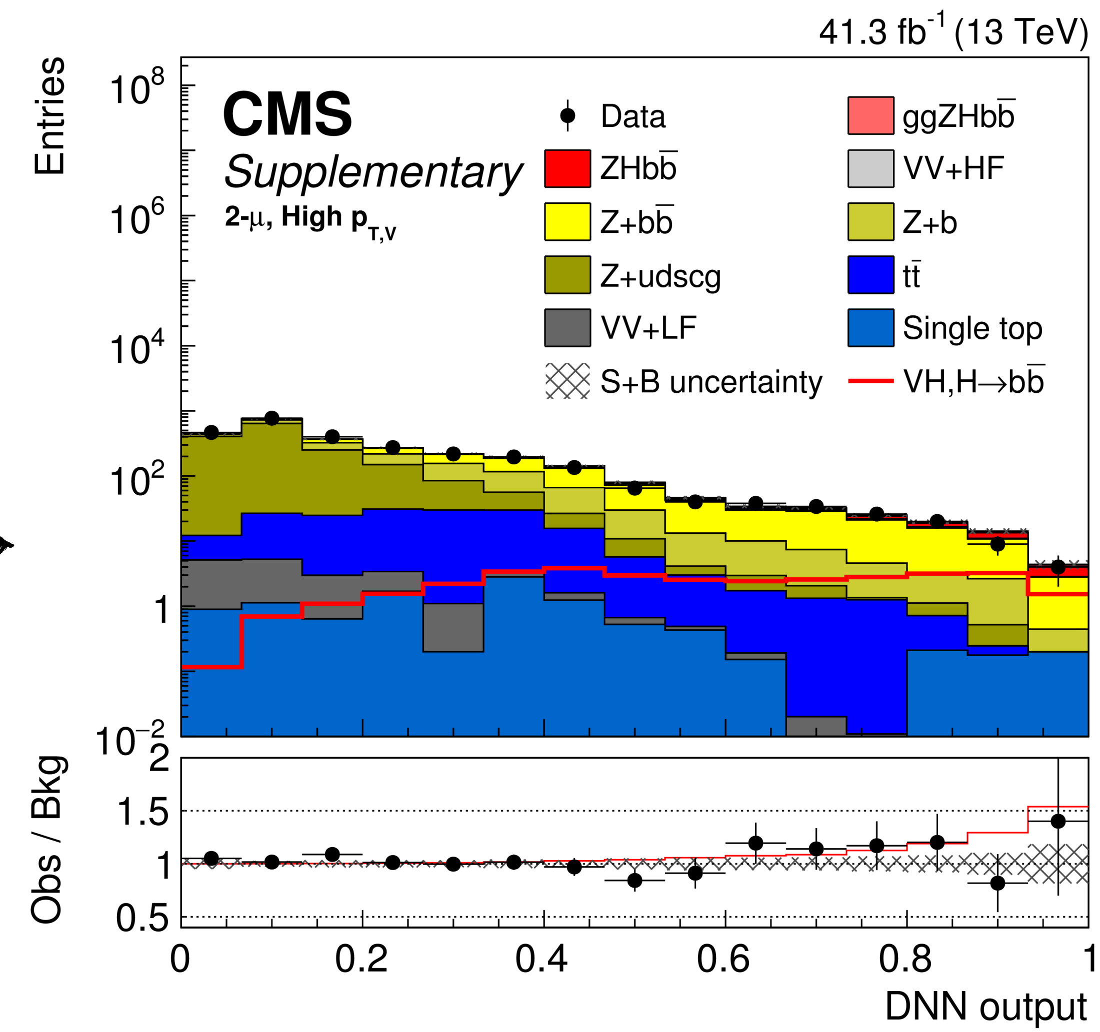


Higgs decays - bb

So what to do?

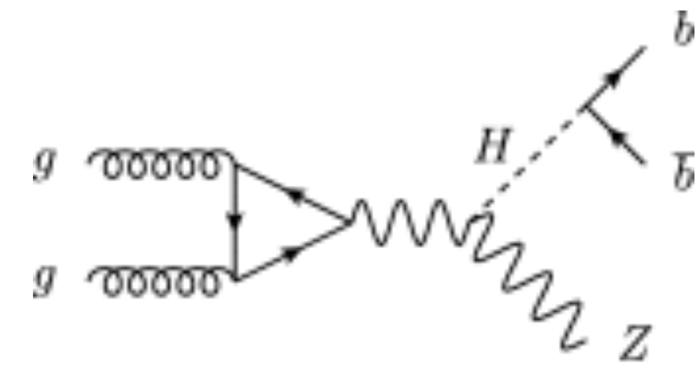


Log plot!



Higgs decays - bb

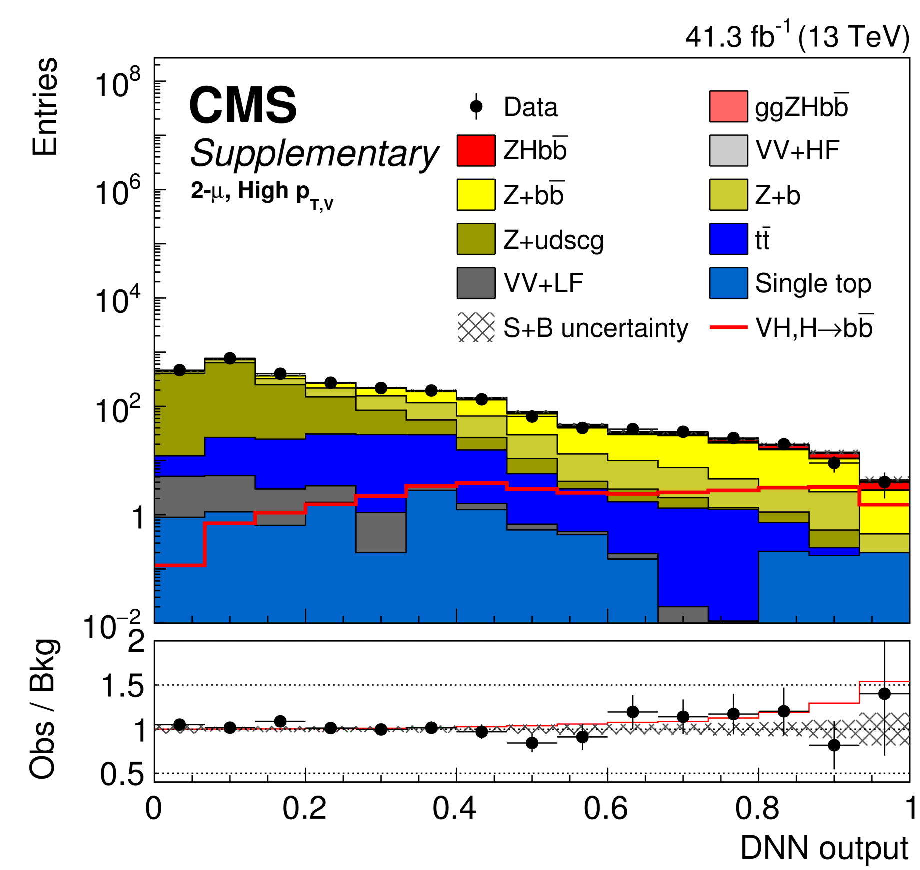
1. Choose smart categories (find regions with better S/B and separate them out)
- different channels depending on the V boson decay



2. Use multivariant discriminator/machine learning!

Deep neural networks used in the CMS analysis:

- b-jet identification
- m_{jj} mass resolution
- signal extraction
  - important variables:
    - m_{jj}, pt(V)
    - b-jet identification



Two pages about multivariate analyses in HEP

If we just apply sequential selection cuts, we lose efficiency and correlations => plug into MVA **[Caveat: need to understand inputs well!]**

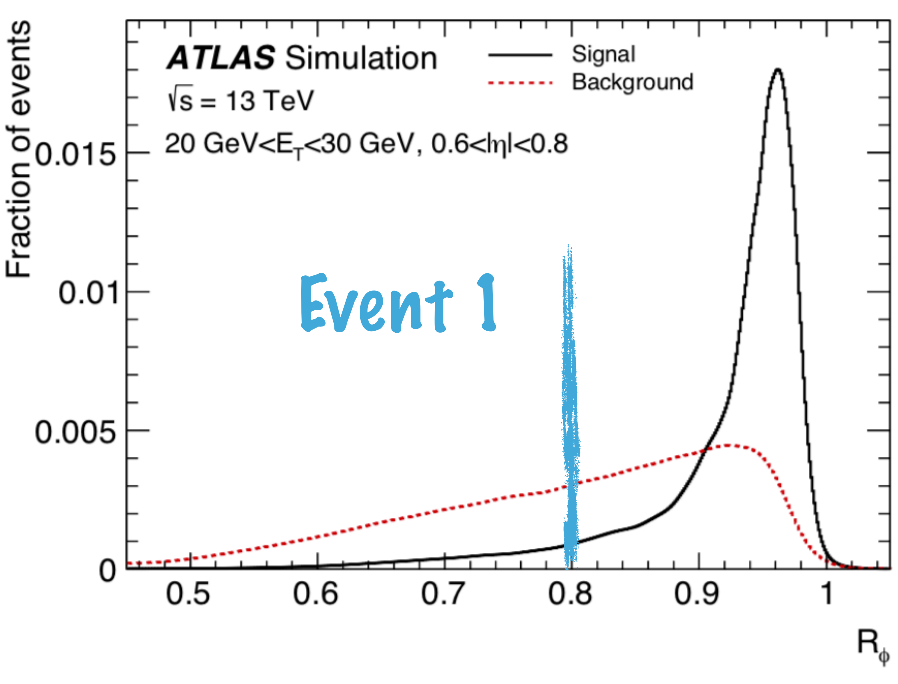
Simplest way of combining multiple selection cuts: Likelihood built from probability density functions (from known signal/background samples)

$$d_{\mathcal{L}} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B}, \qquad \mathcal{L}_{S(B)}(\vec{x}) = \prod_{i=1}^{n} P_{S(B),i}(x_i)$$

Observable i

For each event: check where it falls on the spectrum of each observable

=> probability for each event to be S vs B

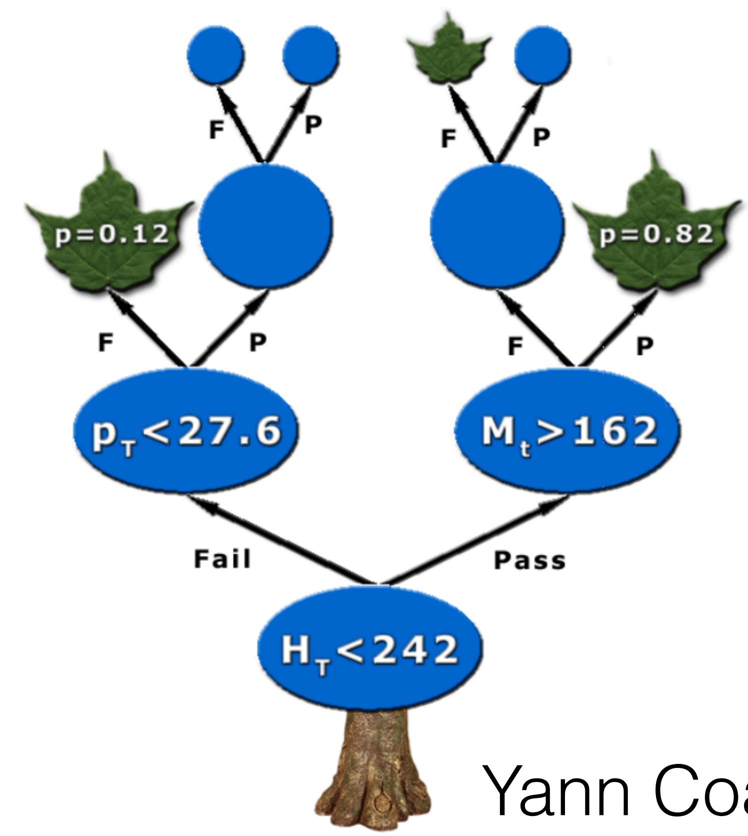


Two pages about multivariate analyses in HEP

More advanced (all “trained” using known signal/ background samples)

Boosted decision tree

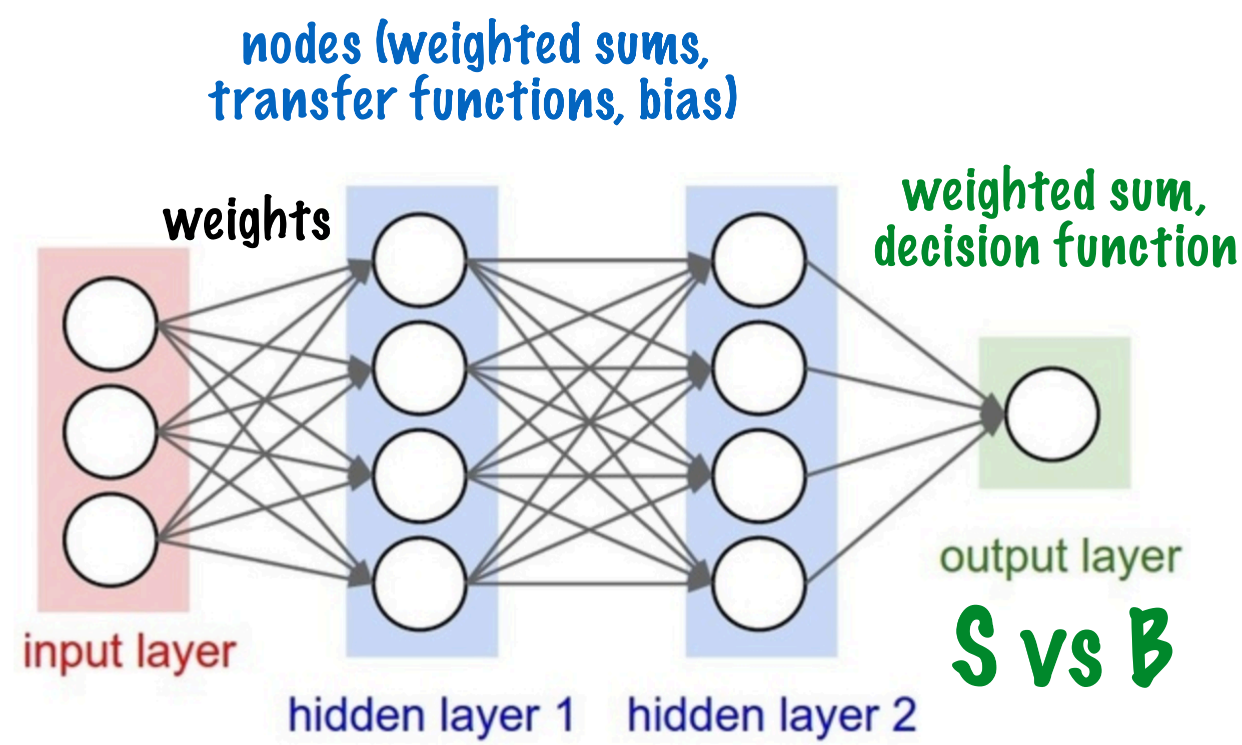
- build tree by picking most discriminant variable
- choose cut values to be the most discriminant
- move one node down, repeat
- choose path that is the most discriminant
- boosting: multiple trees



Yann Coadou

Neural Network

- mimicks brain
- start with discriminating variables
- adjust weights to minimize error function

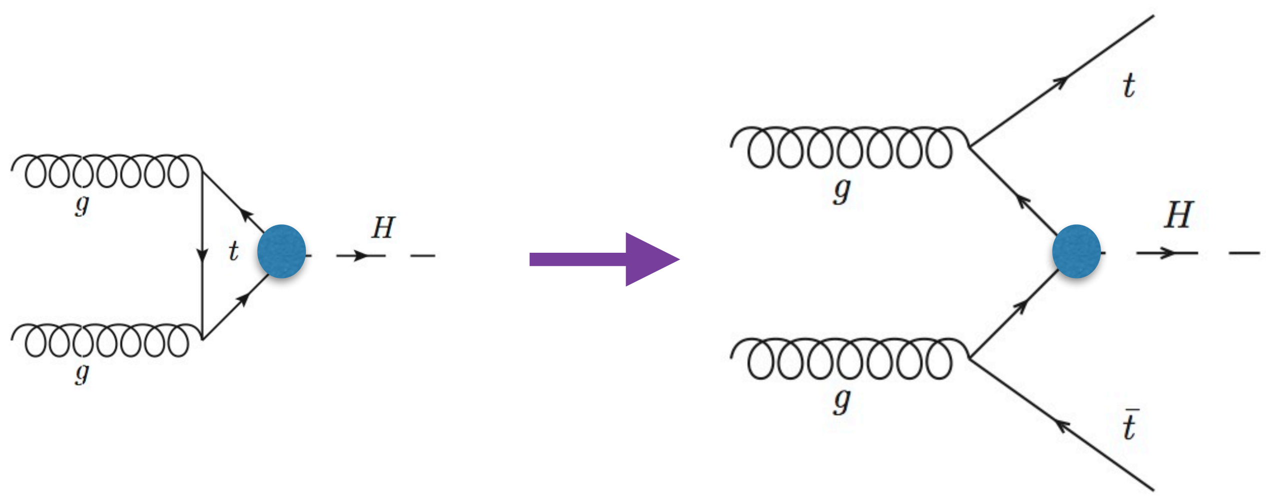


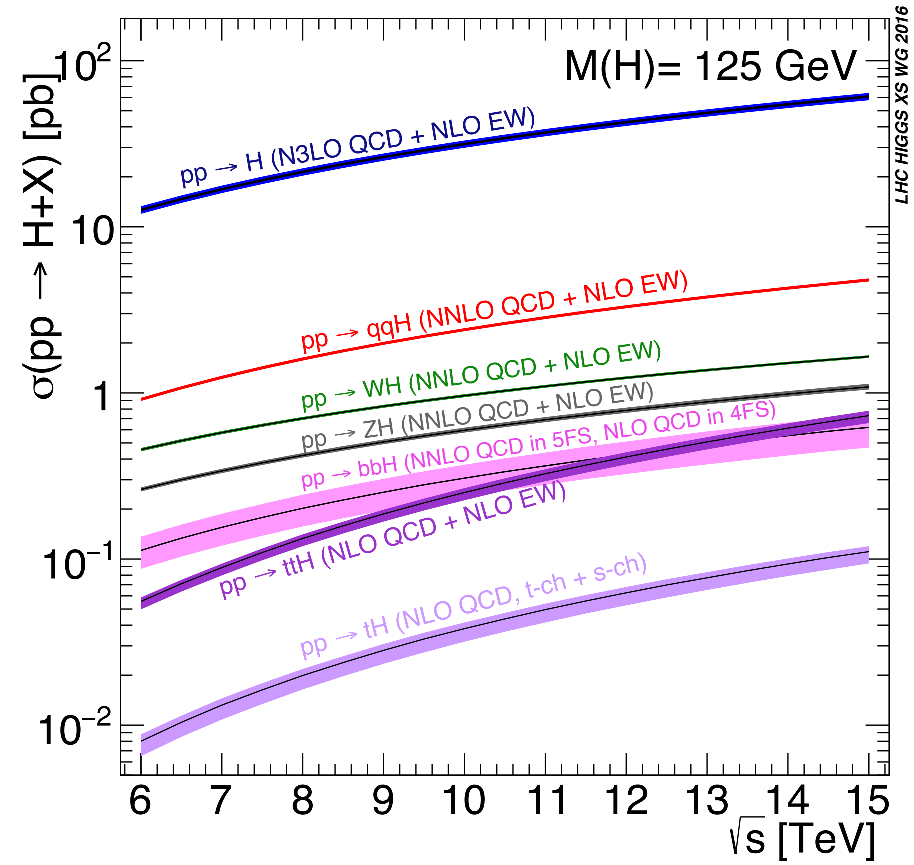
Higgs production

All major production modes measured by now with 5 sigma significance

- latest one was **ttH** last year

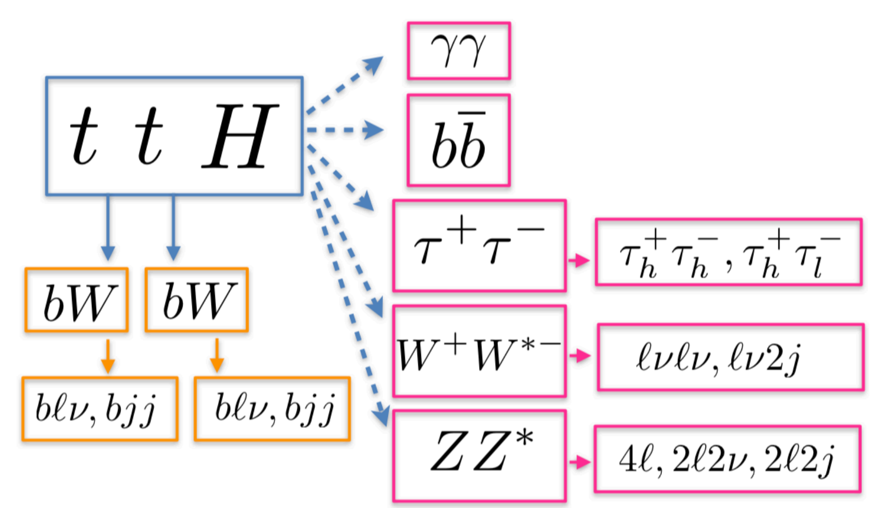
- important: tests directly the Higgs-top coupling





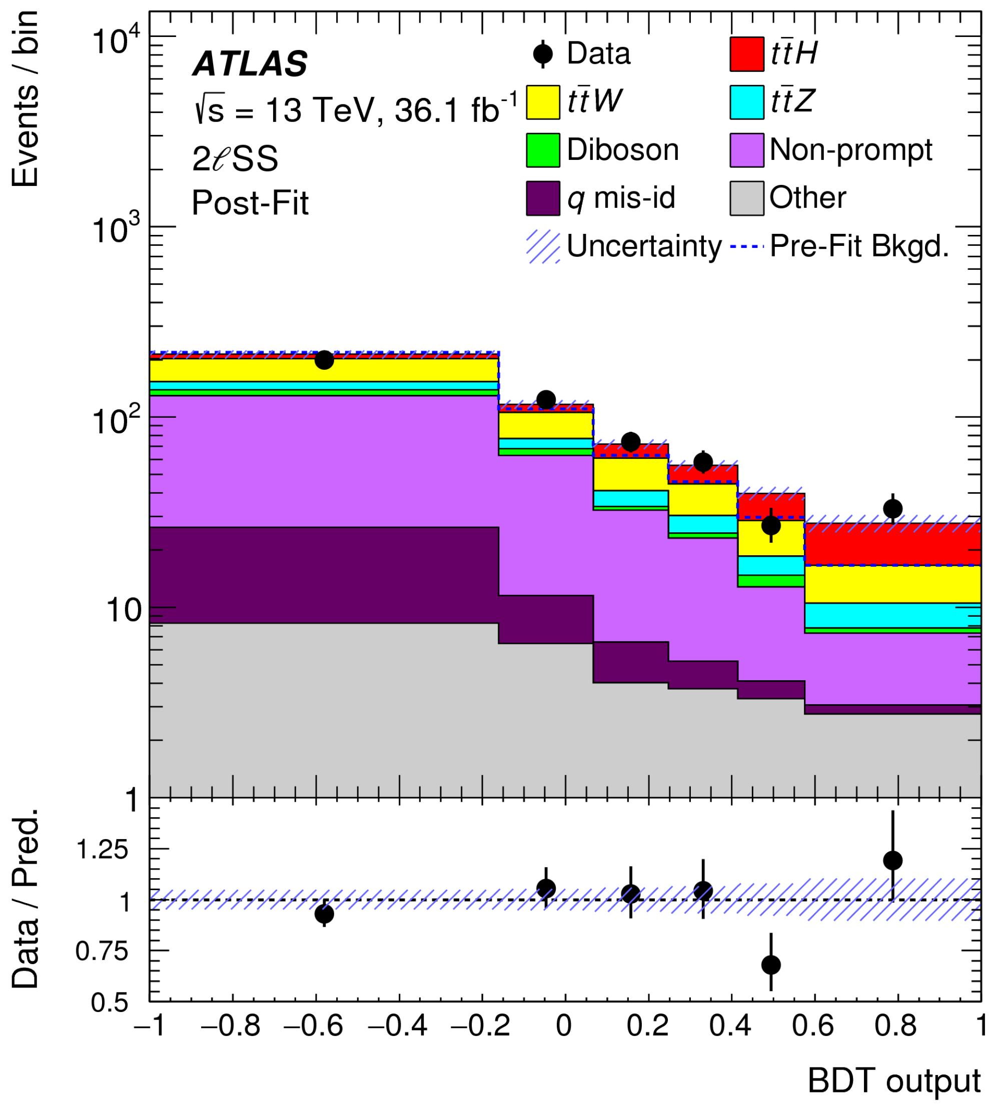
Very challenging!

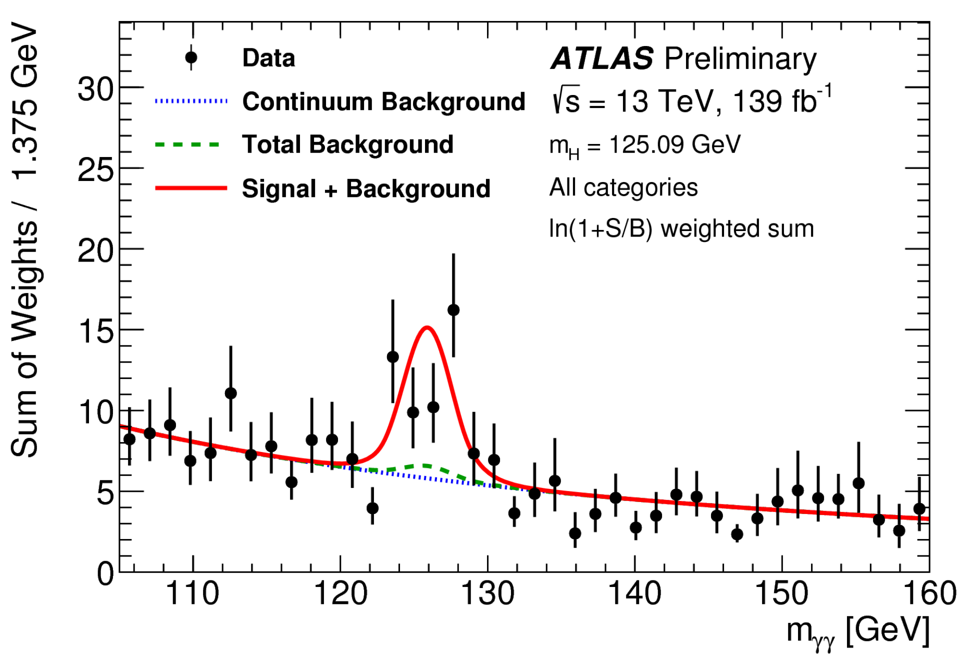
- very small production cross sections
- large backgrounds
- many different final states (both the Higgs and the top quark can decay into a variety of final states)

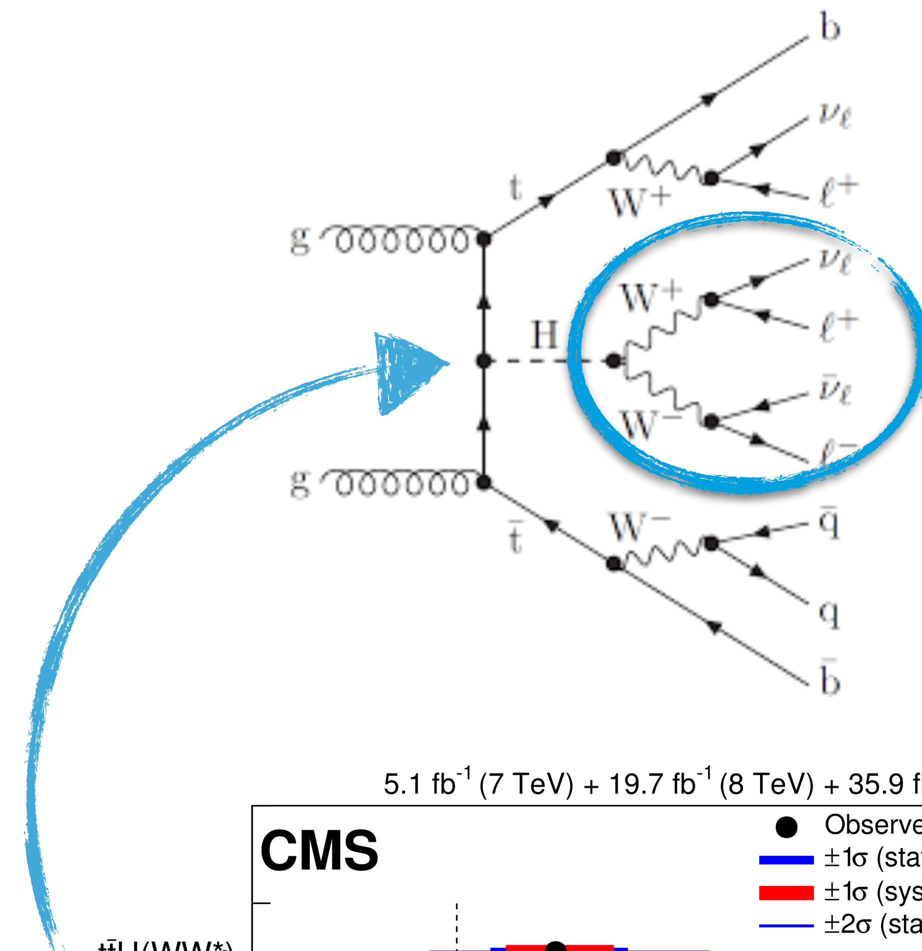


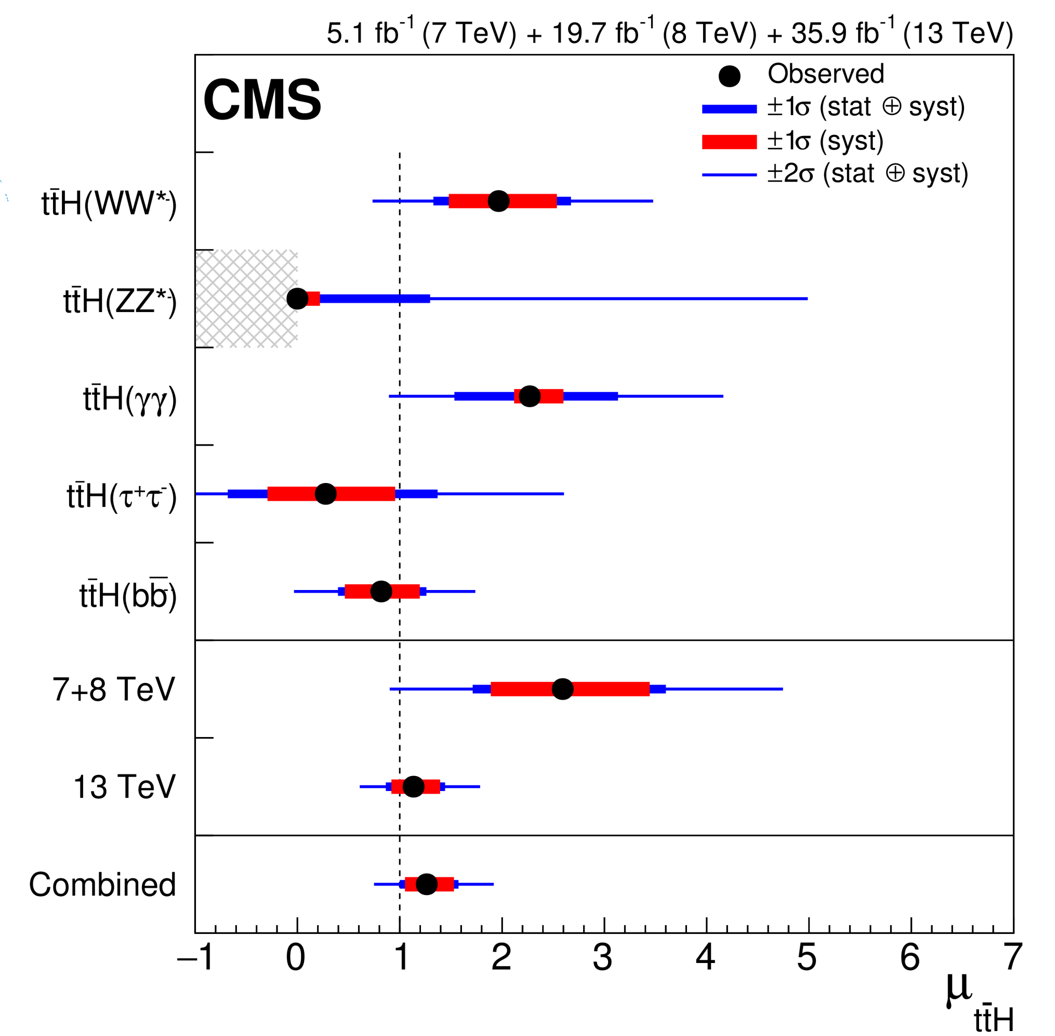
Marumi Kado

Higgs production in ttH

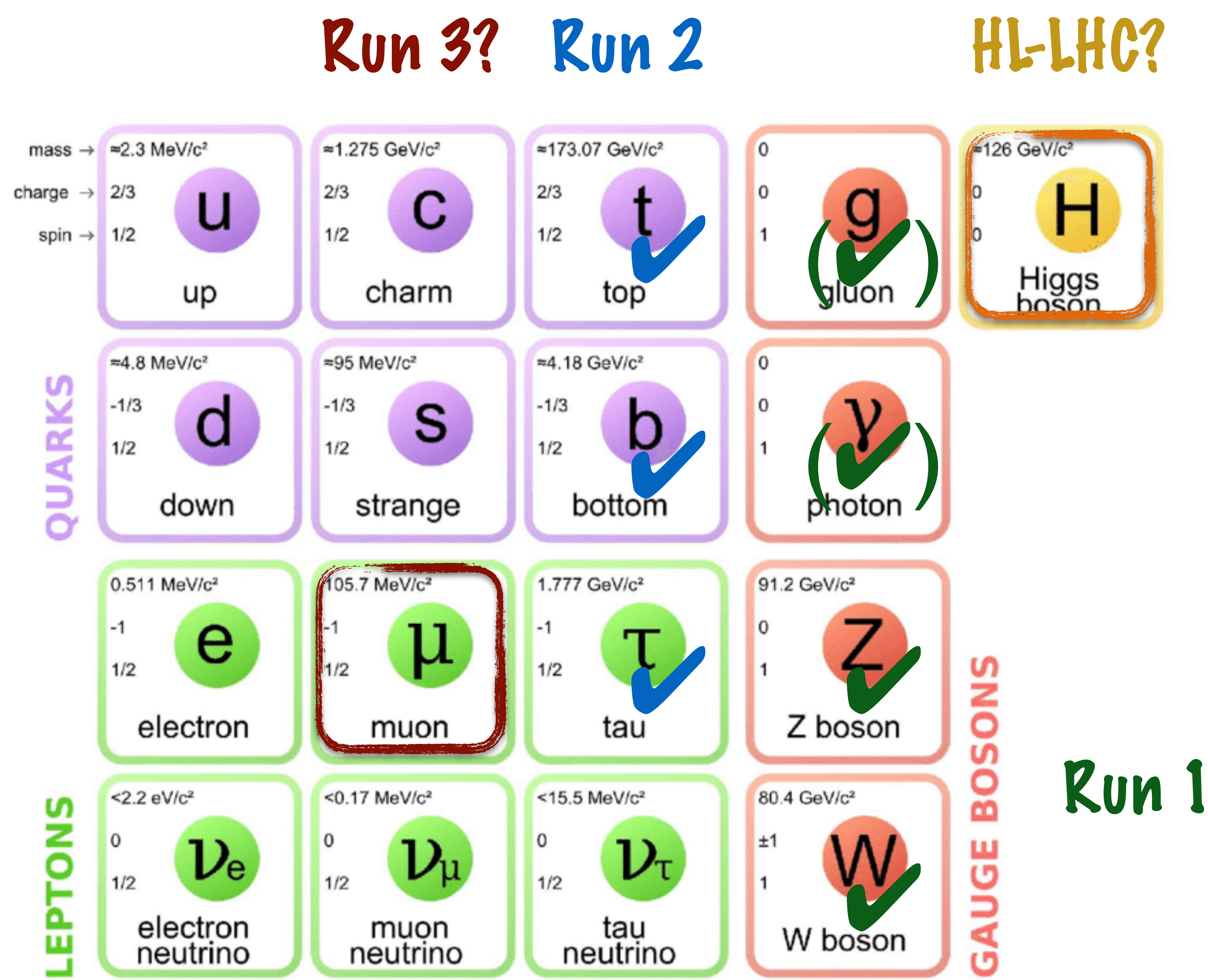






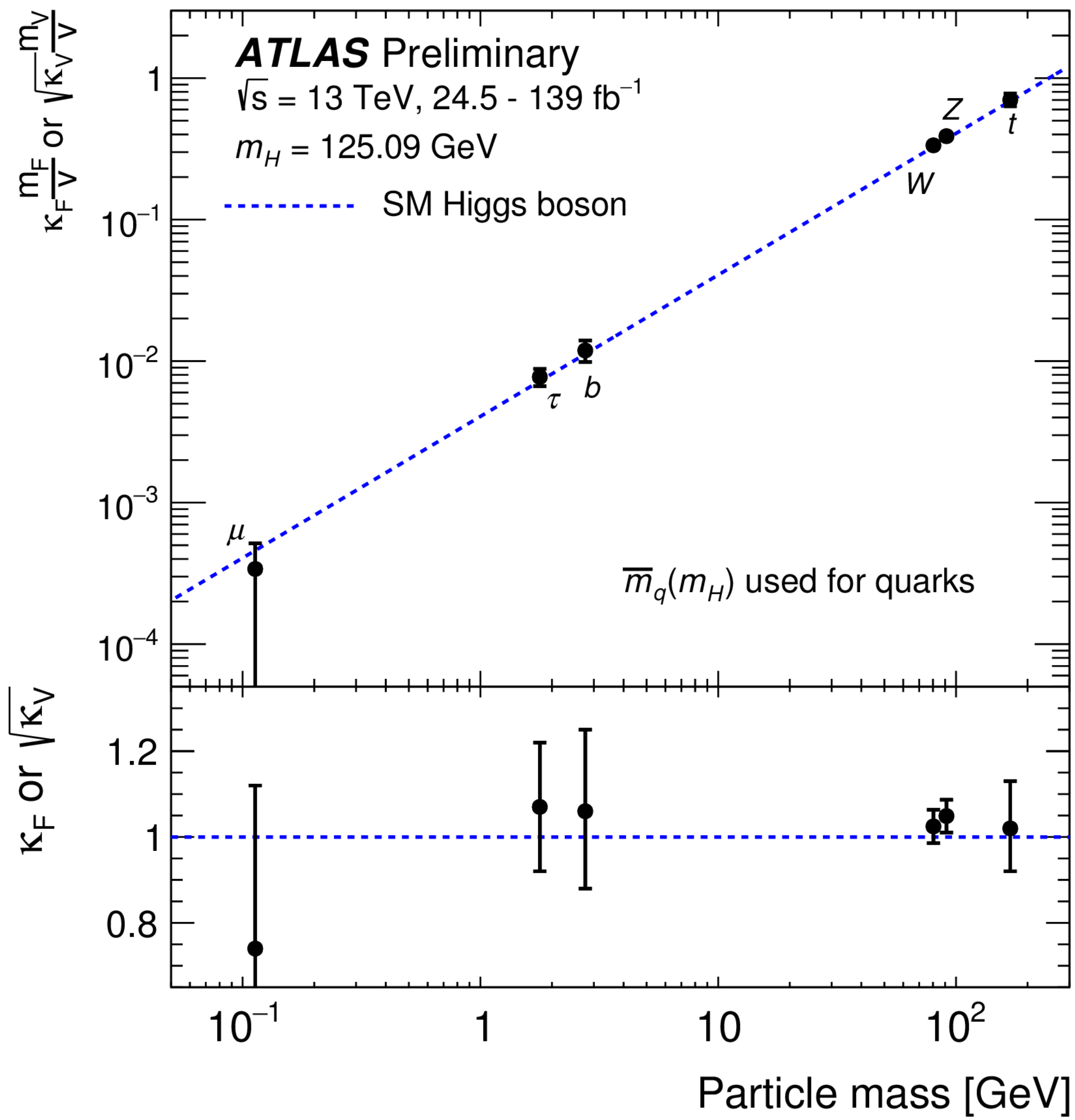


Higgs couplings to other particles



Important to test up and down-type couplings!

Higgs couplings to other particles



(**κ**: scaling factors to SM couplings)

There are a number of assumptions that go into this plot

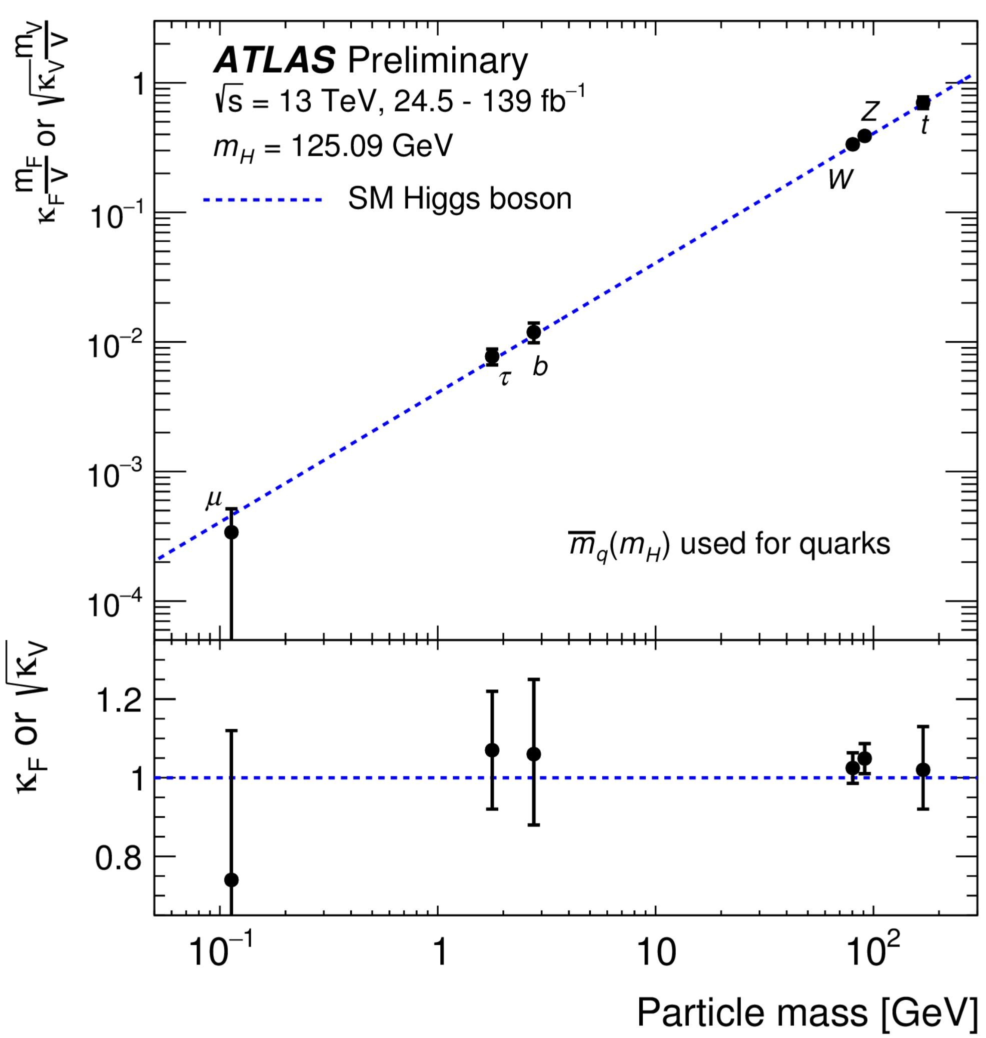
Higgs is looking very SM like!

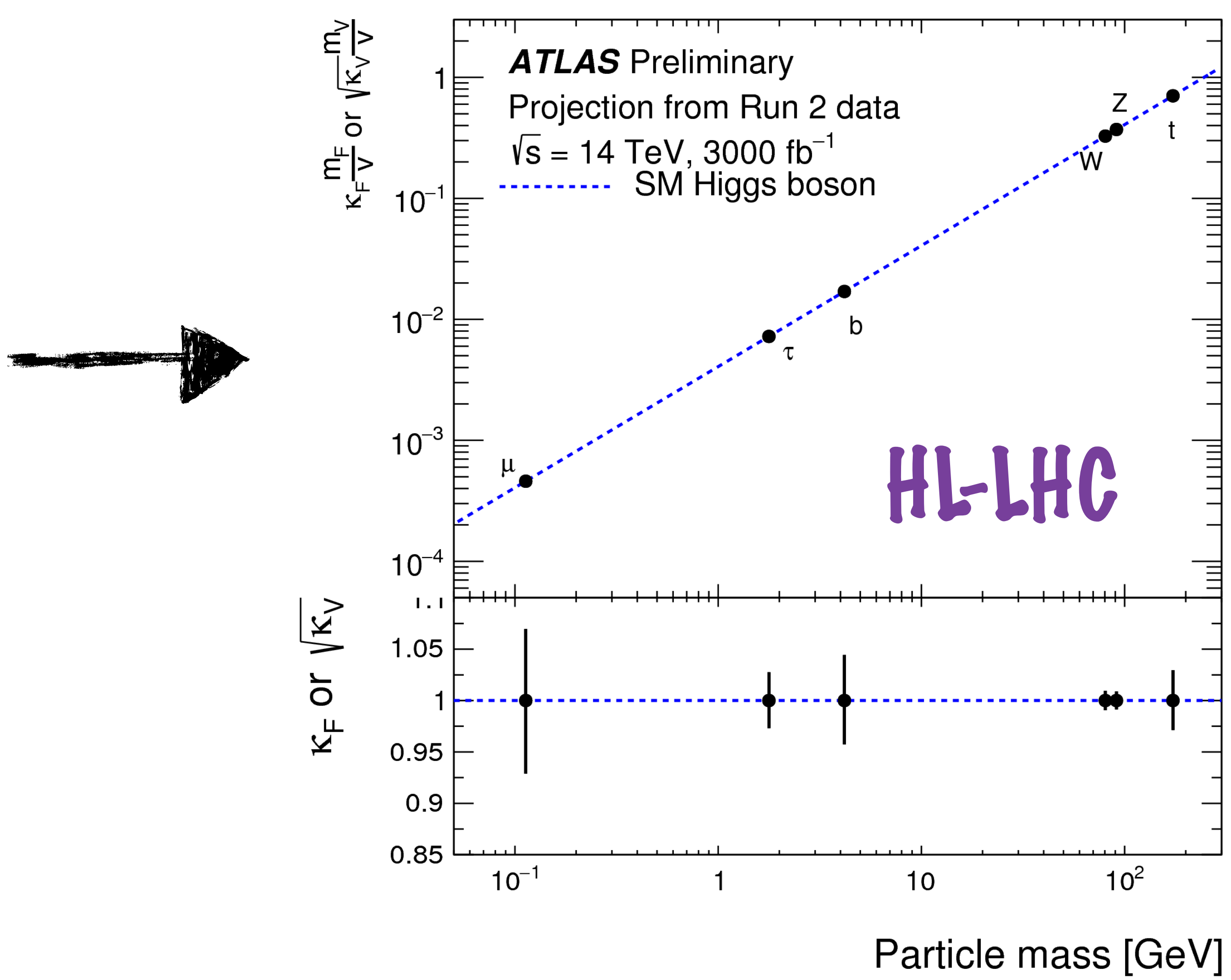
- deviations can be small….

If new physics is at 1 TeV:

Snowmass 2013 (1310.8361)

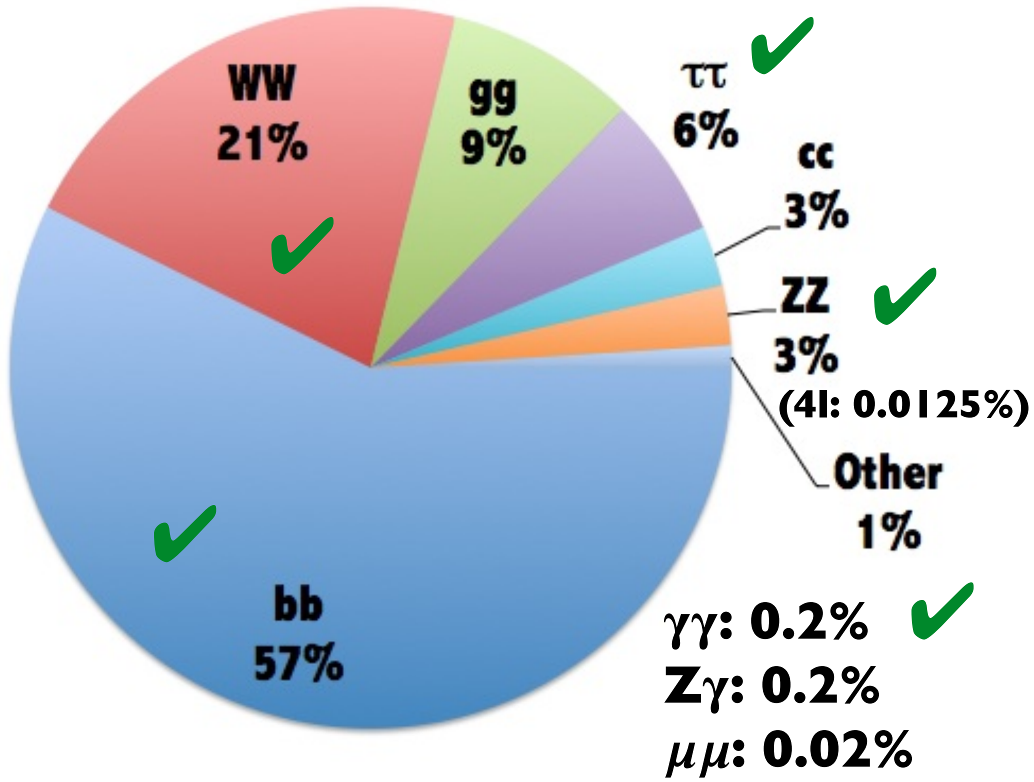
	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	~6%	~6%	~6%
2HDM	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

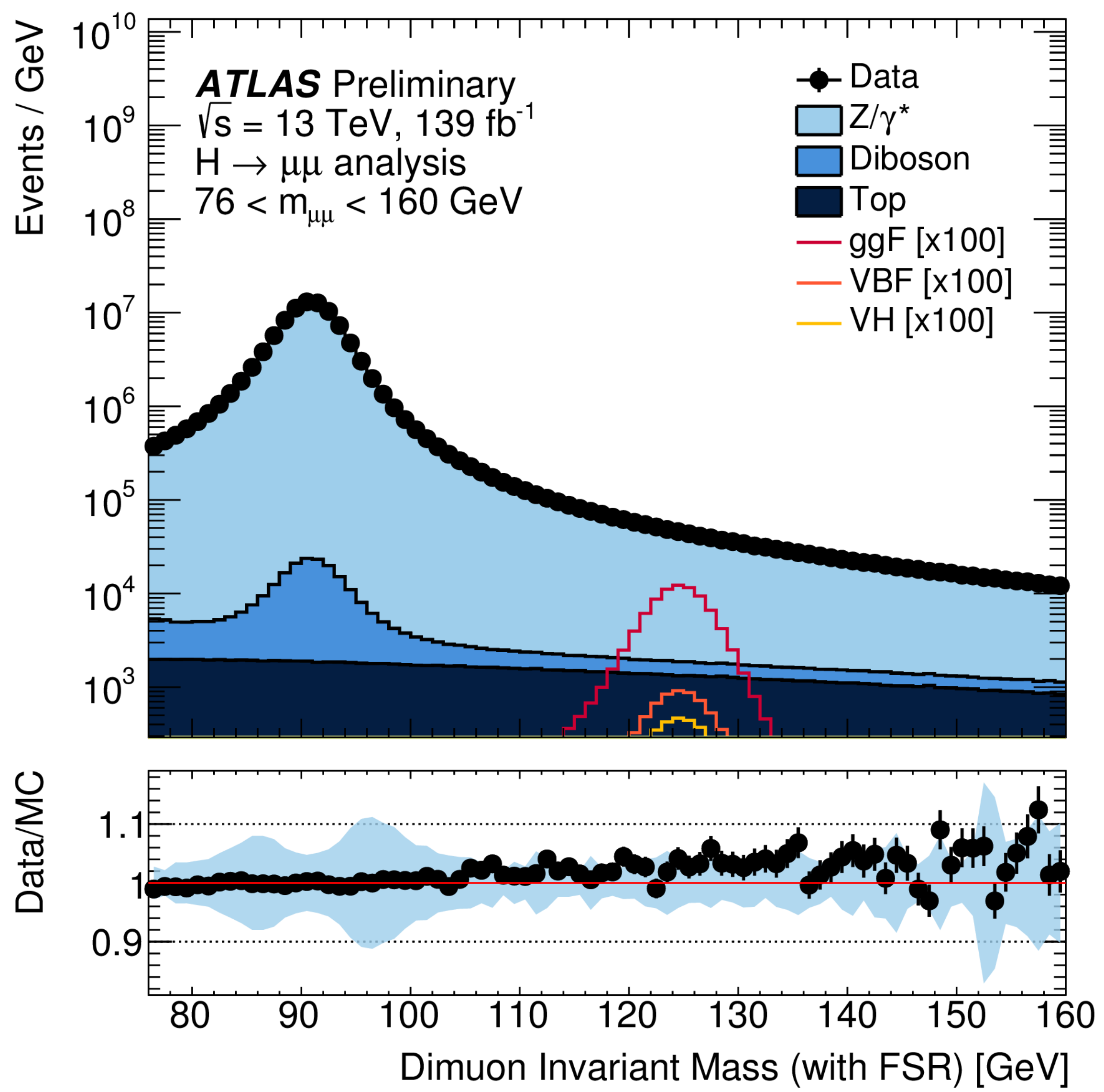


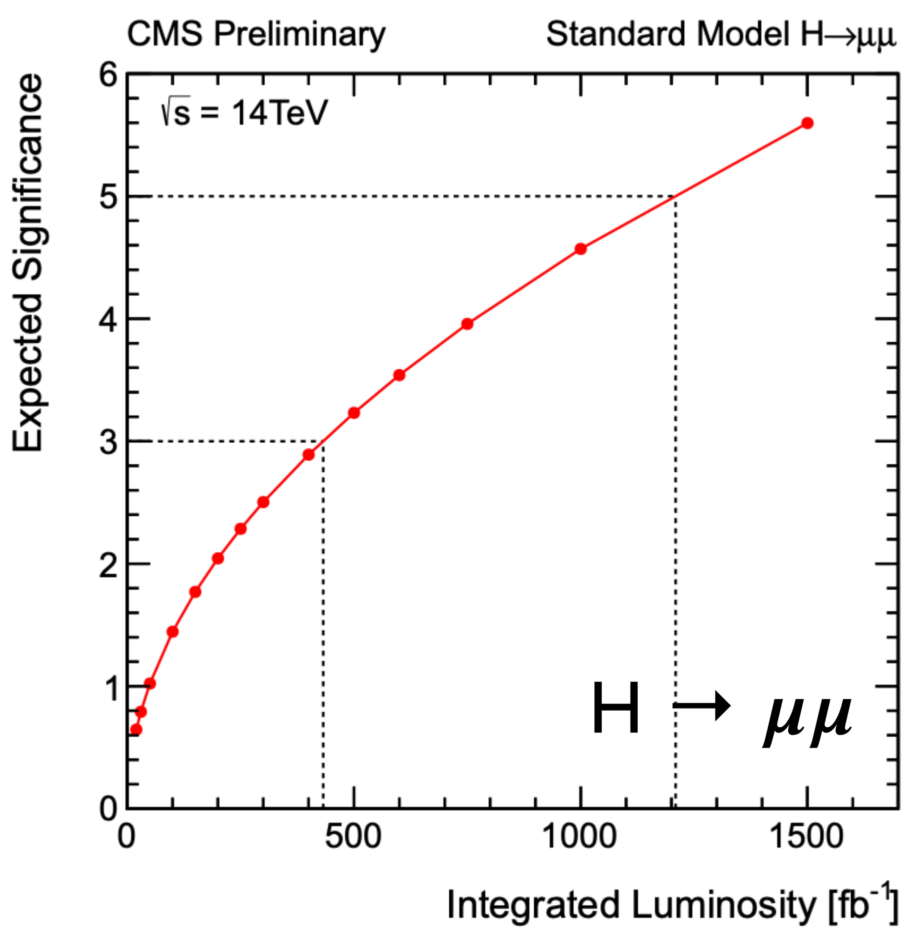


So-far undiscovered decays

Example H->μμ
challenging: small coupling, large Drell-Yan background
=> make categories based on a boosted decision tree



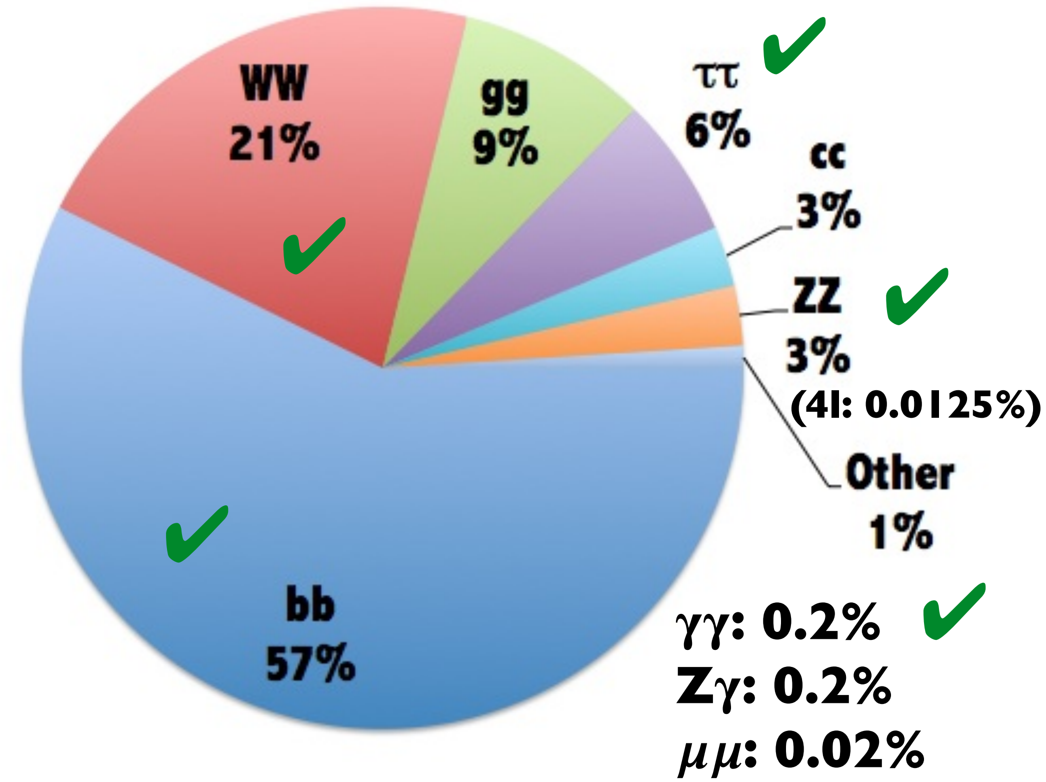


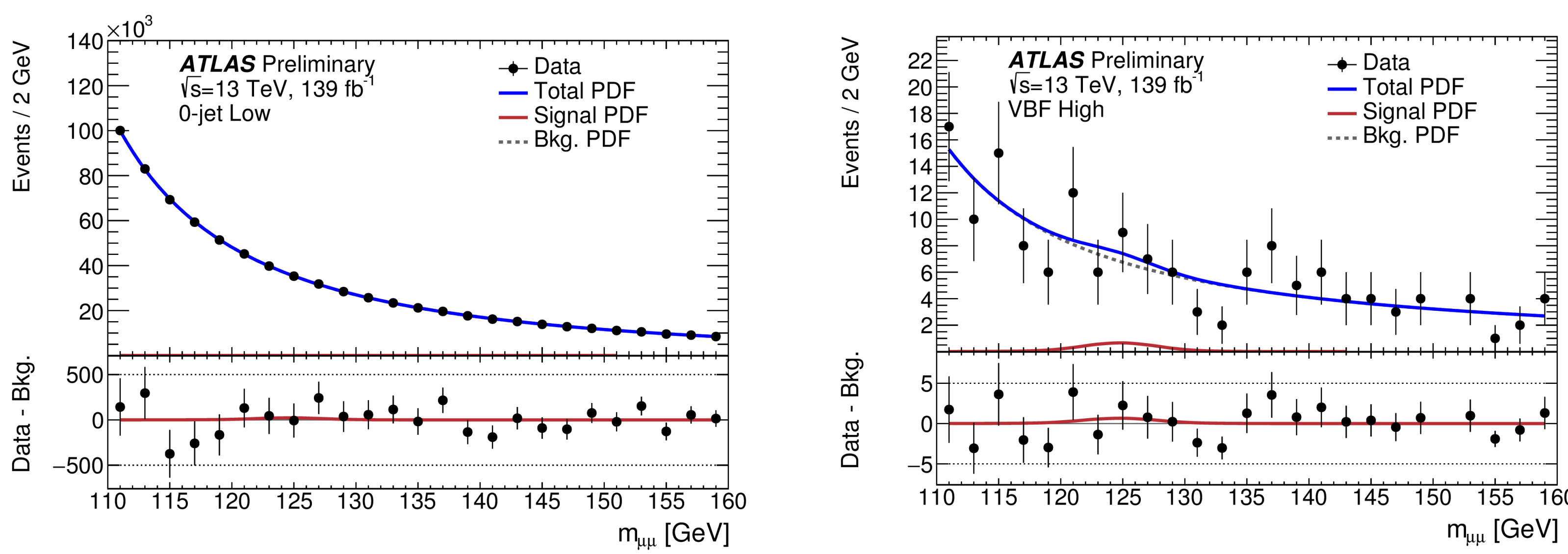


So-far undiscovered decays

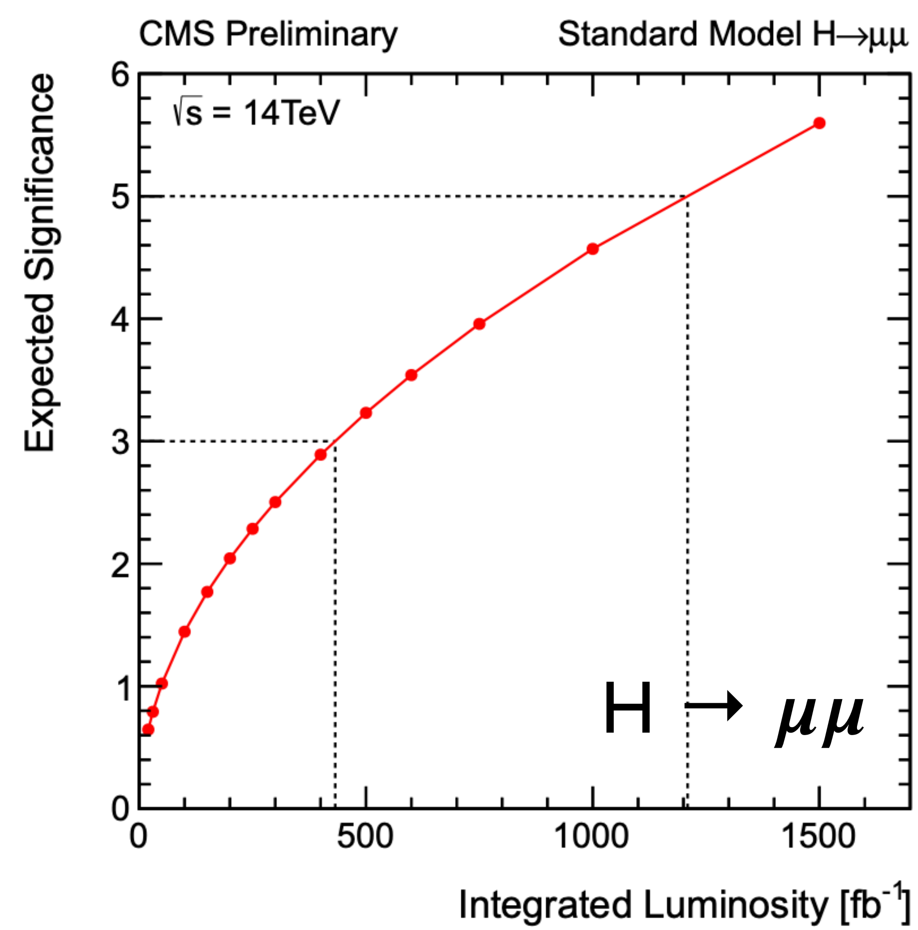
Example H->μμ
challenging: small coupling, large Drell-Yan background
=> make categories based on a boosted decision tree

=> VBF production:
less statistics, better S/B





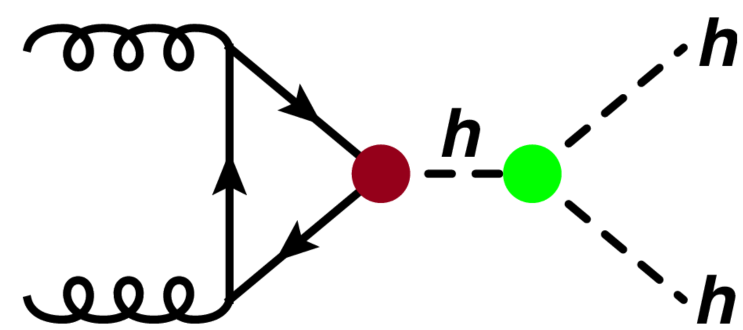
2 of the 12 categories



Higgs self couplings

Why is the Higgs self-coupling interesting?

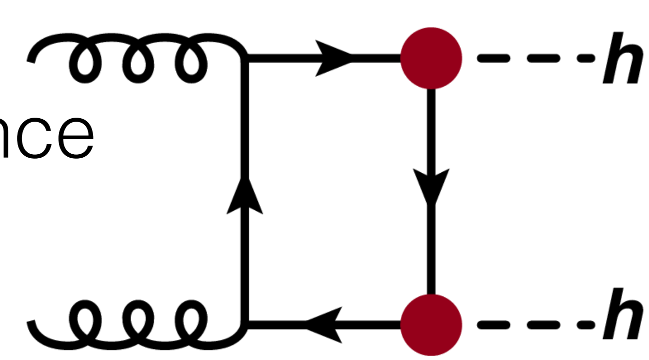
- allows to test the shape of the Higgs potential



$$\mathcal{L} = -\frac{m_h^2}{2}h^2 - \lambda_3 v h^3 - \lambda_4 h^4$$

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

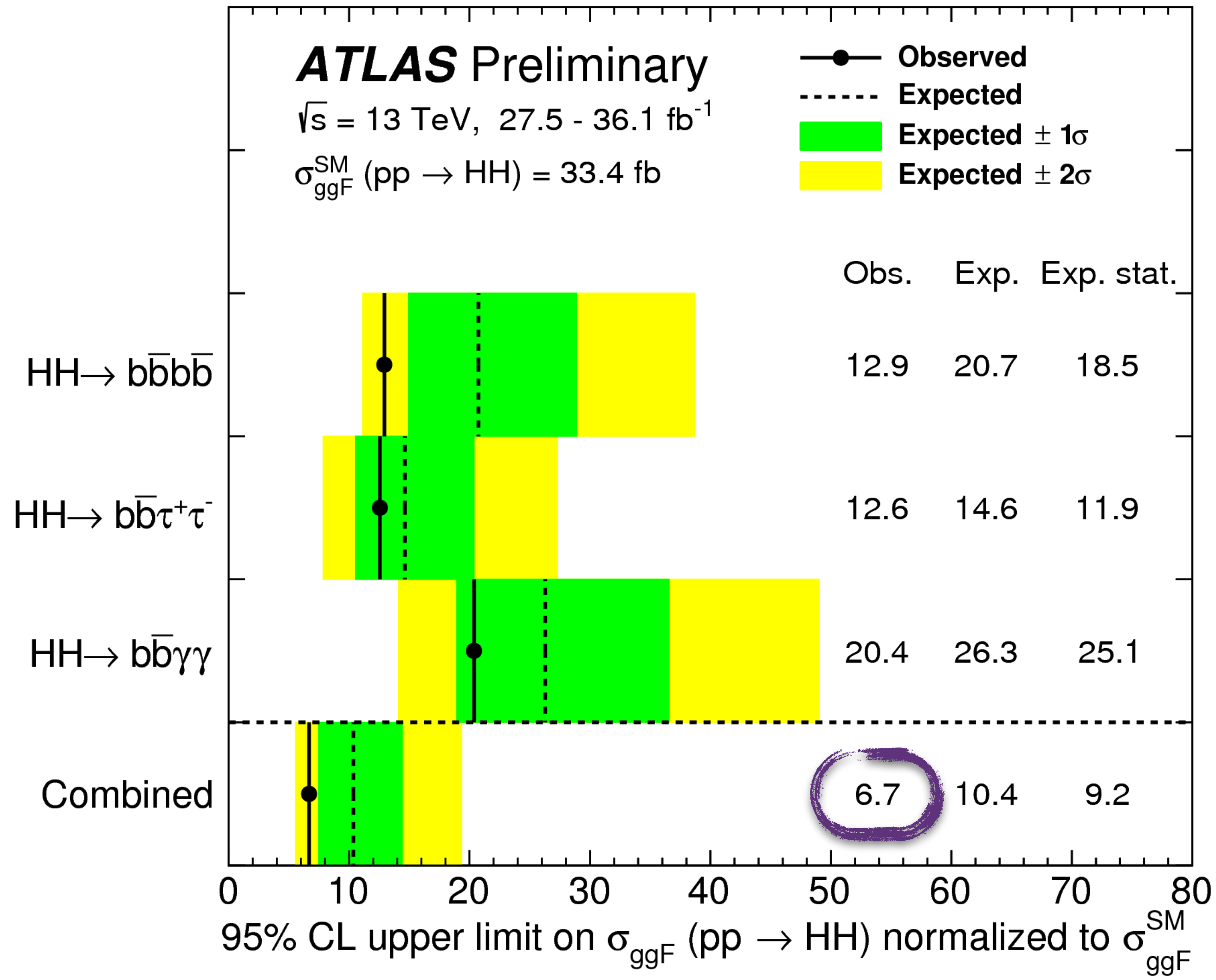
- Deviations from the SM predictions expected in many BSM models

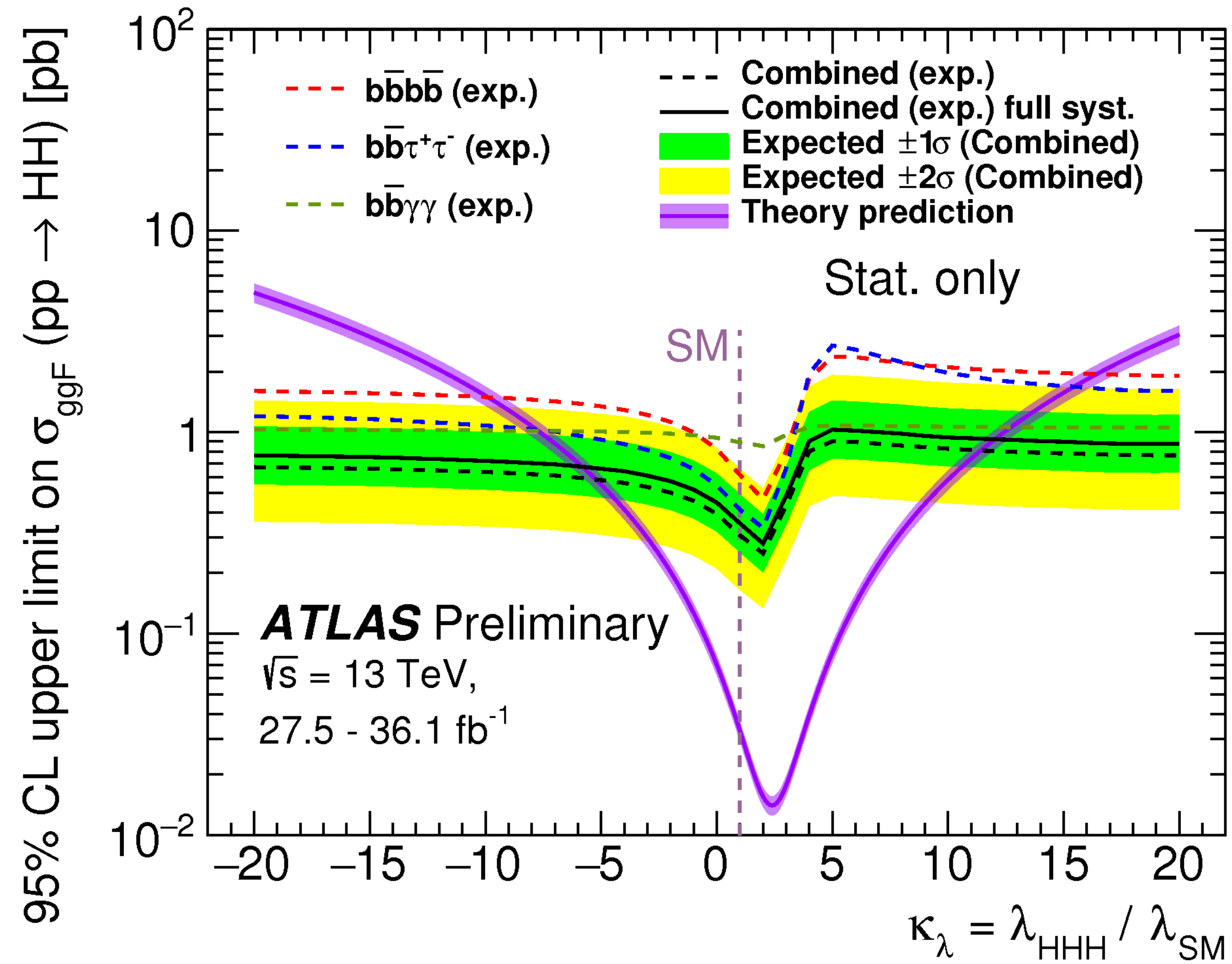


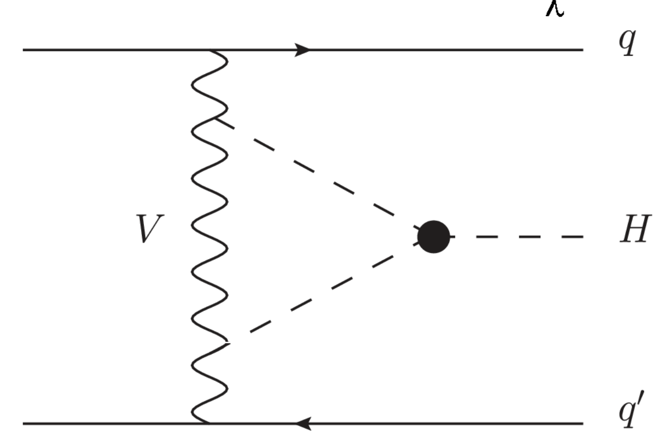
- challenging measurement, due to negative interference with box diagram

Higgs self coupling

Assume $\kappa_t = 1$







It is also possible to extract the self-coupling in single-Higgs events through NLO EW corrections

=> comparable κ_λ ranges
 (assuming only κ_λ differs from SM)

HL-LHC ~5 sigma expected

Direct searches for Higgs beyond the SM

Flavor violating searches => H-> eμ for example

Search for invisible decays => see next lecture

Searches for additional, lighter or heavier or even charged Higgs bosons (predicted by SUSY models, see next lecture)