Models and Methods for Beyond Standard Model Physics at colliders

Lectures for the Ph.D. Program in Physics, XXXVI Cycle

15/04/2021

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Chapter III

Higgs phenomenology and measurements

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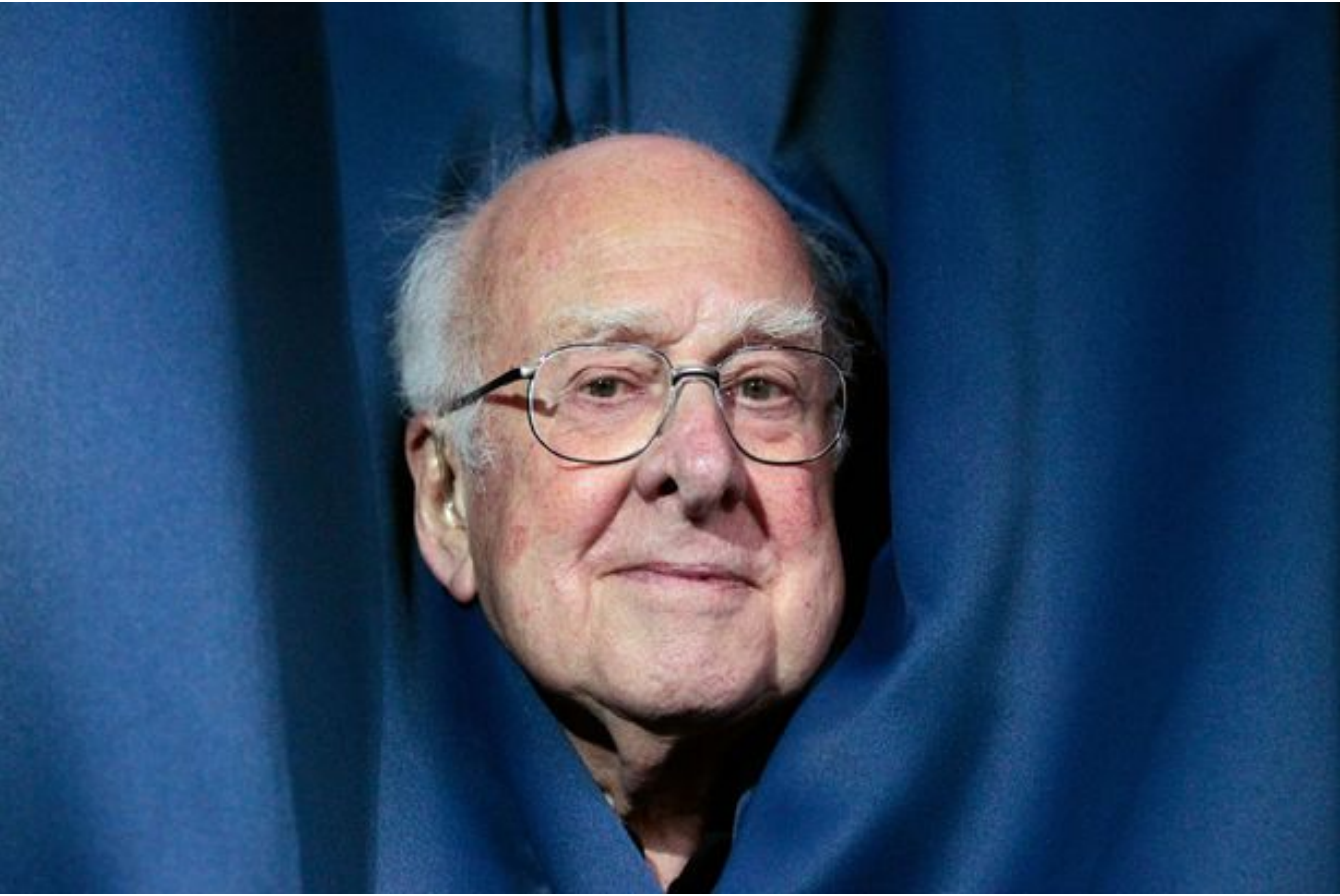


The Higgs Boson Timeline

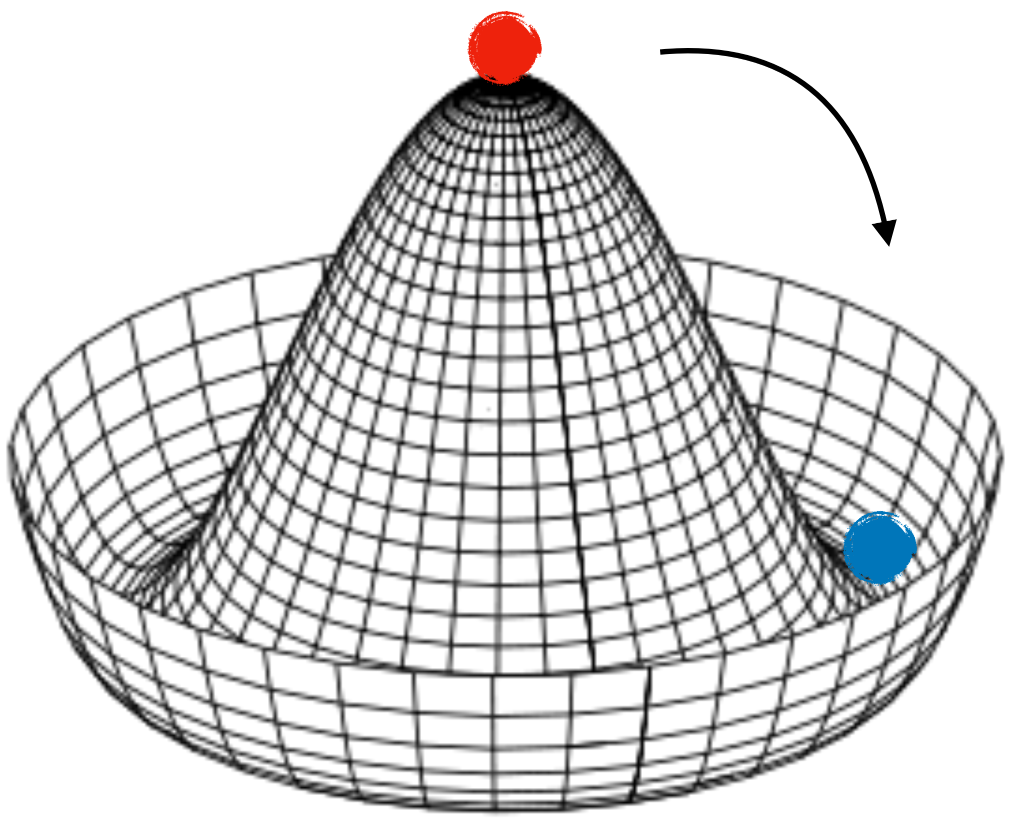
- Gauge invariance of Electroweak theory requires all fermions and W and Z to be massless
- Discovery of W and Z in 1983 proved them to be pretty heavy
- Need a mechanism to dynamically generate mass for all particles and conserve the gauge invariance
- Higgs mechanism and goldstone bosons address this problem
- Experimental evidence needed to validate theory
  - Predict Higgs production processes and decay rates
- Direct search
  - produce Higgs and look for decay products: invariant mass and characteristic kinematics
- Indirect search
  - Calculate contribution of Higgs in corrections to well known SM processes
  - Combined analysis of all precisely measured Z-pole observables and check validity with different Higgs mass assumptions

The EW Symmetry Breaking

<u>local max</u>
perfect symmetry,
metastable,
nomass

$$\mathscr{L} = \frac{1}{2}\partial_\mu \partial^\mu \phi - m^2 \phi \phi^\dagger + \frac{1}{4}(\phi\phi^\dagger)^2$$

without this, reality makes no sense



$v = < 0 | \phi | 0 >$
void expectation value

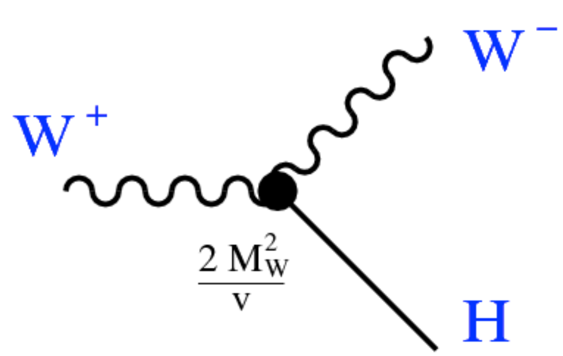
<u>local min</u>
broken symmetry,
stable,
massive

add the scalar field in the SU(2)xU(1) theory to have mass terms for fermions and bosons

Spontaneous Symmetry Breaking SU(2)xU(1) ⟶ U(1) **Electroweak Symmetry Breaking**

Higgs coupling
—> mass terms

$$M_W = \frac{1}{2} v \cdot g_W$$

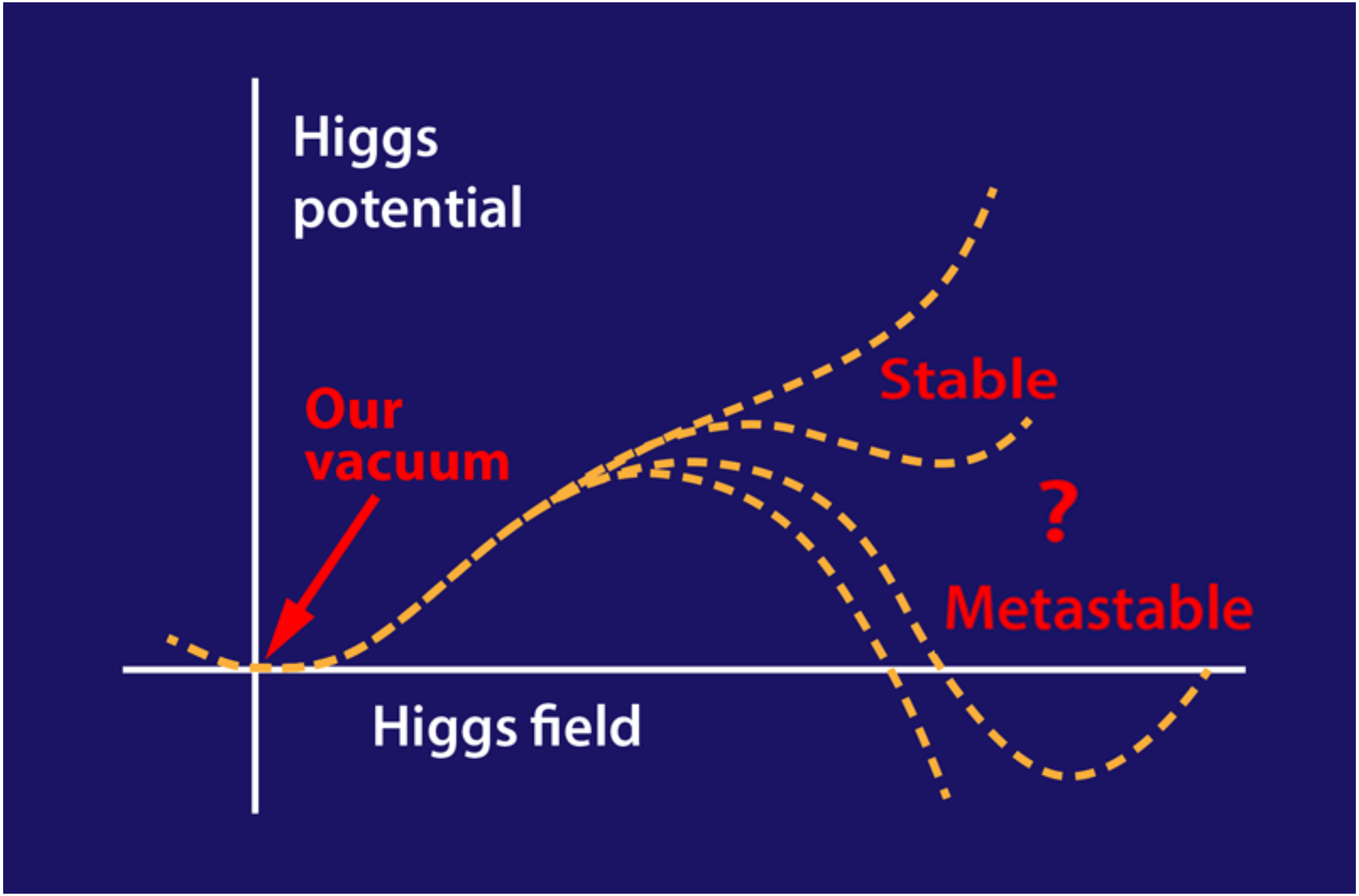


$$L_h = \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2} h^2 - \frac{M_h^2}{2v} h^3 - \frac{M_h^2}{8v^2} h^4 + \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \right)\left(1 + \frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right).$$

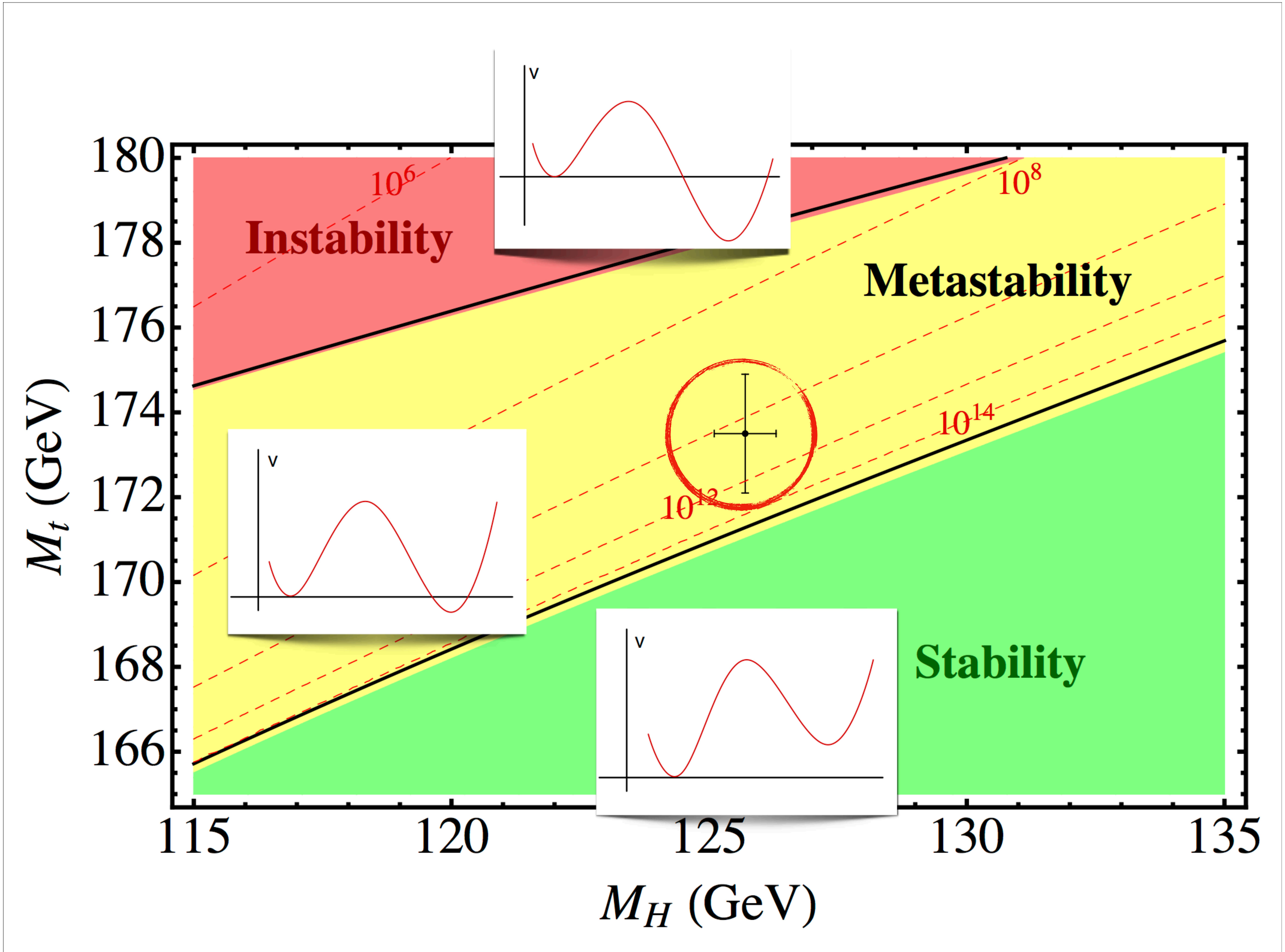
bosons masses

fermion masses

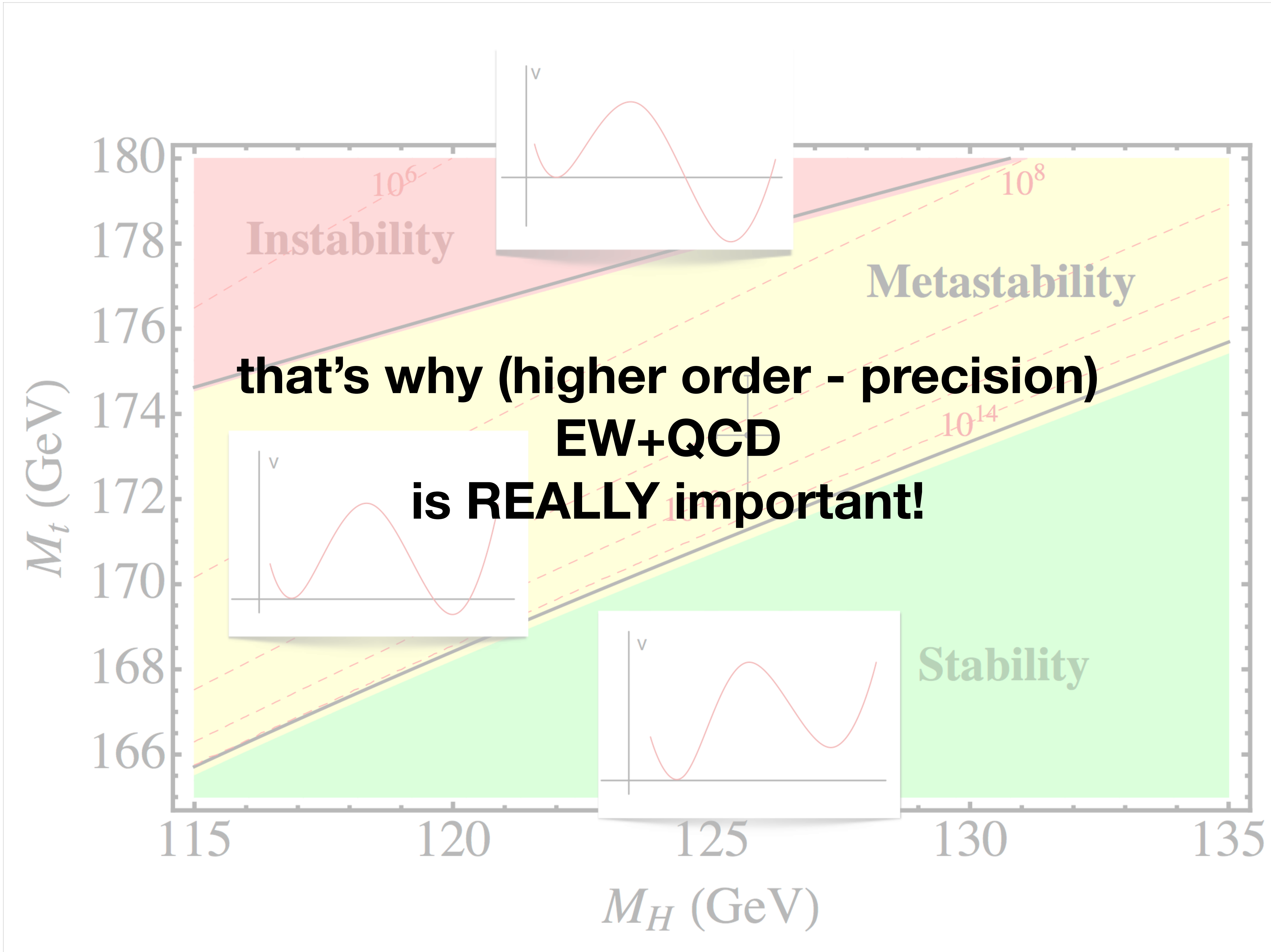
The Higgs & the Universe - th



The Higgs & the Universe - exp



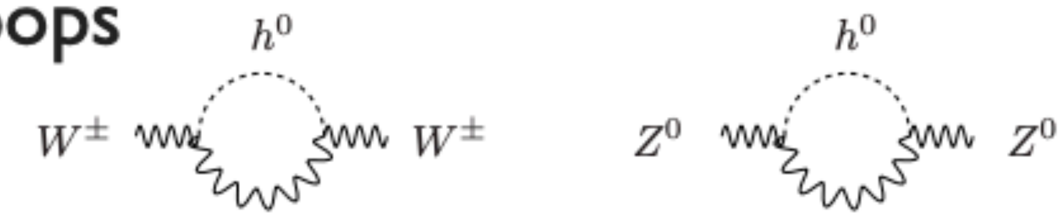
The Higgs & the Universe



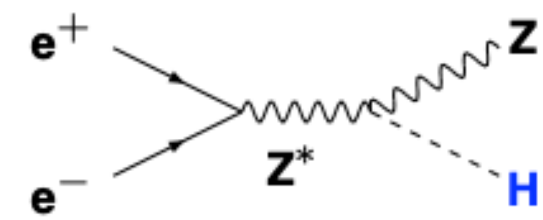
that's why (higher order - precision)
EW+QCD
is REALLY important!

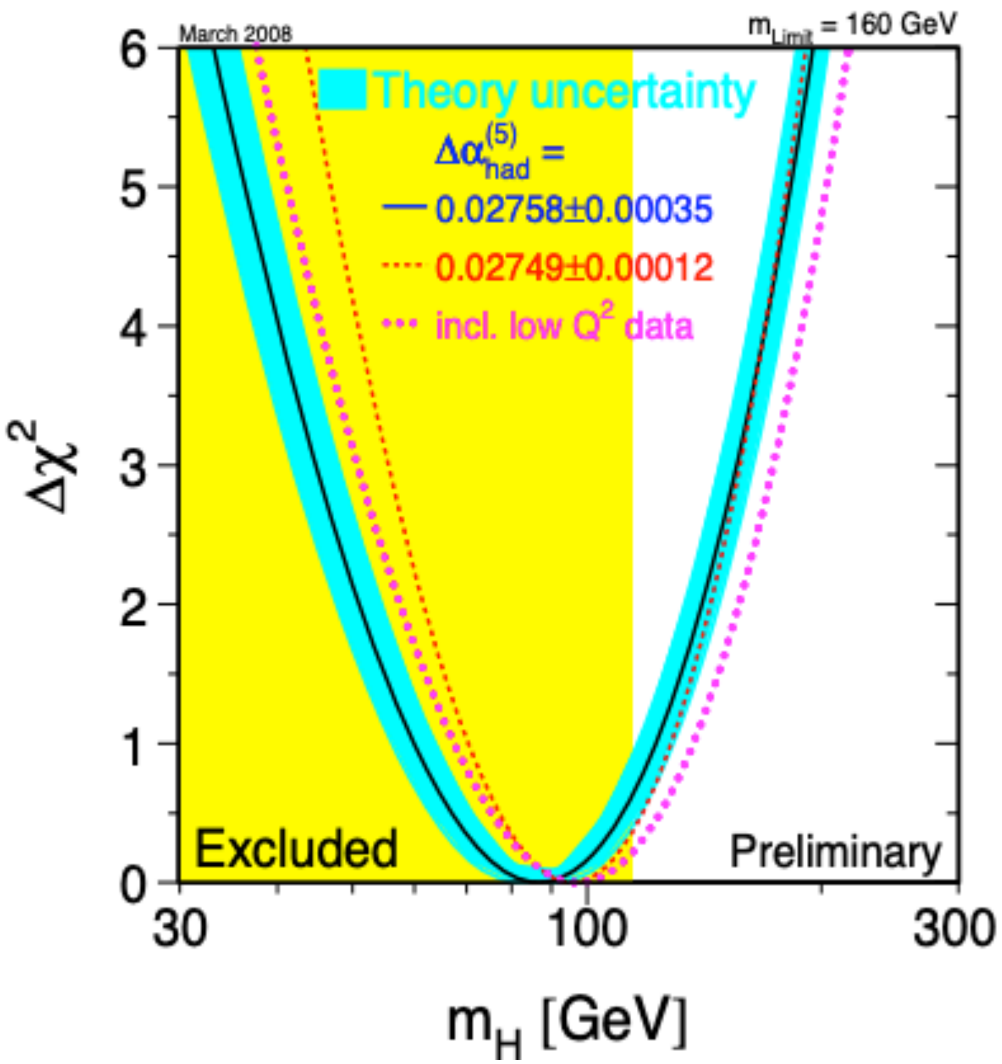
Indirect Searches at LEP

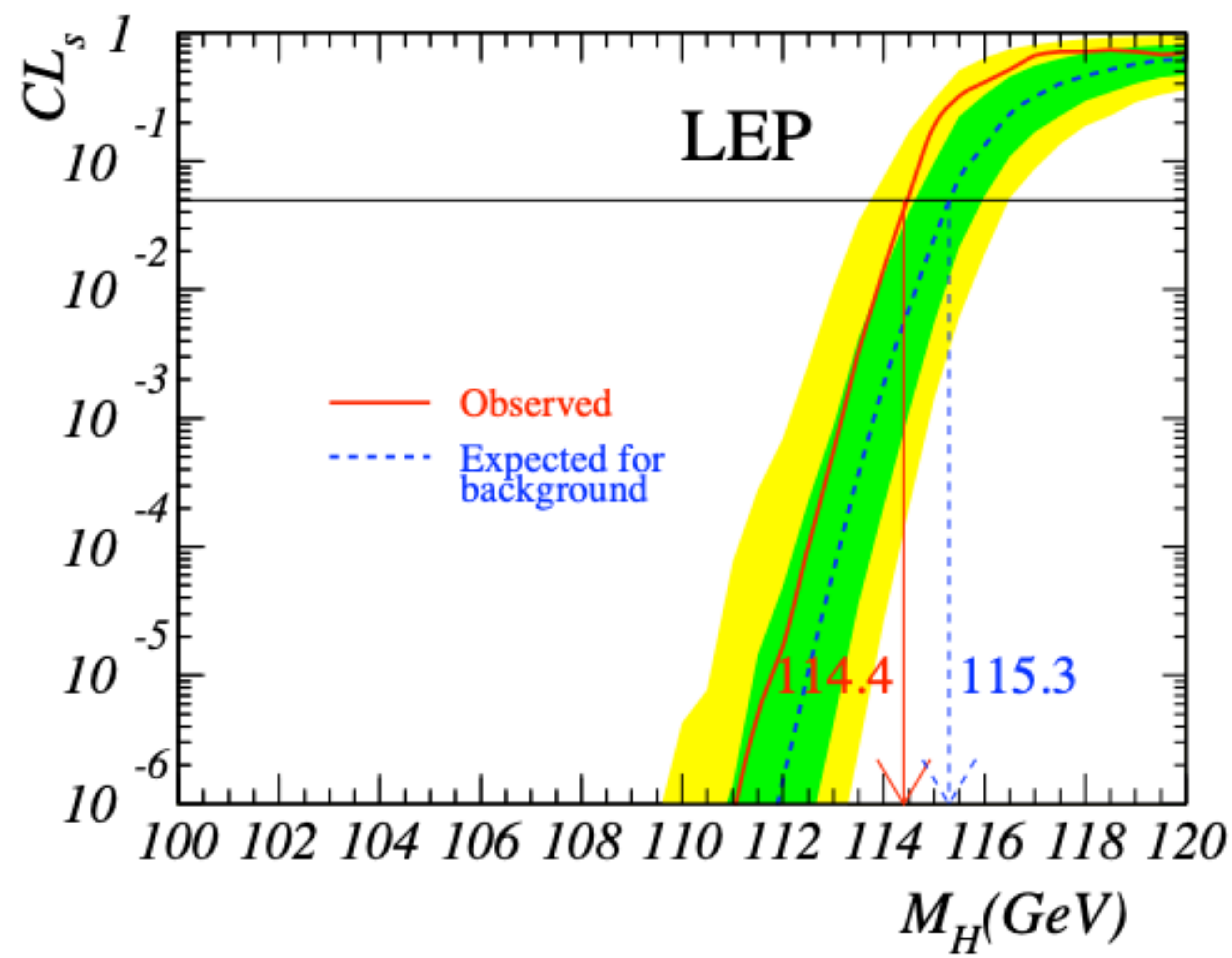
- Indirect search through precision measurement of SM sensitive to radiative corrections to Higgs in loops



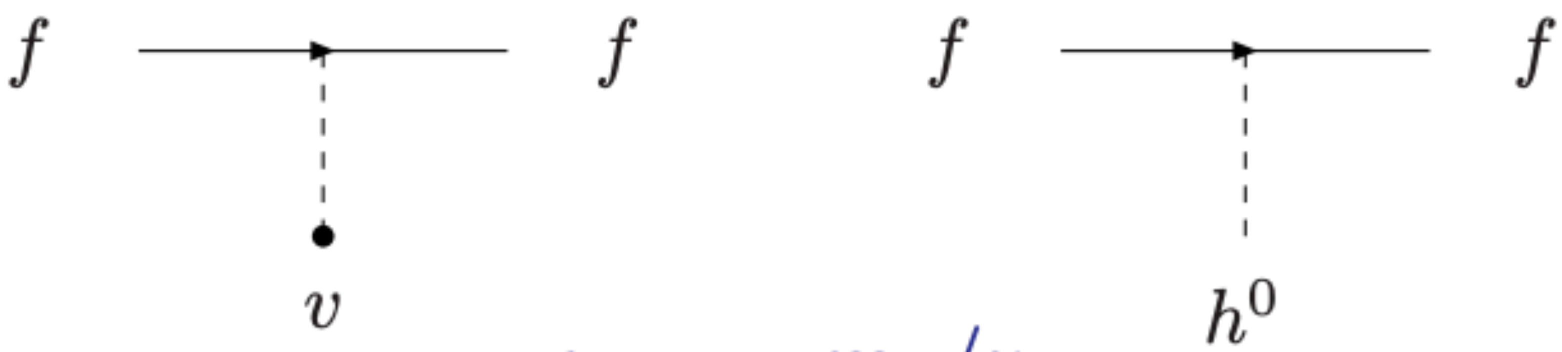
- Direct search at LEP in Higgs-strahlung production channel



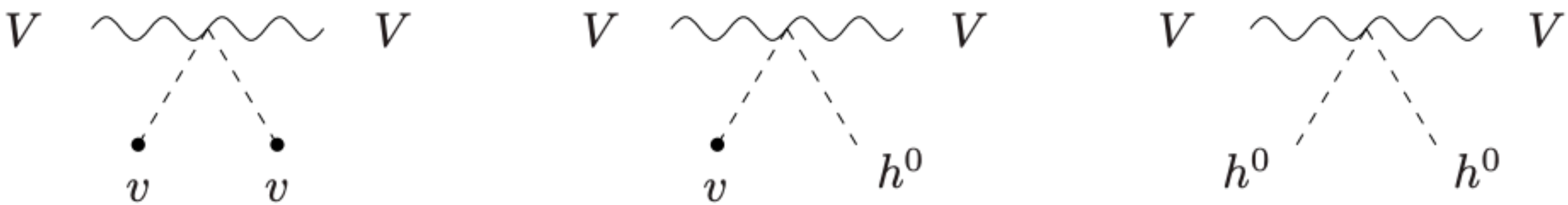




Higgs Couplings



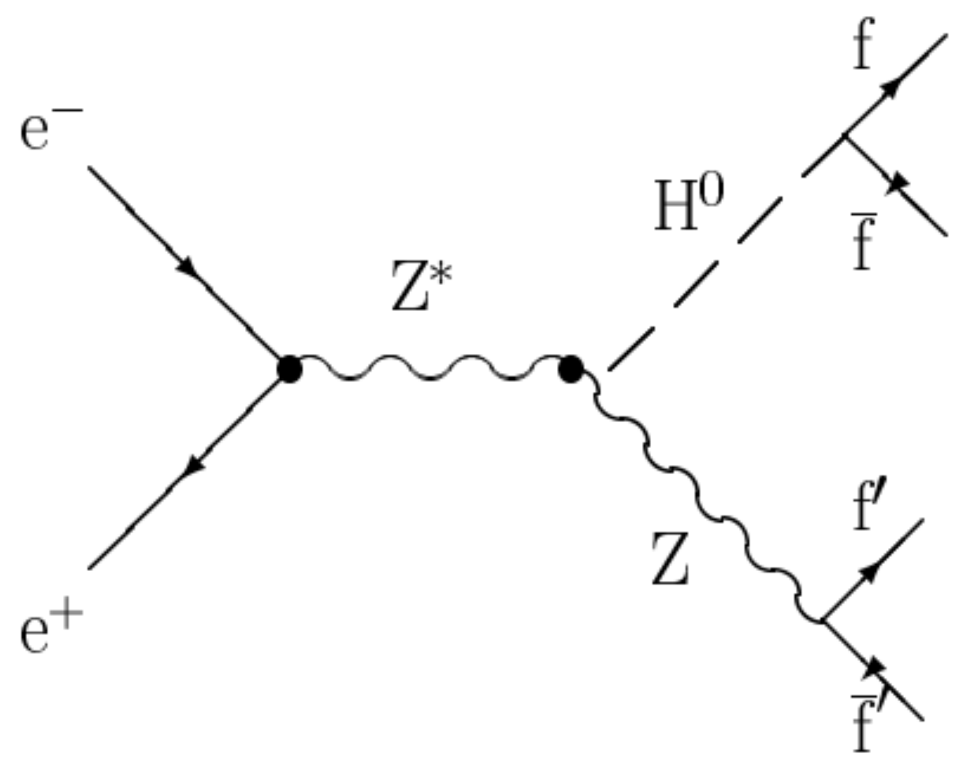
$$g_{hf\bar{f}} = m_f/v$$



$$g_{hVV} = 2m_V^2/v \qquad g_{hhVV} = 2m_V^2/v^2$$

- Higgs coupling enhanced for heavier particles
- Vector bosons always preferred to fermions
  - But must be kinematically allowed
- Fixing mass of Higgs fixes decay rates for all final states

Higgs Production in e^+e^-



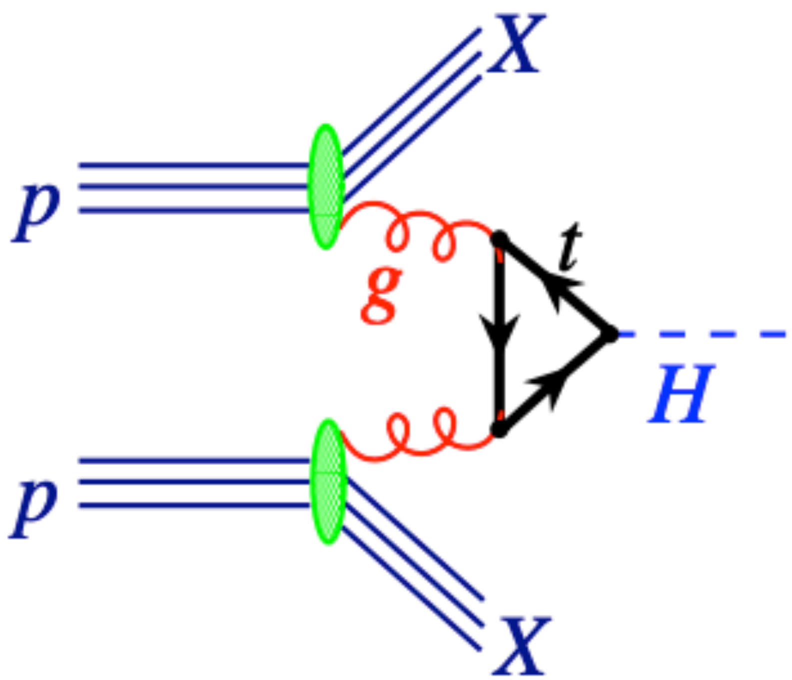
$\mathbf{H^0 \to b\bar{b}}$ **dominant (BR $\approx$ 84%)**

$\mathbf{H^0(\to b\bar{b})Z(\to q\bar{q}) \sim 60\%}$

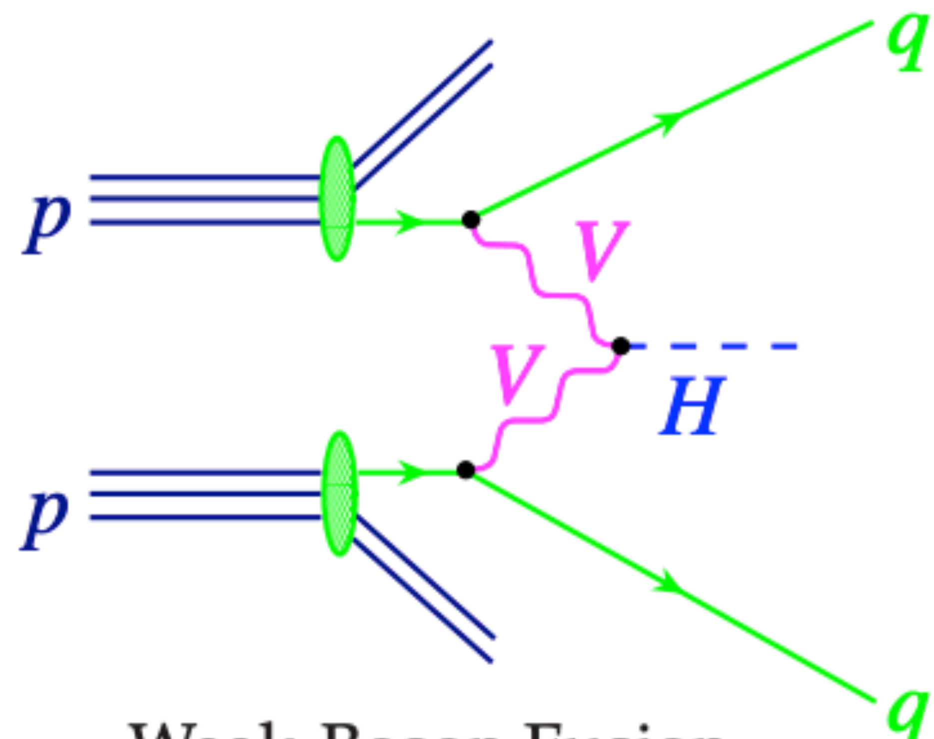
$\mathbf{H^0(\to b\bar{b})Z(\to \nu\bar{\nu}) \sim 17\%}$

$\mathbf{H^0(\to b\bar{b})Z(\to \ell^+\ell^-)}$ **and** $\mathbf{H^0(\to \tau^+\tau^-)Z(\to q\bar{q}) \sim 14\%}$

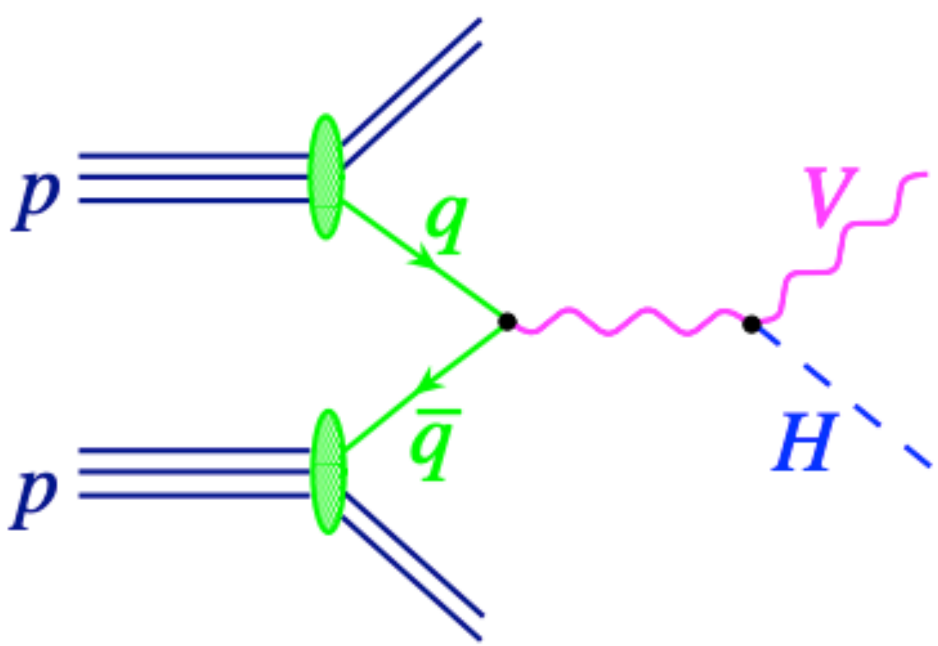
Higgs Production in pp



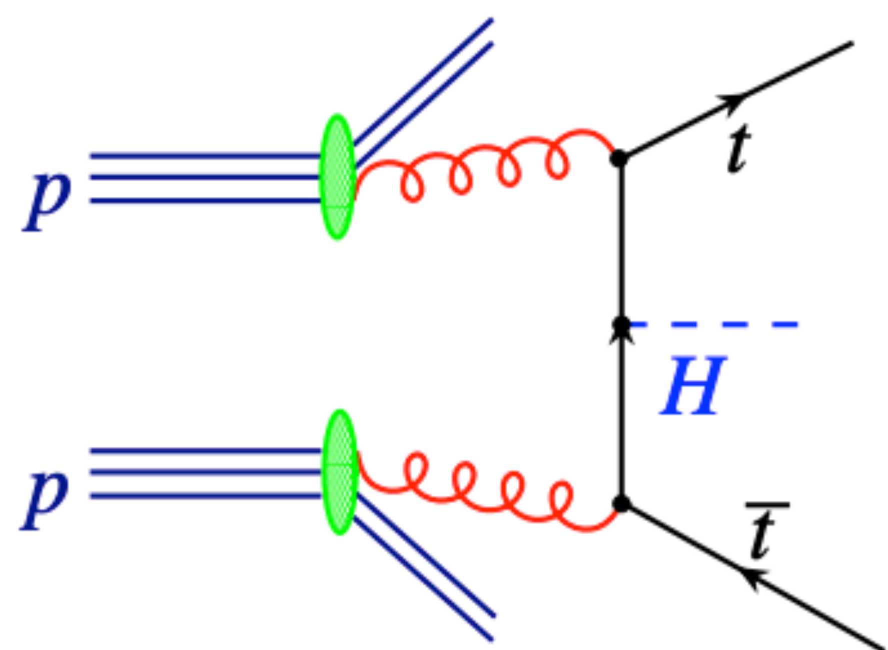
Gluon fusion



Weak-Boson Fusion

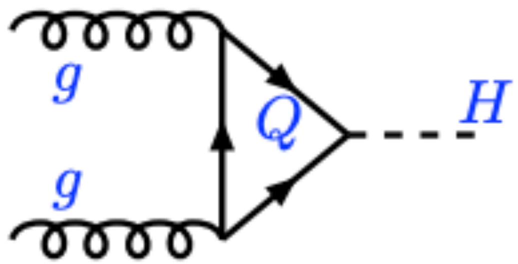


Higgs Strahlung



$t\bar{t}H$

The gluon-gluon fusion



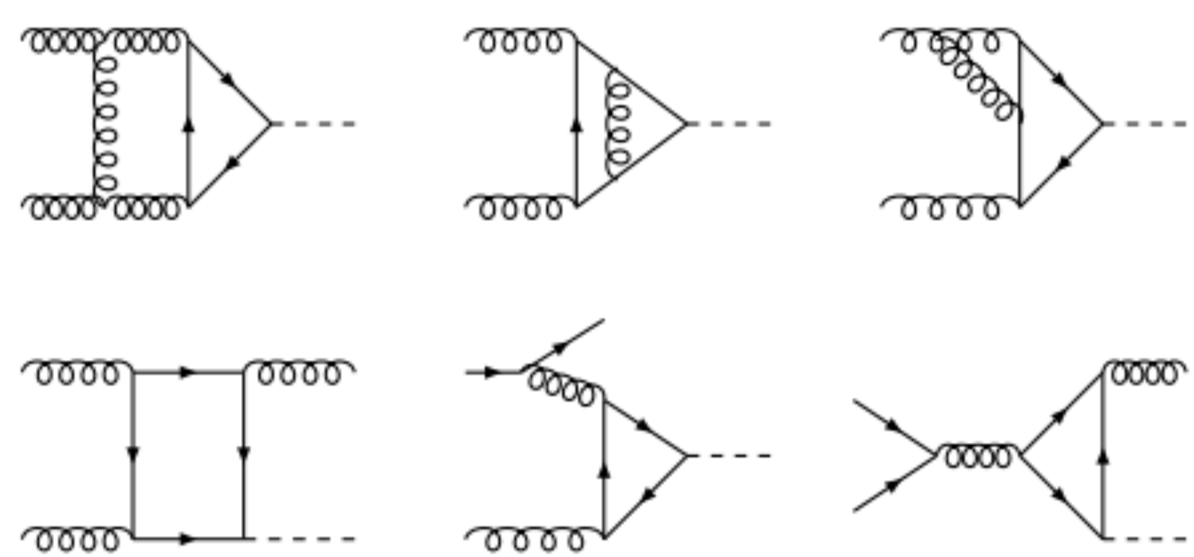
$$\hat{\sigma}_{\rm LO}(\mathbf{gg \to H}) = \frac{\pi^2}{8\mathbf{M_H}}\Gamma_{\rm LO}(\mathbf{H \to gg})\delta(\hat{\mathbf{s}} - \mathbf{M_H^2})$$

$$\sigma_0^{\mathbf{H}} = \frac{\mathbf{G}_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q \mathbf{A}_{1/2}^{\mathbf{H}}(\tau_Q) \right|^2$$

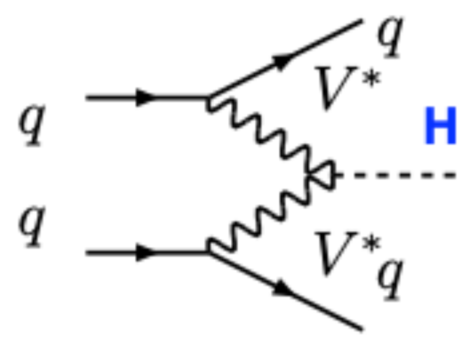
$$\mathbf{A}_{1/2}^{\mathbf{H}}(\tau) = 2[\tau + (\tau - 1)\mathbf{f}(\tau)]\,\tau^{-2}$$

$$\mathbf{f}(\tau) = \arcsin^2\sqrt{\tau} \ \mathbf{for}\ \tau = \mathbf{M_H^2/4m_Q^2} \le 1$$

- Leading production mechanism at LHC
  - Recall: parton luminosity highest for gluons
- In Standard Model only top quark matters
  - b quark contribution ~5%
  - In models beyond SM other particles could enter the loop
    - modification to expected cross section
- Cross section known with uncertainty at the level of 5%
  - many additional radiative terms included



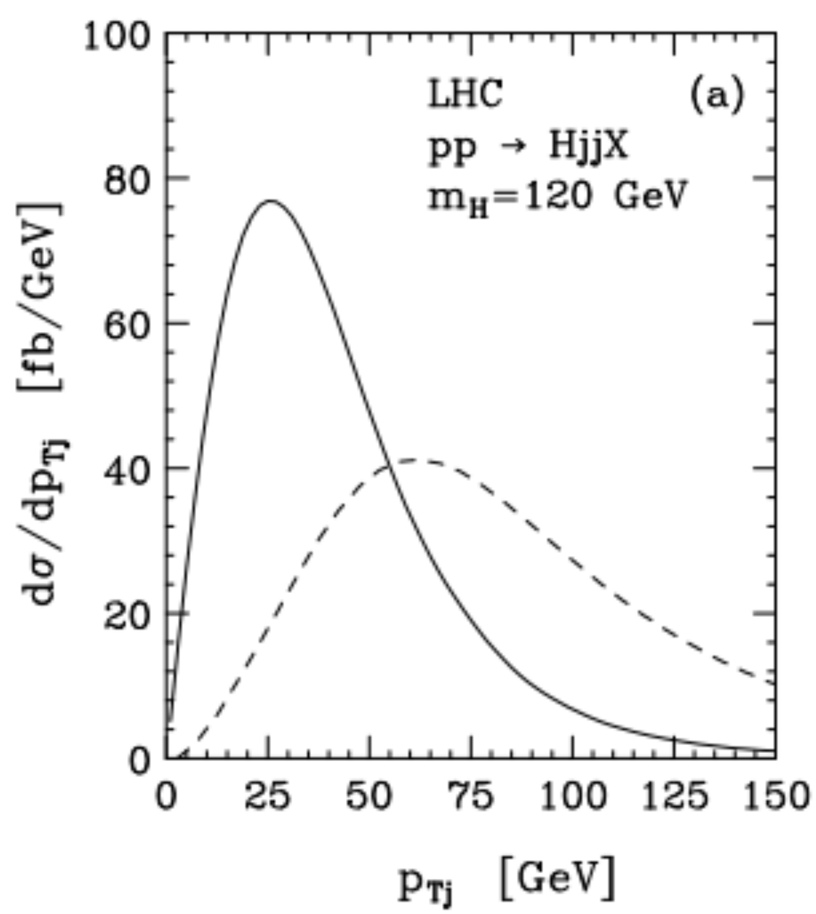
The VBF mode

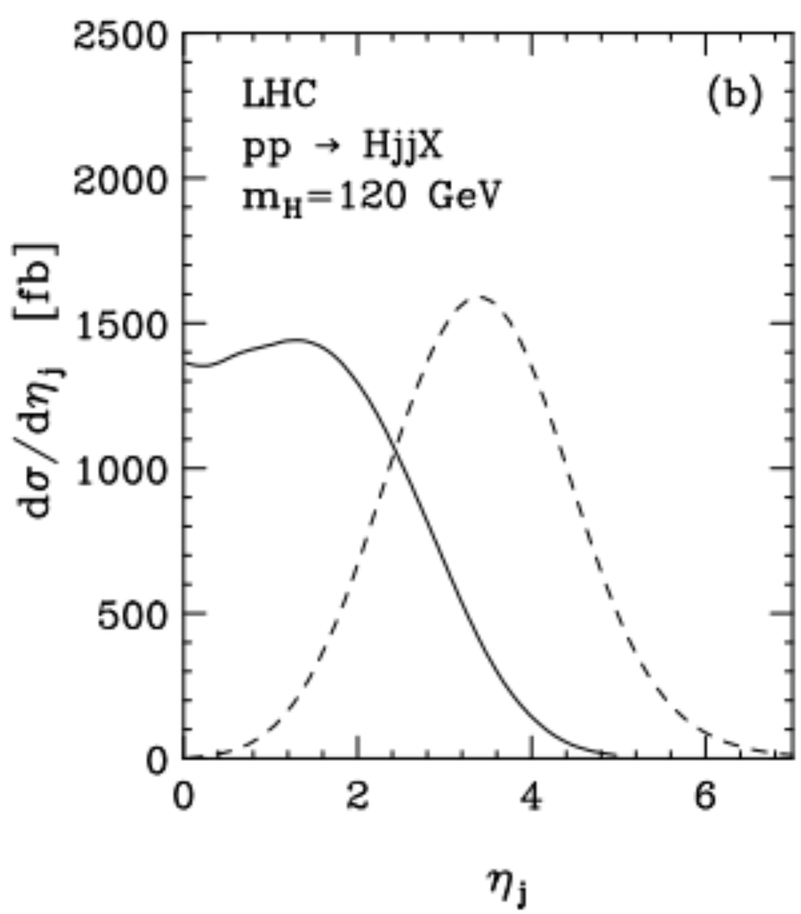


$$\hat{\sigma}_{\mathrm{LO}} = \frac{16\pi^2}{M_H^3}\Gamma(H \to V_L V_L)\frac{d\mathcal{L}}{d\tau}\Big|_{V_L V_L/qq}$$

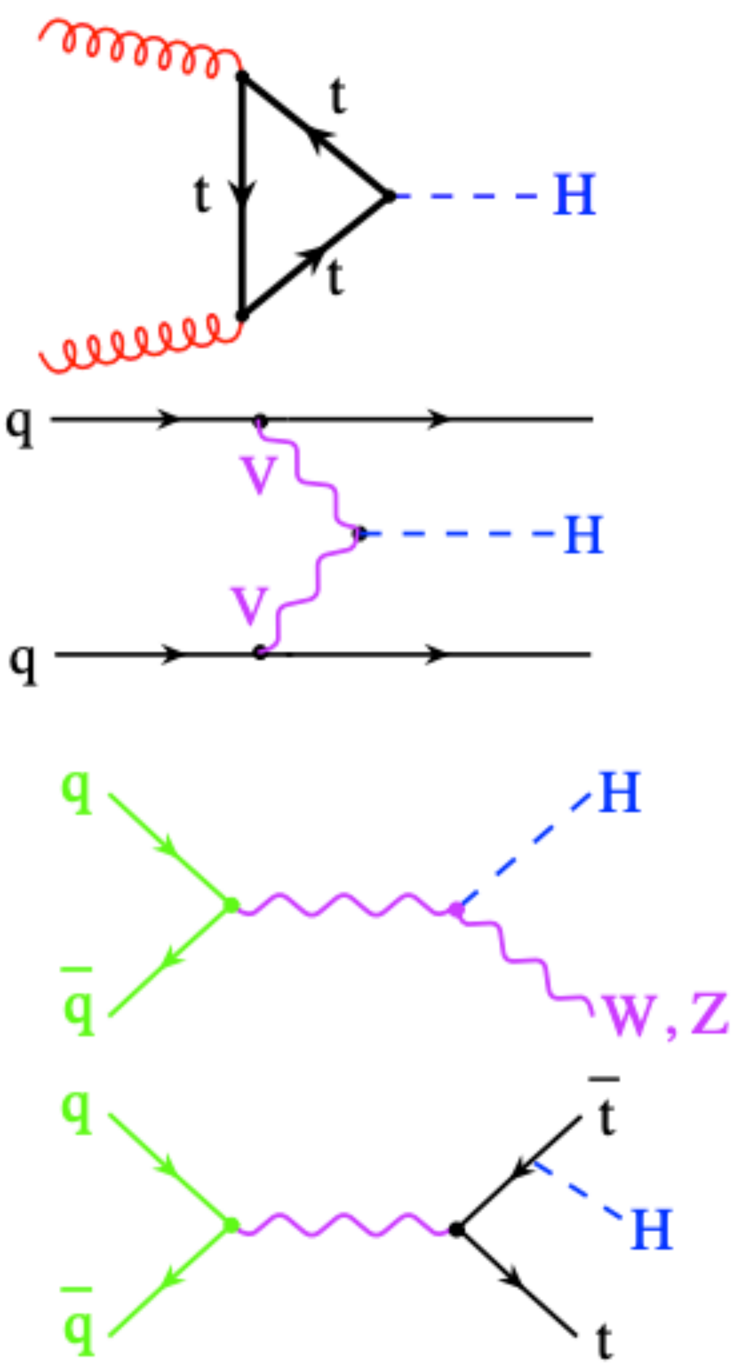
$$\frac{d\mathcal{L}}{d\tau}\Big|_{V_L V_L/qq} \sim \frac{\alpha}{4\pi^3}(v_q^2 + a_q^2)^2 \log\left(\frac{\hat{s}}{M_H^2}\right)$$

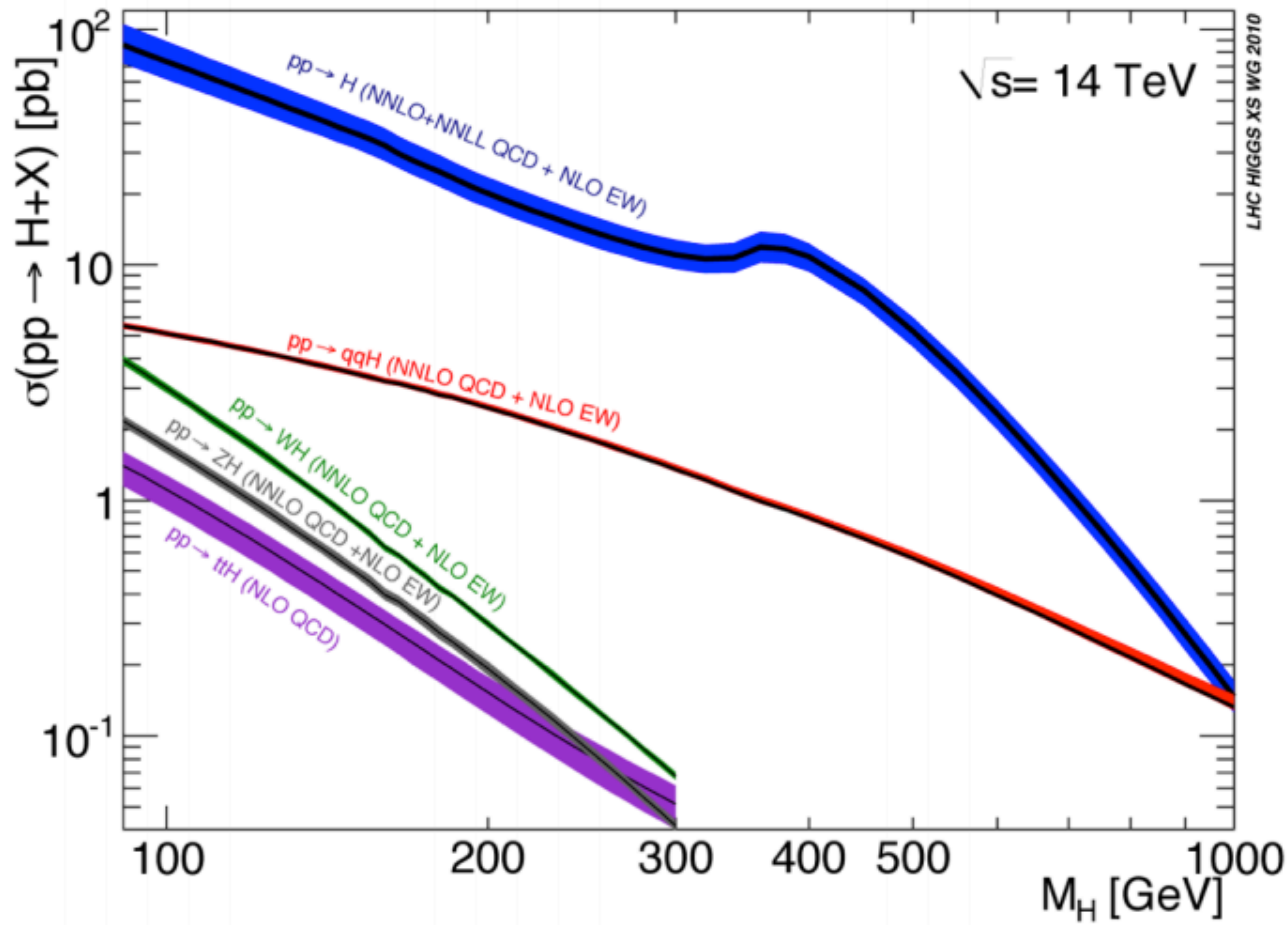
- Cross section grows with center-of-mass energy
- Process becomes more important at higher energy and for lighter Higgs
- Radiative corrections relatively small at 10% level
- Distinctive kinematic signature: forward jets with high transverse momentum



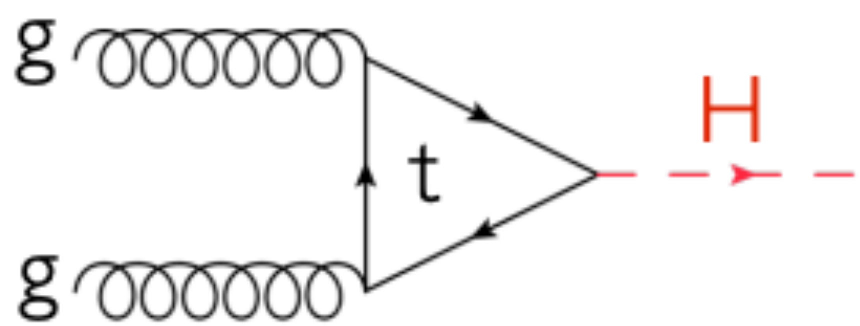


Higgs Production at LHC phase II

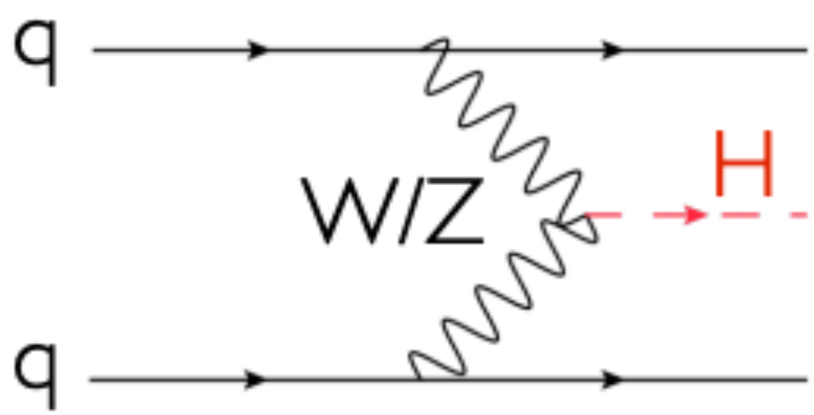




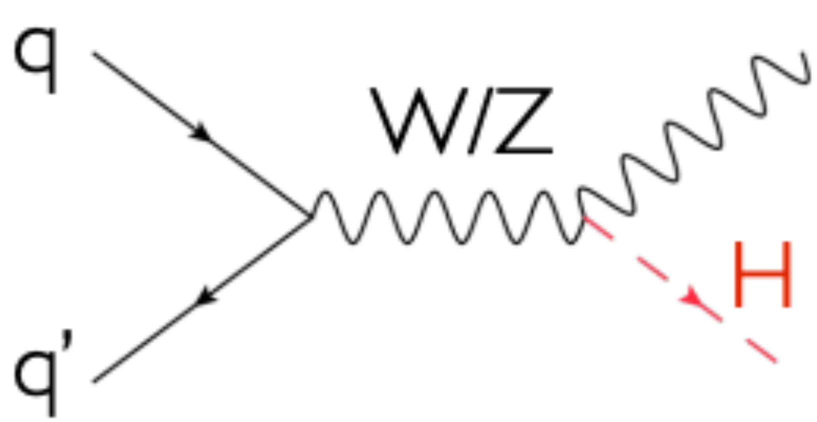
Summary of the Higgs production at LHC



Gluon-gluon Fusion
Cross section: 19.5 pb
Final state: Higgs alone



Vector Boson Fusion
Cross section: 1.56 pb
Final state: two forward jets

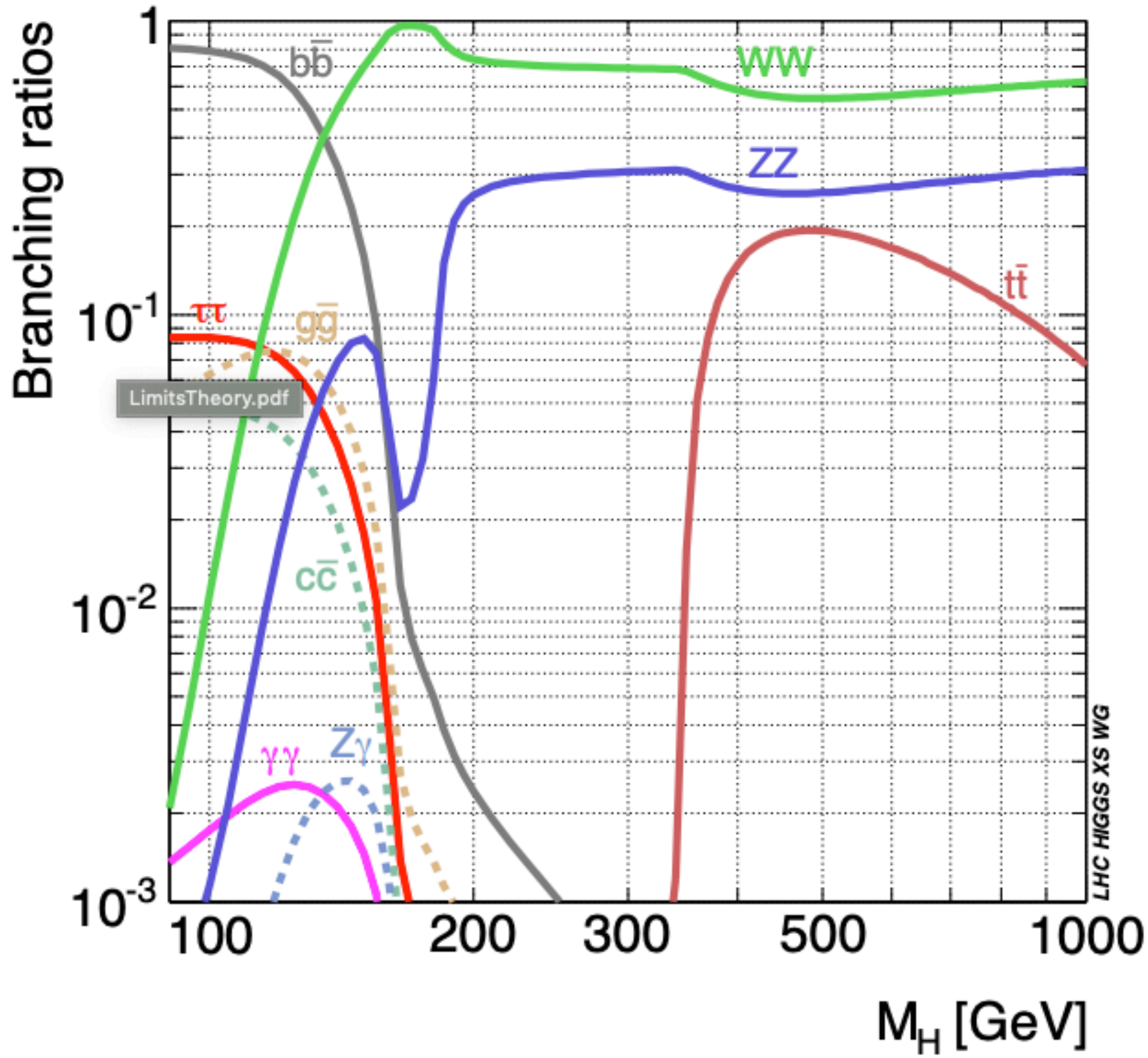


Associated Production
Cross section: 1.09 pb
Final state: W/Z boson

Higgs Branching Ratios

- Low Mass < 140 GeV
  - $H \to b\bar{b}$ dominant, BR = 60–90%
  - $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
  - $H \to \gamma\gamma, \gamma Z$, BR = a few permille

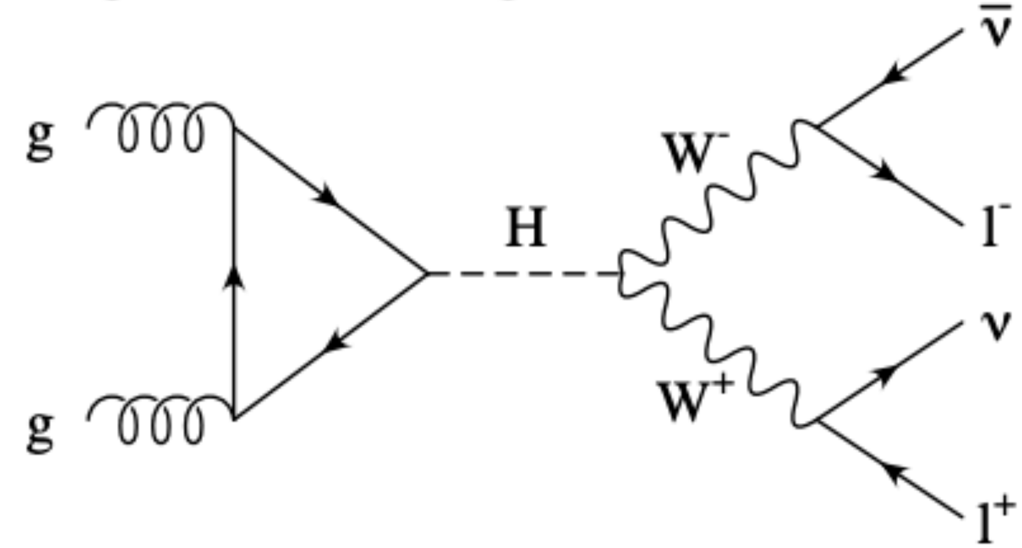
- High Mass > 140 GeV
  - $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
  - $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
  - $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.



Analysis of the decay modes (as done by ATLAS and CMS)

$H \to WW \to 2\ell 2\nu$

- Most promising decay mode for mid-high mass region



- De facto discovery channel for 160-170 GeV when ZZ is suppressed

$$\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$$

- Main disadvantage: no peak of invariant mass
  - only transverse mass of W
  - No Higgs peak
  - need very good missing transverse energy measurement
  - must determine very precisely background shape

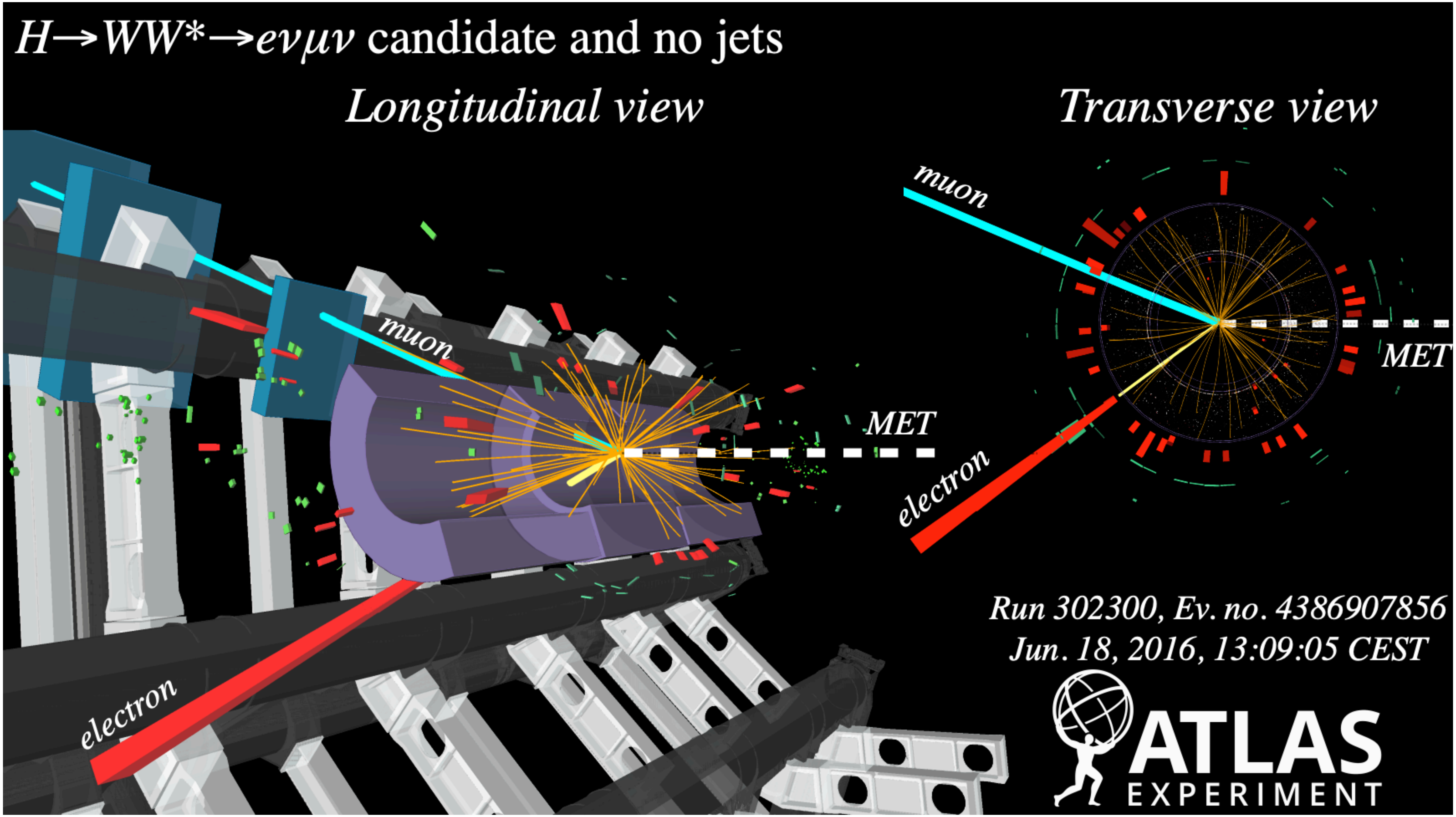
$H \to WW \to 2\ell 2\nu$

main backgrounds

$$qq/qg \to WW$$
$$gg \to WW$$
$$pp \to t\bar{t}$$
$$Z \to \tau\tau\text{+jets}$$
$$W\text{+iets}$$

- Handles to remove background:
  - 2 opposite sign isolated leptons
    - Removes QCD & W+jets
  - large MET
    - Removes DY
  - classify events in #jets & b-jet veto
    - Remove top contamination
  - kinematics: low m_{ll} and small $\Delta\phi_{ll}$
    - To discriminate against WW

$$H \to WW \to 2\ell 2\nu$$

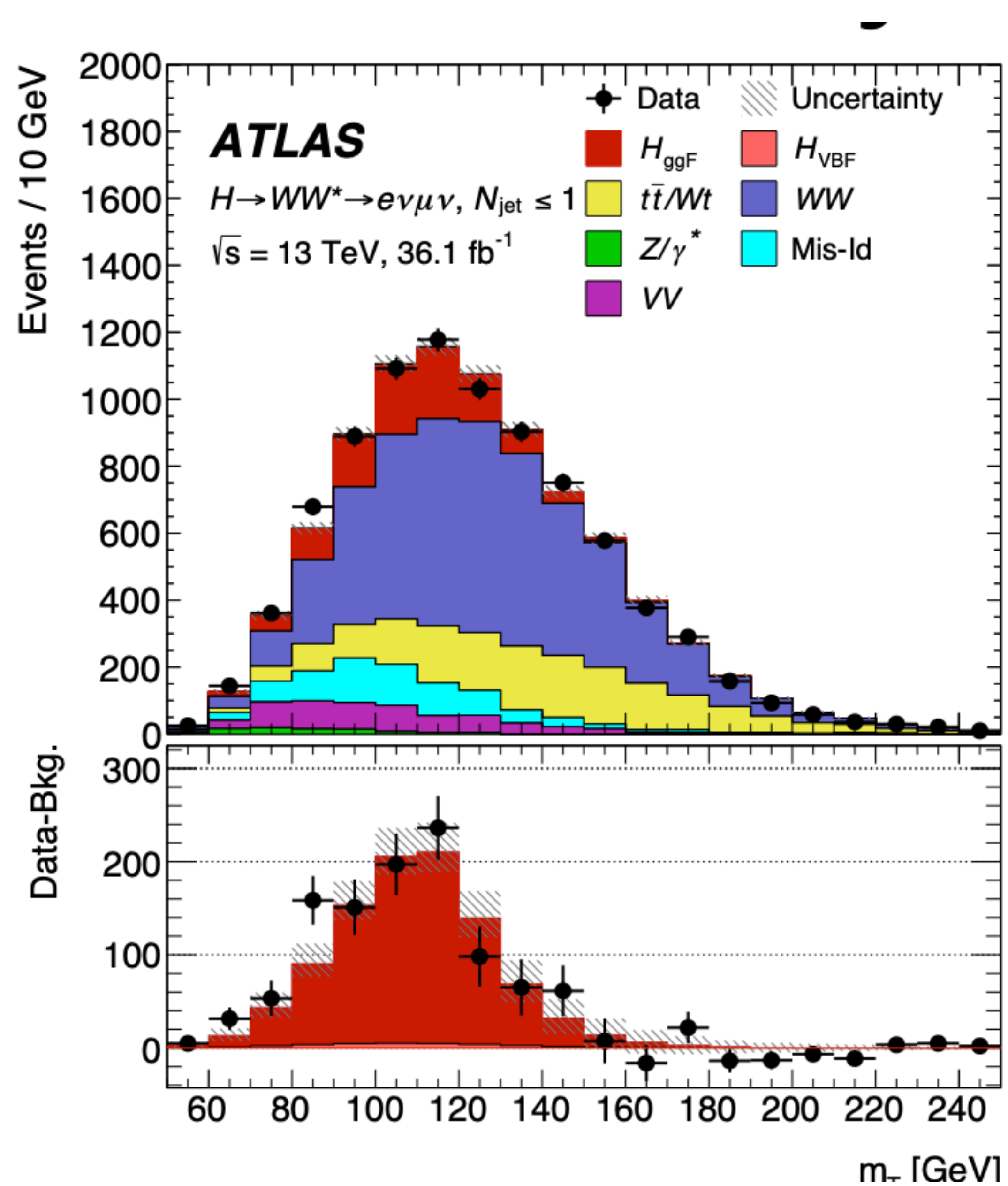


$H \to WW \to 2\ell 2\nu$

2020 plot

WW background constrained by CR (ATLAS) or as part of the final fit (CMS)

Top quark and Drell-Yan backgrounds constrained by CR's



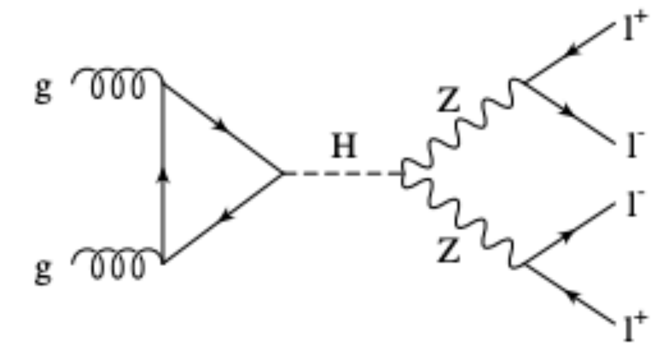
Non-WW diboson backgrounds constrained by CRs or taken from MC

Misidentified lepton backgrounds estimated from data

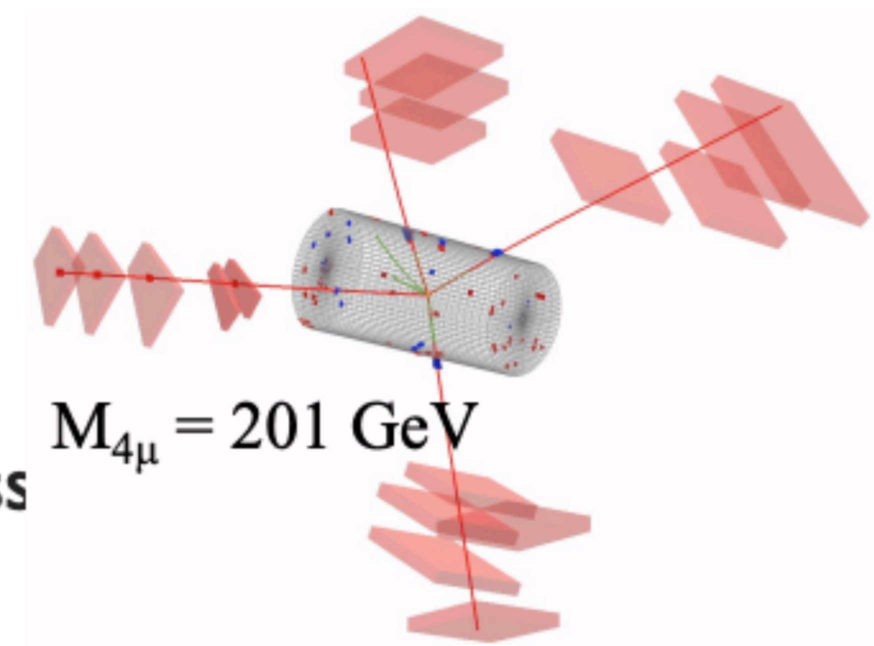
•Much higher BR than H→ZZ* →4l, ~1% •More backgrounds, final state not fully reconstructed •STXS stage 1 difficult but stage 0 (production modes) possible

$H \to ZZ^* \to 4\ell$

- Potentially the cleanest mode for Higgs discovery
  - 2 Z invariant mass
    - very clean with little background from SM
  - narrow Higgs mass peak



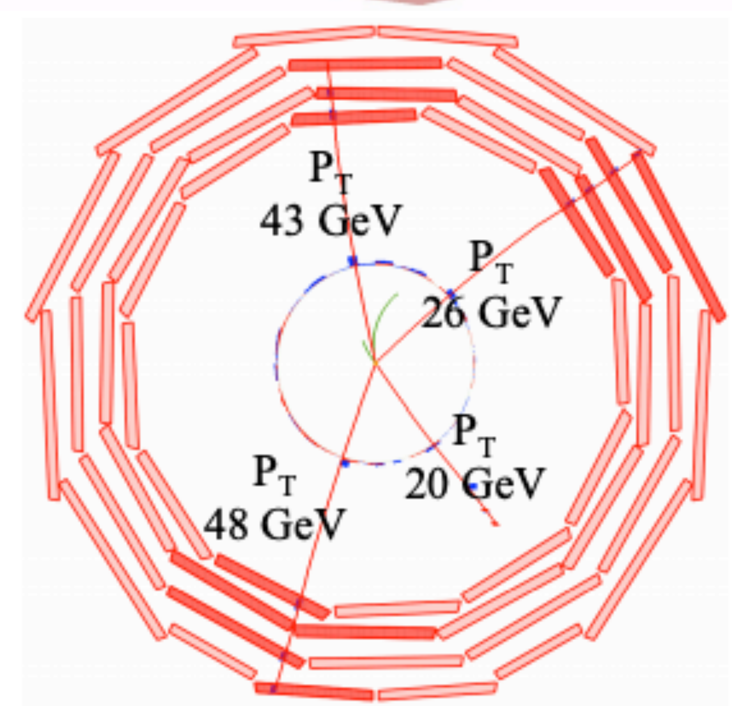
- Small branching fraction $\mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$
  - even worse below ZZ threshold $m_H < 2\,M_Z$



- Limited background mainly from continuum process
  - lepton identification and b-tagging very important

Irreducible

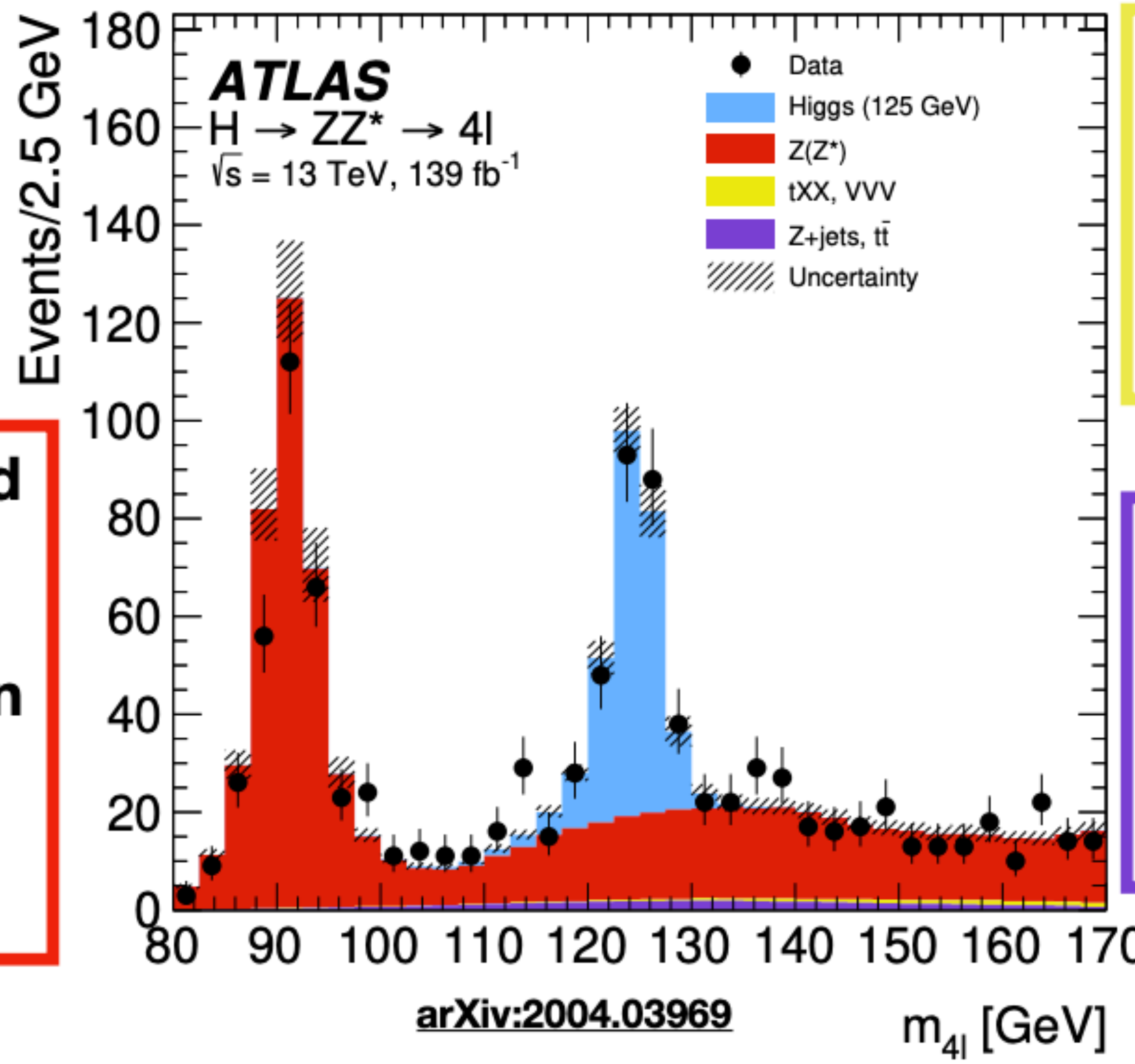
$$q\bar{q} \to ZZ \to 4\ell$$
$$gg \to Zb\bar{b} \to 2\ell b\bar{b}$$
$$gg \to Zb\bar{b} \to 2\ell b\bar{b}$$
$$gg, q\bar{q} \to t\bar{t}$$
$$q\bar{q} \to WZ$$
$$q\bar{q} \to Z \text{ inclusive}$$



$H \to ZZ^* \to 4\ell$

2020 plot

Dominant background from SM ZZ* production is estimated using MC in CMS; normalization constrained in sidebands in ATLAS



arXiv:2004.03969

Background from ttV, ttt, ttVV can be constrained in sidebands or taken from MC; VVV from MC

Background from lepton fakes/heavy flavor decays estimated in data-driven fashion

- Low BR of ~0.01%, but high purity with S/B~2 in the mass peak
- Useful for many Higgs boson properties measurements
- ATLAS and CMS both have ~200 signal events with the full Run-2 sample

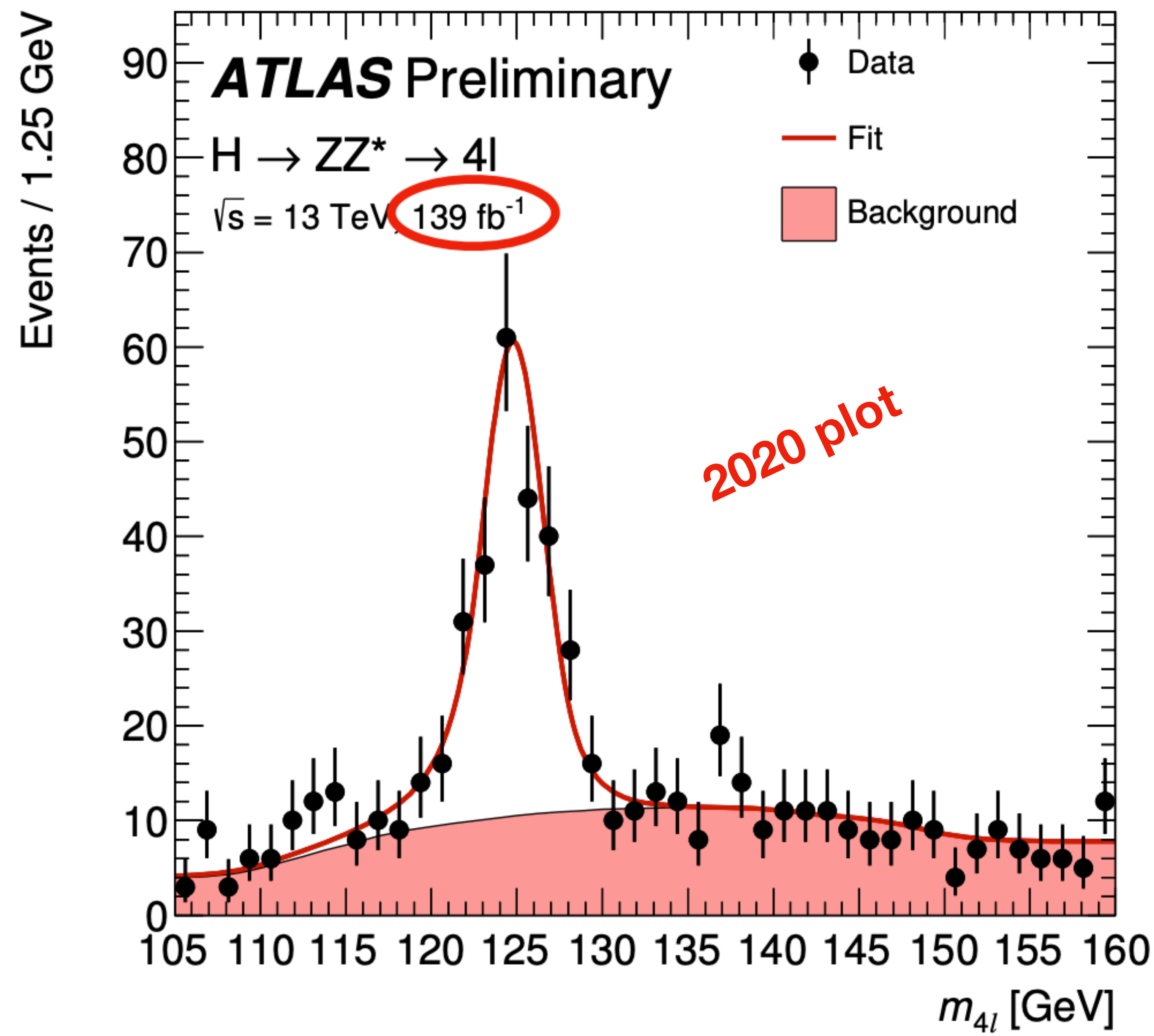
$H \to ZZ^* \to 4\ell$

First mass measurement with full Run-2 dataset

•Recover FSR, constrain m12 to mZ (15% resolution gain)

•Parametrize m4l distribution as double-sided Crystal Ball function

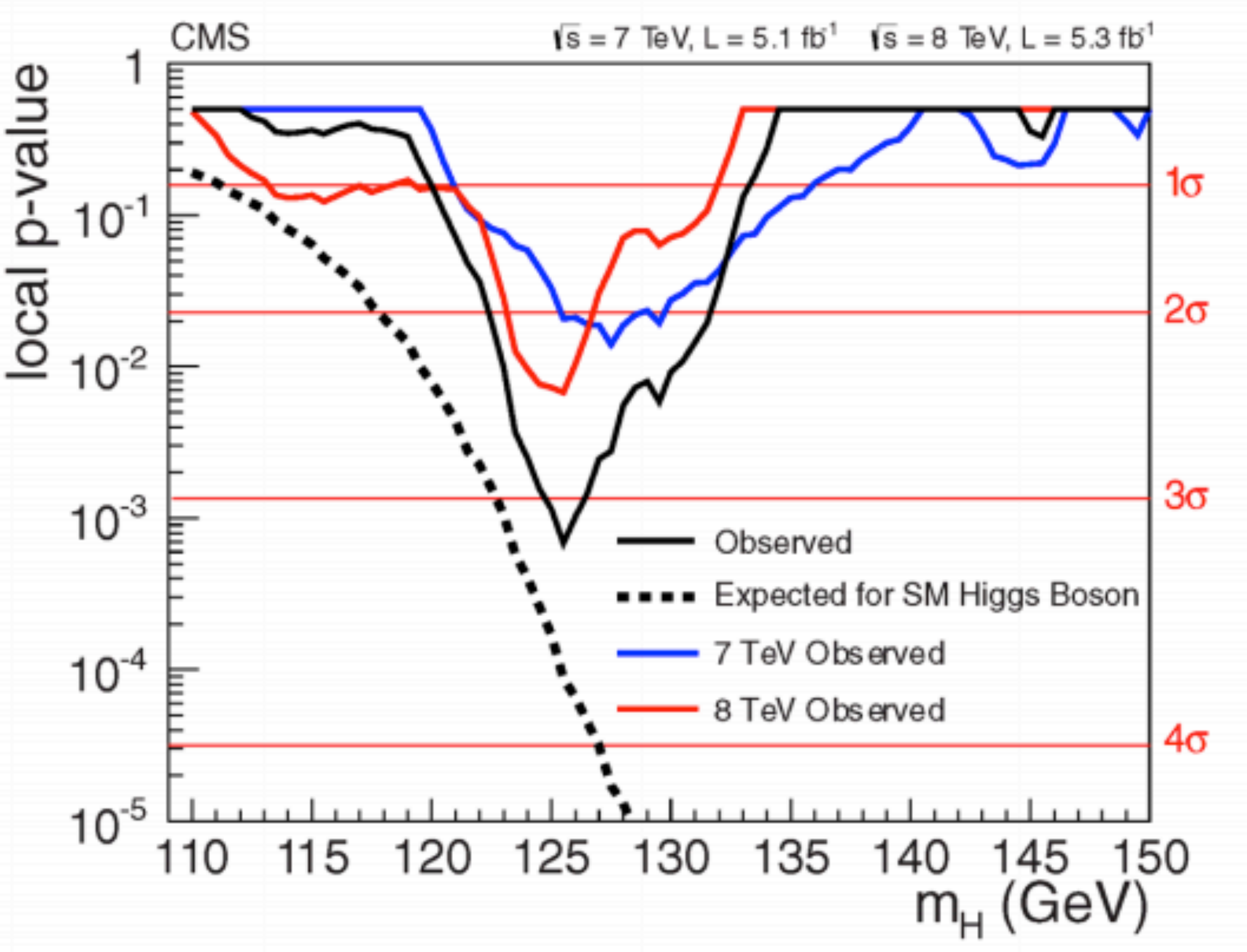
‣ Analysis categories based on final state (resolution) and BDT (for better S/B)
‣ Background shapes from smoothed MC, ZZ* norm floats

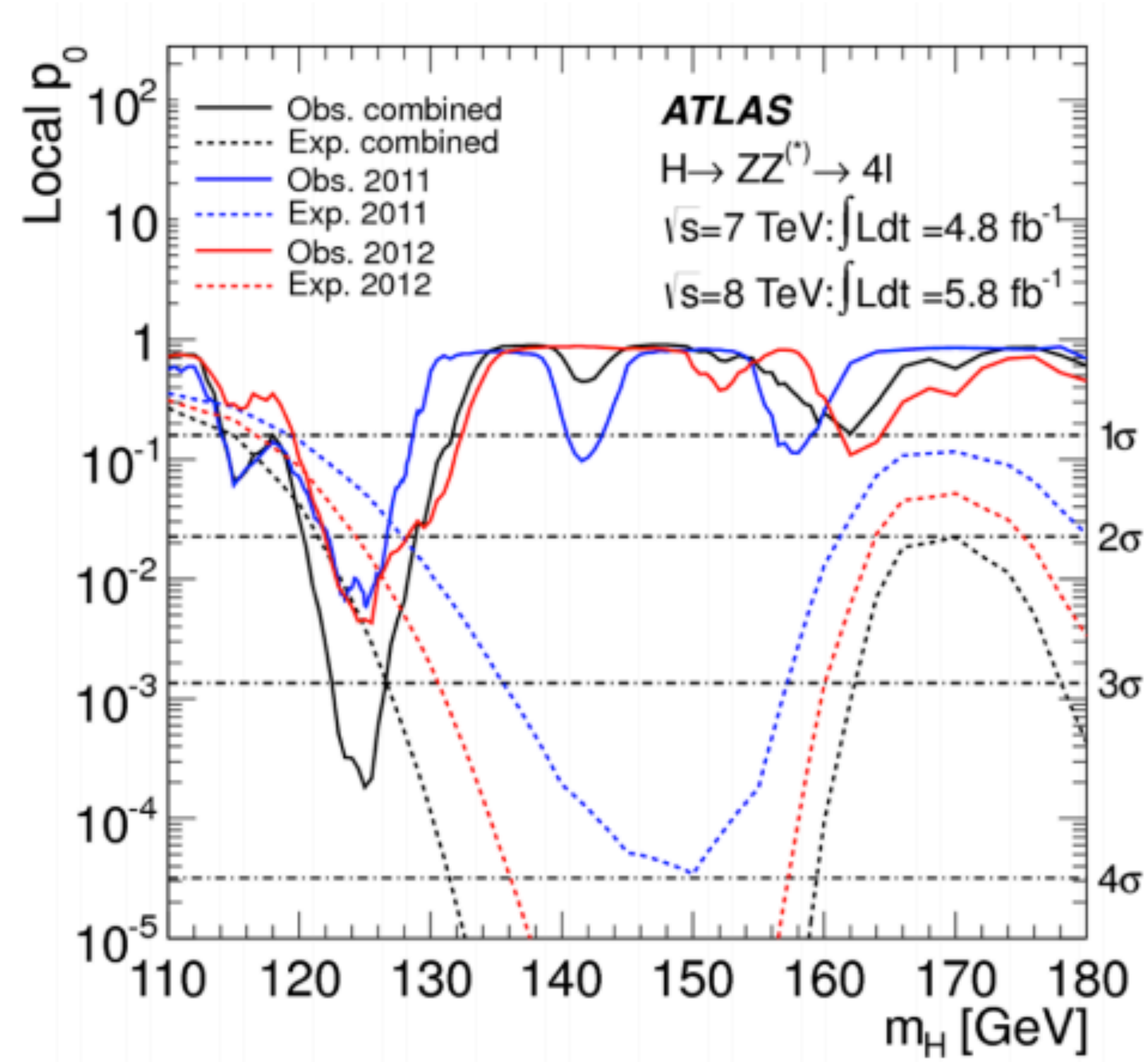


mH=124.92±0.21 GeV

$$m_{4\ell} = \sqrt{(p_1 + p_2 + p_3 + p_4)^2}$$

$H \to ZZ^* \to 4\ell$



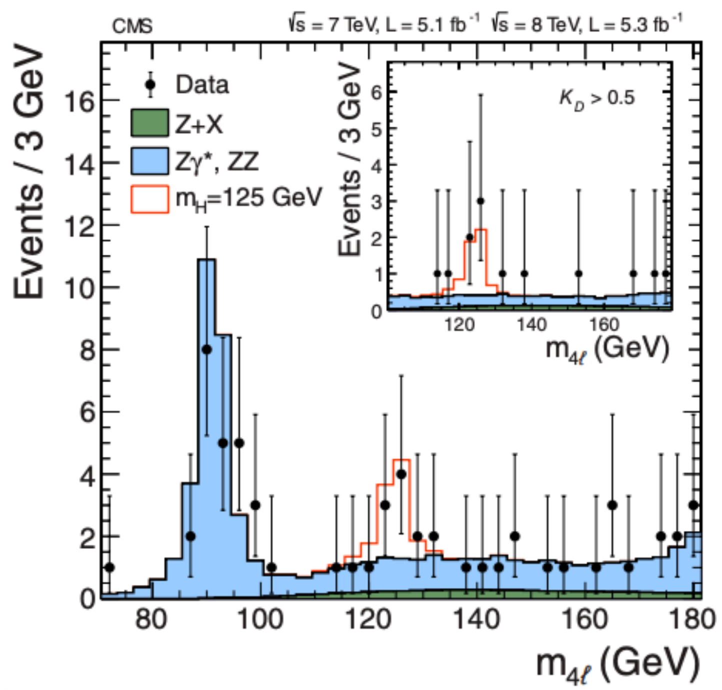


- CMS: strength at 125.5 GeV: $\mu = \sigma/\sigma_{SM} \sim 0.7$
- ATLAS: strength at 126 GeV: $\mu = \sigma/\sigma_{SM} \sim 1.2$

discovery plot

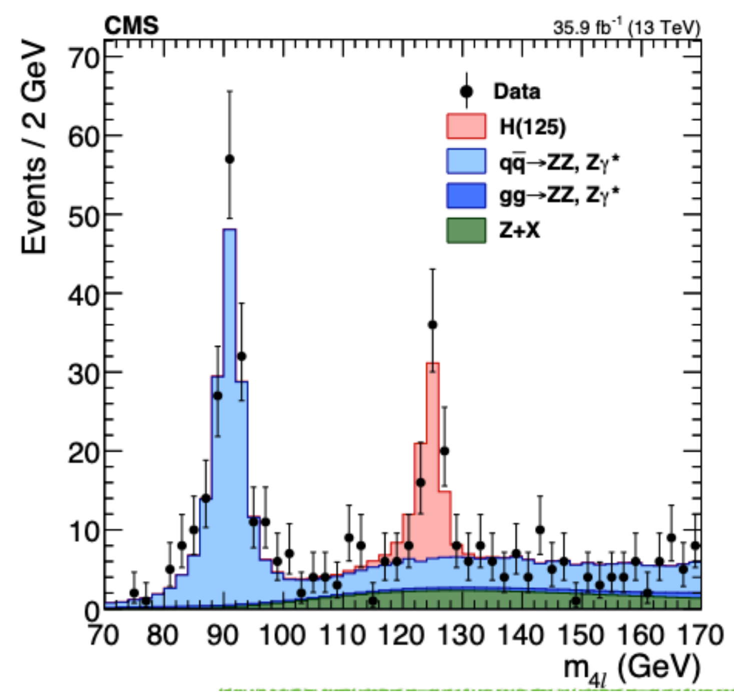
$$H \to ZZ^* \to 4\ell$$

An illustration of progress in the past years: H→ZZ



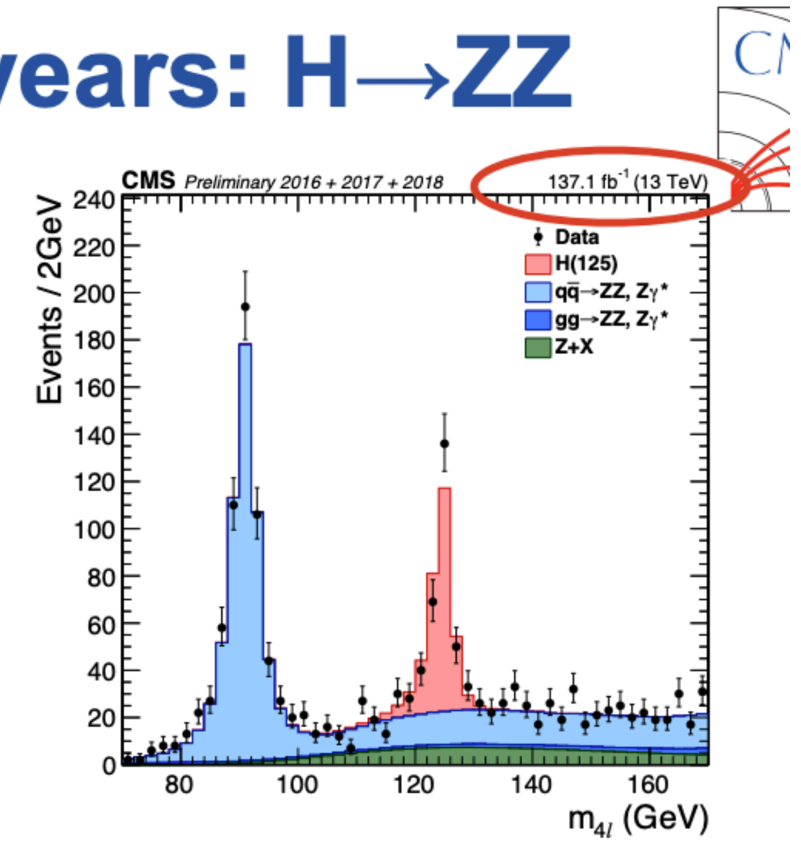
discovery, 5/fb

like 10 *HZZ*



35/fb

like 100 *HZZ*

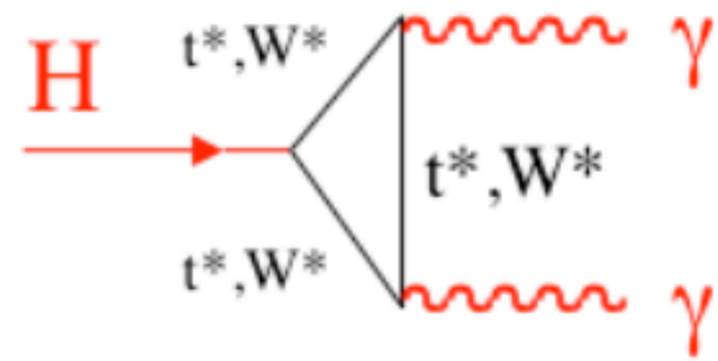


today - 140/fb

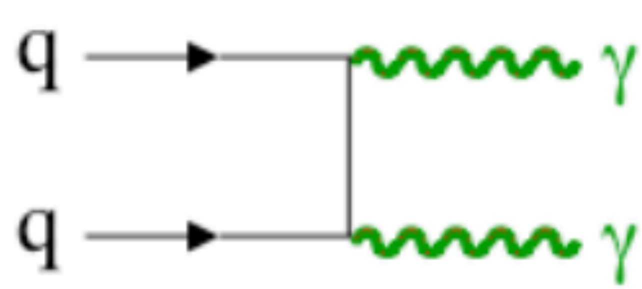
like 400 *HZZ*

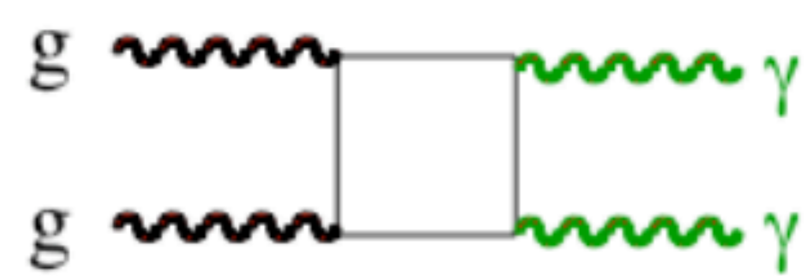
$H \to \gamma\gamma$

- Signal
  - nice mass peak
  - energy and angular resolution are critical ingredients
  - Selection: isolated high p_T photons

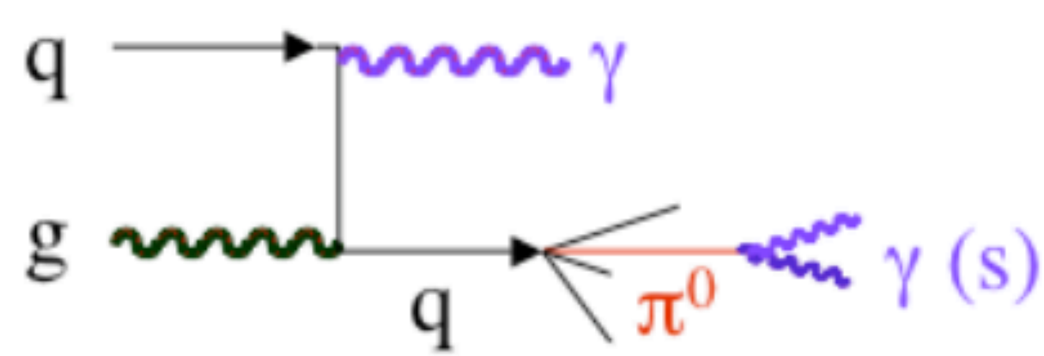


- Irreducible background: direct production of di-photon events in Standard Model
  - Any signal selection selects also these events
  - no peak in invariant mass but lots and lots of then





- Reducible background
  - gamma + jet: jet mis-identified as photon
  - di-jet: two jets with misidentified photons



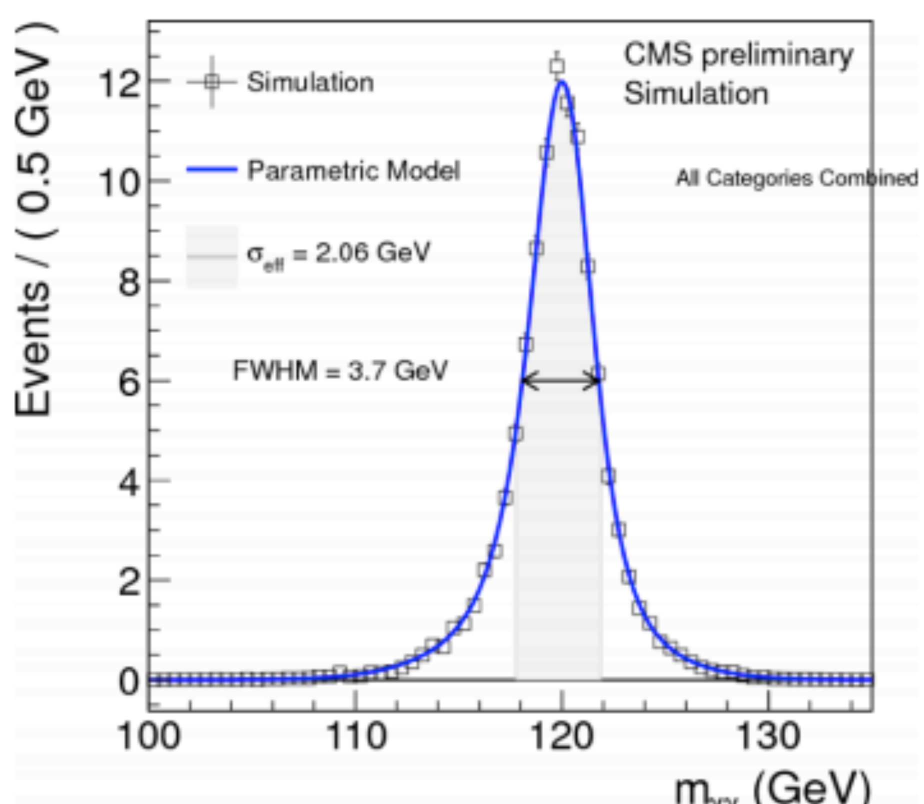
$H \to \gamma\gamma$

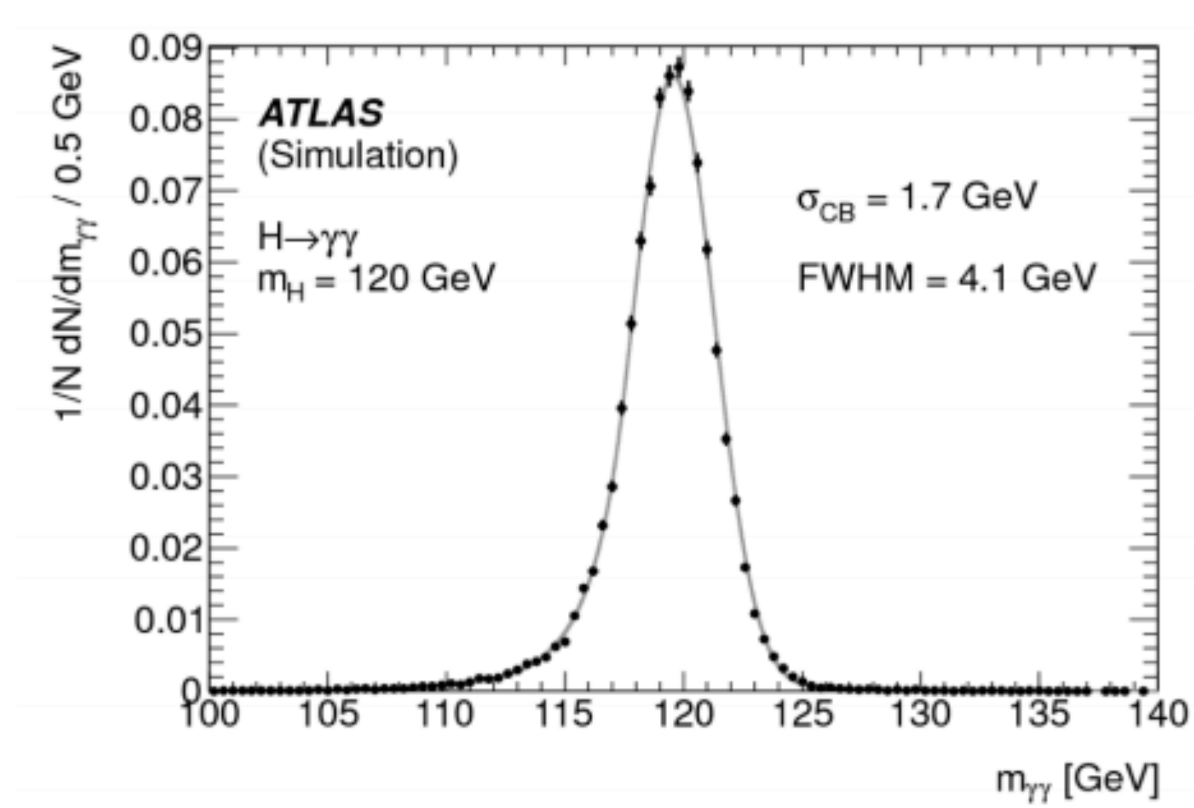
STEP	CRITICAL ISSUES
1) two isolated photons with large transverse momentum	• isolation to reject γ+jet and QCD background • determine efficiency from data
2) di-photon mass reconstruction $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{\gamma\gamma})}$ $\frac{\sigma_m}{m} = \frac{1}{2}\sqrt{\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{\tan\theta/2}\right)^2}$	• vertex determination in presence of multiple interactions pile-up (PU) • energy scale and resolution • At θ=90º 15 mrad of angular resolution equivalent to 1% of energy resolution!
3) signal extraction	• event categories to maximize sensitivity • background shape

$H \to \gamma\gamma$

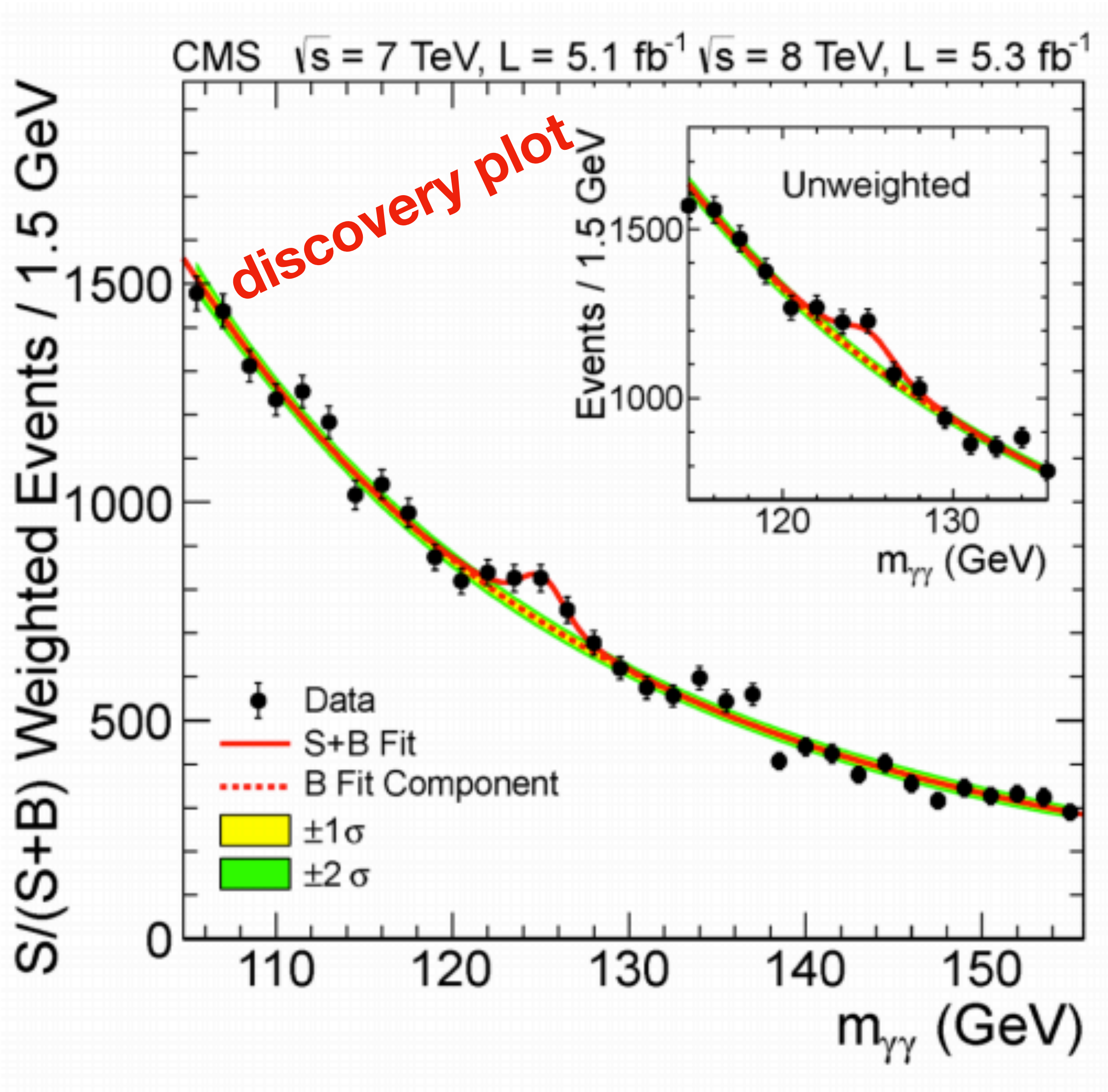
- In both detectors m(γγ) resolution depends on photon kinematics, conversion probability, and pseudorapidity
- CMS performs better in central region, ATLAS in forward
- Overall performance for Higgs signal quite similar

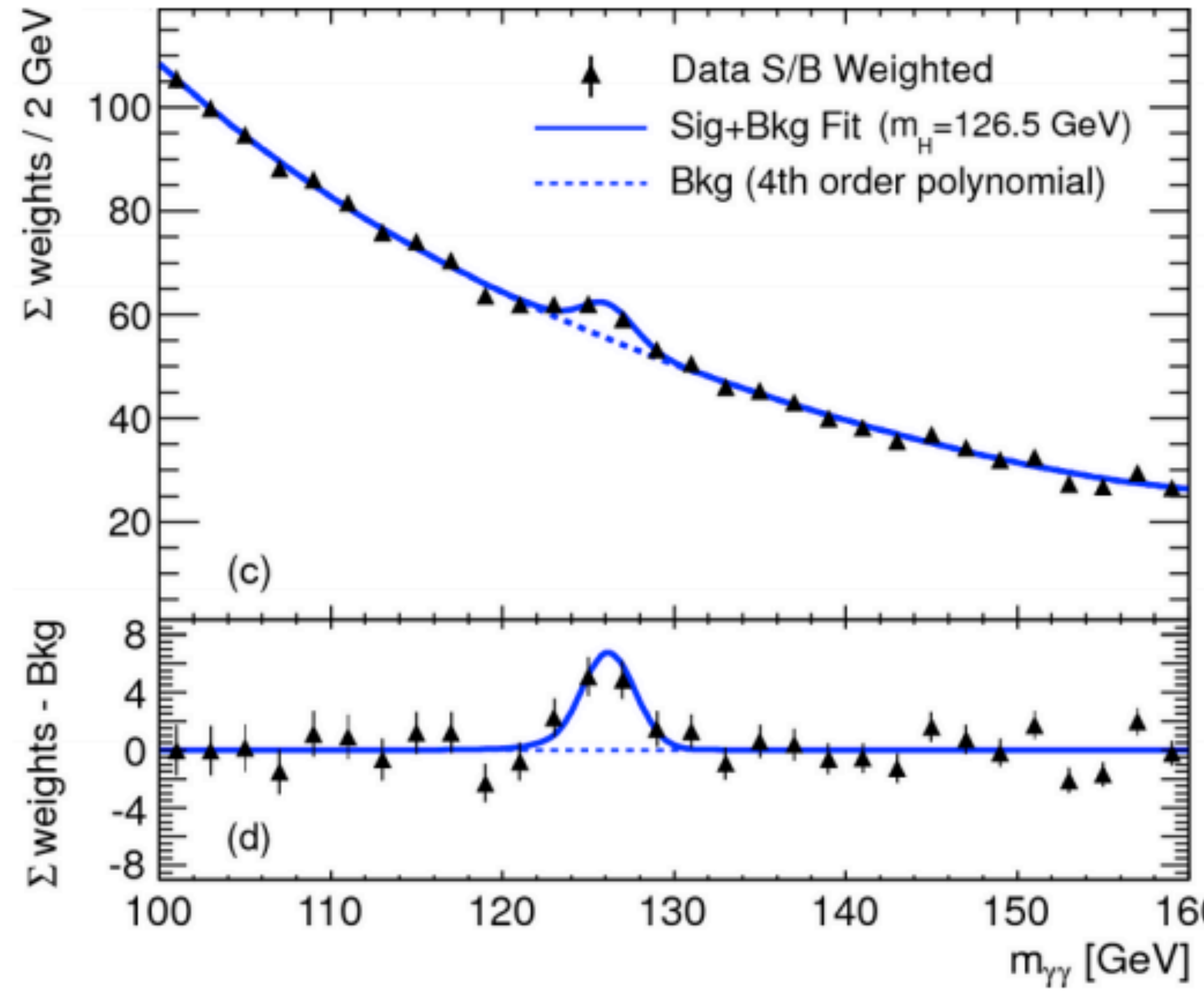
CMS (after cut on MVA)		ATLAS (2011 analysis)	
best resolution cat.	worst resolution cat.	best resolution cat.	worst resolution cat.
FWMH ~ 2.5GeV	FWMH ~ 5.5GeV	FWMH~3.3GeV	FWMH~5.9GeV



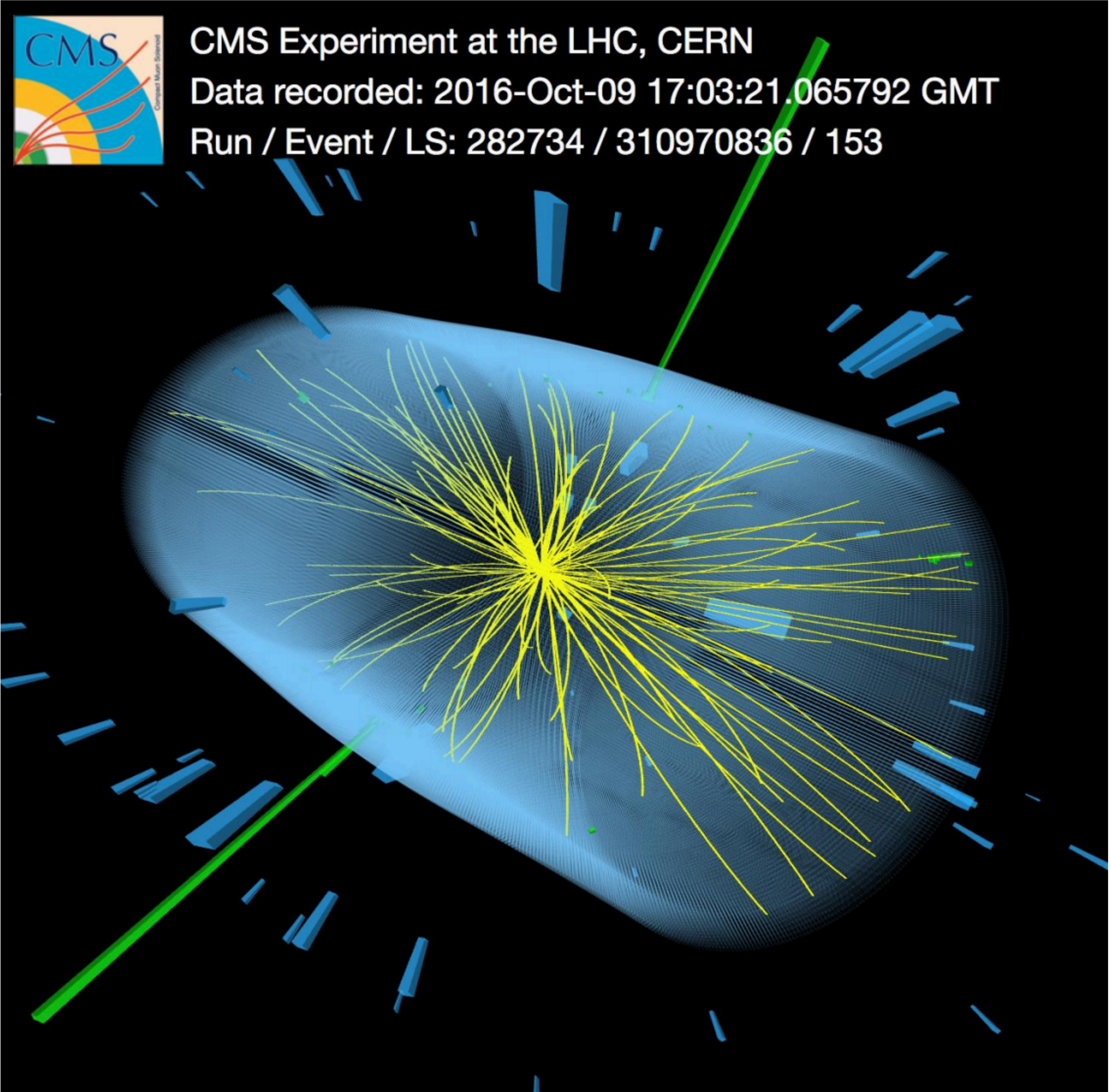


$H \to \gamma\gamma$



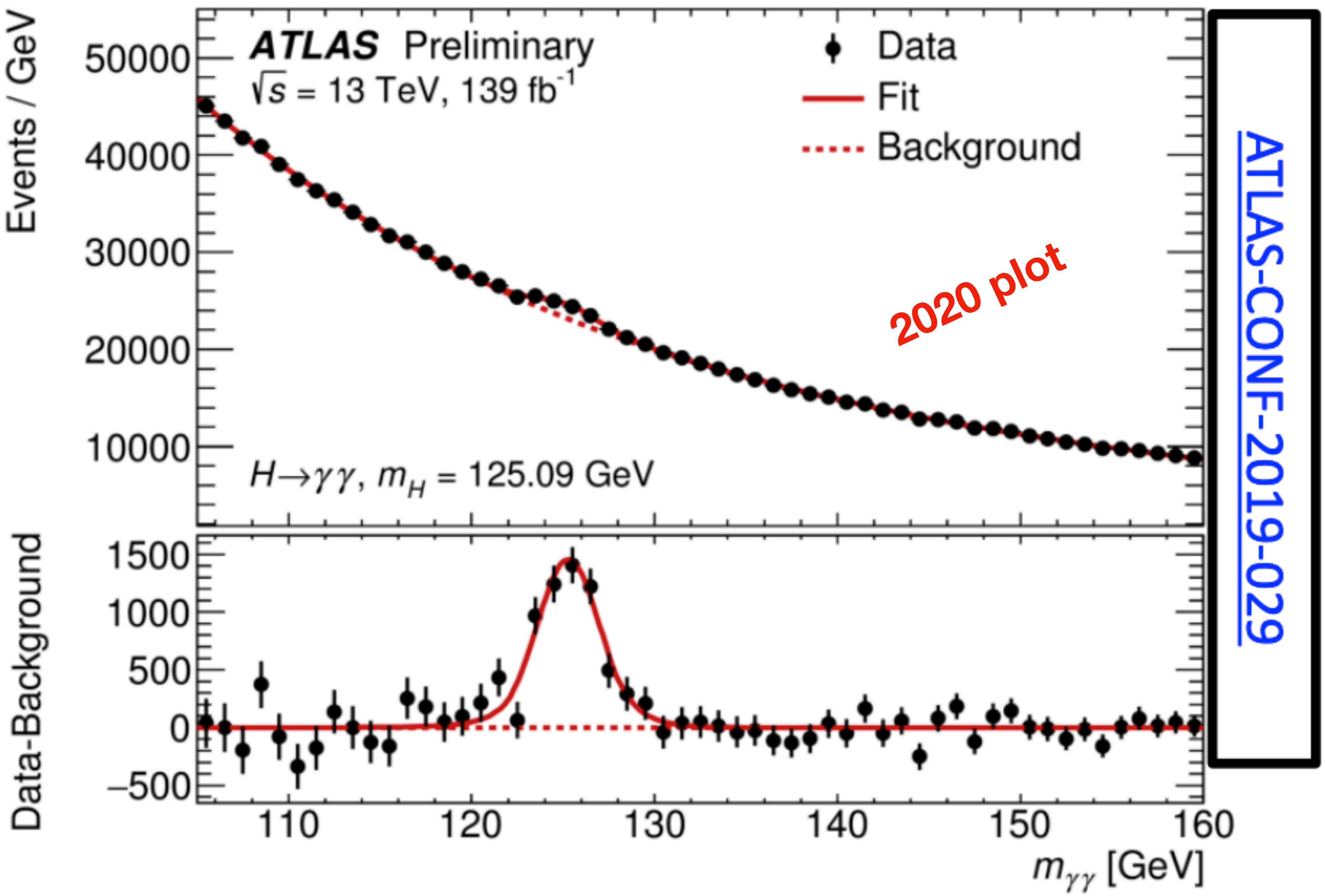


- Improved visualization of events by weighting events from each category
  - CMS: weight S/(S+B)
  - ATLAS: S/B
- Same events by cleaner categories provide larger weight in the histogram



$$H \to \gamma\gamma$$

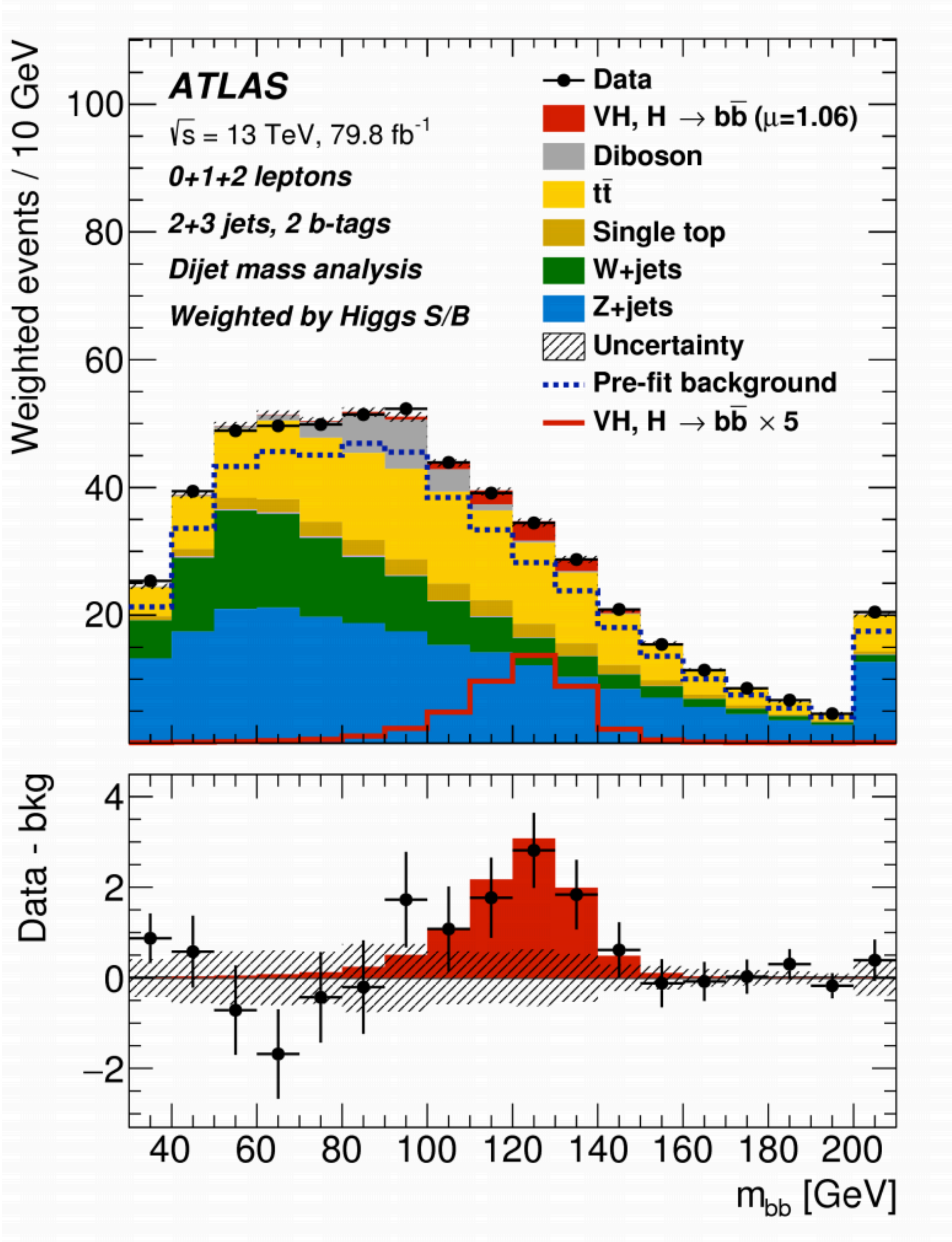
$H \to \gamma\gamma$



$H \to b\bar{b}$

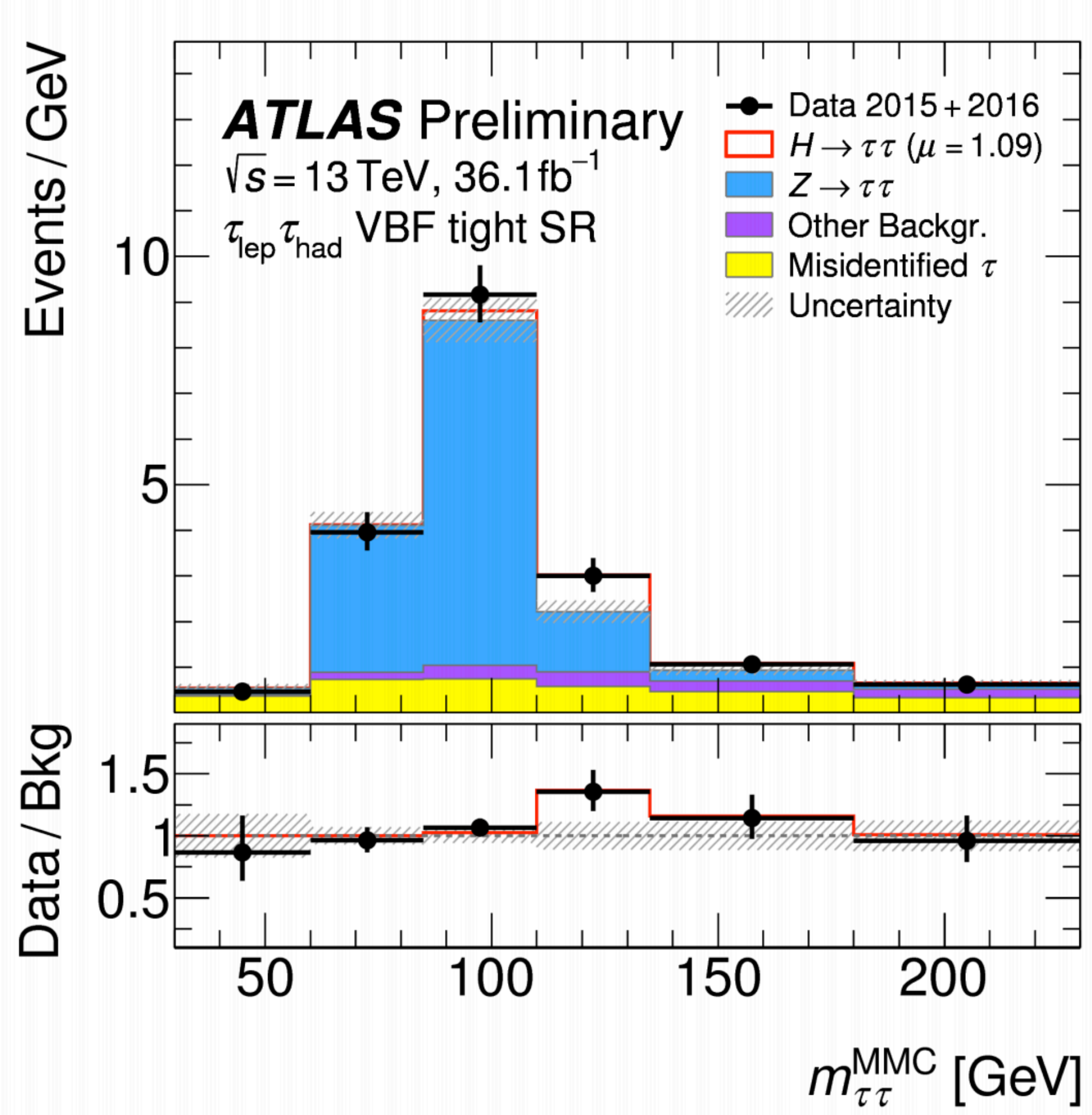
H➞bb takes the largest BR~58% ➞ drives the size of the total decay width à measurements of absolute couplings and constrain on BSM BR allowed

The most sensitive VH, H➞bb analysis, has 3 channels 0-, 1-, 2 charged leptons à final states Zàvv, Wàlv and



$H \to \tau\tau$

Main discriminant variable: mττ, crucial to discriminate and constrain (normalize) the large Z → ττ bkg



3 channels targeting all possible decay modes: two reconstructed taus in ll, lh and hh decay modes

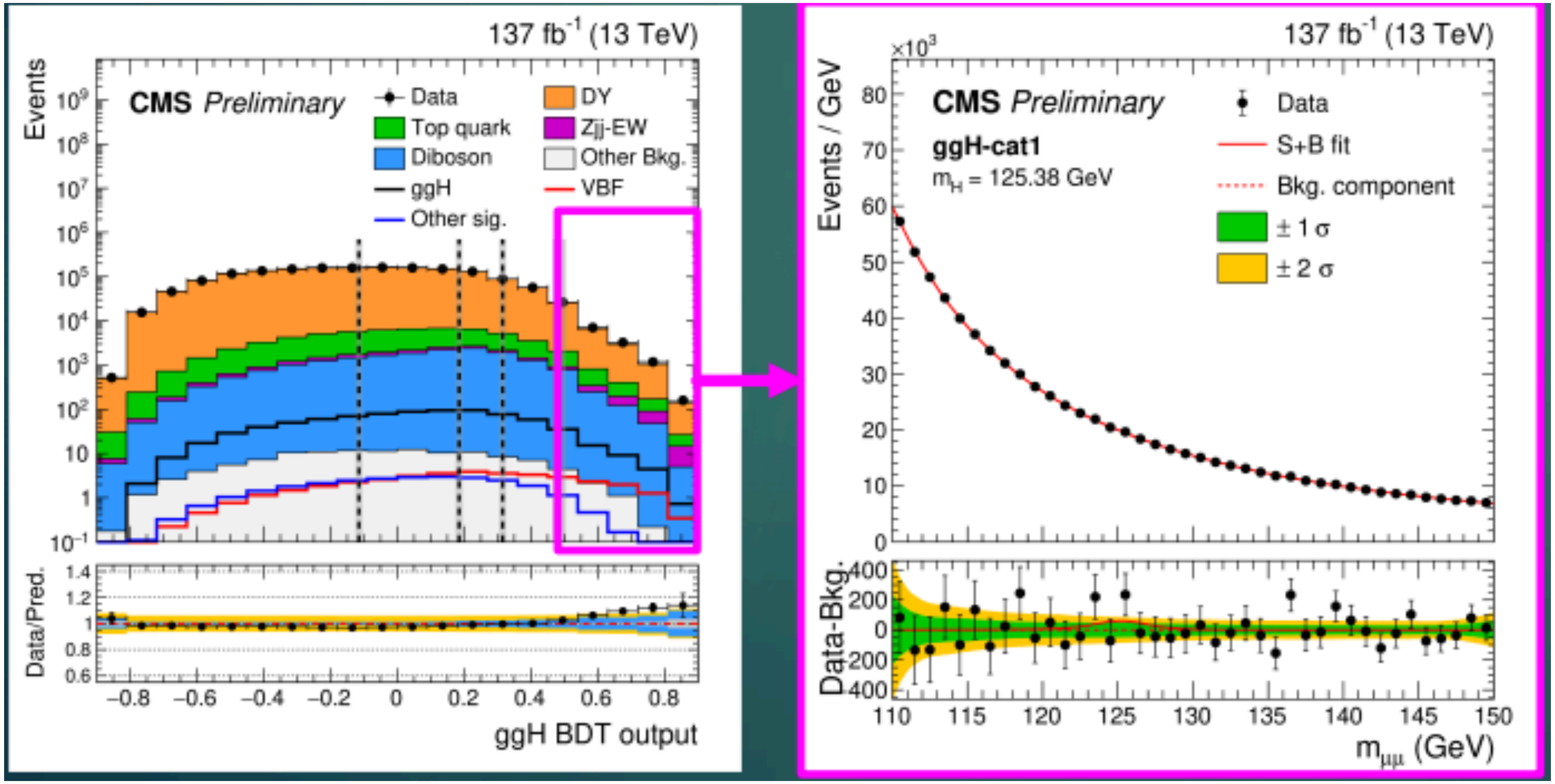
$H \rightarrow \mu^+\mu^-$

golden channel for probing the Higgs boson coupling with the 2nd generation fermions!

BR(H→μμ) ~ 2.19 x 10-4

Select events with two well-isolated opposite-signed muons.
Classify events on the topology of the production modes

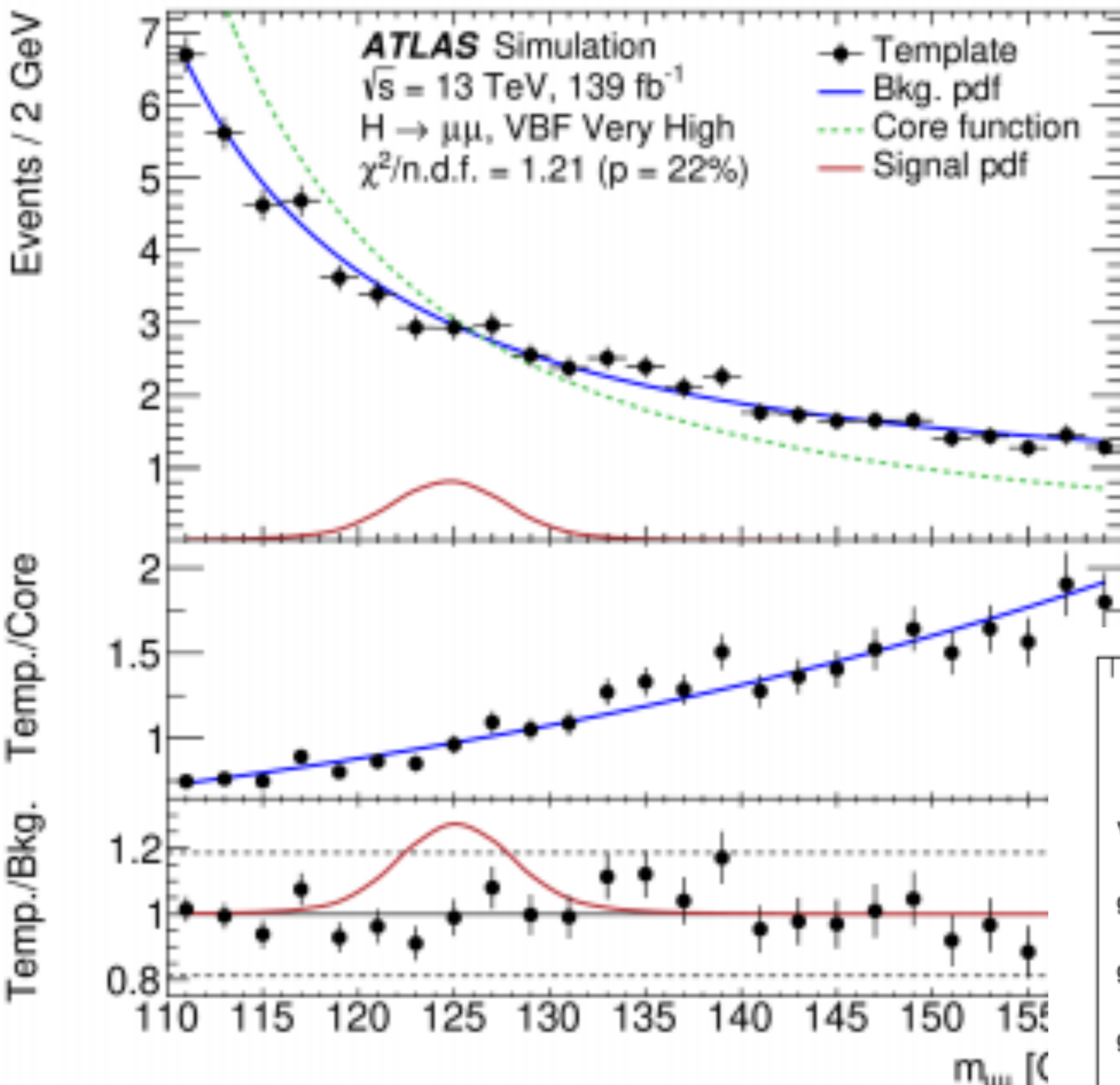
ggH, VBF, VH and ttH are targeted by both collaborations.



Isolate signal with binary BDT or DNN output

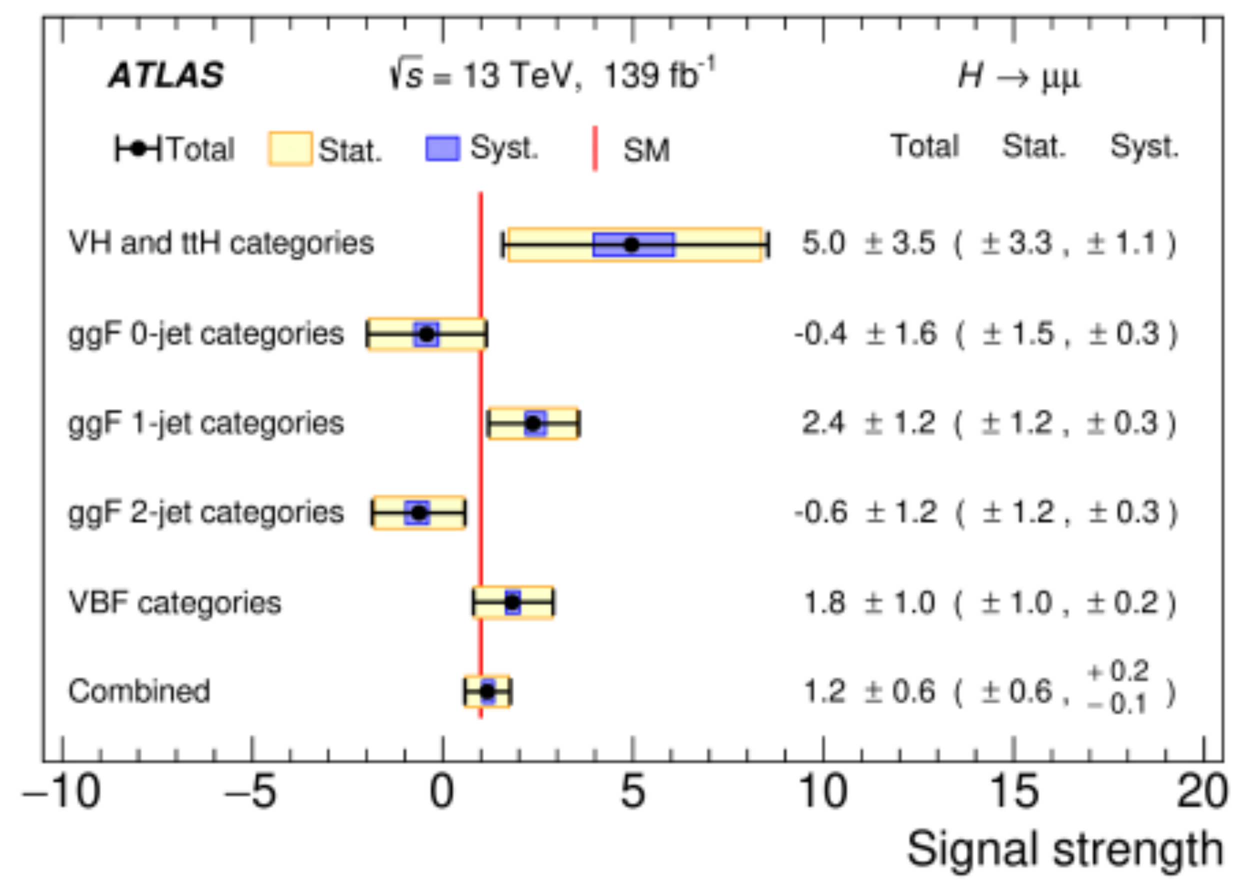
Extract signal strength and background shape in fit to data

$H \to \mu^+\mu^-$

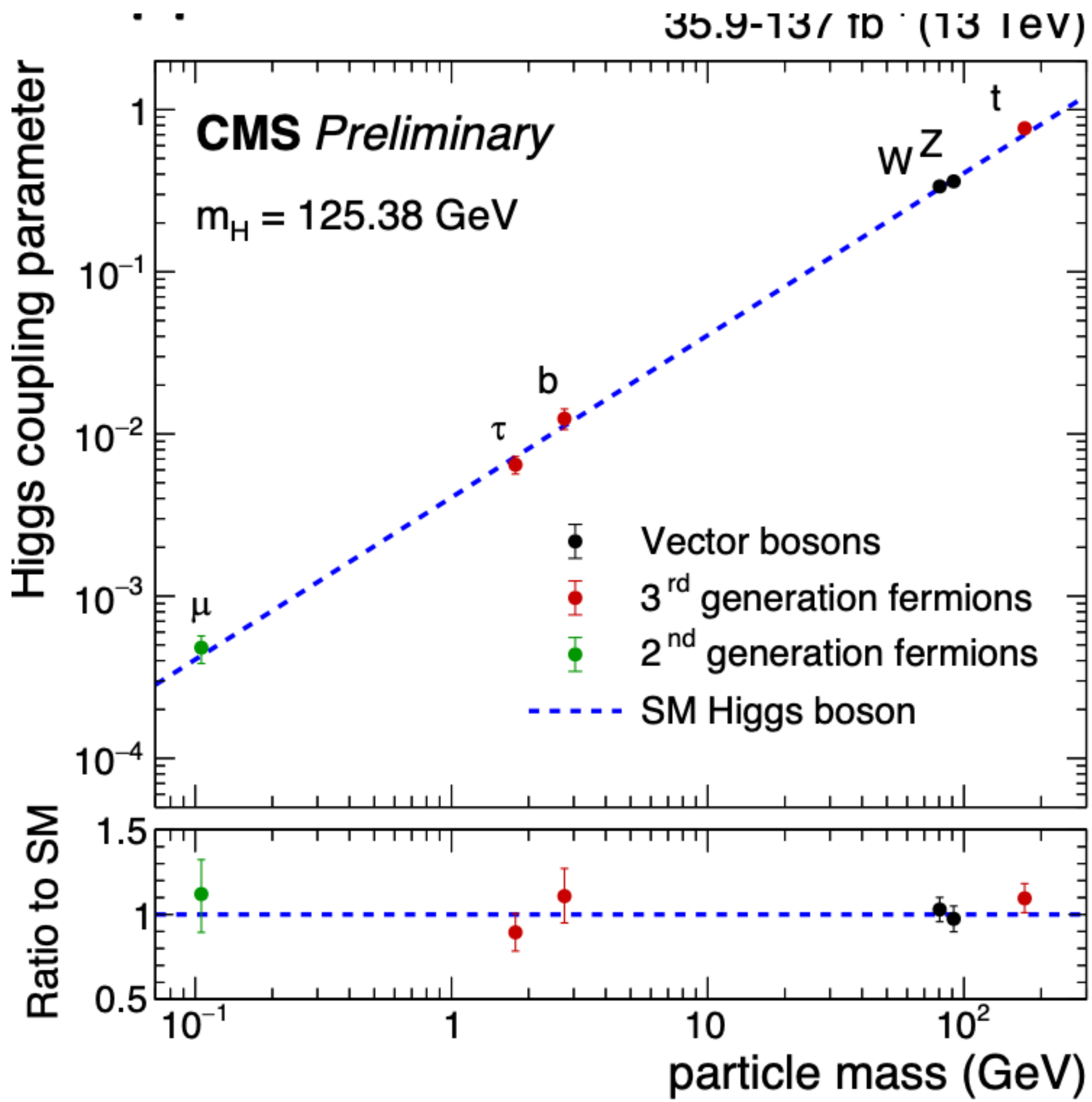


Obs (exp)

3.0 (2.5) σ



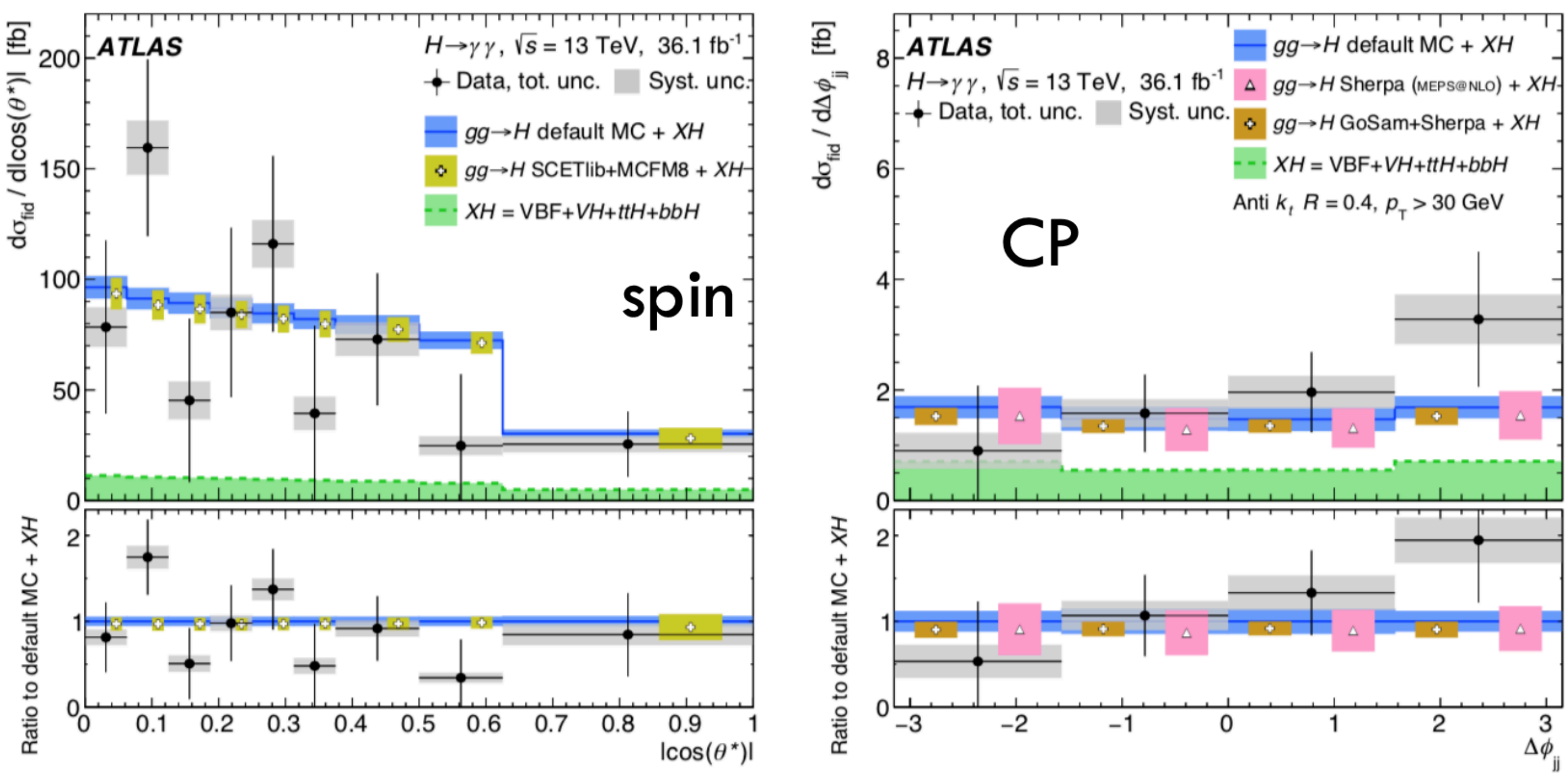
Higgs Couplings @ 2021



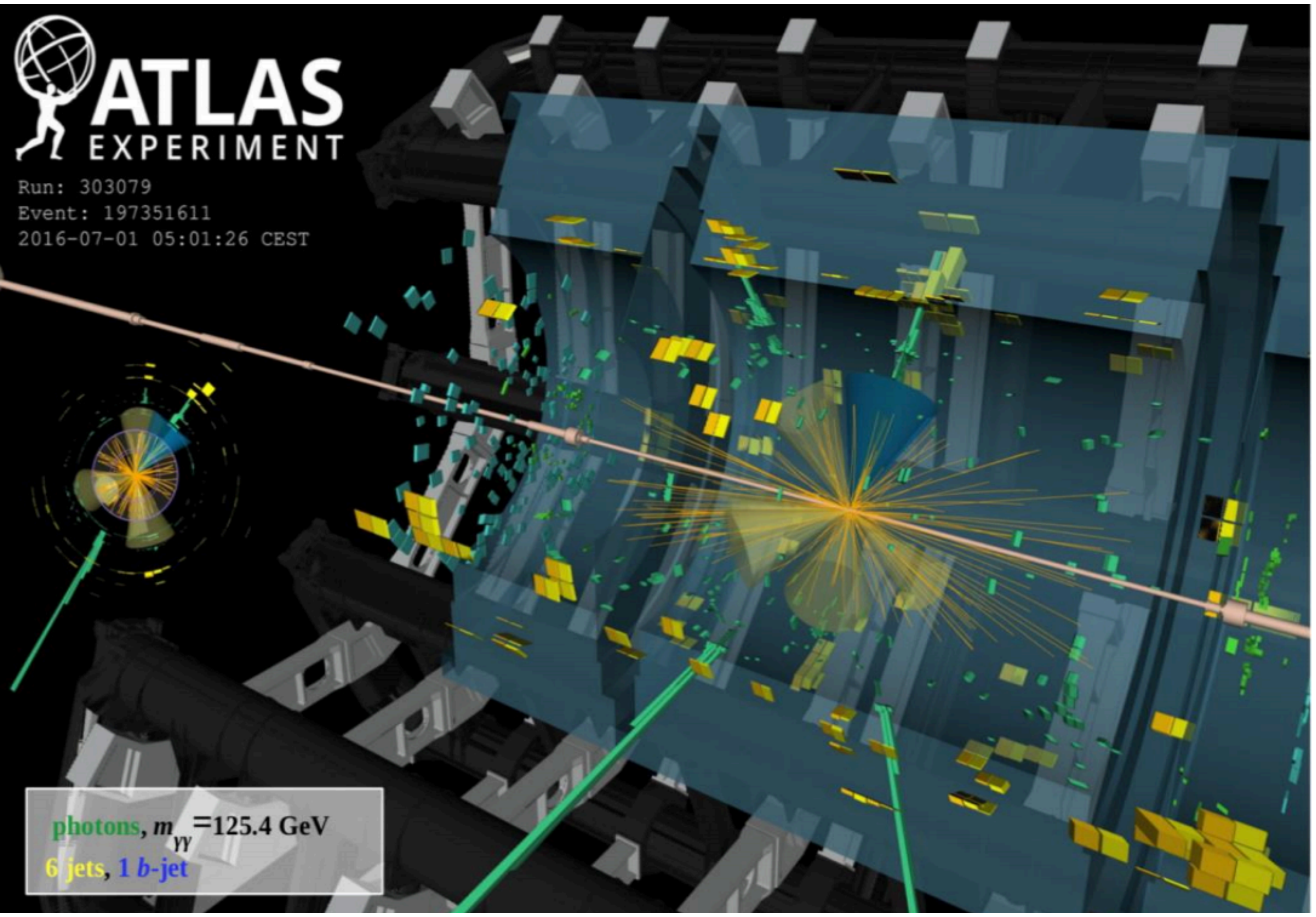
Spin-Parity

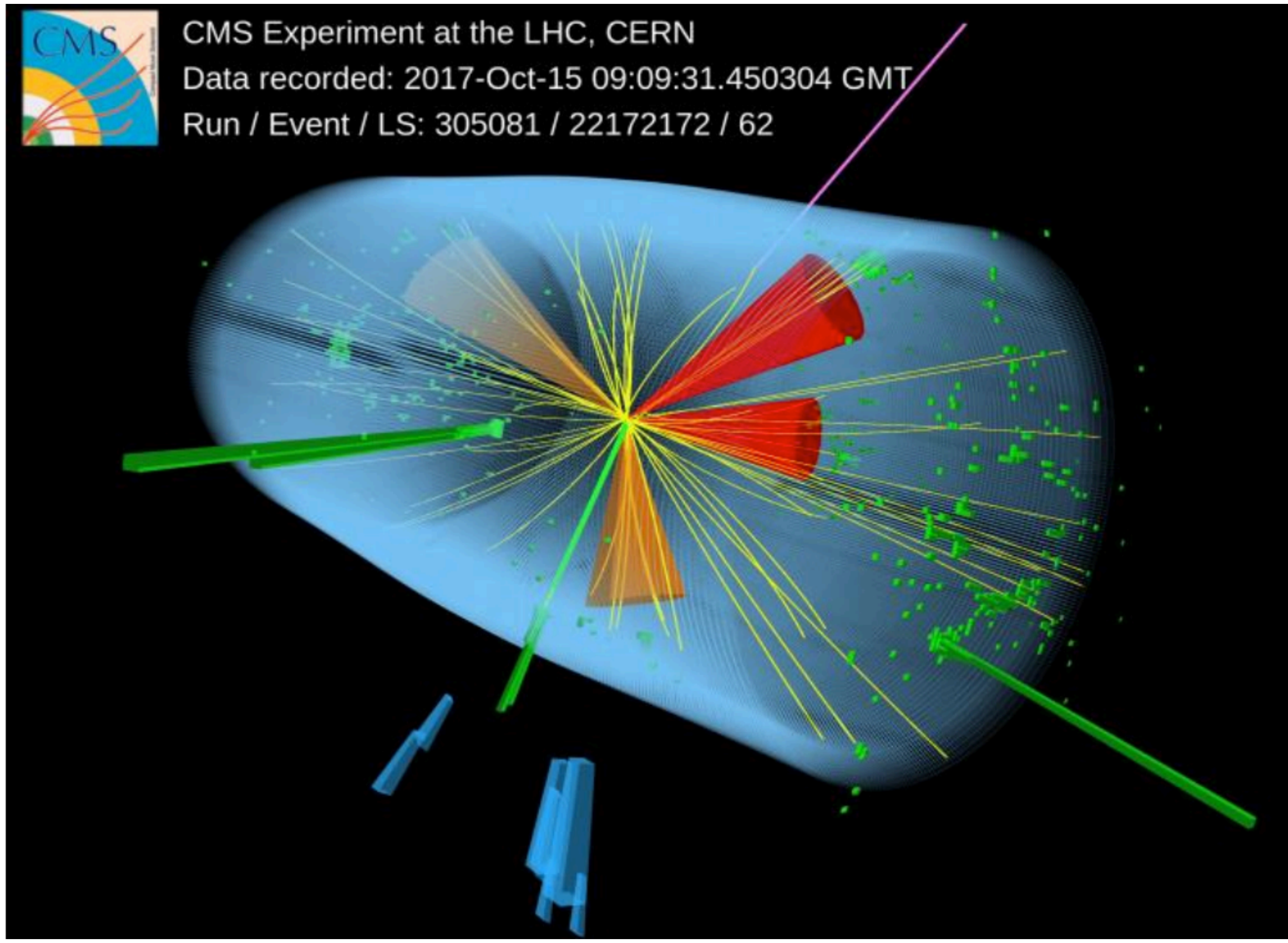
Spin and Parity of the Higgs boson measured in WW*/ZZ* final states using Run-I 7 TeV and 8 TeV data (~25/ fb). SM Higgs boson hypothesis, JP = 0+, tested against alternative spin scenarios, which were excluded at 99.9% CL

In Run2 Higgs boson spin-CP tested, e.g. in γγ decays, with angle distributions of photons and jets sensitive to these properties ¤ For a scalar particle |cos θ∗| shows a strong drop around 0.6



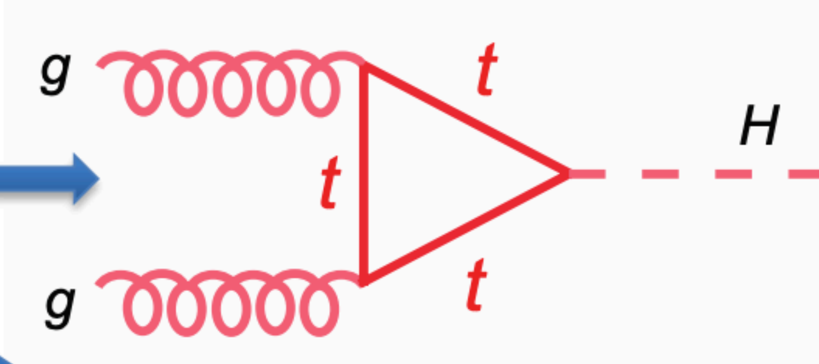
ttH

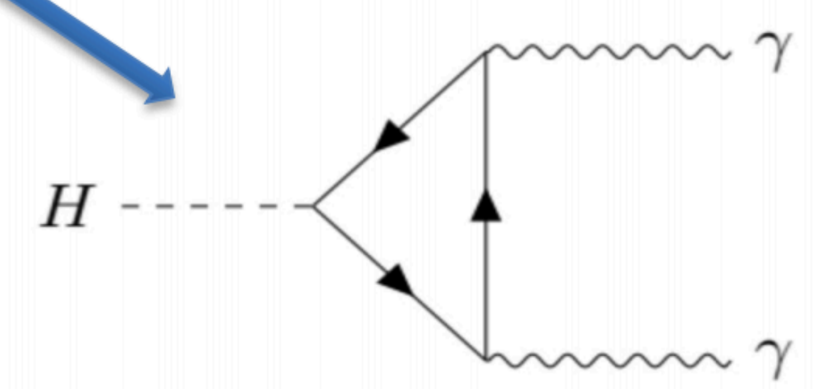

ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST
photons, $m_{\gamma\gamma}$=125.4 GeV
6 jets, 1 b-jet

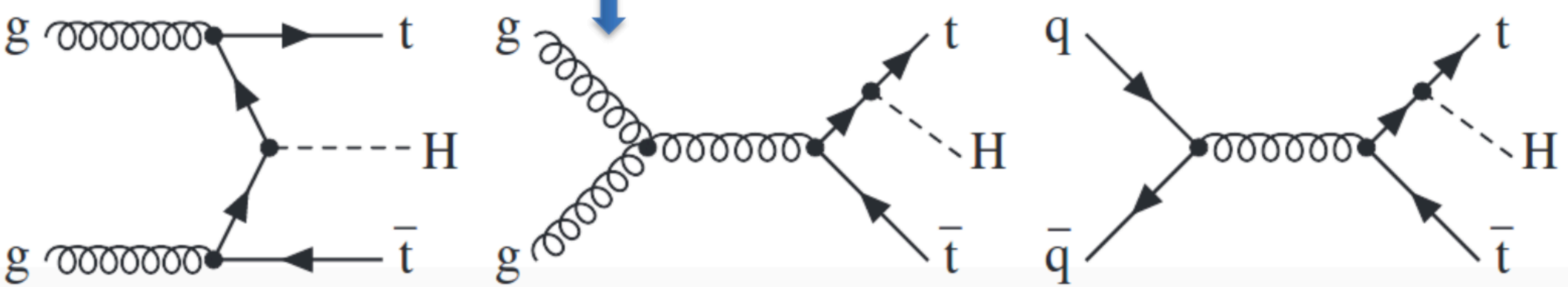

CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-15 09:09:31.450304 GMT
Run / Event / LS: 305081 / 22172172 / 62

ttH

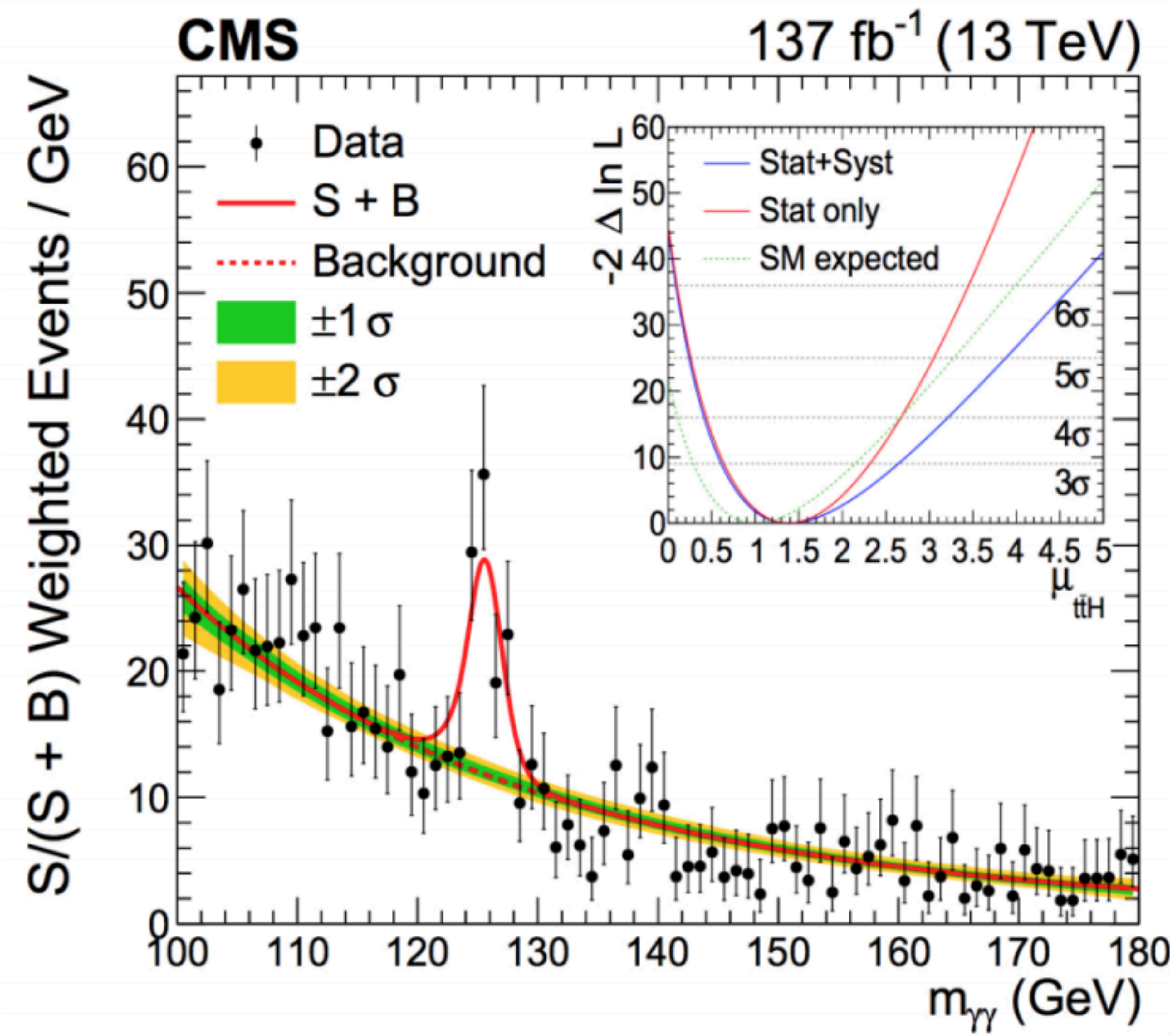
- Fermions couple to the Higgs boson via the Yukawa interaction.
  - The coupling is proportional to the fermion mass. Hence largest for the top quark.
- The t-H Yukawa coupling can be constrained indirectly in the production of the Higgs boson via gluon-gluon fusion and in the diphoton decay mode.
  - Requires assumptions on the contribution from BSM particles in the loops.
- ttH and tH production allows for a direct observation and measurement of the t-H Yukawa coupling







ttH

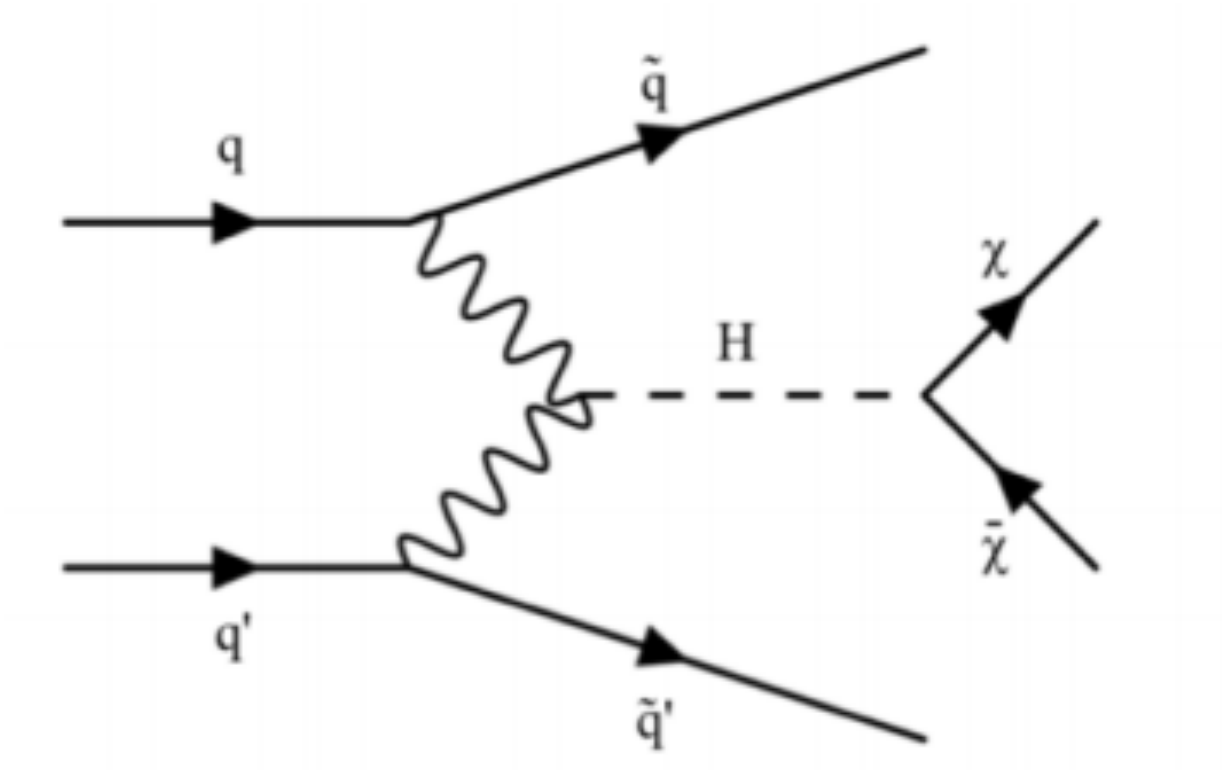


observed!

Higgs Invisible

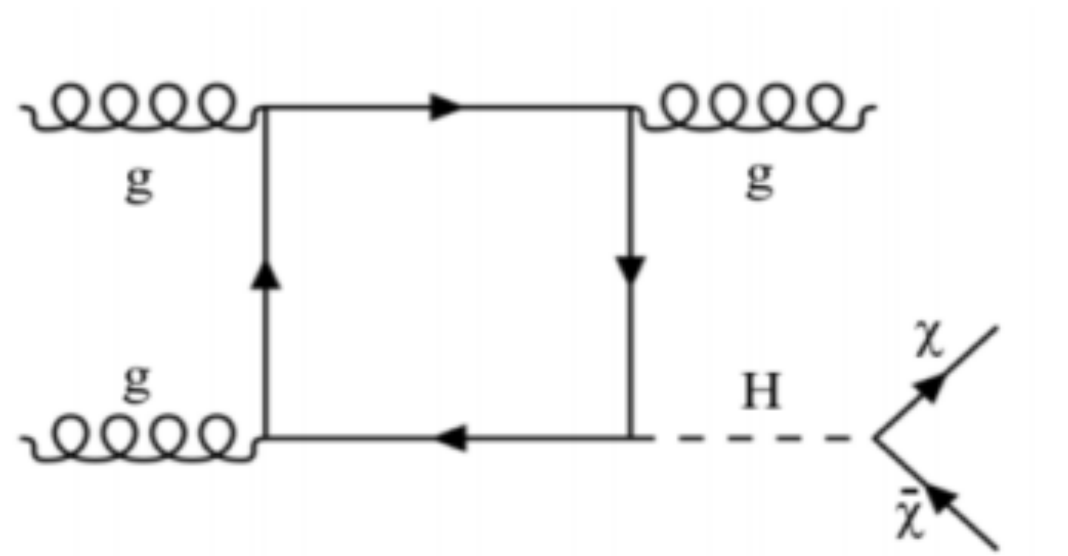
BR(H→$\nu\bar{\nu}\nu\bar{\nu}$) ~ 0.1%

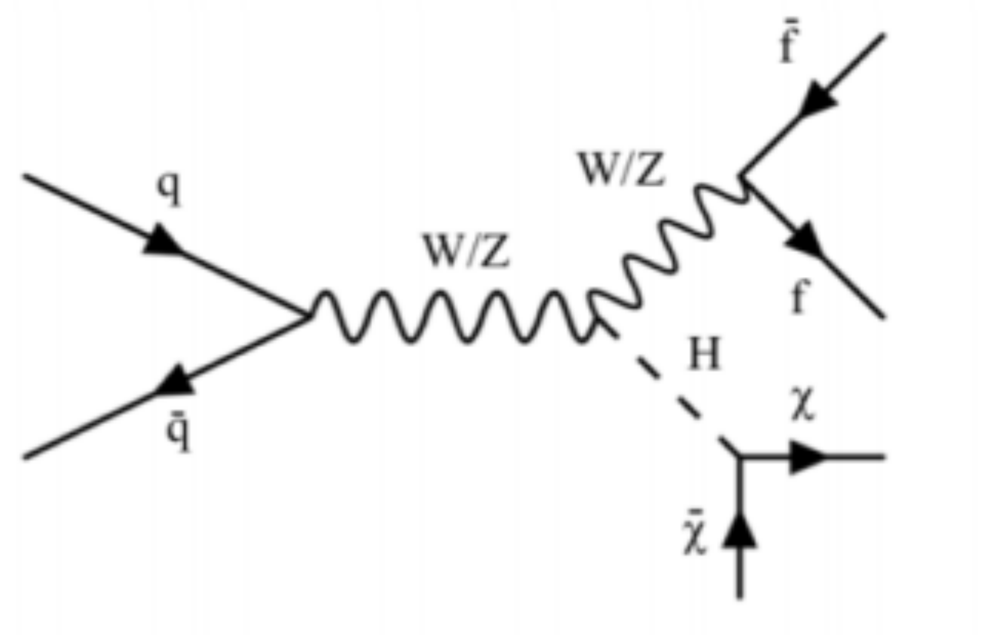
Higgs and invisible particles can be a way to look a the dark (matter) side



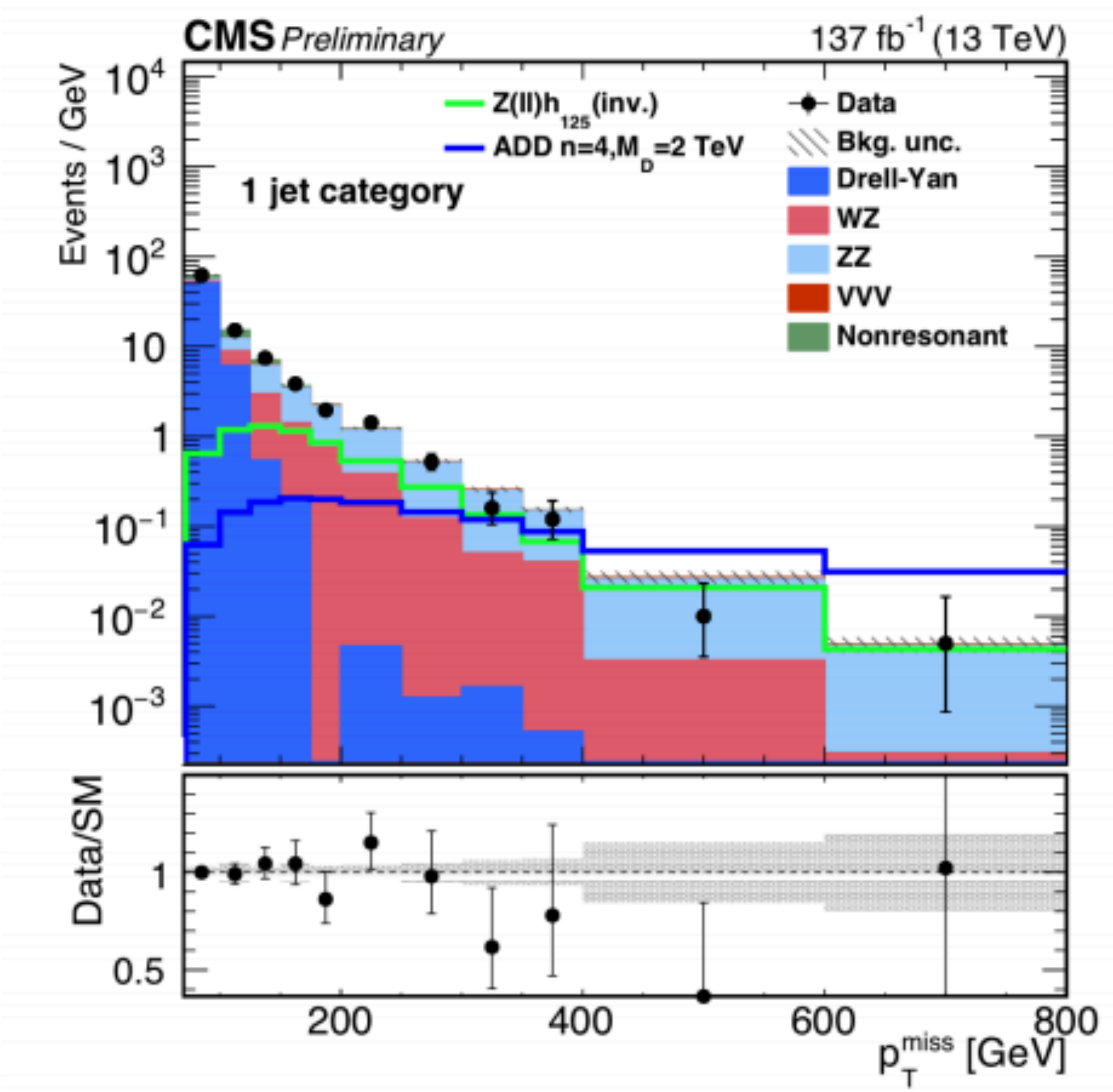
Missing Energy + Jets

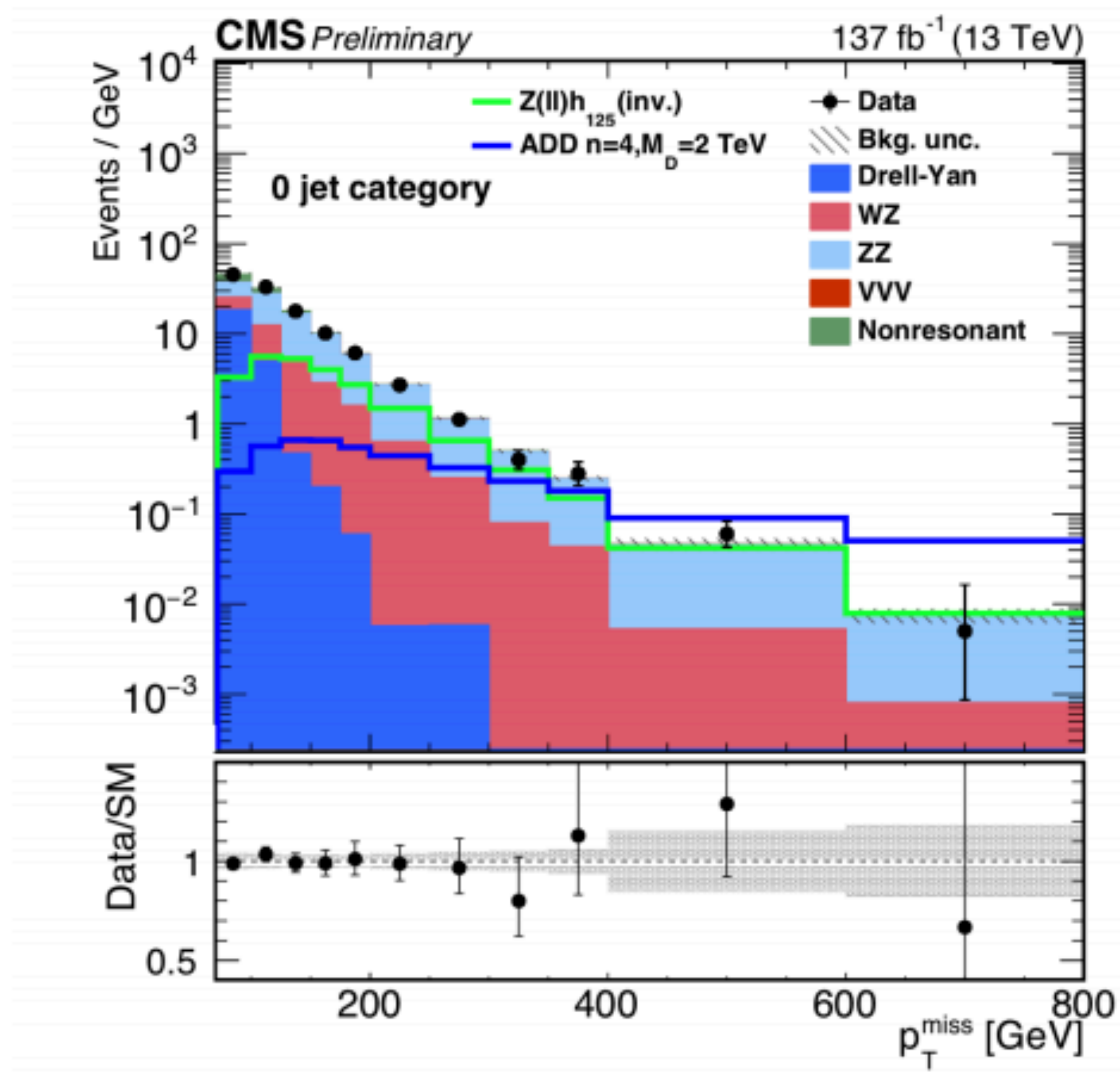
a *mediator* between SM and DM particles?





Higgs Invisible



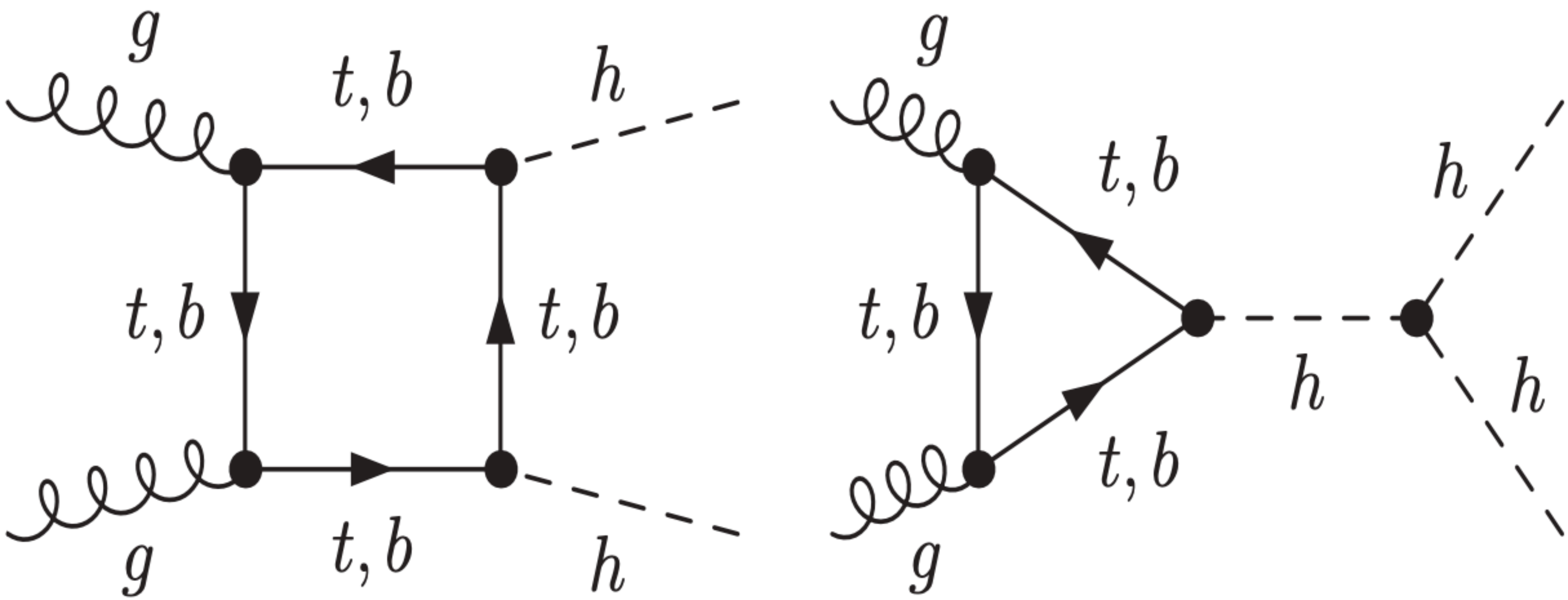


assuming Mh=125 GeV => expected (observed) = 0.29 (0.25)

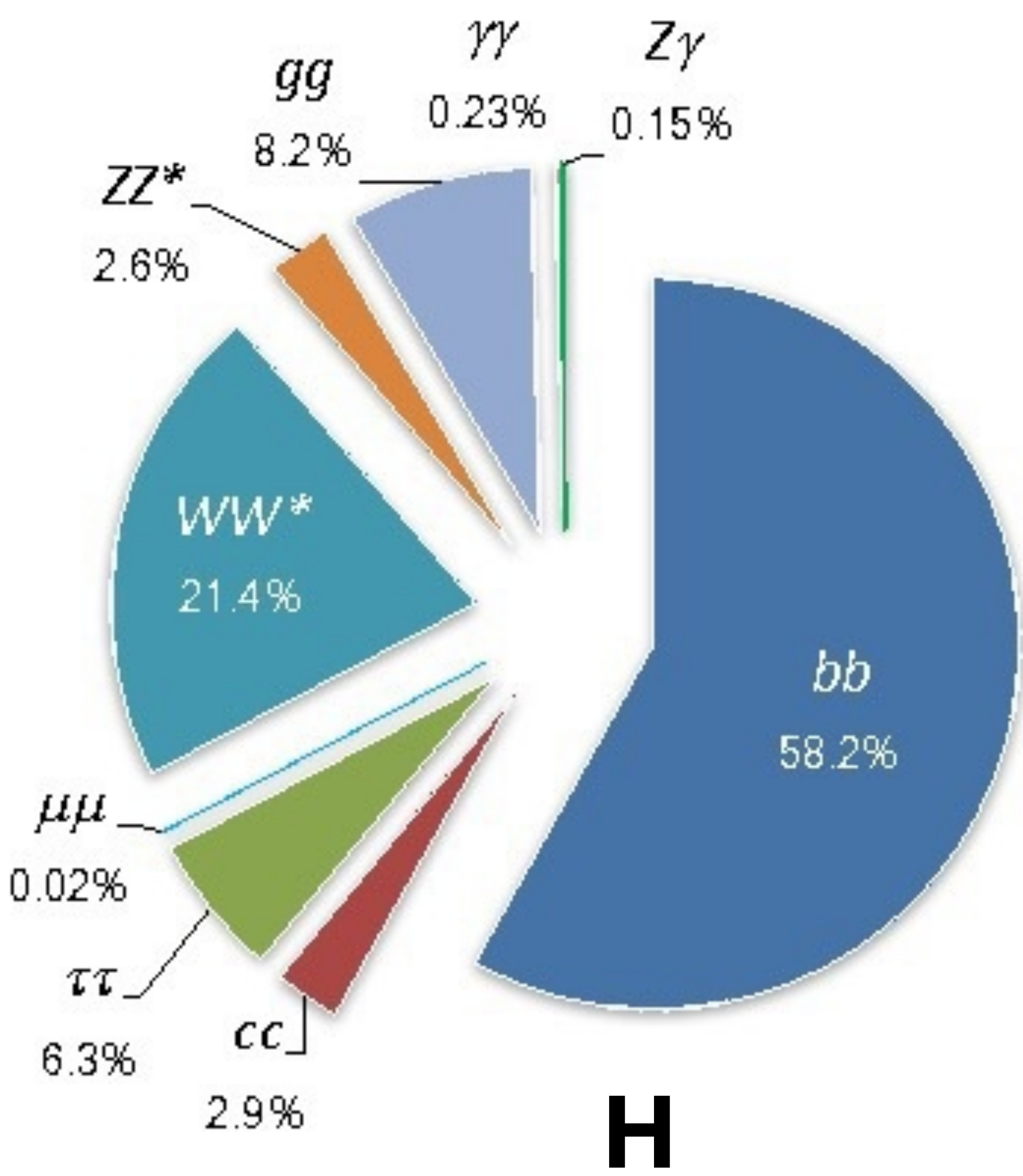
double Higgs production

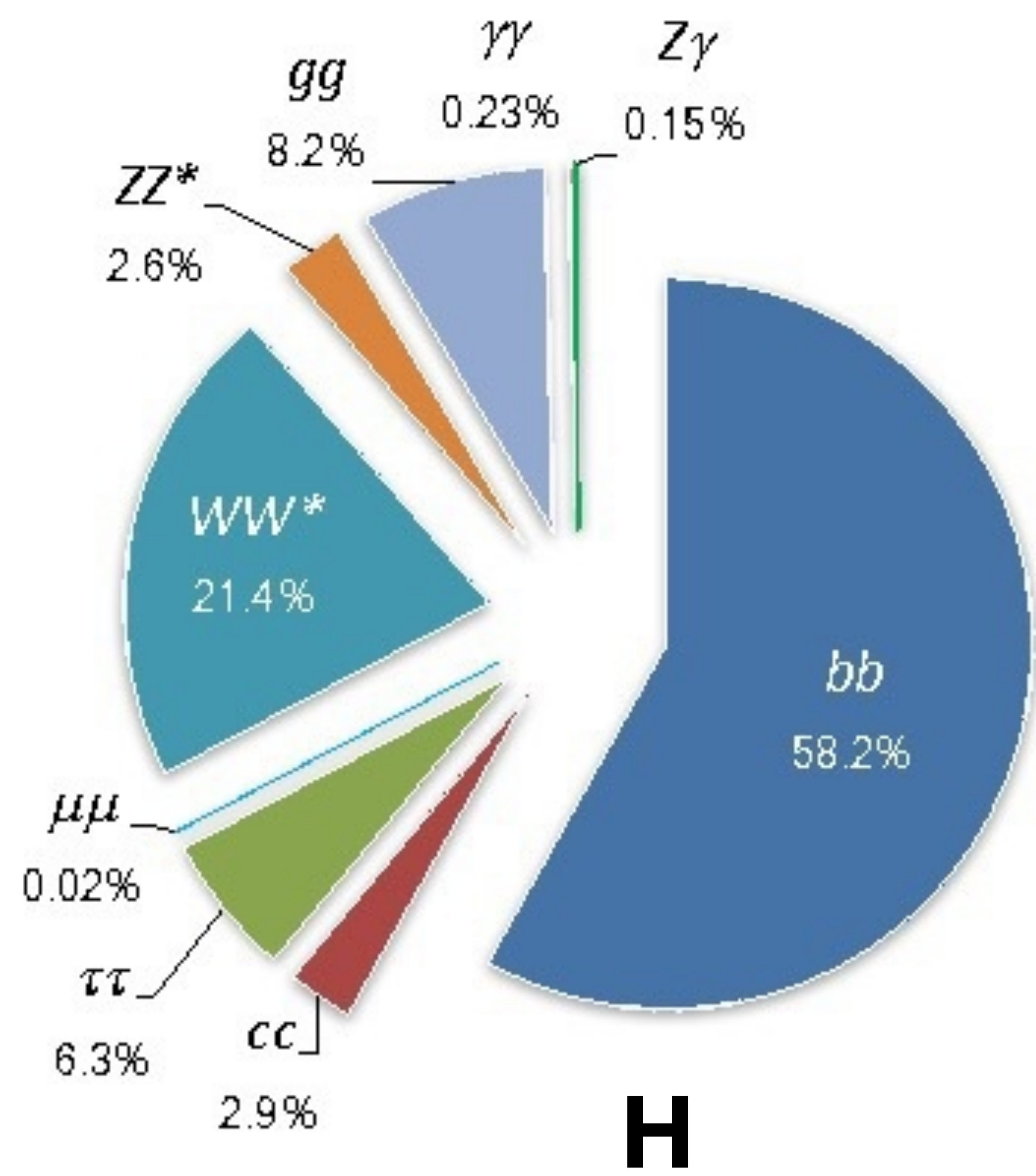
only way to access to the self-interaction

and measure the trilinear coupling λ = m2 h /2v



double Higgs decay modes

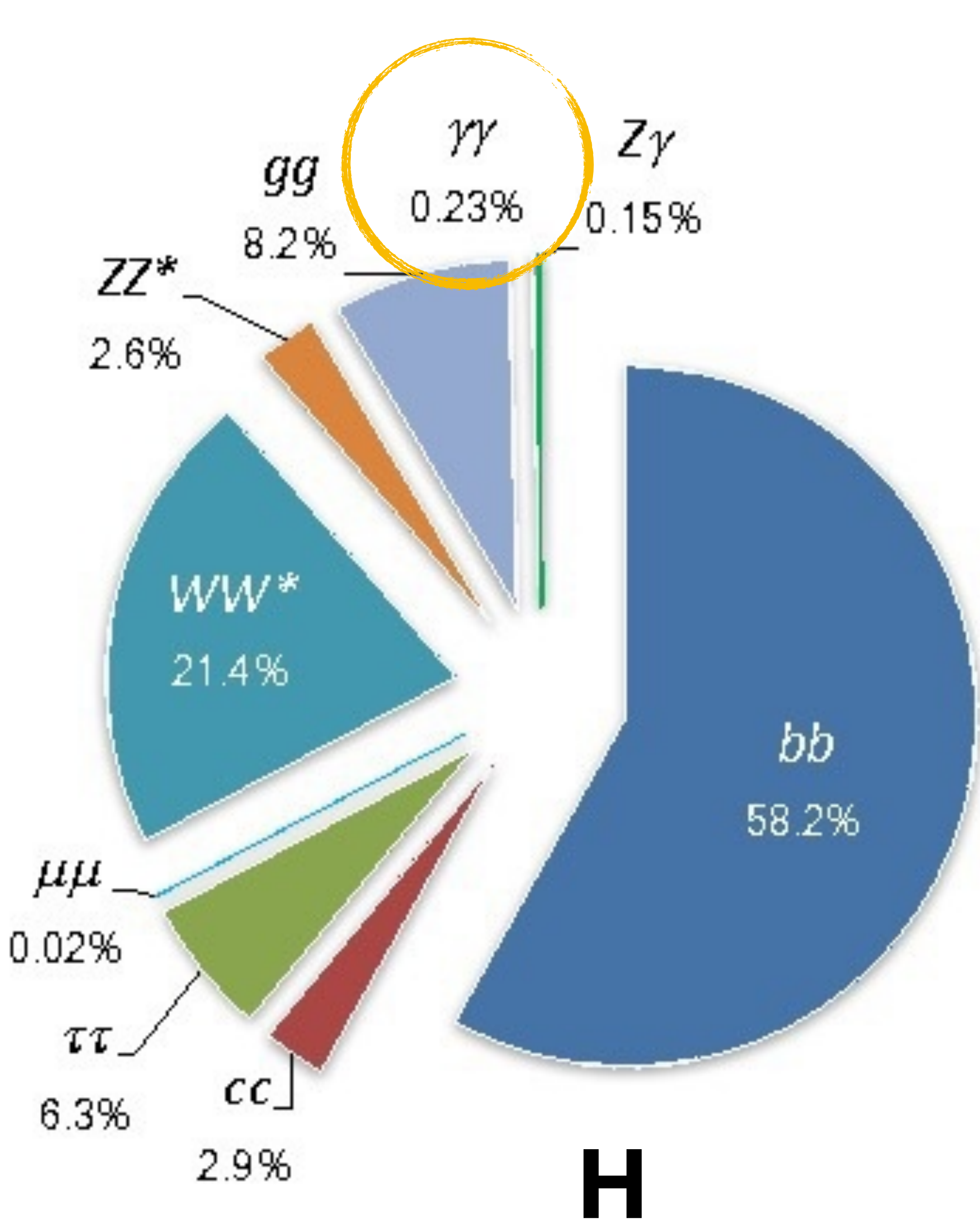


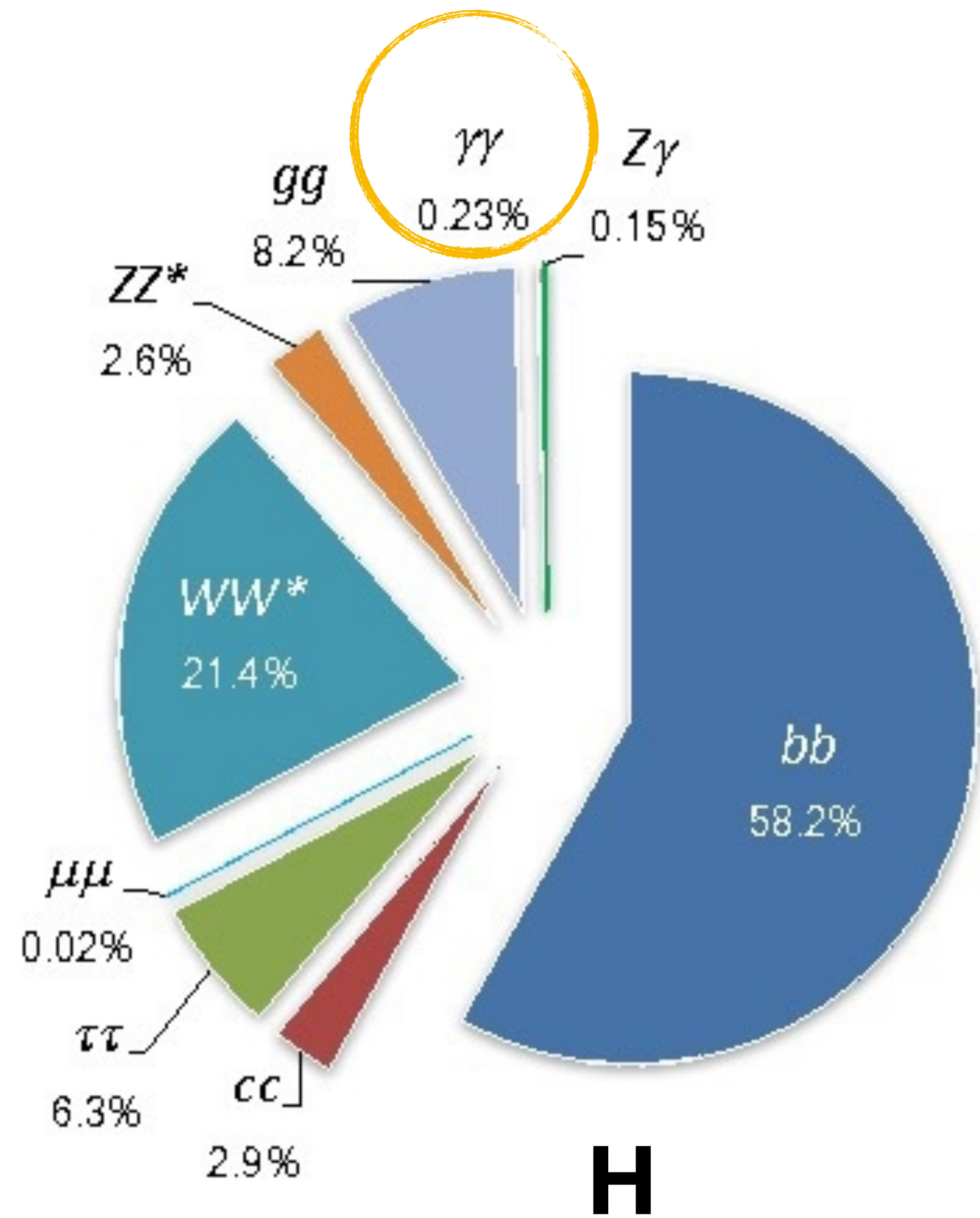


need to gain as much statistics as possible but with realistic bkg fight

production xsec @ LO: 16 fb (~ 1500 times smaller than single Higgs production)

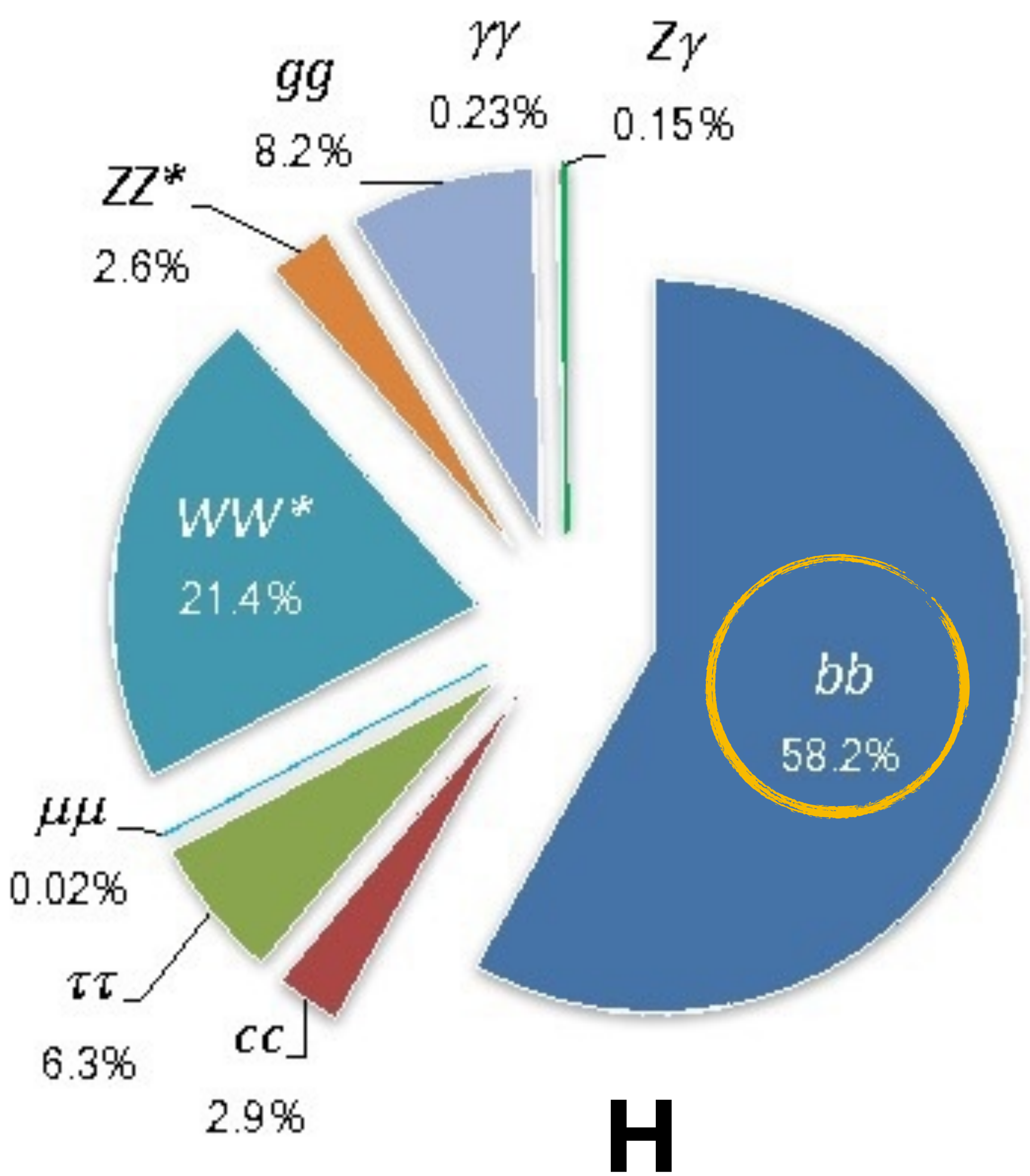
double Higgs decay modes

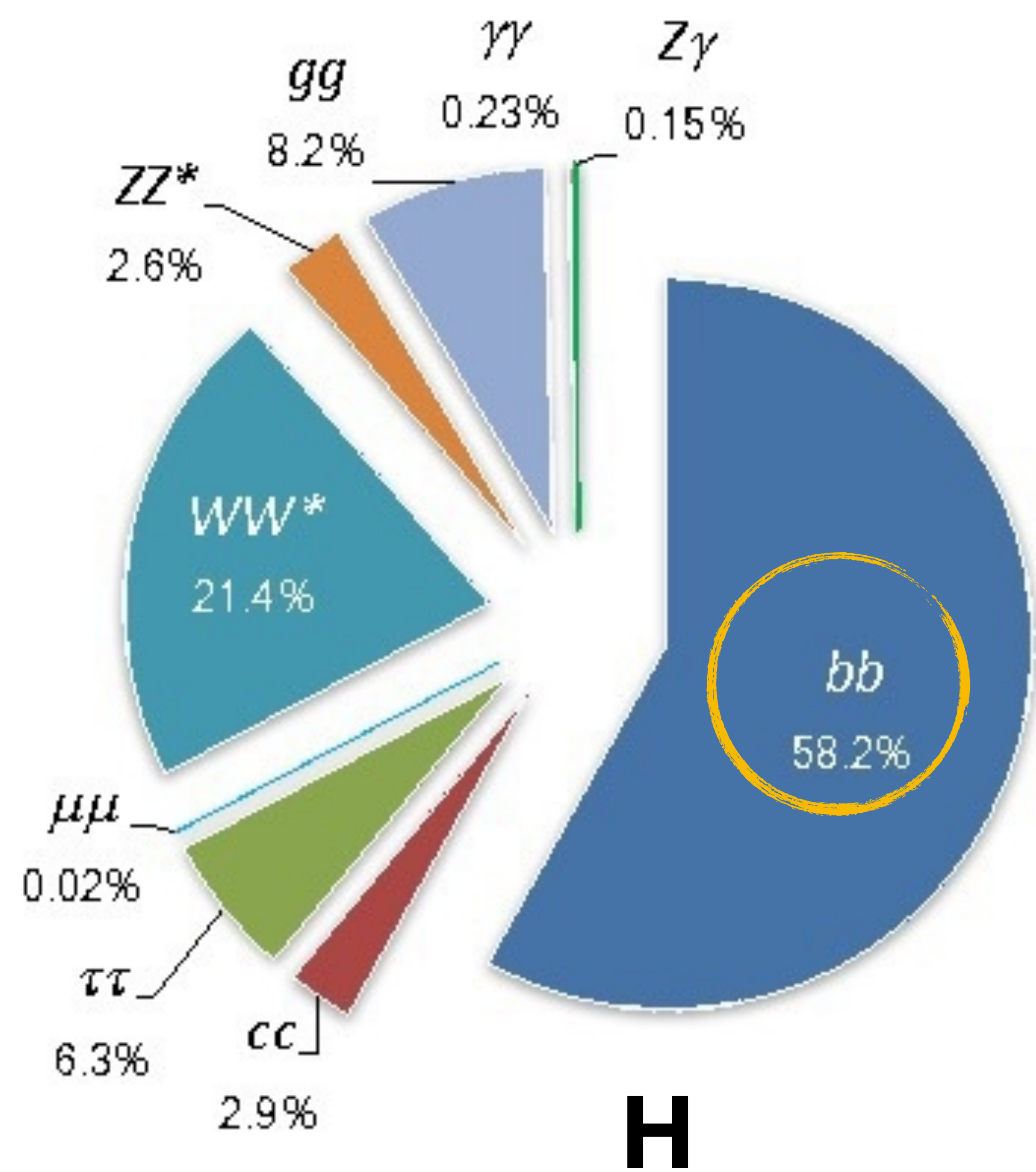




very clean signature, very low BR…

double Higgs decay modes

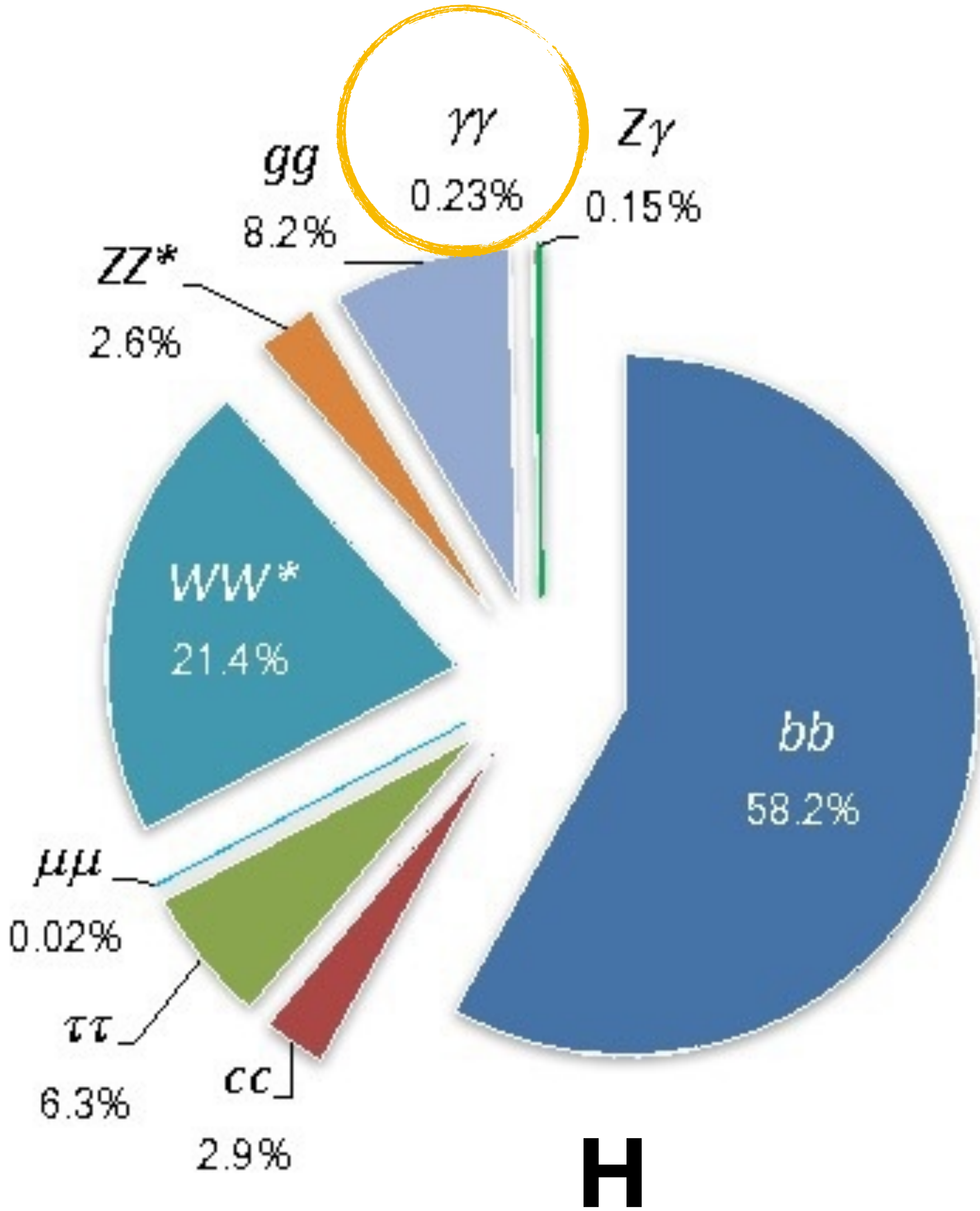


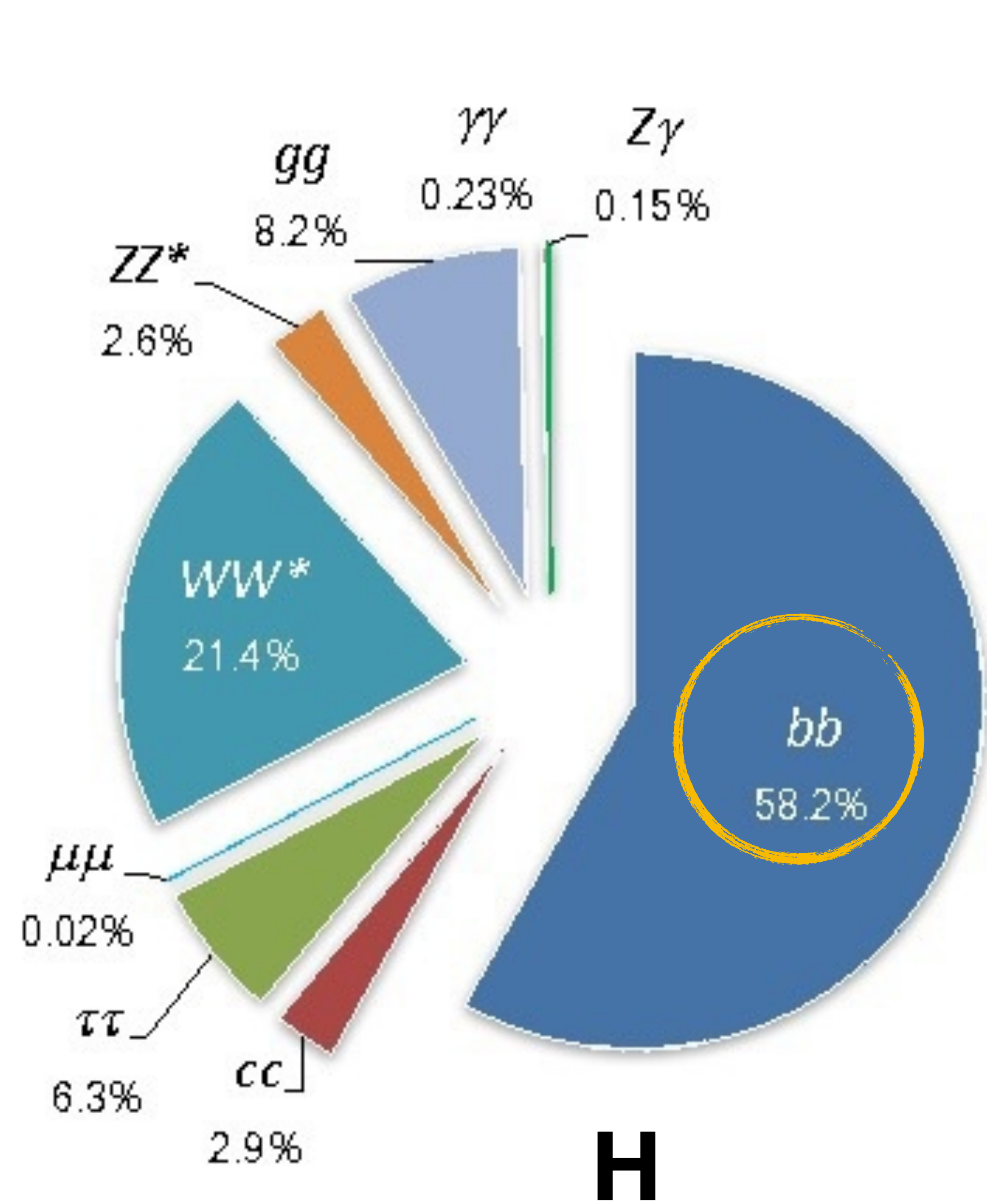


best possible BR, worst s/b (multijet QCD dominates)

but we could use sub-structure…

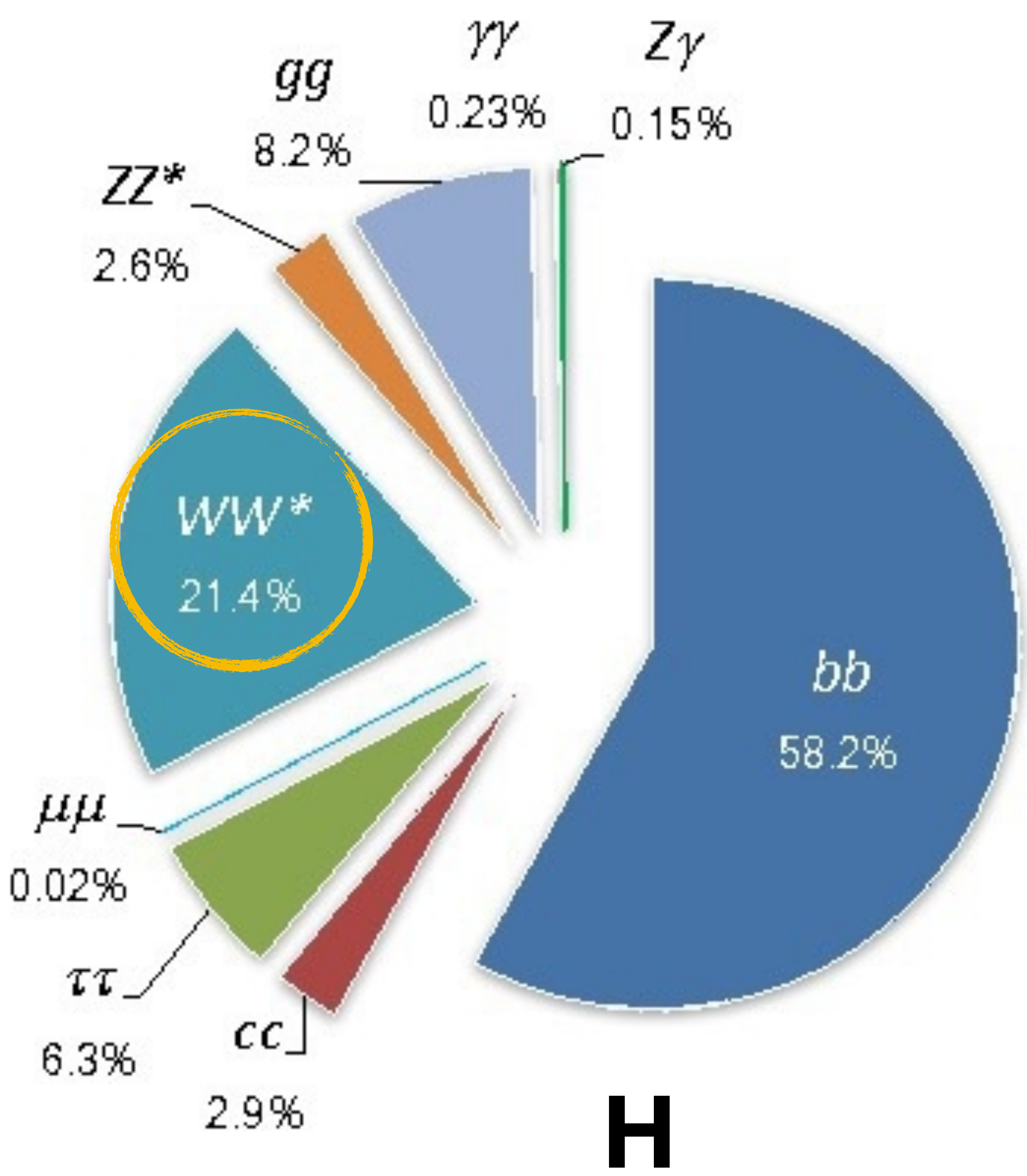
double Higgs decay modes

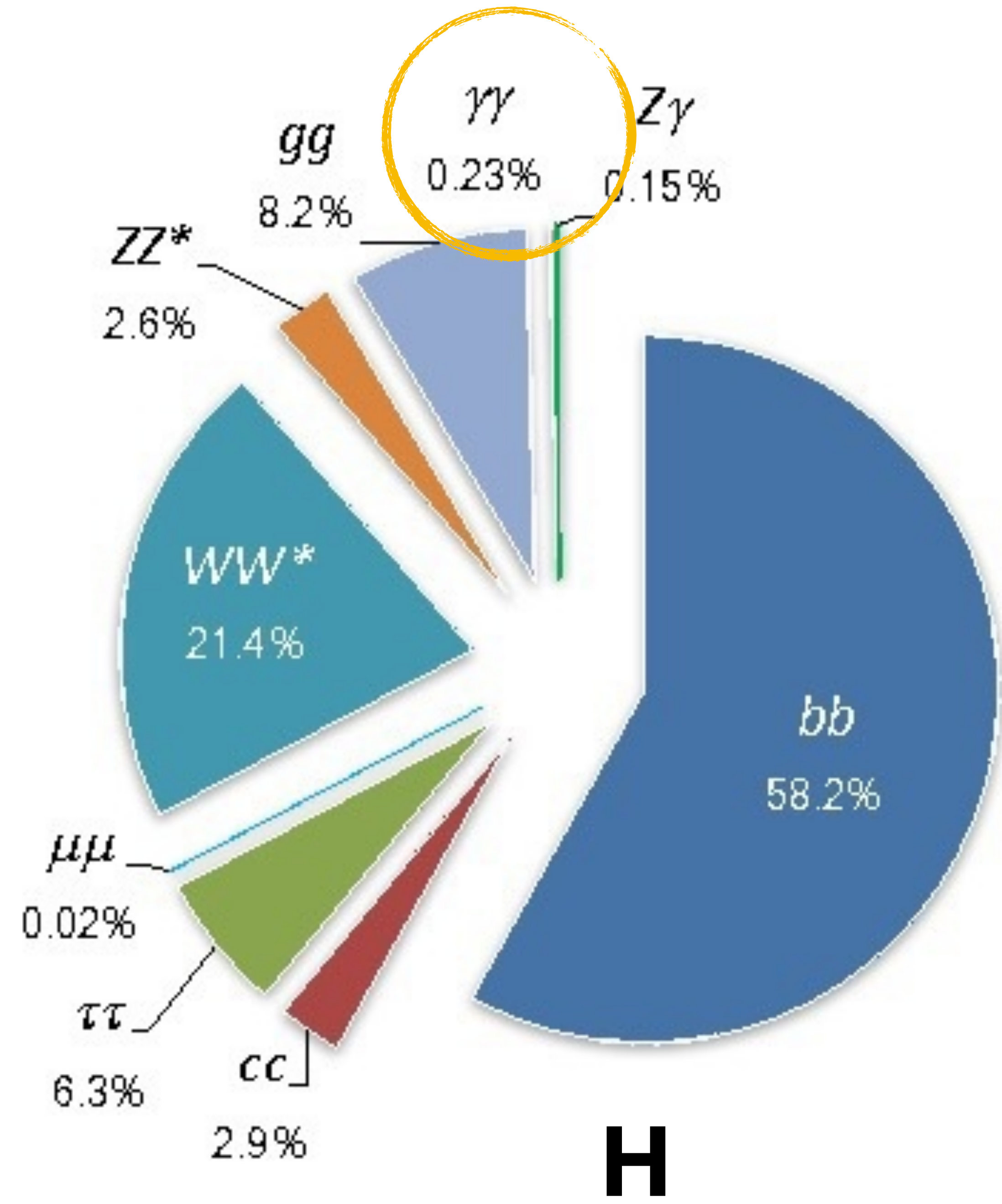




interesting mixed alternatives #1

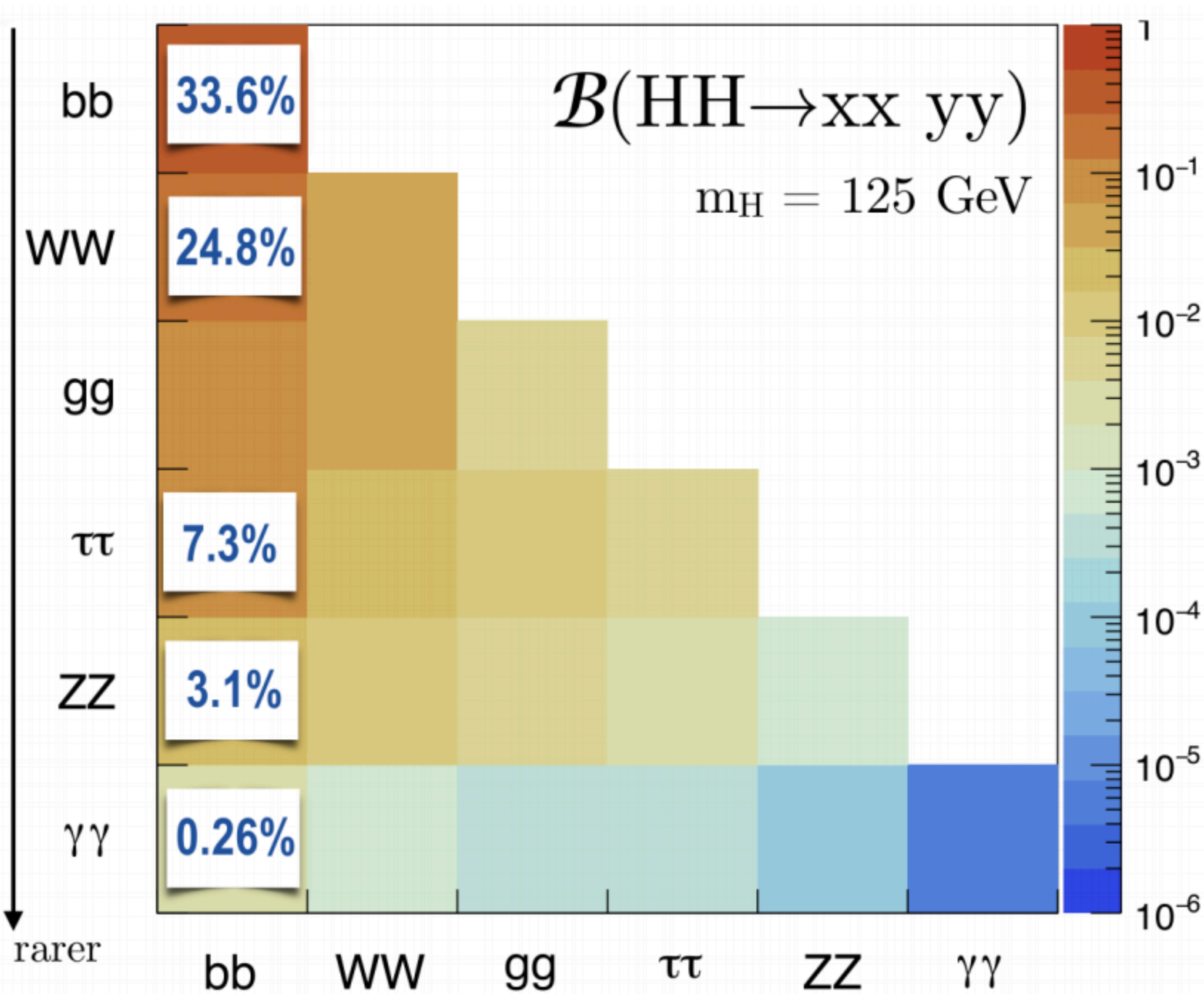
double Higgs decay modes





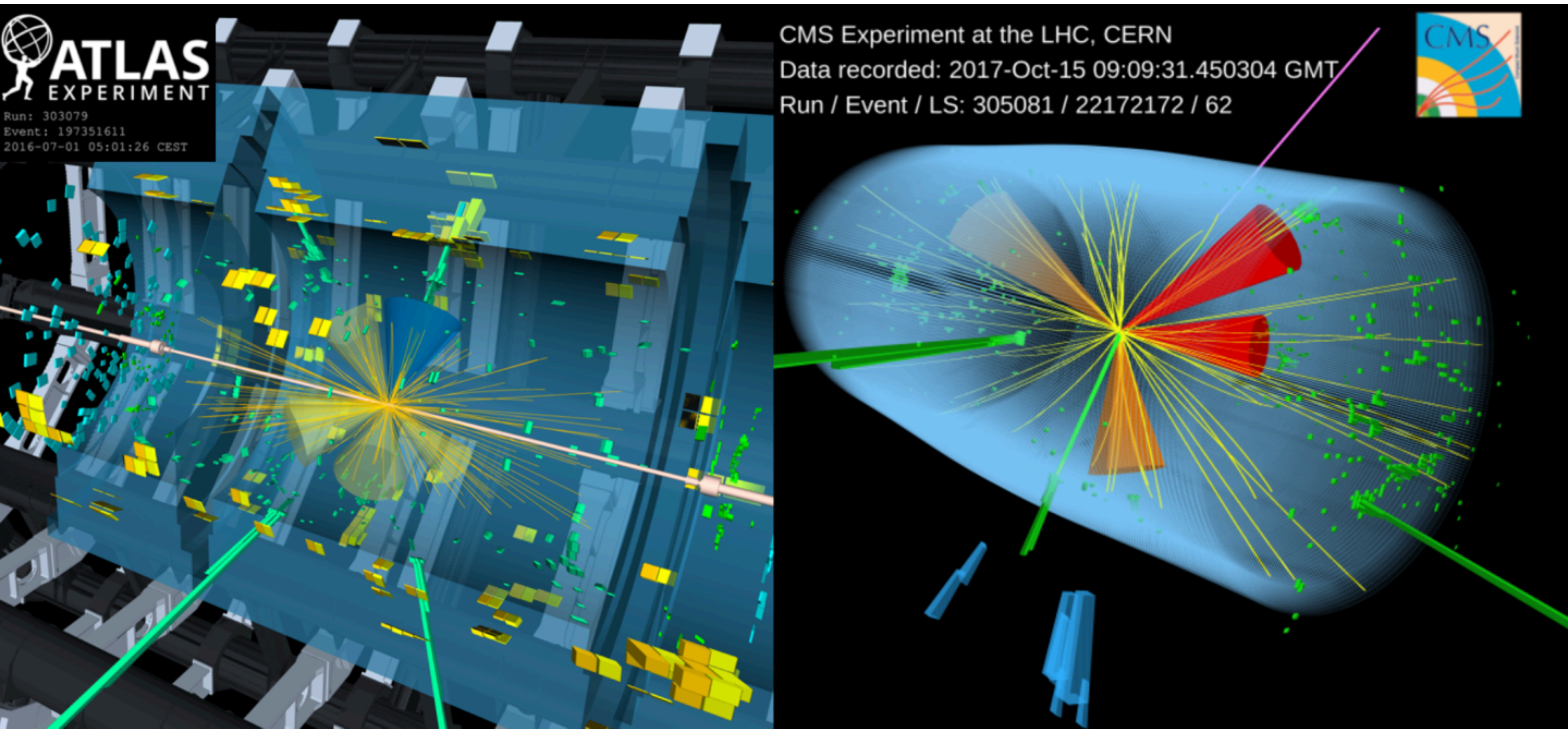
interesting mixed alternatives #2

double Higgs decays



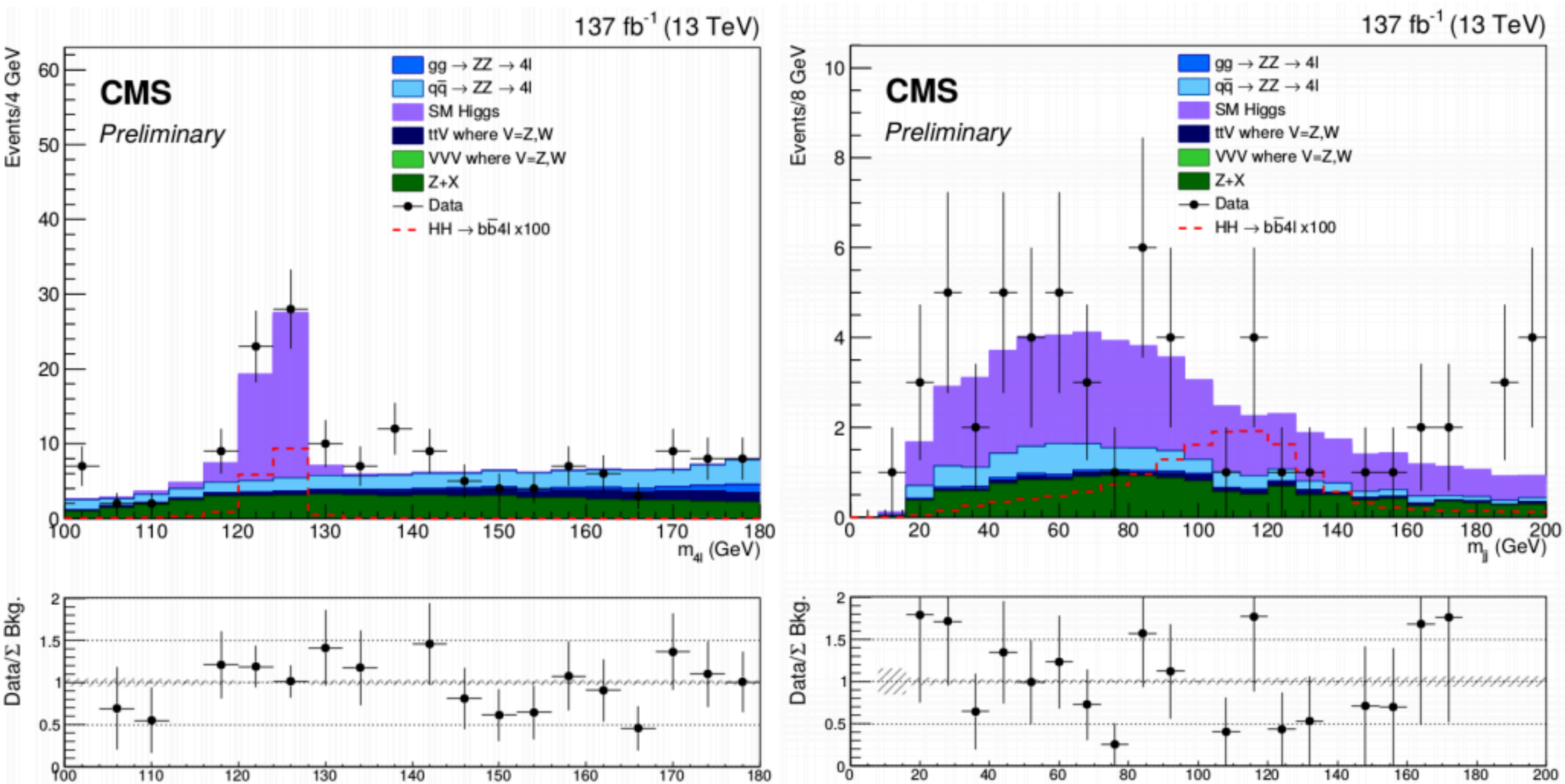
- **bbbb:** largest BR, large QCD and $t\bar{t}$ contamination
- **bbVV:** large BR, large $t\bar{t}$ contamination
- **bb$\tau\tau$:** sizeable BR, relatively small background
- **bb$\gamma\gamma$:** small BR, good $\sigma(m_{\gamma\gamma})$, relatively small background

double Higgs decay modes



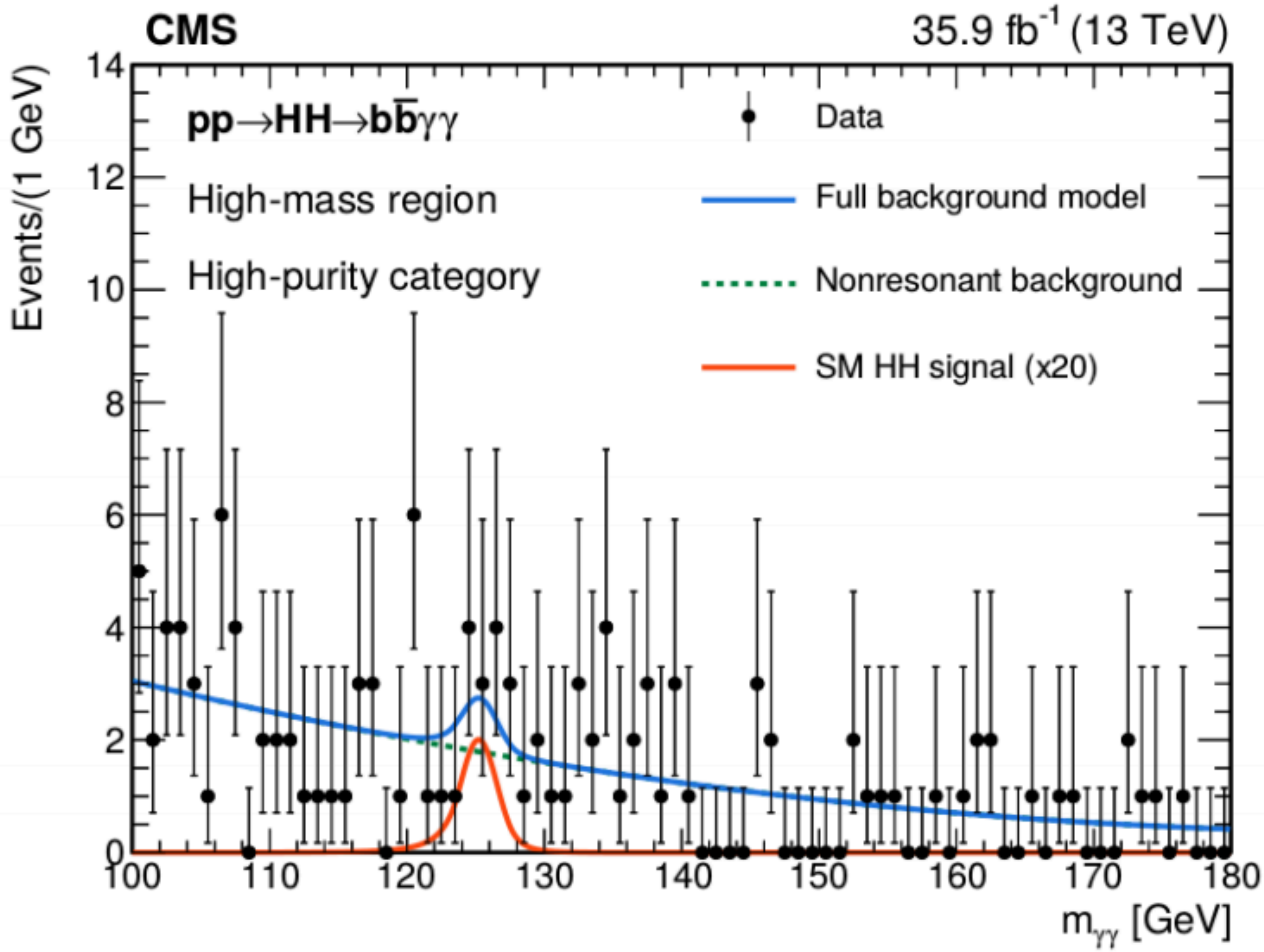
pp→HH→bbbb

double Higgs decay modes



$$HH \to b\bar{b}ZZ \to 4\ell 2b$$

double Higgs decay modes



$$HH \to b\bar{b}\gamma\gamma$$

Why just one?

<u>Q: Who said that there is only one Higgs boson?</u>

<u>A:</u>

Not the Standard Model Theory: one doublet introduced to give bosons mass

Not any symmetry or selection rule, quantic number!

There are NO constraint on how many Higgs doublet must/can/should exist!

Minimal addition: one extra doublet ***2HDM***

- After EW symmetry breaking, 3 scalars are absorbed by W and Z
- 5 remaining scalar degrees of freedom and two vacuum expectation value

$$v^2 \equiv v_d^2 + v_u^2 = 4m_W^2/g^2 = (246\ \text{GeV})^2$$

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$

$$\tan\beta \equiv \frac{v_u}{v_d}$$

2HDM

2HDM

- Two doublets with opposite hypercharge

$$H_d = \begin{pmatrix} H_d^1 \\ H_d^2 \end{pmatrix} = \begin{pmatrix} \Phi_1^{0\,*} \\ -\Phi_1^- \end{pmatrix}, \qquad H_u = \begin{pmatrix} H_u^1 \\ H_u^2 \end{pmatrix} = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

$$Y = -1 \qquad\qquad Y = +1$$

  - 8 total degrees of freedom
- Different coupling to quarks for each doublet
  - H_u to up quarks
  - H_d to down quarks

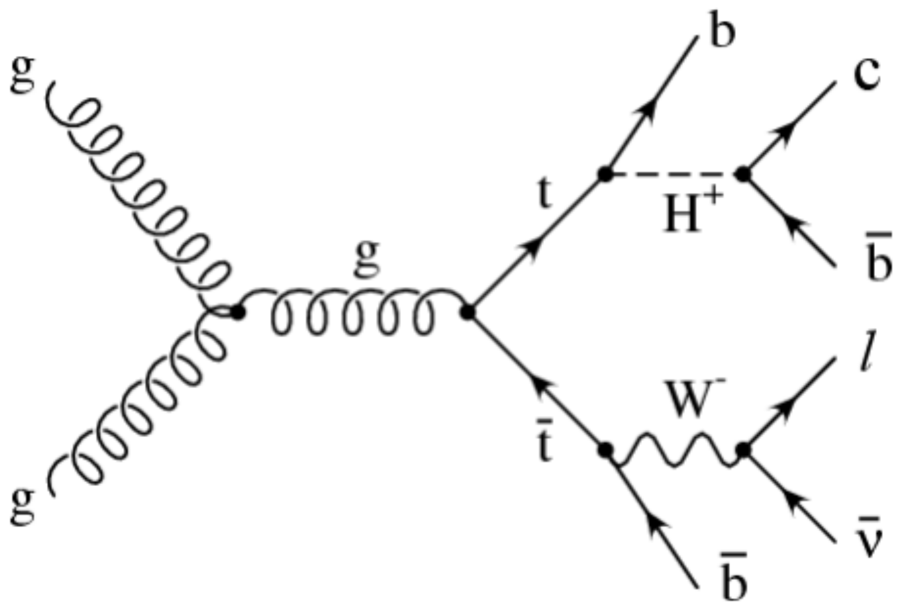
$$\mathcal{L}_{\text{Yukawa}} = -h_u^{ij}(\bar{u}_R^i u_L^j H_u^2 - \bar{u}_R^i d_L^j H_u^1) - h_d^{ij}(\bar{d}_R^i d_L^j H_d^1 - \bar{d}_R^i u_L^j H_d^2) + \text{h.c.}$$

- Slightly more complicated Higgs potential

$$V = \left(m_d^2 + |\mu|^2\right) H_d^{i*} H_d^i + \left(m_u^2 + |\mu|^2\right) H_u^{i*} H_u^i - m_{ud}^2 \left(\epsilon^{ij} H_d^i H_u^j + \text{h.c.}\right)$$
$$+ \tfrac{1}{8}\left(g^2 + g'^2\right)\left[H_d^{i*} H_d^i - H_u^{j*} H_u^j\right]^2 + \tfrac{1}{2} g^2 |H_d^{i*} H_u^i|^2 ,$$

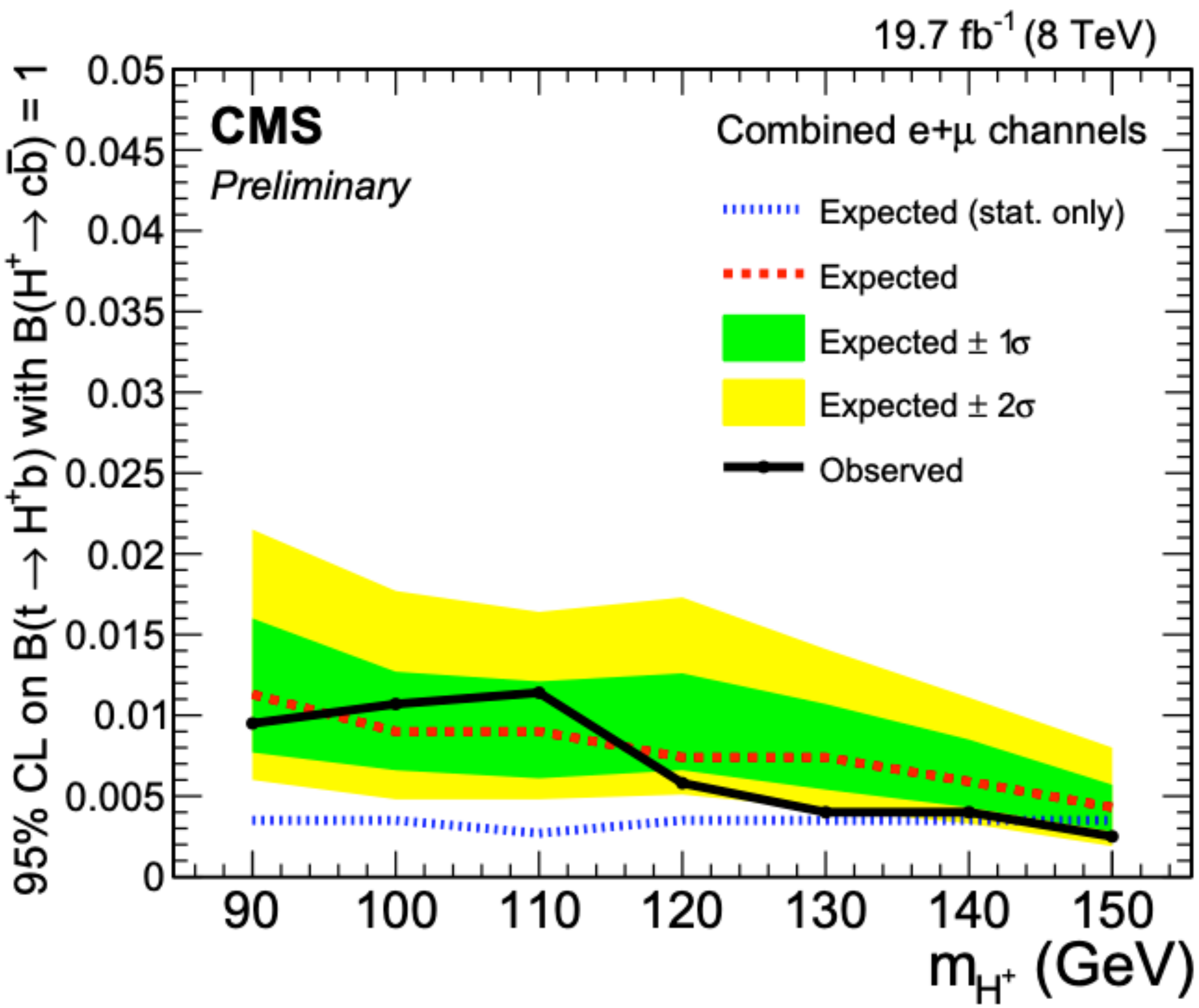
$$\epsilon^{12} = -\epsilon^{21} = 1 \text{ and } \epsilon^{11} = \epsilon^{22} = 0$$

2HDM



???

how to read this??



Next 2 lectures on: what CL limits are and what do they tell us

The discovery: how to read this??