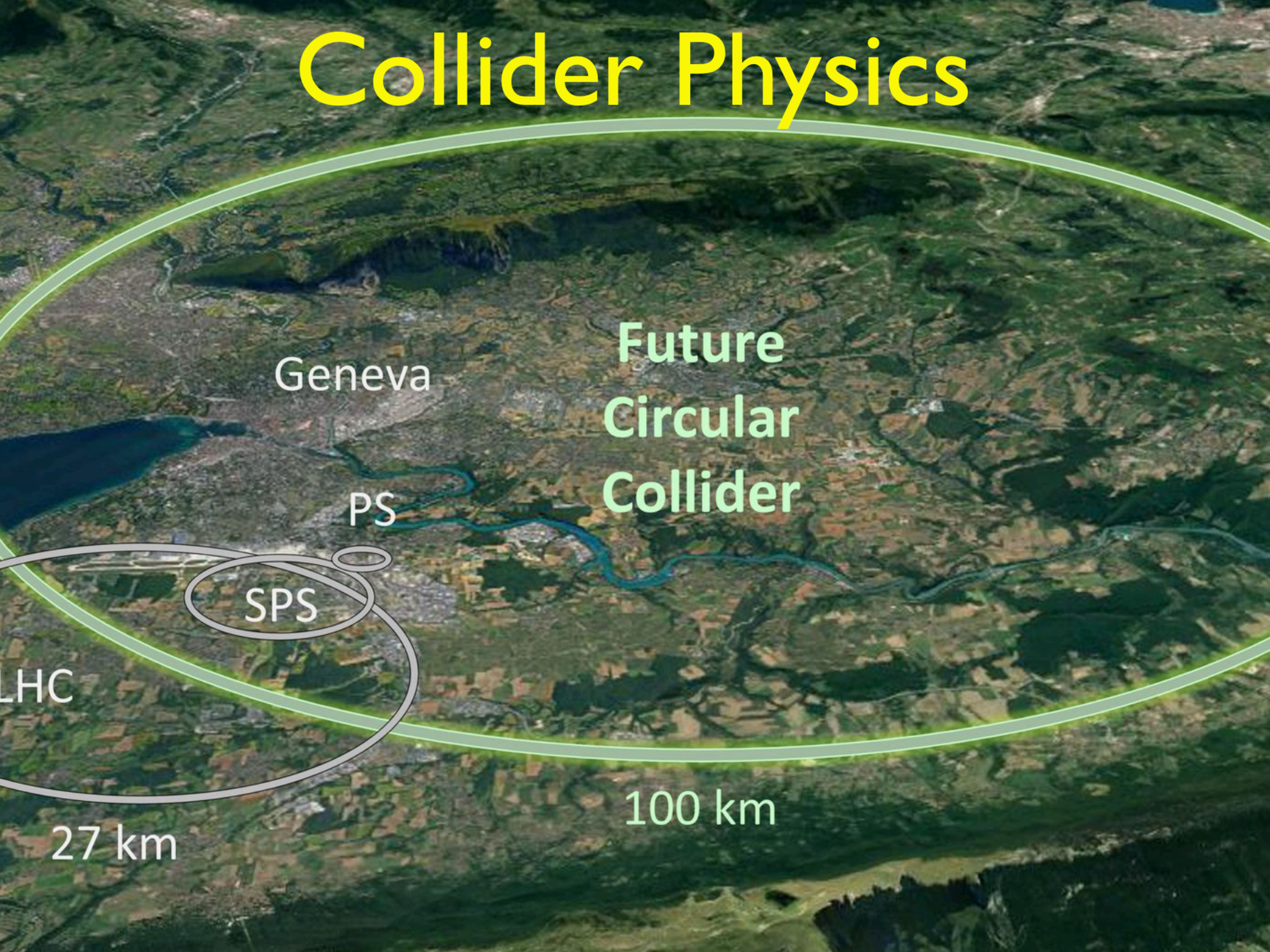
Collider Physics



Electroweak symmetry breaking in the SM: the quest for the Higgs

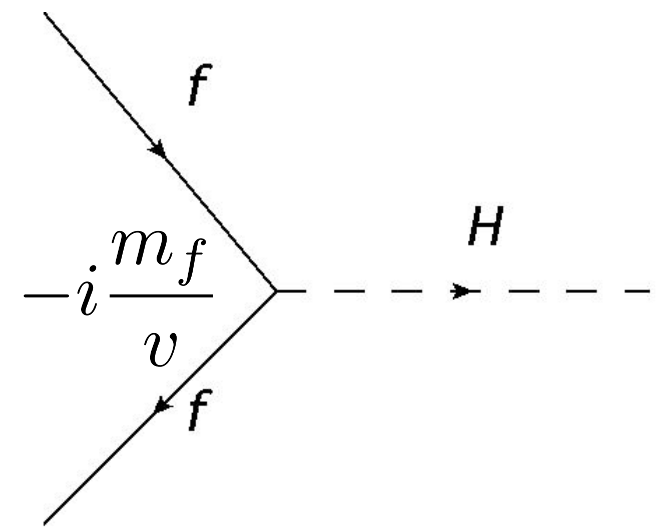
- Properties of SM Higgs
- Production mechanisms
- A few results
- Unitarity of the SM
- Triviality constraint on the SM Higgs
- Stability of the SM

1. Properties of the SM Higgs

unknown parameter

★ The SM Higgs boson is undetermined: $M_H^2 = 2\lambda v^2$

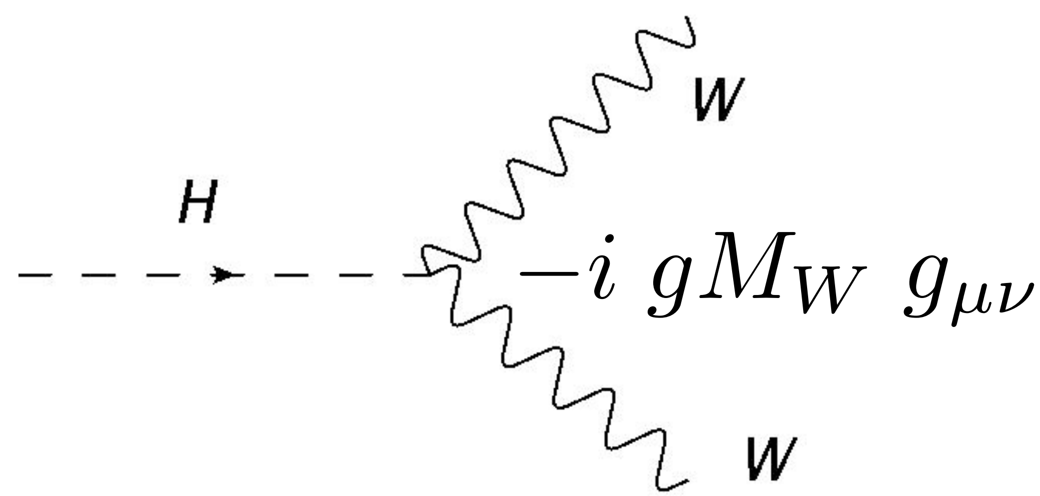
★ Its couplings to fermions is "rather weak"



★ Its width into fermions is

$$\Gamma(H \to \bar{f}f) = \frac{G_F M_H m_f^2}{4\pi\sqrt{2}}$$

★ H couplings to W and Z are sizeable



★ The partial width into W's is $\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{32\sqrt{2}\pi}\,(1-x^2)^{1/2}\,(3x^2-4x+4)$

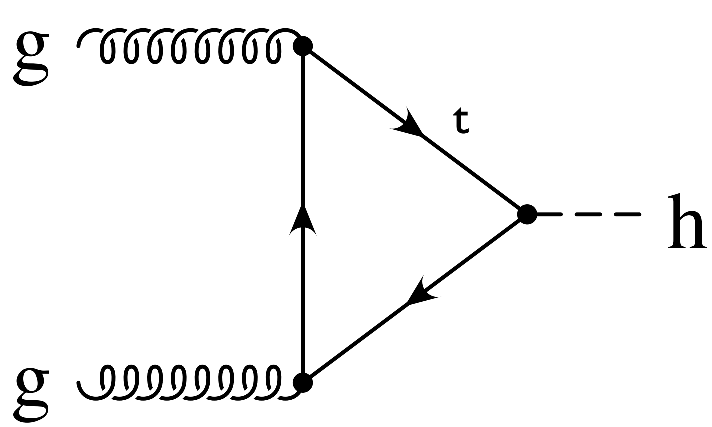
with $x = \frac{4M_W^2}{M_H^2}$

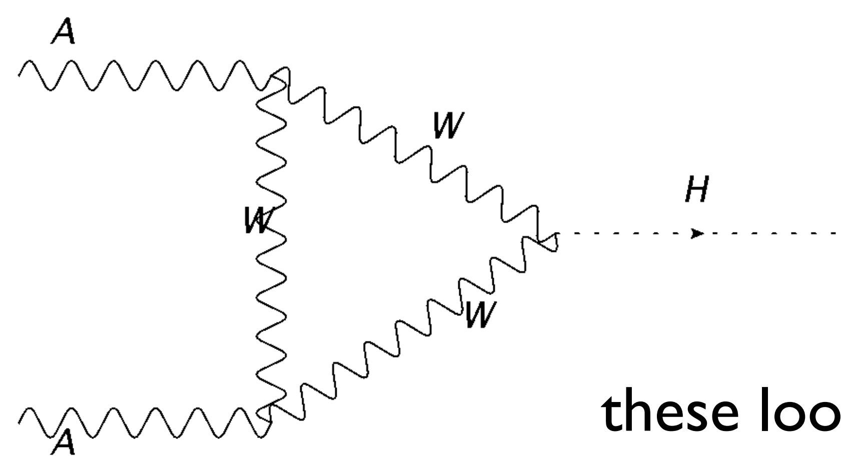
dominates at high higgs masses

★ The width into Z's is $\Gamma(H \to ZZ) = \frac{G_F M_H^3}{64\sqrt{2}\pi}\,(1-x^2)^{1/2}\,(3x^2-4x+4)$

with $x = \frac{4M_Z^2}{M_H^2}$

★ It is important to add some decay modes taking place via loops $H \to \gamma\gamma$ and $H \to gg$





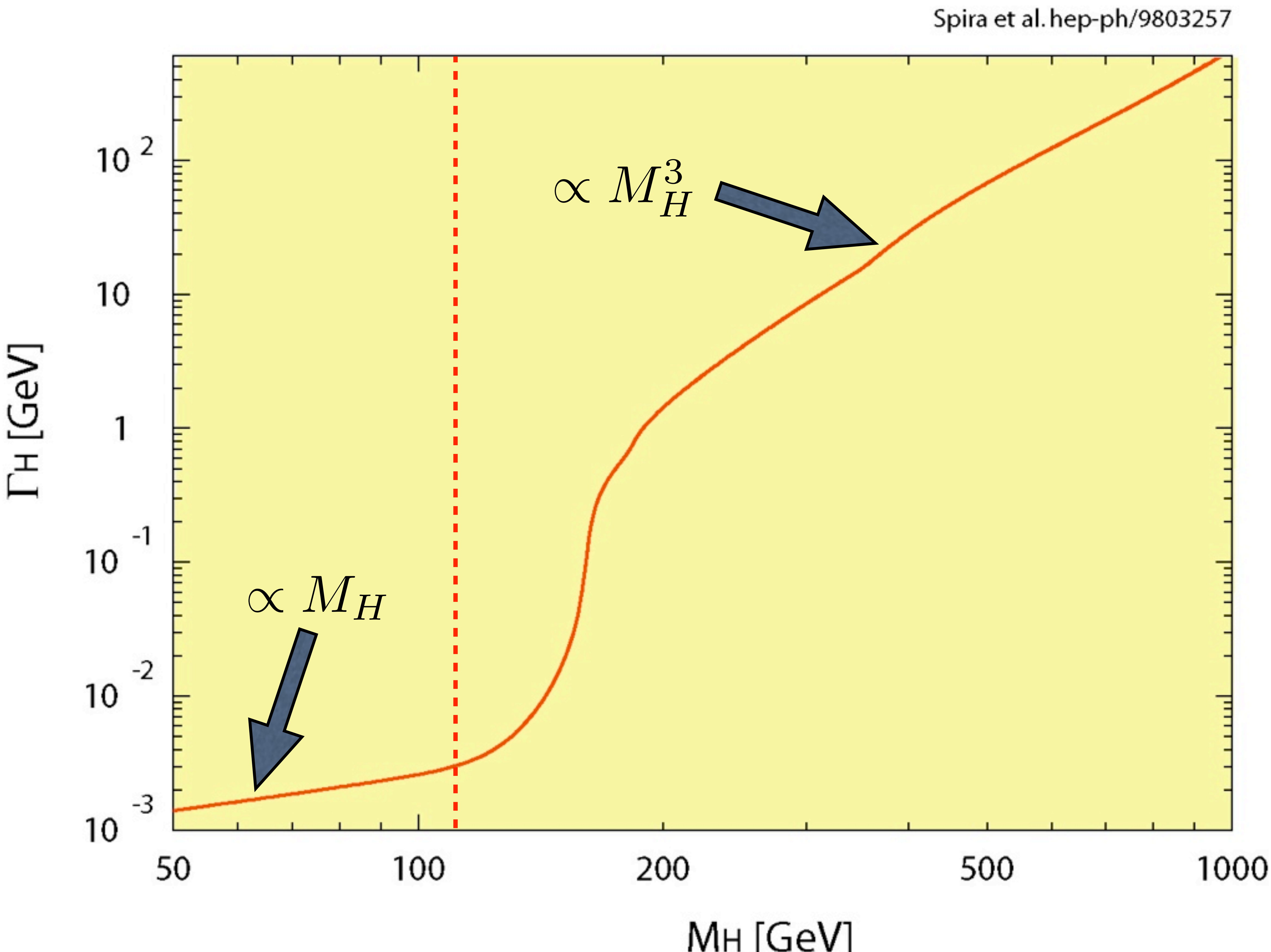
these loops are finite

$$\boxed{\mathscr{L}_{ggH} \supset \frac{1}{v}\, g_{ggH}\; H\, G^{\mu\nu} G_{\mu\nu}}$$

with $\frac{1}{v}\, g_{ggH} = -i\,\frac{\alpha_s}{8\pi}\,\frac{1}{v}\,\tau\,[1+(1-\tau)f(\tau)]$ $\quad \tau = 4\frac{m_{top}^2}{m_H^2}$

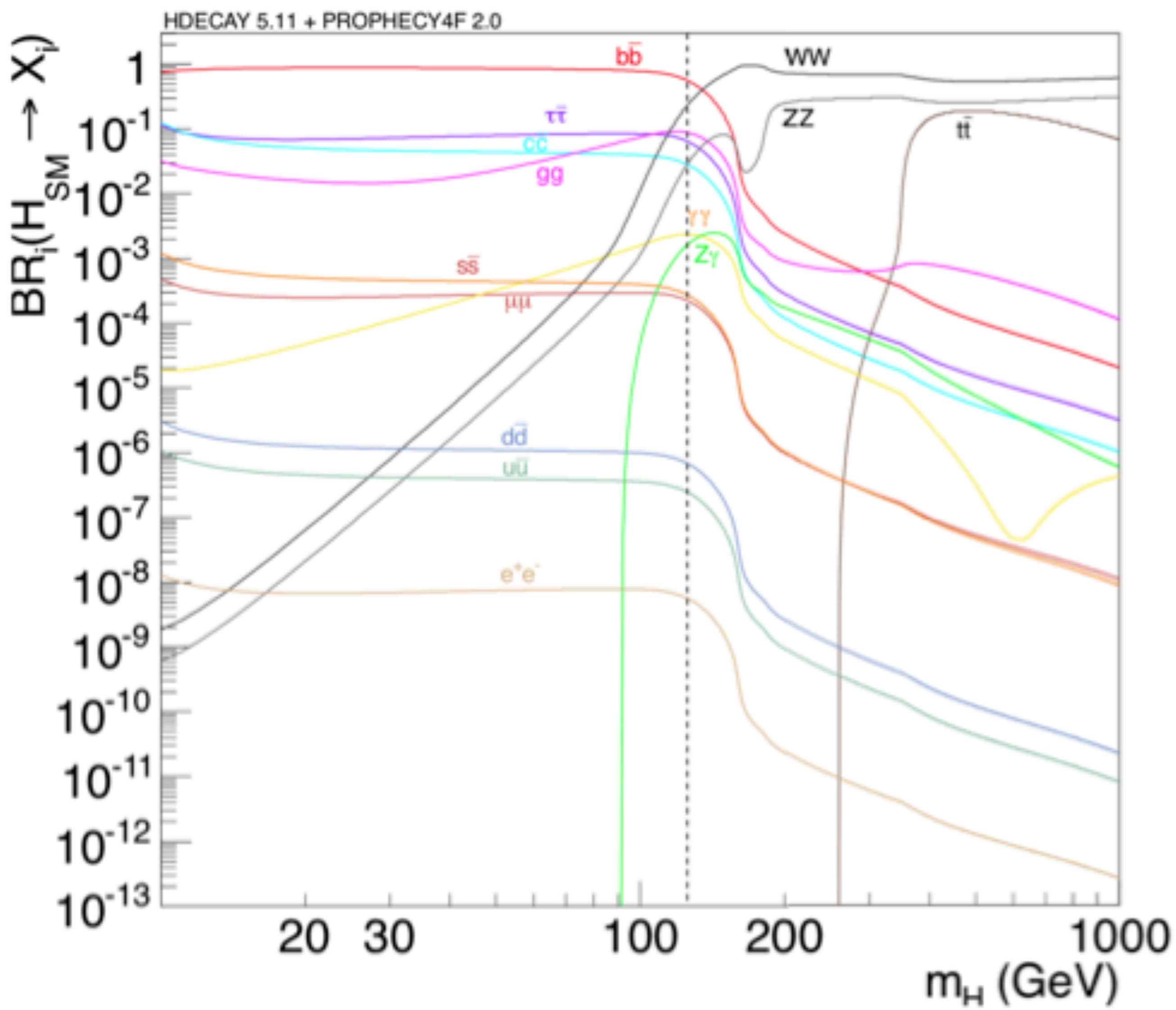
$$f(\tau) = \arcsin\sqrt{\frac{1}{\tau}} \quad \text{for} \quad \tau > 1$$

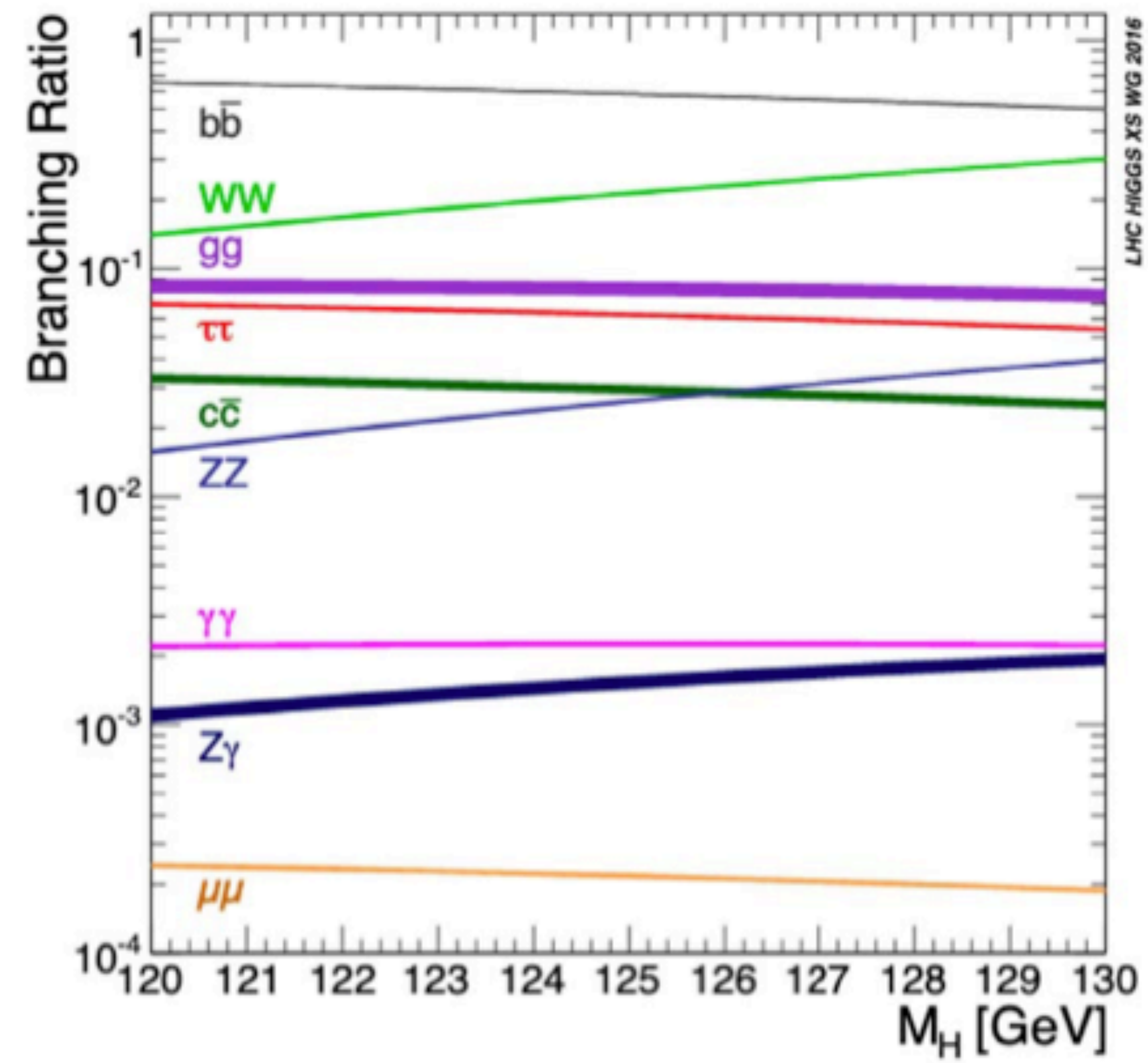
★ a light H is a narrow resonance



$$\Gamma_H = 4.07 \times 10^{-3}\ \text{GeV}$$

★The dominant decay modes vary with the Higgs mass



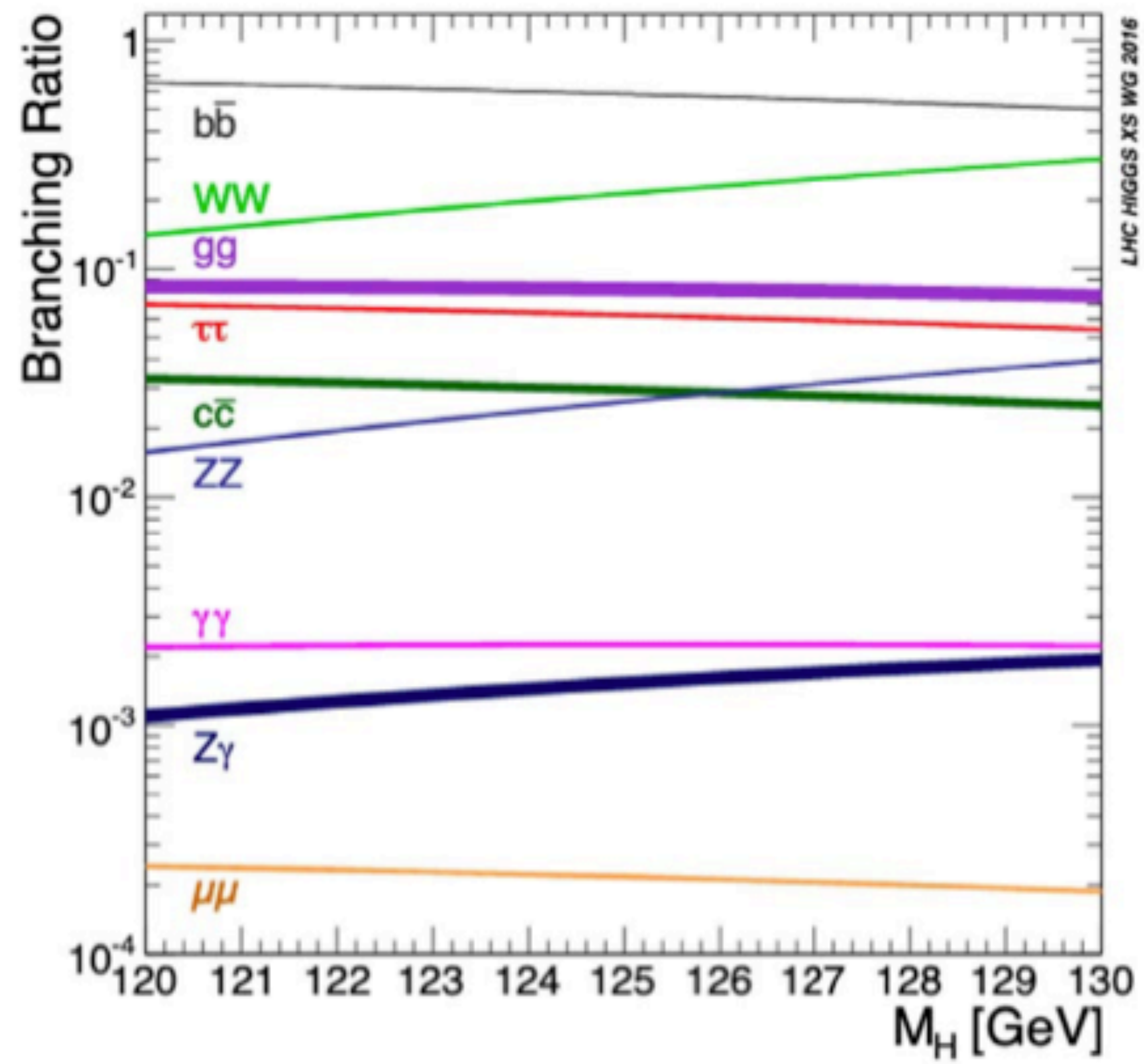


The decay modes $H \to WW^*$ and $H \to ZZ^*$ have been included

- The QCD background for Higgs decaying into b pairs is HUGE $\sigma_{\rm QCD}(b\bar{b}) = 200\mu{\rm b}$

★The dominant decay modes vary with the Higgs mass

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$



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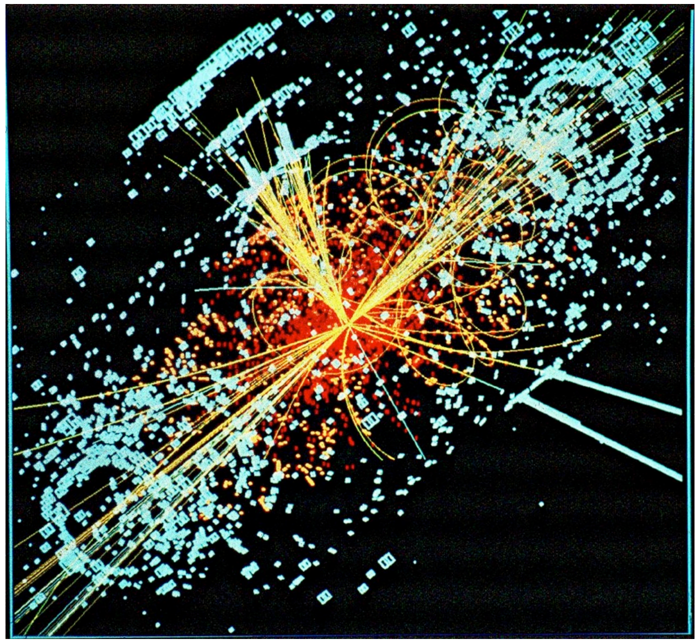
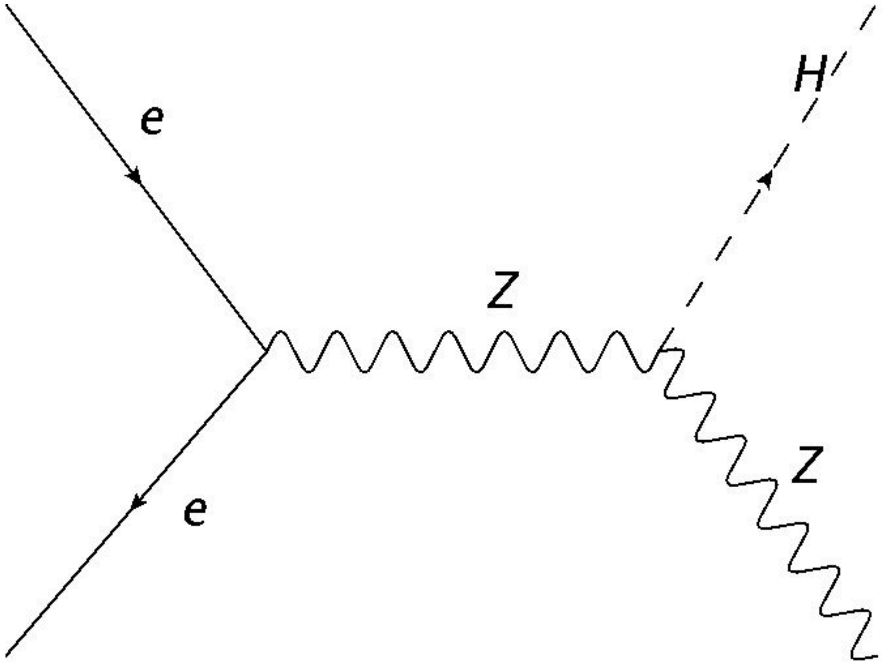
2. Production mechanisms

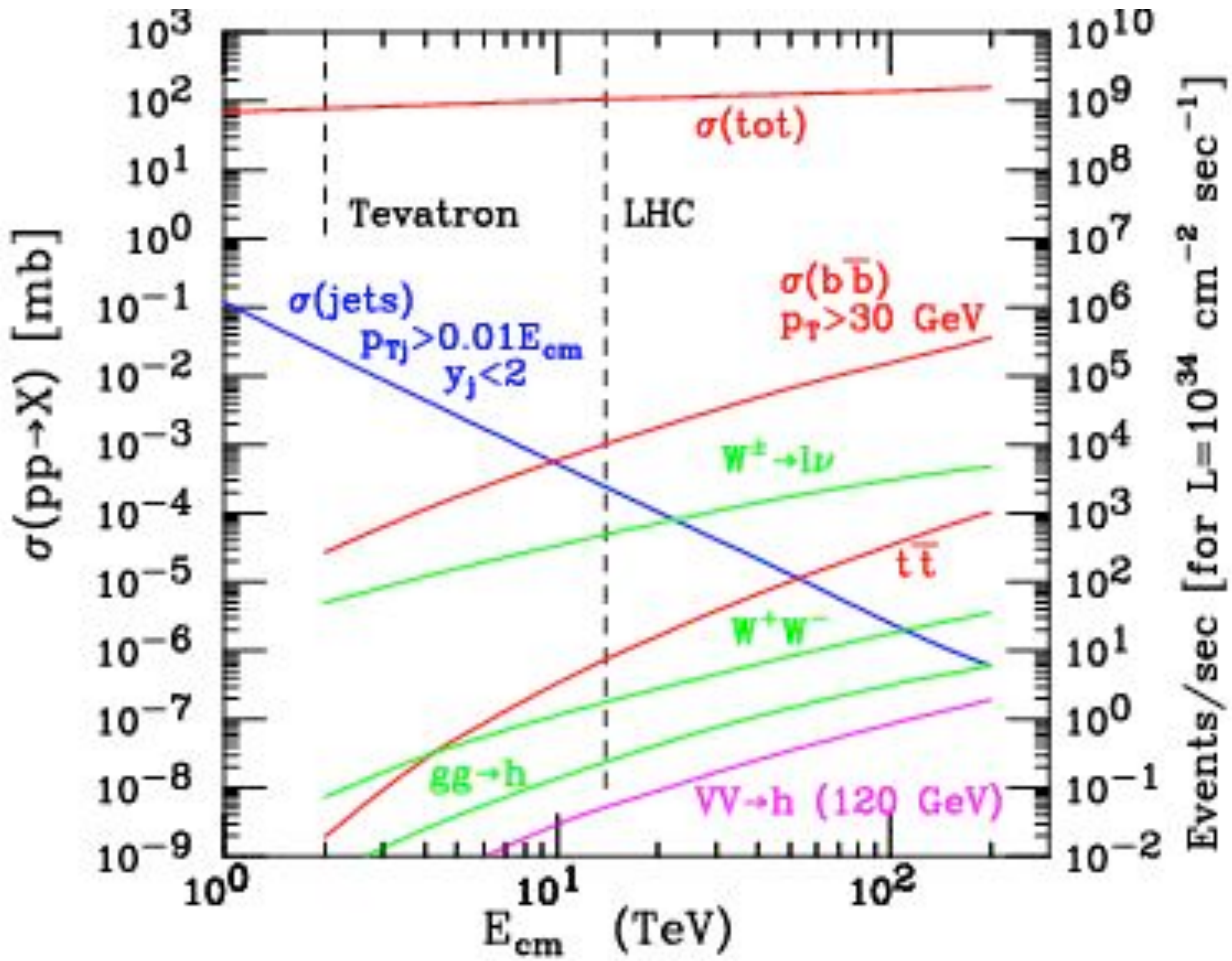


- At LEP the Higgs produced was dominated by the Bjorken mechanism $e^+e^- \to HZ$
  - Many Z decays can be reconstructed
  - Kinematics fixes the energy of the Z
  - For a SM Higgs, the b-jets can be reconstructed



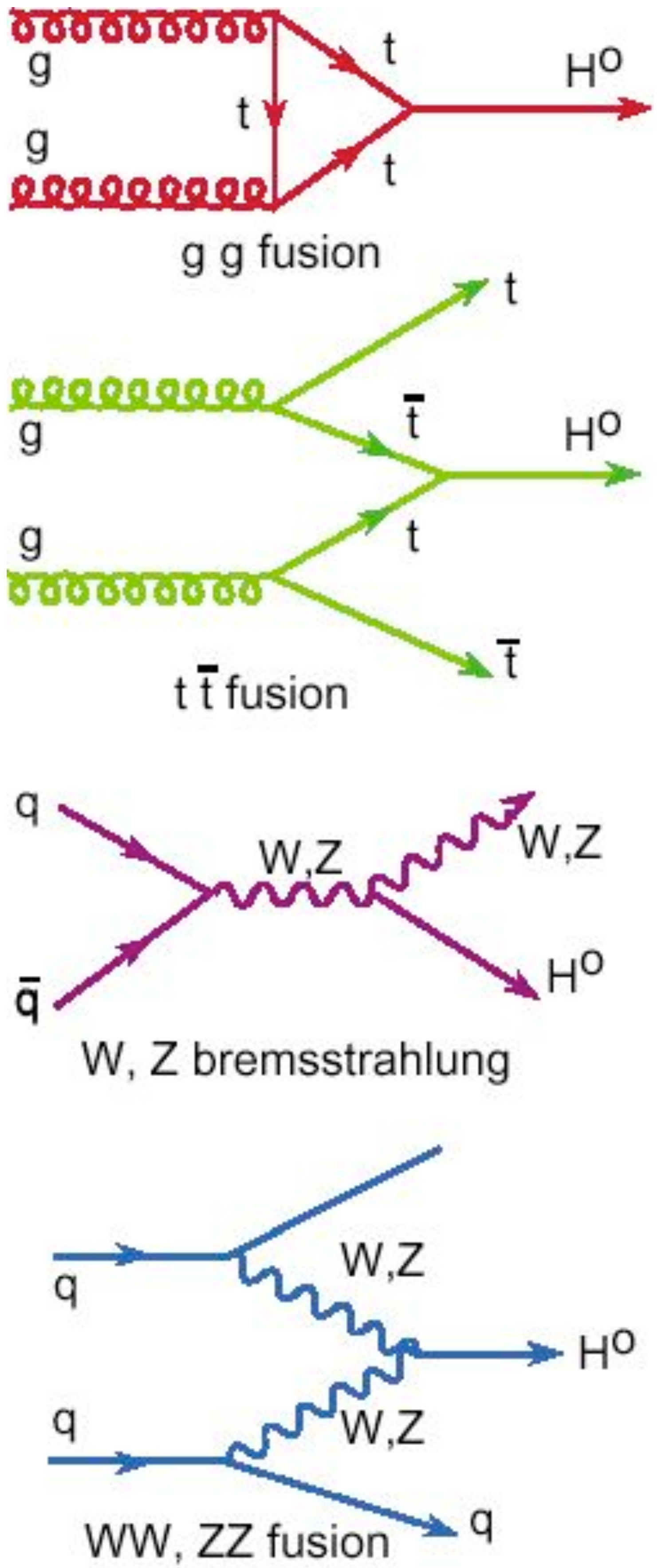
$$\text{LEP direct limit } M_H > 114.4 \text{ GeV}$$

before we talk about Higgs: main reactions at the Tevatron and LHC



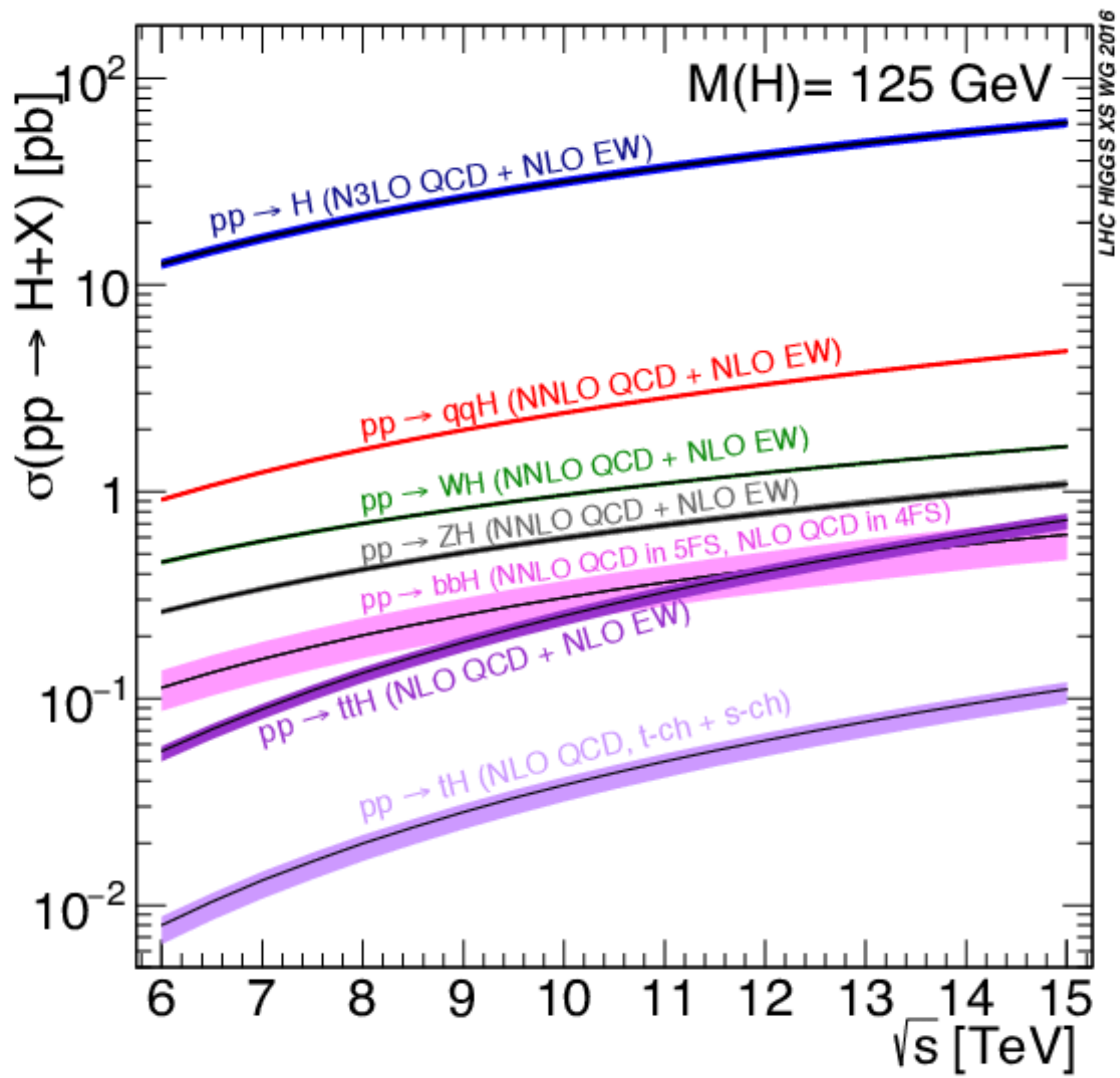
good to understand the difficulties of the Higgs searches

• At hadronic colliders the main production mechanisms are



• The importance of a process depends on the collider energy

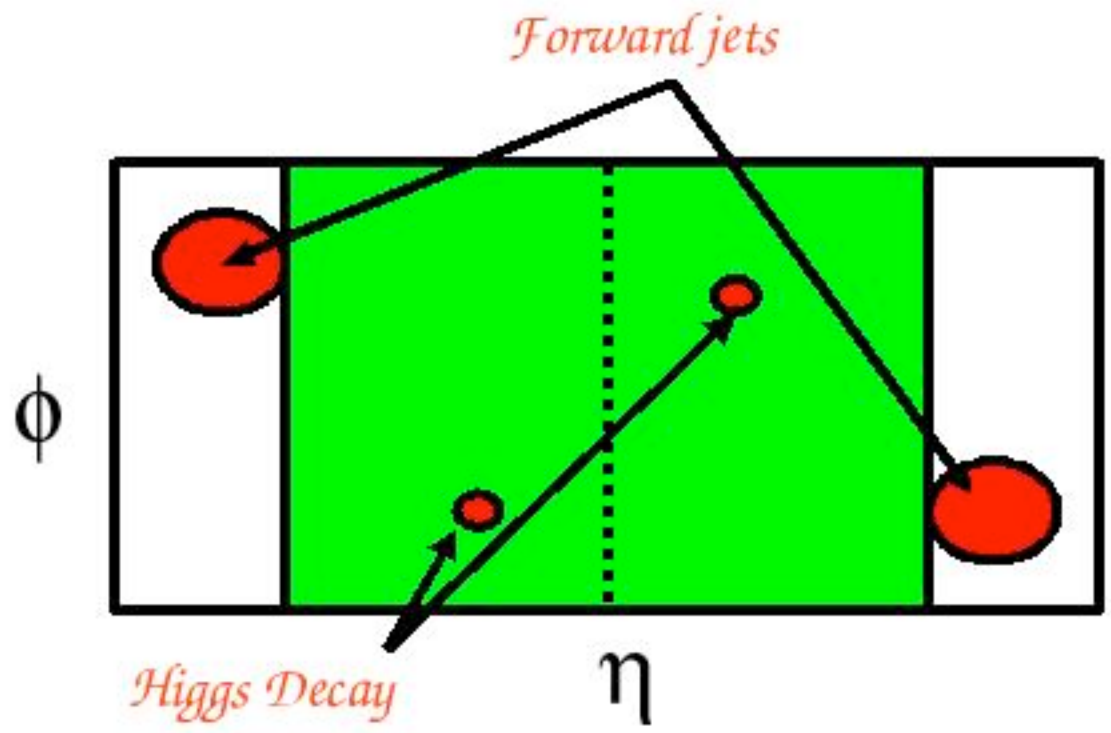
• At the LHC the cross sections are



•Cross sections known at least in NLO

- WW fusion process play an important role at the LHC

- A feature of WW fusion is the presence of forward jets that can be tagged $qq \to Hqq \to Hjj$



- Two useful decay modes are

$$H \to \tau^+\tau^- \quad \text{and} \quad H \to W^+W^-$$

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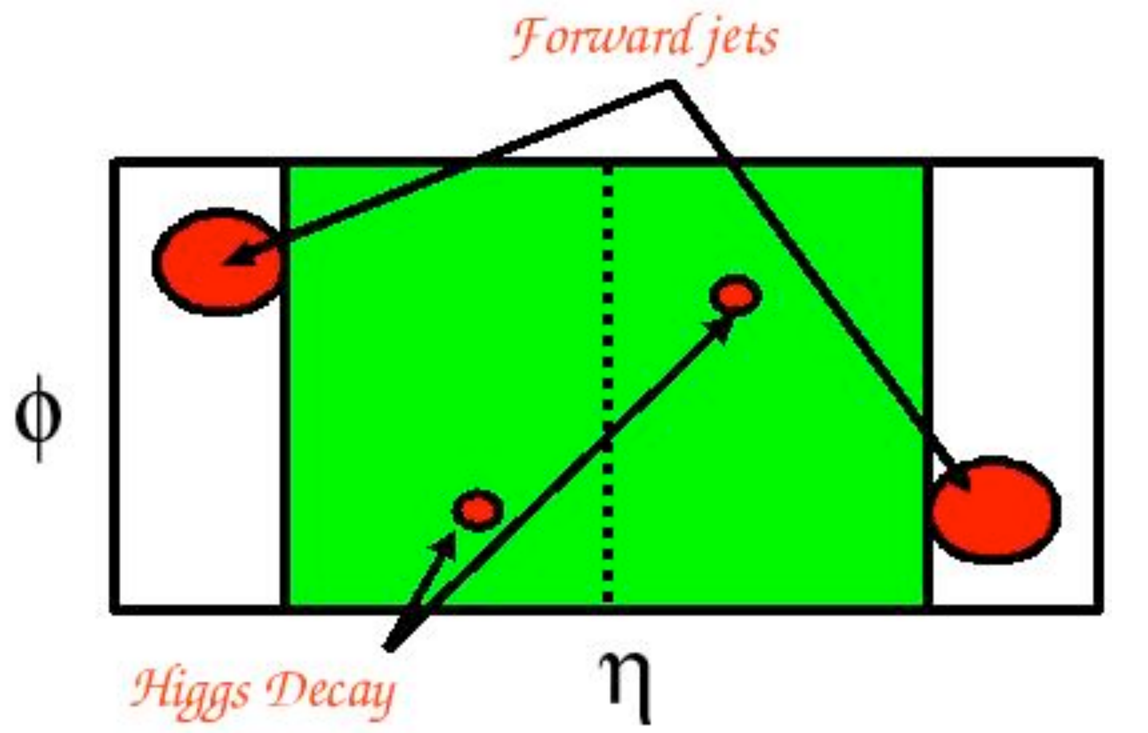


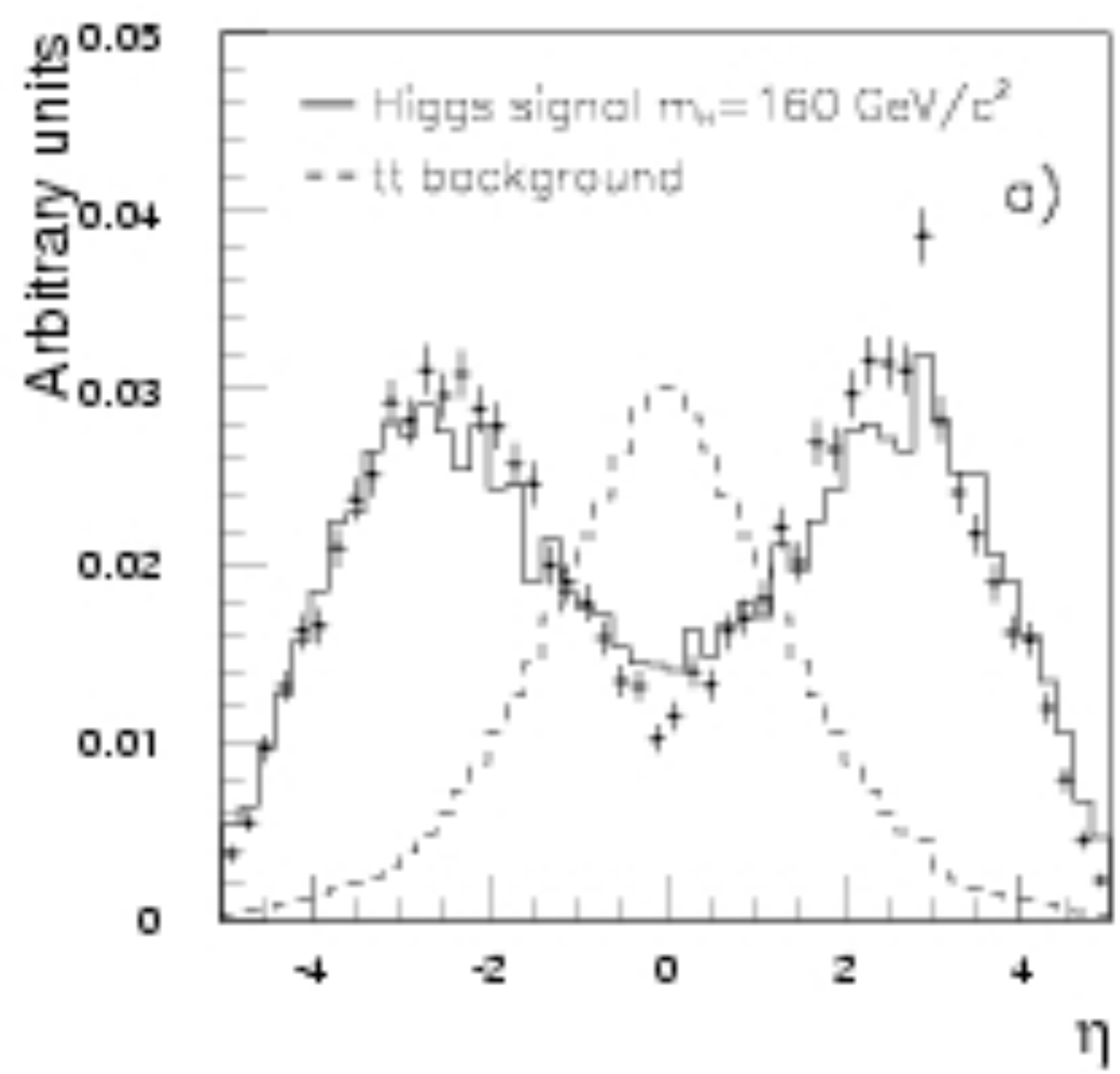
- Two useful decay modes are

$$H \to \tau^+\tau^- \quad \text{and} \quad H \to W^+W^-$$

- The main background is the associated production of top pairs and jets

- The separation between the tagging jets can be used to reduce the backgrounds

- It is possible to extract the signal



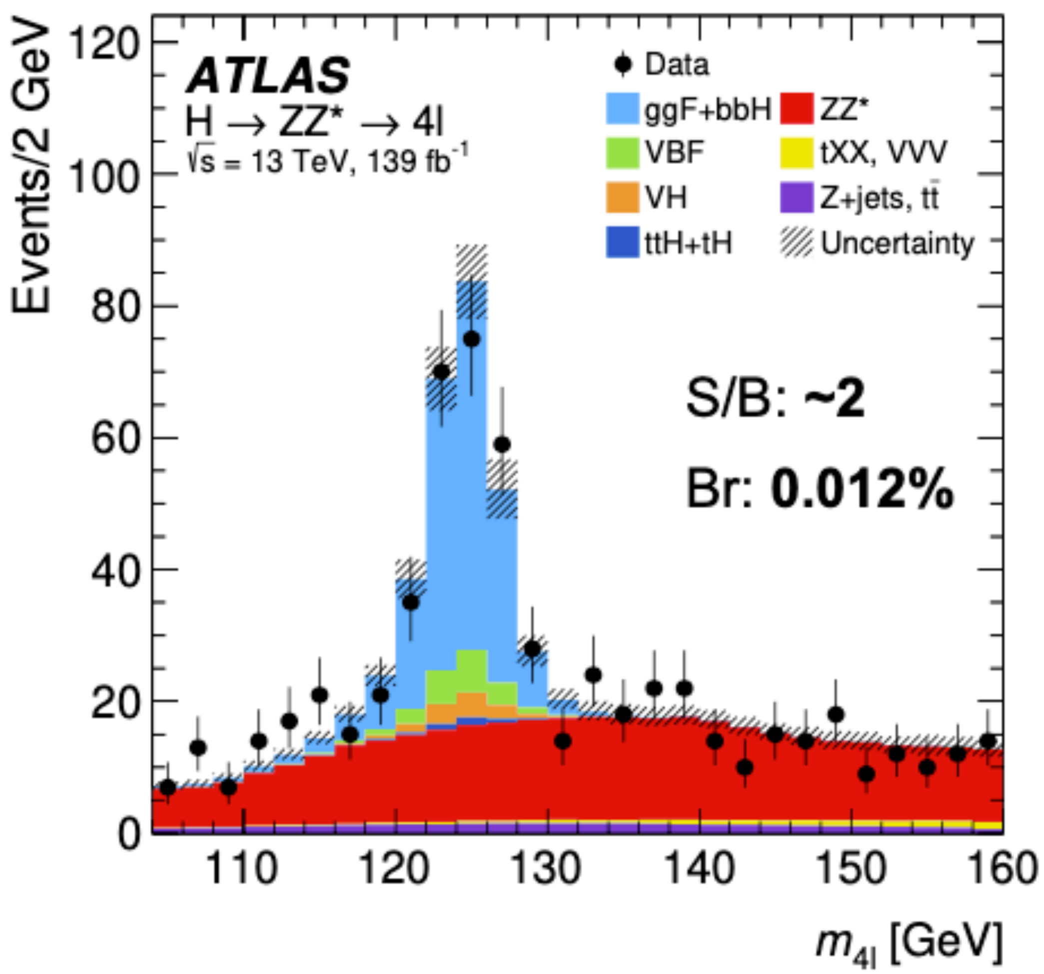
- Higgs produced at run 2 per experiment

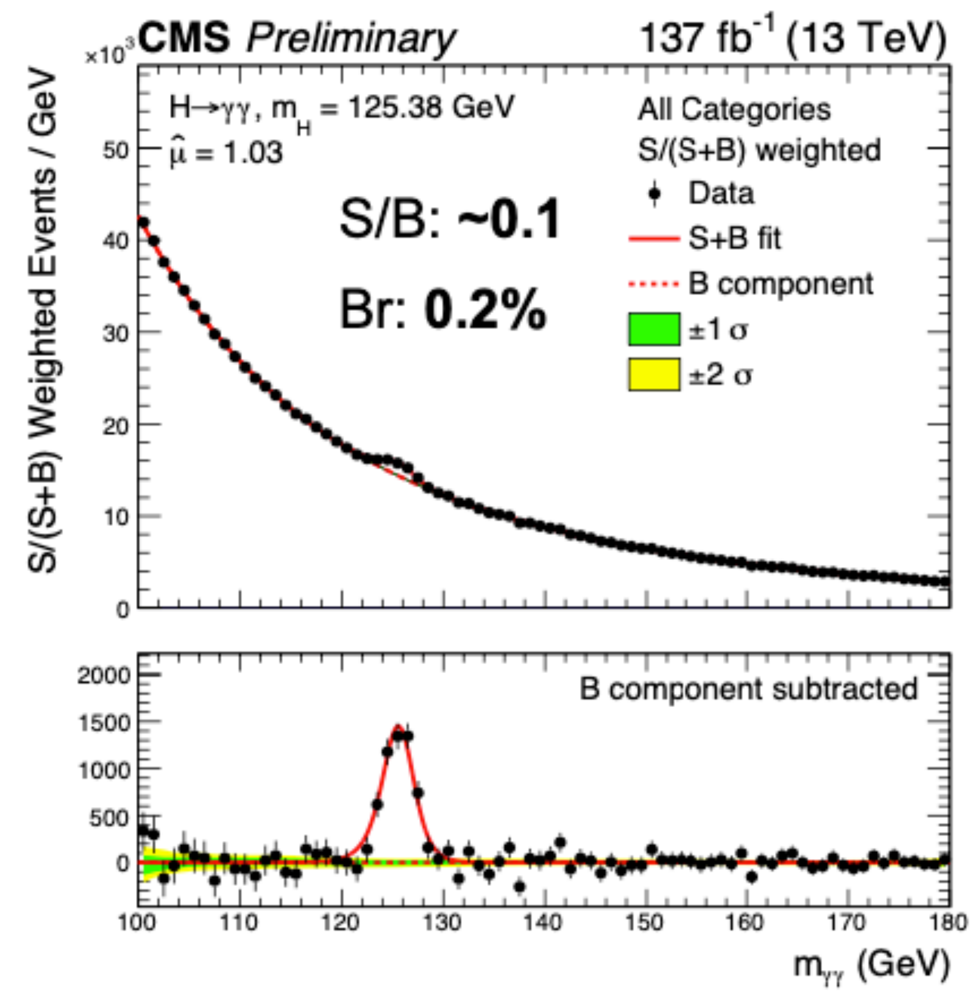
Mode	Number
total	7000000
AA	16000
ZZ to 4 leptons	900
WW to e mu	3000
tau tau	440000
mu mu	1500

3. A few results

• Precision channels

✦ Precision channels (H→ZZ*→4l, H→γγ) have driven the discovery and subsequent measurements in the Higgs sector



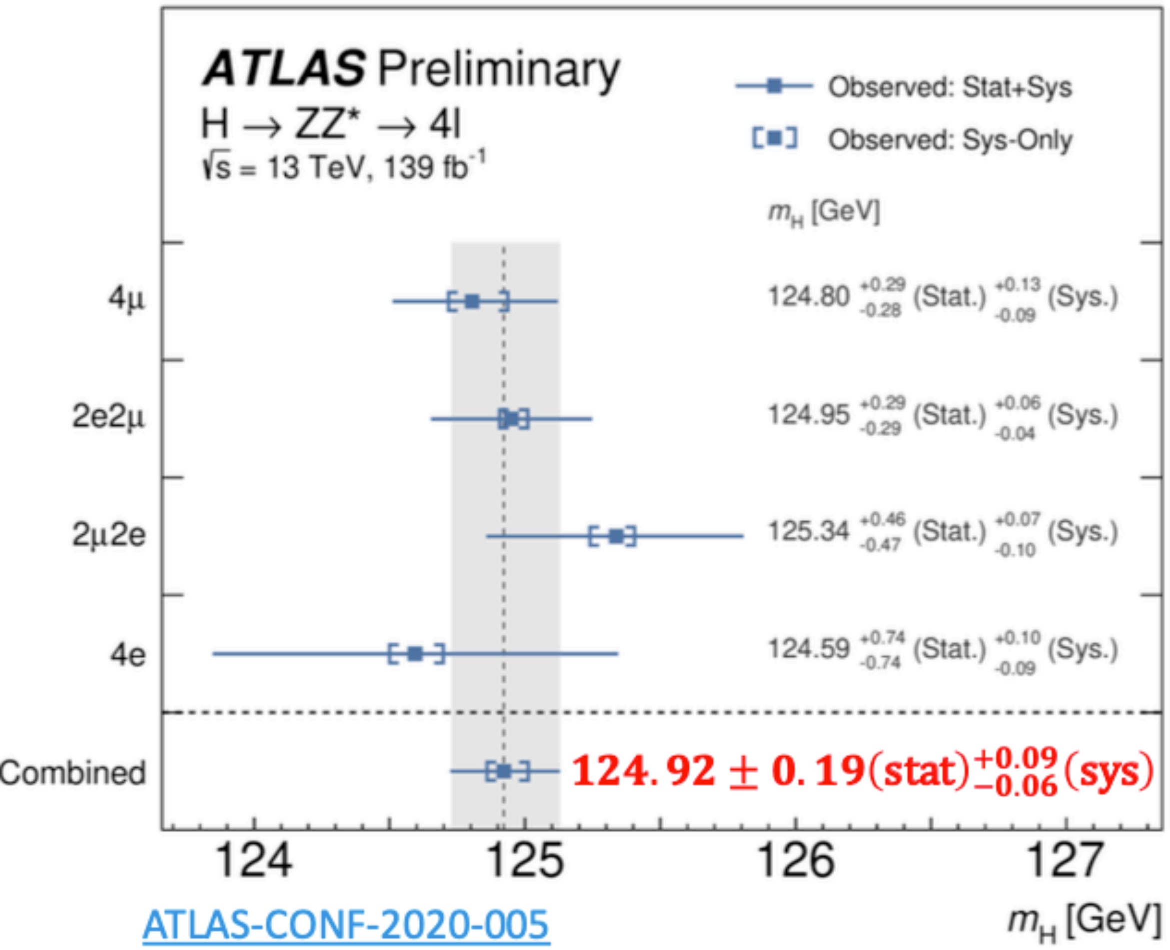


✦ ***Fully reconstructed final states, excellent precision!***

- ✦ powerful electron/muon/photon reconstruction, identification and calibration (few GeV detector resolution)
- ✦ can easily identify the Higgs candidate and then concentrate on the rest of the event

- The Higgs mass is well known

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



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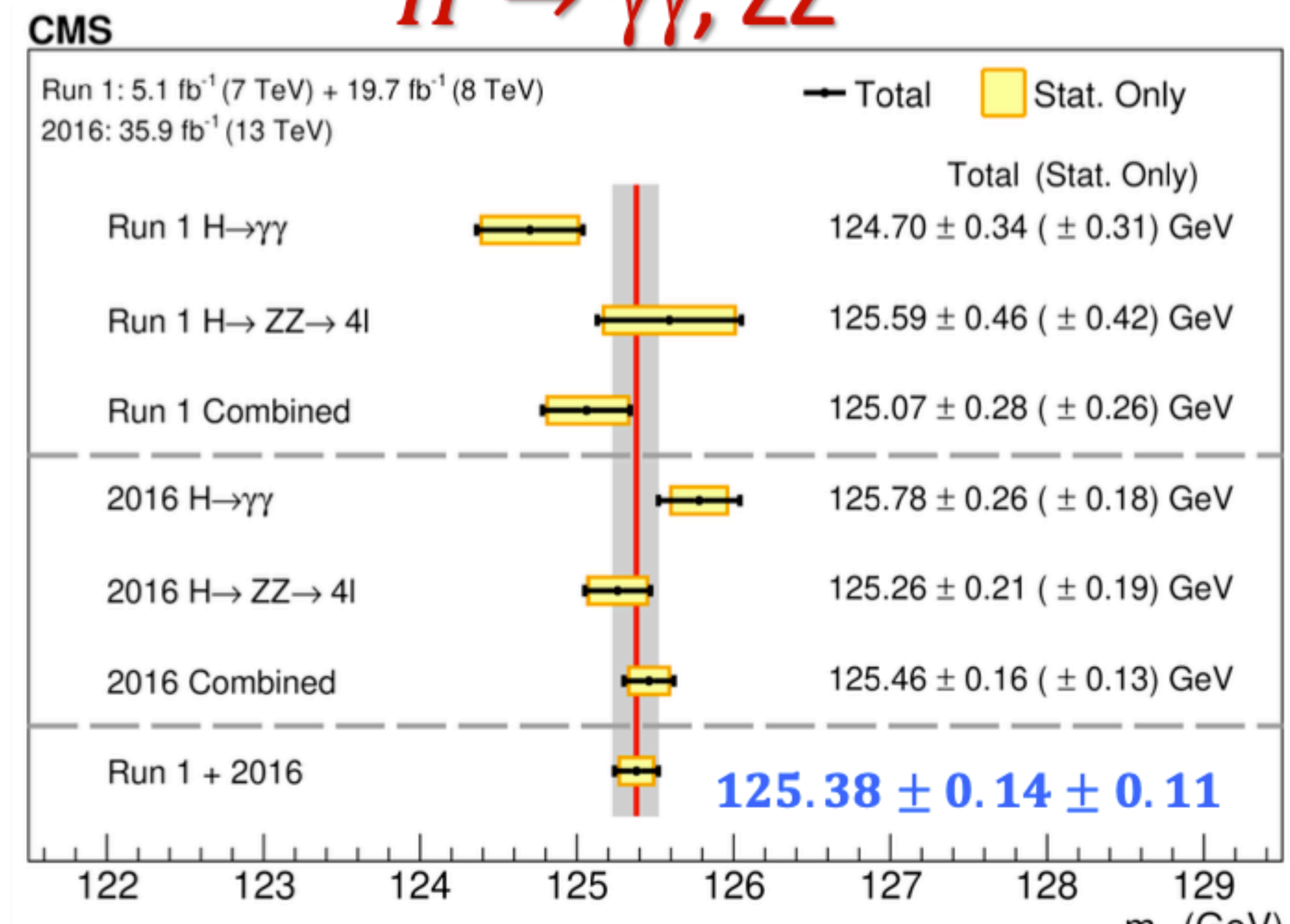
$H \to \gamma\gamma, ZZ^*$



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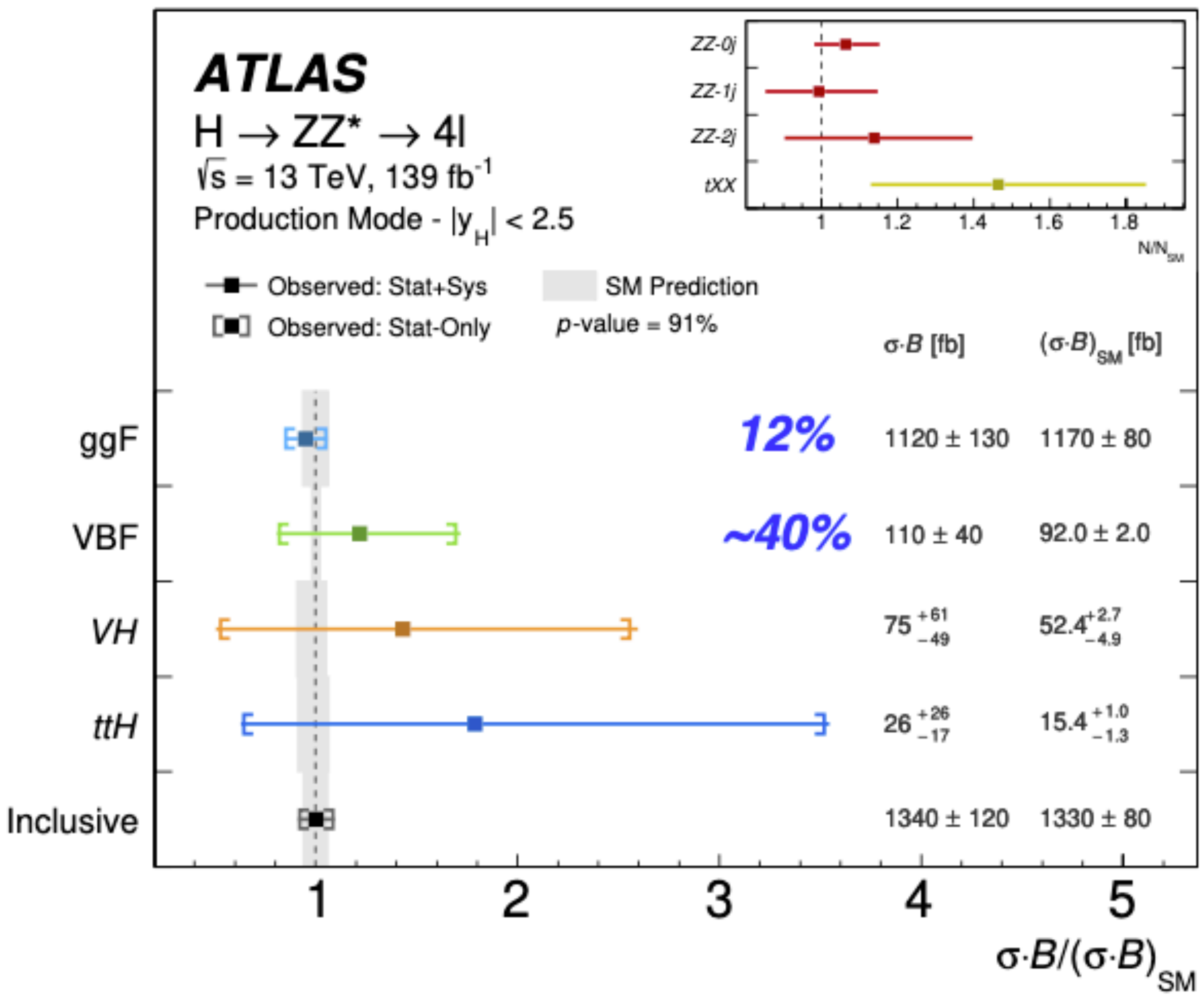
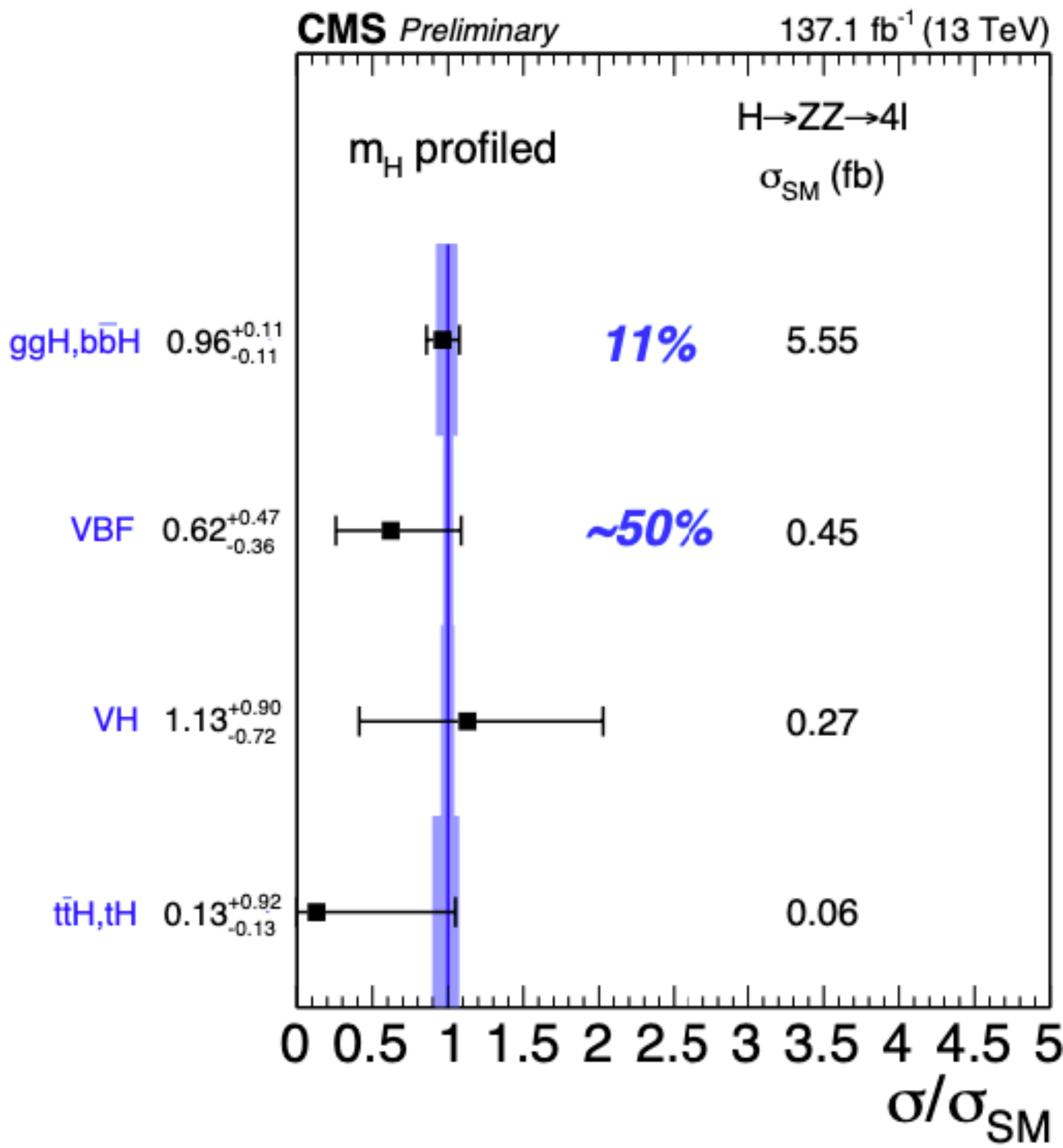
Precision reaching 0.1%, measurements still dominated by statistical uncertainty.

$m_h = 125$ GeV, $v = 246$ GeV $\to \lambda \approx 0.13$

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

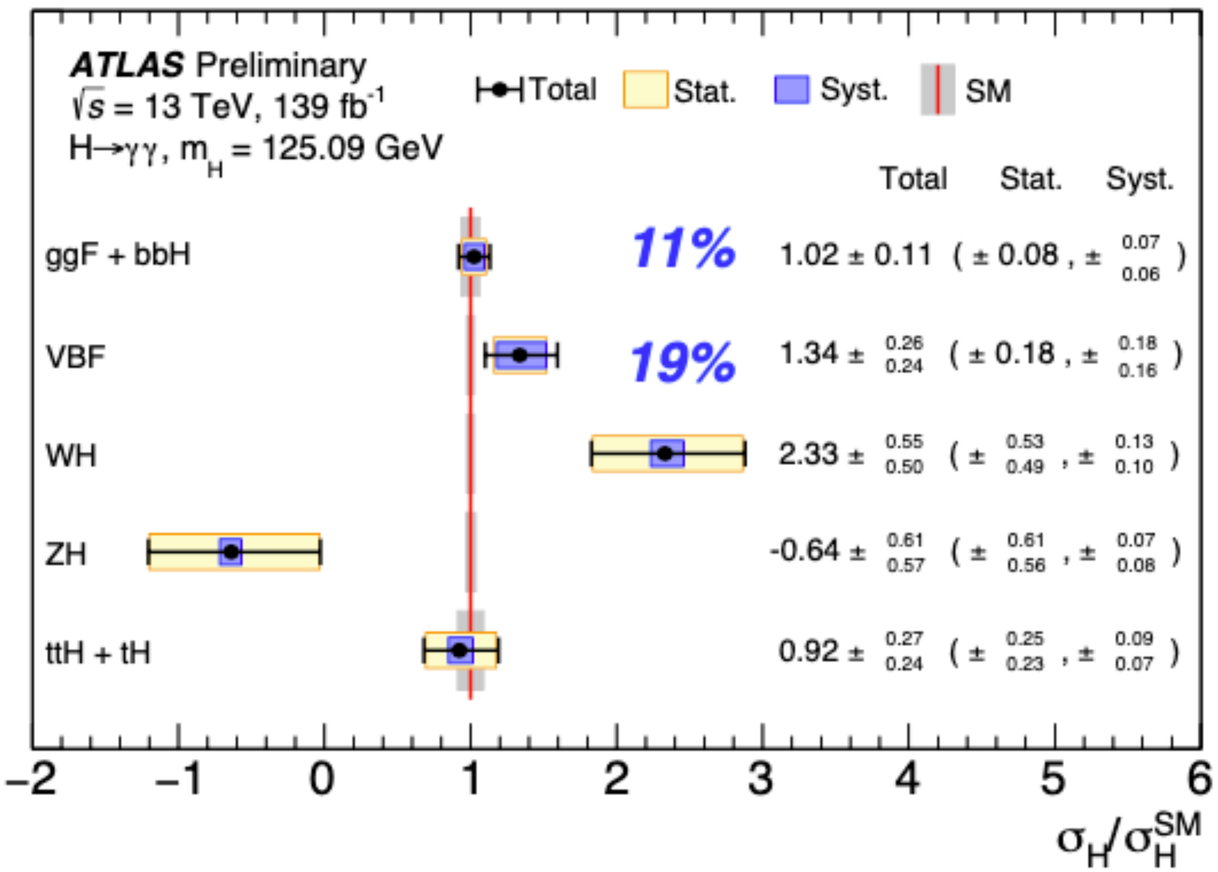


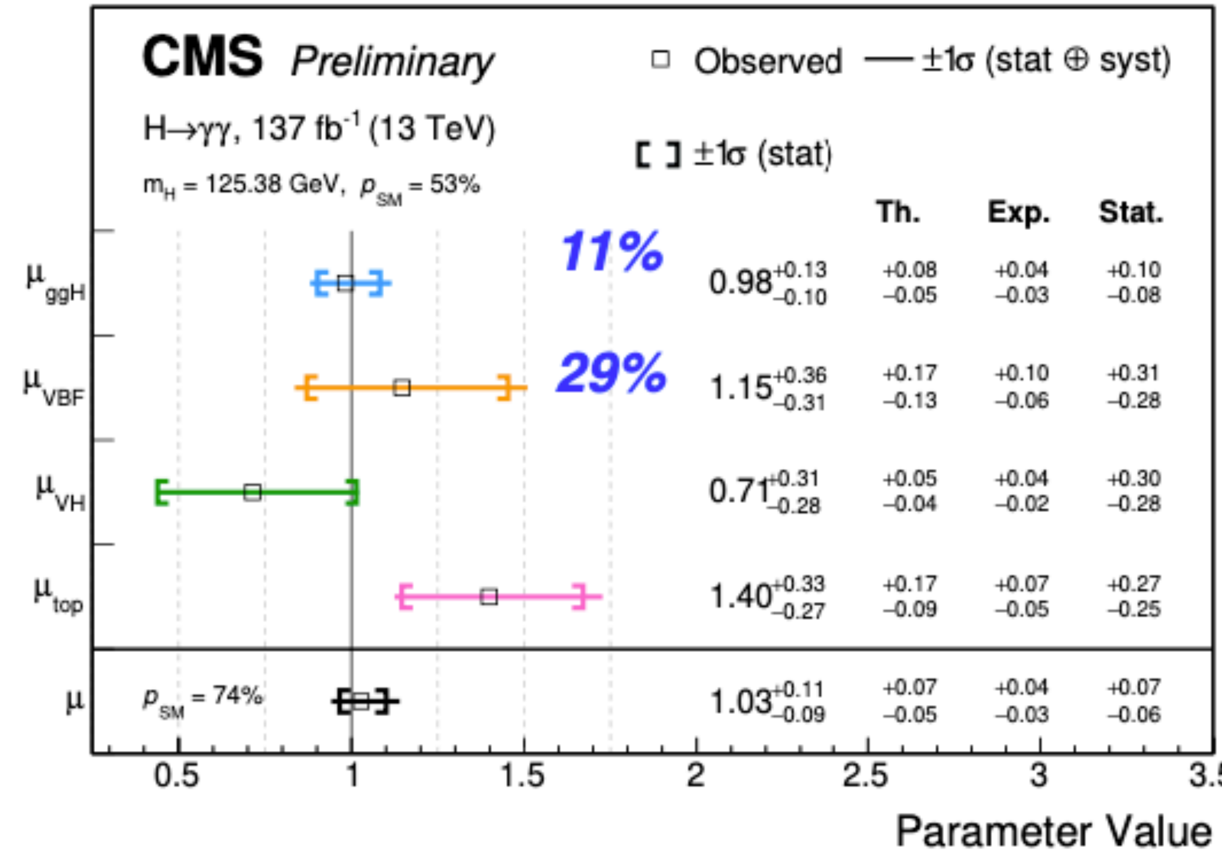


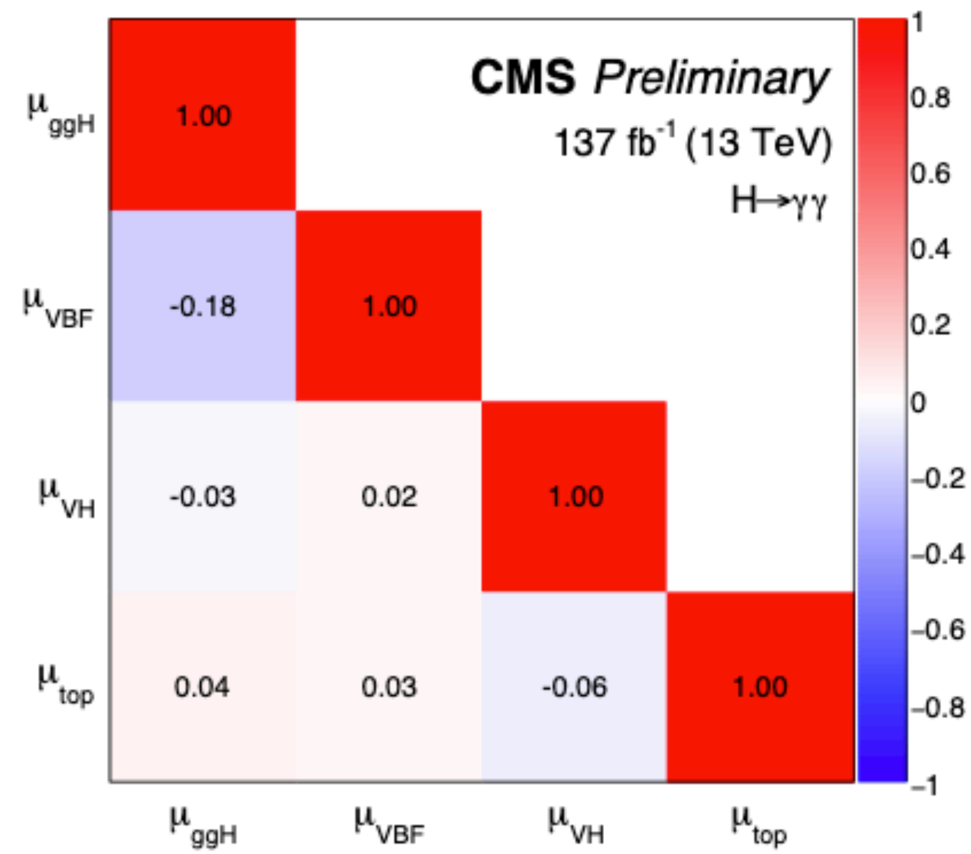
- ***Good agreement with SM predictions:***
  - ggH measurement at 12% level
  - other production modes more significantly stat. limited

$H \to \gamma\gamma$

- ***Good agreement with SM predictions:***
  - ggH measurement at 10% level (stat. and sys at similar level)
  - other production modes at 20%-50% precision







- Strong anti-correlation (-42%) between WH and ZH due to process cross-contamination:
  - 5 POI: p_{SM}= 3%
  - merging WH and ZH: p_{SM}= 50%

$H \to WW^{\star} \to e^{\pm}\nu\mu^{\mp}\nu$

- there are large backgrounds

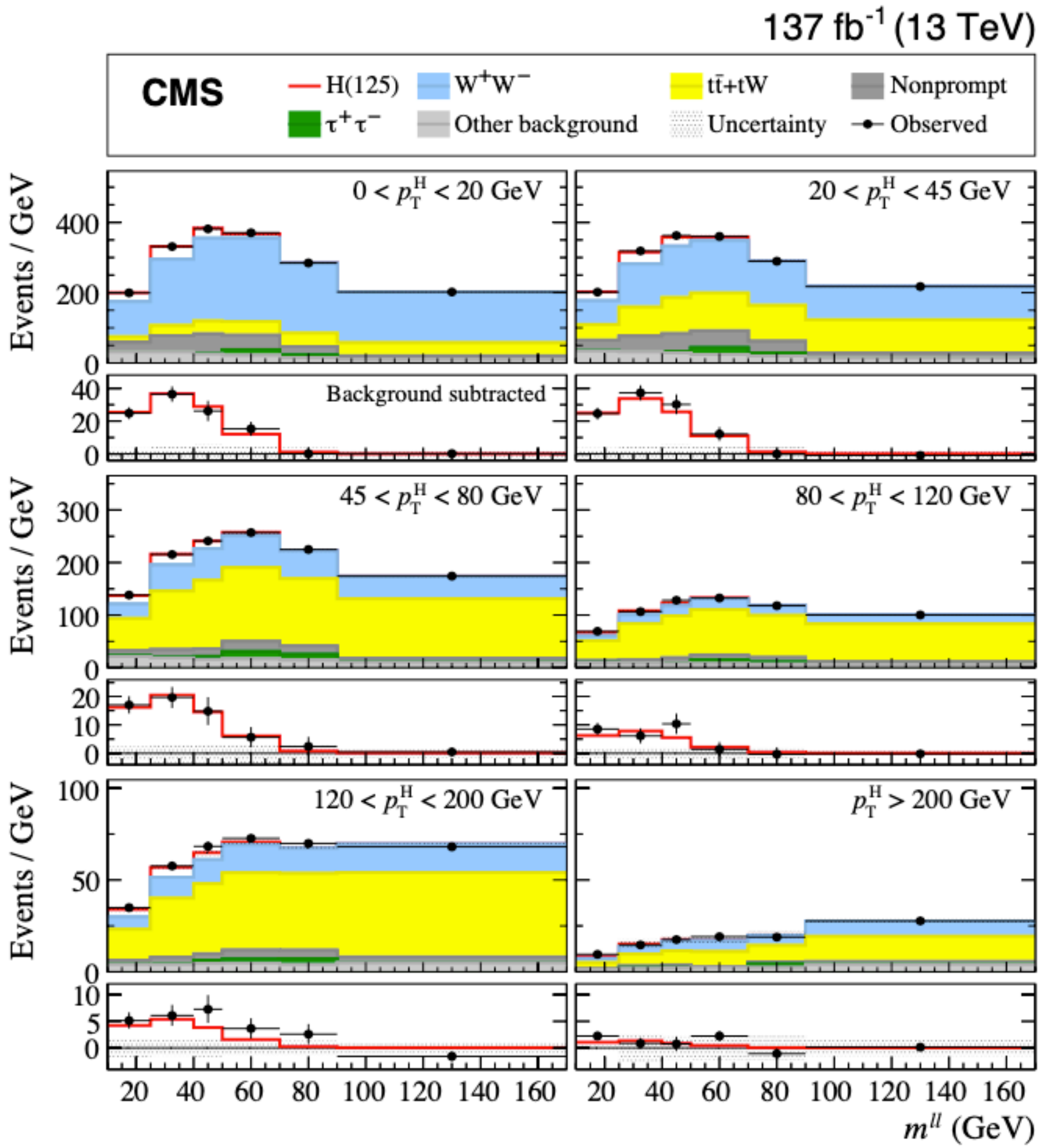
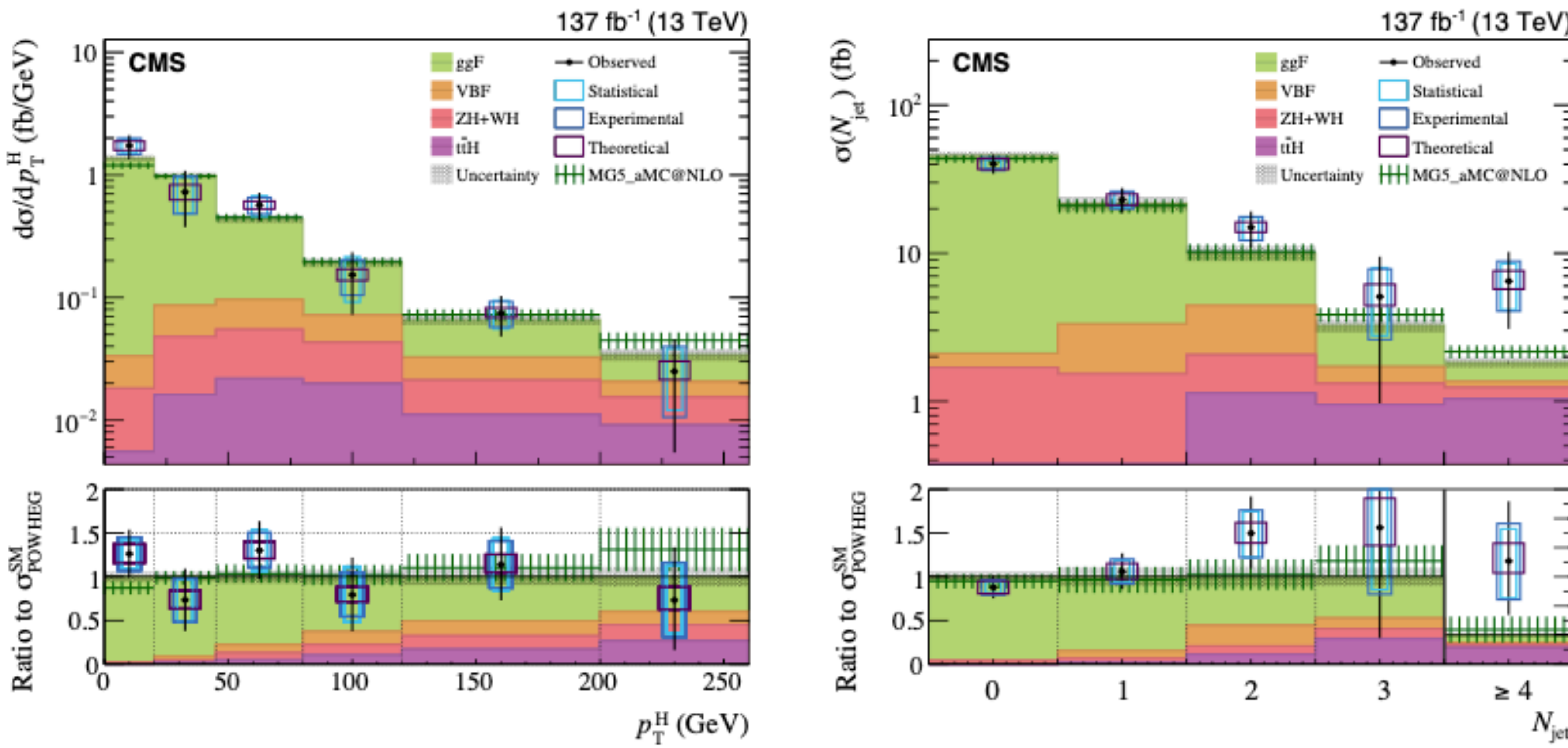


Table 1: Definition of the fiducial region.

Observable	Condition
Lepton origin	Direct decay of $H \to W^+W^-$
Lepton flavors; lepton charge	e μ (not from τ decay); opposite
Leading lepton p_T	$p_T^{l_1} > 25\,\text{GeV}$
Trailing lepton p_T	$p_T^{l_2} > 13\,\text{GeV}$
$\|\eta\|$ of leptons	$\|\eta\| < 2.5$
Dilepton mass	$m^{ll} > 12\,\text{GeV}$
p_T of the dilepton system	$p_T^{ll} > 30\,\text{GeV}$
Transverse mass using trailing lepton	$m_T^{l_2} > 30\,\text{GeV}$
Higgs boson transverse mass	$m_T^{H} > 60\,\text{GeV}$

- Good agreement with SM



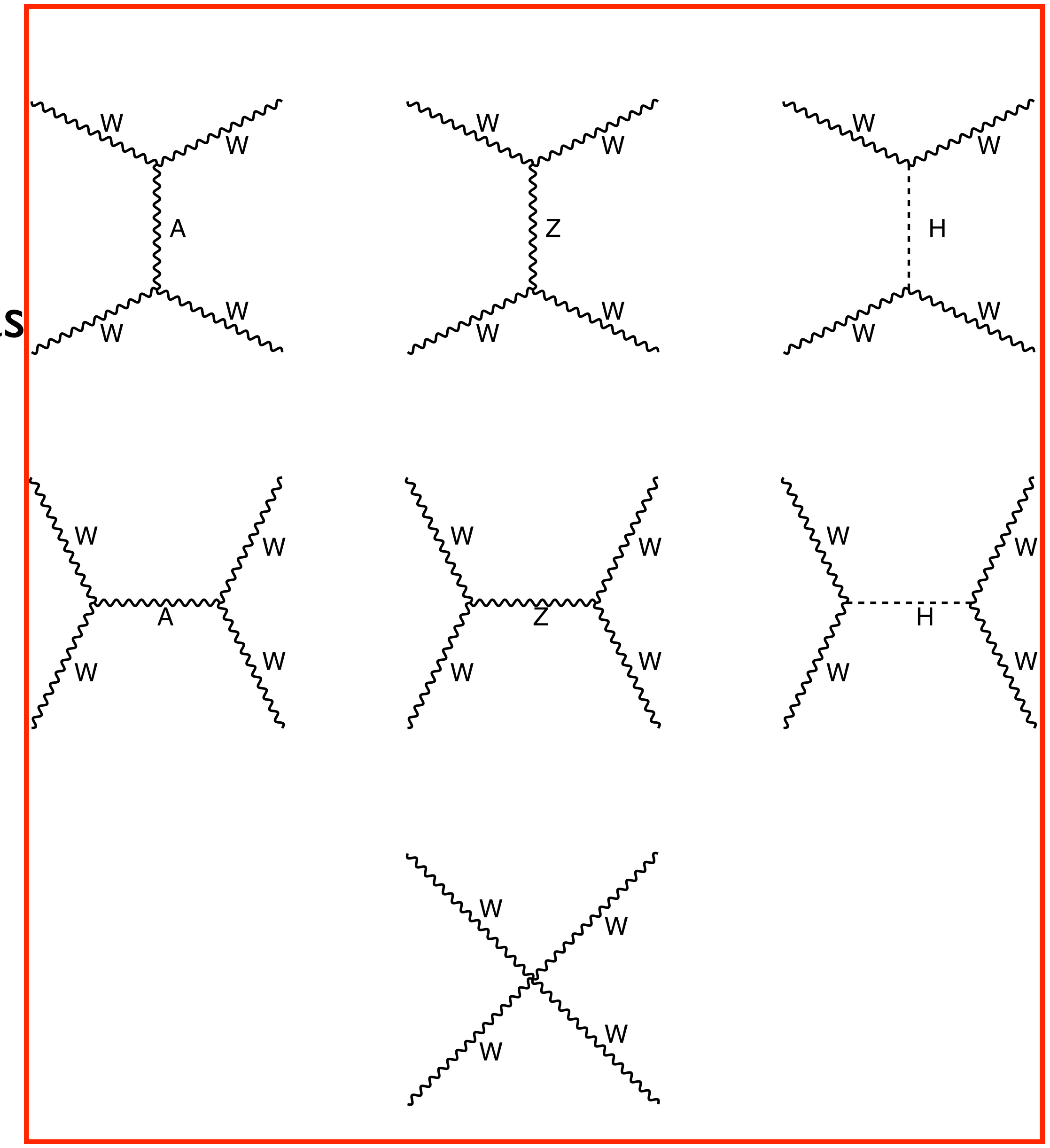
$$\mu^{\text{fid}} = 1.05 \pm 0.12 \left(\pm 0.05\,(\text{stat}) \pm 0.07\,(\text{exp}) \pm 0.01\,(\text{signal}) \pm 0.07\,(\text{bkg}) \pm 0.03\,(\text{lumi})\right).$$

$$\sigma^{\text{fid}} = 86.5 \pm 9.5\ \text{fb}.$$

3. Unitarity in WW scattering (Lee-Quigg-Thacker, Cornwall, etc)

- Let us analyze the scattering of longitudinal W's ("Goldstone bosons") at high energies

$$W_L^+ W_L^- \to W_L^+ W_L^-$$



- We can approximate $\epsilon_W^\mu \simeq p_W^\mu$
- A 2 to 2 elastic scattering cross section can be written as

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \mid \mathcal{A} \mid^2$$

- the partial wave decomposition is

$$\mathcal{A} = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

- However,

$$\sigma = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) \mid a_l \mid^2 = \frac{1}{s} Im\Big[\mathcal{A}(\theta=0)\Big] = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) \mid a_l \mid^2$$

- Therefore, unitarity implies that

$$| a_l |^2 = Im(a_l) \quad \text{or the equivalent form} \quad | Re(a_l) | < \frac{1}{2}$$

- Let's analyze the J=0 partial wave. In the $M_W^2 << s$ limit

$$\begin{aligned} a_0^0(W_L^+ W_L^- \to W_L^+ W_L^-) &\equiv \frac{1}{16\pi s}\int_{-s}^{0} | \mathcal{A} | \, dt \\ &= -\frac{M_h^2}{16\pi v^2}\left[2 + \frac{M_h^2}{s - M_h^2} - \frac{M_h^2}{s}\log\left(1 + \frac{s}{M_h^2}\right)\right] \end{aligned}$$

- Taking the high-energy limit $M_H^2 << s$

$$a_0^0 \longrightarrow -\frac{M_h^2}{8\pi v^2}$$

- Using the above unitarity condition leads to

$$M_H < 870 \text{ GeV}$$ (710 GeV)

- In the observed value of the Higgs mass is compatible with unitarity

4. Triviality constraints

✳ The Higgs quartic coupling “changes with the scale due to loop corrections” (it’s a way to improve the convergence of PT):

$$\text{defining } t \equiv \log(Q^2/Q_0^2) \quad \text{we have} \quad \frac{d\lambda}{dt} = \frac{3\lambda^2}{4\pi^2}$$

whose solution is

$$\lambda(Q) = \frac{\lambda(Q_0)}{\left[1 - \frac{3\lambda(Q_0)}{4\pi^2}\log(\frac{Q^2}{Q_0^2})\right]}$$

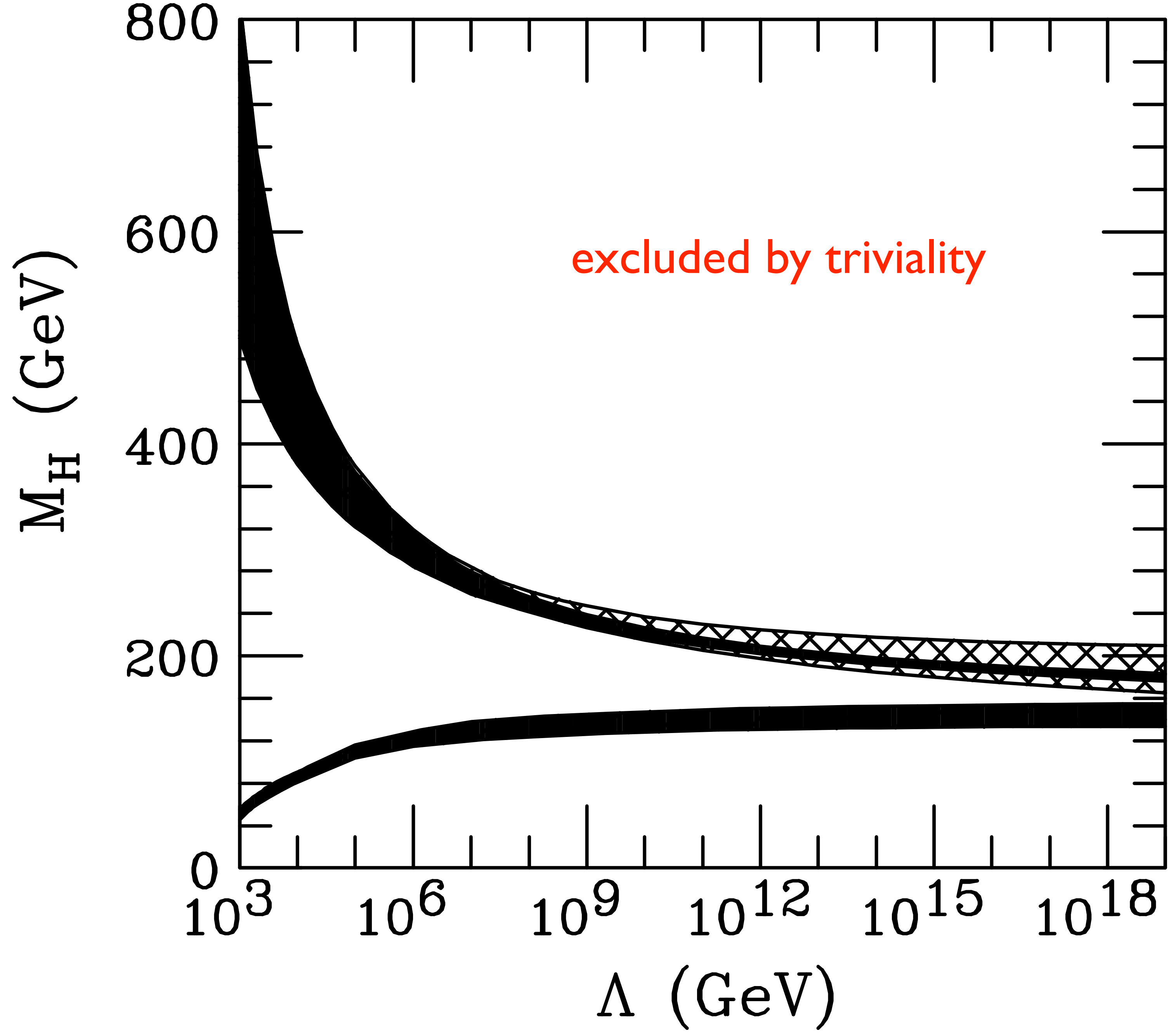
✳ The SM stops being valid at the energy scale Q such that

$$\ln\left(\frac{Q}{Q_0}\right) = \frac{4\pi^2}{3\lambda(Q_0)}$$

✳ Requiring the SM to be valid up to the scale Λ leads to a constraint on the Higgs mass

$$\mathrm{M}_H^2 < \frac{8\pi^2 v^2}{3\log(\Lambda^2/v^2)} \quad \text{where we used that} \quad \mathrm{M}_H^2 = 2\lambda(Q_0)v^2$$

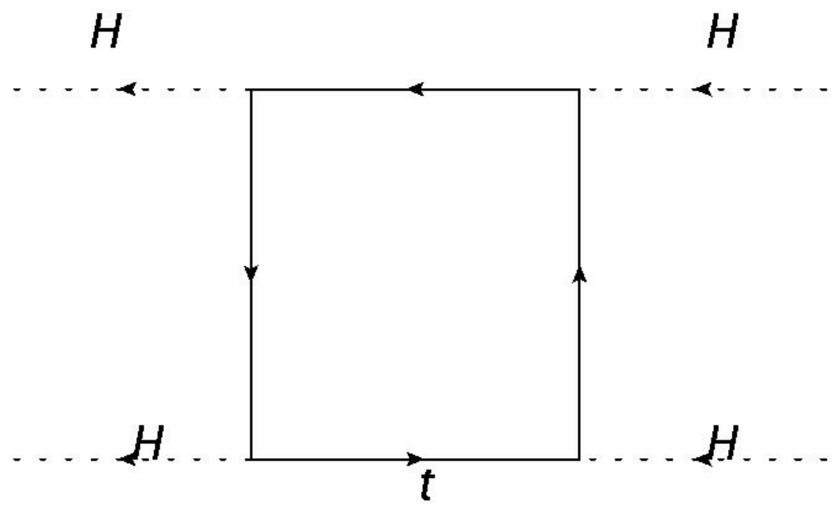
✳ excluded Higgs masses



5. Stability of the SM

- Top loop corrections to the quartic Higgs couplings are sizeable and negative.

- If λ is small the scalar effective potential can be unbound from below



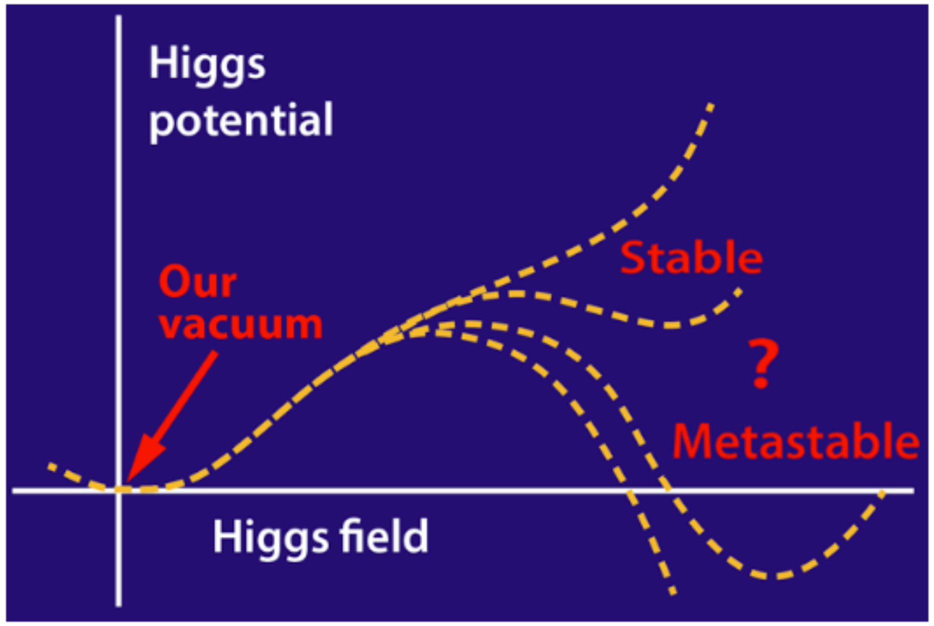
$$V_{\text{eff}} = V_{\text{tree}} + \frac{6M_W^4 + 3M_Z^4 - 12m_t^4}{64\pi^2 v^4}\ \phi^4 \ln\frac{\phi^2}{M^2}$$

- This expression must be improved using the RGE due to the appearance of large log's of the Higgs

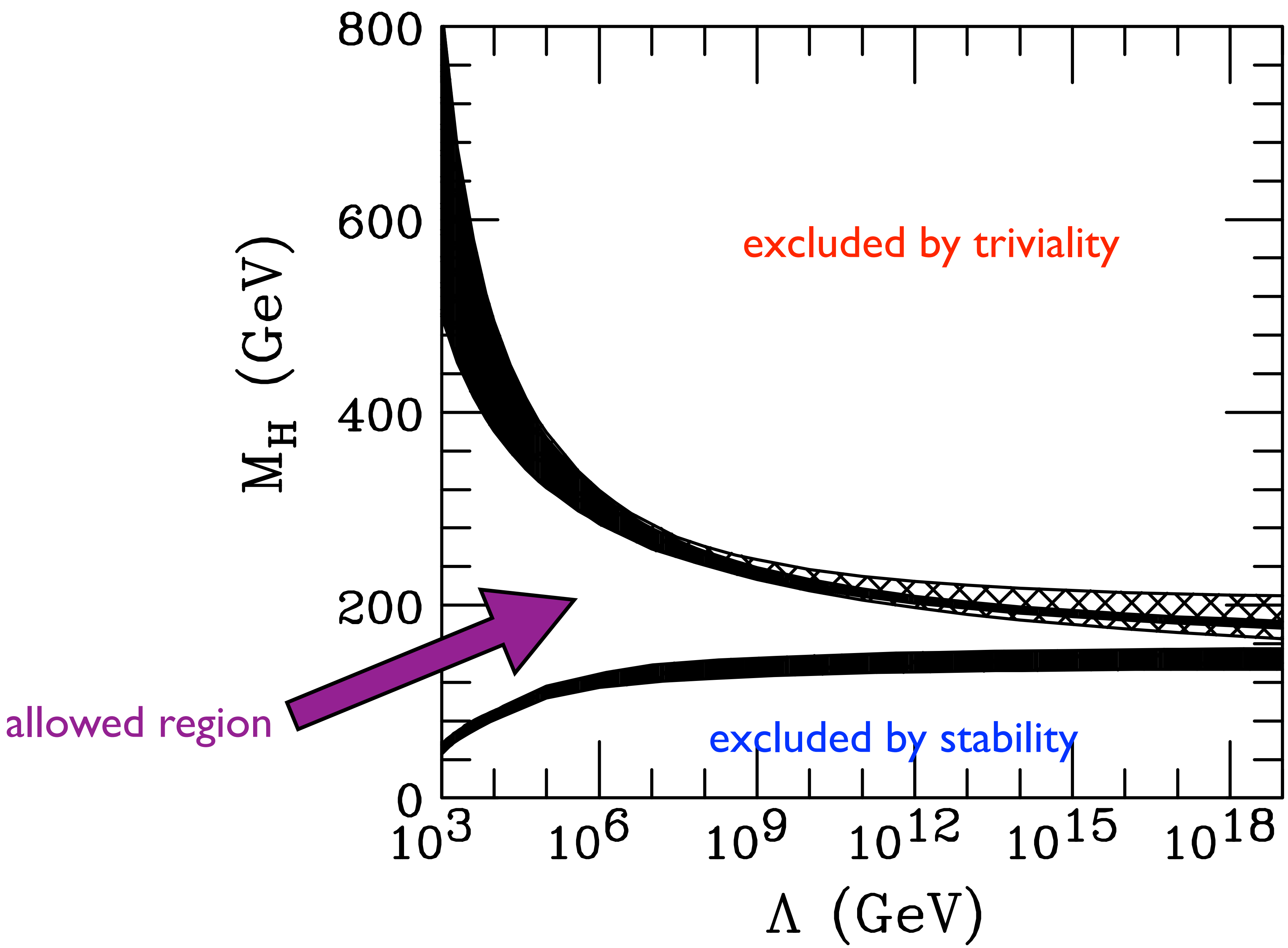
- This calculation has been don using two-loop RGE's, extracting the physical Higgs mass, etc

- bounds were obtained requiring that $\lambda(\Lambda) > 0$

new physics scale (limit for the validity of the SM)

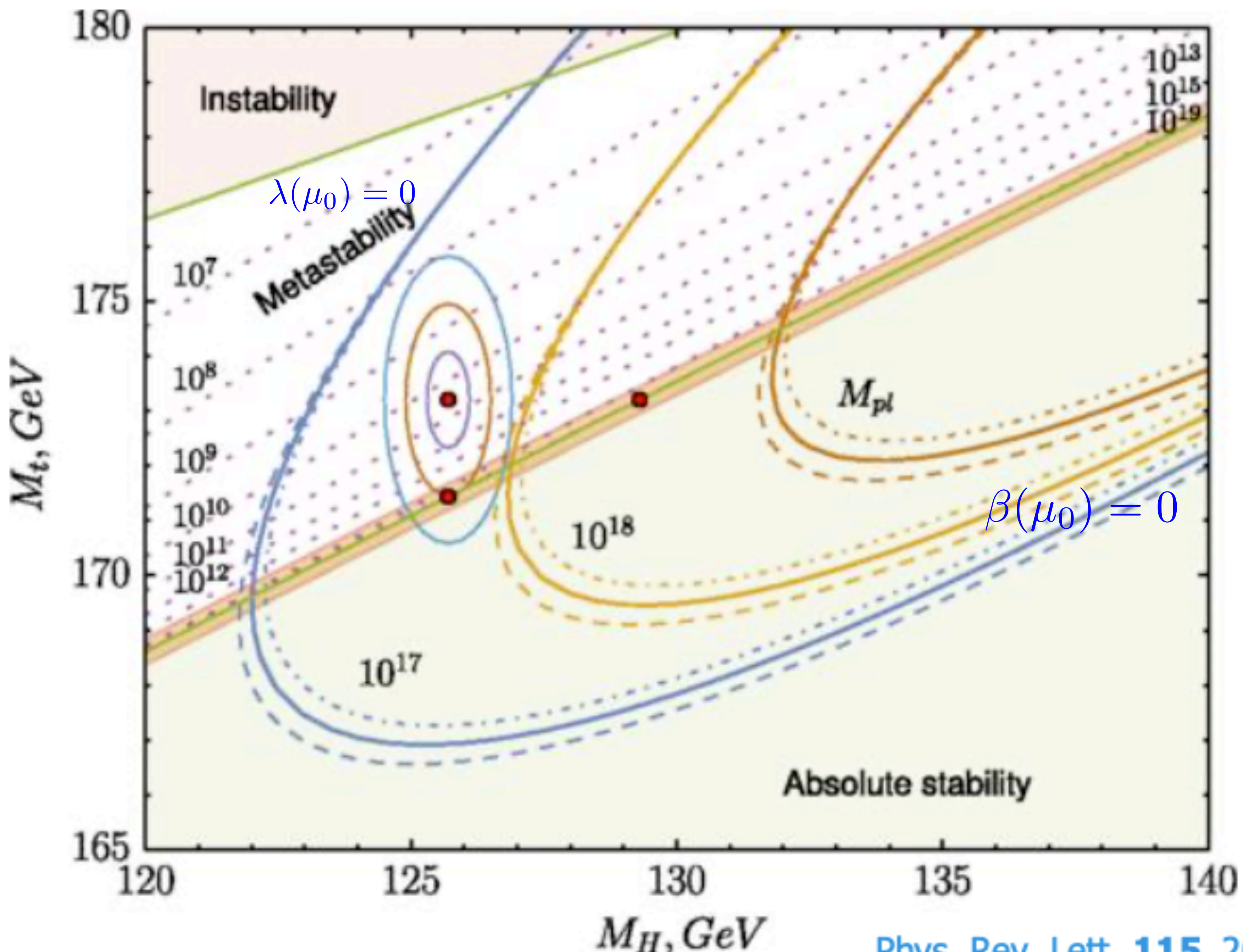


✳ excluded Higgs masses (Sher et al; Hambye and Riesselmann)



✳ the Higgs mass is restricted to be between approximately 126 GeV and 160 GeV for $\Lambda \simeq 10^{16}$ GeV

Stability of our vacuum depends on the Higgs potential and the top quark mass.



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