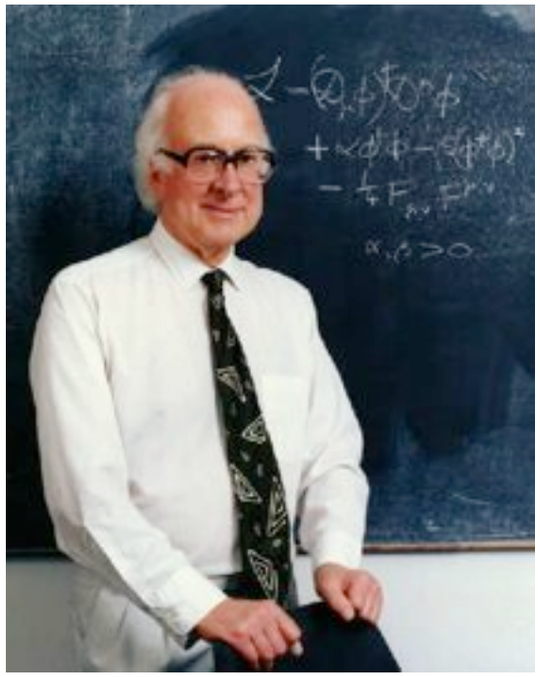


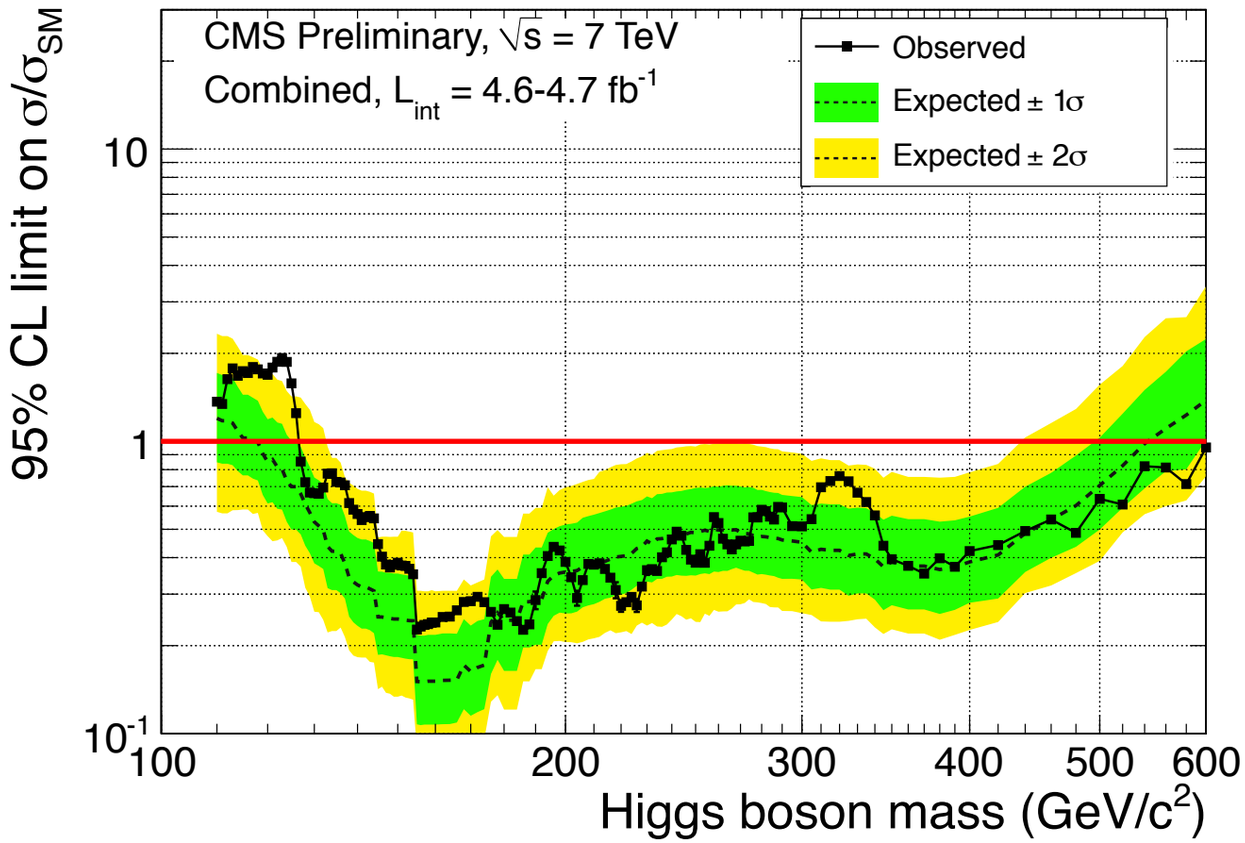
# Higgs Searches

## - running but not there yet -

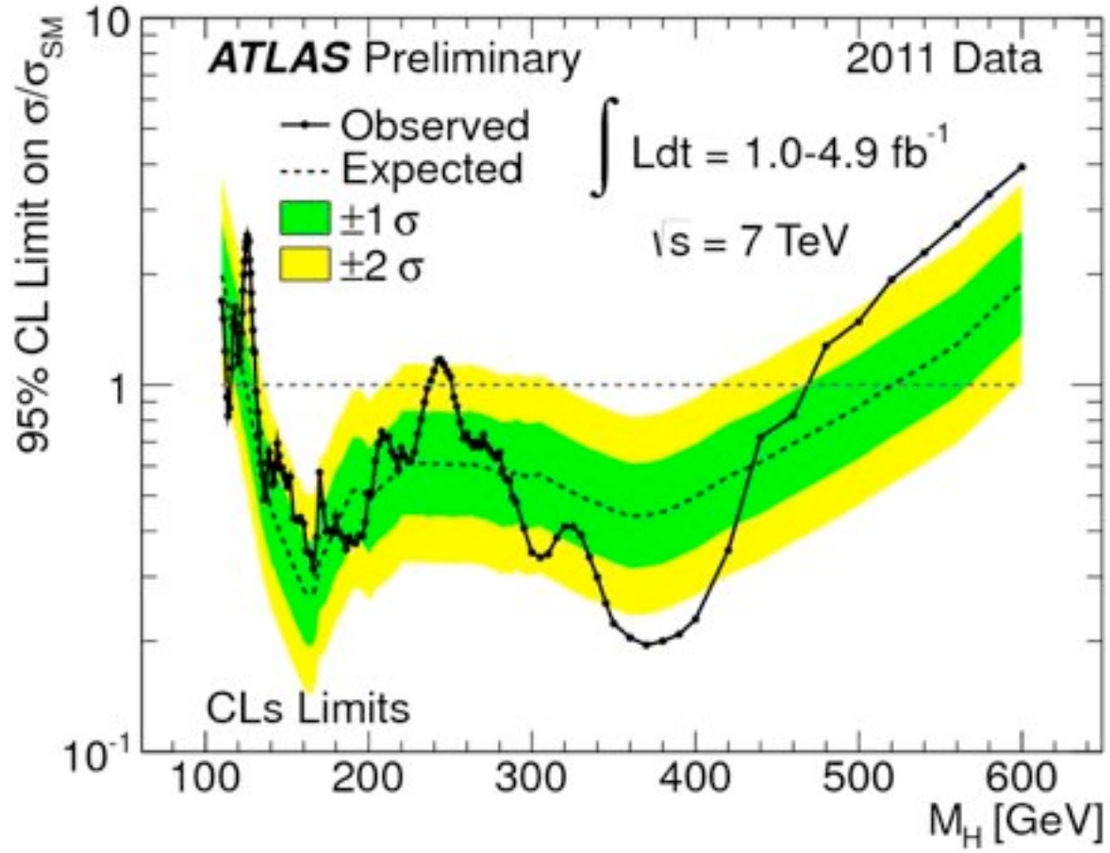
Michael Spannowsky

IPPP Durham

## CMS combined




## ATLAS combined



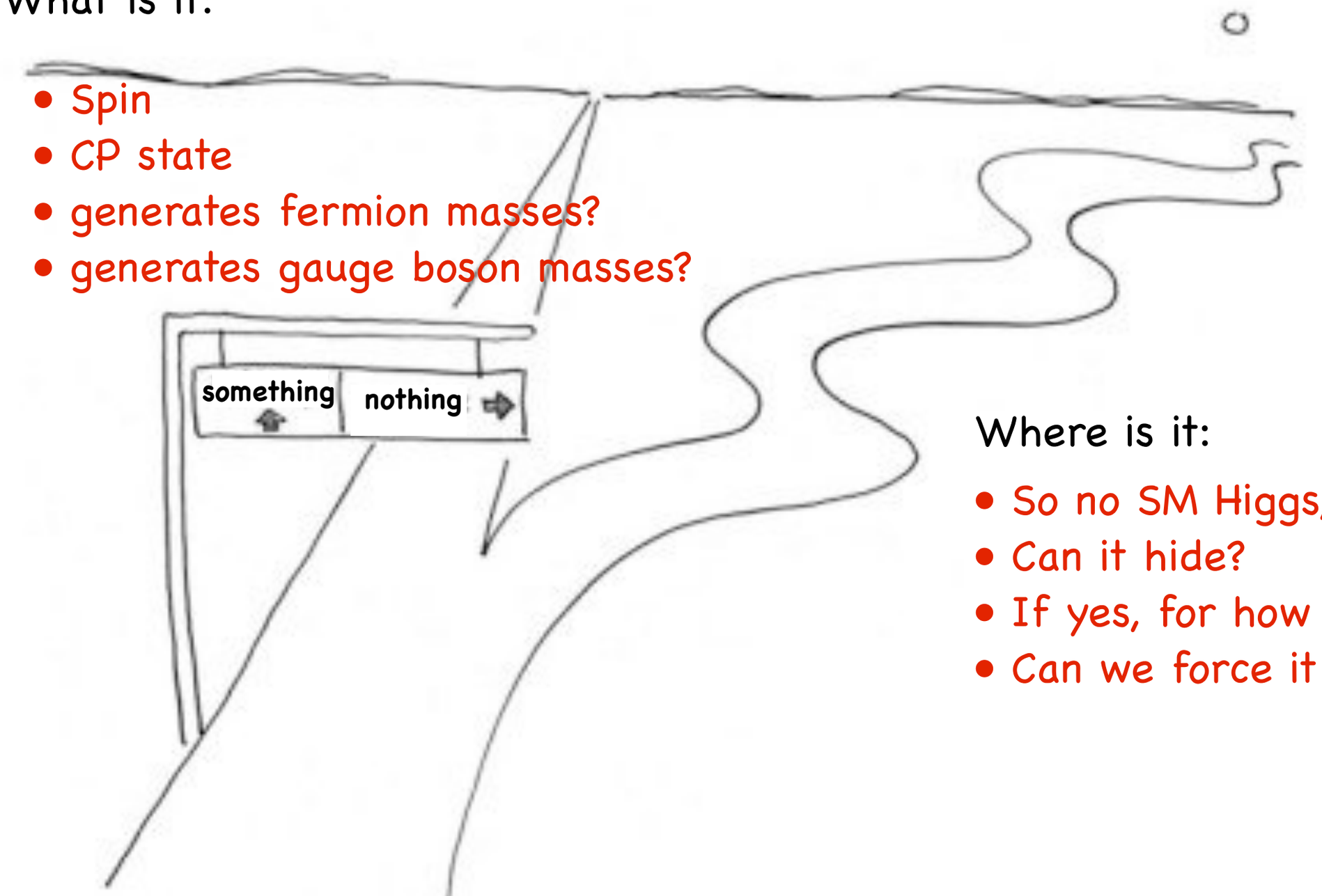

- Several excesses over allowed Higgs mass range
- However SM Higgs exclusion over large mass range
- Are we just lucky/unlucky?
- Are the backgrounds correctly estimated?

# Status end of 2011:
# We have (weak?) hints for some small excesses

→ We can go down two different roads

What is it:

- Spin
- CP state
- generates fermion masses?
- generates gauge boson masses?




Where is it:

- So no SM Higgs, but how simple?
- Can it hide?
- If yes, for how long?
- Can we force it to show up?

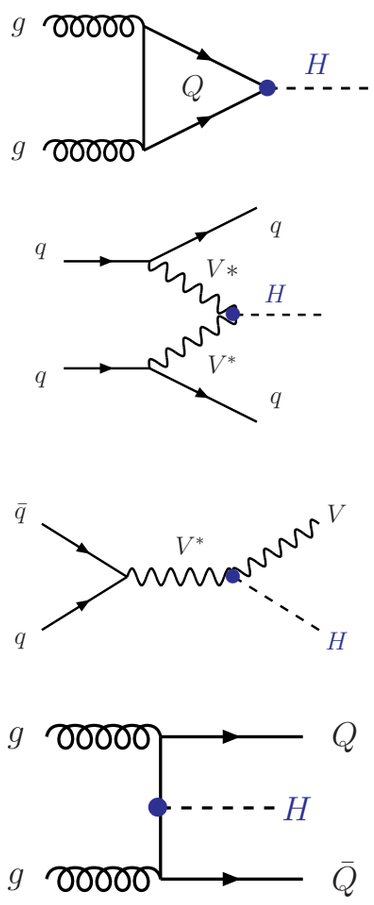
# What if we found a bump of around SM Higgs size?

- If observed in ZZ and photons:

  Spin 1 ruled out by Landau-Yang theorem (photons)

  CP-odd ruled out by Z decay (if no CP-violation in Higgs sector)

- If the Higgs is SM-like it has to show up in several channels

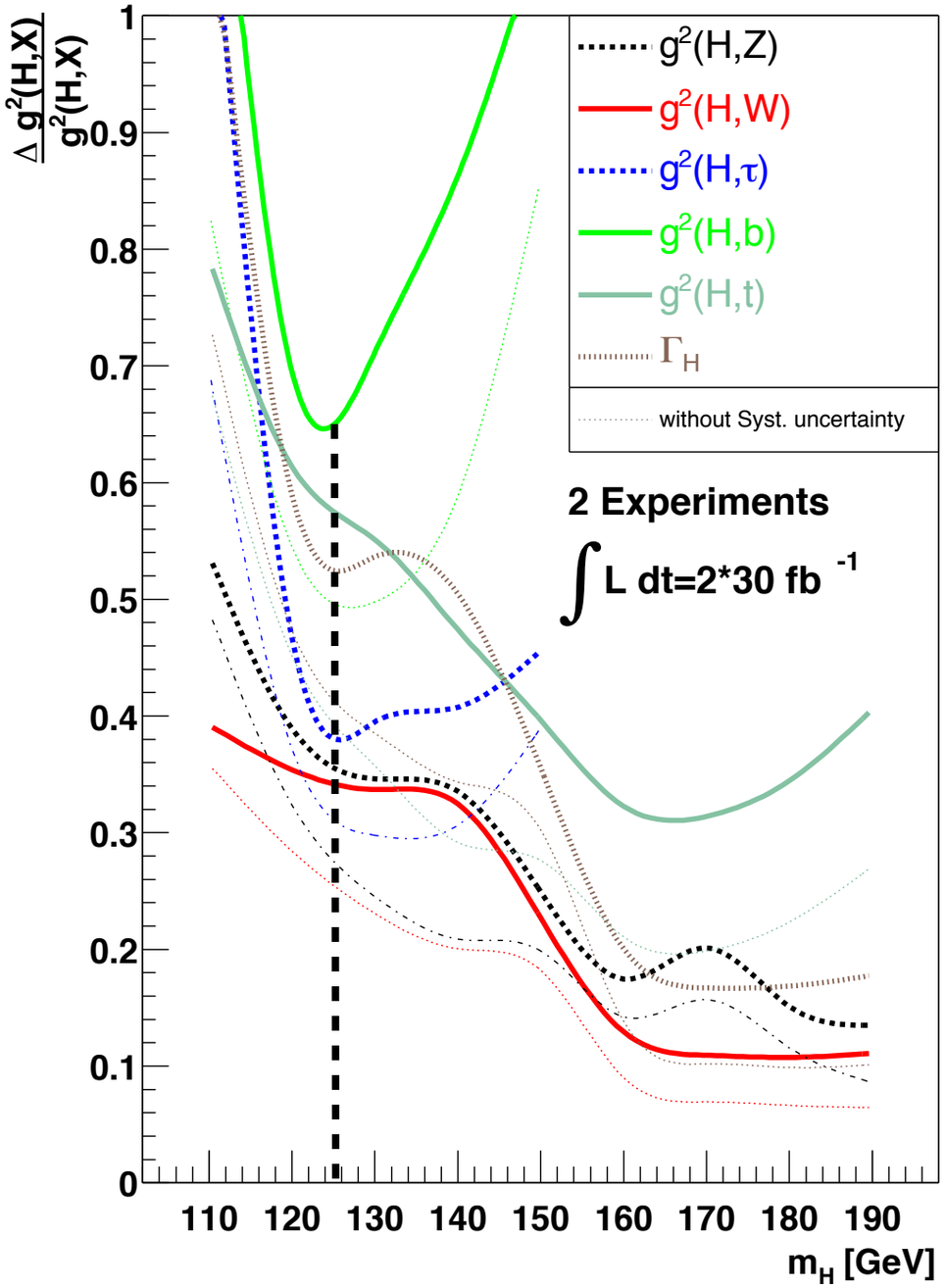



| production | decay |
|---|---|
| $gg \to H$ | $ZZ$ |
| $qqH$ | $ZZ$ |
| $gg \to H$ | $WW$ |
| $qqH$ | $WW$ |
| $t\bar{t}H$ | $WW(3\ell)$ |
| $t\bar{t}H$ | $WW(2\ell)$ |
| inclusive | $\gamma\gamma$ |
| $qqH$ | $\gamma\gamma$ |
| $t\bar{t}H$ | $\gamma\gamma$ |
| $WH$ | $\gamma\gamma$ |
| $ZH$ | $\gamma\gamma$ |
| $qqH$ | $\tau\tau(2\ell)$ |
| $qqH$ | $\tau\tau(1\ell)$ |
| $t\bar{t}H$ | $b\bar{b}$ |
| $WH/ZH$ | $b\bar{b}$ (subjet) |

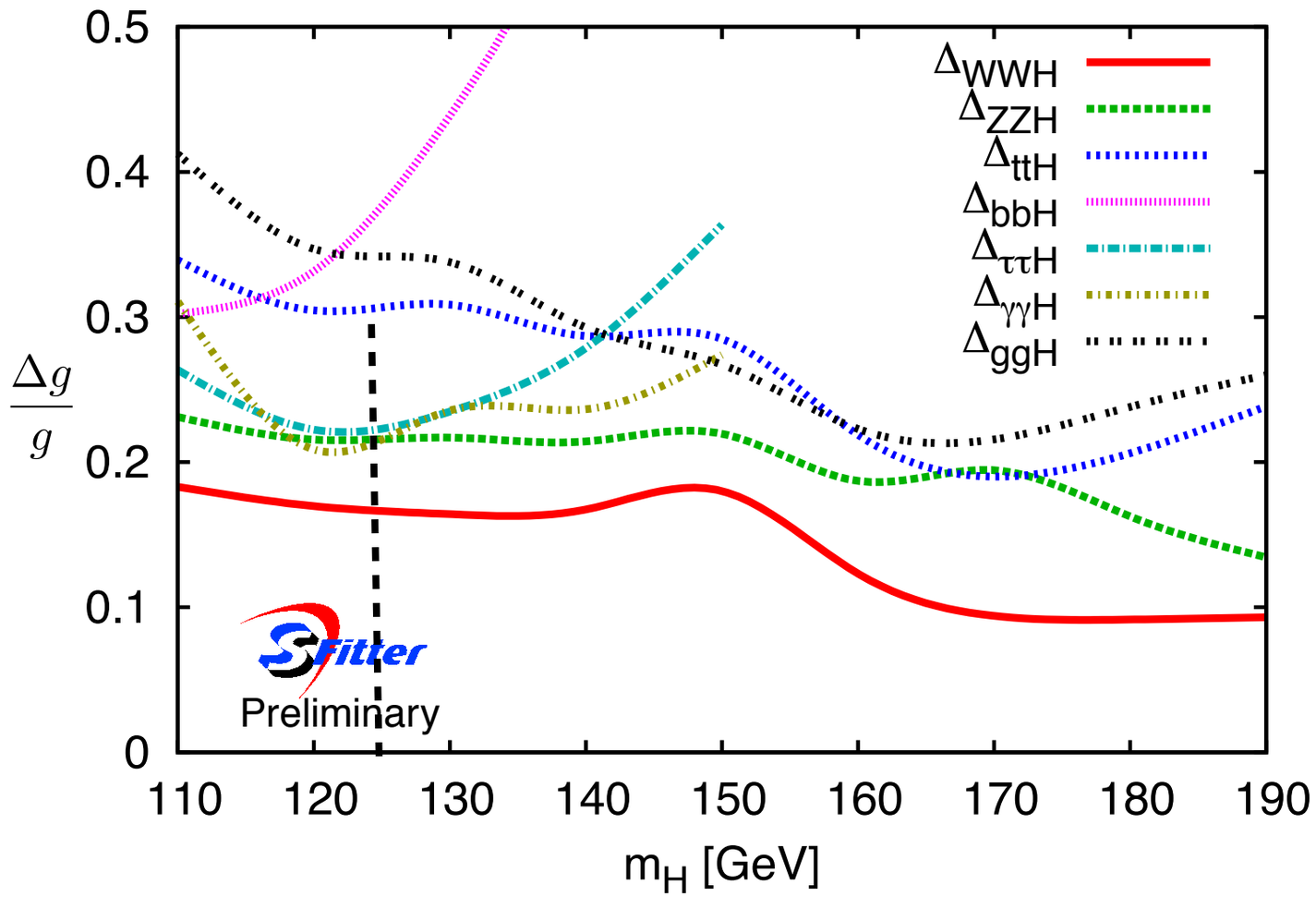
Some couplings/channels very challenging:

- Higgs decay to light fermions
- Extracting $HZ\gamma$

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was PRD 62 (2000); Duehrssen (2005)]




[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]



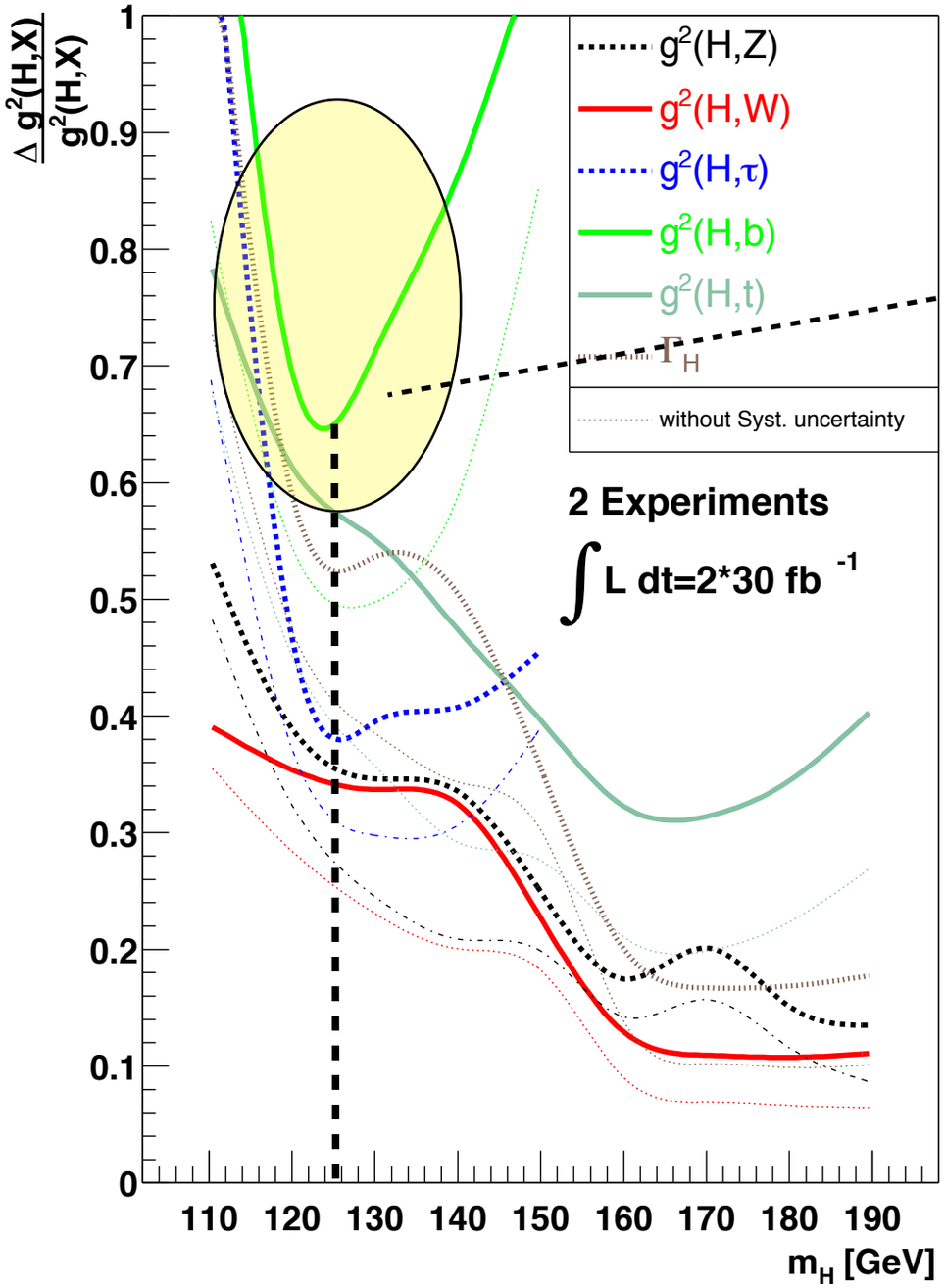

- Huge improvement from boosted Higgs analysis
- also for non-b decay modes due to better knowledge of total width

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

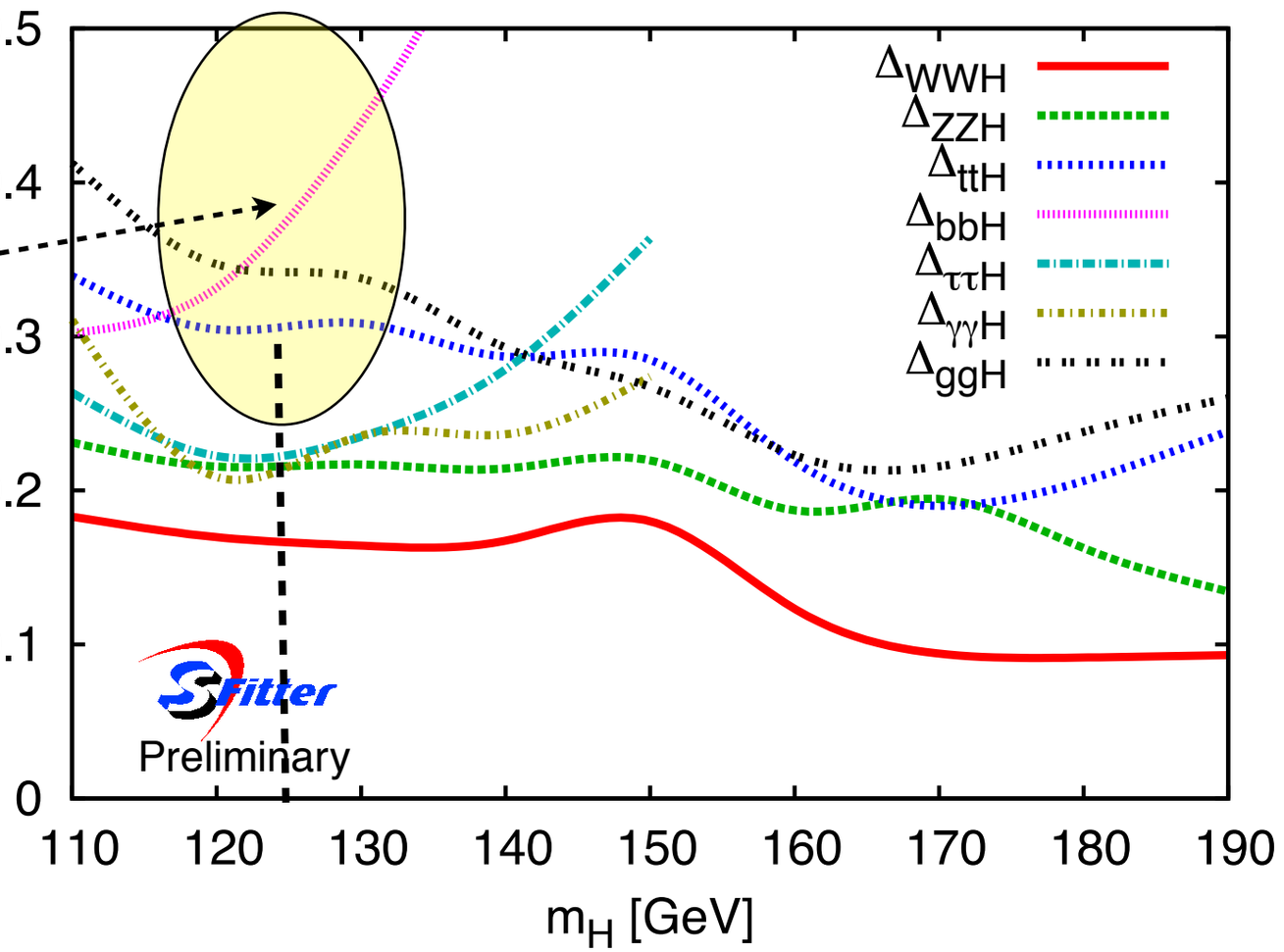
assumed: $\Gamma_H = \Sigma_{SM}\Gamma_i \quad \Gamma_i \sim g_d^2$

Need to study/understand hadronic final states

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was PRD 62 (2000); Duehrssen (2005)]




[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]

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Need to study/understand hadronic final states

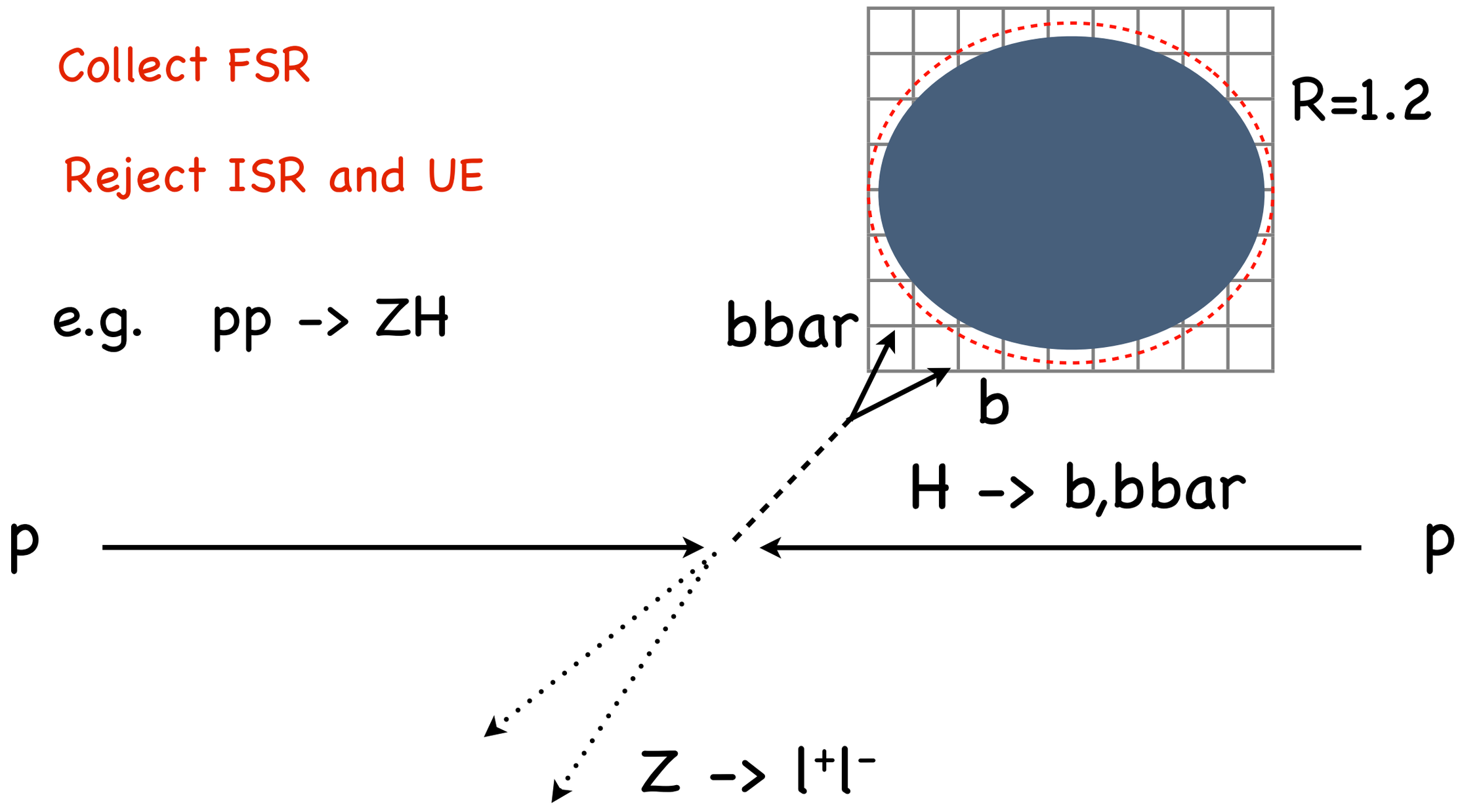
# What is meant by boosted Higgs analysis?

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



# What is meant by boosted Higgs analysis?

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

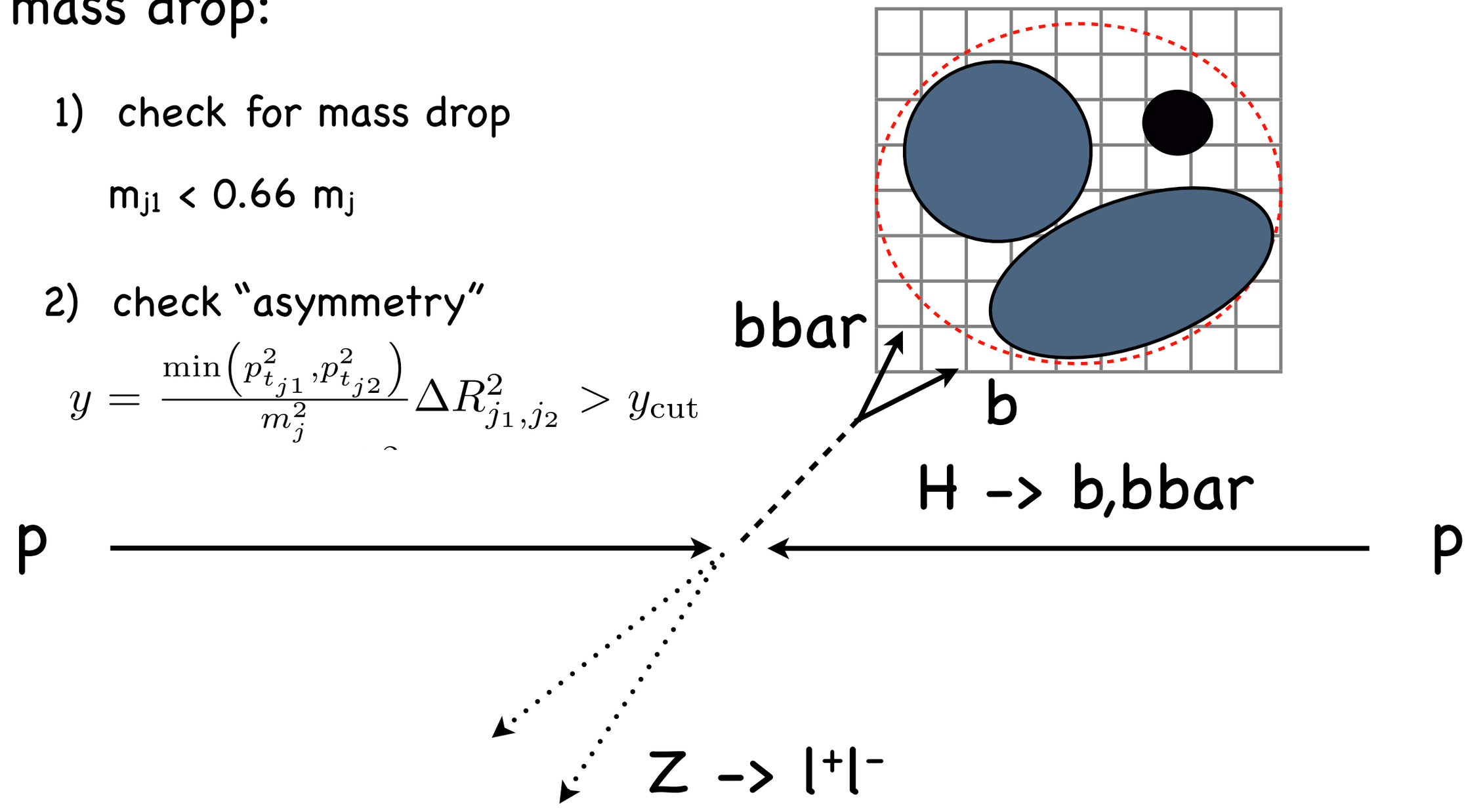
## mass drop:

1) check for mass drop

$m_{j1} < 0.66\ m_j$

2) check "asymmetry"

$$y = \frac{\min\left(p_{t_{j1}}^2, p_{t_{j2}}^2\right)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\text{cut}}$$

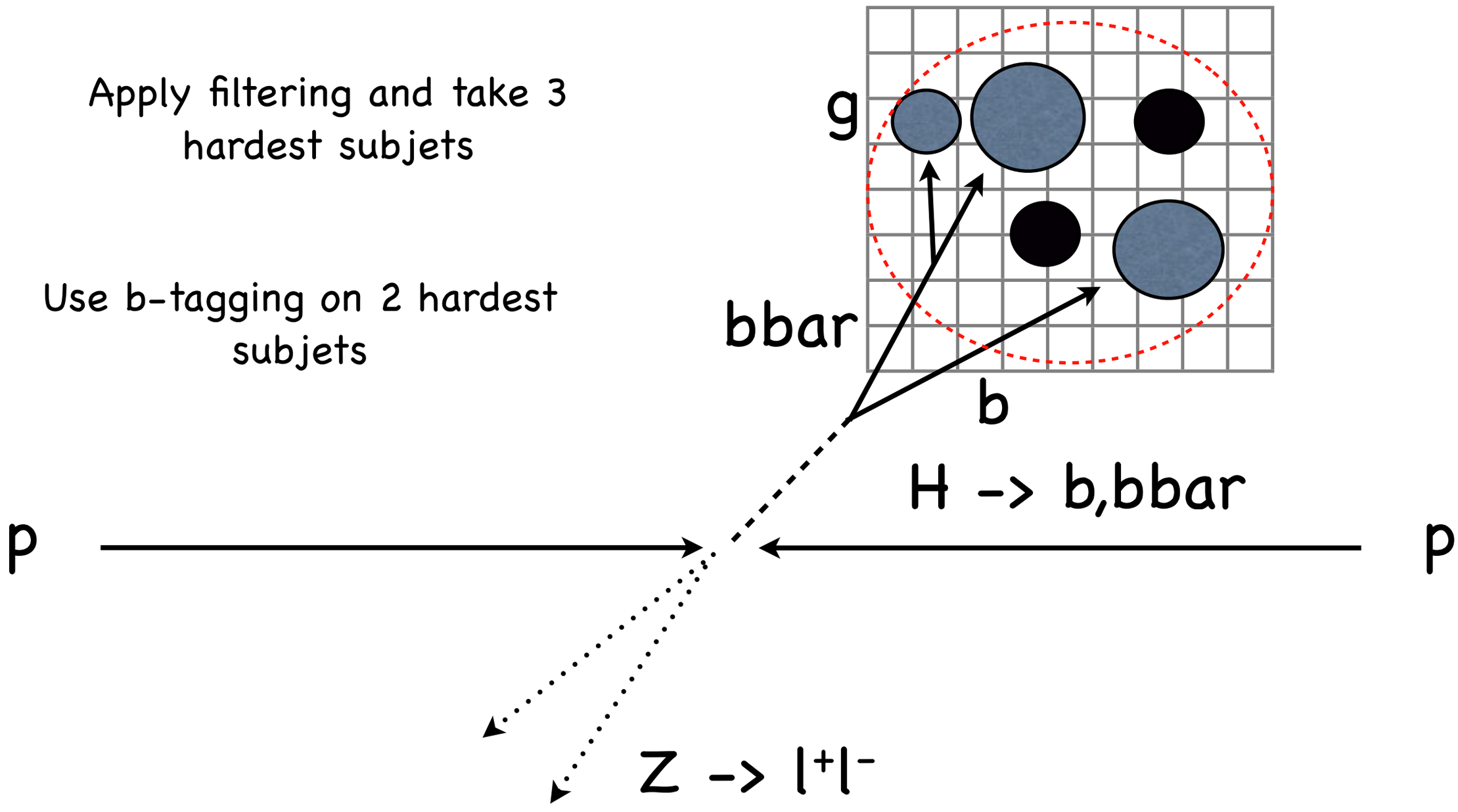


# What is meant by boosted Higgs analysis?

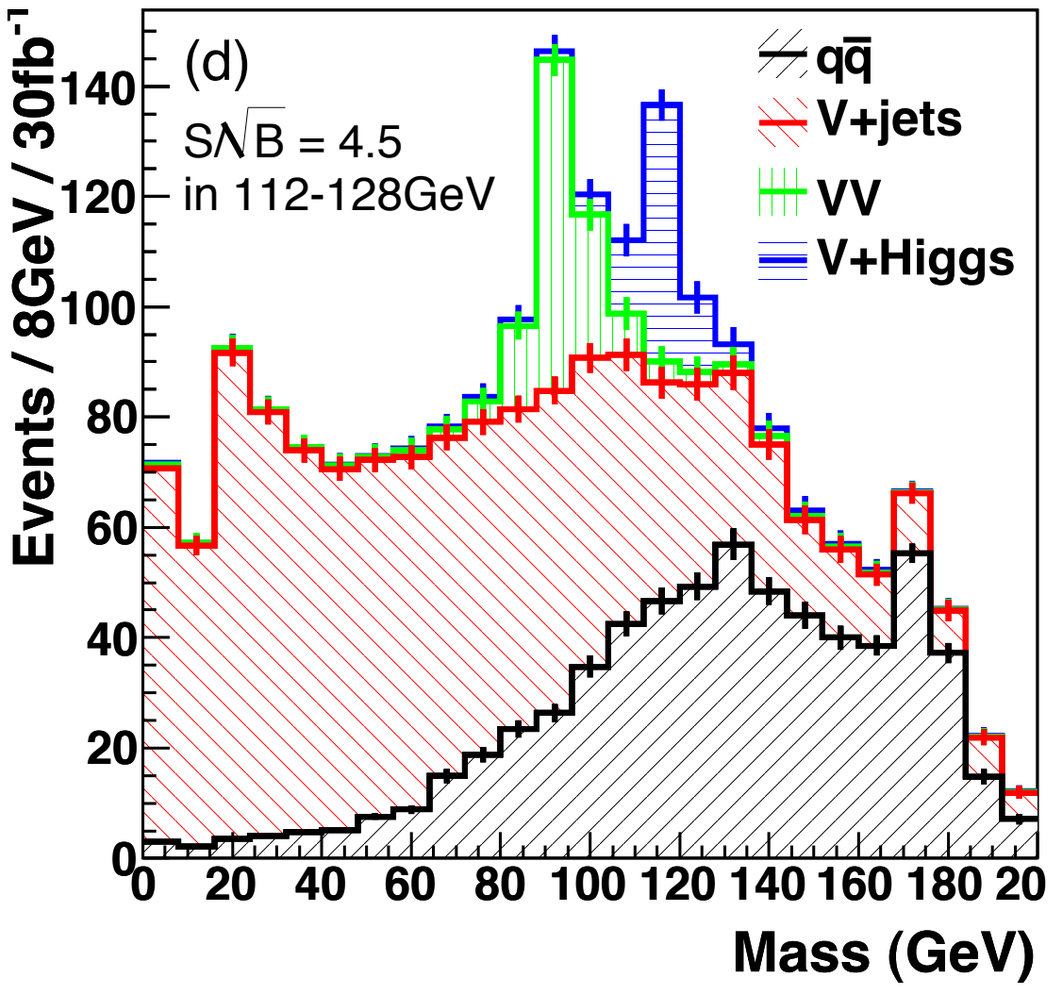
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets



# BDRS Result




- LHC 14 TeV; 30 $fb^{-1}$
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- Combination of HZ and HW channels

Confirmed in ATLAS full detector simulation

- Further improvement in this channel possible [Soper, MS, JHEP (2010); Soper, MS PRD 84 (2011)]
- substructure also useful for tth coupling [Plehn, Salam, MS PRL 104 (2010)]

# Back to the long and windy road....

## Assumption:

By the end of 2012 we don't observe an excess over null hypothesis

- Do we have to give up Higgs hypothesis? Not yet

- How can the Higgs hide? Which models motivate invisible Higgs?

  Plenty: NMSSM, Higgs portal to invisible of any kind,....

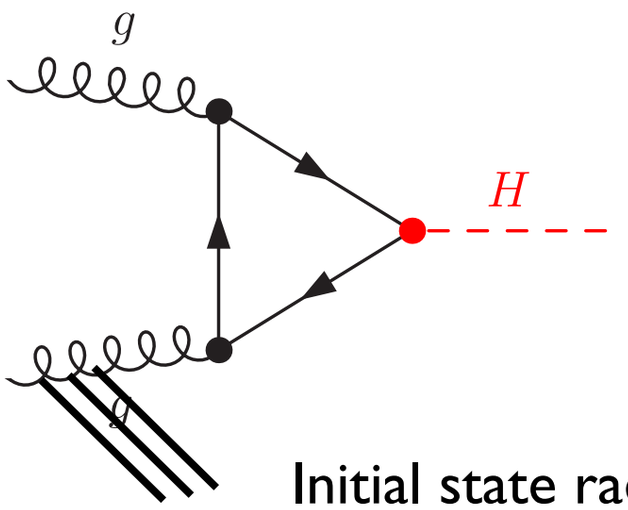
- Where can the Higgs boson hide?

  Backgrounds, long-lived decays, invisible decays, ...

# Several hideouts have recently been discussed

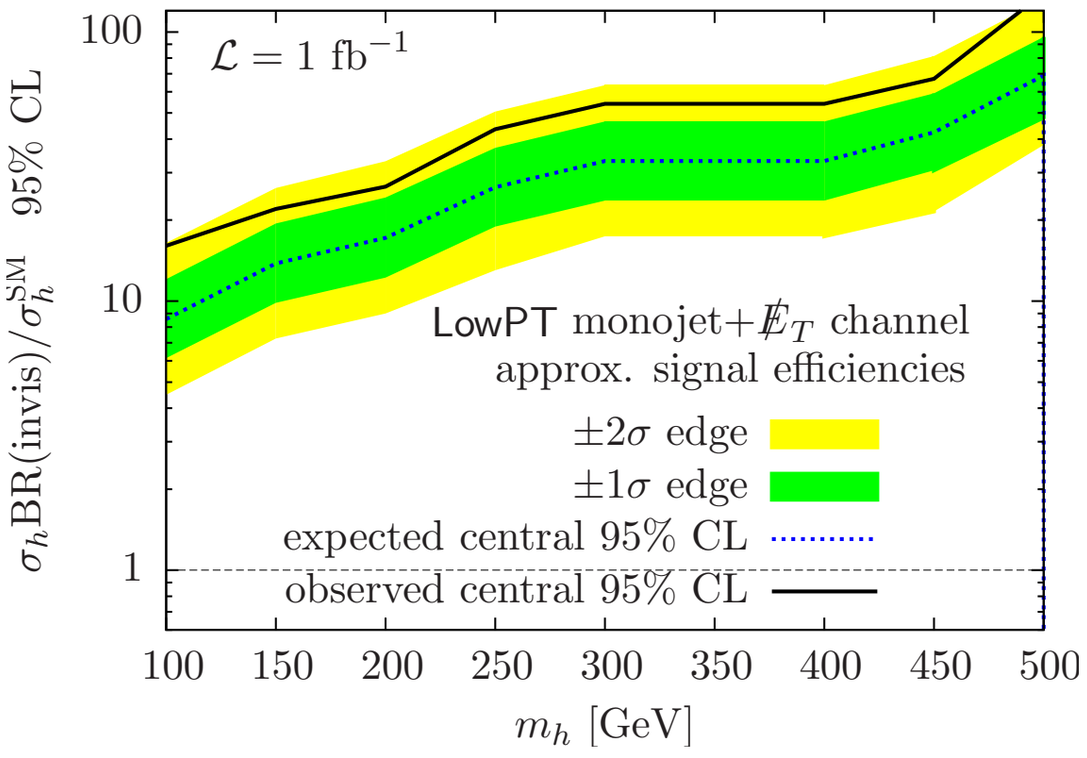
- Higgs decays invisibly (unbroken U(1))

  - WBF challenging, HV less sensitive




Initial state radiation

[Eboli, Zeppenfeld PLB 495 (2000); Englert, Jaeckel, Re, MS 1111.1719; Bai, Draper, Shelton 1112.4496]




- Higgs decays into long-lived particles (weakly broken U(1))

[Strassler, Zurek PLB 661 (2008)]

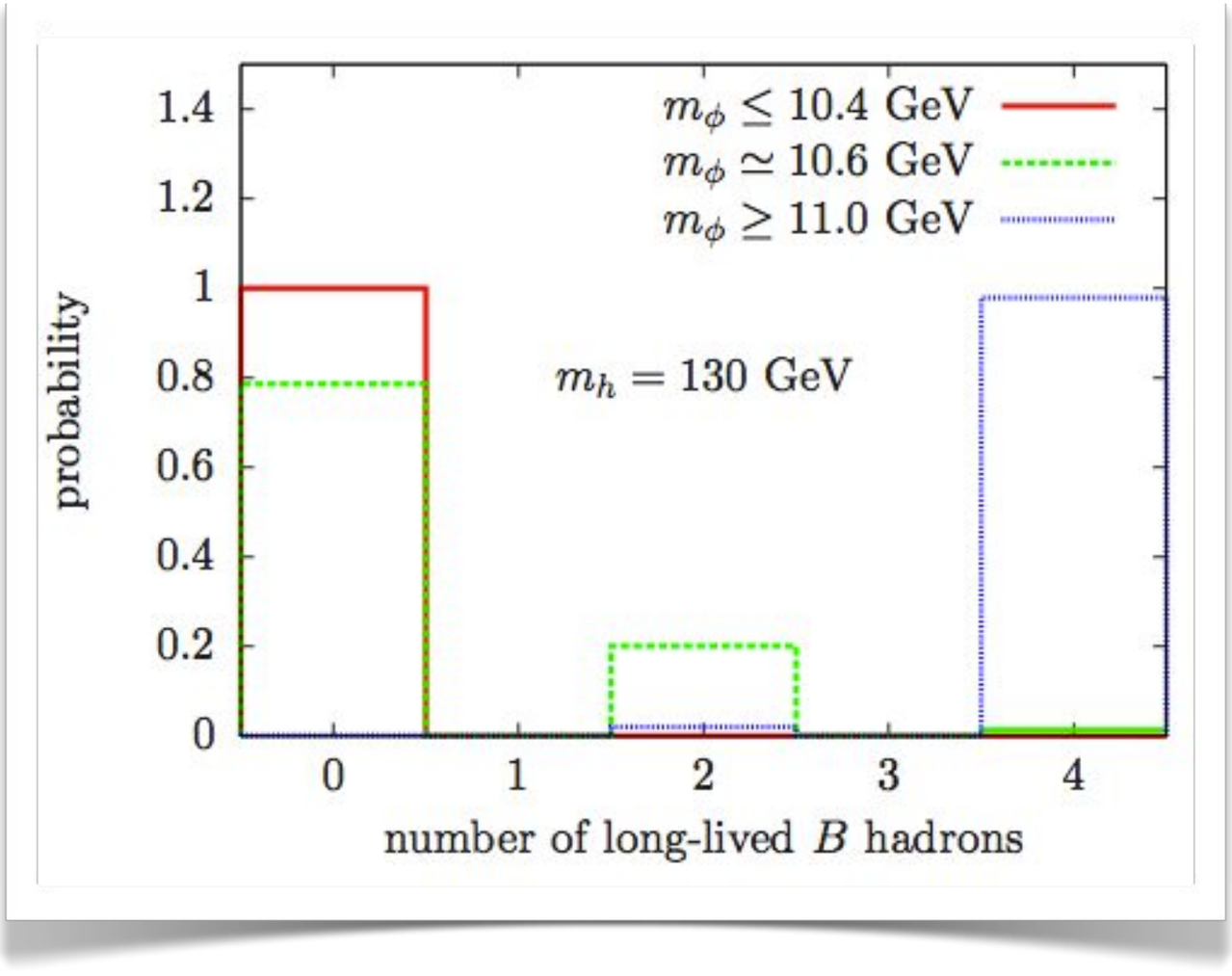
Identification via:
- ★ displaced vertices,
- ★ jets without tracks,
- ★ energy hits only in muon chamber

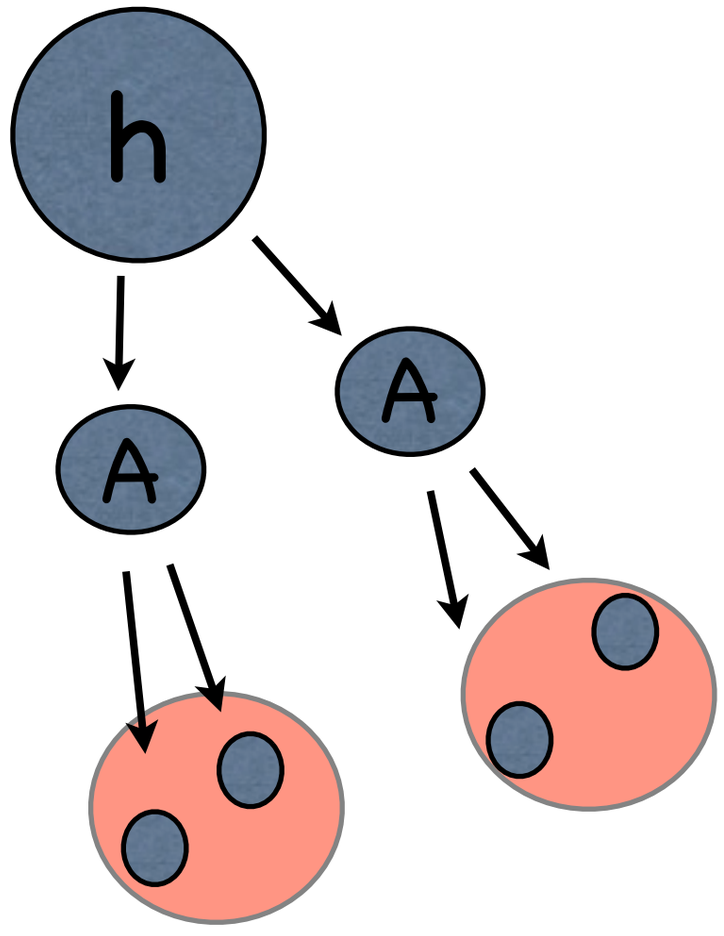
- buried Higgses

Higgs can decay into something common to background,
e.g. gluons or light quarks

★ Higgs can decay via A to gluons (longer cascade possible) [Bellazzini et al `09, `10]

★ Higgs can decay via A to bottoms (mA can be close to b meson resonance)
[Englert, Jaeckel, Re, MS 1111.1719]



# Buried Higgs is difficult case....

Will we never find the Higgs in these channels?

- Not necessarily but it might take a while
- New techniques like studying the substructure of jets can help

[Chen, Nojiri, Sreethawong JHEP 1011 (2010)]

[Falkowski, Krohn, Wang, Shelton, Thalapillil PRD D84 (2011)]

[Englert, Roy, MS PRD 84 (2011)]

# Status end of 2011:
# We have (weak?) hints for some small excesses

→ We can go down two different roads

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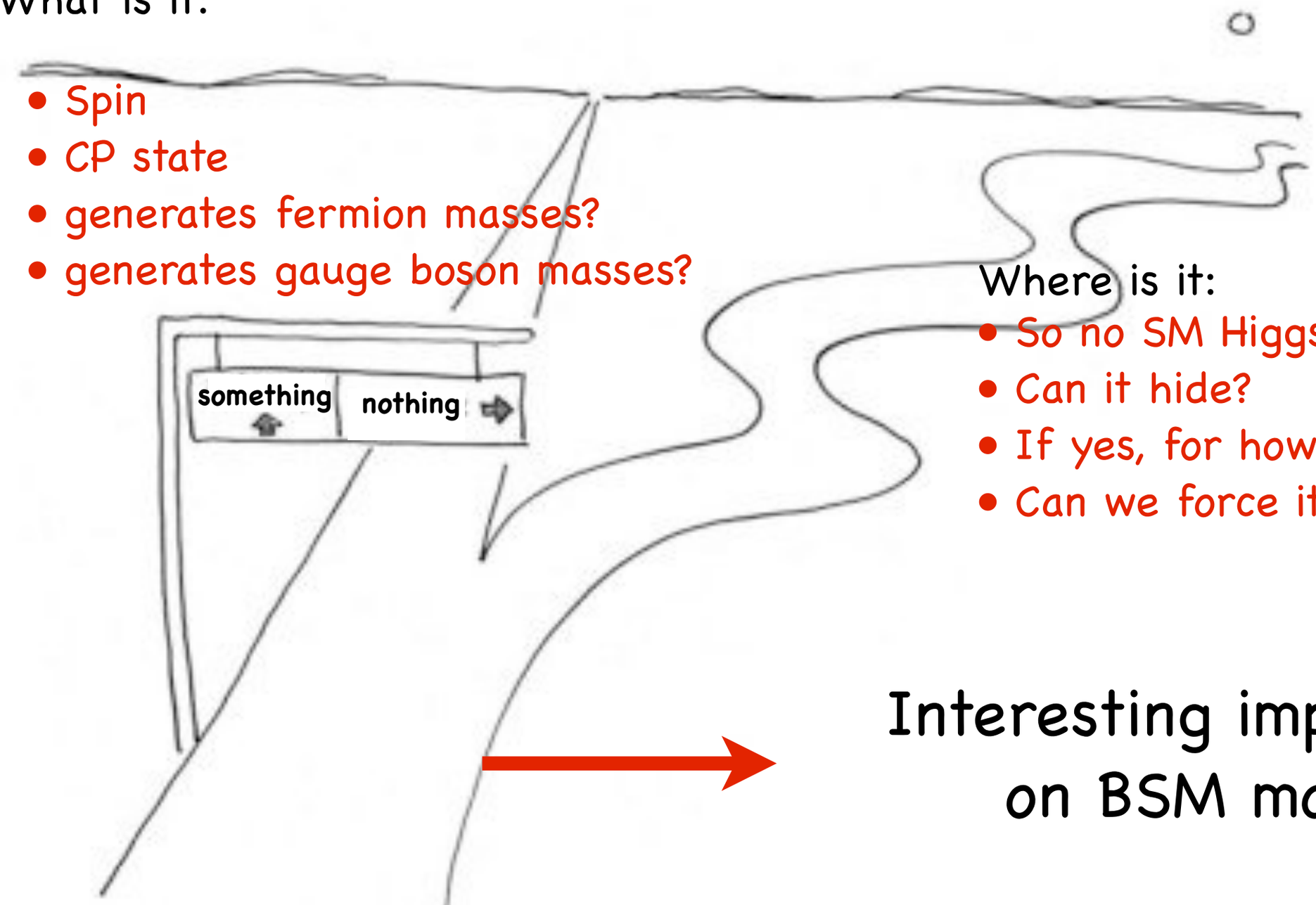
- generates gauge boson masses?




Where is it:

- So no SM Higgs, but how simple?
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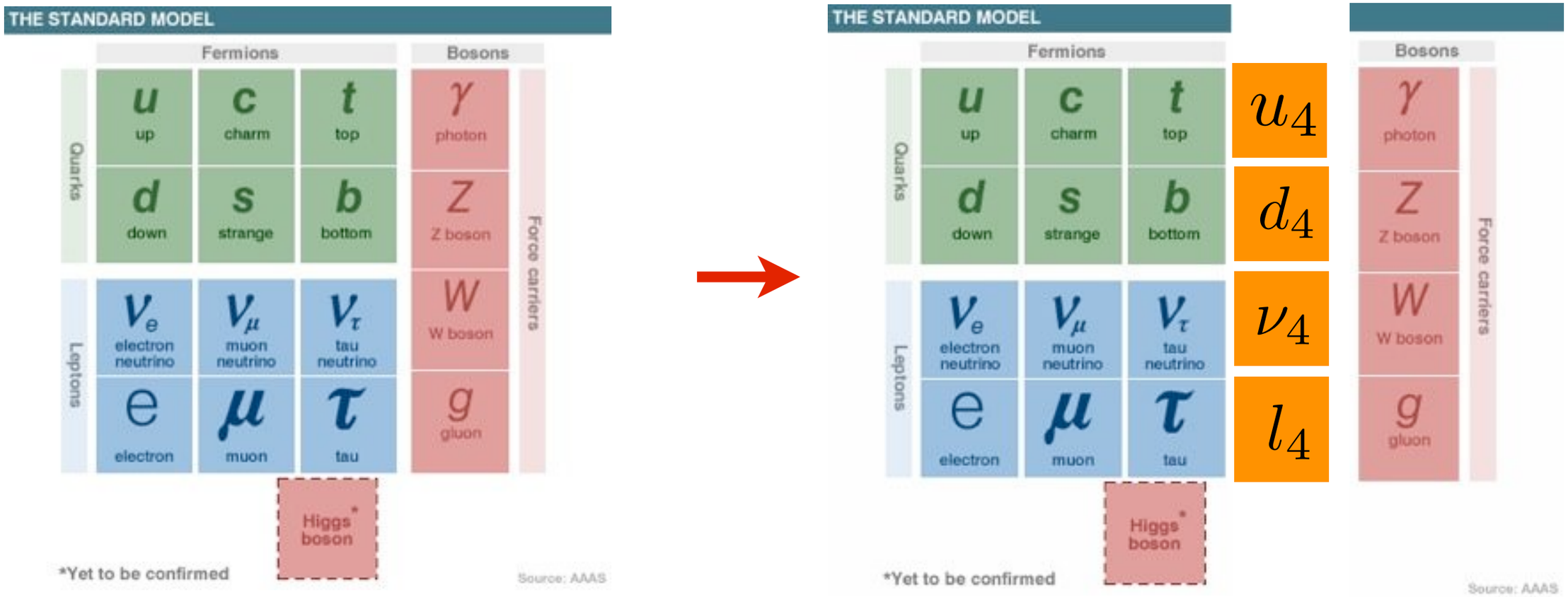
- If yes, for how long?
- Can we force it to show up?

→ Interesting implications on BSM models

# All BSM models affected by (non)observation of Higgs boson

e.g. SM with 4 chiral generations:

- Simplest extension, keeps resurfacing
- Difficult to exclude by direct searches
- Can almost be excluded by Higgs search alone

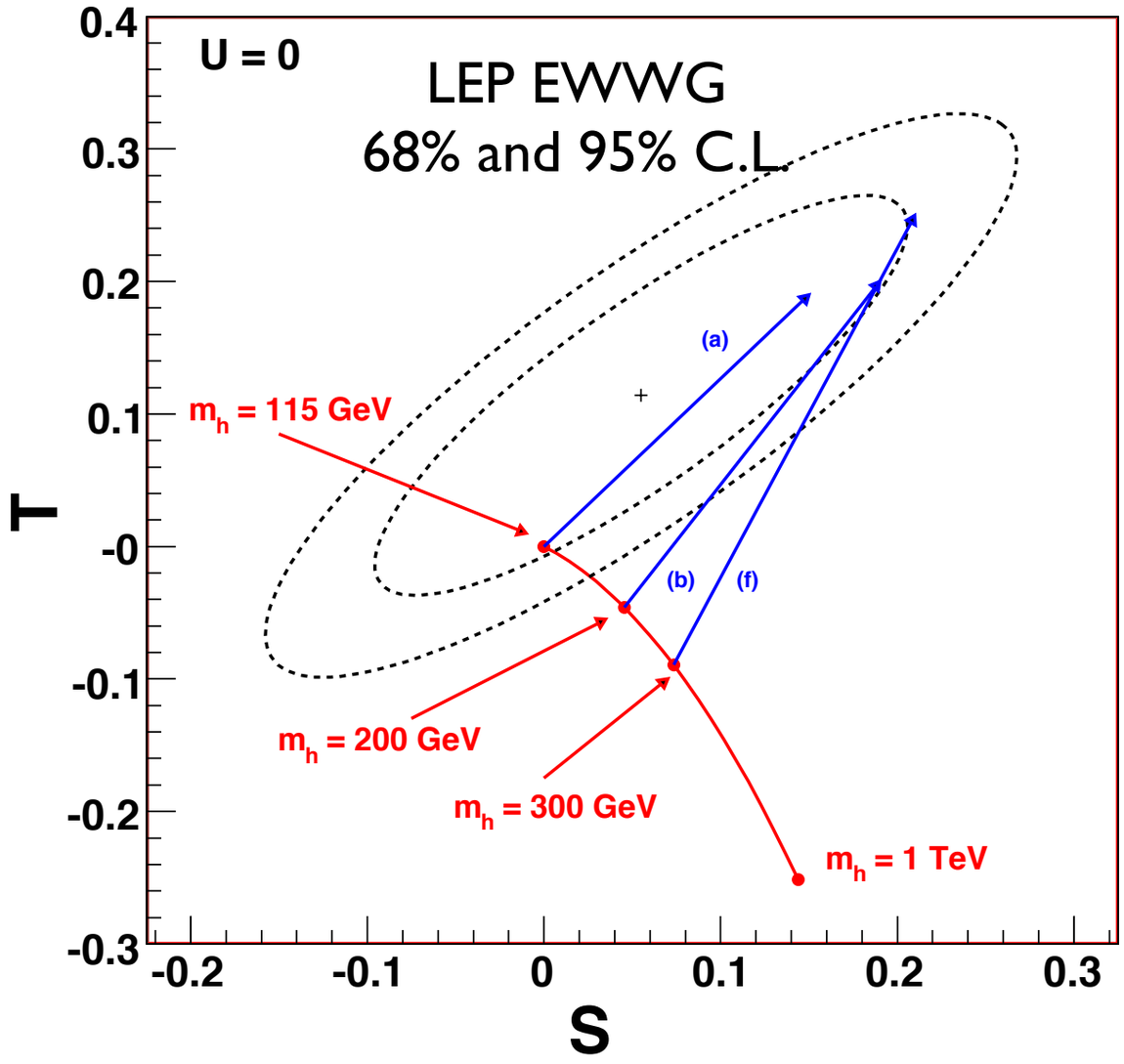


A fourth chiral generation is not excluded by LEP data:

- Constraint from $\Gamma(Z \to \bar{\nu}\nu)$

  easily avoidable by $m_{\nu_4} \geq \frac{M_Z}{2}$

- Constraints from electroweak precision measurements:




[Kribs, Plehn, MS, Tait PRD 76 (2007)]

Can move back into slope with larger T-parameter ⟷ mass splitting

→ Model works with mild assumptions:

$$
\begin{aligned}
m_{\ell_4} - m_{\nu_4} &\simeq 30 - 60\ \text{GeV}, \\
m_{u_4} - m_{d_4} &\simeq \left(1 + \frac{1}{5}\ln\frac{m_H}{115\,\text{GeV}}\right) \times 50\ \text{GeV}, \\
m_{\nu_4,\ell_4} &> 100\ \text{GeV} \quad \text{and} \quad m_{u_4,d_4} > 258\ \text{GeV}.
\end{aligned}
$$

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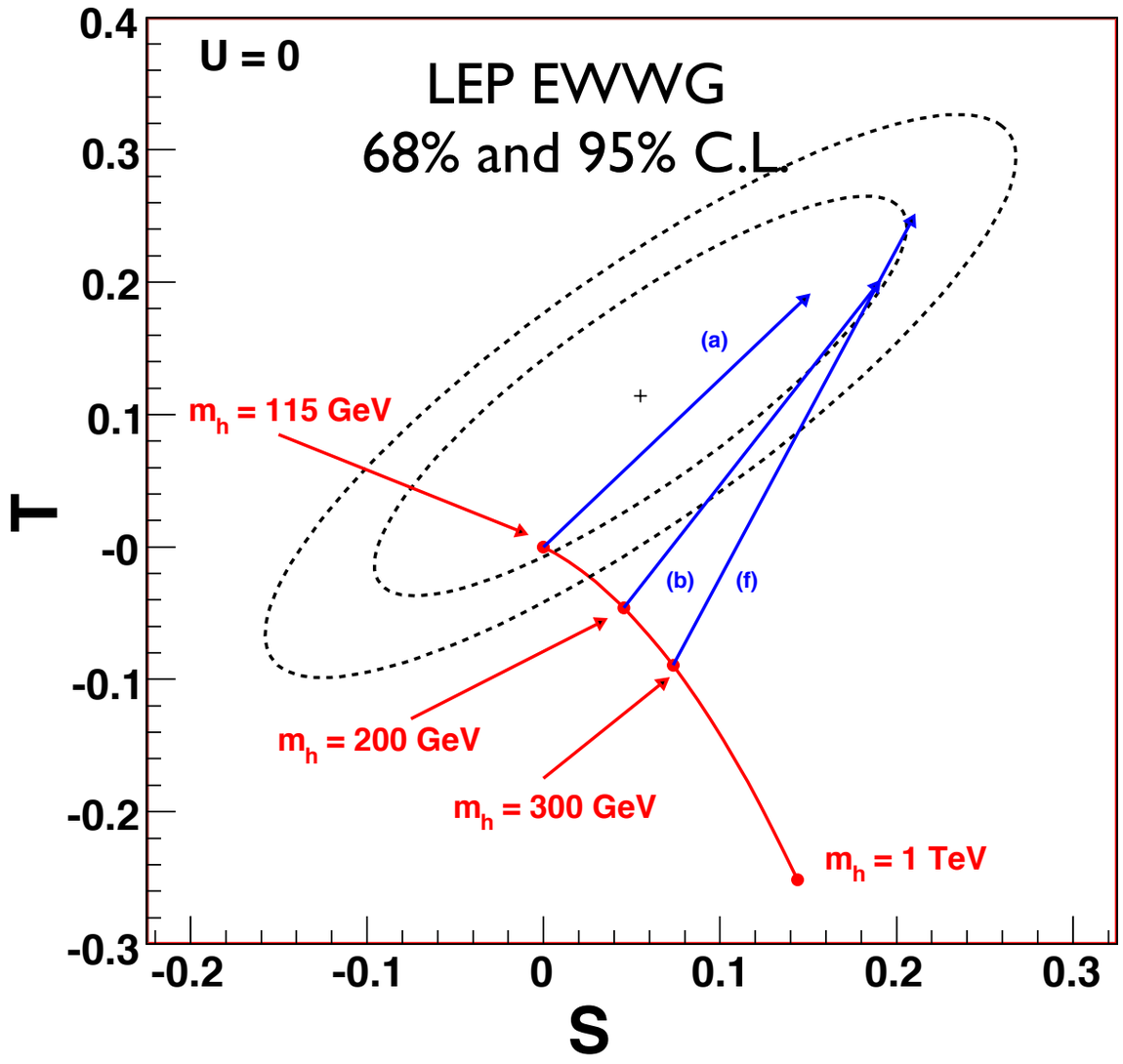


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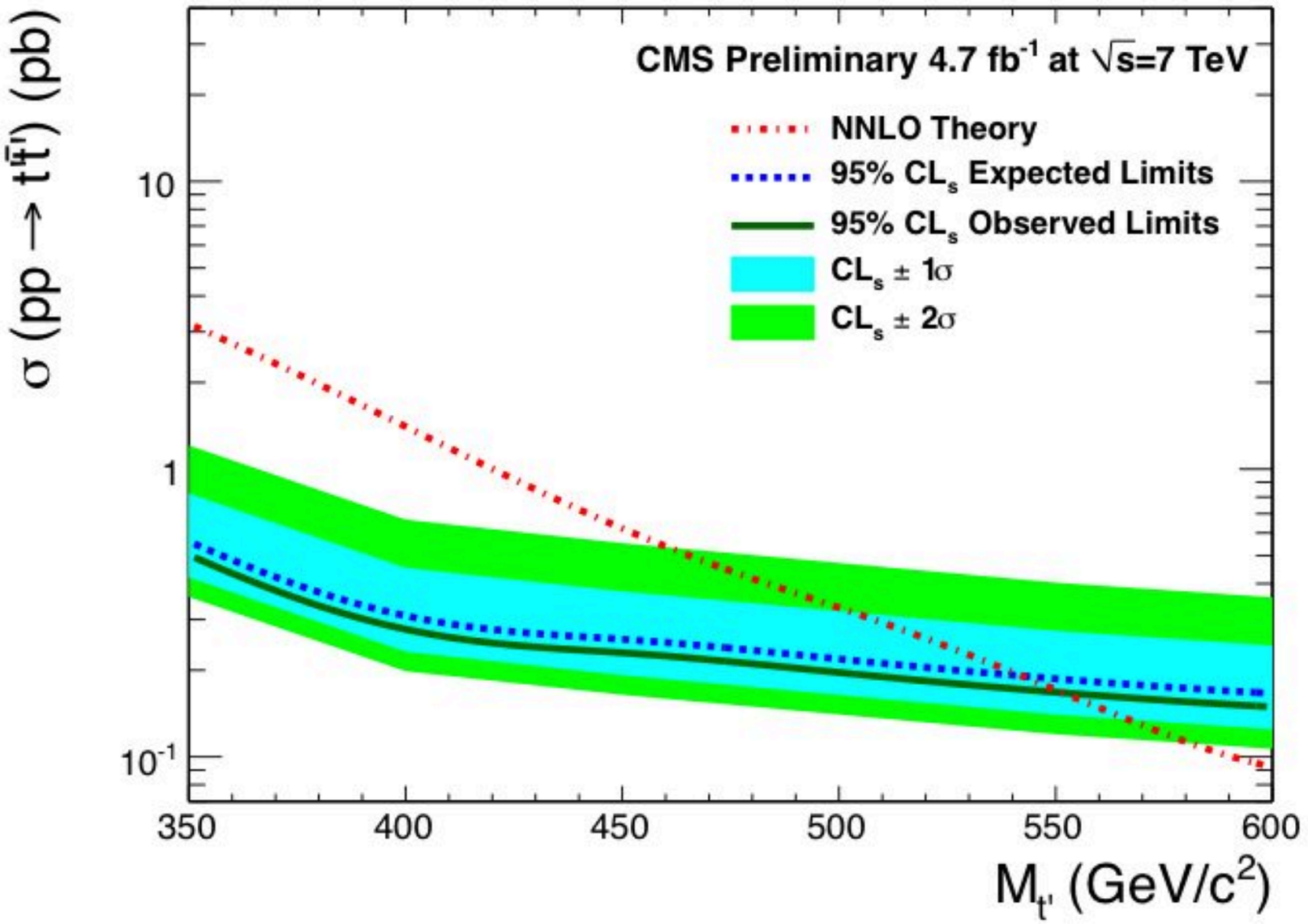
Pre-LHC 7 TeV → $m_{\nu_4,\ell_4} > 100 \text{ GeV}$ and $m_{u_4,d_4} > 258 \text{ GeV}$.




Recent result from CMS in $t'\bar{t}' \to bW^+\bar{b}W^- \to bl^+\nu\bar{b}l^-\bar{\nu}$

$m_{t'} > 552$ GeV **at 95% CL**

# However, Higgs searches give it a sever blow:

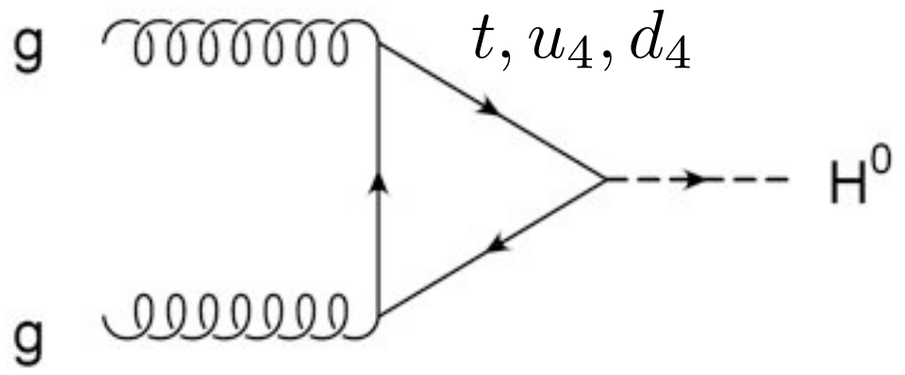
Production cross section enhanced:

$$\sigma^{4th}(gg \to H) \simeq 9\sigma^{SM}(gg \to H)$$

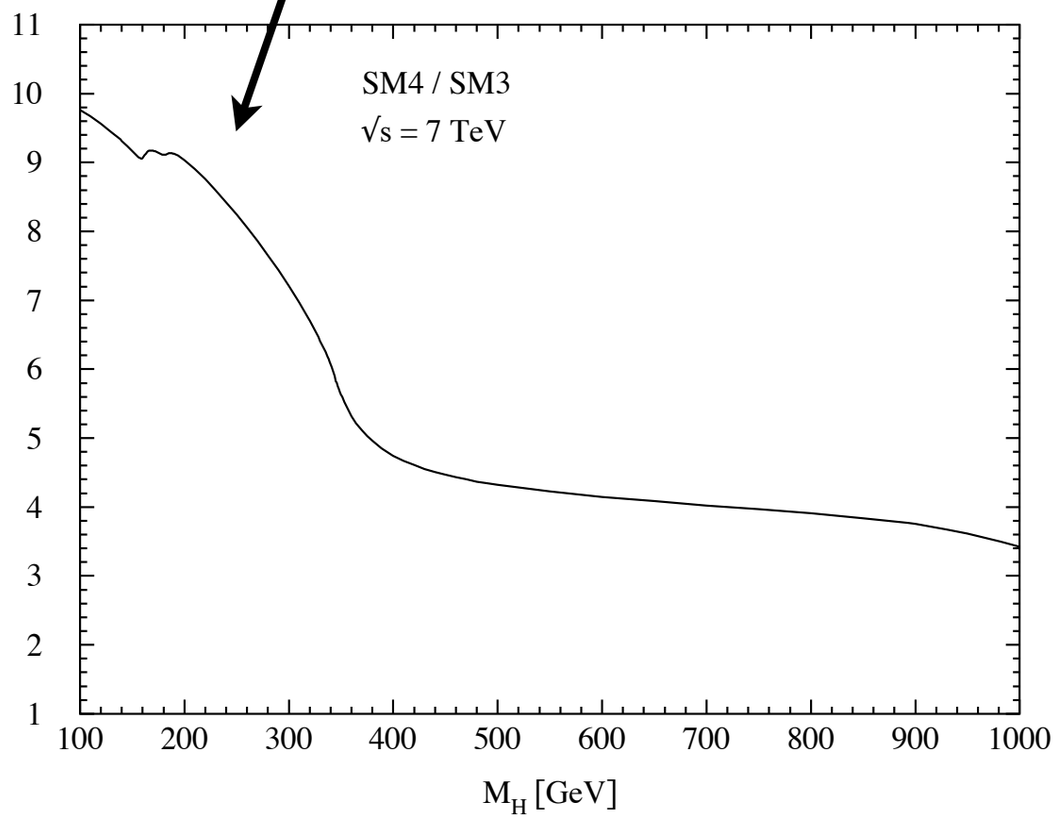
However, decay to photons strongly suppressed due to destructive interference between fermions and W.

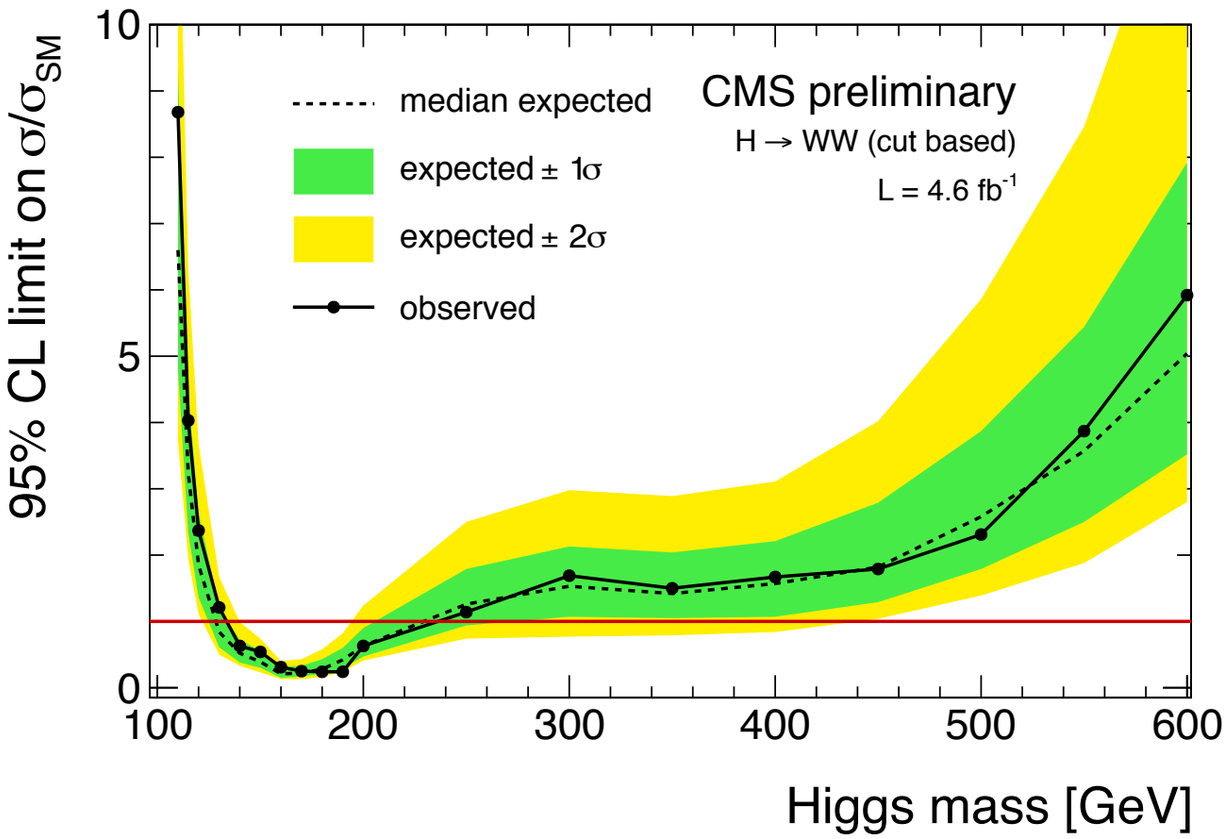
Gain factor of 9 in production, loose factor of 9 in decay

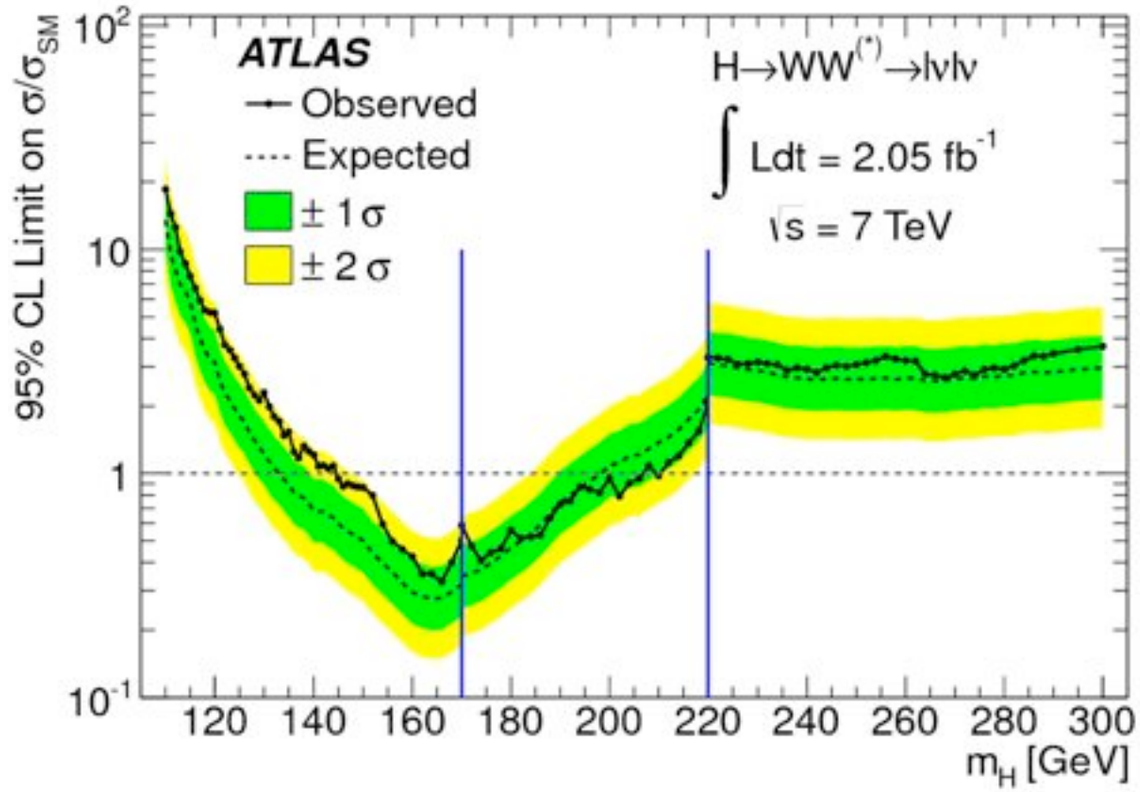
$$\sigma^{4th}(gg \to H)\ \mathrm{BR}^{4\mathrm{th}}(\mathrm{H} \to \gamma\gamma)$$
$$\simeq \sigma^{SM}(gg \to H)\ \mathrm{BR}^{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)$$




[Denner et al., 1112.5142]






## Other channels disfavor a 4th generation strongly!

The last rebellion of the SM 4th generation: [Cetin et al. 1108.4701; Carpenter 1110.4895]

If fourth generation neutrino is $m_Z/2 \leq m_{\nu_4} \leq m_H/2$ the model avoids exclusion.

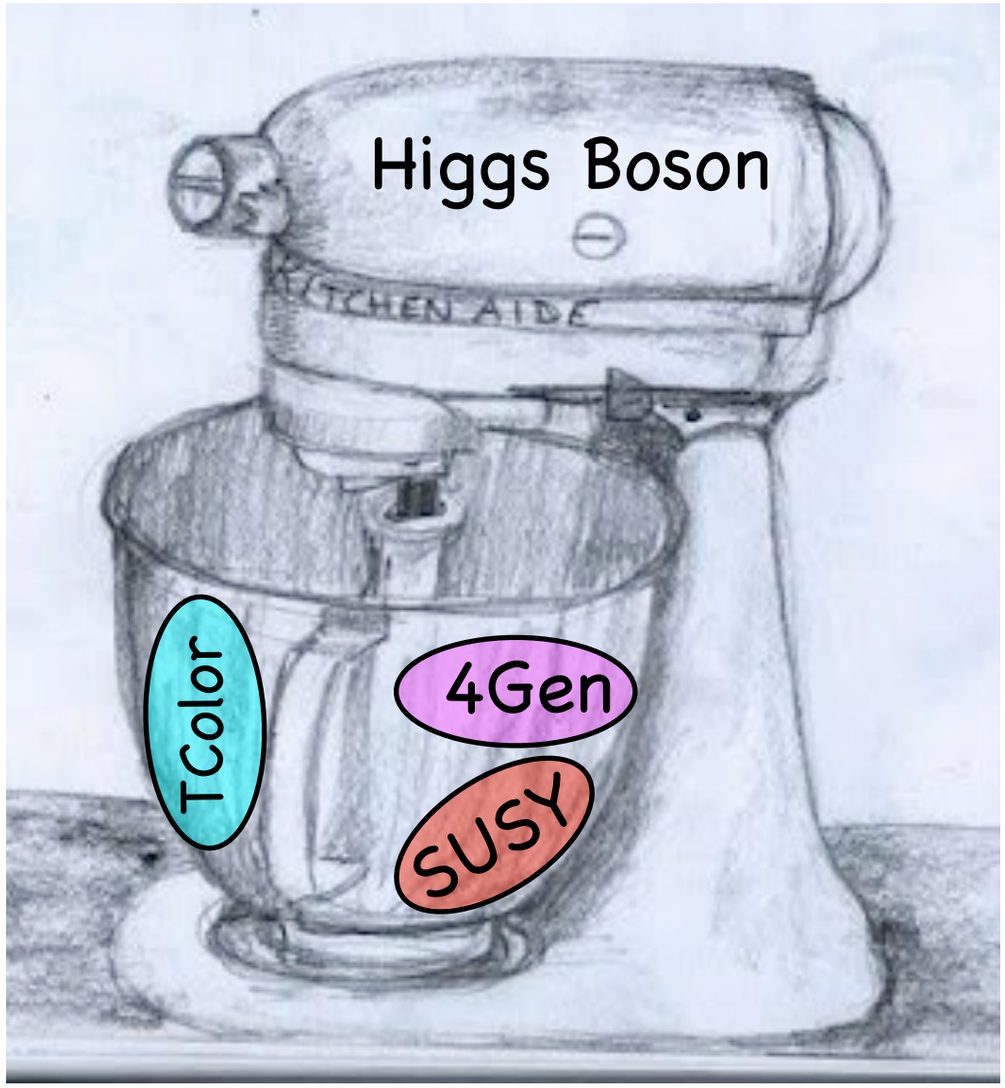
# Summary

- Our knowledge has greatly improved since January 2011 ⟶ Excesses guide research focus

- However, crucial question whether Higgs exists remains unclear

  If Higgs is there next step is to measure:

  - ➡ mass
  - ➡ couplings
  - ➡ Spin and CP




- Fixing properties at 7/8 TeV tough!

- If we don't observe an Excess, Higgs can still be there

- In any case, Higgs search will quickly startle all directions of BSM physics.