Does $H \longrightarrow \gamma\gamma$ taste like vanilla new physics?

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in collaboration with:
Leandro G. Almeida[2], Enrico Bertuzzo[2],
and Renata Zukanovich Funchal[1,2]

[1]Universidade de São Paulo, [2]CEA-Saclay

arXiv:1207.5254

Outline

- The Higgs boson and some old news

- $H \to \gamma\gamma$

- Conclusions

The Higgs boson

The Higgs boson

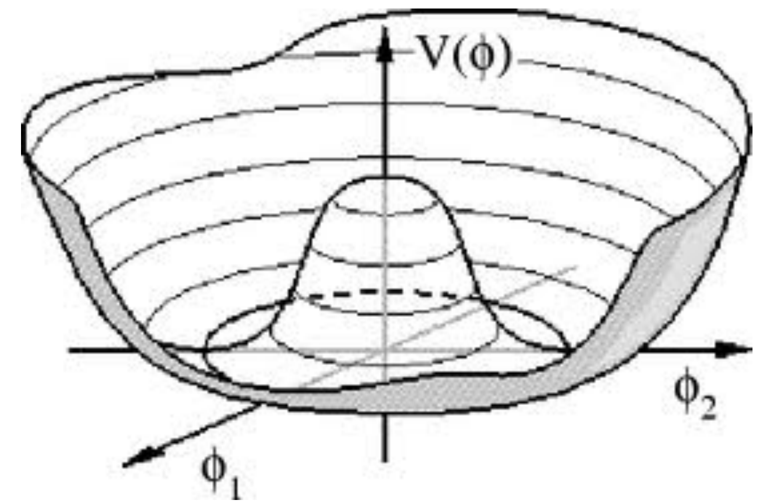
We cannot write a mass term

$$m\,\bar{\psi}_L\psi_R$$

The Higgs boson

We cannot write a mass term

$$m\,\bar{\psi}_L \psi_R$$



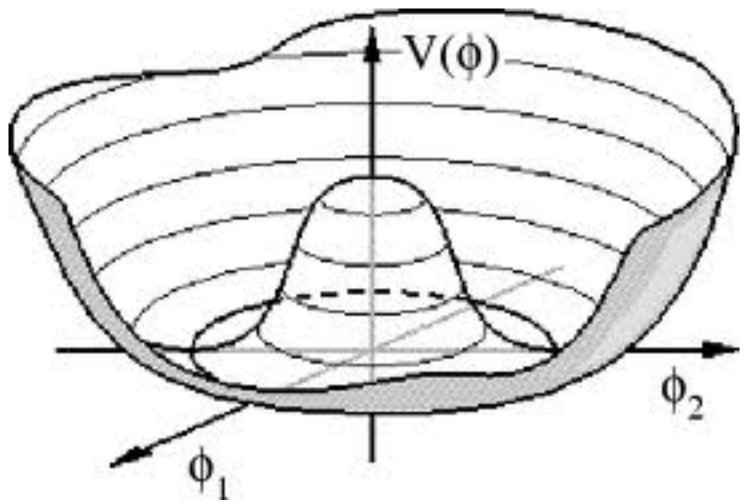
$$c\,\bar{\psi}_L H \psi_R \to c\,\bar{\psi}_L (H+v) \psi_R \longrightarrow cv\,\bar{\psi}_L \psi_R$$

mass term

The Higgs boson

We cannot write a mass term

$$m\,\bar{\psi}_L\psi_R$$



$$c\,\bar{\psi}_L H\psi_R \to c\,\bar{\psi}_L(H+v)\psi_R \longrightarrow cv\,\bar{\psi}_L\psi_R$$

mass term

Gives mass to particles

Breaks $SU(2)_L$

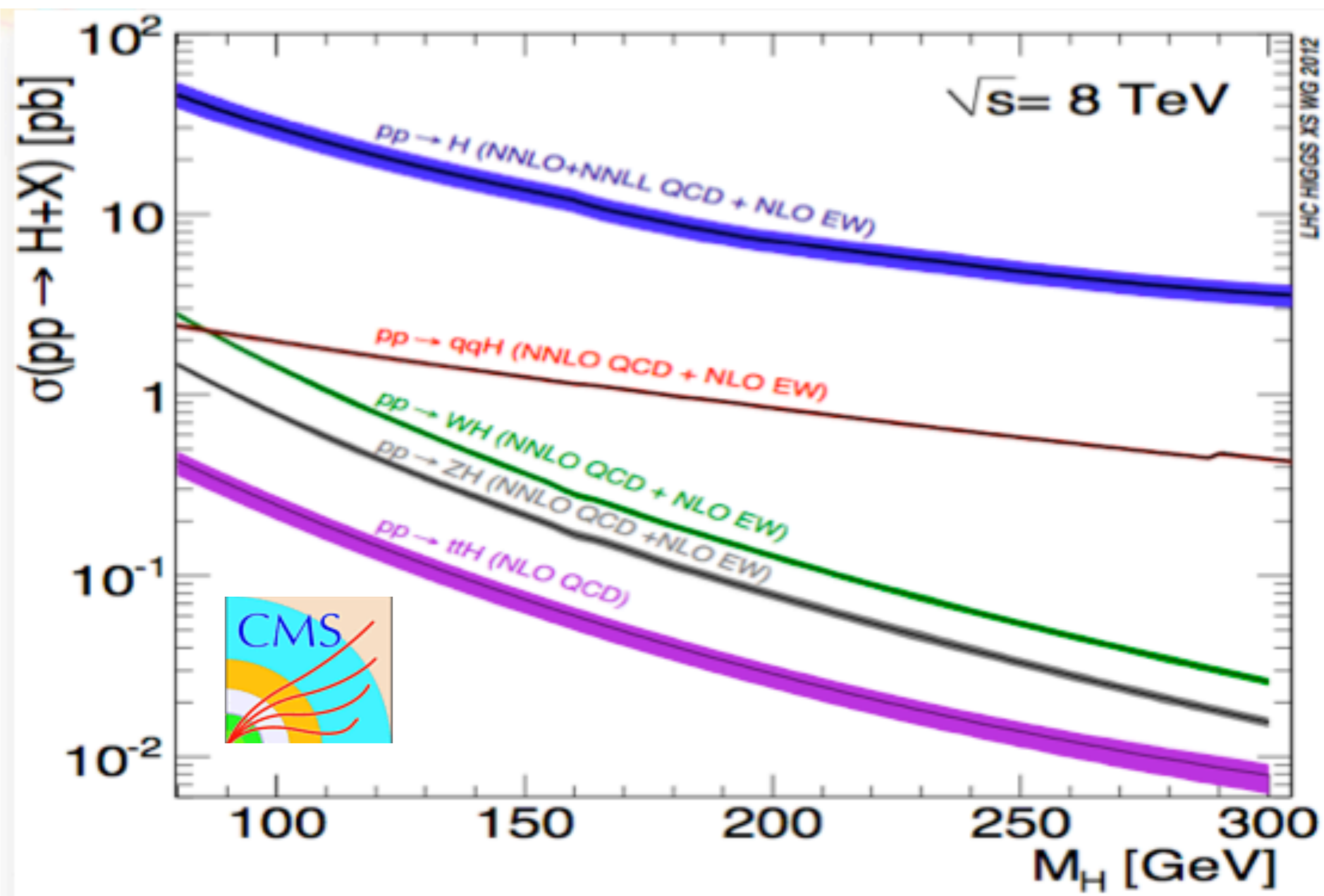
The Higgs boson

How do you see a Higgs boson?

The Higgs boson

How do you see a Higgs boson?

1) You have to produce it



The Higgs bo

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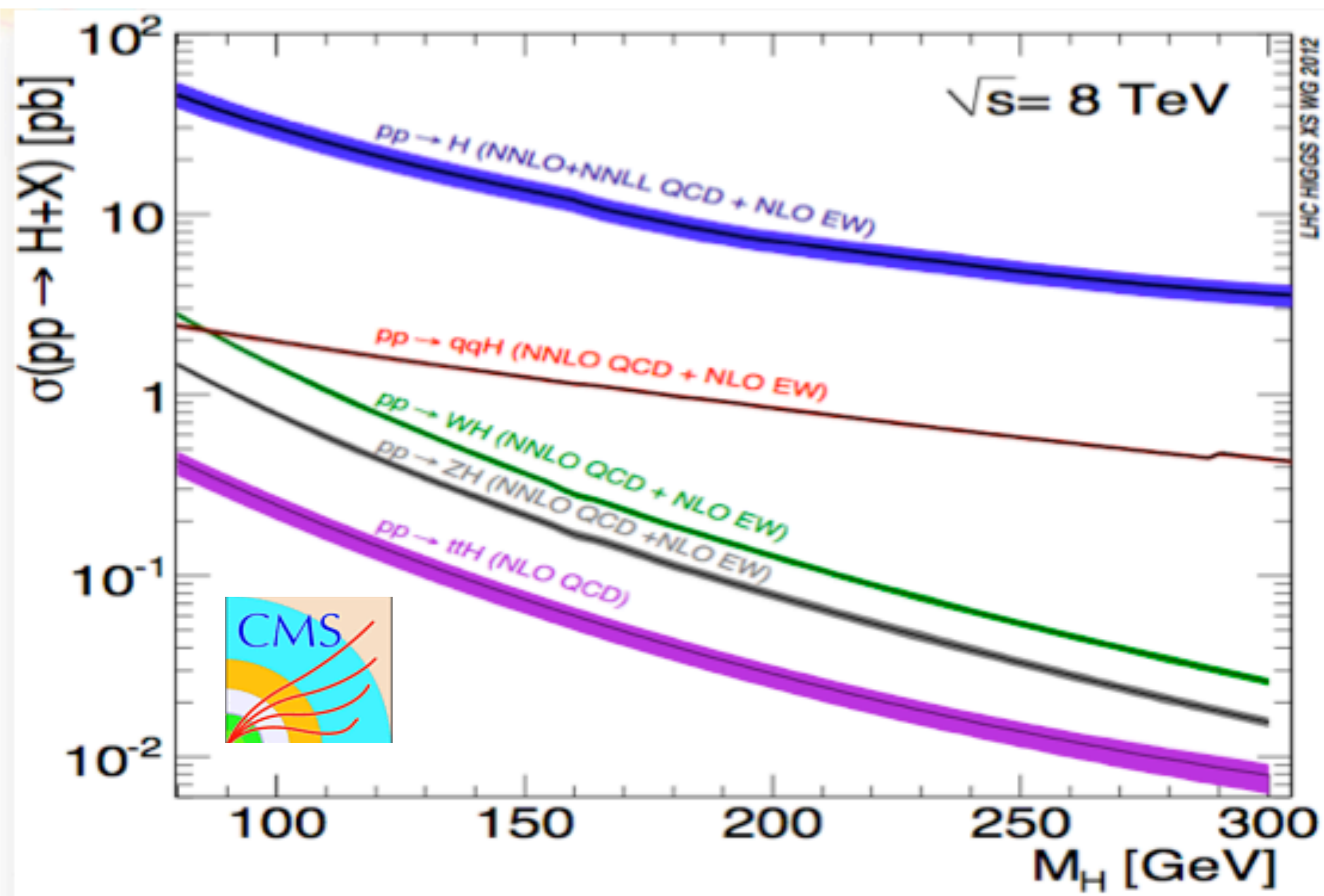

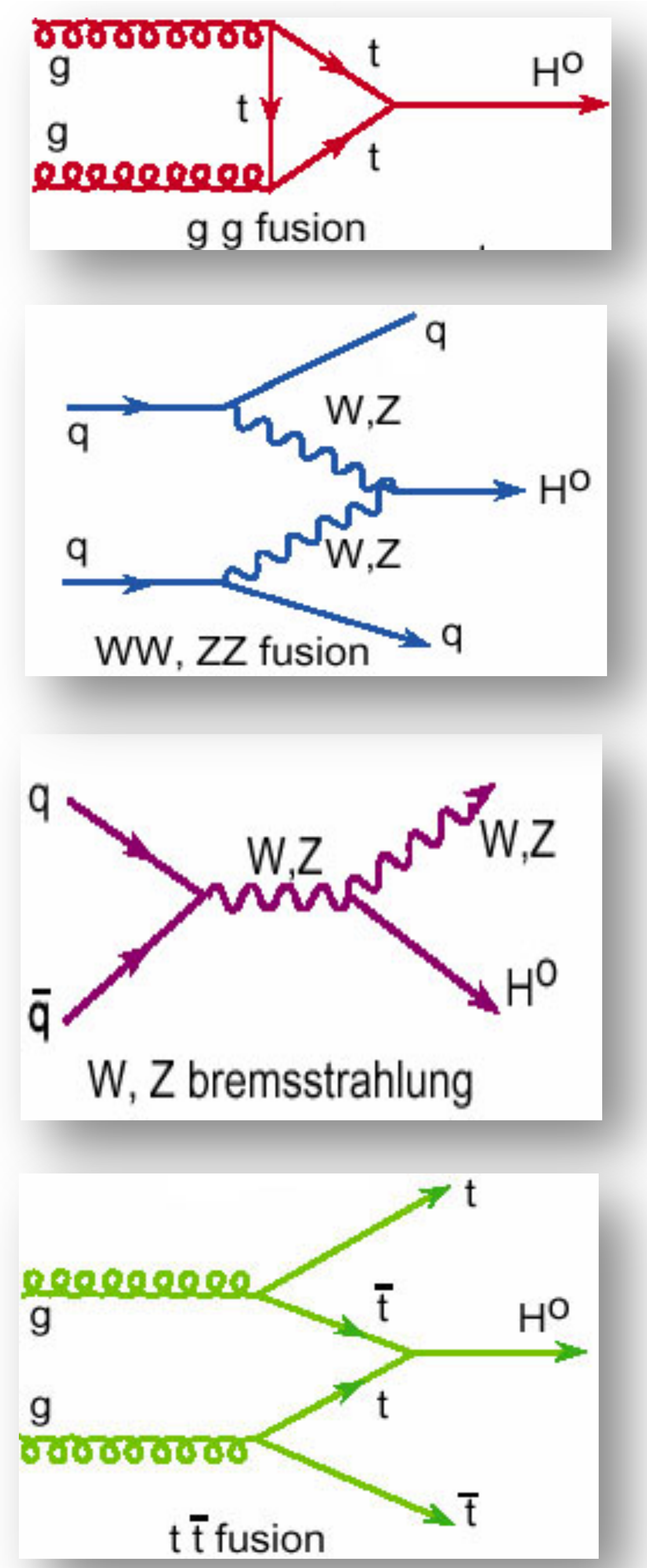

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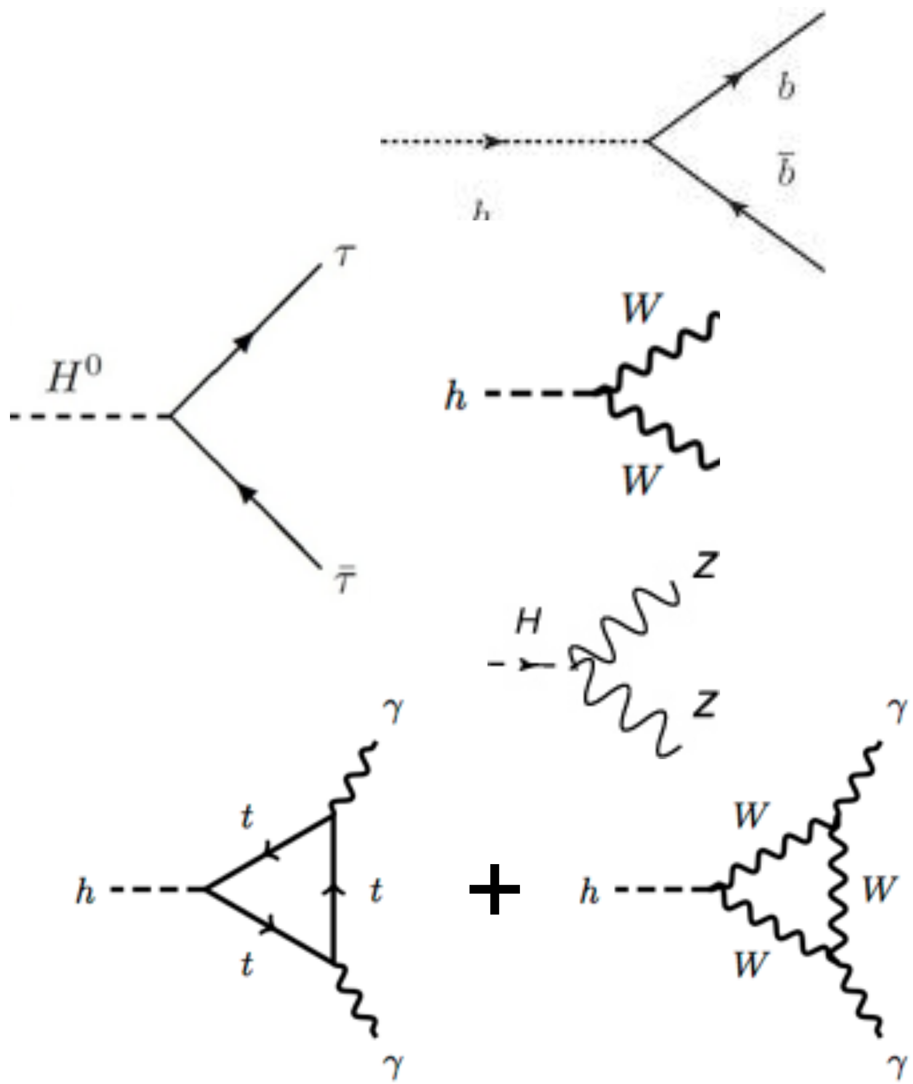
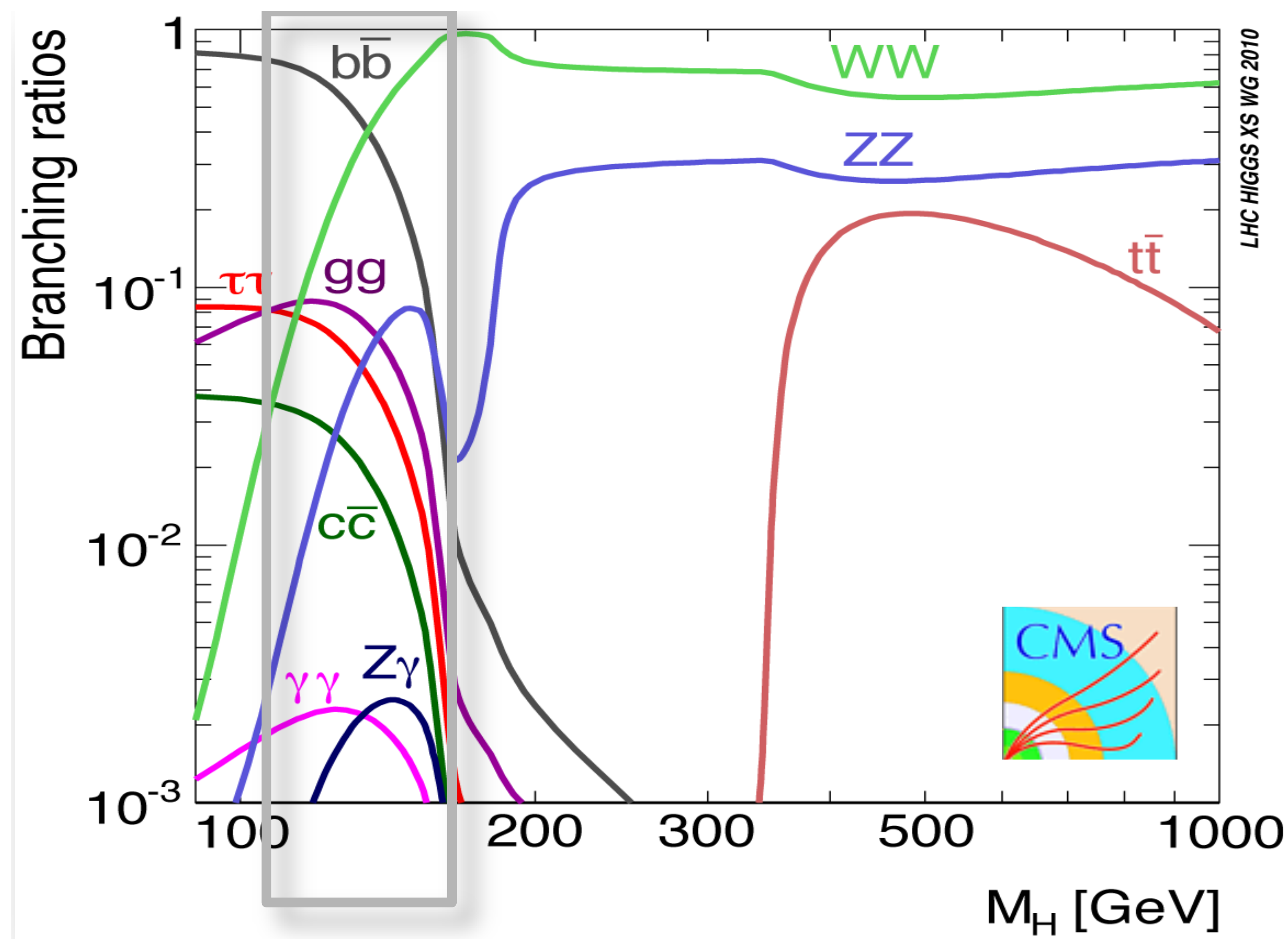
The Higgs boson

How do you see a Higgs boson?

1) You have to produce it

2) and see its decay products





The Higgs boson

$$\sim \sum_i \sigma_i(pp \to H + X) \times \mathrm{BR}(H \to \mathrm{whatever})$$

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LARGER is not always BETTER

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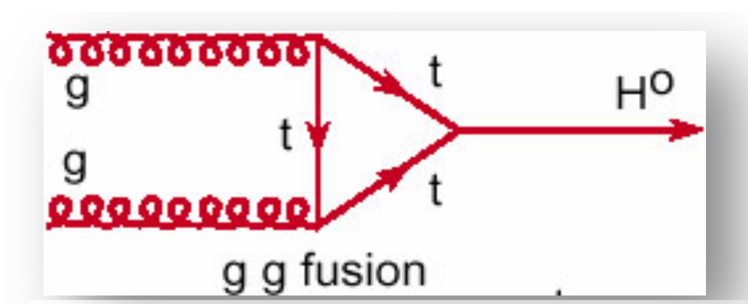

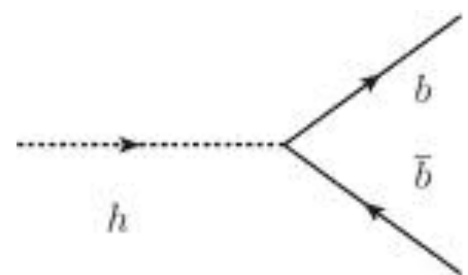

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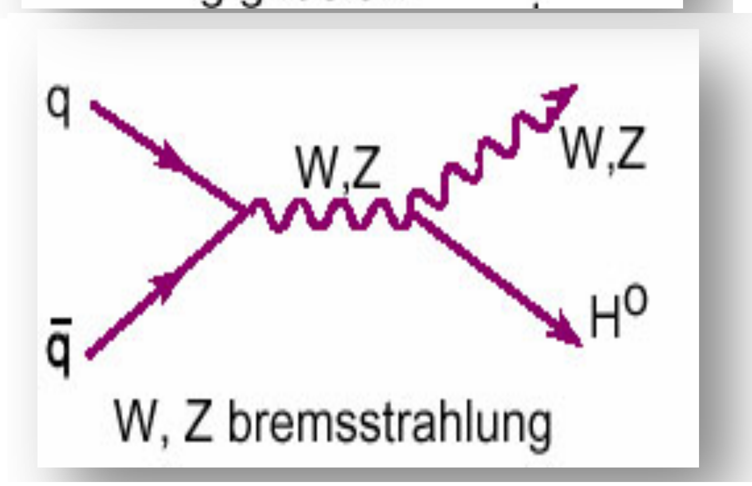

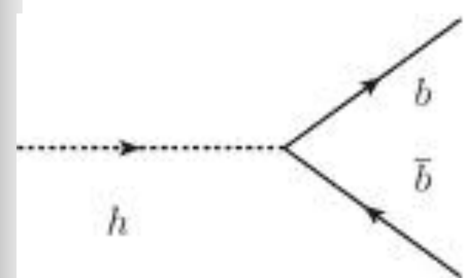

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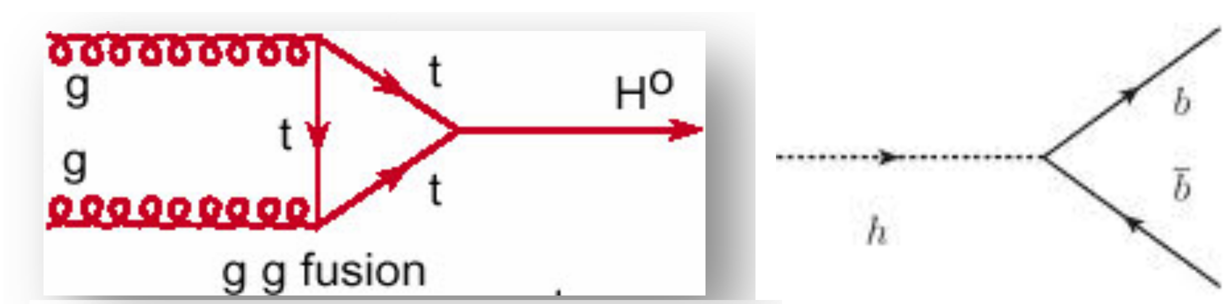

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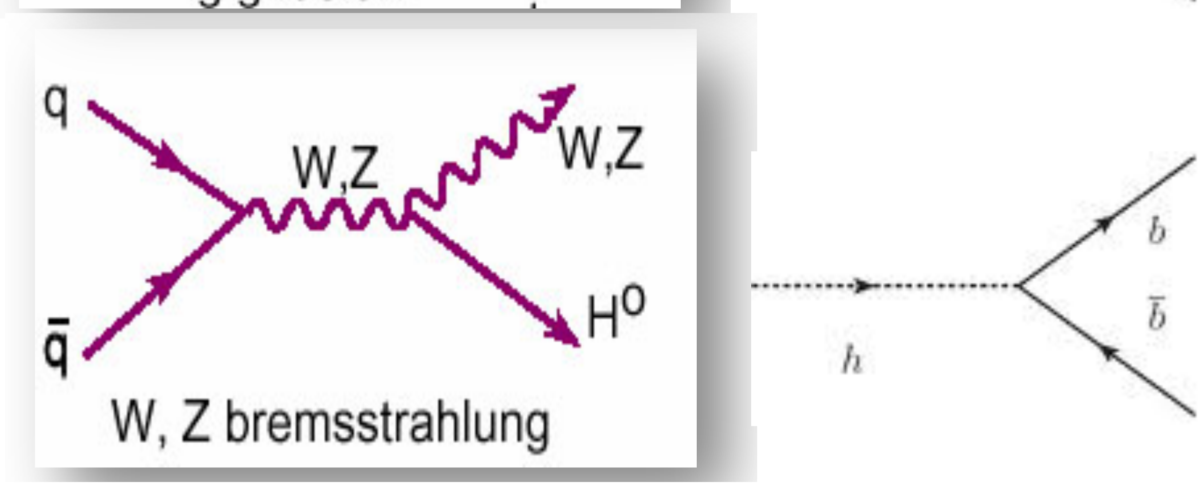

This looks like the QCD background!

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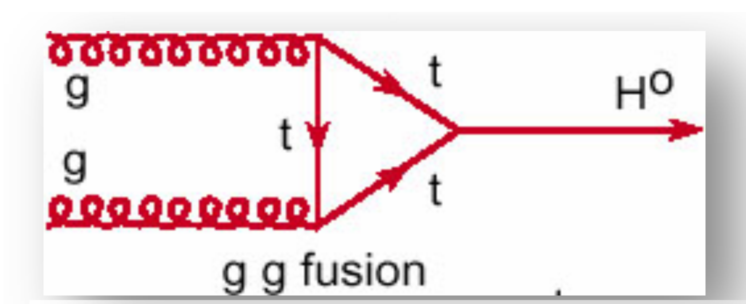

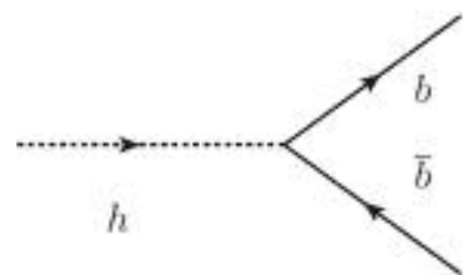

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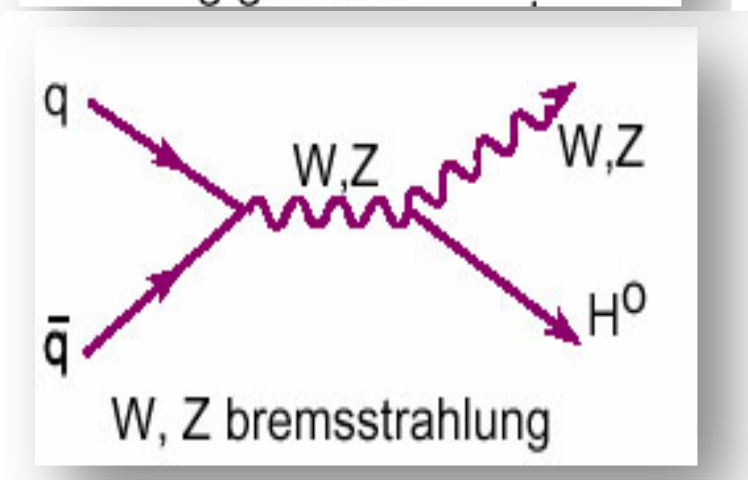

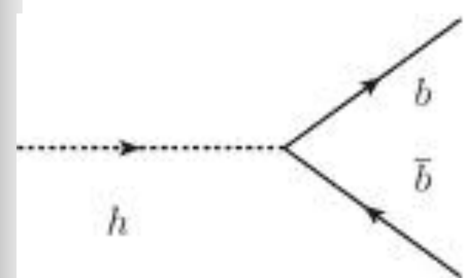

tag the W,Z decays, boosted Higgs

The Higgs boson

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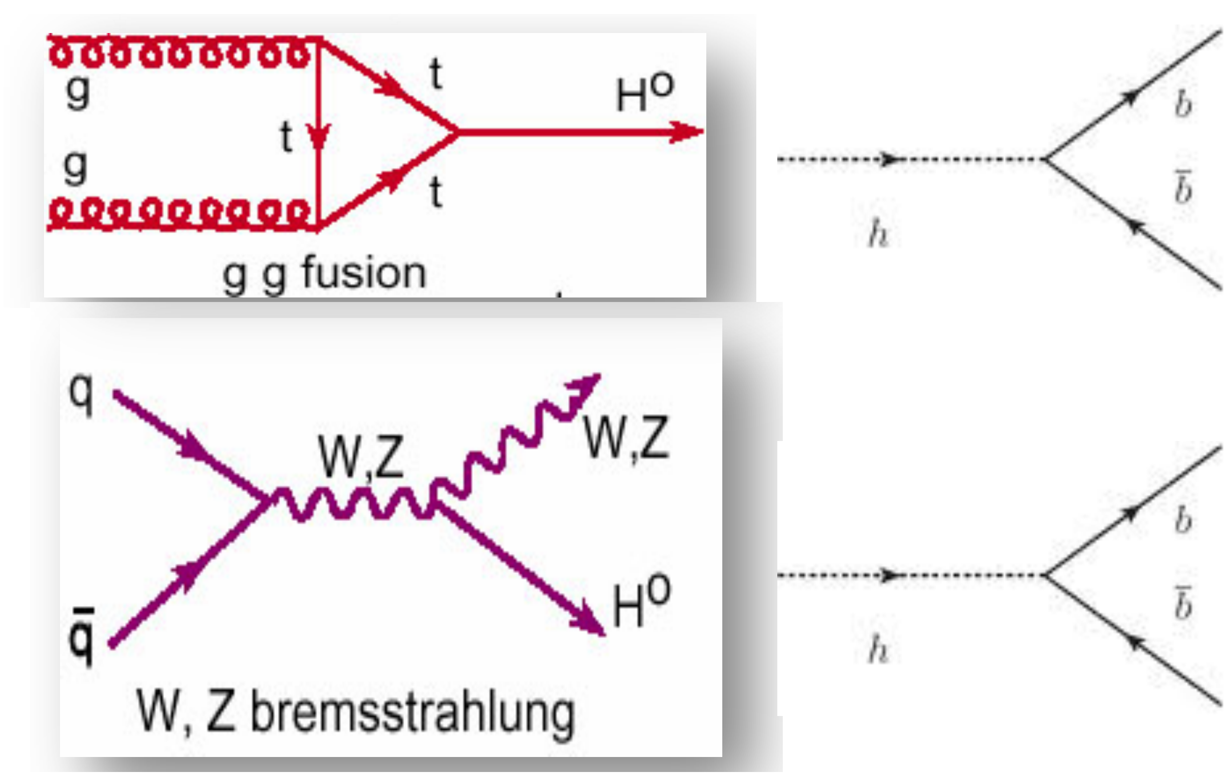

here, tagging the W,Z decays and requiring high p_T reduces QCD background but kills highest production mode (overall improved signal/BG)

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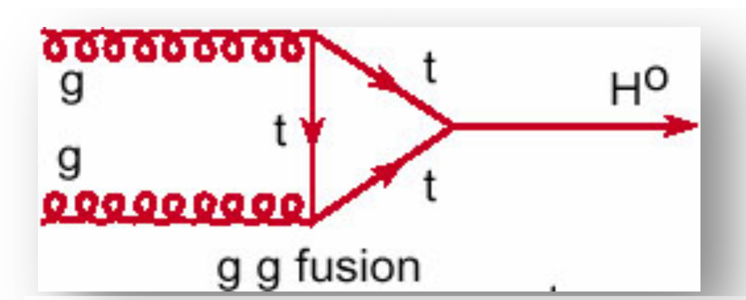

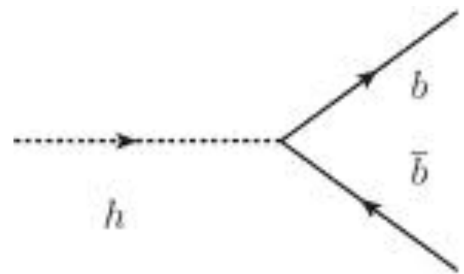

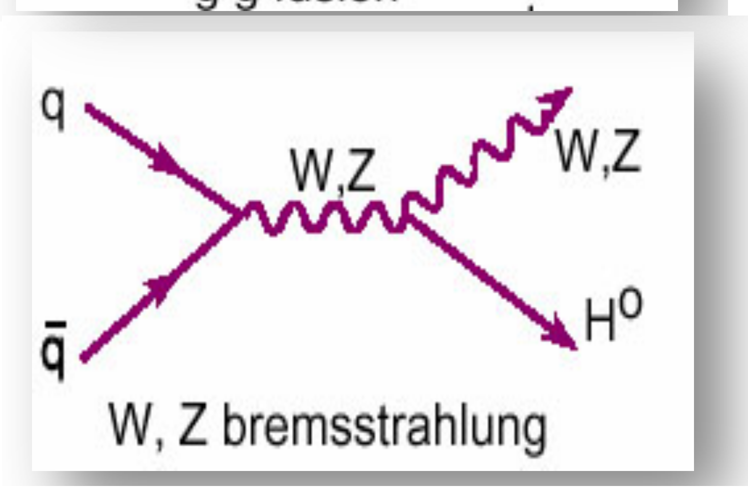

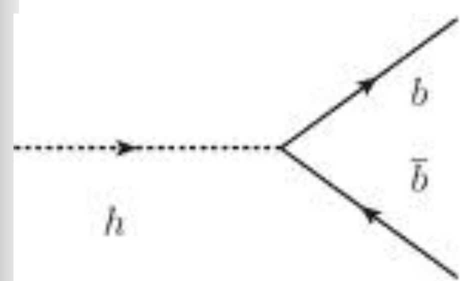

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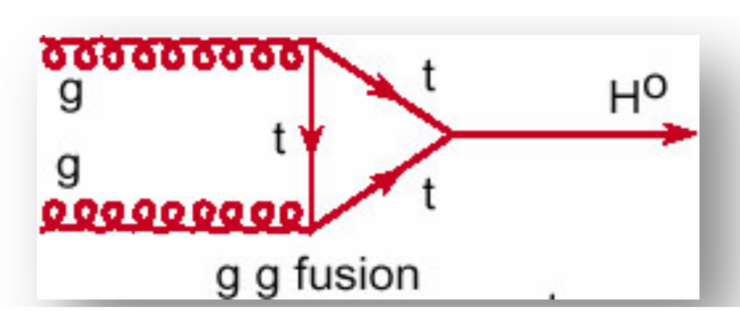

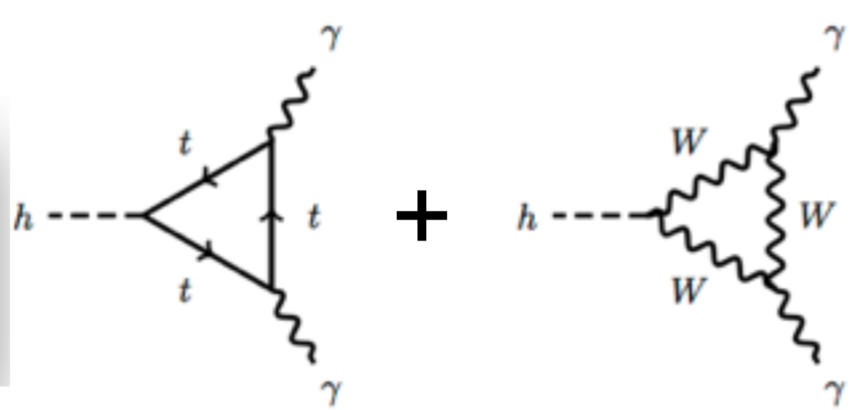

γγ: clean signal

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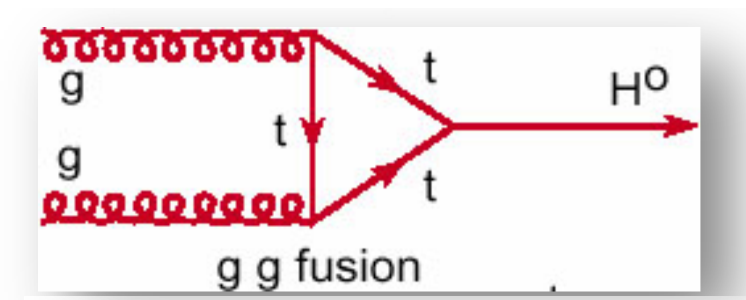

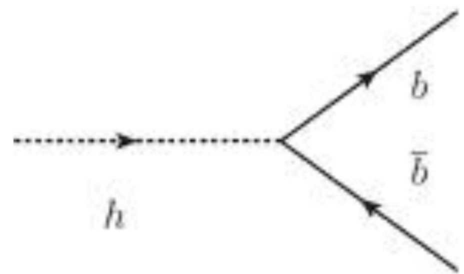

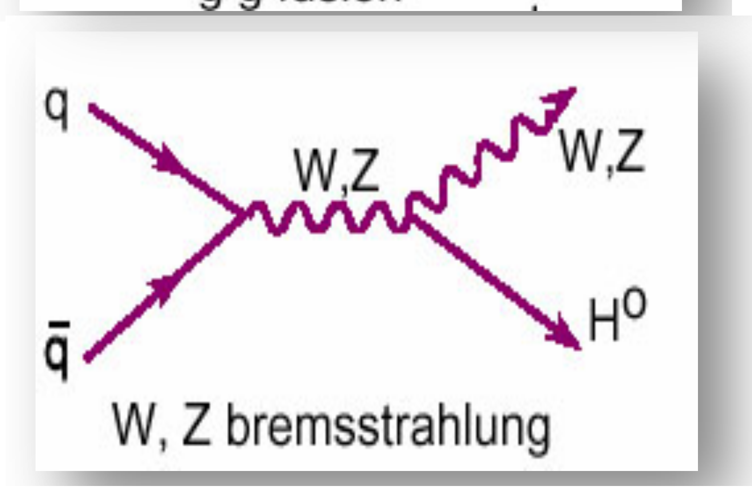

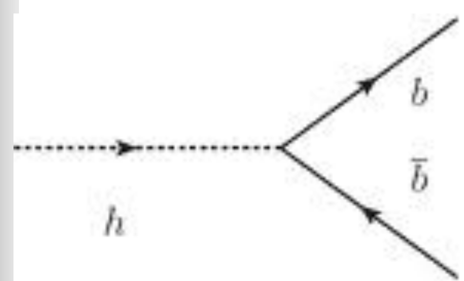

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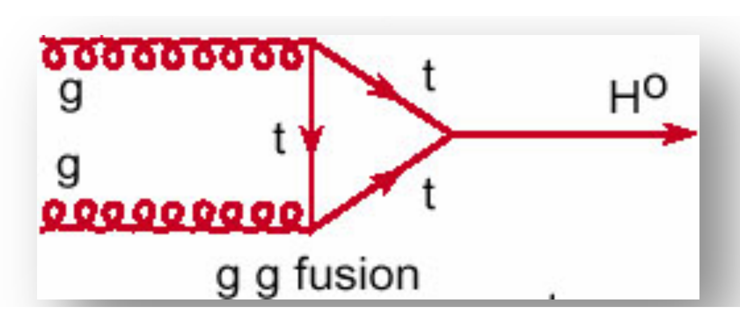

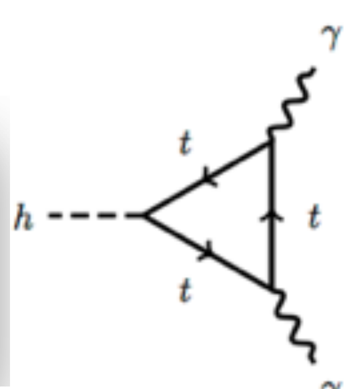

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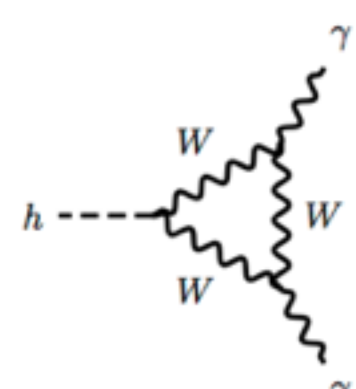

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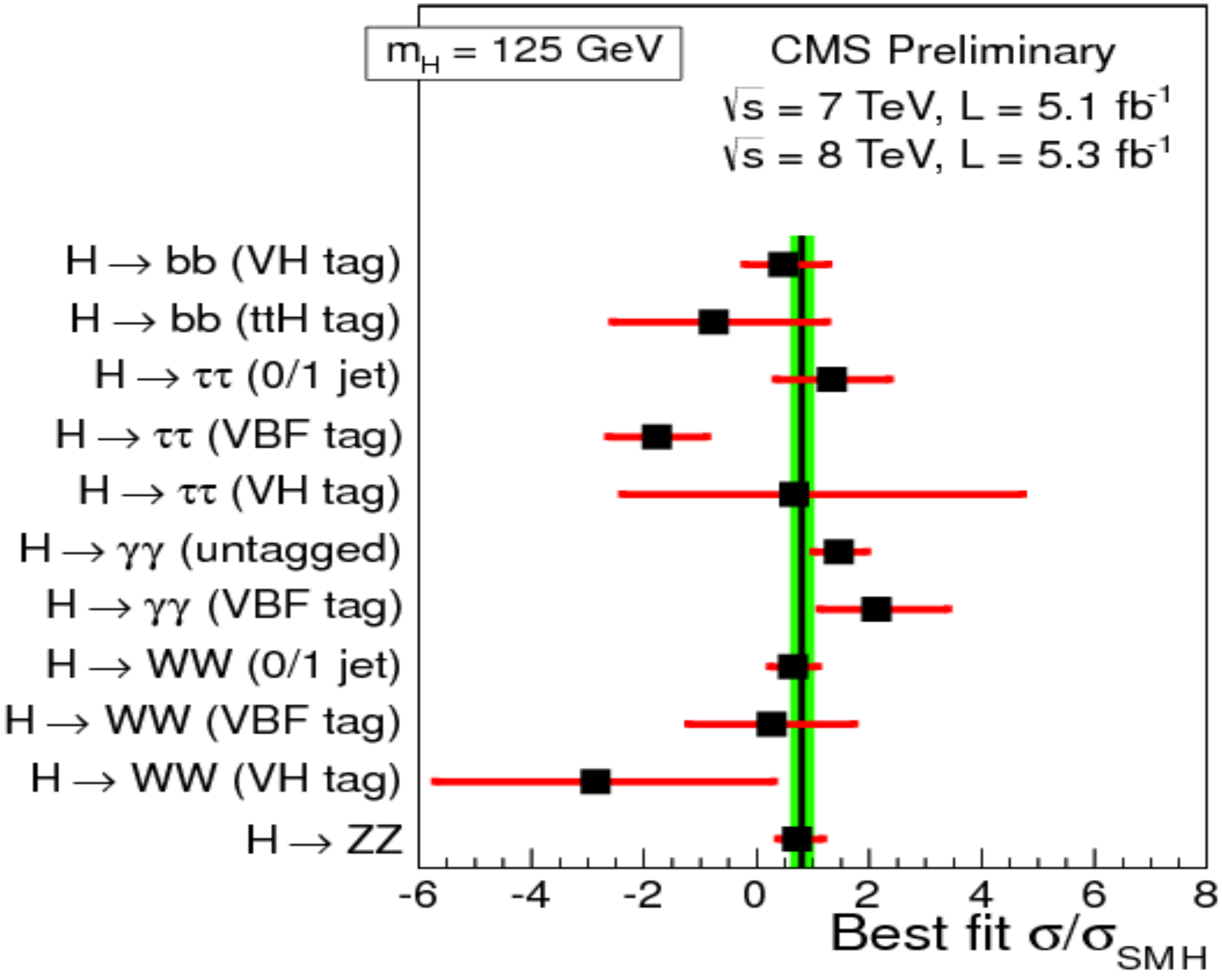
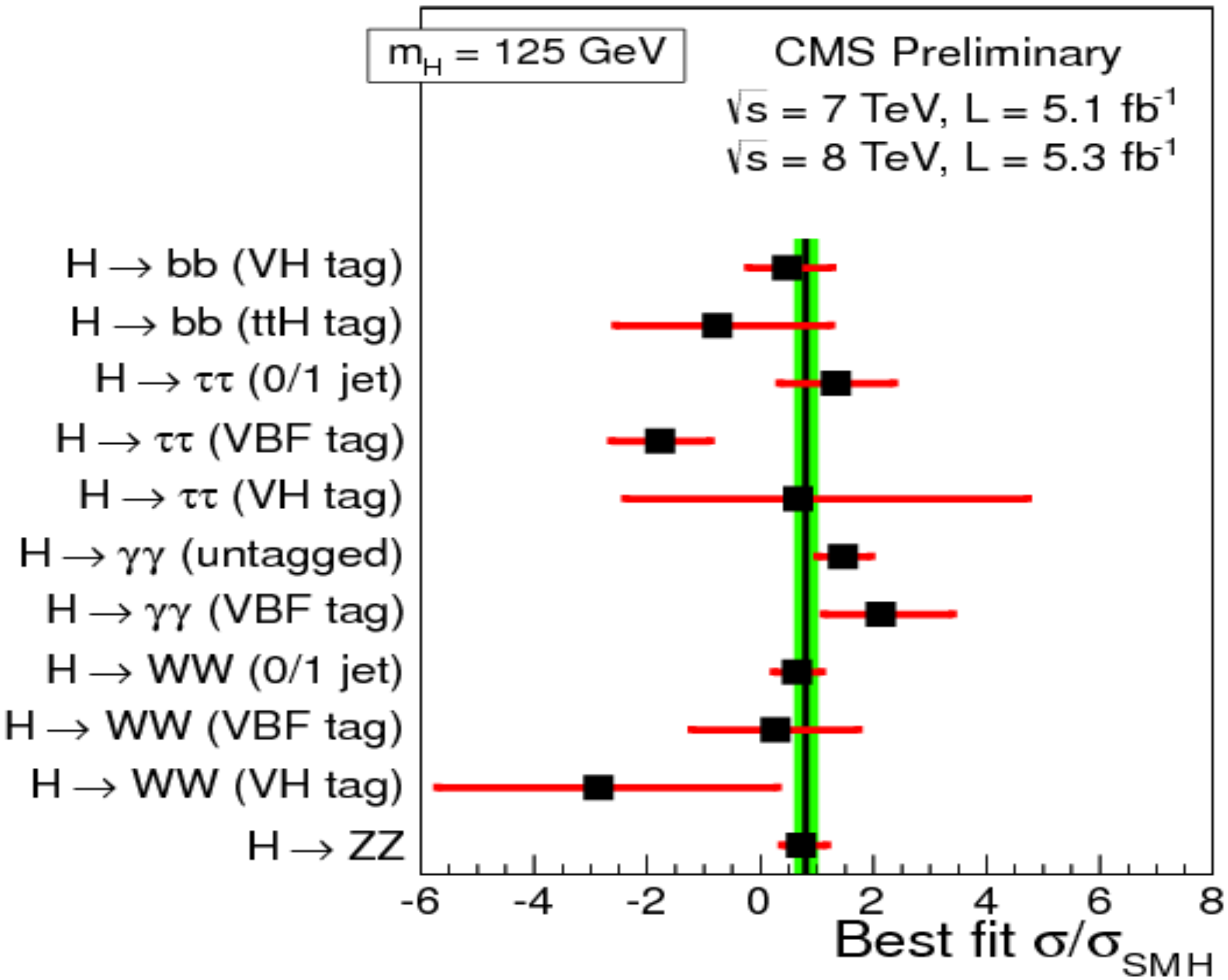


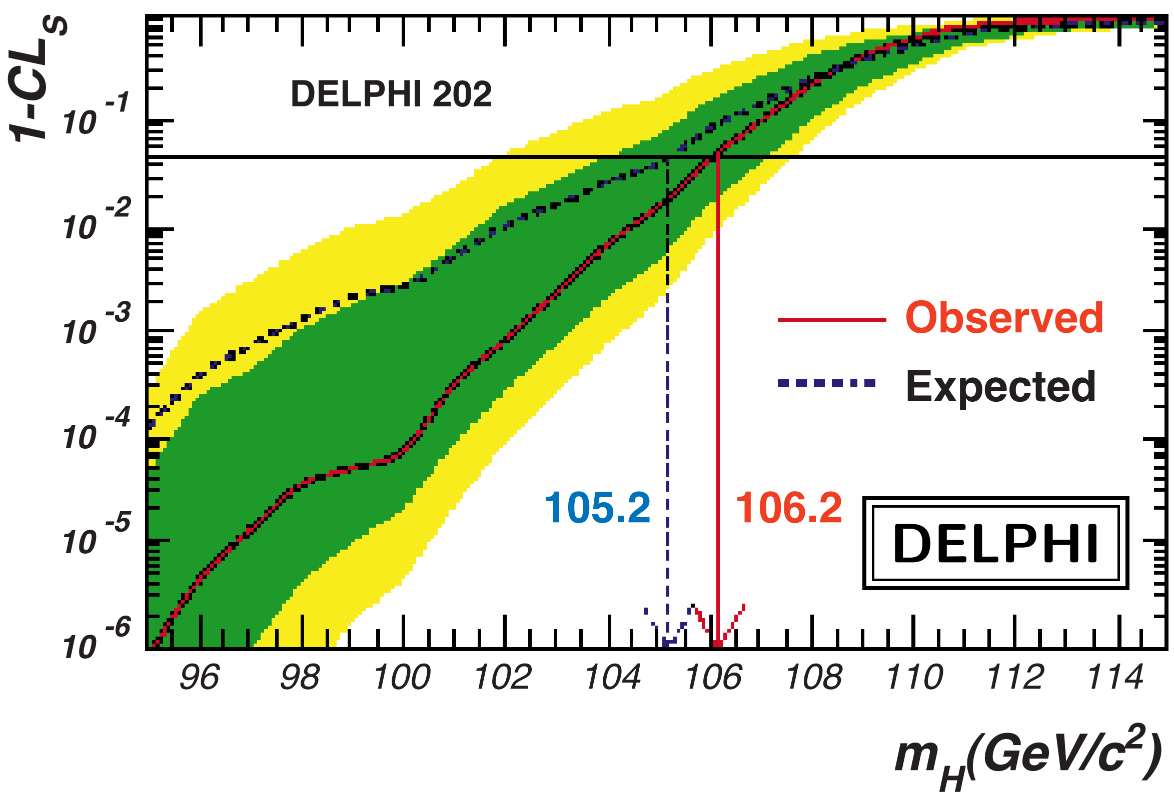
The Higgs boson

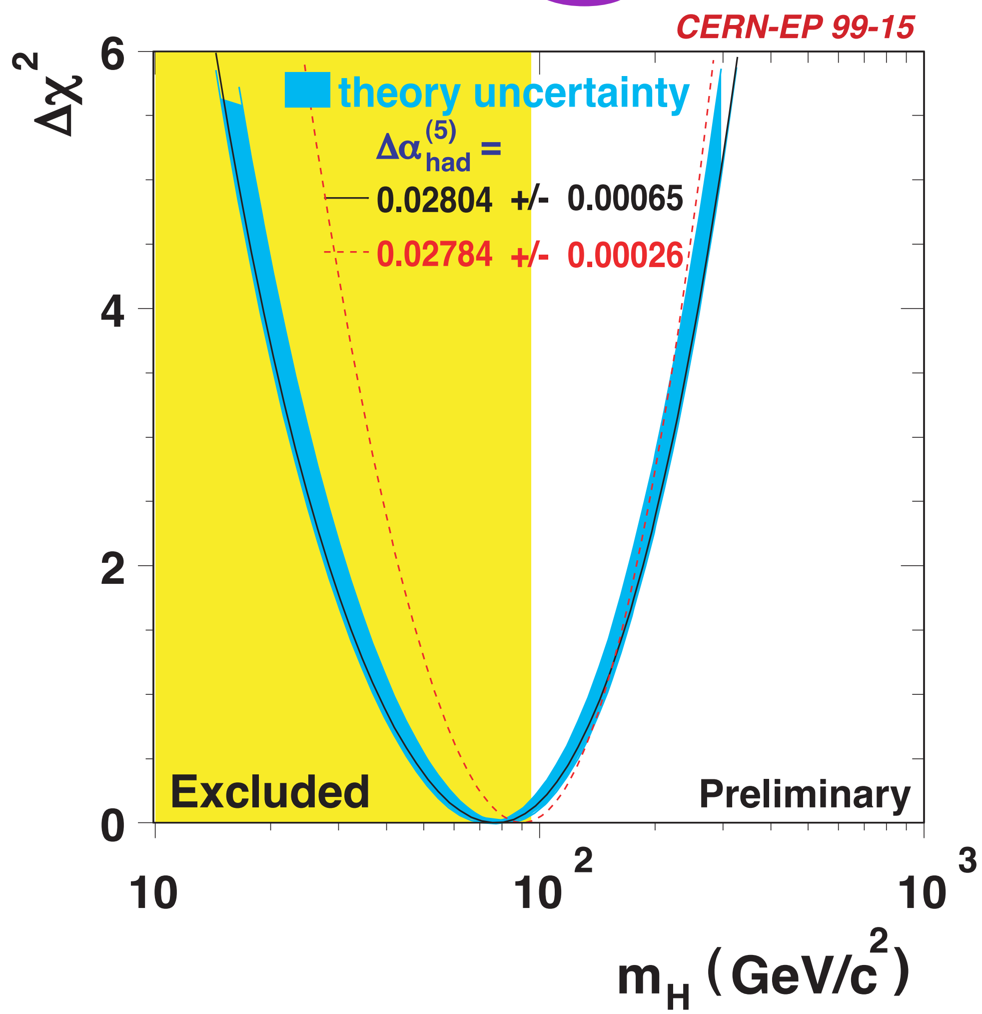


Probe many channels to disentangle production cross sections and decay widths

The Higgs boson

@ LEP





Expected Limit: 105.2 GeV/c^2 @ 95% C.L.

Observed Limit: 106.2 GeV/c^2 @ 95% C.L.

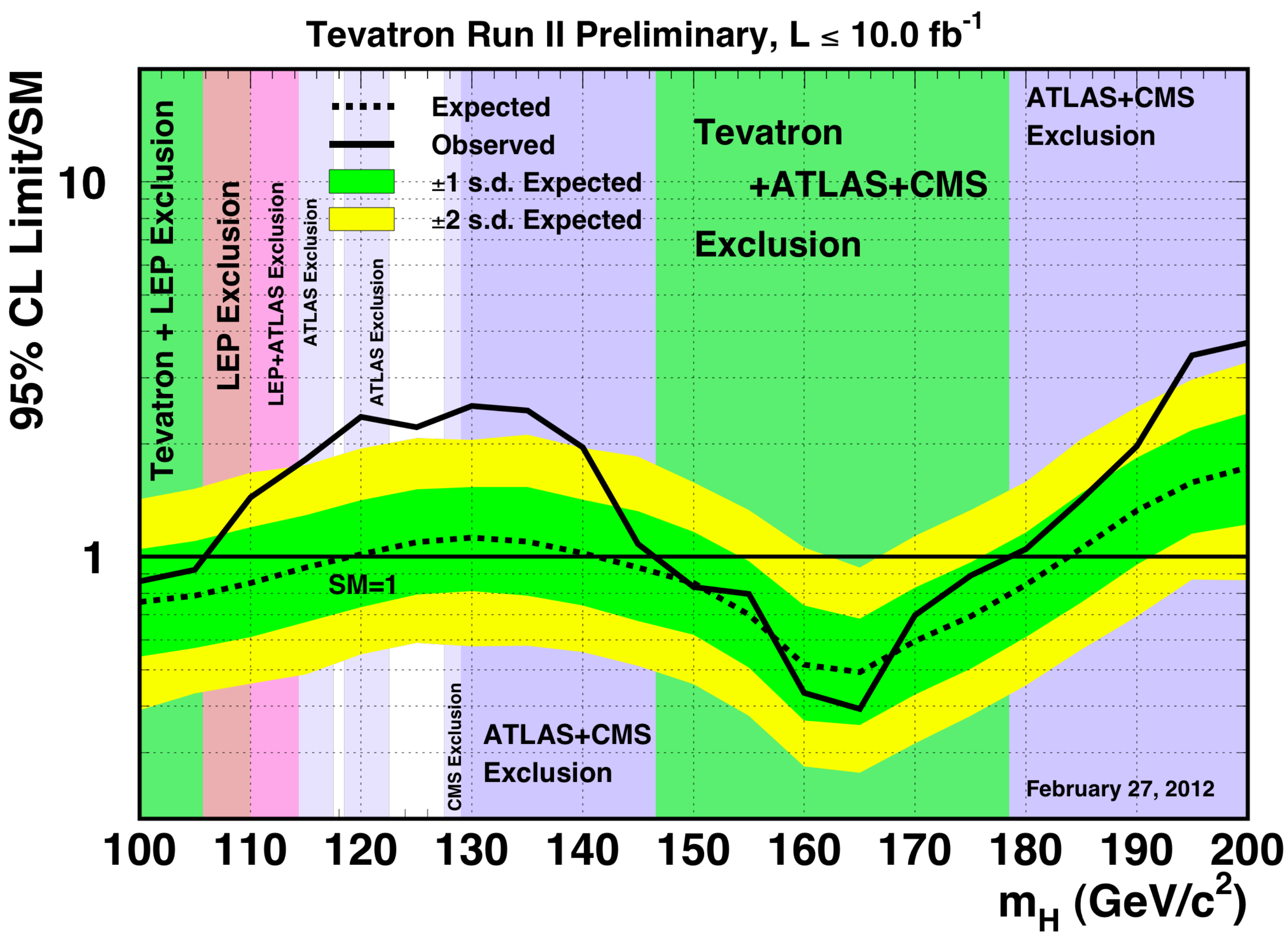
LEP EW Working Group fits from LP99:

$$m_H = 77^{+69}_{-39}\ \mathrm{GeV}/c^2$$
$$m_H < 215\ \mathrm{GeV}/c^2 \text{ at } 95\%\ \text{C.L.}$$

Source: Sau Lan Wu talk, 1999, California, see http://www-wisconsin.cern.ch/~wus/talks/mumutalk.pdf

The Higgs boson

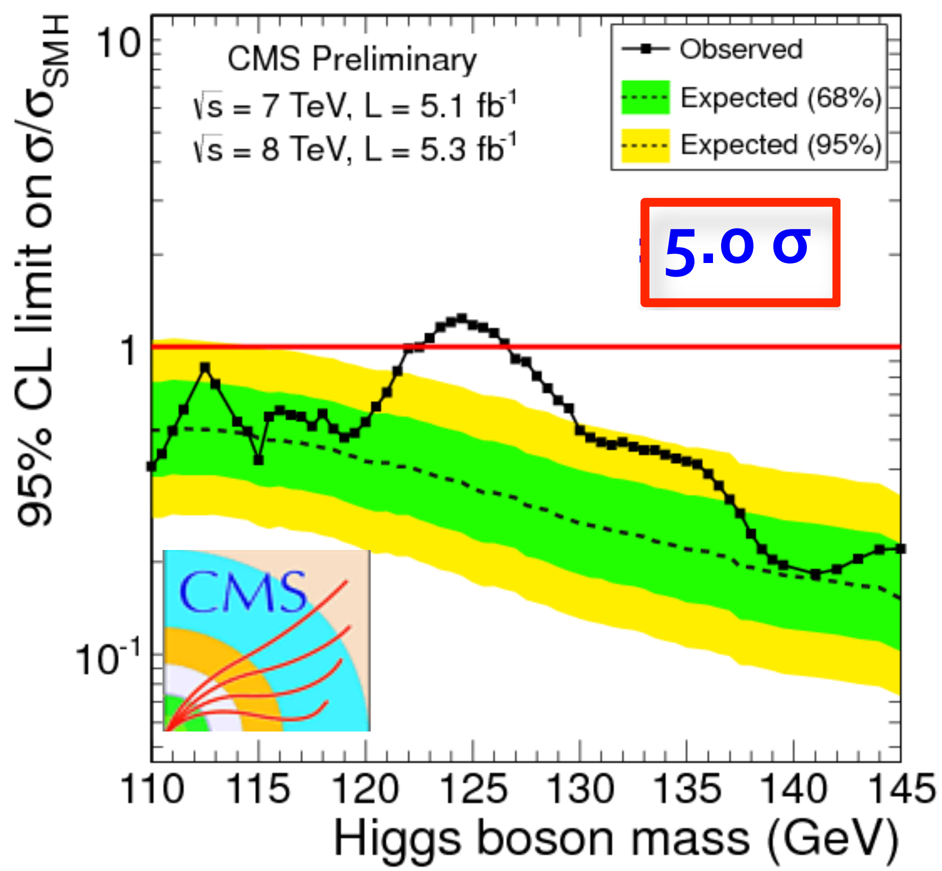
@ TEVATRON

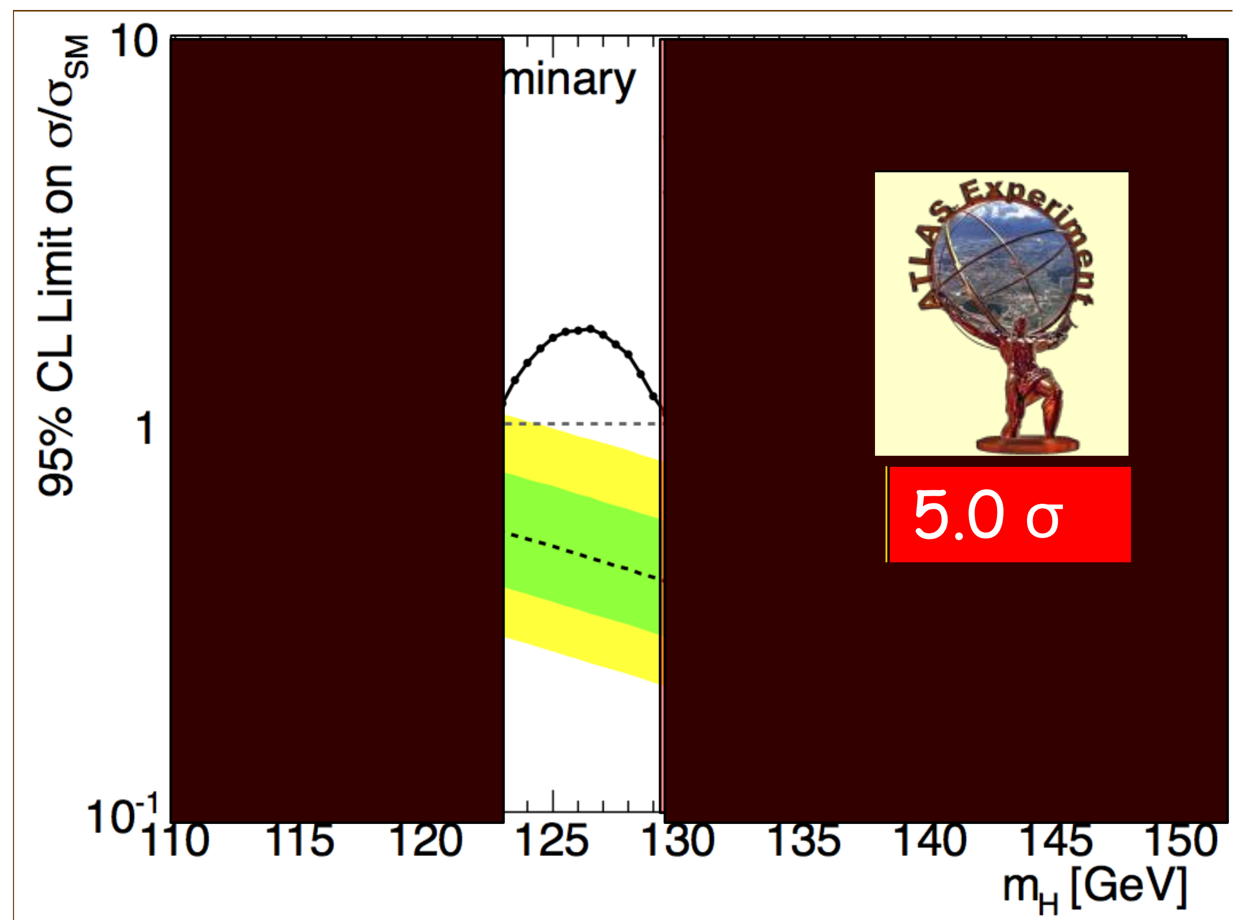


Source: Fermilab Wine and Cheese seminar July 2nd
http://theory.fnal.gov/jetp/talks/ejames_jul02_wine_cheese.pdf

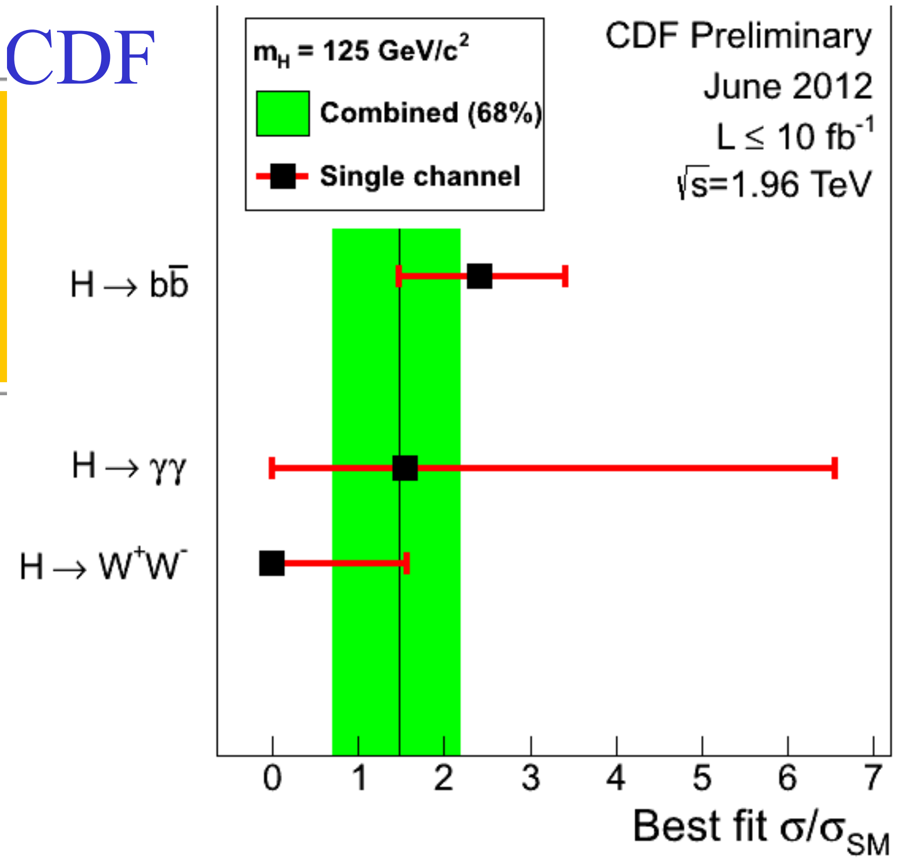
The Higgs boson

@ LHC

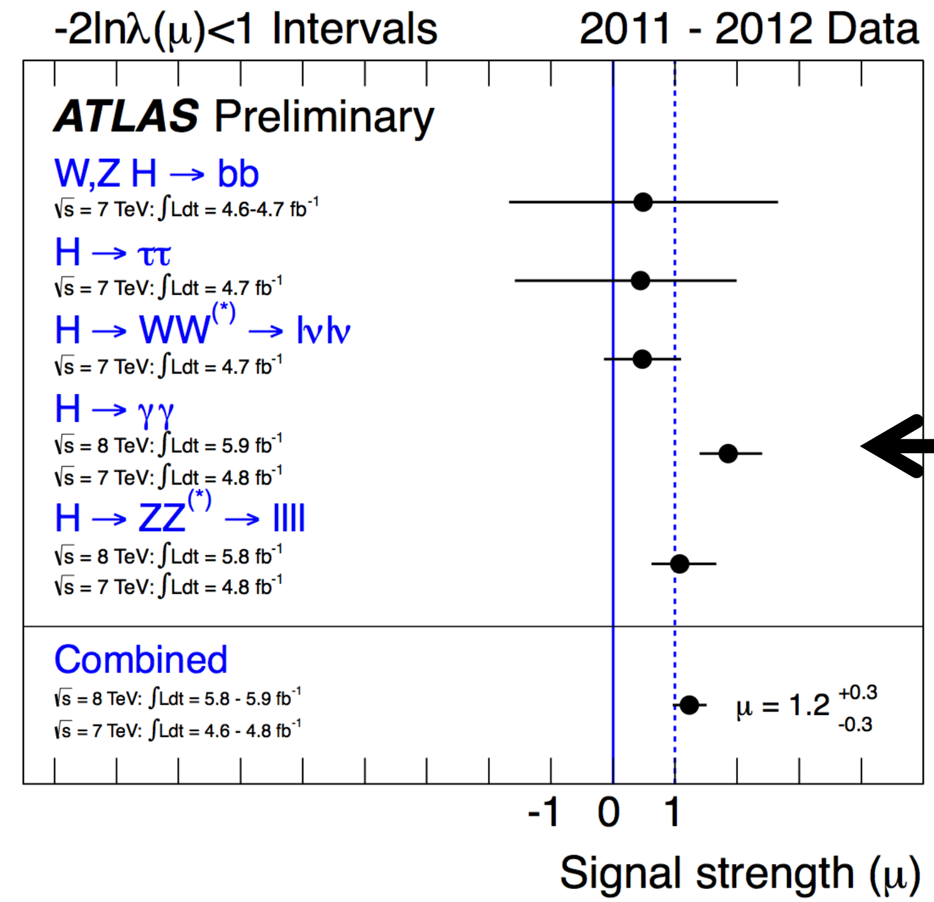




CDF



m_H = 125 GeV/c^2
Combined (68%)
Single channel
CDF Preliminary
June 2012
L ≤ 10 fb^{-1}
$\sqrt{s}$=1.96 TeV
H → b$\bar{b}$
H → γγ
H → W$^+$W$^-$
0 1 2 3 4 5 6 7
Best fit σ/σ$_{SM}$



-2lnλ(μ)<1 Intervals
2011 - 2012 Data
ATLAS Preliminary
W,Z H → bb
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6-4.7 fb^{-1}
H → ττ
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb^{-1}
H → WW$^{(*)}$ → lνlν
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb^{-1}
H → γγ
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.9 fb^{-1}
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb^{-1}
H → ZZ$^{(*)}$ → llll
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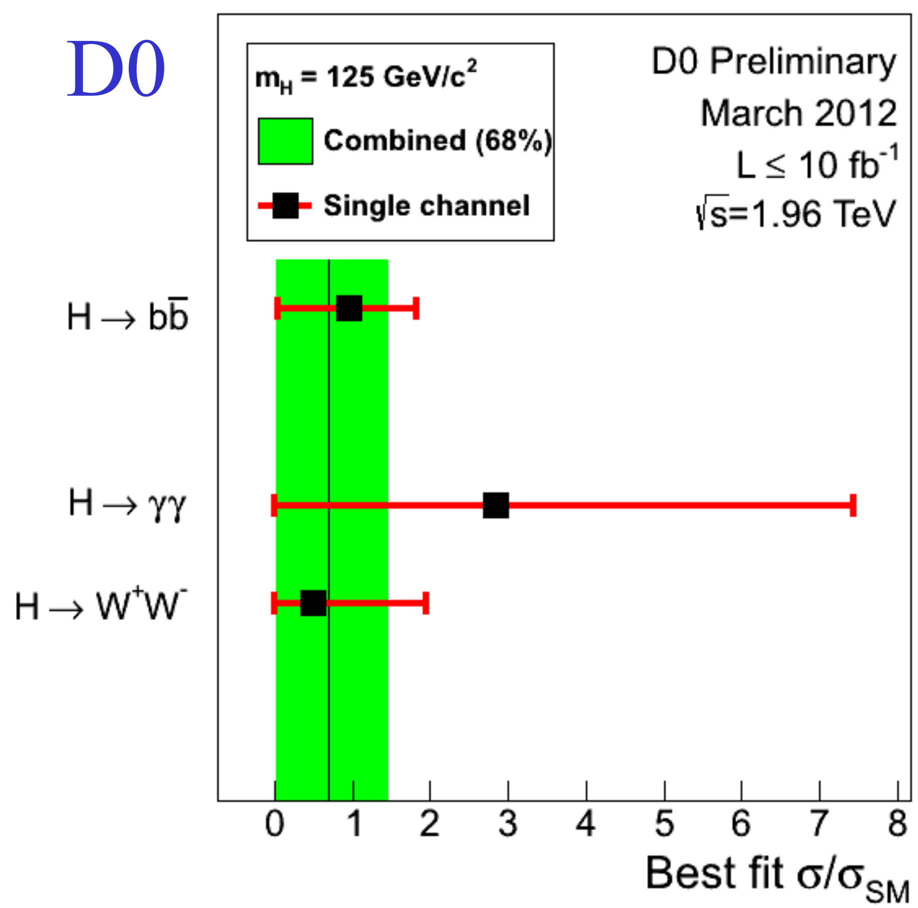
Combined
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 - 5.9 fb^{-1}
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 - 4.8 fb^{-1}
μ = 1.2 $^{+0.3}_{-0.3}$
-1 0 1
Signal strength (μ)

D0



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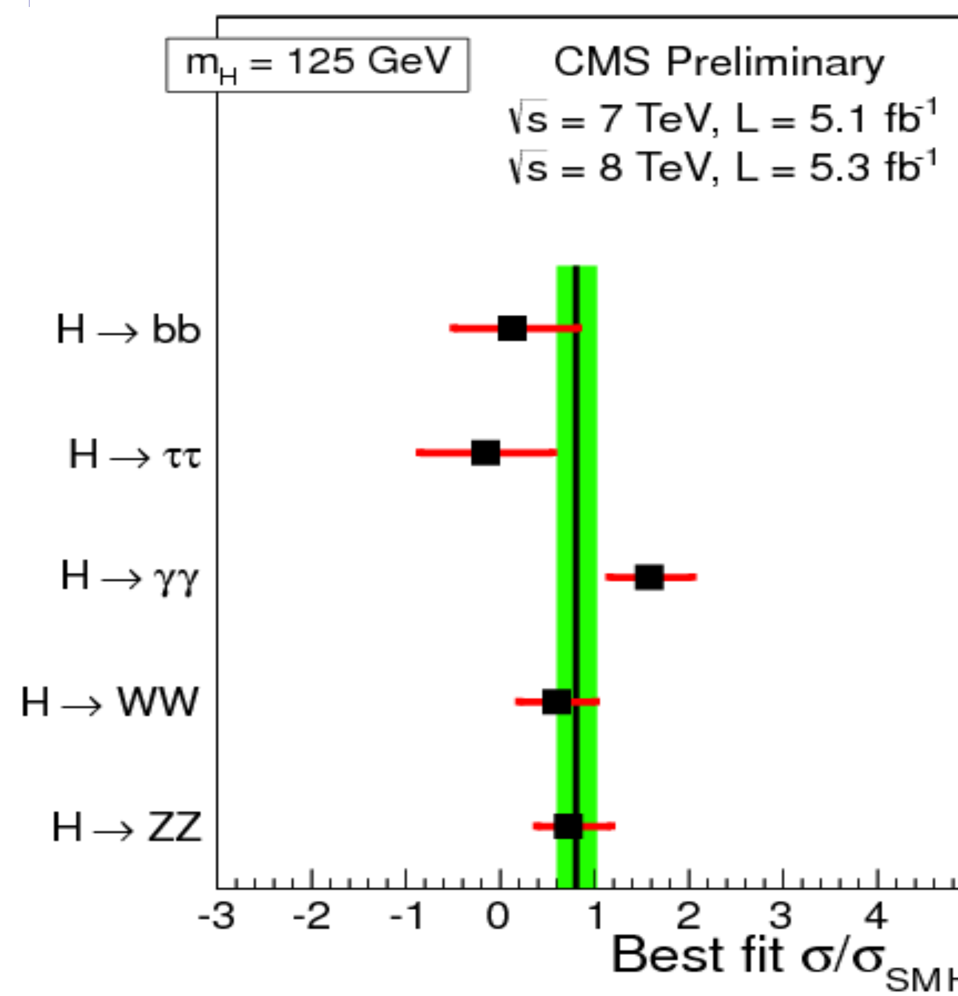
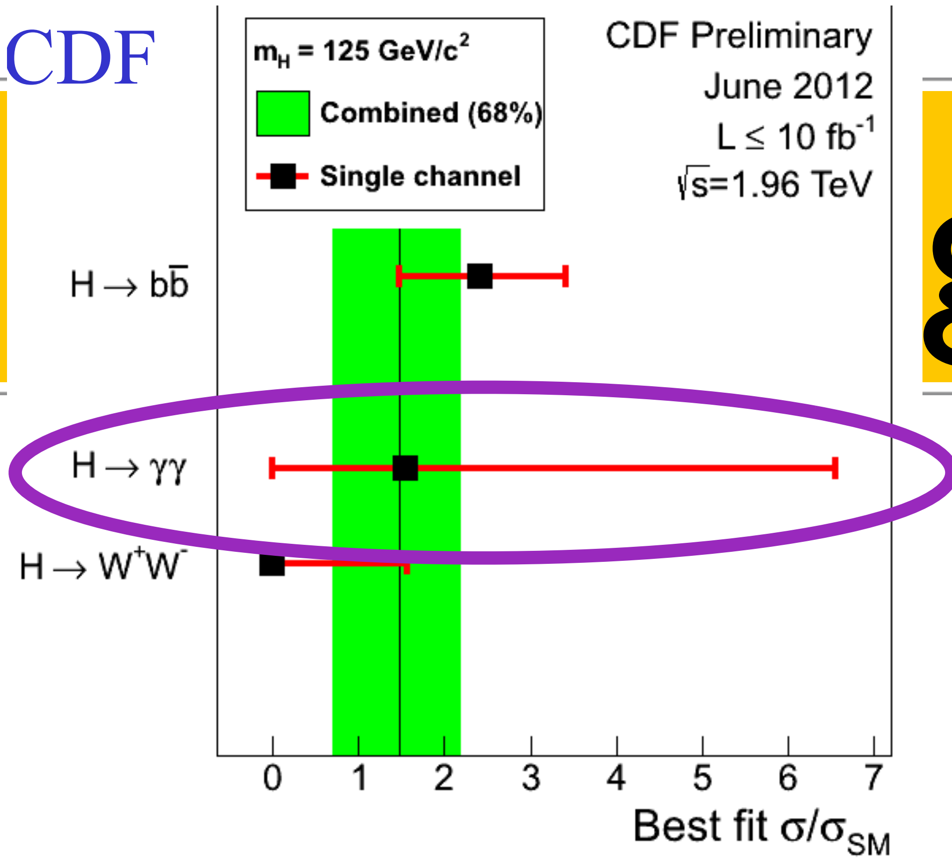


m_H = 125 GeV
CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
-3 -2 -1 0 1 2 3 4 5
Best fit σ/σ$_{SM H}$

CDF



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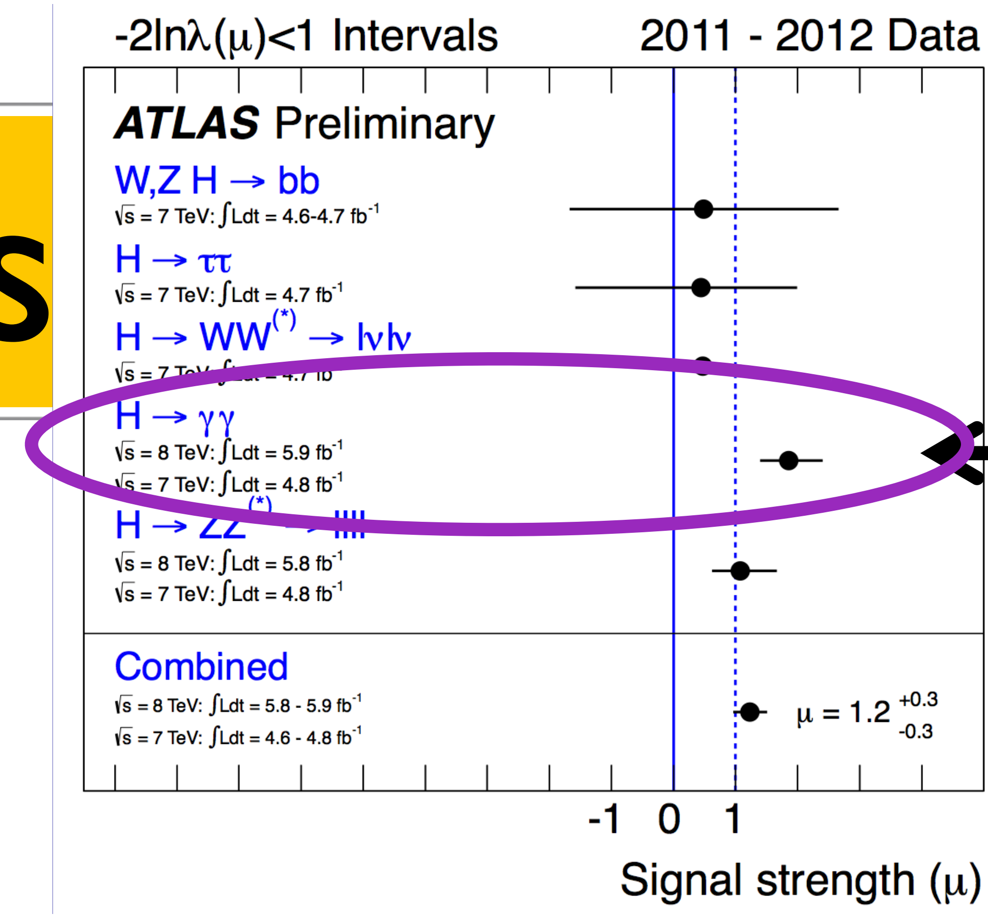

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$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb^{-1}
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$\mu = 1.2^{+0.3}_{-0.3}$
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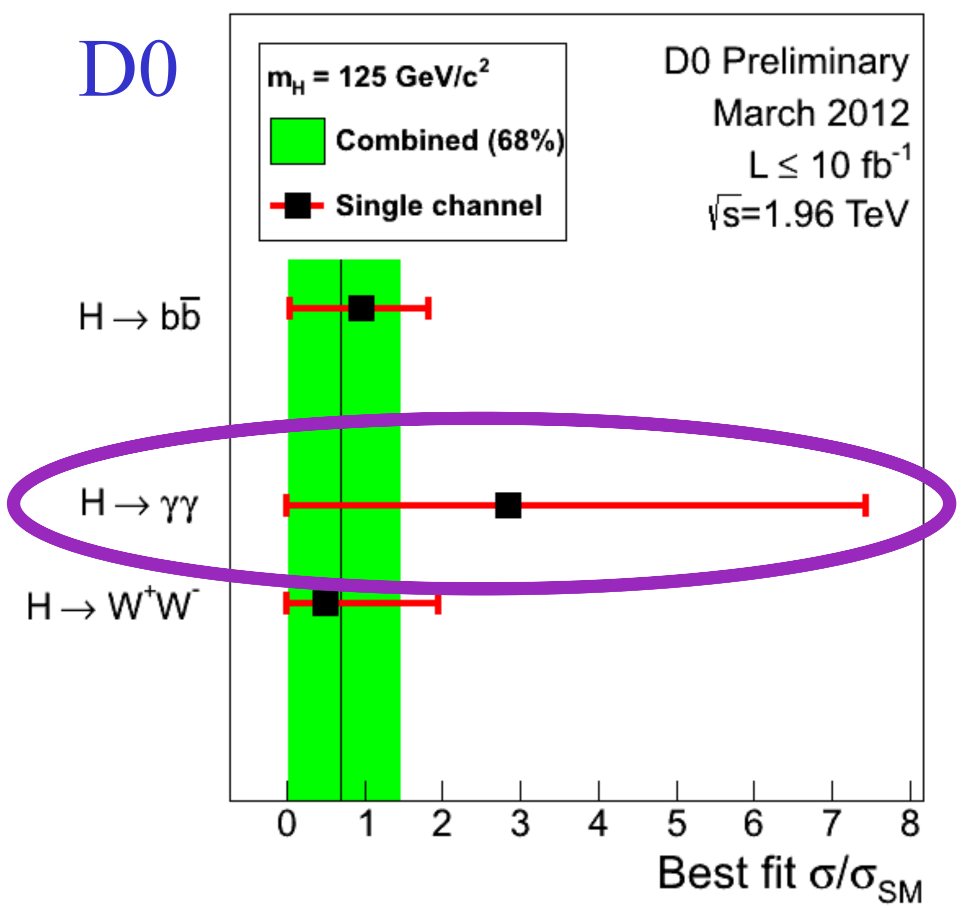
Signal strength (μ)

D0



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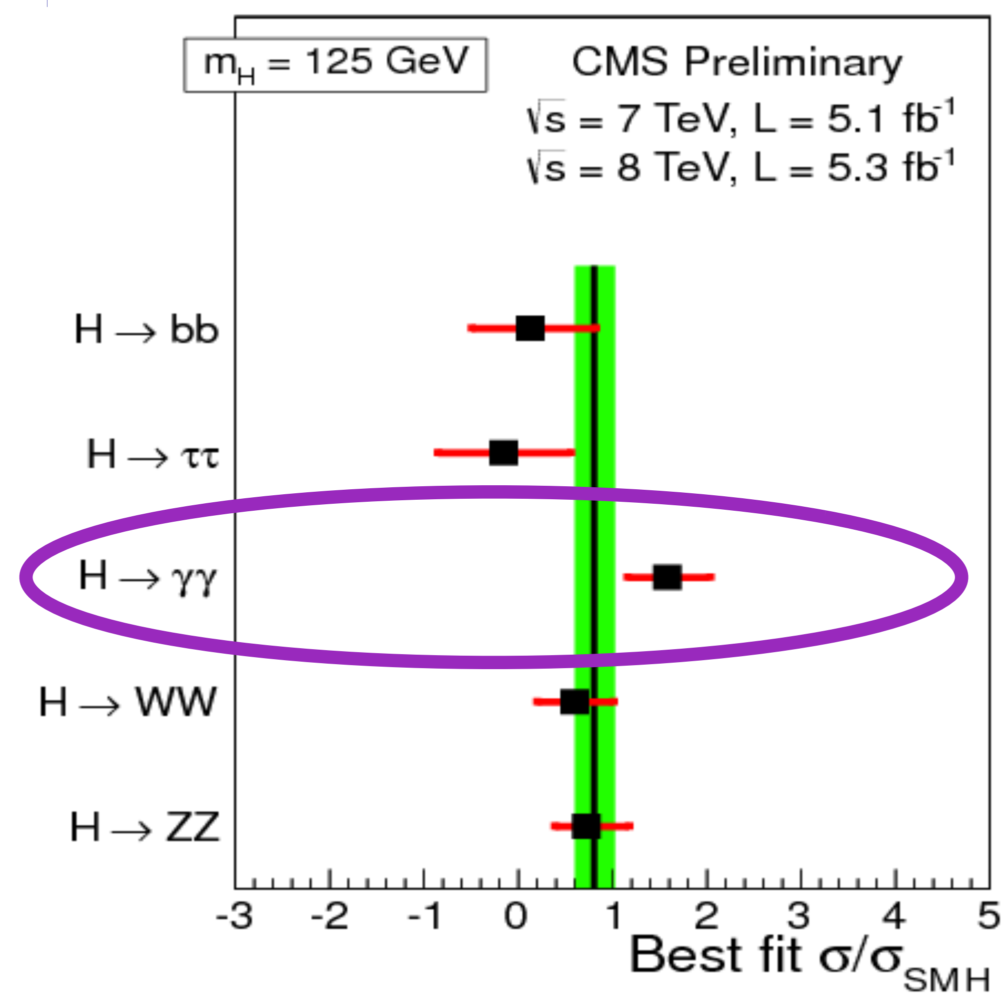

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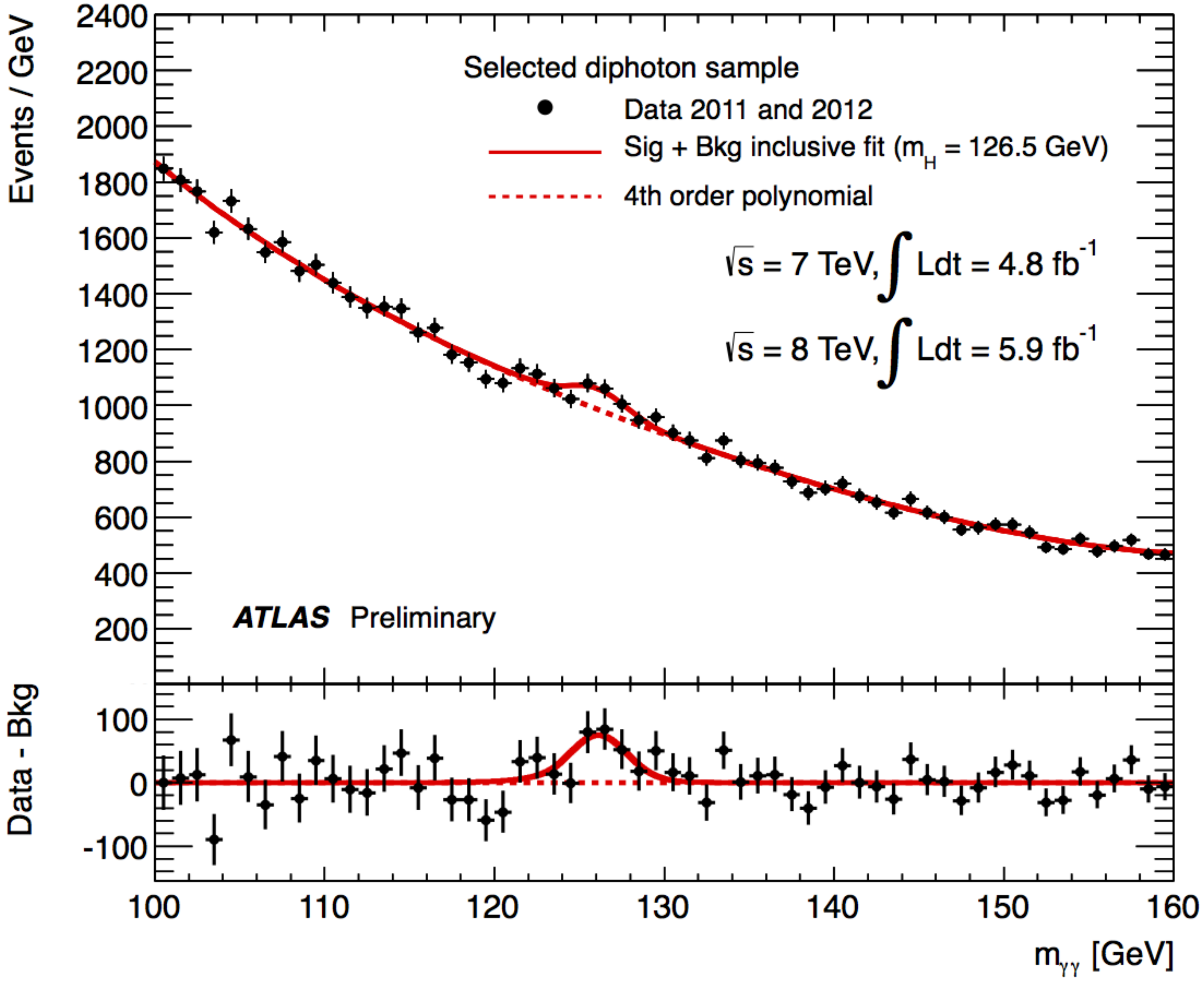
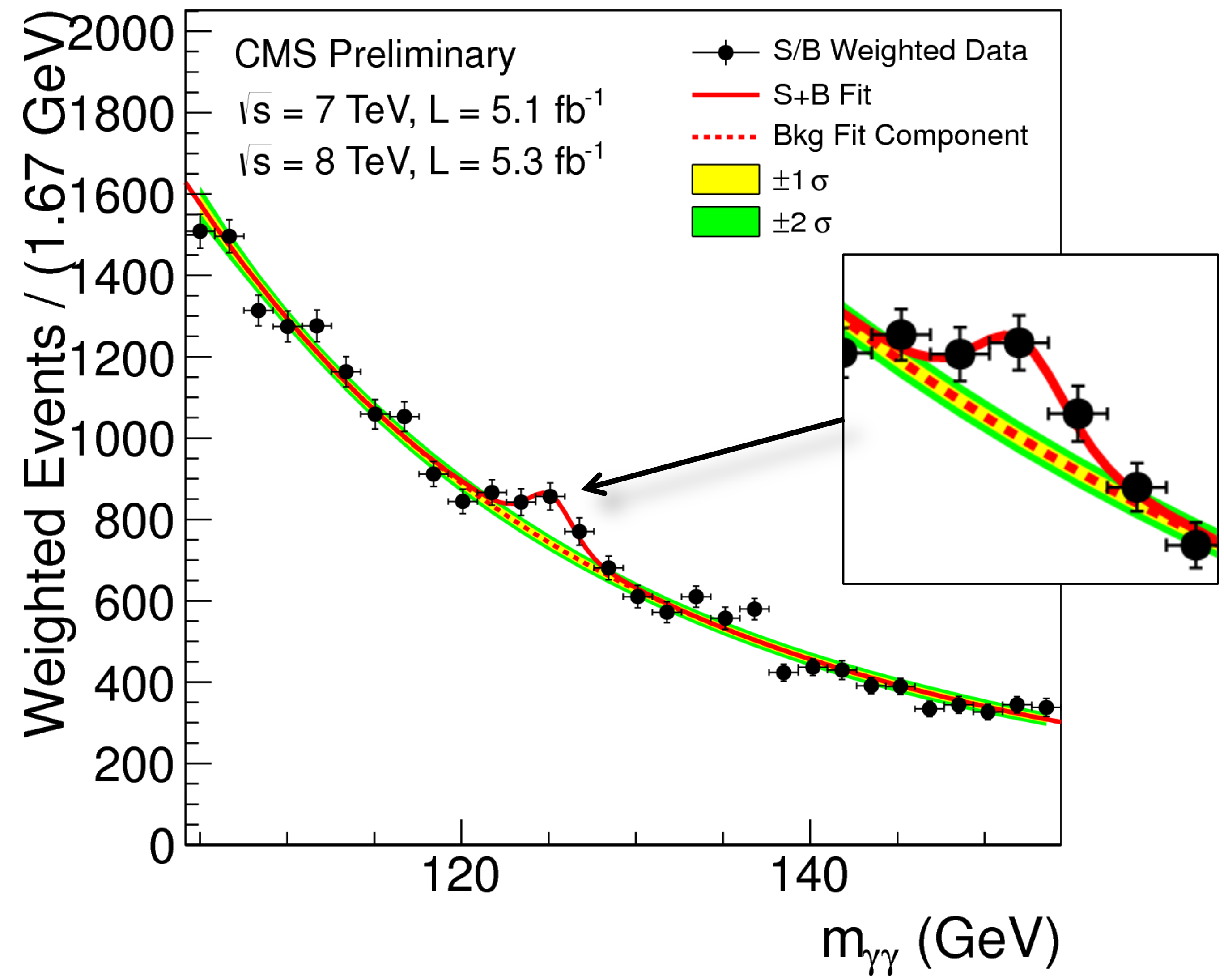
Best fit σ/σ_{SMH}

The Higgs boson





The Higgs boson

The question is:
Is this particle the standard model Higgs?

The Higgs boson

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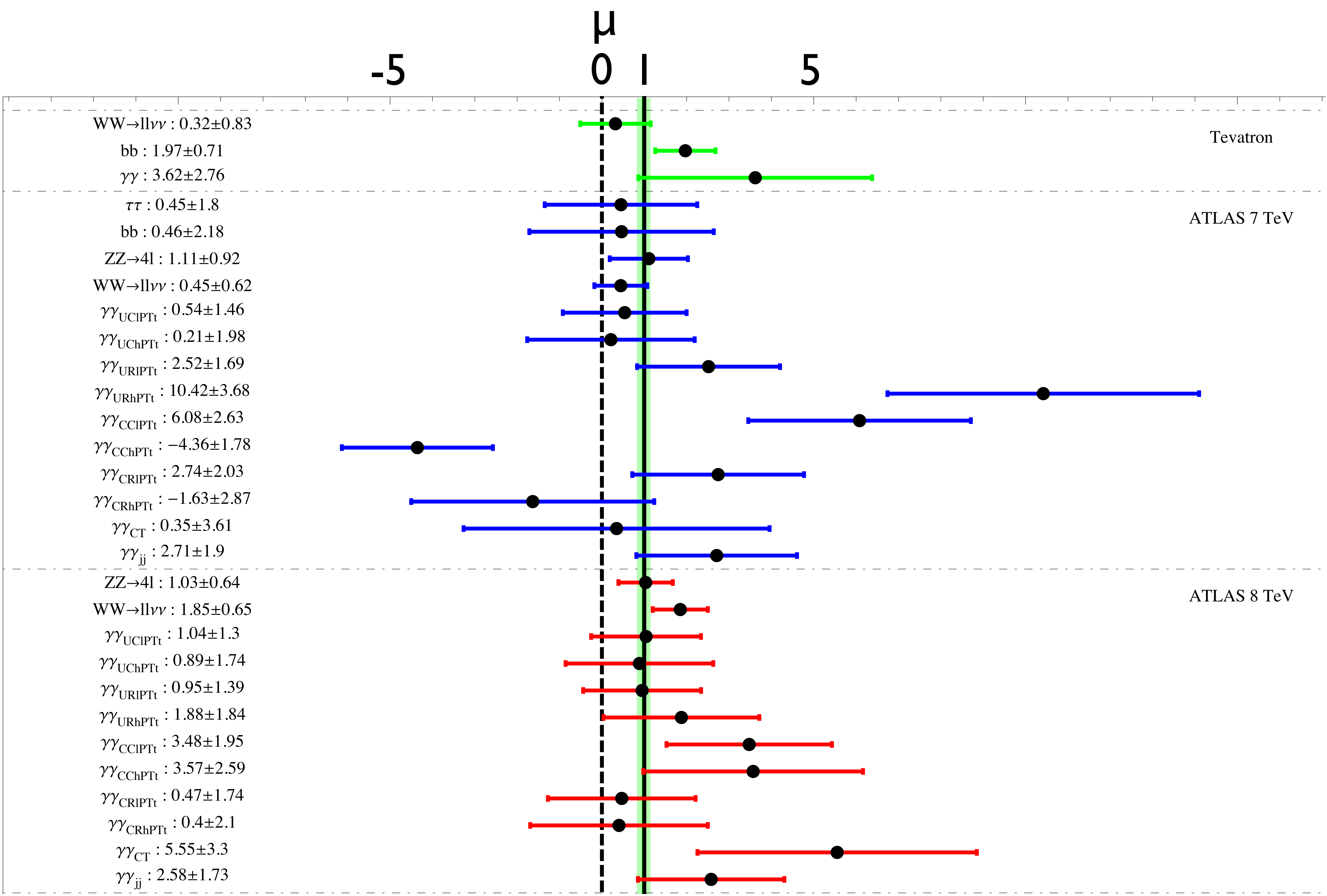
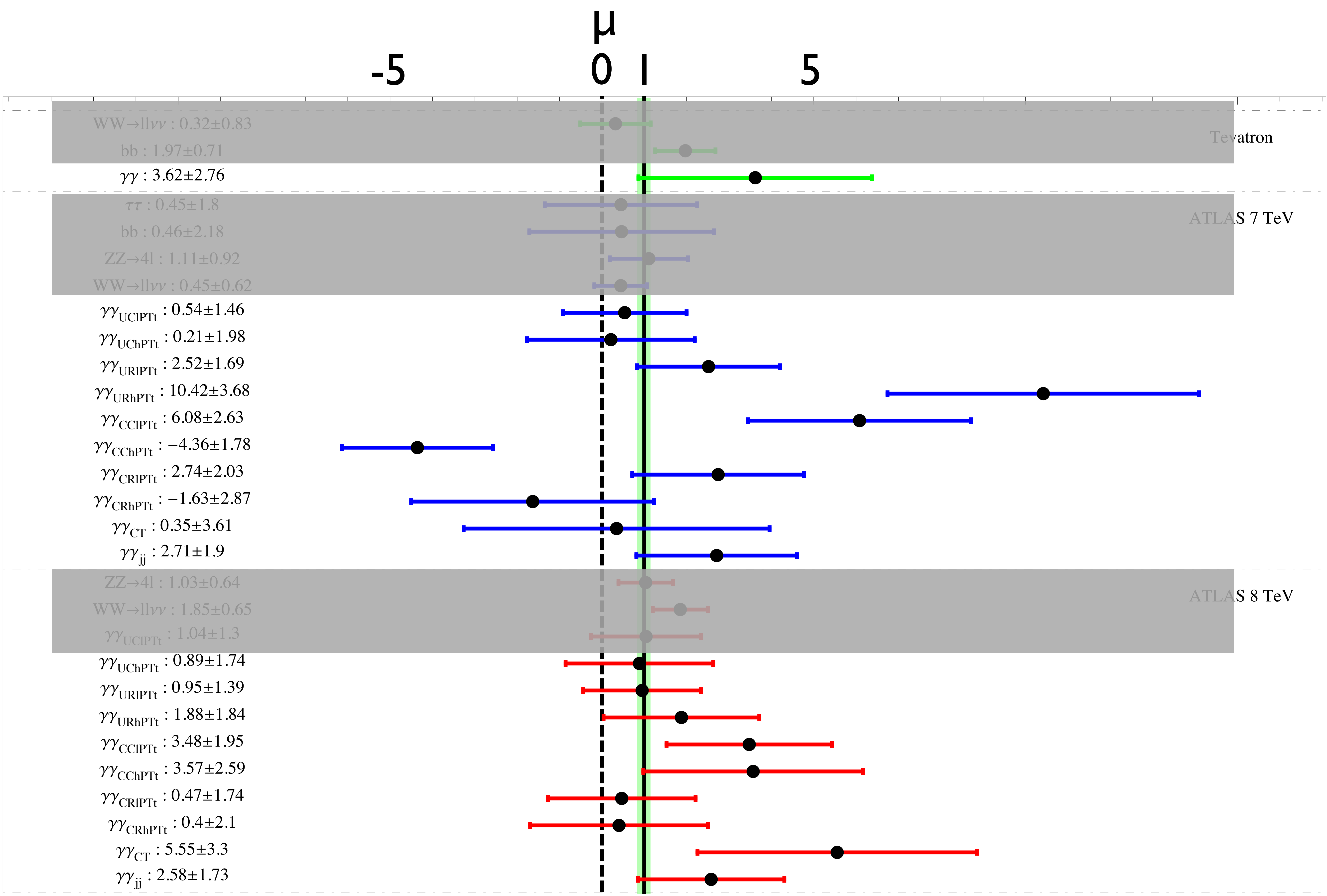
Let's see the Higgs signal strength data

$$\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}}$$



Espinosa et al 1207.1717



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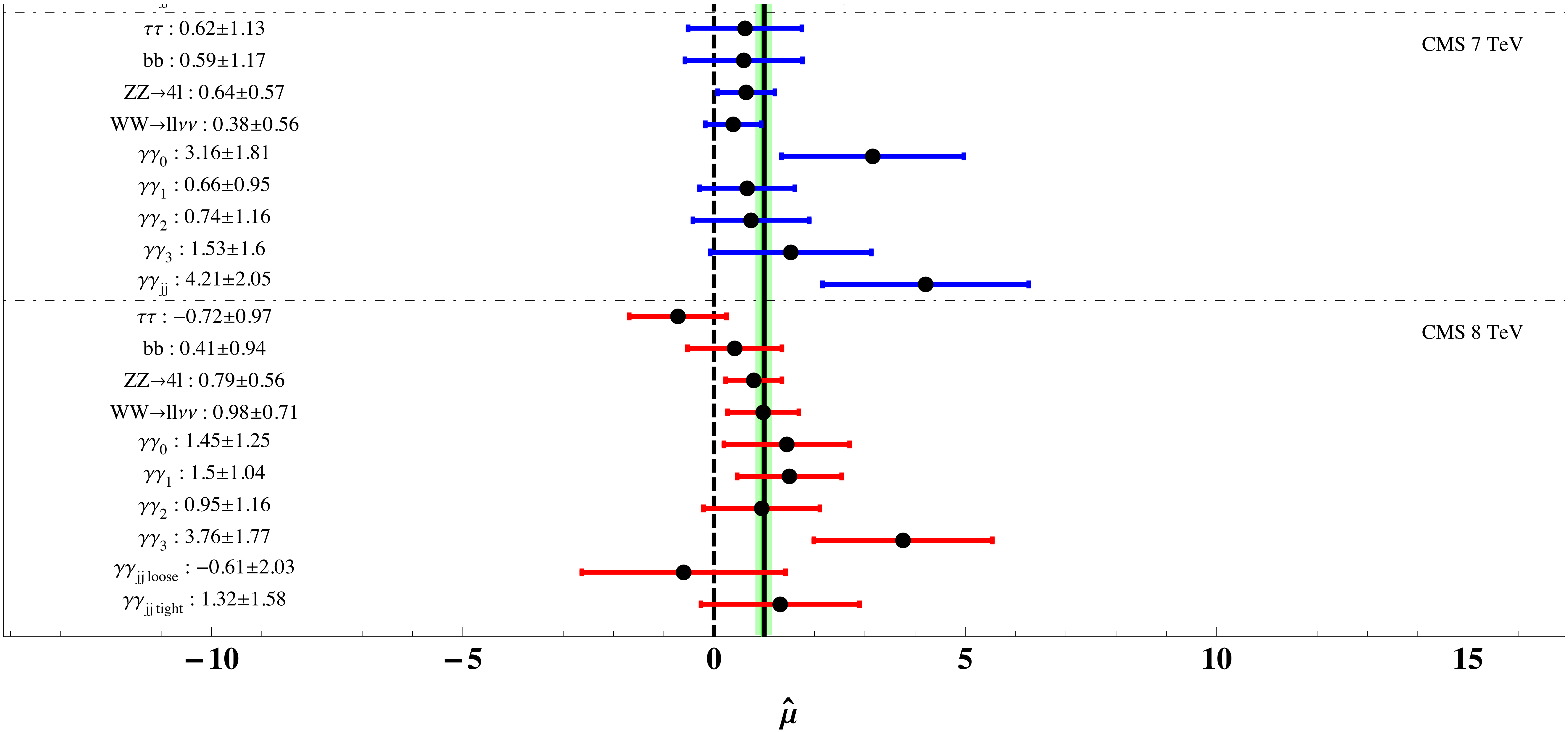

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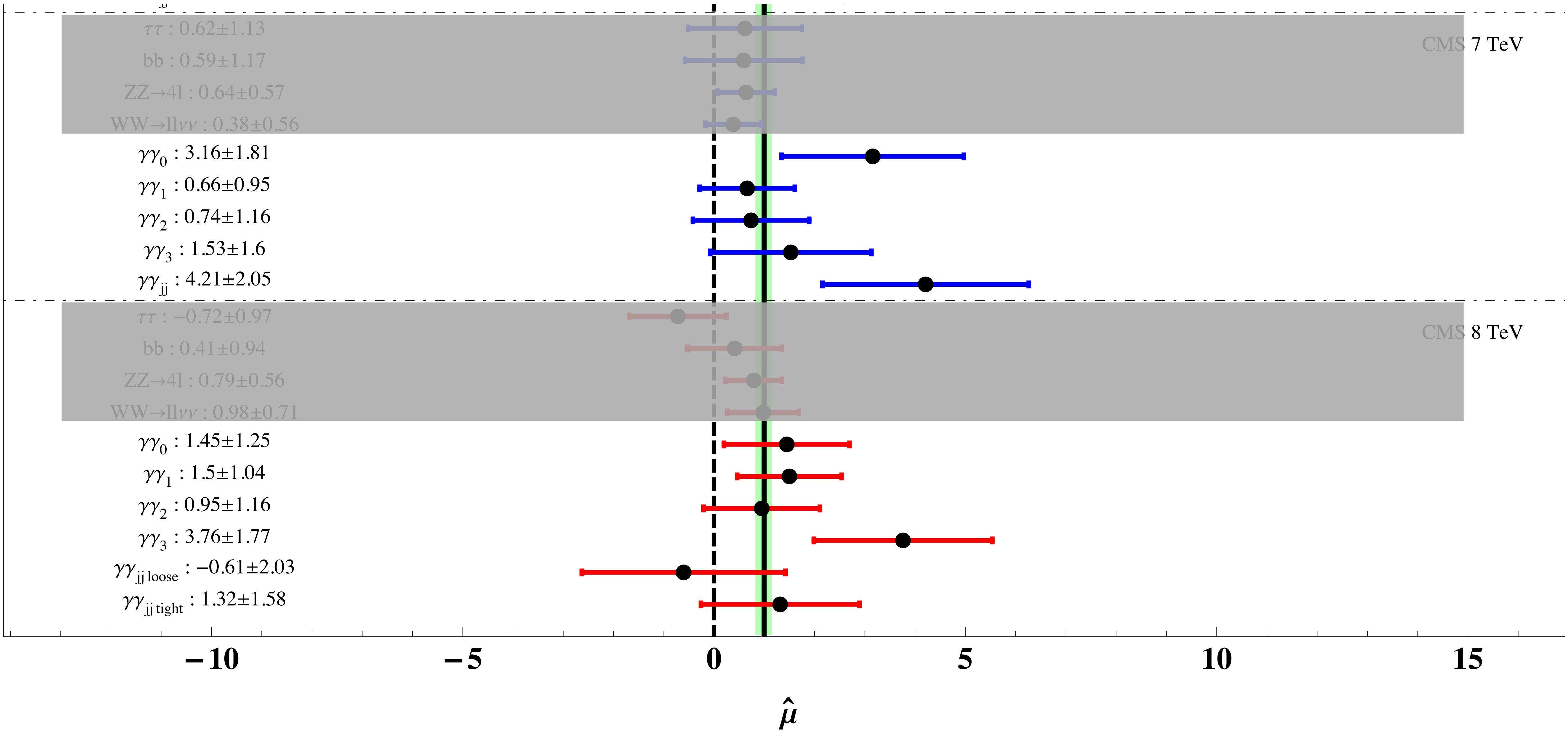
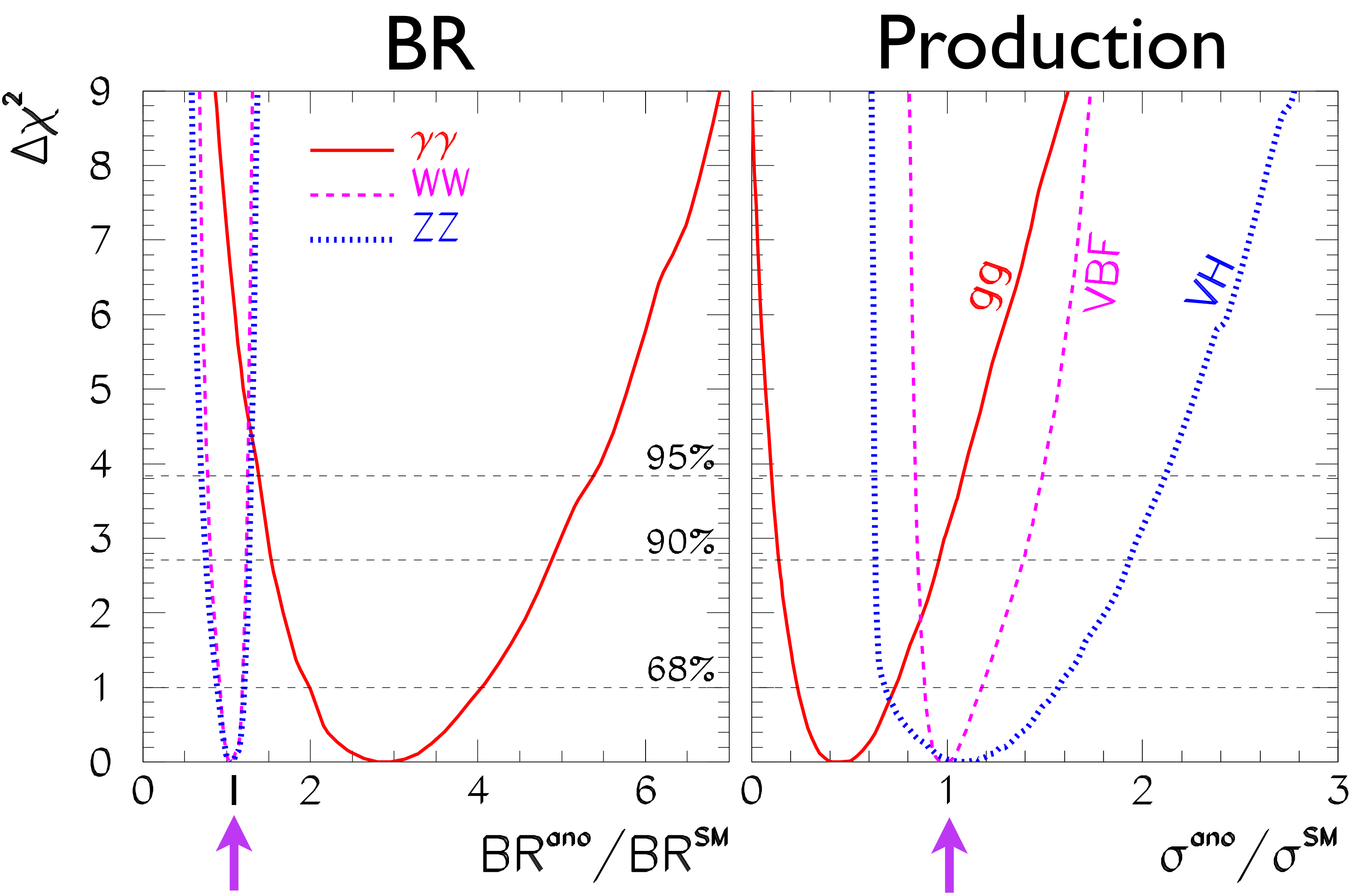


Espinosa et al 1207.1717

The Higgs boson

How well this data agrees with the SM expectations?

The Higgs boson



	Best fit	95% CL allowed range
$f_W = f_B$ (TeV^{-2})	-0.8	$[-13, 20]$
$f_{WW} = f_{BB}$ (TeV^{-2})	-0.4, (1.8)	$[-0.8, -0.1]$ and $[1.5, 2.2]$
f_g (TeV^{-2})	3.7, 19	$[-0.3, 7.3]$ and $[15, 23]$
$BR^{ano}_{\gamma\gamma}/BR^{SM}_{\gamma\gamma}$	2.9	$[1.4, 5.4]$
$BR^{ano}_{WW}/BR^{SM}_{WW}$	1.1	$[0.8, 1.3]$
$BR^{ano}_{ZZ}/BR^{SM}_{ZZ}$	1.1	$[0.7, 1.3]$
$\sigma^{ano}_{gg}/\sigma^{SM}_{gg}$	0.4	$[0.1, 1.1]$
$\sigma^{ano}_{VBF}/\sigma^{SM}_{VBF}$	1.0	$[0.8, 1.5]$
$\sigma^{ano}_{VH}/\sigma^{SM}_{VH}$	1.1	$[0.6, 2.1]$

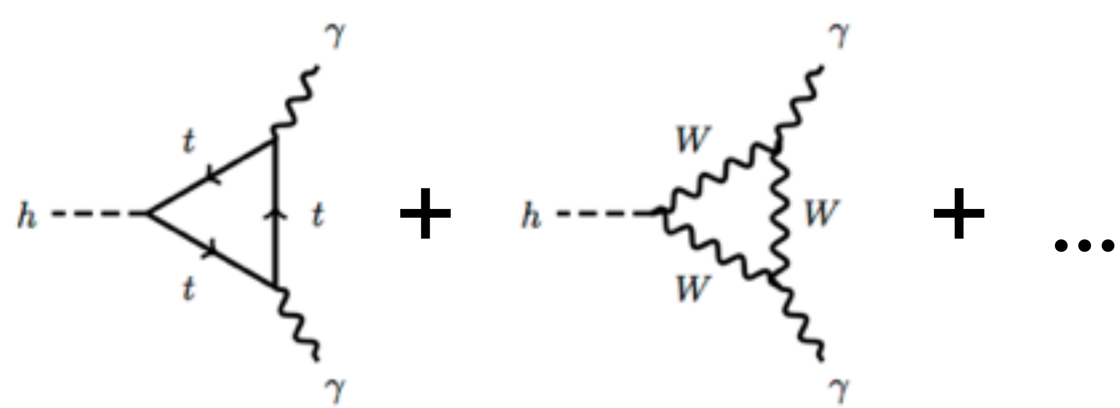
Tevatron + LHC7 + LHC8

Corbett, Éboli, Gonzalez-Fraile, Gonzalez-Garcia 1207.1344

See also Espinosa et al 1207.1717, Carmi et al 1207.1718, Giardino et al 1207.1347, Ellis You 1207.1693, Banerjee Mukhopadhyay Mukhopadhyaya 1207.3588, Plehn Rauch 1207.6108

The Higgs boson

$H \to \gamma\gamma$ would be the perfect channel to find new physics



The Higgs boson

What sort of new physics would be needed to accomodate such a signal?

The Higgs boson

What sort of new physics would be needed to accomodate such a signal?

I am *not* interested in the standard model only scenario

$H \rightarrow \gamma\gamma$

$H \rightarrow \gamma\gamma$

- The BR is $\Gamma_{process}/\Gamma_{total}$

- Hence, changing an individual $\Gamma_{process}$ changes Γ_{total}

- But H to $\gamma\gamma$ is < 1% of Γ_{total}, so we do not need to worry

H ⟶ γγ

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2\, m_H^3}{1024\pi^3} \left| \frac{2}{v} A_1(\tau_W) + \frac{8}{3v} A_{1/2}(\tau_t) + \frac{2 g_{Hf\bar{f}}}{m_f} N_{c,f} q_f^2 A_{1/2}(\tau_f) + \frac{g_{HSS}}{m_S^2} N_{c,S} q_S^2 A_0(\tau_S) \right|^2$$

$H \longrightarrow \gamma\gamma$

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2\, m_H^3}{1024\pi^3} \left| \frac{2}{v} A_1(\tau_W) + \frac{8}{3v} A_{1/2}(\tau_t) \right.$$
$$\left. + \frac{2 g_{Hf\bar{f}}}{m_f} N_{c,f}\, q_f^2 A_{1/2}(\tau_f) + \frac{g_{HSS}}{m_S^2} N_{c,S}\, q_S^2 A_0(\tau_S) \right|^2$$

These are loop functions, $\tau_x = (m_H/2m_x)^2$, see 1207.5254 for details

$H \to \gamma\gamma$

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 m_H^3}{1024\pi^3}\left|\frac{2}{v}A_1(\tau_W) + \frac{8}{3v}A_{1/2}(\tau_t) + \frac{2g_{Hf\bar{f}}}{m_f}N_{c,f}q_f^2 A_{1/2}(\tau_f) + \frac{g_{HSS}}{m_S^2}N_{c,S}q_S^2 A_0(\tau_S)\right|^2$$

Higgs mass

W: – 8.3

top: + 1.8

These are loop functions, $\tau_x = (m_H/2m_x)^2$, see 1207.5254 for details

H ⟶ γγ

– 8.3   + 1.8

Higgs mass   W   top

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new fermion   scalar

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top: + 1.8

new fermion: This will be positive and O(top contribution)

scalar

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new fermion

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This will be positive and O(top contribution)

These are loop functions, $\tau_x = (m_H/2m_x)^2$, see 1207.5254 for details

What about this coupling?

$H \longrightarrow \gamma\gamma$

$$\frac{2 g_{H f_i \bar{f}_i}}{m_{f_i}} = \frac{\partial}{\partial v} \log m_{f_i}^2(v)$$

Ellis Gaillard Nanopoulos 1976, Shifman *et al* 1979

H ⟶ γγ

$$\frac{2 g_{H f_i \bar{f}_i}}{m_{f_i}} = \frac{\partial}{\partial v} \log m_{f_i}^2(v)$$

Eigenvalues of $M^\dagger M$

Ellis Gaillard Nanopoulos 1976, Shifman *et al* 1979

$H \longrightarrow \gamma\gamma$

$$\frac{2g_{Hf_i\bar{f}_i}}{m_{f_i}} = \frac{\partial}{\partial v} \log m^2_{f_i}(v)$$

We want this coupling to be negative

Eigenvalues of $M^\dagger M$

Ellis Gaillard Nanopoulos 1976, Shifman *et al* 1979

$H \longrightarrow \gamma\gamma$

$$\frac{2 g_{H f_i \bar{f}_i}}{m_{f_i}} = \frac{\partial}{\partial v} \log m_{f_i}^2(v)$$

We need mixing!

Eigenvalues of $M^\dagger M$

Ellis Gaillard Nanopoulos 1976, Shifman *et al* 1979

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Eigenvalues of $M^\dagger M$

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- The LHC puts severe bounds on a chiral 4th family

CMS collaboration, PAS EXO-11-098

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H → γγ

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- Renormalizable Higgs coupling: **2–1** and **3–2**

H ⟶ γγ

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- The LHC puts severe bounds on a chiral 4th family
  CMS collaboration, PAS EXO-11-098
- Mixing with the SM can lead to dangerous FCNC
- 2 vector fermions which mix among themselves
- Renormalizable Higgs coupling: **2**–**1** and **3**–**2**
- Assume that these will be the dominant contribution

2–1 model

	$SU(2)_L$		
Field	doublet-singlet	triplet-doublet	$U(1)_Y$
$\chi_{L,R}$	2	3	$\hat{y} = y - \frac{1}{2}$
$\psi_{L,R}$	1	2	y

2–1 model

	$\mathrm{SU(2)_L}$		
Field	doublet-singlet	triplet-doublet	$\mathrm{U(1)_Y}$
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Write most general Lagrangean and the mass matrix is

$$(\bar{\psi}_R \, \bar{\chi}^u_R \, \bar{\chi}^d_R) \begin{pmatrix} m_2 & cv & 0 \\ cv & m_1 & 0 \\ 0 & 0 & m_1 \end{pmatrix} \begin{pmatrix} \psi_L \\ \chi^u_L \\ \chi^d_L \end{pmatrix}$$

2–1 model

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Write most general Lagrangean and the mass matrix is

$$(\bar{\psi}_R \, \bar{\chi}_R^u \, \bar{\chi}_R^d) \begin{pmatrix} m_2 & cv & 0 \\ cv & m_1 & 0 \\ 0 & 0 & m_1 \end{pmatrix} \begin{pmatrix} \psi_L \\ \chi_L^u \\ \chi_L^d \end{pmatrix}$$

$$M_{\omega_1,\omega_2} = \frac{1}{2}\left[(m_1 + m_2) \mp \sqrt{(m_2 - m_1)^2 + 4c^2v^2}\right]$$

2–1 model

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$m_1 = m_2$ leads to largest mixing

$$M_{\omega_1,\omega_2} = \frac{1}{2}\left[(m_1 + m_2) \mp \sqrt{(m_2 - m_1)^2 + 4c^2v^2}\right]$$

Mixing is needed to enhance H to γγ, but may be bad for EW precision tests...

2–1 model

Wait a minute...

Why this is different from the top contribution?

2–1 model

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Why this is different from the top contribution?

$$\frac{2g_{Hf_i\bar{f}_i}}{m_{f_i}} = \frac{\partial}{\partial v} \log m^2_{f_i}(v)$$

$$M^2_{\rm top} = c^2_{\rm top} v^2$$

$$M_{\omega_1,\omega_2} = \frac{1}{2}\left[(m_1 + m_2) \mp \sqrt{(m_2 - m_1)^2 + 4c^2v^2}\right]$$

2–1 model

Wait a minute...

Why this is different from the top contribution?

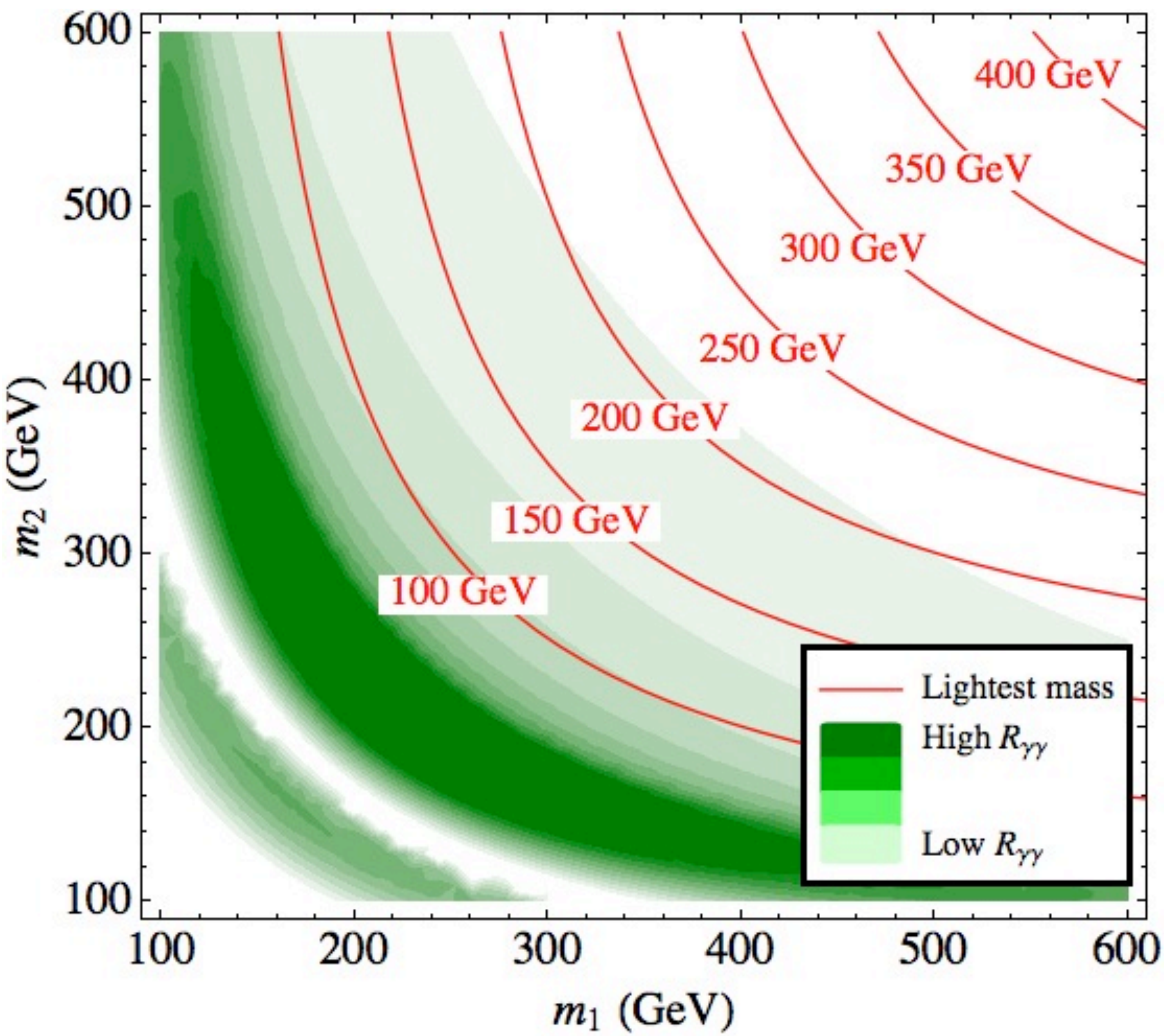
$$\frac{2g_{Hf_i\bar{f}_i}}{m_{f_i}} = \frac{\partial}{\partial v}\log m_{f_i}^2(v)$$

$$M_{\rm top}^2 = c_{\rm top}^2 v^2$$

$$M_{\omega_1,\omega_2} = \frac{1}{2}\left[(m_1+m_2)\mp\sqrt{(m_2-m_1)^2+4c^2v^2}\right]$$

Is it true that more mixing leads to higher H to γγ?

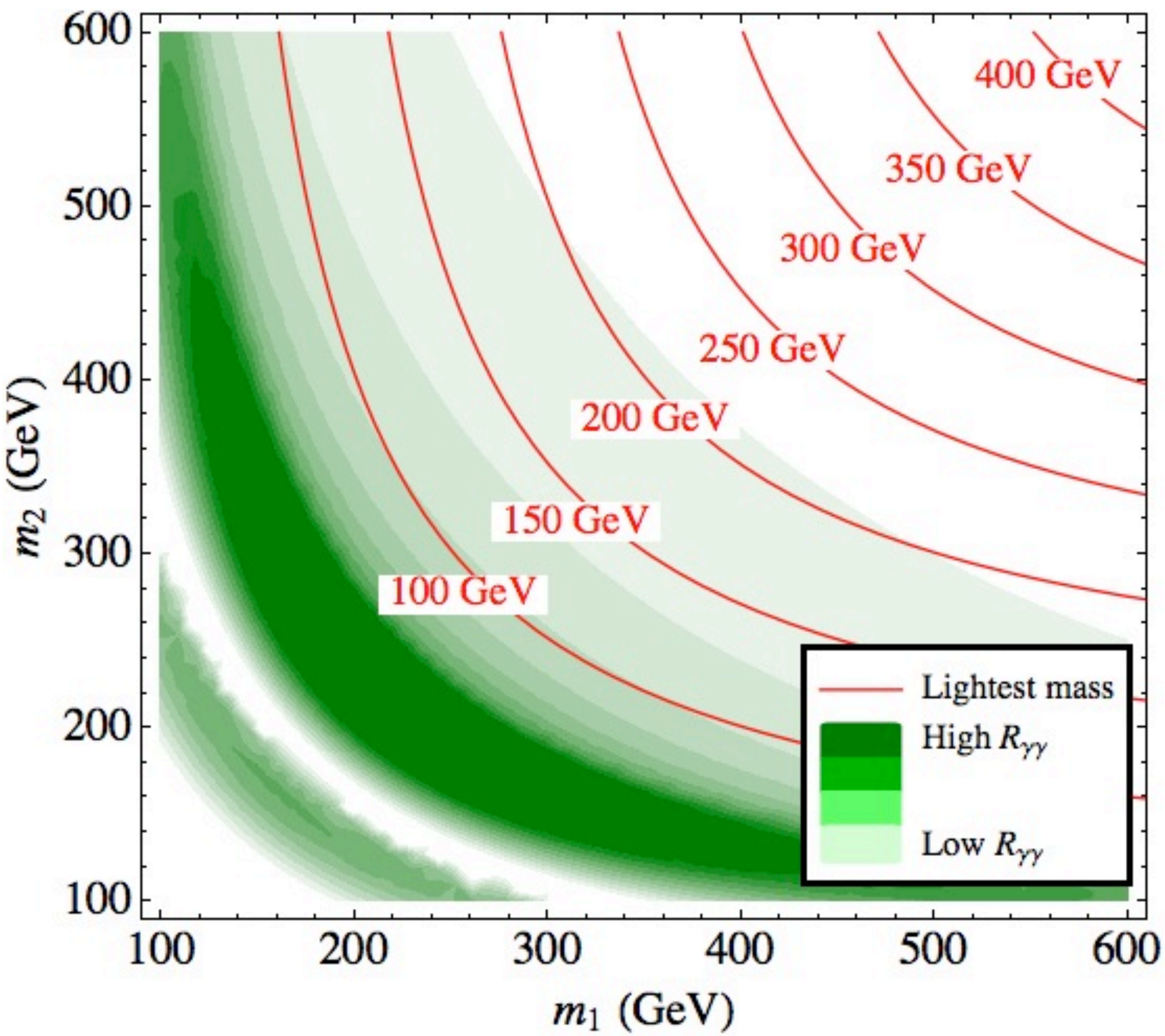
2–1 model



c = 1

$$R_{\gamma\gamma} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma^{\rm SM}(H \to \gamma\gamma)}$$

2–1 model

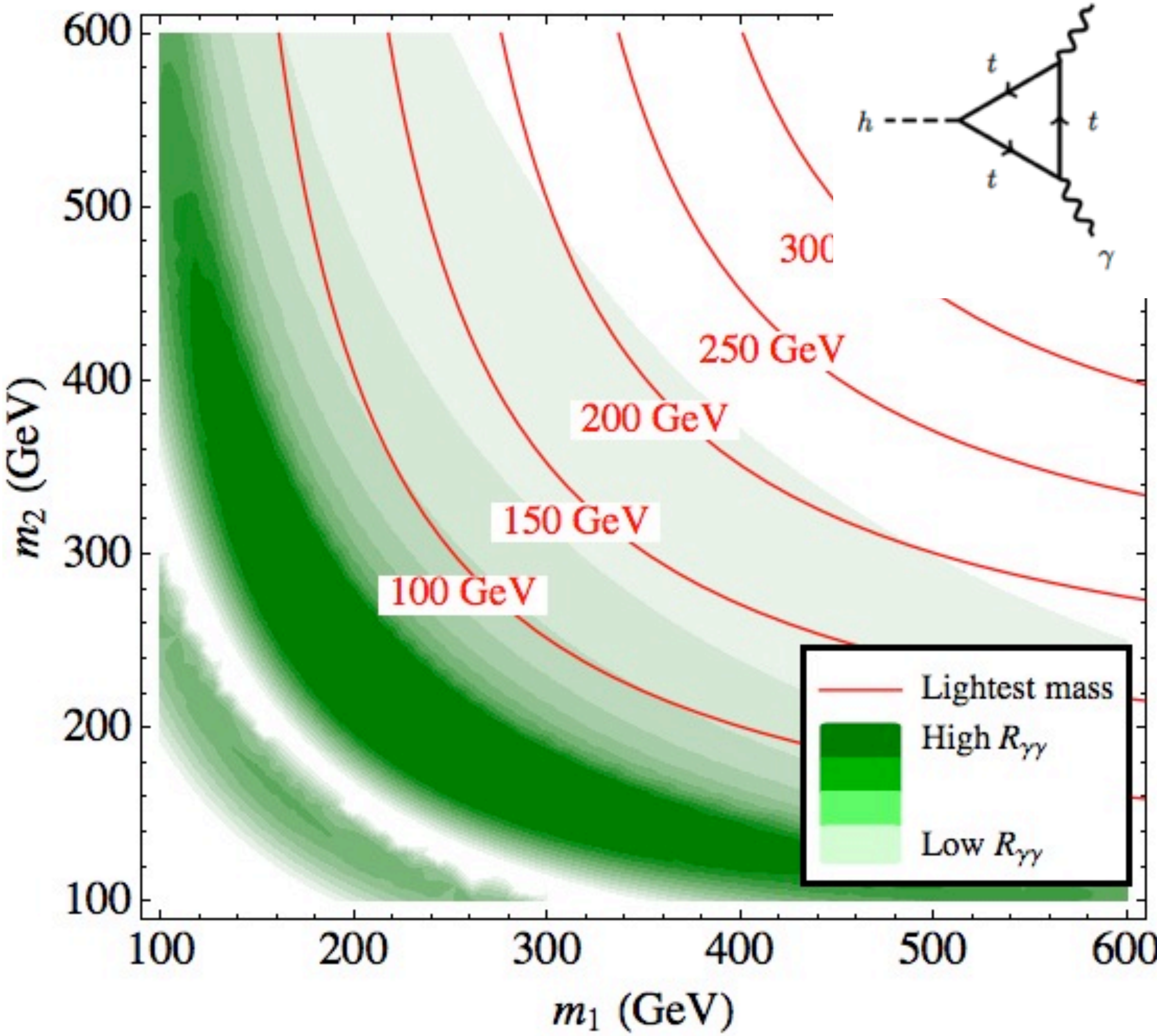


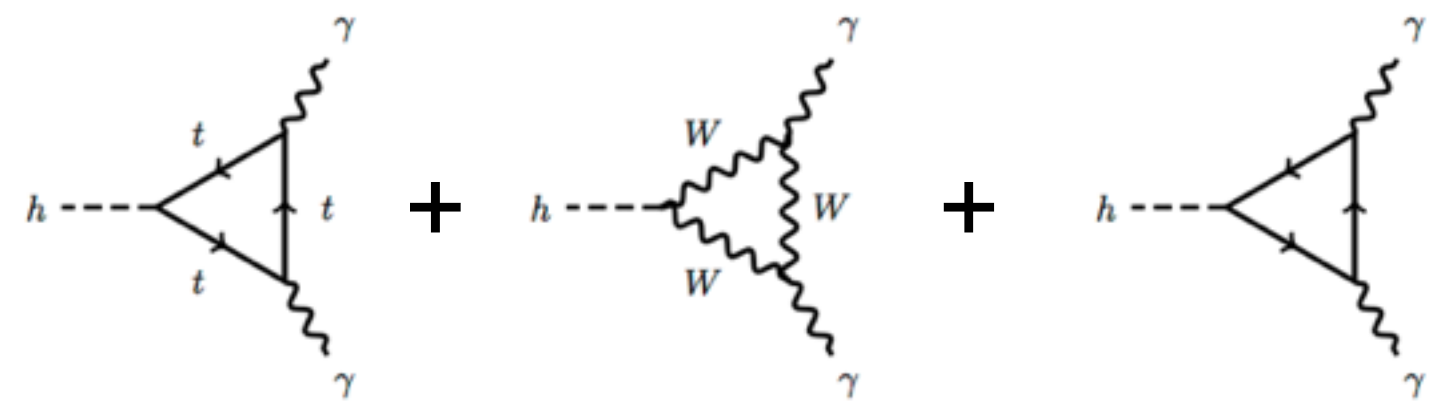
c = 1

$$R_{\gamma\gamma} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma^{\rm SM}(H \to \gamma\gamma)}$$

Yes, more mixing means larger enhancement!
Let's focus on $m_1 = m_2$

2–1 model





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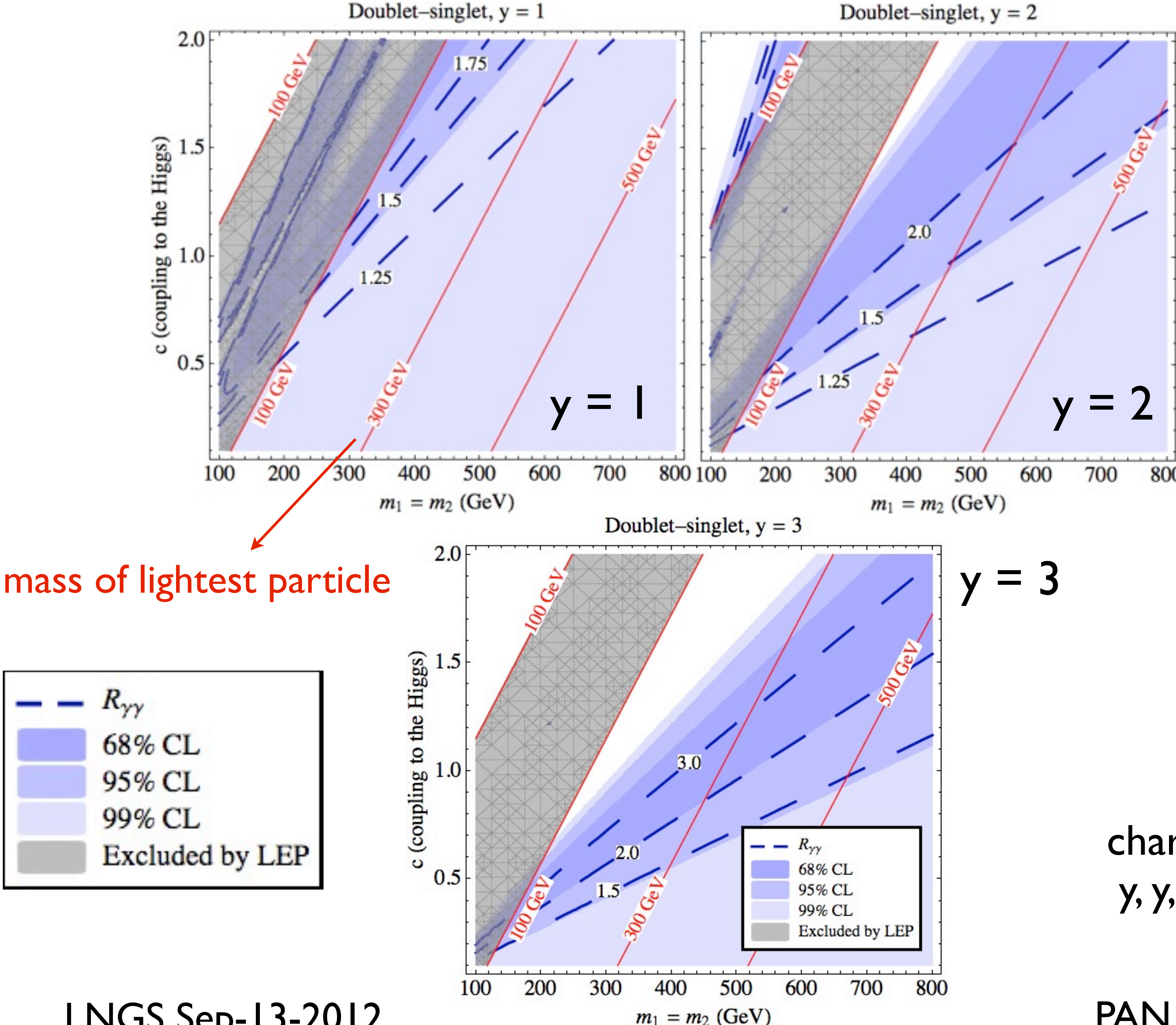


charges are
y, y, y-1

2–1 model

What about the EW precision parameters STU?

2–1 model

What about the EW precision parameters STU?

- S: neutral current at different energy scales

2–1 model

What about the EW precision parameters STU?

- S: neutral current at different energy scales
- T: difference between charged and neutral current

2–1 model

What about the EW precision parameters STU?

- S: neutral current at different energy scales
- T: difference between charged and neutral current
- S+U: charged current at different energy scales

2–1 model

What about the EW precision parameters STU?

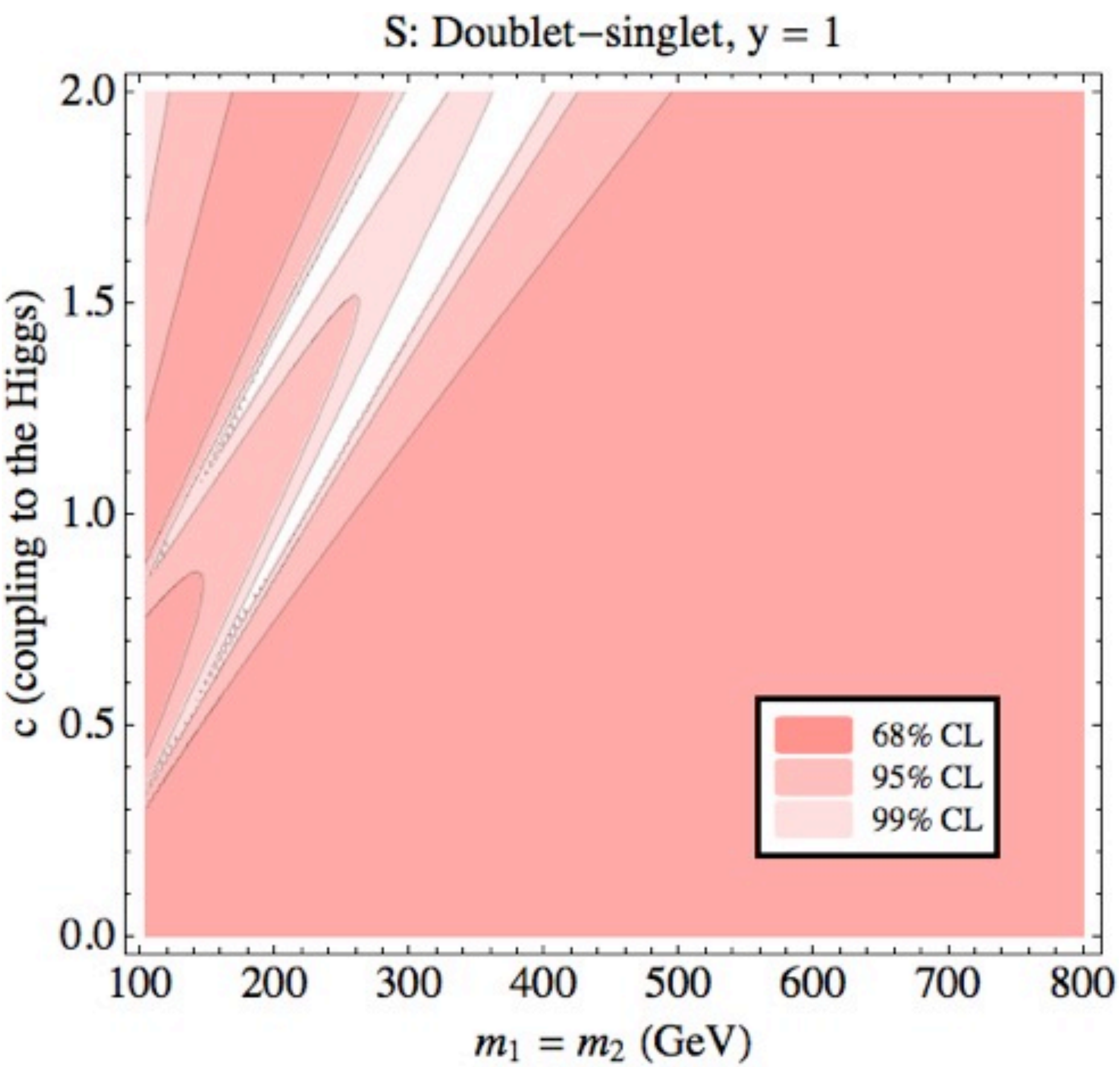
- S: neutral current at different energy scales
- T: difference between charged and neutral current
- S+U: charged current at different energy scales

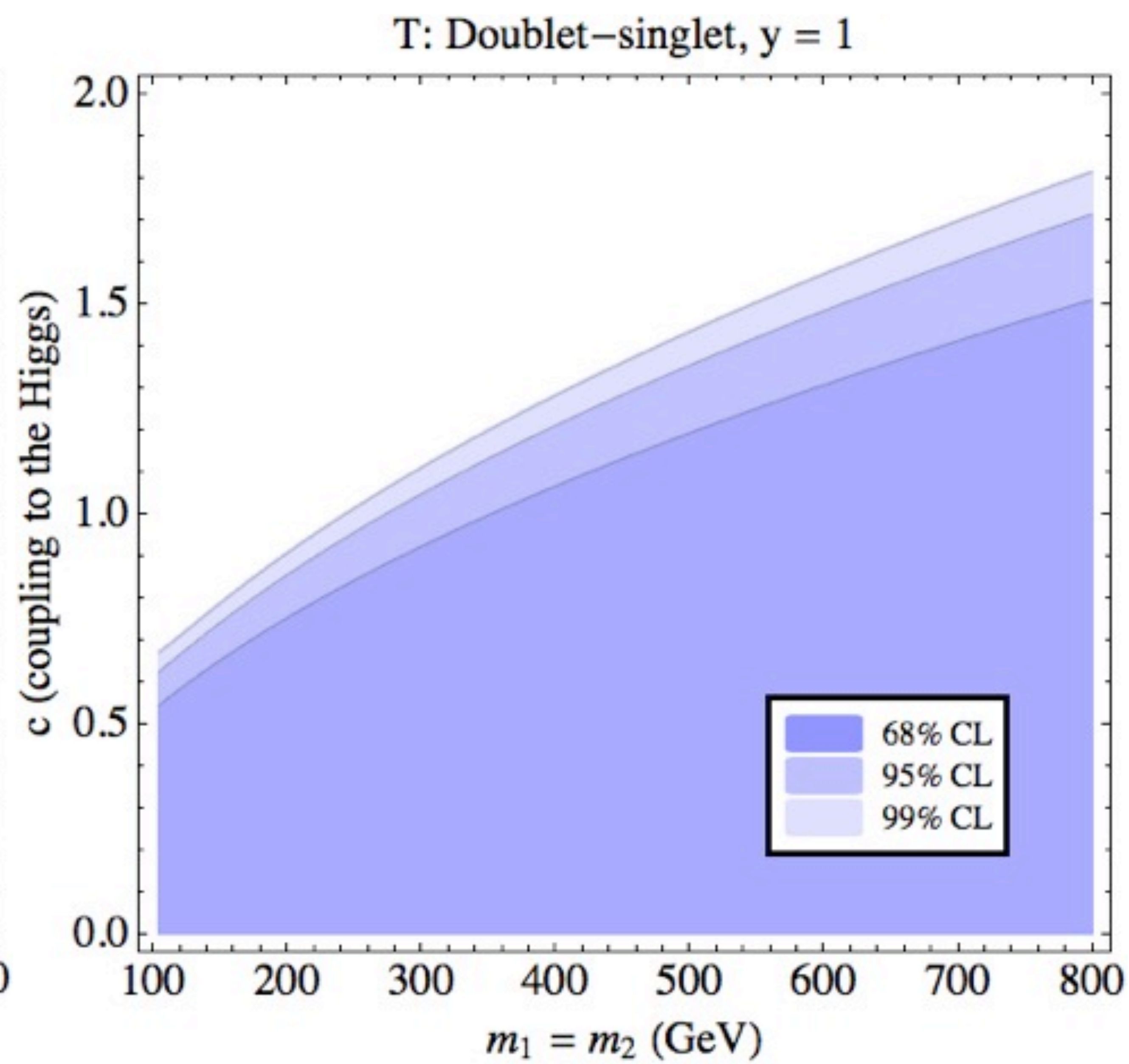
Let’s see the y = 1 case as an example

2–1 model

$$\Delta S = S - S_{\rm SM} = 0.04 \pm 0.10$$
$$\Delta T = T - T_{\rm SM} = 0.05 \pm 0.11$$
$$\Delta U = U - U_{\rm SM} = 0.08 \pm 0.11$$

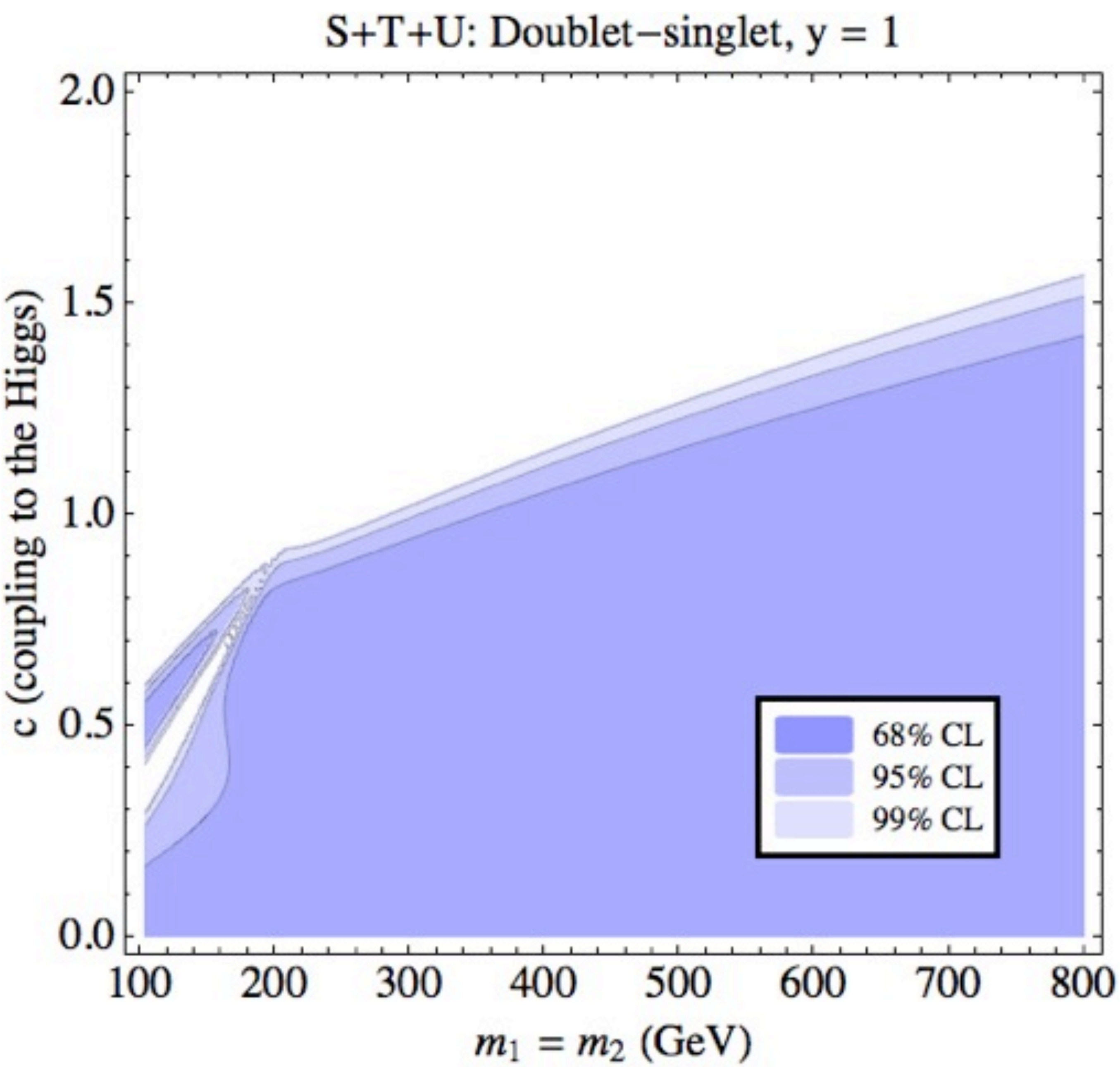
$$V = \begin{pmatrix} 1 & +0.89 & -0.45 \\ +0.89 & 1 & -0.69 \\ -0.45 & -0.69 & 1 \end{pmatrix}$$

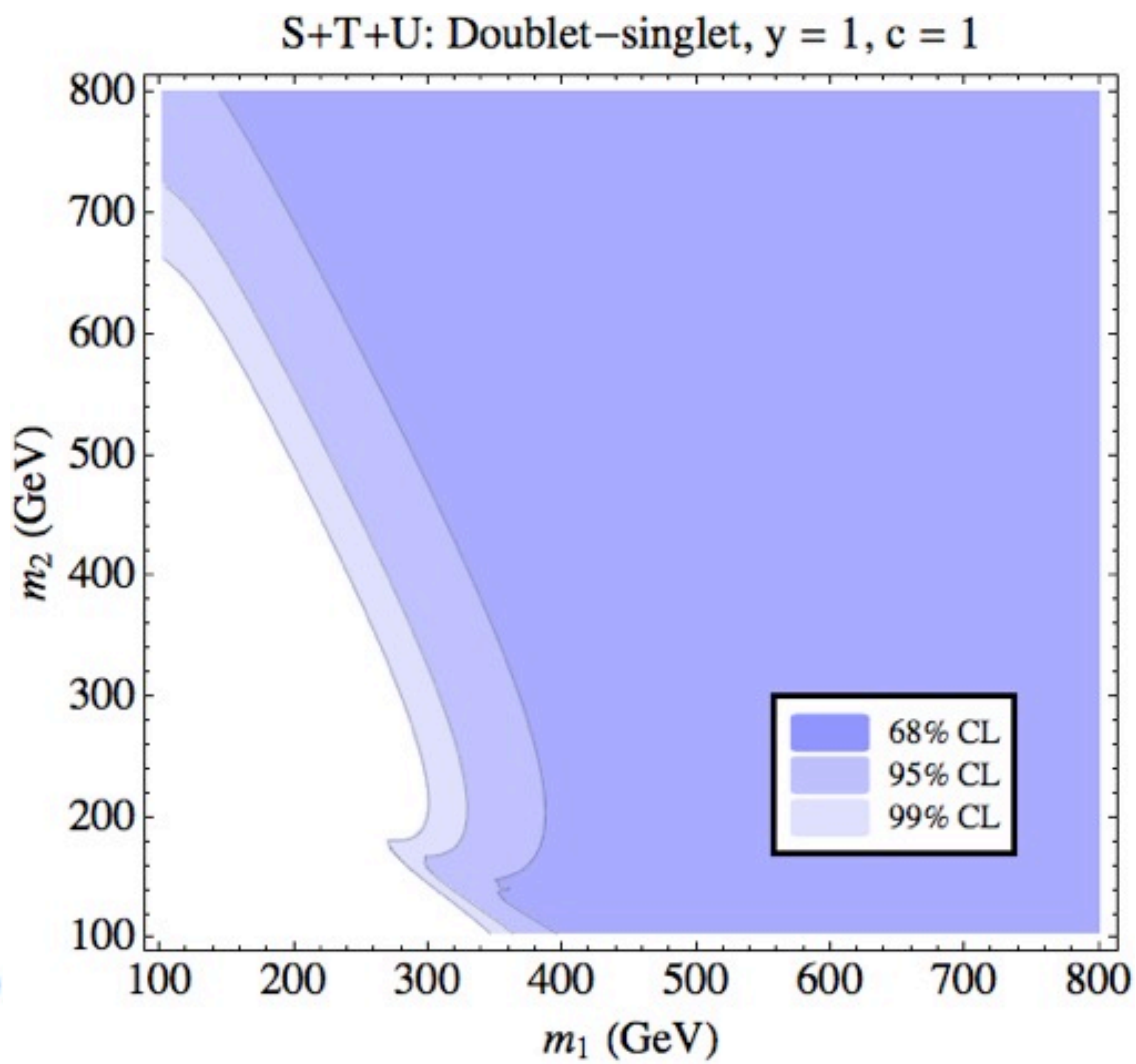




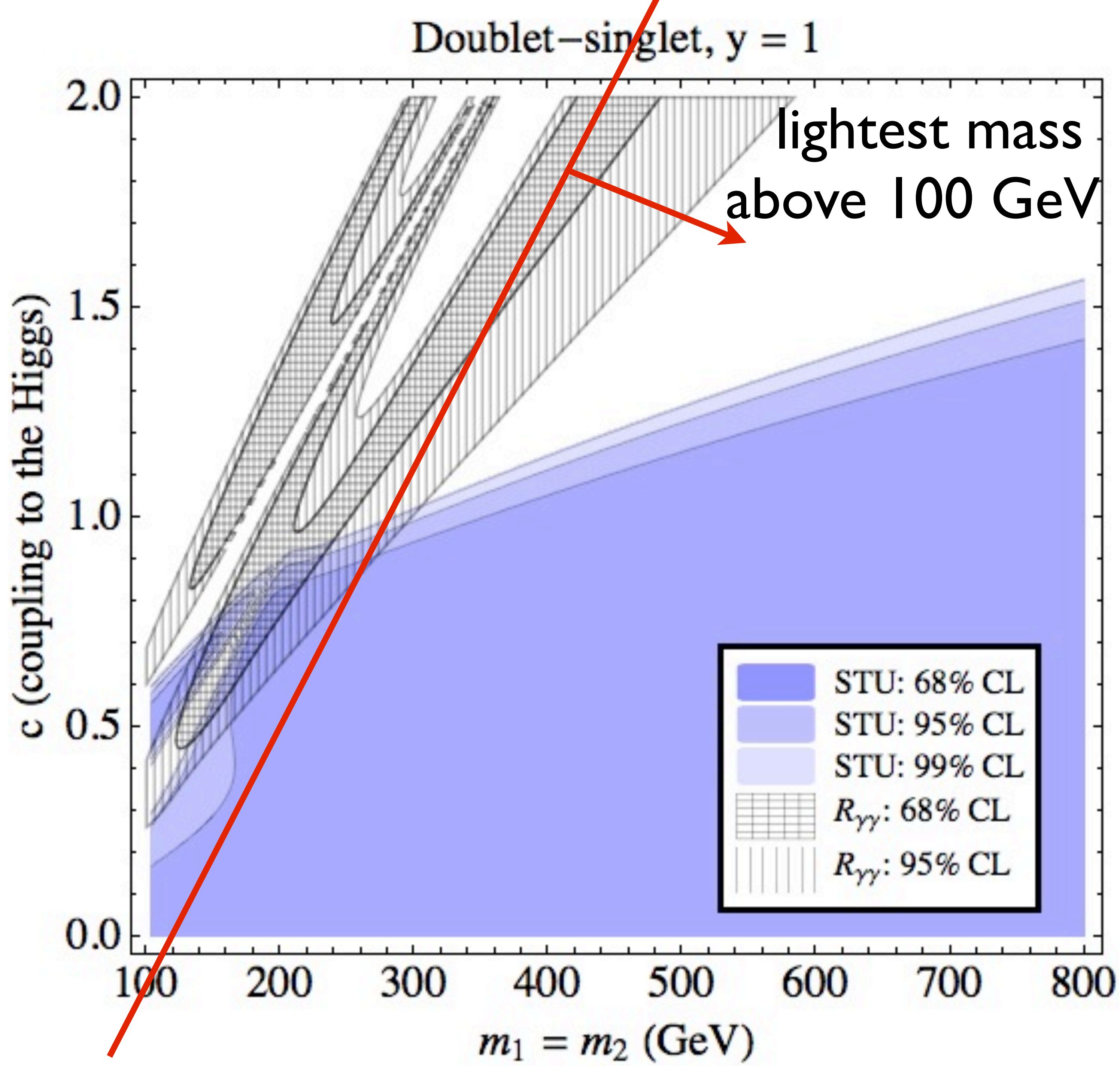
2–1 model

Combined STU fit





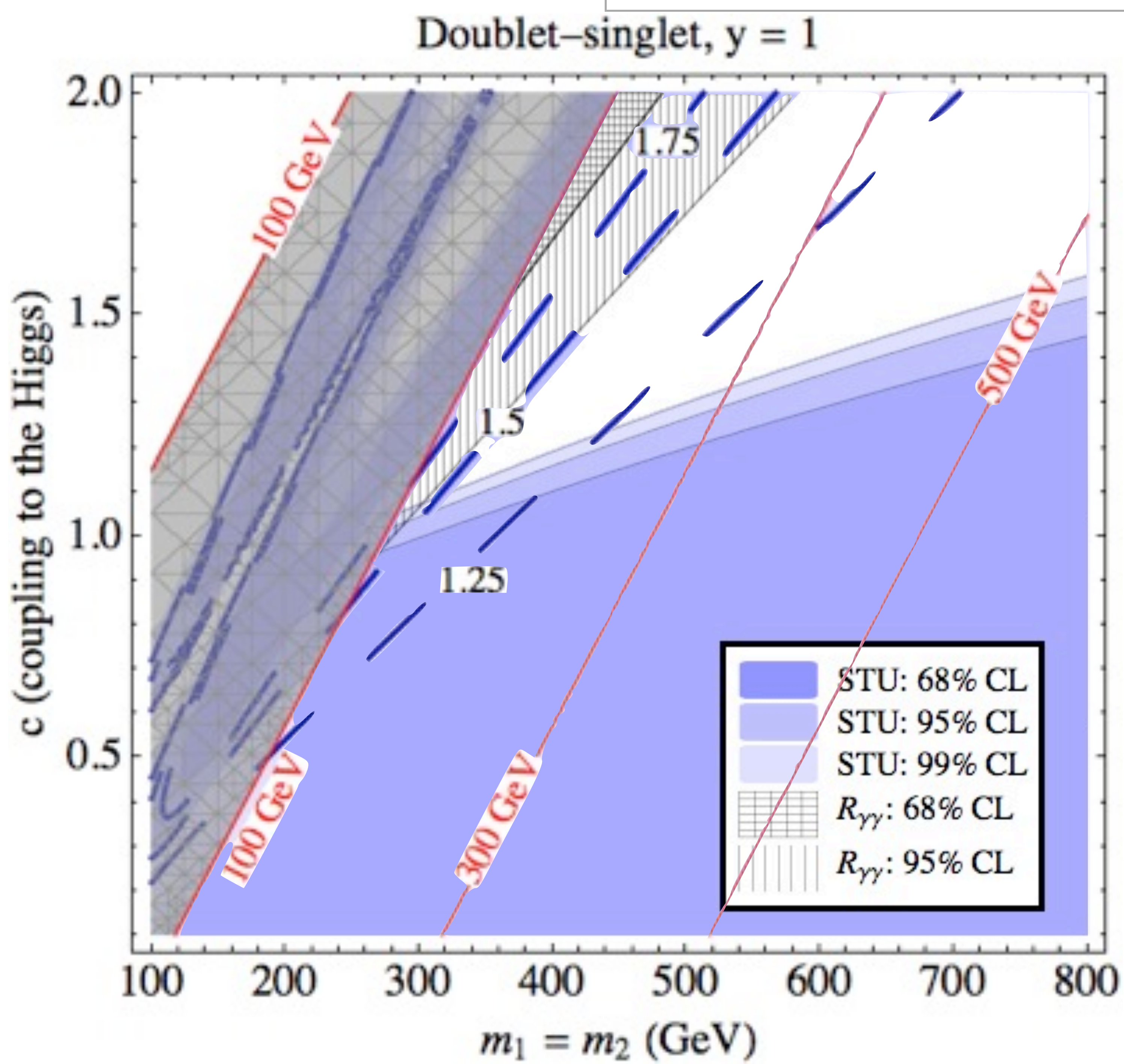
2–1 model



Doublet−singlet, y = 1
c (coupling to the Higgs)
$m_1 = m_2$ (GeV)
2.0
1.5
1.0
0.5
0.0
100
200
300
400
500
600
700
800
STU: 68% CL
STU: 95% CL
STU: 99% CL
$R_{\gamma\gamma}$: 68% CL
$R_{\gamma\gamma}$: 95% CL
lightest mass
above 100 GeV

2–1 model

~ 25% enhancement is feasible



3–2 model

	$SU(2)_L$		
Field	doublet-singlet	triplet-doublet	$U(1)_Y$
$\chi_{L,R}$	2	3	$\hat{y} = y - \frac{1}{2}$
$\psi_{L,R}$	1	2	y

3–2 model

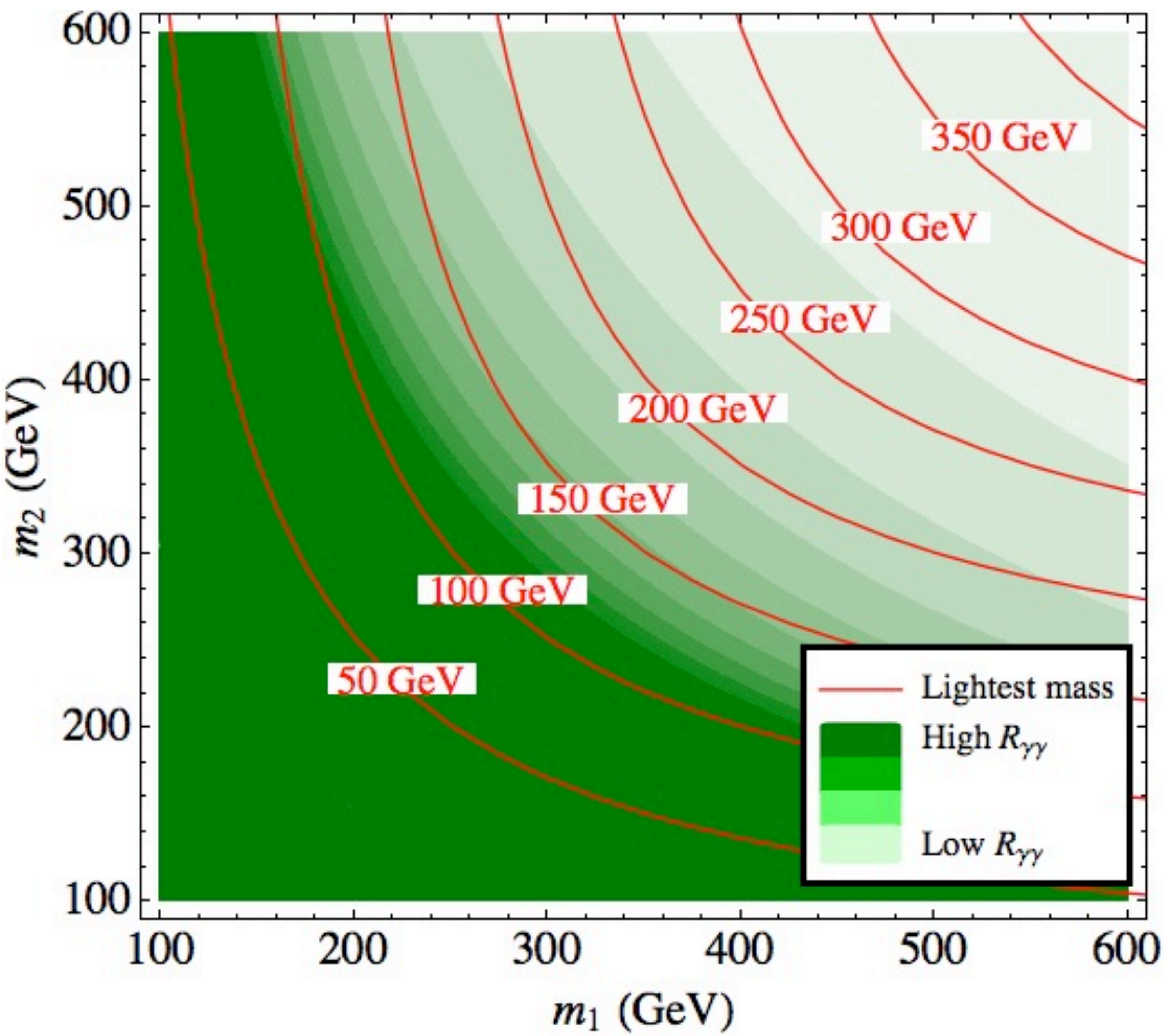
	$\mathrm{SU(2)_L}$		
Field	doublet-singlet	triplet-doublet	$\mathrm{U(1)_Y}$
$\chi_{L,R}$	2	3	$\hat{y} = y - \frac{1}{2}$
$\psi_{L,R}$	1	2	y

Write most general Lagrangean and the mass matrix is

$$M_{3+2} = (\bar{\psi}^u_R\, \bar{\chi}^a_R\, \bar{\psi}^d_R\, \bar{\chi}^b_R\, \bar{\chi}^c_R) \begin{pmatrix} m_2 & cv & 0 & 0 & 0 \\ cv & m_1 & 0 & 0 & 0 \\ 0 & 0 & m_2 & -c\frac{v}{\sqrt{2}} & 0 \\ 0 & 0 & -c\frac{v}{\sqrt{2}} & m_1 & 0 \\ 0 & 0 & 0 & 0 & m_1 \end{pmatrix} \begin{pmatrix} \psi^u_L \\ \chi^a_L \\ \psi^d_L \\ \chi^b_L \\ \chi^c_L \end{pmatrix}$$

Again, $m_1 = m_2$ leads to largest mixing

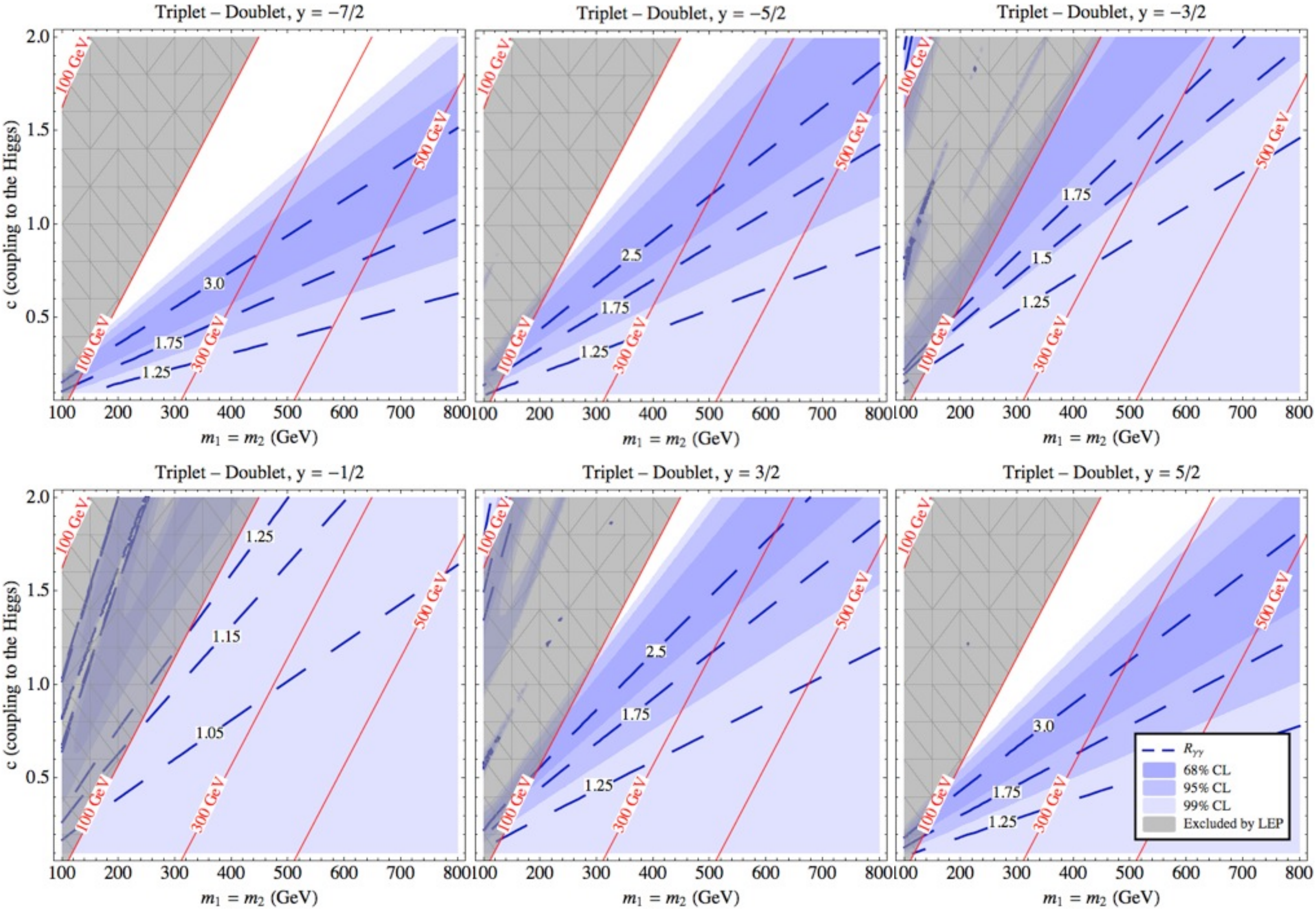
3–2 model



$$R_{\gamma\gamma} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma^{\rm SM}(H \to \gamma\gamma)}$$

Again, more mixing means larger enhancement

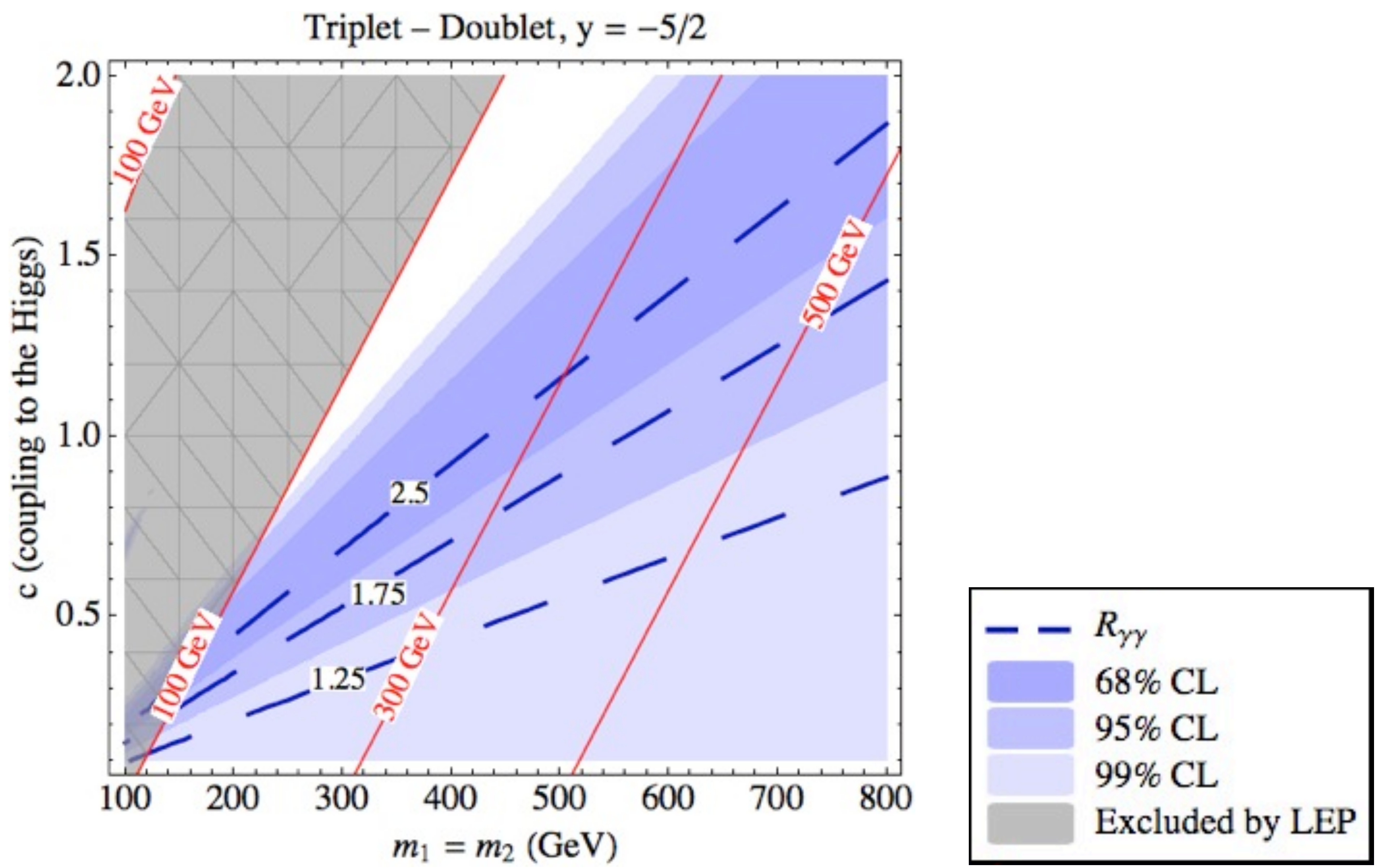
Let's focus on $m_1 = m_2$



LNGS Sep-13-2012

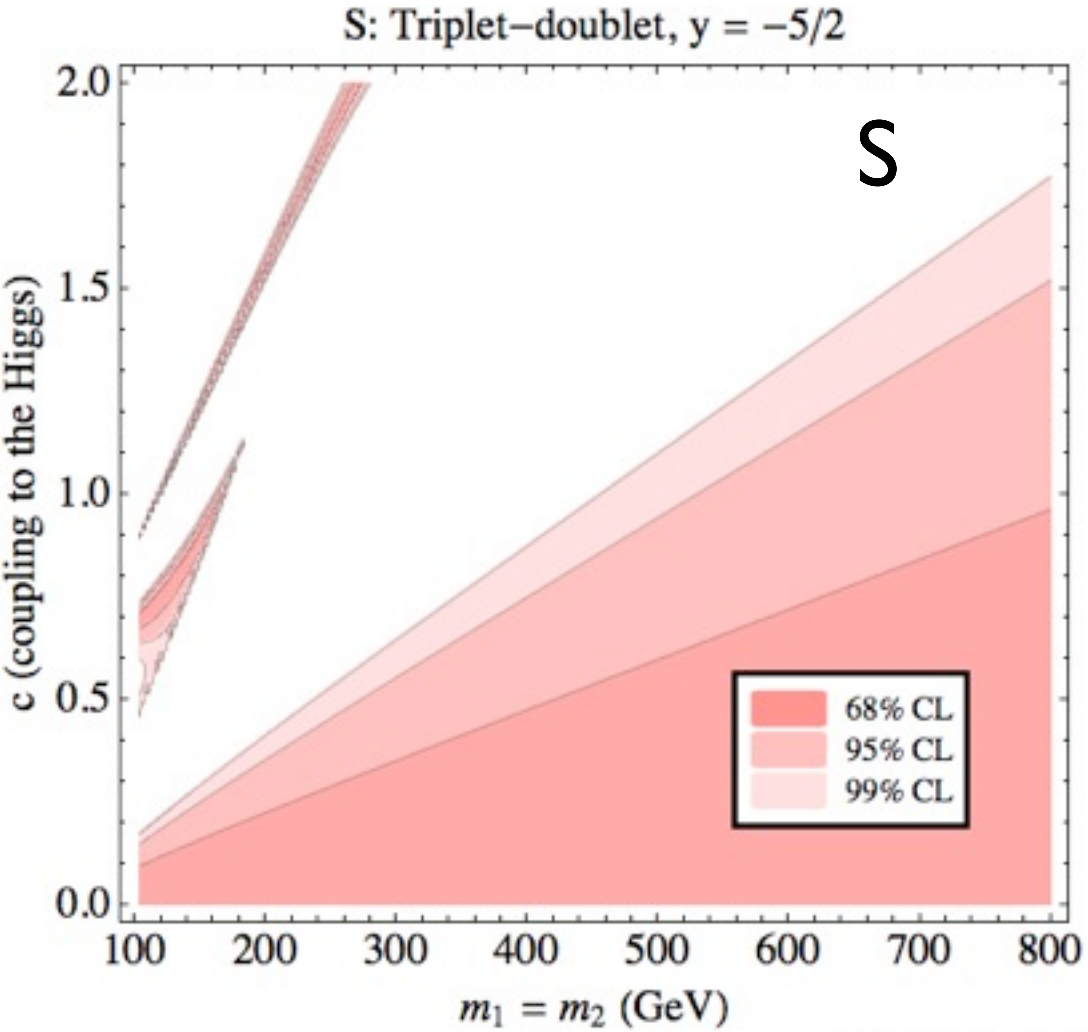
PAN Machado

3–2 model

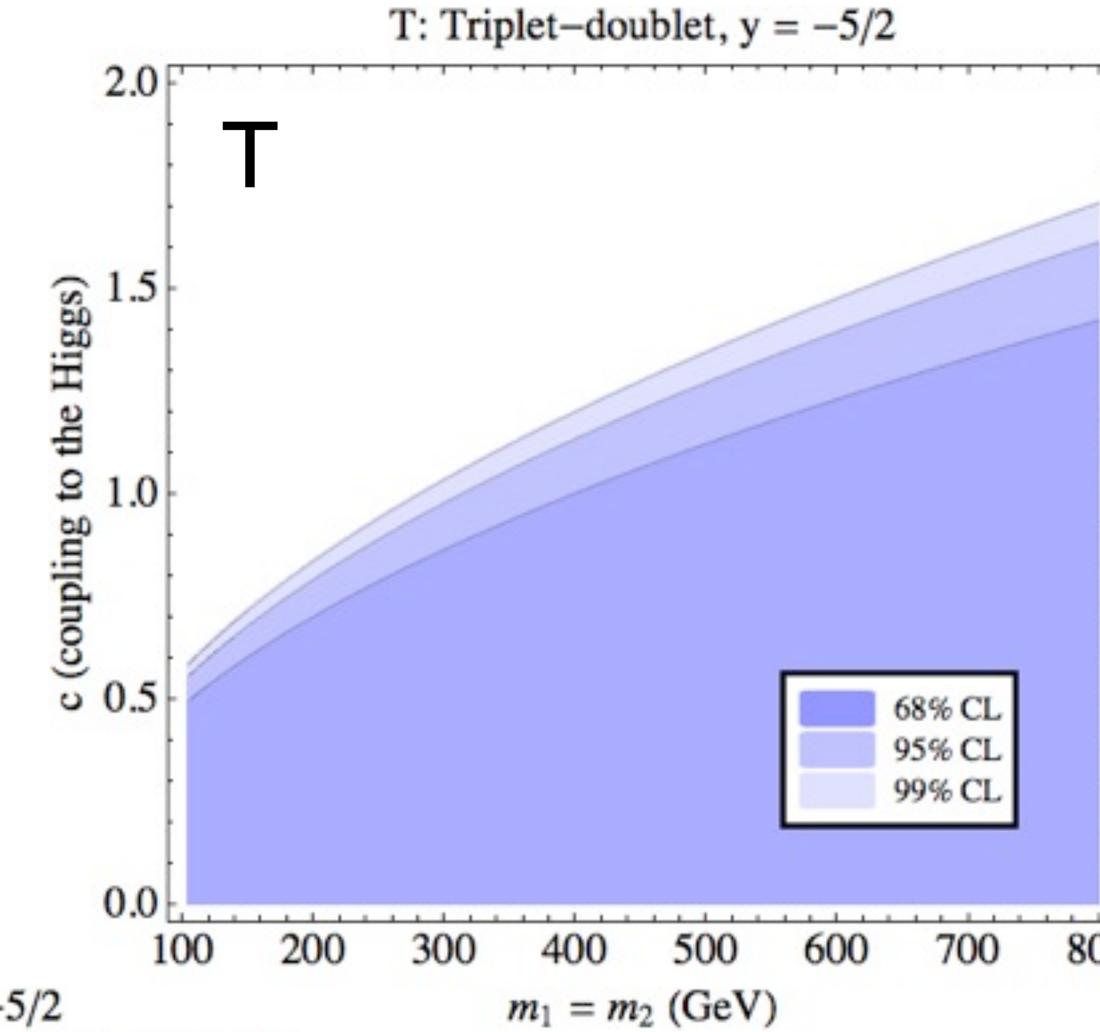


|Q| = (2, 3), (2, 3, 4)

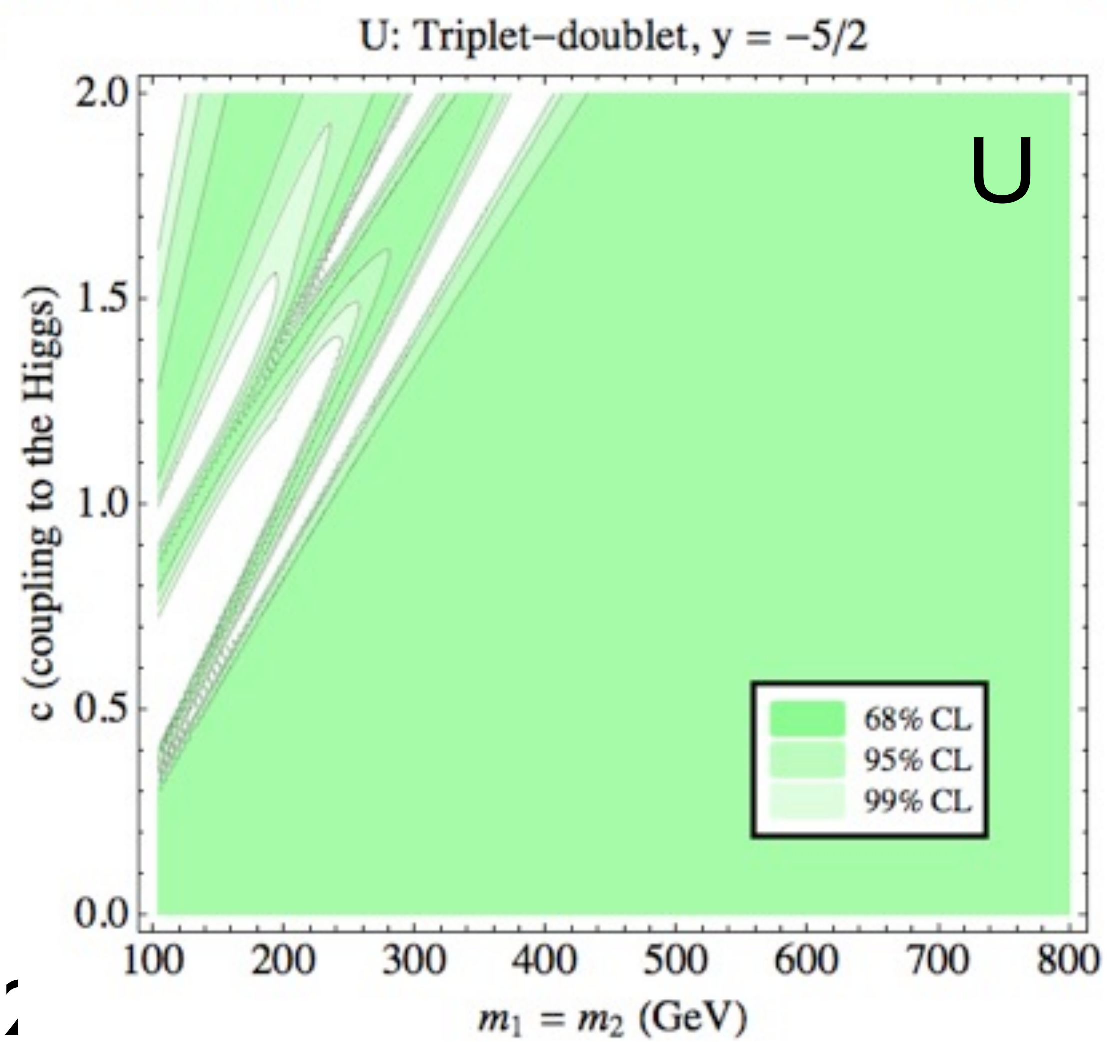
Let's see the y = –5/2 case as an example



S: Triplet−doublet, y = −5/2
S
c (coupling to the Higgs)
$m_1 = m_2$ (GeV)
68% CL
95% CL
99% CL



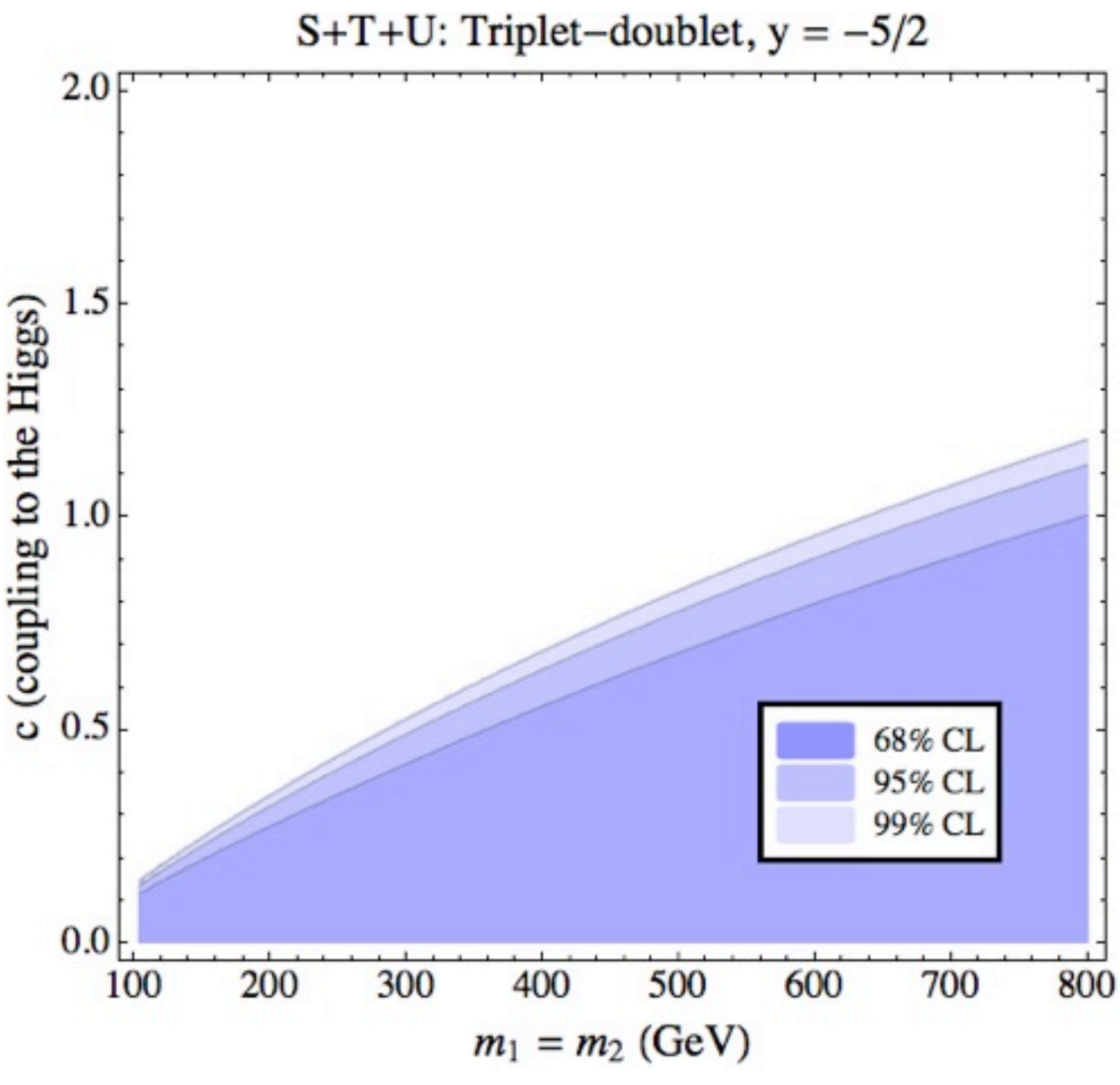
T: Triplet−doublet, y = −5/2
T
c (coupling to the Higgs)
$m_1 = m_2$ (GeV)
68% CL
95% CL
99% CL

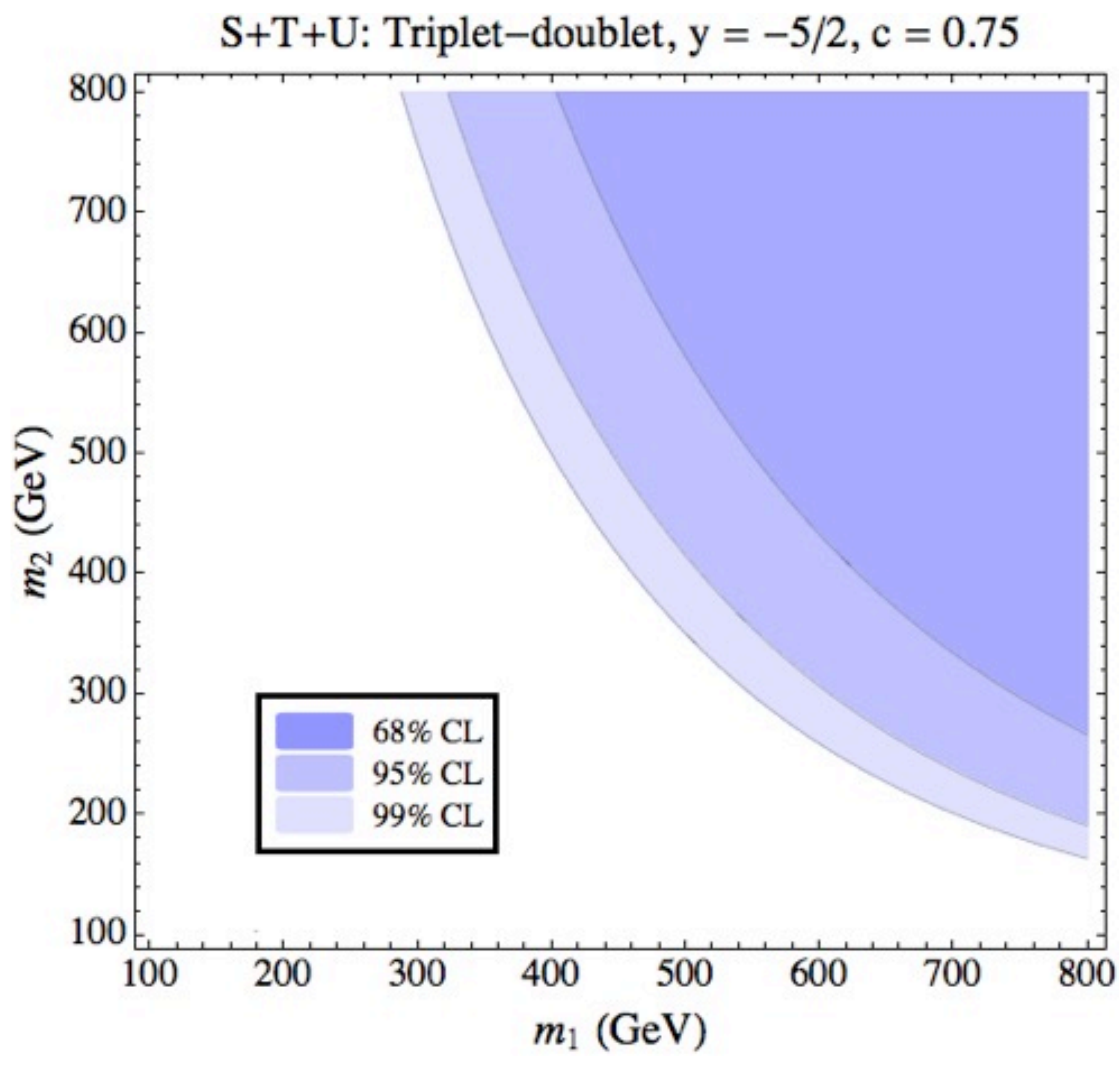


U: Triplet−doublet, y = −5/2
U
c (coupling to the Higgs)
$m_1 = m_2$ (GeV)
68% CL
95% CL
99% CL

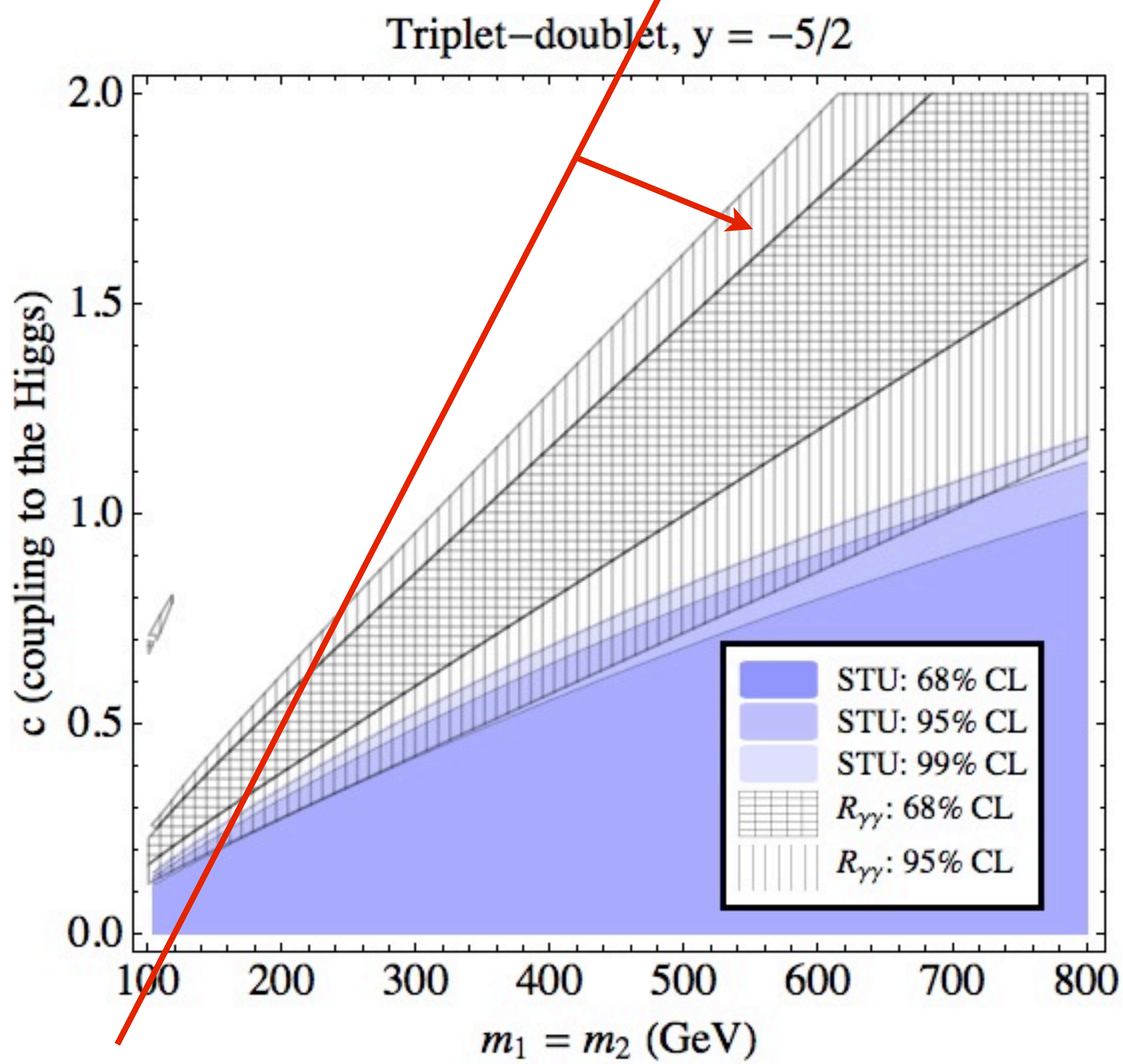
3–2 model

Combined STU fit





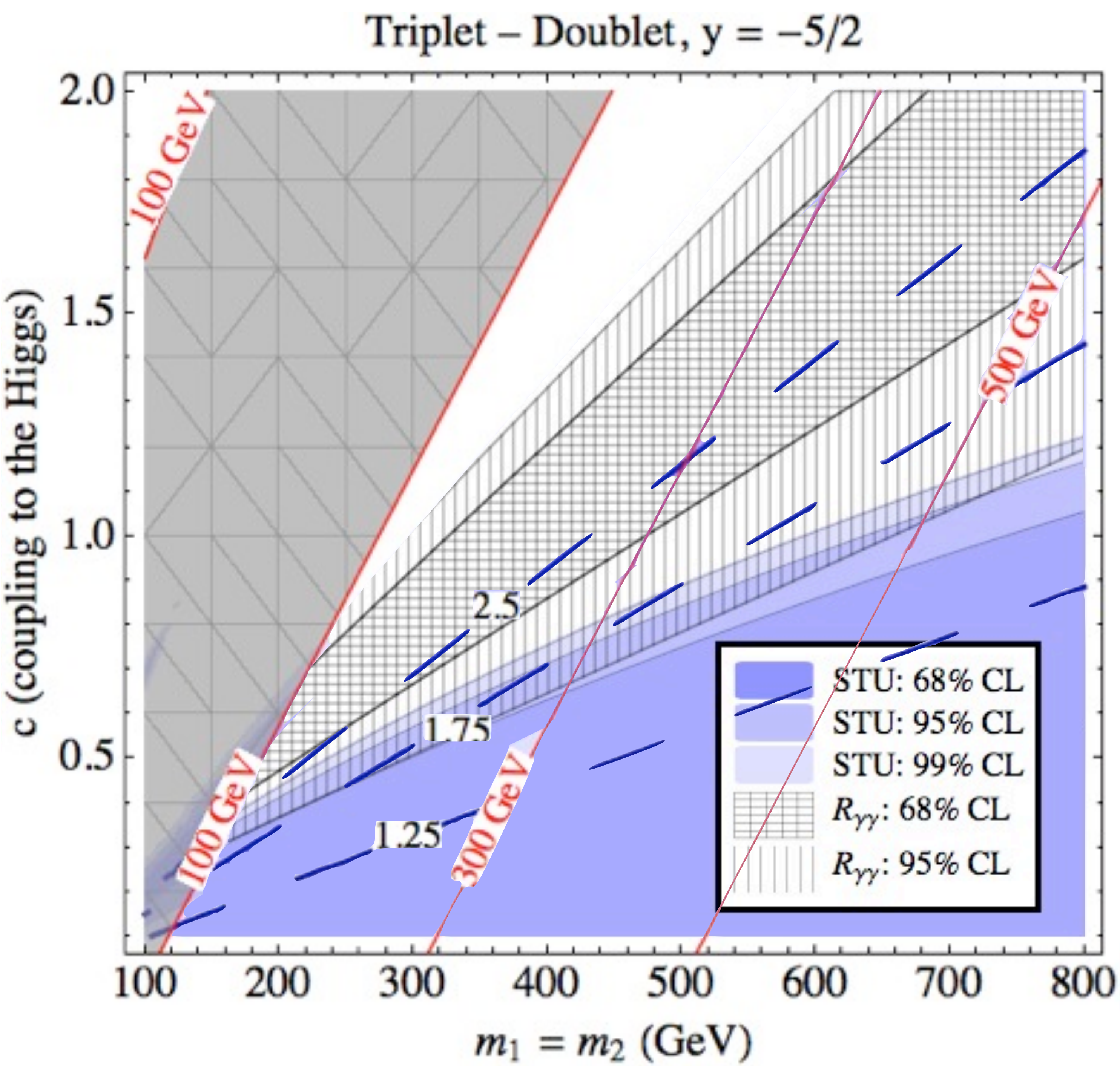
3–2 model



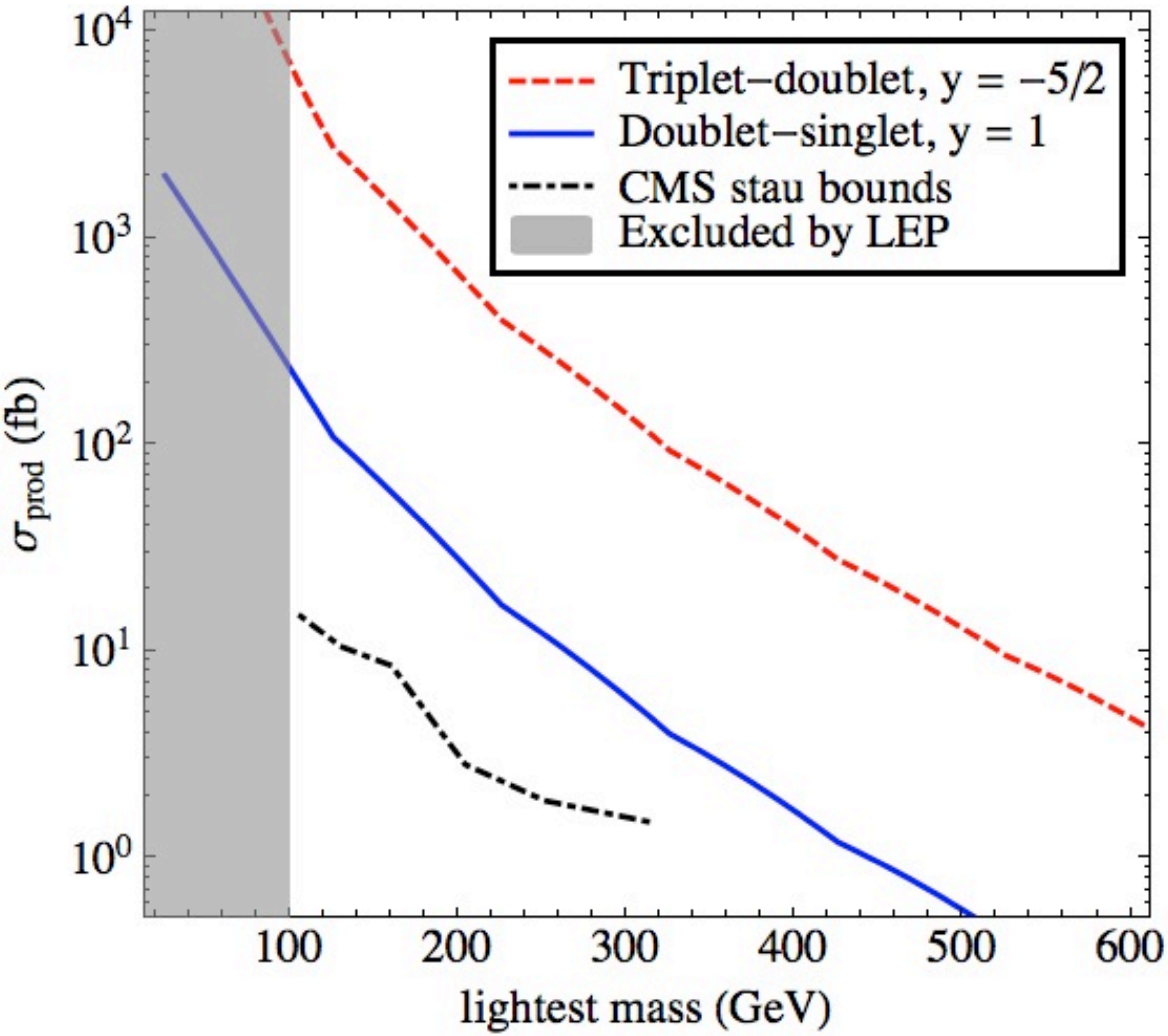
lightest mass above 100 GeV

3–2 model

~ 50% enhancement is feasible



Production @ LHC



some comments

- With |Q| = 1 fermions, the H to γγ enhancement is limited

some comments

- With $|Q| = 1$ fermions, the H to $\gamma\gamma$ enhancement is limited

unless there are many copies of these fermions (e.g. colors)

some comments

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- In a "natural" scenario, a large enhancement of H to γγ confront vacuum stability issues (instable below 10 TeV)

  see Arkani-Hamed Blum Agnolo Fan 1207.4482

some comments

- H to $\gamma\gamma$ is correlated to H to $Z\gamma$ (same particles in the loop)

number. Therefore, simultaneous measurements of the decay widths in the $\gamma\gamma$ and $Z\gamma$ channels would probe the weak isospin charge and the electric charge of the new particles running in the loop.

Carena Low Wagner 1206.1082

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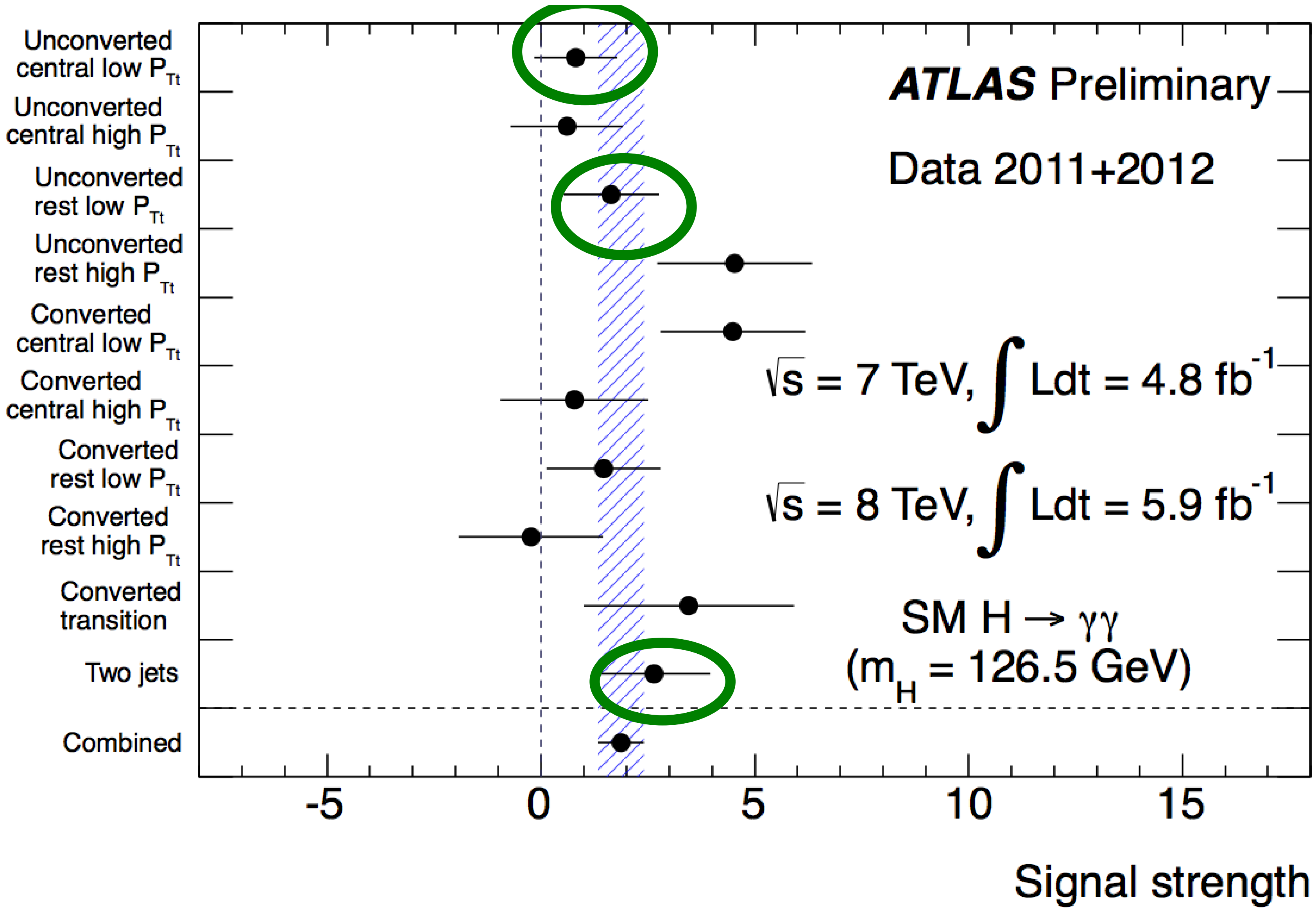
This Christmas (or even before), we may receive a precious gift...

Thank you!

BACKUP


Unconverted central low P_{Tt}
Unconverted central high P_{Tt}
Unconverted rest low P_{Tt}
Unconverted rest high P_{Tt}
Converted central low P_{Tt}
Converted central high P_{Tt}
Converted rest low P_{Tt}
Converted rest high P_{Tt}
Converted transition
Two jets
Combined
ATLAS Preliminary
Data 2011+2012
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 5.9 fb^{-1}
SM $H \rightarrow \gamma\gamma$
(m_H = 126.5 GeV)
-5
0
5
10
15
Signal strength

The Higgs boson

How to fit the Higgs couplings?

Dimension-6 operators invariant under SM gauge groups
These will lead to anomalous Higgs couplings

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

Corbett, Éboli, Gonzalez-Fraile, Gonzalez-Garcia 1207.1344

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$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \; G^a_{\mu\nu} G^{a\mu\nu} \quad , \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \quad ,$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , \qquad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \quad , \qquad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \quad ,$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \, \Phi^\dagger \Phi \, (D^\mu \Phi) \quad , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi \right) \partial_\mu \left(\Phi^\dagger \Phi \right) \quad ,$$

Expanding these terms, we get an effective Lagrangean

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The Higgs boson

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} \;=\;& g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu} \\
+\;& g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\, HZ_\mu Z^\mu \\
+\;& g^{(1)}_{HWW}\, \left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) + g^{(2)}_{HWW}\, HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\, HW^+_\mu W^{-\,\mu} \quad ,
\end{aligned}
$$

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The Higgs boson

$$\mathcal{L}_{\rm eff}^{\rm HVV} = g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu}$$
$$+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\, HZ_{\mu}Z^{\mu}$$
$$+ g^{(1)}_{HWW}\, \left(W^{+}_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \mathrm{h.c.}\right) + g^{(2)}_{HWW}\, HW^{+}_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\, HW^{+}_{\mu}W^{-\,\mu}\ ,$$

These effective couplings are combination of the previous

$$g_{H\gamma\gamma} = -\left(\frac{gM_W}{\Lambda^2}\right)\frac{s^2(f_{BB}+f_{WW}-f_{BW})}{2}$$

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Loop functions

$$
\begin{aligned}
A_1(\tau) &= -[2\tau^2 + 3\tau + 3(2\tau - 1)g(\tau)]/\tau^2 \\
A_{1/2}(\tau) &= 2[\tau + (\tau - 1)g(\tau)]/\tau^2 \\
A_0(\tau) &= -[\tau - g(\tau)]/\tau^2
\end{aligned}
$$

$$g(\tau) = \arcsin^2 \sqrt{\tau}, \text{ for } \tau \leq 1.$$

$$\tau_a \equiv (m_H/2m_a)^2, \ a = W, t, f, S$$

EWPT

$$\alpha(M_Z^2)\, S^{\rm NP} = \frac{4 s_W^2 c_W^2}{M_Z^2}\left[\Pi_{ZZ}^{\rm NP}(M_Z^2) - \Pi_{ZZ}^{\rm NP}(0) - \Pi_{\gamma\gamma}^{\rm NP}(M_Z^2) - \frac{c_W^2 - s_W^2}{c_W s_W}\,\Pi_{\gamma Z}^{\rm NP}(M_Z^2)\right]$$

$$\alpha(M_Z^2)\, T^{\rm NP} = \frac{\Pi_{WW}^{\rm NP}(0)}{M_W^2} - \frac{\Pi_{ZZ}^{\rm NP}(0)}{M_Z^2}$$

$$\alpha(M_Z^2)\, U^{\rm NP} = 4 s_W^2 \left[\frac{\Pi_{WW}^{\rm NP}(M_W^2) - \Pi_{WW}^{\rm NP}(0)}{M_W^2} - c_W^2\left(\frac{\Pi_{ZZ}^{\rm NP}(M_Z^2) - \Pi_{ZZ}^{\rm NP}(0)}{M_Z^2}\right) - 2 s_W c_W \frac{\Pi_{\gamma Z}^{\rm NP}(M_Z^2)}{M_Z^2} - s_W^2 \frac{\Pi_{\gamma\gamma}^{\rm NP}(M_Z^2)}{M_Z^2}\right]$$