A Lepton-Friendly Higgs Boson

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In collaboration with B. Thomas
Work in progress

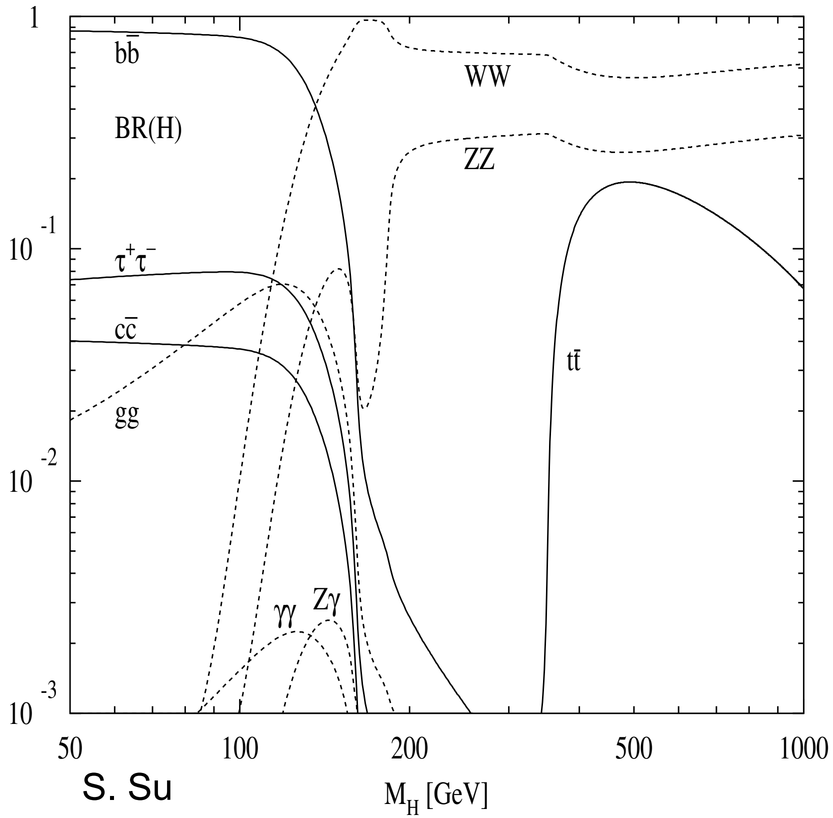
Outline

- Motivation
- Leptonic two Higgs Doublet Model (L2HDM)
- LHC discovery ($h \to \mu\mu$, $h \to \tau\tau$)
  - gluon fusion
  - WBF
  - tth
  - Zh/Wh

Standard Model Higgs

- SM, one Higgs couples to all quarks and charged leptons
  - Higgs coupling is the Yukawa coupling
  - Yukawa coupling ∝ mass

$$\frac{g_{h\tau\tau}}{g_{hbb}}|_{\rm SM} = \frac{y_\tau}{y_b}|_{\rm SM} = \frac{m_\tau}{m_b}$$



- h→bb dominant at low mass region

$$\begin{aligned}{\rm Br}(h\to\tau\tau) &= \frac{\Gamma(h\to\tau\tau)}{\Gamma_{\rm tot}} \\ &\approx \frac{\Gamma(h\to\tau\tau)}{\Gamma(h\to bb)} \approx \frac{y_\tau^2}{y_b^2}|_{\rm SM}\end{aligned}$$

Type II 2HDM: MSSM

- **Type II 2HDM:** one Higgs couples to up-type quarks, the other couples to down-type quarks and charged leptons (e.g., MSSM)

$$\mathcal{L}_{\rm Yukawa} = y_u \bar{u} Q \phi_u - y_d \bar{d} Q \phi_d - y_l \bar{e} L \phi_d + h.c.$$

$$\langle \phi_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \langle \phi_d \rangle = \begin{pmatrix} 0 \\ v_d \end{pmatrix}, \quad \tan\beta = \frac{v_u}{v_d}$$

$$y_b = \frac{m_b}{v_d} = \frac{m_b}{v\cos\beta} = \frac{1}{\cos\beta} y_b^{\rm SM}$$

$$y_\tau = \frac{m_\tau}{v_d} = \frac{m_\tau}{v\cos\beta} = \frac{1}{\cos\beta} y_\tau^{\rm SM}$$

Type II 2HDM: MSSM

$$h_u^0, h_d^0 \to h^0, H^0$$

$$g_{h^0 bb} = -\sin\alpha y_b = \left(-\frac{\sin\alpha}{\cos\beta}\right) y_b|_{\rm SM}$$

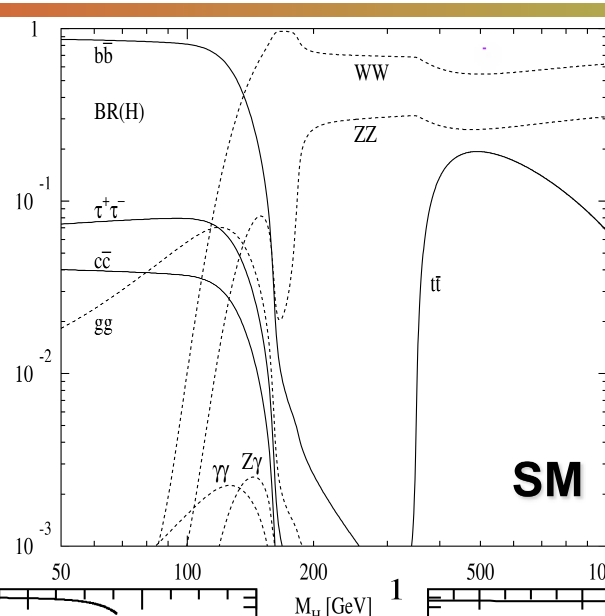
$$g_{h^0 \tau\tau} = -\sin\alpha y_\tau = \left(-\frac{\sin\alpha}{\cos\beta}\right) y_\tau|_{\rm SM}$$

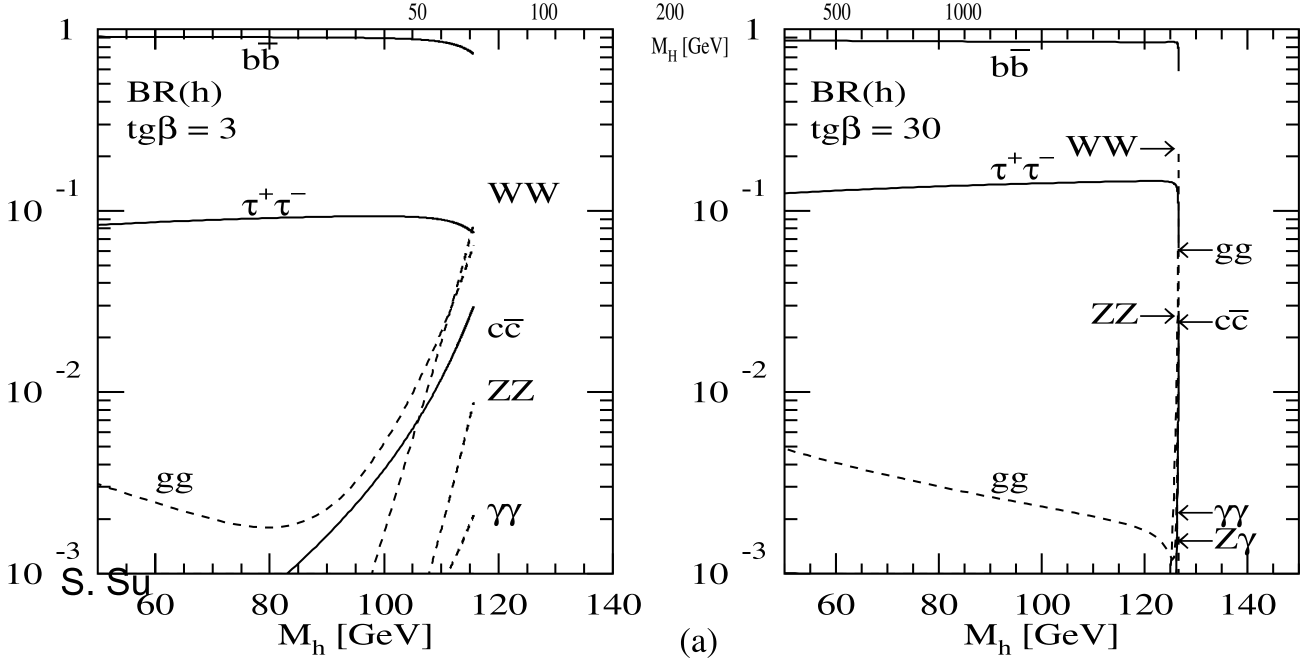
- **enhanced Higgs coupling to b and τ for large tanβ (small v_d)**

$$\frac{g_{h^0\tau\tau}}{g_{h^0 bb}}|_{\rm MSSM} = \frac{y_\tau}{y_b}|_{\rm SM}$$

$$\mathrm{Br}(h \to \tau\tau)_{\rm MSSM} \approx \frac{g^2_{h^0\tau\tau}}{g^2_{h^0 bb}}|_{\rm MSSM} \approx \mathrm{Br}(h \to \tau\tau)_{\rm SM}$$

Type II 2HDM: MSSM





MSSM

- *depend weakly on tanβ*

Leptonic Higgs decay

Could we increase the leptonic decay branching ratio?

For example:

Fan, Goldberger, Ross, Skiba, Grinstein, arXiv:0803.2040, arXiv:0708.1463

+ others ...

- lepton signal: $h\to ee$, $h\to\mu\mu$, $h\to\tau\tau$
- $y_e:y_\mu:y_\tau=m_e:m_\mu:m_\tau$ (lepton universality); consider only μ and τ
- measure μ and τ Yukawa couplings

- $h\to\mu\mu$: clean,
  - ➡ muon easy to identify $\epsilon_\mu \sim 90$ %
  - ➡ reconstruct m_h peak

Leptonic Higgs decay

- $h \to \tau\tau$: relatively clean

➡

τ decay		Br	efficiency
leptonic	$\tau \to e/\mu\ \nu_\tau\ \bar{\nu}_{e/\mu}$	35%	~ 90%
hadronic	$\tau \to \pi^\pm + n\pi^0$ 1 prong	50%	~ 50%
	$\tau \to 3\pi^\pm + n\pi^0$ 3 prongs	15%	

➡ reconstruct $M_{\tau\tau}$ or $M_{\tau\tau}^T$

Leptonic Two Higgs Doublet Model

- **2HDM:** one Higgs couples to quarks, the other couples to leptons

$$\mathcal{L}_{\text{Yukawa}} = y_u \bar{u} Q \phi_q^c - y_d \bar{d} Q \phi_q - y_l \bar{e} L \phi_l + h.c.$$

Z_2 symmetry: ϕ_q, Q, u, d, L even; ϕ_l, e odd

- **After EWSB** $\langle \phi_q \rangle = \begin{pmatrix} 0 \\ v_q \end{pmatrix}, \quad \langle \phi_l \rangle = \begin{pmatrix} 0 \\ v_l \end{pmatrix}, \quad \tan\beta = \frac{v_q}{v_l}$

$$y_b = \frac{m_b}{v_q} = \frac{m_b}{v \sin\beta} = \frac{1}{\sin\beta} y_b^{\text{SM}}$$

$$y_\tau = \frac{m_\tau}{v_l} = \frac{m_\tau}{v \cos\beta} = \frac{1}{\cos\beta} y_\tau^{\text{SM}}$$

enhanced τ coupling for large tanβ (small v_l)

Leptonic 2HDM

- **CP even Higgses**

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}[\phi_q^0] - v_q \\ \mathrm{Re}[\phi_l^0] - v_l \end{pmatrix}$$

$$g_{h^0 bb} = \cos\alpha\, y_b = \left(\frac{\cos\alpha}{\sin\beta}\right) y_b|_{\mathrm{SM}}$$

$$g_{h^0 \tau\tau} = -\sin\alpha\, y_b = \left(-\frac{\sin\alpha}{\cos\beta}\right) y_\tau|_{\mathrm{SM}}$$

$$\frac{g_{h^0\tau\tau}}{g_{h^0 bb}}|_{\mathrm{L2HDM}} = -\left(\frac{\tan\beta}{\cot\alpha}\right)\frac{y_\tau}{y_b}|_{\mathrm{SM}}$$

$$\mathrm{Br}(h^0 \to \tau\tau)_{\mathrm{L2HDM}} = \frac{g^2_{h^0\tau\tau}}{g^2_{h^0 bb}}|_{\mathrm{L2HDM}} \approx \left(\frac{\tan^2\beta}{\cot^2\alpha}\right)\mathrm{Br}(h \to \tau\tau)_{\mathrm{SM}}$$

Leptonic 2HDM

- decoupling limit: ⇒ SM

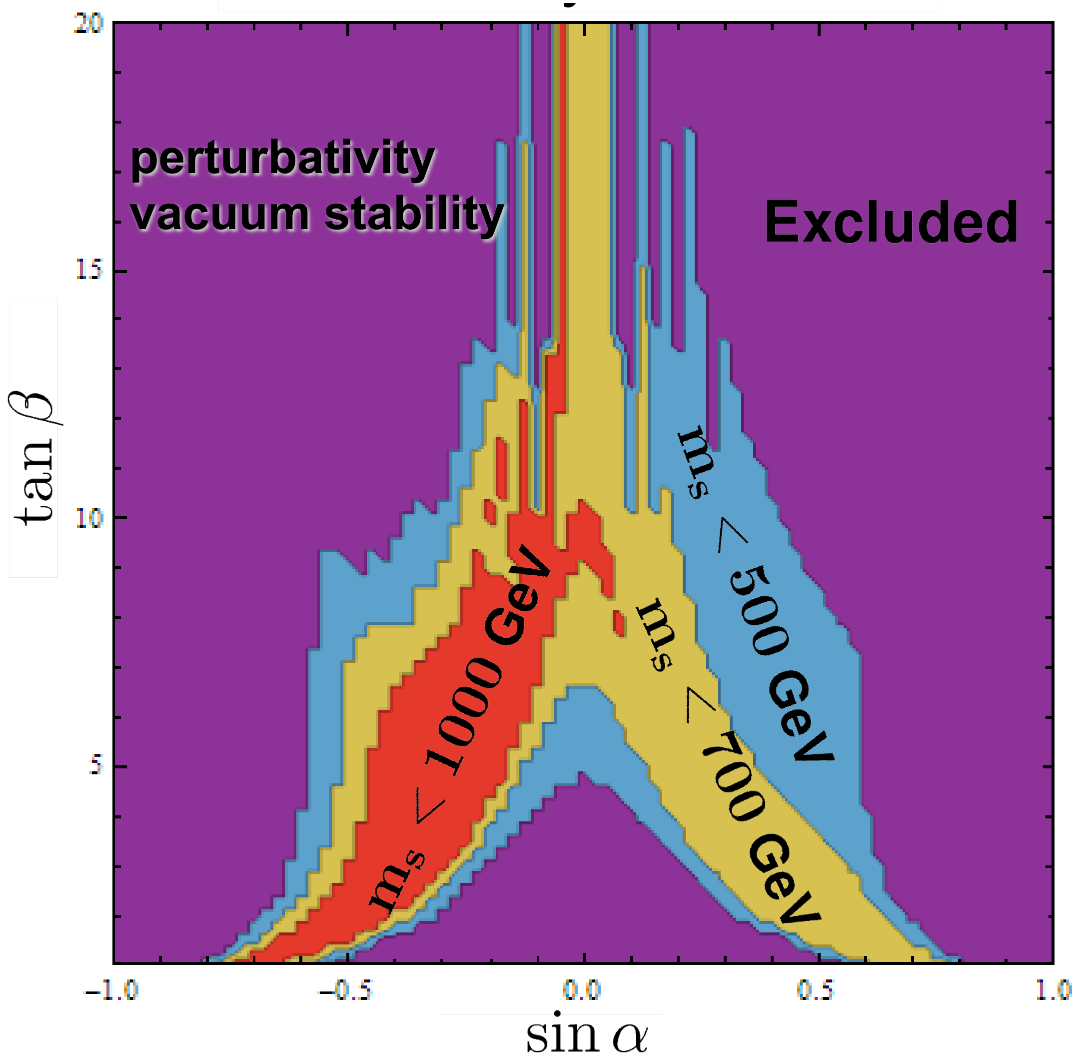
$$m_H, m_{A^0}, m_{H^\pm} \gg m_h \qquad \alpha \approx \beta - \frac{\pi}{2}$$

$$\mathrm{Br}(h \to \tau\tau)|_{\mathrm{L2HDM}} \approx \mathrm{Br}(h \to \tau\tau)|_{\mathrm{SM}}$$

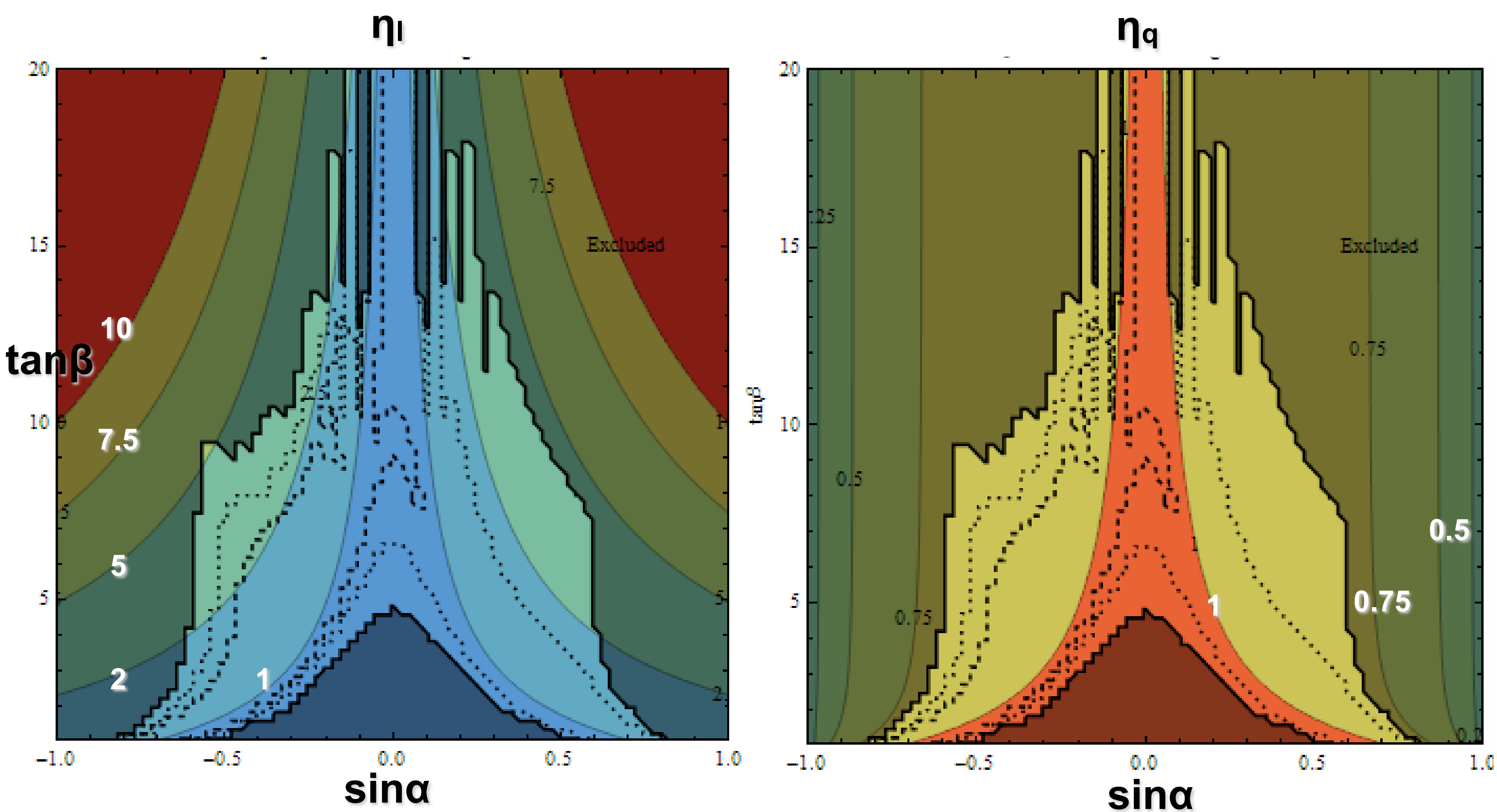
- non-decoupling, could have large tanβ enhancement
- parametrize light Higgs h^0 coupling

$$\eta_l = \frac{g_{h^0 ll}}{g^{\mathrm{SM}}_{h^0 ll}} = -\frac{\sin\alpha}{\cos\beta} \qquad \eta_q = \frac{g_{h^0 qq}}{g^{\mathrm{SM}}_{h^0 qq}} = \frac{\cos\alpha}{\sin\beta} \qquad \eta_{W,Z} = \frac{g_{h^0 VV}}{g^{\mathrm{SM}}_{h^0 VV}} = \sin(\beta - \alpha)$$

Higgs masses



h^0_{qq}, h^0_{ll} couplings



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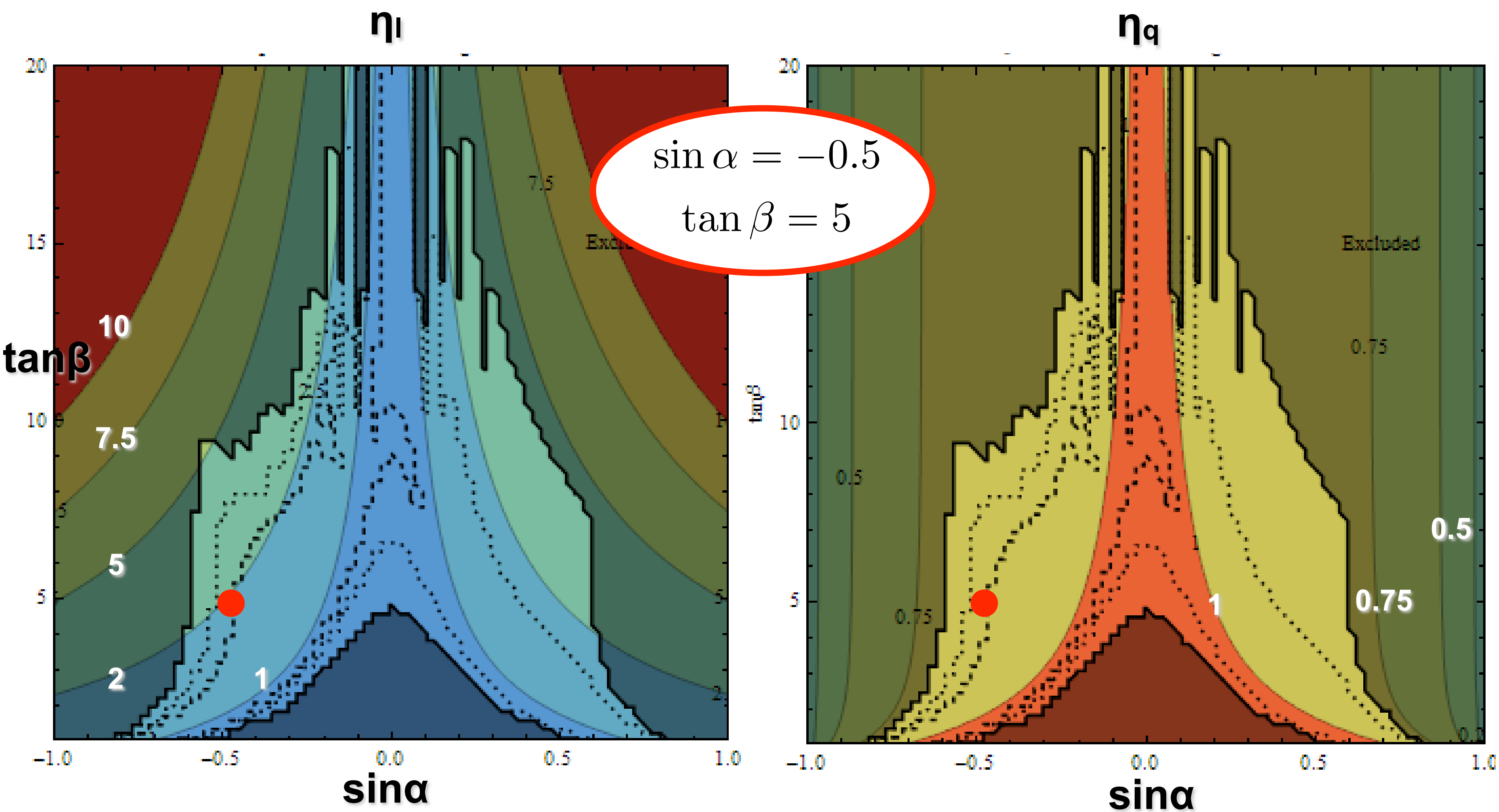

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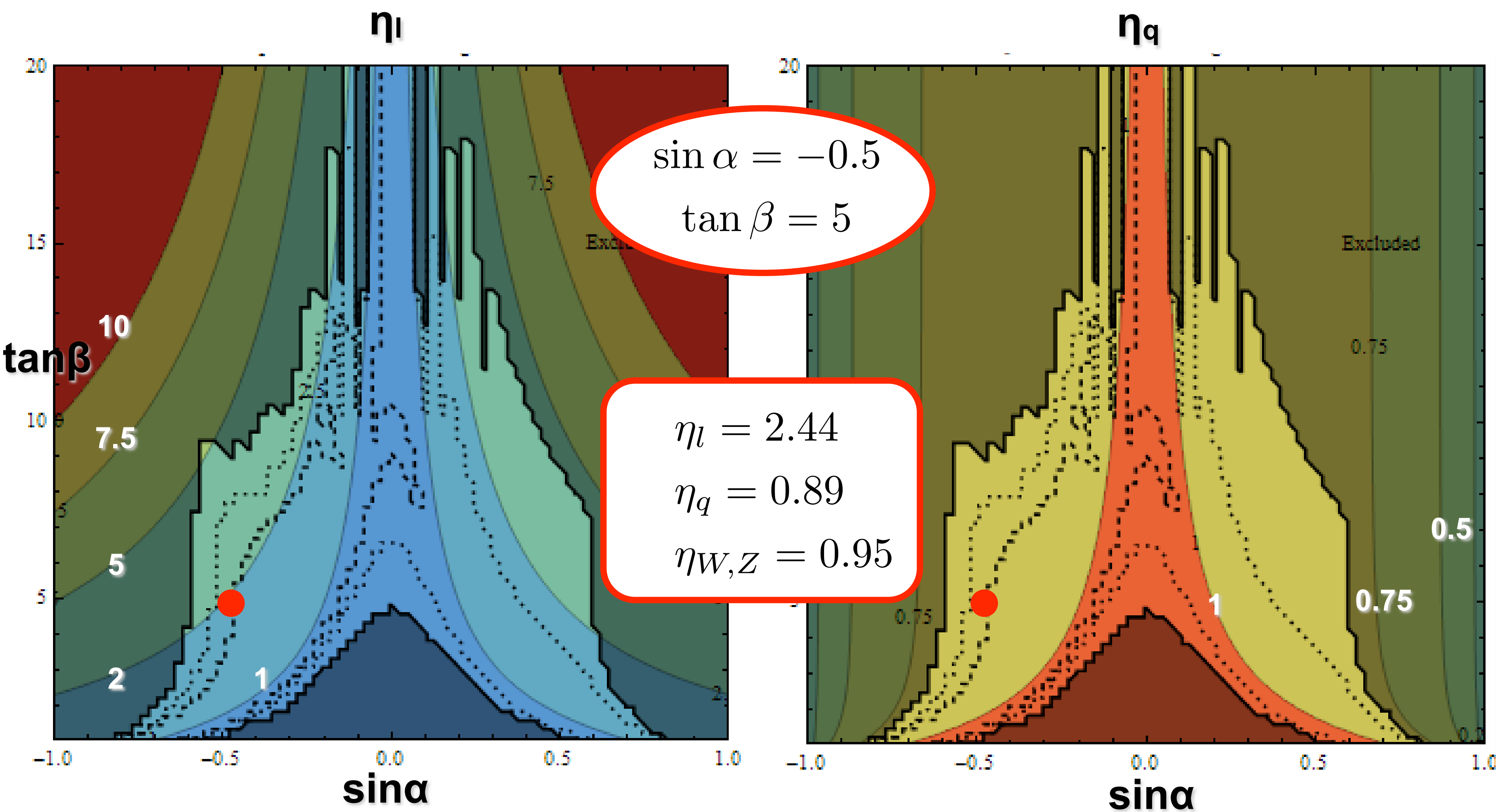

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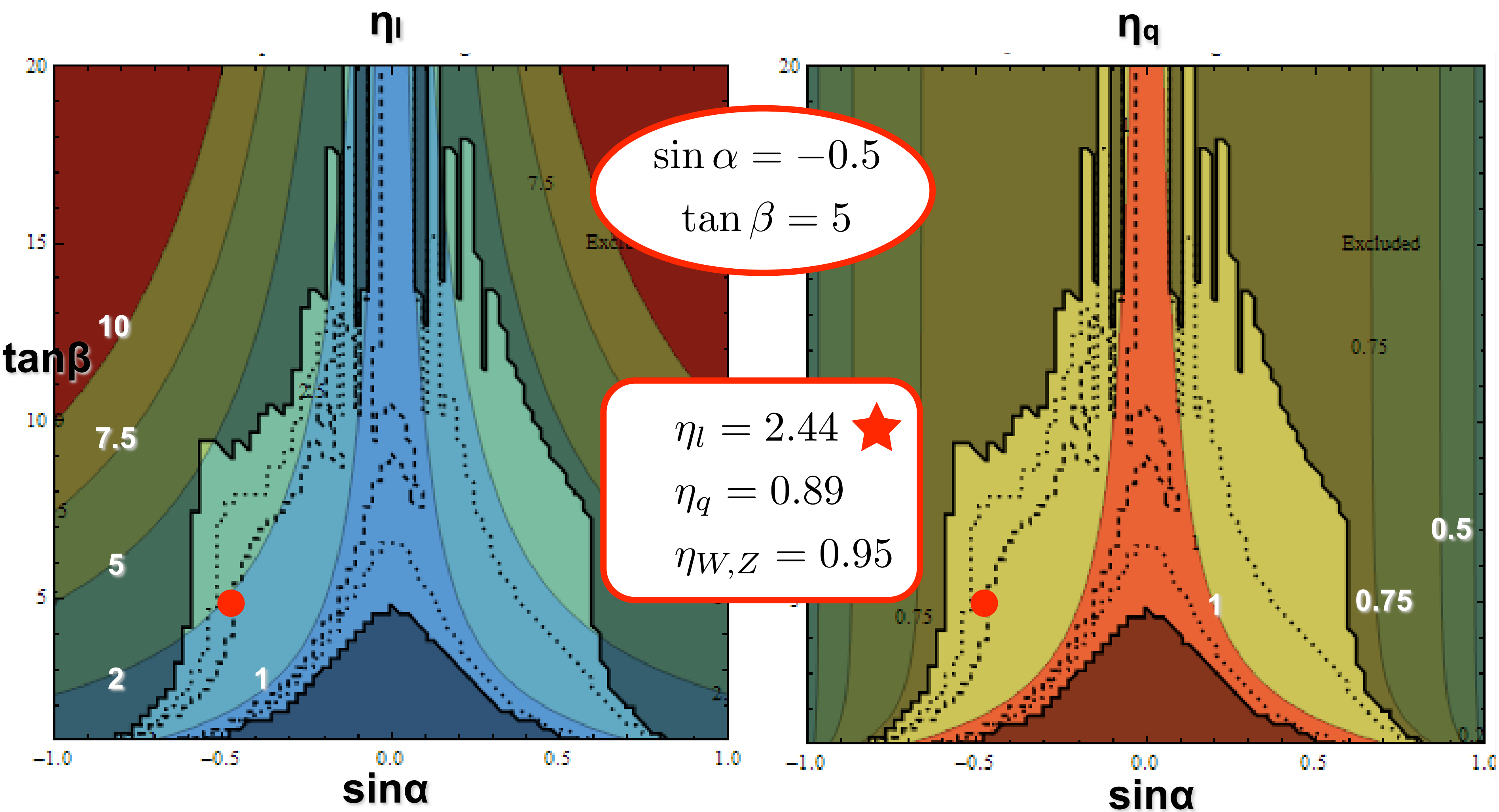
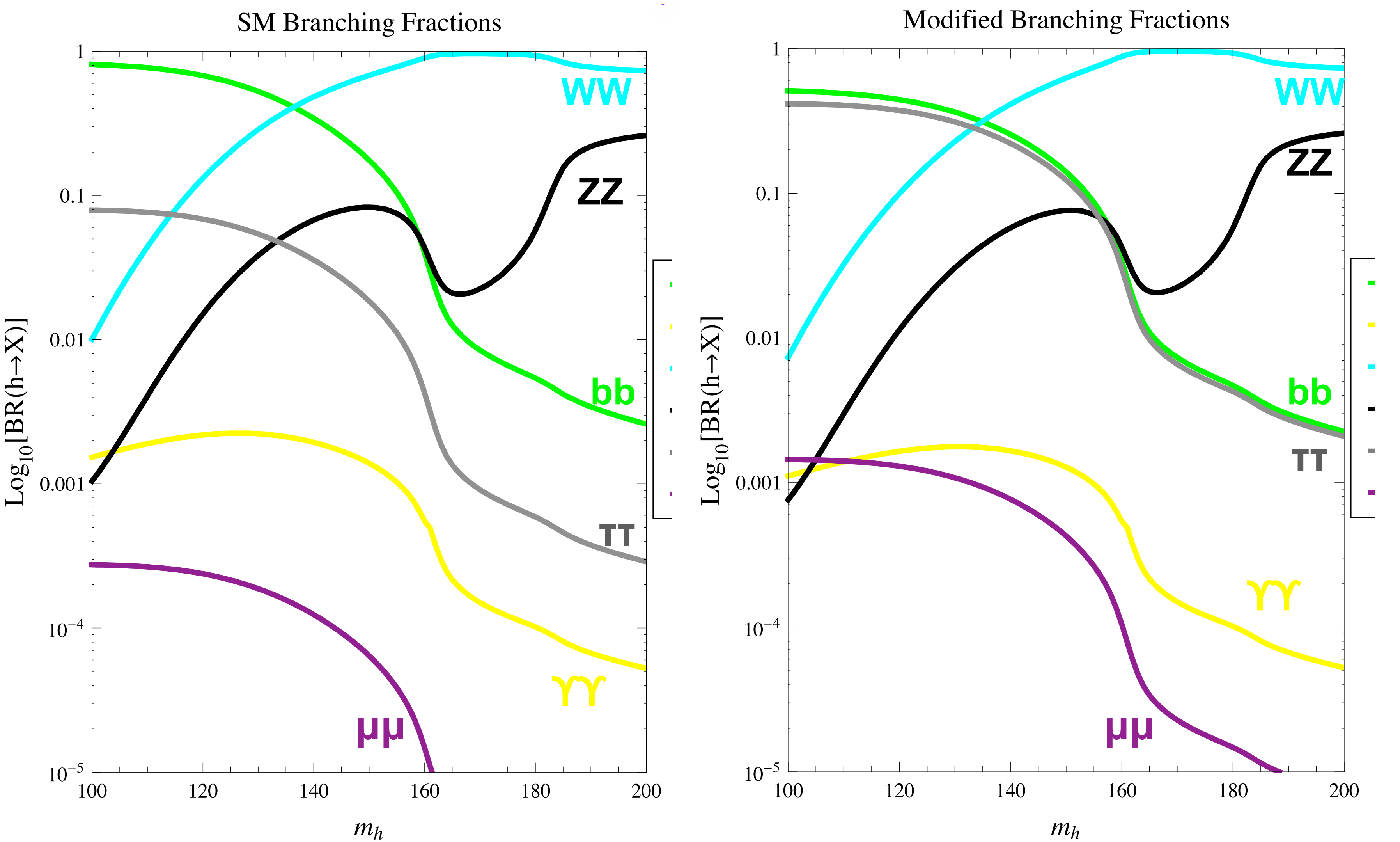


$$\sin\alpha = -0.5$$
$$\tan\beta = 5$$

$$\eta_l = 2.44$$
$$\eta_q = 0.89$$
$$\eta_{W,Z} = 0.95$$

Light Higgs Decay



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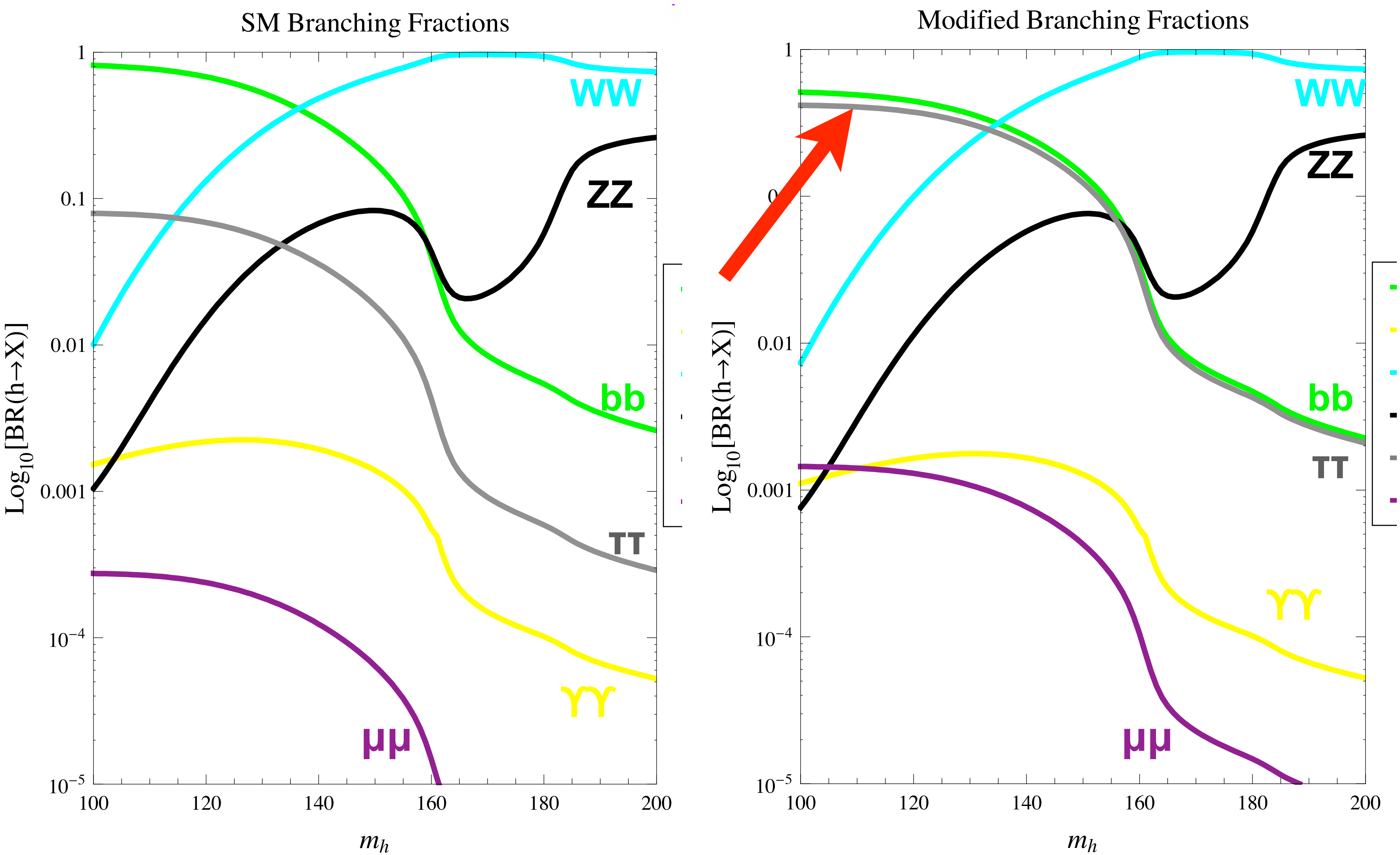
Light Higgs Decay



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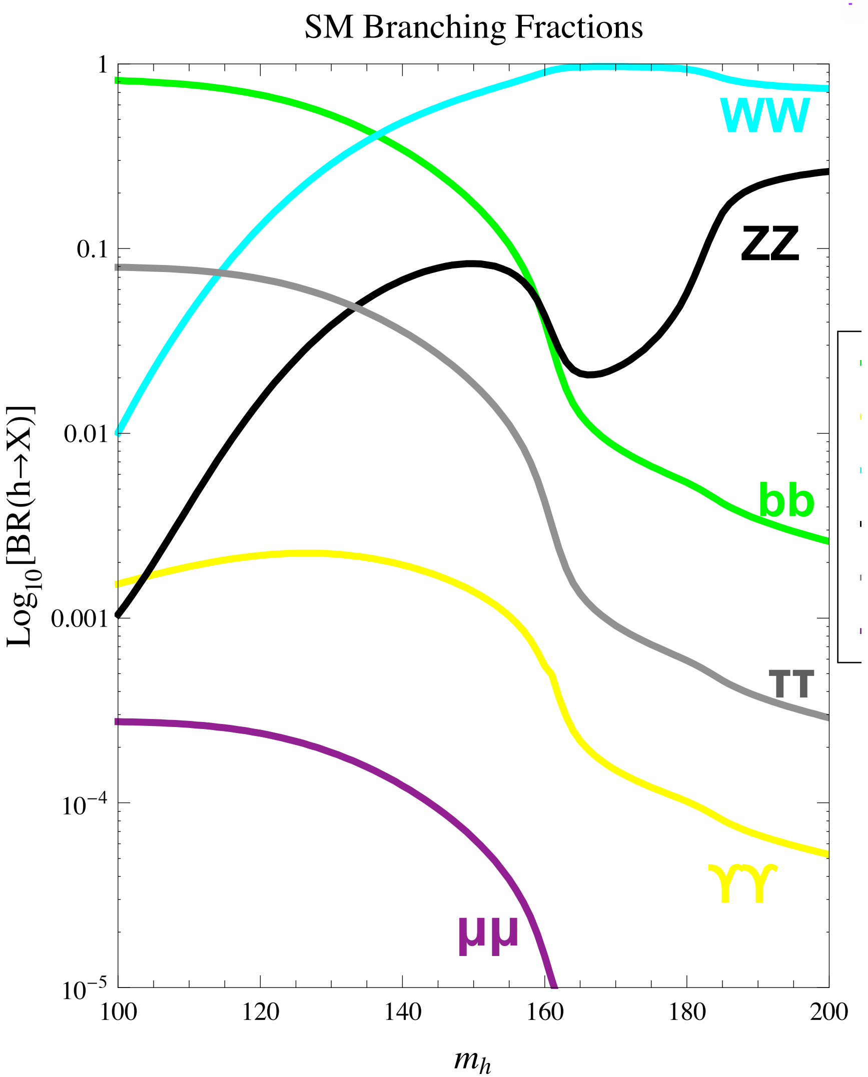
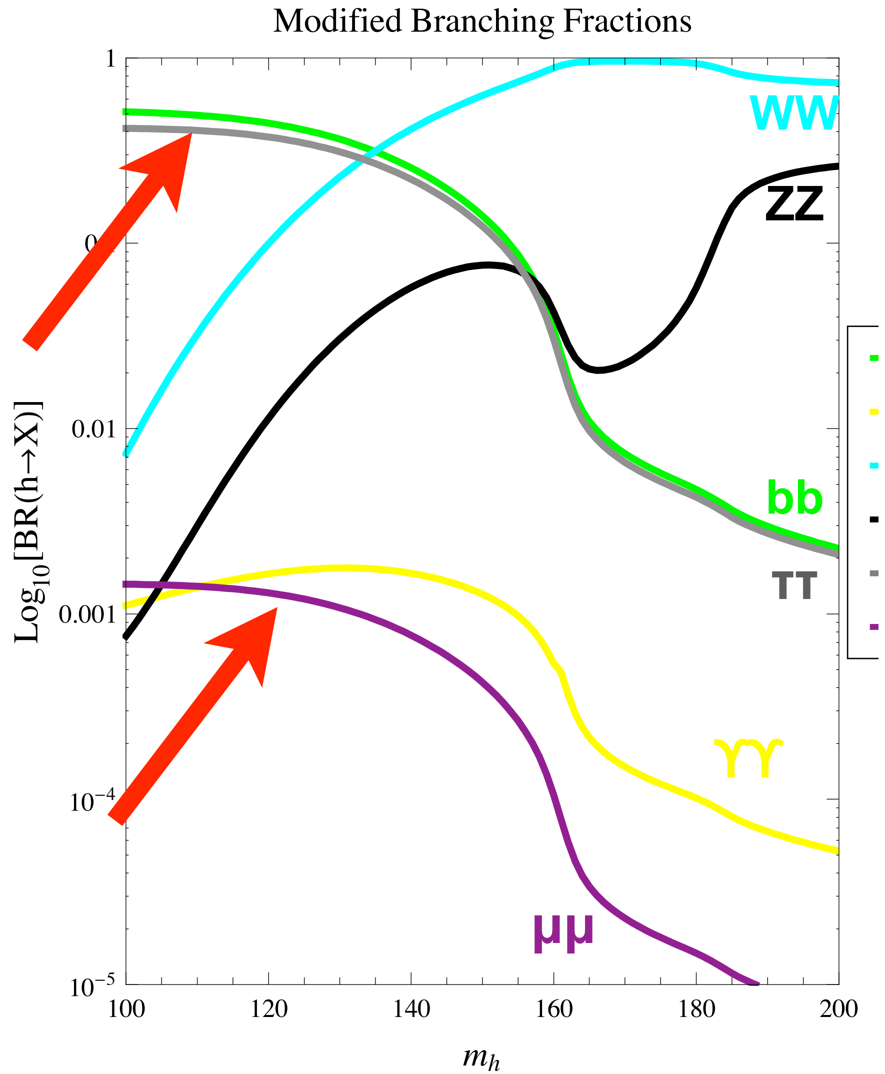
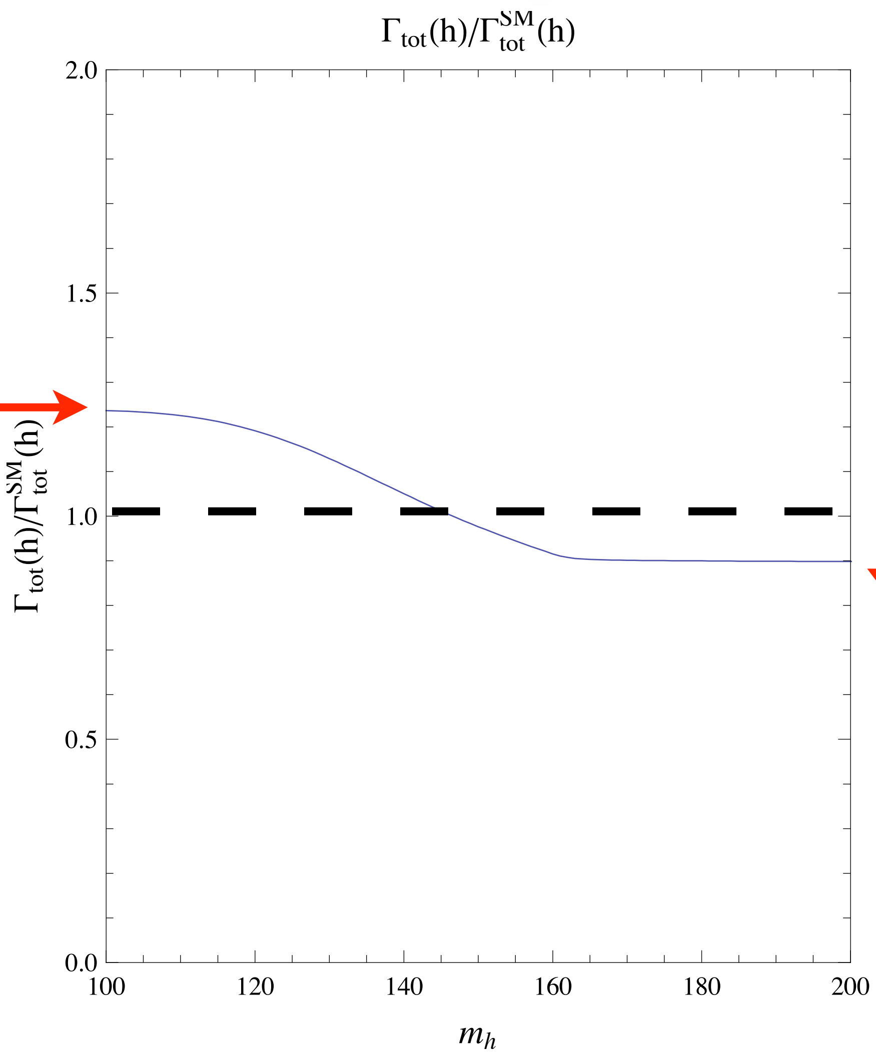




Higgs Decay Width

bb, ττ both contribute



WW, ZZ dominant

η_V^2

LHC Observation

gluon fusion
WBF
tth
WH/ZH

$\longrightarrow$ h $\longrightarrow$

γγ
μμ
ττ
WW,ZZ...

$$\frac{\sigma(X \to h \to Y)}{\sigma(X \to h \to Y)^{\rm SM}} = \frac{\Gamma(h \to X)}{\Gamma(h \to X)^{\rm SM}} \frac{{\rm Br}(h \to Y)}{{\rm Br}(h \to Y)^{\rm SM}}$$

$$= \frac{\Gamma(h \to X)}{\Gamma(h \to X)^{\rm SM}} \frac{\Gamma(h \to Y)}{\Gamma(h \to Y)^{\rm SM}} \frac{\Gamma_{\rm tot}^{\rm SM}}{\Gamma_{\rm tot}}$$

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↑ $\propto \eta_X^2$

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$\uparrow$ $\propto \eta_X^2$

$\uparrow$ $\propto \eta_Y^2$

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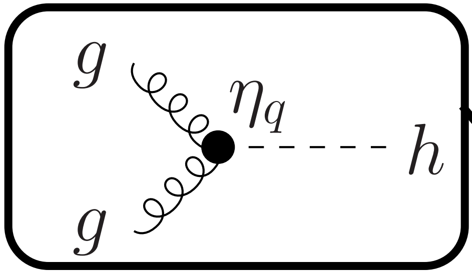
$\propto \eta_X^2$ $\quad\propto \eta_Y^2$ $\quad\approx 1$

LHC Observation



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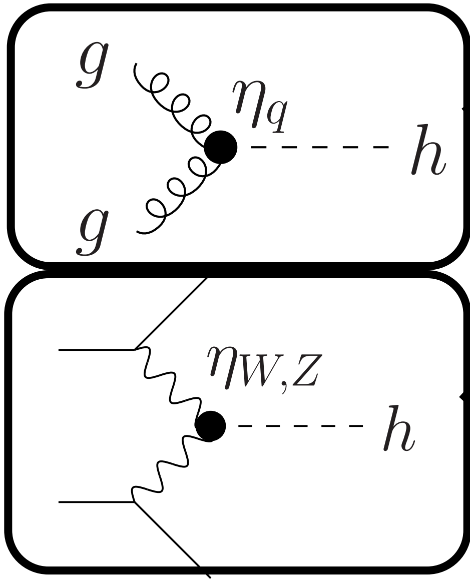

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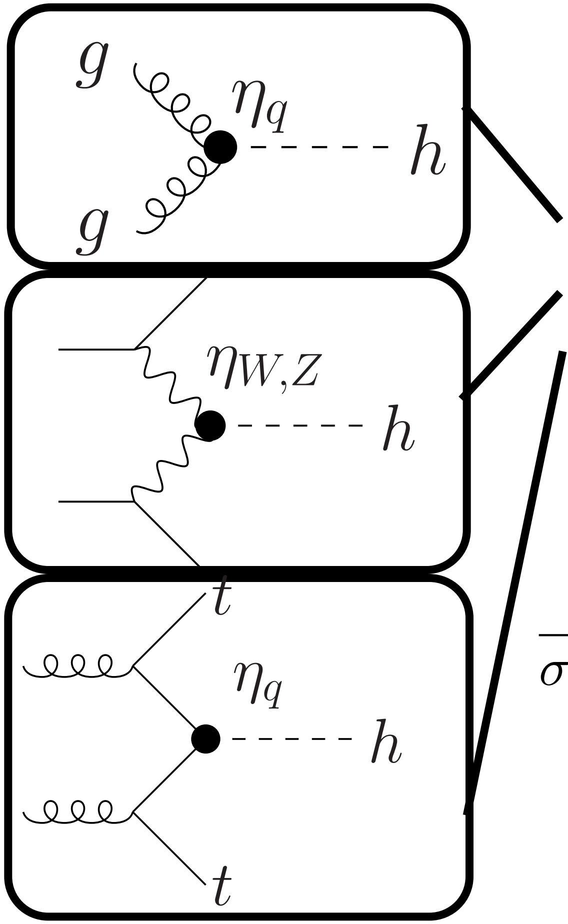
LHC Observation



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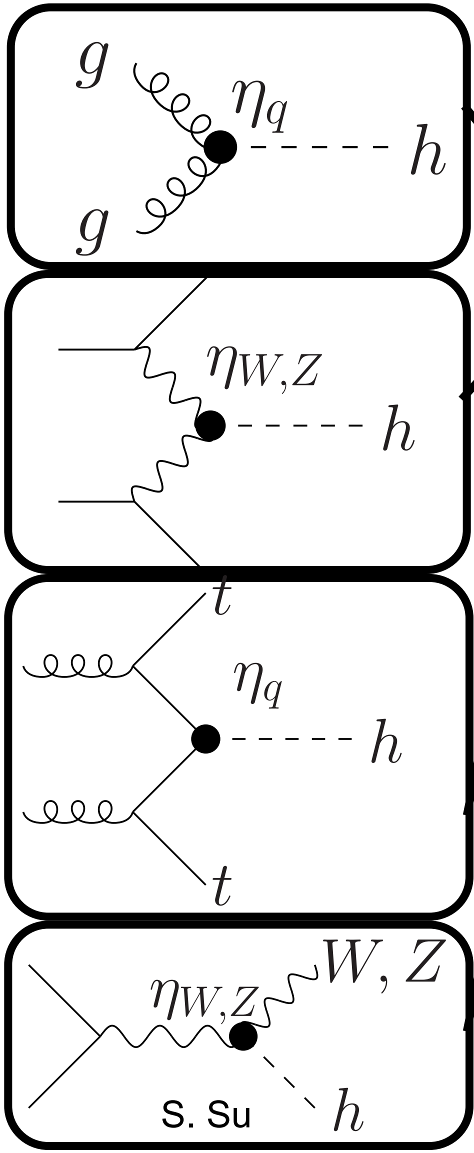

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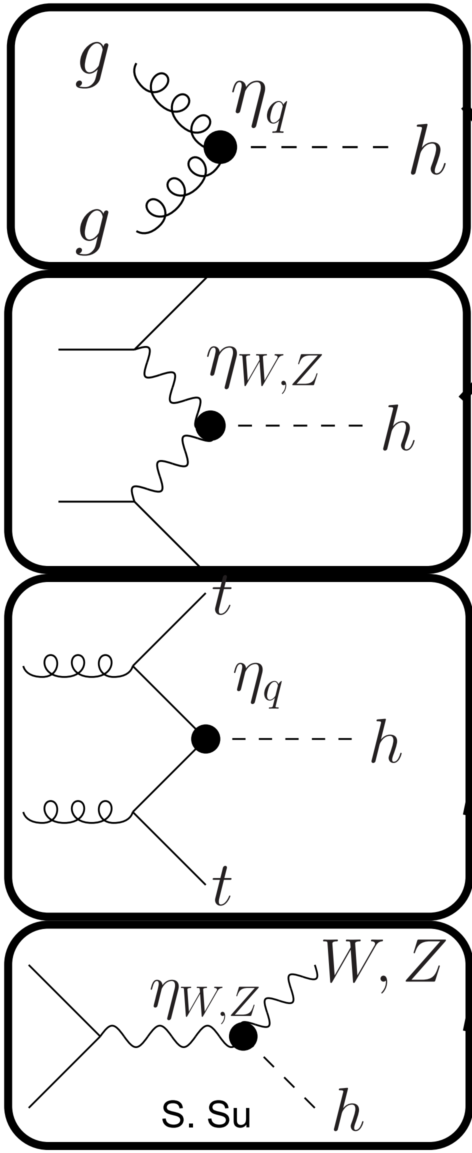

slightly suppressed

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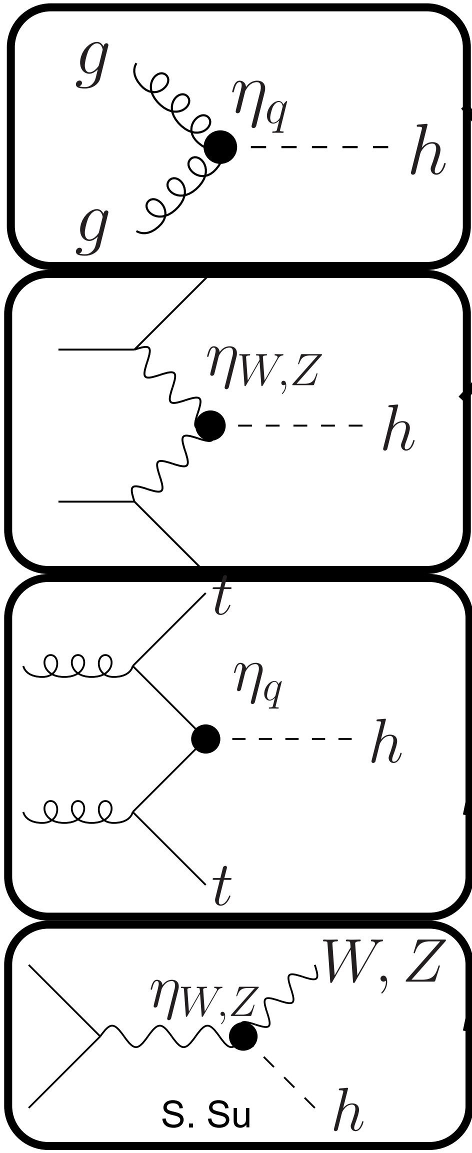

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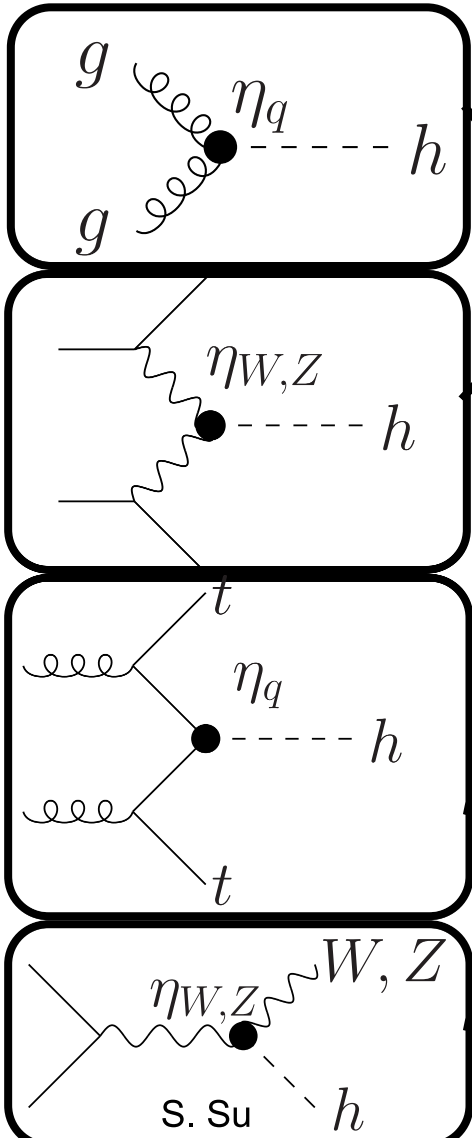

slightly suppressed

greatly enhanced

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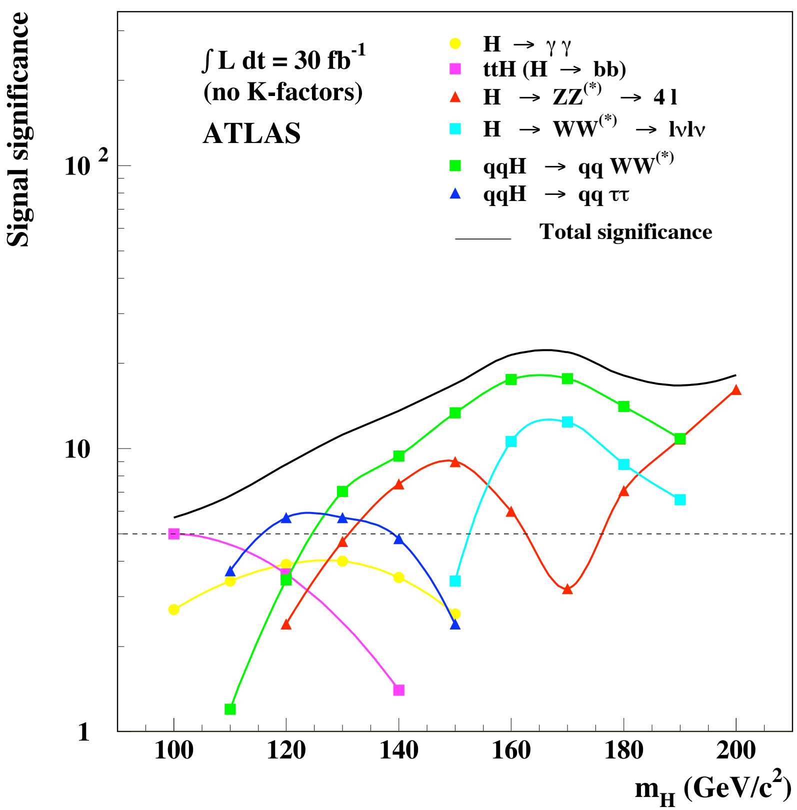
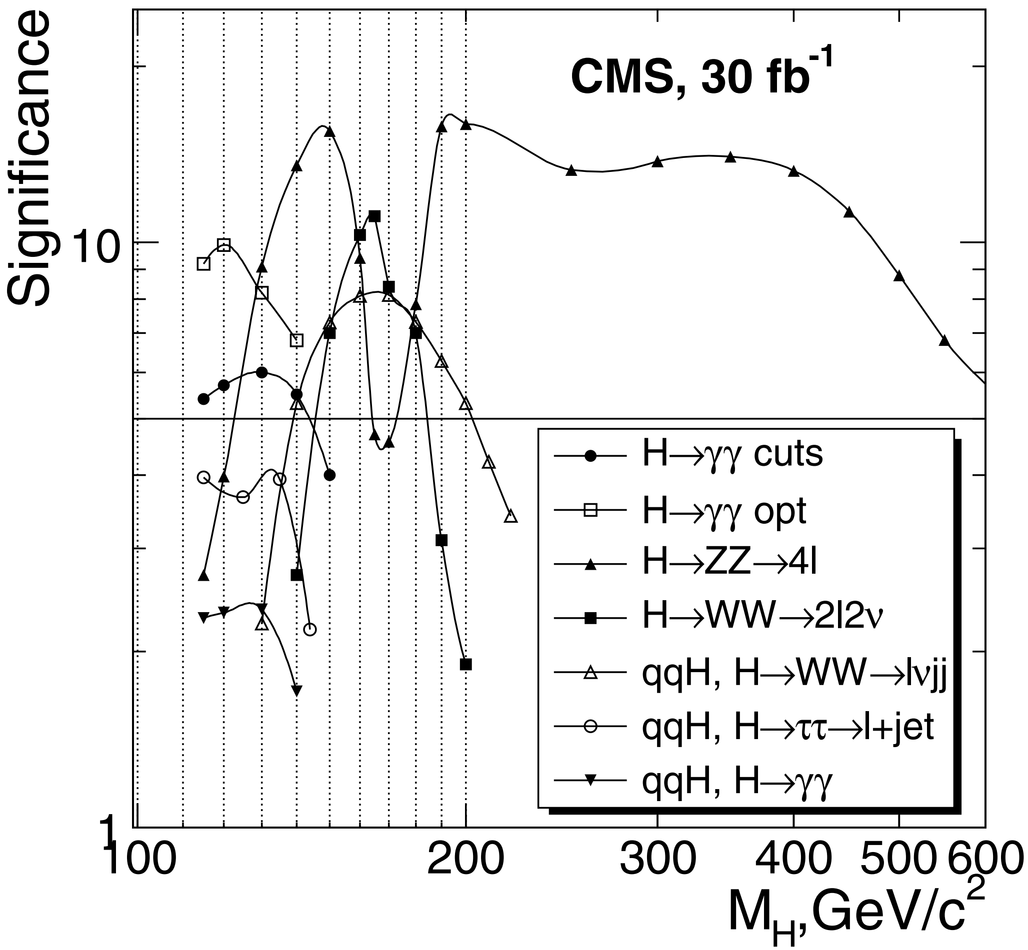
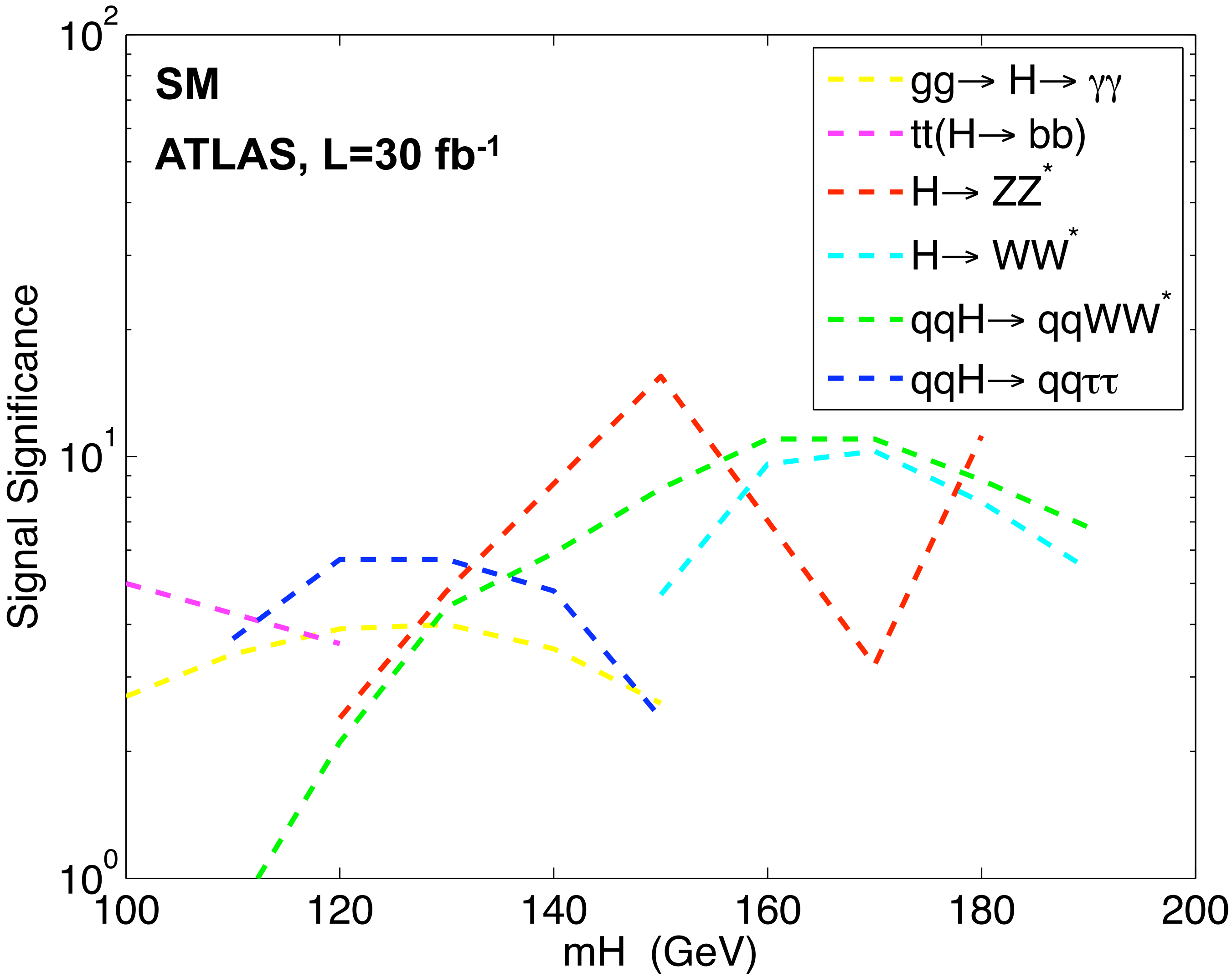
LHC Higgs Reach: SM

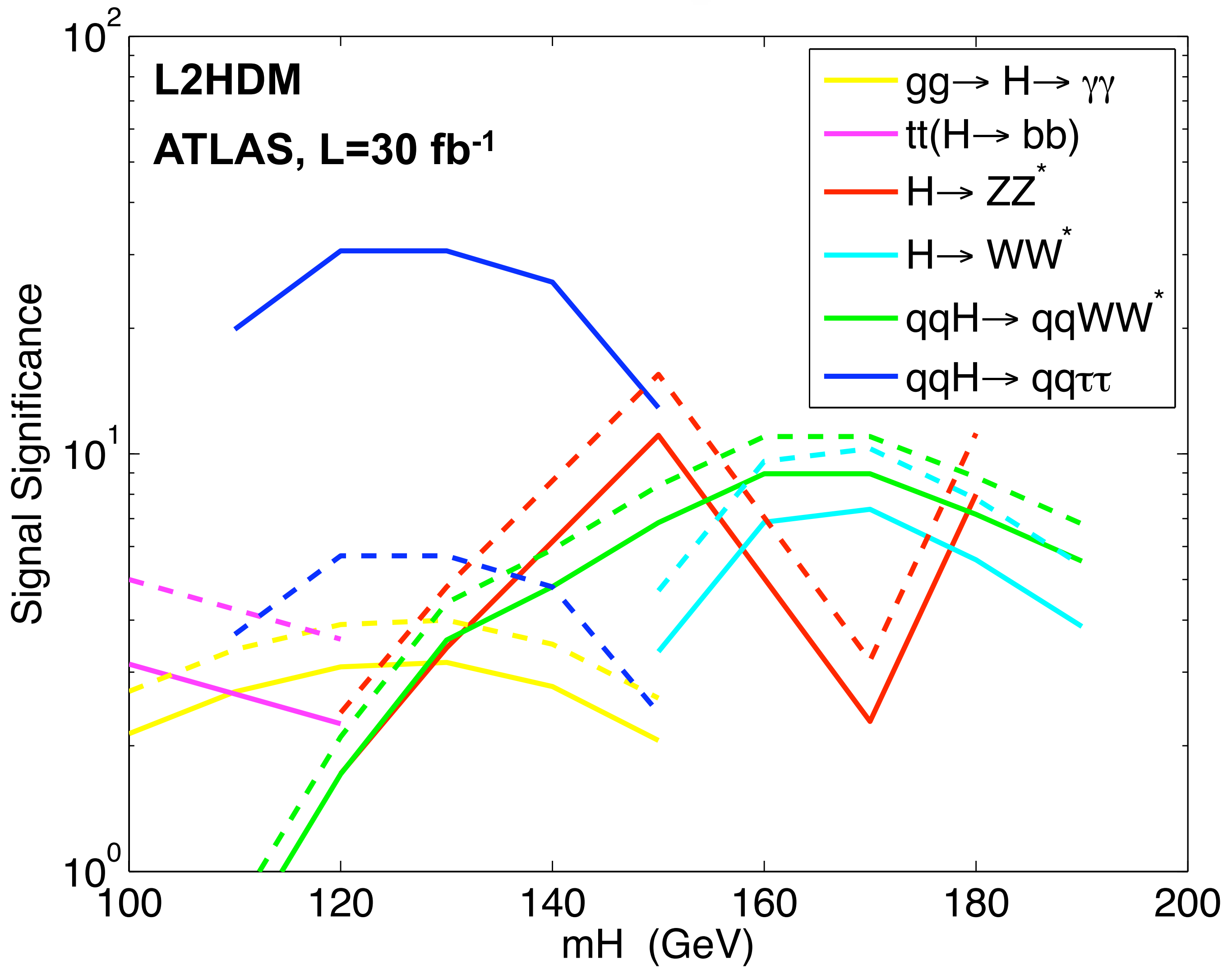




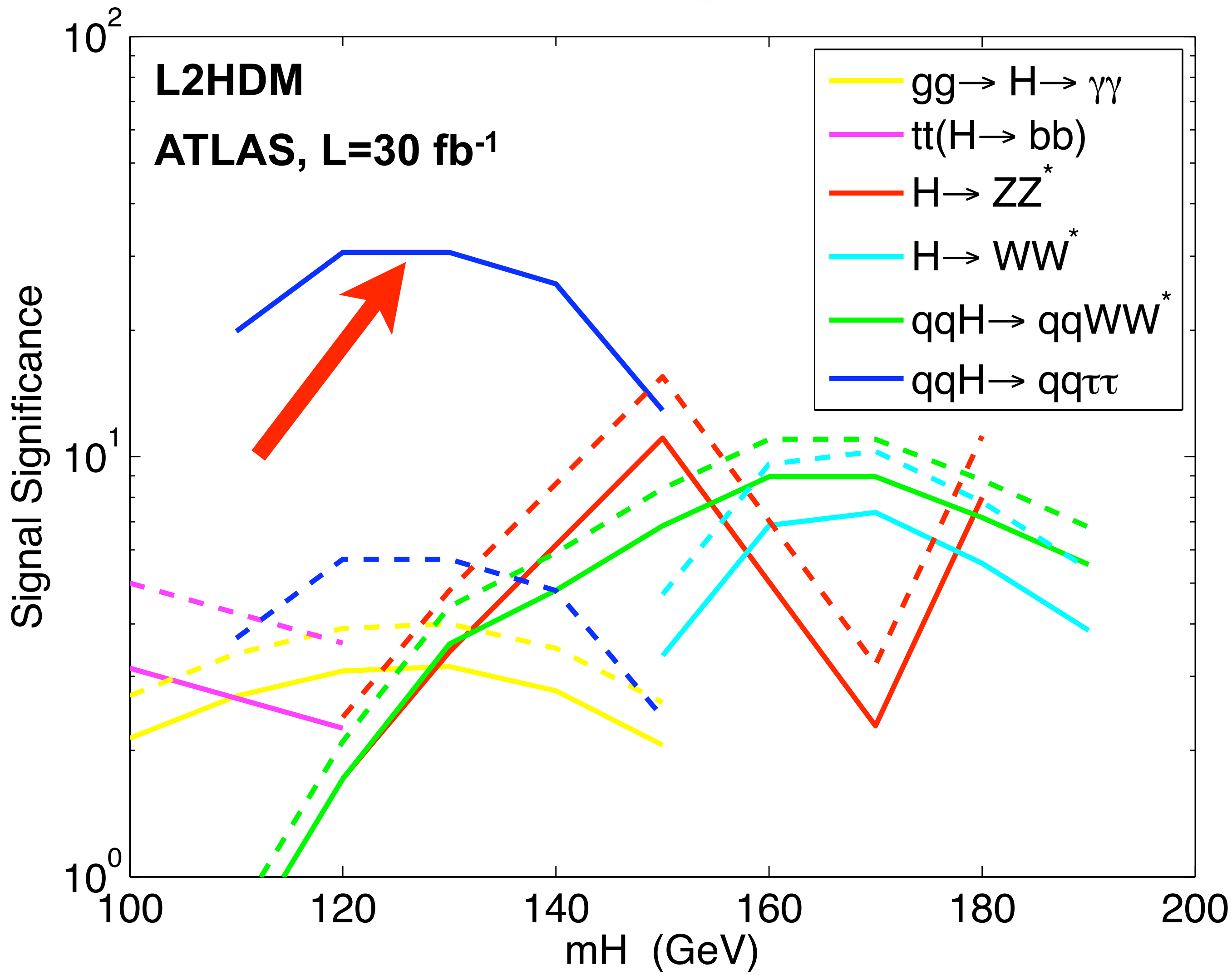
LHC Higgs Reach: L2HDM



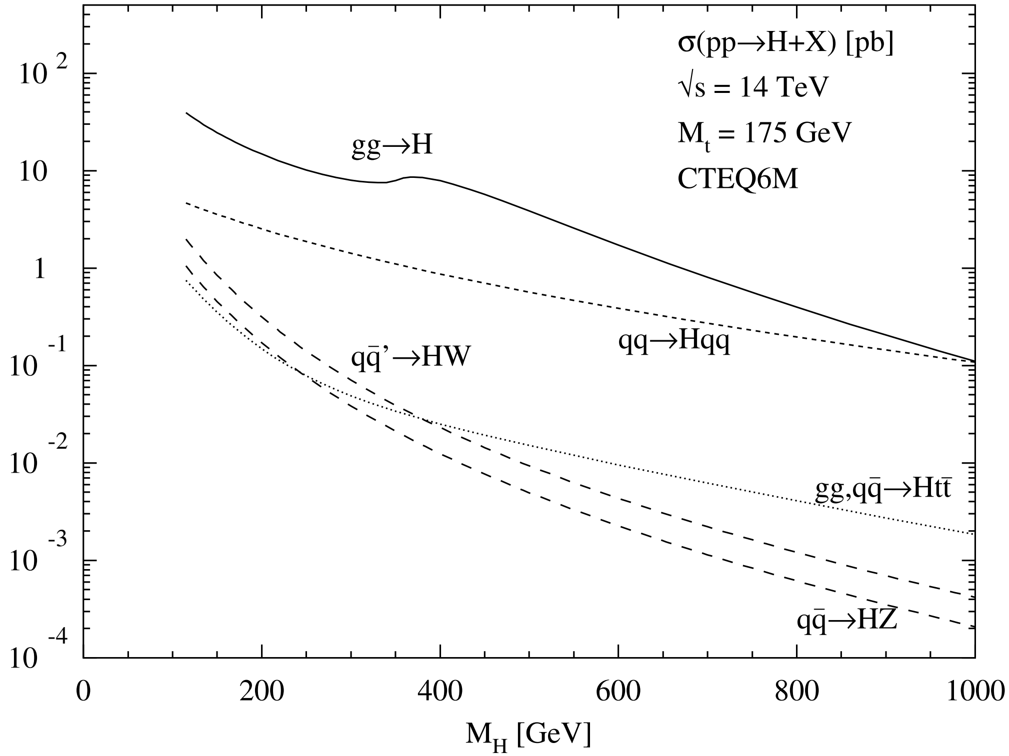
LHC Higgs Reach: L2HDM



LHC Higgs Reach: L2HDM



LHC Higgs Production

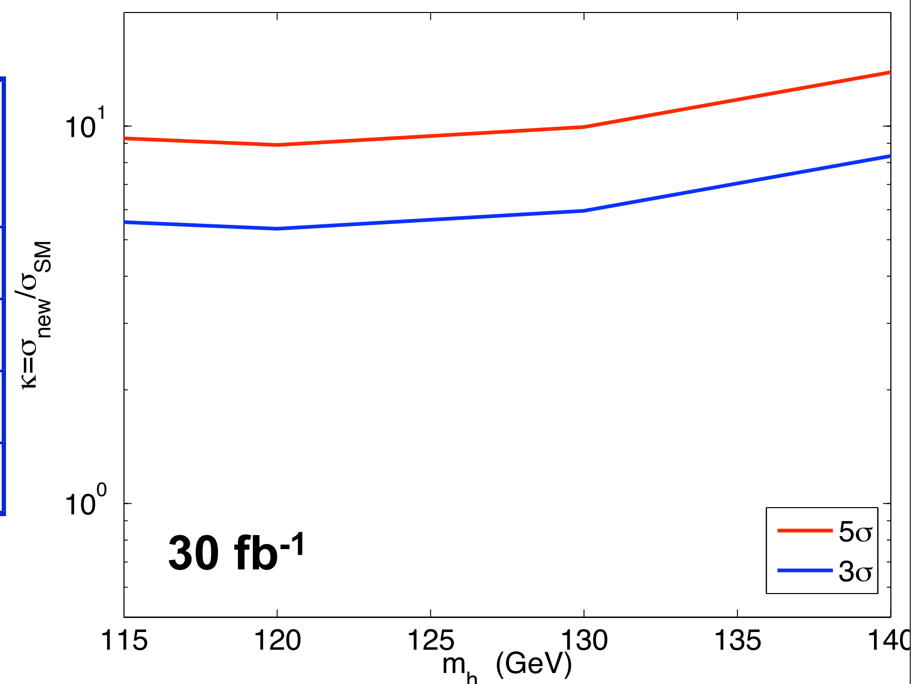


$gg \to h \to \mu\mu$

Han, McElrath, hep-ph/0201023

- irreducible SM background: $pp \to Z^*, \gamma^* \to \mu\mu$
- Cuts: two μ $p_T > 20$ GeV, $\eta < 2.5$; m_h-2.24 GeV< $m(\mu\mu) < m_h$ +2.24 GeV, ϵ_μ=0.90

m_h (GeV)	Signal (fb)	Bg (fb)	$S/\sqrt{B}\,\|_{SM}$ (600 fb^{-1})	$S/\sqrt{B}\,\|_{L2HDM}$ (30 fb^{-1})
115	4.50	2085	2.41	2.10
120	3.89	1441	2.51	2.22
130	2.63	821	2.25	2.10
140	1.51	526	1.61	1.62



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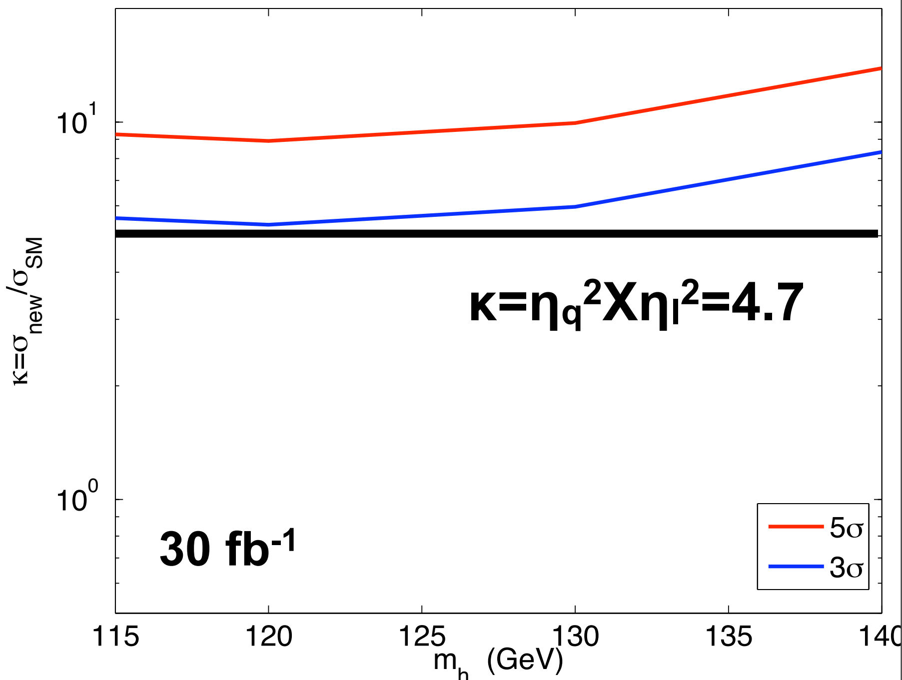


$gg \to h \to \tau\tau$

Tevatron: Belyaev, Han, Rosenfeld, hep-ph/0204210

- **signal: pp→hj→ττj tau pair not back-to-back in the transverse plane**

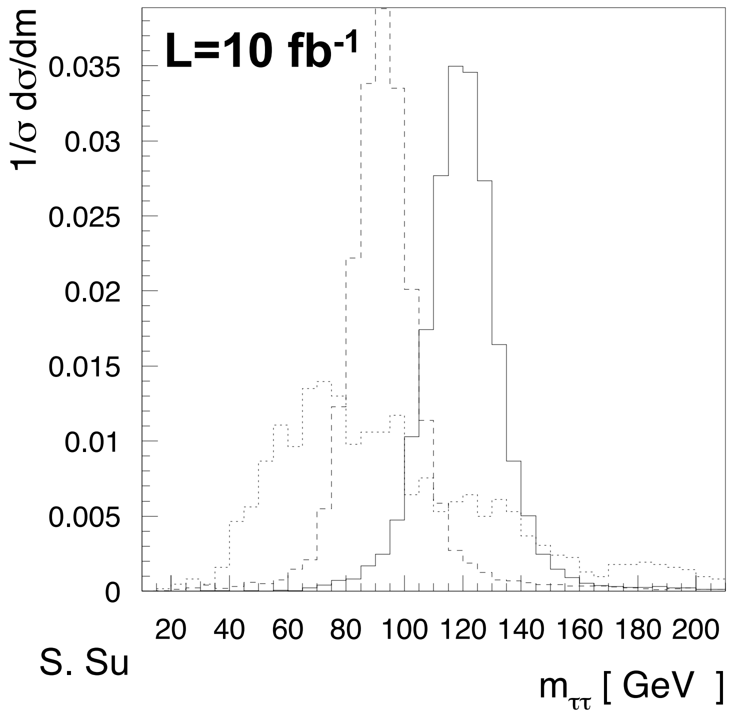
$$\sigma(p\bar{p} \to hj \to \tau^+\tau^- j) = 44,\ 28,\ 15 \text{ fb for } m_h = 120,\ 130,\ 140 \text{ GeV}$$

- **Bg: pp→Zj→ττj, pp→jjj**

$$\sigma(p\bar{p} \to Zj \to \tau^+\tau^- j) = 7 \times 10^4 \text{fb},$$
$$\sigma(p\bar{p} \to jjj) = 2.5 \times 10^8 \text{fb}.$$

$\varepsilon_{j\to\tau j}=0.005$

$\varepsilon_{j\to\tau l}=0.0001$



m_h	120 GeV			
channels	hj	Zj	jjj	S/B(%)
jj	32	713	559	2.5
$j\mu$	18	430	13	4.1
je	17	338	13	4.8
$\mu\mu$	1.4	18	0.26	7.7
ee	1.2	18	0.26	6.5
μe	2.5	40	0.26	6.2

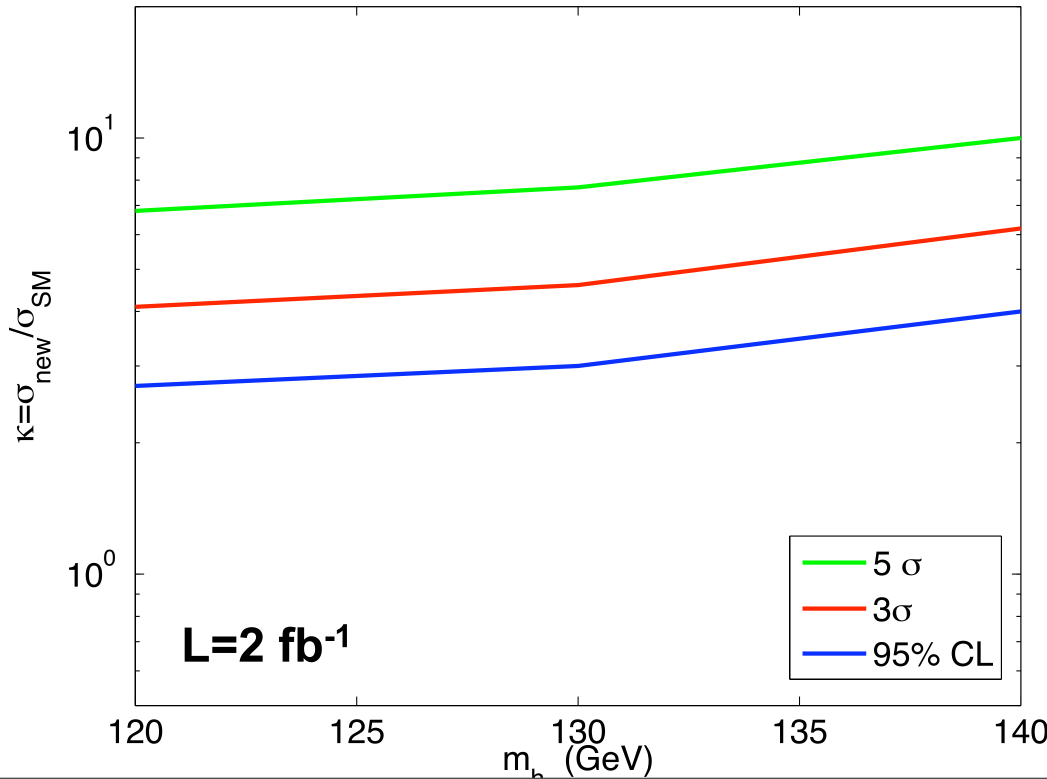
L=10 fb^{-1}

$gg \to h \to \tau\tau$ (Tevatron)

m_h	120 GeV	130 GeV	140 GeV
95% CL exclusion $L(\mathrm{fb}^{-1})$	14	18	32
3σ discovery $L(\mathrm{fb}^{-1})$	33	42	77
5σ discovery $L(\mathrm{fb}^{-1})$	93	120	210

95% CL $L(\mathrm{fb}^{-1})$	**0.89**	**1.03**	**1.59**
3σ $L(\mathrm{fb}^{-1})$	**2.10**	**2.41**	**3.82**
5σ $L(\mathrm{fb}^{-1})$	**5.94**	**6.88**	**10.42**

LHC study:
SS, B. Thomas, work in progress



S. Su

$gg \to h \to \tau\tau$ (Tevatron)

m_h	120 GeV	130 GeV	140 GeV
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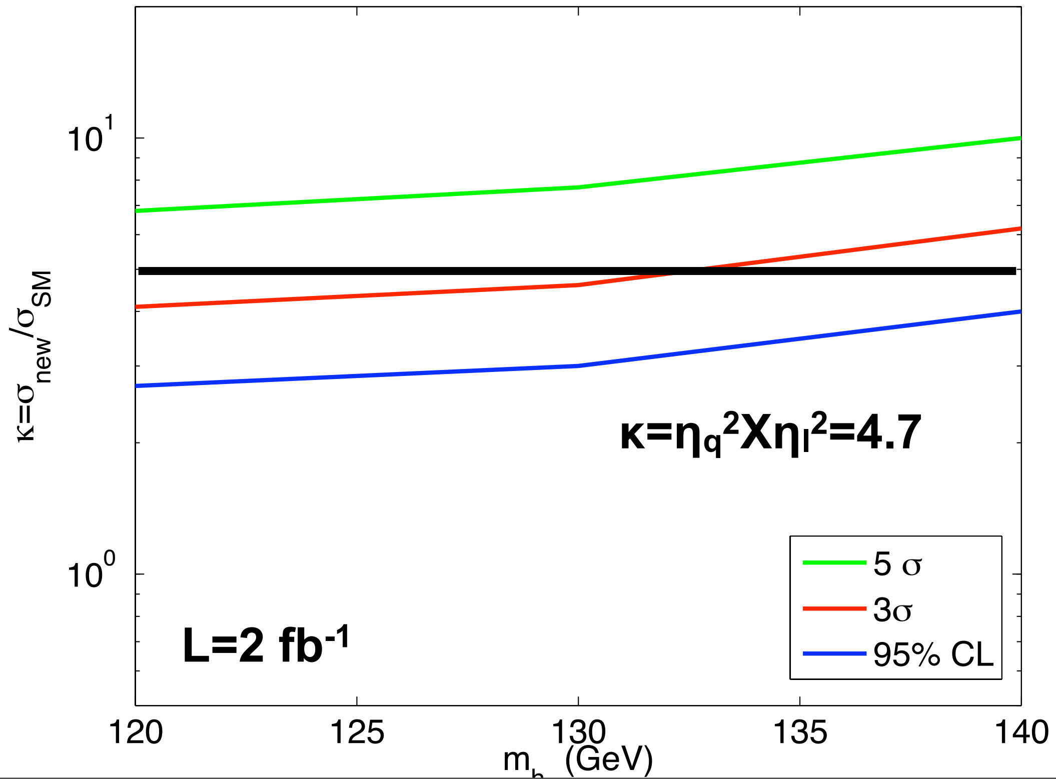


LHC study:
SS, B. Thomas, work in progress

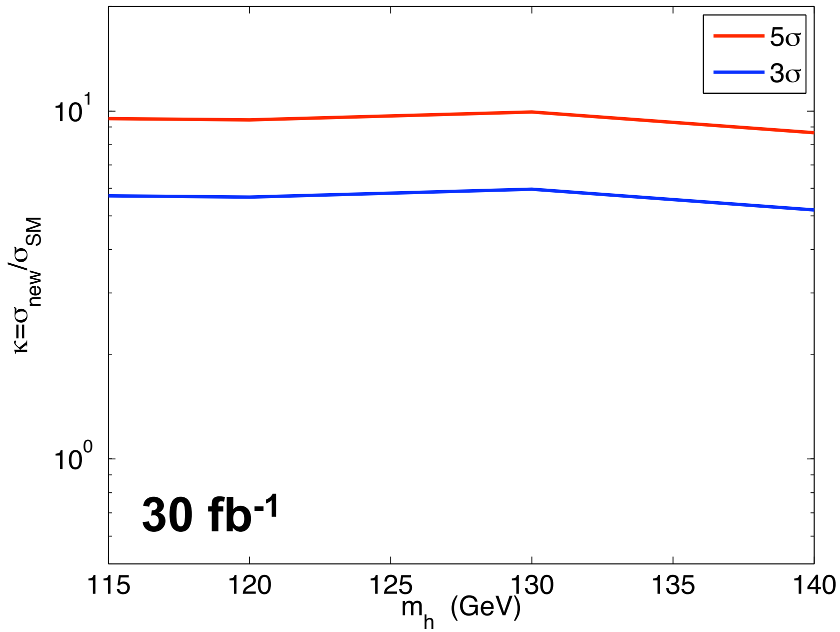
S. Su

WBF, $h \to \mu\mu$

Plehn and Rainwater, hep-ph/0107180

- irreducible SM background: QCD Zjj, EW Zjj, WWjj, tt+jets, bbjj
- cuts: forward tagging jets, m_{jj}>500 GeV, isolated energetic muons, m_H ± 1.6 GeV window, minijet veto

m_h (GeV)	Signal (fb)	Bg (fb)	$S/\sqrt{B}\,\|_{SM}$ (600 fb^{-1})	$S/\sqrt{B}\,\|_{L2HDM}$ (30 fb^{-1})
115	0.092	0.82	2.35	2.34
120	0.081	0.62	2.37	2.39
130	0.062	0.40	2.25	2.40
140	0.037	0.28	2.58	2.95



WBF, $h \to \mu\mu$

Plehn and Rainwater, hep-ph/0107180

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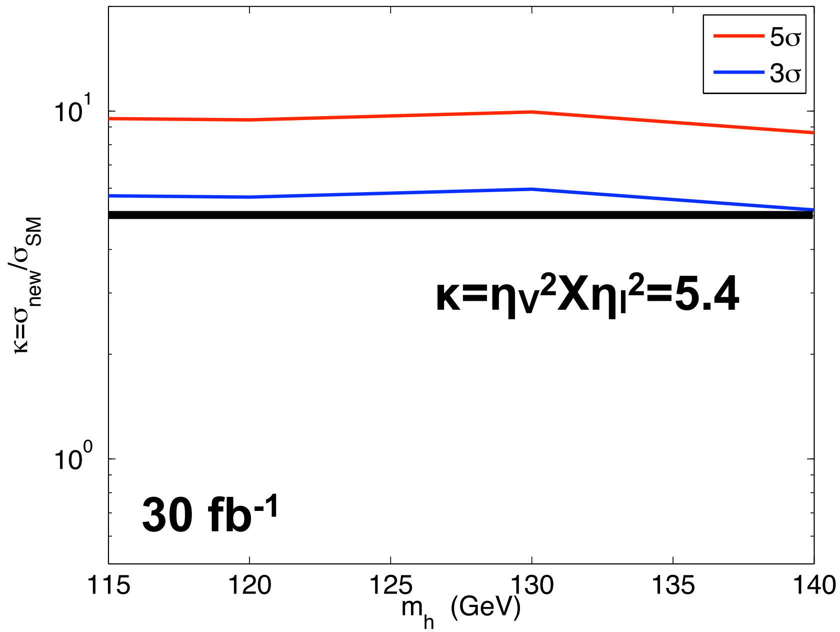


WBF, $h \to \tau_j \tau_l$

Rainwater, Zeppenfeld, Hagiwara, hep-ph/9808468

- **reducible SM background: QCD Zjj, EW Zjj, Wj+jj, bbjj**

	signal (fb)		background (fb)				
	VV	gg	$t\bar{t}$	$\gamma^*/Z + jets$ QCD	$\gamma^*/Z + jets$ EW	W+jet	Total
Lepton acceptance	13.7	50.3	$1.6 \cdot 10^4$	6925	22.0	$3.4 \cdot 10^4$	$5.7 \cdot 10^4$
+ Identified had. τ	6.18	22.7	4274.	1842	8.03	3200.	9462
+ Forward Tagging	1.97	0.18	29.7	23.6	1.72	30.0	85.0
+ Tau reconstruction	1.27	0.11	6.06	13.8	1.09	5.9	26.9
+ Transverse mass	1.02	0.07	1.74	11.9	0.92	0.63	15.2
+ P_T^{miss}	0.81	0.05	1.38	8.31	0.71	0.58	11.0
+ Jet mass	0.71	0.03	1.01	6.63	0.69	0.37	8.70
+ Jet veto	0.63	0.02	0.14	4.24	0.66	0.21	5.25
+ Mass window	0.52	0.01	0.01	0.19	0.06	<0.01	0.27

ATLAS study: S. Asai et. al, hep-ph/0402254

WBF, $h \to \tau_l \tau_l \to e\mu p\!\!\!/_T$

Plehn, Rainwater, Zeppenfeld, hep-ph/9911385

- **irreducible SM background: QCD Zjj, EW Zjj, tt+jets, bbjj, QCD WWjj, EW WWjj**

	signal (fb)		background (fb)					
	VV	gg	$t\bar{t}+jets$	$WW+jets$		$\gamma^*/Z+jets$		Total
				EW	QCD	EW	QCD	
Lepton acceptance	5.55		2014.	18.2	669.8	11.6	2150.	4864.
+ Forward Tagging	1.31		42.0	9.50	0.38	2.20	27.5	81.6
+ P_T^{miss}	0.85		29.2	7.38	0.21	1.21	12.4	50.4
+ Jet mass	0.76		20.9	7.36	0.11	1.17	9.38	38.9
+ Jet veto	0.55		2.70	5.74	0.05	1.11	4.56	14.2
+ Angular cuts	0.40		0.74	1.20	0.04	0.57	3.39	5.94
+ Tau reconstruction	0.37		0.12	0.28	0.001	0.49	2.84	3.73
+ Mass window	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \to \tau\tau \to e\mu$	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \to \tau\tau \to ee$	0.13	0.01	0.01	0.01	0.0	0.02	0.07	0.11
$H \to \tau\tau \to \mu\mu$	0.14	0.01	0.01	0.01	0.0	0.02	0.07	0.11

ATLAS study: S. Asai et. al, hep-ph/0402254

WBF, $h \to \tau\tau$

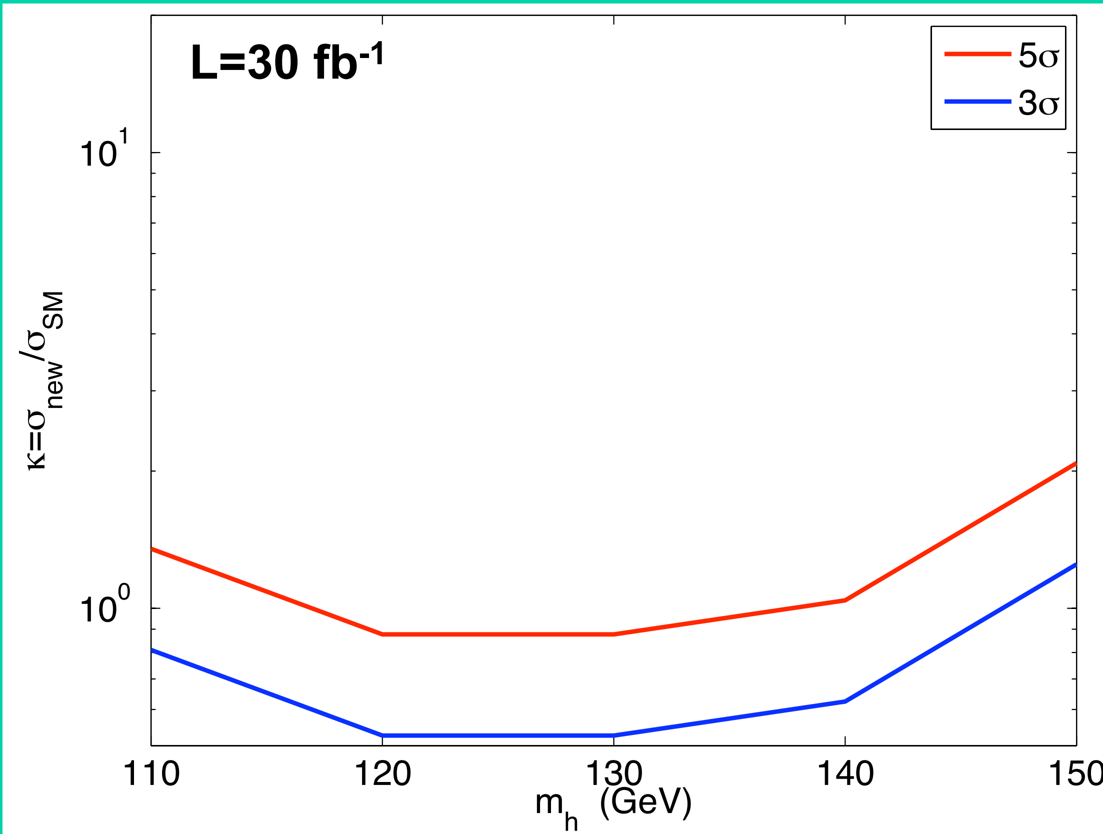
ATLAS study: S. Asai et. al, hep-ph/0402254 **L=30 fb^{-1}**

m_H (GeV)	110	120	130	140	150
$H \to \tau\tau \to e\mu P_T^{miss}$					
Signal	9.7	8.4	6.3	3.8	1.8
Background	17.3	7.1	4.1	3.0	2.6
Stat. significance	1.9	2.5	2.3	1.7	0.7
$H \to \tau\tau \to ee/\mu\mu P_T^{miss}$					
Signal	9.7	8.3	6.3	3.8	1.8
Background	16.2	6.6	4.5	3.5	2.6
Stat. significance	1.9	2.6	2.3	1.5	0.7
$H \to \tau\tau \to \ell\ had\ P_T^{miss}$					
Signal	16.8	15.6	11.8	8.9	3.8
Background	31.9	7.7	3.6	2.5	2.5
Stat. significance	2.4	4.2	4.4	3.9	1.7
combined					
Stat. significance	3.7	5.7	5.7	4.8	2.4
L2HDM	**16.2**	**25.7**	**27.1**	**24.6**	**13.2**

WBF, $h \to \tau\tau$

ATLAS study: S. Asai et. al, hep-ph/0402254 **L=30 fb^{-1}**

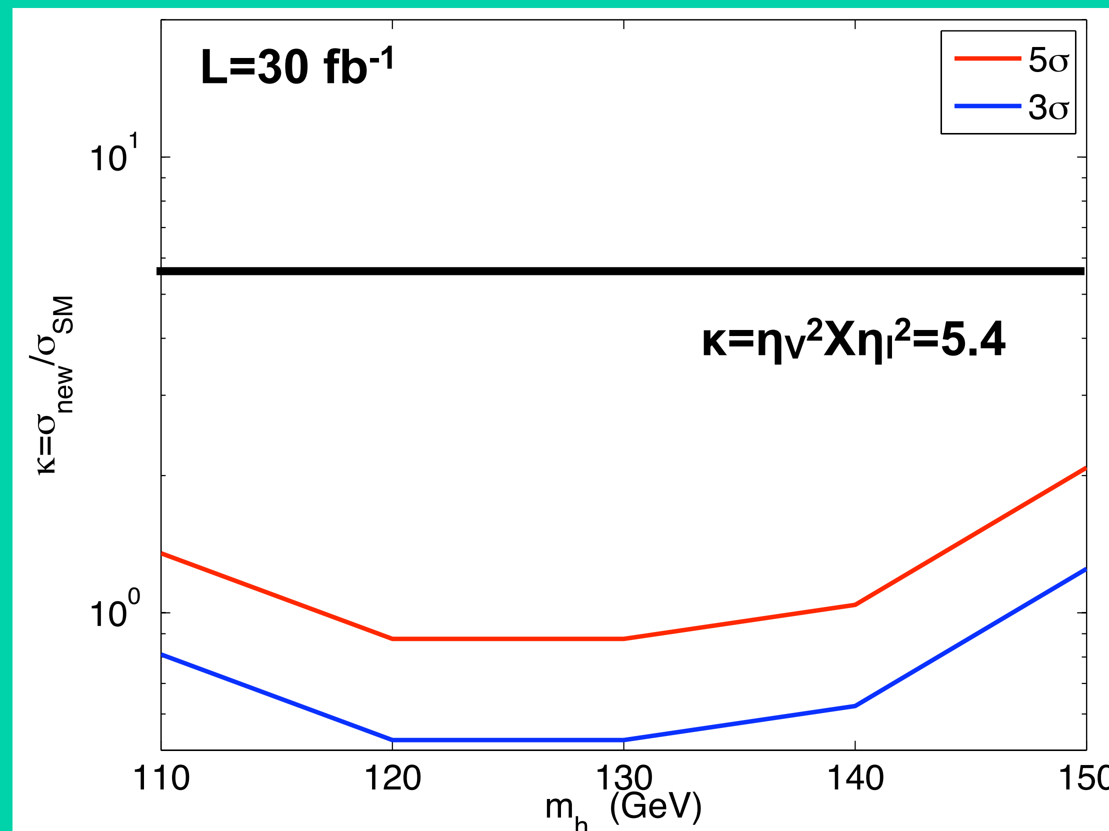
m_H (GeV)	110	120	130	140	150
$H \to \tau\tau \to e\mu P_T^{miss}$					
Signal	9.7				
Background	17.3				
Stat. significance	1.9				
$H \to \tau\tau \to ee/\mu\mu P_T^{miss}$					
Signal	9.7				
Background	16.2				
Stat. significance	1.9				
$H \to \tau\tau \to \ell\ had\ P_T^{miss}$					
Signal	16.8				
Background	31.9				
Stat. significance	2.4				
combined					
Stat. significance	3.7				
L2HDM	**16.2**	**25.7**	**27.1**	**24.6**	**13.2**



WBF, h→ττ

ATLAS study: S. Asai et. al, hep-ph/0402254 **L=30 fb^{-1}**

m_H (GeV)	110	120	130	140	150
$H \to \tau\tau \to e\mu P_T^{miss}$					
Signal	9.7				
Background	17.3				
Stat. significance	1.9				
$H \to \tau\tau \to ee/\mu\mu P_T^{miss}$					
Signal	9.7				
Background	16.2				
Stat. significance	1.9				
$H \to \tau\tau \to \ell\ had\ P_T^{miss}$					
Signal	16.8				
Background	31.9				
Stat. significance	2.4				
combined Stat. significance	3.7				
L2HDM	**16.2**	**25.7**	**27.1**	**24.6**	**13.2**

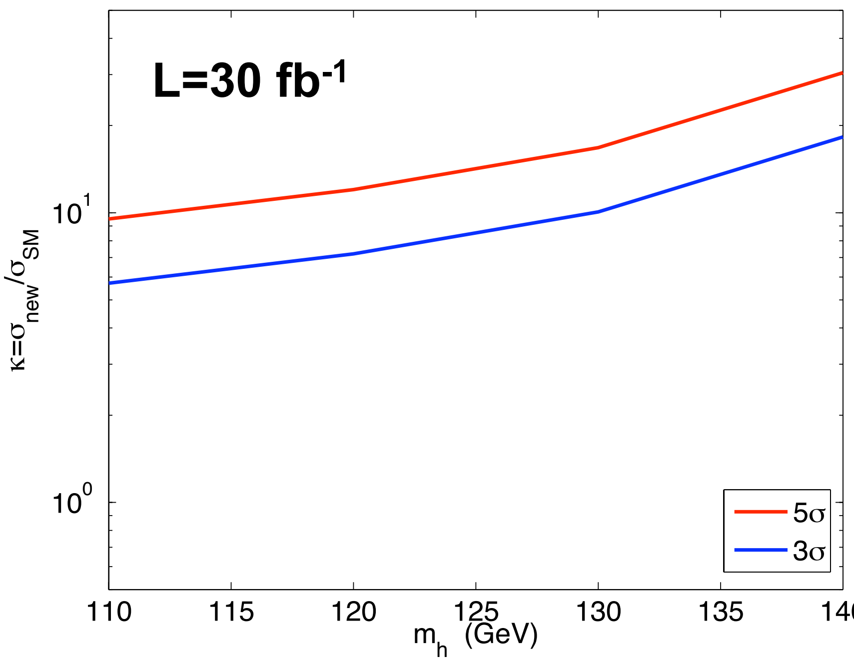


$t\bar{t}h$, $h \to \mu\mu$

SS, B. Thomas, prelimenary

- Signal: $t \to bqq$, $\bar{t} \to \bar{b}qq$, $h \to \mu\mu$; $b\bar{b}qqqq\mu\mu$
- background: $t\bar{t}Z/\gamma^*$
- cuts: 2b, 4 jets, 2μ, top reconstruction, $m_H \pm 2.5$ GeV window

m_h (GeV)	Signal (fb)	Bg (fb)	$S/\sqrt{B}\,\|_{SM}$ (600 fb^{-1})	$S/\sqrt{B}\,\|_{L2HDM}$ (30 fb^{-1})
110	0.02	0.045	2.35	2.02
120	0.015	0.037	1.86	1.65
130	0.009	0.027	1.33	1.24
140	0.005	0.026	0.73	0.74



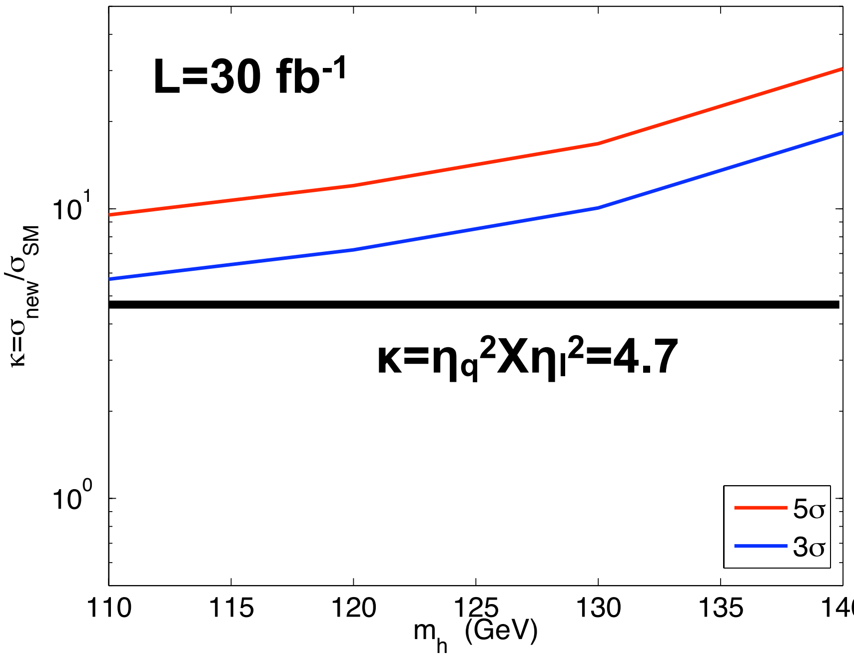
reach comparable to gluon fusion and WBF channel

tth, $h \to \mu\mu$

SS, B. Thomas, prelimenary

- Signal: $t \to bqq$, $t \to bqq$, $h \to \mu\mu$; $bbqqqq\mu\mu$
- background: ttZ/γ^*
- cuts: 2b, 4 jets, 2μ, top reconstruction, $m_H \pm 2.5$ GeV window

m_h (GeV)	Signal (fb)	Bg (fb)	$S/\sqrt{B}\,\|_{SM}$ (600 fb^{-1})	$S/\sqrt{B}\,\|_{L2HDM}$ (30 fb^{-1})
110	0.02	0.045	2.35	2.02
120	0.015	0.037	1.86	1.65
130	0.009	0.027	1.33	1.24
140	0.005	0.026	0.73	0.74



reach comparable to gluon fusion and WBF channel

$t\bar{t}h$, $h \to \tau\tau$

Belyaev, Reina, hep-ph/0205270

- **Signal: $t \to bl\nu$, $t \to bqq$, $2\tau_j$; $bbl\nu qq\tau_j\tau_j$**
- **background: ttZ/γ^***
- **cuts: 2jets, 2b, one e/μ, 2 hadronic τ, top reconstruction**

	Background: $pp \to t\bar{t}\tau^+\tau^-$	Signal: $pp \to t\bar{t}H$, $H \to \tau^+\tau^-$			
		110 GeV	120 GeV	130 GeV	140 GeV
Eff. of CUTS I+II+III (%)	0.42	0.50	0.52	0.55	0.58
Number of events/100 fb^{-1}	12	34	25	16	8.8
$S/\sqrt{S+B}$		5.0	4.1	3.0	1.9
S/B		2.8	2.1	1.3	0.7
$\delta\sigma/\sigma$		0.20	0.24	0.33	0.52
L2HDM (L=30 fb^{-1})		**10.5**	**8.89**	**6.86**	**4.67**

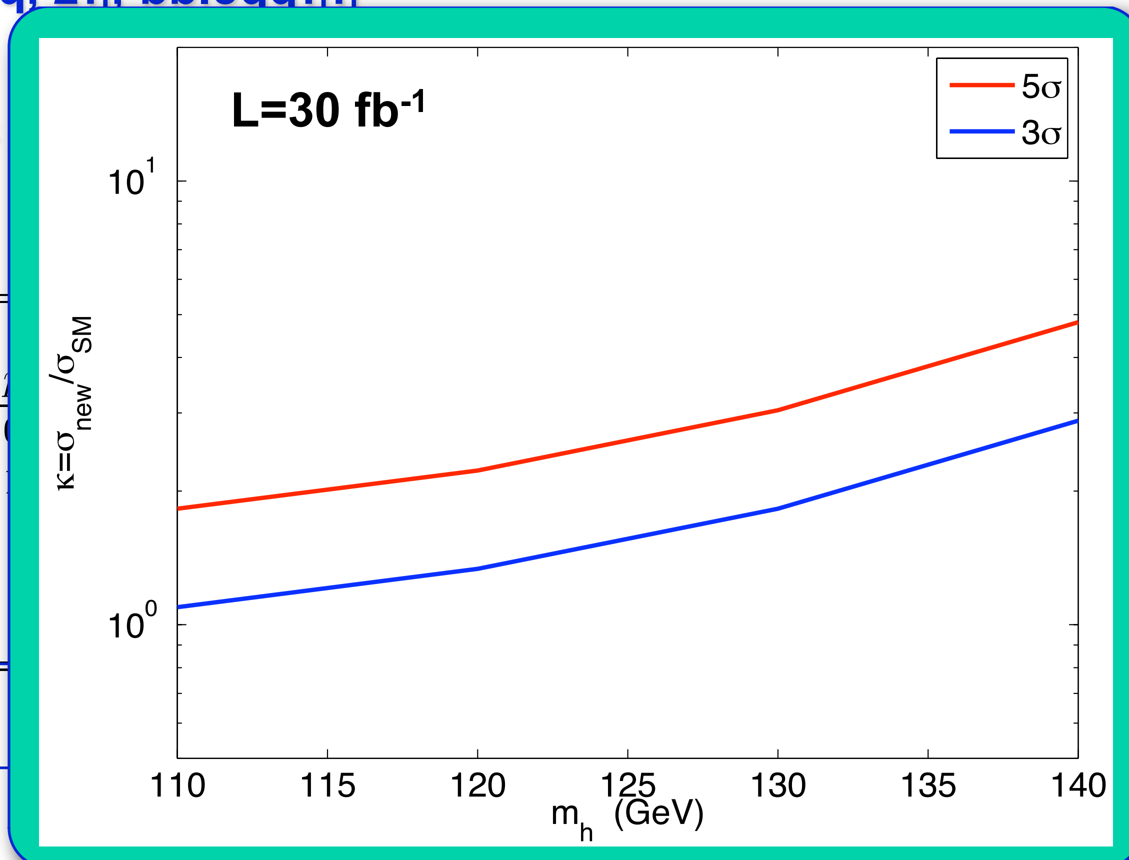
tth, $h \to \tau\tau$

Belyaev, Reina, hep-ph/0205270

- **Signal: $t \to bl\nu$, $t \to bqq$, $2\tau_j$; $bbl\nu qq\tau_j\tau_j$**
- **background: ttZ/γ^***
- **cuts: 2jets, 2b, one**

Eff. of CUTS I+II+III (%)
Number of events/100 fb^{-1}
$S/\sqrt{S+B}$
S/B
$\delta\sigma/\sigma$

L2HDM (L=30 fb^{-1})



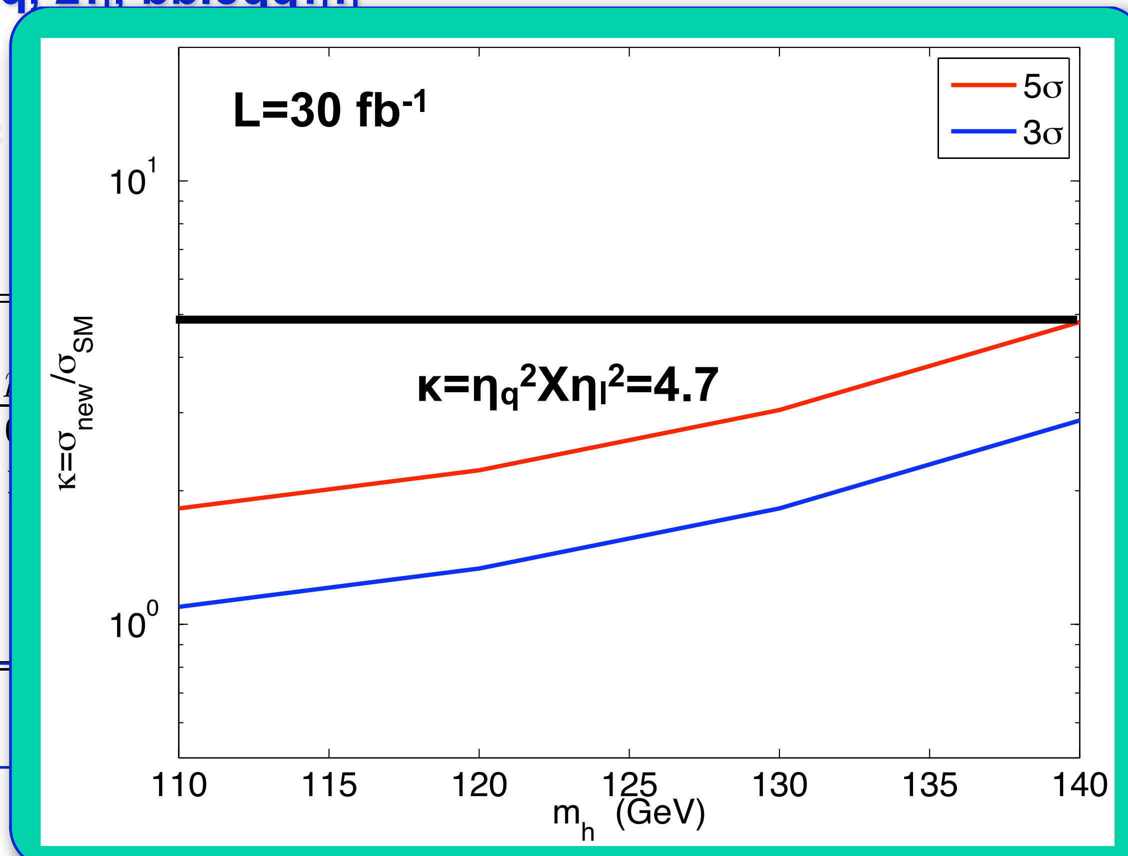
tth, h→ττ

Belyaev, Reina, hep-ph/0205270

- **Signal: t→blν, t→bqq, $2\tau_j$; $bbluqq\tau_j\tau_j$**
- **background: ttZ/γ***
- **cuts: 2jets, 2b, one**

Eff. of CUTS I+II+III (%)	
Number of events/100 fb^{-1}	
$S/\sqrt{S+B}$	
S/B	
$\delta\sigma/\sigma$	

L2HDM (L=30 fb^{-1})



Wh, Zh, $h \to \mu\mu$, $\tau\tau$

SS, B. Thomas, preliminary

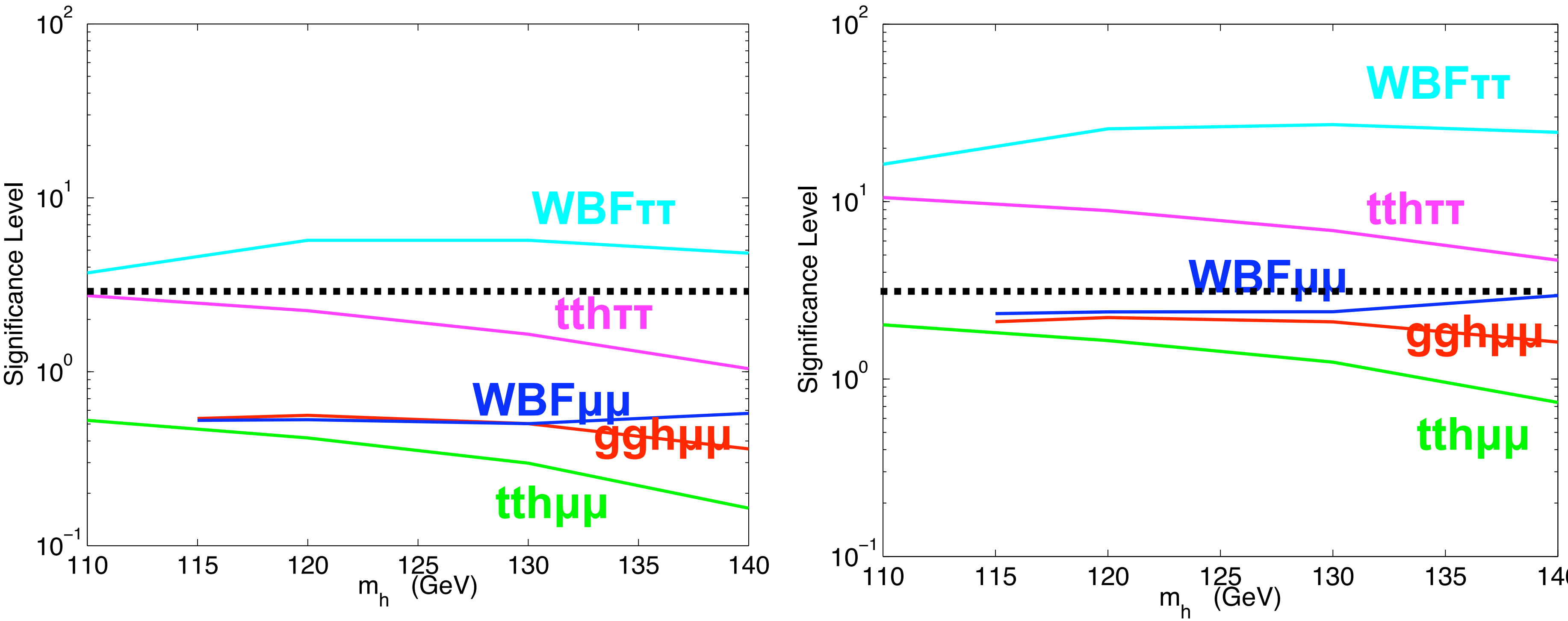
- Signal: leptonic decay of W and Z
- background: WZ and ZZ

SM	m_h (GeV)	Signal (fb)	Bg (fb)	before cuts
$h \to \mu\mu$	ZH	0.011	39.18	signal too small
	WH	0.015	102	
$h \to \tau\tau$	ZH	3.195	26.12	possible
	WH	12.26	102	

LHC reach of L2HDM

prelimenary

SM **30 fb^{-1}** **L2HDM**



Conclusions

- Higgs decay to muon or tau pair: clean channel
- L2HDM: enhanced leptonic Higgs decay branching ratio
- $h \to \tau\tau$
  * WBF: SM Higgs discovery channel
  * tth: 3 σ possible @ 100 fb^{-1}
  * $gg \to h$ and WH/ZH: study in progress ...
- $h \to \mu\mu$
  * SM $gg \to h$, WBF, tth: need high luminosity
  * discovery possible at low L with enhanced Higgs coupling