$pp(gg+gq) \to h + jet \to \tau^+\tau^- + jet$ at the LHC

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arXiv: 0912.2620 and 0912.4150

Outline

- Why

$$pp(gg+gq) \to h + jet \to \tau^+\tau^- + jet \ ?$$

- The signal
- The background
- A very light Higgs
- Conclusions and outlook

Why Higgs production via gluon fusion with $H \rightarrow \tau^+\tau^-$?

- Very light Higgs is not ruled out (reduced coupling to gauge bosons)
- BSM may enhance both production and decay
- Test Yukawa couplings

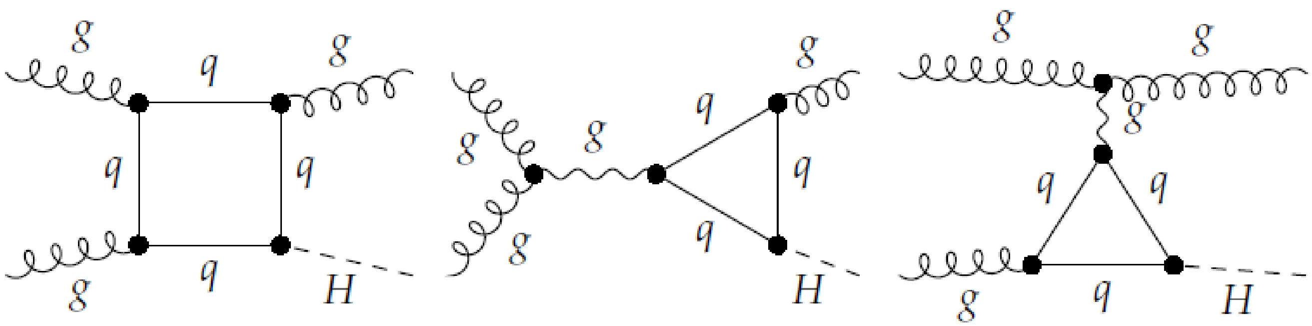
Why Higgs + jet with $H \rightarrow \tau^+\tau^-$?

- When the transverse momentum of the Higgs is small the two taus are moving back to back.
- The resolution in the tau pair invariant mass will be poor and the signal difficult to extract.
- A high p_T jet allows the reconstruction of the transverse momentum of the taus.

R. K. Ellis *et al*, NPB297 (1988).

Signal

- Generic diagrams for $gg \to hg$



- $gq \to hq$ also included (approx 20% of total cross section)
- $qq \to hg$ negligible

Analysis done with CalcHep (and MadGraph)

$$L_{eff} = \frac{\alpha_s}{24\pi} \frac{g_W}{M_W} G^A_{\alpha\beta} G^{\alpha\beta}_A H$$ effective local interaction

All other calculations of total cross sections for BSM models done with FeynArts/FormCalc/LoopTools.

Signal and Background

Two scenarios

$$\frac{\Delta E}{E} = \frac{0.5(0.15)}{\sqrt{E}} GeV$$

- both taus decay leptonically (ll)
- one tau decays leptonically and the other hadronically (lj)

Backgrounds calculated with CalcHep (MadGraph)

- $pp \to Z/\gamma^* j$
- $pp \to W^+W^- j$
- $pp \to Wjj$
- $pp \to t\bar{t}$
- $pp \to jjj$

CMS Coll., JPG34 (2007).

ATLAS Coll., arXiv: 0901.0512.

- probability of a jet faking a lepton 10^{-3}
- tau reconstruction efficiency 0.3 $\Longrightarrow$ tau rejection factor against jets based on ATLAS study as a function of p_T (from 10^{-2} to 10^{-3})

The analysis highlights

- We require one electron with $p_T^e > 22\,GeV$ or one muon with $p_T^\mu > 20\,GeV$ for triggering purposes. The additional lepton in the event has $p_T^e > 15\,GeV$ and $p_T^\mu > 10\,GeV$. A 90 % efficiency is assumed for the reconstruction of the electron and muon and the separation between leptons and/or jets was chosen as $\Delta R_{j(l)j(l)} > 0.4$ and $|\eta_l| < 3.5$ for all leptons.

- We require that at least one jet has $p_T^j > 40GeV$ and $|\eta_j| < 4$.

- We veto the event if there is an additional jet with $p_T^j > 20GeV$ and $|\eta_j| < 5$.

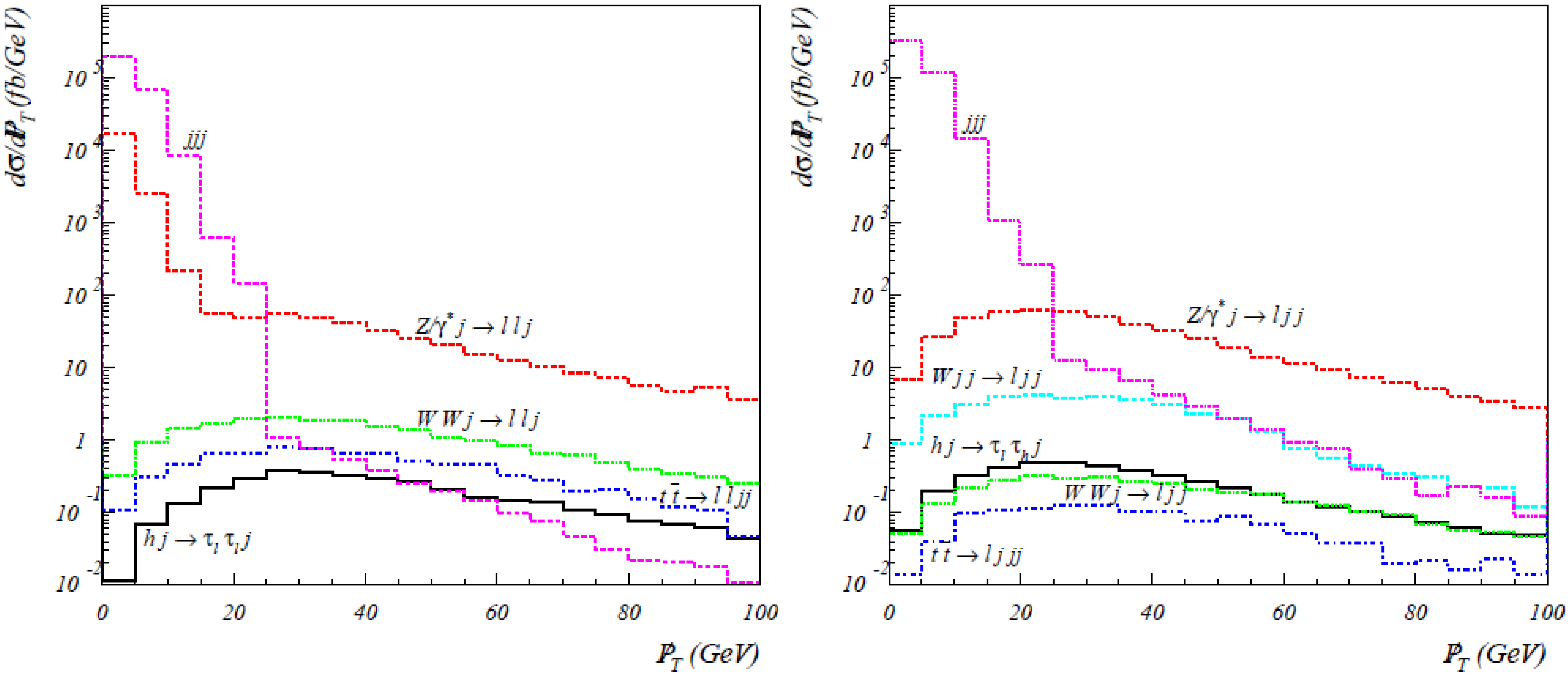
- We apply a mass window $m_h - 15\,GeV < m_{\tau\tau} < m_h + 15\,GeV$.

- Events are vetoed if the tagging jet consistent with a b-jet hypothesis is found with $|\eta| < 2.5$ (we assume a b-jet tagging efficiency of 60 %).

- Finally we require the transverse missing energy to be $\not{E}_T > 30\,GeV$.

Process (fb)	hj	$(Z/\gamma^* \to ll)j$	WWj	Wjj	$t\bar{t}$	jjj
Minimal Cuts	1.2×10^3	2.1×10^6	8.7×10^4	1.7×10^7	8.3×10^5	2.9×10^{10}
Final (ll)	13.8	93.8	13.0	~ 0	4.7	2.9
Final (lj)	14.1	83.9	2.3	56.8	0.7	31.1

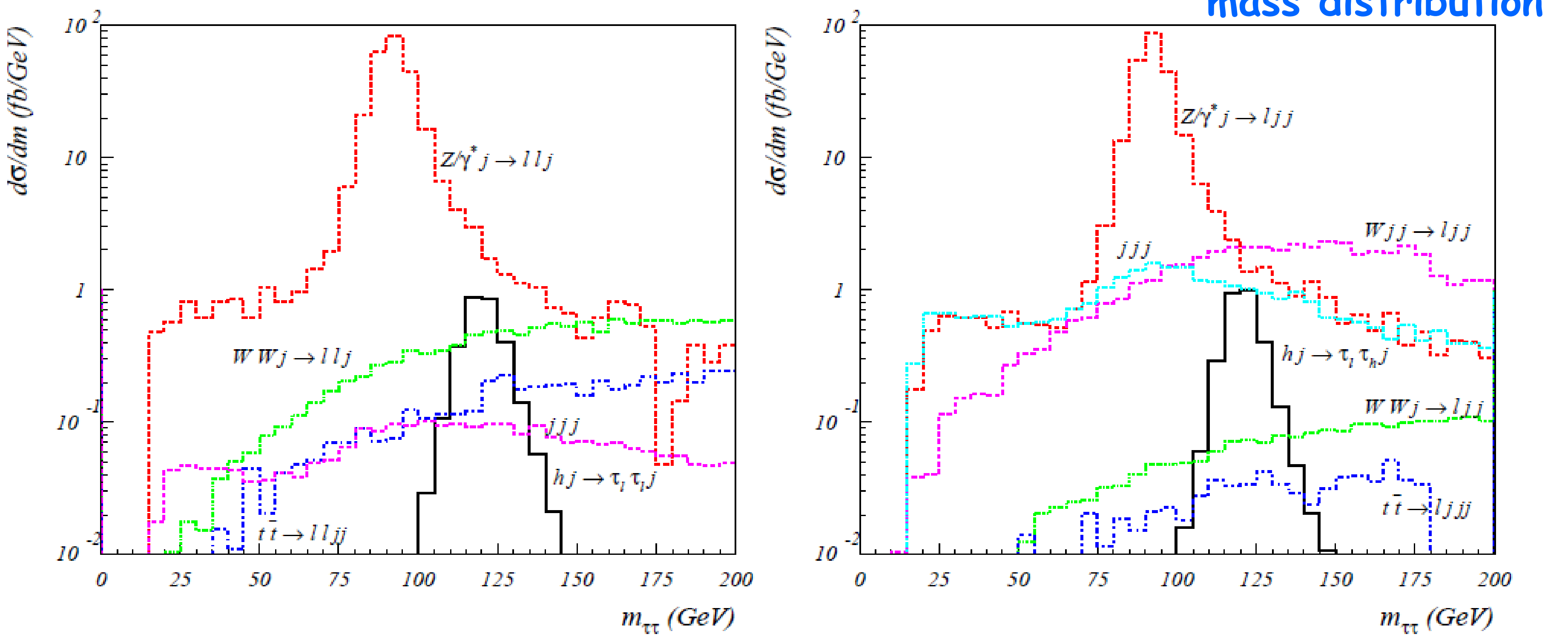
The QCD background



It is the missing energy cut of 30 GeV that eliminates most of the QCD background. Still, especially for lj, the final result depends on the fake rates chosen.

Results for a 120 GeV SM Higgs boson

Reconstructed invariant mass distribution



m_h (GeV)	$\sigma_{S_{(ll)}}$ (fb)	$\sigma_{B_{(ll)}}$ (fb)	$\sigma_{S_{(lj)}}$ (fb)	$\sigma_{B_{(lj)}}$ (fb)	σ_S/σ_B (%)
120	13.8	109.3	14.1	174.7	15.0

m_h (GeV)	95 % CL exclusion $L(fb^{-1})$	3σ discovery $L(fb^{-1})$	5σ discovery $L(fb^{-1})$
120	1.4	3.1	8.7

Looks promising – study beyond parton level is needed!

A very light Higgs

Results for a very light Higgs with SM couplings

Mass (GeV)	$\sigma_{S_{(ll)}}$ (fb)	$\sum \sigma_{B_{(ll)}}$(fb)	$\sigma_{S_{(lj)}}$ (fb)	$\sum \sigma_{B_{(lj)}}$ (fb)	σ_S/σ_B (%)
20	11.6	14.1	5.4	28.8	84.1
30	11.8	23.0	9.9	35.4	58.4
40	11.5	27.1	10.6	41.2	49.7
50	11.3	30.4	10.9	47.9	43.4
60	11.9	41.2	11.3	63.3	34.0
70	13.0	169.5	12.0	149.0	11.2
80	13.8	890.0	12.9	856.2	2.2
90	14.4	1178.3	14.1	1145.6	1.7
100	14.9	1124.7	15.5	1142.6	1.9

Mass (GeV)	95 % CL exclusion L (fb^{-1})	3σ discovery L (fb^{-1})	5σ discovery L (fb^{-1})
20	0.38	0.86	2.38
30	0.45	1.02	2.84
40	0.53	1.18	3.28
50	0.60	1.35	3.76
60	0.73	1.64	4.56
70	2.02	4.56	12.7
80	9.76	22.0	61.0
90	11.4	25.7	71.3
100	9.87	22.2	62.0

Where does a very light Higgs comes from?

- Make Higgs-gauge bosons coupling small (LEP bound)

S. Schael *et al*, EPJC47 (2006).

$$\begin{cases} \sigma(e^+e^- \to H_1 Z)\,\mathrm{BR}(H_1 \to b\bar{b}) \\ \sigma(e^+e^- \to H_1 Z)\,\mathrm{BR}(H_1 \to \tau^+\tau^-) \\ \sigma(e^+e^- \to H_1 H_2) \end{cases}$$

- Lightest Higgs coupling to Z small
- Other Higgs out of reach

- Extend the scalar sector – but make sure Yukawa couplings are not too small either – add a singlet

$$g_{VVh} \to f_\chi\, g_{VVh} \quad \Longrightarrow \quad g_{ffh} \to f_\chi\, g_{ffh}$$

Other processes would have to be used to look for such a light Higgs

Where does a very light Higgs comes from?

- **Extend the scalar sector – now add a doublet**

$$
\boxed{\begin{aligned}
V(\Phi_1,\Phi_2) &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
&+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}]
\end{aligned}}
$$

$$M_h,\ M_H,\ M_A,\ M_{H^\pm},\ \tan\beta,\ \alpha,\ M^2$$

$$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

	I	II	III	IV
up	Φ_2	Φ_2	Φ_2	Φ_2
down	Φ_2	Φ_1	Φ_1	Φ_2
lepton	Φ_2	Φ_1	Φ_2	Φ_1

- **Bounds on Higgs-gauge bosons coupling are now**

$$\frac{\sigma(e^+e^- \to H_1^{2\mathrm{HDM}} Z)\,\mathrm{BR}(H_1^{2\mathrm{HDM}} \to b\bar{b})}{\sigma(e^+e^- \to H_1^{\mathrm{SM}} Z)\,\mathrm{BR}(H_1^{\mathrm{SM}} \to b\bar{b})} = \sin^2(\alpha-\beta)\,\frac{\mathrm{BR}(H_1^{2\mathrm{HDM}} \to b\bar{b})}{\mathrm{BR}(H_1^{\mathrm{SM}} \to b\bar{b})}$$

$$\frac{\sigma(e^+e^- \to H_1^{2\mathrm{HDM}} Z)\,\mathrm{BR}(H_1^{2\mathrm{HDM}} \to \tau^+\tau^-)}{\sigma(e^+e^- \to H_1^{\mathrm{SM}} Z)\,\mathrm{BR}(H_1^{\mathrm{SM}} \to \tau^+\tau^-)} = \sin^2(\alpha-\beta)\,\frac{\mathrm{BR}(H_1^{2\mathrm{HDM}} \to \tau^+\tau^-)}{\mathrm{BR}(H_1^{\mathrm{SM}} \to \tau^+\tau^-)}$$

Where does a very light Higgs comes from?

- Bound depends on the Higgs mass, $\tan\beta$ and α (and on Yukawa type) – through the branching ratios

- We choose a benchmark Yukawa and mass independent

$$\boxed{\sin(\beta-\alpha) \approx 0.1}$$

Other experimental and theoretical constraints?

- Vacuum stability and perturbative unitarity

- $Z \to b\bar{b}$ $B_q\bar{B}_q$ $\tan\beta > 1$

- $\boxed{|\delta\rho| \lesssim 10^{-3}}$

Further extensions of the scalar sector

V. Barger *et al*, PRD79 (2009).

$$\boxed{g_{VVh} = \left(\cos\Omega\cos\theta\sin(\beta-\alpha) + \sin\Omega\sin\theta\right) g_{VVh}^{SM}}$$

General coupling to gauge bosons

- **2HDM+nD (non participating in the mass generations process)**

$$\sin\Omega = v_0/v \qquad\qquad h = \cos\theta h' + \sin\theta\phi_0$$

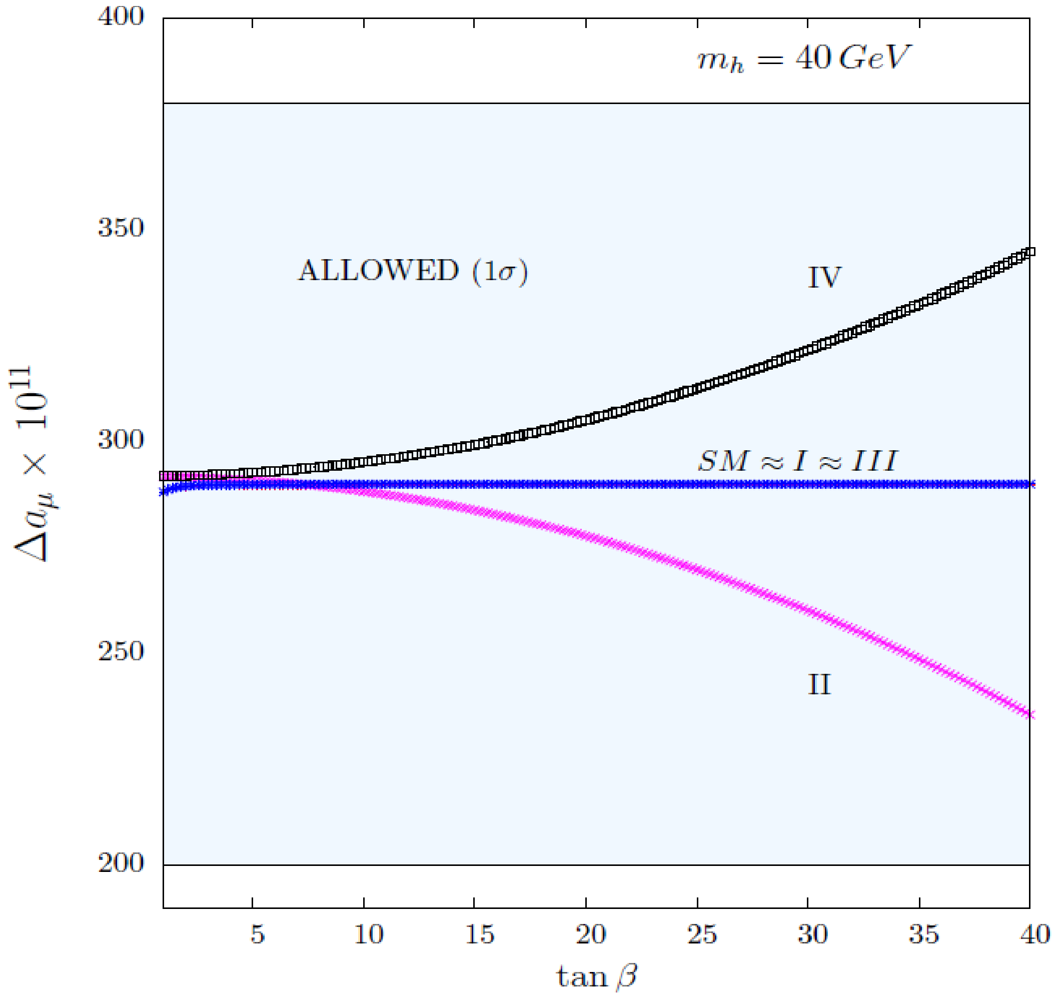
$$g_{\bar{u}uh} = \frac{\cos\theta}{\cos\Omega}\frac{\cos\alpha}{\sin\beta}g_{ffh}^{SM} \qquad g_{\bar{d}dh} = g_{\bar{l}lh} = -\frac{\cos\theta}{\cos\Omega}\frac{\sin\alpha}{\cos\beta}g_{ffh}^{SM}$$

- **3HDM (D)**

$$\sin\Omega = v_l/v$$

$$g_{\bar{u}uh} = \frac{\cos\theta}{\cos\Omega}\frac{\cos\alpha}{\sin\beta}g_{ffh}^{SM} \quad g_{\bar{d}dh} = -\frac{\cos\theta}{\cos\Omega}\frac{\sin\alpha}{\cos\beta}g_{ffh}^{SM} \quad g_{\bar{l}lh} = \frac{\sin\theta}{\sin\Omega}g_{ffh}^{SM}$$

Could help solve discrepancies

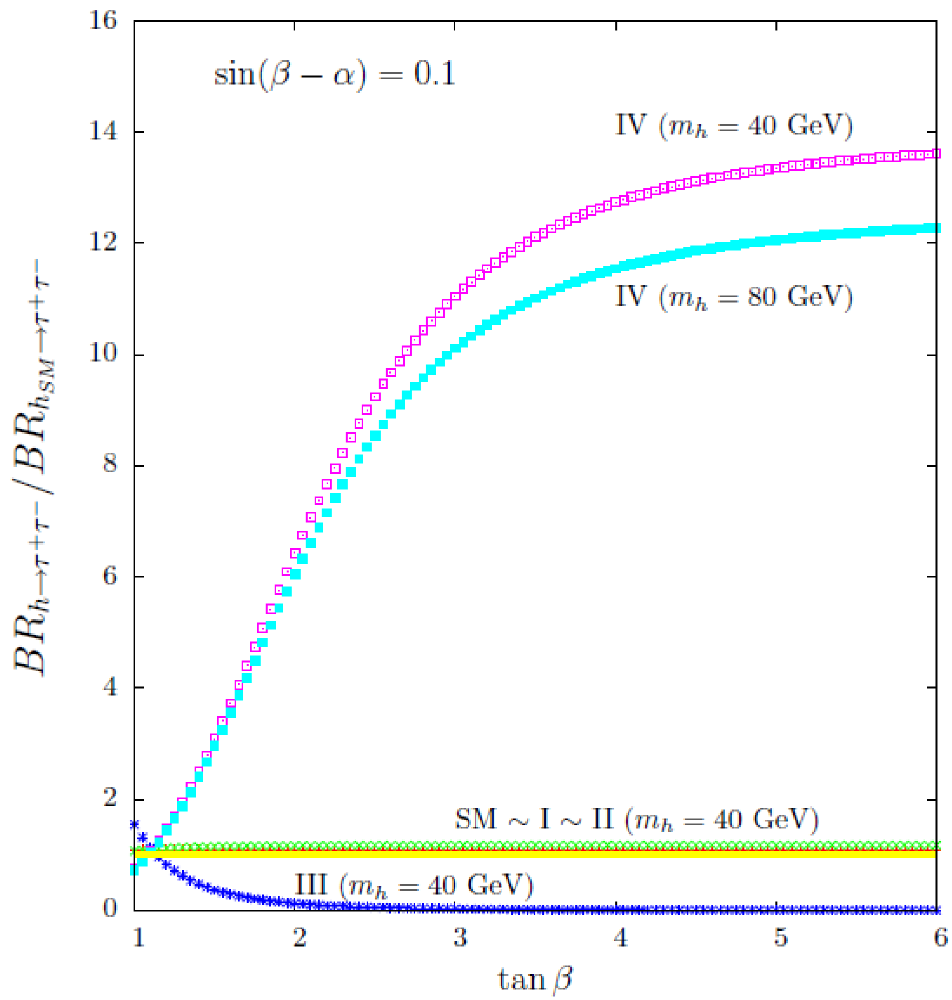


The one loop contribution does not change sign

The two-loop contribution can change sign

Models I and III and are not affected but the leptonic model moves the muon anomalous magnetic moment in the right direction.

The pure 2HDM(s)

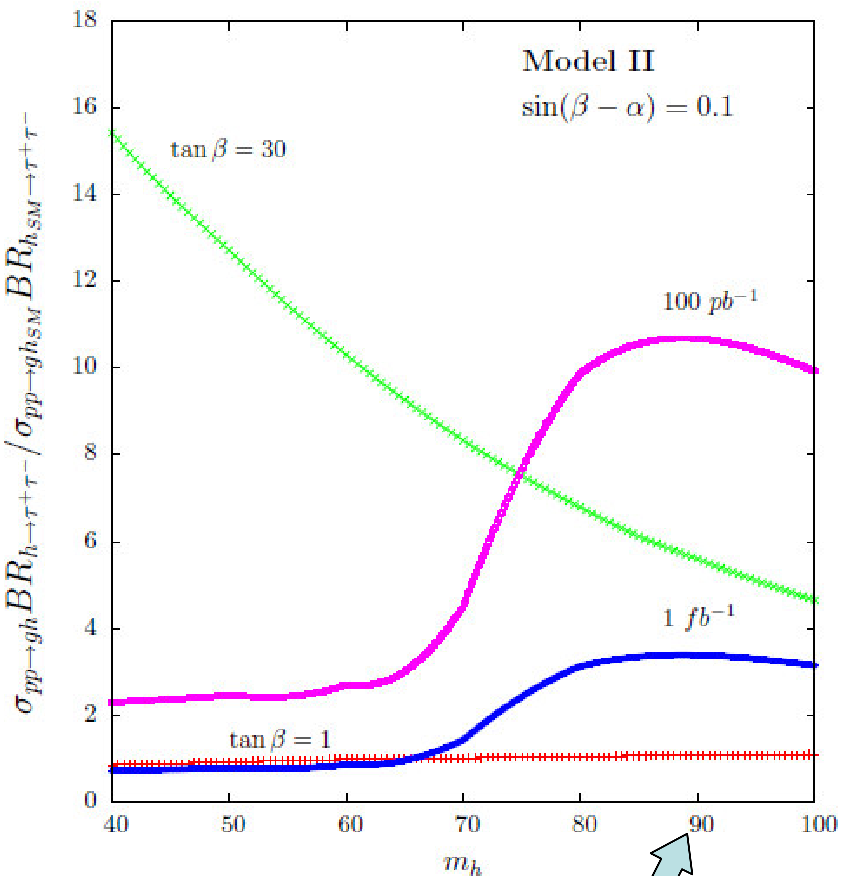


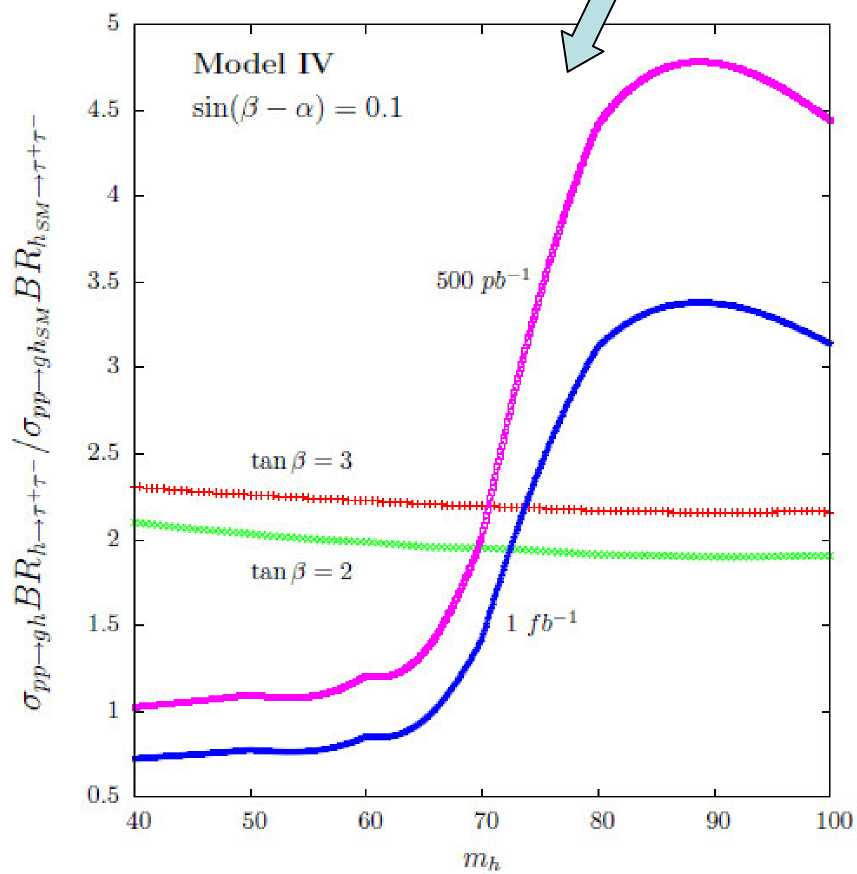
In the case of pure 2HDM, only the leptonic model has an increased branching ratio to taus for large tanβ.

Models I and II are SM-like and Model III has an increased branching ratio only for small tanβ.

2HDM(s) and 2HDM(s)+nD

$$\sigma^{2\text{HDM}}(pp \to gg \to h) = \frac{1}{\tan^2\beta} \quad \sigma^{SM}(pp \to gg \to h)$$





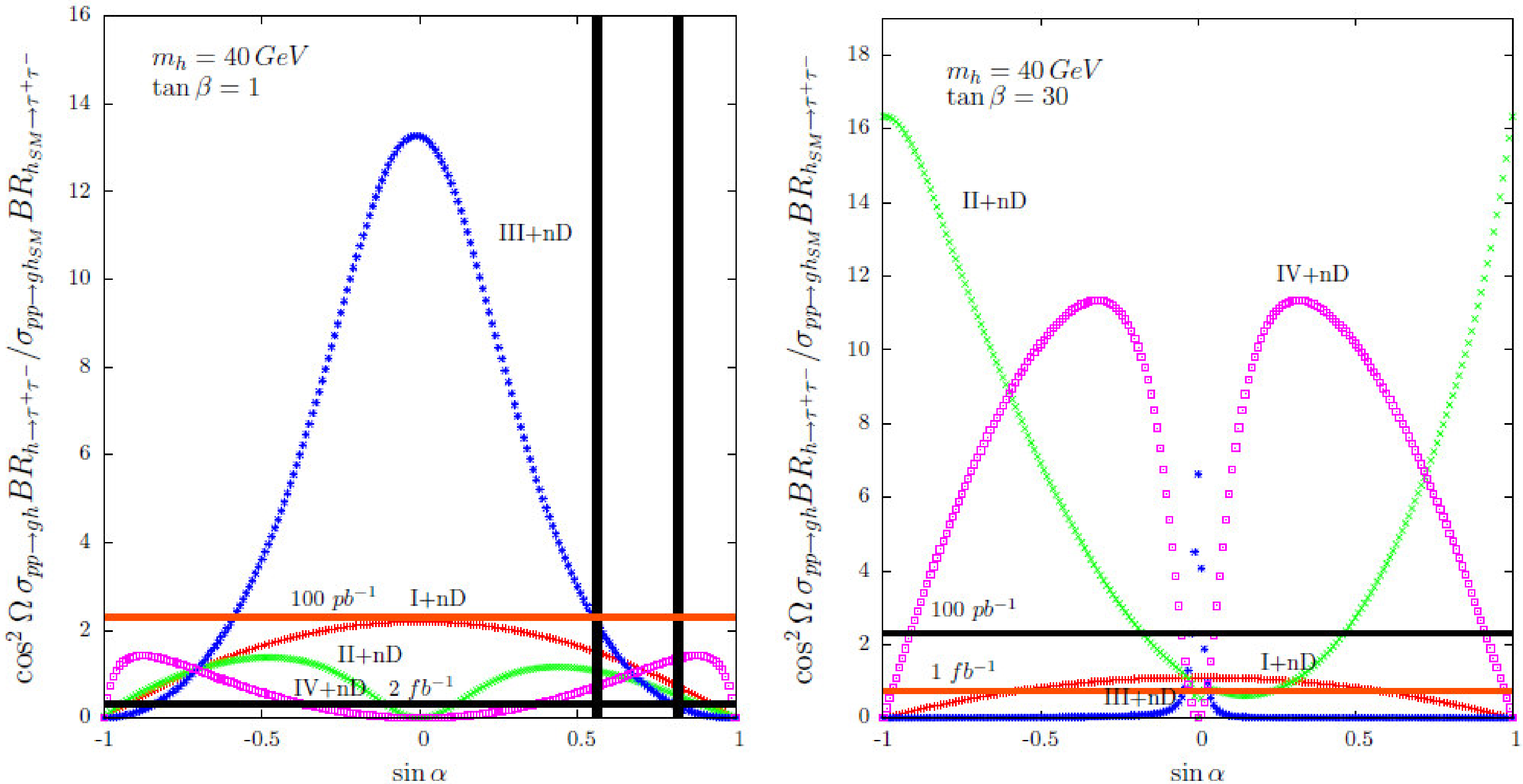
$$F_{loop} = \left|\frac{\cos\alpha}{\sin\beta} t^{SM}_{loop} - \frac{\sin\alpha}{\cos\beta} b^{SM}_{loop}\right|^2$$

$$\sin\theta << 1 \Longrightarrow \sigma^{2\text{HDM}} \to \frac{1}{\cos^2\Omega}\sigma^{2\text{HDM}}$$

Easily probed at the LHC - models II and IV.

Even better in extensions with very week mixing.

The 2HDM(s)+nD

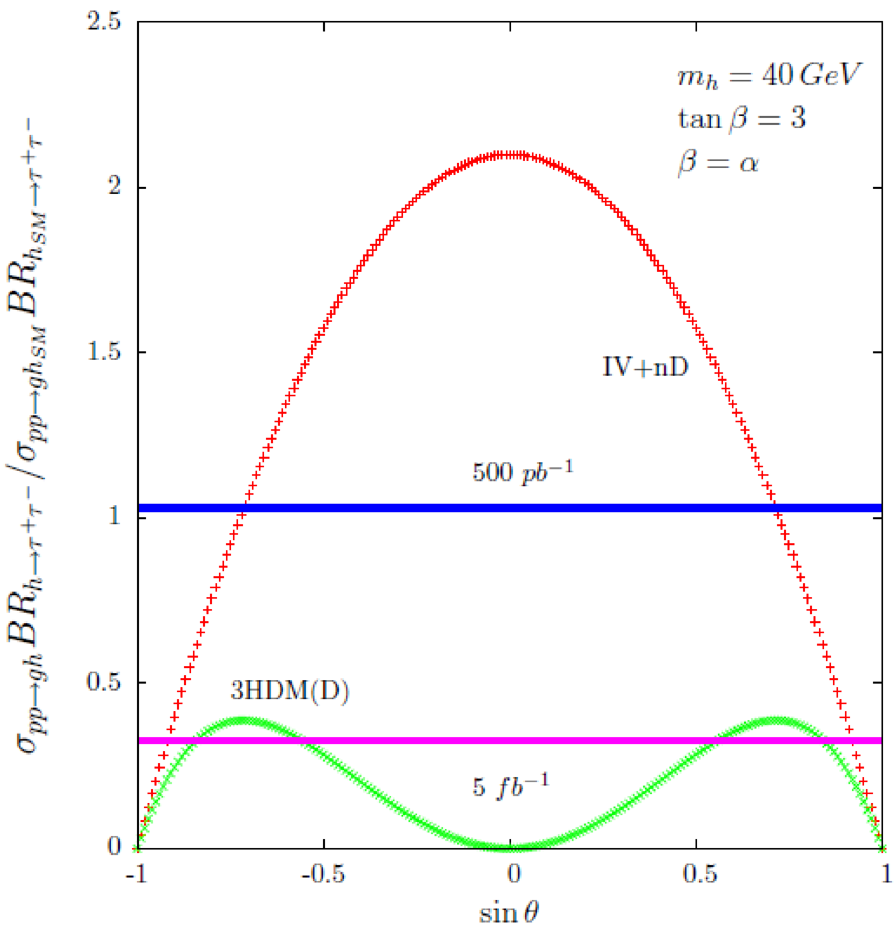


$$\cos\Omega \ll 1 \qquad \sin\theta \ll 1 \qquad \Longrightarrow \qquad \sigma^{2\mathrm{HDM}} \to \frac{1}{\cos^2\Omega}\,\sigma^{2\mathrm{HDM}}$$

Adding more doublets increases the freedom in the parameter space.

The 3HDM(D)

$$\sin\Omega \ll 1 \quad \alpha \approx \beta \Longrightarrow \quad \sigma^{2\mathrm{HDM}} \to \cos^2\theta\, \sigma^{2\mathrm{HDM}}$$



A light Higgs from a 3HDM will not be easy to find except if

$$(\cos\Omega\cos\theta\sin(\beta-\alpha) + \sin\Omega\sin\theta)\, g_{VVh}^{SM} = 0$$

$$\Downarrow$$

$$\sin(\beta-\alpha) = -\tan\Omega\tan\theta$$

$$\begin{cases} \sin(\beta-\alpha) = -\tan\Omega = -\tan\theta = -1 \\ \sin(\beta-\alpha) = -1 \quad \tan\Omega = 1/\tan\theta << 1 \end{cases}$$

In 3HDM moderate enhancement can happen while in 2HDM+(nD) a huge enhancement can be achieved in this limit.

Conclusion and outlook

- $pp(gg+gq) \rightarrow h+jet \rightarrow \tau^+\tau^- + jet$ looks promising!
- A more detailed study is needed.
- We have a big machine working – searching for a very light Higgs is mandatory!
- In pure 2HDMs, $\sin(\beta-\alpha)$ has to be small. This limit constrains Yukawa couplings but regions of the parameter space of models II and IV can be tested with less than 1 fb^{-1}
- In 2HDM+nD and 3HDM there is more freedom. Large enhancement of production cross section.
- Other extension can be studied with the same process

The end