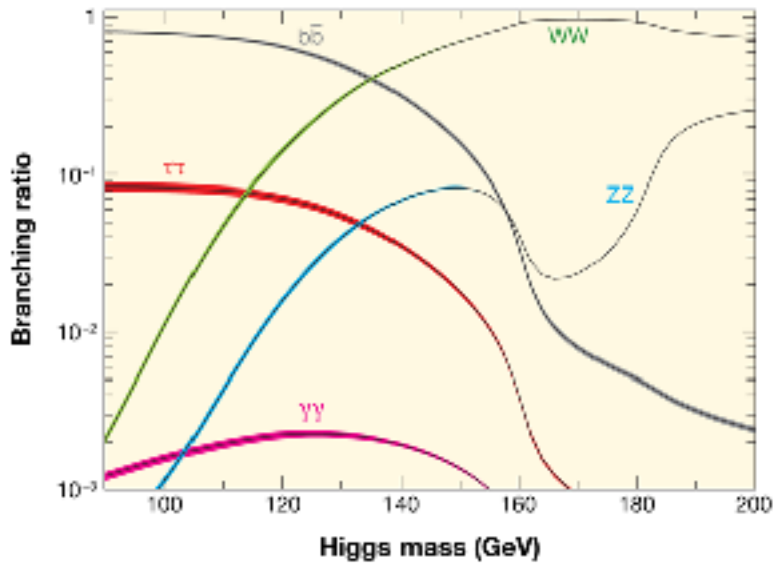
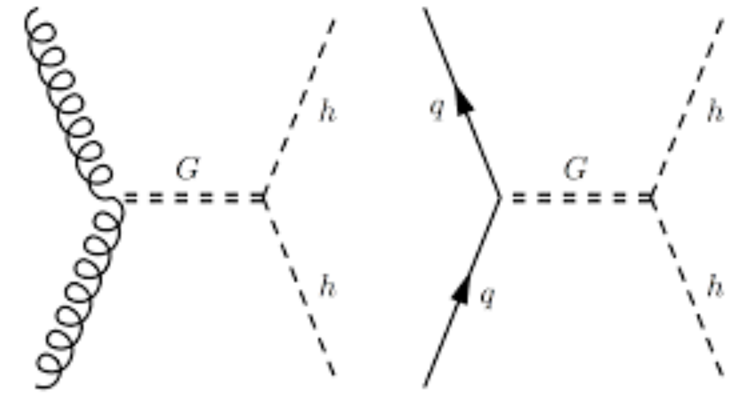




Rare decays in HH at FCC-hh with 100 TeV

Michael Spannowsky

IPPP, Durham University

Motivation to look for di-Higgs final states

- Measure Higgs selfcoupling of the Standard Model
  - stability of the Higgs potential
  - Order of Phase Transition

see also talks by M. Ramsey-Musolf and B. Di Micco

- Observe di-Higgs final states, possibly enhanced in BSM
  - Resonant and loop-enhanced di-Higgs production predicted in many BSM models

Current status for expected sensitivity at HL-LHC and 100 TeV

- ATLAS and CMS performed studies for HL-LHC

$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ predicting

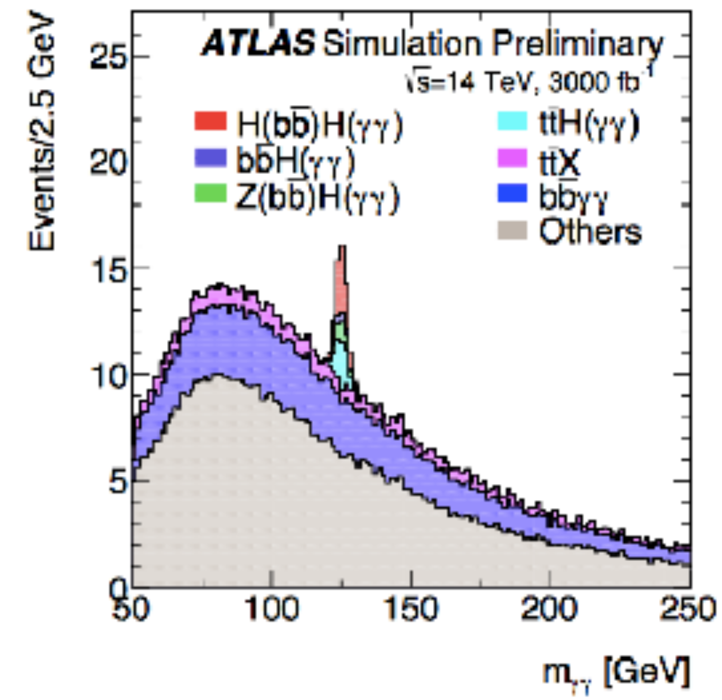
$b\bar{b}\gamma\gamma$: 1.3σ for ATLAS and 1.6σ for CMS

$b\bar{b}\tau\tau$: 0.6σ for ATLAS and 0.9σ for CMS

(still conservative methods)

bbWW rather insensitive...

still, future FCC/ILC might not do better



Predicted sensitivity for cross section and selfcoupling at 100 TeV

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$

Motivation to look for rare decays

- Many models predict:
  - extended scalar sectors (cp-even/odd) ⟶ e.g. H->2 phi -> 4l or H-> MET+X
  - Lepton and quark FCNCs ⟶ e.g. H-> tau mu or H-> b s
  - vector-like fermions ⟶ e.g. enhanced H-> Z gamma

- Higgs portal one of few portals that allow dark sector being uncharged under SM, e.g. $\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$ or $\Delta\mathcal{L} = \frac{\mu}{\Lambda^2} |H|^2 \bar{\psi}\psi$

- Events produced in ; $\mathrm{Br}(h \to \mathrm{BSM}) = 10\%$ before acceptance, trigger and reconstruction efficiencies [Curtin et al '12]

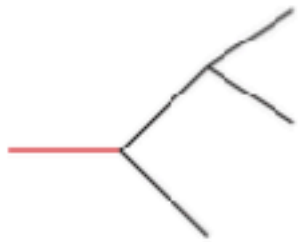
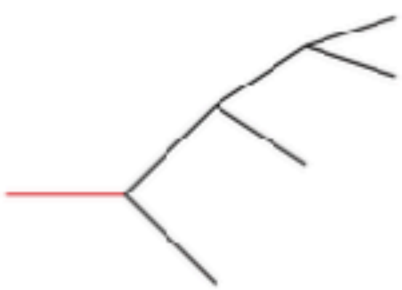
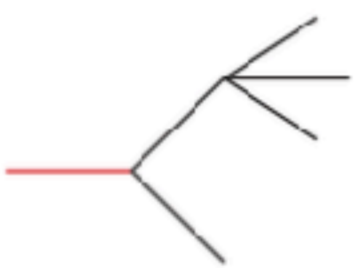
Production	$\sigma_{7\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 5 fb^{-1}	$\sigma_{8\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 20 fb^{-1}	$\sigma_{14\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 300 fb^{-1}
ggF	15.13	7,600	19.27	38,500	49.85	1.5×10^6
VBF	1.22	610	1.58	3,200	4.18	125,000
$hW^\pm$	0.58	290	0.70	1,400	1.5	45,000
$hW^\pm(\ell^\pm\nu)$	$0.58 \cdot 0.21$	62	$0.70 \cdot 0.21$	300	$1.5 \cdot 0.21$	9,600
hZ	0.34	170	0.42	830	0.88	26,500
$hZ(\ell^+\ell^-)$	$0.34 \cdot 0.067$	11	$0.42 \cdot 0.067$	56	$0.88 \cdot 0.067$	1,800
$t\bar{t}h$	0.086	43	0.13	260	0.61	18,300

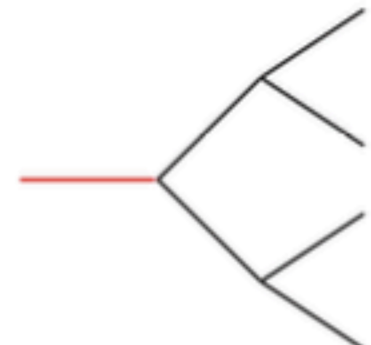
⇒ possible sensitivity at level of $\mathrm{BR} \sim 10^{-6}$ with 300 ifb

Event rate large, yet decays rather weakly limited. Leave no stone unturned!

Large number of possibilities for rare Higgs decays

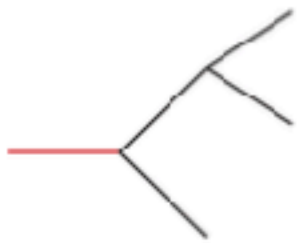
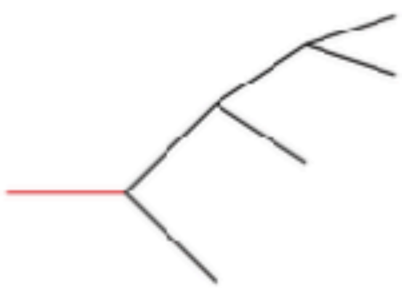
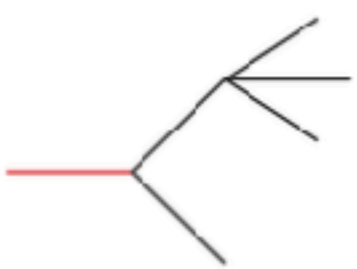
[Curtin et al '12]

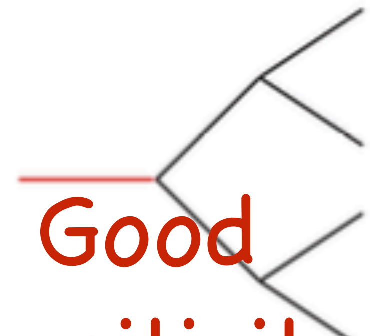
Decay Topologies	Decay mode $\mathcal{F}_i$
 $h \to 2$	$h \to \not\!\!E_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not\!\!E_T$ $h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$ $h \to (\mu^+\mu^-) + \not\!\!E_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not\!\!E_T$ $h \to jj + \not\!\!E_T$ $h \to \tau^+\tau^- + \not\!\!E_T$ $h \to \gamma\gamma + \not\!\!E_T$ $h \to \ell^+\ell^- + \not\!\!E_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not\!\!E_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not\!\!E_T$ $h \to \ell^+\ell^- + \not\!\!E_T + X$

Large number of possibilities for rare Higgs decays

[Curtin et al '12]

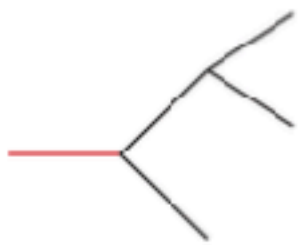
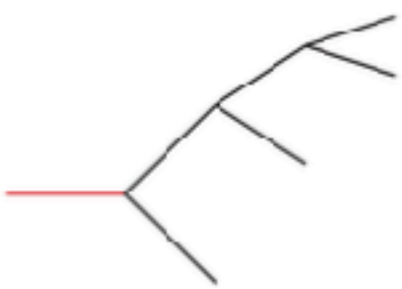
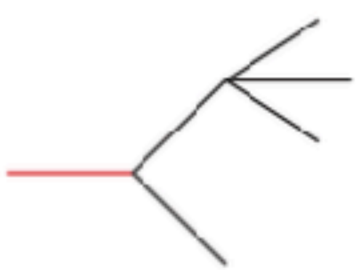
Decay Topologies	Decay mode $\mathcal{F}_i$
 $h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

Good sensitivity in single H and associated production

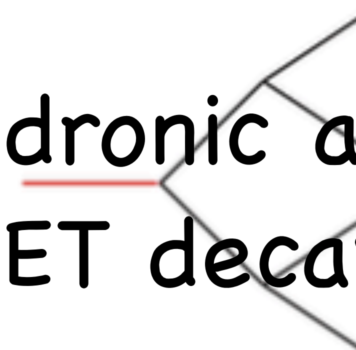
Large number of possibilities for rare Higgs decays

[Curtin et al '12]

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

hadronic and MET decays

difficult in single H production

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Rare decays from SM di-Higgs production

- Rare decays often statistics limited
- Production CS for HH at 100 TeV machine increased 40 times over LHC

[De Florian, Mazzitelli '13]

E_{cm}	14 TeV	100 TeV
$\sigma_{\rm NNLO}$	40.2 fb	1638 fb
Scale [%]	$+8.0-8.7$	$+5.9-5.8$
PDF [%]	$+4.0-4.0$	$+2.3-2.6$
PDF+α_S [%]	$+7.2-7.1$	$+5.8-6.0$

one of largest enhancements compared to other channels

	$gg \to H$ (Sect 3.1)	VBF (Sect 3.5)	HW^+ (Sect 3.4)	HZ (Sect 3.4)	$t\bar{t}H$ (Sect 3.6)
σ(pb)	802	69	15.7	11.2	32.1
σ(100 TeV)/σ(14 TeV)	16.5	16.1	10.4	11.4	52.3

- However, within SM other production mechanisms for single Higgs production larger, e.g. H, HW, HZ, ttH

⟶ kinematic benefit of 2->2 scattering present in other channels

⟶ rare decays likely to show up in other channels first

- Of course, if rare decays enhanced and clean, can help to measure hhh

Two directions to look into:

1) Can scalar interactions be discovered or measured using rare decays?

2) Does discovery of rare decays benefit from di-Higgs final states?

1) At 100 TeV new decay modes become accessible, e.g. $hh \to (b\bar{b})(4\ell)$

channel	BR	σ(14 TeV) (fb)	σ(100 TeV) (fb)
$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(\ell^+\ell^-\ell'^+\ell'^-)$	0.016%	0.006	0.26
$hh \to (b\bar{b})(Z\gamma) \to (b\bar{b})(\ell^+\ell^-\gamma)$	0.013%	0.005	0.21
$hh \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell^+\ell'^- + \not{E})$	1.658%	0.667	27.16
$hh \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell^+\ell'^- + \not{E})$	0.893%	0.360	14.63
$hh \to (b\bar{b})(\mu^+\mu^-)$	0.025%	0.010	0.42
$hh \to (b\bar{b})(\gamma\gamma)$	0.263%	0.106	4.31

at 100 TeV all rates appreciably large

- **bbZZ -> bb 4l:**
  - One Higgs decays into major mode other very clean

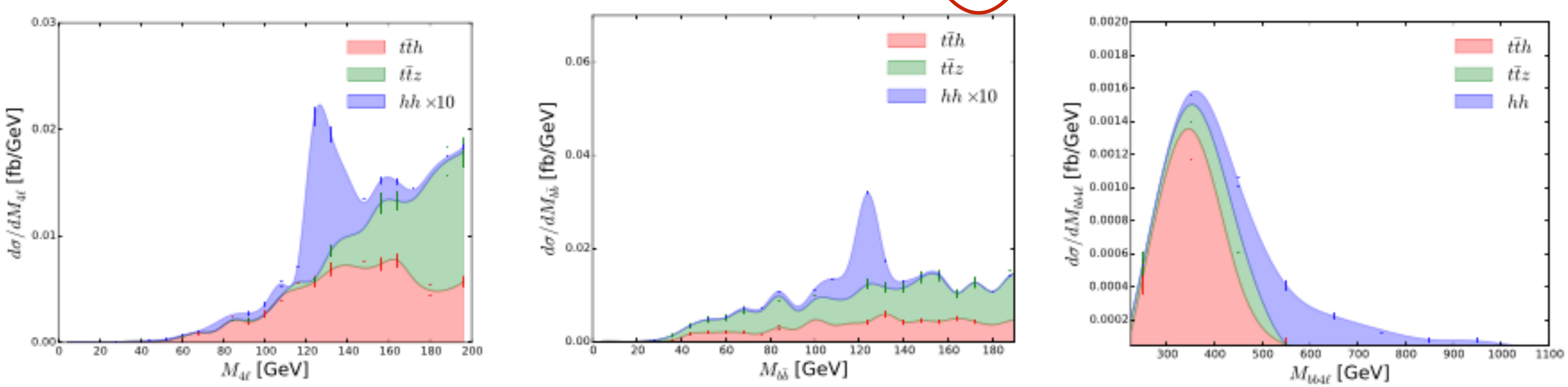
    ⟶ Can extrapolate result to other decay modes
  - Can be simulated rather reliably

[Papaefstathiou '15]

Results for $hh \to (b\bar{b})(4\ell)$

[Papaefstathiou '15]

channel	σ(100 TeV) (fb)	$N_{3\ \mathrm{ab}^{-1}}$(cuts, ideal)	$N_{3\ \mathrm{ab}^{-1}}$(cuts, LHC)
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\ell'^+\ell'^-)$	0.26	$13.0^{+0.3}_{-0.3}$	$4.1^{+0.2}_{-0.2}$
$\mathbf{t\bar{t}h} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	193.6	$30.4^{+1.4}_{-1.4}$	$10.9^{+0.7}_{-0.7}$
$\mathbf{t\bar{t}Z} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	256.7	$6.6^{+2.8}_{-1.5}$	$2.5^{+1.7}_{-0.7}$
$\mathbf{Zh} \to (b\bar{b})(4\ell)$	2.29	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$
$\mathbf{ZZZ} \to (4\ell)(b\bar{b})$	0.53	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$
$\mathbf{b\bar{b}h} \to b\bar{b}(4\ell)$, $p_{T,b} > 15$ GeV	0.26	$\mathcal{O}(1)$	$\mathcal{O}(10^{-1})$
$\mathbf{ZZh} \to (4\ell)(b\bar{b})$	0.12	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-3})$
$\mathbf{ZZ} \to (4\ell)$+mis-tagged $b\bar{b}$	781.4	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\mathbf{hZ} \to (4\ell)$+mis-tagged $b\bar{b}$	68.2	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-3})$
$\mathbf{W\pm ZZ} \to (\ell\nu_\ell)(\ell^+\ell^-)(b\bar{b})$ + mis-tagged ℓ	7.5	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\mathbf{W^\pm Zh} \to (\ell\nu_\ell)(\ell^+\ell^-)(b\bar{b})$ +mis-tagged ℓ	1.4	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-3})$



→ In general, relatively good S/B

→ statistics though very challenging

- **bbWW/bbtautau/bbmumu -> bb 2l+MET:**

[Papaefstathiou '15]

  - collinear approximation for tau decays
  - mass reconstruction via (best for taus) $M_{\text{reco.}} = [p_{b_1} + p_{b_2} + (1+f_1)p_{\ell_1} + (1+f_2)p_{\ell_2}]^2$

$$p_{\nu_i} = f_i p_{\ell_i}$$

channel	σ(100 TeV) (fb)	$N_{3\ \text{ab}^{-1}}$(cuts, ideal)	$N_{3\ \text{ab}^{-1}}$(cuts, LHC)
$\mathbf{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	27.16	$20.9^{+1.8}_{-1.8}$	$19.9^{+1.5}_{-1.5}$
$\mathbf{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$	14.63	$38.5^{+4.7}_{-4.7}$	$24.3^{+3.2}_{-3.2}$
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$, cuts as in Eq. 1	25.08×10^3	$34.3^{+23.2}_{-9.4}$	$15.8^{+15.3}_{-4.8}$
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	107.36×10^3	$257.9^{+203.7}_{-74.6}$	$493.7^{+224.9}_{-113.4}$
$\mathbf{ZZ} \to b\bar{b}(\ell^+\ell^-)$	356.0	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$
$\mathbf{hZ} \to b\bar{b}(\ell^+\ell^-)$	99.79	$49.8^{+2.9}_{-2.9}$	$40.4^{+2.3}_{-2.3}$
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	26.81	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{b\bar{b}W^\pm} \to b\bar{b}(\ell^\pm\nu_\ell)$, $p_{T,b} > 30$ GeV +mis-tagged ℓ	1032.6	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\ell^+\ell^- +$jets $\to (\ell^+\ell^-)$ + mis-tagged $b\bar{b}$	2.14×10^3	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

- **bbZgamma:**
  - signal cs similar to bb4l, but backgrounds larger

channel	σ(100 TeV) (fb)	$N_{3\ \text{ab}^{-1}}$(cuts, ideal)	$N_{3\ \text{ab}^{-1}}$(cuts, LHC)
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\gamma)$	0.21	$14.0^{+0.3}_{-0.3}$	$7.5^{+0.2}_{-0.2}$
$\mathbf{b\bar{b}Z\gamma} \to b\bar{b}(\ell^+\ell^-)\gamma$, $p_{T,b} > 30$ GeV	26.00×10^3	266^{+609}_{-77}	203^{+455}_{-59}
$\mathbf{t\bar{t}\gamma} \to (L^+ b\nu_L l)(L^- \bar{b}\bar{\nu}_L)\gamma$	7.94×10^3	78^{+75}_{-23}	79^{+62}_{-23}
$\mathbf{hZ\gamma} \to (b\bar{b})(\ell^+\ell^-)\gamma$	1.72	3^{+2}_{-1}	2^{+1}_{-1}
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$+mis-tagged γ , $p_{T,b} > 30$ GeV	107.36×10^3	20^{+22}_{-9}	21^{+16}_{-6}
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$+mis-tagged γ, cuts as in Eq. 1	25.08×10^3	14^{+2}_{-2}	10^{+1}_{-1}

result for all channels

	prec. cross sec	68% CL on hhh
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–

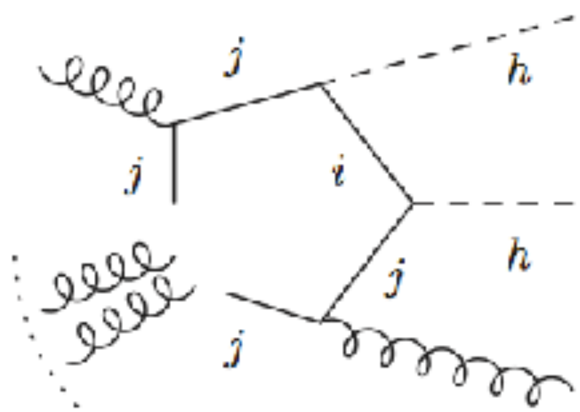
2) Does discovery of rare decays benefit from di-Higgs final states?

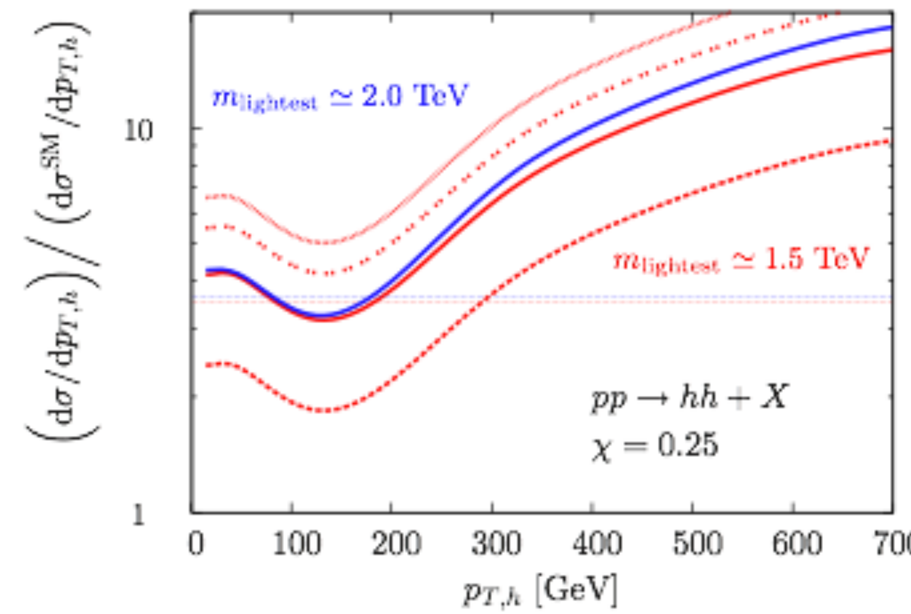
Yes, if final states benefits from kinematic features of 2->2 production and if other production channels are suppressed

Two ways to enhance HH production cross section:

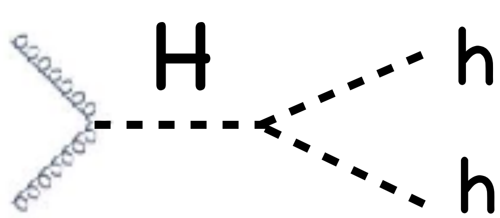
New physics in Loop:

- Composite Higgs
- $\Delta\mathcal{L} = \frac{\mu}{\Lambda^2}|H|^2\bar{\psi}\psi$





Resonant new physics:



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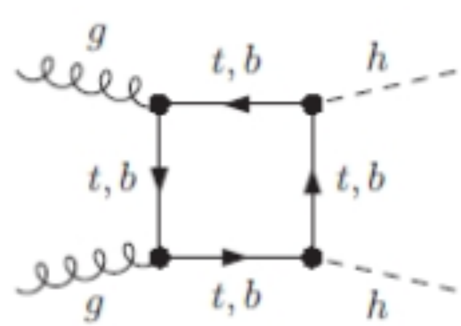
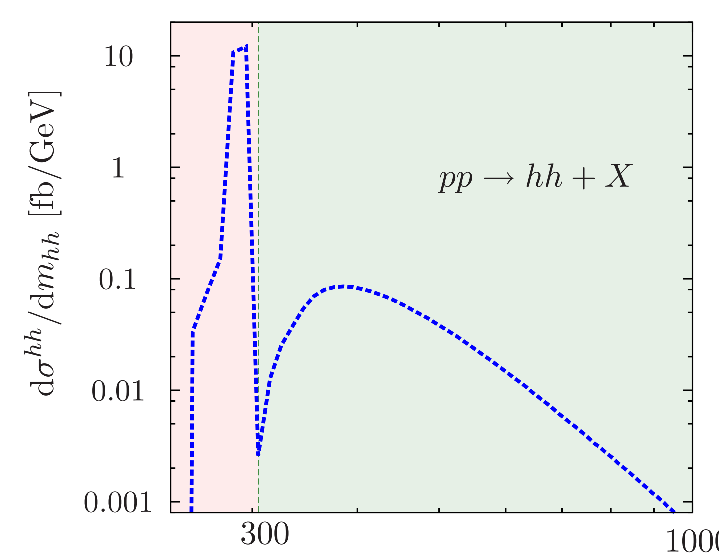


- However, often in singlet, NHDM, multi-scalar extensions cross section enhancement in small mhh region



- Loop enhancement increases boosted rates
- In resonance enhancement allows to exploit large N100/N14 improvement

xSM typical/minimal model to increase the hh cross section
(SM extended by real singlet scalar S)

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

[Profumo, Ramsey-Musolf, Saughnessy '07]
[Kotwal, Ramsey-Musolf, No, Winoslow '16]

14 TeV benchmark points to allow for strong first-order PT and search inv. Higgs dec

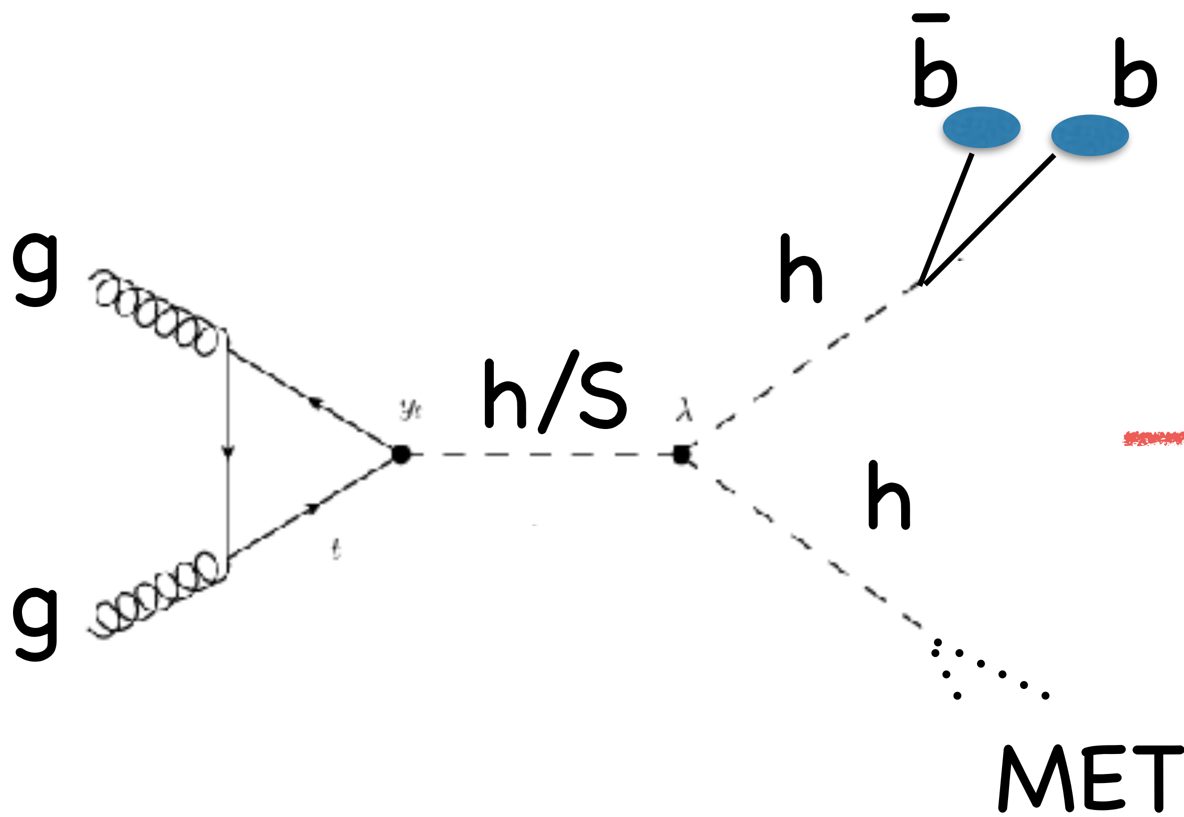
	$\cos\theta$	m_2 (GeV)	Γ_{h_2} (GeV)	x_0 (GeV)	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	λ_{111} (GeV	λ_{211} (GeV)	σ (pb)	BR
B1	0.961	258	0.68	307	0.52	-266	0.26	-138	0.26	110	-94.6	1.19	0.50
B2	0.976	341	2.42	257	0.92	-377	0.39	-403	0.77	204	-150	0.59	0.74
B3	0.982	353	2.17	265	0.99	-400	0.45	-378	0.69	226	-144	0.44	0.76

→ rate enhanced by factor ~ 14 compared to SM for B1

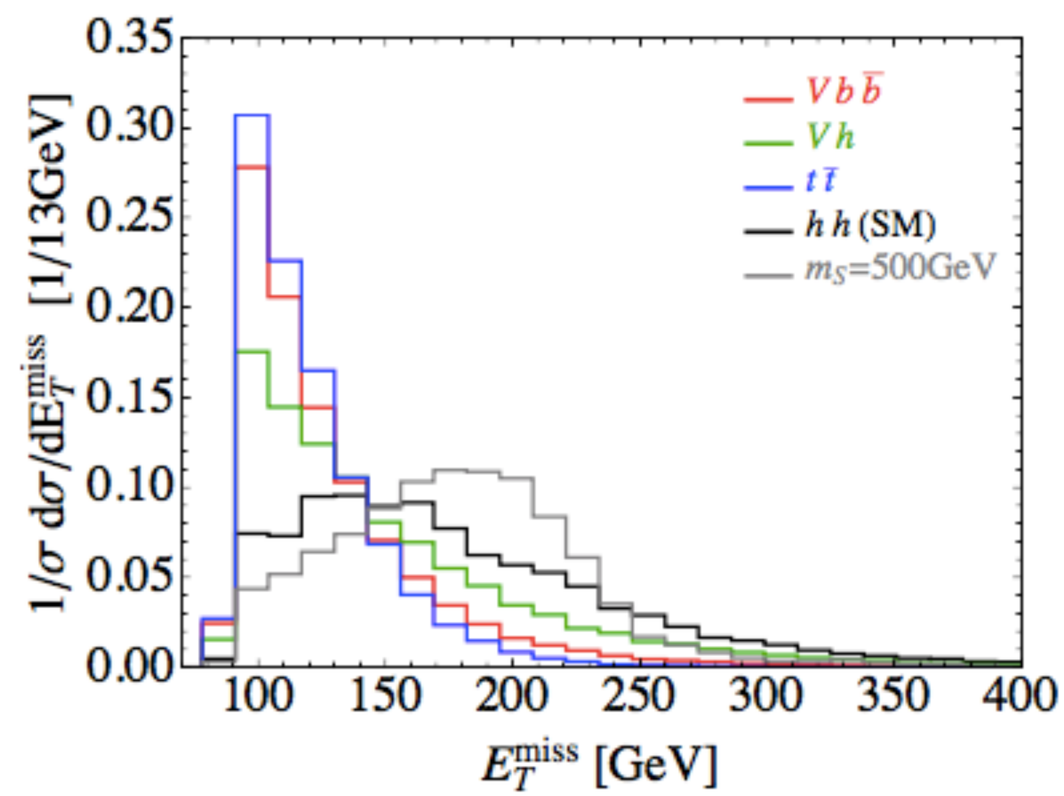
100 TeV benchmark points to allow for strong first-order PT and search inv. Higgs dec

Benchmark	$\cos\theta$	$\sin\theta$	m_2 (GeV)	Γ_{h_2} (GeV)	x_0 (GeV)	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	λ_{111} (GeV	λ_{211} (GeV)	σ (pb)	BR
B1	0.976	0.220	341	2.42	257	0.92	-377	0.392	-403	0.77	204	-150	23.9	0.74
B2	0.982	0.188	353	2.17	265	0.99	-400	0.446	-378	0.69	226	-144	19.0	0.76
B3	0.983	0.181	415	1.59	54.6	0.17	-642	3.80	-214	0.16	44.9	82.5	20.1	0.33

Example: Invisible Higgs decays in hh final state



[Banerjee, Batell, MS '16]



- MT2 very helpful observable, as for bbtautau or bbWW
  [Barr, Dolan, Englert, MS '13]

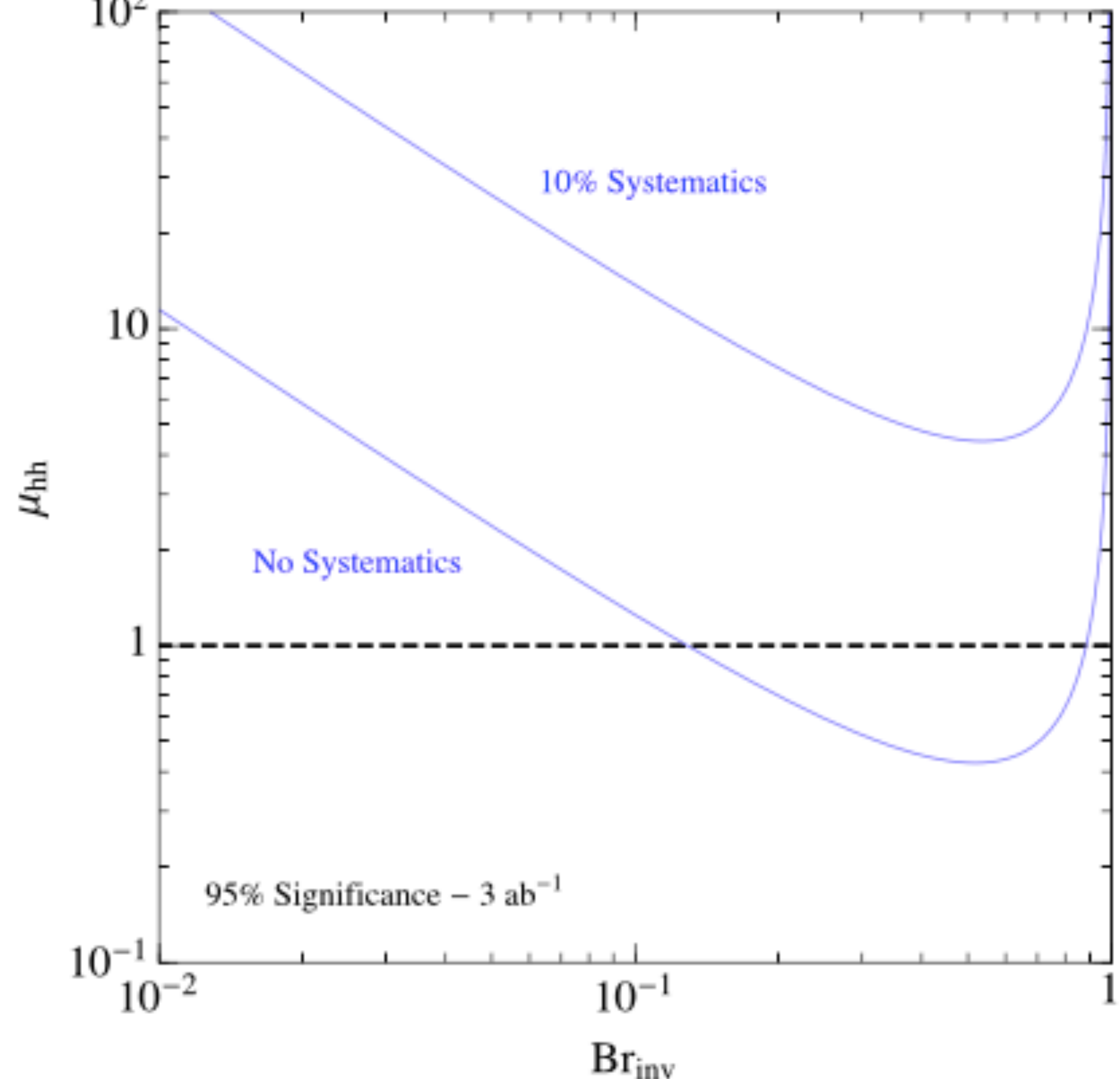
- Exploiting jet substructure could further improve result

efficiency cut-flow for SM production

	Signal	$Wb\bar{b}$ (no h) ($2b\ell\nu$)	$Zb\bar{b}$ (no h) ($2b2\nu/2b2\ell$)	Wh ($2b\ell\nu$)	Zh (1) ($(2\nu/2\ell)(2b)$)	Zh (2) ($(2b)(\not{E}_T)$)	$t\bar{t}$ (lep+semi-lep)
K-factor	[112]	[133]	[133]	[134]	[134]	[134]	[135]
$\not{E}_T$ trigger + 2b+0,1j	1.35×10^{-1}	2.81×10^{-2}	5.63×10^{-2}	1.72×10^{-2}	5.21×10^{-2}	8.60×10^{-2}	7.92×10^{-3}
$p_T(b)$	1.31×10^{-1}	2.64×10^{-2}	5.12×10^{-2}	1.65×10^{-2}	4.99×10^{-2}	8.10×10^{-2}	7.37×10^{-3}
m_{bb}	4.84×10^{-2}	7.54×10^{-3}	1.50×10^{-2}	7.16×10^{-3}	2.01×10^{-2}	1.73×10^{-3}	2.31×10^{-3}
$\Delta R(b_1, b_2)$	4.38×10^{-2}	5.20×10^{-3}	9.95×10^{-3}	5.97×10^{-3}	1.67×10^{-2}	1.32×10^{-3}	1.41×10^{-3}
$\Delta\phi(bb, \not{E}_T)$	3.82×10^{-2}	5.14×10^{-3}	9.56×10^{-3}	5.78×10^{-3}	1.58×10^{-2}	1.24×10^{-3}	1.07×10^{-3}
$\not{E}_T$	2.35×10^{-2}	9.79×10^{-4}	2.29×10^{-3}	1.62×10^{-3}	7.18×10^{-3}	6.51×10^{-4}	9.50×10^{-5}
$p_T(bb)$, M_{T2}	1.44×10^{-2}	4.87×10^{-4}	8.82×10^{-4}	1.21×10^{-3}	4.54×10^{-3}	3.95×10^{-4}	5.73×10^{-6}
Scaling	μ_{hh} Br$_{inv}$ (1-Br$_{inv}$)	1	1	(1-Br$_{inv}$)	(1-Br$_{inv}$)	Br$_{inv}$	1

Non-resonant case suffers from relatively bad S/B=0.026 for BR(H->inv) = 20%

Hence, strongly systematics limited



With resonance enhancement

Benchmark

$$\sigma(pp \to S \to hh)_{14\,\mathrm{TeV}} = 5 \times \sigma^{hh}_{\mathrm{SM}},$$

$$m_S = 500\,\mathrm{GeV},$$

$$\Gamma_S / m_S = 0.01.$$

		Integrated Luminosity 300 fb^{-1}	Integrated Luminosity 3 ab^{-1}
Systematics	0%	4%	1%
Systematics	10%	18%	17%

Some scenarios BR(h->inv) better or earlier constrained than in WBF single Higgs production

[Eboli, Zeppenfeld '00]

[Bernaciak et al, '14]

Limits at 100 TeV

- Cuts not optimised for 100 TeV!
- signal CS enhanced by factor 40-50
- backgrounds mostly 10-20, except ttbar (~40)
- results for BR(H->inv) = 5%

thanks to S. Banerjee

Non-resonant case

For MET > 160 GeV, pTbb > 180 GeV, MT2 > 160 GeV

Process	Number of events @ 100 TeV and 3 ab^{-1}
Signal (SM production)	4166
W b bbar	23652
t tbar (leptonic)	2790
Z b bbar	170808
Z h (Born) Z -> nu nu/ l l, h -> b bar	21289
W h	8207
t tbar (semi-leptonic)	13812
Z h (Born) Z -> b bbar, h -> MET	66
tb	111

S=4166

B=240735

S/B~0.017

resonant case

For the resonant case, MET > 160 GeV, pTbb > 180 GeV, MT2 > 180 GeV

Process	Number of events @ 100 TeV and 3 ab^{-1}
Signal (Resonant)	33167
W b bbar	19308
t tbar (leptonic)	1860
Z b bbar	128106
Z h (Born) Z -> nu nu/ l l, h -> b bar	18120
W h	6986
t tbar (semi-leptonic)	9866
Z h (Born) Z -> b bbar, h -> MET	57
tb	111

S=33167

B=184413

S/B~0.18

Summary

- Both, rare Higgs decays and di-Higgs final states are amongst most important measurements at LHC and beyond

- 100 TeV machine can significantly boost our sensitivity in both directions

- If resonantly enhanced some rare decays can be found earlier in di-Higgs final states than in single-Higgs production

- Other interesting channels for resonant HH scenario could be

$$hh \to \gamma\gamma + MET$$

$$hh \to (aa \to 4b)(WW/\tau\tau) \to 4b + 2l + MET$$

$$hh \to (aa \to 2b2\tau)(b\bar{b}) \to 4b + 2\tau$$

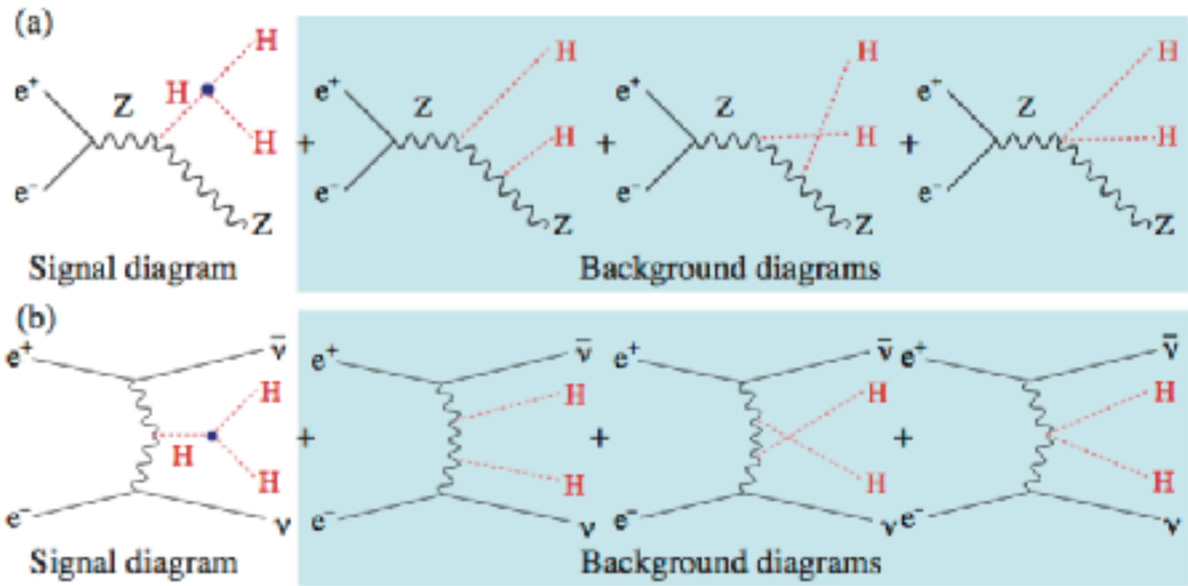
$$hh \to (2b + MET)(2b) \to 4b + MET$$

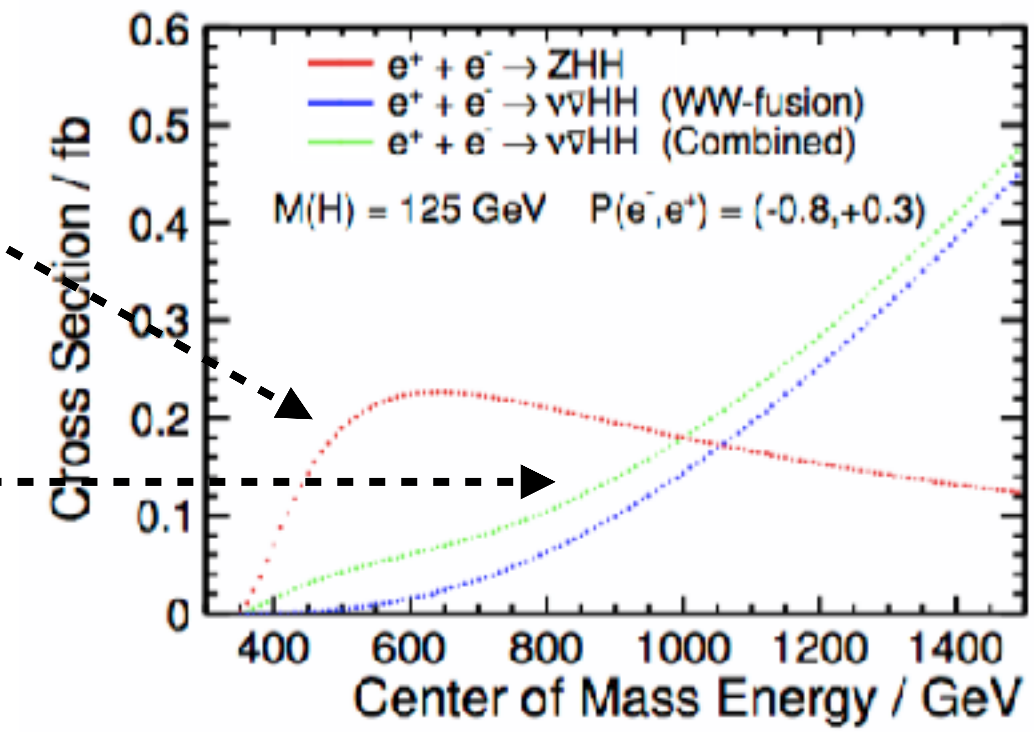
Not more promising at FCC-ee or ILC

[Tian, Fujii 1311.6528]

- ILC very good for many couplings, but self-coupling difficult to probe
- WBF most sensitive channel for large energies > 500 GeV
- Decay via H->bb
- Unless 1 TeV ILC precision low

$\Delta g/g$	Baseline 250 GeV	Baseline + 500 GeV	Baseline + 1 TeV	LumiUP 250 GeV	LumiUP + 500 GeV	LumiUP + 1 TeV
g_{HZZ}	1.3%	1.0%	1.0%	0.61%	0.51%	0.51%
g_{HWW}	4.8%	1.2%	1.1%	2.3%	0.58%	0.56%
g_{Hbb}	5.3%	1.6%	1.3%	2.5%	0.83%	0.66%
g_{Hcc}	6.8%	2.8%	1.8%	3.2%	1.5%	1.0%
g_{Hgg}	6.4%	2.3%	1.6%	3.0%	1.2%	0.87%
$g_{H\tau\tau}$	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
$g_{H\gamma\gamma}$	18%	8.4%	4.0%	8.2%	4.5%	2.4%
$g_{H\mu\mu}$	-	-	16%	-	-	10%
g_{Htt}	-	14%	3.1%	-	7.8%	1.9%
Γ_H	11%	5.0%	4.6%	5.4%	2.5%	2.3%
λ_{HHH}	-	83%	21%	-	46%	13%

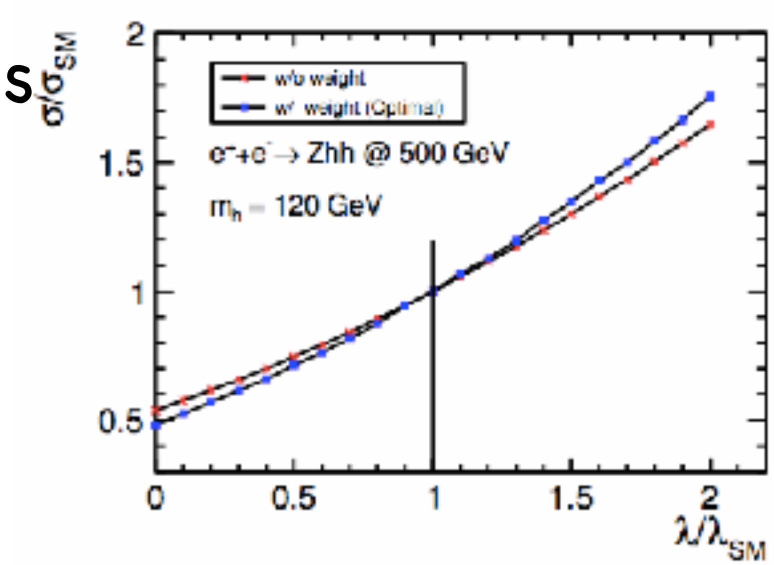


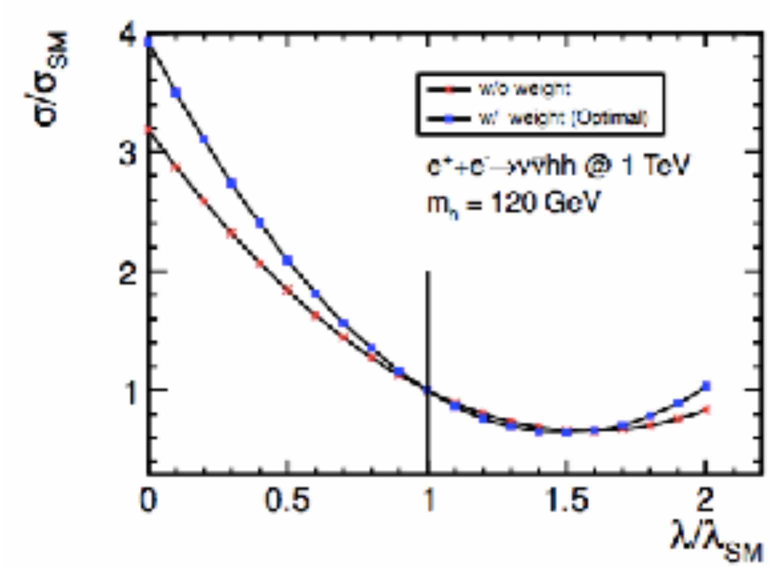


(interference)

- $\sigma = a\lambda^2 + b\lambda + c$ scaling of cross section with self-coupling

- Small total cross sections





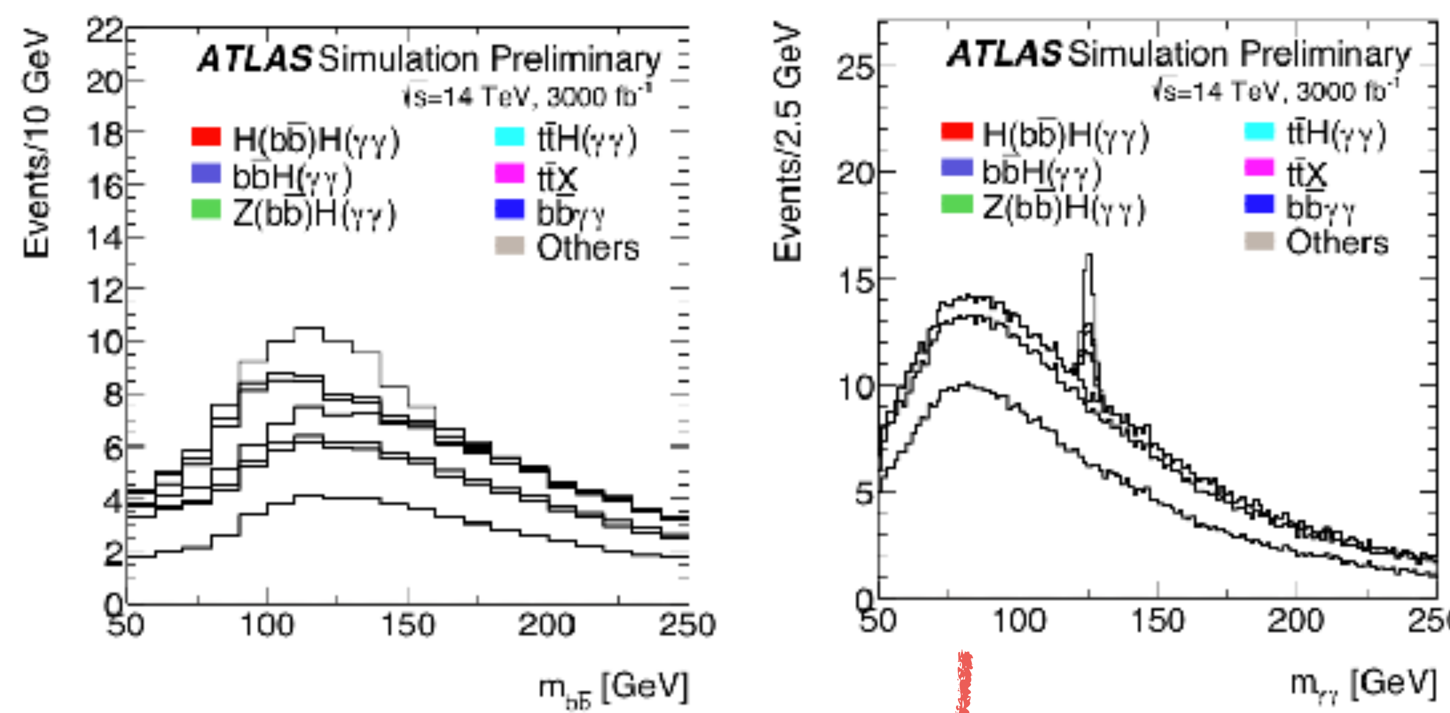
- Positive is scaling with Higgs self-coupling:

- Analyses in HH->4b and HH->bbWW give precision of 80% (500 GeV) and 20% (1 TeV)

$b\bar{b}\gamma\gamma$

[ATL-PHYS-PUB-2014-019]

- Estimates from experiments far worse than theory estimates
- Background estimates between both experiments quite different



3000 ifb

process	ATLAS		CMS
SM HH→bbγγ	8.4± 0.1		9.9
bbγγ	9.7 ± 1.5	γγ+jets	8.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2	γ+jets, jets	7.4
top background	3.4 ± 2.2		1.1
ttH(γγ)	6.1 ± 0.5		1.5
Z(bb)H(γγ)	2.7 ± 0.1		3.3
bbH(γγ)	1.2 ± 0.1		0.8
Total background	47.1 ± 3.5		22.6
S/√B (barrel+endcap)	1.2		
S/√B (split barrel and endcap)	1.3		

CMS gives 60% uncertainty on signal CS measurement

Search for $HH \to b\bar{b}WW \to b\bar{b}l\nu l\nu$

CMS feasibility study for ECFA

Event preselection:

- 2 b-jets Medium WP, $pT > 30$ GeV
  2 leptons, muons: $pT > 20$ GeV, electrons: $pT > 25$ GeV
- MET >20GeV
  Clean up cuts (mjj , mll , ΔRjj , ΔRll , $\Delta\phi jj,ll$)

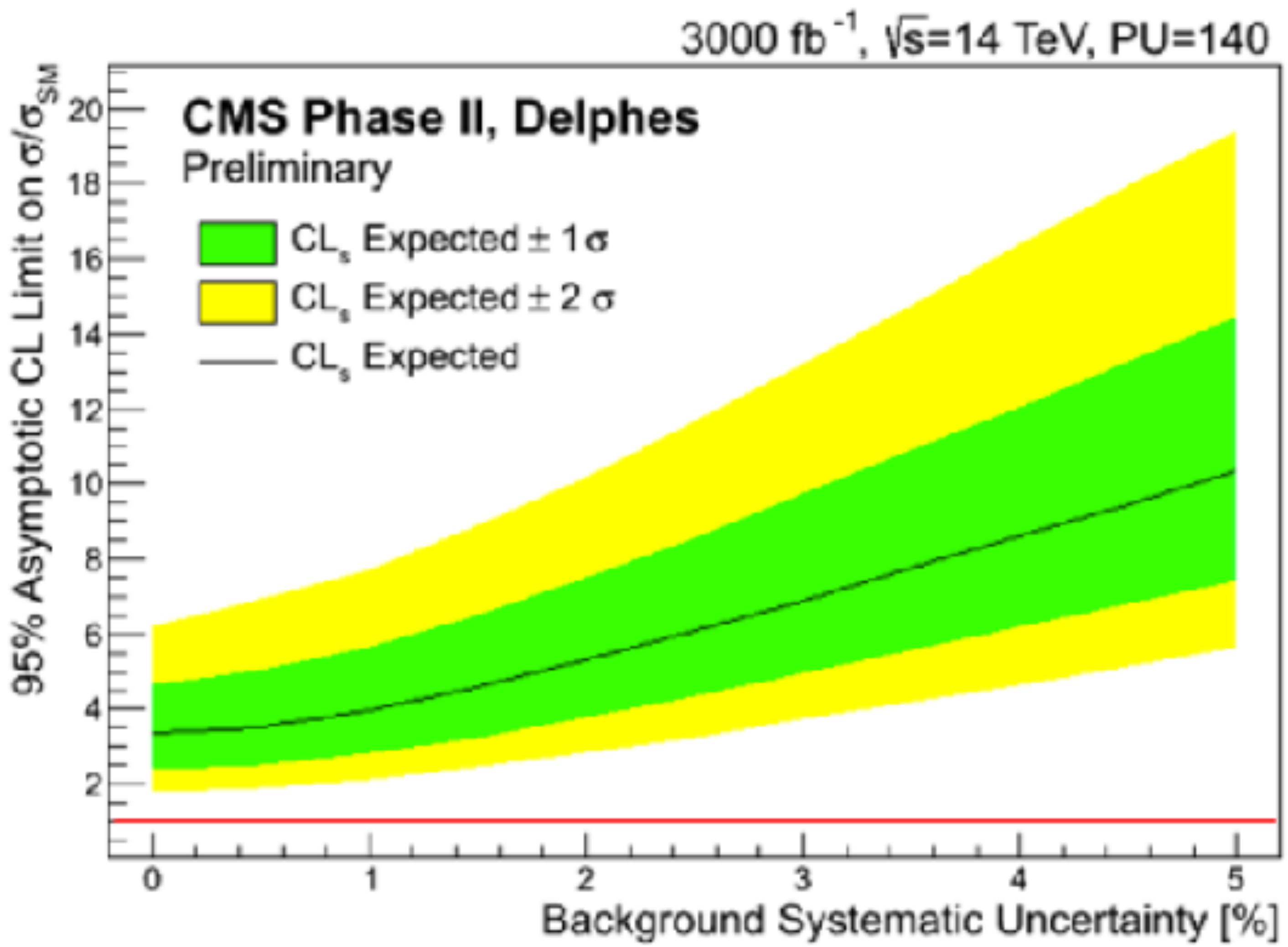
Analysis Optimization:

- Neural network discriminant from kinematic variables
- Variables: Mll, Mjj, ΔRll, ΔRjj, ΔRjl, MET, $\Delta\phi ll,jj$, pjj , and MT

Very large uncertainties in fit
Huge systematic uncertainties

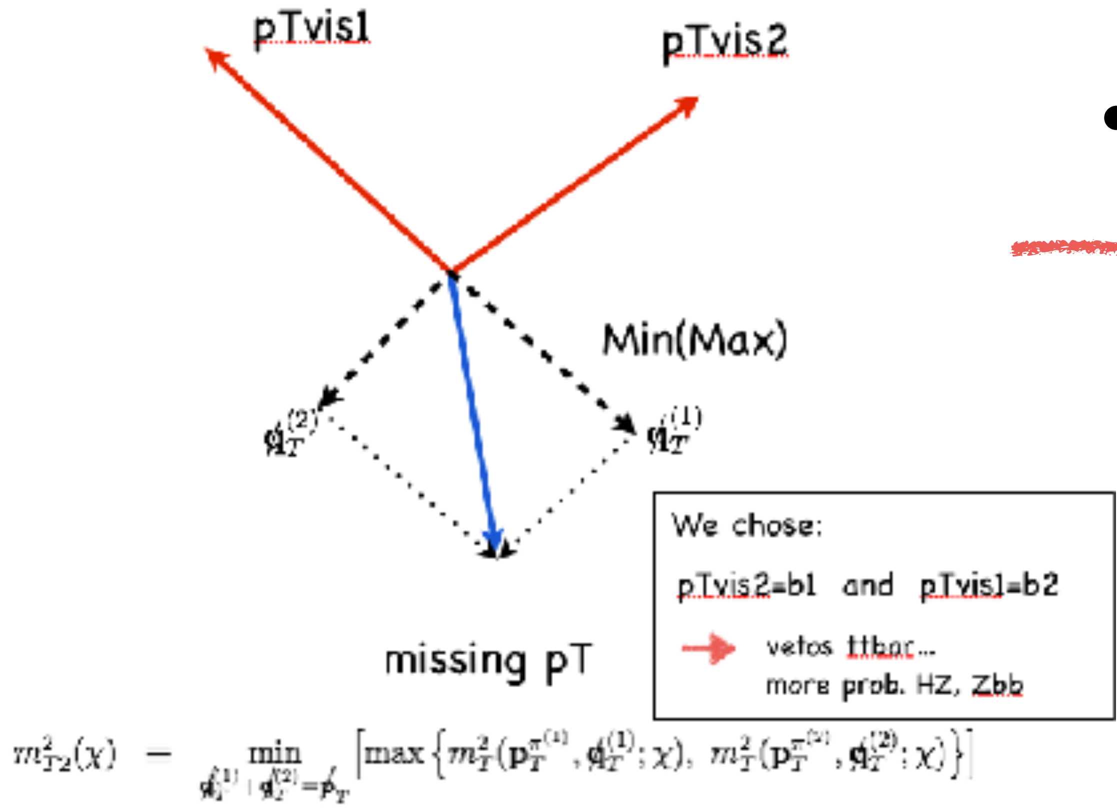
Analysis Setup:

- Phase II scenario Assuming 3000/fb
- Based on Delphes reconstruction
- Considering only the main background: $t\bar{t}$
- The rest of the SM processes are negligible



$b\bar{b}\tau^+\tau^-$

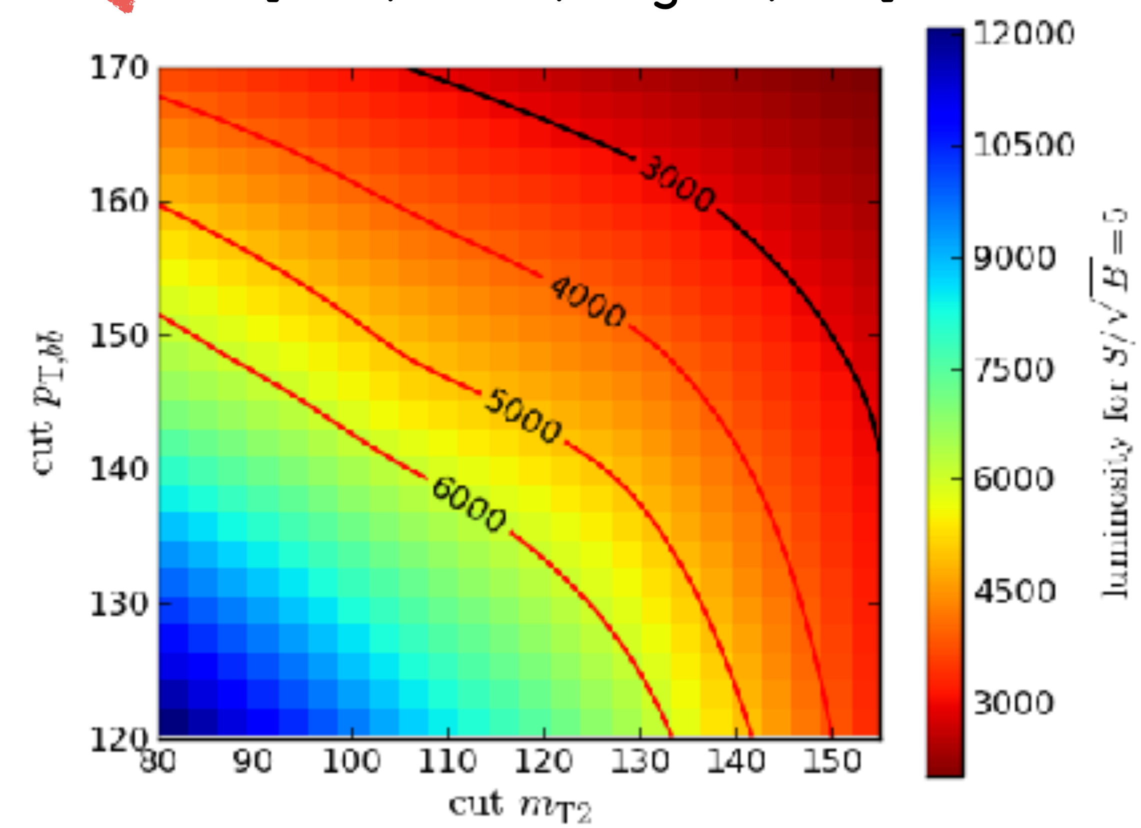
- Here, major background ttbar -> MT2 can change that
- Handles to suppress background: leptons, b-jets and MET



- Jet substructure can help in addition to mT2

  known to go very well together

[Barr, Dolan, Englert, MS]



- MT2 distribution discriminates between HH and ttbar

- Without jet substructure we find S/B ~ 1/5

  Exclusion at 95% CL: $\lambda > \lambda^{3000/\text{fb}}_{95\%\ \text{CL}} \simeq 3.0 \times \lambda_{\text{SM}}$