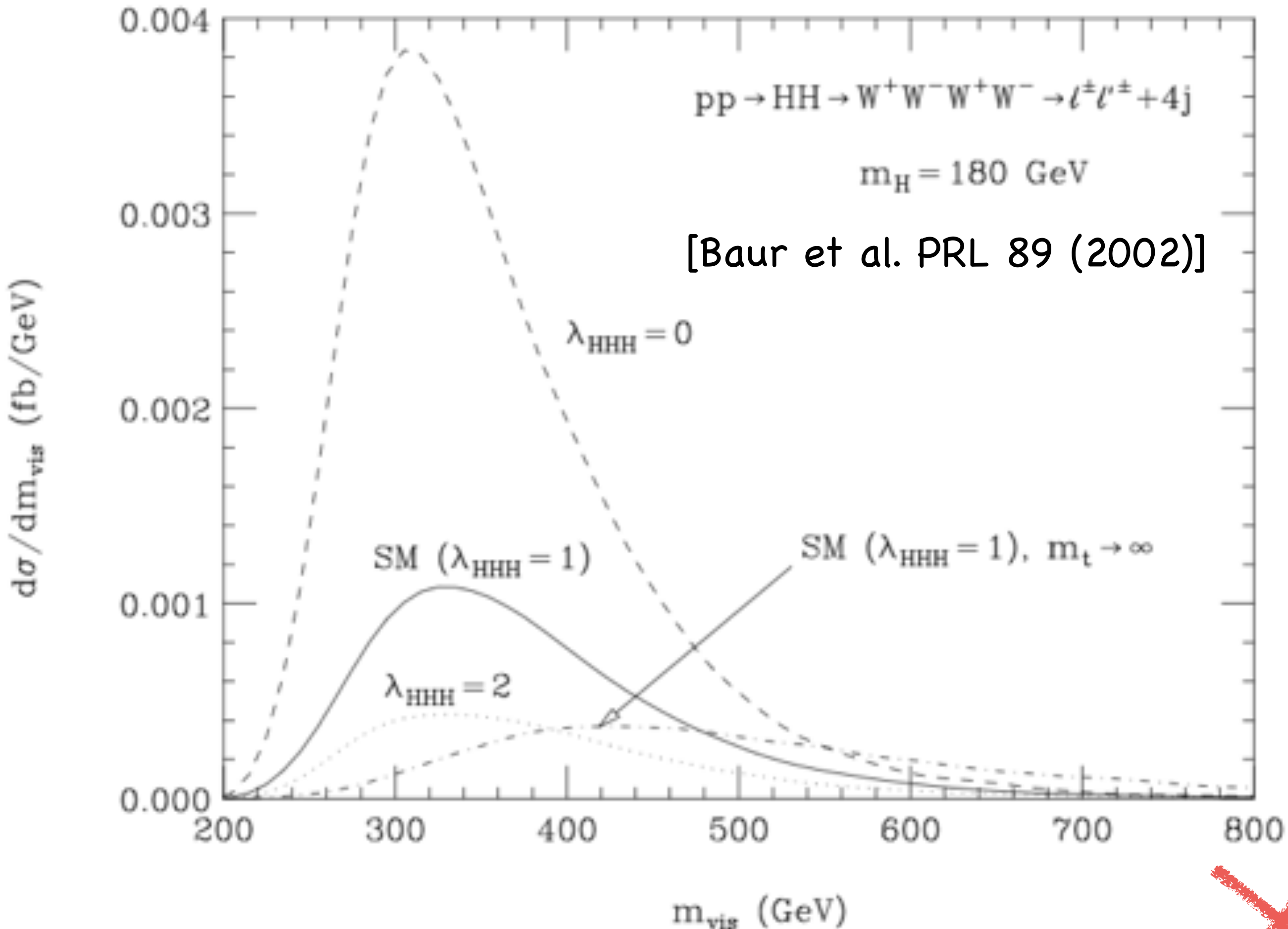
HH in the boosted regime

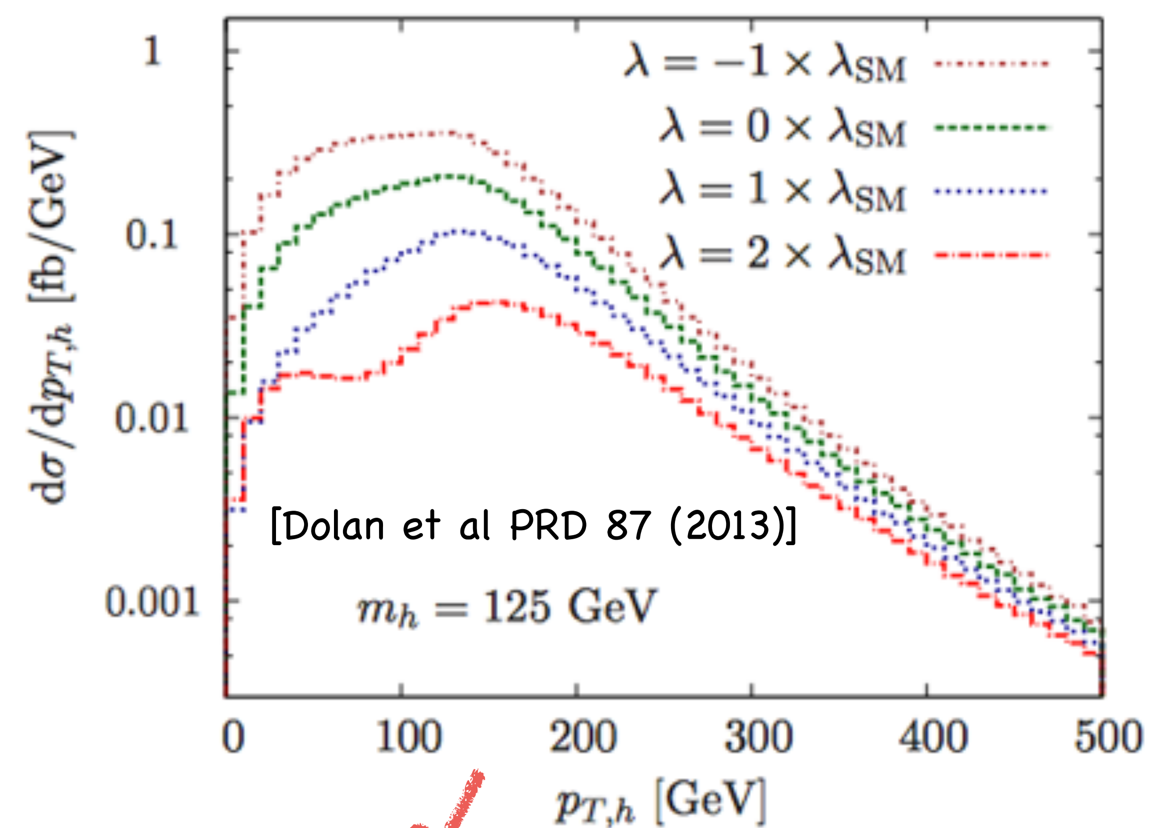
Michael Spannowsky

IPPP, Durham University

Kinematics for gg -> HH

2->2 scattering process completely determined by 2 variables,
e.g. S and T, E and scattering angle

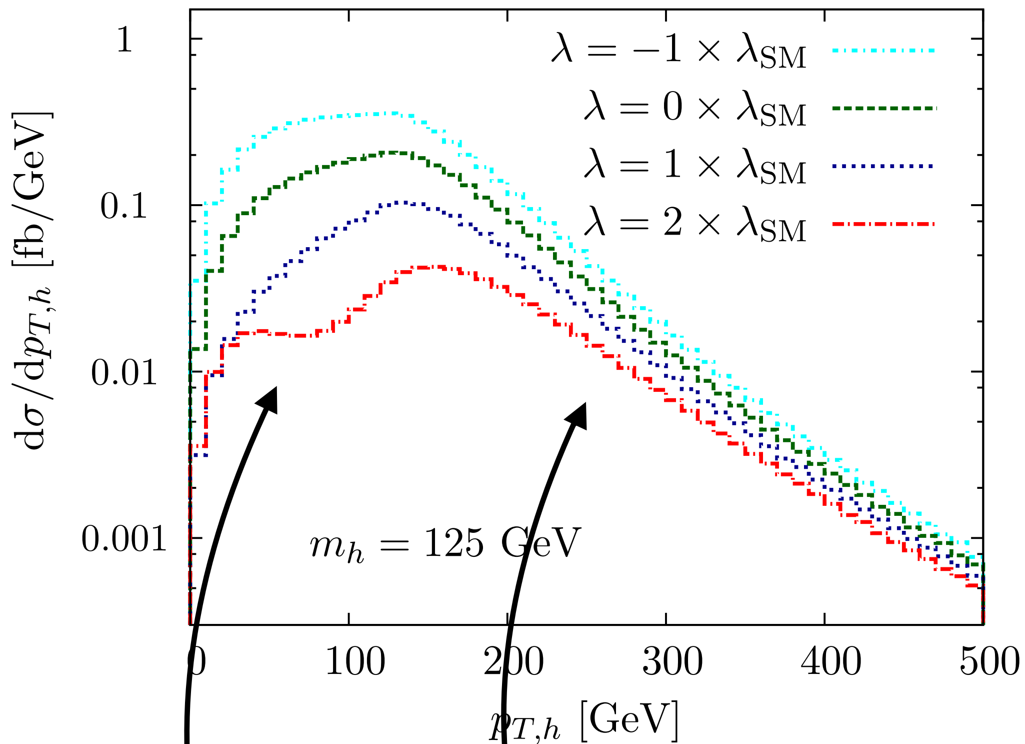


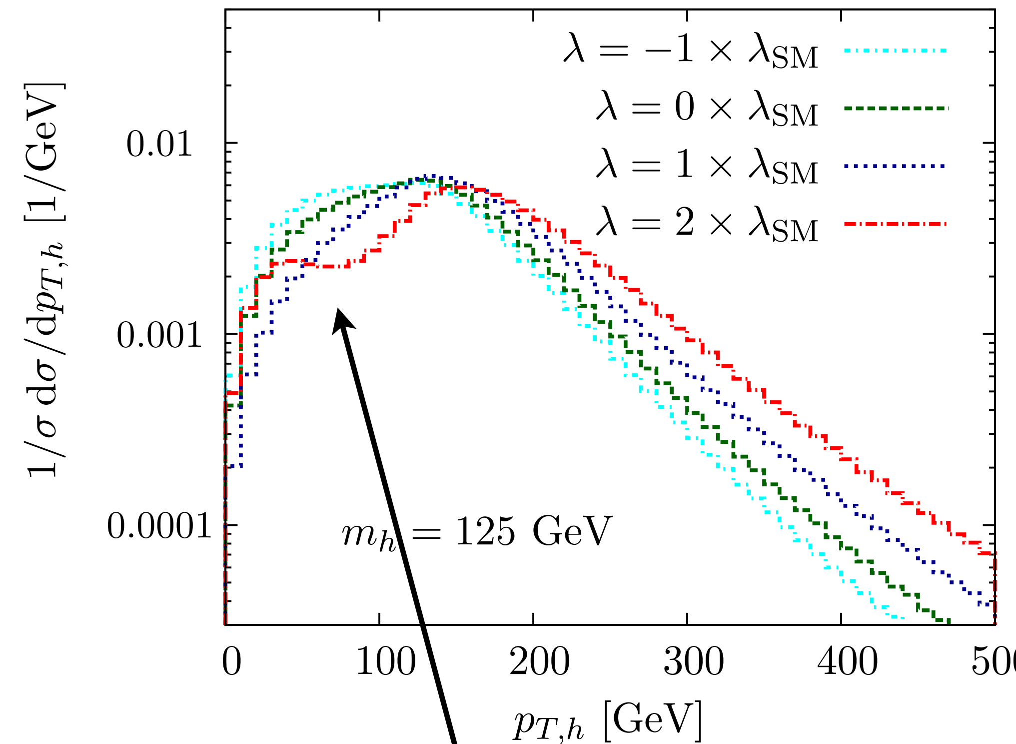


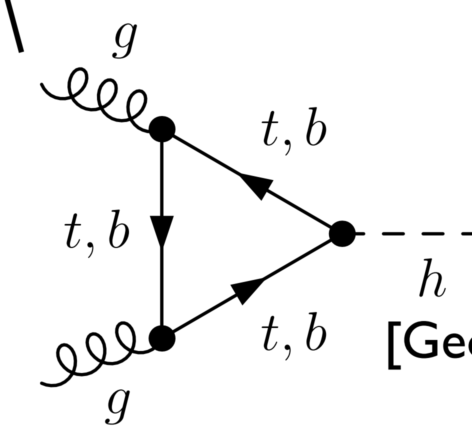
variables more close to reconstructed objects: m_{HH} and pT,H

- All SM and BSM effects covered by double-differential measurement of two variables
- Whether possible depends on signal rate and sensitivity in phase space (backgrounds)

Higgs selfcoupling in HH+X



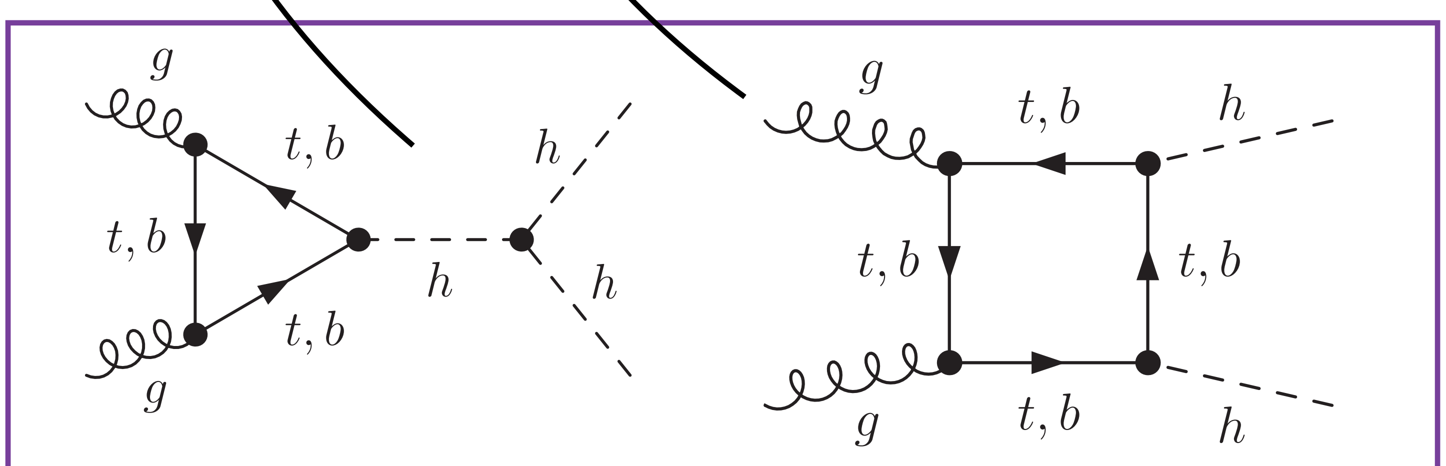




[Georgi et al. `78]

has maximum contribution for

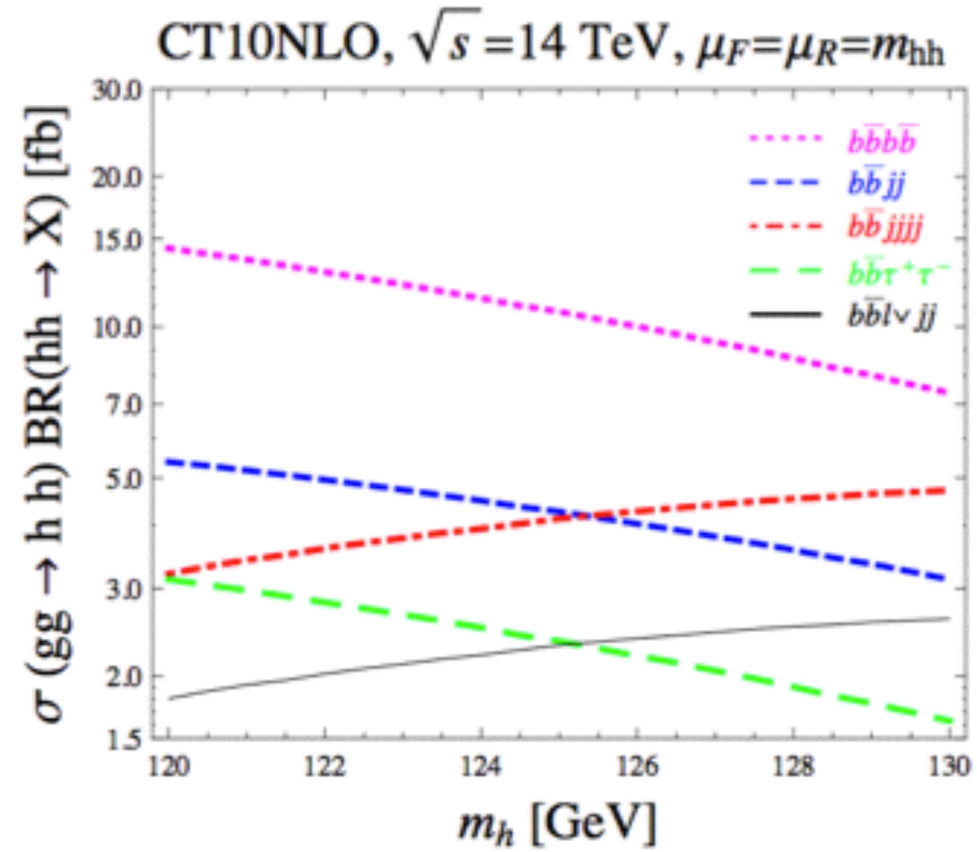
$$s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$$



Where is sensitivity located?

Measuring this small cross section in an inclusive search is very challenging at the HL-LHC: compromise between branching ratio and cleanliness of the signal

Channel	BR (%)	Events/3 ab
$bbWW$	24.7	30000
$bb\tau\tau$	7.3	9000
$WWWW$	4.3	5200
$bb\gamma\gamma$	0.27	330
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015	19
$\gamma\gamma\gamma\gamma$	0.00052	1



Several channels are currently under study by the collaborations

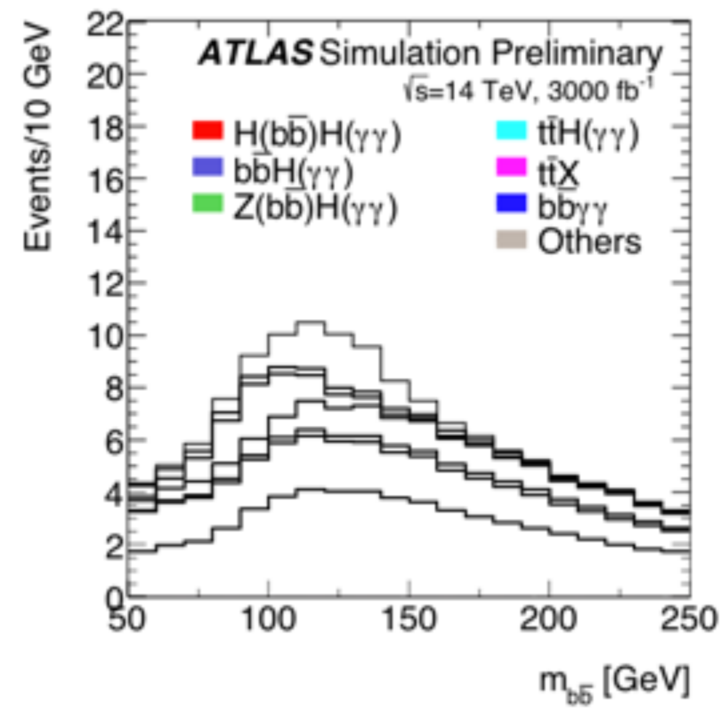
[James Ferrando, Talk at Royal Society Meeting]

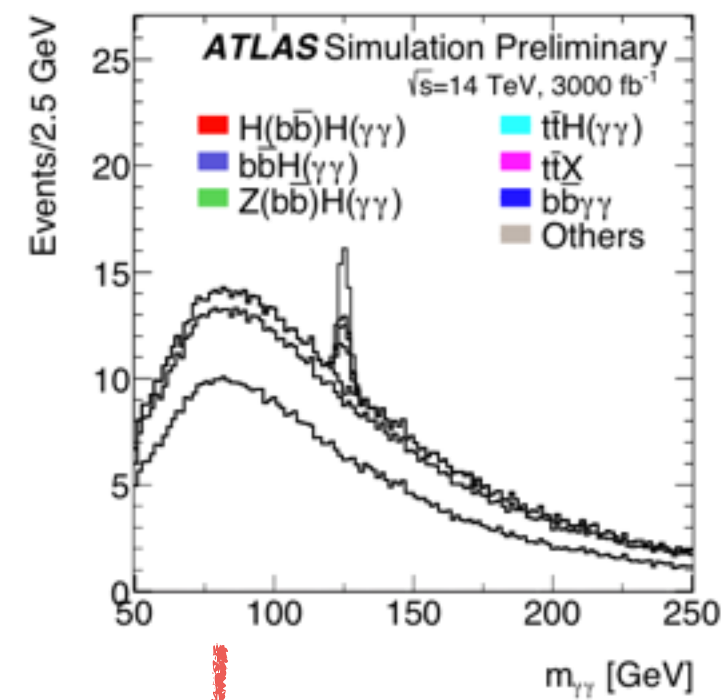
Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

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

[ATL-PHYS-PUB-2014-019]

- Rate challenging for creative reconstruction
- While side-band for photons clear, bump from bb very broad and background biased





3000 ifb

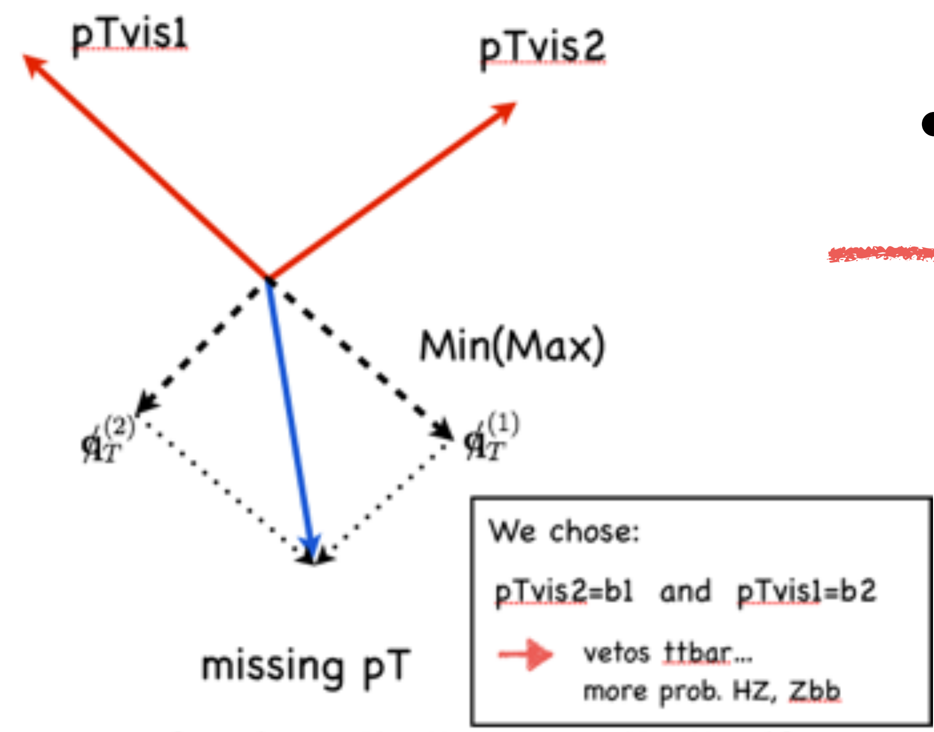
process	ATLAS		CMS
SM HH→bbγγ	8.4± 0.1		9.9
bbγγ	9.7 ± 1.5	γγ+jets	8.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2	γ+jets, jets	7.4
top background	3.4 ± 2.2		1.1
ttH(γγ)	6.1 ± 0.5		1.5
Z(bb)H(γγ)	2.7 ± 0.1		3.3
bbH(γγ)	1.2 ± 0.1		0.8
Total background	47.1 ± 3.5		22.6
S/√B (barrel+endcap)	1.2		
S/√B (split barrel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

CMS gives 60% uncertainty on signal CS measurement

BKG quite different!

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

- Handles to suppress background: leptons, b-jets and MET

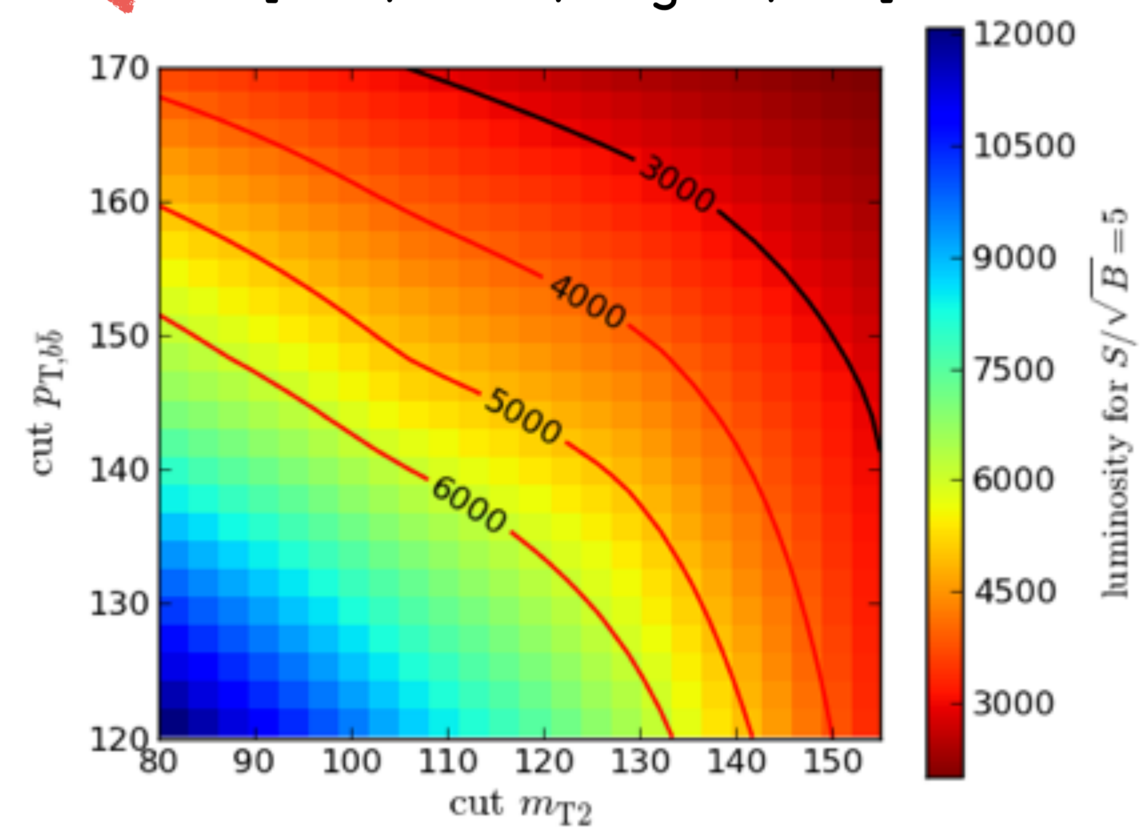


$$m_{T2}^2(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{p}_T} \left[\max\left\{m_T^2(\mathbf{p}_T^{\pi^{(1)}}, \not{q}_T^{(1)};\chi),\ m_T^2(\mathbf{p}_T^{\pi^{(2)}}, \not{q}_T^{(2)};\chi)\right\}\right]$$

- Jet substructure can help in addition to mT2

known to go very well together

[Barr, Dolan, Englert, MS]



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

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

- However, tau reconstruction using optimistic kinematic fitting approach and no discrimination between lepton/hadron taus

$\bar{b}bW^+W^-$:

$$hh \to b\bar{b}W^+W^- \to b\bar{b}\ell\nu jj$$

- Fully reconstructable final state
- Triggering easy due to lepton
- But looks like ttbar...

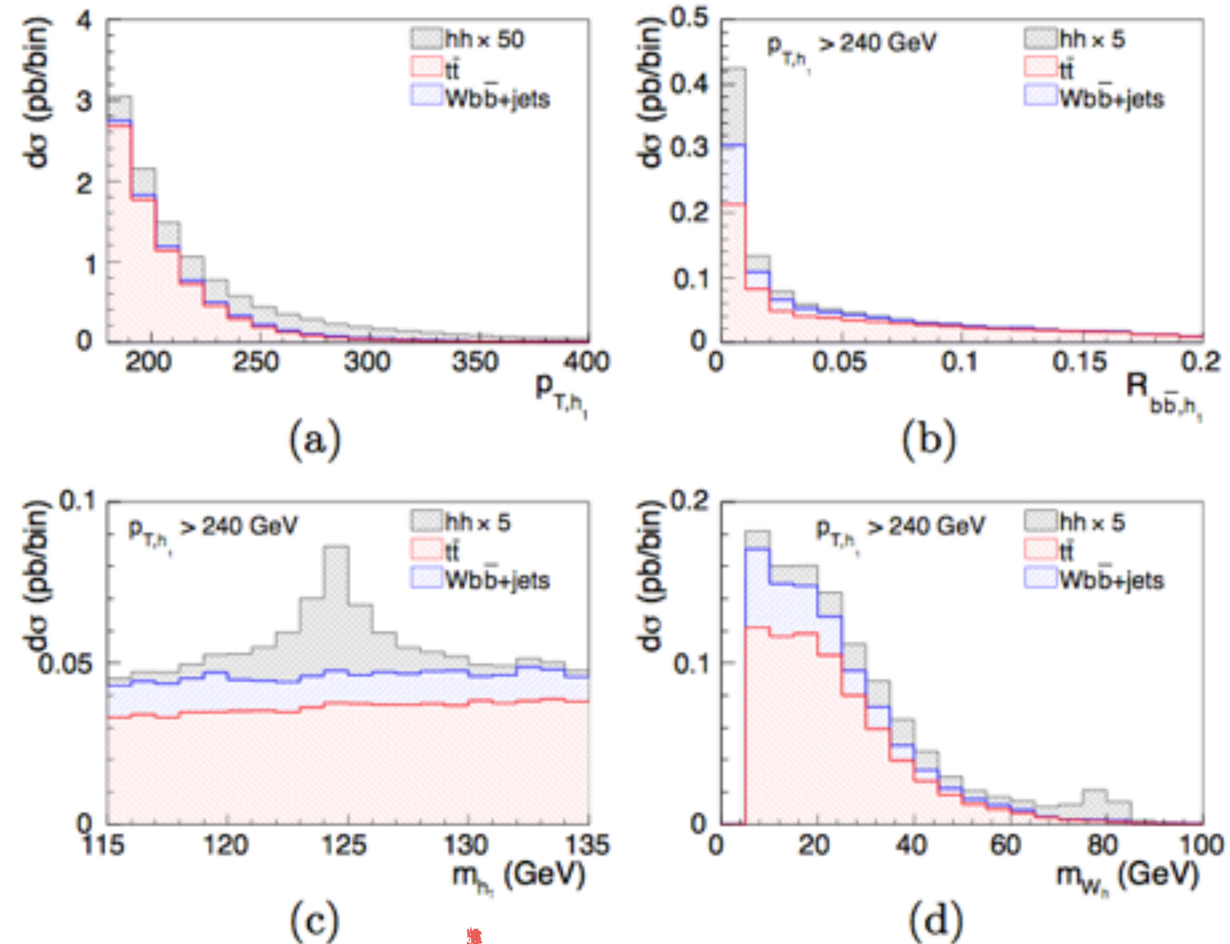
Process	$\sigma_{\rm initial}$ (fb)	$\sigma_{\rm basic}$ (fb)
$hh \to b\bar{b}\ell\nu jj$	2.34	0.134
$t\bar{t} \to b\bar{b}\ell\nu jj$	240×10^3	15.5
$W(\to \ell\nu)b\bar{b}$+jets	2.17×10^3	0.97
$W(\to \ell\nu)$+jets	2.636×10^6	$\mathcal{O}(0.01)$
$h(\to \ell\nu jj)$+jets	36.11	$\mathcal{O}(0.0001)$
$h(\to \ell\nu jj)b\bar{b}$	6.22	$\mathcal{O}(0.001)$
$h(\to b\bar{b}) + WW(\to \ell\nu jj)$	0.0252	-

For SM coupling

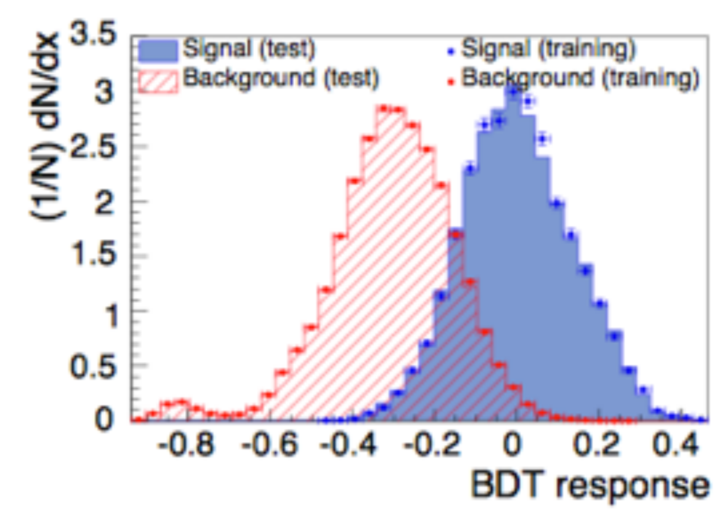
$S/\sqrt{S+B} \sim 2.4$ $\quad$ 3.1σ

with S=9 and B=6 after 600 ifb

[Papaefstathiou, Yang, Zurita]



BDT



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:

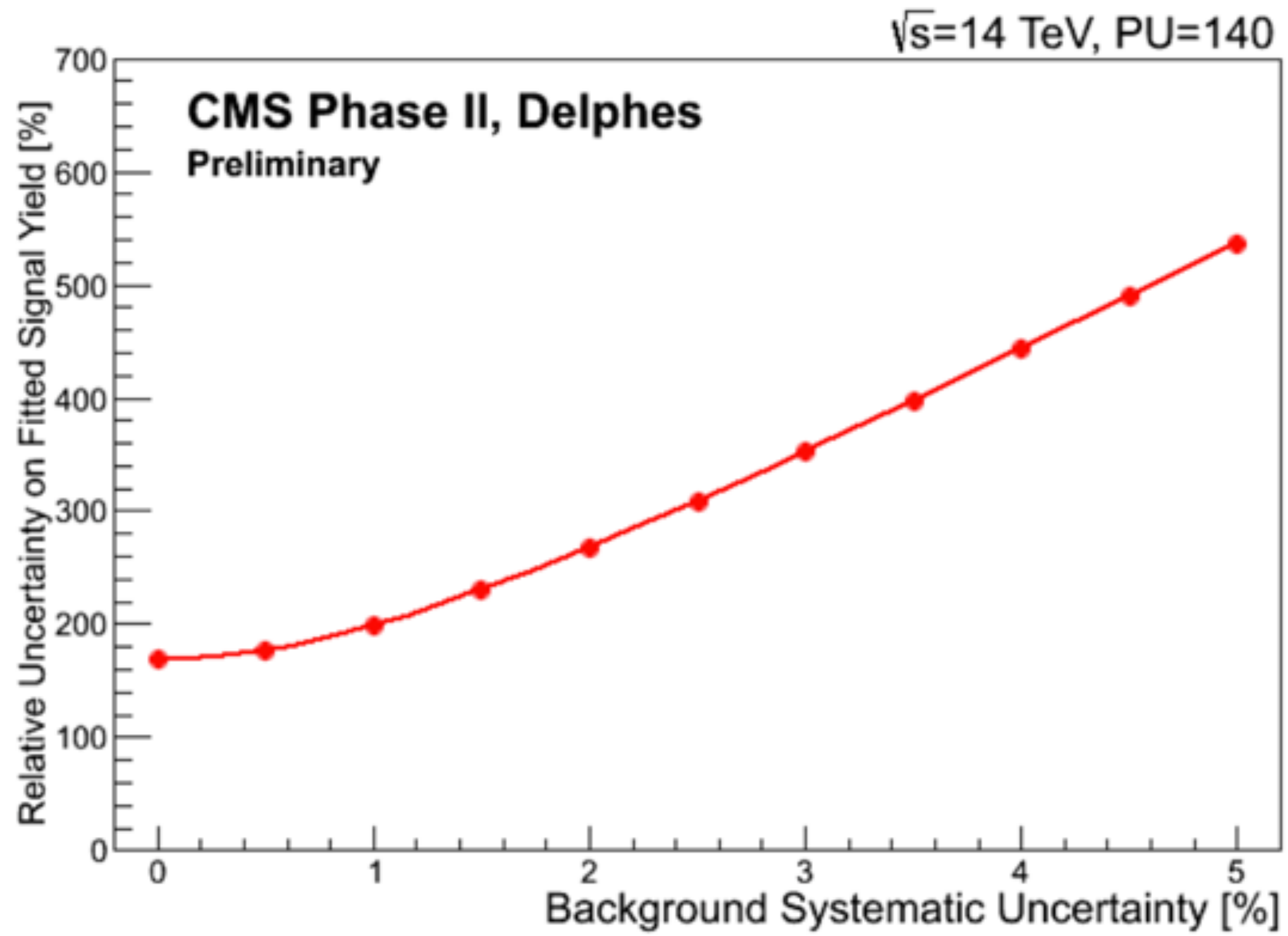
- Neural network discriminant from kinematic variables
- Variables: Mll, Mjj, ΔRll, ΔRjj, ΔRjl, MET, $\Delta\phi ll,jj$, pjj , and MT

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



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

[Baur, Plehn, Rainwater]

[Dolan, Englert, MS]

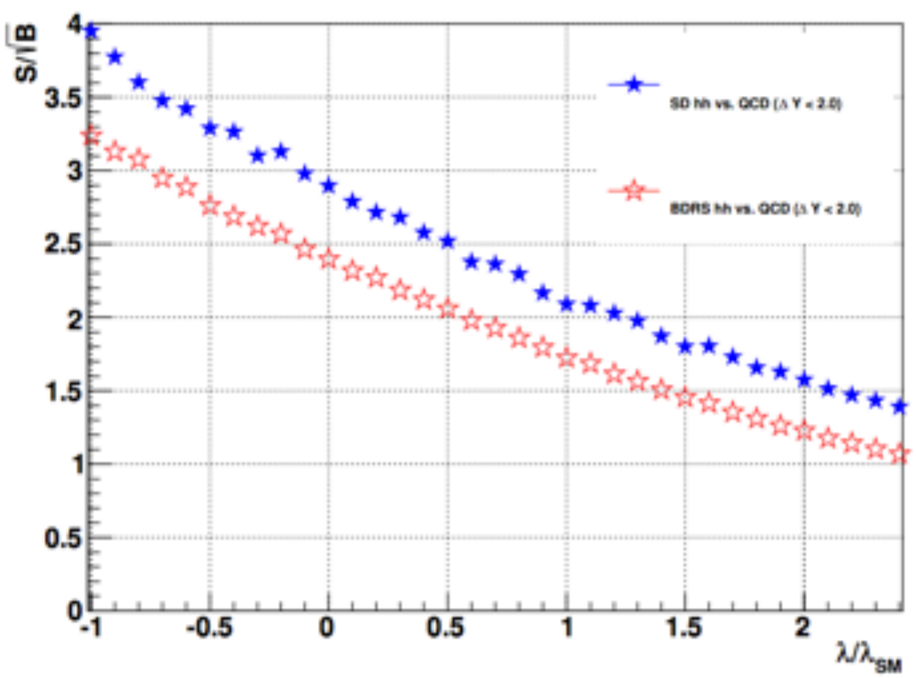
[Papaefstathiou, Ferreira, MS]

[Wardrope, Jansen, Konstantinidis, Cooper, Falla, Norjoharudeen]

- Difficult to trigger (requires large pT cuts or fat jet)
- Huge QCD backgrounds
- Can try to use jet substructure techniques to overcome large backgrounds
- Maybe sideband possible?
- After reconstruction and 3000 ifb:
- S/B ~ 1/20

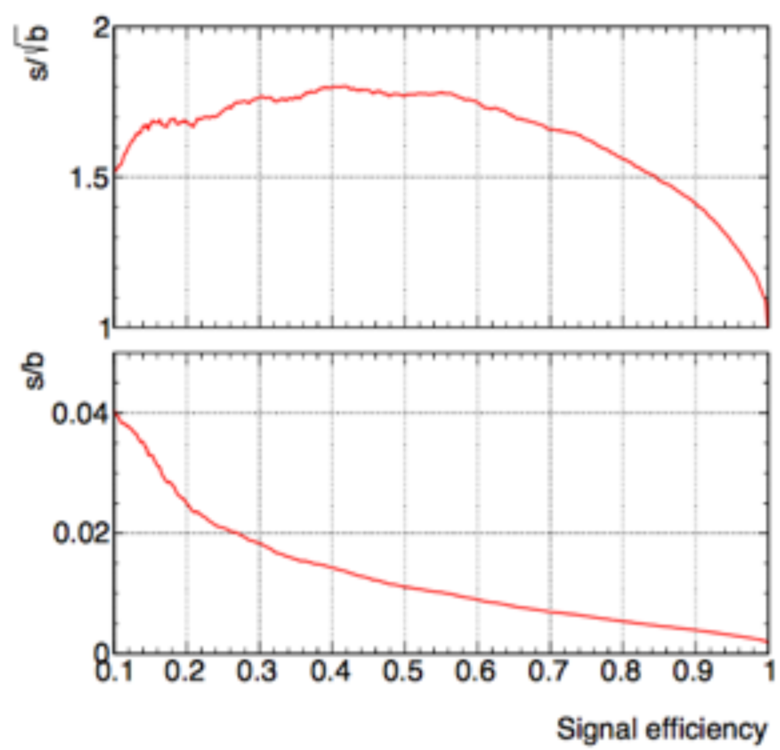
sample	σ_{initial} (fb)
$hh,\ h \to b\bar{b}$ (SM)	10.7
QCD $(b\bar{b})(b\bar{b})$	151.1×10^3
$Zb\bar{b},\ Z \to b\bar{b}$	8.8×10^3
$hZ,\ h \to b\bar{b},\ Z \to b\bar{b}$	70.0
$hW,\ h \to b\bar{b},\ W \to c\bar{b}(\bar{c}b)$	96.4

Boosted + Jet substructure



consistent

Resolved + BDT (incl. ttbar BKG)



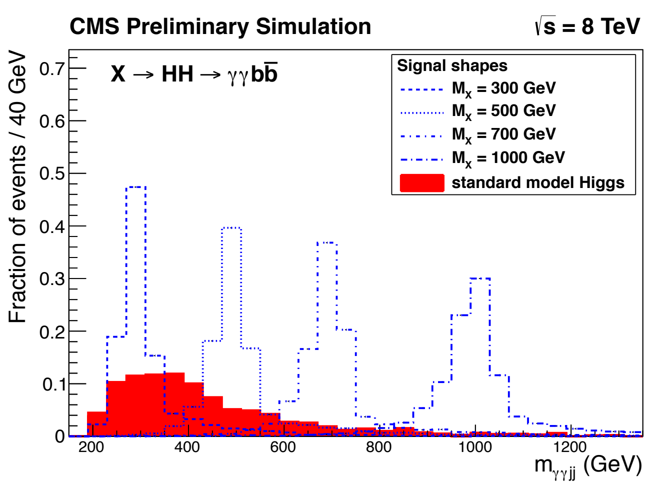
New Physics for HH

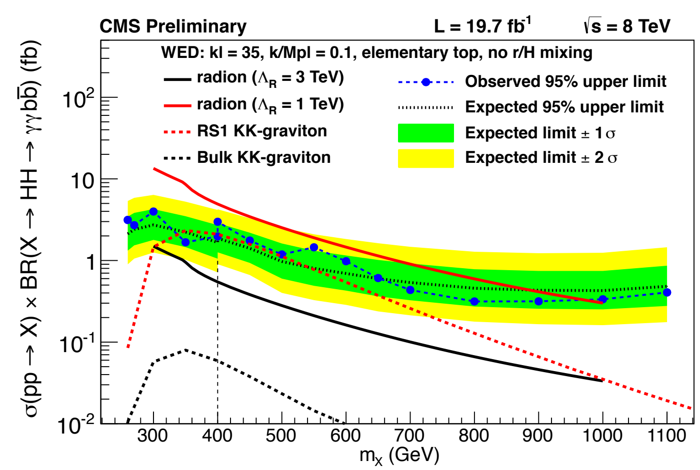
Resonant enhancement:

- SUSY, H -> hh [A lot..]
- E-dim, G -> hh -> 4b [Gouzevitch et al. 1303.6636]
- Higgs portal [No, Ramsey-Musolf 1310.6035]

Cross section can be significantly enhanced -> interesting for small BR

[CMS-PAS-HIG-13-032]

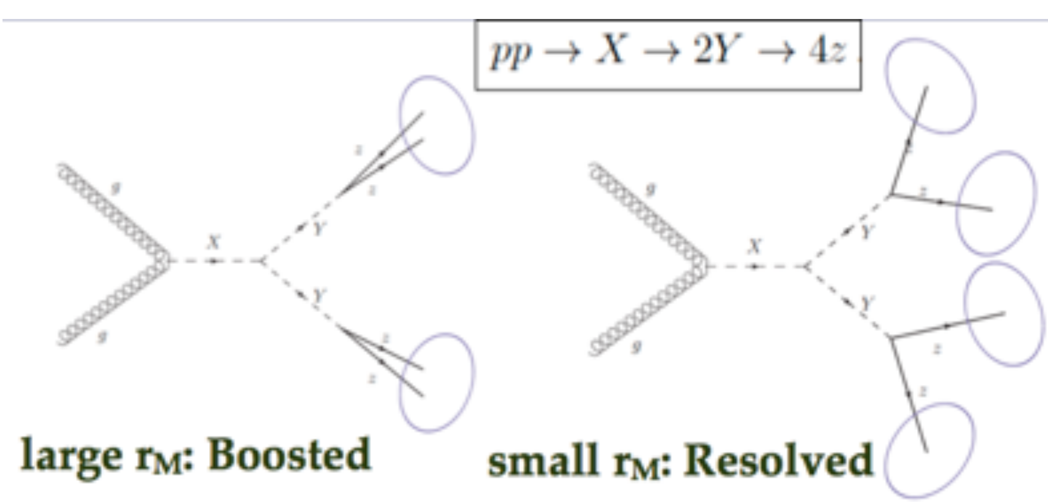


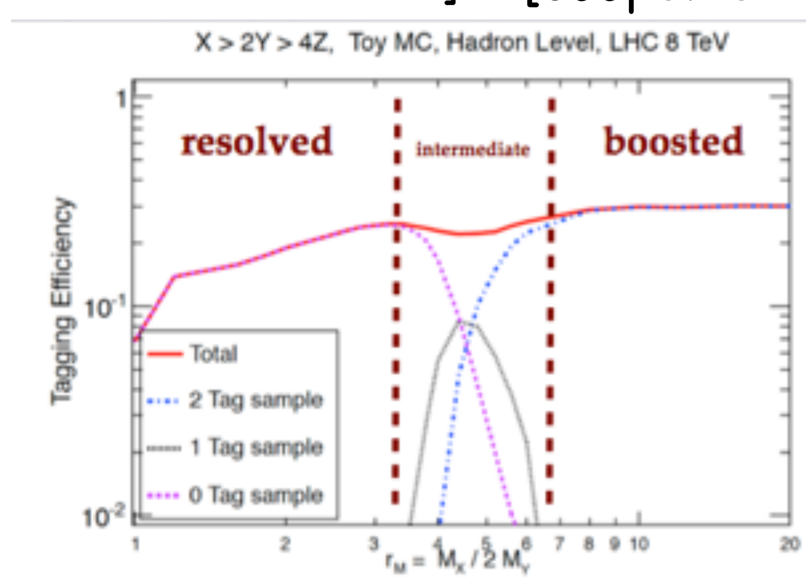


Constraint on heavy resonances, e.g. radion

Relevant phase space region shifted to high pT -> interesting for 4b

[Gouzevitch et al. 1303.6636] [ATLAS-CONF-2014-005] [Cooper et al]



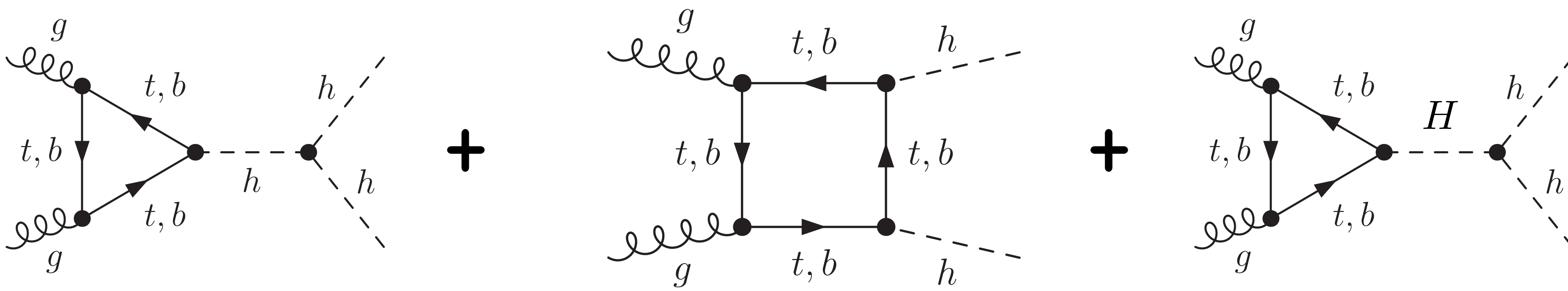


scale invariant reconstruction

New Physics for HH

Resonant enhancement:

- SUSY, H -> hh [A lot..]
- E-dim, G -> hh -> 4b [Gouzevitch et al. 1303.6636]
- Higgs portal [No, Ramsey-Musolf 1310.6035]

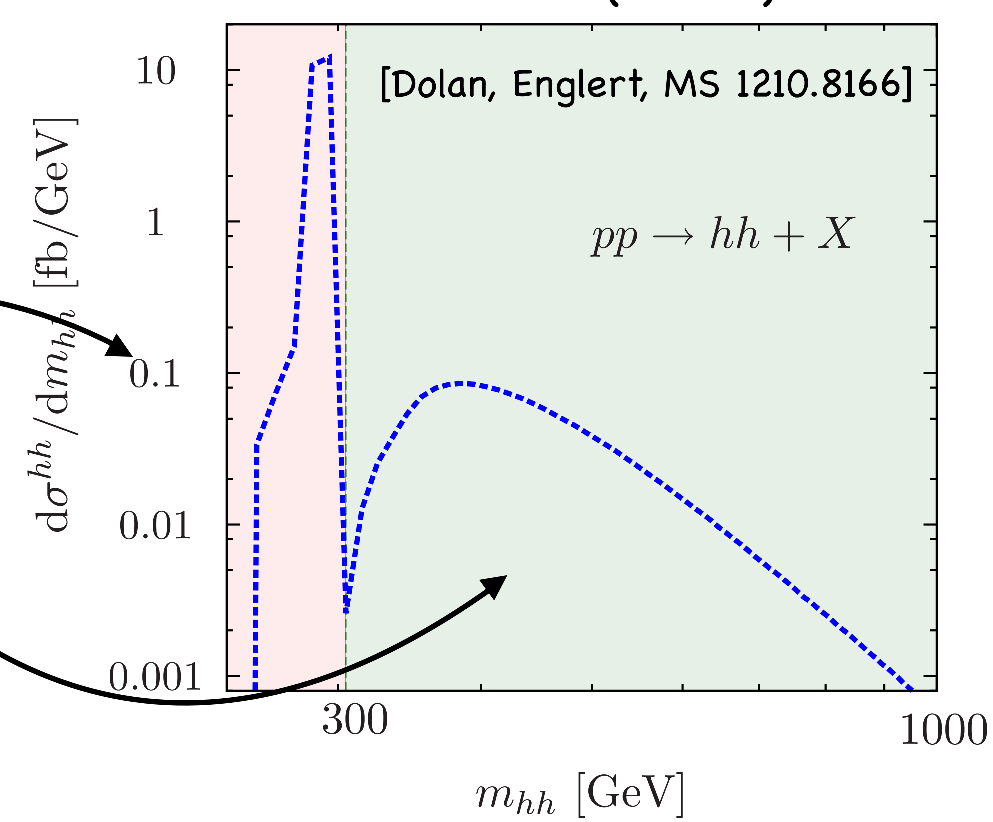


Interplay between BSM resonance and SM results in characteristic resonant/continuum m_{inv} pattern

$$\lambda_{Hhh} = 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha)$$
$$\lambda_{hhh} = 3\cos 2\alpha \sin(\beta+\alpha)$$

Measurement of rel. CS Hhh and hhh translates directly to measurement of α and β

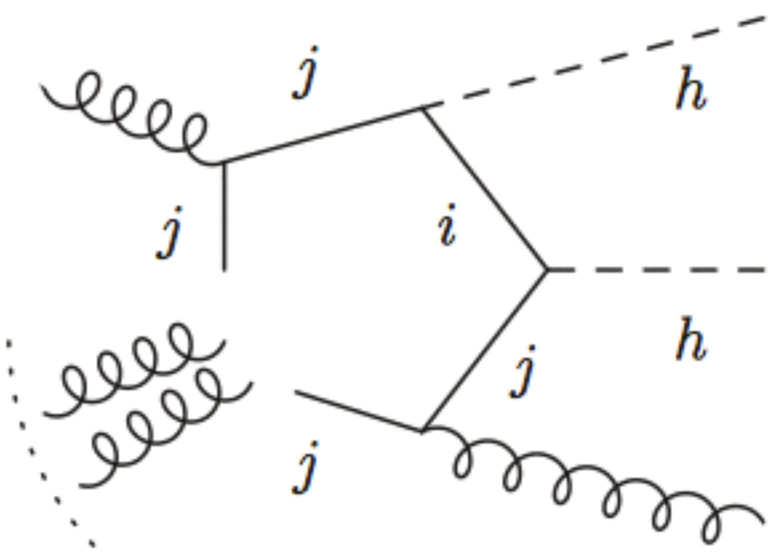
Assuming decoupling limit such that MH > 2 Mh and BR(H->hh) = 45%

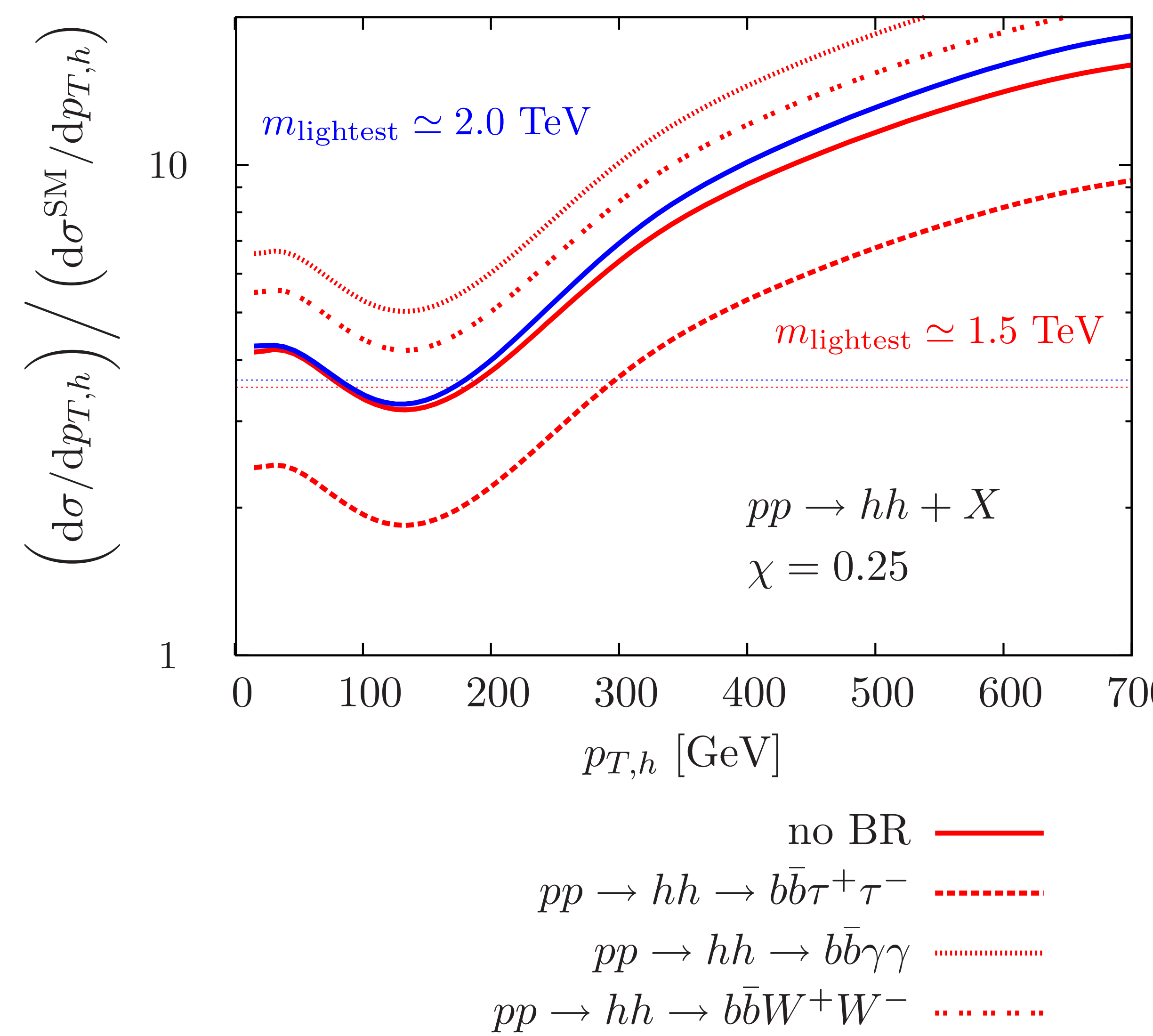


New Physics for HH

Continuum/Loop enhancement

- Composite Higgs [Contino et al. JHEP 1208]
- 4th generation [Kribs, Plehn, Tait, MS 0706.3718]
- Other theories modifying $hh\bar{t}_i t_j$ or $h\bar{t}_i t_j$



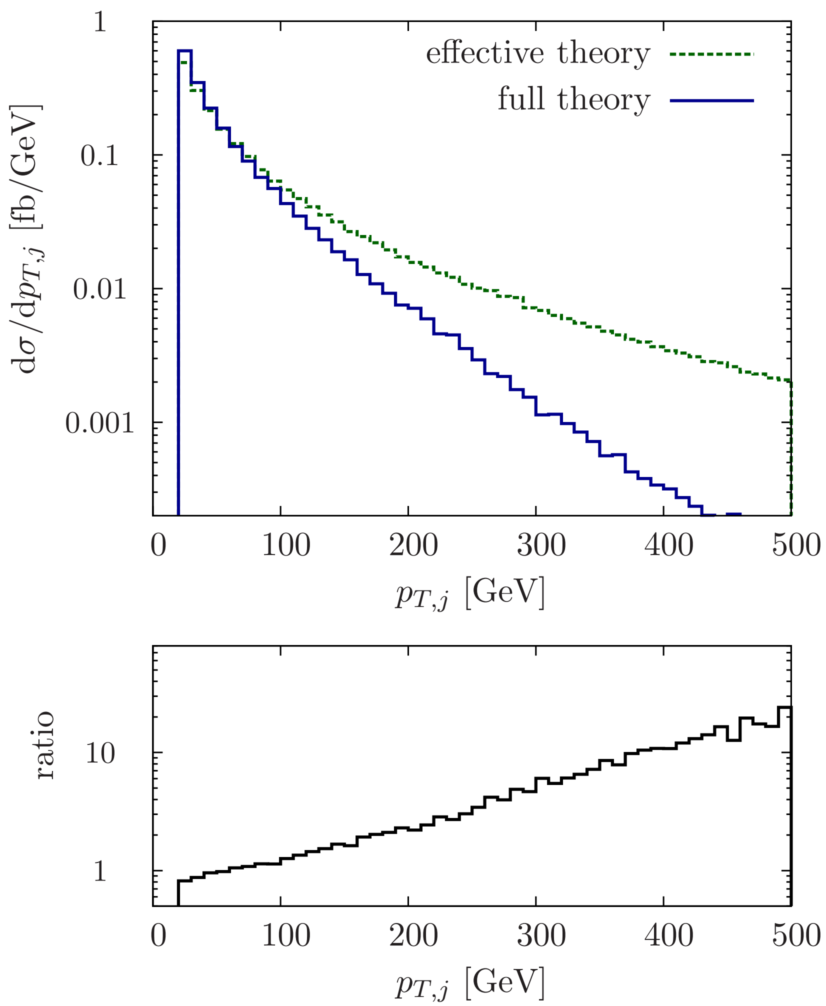


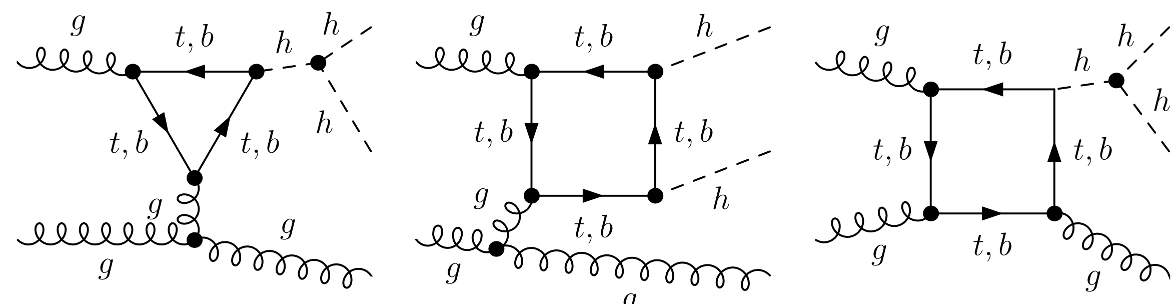
- Model-dependent and possibly complicated loop structure
- Can obtain strong enhancement in large pT,H region

More jets can keep m_{inv} small and pT,H large

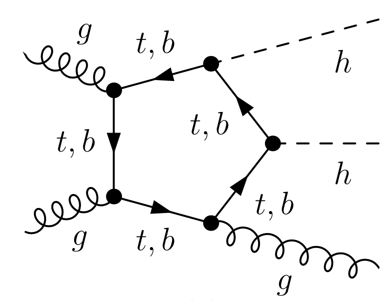
- need to work a little harder

Eff. theory breaks down quickly





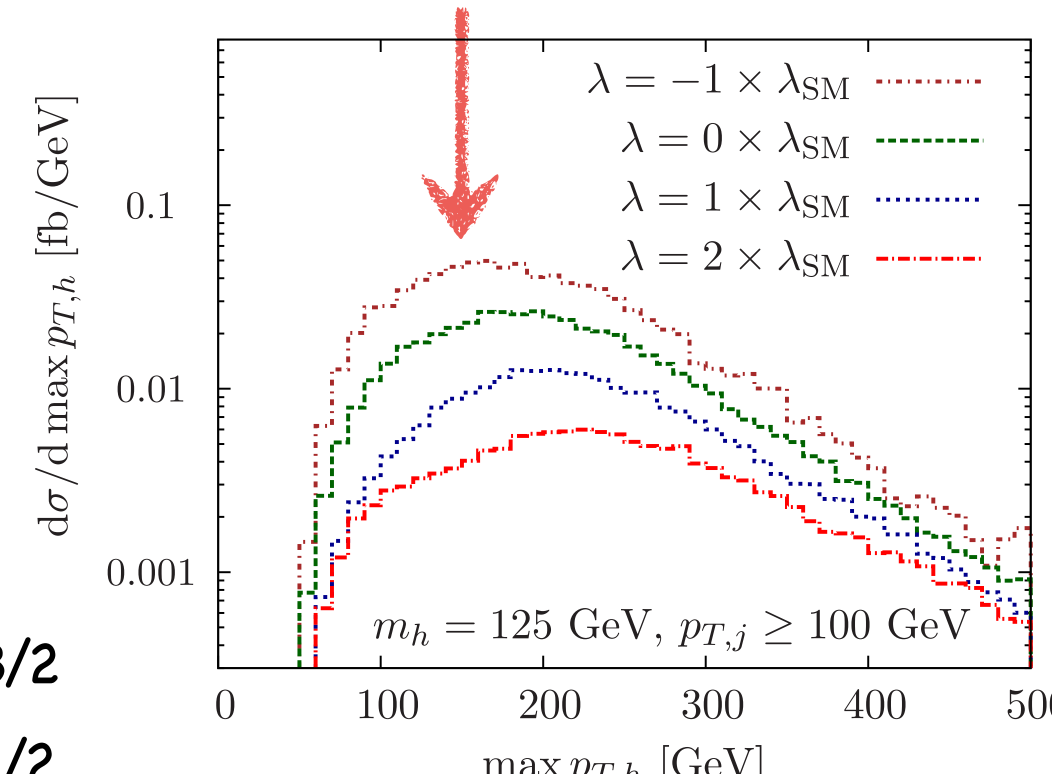
(a) (b) (c)



(d)

+ quark & gluon induced

retain sensitivity for boosted Higgs

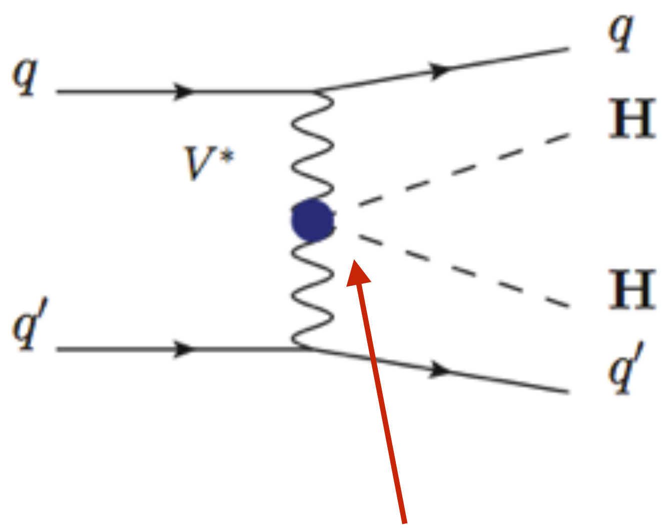


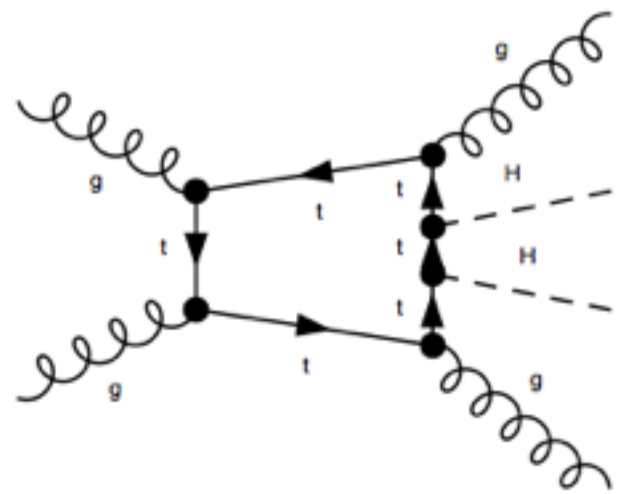
Additional jet can help to suppress backgrounds:

$hhj \to b\bar{b}\tau^+\tau^- j$ S/B ~ 3/2

$hh \to b\bar{b}\tau^+\tau^-$ S/B ~ 1/2

Higgs selfcoupling in HHjj+X





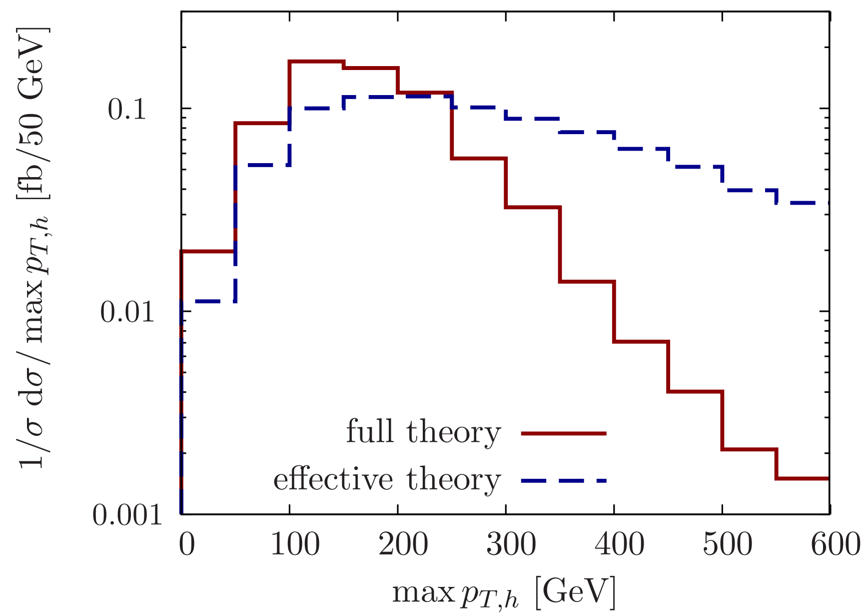
[Contino et al. JHEP 1005]

[Baglio et al. JHEP 1304]

[Dolan, Englert, Greiner, MS]

- Want to study VVHH
  Directly related to long. gauge boson scattering $V_L V_L \to hh$
- In SM fixed: $g_{WWhh} = e^2/(2s_w^2)$ $g_{ZZhh} = e^2/(2c_w^2 s_w^2)$
- However in BSM models, e.g. composite (strongly coupled light) Higgs models, can be strongly modified
- Higher-dim operators momentum dependent -> enhanced in high-pT region

Higgs selfcoupling in HHjj+X



- For kinematic distributions full loop recommended in gluon fusion
- Analysis in $\bar{b}b\tau^+\tau^-$
- Very bad S/B, but expected to improve easily...

So far very rudimentary analysis:

	Signal with $\xi \times \lambda$			Background		S/B
	$\xi = 0$	$\xi = 1$	$\xi = 2$	$t\bar{t}jj$	Other BG	ratio to $\xi = 1$
tau selection cuts	0.212	0.091	0.100	3101.0	57.06	0.026×10^{-3}
Higgs rec. from taus	0.212	0.091	0.100	683.5	31.92	0.115×10^{-3}
Higgs rec. from b jets	0.041	0.016	0.017	7.444	0.303	1.82×10^{-3}
2 tag jets	0.024	0.010	0.012	5.284	0.236	1.65×10^{-3}
incl. GF after cuts/re-weighting	0.181	0.099	0.067	5.284	0.236	1/61.76

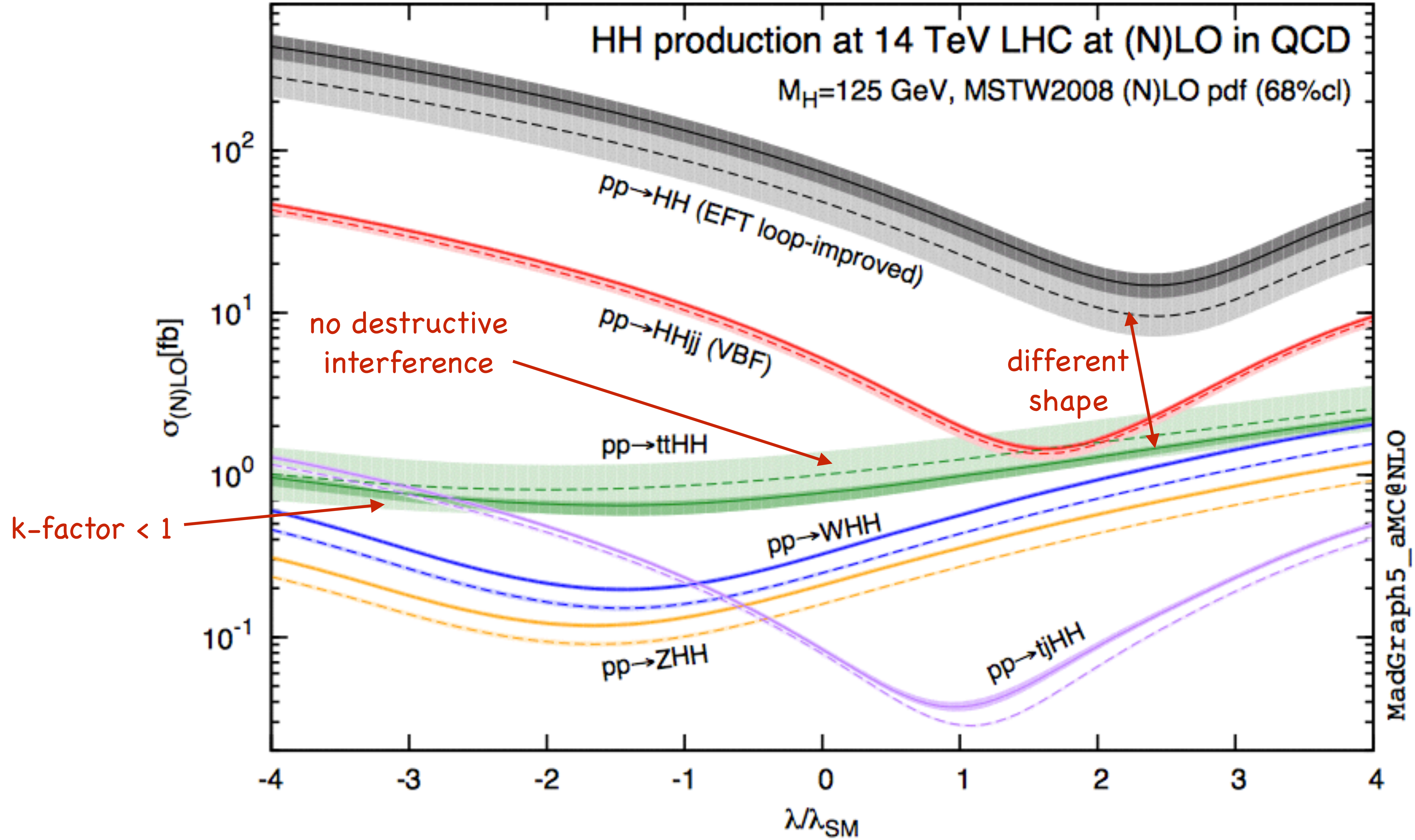
WBF only

GF+WBF

	Signal with $\zeta \times \{g_{WWhh}, g_{ZZhh}\}$			Background	
	$\zeta = 0$	$\zeta = 1$	$\zeta = 2$	$t\bar{t}jj$	Other BG
tau selection cuts	1.353	0.091	0.841	3101.0	57.06
Higgs rec. from taus	1.352	0.091	0.840	683.5	31.92
Higgs rec. from b jets	0.321	0.016	0.207	7.444	0.303
2 tag jets/re-weighting	0.184	0.010	0.126	5.284	0.236
incl. GF after cuts/re-weighting	0.273	0.099	0.214	5.284	0.236

Higgs selfcoupling in ttHH

[Frederix et al. PLB 732 (2014)]



Higgs selfcoupling in ttHH

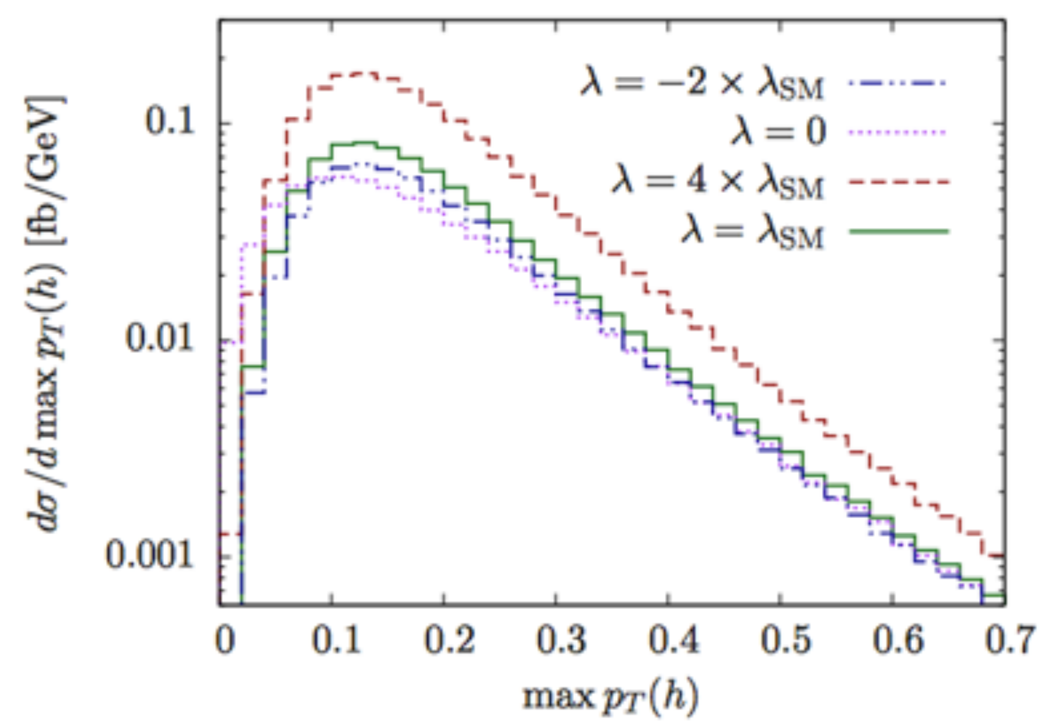
[Englert, Krauss, MS, Thompson]

[Liu, Zhang]

	signal		backgrounds					
	$\xi = 1$	$\xi = 4$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}hb\bar{b}$	$t\bar{t}hZ$	$t\bar{t}Zb\bar{b}$	$t\bar{t}ZZ$	$Wb\bar{b}b\bar{b}$
trigger	0.10	0.23	4.75	1.38	0.64	1.37	1.36×10^{-2}	1.33
jet cuts	7.40×10^{-2}	0.17	1.44	0.76	0.40	0.65	8.74×10^{-3}	7.46×10^{-2}
5 b tags	1.23×10^{-2}	2.83×10^{-2}	4.46×10^{-2}	6.19×10^{-2}	7.24×10^{-3}	4.43×10^{-2}	1.25×10^{-3}	5.35×10^{-4}
$2\times h\to b\bar{b}$	7.33×10^{-3}	1.69×10^{-2}	1.59×10^{-2}	2.71×10^{-2}	3.41×10^{-3}	1.56×10^{-2}	4.28×10^{-4}	$<1\times10^{-4}$
lep./had. t	5.04×10^{-3}	1.12×10^{-2}	9.50×10^{-3}	1.66×10^{-2}	2.29×10^{-3}	9.42×10^{-3}	2.69×10^{-4}	$<1\times10^{-4}$
lep. t only	2.33×10^{-3}	5.29×10^{-3}	5.03×10^{-3}	9.36×10^{-3}	1.14×10^{-3}	4.90×10^{-3}	1.39×10^{-4}	$<1\times10^{-4}$
had. t only	2.71×10^{-3}	5.93×10^{-3}	4.47×10^{-3}	7.20×10^{-3}	1.16×10^{-3}	4.44×10^{-3}	1.30×10^{-4}	$<1\times10^{-4}$
6 b tags	2.21×10^{-3}	4.97×10^{-3}	3.80×10^{-3}	8.01×10^{-3}	9.57×10^{-4}	5.10×10^{-3}	1.86×10^{-4}	$<1\times10^{-4}$
$2\times h\to b\bar{b}$	1.81×10^{-3}	5.94×10^{-3}	2.01×10^{-3}	5.47×10^{-3}	6.60×10^{-4}	3.28×10^{-3}	1.11×10^{-4}	$<1\times10^{-4}$

- Signal rate too small for inventive reconstruction
- Though Backgrounds for 5+ b-tags already small
- 13-22 signal event with 3000 ifb

$$\lambda \lesssim 2.51\ \lambda_{SM} \text{ at } 95\% \text{ CLs.}$$



Summary

- Separation of signal and background most limiting factor to measure Higgs selfcoupling at LHC

- Exploiting boosted topologies in leptonic or hadronic decays can help to increase sensitivity

- However, sensitivity in individual channels expected to be low in any case. Combination of many channels necessary.

- New Physics is expected to give rise to enhancement in Higgs pT tail