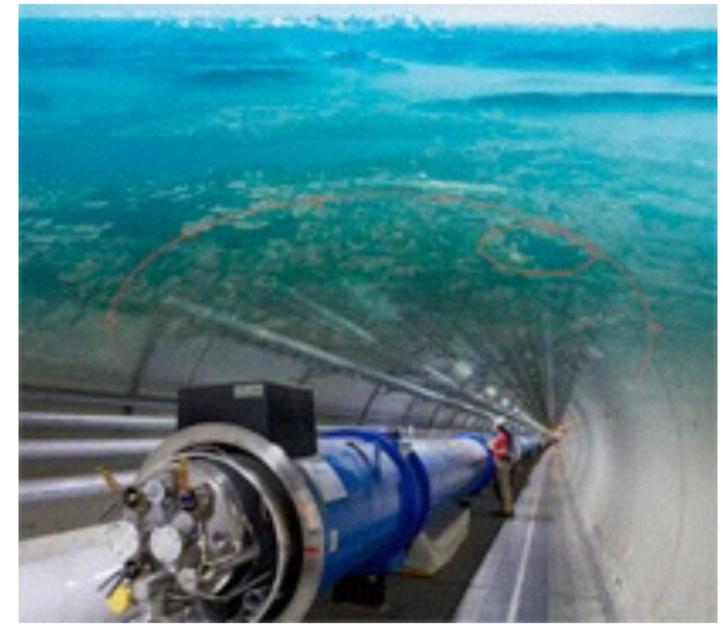


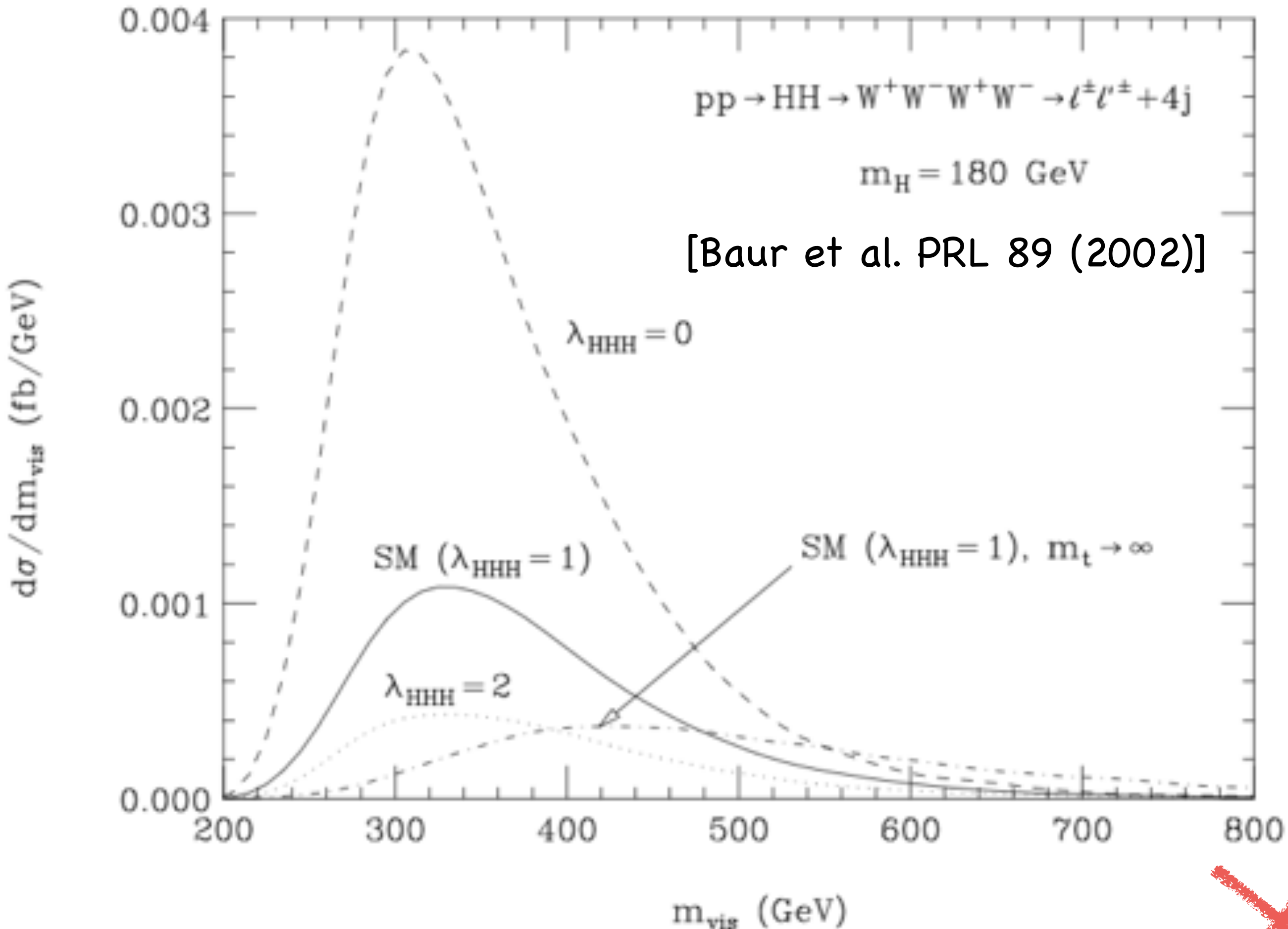
SM HH @ LHC: viable channels

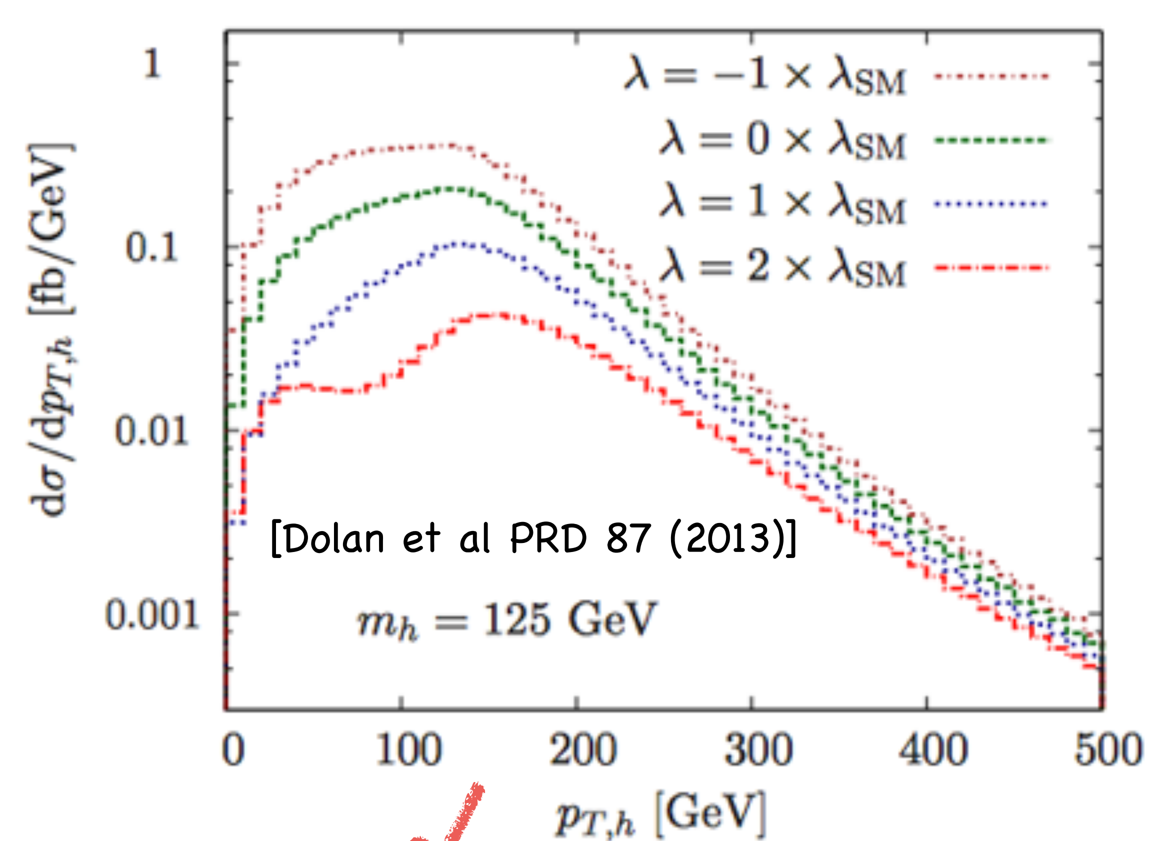
Michael Spannowsky

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

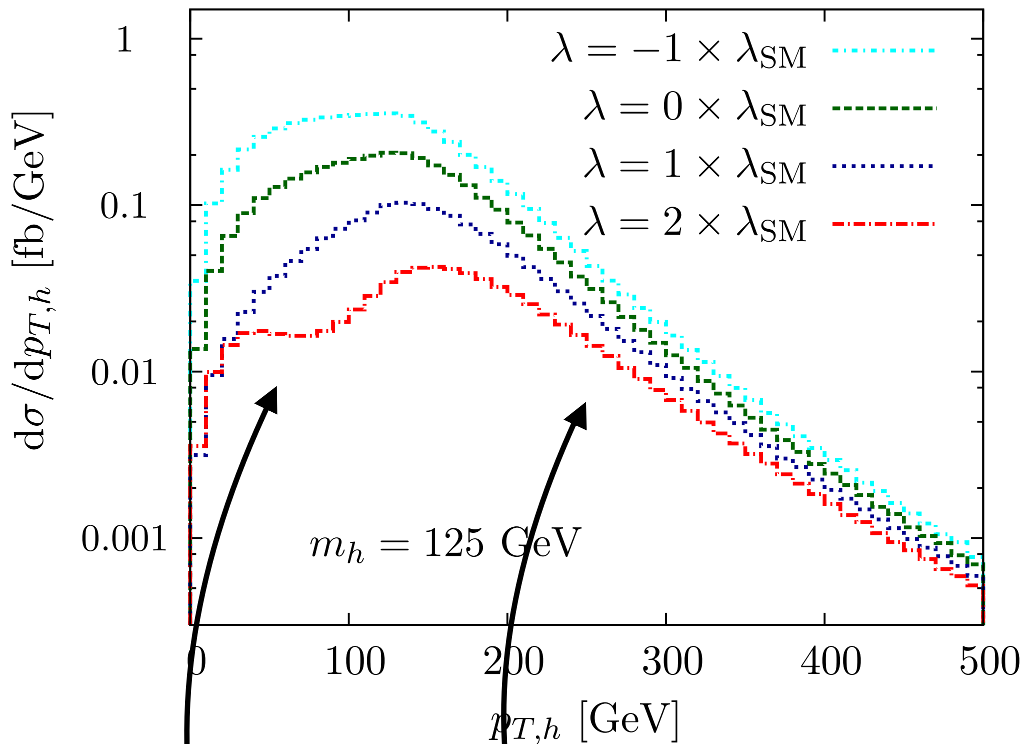


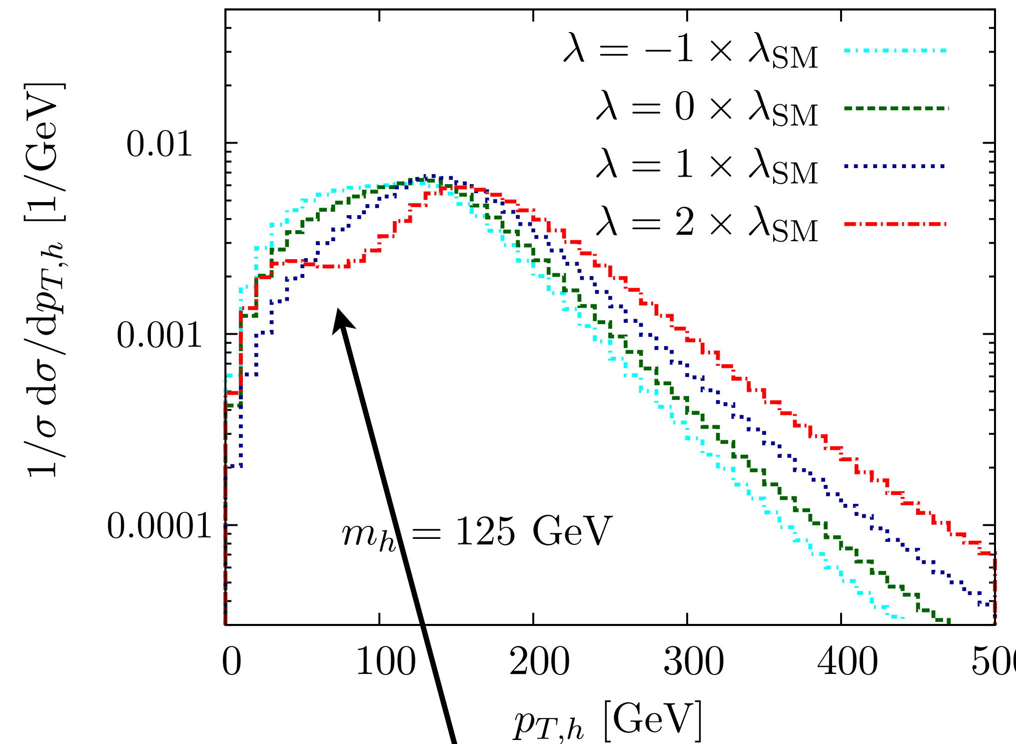


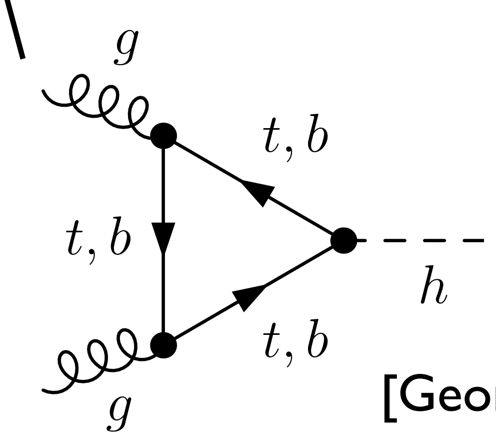
variables more close to reconstructed objects: m_{HH} and pT,H

- 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



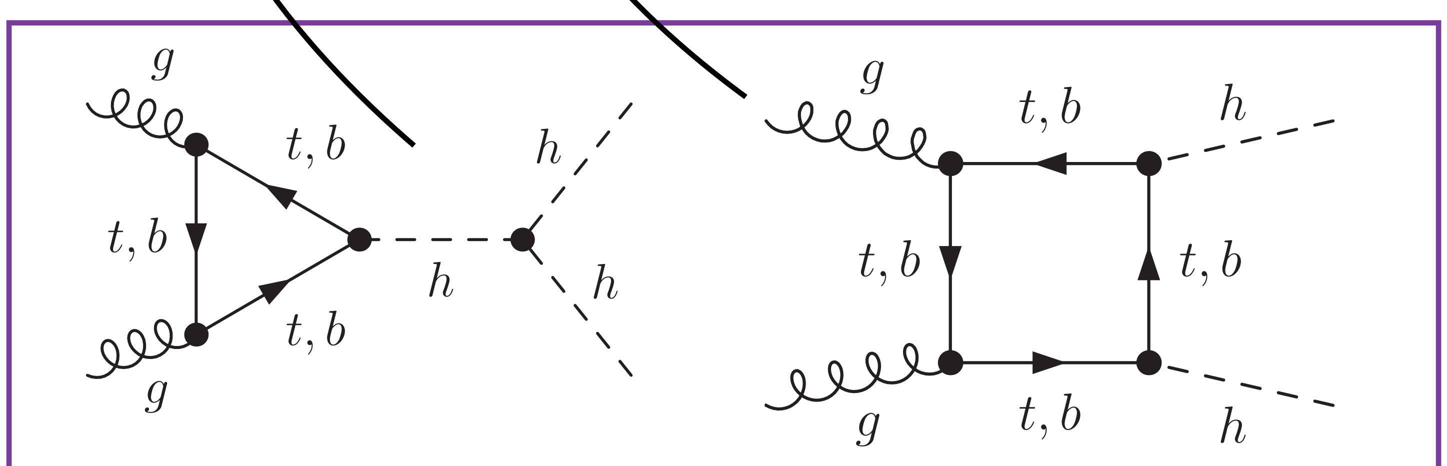




[Georgi et al. `78]

has maximum contribution for

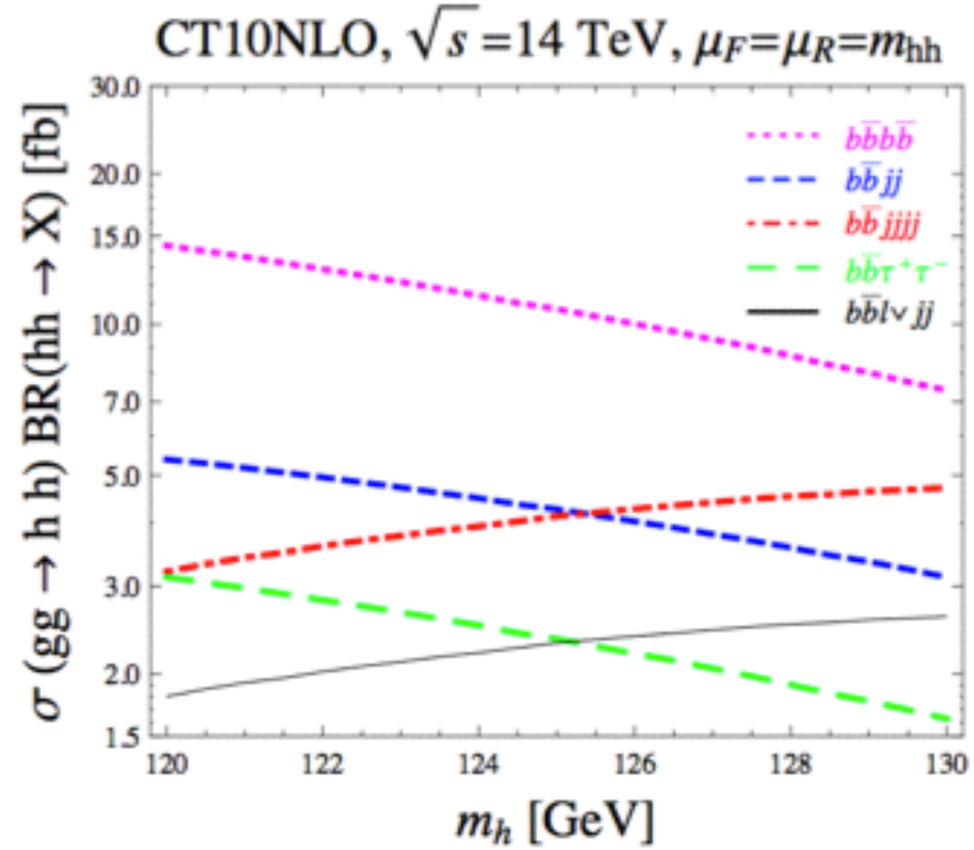
$$s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$$



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

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		

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

- Rate small for creative reconstruction ~ 300 events with 3 iab
- While side-band for photons clear, bump from bb very broad and background biased

Baur, Plehn, Rainwater (2003) W. Yao (2013) Baglio et al (2012)

Barger, Everett, Jackson, Shaughnessy (2013) Azatov, Contino, Panico, Son (2015)

For 3 iab: $S/\sqrt{B} \simeq 3$ $S/\sqrt{B} \simeq 6.46$ $S/\sqrt{B} \simeq 2.3$ $S/\sqrt{B} \simeq 2.1$

Difficulties:

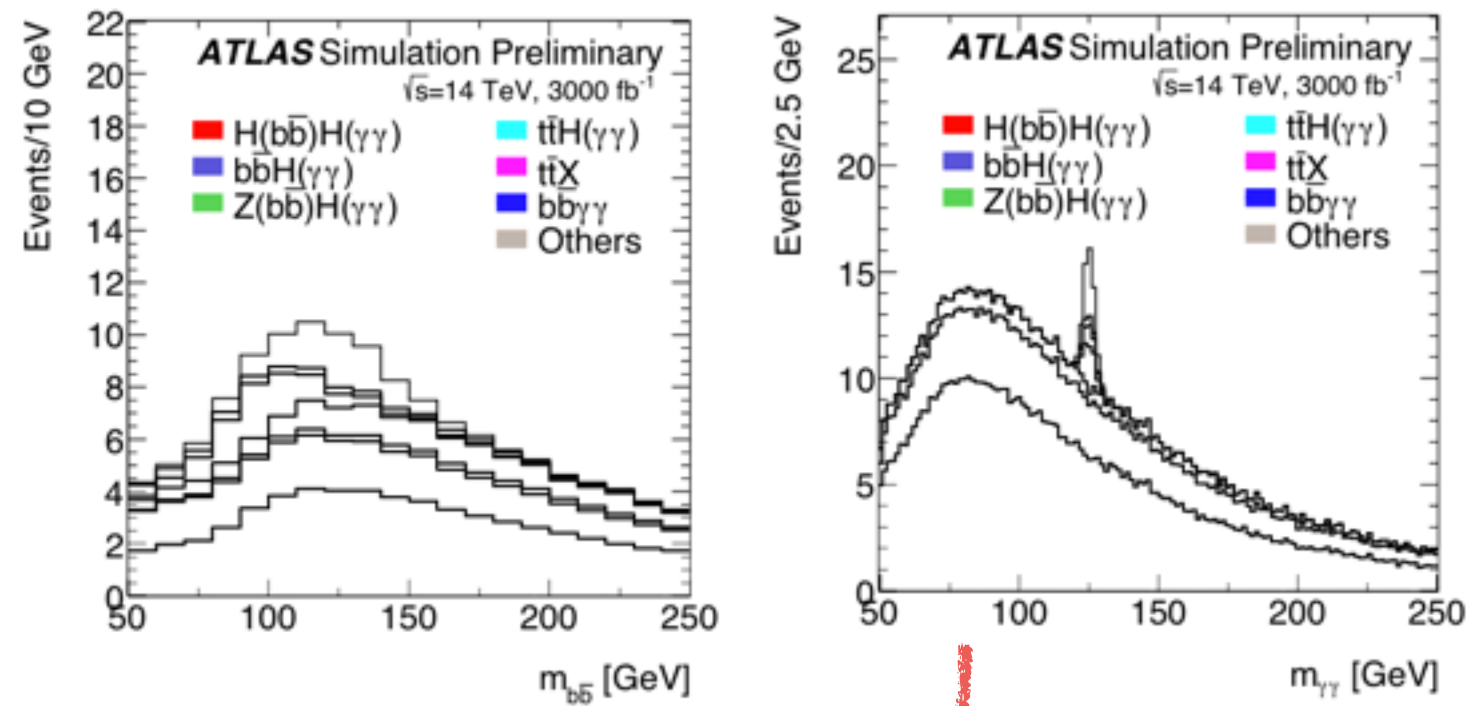
- Need to include hadronisation and parton shower
  -> changes mass windows, # jets, fake rates
- Need to include reducible backgrounds
- Need exp. input on fake-rates and mass windows
- Need multi-jet merging for (ir)reducible backgrounds

➡ Reliable background simulation and fake rates true challenge for sensitivity estimate

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

[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		

BKG quite different!

CMS gives 60% uncertainty on signal CS measurement

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

[Dolan, Englert, MS (2012)]

[Baglio et al (2012)]

[Barr, Dolan, Englert, MS (2013)]

- Inclusive rate 9000 events for 3 iab
- Rate can be used for advanced reconstruction (jet substructure, MT2)
- b and tau most complicated objects to reliably simulate

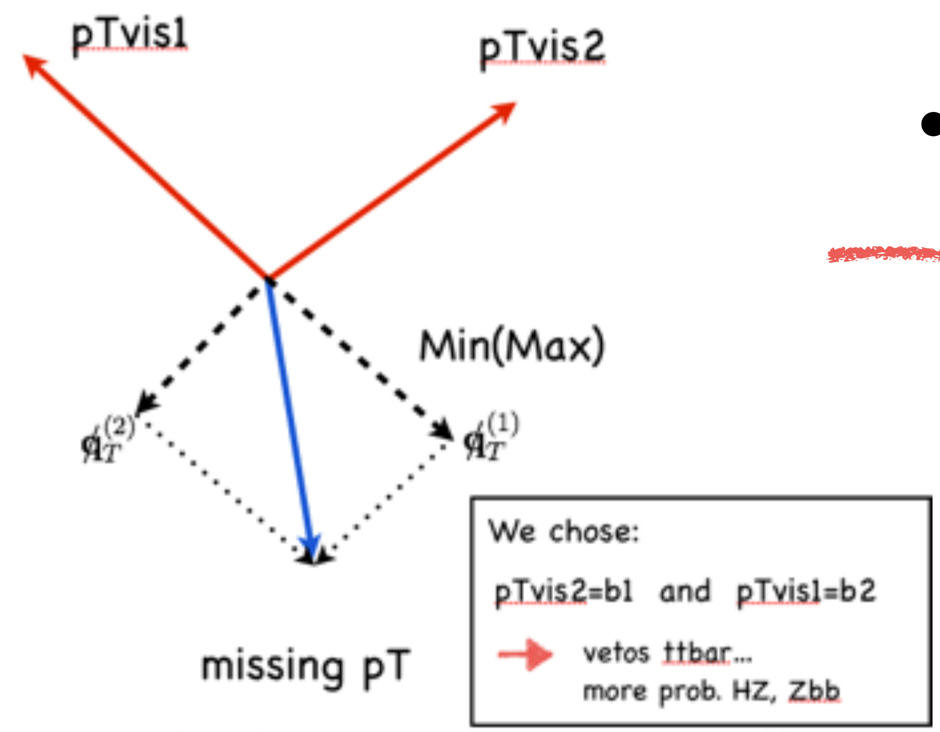
	$\xi = 0$	$\xi = 1$	$\xi = 2$	$b\bar{b}\tau\tau$	$b\bar{b}\tau\tau$ [ELW]	$b\bar{b}W^+W^-$	ratio to $\xi = 1$
cross section before cuts	59.48	28.34	13.36	67.48	8.73	873000	$3.2 \cdot 10^{-5}$
reconstructed Higgs from τs	4.05	1.94	0.91	2.51	1.10	1507.99	$1.9 \cdot 10^{-3}$
fatjet cuts	2.27	1.09	0.65	1.29	0.84	223.21	$4.8 \cdot 10^{-3}$
kinematic Higgs reconstruction ($m_{b\bar{b}}$)	0.41	0.26	0.15	0.104	0.047	9.50	$2.3 \cdot 10^{-2}$
Higgs with double b-tag	0.148	0.095	0.053	0.028	0.020	0.15	0.48

For 3 iab: $S/\sqrt{B} \simeq 11.70$ $S/\sqrt{B} \simeq 9.37$ $S/\sqrt{B} \simeq 5.94 - 2.71$

- Some studies tau efficiency/fake over optimistic
- Need better simulation of tau decays
- Need detailed sensitivity study of hadronic, semilep, leptonic taus
- Need hadronic backgrounds for hadronic tau decays
- Need JES uncertainties for subjets

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

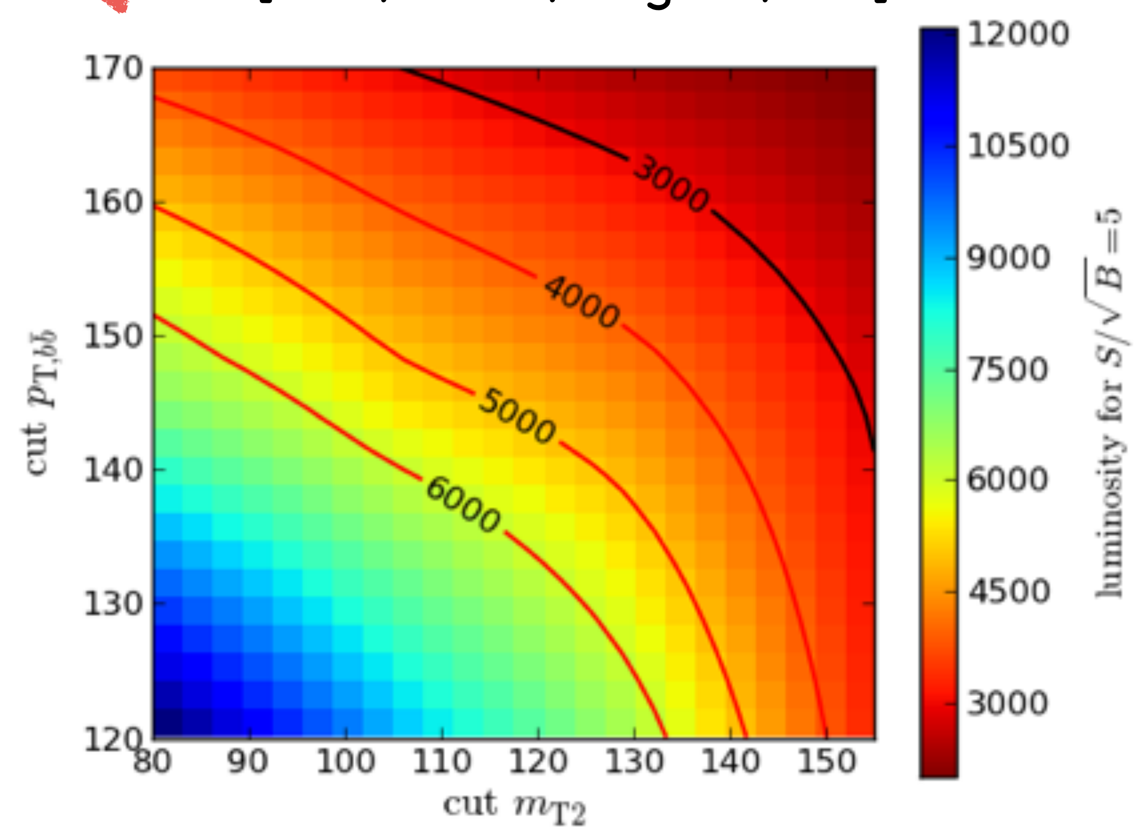
- Here, major background ttbar -> MT2 can change that
- Handles to suppress background: leptons, b-jets and MET



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

- Jet substructure can help in addition to mT2 known to go very well together

[Barr, Dolan, Englert, MS]



- MT2 distribution discriminates between HH and ttbar

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

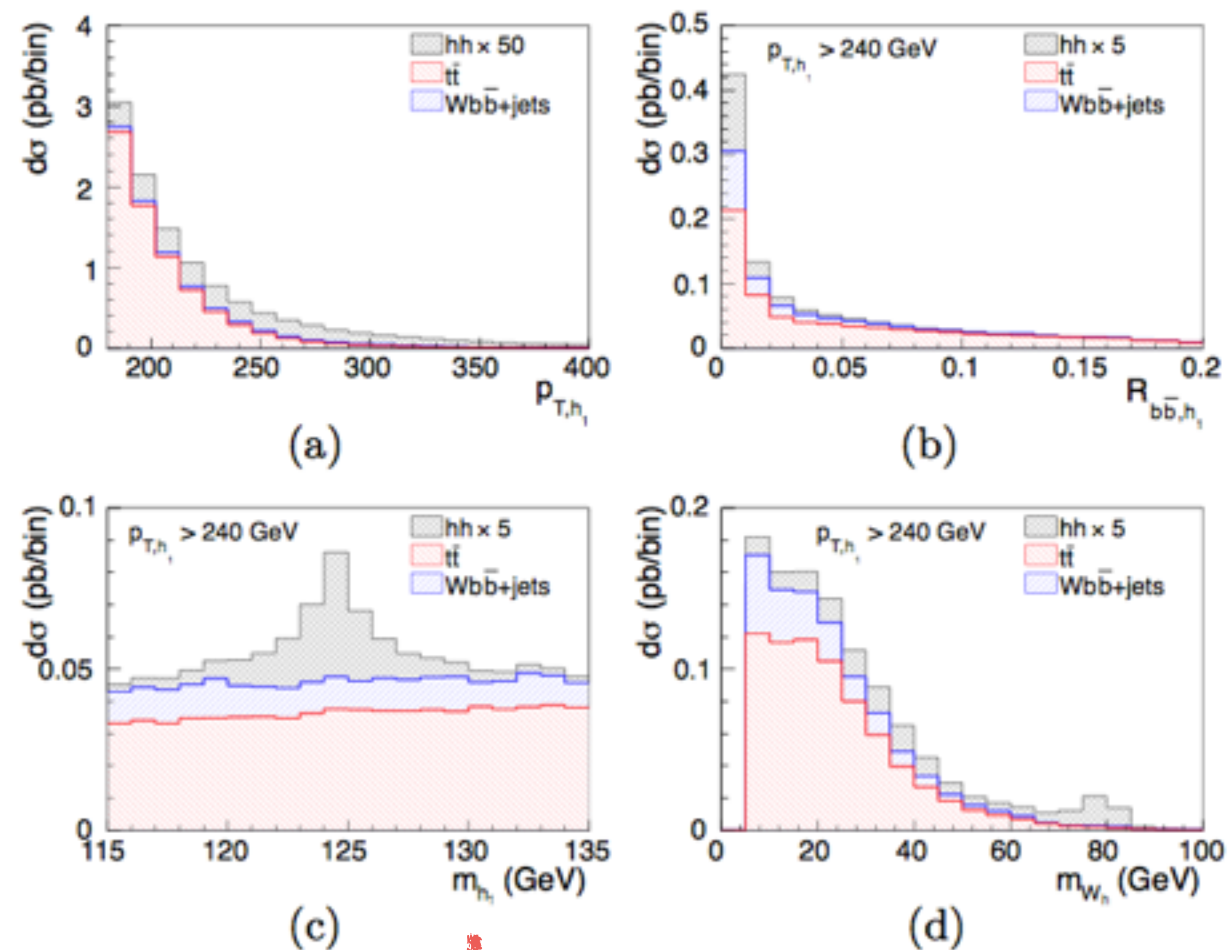
Exclusion at 95% CL: $\lambda > \lambda_{95\%\ \mathrm{CL}}^{3000/\mathrm{fb}} \simeq 3.0 \times \lambda_{\mathrm{SM}}$

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

[Dolan, Englert, MS (2012)]
[Baglio et al (2012)]
[Papaefstathiou, Yang, Zurita (2012)]

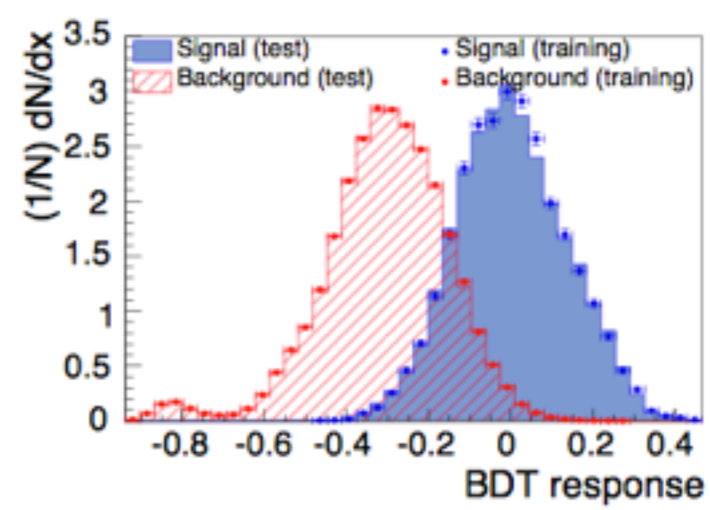
$$hh \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}\ell\nu jj$$

- Fully reconstructable final state
- Triggering easy due to lepton
- But looks like ttbar...
- Resolved analysis considered hopeless, but how about boosting?



Process	σ_{initial} (fb)	σ_{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	-

BDT



For SM coupling

$$S/\sqrt{S+B} \sim 2.4 \quad 3.1\sigma$$

with S=9 and B=6 after 600 ifb

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 , $\Delta\phi jj,ll$)

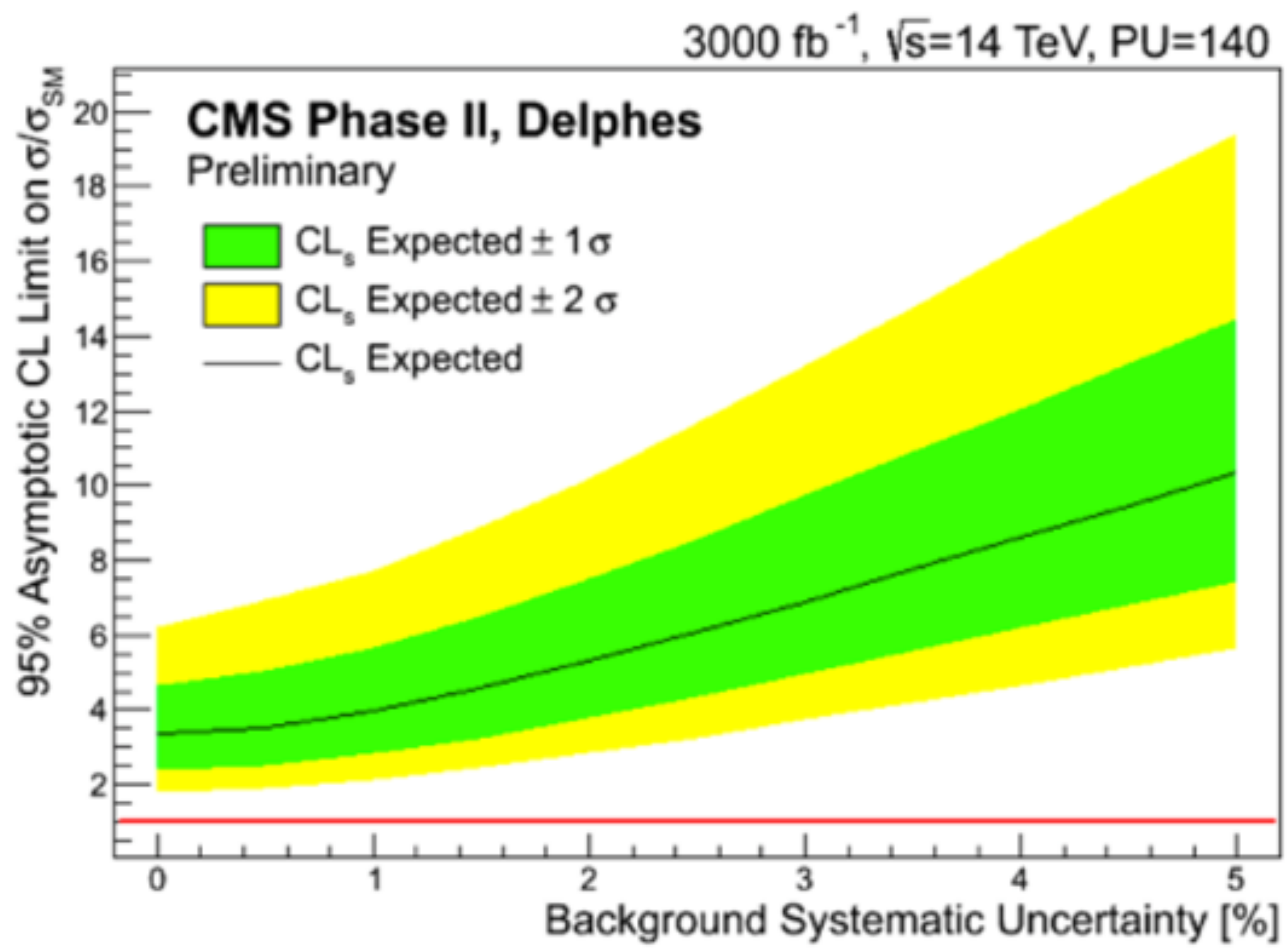
Analysis Optimization:

- 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]

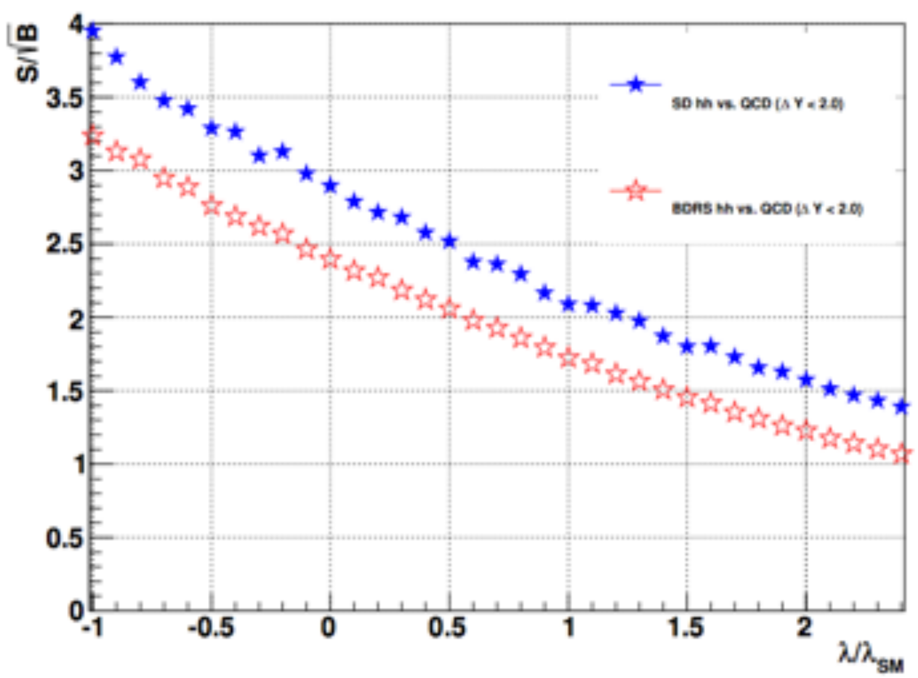
[Papaefstathiou, Ferreira, MS]

[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

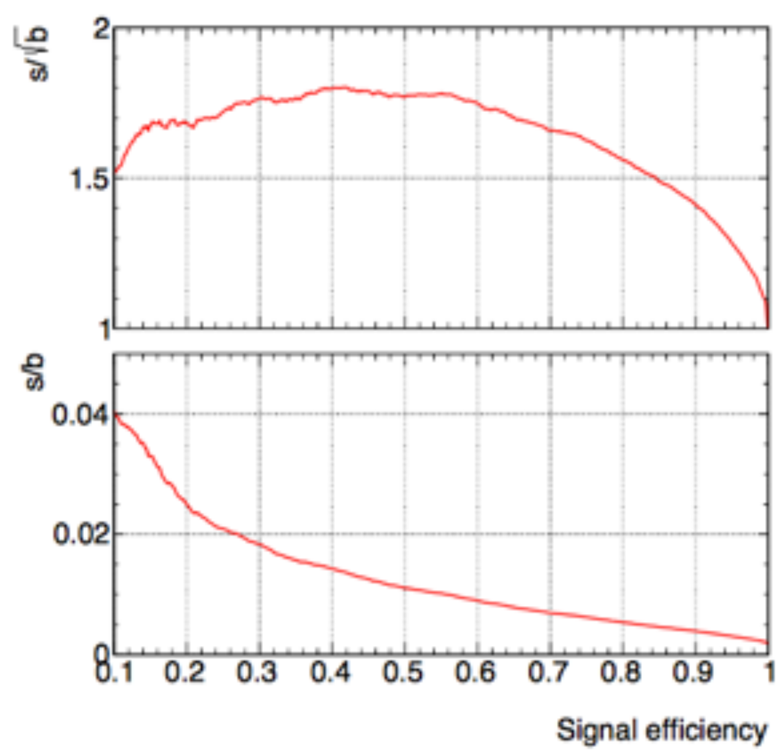
sample	σ_{initial} (fb)
hh, $h \to b\bar{b}$ (SM)	10.7
QCD $(b\bar{b})(b\bar{b})$	151.1×10^3
$Zb\bar{b}$, $Z \to b\bar{b}$	8.8×10^3
hZ, $h \to b\bar{b}$, $Z \to b\bar{b}$	70.0
hW, $h \to b\bar{b}$, $W \to c\bar{b}(\bar{c}b)$	96.4

Boosted + Jet substructure



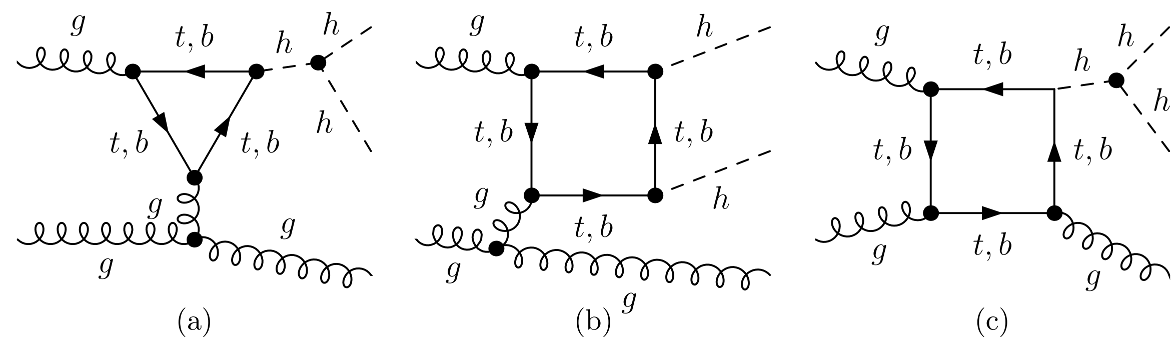
consistent

Resolved + BDT (incl. ttbar BKG)

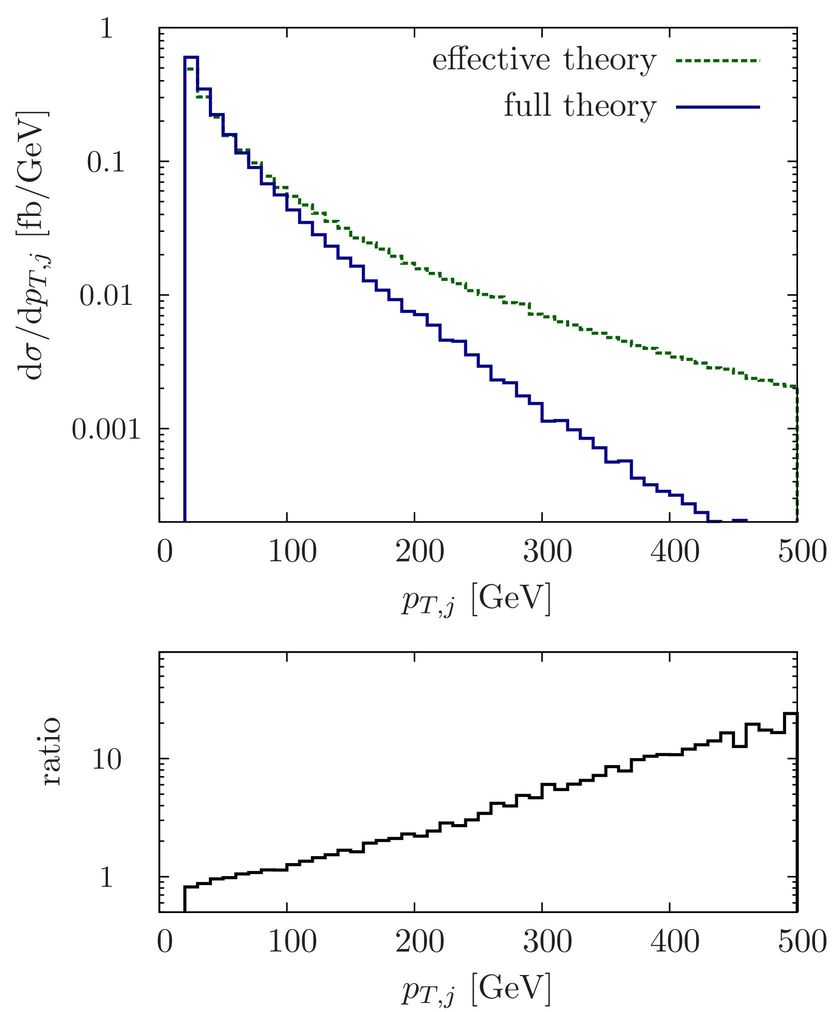


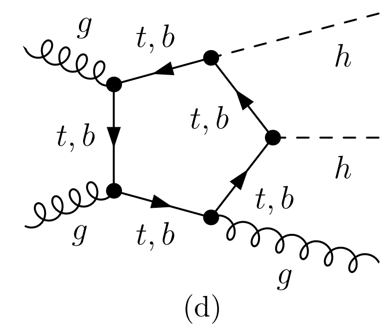
More jets can keep m_{inv} small and pT,H large

- need to work a little harder



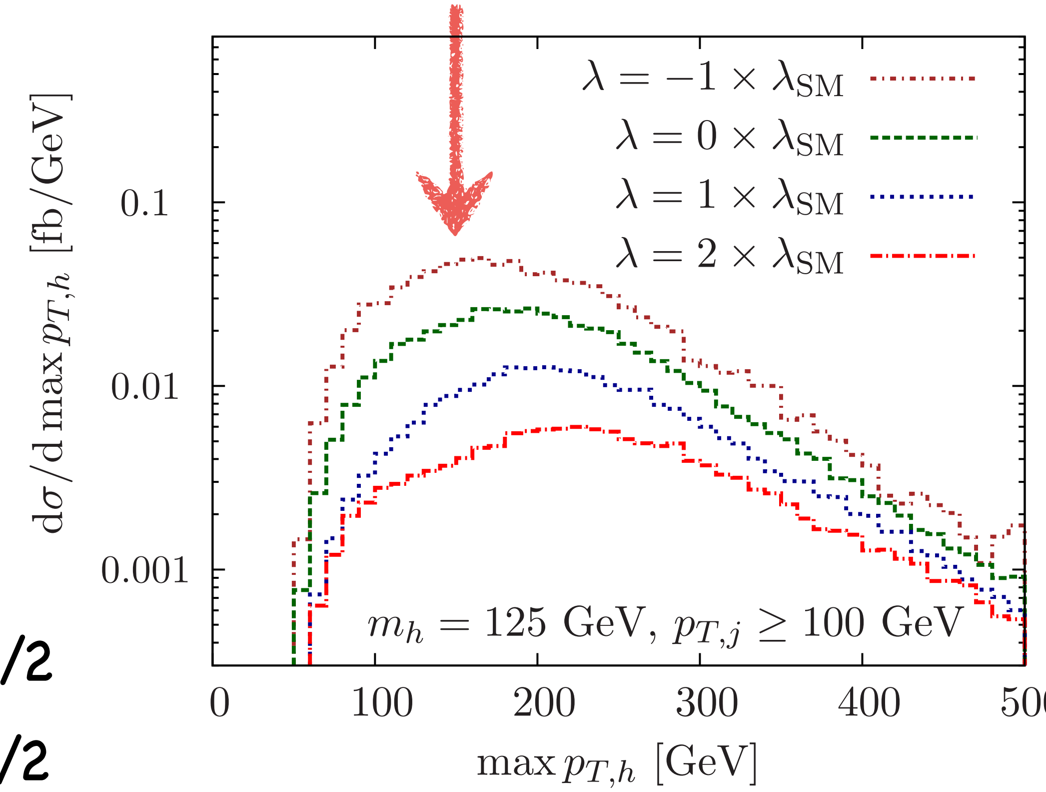
Eff. theory breaks down quickly





+ quark & gluon induced

retain sensitivity for boosted Higgs

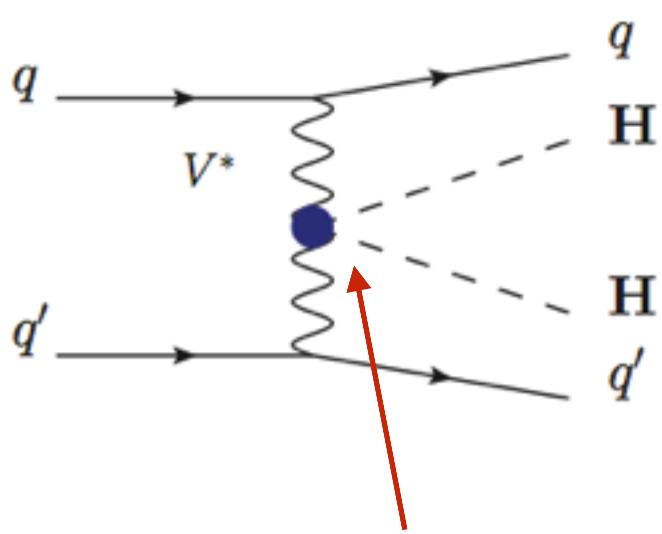


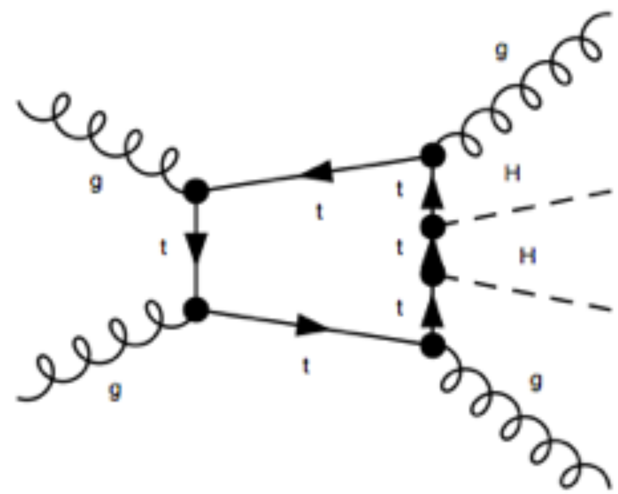
Additional jet can help to suppress backgrounds:

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

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

Higgs selfcoupling in HHjj+X





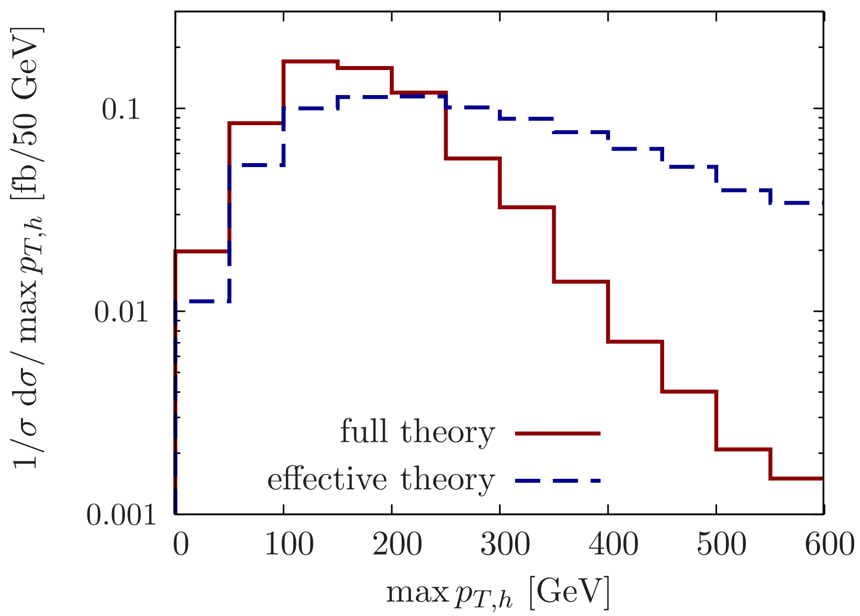
[Contino et al. JHEP 1005]

[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

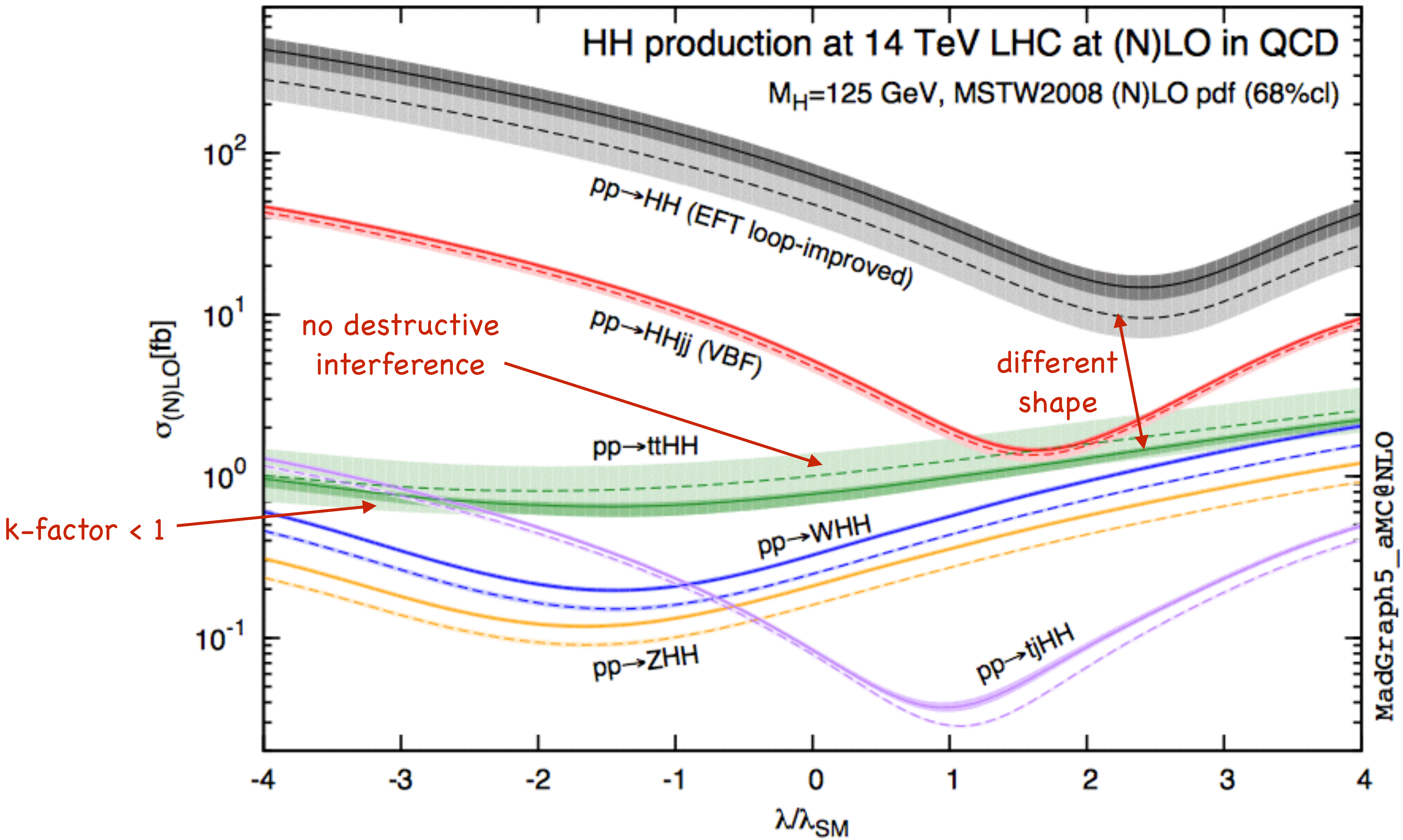
WBF only

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, Frixione, Hirschi, Maltoni, Mattelaer, Torielli, Vryonidou, Zaro '14]



Higgs selfcoupling in ttHH

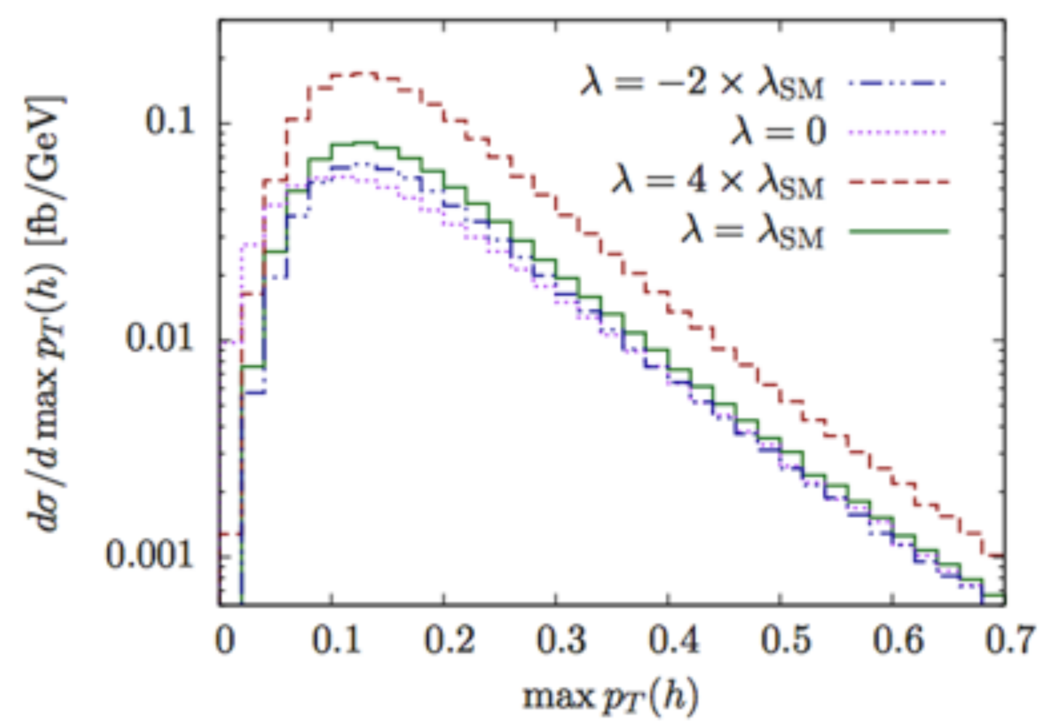
[Englert, Krauss, MS, Thompson]

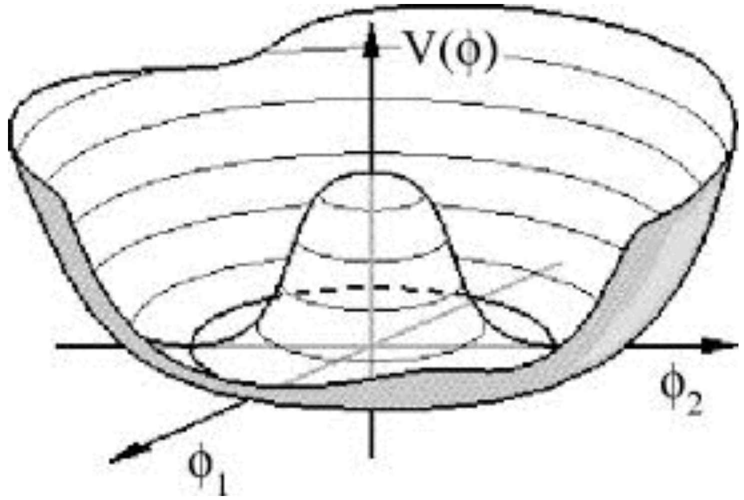
[Liu, Zhang]

	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}	$<1\times10^{-4}$

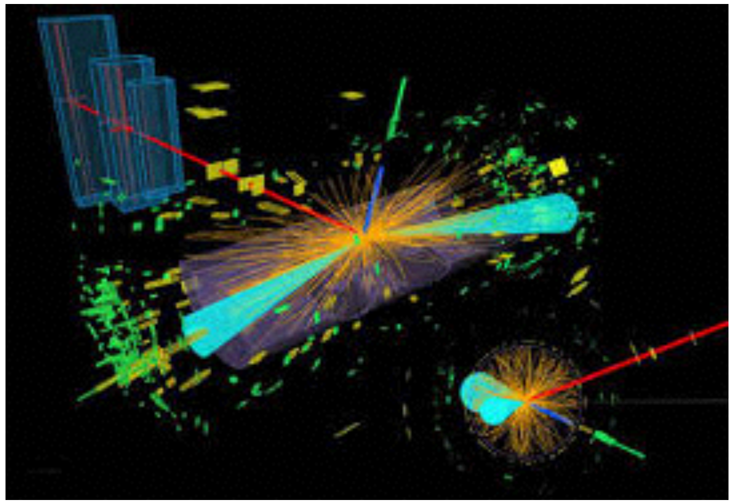
- Signal rate too small for inventive reconstruction
- Though Backgrounds for 5+ b-tags already small
- 13-22 signal event with 3000 ifb

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





Summary



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

  → Still reconstruction more important than normalisation of S

  → Need **FINALLY** input from experimentalists

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

- However, sensitivity in individual channels expected to be low

  Combination of many channels necessary