The Once and Future Higgs

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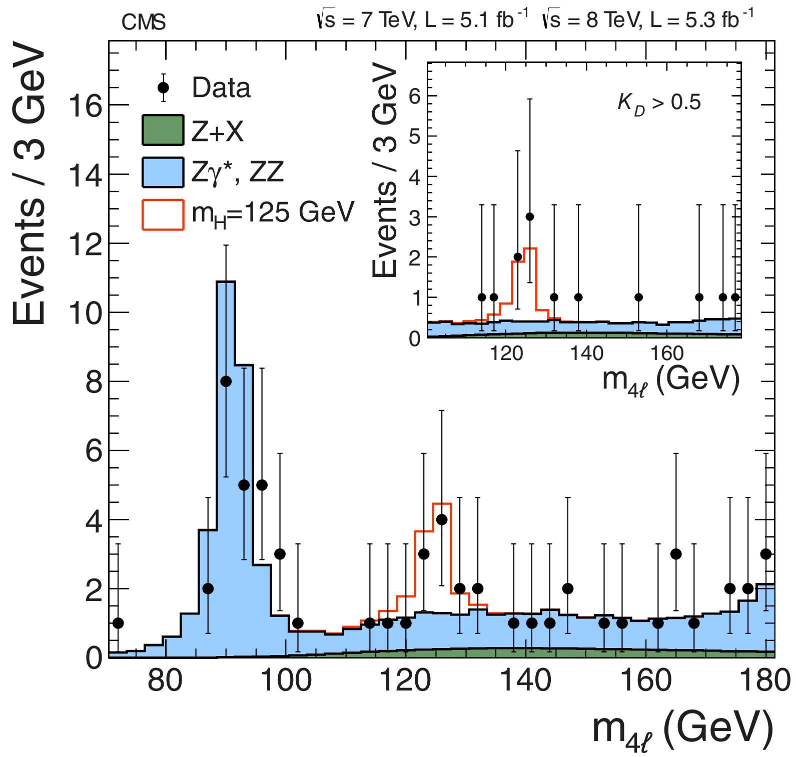
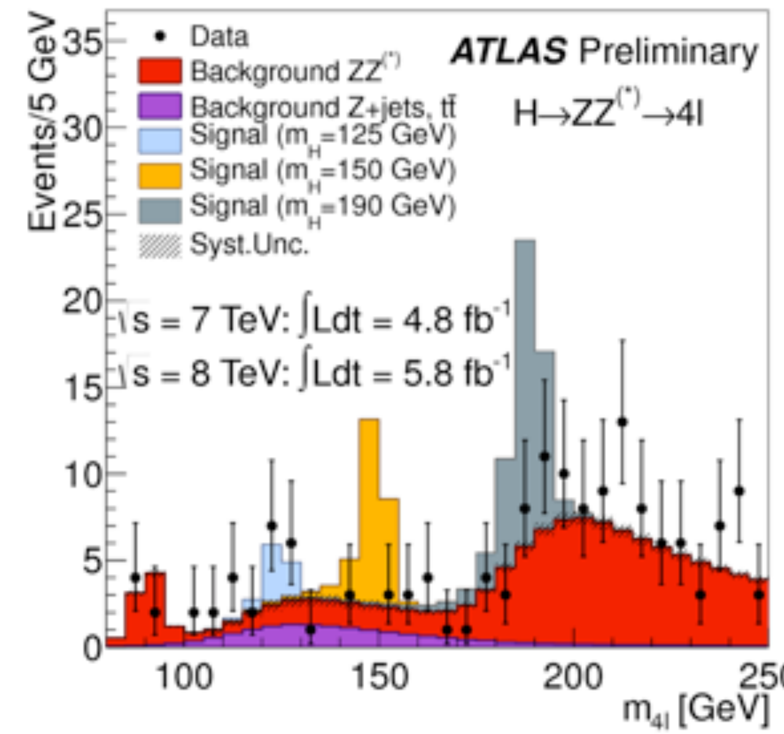
Conquering Post-Higgs Tristesse

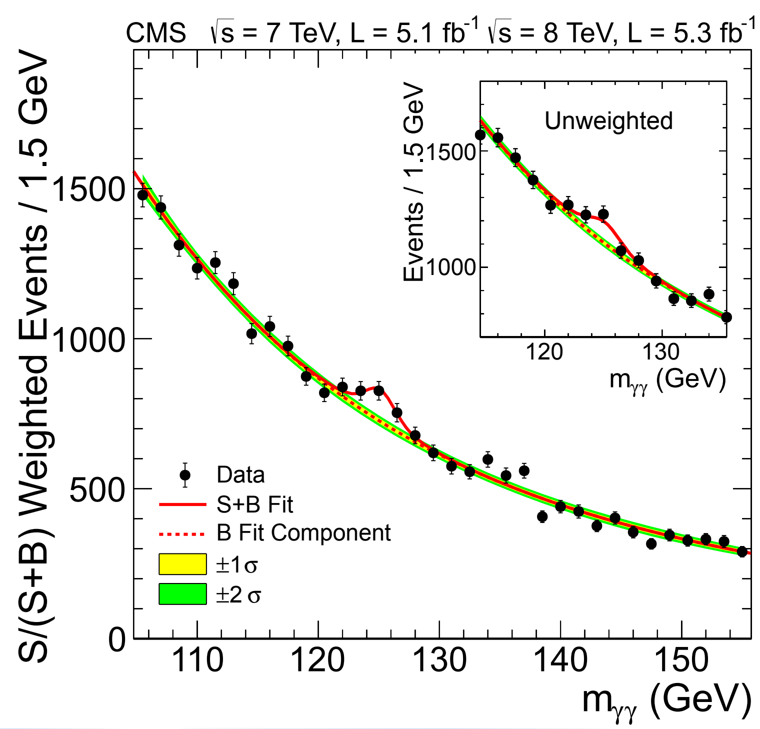
- The Higgs is our best hope so far for discovering new physics at the LHC.

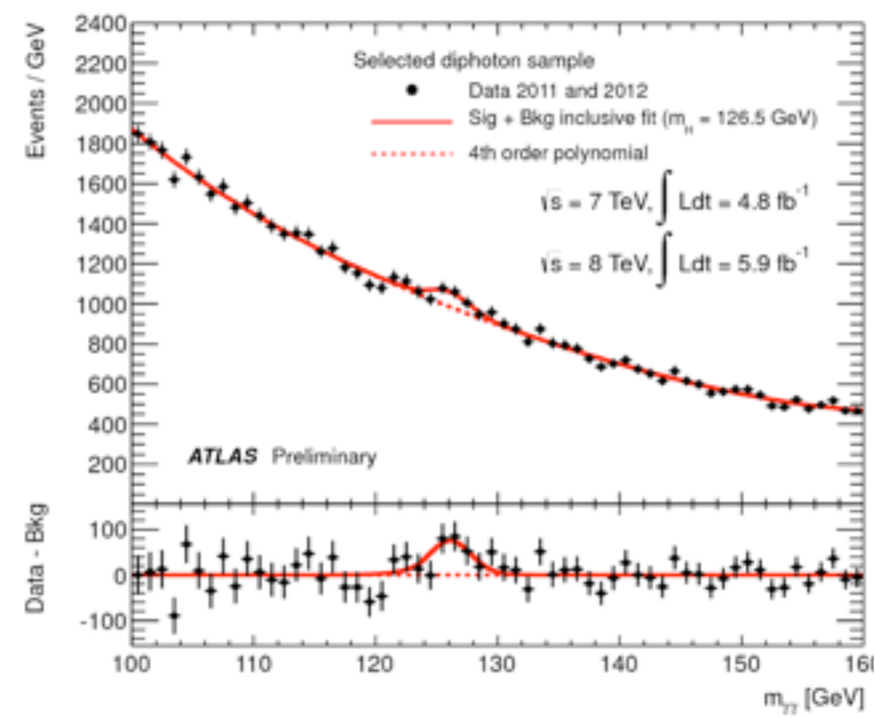
- Last year's discovery is this year's tag: Using the Higgs as a direct probe of new physics.
- If one, why not more?: Looking for signs of extended electroweak symmetry breaking.
- Even if we're unlucky: Using the Higgs as an indirect probe of new physics.

Based on recent work with Scott Thomas, Jared Evans, Can Kilic, Michael Park, Alex Azatov, Spencer Chang, Jamison Galloway, Emmanuel Contreras-Campana, Richard Gray, Sunil Somalwar, Matt Walker;
arXiv:1112.2298, 1206.1058, 1207.4835, 1207.6794, 1210.0559 + ongoing work


CMS
√s = 7 TeV, L = 5.1 fb^{-1} √s = 8 TeV, L = 5.3 fb^{-1}
Events / 3 GeV
Data
Z+X
Zγ*, ZZ
m_H=125 GeV
K_D > 0.5
$m_{4\ell}$ (GeV)

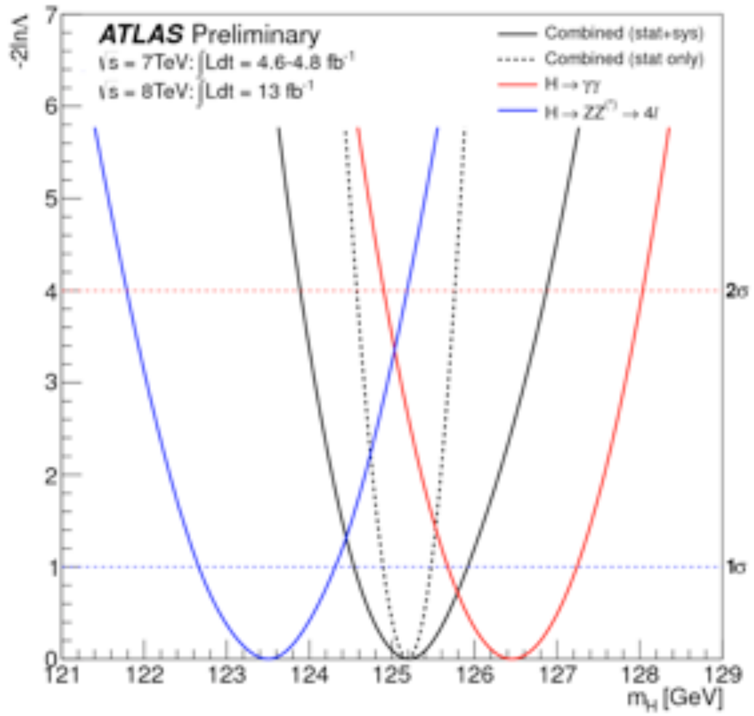

Events/5 GeV
Data
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ$^{(*)}$→4l
√s = 7 TeV: ∫Ldt = 4.8 fb^{-1}
√s = 8 TeV: ∫Ldt = 5.8 fb^{-1}
m_{4l} [GeV]

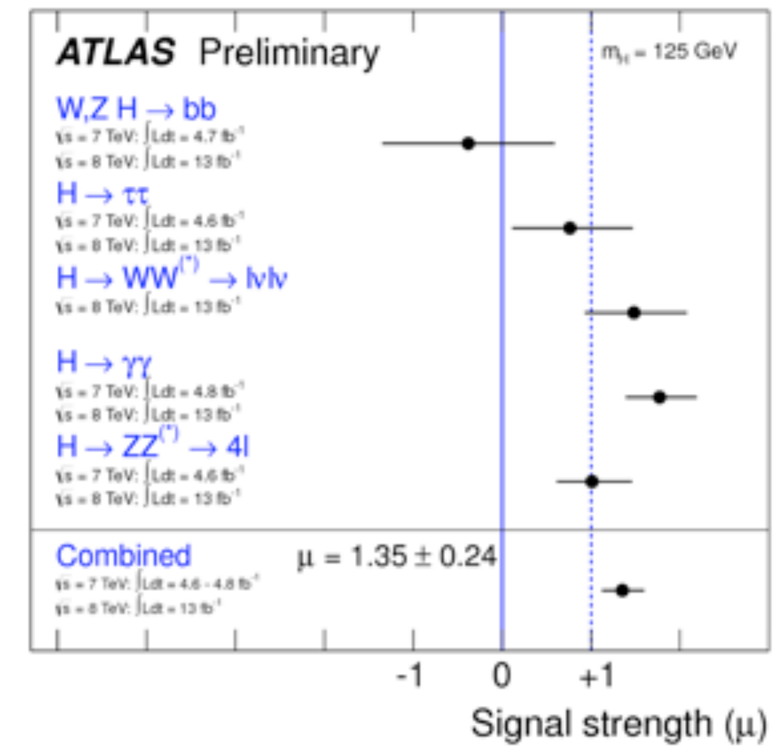

CMS √s = 7 TeV, L = 5.1 fb^{-1} √s = 8 TeV, L = 5.3 fb^{-1}
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2σ
$m_{\gamma\gamma}$ (GeV)

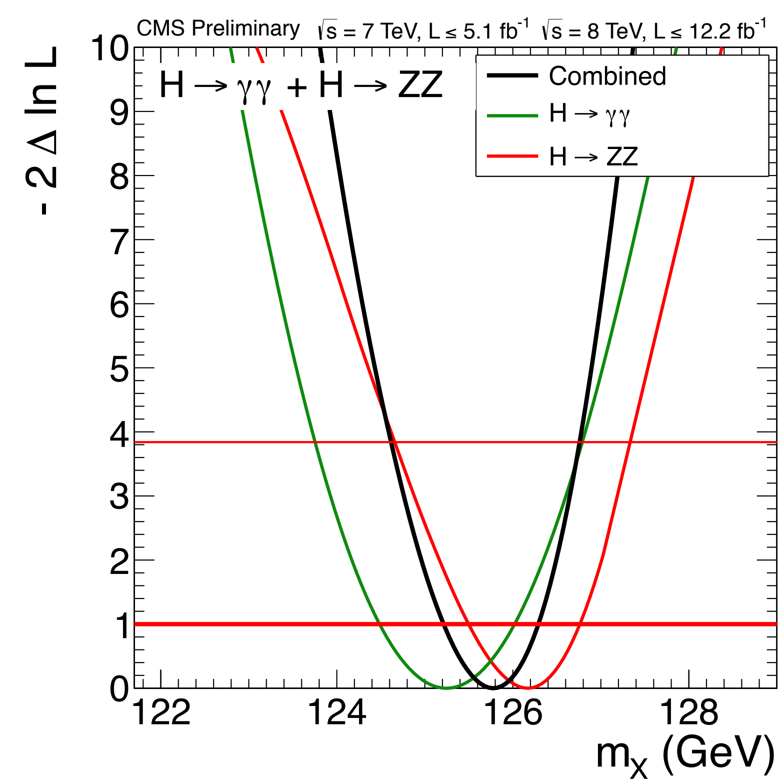

Events / GeV
Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb^{-1}
√s = 8 TeV, ∫ Ldt = 5.9 fb^{-1}
ATLAS Preliminary
Data - Bkg
$m_{\gamma\gamma}$ [GeV]

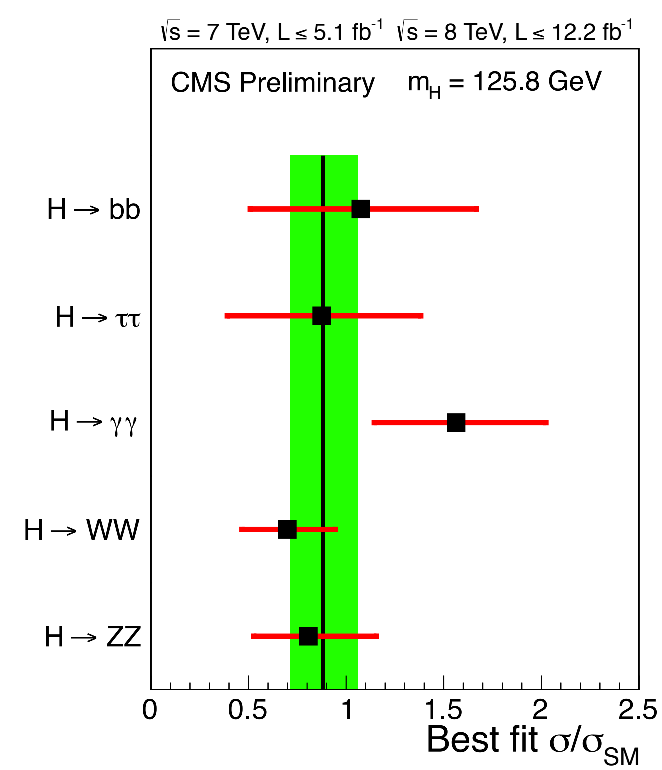
Discovery!

What did we discover?









Mostly SM-like and $m_h \sim 126$ GeV

New physics via the Higgs

- Now that we've discovered the Higgs, we have a priceless tool in the search for new physics!
- Can make use of it as a probe by studying its couplings directly, or by leveraging it to look for new states.
- One possibility is to look for BSM Higgs production in association with additional tagging information (leptons, MET, HT, etc.)
- Another is to look for direct production/decays of new states in the EWSB sector.
    - Quite likely that these new states have (at least) electroweak quantum numbers. So a good place to look is in leptonic final states. There may or may not be significant MET or hadronic energy, so it's useful to cast as wide a net as possible.
    - It helps that the CMS multi-lepton search is produced down the hall at Rutgers...

CMS Multi-leptons: a theorist's dream study

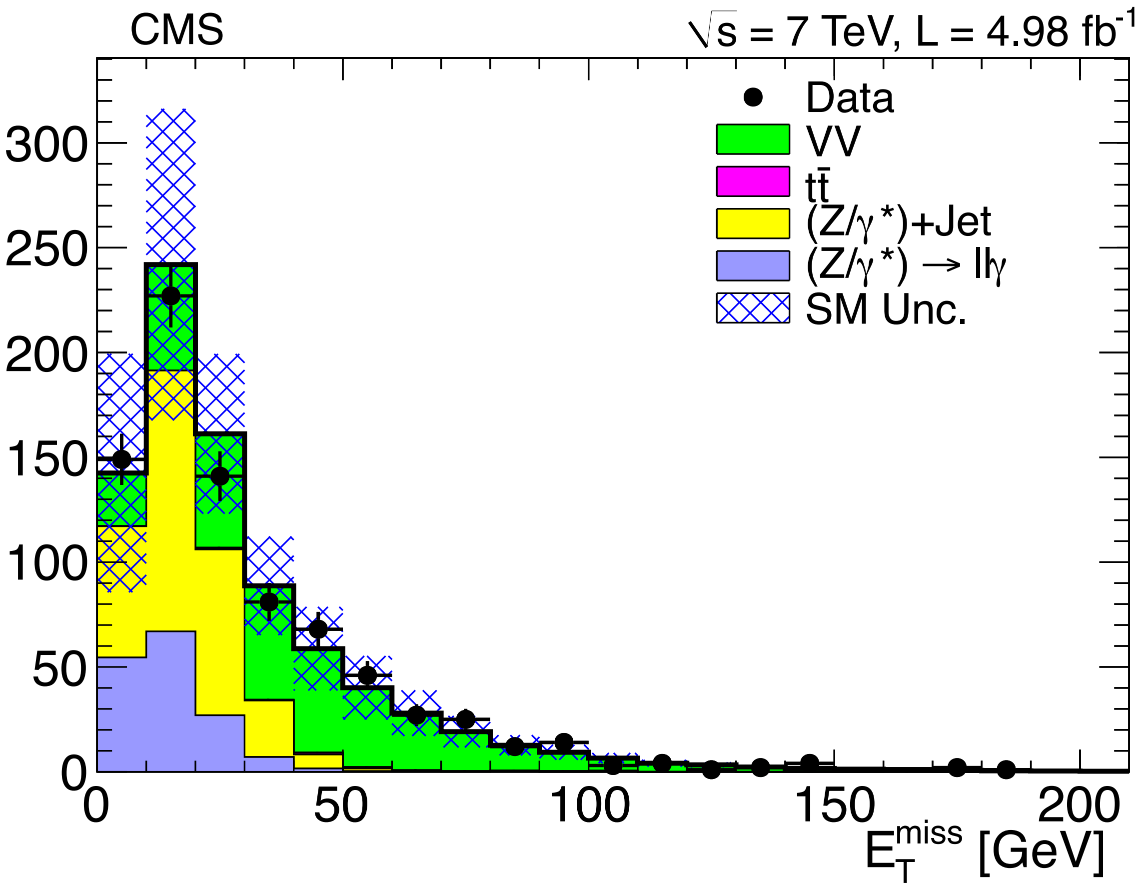
Selection	N(τ)=0		N(τ)=1		N(τ)=2	
	obs	expect	obs	expect	obs	expect
4ℓ Lepton Results						
4ℓ >50,>200, no Z	0	0.018 ± 0.005	0	0.09 ± 0.06	0	0.7 ± 0.7
4ℓ >50,> 200, Z	0	0.22 ± 0.05	0	0.27 ± 0.11	0	0.8 ± 1.2
4ℓ >50,<200, no Z	1	0.20 ± 0.07	3	0.59 ± 0.17	1	1.5 ± 0.6
4ℓ >50,<200, Z	1	0.79 ± 0.21	4	2.3 ± 0.7	0	1.1 ± 0.7
4ℓ <50,>200, no Z	0	0.006 ± 0.001	0	0.14 ± 0.08	0	0.25 ± 0.07
4ℓ <50,>200, Z	1	0.83 ± 0.33	0	0.55 ± 0.21	0	1.14 ± 0.42
4ℓ <50,<200, no Z	1	2.6 ± 1.1	5	3.9 ± 1.2	17	10.6 ± 3.2
4ℓ <50,<200, Z	33	37 ± 15	20	17.0 ± 5.2	62	43 ± 16
3ℓ Lepton Results						
3ℓ >50,>200,no-OSSF	2	1.5 ± 0.5	33	30.4 ± 9.7	15	13.5 ± 2.6
3ℓ >50,<200,no-OSSF	7	6.6 ± 2.3	159	143 ± 37	82	106 ± 16
3ℓ <50,>200,no-OSSF	1	1.2 ± 0.7	16	16.9 ± 4.5	18	31.9 ± 4.8
3ℓ <50,<200,no-OSSF	14	11.7 ± 3.6	446	356 ± 55	1006	1026 ± 171
3ℓ >50,>200, no Z	8	5.0 ± 1.3	16	31.7 ± 9.6	–	–
3ℓ >50,>200, Z	20	18.9 ± 6.4	13	24.4 ± 5.1	–	–
3ℓ >50,<200, no Z	30	27.0 ± 7.6	114	107 ± 27	–	–
3ℓ <50,>200, no Z	11	4.5 ± 1.5	45	51.9 ± 6.2	–	–
3ℓ >50,<200, Z	141	134 ± 50	107	114 ± 16	–	–
3ℓ <50,>200, Z	15	19.2 ± 4.8	166	244 ± 24	–	–
3ℓ <50,<200, no Z	123	144 ± 36	3721	2907 ± 412	–	–
3ℓ <50,<200, Z	657	764 ± 183	17857	15519 ± 2421	–	–
Total 4ℓ	37	42 ± 15	32.0	24.9 ± 5.4	80	59 ± 16
Total 3ℓ	1029	1138 ± 193	22693	19545 ± 2457	1121	1177 ± 172
Total	1066	1180 ± 194	22725	19570 ± 2457	1201	1236 ± 173

Every channel is a signal channel (data-driven backgrounds inferred from dilepton sample)

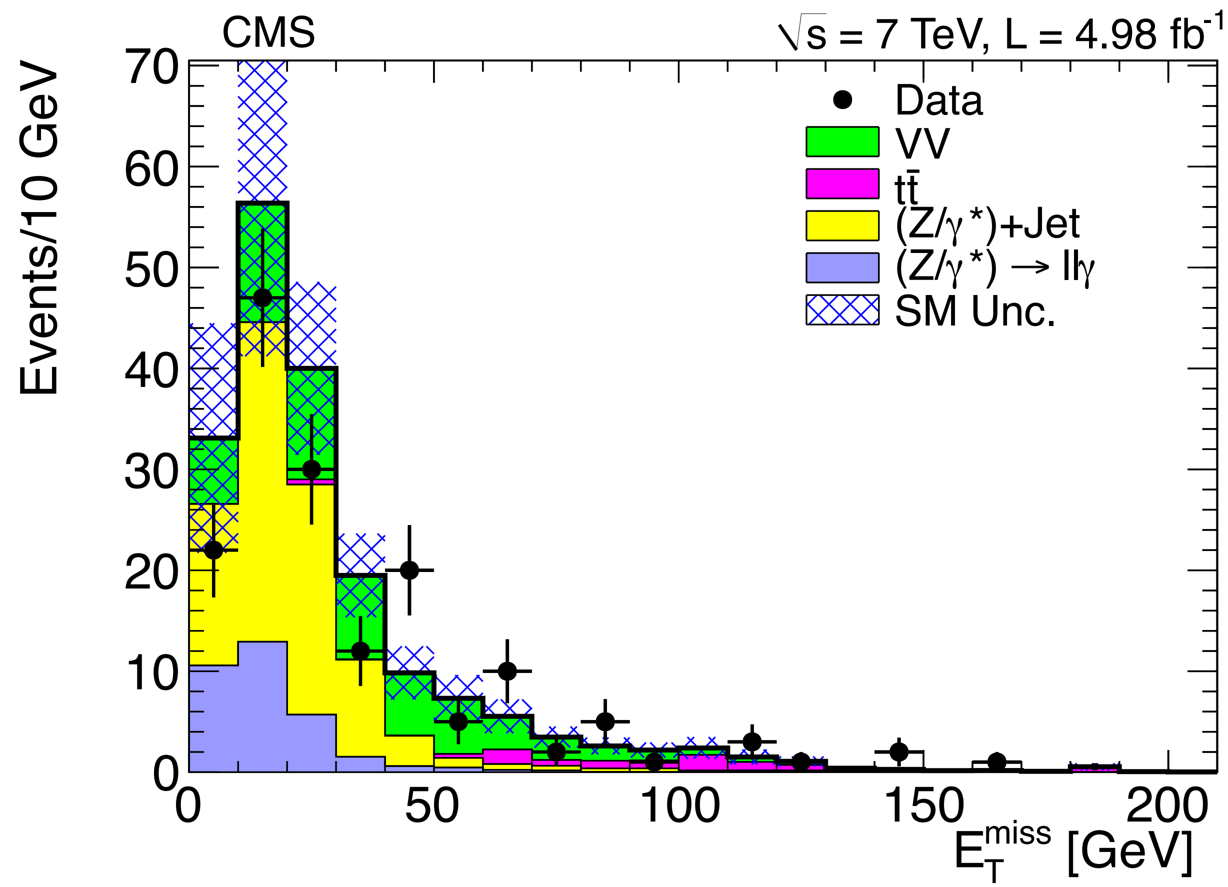
Power of the search arises from the exclusive combination of all channels; sensitive to correlated signals arising in multiple channels

Particularly useful for nonresonant electroweak production/decay of new physics.

Multi-leptons and MET



3L HT LOW; 0 tau; Z+no Z

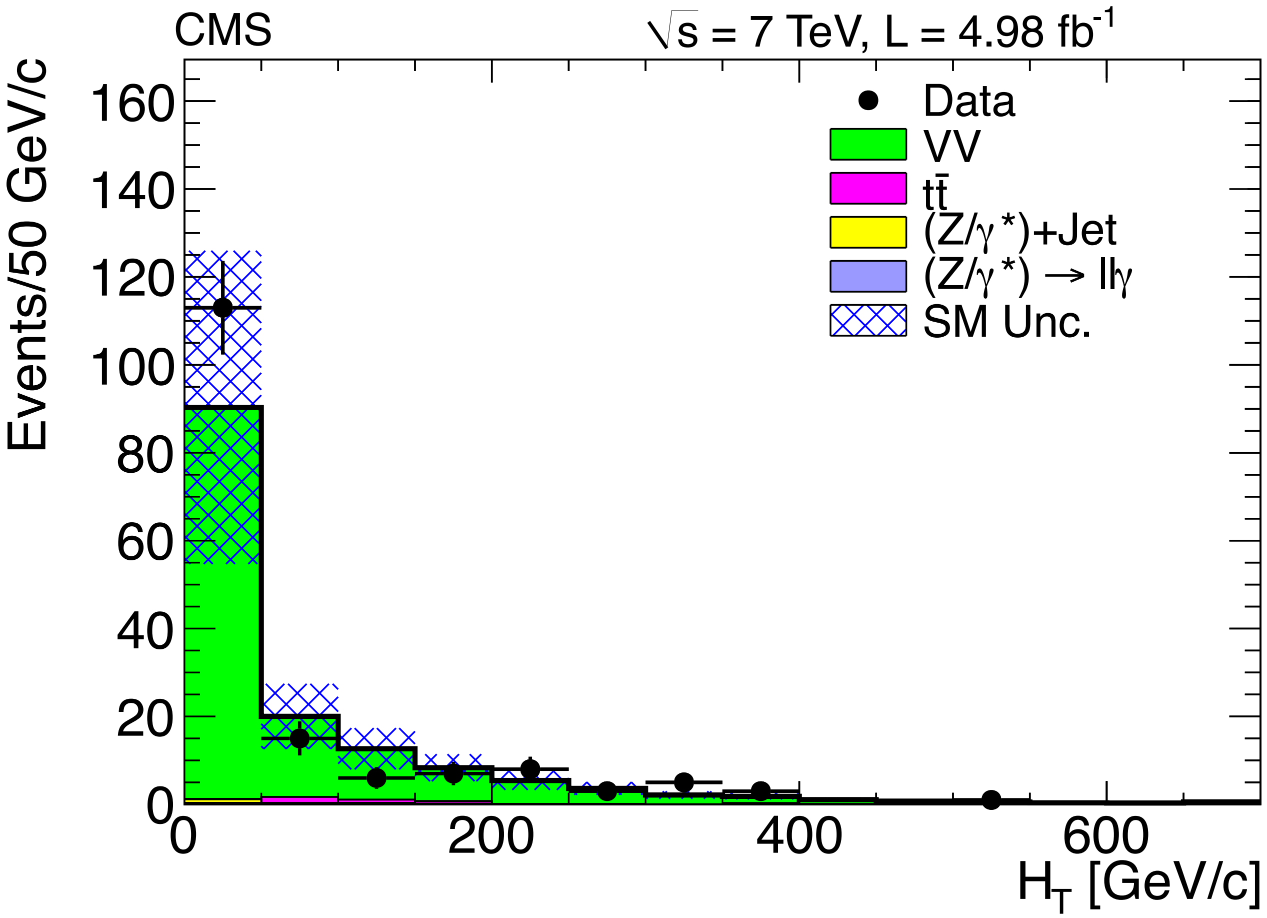


3L HT LOW; 0 tau; no Z

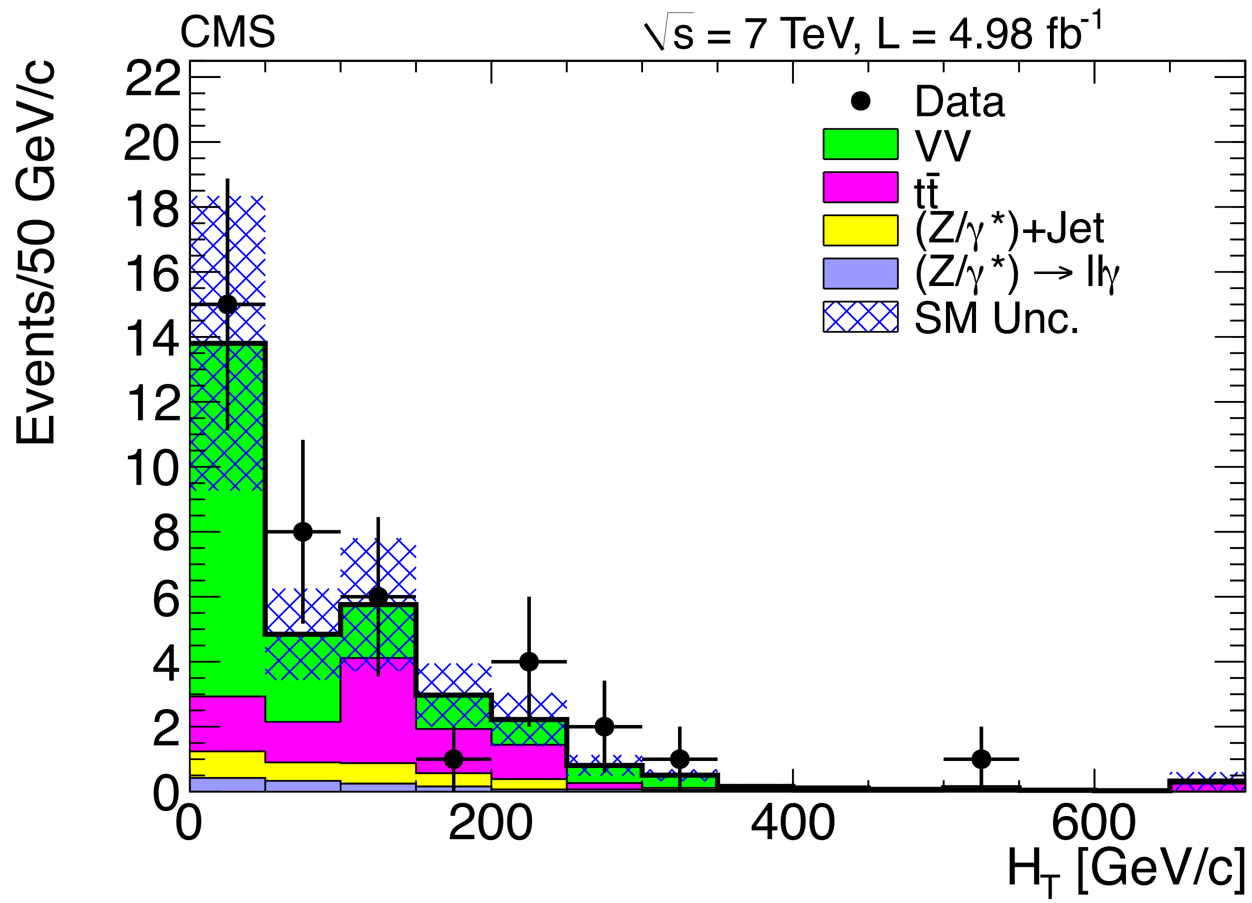
Added sensitivity from looking off Z; both high and low MET regions have sensitivity

Can factorize off-Z events further by whether or not there are OSSF pairs

Multi-leptons and HT



3L MET LOW; 0 tau; Z+no Z



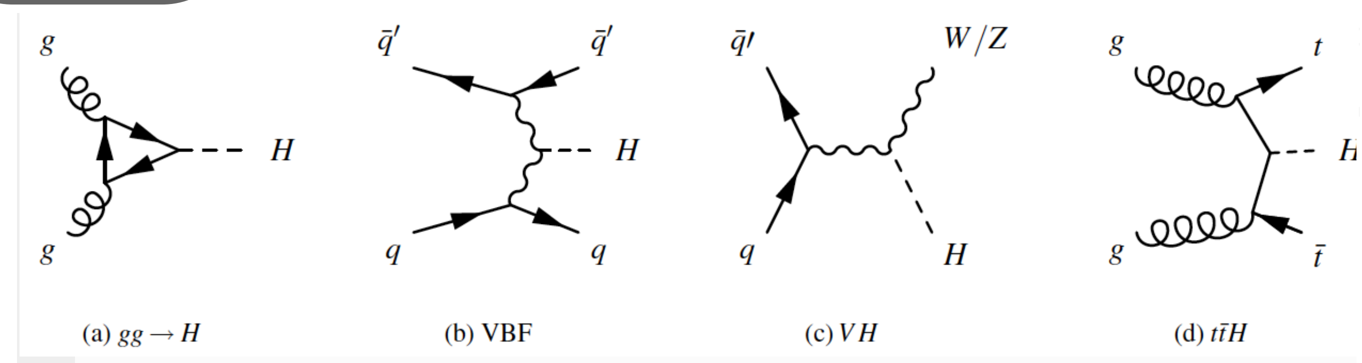
3L MET LOW; 0 tau; no Z

Added sensitivity from looking off Z; both high and low HT regions have sensitivity

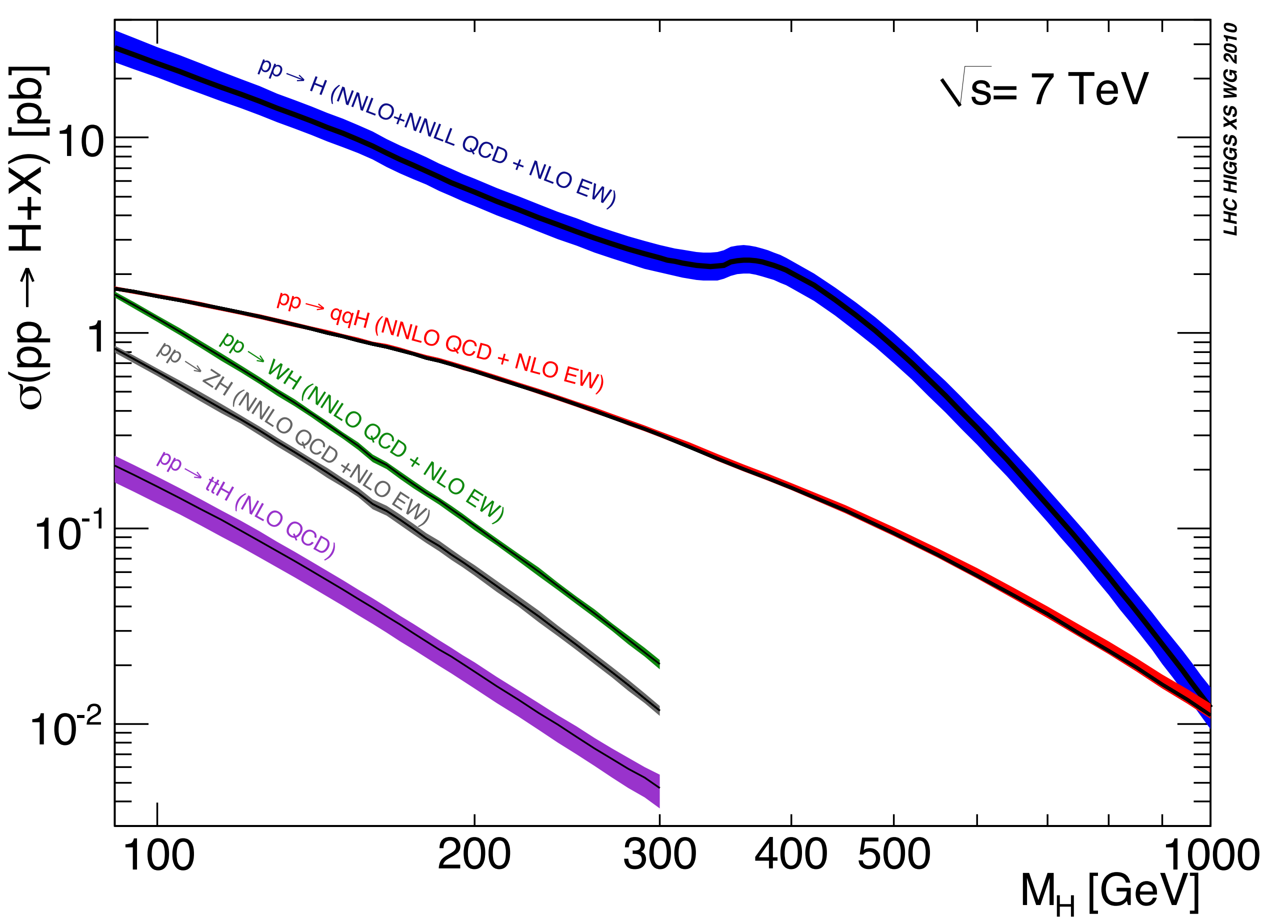
*8 TeV search now includes b-tags

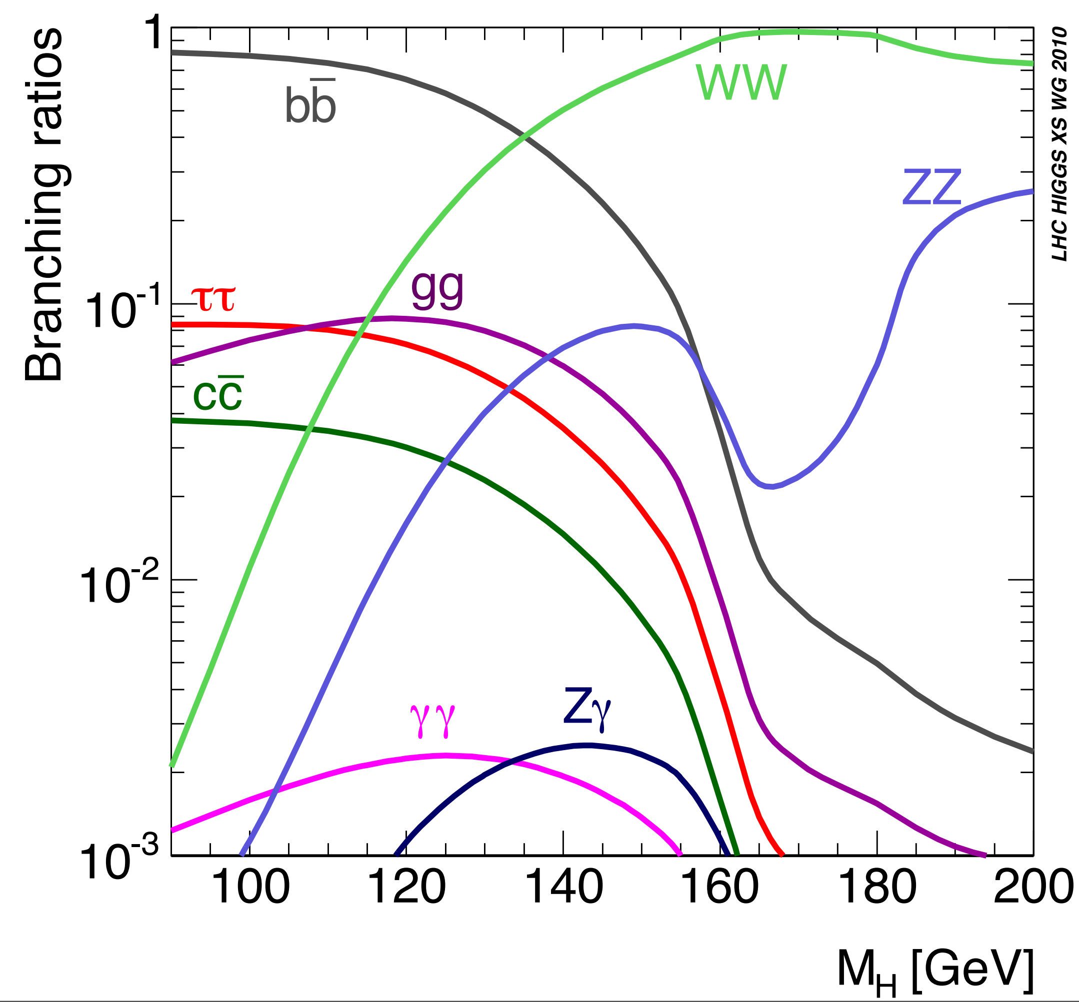
[NC, R.Gray, C.Kilic, M.Park, S.Somalwar, S.Thomas ’11]

Searching for the Higgs



The Higgs contributes to multi-lepton states through both associated production and decays

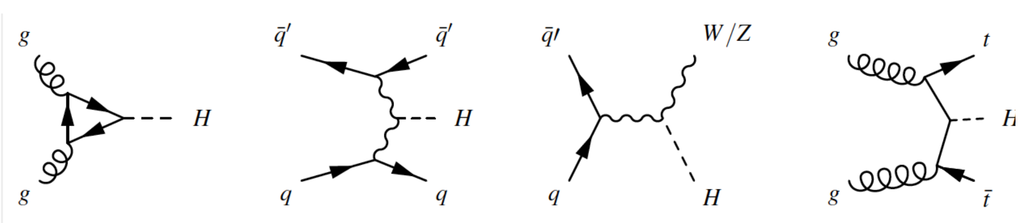




A Higgs multilepton search

Simulate 11 exclusive modes

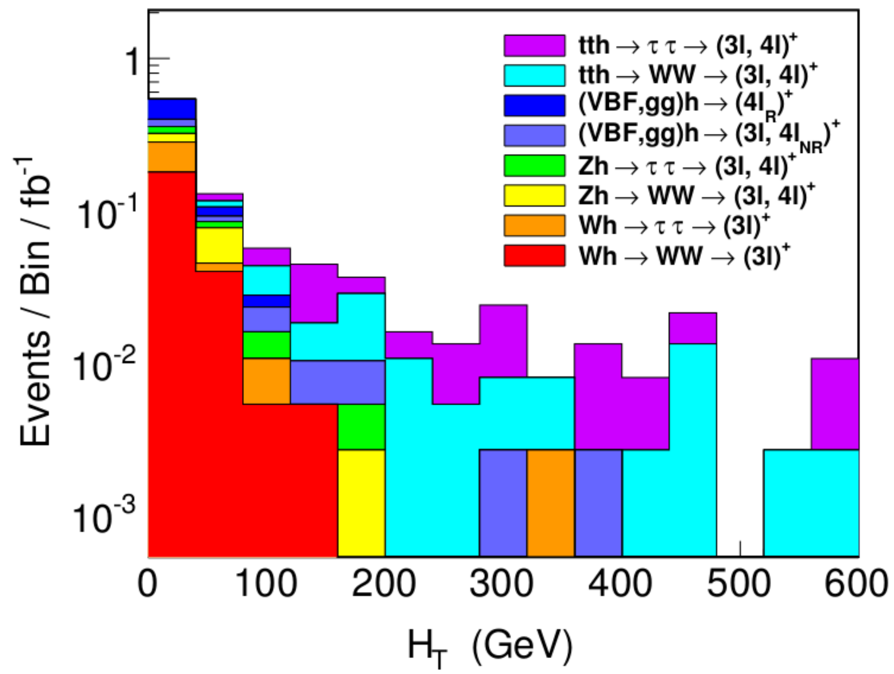
Production	Decay
$gg \to h$	$h \to 4\ell$
$\mathrm{VBF} \to h$	$h \to 4\ell$
$q\bar{q} \to Wh$	$Wh \to WWW, WZZ, W\tau\tau$
$q\bar{q} \to Zh$	$Zh \to ZWW, ZZZ, Z\tau\tau$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}ZZ, t\bar{t}\tau\tau$

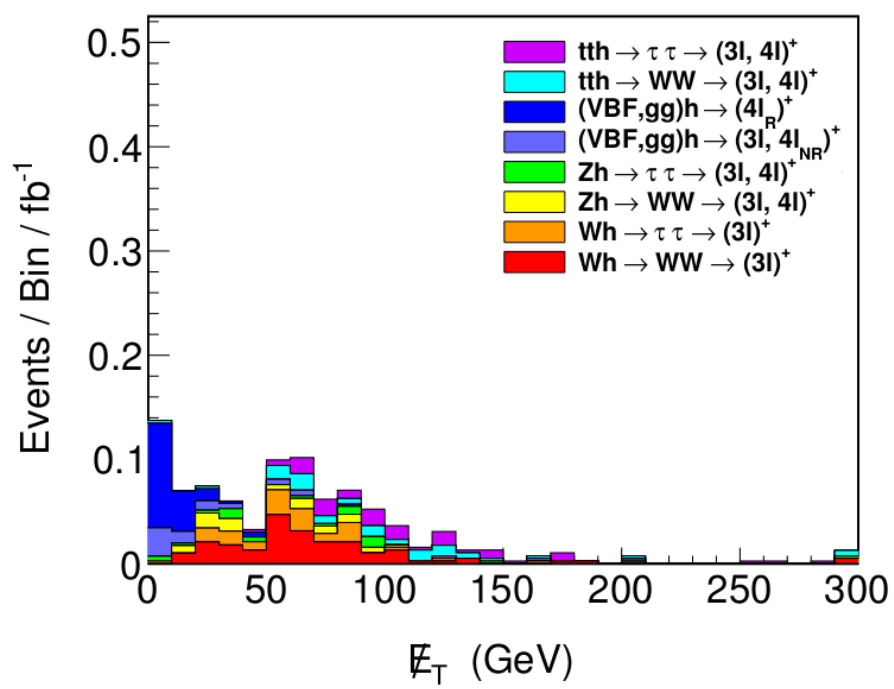


(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

Use exclusive combination of 20 signal channels and results from CMS 7 TeV search with 5/ fb for a “new” Higgs search

			Observed	Expected	SM Higgs Signal
4 Leptons					
†MET HIGH	HT HIGH	No Z	0	0.018 ± 0.005	0.03
†MET HIGH	HT HIGH	Z	0	0.22 ± 0.05	0.01
†MET HIGH	HT LOW	No Z	1	0.20 ± 0.07	0.06
†MET HIGH	HT LOW	Z	1	0.79 ± 0.21	0.22
†MET LOW	HT HIGH	No Z	0	0.006 ± 0.001	0.01
†MET LOW	HT HIGH	Z	1	0.83 ± 0.33	0.01
†MET LOW	HT LOW	No Z	1	2.6 ± 1.1	0.36
†MET LOW	HT LOW	Z	33	37 ± 15	1.2
3 Leptons					
†MET HIGH	HT HIGH	DY0	2	1.5 ± 0.5	0.15
†MET HIGH	HT LOW	DY0	7	6.6 ± 2.3	0.67
†MET LOW	HT HIGH	DY0	1	1.2 ± 0.7	0.04
†MET LOW	HT LOW	DY0	14	11.7 ± 3.6	0.63
†MET HIGH	HT HIGH	DY1 No Z	8	5.0 ± 1.3	0.38
†MET HIGH	HT HIGH	DY1 Z	20	18.9 ± 6.4	0.19
†MET HIGH	HT LOW	DY1 No Z	30	27.0 ± 7.6	1.8
MET HIGH	HT LOW	DY1 Z	141	134 ± 50	1.6
†MET LOW	HT HIGH	DY1 No Z	11	4.5 ± 1.5	0.13
†MET LOW	HT HIGH	DY1 Z	15	19.2 ± 4.8	0.09
MET LOW	HT LOW	DY1 No Z	123	144 ± 36	1.8
MET LOW	HT LOW	DY1 Z	657	764 ± 183	4.3





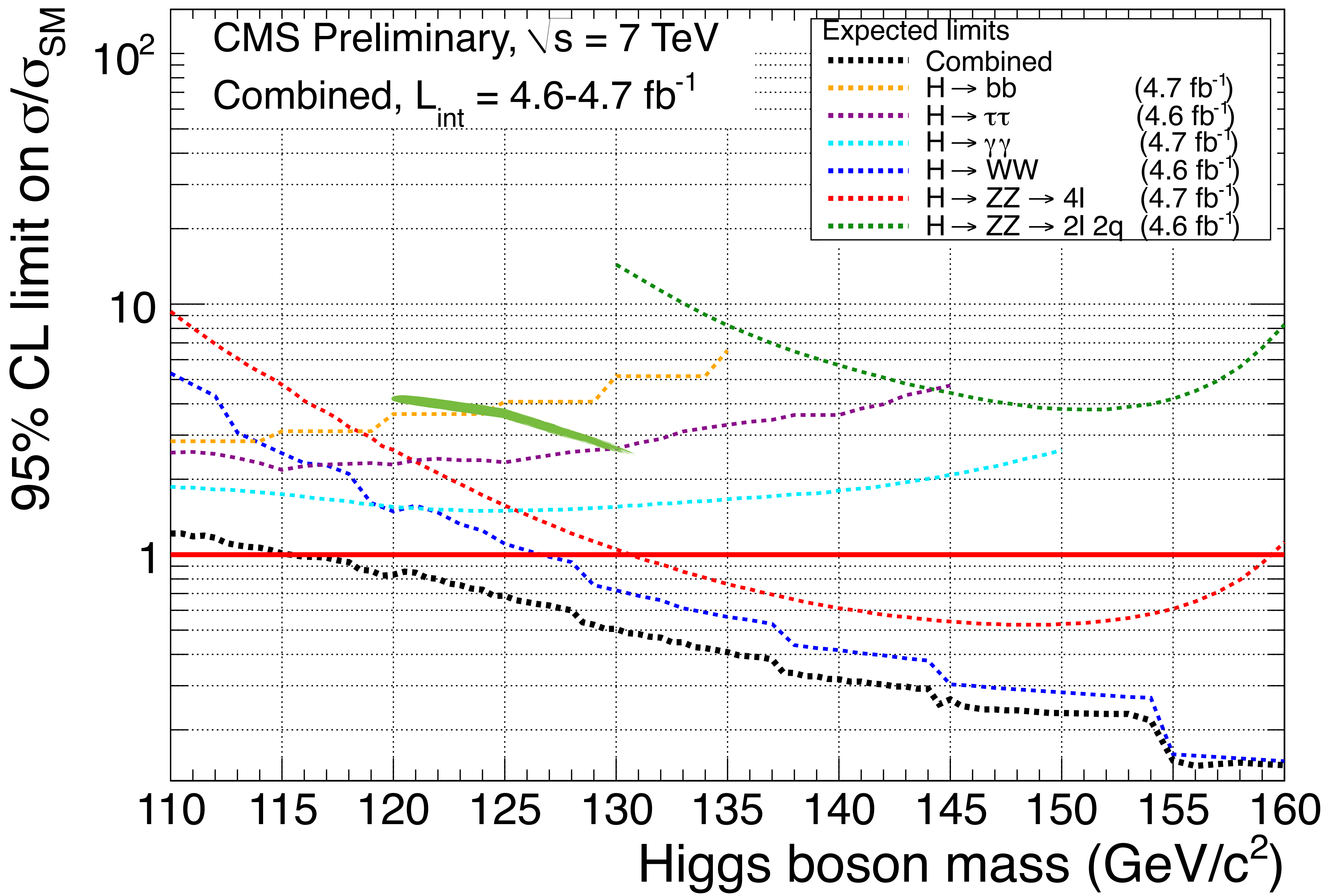
The Higgs in multileptons

Various channels populate various signal regions:

High HT events from ttH prodution and hadronic tau decays.

MET evenly distributed on both sides of the hi/lo cut.

Power of the search arises from the exclusive combination of all channels; sensitive to correlated signals arising in multiple channels



A guerilla Higgs search

m_h	120 GeV	125 GeV	130 GeV
Observed	5.4	4.9	3.5
Expected	4.2	3.8	2.8

Looking forward

- This home-made Higgs search using multi-leptons highlights the impressive nature of Higgs-specific search refinements! Focused searches several times stronger, even though signals are roughly equivalent.
- But also indicates that multi-leptons are a promising avenue to look for less specific related physics. We've found one Higgs, but we have a less focused idea about what else could be out there in terms of couplings and production/decays.
- It's apparent that the sensitivity of multi-leptons (and other NP searches) is such that new states could be near the Higgs with discovery just around the corner.

- Given the multi-lepton sensitivity to the Higgs, there are two interesting ideas to pursue:
- Look for indirect evidence of NP by searching for the Higgs in rare decays, ideally ones that provide additional leptons.
- Look for direct evidence of NP by looking for the totality of multi-lepton signals in an extended EWSB sector.

[NC, J.Evans, R.Gray, M.Park, S.Somalwar, S.Thomas, M.Walker '12]

Higgs as probe

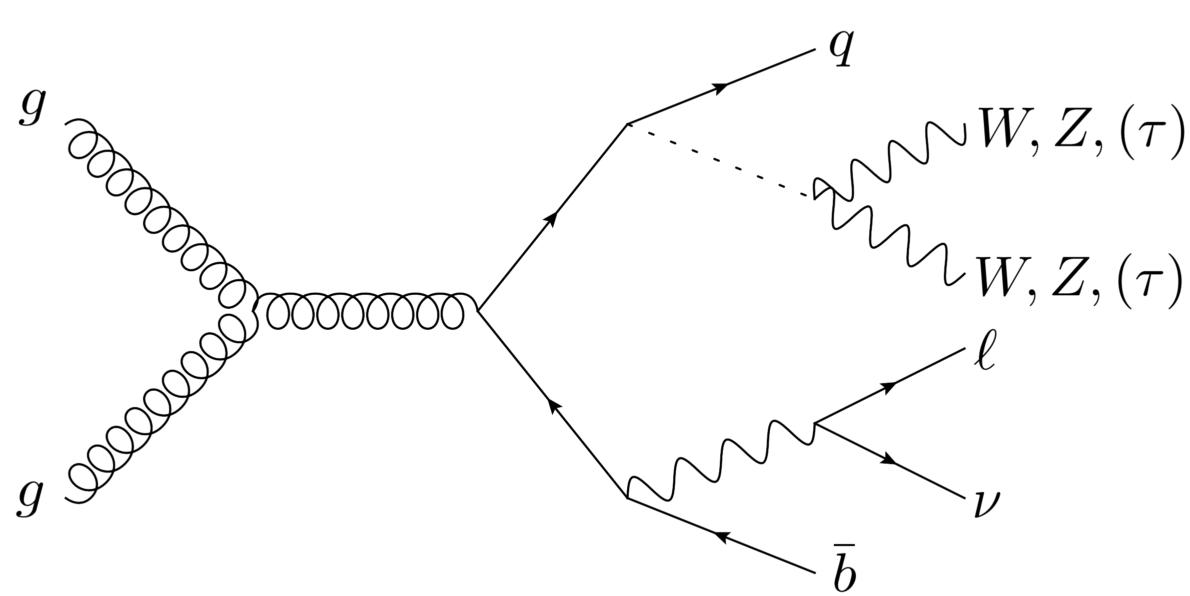
- Could either aim for Higgs in rare decays of SM states w/ large cross section, or in cascades of new physics.

- A good example of the former is $t\bar{t}$ production followed by the rare decay

$$t \longrightarrow hq$$

- LHC 7 TeV cross section is ~165 pb, so the sample is large! SM Br is 10^{-13}, so any signal is NP!

- Multi-lepton final states primarily from leptonic decay of one top, h+j decay of the other top, with $h \rightarrow WW^* \rightarrow \ell\ell\nu\nu,\ h \rightarrow \tau_\ell\tau_\ell$



			Observed	Expected	Signal
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MET HIGH	HT HIGH	Z	0	0.22 ± 0.05	0.0
MET HIGH	HT LOW	No Z	1	0.2 ± 0.07	0.11
MET HIGH	HT LOW	Z	1	0.79 ± 0.21	0.04
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MET LOW	HT HIGH	Z	1	0.83 ± 0.33	0.04
MET LOW	HT LOW	No Z	1	2.6 ± 1.1	0.08
MET LOW	HT LOW	Z	33	37 ± 15	0.15
3 Leptons					
MET HIGH	HT HIGH	DY0	2	1.5 ± 0.5	0.48
MET HIGH	HT LOW	DY0	7	6.6 ± 2.3	2.1
MET LOW	HT HIGH	DY0	1	1.2 ± 0.7	0.26
MET LOW	HT LOW	DY0	14	11.7 ± 3.6	1.68
MET HIGH	HT HIGH	DY1 No Z	8	5 ± 1.3	1.54
MET HIGH	HT HIGH	DY1 Z	20	18.9 ± 6.4	0.41
MET HIGH	HT LOW	DY1 No Z	30	27 ± 7.6	5.8
MET HIGH	HT LOW	DY1 Z	141	134 ± 50	2.0
MET LOW	HT HIGH	DY1 No Z	11	4.5 ± 1.5	0.80
MET LOW	HT HIGH	DY1 Z	15	19.2 ± 4.8	0.72
MET LOW	HT LOW	DY1 No Z	123	144 ± 36	3.1
MET LOW	HT LOW	DY1 Z	657	764 ± 183	2.4

Signal for 1% Br

Expect

$$\mathrm{Br}(t \to hq) < 1.7\%$$

Observe

$$\mathrm{Br}(t \to hq) < 2.7\%$$

Corresponds to

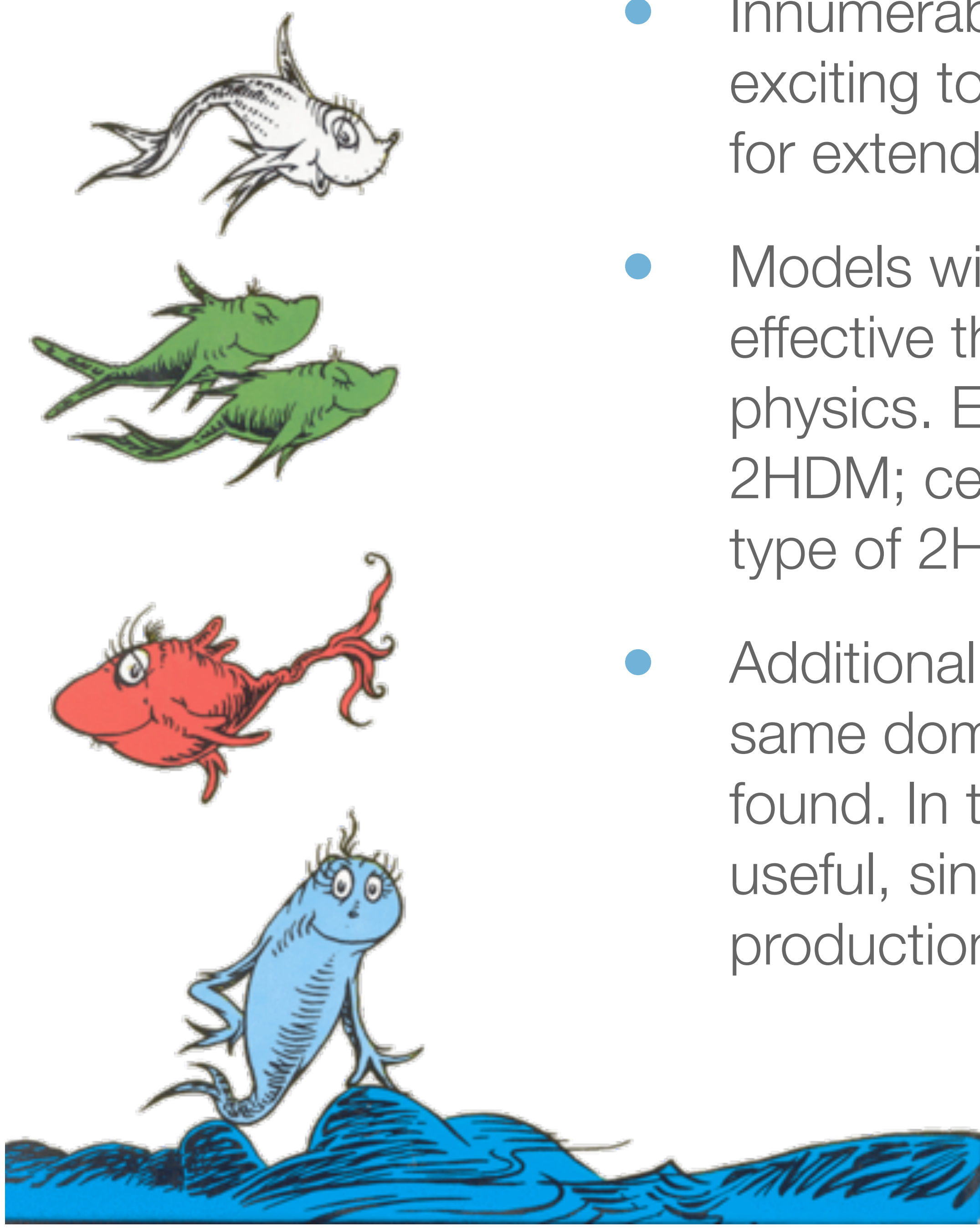
$$\sqrt{|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2} < 0.31$$

Best limit on these couplings.

Can improve significantly with b-tags, top tagging

Motivated new physics signals begin around ~10^{-4}

One Higgs, Two Higgs



- Innumerable uses of the Higgs as probe! But particularly exciting to look close to home by searching for evidence for extended electroweak symmetry breaking.
- Models with two (or more!) Higgs doublets are generic effective theory descriptions for many models of new physics. E.g., supersymmetry is a particular type of 2HDM; certain composite Higgs models are another type of 2HDM.
- Additional states in the Higgs sector unlikely to have the same dominant decay modes as the Higgs we've found. In this respect multi-leptons are particularly useful, since they're sensitive to the totality of production and decay modes.

Look for $h, H, A, H^{\pm}$

in direct decays, cascade decays, etc.

Two Higgs in one slide

$$H_1, H_2 \xrightarrow{\text{EWSB}} H \quad h \quad A \quad H^\pm \quad \boxed{G^0 \quad G^\pm}$$

- Physical spectrum consists of five real scalar fields

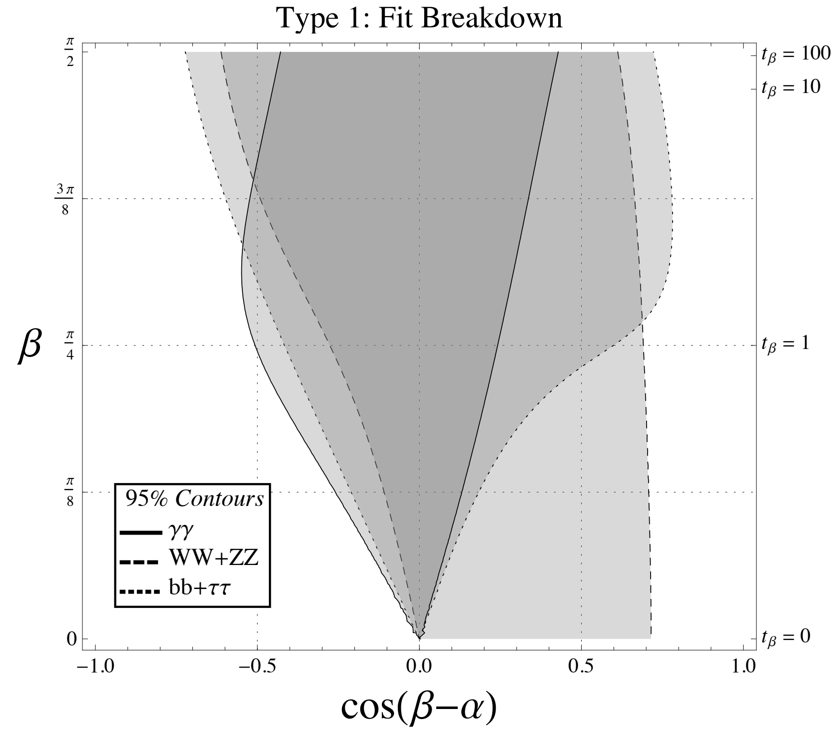
$$g_{hVV}^2 + g_{HVV}^2 = g_{h_{SM}VV}^2$$

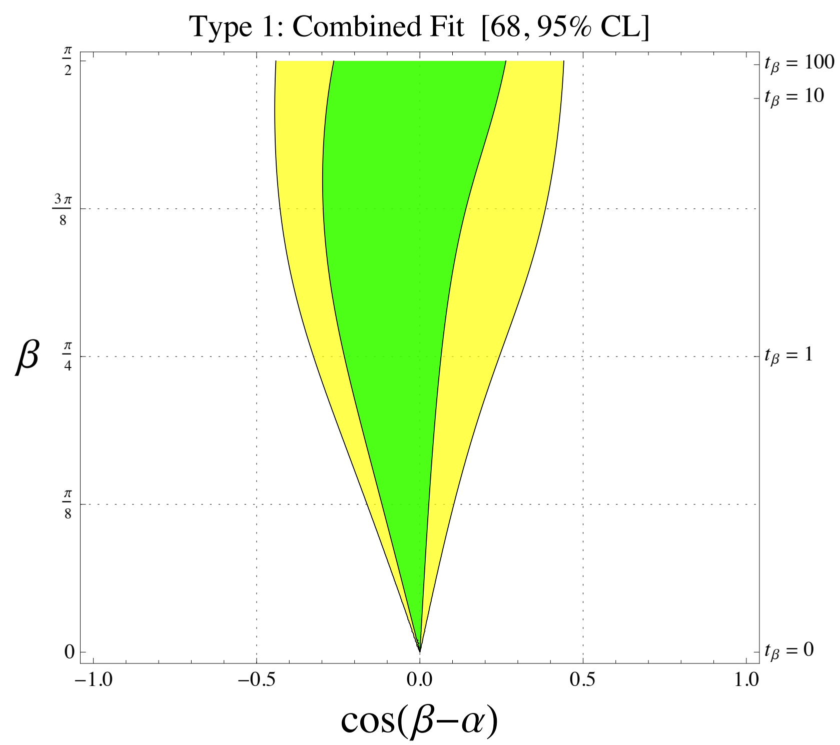
- The more h is SM-like, the less H is SM-like

- Two common types: “Type 1” leads to fermiophobic Higgs; “Type 2” is MSSM-like.

- Although total parameter space is vast, there is a motivated subspace given by theories without tree-level flavor violation.
- Reduces to four discrete types of models. In each, couplings to SM fermions and vector bosons are fixed in terms of two angles, α and β
- (Scalar self-couplings have somewhat more parametric freedom)
- *Gives a map between current fits to the Higgs couplings and the possible size of NP signals!*

[NC, J.Galloway, S.Thomas '13]





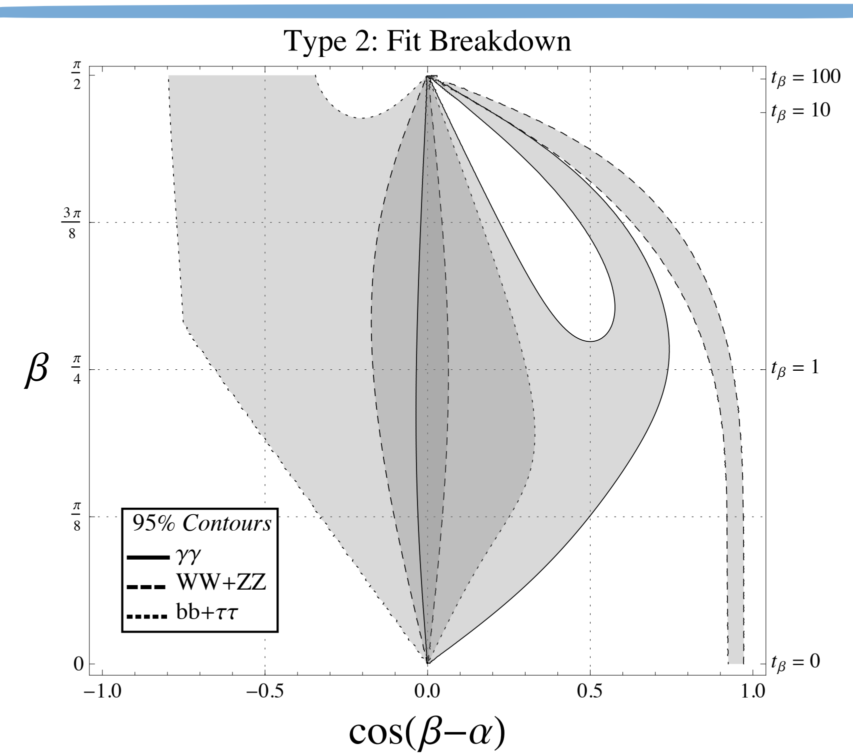
Making the map

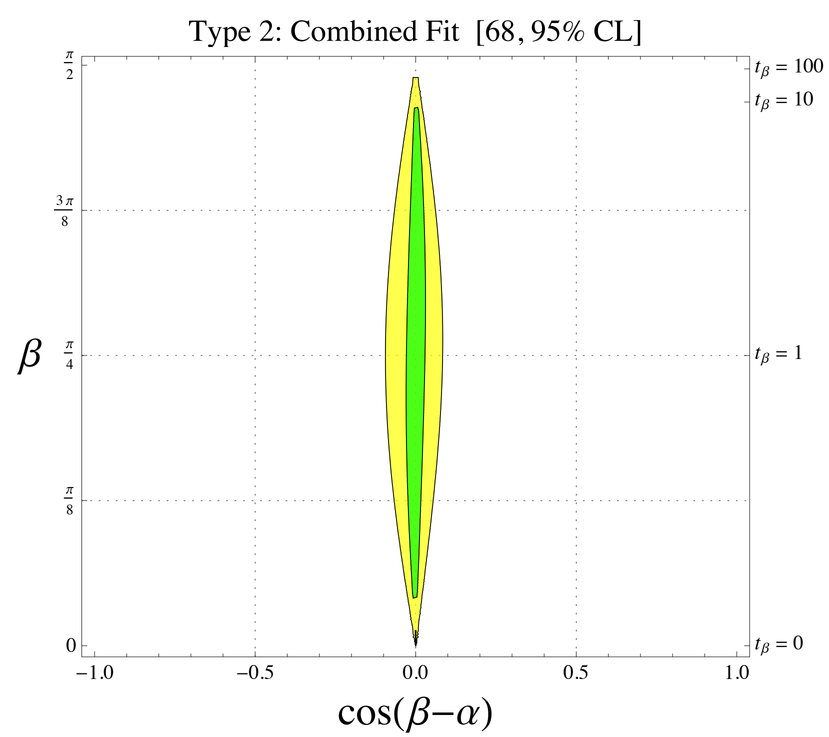
Assuming that the state at 126 GeV is the lightest CP-even Higgs h, and that the remaining states are heavier, we can map the current Higgs measurements onto the two angles that parameterize the 2HDM space.

Since the 126 GeV Higgs is SM-like, it's convenient to work in terms of the departure from the decoupling limit.

This is the case of Type 1 couplings, i.e., all fermions couple to one Higgs doublet.

Note: these are inadequate theorist fits.



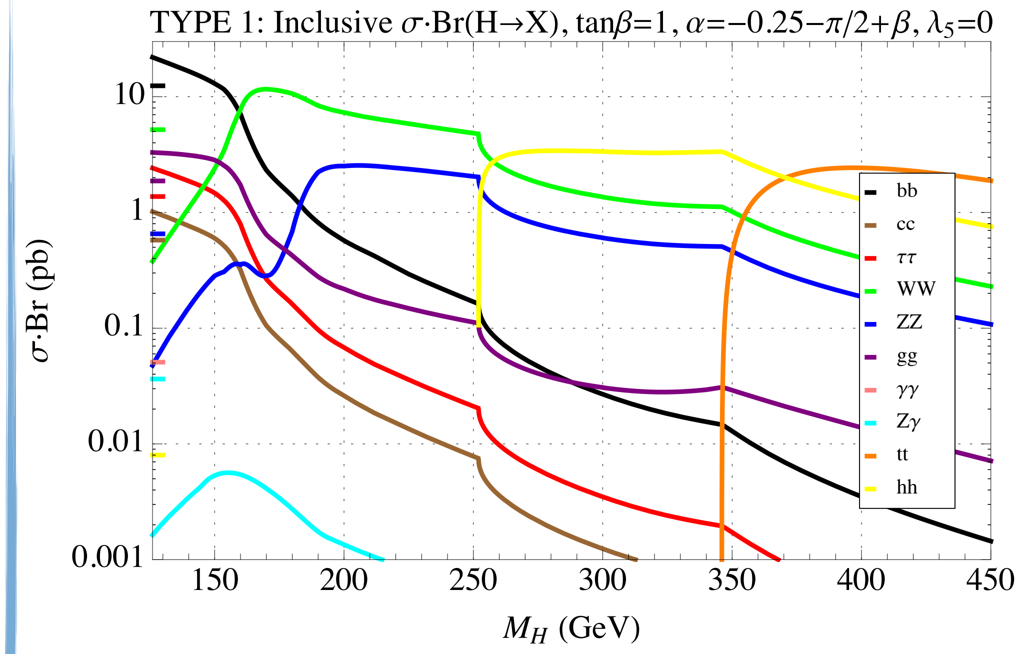


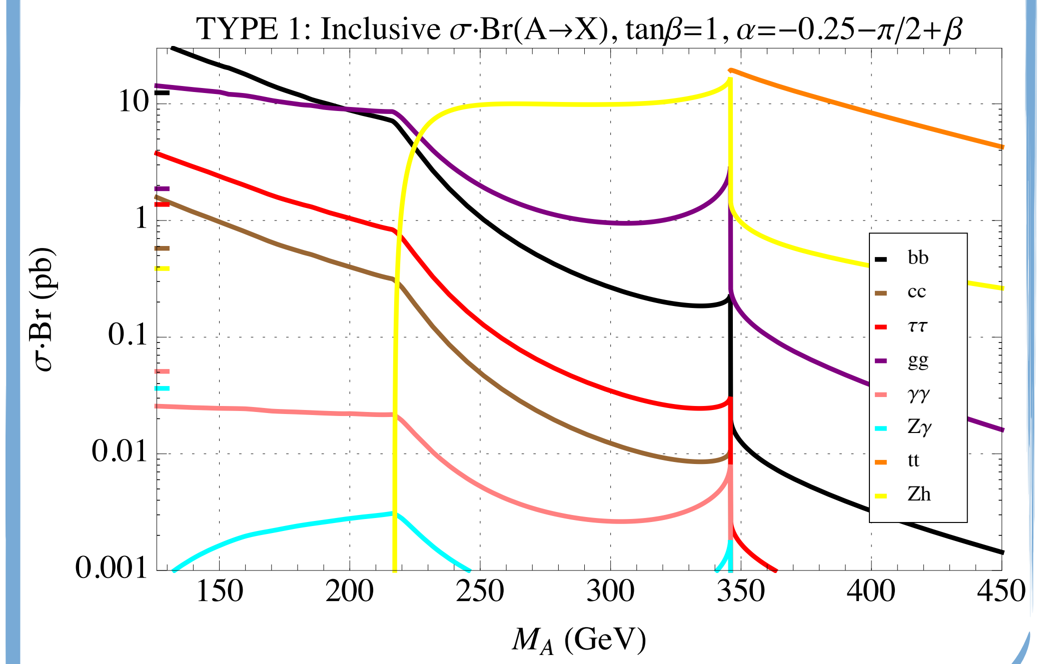
Making the map

The same thing, but for Type 2 (MSSM-like), where down-type quarks and leptons couple to a separate doublet from up-type quarks.

Note the much tighter constraint around the decoupling limit; this is in large part because the bottom coupling changes rapidly on either side of the alignment limit.

Now the fun part: map these fits onto the production and decay modes of the remaining scalars.





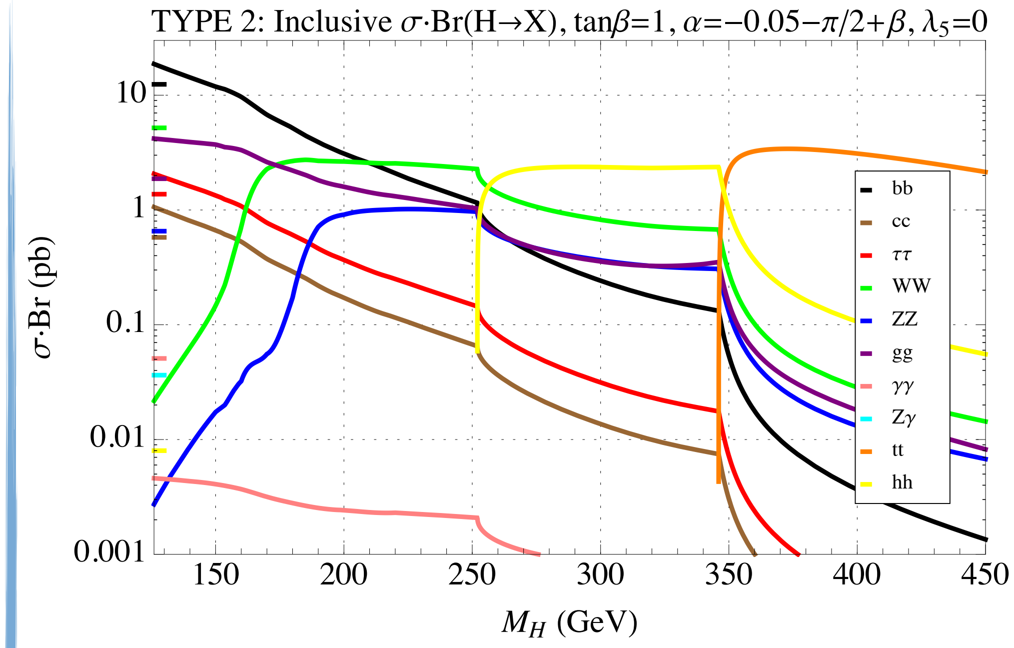
Signs of H&A

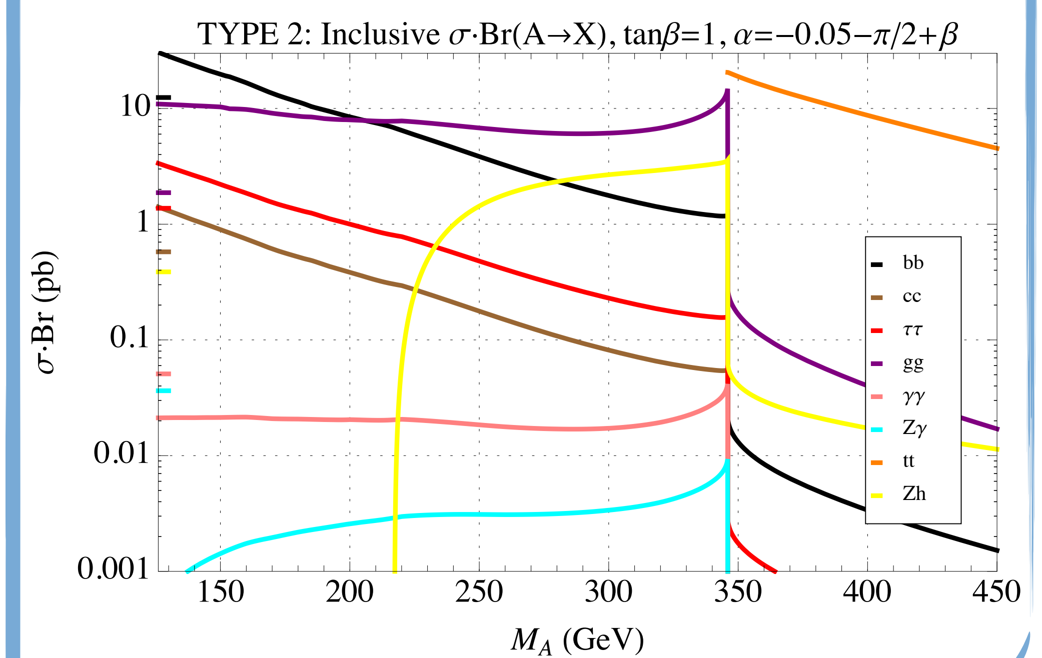
Both H and A are still dominantly produced by gluon fusion, so we expect O(pb) production cross sections.

Here I've chosen a benchmark point on the edge of the 68% contour for Type 1 couplings.

Rates to SM states are still appreciable due to interplay between total width and vector couplings.

Modes involving h (Zh, hh) dominate when kinematically accessible.



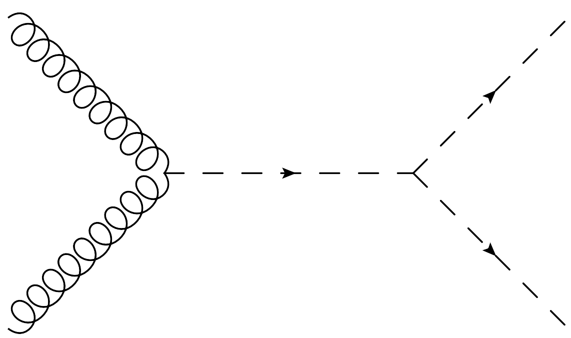


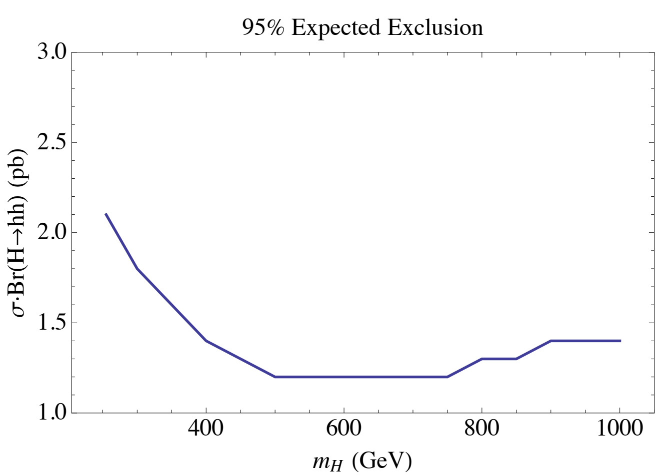
Signs of H&A

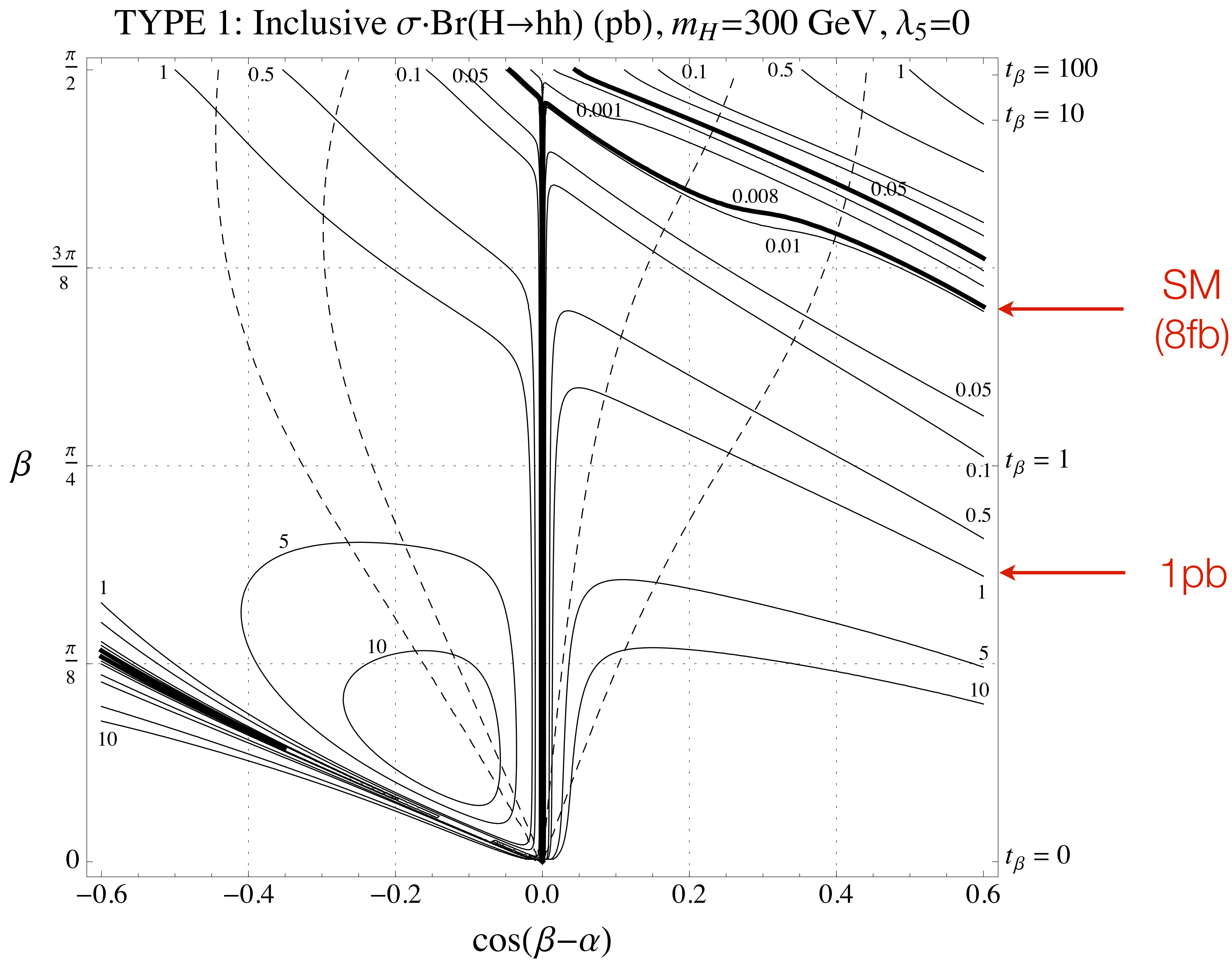
The same exercise for Type 2. Here the benchmarks are much closer to the decoupling limit. Rates are correspondingly reduced.

However, when kinematically accessible, Zh and hh can still have appreciable production rates, on the order of ~pb.

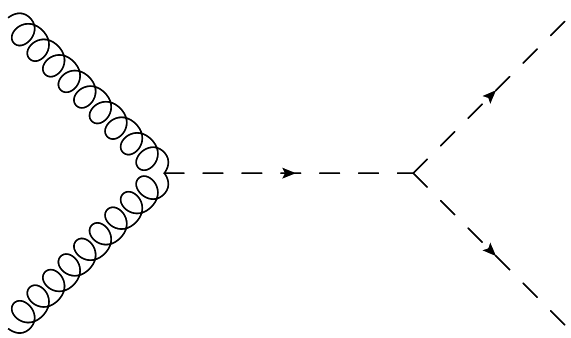
Even though the Higgs is mostly SM-like, there's a tremendous amount of room for BSM signals right around the corner.

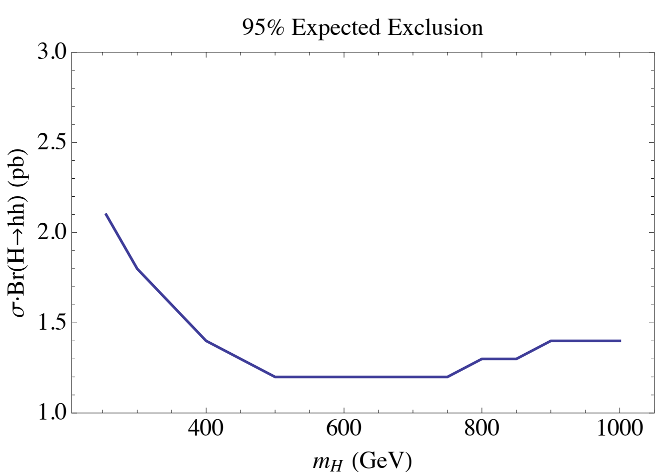




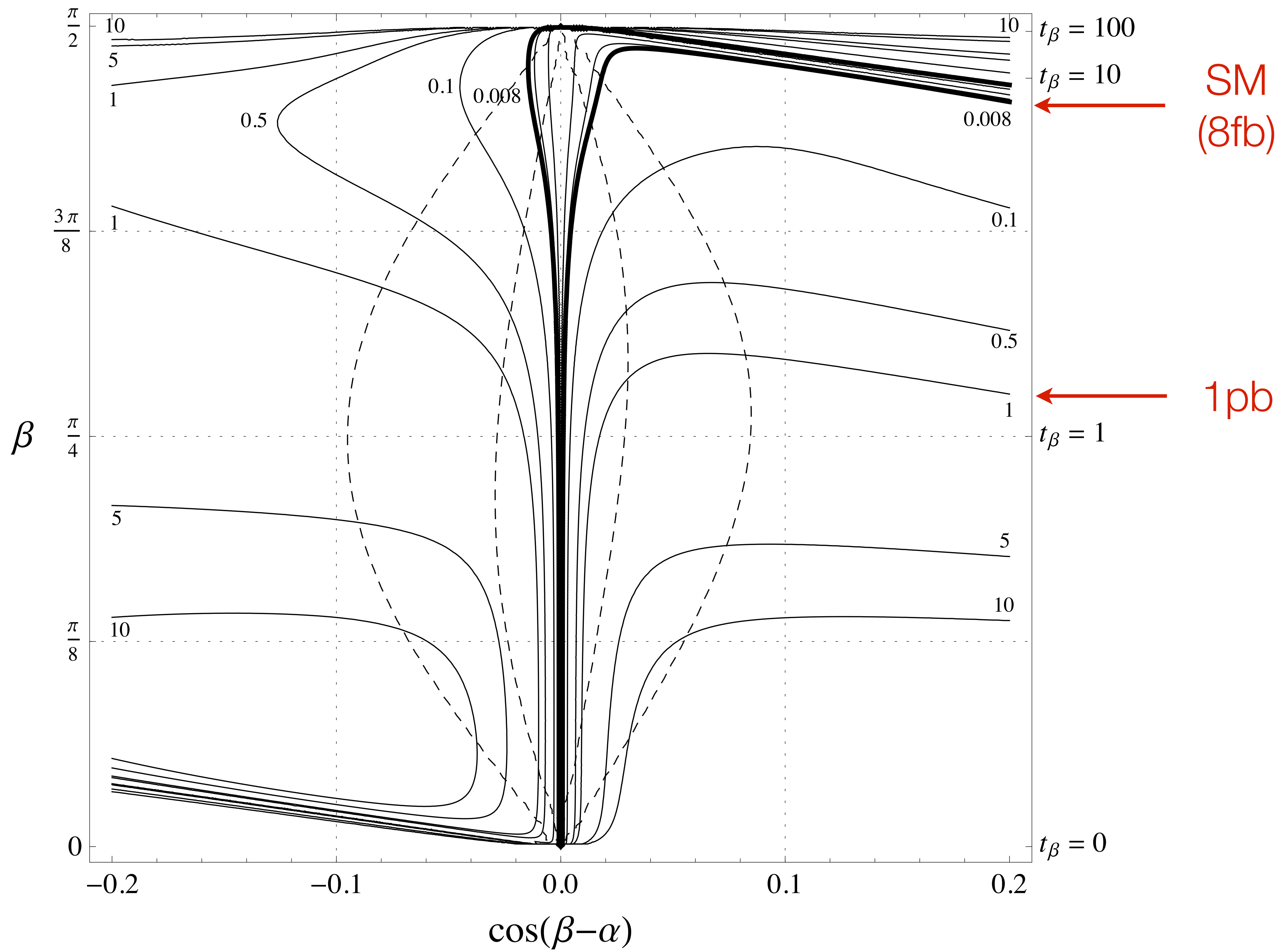


Drilling down on $H \rightarrow hh$





TYPE 2: Inclusive $\sigma\cdot$Br(H→hh) (pb), m_H=300 GeV, λ_5=0



Drilling down on $H \rightarrow hh$

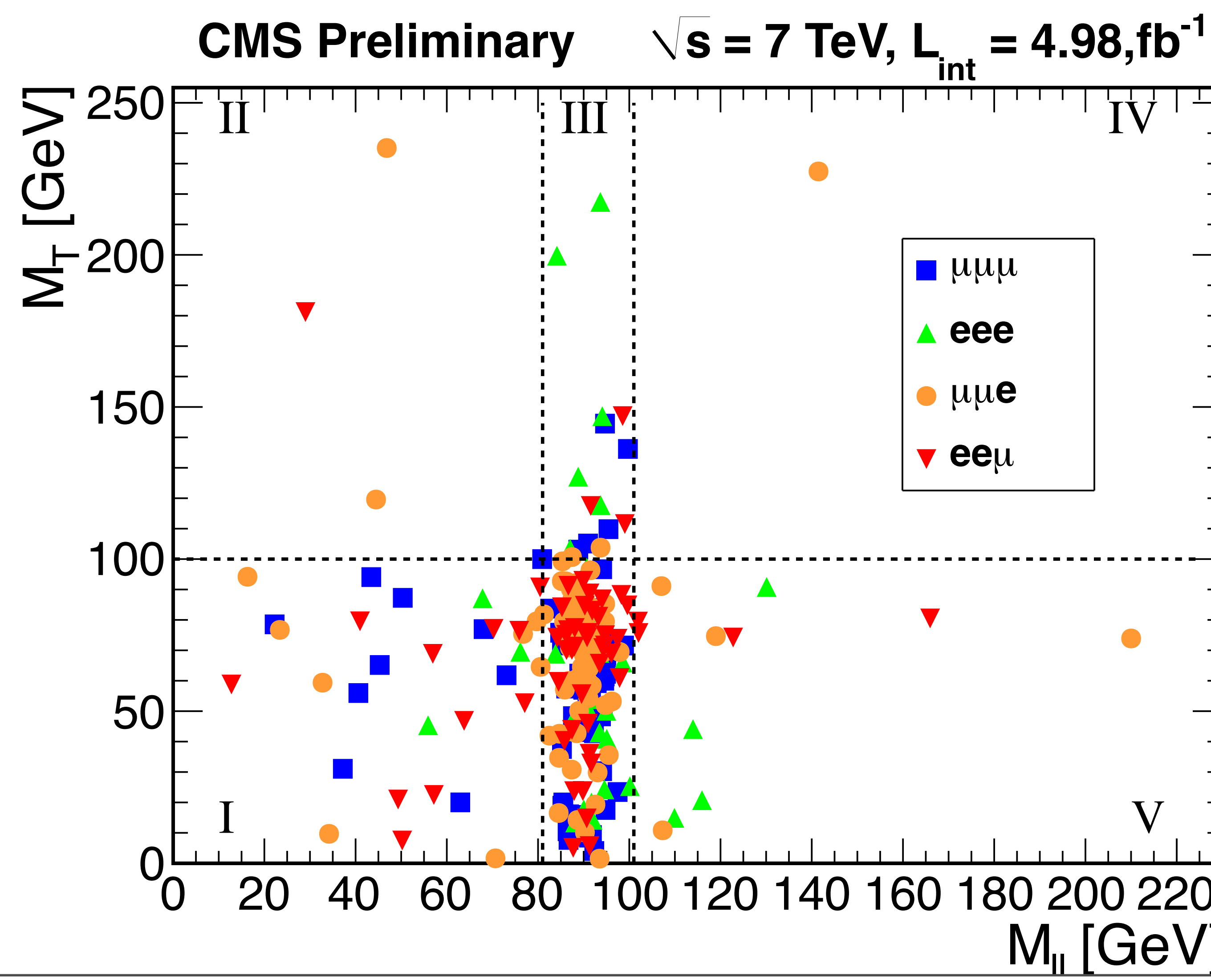
Drilling further down on di-Higgs

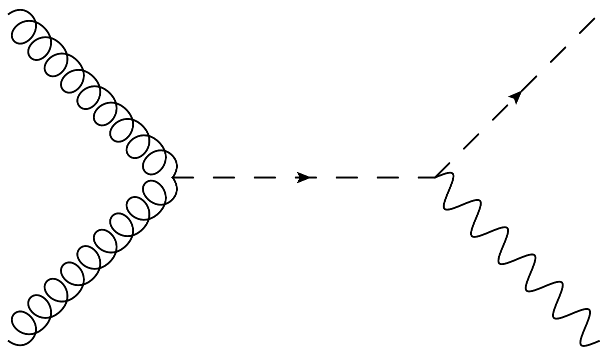
Region	WZ	Non-prompt	Rare SM	Total background	Data
I	16.2 ± 2.9	4.7 ± 2.4	2.1 ± 1.5	23.0 ± 5.1	31
II	3.6 ± 0.8	1.94 ± 1.02	0.4 ± 0.2	6.0 ± 1.3	3
III	15.6 ± 5.7	0.2 ± 0.1	0.8 ± 0.4	16.6 ± 5.7	17
IV	1.6 ± 0.4	0.2 ± 0.1	0.4 ± 0.2	2.2 ± 0.5	2
V	8.7 ± 1.7	1.4 ± 0.8	0.9 ± 0.4	11.0 ± 1.9	12
VI	150.6 ± 25.7	2.6 ± 1.4	11.7 ± 5.8	164.90 ± 26.4	173

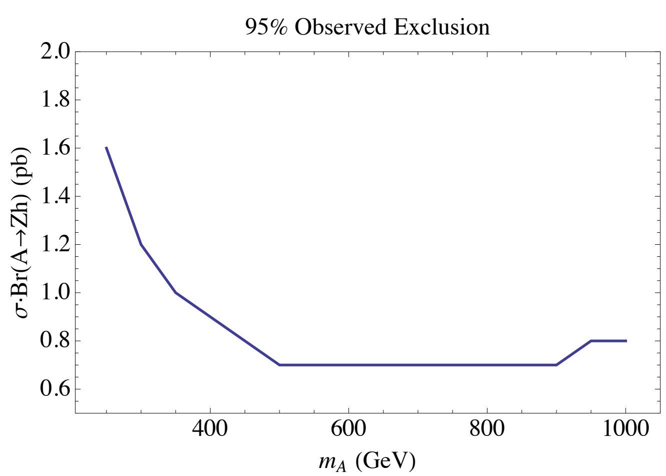
Now we also have more kinematic information about 3L events. Useful for di-Higgs production.

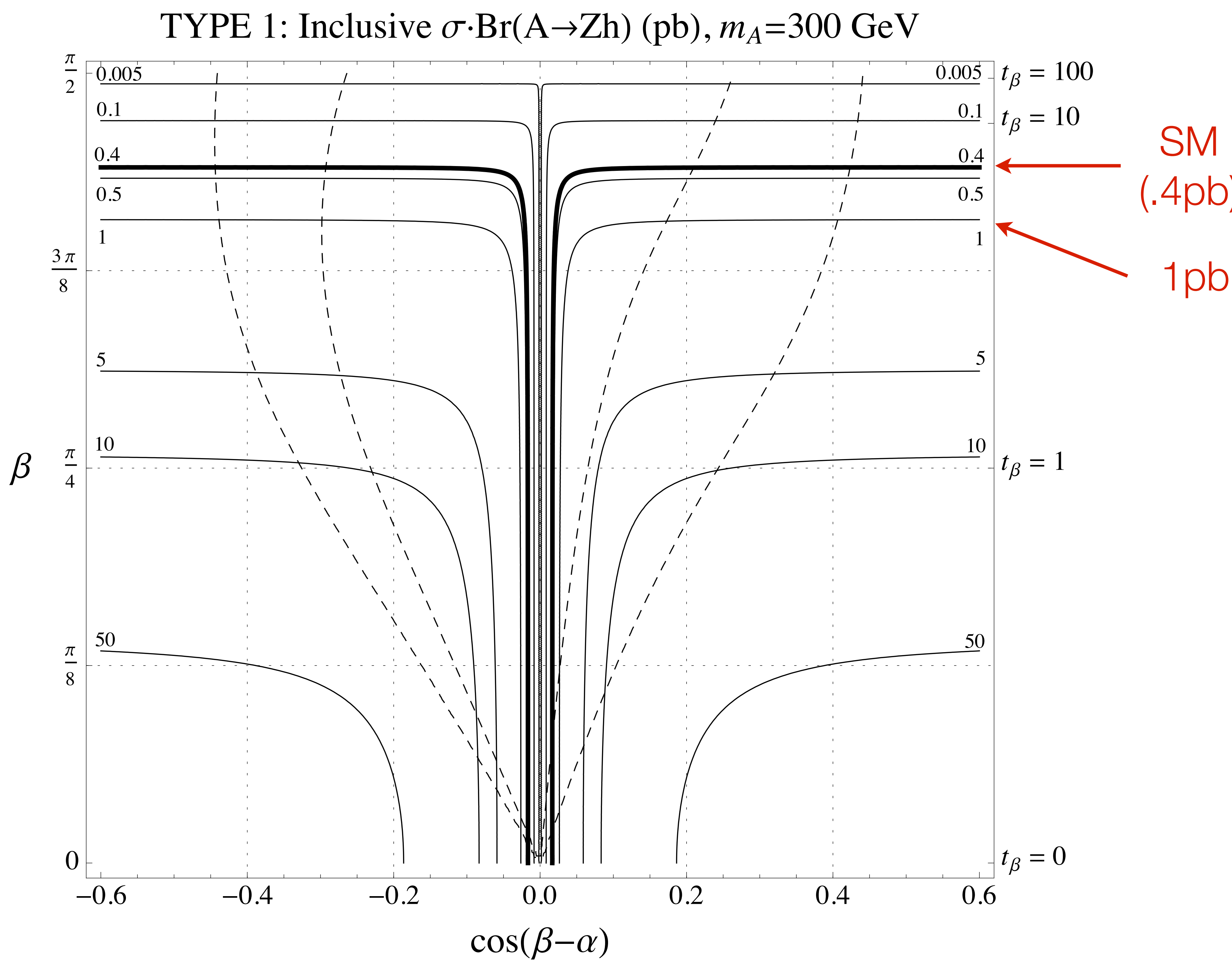
$$h \rightarrow WW^* \rightarrow \ell\ell\nu\nu$$
$$h \rightarrow WW^* \rightarrow \ell\nu q\bar{q}'$$

Leptons from the fully leptonic decay will be collinear; events populate the low-bkgd Region II

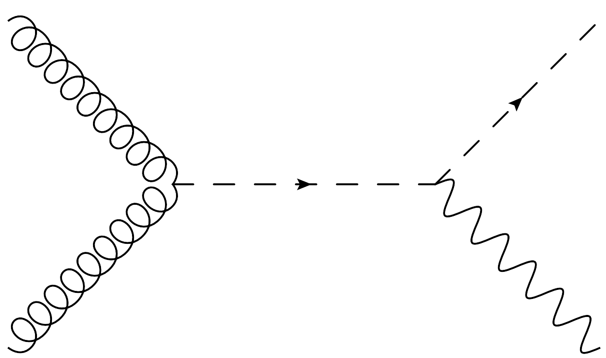


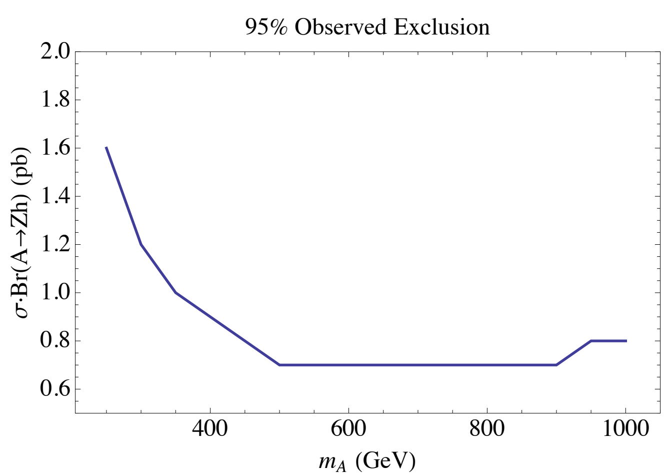


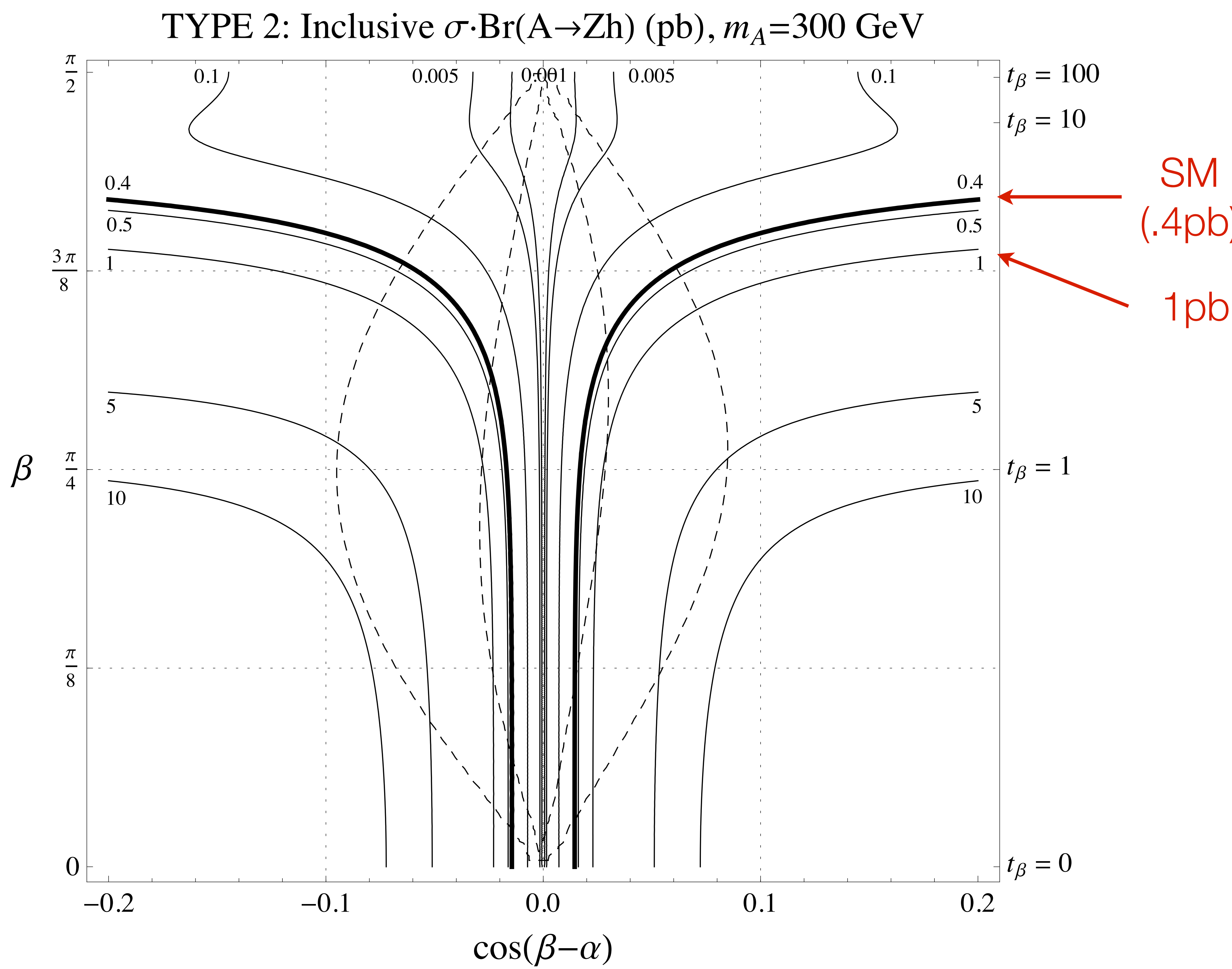




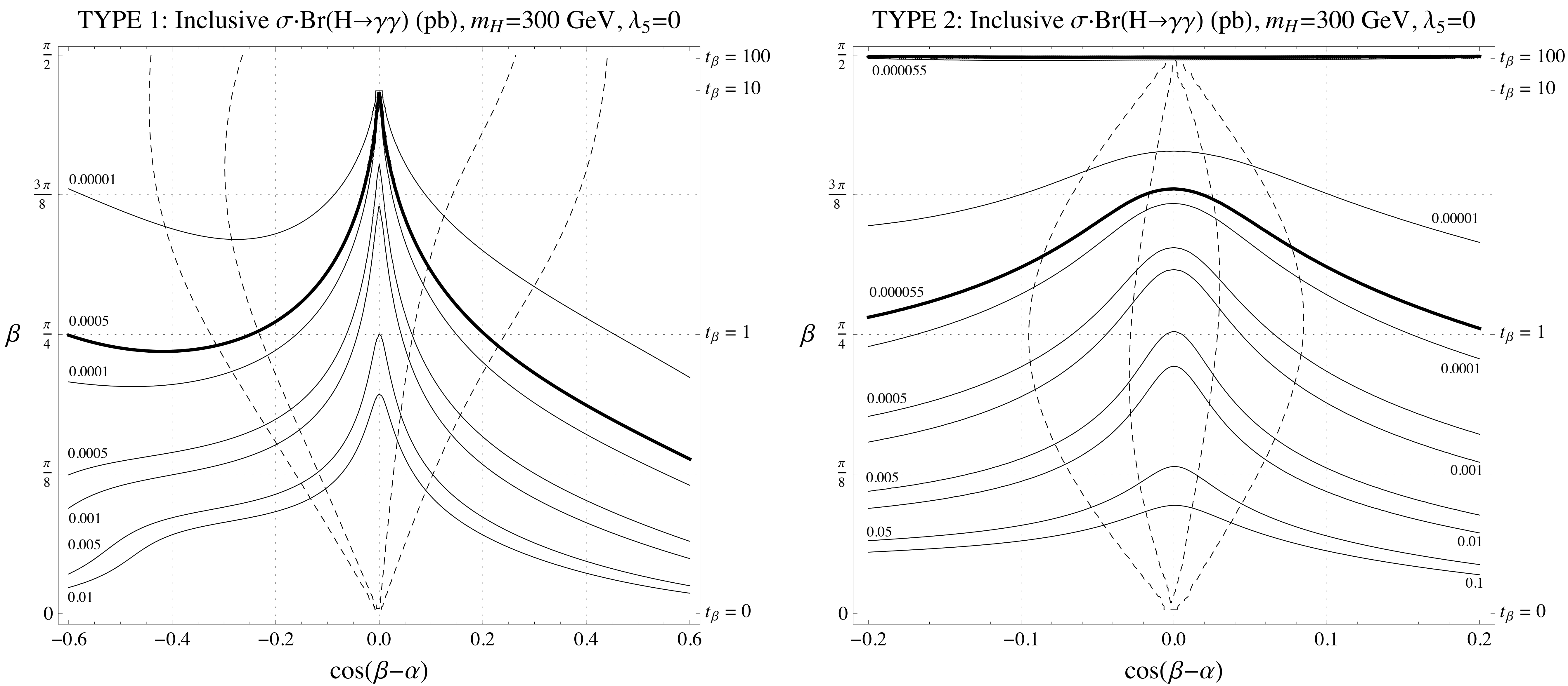
Drilling down on $A \to Zh$







Drilling down on $A \to Zh$



Complementarity

Zh, hh (also VV) turn off in decoupling limit, but fermion couplings are nonzero; diphoton and ditau final states most promising avenues.

[NC, J.Evans, R.Gray, C.Kilic, M.Park, S.Somalwar, S.Thomas ’12]

Collective signal

Can also search for the sum total of production and decay modes

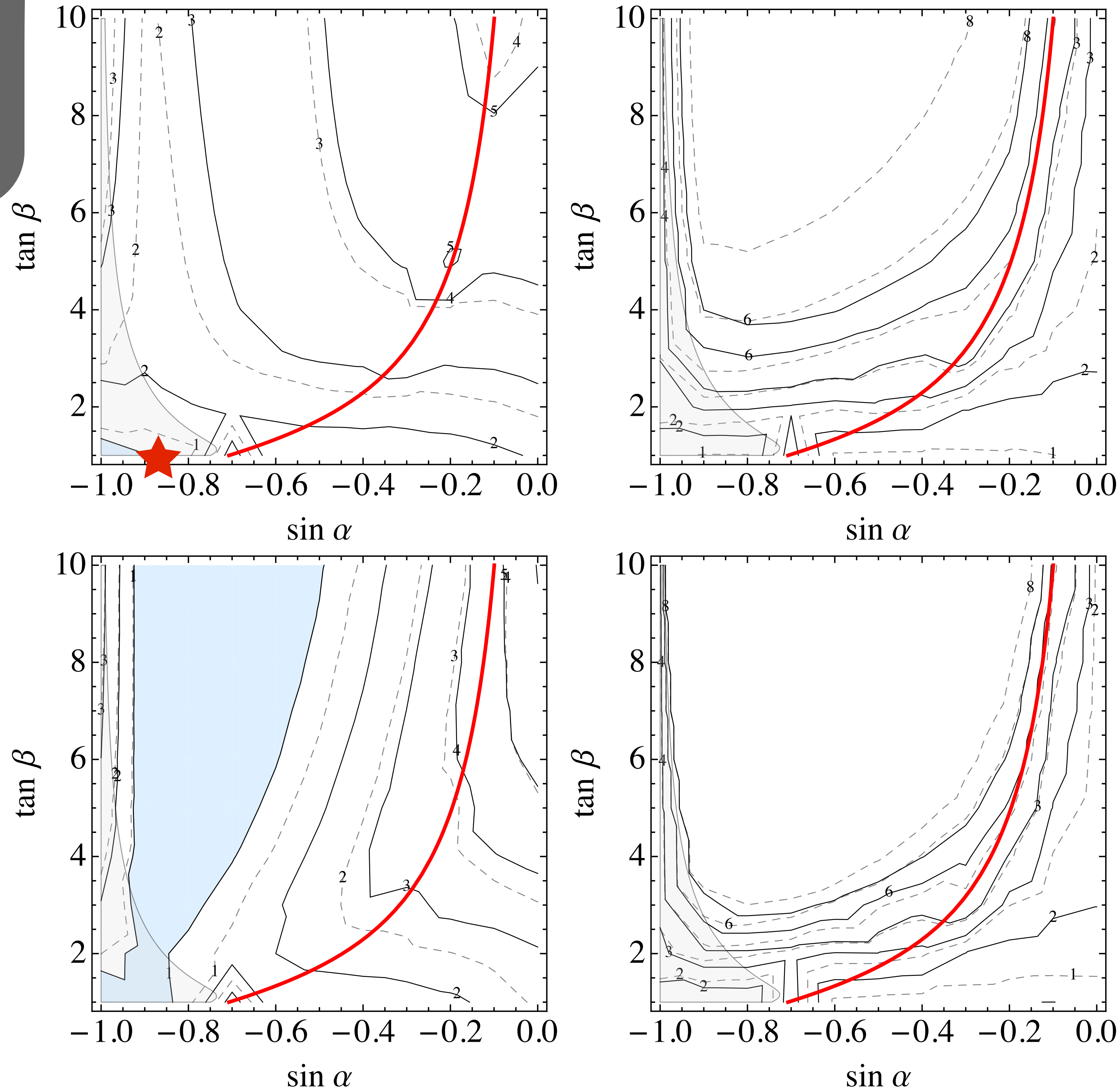
$h/A/H^{\pm}/H: \; 125/500/500/300 \text{ GeV}$

Production	Decay
$gg \to h$	$h \to 4\ell$
$\text{VBF} \to h$	$h \to 4\ell$
$gg \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
$\text{VBF} \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
$gg \to A$	$A \to Zh \to ZWW, Z\tau\tau, ZZZ$
	$A \to ZH \to ZWW, Z\tau\tau, ZZZ$
	$A \to ZH \to Zhh \to ZWWWW, ZWW\tau\tau, Z\tau\tau\tau\tau, ZZZb\bar{b}, ZZZWW, 5Z, ZZZ\tau\tau$
$q\bar{q} \to Wh$	$Wh \to WWW, W\tau\tau$
$q\bar{q} \to Zh$	$Zh \to ZWW, Z\tau\tau$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau$

37 channels

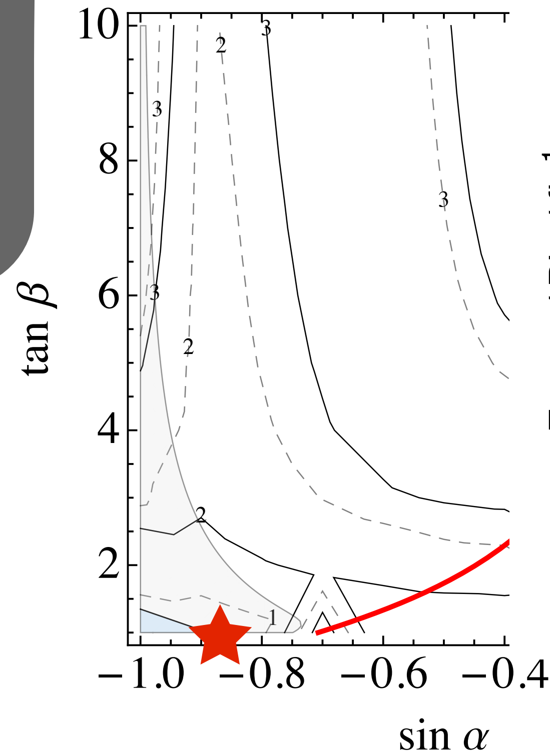
Many possible multi-lepton channels for each benchmark. Would be prohibitive to simulate inclusively as a function of the mixing angles. Instead factorize into topologies, compute acceptance for each topology, then re-weight analytically using functional dependence of cross section and branching ratios.

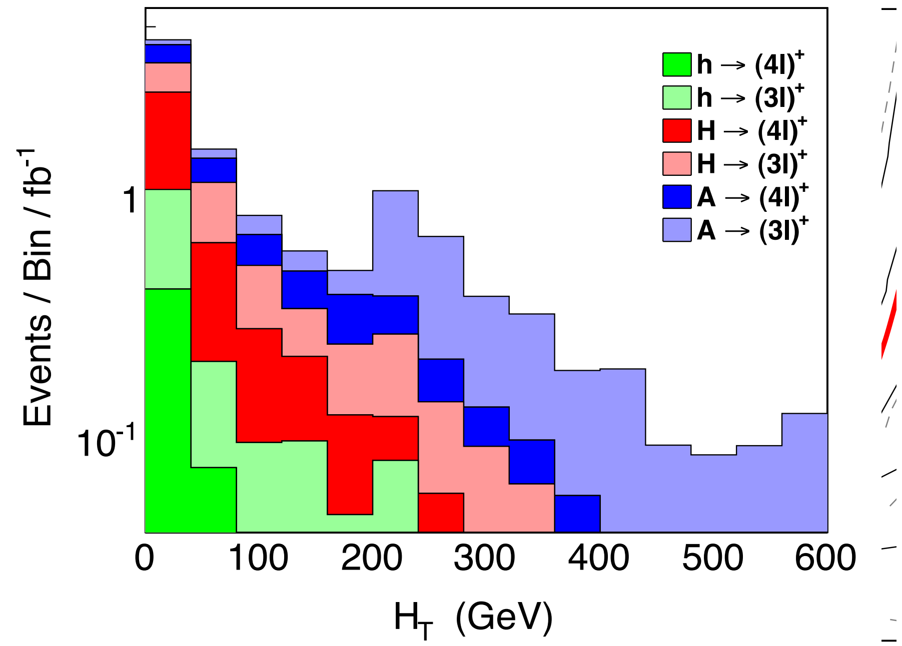
$$\sigma \cdot \text{Br} \cdot \mathcal{A}(pp \to f) = \sum_t \sigma(pp \to t)\mathcal{A}(pp \to t \to f) \prod_a \text{Br}_a(t \to f)$$

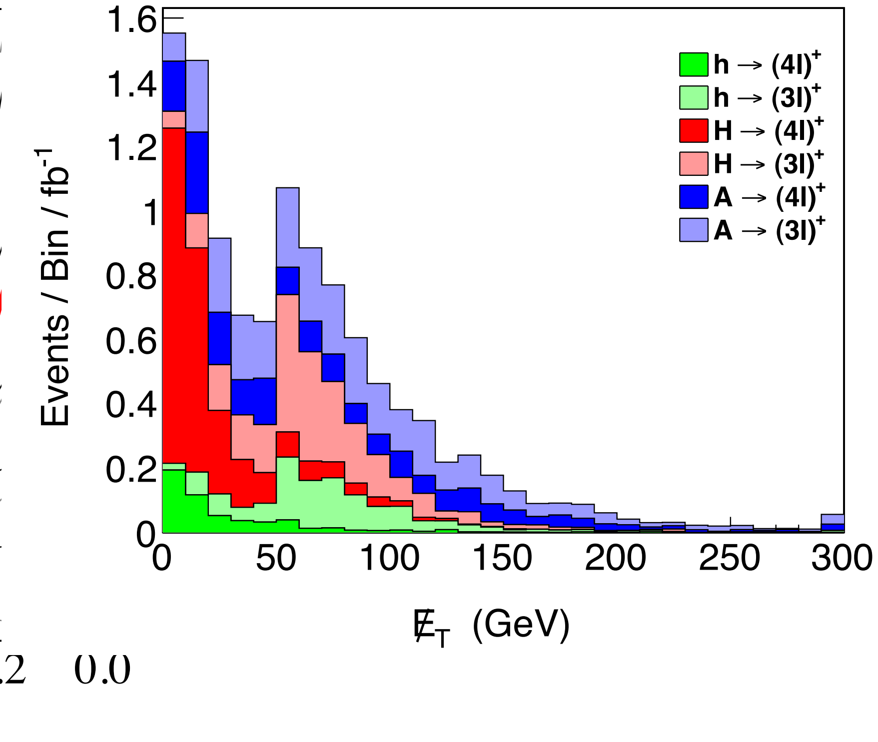


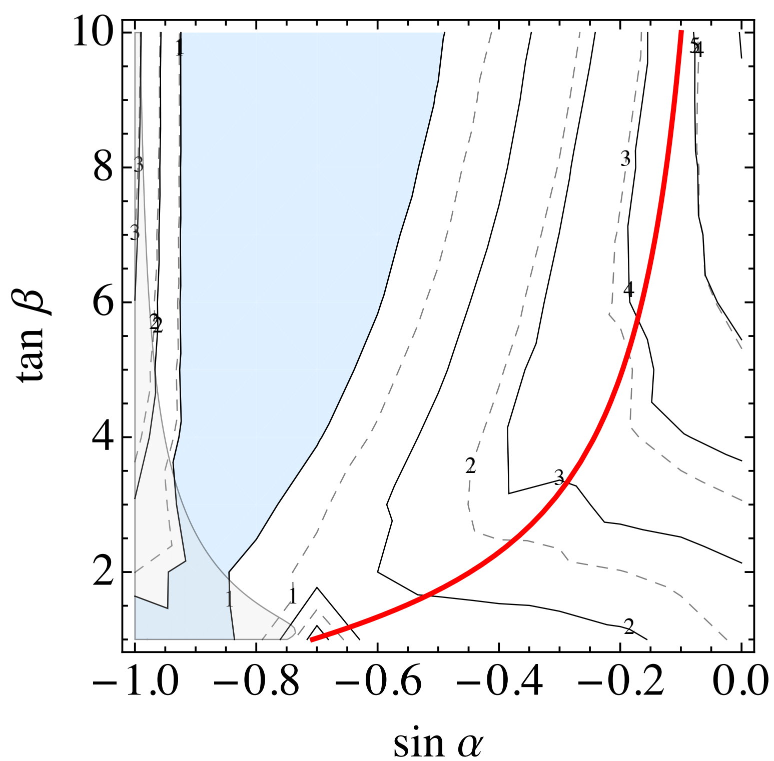
New regions of parameter space already excluded with 5/fb of 7 TeV data

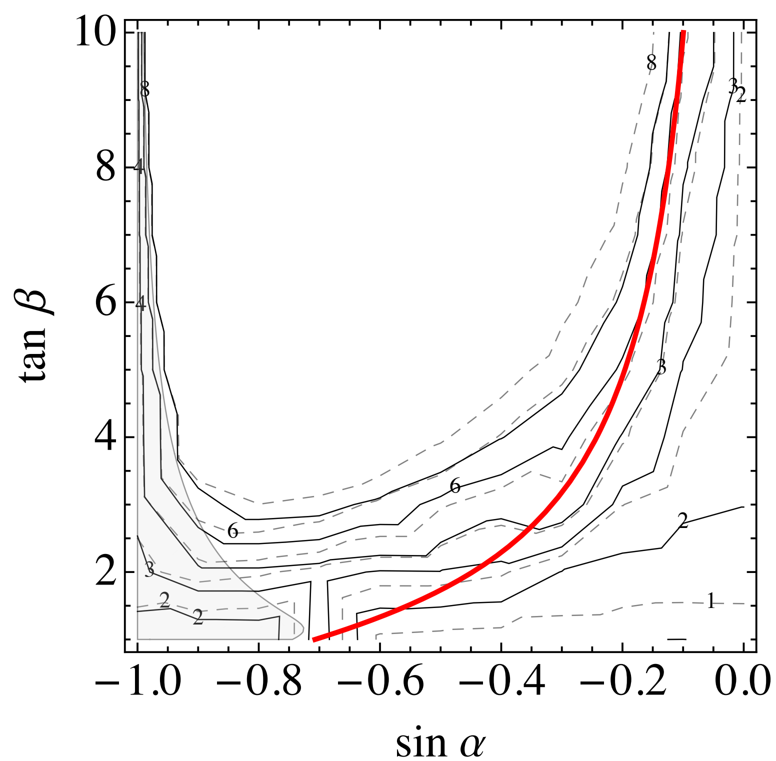
Further improvements with b-tagging, etc.











New regions of parameter space already excluded with 5/fb of 7 TeV data

Further improvements with b-tagging, etc.

[NC, S.Thomas '13]

Precision physics

Can write NP in terms of effective operators involving the Higgs...

$$\frac{\xi_T}{M^2}(H^\dagger D_\mu H)(H^\dagger D^\mu H) \quad \leftrightarrow \quad \text{one-to-one with } T \text{ parameter}$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2} H^\dagger W_{\mu\nu} H\, B^{\mu\nu} \quad \leftrightarrow \quad \text{one-to-one with } S \text{ parameter}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2} H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$$

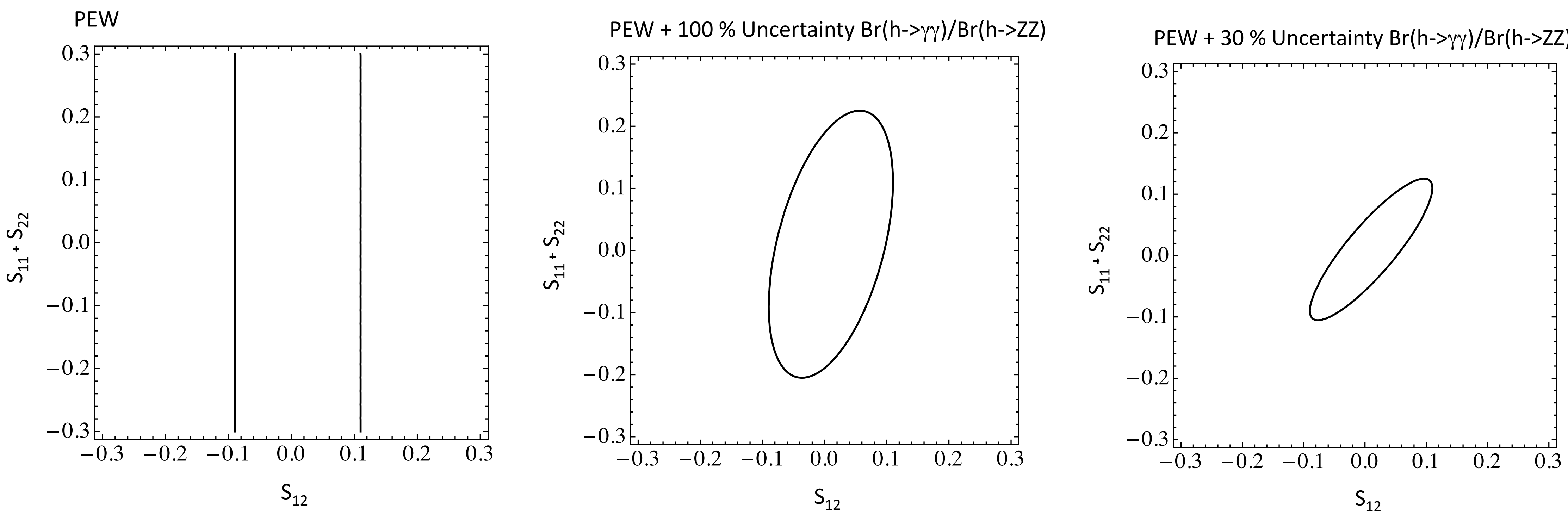
New information from Higgs!

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2} H^\dagger H\, W_{\mu\nu} W^{\mu\nu} \quad \leftrightarrow \quad \mathrm{Br}(h \to \gamma\gamma) \propto S_{11} + S_{22} - S_{12}$$

Isolate this by measuring inclusive ratios to find

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)} \simeq \left.\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}\right|_{\mathrm{SM}} \left[1 + \mathcal{O}\left(\frac{4\pi v^2}{\alpha}\frac{\xi}{M^2}\right)\right]$$

Sensitive because the leading SM contribution starts at one loop



Systematics: m_t, $\log(m_h)$, α_s

Systematics: statistics, resonance-continuum interference

S = 0.01 +- 0.10

T = 0.03 +- 0.11

Also can get orthogonal information from $Z\gamma$

Higgs+Dark Matter

- We've discovered the Higgs, we know there's dark matter, so it's fruitful to contemplate the intersection no matter what other BSM physics is out there.

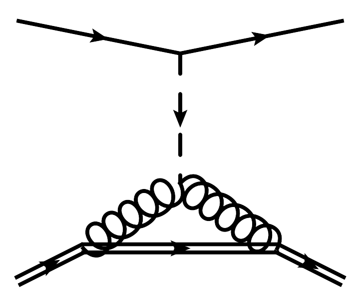
Scalar DM: $\lambda\chi^2|H|^2$

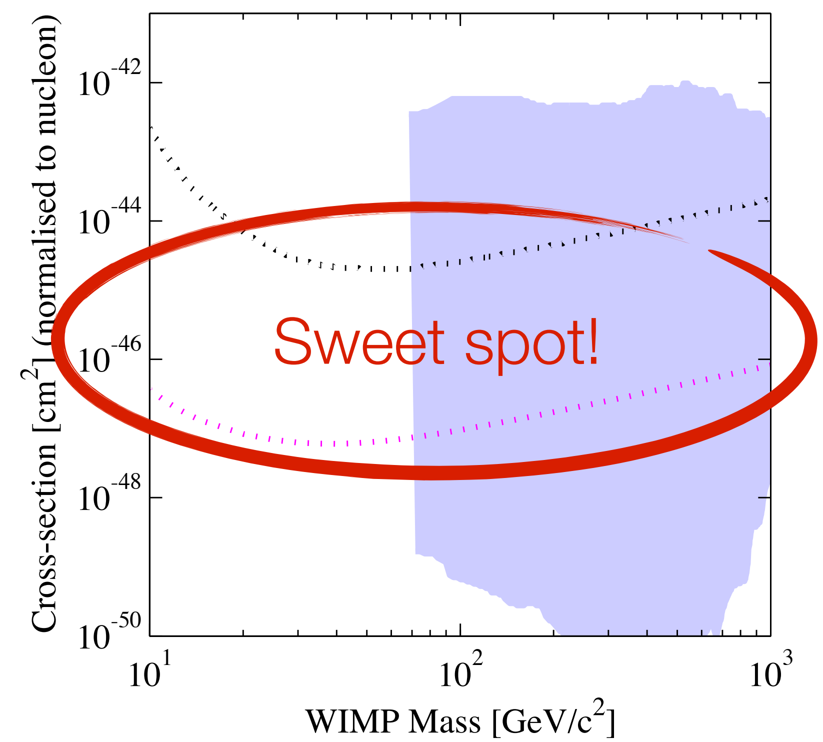
Vector DM: $g^2\chi_\mu\chi^\mu|H|^2$

Fermion DM: $yH\chi_1\bar{\chi}_2$

NB, fermion requires additional electroweak charged state

Higgs mediated direct detection



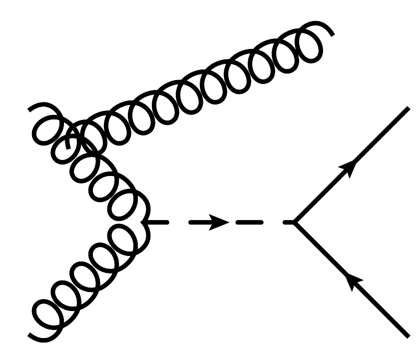


Higgs mediated LHC production

$m_\chi < m_h/2$ Look for invisible width of the Higgs

$m_\chi > m_h/2$ Monojet + MET, multi-leptons, ????

Room for improvement w/ soft leptons



Onwards!

The discovery of the Higgs suggests many novel approaches to the search for new physics:

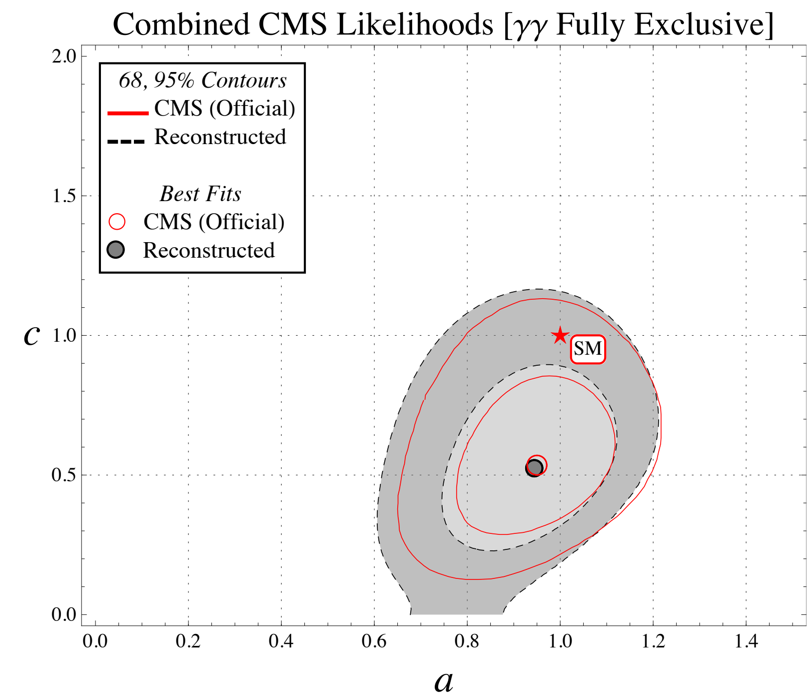
- Via Higgs couplings, which improve our sensitivity to new physics even if not directly produced.
- Via appearance in NP-induced decays of SM states, especially the top.
- Via appearance in conjunction with additional Higgs scalars or other states.
- Via its potential relationship to dark matter, with various detection prospects.

Many of these can be efficiently probed with multi-leptons, but we also need to mobilize the Higgs groups for more BSM searches. We're at the dawn of an exciting era, with much to be done!

Thank you!

Supplemental

Higgs fits



- Fit constructed with all available LHC+Tevatron data.
- Use fully exclusive channel breakdowns. Profile of signal strength modifier is fit with a two-sided Gaussian when available, likelihood constructed as

$$L_i^{\pm}(\mu) \propto \exp \frac{-(\mu - \hat{\mu}_i)^2}{2(\sigma_i^{\pm})^2}$$

- Otherwise, construct likelihood for each channel with corresponding rescaling using event counts,

$$\frac{n_{\rm obs} - n_{\rm B}}{n_{\rm B}} \ll 1 \quad \Longrightarrow \quad L(\mu) \to \exp\left[-\frac{1}{2}\left(\mu \frac{n_{\rm S}}{\sqrt{n_{\rm B}}} + \delta\right)^2\right]$$

$$\delta = \frac{n_{\rm B} - n_{\rm obs}}{\sqrt{n_{\rm obs}}}$$

$$\alpha = \int_0^{\mu_{\rm obs}^{(\alpha)}} d\mu \exp\left[-\frac{1}{2}\left(\frac{\sqrt{2}\,\mu}{\mu_{\rm exp}}\,{\rm erf}^{-1}(\alpha) + \delta\right)^2\right]$$

- Neglects correlations between channels, which is reasonable currently while data is statistics limited.