Illuminating New Physics at the LHC with the Higgs Boson

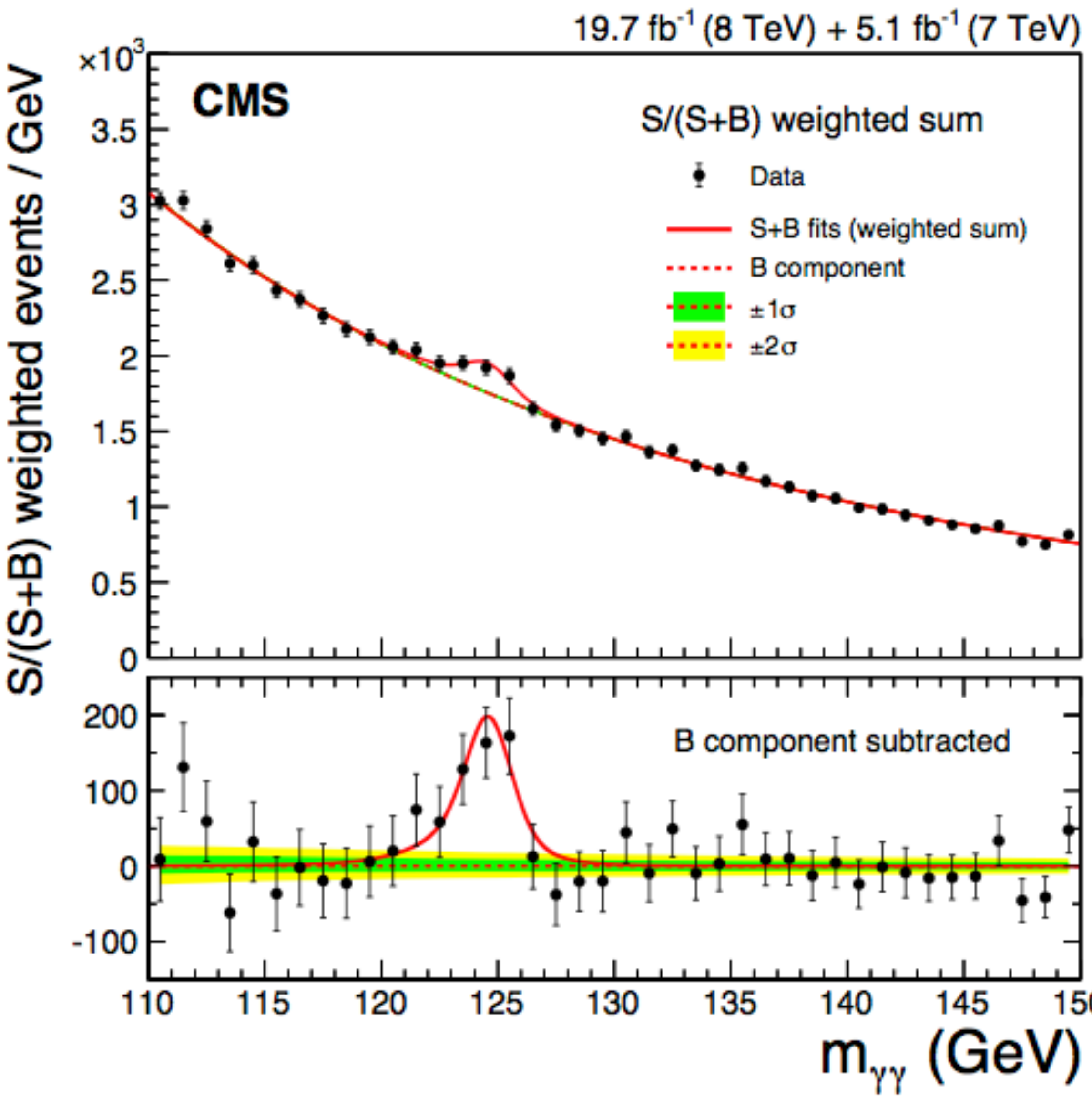
Yuri Gershtein

"Rambling Through The Higgs Field"
by Scott Evers

Outline

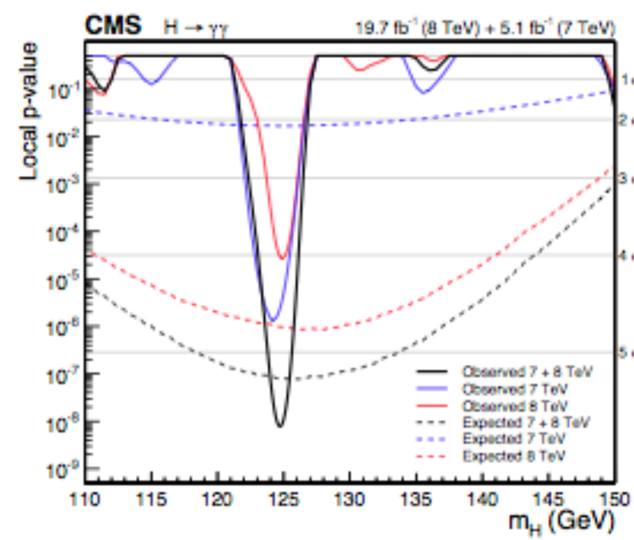
- LHC physics post Higgs discovery
- Searches with Higgs
  - couple of Run 1 examples (SUSY)
  - more higgses and top FCNC
- Outlook for Run 2

Definitely a new particle

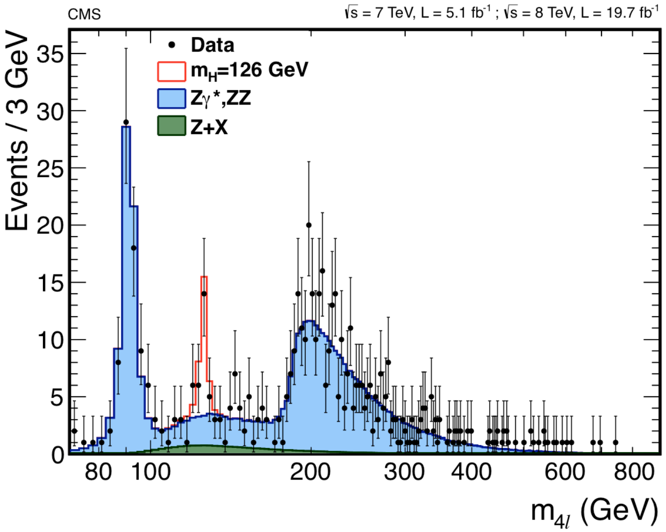


Final calibrations, reduced systematic errors, etc

5.7 σ expected
5.2 σ observed

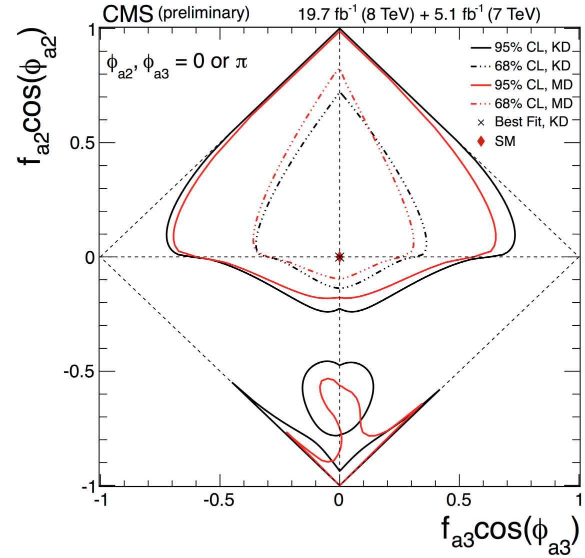


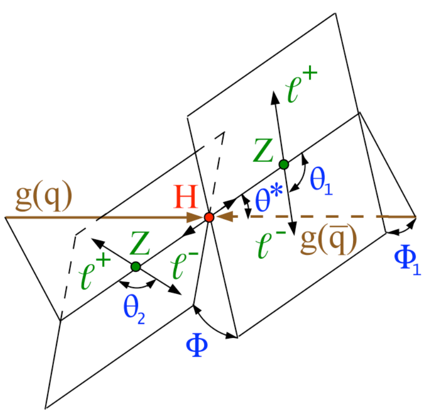
Looks like a 0^+

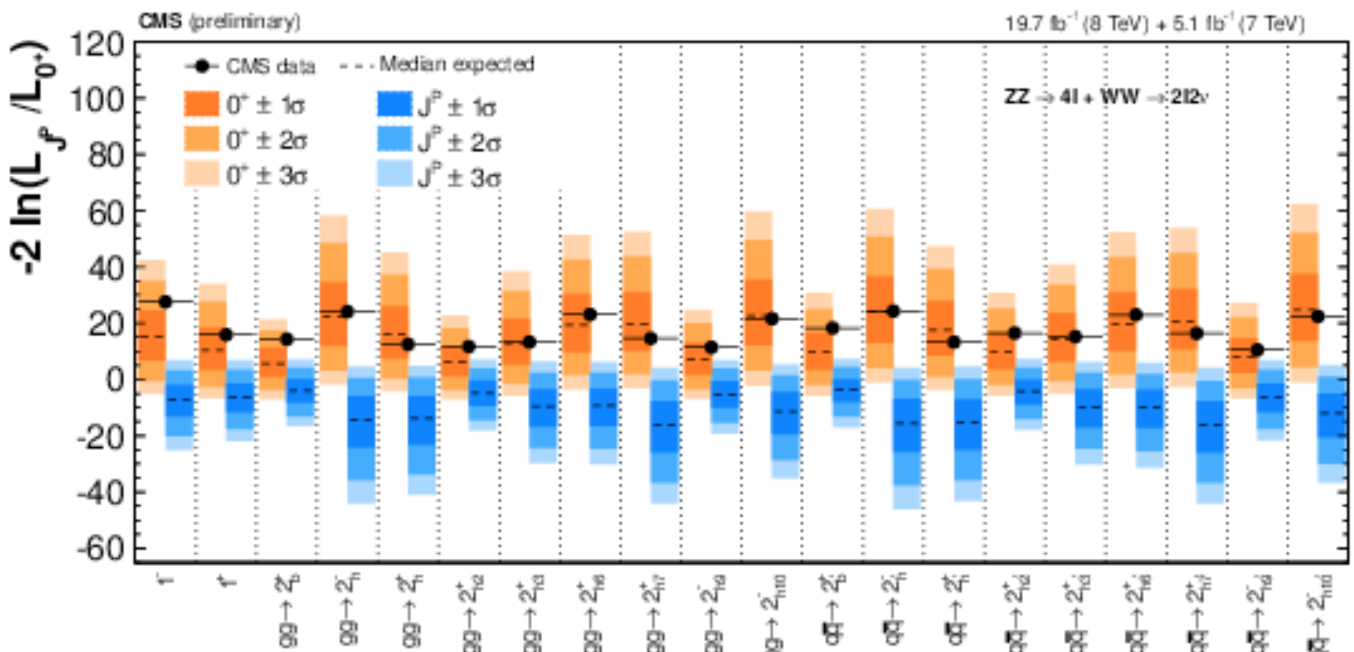


Probing anolmalous interaction to Z boson and tests of spin-parity

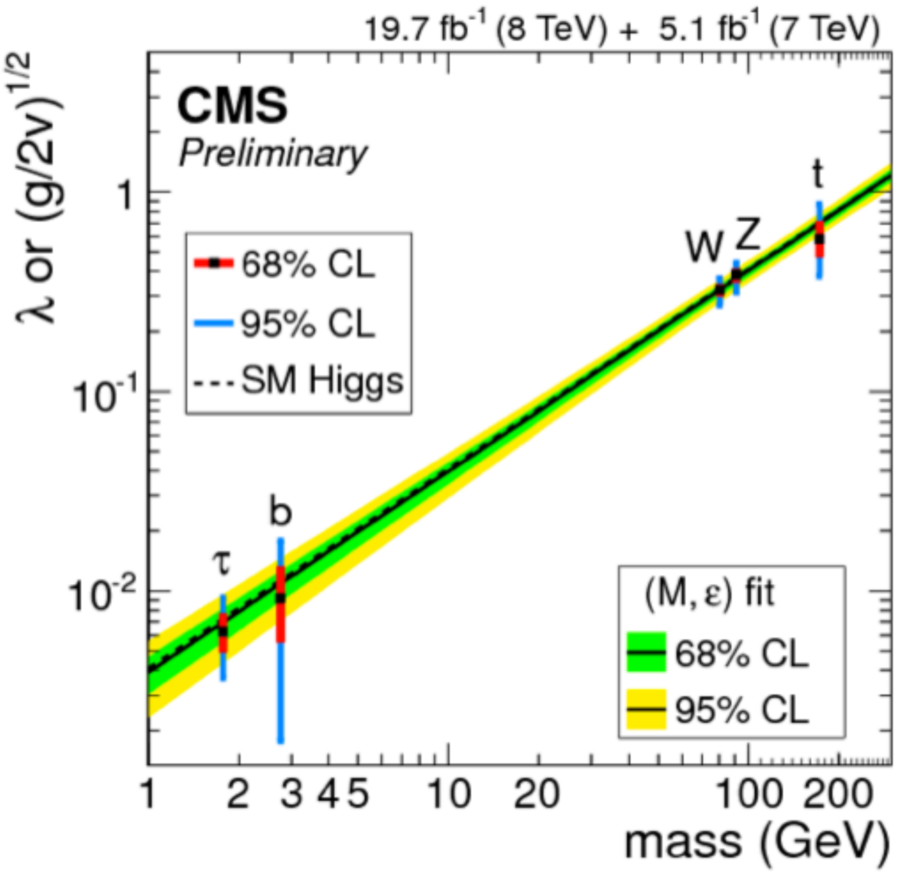
Consistent with SM
All tested J^P hypotheses are excluded at 99.9%

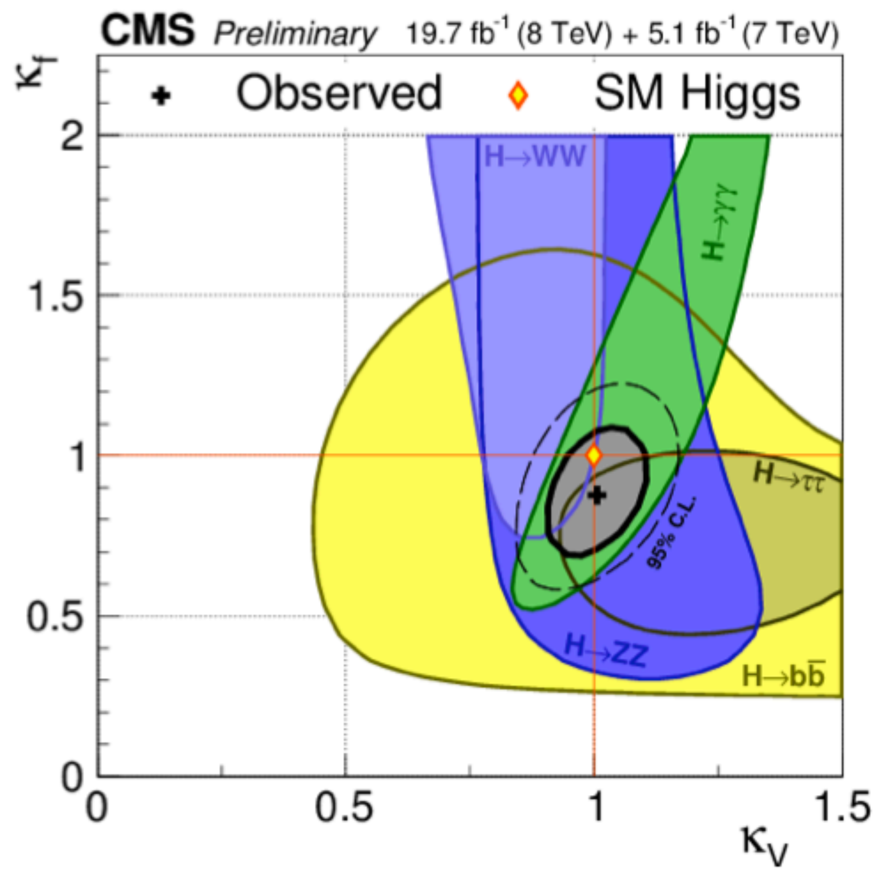






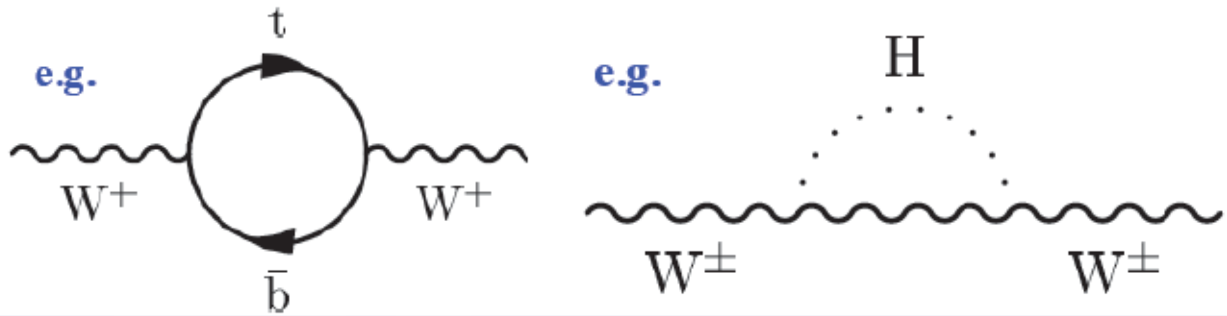
Higgs Couplings





Higgs indeed couples to mass!

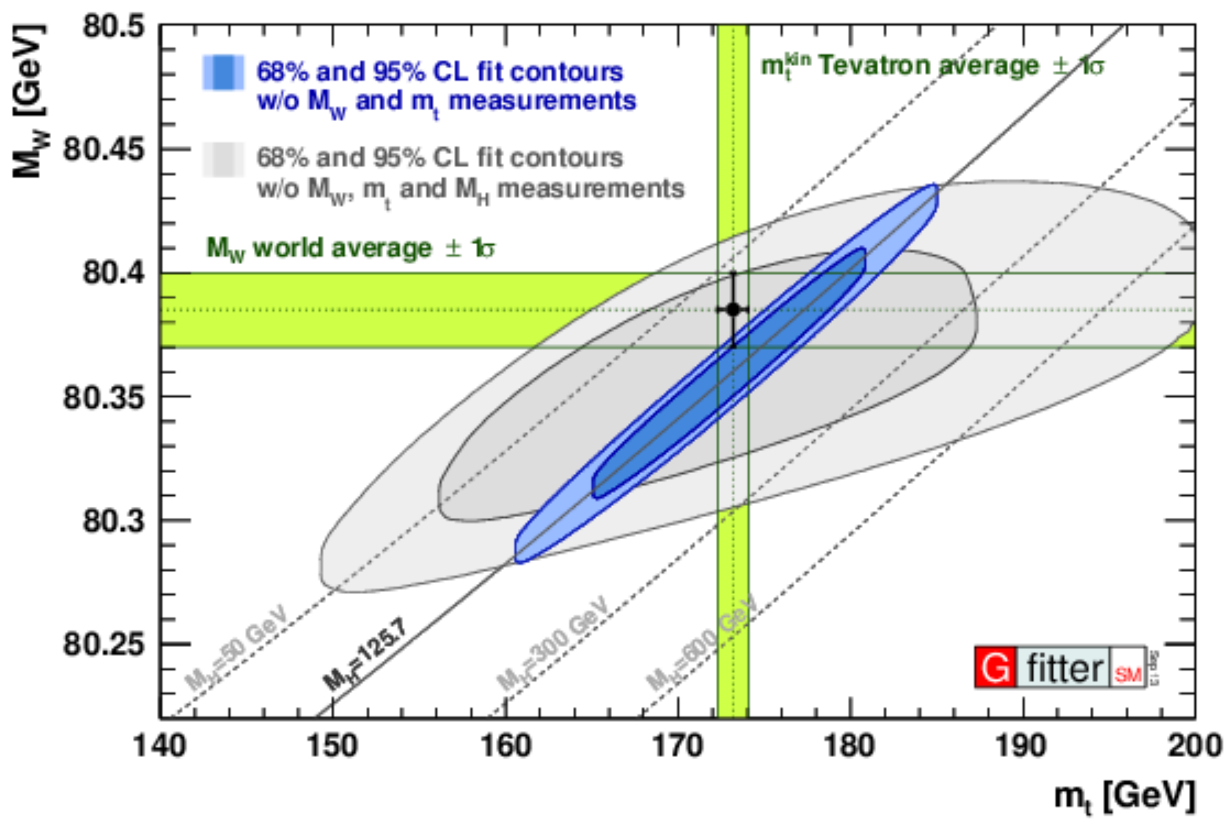
State of the Electroweak Theory



Radiative corrections to precision EWK **measurements of W, Z sensitive to Mt, MH**

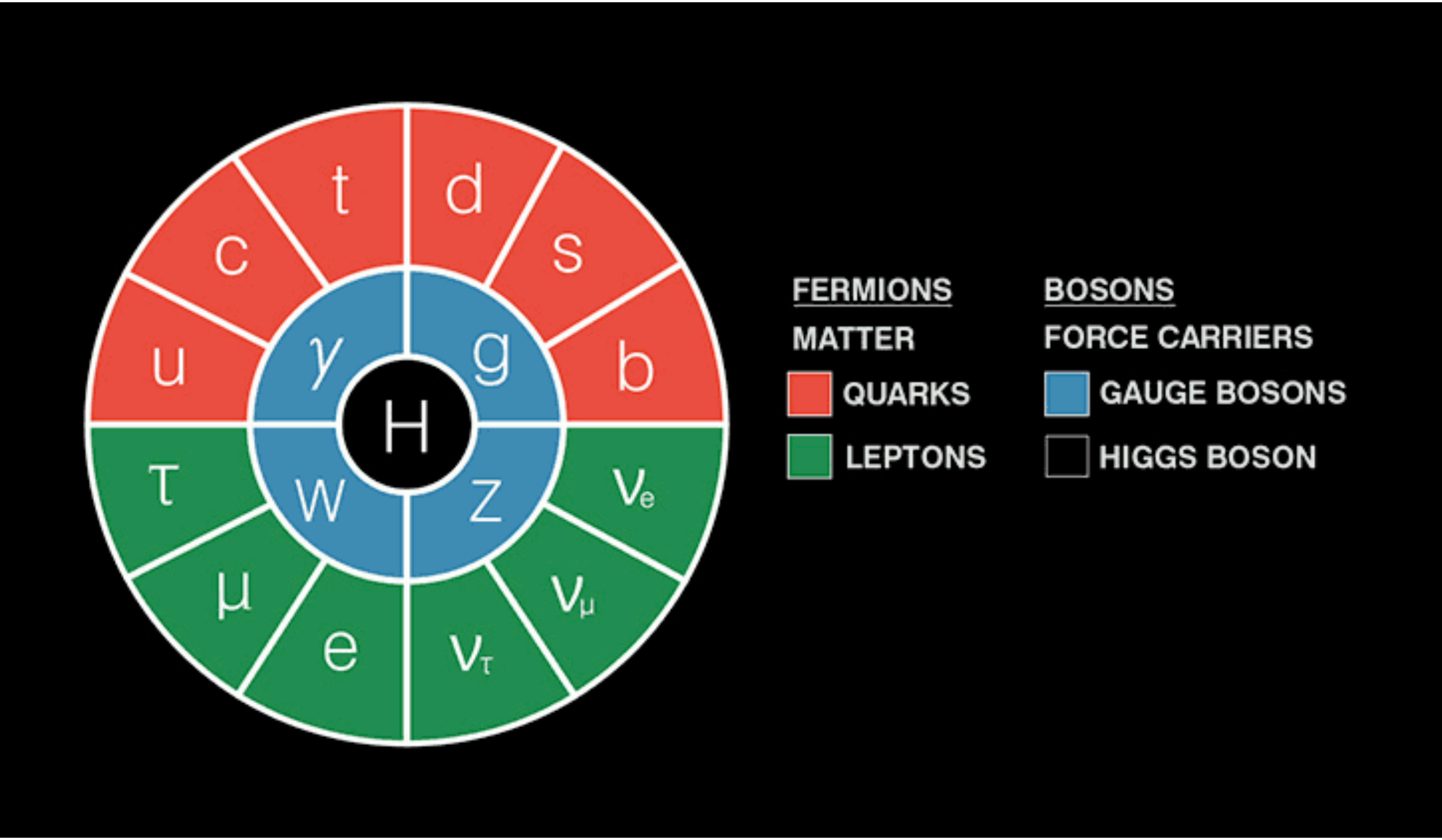
SM-like Higgs discovery at ~126 GeV is compatible
with global EWK data
at 1.3 sigma (p = 0.18)

Indirect constraints are now superior to precise direct W, Z measurements
(MW, $\sin^2\theta_{eff}$)



http://project-gfitter.web.cern.ch/project-gfitter/

So, what's left to be done?



Lt. Cmdr. Albert A Michelson

"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote."

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1894, seven years after his experiment disproving existence of aether

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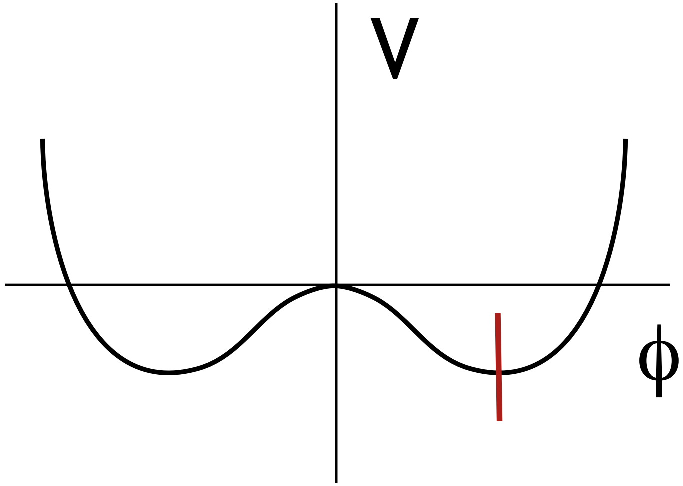
Aether is back!

Why Electroweak Symmetry is Spontaneously broken?



$$V(\phi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

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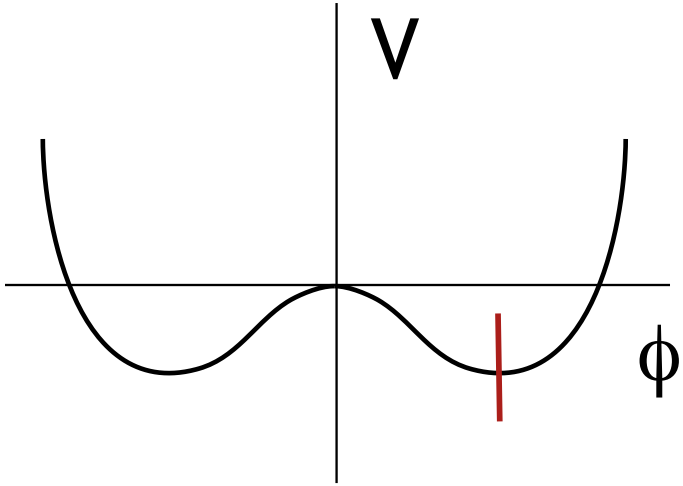

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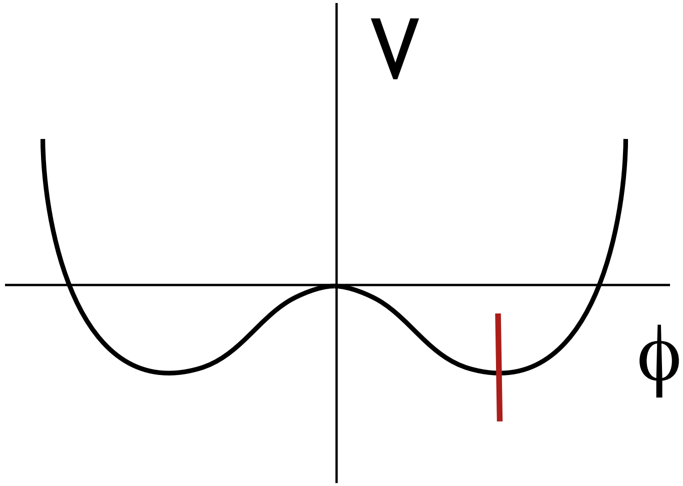
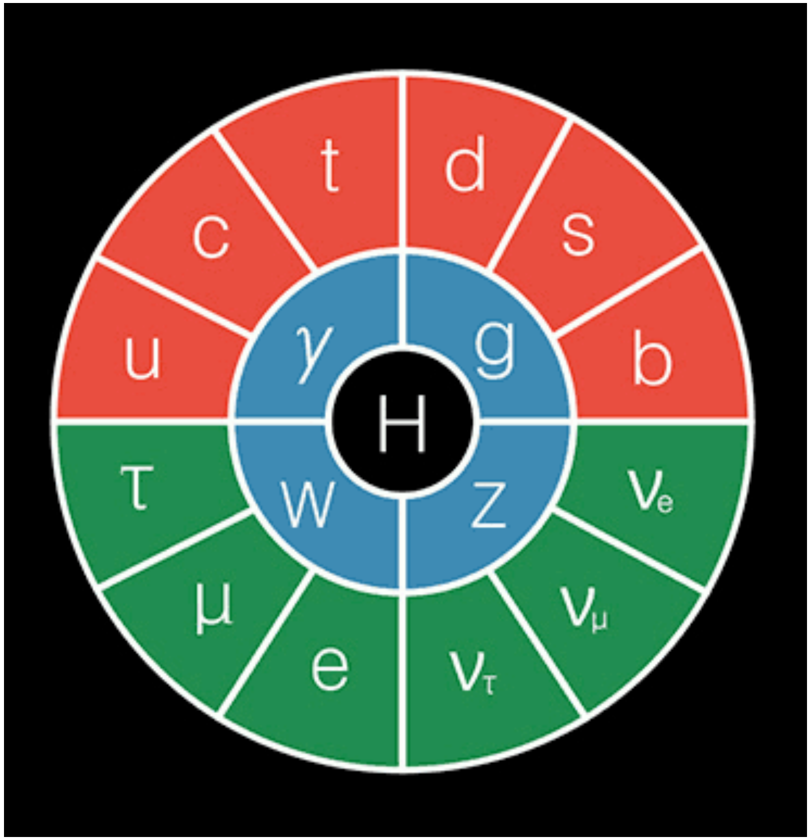


$$V(\phi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

- The Standard Model "explanation" is that $\mu^2<0$
- That is similar to saying that Ginzburg-Landau superconductivity model explains superconductivity
  - but then we'd be missing the microscopic explanation of electron-phonon interactions

Any real explanation of SSB requires new forces between SM particles – and, therefore, new particles



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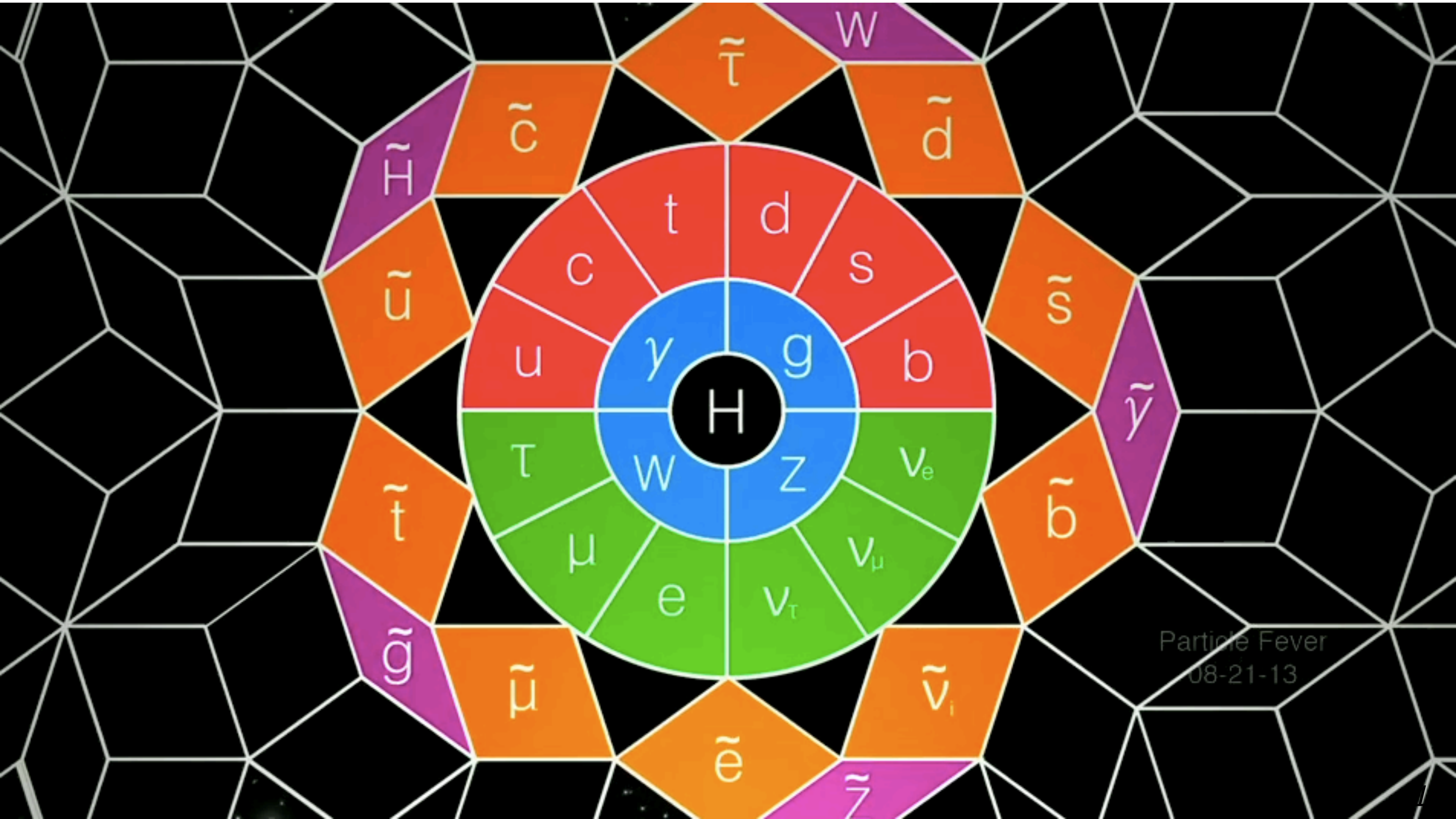
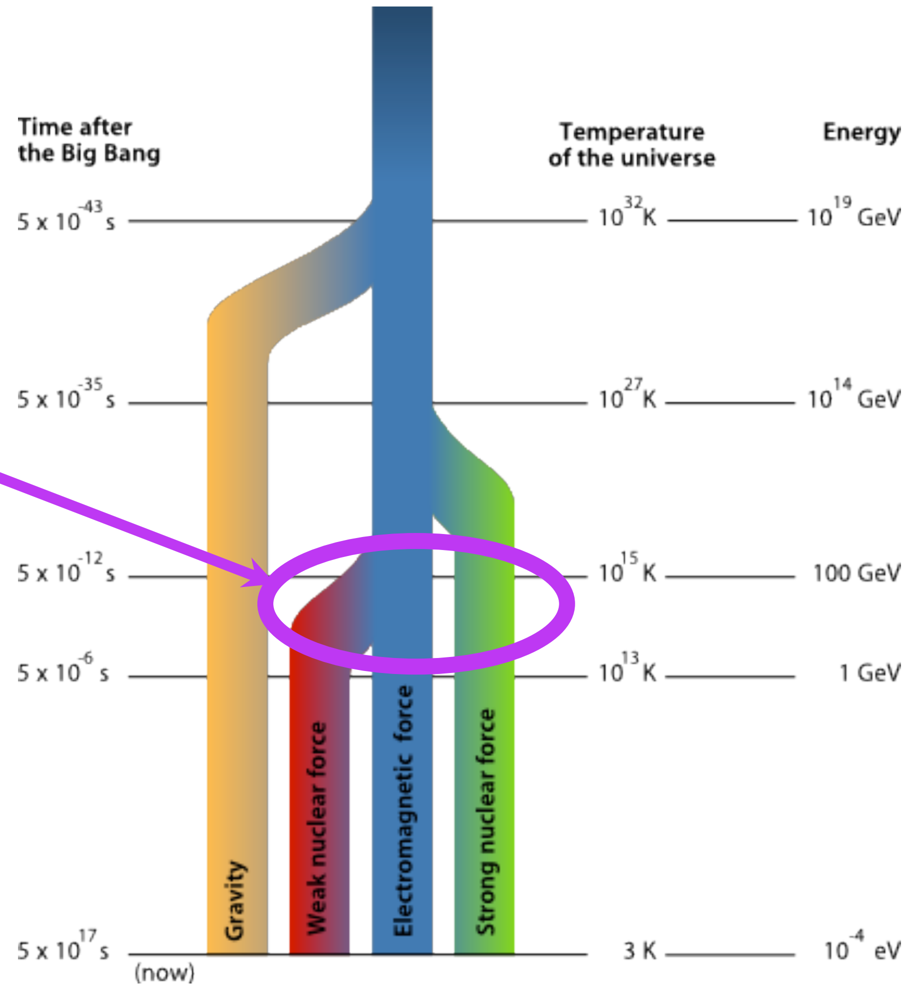


LHC is exploring Electroweak Scale

We are here

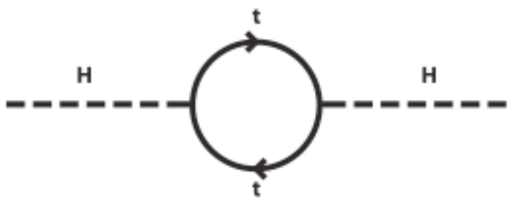


Frontier!

- Exploring Electroweak Symmetry Breaking Scale
  - had to find something – (and did!)
    - something that looks a lot like a **fundamental scalar** - is the small Higgs mass anthropic or a consequence of some new symmetry? The answer is likely to lie at O(EWSB scale)
  - every time we produce a Higgs (or a W, or a Z at large $\sqrt{s}$) at the LHC we learn more about EWSB
- Are there more fundamental scalars?
  - *cMSSM is dead, but SUSY never looked more attractive*
- Can we produce Dark Matter at the LHC?
  - *especially given hints of indirect detection of DM with preferential coupling to the third generation*
- LHC probes Unknown territory - have to watch out for new things: ***Occama razor has a terrible record in our field***

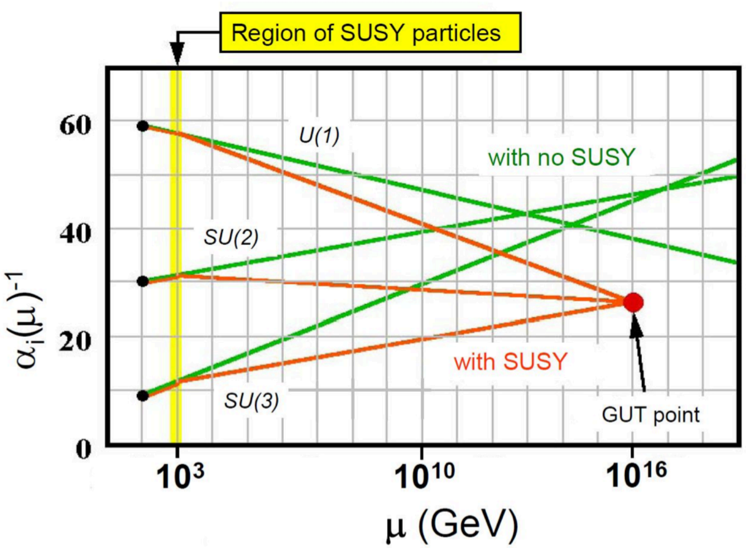
Supersymmetry

- Symmetry between fermions and bosons
  - Path to strings, etc
- Provides microscopic explanation of EWSB
- Explains why Higgs mass is much smaller then the Plank scale (Naturalness problem)



cancelled by

- Allows for next big (aka Grand) unification



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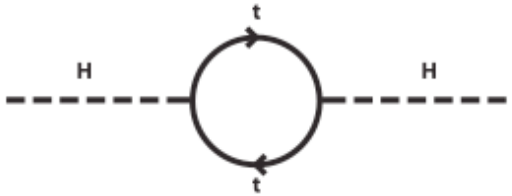

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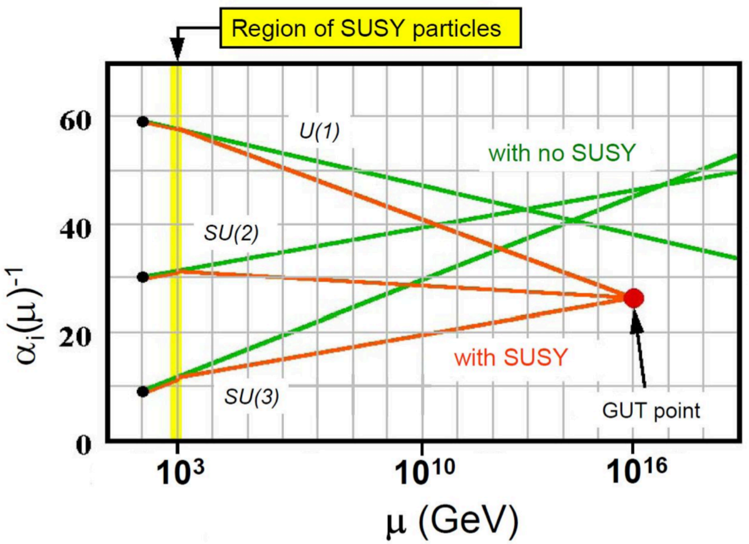
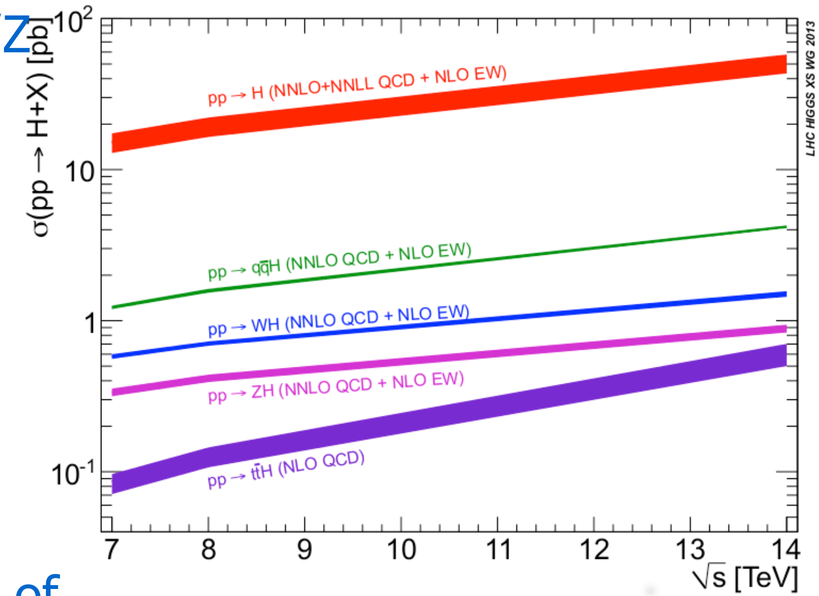
Not the only possibility for new physics, but as strong contender as ever!



Higgs as New Physics Tag

- New physics (SUSY?) cascades may produce higgses as copiously as W's and Z's - but the SM Higgs cross section is tiny compared to W/Z
  - single W: 10^5 pb
    - W+lots of jets (aka top): 10^3 pb
  - single h: 20 (50) pb
    - h + lots of jets (tth): 0.1 (0.6) pb
  - ***requiring higgs production is a New Physics booster***
  - even paying $2 \cdot 10^{-3}$ penalty for $\gamma\gamma$ branching one gets ~reasonable number of events
    - $20/\text{fb} \cdot 1\text{pb} \cdot 2 \cdot 10^{-3} =$ 40 events



- Impact way beyond just SUSY - every time you produce a Higgs you explore EWSB: SUSY here is just a great way to "generate signatures" with Higgs + stuff.

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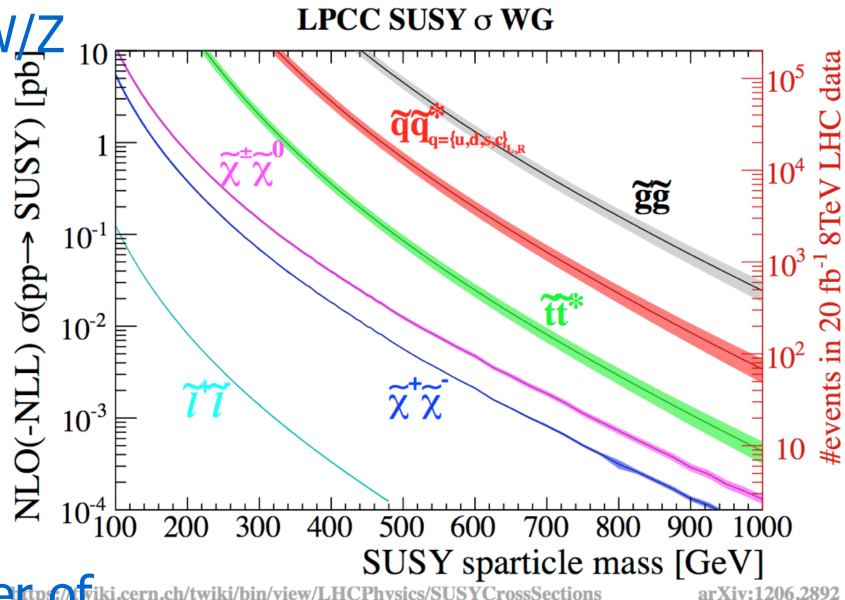

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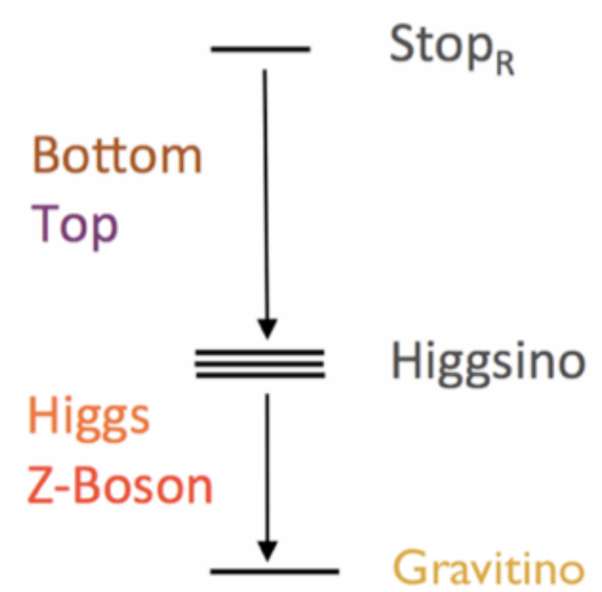
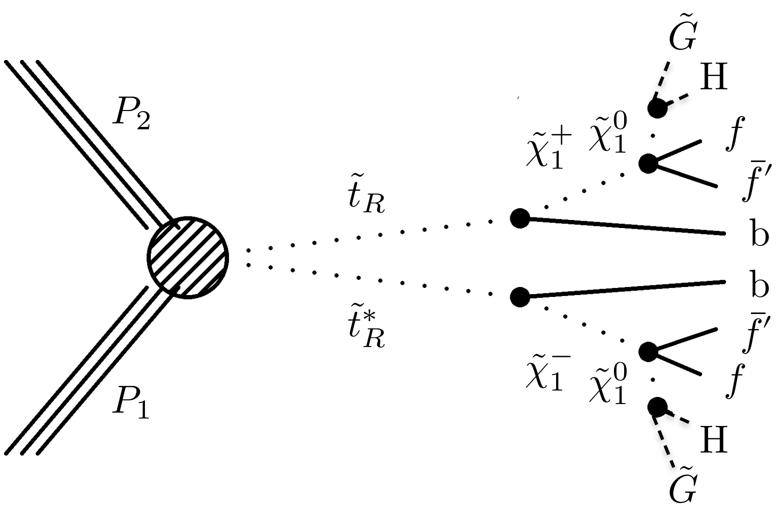
Natural SUSY



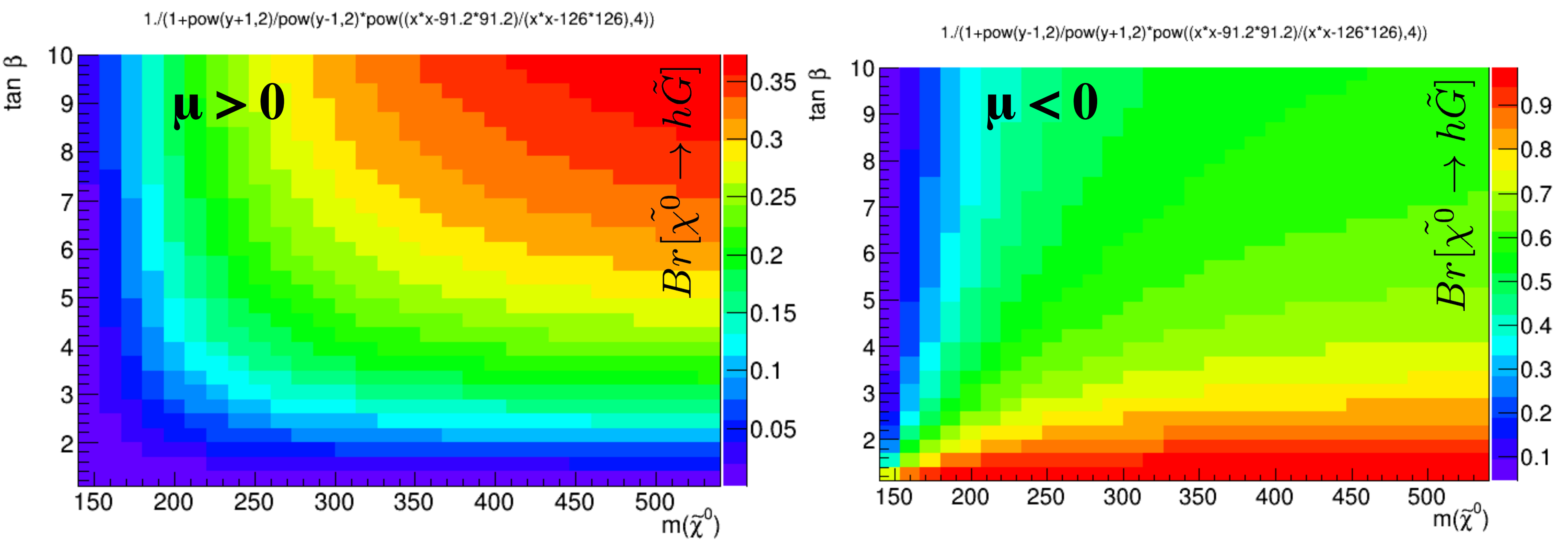


- To keep Higgs mass small, partners of higgs and top quarks should be relatively light
- If SUSY is broken at low scale such events can masquerade as SM QCD – almost no missing energy
  - ie: stop at 290 GeV, higgsino at 130 GeV, gravitino is soft: final state of HH+almost no MET
  - An important gap in searches for stops and higgsinos that one need to check!

$Br[\tilde{\chi}^0 \to h\tilde{G}]$ and $Br[\tilde{\chi}^0 \to Z\tilde{G}]$

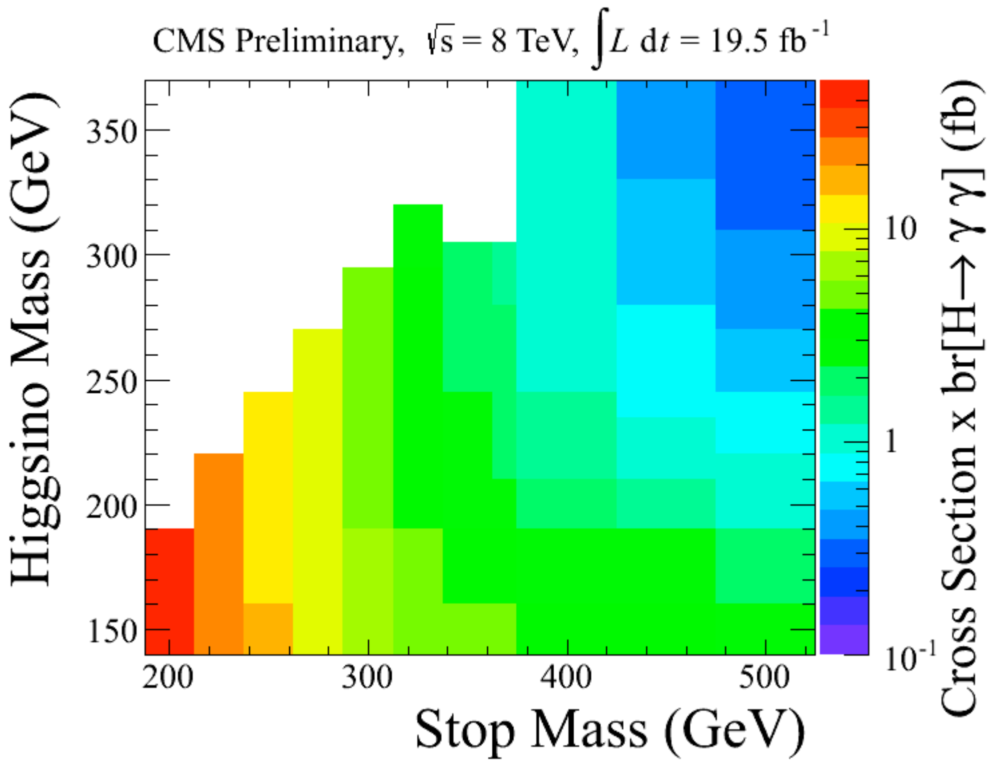
- using formulae from Meade, Reece & Shih arXiv:0911.4130 [hep-ph]
  - assume large M_1 and M_2, $m_h \ll m_H, m_A$

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + Z) \; = \; \frac{1}{4}(s_\beta + \eta c_\beta)^2 \left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A} \qquad \Gamma(\tilde{\chi}_1^0 \to \tilde{G} + h) \; = \; \frac{1}{4}(s_\beta - \eta c_\beta)^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A}$$



$\gamma\gamma$ channel for searches

- Start with $2 \cdot 10^{-3}$ suppression
- But
  - looking for relatively quiet events without large MET or very energetic jets - huge QCD and EWK backgrounds otherwise
- still, a few pb $\sigma \cdot$Br
- narrow peak gives a very reliable way to estimate the backgrounds
- SM Higgs background is negligible



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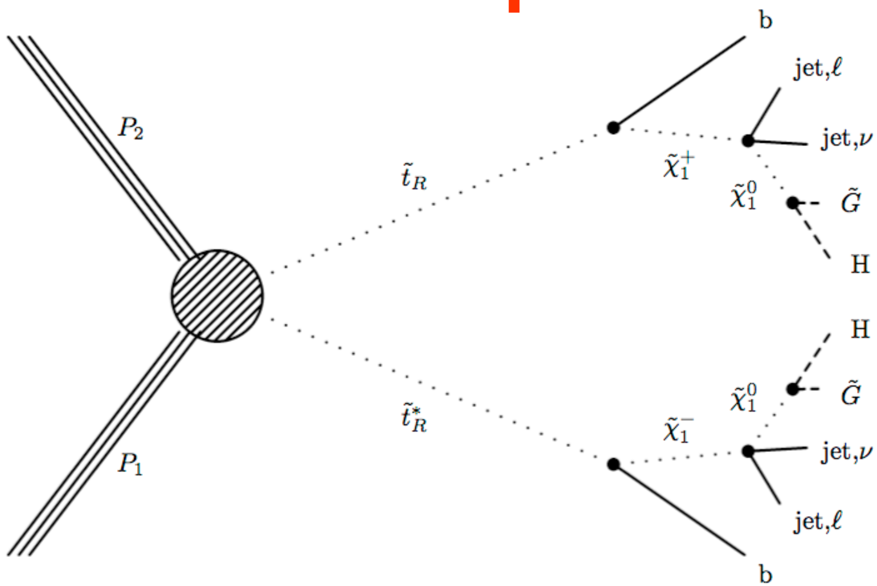
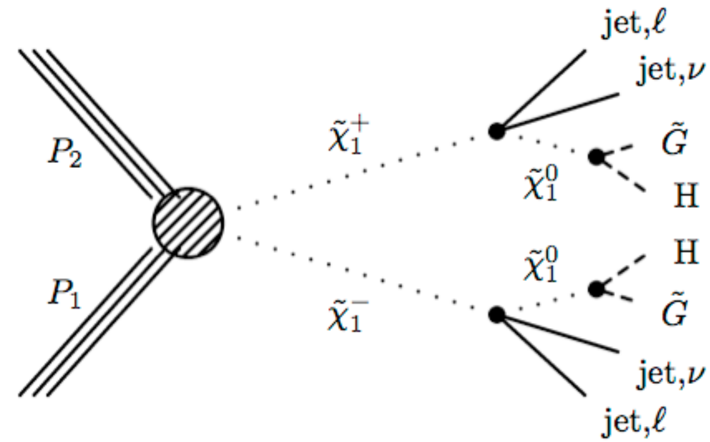
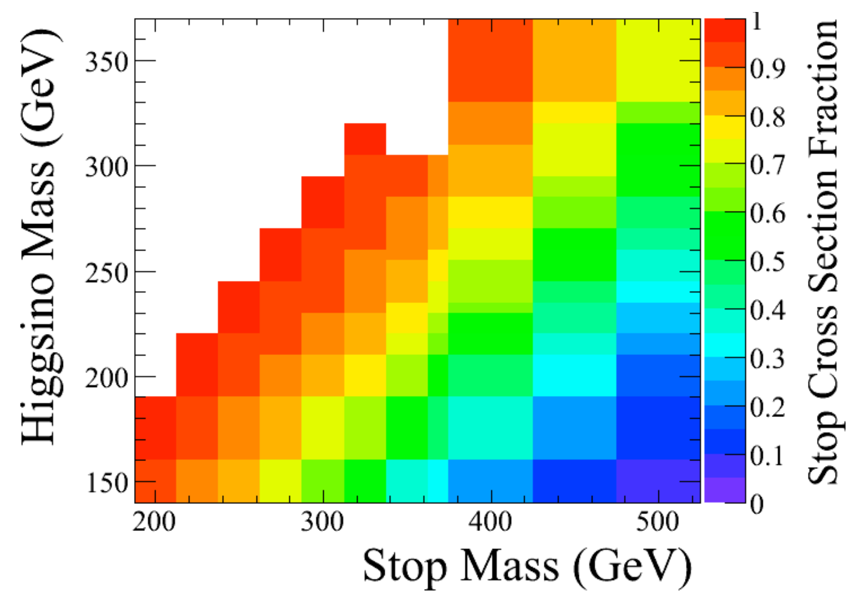
Minimal particle content model



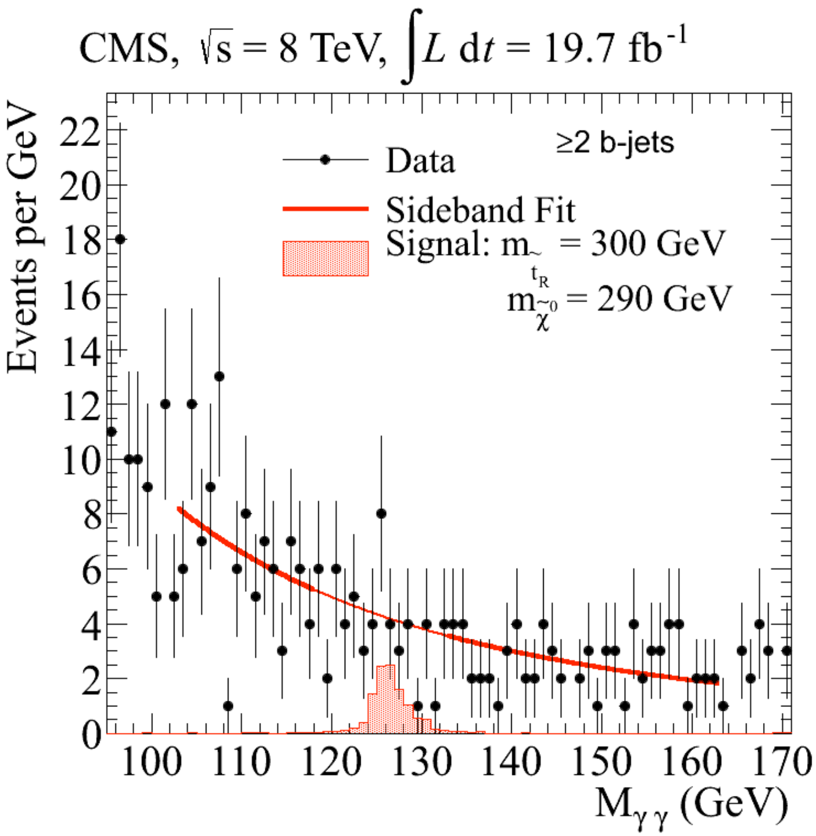


- Consider both strong and direct EWK production
- Two higgses per event, plus *b*-jets from stop: **$\gamma\gamma$**bb final state
- For cases when $\tilde{\chi}^0 \to Z\tilde{G}$ is large, need to combine with multi-leptons



Event Selection

- $\geq$2 isolated photons, E_T>40, 25 GeV, | η |<1.44 (barrel)
- $\geq$2 b-jets (CSV-medium + CSV-loose)
- Higgs mass window: 120 < $m_{\gamma\gamma}$ < 131 GeV



- Fit excluding 118-133 GeV window
- negligible dependence on fit function, use power law
- 46 events, 46.5±3.8 expected
- Looking in mass window looses us a bit of sensitivity, but allows us to easily scan a variety of kinematic distributions in the events
- determine background from sidebands
- average lower and upper, add half of the difference as extra error

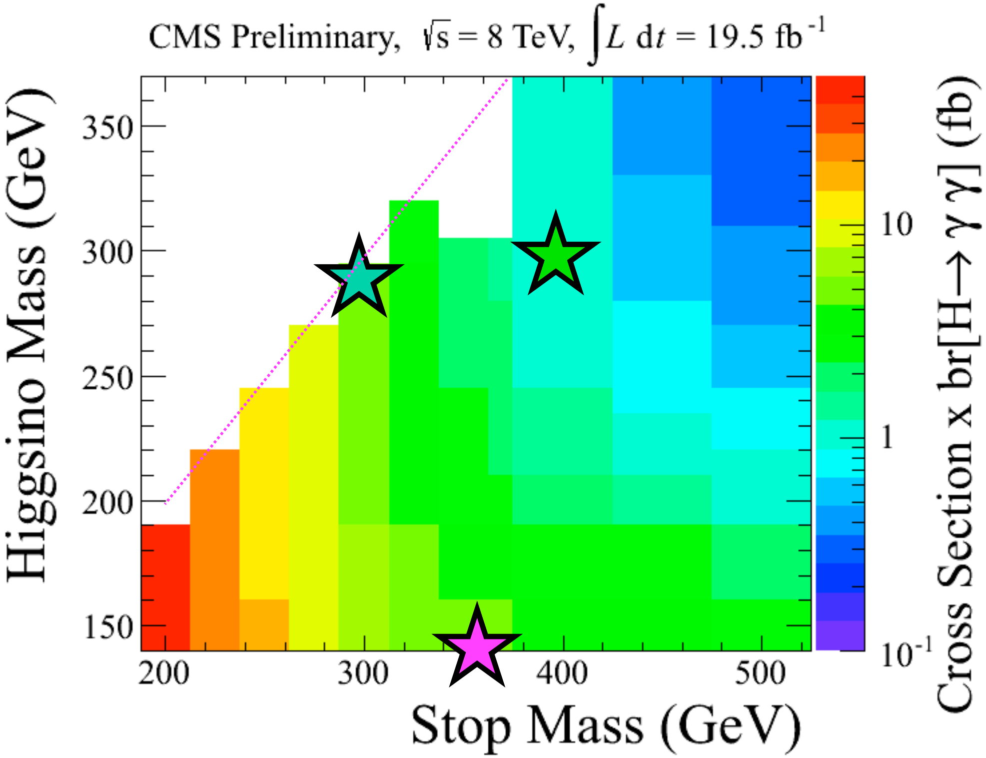
Event Kinematics

- kinematics is different from point to point
  - number of taggable b-jets
  - fraction of events where the two b-jets from higgs

★ χ^0 ~ at rest, moderate p_T(h), MET

★ moderate p_T(h), MET + extra b's

★ very small MET



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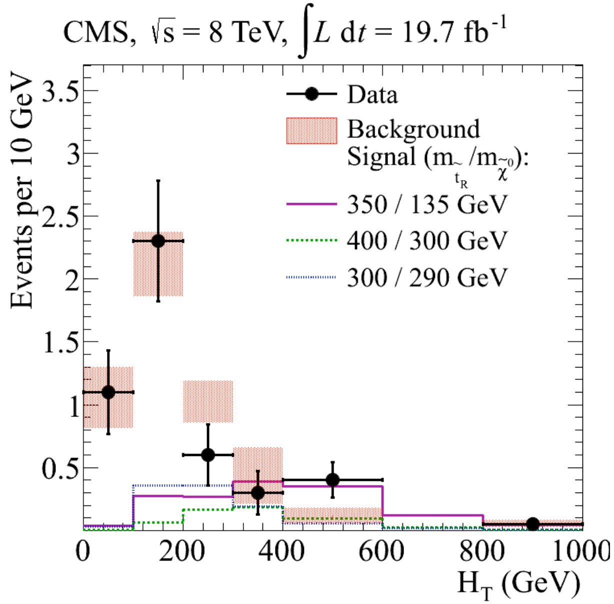
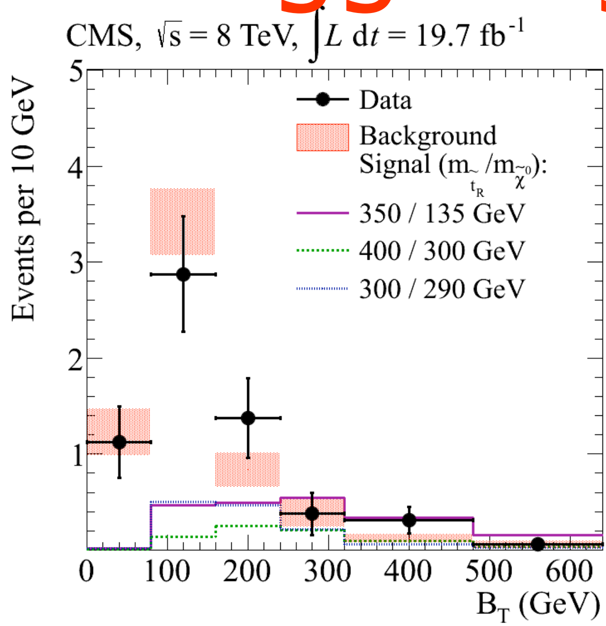
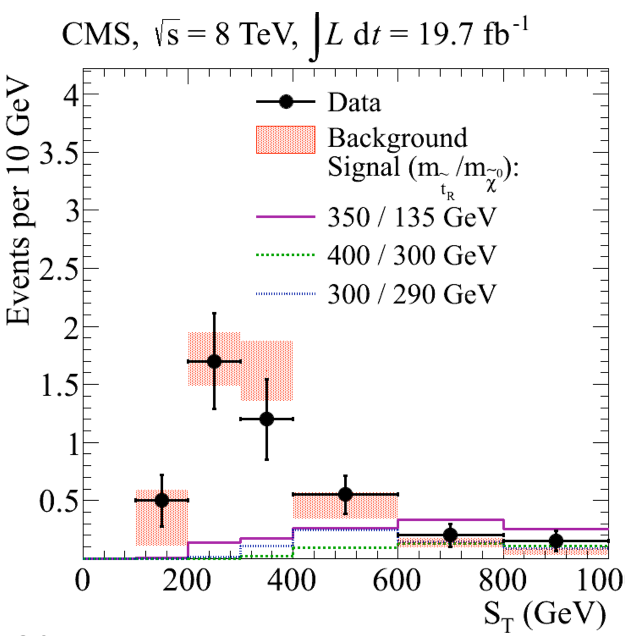
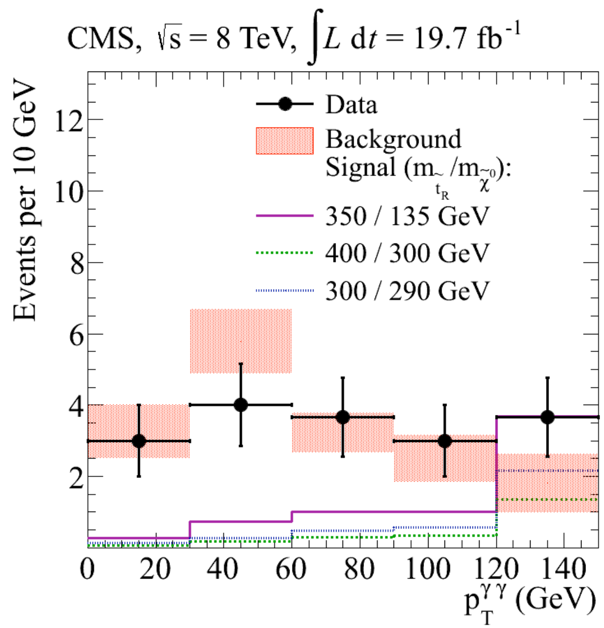
Events with higgs tag + 2 b's

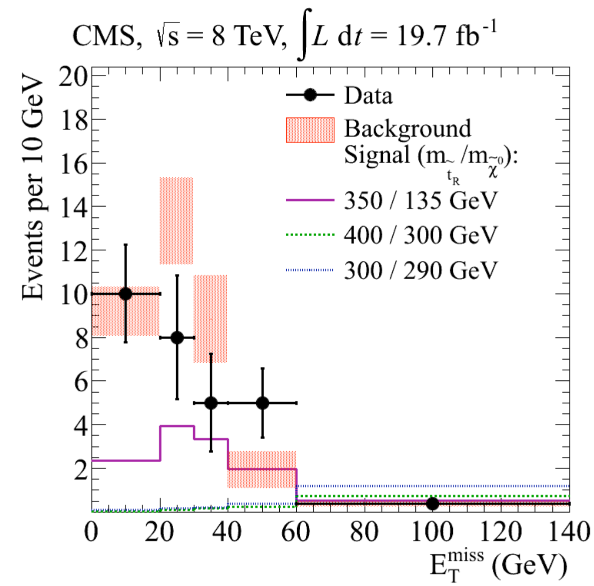




- Points - evts with higgs tag
- Rectangles - sidebands
- Lines - stop MC
- Simple and robust BG prediction allows for quick exploration





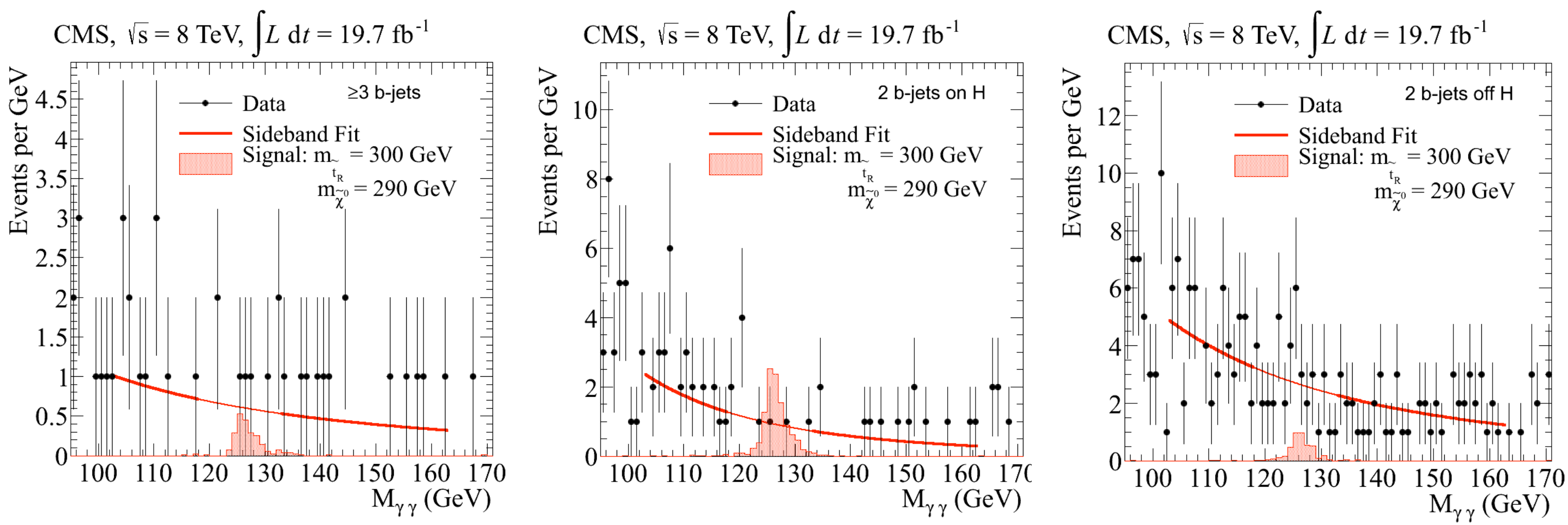


Further Event Categorization

Divide events into three categories

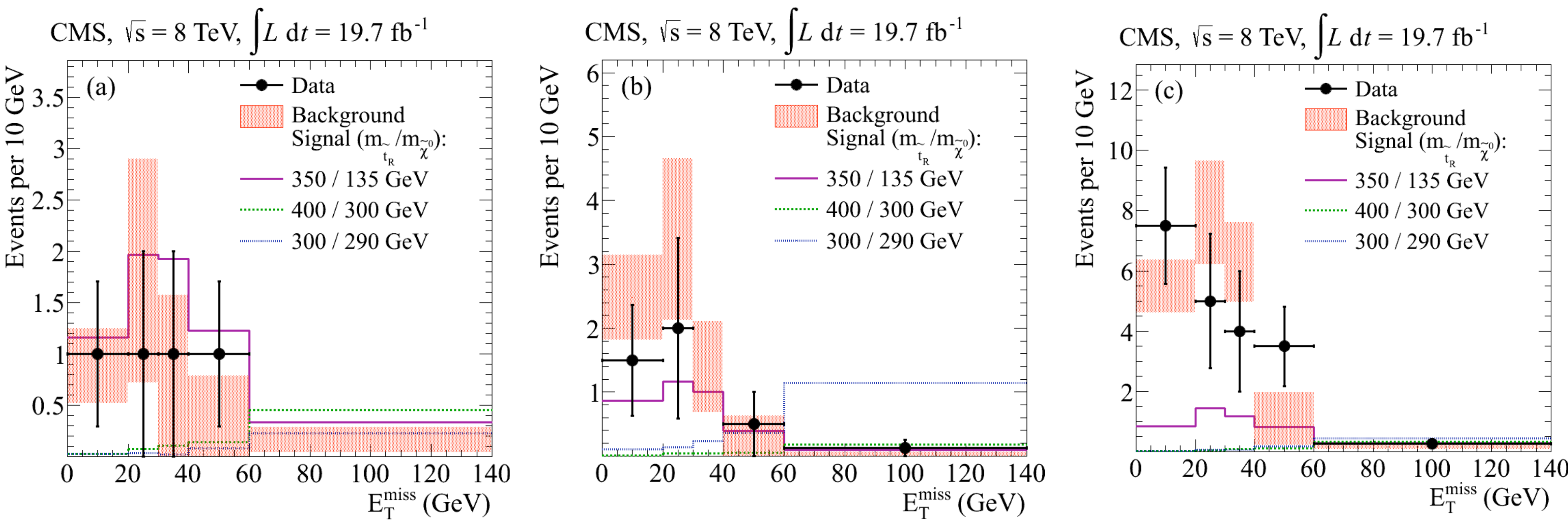
- events with ≥3 b’s
- =2 b’s and 95 < m_{bb} <155 GeV
- all other events with =2 b’s

Category	(i)	(ii)	(iii)
signal 350 / 135	10.7	2.0	6.8
signal 300 / 290	2.1	10.1	3.9
signal 400 / 300	4.0	1.4	2.8
expected background	6.7 ± 1.4	10.5 ± 1.8	29.7 ± 2.8
observed	6	7	33



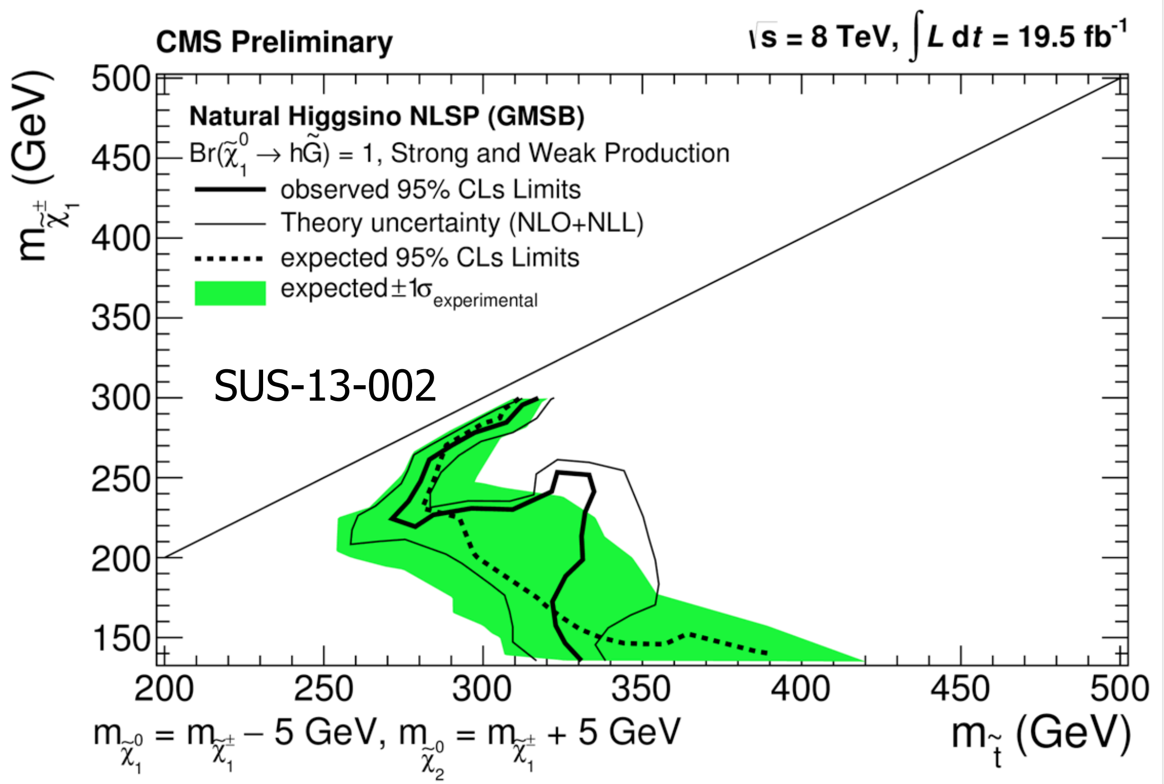
MET in categories

- Use binned MET distributions in the three categories for the statistical analysis of the data



Comparison with multileptons

- Higgs decays into leptons
  - mostly though WW and $\tau\tau$
  - Br[h→1 e/μ]≈11%, Br[h→2 e/μ]≈1.8%
  - Br[hh→3 e/μ]≈0.4% - comparable to $\gamma\gamma$
    - in reality, a little less sensitive - soft leptons from τ, W^* and larger background (no mass peak!)



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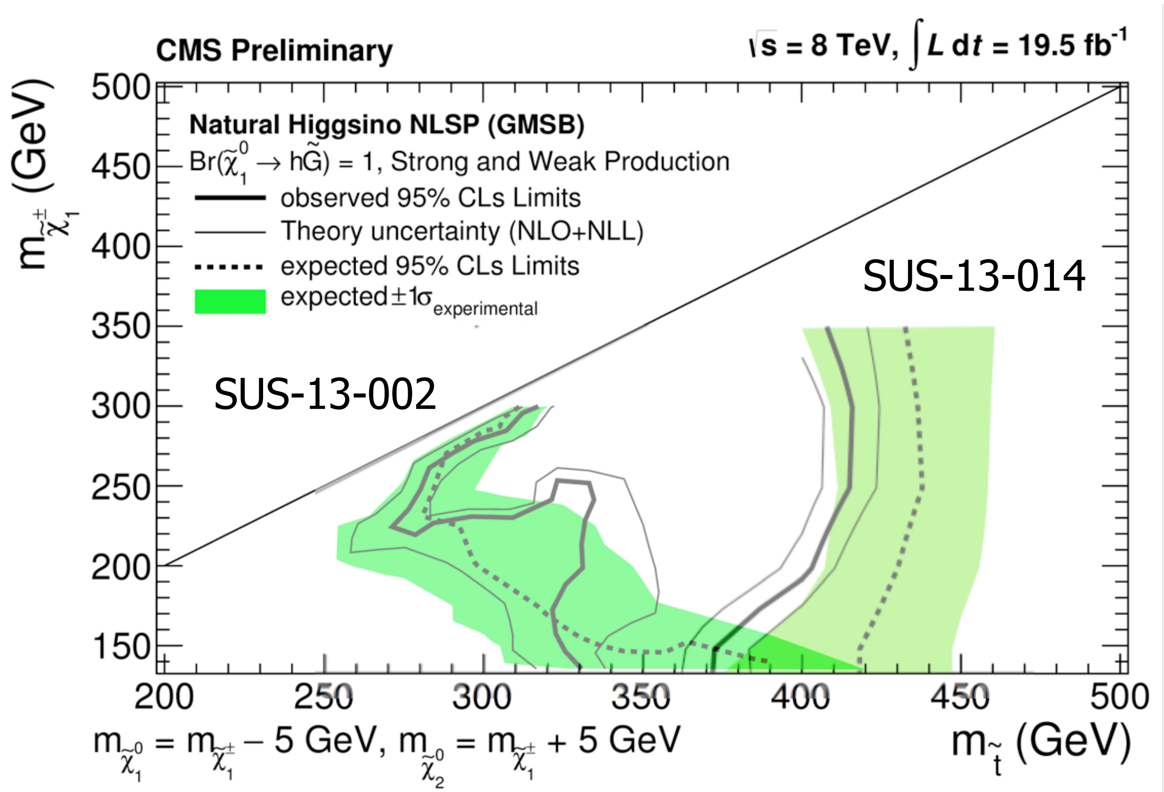
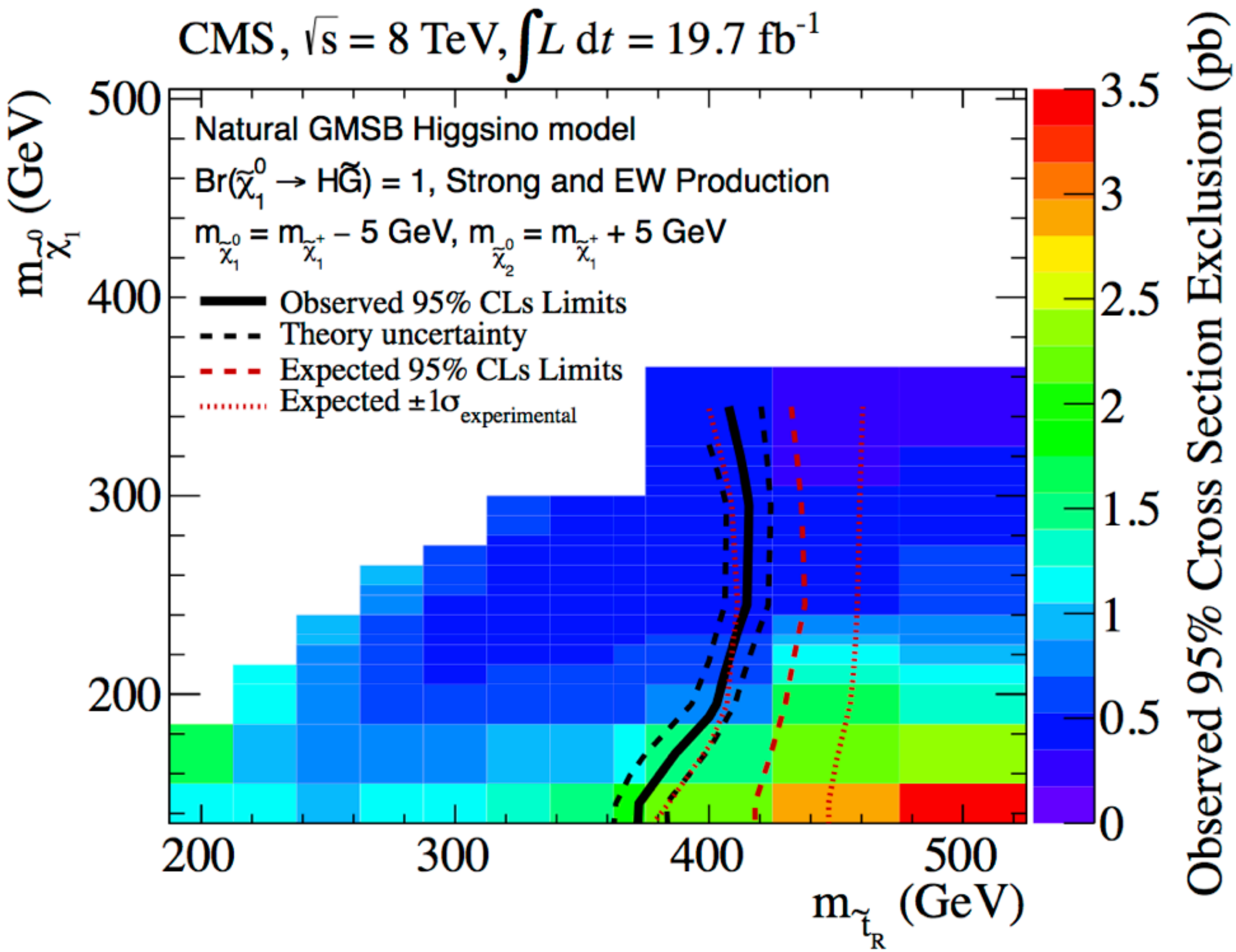


The limit

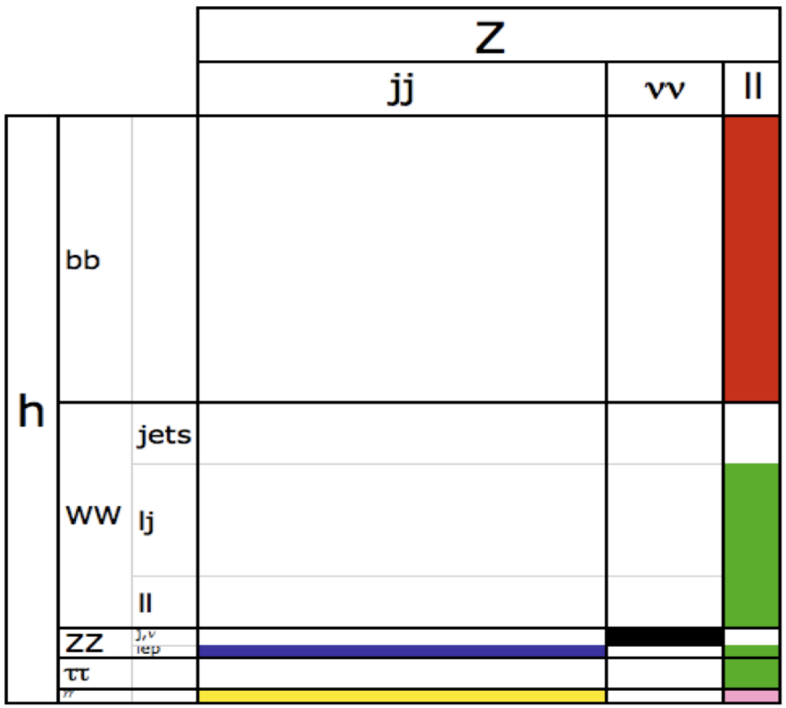


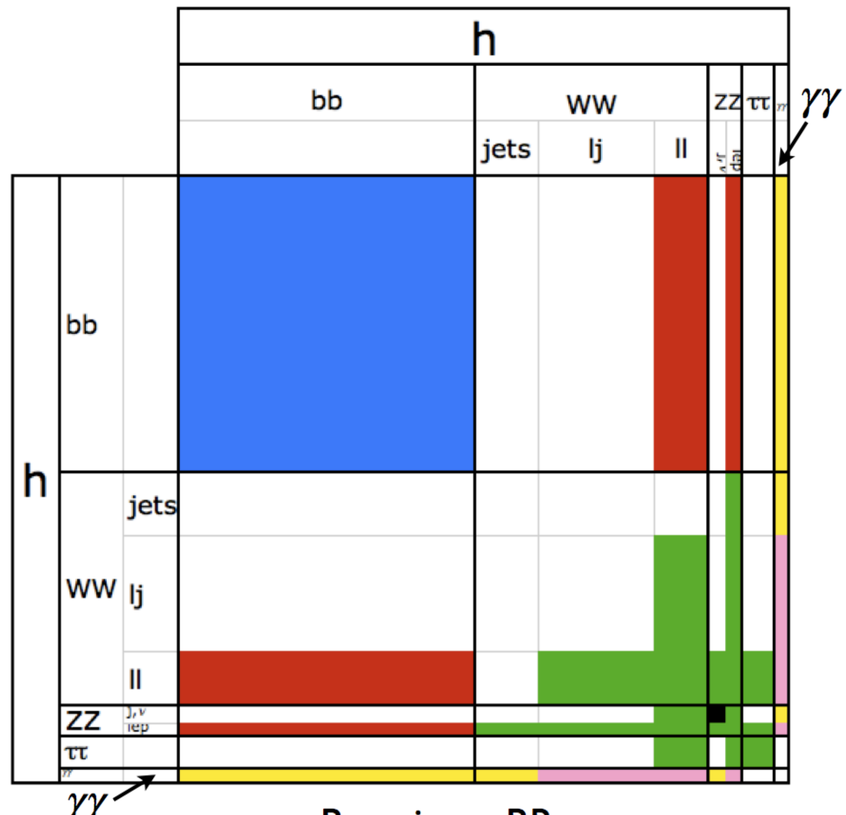
CMS, $\sqrt{s}$ = 8 TeV, $\int L\,dt$ = 19.7 fb^{-1}
Natural GMSB Higgsino model
Br($\tilde{\chi}_1^0 \rightarrow H\tilde{G}$) = 1, Strong and EW Production
$m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^+} - 5$ GeV, $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^+} + 5$ GeV
Observed 95% CLs Limits
Theory uncertainty
Expected 95% CLs Limits
Expected $\pm 1\sigma_{experimental}$
$m_{\tilde{\chi}_1^0}$ (GeV)
$m_{\tilde{t}_R}$ (GeV)
Observed 95% Cross Section Exclusion (pb)

Pure EWK production

- no single channel has sensitivity at 20/fb – need to combine

h(γγ)+jets
h(γγ)+lepton(s)
h(bb)+Z(ll)
h(bb)+h(bb)
Z(ll) +Z(jj)
multileptons

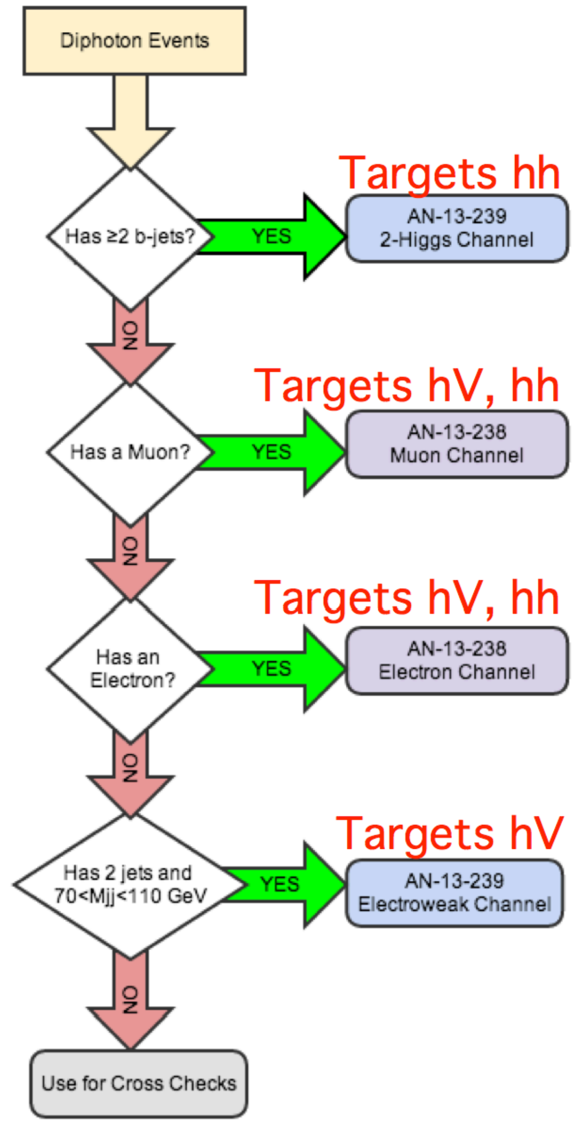




Box size ∝ BR

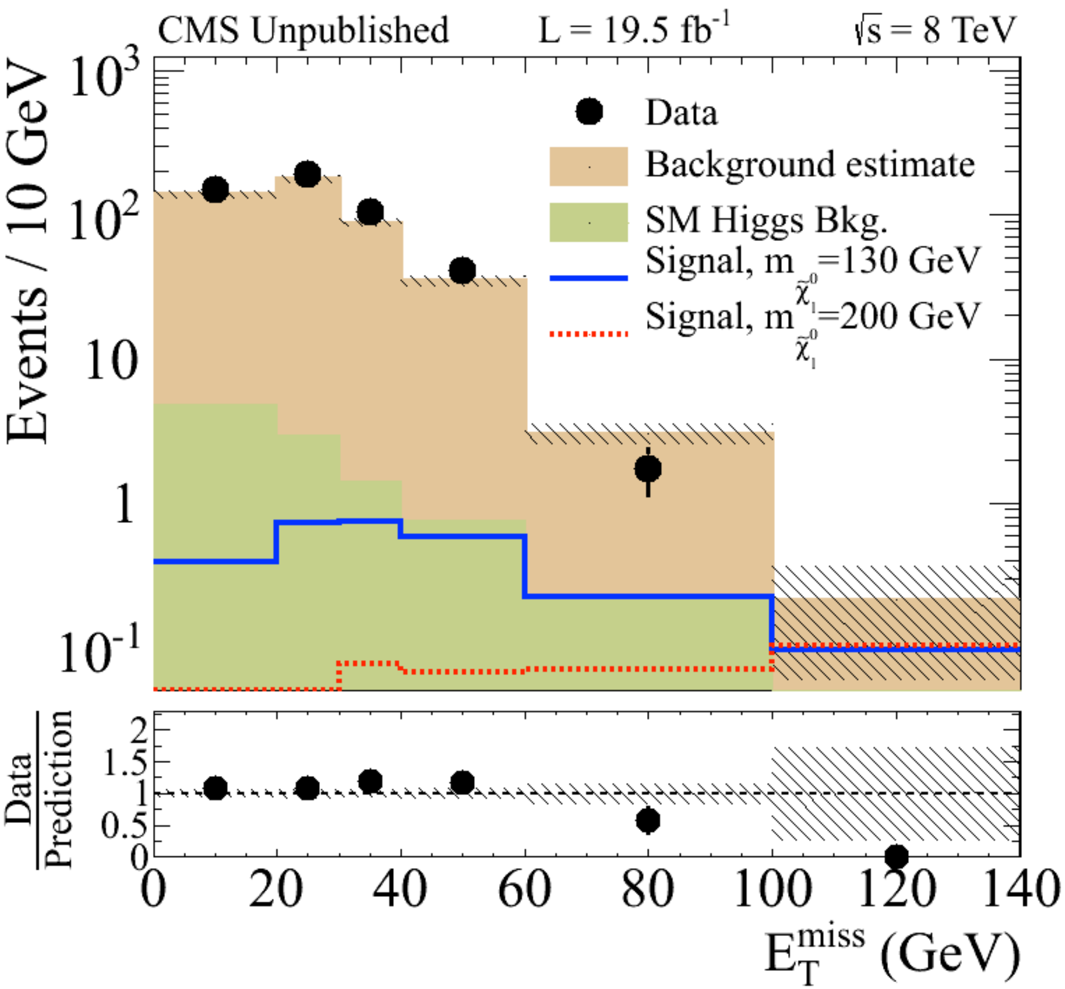
Diphoton channels

- As before, sort events into boxes in order of decreasing purity
- With EWK production in 20/fb the limiting factor is the number of events
- Will not be the case for Run 2 & beyond



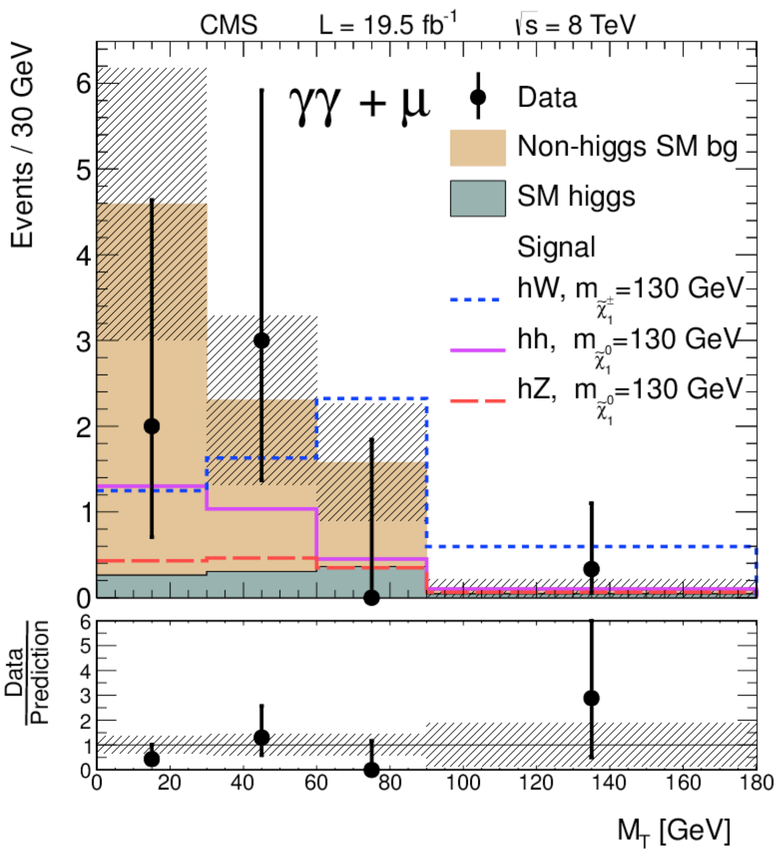
$\gamma\gamma$ + V(jj)

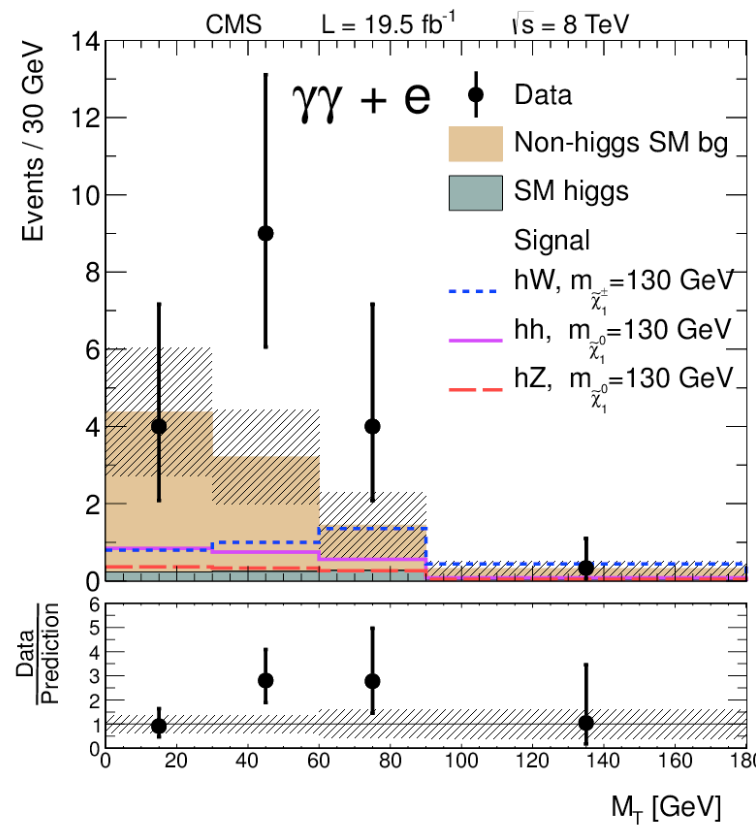
- Pretty much hopeless



$\gamma\gamma$ + leptons

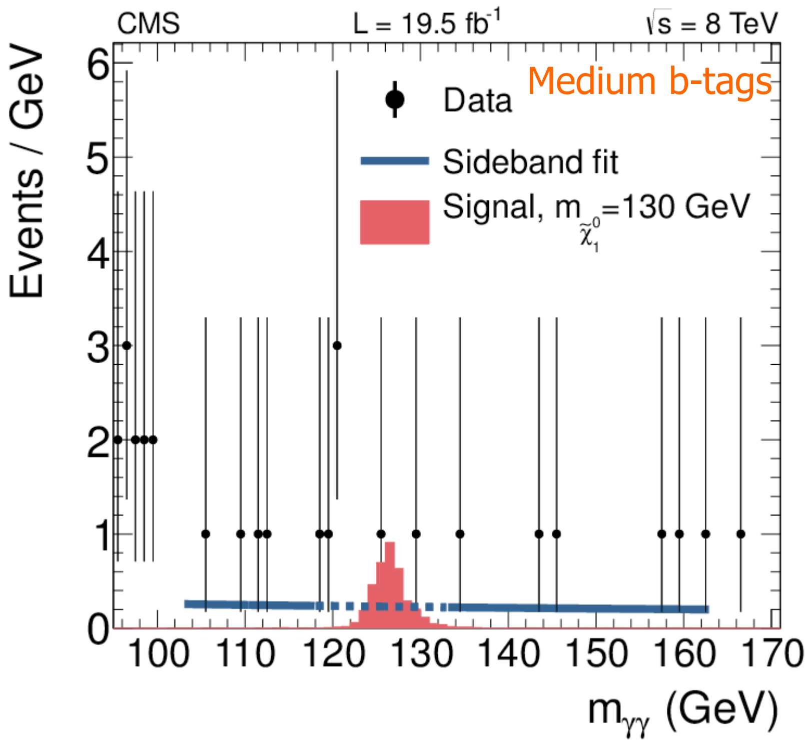
- Very low efficiency – but very clean – room for unexpected signals
- pT > 15 GeV, more then 0.3 away from photons
  - for electrons, also veto e-photon mass around Z
- Use MET for hh/hZ and MT for hW

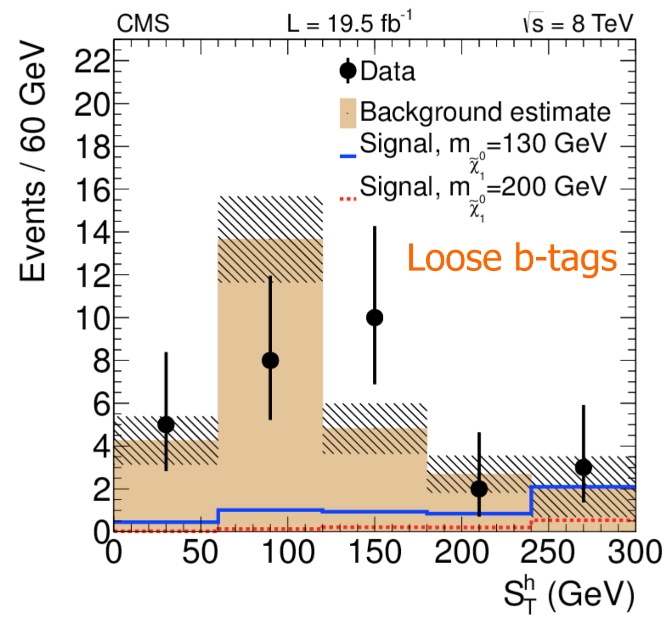


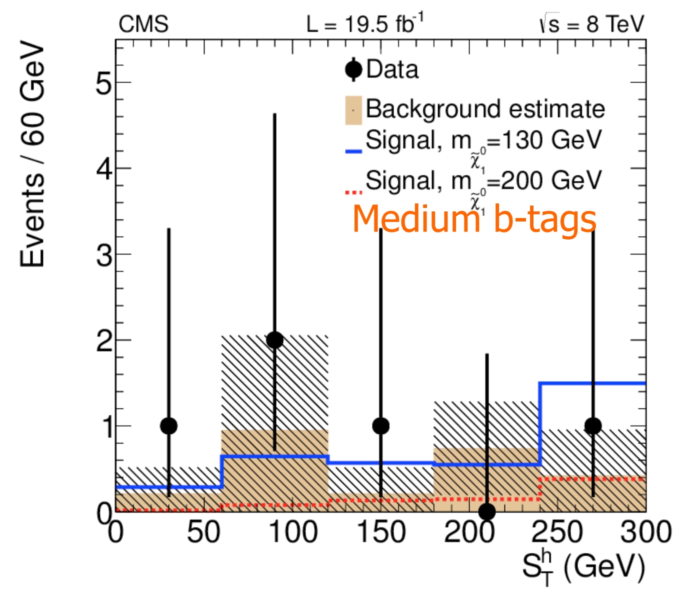


$\gamma\gamma$ + h(bb)

- Re-optimize b-tag
- HST -> scalar sum pT of both Higgs candidates

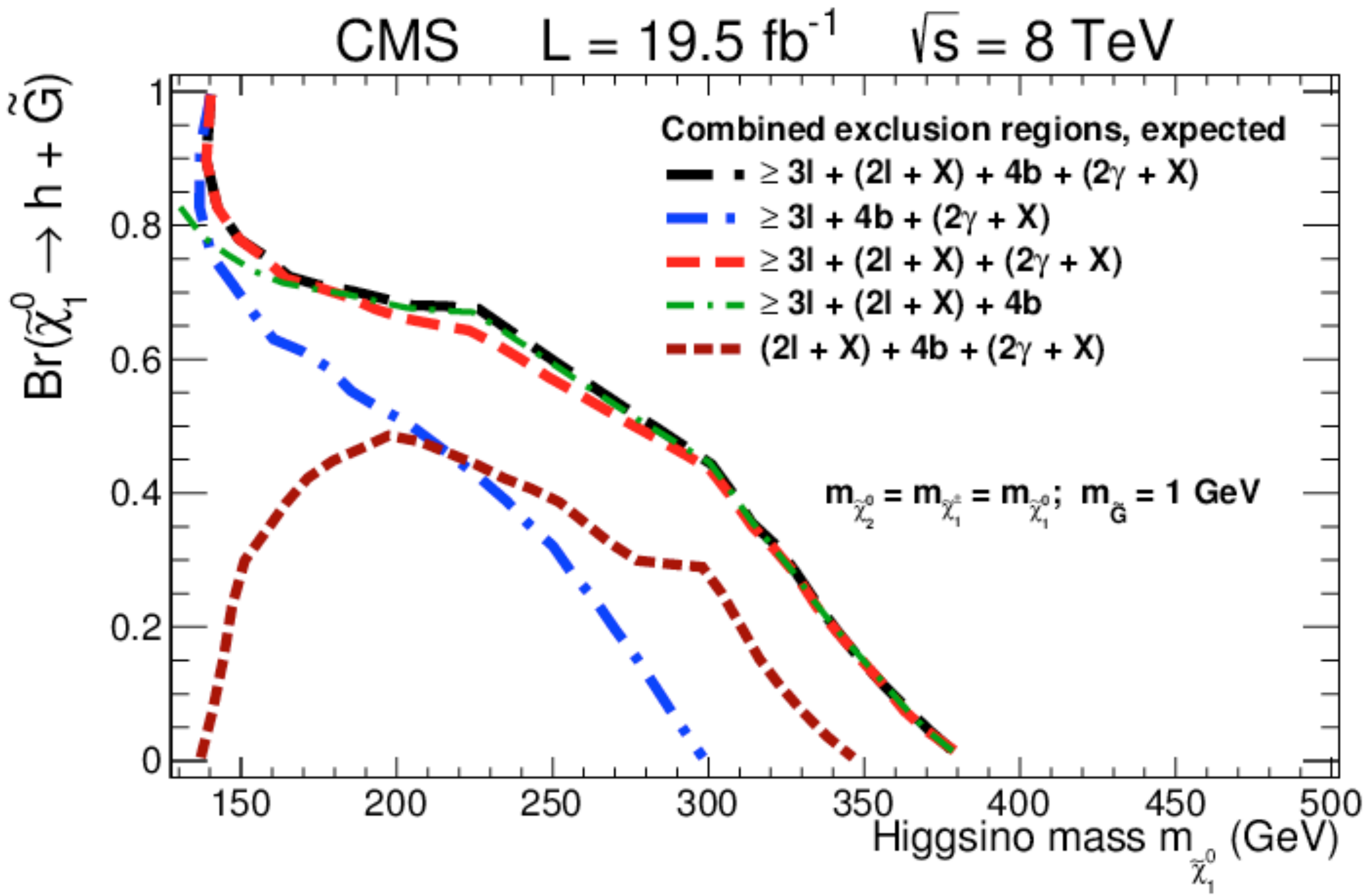




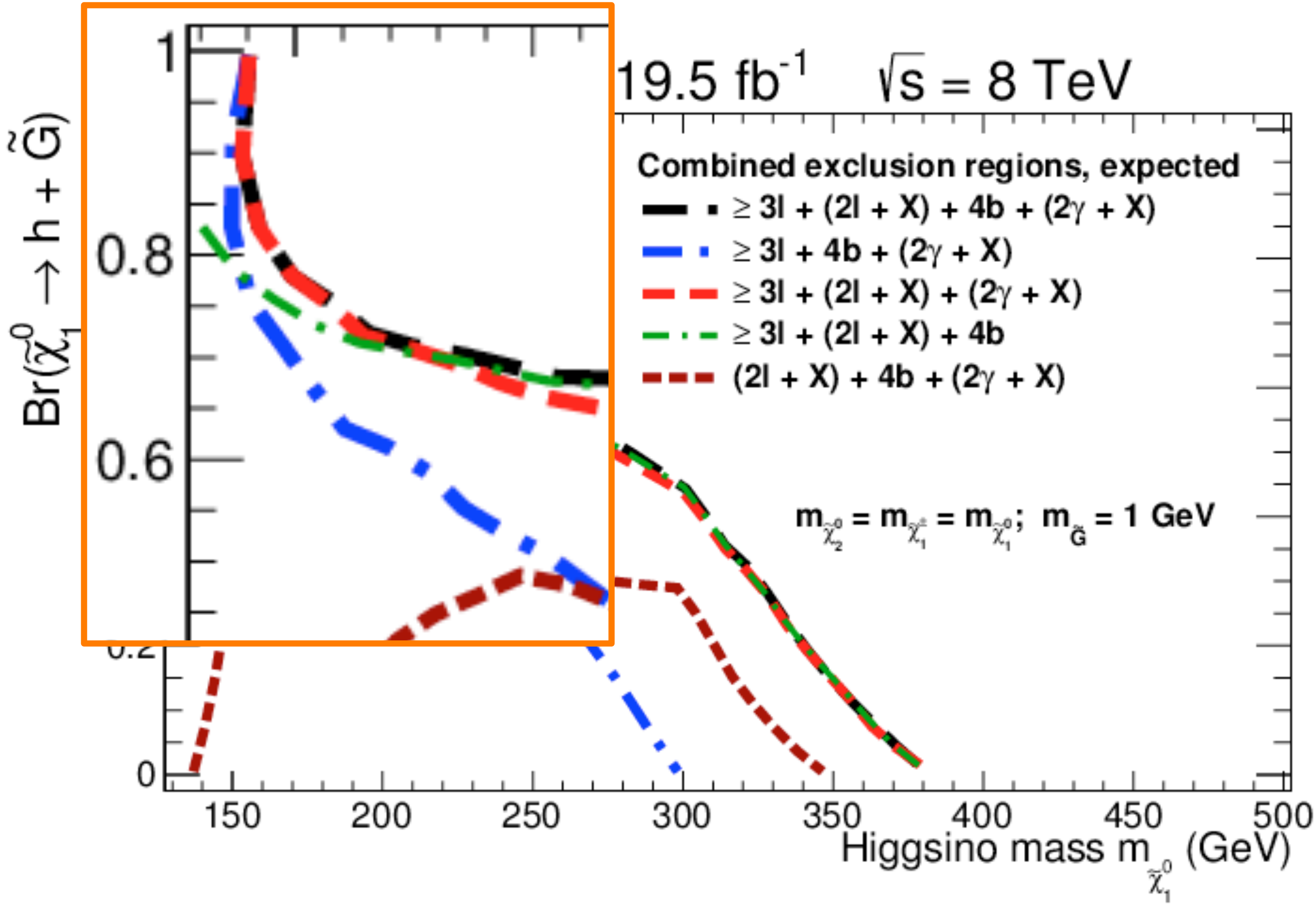


S_T^h bin (GeV)	SM background	Data	hh events, $m_{\tilde{\chi}_1^0} = 130\,\text{GeV}$
0–60	$0.21^{+0.28}_{-0.21}$	1	0.28 ± 0.03
60–120	$0.95^{+0.99}_{-0.95}$	2	0.63 ± 0.04
120–180	$0.21^{+0.29}_{-0.21}$	1	0.55 ± 0.04
180–240	0.74 ± 0.38	0	0.53 ± 0.04
>240	$0.42^{+0.49}_{-0.42}$	1	1.46 ± 0.06

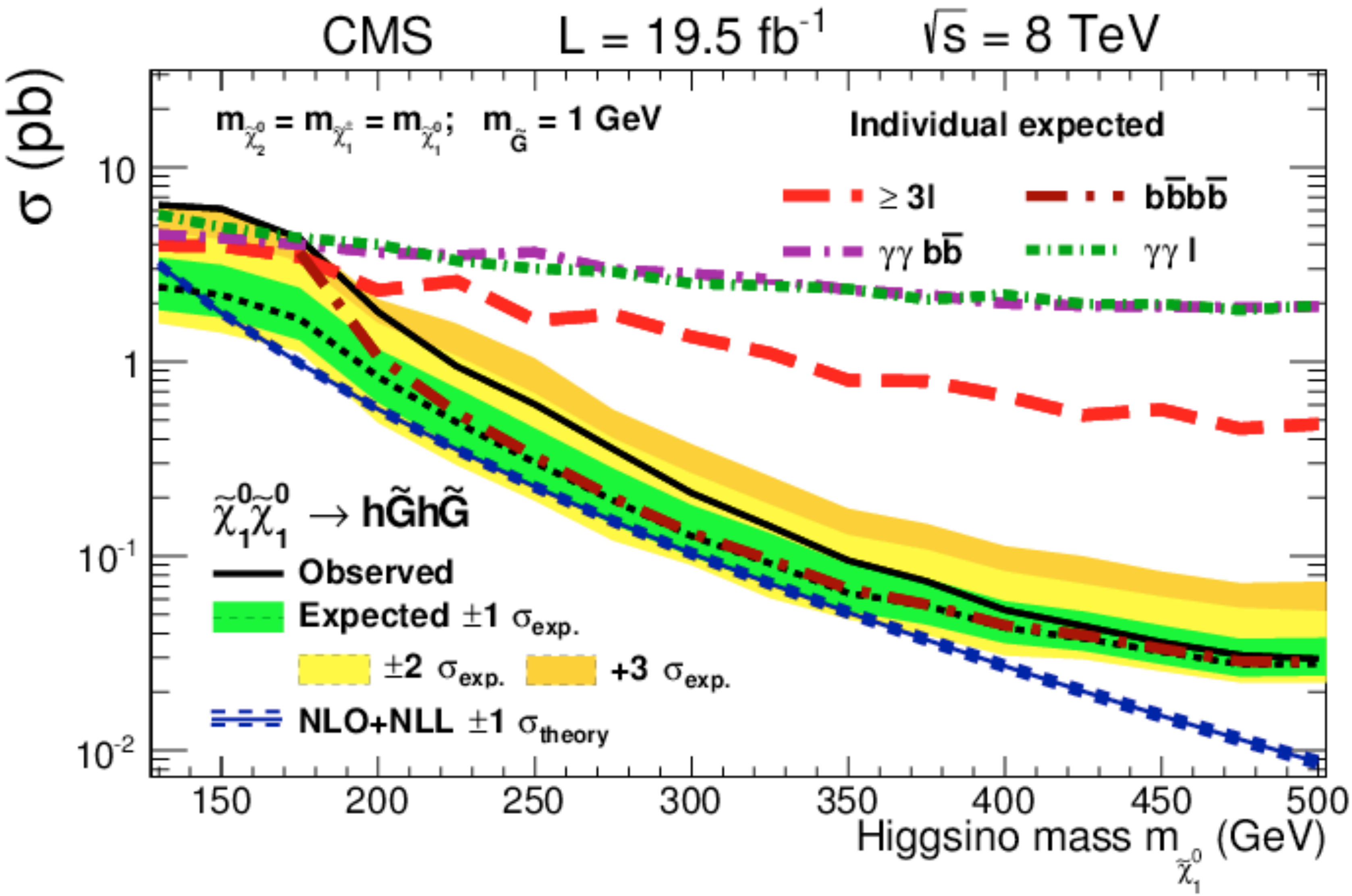
Combination



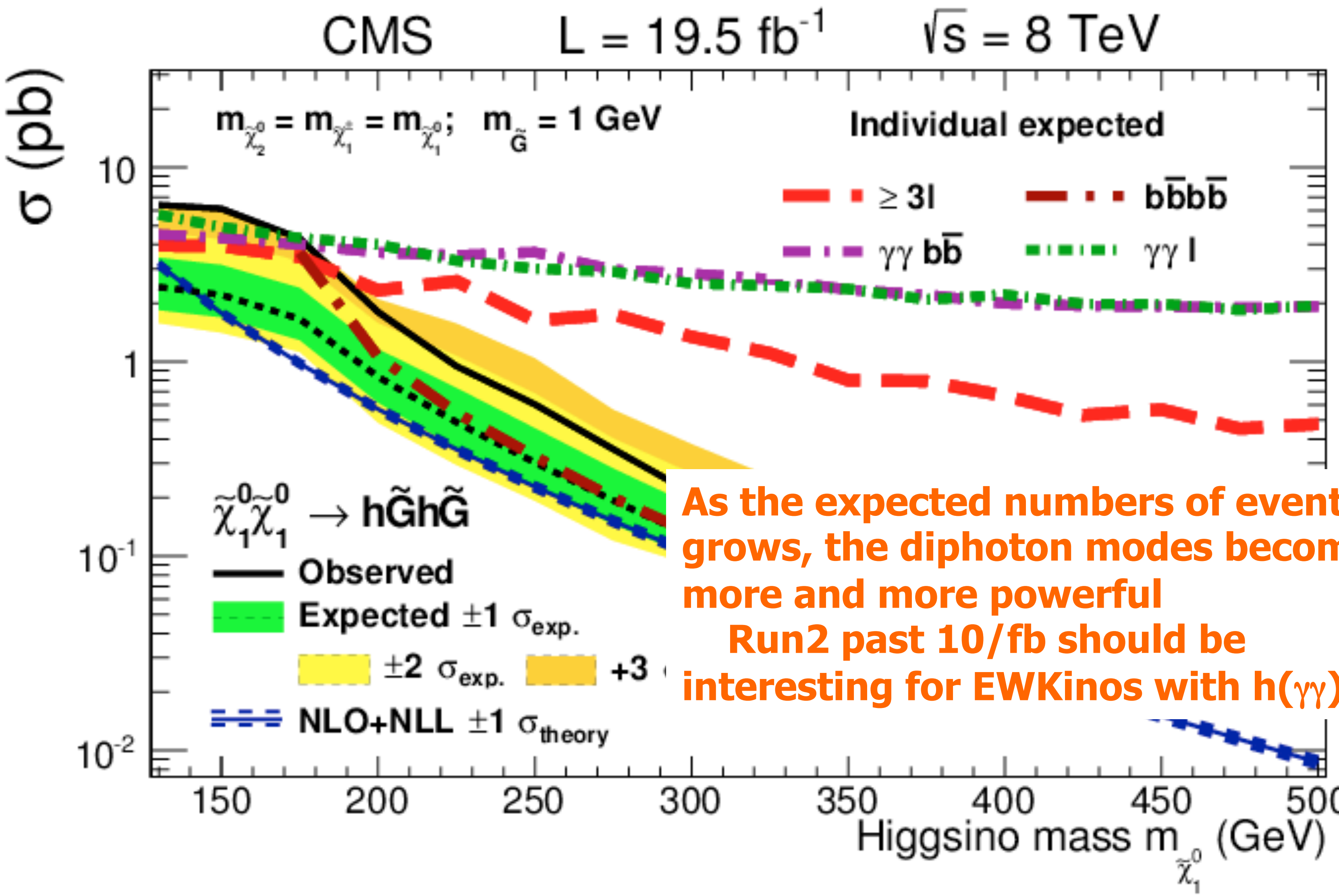
Combination



Combination



Combination



As the expected numbers of events grows, the diphoton modes become more and more powerful

Run2 past 10/fb should be interesting for EWKinos with h(γγ)

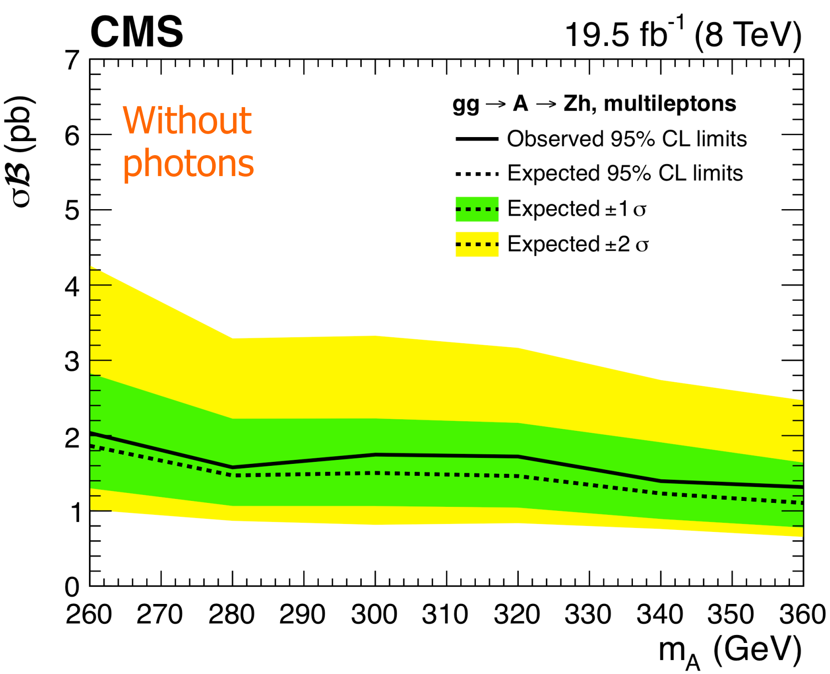
Another angle on HH/HZ final states

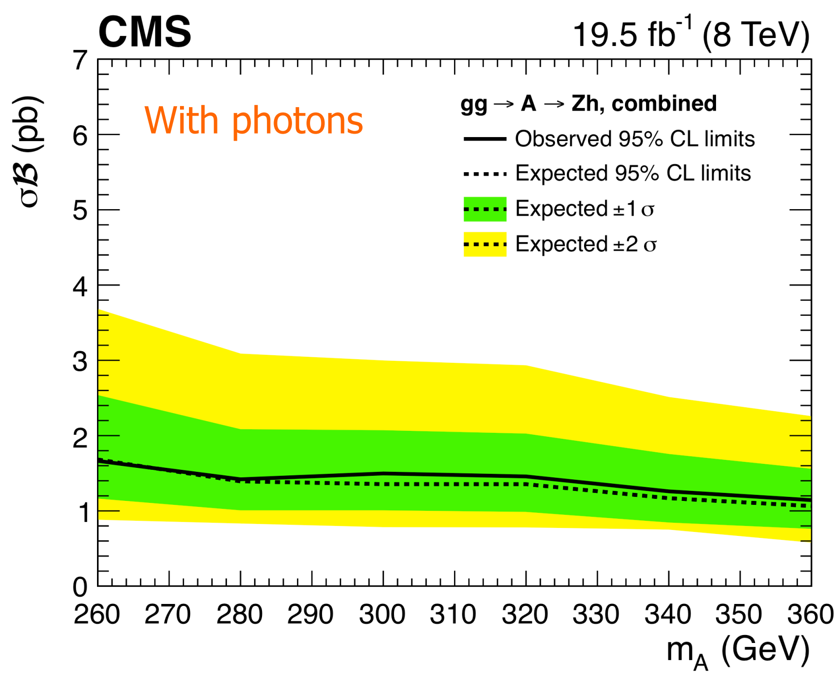
N. Craig et al arXiv:1207.4835

$y_{\rm 2HDM}/y_{\rm SM}$	2HDM I	2HDM II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
AVV	0	0
AQu	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$

- even harder: no MET
- multileptons and diphoton+tau / e / μ

HIG-13-025





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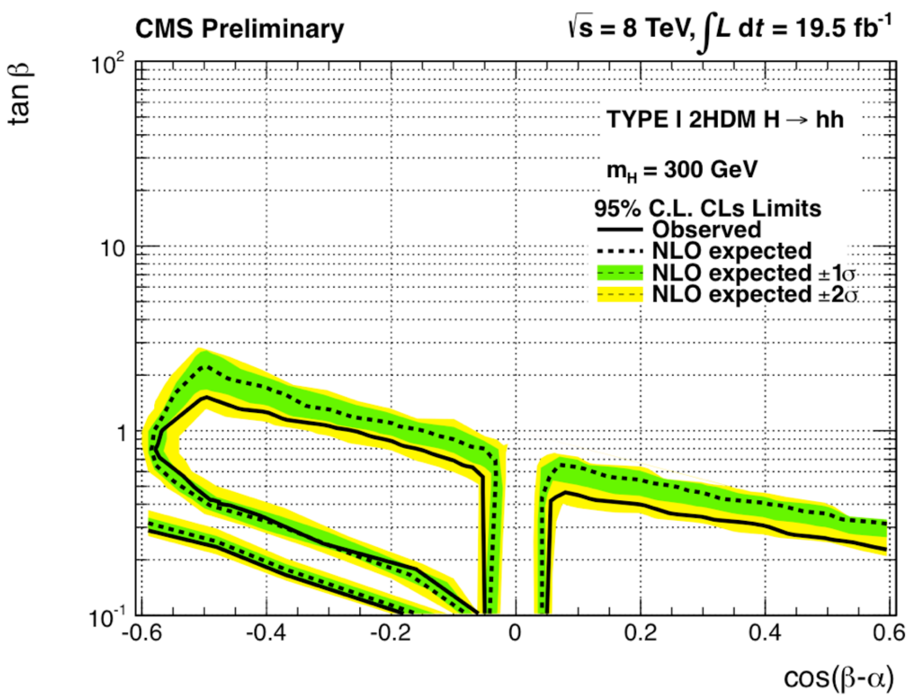
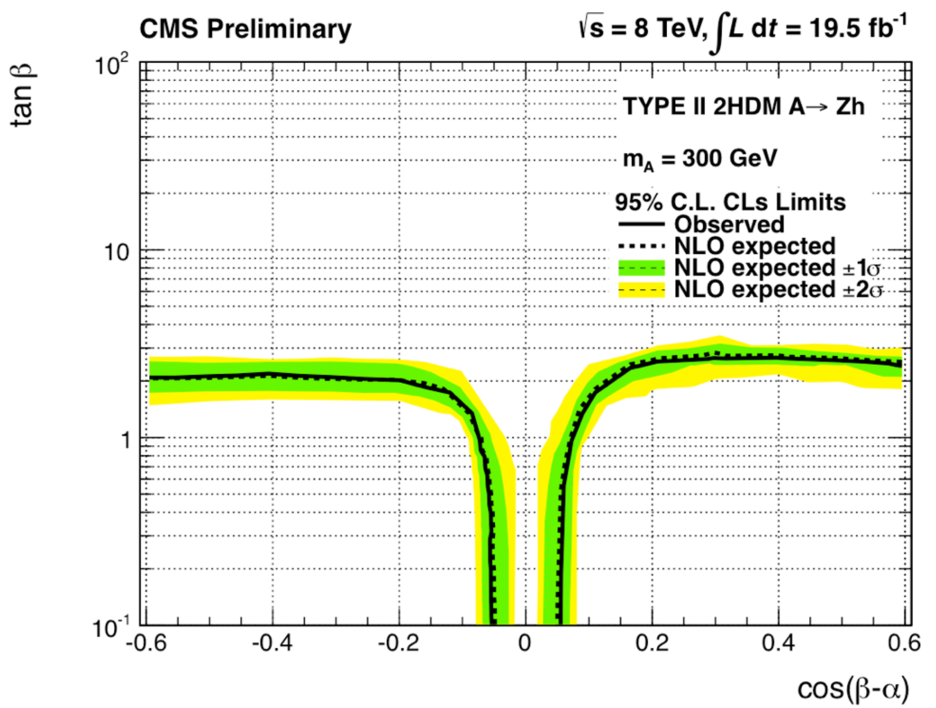
HIG-13-025





Higgs in Top

N. Craig *et al* PRD 86 075002 (2012)

- A complementary way to probe tiny BSM Higgs couplings: use huge top production cross section
  - i.e. FCNC $t \to Hc$
  - diphotons have the best sensitivity
  - limit FV couplings

$$\sqrt{|\lambda^{\mathrm{H}}_{\mathrm{tc}}|^2 + |\lambda^{\mathrm{H}}_{\mathrm{ct}}|^2} < 0.14.$$

most sensitive channels with $H \to \gamma\gamma$ + e/μ

E_T^{miss} [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
50–100	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39	3.1 ± 0.4
30–50	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30	2.4 ± 0.3
0–30	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24	1.9 ± 0.3
50–100	0	7	9.5 ± 4.4	2.22 ± 0.31	2.4 ± 0.3
> 100	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14	1.0 ± 0.2
> 100	0	1	2.2 ± 1.0	0.94 ± 0.17	1.0 ± 0.2

HIG-13-034

Higgs Decay Mode	observed	expected	1σ range
$\mathrm{H} \to \mathrm{WW}^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$\mathrm{H} \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$\mathrm{H} \to \mathrm{ZZ}^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$\mathrm{H} \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

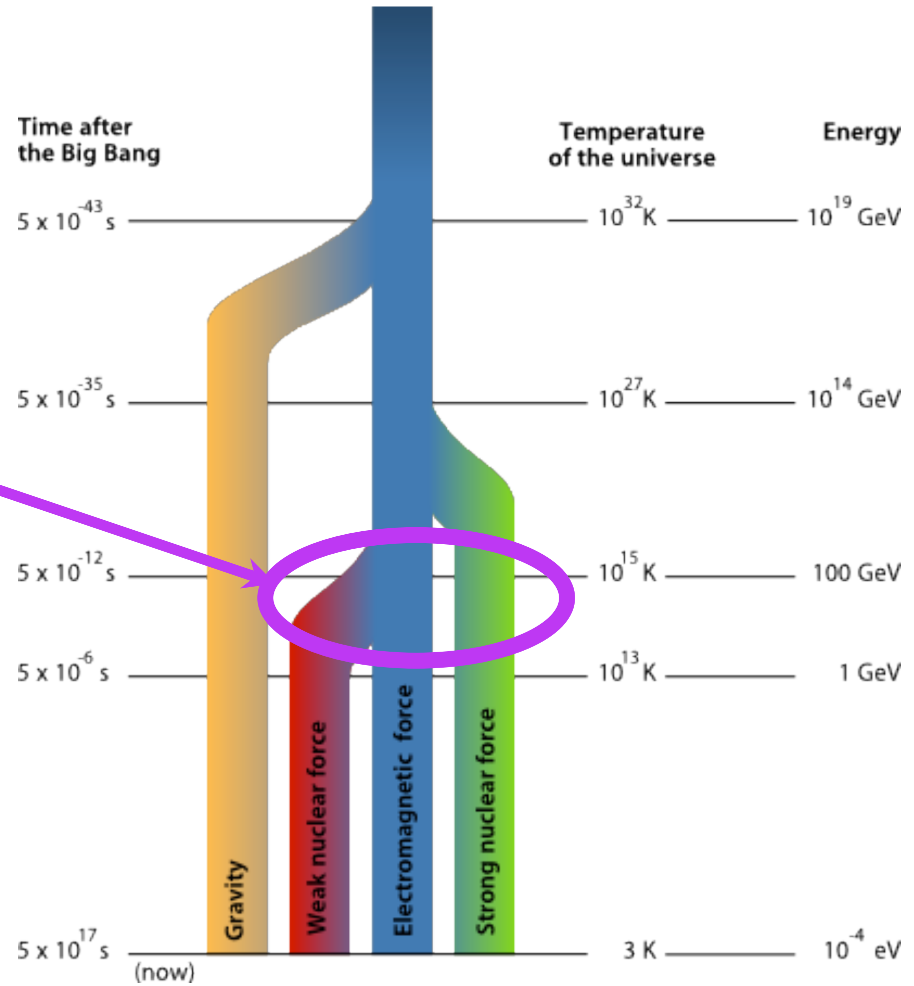
Summary

- Higgs was a huge discovery
  - a completely new type of field (scalar with non-zero vev)
- Understanding the nature of the Higgs potential is the next undertaking of particle physics
  - Higgs measurements
  - searches for more scalars
  - searches for new Higgs production mechanisms (i.e. in SUSY cascades)
- Di-photon decay mode, despite its low branching, is a good or the best way to look once a lot of statistics is gathered

Run 2 and HL-LHC should be a lot of fun

LHC exploration only just begun!

An amazingly interesting place to be



Yuri Gershtein, FNAL W&C March 2014