Higgs (→γγ) + X and New Physics

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Higgs Identification
KITP
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http://higgs-m12.wikispaces.com/

Introduction

- A confession:

  I initially wasn't very interested in Higgs physics at the LHC

- I figured we would find it
  - where it was expected in SM (~115 – 140 GeV)
  - with SM BR's
  - with SM production rates

- The analyses are relatively straightforward

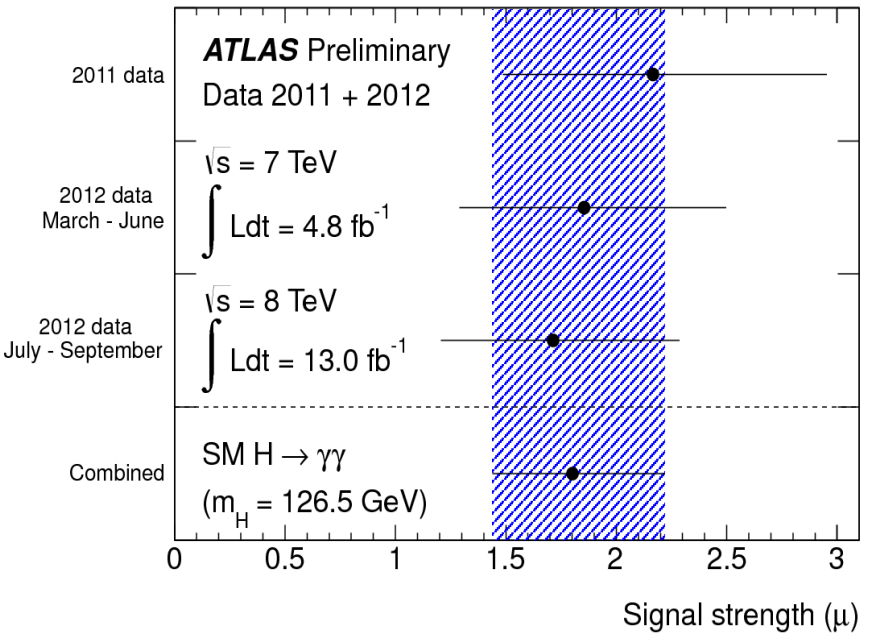
- Interested in New Physics beyond the SM

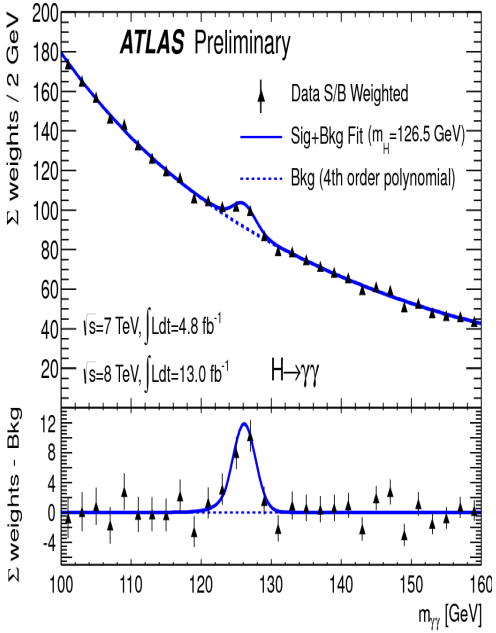
- Bitter we didn't get it at the Tevatron (while I was Higgs convener) :)

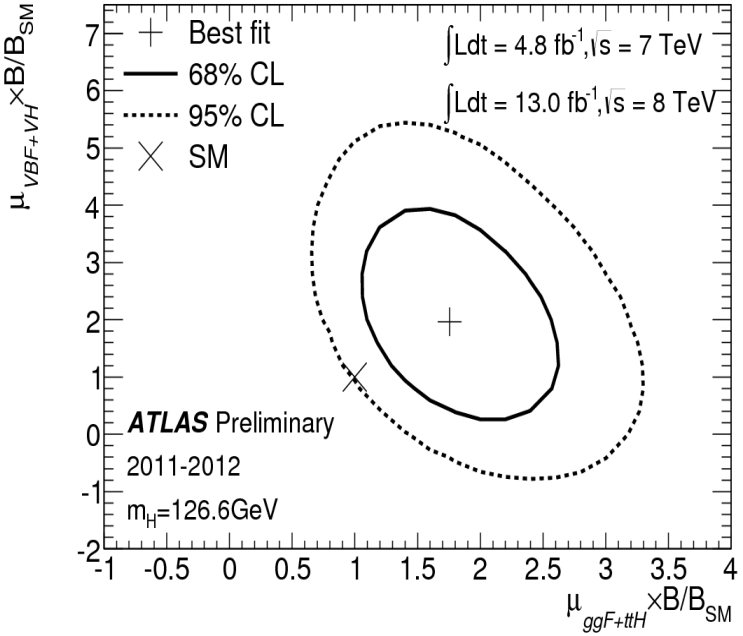
Introduction

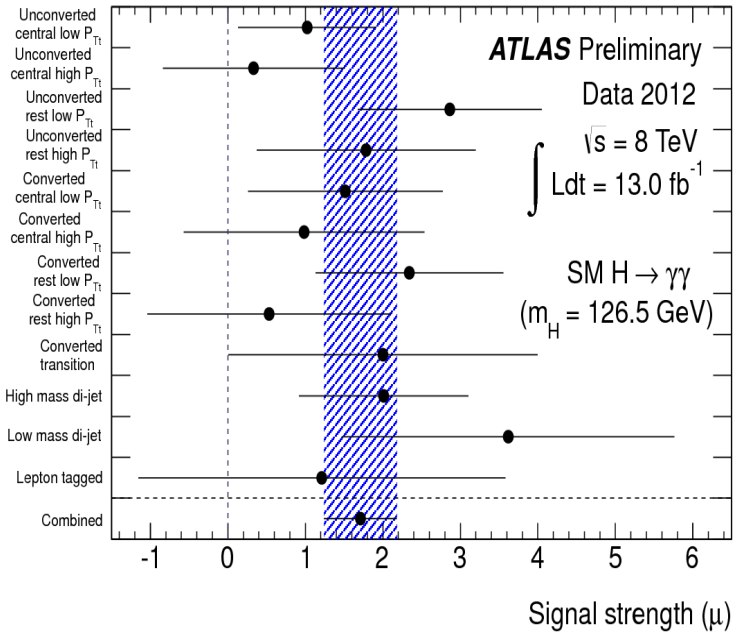
- This got me interested…
- Steady in time and across channels

$$1.80 \pm 0.30\ (\text{stat})\ ^{+0.21}_{-0.15}\ (\text{syst})\ ^{+0.20}_{-0.14}\ (\text{theory})$$









Introduction

- The second thing, which has always interested me:

  Large BR $x_2^0 \rightarrow h\, x_1^0$: "Could discover Higgs in SUSY decays"

- Unfortunately, it didn't turn out this way…

- But, the corollary is still true: "Could discover SUSY using Higgs decays" !

- Still possible that ~10% (?) of Higgs production is through SUSY production and decay!

Particle	Point 1
$\tilde{g}$	1004
$\tilde{\chi}_1^\pm$	325
$\tilde{\chi}_2^\pm$	764
$\tilde{\chi}_1^0$	168
$\tilde{\chi}_2^0$	326
$\tilde{\chi}_3^0$	750
$\tilde{\chi}_4^0$	766
$\tilde{u}_L$	957
$\tilde{u}_R$	925
$\tilde{d}_L$	959
$\tilde{d}_R$	921
$\tilde{t}_1$	643
$\tilde{t}_2$	924
$\tilde{b}_1$	854
$\tilde{b}_2$	922
$\tilde{e}_L$	490
$\tilde{e}_R$	430
$\tilde{\nu}_e$	486
$\tilde{\tau}_1$	430
$\tilde{\tau}_2$	490
$\tilde{\nu}_\tau$	486
h	95
H	1046
A	1044
$H^\pm$	1046

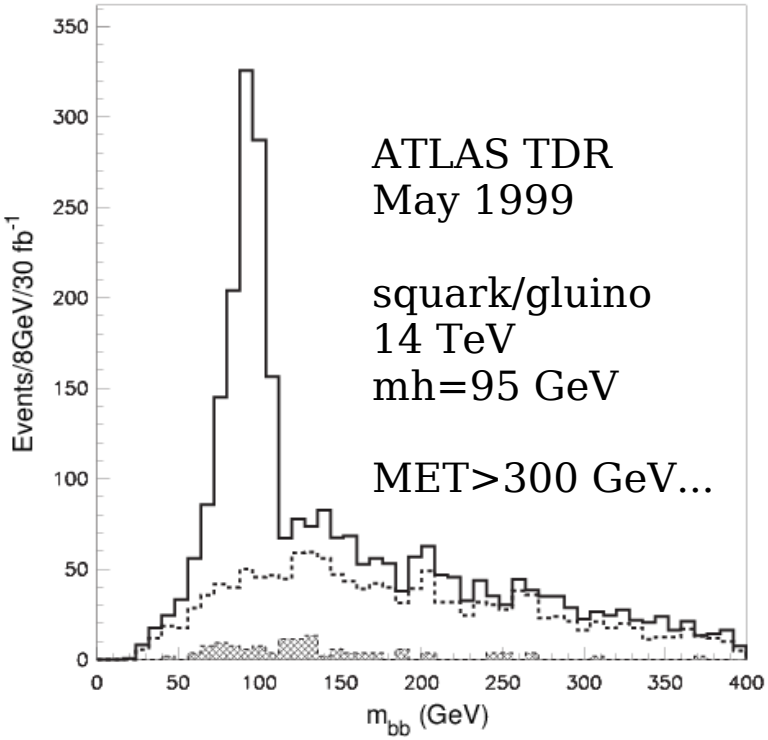
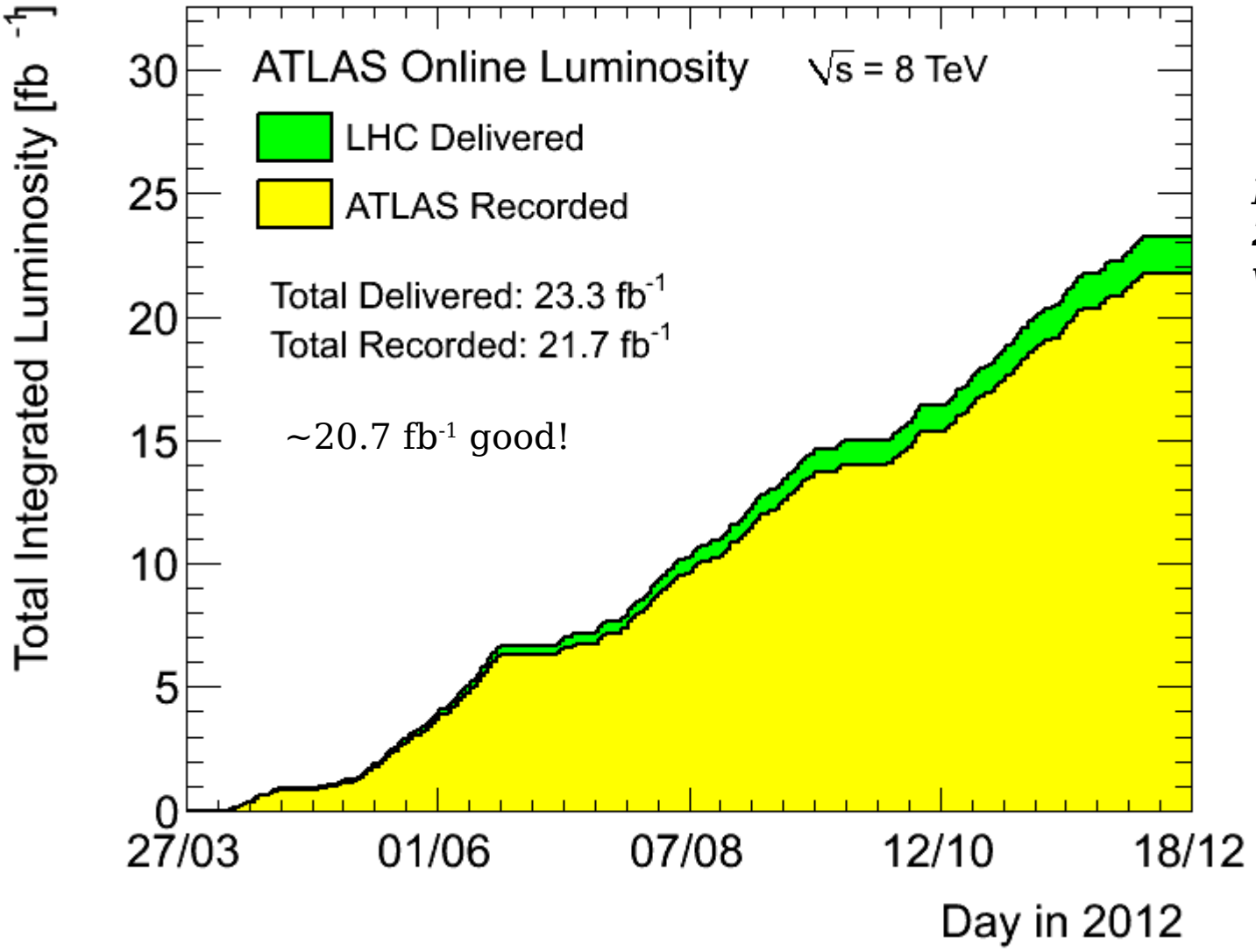


Figure 20-23 Mass distribution for two tagged b-jets at Point 1 for 30fb^{-1}. The dotted curve is the SUSY background, and the shaded histogram is the sum of all Standard Model backgrounds.

Data Taking

- Now: ~13(5) + 5/fb : γγ ~3σ high
- Moriond (March 2013): ~21+5/fb: γγ ~4σ high?



Now a 2-year wait!

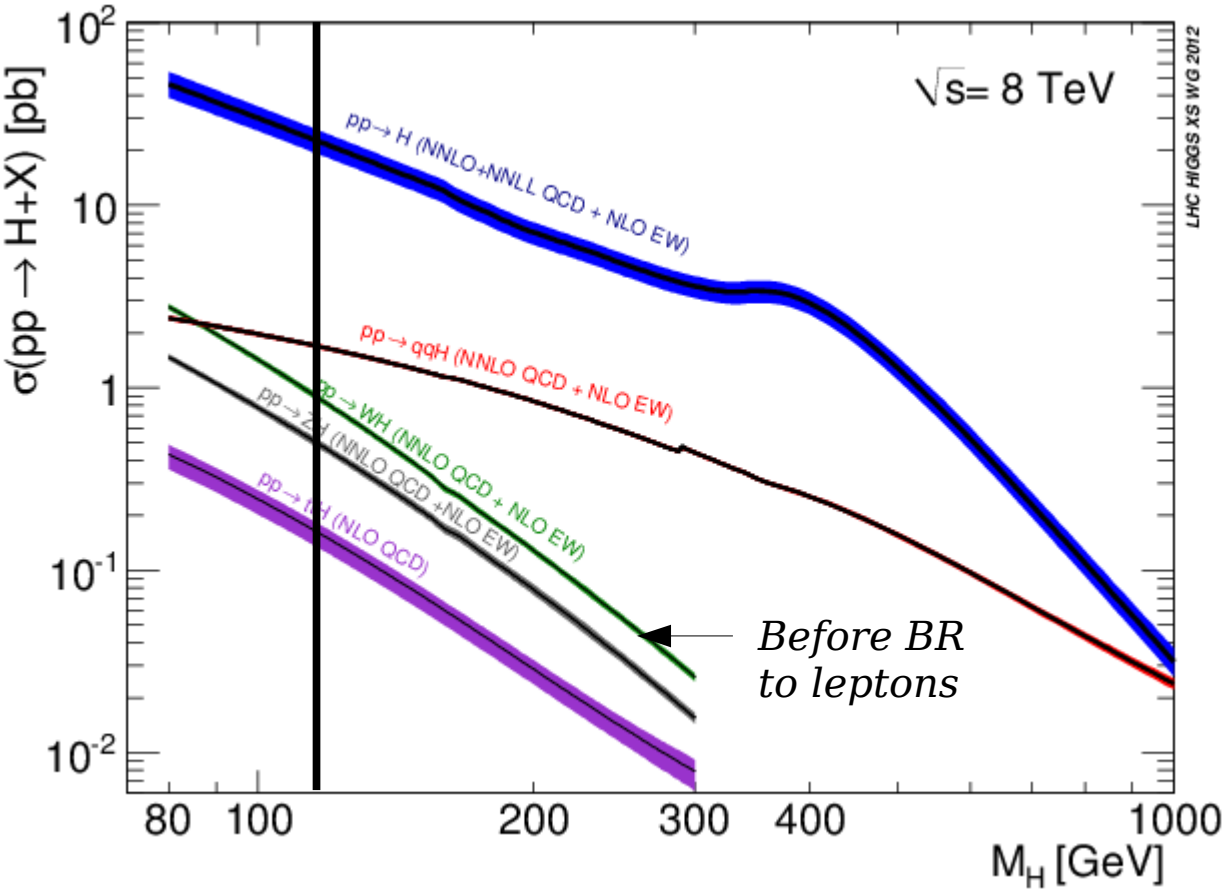
Plenty to do in the meantime…

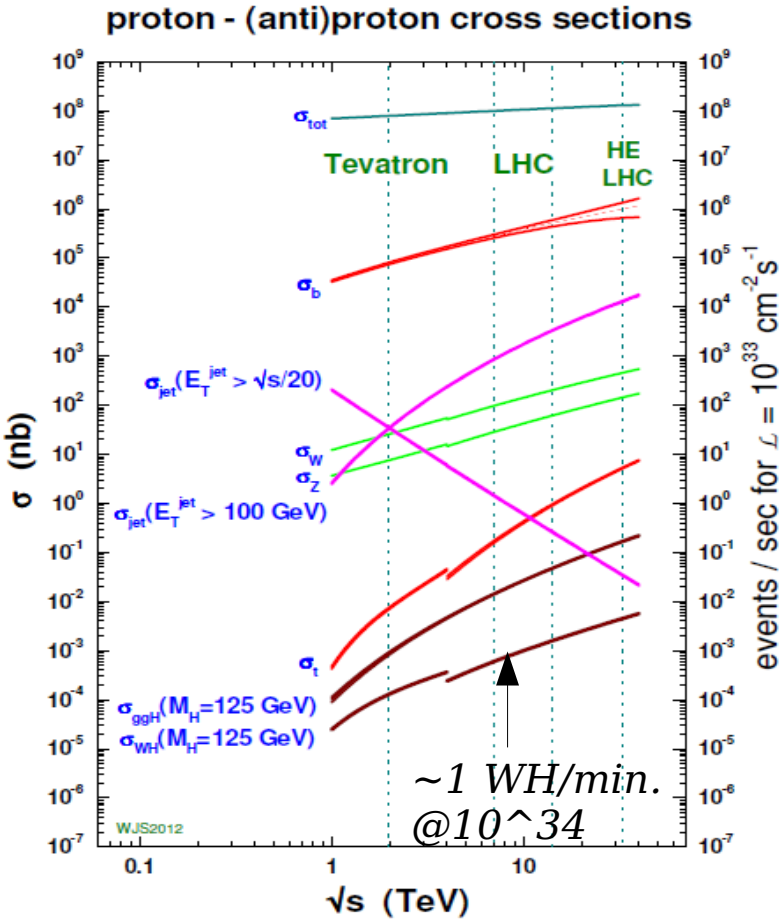
Improve analyses!
Study new channels!

SM Higgs Production at the LHC

- Critical to study h→γγ carefully
  - Measure BR(h→γγ) as accurately as possible
  - Understand rates in each production mode independently

(New grad students won't see plots vs. m_H anymore!)



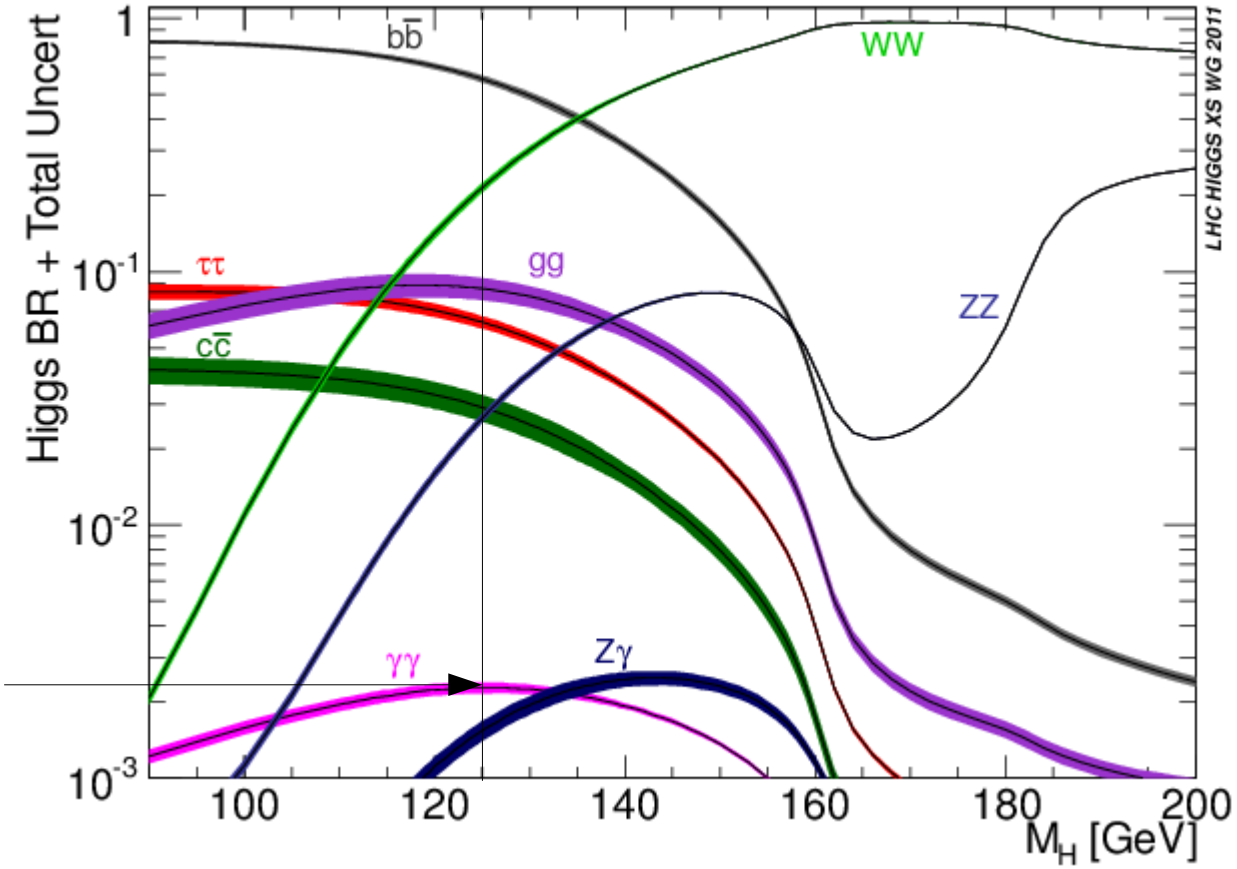


SM Higgs Decays

- Measure bb, ττ, WW, ZZ, γγ (and later Zγ and μμ?) at the LHC

- γγ has reasonable rate (no BR to leptons), good mass resolution, decent S/B, *and no MET*

BR(H→γγ) = 0.25%

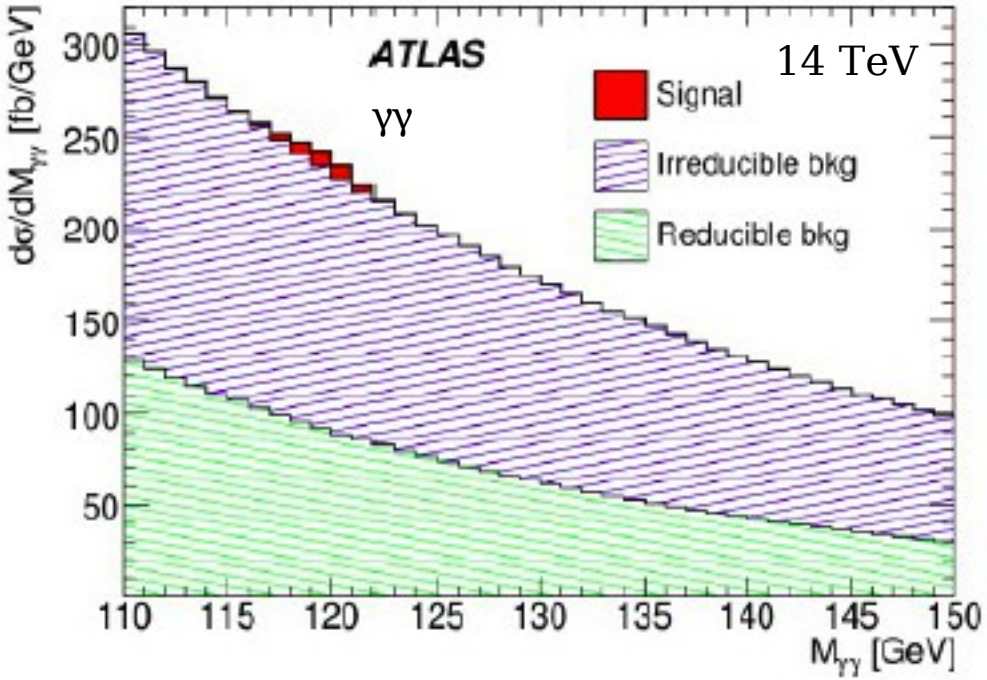


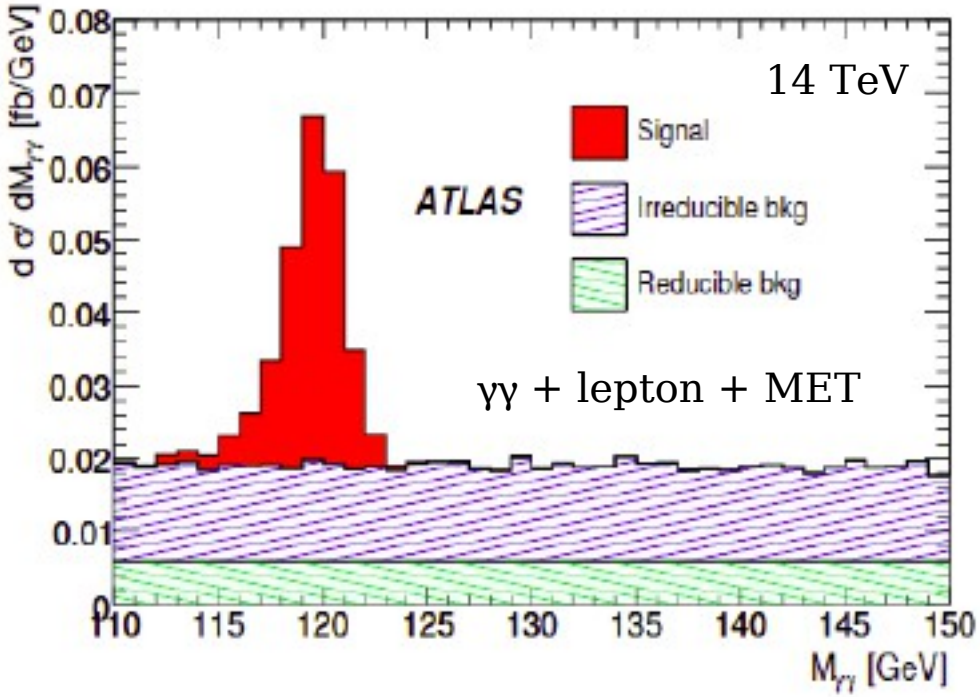
Higgs (→γγ) + X

- With 26/fb, can start to see modes with smaller cross-sections!
  - WH(→γγ) : lepton + MET + γγ *(hadronic decay channels dirtier…)*
  - ttH(→γγ) : lepton + MET + b(b) + γγ, MET + b(b) + γγ
  - ZH(→γγ) : 2-lepton + γγ, MET + γγ
- If BR(H→γγ) is enhanced, these channels may be enhanced
  - Important to measure many production channels to know whether enhancement is due to production rate or decay BR
  - Measure Higgs couplings to W/Z/t in new way
- Sensitive to new physics directly – low SM "Higgs background" !!
  - SUSY can produce Higgs in decay chains, associated with leptons and/or MET and/or b-jets (and countless other models of new physics)
  - Keep selections as inclusive as possible!
  - Important to have BSM benchmarks in these channels:
    J. Wacker / J. Olsen / S. Thomas / A. Haas → "KITP BSM Higgs Points"

W + Higgs (→γγ)

- **Clean!**
  - S/B = ~2 compared to ~0.02 for inclusive analysis
- But low rate (in SM)
  - Events of WH(→γγ) in 30/fb:
    ~1pb * 30/fb * (20% * 0.5) * (0.25% * 0.6) * (80% * 0.7) = **~2.5 events**
    lepton*eff H → γγ * eff MET * eff
  - See 4, expect 1.5 bkgd. events → ~2σ expected sensitivity to SM WH





New Physics in the "WH" channel

- We don't know BR ($H \rightarrow \gamma\gamma$) directly, just $\sigma * BR$
- If BR ($H \rightarrow \gamma\gamma$) is 2x SM rate and $\sigma(WH)$ is SM:
  See 7, expect 4 (SM Higgs) → ~1.5σ evidence for BSM

- Could also have additional non-SM production !
- $pp \rightarrow x_1^+ x_2^0 (\rightarrow G\ W^+\ G\ h)$ could be ~1 pb @ 8TeV
  - comparable to SM WH rate!
- $pp \rightarrow x_1^+ x_2^0 (\rightarrow x_1^0\ W^+\ x_1^0\ h)$ *"Mini-split", Craig, Domopolos, arXiv:1210.0555*
  - dominant x_2^0 BR for the Bino LSP case with heavy SUSY scalars
- See 12, expect 4 (SM) → ~4σ evidence for larger rate from BSM!

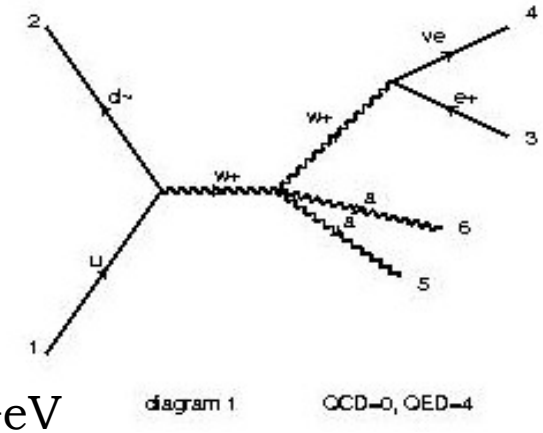
- Could also have softer lepton, less MET, lower mT(MET, lepton), etc. from new physics, e.g. $m(x_1^+) - m(x_1^0) < m(W^+)$
  - Study "lepton + MET + $H(\rightarrow \gamma\gamma)$" : keep cuts as inclusive as possible!

W + Higgs (→γγ) analysis

- Standard γγ selections, as in inclusive analysis *
- Tight electron within acceptance, pT>15 GeV
  or
  Tight muon within acceptance, pT>10 GeV
- Calorimeter and track isolation (corrected for pileup)
- MET>40 GeV (not a lot of MET these days!)
  - Sensitive to primary vertex, calibrations, and pileup suppression!
    - Use same primary vertex for photon pT as pileup corrections and lepton
    - Same photon and lepton object energy corrections in MET calculation
- Remove events with m(eγ) near m(Z), remove Zγ→eeγ, e→γ fake
  - * some additional photon selections to reduce e → γ fake

- Not cutting on mT(l,MET)!
- Using minimal cut on pT and MET needed to reduce background…
  - Would cut harder to optimize SM WH sensitivity

W + Higgs (→γγ) analysis



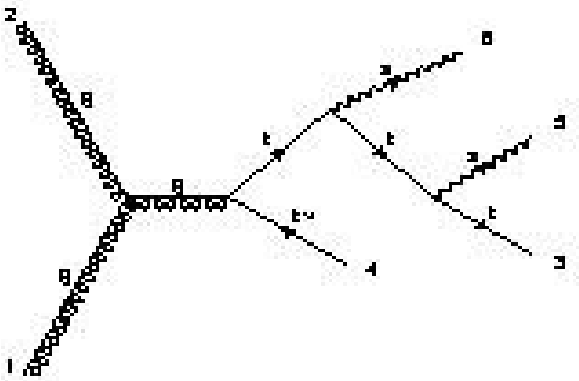
- Blind the m(γγ) signal region!
- Study backgrounds to lepton+MET+γγ
  - Irreducible W+γγ, MadGraph MC
    - 0.37 fb for 100<m(γγ)<180 GeV
    - pT(γ)>20 GeV, pT(l)>10 GeV, |η(γ,l)|<2.5, MET>40 GeV
    - 9 events in 30/fb * ~20% efficiency → **~2 events**
  - W+γj (j->γ fake), W+jj (j->γ fake)*(j->γ fake)
    - Scale W+γγ using ratios from inclusive γγ analysis
    - Will be tested further with W+γj MC soon…
    - 16 : 5 : 1 → W+γγ multiplied by (6/16) → **~1 event**
  - (γγ, real or fake) * fake lepton * fake MET
    - ABCD data-driven method (working on cross-checks) → **~6 events**
      - measure fake MET rate in non-isolated leptons
      - apply to isolated leptons in low-pt data

- <u>Total of just ~2 events expected in m(γγ) signal region</u> (120-130 GeV)

tt + Higgs (→γγ)

- Baseline analysis would be lepton + MET + b-jet(s) + γγ
  ("WH analysis + b-jet(s)")
  - Also studying all-hadronic channel
  - Di-lepton channel could be added, but rate is ~9x smaller

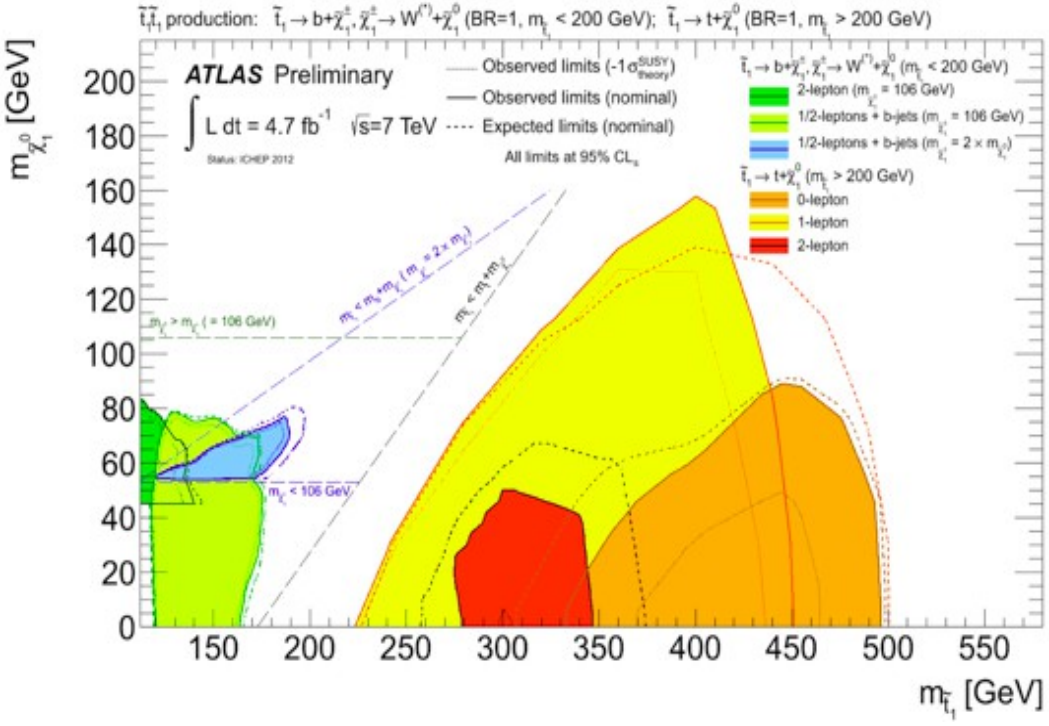
- ttH cross-section is ~4x smaller than WH, but have 2 W's and higher-pt / larger acceptance
  - Expect ~1.5 SM ttH(→γγ), lepton+MET+b+γγ, events in 30/fb
  - So maybe 3, or 6 with new physics ?



- Irreducible ttγγ background is small
- The problem is ttγ with with j→γ fake,
  and tt with 2 j→γ fakes
  - Every tt event has several jets, unlike W or Z !
  - Working to reduce this background with tighter photon cuts
  - Should be able to recover a S/B of ~2

New Physics in the "ttH" channel

- Plenty of ways to make lepton(s), b-jets, MET, and h(→γγ) in SUSY
  - For example: light stop/sbottom not excluded (yet)
  - Can give: tt x_2^0 x_2^0 → tt x_1^0 x_1^0 hh → bb WW h→(bb) h(→γγ) + MET
  - ~80 fb for 500 GeV stop/sbottom
    - 80 fb *30/fb *0.25% * 0.2 BR * 2*2 combinatoric * 30% eff = **~1.5 events**
    - Or larger if BR h(→γγ) is enhanced or ~t is lighter!



...and this is for simple ~t decays to t+MET, etc...

New Physics in the "ttH" channel

- Other models could just give MET + b + h(→γγ), *no leptons*
  - Similar to all-hadronic ttH(→γγ) channel
  - Background could be reduced by raising MET cut?

- Also b + h(→γγ), *no MET or leptons*
  - Something decaying to bh? (vector-like quark model?)
    - Look for bump in m(bh) ?
  - Backgrounds are moderate
    - About ~50 events in m(γγ) signal region for 30/fb, for pT(b)>50 GeV

- <u>More phenomenological studies needed – what are the best channels / selections for these signatures?!</u>

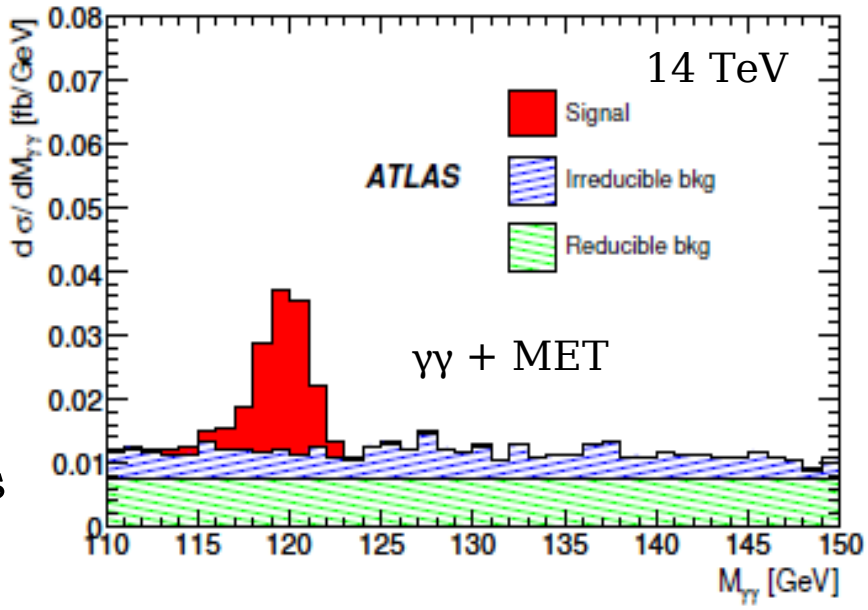
hh production

- Double Higgs production is very small in the SM
- Makes it hard to measure the Higgs self-coupling (sLHC)
- Look on the bright side: very low di-Higgs background to BSM! :)
  - Can be strongly enhanced by new physics arXiv:1208.1542
    - h(→bb) + h(→γγ)
    - Look for bump in m(bb) ?
  - Backgrounds with 2 b-jets are not so large
    - About ~5 events expected in m(γγ) signal region for 30/fb, pT(b)>20 GeV

- Best channel / selections to see hh?
  - Maybe h(→WW) + h(→WW) → tri-lepton?
  - Maybe h(→ττ) + h(→WW) → lepton + ττ + MET + jets ??
- Benchmark model : H → hh, mH=300 GeV (2HDM), 3.6pb@8TeV
  - ATLAS/CMS/theorists(?) can study simulations to optimize
  - A limit on pp→hh will help constrain many BSM models!

Z + Higgs (→γγ)

- MET + γγ
  - For SM ZH, require MET>80 GeV
  - Almost as clean as WH(→γγ)
  - Rate about 2x smaller:
    just ~1 event expected in 30/fb
  - Could see ~4 events with BSM physics



Cut	$ZH \to \nu\nu\gamma\gamma$ σ (fb)	$WH \to \ell\nu\gamma\gamma$ σ (fb)	$t\bar{t}H \to x\gamma\gamma$ σ (fb)	$Z\gamma\gamma \to \nu\nu\gamma\gamma$ σ (fb)	$W^{\pm}\gamma\gamma \to \ell\nu\gamma\gamma$ σ (fb)	$t\bar{t}\gamma\gamma$ σ (fb)	$b\bar{b}\gamma\gamma$ σ (fb)	$W^{\pm}\gamma \to e\nu\gamma$ σ (fb)	$\gamma\gamma$ σ (fb)
Va	0.115	0.207	0.364	0.325	0.360	1.95	3.77	17.55	2558
Vb	0.058	0.062	0.080	0.126	0.071	0.461	0.010	0.789	0.211
Vc	0.046	0.049	0.064	0.096	0.056	0.377	0.010	0.191	0.141
Vd	0.042	0.042	0.006	0.093	0.050	0.021	0.005	0.120	0.073
Mass Win.	0.034	0.033	0.0056	0.009	0.006	0.002	0.0005	0.012	0.007

Signal
Irreducible bckground
Reducible background
Dominant backgroud:
$W\gamma \to e\nu\gamma$ and
$Z\gamma\gamma \to \nu\nu\gamma\gamma$

- 2-lepton + γγ
  - Even cleaner than WH, but rate is ~6x smaller, ~0.4 SM events
  - Seeing 1 event would be interesting… 2 would be exciting!

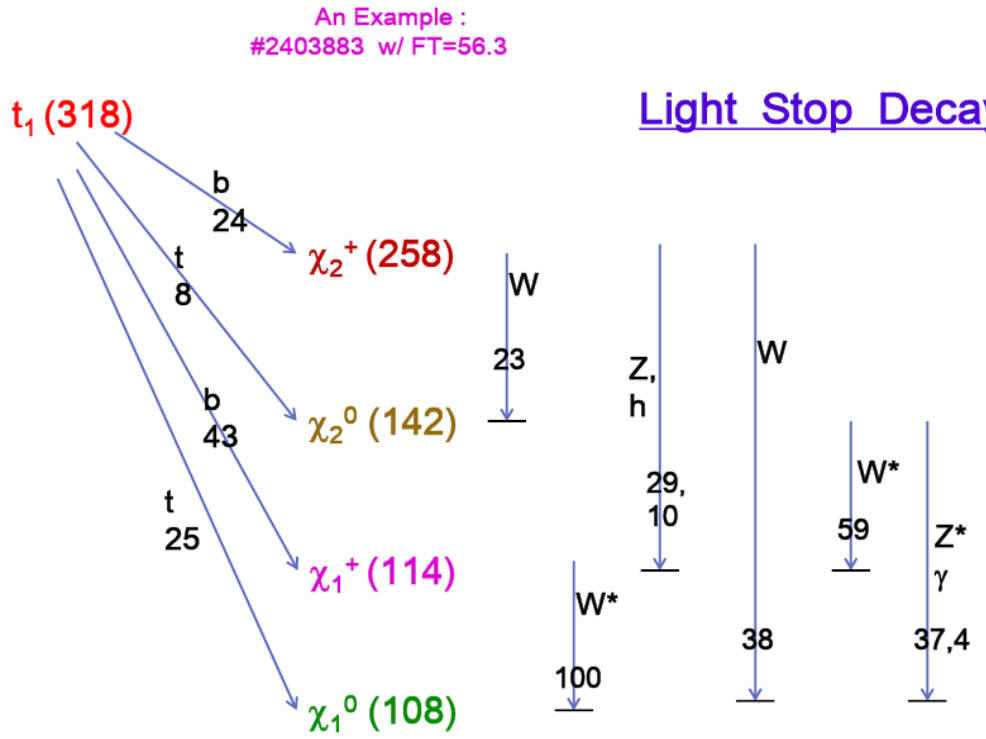
New Physics in the "ZH" channels

- MET + γγ
  - Could have signals with lower MET but larger rate
    or larger MET but smaller rate
  - Important to study MET *shape* in H → γγ events compared to SM
  - Difficult analysis (at low MET) due to increasing pile-up
    - Which vertex is the γγ one?
    - How to subtract off "soft" energy using tracks?
    - Systematics from MET shape modeling in simulation
      - Use "overlay MC" to simulate pile-up background more accurately?

- 2-lepton + γγ
  - New physics could give off-shell Z* decays ($x_2^0 \rightarrow Z^* x_1^0$)
    or even like-sign leptons or opposite-flavor leptons !
  - Don't require opposite-sign, or same-flavor !
  - Don't require m(ll)=m(Z) !
  - Or on-shell decays, $x_2^0 \rightarrow Z x_1^0$

Less minimal new physics in h+X channels

- In general can have a more complicated spectrum / decays
  - $\tilde{t}\,\tilde{t} \rightarrow b\, x_2^+\, t\, x_1^0 \rightarrow b\, h\, W^*\, x_1^0\, t\, x_1^0 \rightarrow b\, h(\rightarrow\gamma\gamma) + \text{lepton} + \text{jets} + \text{MET}$
  - Rate could be ~1pb*.24*0.1*2 = 50fb*0.25% *eff ~ **2 events in 30/fb**
    - Or larger if BR h(→γγ) is enhanced or ~t is lighter!



"The Higgs Sector and Fine-Tuning in the pMSSM"
J. Hewett, T. Rizzo, et al., arXiv:1206.5800

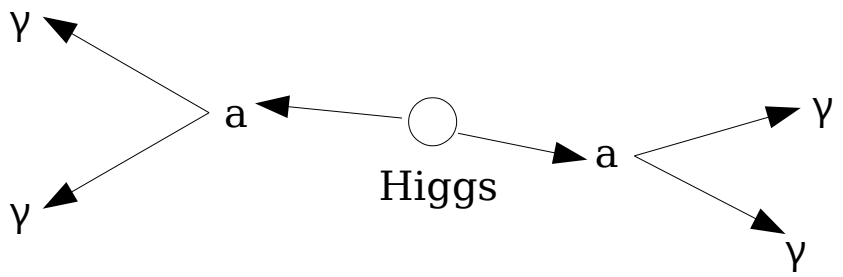
Can have:

off-shell Z* decays
on-shell Z decays
3rd photon
high pT lepton
soft lepton
large MET
…

Non-SM Higgs Production / Decay

- Look for “Higgs” final states with photons not predicted by the SM

- H(→γγ) + γ
  - SM H(→γγ) + γ is just ~0.1 events in 30/fb
  - Extra photon from SUSY?
  - Higgs is a WW bound state? : H(→γγ) + γ ~100 events in 30/fb ! arXiv:1209.2831



- H → a a → γγ γγ
  - For m(a)<~400 MeV, photons not isolated (ATLAS-CONF-2012-079)
  - Study range from 400 MeV < m(H)/2, **≥3 <u>isolated</u> photons**

- Final-state with ≥3 photons, not previously studied?!

Non-SM Higgs Production / Decay

- Commissioned new 3-photon trigger (pT=15,15,15 GeV) for 2012
  - ~50% more efficient than standard pT=24,22 GeV trigger
  - (pT=20,20 GeV was unprescaled in 2011…)

- Offline require ≥3 tight, isolated photons, pT>15 GeV (or trig. thresh.)
- Look for excess rate, and/or invariant mass bumps

- Working on data-driven understanding of fake-photon rate
  - Loose → tight rate in di-photon data/MC
  - Isolation studies in data/MC

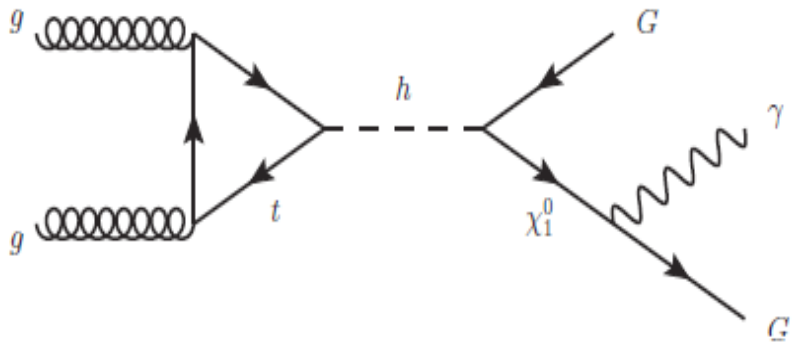
Rough numbers for 3 photons in 0.5/fb:

Ph-Jet	4.22 +- 1.08
Ph-Ph	2.08 +- 0.49
DY	3.10 +- 0.51
Zee+Ph	1.71 +- 0.41
3ph	1.42 +- 0.01
D-D 2Ph-1Jet	1.33 +- 0.90
B_tot	13.85 +- 1.63

- ~600 background events in 30/fb with 3 photons
- Just ~1 background event in 30/fb with ≥4 photons

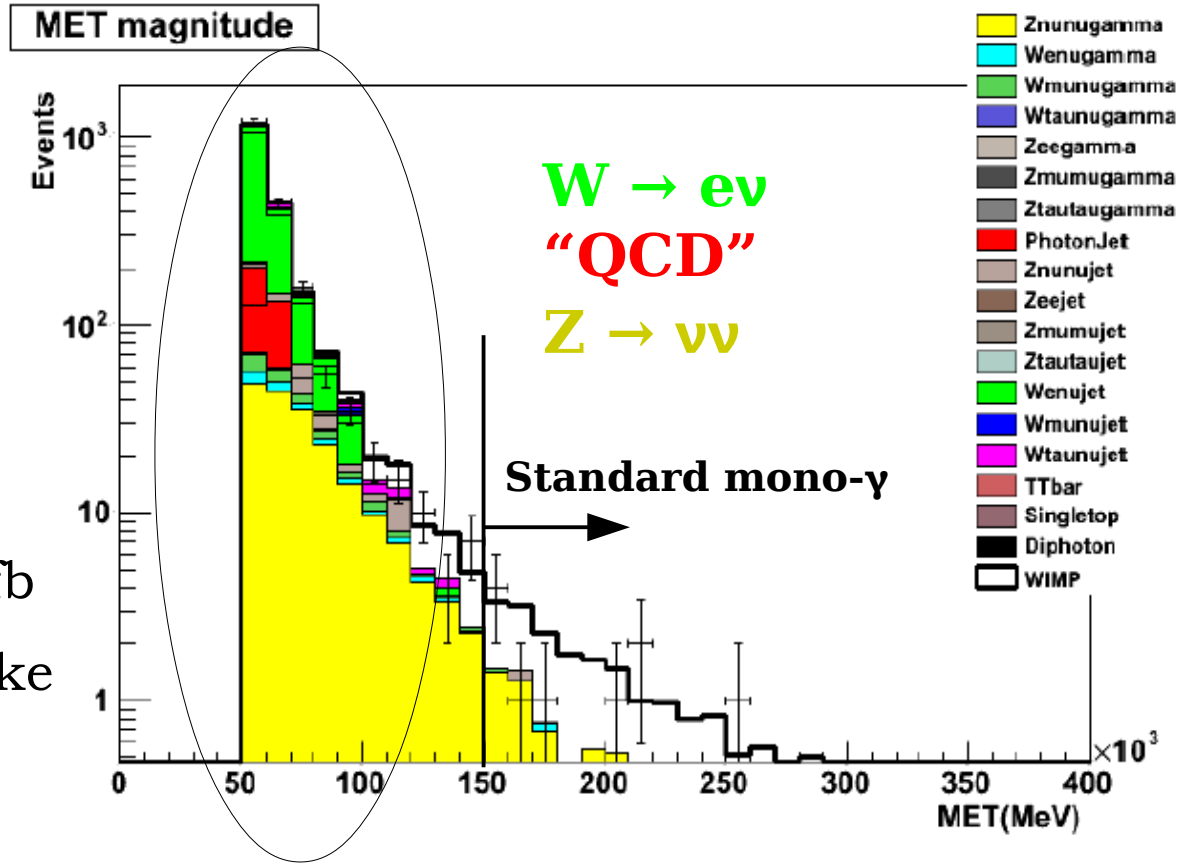
Non-SM Higgs Production / Decay

- Higgs ($\rightarrow G\, x^0 \rightarrow G\, \gamma G$)
  - $m(H)/2 < m(x^0) < m(H)$
  - Could be ~10% of Higgs decays? ~25,000 events in 30/fb ?!
    arXiv:1203.4563



- Mono-photon + MET
  - pT(γ) ~ 50 GeV
  - Use γ+MET trigger

- Large background from W → e → γ-fake
  - ~100,000 events in 30/fb
  - Need specialized e→γ-fake rejection algorithm!



Conclusions

- **H(→γγ) is a good channel for studying "W/Z/tt" + H production**
  - Low backgrounds, reasonable BR (maybe larger), and *no inherent MET*
- With 30/fb, can start to see:
  - Worst case: evidence for SM production / measure couplings directly
  - Better: confirmed evidence for enhanced BR(H→γγ) beyond SM rate
  - Even better: see evidence for extra production from BSM physics!
- Also study non-SM-like modes:
  - Di-higgs, h + b, h + γ, h(→4γ), low-pT mono-γ, …
- More studies of new physics would be useful here!
  - What are the best decay channels / selections for seeing new physics using Higgs decays? *(Now have "KITP BSM Higgs Points" to optimize!)*
  - How to separate new physics from SM associated Higgs backgrounds?
  - What new physics can we expect / put limits on given measurements of rates in these channels? The inverse problem if we see a signal?

* Postscript Comment

- "LHC7/8 found no new physics.
  We have to wait at least ~3 years before having a discovery."

- Too soon to claim this! (though likely correct in the end)

- Many analyses only done with 5/fb @ 7TeV, or 5+6/fb

- Many analyses have yet to be done at all!
  - all the ones in this talk!
  - longish-lived gluinos (mini-split!)
  - better searches for special SUSY points
  - …

- <u>Plenty of new results during shutdown</u>
  (BaBar is still releasing results!)