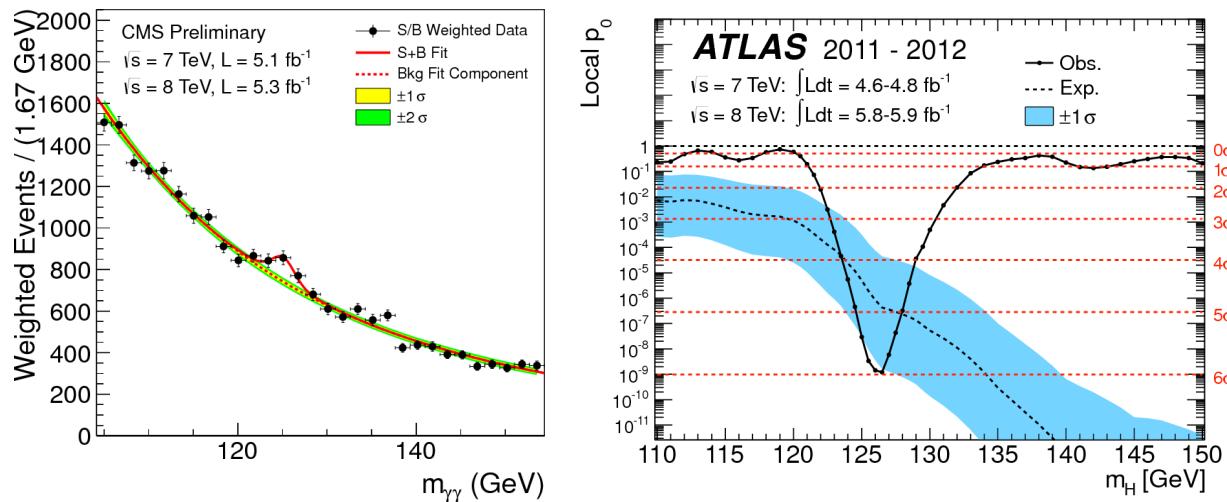


Latest Results from the LHC



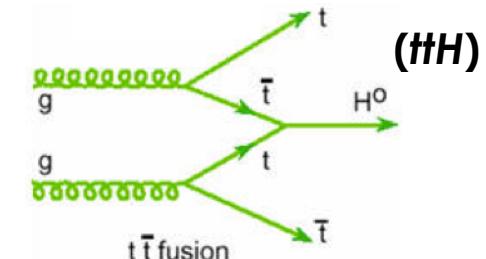
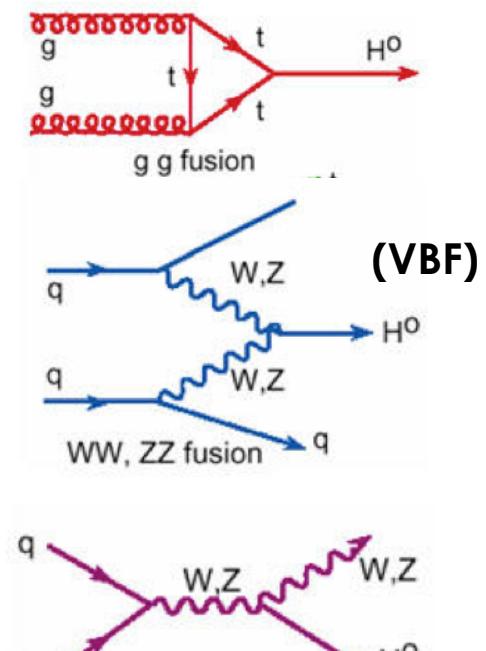
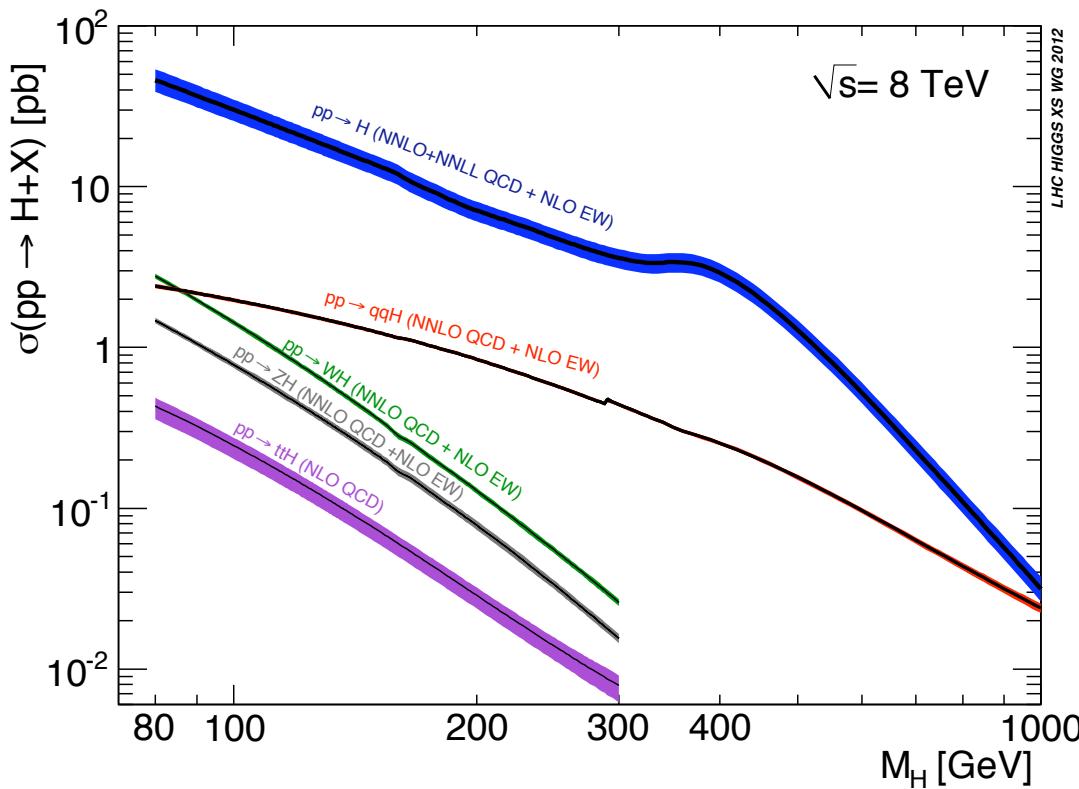
Ariel Schwartzman
SLAC

SiD Workshop
SLAC, 22-Aug-2012

Outline

- **LHC results:**
 - Higgs
 - Observation and initial measurements of properties
 - SUSY
 - 3rd generation searches
 - Higgs
 - Top
 - Cross-section, mass, $t\bar{t}H$
- **Prospects for high luminosity upgrades**
 - Higgs properties
 - SUSY searches

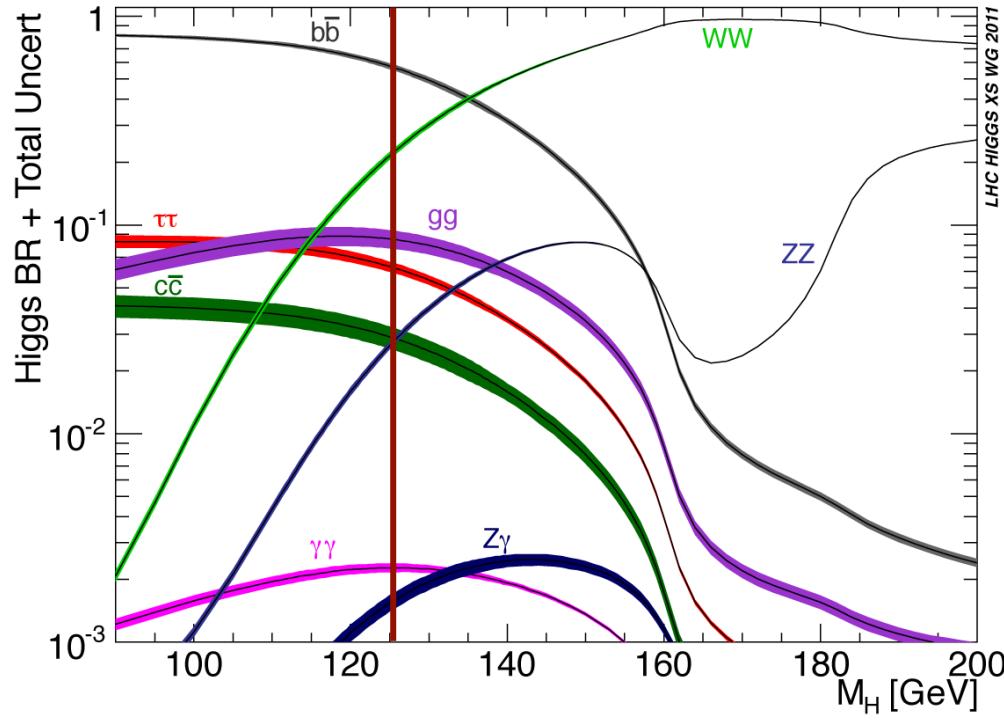
Higgs production



- **Gluon fusion production** dominates: 19.5 pb @ 125 GeV
- **Vector boson fusion (VBF)**: 1.6 pb
- **Associated W/Z production** useful for high QCD background decay modes ($H \rightarrow bb$): 0.7 pb / 0.39 pb
- **Associated production with top quarks**: 0.13 pb (important for coupling measurements)

Higgs Decay

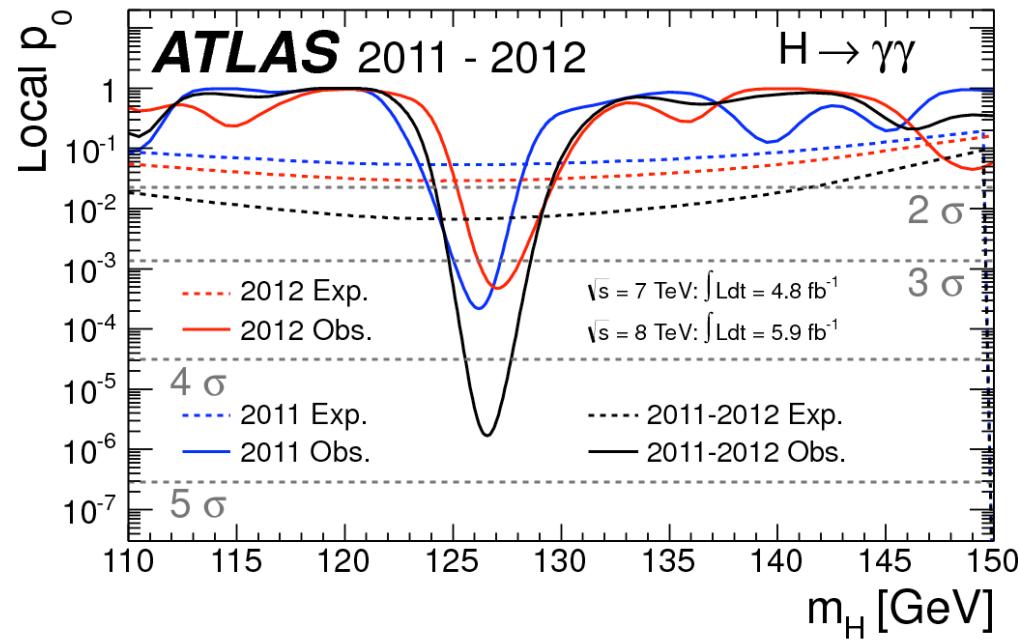
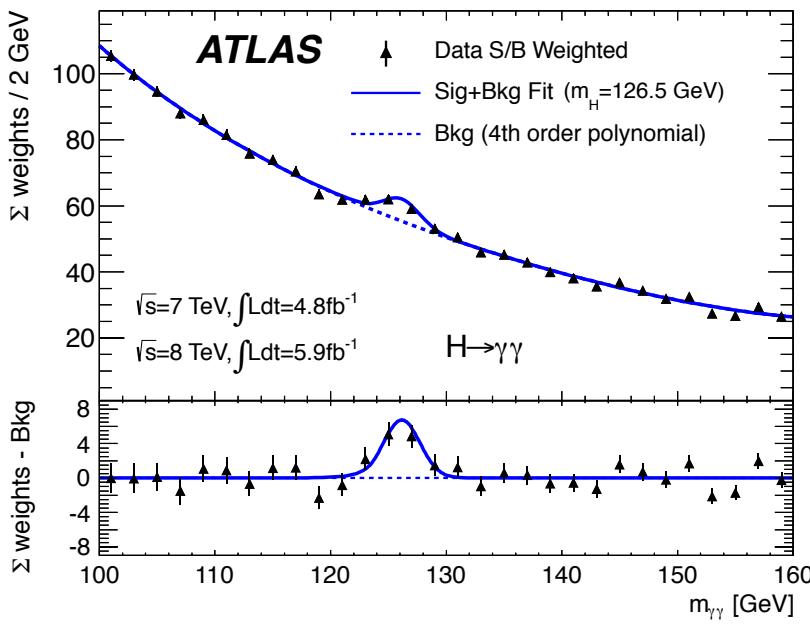
- Multiple decay channels at 125GeV
- Dominant modes:
 - $H \rightarrow b\bar{b}$ ($m_H < 135$ GeV)
 - $H \rightarrow WW$ ($m_H > 135$ GeV)
- Low mass modes:
 - **$b\bar{b}$** decay channel suffers from large QCD background
 - **WW** : easy to identify in di-lepton channel , but poor resolution due to missing neutrinos, soft lepton and missing ET from W^* and no full reconstruction
 - Rare decay and production processes become important



- Main search decay modes:
 - $H \rightarrow \gamma \gamma$: 0.23% BR (one-loop process)
 - $H \rightarrow ZZ \rightarrow 4l$ (2.6%) **High resolution**
- $H \rightarrow WW \rightarrow l\nu l\nu$ (21.5%)
- $WH \rightarrow l\nu b\bar{b} / \tau \tau$ (58%) **Low resolution**

ATLAS Higgs $\rightarrow \gamma\gamma$

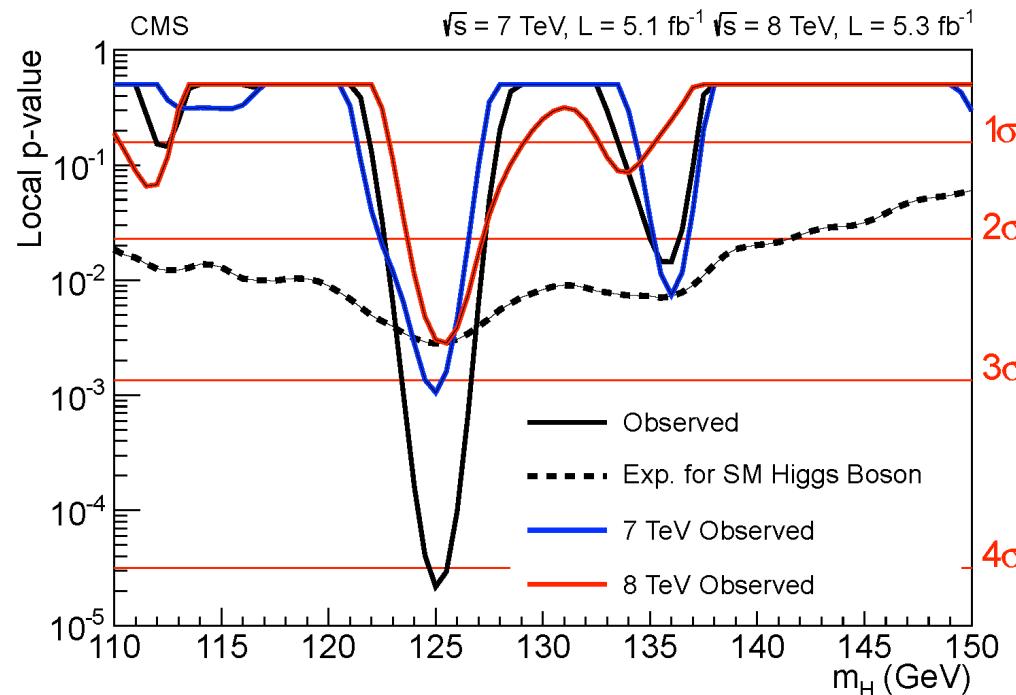
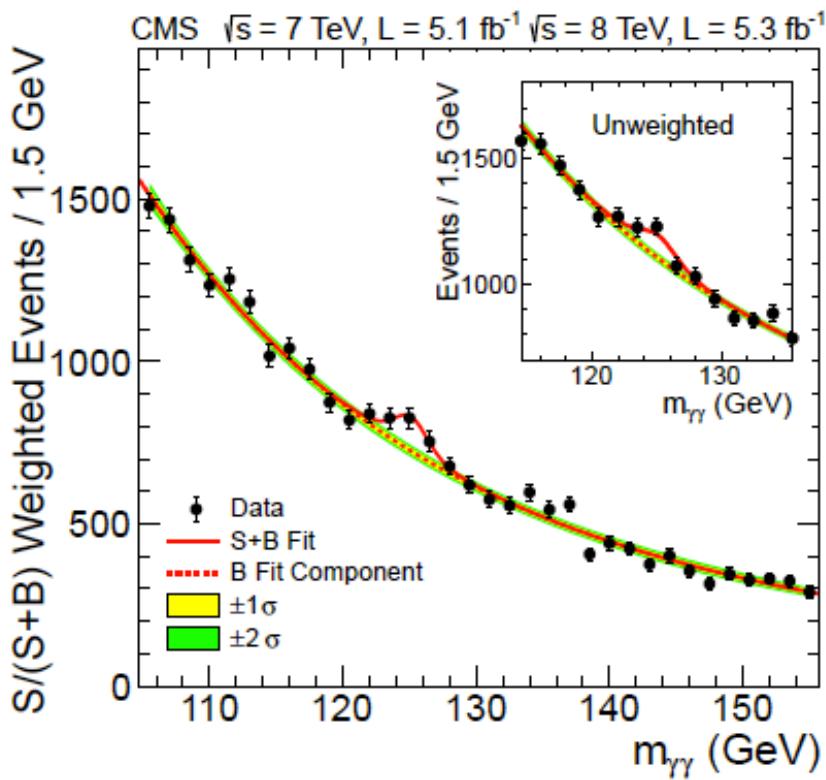
- Search for a narrow peak in the di-photon mass spectrum
- Analysis performed in 10 categories based on S/B and resolution
- 1 specific di-jet tag category for VBF



- Local significance 4.5 sigma

CMS Higgs $\rightarrow \gamma\gamma$

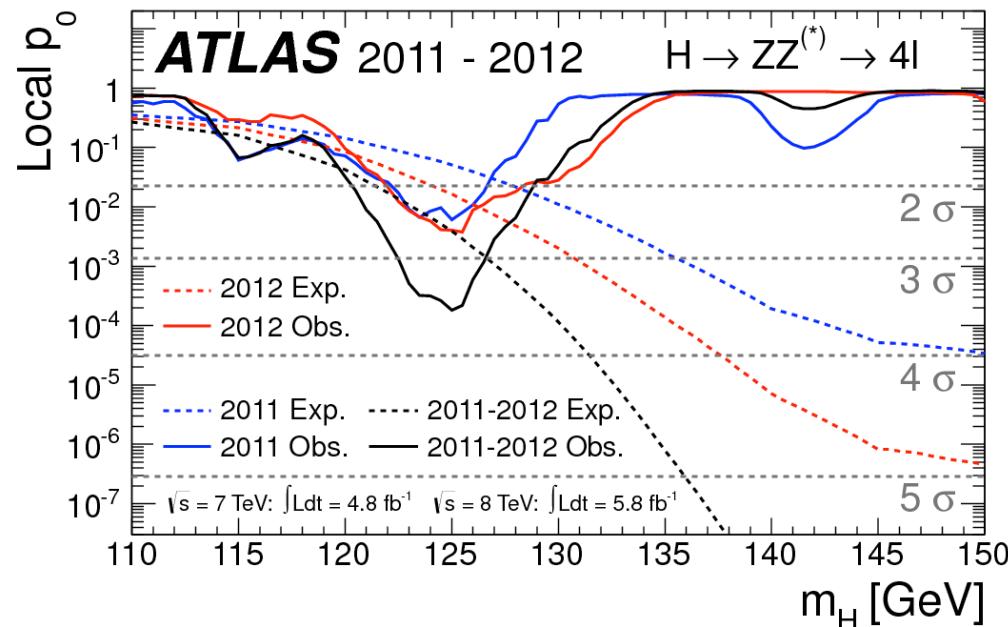
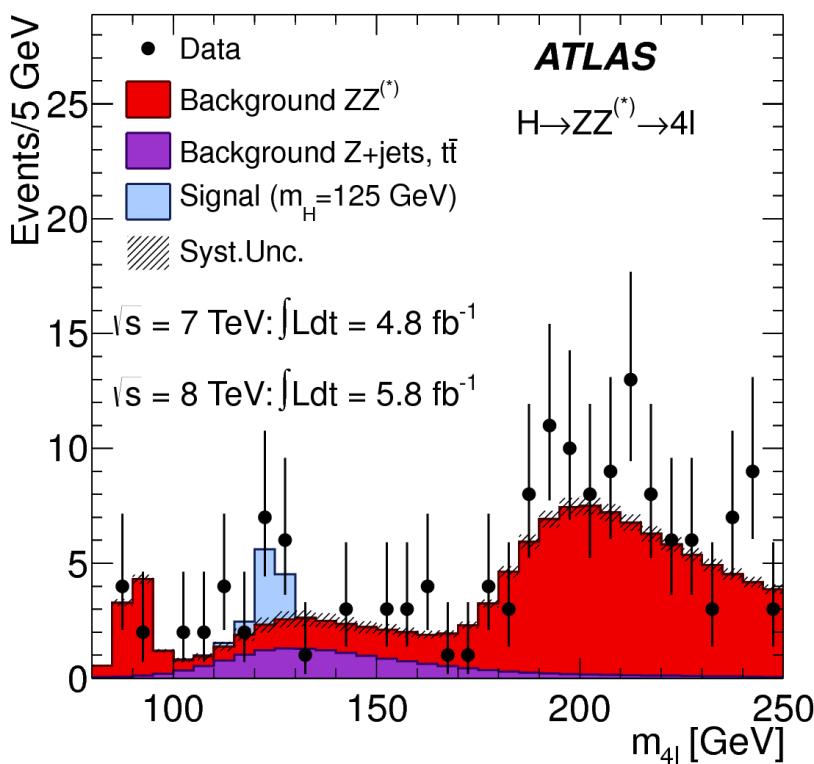
- 6 (7 TeV) and 7 (8 TeV) categories
 - 1-2 di-jet VBF



- Local significance 4.1 sigma

ATLAS H \rightarrow ZZ * \rightarrow 4l

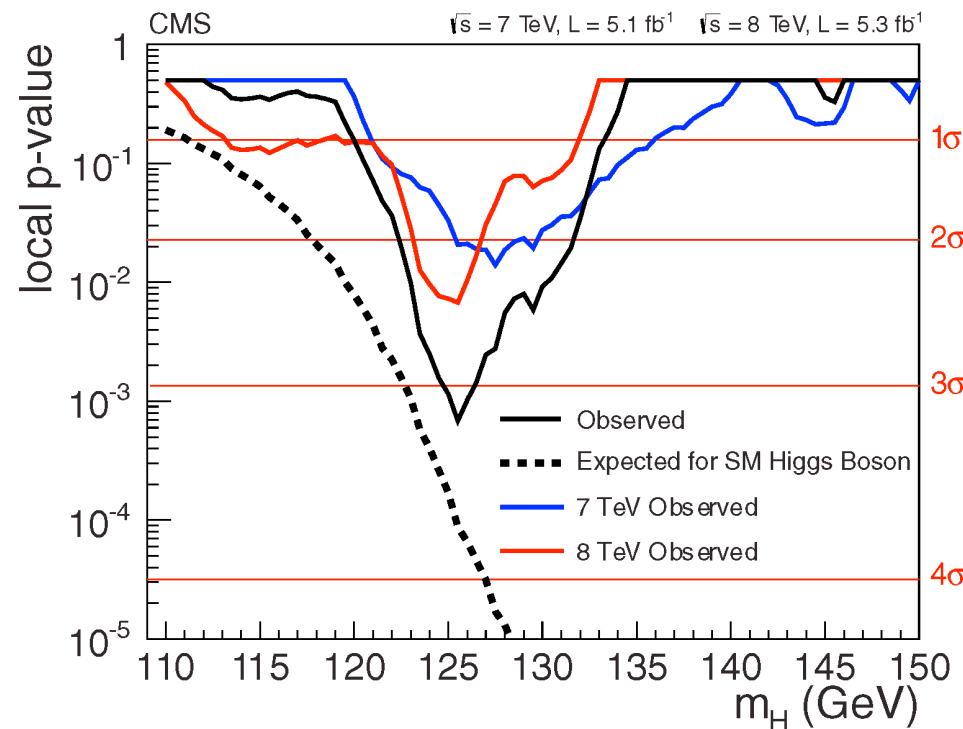
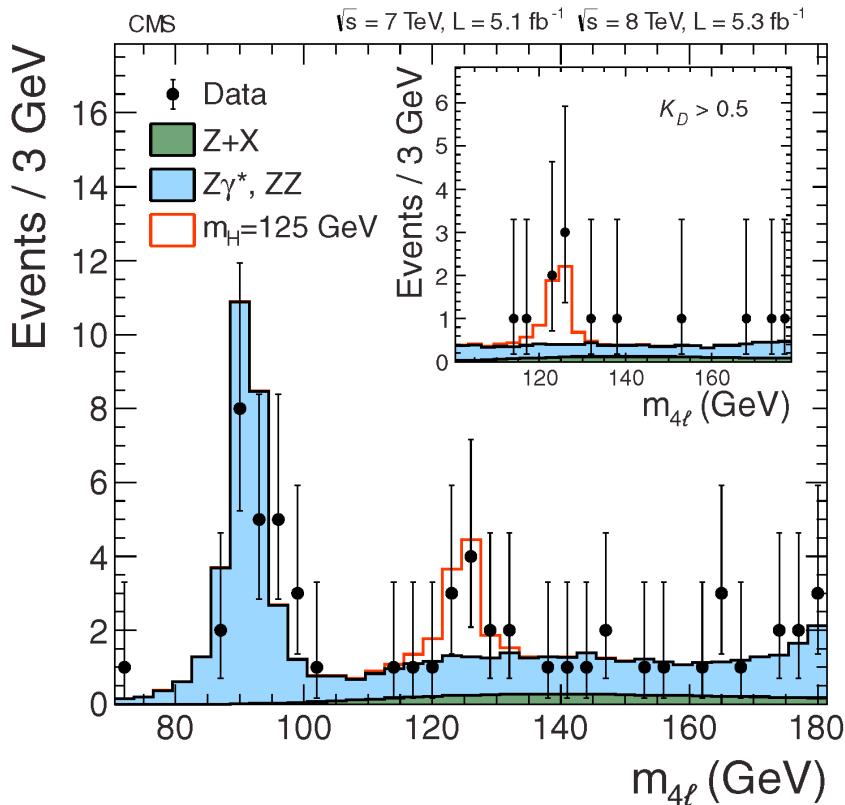
- Clean signature, high mass resolution, and small backgrounds
- Low cross section times branching ratio: 2.2 (2.6) pb @ 7 (8) TeV:
 - ~25 events



- Local significance 3.6 sigma

CMS $H \rightarrow ZZ^* \rightarrow 4l$

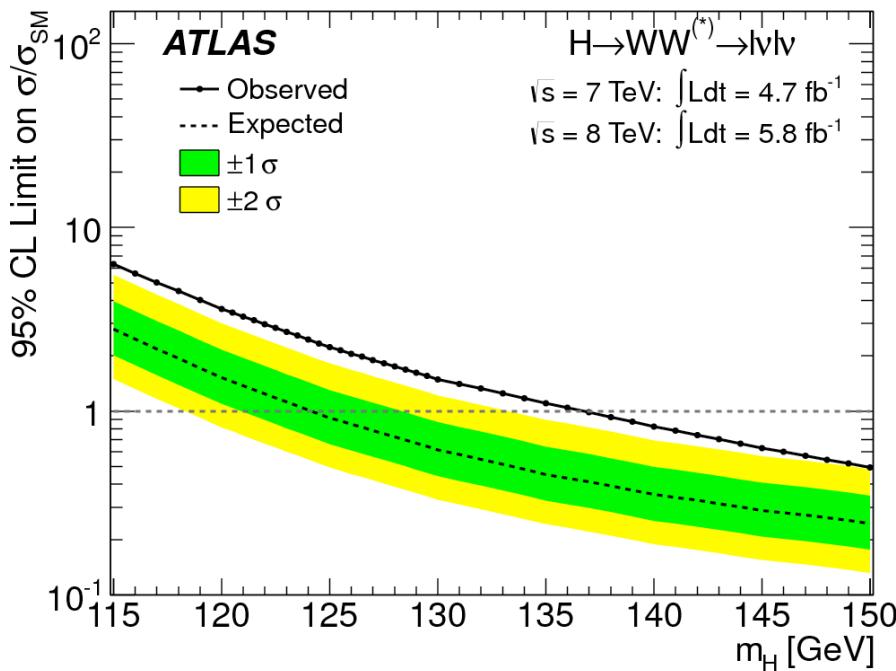
- Use angular information to separate signal from ZZ background (MELA: Matrix Element Likelihood analysis)



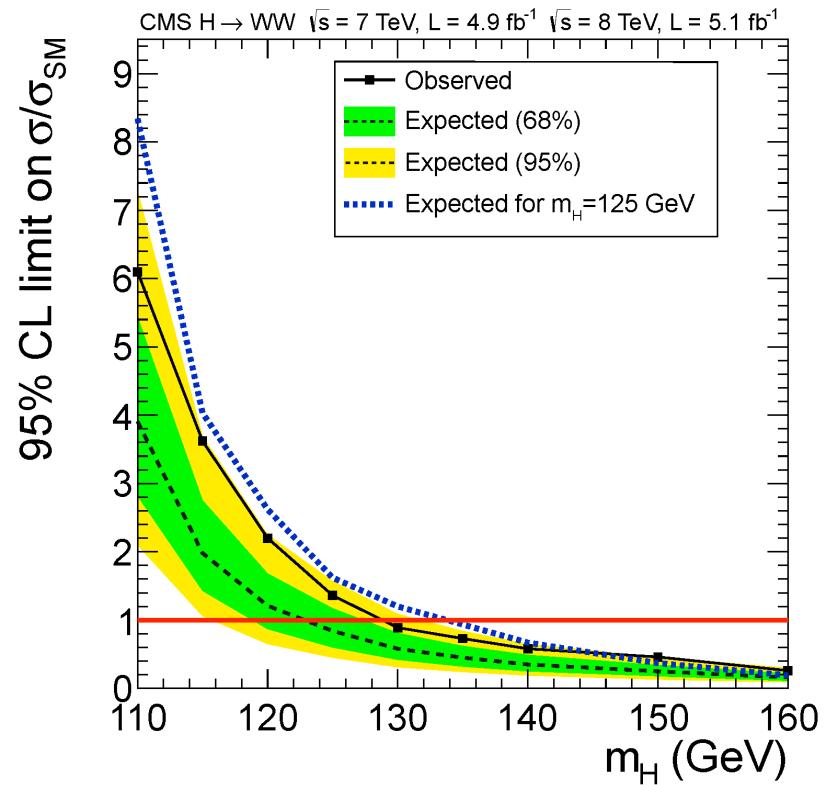
- Local significance 3.2 sigma

Higgs \rightarrow WW* \rightarrow lνlν

- Di-lepton analysis (0,1,2 jets)
- Main backgrounds: WW, W/Z+jets, tt
- $\sigma(HH \rightarrow WW^* \rightarrow l\nu l\nu) \sim 220\text{fb}$ (~ 2300 events)

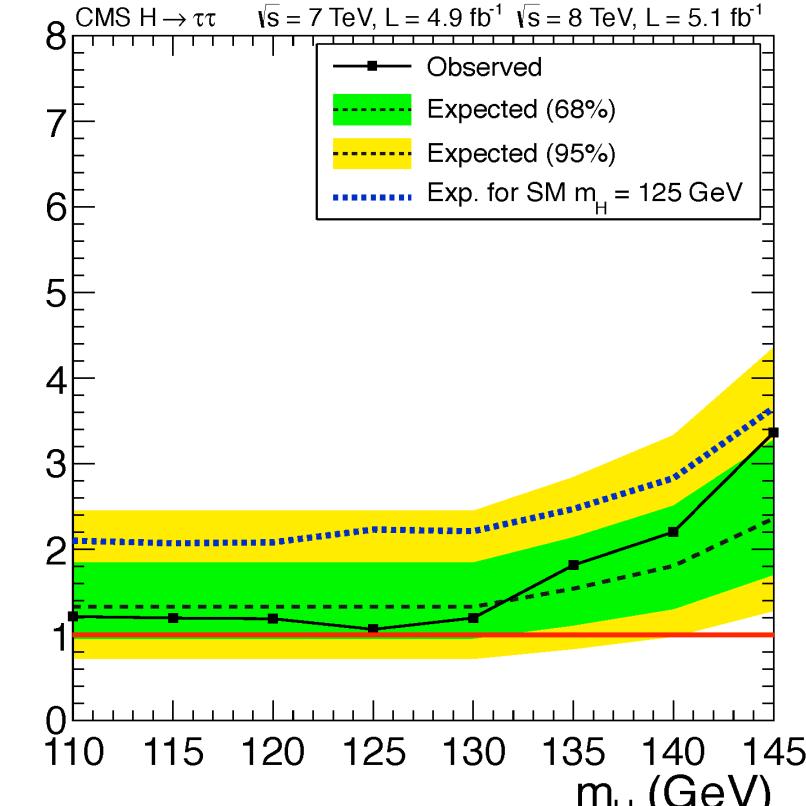


- Low mass resolution
 - Two missing neutrinos
- Broad excess of events in the low mass region



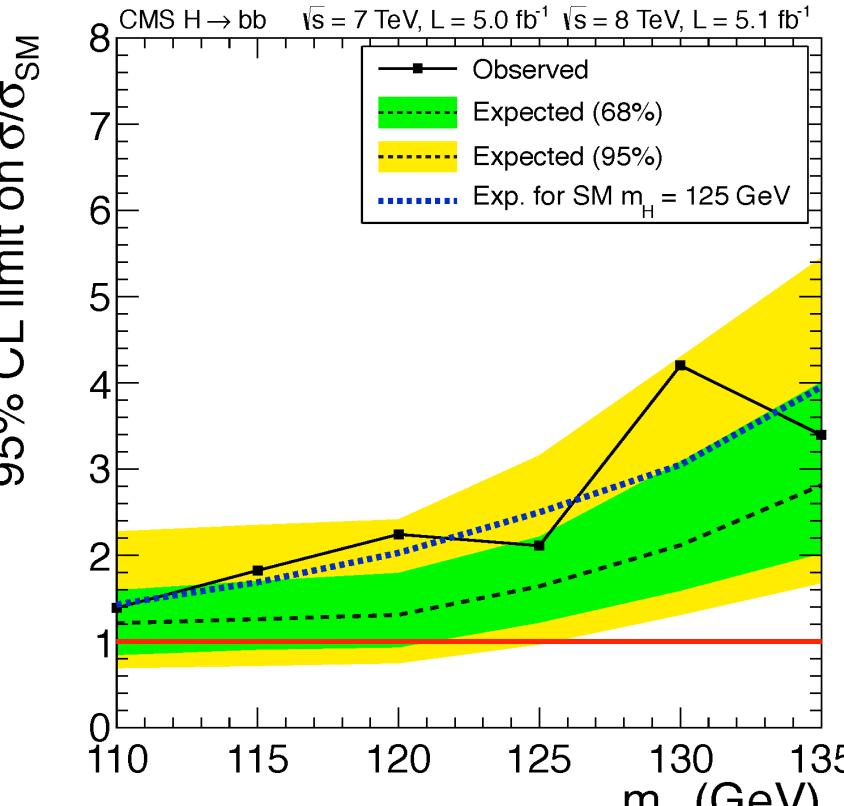
- ATLAS (CMS) Local significance at 125 GeV: 2.8 (1.6) sigma

Fermions

- **$H \rightarrow \tau \tau$ channel:**
 - 4 channels ($e\mu, \mu\mu, e\tau_h, \mu\tau_h$)
 - 5 event categories: 0-jet, 1-jet (low, high p_T) and 2-jet VBF

CMS $H \rightarrow \tau\tau$ $\sqrt{s} = 7 \text{ TeV}, L = 4.9 \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}, L = 5.1 \text{ fb}^{-1}$

95% CL limit on σ/σ_{SM}

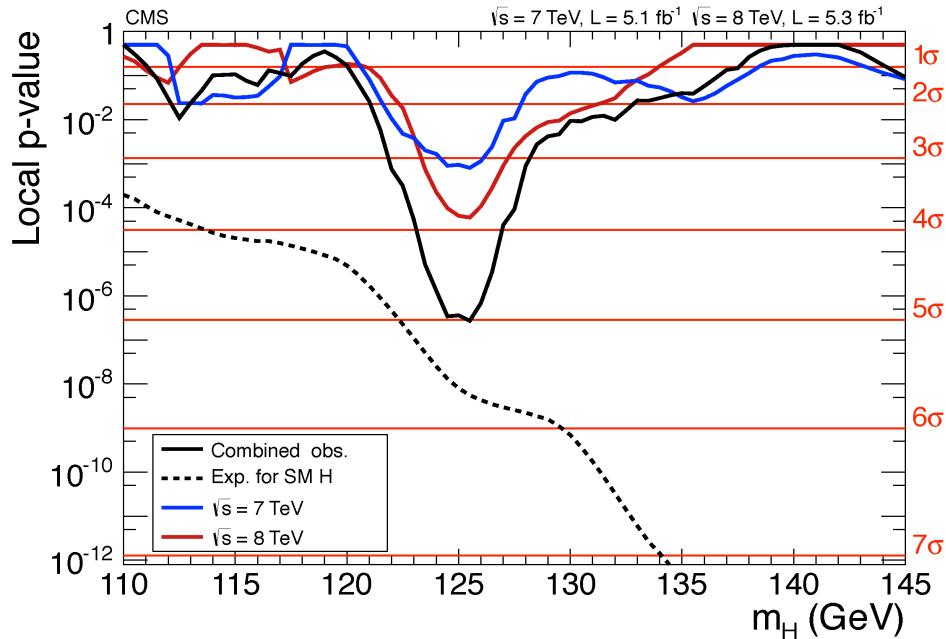
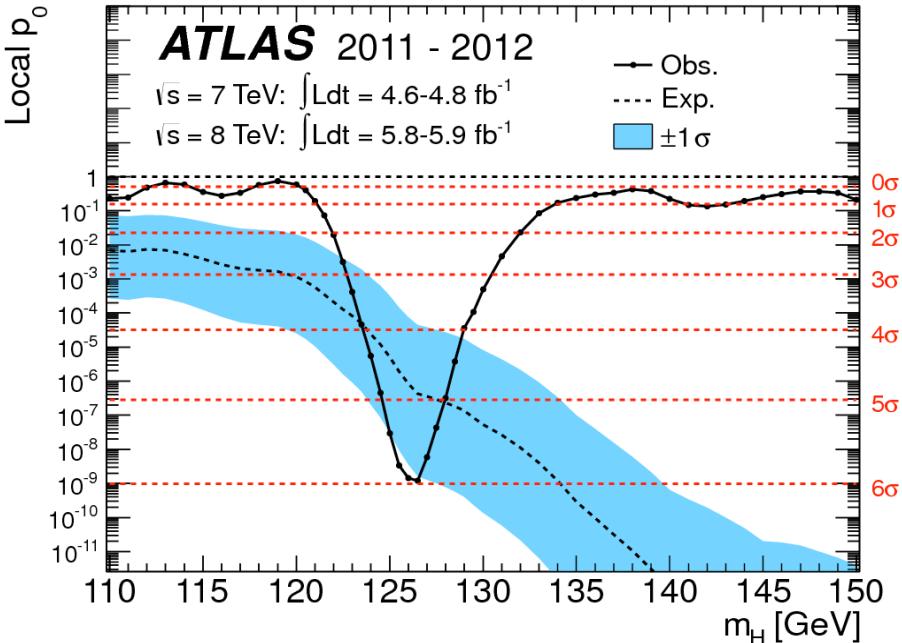
m_H (GeV)
- Expected (observed) significance for a SM Higgs @ 125 GeV is 1.4 (0) σ
- **$W/Z+H, H \rightarrow bb$ channel**
 - 5 categories: $Z(l\bar{l})H, Z(\nu\bar{\nu})H, W(l\nu)H$
 - Medium and high boost
 - BDT discriminant

CMS $H \rightarrow bb$ $\sqrt{s} = 7 \text{ TeV}, L = 5.0 \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}, L = 5.1 \text{ fb}^{-1}$

95% CL limit on σ/σ_{SM}

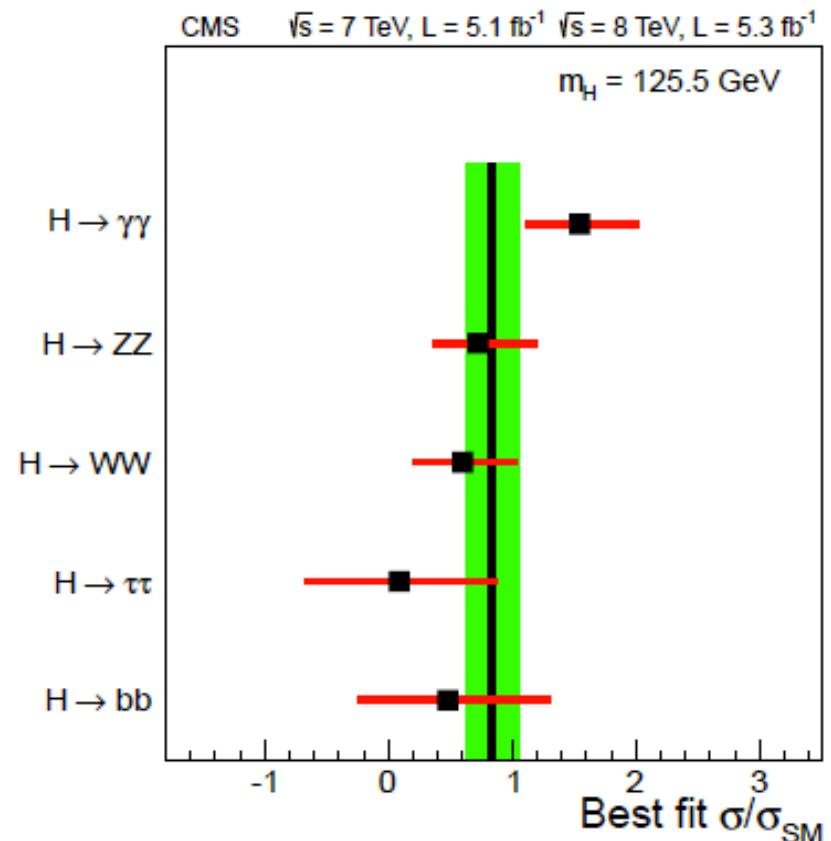
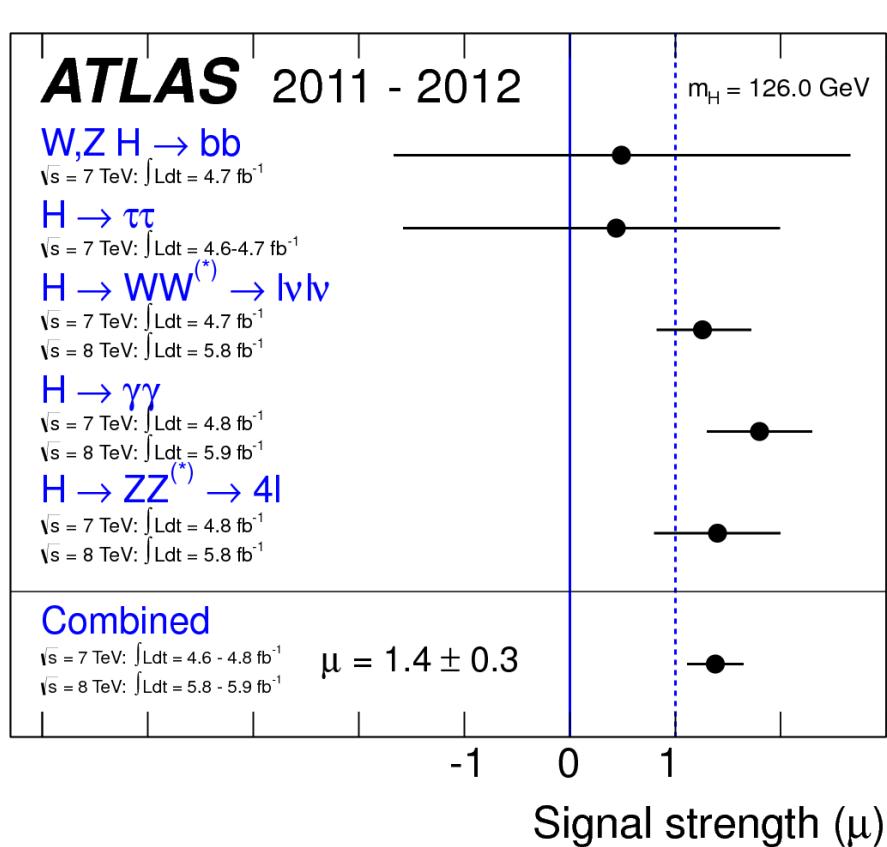
m_H (GeV)
- Expected (observed) significances for SM Higgs @ 125 GeV: 1.9 (0.7) σ^{10}

Combination (I)



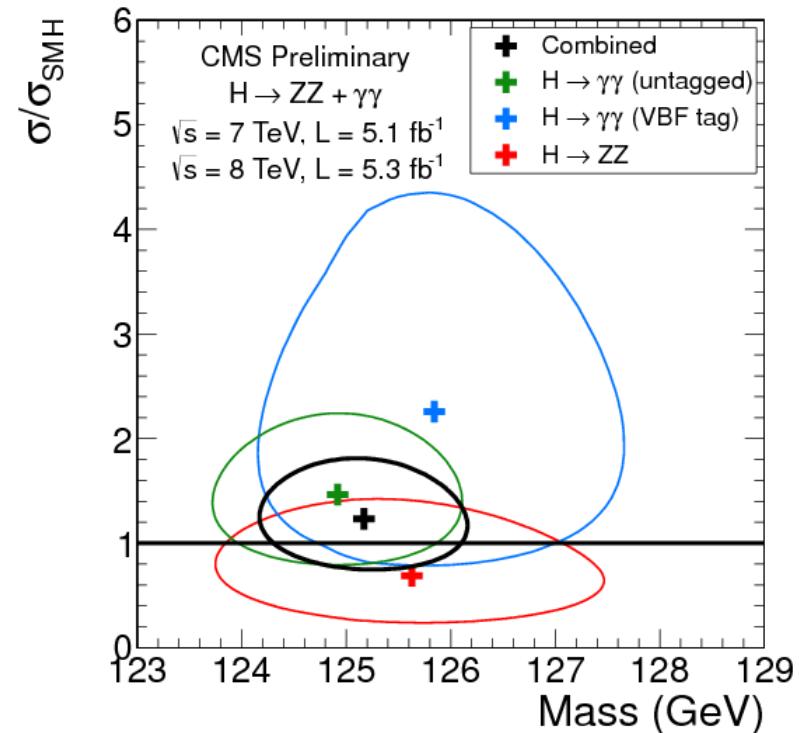
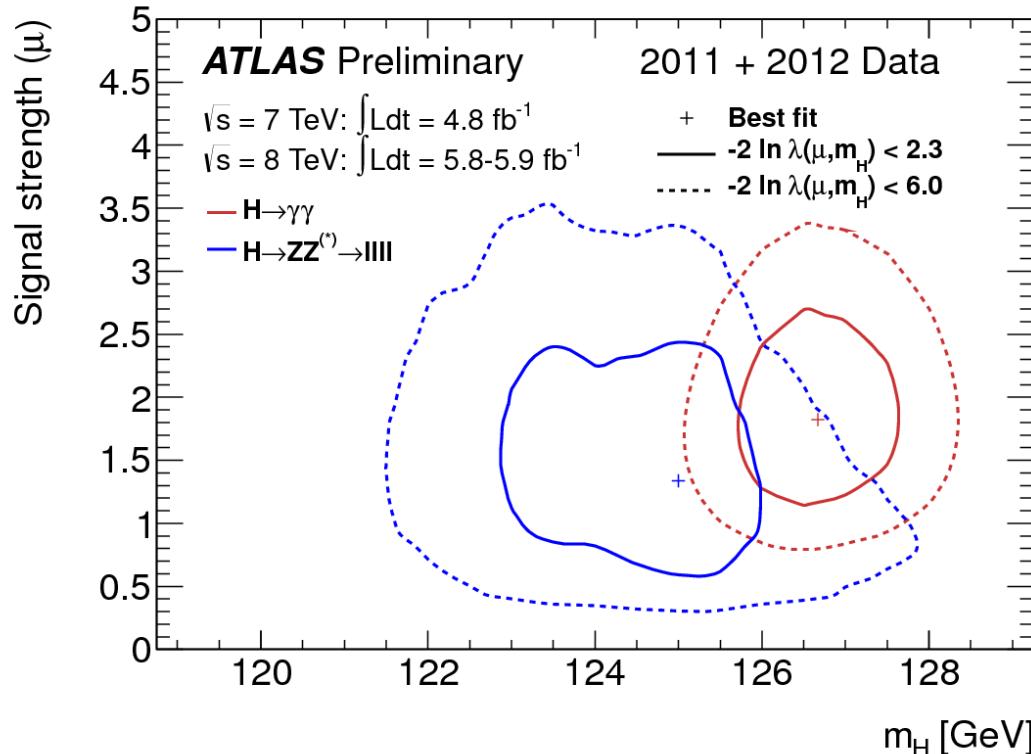
- Local significance of 6.0σ (expected for SM Higgs signal: 4.9σ)
- Local significance of 5.0σ (expected for SM Higgs signal: 5.8σ)

Combination (II)



- Signal strength consistent with a Standard Model Higgs
- All channels consistent within uncertainties

Combination (III)

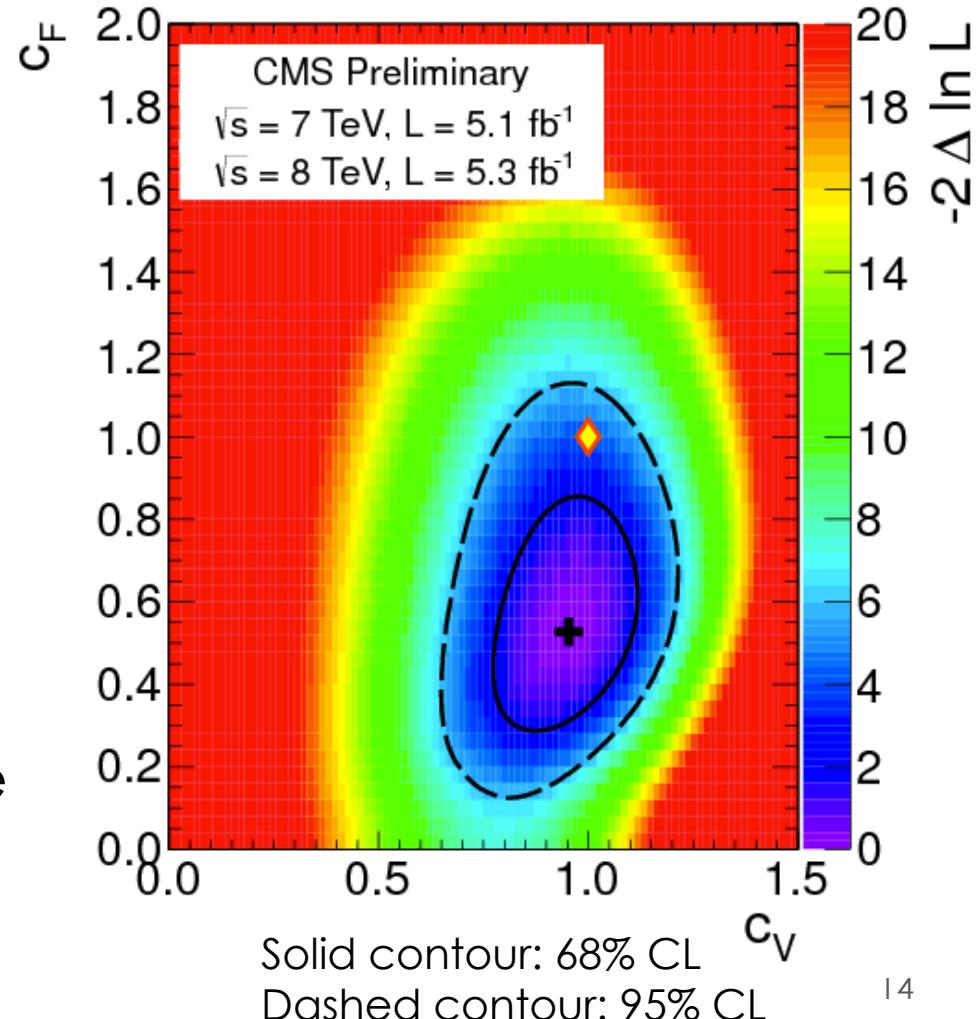


- **Production rates and mass consistent across channels**
- Best estimate of the mass:
 - $126.0 \pm 0.4 \pm (\text{stat}) \pm 0.4 \text{ (sys)} \text{ GeV}$ (ATLAS)
 - $125.3 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (sys)} \text{ GeV}$ (CMS)

Combination (IV)

- Test compatibility with SM Higgs predictions
 - Group couplings into two parameters C_V and C_F

Production	Decay	LO SM
VH	$H \rightarrow bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$
tH	$H \rightarrow bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$
VBF	$H \rightarrow \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$
ggH	$H \rightarrow \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$
ggH	$H \rightarrow ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$
ggH	$H \rightarrow WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$
VBF	$H \rightarrow WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$
ggH	$H \rightarrow \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$
VBF	$H \rightarrow \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$



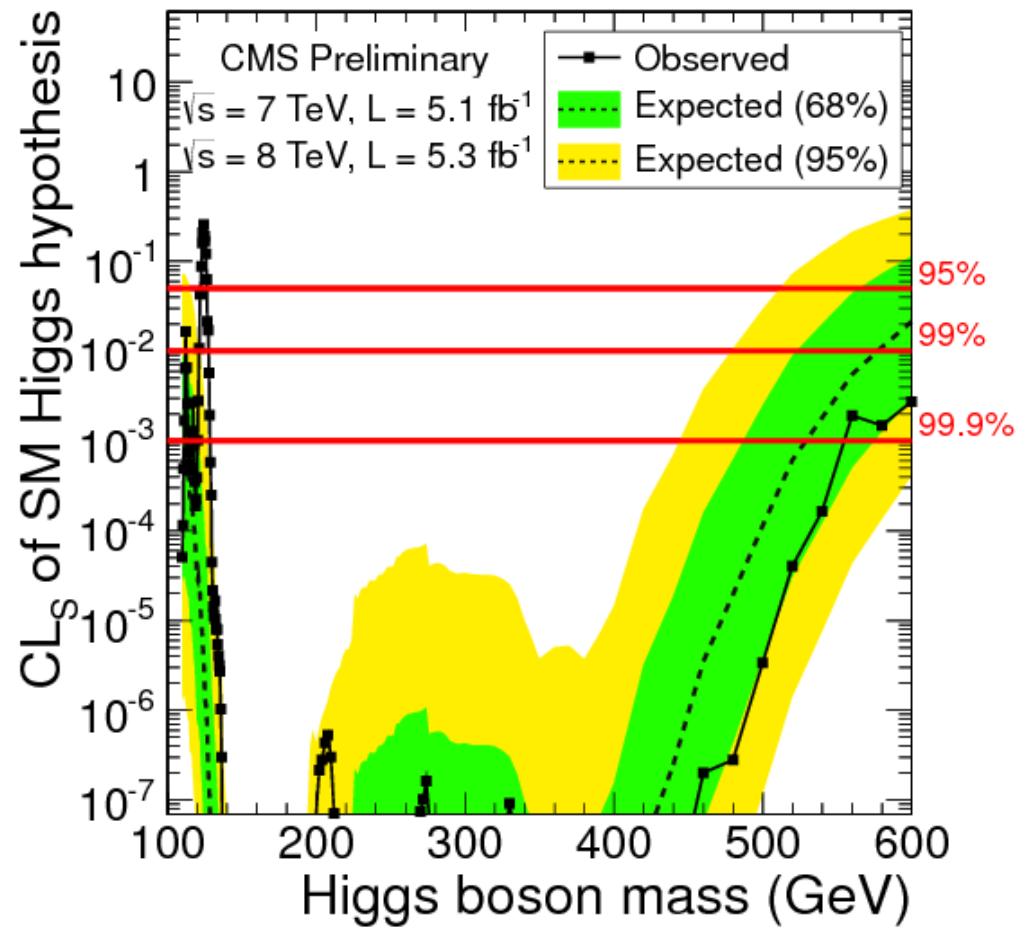
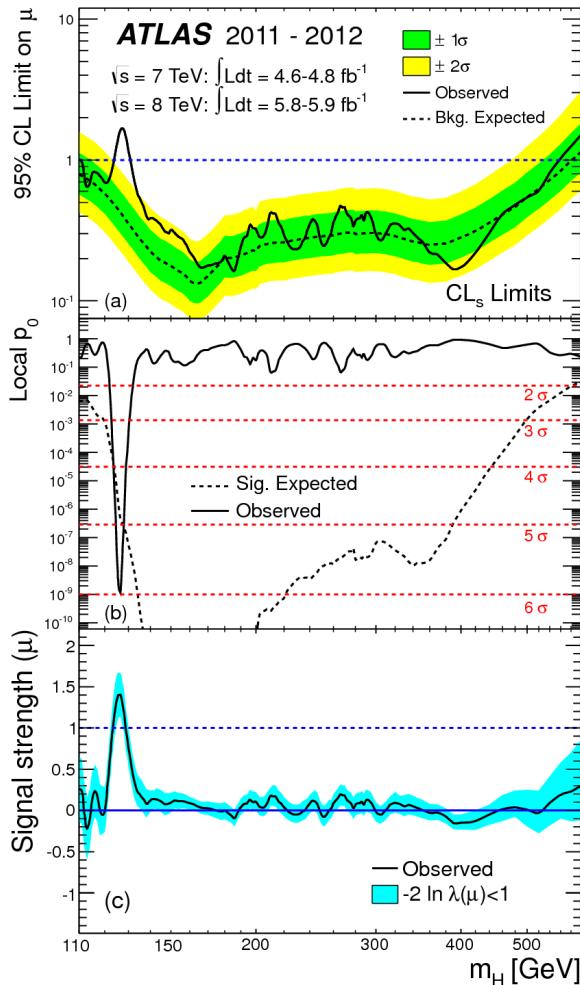
- Agreement with SM Higgs within 95% confidence range
 - Low C_F value driven by $\tau\tau$ deficit and VBF $\gamma\gamma$ excess

Next steps

- After the discovery of a new Higgs-like particle at the LHC, the major next step is to **establish the nature of this particle**:
 - **Improve mass measurement**
 - Current precision: 0.4 GeV (stat), 0.4-0.5 GeV (syst) dominated by $\gamma\gamma$ and 4l channels
 - **Measurements of spin and CP quantum numbers**
 - Observation in $\gamma\gamma$ strongly disfavors spin-1
 - **Precision measurements of couplings to fermions and vector bosons**
 - Sensitive to new physics contributions
 - **Continue to look for other particles and non-standard decays. Is there a charged Higgs?**
 - **Higgs self coupling**
 - Triple Higgs coupling as interference effect in the Higgs boson pair production

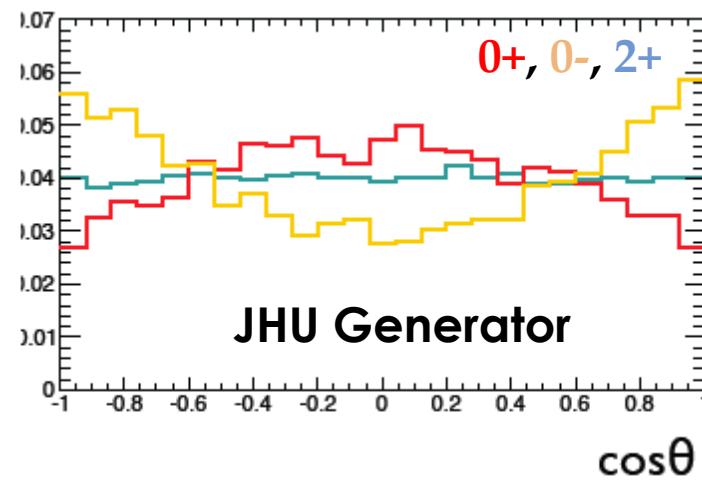
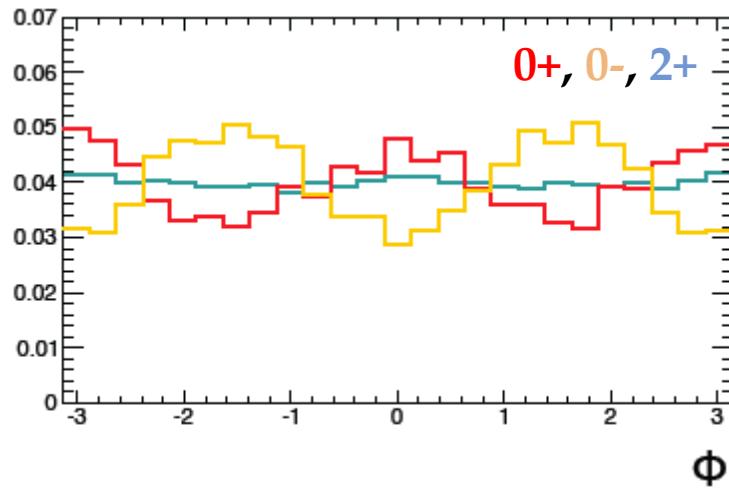
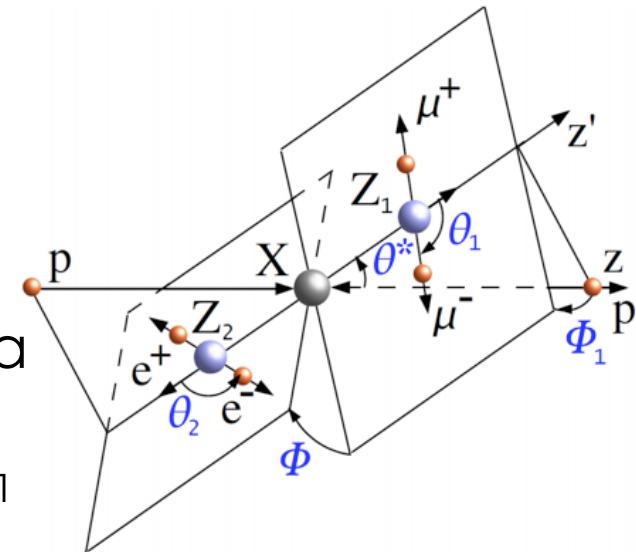
Other resonances?

No evidence for another SM-like Higgs particle up to 500 GeV



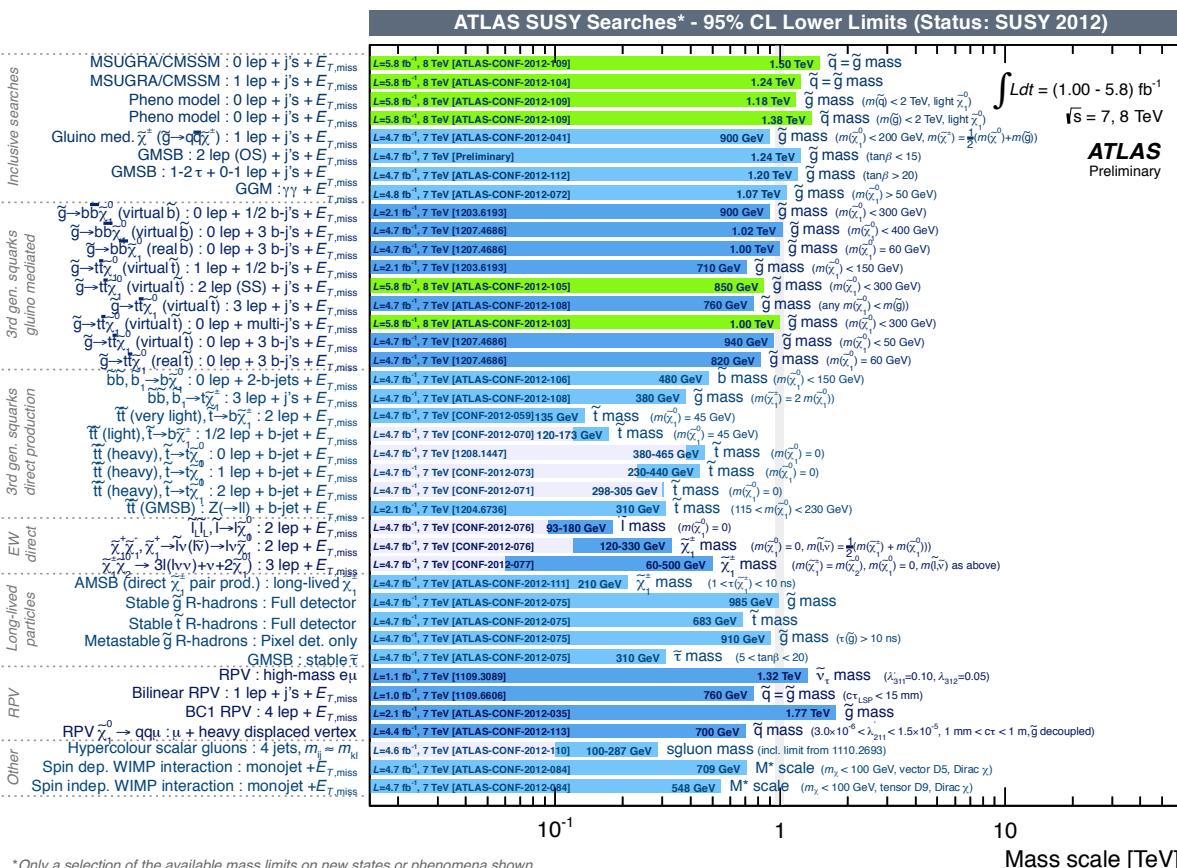
Spin/Parity

- Use angular analysis to separate $0^+/0^-/2^+$ spin/parity hypotheses
 - $H \rightarrow ZZ \rightarrow 4l$ (full reconstruction, good resolution, low backgrounds)
 - $H \rightarrow WW \rightarrow l\nu l\nu$
- $0^+/0^-$ separation at 1.6σ with current data
 - Expect 3σ separation with 30 fb^{-1} of data
- Expect 5σ separation of $0^+/2^+$ with 30 fb^{-1} of data (generator level study)



SUSY searches

- What stabilizes the Higgs mass (hierarchy problem)
- Dark matter
- Unification of gauge couplings

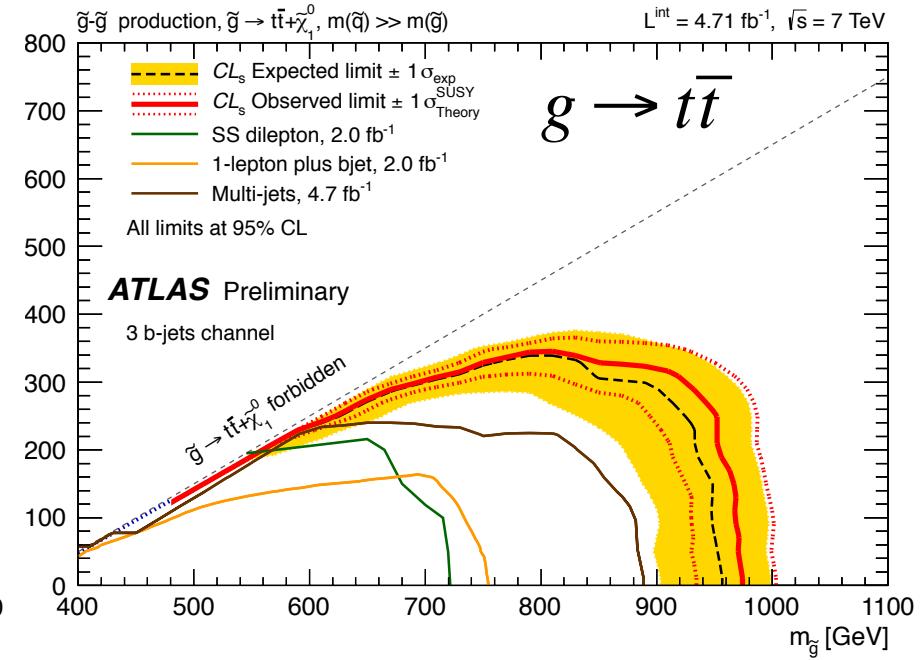
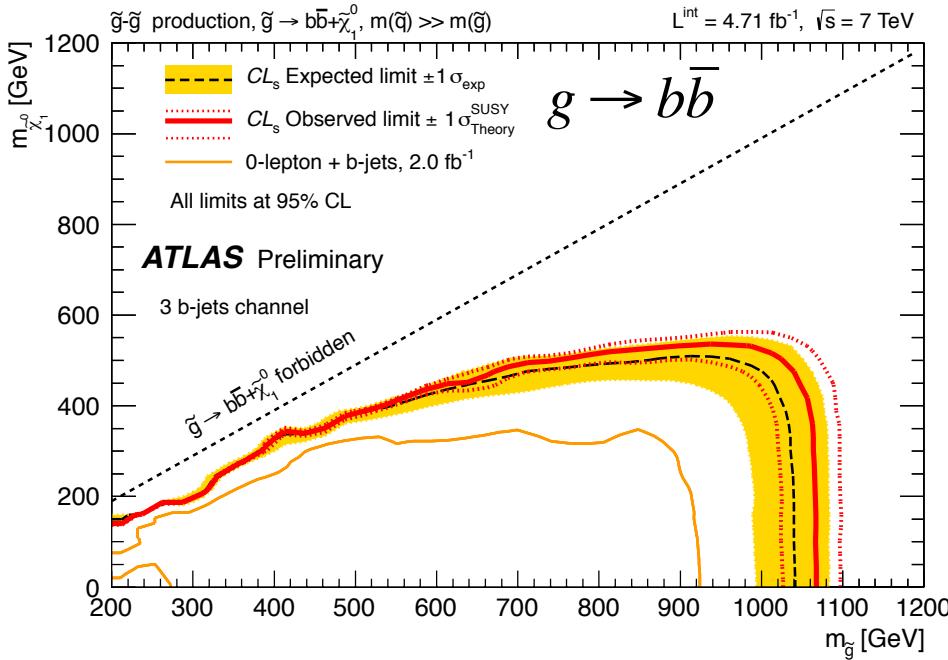
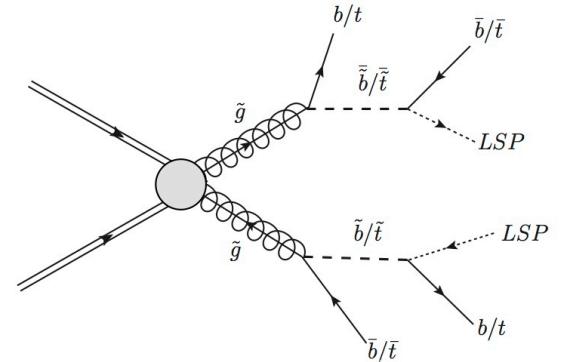


- ATLAS and CMS have excluded squarks and gluinos up to 1 TeV (depending on models)
- Natural SUSY requires a light 3rd generation

- » Gluino-mediated stops (high sensitivity if gluino can be produced)
- » Direct stop production (low cross-section, low S/B)

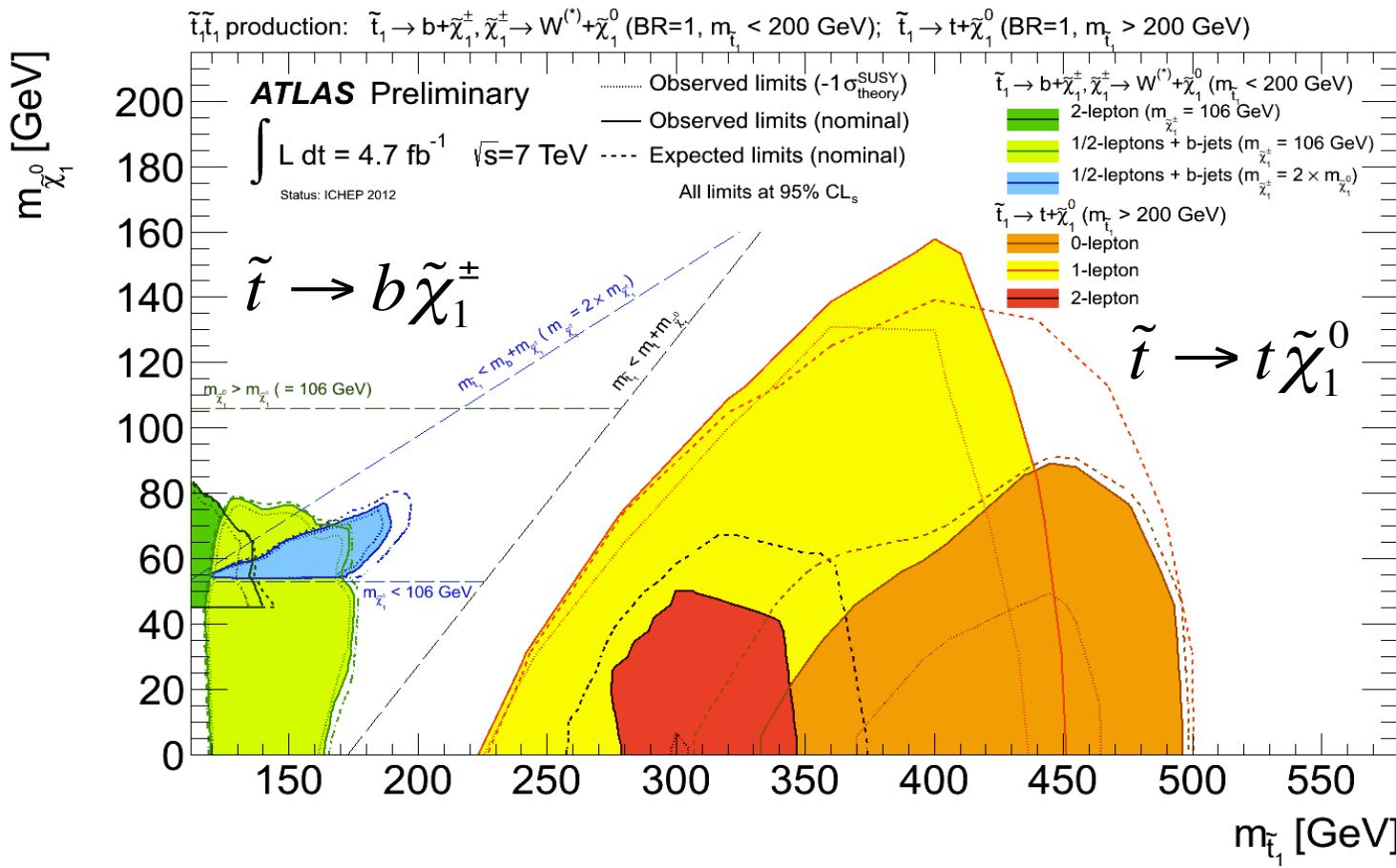
Gluino mediated stop/sbottom searches

- 3-btag final state has the highest sensitivity
- **Limits on gluino mass ~ 1 TeV**



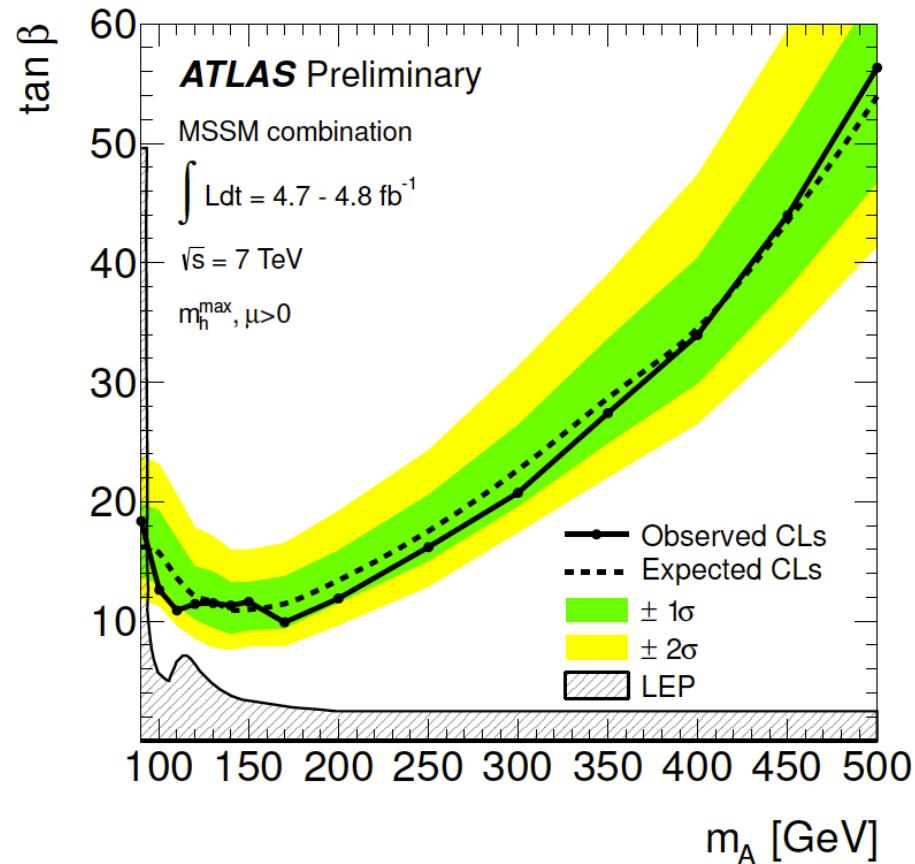
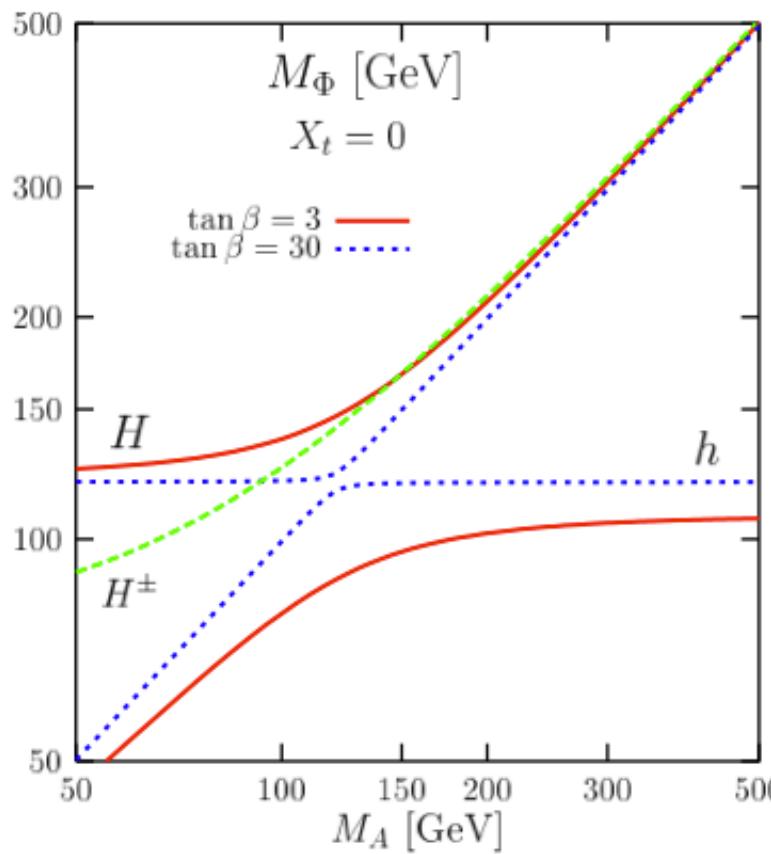
Direct stop searches

- Heavy stop ($m_{\text{stop}} > m_{\text{top}}$): top pair decays plus missing ET
- Light stop ($m_{\text{stop}} < m_{\text{top}}$): top-like decays via chargino (low p_T leptons)
- **Exclusion up to ~ 500 GeV**
 - Expect to reach $m(s_{\text{top}}) \sim 650$ GeV with 20 fb^{-1} at 8 TeV



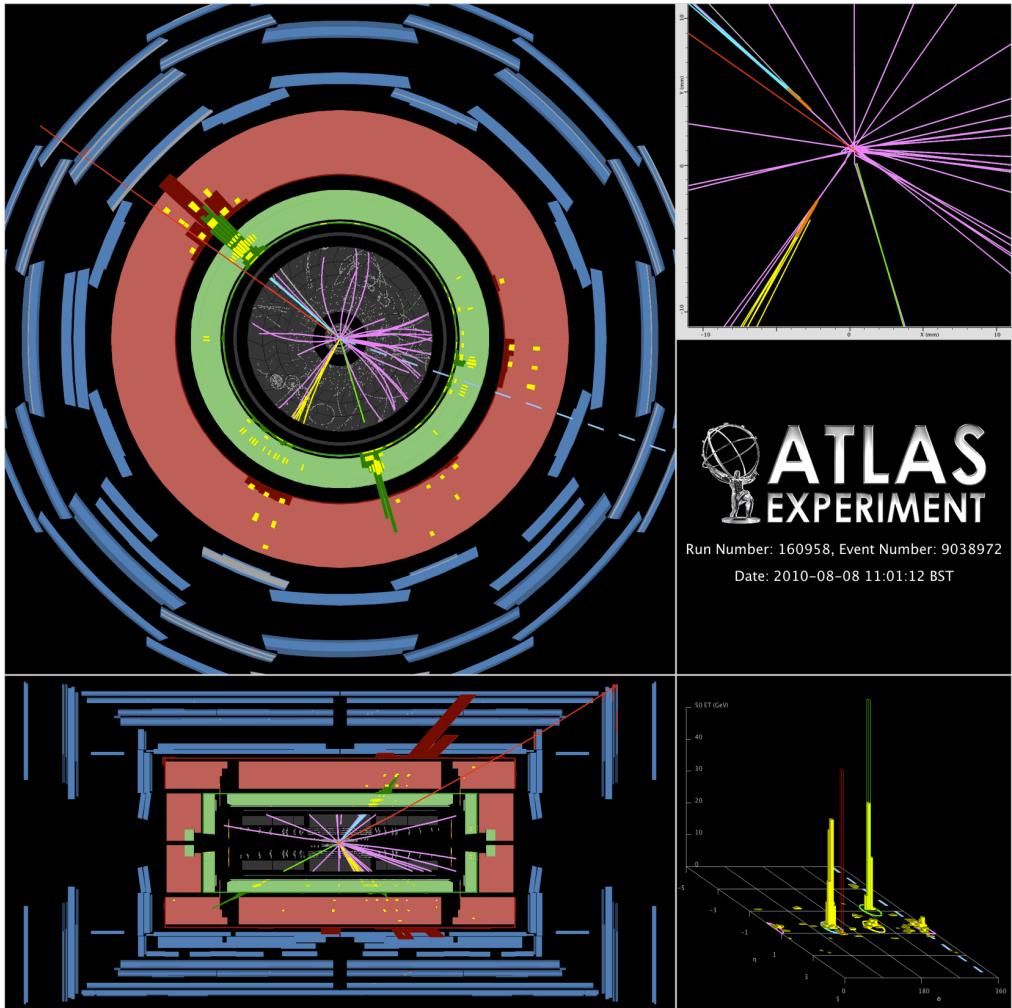
SUSY Higgs search

- MSSM requires two Higgs doubles $\rightarrow (h, H, A, H^\pm)$
- For high $\tan(\beta) > 3$, m_A and either m_h or m_H are degenerate
 - SM-like h could have $m < 100$ GeV while the observed new boson is H



Top

- Heaviest known elementary particle
 - Key role in the mechanism of EWSB
 - Window to new physics related to EWSB
 - Top anti-top production is a background to many searches for new physics
 - Top anti-top resonances predicted by non-SUSY new physics models
- Very broad program of top precision measurements at LHC and Tevatron



Top cross section at 7 TeV

$$\sigma = 177 \pm 3 \text{ (stat)} \pm 7 \text{ (syst)} \pm 7 \text{ (lum)} \text{ pb}$$

ATLAS Preliminary

Data 2011

Channel & Lumi.

Single lepton 0.70 fb^{-1}

Dilepton 0.70 fb^{-1}

All hadronic 1.02 fb^{-1}

Combination

New measurements

$\tau_{\text{had}} + \text{jets}$ 1.67 fb^{-1}

$\tau_{\text{had}} + \text{lepton}$ 2.05 fb^{-1}

All hadronic 4.7 fb^{-1}

15 May 2012
 Theory (approx. NNLO)
 for $m_t = 172.5 \text{ GeV}$
 stat. uncertainty
 total uncertainty
 $\sigma_{t\bar{t}} \pm (\text{stat}) \pm (\text{syst}) \pm (\text{lumi})$

$179 \pm 4 \pm 9 \pm 7 \text{ pb}$

$173 \pm 6 \pm 14 \pm 8 \text{ pb}$

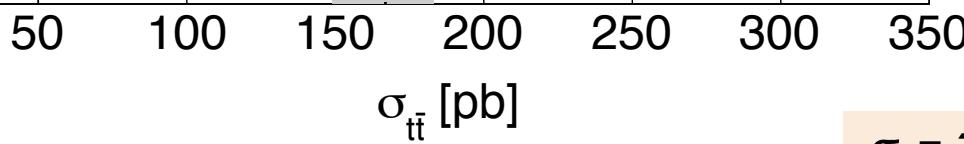
$167 \pm 18 \pm 78 \pm 6 \text{ pb}$

$177 \pm 3 \pm 8 \pm 7 \text{ pb}$

$200 \pm 19 \pm 42 \pm 7 \text{ pb}$

$186 \pm 13 \pm 20 \pm 7 \text{ pb}$

$168 \pm 12 \pm 60 \pm 6 \text{ pb}$



**Measurements consistent
With NNLO predictions**

CMS Preliminary, $\sqrt{s}=7 \text{ TeV}$

CMS e/ μ +jets
 TOP-11-003 ($L=0.8\text{--}1.1/\text{fb}$)

$164 \pm 3 \pm 12 \pm 7 \text{ pb}$
 $(\text{val.} \pm \text{stat.} \pm \text{syst.} \pm \text{lumi.})$

CMS $\tau+\text{jets}$
 TOP-11-004 ($L=3.9/\text{fb}$)

$156 \pm 12 \pm 33 \pm 3 \text{ pb}$
 $(\text{val.} \pm \text{stat.} \pm \text{syst.} \pm \text{lumi.})$

CMS dilepton (ee, $\mu\mu$, e μ)
 TOP-11-005 final ($L=2.3/\text{fb}$)

$162 \pm 2 \pm 5 \pm 4 \text{ pb}$
 $(\text{val.} \pm \text{stat.} \pm \text{syst.} \pm \text{lumi.})$

CMS dilepton ($e\tau, \mu\tau$)
 arXiv:1203.6810 ($L=2.2/\text{fb}$)

$143 \pm 14 \pm 22 \pm 3 \text{ pb}$
 $(\text{val.} \pm \text{stat.} \pm \text{syst.} \pm \text{lumi.})$

CMS all-hadronic
 TOP-11-007 ($L=1.1/\text{fb}$)

$136 \pm 20 \pm 40 \pm 8 \text{ pb}$
 $(\text{val.} \pm \text{stat.} \pm \text{syst.} \pm \text{lumi.})$

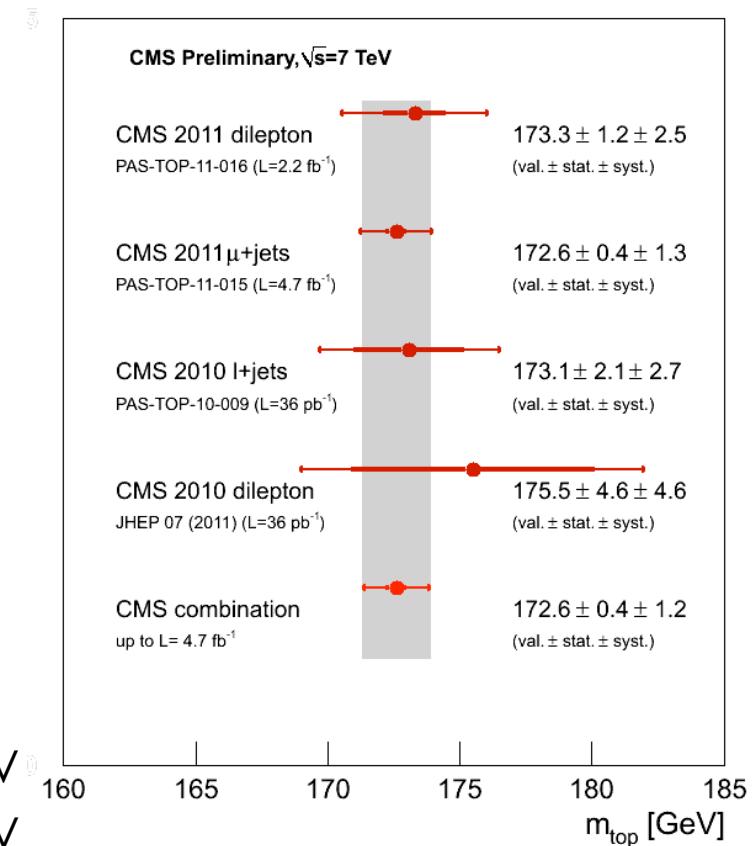
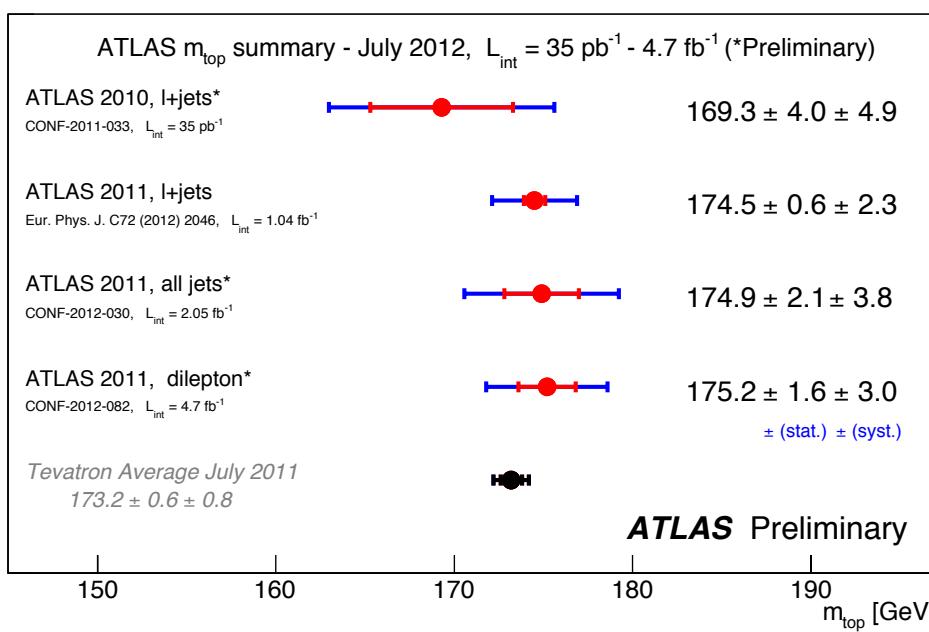
Approx. NNLO QCD, Aliev et al., Comput.Phys.Commun. 182 (2011) 1034
 Approx. NNLO QCD, Kidonakis, Phys.Rev.D 82 (2010) 114030
 Approx. NNLO QCD, Ahrens et al., JHEP 1009 (2010) 097
 NLO QCD

$$\sigma = 165 \pm 2.2 \text{ (stat)} \pm 10.6 \text{ (syst)} \pm 7.8 \text{ (lum)} \text{ pb}$$

Dominant uncertainties: jet energy scale, W+jet background shape, ISR/FSR modeling, and b-tagging

Top mass

- Fundamental parameter of the Standard Model
- Key role in precision EW analyses (loop corrections $\sim (m_t)^2$)



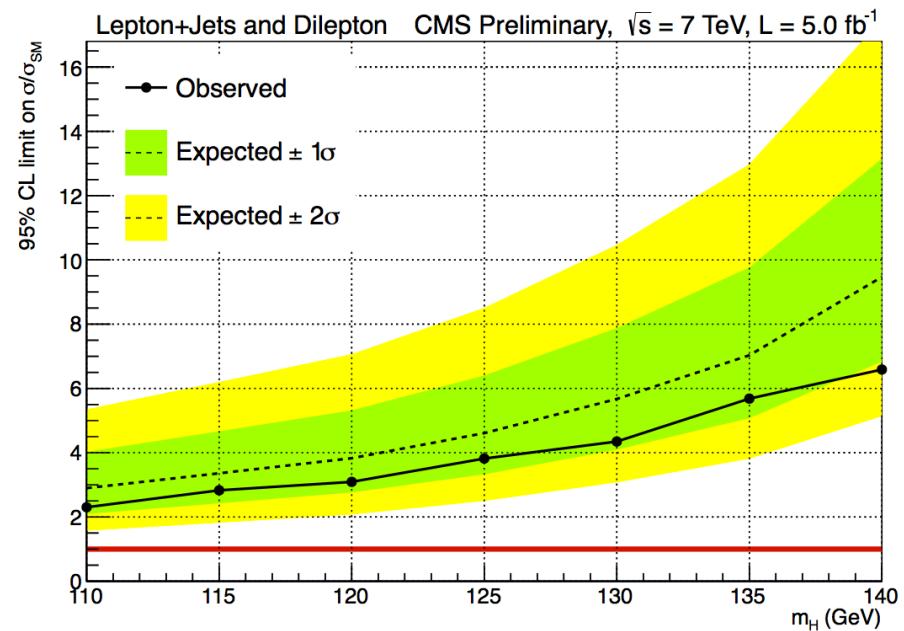
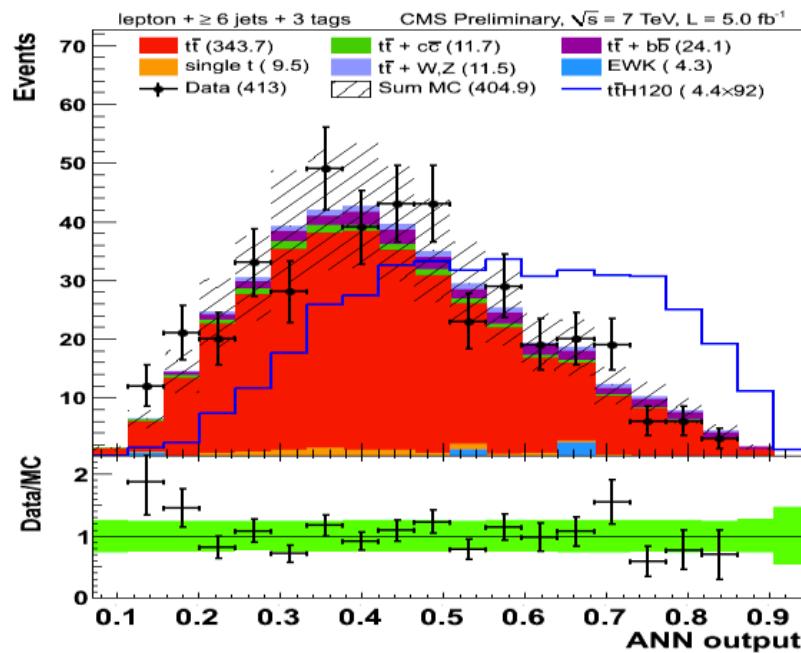
Top mass combination:

- Tevatron: $m_t = 173.2 \pm 0.6 \text{ (stat)} \pm 0.8 \text{ (syst)} \text{ GeV}$
- LHC: $m_t = 173.3 \pm 0.5 \text{ (stat)} \pm 1.3 \text{ (syst)} \text{ GeV}$

Dominant uncertainties due to jet energy scale, b-jet energy scale, and modeling of initial and final state radiation

$t\bar{t}H$, $H \rightarrow b\bar{b}$

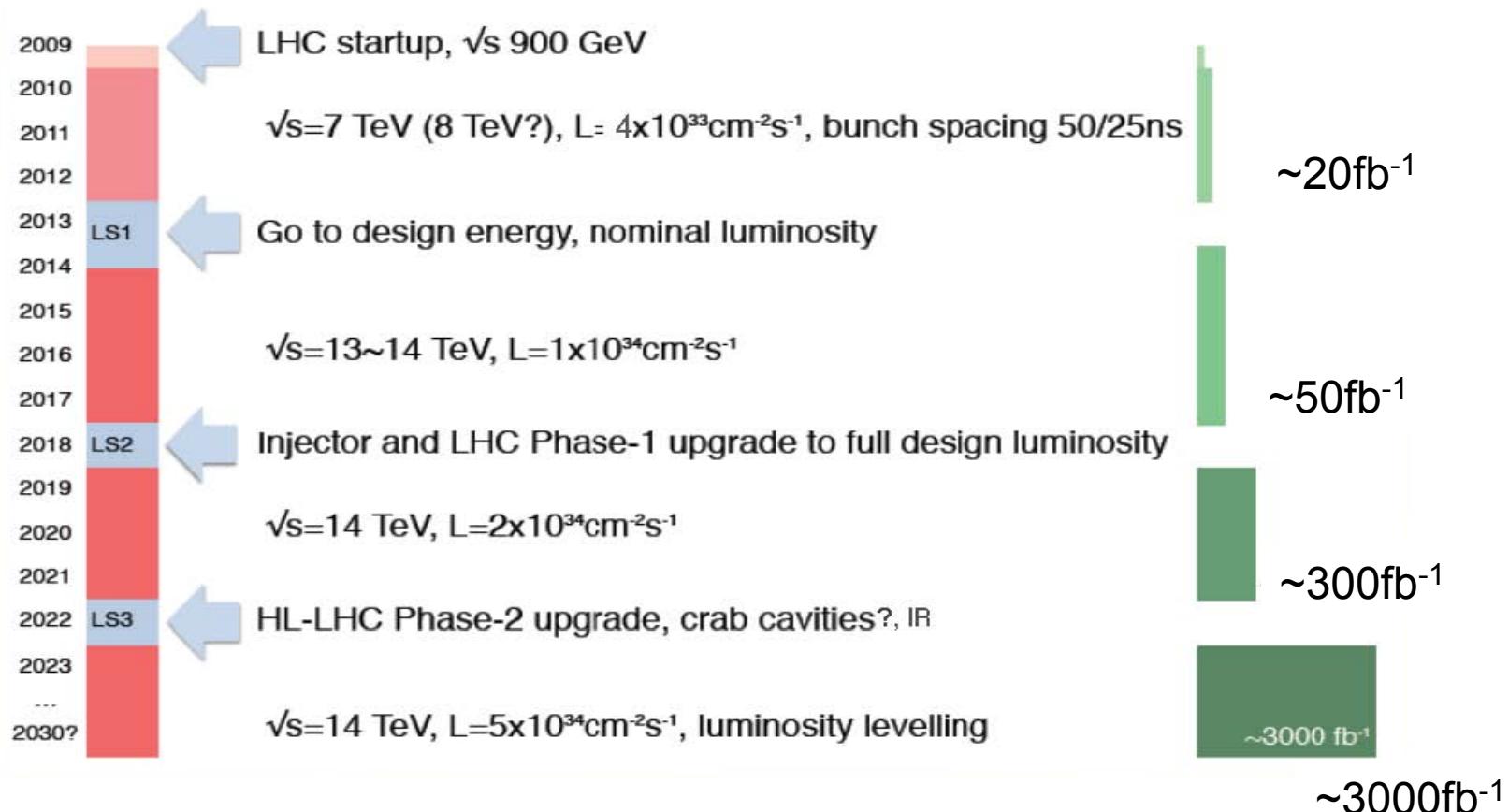
- **Important channel to probe Higgs couplings**
 - Same coupling than ggH, but at tree level
 - Multivariate analysis in different categories
(top decay mode, number of jets, number of b-tags)



- 2011 analysis not yet sensitive to SM Higgs signal
- Expect to reach sensitivity with $\sim 20\text{fb}^{-1}$ @ 8 TeV
- x5 cross section increase from 8 to 14 TeV

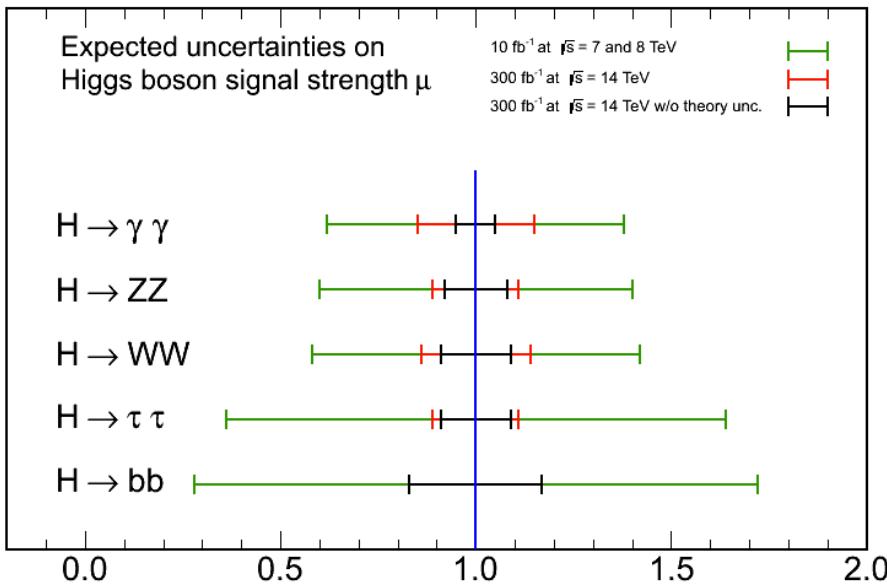
Prospects

- LHC plans (LS1, LS2< LS3)

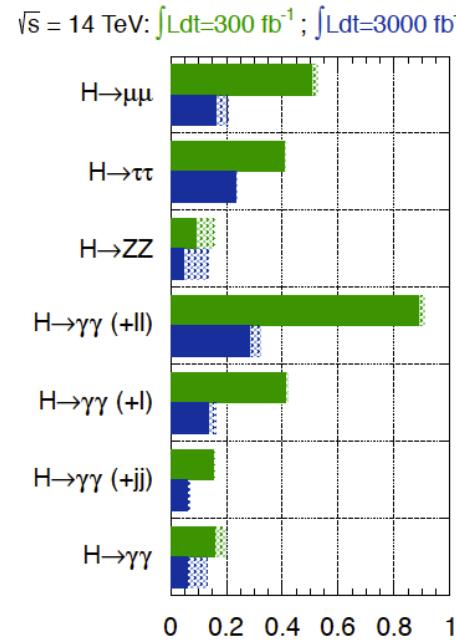


Measurements of Higgs couplings

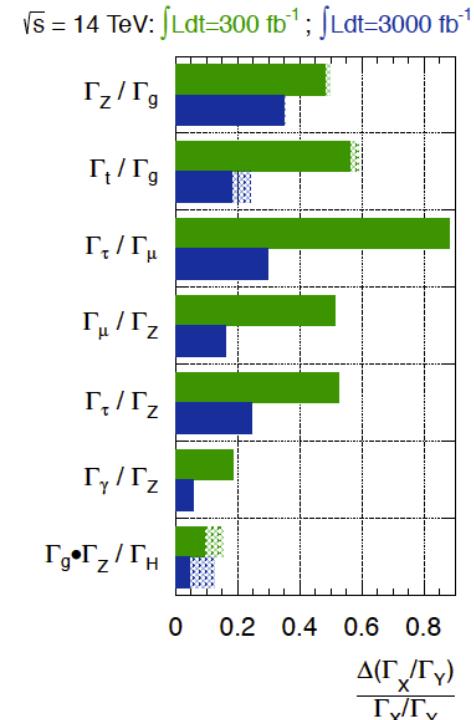
CMS Projection



ATLAS Preliminary (Simulation)



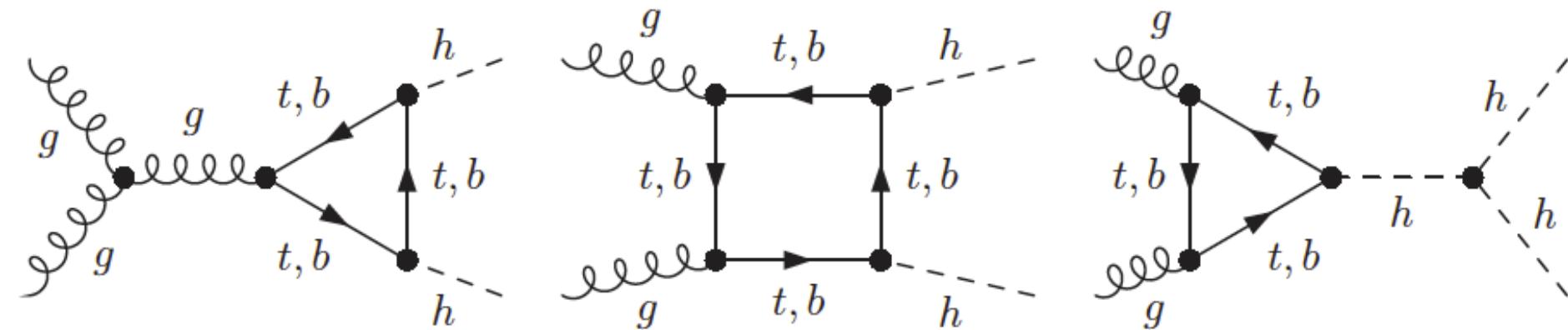
ATLAS Preliminary (Simulation)



- High luminosity will enable higher precision and the study of rare production and decay modes:
 - $t\bar{t}H, H \rightarrow \gamma\gamma$ (1/2-lepton channels)
 - $H \rightarrow \mu\mu$ (low signal rate and S/B~0.2%) Expect signal significance of 6σ @ 3000 fb^{-1}
- Γ_τ / Γ_Z and Γ_t / Γ_g constrain new physics contributions to $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops at the 5-20% level
- Γ_τ / Γ_μ sensitive to coupling relation between 2nd and 3rd fermion generation

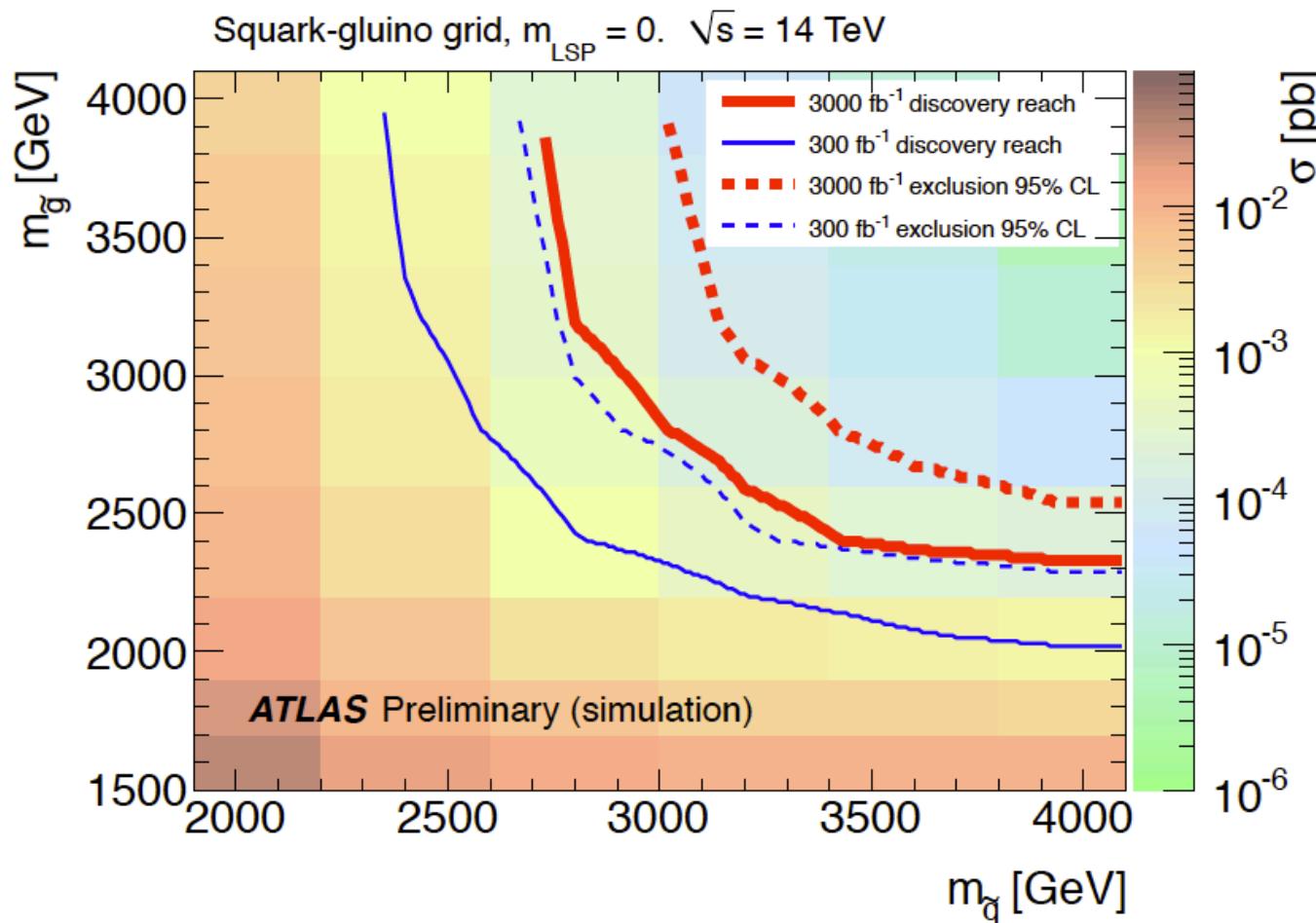
Higgs self-coupling

- Establish the Higgs mechanism as being responsible for the EWSB
- Probe the Higgs trilinear self-coupling through the measurement of Higgs boson pair production



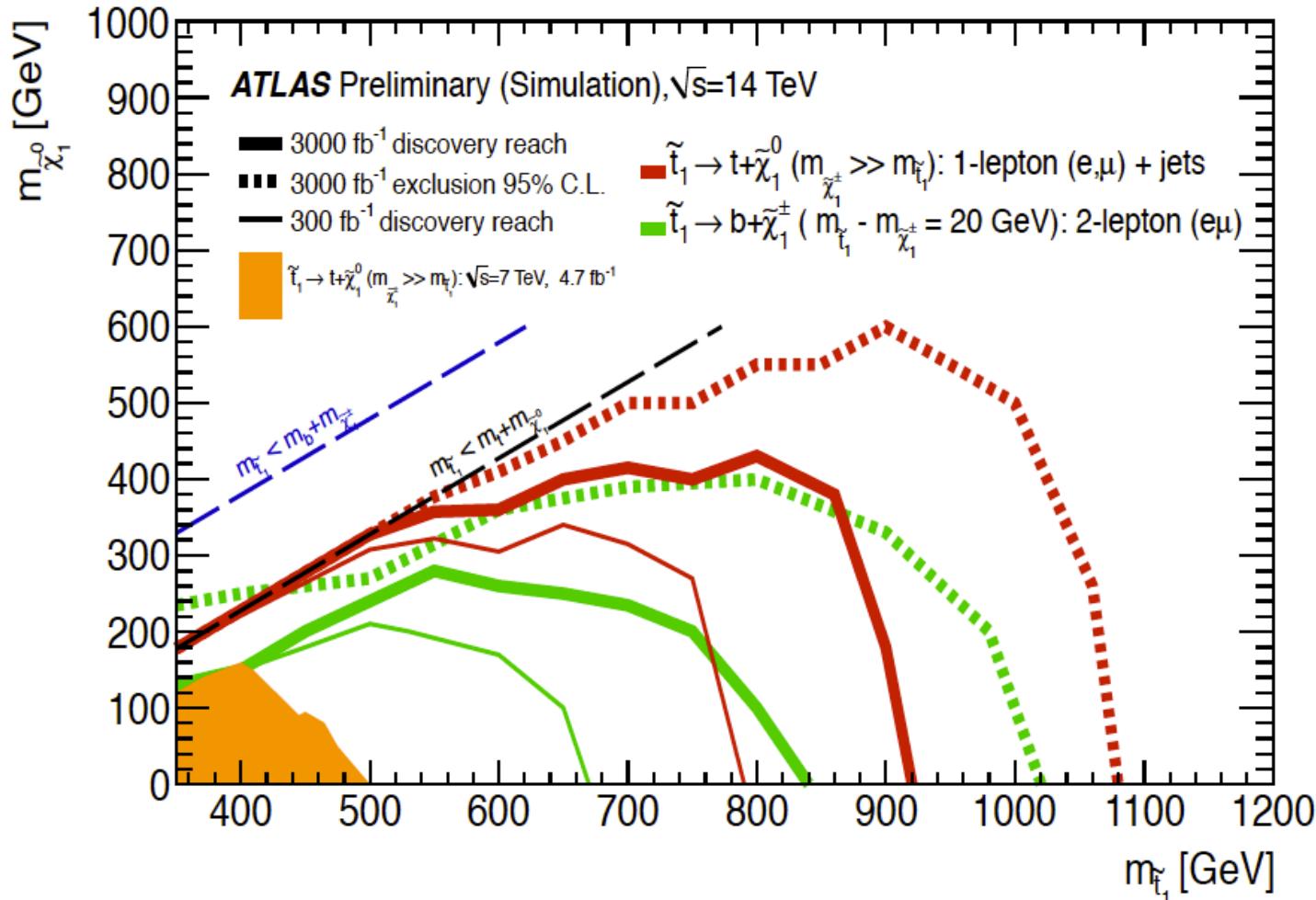
- **$HH \rightarrow bb \gamma\gamma$ channel** can provide first evidence ($3\sigma/\text{experiment}$) of double-Higgs boson production (expect ~ 12 signal events with $S/B \sim 0.7$. Main backgrounds are $\gamma\gamma bb$ and $t\bar{t}H$)
- By adding more decay modes ($HH \rightarrow bb \tau\tau$) and combining experiments a **~30% measurement of the Higgs self-coupling may be within reach at 3000fb^{-1}**

Supersymmetry searches



- Searches for squark and gluinos with jets and missing ET
- Increased integrated luminosity from 300fb^{-1} to 3000fb^{-1} improves the sensitivity by ~ 500 GeV
- High luminosity scenario will enable studies of properties

3rd generation SUSY searches



- 3000 fb^{-1} dataset significantly increases the stop discovery potential and will enable measurements of stop properties, if it exists.
- Improvements expected using boosted jets, missing ET shape, angular correlations, etc.

Summary

- **ATLAS and CMS have observed a new boson**
 - Initial measurements are compatible with a SM Higgs boson
 - More data is needed to fully establish its nature
 - Program underway to measure spin/parity and couplings to vector bosons and fermions
- **Broad range of searches for new physics and top precision measurements:**
 - No signs of new new physics yet
 - New analyses with more data and improved techniques will increase/extend discovery reach by the end of 2012
- **High luminosity LHC upgrade:**
 - Improve the precision on Higgs production cross section times branching ratio by a factor od two or three, enable the $H \rightarrow \mu^+ \mu^-$ decay mode, and provide first evidence for the Higgs self-coupling by combing experiments and channels
 - Increase sensitivity to first and second generation squark and gluinos by ~500GeV, and stops by ~200GeV
 - If evidence for new particles is found, the analysis of the 3000fb^{-1} dataset will enable measurements of mass, spin, and couplings of SUSY particles

Backup