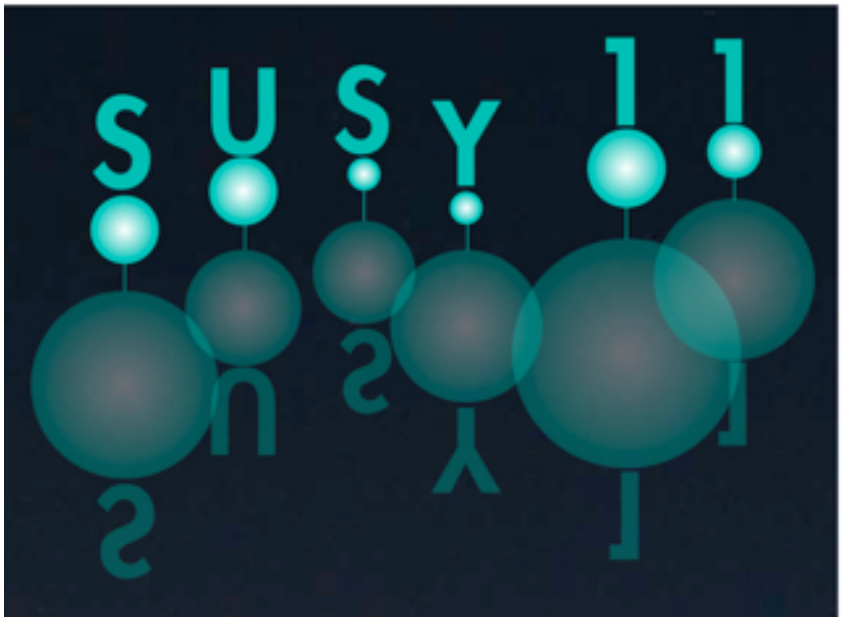


Imperial College London

# Supersymmetry 2011 Conference
# FNAL, 30/08/2011

# Higgs Searches at the LHC

**Mónica L. Vázquez Acosta - Imperial College**

**(on behalf of the ATLAS and CMS Collaborations)**

# Origin of Mass: the Higgs Boson

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**Standard Model does great job describing physics at weak scale**

**One of the open questions within the SM:**

**How to generate masses of fermions and gauge bosons within the fundamental theory of particle interactions?**

**What is the Electroweak symmetry breaking mechanism?**

**Higgs mechanism provides a gauge invariant theory of Electroweak interactions with massive $W^{\pm}$ and Z bosons**

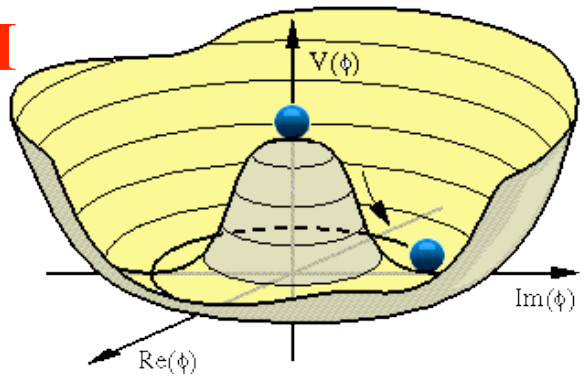
**One complex scalar field doublet $\phi$**

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

**After spontaneous symmetry breaking:**

- **Goldstone bosons become $W^{\pm}$, Z gauge bosons**
- **Second component of $\phi$ generates Higgs boson H**




**Theory predicts:**

$$g_{Hff} \propto m_f$$
$$g_{HVV} \propto m_V^2$$
$$g_{HHH} \propto m_H^2 / m_W$$
$$g_{HHHH} \propto m_H^2 / m_W^2$$

**The Higgs Mass $m_H$ is unknown in the SM but expected to be < 1 TeV**

**vacuum expectation: $\nu \approx 246$ GeV**

# Experimental constrains on the Higgs Mass

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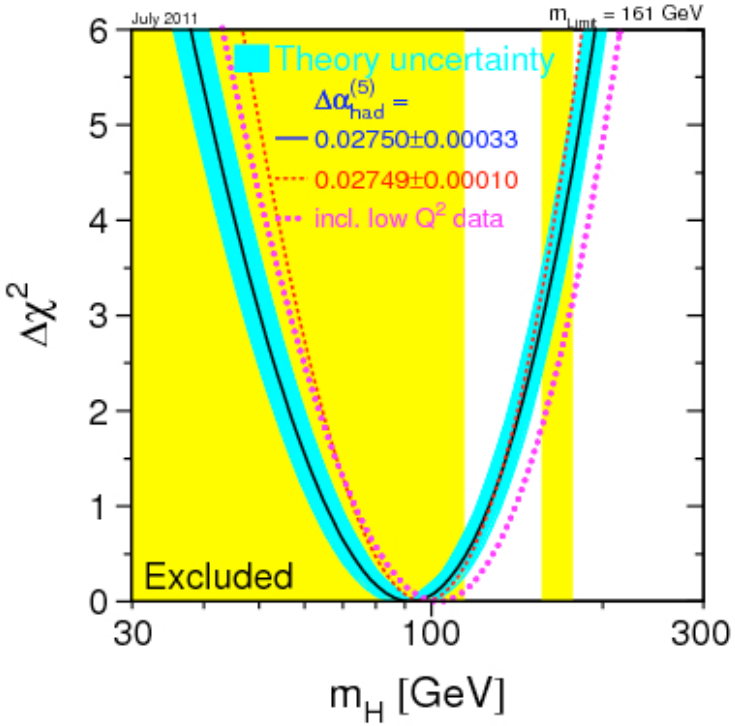


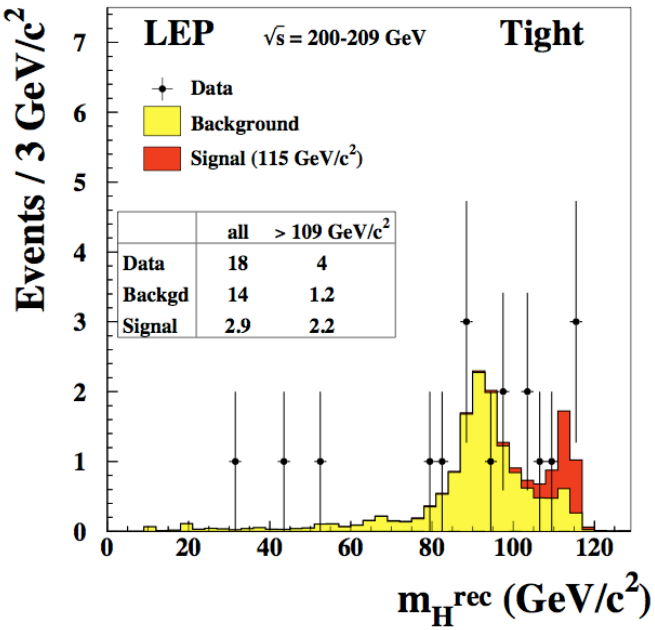

$\Delta\chi^2$ from fit to electroweak measurements from LEP, SLD and Tevatron assuming the SM

**Preferred value for the mass:** $92^{+34}_{-26}$ GeV

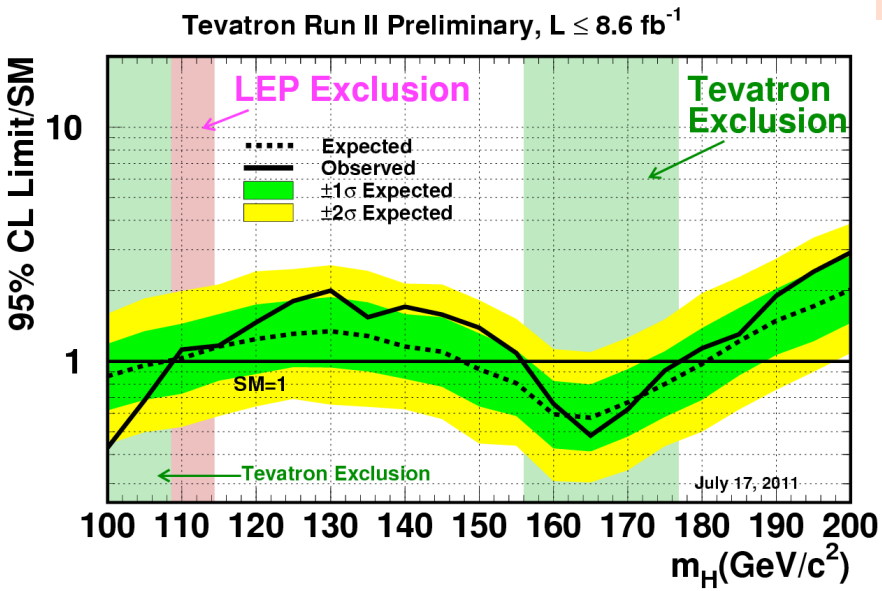
**Upper bound:** $M_H < 161$ GeV

**LEP direct search:**

$M_H > 114.4$ GeV




| | all | > 109 GeV/$c^2$ |
|---|---|---|
| Data | 18 | 4 |
| Backgd | 14 | 1.2 |
| Signal | 2.9 | 2.2 |




**Tevatron exclusion @ 95% CL (July 2011):**

$100 - 108$ GeV $\quad$ $156 - 177$ GeV

# Search for the Higgs @ the LHC

# Large Hadron Collider

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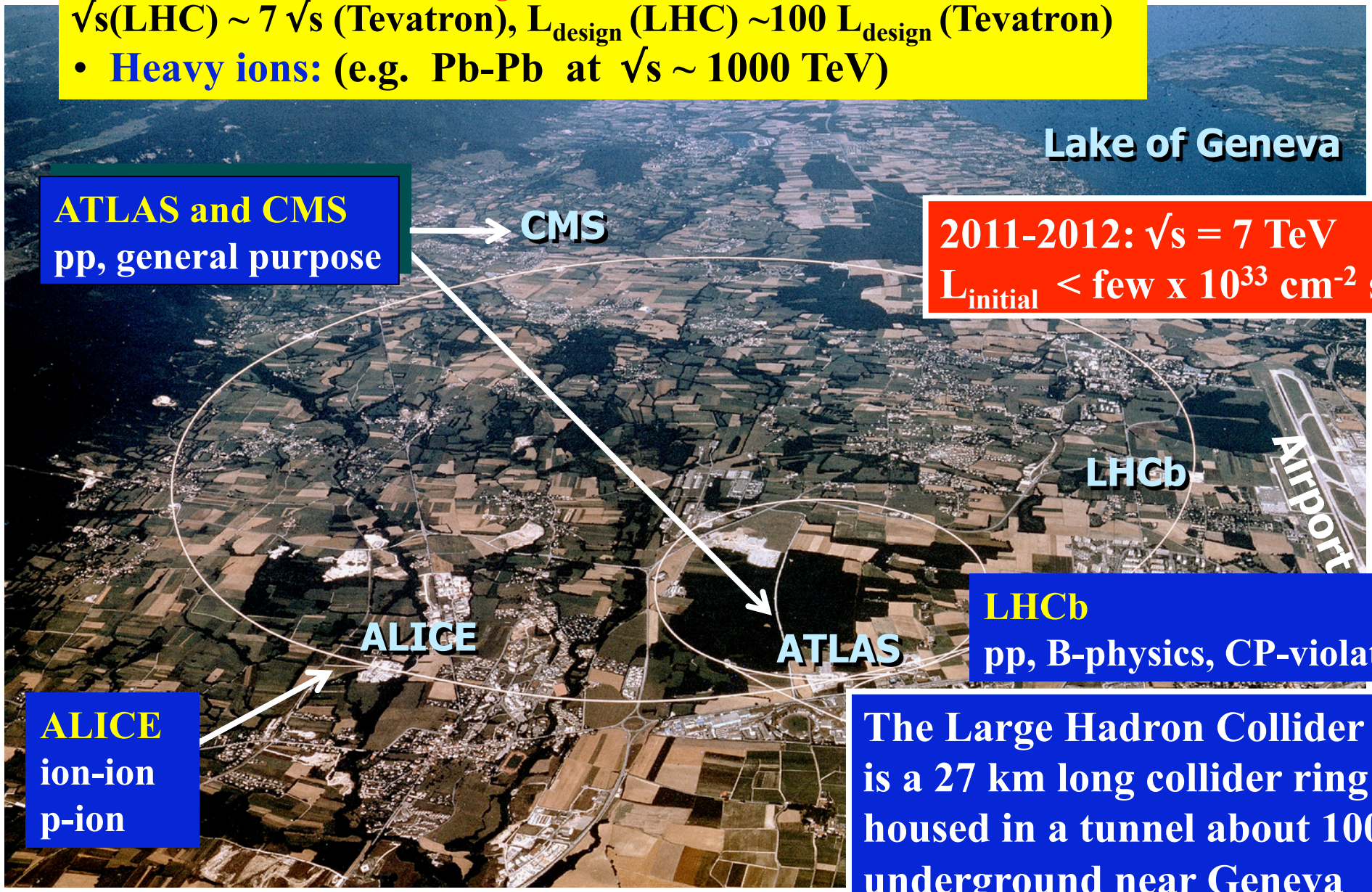
- pp: $\sqrt{s}$ = 14 TeV, $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2014)

$\sqrt{s}$(LHC) ~ 7 $\sqrt{s}$ (Tevatron), $L_{design}$ (LHC) ~100 $L_{design}$ (Tevatron)

- Heavy ions: (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)




**ATLAS and CMS**
pp, general purpose

**2011-2012: $\sqrt{s}$ = 7 TeV**
**$L_{initial}$ < few x $10^{33}\ cm^{-2}\ s^{-1}$**

**LHCb**
pp, B-physics, CP-violation

**ALICE**
ion-ion
p-ion

The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

# LHC: Integrated Luminosity

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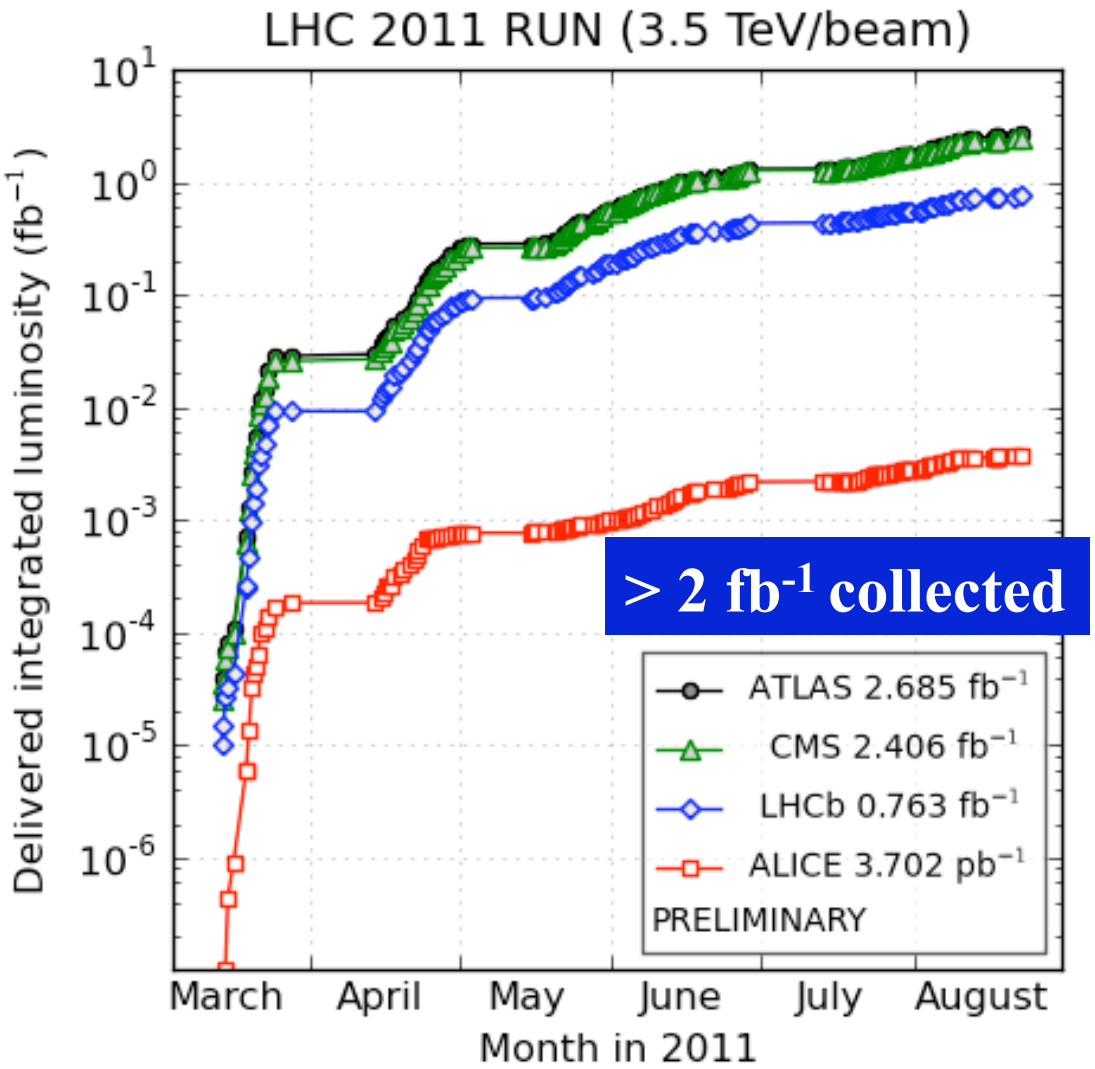
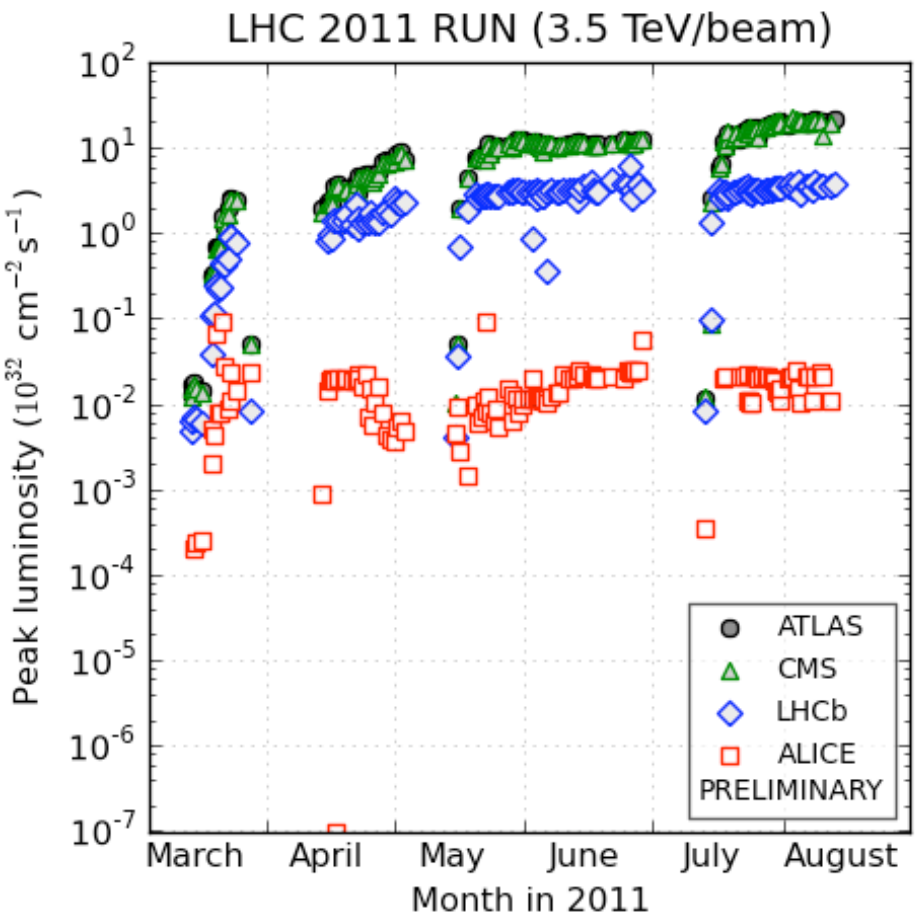



**> 2 fb$^{-1}$ collected**

**Initial Goal:**
**1 fb$^{-1}$ by end of 2011!**




**The data collected has opened up the door for Higgs searches @LHC!**

**Peak luminosity: 2E33 cm$^{-2}$ s$^{-1}$**

**<number Pile-Up events> ~ 6**

# ATLAS and CMS Experiments

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**ATLAS**

**Inner detector: pixel+SCT+TRT B = 2T solenoid**

$\sigma/p_T \approx 10.05\% p_T \oplus 1\%$ $|\eta| < 2.5$

**EM Calo: Lead-LAr calorimeter**

$\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$ $|\eta| < 3.2$

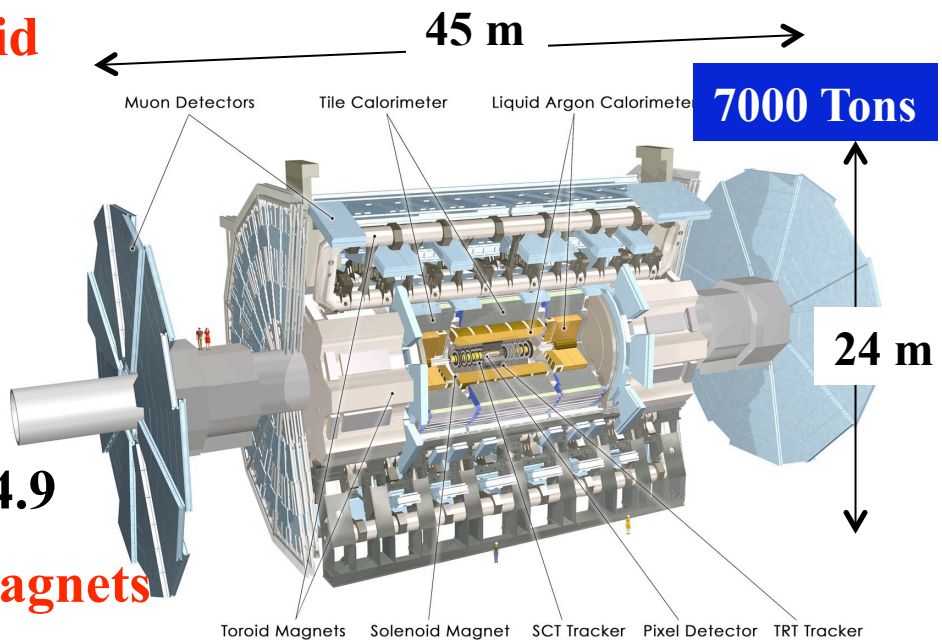
**Hadronic calorimeter:**

**Steel+Scintillator** $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$ $|\eta| < 3.2$

**Copper+LAr** $\sigma/E \approx 100\%/\sqrt{E} \oplus 10\%$ $3.1 < |\eta| < 4.9$

**Muon spectrometer: superconducting toroid magnets**

$\sigma/p_T \approx 2\%$ @ 50 GeV $|\eta| < 2.7$




**CMS**

**Silicon tracker $|\eta| < 2.5$, B = 3.8T solenoid**

$\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T \oplus 0.005$

**Calorimetry** $|\eta|_{ECAL} < 3$, $|\eta|_{HCAL} < 5$

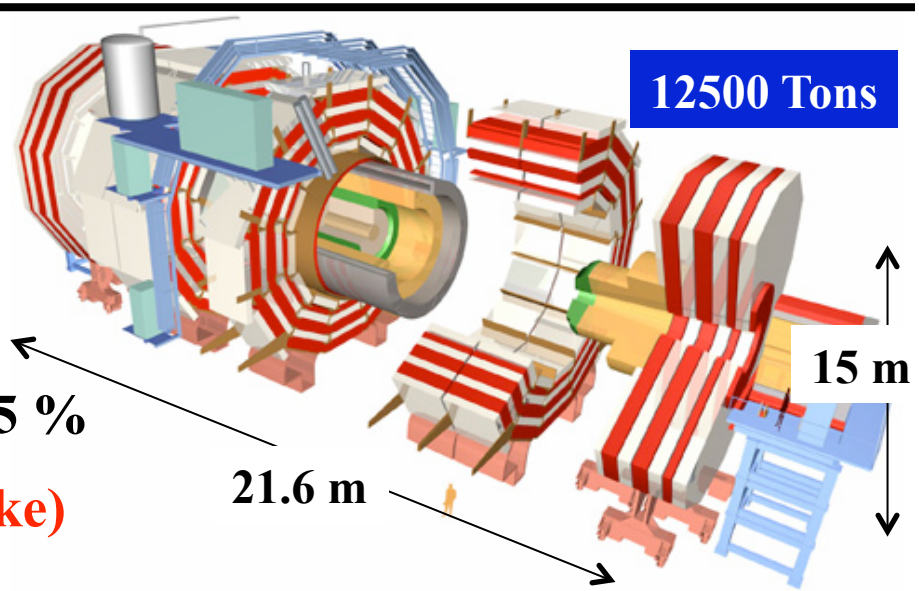
**ECAL: PbWO4 crystals, high resolution M(γγ)**

$\sigma/E \approx 2.8\%/\sqrt{E} \oplus 12\%/E \oplus 0.3\%$

**HCAL: brass+Scintillator** $\sigma/E \approx 100\%/\sqrt{E} \oplus 0.05\%$

**Muon Spectrometer: B = 2T (solenoid return yoke)**

$\sigma/p_T \approx 1\%$ @ 40 GeV $|\eta| < 2.4$



# Standard Model Higgs Production @LHC

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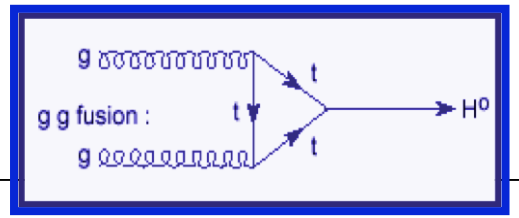
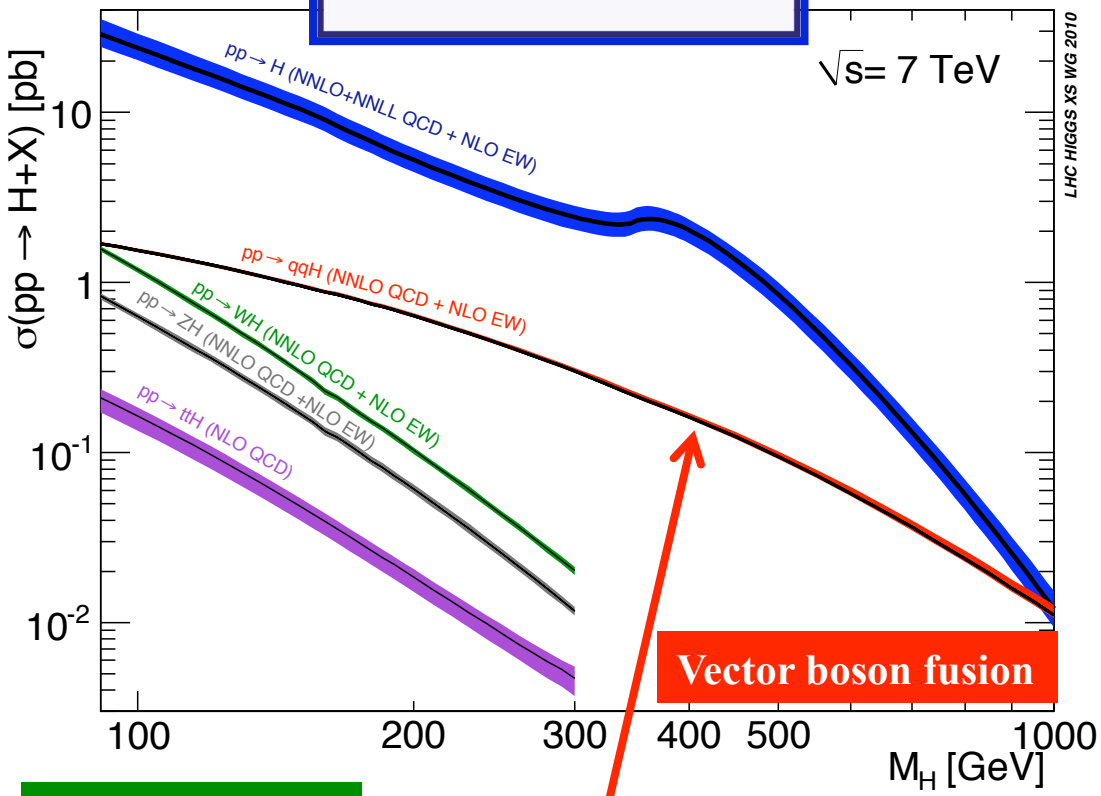
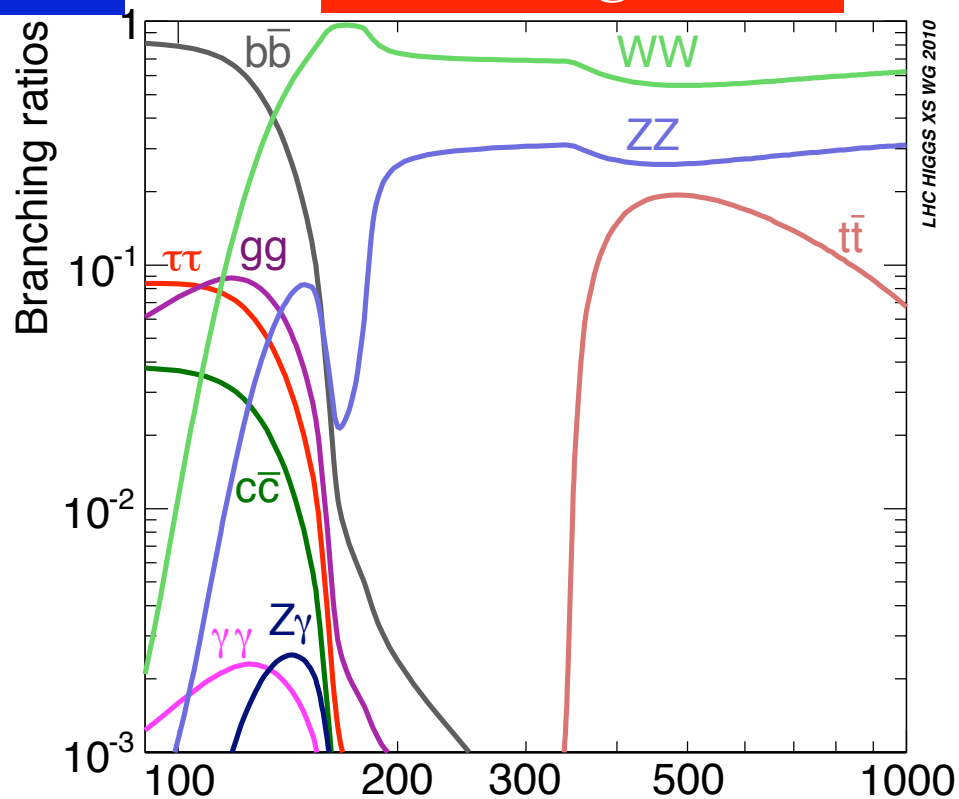
## gluon-gluon fusion dominant production mechanism

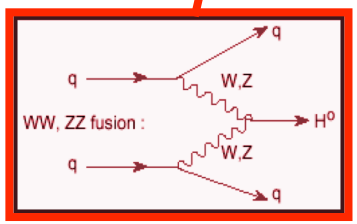


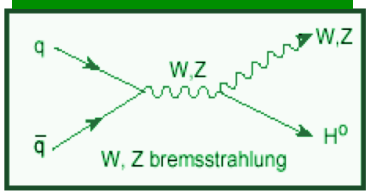

## Branching Ratios



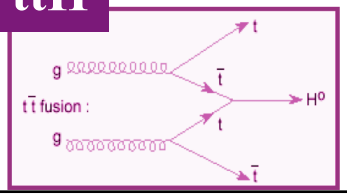

**Vector boson fusion**




**Higgs Strahlung**




**ttH**




## Decay modes studied:

- γγ
- ττ
- bb

} **low $M_H$ range**

- WW
- ZZ

# Standard Model Higgs Searches @LHC

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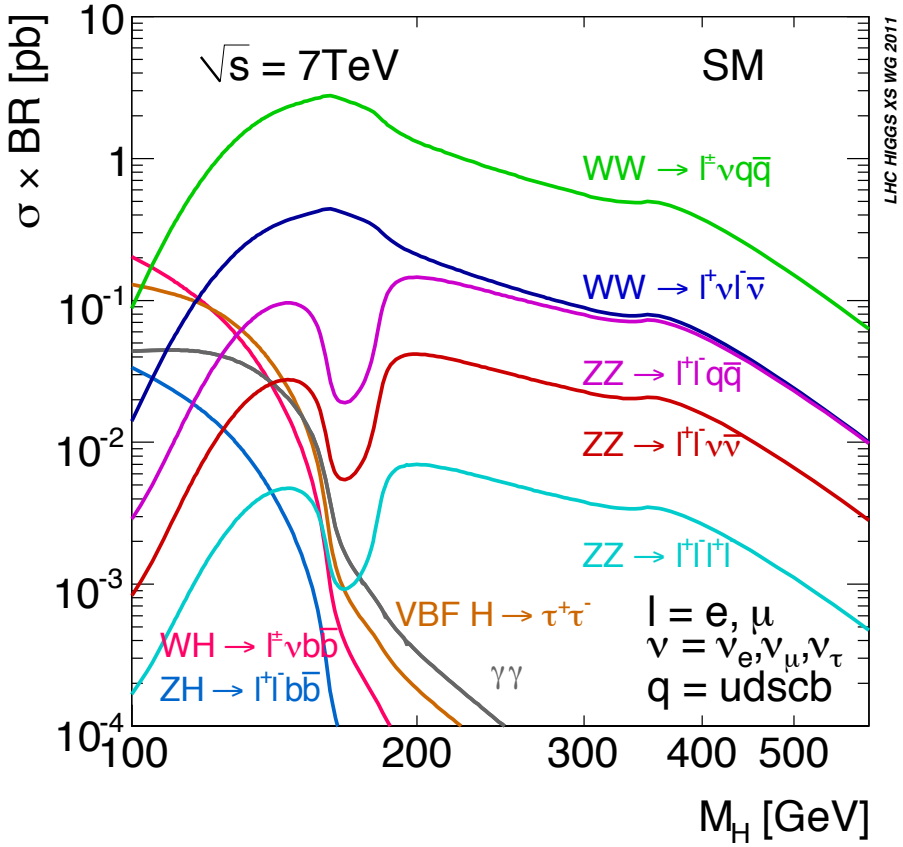
## Cross Section x BR



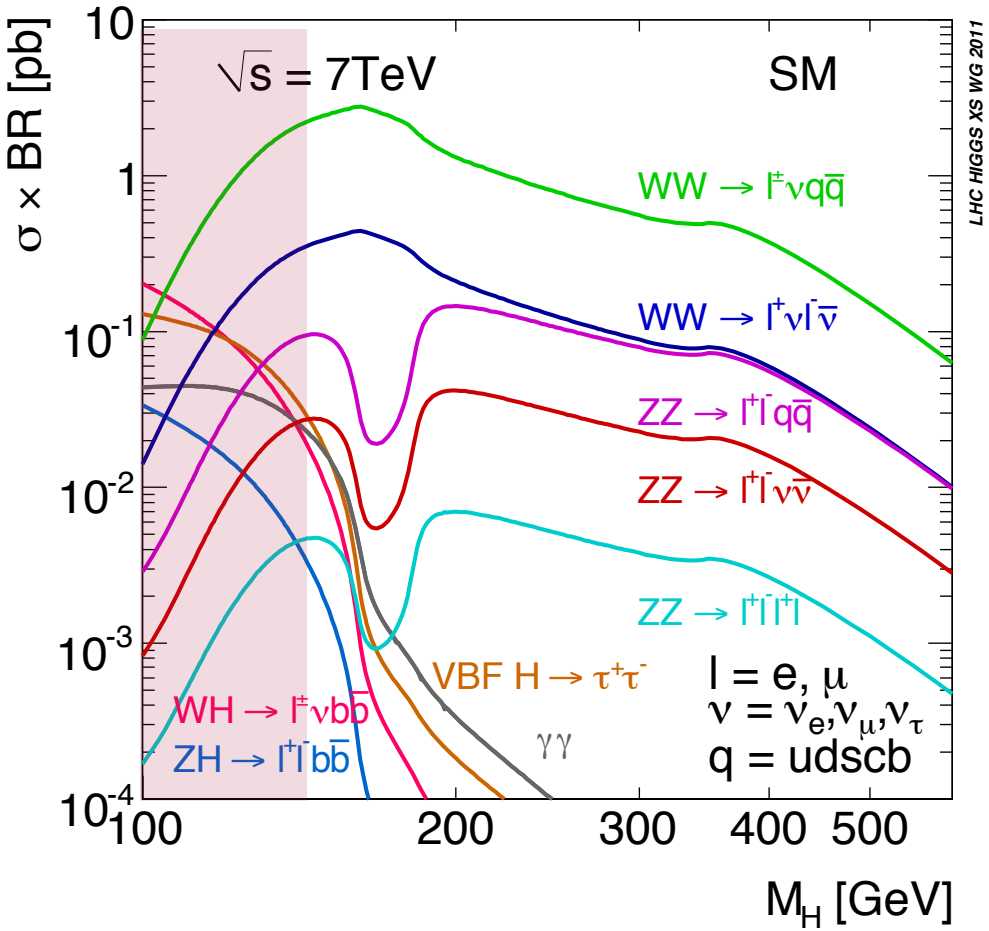

**LHC Higgs Cross Section WG**
**arXiv:1101.0593 [hep-ph]**

**Common inputs in ATLAS/CMS**

## Searches performed

| Channel | Exp. | Lumi $fb^{-1}$ | $m_H$ (GeV) |
|---|---|---|---|
| $H\to\gamma\gamma$ | ATLAS<br>CMS | 1.1<br>1.7 | 110-150<br>110-150 |
| VBF $H\to\tau\tau$ | ATLAS<br>CMS | 1.1<br>1.6 | 100-150<br>110-145 |
| $WH\to bb$, $ZH\to bb$ | ATLAS<br>CMS | 1.0<br>1.1 | 110-130<br>110-135 |
| $H\to WW\to l\nu l\nu$ (0 & 1 jet) | ATLAS<br>CMS | 1.7<br>1.5 | 110-240<br>110-600 |
| VBF $H\to WW\to l\nu l\nu$ | CMS | 1.5 | 110-600 |
| $H\to WW\to l\nu qq$ (0 & 1 jet) | ATLAS | 1.0 | 240-600 |
| $H\to ZZ\to 4l$ | ATLAS<br>CMS | 2.0-2.3<br>1.7 | 110-600<br>110-600 |
| $H\to ZZ\to 2l2\tau$ | CMS | 1.1 | 180-600 |
| $H\to ZZ\to 2l2\nu$ | ATLAS<br>CMS | 1.0<br>1.6 | 200-600<br>250-600 |
| $H\to ZZ\to 2l2q$<br>(0, 1, 2 b-tags) | ATLAS<br>CMS | 1.0<br>1.6 | 200-600<br>226-600 |

# SM Higgs Searches @ LHC: low mass searches




- $H \to \gamma\gamma$
- $H \to \tau\tau$
- $H \to bb$

# ATLAS & CMS: H→γγ

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**Small branching fraction but clean narrow peak on top steep falling background**

**Challenges:**

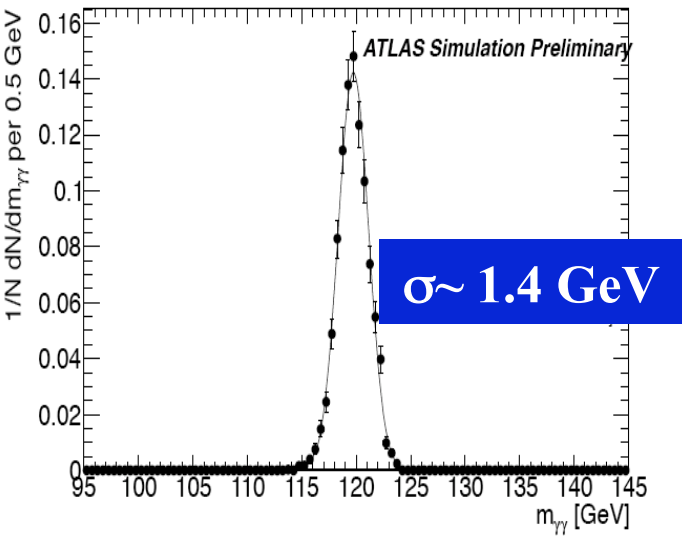
- Electromagnetic calorimeter calibration
- Determination of primary vertex in events with ~ 6 pile-up events

• **Improve sensitivity:**

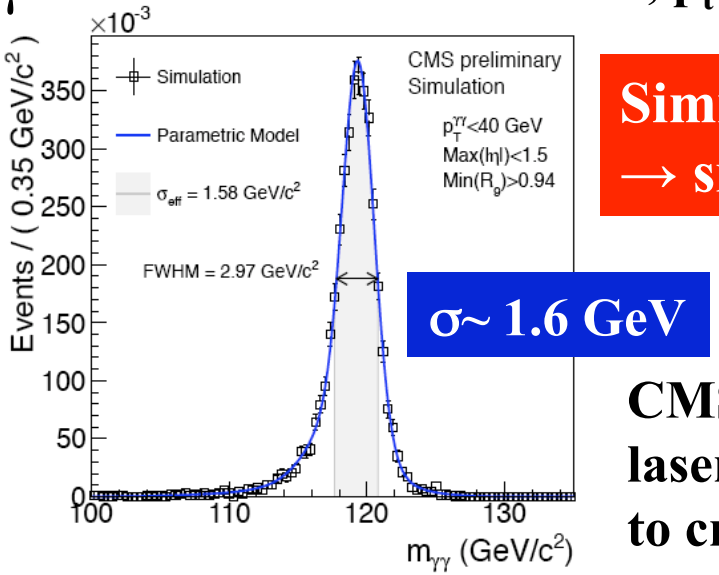
**Different γ categories with different expected di-γ mass resolution**

| | | | | |
|---|---|---|---|---|
| CMS | Converted<br>Uncoverted | Both in the barrel<br>Other combinations | $p_t(\gamma\gamma)$> 40 GeV<br>$p_t(\gamma\gamma)$< 40 GeV | for fermiophobic searches |
| ATLAS | Converted & Uncoverted | Central & Transition & Other | | |

**ATLAS: barrel unconverted γ**




**CMS: barrel uncoverted, $p_t^{\gamma\gamma}$< 40 GeV**




**Similar di-γ mass resolution:**
**→ similar Higgs sensitivity**

**CMS: expected improvements on laser calibration corrections due to crystal transparency loss**

# ATLAS & CMS: H→γγ

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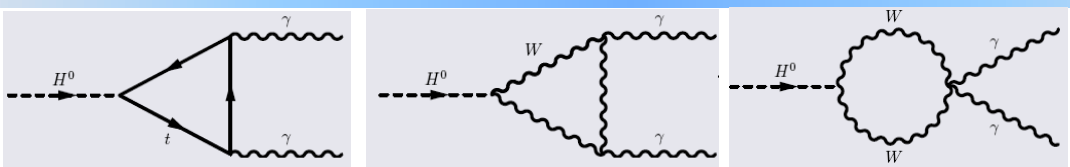
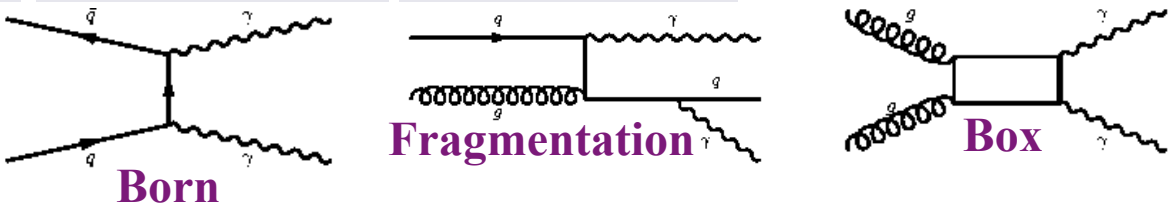
**Signal:**




**Backgrounds**

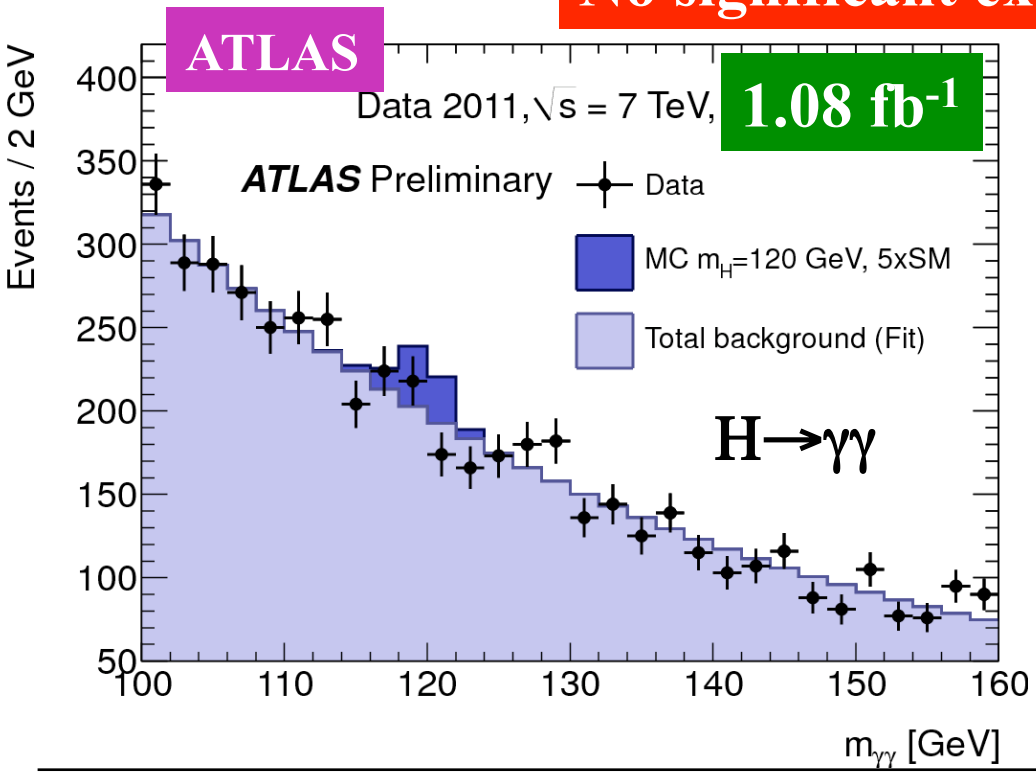
- **Irreducible: γγ (+jets)**

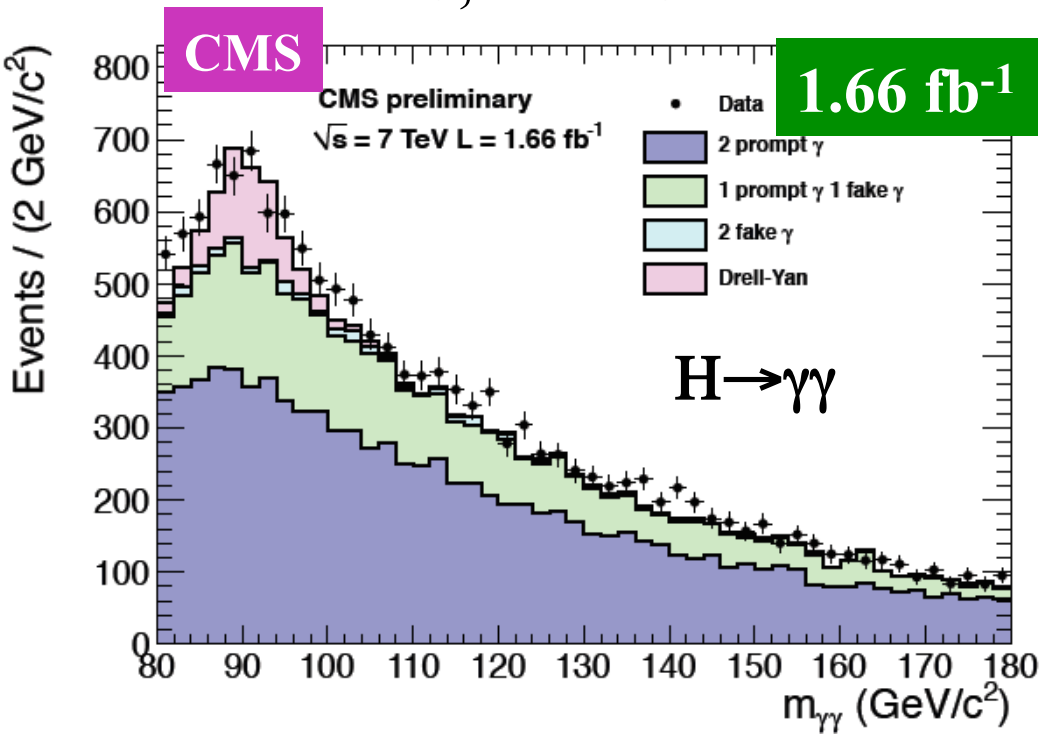



- **Reducible: γ/ jet(s),jet(s)/jet(s)**
- **Drell-Yan: both e misidentified as γ**

**No significant excess seen!**

**~15-20% uncertainty in MC, but MC is not used!**



# ATLAS & CMS: H→γγ

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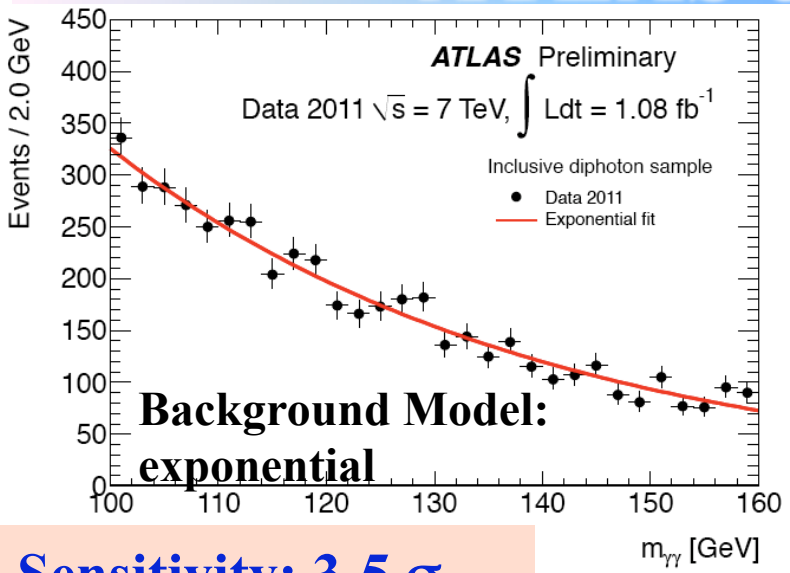
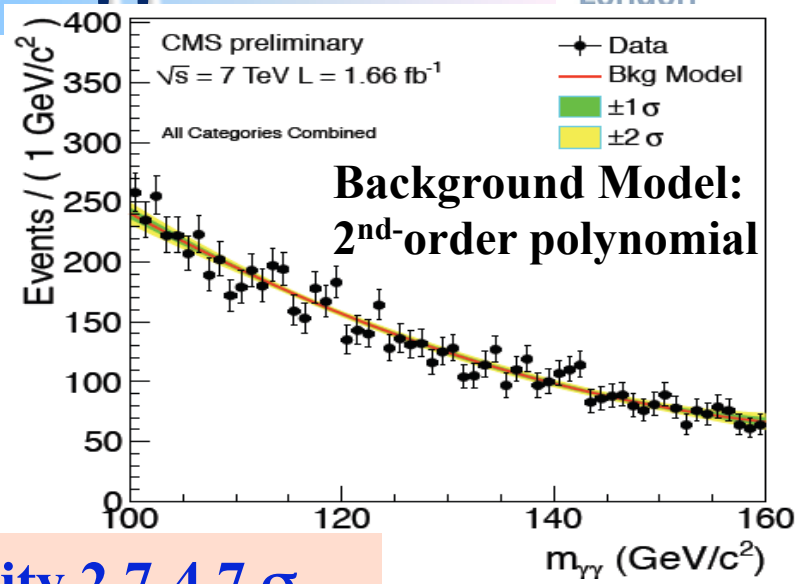
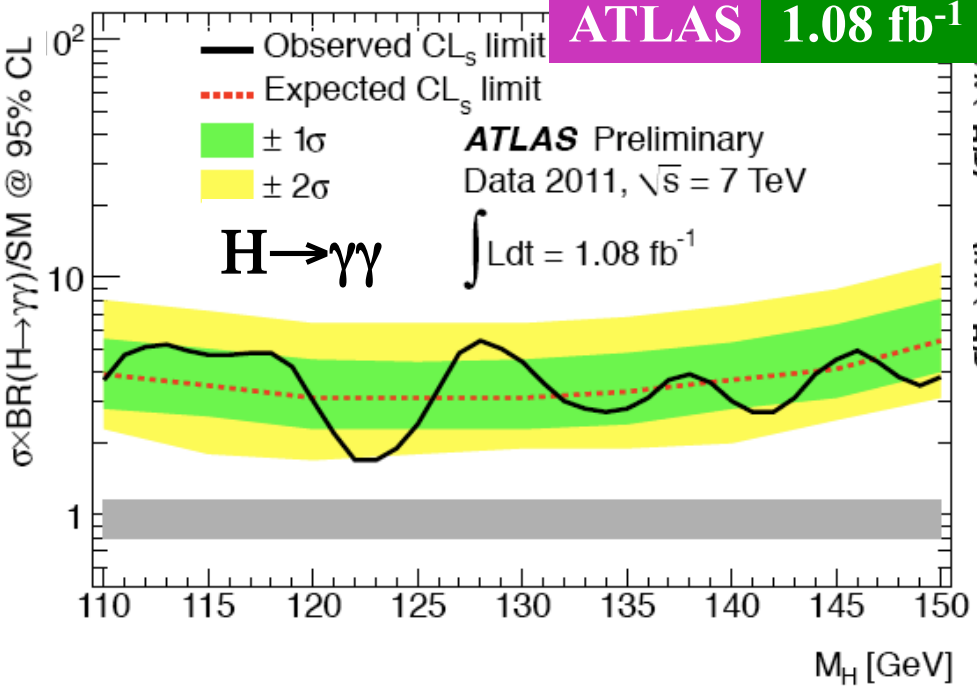



**Background: fit to the data**



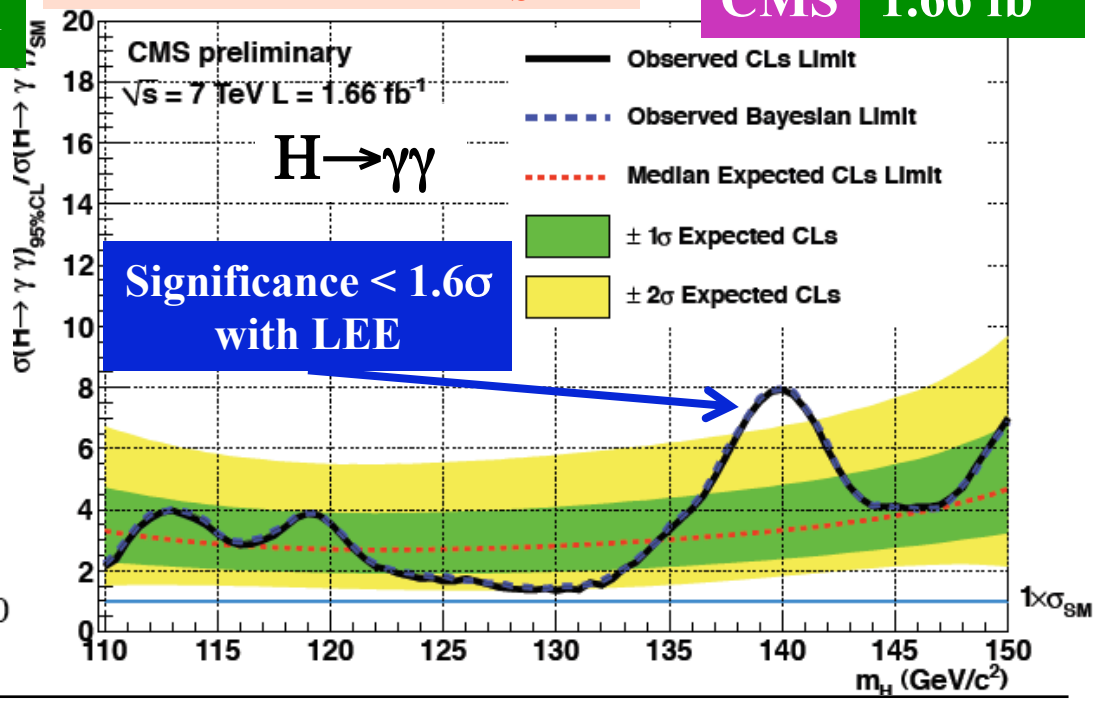

**Sensitivity: 3-5 $\sigma_{SM}$**
**Observed: 2-10 $\sigma_{SM}$**

**ATLAS 1.08 fb$^{-1}$**




**Sensitivity 2.7-4.7 $\sigma_{SM}$**
**Observed: 1.3-8 $\sigma_{SM}$**

**CMS 1.66 fb$^{-1}$**



# CMS Fermiophobic Higgs: H→γγ

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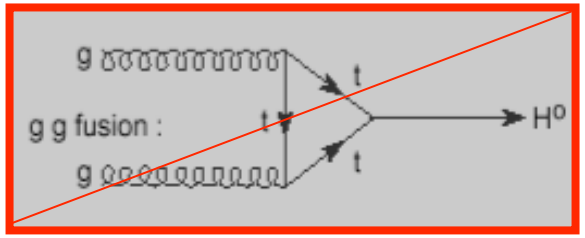
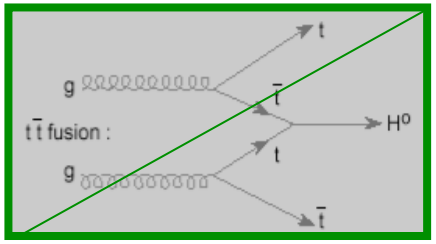
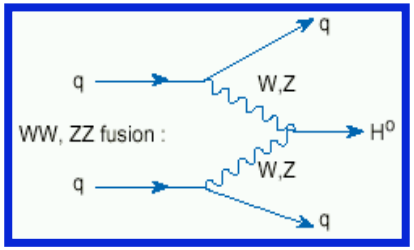
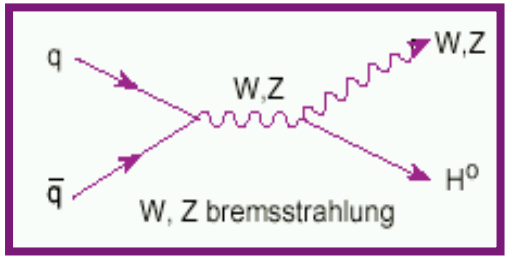
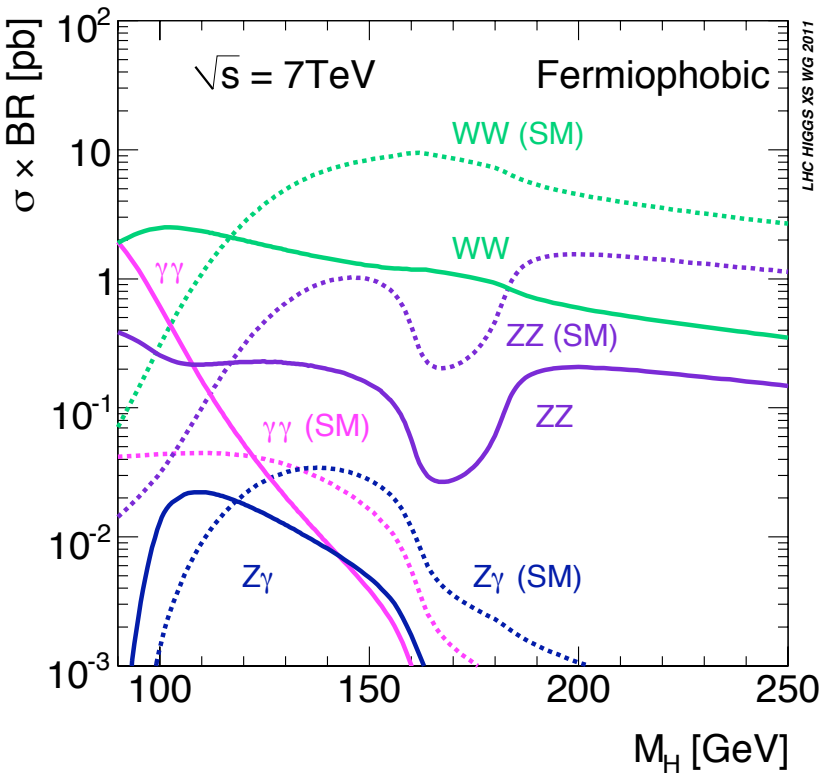


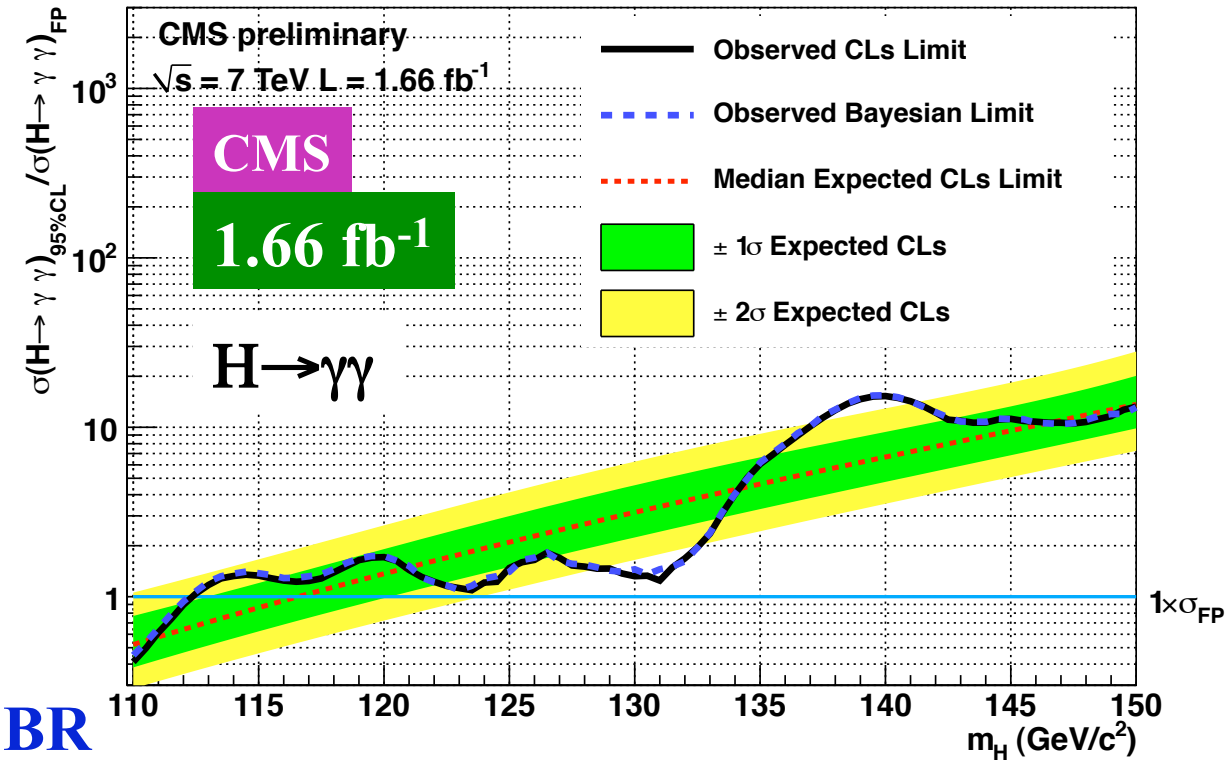




**No gg fusion or associated production**




**Expected Exclusion: 110-116.5 GeV**

**Observed Exclusion: 110-112 GeV**




**Enhanced γγ cross section x BR**

# ATLAS & CMS: H→ττ

Imperial College London

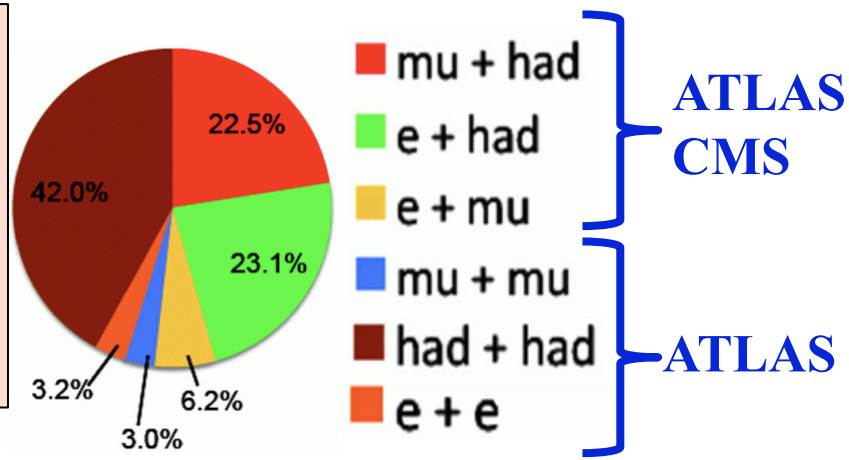
**2nd largest Branching Ratio (~8%) at low mass**

**Challenges:**

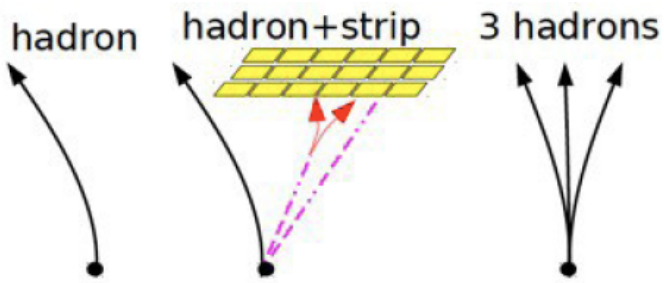
- **Reconstruction of different tau decay modes**

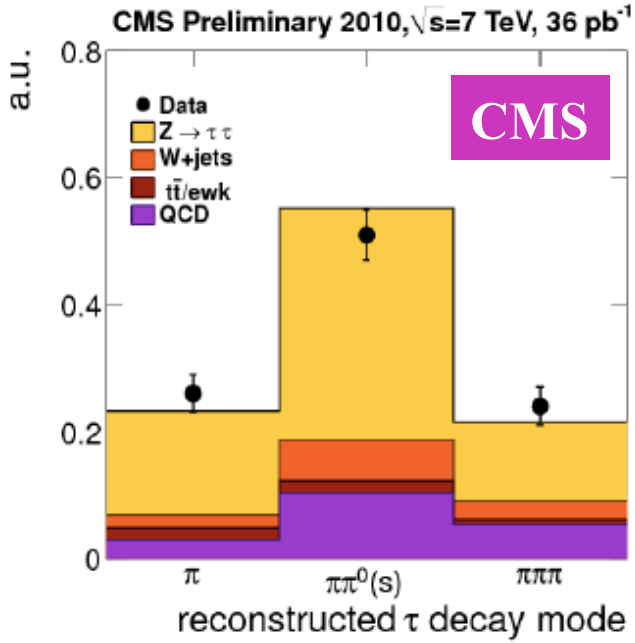
  **Hadronic tau ($\tau_{had}$) reconstruction**

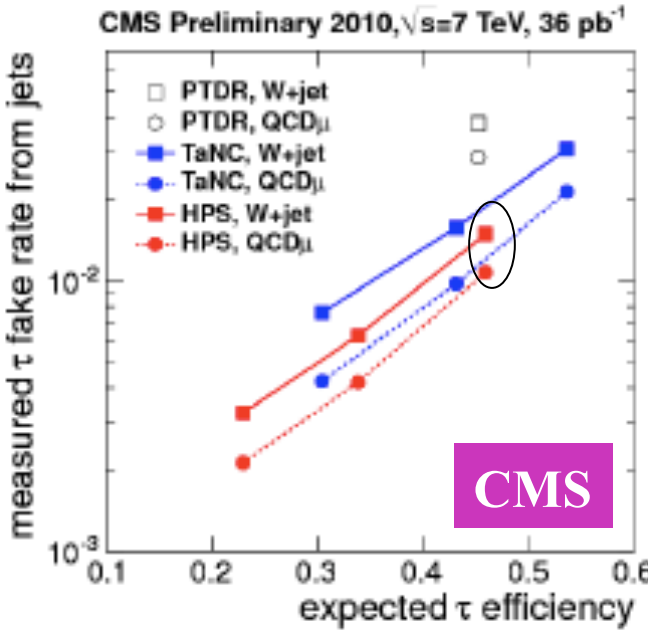
- **Reconstruction of di-τ mass (presence of ν's)**




**CMS: $\tau_{had}$ reconstruction**
**particle-flow based algorithm**




**Di-τ mass reconstruction**

**CMS: Visible mass – full mass results in preparation**

**ATLAS: Full mass with Missing Mass Calculator (MMC)**

**Sophisticated version of the Collinear Approximation**

- **Fake rate ~ 1%**
- **$\tau_{had}$ Eff: ~ 50%**
  **6% uncertainty**

# ATLAS: H→ττ

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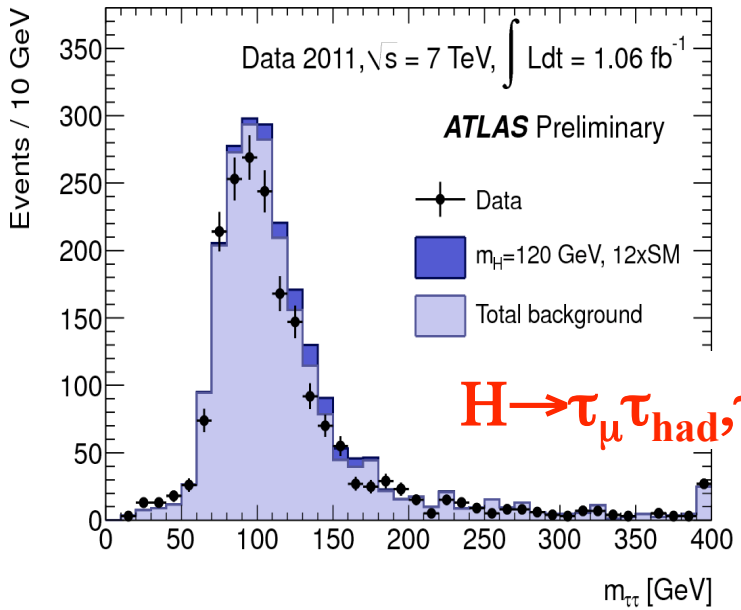
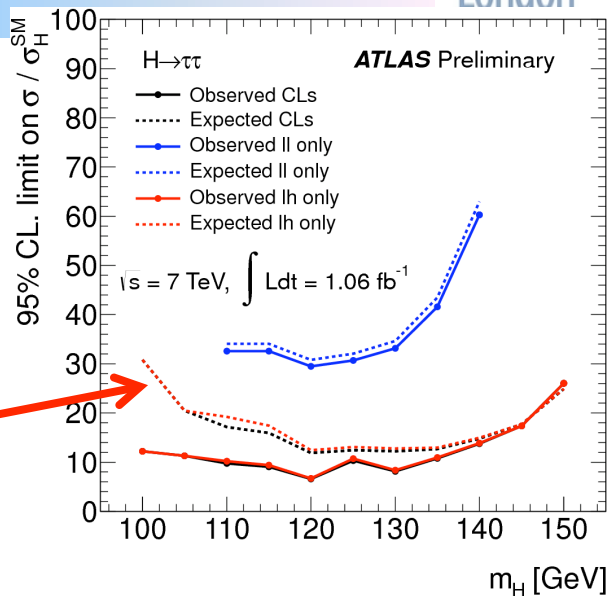
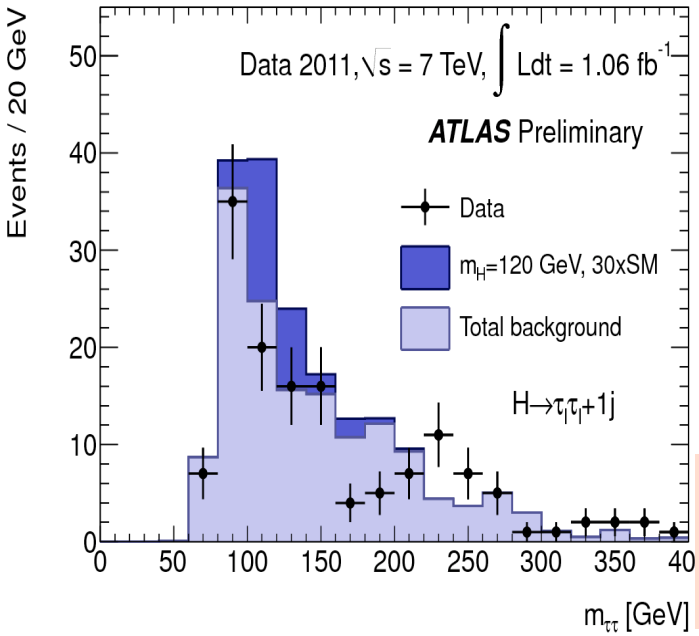



$H \to \tau_\mu \tau_{had}, \tau_e \tau_{had}$

**Most sensitivity from this channel**

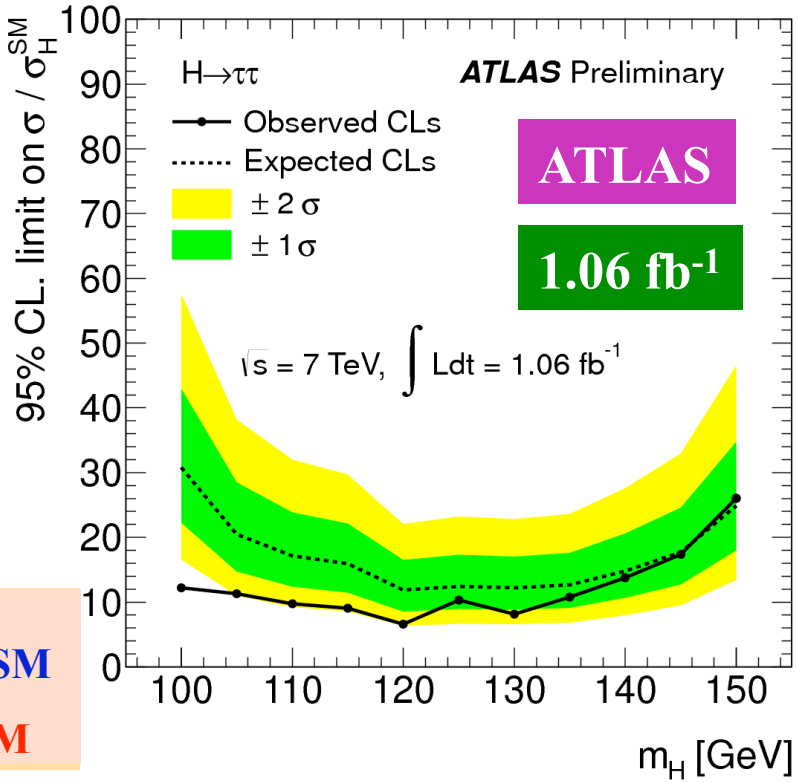



$H \to \tau_e \tau_e, \tau_\mu \tau_\mu, \tau_e \tau_\mu$

**+1 jet**

**Vector Boson Fusion enhanced**




**Sensitivity ~ 15-30 $\sigma_{SM}$**

**Observed ~ 10-25 $\sigma_{SM}$**

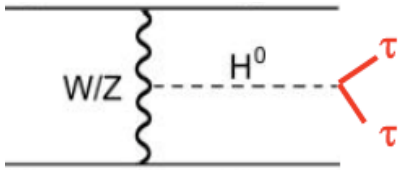
# CMS: H→ττ - Vector Boson Fusion

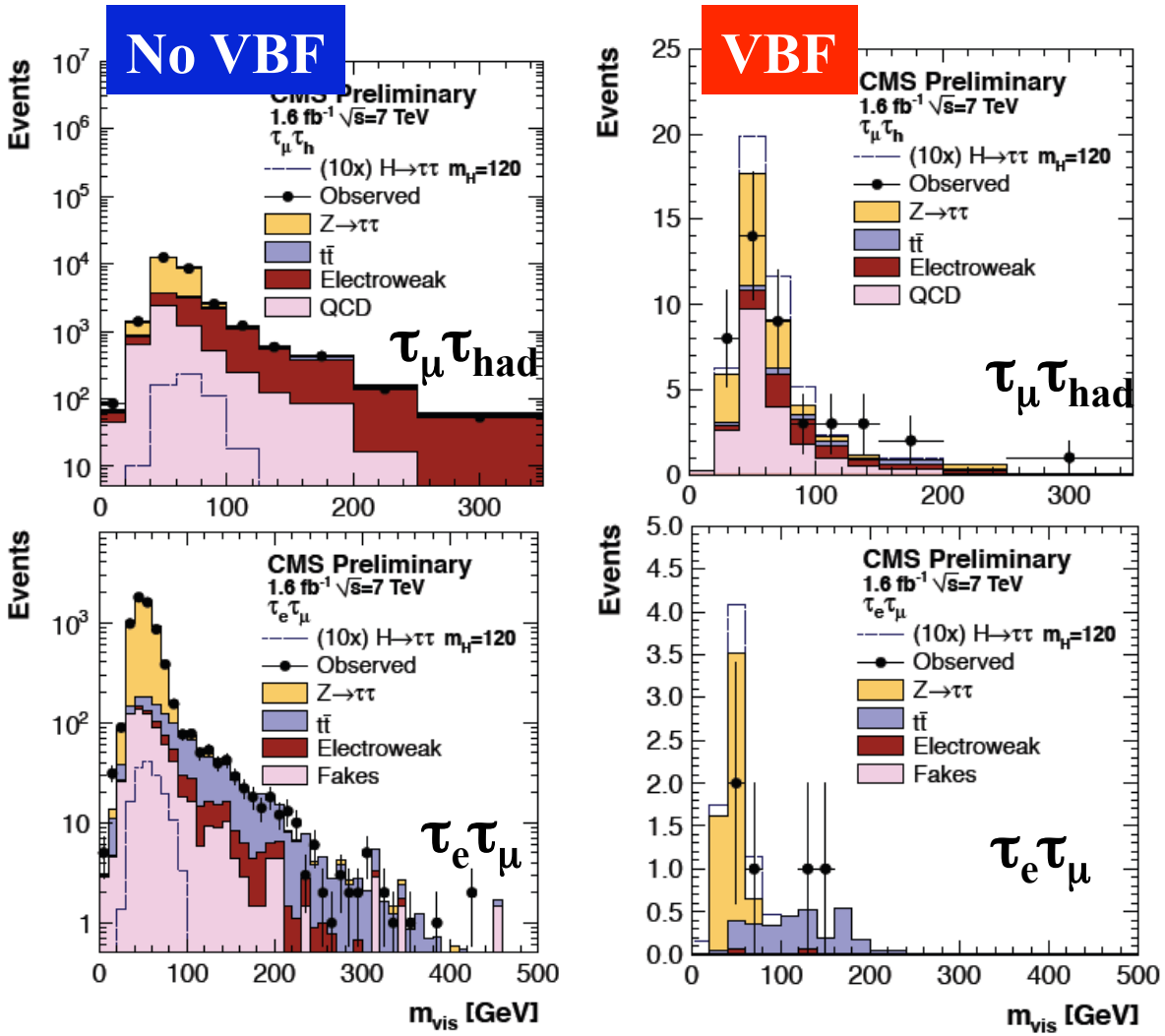
Imperial College London

- **VBF Category**

  exactly 2 jets with $p_t$> 30 GeV in opposite hemispheres: $\Delta\eta_{jj}$> 3.5, $M_{jj}$> 350 GeV
- **no VBF Category**

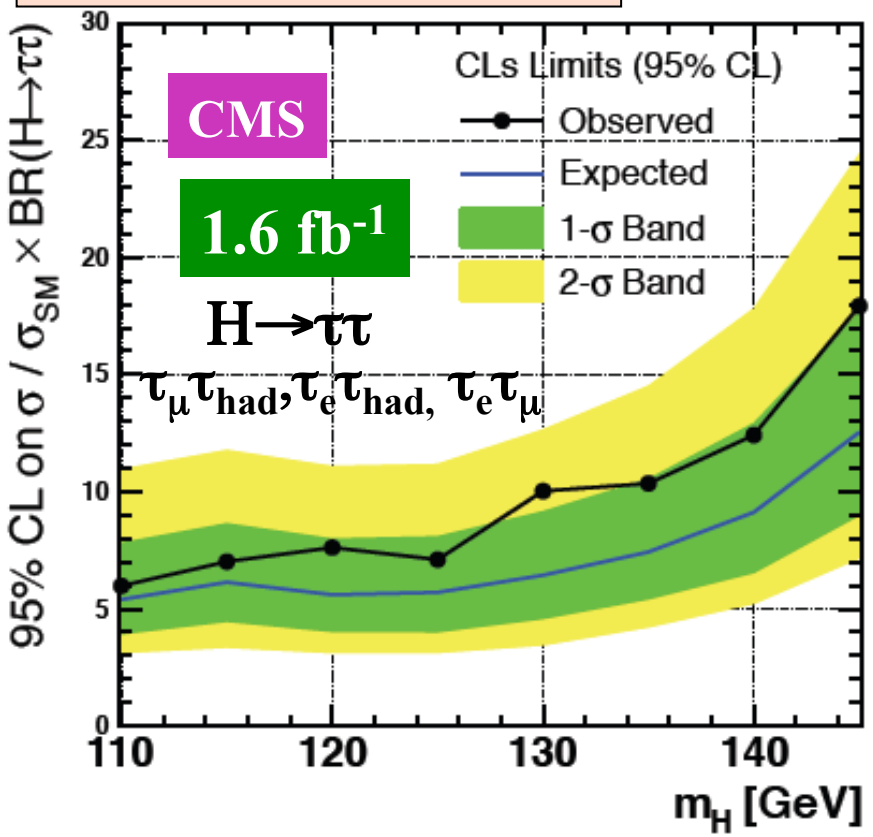
  < 2 jets with $p_t$> 30 GeV or 2 jets failing VBF criteria




**Sensitivity: 5-12 $\sigma_{SM}$**

**Observed: 6-16 $\sigma_{SM}$**



# ATLAS & CMS: H→bb
# W/Z Associated production

Imperial College London

**Largest Branching Ratio at low mass**

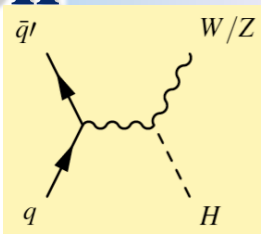
**Challenges:**

**Control of large SM background**

**→ study of Higgs associated production**

**B-tagging**

**Increased sensitivity: boosted analysis in CMS**

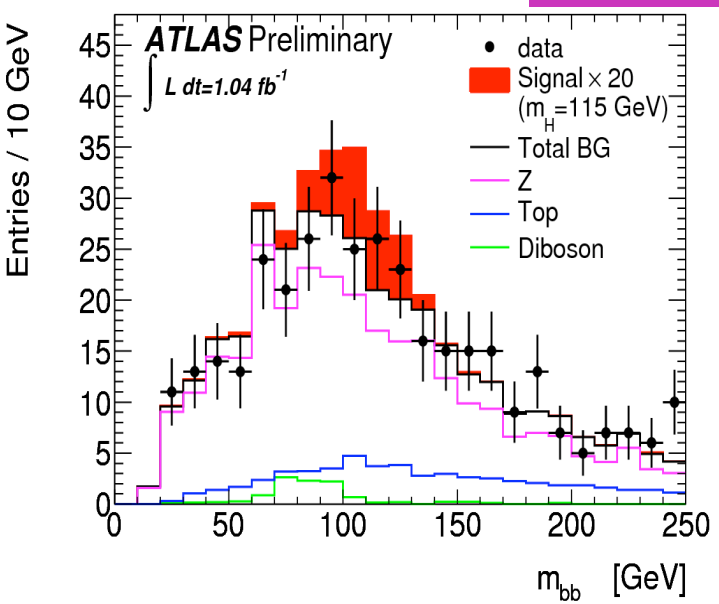



**Talk Thursday**
**Conde Muino**

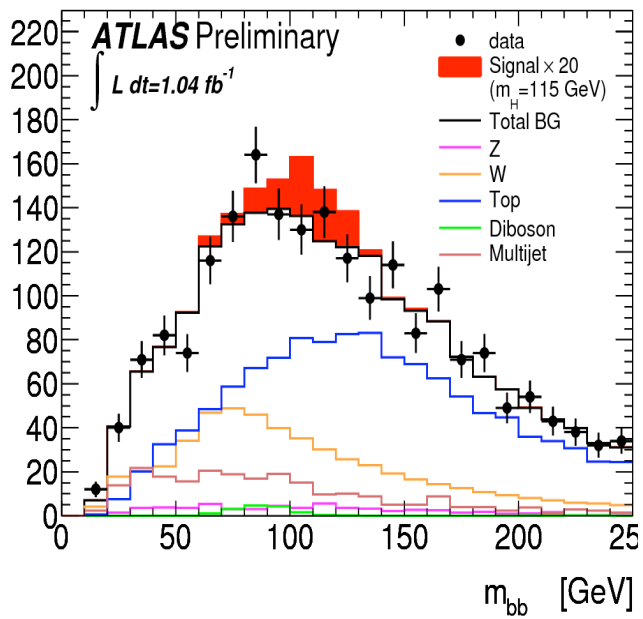
| CMS | $p_t(jj)$ | $p_t(V)$ |
|---|---|---|
| WH→lνbb | 165 GeV | 160 GeV |
| ZH→llbb | 100 GeV | 100 GeV |
| ZH→ννbb | 160 GeV | |

**ATLAS: main systematics from b-tagging ~16 %**
**and jet-energy-scale ~9%**

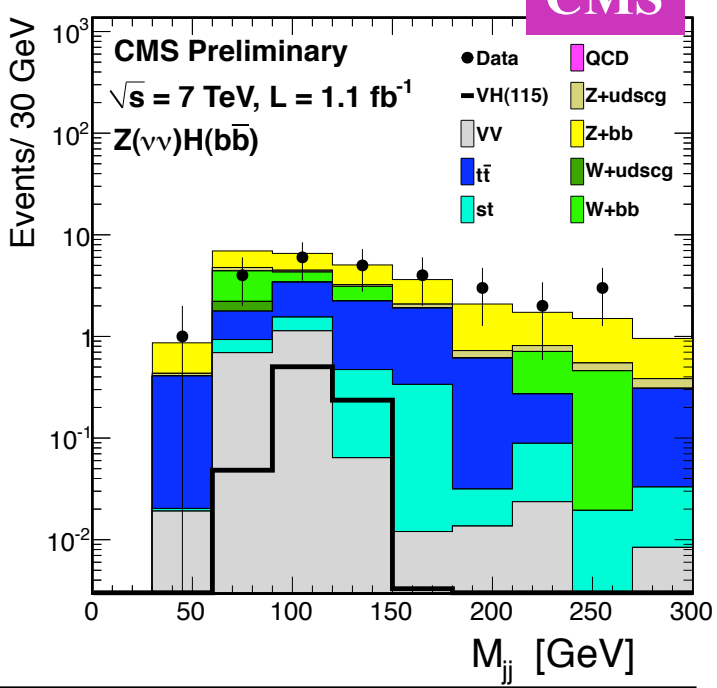
**ZH→llbb** ATLAS




**WH→lνbb** ATLAS




**ZH→ννbb** CMS



# ATLAS & CMS: H→bb

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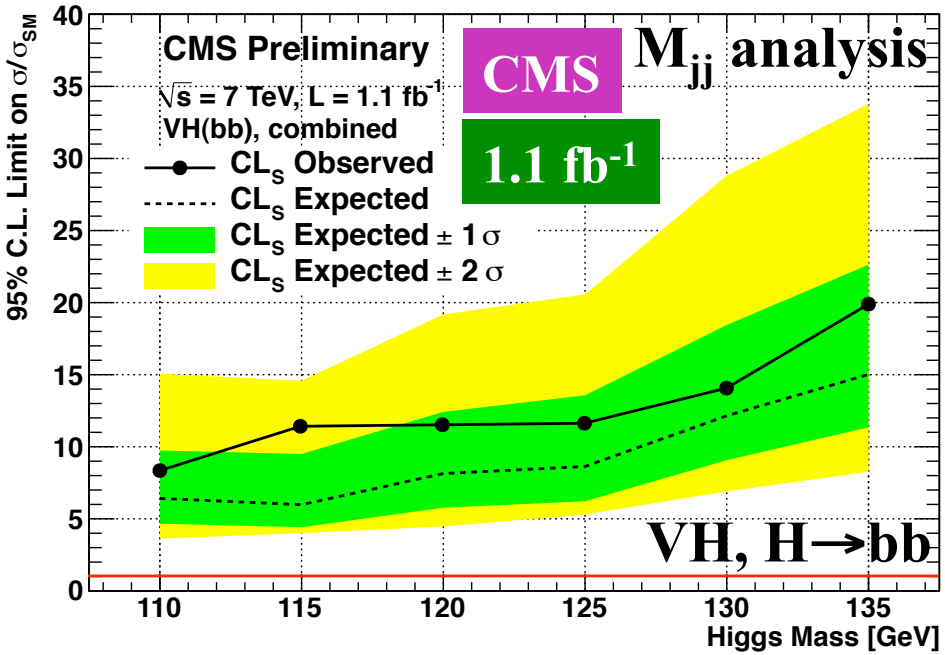
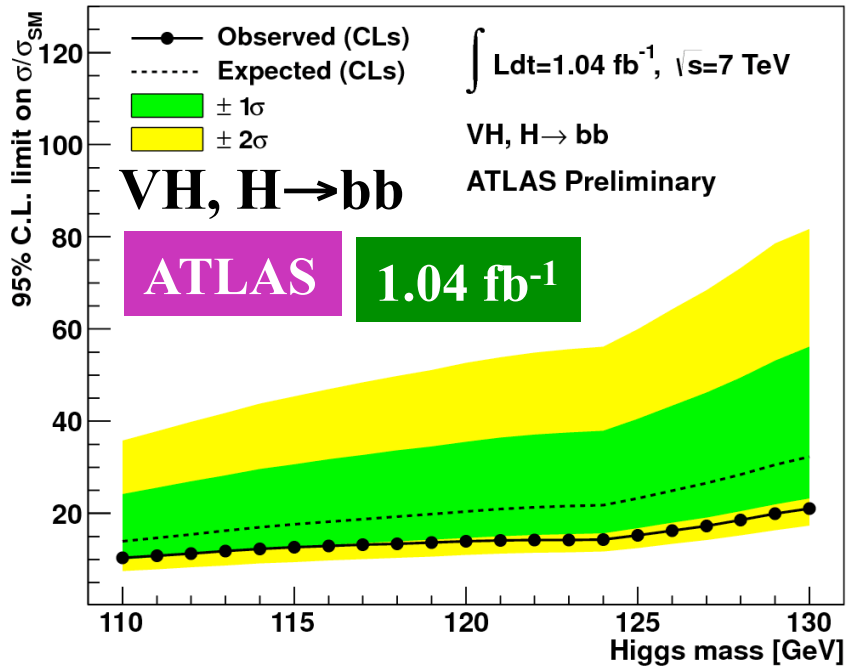
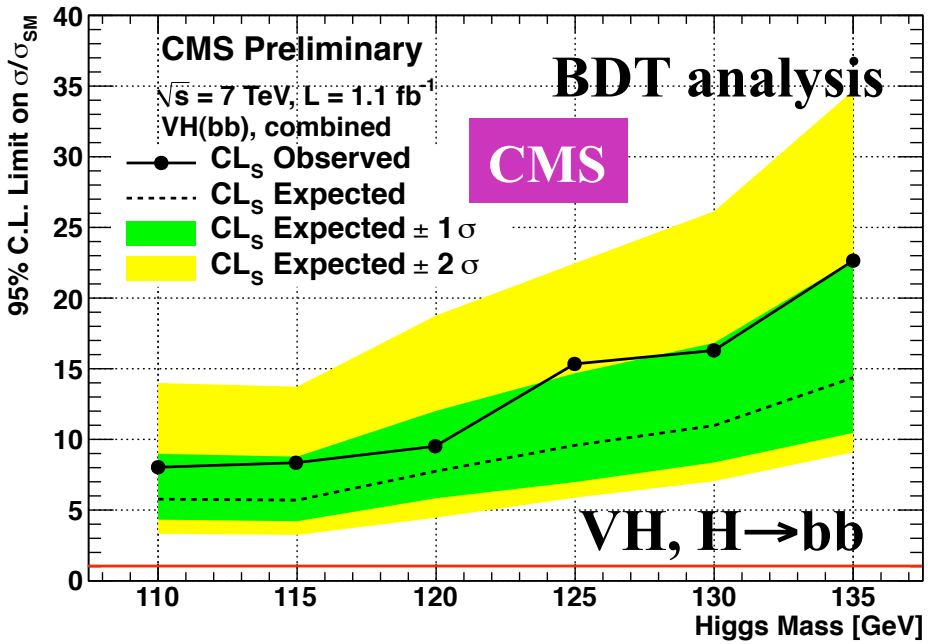



**ATLAS**

**Sensitivity: 15-25 $\sigma_{SM}$**

**Observed: 10-20 $\sigma_{SM}$**

**CMS**

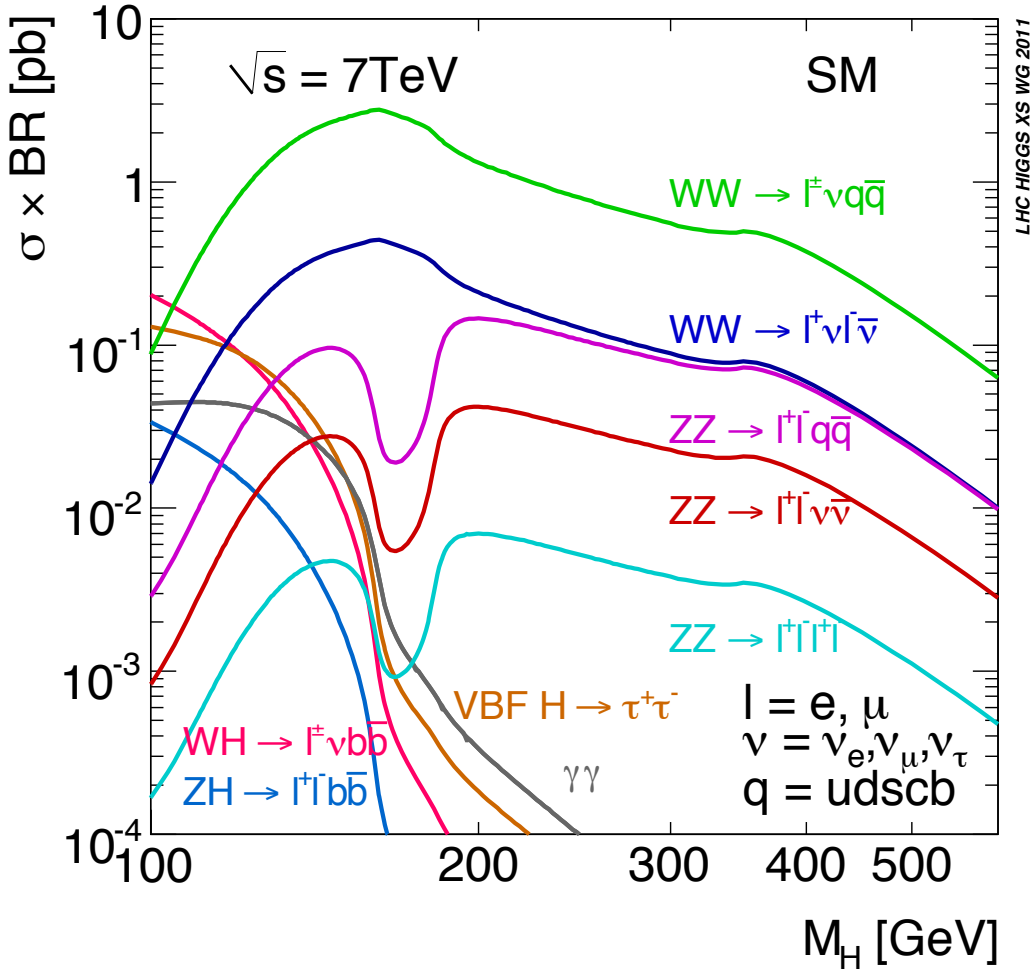
**Sensitivity: 6-14 $\sigma_{SM}$**

**Observed: 8-23 $\sigma_{SM}$**

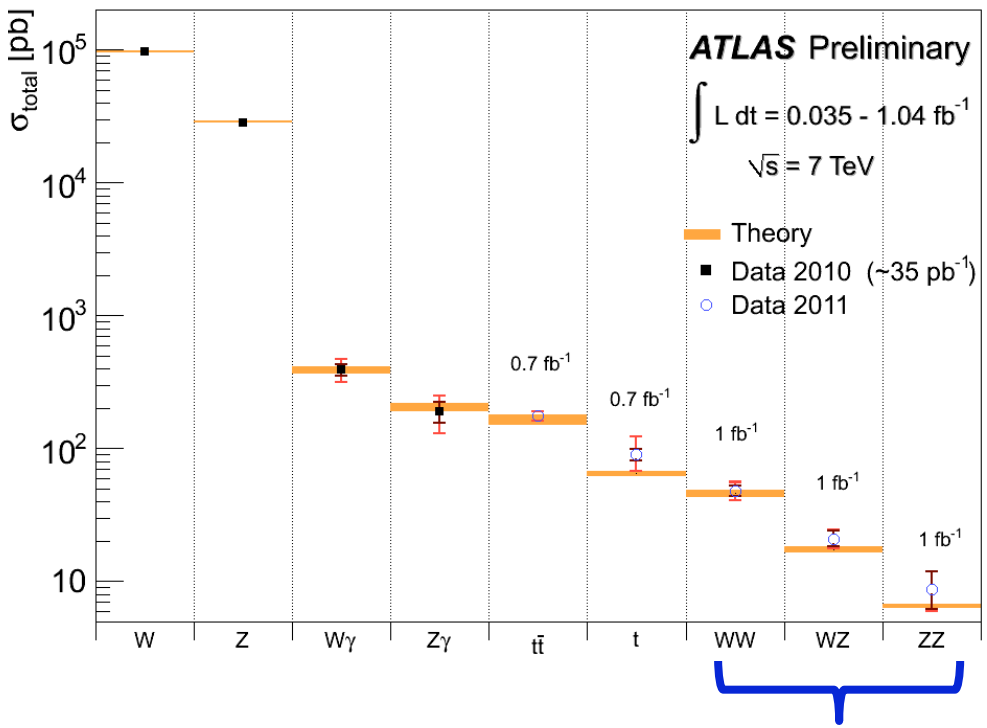
**Boosted Decision Tree (BDT) Analysis:**

**5-10% better**

# SM Higgs Searches @ LHC: extension to high mass




- H→WW
- H→ZZ




SM di-boson production well understood

# ATLAS & CMS: H→WW→lνlν

Imperial College London

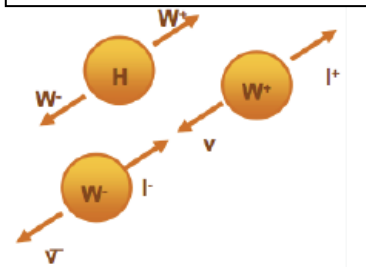
**Highest sensitivity channel in $M_H$~130-200 GeV range**

**Challenges:**

- **Full mass reconstruction not possible:** $m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (p_T^{ll} + p_T^{miss})^2}$
- **Large SM backgrounds: WW (irreducible), Drell-Yan and top**

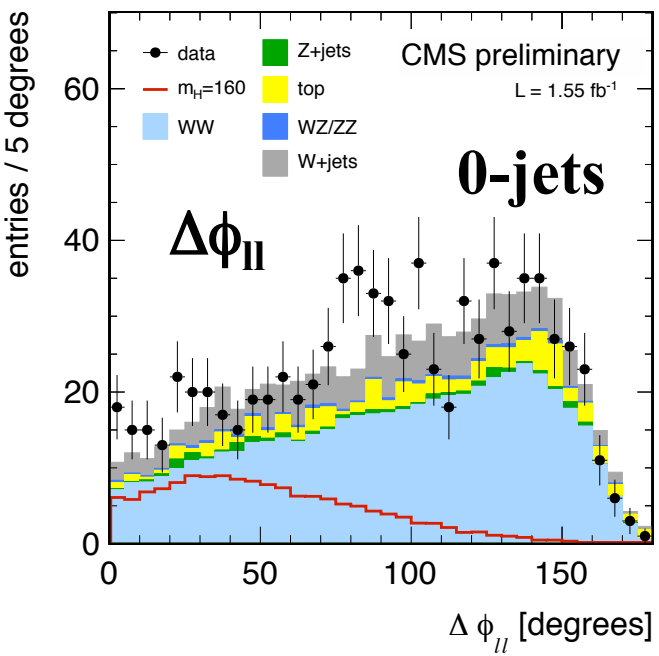
**Increased sensitivity: 0, 1, 2 jet categories. 2-jets: VBF selection**

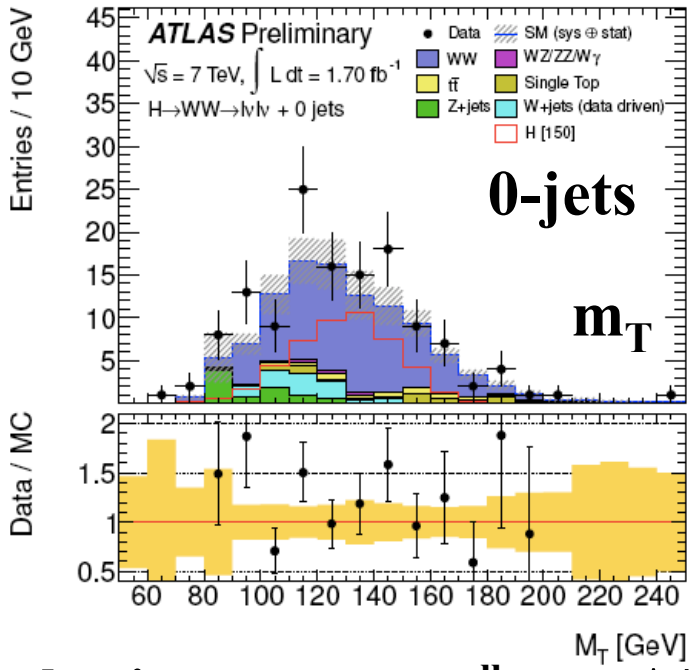
**Talks Thursday**
**G. Cerati**
**H. Gray**

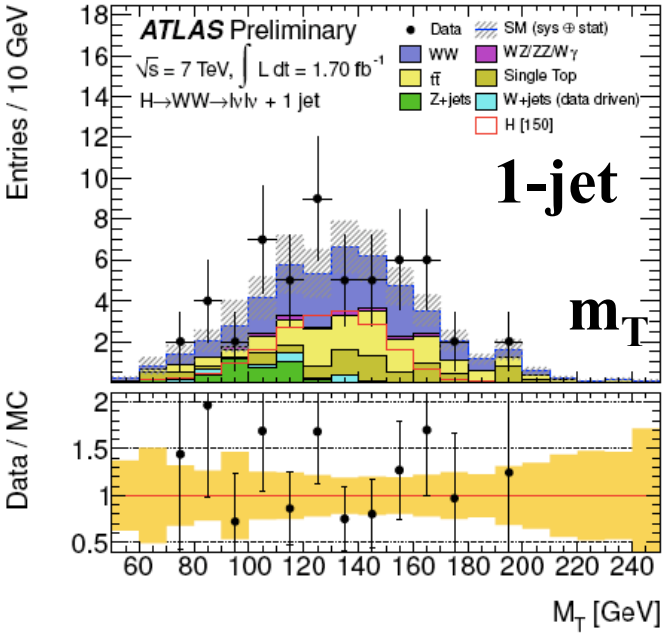



**H→WW: small lepton opening angle $\Delta\phi_{ll}$ due to spin correlations compared to WW**

**Z+jets, WZ,ZZ: Large $E_T^{miss}$ & Z mass window cuts, tt+jets: anti b-tag selection**



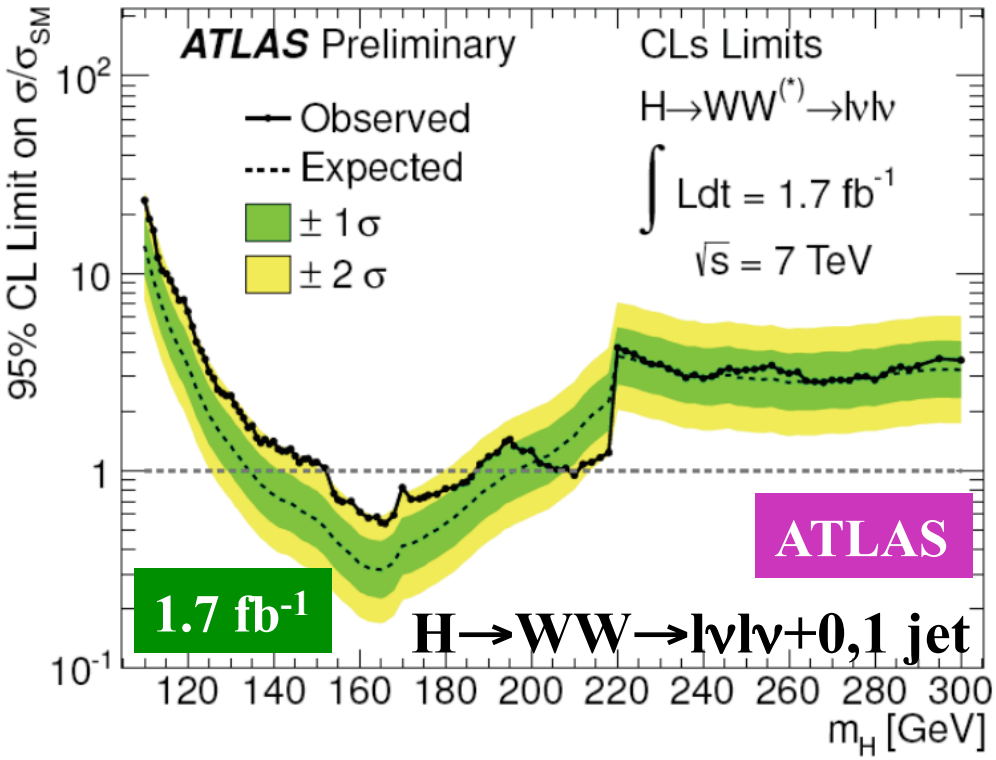



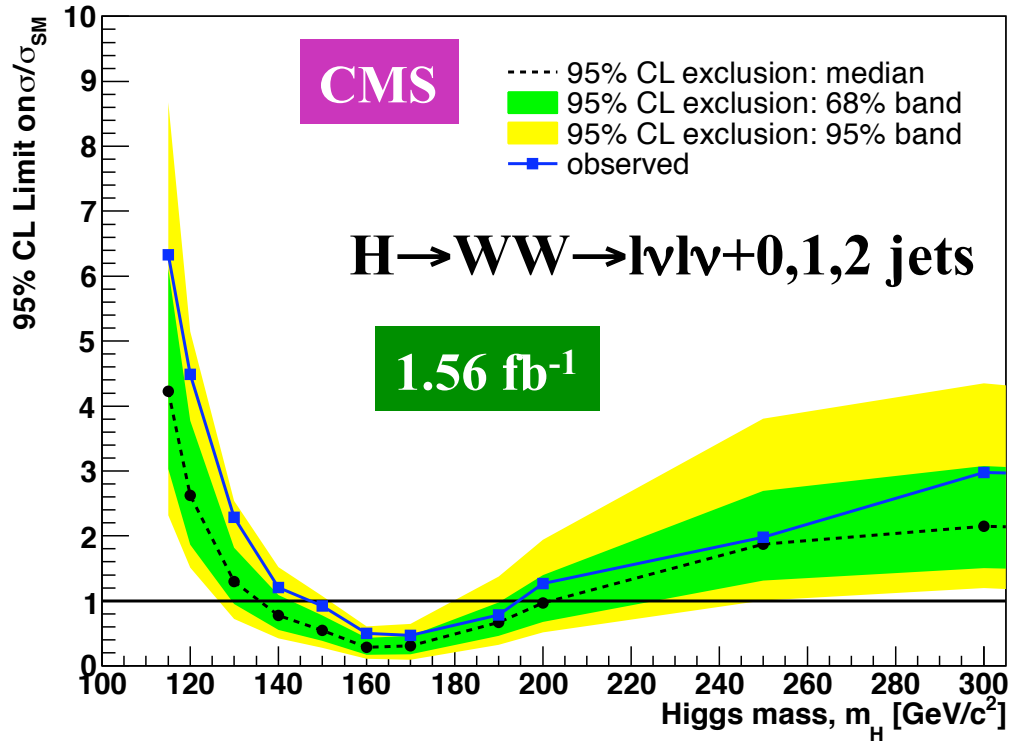

**Cut analysis: topological selections on $m_{ll}$, $p_T^{ll}$, $m_T$, $\Delta\phi_{ll}$ for different $m_H$**

**Multi-variant analysis in preparation**

# ATLAS & CMS: H→WW→lνlν

Imperial College London




**A Standard Model Higgs boson with $154 < m_H < 186$ GeV is excluded at 95% CL**

**A Standard Model Higgs boson with $147 < m_H < 194$ GeV is excluded at 95% CL**

**Expected exclusion:**
**$135 < m_H < 196$ GeV**

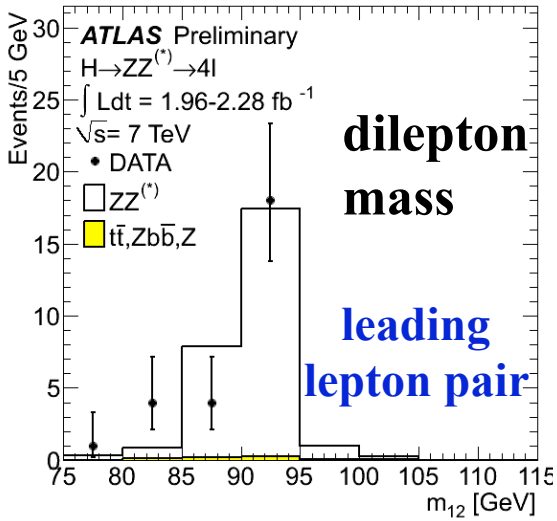
**Expected exclusion:**
**$136 < m_H < 200$ GeV**

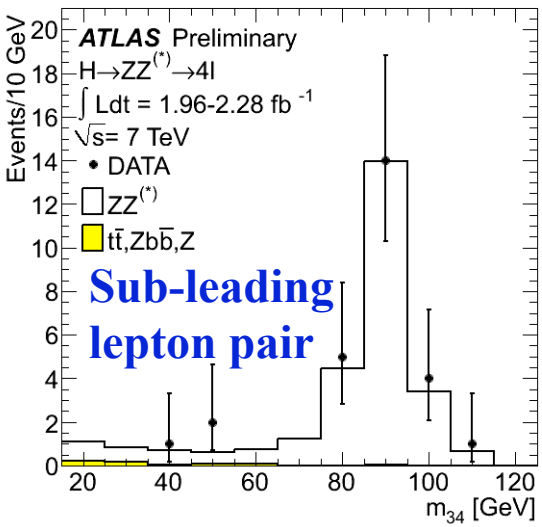
**Observed limit is within 2σ of expected one in mass range 130-150 GeV**

# ATLAS & CMS: H→ZZ→4l

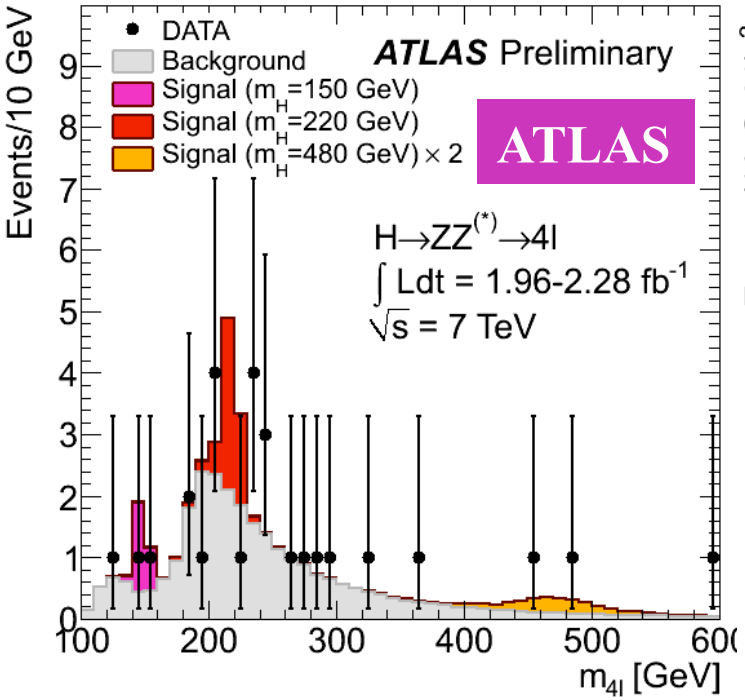
Imperial College London

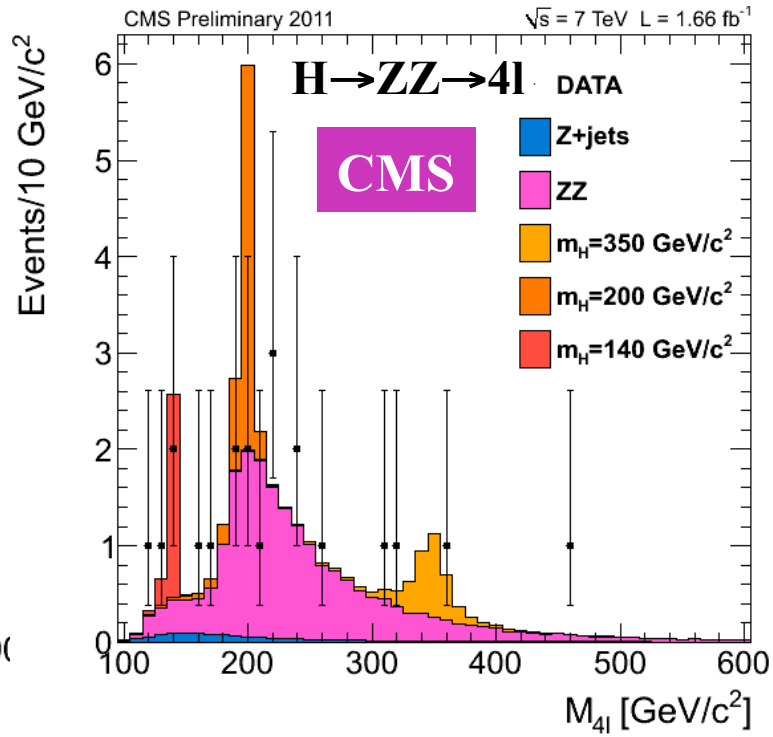
**Cleanest channel at high mass with good mass resolution but low statistics**
**Main background from ZZ**
**Challenge: reconstruction of low-$p_t$ isolated leptons with pile-up**




**Two Z bosons selection:**
**1 tight (on shell) + 1 loose (off shell)**

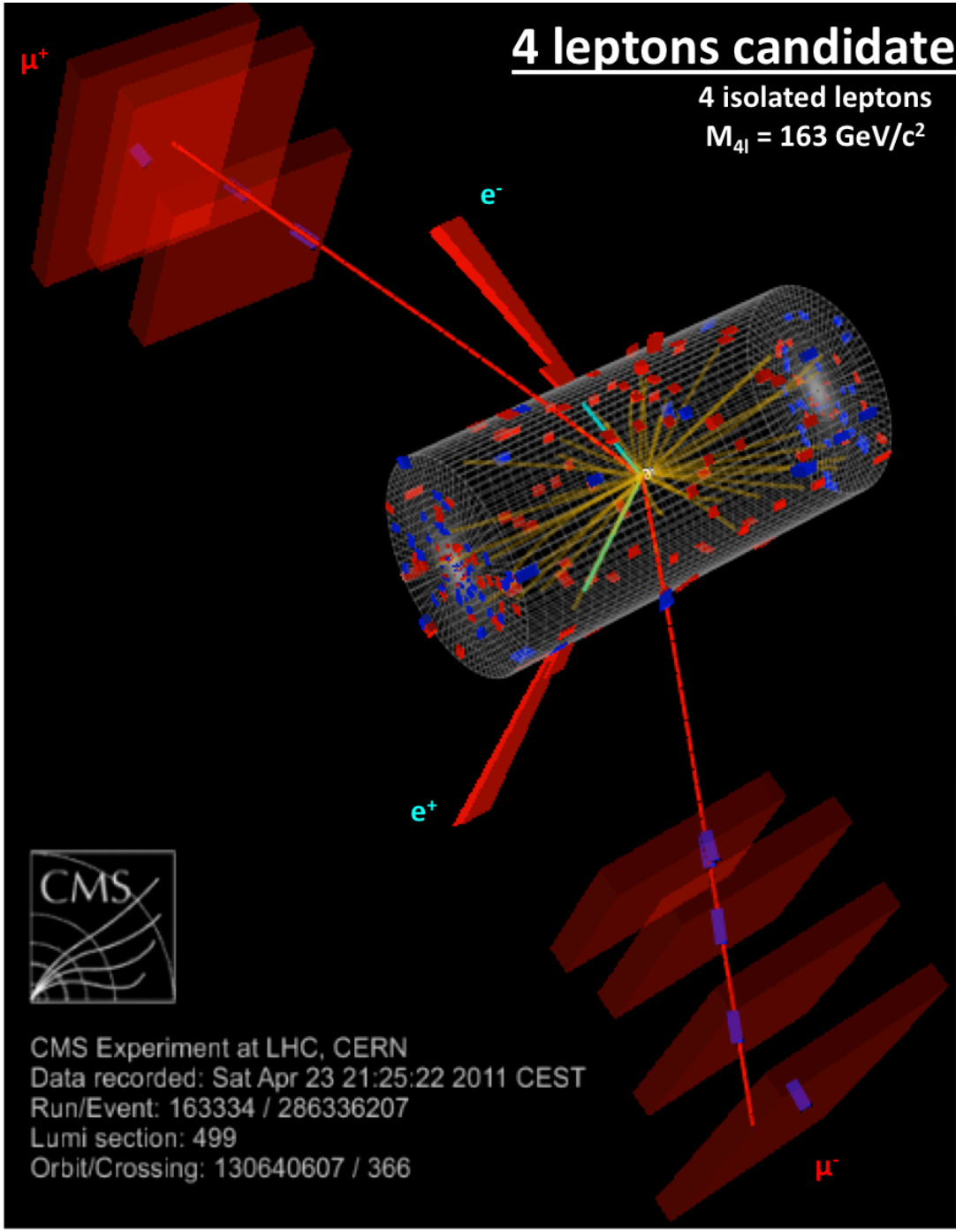


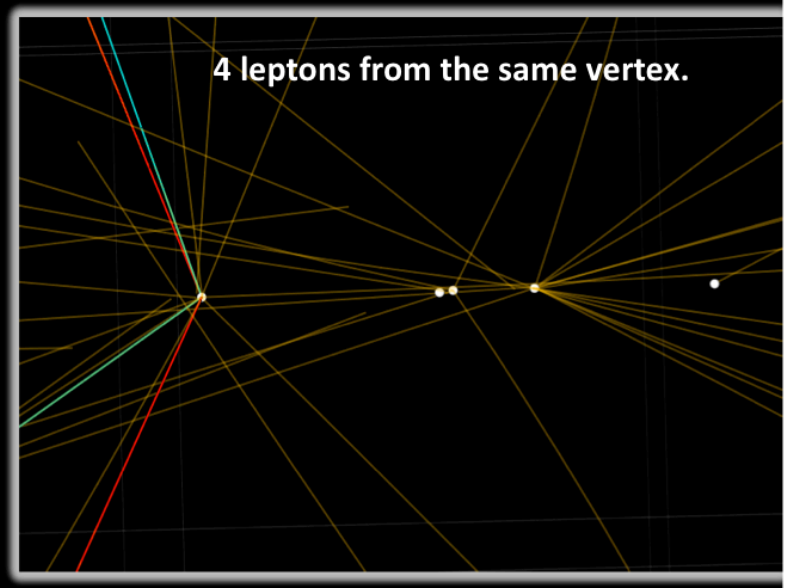



# 4 leptons candidate : 2e2μ

4 isolated leptons

$M_{4l}$ = 163 GeV/$c^2$

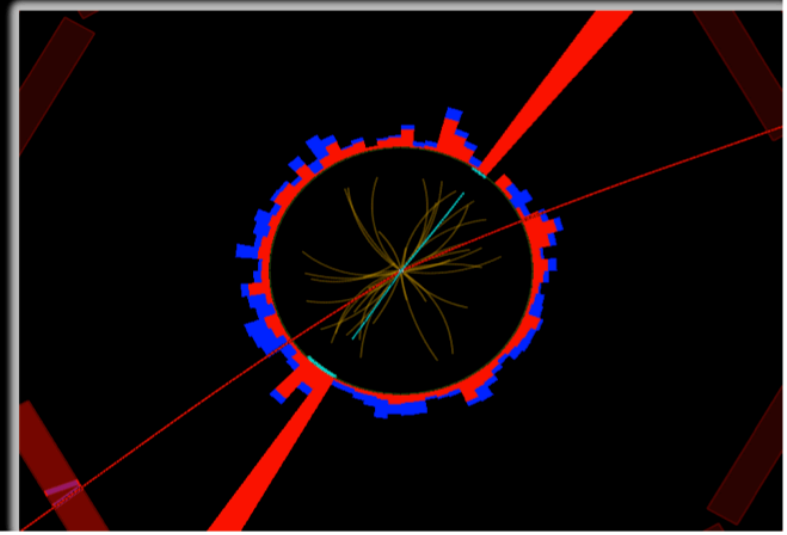



2 leptons pairs

Z (μ+μ-) : m = 94 GeV/$c^2$

Z*(e+e-) : m = 65 GeV/$c^2$



# ATLAS & CMS: H→ZZ→4l

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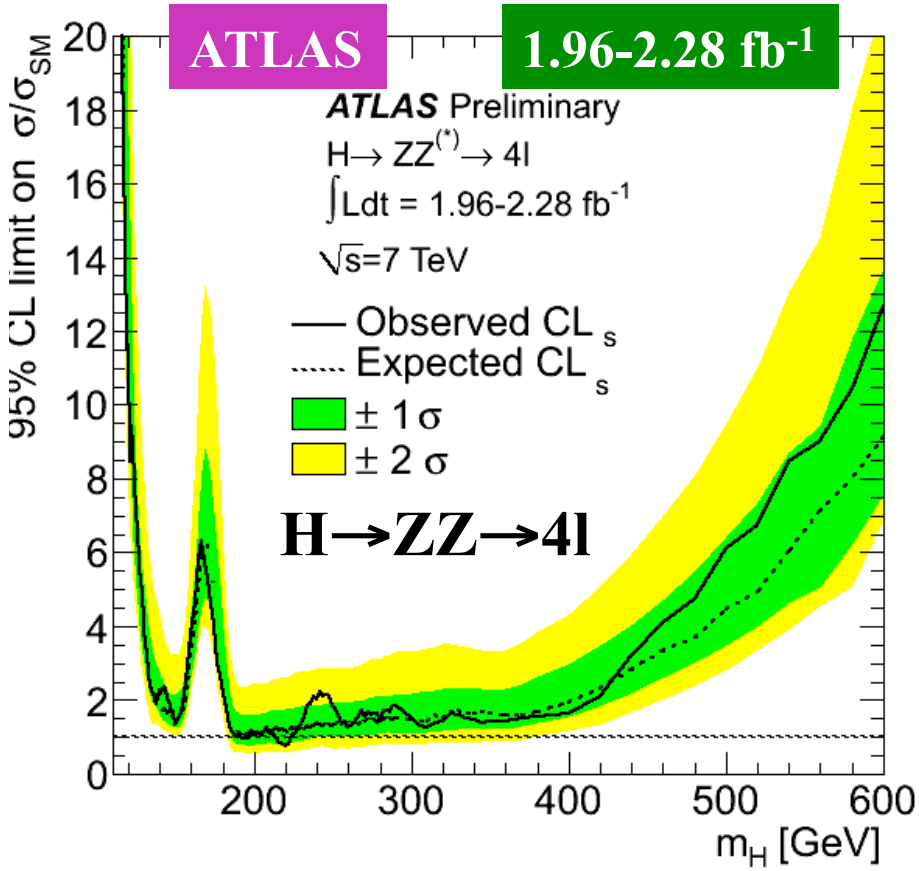
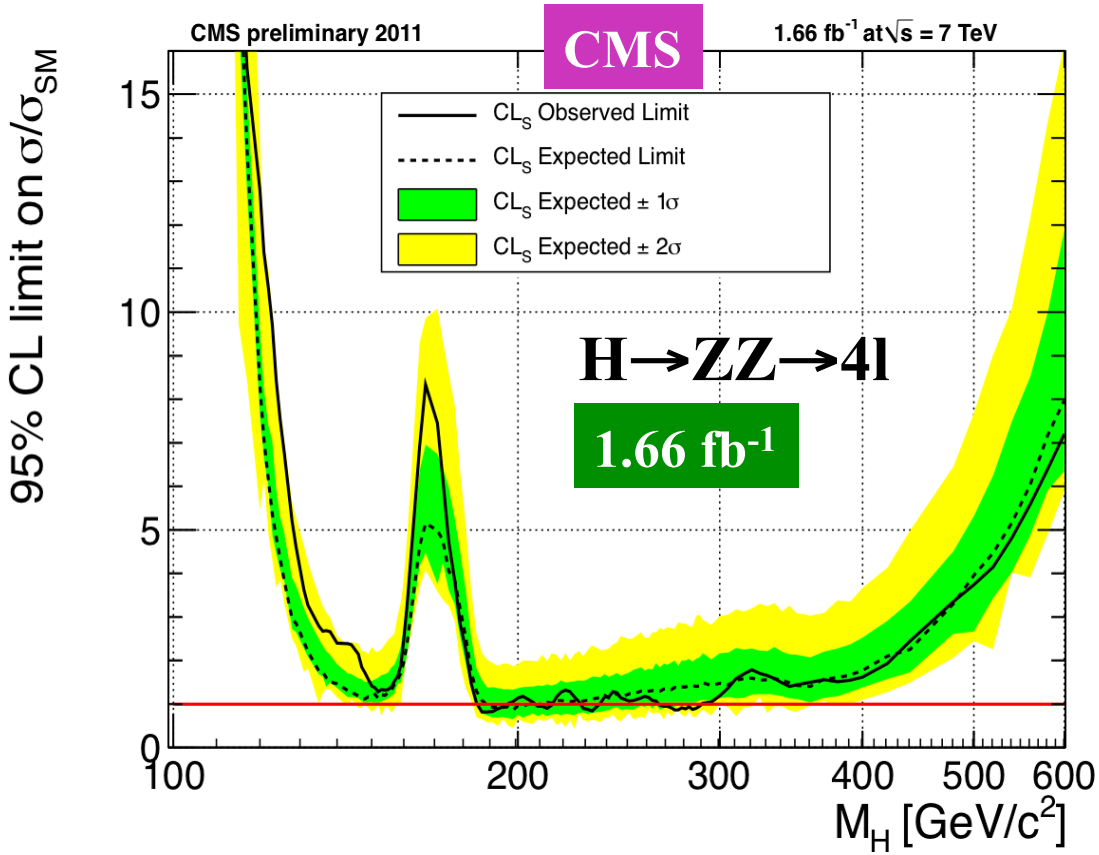



**Sensitivity very close to the SM cross section at high mass**

**1-2 $\sigma_{SM}$ excluded at 95% CL in mass range $150 < m_H < 420$ GeV**

**CMS also studied H→ZZ→2l2τ (backup): excluded 10 $\sigma_{SM}$ between 200-400 GeV**

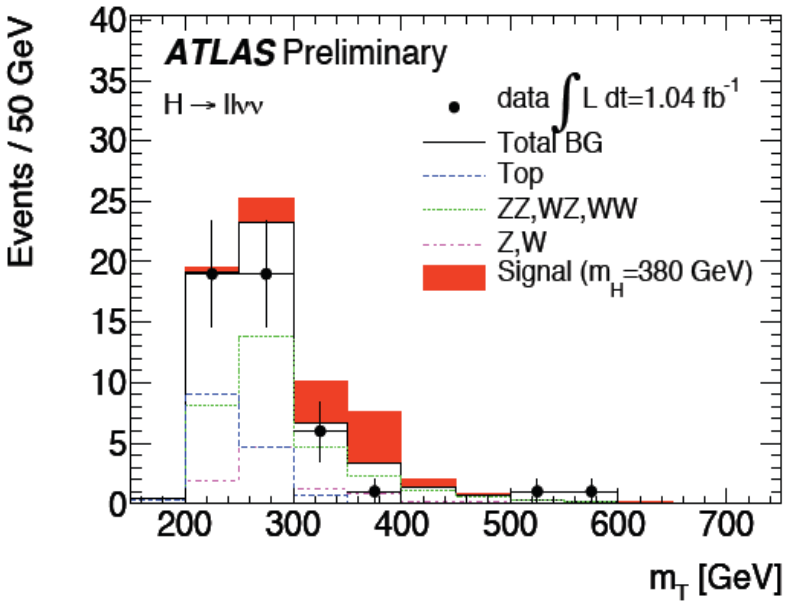
# ATLAS & CMS: H→ZZ→2l2ν

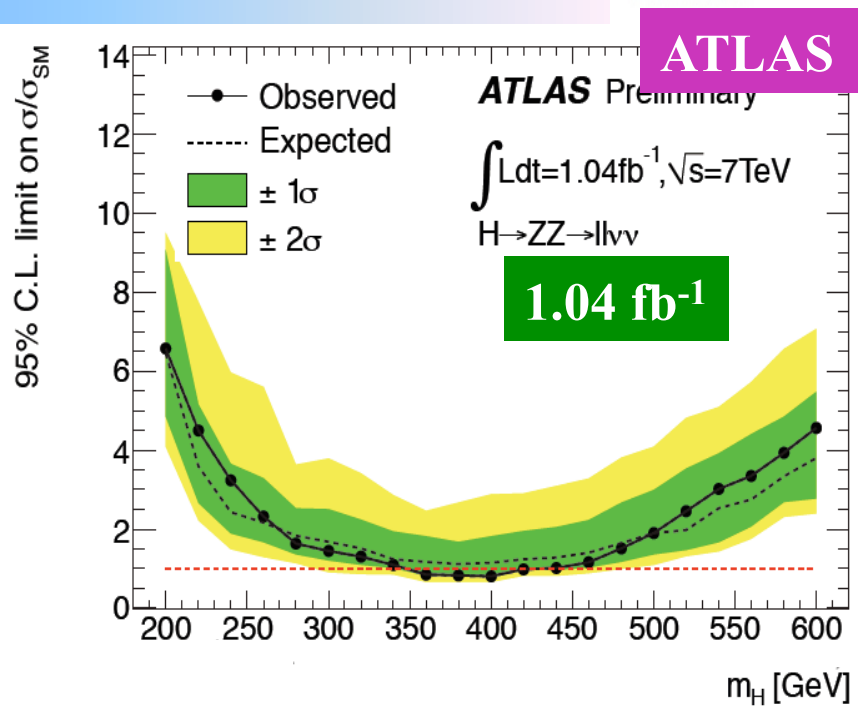
Imperial College London

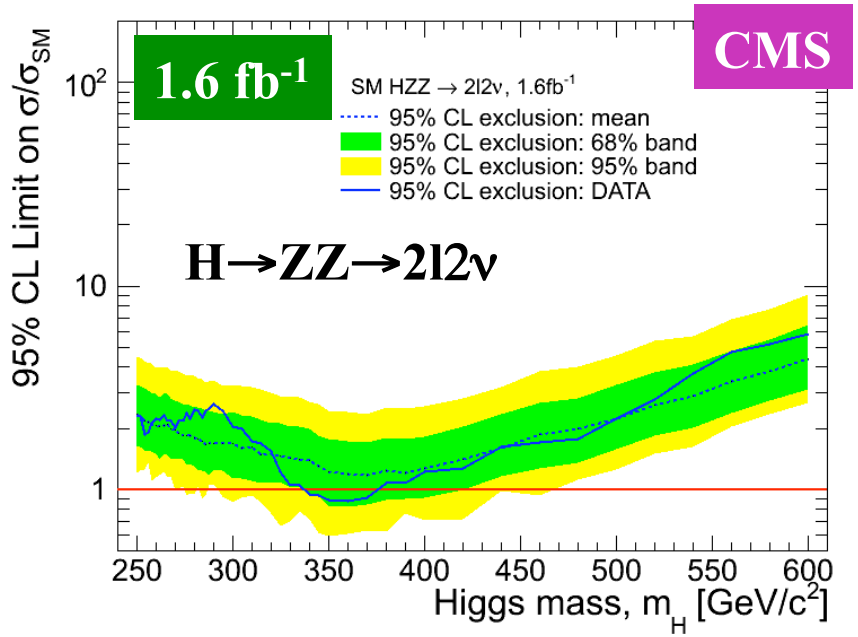
**Benefits from large BR(Z→νν)**

**Challenges:**

* no mass peak: use $M_T(ll\nu\nu)$
* backgrounds: diboson/top suppressed with 3rd lepton & b-tag veto




**Standard Model Higgs boson**

**ATLAS: 350 < $m_H$<450 GeV**

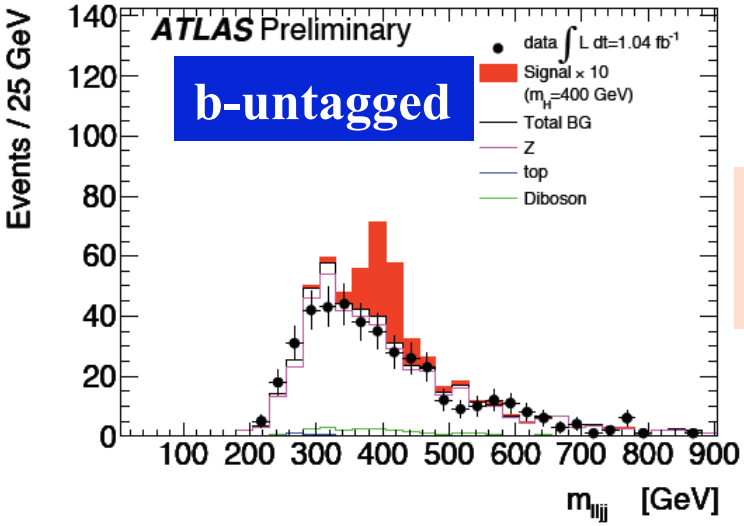
**CMS: 340 < $m_H$< 375 GeV**

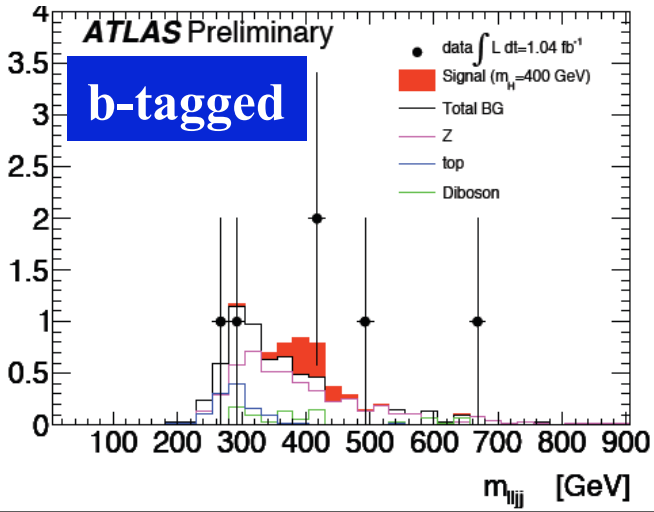
**is excluded at 95% CL**

# ATLAS & CMS: H→ZZ→2l2q

Imperial College London

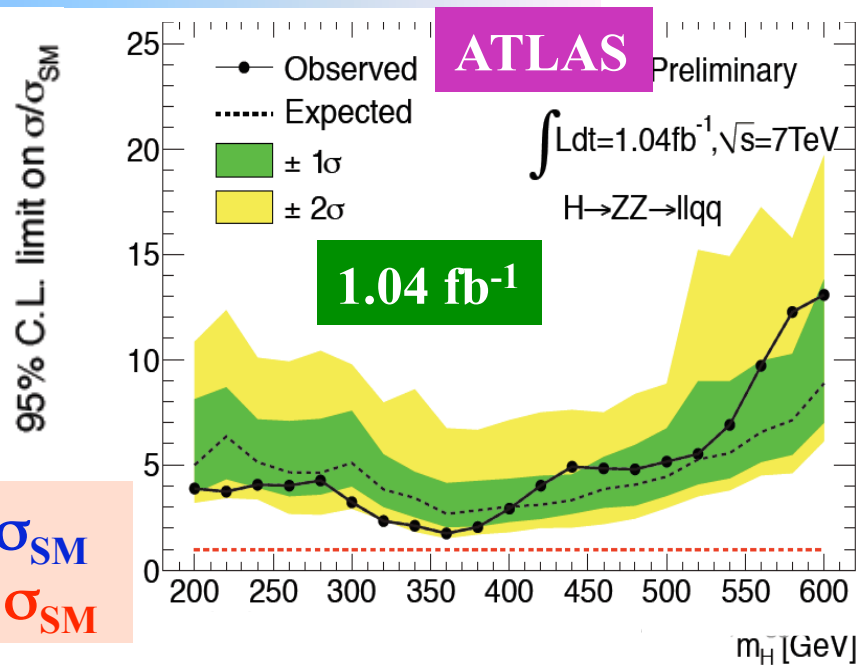
**Benefits from large BR(Z→jj)**
**Dominant background Z+jets**
**Improved Signal/Background ratio:**
**split sample in <2 b-tag and =2 b-tag**

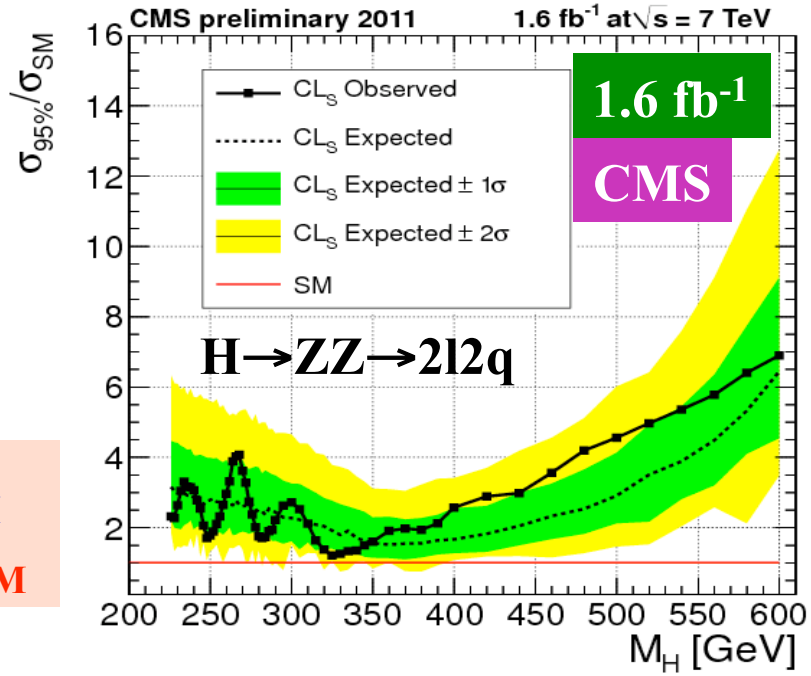



**Sensitivity: 2.7-9 $\sigma_{SM}$**
**Observed: 1.7-13 $\sigma_{SM}$**

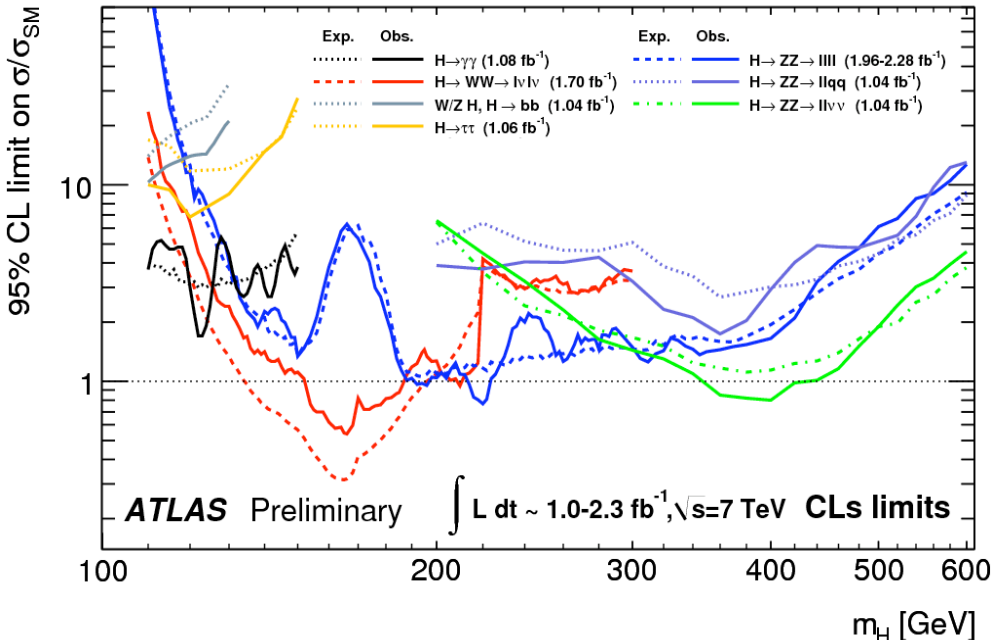
**Sensitivity: 2-5 $\sigma_{SM}$**
**Observed: ~ 1-7 $\sigma_{SM}$**

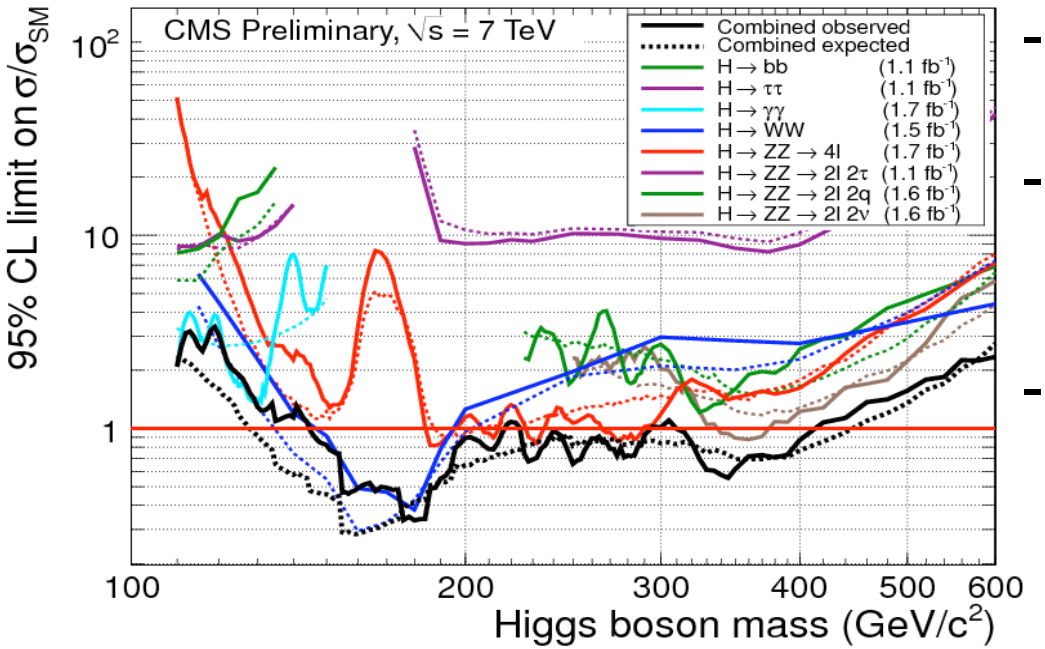


# ATLAS+CMS: Standard Model Higgs Combined Exclusion Limits

Imperial College London




**ATLAS and CMS have agreed on statistical methods for Higgs searches:**

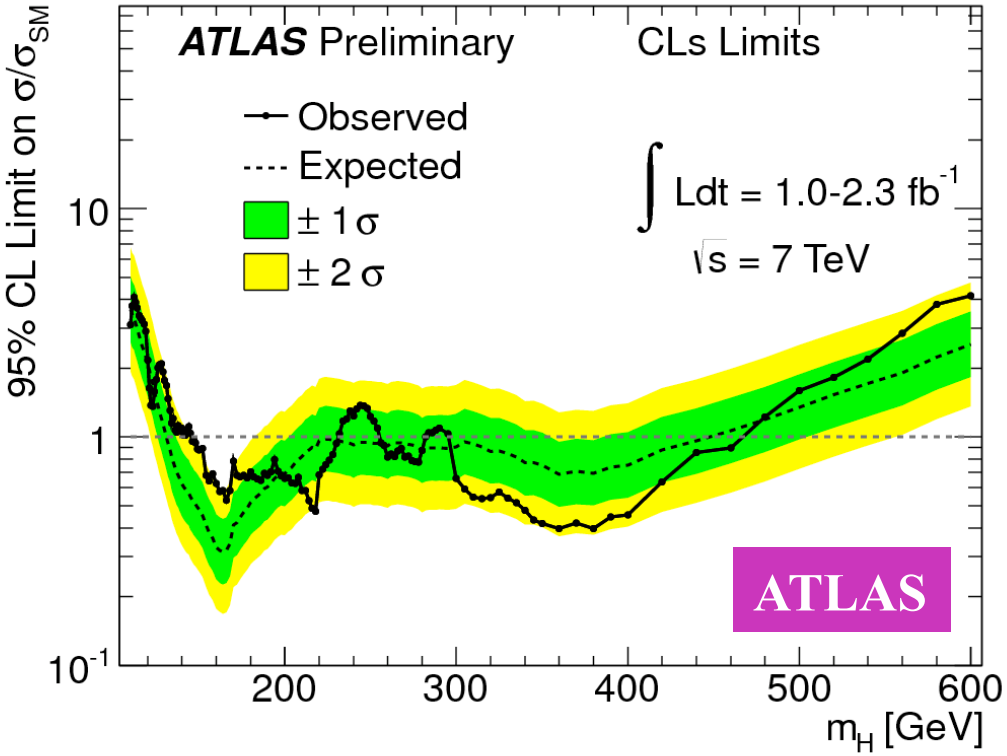
**Modified Frequentist $CL_S$ limits**

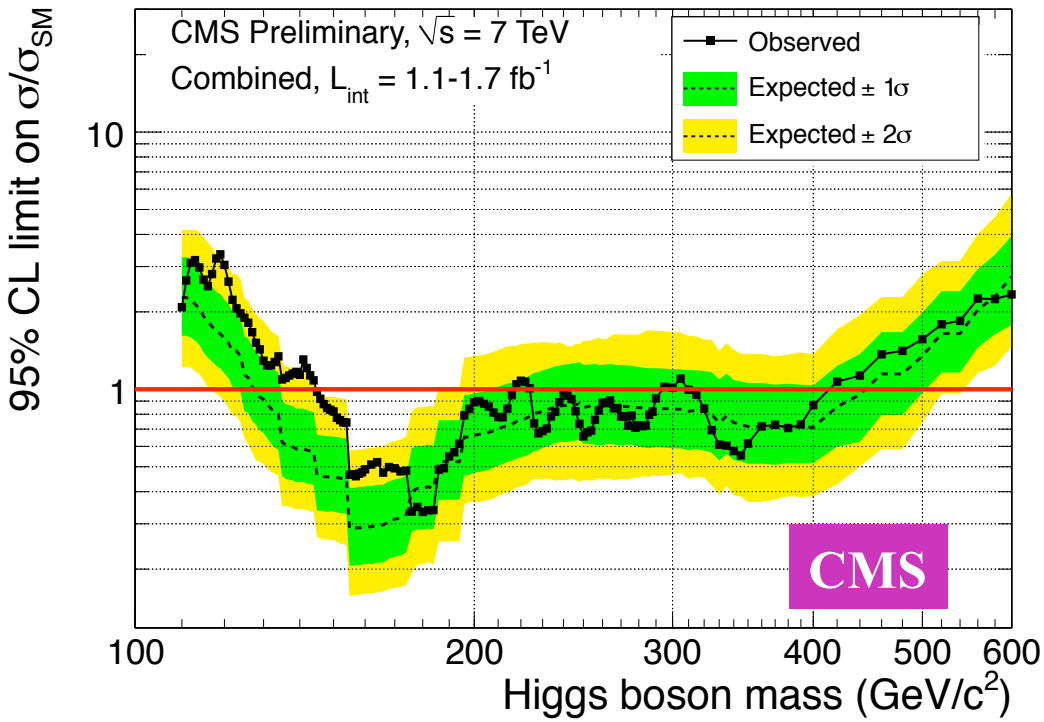
**Bayesian approach used as cross-check**

- **Backgrounds are obtained from data-driven methods**
- **Correlated uncertainties (eg. lumi) considered**
- **Systematics uncertainties are treated as nuisance parameters θ & are "profiled" based on the data**
- **Careful treatment of theoretical uncertainties (common to ATLAS and CMS)**

# ATLAS & CMS: Standard Model Higgs Combined Exclusion Limits

Imperial College London




**Standard Model Higgs boson**
**is excluded at 95% CL:**

$146 < m_H < 232$ GeV
$256 < m_H < 282$ GeV
$296 < m_H < 466$ GeV

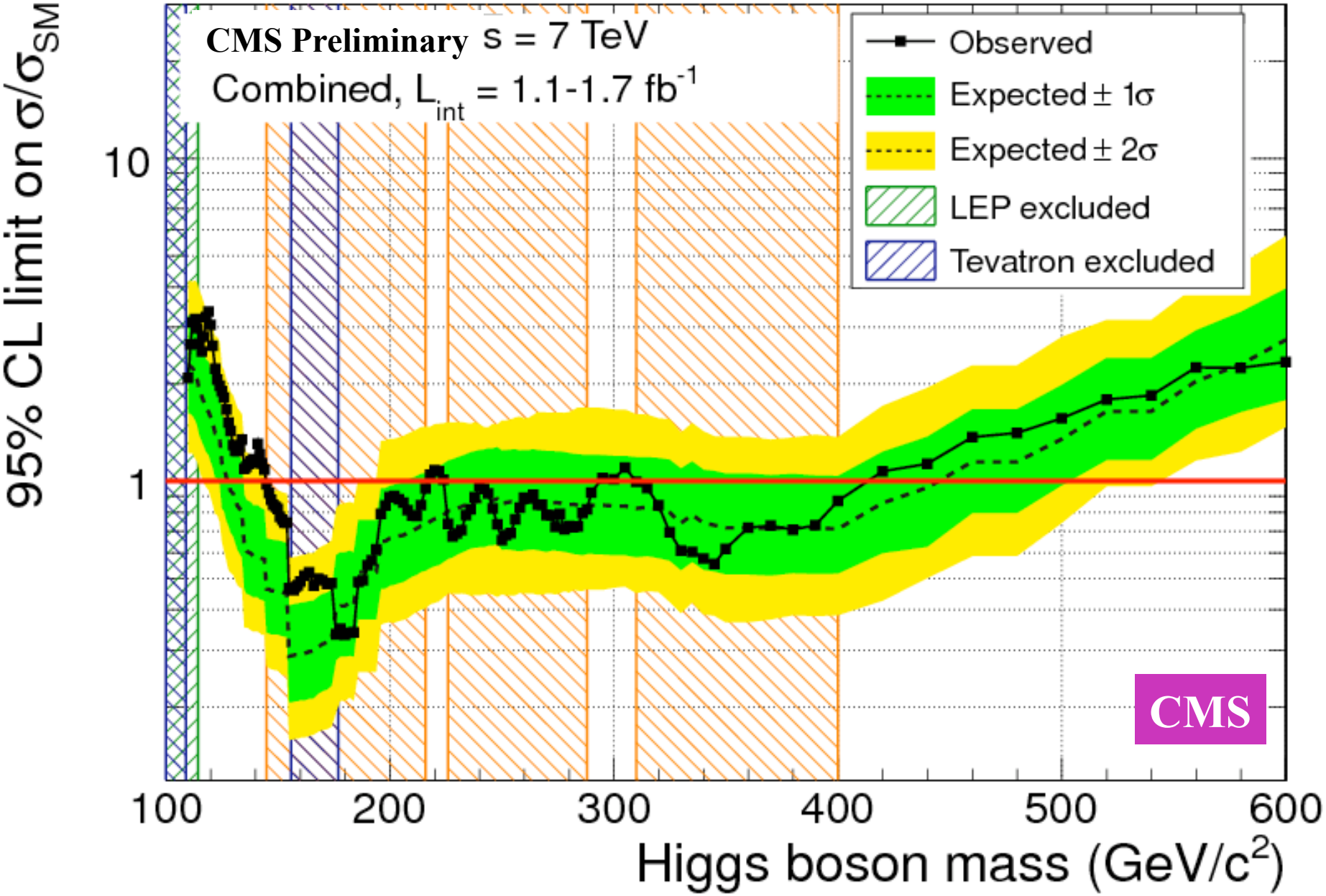
**Standard Model Higgs boson**
**is excluded at 95% CL:**

$145 < m_H < 216$ GeV
$226 < m_H < 288$ GeV
$310 < m_H < 400$ GeV

**No significant excess (<2σ) is found in mass range between 110-600 GeV**

# CMS: Standard Model Higgs Combined Exclusion Limits

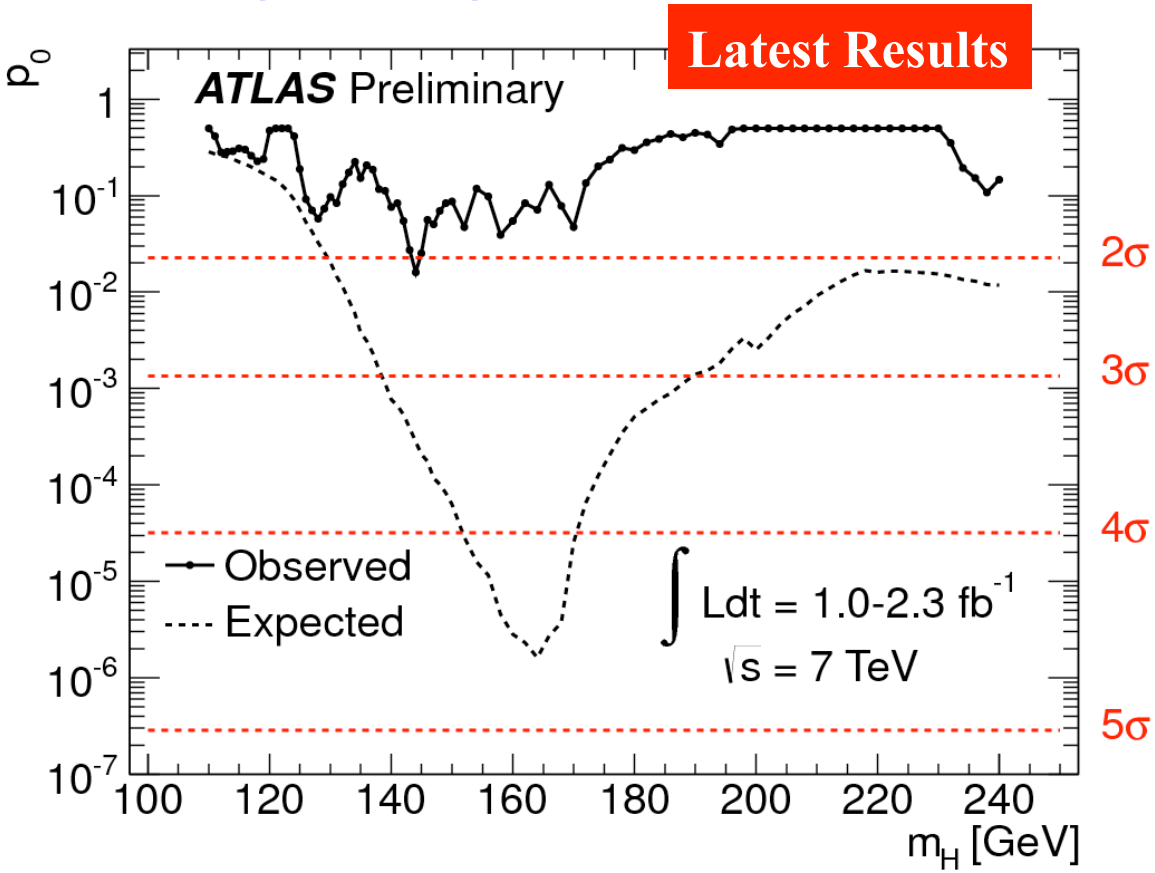
Imperial College London

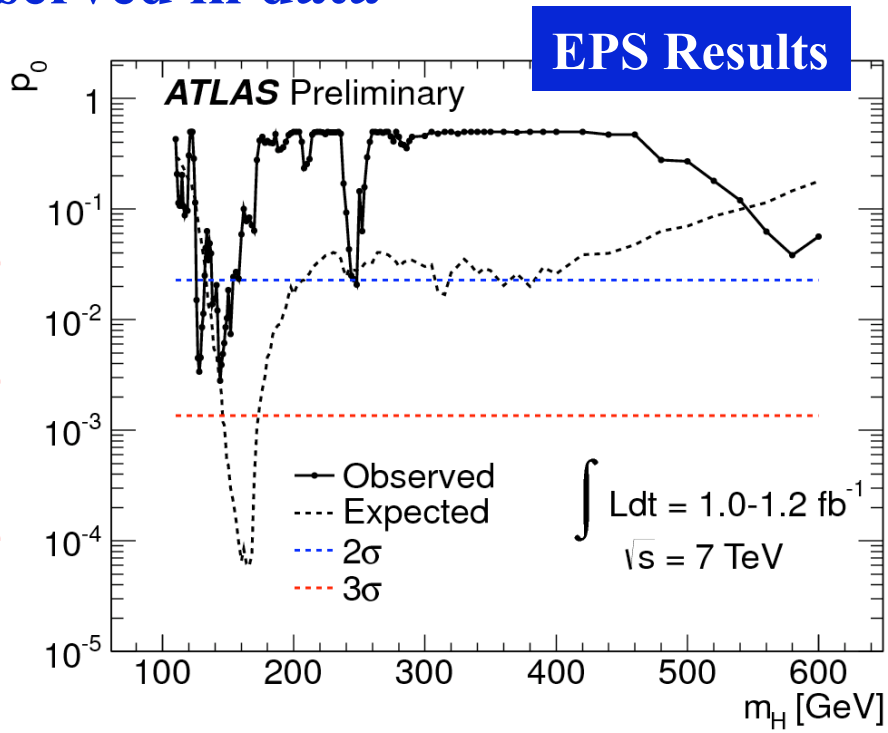


# ATLAS: Observed Combined p-value

Imperial College London

**p-value estimates probability of upward background fluctuation as high or higher than the excesses observed in data**




**The overall consistency of excesses with expected signal from presence of Standard Model signal is displayed**

## EPS results

**127 GeV: broad excess in WW→lνlν and excess in H→γγ ➔more data less significant**

**245 GeV: 2σ excess due to accumulation of ZZ→4l events ➔more data less significant**

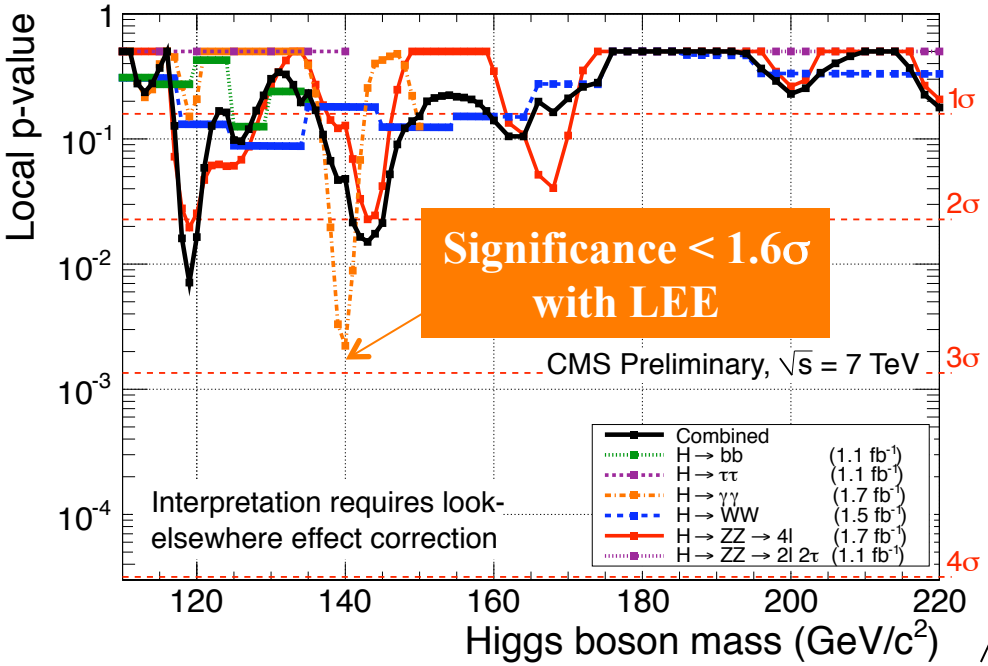
**144 GeV: 2.8σ excess due to broad excess in WW→lνlν and 1 ZZ→4l event ➔more data significance 2σ, with probability of a background fluctuation at the percent level**

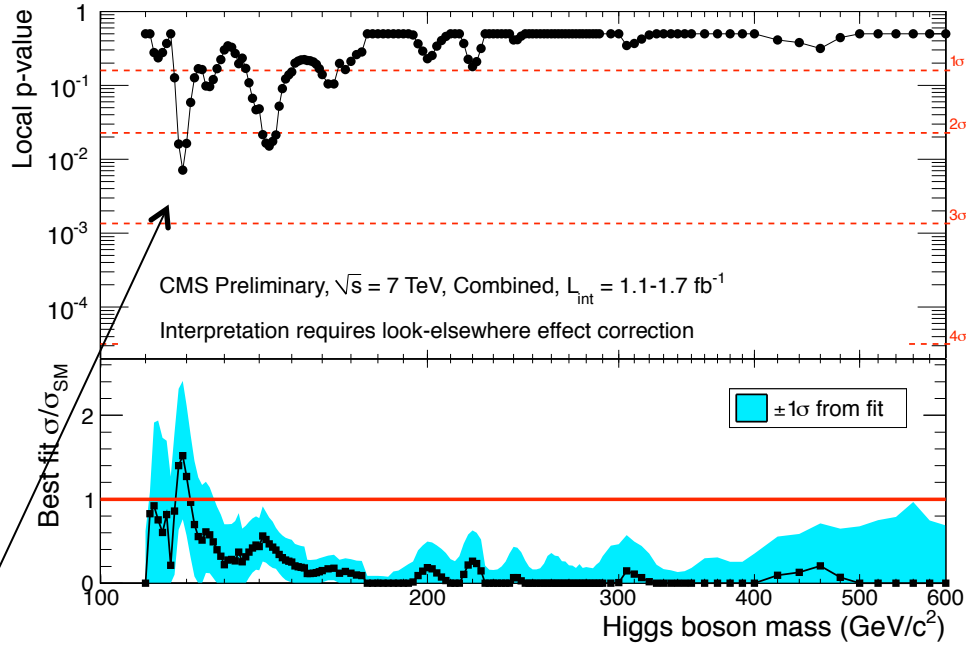
# CMS: Observed Combined p-value

Imperial College London

## Consistency of the observed results with background-only hypothesis

**The p-value curve dips downward over a broad range of low masses, driven by broad excess seen in WW→lνlν, with a few narrower features corresponding to ZZ→4l events and modulations seen in H→γγ**




**The minimum local p-value is $p_{min}$ =0.01 with local significance $Z_{max}$ = 2.3σ.**

**After considering the look-elsewhere effect, the probability to see an excess at least as large as the one observed in data is 0.4.**

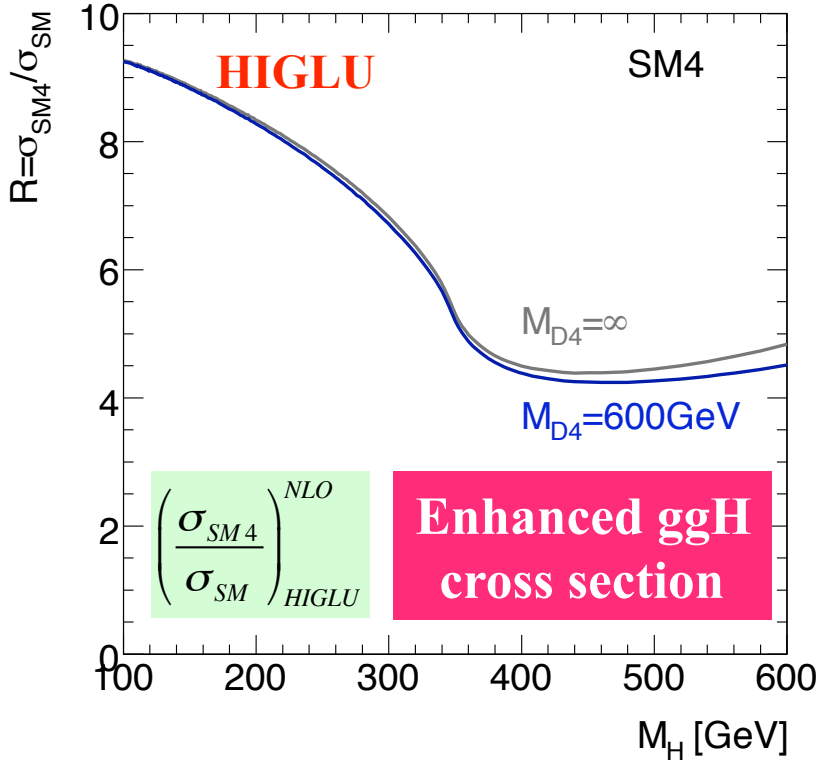
**Best fit for $\hat{\mu} = \sigma / \sigma_{SM}$ $M_H$: 117-120 GeV: 1xSM, 140 GeV: 0.6xSM**

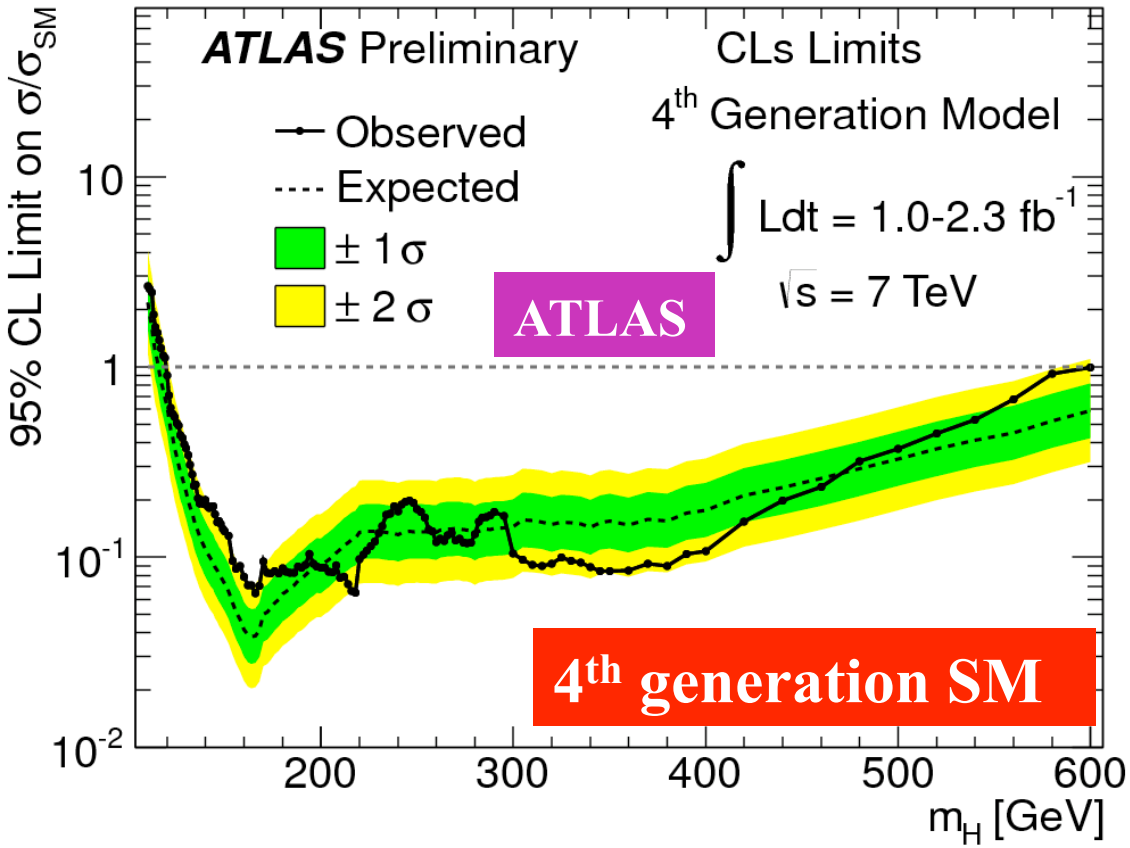
**→ With the current amount of data, the excess is not significant**

# Standard Model + 4th generation

Imperial College London

## Enhanced WW/ZZ cross section




**Unitarity arguments: $M_{Q4}$< 500 GeV**

**Phys.Rev. D 40 (1989) 1725**

**Interesting mass range: 400-600 GeV**

**Phys. Rev. D76 (2007) 075016**

**$M_{D4}=M_{L4}=600$ GeV**

**$M_{U4} - M_{D4} = [\ 1 + 1/5*\ln(M_H/115)\ ] * 50$ GeV**

**Higgs boson in SM+4th Generation excluded @95% CL:**

**$120 < m_H < 600$ GeV**

# BSM Higgs Searches @LHC

# Standard Model and Supersymmetry

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**Standard Model does great job describing physics at weak scale, but Hierarchy problem in Higgs sector**

**If Higgs boson is fundamental particle**

**i) there are no high-mass particles which couple to the Higgs field (even indirectly)**

**ii) Striking cancellation are needed in high-order loop corrections to $m_H$**

**SUSY at TeV scale elegant solution to hierarchy problem**

**- Introduces super-partners of SM particles and cancels problematic loop corrections**

**Minimal supersymmetric extension of SM there are 2 scalar doublets $\Phi_1, \Phi_2$**

**After EW symmetry breaking:**

**5 physical Higgs bosons**
- **h, H (scalar, CP-even)**
- **A (pseudo-scalar, CP-odd)**
- **$H^\pm$ (charged)**

**β (VEVs): $\tan\beta = v_2/v_1$ $[v_1^2+v_2^2 = v^2 = 2M_Z^2/(g_2^2+g_1^2) = (246\ \text{GeV})^2]$**

- **MSSM Higgs sector @ tree level determined by: $M_A$ & tanβ**

# MSSM: Neutral Higgs Production

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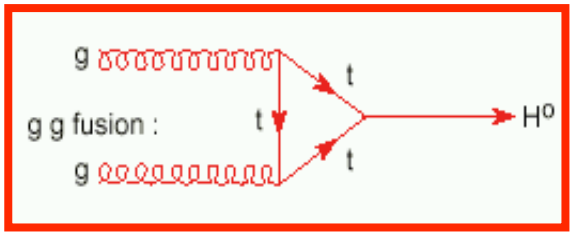
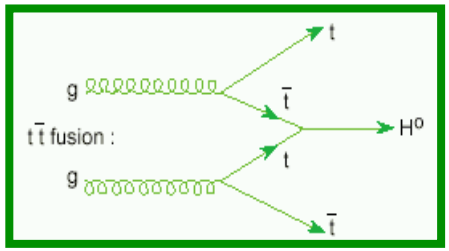


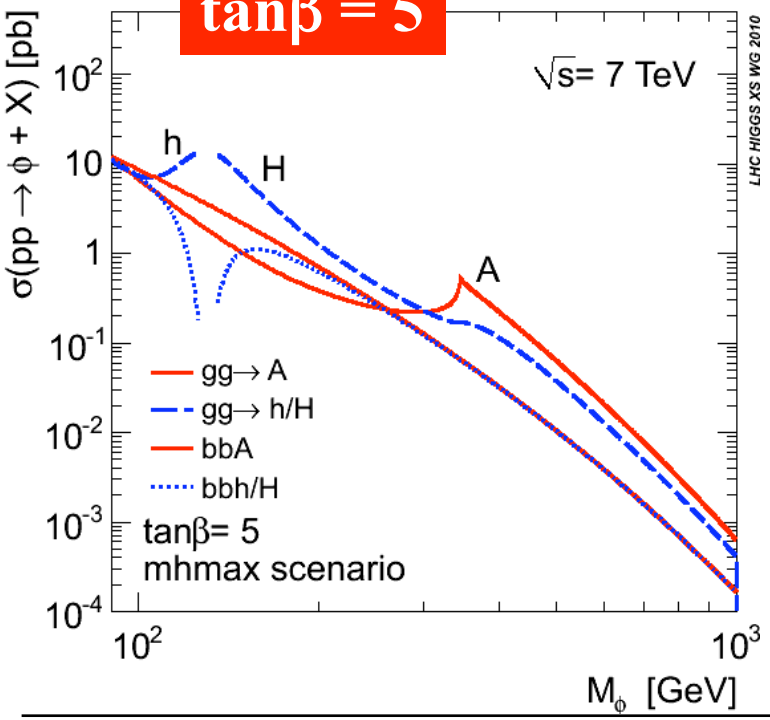

**gg fusion: dominant at small & moderate tanβ compared to associated production. Mediated by top/ bottom loops (also stop/sbottom loops for M < 400 GeV)**

**Associated production: ttΦ only important for h**
**bbΦ dominant process for large tanβ**

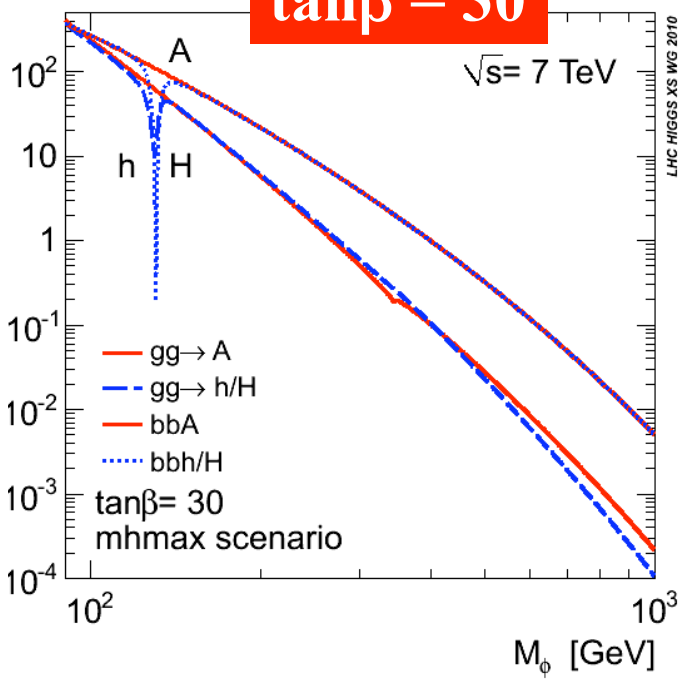



**mhmax scenario**

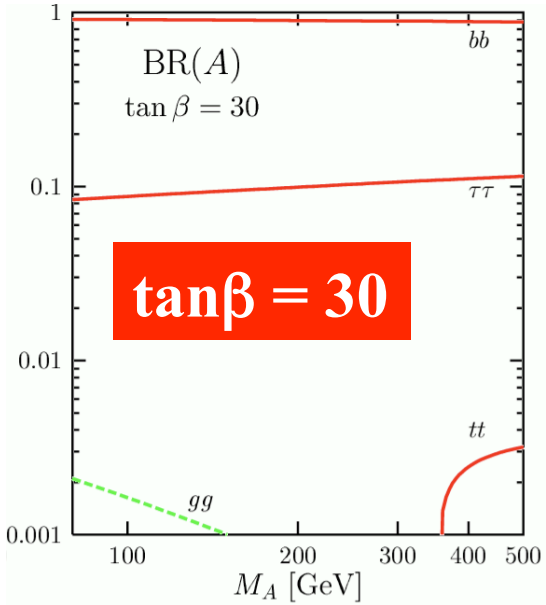
**tanβ = 5**




**tanβ = 30**




**Enhanced ττ coupling**




**tanβ = 30**

# ATLAS+CMS: MSSM H→ττ

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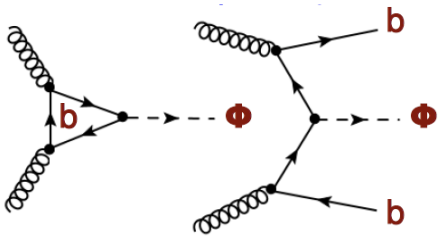
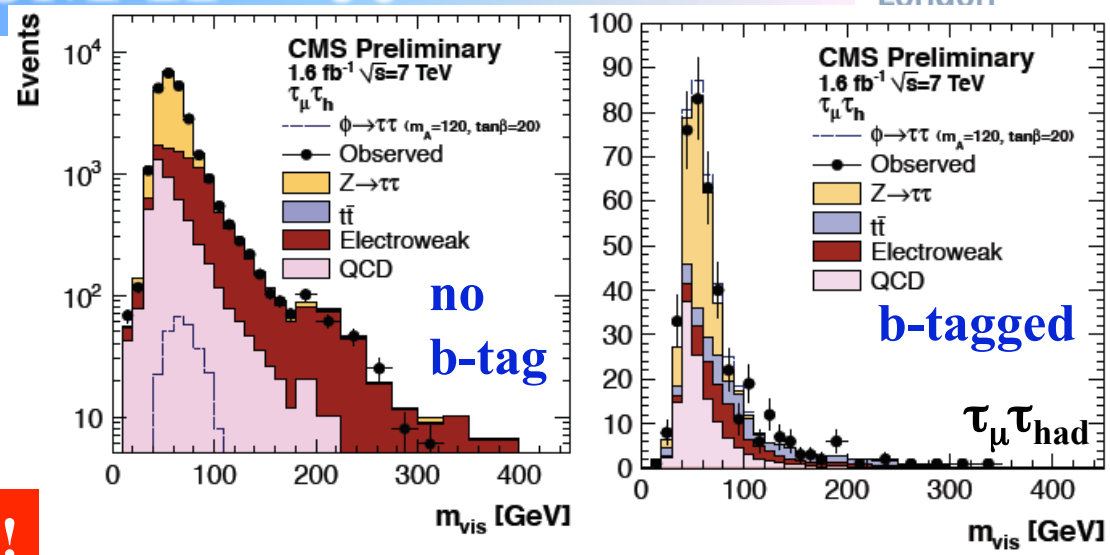
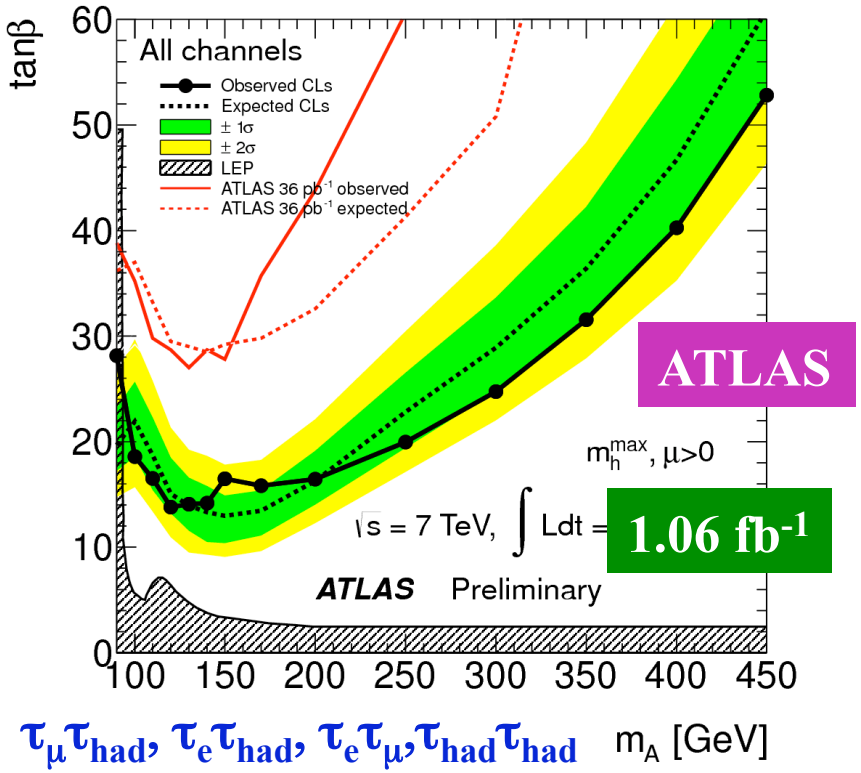
**Increase sensitivity:** samples with/ without at least one b-tagged jet

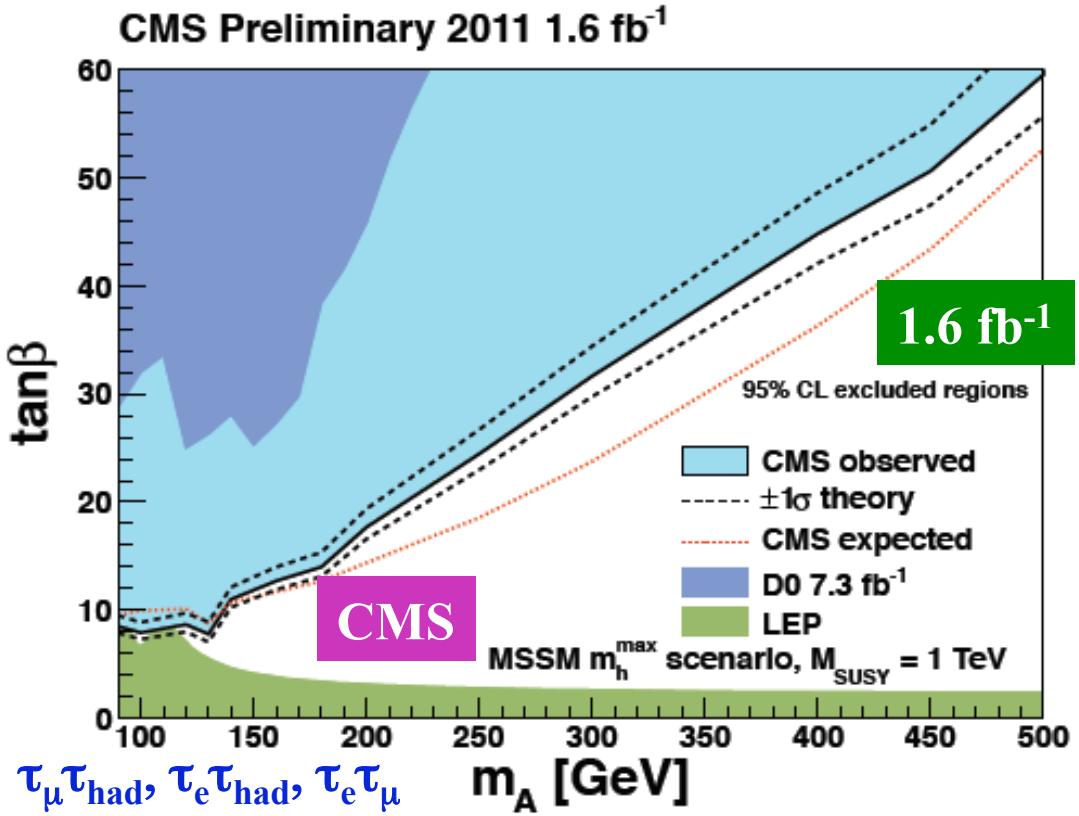



**Large region in $m_A$-tanβ excluded!**




$\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_e\tau_\mu$, $\tau_{had}\tau_{had}$




$\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_e\tau_\mu$

# MSSM: Charged Higgs Production

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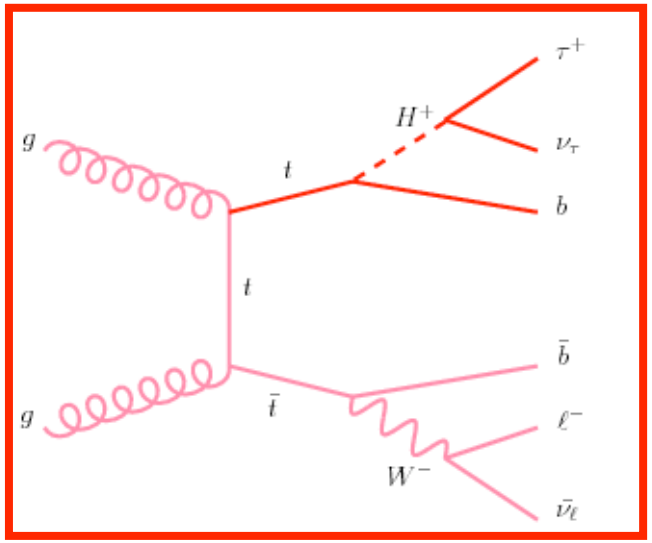
## top quark decay



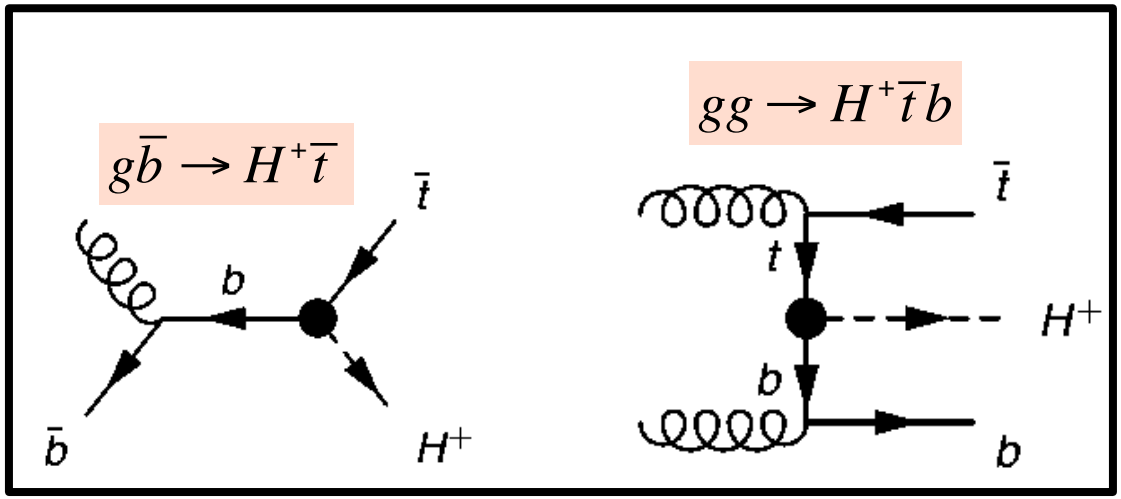

**Light Charged Higgs**

$$t \to bH^{\pm} + X \quad M_{H^{\pm}} \leq m_t$$

**$H^+$ Decays**

- Small tanβ: $H^+ \to cs$ important
- Large tanβ: $H^+ \to \tau\nu$ important

## Associated production




**Heavy Charged Higgs**

$$pp \to tbH^{\pm} + X \quad M_{H^{\pm}} \geq m_t$$

# ATLAS+CMS: MSSM Charged Higgs

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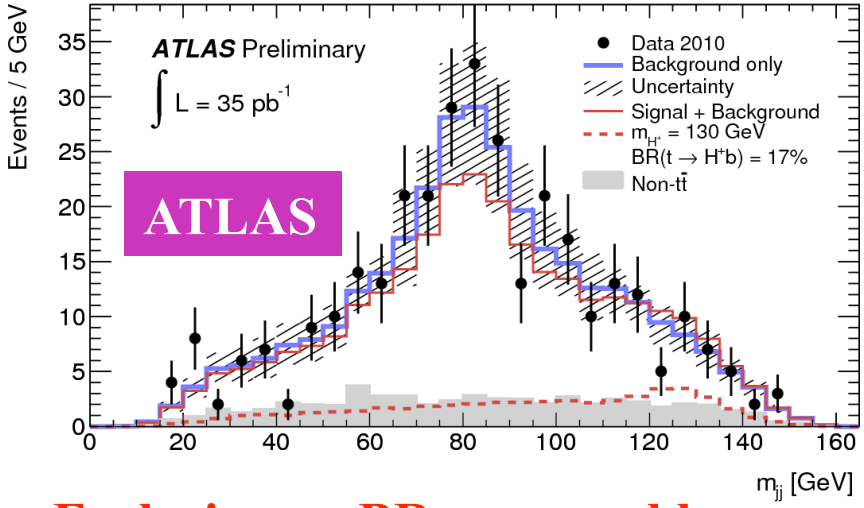
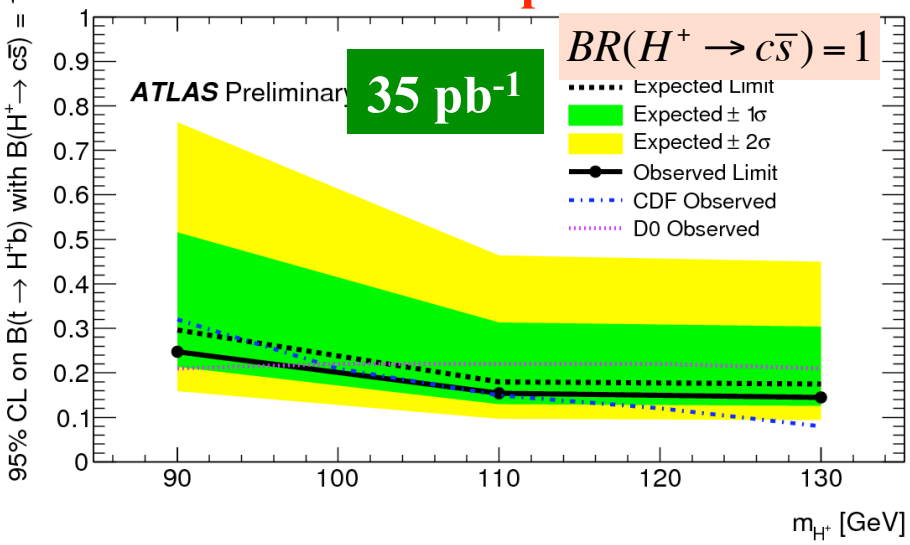
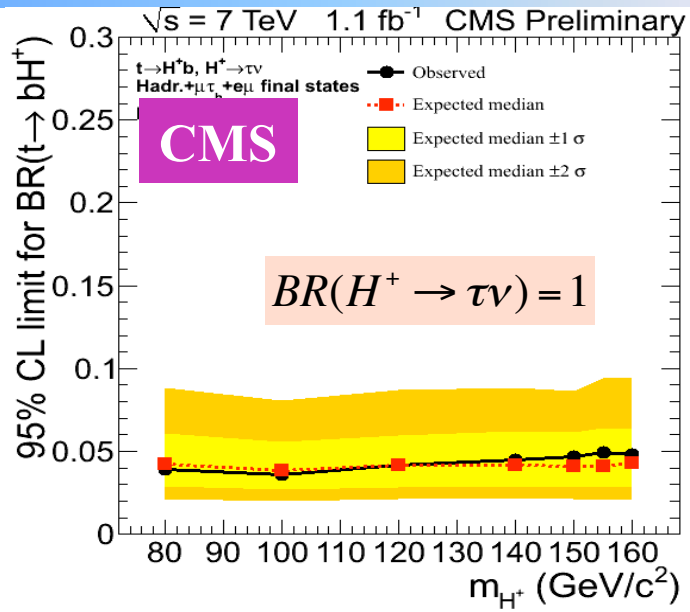
$t \to bH^+ \to bc\bar{s}$

high $p_t$ isolated lepton, large $E_t^{miss}$, ≥4 jets, ≥1 bjet, $m_T$ consistent with W



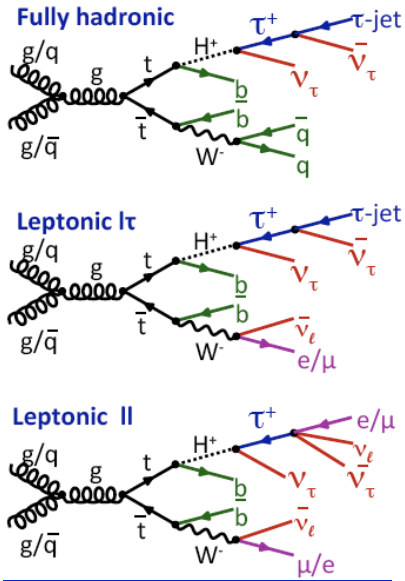

**Exclusion on BR comparable to Tevatron with 35 pb$^{-1}$**

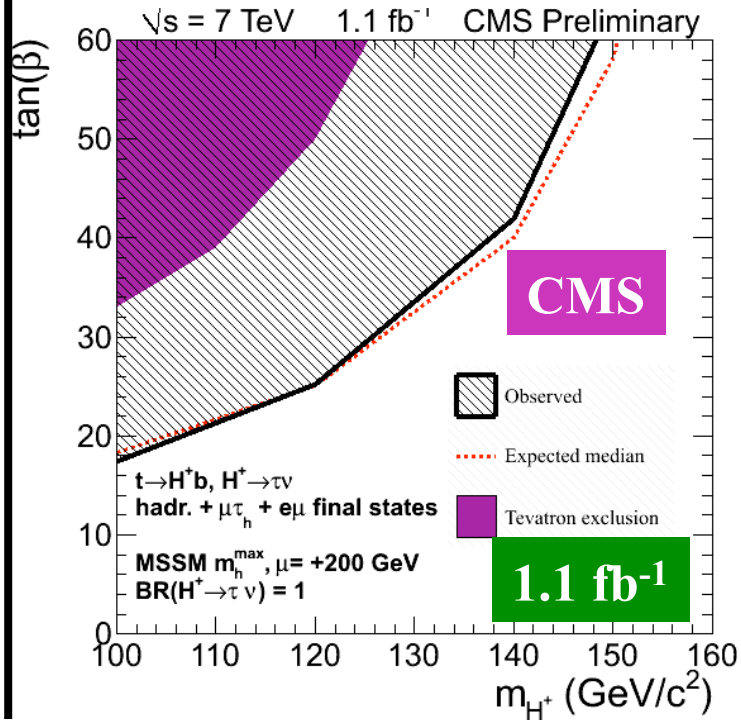



$t \to bH^+ \to b\tau\nu$

**3 final states:**




**Exclusion in tanβ-mH$^+$ and comparison to the Tevatron**

**Talks Thursday A. Ferrari & Girao de Almeida**

# ATLAS+CMS: Beyond MSSM

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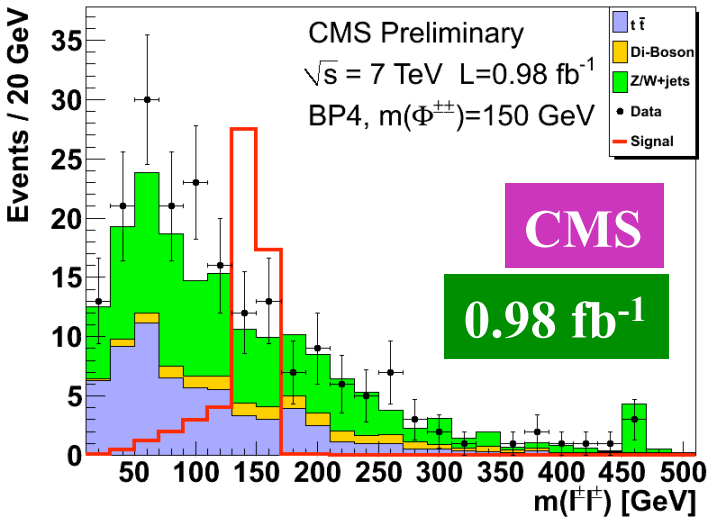
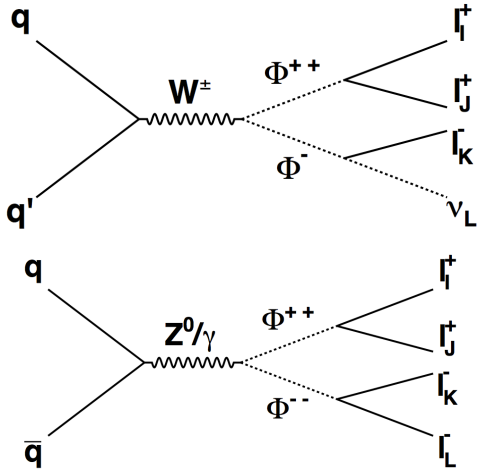
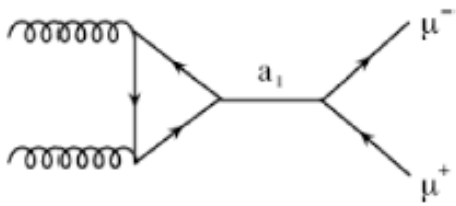
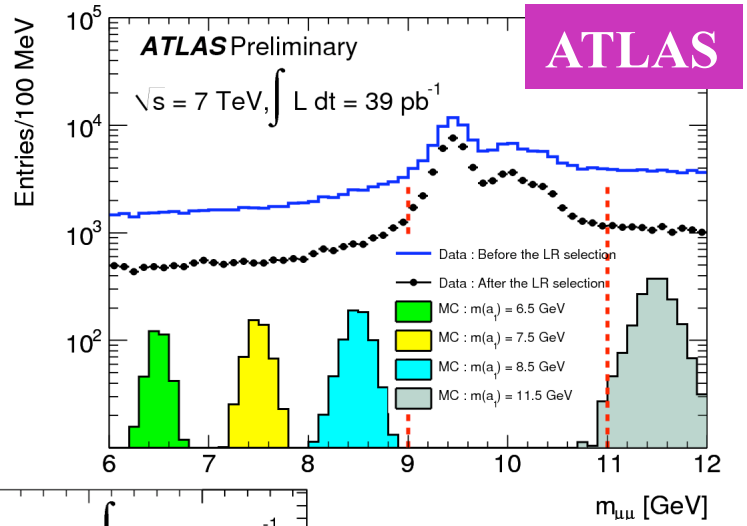
## Doubly-charged Higgs $\Phi^{++} \rightarrow l_i^+ l_j^+$ (from Higgs triplet)



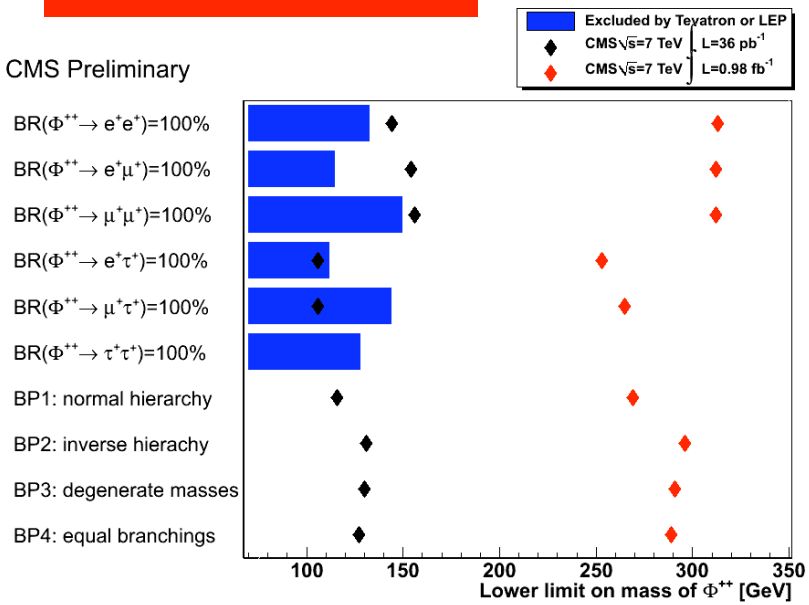



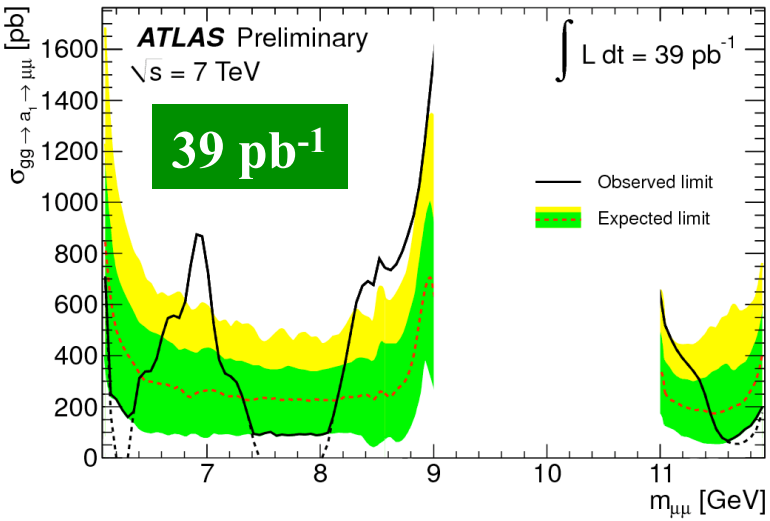

## NMSSM: light CP-odd scalar $a_1$




## World best limits




**Search in low mass di-μ spectrum**

# Summary

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- The LHC has delivered more than 2 $fb^{-1}$ of data allowing ATLAS and CMS to start the hunt for the Higgs boson both in the context of the Standard Model and beyond
- No significant excess ($<2\sigma$) is found in the mass range between 110-600 GeV studied by both experiments
- Exclusion limits have been placed at 95% CL in the regions:

| ATLAS | CMS |
|---|---|
| $146 < m_H < 232$ GeV | $145 < m_H < 216$ GeV |
| $256 < m_H < 282$ GeV | $226 < m_H < 288$ GeV |
| $296 < m_H < 466$ GeV | $310 < m_H < 400$ GeV |

- Both experiments use common statistical methods and theoretical input which will make future combinations easier
- Stringent limits have been placed in the MSSM parameter space and other models BSM are starting to be explored

# THE HUNT FOR THE HIGGS AT THE LHC HAS JUST STARTED, STAY TUNED!

# BACKUP

# Profile Likelihood Ratio

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**For each measurement outcome depends on:**

- **Lack or presence of a Higgs signal, represented by signal strength $\mu=\sigma/\sigma_{SM}$**
- **Quantities affected by systematic uncertainties represented by nuisance parameters $\theta$**

**These parameters have an associated measurement which gives a preferred value $\theta_0$**

**Likelihood is built as product:**

$$L(data\,|\,\mu,\theta) = L_{obs}(data\,|\,\mu,\theta)\bullet p(\theta_0\,|\,\theta)$$

**Probability of observing data given $\mu$ ,$\theta$. In counting experiment with background $b(\theta)$ and signal $s(\theta)$ it is a Poisson(data|$\mu$ $s(\theta)$+$b(\theta)$)**

**Probability of having $\theta$ given measurement $\theta_0$**
**- assuming a flat prior on $\theta$ (Bayesian)**
**- measuring $\theta_0$ given $\theta$ (Frequentist)**

**pdf's for nuisance parameters**

**- Yields measured from control samples: Gamma**
**- Other yields: log-normal**
**- No prior knowledge (eg. $\gamma\gamma$ background): flat**

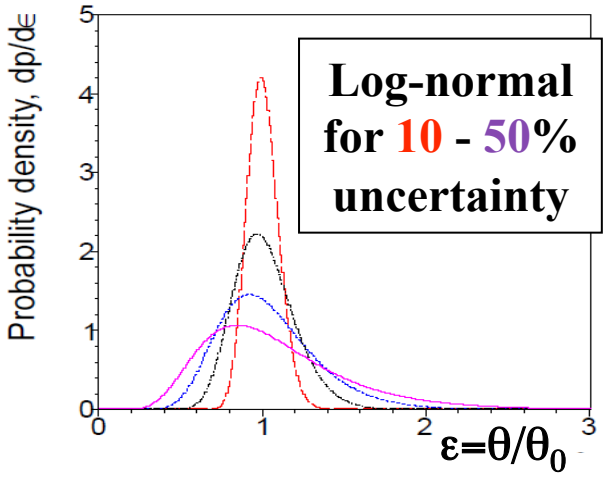
$$\rho(\theta\,|\,\theta_0) \sim p(\theta_0,\theta)\bullet\pi_\theta(\theta)$$

| posterior as a prior for Bayesian | measurement pdf: frequentist | primordial flat prior |
|---|---|---|

**Poisson(data|$\mu$s+b)**

$$L_{obs}(data\,|\,\mu,\theta) = \prod_i \frac{(\mu s_i + b_i)n_i^{data}}{n_i^{data}!}e^{-\mu s_i - b_i}$$

**product of probabilities to observe $n_i^{data}$ events in bin i**




| Type of syst. error | posterior $\rho(\theta\|\tilde{\theta})$ | frequentist $p(\tilde{\theta}\,\|\,\theta)$ | prior $\pi_\theta(\theta)$ |
|---|---|---|---|
| Unconstrained | flat | flat | flat |
| Gaussian, Lognormal | $\rho(\theta\,\|\,\tilde{\theta}) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{(\theta-\tilde{\theta})^2}{2}\right)$ | $p(\tilde{\theta}\,\|\,\theta) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{(\tilde{\theta}-\theta)^2}{2}\right)$ | flat |
| Statistical | $\rho(\theta\,\|\,N) = \frac{\theta^N}{N!}\exp(-\theta)$ | $p(N\,\|\,\theta) = \frac{\theta^N}{N!}\exp(-\theta)$ | flat |

# Modified Frequentist $CL_S$ limits: reject signal+background hypothesis

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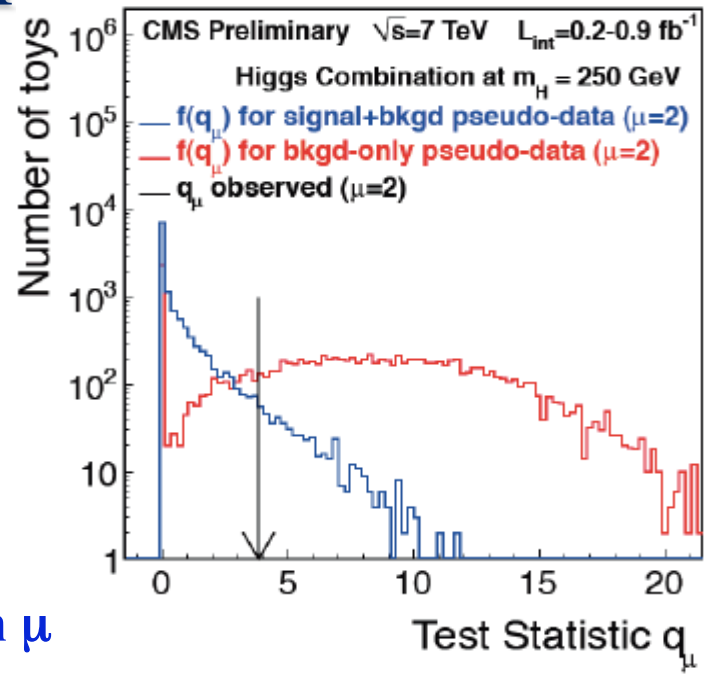
**Frequentist:** test values of $\mu=\sigma/\sigma_{SM}$ by running pseudo-experiments and evaluating how often they are more signal-like than the real data observation




For each value of the signal strength $\mu=\sigma/\sigma_{SM}$

- Evaluate the test statistics (profile likelihood)

$$q_\mu = -2\ln\frac{L(data\,|\,\mu,\hat{\theta}_\mu)}{L(data\,|\,\hat{\mu},\hat{\theta})} \qquad 0 \le \hat{\mu} \le \mu$$

$\hat{\theta}_\mu$ :value of $\theta$ which maximizes likelihood given $\mu$

- Determine the value of $\theta$ which give the best global fit of the data and measured $\theta_0$. Do it separately for the case of no signal and for the tested
- Use values to generate pseudo-experiments for background-only and signal+background In each pseudo-experiment generate also values of the external measurements $\theta_0$
- Evaluate test statistics for pseudo-experiments comparing with the data building $CL_S$

$$CL_S = \frac{CL_{S+B}}{CL_B} = \frac{p_\mu}{p_0} = \frac{P\left(q_\mu \ge q_\mu^{obs}\,|\,\mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \ge q_\mu^{obs}\,|\,b(\hat{\theta}_\mu^{obs})\right)}$$

signal+background hypothesis

background-only hypothesis

**If $CL_S < 0.05$: value $\mu$ is excluded at 95% CL**

# Bayesian limits: reject signal+background hypothesis

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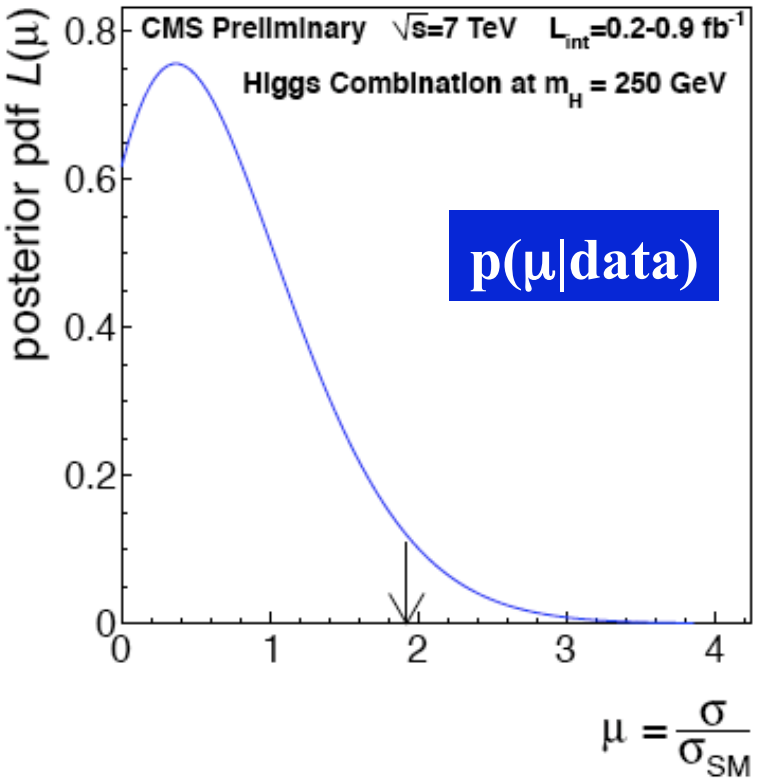
**Bayesian:** interpret the likelihood function as a pdf for $\mu=\sigma/\sigma_{SM}$ assuming a flat prior, compute the interval $[0,\mu]$ that contains 95% of probability




**Posterior probability function p(μ|data) on the signal strength μ**

$$p(\mu \mid data) = \frac{1}{C}\int_{\theta} p(data \mid \mu s(\theta) + b(\theta))\, \rho_{\theta}(\theta)\, \pi_{\mu}(\mu) d\theta$$

$\rho_{\theta}(\theta)$: pdfs of prior belief on scale and description of uncertainties, or systematic errors

$\pi_{\mu}(\mu)$: prior on the signal strength. Taken flat for $\mu \geq 0$ and zero otherwise

C: set to normalize p(μ|data) to 1

**The Bayesian one-sided 95% CL limits on μ are extracted from:**

$$\int_{0}^{\mu 95\% CL} p(\mu \mid data)\, d\mu = 0.95$$

**$CL_S$ and Bayesian are different definitions, obtained results agree within 10%**

# Discovery: reject background-only hypothesis

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**To characterize the scale of the observed excesses versus Higgs mass calculate the local approximate $p^{estimate}$-value from the asymptotic approximation:**

$$p^{estimate} = \frac{1}{2}\left[1 - erf\left(\sqrt{q_0^{obs}/2}\right)\right]$$

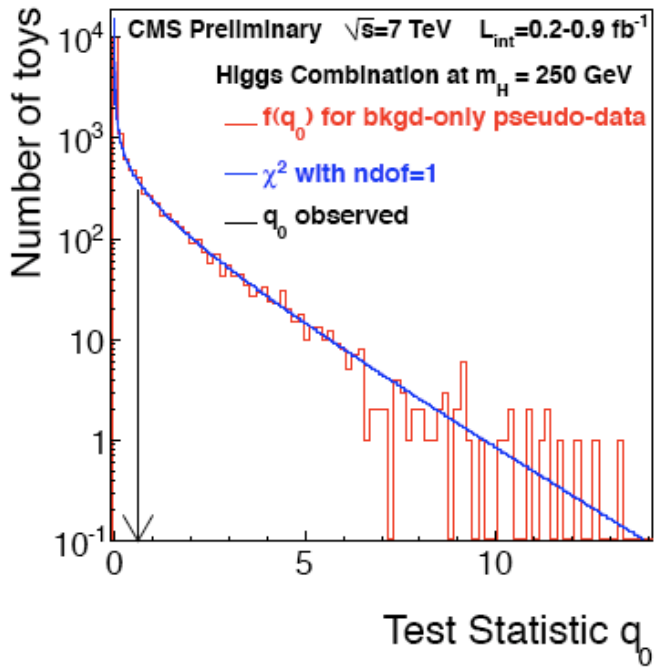
**Test statistics:** $$q_0 = -2\ln\frac{L(data\,|\,0,\hat{\theta}_0)}{L(data\,|\,\hat{\mu},\hat{\theta})} \quad \hat{\mu} \geq 0$$

**The true p-value** $$p = P(q_0 \geq q_0^{obs}) = \int_{q_0^{obs}}^{\infty} f(q_0\,|\,\mu = 0, \hat{\theta}_0^{obs})\,dq_0$$ **of such an observation obtained from the sampling distribution (red curve) agrees well with $p^{estimate}$ (blue curve)**

**To quote significance Z the following is used:**

$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\,dx$$

**5σ (Z=5): p=2.8E-7**




**Small local p-value means one has an excess w.r.t. expectations**

**It does not tell whether the excess:**

- **is due to signal or not**
- **is consistent with the expected signal**

**A large look-elsewhere effect can reduce significance**

# Look Elsewhere Effect

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**LEE: the significance of observing a local excess of events needs to take into account the probability of observing such excess anywhere in the range**

**The test statistics is modified to include multiple testing (equivalent to floating mass fit)**

$$q_0(\hat{m}_H) = \max_{m_H} q_0(m_H)$$

**In the asymptotic regime for small p-values the probability of a fluctuation above $q_{ref}$:**

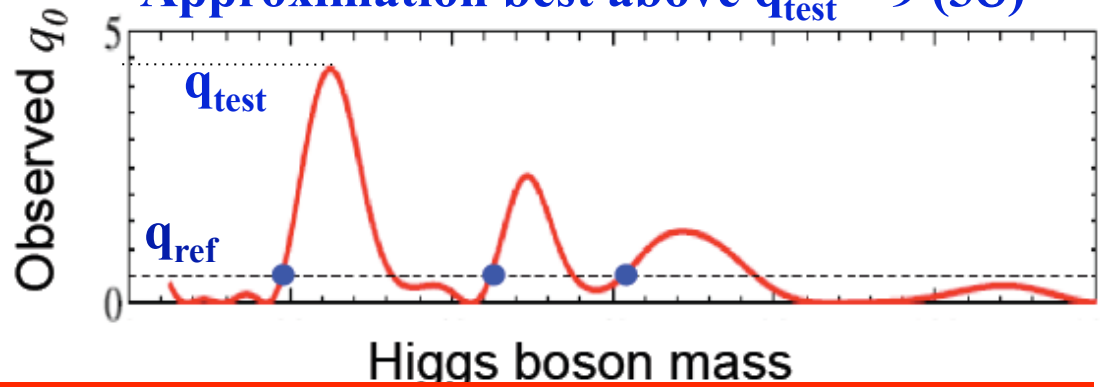
$$P\left(q_0(\hat{m}_H) > q_{ref}\right) = N_{q_{ref}} e^{-q_{ref}/2} + \frac{1}{2} P\left(\chi^2_{q_{ref}} > q_{ref}\right)$$

- **$Nq_{ref}$ average number of up-crossings of likelihood ratio scan $q_0(m_H)$ at level $q_{ref}$**
- **Determined with a small set of MC simulations**

**The expected number of fluctuations at $q_{test}$ is given by:**

$$\left\langle N_{q_{test}} \right\rangle = \left\langle N_{q_{ref}} \right\rangle e^{-(q_{test} - q_{ref})/2}$$

**Approximation best above $q_{test} \sim 9$ ($3\sigma$)**




**The more regions probed the larger $Nq_{ref}$**

$$p^{global} \leq \left\langle N_{q_{test}} \right\rangle + p^{local}$$

**The p-values need to be scaled by the LEE trial-factor ➔ reduced significance**

# CMS: H→ZZ→2l2τ

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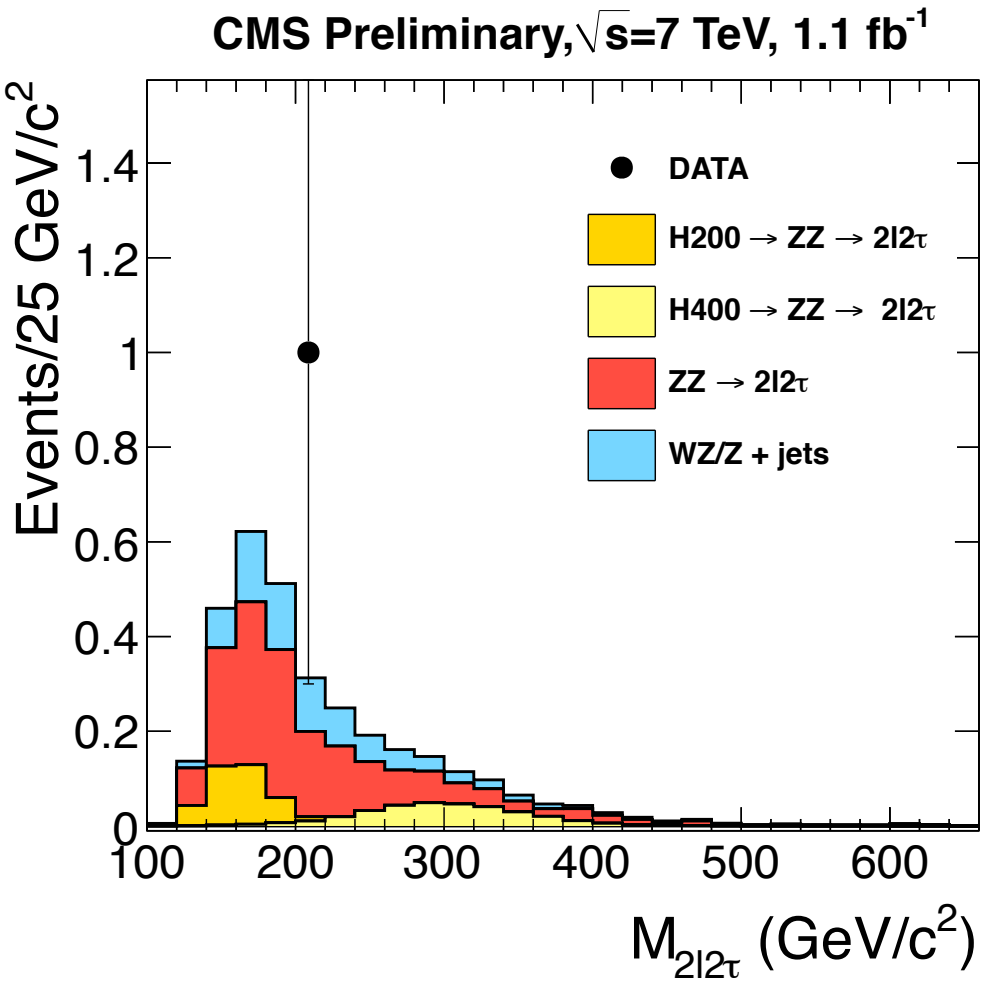


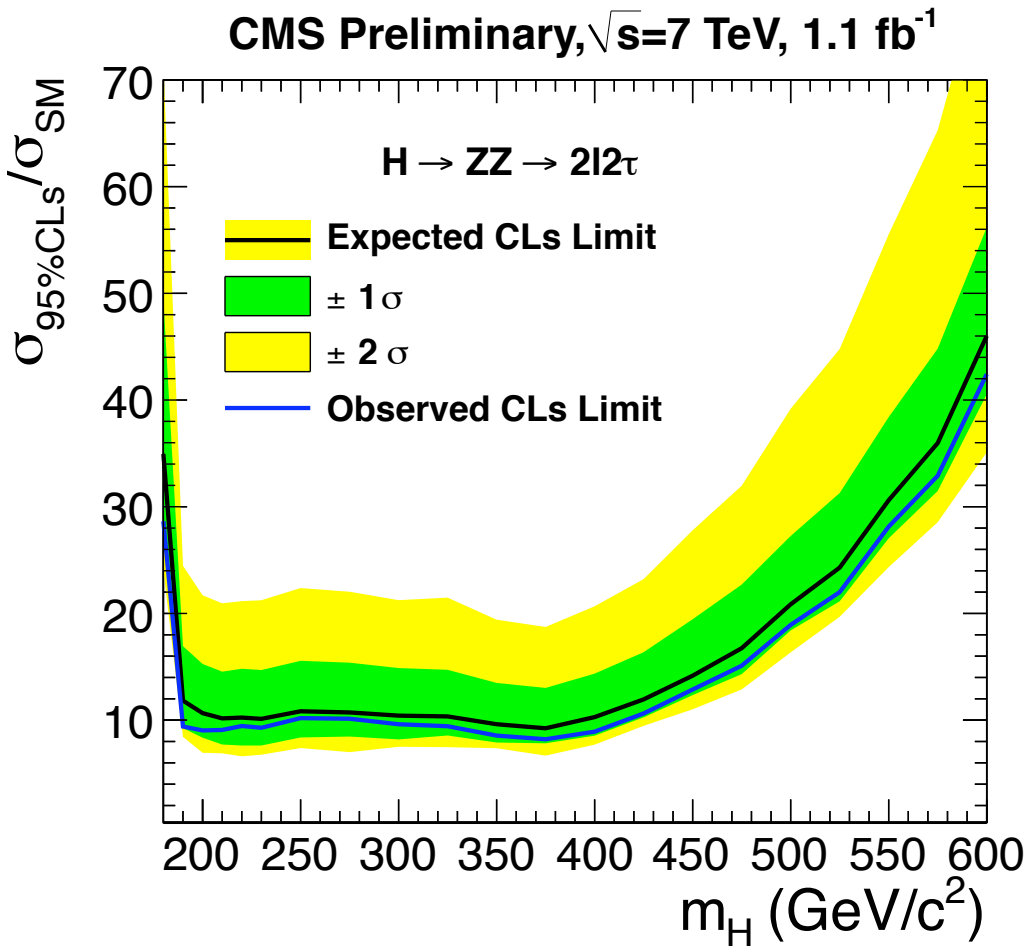


**Exclusion @95% CL of 10 $\sigma_{SM}$**

# ATLAS: H→WW→lνqq

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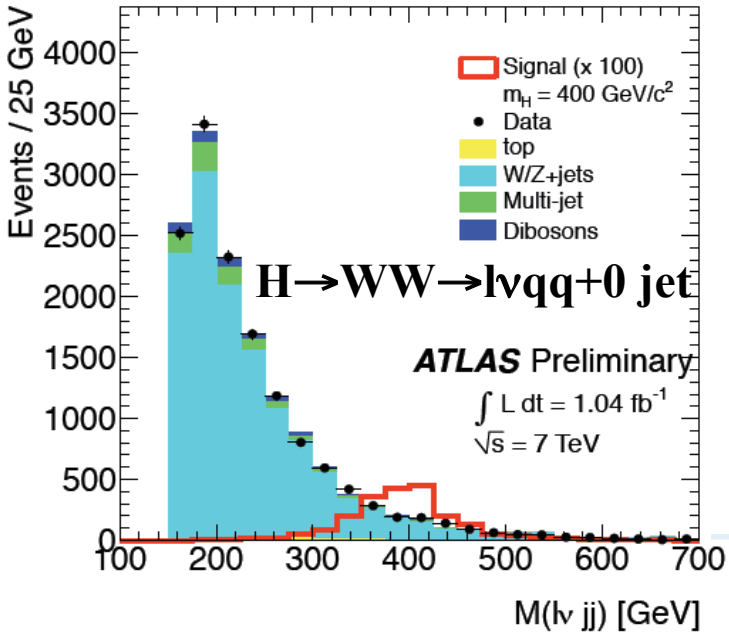
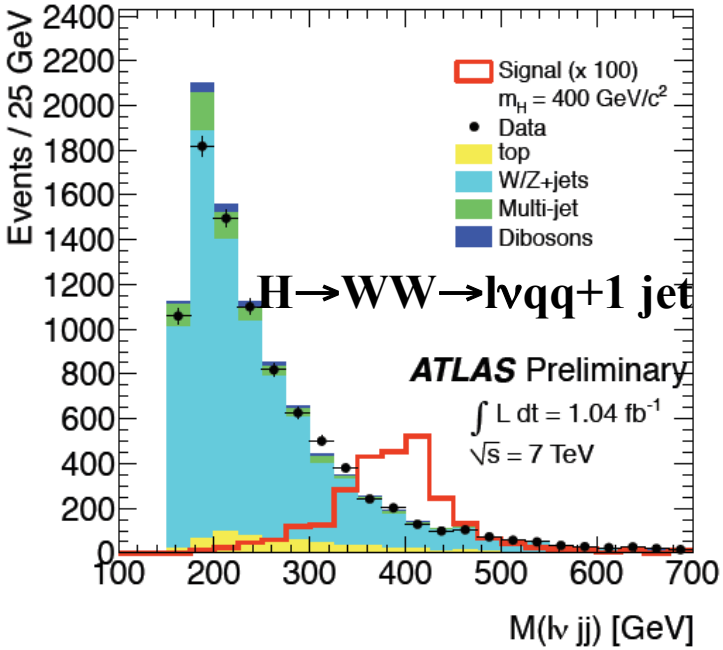


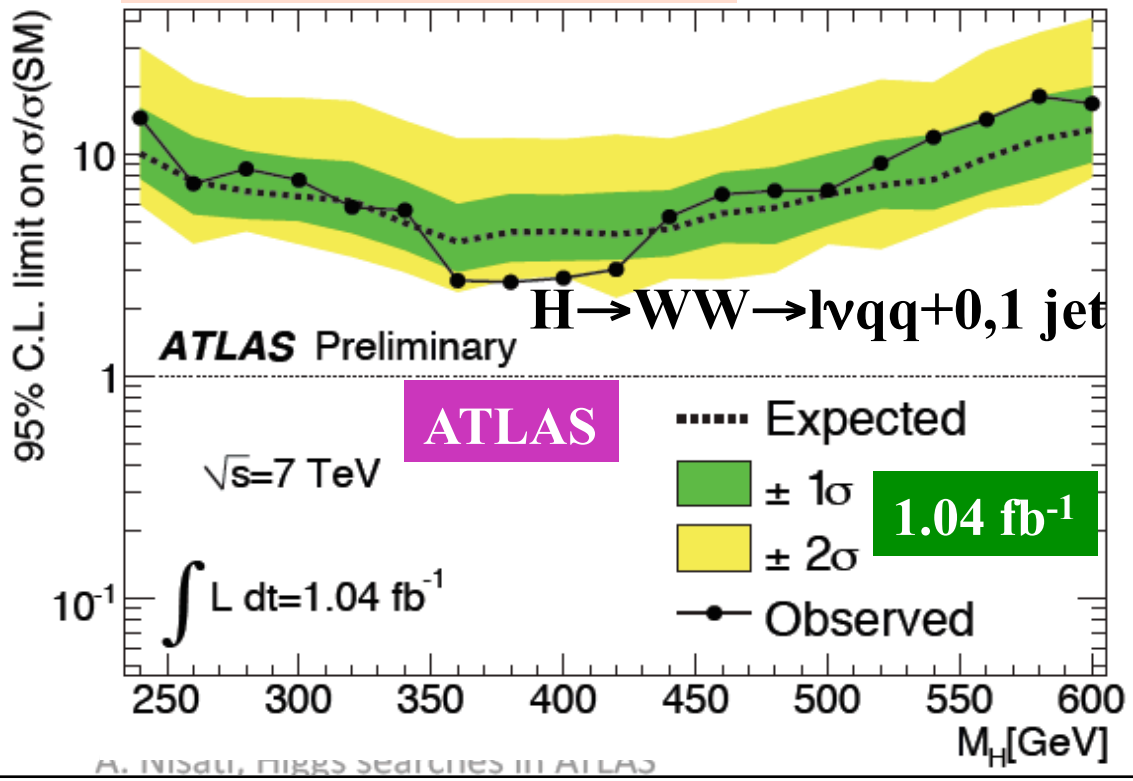

**Largest σ•BR and good signal/background ratio in high mass region $m_H$~240-600 GeV**

**Challenge:**

**Reconstruction of the $m_{l\nu qq}$ mass**

**- Require exactly one high-$p_t$ lepton, larger $E_t^{miss}$, exactly two high-$p_t$ jets associated to a W decay**

**Observed: ~5-10 $\sigma_{SM}$**



# ATLAS+CMS: H→γγ Vertex Determination

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**Di-photon mass resolution depends on correct choice of Higgs production vertex**

- **High pile-up conditions: $\langle N_{PU} \rangle \sim 5$**

**Vertex determination based on:**

**CMS**

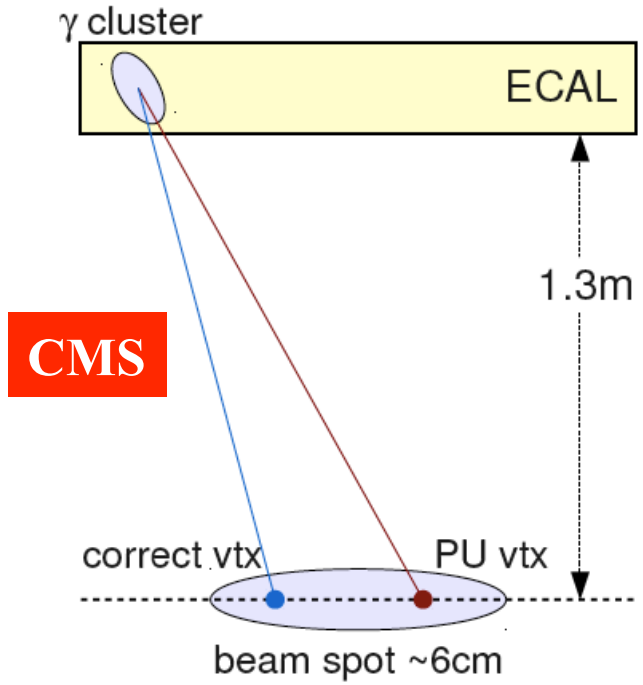
- **Kinematics of tracks belonging to vertex $\Sigma p_T^2$**
- **$p_T$ balance between tracks in vertex and photon pair**
- **Conversion track finding and projection on beam line**

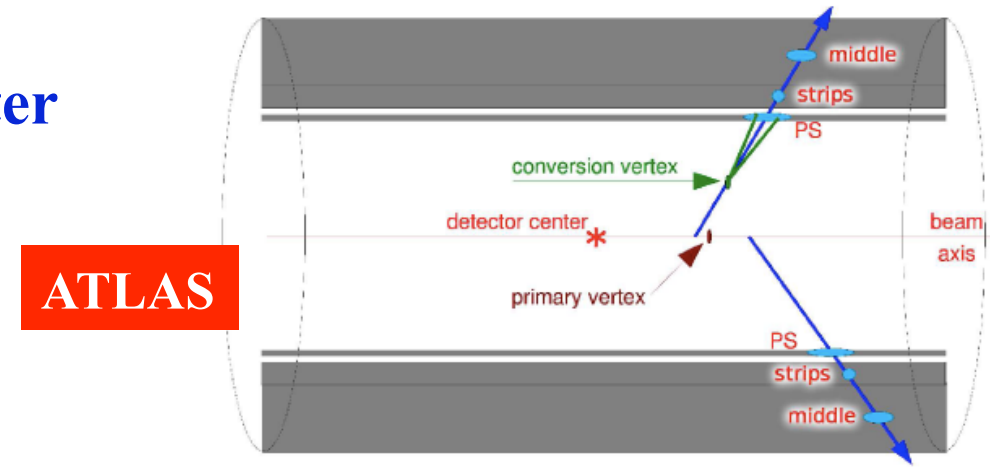
**Performance tested with Z events after removing muon tracks**

**ATLAS**

- **Only γ candidates are used**

**→ Use of calorimeter pointing + conversion vertex**



# ATLAS SM Higgs: Systematics

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Table 3: Main correlated systematic uncertainties used in the analysis. These relative uncertainties (%) correspond to the overall effect on the per-event signal efficiency of the $\pm 1\sigma$ variation of the source of systematic uncertainty. Some of them, such as the energy scale in the $H \to \gamma\gamma$ search, are included but are not apparent in this table as they do not affect event rates.

| | $H \to \tau^+\tau^-$ | | $H \to \gamma\gamma$ | $H \to b\bar{b}$ | $H \to WW^{(*)}$ | $H \to ZZ^{(*)}$ | | |
|---|---|---|---|---|---|---|---|---|
| | $\tau_\ell \tau_{had}$ | $\tau_\ell \tau_\ell + jet$ | | | $\ell\nu\ell\nu$ | $\ell\ell\ell\ell$ | $\ell\ell\nu\nu$ | $\ell\ell qq$ |
| Luminosity | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ |
| $e/\gamma$ eff. | $\pm 3.5$ | $^{+2.0}_{-2.1}$ | $^{+11.6}_{-10.4}$ | $\pm 2.3$ | $\pm 2.2$ | $\pm 3.3$ | $\pm 1.2$ | $\pm 1.1$ |
| $e/\gamma$ E. scale | $^{+1.3}_{-0.1}$ | $^{+0.2}_{-0.5}$ | - | $^{+1.5}_{-1.6}$ | $\pm 0.1$ | - | $^{+0.8}_{-1.1}$ | - |
| $e/\gamma$ res. | - | $\pm 3.7$ | - | $^{+2.1}_{-1.5}$ | $\pm 0.1$ | - | - | - |
| $\mu$ eff. | $\pm 1.0$ | $^{+2.0}_{-2.1}$ | - | $^{+1.1}_{-2.0}$ | $\pm 0.6$ | $\pm 1.2$ | $^{+0.8}_{-0.7}$ | $\pm 0.6$ |
| $\mu$ res. | - | $^{+0.4}_{-0.6}$ | - | $\pm 5.8$ | $\pm 1.6$ | - | - | - |
| Jet/$\tau$/MET E. scale | $^{+19}_{-16}$ | $^{+3.3}_{-10.0}$ | - | $^{+21}_{-17}$ | $\pm 6.1$ | - | $^{+5.9}_{-4.0}$ | $^{+3.7}_{-10.4}$ |
| JER | - | $\pm 2.0$ | - | $\pm 2.5$ | $^{+2.2}_{-1.8}$ | - | - | $^{+2.1}_{-0.0}$ |
| MET | - | $^{+4.4}_{-5.3}$ | - | $^{+5.5}_{-6.1}$ | - | $\pm 0.6$ | $^{+6.6}_{-4.2}$ | - |
| $b$-tag eff. | - | - | - | $^{+37}_{-33}$ | $\pm 0.1$ | - | $^{+4.3}_{-4.4}$ | - |

# CMS SM Higgs: Systematics

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| | | $\gamma\gamma$ | $\tau\tau$ | WW $l\nu l\nu$ | ZZ llll | ZZ $ll\nu\nu$ | ZZ llqq |
|---|---|---|---|---|---|---|---|
| luminosity | 6% | | | | | | |
| trigger | e<br>$\mu$<br>$\gamma$ | | <br><br>1% | | 2%<br>2% | 2%<br>1% | 2%<br>1% |
| reconstruction efficiency | $\mu$<br>e<br>$\gamma$<br>$\tau_{had}$<br>b-tag | 1−3% | 1%<br>2%<br><br>6% | 3%<br>4% | 3%<br>3% | 2%<br>2% | 1%<br>2%<br><br><br>20% |
| $p_t$ scale (event yield) | $\mu$<br>e<br>jets/MET | | 2%<br>2%<br>4% | 2%<br>2%<br>2-10% | 1%<br>2% | 2%<br>5%<br>2% | 1%<br>2%<br>0.2% |
| $p_t$ scale (shape) | $\mu$<br>e<br>$\gamma$<br>$\tau_{had}$ | 0.1-0.3% | <br><br><br>3% | | | | |
| $p_t$ resolution | $\mu$<br>e<br>$\gamma$ | <br><br>20% | | | 10%<br>10% | | |

# CP-Conserving Benchmark Scenarios

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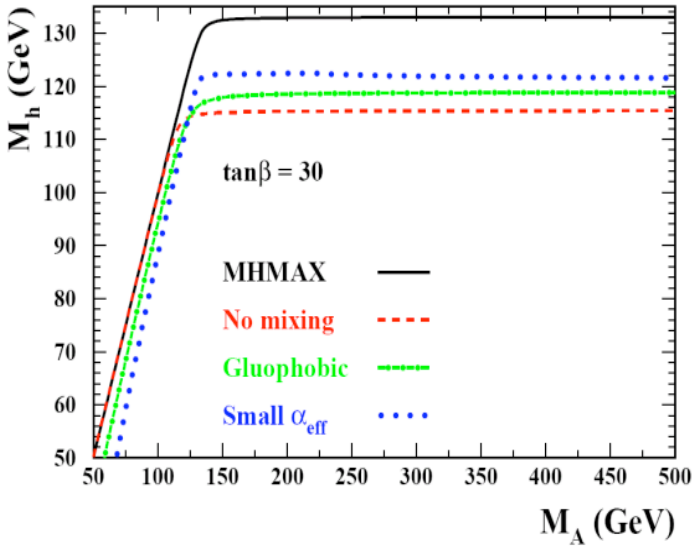
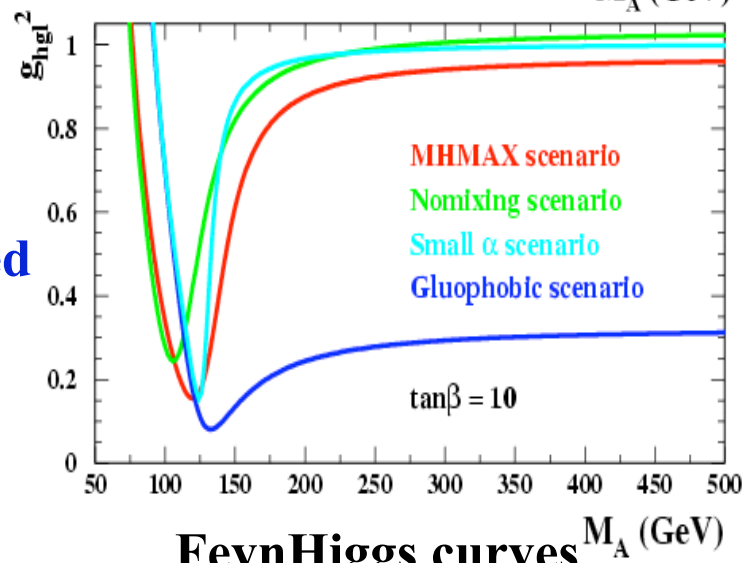
**Unconstrained MSSM has large number of free parameters. Choose specific parameter points: benchmark scenarios**

**Proposed by Carena et al., Eur.Phys.J.C26,601(2003)**

- **$M_h^{max}$ scenario**
  - maximal $M_h$< 133 G eV
  - Conservative exclusion bounds on tan β and $M_A$
  - Used at LEP/Tevatron, $M_{SUSY}$= 1 TeV
- **No-mixing scenario**
  - Small $M_h$<116GeV
  - No stop mixing, $X_t$=0, $M_{SUSY}$=2TeV
- **Gluophobic scenario**
  - small $g_{h,gluon}$
    main production channel gg→h strongly suppressed
  - $M_h$<119 GeV, $M_{SUSY}$=350GeV
- **Small-α scenario**
  - small $g_{hbb}$ and $g_{h\tau\tau}$
  - $M_h$<123 GeV, $M_{SUSY}$=800GeV

$$g_{hbb} = g_{Hbb}^{SM} \frac{\sin\alpha}{\cos\beta}$$




**FeynHiggs curves**

# MSSM: $m_h^{max}$ scenario

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- $M_{top}$= 172.5 GeV
- $m_b(m_b)_{MSbar}$= 4.213 GeV
- $\alpha_S(M_Z)$=0.119

- $M_{SUSY}$ = 1000 GeV soft SUSY-breaking squark mass
- $X_t$ = 2000 GeV stop mixing parameter
- M2 = 200 GeV SU2 gaugino mass parameter
- $\mu$ = 200 GeV Higgs mixing parameter
- M3 = 800 GeV gluino mass parameter

**Susy loop corrections are negligible in this scenario**

# Neutral Higgs: associated b production

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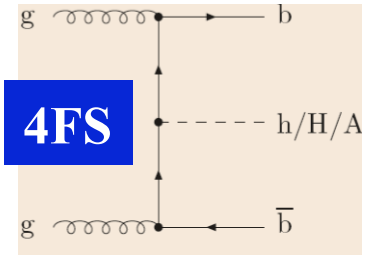
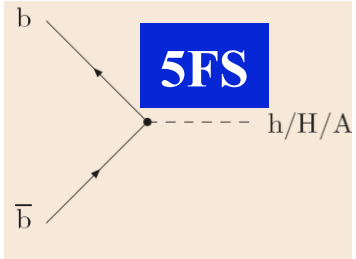
$$q\bar{q} / gg \rightarrow b\bar{b} + h / H / A$$

**Dominant Higgs production process at high values of tanβ**



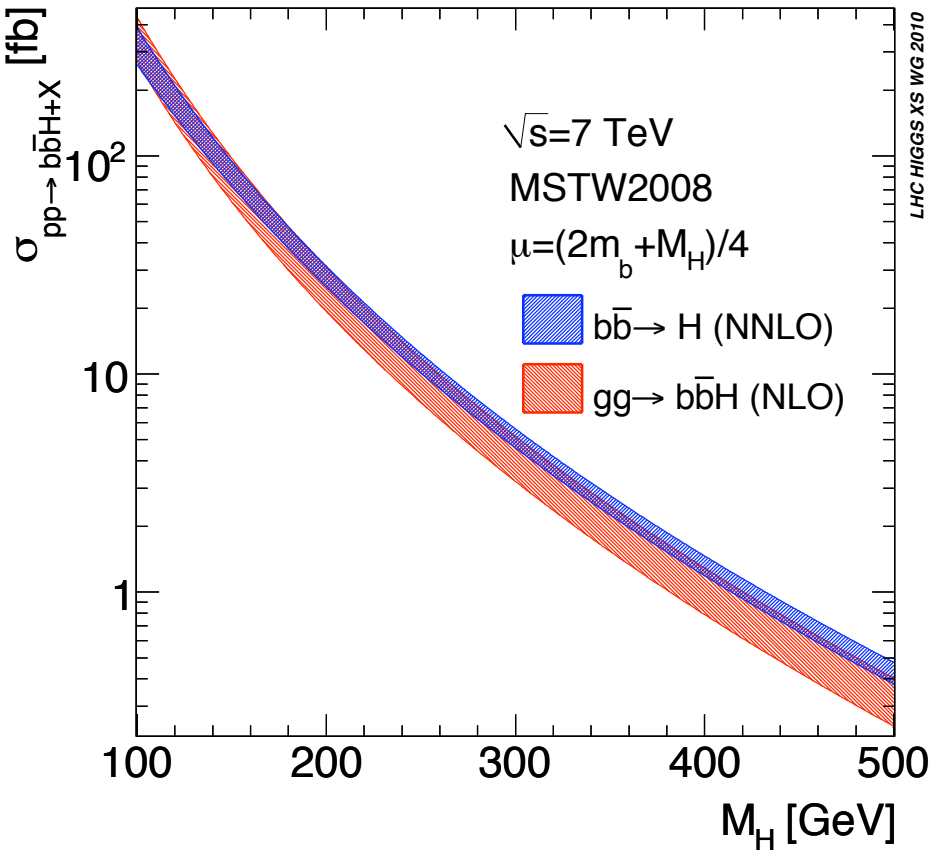

**Exclusive** $gg \rightarrow b\bar{b} + h / H / A$ **four active parton flavours**

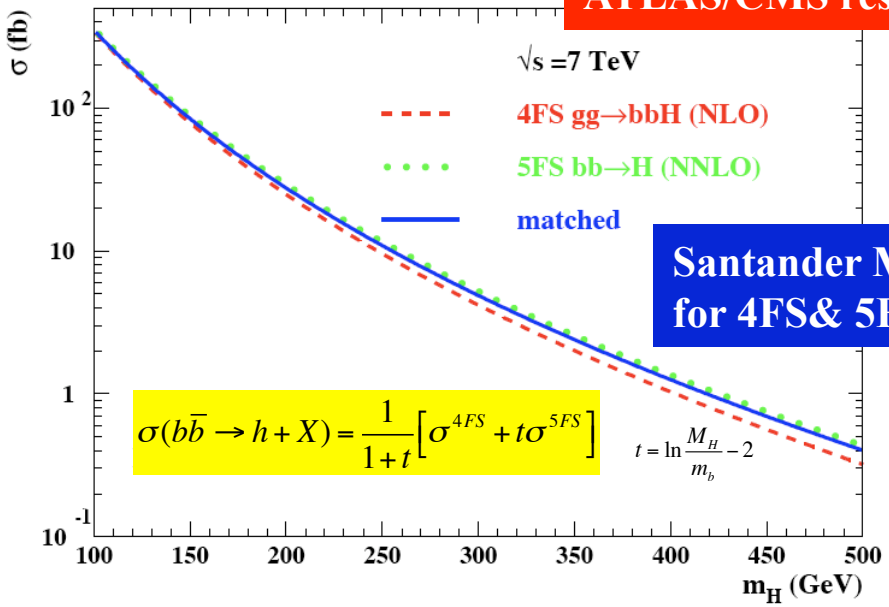



**Start with** $b\bar{b} \rightarrow h / H / A$ **at LO**

**At NNLO** $gg \rightarrow b\bar{b} + h / H / A$ **contributes in the real corrections**

**Common approach for ATLAS/CMS results**




**Santander Matching for 4FS& 5FS bbH**

**Difference between 4FS & 5FS is logarithmic**

- **Large Higgs mass: 5FS more reliable as it resums collinear logs $\ln(M_H/m_b)$**
  - **use 5FS for $m_H \rightarrow \infty$**
- **For small logs [$\ln(M_H/m_b)=2$] 4FS dominates**

# MSSM Neutral Higgs Couplings

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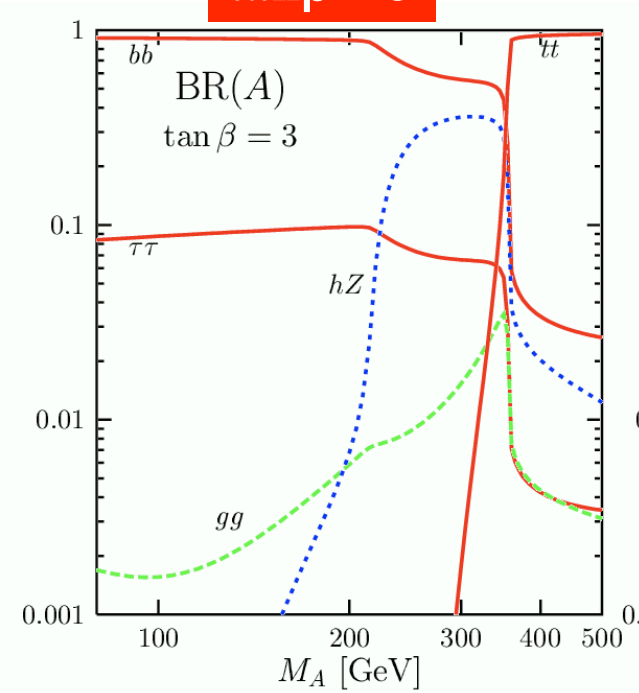
| coupling | $h$ | $H$ | $A$ |
|---|---|---|---|
| up-type fermions | $\cos\alpha/\sin\alpha$ | $\sin\alpha/\sin\beta$ | $\cot\beta$ |
| down-type fermion | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\cos\beta$ | $\tan\beta$ |
| W,Z | $\sin(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | 0 |

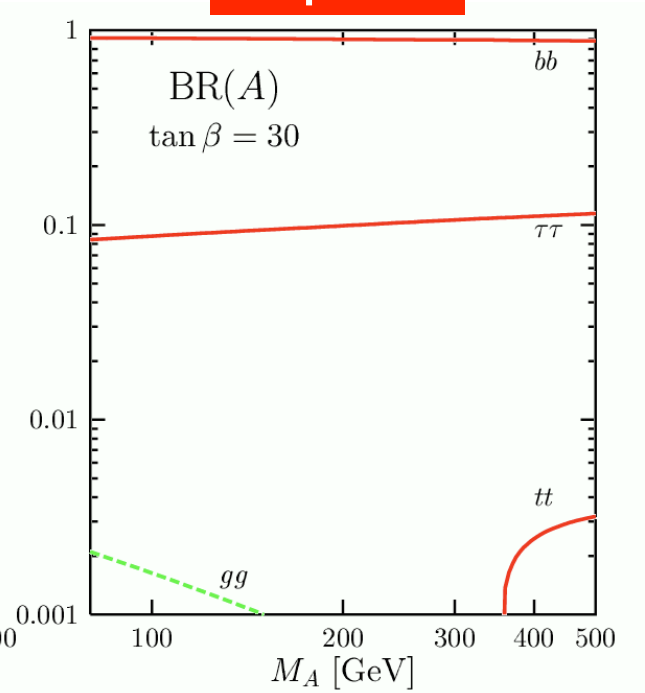
**For large tan β coupling enhanced for down-type fermions. Important for b-quarks and τ since Higgs coupling proportional to mass**

**α is a mixing angle between neutral components for two Higgs doublets $H_1^0$, $H_2^0$ to give the physical CP-even Higgs bosons h, H: $\cos 2\alpha = -\cos 2\beta\ [(M_A^2-M_Z^2)/(M_H^2-M_h^2)]$**

**tanβ = 5**



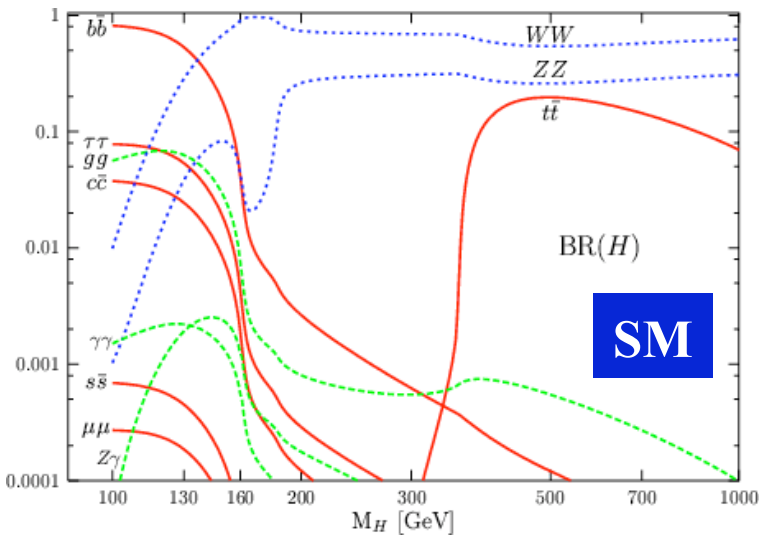

**tanβ = 30**




**Djouadi, Kalinowski, Spira**

**For large $M_A \rightarrow \cos(\beta-\alpha) \ll 1$**

- **h couplings SM-like**
- **H coupling to W,Z suppressed**



# Sakurai Prize for Theoretical Physics 2010

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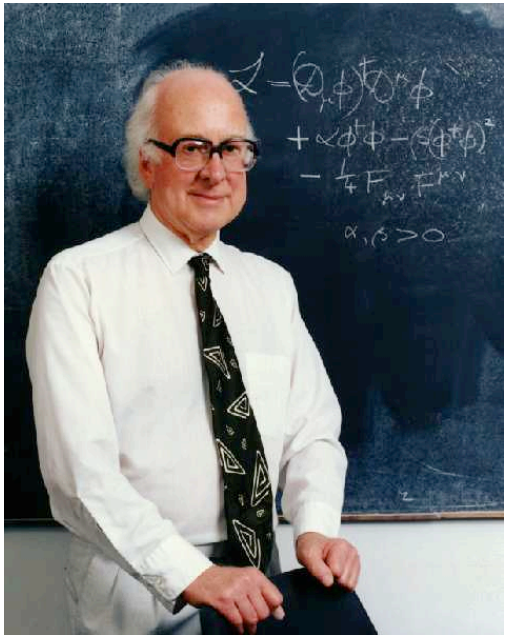
## Kibble, Guralnik, Hagen, Englert, Brout, Higgs



**"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."**