# Higgs Summary and Discussion

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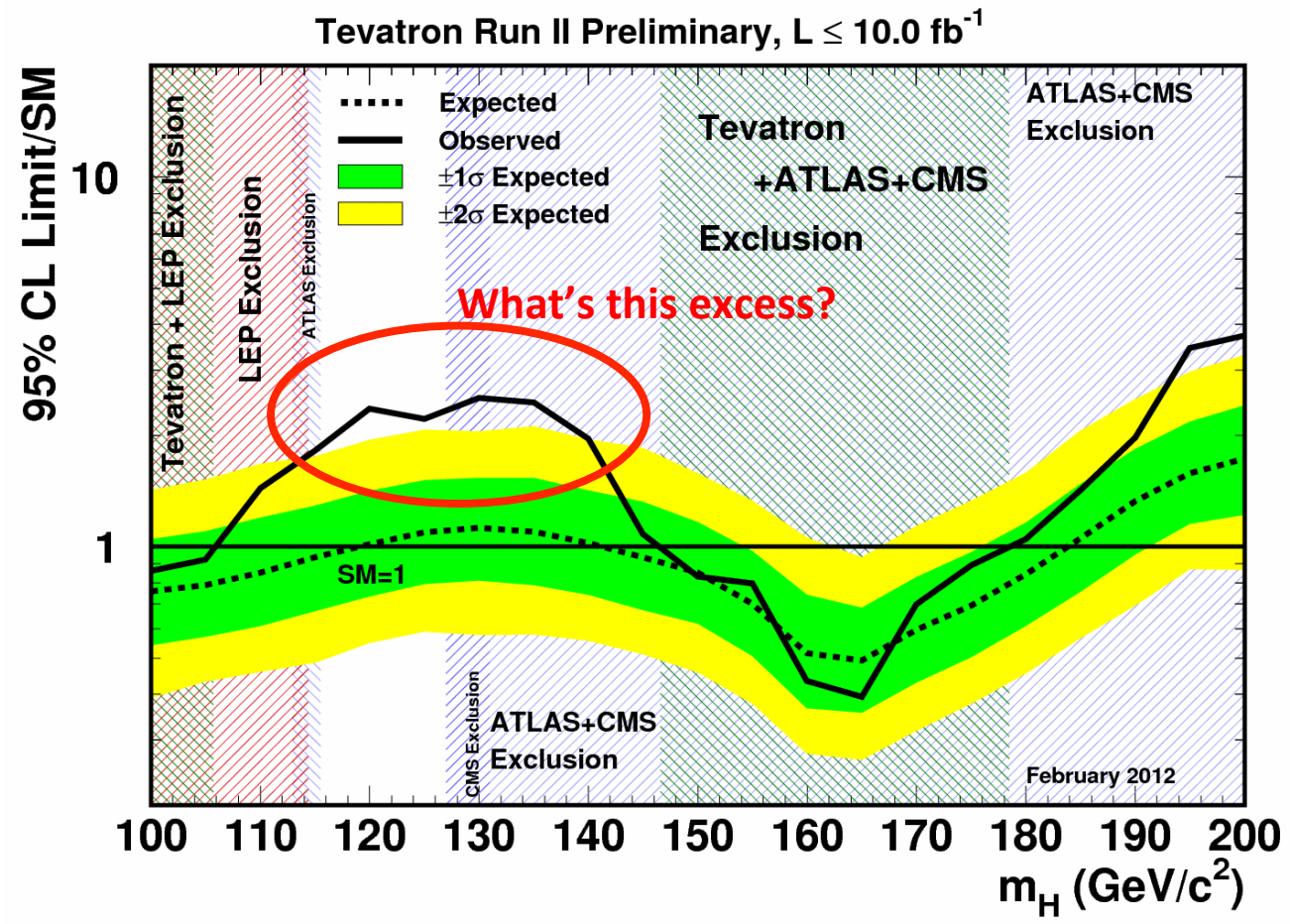
# Tevatron Combined Limit




Koji Sato

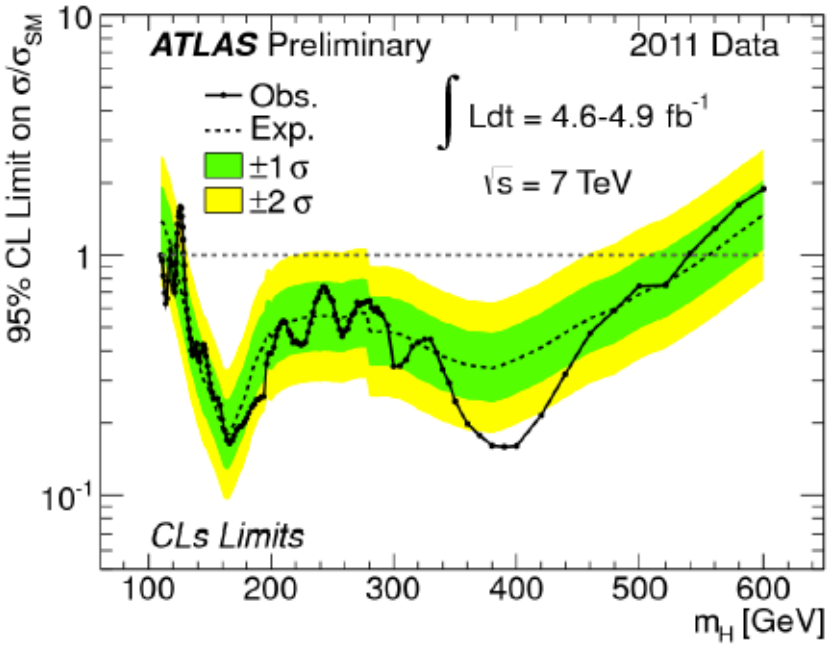
Expected exclusion: $100<m_H<119$, $141<m_H<184$ GeV/$c^2$

**Observed exclusion: $100<m_H<106$, $147<m_H<179$ GeV/$c^2$**

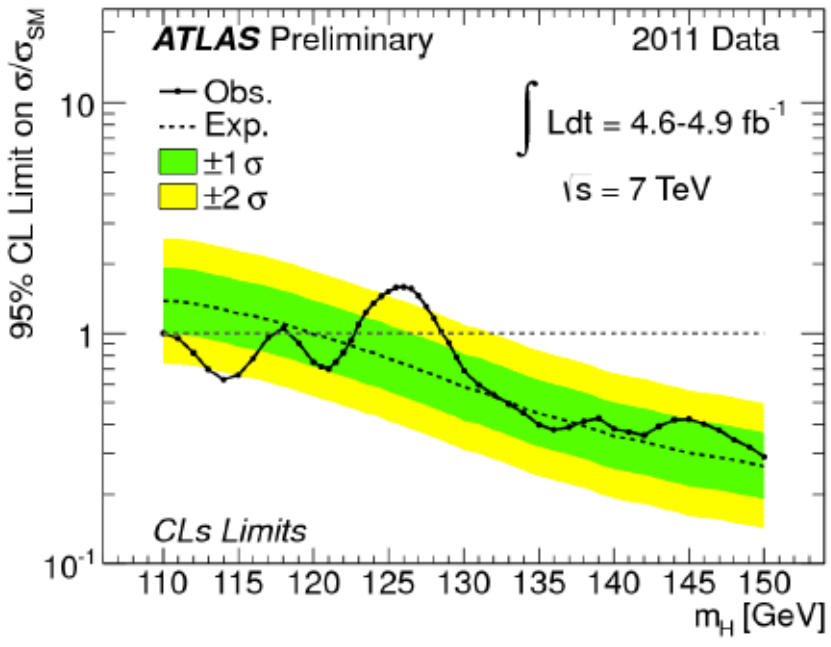
Rustem Ospanov

# SM Higgs combination

## Combined upper limits



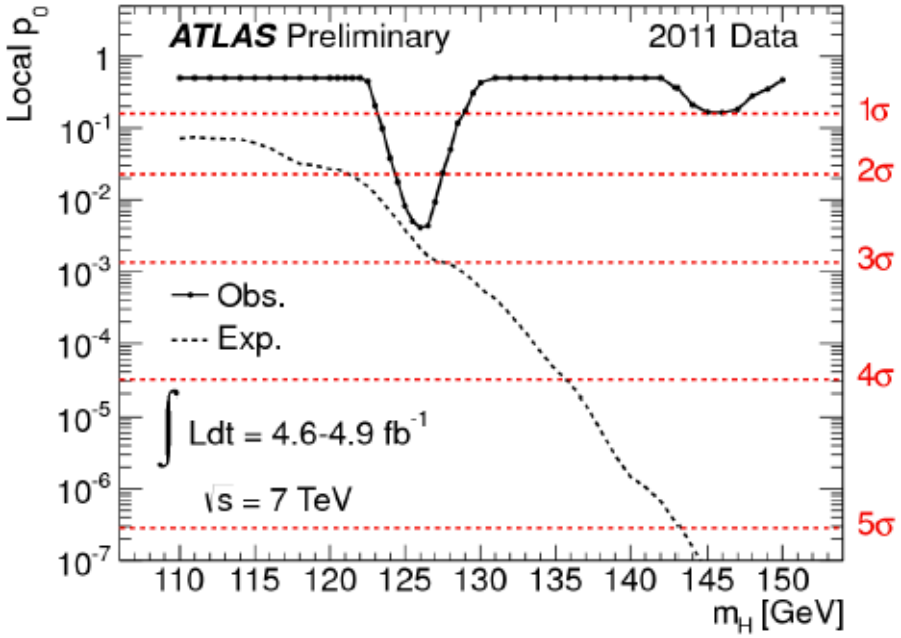

## Zoom at the low mass



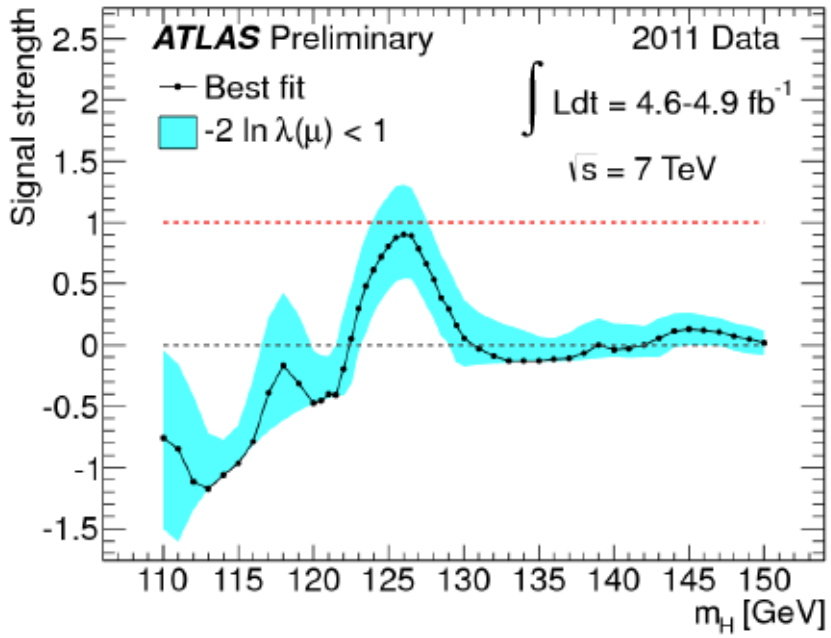

- SM Higgs boson is excluded in the ranges:
  110-117.5, 118.5-122.5, 129-539 GeV at the 95% CL
- The combination includes additional channels:
  $H \to \tau\tau$, $H \to bb$, $H \to WW \to l\nu qq$, $H \to ZZ \to llqq$

# SM Higgs combination

## Background-only probability




## Best-fit signal strength $\mu = \sigma/\sigma_{SM}$

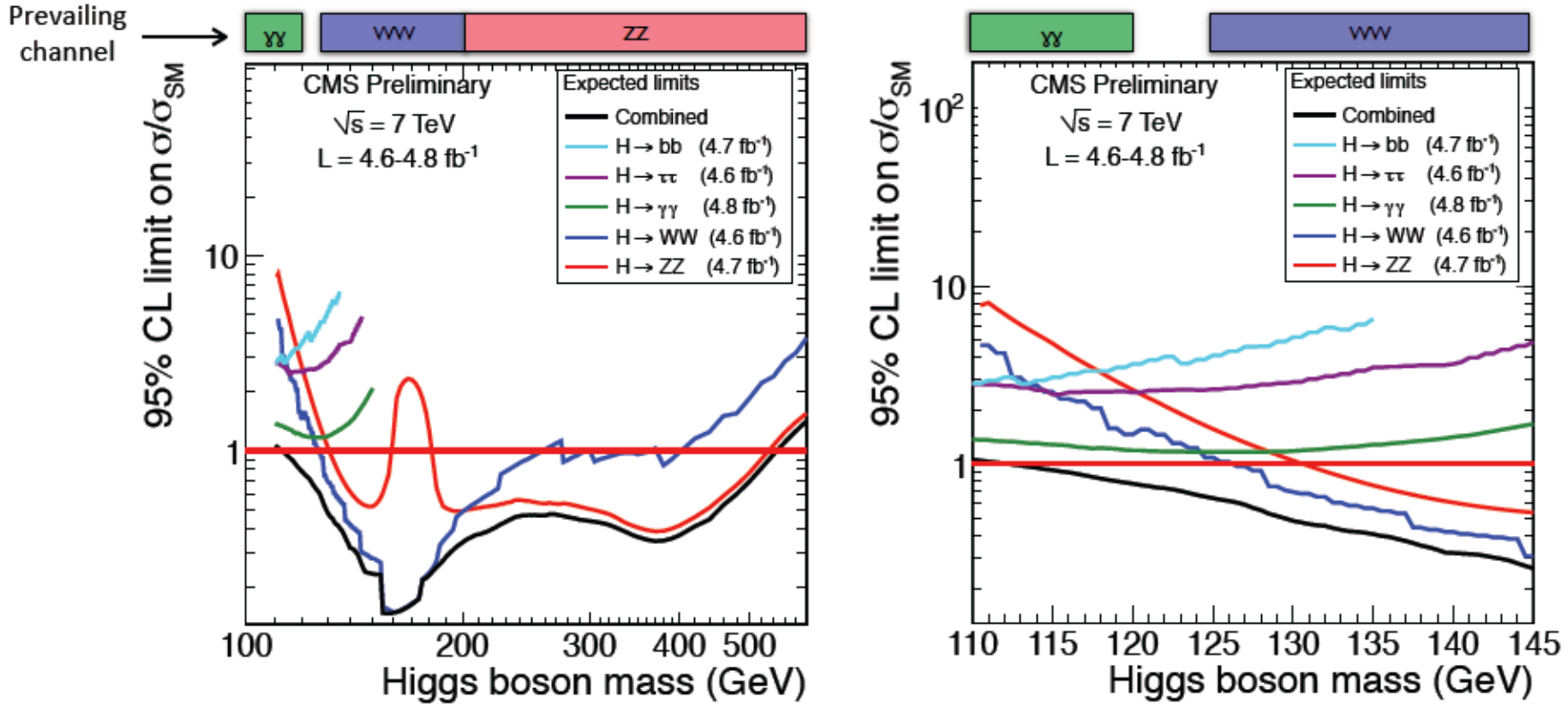



- An excess of events at $m_H \approx 126.5$ with a local significance 2.5 $\sigma$
  Expected significance for SM Higgs 2.9 $\sigma$
  Best-fit signal strength $\mu = 0.9 + 0.4 - 0.3$
- Global probability for such background fluctuation:
  $\approx 30\%$ in the range $110 - 600$ GeV
  $\approx 10\%$ in the range $110 - 146$ GeV

Rustem Ospanov

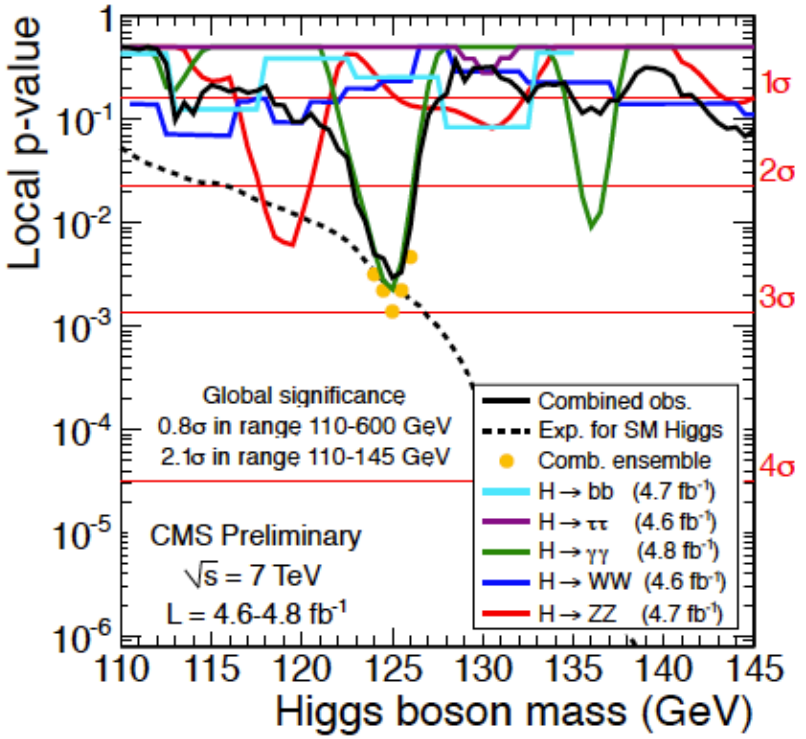
# Expected Sensitivity with 4.7 fb$^{-1}$

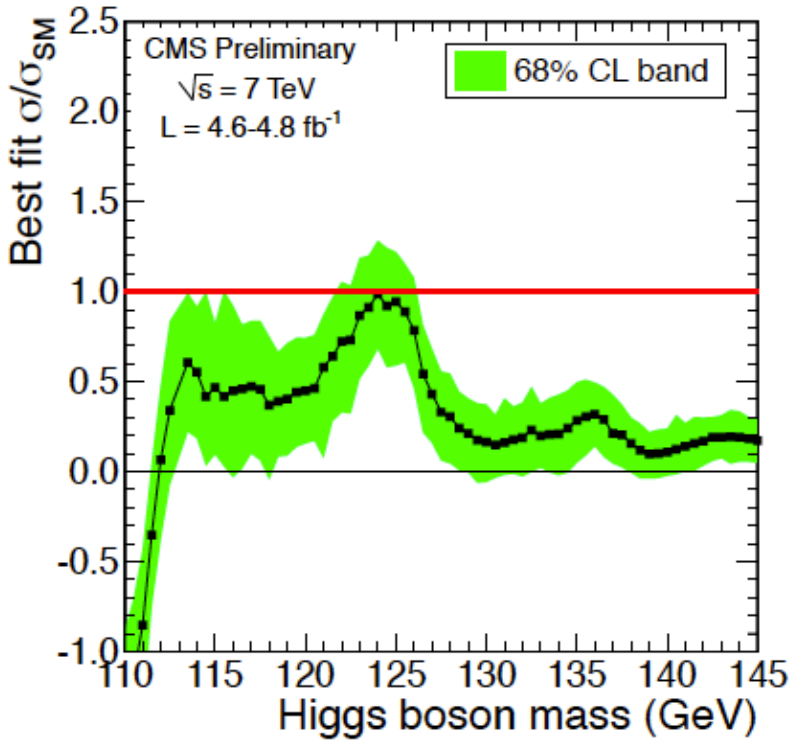
ETH Zürich




**95% CL expected exclusion: 114.5—543 GeV**

# Quantifying The Low Mass Excess




- Minimum p-value observed at 125 GeV with local significance:
  - 2.8 σ – Similar significance expected from signal
- Estimated global significance:
  - 0.8 σ in [110–600] GeV, 2.1 σ in [110–145] GeV
- Not inconsistent (±1σ) with SM Higgs

# Higgs decay channels

LHC Higgs Cross Section Working Group (LHC Higgs XS WG) calculation based on

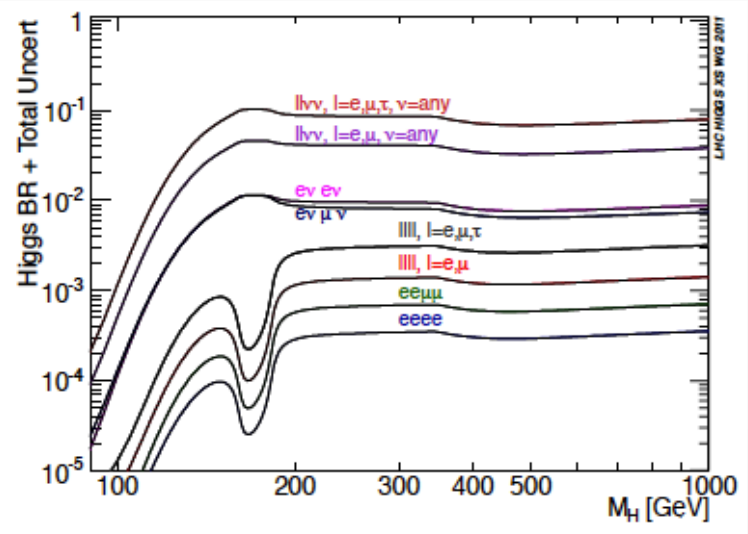
- ⋆ HDECAY [Djouadi, Kalinowski, Mühlleitner, Spira (1996,2006)]
- ⋆ PROPHECY4F [Bredenstein, Denner, Dittmaier, Mück, Weber (2010)]

$$\Gamma_{\rm tot} = \Gamma_{\rm tot}^{\rm HDECAY} - \Gamma_{WW}^{\rm HDECAY} - \Gamma_{ZZ}^{\rm HDECAY} + \Gamma_{4f}^{\rm PROPHECY4F}$$

- HDECAY

  all relevant higher-order corrections, in particular with NNLO running of $\alpha_s$ and 4–loop QCD corrections to $H \to gg$ [Baikov,Chetyrkin (2012)]
- PROPHECY4F

$H \to WW, ZZ \to 4f$ including complete NLO QCD+EW correction and interference effects

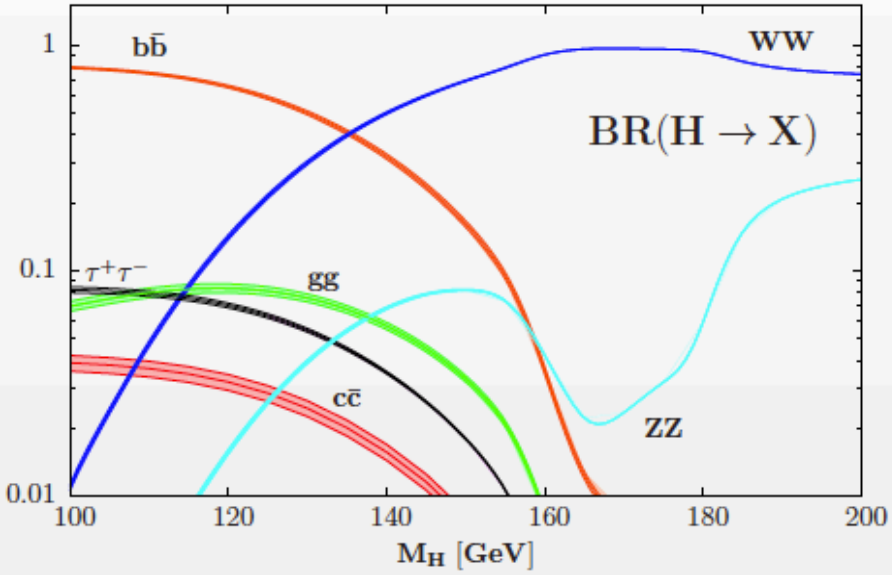



[LHC Higgs XS WG (2012)]

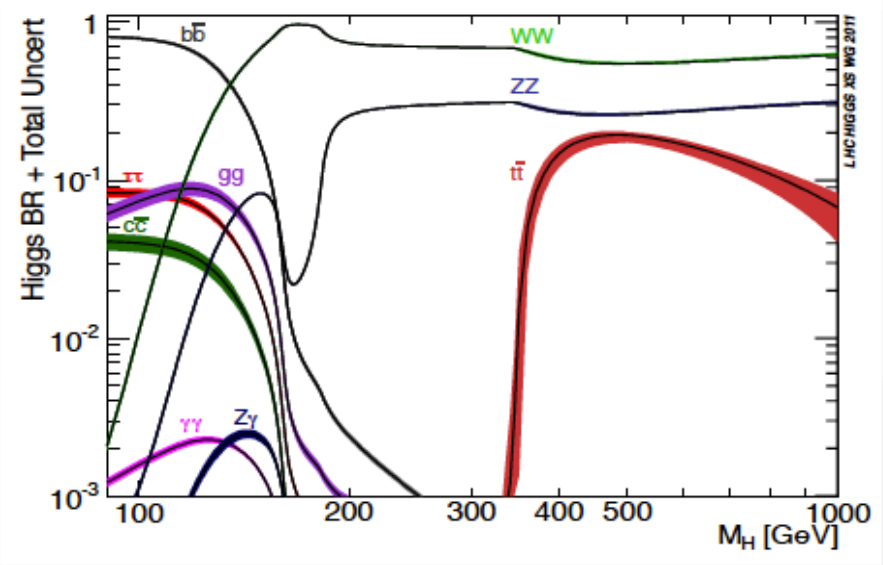
# Parameters and uncertainties

Higgs decay branching ratios affected by uncertainties:

- ⋆ parametric: $\bar{m}_b(\bar{m}_b) = (4.16 \pm 0.06)$ GeV, $\bar{m}_c(\bar{m}_c) = (1.27 \pm 0.03)$ GeV, $\alpha_s(M_Z^2) = 0.1171 \pm 0.0014$ [NNLO MSTW] or $\alpha_s(M_Z^2) = 0.118 \pm 0.002$ [LHC Higgs XS WG]
- ⋆ theory: missing higher-order contributions estimated by scale variation




[J. B., Djouadi (2011)]

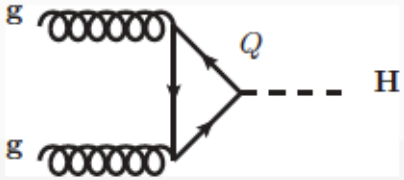



[LHC Higgs XS WG (2012); Denner *et al* (2011)]

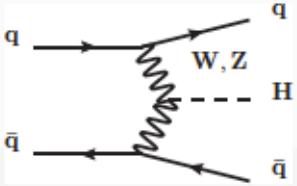
In most relevant channels at $M_H = 120$ GeV:
$\Delta_{\rm BR}(H \to \gamma\gamma) = \pm 5.5\%$, $\Delta_{\rm BR}(H \to WW, ZZ) = \pm 4.8\%$
$\Delta_{\rm BR}(H \to b\bar{b}) = \pm 2.8\%$

# The four main production channels

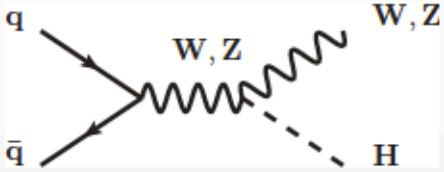
- gluon fusion



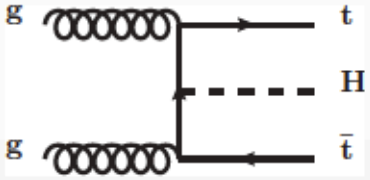

- vector boson fusion

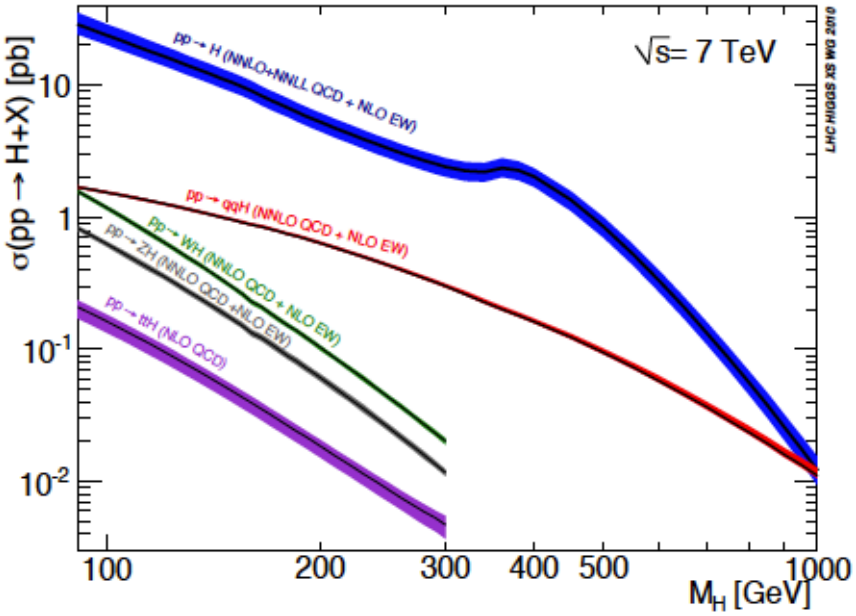



- Higgsstrahlung




- associated production

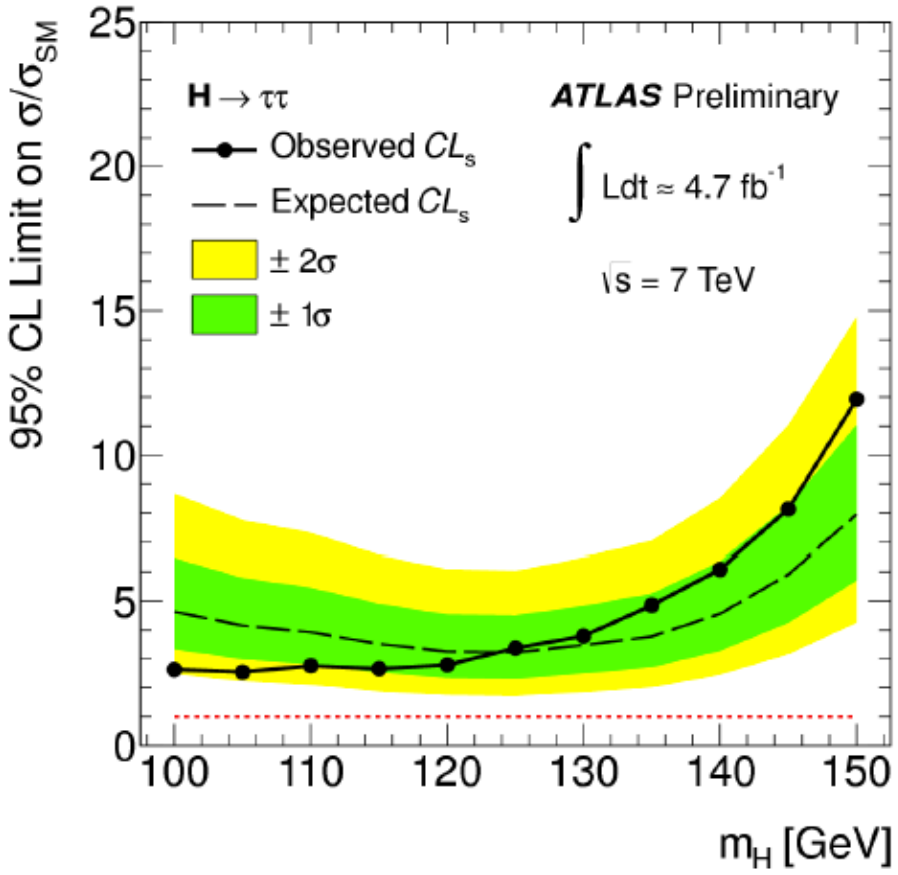



[LHC Higgs XS WG (2011)]

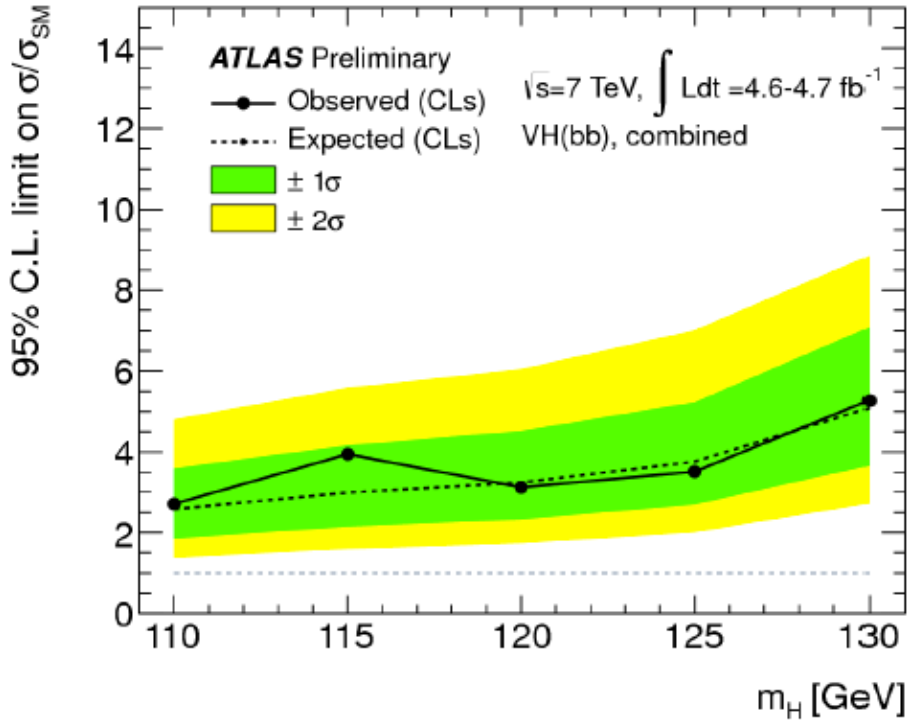
- **Theory meets high precision accuracy:** up to NNLO in the three main inclusive production channels, huge efforts in exclusive production predictions ⇒ **uncertainties from ∼ 100% reduced below $\lesssim$ 15 – 20%**
- **LHC Higgs Cross Section Working Group**: a collective effort from theorists and experimentalists to give the most up-to-date predictions and assessments on uncertainties

# H→ττ Exclusion Limit




- No significant excess
- 95% confidence level exclusion limit based on $CL_s$
- Observed (expected) exclusion between 2.5 (3.2) and 11.9 (7.9) x Standard Model cross section

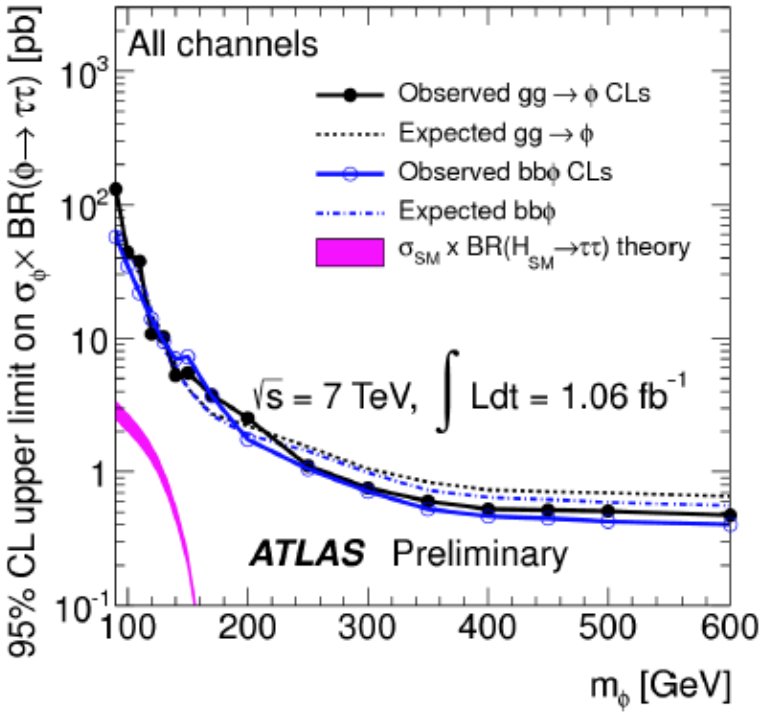
# VH, H→bb: Exclusion Limit

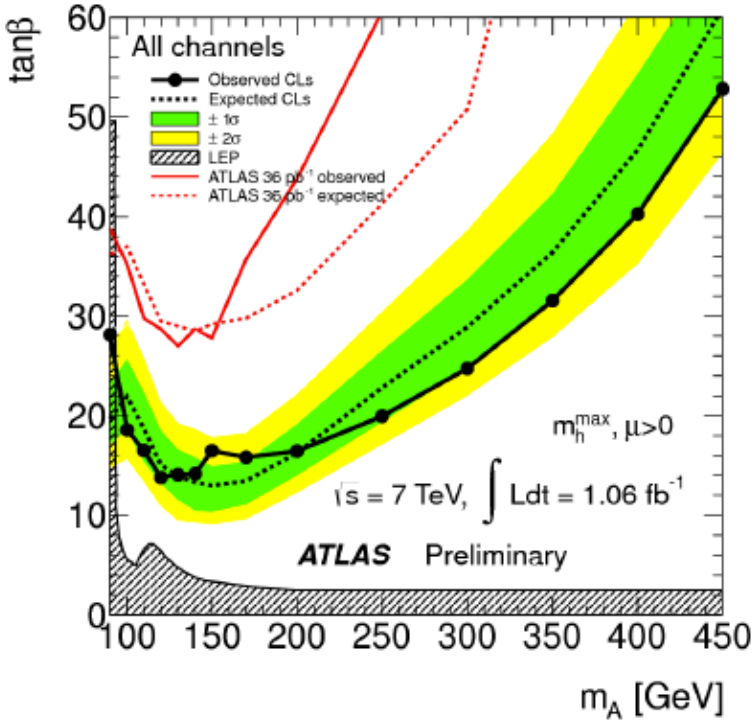



- No excess of events over the expected background was found in data
- 95% confidence limit exclusion limit based on $CL_s$

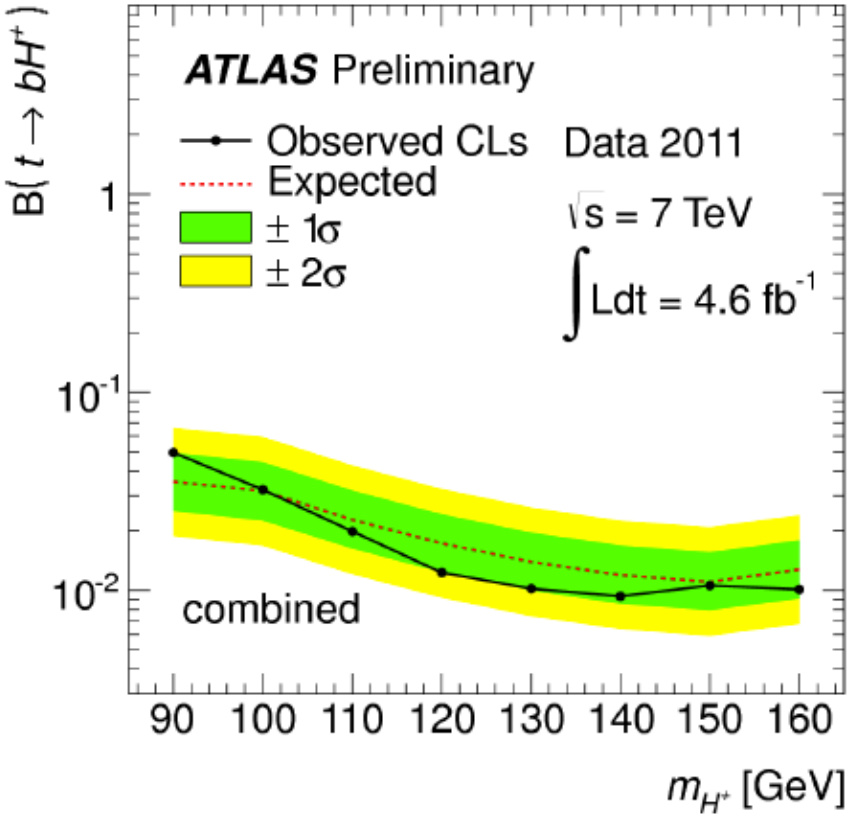
# MSSM h/A/H → ττ

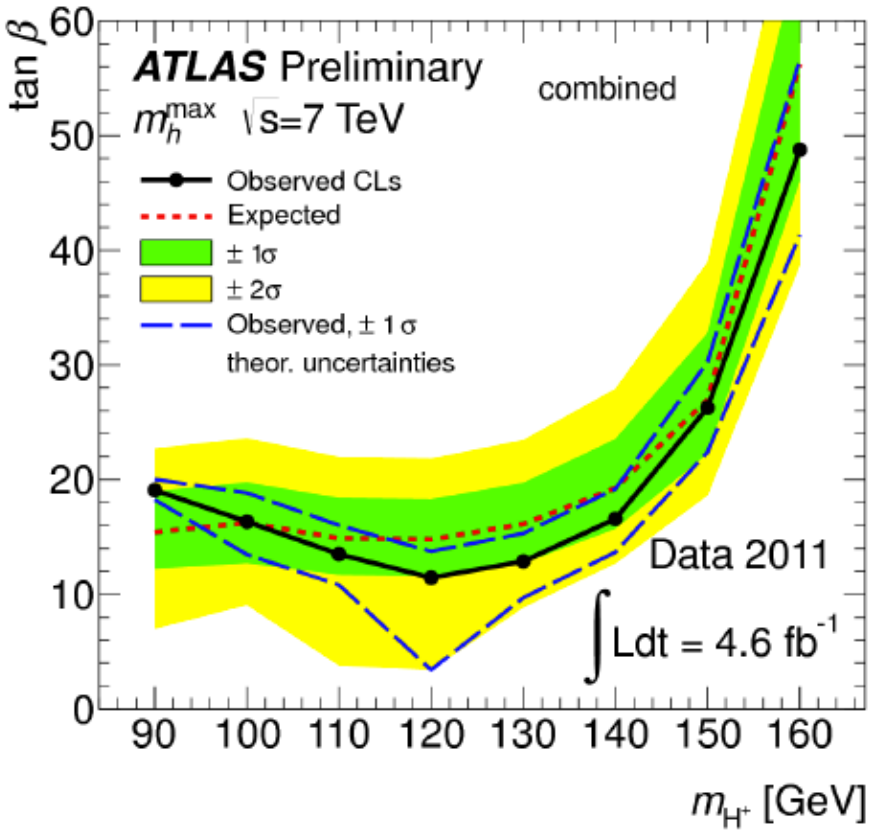
- For high tanβ decay into ττ enhanced
- Analysis selection and background estimation very similar to Standard Model analysis in the 0 jet channel



# Charged Higgs: Exclusion Limit

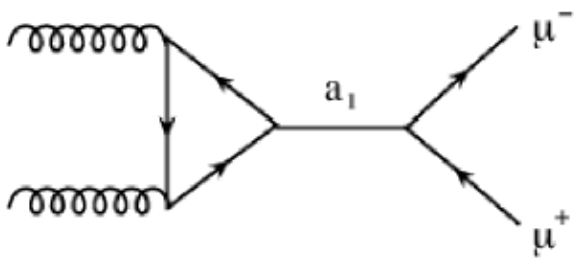


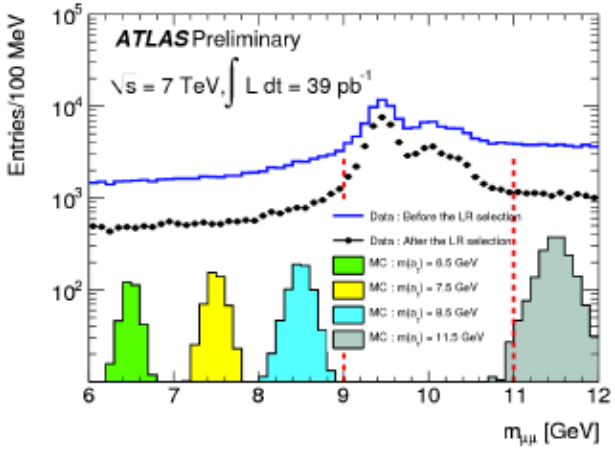



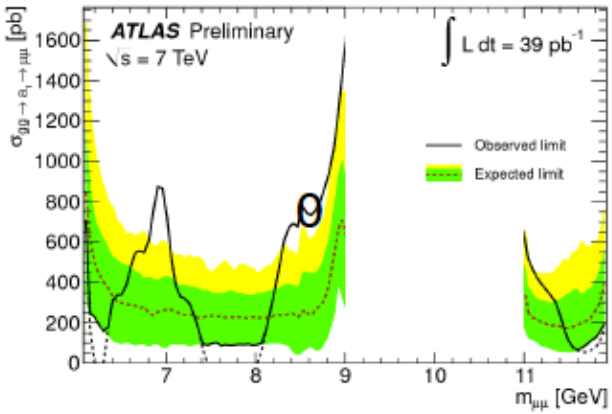

MSSM

# NMSSM $a_1 \rightarrow \mu\mu$

- NMSSM: additional scalar singlet S
  - 2 CP odd Higgs fields: $a_1$,$a_2$
  - $a_1$ can be very light (10 GeV)
- Analysis selection:
  - 2 μ with $p_T$>4 GeV
  - 4.5 GeV < $m_{\mu\mu}$ < 14 GeV
  - Construct likelihood ratio from isolation and vertex fit quality
  - Background from $m_{\mu\mu}$ sidebands

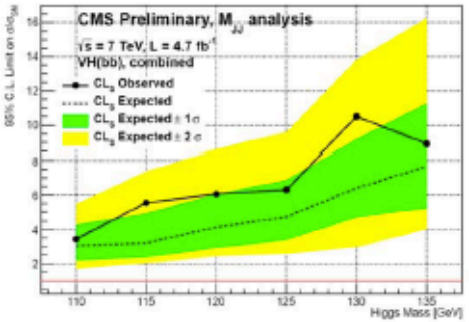


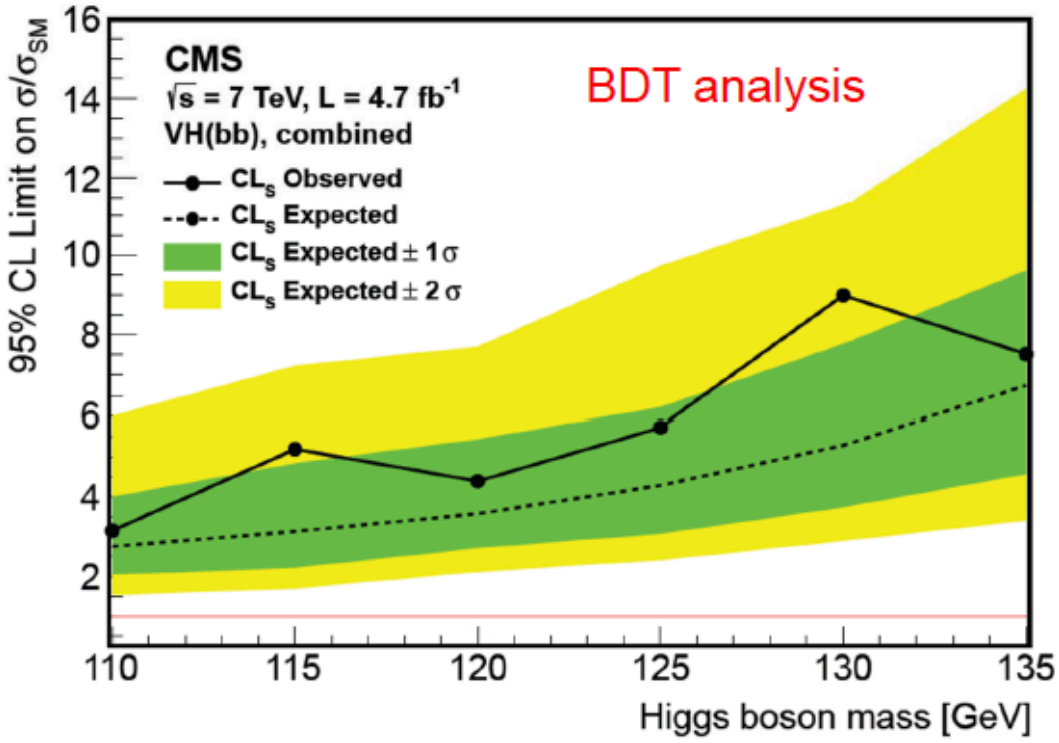



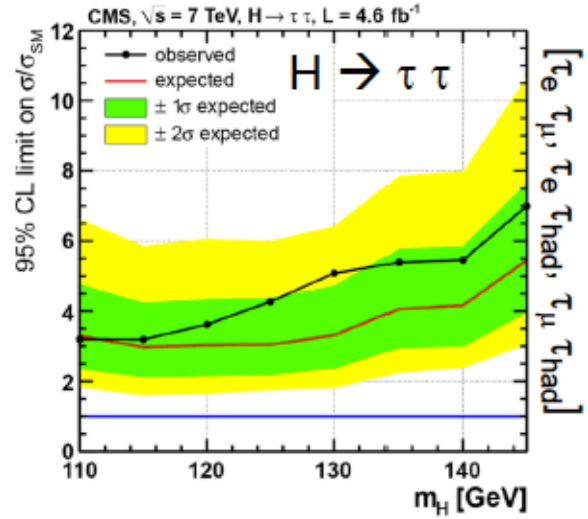
# VH→V(bb̄): Results

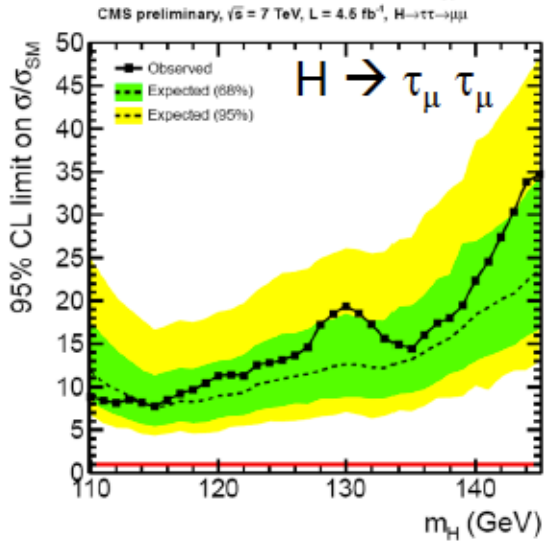
- No significant signal observed in any of the channels
- Total expected limit ~ 3x SM expectation ($m_H$=115 GeV)
- Observed limit from combination consistent with expectation
- BDT analysis (lower plot) performs 2-20% better than the mass-spectrum-based analysis (upper)



# H → τ τ (cont'd)



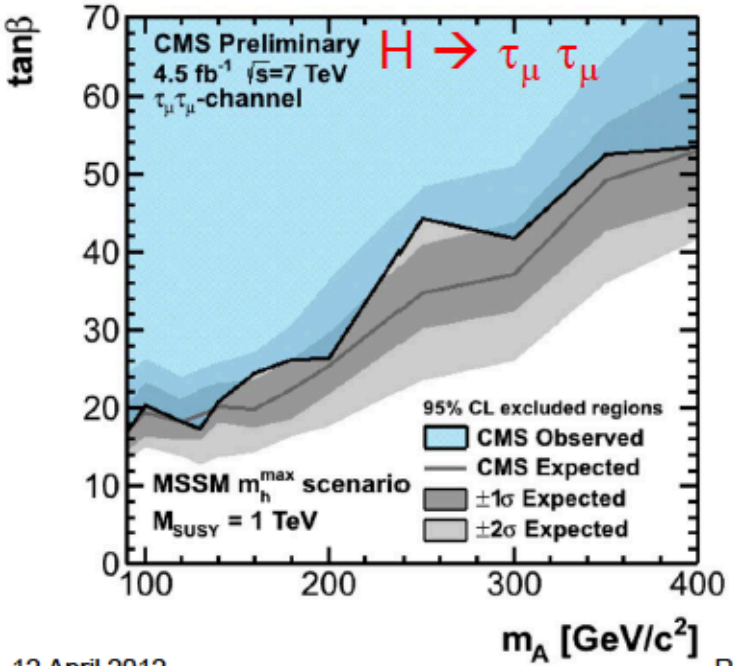



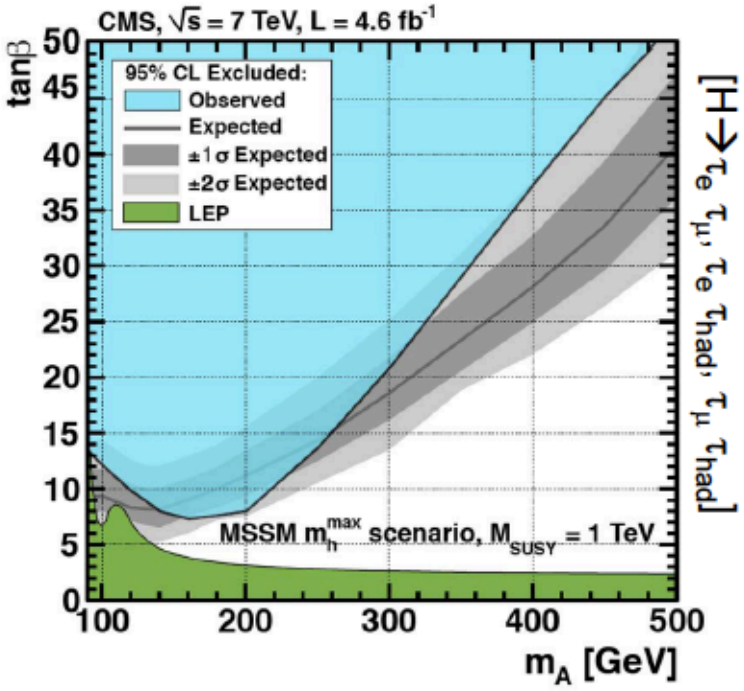

- No significant excess over the expected standard model background contributions is observed
- Combination $\tau_e\ \tau_\mu$, $\tau_e\ \tau_{had}$, $\tau_\mu\ \tau_{had}$ :
  - → expected & observed 95% CL limit ~ 3x SM expectation ($m_H$=115 GeV)
  - → observed limit consistent

→ Addition of H→$\tau_\mu\ \tau_\mu$ channel improves on combined limit from the other three decay
  - combination result in preparation

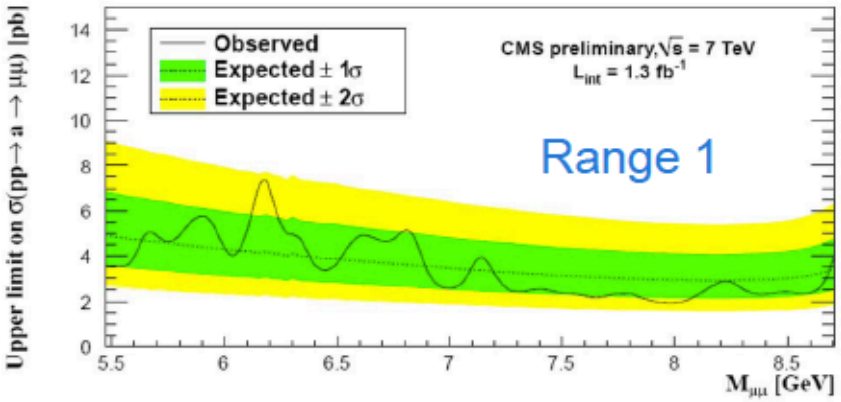
# Φ→ττ MSSM Search

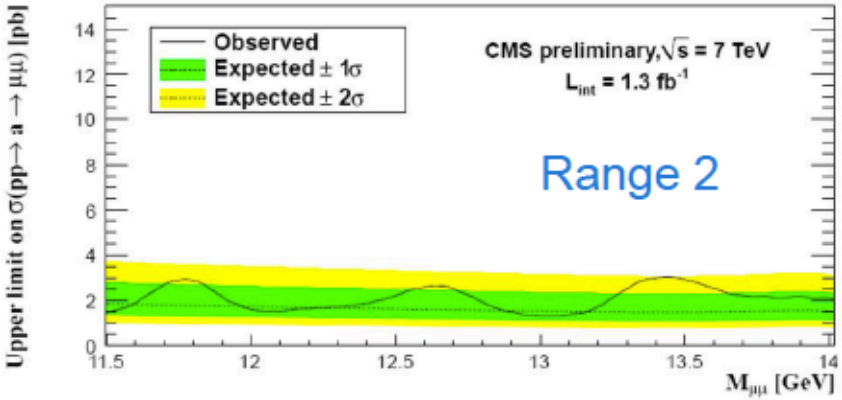
- Excludes previously unexplored territory
- 95% CL exclusion range for tan β extends down to 7.1 at $m_A$~160 GeV
  - → narrowed parameter space at low $m_A$
- $\tau_\mu\ \tau_\mu$ channel alone fairly competitive with other measurements

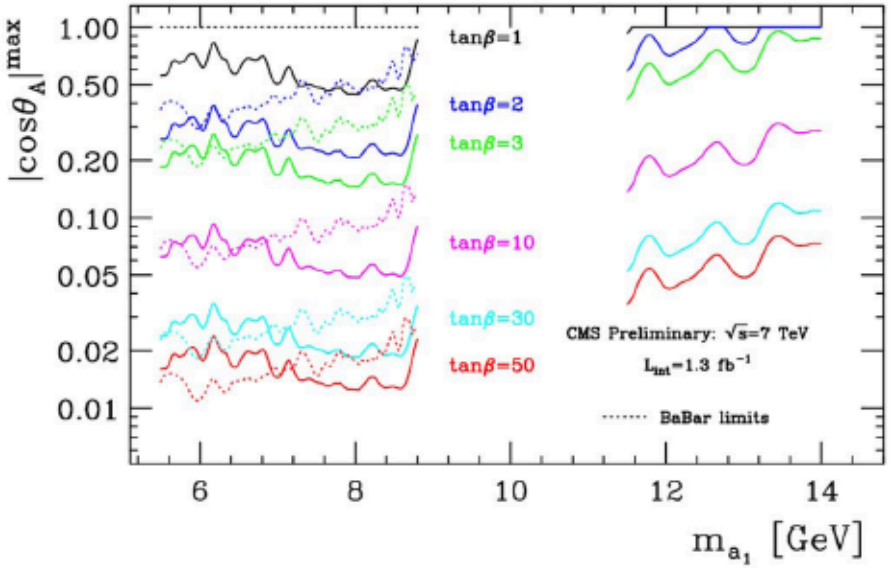


# a→μμ (cont'd)



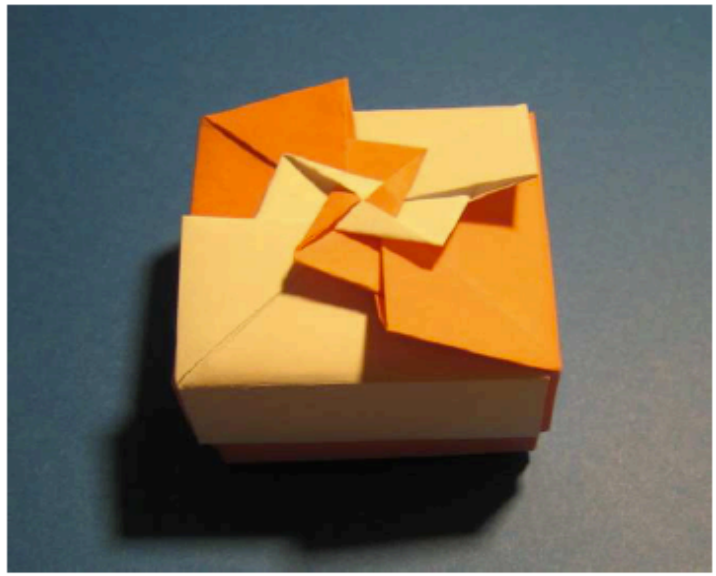

- Improvements on BaBar limits for NMSSM parameter $|\cos\theta_A|$ in lower mass range
- CDF published limits relative to $\Upsilon(1S)$ cross section (not shown)
- No BaBar or CDF limits in upper mass region

# NLO Monte Carlo Tools for Higgs Physics at the LHC

## Conclusions

- There are several NLO+PS programs that describe the production of a Higgs boson in different channels
- Although they formally all agree at NLO, NNLO terms can be large for processes with large $K$ factors.
- Differences among each other are well understood and have been studied in the past few years
- For processes in the POWHEG BOX, please visit the web page

`http://powhegbox.mib.infn.it`



Carlo Oleari

# NNLO QCD predictions for Higgs Physics at the LHC

## Conclusions

- The most relevant Standard Model Higgs inclusive cross sections known with high precision through NNLO QCD.
- Calculations implemented in public available codes: ggh@nnlo, vh@nnlo, bbh@nnlo, higlu, ihixs, vbfnnlo.
- Threshold resummation effects are relevant.
- Important progress in NNLO fully-exclusive calculations. E.g.
  - Fully exclusive NNLO QCD calculation for associated $W$-Higgs production through $q_T$-subtraction method.
  - NNLO QCD corrections for $H \to b\bar{b}$ through non-linear mapping method.
- NNLL+NLO Higgs $q_T$-resummation:
  - New version of the HqT code: better estimate of perturbative uncertainty.
  - The HRes code: full kinematical dependence on the Higgs and its decay products. Possible to implement experimental cuts.

# SUSY Higgs and Composite Higgs

## Which Higgs Boson?

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

# SUSY Higgs and Composite Higgs

## Conclusions

**(i) MSSM Higgs boson production** including HO corrections available

**(ii) Interpretation of LHC Higgs search results within**

* MSSM: requires 'finetuning'
* NMSSM: less finetuned
* Composite Higgs: compatible with LHC results
* Model-independent
  - effective theory: global fits to best signal strengths and exclusion regions
  - SM Higgs hypothesis consistent w/ data at 94% CL

# Some items for discussion

- Could one reduce the uncertainties in the H +0j,1j,2j prediction from data for V+0j,1j,2j?
- hat is the least theory-model independent way to present BSM Higgs search data?