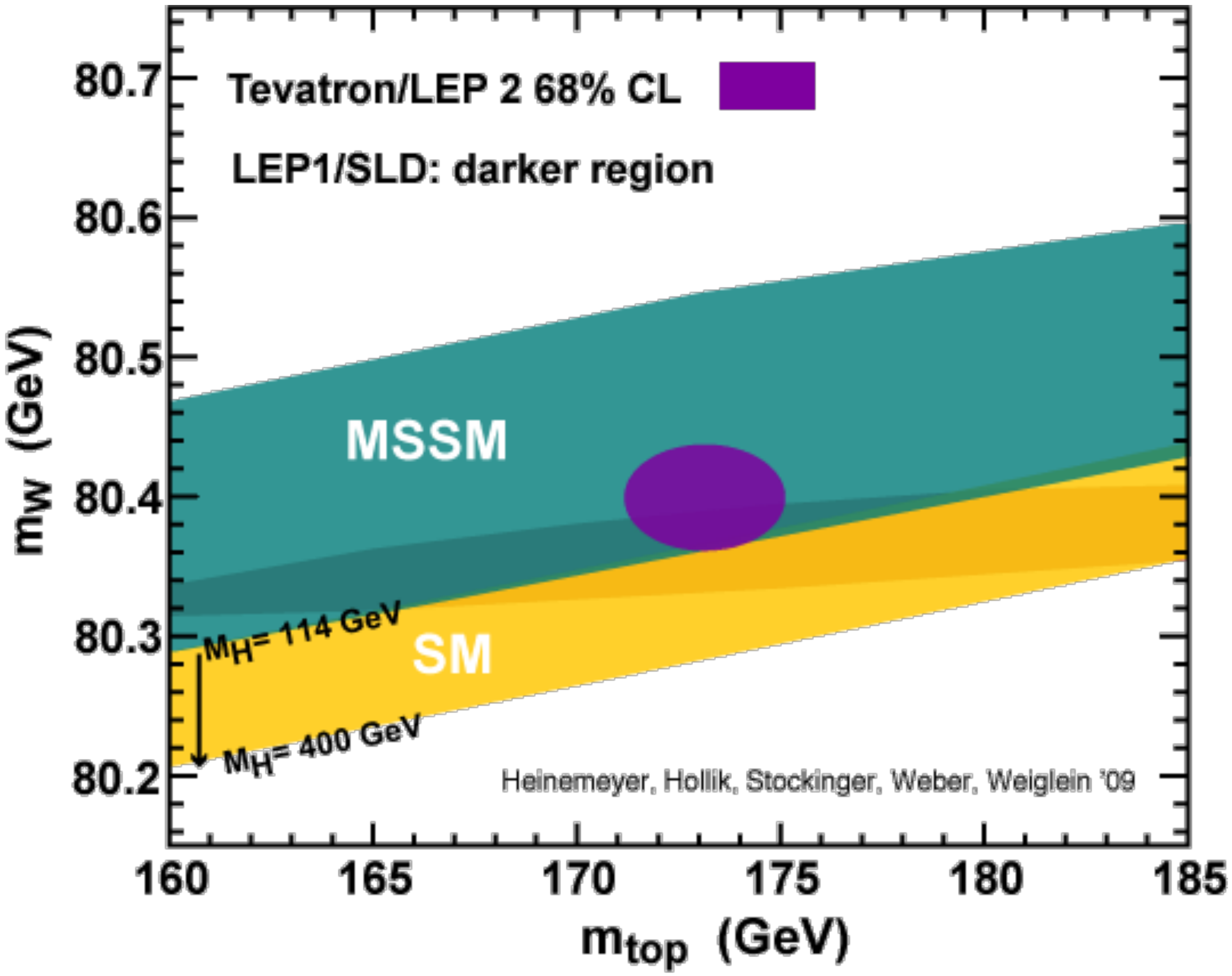
Properties of the Higgs Boson

John Conway
University of California, Davis

SLAC Summer Institute
August 6, 2018

The situation before the LHC



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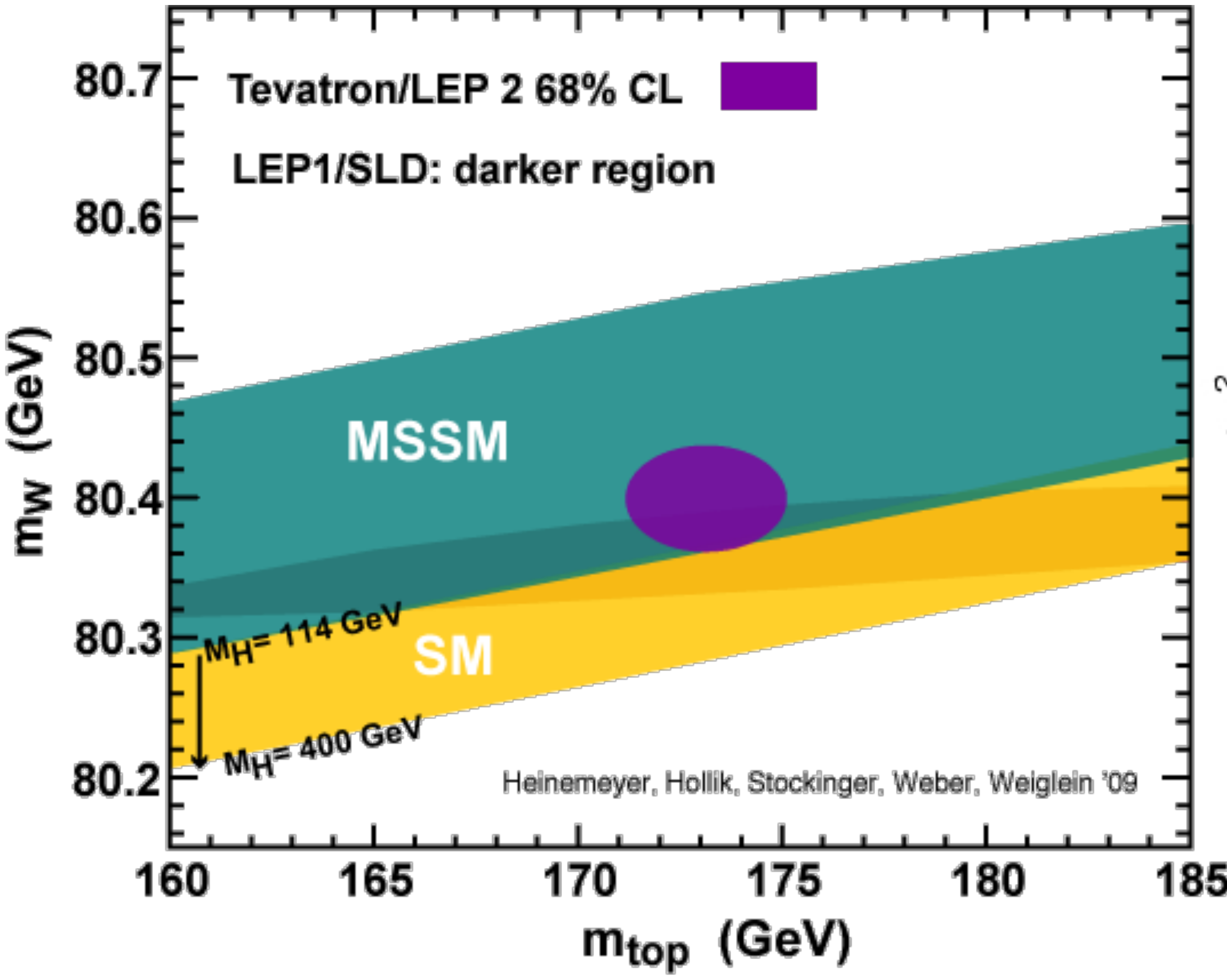
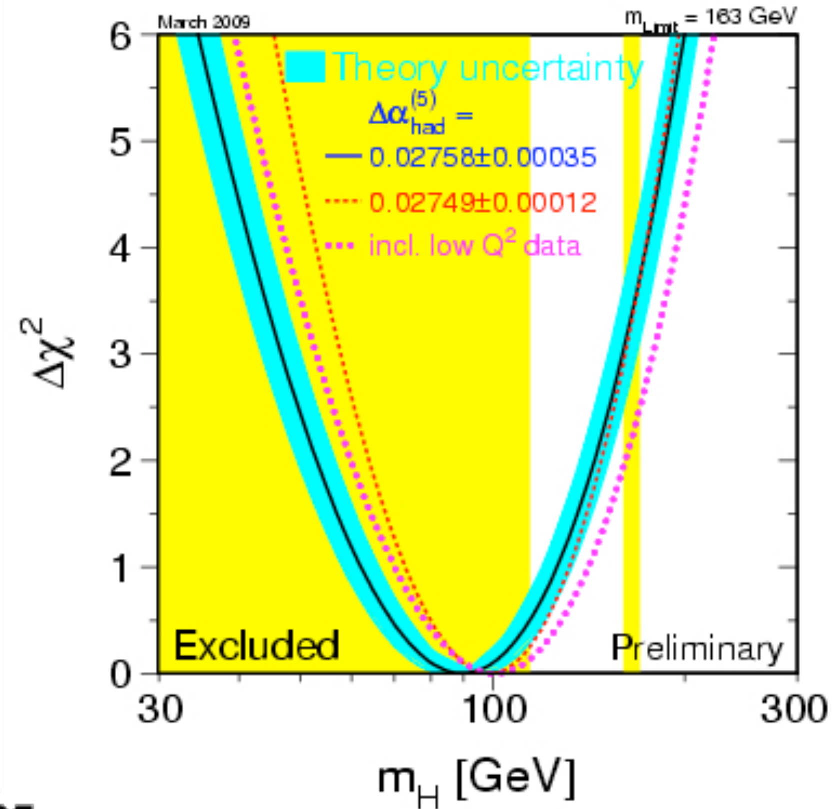
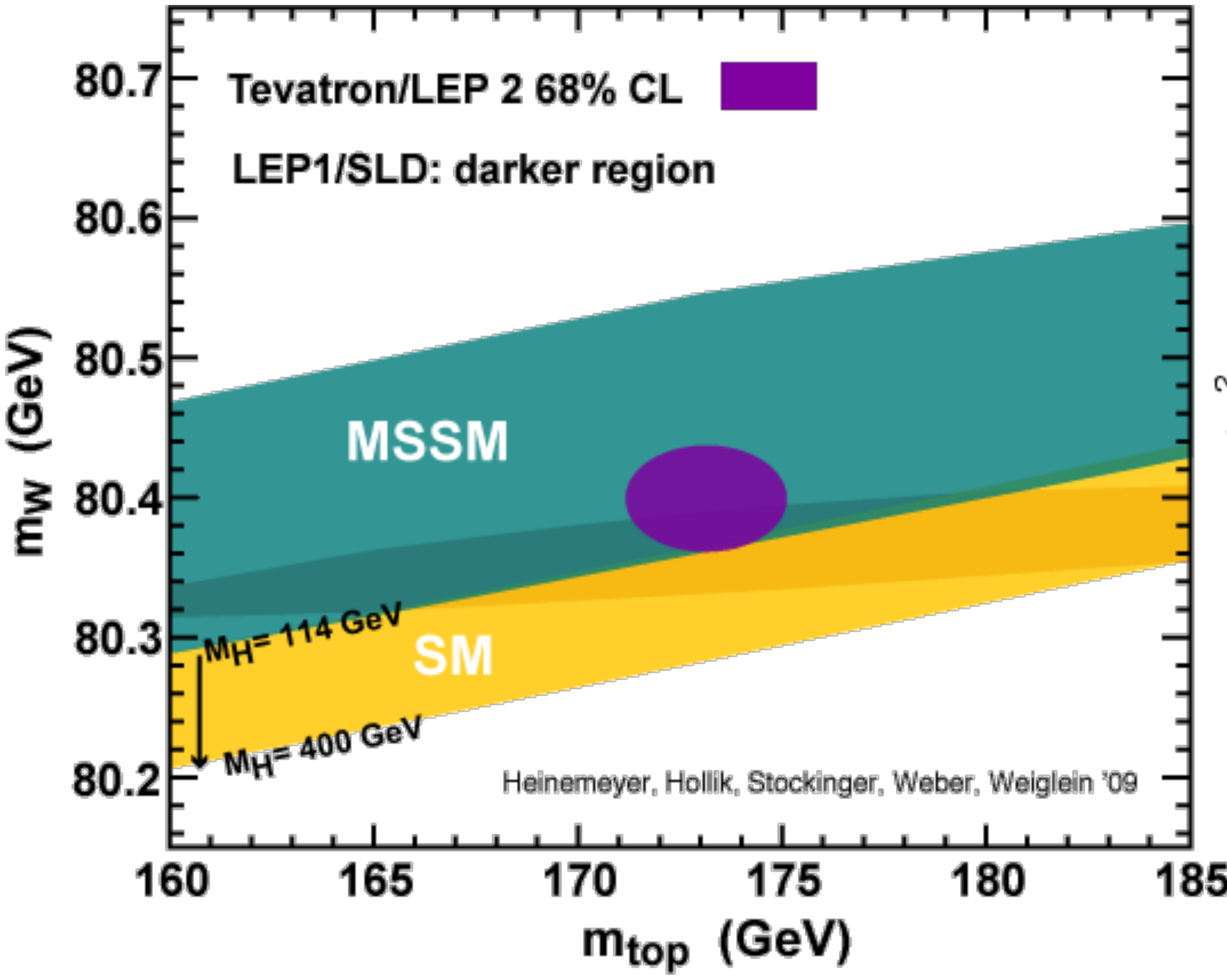
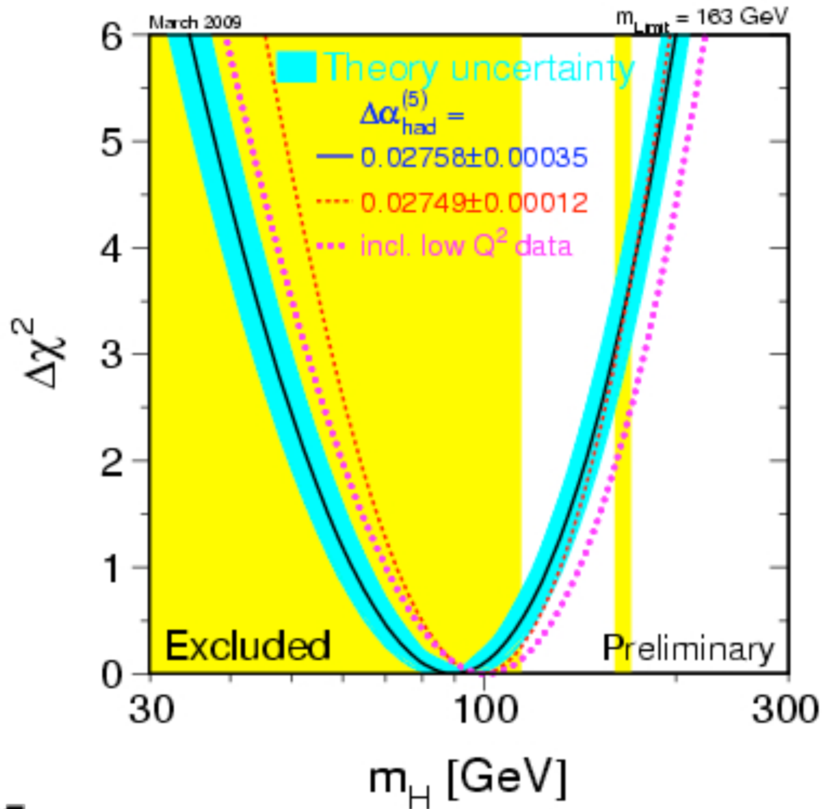




The situation before the LHC





LEP 2/Tevatron/ν precision measurements

⇒ light SM Higgs boson was strongly favored…but excluded?

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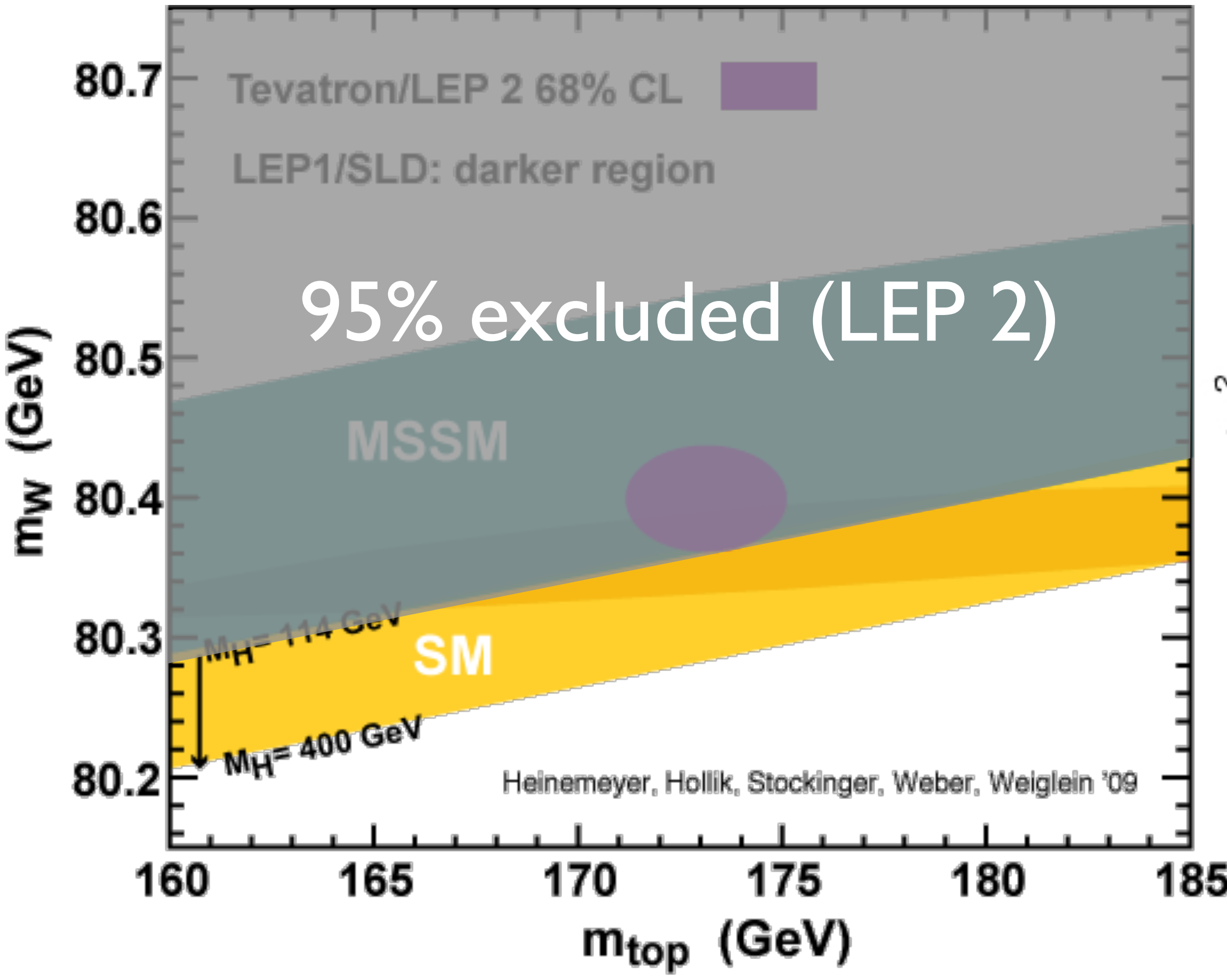

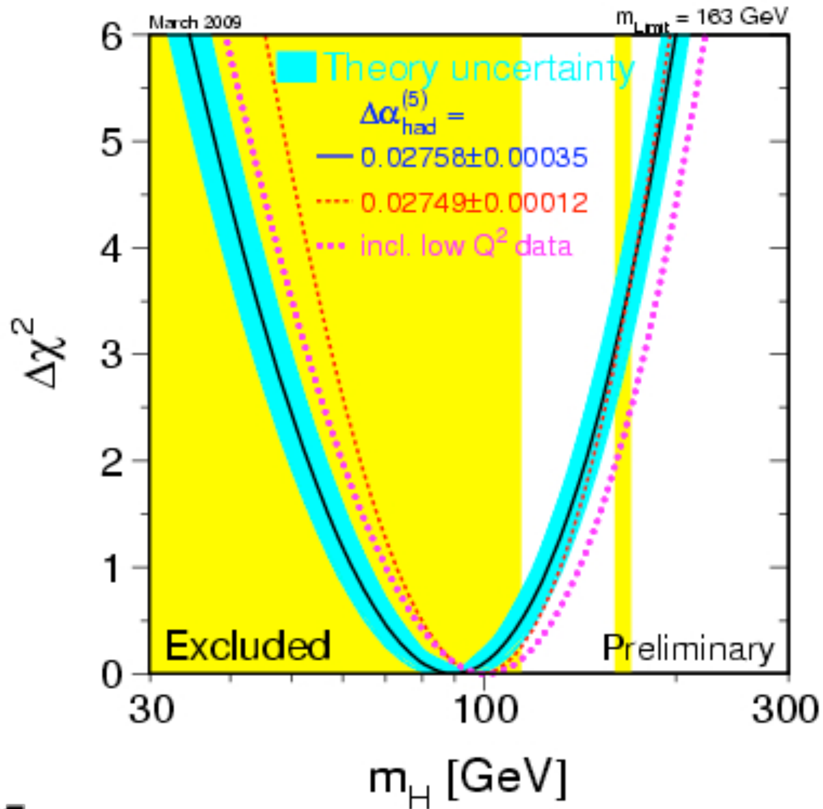

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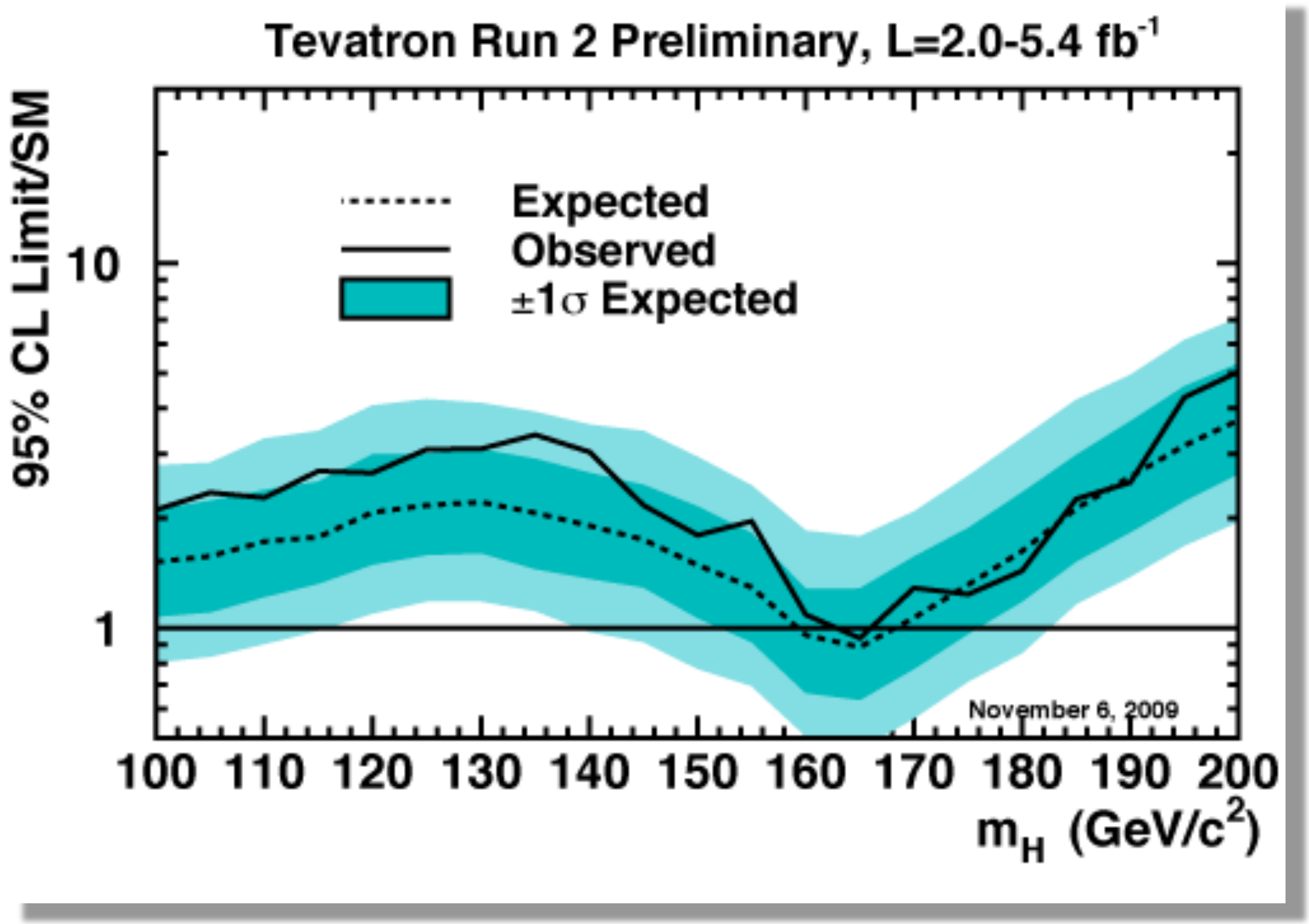
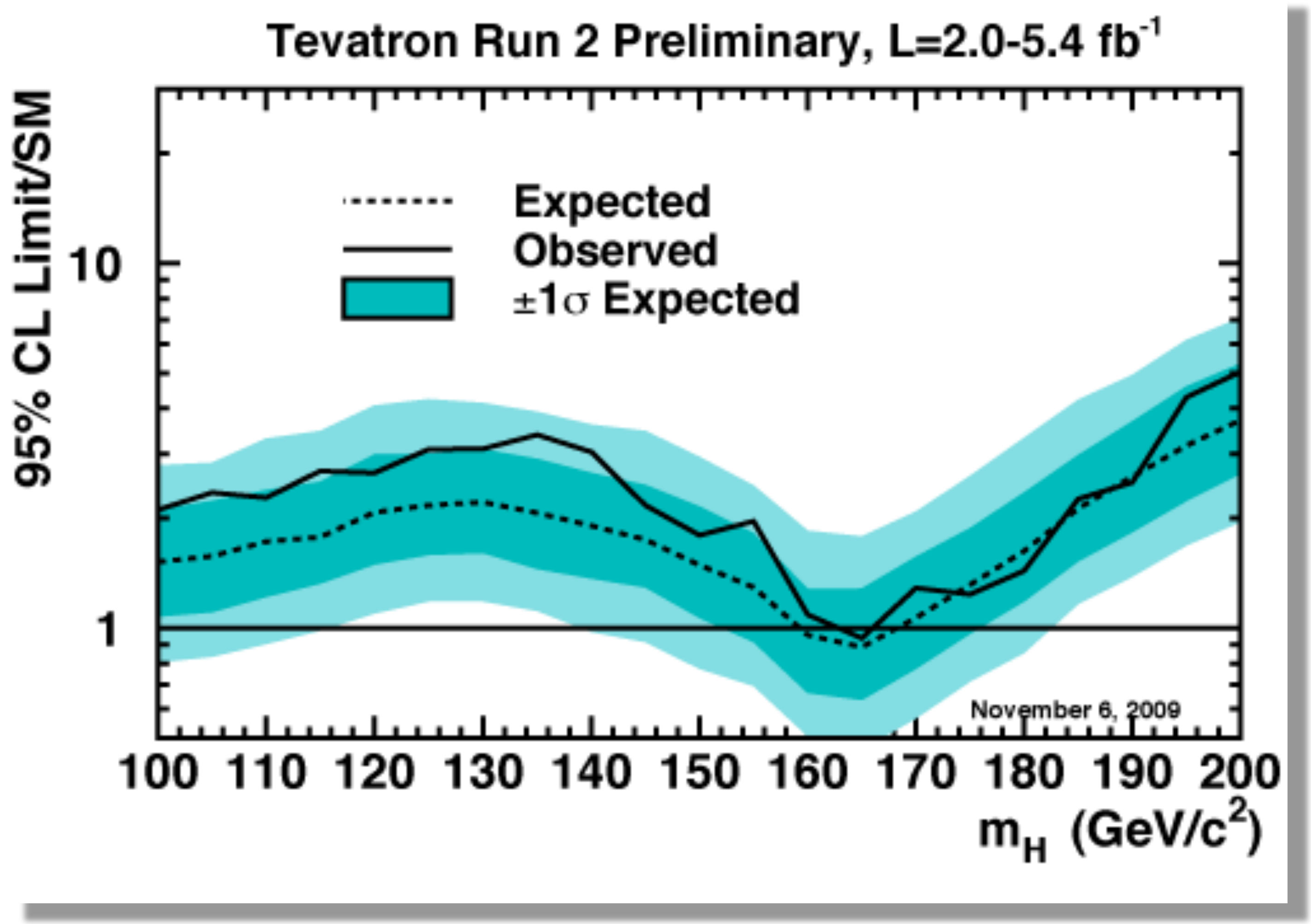
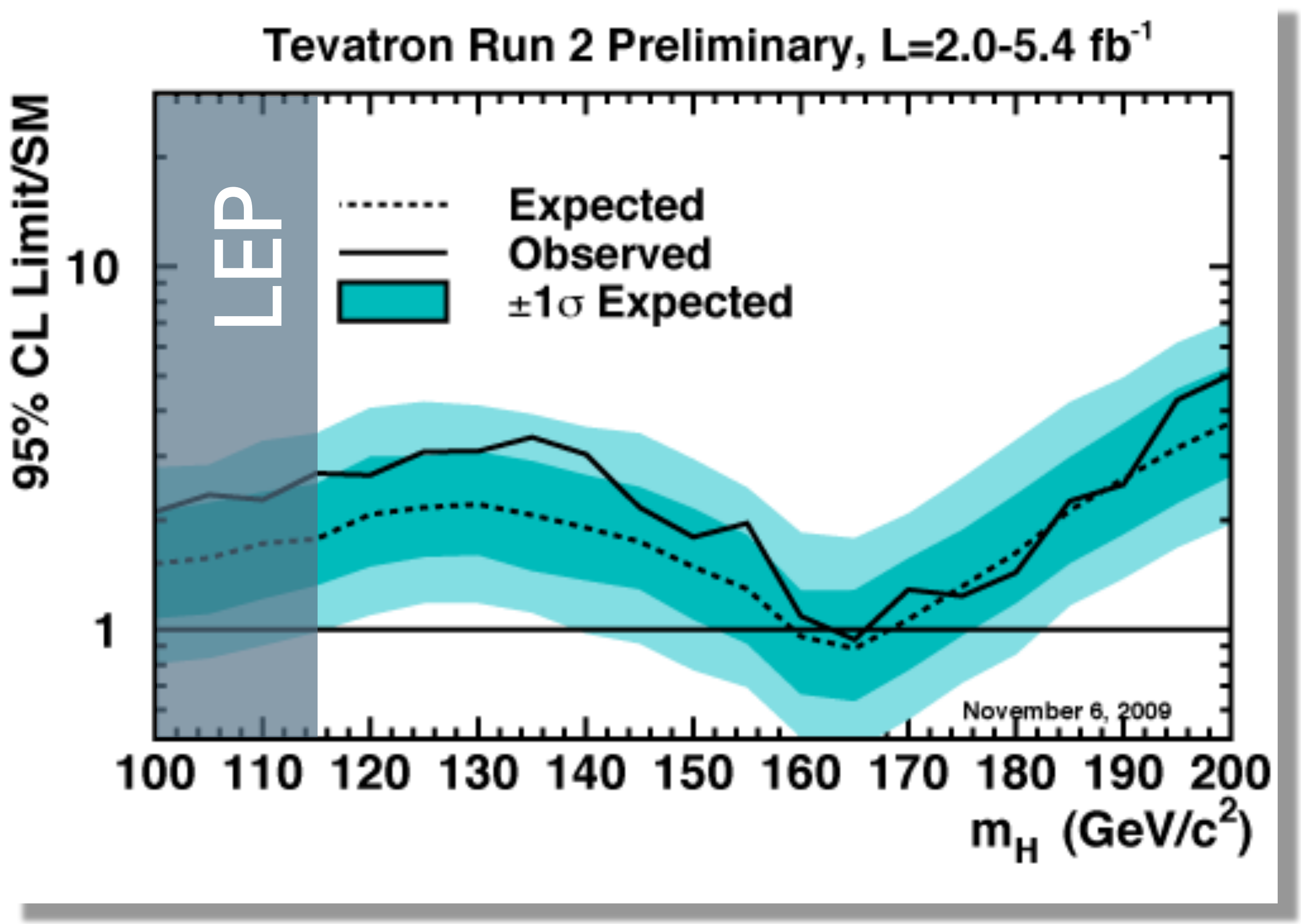


The situation before the LHC



Tevatron reached 95% CL exclusion in 2009 - but could it see the SM Higgs before the LHC?

The situation before the LHC



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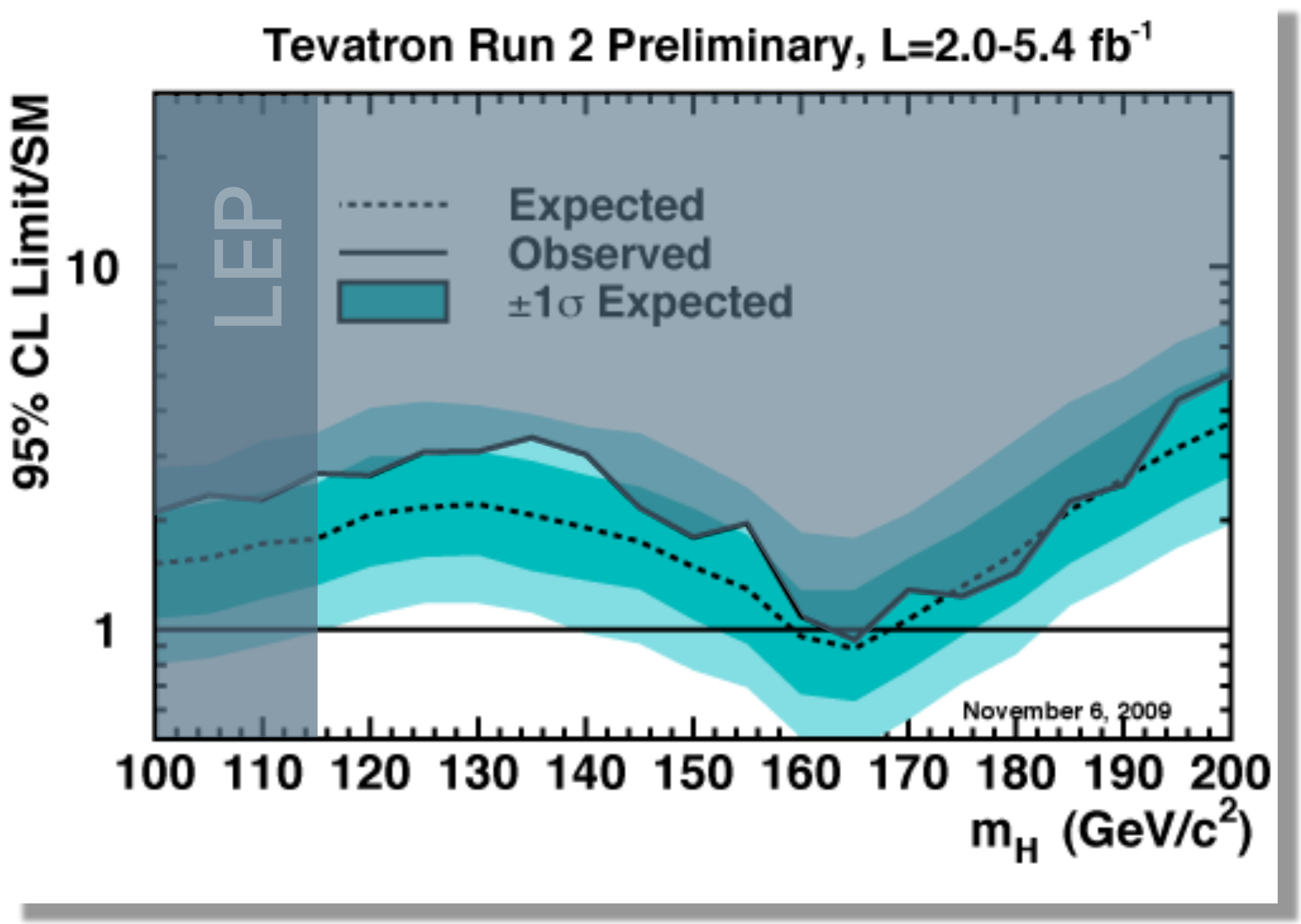

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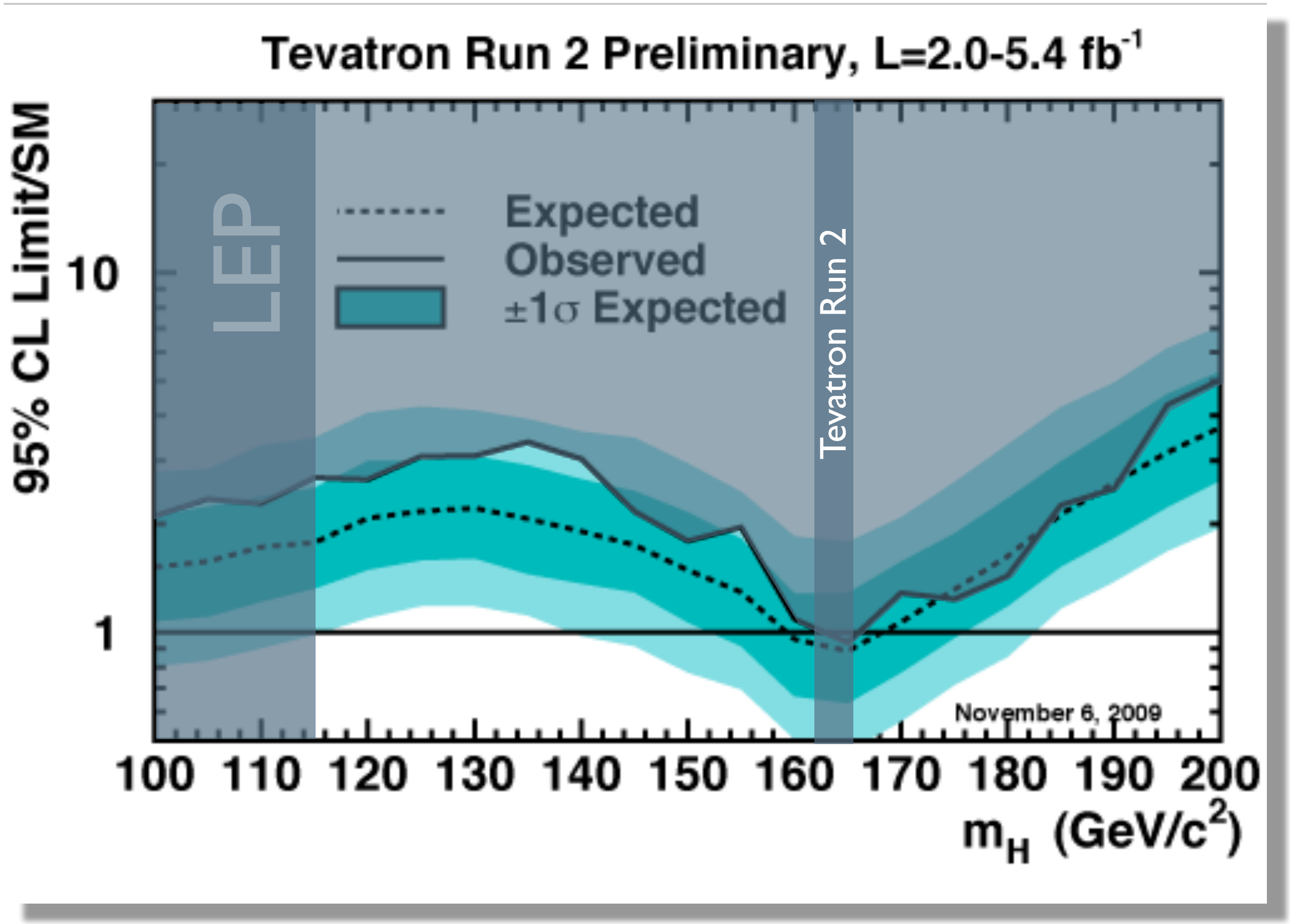

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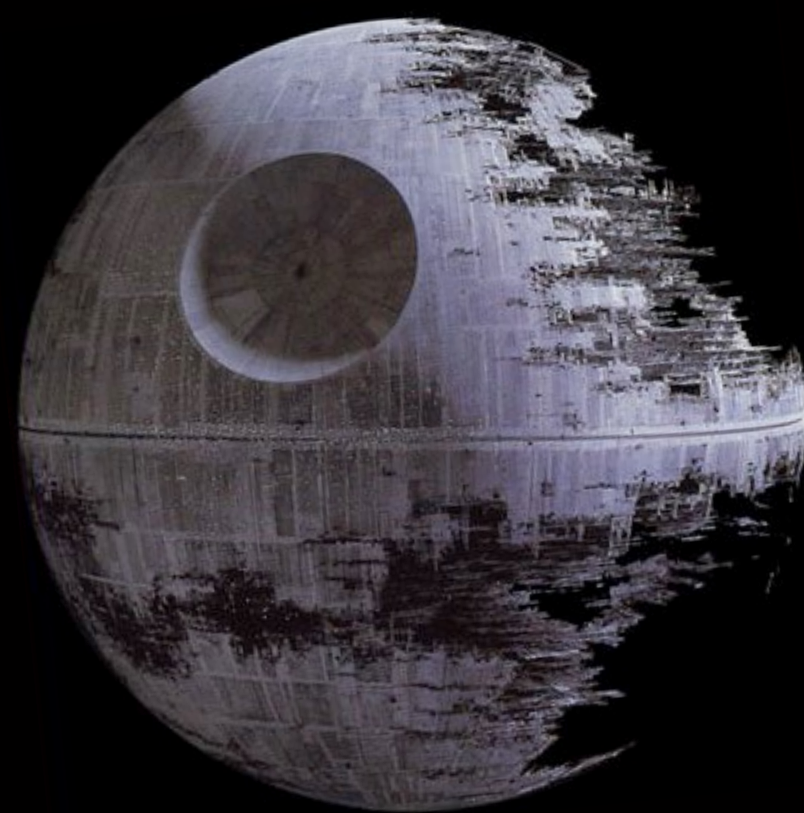
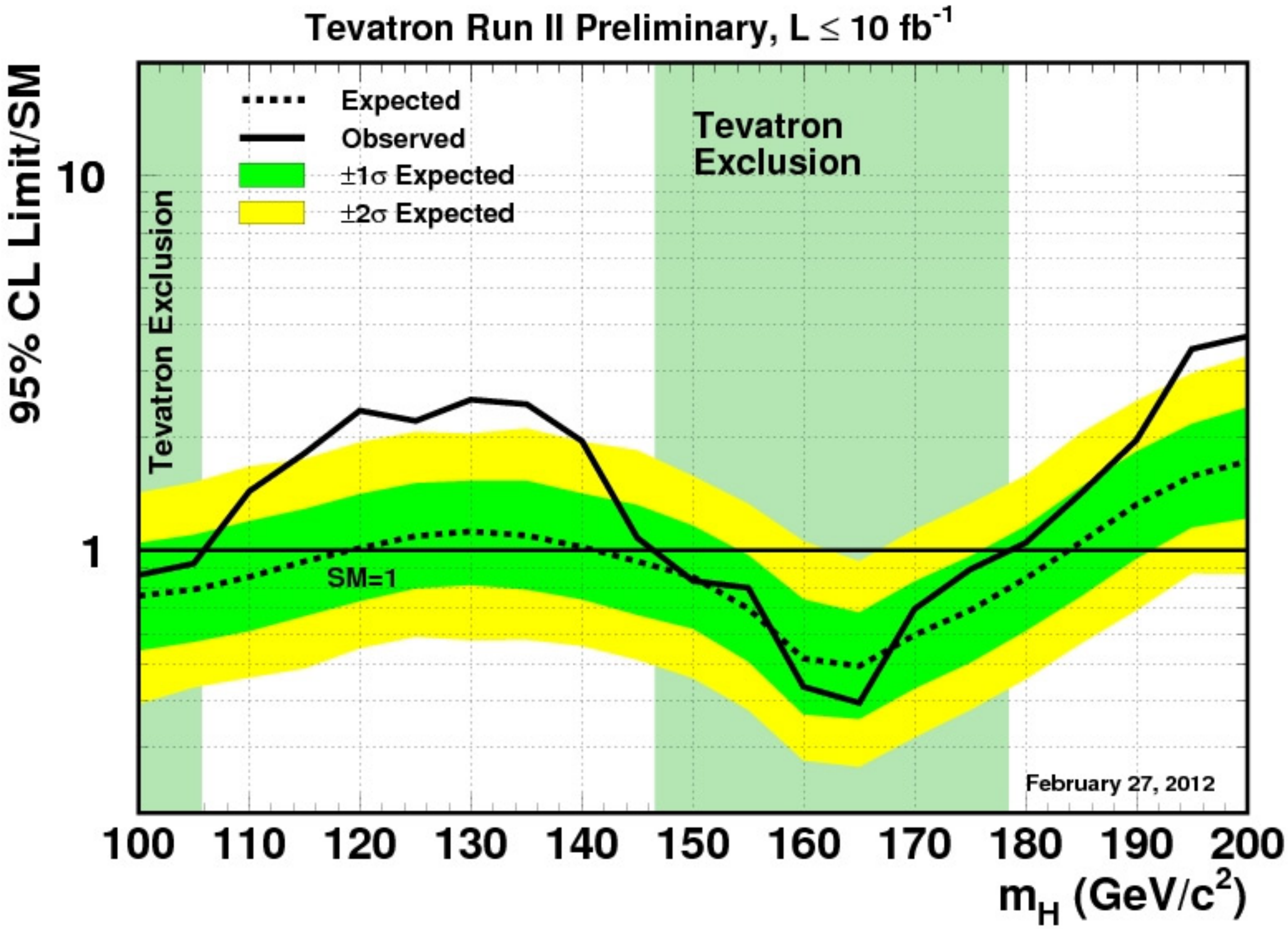
Meanwhile, back in Geneva construction continued....



The situation before the LHC



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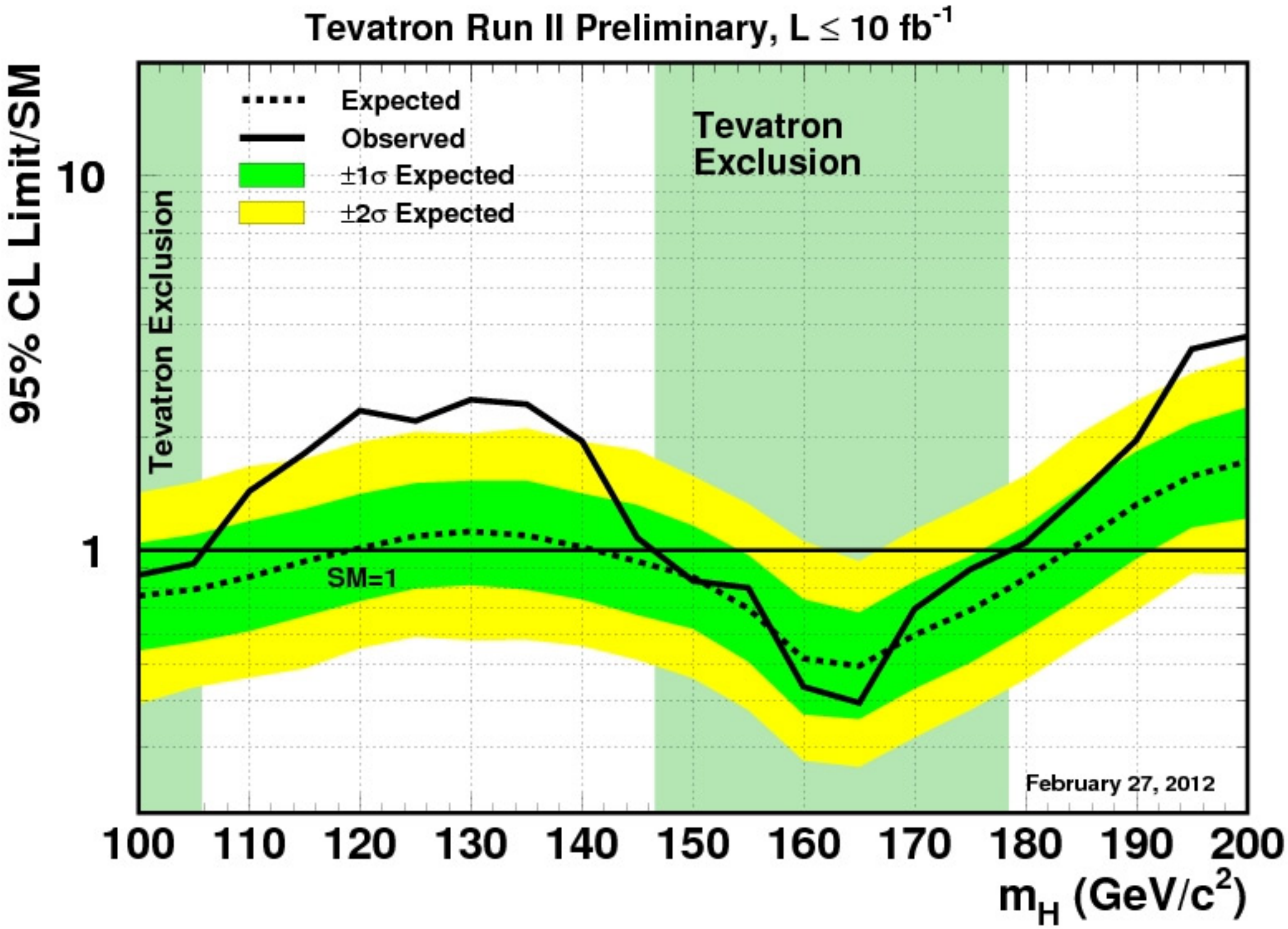
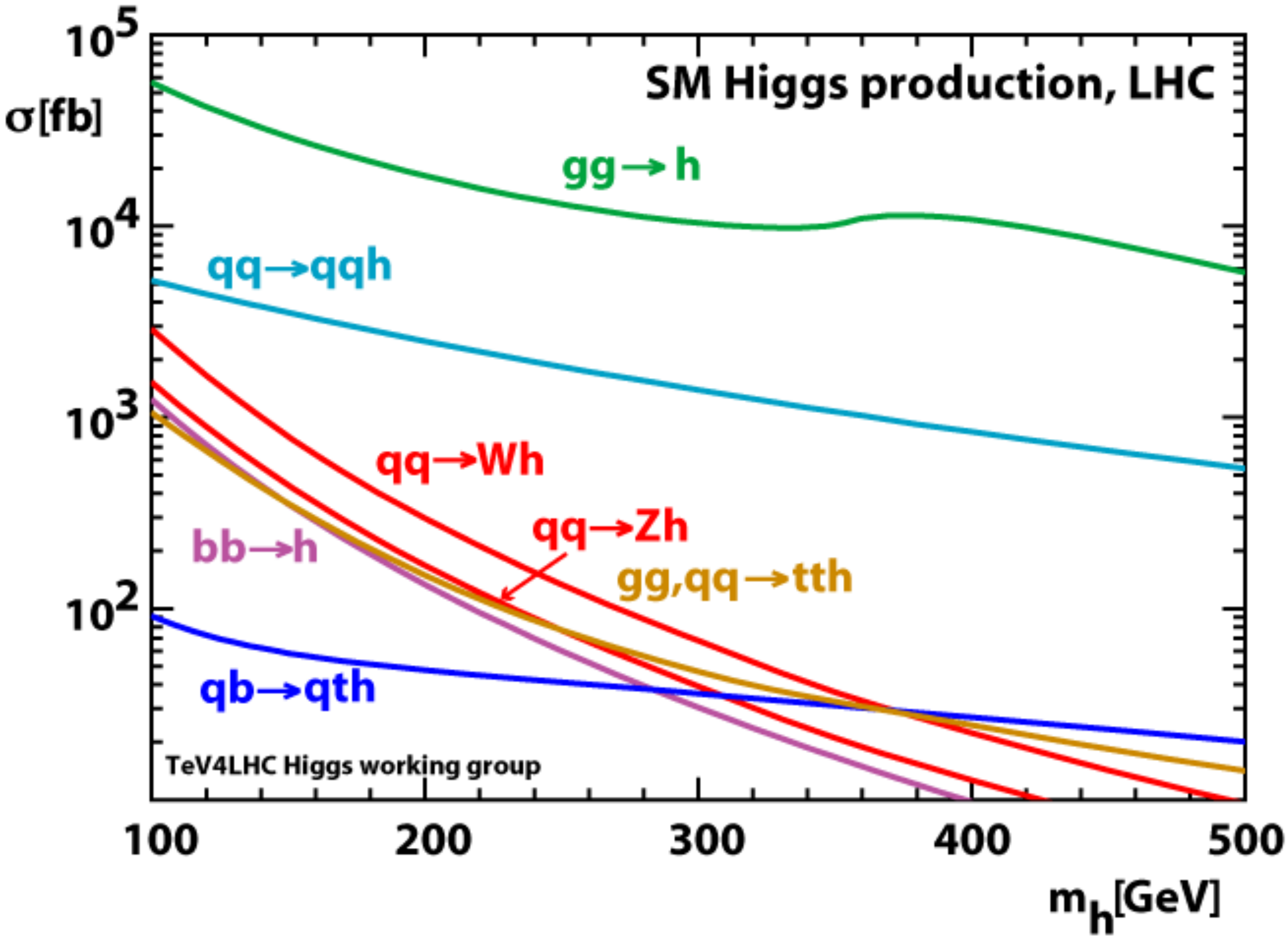


By early 2012 the Tevatron had excluded 147-178 GeV…and had an excess in the 120-130 GeV range!

LHC SM Higgs Production



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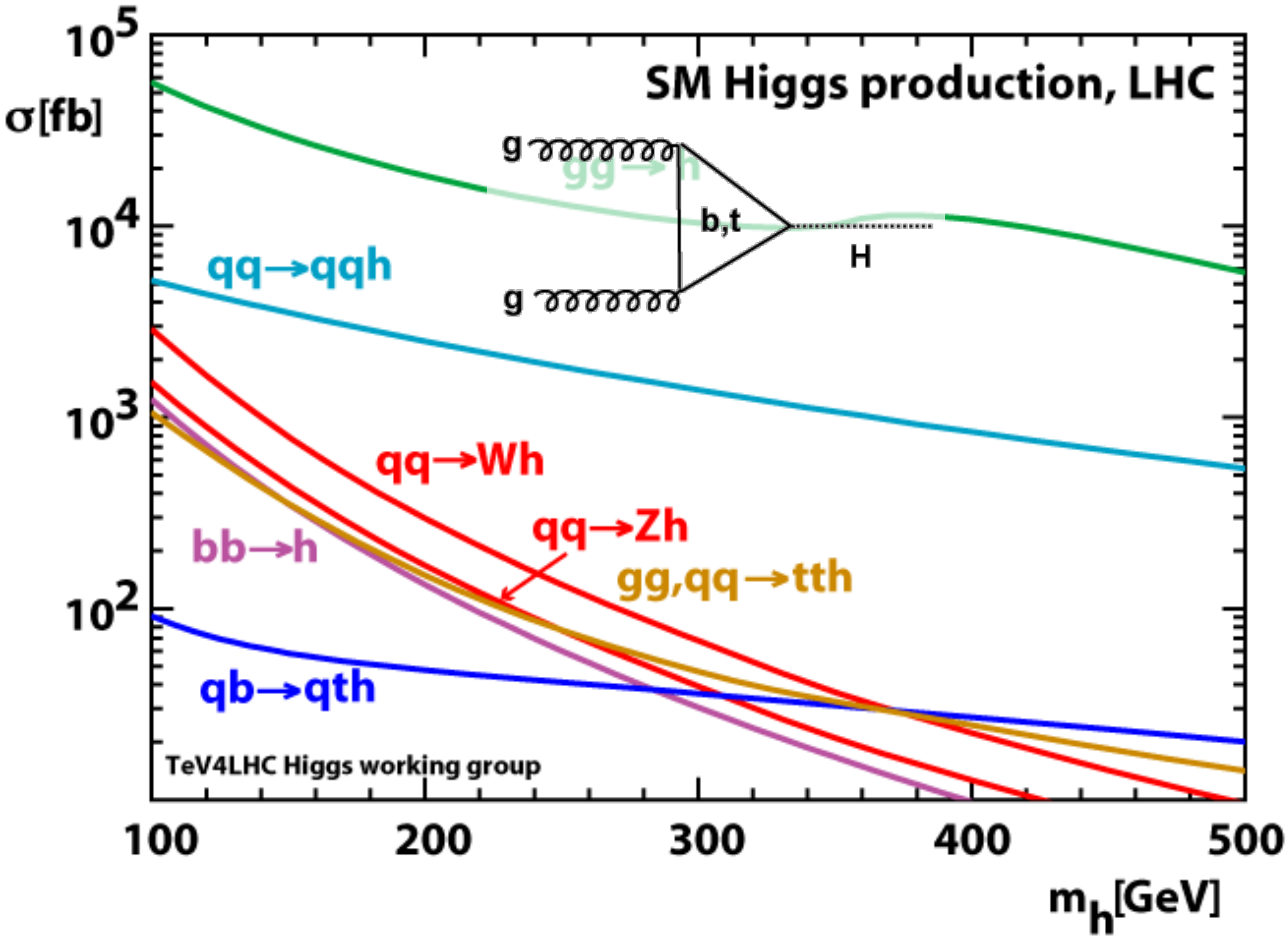

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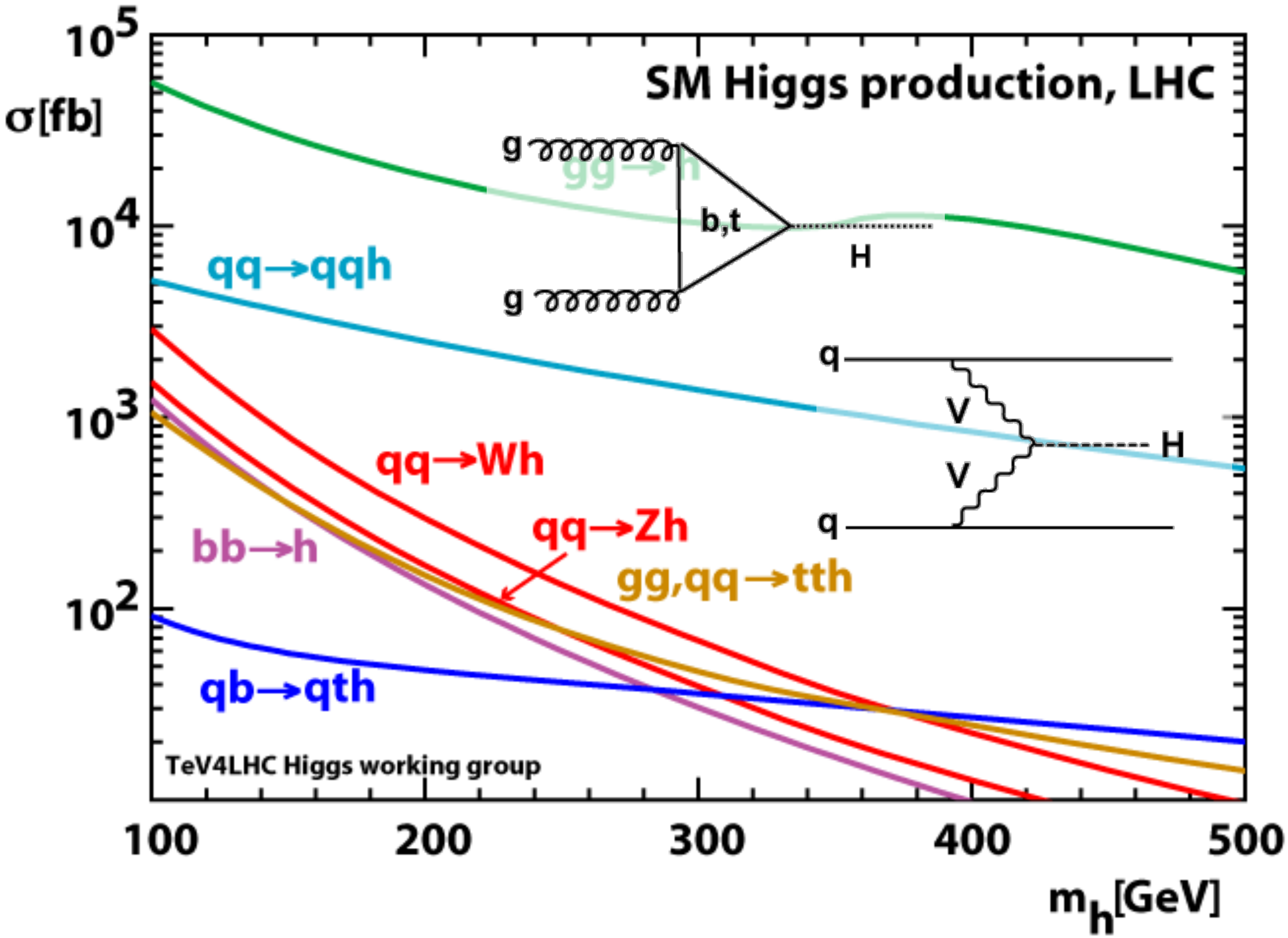
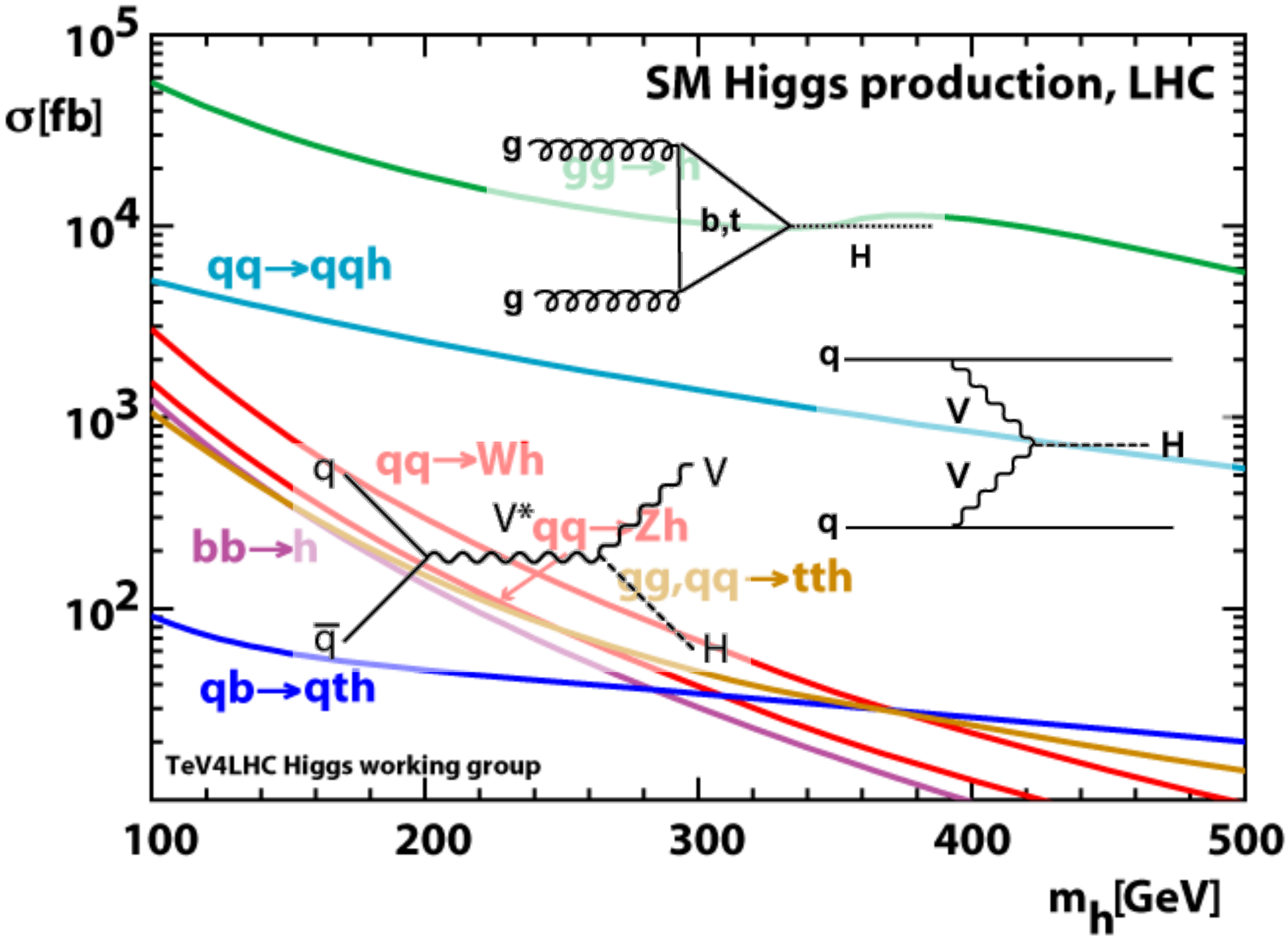
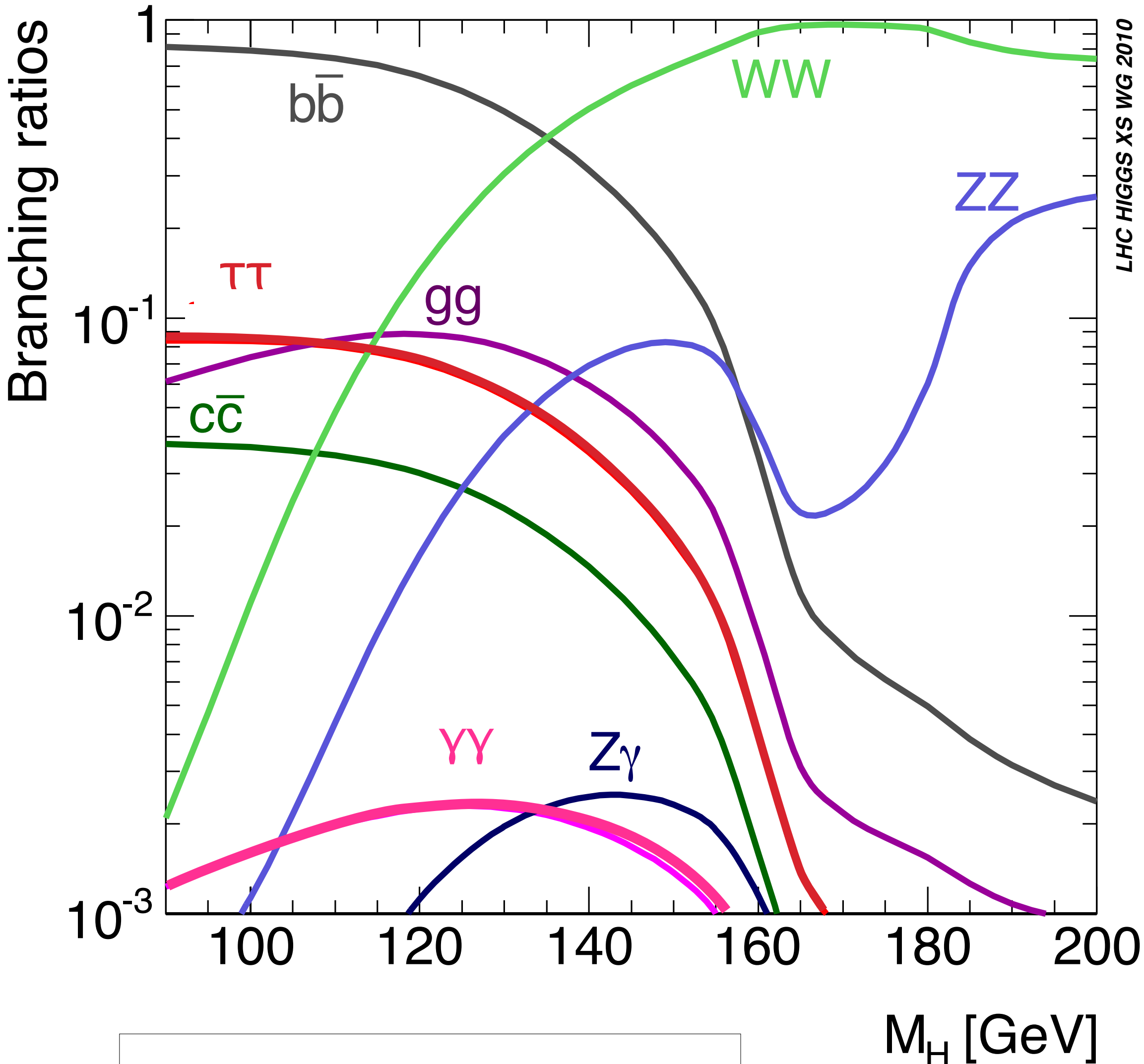


LHC SM Higgs Production





WW: dominates over wide mass range, clean final state (ℓνℓν); high mass

ZZ: three channels, sharp mass resolution

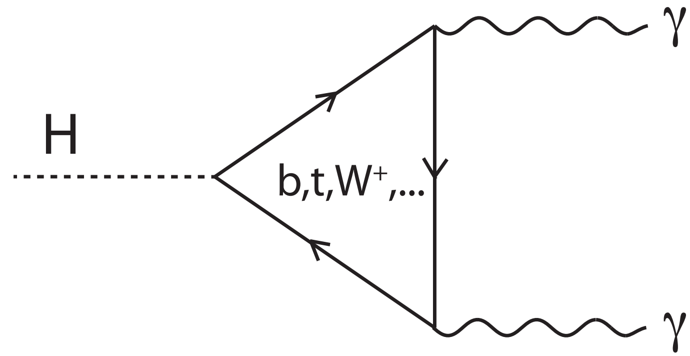
ττ: four channels, can use VBF production

bb: huge background, need to use boosted Higgs production

γγ: small BR, sharp mass resolution

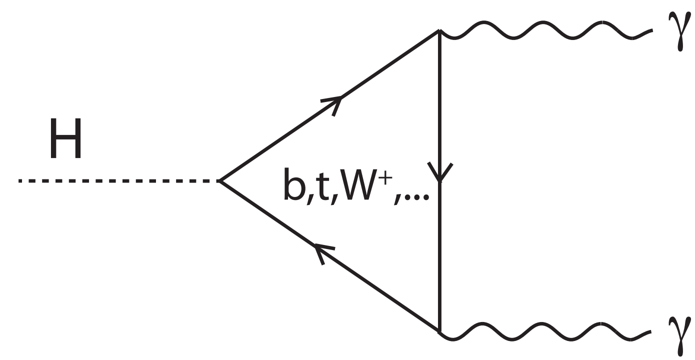
SM Higgs Branching Ratios

H→γγ



- Small branching ratio: 1/500
- Excellent em calorimeter resolution leads to a sharp mass peak
- Large background from fake photons
- Cannot model background well so need to use analytic functional forms
- Sensitive to new physics
- Most sensitive channel overall!

H→γγ



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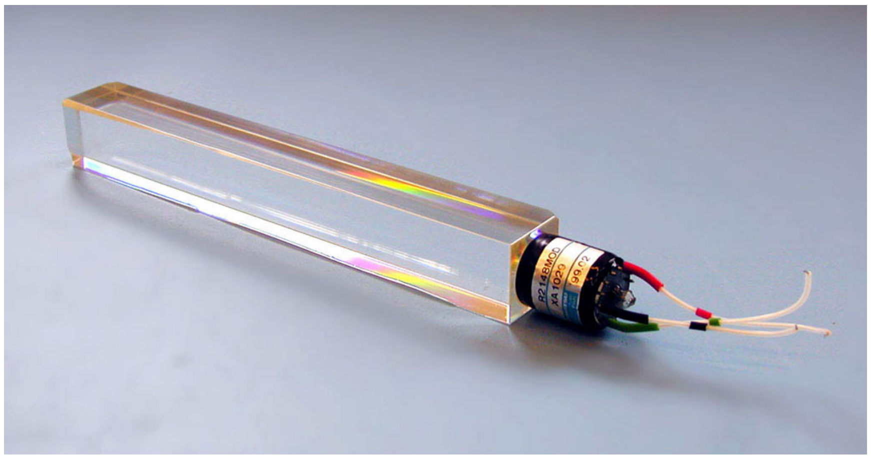
How do CMS and ATLAS achieve sensitivity?

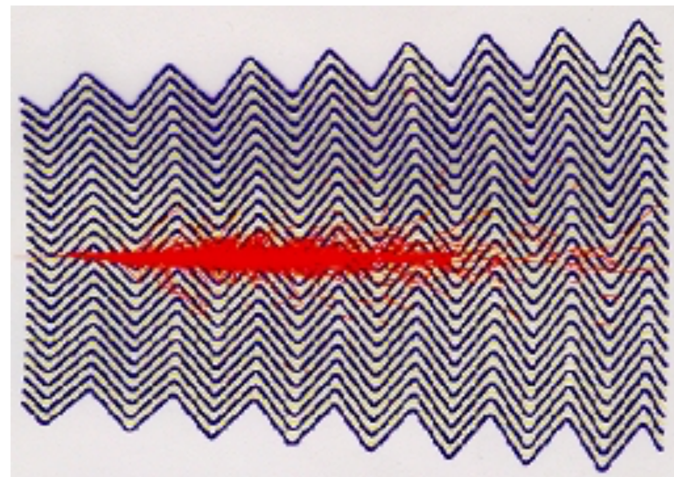
Electromagnetic Resolution

- lead tungstate crystals
- projective geometry

- liquid argon/lead
- spatial sampling



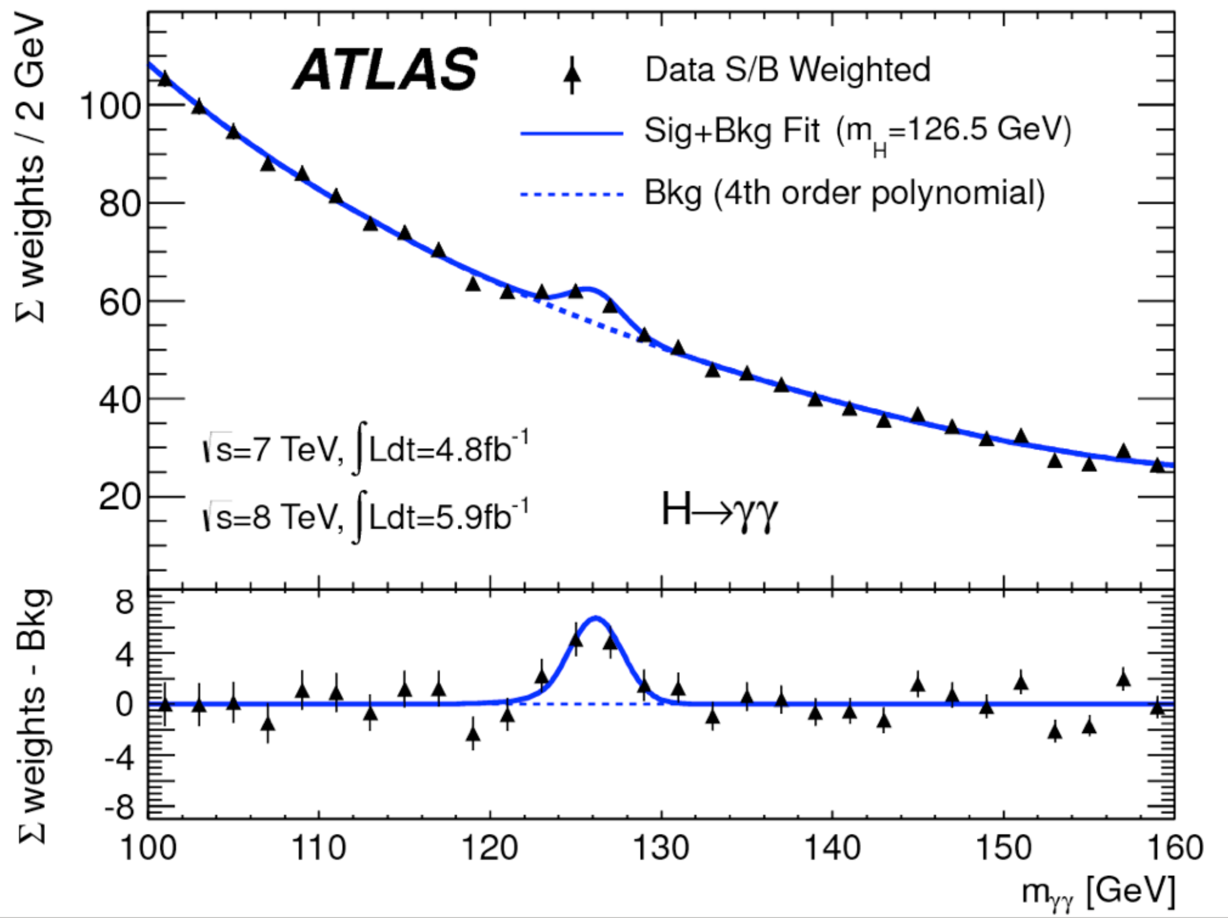
CMS



ATLAS

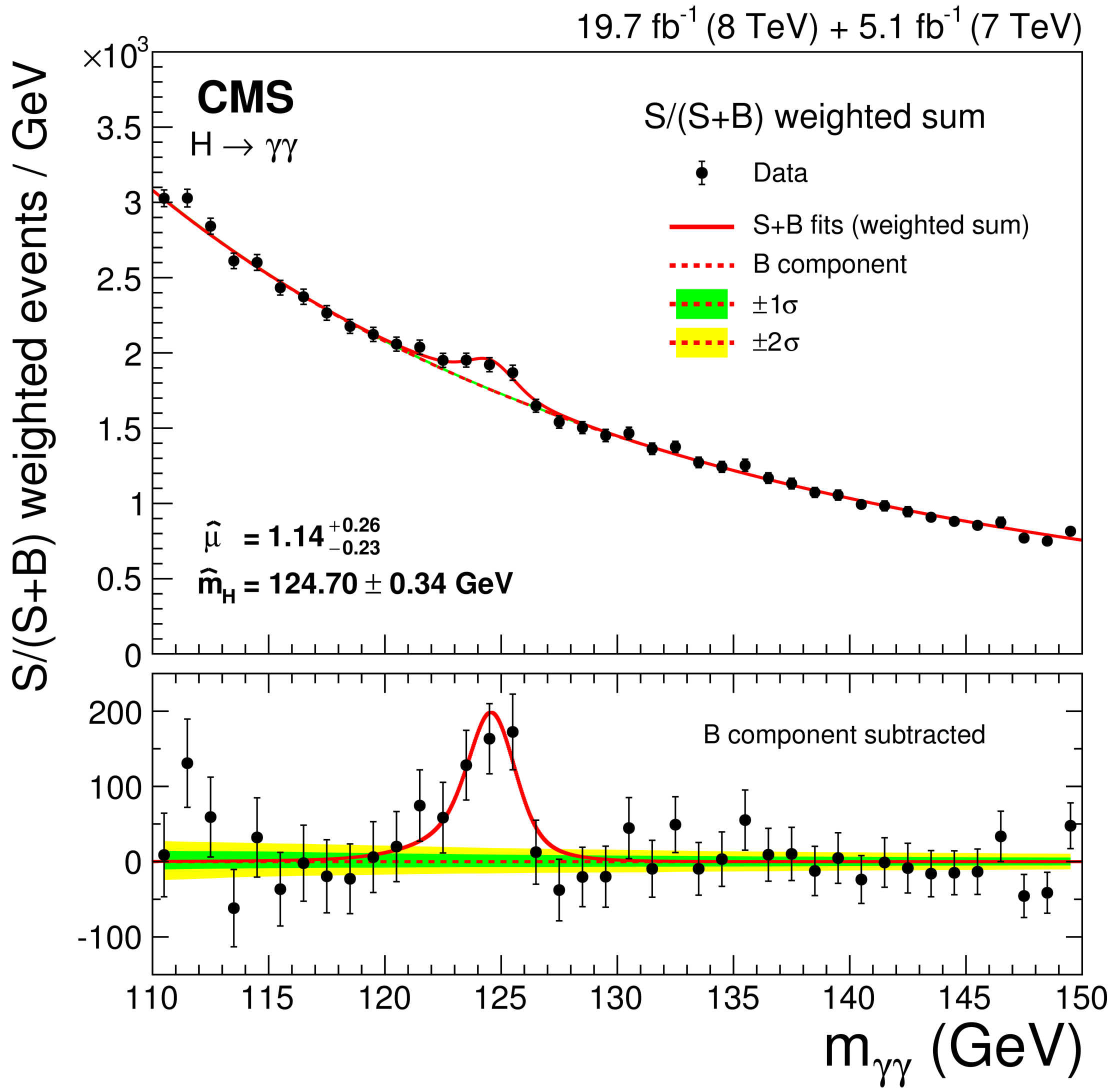
CMS, ATLAS e.m. calorimeters: order of magnitude better resolution than Tevatron experiments

July 2012



At the time of the discovery the γγ signal was clear

CMS full Run 1 γγ result

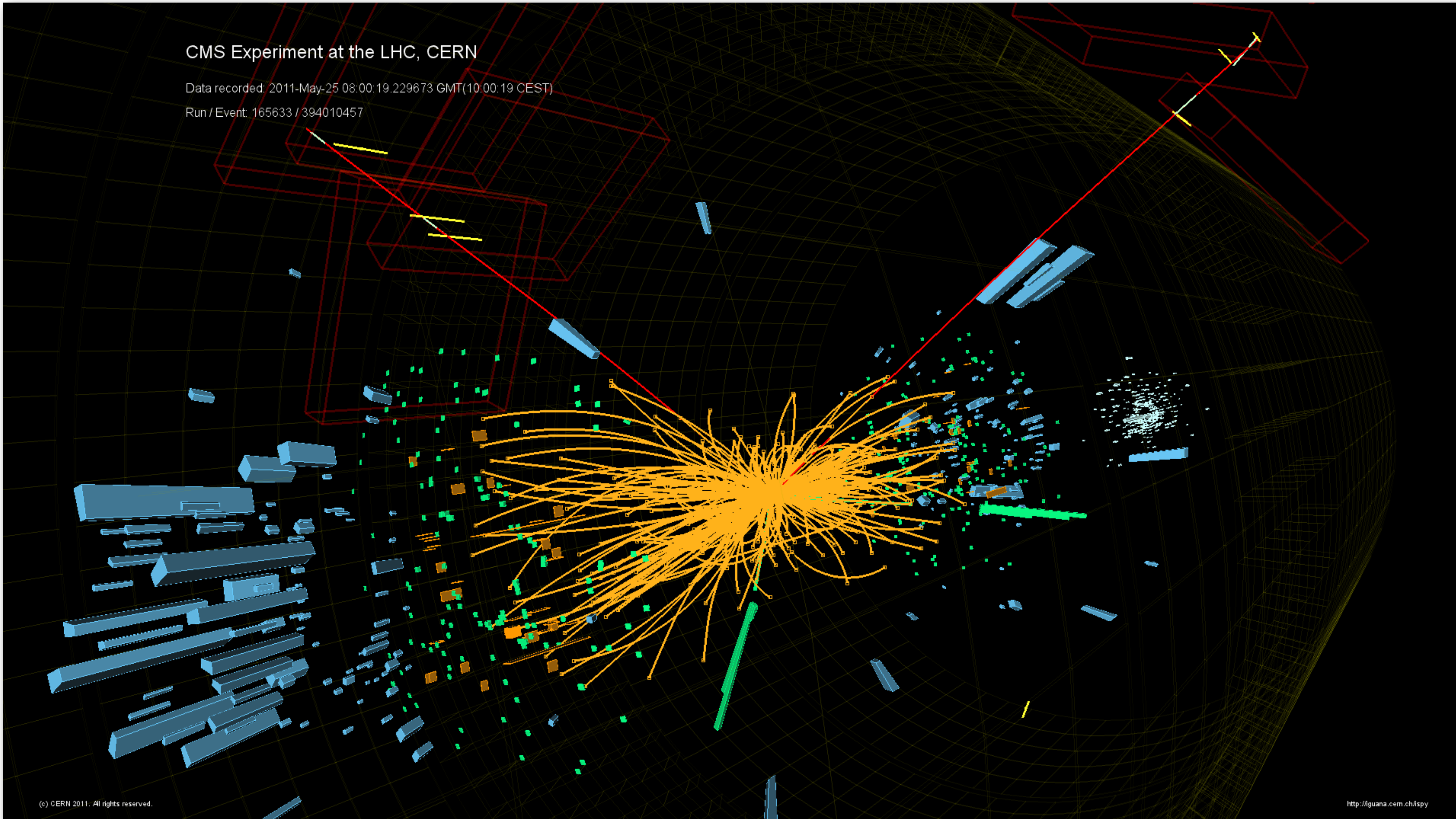


$\sigma_m/m \sim 1.1\%$ per event

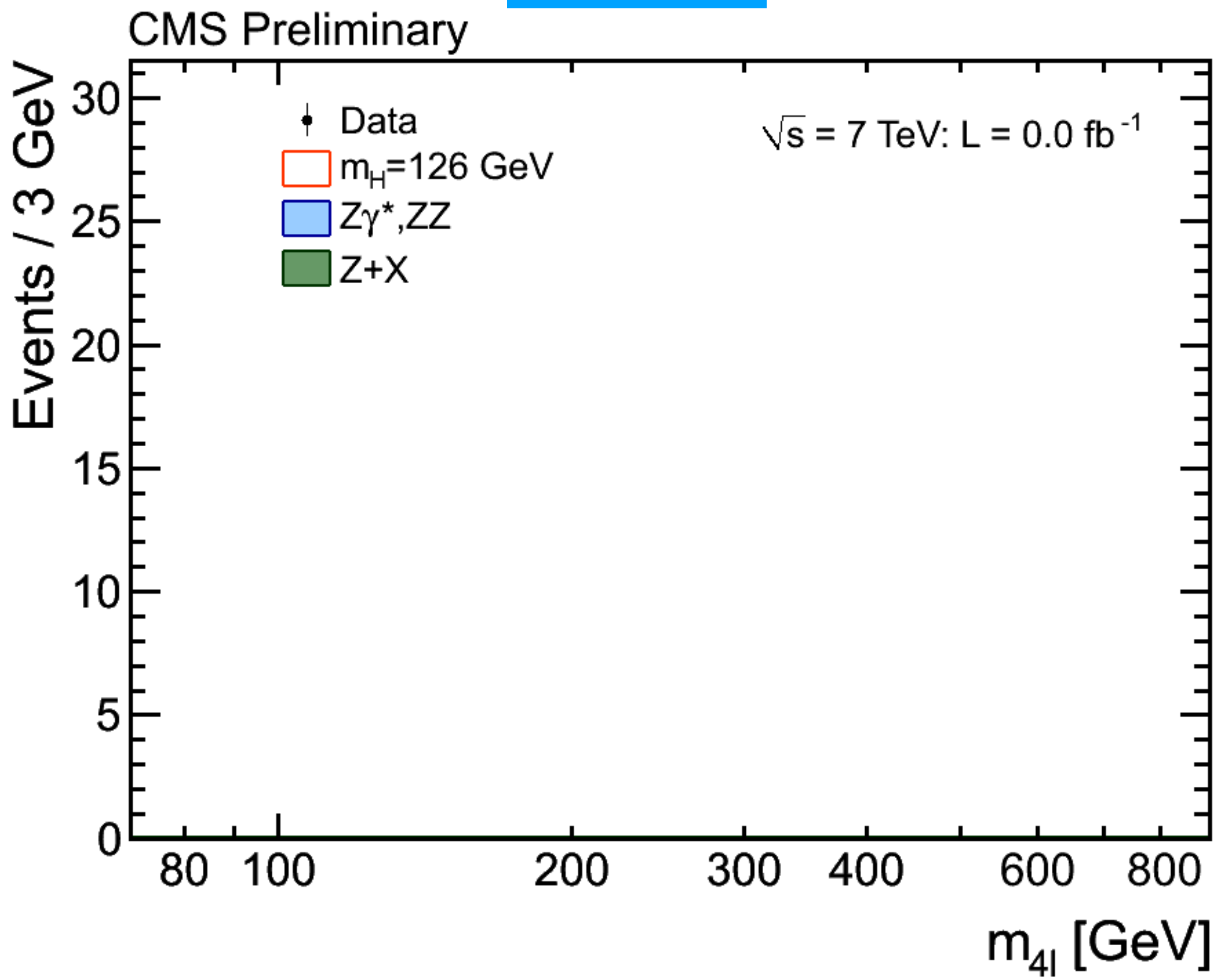
$H \rightarrow ZZ^*$

- Branching ratio ~3%
- Demand each Z decays to ee or μμ: this brings an additional reduction of 0.068^2
- One Z on shell, other Z off shell
- Invariant mass of all four leptons has very good resolution
- Background is minor

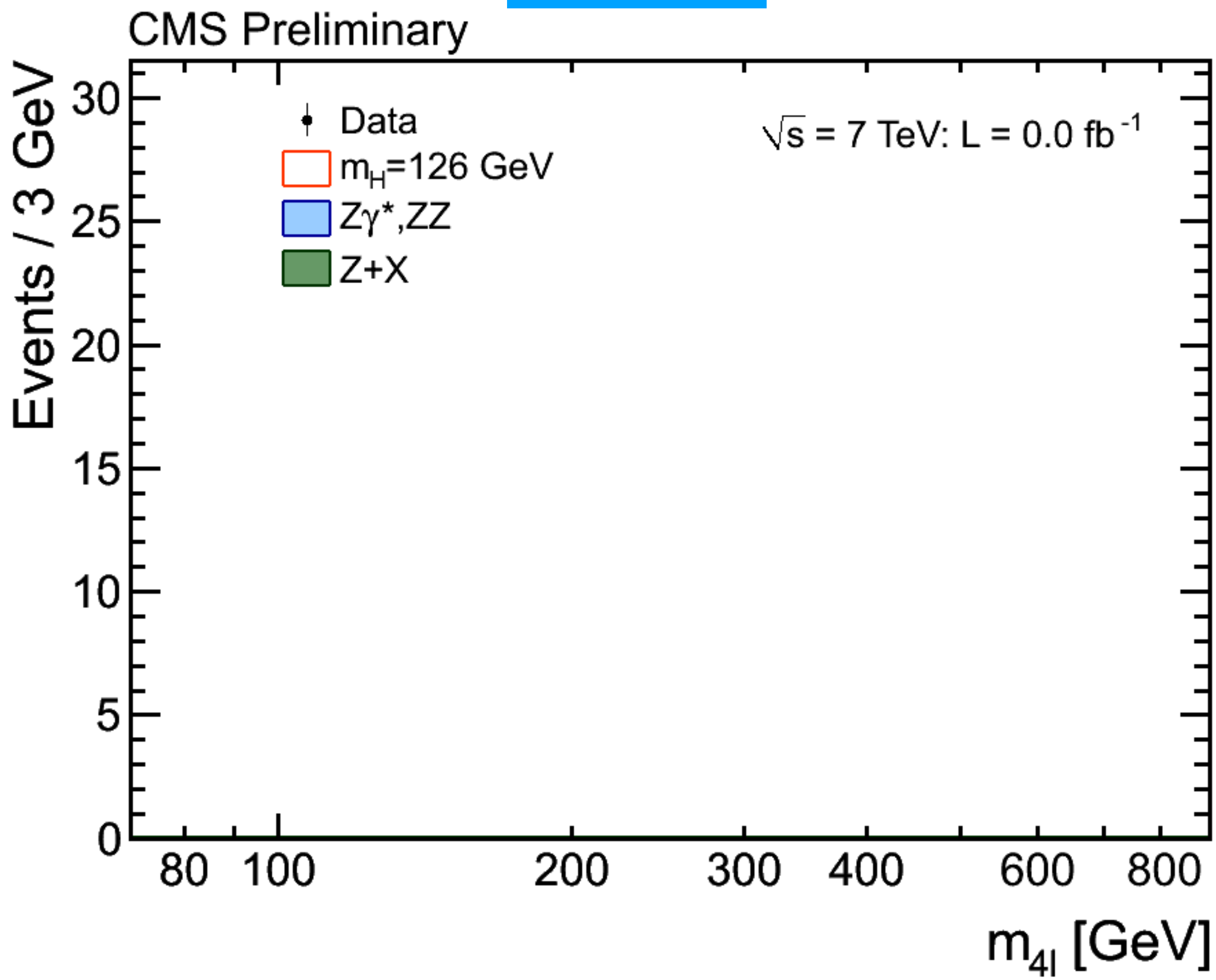
H→ZZ*


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
(c) CERN 2011. All rights reserved.
http://iguana.cern.ch/ispy

H→ZZ*


CMS Preliminary
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
√s = 7 TeV: L = 0.0 fb -1
Events / 3 GeV
30
25
20
15
10
5
0
80
100
200
300
400
600
800
m_4l [GeV]

H→ZZ*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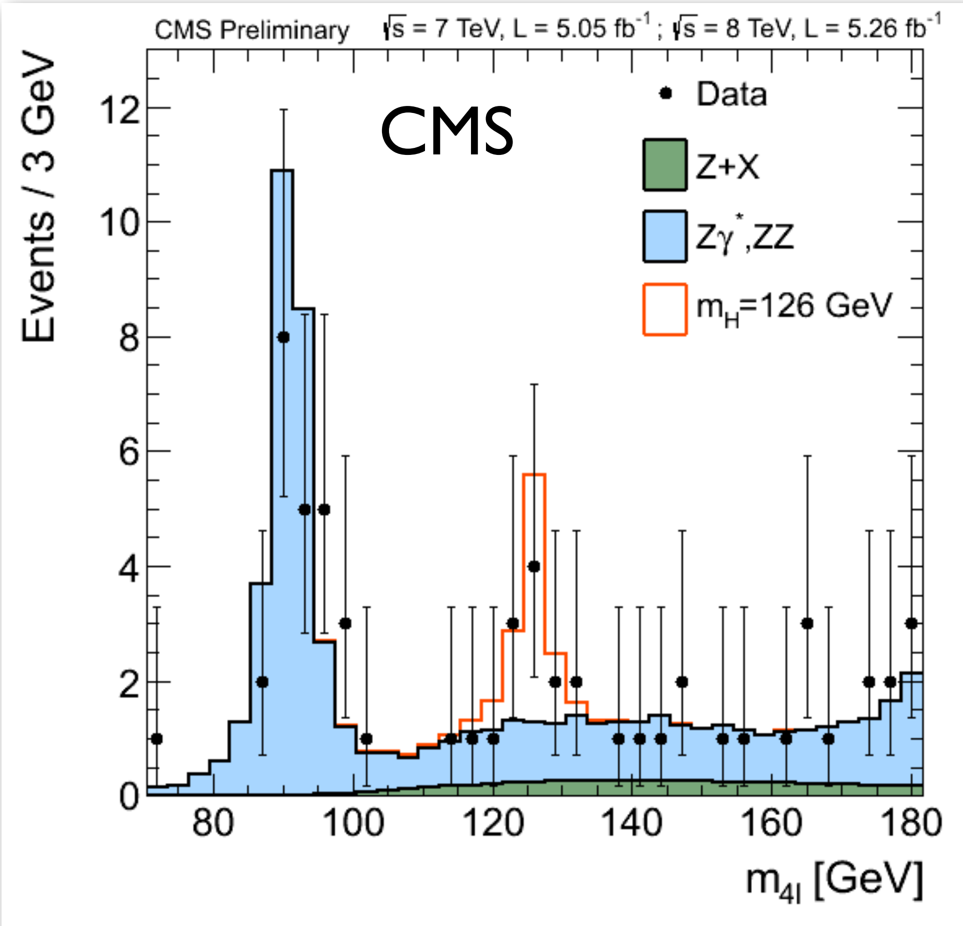
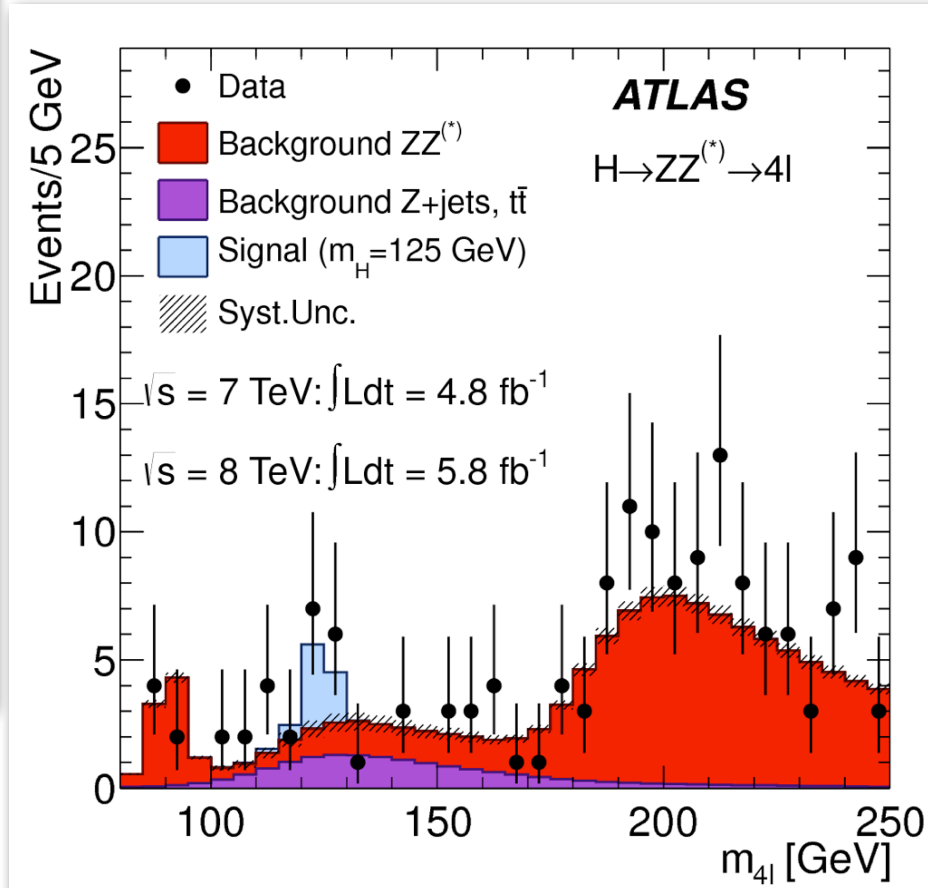
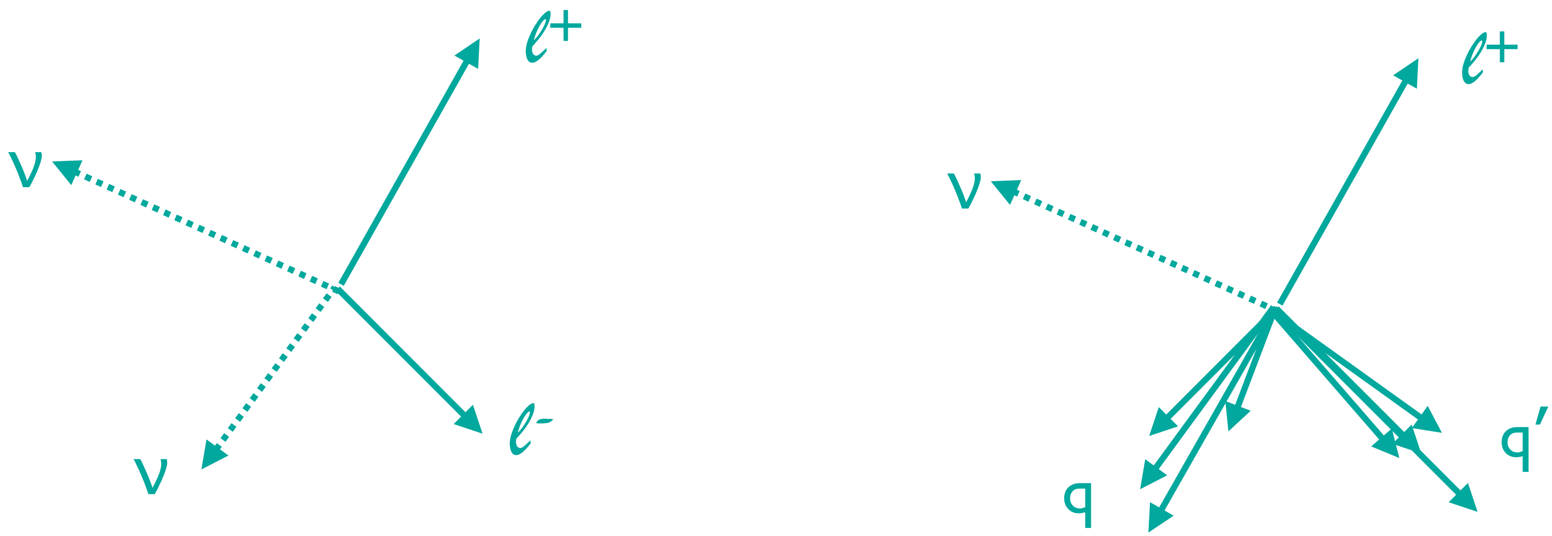
H→ZZ*


CMS Preliminary √s = 7 TeV, L = 5.05 fb-1 ; √s = 8 TeV, L = 5.26 fb-1
CMS
Data
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]


Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m4l [GeV]

H→WW*

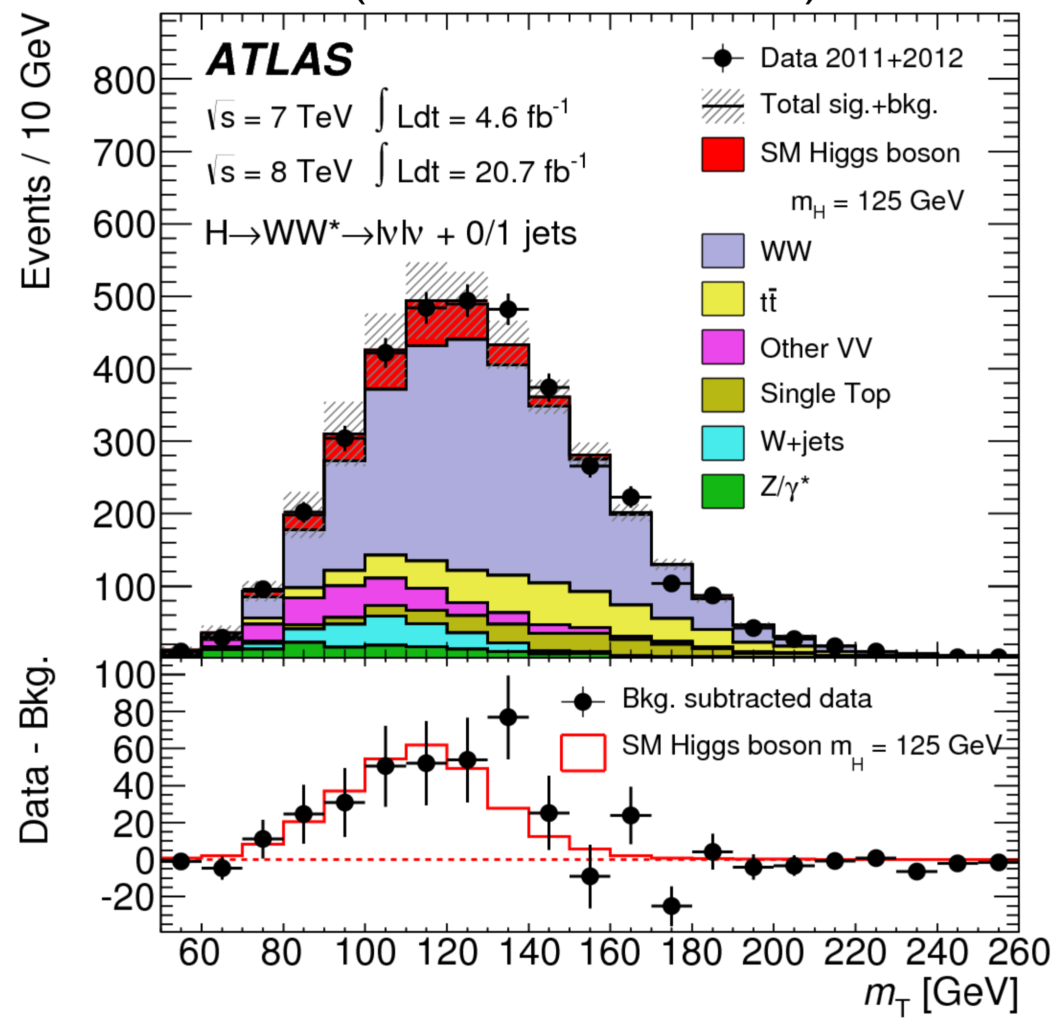
- Branching ratio ~20%
- Two main modes: ℓν ℓν and ℓν qq′ (high mass)
- One W on shell, other W off shell
- Missing neutrinos preclude this mode for H mass



H→WW*

- Quite good sensitivity using transverse mass
- Dominant background is from SM WW production
- With additional jets dominant background comes from tt

(full Run 1 data set)



Higgs Couplings to Fermions

- Strongest coupling (obviously) is to tt but the Higgs boson cannot decay to top pairs directly
- Next strongest is to bb - this is the dominant branching fraction of the Higgs boson at ~70%
- Coupling to ττ gives a ~7% branching fraction and was the first to be observed
- Coupling to cc gives a ~3% branching fraction but this is experimentally challenging - need e^+e^- collider
- Muon pair coupling is suppressed; 2×10^{-4} branching fraction

$H \to \tau\tau$

- 35% of the time taus decay semileptonically, 65% hadronically
- reconstruction and identification of hadronic tau decays ("τ_h") in ATLAS and CMS is well advanced
- dedicated triggers for τ_h
- $H \to \tau\tau$ final states:
  - $e\tau_h$, $\mu\tau_h$
  - $\tau_h\tau_h$
  - $e\mu$

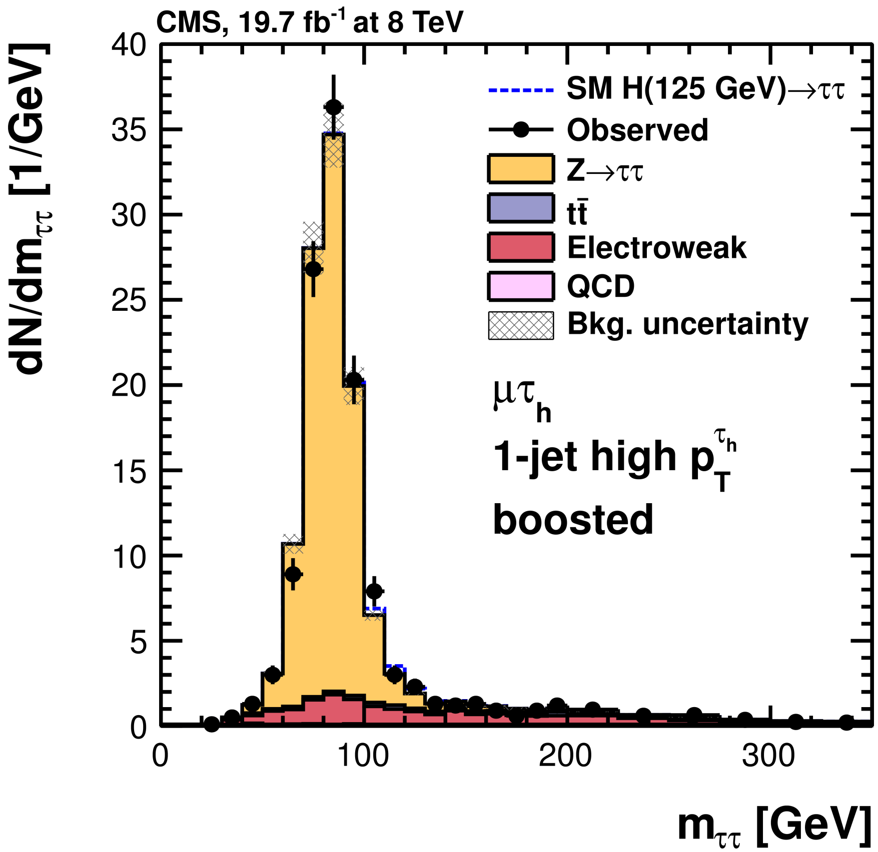
tau decays

$e^- \nu\nu$	0.178
$\mu^- \nu\nu$	0.174
$h^- \nu$	0.49
$\pi^- \nu$	0.11
$K^- \nu$	0.007
$\rho^- \nu$	0.254
$h^+h^-h^- \nu$	0.15

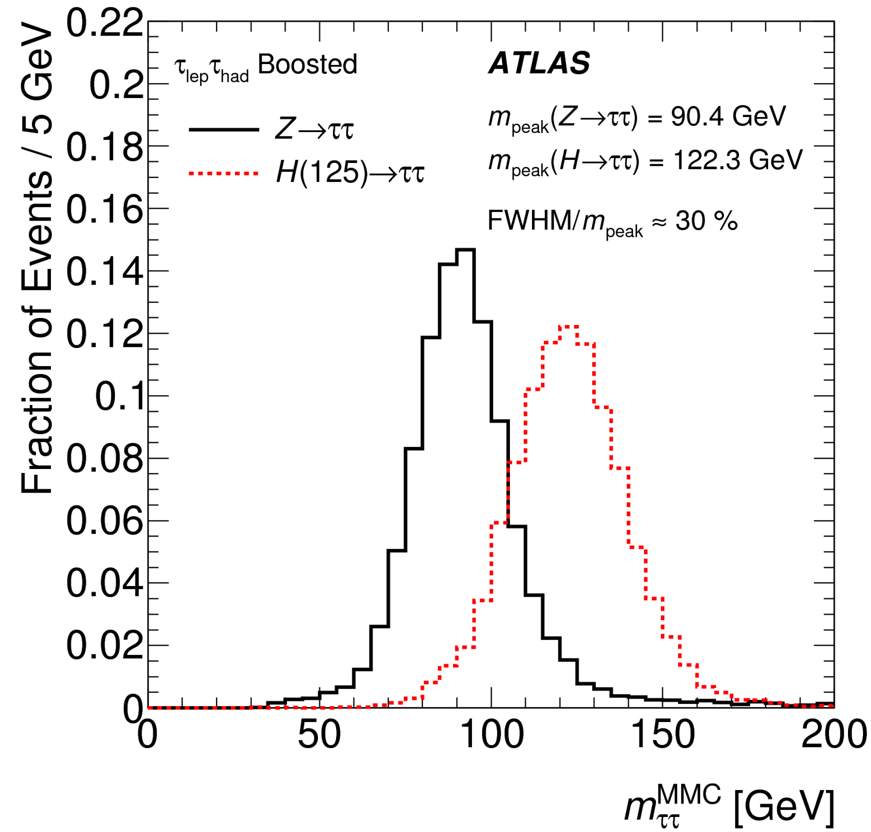
missing neutrinos!
- add missing p_T
- complicates $\tau\tau$ mass

H→ττ

CMS and ATLAS have developed powerful multivariate tools to reconstruct tau pair invariant mass: key to sensitivity



CMS: SVfit

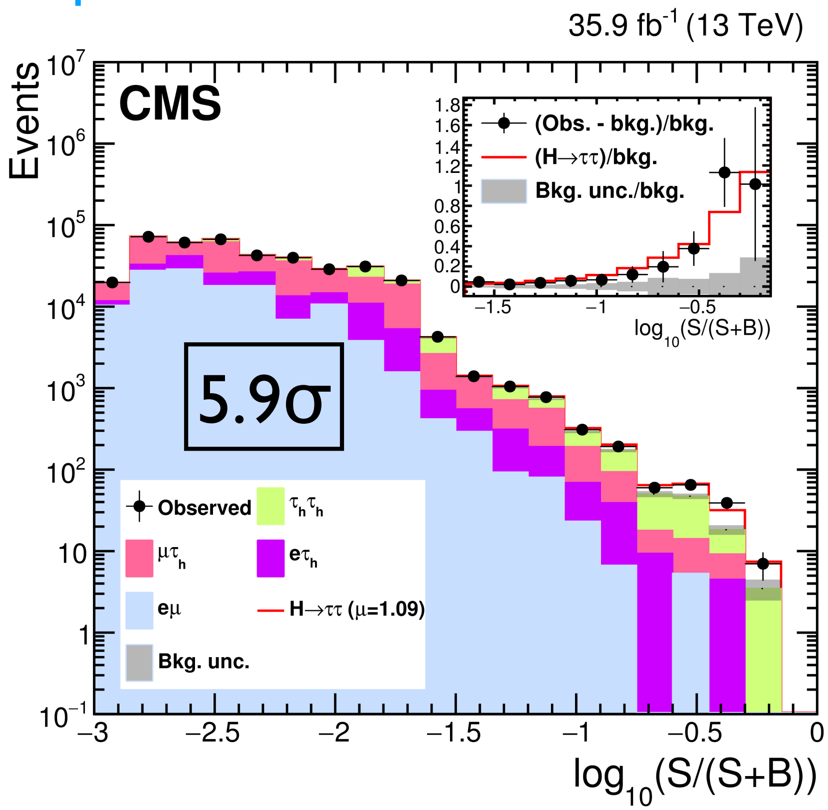


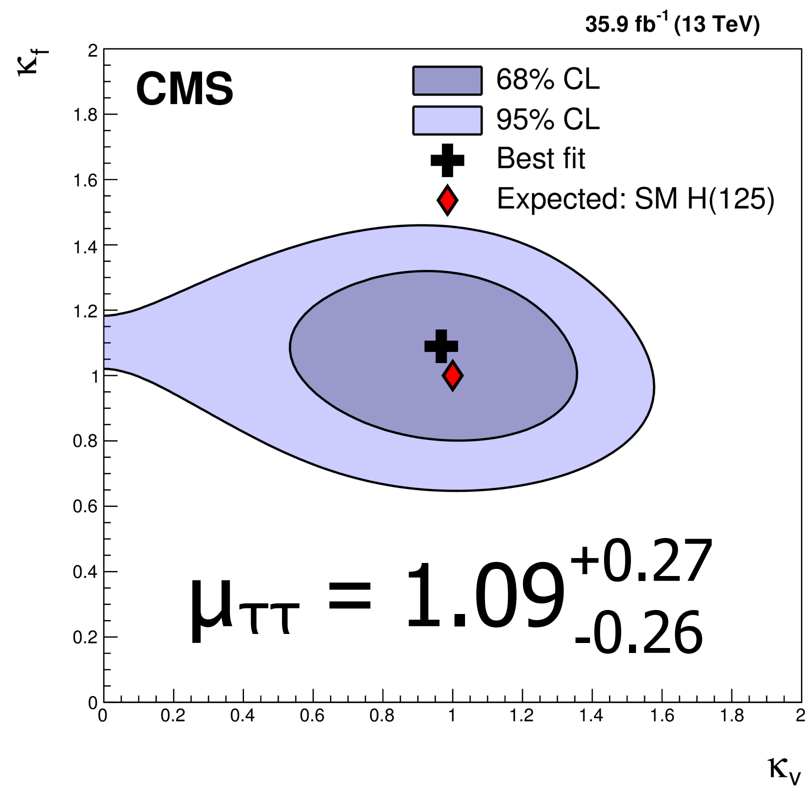
ATLAS: MMC

H→ττ

- Analyses utilize multiple final state categories in terms of additional jets and Higgs p_T to optimize sensitivity

- By demanding two forward tagging jets, can be sensitive to VBF production: simultaneous measure of κ_V and κ_f





$\mu_{\tau\tau} = 1.09^{+0.27}_{-0.26}$

H→ττ

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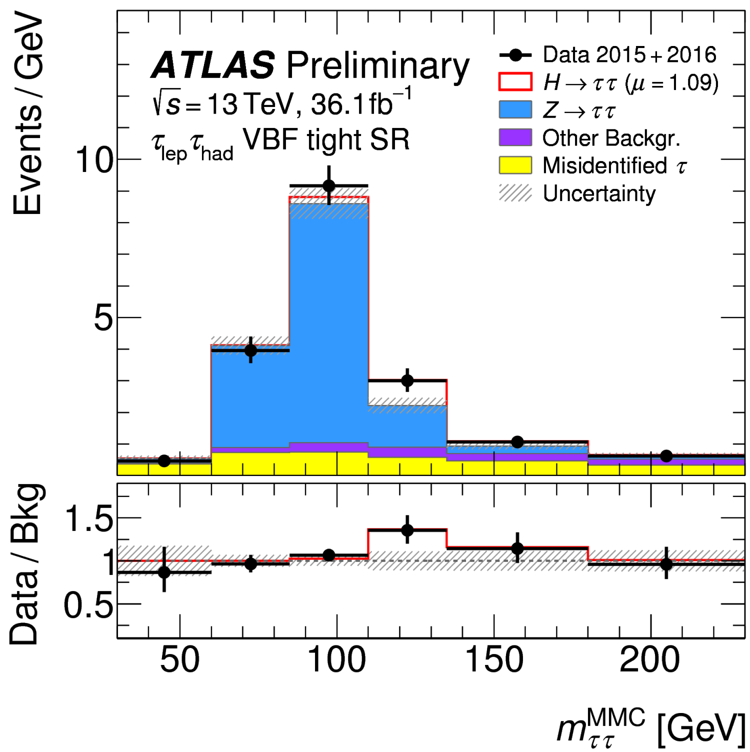

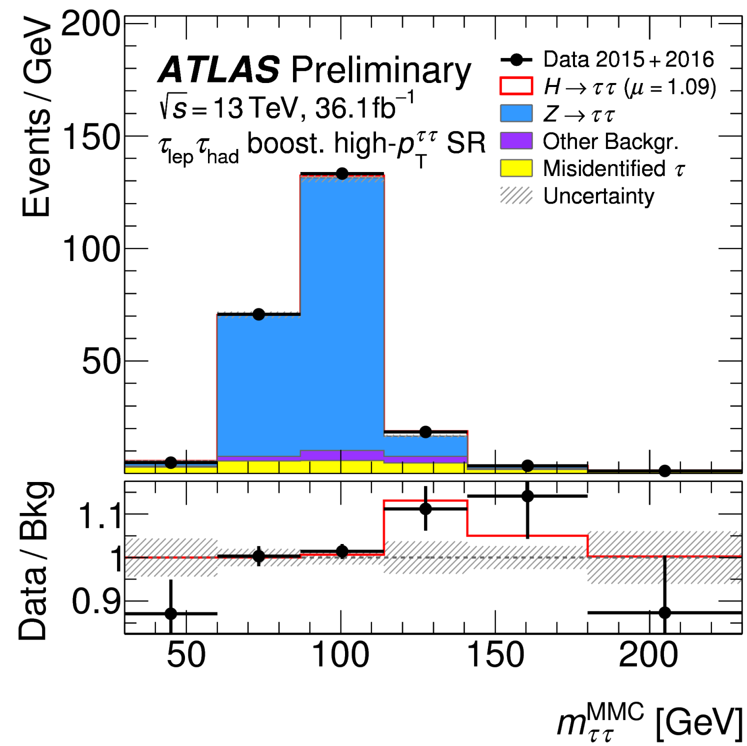

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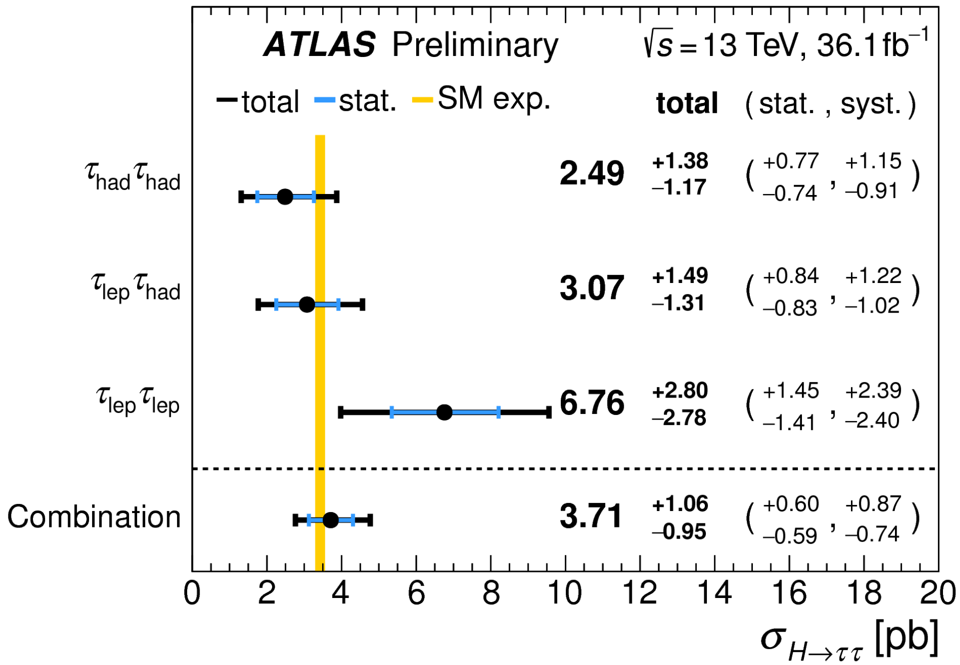
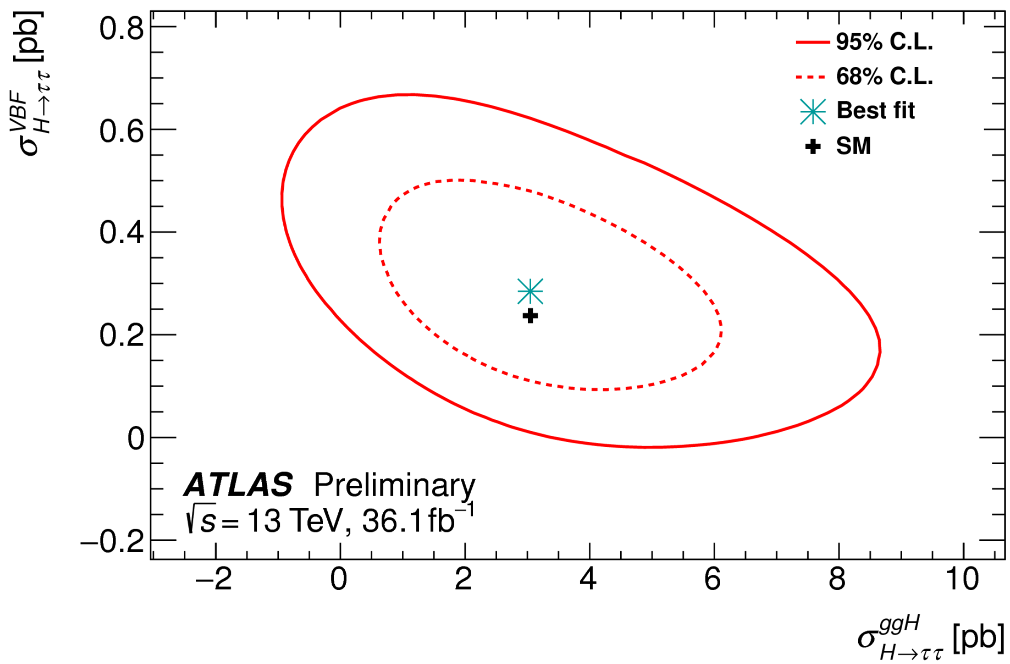
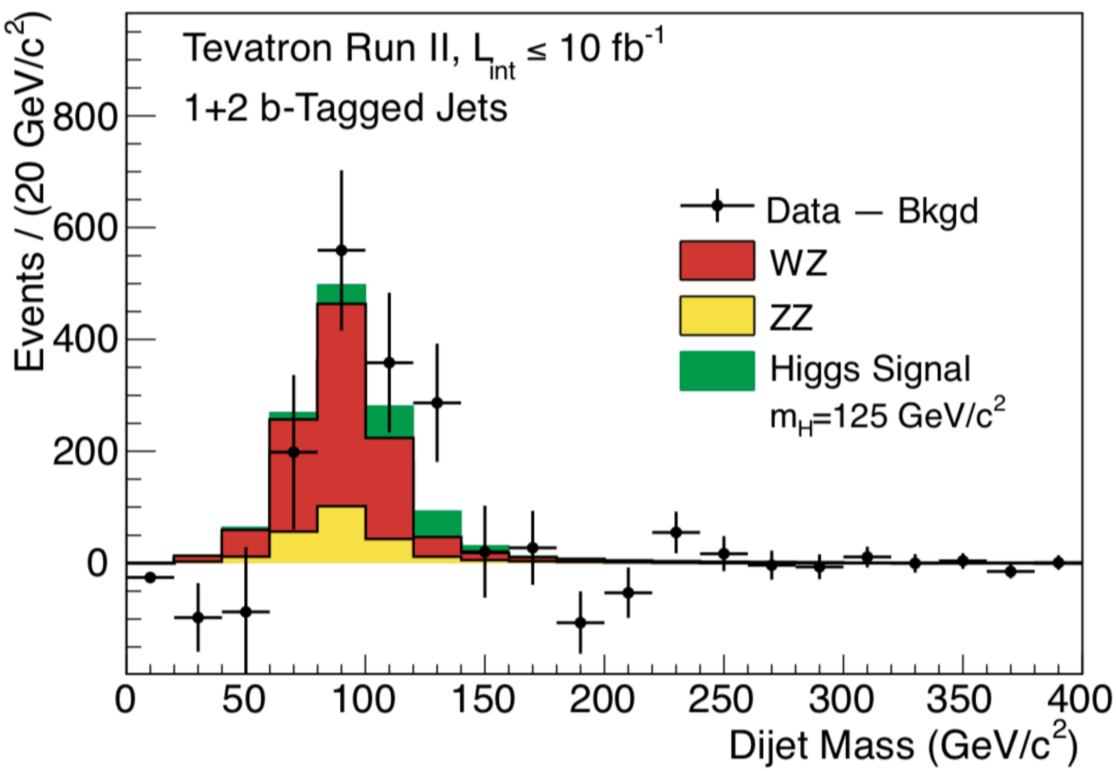




ATLAS: $6.4\sigma_{obs}$ ($5.6\sigma_{exp}$) (comb. with Run 1)

H→bb at Tevatron

- As of Higgs discovery in 2012, strongest evidence (3.2σ) for H→bb came from the Tevatron experiments, which can utilize the VH production modes: leptonic tags



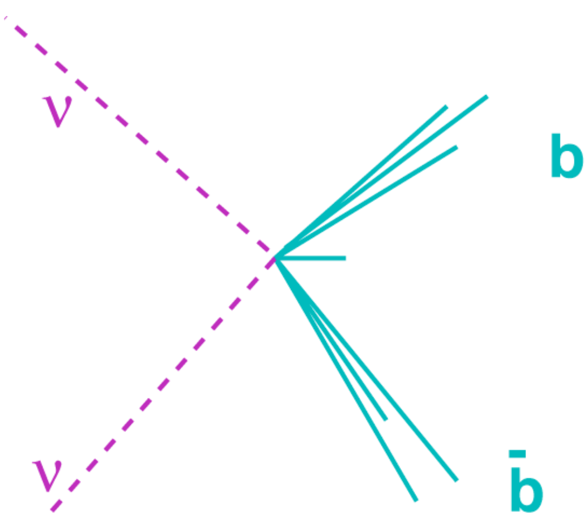
This result used 10 fb^{-1} of integrated luminosity, combining CDF and D0

Observed significance was 3.0σ

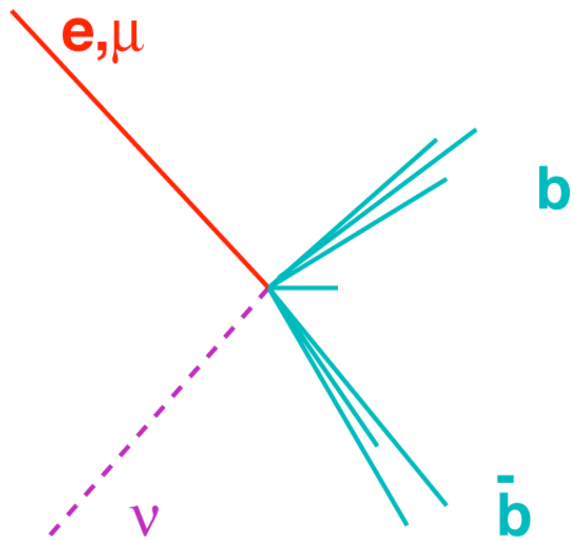
H→bb at LHC

- Huge background from QCD bb production
- VH production at LHC suppressed relative to gg mode

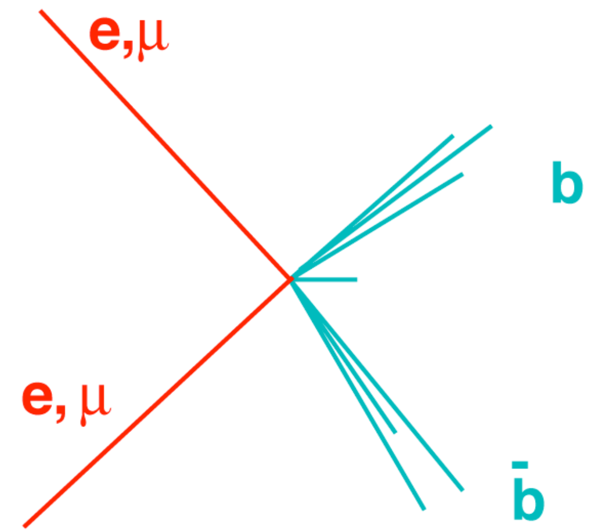
  ⇒ need more data relative to other final state



0 lepton

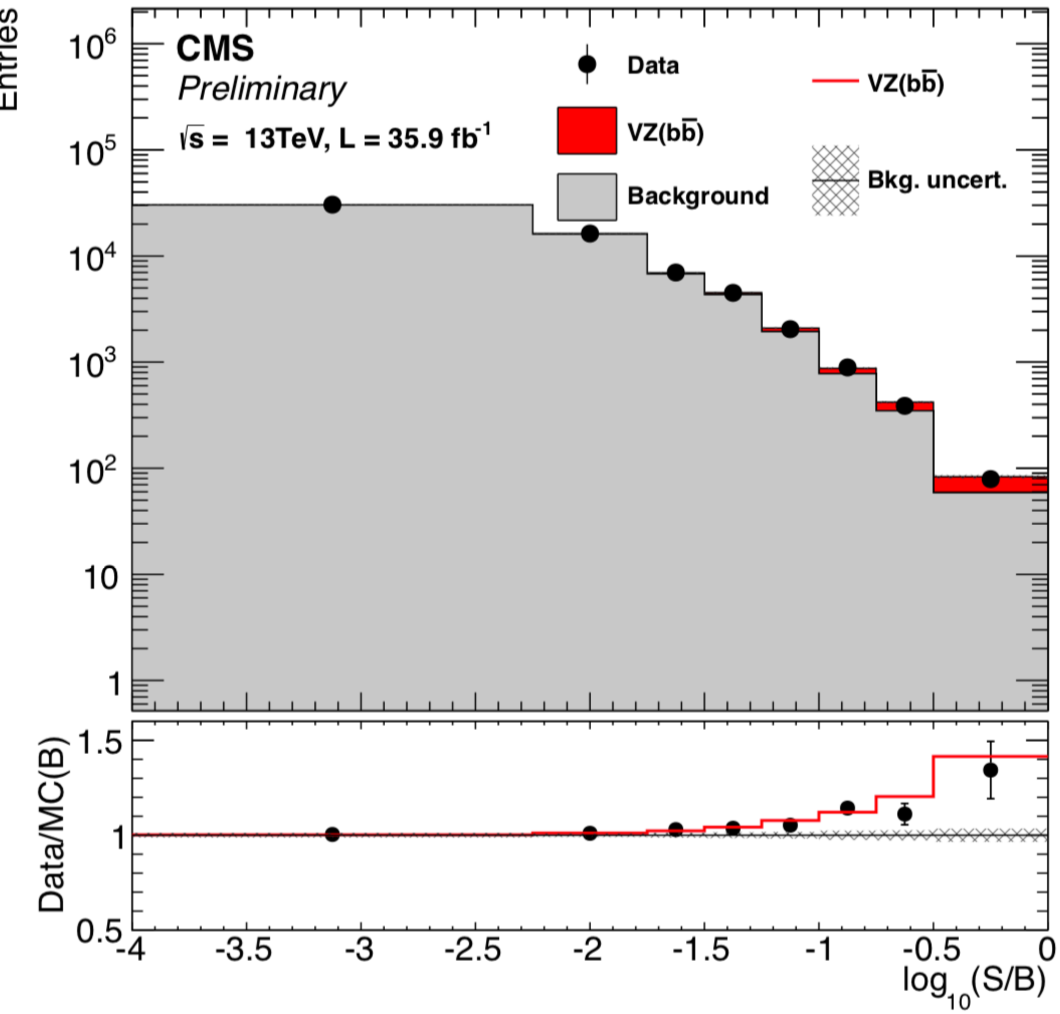


1 lepton



2 lepton

H→bb



- CMS results from last year: 3.8σ
- μ_{bb} = $1.06^{+0.31}_{-0.29}$
- New results from ATLAS and CMS!
- See C. Vernieri talk this afternoon!

Htt coupling

- to see the Htt coupling we look for Higgs bosons produced in association with a top quark pair

⇒ can utilize all Higgs decay modes; very busy events!

Analyses focus on tt decays to ℓνjjbb + H

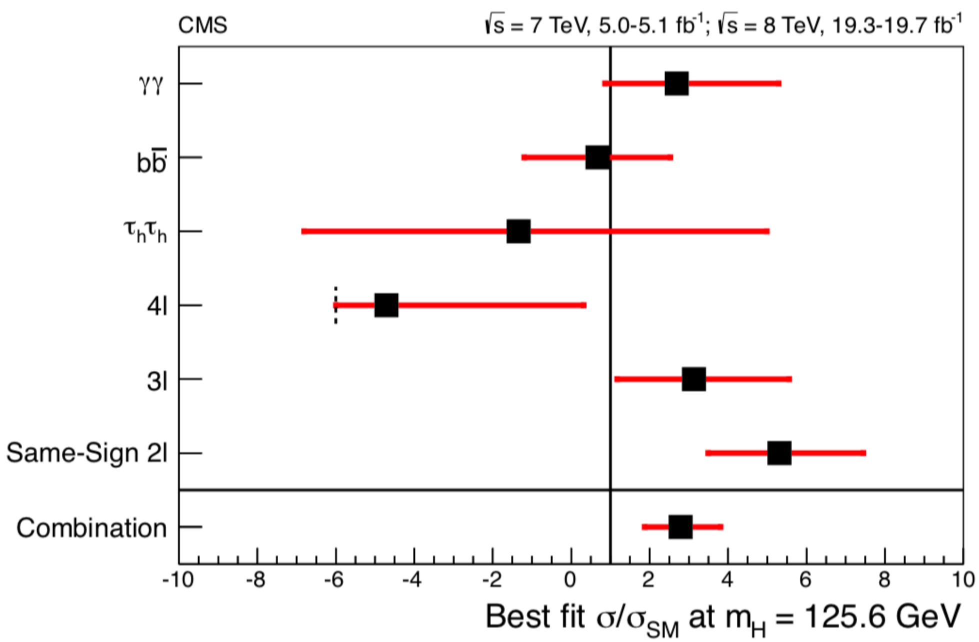
H decays to hadrons, photons, or leptons

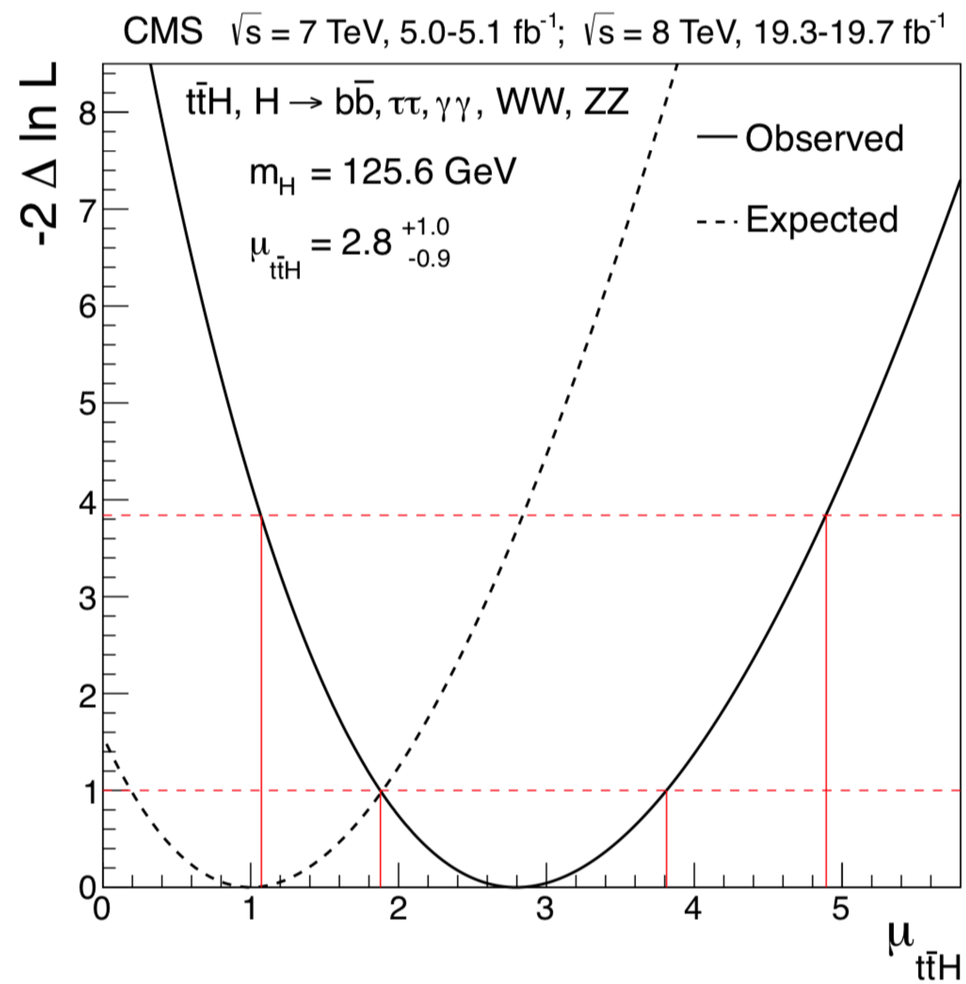
Category	Signature	Trigger	Signature
H → Hadrons H → $b\bar{b}$ H → $\tau_h\tau_h$ H → WW	Lepton + Jets ($t\bar{t}$H → $\ell\nu$jjbbbb)	Single Lepton	1 e/μ, $p_T > 30$ GeV ≥4 jets + ≥2 b-tags, $p_T > 30$ GeV
	Dilepton ($t\bar{t}$H → $\ell\nu\ell\nu$bbbb)	Dilepton	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV ≥3 jets + ≥2 b-tags, $p_T > 30$ GeV
	Hadronic τ ($t\bar{t}$H → $\ell\nu\tau_h[\nu]\tau_h[\nu]$jjbb)	Single Lepton	1 e/μ, $p_T > 30$ GeV 2 τ_h, $p_T > 20$ GeV ≥2 jets + 1-2 b-tags, $p_T > 30$ GeV
H → Photons H → $\gamma\gamma$	Leptonic ($t\bar{t}$H → $\ell\nu$jjbb$\gamma\gamma$, $t\bar{t}$H → $\ell\nu\ell\nu$bb$\gamma\gamma$)	Diphoton	2 γ, $p_T > m_{\gamma\gamma}/2$ (25) GeV for 1st (2nd) ≥1 e/μ, $p_T > 20$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV
	Hadronic ($t\bar{t}$H → jjjjbb$\gamma\gamma$)	Diphoton	2 γ, $p_T > m_{\gamma\gamma}/2$ (25) GeV for 1st (2nd) 0 e/μ, $p_T > 20$ GeV ≥4 jets + ≥1 b-tags, $p_T > 25$ GeV
H → Leptons H → WW H → $\tau\tau$ H → ZZ	Same-Sign Dilepton ($t\bar{t}$H → $\ell^{\pm}\nu\ell^{\pm}[\nu]$jjj[j]bb)	Dilepton	2 e/μ, $p_T > 20$ GeV ≥4 jets + ≥1 b-tags, $p_T > 25$ GeV
	3 Lepton ($t\bar{t}$H → $\ell\nu\ell[\nu]\ell[\nu]$j[j]bb)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 1 e(μ), $p_T > 7(5)$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV
	4 Lepton ($t\bar{t}$H → $\ell\nu\ell\nu\ell[\nu]\ell[\nu]$bb)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 2 e(μ), $p_T > 7(5)$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV

Htt coupling

CMS run 1 result:

$$\mu_{ttH} = 2.8^{+1.0}_{-0.9}$$





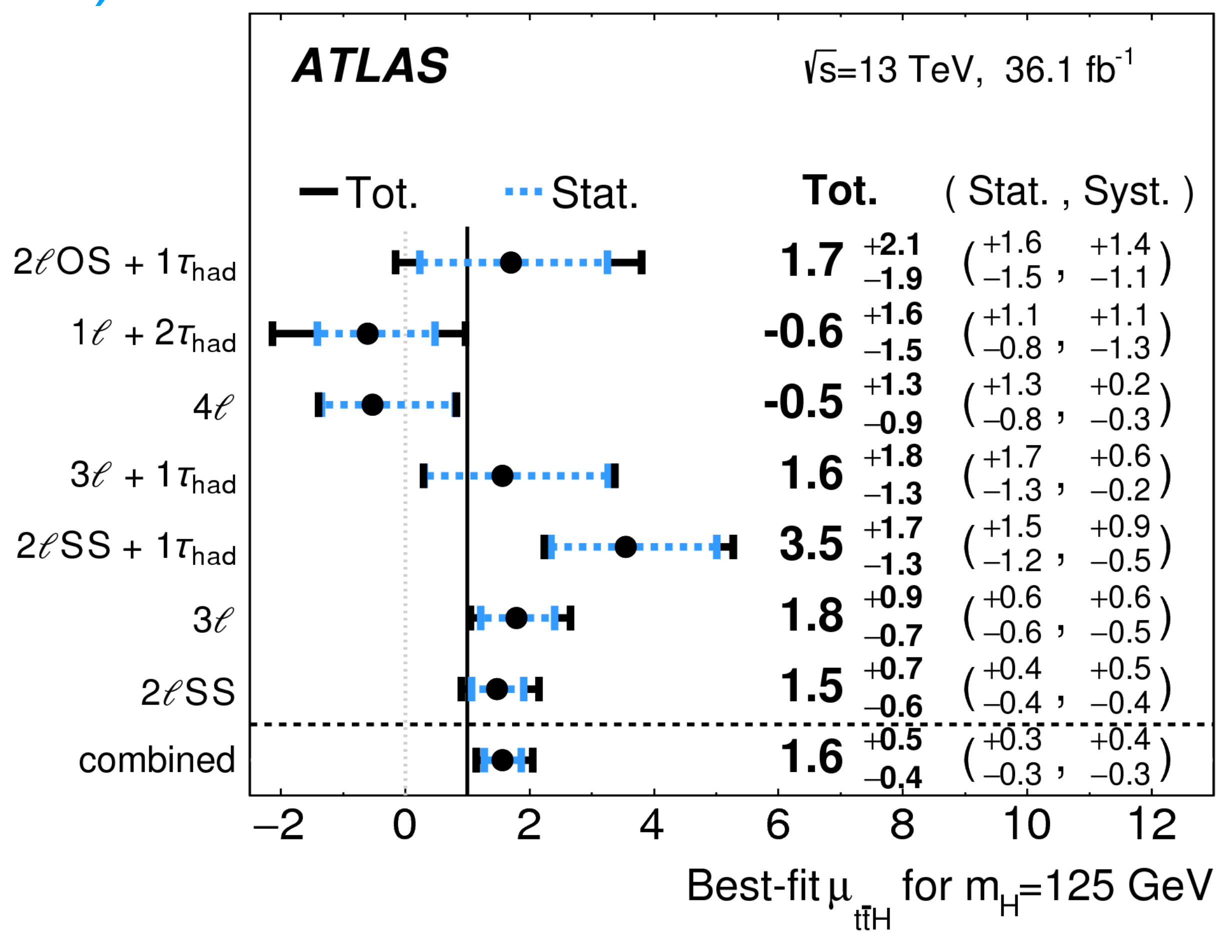
Htt coupling

ATLAS Run 2 (2016)

$\mu_{ttH} = 1.6 ^{+0.5}_{-0.4}$

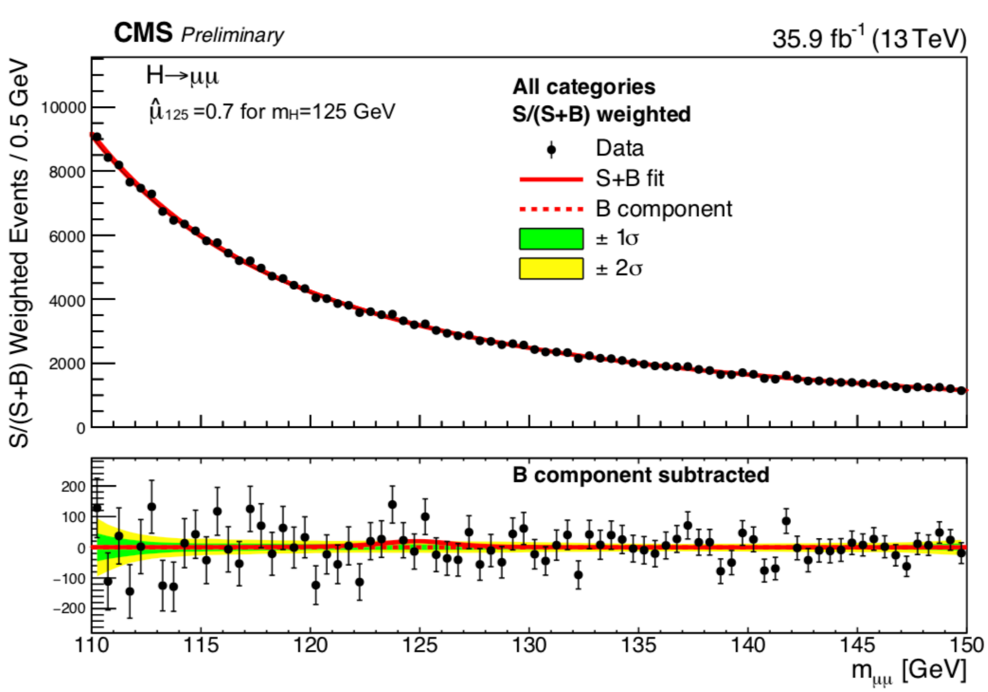
ATLAS and CMS now have results based on ~80 fb^{-1}

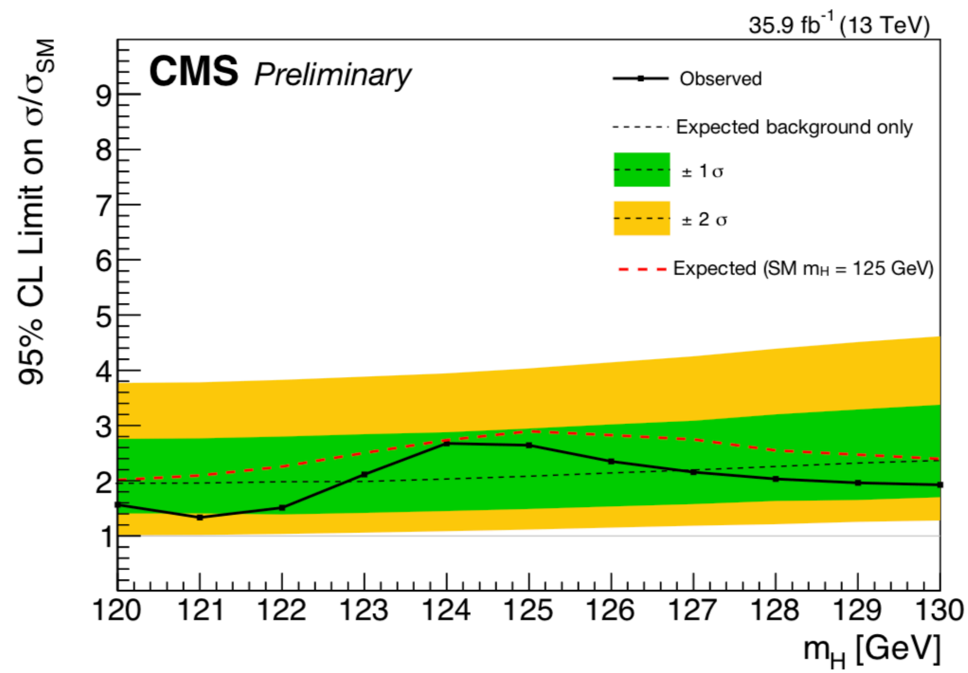
See Caterina's talk!



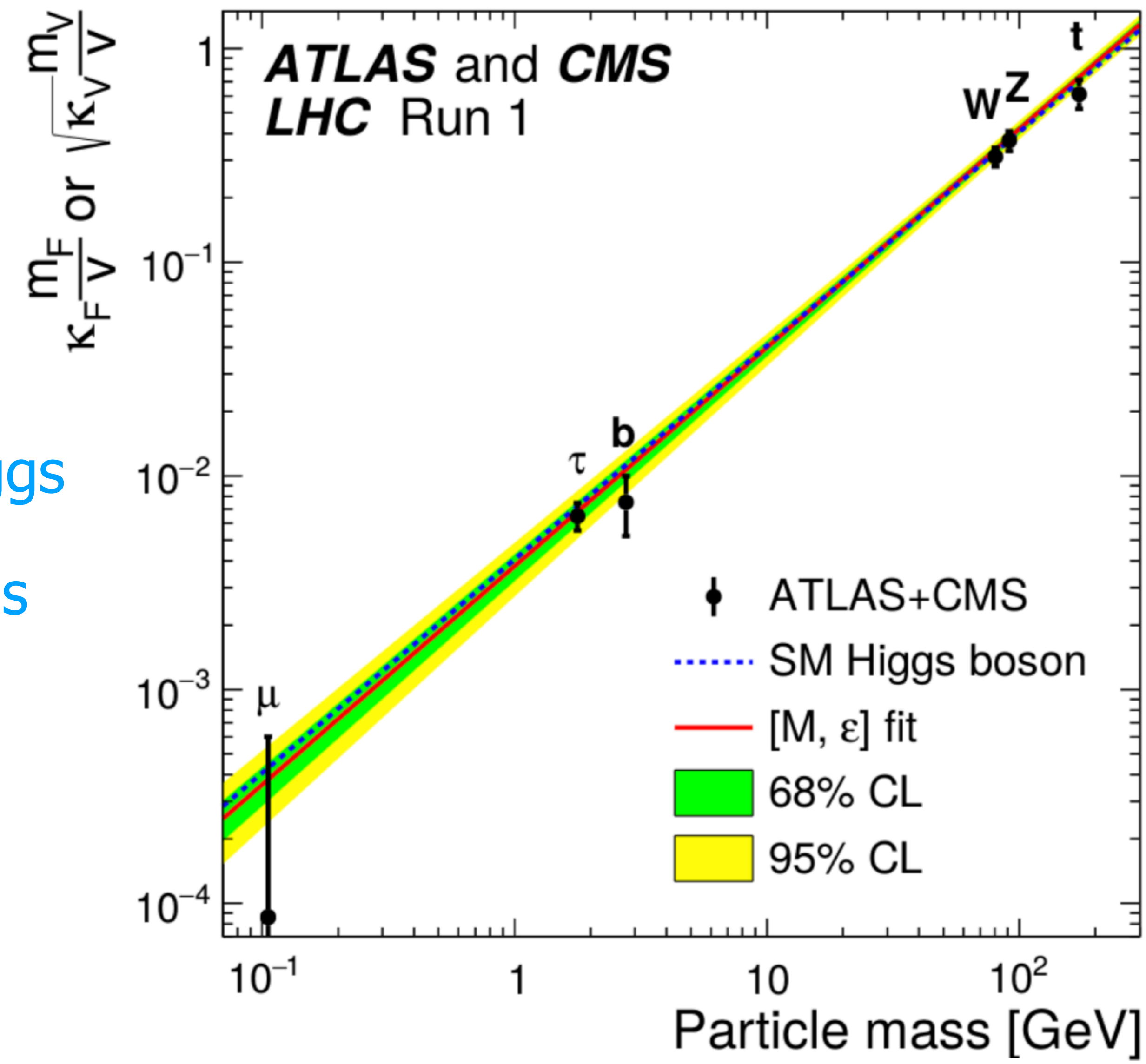
H→μμ

- LHC sensitivity to H→μμ is approaching
- CMS result with 2016 data only shows mild rise consistent with SM expectations…stay tuned for Run 3

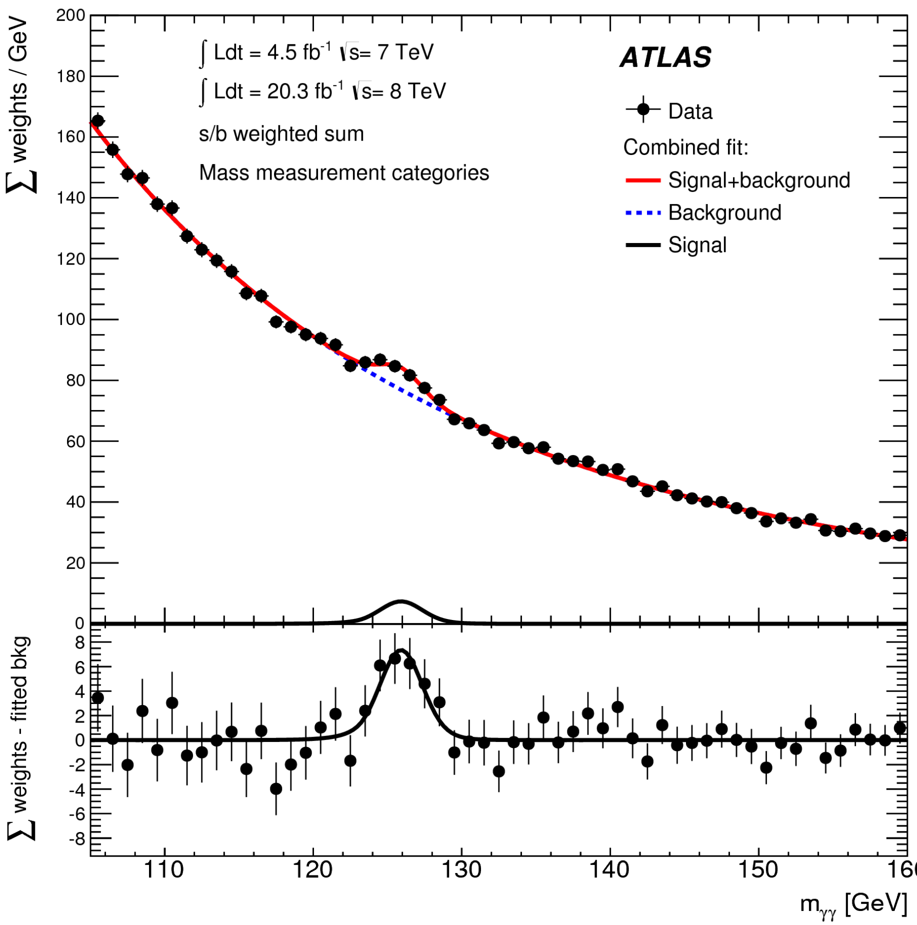


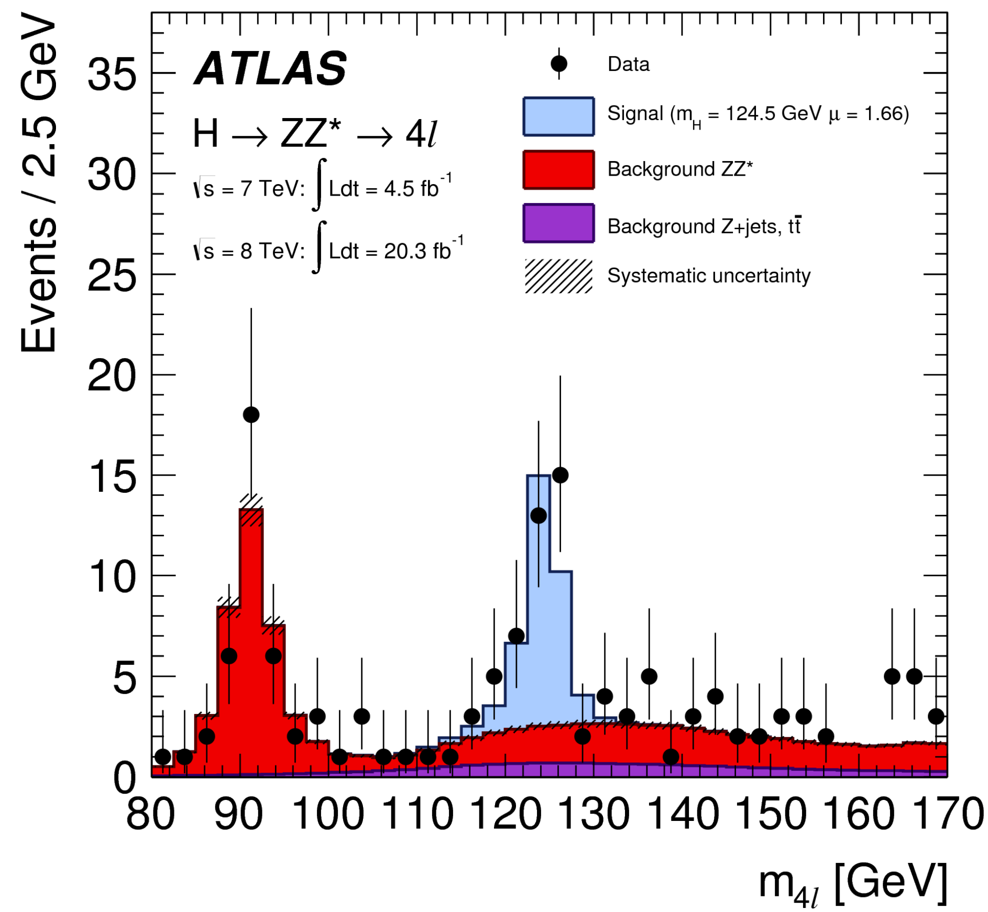


- as of the end of Run 1, ATLAS and CMS had established that the couplings are consistent with those of the SM Higgs
- the era of precision Higgs physics has begun
- See C. Vernieri talk this afternoon for the latest Run 2 updates



- the best resolution on the Higgs boson mass comes from the two main discovery modes, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$





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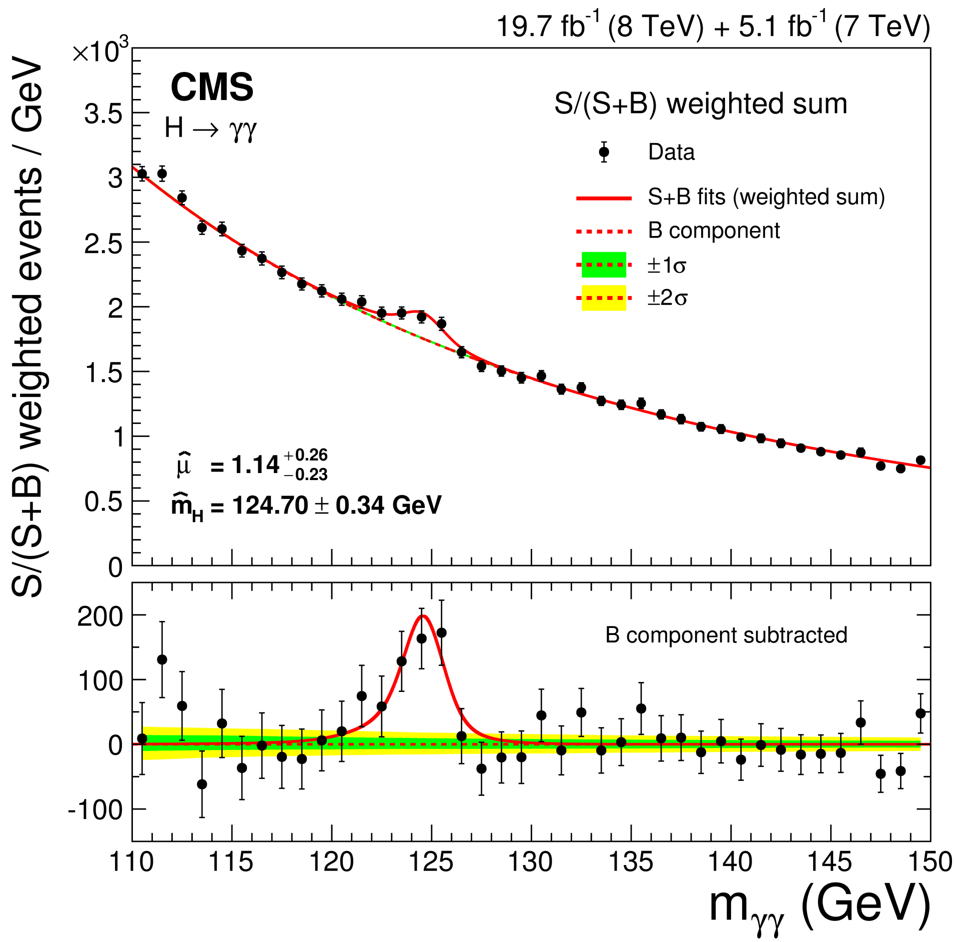
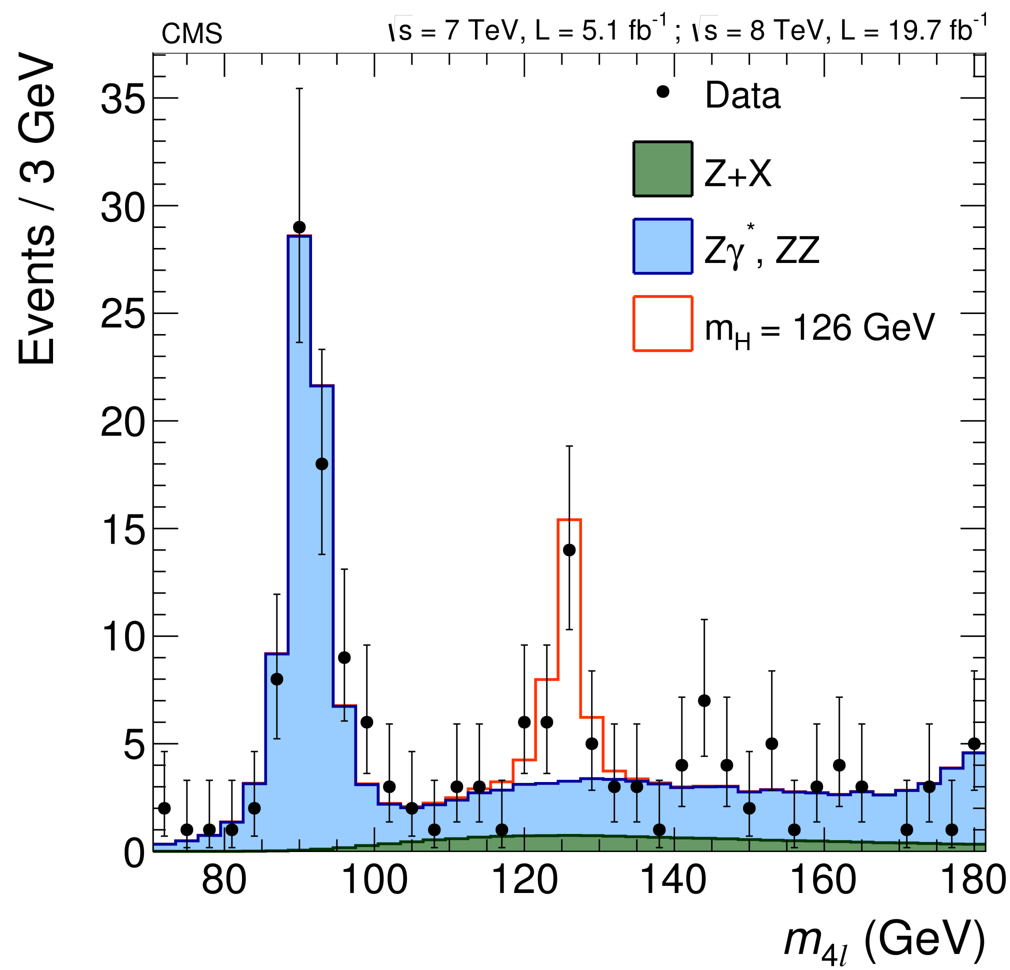
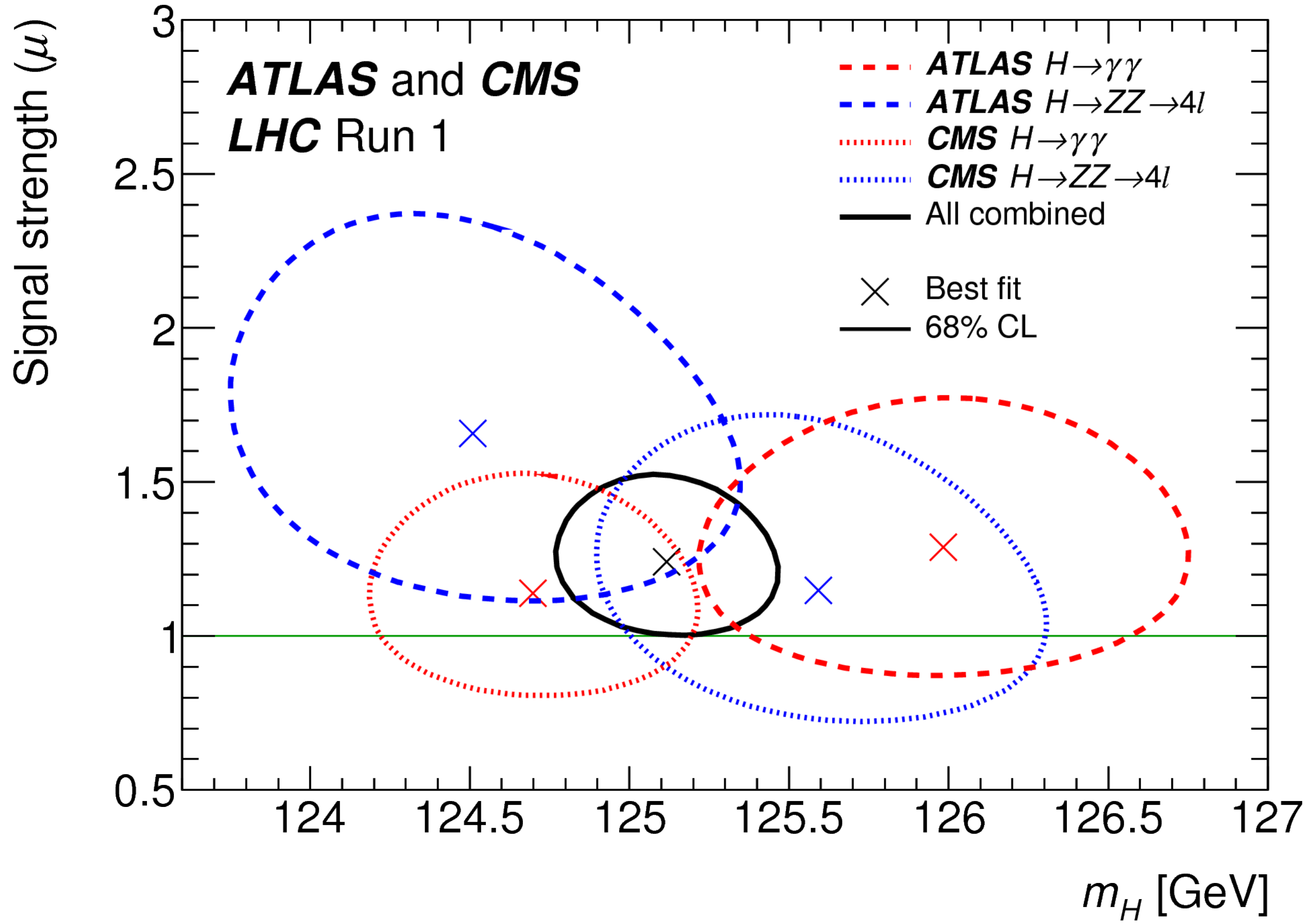


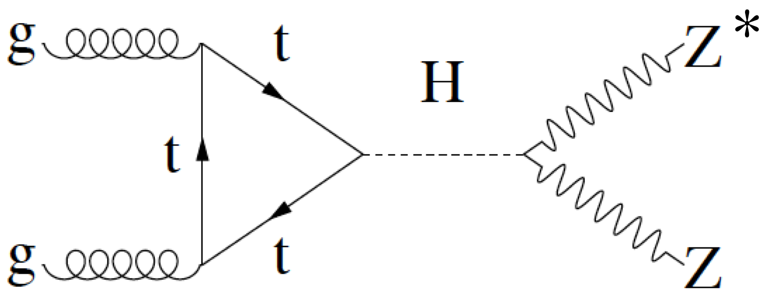


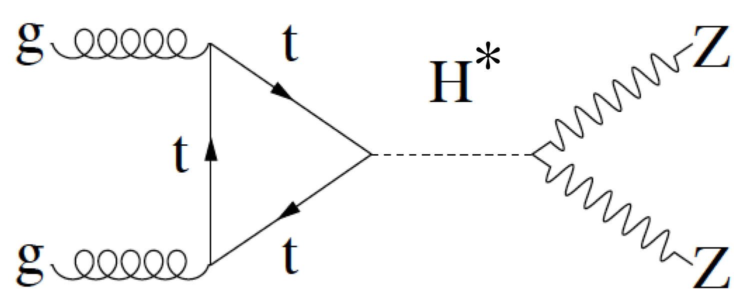
- CMS and ATLAS combined all the mass data from Run 1 and arrived at a consistent picture



$m_H = 125.09 \pm 0.21\ (stat) \pm 0.11\ (sys)$ GeV

- In the SM, the Higgs boson width is expected to be 4.15 MeV
- Far too narrow to measure directly due to resolution!
- However gg→H can be sensitive to the Higgs width

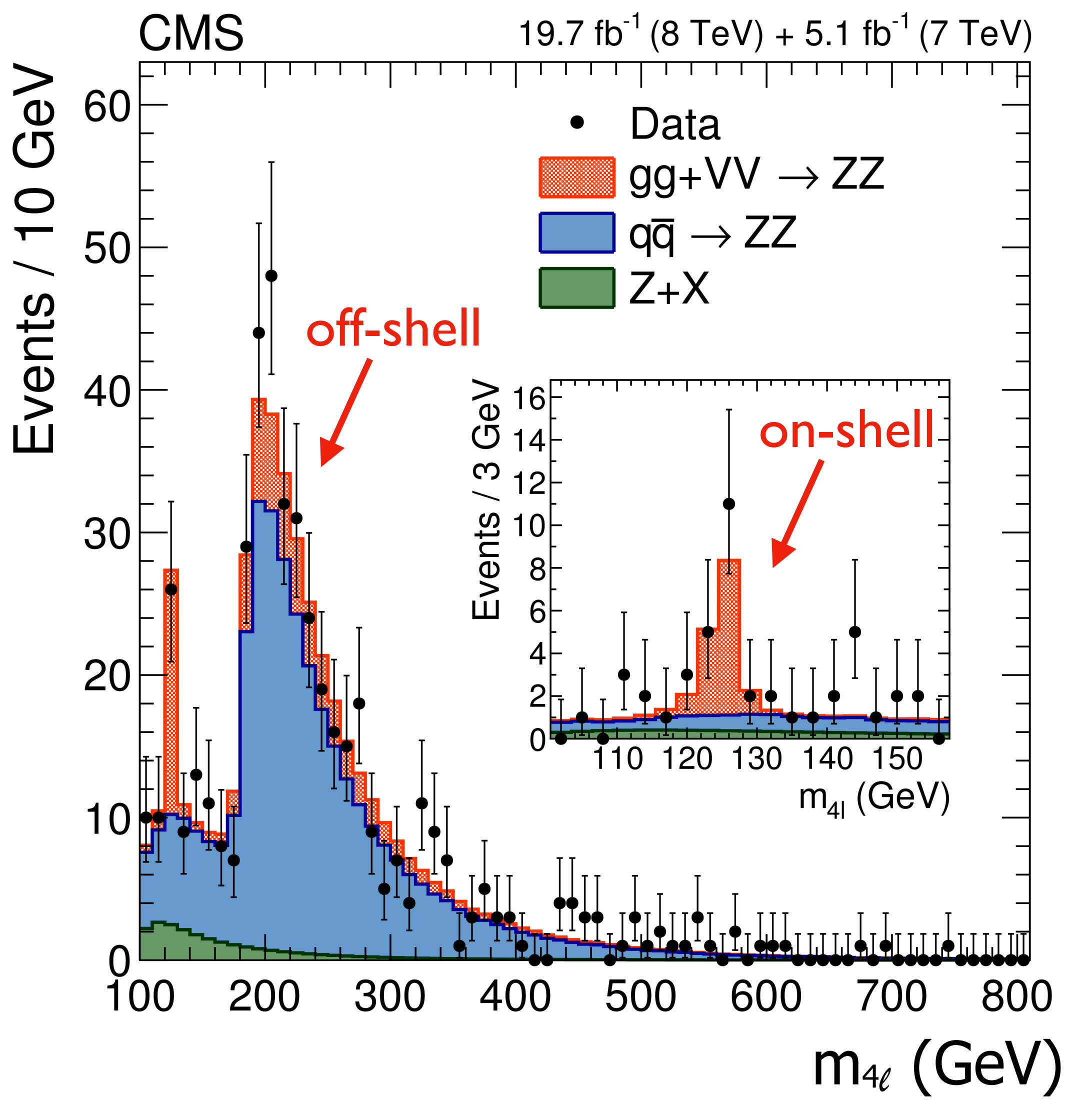




$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

⇒ Measure the ratio of on-shell to off-shell cross sections to constrain Higgs width

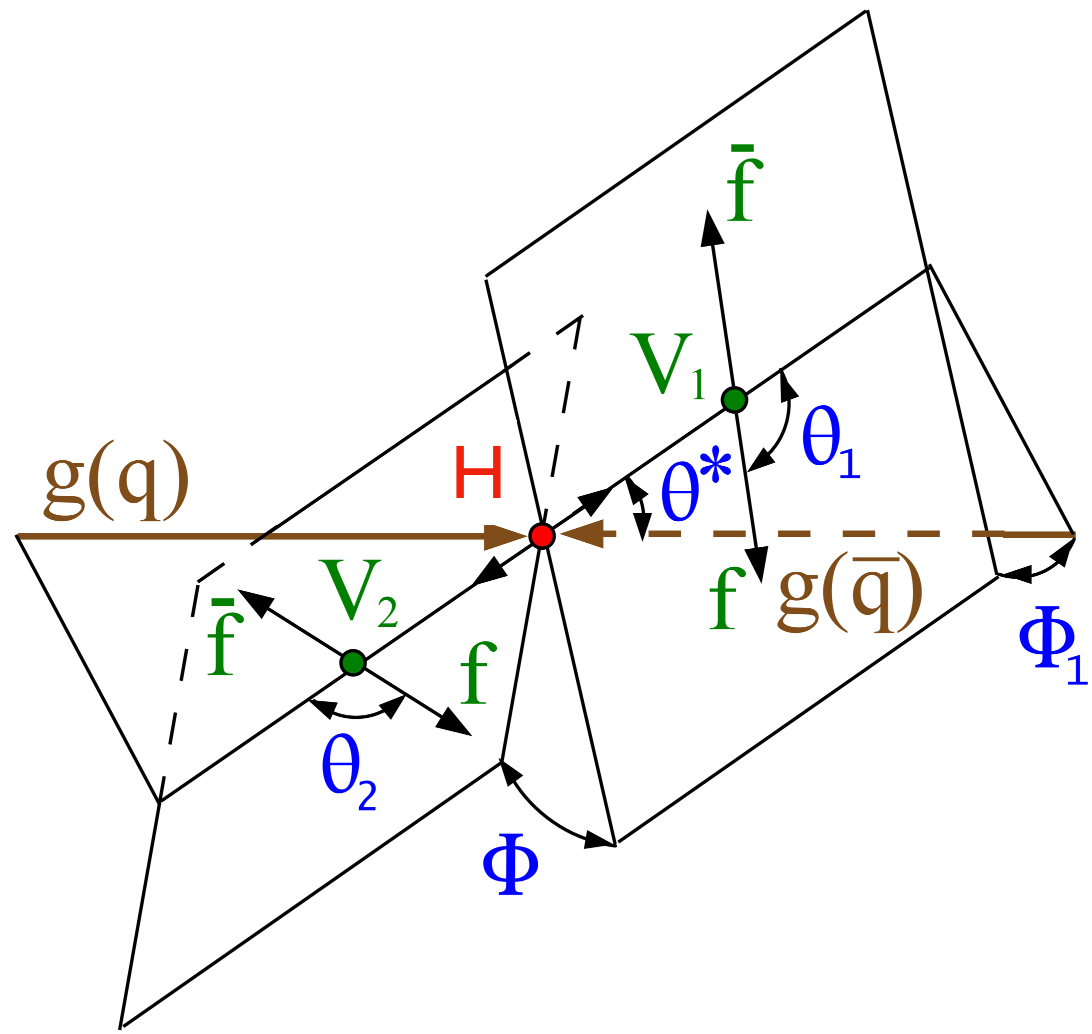


- Can also use $2\ell 2\nu$ channel
- CMS Run 1 result:

  Γ_H < 22 MeV at 95% CL
- Can also do similar measurement in WW(*) final states
- ATLAS Run 1 result:

  Γ_H < 22.7 MeV at 95% CL

- The SM Higgs boson is a scalar with even parity: $J^P = 0^+$
- The Higgs decays to γγ, ZZ*, WW* can be used to probe this
- In H→ZZ*→4ℓ we can measure a 5-D angular distribution



$$A_{00} = \frac{m_X^4}{m_1 m_2\sqrt{6}}\frac{c_1}{8} + \frac{m_1 m_2}{\sqrt{6}}\left[c_1\frac{1}{2}(1+x) - c_2 2x + c_{41}2x + c_{42}2x\right] - \frac{(m_1^4+m_2^4)}{m_1 m_2\sqrt{6}}\frac{c_1}{4} + \frac{m_1 m_2(m_1^2-m_2^2)}{m_X^2\sqrt{6}}(c_{41}-c_{42})2x$$

$$+ \frac{(m_1^8+m_2^8)}{m_X^4 m_1 m_2\sqrt{6}}\frac{c_1}{8} + \frac{m_1^3 m_2^3}{m_X^4\sqrt{6}}\left[c_1\left(\frac{3}{4}+x\right) - c_2\left(4x+8x^2\right) - c_3 8x^2\right] + \frac{m_1 m_2(m_1^4+m_2^4)}{m_X^4\sqrt{6}}\left[-c_1\frac{1}{2}(1+x) + c_2 2x\right],$$

$$A_{++} = \frac{m_X^2}{\sqrt{6}}\frac{c_1}{4} - \frac{(m_1^4+m_2^4)}{m_X^2\sqrt{6}}\frac{c_1}{4} + \frac{m_1^2 m_2^2}{m_X^2\sqrt{6}}\left[c_1\left(\frac{1}{2}+x\right) + c_2 8x\right] - i\frac{m_1 m_2}{\sqrt{6}}c_6 4\sqrt{x} + i\frac{m_1^3 m_2^3}{m_X^4\sqrt{6}}c_5 8x\sqrt{x},$$

$$A_{--} = \frac{m_X^2}{\sqrt{6}}\frac{c_1}{4} - \frac{(m_1^4+m_2^4)}{m_X^2\sqrt{6}}\frac{c_1}{4} + \frac{m_1^2 m_2^2}{m_X^2\sqrt{6}}\left[c_1\left(\frac{1}{2}+x\right) + c_2 8x\right] - i\frac{m_1 m_2}{\sqrt{6}}c_6 4\sqrt{x} - i\frac{m_1^3 m_2^3}{m_X^4\sqrt{6}}c_5 8x\sqrt{x},$$

$$A_{+0} = \frac{m_X^3}{m_2\sqrt{2}}\frac{c_1}{8} + \frac{m_X m_2}{\sqrt{2}}\left(1-\frac{m_1^2}{m_2^2}\right)\frac{c_1}{8} + \frac{m_1^2 m_2}{m_X\sqrt{2}}\left[c_1\left(\frac{1}{4}+\frac{1}{2}x-\frac{m_2^2}{8m_1^2}-\frac{m_1^2}{8m_2^2}\right) + c_{41}2x\right]$$

$$+ \frac{m_1^2 m_2^3}{m_X^3\sqrt{2}}c_1\left[\frac{1}{8}\left(\frac{m_1^4}{m_2^4}-\frac{m_2^2}{m_1^2}\right) + \left(1-\frac{m_1^2}{m_2^2}\right)\left(\frac{3}{8}+\frac{1}{2}x\right)\right] - i\frac{m_X m_1}{\sqrt{2}}c_6\sqrt{x} + i\frac{m_1^3}{m_X\sqrt{2}}c_6\left(1-\frac{m_2^2}{m_1^2}\right)\sqrt{x} - i\frac{m_1^3 m_2^2}{m_X^3\sqrt{2}}c_7 4x\sqrt{x},$$

$$A_{0+} = \frac{m_X^3}{m_1\sqrt{2}}\frac{c_1}{8} + \frac{m_X m_1}{\sqrt{2}}\left(1-\frac{m_2^2}{m_1^2}\right)\frac{c_1}{8} + \frac{m_1 m_2^2}{m_X\sqrt{2}}\left[c_1\left(\frac{1}{4}+\frac{1}{2}x-\frac{m_2^2}{8m_1^2}-\frac{m_1^2}{8m_2^2}\right) + c_{42}2x\right]$$

$$+ \frac{m_1^3 m_2^2}{m_X^3\sqrt{2}}c_1\left[\frac{1}{8}\left(\frac{m_2^4}{m_1^4}-\frac{m_1^2}{m_2^2}\right) + \left(1-\frac{m_2^2}{m_1^2}\right)\left(\frac{3}{8}+\frac{1}{2}x\right)\right] - i\frac{m_X m_2}{\sqrt{2}}c_6\sqrt{x} + i\frac{m_2^3}{m_X\sqrt{2}}c_6\left(1-\frac{m_1^2}{m_2^2}\right)\sqrt{x} - i\frac{m_1^2 m_2^3}{m_X^3\sqrt{2}}c_7 4x\sqrt{x},$$

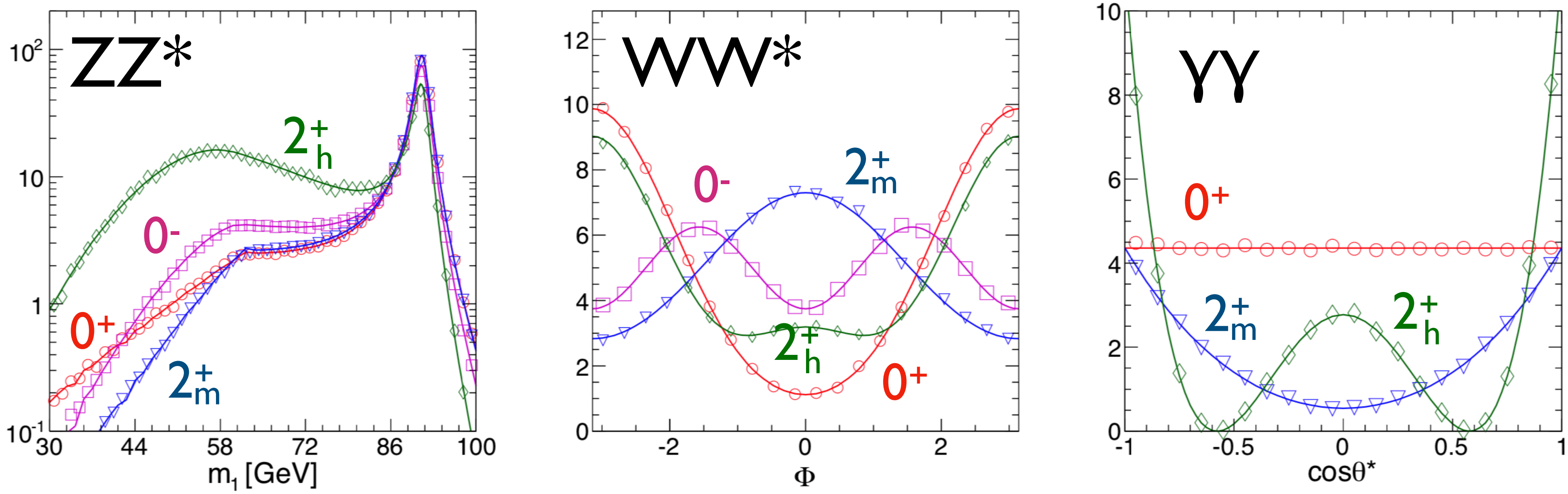
$$A_{-0} = \frac{m_X^3}{m_2\sqrt{2}}\frac{c_1}{8} + \frac{m_X m_2}{\sqrt{2}}\left(1-\frac{m_1^2}{m_2^2}\right)\frac{c_1}{8} + \frac{m_1^2 m_2}{m_X\sqrt{2}}\left[c_1\left(\frac{1}{4}+\frac{1}{2}x-\frac{m_2^2}{8m_1^2}-\frac{m_1^2}{8m_2^2}\right) + c_{41}2x\right]$$

$$+ \frac{m_1^2 m_2^3}{m_X^3\sqrt{2}}c_1\left[\frac{1}{8}\left(\frac{m_1^4}{m_2^4}-\frac{m_2^2}{m_1^2}\right) + \left(1-\frac{m_1^2}{m_2^2}\right)\left(\frac{3}{8}+\frac{1}{2}x\right)\right] + i\frac{m_X m_1}{\sqrt{2}}c_6\sqrt{x} - i\frac{m_1^3}{m_X\sqrt{2}}c_6\left(1-\frac{m_2^2}{m_1^2}\right)\sqrt{x} + i\frac{m_1^3 m_2^2}{m_X^3\sqrt{2}}c_7 4x\sqrt{x},$$

$$A_{0-} = \frac{m_X^3}{m_1\sqrt{2}}\frac{c_1}{8} + \frac{m_X m_1}{\sqrt{2}}\left(1-\frac{m_2^2}{m_1^2}\right)\frac{c_1}{8} + \frac{m_1 m_2^2}{m_X\sqrt{2}}\left[c_1\left(\frac{1}{4}+\frac{1}{2}x-\frac{m_2^2}{8m_1^2}-\frac{m_1^2}{8m_2^2}\right) + c_{42}2x\right]$$

$$+ \frac{m_1^3 m_2^2}{m_X^3\sqrt{2}}c_1\left[\frac{1}{8}\left(\frac{m_2^4}{m_1^4}-\frac{m_1^2}{m_2^2}\right) + \left(1-\frac{m_2^2}{m_1^2}\right)\left(\frac{3}{8}+\frac{1}{2}x\right)\right] + i\frac{m_X m_2}{\sqrt{2}}c_6\sqrt{x} - i\frac{m_2^3}{m_X\sqrt{2}}c_6\left(1-\frac{m_1^2}{m_2^2}\right)\sqrt{x} + i\frac{m_1^2 m_2^3}{m_X^3\sqrt{2}}c_7 4x\sqrt{x},$$

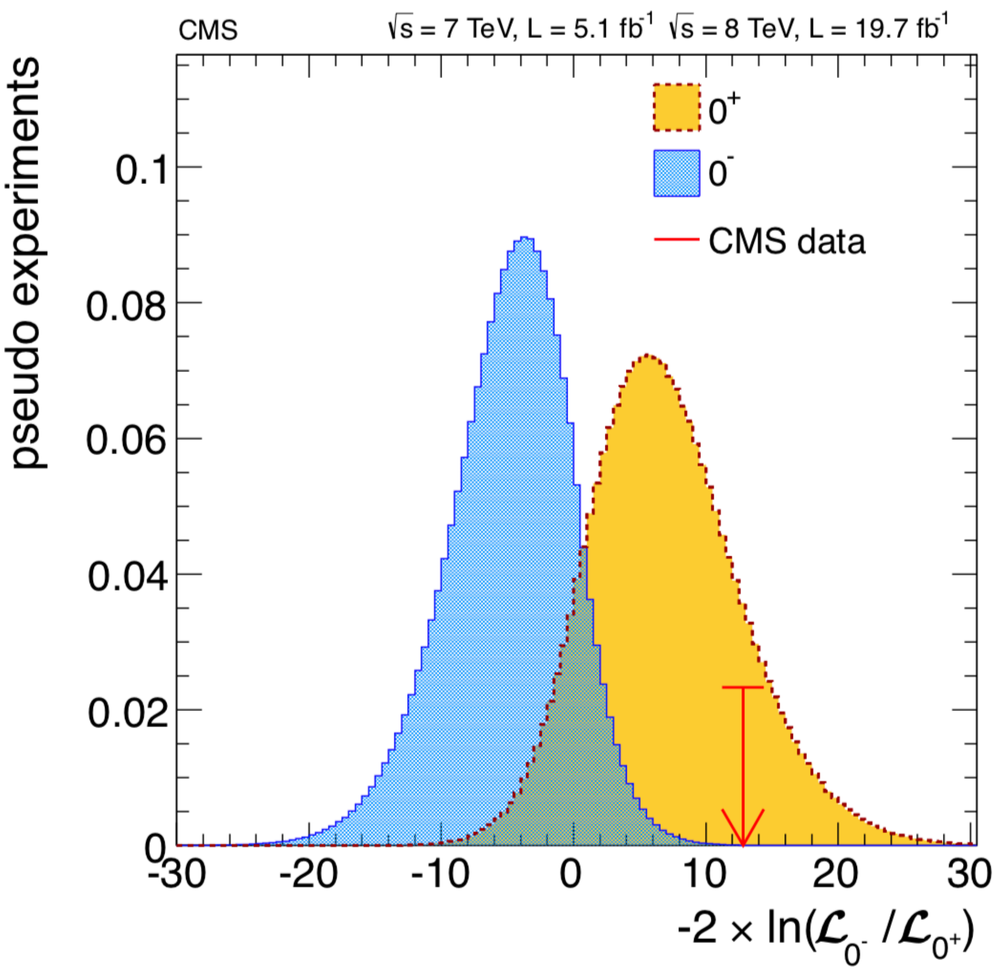
S. Bolognesi et al. Phys.Rev. D86 (2012) 095031

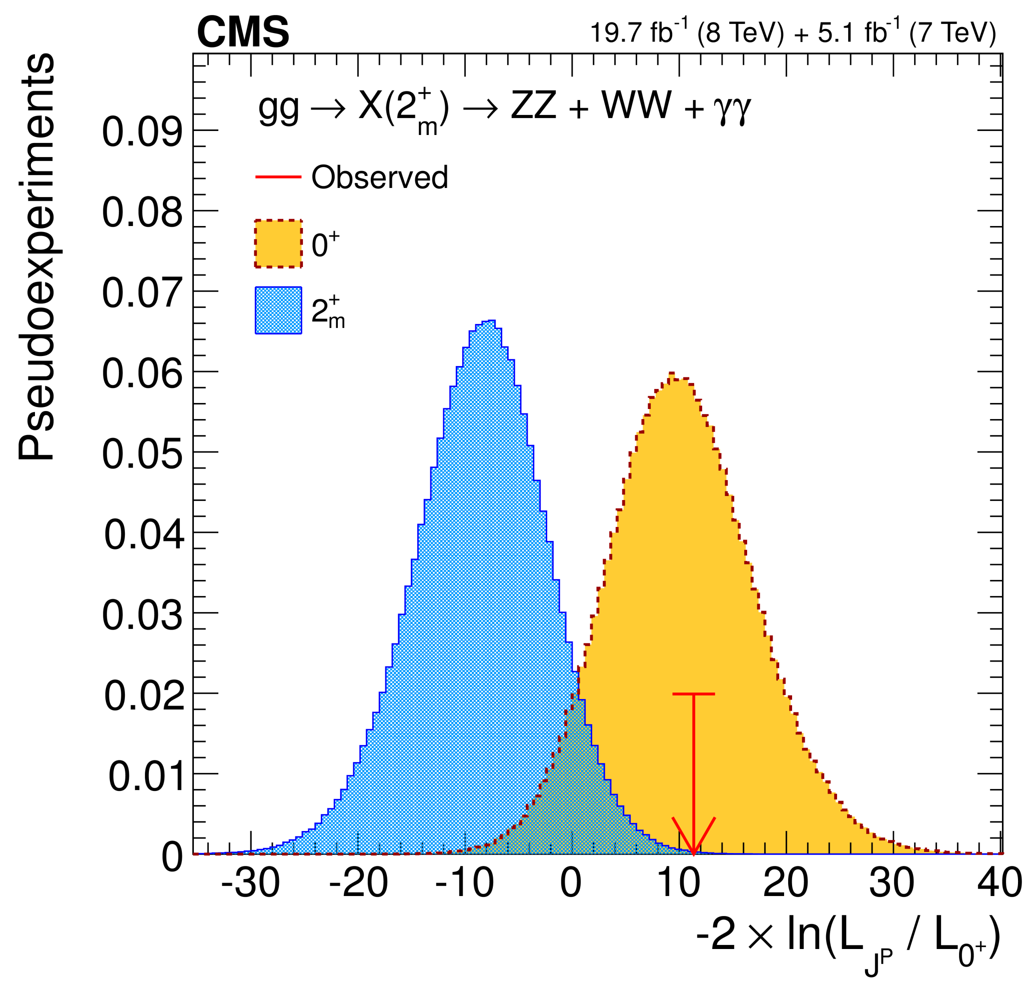


- Form ratio of likelihoods for alternative and SM hypothesis (0^+)
- Compare observed likelihood ratio to expected distributions under each alternative hypothesis

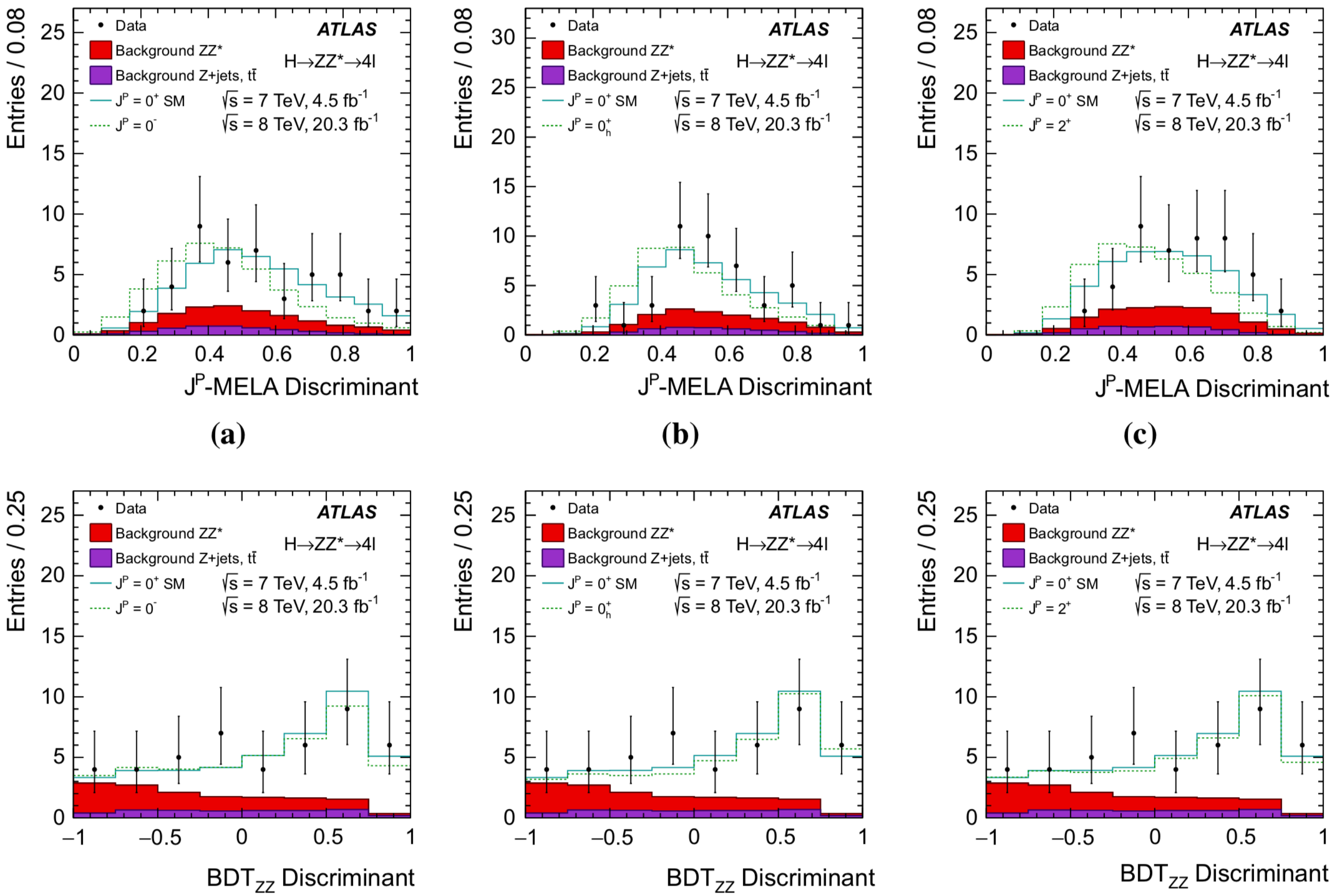
S. Bolognesi et al. Phys.Rev. D86 (2012) 095031

With data from Run 1 CMS was able to exclude a wide range of alternative hypotheses at > 99% CL





ATLAS as well did an exhaustive search using a matrix element likelihood analysis (MELA) with similar conclusions



LHC Higgs so far…

There exists a boson consistent with $J^P = 0^+$ with mass ~125 GeV and couplings to fermions and vector bosons consistent with this predicted in the standard model

- But such a Higgs boson might not be the only one!
  - the SM has <u>minimal</u> Higgs content
  - can be more Higgs doublets, as in supersymmetry
  - the light Higgs scalar in MSSM could be very SM-like

SM Higgs suffers hierarchy problem

⇒ Higgs sector is more complicated?

SM Higgs suffers hierarchy problem

$\Rightarrow$ Higgs sector is more complicated?

MSSM: minimal supersymmetric model greatly reduces hierarchy problem (scalars cancel fermion loops)

SM Higgs suffers hierarchy problem

⇒ Higgs sector is more complicated?

MSSM: minimal supersymmetric model greatly reduces hierarchy problem (scalars cancel fermion loops)

MSSM: Type-II two-Higgs doublet models

- one doublet gives mass to up type quarks
- other doublet gives mass to down-type quarks/leptons

SM Higgs suffers hierarchy problem

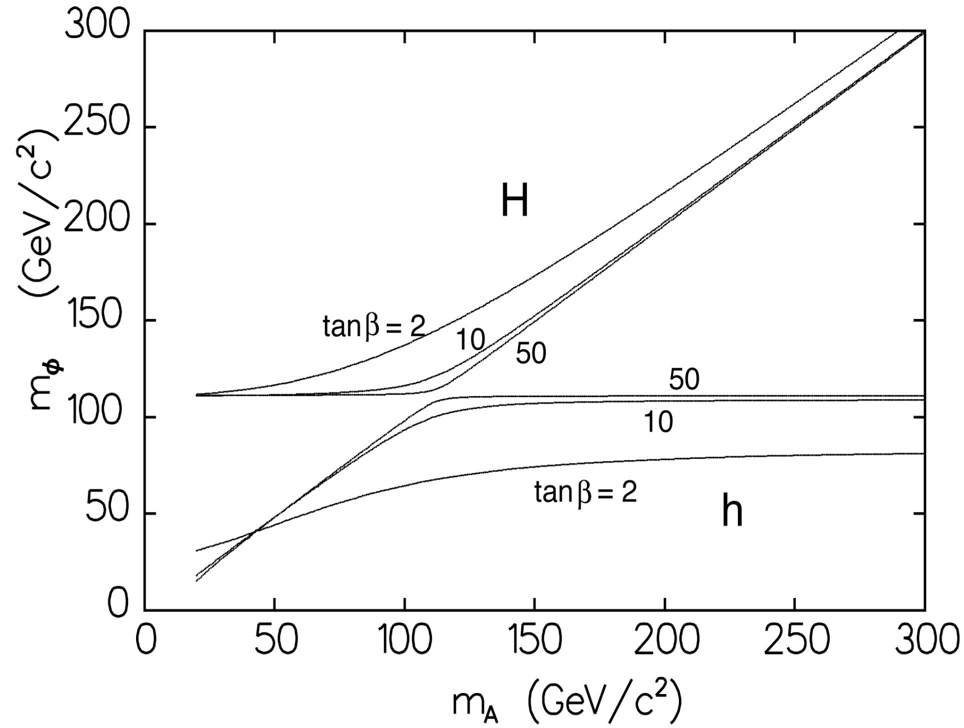
⇒ Higgs sector is more complicated?

MSSM: minimal supersymmetric model greatly reduces hierarchy problem (scalars cancel fermion loops)

MSSM: Type-II two-Higgs doublet models

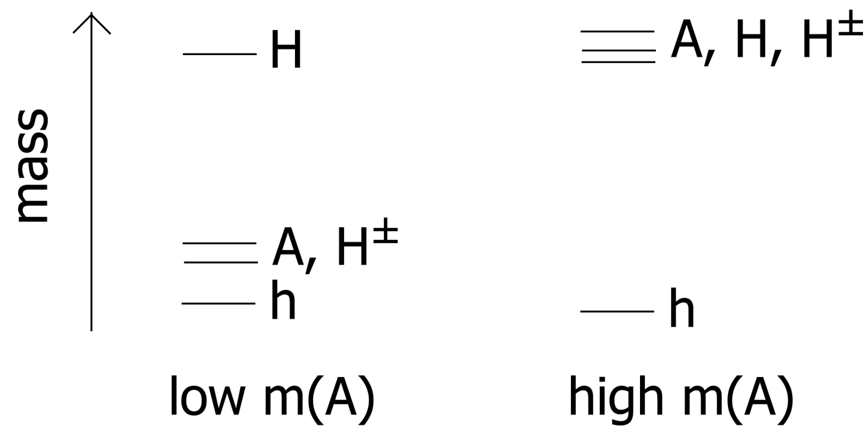
- one doublet gives mass to up type quarks
- other doublet gives mass to down-type quarks/leptons

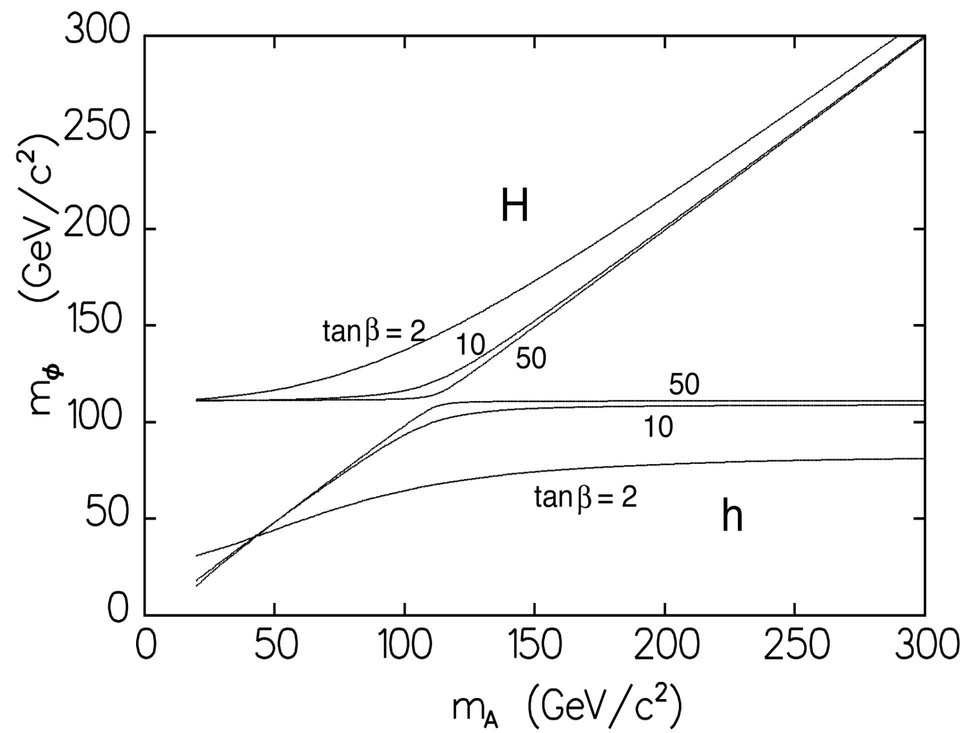
Five Higgs bosons, masses governed by m_A, $\tan\beta$



MSSM a no-lose situation: must be a light scalar h

Even more striking the mass of the light scalar ~120 GeV





MSSM a no-lose situation: must be a light scalar h

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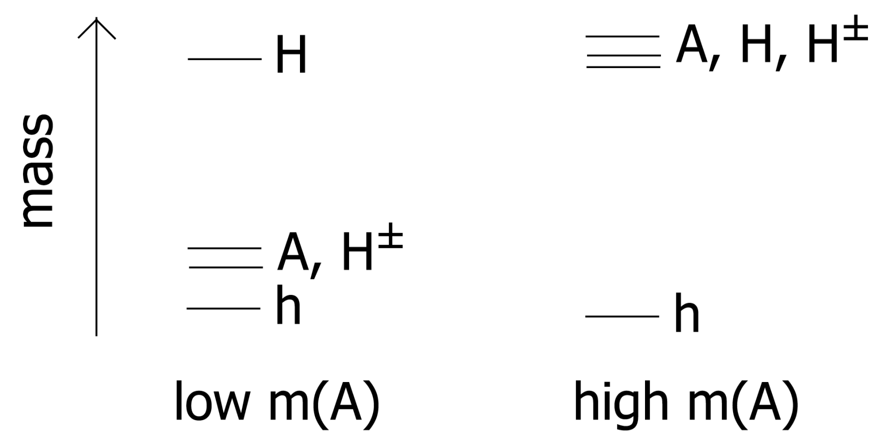
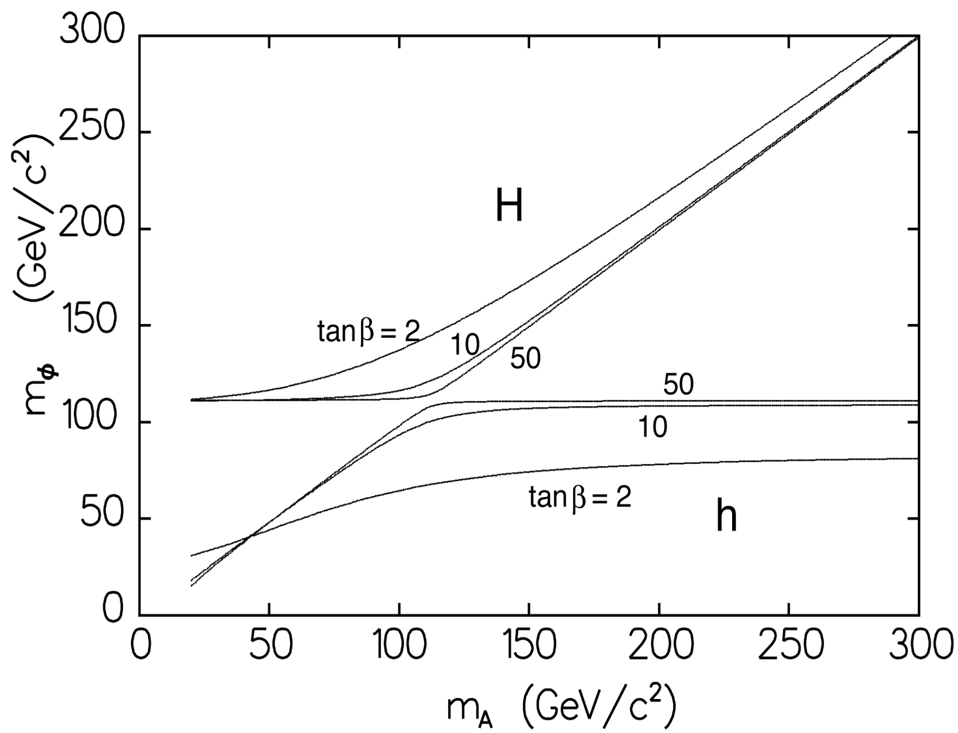
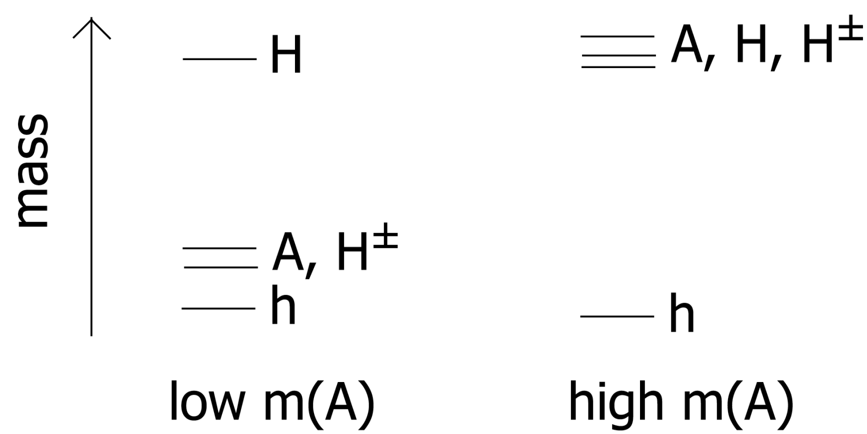
H/A/H± nearly equal mass when m_A large







MSSM a no-lose situation: must be a light scalar h

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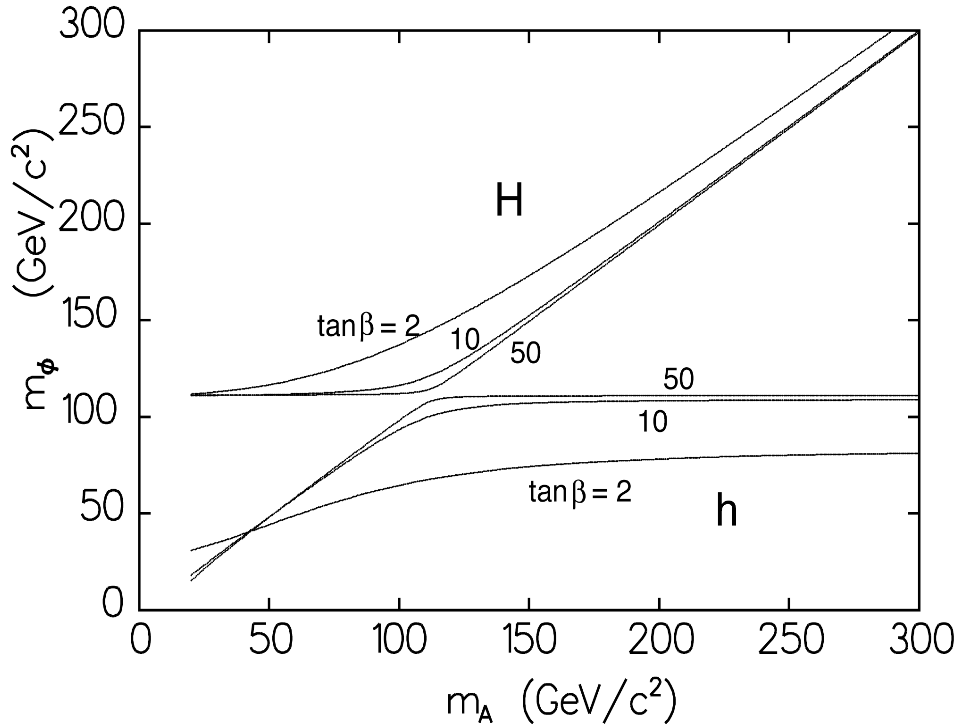
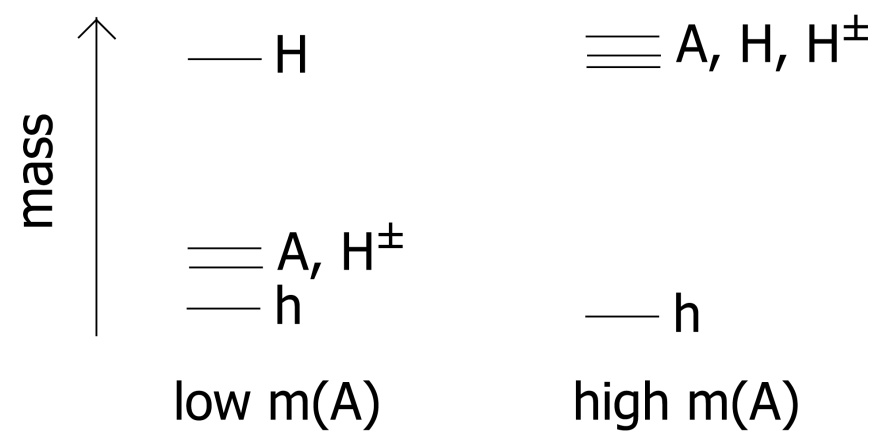
$H/A/H^{\pm}$ nearly equal mass when m_A large

Production of H/A greatly enhanced if tanβ large





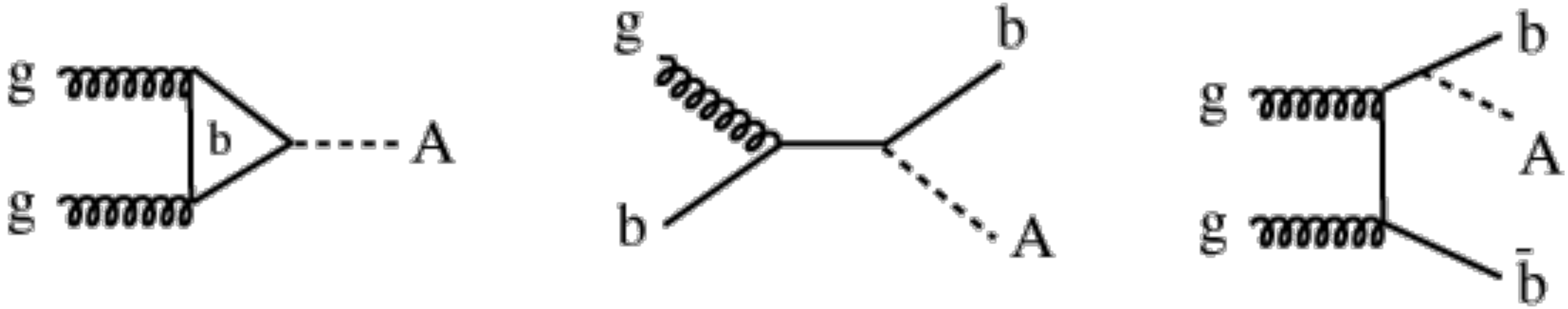
MSSM a no-lose situation: must be a light scalar h

Even more striking the mass of the light scalar ~120 GeV

H/A/H± nearly equal mass when m_A large

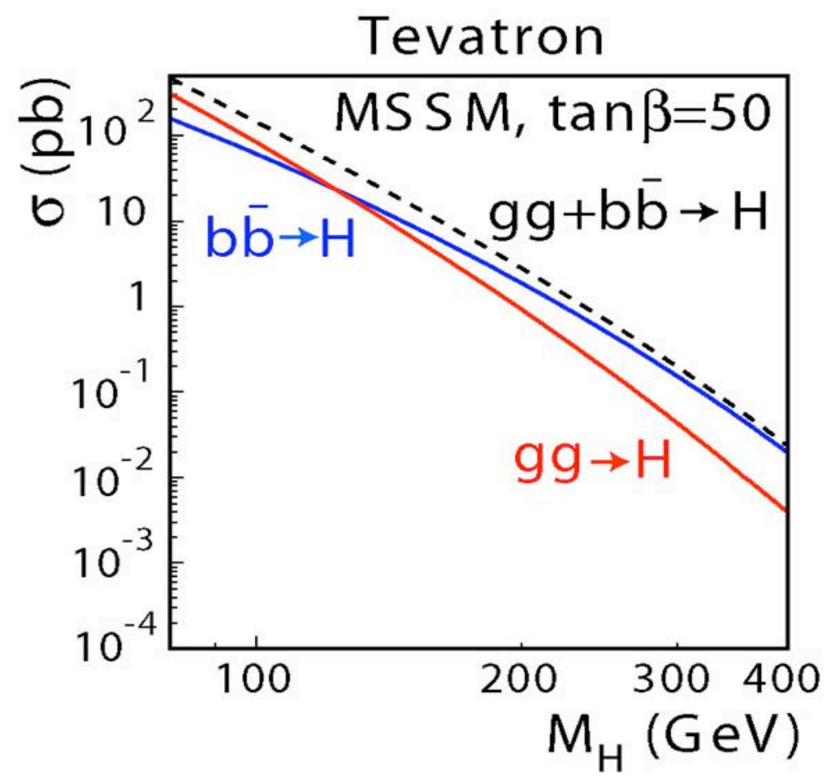
Production of H/A greatly enhanced if tanβ large

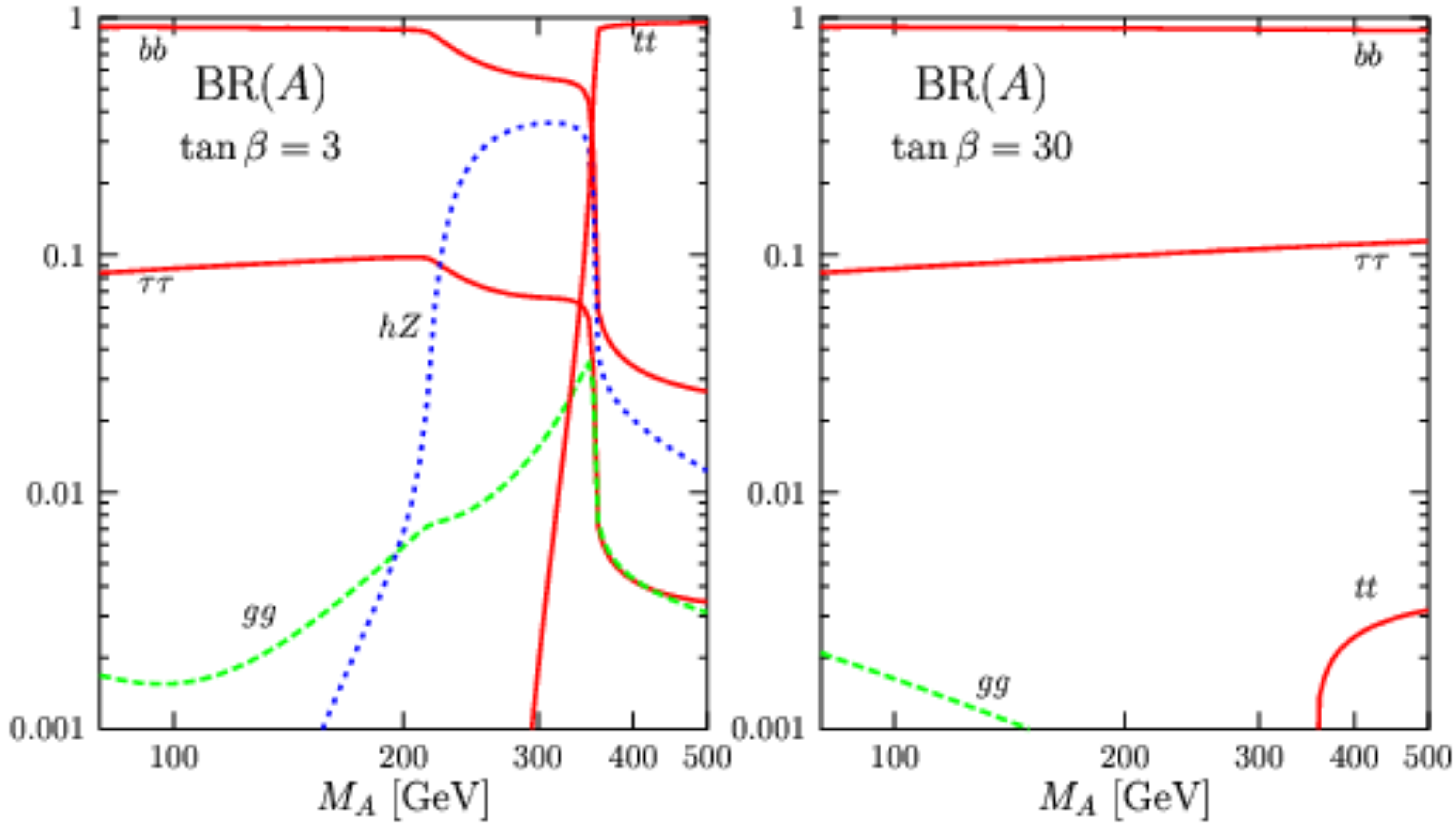
If m_A large may not be able to distinguish SM/MSSM



These processes all have cross sections proportional to $\tan^2\beta$

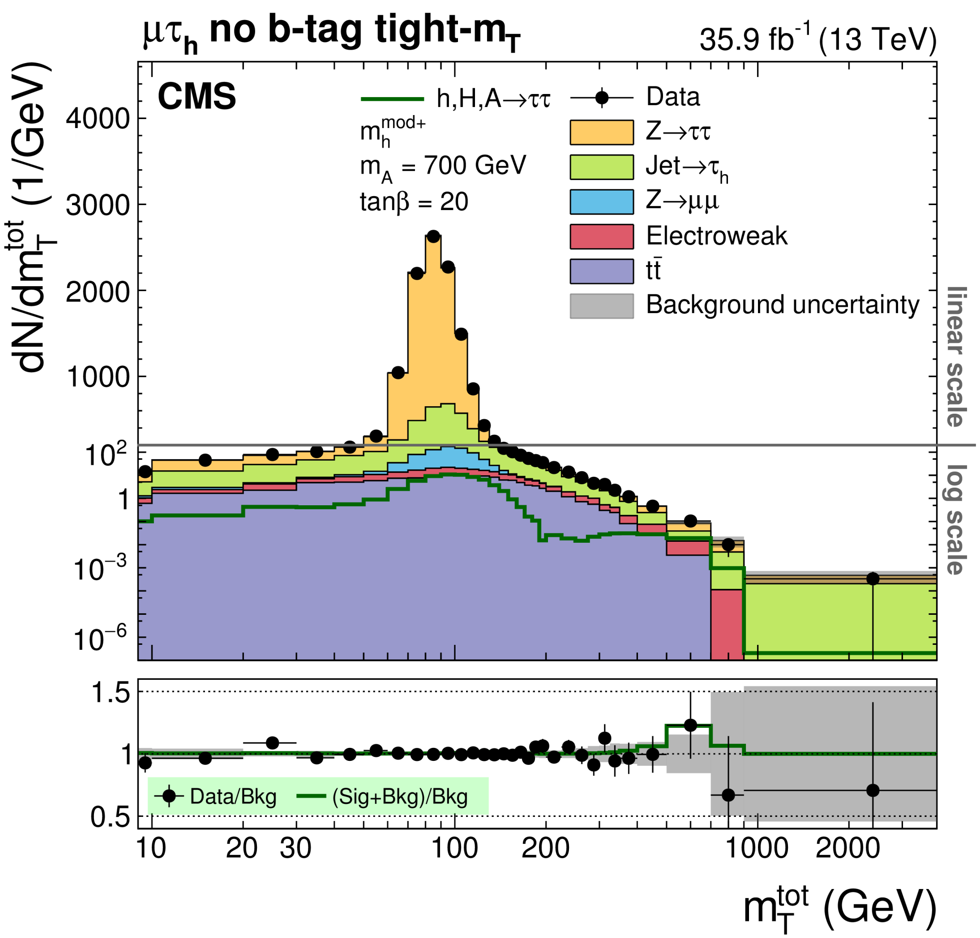
$\tan\beta \sim m_t/m_b \sim 35$?

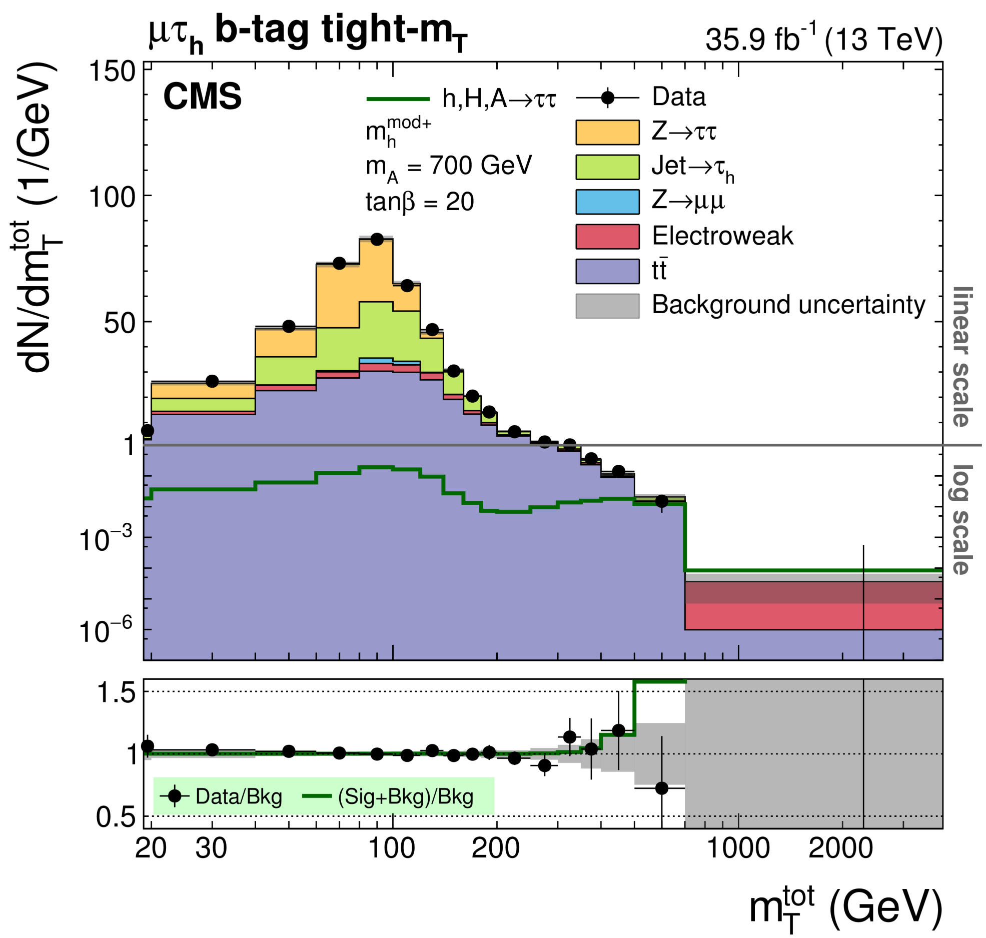




- bb and ττ decay modes dominate experimentally
- ττ is the most sensitive: main background is Z

MSSM H/A → ττ has the best sensitivity here
Use eμ, eτ, μτ, ττ modes with/without b tagging





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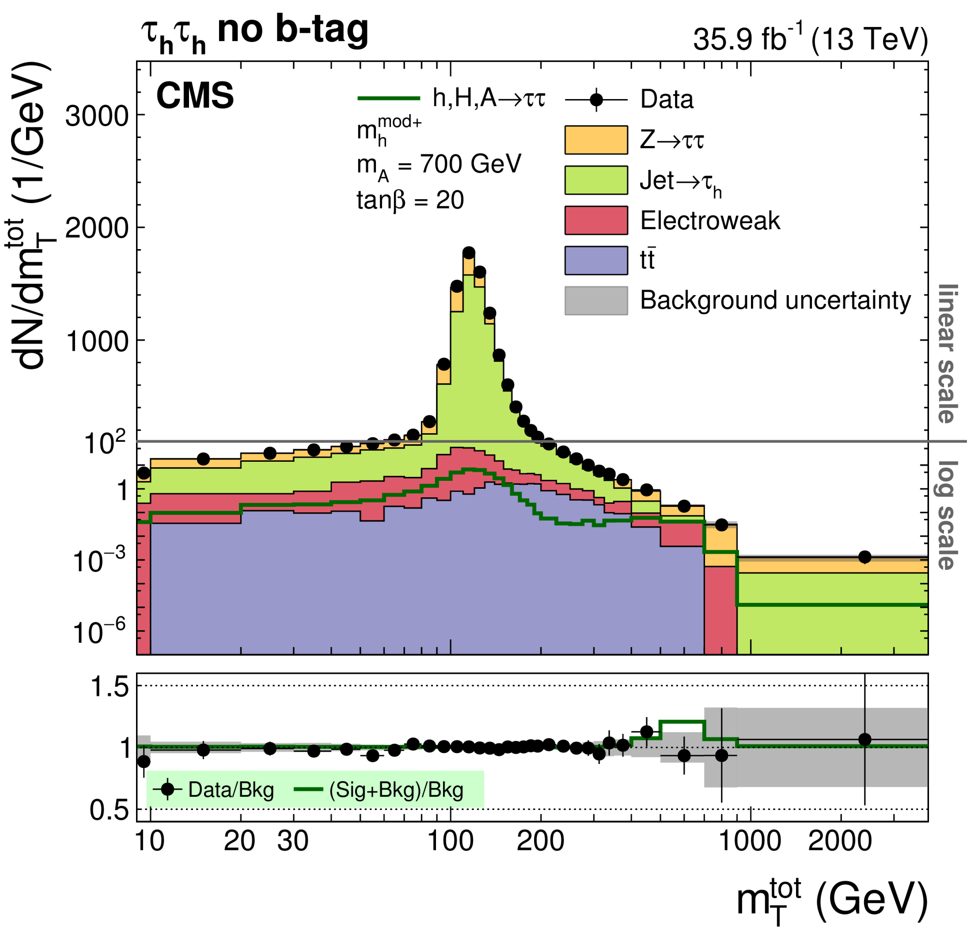
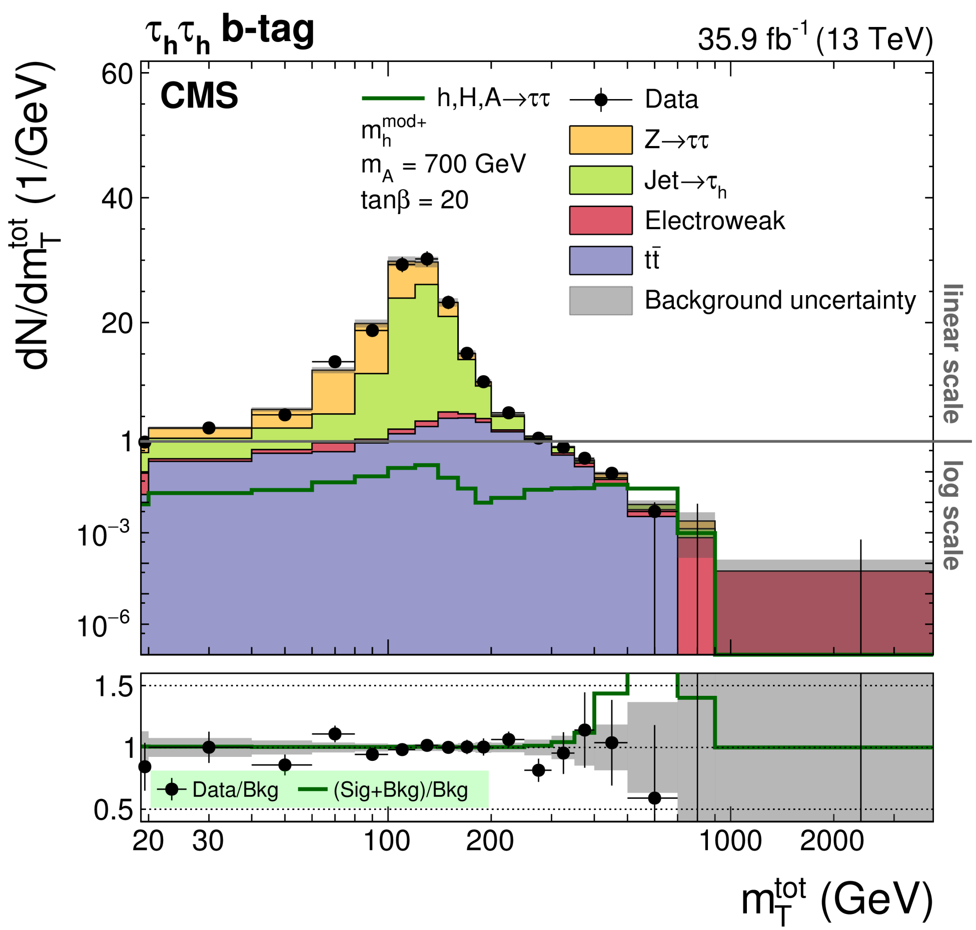
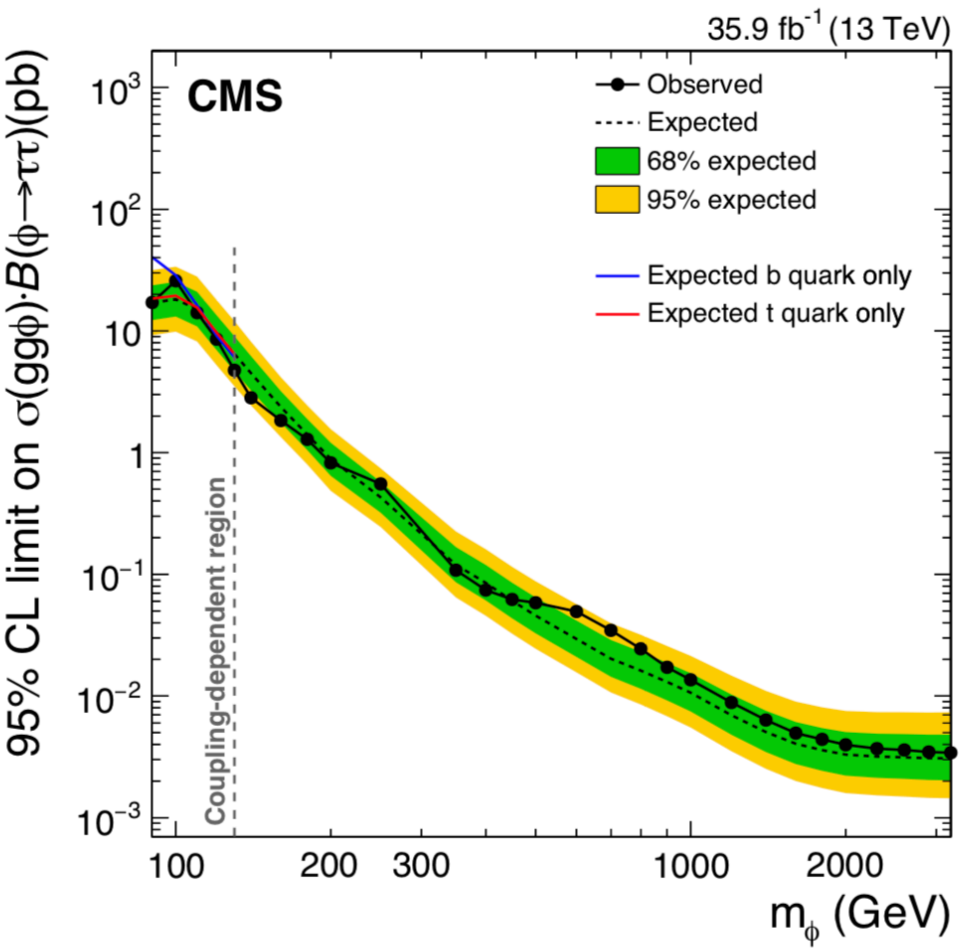
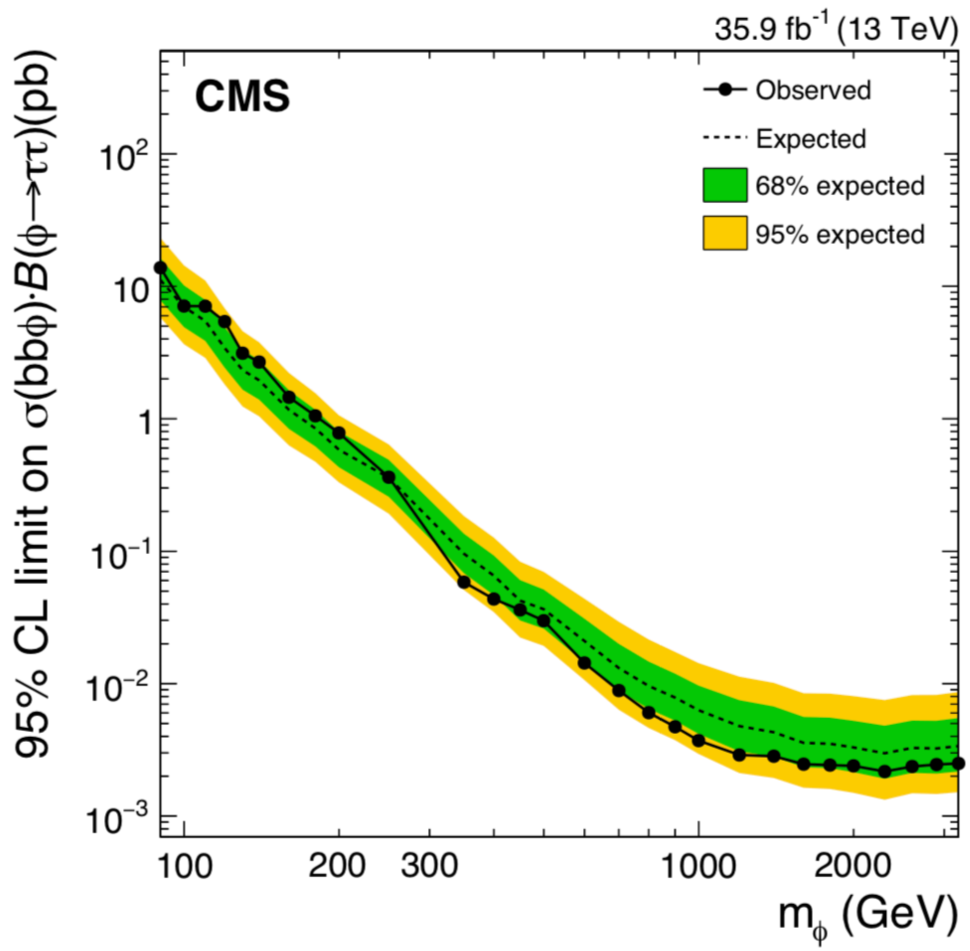




Model-independent limits on ggϕ and bbϕ

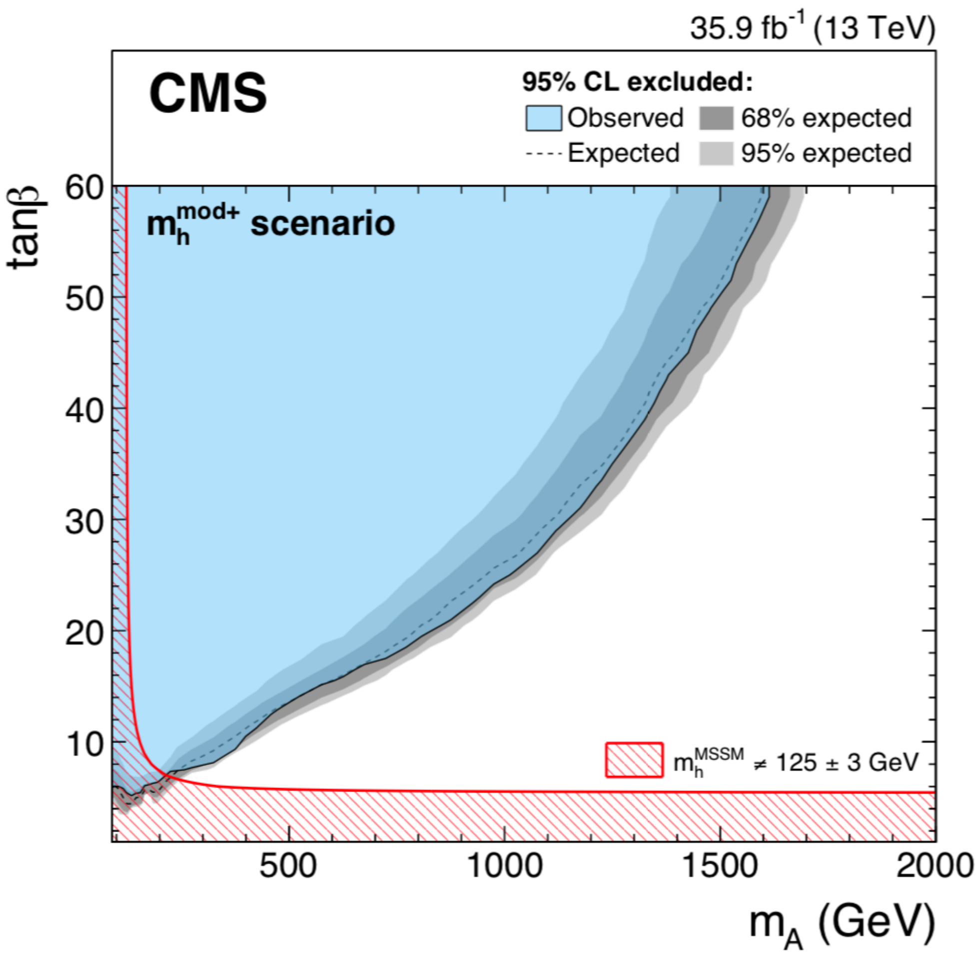


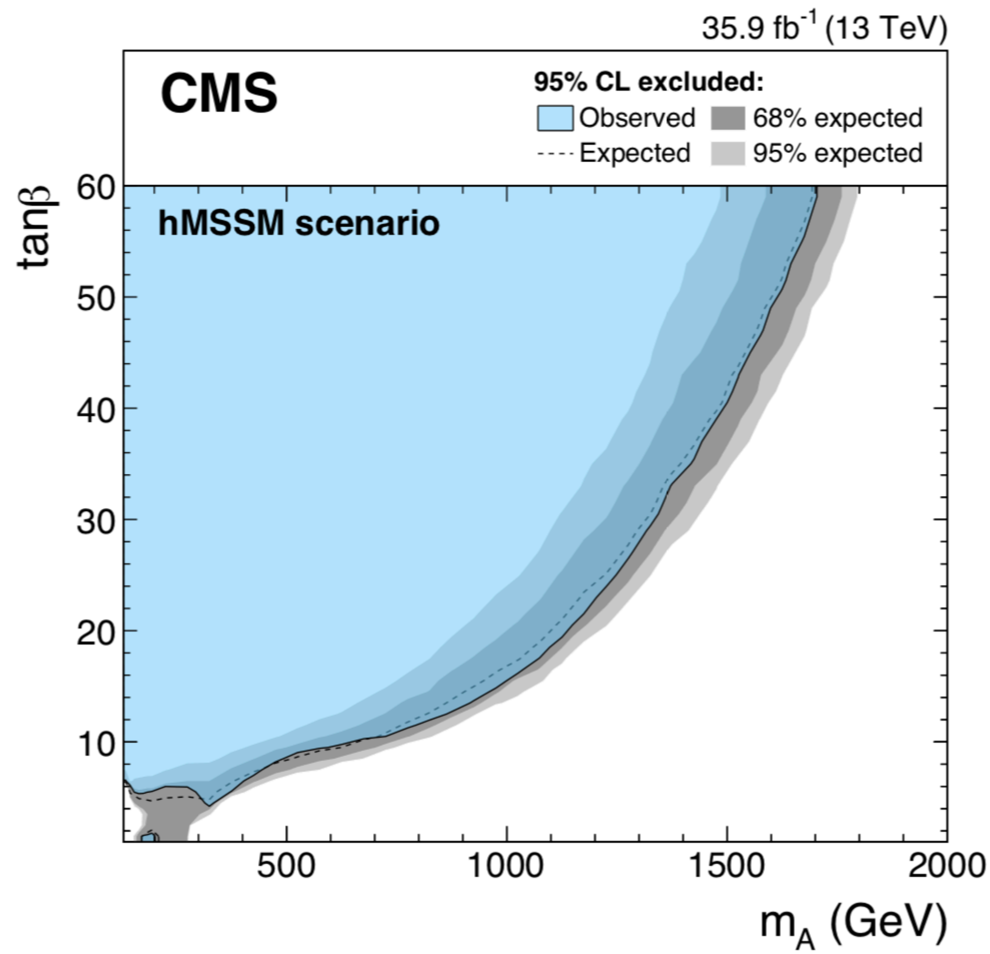
ggϕ



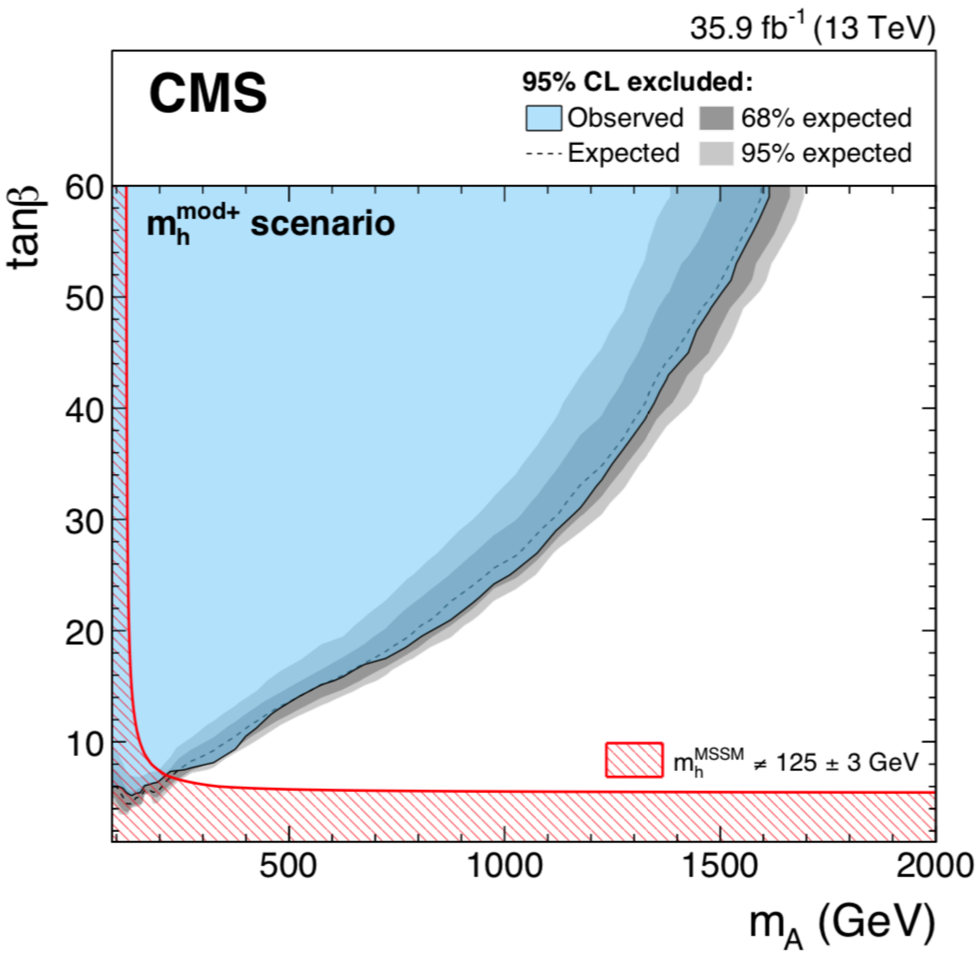
bbϕ

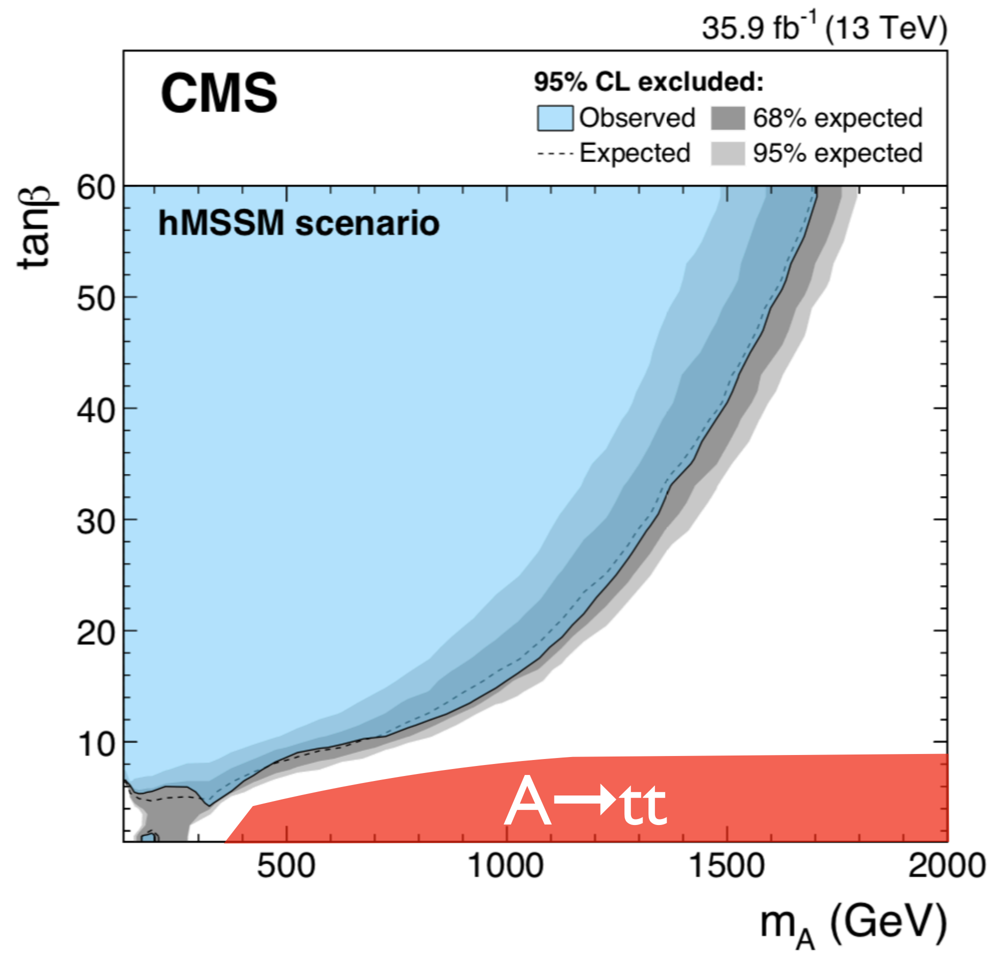
Limits on particular MSSM scenarios





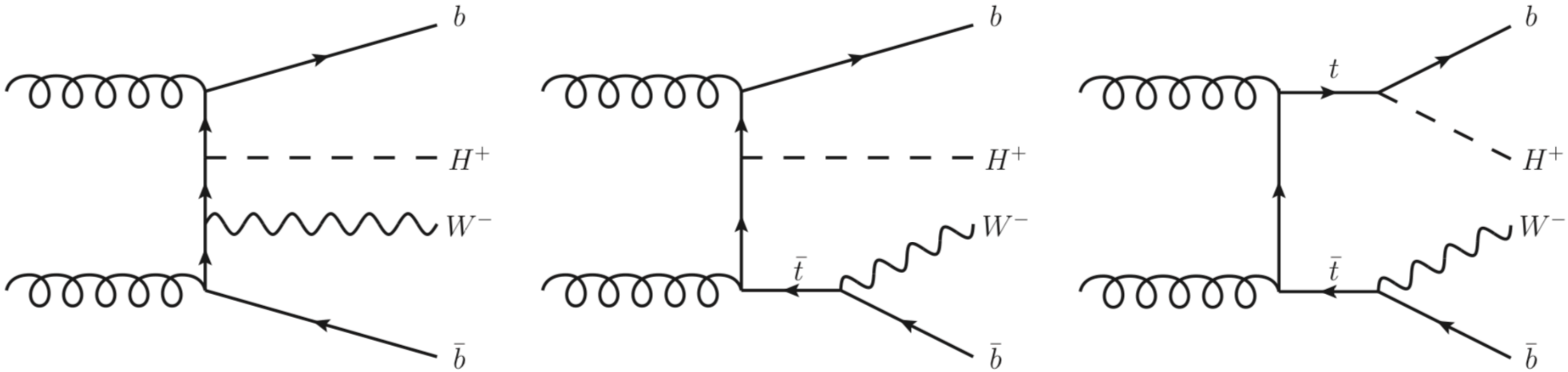
Limits on particular MSSM scenarios





We may always have "the wedge" at the LHC…

Charged Higgs in SUSY/2HDM scenarios

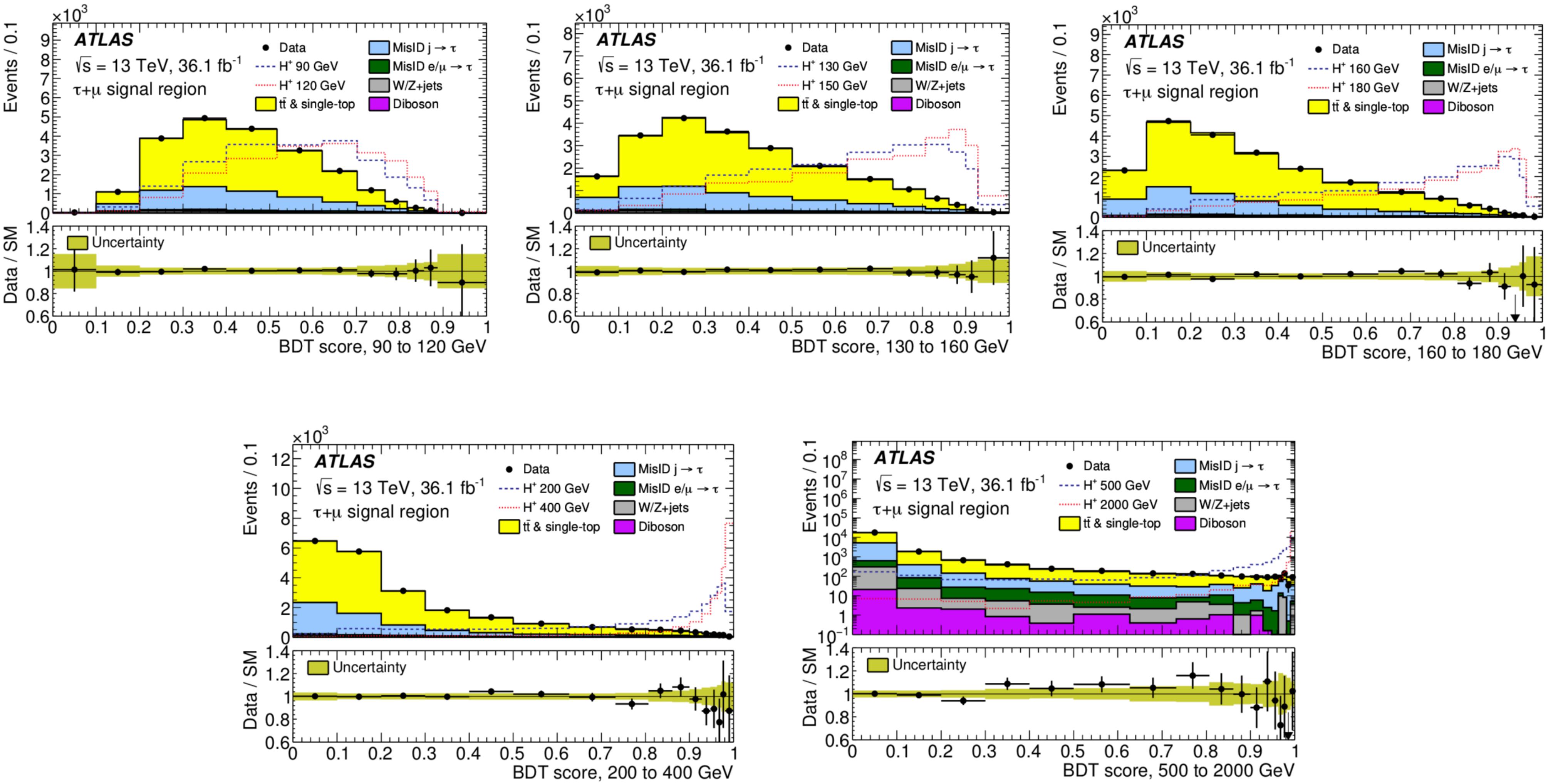


ATLAS search (Jul 2018): $H^+ \to \tau\nu$ produced with top quark

- τ_h + jets (inc. b tag)
- τ_h + lepton + jets (inc. b tag)

- form BDT discriminant

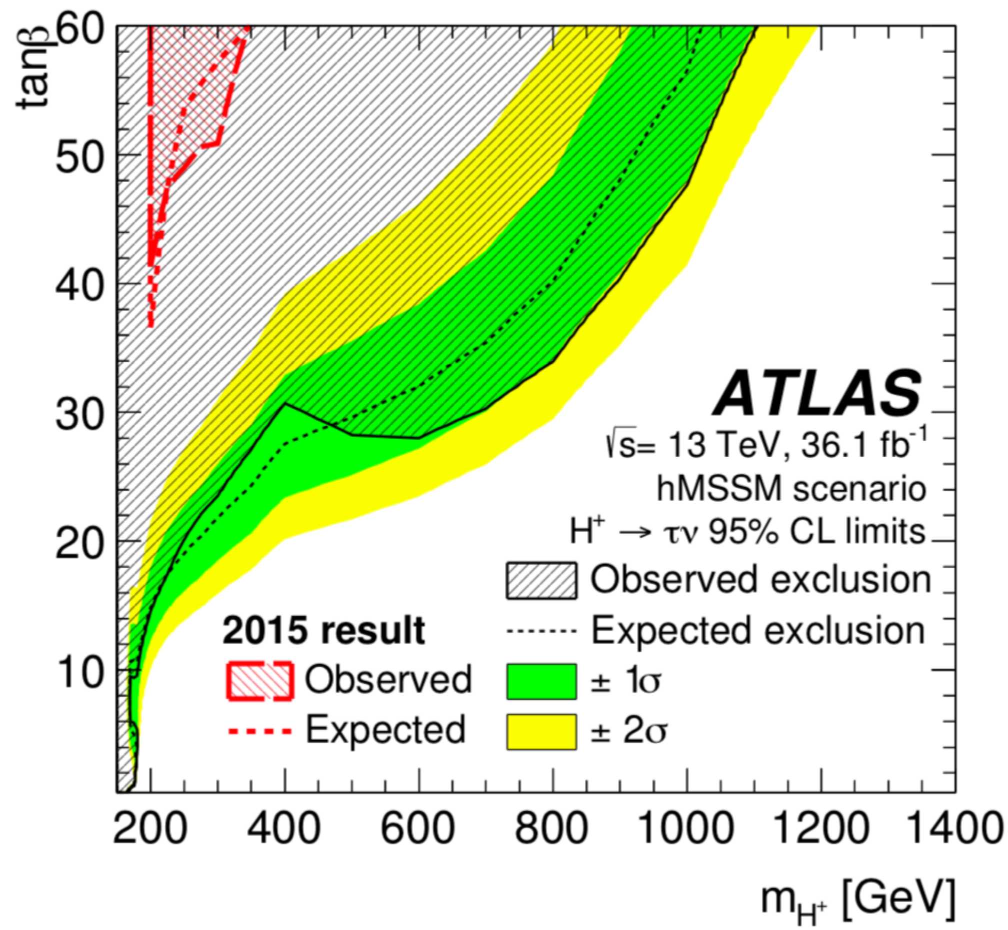
Charged Higgs in SUSY/2HDM scenarios



Charged Higgs in SUSY/2HDM scenarios

Bottom line: no excess observed, set limits in the plane of tanβ versus m_A

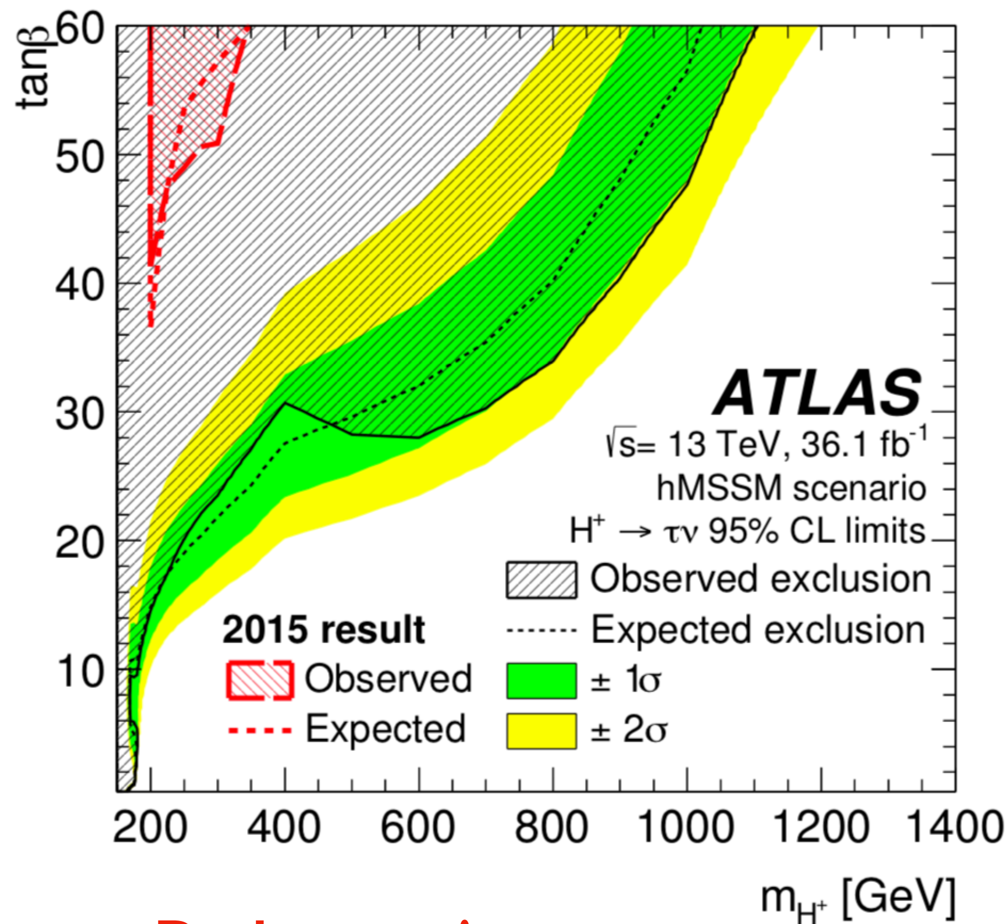
Dramatic improvement over Run 1



Charged Higgs in SUSY/2HDM scenarios

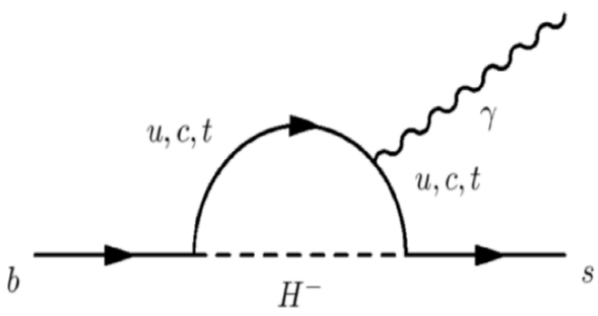
Bottom line: no excess observed, set limits in the plane of tanβ versus m_A

Dramatic improvement over Run 1

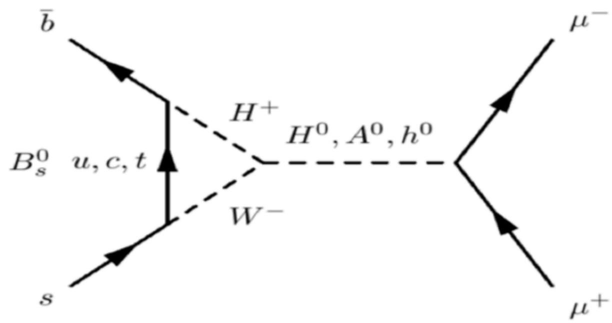


However…constraints from B decays!

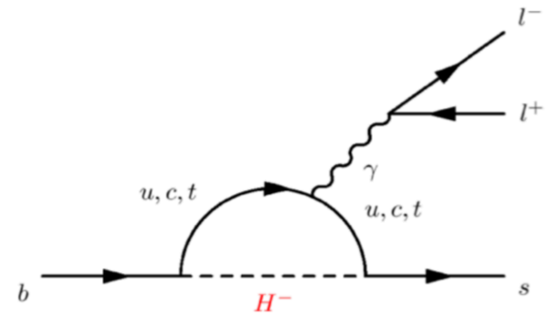
BSM Higgs has an effect on B meson decay:



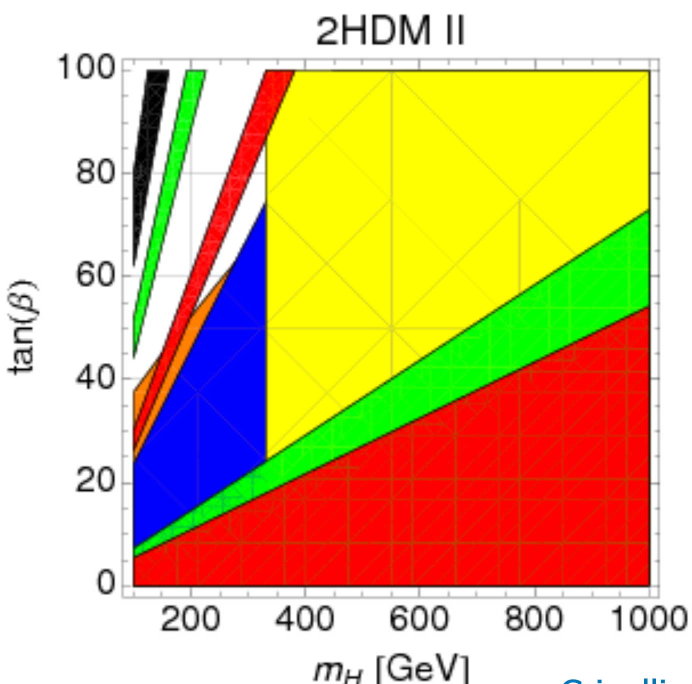
(a) $b \to s\,\gamma$



(b) $B_s \to \mu^+\,\mu^-$



(c) $B \to K^*\mu^+\mu-$



I'm not an expert here…but rare B decays seem to rule out a great deal if not all 2HDM space!

Crivellin, Andreas et al. Phys.Rev. D87 (2013) no.9, 094031 arXiv:1303.5877 [hep-ph]

Highlighted just two BSM searches here…there are many more!

- nMSSM: light pseudoscalars in the < 60 GeV range? $H \rightarrow aa$
- Higgs+DM production: EFT searches in multiple channels
- New heavy vector bosons, vector-like quarks with Higgs decays
- LFV Higgs decays
- invisible Higgs decays

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- nMSSM: light pseudoscalars in the < 60 GeV range? $H \to aa$
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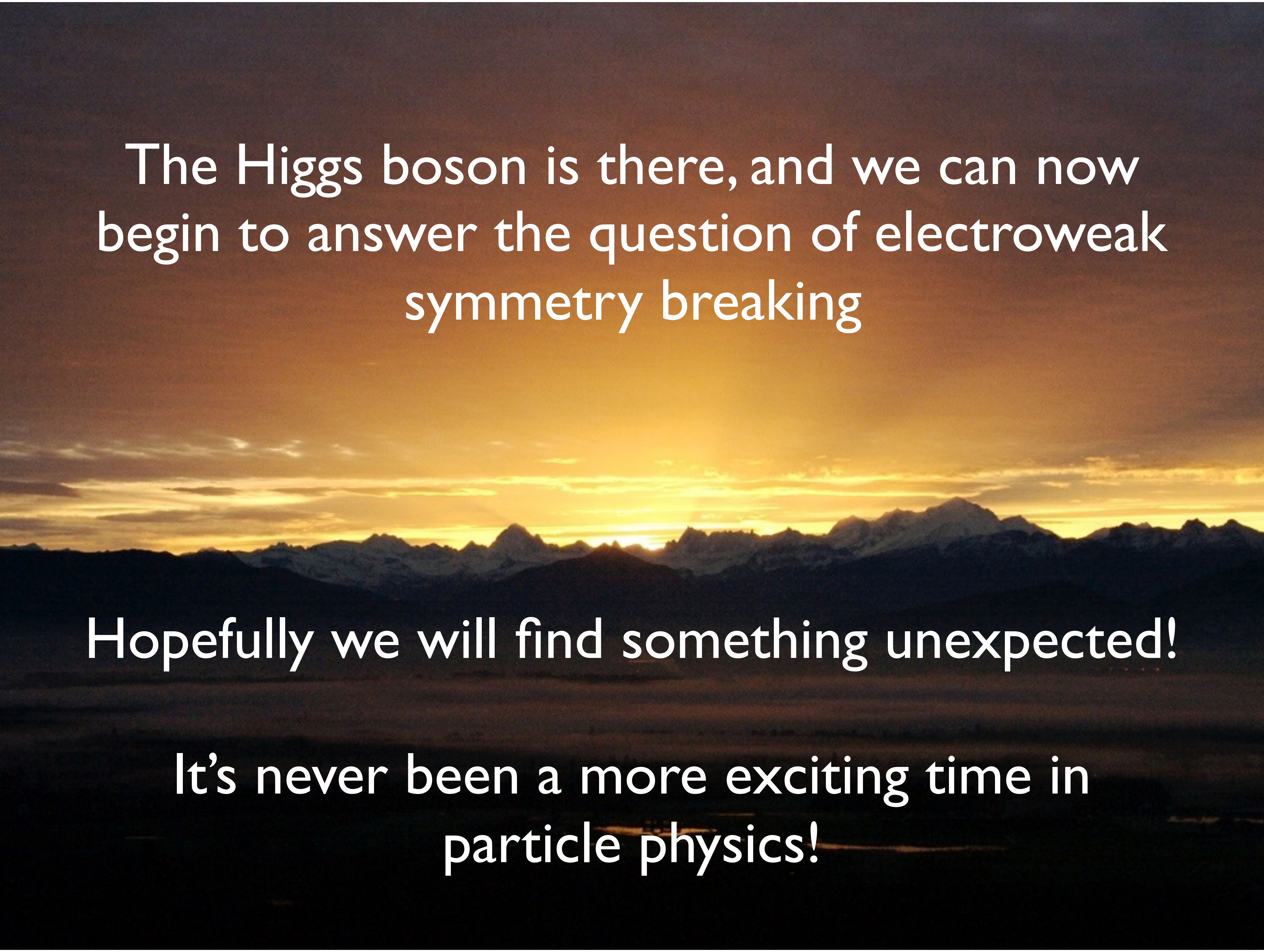
BSM Higgs searches are statistics-limited: stay tuned for Run 3 and HL-LHC!


The Higgs boson is there, and we can now begin to answer the question of electroweak symmetry breaking
Hopefully we will find something unexpected!
It’s never been a more exciting time in particle physics!