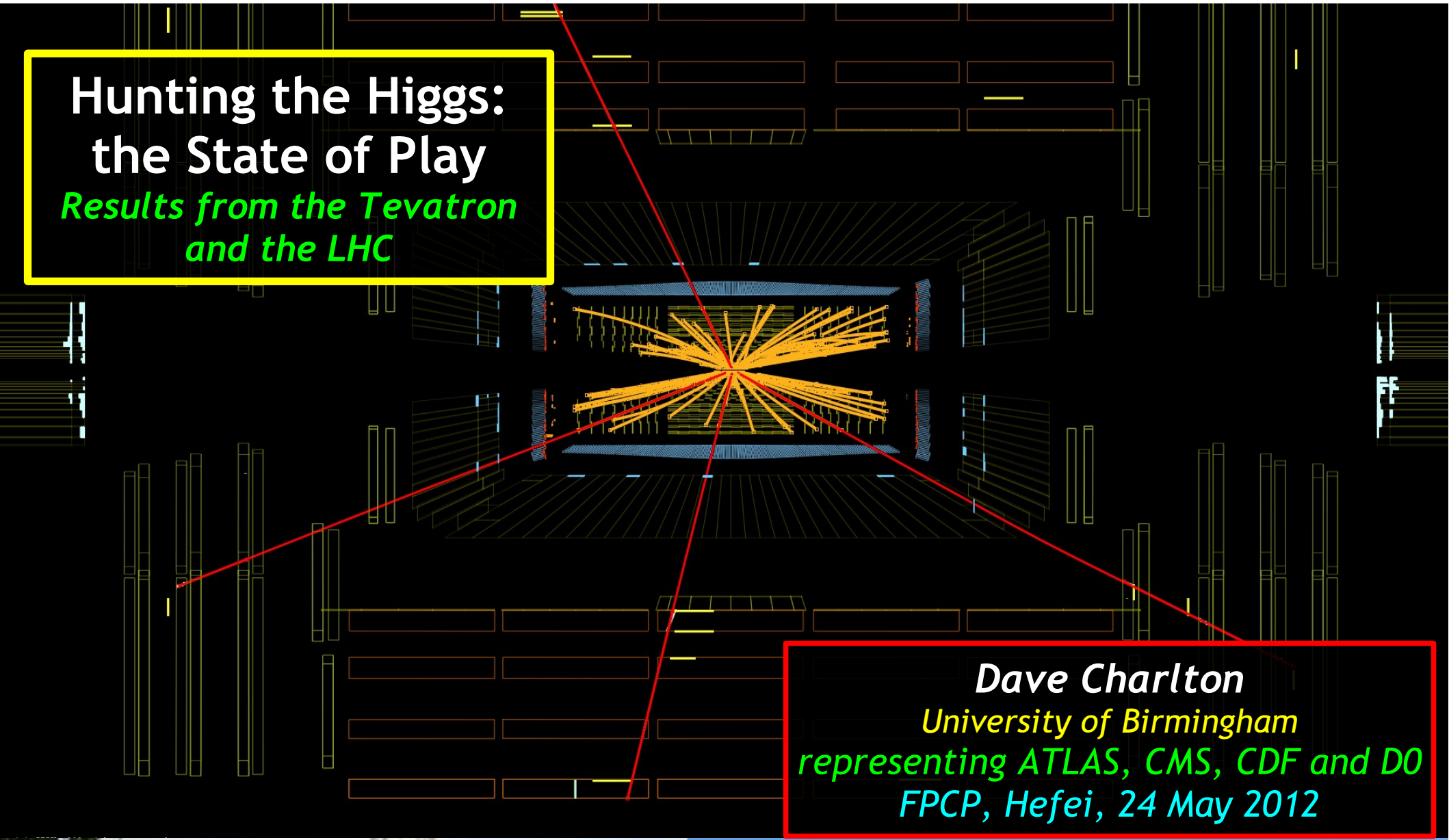
Hunting the Higgs: the State of Play

Results from the Tevatron and the LHC



Dave Charlton

University of Birmingham

representing ATLAS, CMS, CDF and D0

FPCP, Hefei, 24 May 2012

CDF HIGGS PAGE

Welcome | Results | Plain English | Published | Graphics | Links | Milestones

MISSING PARTICLE:

Name: Higgs boson
Age: 13.7 billion years
Missing: 45 years
Birthday: Every few days at Fermilab
Favorite trait: Mass
Favorite particle: top quark
Favorite Hangout: Tevatron

I've no time to cover non-Standard Model Higgs searches, of which there are many...

- H in 4th generation model
- Fermiophobic H
- MSSM $H \to \tau^+\tau^-$
- MSSM $H^\pm \to \tau^\pm \nu$
- $H^{++} \to \ell^+\ell^+$
- NMSSM $a^0 \to \mu^+\mu^-$
- Hidden-valley Higgs
- And more...

PHYSICS

Higgs Physics Results

Preliminary, submitted or published Run II results of Higgs searches as well as SM and non-SM heavy flavor production in association of a W or Z boson. *Other search results can be found* ... Figures can be found in the same directory as the paper. Please contact Conveners if you have questions.

Archival listings of all Preliminary Results & Submitted/Accepted Papers are also available

Standard Model Higgs Boson Production with up to 10 fb-1 of Data 03/05/12, up to 10 fb-1 NEW
Model Higgs Boson from the D0 experiment in up to 9.7 fb-1 of Data 03/05/12, up to 9.7 fb-1 NEW
nt of WZ and ZZ production in final states with b-tagged jets 03/05/12, 7.5-9.5 fb-1 NEW
Production VH --> e+- nu- e mu+- nu- mu with Like Charged Electron Muon pairs using 9.7 fb-1 of ppbar Collisions at sqrt(s) = 1.96 TeV 03/05/12,
in dilepton plus missing transverse energy final states with 8.6-9.7 fb-1 of ppbar collisions at sqrt(s)=1.96 TeV 03/05/12, 8.6-9.7 fb-1 NEW
es with lepton, missing energy and at least two jets using b-jet identification in 9.7 fb-1 of Tevatron data 03/05/12, 9.7 fb-1 NEW
.7 fb-1 of ppbar collisions 03/05/12, 9.7 fb-1 NEW
s boson in the ZH-->vbb channel in Run II data 03/05/12, 9.5 fb-1 NEW
oson in the tau tau mu + X final state in 7.0 fb-1 of ppbar collisions at sqrt(s) = 1.96 TeV 02/29/12, 7.0 fb-1 NEW
oson with trileptons and missing transverse energy with 9.7 fb-1 of ppbar collisions at sqrt(s) = 1.96 TeV 02/28/12, 9.7 fb-1 NEW
oson in the di-photon final state using using 9.7 fb-1 of D0 data 02/28/12, 9.7 fb-1 NEW
s Boson in gammagamma + X final states at D0 using 9.7 fb-1 data 02/28/12, 9.7 fb-1 NEW
n final states with b-tagged jets 11/15/11, 7.5-8.4 fb-1 NEW
Fermiophobic Higgs Boson Production with up to 8.2 fb-1 of data 09/01/11, up to 8.2 fb-1

CMS Higgs Physics Results

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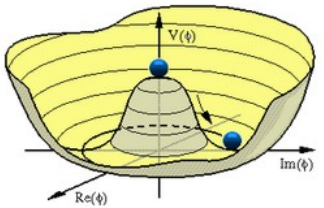


- Publications
  - Publications 2011 data, part 1
  - Publications 2010 data
- Preliminary -- Plots and Results
  - Preliminary 2011 data for Moriond 2012
  - Preliminary 2011 data for ATLAS/CMS Jamboree (Dec 13)
  - Preliminary 2011 data for HCP Conference
  - Preliminary 2011 data for SUSY11
  - Preliminary 2011 data for Lepton-Photon
  - Preliminary 2011 data for EPS
  - Preliminary 2010 data for Moriond 2011
  - MC Based Analyses
- Publications

Publications

Publications 2011 data, part 1

ATLAS

Higgs Public Results

Convenors: Sandra Kortner and Eilam Gross

- Summary of latest results in all channels
- Higgs boson production and decays
- Explantory figures for exclusion plots
- Simulation-based projections for runs at 7 TeV and 8 TeV
- Public documents in historical order
  - Data 2012
    - Post-Moriond 2012 publications (full 2011 dataset)
    - Moriond EW 2012
    - February 2012 Pub
  - Data 2011
    - CERN Council 201
    - HCP 2011
    - LP 2011
    - EPS and more 201
    - Moriond-timescale
  - MC 2011
  - Data 2010
  - MC 2010
  - Material before 2010

Summary of latest res

Channel	Confere						
SM H combination	ATLAS-C						
SM H to diphoton	ATLAS-C						
SM H to ZZ(*) to 4l	ATLAS-CONF-2011-162	4.8	Dec 2011	arXiv:1202.1415	4.8	Feb 2012	
SM H to WW(*) to lvlv	ATLAS-CONF-2012-012	4.7	Mar 2012	arXiv:1112.2577	2.05	Dec 2011	

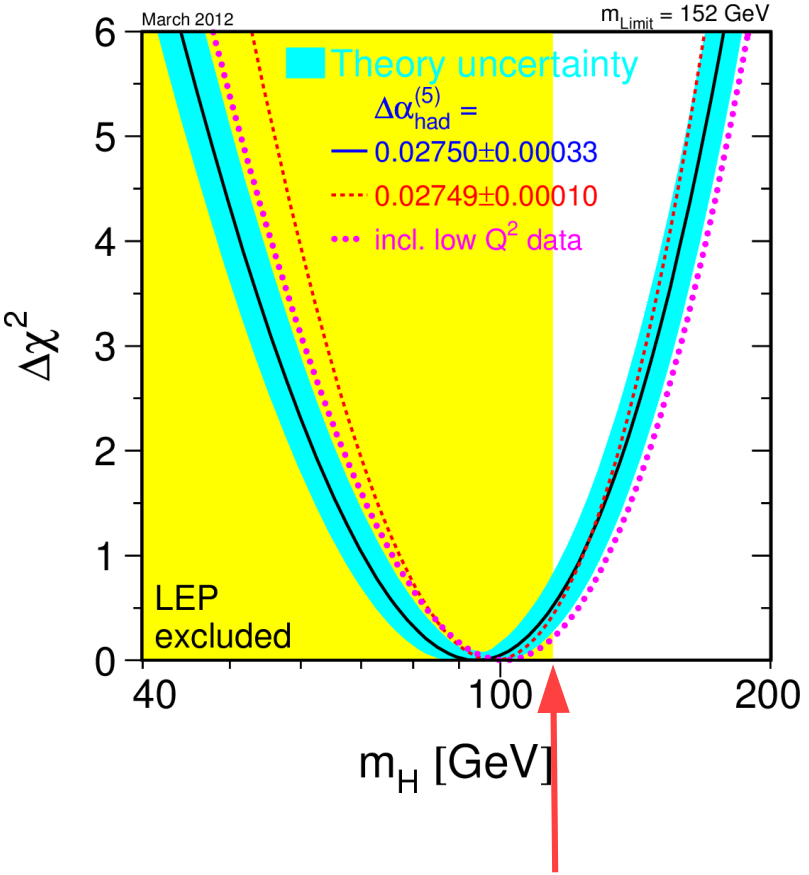
More Information...

http://www-cdf.fnal.gov/physics/new/hdg/Welcome.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_12/
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

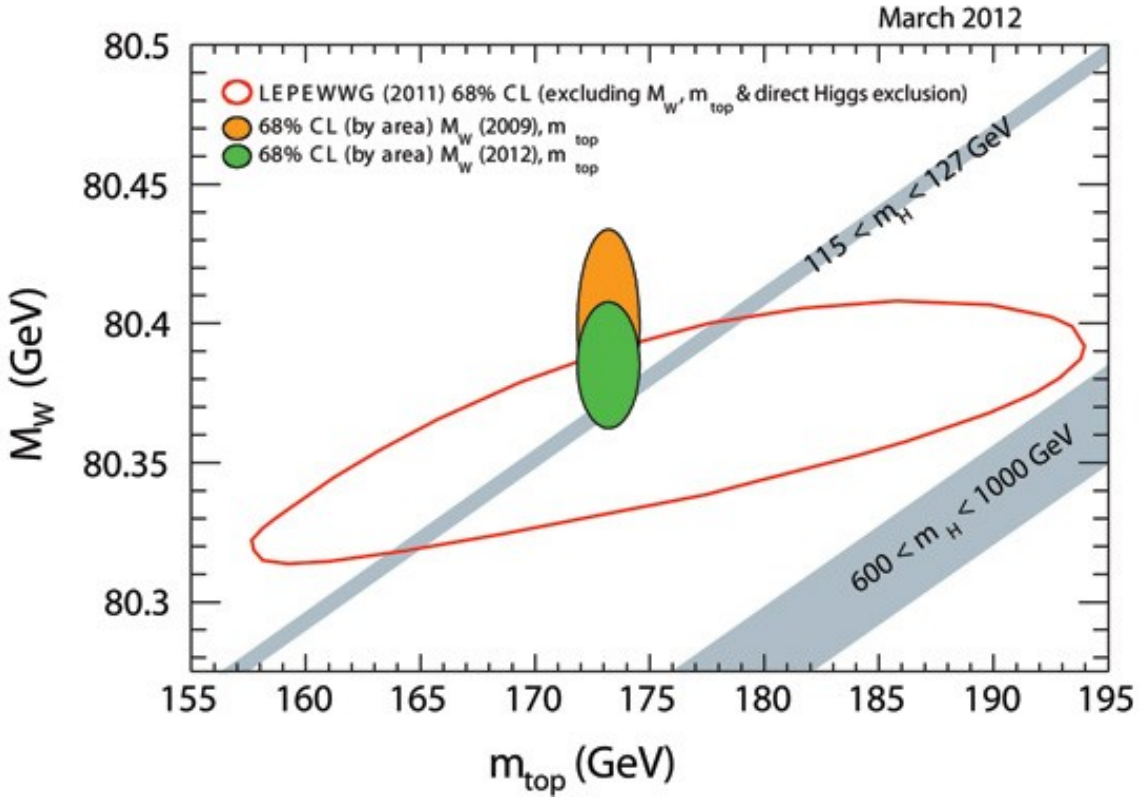
Precision Electroweak Measurements

LEP, SLD, CDF/D0 and lower energy experiments

Sensitive to m_H via radiative corrections



LEP direct search:
m_H>114.4 GeV at 95% CL



New high-precision m_W measurements from CDF/D0

→ new world-average

arXiv:1204.0042

m_W = 80.385 ± 0.015 GeV

SM prediction from precision EW fit suggests
m_H < 152 GeV at 95% CL
relies on structure of SM radiative corrections

H Decays

Standard Model specifies decay branching ratios vs. m_H

At high mass (m_H > 160 GeV):

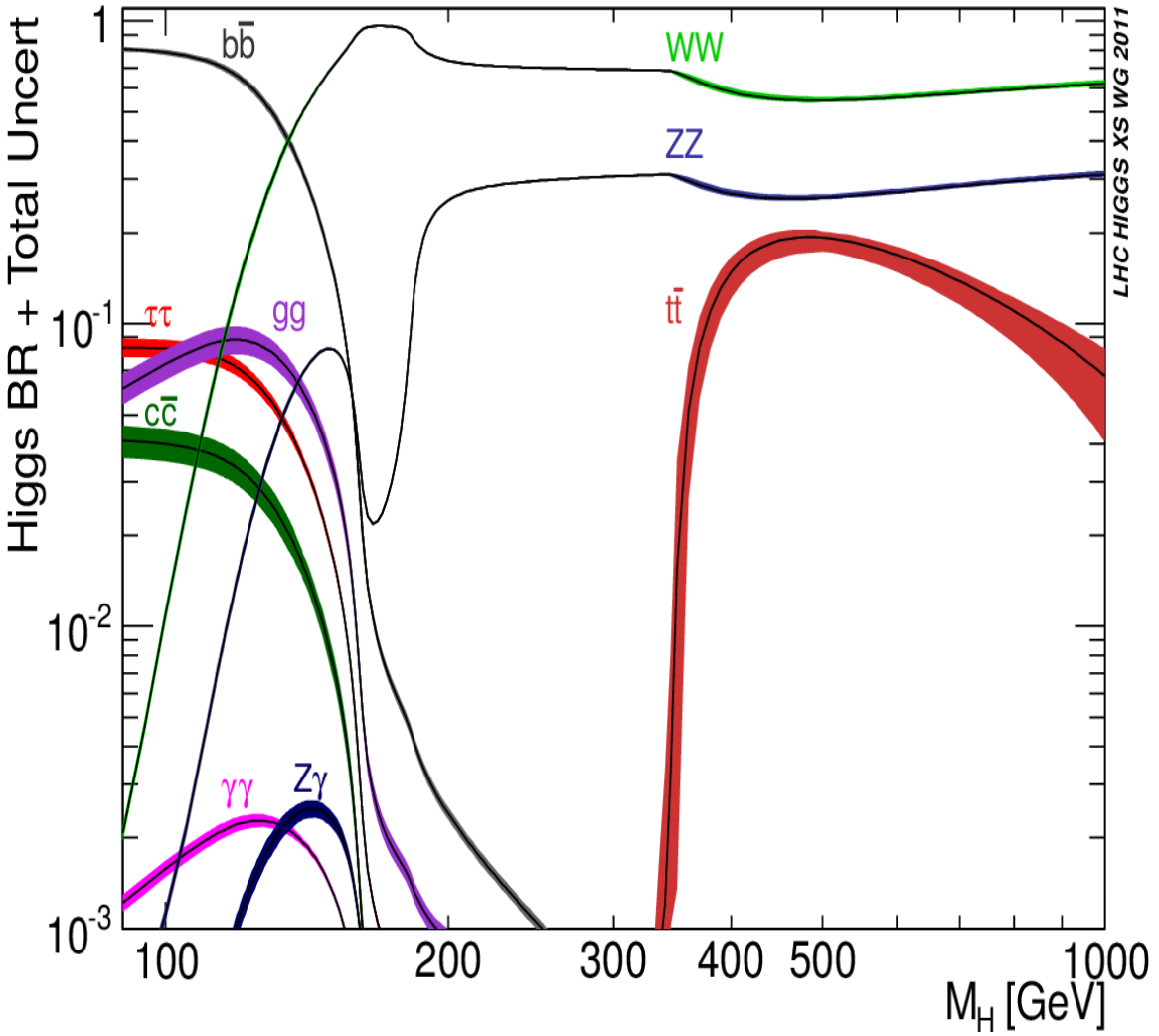
- $H \rightarrow W^+W^-$
- $H \rightarrow ZZ$

provide ~all the sensitivity, we subdivide by the W/Z decay modes

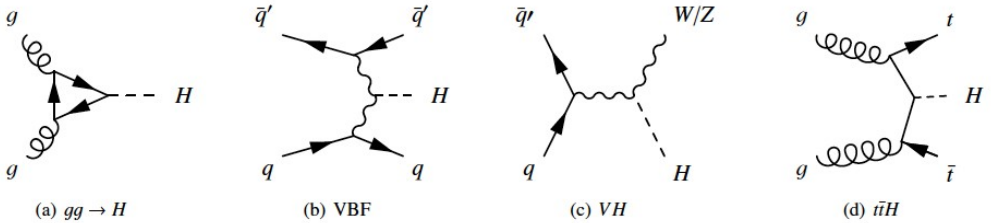
At low mass (m_H < 160 GeV):

- $H \rightarrow b\bar{b}$
- $H \rightarrow \tau^+\tau^-$
- $H \rightarrow \gamma\gamma$ *(BR < ~0.2%)*
- $H \rightarrow WW(*)$
- $H \rightarrow ZZ(*)$

all play a role...



H Production



Tevatron ($p\bar{p}$)

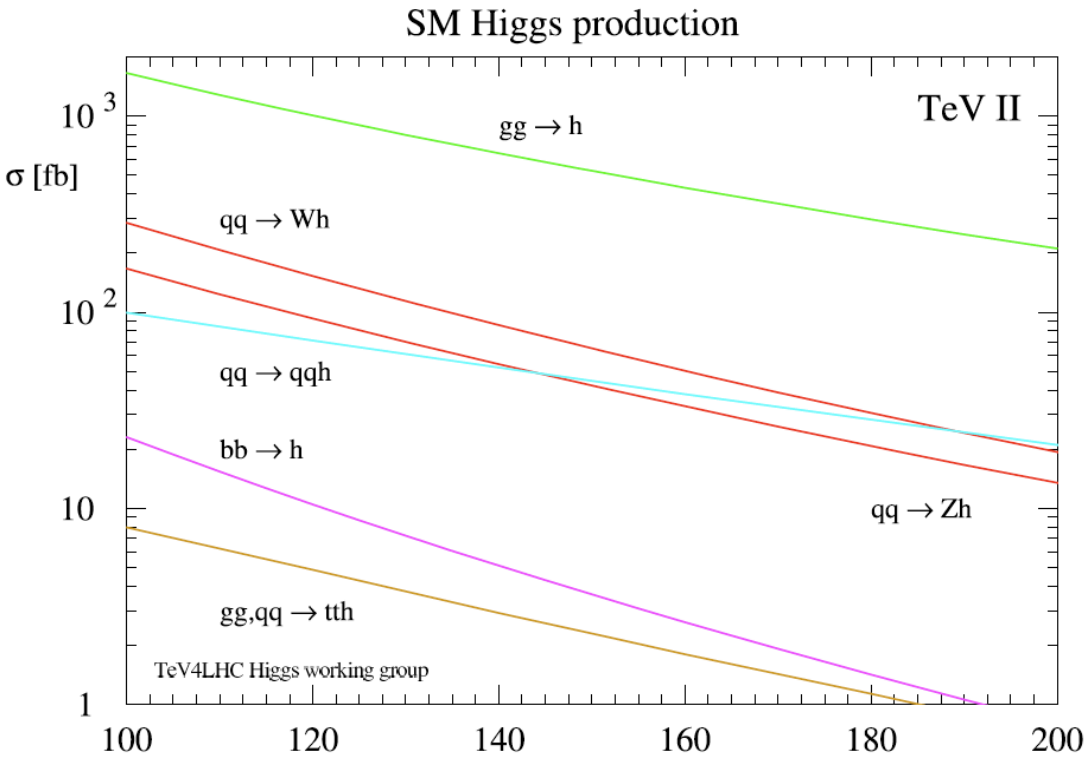
- Total σ_H~1 pb at m_H=120 GeV
- WH, ZH provide *lepton trigger* from W/Z, for bb decay modes

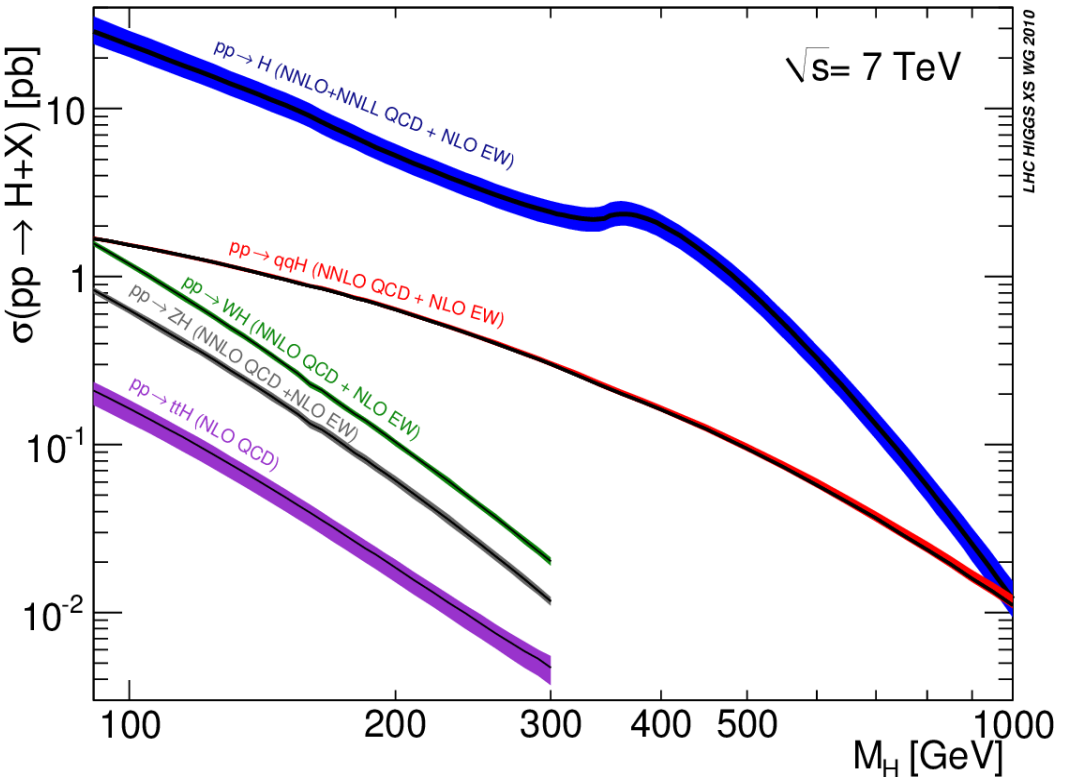
Reach limited to <200 GeV with 10 fb^{-1}

LHC (pp)

- Total σ_H~15 pb at m_H=120 GeV
- Relative importance of vector-boson fusion VBF and associated WH/ZH production swaps

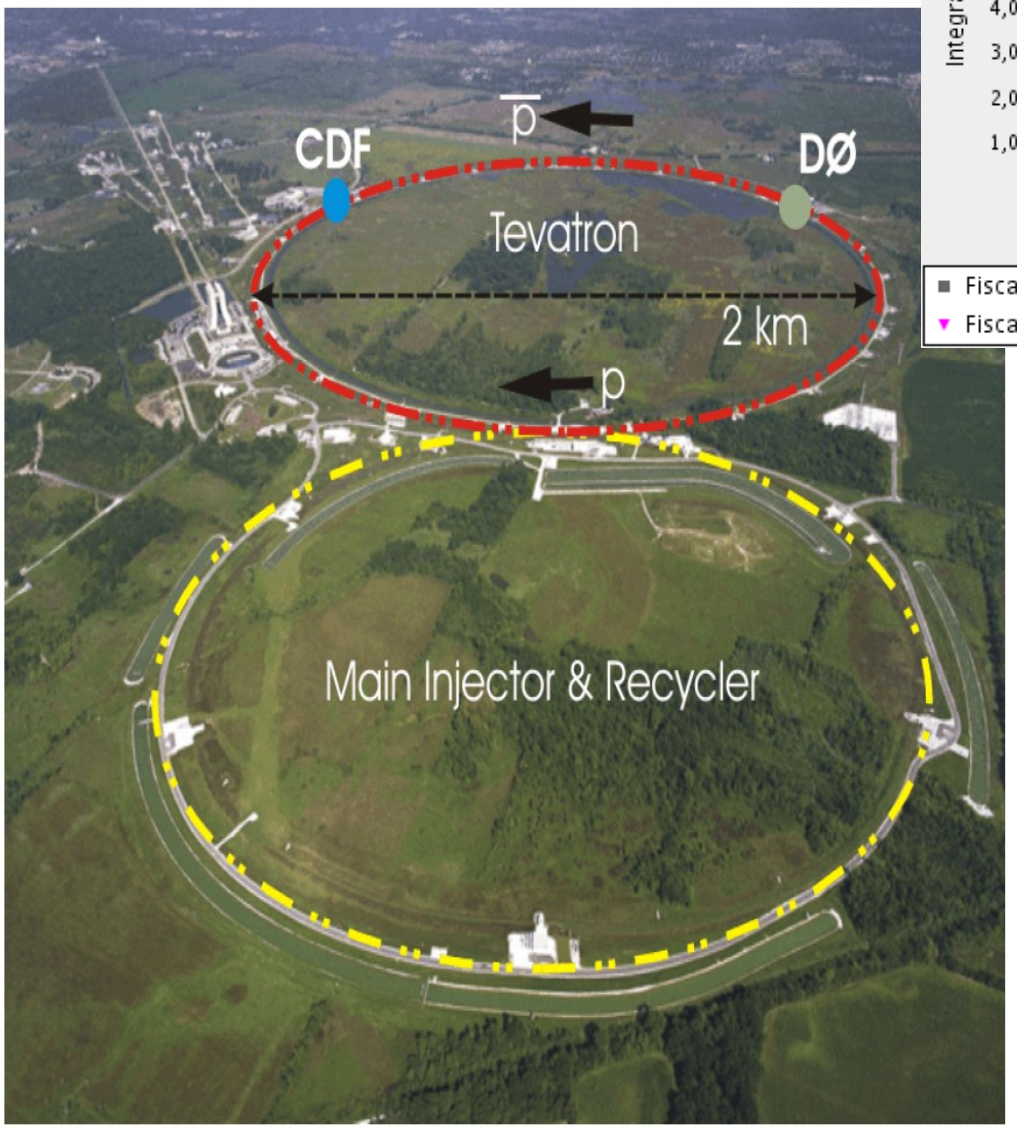
Reach over full mass range to 1 TeV

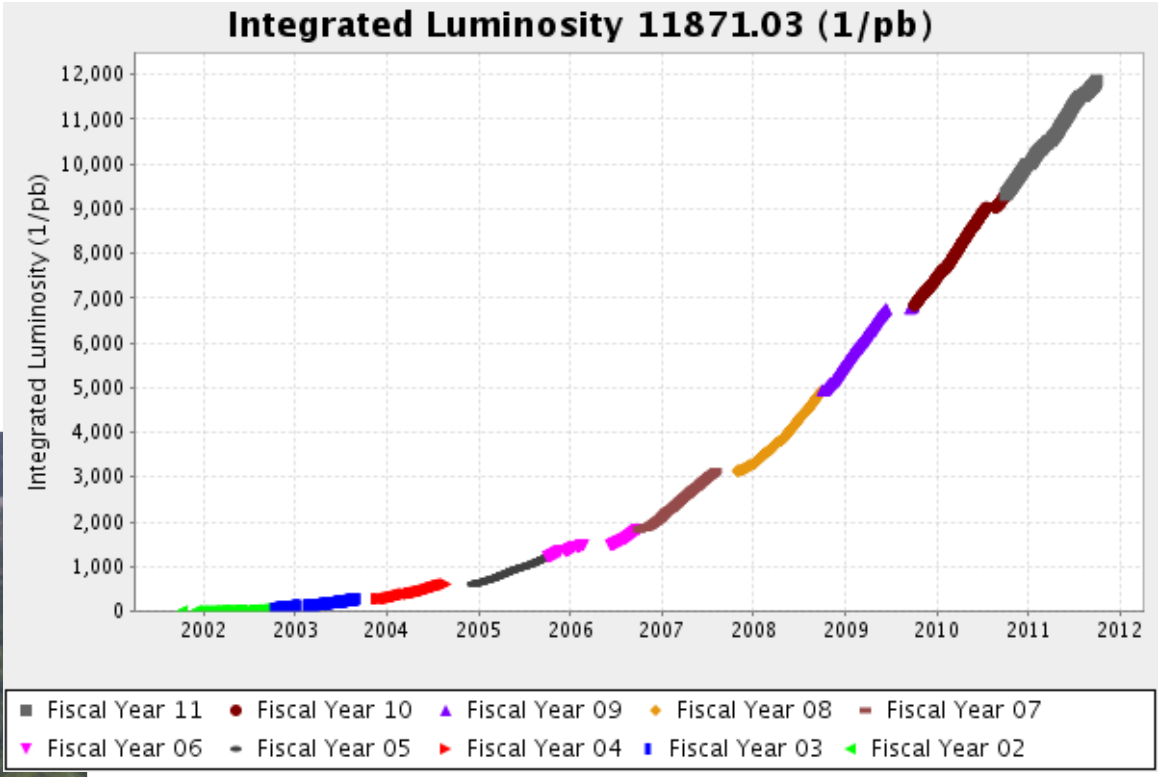




Tevatron Data Sample

Run-2 2001-2011
√s=1.96 TeV



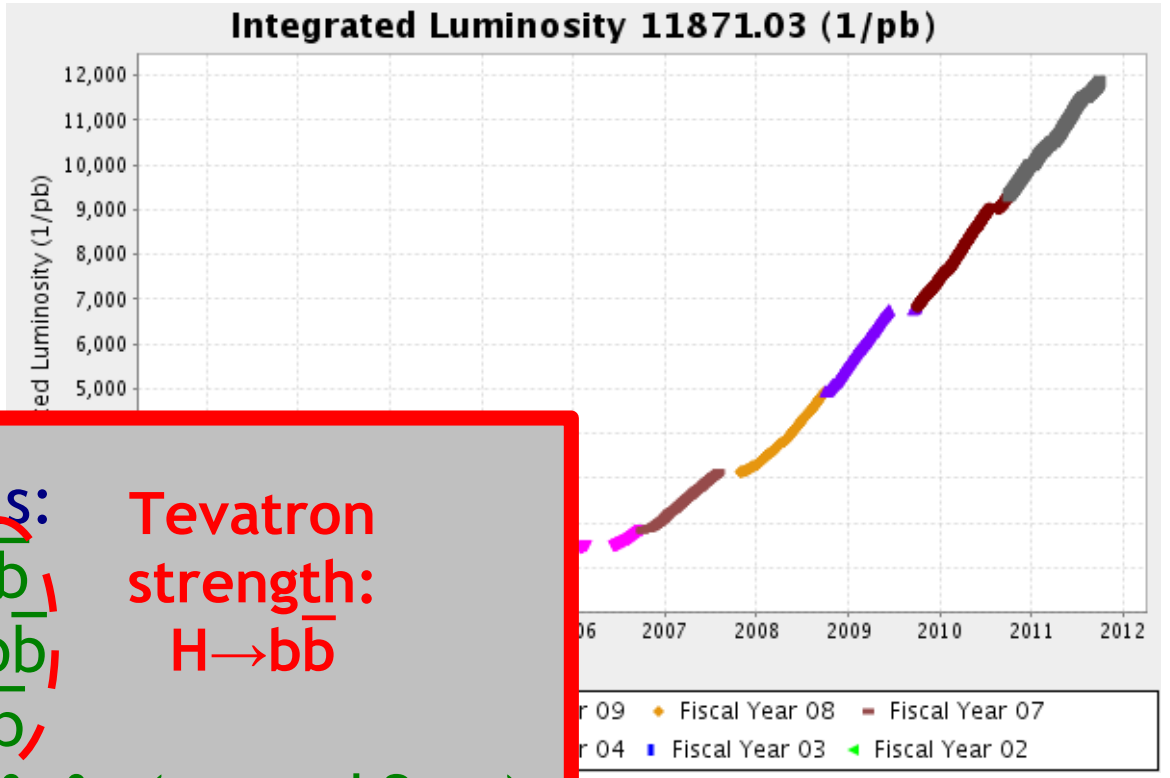


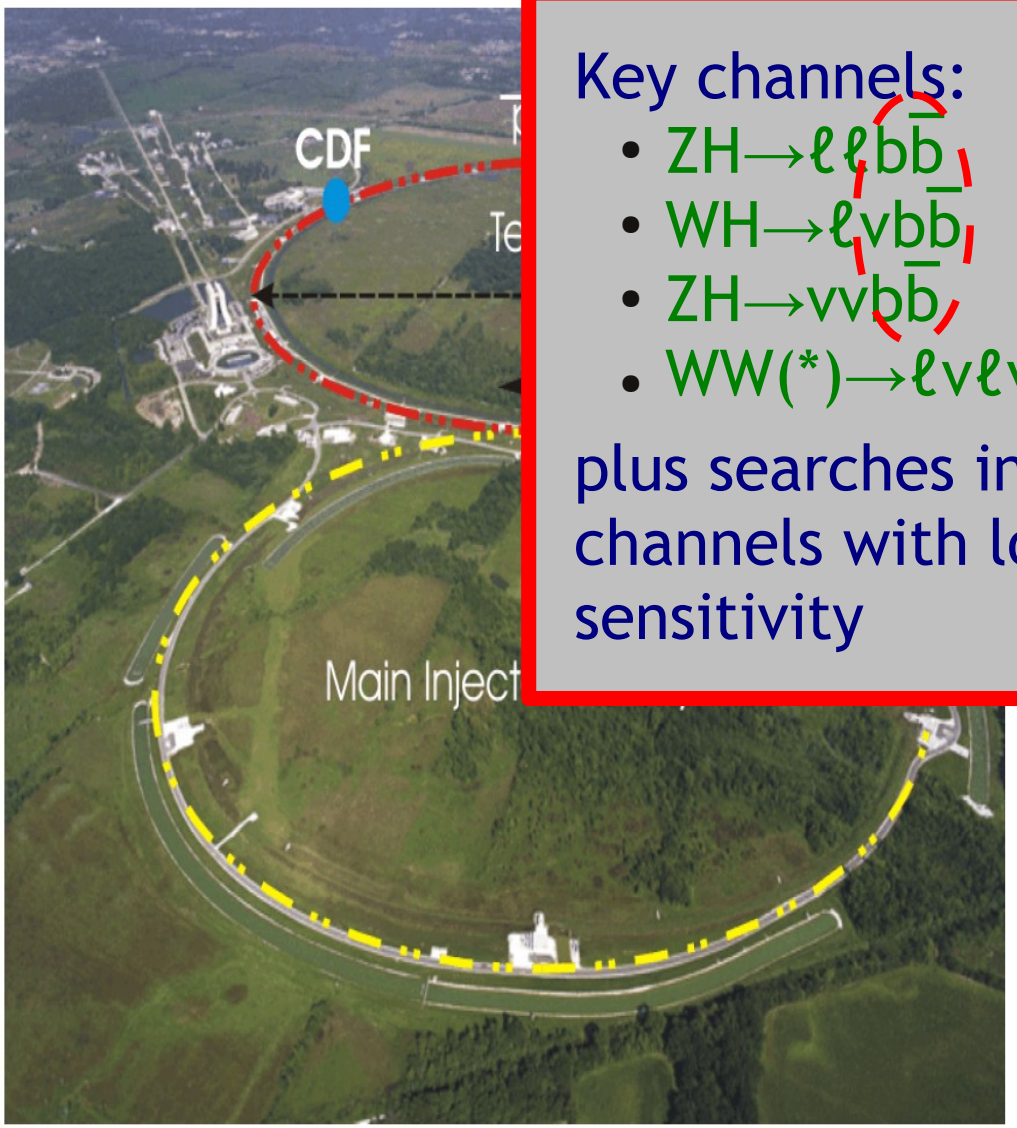
12 fb^{-1} delivered at 1.96 TeV
10-11 fb^{-1} recorded by CDF and D0

Peak luminosity 4.3 x 10^{32} $cm^{-2}s^{-1}$

Tevatron Data Sample

Run-2 2001-2011
$\sqrt{s}$=1.96 TeV





Key channels:

- $ZH \rightarrow \ell\ell b\bar{b}$
- $WH \rightarrow \ell\nu b\bar{b}$
- $ZH \rightarrow \nu\nu b\bar{b}$
- $WW(*) \rightarrow \ell\nu\ell\nu$ (around $2m_W$)

plus searches in many other channels with lower sensitivity

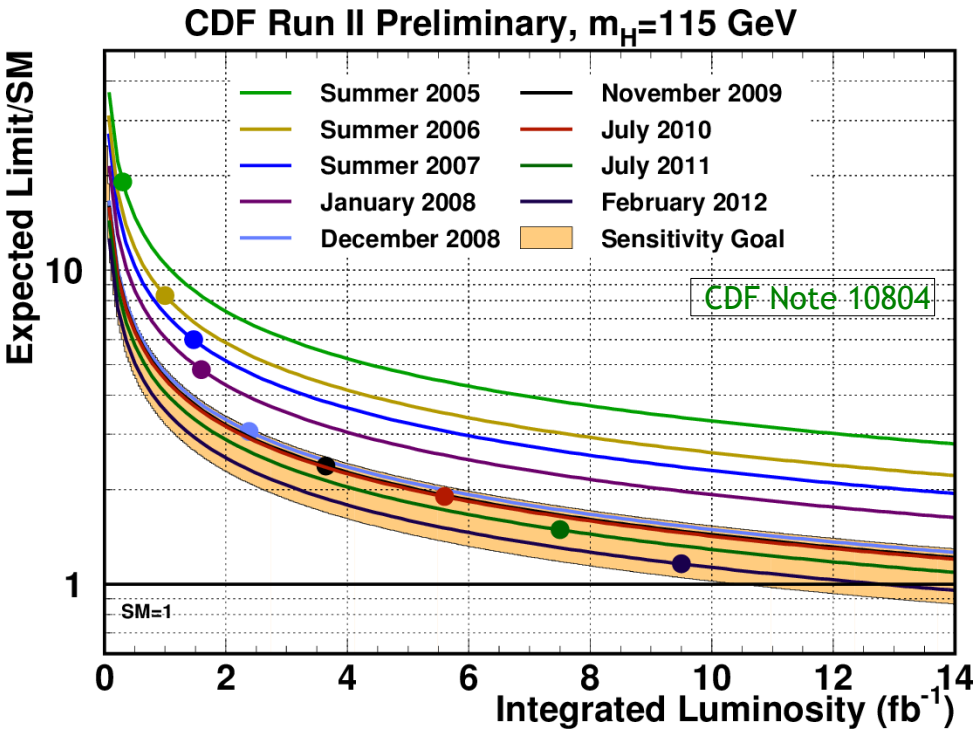
Tevatron strength:
$H \rightarrow b\bar{b}$

ered at 1.96 TeV
ded by CDF and D0

Peak luminosity 4.3 x 10^{32} $cm^{-2}s^{-1}$

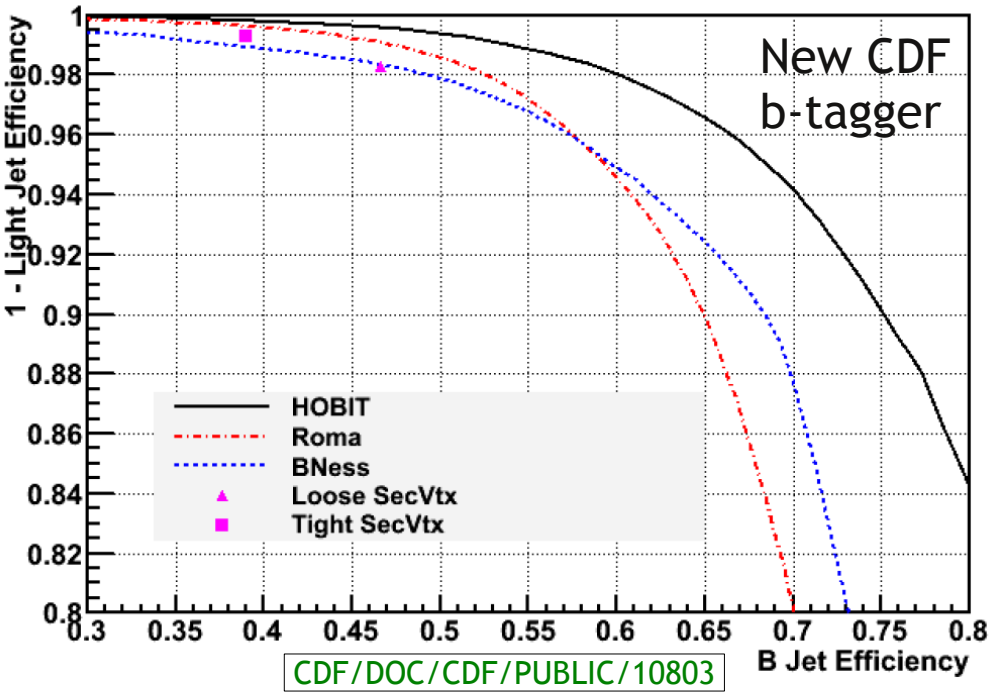
Tevatron H Search

Tevatron Higgs searches are well established, major improvements vs time have been delivered



For new 2012 results:

- Very high performance, optimised, b taggers
- b-jet specific energy scale corrections (CDF updated)
- Tuned and improved lepton ID, missing-E_T algorithms
- Multivariate discriminant analyses



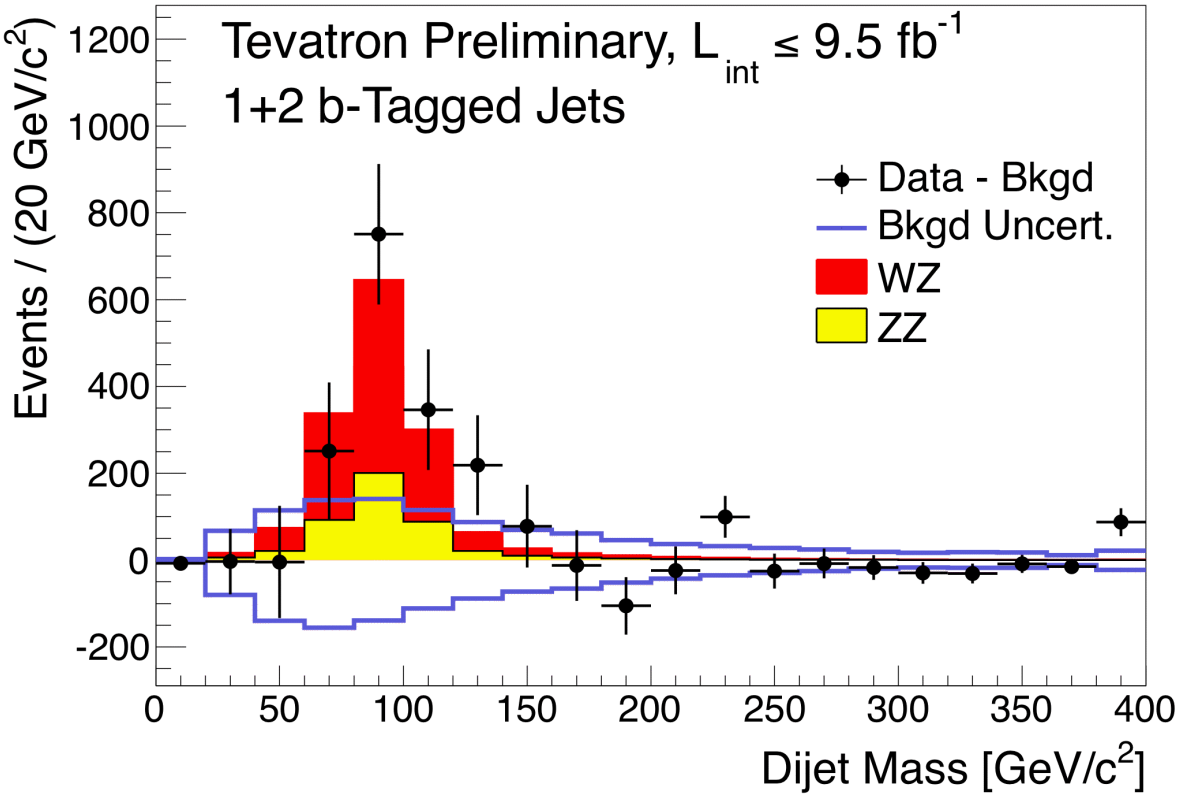
New CDF b-tagger gives 25-40% improvement in relative efficiency at same fake rate

Tevatron - Proof of Principle

arXiv:1203.3782

Measurement of WZ/ZZ production

- One leptonic W or Z decay
- Other $Z \rightarrow b\bar{b}$: use b-tagging algorithms as developed for the H search



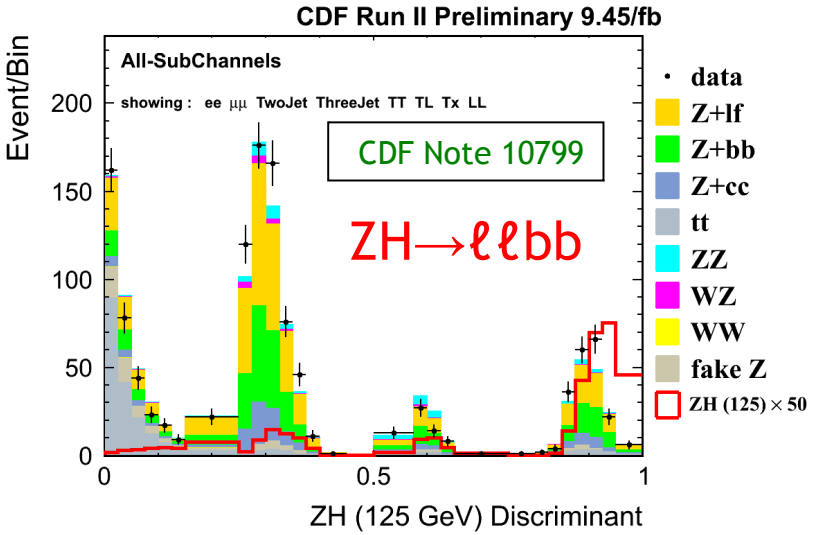
$\sigma(WZ+ZZ) = 4.47 \pm 0.64(stat) \pm 0.73(syst)$ pb

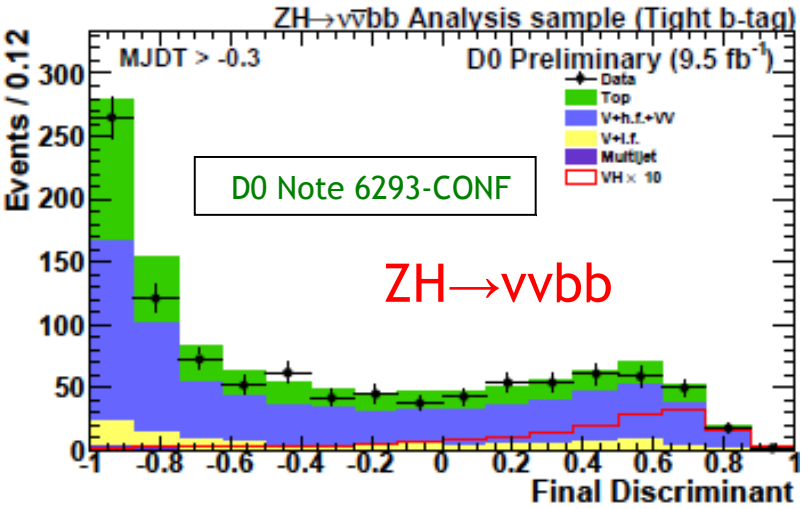
Cf: 4.4 ± 0.3 pb expected from SM

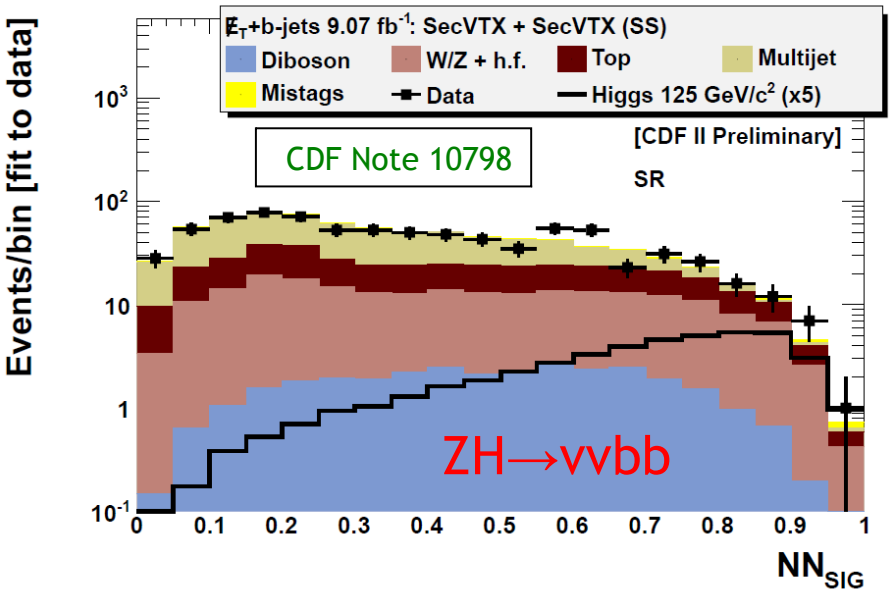
Significance is ~4.6σ from zero

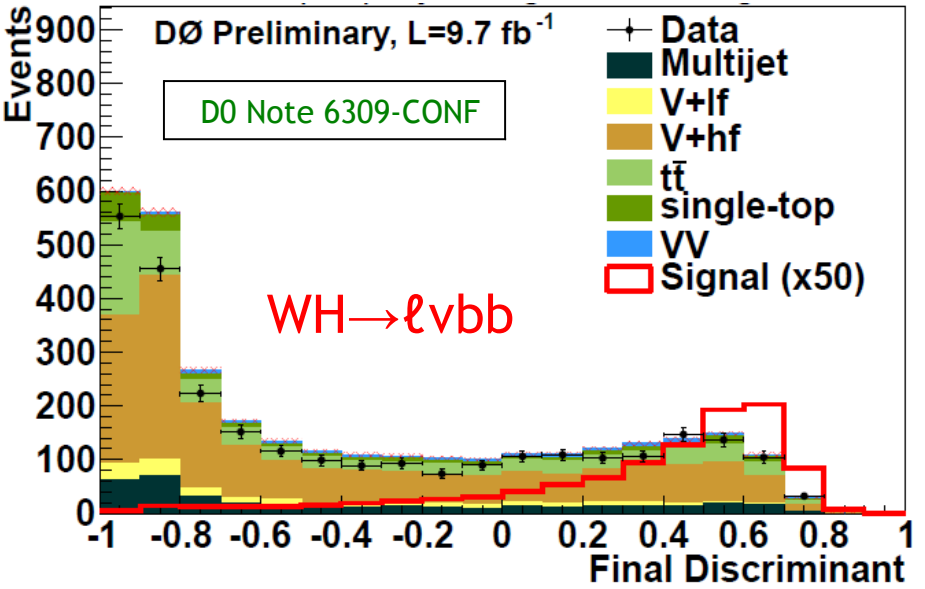
Tevatron - Discriminants

Analyses use highly-optimised multivariate analysis (MVA) discriminants to get the most from the data







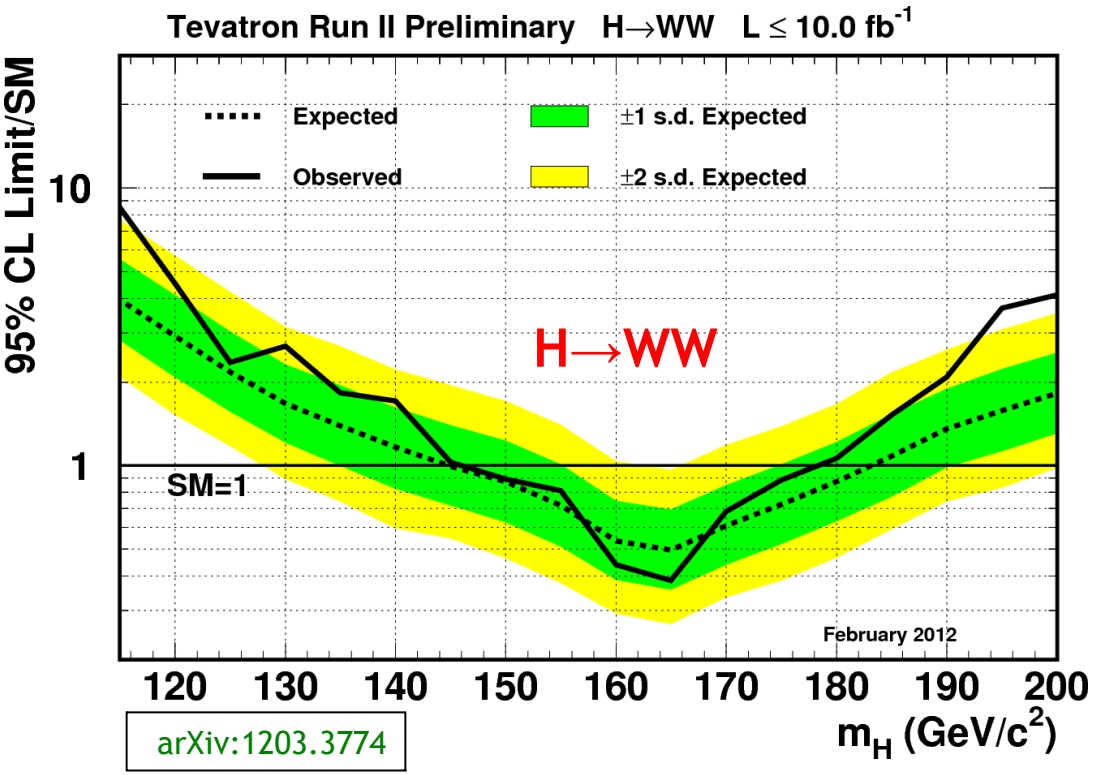


Main Channel Limits

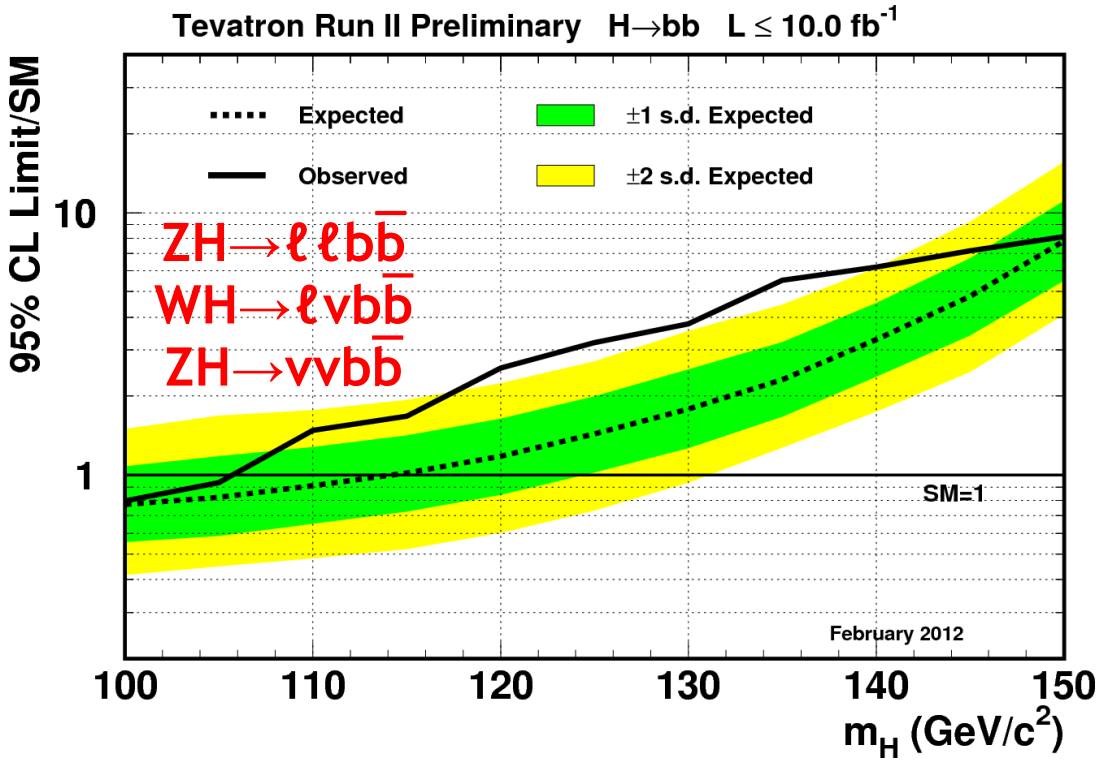
Combination of CDF & D0 includes detailed consideration of correlated errors, especially systematics

This page: combined subchannels and experiments for $b\bar{b}$ and WW analyses separately

"Broad excess" seen in $H \to b\bar{b}$ analysis, mainly from CDF



arXiv:1203.3774



Tevatron Combined

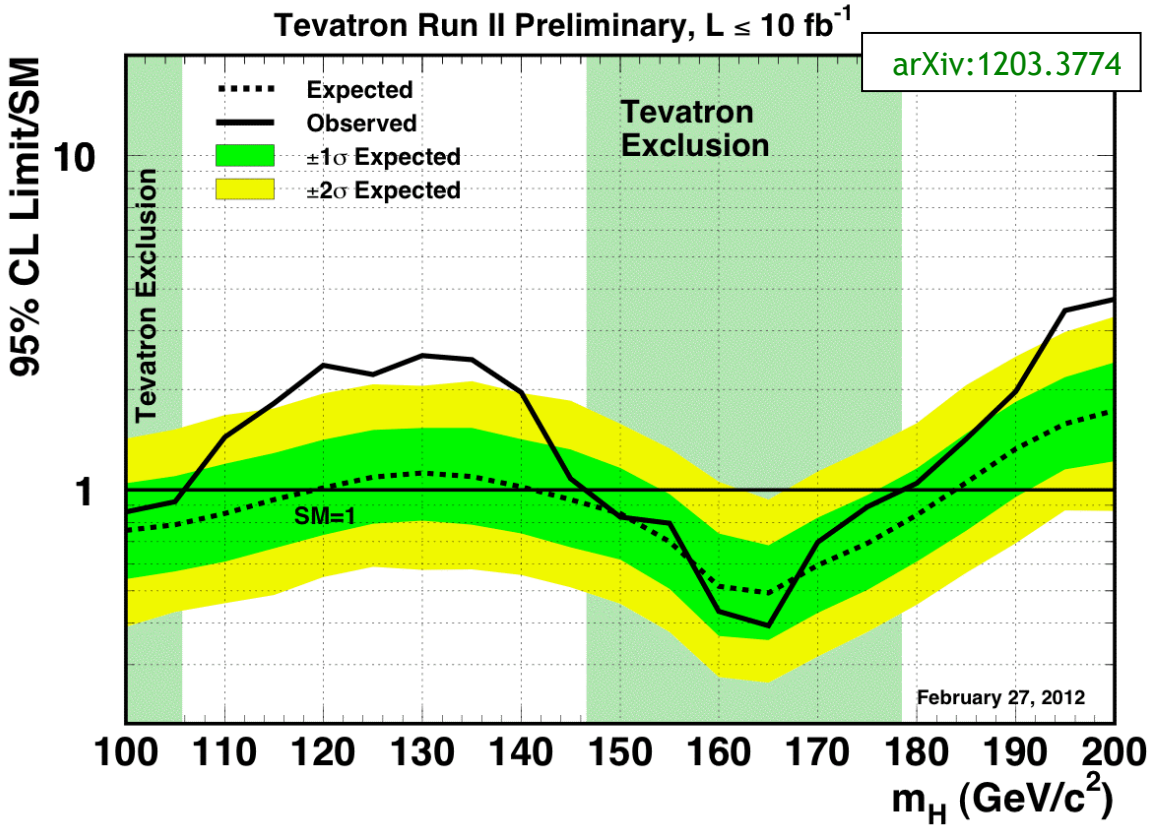
Putting all channels together...

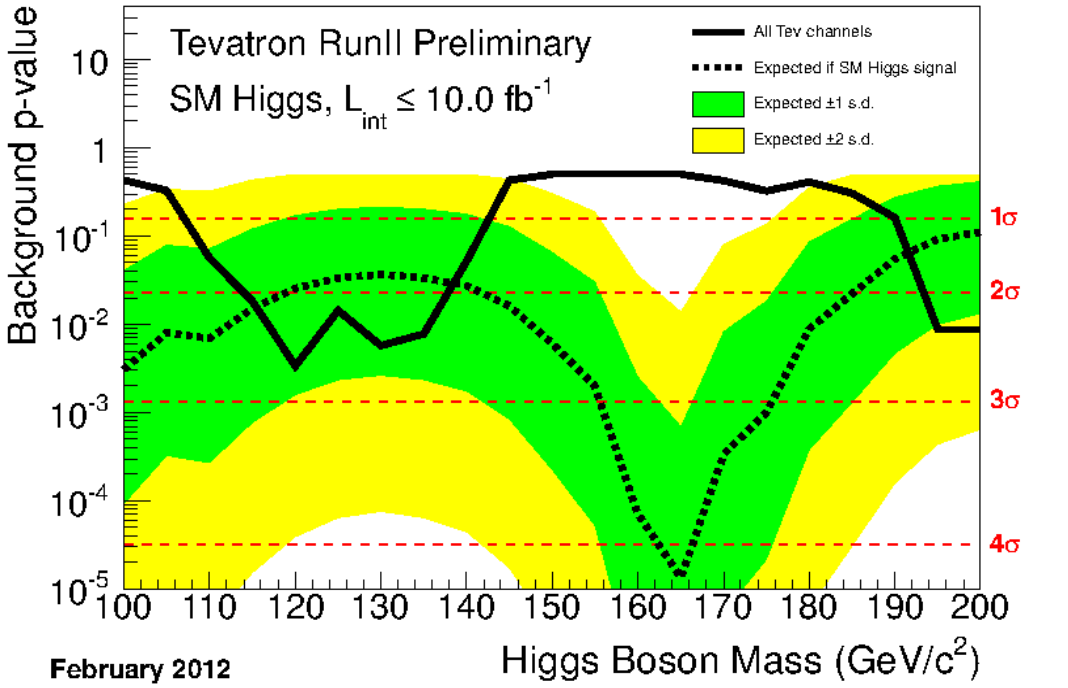
Expected 95% CL exclusion in the absence of a Higgs signal
$100 < m_H < 119$ GeV and
$141 < m_H < 184$ GeV

Actual exclusion at 95% CL
$100 < m_H < 106$ GeV and
$147 < m_H < 179$ GeV

Local p-value:
Probability that a background-only experiment is as signal-like as the data
Interpretation requires correcting for the *look-elsewhere effect* (LEE)

Max local significance: 2.7σ
Global significance after LEE (100-200 GeV range): 2.2σ



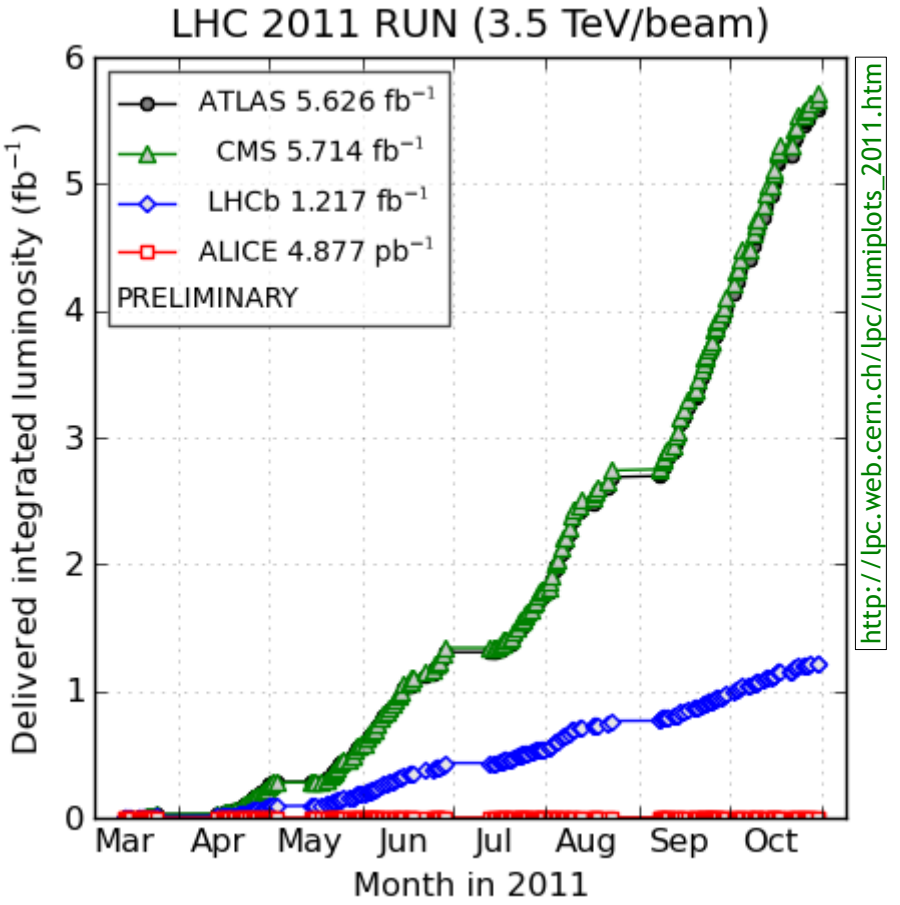


LHC Data Sample

2010/2011 $\sqrt{s}$=**7 TeV** limited by assessed risk of dipole magnet quenches *raised to **8 TeV** in 2012*

2010: ~0.04 fb^{-1} delivered to ATLAS, CMS

2011: initial goal 1 fb^{-1}, delivered by June
Total delivered close to 6 fb^{-1}
Superb LHC performance



ATLAS and CMS
- data-taking efficiencies ~90-94%
- data quality efficiencies ~90%
- ~5 fb^{-1} used for analyses shown here

2011 peak luminosity
3.6×10^{33} $cm^{-2}s^{-1}$

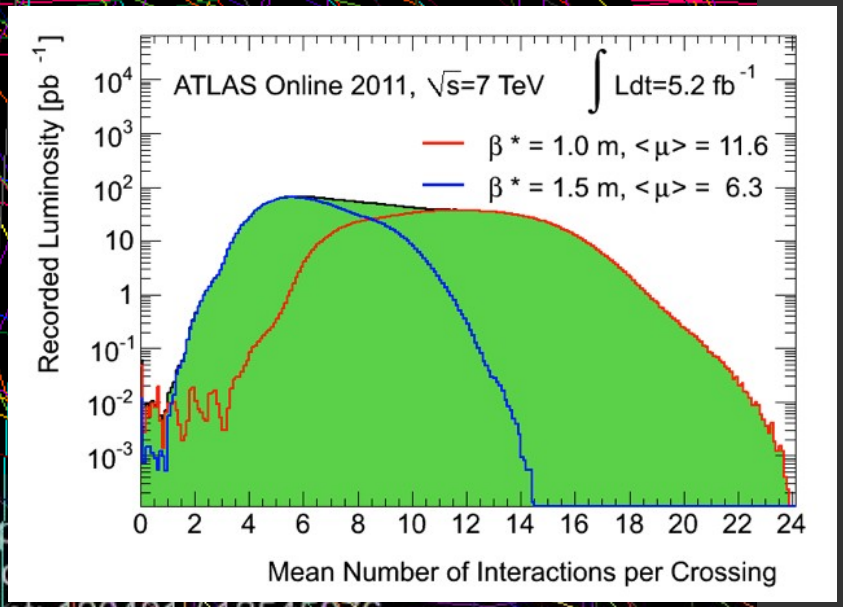
2012 is just starting, peak luminosity already reached 6.0×10^{33} $cm^{-2}s^{-1}$

Pileup

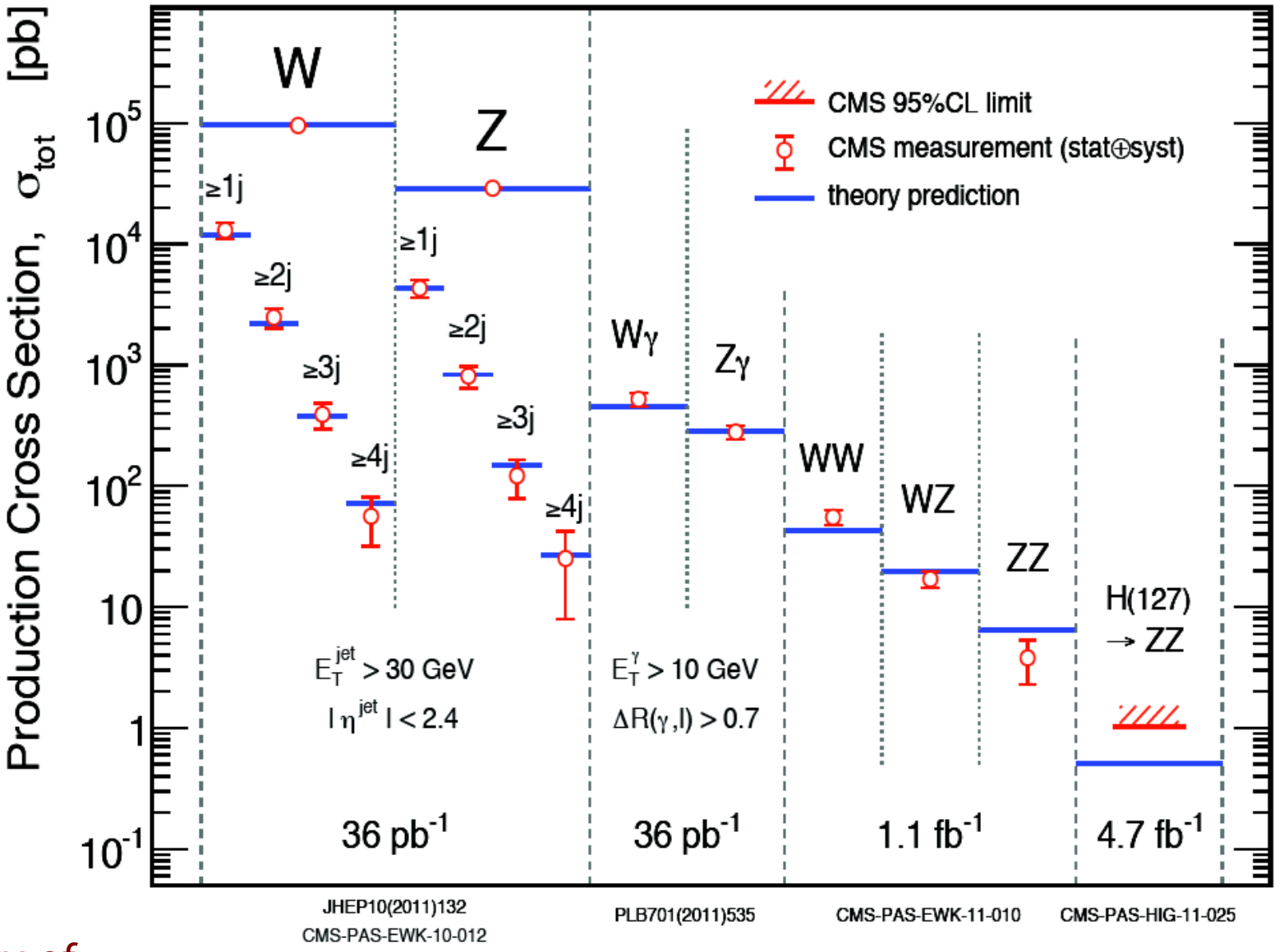
~10 interactions per bunch-crossing in 2011

Now ~20, expect up to ~30, in 2012

Event with 29 reconstructed vertices



Measuring other SM Processes



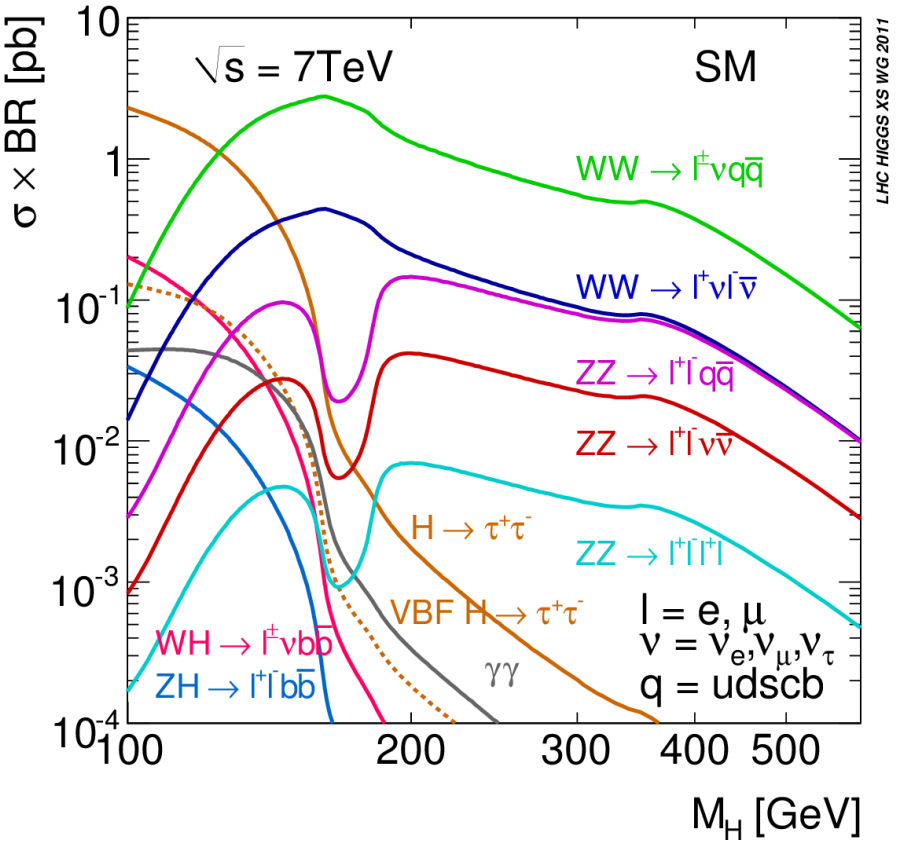
Illustrates quality of

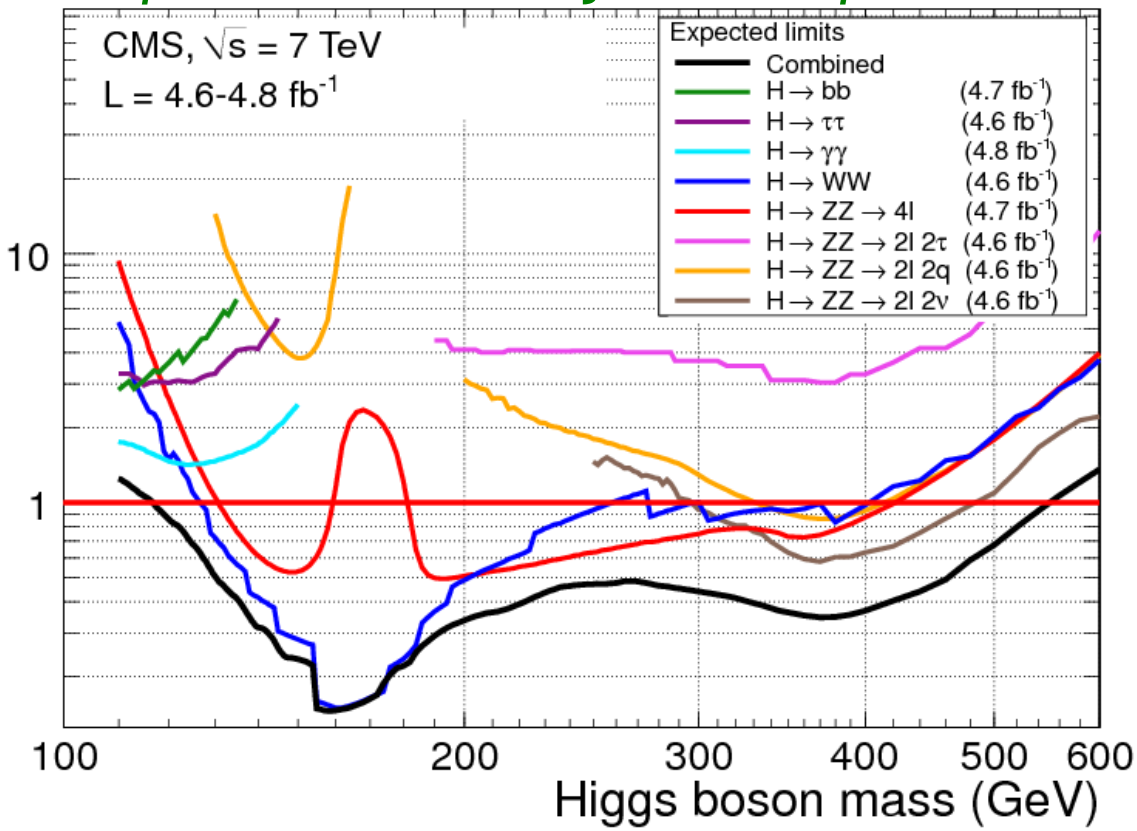
- Theoretical background calculations/models
- Understanding of detector performances

LHC Sensitivity with 2011 Data

CMS-PAS-HIG-12-008

Expected sensitivity – one experiment





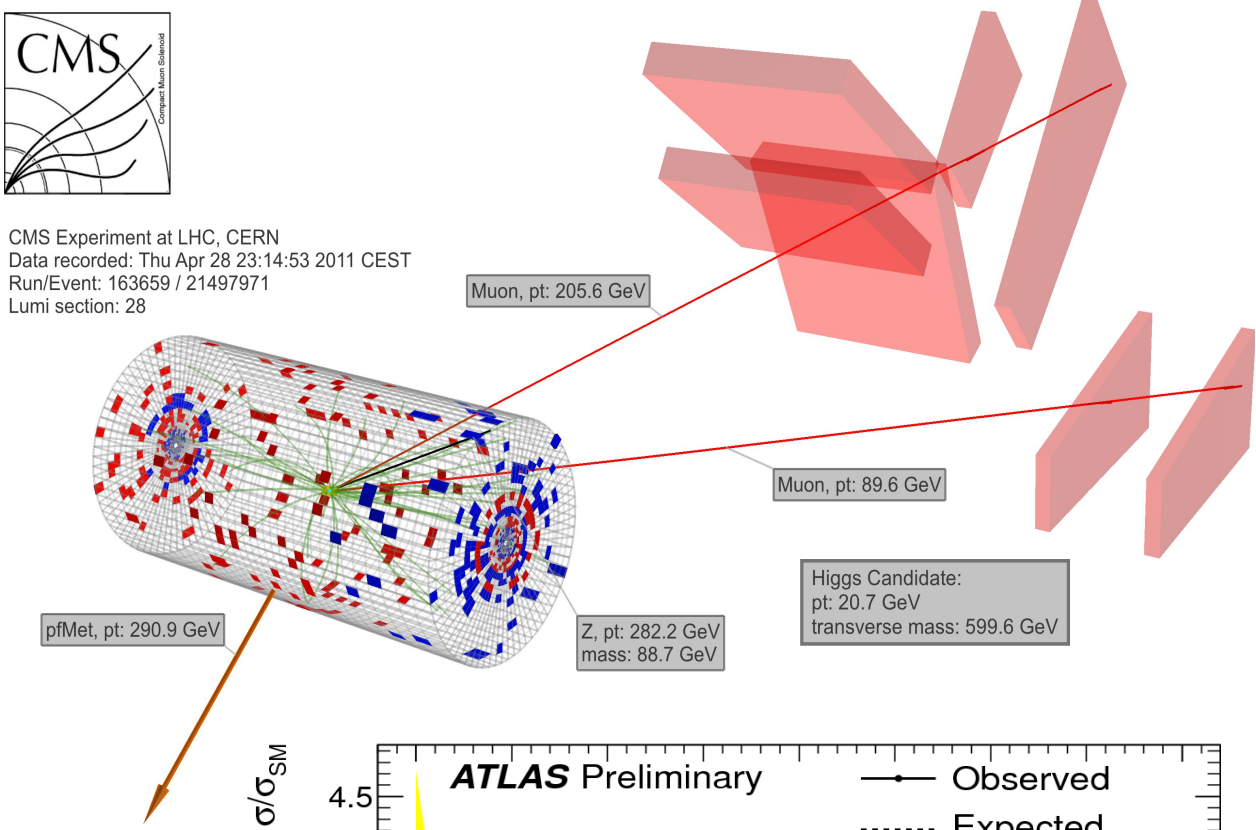
Most sensitive channels (each in turn, as m_H increases)

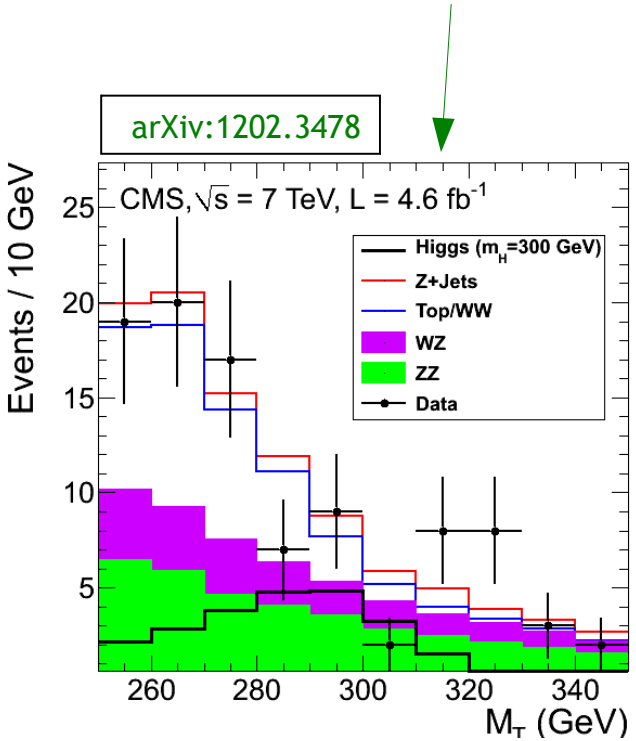
$H \to \gamma\gamma$ $H \to WW^{(*)} \to \ell\nu\ell\nu$ $H \to ZZ^{(*)} \to \ell\ell\ell\ell$ $H \to ZZ \to \ell\ell\nu\nu$

Crucial further consideration: event-by-event mass resolution – here $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell\ell\ell\ell$ dominate: fully reconstructed, no-jets, decay products

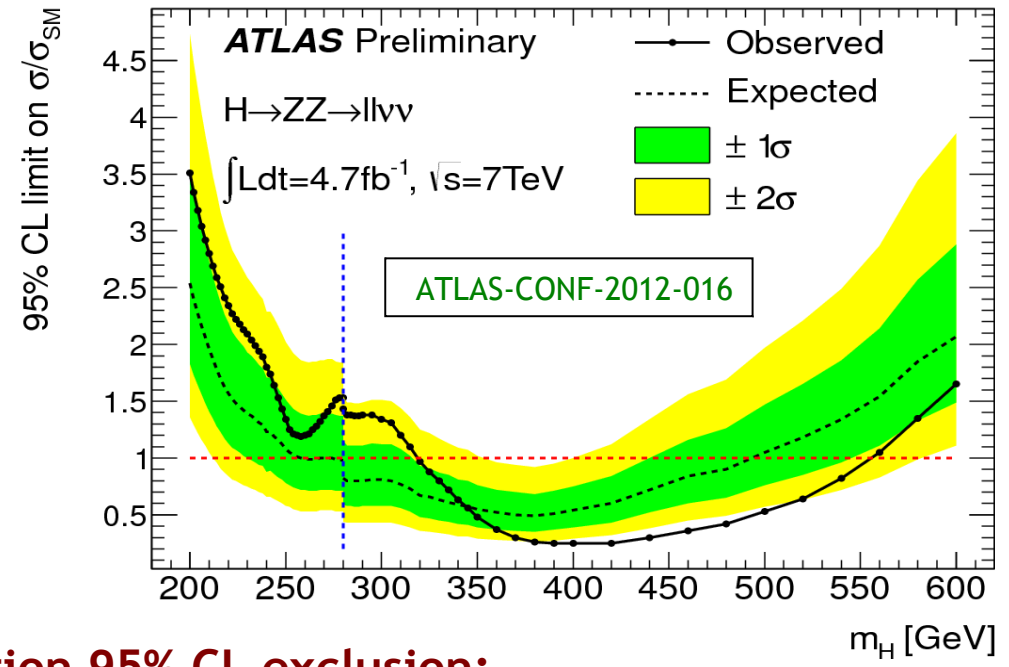
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$

- Most sensitive channel at high m_H
- Missing neutrinos, so mass resolution poorer than $H \rightarrow 4\ell$
- Selection adjusted for different m_H
- Use transverse mass (m_T) of E_T^{miss} and $\ell\ell$ system as discriminating variable to derive limits





$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M(\ell\ell)^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$

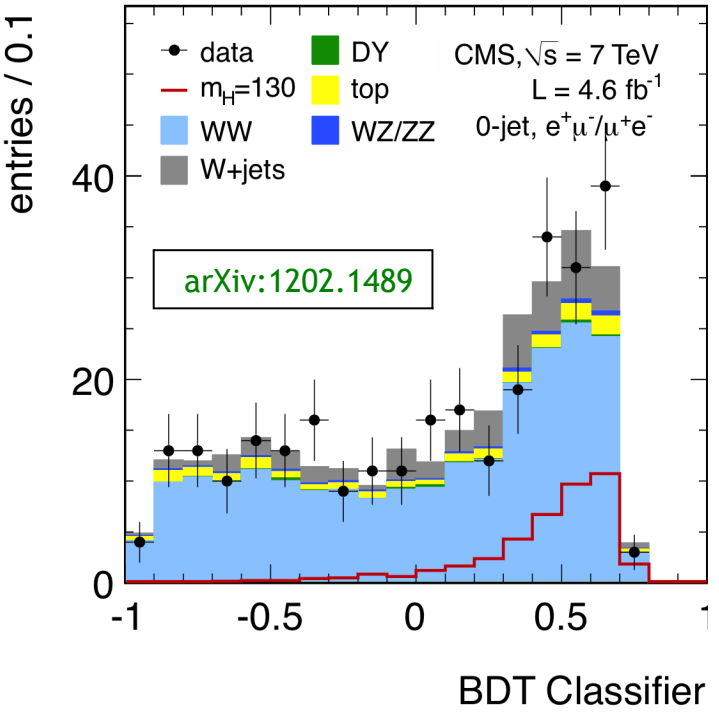


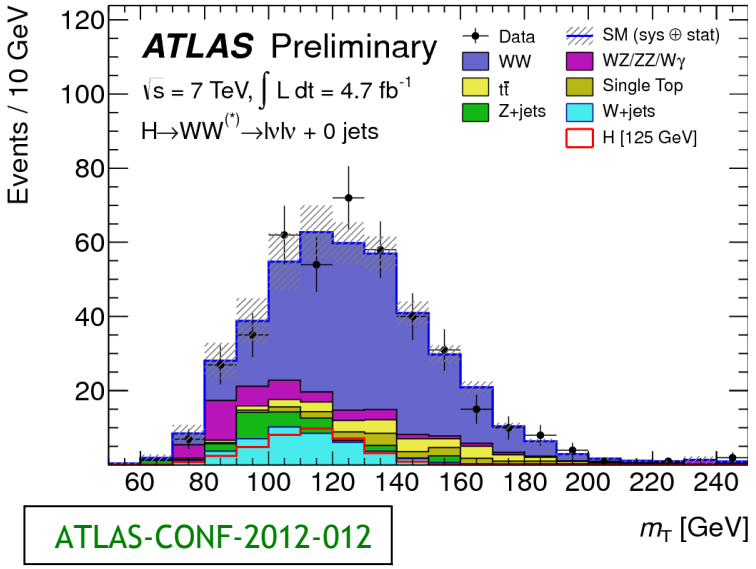
SM H production 95% CL exclusion:

- **CMS: 270-440 GeV** ***expect 290-480 GeV***
- **ATLAS: 320-560 GeV** ***expect 260-490 GeV***

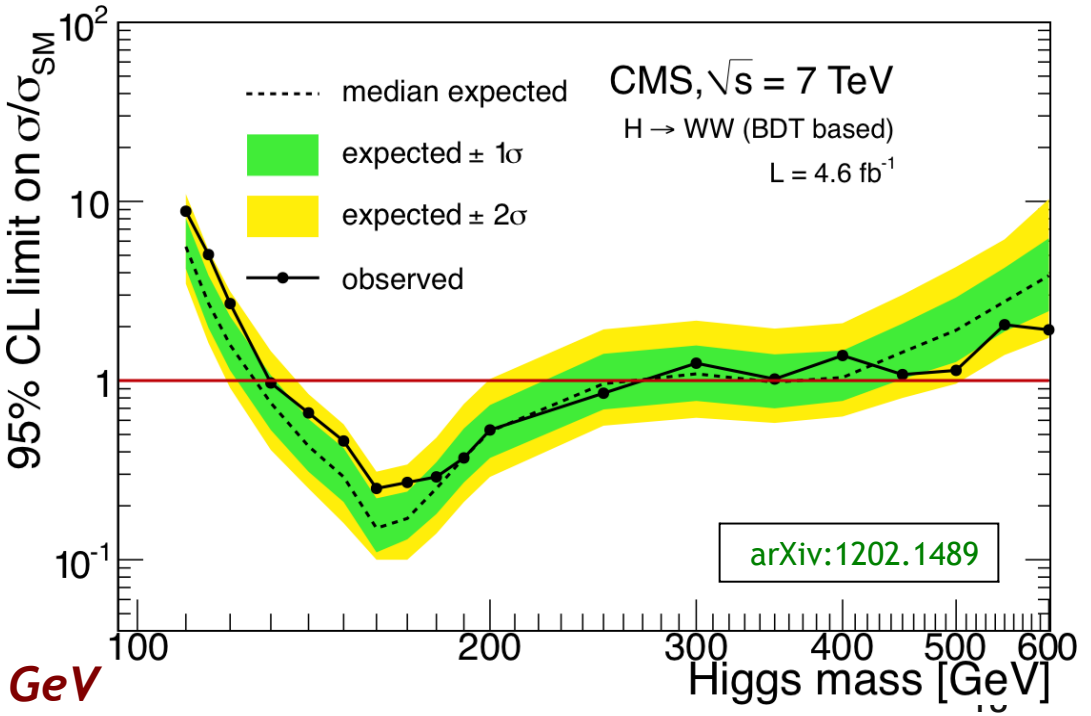
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$

- Statistically powerful, but poor mass resolution ~20%
- Important especially at low to intermediate m_H
- Analyses subdivided by ℓ flavour & jet multiplicity
- Large backgrounds (WW, $t\bar{t}$, ...), main ones measured with data control regions
- Typically use m_T distribution or multivariate classifier output to set limits





ATLAS-CONF-2012-012



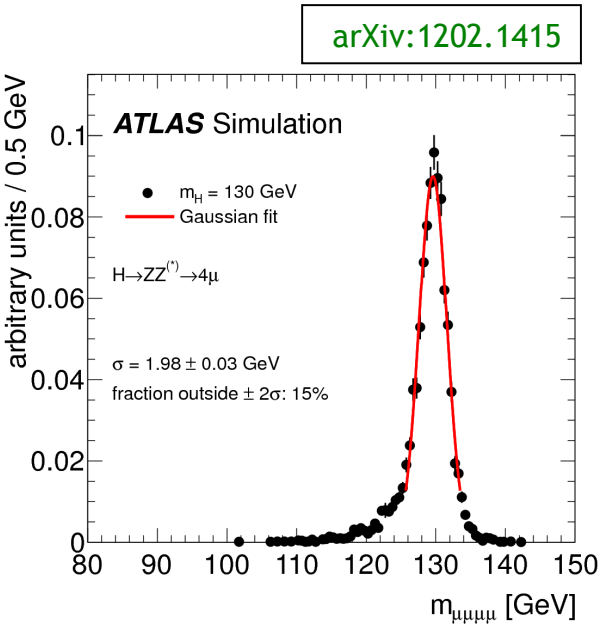
SM H production 95% CL exclusion:

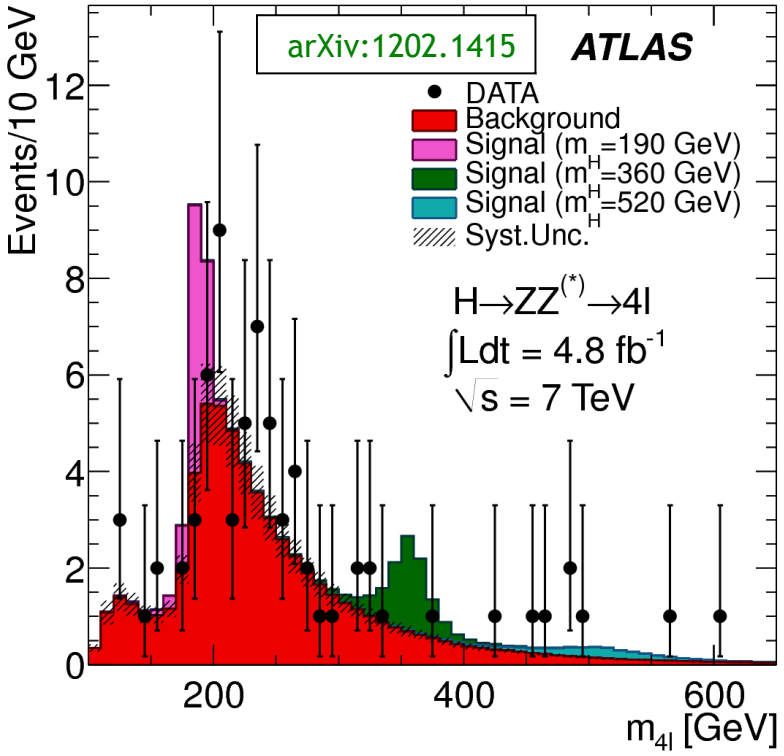
- **ATLAS: 130-260 GeV *expect 127-234 GeV***
- **CMS: 129-270 GeV *expect 127-270 GeV***

$H \to \ell\ell\ell\ell$

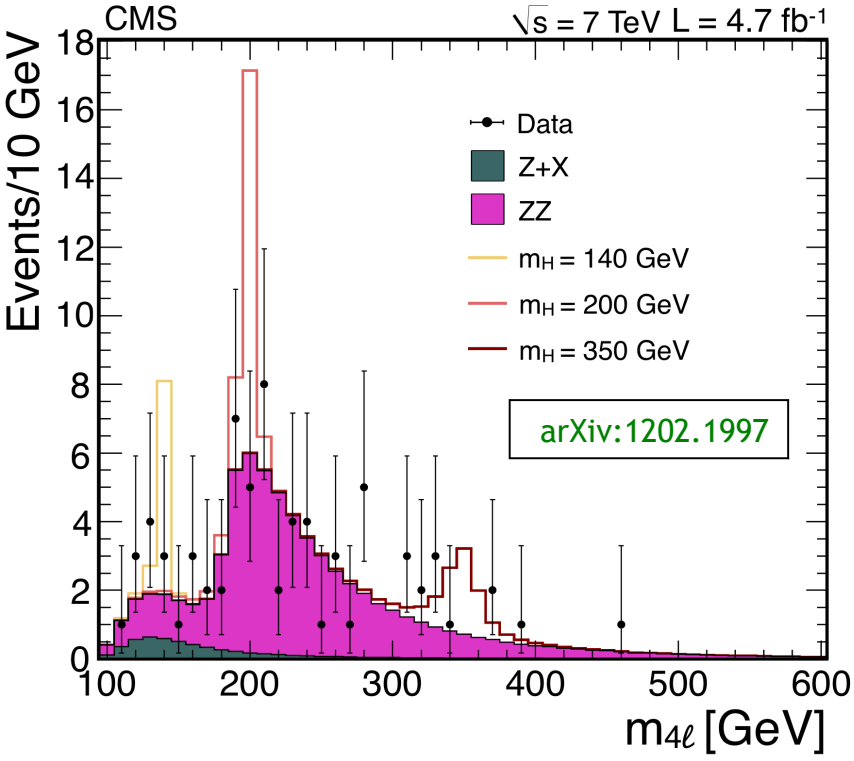
"Golden channel"

- Clean - low background, offers best S/B ratio
- Full reconstruction – excellent mass resolution
  - σ/m ~ 1-2% at low mass
  - dominated by Γ_H above ~350 GeV
- Low mass: at least one Z off-shell, but clean signature, excellent lepton ID, allows $p_T(\ell)$ cut as low as 5-7 GeV





Full mass range

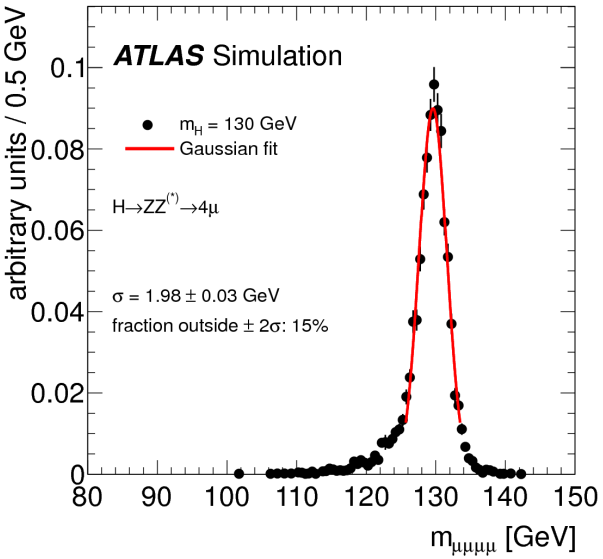


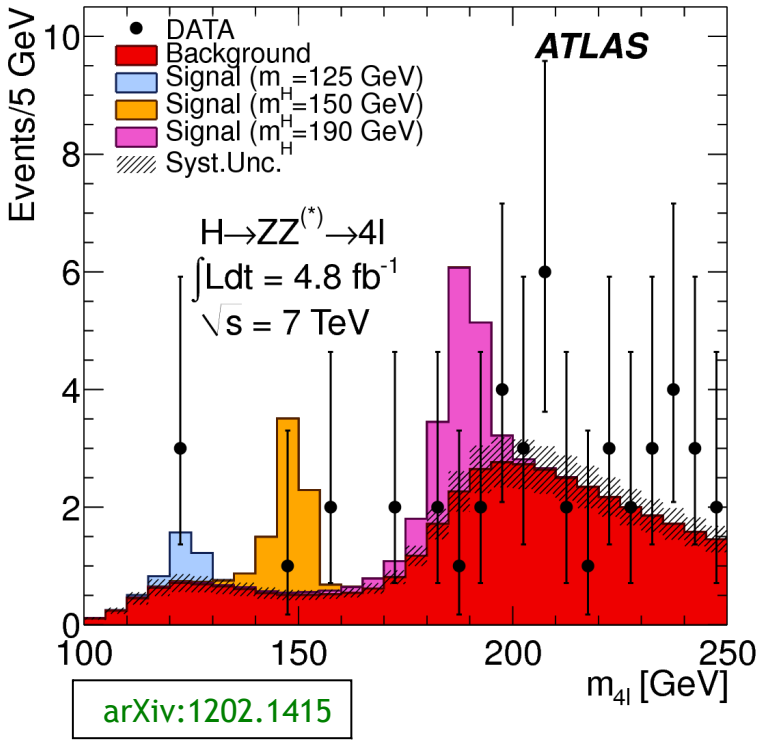
$H \to \ell\ell\ell\ell$

"Golden channel"

- Clean - low background, offers best S/B ratio
- Full reconstruction – excellent mass resolution
  - σ/m ~ 1-2% at low mass
  - dominated by Γ_H above ~350 GeV
- Low mass: at least one Z off-shell, but clean signature, excellent lepton ID, allows $p_T(\ell)$ cut as low as 5-7 GeV

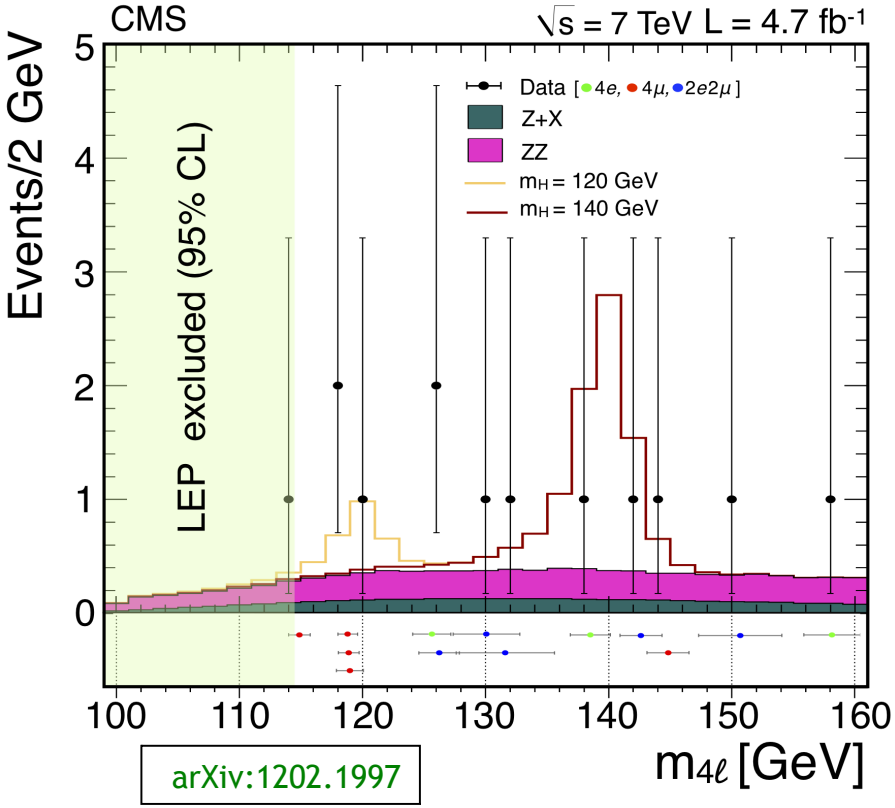
arXiv:1202.1415



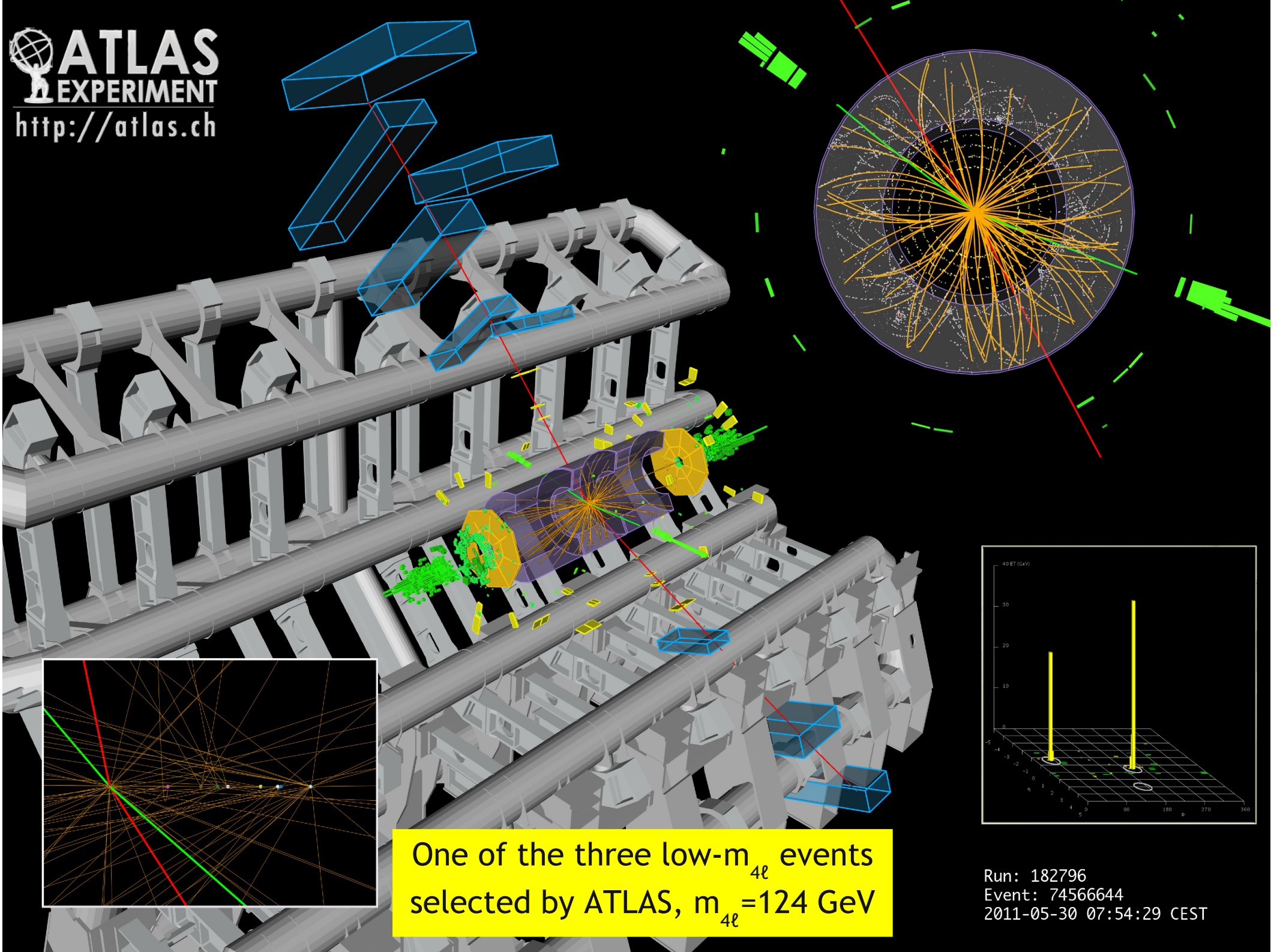


arXiv:1202.1415

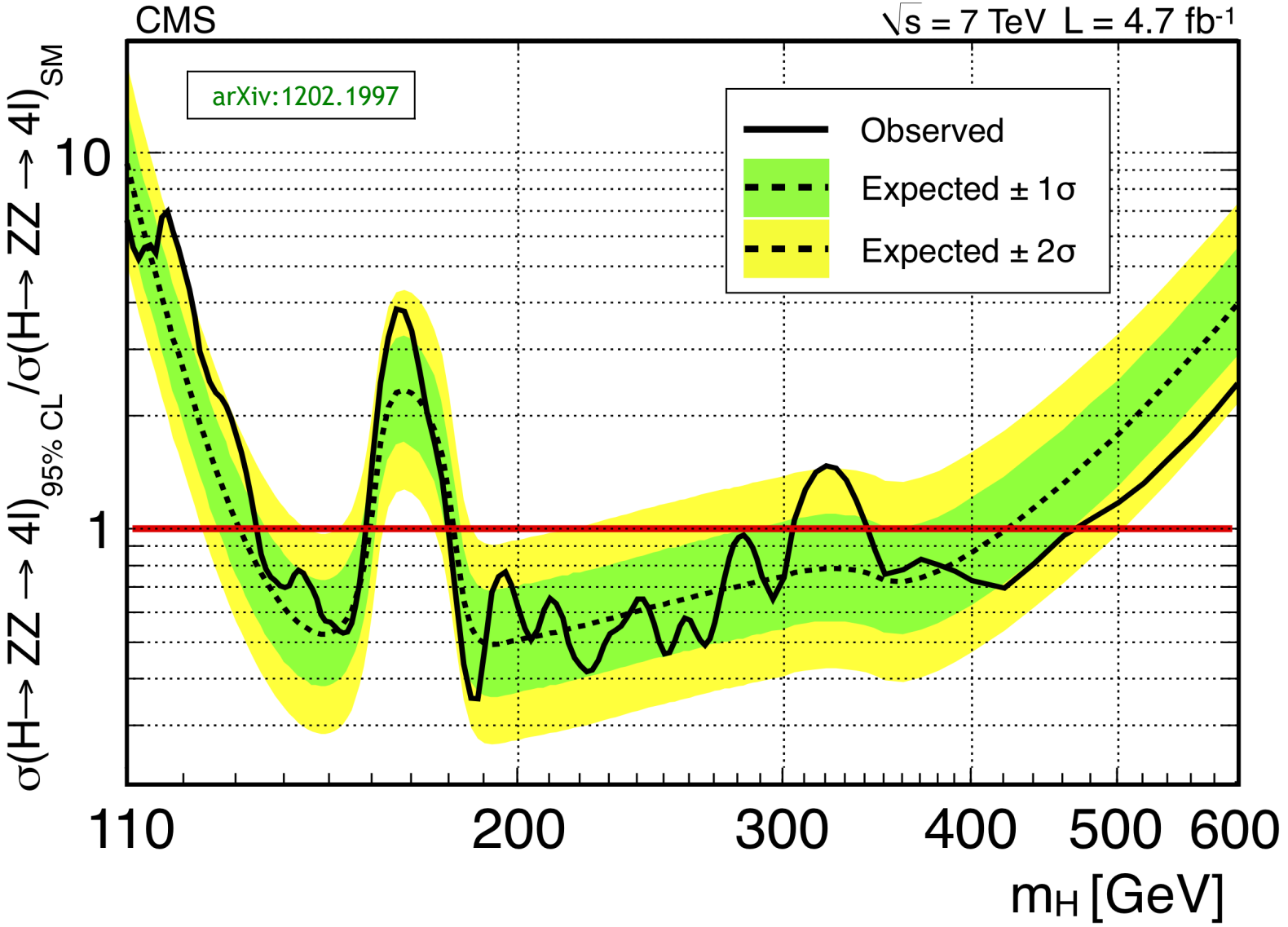
Low mass range



arXiv:1202.1997


ATLAS
EXPERIMENT
http://atlas.ch
One of the three low-m$_{4\ell}$ events
selected by ATLAS, m$_{4\ell}$=124 GeV
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

Limits from H → ℓℓℓℓ



SM H production 95% CL exclusion:

- **ATLAS: 134-156, 182-233, 256-265, 268-415 GeV *expect 136-157, 184-400 GeV***
- **CMS: 134-158, 180-305, 340-465 GeV**

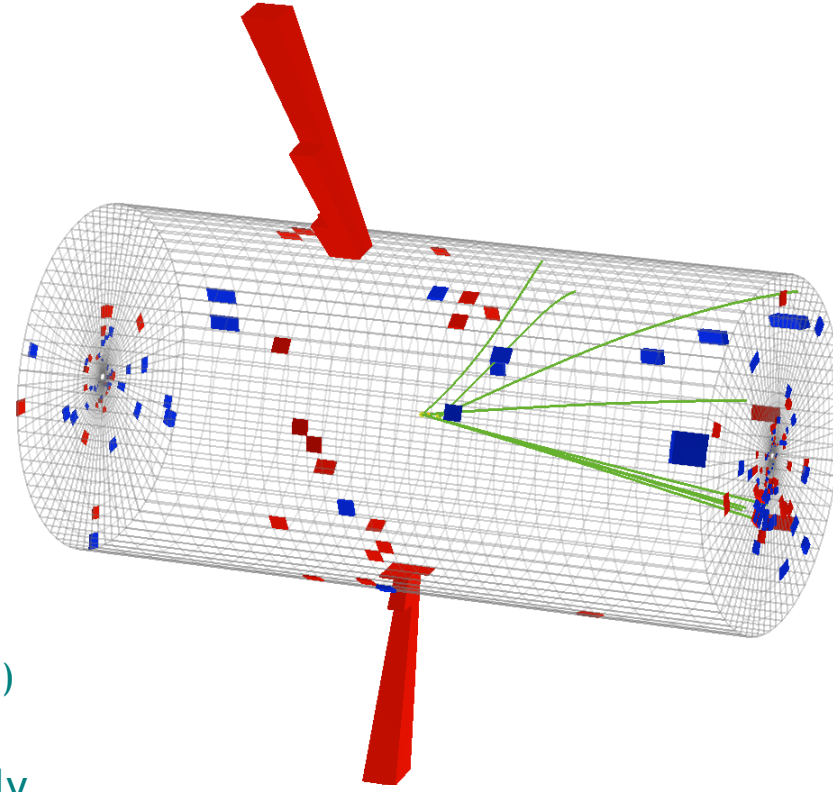
$H \rightarrow \gamma\gamma$

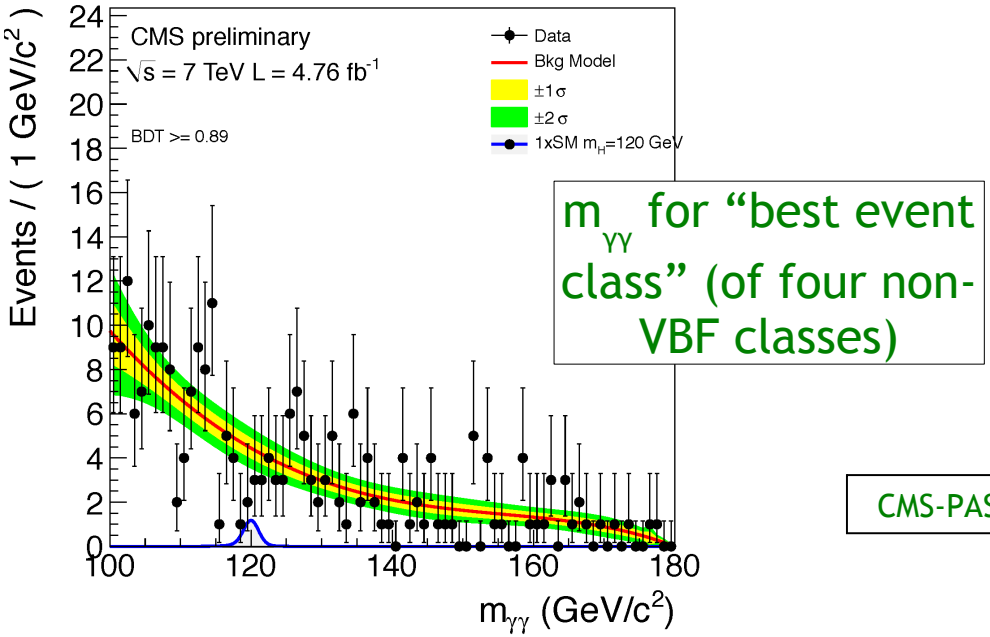
Full reconstruction of H decay

- Excellent mass resolution ~ 1.5% at best
- But tiny BR ~0.2%
- Backgrounds are large, but smoothly varying

Look for a peak in the $m_{\gamma\gamma}$ spectrum...

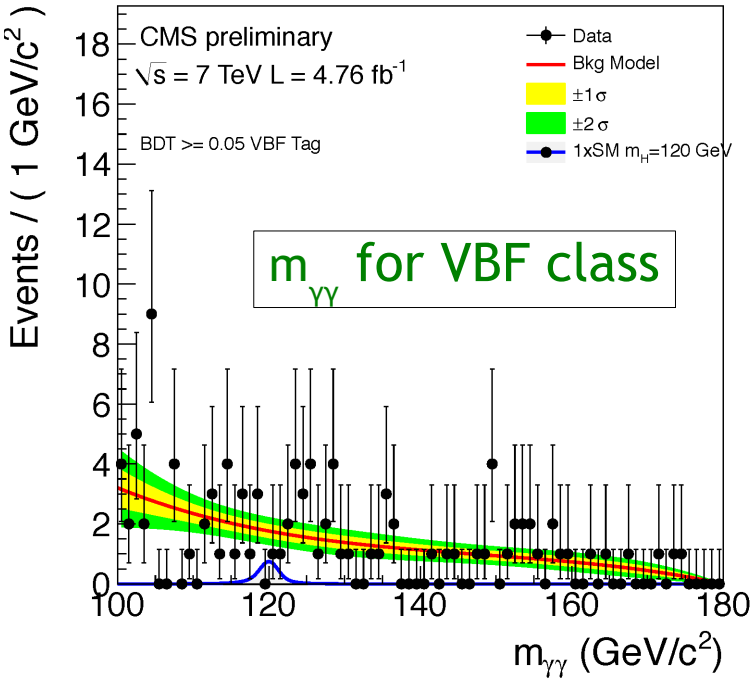
- Account for varying mass resolution
  - either binning (e.g. $p_{Tt}(\gamma\gamma)$, , shower shape, η, conversions, ...)
  - or event-by-event in a multivariate analysis (CMS)
  - CMS finds VBF channel (exclusive forward jets) particularly sensitive





$m_{\gamma\gamma}$ for "best event class" (of four non-VBF classes)

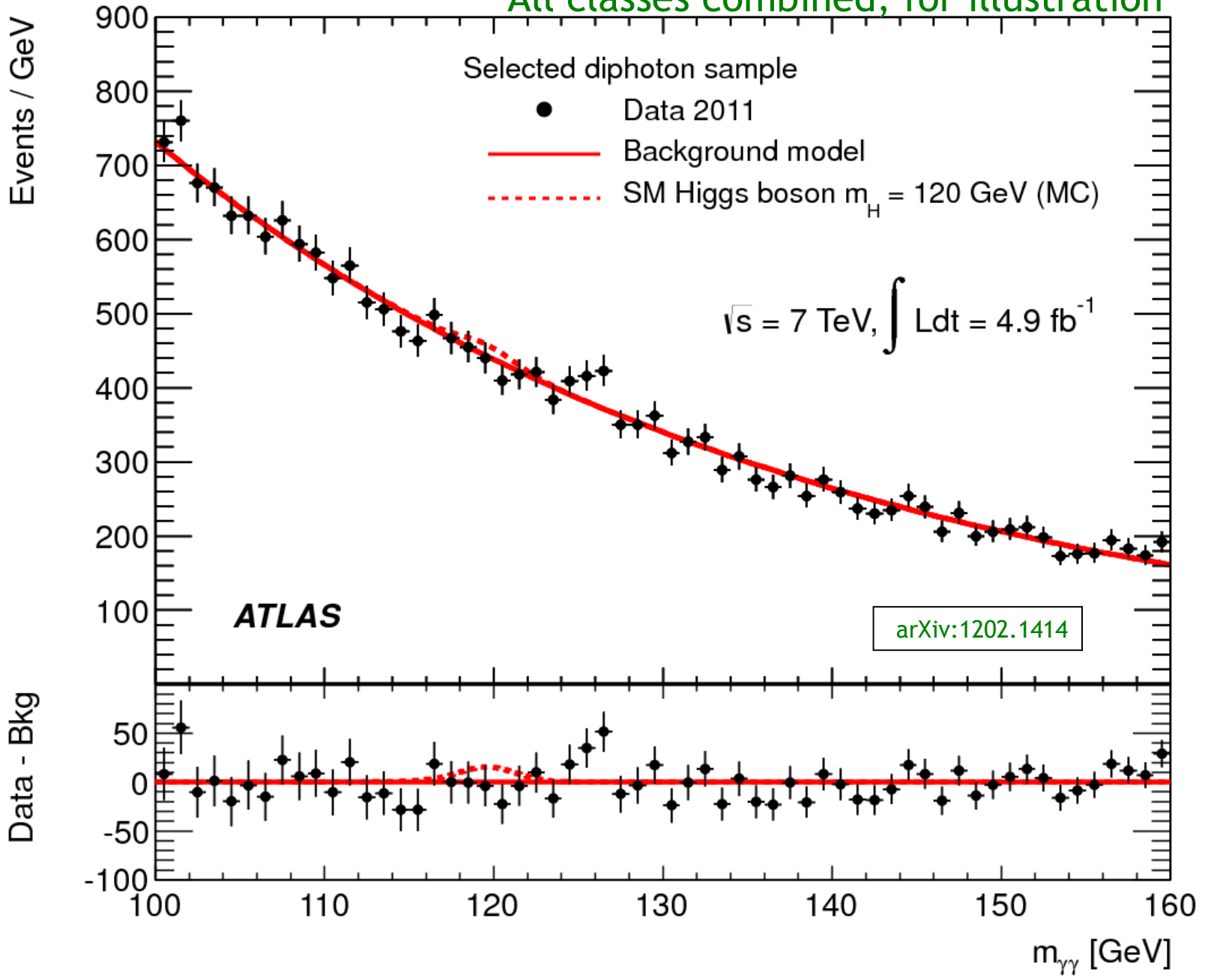
CMS-PAS-HIG-12-001



$m_{\gamma\gamma}$ for VBF class

$H \rightarrow \gamma\gamma$

All classes combined, for illustration

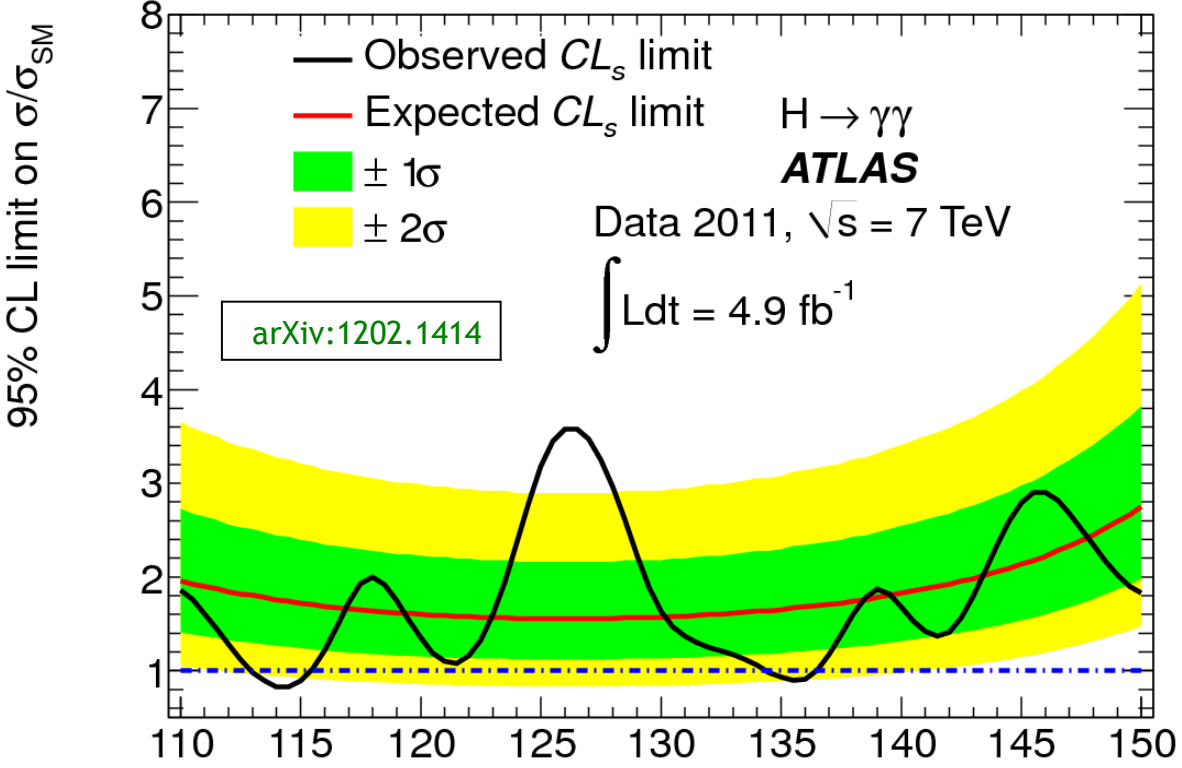


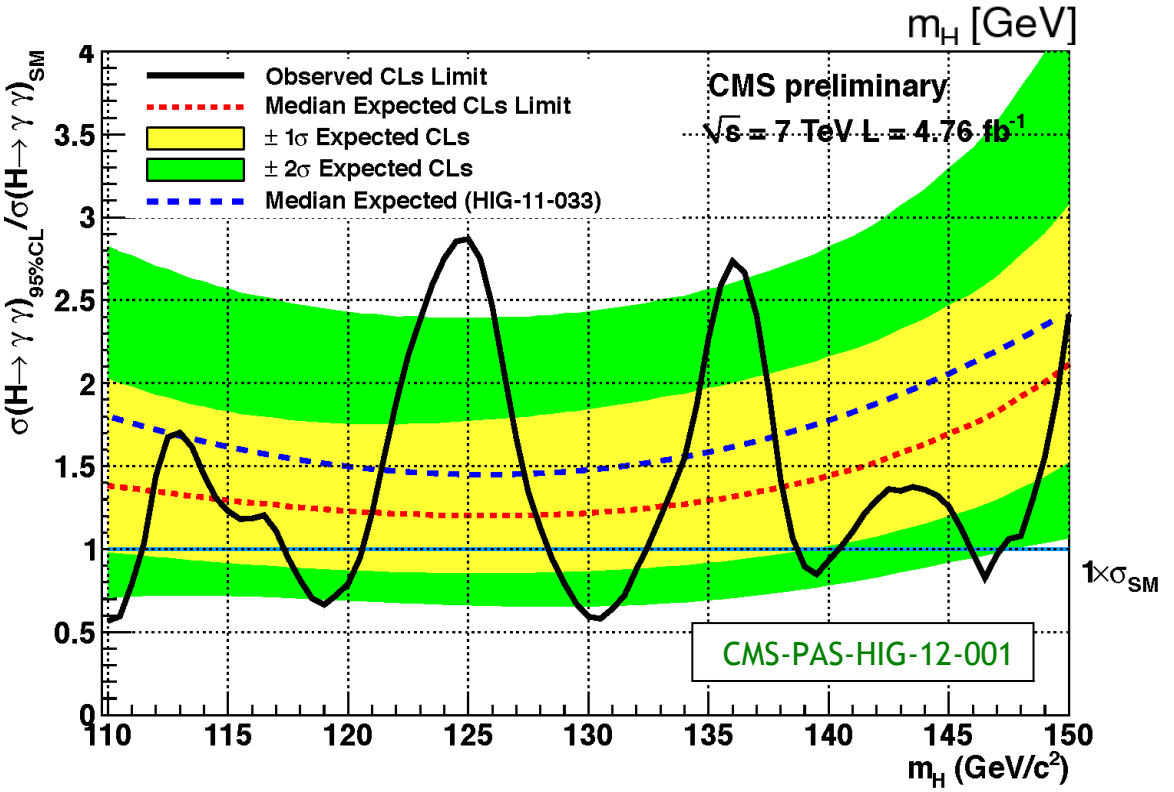
$H \rightarrow \gamma\gamma$

Expected limit is around 1.2-1.6 times SM cross-section

We do expect fluctuations due to statistics and the good mass resolution

To analyse if the fluctuations seen are significant, we need to look at the p-value





$H \rightarrow \gamma\gamma$

Local p-value

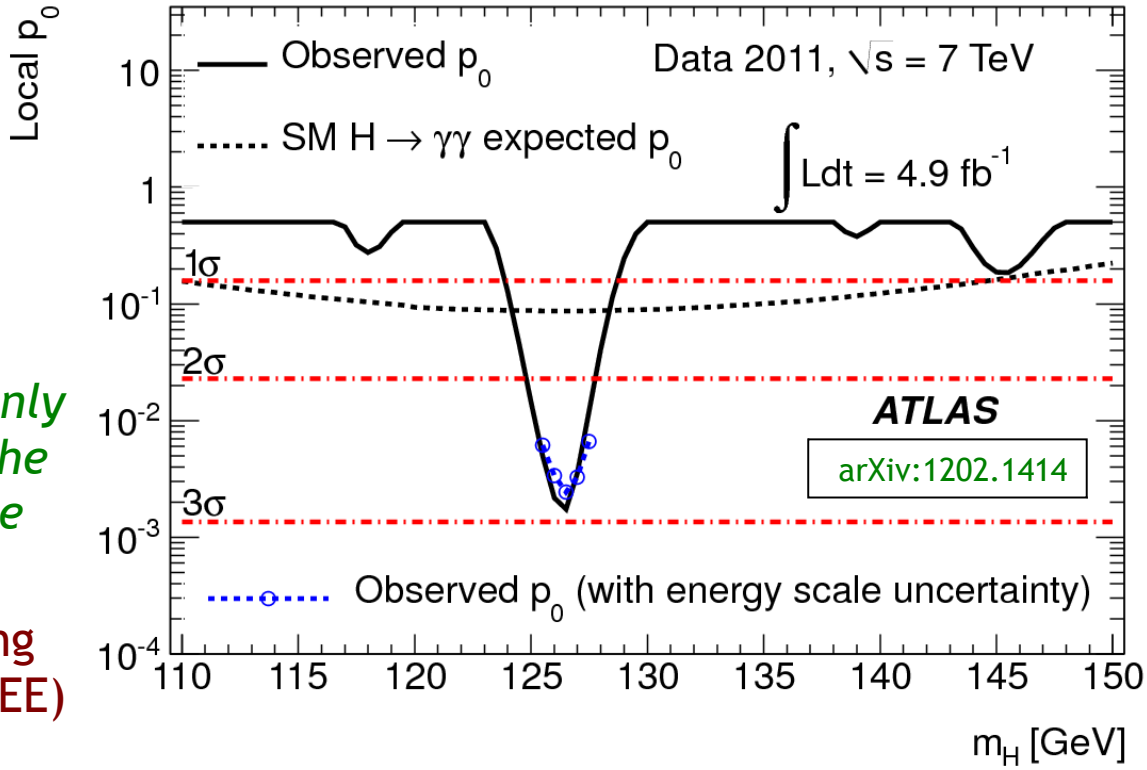
Probability that a background-only experiment is as signal-like as the data, for a given m_H signal shape

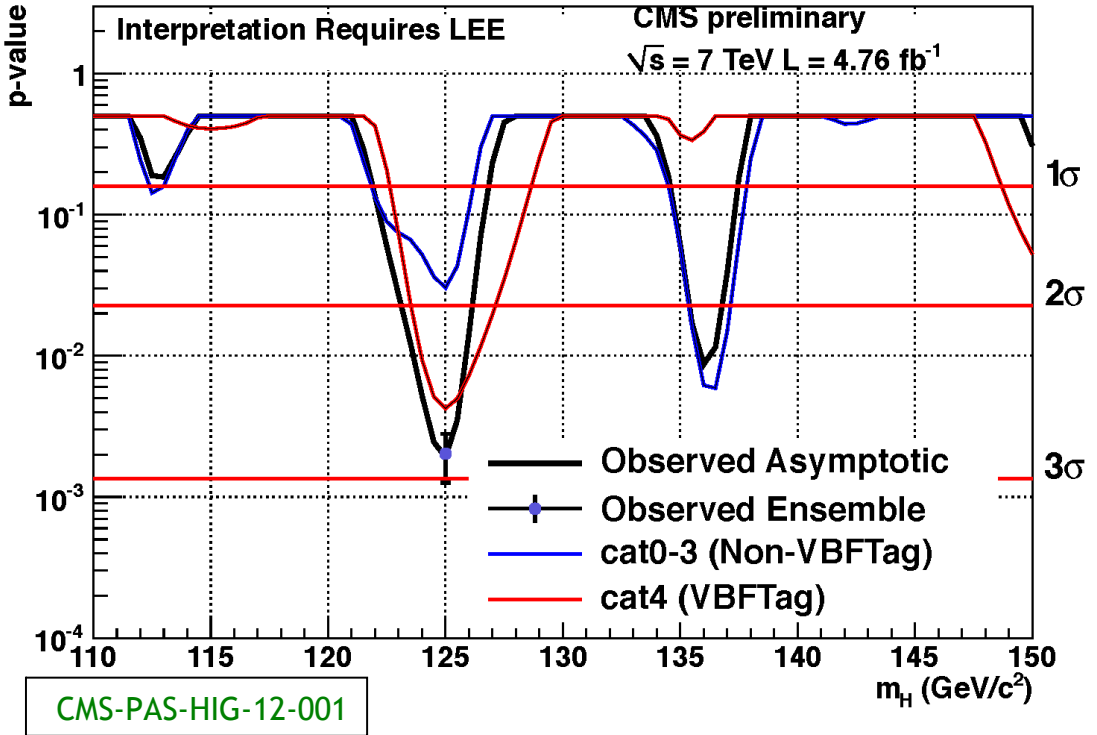
Interpretation requires correcting for the look-elsewhere effect (LEE)

Significances:

- ATLAS at 126.5 GeV
  - Local 2.9σ, global 1.5σ
- CMS at 125 GeV
  - Local 2.9σ, global 1.6σ

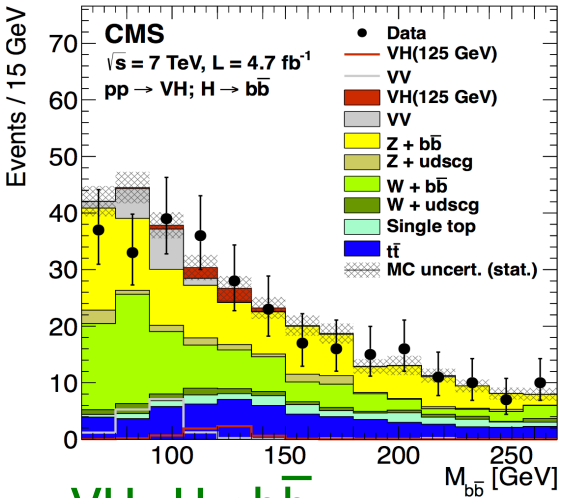
LEE over range 110-150 GeV



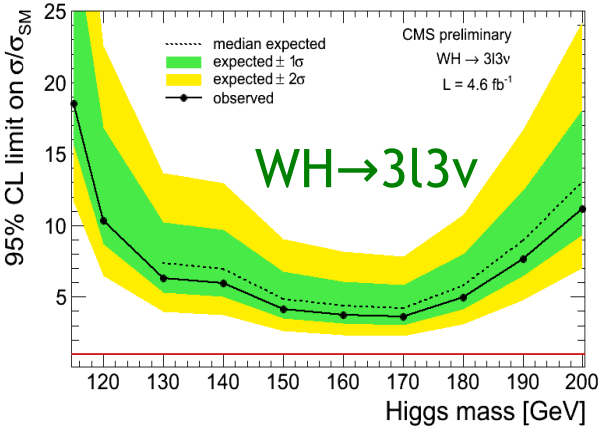


Other SM Higgs Search Channels

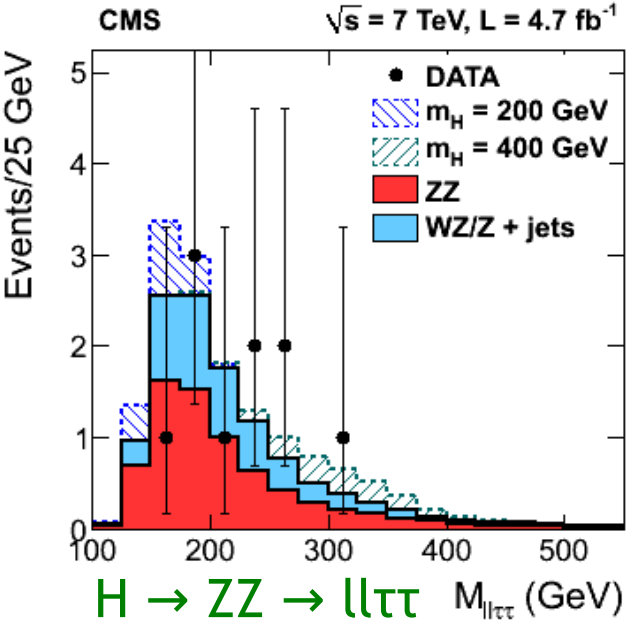
Many other channels investigated in detail by CMS and ATLAS, but I have no time...



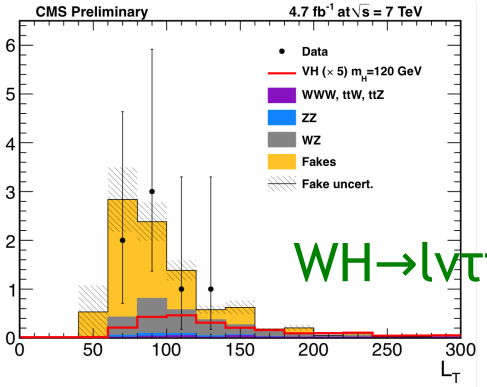
VH, H→bb̄



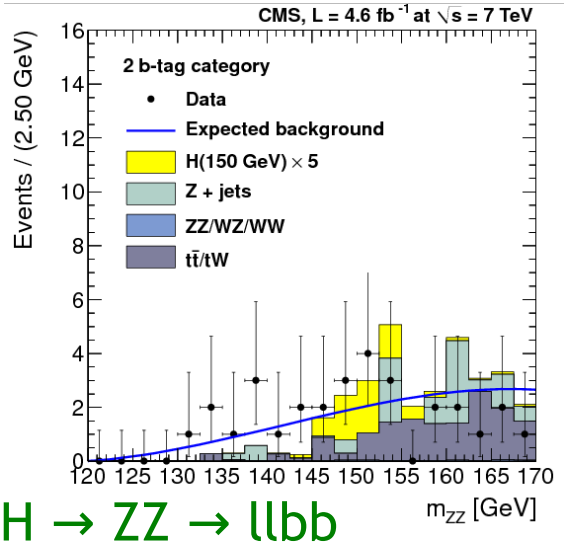
WH→3l3ν



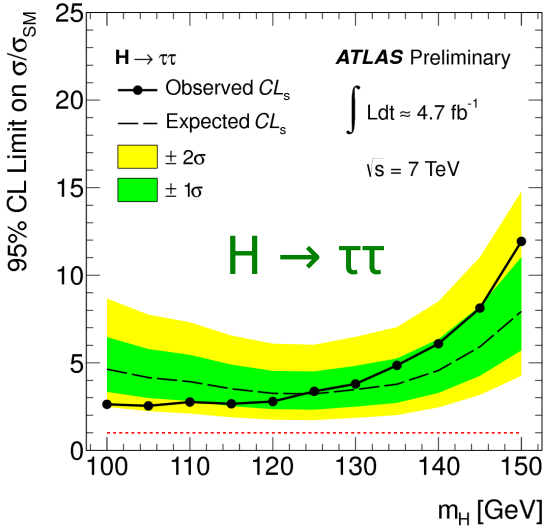
H → ZZ → llττ



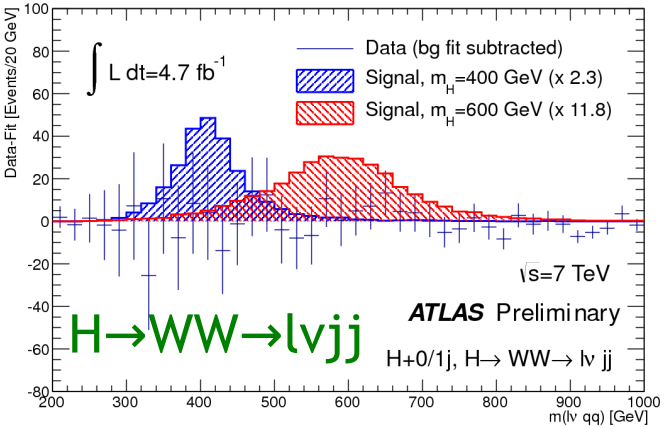
WH→lνττ



H → ZZ → llbb



H → ττ

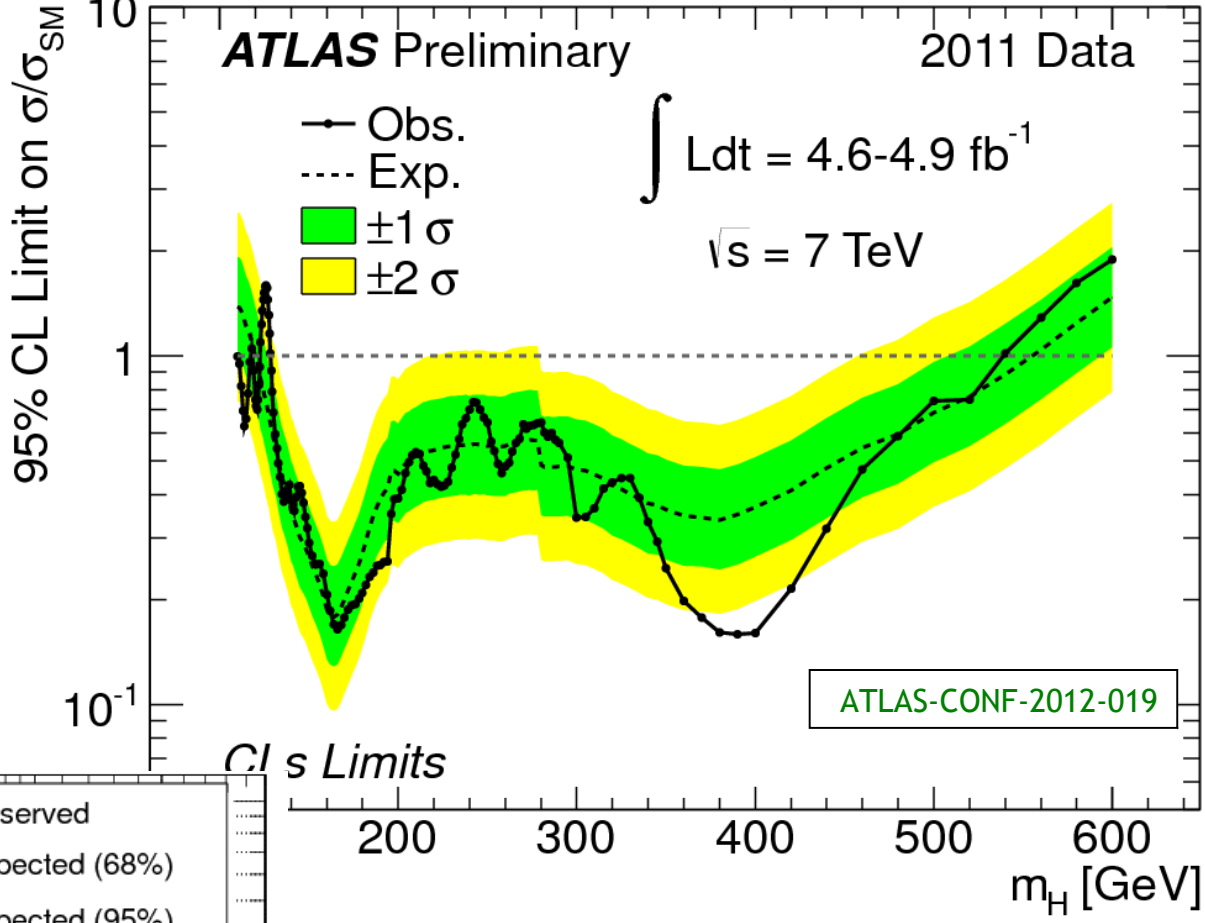


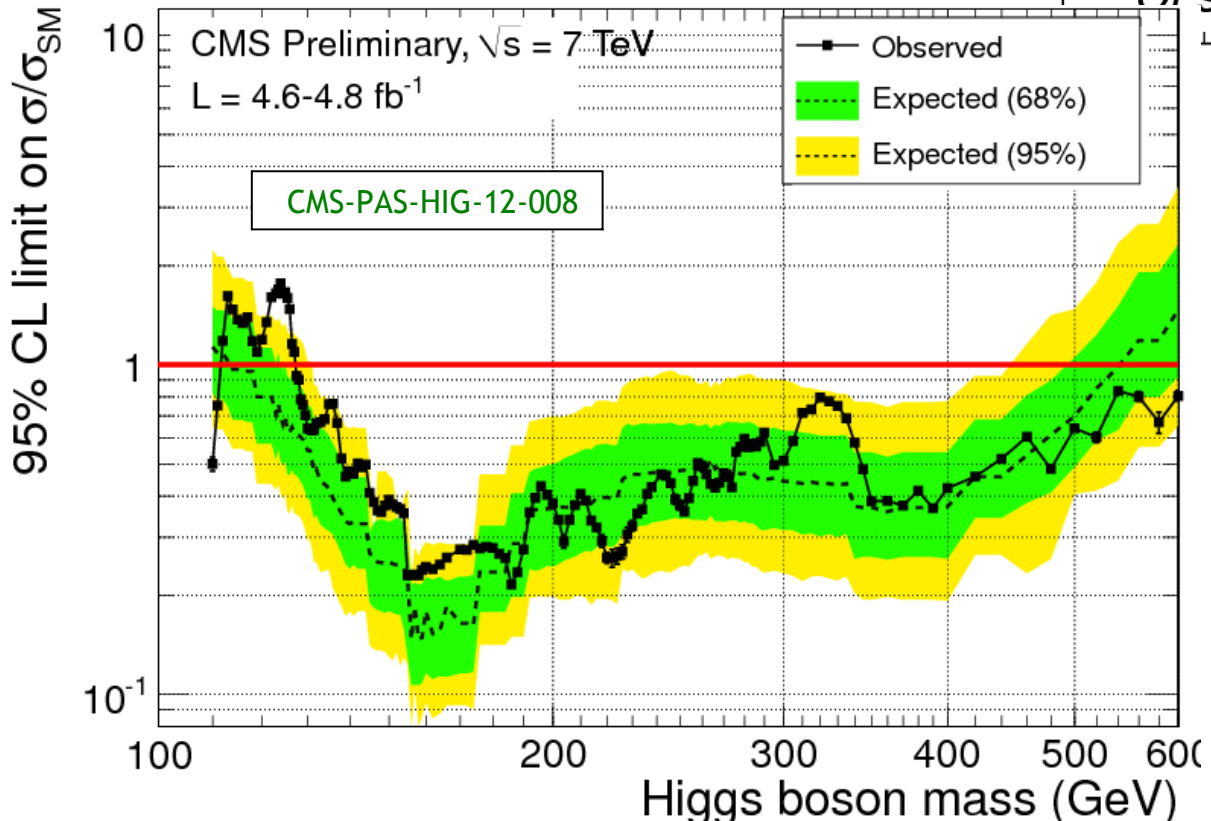
H→WW→lνjj

Combining All Channels

Wide continuous 95% CL exclusion range at **high mass**

ATLAS: 129-539 GeV
Expect 120-555 GeV
CMS: 127.5-600 GeV
Expect 114.5-543 GeV





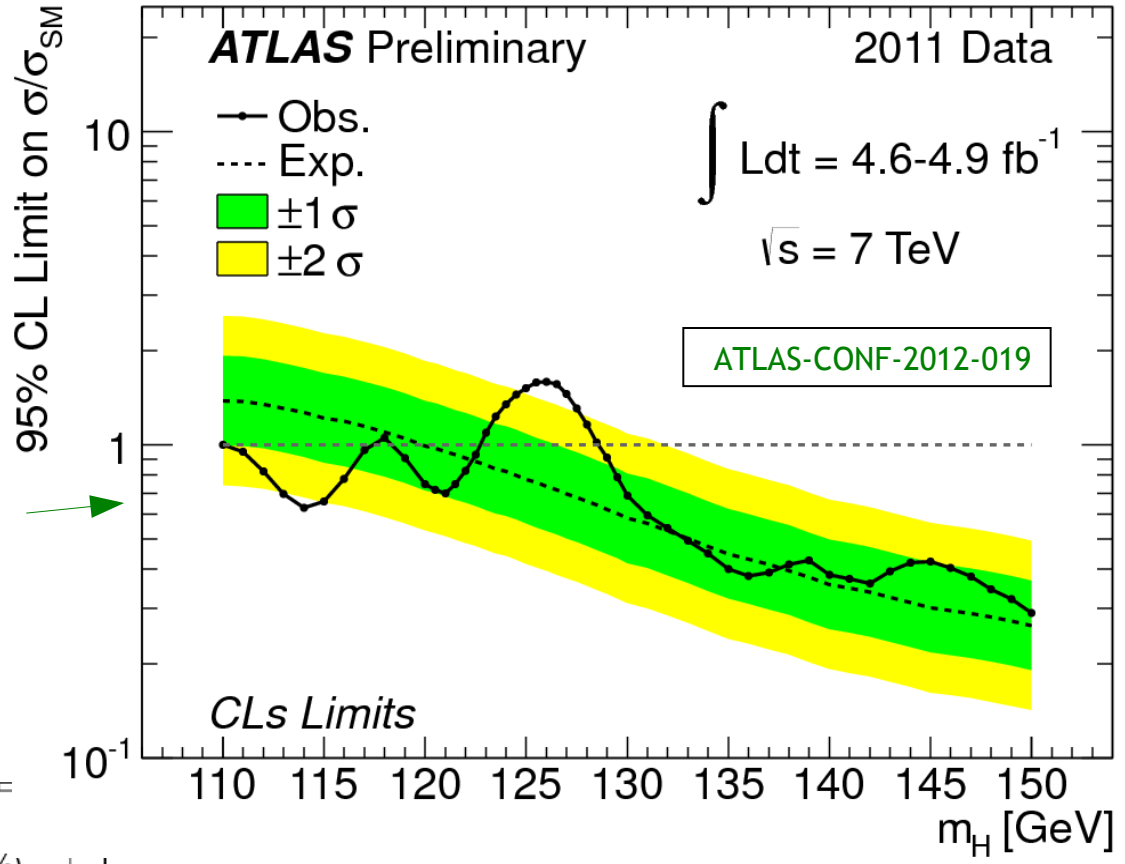
Even at 99% CL, exclude:
ATLAS: 130-486 GeV
CMS: 129-525 GeV

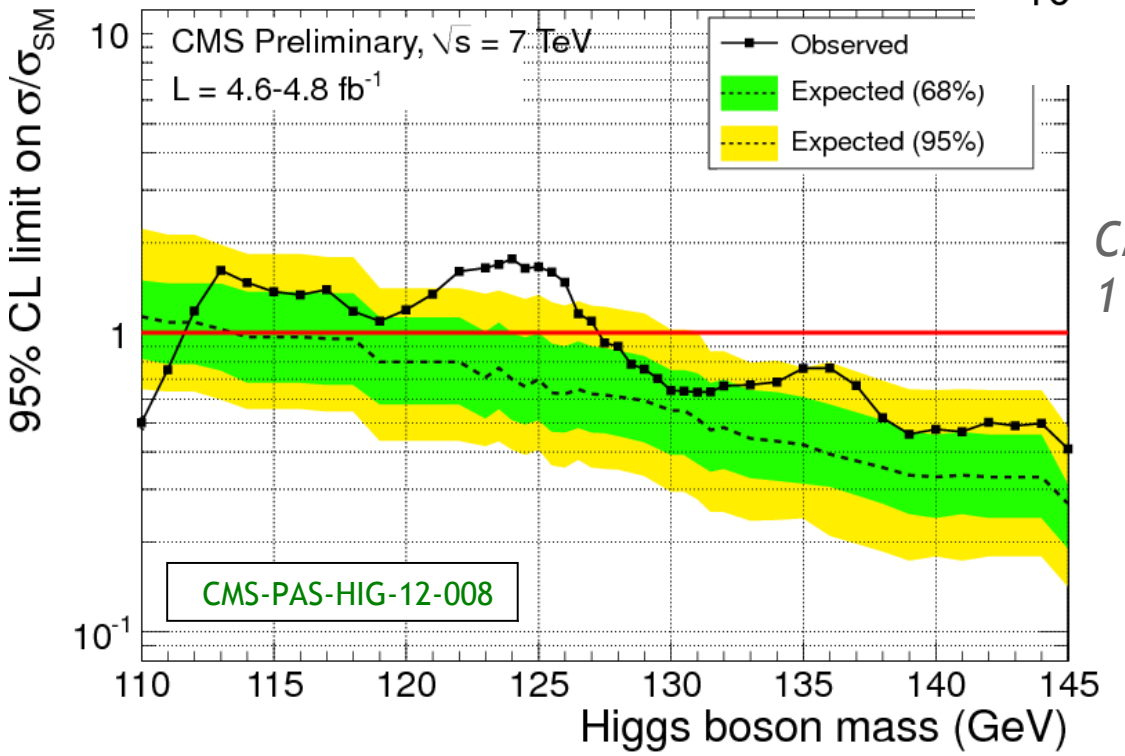
and at low mass...

Low Mass Region

Low-mass range below 130 GeV
some excesses in data "spoil"
expected exclusions

ATLAS exclude at 95% CL
110-117.5 and 118.5-122.5 GeV

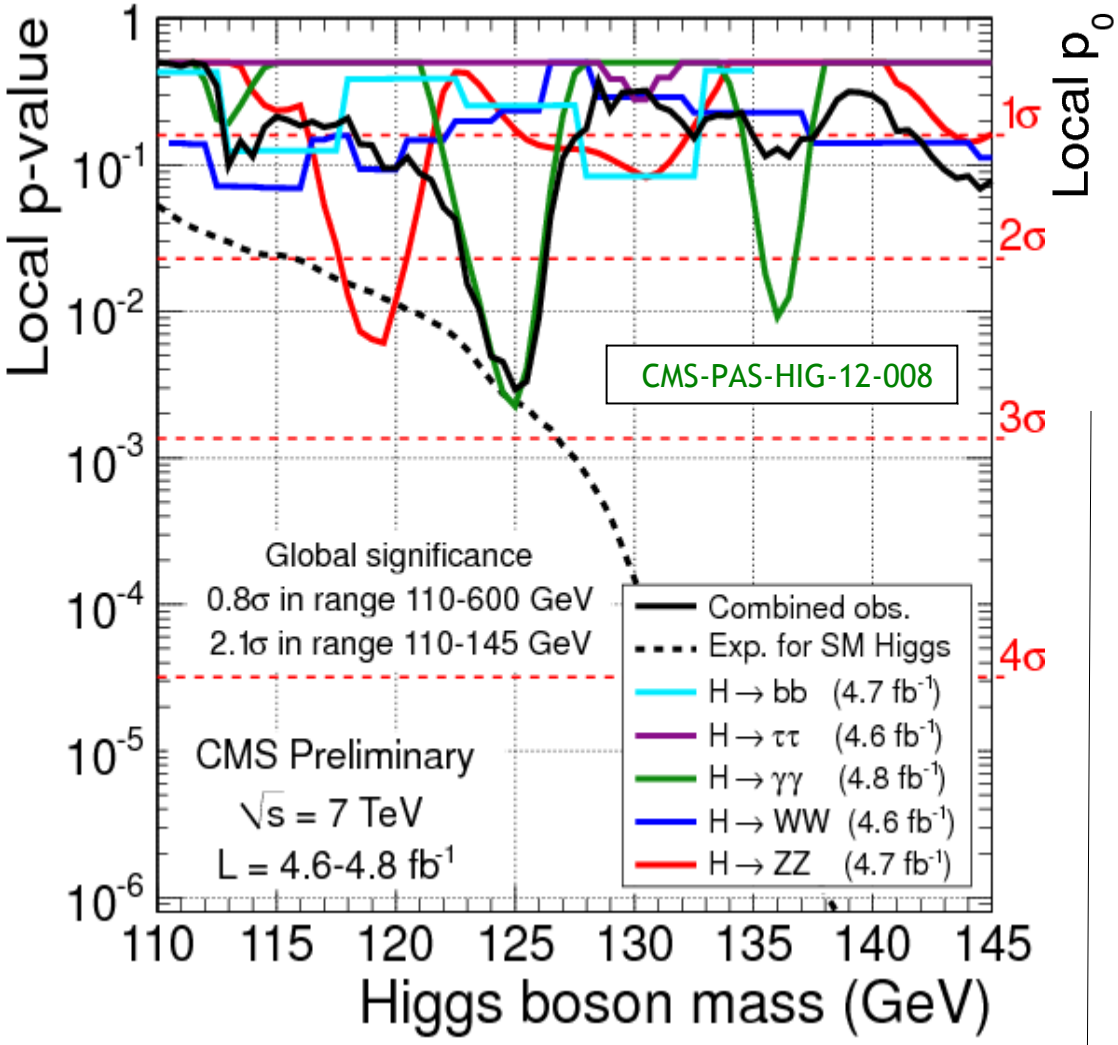


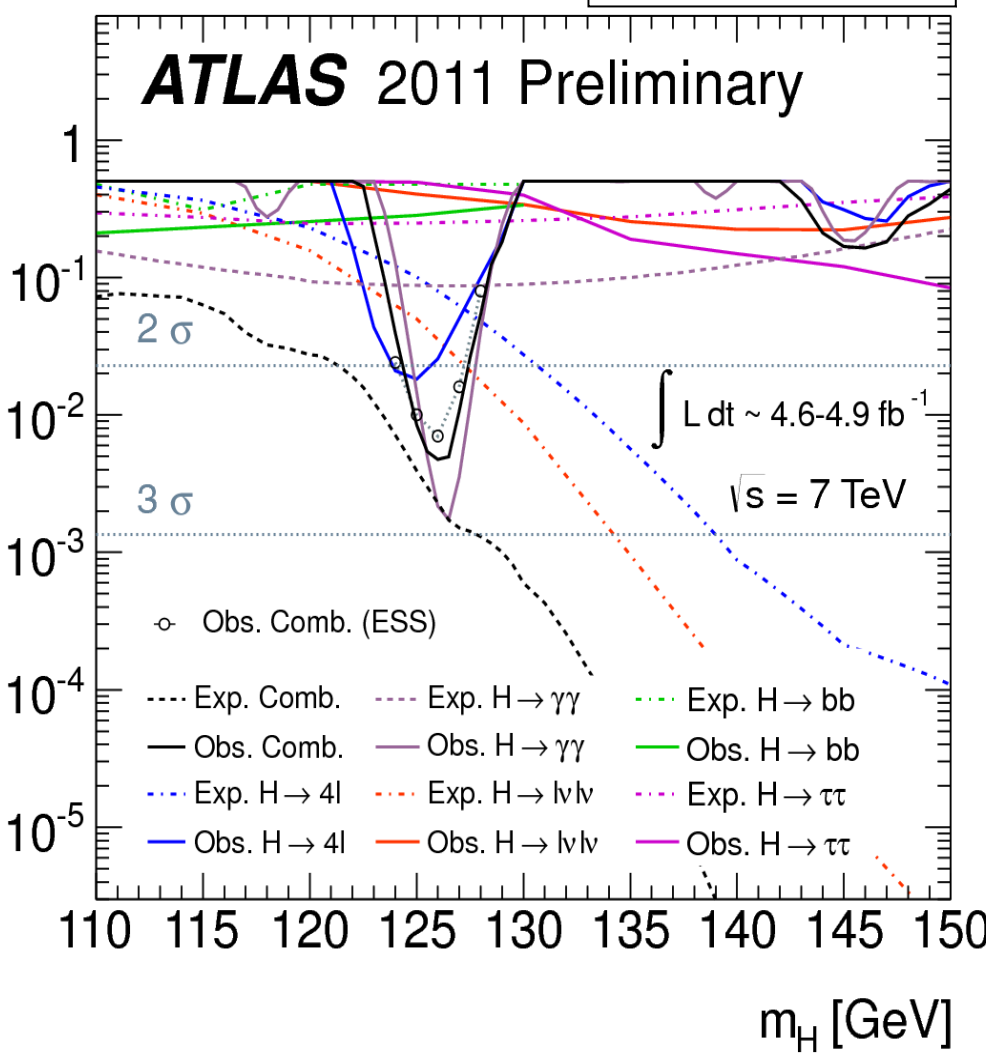


CMS expected exclusion at 95% CL
114.5 up to 543 GeV

Significance of excesses should rather be considered with the p-value plots...

Individual Experiment Combination p-values





Minimum p-value at 125 GeV
Local significance 2.8σ
Estimated global significance
- **0.8σ (LEE over range 110-600 GeV)**
- **2.1σ (LEE over range 110-145)**

Minimum p-value at 126 GeV
Local significance 2.5σ
Estimated global significance
- **30% *(~0.5σ)* (LEE over 110-600 GeV)**
- **10% *(~1.6σ)* (LEE over 110-145)**

Summary (not Conclusion!)

Major steps forward in Higgs searches in the last year

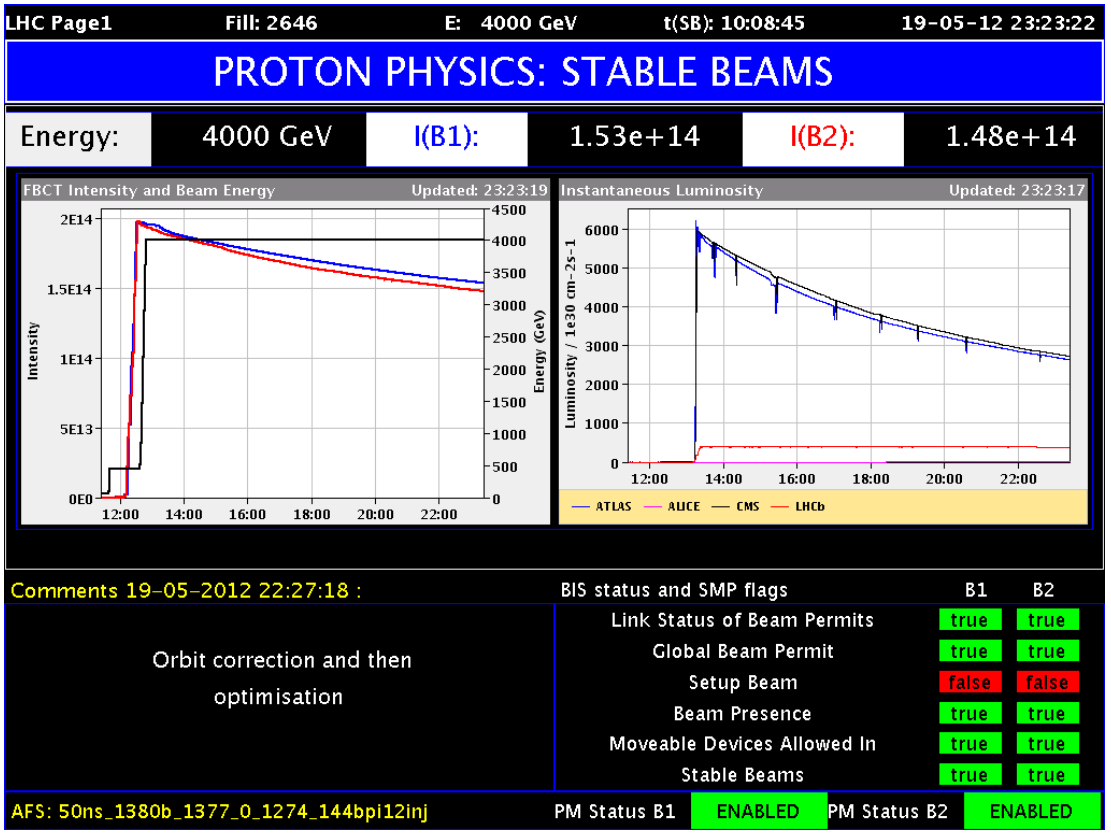
- Tevatron
  - Substantial step forward in analysis sensitivity
  - Full data sample analysed in main channels
  - Modest excess in the low-mass region, dominated by the $b\bar{b}$ channel
  - Global significance of the excess is ~2.2σ

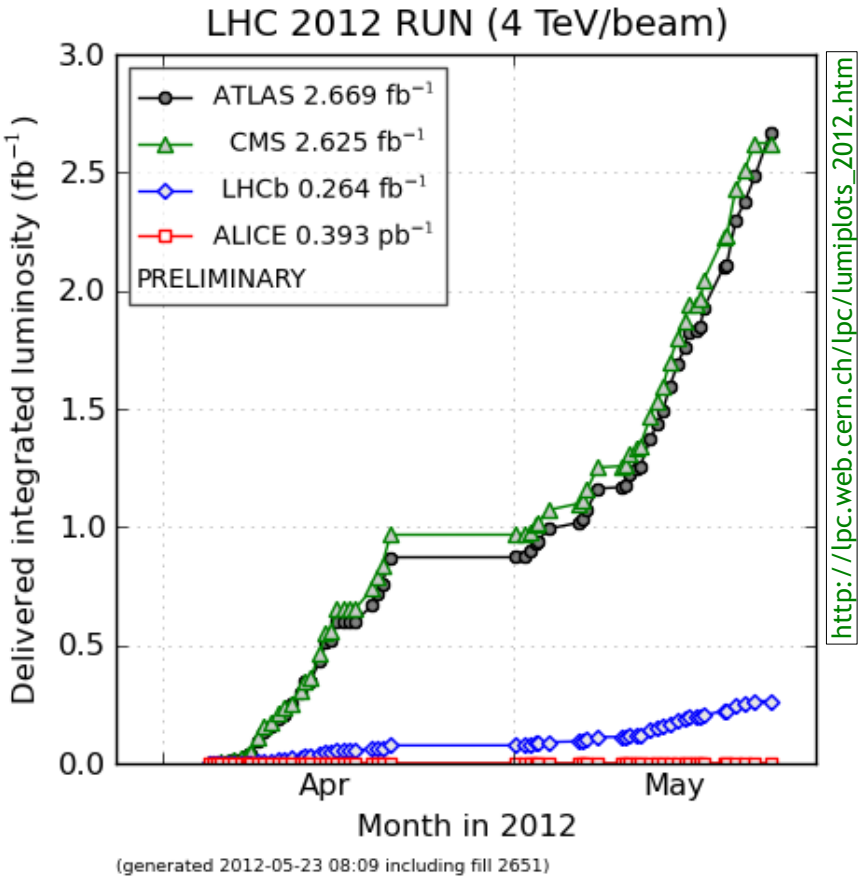
- LHC
  - Production of the Standard Model Higgs now excluded over a huge mass range ~128-600 GeV
  - In the low-mass region around 125 GeV
    - both ATLAS and CMS see an excess of events, individually of marginal significance
    - consistent both with background fluctuations or a SM Higgs being there...

Forward Look

The LHC is running in 2012 at $\sqrt{s}$ = 8 TeV, aiming for ~15 fb^{-1}

- By the end of this year we should have a *much* clearer picture

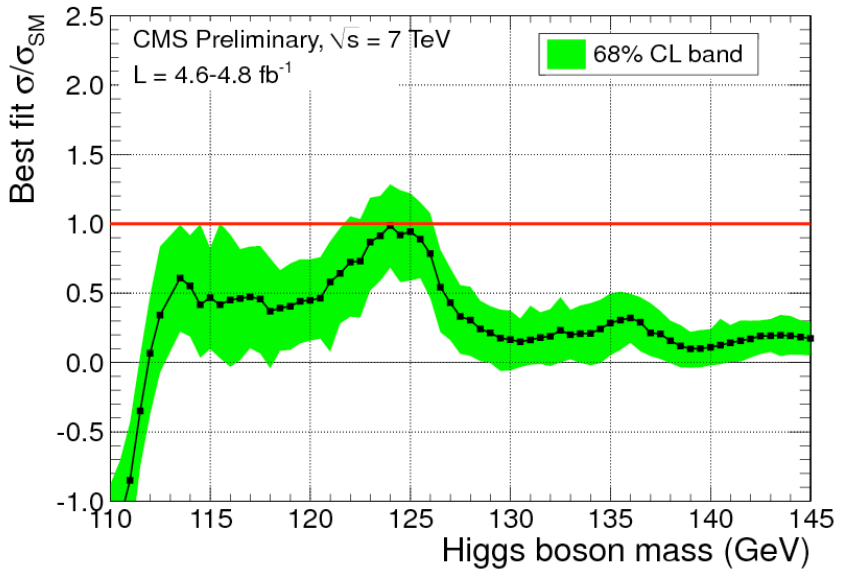


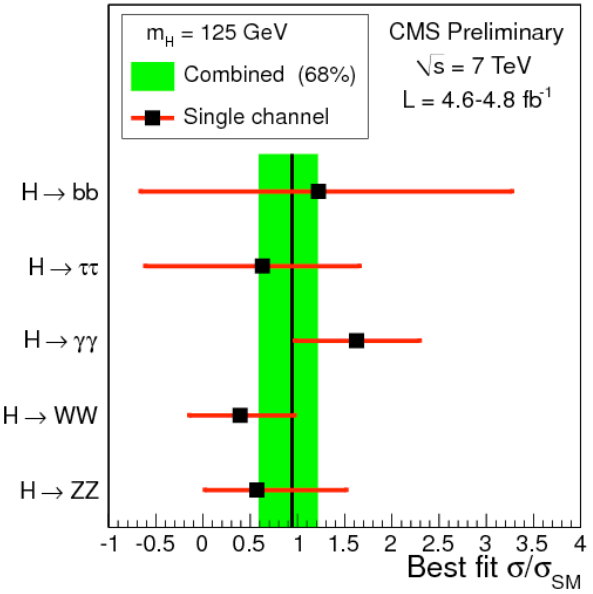


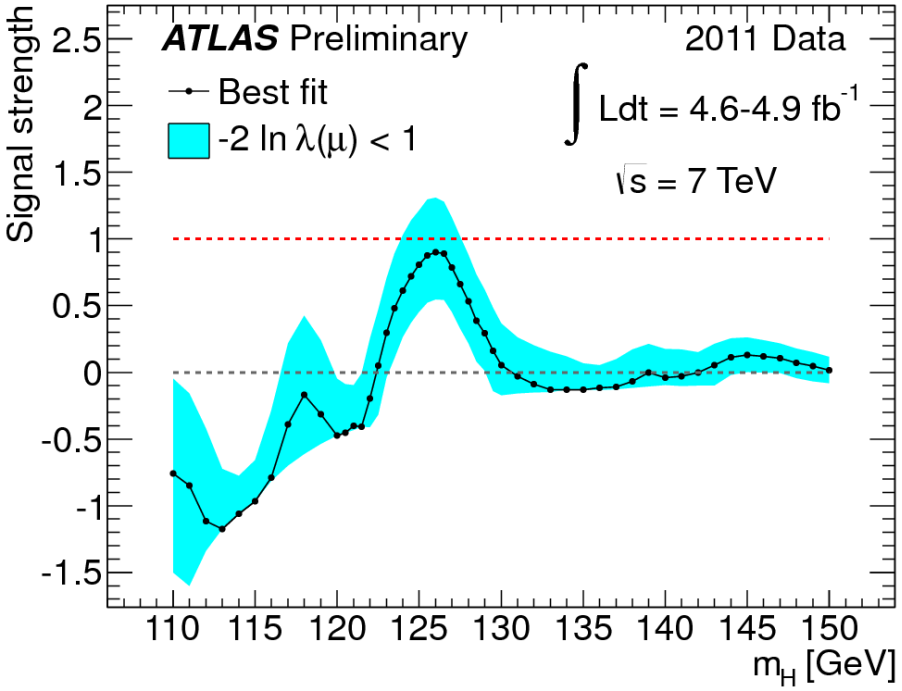
By yesterday evening, LHC had delivered 2.8 fb^{-1} at 8 TeV

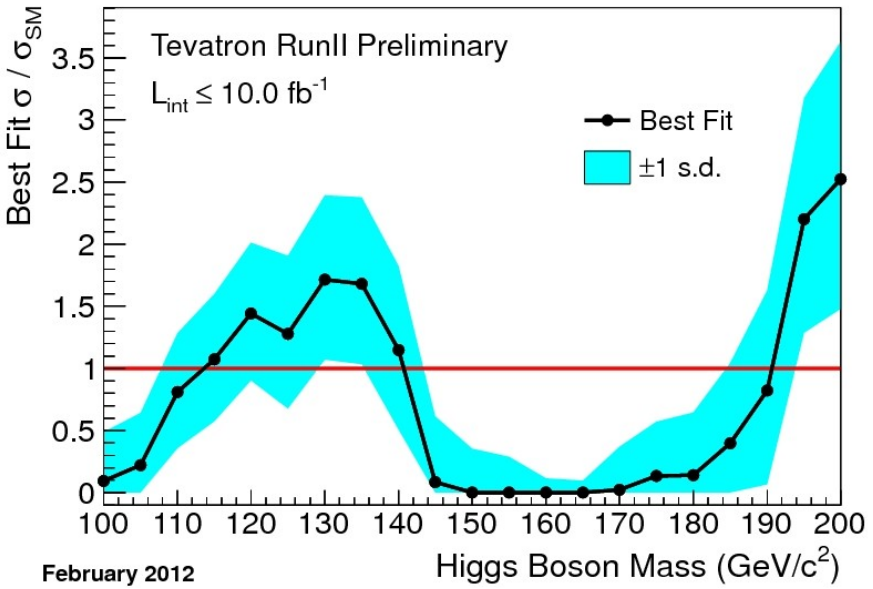
Backup

Does the Excess Look Like a SM Higgs?

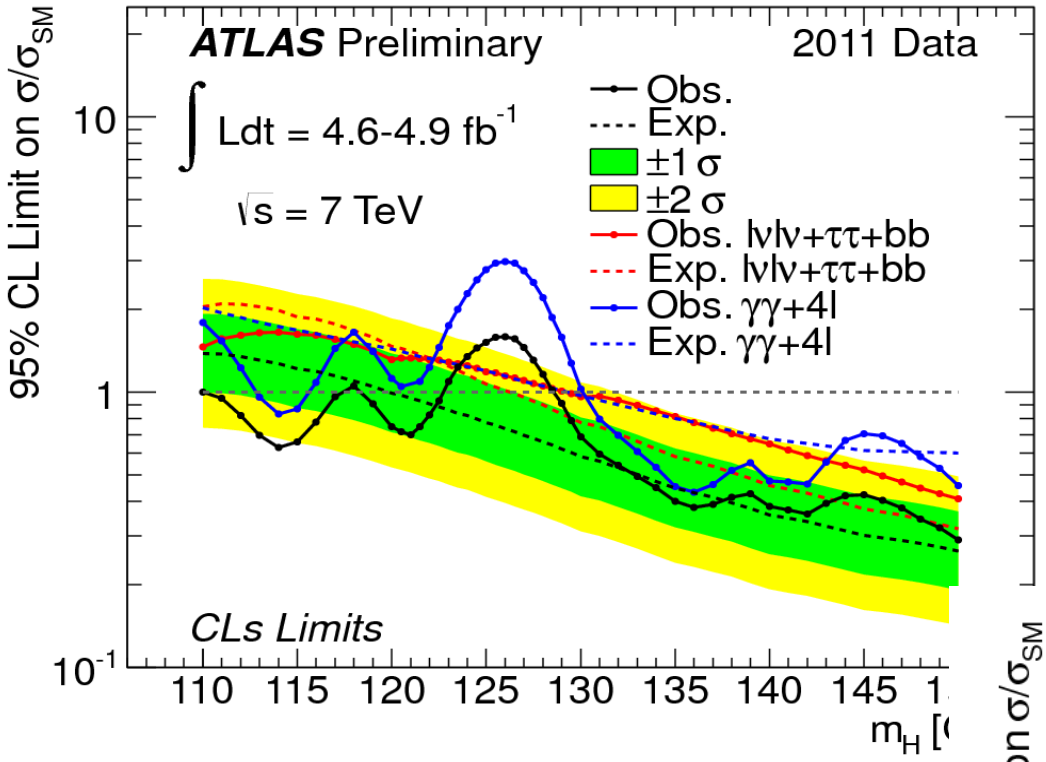


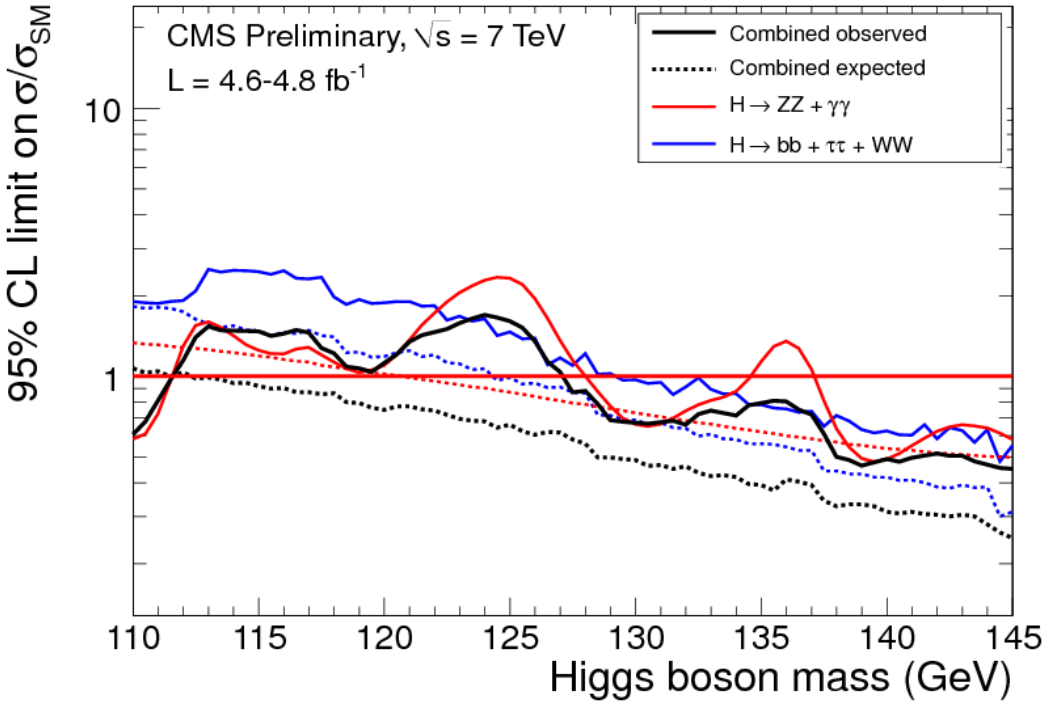




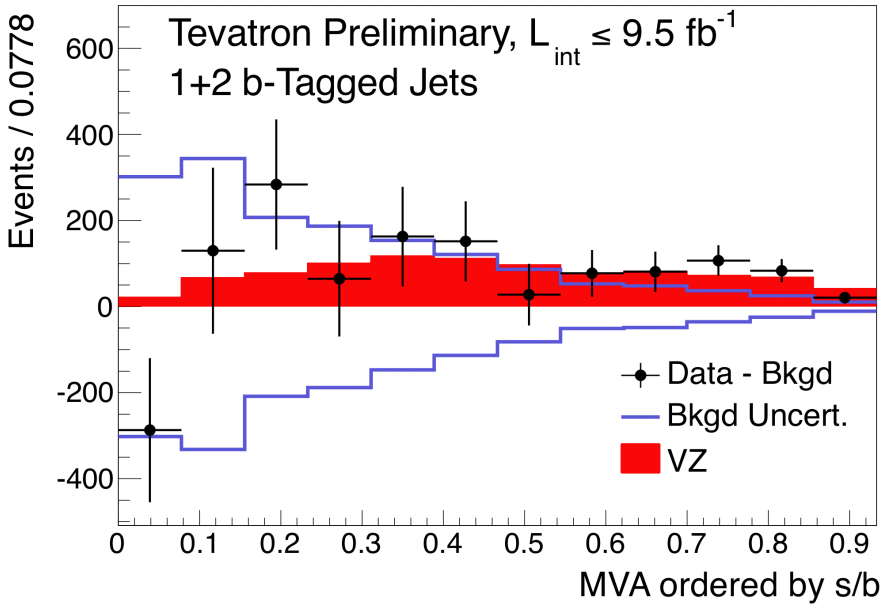


Does the Excess Look Like a SM Higgs?

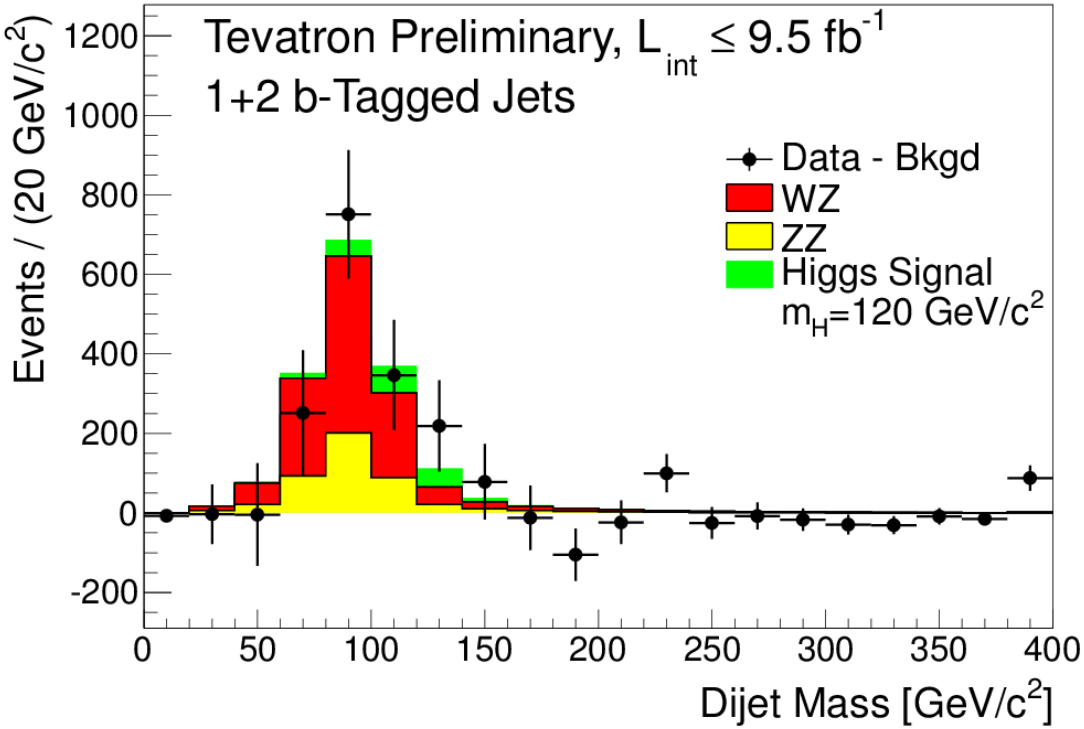


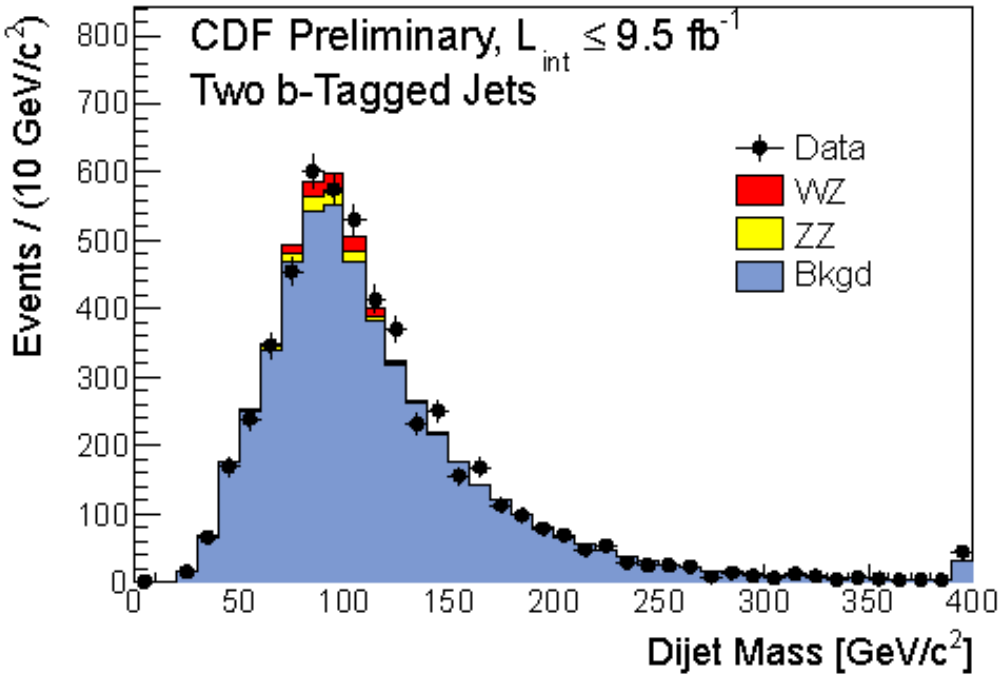


Tevatron - Proof of Principle



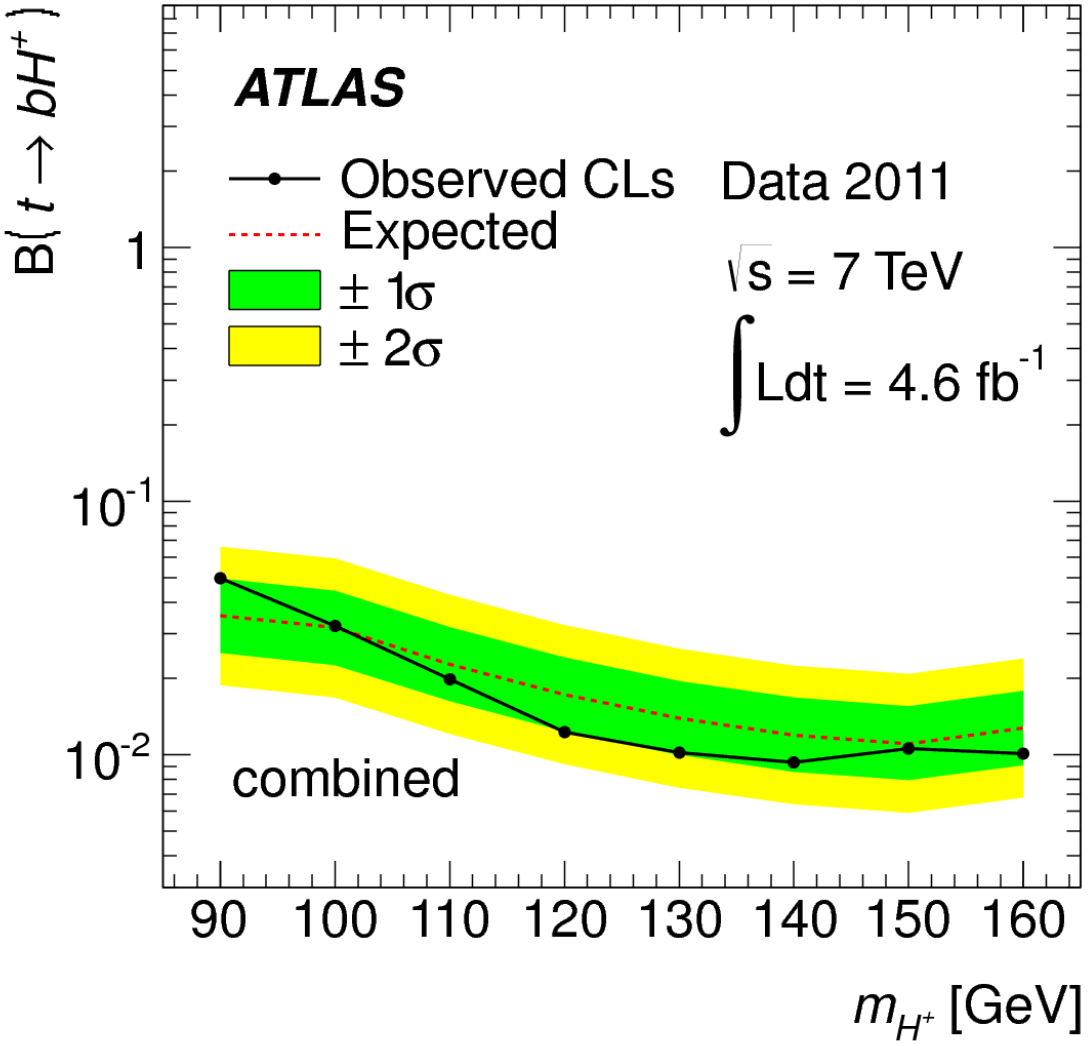
W Fisher, Moriond EW 2012

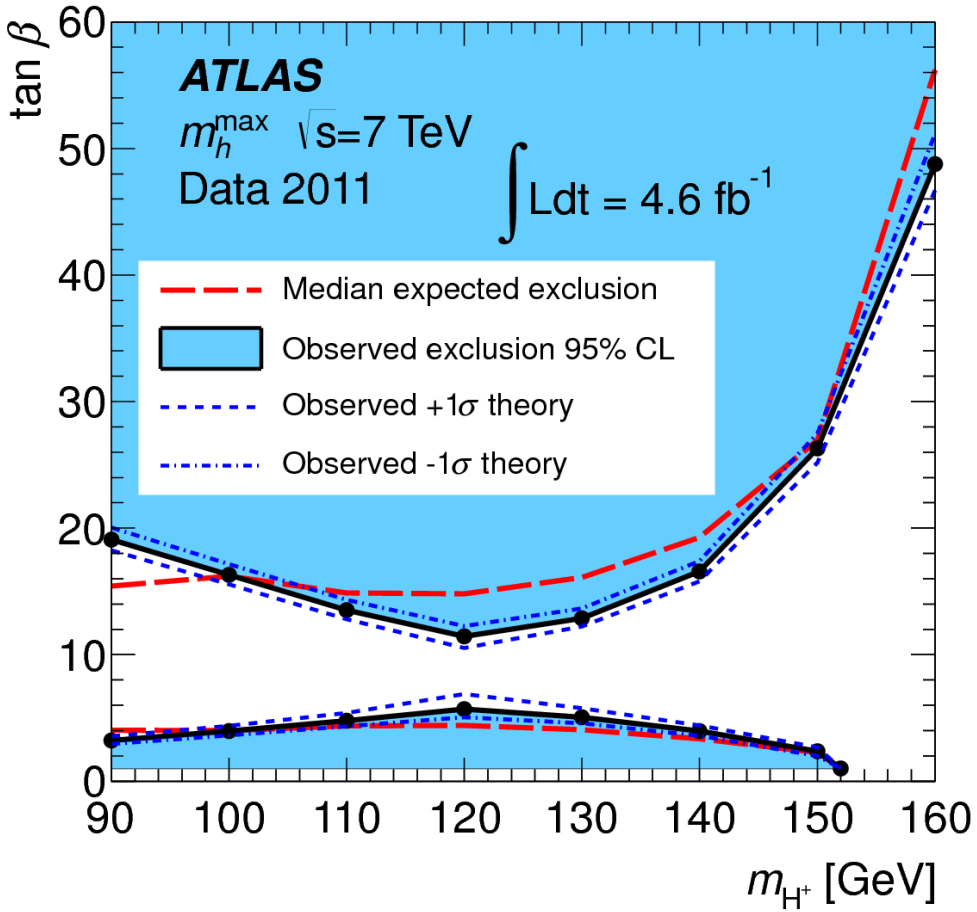


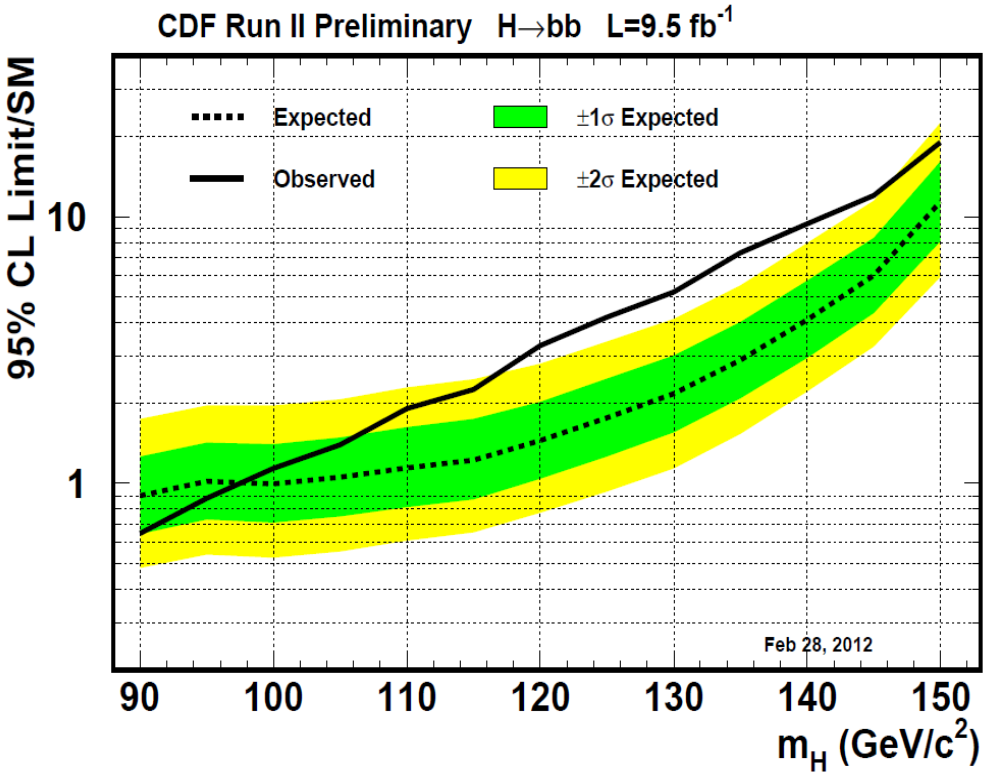


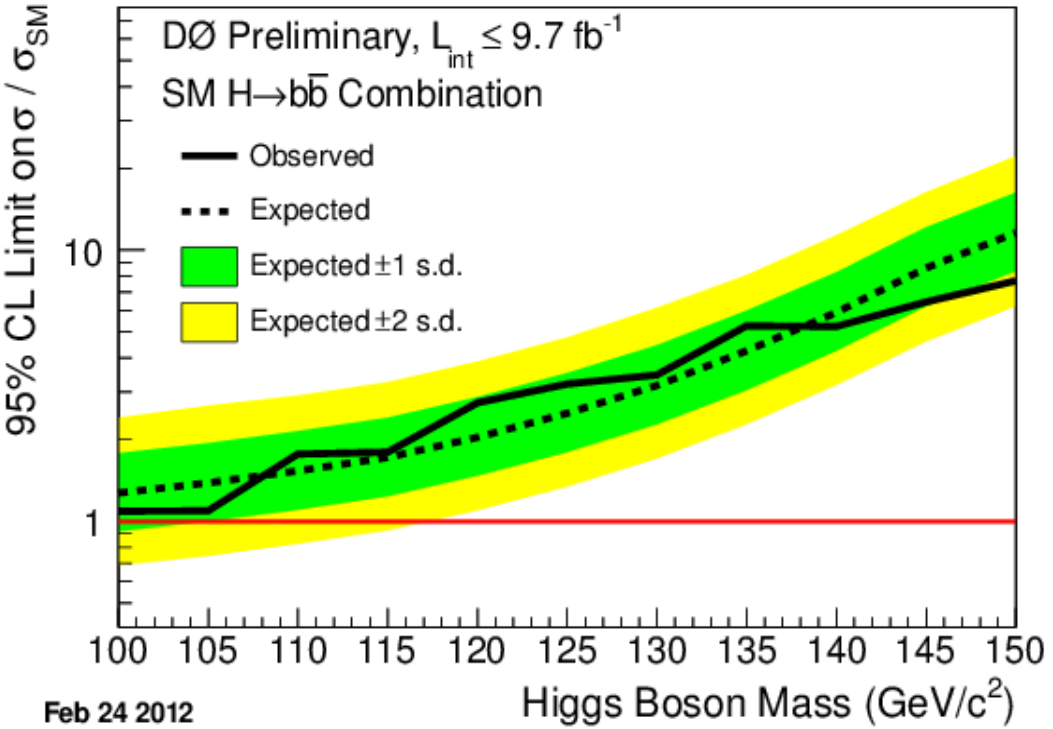
Charged Higgs

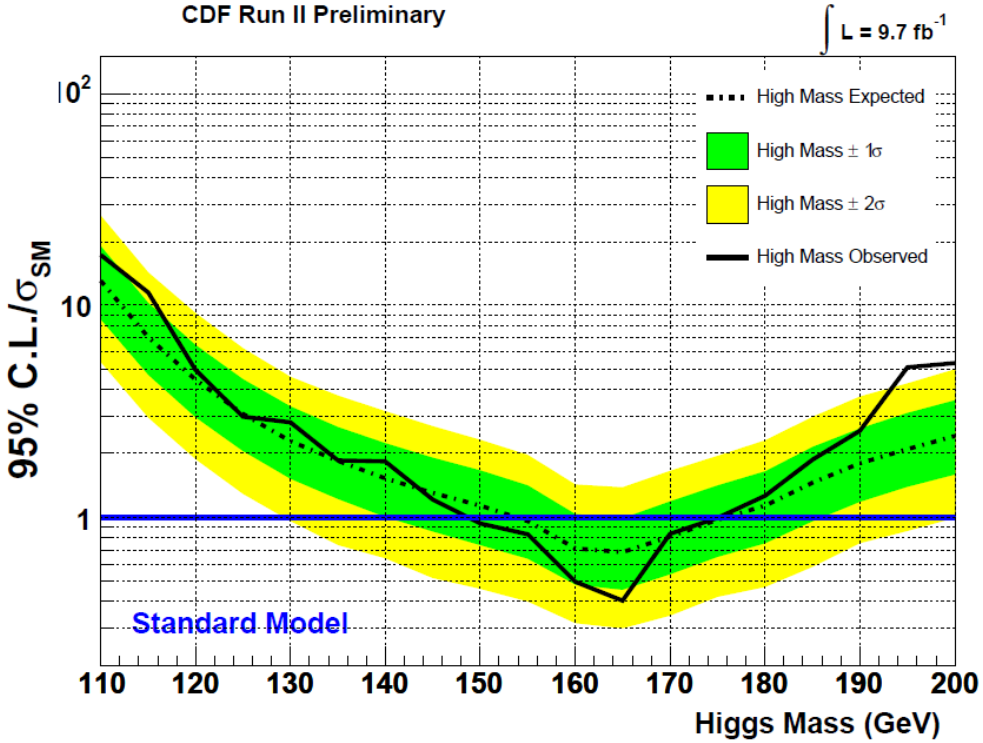
ATLAS as example

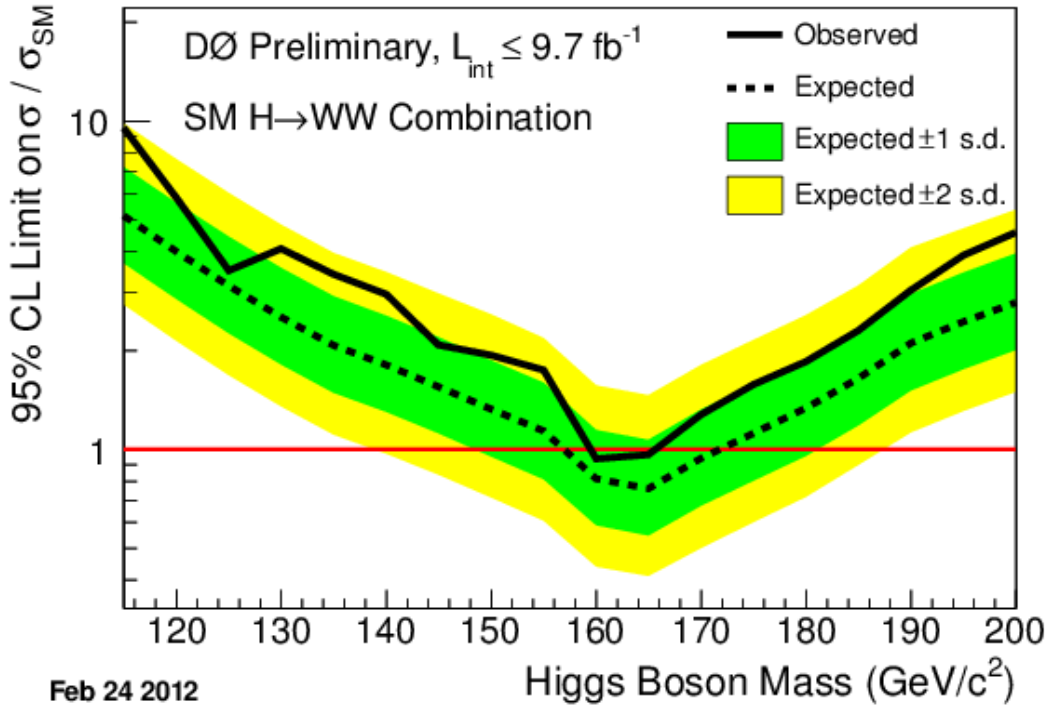




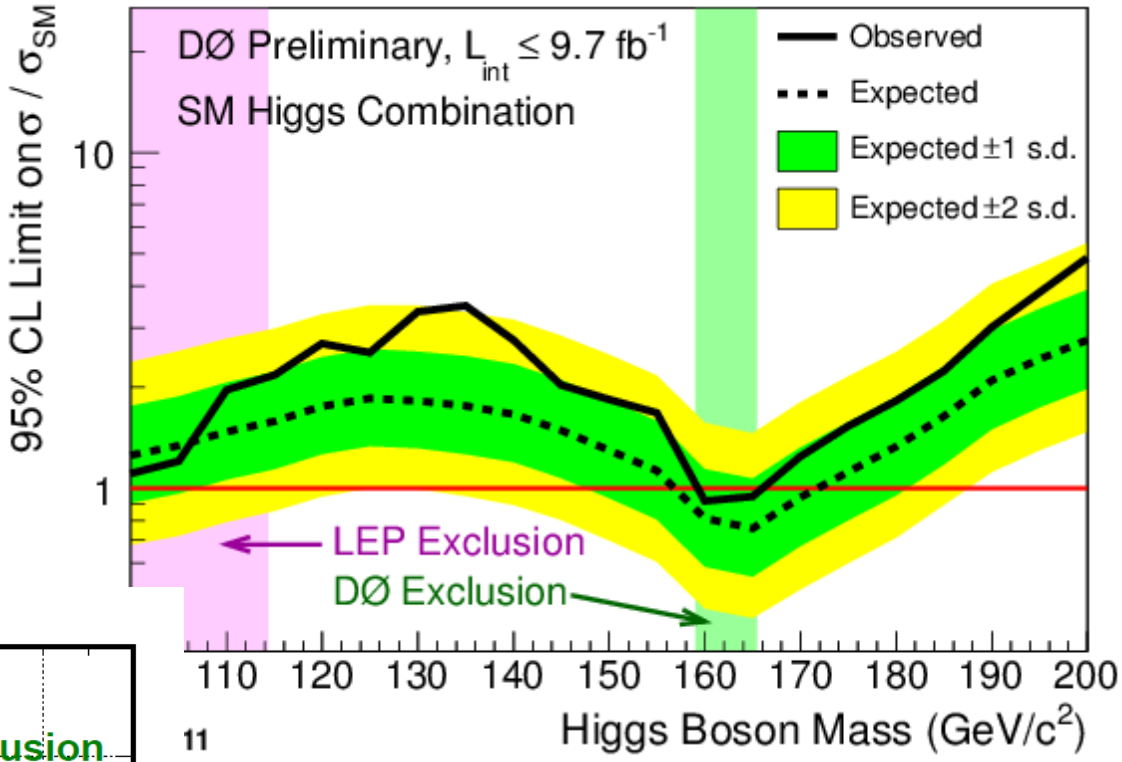

CDF Run II Preliminary H→bb L=9.5 fb-1
Expected
±1σ Expected
Observed
±2σ Expected
Feb 28, 2012
95% CL Limit/SM
10
1
90
100
110
120
130
140
150
mH (GeV/c2)

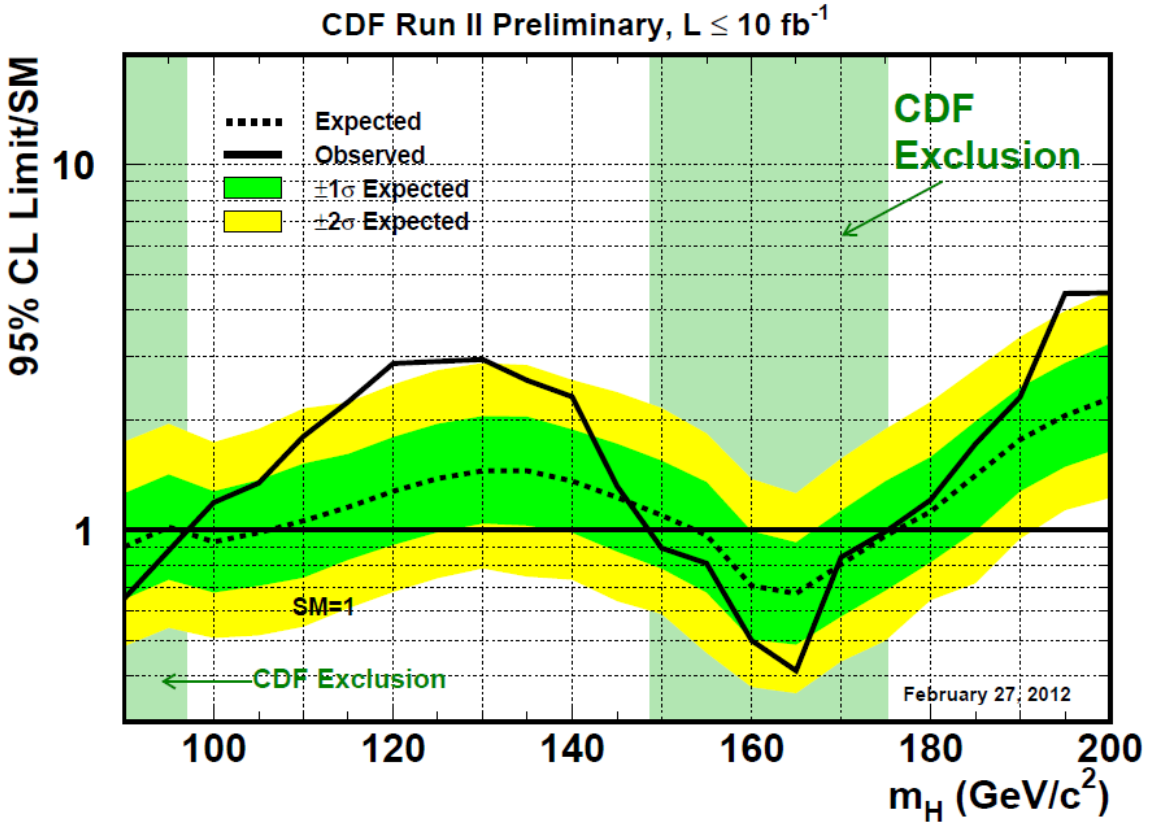

DØ Preliminary, Lint ≤ 9.7 fb-1
SM H→bb̄ Combination
Observed
Expected
Expected ±1 s.d.
Expected ±2 s.d.
95% CL Limit onσ / σSM
10
1
100
105
110
115
120
125
130
135
140
145
150
Feb 24 2012
Higgs Boson Mass (GeV/c2)


CDF Run II Preliminary
∫ L = 9.7 fb-1
High Mass Expected
High Mass ± 1σ
High Mass ± 2σ
High Mass Observed
95% C.L./σSM
10
1
Standard Model
110
120
130
140
150
160
170
180
190
200
Higgs Mass (GeV)

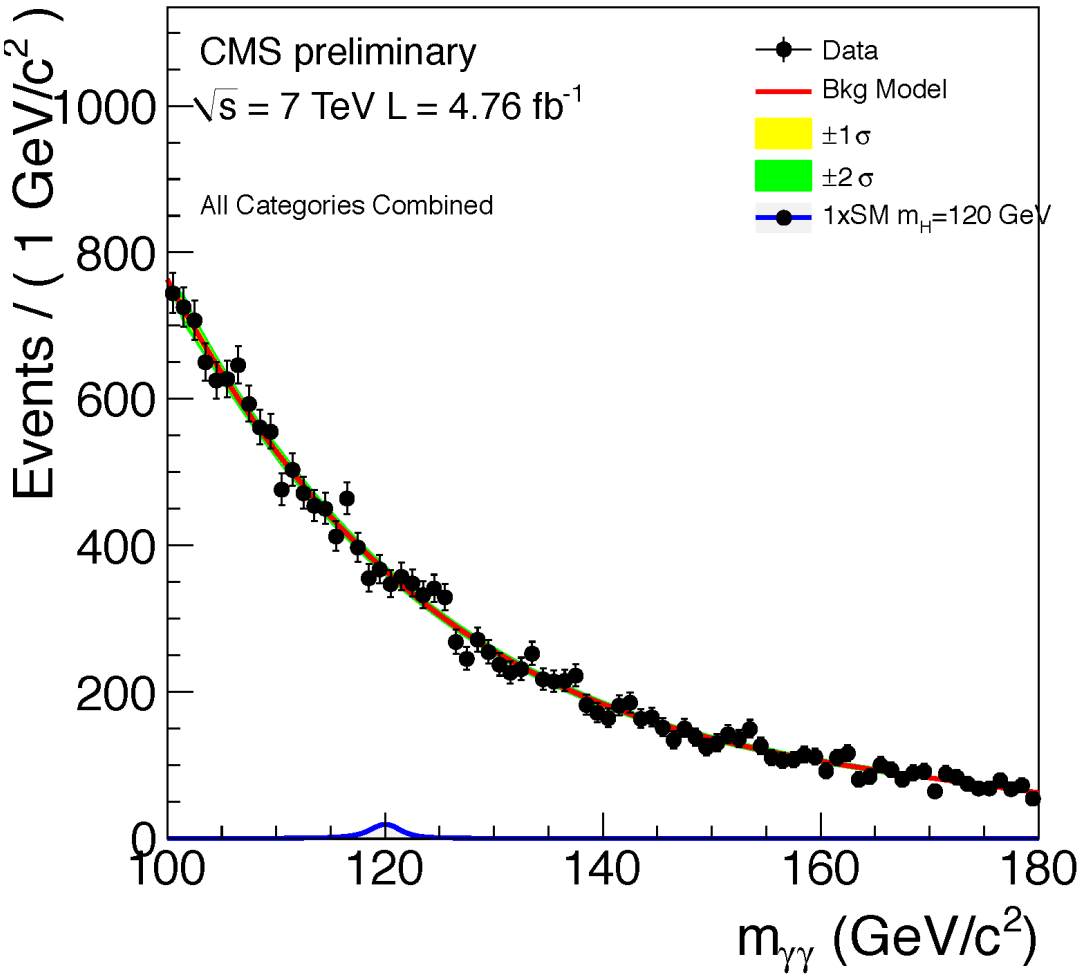

DØ Preliminary, Lint ≤ 9.7 fb-1
SM H→WW Combination
Observed
Expected
Expected ±1 s.d.
Expected ±2 s.d.
95% CL Limit onσ / σSM
10
1
120
130
140
150
160
170
180
190
200
Feb 24 2012
Higgs Boson Mass (GeV/c2)

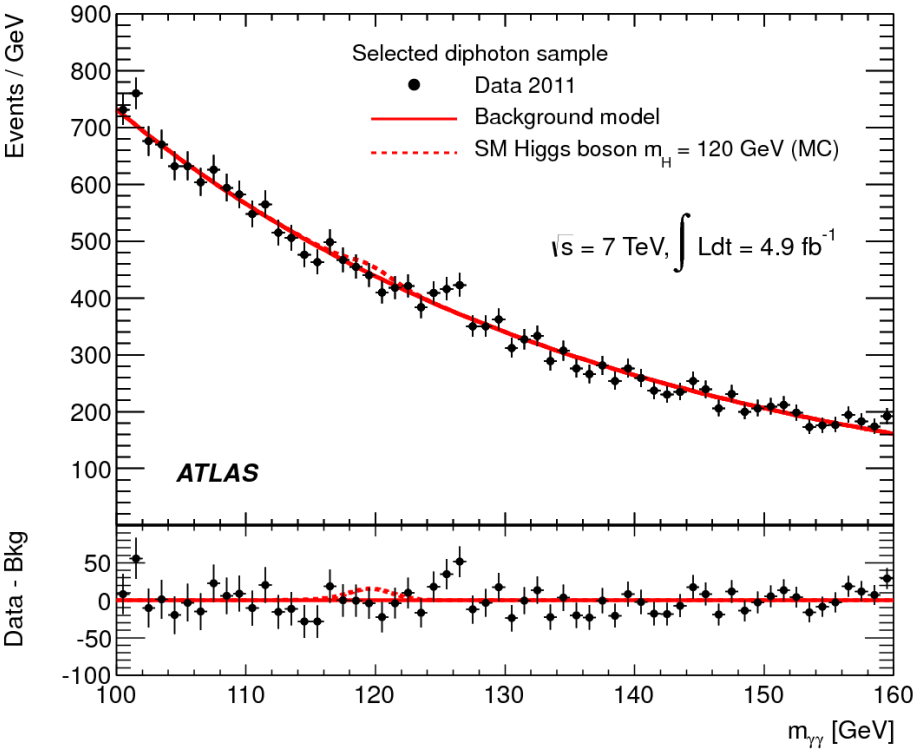
Tevatron - Individual Experiment Limits





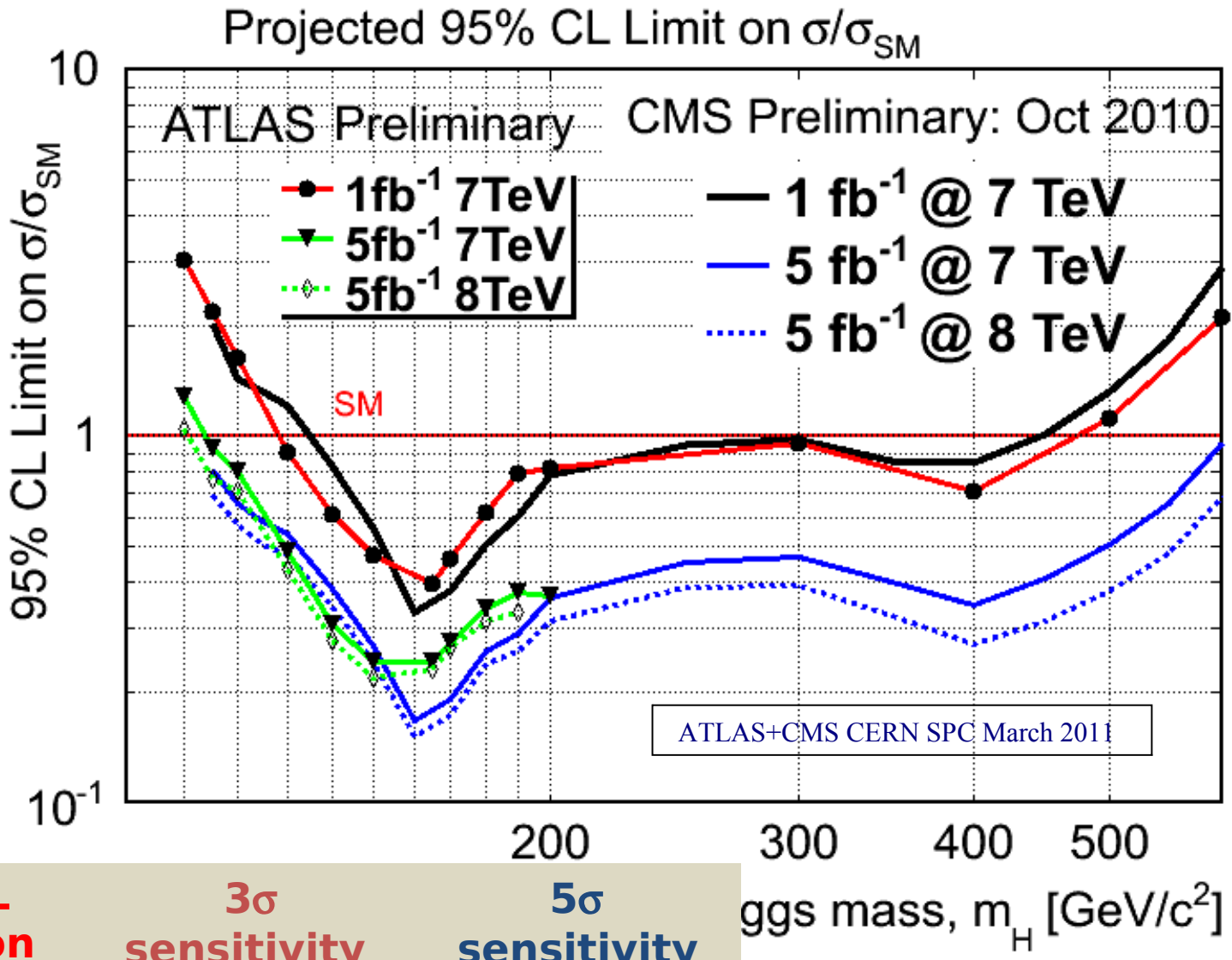
H → γγ


CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1σ
±2σ
1xSM mH=120 GeV
Events / (1 GeV/c2)
mγγ (GeV/c2)


Selected diphoton sample
Data 2011
Background model
SM Higgs boson mH = 120 GeV (MC)
√s = 7 TeV, ∫ Ldt = 4.9 fb-1
ATLAS
Events / GeV
Data - Bkg
mγγ [GeV]

March 2011

In the "good old days"

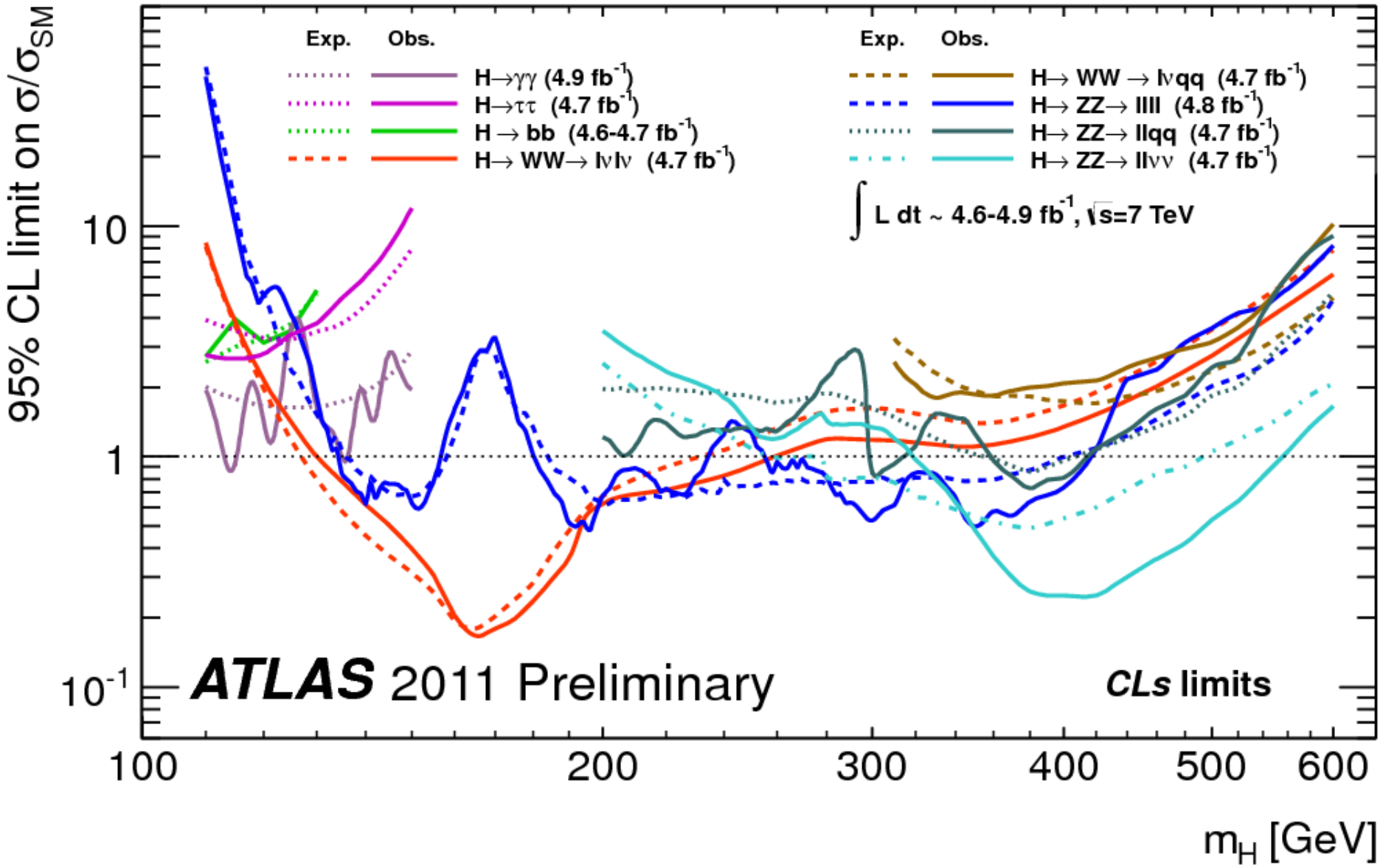


NB: ATLAS+CMS

ATLAS+CMS 7 TeV	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

ATLAS Combination

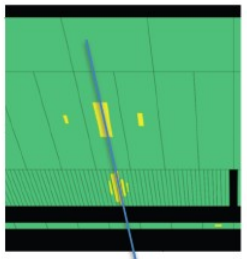
ATLAS-CONF-2012-019



Detectors Designed for the Higgs Search

The LHC detectors are designed for the Higgs search

- Excellent lepton and photon ID (η coverage, jet rejection, resolution...) despite "thick" trackers
- Excellent E_T^{miss} performance
- Hermetic calorimetry out to $|\eta| \sim 5$
- Detector design and sophisticated algorithms against pileup

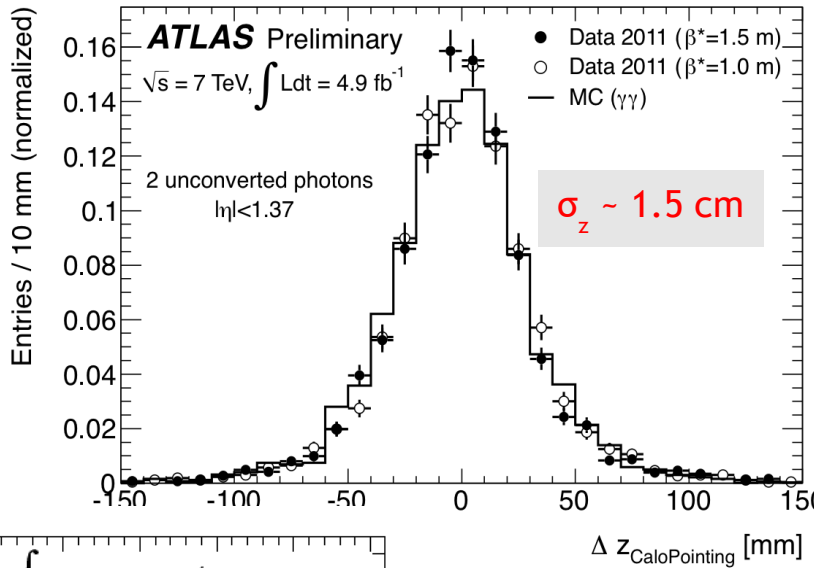


1.- Measure photon direction

ϑ

2.- Deduce z of PV

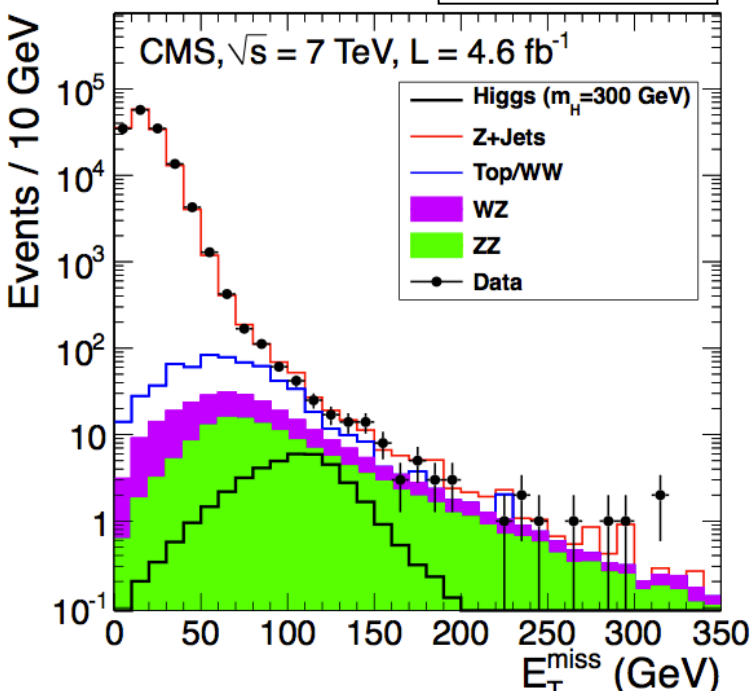
z-vtx pointing - important for $m_{\gamma\gamma}$

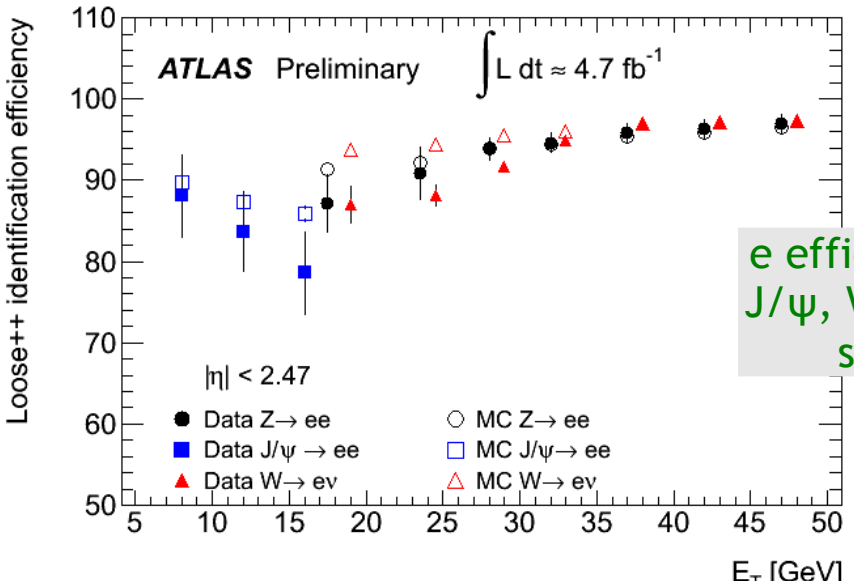


$\sigma_z \sim 1.5$ cm

E_T^{miss} in $Z \to \ell\ell$ events from $\ell\ell\nu\nu$ preselection

arXiv:1202.3478





e efficiency from J/ψ, W, Z control samples