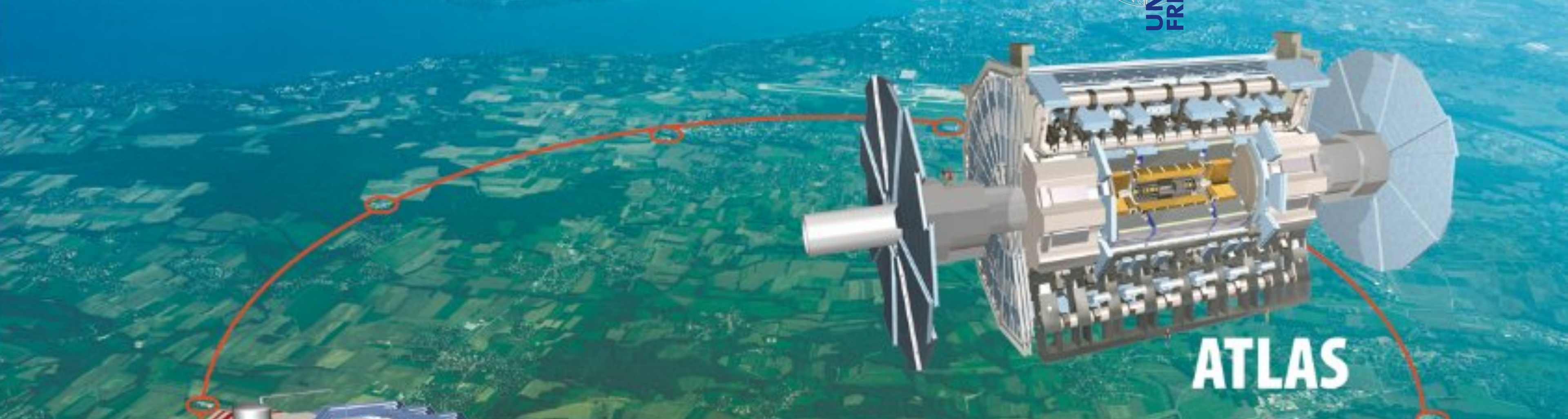
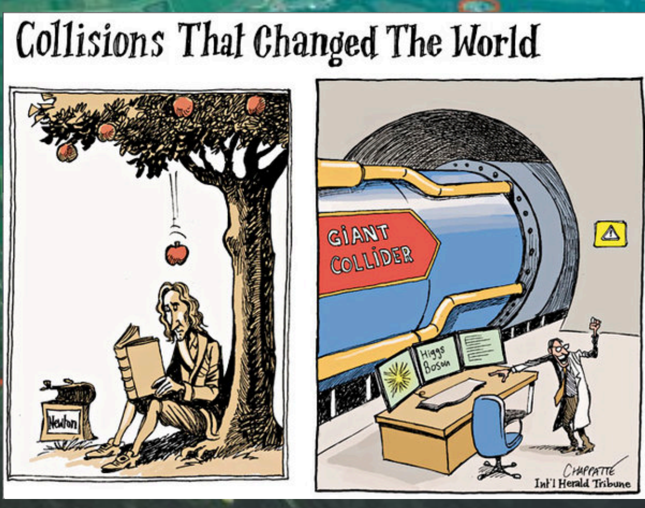
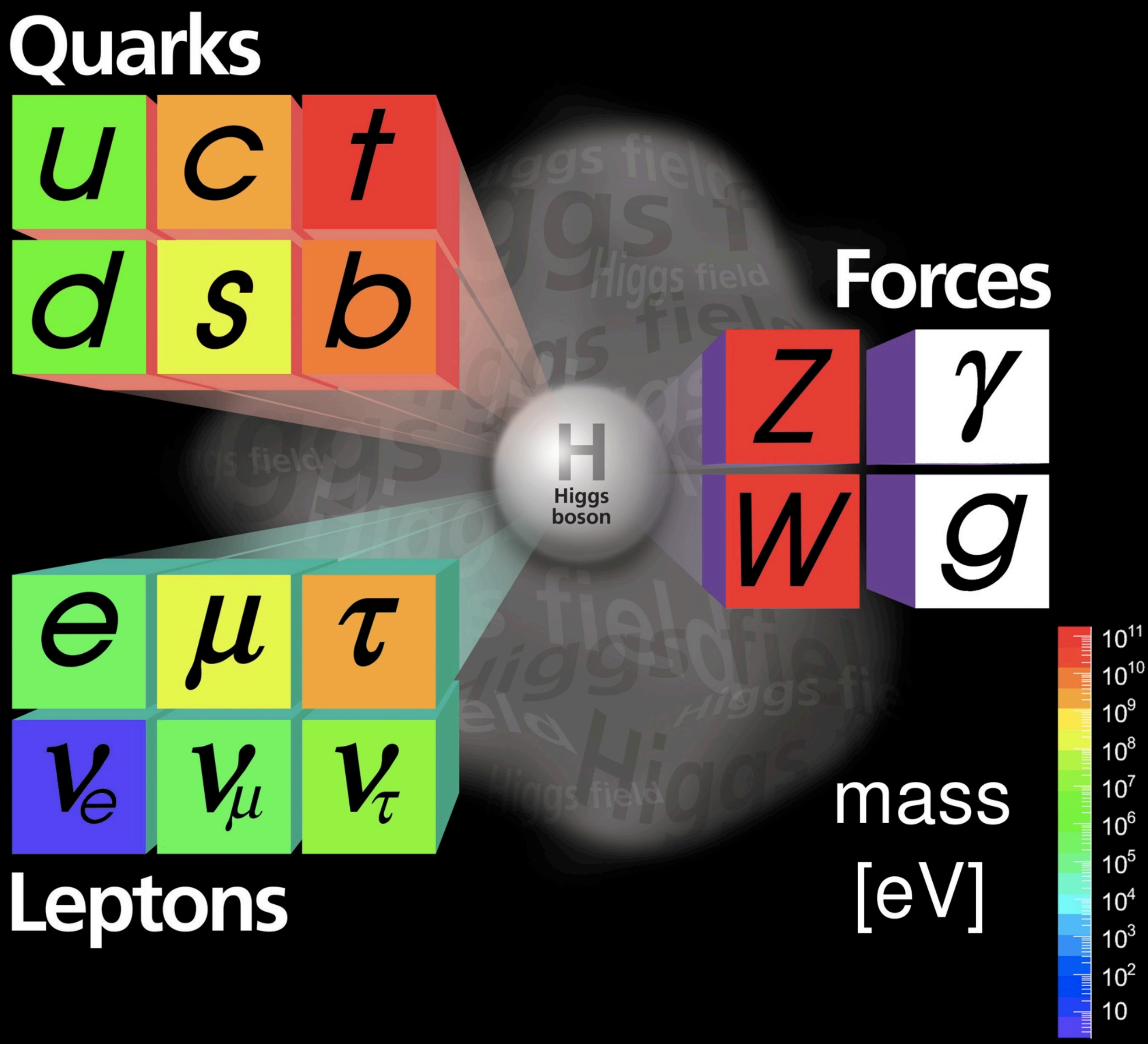
Search for the Higgs Boson of the Standard Model at the LHC

Markus Schumacher
Neckarzimmern, 22 February 2012





Without the Higgs Boson the SM is Incomplete

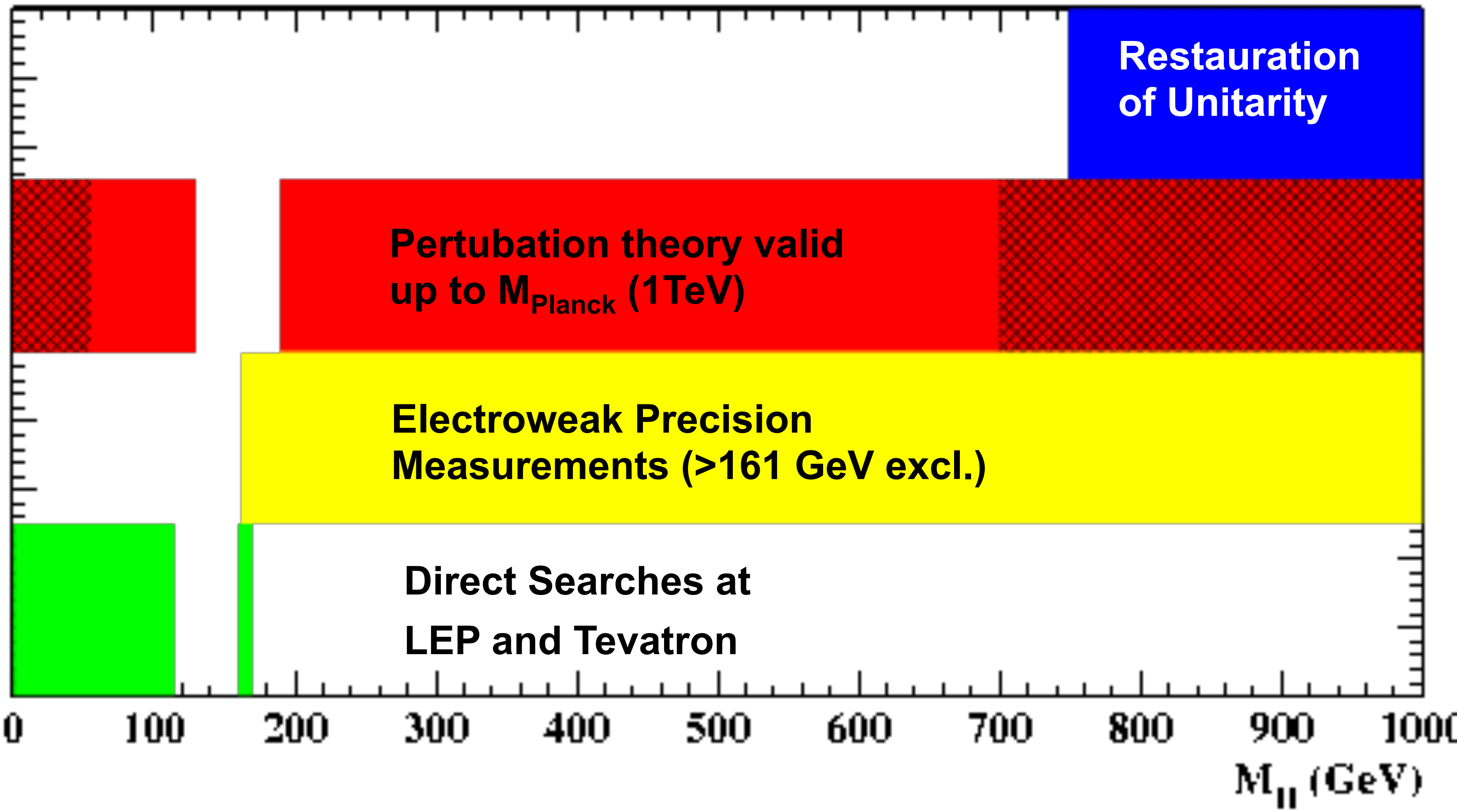


in the SM the complete profile of the Higgs is known if we specify its mass

the Higgs boson mass is the last unknown parameter of the SM

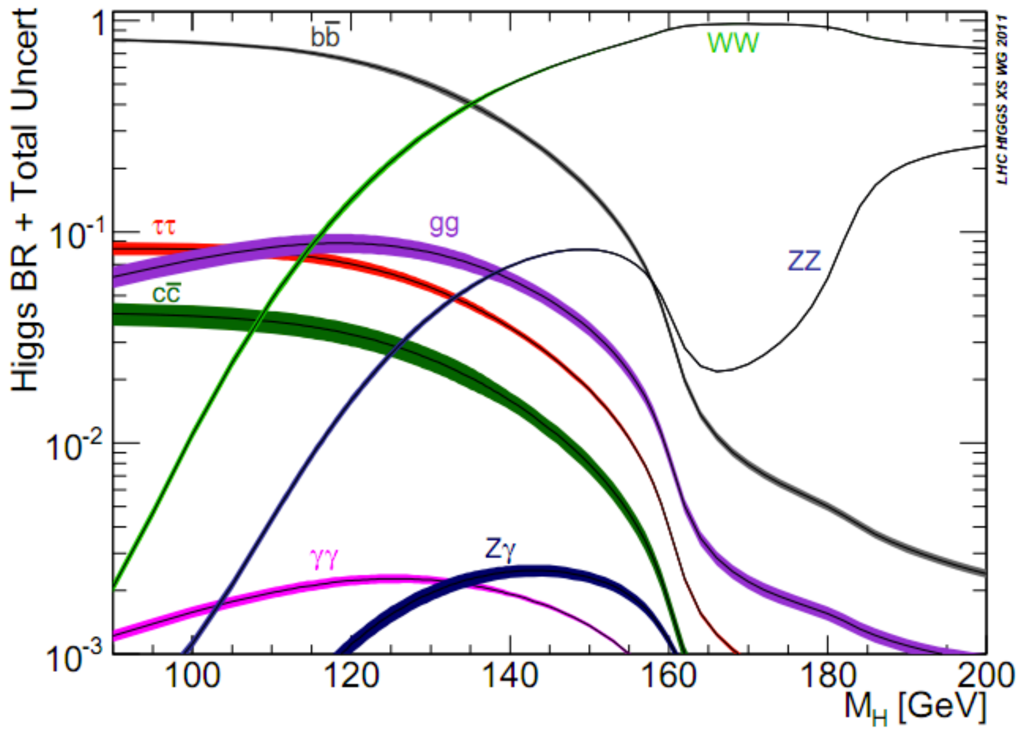
whether a Higgs boson is realised in nature is unclear

Knowledge About the Higgs Boson Mass Before LHC

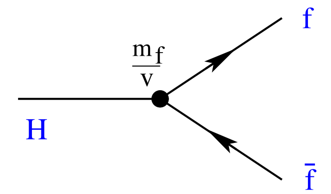


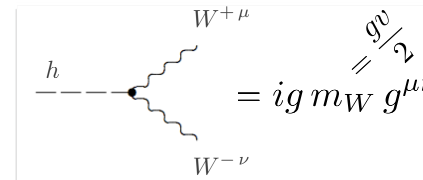
the Standard Model prefers a light Higgs boson

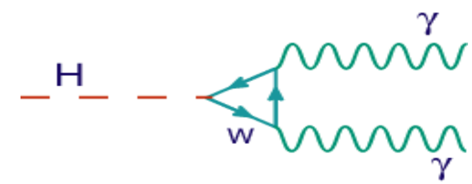
Higgs Boson Decay: Branching Ratios



$$g_{Hff} = i\frac{m_f}{v} \;,\; g_{HVV} = -2i\frac{M_V^2}{v} \;,\; g_{HHVV} = -2i\frac{M_V^2}{v^2}$$



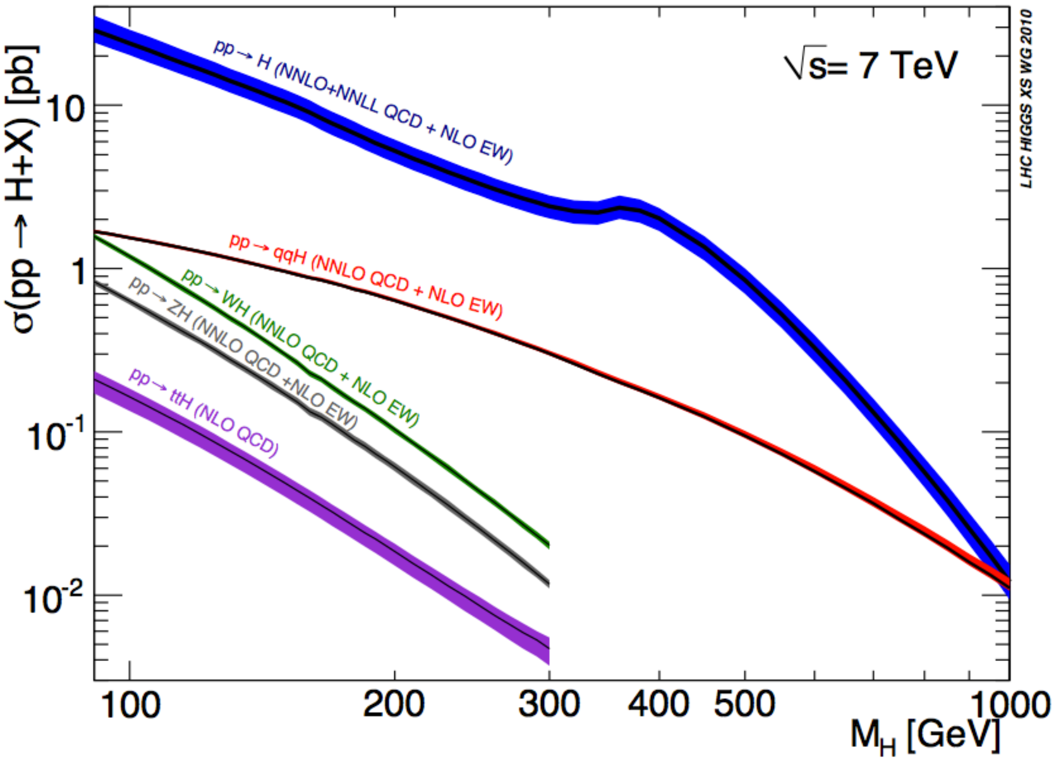




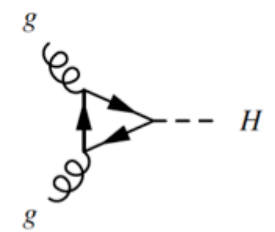
MH	Decay	THU	PU	Total
120 GeV	H→γγ	±2.9%	±2.5%	±5.4%
	H→bb	±1.3%	±1.5%	±2.8%
	H→ττ	±3.6%	±2.5%	±6.1%
150 GeV	H→WW	±0.3%	±0.6%	±0.9%
	H→ZZ	±0.3%	±0.6%	±0.9%

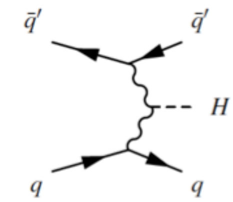
huge common effort by theorists and experimentalists to compile and agree on central values and uncertainties
(LHC Higgs Cross Section WG)

Higgs Boson Production at LHC



ggF: NNLO+NNLL QCD+NLO EW

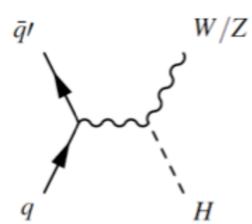


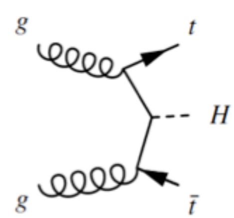


qqH: NNLO QCD + NLO EW

WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW

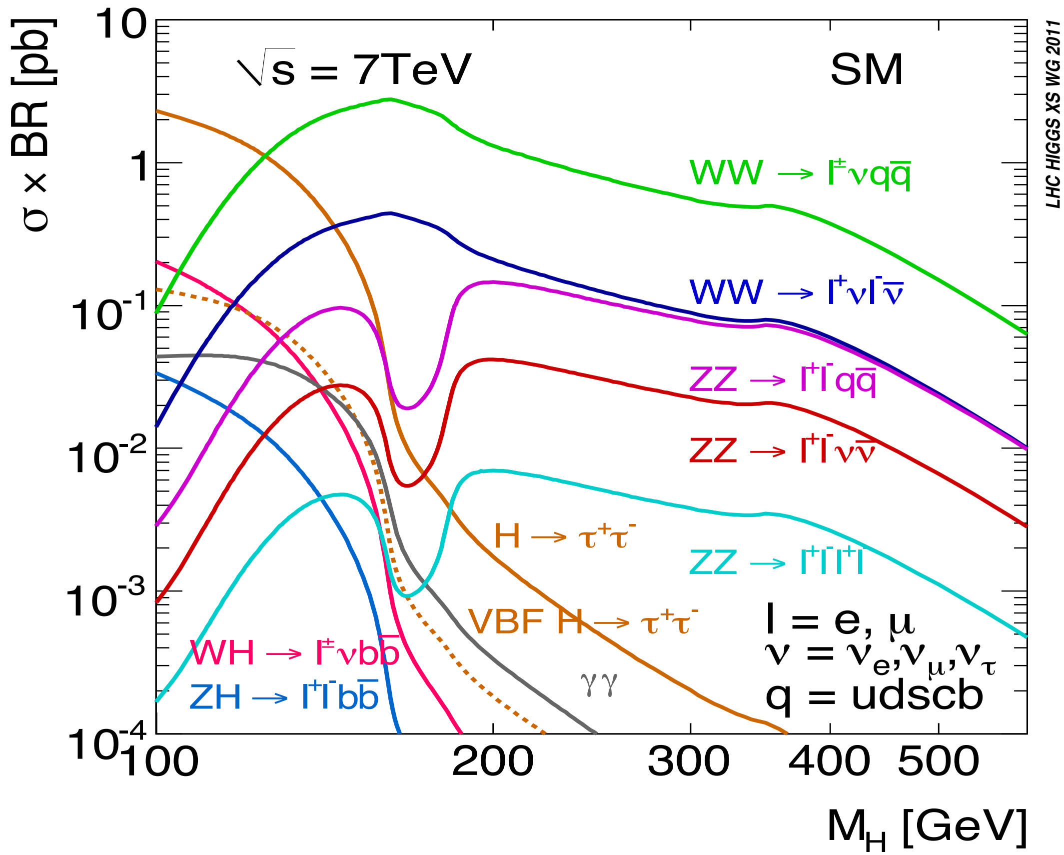




ttH: NLO QCD

	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF $+\alpha_S$	Total error
ggF	+25% (+100%)	+12% -7%	±8%	+20 -15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% -10%	±8%	+12 -18%

Signal Rates in Accessible Channels

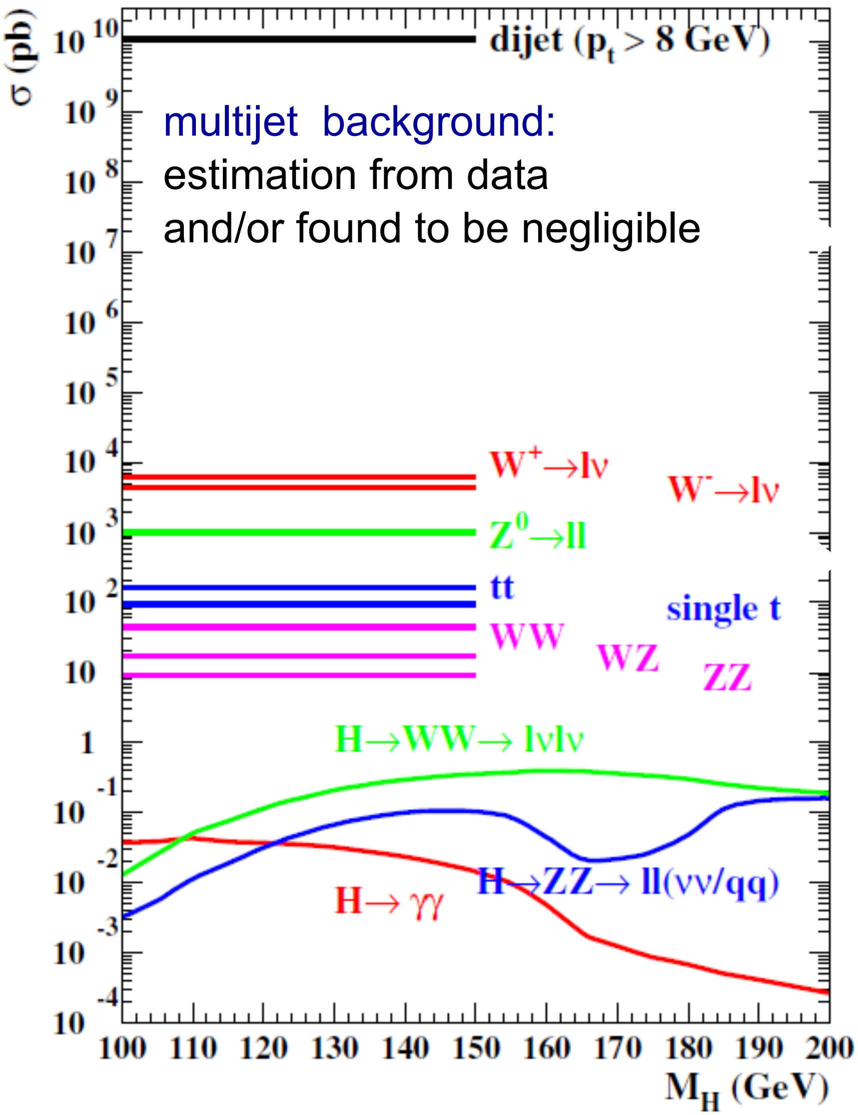


Events expected to be produced with L=1 fb^{-1}

m_H, GeV	WW→lvlv	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

trigger issues and overhelming backgrounds
forbid to search in highest rate channels
ggf and VBF with H→bb and H→VV→4q

Reminder of the Challenge and Tasks



choose production times decay, which can be triggered and has sufficient rate

suppress reducible backgrounds
→ identification and reconstruction of physics objects in final state

suppress irreducible backgrounds
→ find discriminating variables
e.g. topological cuts, mass of H candidate

evaluate backgrounds
if possible with as less input from simulation as possible → data-driven

investigate systematic uncertainties

look at findings and interprete results

Luminosity and Pile-up

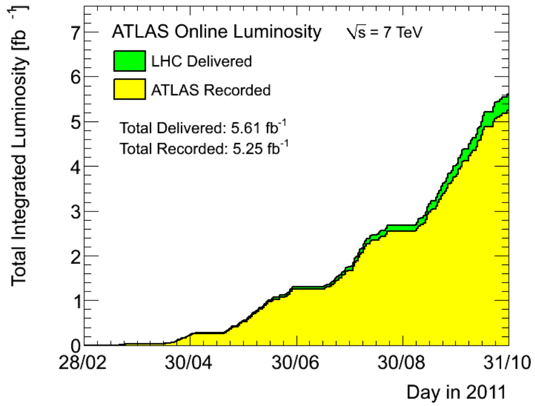
Proton Runs 2010 & 2011

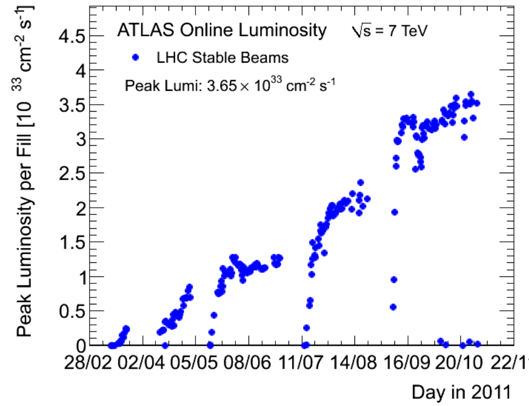
Highest luminosity = $3.65 \cdot 10^{33}$ cm^{-2}s^{-1}

Total Collisions = $350 \cdot 10^{12}$ = 350 000 000 000 00(

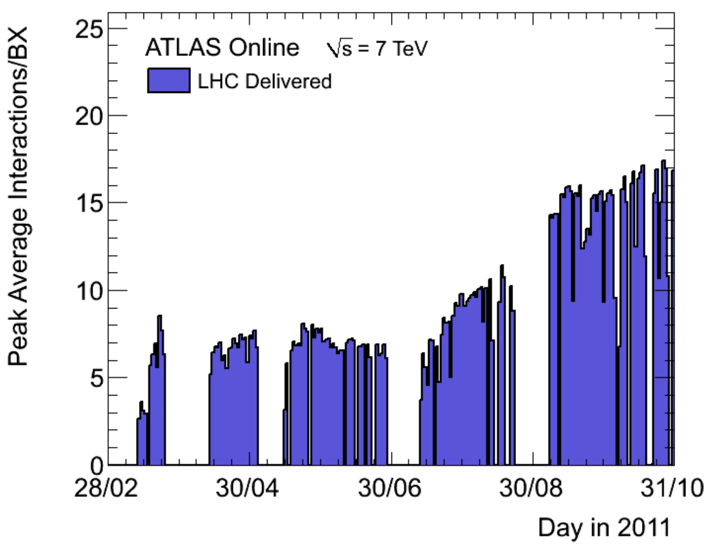
Recorded luminosity = 5.257 fb^{-1}

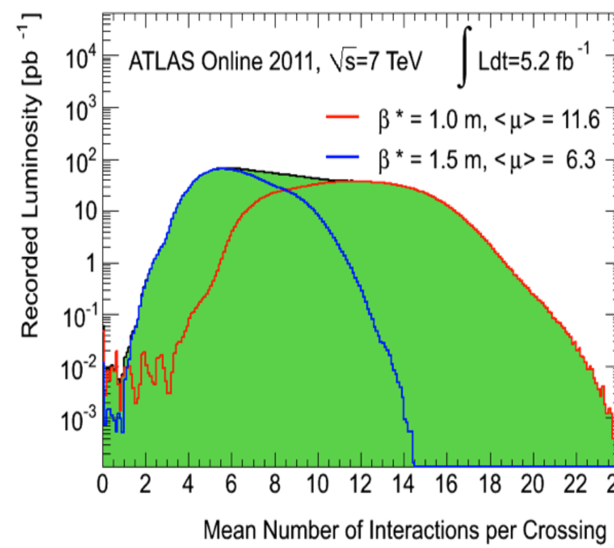
excellent performance of LHC





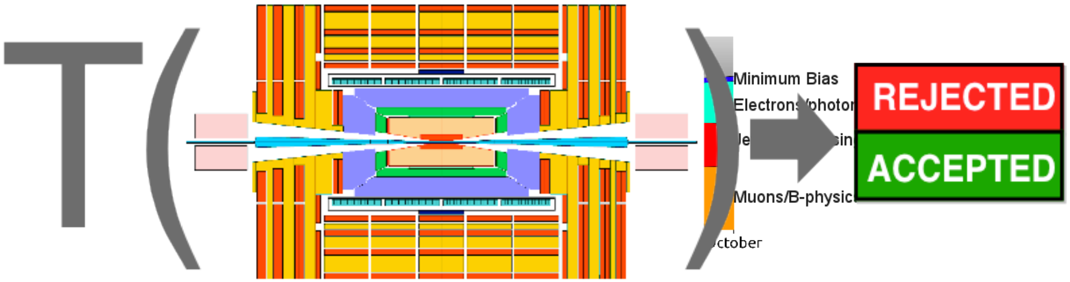
the price to pay: up to 25 overlayed minimum bias interactions





Event Selection: 1st Step is the Trigger

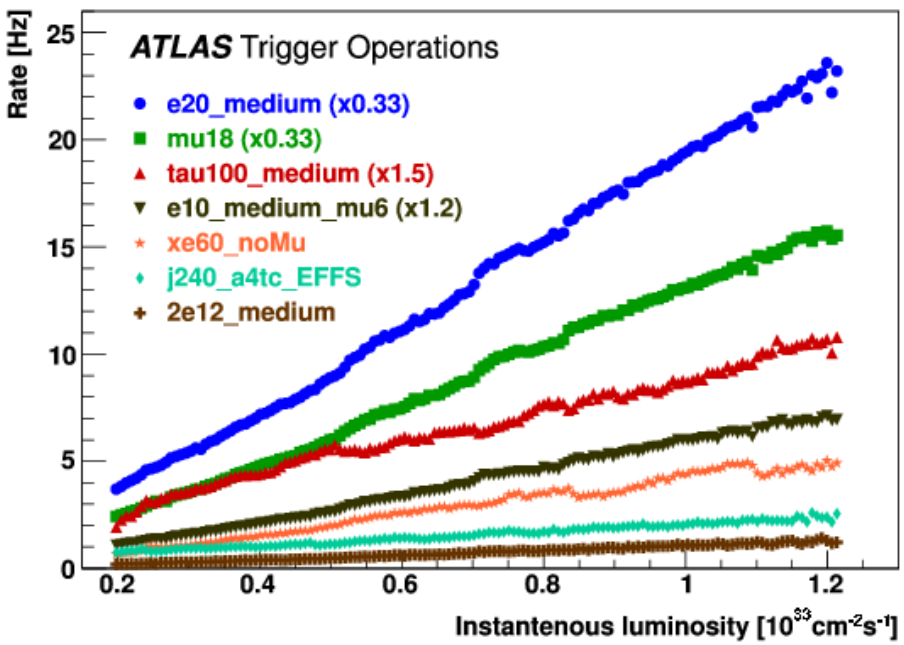
The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

reduce collision rate of 20 MHz

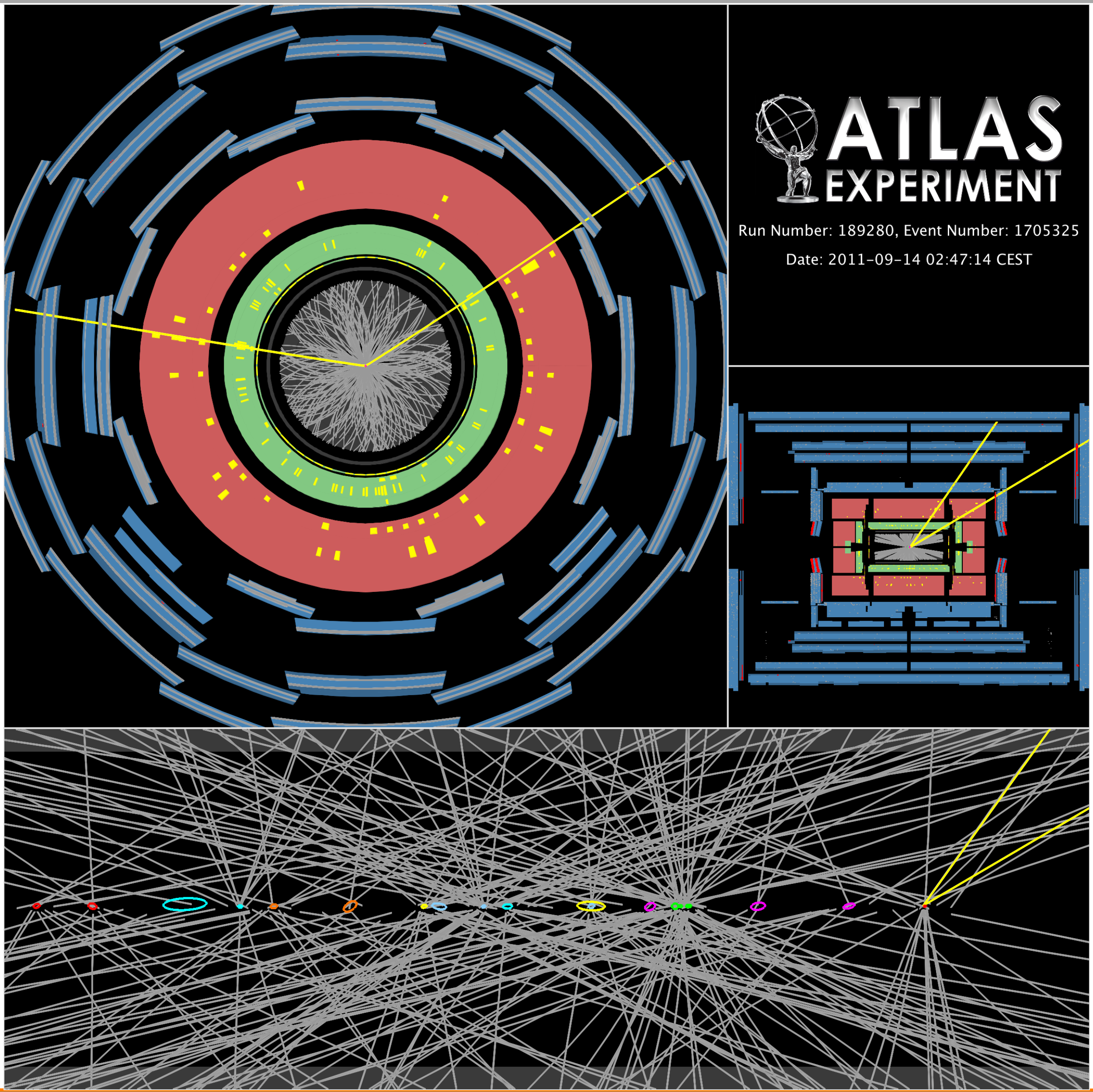
to recording rate of few 100 Hz



Higgs searches mostly rely
on lepton and photon triggers

increase in peak luminosity
→ increase in trigger rate
→ increase in p_t thresholds
and use di-object triggers

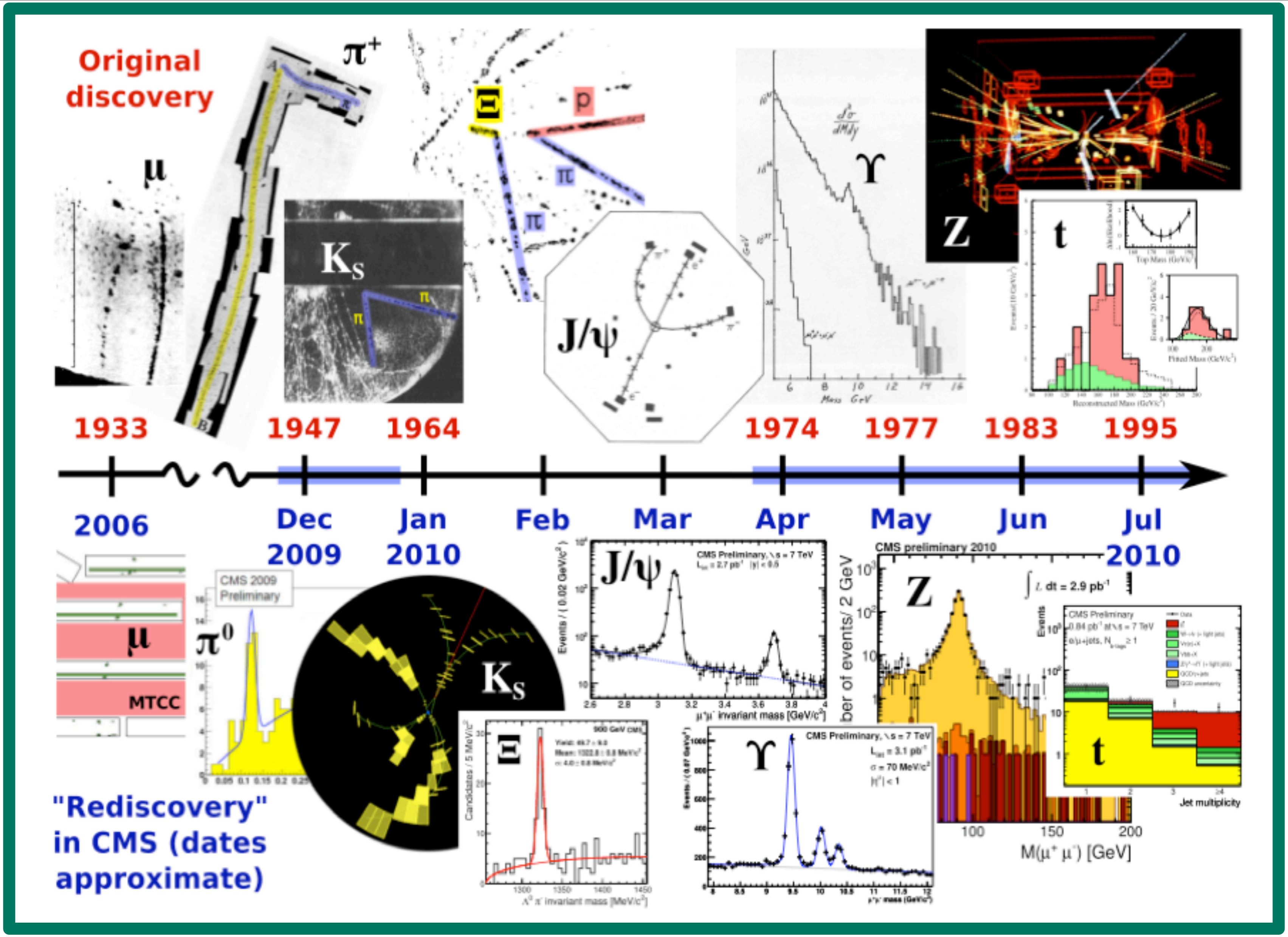
The Challenge of Pile-Up



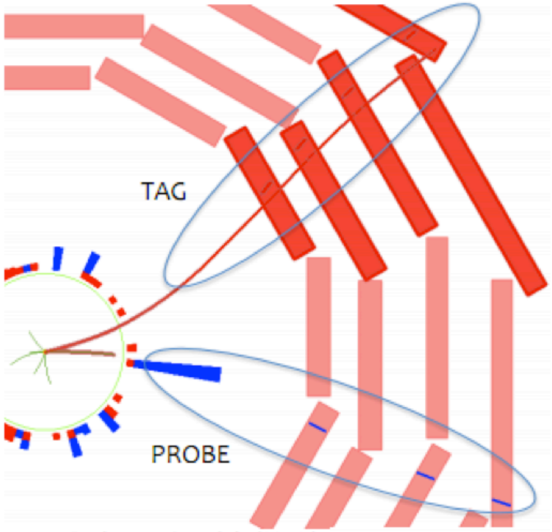
detoriates in principle:
- identification(ID) efficiencies
- isolation efficiencies
- jet energy and missing transverse energy MET resolutions

tools to recover:
- develop robust ID algorithms
- assign tracks and jets to primary vertex
- correct for pile-up contribution on event by event basis

Rediscovery of the SM in 2010



Understanding of Detector: Example Muons

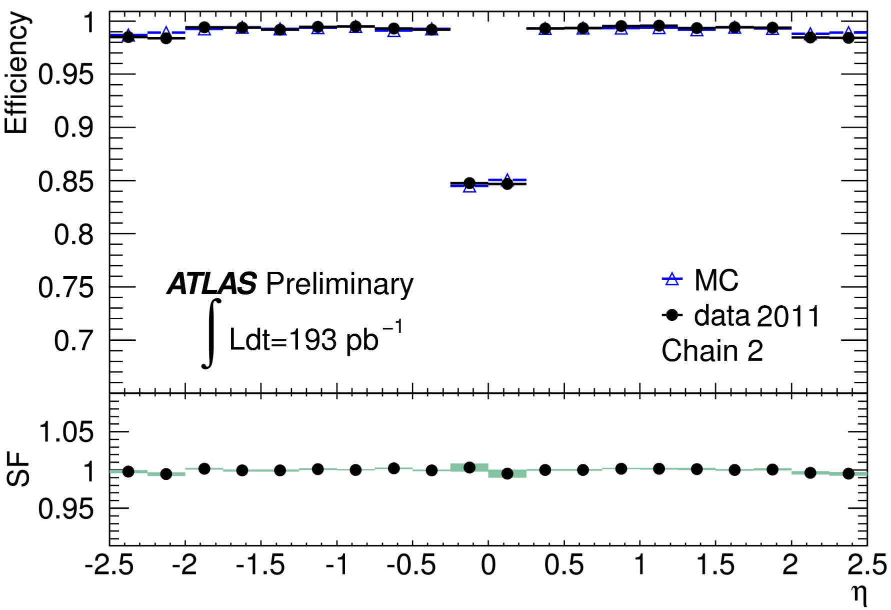


select samples with one tight muon and one track

Z and J/Ψ → $\mu_{tight}\ \mu_{candidate}$ („tag“&“probe“)

→ determine efficiencies in data and simulation

$$\varepsilon_{\mu} = \varepsilon_{reco/(track)} * \varepsilon_{ID/reco} * \varepsilon_{ISO/ID} * \varepsilon_{trigger1leg/ISO}$$

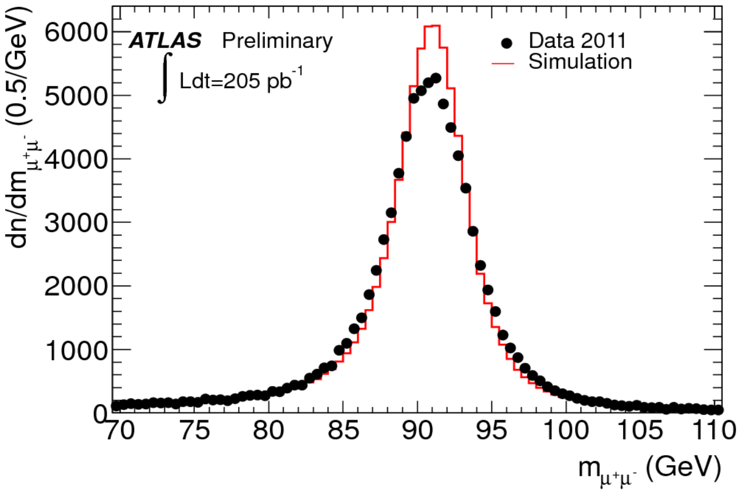


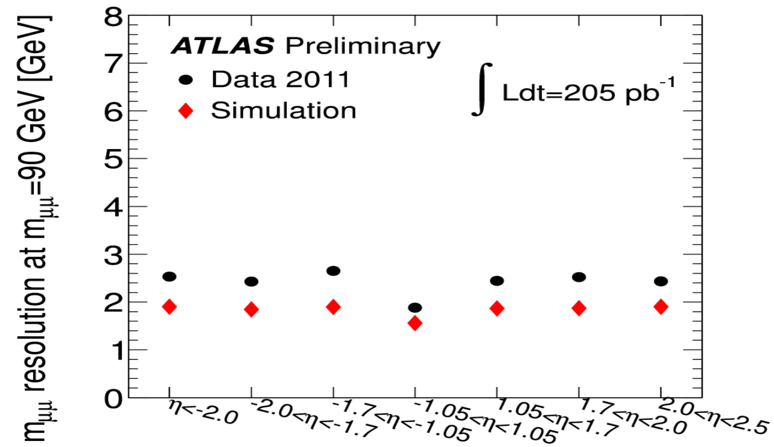
scale factor = data/simulation
- correct simulation
- use uncertainty to derive systematic uncertainty on event yield

same procedure for electron, taus, flavour tagging, ...

Understanding of Detector: Example Muons (2)

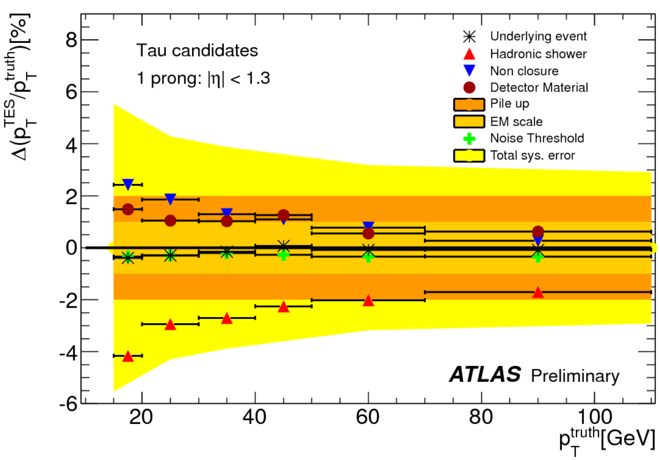
momentum scale and resolution from Z → μμ peak position and width

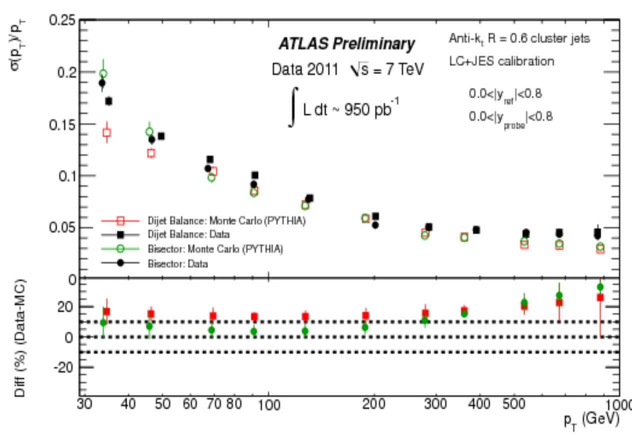




correct simulation for difference

use uncertainty of correction to determine uncertainty on event yield

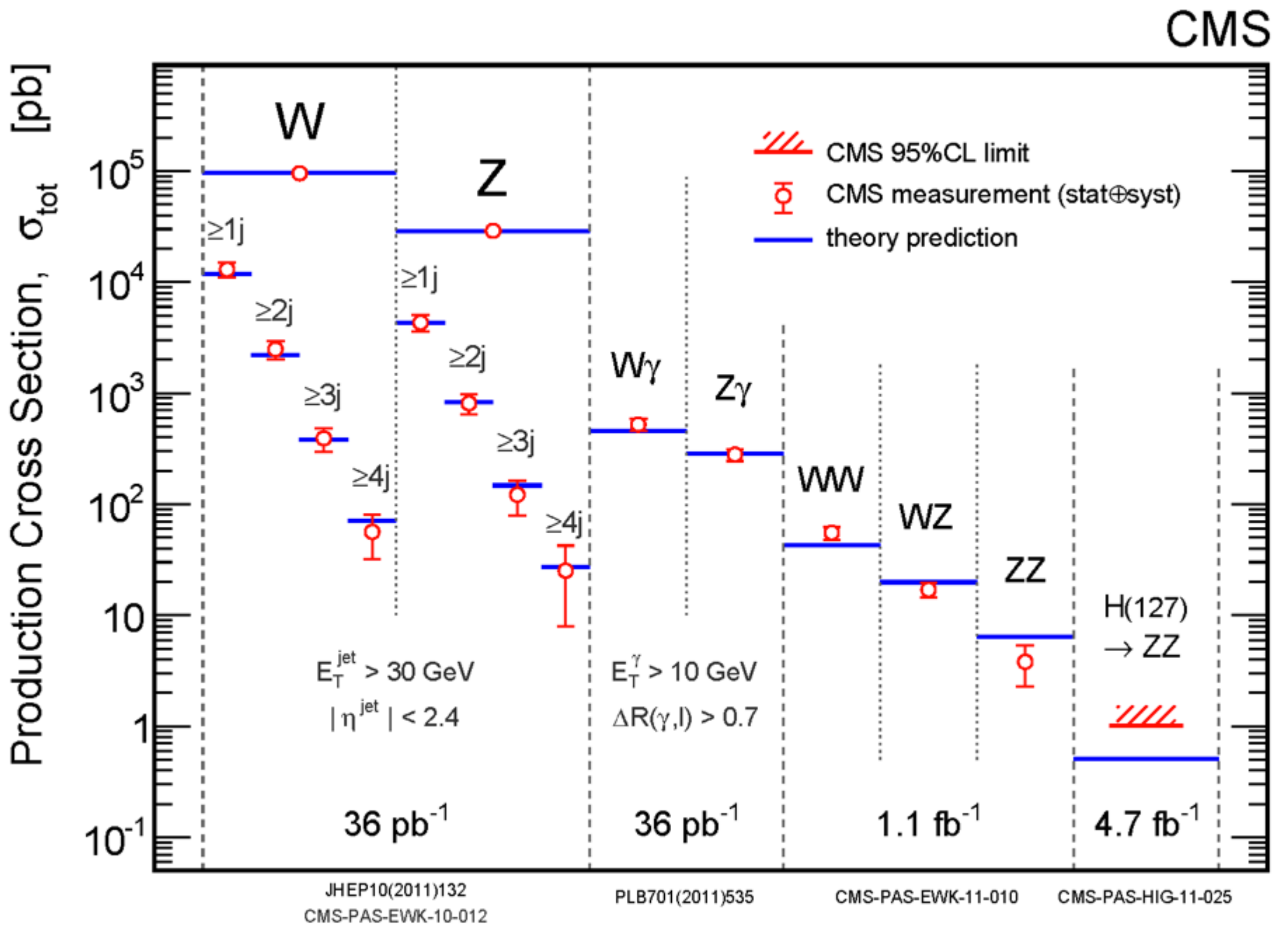




in similar way
for electron,
tau leptons, jets,
b-jets,
missing trans. energy

Understanding the Background Processes

In ~ 5 fb^{-1} after selection cuts: ~30M W→ μ(e)ν, ~3M Z → μμ,ee, ~60k top pairs



Excellent agreement between theory prediction and measurement due to very precise calculations and good understanding of detector performance

Estimating the Background

a) from simulation only $N^B = \varepsilon_{reco,ID,isolation,cuts} * A * \sigma_{theo} * L$

ε = efficiency (reco., ID, isolation, topological cuts)
A = acceptance (phase space cuts)
σ_{theo} = inclusive cross section, mostly from theory
L = integrated luminosity

uncertainties: detector performance related $\varepsilon_{reco,ID,isolation}$
vary efficiency scale factor, E resolutions and scales

acceptance A: compare event generators, choice of αs, renormalisation μ_r and factorisation μ_r scales PDF sets

σ_{theo}: evaluate uncertainty from μ_f, μ_r, α_s, PDF sets

L: ~ 4%

for signal process: only way to estimate uncertainties on expected event yield and shape of final discriminating observable

Estimating the Background (2)

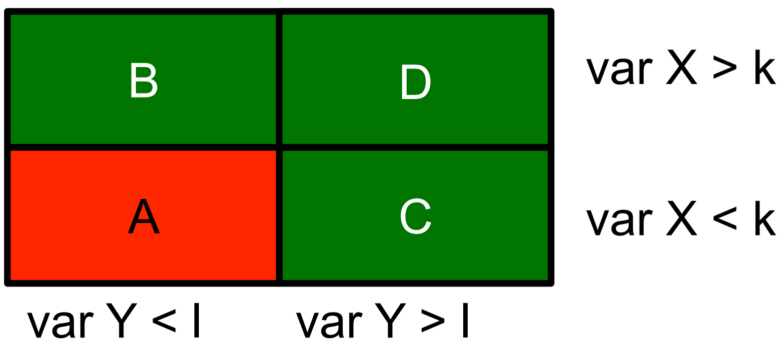
b) almost completely data driven

- use parametric model for description of mass distribution, fixed in side band

  uncertainties from model choice, statistics in sidebands, …

- select signal free control sample in data to obtain shape and to large extend also normalisation from data

  uncertainties from selection of control sample, pollution of other processes, agreement of shape in signal and control region, …



"ABCD-method" assumptions:

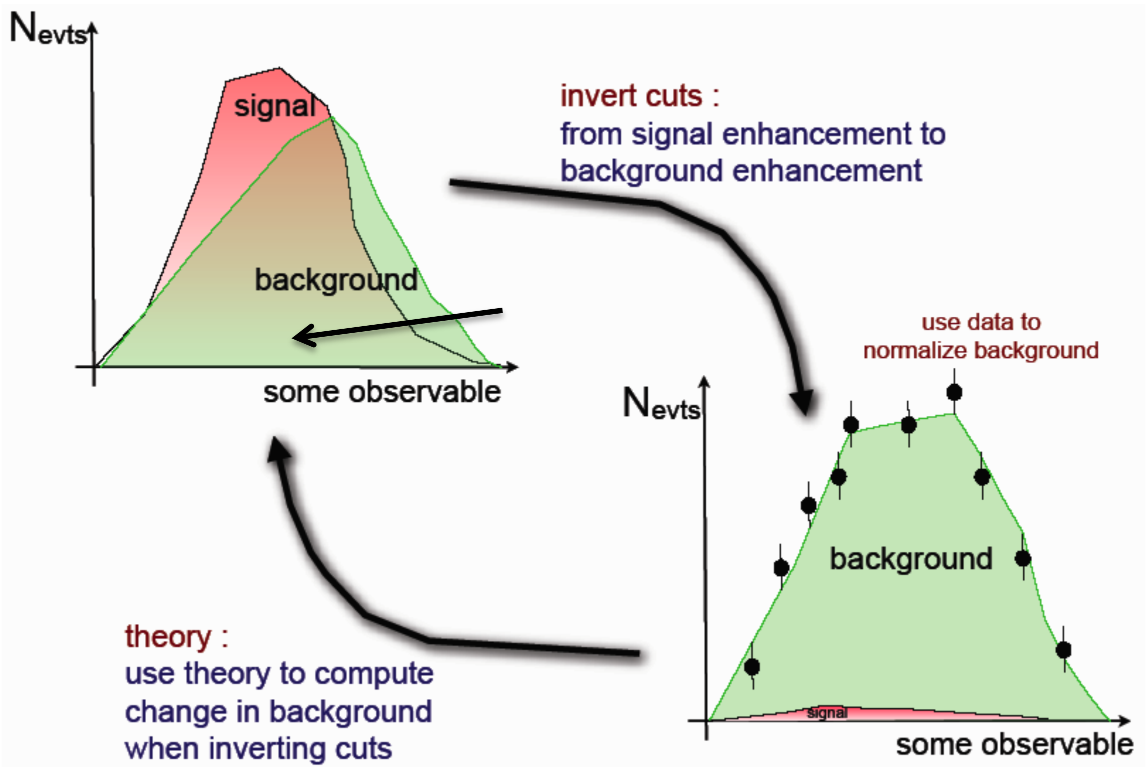
- observables X and Y uncorrelated
- control regions B,C,D dominated by background to be estimated
- shape of obervable of interest same in A and B or A and C or all regions

prediction in signal region A: $n_A(m) = B/D\ n_C(m)$

Estimating the Background (3)

c) normalisation from control region in data (inversion of some selection criteria)
ratio of signal/control region and shape of observable from simulation

$$N^B_{\text{signal region}} = k_{\text{Extrapolation}} * N^B_{\text{control region}}$$

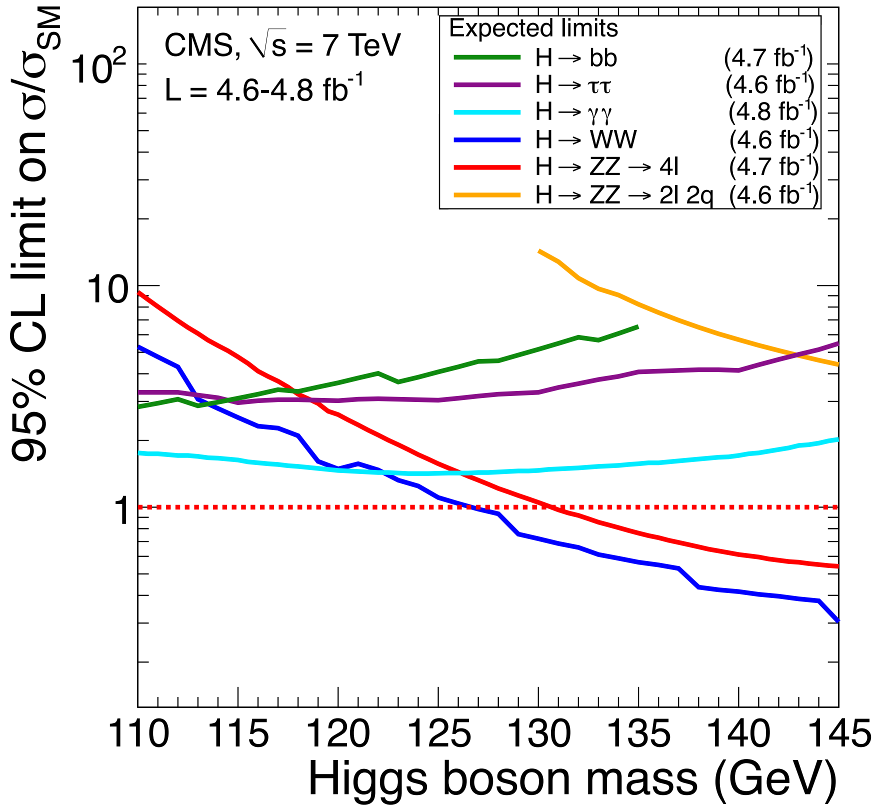


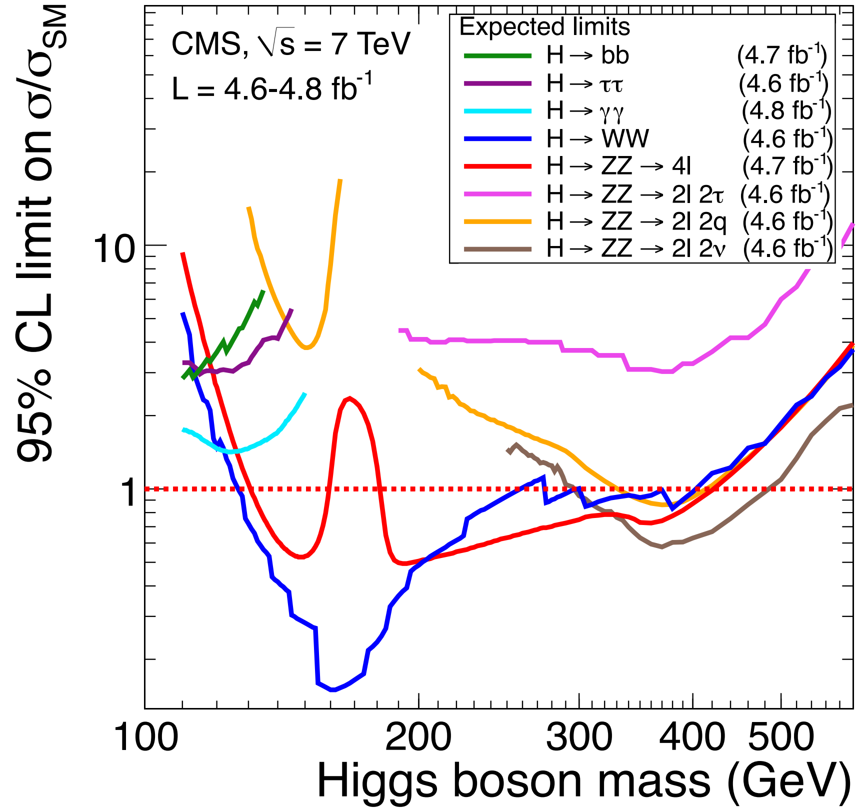
uncertainties:
pollution of control region
with other processes

knowledge of $k_{\text{Extrapolation}}$
- theory uncertainties
  (μ_f,μ_r,α_s,PDF, …)
- detector performance
  (identification, resolution,…)

most common method, called "data-driven" but still … input from simulation

Sensitive Search Channels in Different Mass Ranges





m_H < 120/125 GeV:
H → 2γγ
H→ WW*→lνlν
H → ττ (VBF)
H → bb in VH

125 < m_H < 200 GeV
H → WW->2l2ν
H → ZZ->4l

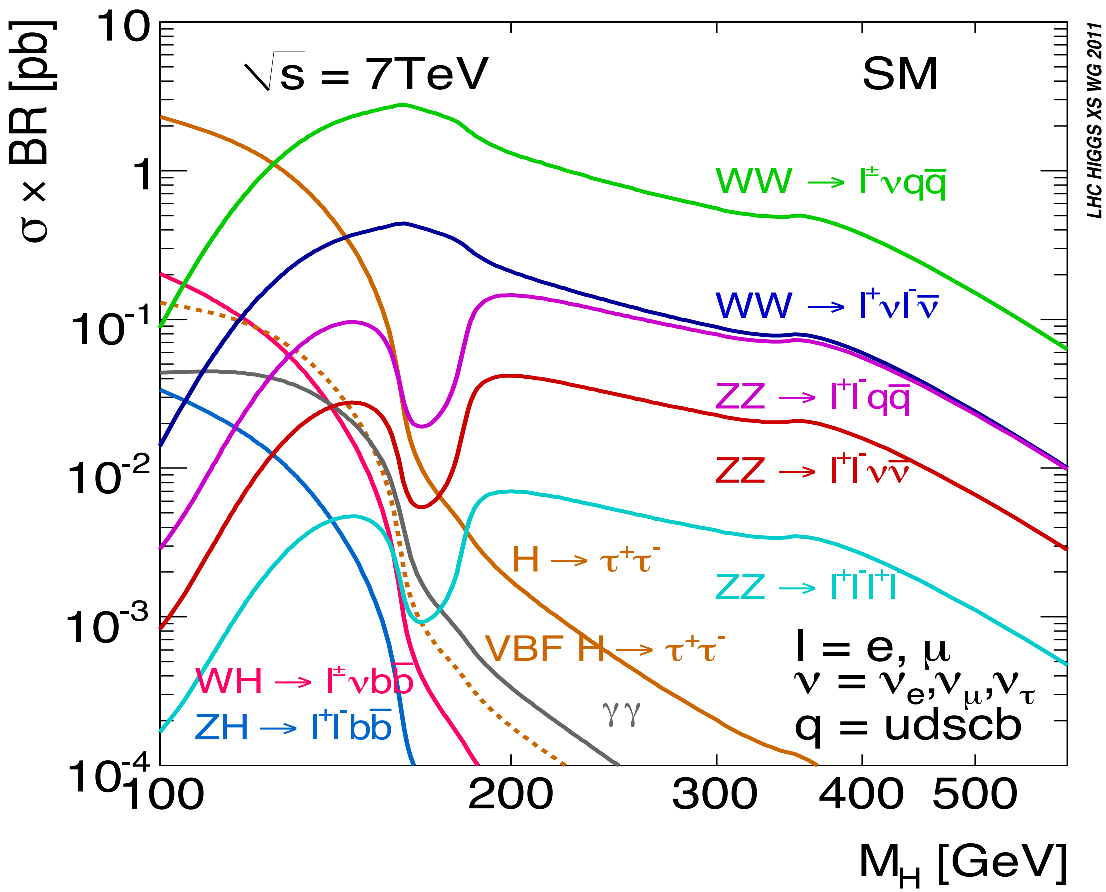
m_H> 200 GeV
H → ZZ → 4l, llνν, lljj
H →WW->lνlν, lνjj

Higgs Boson Search Channels

	ATLAS			CMS		
channel	Lumi	Mass Range	Sub chan.	Lumi	Mass range	Sub chan.
$H \rightarrow \gamma\gamma$	4.9	110-150	9	4.8	110-150	5
$H \rightarrow \tau\tau$	1.1	100-150	4	4.6	110-145	9
$H \rightarrow bb$	1.1	110-130	4	4.7	110-135	5
$H \rightarrow WW \rightarrow l\nu l\nu$	2.1	110-300	6	4.6	110-600	5
$H \rightarrow WW \rightarrow l\nu qq$	1.1	240-600	2	---	----------	-
$H \rightarrow ZZ \rightarrow 4l$	4.8	110-600	3	4.7	110-600	3
$H \rightarrow ZZ \rightarrow 2l2\tau$	----	---------		4.7	190-600	8
$H \rightarrow ZZ \rightarrow 2l2\nu$	2.1	200-600	2	4.6	250-600	2
$H \rightarrow ZZ \rightarrow 2l2q$	2.1	200-600	4	4.6	130-164 225-600	6

CMS: 42 subchannels, all published with full 2011 data set
ATLAS: 34+n subchannels, hopefully all finalized for Moriond 2012

High Signal Rates → Early Sensitivity



rule of thumb:
you need to
expect 3 signal events
after full selection
to exclude such a
hypothesis

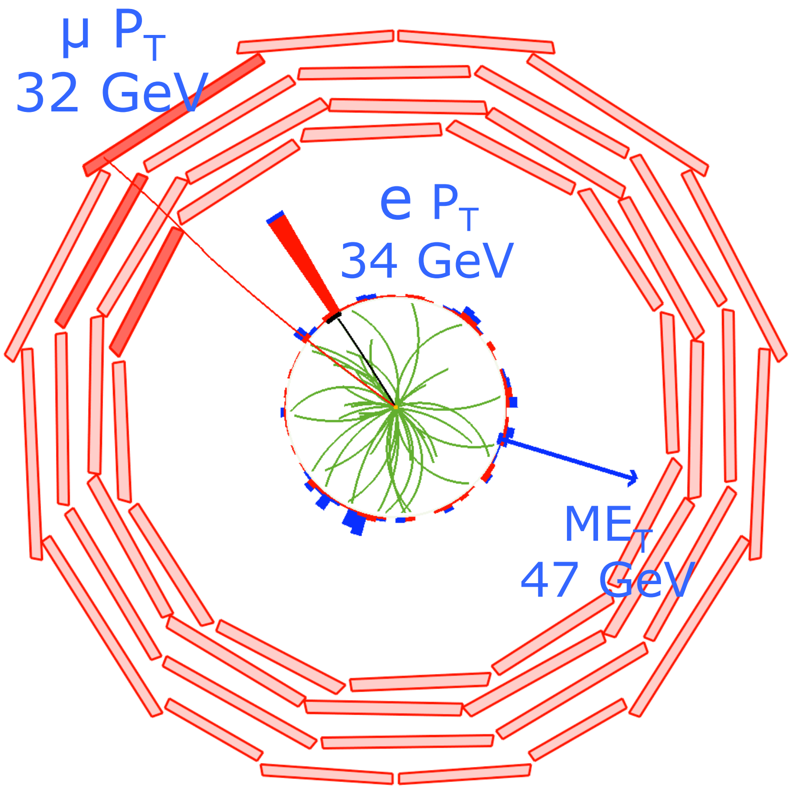
Events expected to be produced with L=1 fb^{-1}

m_H, GeV	WW→lνlν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

H→WW→lνlν second highest rate for M_H>150 GeV, earliest sensitivity at LHC

H→WW→lνqq suffers from large W+jets background
ony considered for M_H>240 GeV in ATLAS

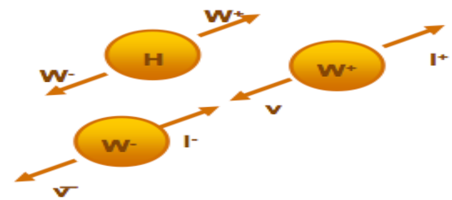
CMS: H → WW→lνlν



No mass reconstruction
→ signal extraction from event counting

Signature: (ee, eμ,μμ considered)

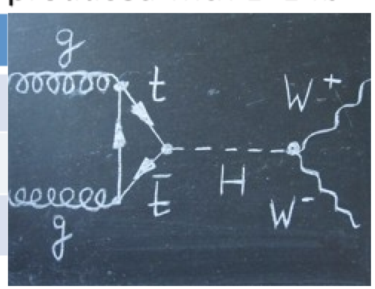
- 2 isolated, high p_T leptons with small opening angle $\Delta\phi$



- Large Missing Transverse Energy MET

Events expected to be produced with L=1 fb^{-1}

m_H, GeV	WW→lνlν
120	127
150	390
300	89

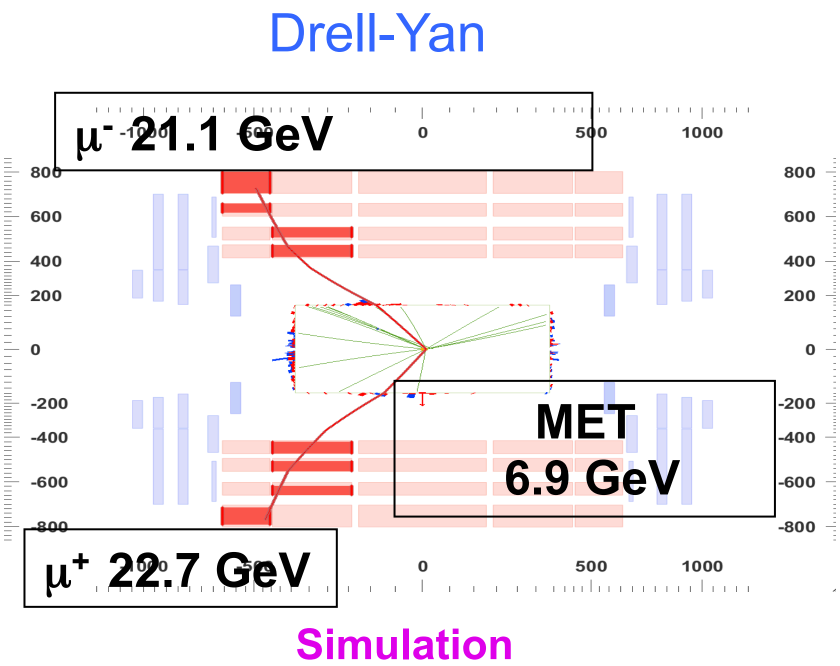


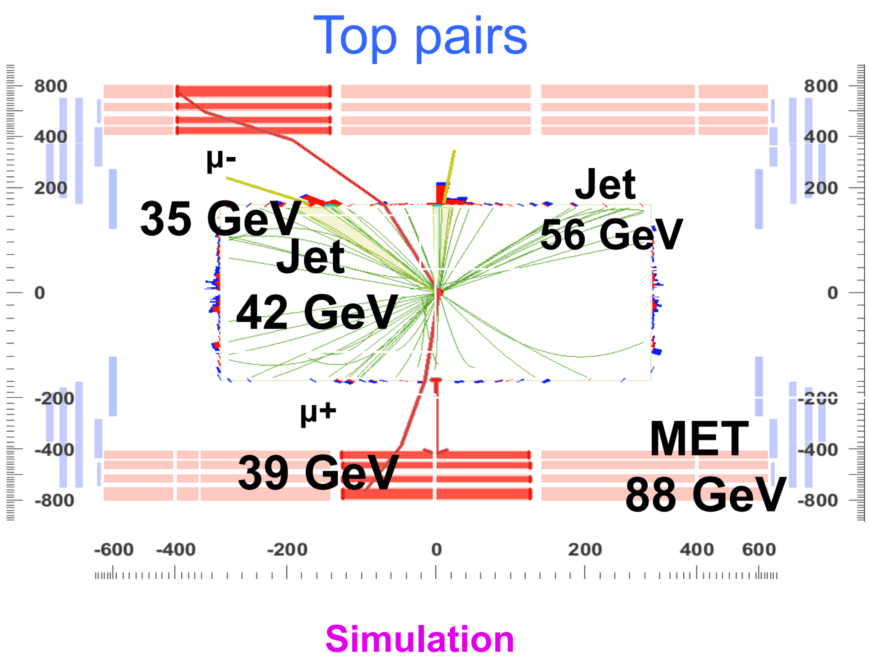
Analysis optimized for 3 exclusive jet multiplicities (0,1,2 jets) and for different Higgs mass hypotheses

- p_T^l, M_{ll}, M_T, $\Delta\phi$ discriminating variables
- VBF selections for the 2-jet case

For 0,1 jet bin: also multivariate technique

WW → lν lν Preselection





veto on Z: $|M_{ll}-M_Z|>30$ GeV
MET requirement

apply top-tagger (soft muon, etc.)
veto tagged events

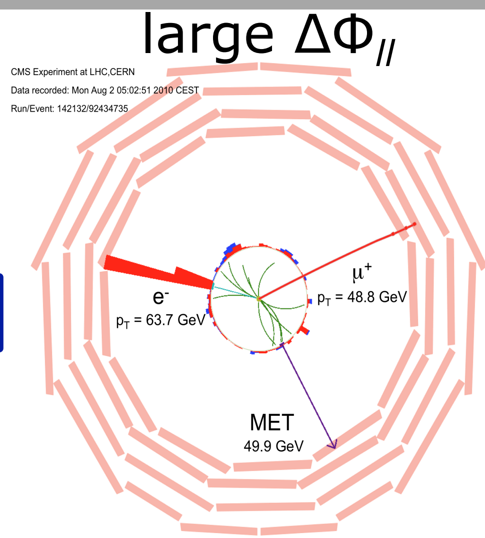
against WZ,ZZ backgrounds: veto 3rd lepton

at this stage 1359/909/703 events in 0,1,2 jet topologies
signal efficiency (M_H=130 GeV) = 5.5%

After WW→lνlν Preselection

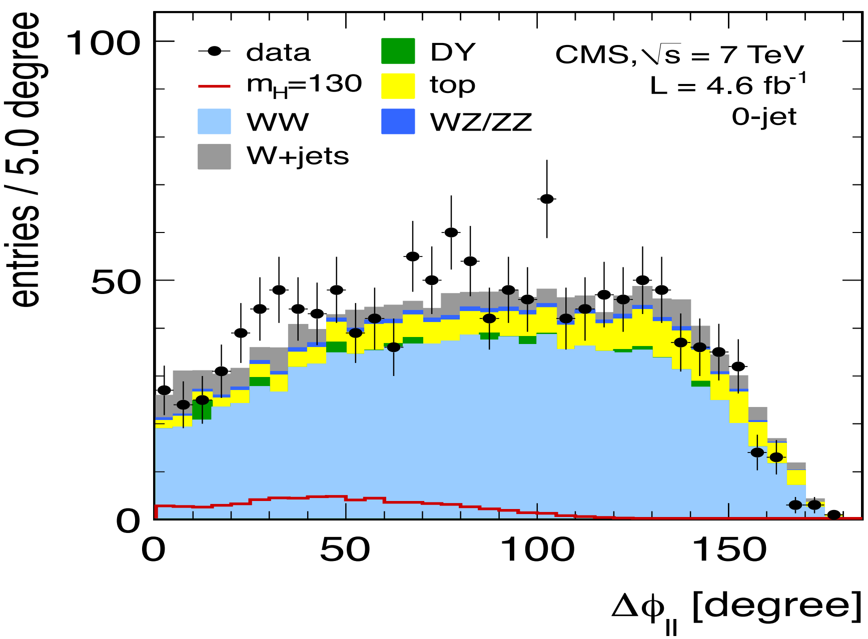
large $\Delta\Phi_{ll}$

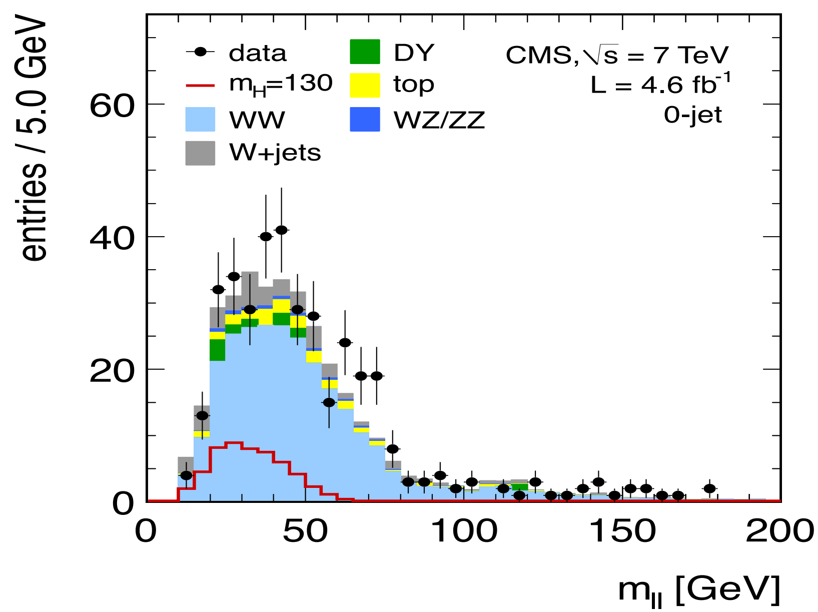
2010 Data



background dominated by WW→lνlν

further jet topology dependent selection

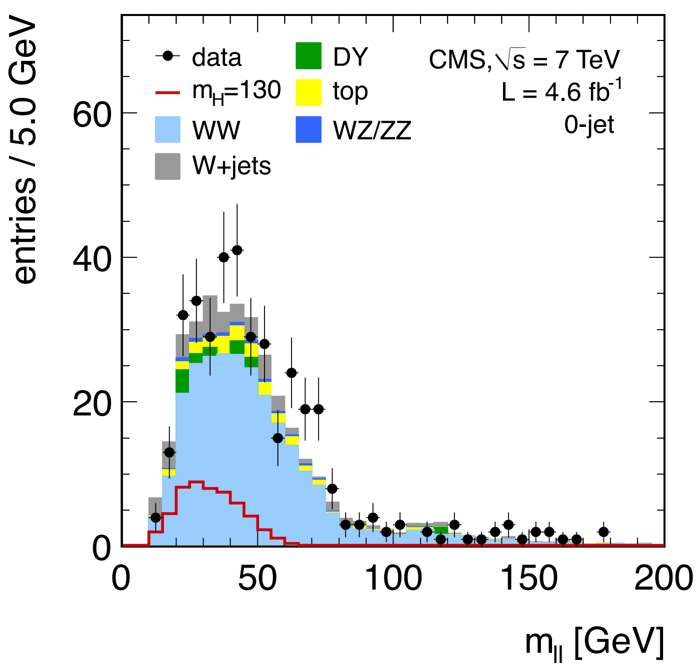


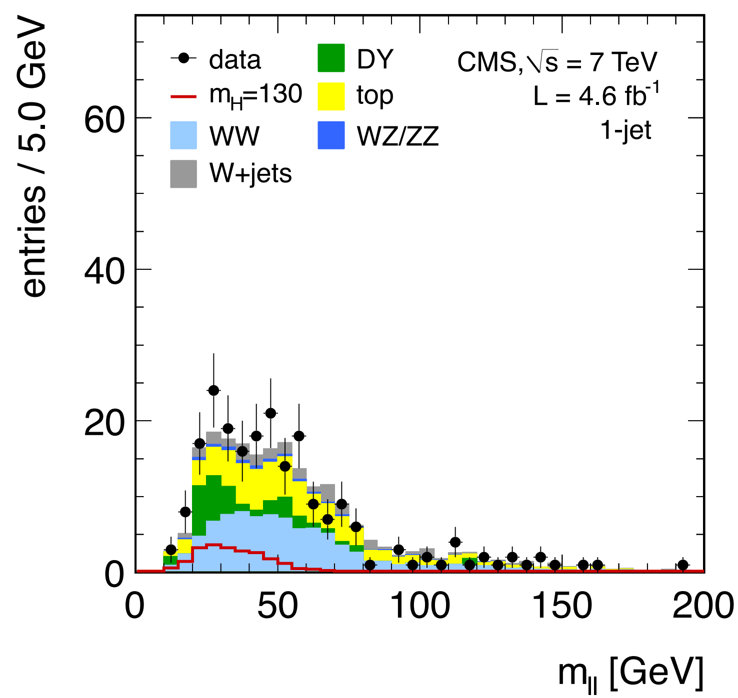


Final selection for H → WW→lνlν

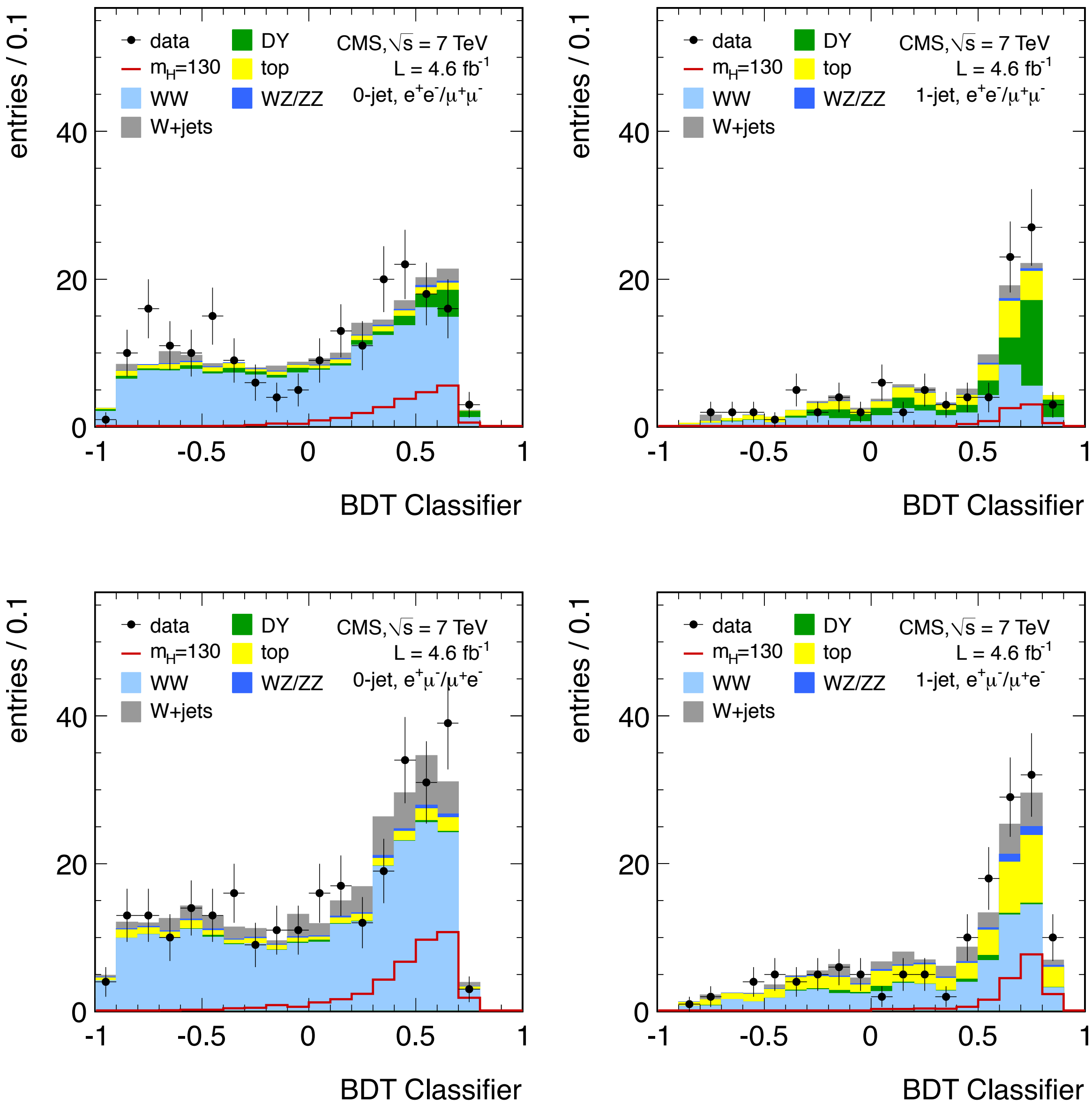
m_H	data	all bkg.	$pp \to W^+W^-$	top	W + jets	$WZ+ZZ+W\gamma^{(*)}$	$Z/\gamma^* \to \ell^+\ell^-$	$H \to W^+W^-$
			0-jet category					
120	136	136.7 ± 12.7	100.3 ± 7.2	6.7 ± 1.0	14.7 ± 4.7	6.1 ± 1.5	8.8 ± 9.2	15.7 ± 0.8
130	193	191.5 ± 14.0	142.2 ± 10.0	10.6 ± 1.6	17.6 ± 5.5	7.4 ± 1.6	13.7 ± 7.8	45.2 ± 2.1
160	111	101.7 ± 6.8	82.6 ± 5.4	10.5 ± 1.4	3.0 ± 1.5	2.2 ± 0.4	3.4 ± 3.4	122.9 ± 5.6
200	159	140.8 ± 6.8	108.2 ± 4.5	23.3 ± 3.1	3.4 ± 1.5	3.2 ± 0.3	2.7 ± 3.7	48.8 ± 2.2
400	109	110.8 ± 5.8	59.8 ± 2.7	35.9 ± 4.7	5.5 ± 1.8	9.3 ± 1.1	0.2 ± 0.2	17.5 ± 0.8
			1-jet category					
120	72	59.5 ± 5.9	27.0 ± 4.7	17.2 ± 1.0	5.4 ± 2.4	3.2 ± 0.6	6.6 ± 2.3	6.5 ± 0.3
130	105	79.9 ± 7.7	38.5 ± 6.6	25.6 ± 1.4	6.5 ± 2.5	4.0 ± 0.6	5.3 ± 2.5	17.6 ± 0.8
160	86	70.8 ± 6.0	33.7 ± 5.5	27.9 ± 1.4	3.2 ± 1.4	1.9 ± 0.3	4.2 ± 1.4	60.2 ± 2.6
200	111	130.8 ± 6.7	49.3 ± 2.2	59.4 ± 2.8	5.2 ± 1.8	2.2 ± 0.1	14.6 ± 5.3	25.8 ± 1.1
400	128	123.6 ± 5.3	44.6 ± 2.2	60.6 ± 2.9	6.2 ± 2.1	3.9 ± 0.5	8.3 ± 3.2	12.2 ± 0.5
			2-jet category					
120	8	11.3 ± 3.6	1.3 ± 0.2	5.5 ± 2.8	0.7 ± 0.6	1.8 ± 1.5	1.9 ± 1.4	1.1 ± 0.1
130	10	13.3 ± 4.0	1.6 ± 0.2	6.5 ± 3.2	0.7 ± 0.6	1.8 ± 1.5	2.7 ± 1.9	2.7 ± 0.2
160	12	15.9 ± 4.6	1.9 ± 0.2	8.4 ± 3.9	1.2 ± 0.8	1.8 ± 1.5	2.7 ± 1.9	12.2 ± 0.7
200	13	17.8 ± 5.0	2.2 ± 0.2	9.4 ± 4.2	1.2 ± 0.8	1.8 ± 1.5	3.2 ± 2.1	8.4 ± 0.5
400	20	23.8 ± 6.4	3.5 ± 0.3	14.1 ± 5.8	1.1 ± 0.8	1.9 ± 1.5	3.3 ± 2.1	2.5 ± 0.1

m_H	$p_T^{\ell,max}$	$p_T^{\ell,min}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	m_T
[GeV]	[GeV]	[GeV]	[GeV]	[°]	[GeV]
	>	>	<	<	[,]
120	20	10 (15)	40	115	[80,120]
130	25	10 (15)	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]





H → WW→lνlν: Boosted Decision Tree Analysis



no significnt deviation from background expectation observed

$H \to WW \to l\nu l\nu$ Background Estimation

signal region (SR): 2 tight leptons, small m_{ll}, veto on top-tagged events

W+jets and multijet with „fake" leptons: Δ_{BG}~35%

define control region (CR) with 1 tight (t) and 1 loose (l) lepton

determine $\varepsilon_{l \to t}$ from independent sample with non-prompt lepton

weight events in CR by $\varepsilon_{l \to t}$ / (1- $\varepsilon_{l \to t}$)

top quark production: Δ_{BG}~10 to 25%

CR= top-tagged events determine $\varepsilon_{top\text{-}tag}$ from top enriched b-tagged sample

SR= CR x $(1-\varepsilon_{top\text{-}tag}) / \varepsilon_{top\text{-}tag}$

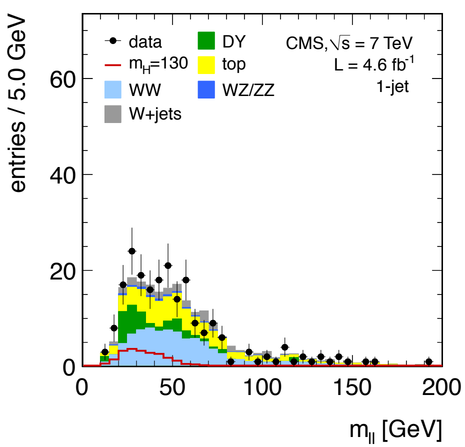
WW production (for M_H<200 GeV, otherwise from simulation only): Δ_{BG}~10%

CR= m_{ll}>100 GeV SR= k_{MC} CR

Drell-Yan: Δ_{BG}~50%

CR = $|m_{ll}-M_Z|$<7.5 GeV subtract non Z background

SR = k_{MC} CR from eμ sample

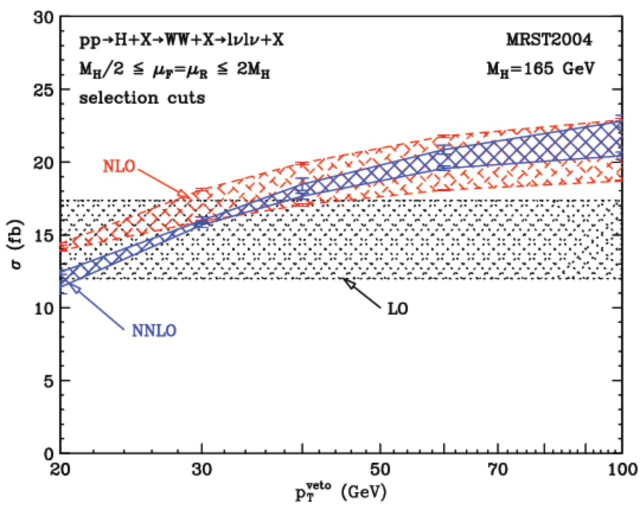


other backgrounds (WZ,ZZ, Wγ) from simulation

H→WW→lνlν Uncertainties

background yield: 15% (stat. uncertainty in CRs, dominated by WW)

signal efficiency: 20% dominated by theory uncertainties



WW + 0 jet: Veto jet of p_T>30 GeV
WW + 1 jet: 1 jet of p_T>30 GeV
WW + 2 jet: 2 jet of p_T>30 GeV - VBF like

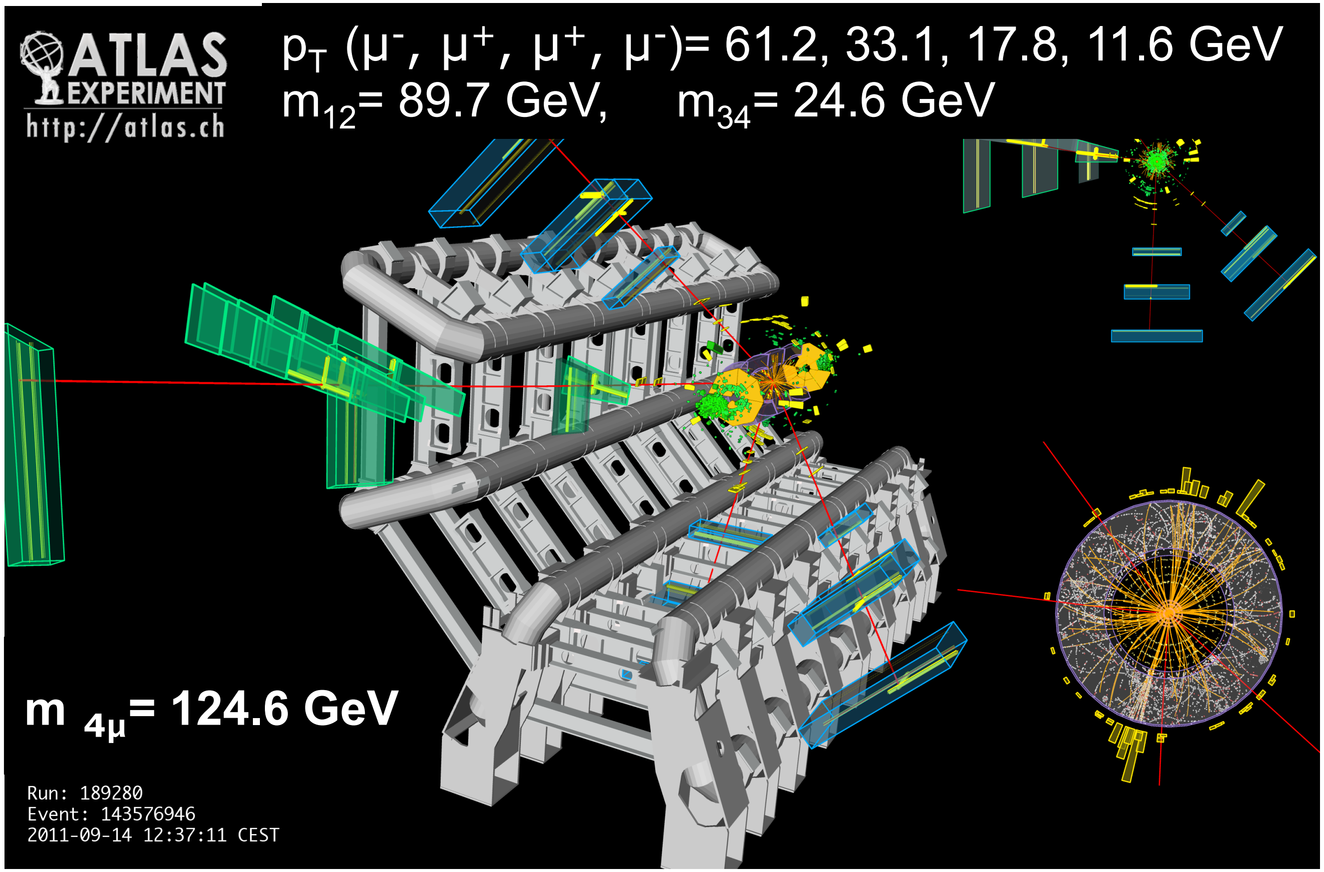
$\delta\sigma_{\geq 0}$	+12-7%
$\delta\sigma_{\geq 1}$	±20%
$\delta\sigma_{\geq 2}$	±30% (NLO) ±70% (LO)

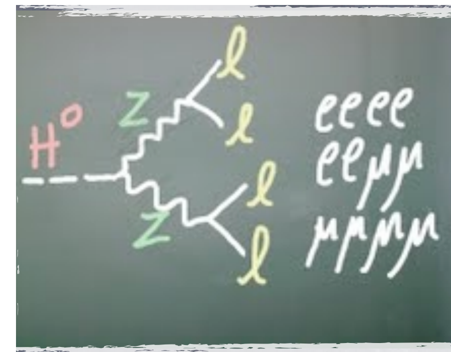
Theoretically best computation for incl. σ_{total}, $\sigma_{\geq 1}$, $\sigma_{\geq 2}$

→ $\sigma_0 = \sigma_{total} - \sigma_{\geq 1}$, $\sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}$, $\sigma_{\geq 2}$

→ correlated uncertainties on jet bin cross sections with size between 10 and 30%

Still the golden channel: H → ZZ(*) → 4l





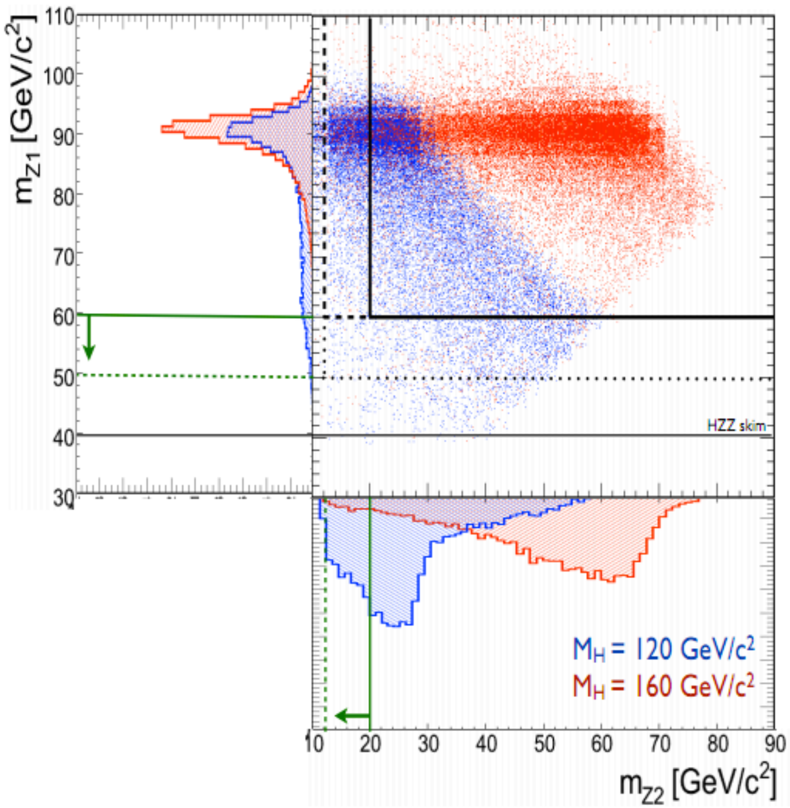
Events expected to be produced with L=1 fb^{-1}

m_H, GeV	WW→lνlν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

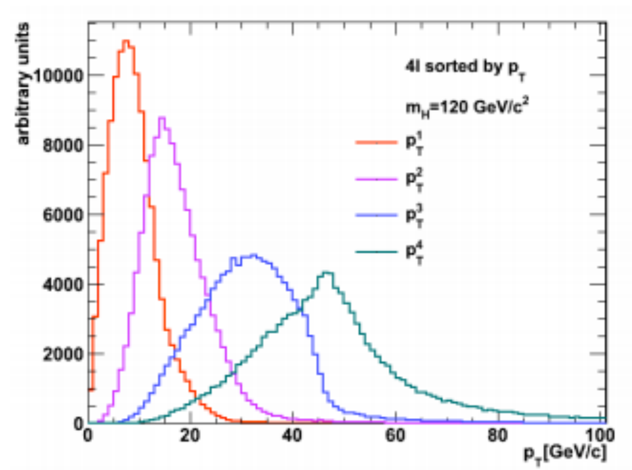
Very tiny cross section →
thus high efficiency must be conserved

Very clean final state:
4 high pt leptons, isolated from primary vertex

M_{Z1} versus M_{Z2} and Lepton p_t-spectra



lowering the p_t-thresholds increases signifcantly the sensitivity to low mass Higgs boson



challenge: lower the p_t-threshold as much as possible but retain good separation and understanding

Trigger: 2e 12 GeV or 1e 20 to 22 GeV or 2μ 10 GeV or 1 μ 18 GeV

Offline: 4 l p_t>7 GeV, 2 l with pt > 20 GeV

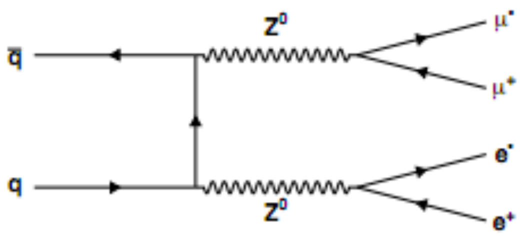
Z1: $|M_{12}-M_Z| < 15$ GeV

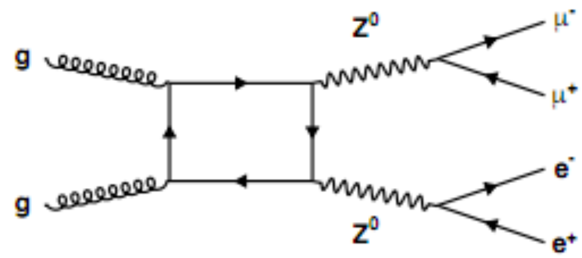
Z2: $M_{min} < M_{34} < 115$ GeV

$m_{4\ell}$ (GeV)	≤120	130	140	150	160	165	180	190	≥200
m_{34} threshold (GeV)	15	20	25	30	30	35	40	50	60

Irreducible Background processes

Irreducible background: $qq \rightarrow ZZ^{(*)} \rightarrow 4l$ $gg \rightarrow ZZ^{(*)} \rightarrow 4l$





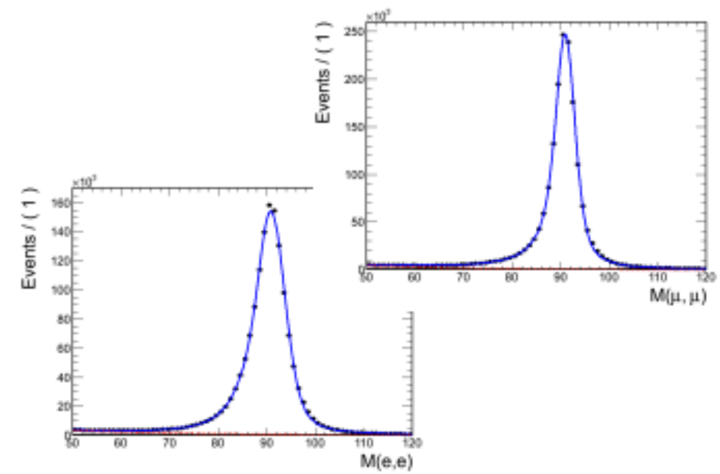
precise reconstruction of M_Z and M_{4l}

estimate from MC simulation (uncertainties as for signal):

$$\left(\sigma_{NLO}^{q\bar{q}\to ZZ\to 4l} \times \varepsilon_{MC}^{q\bar{q}\to ZZ\to 4l} + \sigma_{LO}^{gg\to ZZ\to 4l} \times \varepsilon_{MC}^{gg\to ZZ\to 4l}\right) \times L$$

crosscheck: normalisation to $Z \rightarrow ll$ rate in data

$$\frac{\sigma_{NLO}^{q\bar{q}\to ZZ\to 4l} + \sigma_{LO}^{gg\to ZZ\to 4l}}{\sigma_{NNLO}^{q\bar{q}\to Z\to 2l}} \times \frac{\varepsilon_{MC}^{ZZ\to 4l}}{\varepsilon_{MC}^{Z\to 2l}} \times N_{data}^{Z\to ll}$$

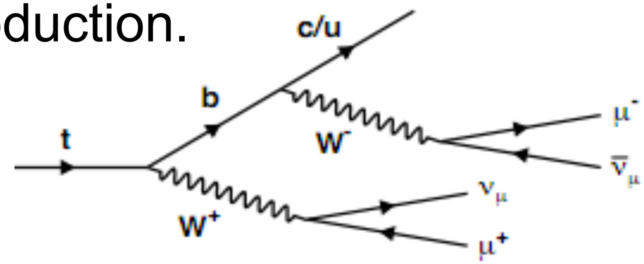


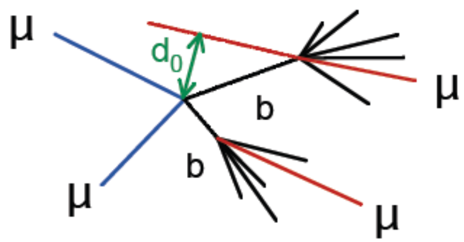
luminosity uncert. cancel in the ratio the TH uncertainties ~ 10%

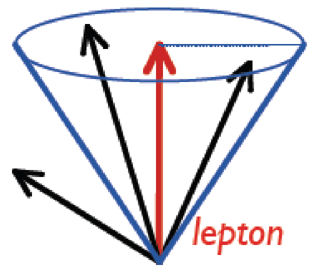
(PDF4LHC prescription + QCD scales)

Reducible Background Processes

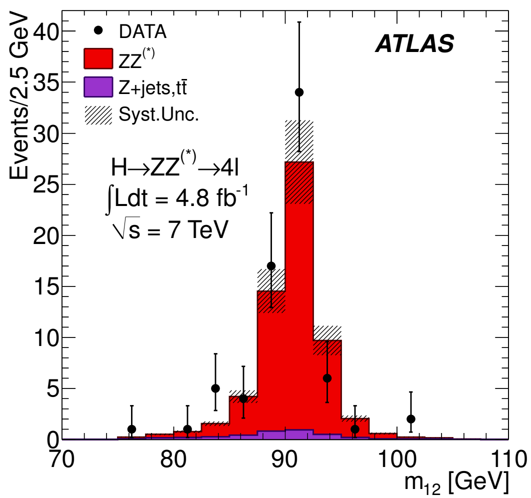
Reducible background: Zbb/Zcc, and tt pair production.
i.e. semileptonic B(D) decays
Leptons inside jets, from secondary vertex

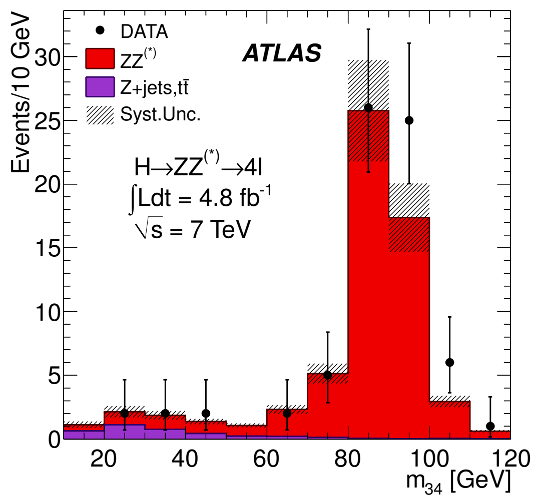




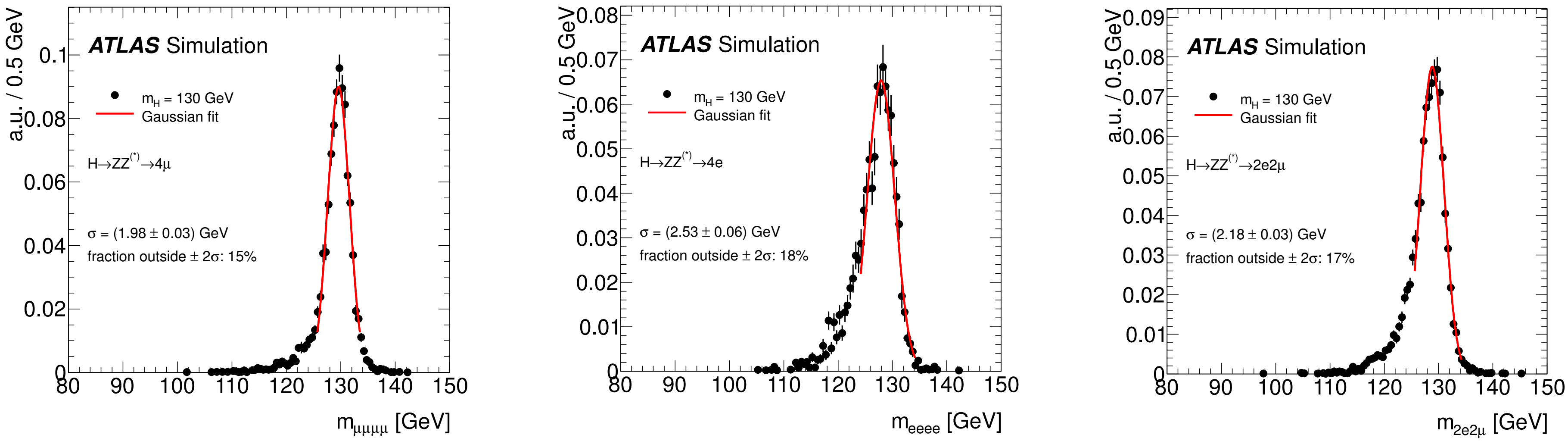


Instrumental background:
QCD and Z/W+light jets. Events with jets faking leptons (mostly electrons)





Signal: Mass Resolution and Efficiencies



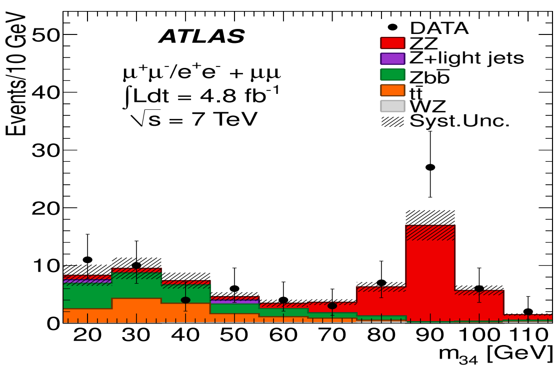
Signal:
Efficiency: 4e/4μ/2e2μ 14/27/18% at 130 GeV (45/60/52% at 360 GeV)
Mass resolution: 2.5/2.0/2.2 GeV for 4e/4μ/2e2μ at 130 geV
For M_H>350 width dominated by natural width of Higgs boson

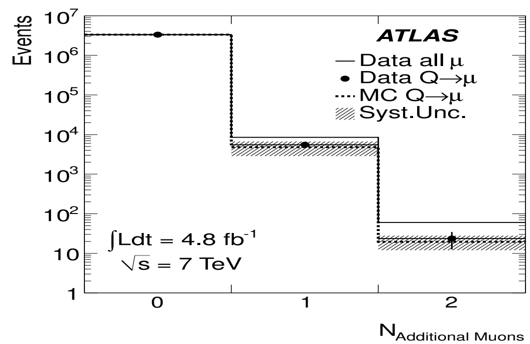
Systematic uncertainties:
μ efficiency: 0.2% e efficiency: 2 to 8%
e energy resolution: 0.6% on M_{4l} in 4e channel
+ theory uncertainties from total σ and modeling of signal in simulation

Estimation of Reducible Backgrounds

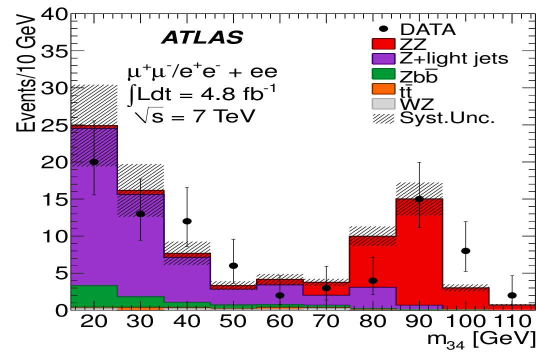
Z+jets control sample: full selection w/o isolation and impact parameter requirements on leptons building m_{34} pair

Z+$\mu\mu$: dominated by Zbb and Zcc (subtract Z+light jets by applying fake rate)





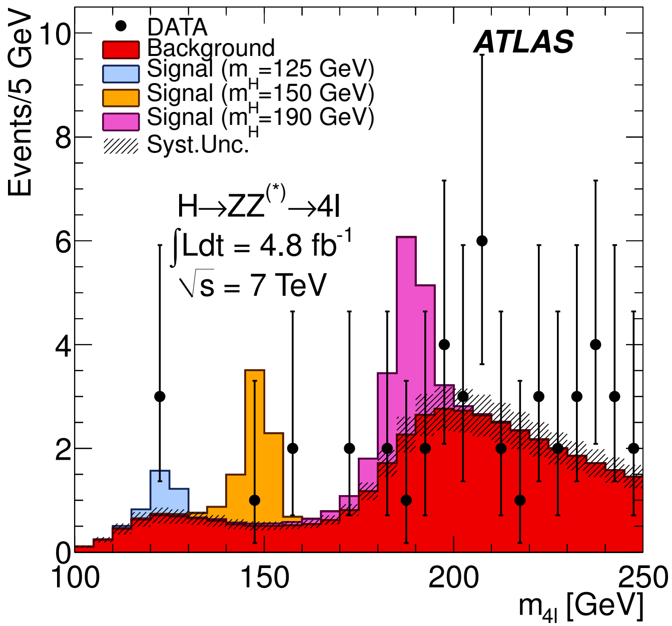
Z+ee: dominated by Z+ light jets

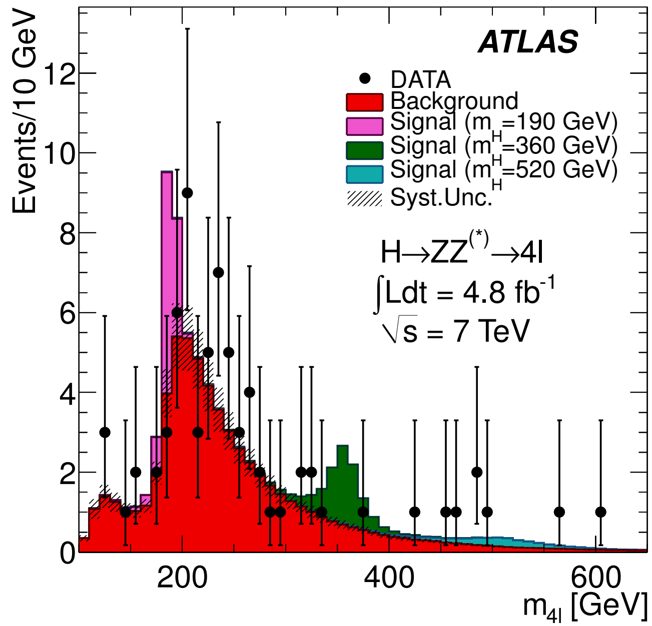


for both extrapolate from CR to SR uncertainty 45 and 40%

top pairs: control region M_{12} from eμ + M_{34} from same flavour confirms normalisation from simulation

Results: H→ZZ→4l





Data: 71 observed
4μ/2e2μ/4e: 24,30,17

Background exp:
62 ± 9

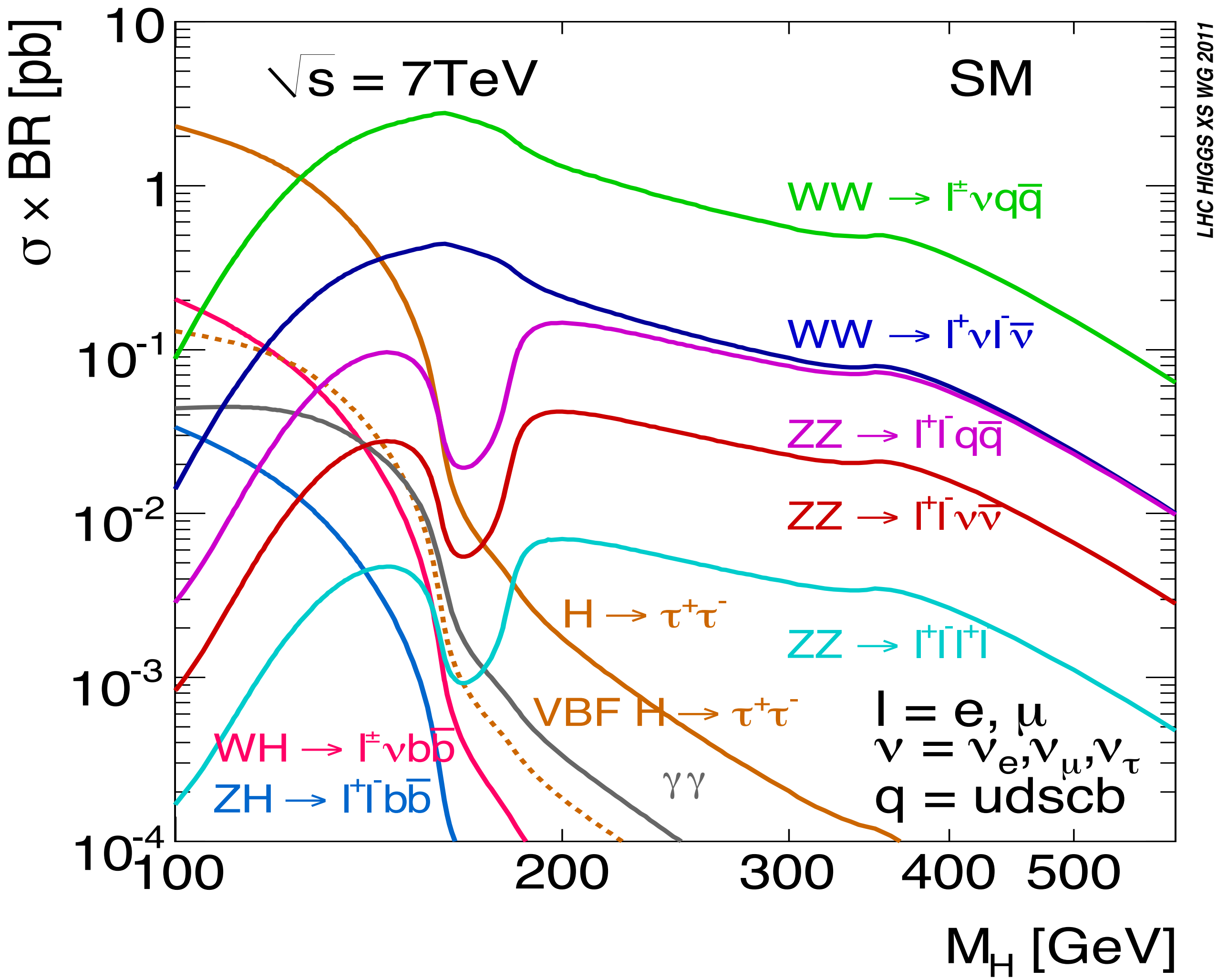
4μ: 19±3
2μ/2e: 30±5
4e: 13±2

	$\mu^+\mu^-\mu^+\mu^-$		$e^+e^-\mu^+\mu^-$		$e^+e^-e^+e^-$	
	Low-$m_{4\ell}$	High-$m_{4\ell}$	Low-$m_{4\ell}$	High-$m_{4\ell}$	Low-$m_{4\ell}$	High-$m_{4\ell}$
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	2.1 ± 0.3	16.3 ± 2.4	2.8 ± 0.6	25.2 ± 3.8	1.2 ± 0.3	10.4 ± 1.5
$Z+$ jets and $t\bar{t}$	0.16 ± 0.06	0.02 ± 0.01	1.4 ± 0.5	0.17 ± 0.08	1.6 ± 0.7	0.18 ± 0.08
Total Background	2.2 ± 0.3	16.3 ± 2.4	4.3 ± 0.8	25.4 ± 3.8	2.8 ± 0.8	10.6 ± 1.5
Data	3	21	3	27	2	15
$m_H = 130$ GeV	1.00 ± 0.17		1.22 ± 0.21		0.43 ± 0.08	
$m_H = 150$ GeV	2.1 ± 0.4		2.9 ± 0.4		1.12 ± 0.18	
$m_H = 200$ GeV	4.9 ± 0.7		7.7 ± 1.0		3.1 ± 0.4	
$m_H = 400$ GeV	2.0 ± 0.3		3.3 ± 0.5		1.49 ± 0.21	
$m_H = 600$ GeV	0.34 ± 0.04		0.62 ± 0.10		0.30 ± 0.06	

M_{4l}<190 GeV
obs.: 8 exp 9.4

M_{4l}>190 GeV
obs: 63 exp: 52.3

Very Low Mass Channels (M_H<130 GeV)



H→γγ H→ττ (mainly VBF) VH,H→bb

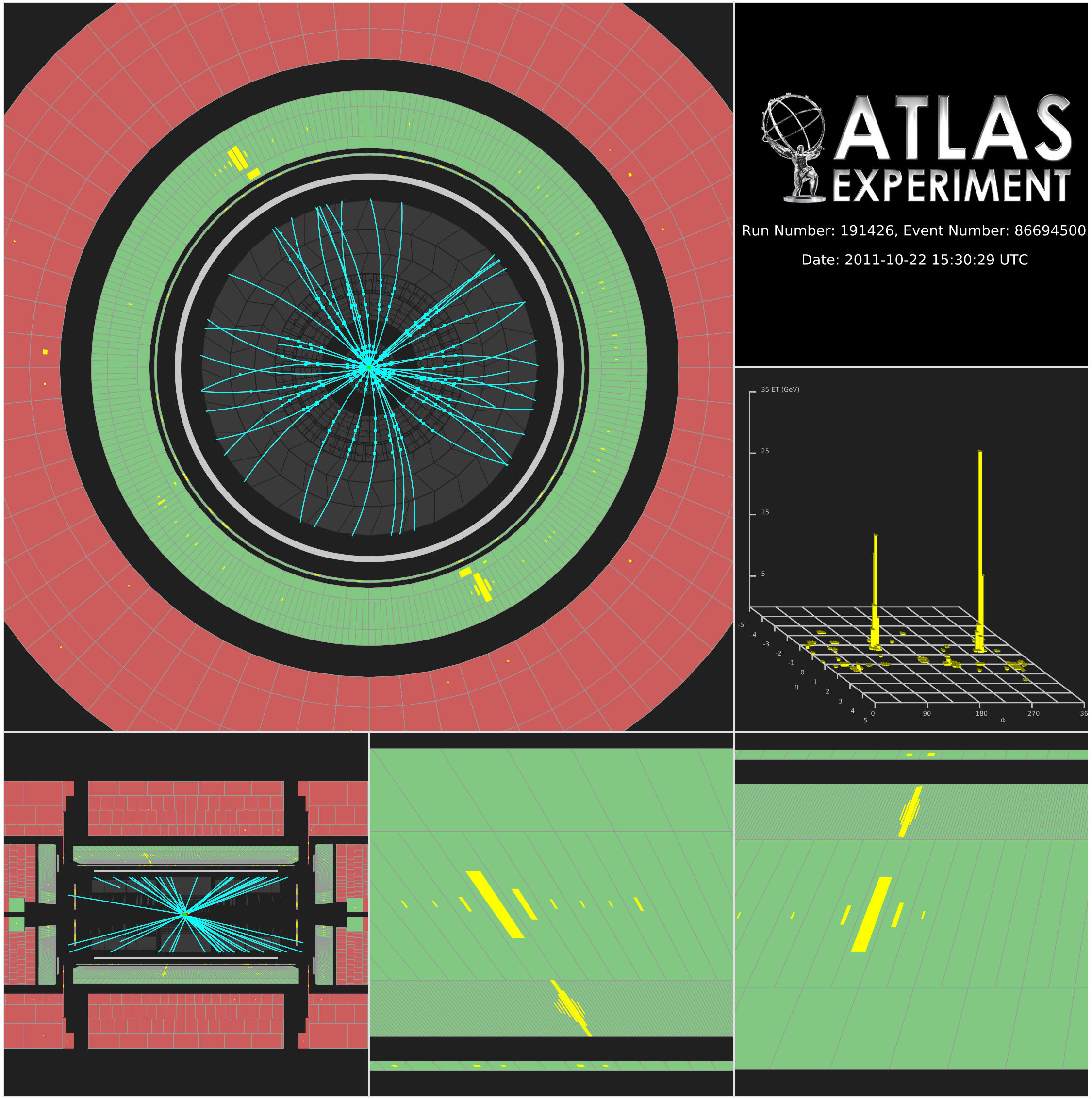
H→ 2 Photons (M_H from 110 to 150 GeV)

signal topology: 2 isolated photons

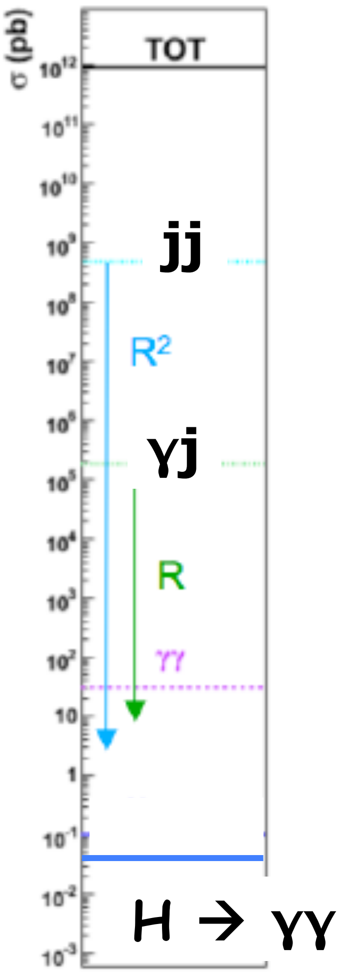
ATLAS

Trigger:
2 γ E_T>20 GeV

Offline:
$E_T(1)$> 40GeV
$E_T(2)$> 25 GeV

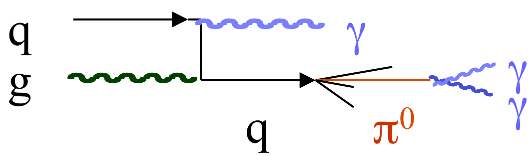


H→ 2 Photons: Background Suppression



R ~ O(8000)

reducible: γ-jet , 2jet-jet



→ discriminate photon from jet

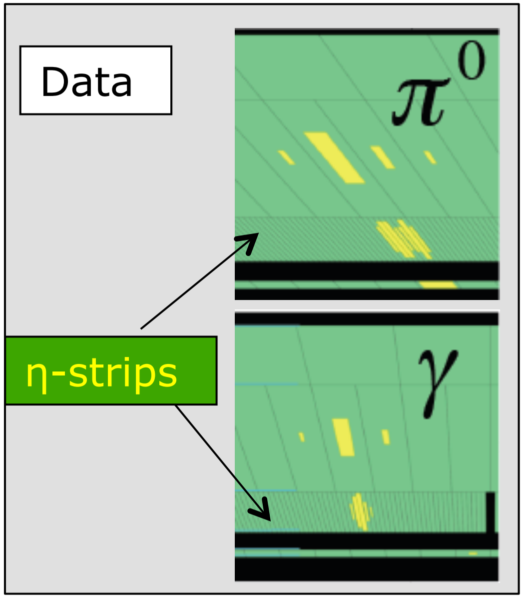
ID efficiency = 65 to 95%

(E_T 25 to 80 GeV)

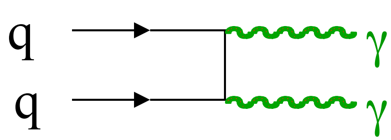
rejection of jets R ~ O(8000)

isolation: E< 5 GeV in ΔR=0.3

ε^2 = 87%



irreducible: γγ

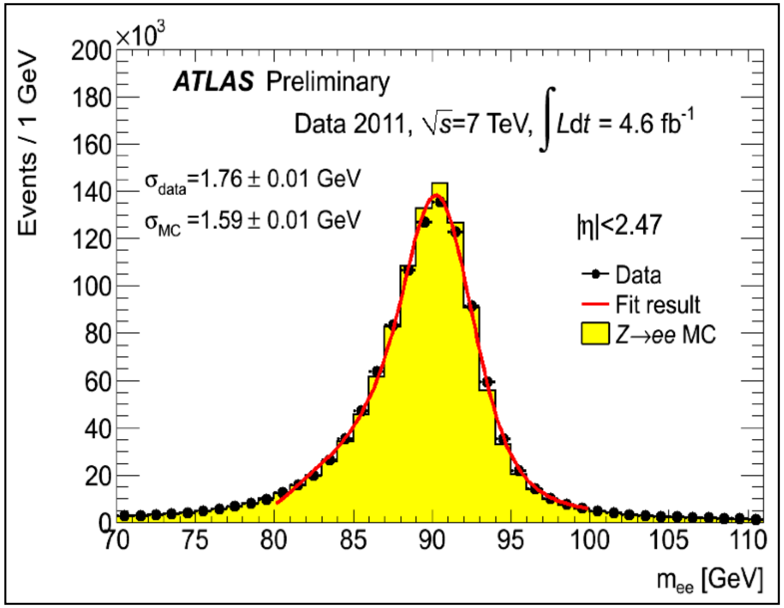


→ excellent reconstruction of $M_{\gamma\gamma}$

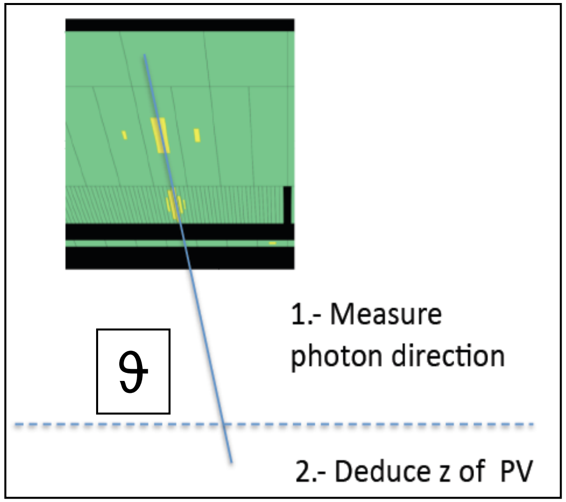
H→ 2 γ: Mass Reconstruction $m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$

energy E

from Z, J/ψ → ee, W→ eν data +MC:
- energy scale at m_Z known to ~ 0.5%
- linearity better than 1%
- "uniformity" (constant term of resolution) 1% (barrel) -1.7 % (end-cap)



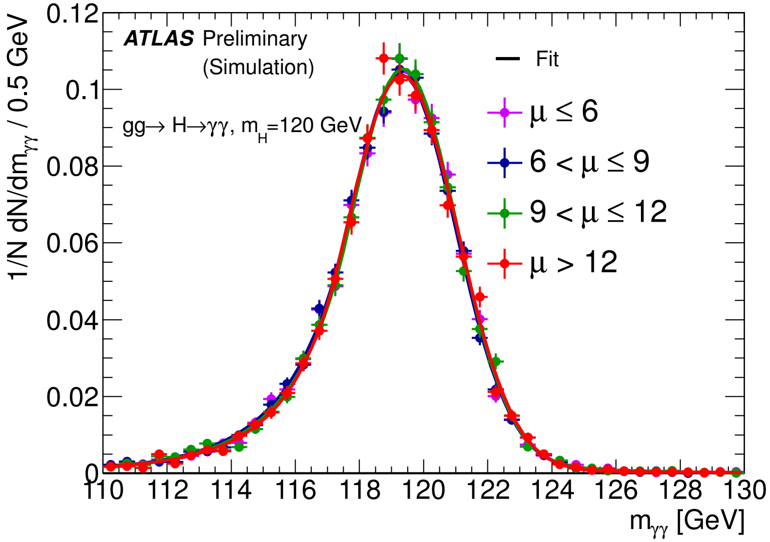
opening angle α



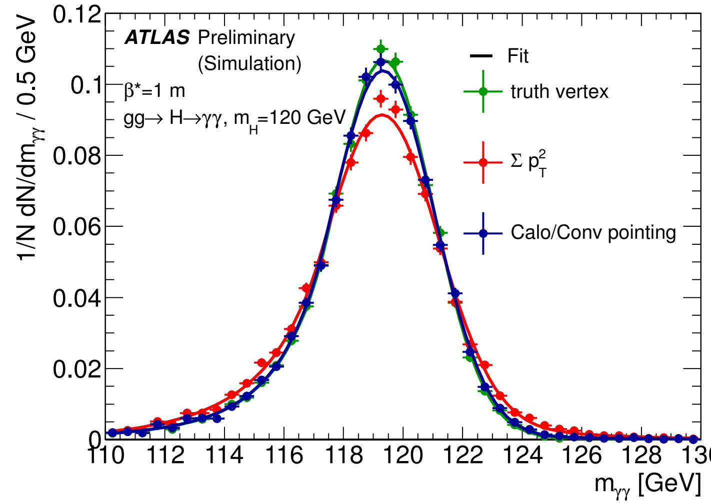
select primary vertex (~10/BX in 6 cm) via
a) non converted photons:
intersect of photon direction from 1^{st} and 2^{nd} sampling with beam line
b) converted photons:
impact in calo. and conversion vertex

H→ 2 γ: Mass Reconstruction $m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$

robust against pileup



contribution to resolution from α negligible

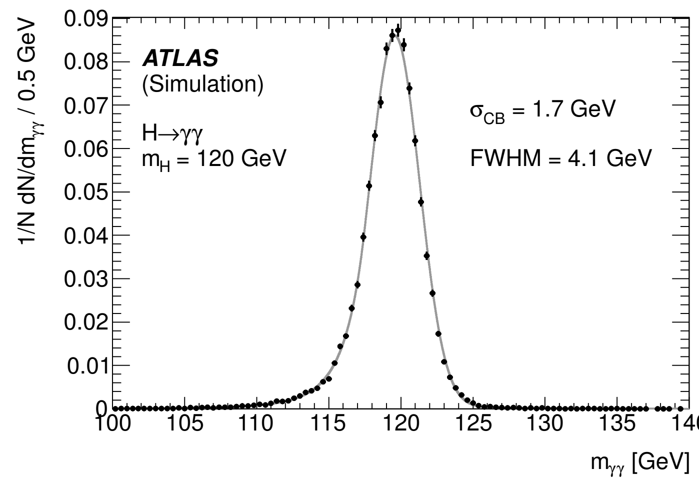


mass resolution 1.7 GeV

80% in +-1.4σ window

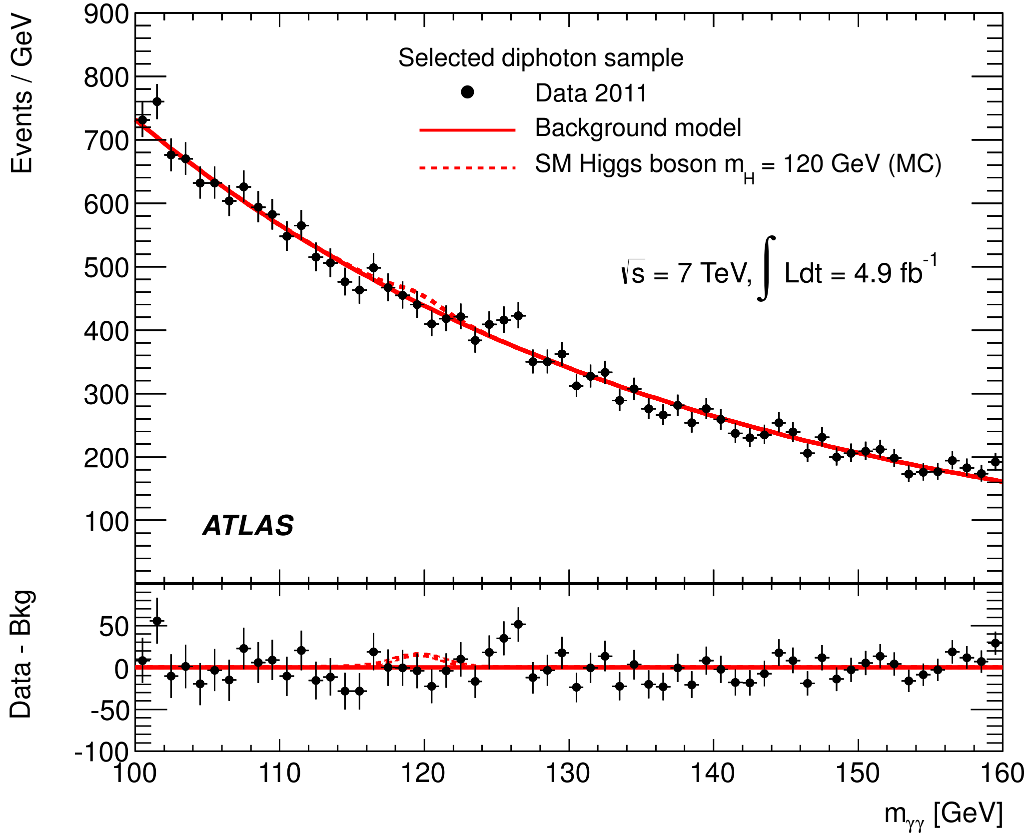
$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } t > -\alpha_{CB} \\ \left(\frac{n_{CB}}{\alpha_{CB}}\right)^{n_{CB}} \cdot e^{-\alpha_{CB}^2/2} \cdot \left(\frac{n_{CB}}{\alpha_{CB}} - \alpha_{CB} - t\right)^{-n_{CB}} & \text{otherwise} \end{cases}$$

$$t = (m_{\gamma\gamma} - m_H - \delta_{m_H})/\sigma_{CB},$$



H→ 2 Photons: Inclusive Mass Spectrum

inclusive mass spectrum (ε_{Signal}~35%)   22489 events



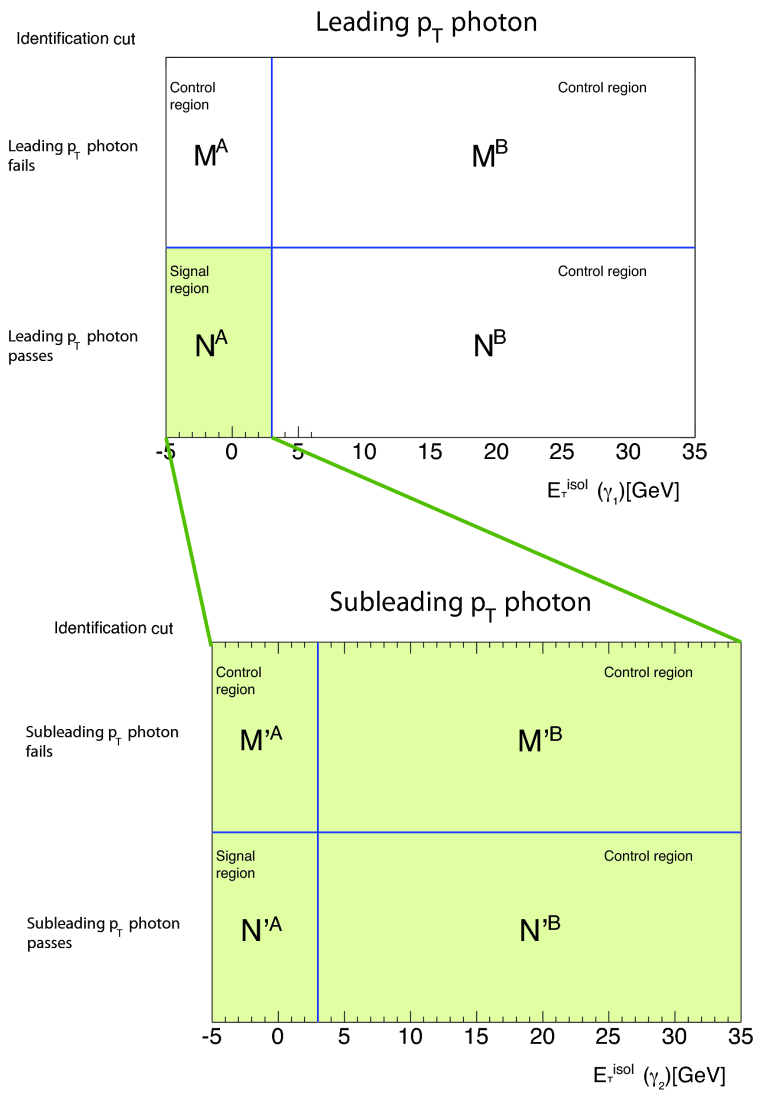
m_H [GeV]	110	115	120	125	130	135	140	145	150
$\sigma \times BR$ [fb]	45	44	43	40	36	32	27	22	16
Signal events	69	72	72	69	65	58	50	41	31
Efficiency [%]	31	33	34	35	37	37	38	38	39

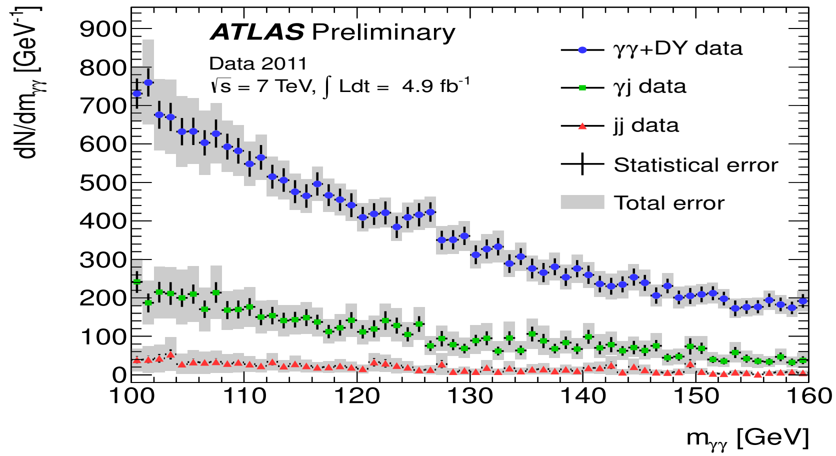
background shape described by a single exponential (no simulation used)
(checked with double exponential and 2nd order Bernstein polynom)

syst. uncertainty: difference in 4 GeV window between exp. and MC prediction

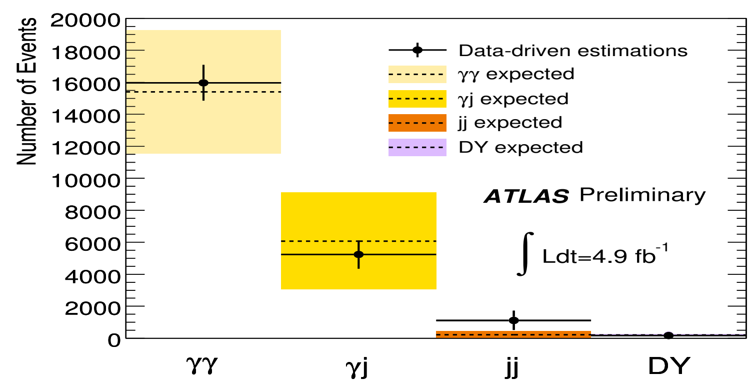
H→ 2 Photons: Sample Composition

from double-sideband „A=B*C/D“ method





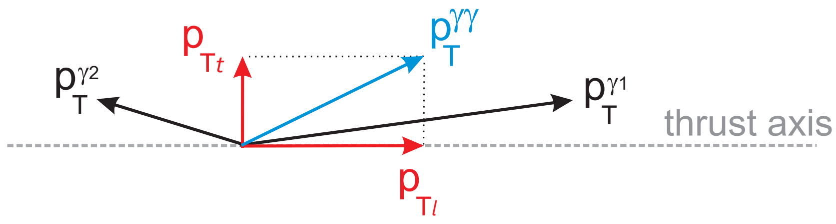
	$\gamma\gamma$	γj	jj	Drell-Yan
Events	16000 ± 1100	5230 ± 890	1130 ± 600	165 ± 8
Fraction	$(71 \pm 5)\,\%$	$(23 \pm 4)\,\%$	$(5 \pm 3)\,\%$	$(0.7 \pm 0.1)\,\%$



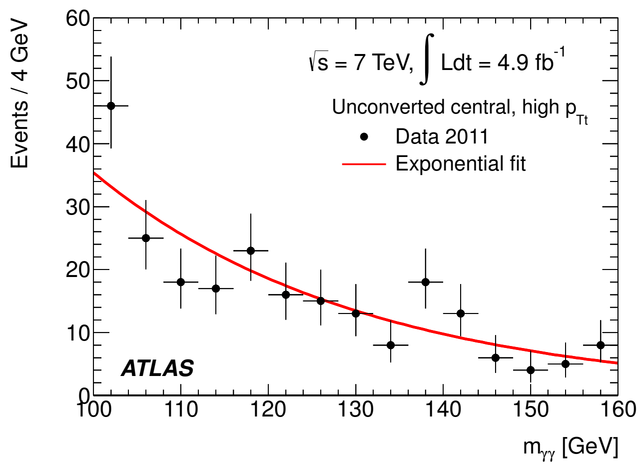
ATLAS: H→ 2 Photons - Analysis Optimisation

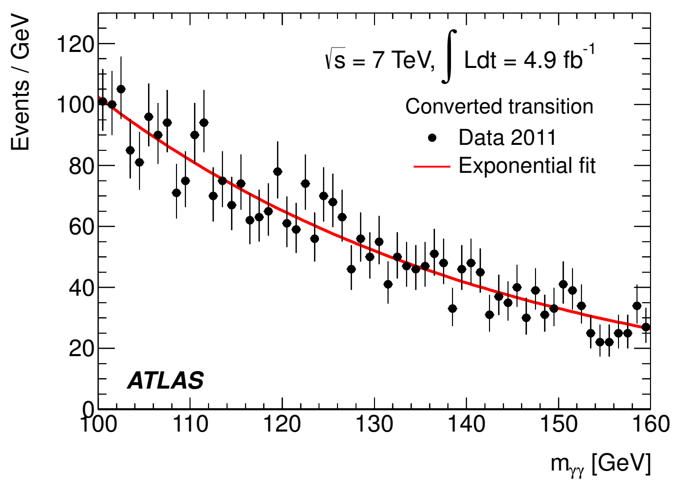
enhance signal/background ratio and mass resolution by splitting in 9 categories:

converted/ non converted
central / foward/ transition
low high $p_T^{\gamma\gamma}$ > (≤)40 GeV



Category	σ_{CB}	FWHM	N_S	N_D	S/B
Unconverted central, low p_{Tt}	1.4	3.4	9.1	1763	0.05
Unconverted central, high p_{Tt}	1.4	3.3	2.6	235	0.11
Unconverted rest, low p_{Tt}	1.7	4.0	17.7	6234	0.02
Unconverted rest, high p_{Tt}	1.6	3.9	4.7	1006	0.04
Converted central, low p_{Tt}	1.6	3.9	6.0	1318	0.03
Converted central, high p_{Tt}	1.5	3.6	1.7	184	0.08
Converted rest, low p_{Tt}	2.0	4.7	17.0	7311	0.01
Converted rest, high p_{Tt}	1.9	4.5	4.8	1072	0.03
Converted transition	2.3	5.9	8.5	3366	0.01
All categories	1.7	4.1	72.1	22489	0.02





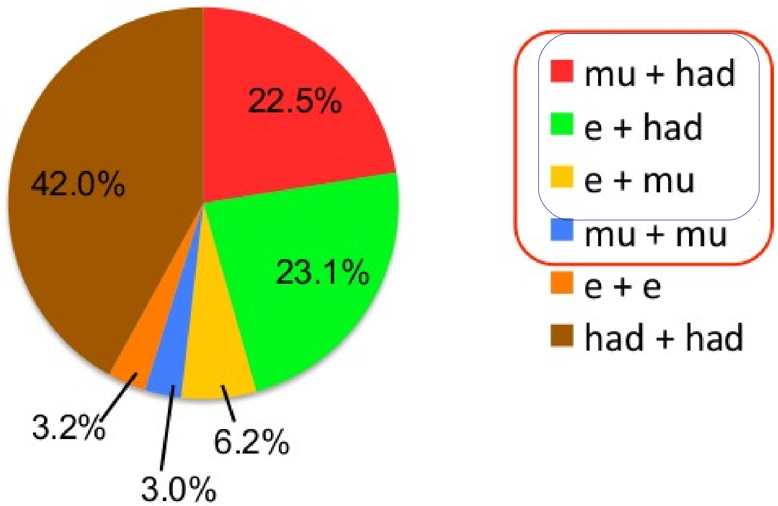
ATLAS H→ 2 γ: Systematic Uncertainties

Signal event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section (scales)	$^{+12}_{-8}$%
Higgs boson cross section (PDF+α_s)	±8%
Higgs boson p_T modeling	±1%
Luminosity	±3.9%
Signal mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
Signal mass position	
Photon energy scale	±0.7 GeV
Signal category migration	
Higgs boson p_T modeling	±8%
Conversion rate	±4.5%
Background model	±(0.1 – 7.9) events

Category	Events
Unconverted central, low p_{Tt}	±2.8
Unconverted central, high p_{Tt}	±0.1
Unconverted rest, low p_{Tt}	±5.9
Unconverted rest, high p_{Tt}	±0.7
Converted central, low p_{Tt}	±1.8
Converted central, high p_{Tt}	±0.1
Converted rest, low p_{Tt}	±7.9
Converted rest, high p_{Tt}	±0.8
Converted transition	±1.7

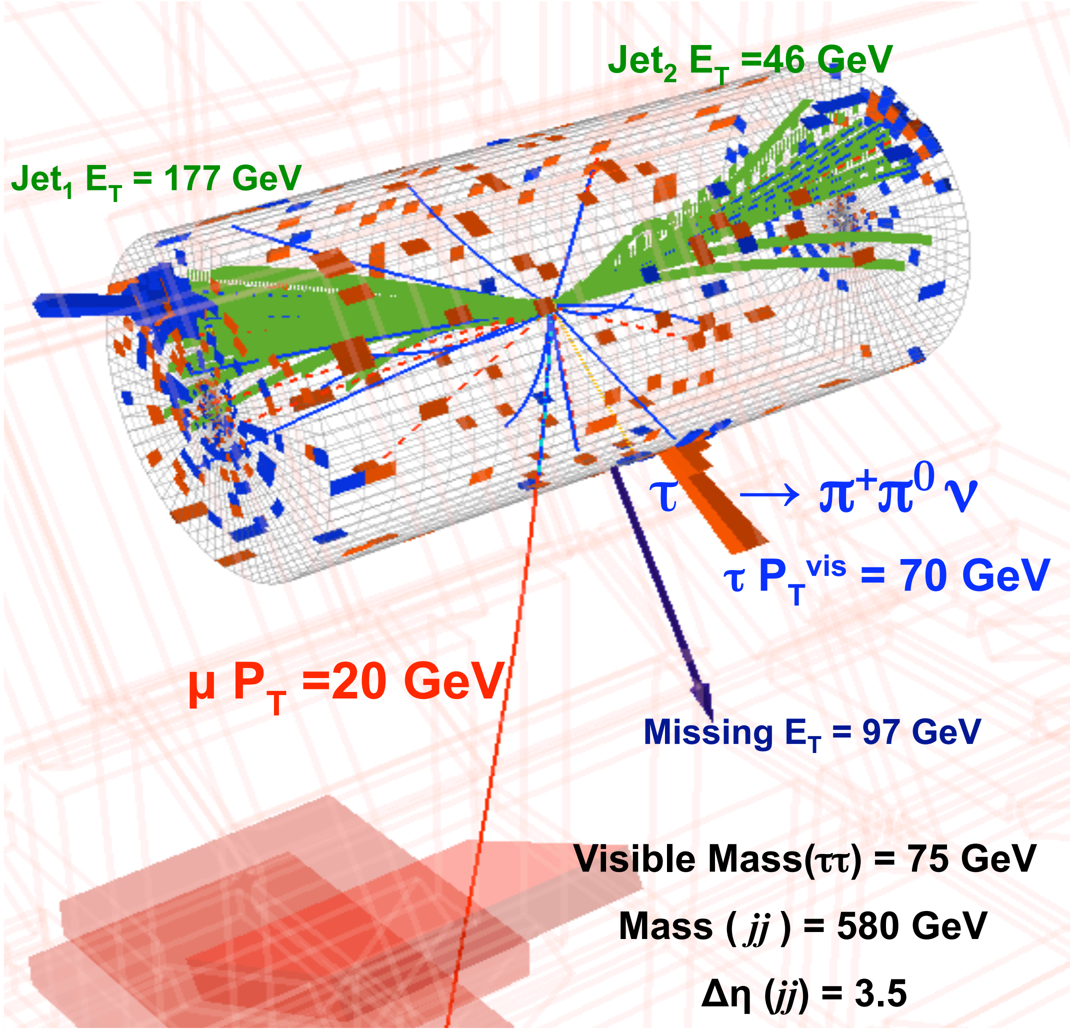
CMS: SM H→ττ with 4.6 fb^{-1} (110-145 GeV)

$\tau \to e\nu\nu$ 18 %
$\tau \to \mu\nu\nu$ 17 %
$\tau \to \tau_{had}\,\nu$ 65 %

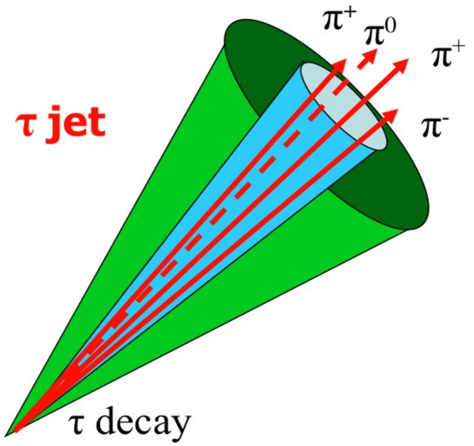


three combinations of decay modes considered

$\mu+\tau_{had}$, $\mu+\tau_{had}$, $\mu+e$

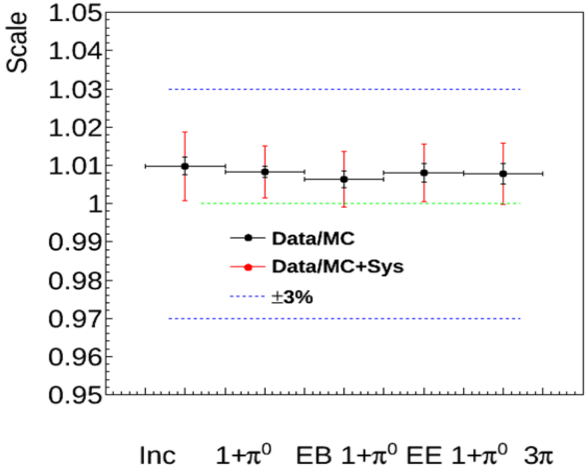


CMS: SM $H \rightarrow \tau\tau$ with 4.6 fb^{-1} (110-145GeV)

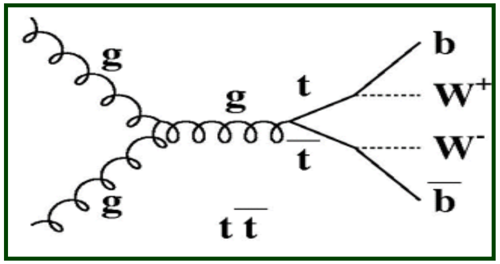


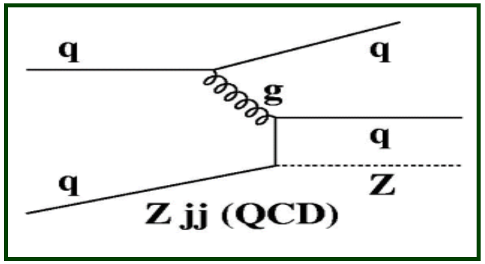
select τ decay products

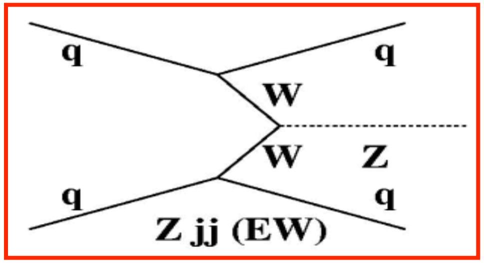
- τ_{had} energy scale Δ=3%
- τ_{had} efficiency Δ= 6%



backgrounds: reducible --→ irreducible
vor VBF







500xsignal 10000xsignal 17xsignal

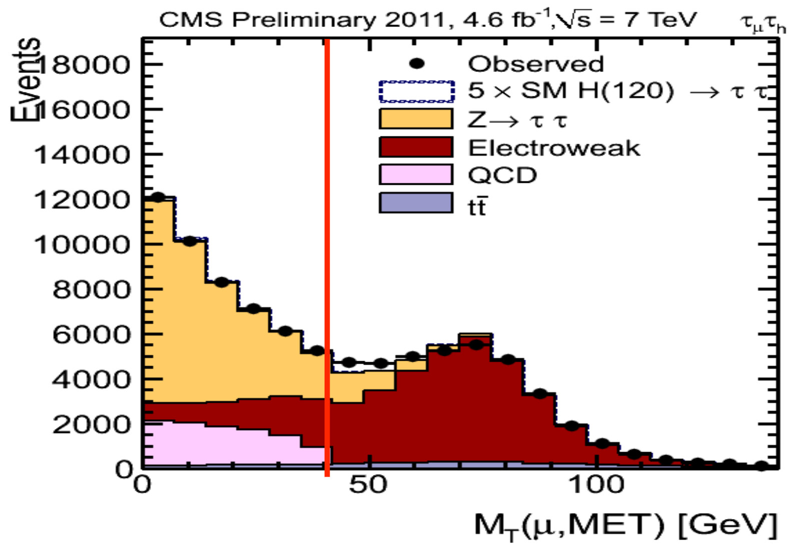
kinematics, colour flow,… mass reconstruction

CMS: SM H→ττ examples of topological cuts

$e(\mu)\ \tau_{had}$ channels:

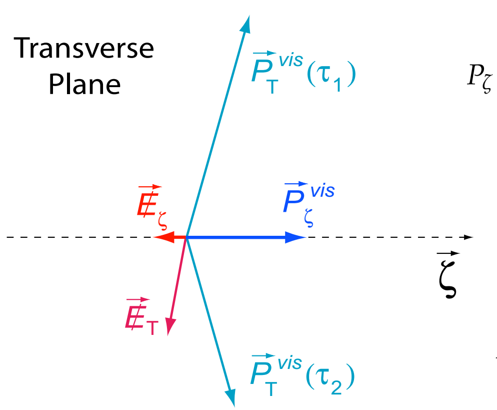
M_T(l,MET) < 40 GeV

→ suppress W backgrounds



eμ channel:

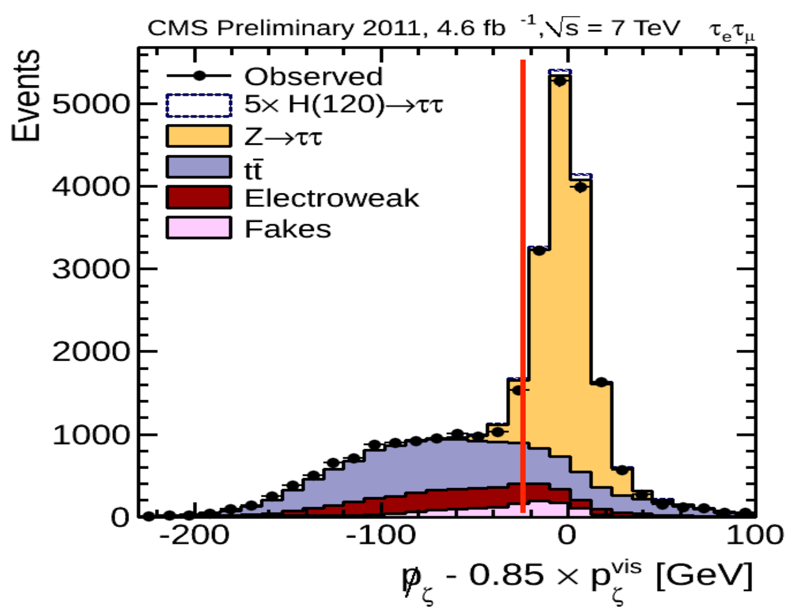
projection on bisector of tau decays



$$P_\zeta = p_{T,1}\cdot\zeta + p_{T,2}\cdot\zeta + \not{E}_T\cdot\zeta.$$

$$P_\zeta^{vis} = p_{T,1}\cdot\zeta + p_{T,2}\cdot\zeta$$

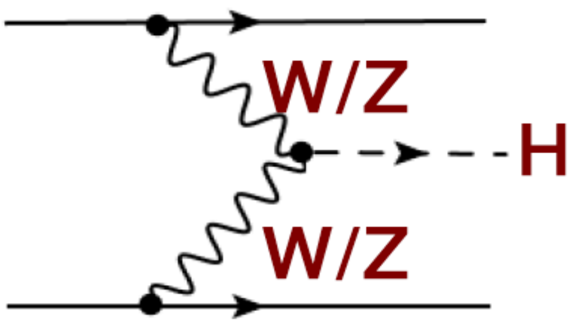
$$P_\zeta - 0.85P_\zeta^{vis} > -25\ \mathrm{GeV}$$



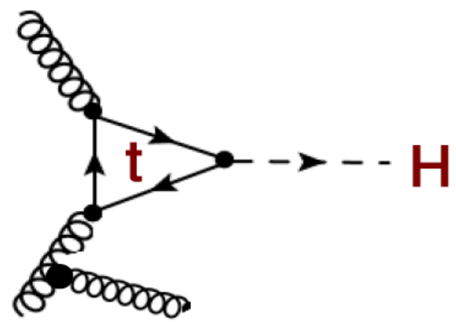
CMS: SM H→ττ categories

optimize sensitivity by splitting in jet/topology categories
→ past has shown: VBF has highest sensitivity
but all production modes considered: gg→H, VBF, W(Z)H, ttH

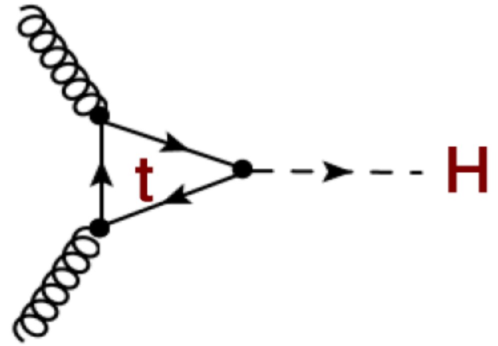
VBF



Boosted



0/1 Jet

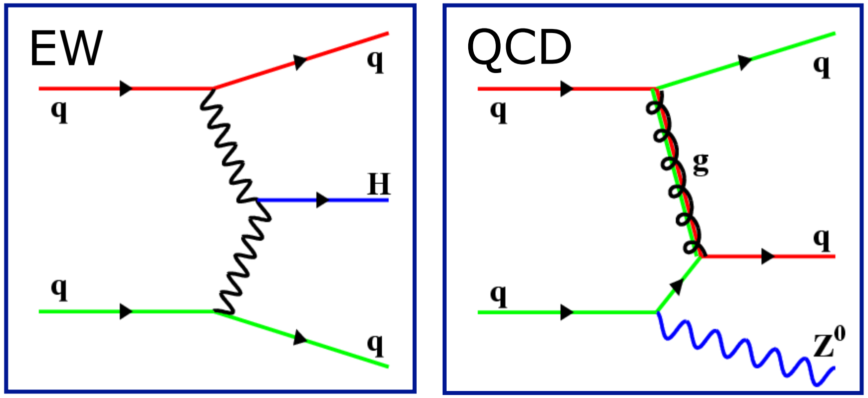


VBF
>= 2jets >30GeV
$\Delta\eta$>4, M_{jj}>400GeV
No additional jets with P_T>30GeV
In the rapidity gap

BOOSTED
One jet P_T>150GeV

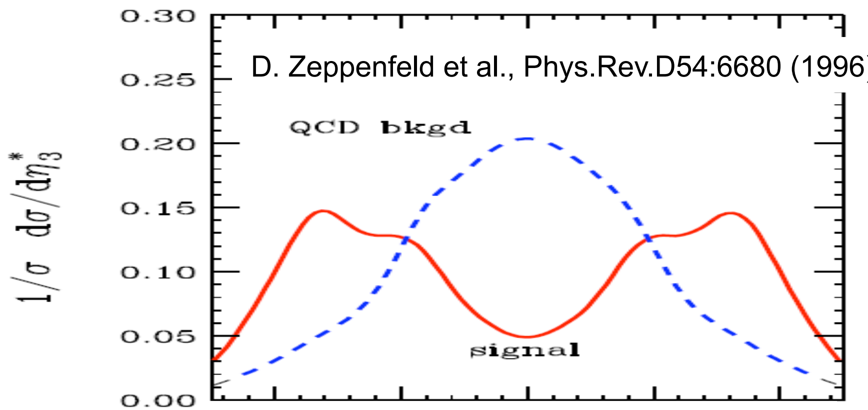
0/1 Jet
at most 1 jet with P_T>30 GeV
if 1 jet, then P_T<150 GeV

CMS: SM H→ττ VBF selection

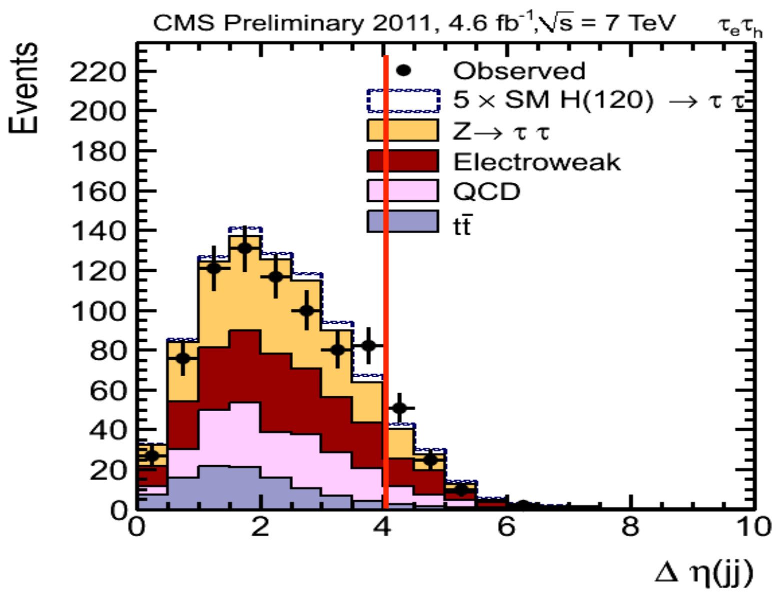


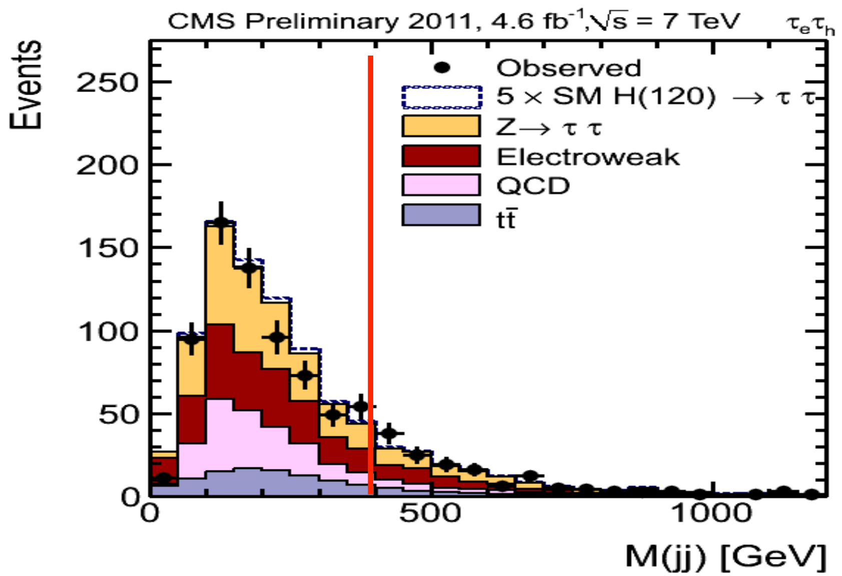
exploit different colour flow

veto on 3rd jet btw. tagging jets



$$\eta_3^* = \eta_3 - \bar{\eta} = \eta_3 - \frac{\eta_j^{tag1} + \eta_j^{tag2}}{2}$$



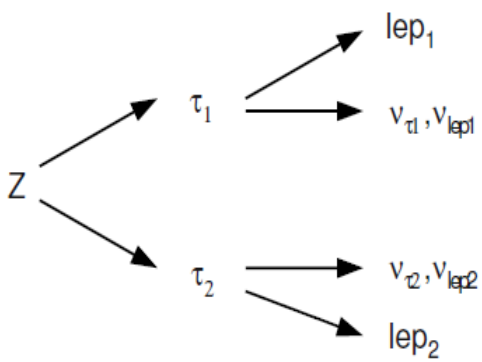


Mass Reconstruction: Missing Mass Calculator

Elagin, Murat, Pranko, Safonov, Nucl.Instrum.Meth. A654 (2011) 481

idea: also fully reconstruct τ 4-vectors → invariant di-tau mass

assumption: MET only from neutrinos



$\tau\tau$→had had 2ν: 6 unknowns 2x (px,py,pz)

$\tau\tau$→lep had 3ν: 7 unknowns: 2 x(Px,Py,Pz) +$m_{\nu\nu}$

$\tau\tau$→lep lep 4ν: 8 unknowns: 2 x(Px,Py,Pz) + 2x $m_{\nu\nu}$

four kinematic constraints (non linear equations)

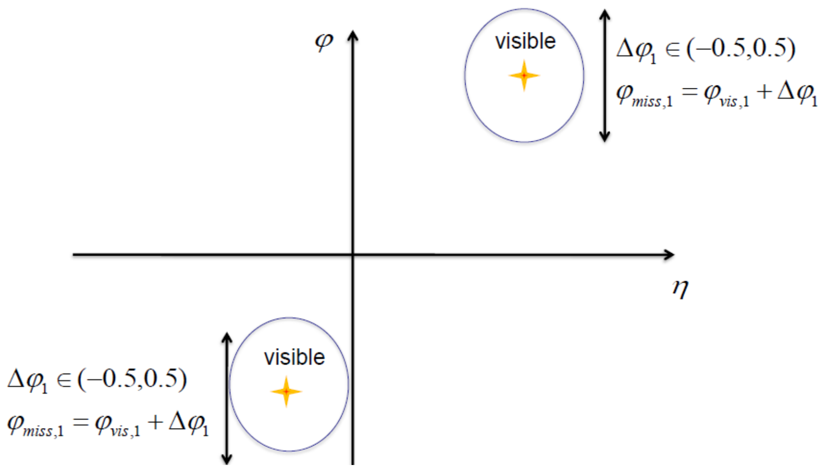
2 $MET_{x/y}$ from νs only 2 m_τ constraints

→ need to assume 2 to 4 values for neutrino momenta to solve equations

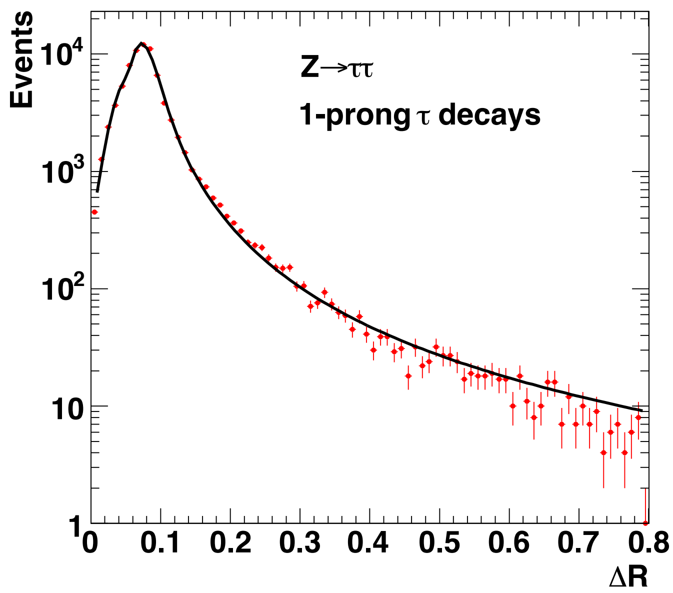
scan phase space and solve equations for each point

Missing Mass Calculator

scan phase space
solve equations for each point



calculate probability for each phase-space point to stem from 2 tau decays

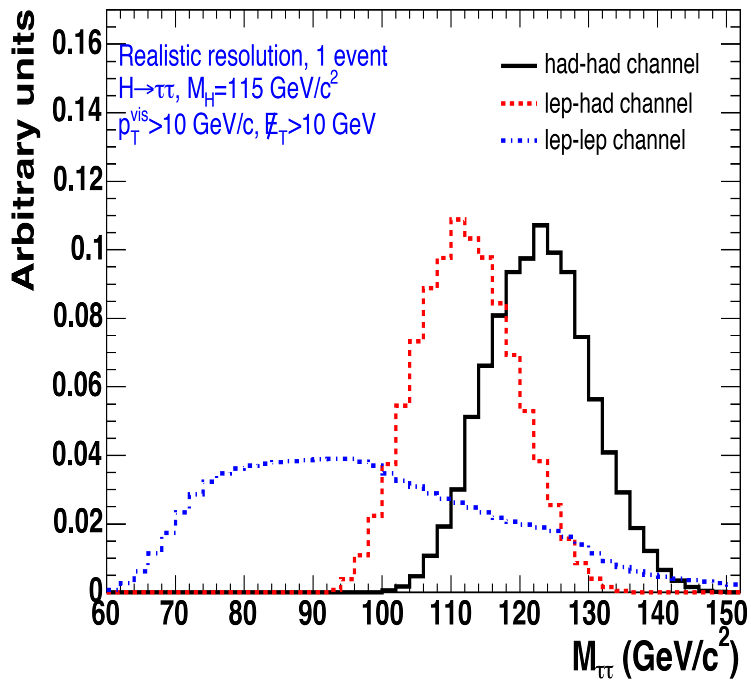


phase space weight = $\mathcal{P}(\Delta R_1, p_{\tau 1}) \times \mathcal{P}(\Delta R_2, p_{\tau 2}) \times \mathcal{P}(\Delta \not{E}_{T_x}) \times \mathcal{P}(\Delta \not{E}_{T_y})$

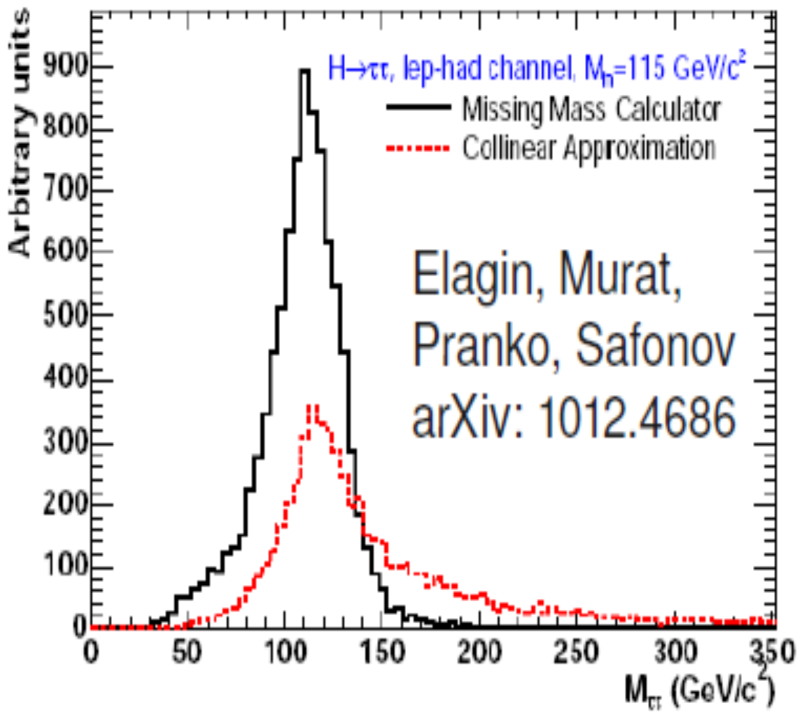
includes weight for MET resolution $\mathcal{P}(\not{E}_{T_{x,y}}) = \exp\left(-\frac{(\Delta \not{E}_{T_{x,y}})^2}{2\sigma^2}\right)$

Missing Mass Calculator

distribution of weighted mass solutions for one event



choose the mass bin with highest weight sum

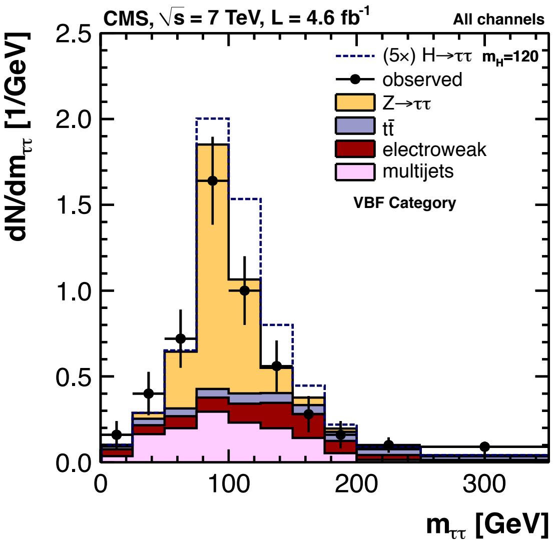


ATLAS and CMS are using a similar method   CMS: $\sigma_M/M \sim 21\%$

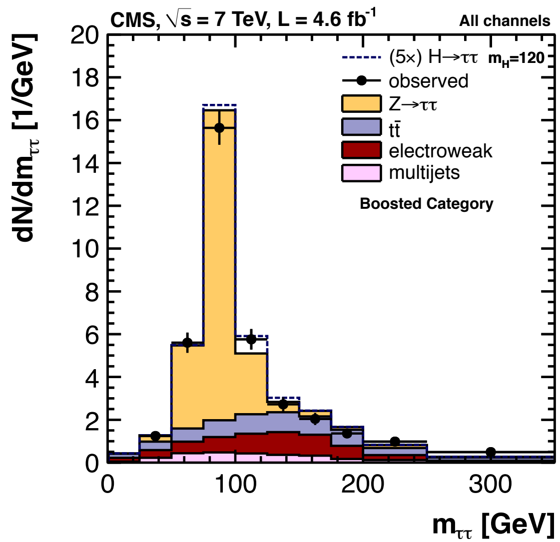
no detailed comparison for VBF topology btw. collinear mass and MMC

CMS: SM H→ττ Mass Distributions and Event Yields

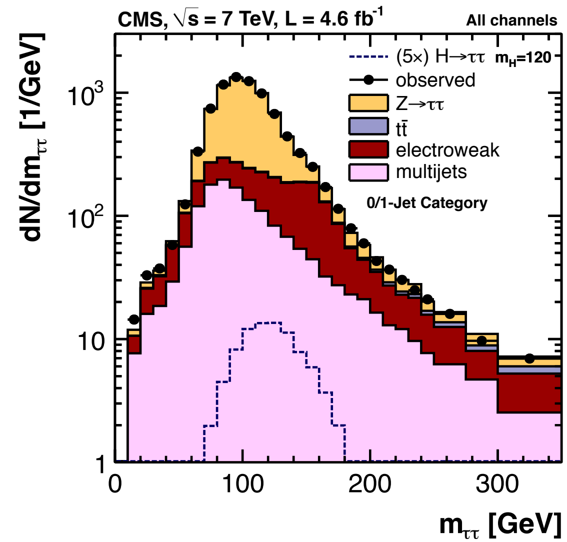
VBF



Boosted



0/1 Jet

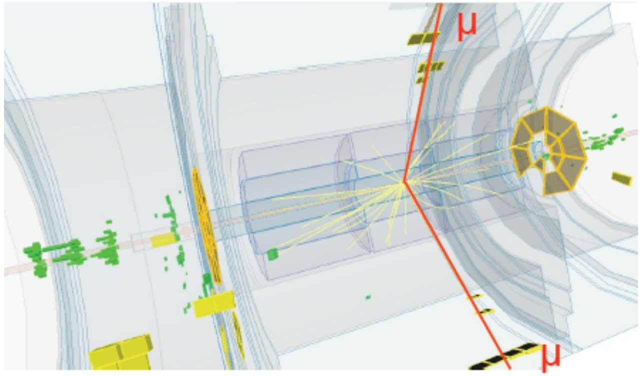


Sig/BG	**1/24**	**1/75**	**1/460**
Signal	6±1	14±2	180±20
Background	140±10	1050±170	83000±4000

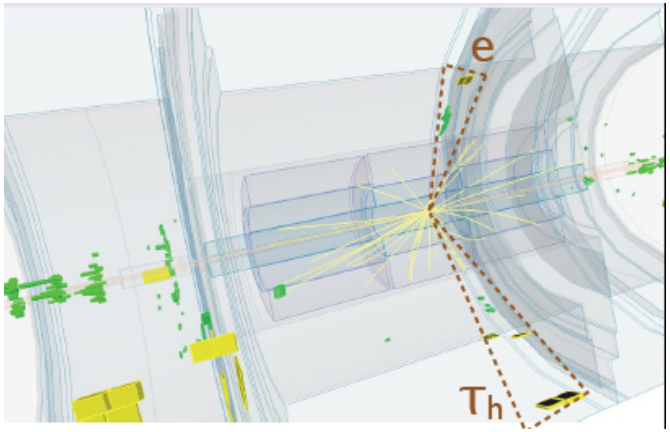
largest background Z→ττ → estimate from "embedding"
W+jets, multijet with fake τs → use events with same charge sign

Estimation of Z→ ττ via „Embedding“

- Z→ττ: Z→μμ same topology in collinear approximation
  apart from energy deposits of myon and tau lepton decay products
  BR(H→μμ) negligible → signal free



- select Z→μμ in data
- replace μ in data with τ decay from simulation
- re-reconstruct event (e.g. MET)

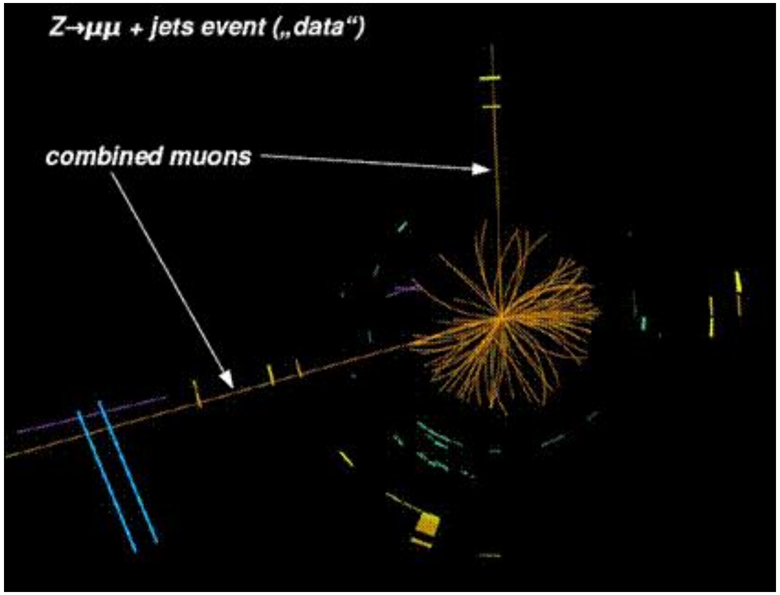


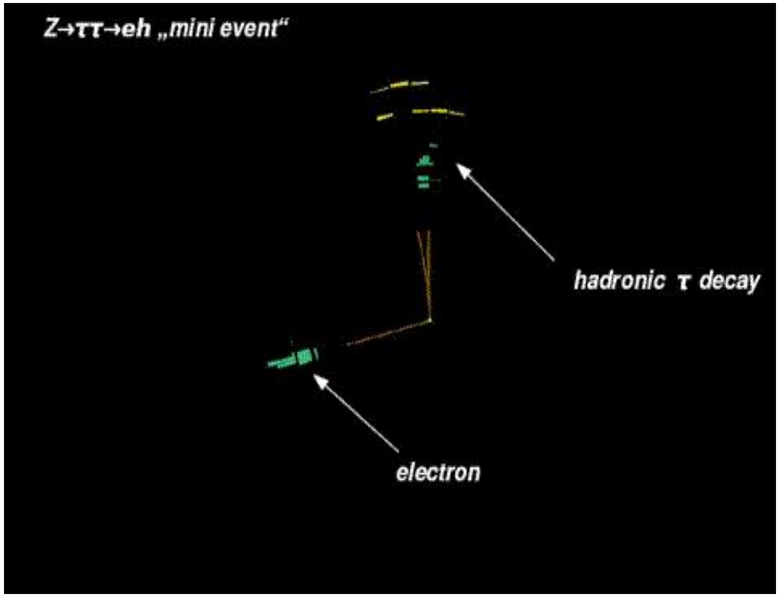
Advantage:

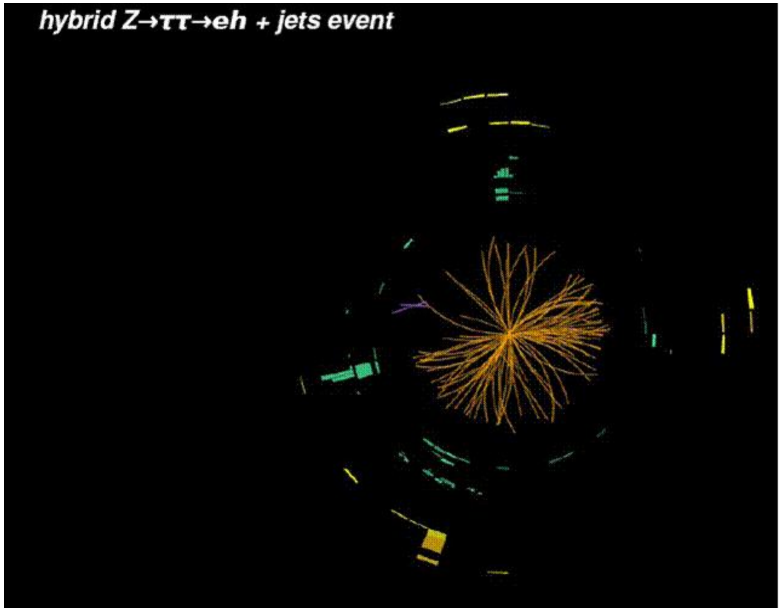
- underlying event - pile up
- detector noise - fake MET

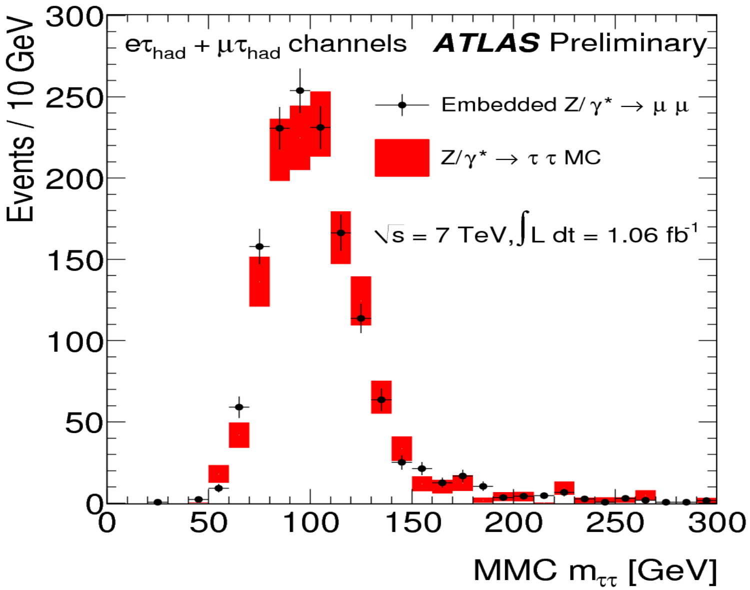
from data itself

ATLAS: „Embedding“ Works Well



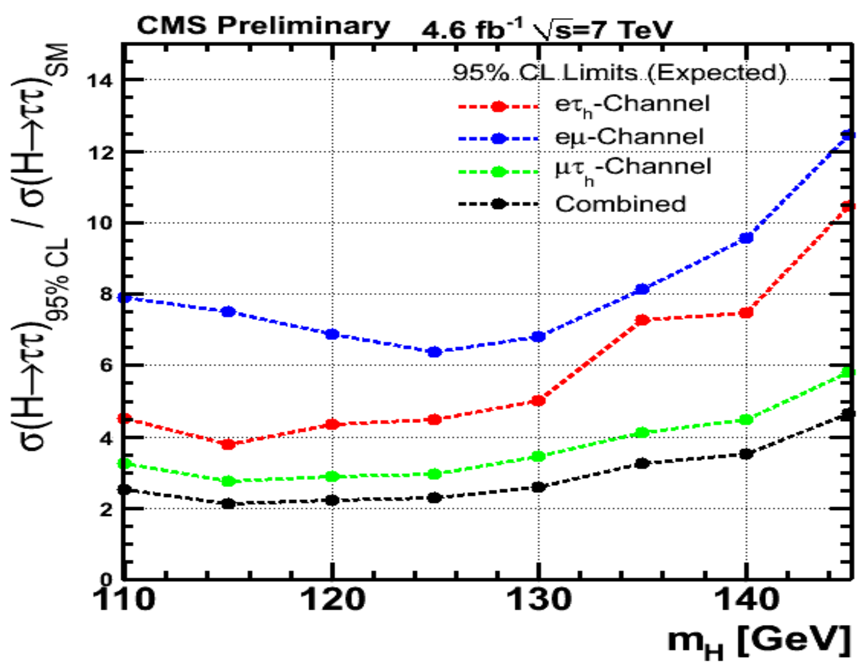


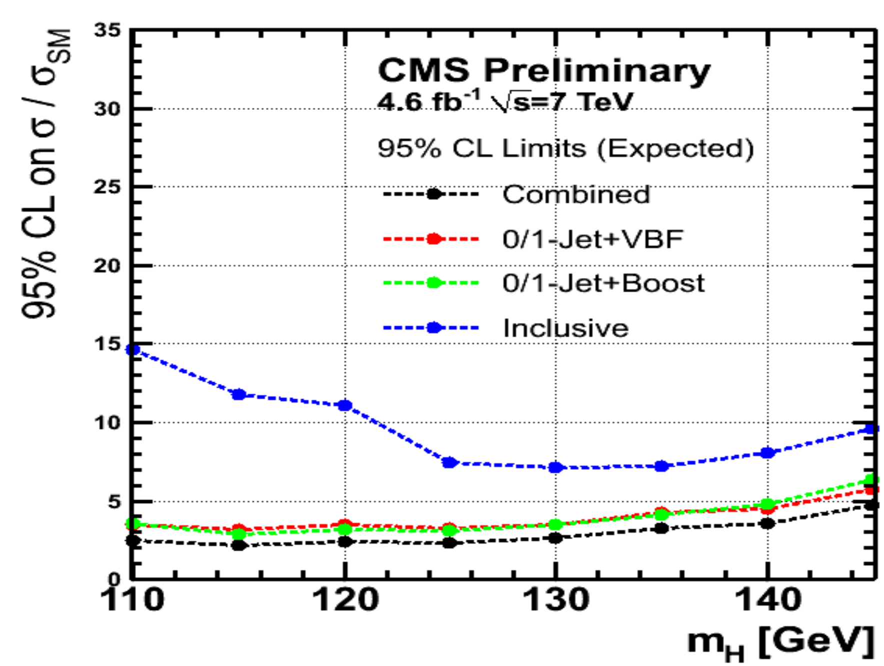




CMS: SM H→ττ Expected Sensitivity

beware: December expected limits, now ~15% worse (source unknown)





$\mu\tau_{had}$ > $e\tau_{had}$ > $e\mu$

BR($H \rightarrow l\tau_{had}$) ~ 3.5 x BR($H \rightarrow e\mu$)

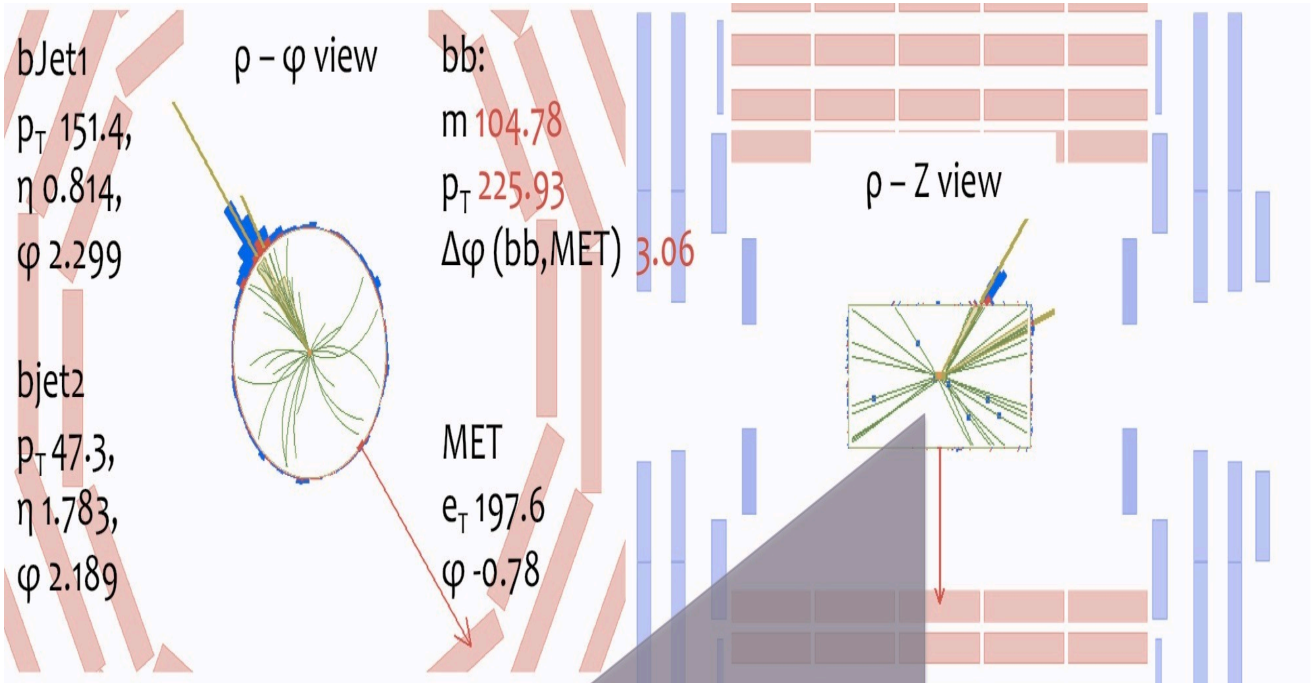
lower P_T threshold and fake rate for μ w.r.t e

0/1-jet+VBF~0/1Jet+Boost

significant improvement over inclusive analysis

CMS: H→bb with 4.7 fb^{-1} (110 - 135 GeV)

gluon fusion and VBF not usable, overwhelmed by backgrounds
→ associated production with weak gauge boson



2 b-tagged jets

l+MET

ll

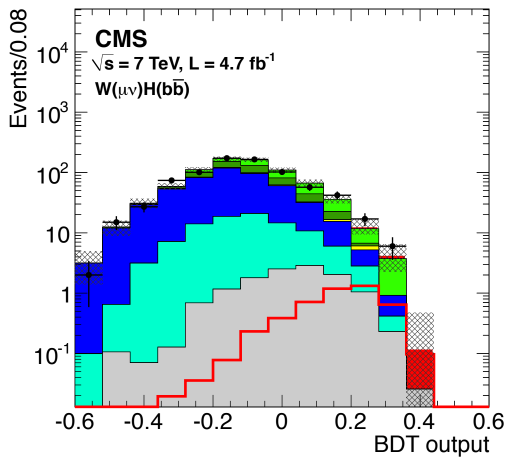
MET

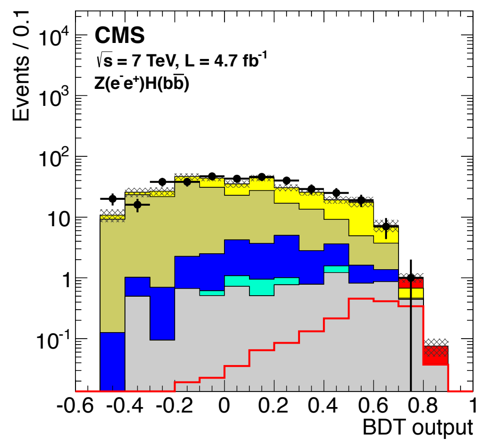
use topologies with large boost of Higgs (100 to 160 GeV on $P^{T}_{H/V}$)
→ better signal-to-background ratio by supression of top backgrounds

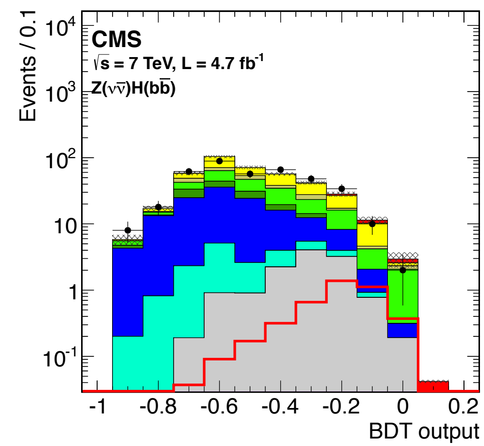
mass resolution ~10%

5 subchannels: WH→lν bb   ZH→ll bb ZH→νν bb (l=e,μ)

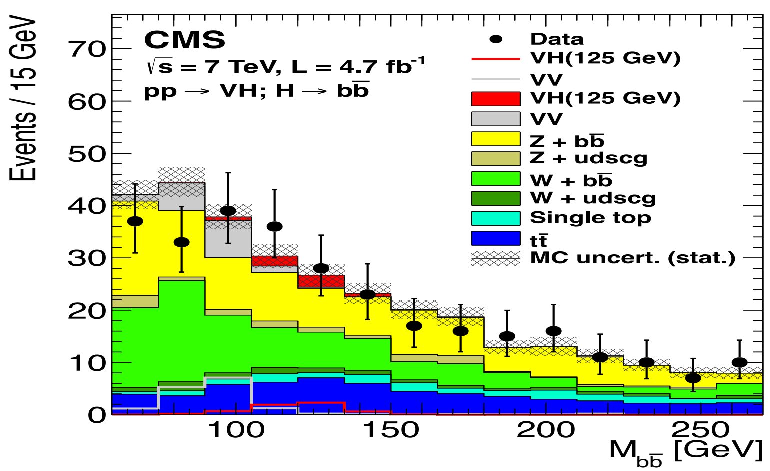
boosted decision tree analysis







m_{bb} analyis

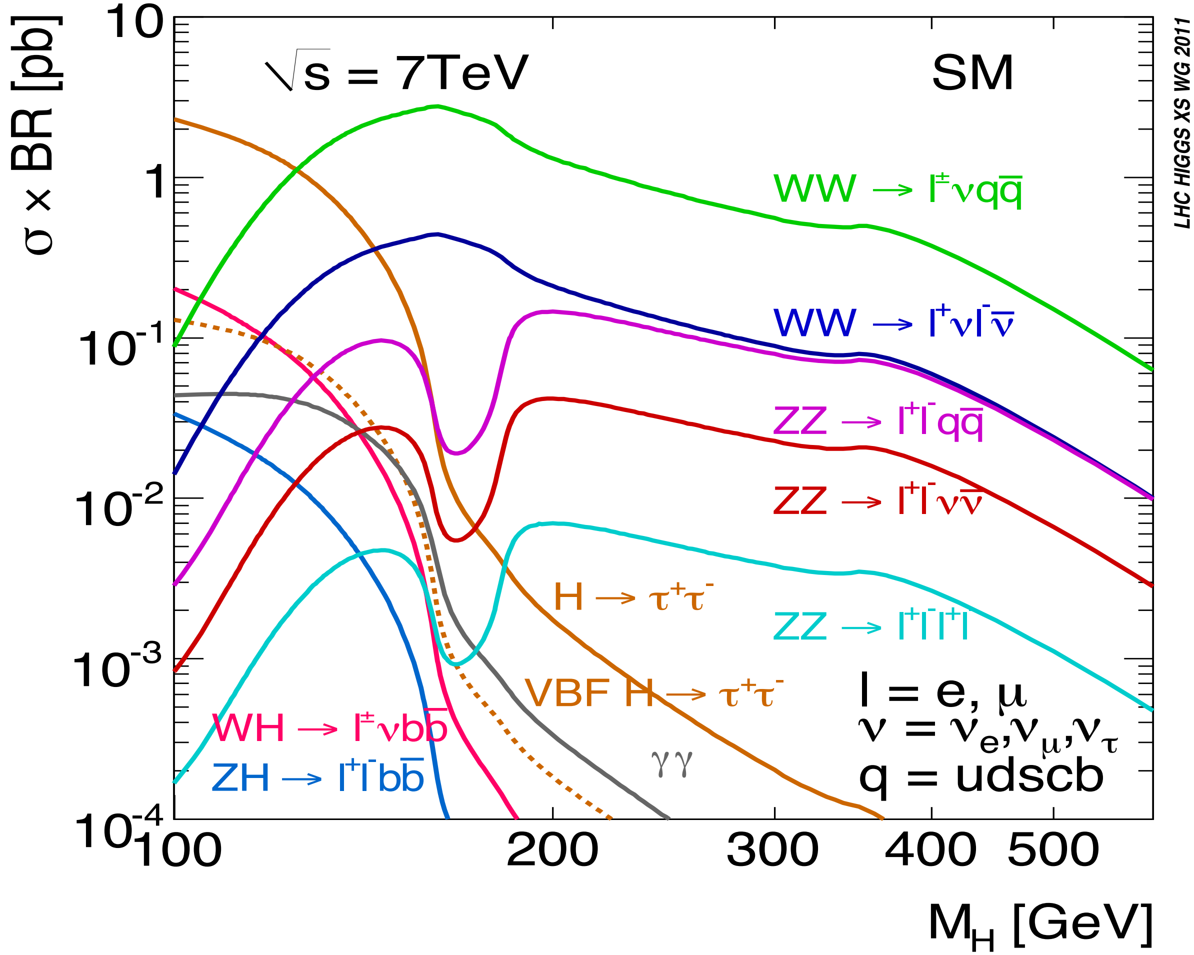


no siginficant excess

signal/background ~1/10

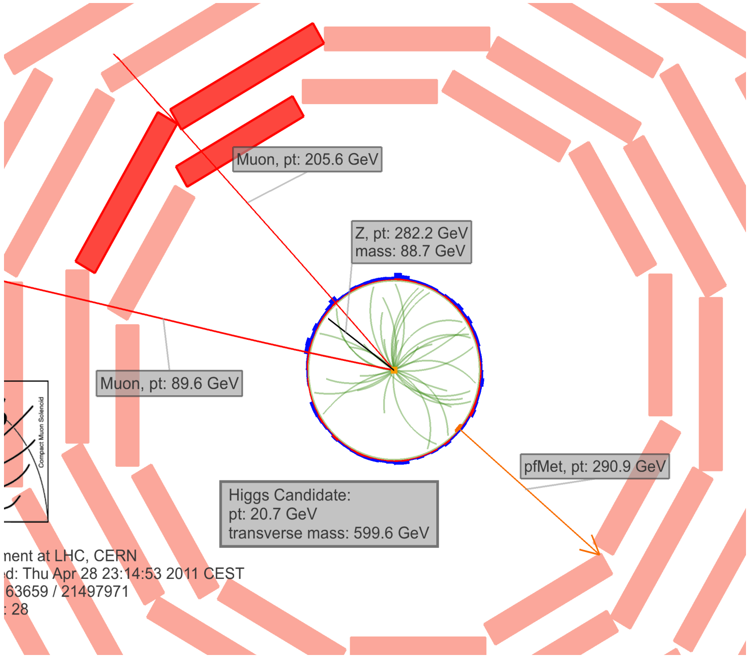
backgrounds from various control regions: uncertainty 10 to 35%

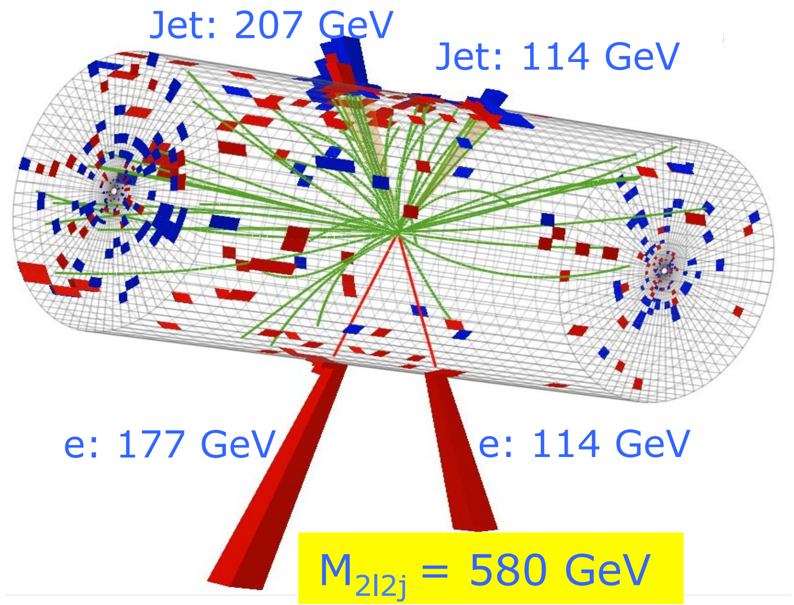
Additional high mass channels



ZZ→llqq ZZ→llνν ZZ→llττ WW→lνqq

H→ZZ→ll νν and Z → ll qq





$M_{ll} = M_Z \pm 15$ GeV $P_T^{ll} > 55$ GeV

MET, b-veto, veto 3rd lepton

final discriminant: transverse mass

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

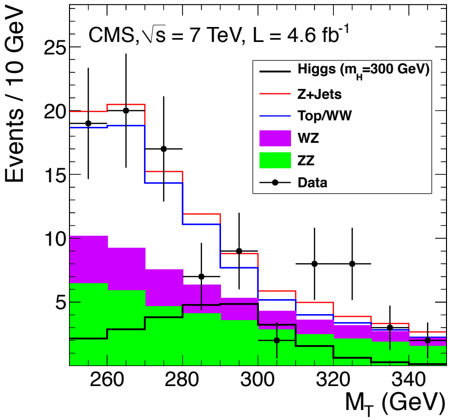
one or two Z candidates, no MET

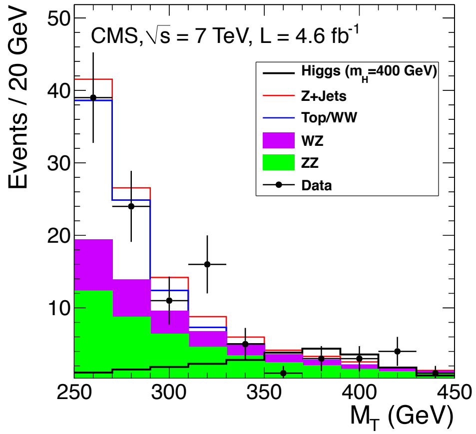
separate in 0,1,2 bjets,

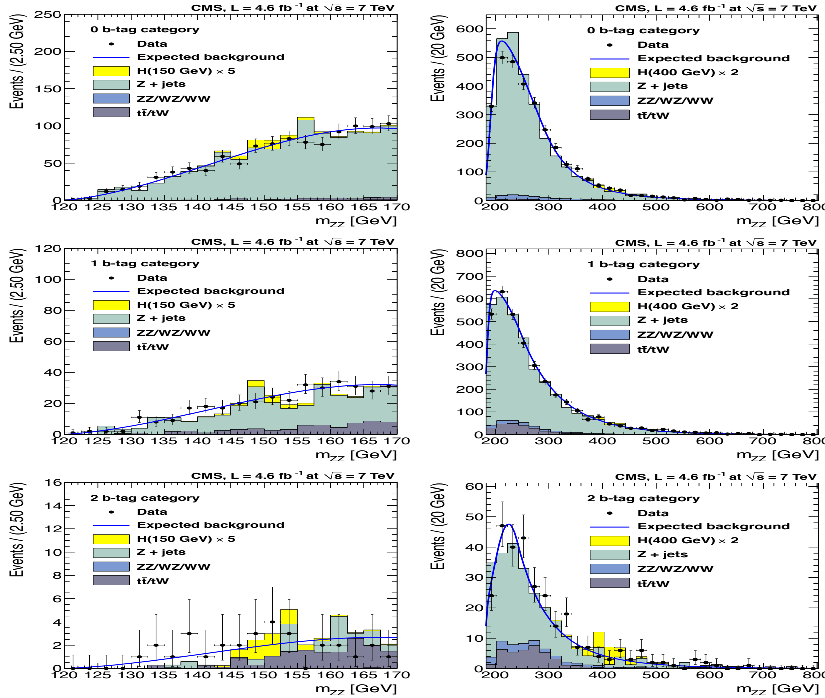
final discriminat M_{2l2j}

mass resolution~10GeV

CMS: H→ZZ→ll νν and Z → ll qq







m_H (GeV)	ZZ	WZ	Top/WW/ W+jets/Z→ ττ	Z+Jets	Total Background	Expected Signal	Data
250	$36.0\pm0.2\pm2.6$	$24.0\pm0.3\pm2.0$	$65.0\pm3.8\pm5.8$	15.0 ± 15.0	$140.0\pm3.8\pm16.0$	22.0 ± 2.2	142
300	$23.0\pm0.2\pm1.7$	$13.0\pm0.2\pm1.1$	$18.0\pm1.1\pm3.0$	6.3 ± 6.3	$60.0\pm1.1\pm7.3$	21.0 ± 2.1	64
350	$16.0\pm0.1\pm1.1$	$7.0\pm0.2\pm0.6$	$2.0\pm0.1\pm1.0$	4.1 ± 4.1	$29.0\pm0.3\pm4.4$	21.0 ± 2.5	26
400	$12.0\pm0.1\pm0.9$	$4.6\pm0.1\pm0.4$	<1.1	2.7 ± 2.7	$19.0\pm0.2\pm2.9$	17.0 ± 2.0	18
500	$7.5\pm0.1\pm0.5$	$2.0\pm0.1\pm0.2$	<1.1	1.4 ± 1.4	$11.0\pm0.1\pm1.5$	7.4 ± 1.3	14
600	$3.9\pm0.1\pm0.3$	$0.8\pm0.1\pm0.1$	<1.1	0.6 ± 0.6	$5.3\pm0.1\pm0.7$	2.9 ± 0.7	5

	0 b-tag	1 b-tag	2 b-tag
$m_{ZZ} \in [125, 170]$			
observed yield	1087	360	30
expected background (m_{jj} sideband)	1050 ± 54	324 ± 28	19 ± 5
expected background (MC)	1089 ± 39	313 ± 20	24 ± 4
$m_{ZZ} \in [183, 800]$			
observed yield	3036	3454	285
expected background (m_{jj} sideband)	3041 ± 54	3470 ± 59	258 ± 17
expected background (MC)	3105 ± 39	3420 ± 41	255 ± 11
signal expectation (MC)			
m_H=150 GeV	10.1 ± 1.5	4.1 ± 0.6	1.6 ± 0.3
m_H=250 GeV	24.5 ± 3.5	21.7 ± 3.0	8.1 ± 1.7
m_H=350 GeV	29.6 ± 4.3	26.0 ± 3.7	11.8 ± 2.5
m_H=450 GeV	16.5 ± 2.4	15.8 ± 2.2	7.9 ± 1.7
m_H=550 GeV	6.5 ± 1.0	6.5 ± 0.9	3.6 ± 0.8

Interlude: Methodology of Hypothesis Testing at LHC

only basic ideas, for details and technical issues see:

profile likelihood

Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur.Phys.J.*, C71:1554, 2011.

look elsewhere effect

Eilam Gross and Ofer Vitells. Trial factors for the look elsewhere effect in high energy physics. *The European Physical Journal C - Particles and Fields*, 70:525–530, 2010. 10.1140/epjc/s10052-010-1470-8.

CL_S method

A. L. Read. Presentation of search results: the CLs technique. *J. Phys. G: Nucl. Part. Phys.*, 28, 2002.

A. L. Read. Modified frequentist analysis of search results (the CLs method). *in Proceedings of the First Workshop on Confidence Limits, CERN, Geneva, Switzerland*, 2000.

Thomas Junk. Confidence level computation for combining searches with small statistics. *Nucl.Instrum.Meth.*, A434:435–443, 1999.

LHC combination procedure

ATL-PHYS-PUB-2011-11 CMS NOTE-2011/005

Basics of Hypothesis Testing

Specify what are you looking for: obervation or exclusion of signal

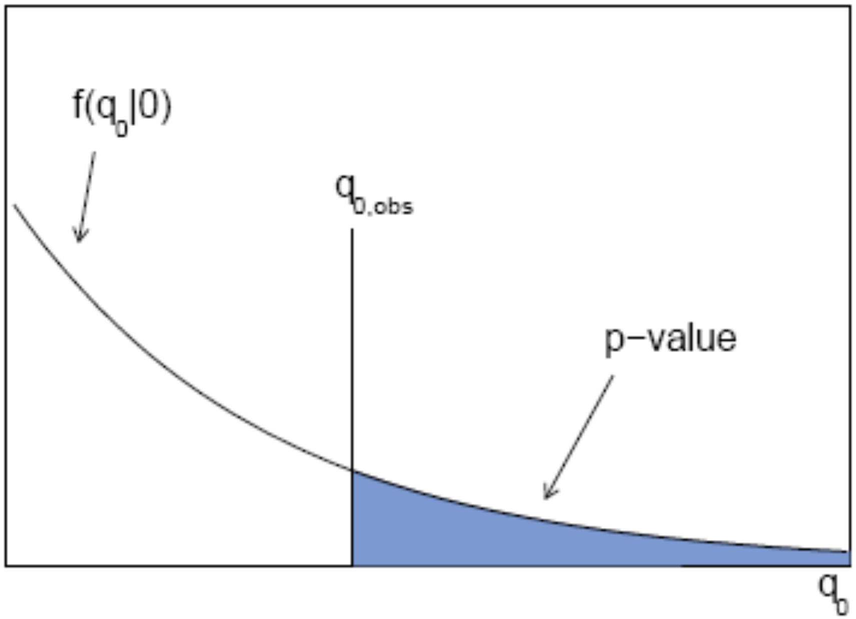
Phrase null hypothesis H_0 as opposite to what you are interested in as you can only falsify/reject hypothesis but not approve them

Observation of Higgs → H_0: no Higgs, only SM background processes
Exclusion of Higgs → H_0: Higgs and SM background processes

Quantify agreement with H_0
by choosing a test statistic t
(any function of your data)
at LHC: perfect agreement t=0
deviation t>0

Get probability densitiy function for $t=q_0$ and calculate p-value

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$

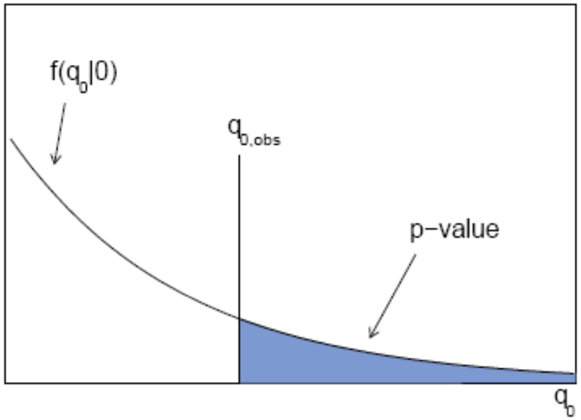


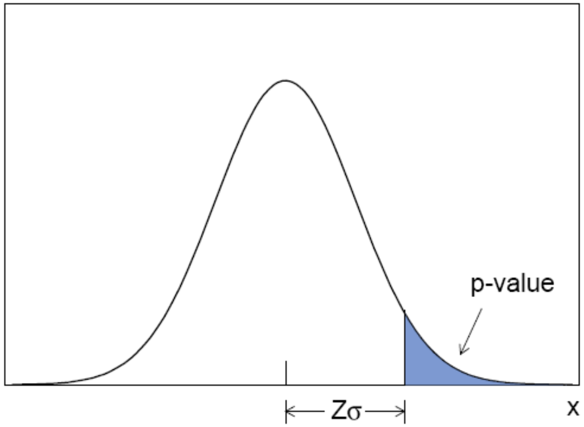
P-Value, Significance and Confidence Level

if p-Value < predefined value (signifcance level, error of first kind) then reject null hypothesis

convention: for discovery require p-value (BG only) $< 2.87\times10^{-7}$

for exclusion require p-value (Higgs+BG) < 0.05





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

$$Z = \Phi^{-1}(1-p)$$

p-value can be translated in significance via Standard Gauss pdf.

a significance of 5 (1.64) corresponds to P= 2.87×10^{-7} (0.05)

if p-Value is x then one says „this hypothesis is excluded with a confidence level of CL=1-x“

the frequency of false exclusion (error of 1st kind) is x.

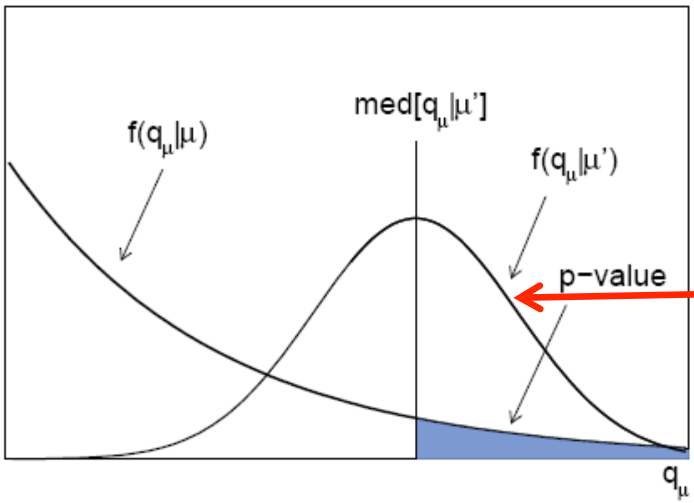
Choices to take and optimal test

Decisions to take:

i) test statistics t → ratio of (profiled) likelihoods

ii) how to deal with syst. uncertainties → nuisance parameters + profiling

iii) derivation of pdfs for t under hypotheses → often asymptotics usable



fixing the significance level α for H_0
i.e. for p-value < α reject H_0

best test maximizes power of H_0
w.r.t. alternative hypothesis H_1

without systematics best test is given by the Neyman-Pearson-Lemma:
best test statistic = ratio of likelihoods under simple hypothesis H_1 and H_0

$$t_{NP} = L(\text{data} \mid \text{signal+background}) / L(\text{data} \mid \text{background})$$

Test Statistic at LHC: Ratio of Profiled Likelihood

$\mu \cdot s(\theta)$ signal yield and shape of final discriminant $\sigma = \mu \cdot \sigma_{\mathrm{SM}}$

$b(\theta)$ background yield and shape of final discriminant

$\tilde{\theta}_i$ estimate for nuisance parameters θ

→ parametrize systematic uncertainties on yields and shapes from

e.g. efficiencies, theo.σ, extrapolation from control to signal region

contrained from data via auxilary measurements $p(\tilde{\theta}|\theta)$

Complete likelihood function is given by:

$$\mathcal{L}(\mathrm{data} \,|\, \mu \cdot s(\theta) + b(\theta)) = \mathcal{P}(\mathrm{data} \,|\, \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta}|\theta)$$

Fix μ only under null hypothesis H_0 and estimate it from data via maximum likelihood method under alternative hypothesis H_1

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

μ fixed under H_0

$\hat{\hat{\boldsymbol{\theta}}}$ maximum likelihood estimate under H_0

$\hat{\mu}, \hat{\boldsymbol{\theta}}$ maximum likelihood estimates under H_1

Ratio of Profiled Likelihoods: Simple Example

Assume: simple counting experiment in signal region SR with unknown background expecation b (b is nuisance parameter)

Control region CR for background e.g sideband
yields in SR and CR related via SR =1/ τ CR
(τ known, uncertainty would give additional nuisance parameter)

Observation gives: *n* events in SR *m* events in CR

Each follow Poisson distribution: $n \sim \mathrm{Poisson}(s+b)$ $m \sim \mathrm{Poisson}(\tau b)$

Common likelihood function: $$L(s,b) = \frac{(s+b)^n}{n!} e^{-(s+b)} \frac{(\tau b)^m}{m!} e^{-\tau b}$$

Test statistic = ratio of profiled likelihoods:

(in nominator s is fixed under H_0
s=0 for discovery,
s= nominal signal value for exclusion)

$$\lambda(s) = \frac{L(s, \hat{\hat{b}})}{L(\hat{s}, \hat{b})}$$

Profiled Likelihood Test Statistic for Discovery

H_0: only background → $\mu=0$ H_1: signal and background,
μ parametrises strength w.r.t. SM Higgs predicton

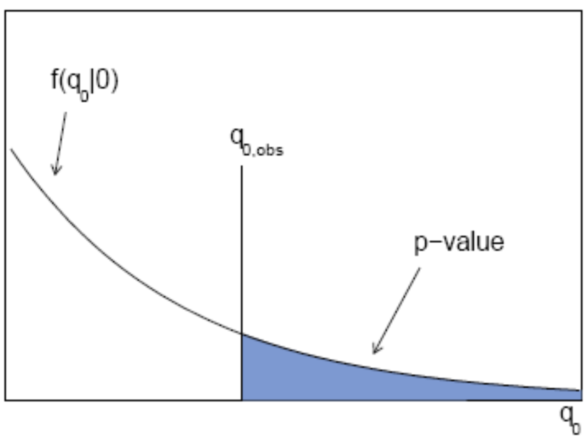
test statistic q_0:

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

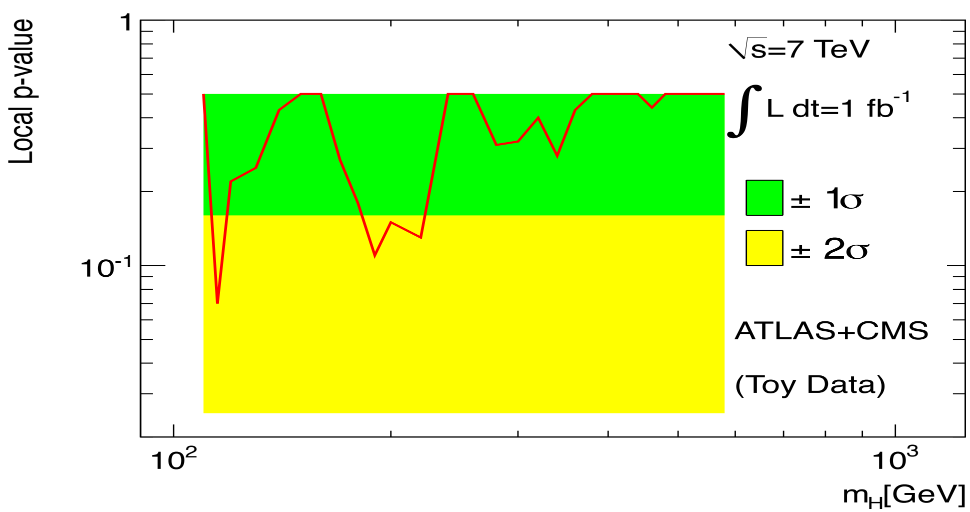
$\lambda(0)$ btw. 0: H_1 like and 1:H_0 like

→ q_0 between 0 and infinifity
0: H_0 like >> 0 H_1-like

one sided test, only positive signal strength considered as deviation from H_0



$$p_0 = \int_{q_{0,obs}}^{\infty} f(q_0|0)\, dq_0$$



The „Look Elsewhere Effect“ (LEE)

So far: local p-value/ significance = prob. to see such an excess at fixed M_H as we specified M_H in the alternative hypothesis H_1

$$t_{\text{fix}} = -2\ln\frac{L(0,m_0)}{L(\hat{\mu},m_0)} \qquad p_{\text{fix}} = \int_{t_{\text{fix,obs}}}^{\infty} f(t_{\text{fix}}|0)dt_{\text{fix}} \qquad Z_{\text{fix}} = \Phi^{-1}(1-p_{\text{fix}})$$

now ask: prob. to see such an excess anywhere in given mass range
→ let mass be a nuisance parameter in fit of new test statistic

$$t_{\text{float}} = -2\ln\frac{L(0)}{L(\hat{\mu},\hat{m})} \qquad p_{\text{float}} = \int_{t_{\text{float,obs}}}^{\infty} f(t_{\text{float}}|0)dt_{\text{float}}$$

p_{float} also called global p-value. calculation very cumbersome. lot of MC experiments

$$F_{\text{trials}} \equiv \frac{p_{\text{float}}}{p_{\text{fix}}}$$

trial factor ~ number of independent search regions in considered mass range.
can be calculated approximately with little MC simulation

Profiled Likelihood Test Statistic for Exclusion

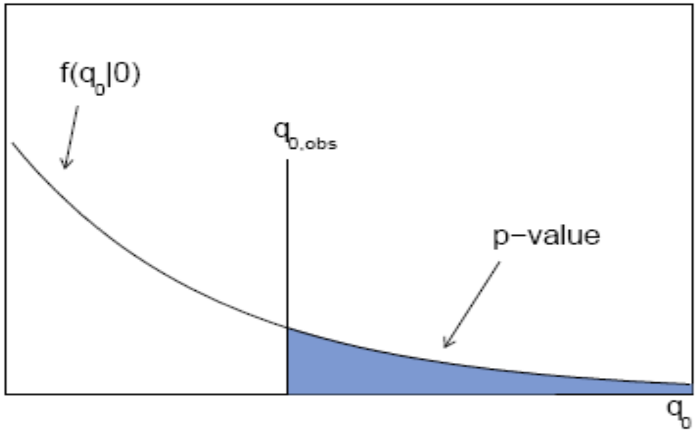
H_0: signal+background → μ=1 H_1: background only
μ parametrises strength w.r.t. SM Higgs predicton

test statistic q_μ:

$$\tilde{\lambda}(\mu) = \begin{cases} \dfrac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} & \hat{\mu} \geq 0, \\ \dfrac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(0, \hat{\hat{\boldsymbol{\theta}}}(0))} & \hat{\mu} < 0\,. \end{cases}$$

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

for negative signal strength set it to 0 and determine then nuisance pars.
one sided test, only signal strength< μ considered as inconsistent with H_0



different test statistic then for discovery

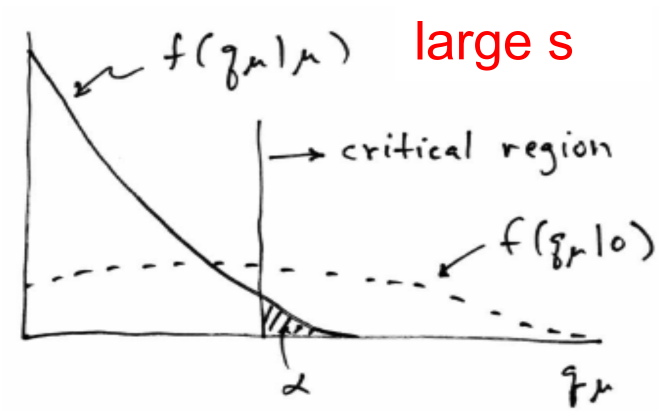
here values ~0 are signal+background like observations

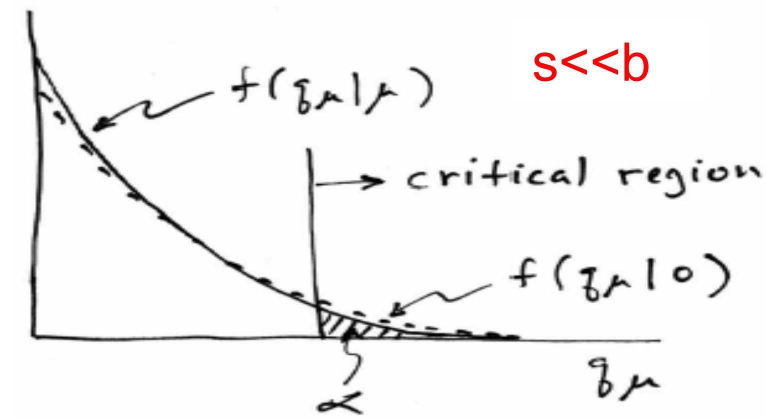
The „Problem“ with the Pure Frequentist Method

$$p_\mu \;=\; P(\,\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\text{signal+background}) \;=\; \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu,\hat{\theta}_\mu^{\text{obs}})\,d\tilde{q}_\mu$$

Pure frequentist would stop and say: „signal+background“ hypothesis is exlcuded with a confidence level CL_{S+B} of 1- p_μ

„Problem“: Spurious exclusion of signals with no sensitivity (s<<b)





signal+BG-like ← → BG only like, even less than exp. from BG only

by construction: probabilty to reject μ if μ is true is α
probability to reject μ if μ=0 is only slighty greater than α for s<<b.
→ probability to exlcude hypotheses with zero signal ~α „spurios exclusion“

A Solution: the CL_S Method

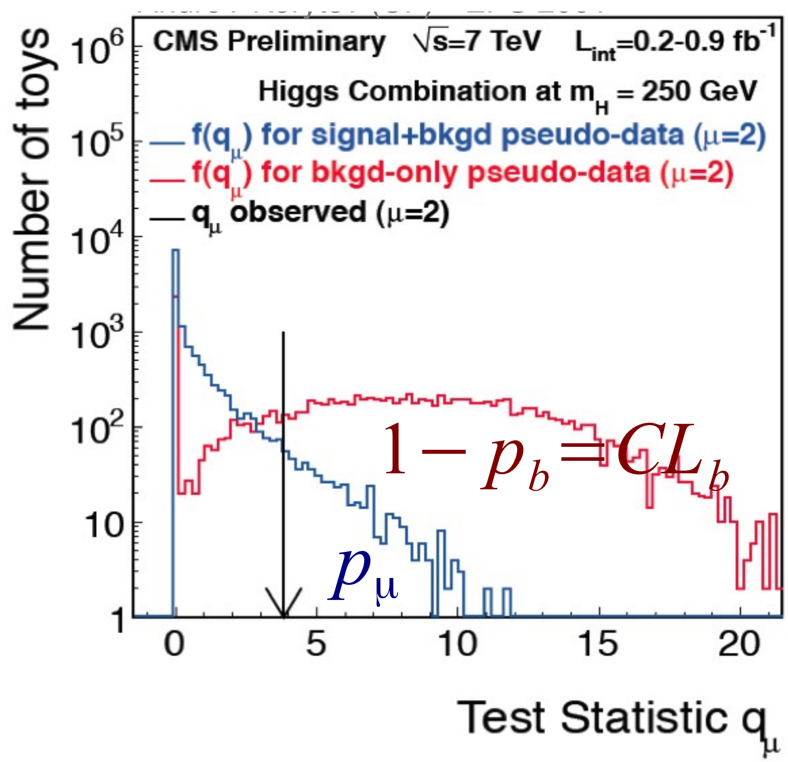
Spurious exclusion caused by downwards fluctuation of background
→ penalize such outcomes in an „ad hoc“ way

$$1 - p_b = P\left(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,\middle|\, \text{background-only}\right) = \int_{q_0^{obs}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}_0^{obs})\, d\tilde{q}_\mu$$

$$p_\mu = P\left(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,\middle|\, \text{signal+background}\right) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{obs})\, d\tilde{q}_\mu$$

$$CL_s = p_\mu / (1 - p_b)$$

Caveat: p_b ist not equal p_0
different test statistic

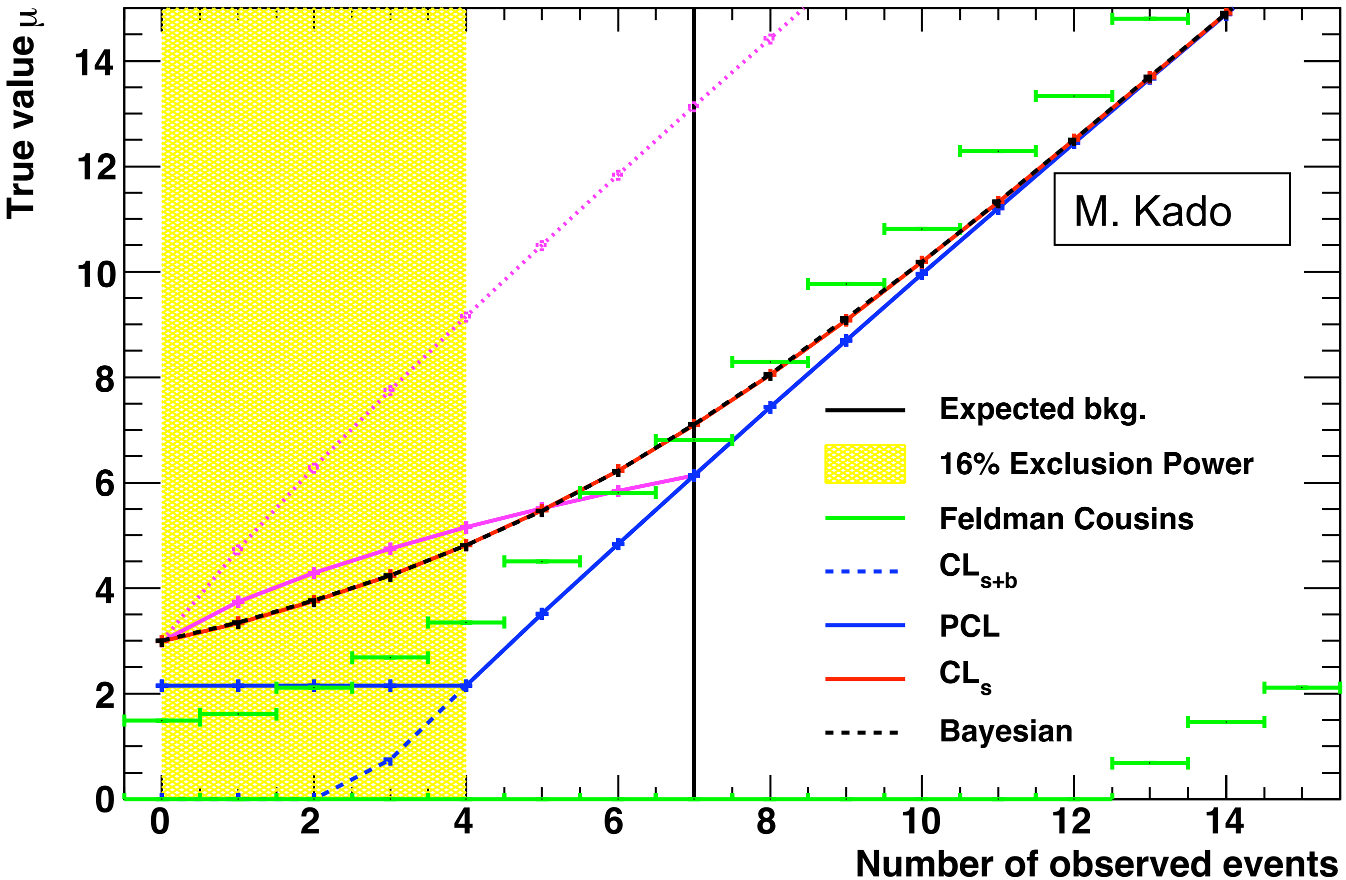


if CL_S<5% we call a μ hypothesis excluded at 95% CL (but true coverage larger)

upper limit on μ: adjust/find smalles value of μ to value for which $CL_S \leq 5\%$

Comparison of Different Limit Derivations at 95% CL

simple counting experiment with a background expectation of 7 events

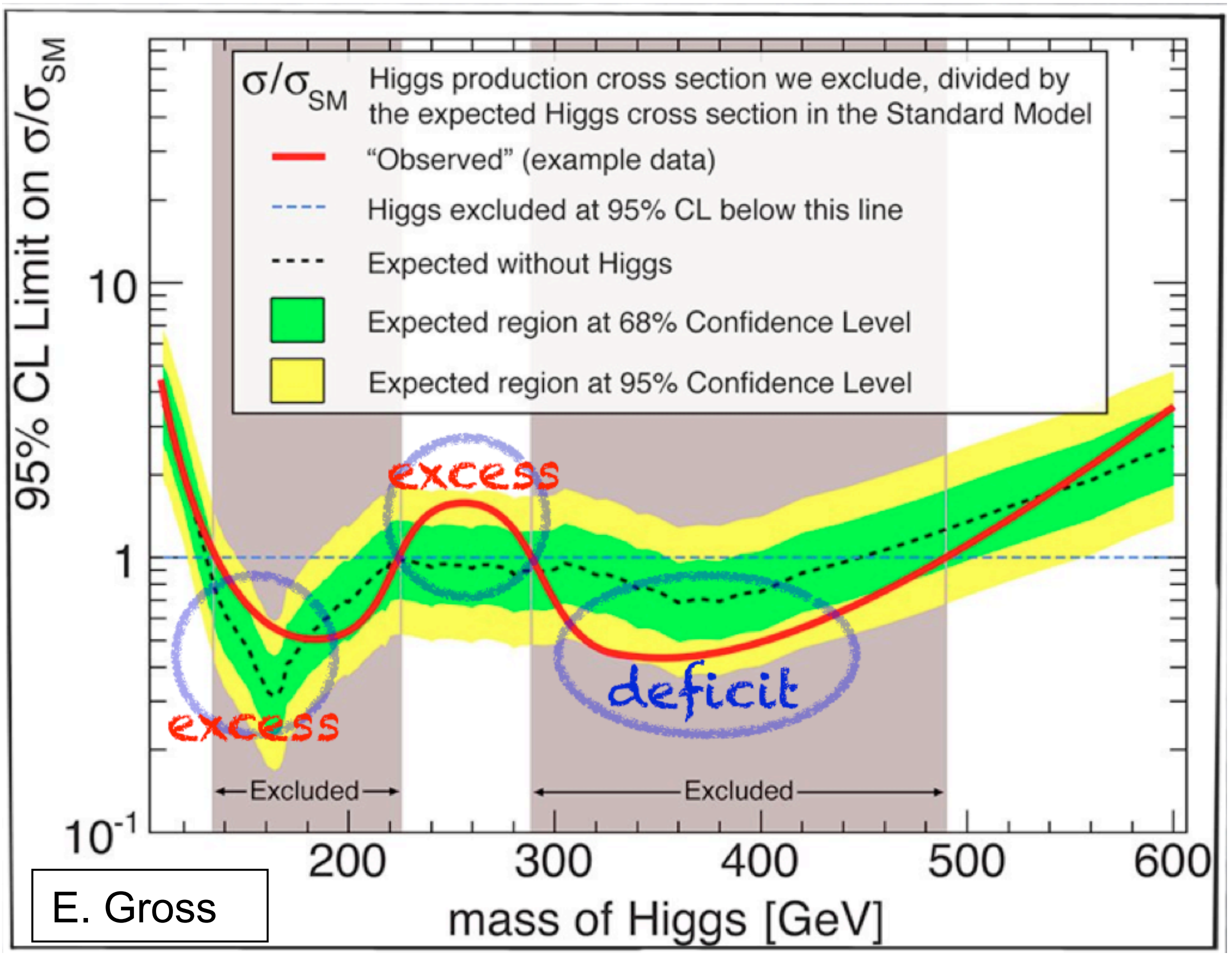


if CL_S<5% we call a μ hypothesis excluded at 95% CL (true coverage larger)

CL_S and Bayesian limit with flat prior in signal rate mathematically identical

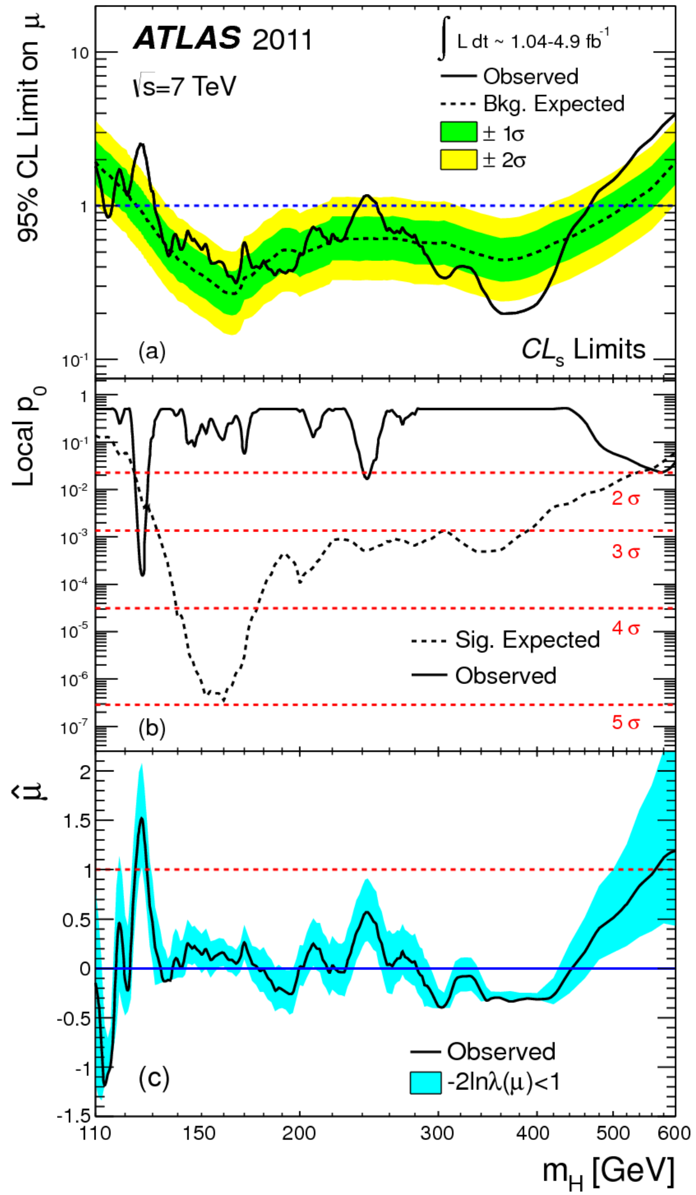
in praxis also very similar results for test statistics used at LHC (Tevatron, LEP)

Typical Exclusion Plot Looks Like This ...



expected limit: median value of μ which will be excluded under H_1 BG-only
green and yellow bands are 68% (95%) confidence ntervals around this

Interpretation of Results is Threefold

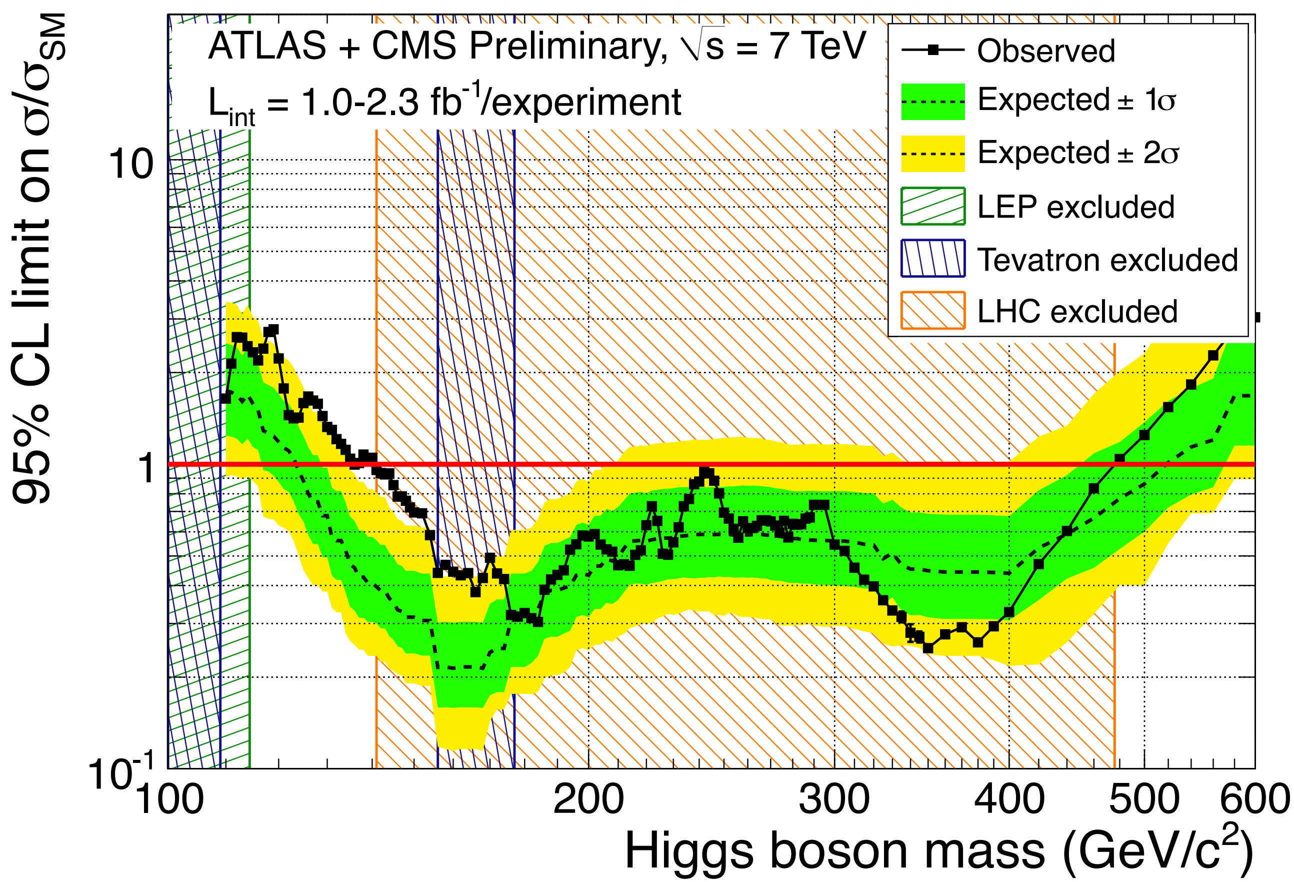


signal +background hypothesis exclusion:
for each hypothetical signal mass determine minimum signal strength μ which can be excluded at 95% CL

background hypothesis compability:
evaluate p-value for each hypothetical signal mass → local p-value
+ global p-value from trials factor

compability with SM Higgs boson hypothesis:
estimate best signal strength compatible with observation

First Combination of ATLAS and CMS on 18.11.2011



CMS PAS HIG-11-023,
ATL-CONF-201-157

based on data recorded until end of August 2011

LEP (95%CL)
$m_H < 114.4$ GeV

Tevatron (95%CL)
$100 < m_H < 109$ GeV
$156 < m_H < 177$ GeV

Excluded 95% CL : 141-476 GeV (exp 124 - 520 GeV)
ATLAS alone: 146-230, 256-282, 296-459 (exp 131 – 450 GeV)
CMS alone: 145-216, 226-288, 310-400 (exp 130 - 440 GeV)
max deviation with local significance of 3σ (m_H~144 GeV)

Combination of Higgs Boson Searches

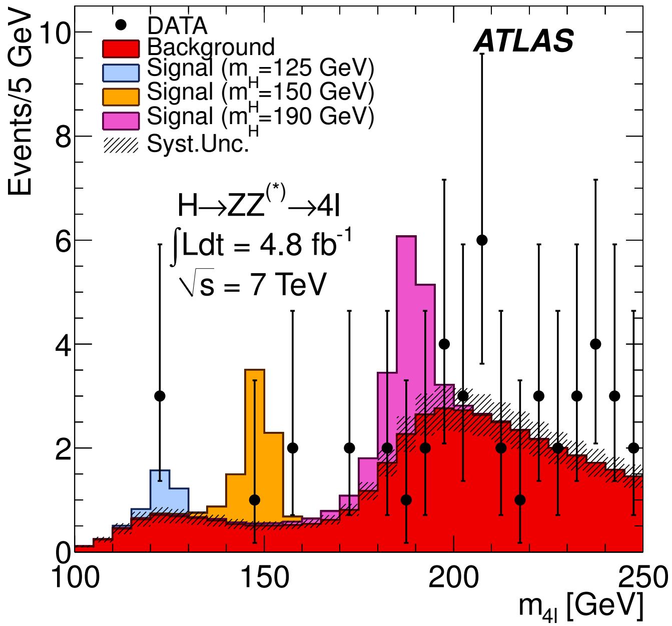
	ATLAS			CMS		
channel	Lumi	Mass Range	Sub chan.	Lumi	Mass range	Sub chan.
$H \rightarrow \gamma\gamma$	4.9	110-150	9	4.8	110-150	5
$H \rightarrow \tau\tau$	1.1	not incl.	4	4.6	110-145	9
$H \rightarrow bb$	1.1	not incl.	4	4.7	110-135	5
$H \rightarrow WW \rightarrow l\nu l\nu$	2.1	110-300	6	4.6	110-600	5
$H \rightarrow WW \rightarrow l\nu qq$	1.1	240-600	2	---	----------	-
$H \rightarrow ZZ \rightarrow 4l$	4.8	110-600	3	4.7	110-600	3
$H \rightarrow ZZ \rightarrow 2l2\tau$	----	---------		4.7	190-600	8
$H \rightarrow ZZ \rightarrow 2l2\nu$	2.1	200-600	2	4.6	250-600	2
$H \rightarrow ZZ \rightarrow 2l2q$	2.1	200-600		4.6	130-164 225-600	6

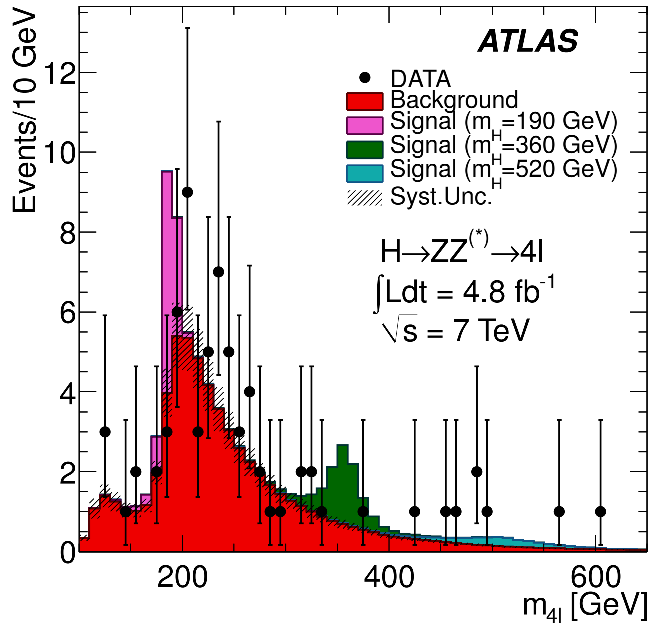
CMS 42 channels + 156 to 222 θ ATLAS 26 channels in combination

correlation of uncertainties taken into account:

eg. luminosity, identification efficiencies, E scale and resolution, PDF, ...

ATLAS: Exclusion limits for H→ZZ→4l



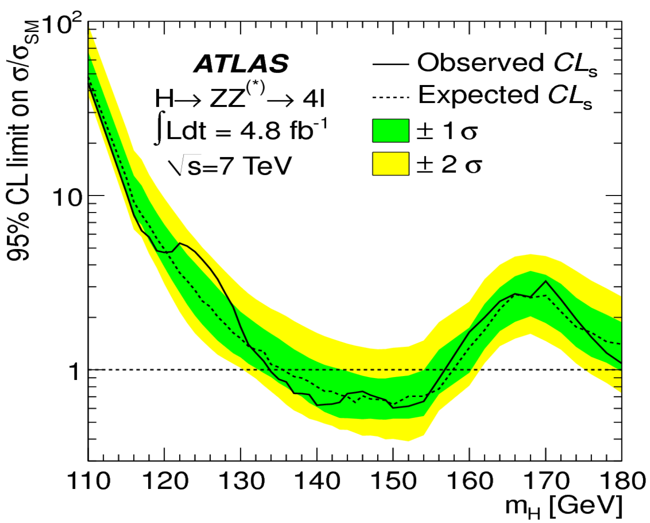


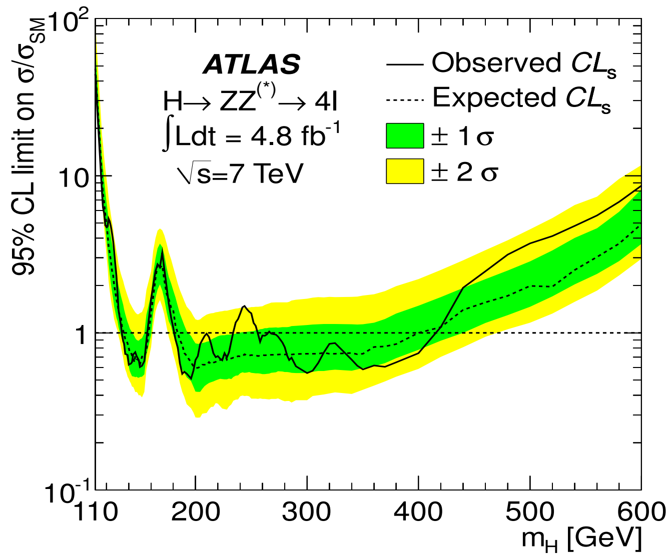
Data: 71 Observed

Bg exp: 62 ± 9

M_{4l}<190 GeV
obs: 8 exp: 9.4

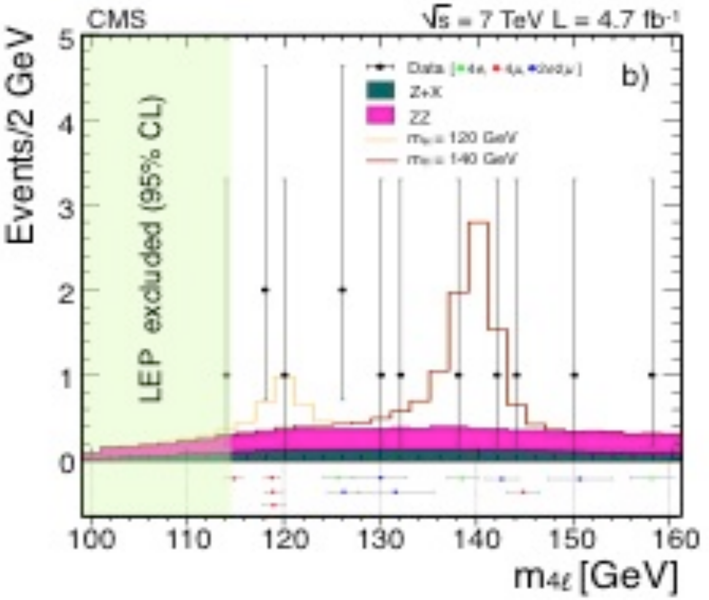
M_{4l}>190 GeV
obs: 63 exp: 52.3

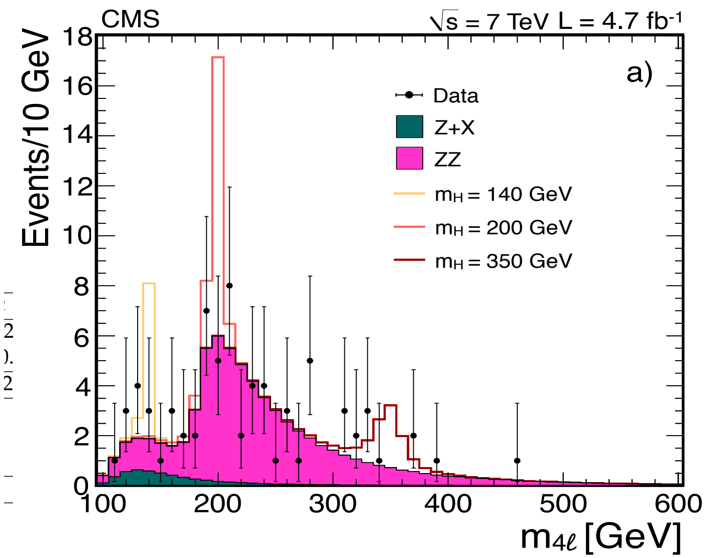




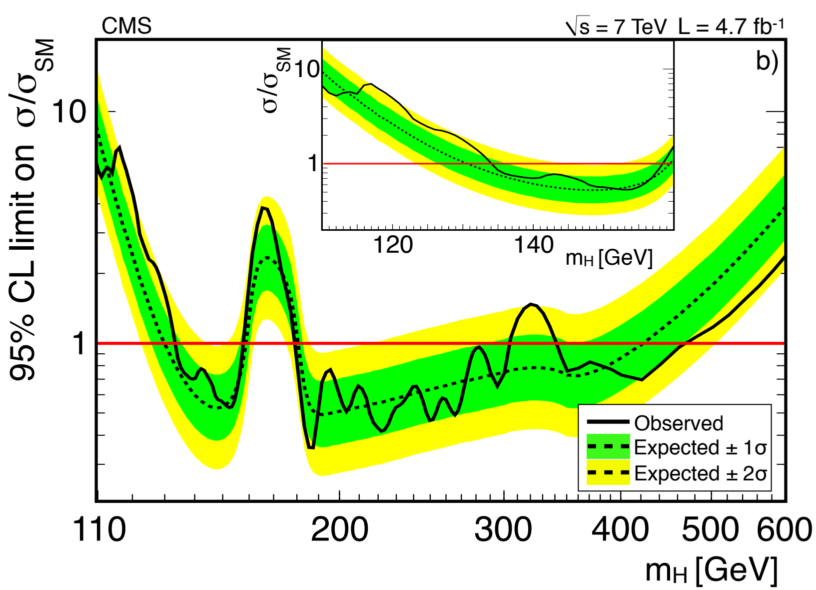
Excluded:
134 to 156 GeV
182 to 233 GeV
256 to 265 GeV
266 to 415 GeV
Expected:
136 to 157 GeV
184 to 400 GeV

CMS: Exclusion limits for H→ZZ→4l





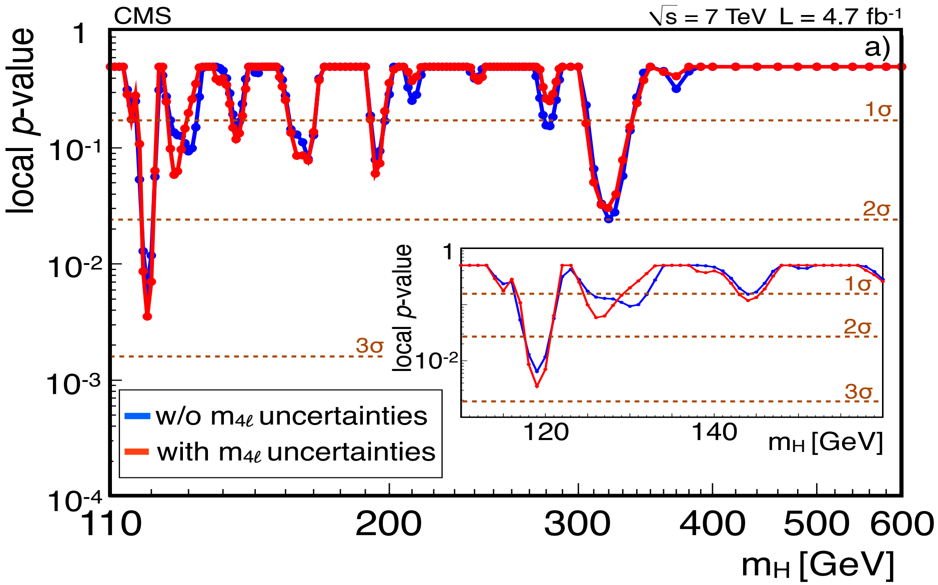
M_{4l}>100 GeV:
Data: 72
BG Exp.: 67 ± 6
100<M_{4l}<160 GeV
Data: 13
BG Exp.:9.5 ± 1.3



CMS excluded: 134 to 158 GeV
180 to 305 GeV
340 to 465 GeV

ATLAS excluded: 134 to 156 GeV
182 to 233 GeV
256 to 265 GeV
266 to 415 GeV

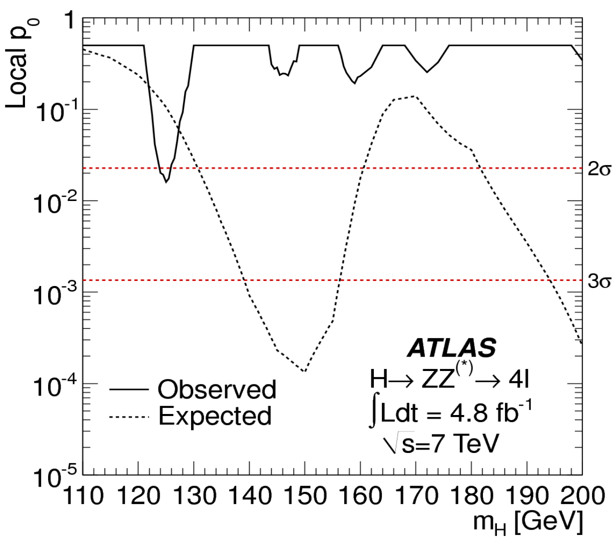
H→ZZ→4l Observed "Excesses"

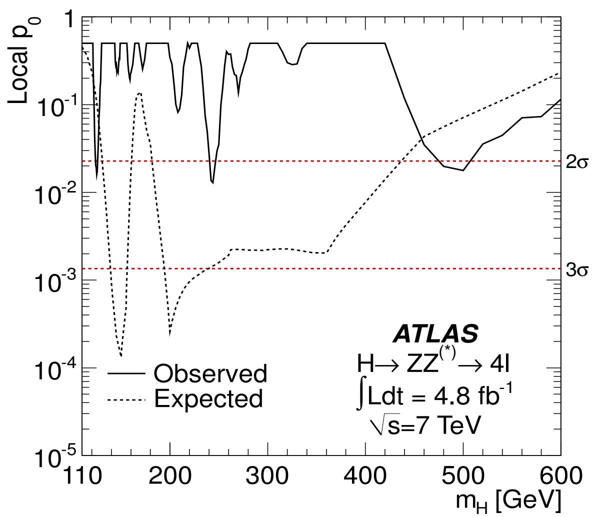


CMS
local: 2σ at 320 GeV
local: 1.5σ at 126 GeV

local: 2.5 σ at 119 GeV
global: <1σ for M<600 GeV
1.5 for M<160 GeV

+ some more in excluded range

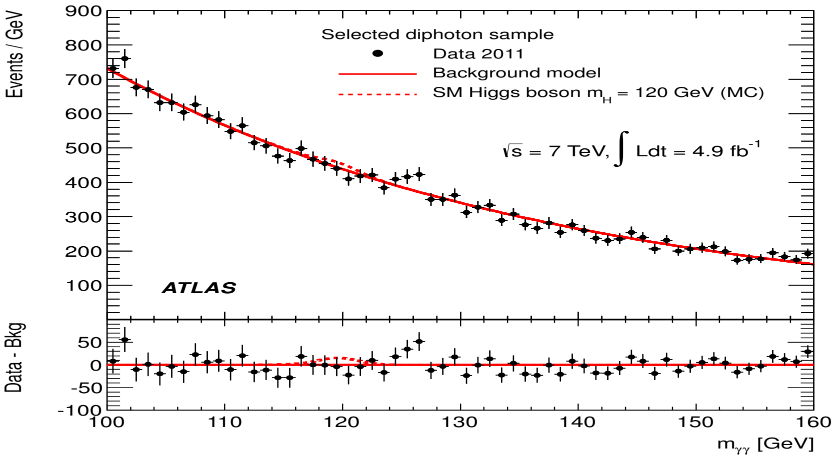


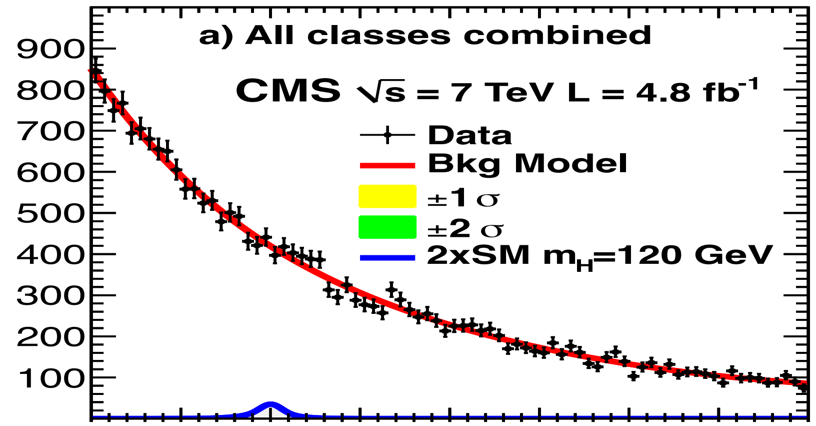


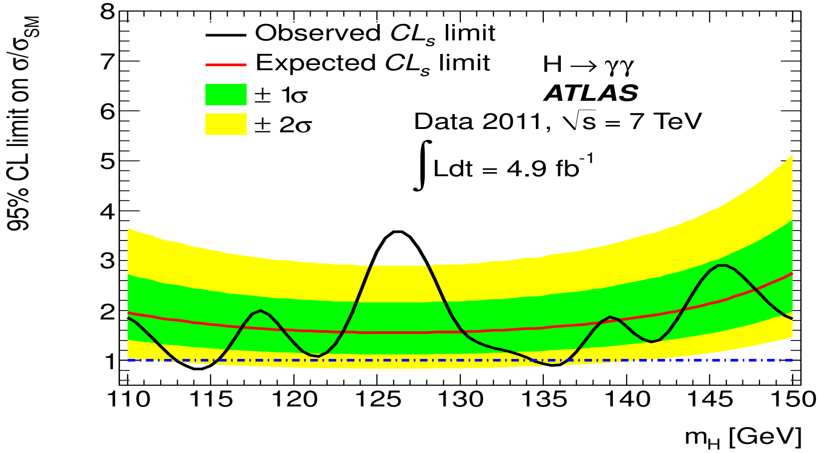
ATLAS
local:
p=1.9%, 2.1σ at 124 GeV
p=1.3%, 2.2s at 244 GeV
p=1.8% 2.1 s at 500 GeV

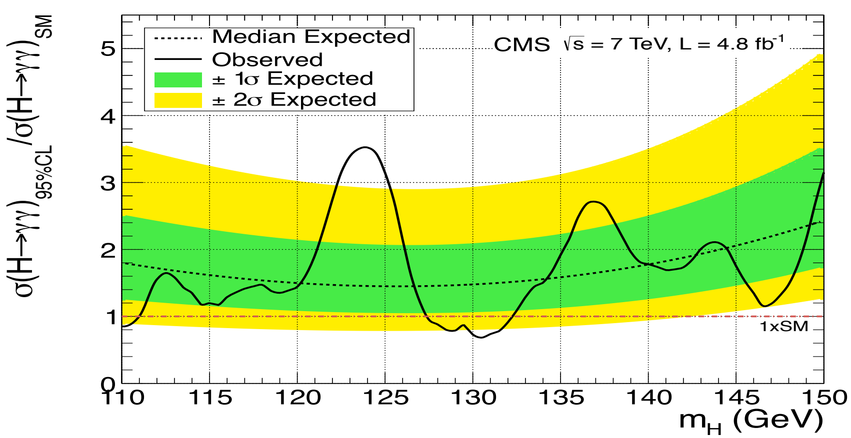
global: ~50% for all

H→2 γ : Exclusion Limits





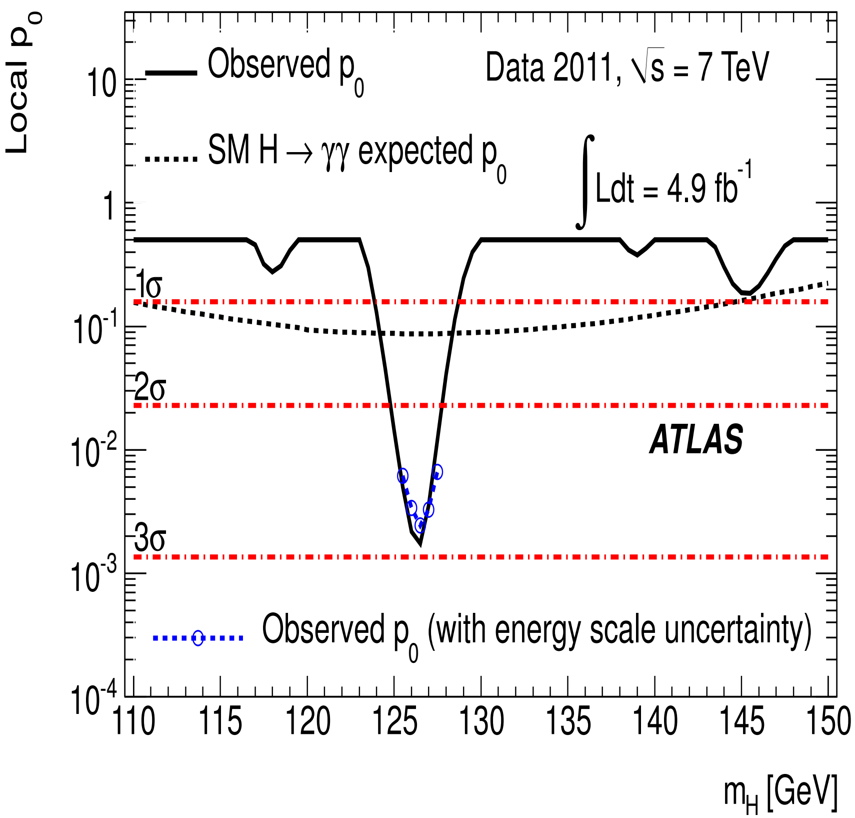


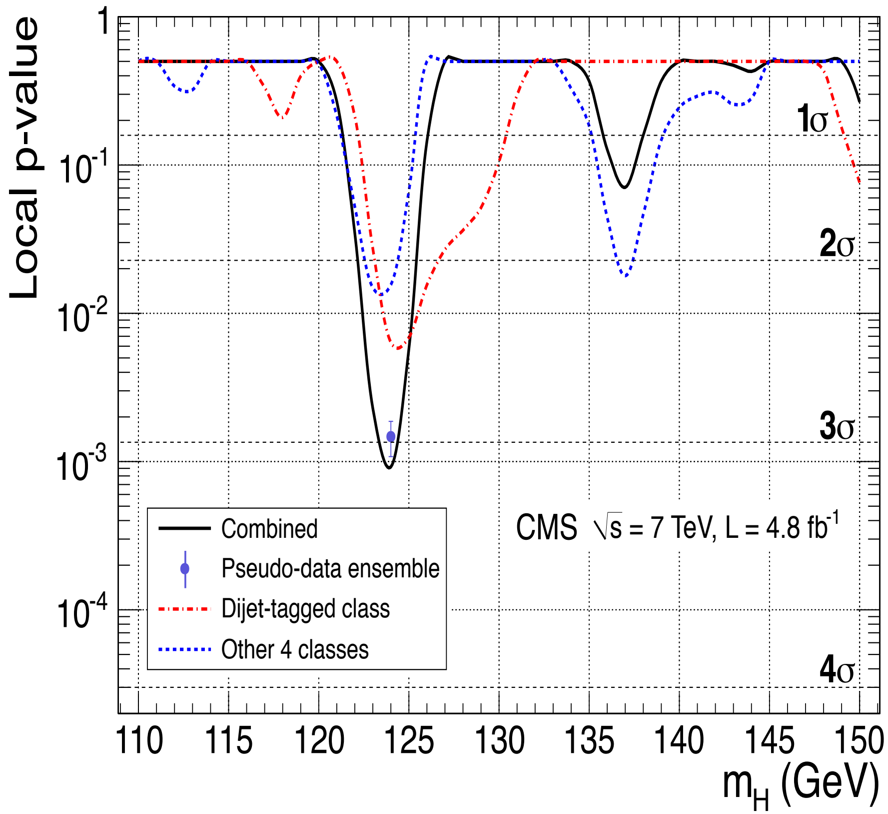


excluded: $113 \leq m_H \leq 115$ GeV,
$134.5 \leq m_H \leq 136$ GeV
(exp: 1.6 to 2.7 x σ_{SM})

excluded: $128 \leq m_H \leq 132$ GeV,
(exp: 1.4 to 2.4 x σ_{SM})

H→2 γ : Observed „Excesses“

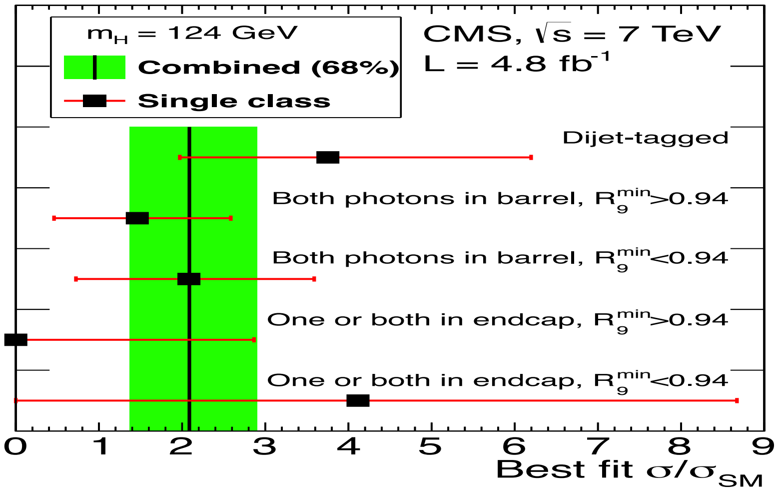


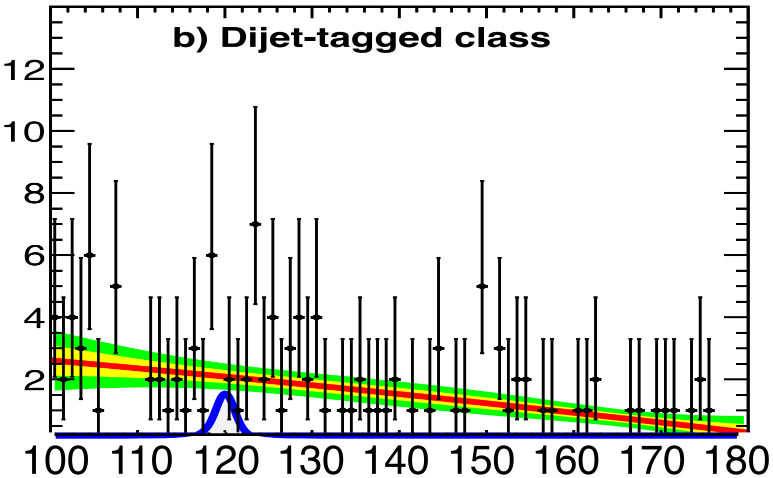


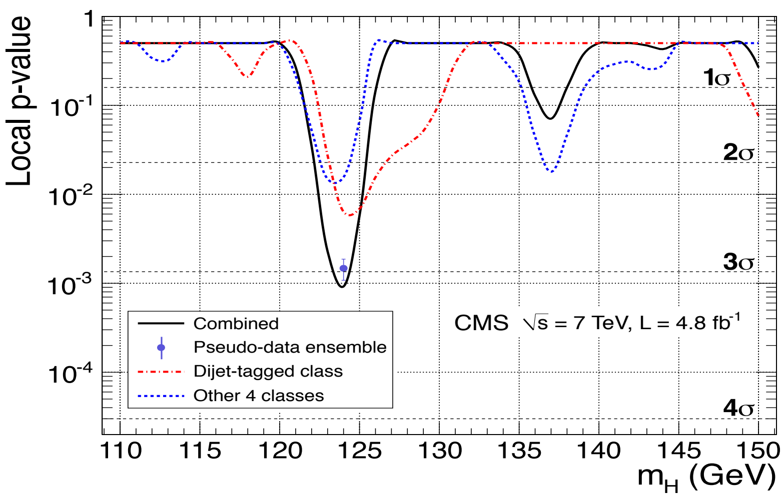
max. deviation at m_H~126.5±0.9 GeV:
local p_0-value: 0.27% (2.9 σ)
global p_0-value: ~7% (1.5σ)
expected from SM Higgs: ~ 1.4σ

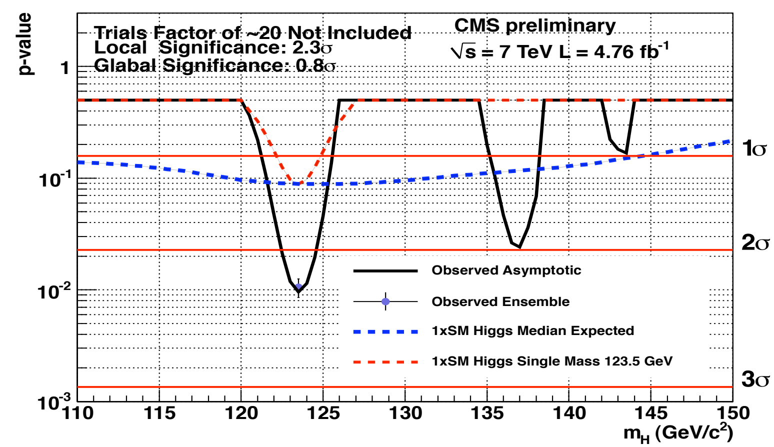
max. deviation at m_H = 124 GeV:
local p_0-value: 0.09% (3.1σ)
global p_0-value: 3.9% (1.8σ)
fitted signal strength: 2.1±0.6 x SM

CMS H→γγ from Dec 11 to Feb 12: New Dijet Class





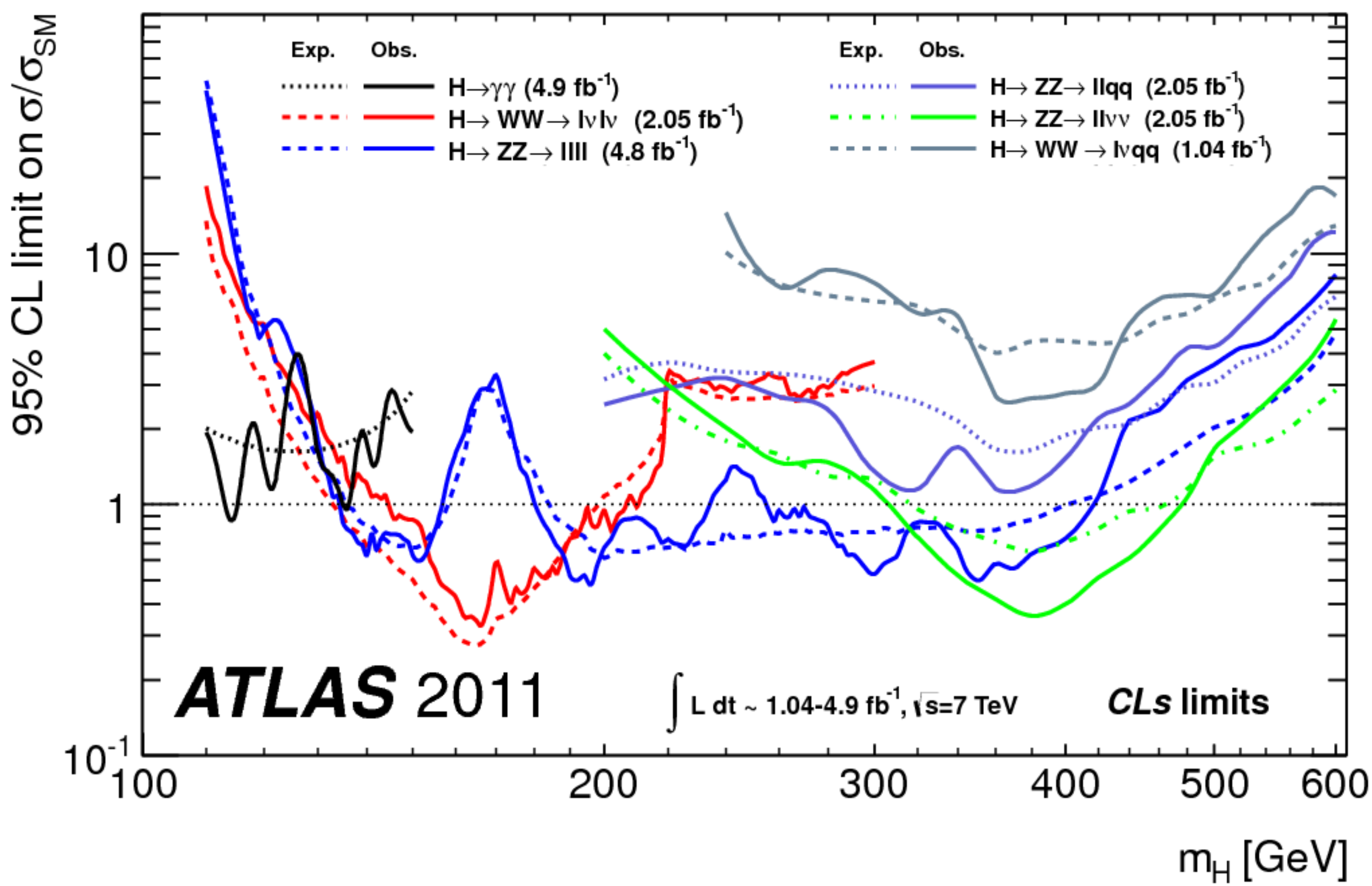




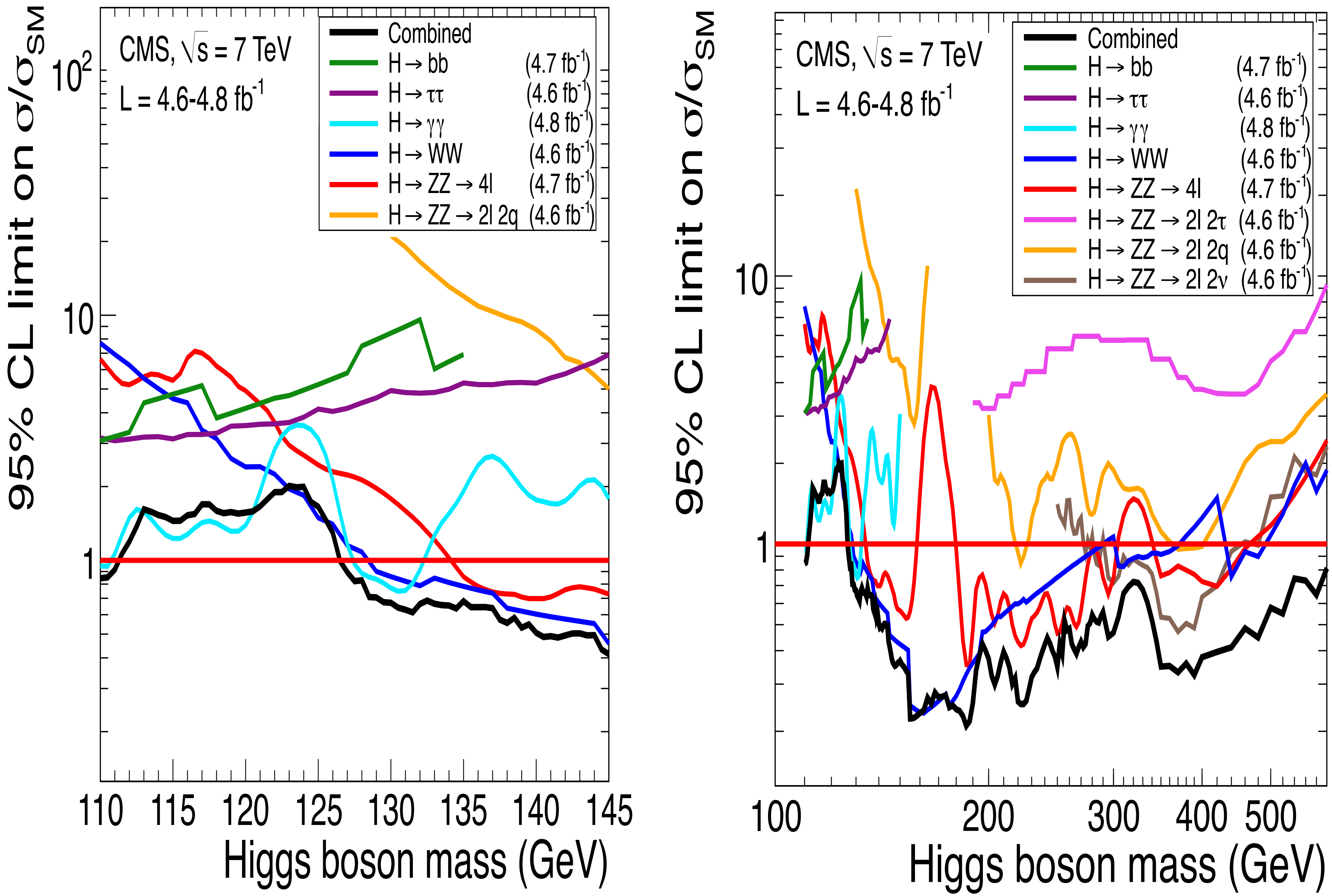
Feb. 2012: m_H = 124 GeV:
local p_0-value: 0.09% (3.1σ)
global p_0-value: 3.9% (1.8σ)

Dec. 2011: m_H = 123.5 GeV:
local p_0-value: 0.96% (2.34σ)
global p_0-value ~21% (0.8σ)

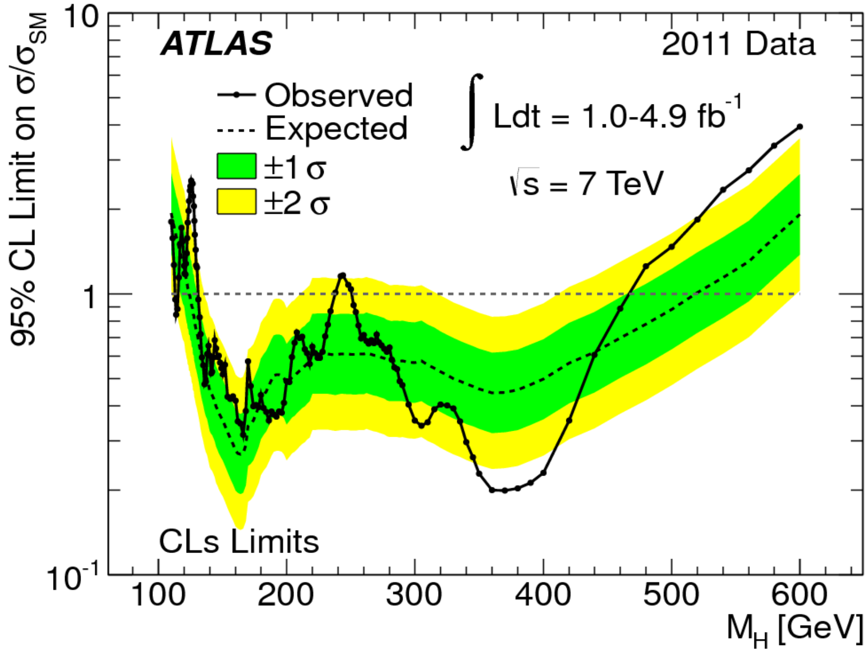
ATLAS: Exclusion by Individual Channels

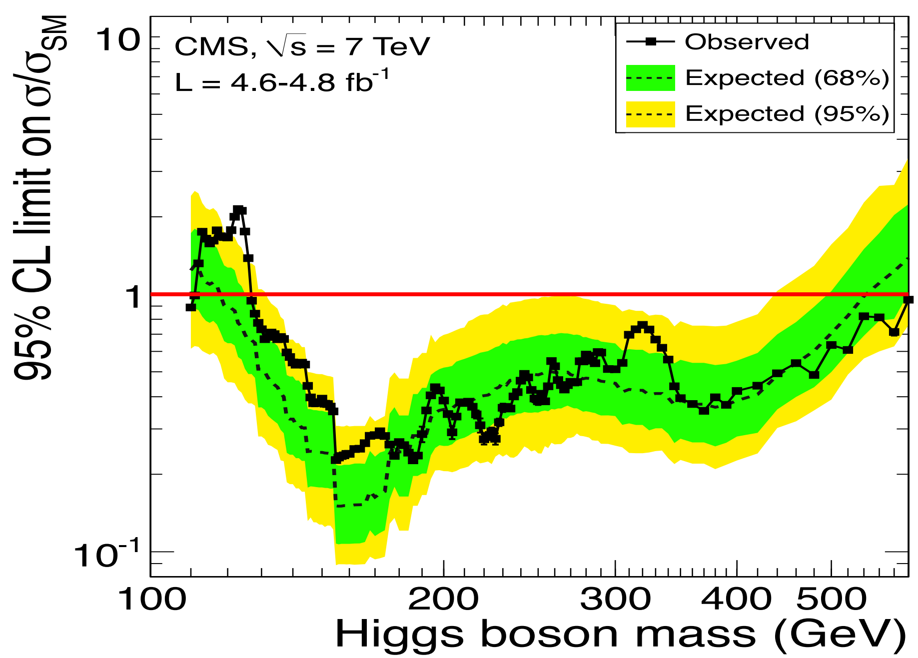


CMS: Exclusion by Individual Channels



Combined Exclusion Limits





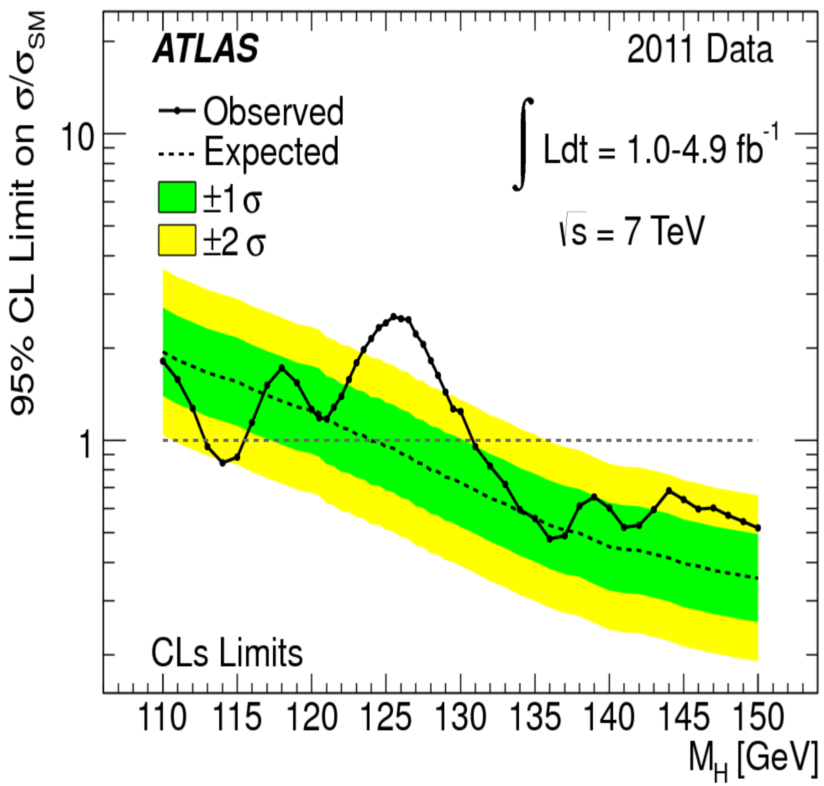
Observed at 95% CL:
112.9 < m_H < 115.5, 131<m_H<231, 251- 466 GeV | 127 < m_H < 600GeV

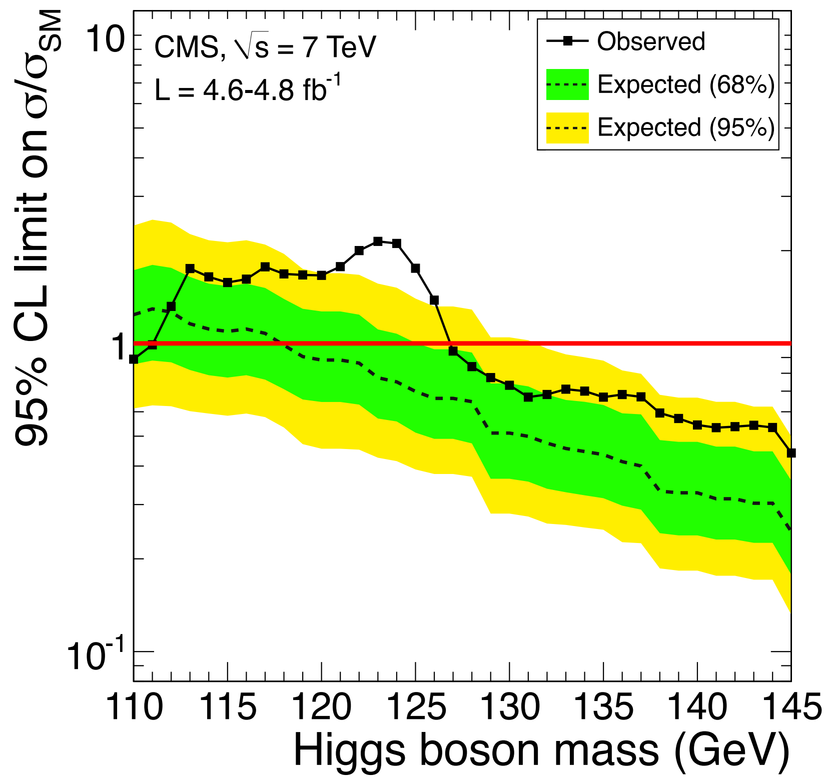
Expected at 95% CL: 124 < M_H < 519 GeV | 118 < m_H < 543 GeV

Observed at 99% CL:
133 <m_H < 230 GeV, 260< m_H <437 GeV | 129 < m_H< 525 GeV

ATLAS: 2.5 σ deficit w.r.t BG only at 300 to 400 GeV, global probability 30%

Combined Exclusion Limit: Low Mass Range





Observed at 95% CL:
$112.9 < m_H < 115.5$ GeV $131 < m_H < 150$++

$127 < m_H < 600$GeV

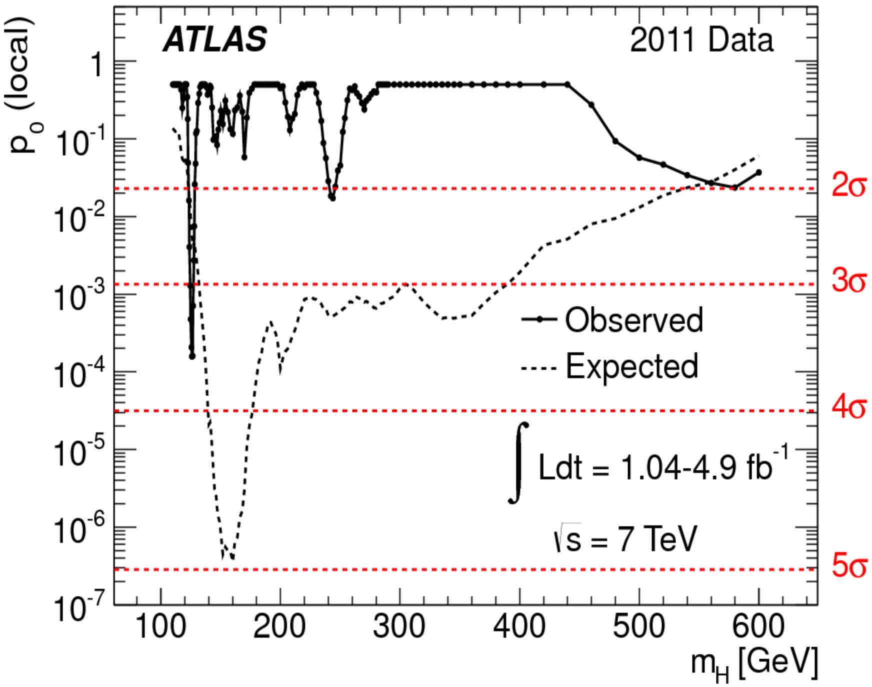
Expected at 95% CL:
$124 < M_H < 519$ GeV

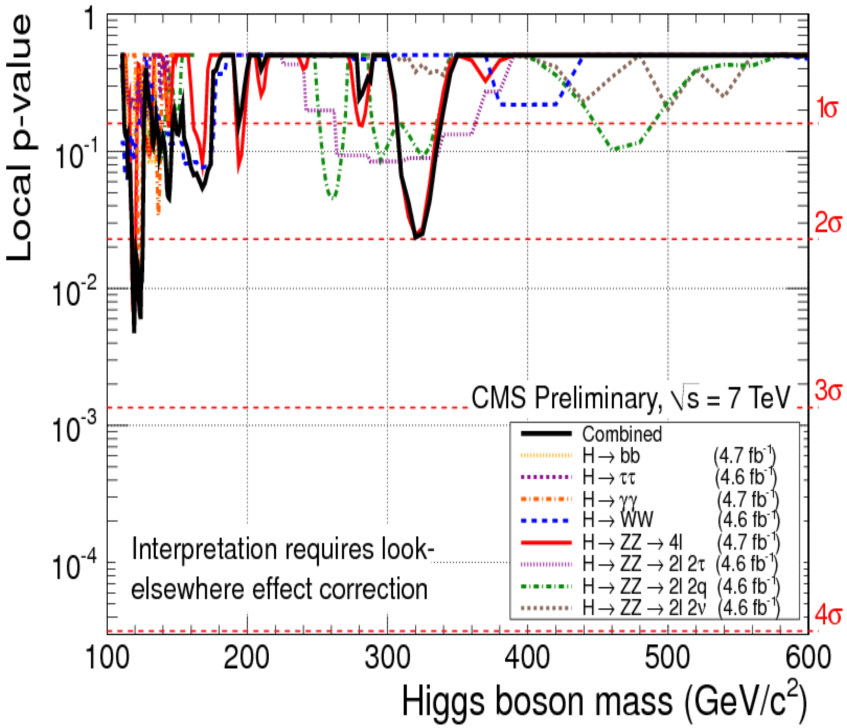
$118 < m_H < 534$ GeV

in both experiments observed exclusion weaker than expected

Consistency with Background-Only Hypothesis

CMS: Dec 2012





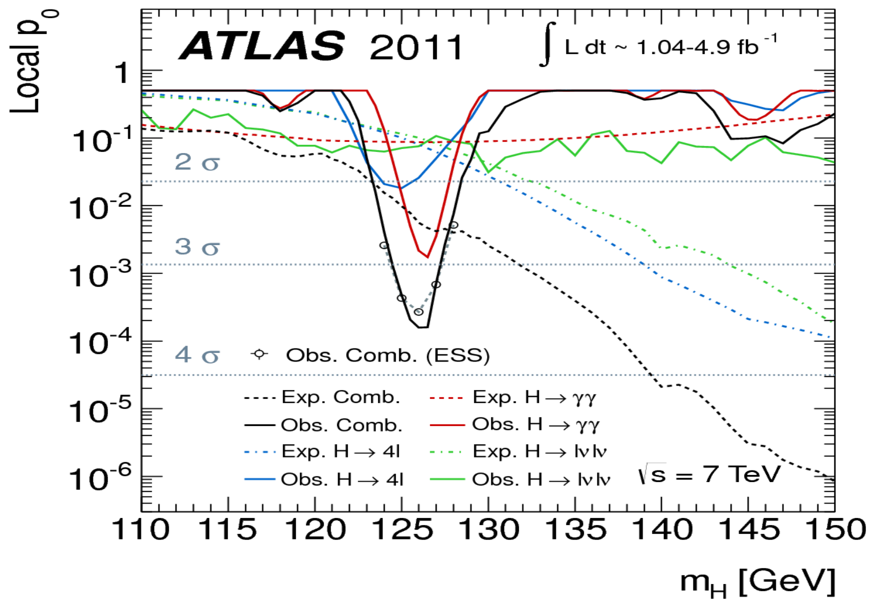
Maximum deviation from background-only expectation observed for m_H~126 GeV

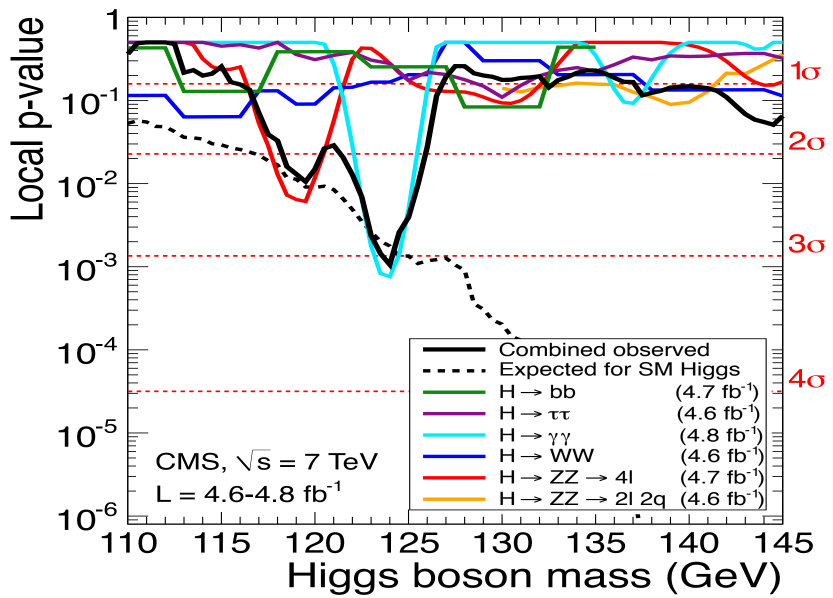
Max. deviation from background-only observed for m_H~119 and 124 GeV

244 GeV: H→ZZ →4l
>460 GeV: several channels

119 GeV: 3 H→4l events
124 GeV: H→2γ events
325 GeV: 9 H→4l events

Consistency with BG-Only: Low Mass





Maximum deviation for m_H~126 GeV

Local p_0-value: 1.9×10^{-4} = 3.6σ
(~2.8σ H→ γγ, 2.1σ H→ 4l, 1.4σ H→ lνlν)

Expected for M_H=126 GeV: 2.5σ
(~ 1.4σ per channel)

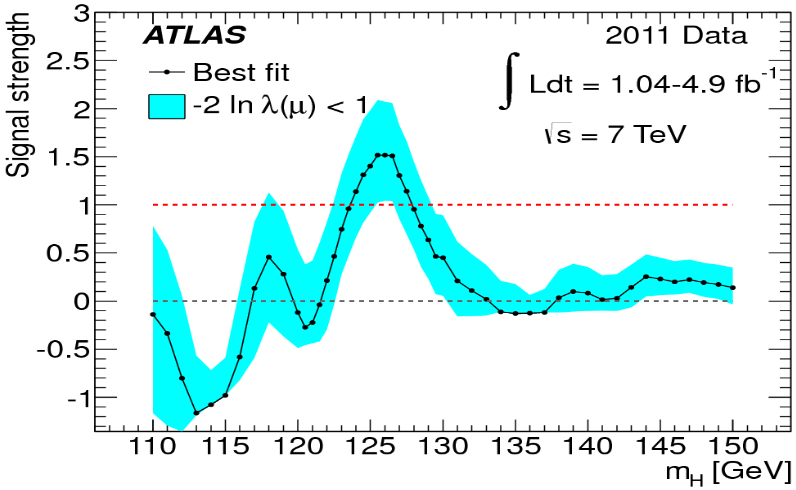
Global p_0-value:
0.6% (2.5σ) mass range 110 to 146 GeV
1.4% (2.2σ) mass range 110 to 600 GeV

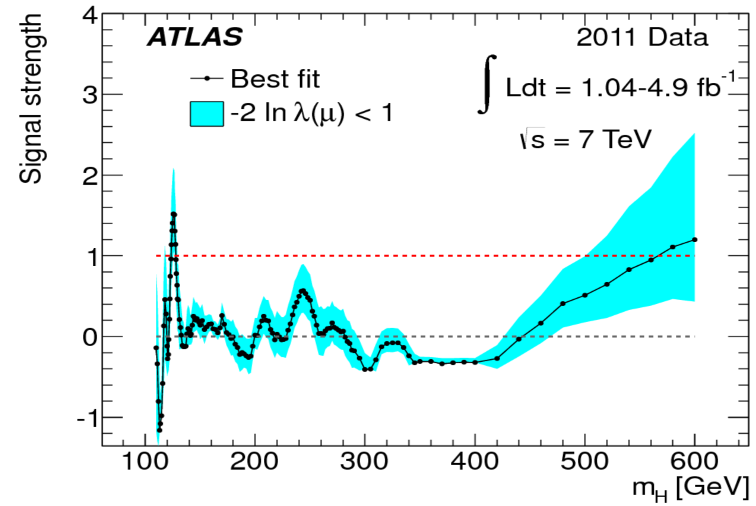
Max. deviation for m_H~ 124 GeV

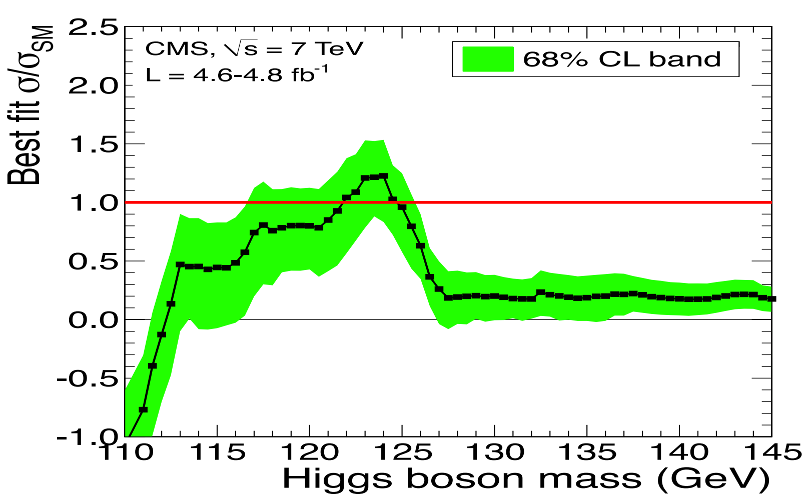
Minimal local p-value 0.001 = 3.1σ

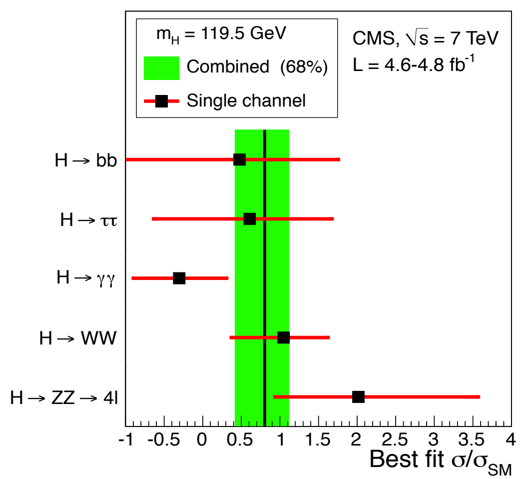
Global p-value
2.1σ mass range 110 to 145 GeV
1.6s mass range 110 to 600 GeV

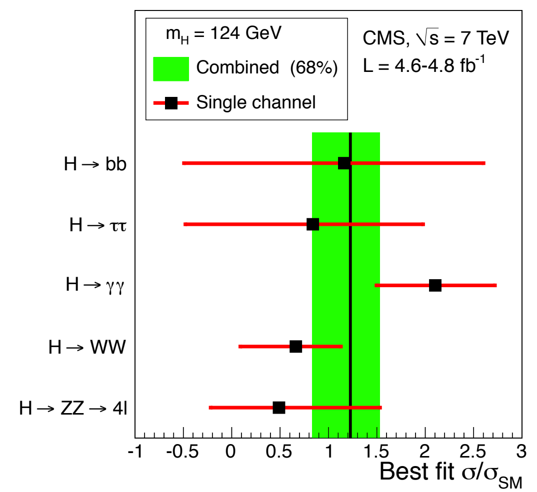
Best Fit for Signal Strength w.r.t. SM Rate





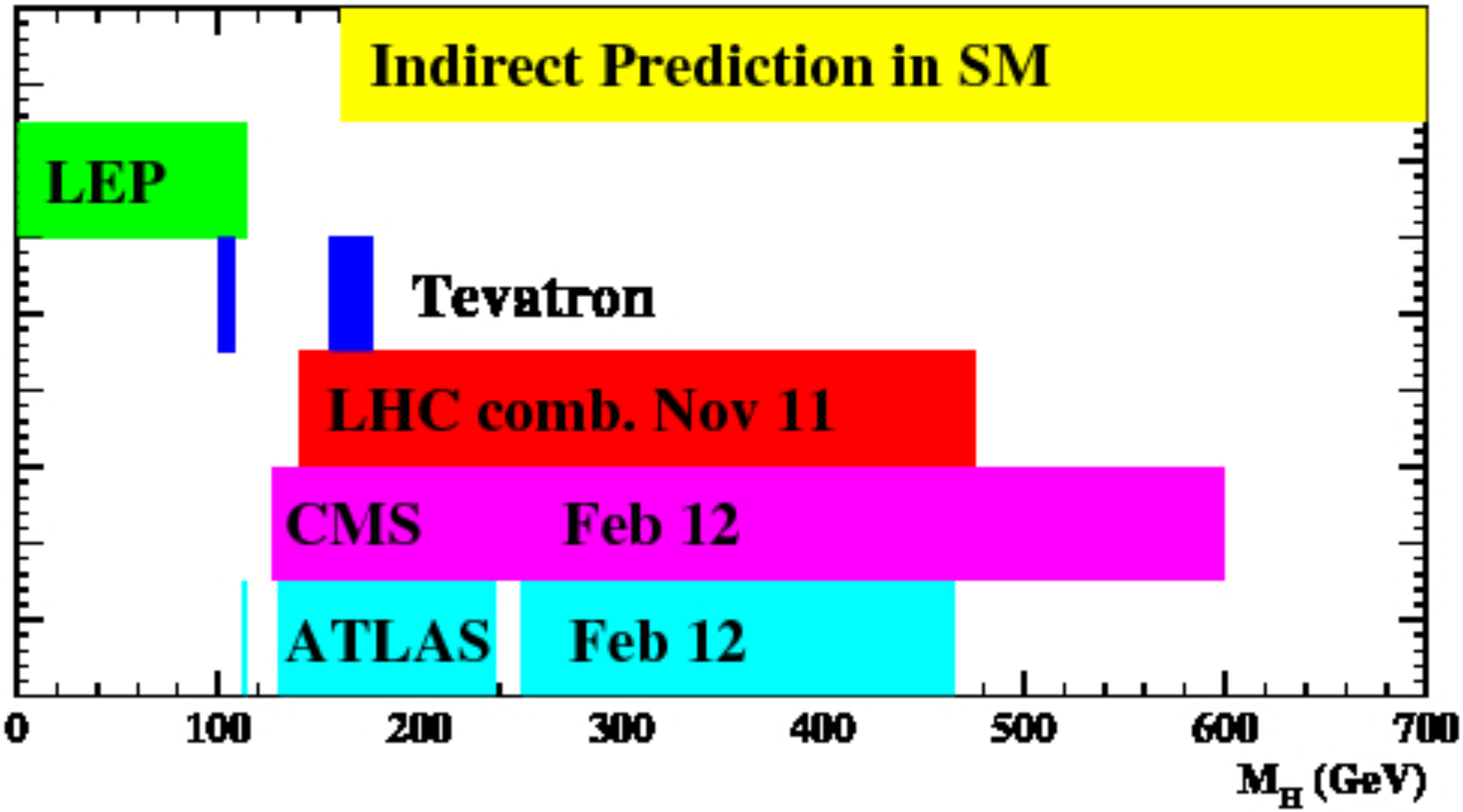






Mass values with highest signal strength parameter slightly different
But not an inconsistent picture

Current Knowledge about the Higgs boson mass

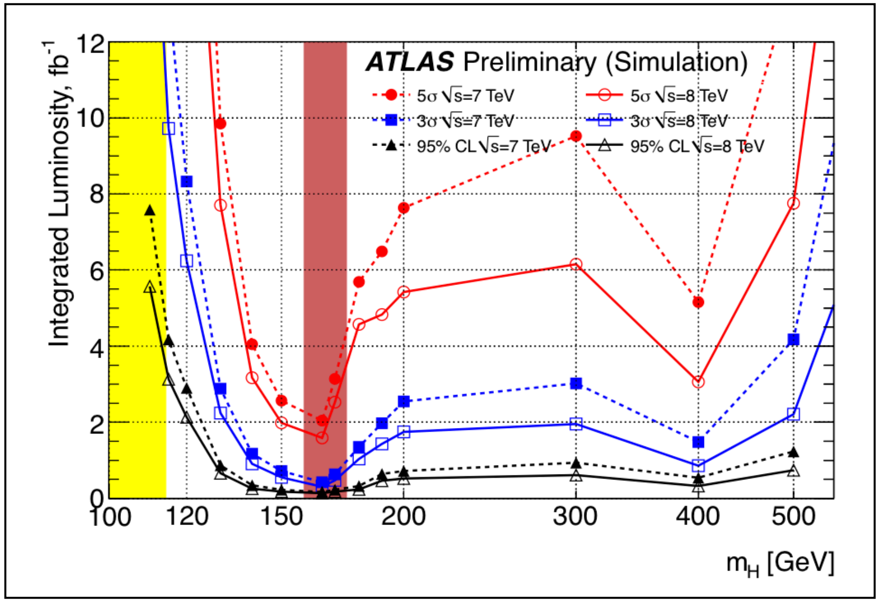


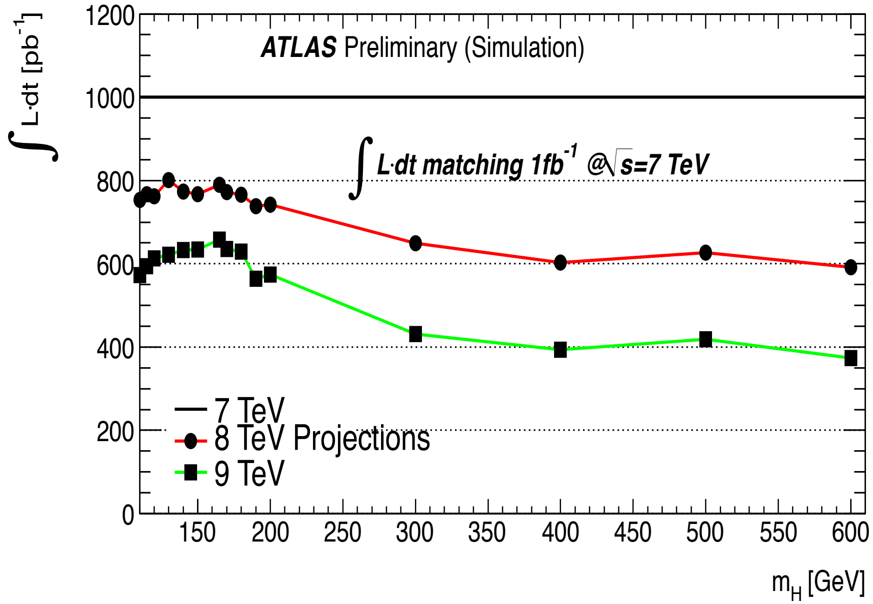
the Standard Model still prefers a light Higgs boson

only M_H= 115.5 to 127 GeV not excluded

only more data can tell whether excesses are hint for a new particle

Prospects





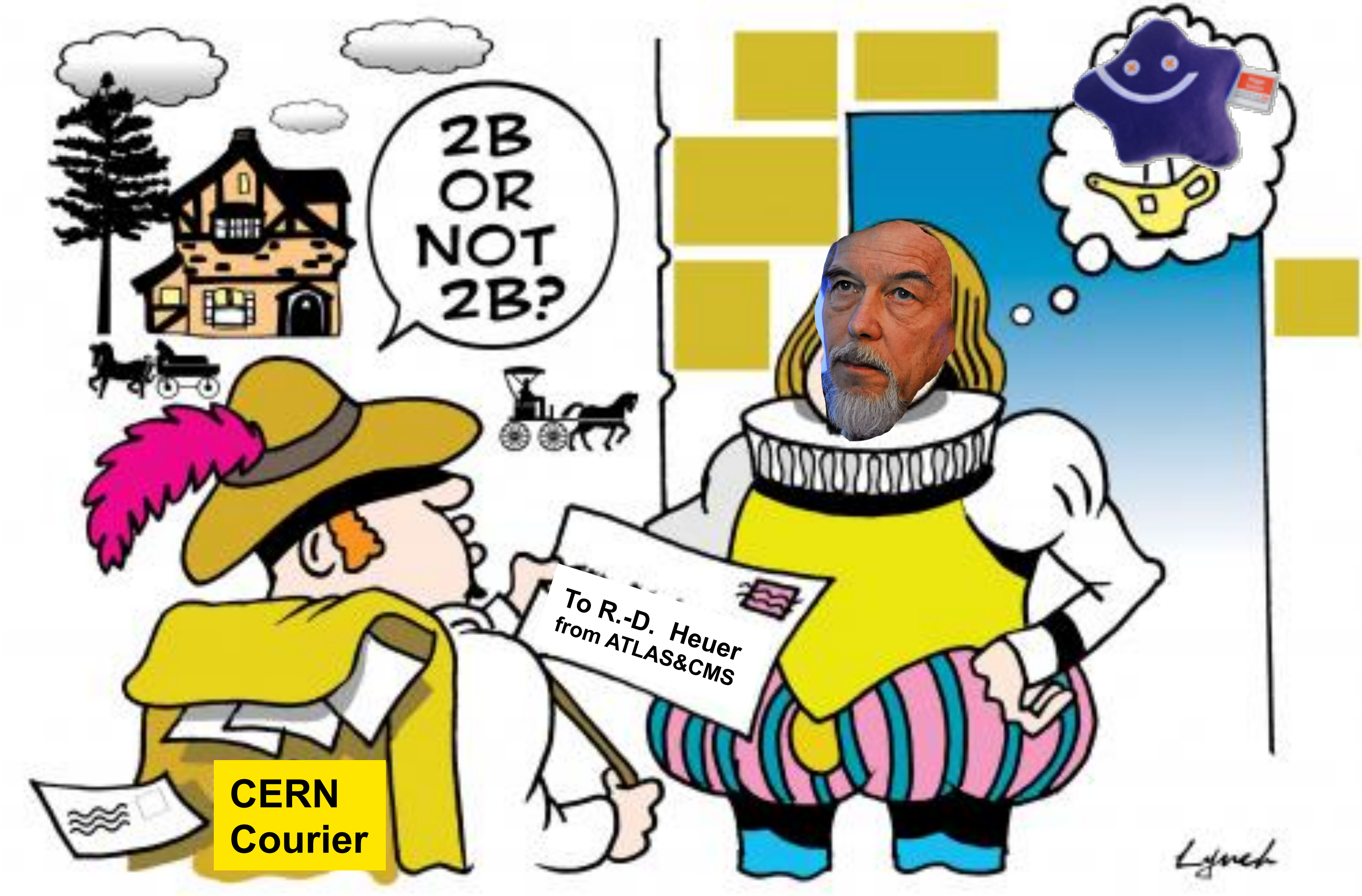
Higgs production at low M_H increased by 20% to 30% from 7 to 8 TeV center-of-mass
rough estimate: 0.8 fb^{-1}@ 8 TeV äquivalent to 1.0 fb^{-1} at 7 TeV

MORE DATA → 2012 run: (Fabiola Gianotti, Dec 13th)
~ 20 fb^{-1} of delivered luminosity needed to:

- ❑ achieve 5σ evidence at m_H~ 125 GeV with ~ 3σ per channel (ATLAS alone)
- ❑ achieve 5σ evidence down to ~ 116 GeV (ATLAS+CMS combined)
- ❑ exclude m_H ~ 125 GeV if the excess is due to a fluctuation

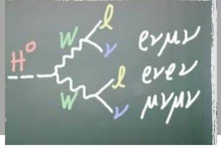
"Contingency": analysis improvements; √s=8 TeV (~ 10% sensitivity gain)

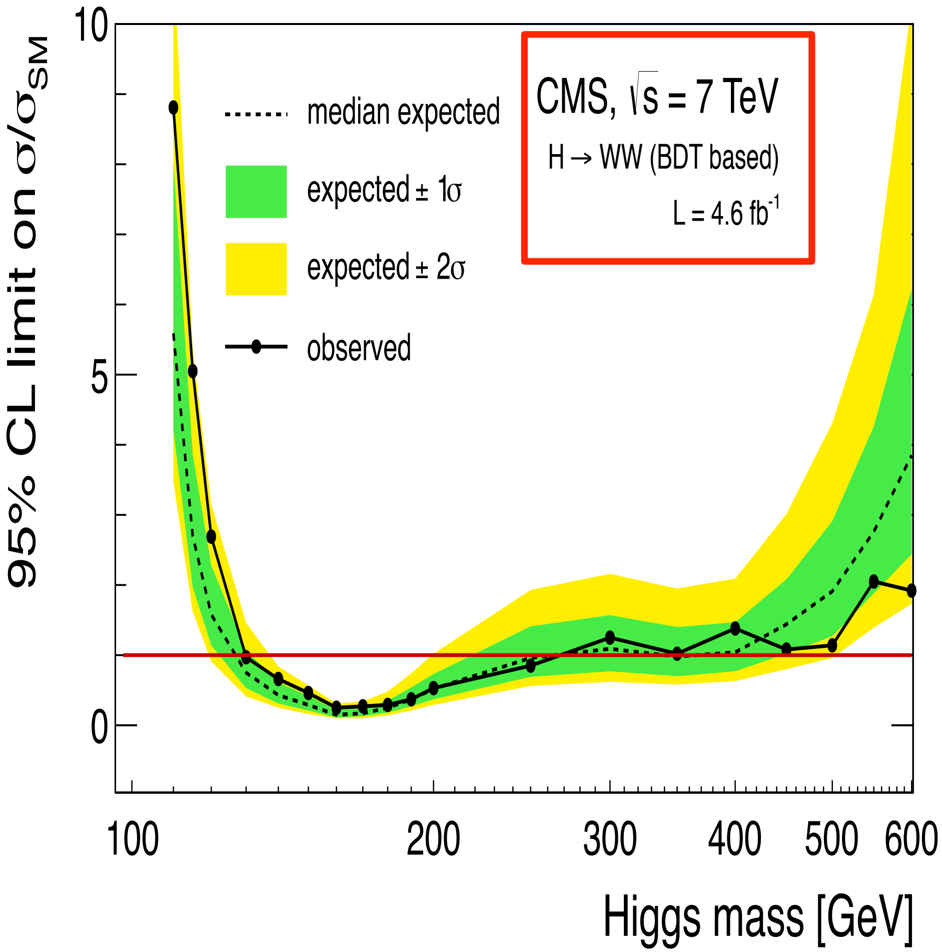
2012: the year of the Higgs boson (or not) …

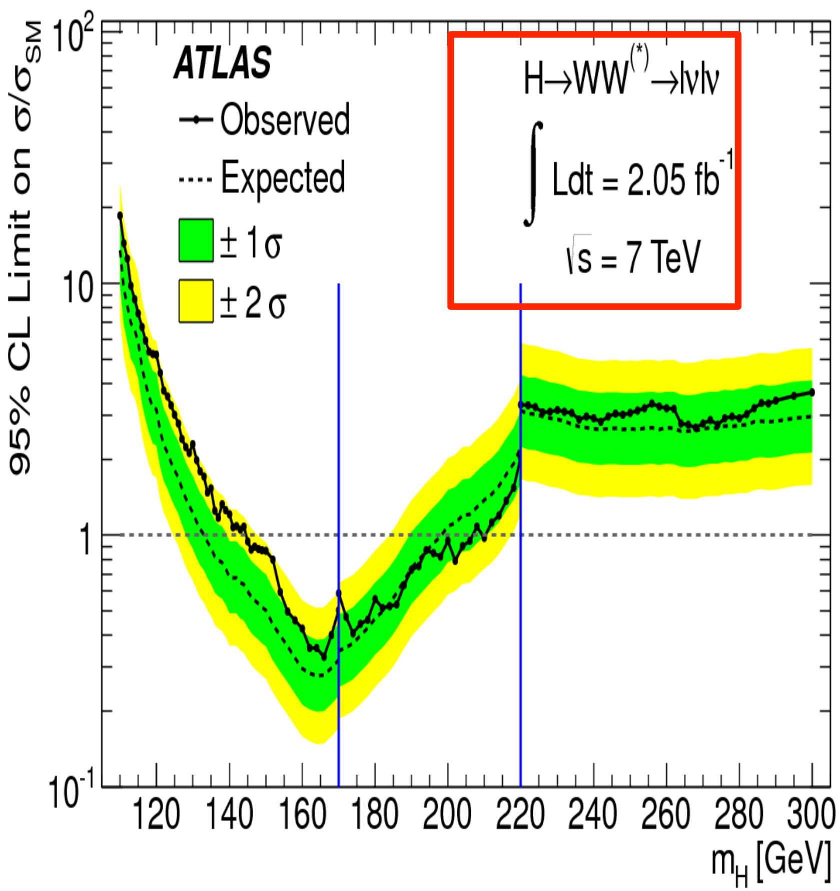


Backup

Exclusion limit for H →WW→lνlν

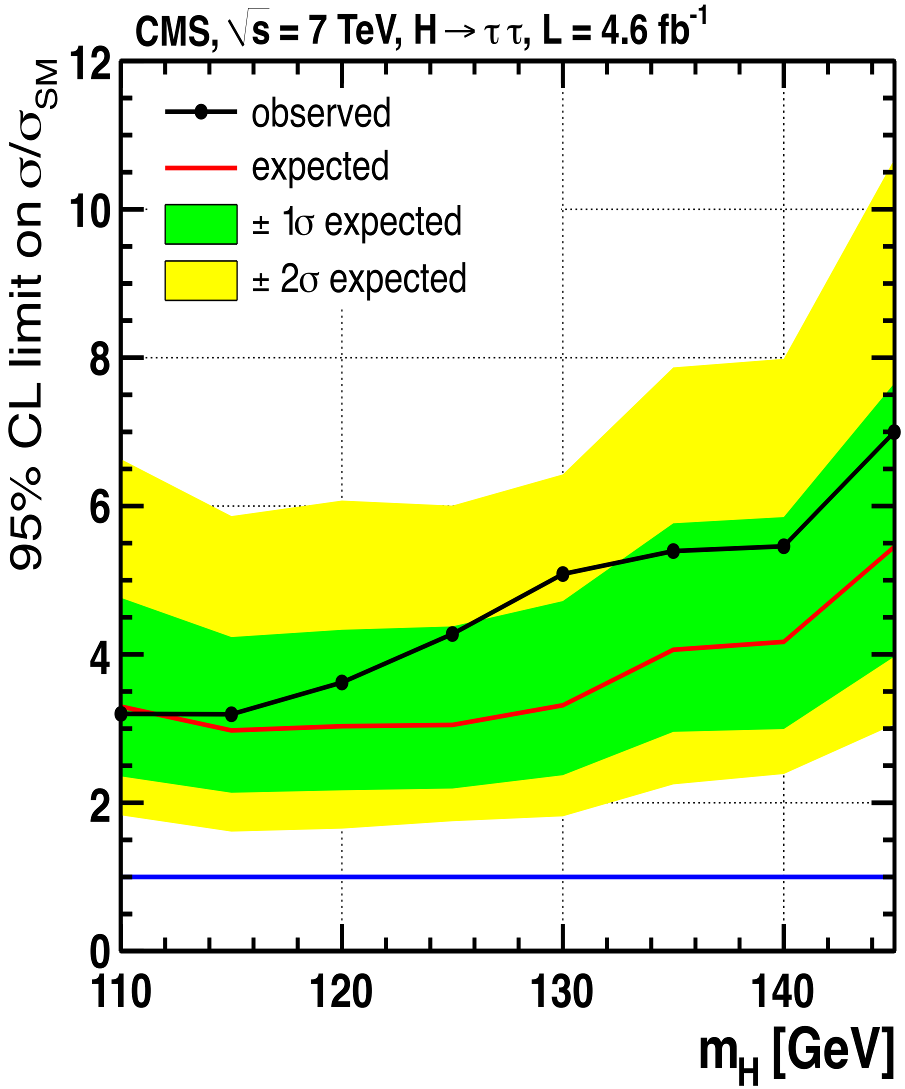


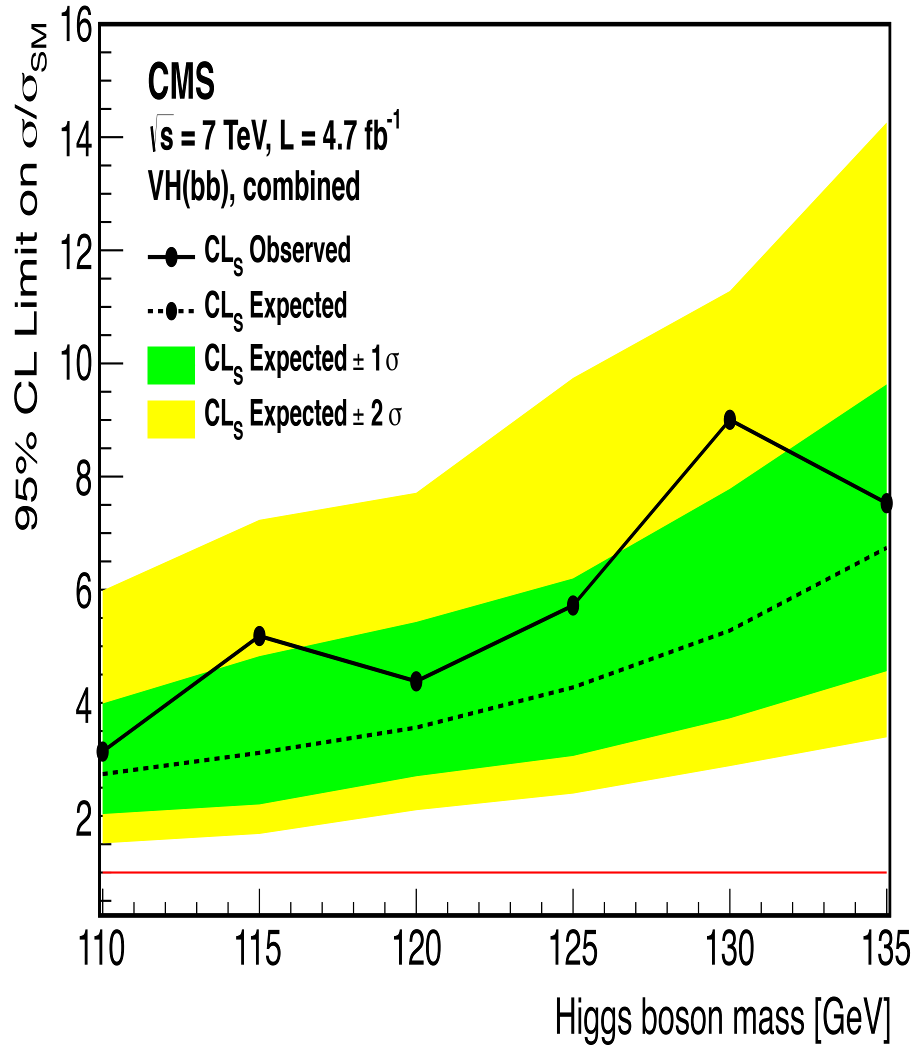




	CMS	ATLAS
Observed exclusion:	129 to 270 GeV	145 to 206 GeV
Expected exclusion :	127 to 270 GeV	134 to 200 GeV

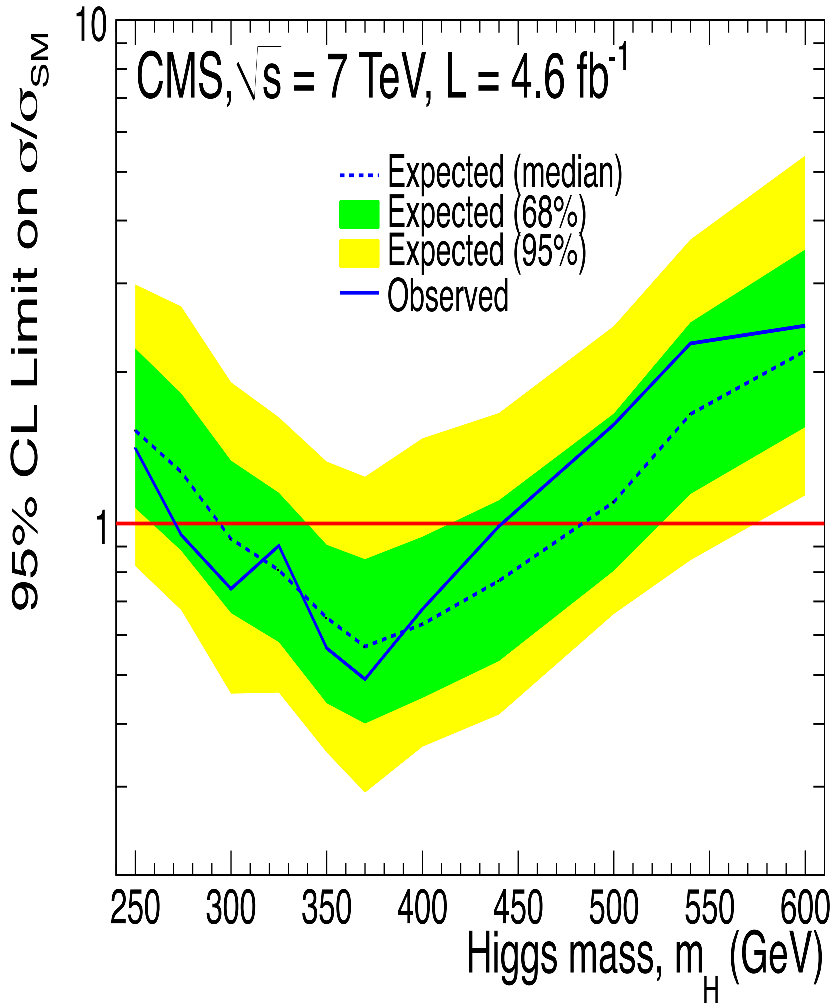
CMS: SM H→ττ and H→bb Exclusion Limits



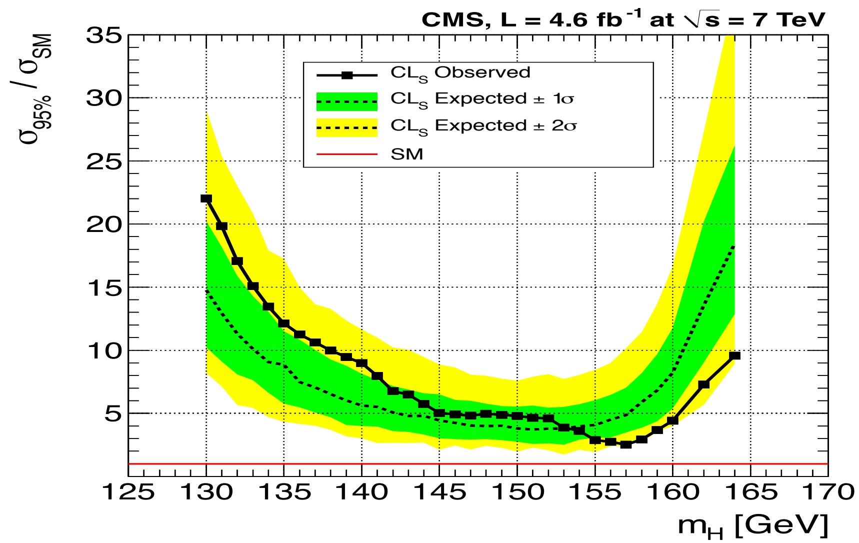


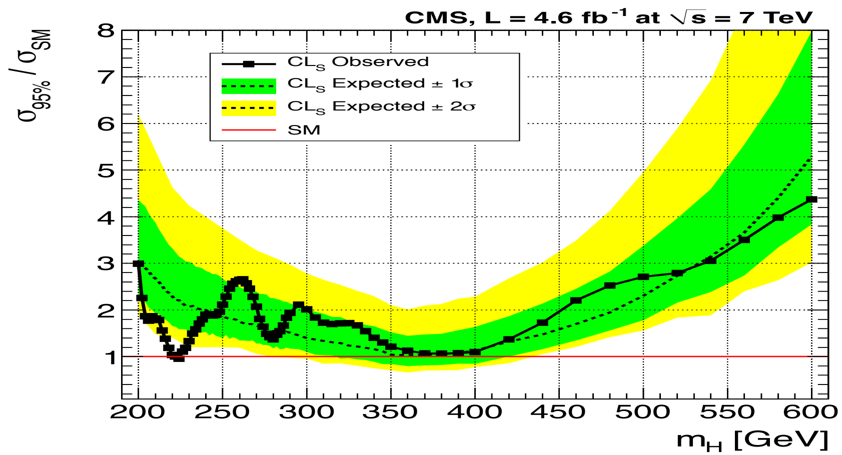
CMS: H→ZZ→ll νν and H→ZZ → ll qq

H→ZZ→ll νν

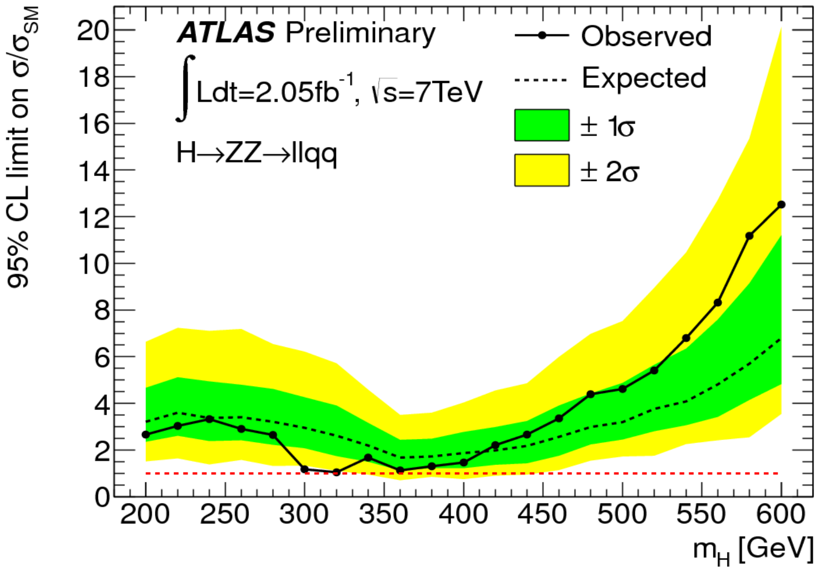


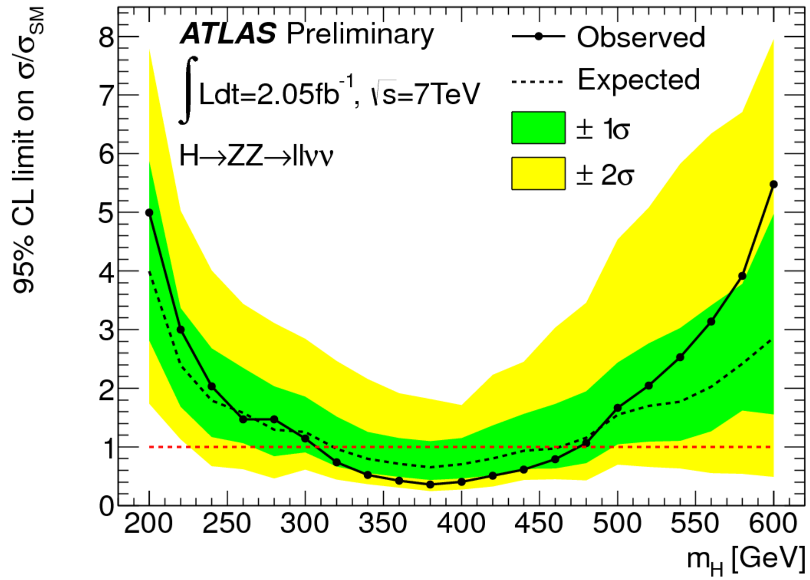
H→Z Z → ll qq

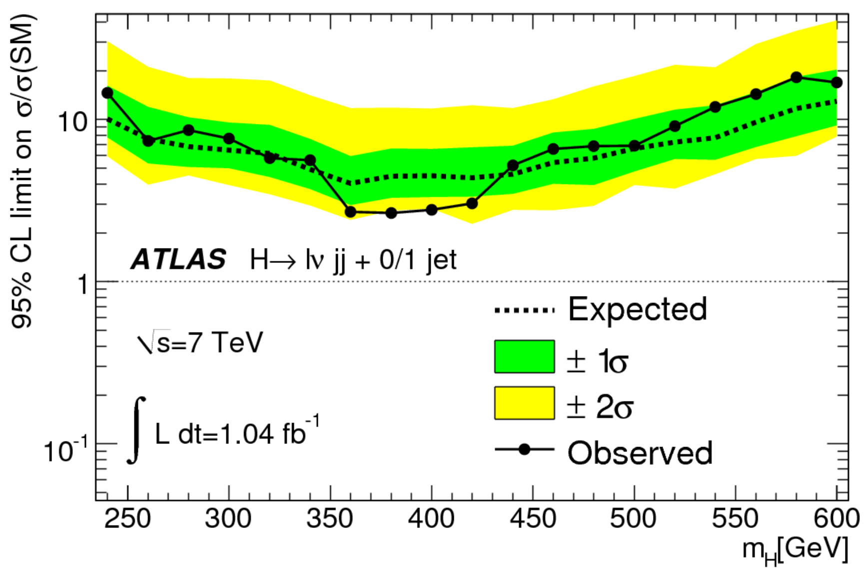




ATLAS: Limits for High Mass Channels



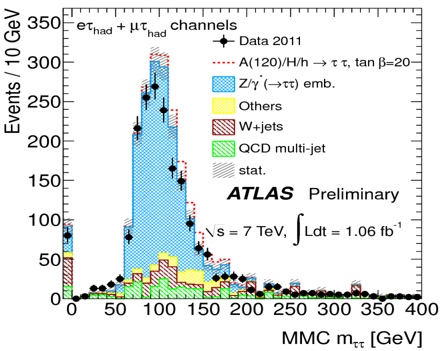




ATLAS: H → ττ and H→bb with 1.1 fb-1

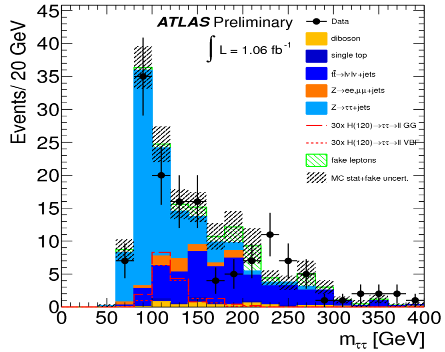
ττ→lτ$_{had}$3ν

inclusive

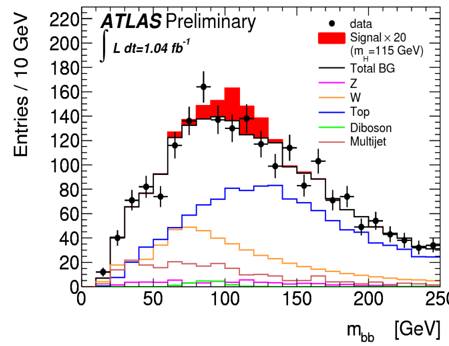


ττ→ll4ν

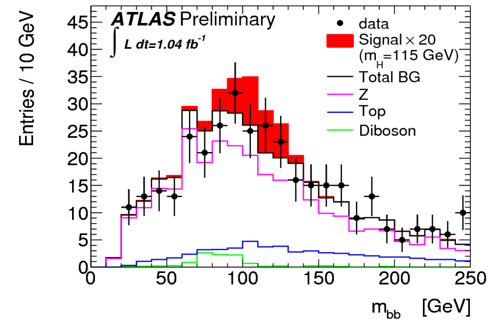
1 jet p$_T$>40 GeV

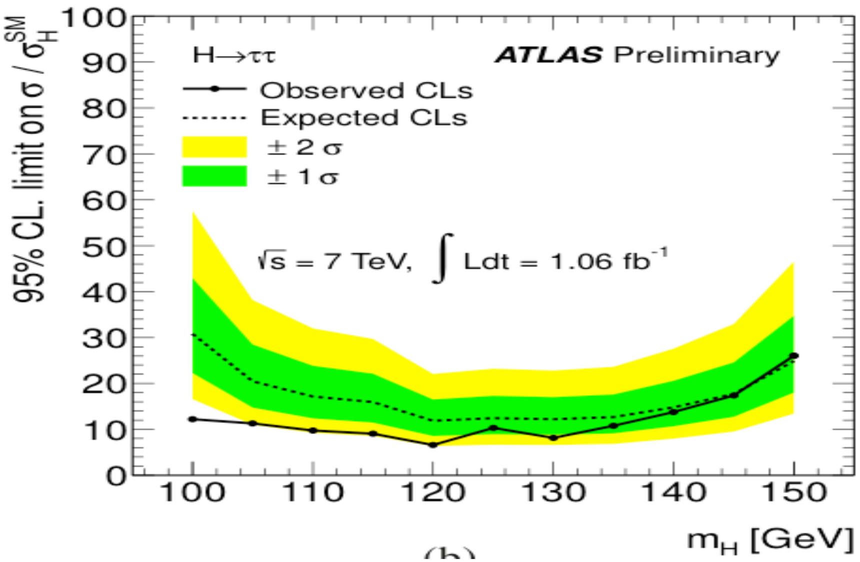


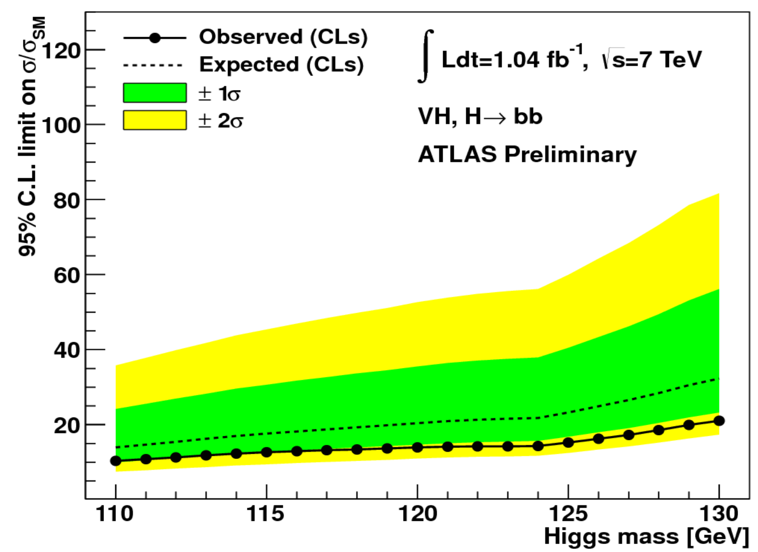
W→lν



Z→ll







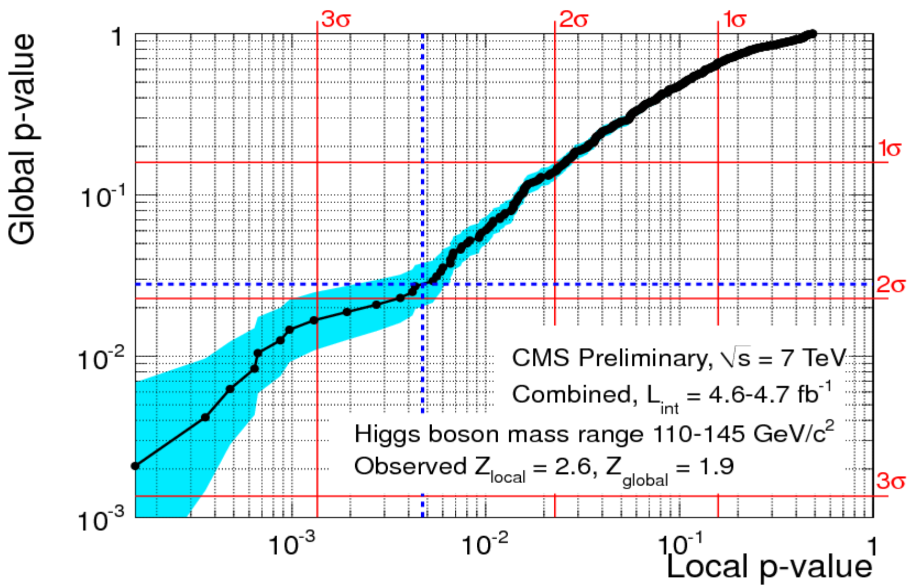
LLR test statistics

	Test statistic	Test statistic	Nuisance parameters	Pseudo-experiments
LEP	$-2\ln\frac{L(\mu,\tilde{\theta})}{L(0,\tilde{\theta})}$	Simple LR	Fixed by MC	Nuisance parameters randomized about MC
Tevatron	$-2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(0,\hat{\theta})}$	Ratio of profiled likelihoods	Extracted from priors	Nuisance parameters randomized from priors
LHC	$-2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$	Profile likelihood ratio	Profiled (fit to data)	New nuisance parameters fitted for each pseudo-exp.

LHC sampling of test statistic is frequentist, LEP and Tevatron Bayes-frequentist hybrid. CL_s can be used together with any of these – must be specified! No longer sufficient to write e.g. “the CL_s method was used”.

Higgs Days at Santander 2011 (A. Read)

CMS: LEE from Local to Global P-values



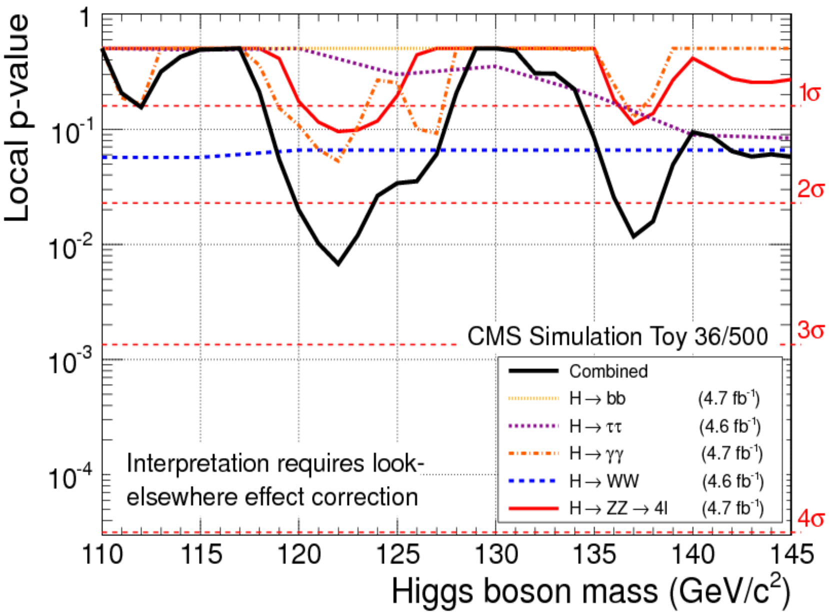
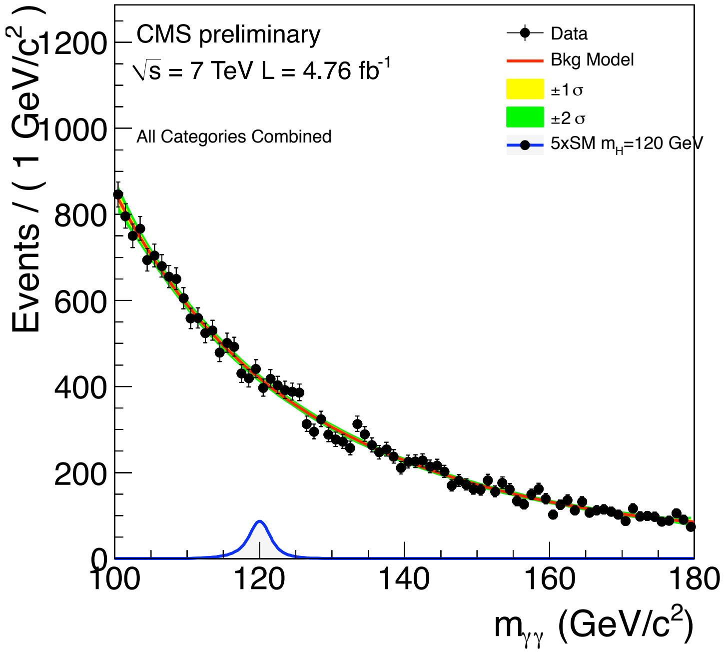
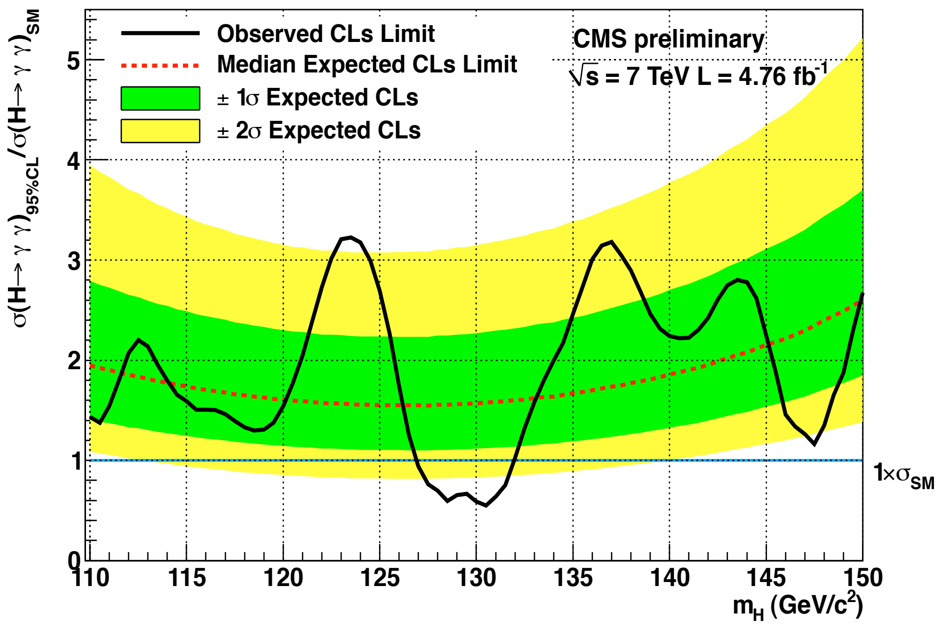


Figure 16 shows the probability of observing a minimum *local* p-value equal or smaller than some predefined threshold. This probability is the *global* p-value. One can see that the *global* p-value corresponding to the observed p_{min} =0.005 is 0.026, which implies a *global* significance of 1.9σ. An example of a p-value scan obtained in one of the 500 pseudo-data sets is shown in Fig. 17.

$$p_{global} = p_{min} + N_0\, e^{-Z_{max}^2/2}$$

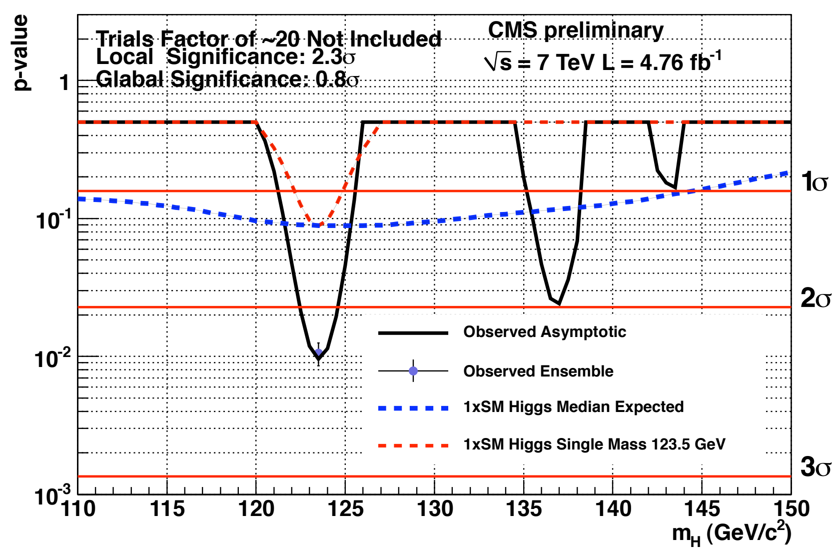
CMS H→2 Photons: November 2011





excluded: $127 \le m_H \le 131$ GeV,
(exp: 1.5 to 2.0 x σ_{SM})

max. deviation from BG at m_H = 123.5 GeV:
local p_0-value: 0.96% or 2.34σ
global p_0-value (includes LEE) ~21% (0.8σ)
fitted signal strength: ~ 1.7 ±0.8 x SM



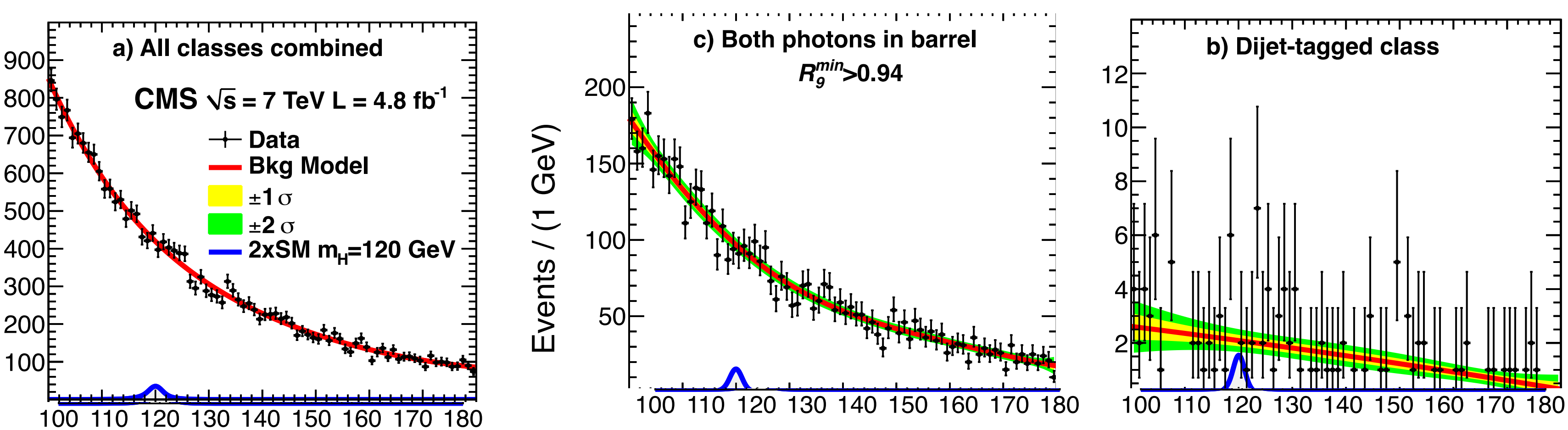
CMS: H→ γγ - Analysis Optimisation

enhance signal/background ratio and mass resolution by splitting in 5 categories:

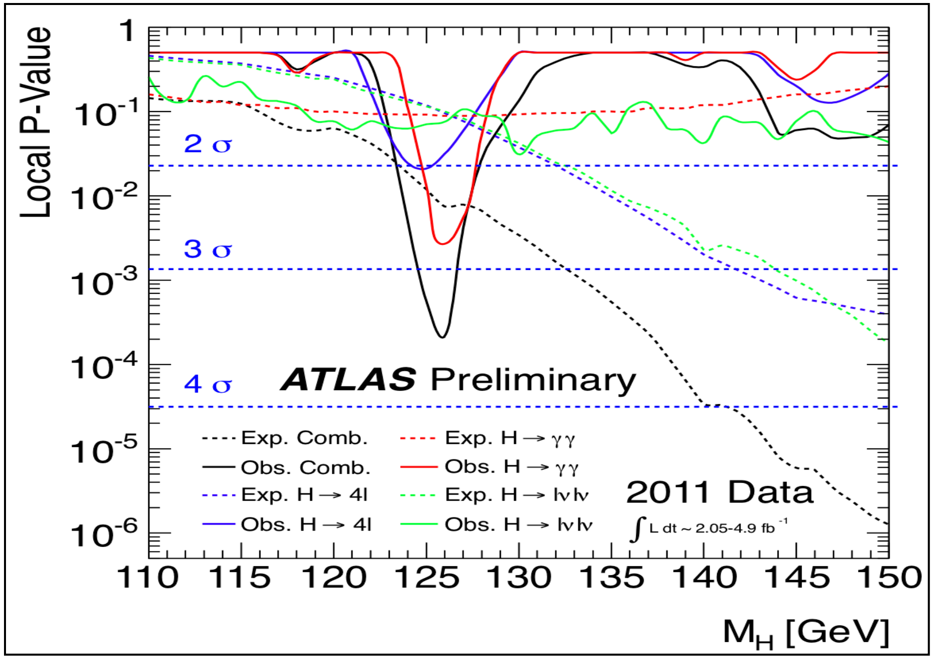
converted/ non converted ($R_9^{min</>.94}$) and barrel/endcap (η_{max}) → 4 classes

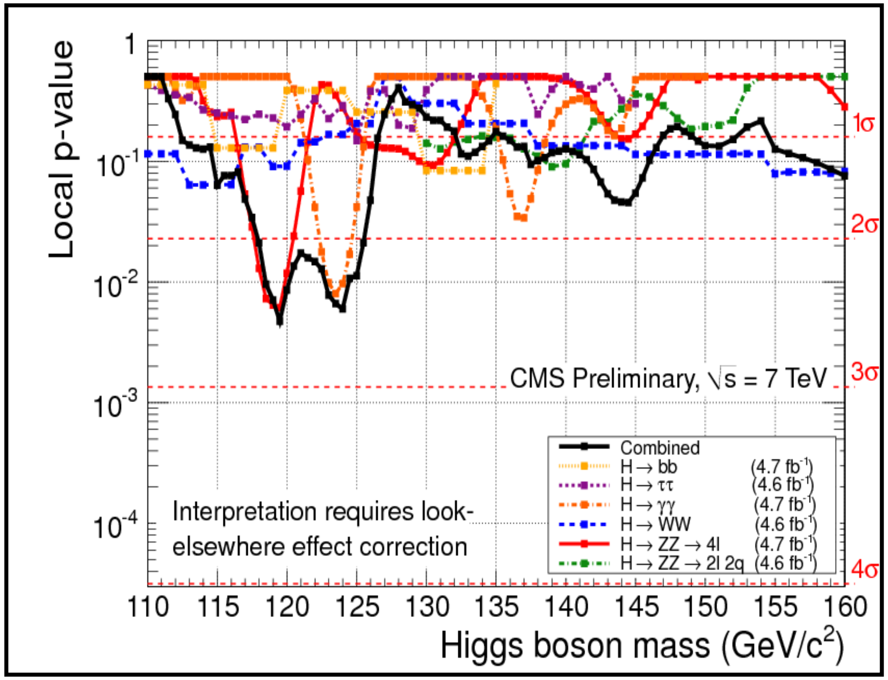
5th class new since December 2011: VBF topology (2 jets, m_{jj}, $\Delta\eta_{jj}$,...)
improves sensitivity by 10%

m_H=120 GeV	Both photons in barrel		One or both in endcap		Dijet tag
	R_9^{min} >0.94	R_9^{min} <0.94	R_9^{min} >0.94	R_9^{min} <0.94	
SM signal expected	25.2 (33.5%)	26.6 (35.3%)	9.5 (12.6%)	11.4 (14.9%)	2.8 (3.7%)
Data (events/GeV)	97.5 (22.8%)	143.4 (33.6%)	76.7 (17.9%)	107.4 (25.1%)	2.3 (0.5%)
σ_{eff} (GeV)	1.39	1.84	2.76	3.19	1.71
FWHM/2.35 (GeV)	1.19	1.53	2.81	3.18	1.37



Dec: 2011 Consistency with BG-Only: Low Mass





Maximum deviation for m_H~126 GeV

Local p_0-value: 1.9×10^{-4} = 3.6σ
(~2.8σ H→ γγ, 2.1σ H→ 4l, 1.4σ H→ lvlv)

Expected for M_H=126 GeV: ~ 2.4σ
(~ 1.4σ per channel)

Global p_0-value:
0.6% (2.5σ) mass range 110 to 146 GeV
1.4% (2.2σ) mass range 110 to 600 GeV

Max. deviation for m_H~119 and 124 GeV

Minimal local p-value: 0.5% (2.6σ)

Global p-value
2.6% (1.9σ) mass range 110 to 145 GeV
38% (0.6σ) mass range 110 to 600 GeV

ATLAS: Best Fit for Signal Strength in H→ 2 Photons