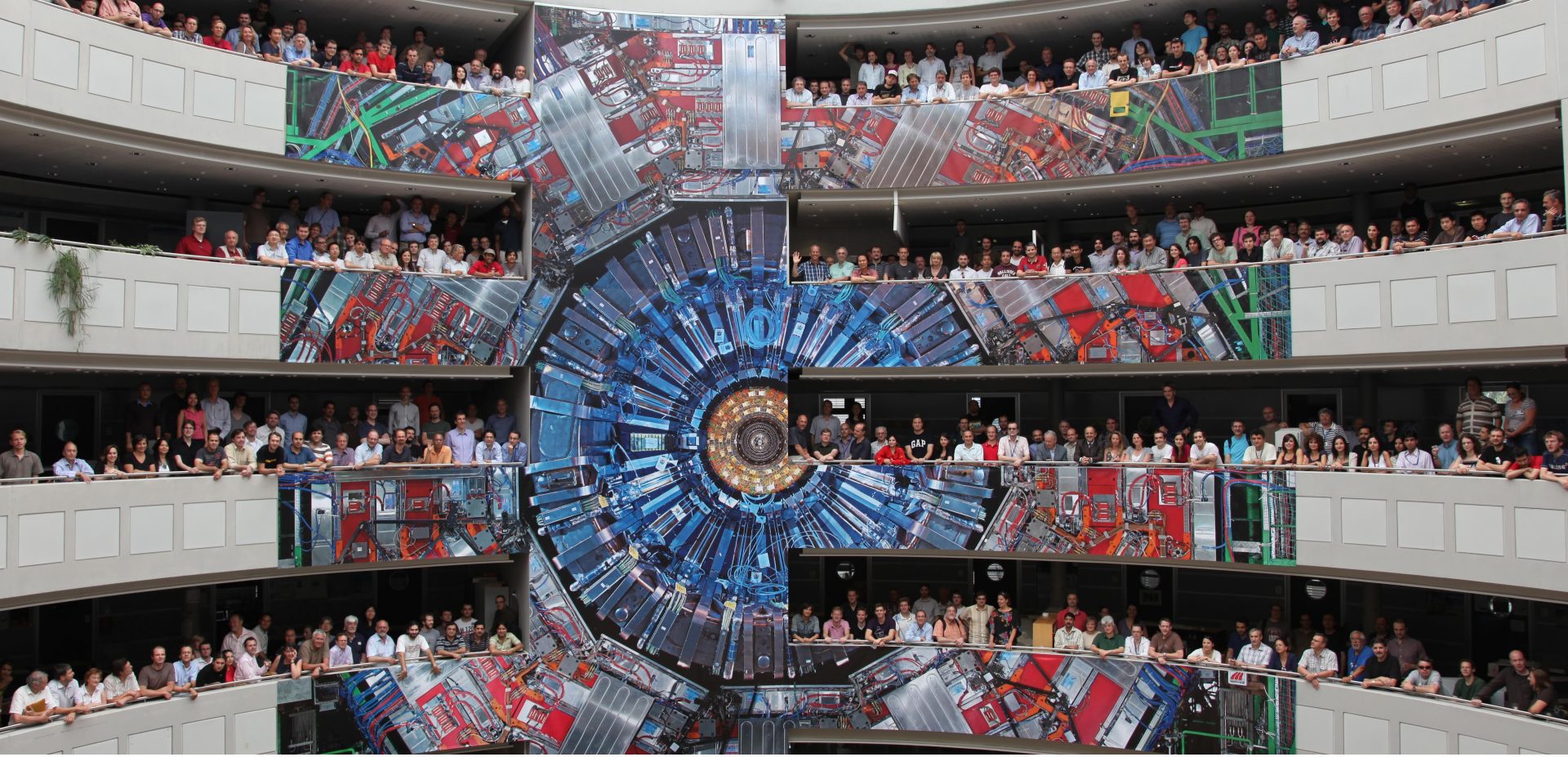


SM Higgs boson search at CMS

Andrey Korytov
University of Florida

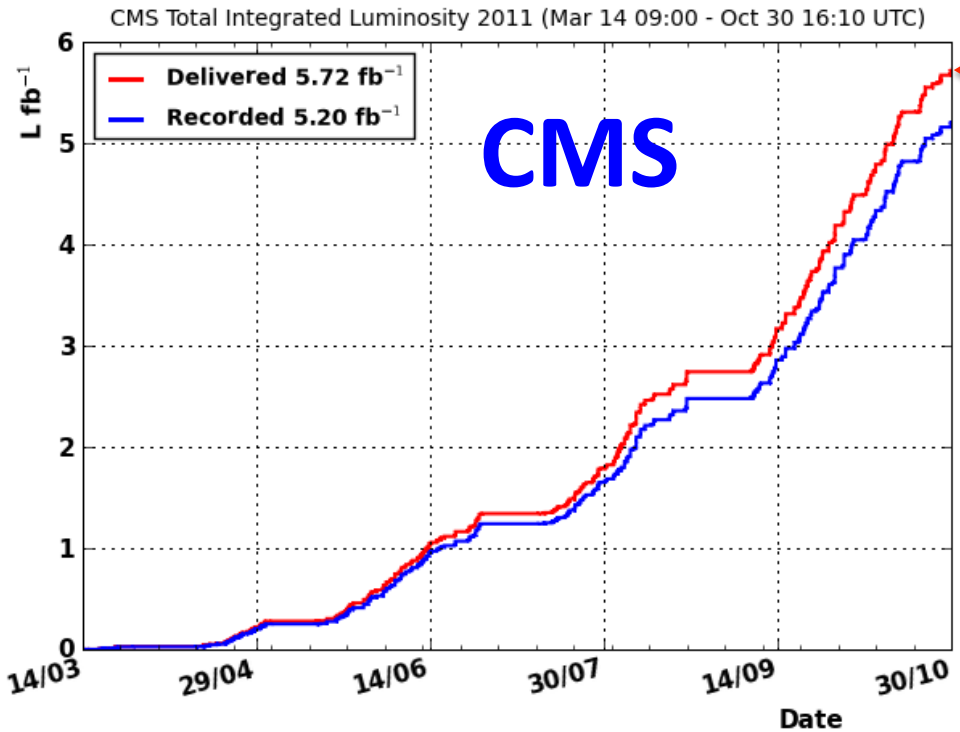
Outline

- **Preamble:**
  - **CMS performance**
  - **Five slides on statistics**
- **SM Higgs searches:**
  - **H → bb**
  - **H → ττ**
  - **H → γγ**
  - **H → WW**
  - **H → ZZ**
  - **Combination**
- **Outlook**

Preamble 1

CMS performance

LHC performance in 2011



>5 fb^{-1}delivered.
LHC target for this year was 1 fb^{-1} per exp.

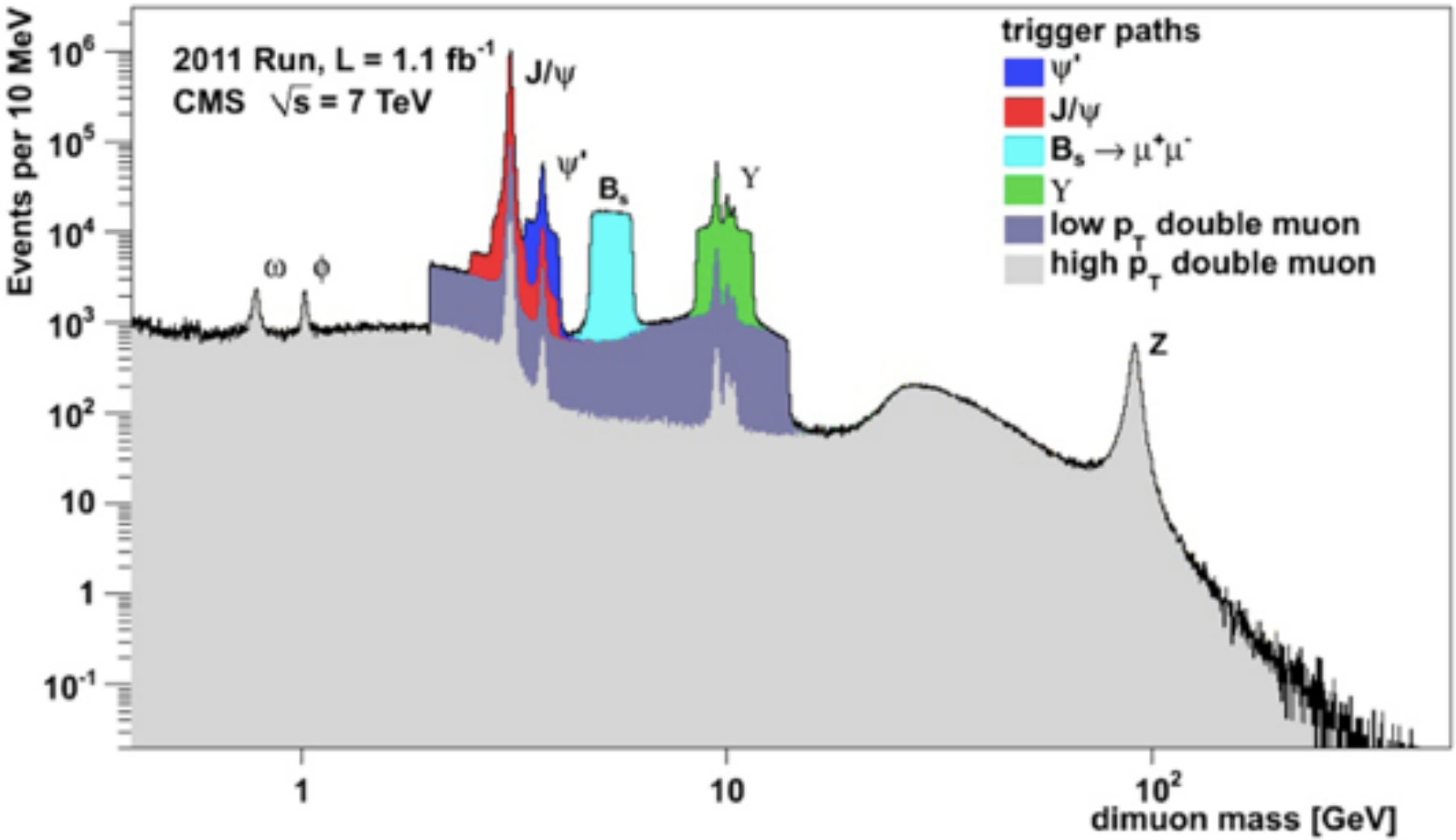
Max luminosity
L = 3.5 x 10^{33} cm^{-2} s^{-1}

Rapid increase in instantaneous luminosity:

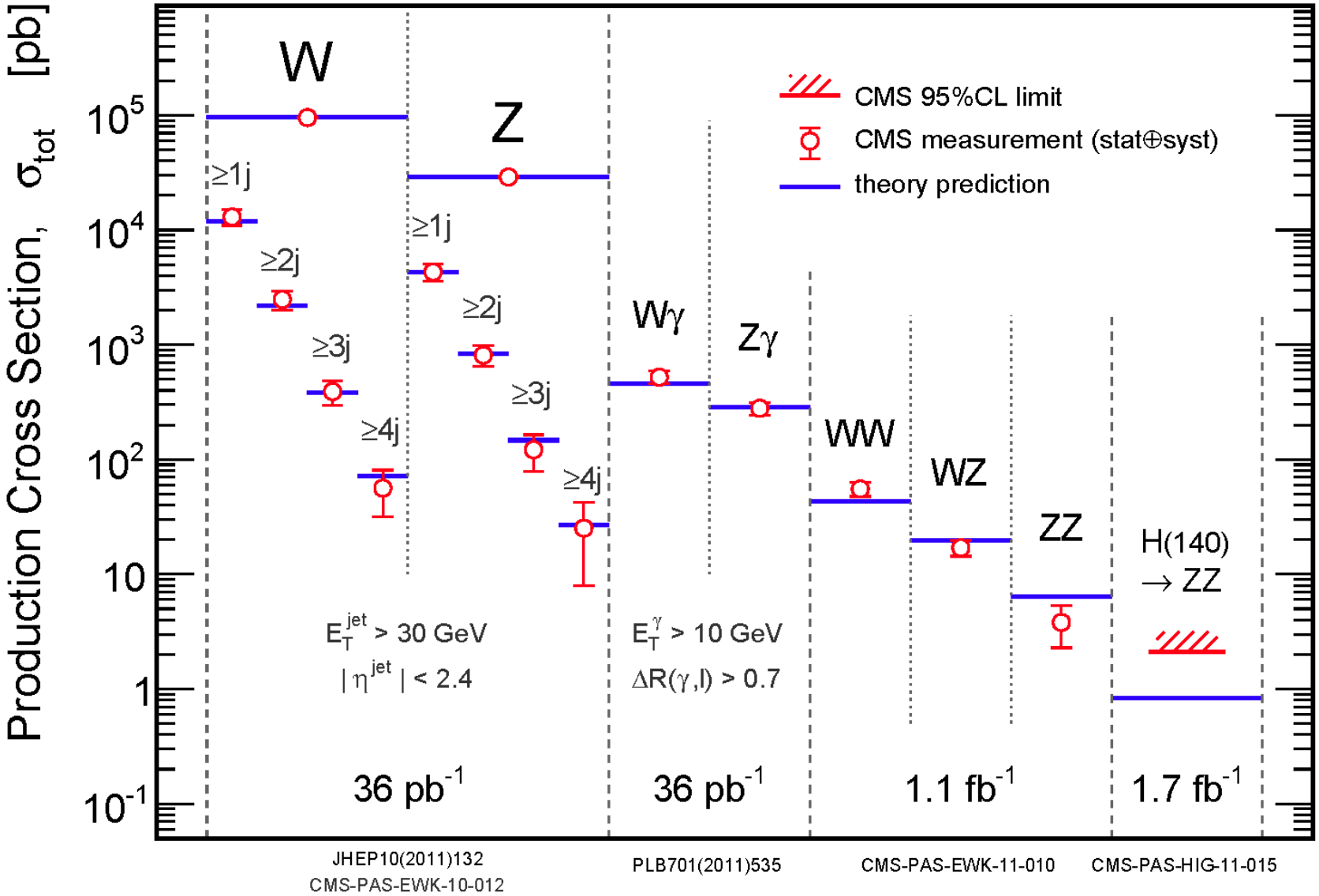
April (L=2x10^{32} cm^{-2}s^{-1}) – October (3.5x10^{33})

1 day in October = more data than 4 x (entire 2010 run)

CMS Performance (1)



CMS Performance (2)



Five slides on statistics

(many more in backup)

What is μ?

SM Higgs boson cross section: σ_{SM}

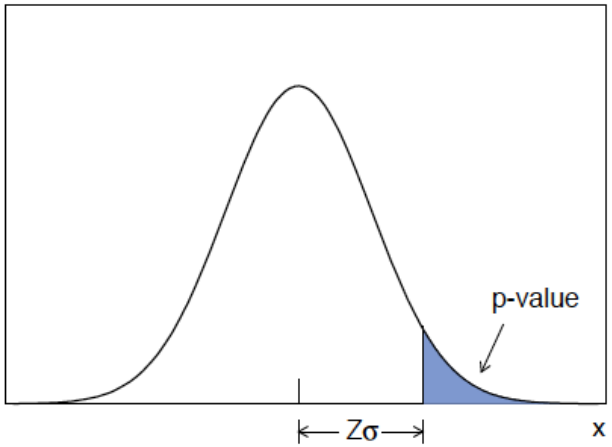
Hypothetical Higgs boson cross section: $\sigma = \mu\ \sigma_{SM}$

Excesses

- ***p-value*:** chance of bkgd fluctuating as high as or higher than what has been observed in data

$$p = \mathrm{P}(\, n \geq n_{\mathrm{obs}} \mid \mathrm{b}\,)$$

- ***significance* Z** is related to *p-value* via the tail probability of the normal distribution

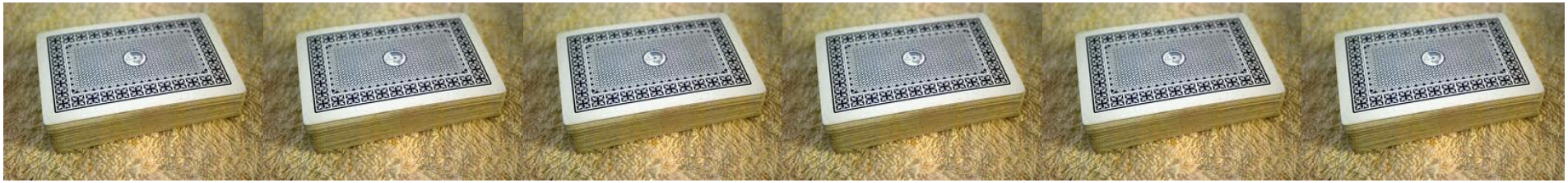


- *p-value* does not tell us whether the excess is consistent with the SM Higgs boson CS. Hence, we also quote the **best-fit value of the signal strength modifier $\hat{\mu}$**

Look-elsewhere effect (LEE)

What is the chance that the top card in a deck is Queen of Hearts?

Local *p-value*



What is the chance that the top card in at least one of N decks is Queen of Hearts?

Global *p-value*

The fact that the two answers are not the same is known under a fancy name **Look-Elsewhere Effect.** The ratio of the two probabilities = **trials factor.**

Limits

- **CL_s method:** "know your odds"

$$CL_S = \frac{P(\, n \le n_{obs} \mid b + s_{SM}\,)}{P(\, n \le n_{obs} \mid b\,)}$$

There are other methods available.
ATLAS and CMS agreed on CL_s,
or, more accurately,
on one particular flavor of it.

- **Confidence Level:**

  $CL_s < \alpha$ ==> "SM signal is excluded with 1-α Confidence Level".

  95% C.L. ($\alpha < 0.05$) is a popular <u>convention</u> for an exclusion…

- **Signal strength modifier μ excluded at 95% C.L.:**
  <u>common factor</u> by which all the SM Higgs boson event yields are to be rescaled ($\sigma = \mu \times \sigma_{SM}$) in order to exclude the modified signal at 95% C.L.

Real multi-channel combination

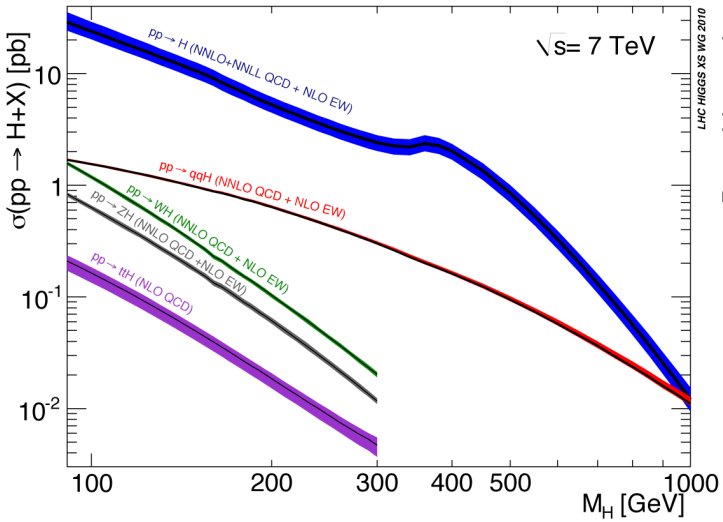
- **Many channels** (n is replaced with test statistic q)
  - **Choices on Observation → TestStatistic conversion**

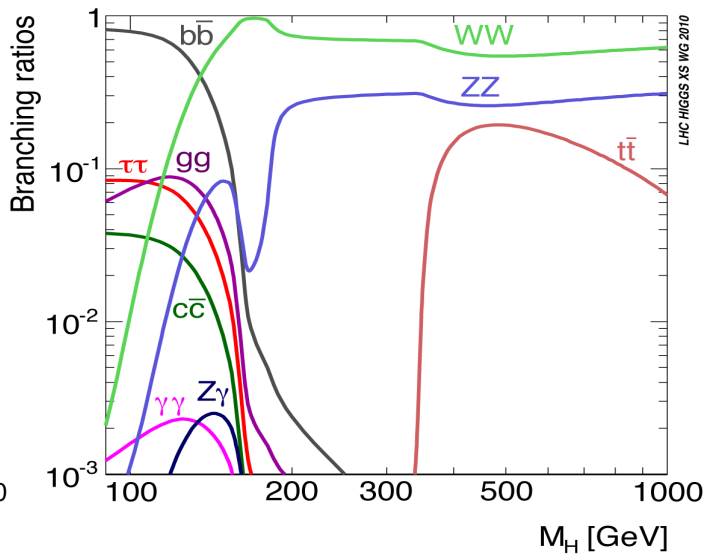
- **Systematic uncertainties:**
  - **Choices on modeling uncertainties**
  - **Choices on handling uncertainties in combination**
  - **Choices on correlations of uncertainties**

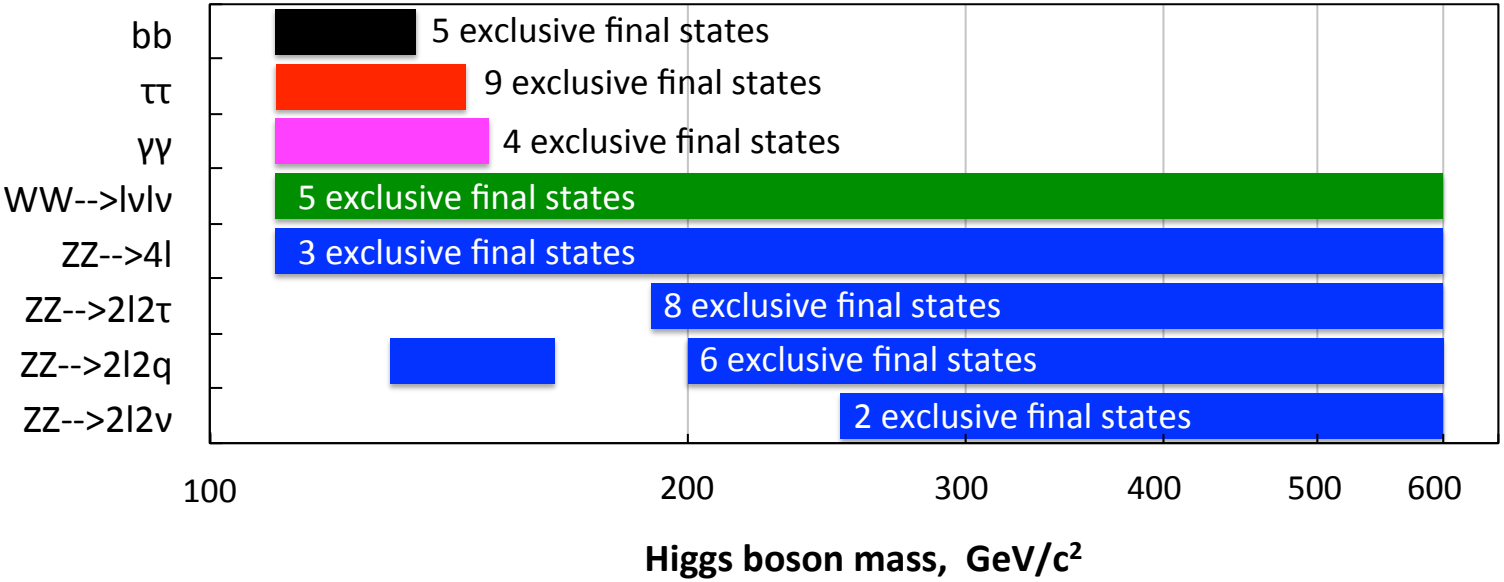
SM Higgs searches

nearly all analyses have crosschecks done with alternative techniques

SM Higgs: production, decays, searches

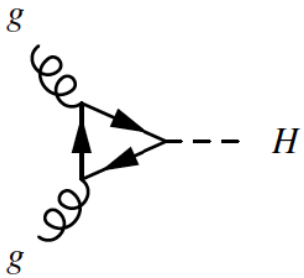


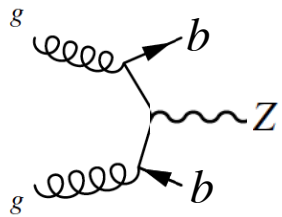




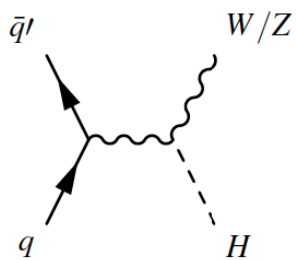
LHC vs Tevatron

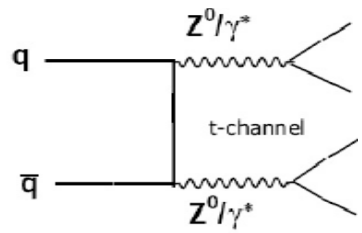
gg-production: x 20

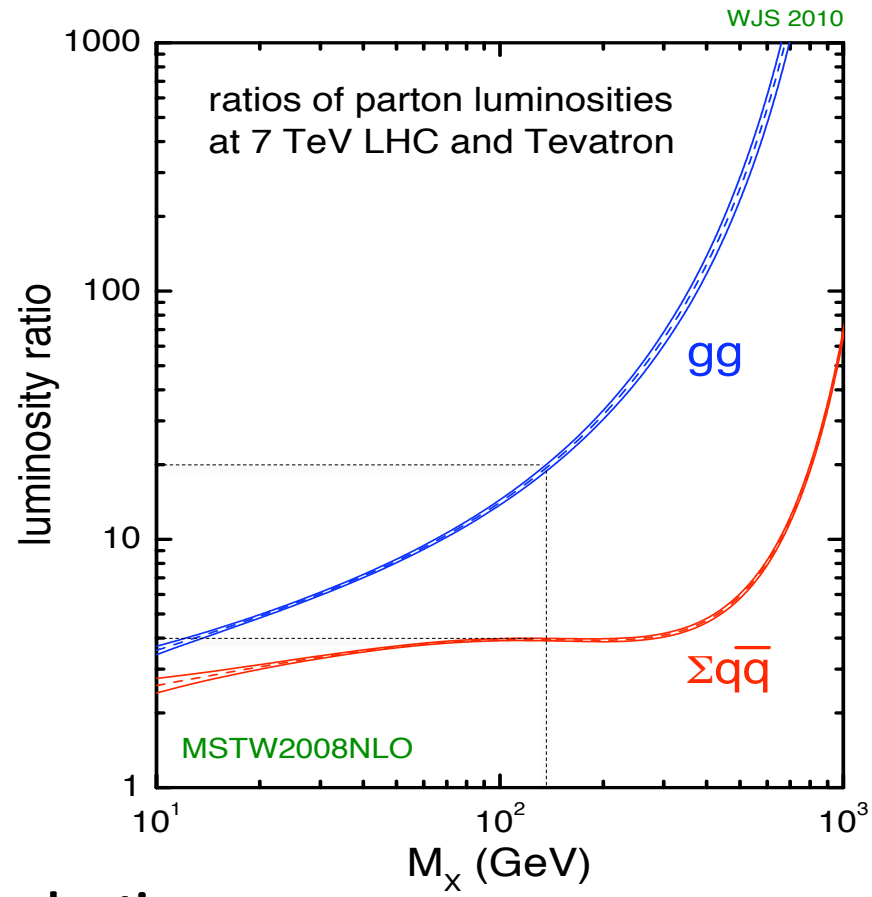




qqbar production: x 4





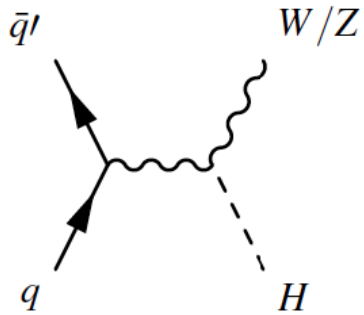


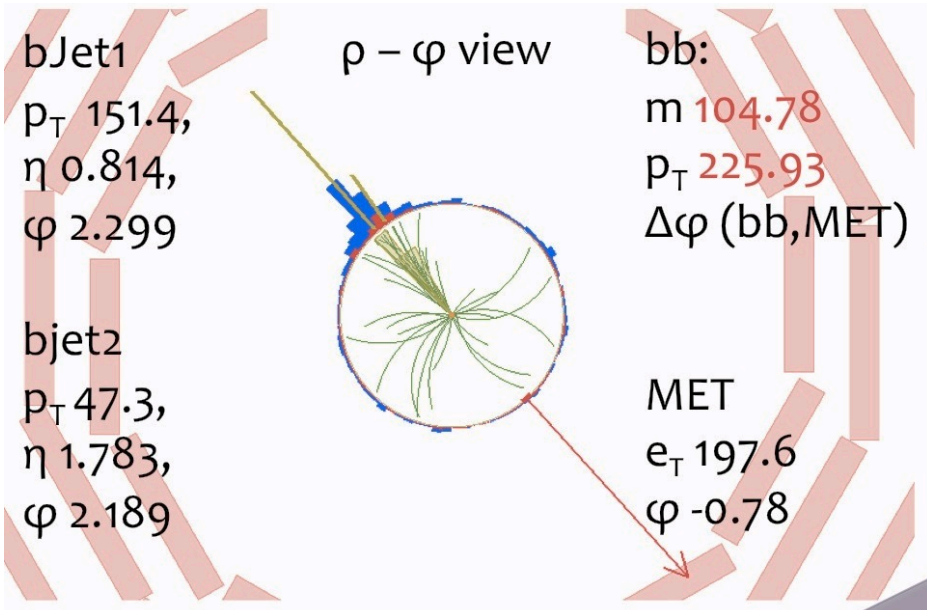
Signal-to-Background ratio:

- **VH(bb): S/B is worse at LHC**
- **γγ/WW/ZZ: S/B is better at LHC**
- **VBF ττ: S/B is about the same**

H -> bb

V+H(bb) signature





Selection:

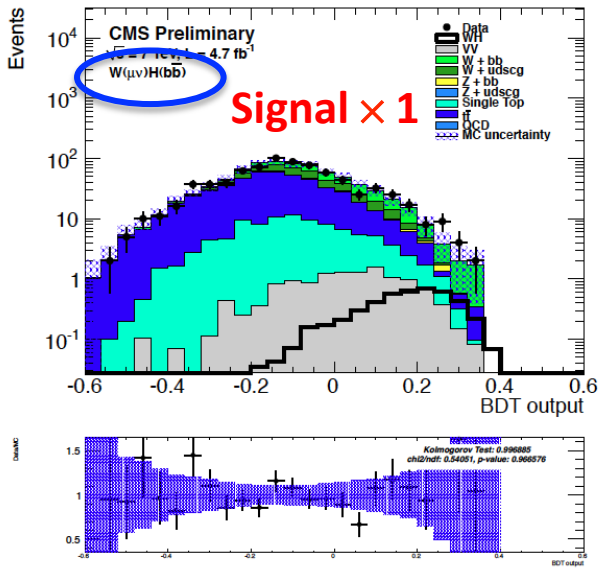
- **5 channels: W→lν, Z→ll, Z→νν**
- **high MET quality for W(lν) and Z(νν)**
- **two jets with tight b-tags**
- **V+H(bb) topology: back-to-back, Δφ(V,H) > 3**
- **p_T(bb)> 100-160 GeV (*but not super boosted*)**
- **Final discriminant: MVA output shape**

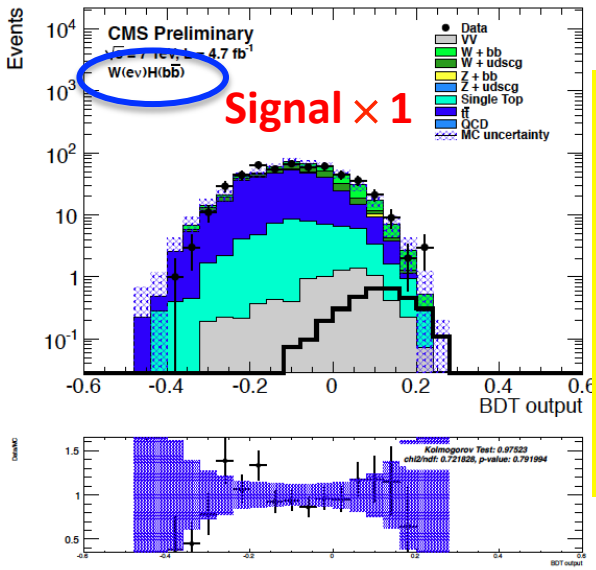
bb mass resolution: 10%
(aided by the bb-system boost)

Main backgrounds:

- **Vbb: from data (invert p_T(bb) boost)**
- **V+jets: from data (invert b-tag)**
- **tt: from data (require extra jet)**
- **QCD: from data (require small Δφ(MET,jet), …)**
- **W+Z(bb) and Z+Z(bb): from MC**

H->bb BDT distributions (m_H=115 GeV)

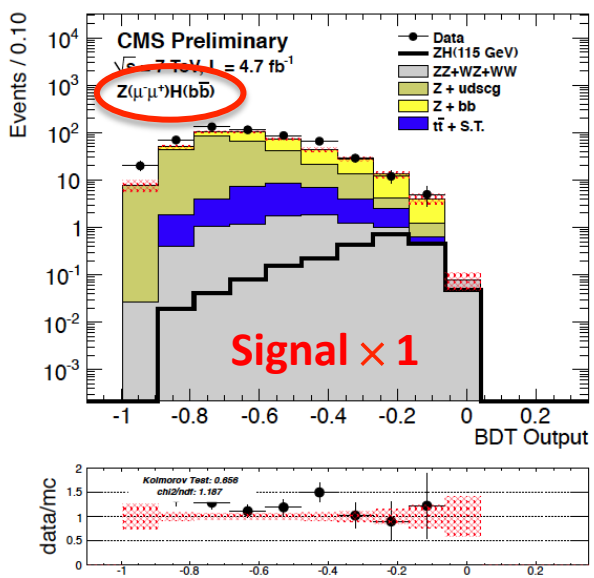


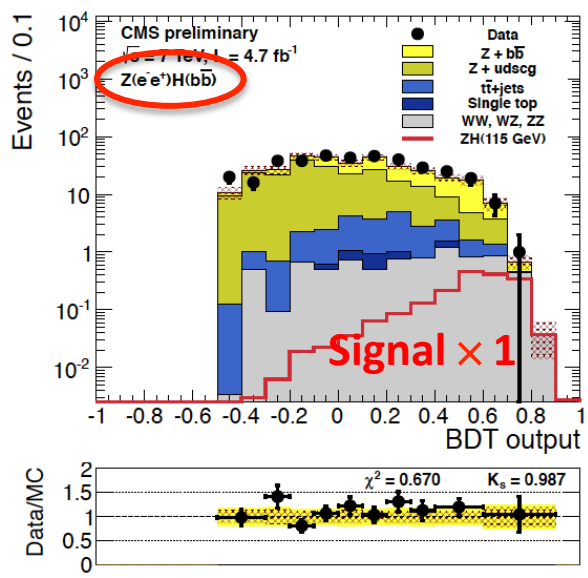


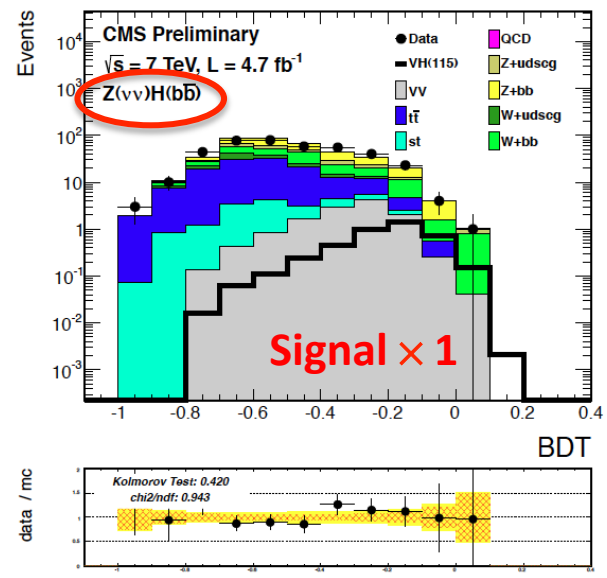
Note:

- S/B in the best bin
- Systematic errors in those bins

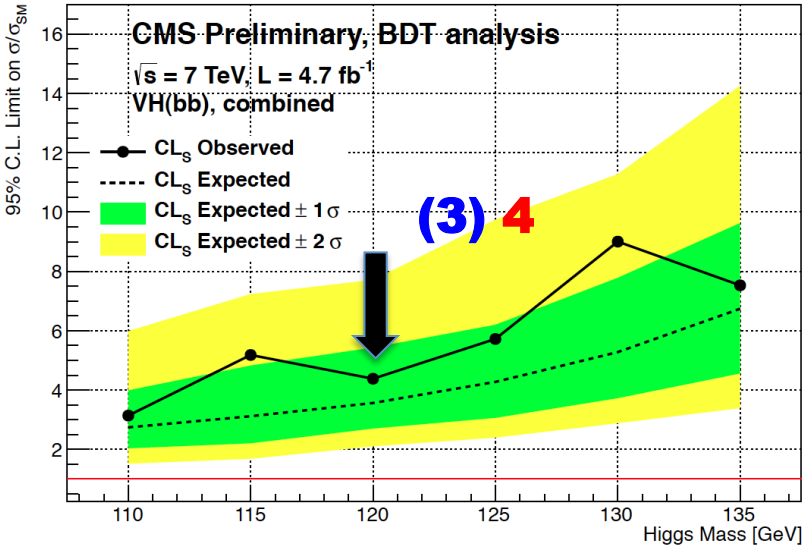
Systematic errors are a persistent challenge as the integrated lumi increases







H->bb results



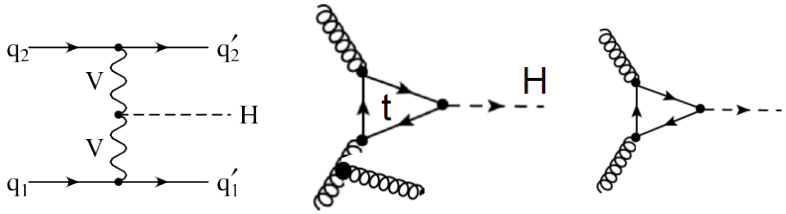
BDT shape analysis

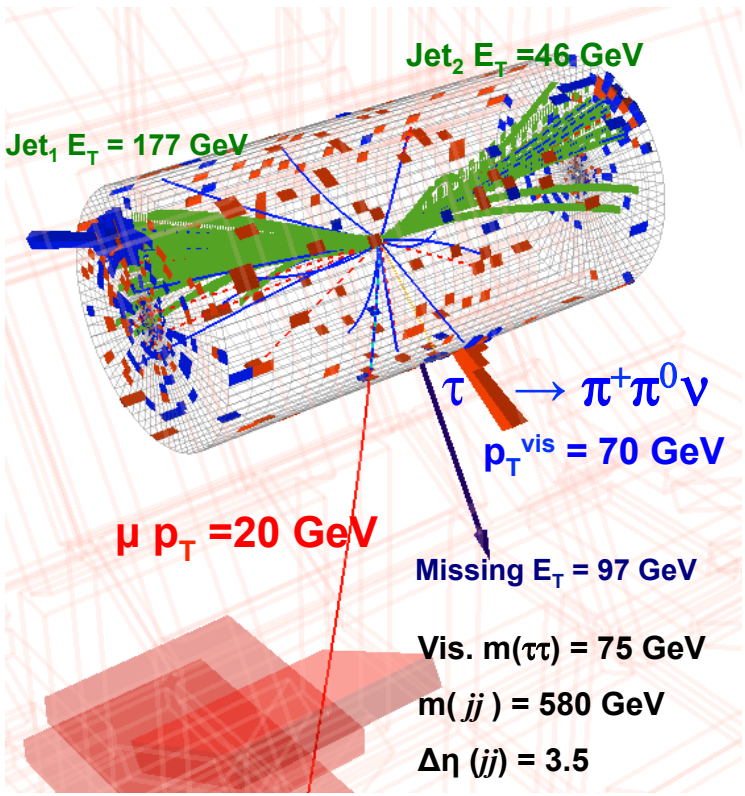
m_H=120 GeV

- **Sensitivity 3**
- **Observed 4**

H -> ττ

H->ττ signature





Selection:

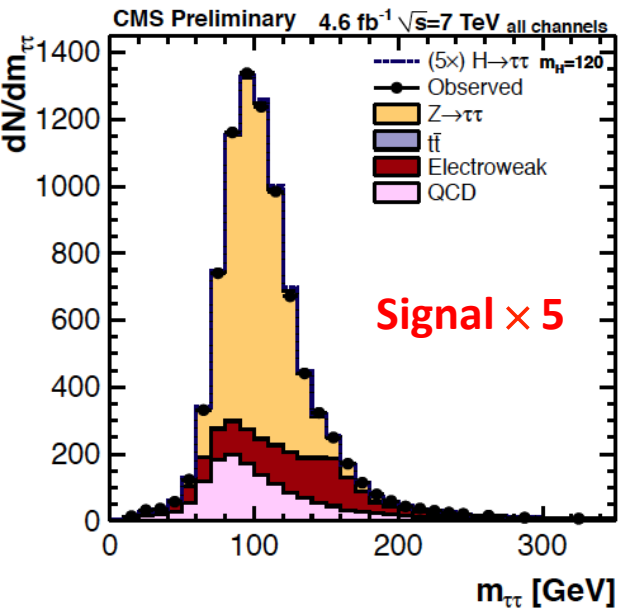
- 9 channels: $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_\mu$ (VBF, 1-jet, the rest)
- main sensitivity from VBF production: two forward jets with no jets in between
- isolated leptons
- CDF topological cut (p_{T1}, p_{T2}, MET)
- final discriminant: ττ-mass distribution

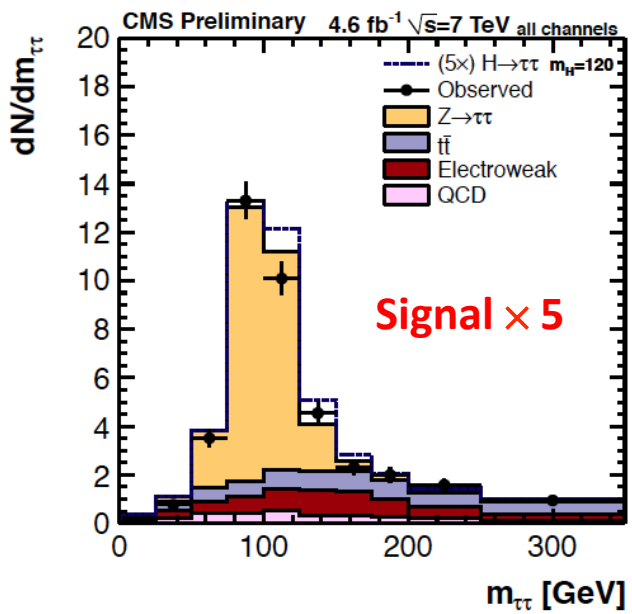
ττ mass resolution: 20%

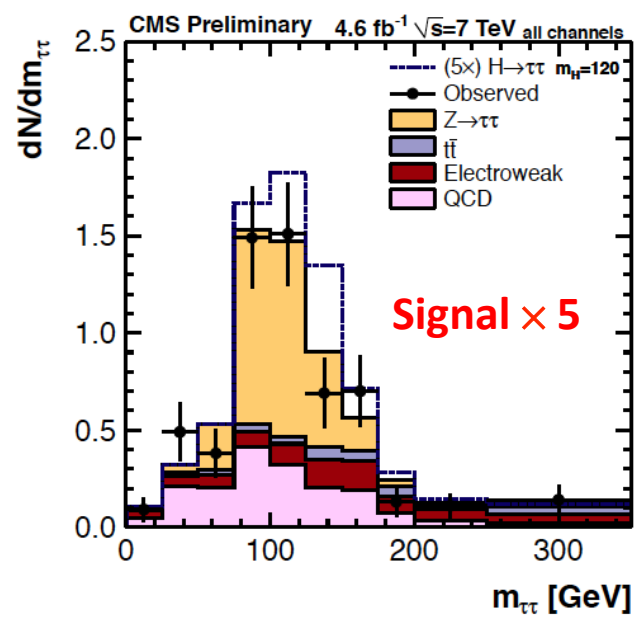
Main backgrounds:

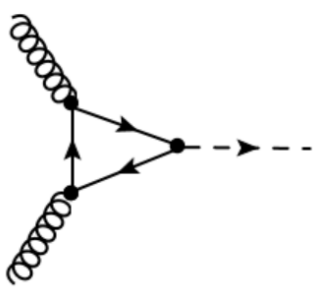
- Z→ττ: from data (mass distr. fit with MC shape)
- W+jets: from data (invert topological cut)
- QCD: from data (same sign ττ)
- tt, di-bosons (e faking τ): from data (ll events)

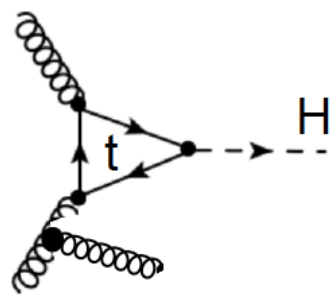
H->ττ distributions (m_H=120 GeV)

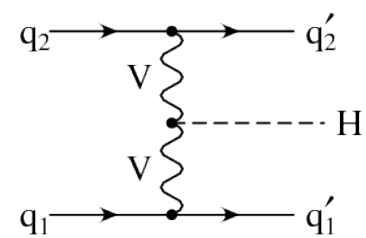




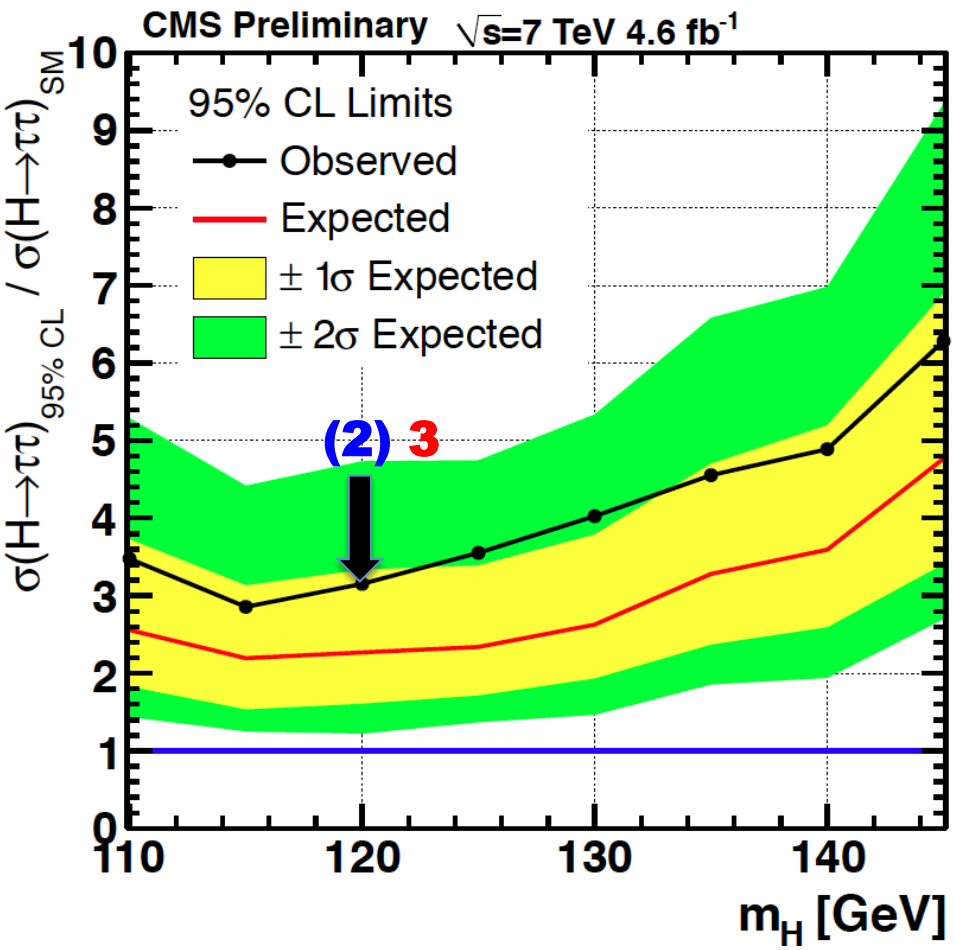








H->ττ results

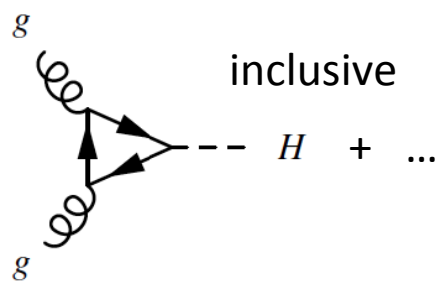


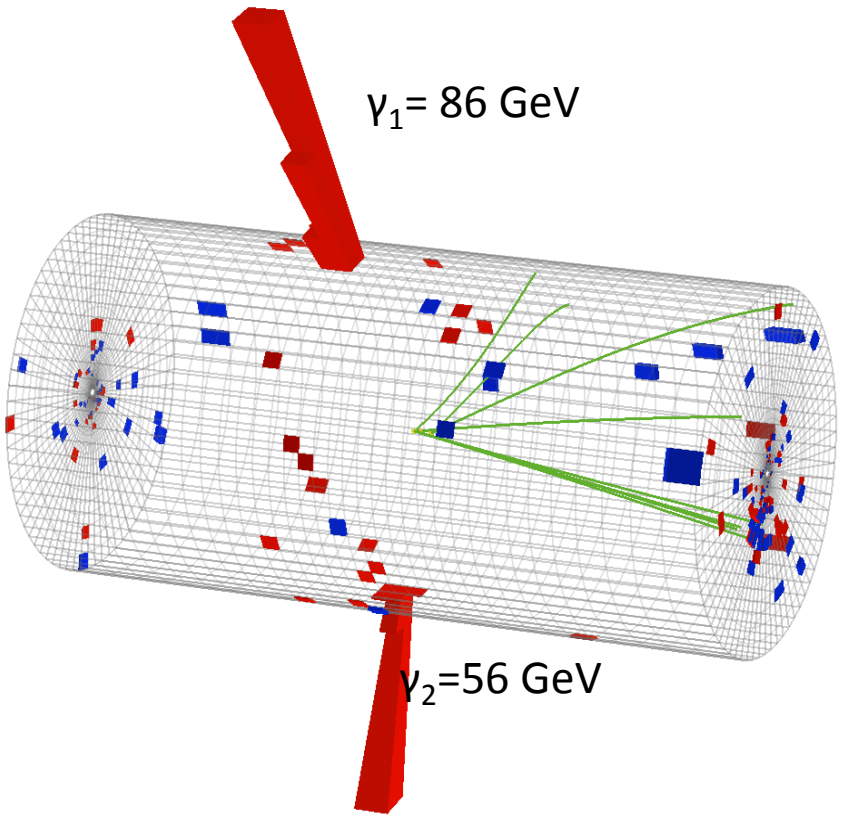
m_H=120 GeV

- Sensitivity 2.3
- Observed 3.2

H -> γγ

H->γγ signature



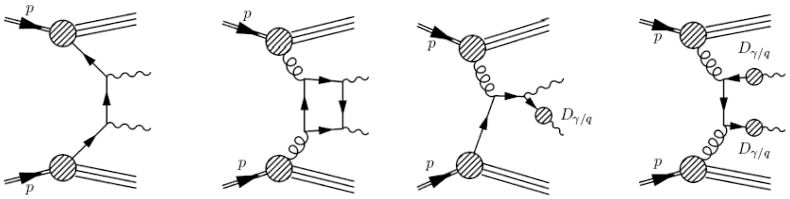


Selection:

- inclusive production
- two isolated photons
- 4 event categories based on quality of photons and, hence, expected $m_{\gamma\gamma}$ resolution
- Events are NOT split based on $p_T(\gamma\gamma)$
- Final discriminant: γγ-mass distributions

Best category $m_{\gamma\gamma}$ resolution: ~1%

Main backgrounds: from sidebands



H->γγ categories

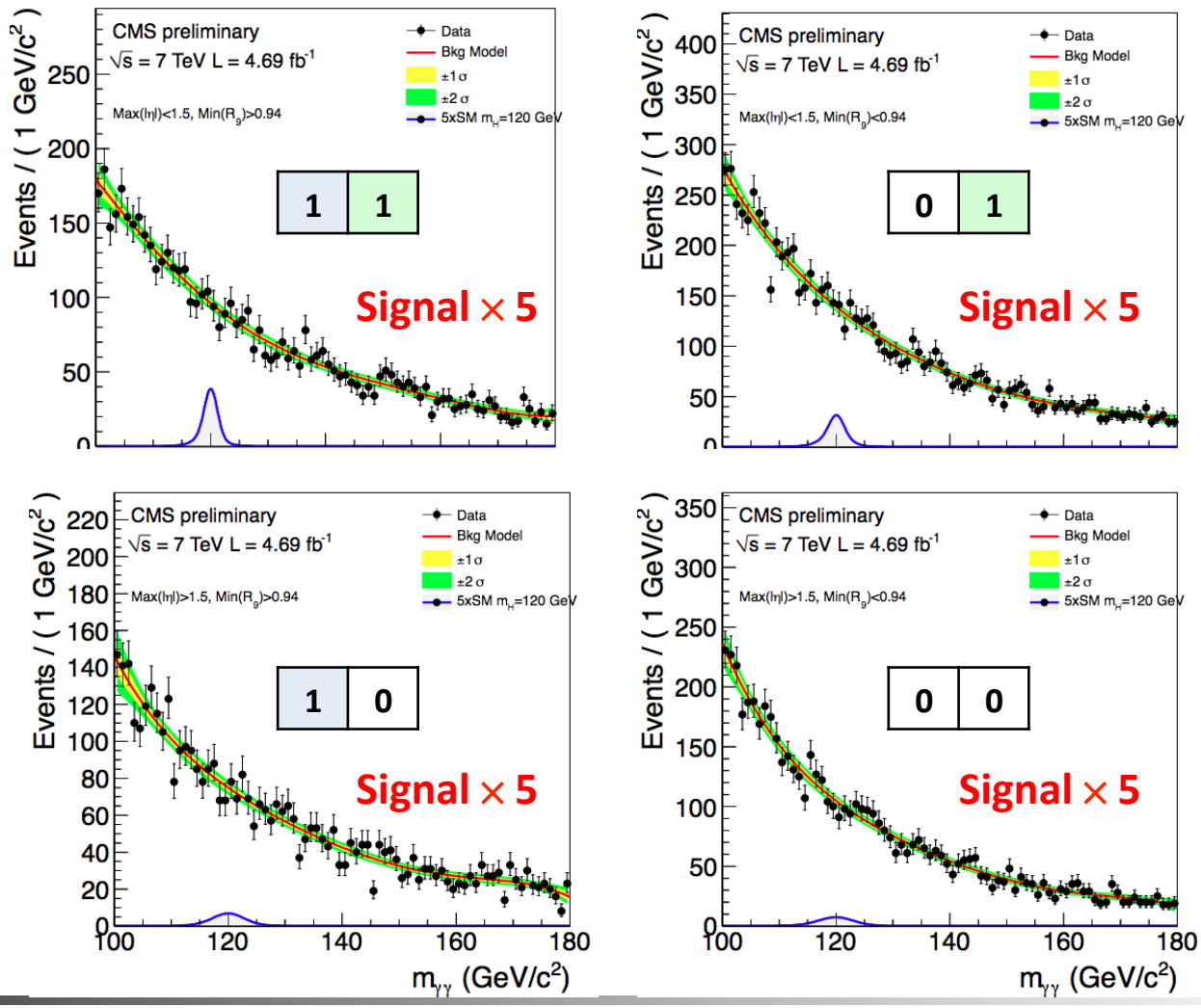
Both photons of high quality?

Both photons in barrel?

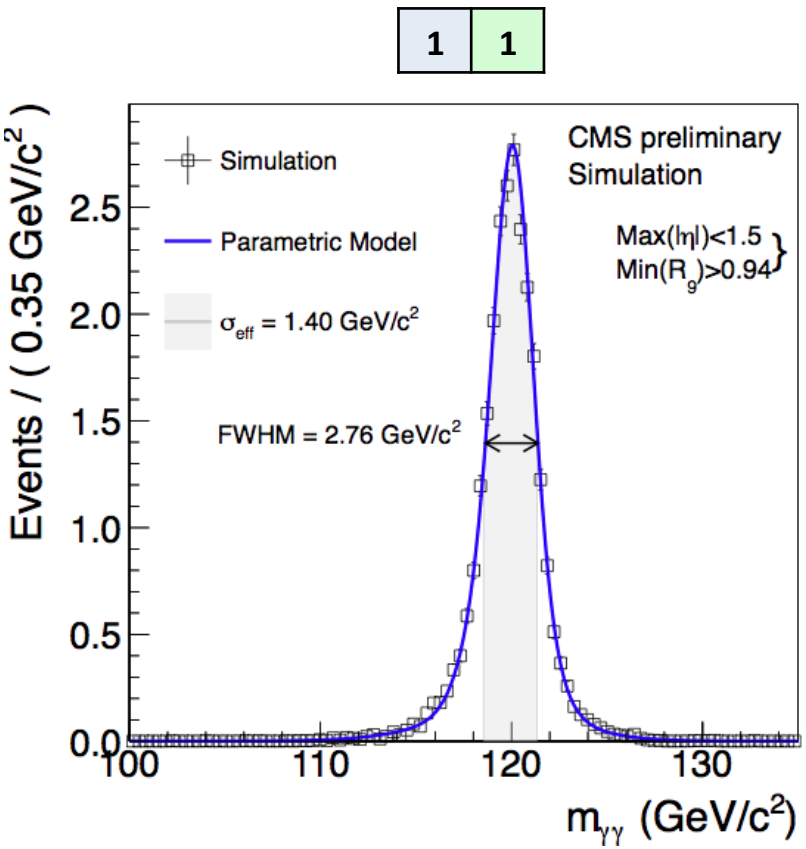
1	1

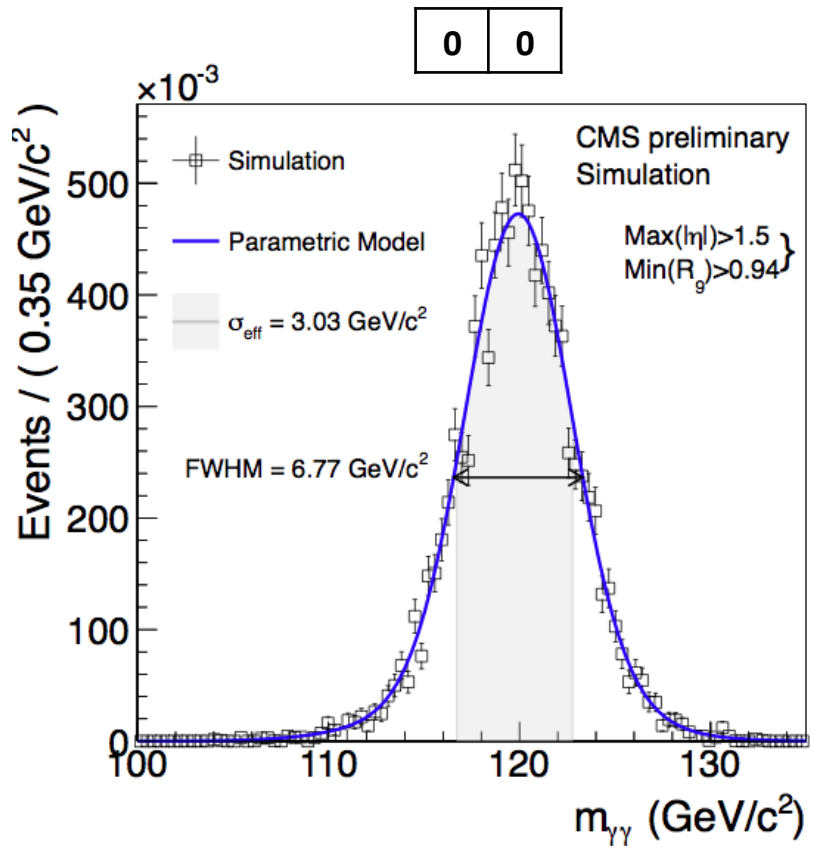
NOTE:
- $m_{\gamma\gamma}$ resolutions
- S/B ratios

Classification helps with both

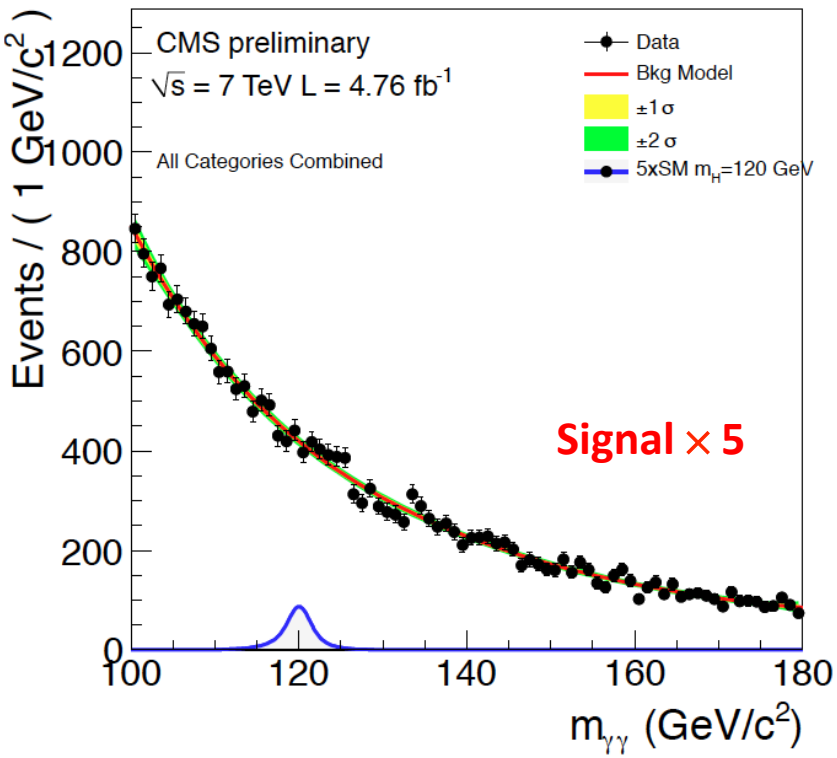


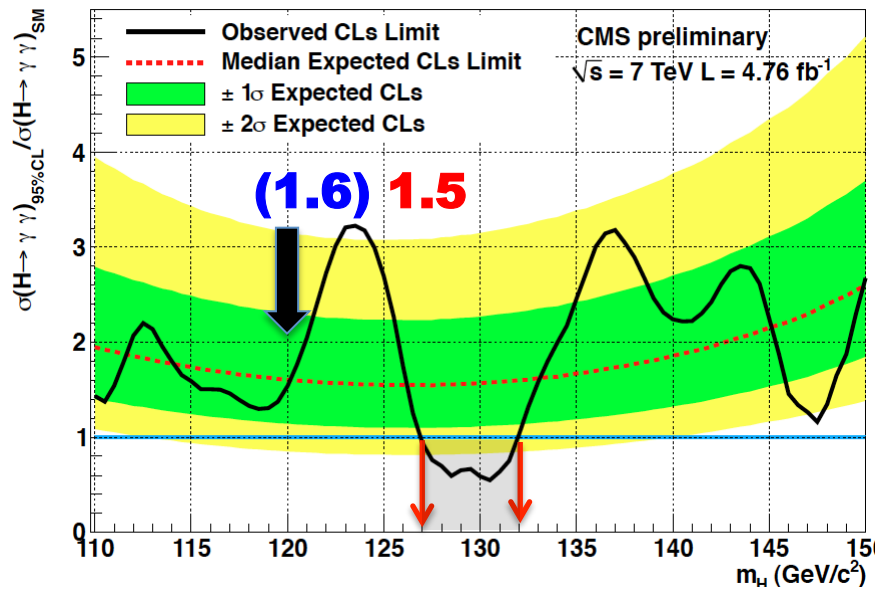
H->γγ mass resolutions

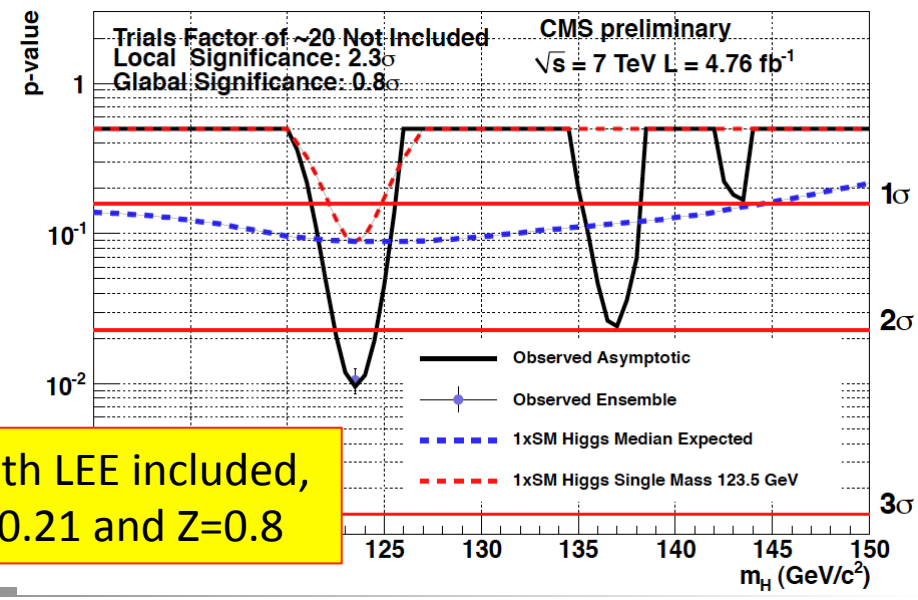




H->γγ results



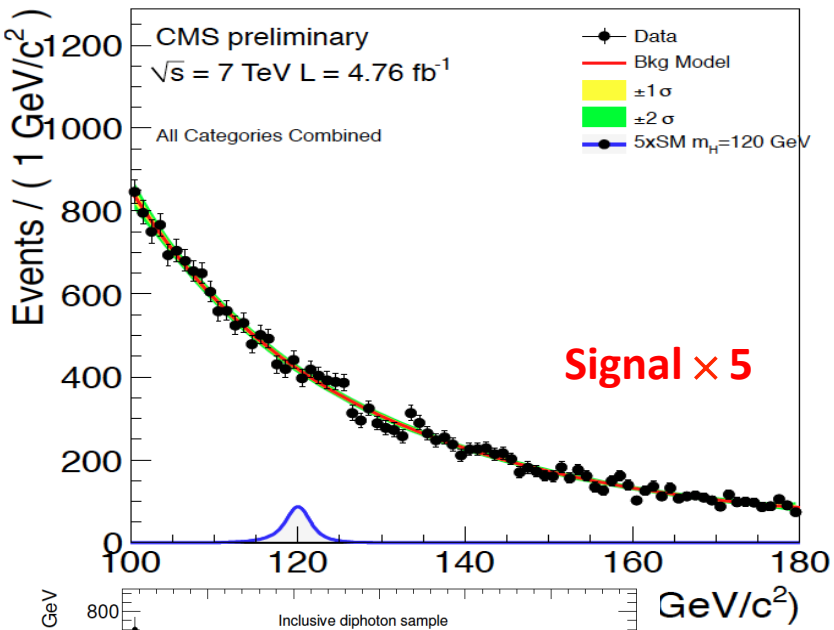


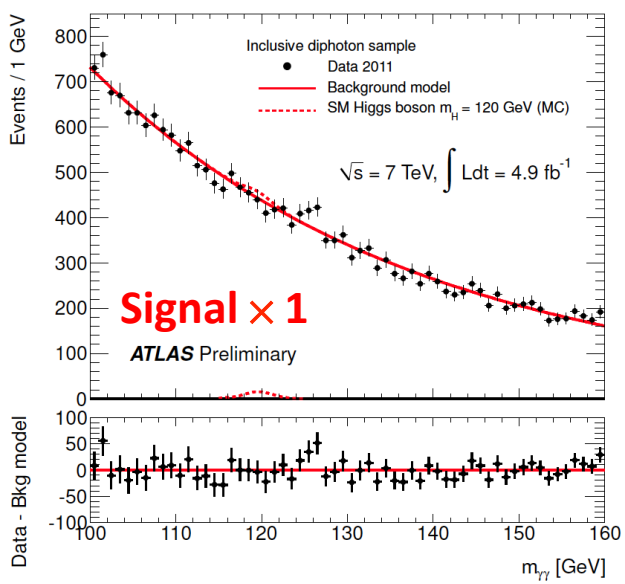


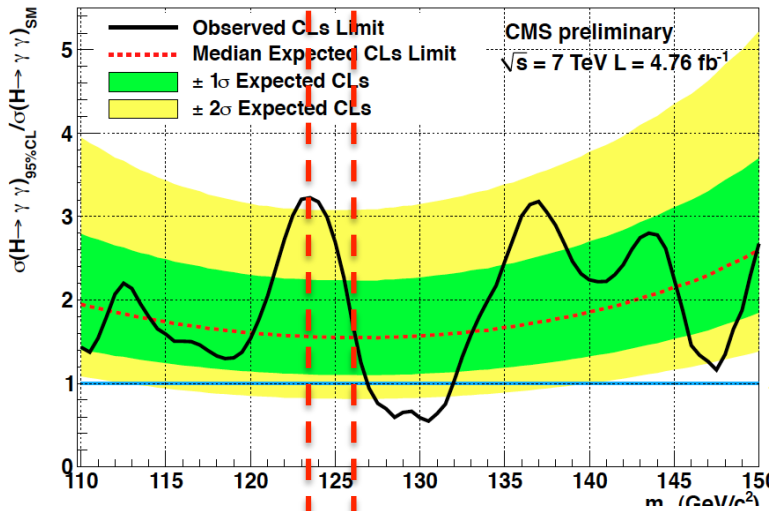
- **Bkgd MC predictions are not used in the analysis**
- **Mass distributions analyzed in 4 event categories**

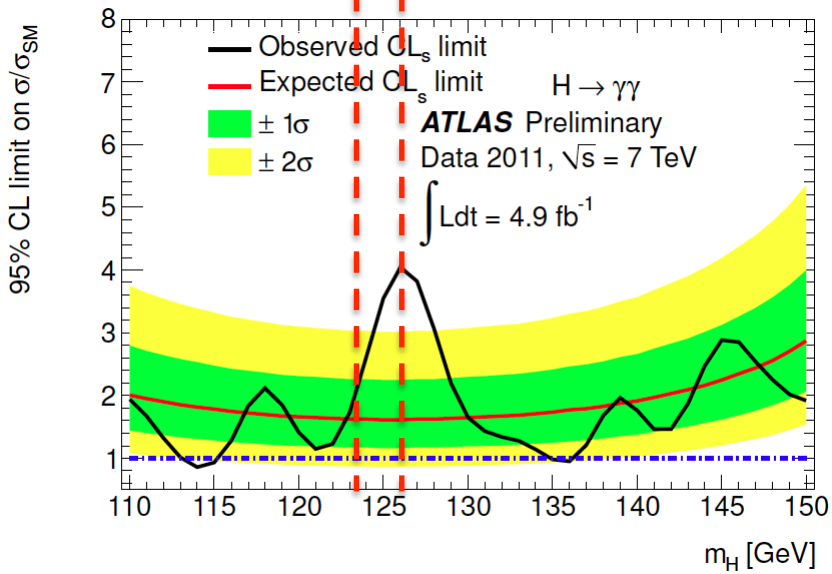
With LEE included, p=0.21 and Z=0.8

H→γγ: CMS vs ATLAS



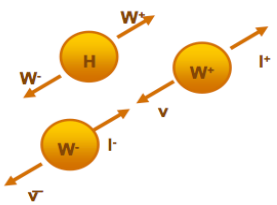


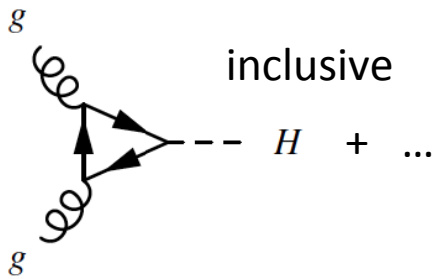


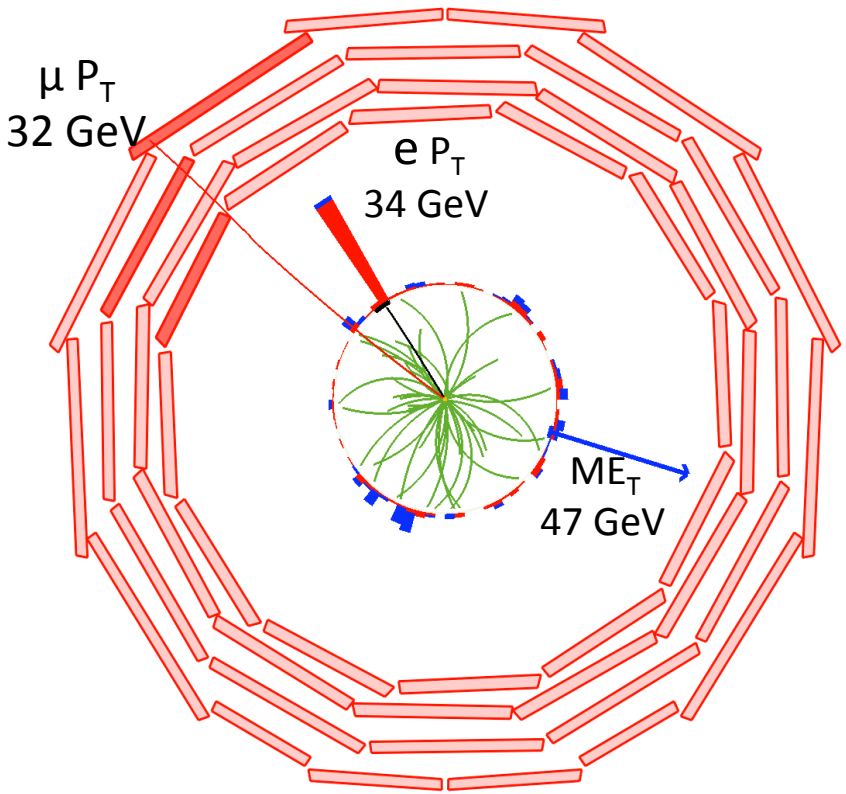


H -> WW

H->WW->lvlv signature







Selection:

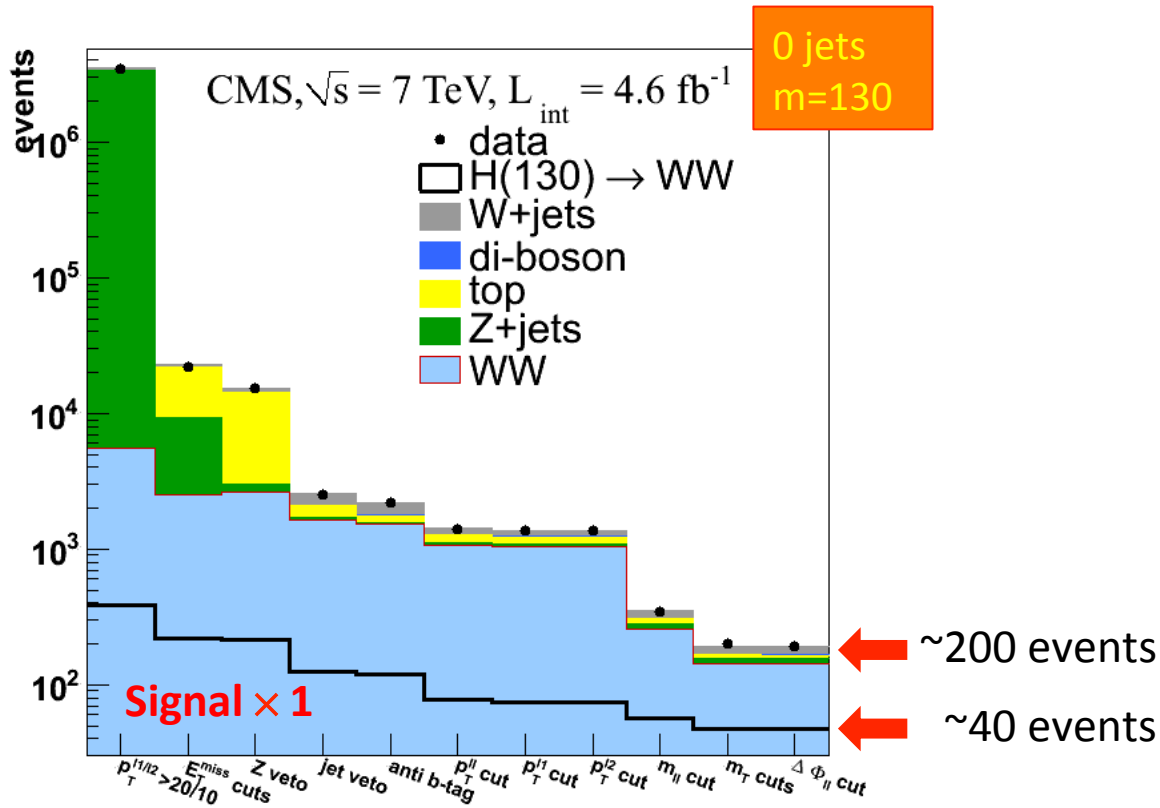
- **two isolated leptons, small Δϕ, small m_{ll}**
- **MET**
- **Transverse mass m_T**
- **Final discriminants: MVA output shape**
  - Same-Flavor di-leptons + 0 jets
  - Opposite-Flavor di-leptons + 0 jets
  - Same-Flavor di-leptons + 1 jet
  - Opposite-Flavor di-leptons + 1 jet
- **and cut-and-count:** SF/OF di-leptons + 2 VBF jets

Mass resolution: 20%

Main backgrounds:

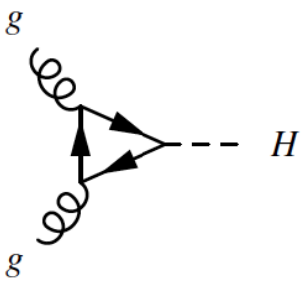
- **WW(m_H<200): from data (small di-lepton mass)**
- **WW(m_H>200): from MC**
- **tt: from data (inverted b-tag)**
- **W: from data (tight-to-loose fake rate)**
- **Drell-Yan: from data (on-shell Z)**
- **WZ, ZZ: from MC**

H->WW->lvlv: cut flow



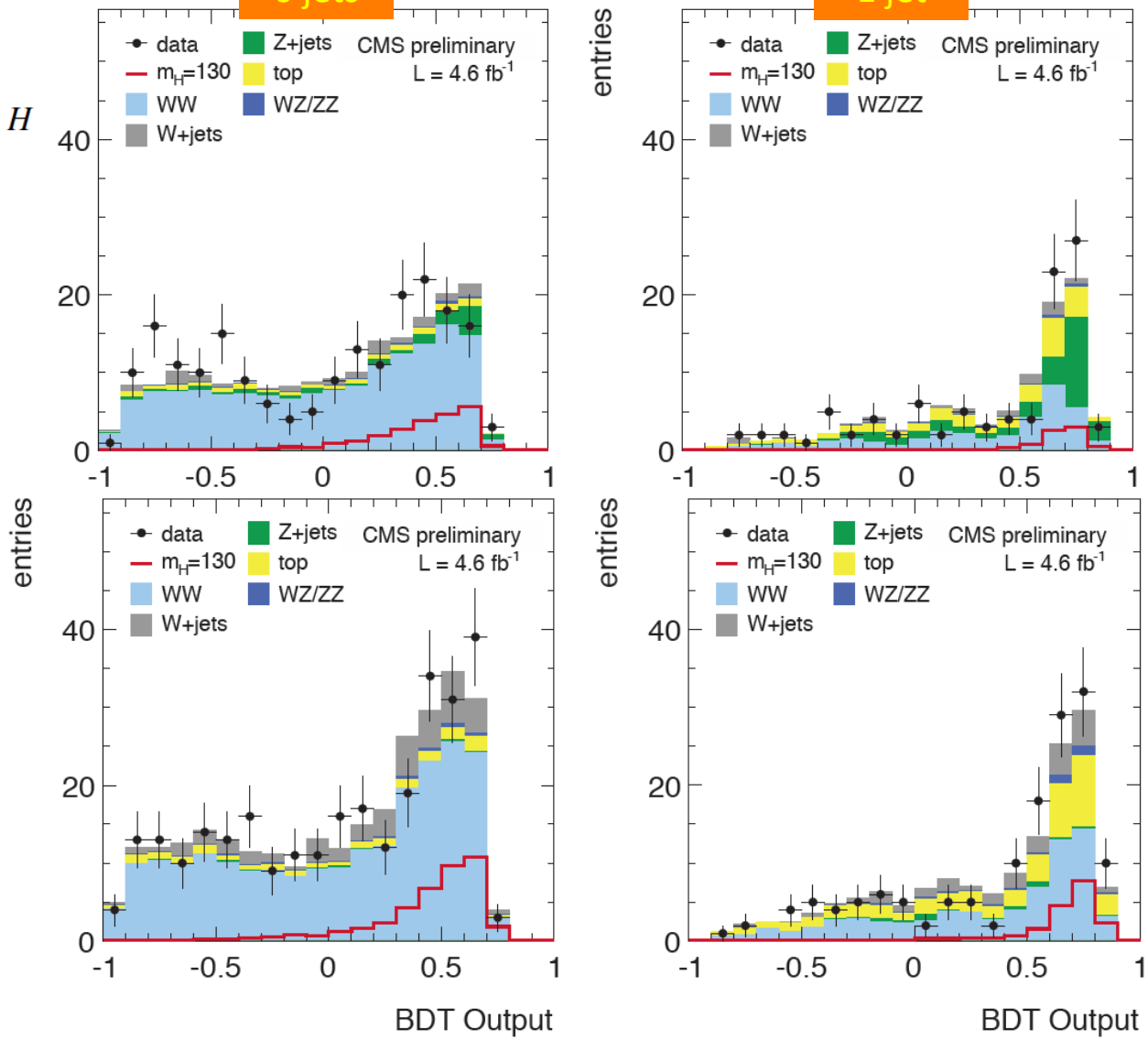
- **Observations:**
  - **remarkable agreement of data and bkgd predictions cut by cut**
  - **we should be close to excluding Higgs boson with m_H=130**

H->WW->lvlv distributions



0 jets

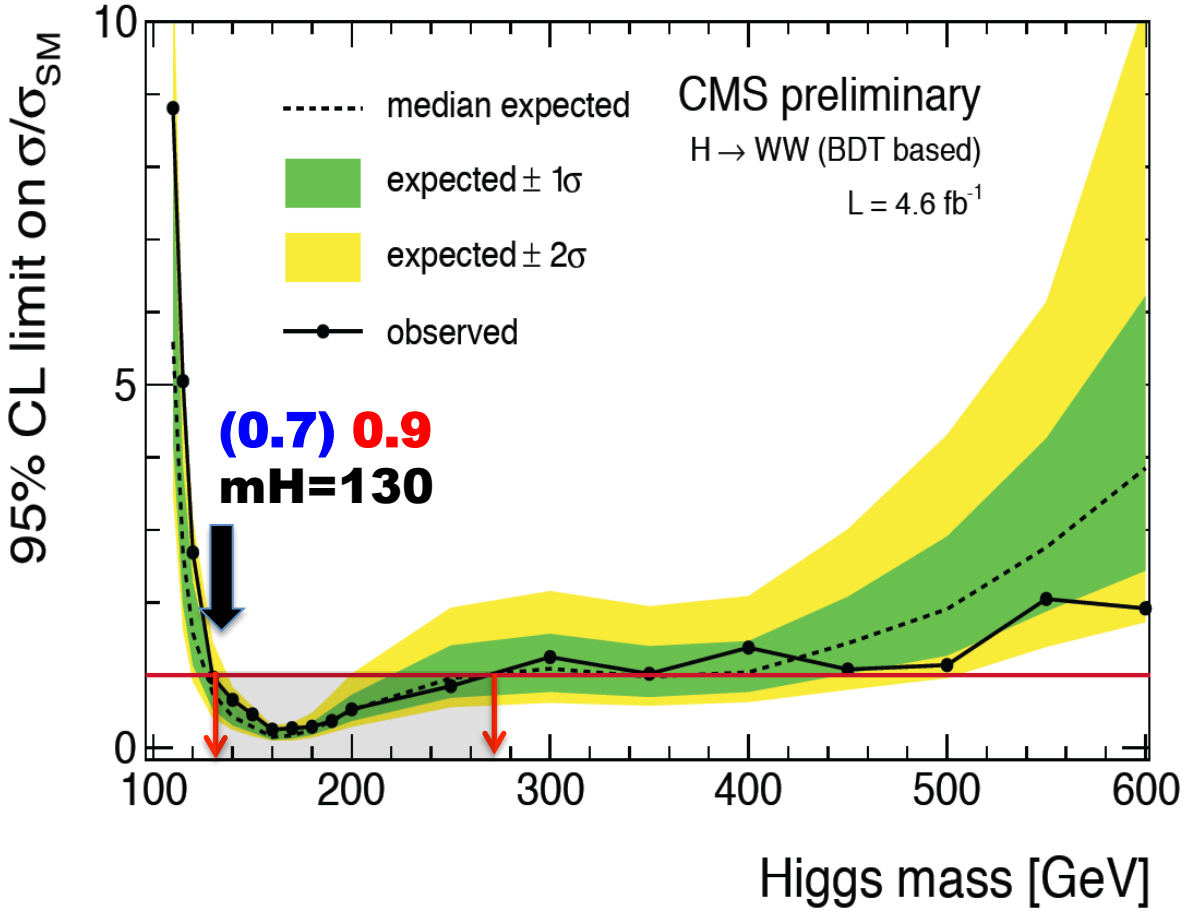
1 jet



ee + μμ

eμ

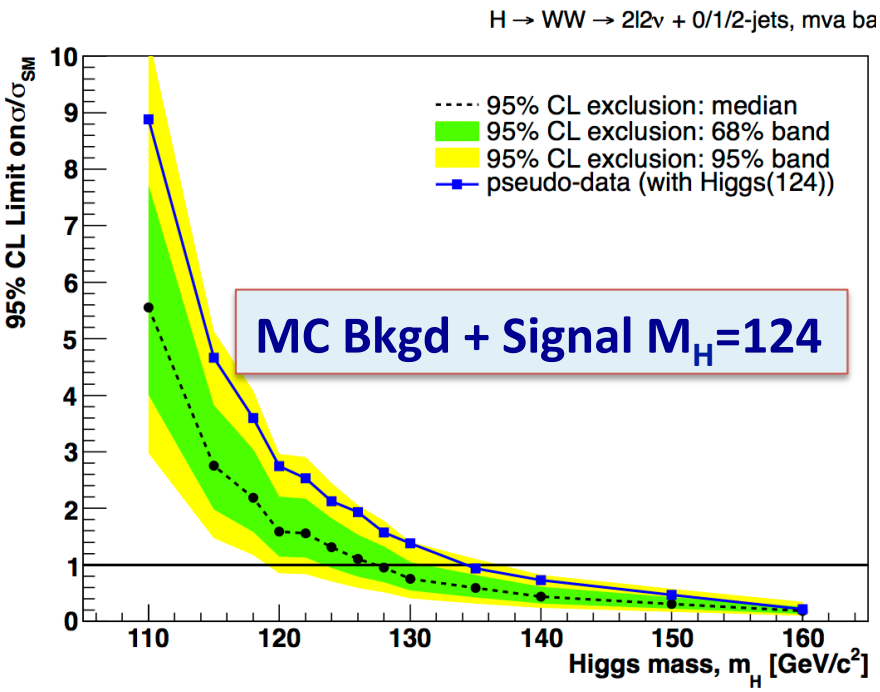
H->WW->lvlv results

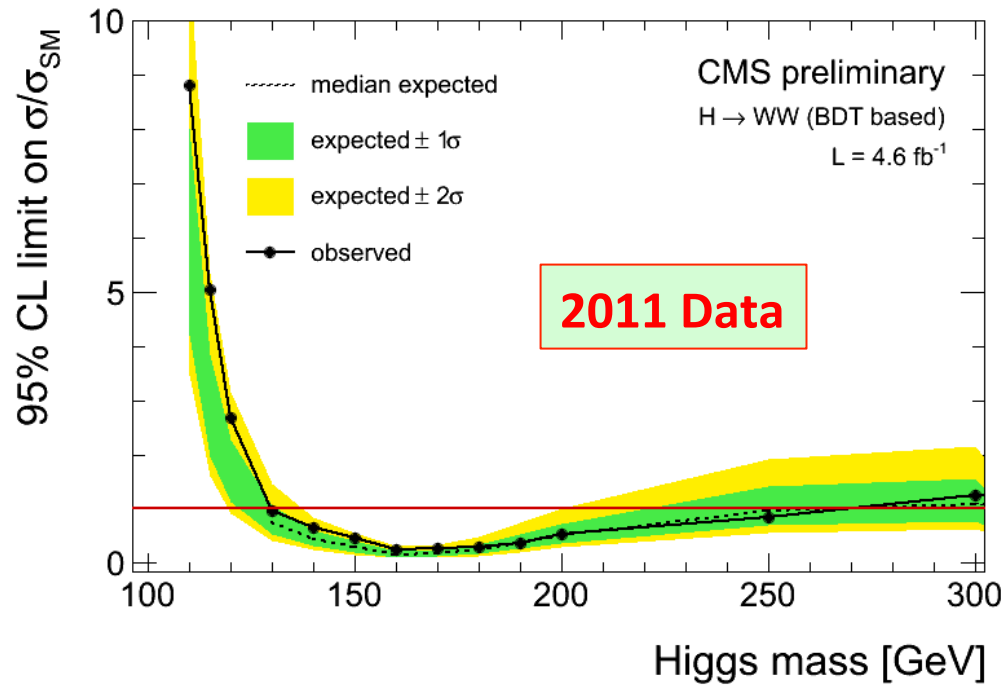


- **SM Higgs boson with mass 129 < M_H < 270 GeV ruled out at 95% CL**
- **SM Higgs boson <u>expected</u> sensitivity 127 < M_H < 270 GeV**

H->WW->2l2ν: what to expect?

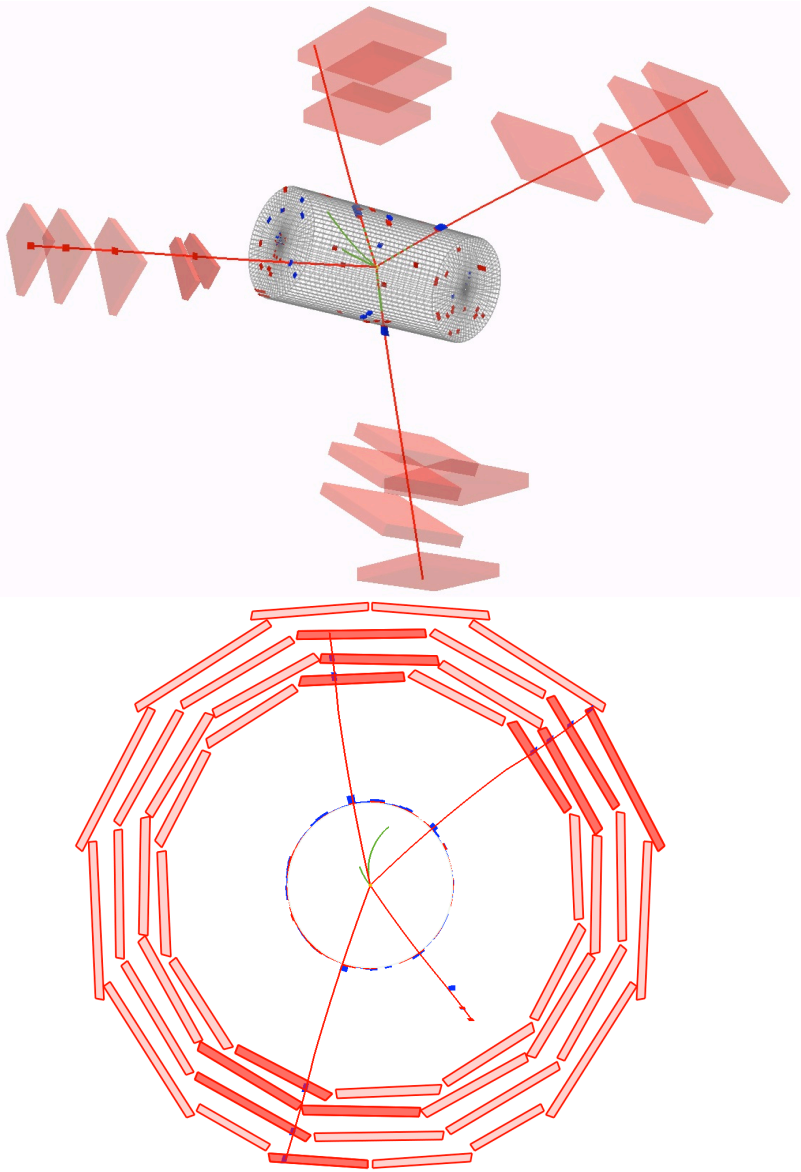
Injecting signal (Azimov dataset):

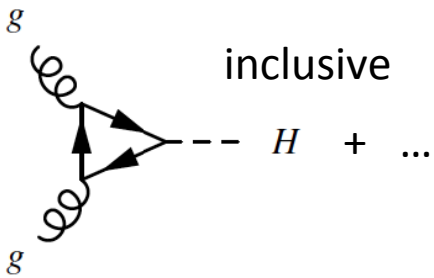




H -> ZZ

H->ZZ->4l signature





Selection:

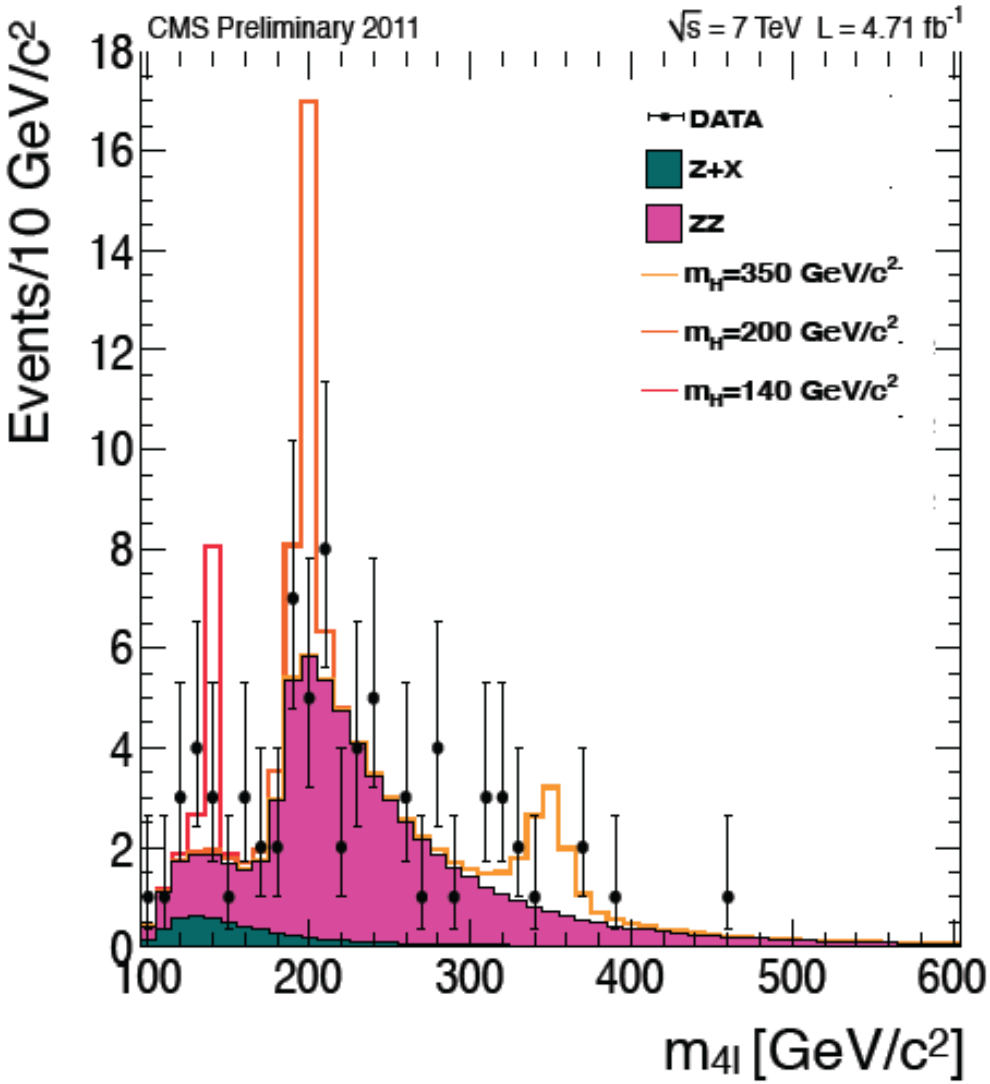
- **4 isolated leptons: 4e, 4μ, 2e2μ**
- **no impact parameter**
- **Final discriminant: m(4l) mass distribution**

Mass resolution: 1%

Main backgrounds:

- **ZZ: from MC ZZ/Z and measured Z**
- **tt and Z+jets: from data (4l with loose leptons), shape and extrapolation from MC**

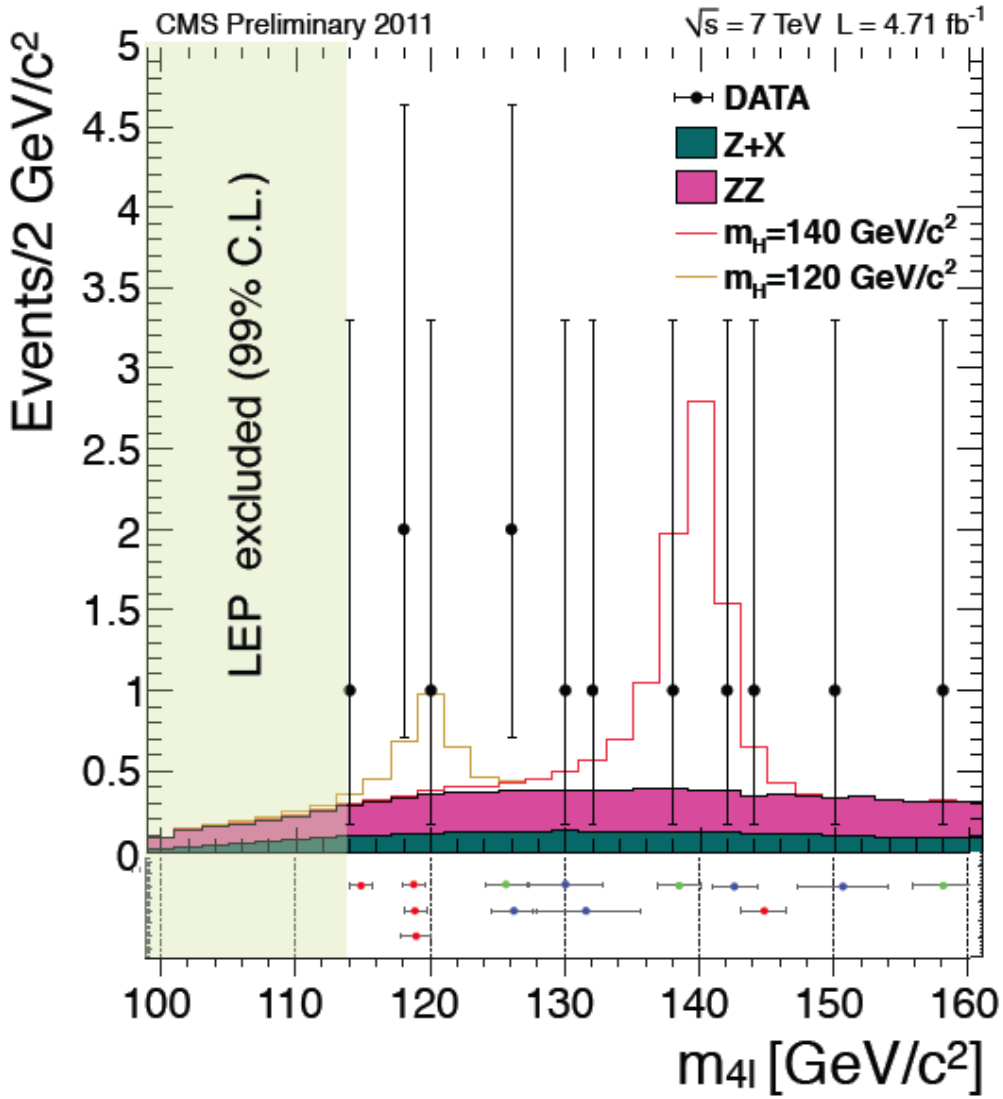
H->ZZ->4l: mass distributions



m_{4l}>100 GeV

- Observed 72 events
- Expected 67.1 ± 6.0

H->ZZ->4l: mass distributions

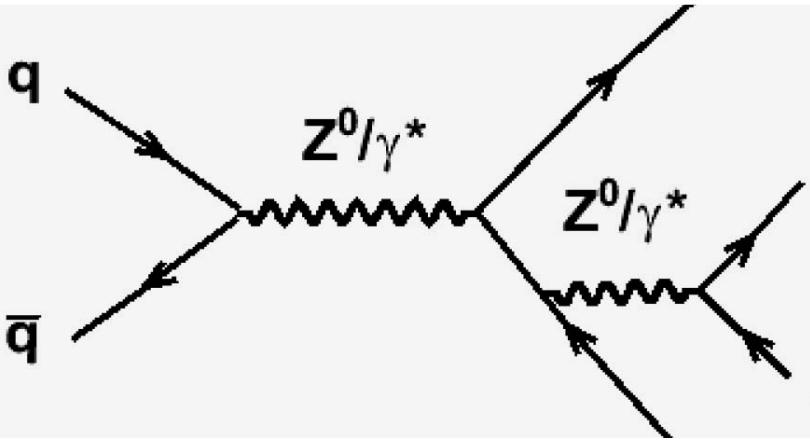


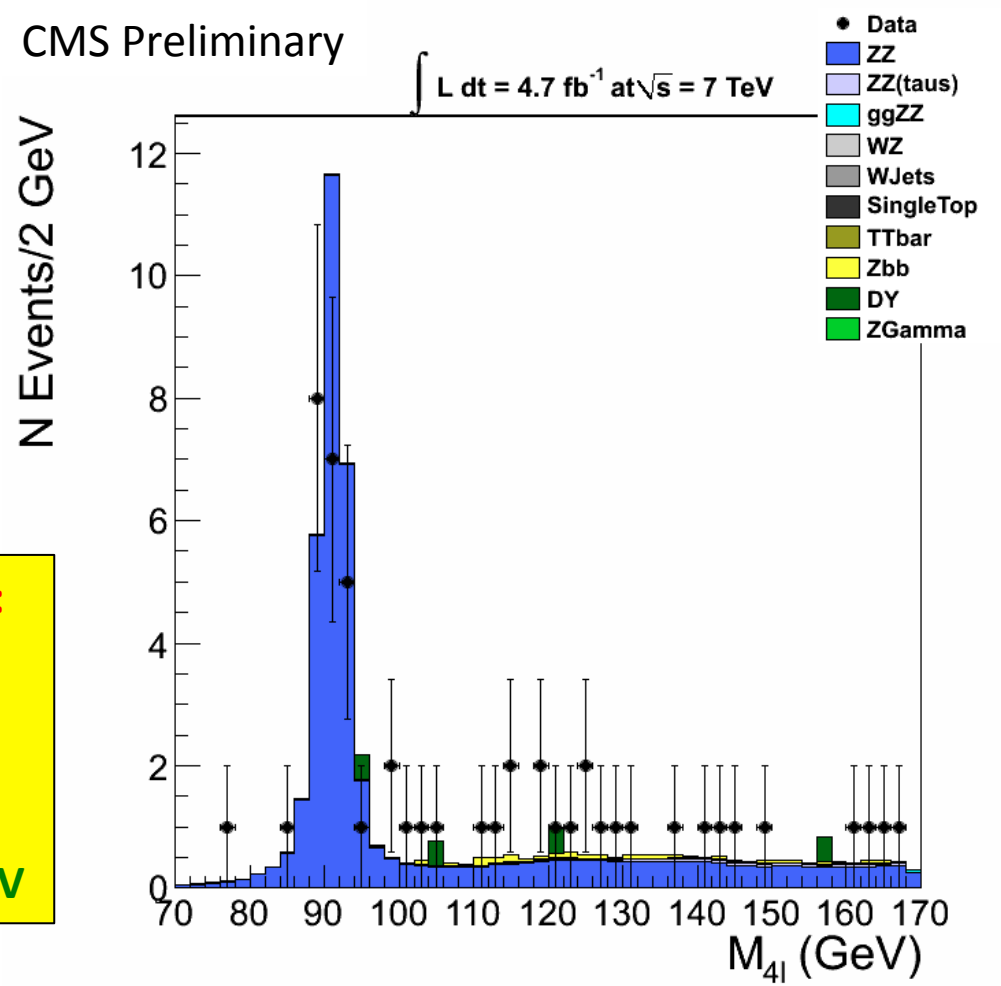
$100<m_{4l}<160$ GeV

- **Observed 13 events**
- **Expected 9.5 ± 1.3**

Note:
- unbinned events in the bottom panel
- **4e**, **4μ**, **2e2μ**
- Event-by-event mass errors (bars)

Observation of Z->4l





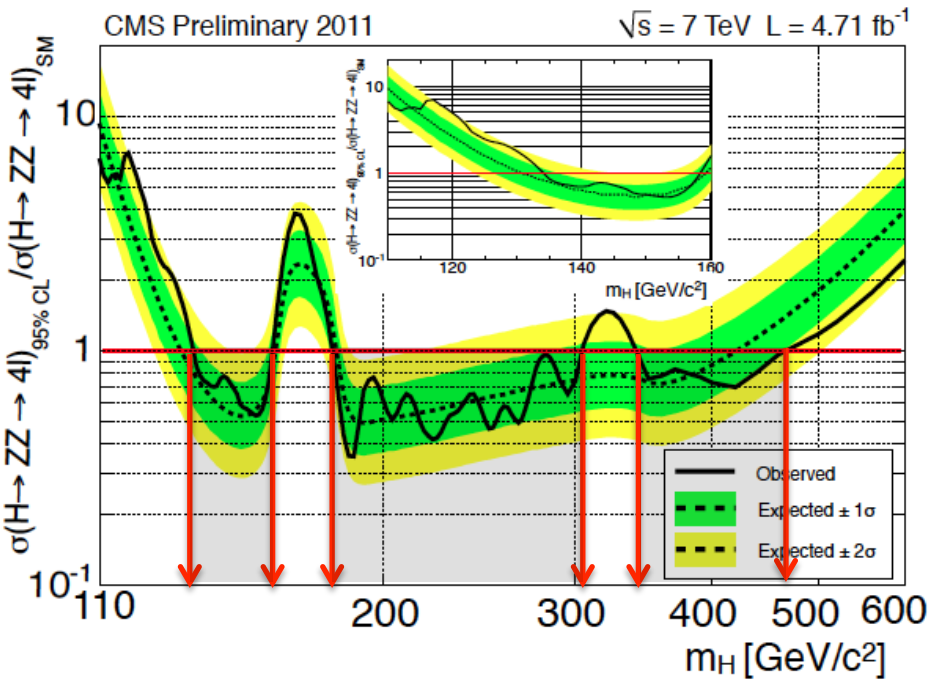
Standard candle for H->ZZ->4l search:

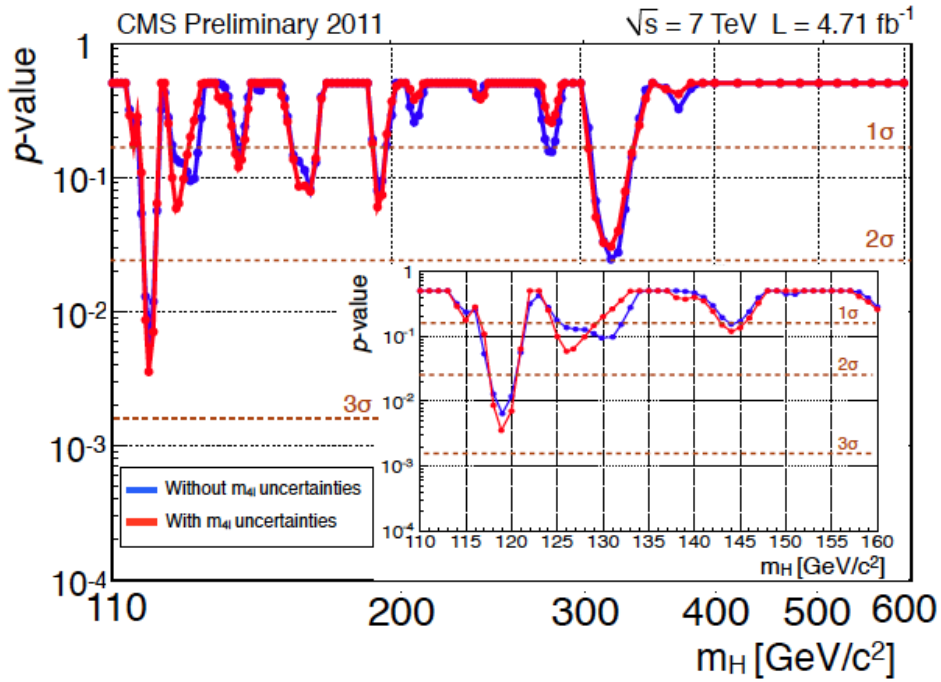
- **direct calibration of m4l scale**
- **direct measure of m4l resolution**
- **validation of efficiencies**

- **With current lumi: m=91.3±0.6 GeV**

Di-lepton mass cut is relaxed to 4 GeV

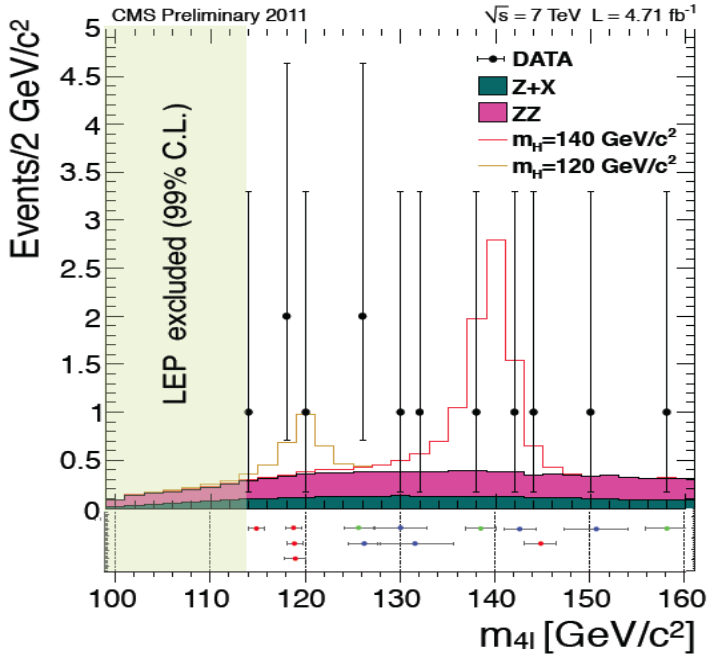
H->ZZ->4l results

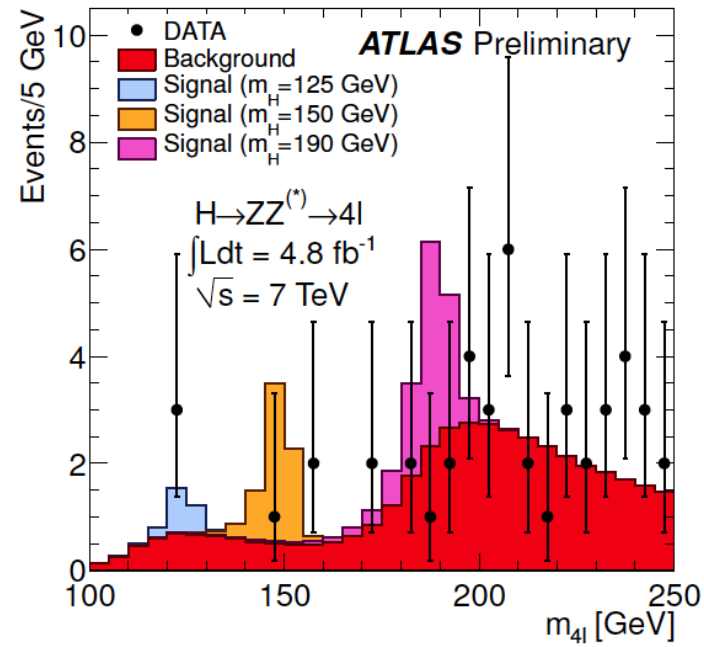




LEE trials factor ≈40 for the full mass range.
Hence, 2σ deviations are not very significant.

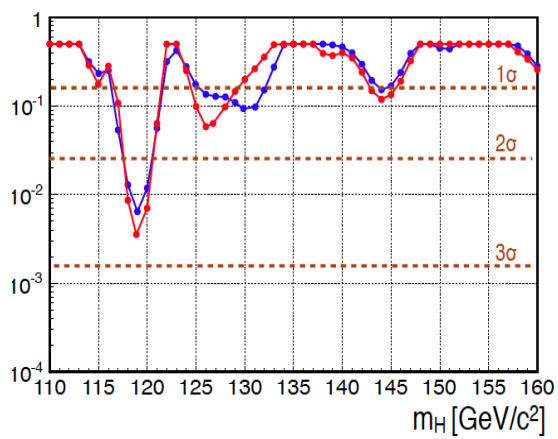
H→ZZ→4l: CMS vs ATLAS

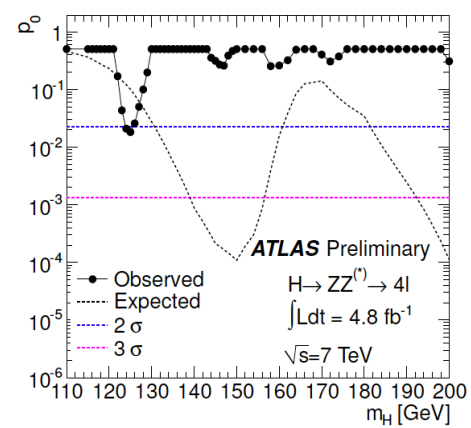




m=118.8 (4μ)
m=118.9 (4μ)
m=119.0 (4μ)

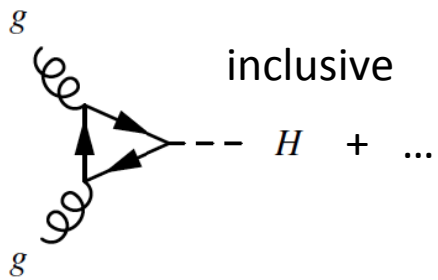
m=125.7 (4e)
m=126.2 (2e2μ)



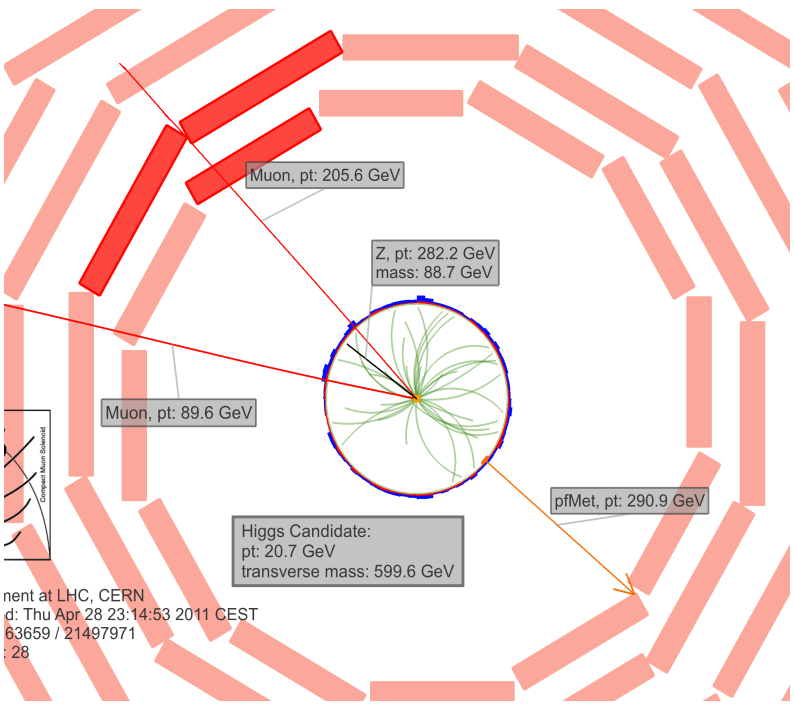


m=123.6 (2μ2e)
m=124.3 (2e2μ)
m=124.6 (4μ)

H->ZZ->2l2ν signature



inclusive



Selection:

- **2 channels: 2 isolated leptons: Z(2e), Z(2μ)**
- **no impact parameter**
- **large p_T(ll)**
- **large MET, not aligned with jets or leptons**
- **Final discriminant: m_T shape**

Mass resolution: 7%

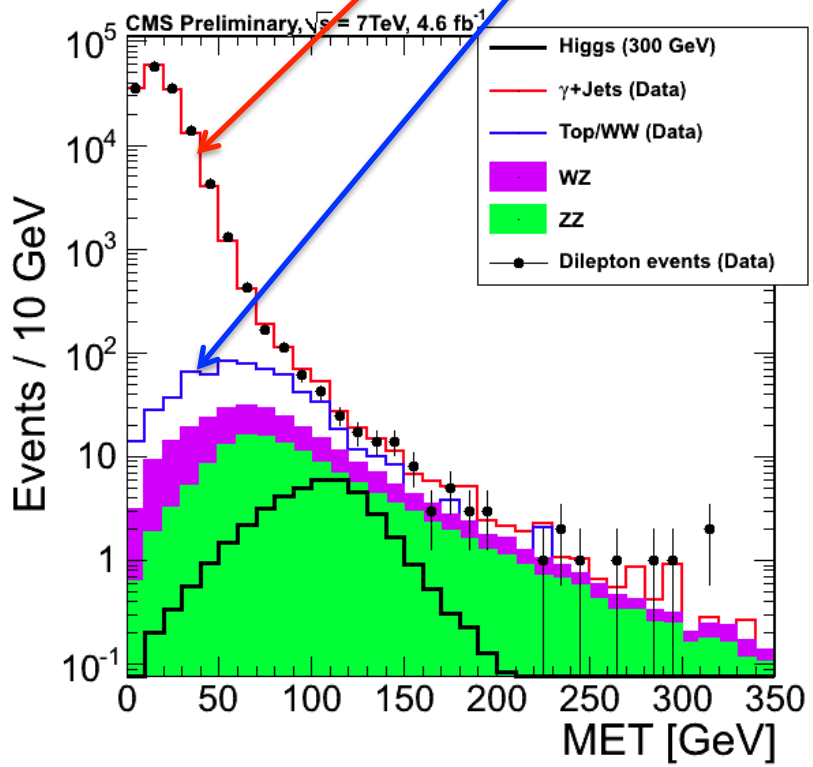
Main backgrounds:

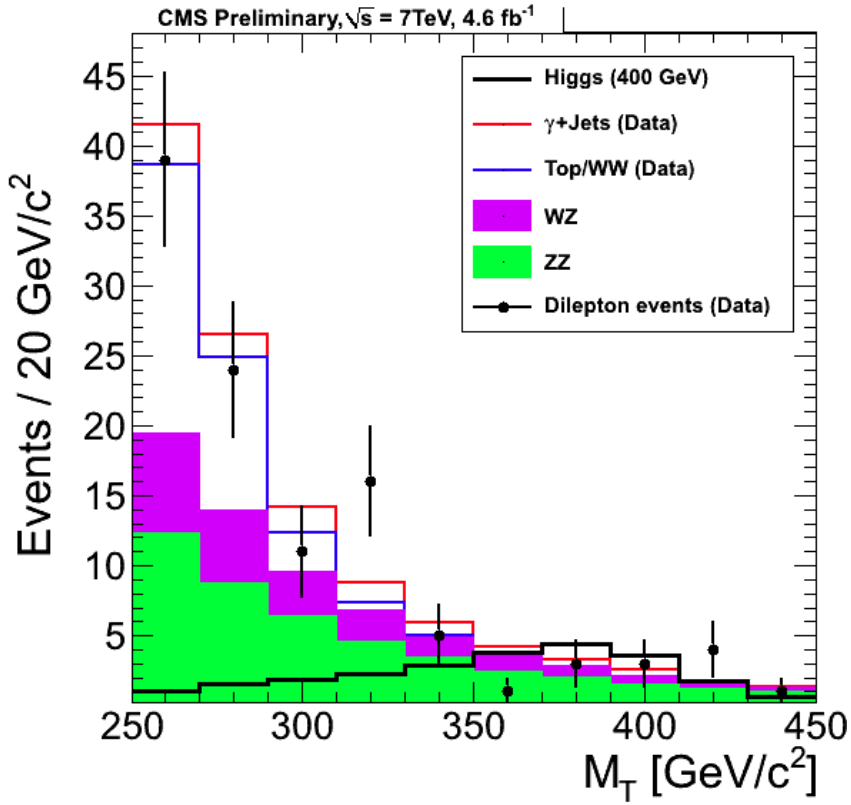
- **Z+jets (sig:bkgd = 1:10^5): from data (γ+jets)**
- **tt, WW, Wjets: from data (off Z-peak)**
- **ZZ, WZ: from MC**

H->ZZ->2l2ν distributions

Data-driven prediction for Z+jets bkgd, using γ+jets events

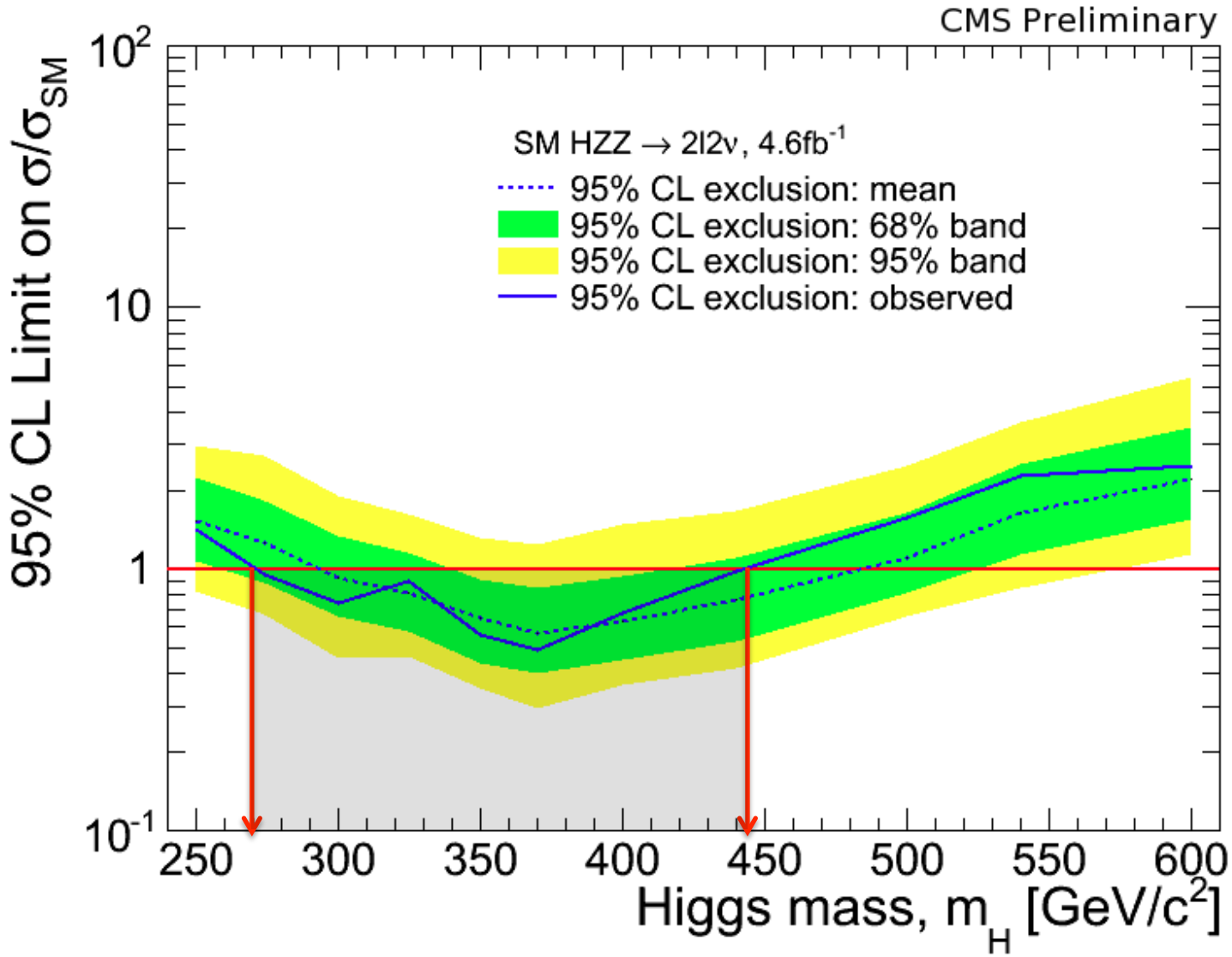
Data-driven prediction for tt̄/WW bkgd, using m_Z sideband



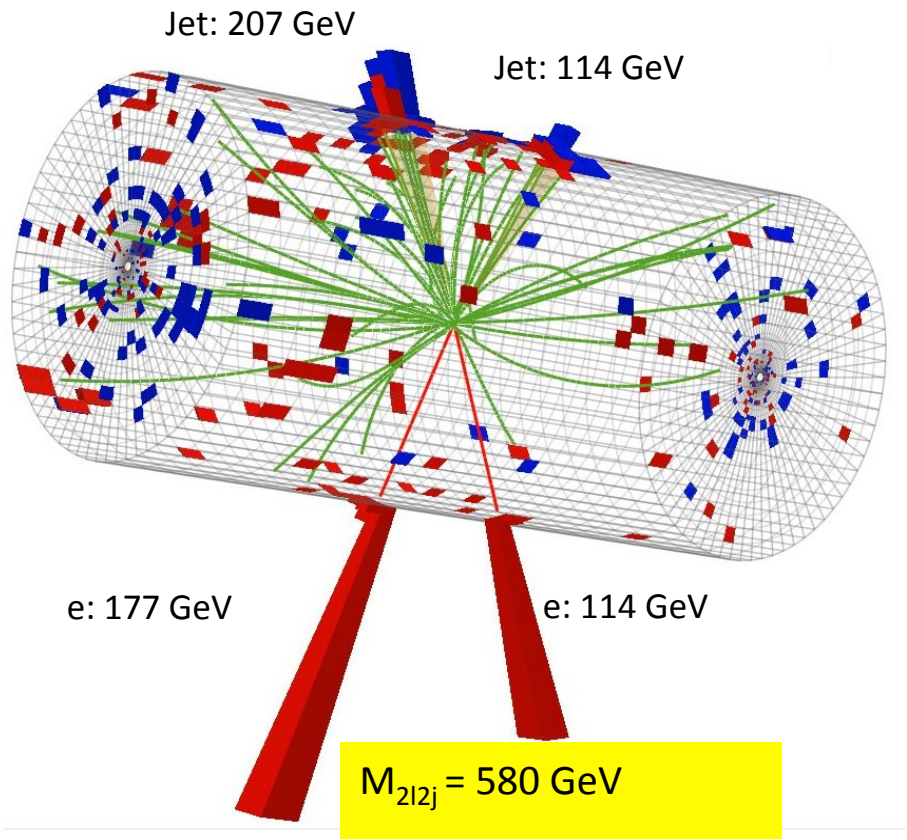


After 250 < MET < 450 GeV

H->ZZ->2l2ν results



H->ZZ->2l2q signature



Selection:

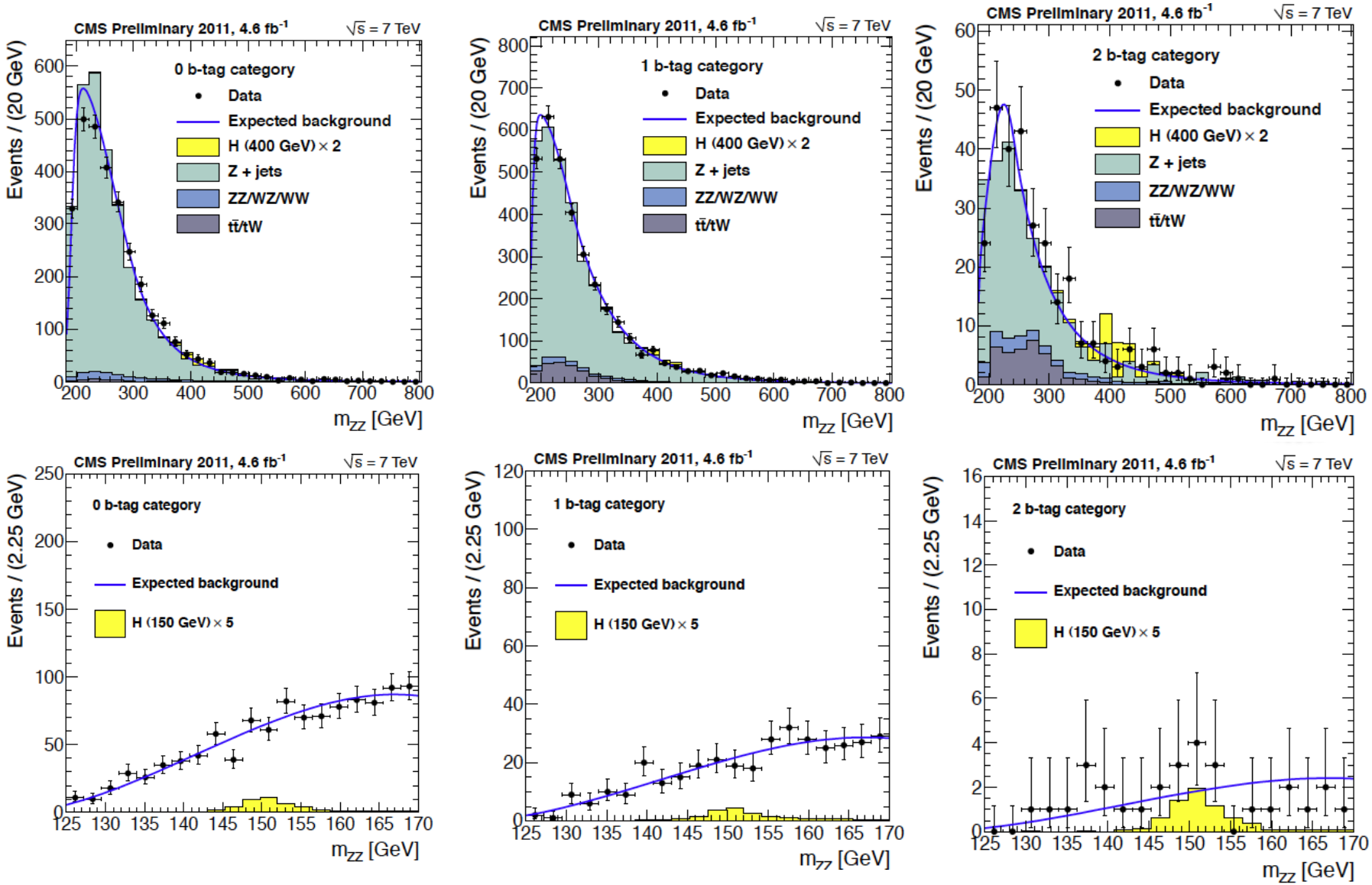
- 2 isolated leptons, Z(2e), Z(2μ), with no impact parameter
- two jets: Z(jj) with 0, 1, 2 b-tags
- most of sensitivity from 2 b-tag category
- no MET
- cut on angular topology (ME-based)
- Final discriminant: m_{lljj} mass distribution

Mass resolution: 3%

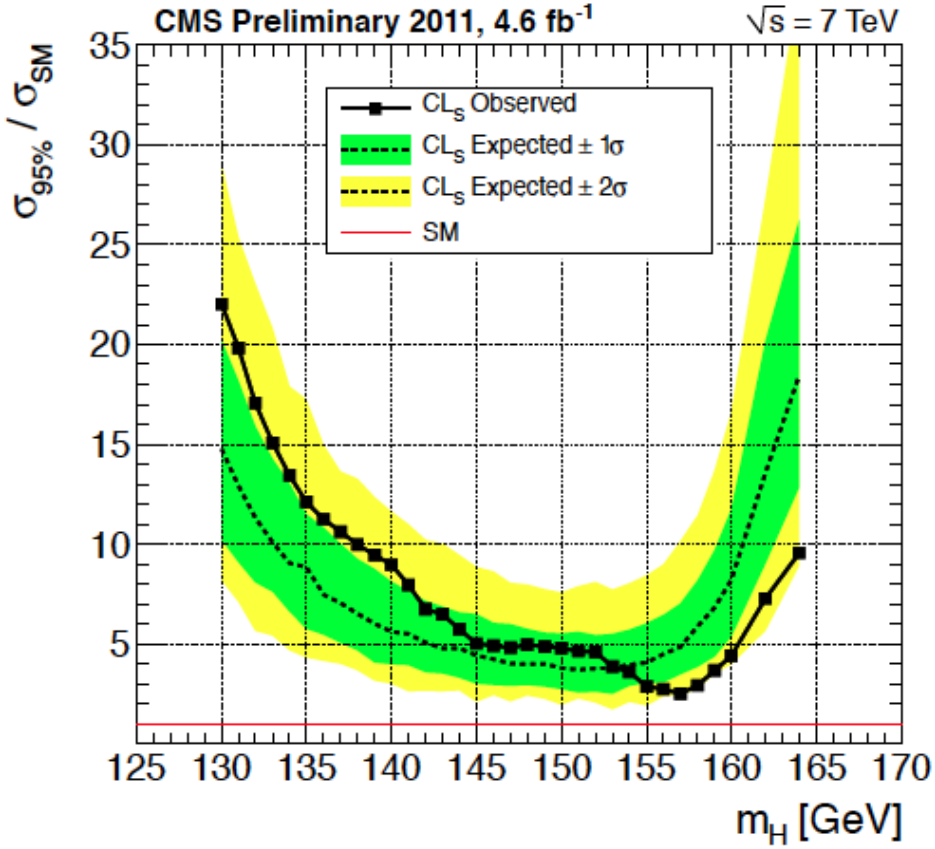
Main backgrounds: from sidebands

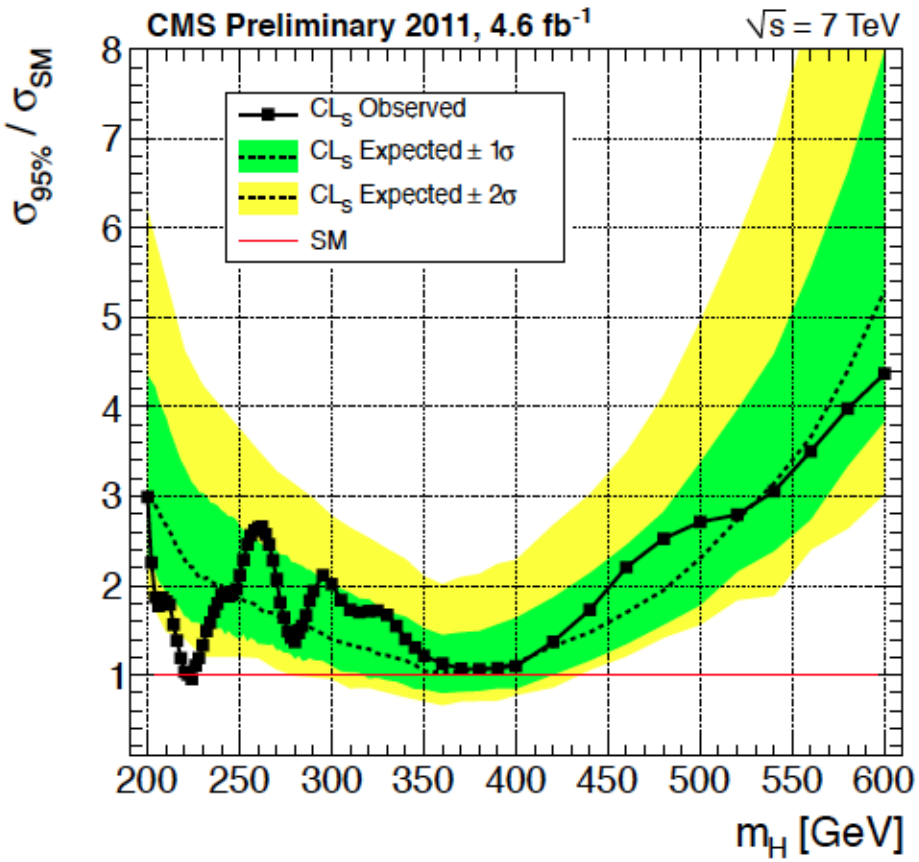
- Z+jets (including heavy flavor jets)
- WZ, ZZ
- tt, WW

H->ZZ->2l2q distributions

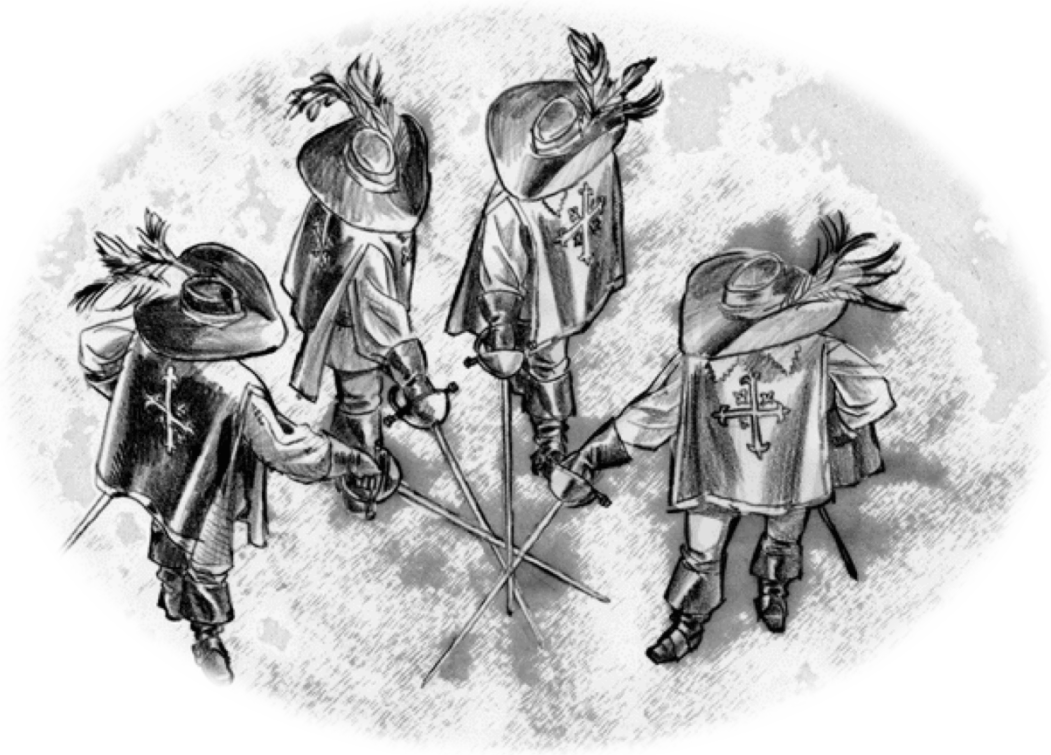


H->ZZ->2l2q results





Combination of searches



Combination scope

Channel	m_H range (GeV/c^2)	Lumi (fb^{-1})	sub-channels	m_H resolution
$H \to \gamma\gamma$	$110 - 150$	4.7	4	1–3%
$H \to \tau\tau$	$110 - 145$	4.6	9	20%
$H \to bb$	$110 - 135$	4.7	5	10%
$H \to WW \to \ell\nu\ell\nu$	$110 - 600$	4.6	5	20%
$H \to ZZ \to 4\ell$	$110 - 600$	4.7	3	1–2%
$H \to ZZ \to 2\ell 2\tau$	$190 - 600$	4.7	8	10–15%
$H \to ZZ \to 2\ell 2\nu$	$250 - 600$	4.6	2	7%
$H \to ZZ \to 2\ell 2q$	$\begin{cases} 130 - 164 \\ 200 - 600 \end{cases}$	4.6	6	3%

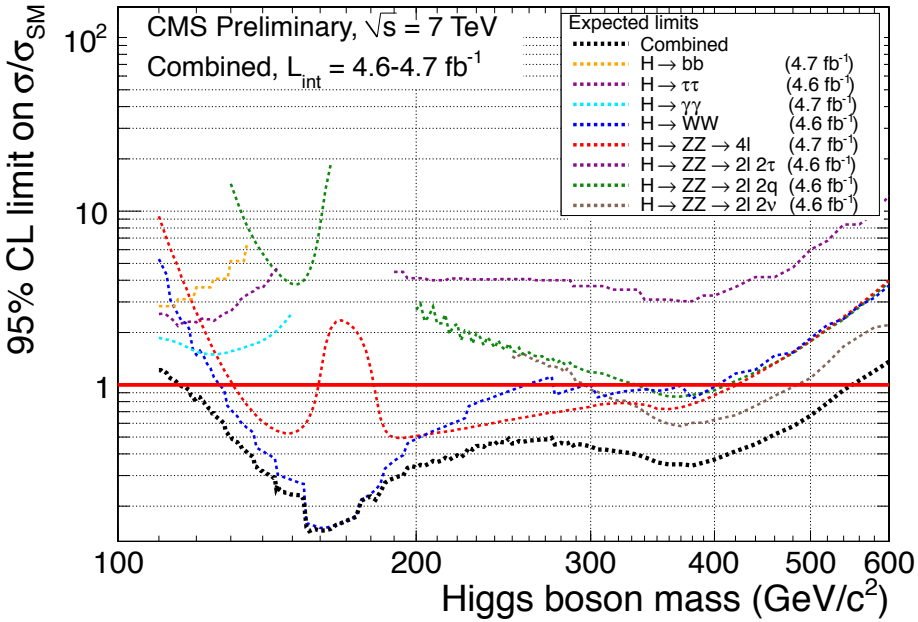
- **42 exclusive final states**
- **about 200 nuisance parameters**

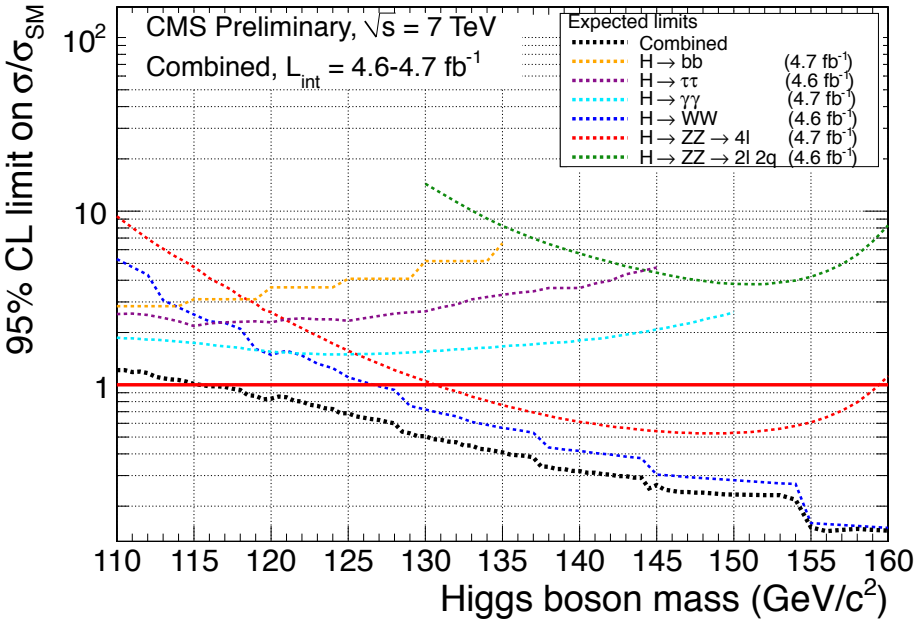
Uncertainties common to many channels

group	nuisance	comments
cross section (pdf)	gg	$gg \to H, t\bar{t}H, VQQ, t\bar{t}, tW, tb$ (s-channel), $gg \to VV$
	qqbar	VBF $H, VH, V, VV, \gamma\gamma$
cross section (QCD scales)	ggH	total inclusive $gg \to H$
	ggH1in	inclusive $gg/qg \to H+ \geq 1$ jets
	ggH2in	inclusive $gg/qg \to H+ \geq 2$ jets
	qqH	VBF H
	VH	associate VH
	ttH	$t\bar{t}H$
	VV	WW, WZ, and ZZ up to NLO
	ggVV	$gg \to WW$ and $gg \to ZZ$
Higgs BR	ZZ	Branching ratio BR($H \to ZZ$)
phenomenology	UE & PS	modeling of underlying event (UE) and parton showering (PS)
luminosity	lumi	uncertainties in integrated luminosity
efficiencies	muon	prompt muon efficiency (includes reconstruction, isolation)
	electron	prompt electron efficiency (includes reconstruction, isolation)
	tau	reconstruction efficiency of prompt hadronicly decaying tau
	b-tag	b-tag efficiency for b-jets (anti-correlated with b-jet veto)
p_T scales	muon	prompt muon p_T-scale
	electron	prompt electron p_T-scale
	tau	p_T scale for prompt hadronicly decaying tau
	jets	jet energy scale
p_T resolutions	electron	prompt electron p_T-resolution
fake rates	lepton	determination of fake lepton rates in data
trigger efficiencies	muon	prompt muon efficiency (includes trigger, reconstruction, isolation)
	electron	prompt electron efficiency (includes trigger, reconstruction, isolation)

LIMITS

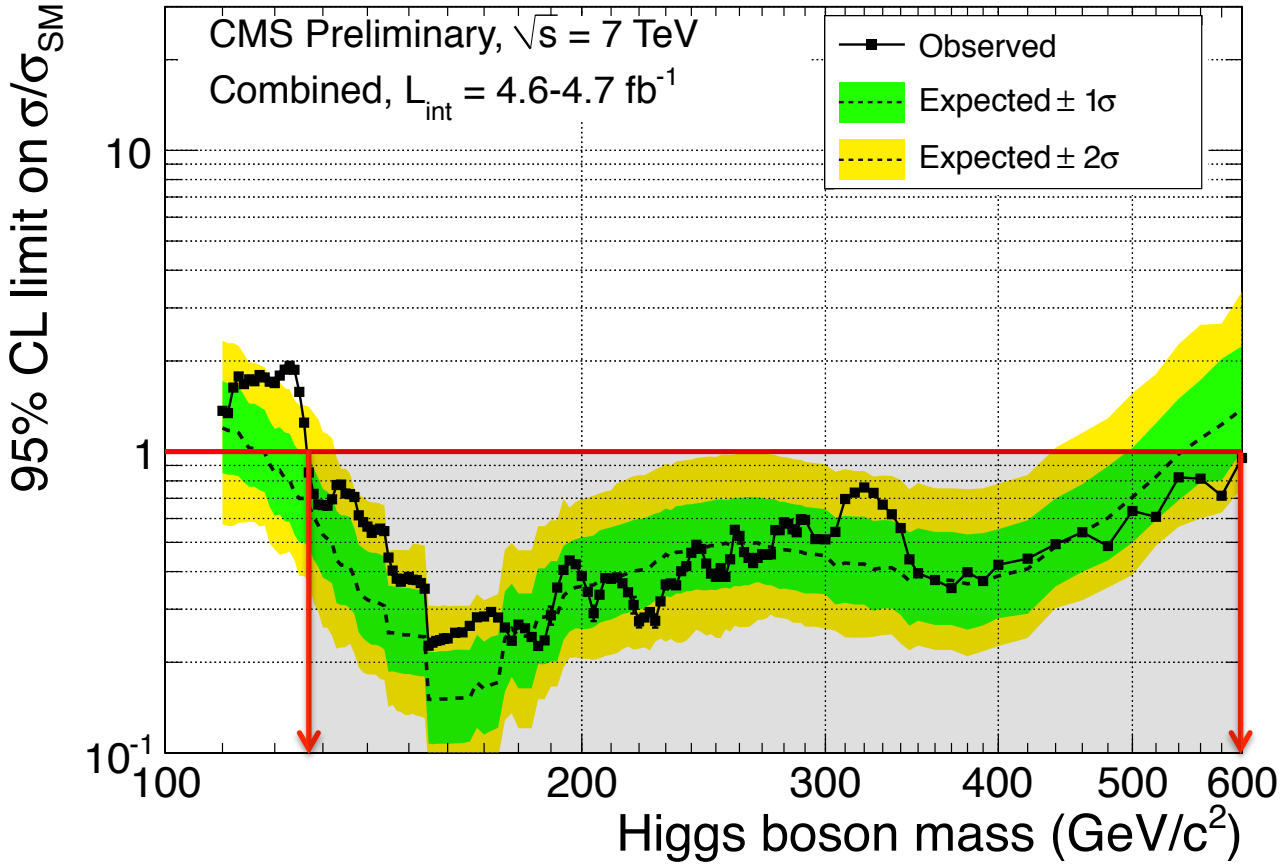
Expected sensitivity





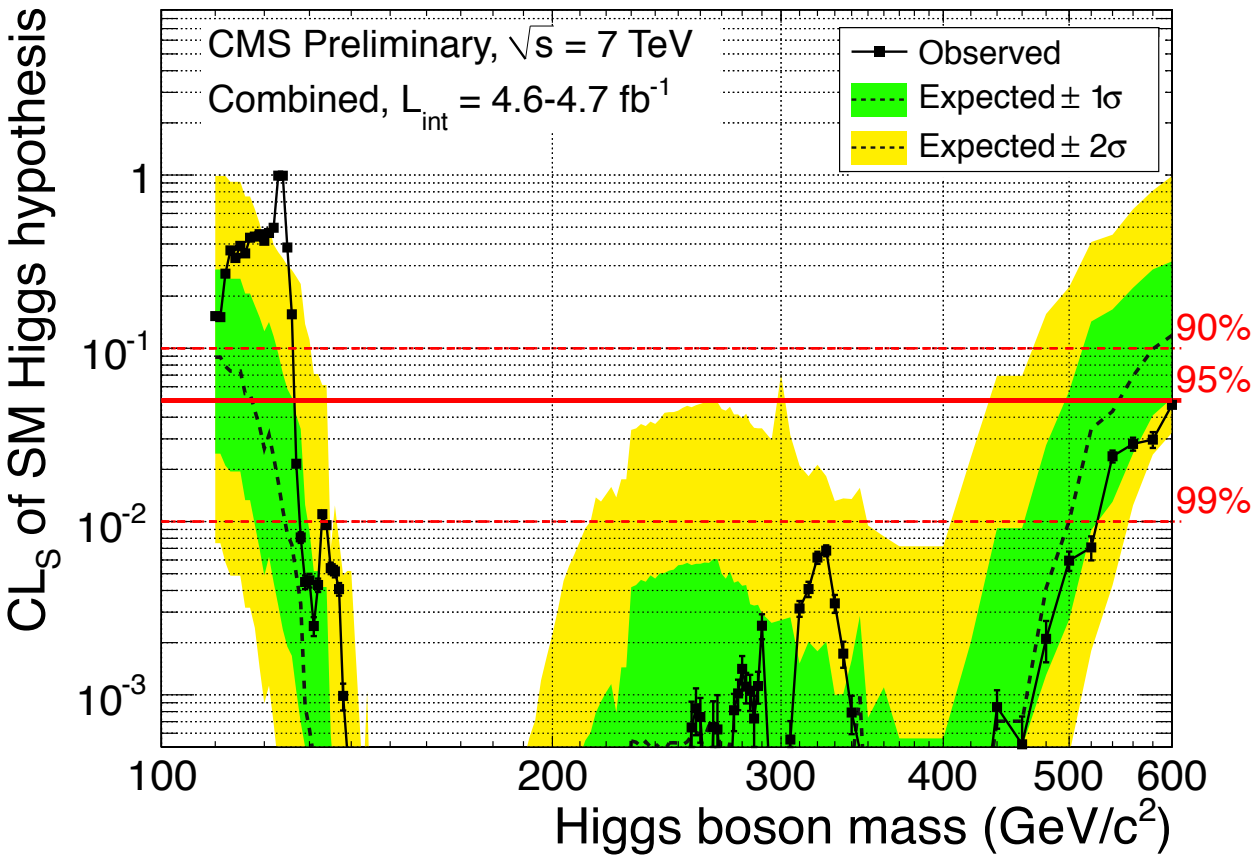
- **95% CL expected sensitivity: 117—543 GeV**

Exclusion limits on μ



- **95% CL expected sensitivity: 117—543 GeV**
- **95% CL observed limits: 127 – 600 GeV**

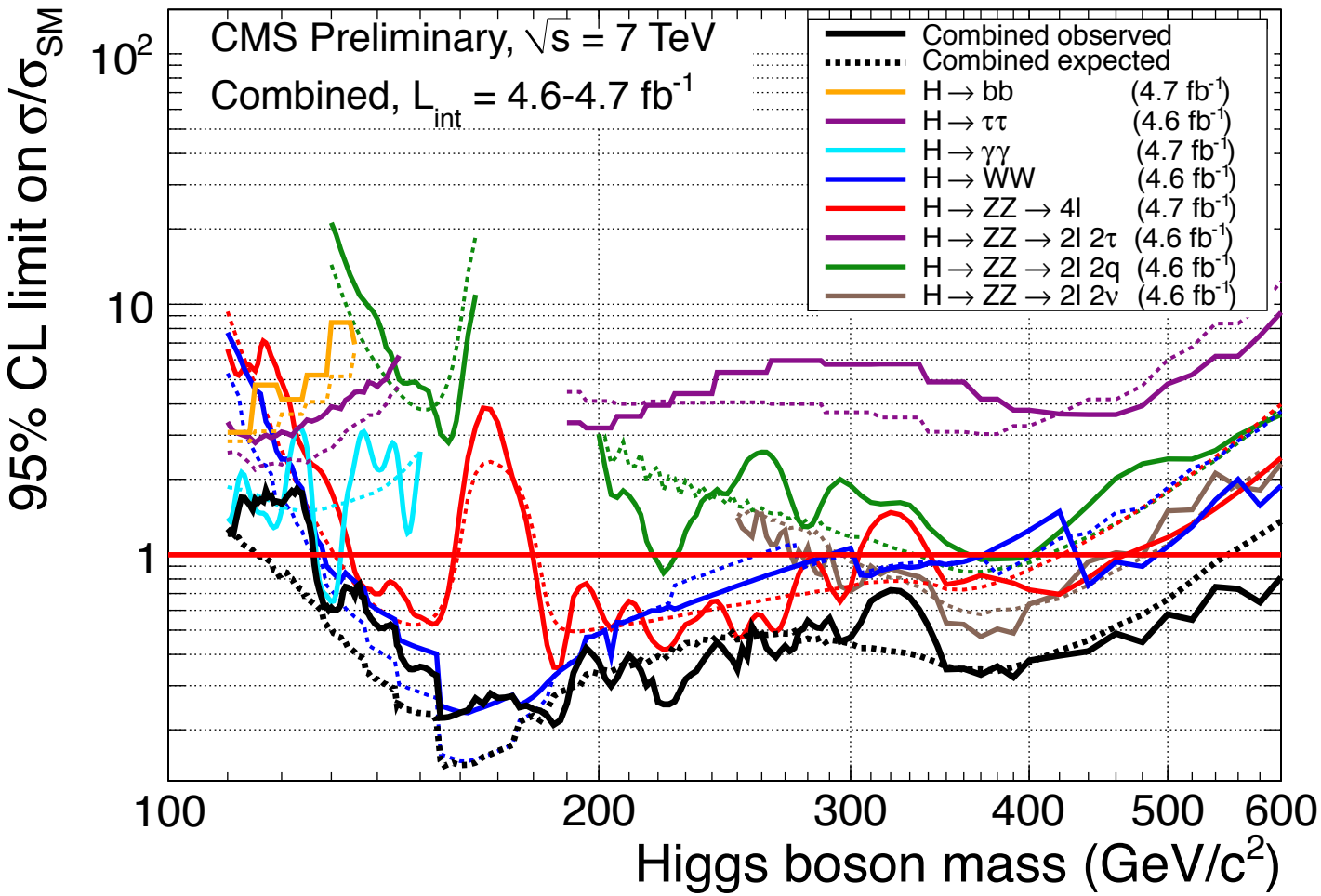
Exclusion CL for SM Higgs



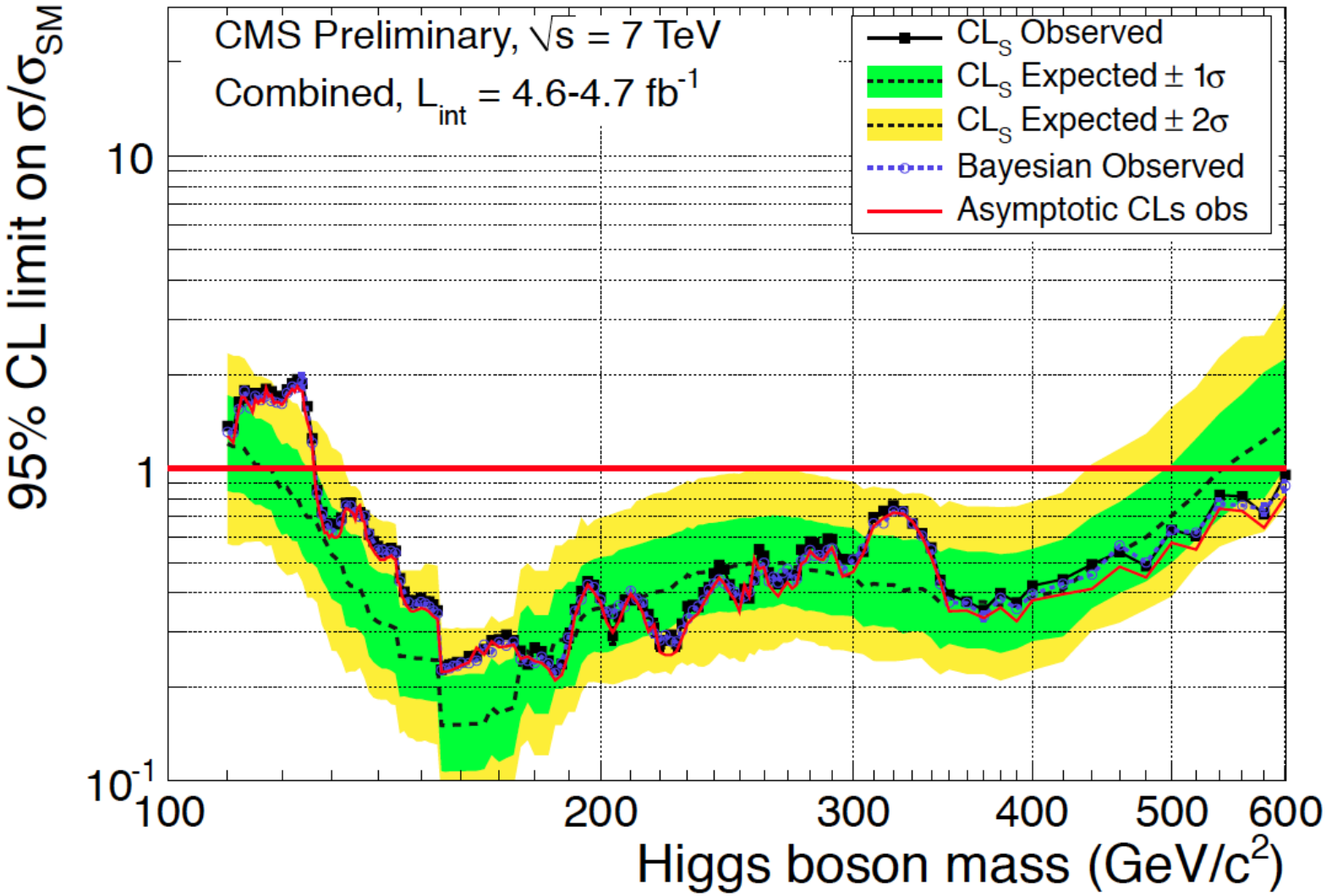
- **95% CL observed limits: 127—600 GeV**
- **99% CL observed limits: 128 – 525 GeV**

Interplay of channels

Solid line – observed limit
Dashed line – median expected

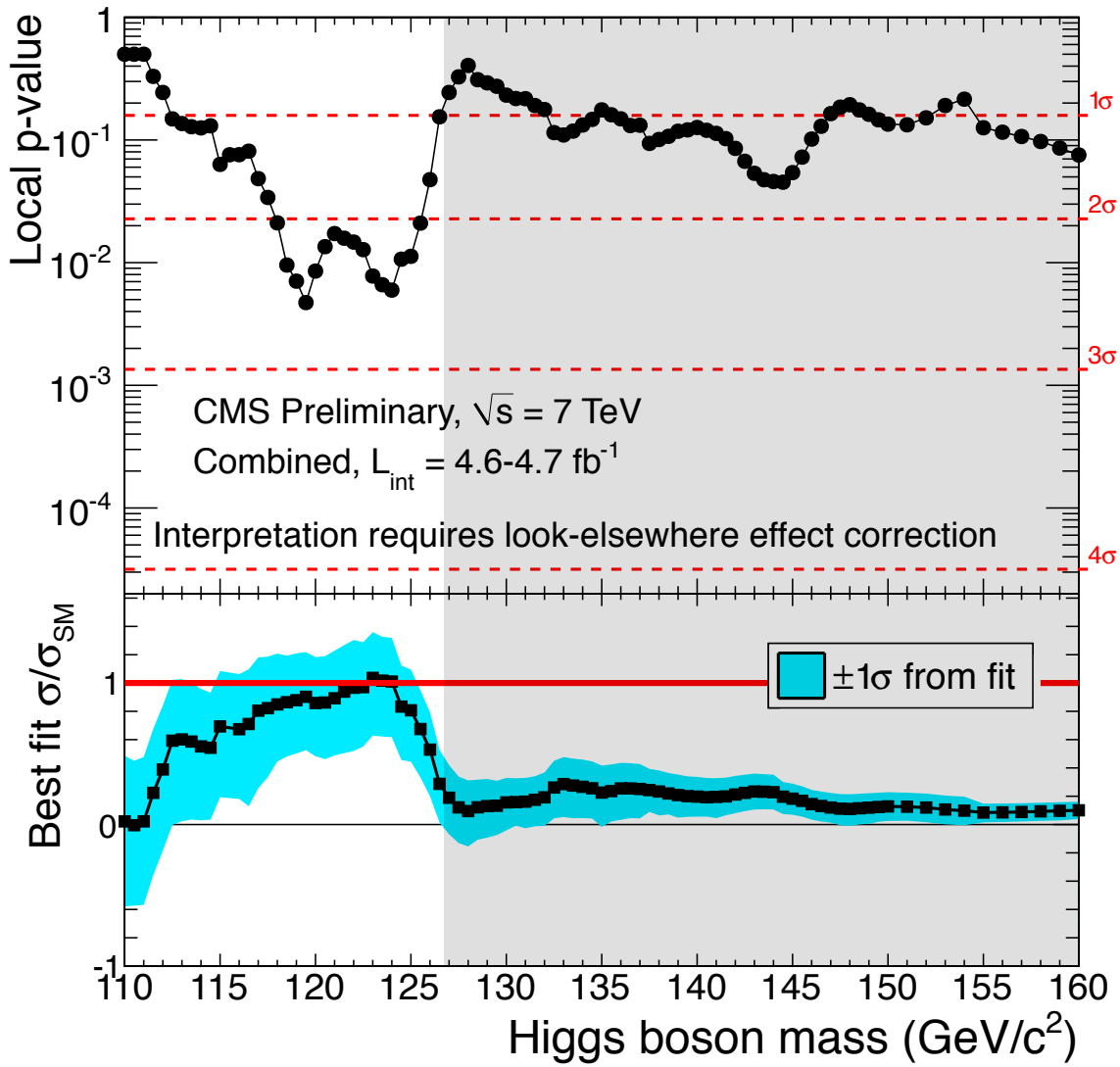


Do the limits depend on the method?

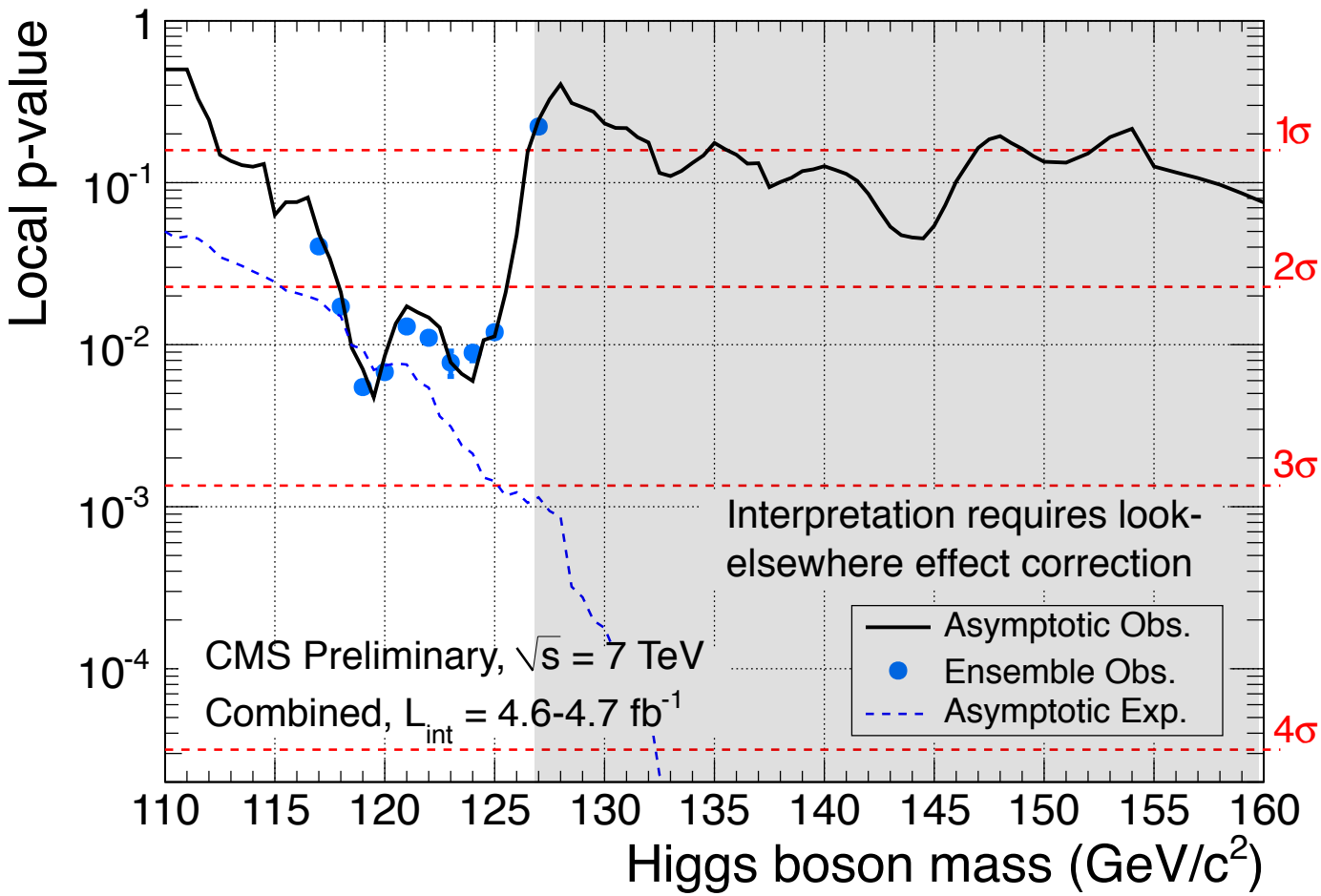


LOW MASS EXCESS

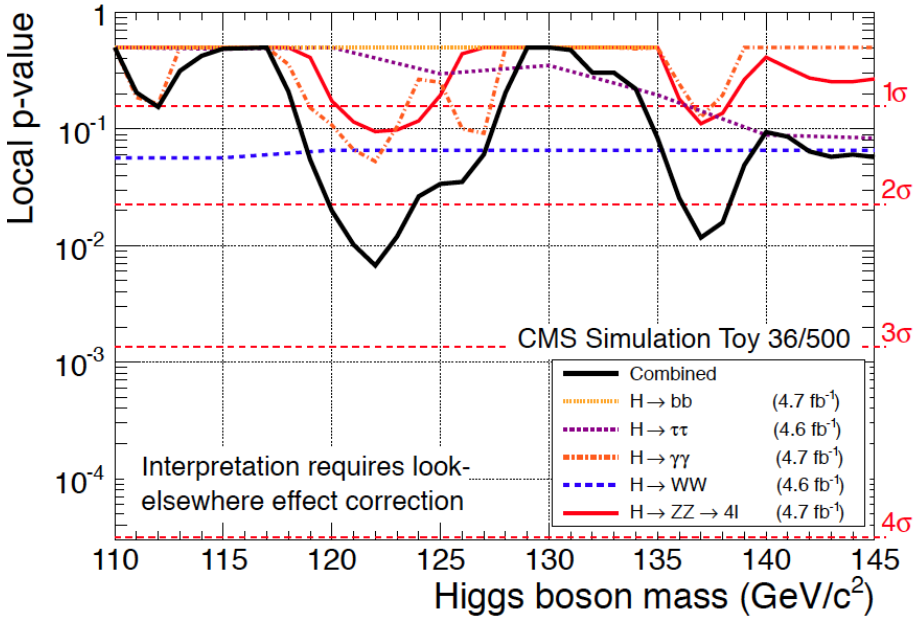
Quantifying excess

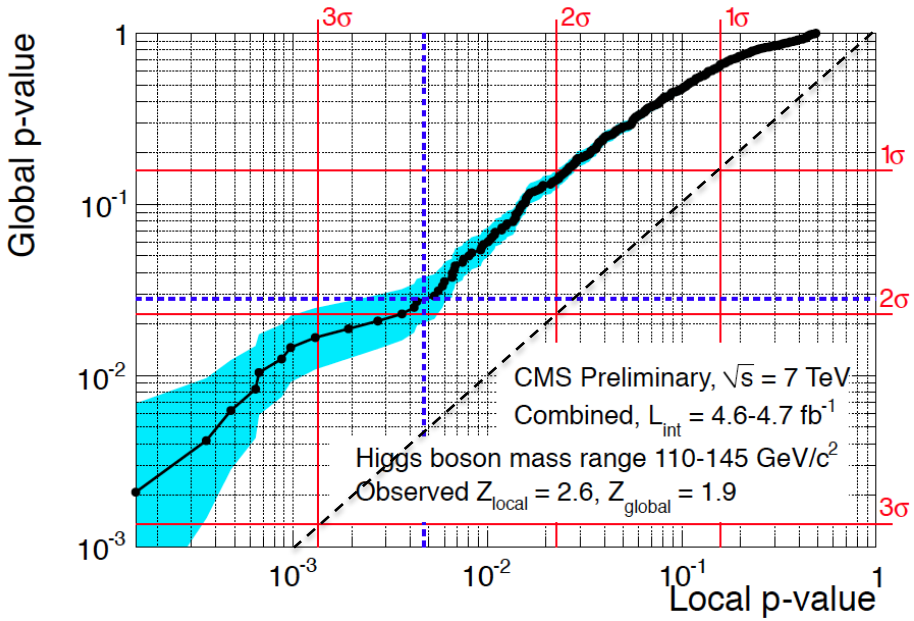


Validation of p-value asymptotic approx.



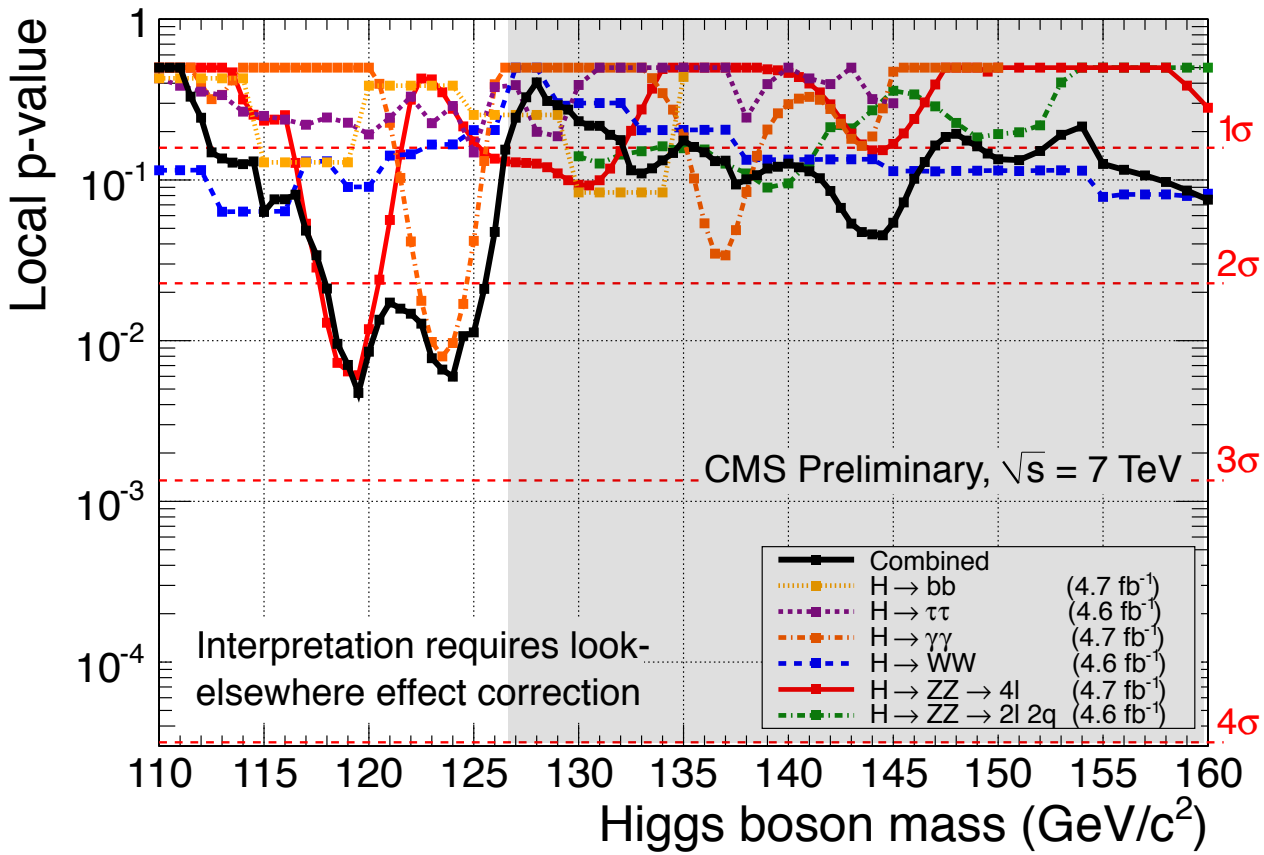
Look-elsewhere effect (LEE)



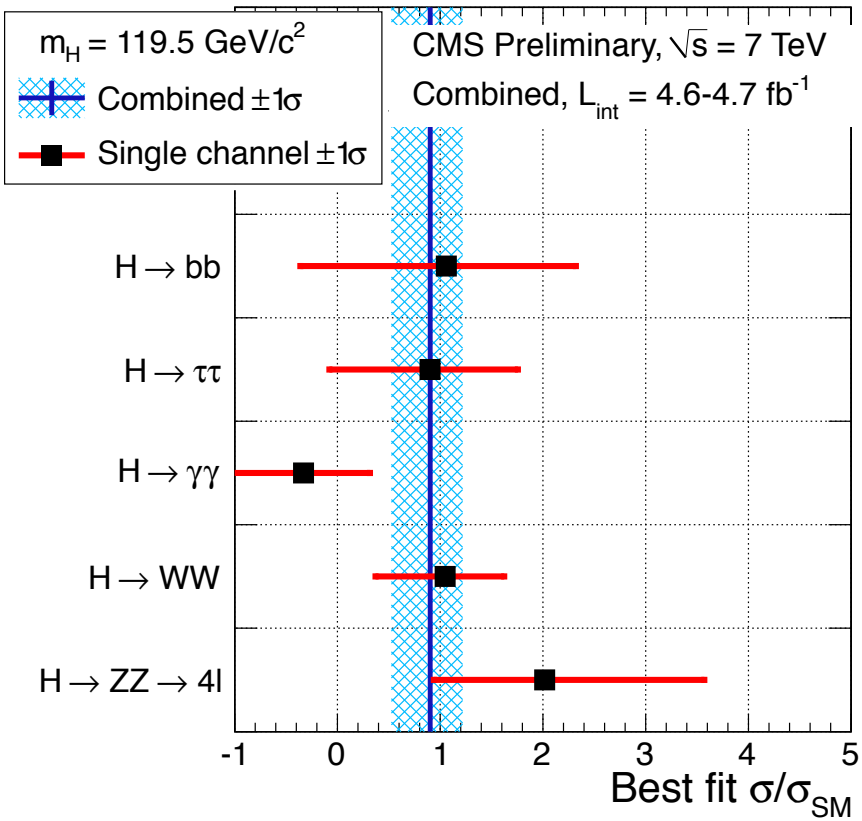


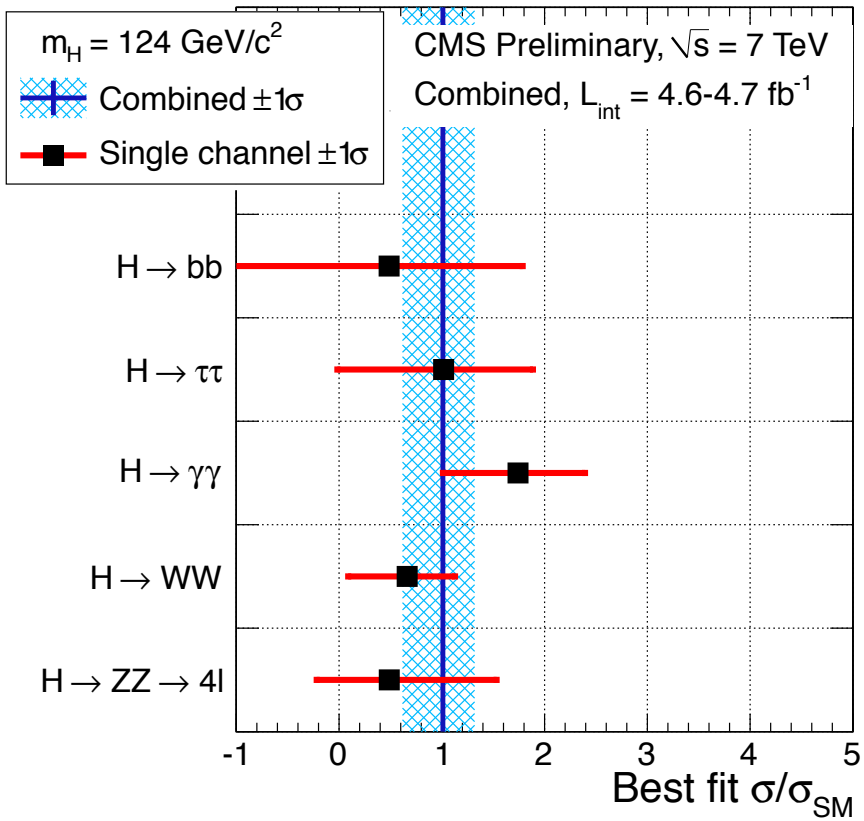
- **Restricted mass range: 110-145 GeV**
- **500 generated pseudo-data sets**
- **Z = 2.6 ➔ Z = 1.9**

Anatomy of the excesses

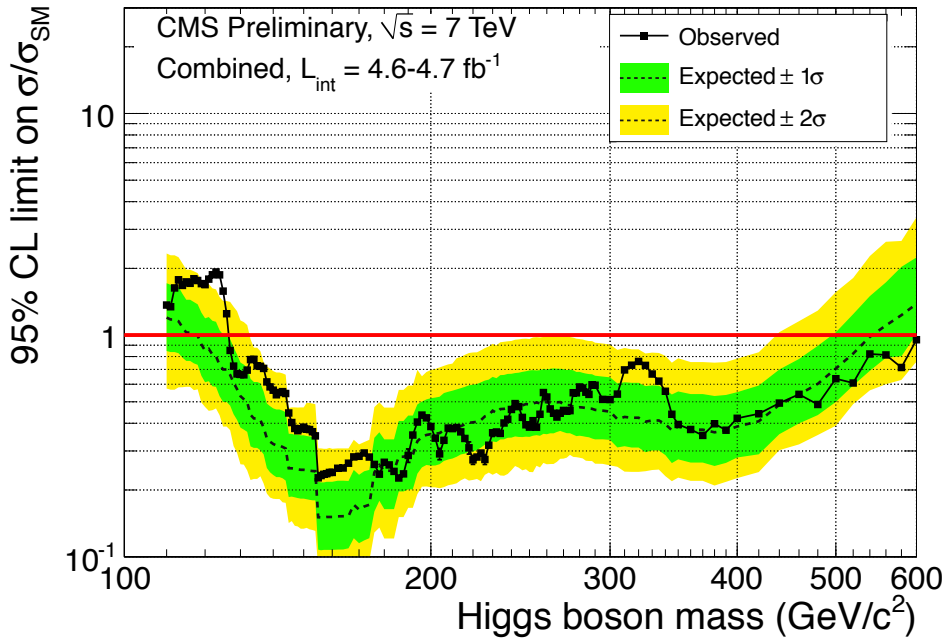


Anatomy of the excesses

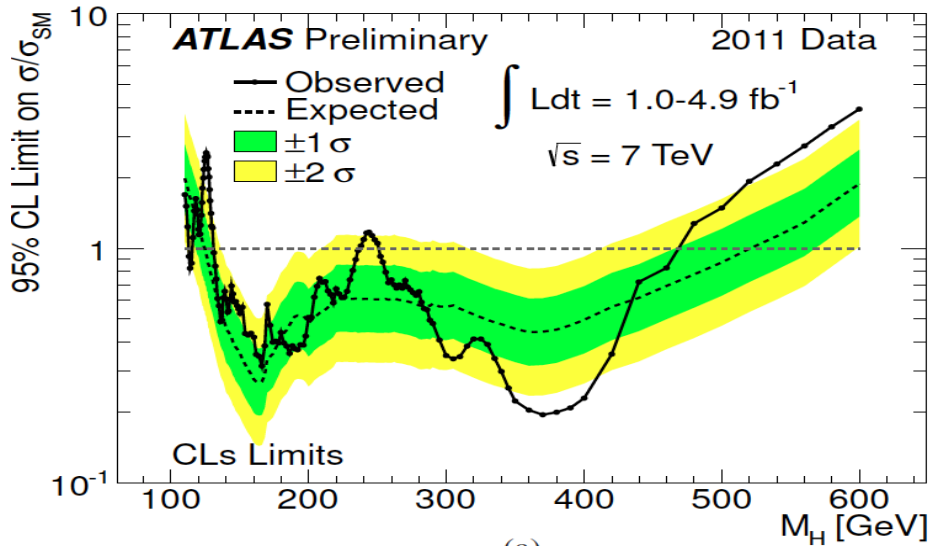




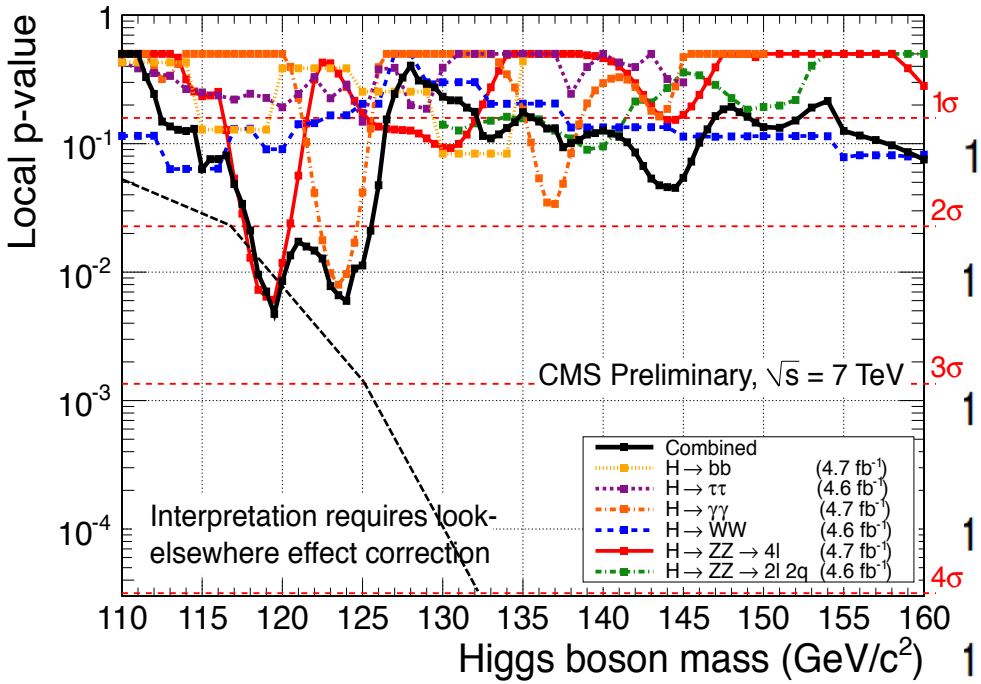
CMS - ATLAS

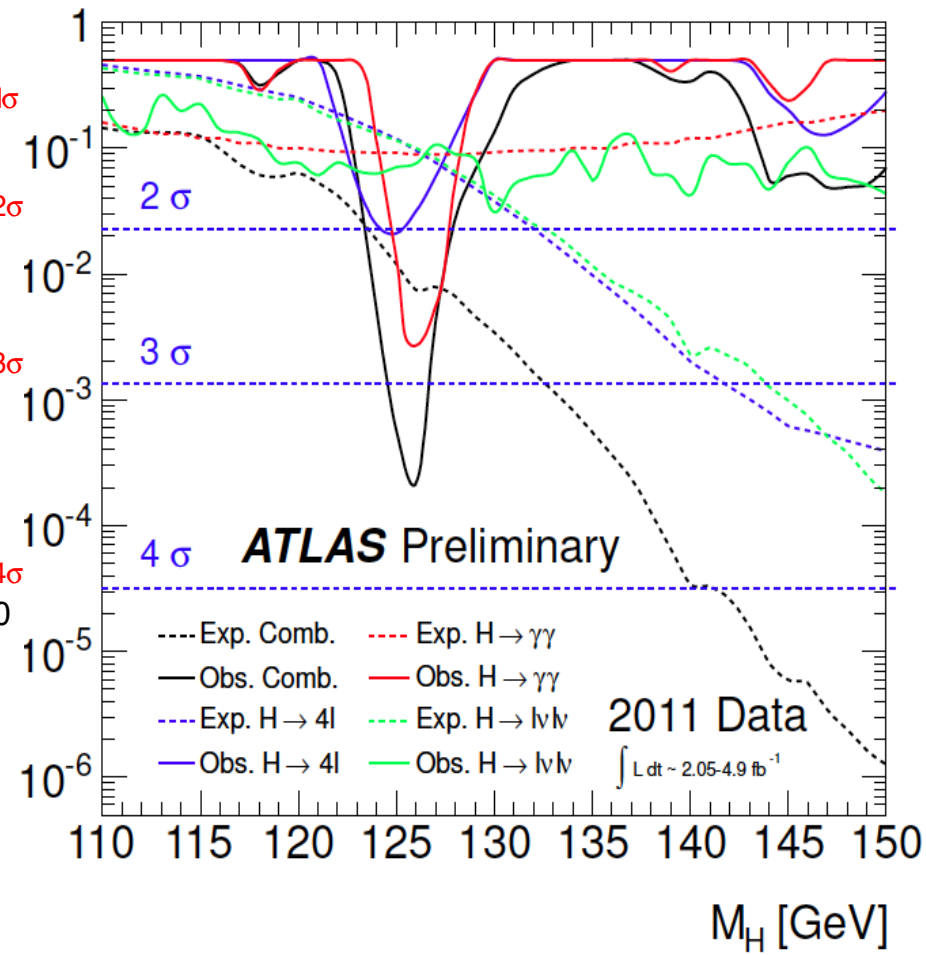


ATLAS: the low mass-resolution channels are still with 1-2.1 fb^{-1}

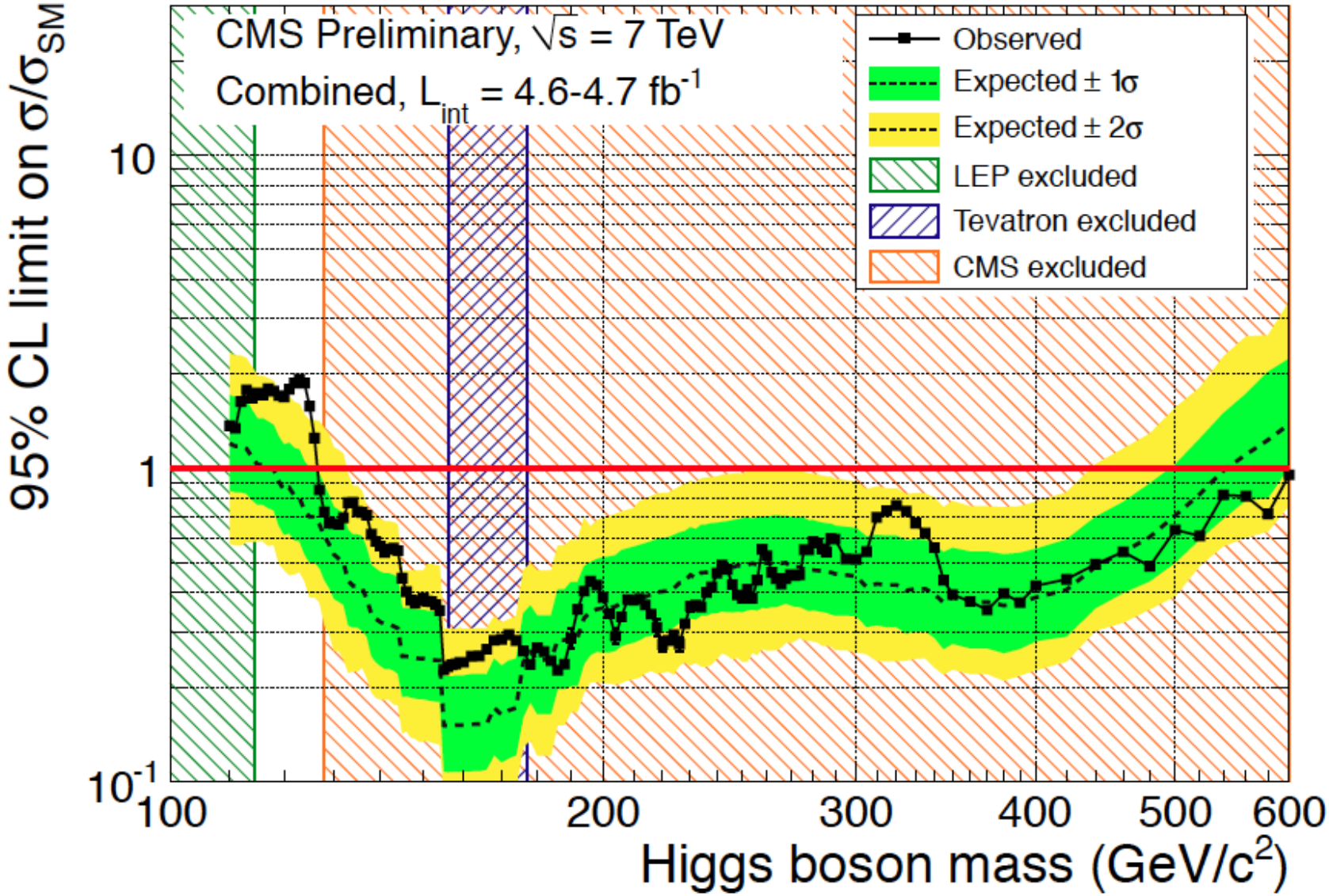


CMS - ATLAS

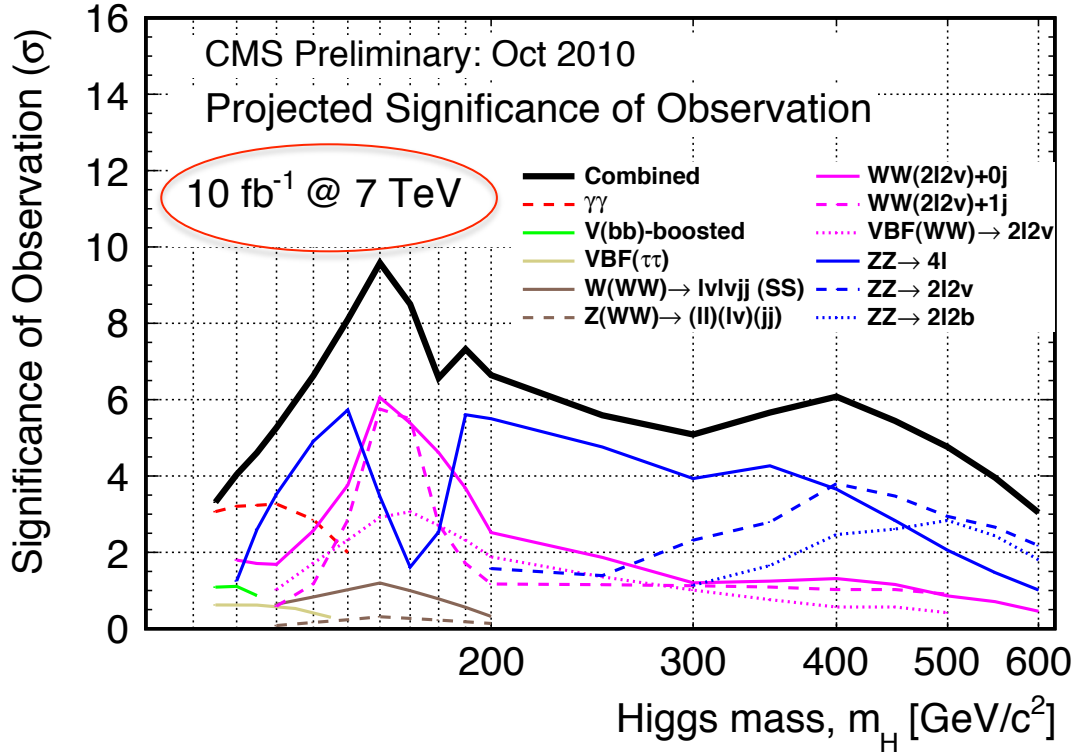

Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1σ
2σ
3σ
4σ
CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined
H → bb (4.7 fb^{-1})
H → ττ (4.6 fb^{-1})
H → γγ (4.7 fb^{-1})
H → WW (4.6 fb^{-1})
H → ZZ → 4l (4.7 fb^{-1})
H → ZZ → 2l 2q (4.6 fb^{-1})
Interpretation requires look-elsewhere effect correction
110 115 120 125 130 135 140 145 150 155 160
Higgs boson mass (GeV/c^2)


1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2 σ
3 σ
4 σ
ATLAS Preliminary
Exp. Comb.
Obs. Comb.
Exp. H → 4l
Obs. H → 4l
Exp. H → γγ
Obs. H → γγ
Exp. H → lνlν
Obs. H → lνlν
2011 Data
∫ L dt ~ 2.05-4.9 fb^{-1}
110 115 120 125 130 135 140 145 150
M_H [GeV]

One-plot summary



Outlook: prospects for 2012



2012 run integrated lumi being discussed is 20-30 fb^{-1}

If SM Higgs is there, discovery is very likely next year

Summary

- **CMS reached SM Higgs <u>exclusion sensitivity</u> in the full mass range**

- **SM Higgs boson excluded at 95% CL for m_H = 127–600 GeV**
  at 99% CL for m_H = 128–525 GeV

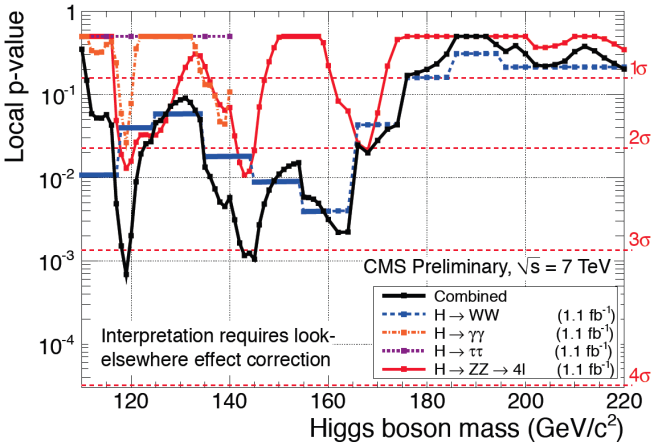
- **The excess at low masses remains.**
  It is not inconsistent with SM Higgs.
  To ascertain the origin of the excess, more data are required.

- **2012: with 30 fb^{-1} per experiment next year, we expect to reach <u>discovery sensitivity</u> in the full mass range**

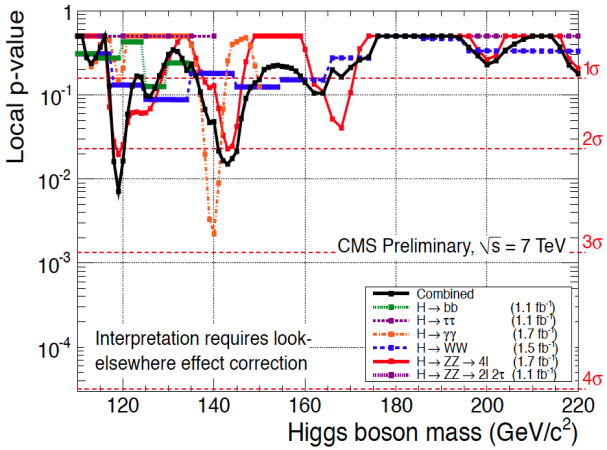
Backup

Combination: evolution

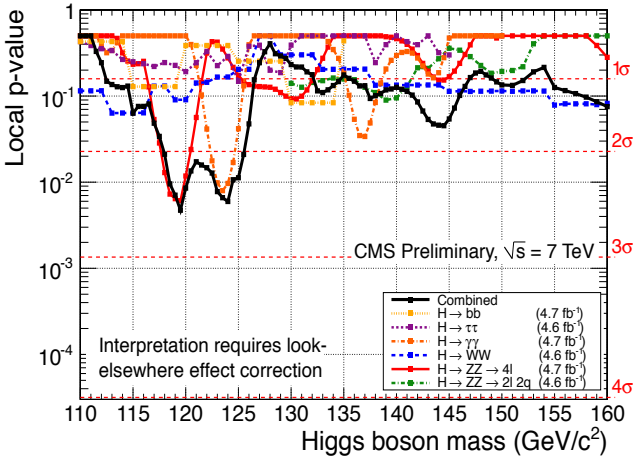
EPS'11



LP'11

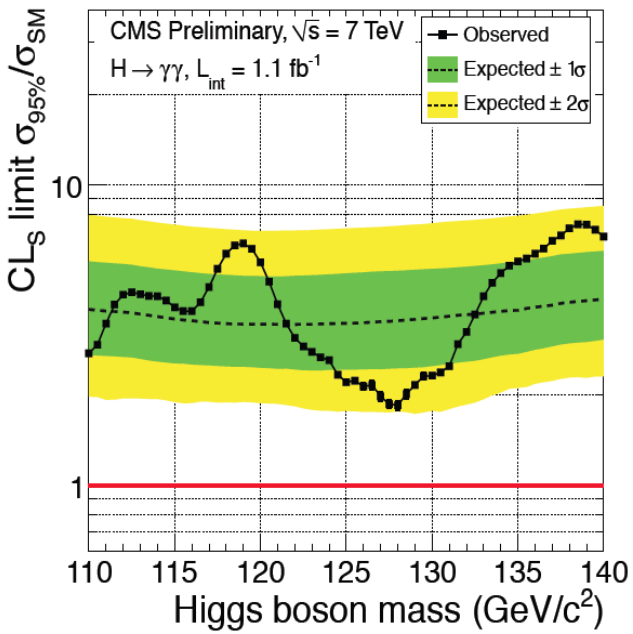


2011 data

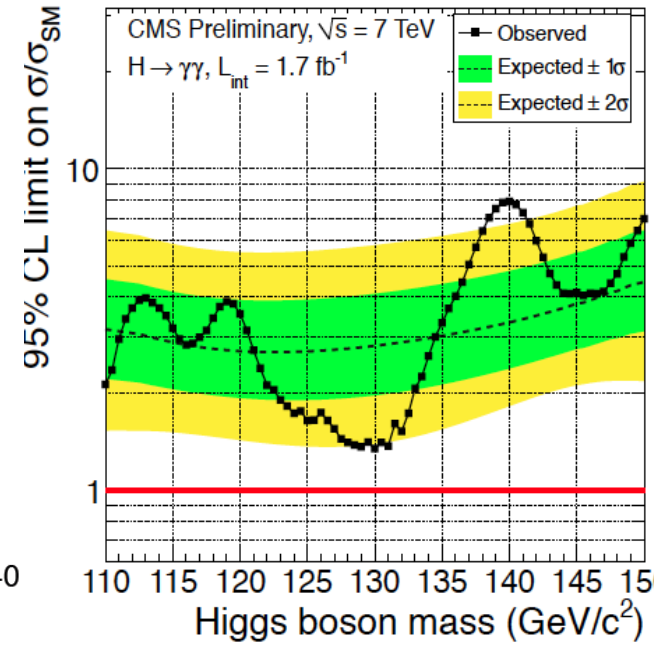


H->γγ: evolution of results

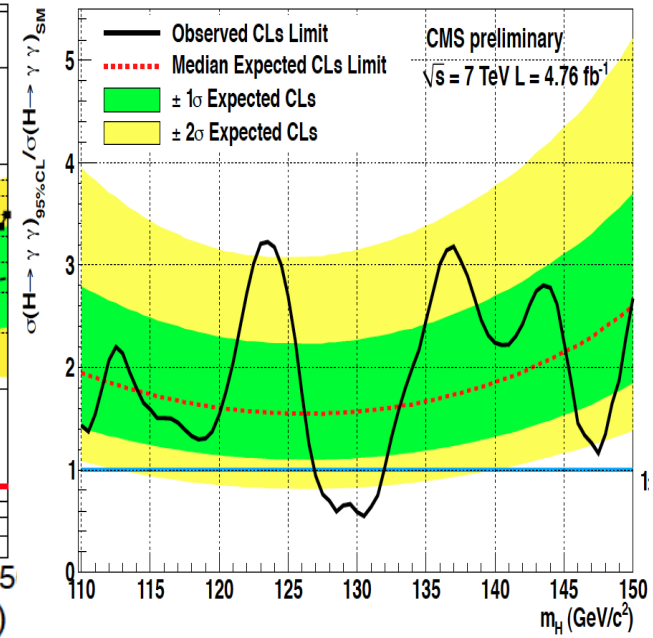
EPS'11



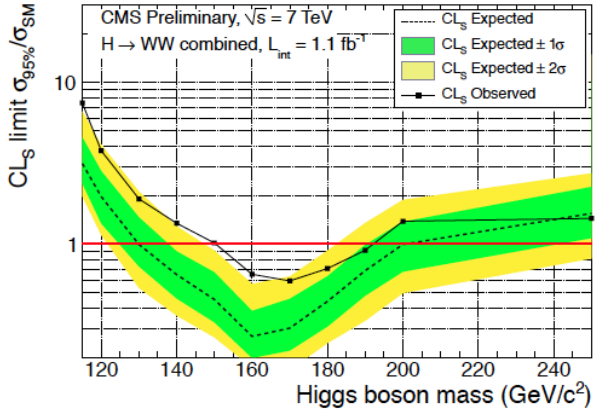
LP'11



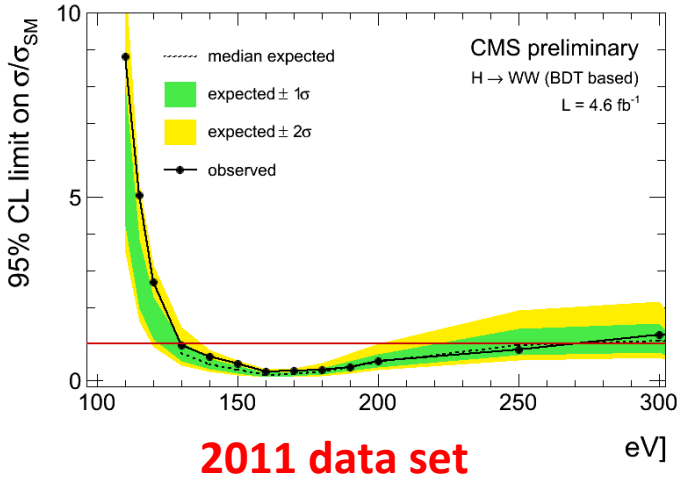
2011



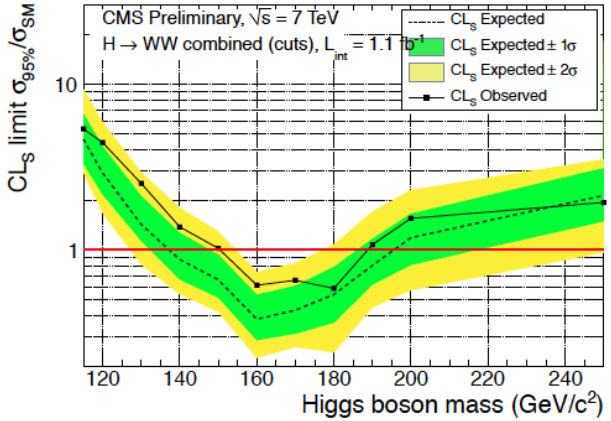
H->WW->lvlv: evolution of results



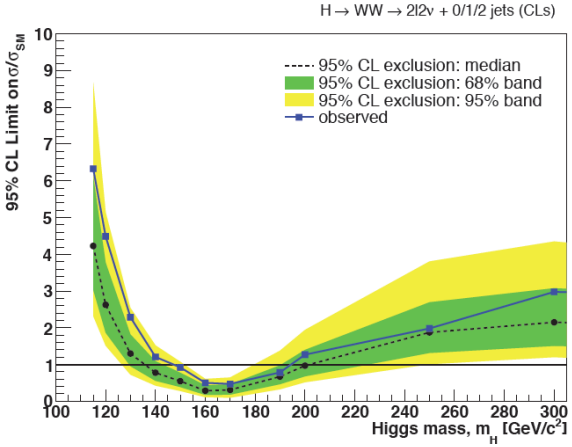
EPS'11
MVA-based analysis



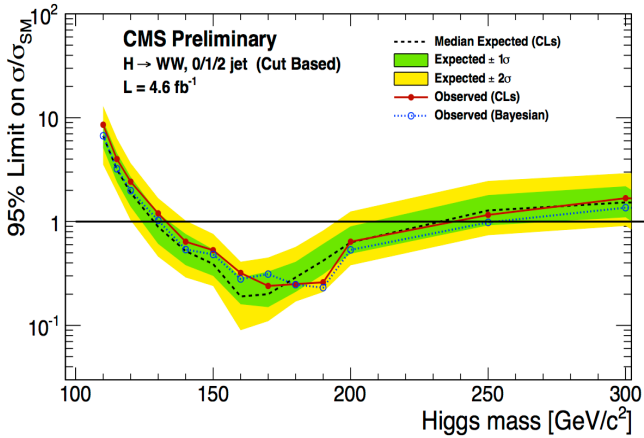
2011 data set
MVA-based analysis



EPS'11
Cut-based analysis



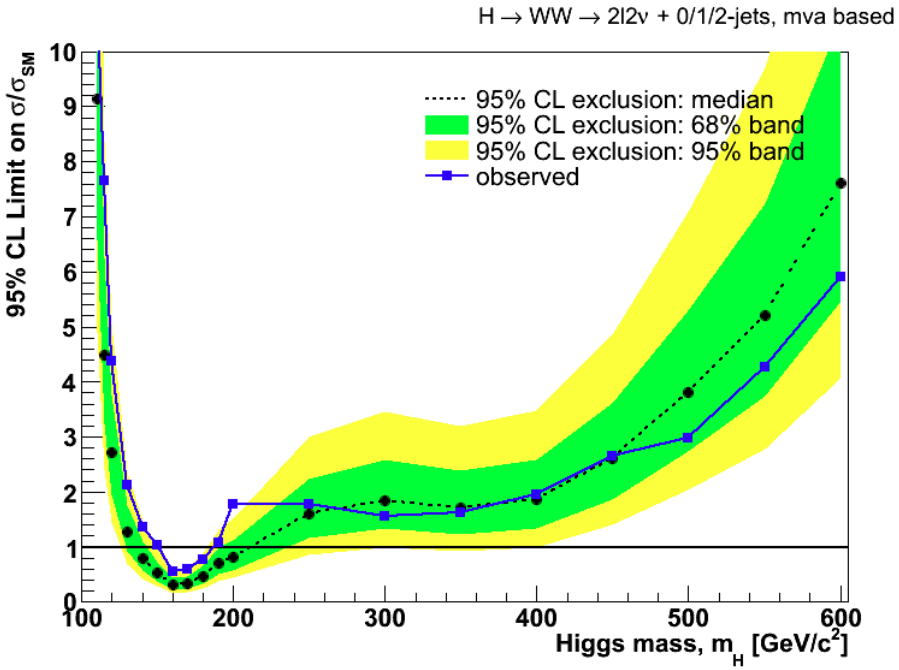
LP'11
Cut-based analysis



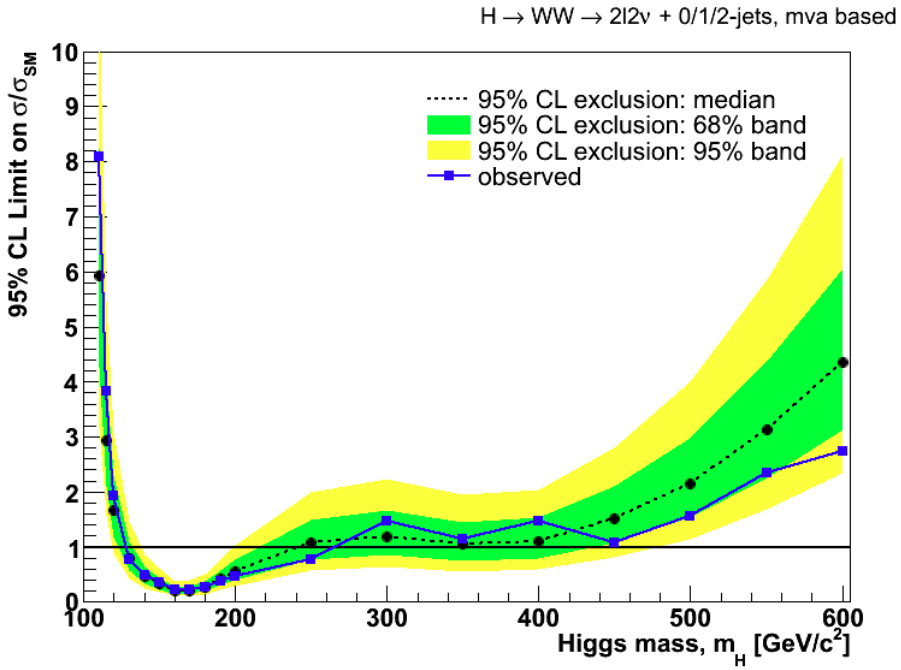
2011 data set
Cut-based analysis

H->WW->lvlv: what about EPS 2σ excess?

EPS'11 data (1.1 fb^{-1})
Dec 2011 MVA analysis



Post-EPS'11 data (3.5 fb^{-1})
Dec 2011 MVA analysis



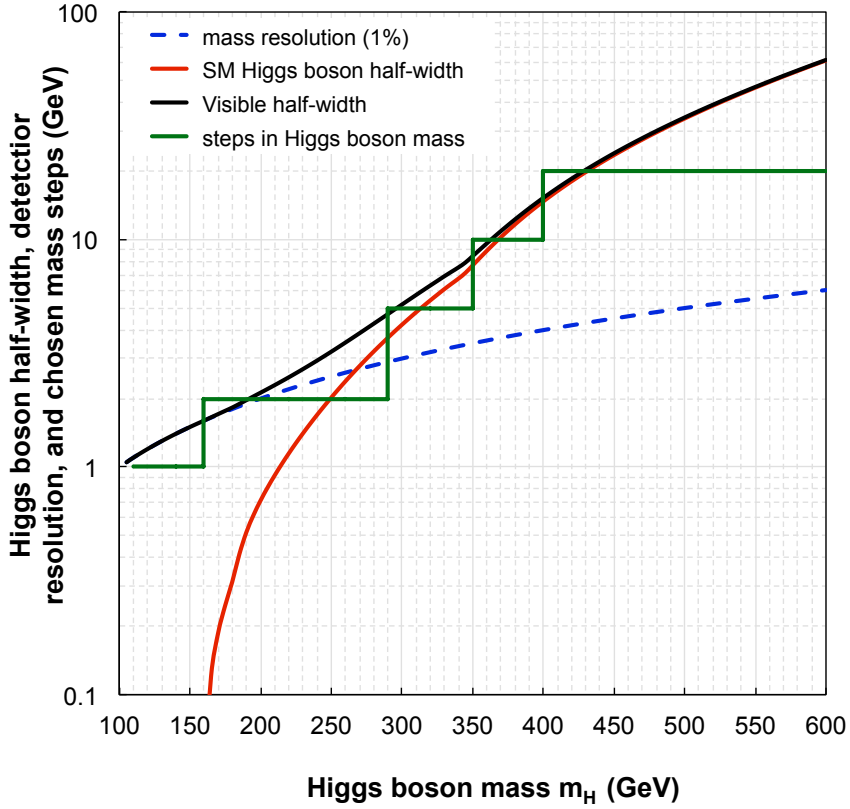
The excess in the EPS data set is still there (the updated analysis still see the same 2σ excess); but it is now dissolved by the more recent data that has a smaller excess.

Test Higgs boson mass points

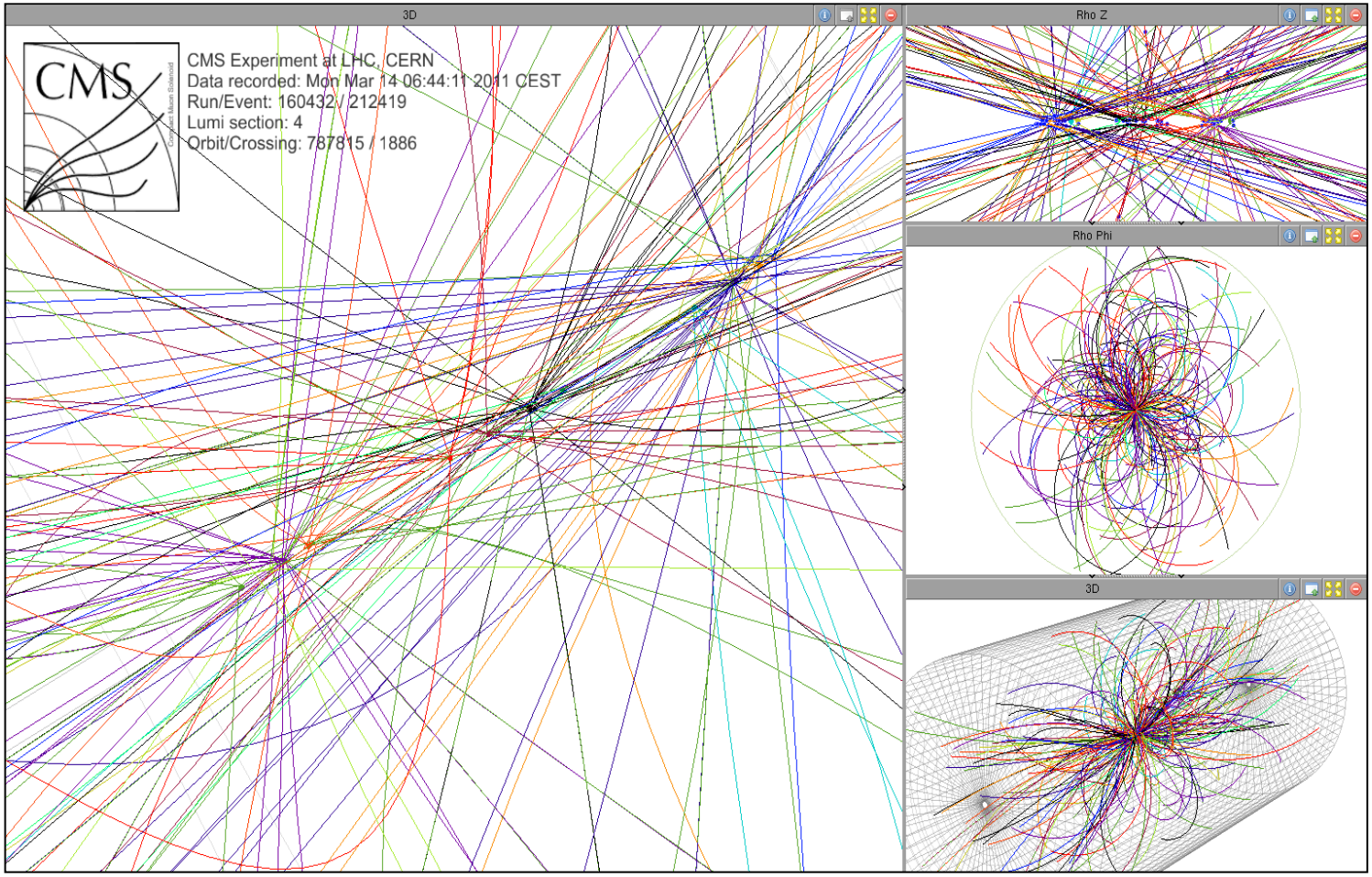
step ≈ 1σ mass resolution

- Loss of sensitivity for a Higgs boson with mH right between the chosen grid points <5%
- With twice larger step, we loose up to 20% in sensitivity

138 mass points in the current combination



Pile-up



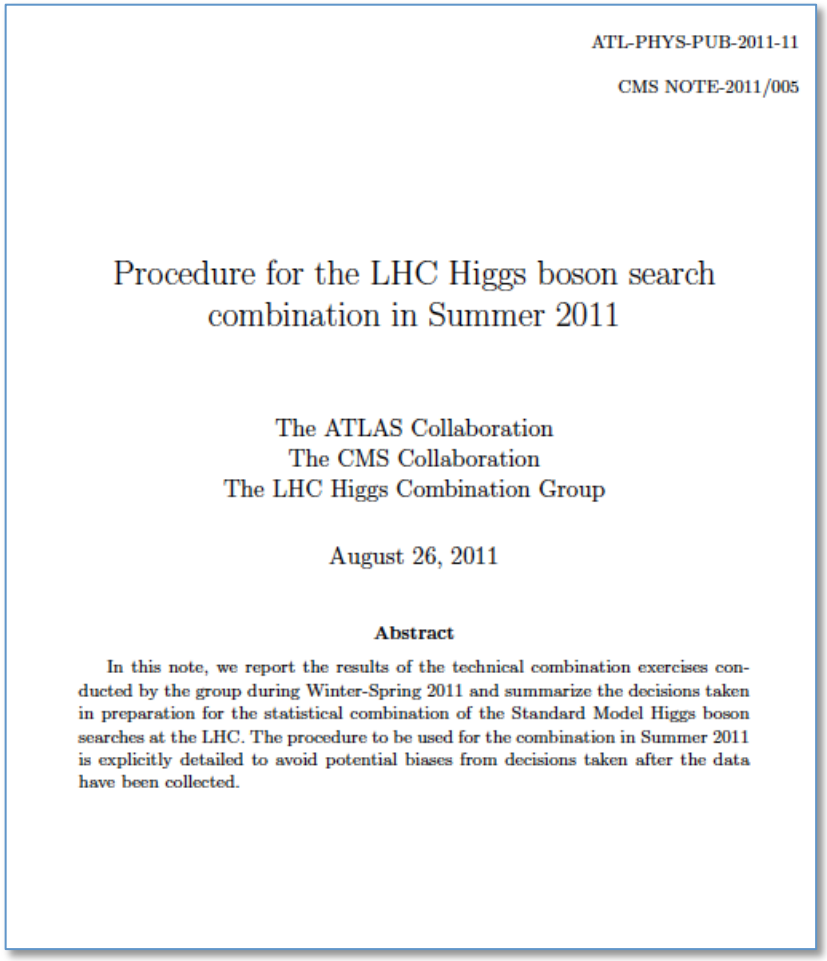
On average, 2011 data have 6 pile-up events per BX

Event shown above has 13 reconstructed vertices

Backup slides on statistical methods

Stat methods used

- **50-page document (6 months of the joint effort)**
  - explicit formulation of the methods to be used
  - record of ATLAS & CMS "handshakes" on toy combinations
- **RooStats – the engine for ATLAS+CMS combination***



ATL-PHYS-PUB-2011-11

CMS NOTE-2011/005

Procedure for the LHC Higgs boson search combination in Summer 2011

The ATLAS Collaboration
The CMS Collaboration
The LHC Higgs Combination Group

August 26, 2011

Abstract

In this note, we report the results of the technical combination exercises conducted by the group during Winter-Spring 2011 and summarize the decisions taken in preparation for the statistical combination of the Standard Model Higgs boson searches at the LHC. The procedure to be used for the combination in Summer 2011 is explicitly detailed to avoid potential biases from decisions taken after the data have been collected.

* CMS-only combination is always validated by requiring the agreement between RooStats and L&S results

Main terms

- SM Higgs signal s
- background b
- nuisance parameters θ
- signal strength modifier $\mu = \sigma / \sigma_{SM}$
- best-fit signal strength modifier μ-hat
- test statistic q
- p-value = $P(q \geq q^{obs})$
- significance Z
- $CL_s = P(q \geq q^{obs} | b+\mu s) / P(q \geq q^{obs} | b)$

Uncertainties (1)

- uncertainties are modeled by introducing independent nuisance parameter
- correlated uncertainties in different channels are associated with the same nuisance parameter
- pdf types for uncertainties:
  - unconstrained: flat prior
  - generic case for observables that can take ± values: normal
  - generic for positive definite observables: lognormal (normal in log space)
  - statistical: gamma distribution

Uncertainties (2)

uncertainty --> nuisance parameter θ, whose best estimate is $\tilde{\theta}$

Bayesian declares his degree of believe on the true value of nuisance θ: $\rho(\theta|\tilde{\theta})$

Frequentist wants to know pdf of "measuring" $\tilde{\theta}$, should nuisance be θ: $p(\tilde{\theta}\,|\,\theta)$

Two paradigms can be connected via Bayes' theorem:

$$\rho(\theta|\tilde{\theta}) \sim p(\tilde{\theta}\,|\,\theta) \cdot \pi_\theta(\theta)$$

posterior as a prior for Bayesian analysis

"measurement" PDF for frequentist analysis

"primordial" hyper prior

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

Typical examples

Gaussian: $b = b_0\,(1 + \varepsilon\theta)$

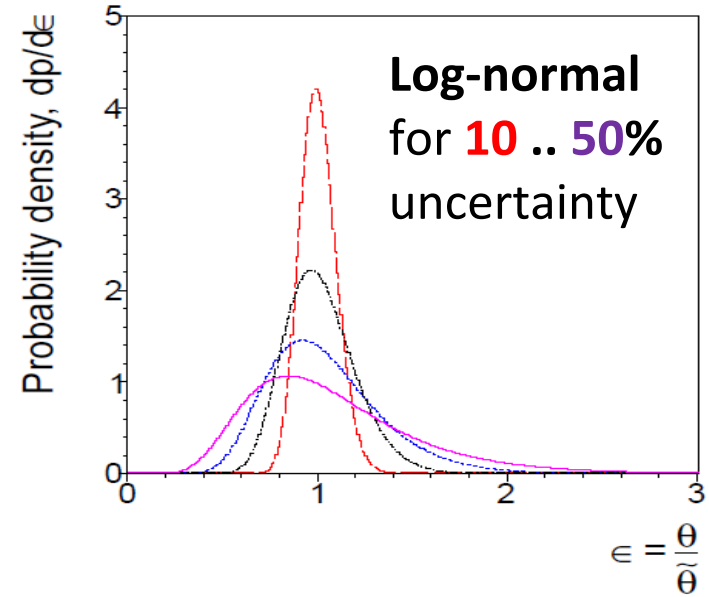
Lognormal: $b = b_0\,\kappa^\theta$

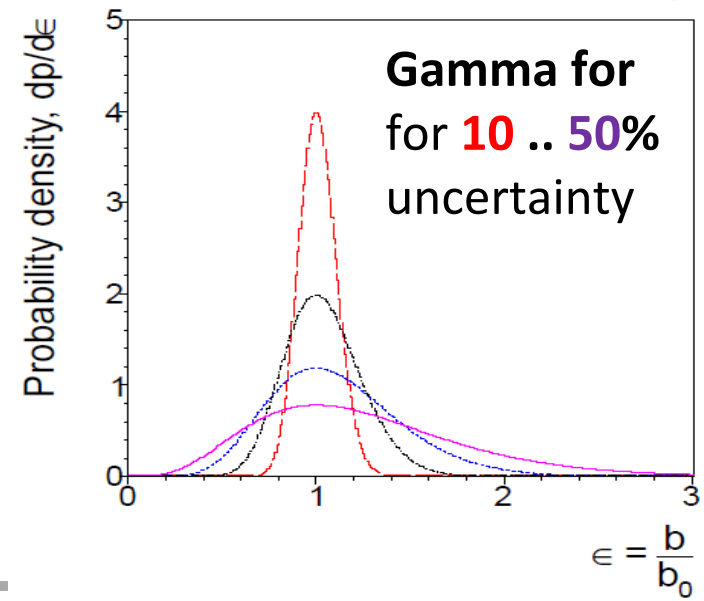
Statistical: $b = \alpha \times \theta$

Modelling of uncertainties

PDFs for nuisance parameters:

- **For yields measured from a control sample with stat. uncertainties: Gamma**
- **Other uncertainties on yields: log-normal** (remains "regular" for large uncertainties)
- **Parameters with no prior knowledge, e.g. the γγ background: uniform distrib.**
- **Other parameters, usually affecting shapes: Gaussians**





Treatment of theory uncertainties

- **LHC Higgs Cross Section group:**
  - **Higgs "QCD scale" errors provided**
  - **Higgs PDF+α_s errors provided**
  - **The two are stated to be independent**
  - **Recommendations**
    - use <u>flat pdf</u> for QCD scale uncertainties
    - use normal (or lognormal) pdf for PDF+α_s uncertainties
    - QCD scale PDF+α_s uncertainties are to be <u>added linearly</u>
- **LHC Higgs Combination group**
  - **takes all this input as is,**
    <u>except for the two underlined recommendations</u>

Treatment of theory uncertainties

Why not flat pdf for QCD scale uncertainties?

- errors are assessed by varying QCD scales up and down by a factor of n (typically 2, e.g. $\mu=\mu_0 \times 2$)
- it appears unphysical to set pdf=0 (exact!) for CS variations corresponding to $\mu=\mu_0 \times 2.000001$, while assign equal pdf density for μ_0 and $\mu_0 \times 2.00000$
- we opted to use lognormal errors for all positive-definite quantities (cross sections belong to this class)
  - tests with toy models show that the difference between using flat and lognormal pdf's is small and its sign is not unique (depends on stat method)
  - Tevatron did such tests too with the same conclusion: the effect is small

Treatment of theory uncertainties

Why not add errors linearly?

- Adding QCD scale and PDF+α_s uncertainties linearly would imply 100% positive correlation between them, contrary to the statement that they are independent
- Note that we also need to worry about correlations of systematics between different processes, not just between QCD scale and PDF+α_s uncertainties for a given signal process
- For example: gg→H→WW and gg→WW
  - QCD scale errors for these two are not correlated (we are told so)
  - PDF+α_s uncertainties for these two are strongly correlated (both of gg-origin; also, explicitly demonstrated by CTEQ folks)
  - Keeping QCD scale and PDF+α_s uncertainties independent allows to accommodate both requirements

Statistical choices for setting limits

Which of the two main paradigms ?

- **Bayesian**
  - which prior ?
- **Frequentist**
  - Classical ?
  - Feldman-Cousins ?
  - CL_s (a.k.a. modified frequentist) ?

How do we deal with systematic uncertainties ?

- this brings even more sub-sub-flavors for each of the above…

Limits: Bayesian paradigm

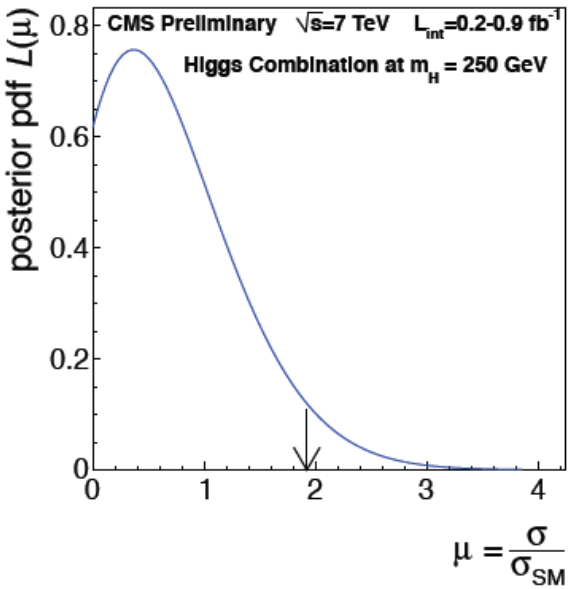
Posterior on signal strength μ

- using flat prior
- marginalization of nuisance parameters

$$p(\mu\,|\,\text{data}) = \frac{1}{C}\int_\theta p\left(\text{data}\,|\,\mu s(\theta) + b(\theta)\right)\ \rho_\theta(\theta)\ \pi_\mu(\mu)\ d\theta.$$

Deriving limit on μ

$$\int_0^{\mu_{95\%CL}} p(\mu\,|\,\text{data})\ d\mu\ =\ 0.95$$



Limits: CL_s flavors

$CL_s = p(q \geq q^{obs} \mid s+b) / p(q \geq q^{obs} \mid b)$

- define test statistic q
- decide on how to include systematic errors
  - in the definition of test statistic
  - in tossing pseudo-data

Three historical choices (in the Higgs world):

LEP, Tevaton, LHC

CL_s: test statistic (no syst. errors)

Likelihood ~ Poisson probability

$$L(data;\ rate) = \text{Poisson}(data;\ rate)$$

$$\lambda(\mu) = \frac{L(obs;\ b+\mu s)}{L(obs;\ b)}$$

LEP and Tevatron start out from here

$$\lambda(\mu) = \frac{L(obs;\ b+\mu s)}{L(obs;\ b+\hat{\mu} s)}$$

$\hat{\mu}$ maximizes likelihod $L(obs;\ b+\hat{\mu} s)$;

$0 < \hat{\mu}$ constrained by physics;

$\hat{\mu} < \mu$ to ensure one-sided limit;

LHC HCG choice

This allows for using quick asymptotic estimate of limits from the **observed q** without tossing pseudo-data

CL_s: including systematics (LEP-type)

Test statistic is not changed, i.e. systematic errors do not enter the definition of q

$$q_\mu = -2\ln\frac{L(data;\ b_0 + \mu s_0)}{L(data;\ b_0)}$$

Before tossing a pseudo-event, $b(\theta)$ and $s(\theta)$ are modified by varying θ according to $\rho(\theta)$

Bayesian treatment of systematic errors

CL_s: including systematics (TEV-type)

Likelihood is changed

$$L\big(data;\ b(\theta)+\mu s(\theta)\big)=\text{Poisson}\big(data;\ b(\theta)+\mu s(\theta)\big)\cdot\rho(\theta;\tilde{\theta})$$

Test statistic is changed:

$$q_\mu=-2\ln\frac{L(data;\ \mu,\ \hat{\theta}_\mu)}{L(data;\ \hat{\theta}_0)}$$

Both numerator and denominator likelihoods are maximized.
This allows for constraining nuisance parameters, given the data.
Signal+bkgd and bkgd-only sampling distributions get narrower.
Construction of sampling distributions takes much longer time.

Before tossing a pseudo-event, b(θ) and s(θ) are modified by varying θ according to ρ(θ)

Bayesian treatment of systematic errors

CL_s: including systematics (LHC-type)

Likelihood is changed

$$L\left(data;\ b(\theta)+\mu s(\theta)\right)=\text{Poisson}\left(data;\ b(\theta)+\mu s(\theta)\right)\cdot p(\tilde{\theta};\theta)$$

Test statistic is changed:

$$q_\mu=-2\ln\frac{L(data;\ \mu,\ \hat{\theta}_\mu)}{L(data;\ \hat{\mu},\ \hat{\theta})}$$

All the same reasons (pros) and penalties (cons) as for TEV-type, but starting out from a different original test statistic

Tossing a pseudo-event is modified (next slide)

Frequentist treatment of systematic errors

CL_s: tossing toys for LHC-type CL_s

- Fit data to find **two best sets of nuisances** $\hat{\theta}_0^{obs}$ and $\hat{\theta}_\mu^{obs}$
  (this is small departure from the pure-pure frequentist approach
  that would require a scan over all possible values of nuisance parameters)

- Prepare sampling distributions of test statistics
  - **bkgd-only pseudo-data:** $(\mathrm{data}, \tilde{\theta})$ **for** $b(\hat{\theta}_0^{obs})$
  - **signal+bkgd pseudo-data:** $(\mathrm{data}, \tilde{\theta})$ **for** $\mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})$

LHC type CL_s (summary)

Pure frequentist. *Aided by Bayes' theorem,* all systematic errors are "measurements"

Likelihood

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

Test statistic

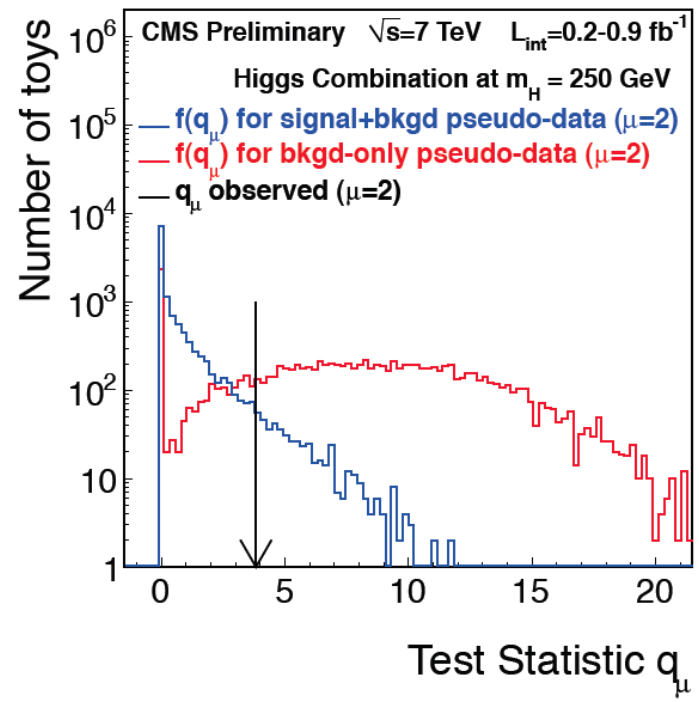
$$\tilde{q}_\mu \;=\; -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}, \qquad \text{with a constraint } 0\le\hat{\mu}\le\mu$$

Pseudo-data (toys)

- fit data to find two best sets of nuisances $\hat{\theta}_0^{obs}$ and $\hat{\theta}_\mu^{obs}$
- prepare sampling distributions of test statistics
  - bkgd-only pseudo-data: $(\text{data}\,,\tilde{\theta})$ for $b(\hat{\theta}_0^{obs})$
  - signal+bkgd pseudo-data: $(\text{data},\,\tilde{\theta}\,)$ for $\mu s(\hat{\theta}_\mu^{obs})+b(\hat{\theta}_\mu^{obs})$

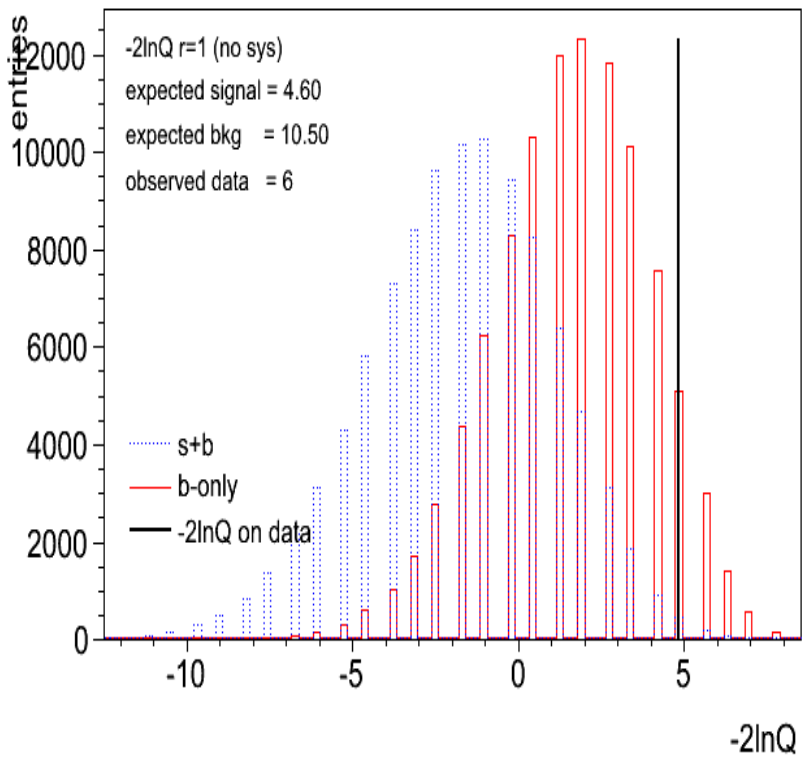
Define

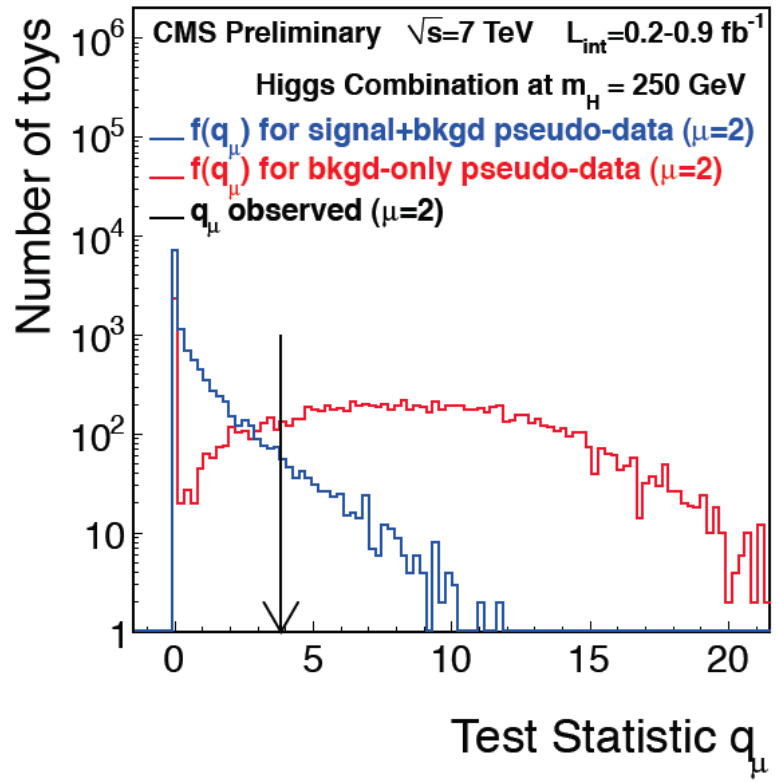
$$CL_s = \frac{P\left(q_\mu \ge q_\mu^{obs}\,|\,\mu s(\hat{\theta}_\mu^{obs})+b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \ge q_\mu^{obs}\,|\,b(\hat{\theta}_0^{obs})\right)}$$



Limits: beware…

Sampling distributions for LEP/TEV and LHC type test statistic look different



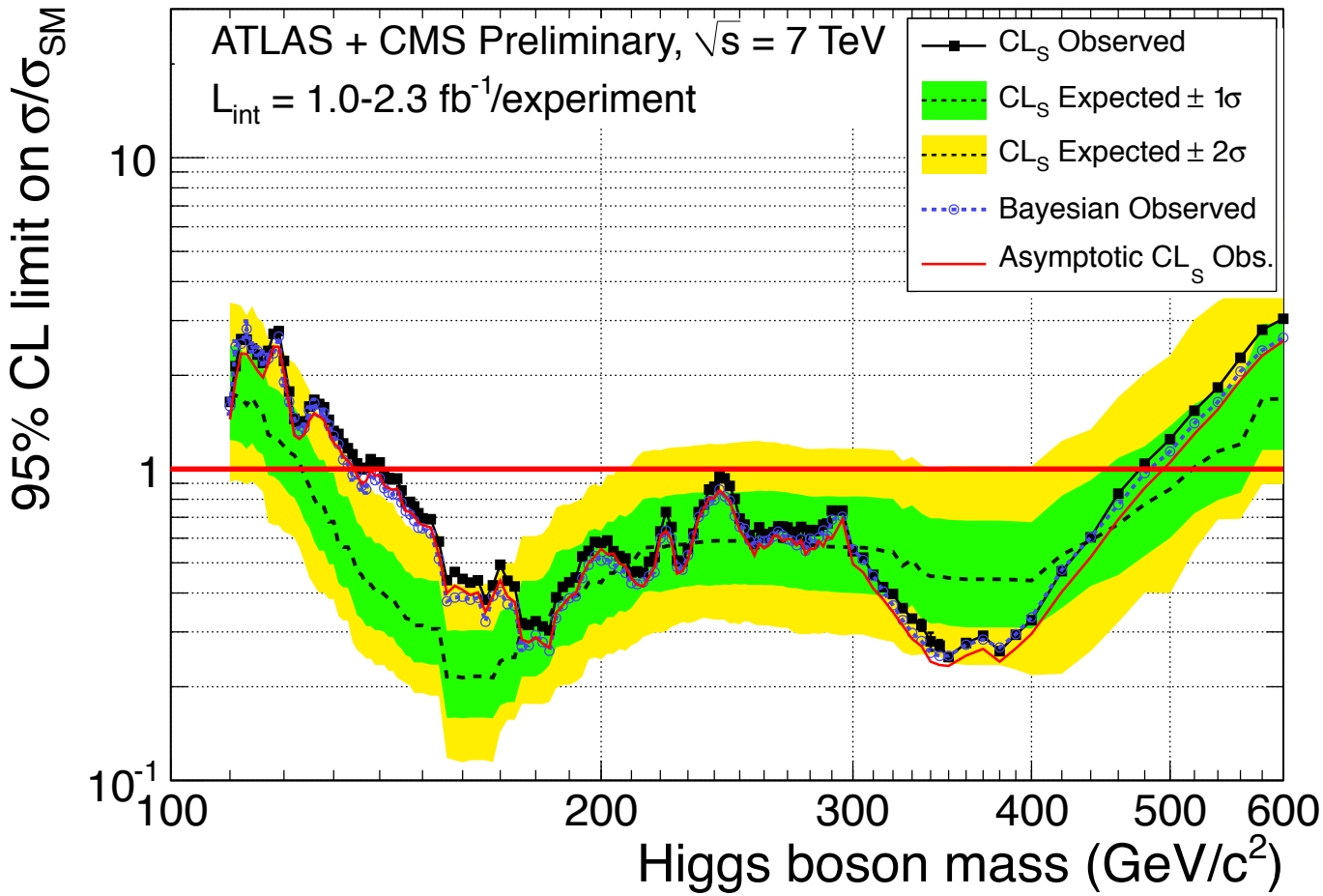


CL_s: do TEV and LHC CL_s types give different answers?

Yes, for bands, when data can significantly constrain uncertainties (e.g. $m_{\gamma\gamma}$ background)

For observed limits, in all practical cases we looked at, we saw very little differences

Limits: does asymptotic approx. work?



YES, within O(10%) for Higgs Combination

Excess: p-value

test statistic – profile likelihood

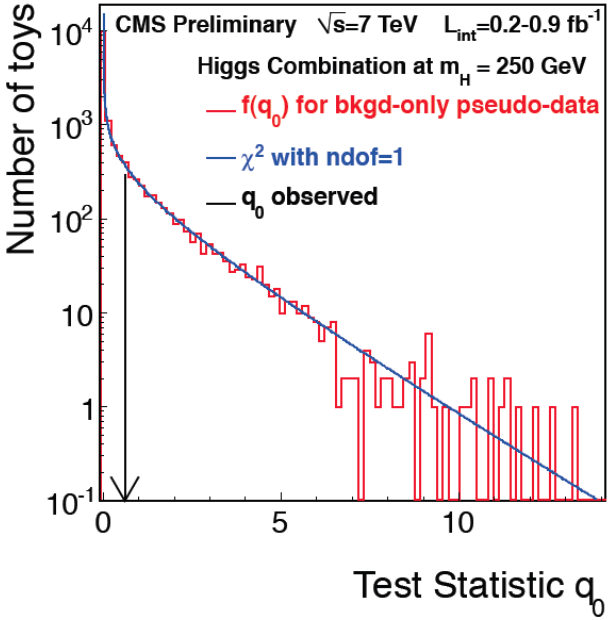
$$q_0 = -2\ln\frac{\mathcal{L}(\text{data}|0,\hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})} \quad \text{and } \hat{\mu} \geq 0$$

"local" p-values – from asymptotic approximation

$$p_0 = P(q_0 \geq q_0^{obs}) = \frac{1}{2}\left[1 - \text{erf}\left(\sqrt{q_0^{obs}/2}\right)\right]$$

significance Z – "one-sided Gaussian tail" convention

$$Z = \sqrt{q_0^{obs}}$$



IMPORTANT:

- **small "local" p-value means one has a "local" excess w.r.t. bkgd-only expectations**
- **it does not tell us whether the excess is due to a signal or not**
- **nor does it tell us whether the excess is consistent with THE expected signal**
  - **overall rate?**
  - **relative contributions of different channels?**
- **moreover, one must be ware of a potentially large look-elsewhere effect (LEE)**

Excess: LEE

"local" p-value and Z: chance to fluctuate at least as high as the observed Z **at a given m_H**

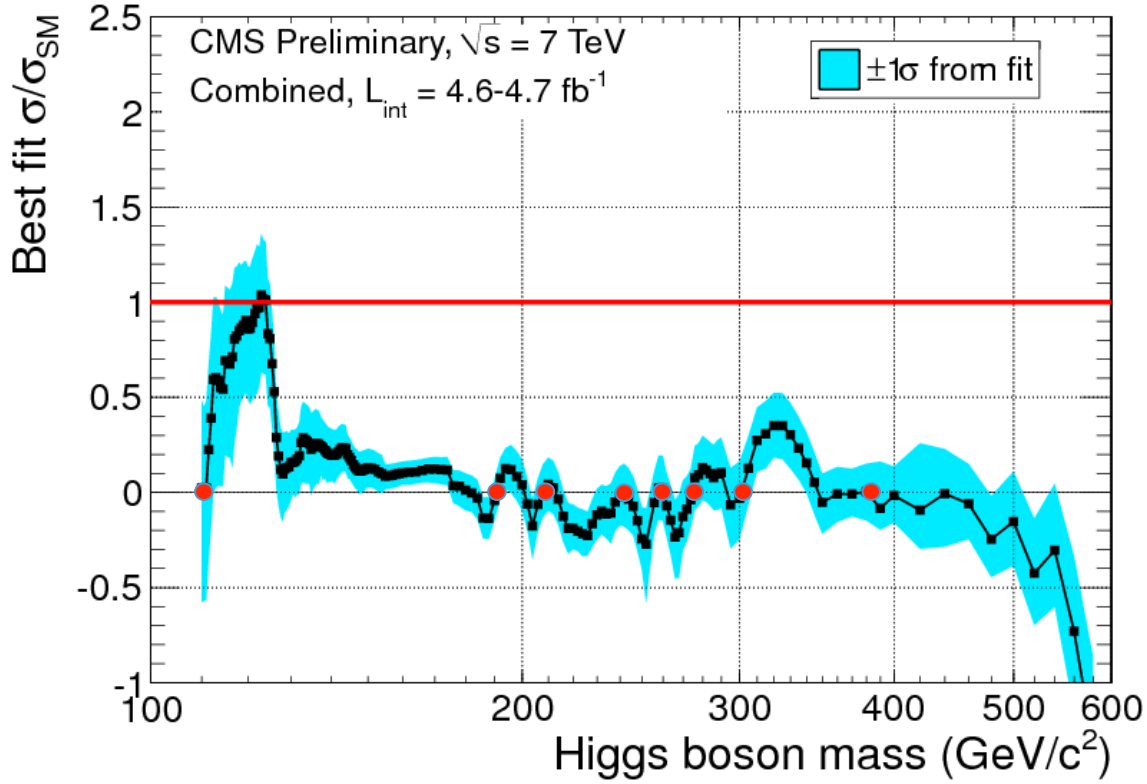
"global" p-value and Z: chance to fluctuate at least as high as the observed Z_{max} **anywhere in the full search range**

trials factor: K = (global p-value for Z_{max}) / (local p-value of Z_{max})

WAYS TO ESTIMATE LEE

- **if bkgd model for a search in the full mass range is available, one can toss toys**
- **if MC sample is much larger than data, one can use MC fragments as pseudo-data**
- **one can assess trials factor from a number of observed low-Z up-crossings**
- **use a plain bound: K cannot be larger than the number of tested mass points**

LEE: full mass range



- **Maximum local significance: Z_{max} = 2.6**
- **Count number of upcrossings at μ-hat=0: N_0=8**
- **Global p-value can be estimated as** $p_0^{\text{global}} \sim p_0^{\min} + N_0\, e^{-\frac{1}{2} Z_{\max}^2}$

- **This corresponds to global p-value=0.28, global Z=0.6**