SM Higgs boson search at CMS

Five slides on statistics

(many more in backup)

What is μ?

SM Higgs boson cross section: σ_{SM}

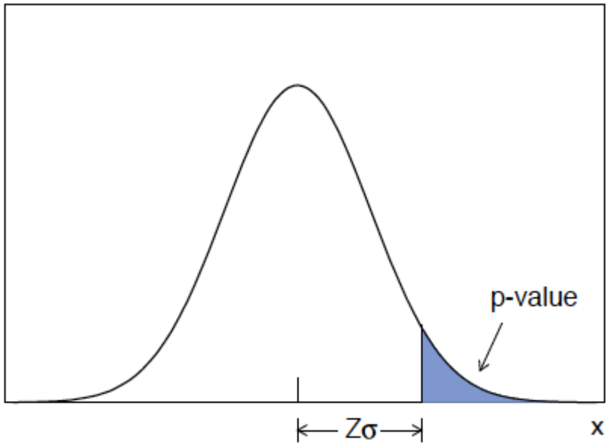
Hypothetical Higgs boson cross section: $\sigma = \mu \, \sigma_{SM}$

Excesses

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

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

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

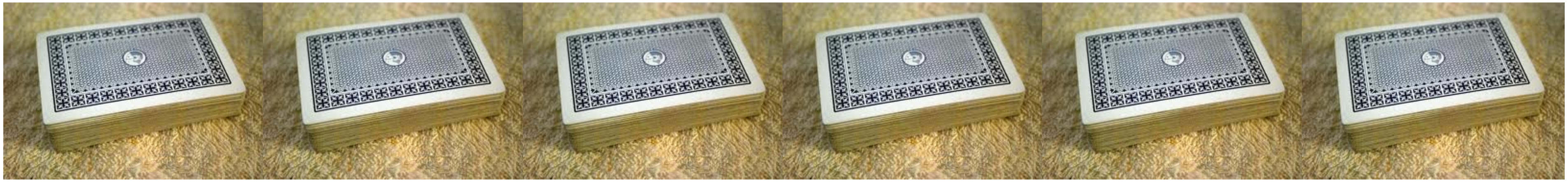


- *p-value* does not tell us whether the excess is consistent with the SM Higgs boson CS. Hence, we also quote the **best-fit value of the signal strength modifier $\hat{\mu}$**

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 convention for an exclusion…

- **Signal strength modifier μ excluded at 95% C.L.:**

  common factor 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.

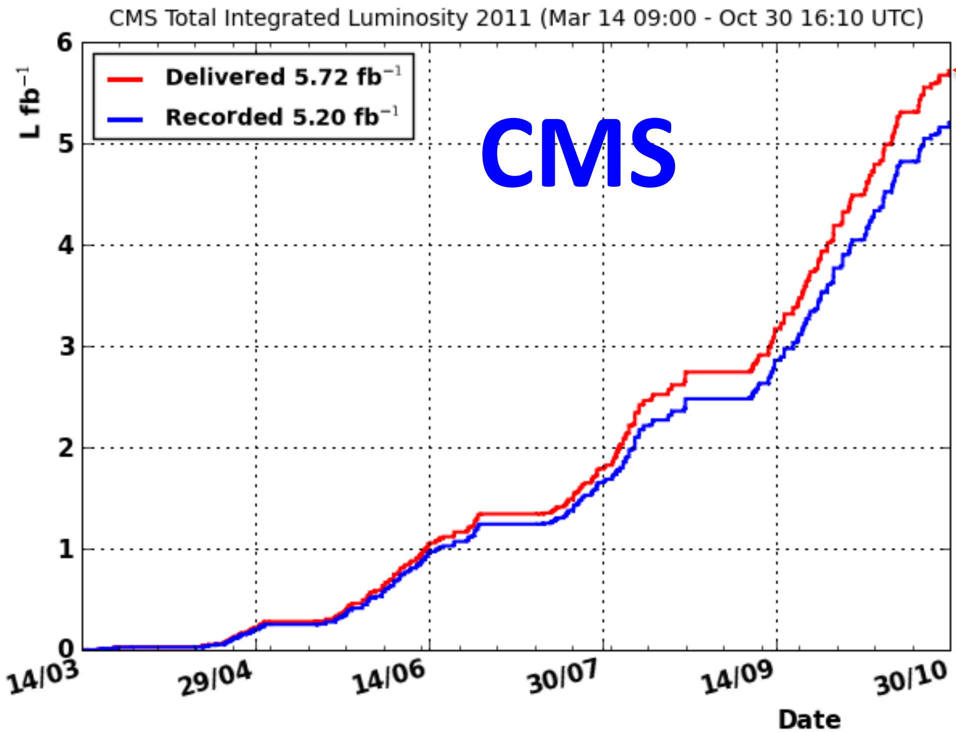
Real multi-channel combination

- **Many channels:**
  - **Choices on Observation → TestStatistic conversion**

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

CMS Performance

LHC performance in 2011



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

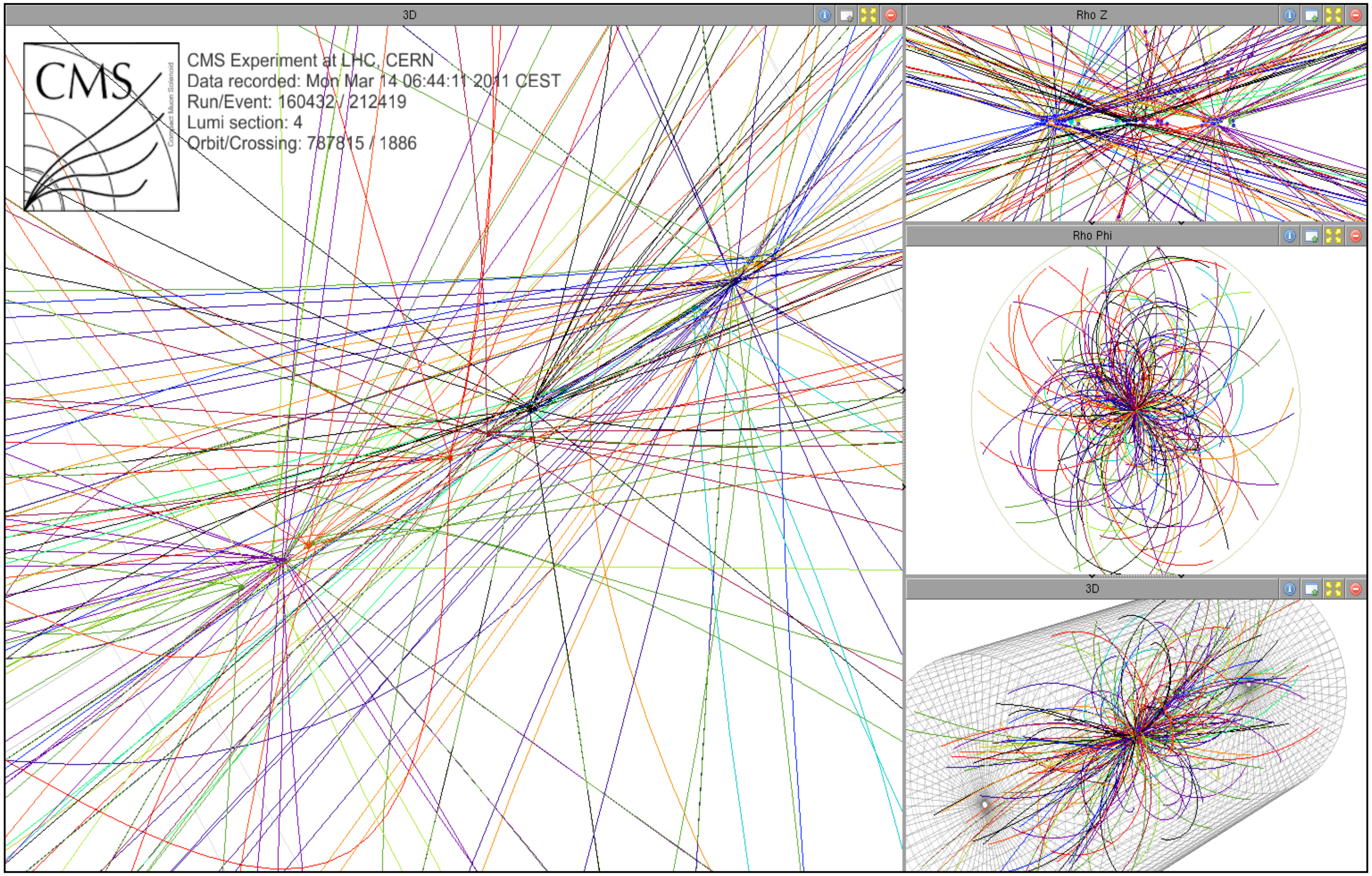
Max luminosity
$L = 3.5 \times 10^{33}$ cm^{-2} s^{-1}

Rapid increase in instantaneous luminosity:

April ($L=2\times10^{32}$ cm^{-2}s^{-1}) – October (3.5×10^{33})

We have been collecting per day more data than 4 x (entire 2010 run)

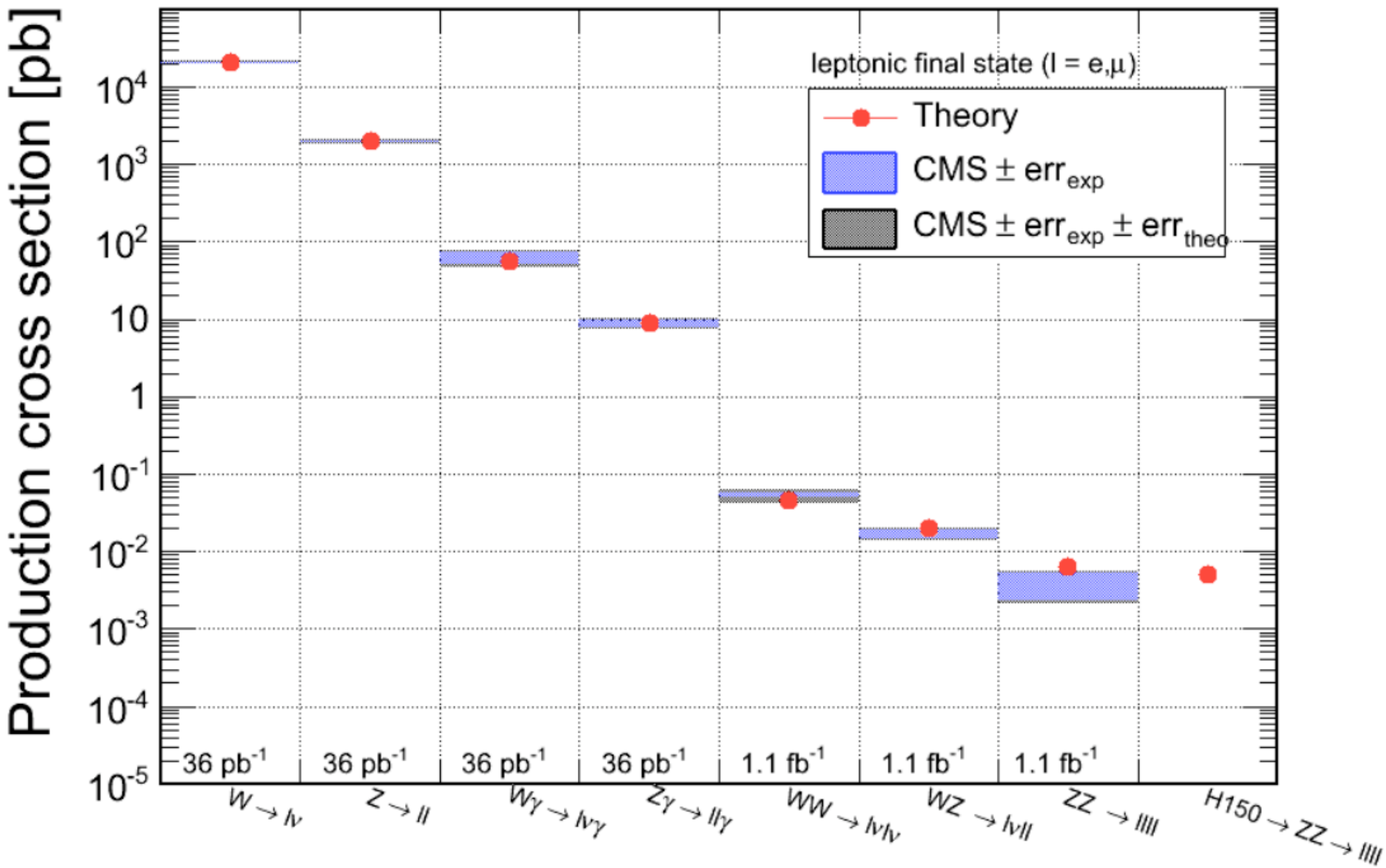
Pile-up



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

Shown event has 13 reconstructed vertices

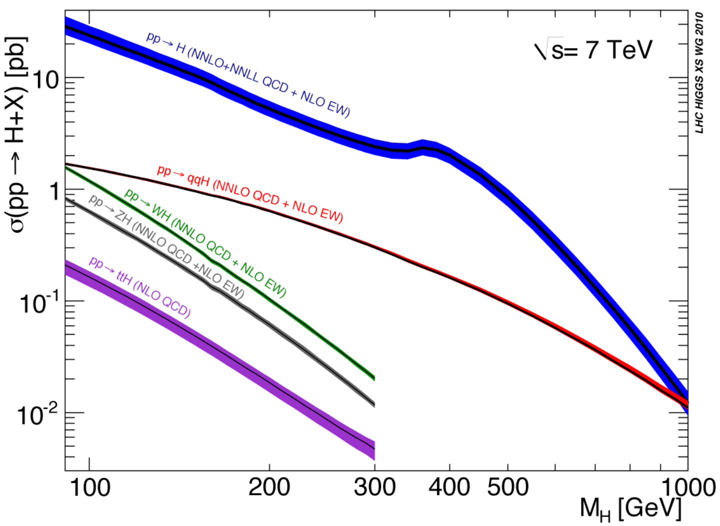
CMS performance

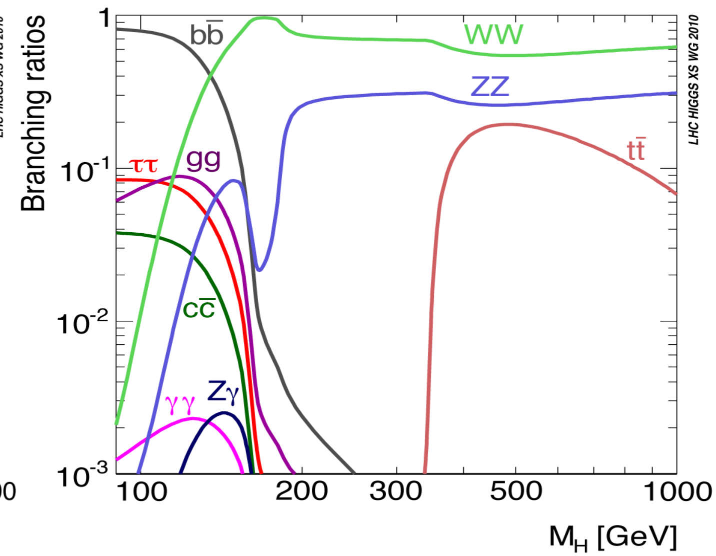


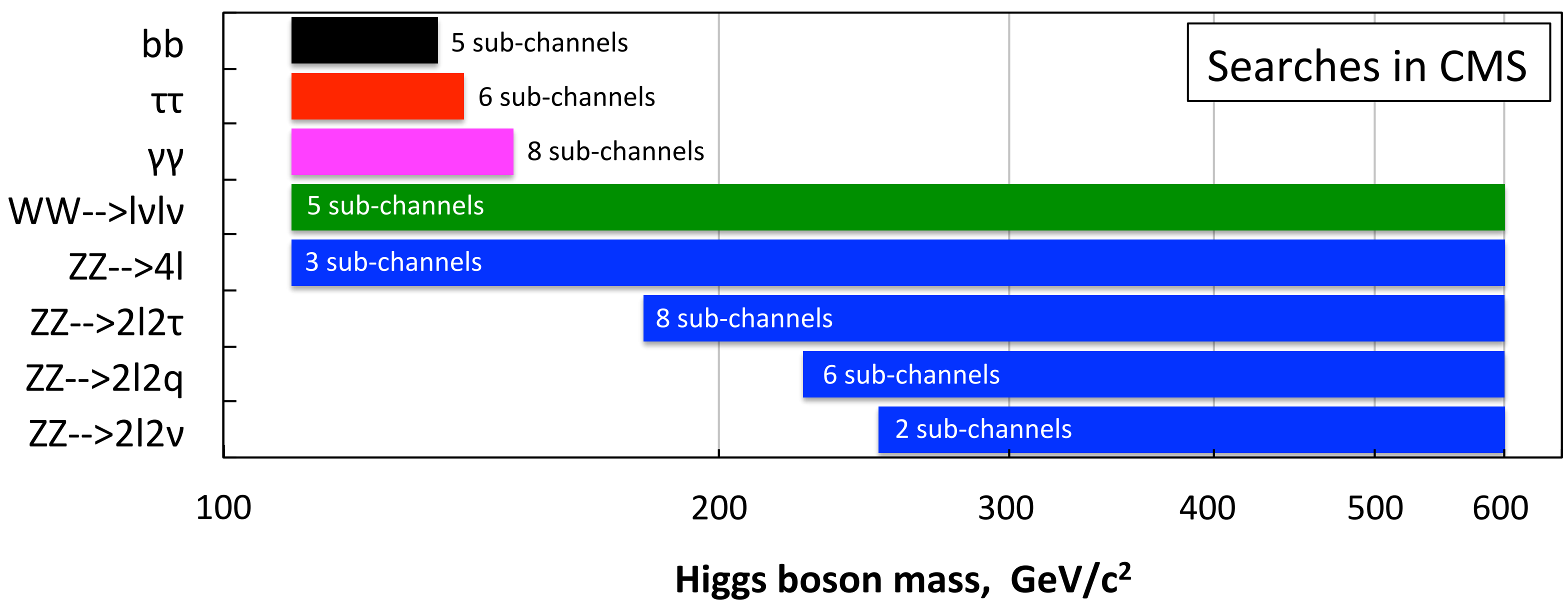
QCD cross section $>10^{10}$ pb

SM Higgs searches

SM Higgs: production, decays, searches

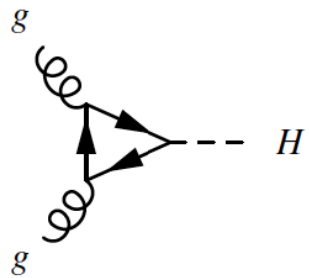




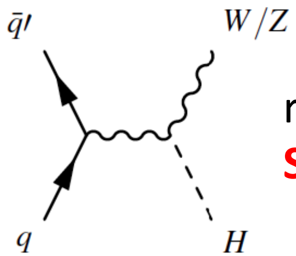


H -> bb

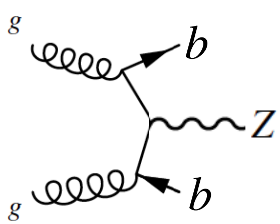
H->bb: why is it so hard at LHC?



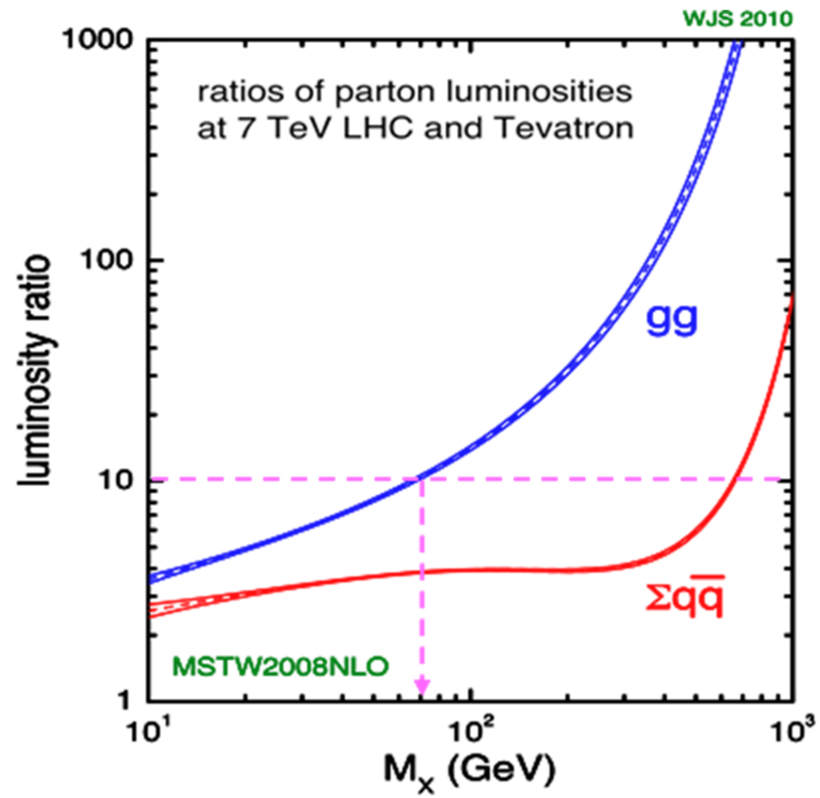
gg-production:
too large bkgd



reduce bkgd by adding W/Z tags;
Signal: qqbar-production

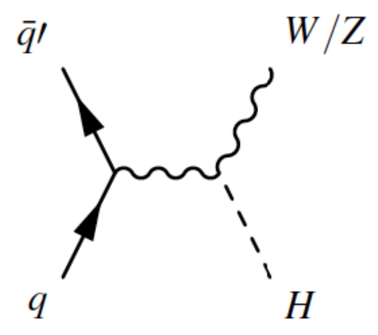


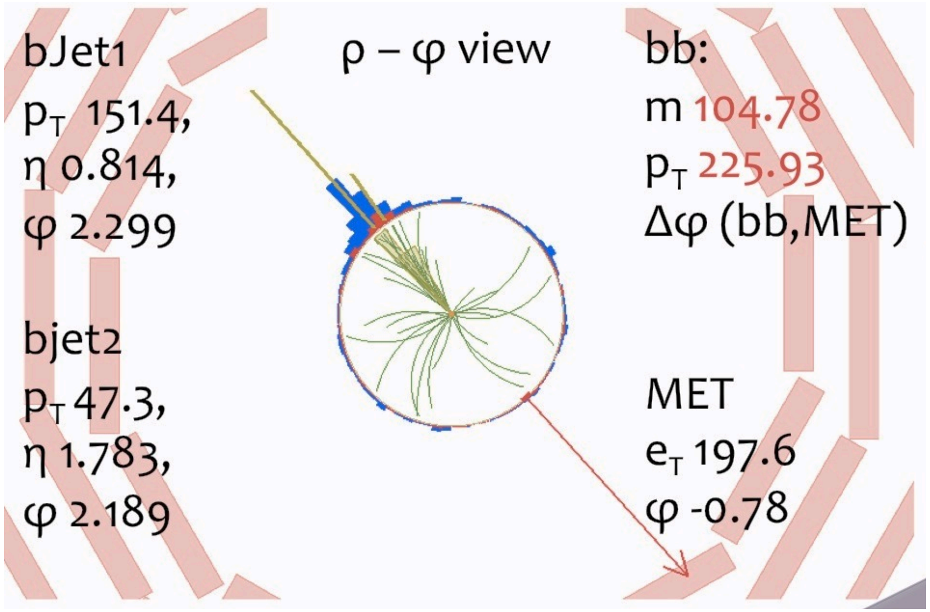
Bkgd: gluon-enriched production



- **W/Z+H(bb) is the main channel for low mass Higgs at Tevatron**
- **At LHC (pp-collisions), S/B is 3-4 times worse than at Tevatron**

V+H(bb) signature





Selection:

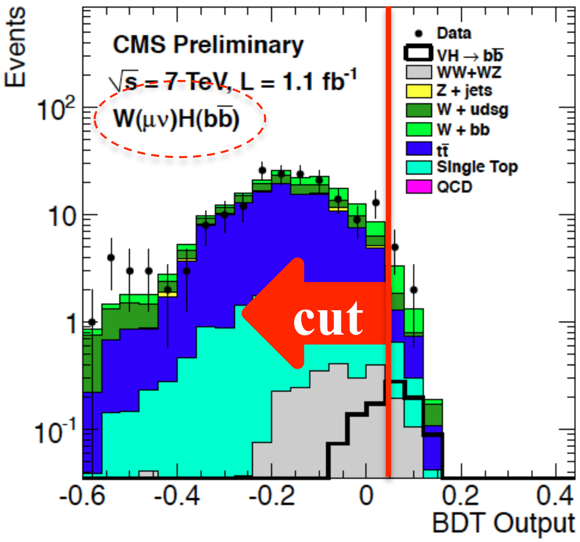
- **5 channels: W→lv, Z→ll, Z→vv**
- **high MET quality for W(lv) and Z(vv)**
- **two jets with tight b-tags**
- **V+H(bb) topology: back-to-back, Δϕ(V,H) > 3**
- **p_T(bb)> 100-160 GeV (but not super boosted)**
- **cut-and-count on MVA output (BDT)**

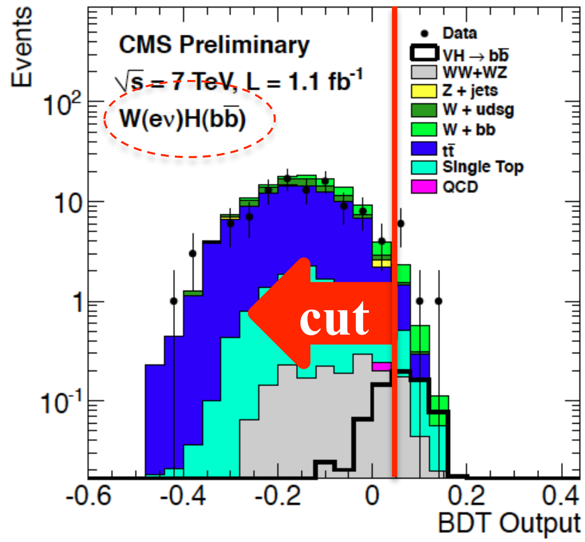
bb mass resolution: 10%
(aided by the bb-system boost)

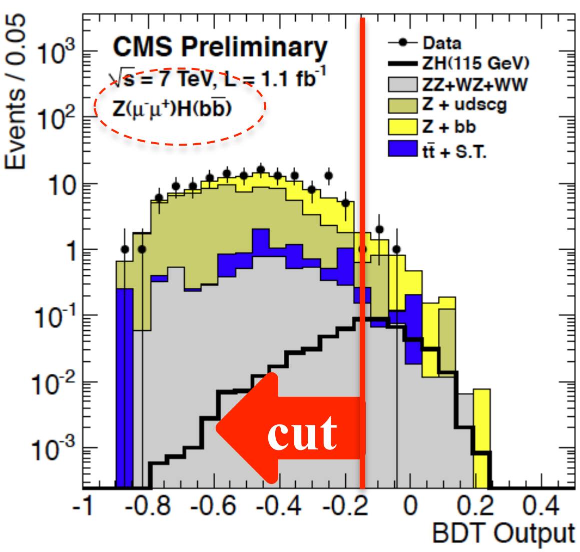
Main backgrounds:

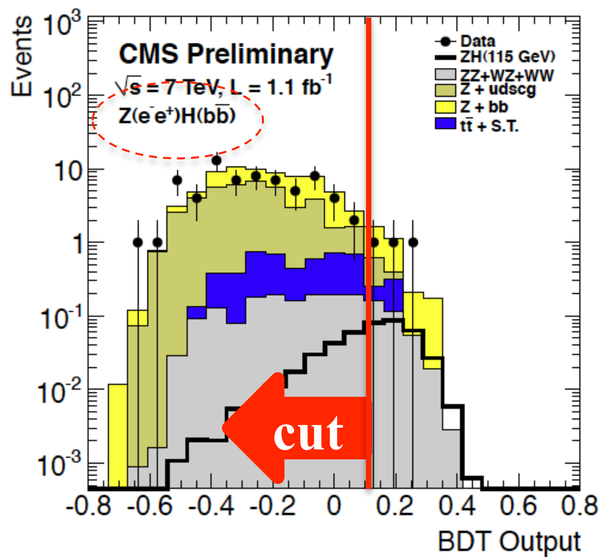
- **Vbb: from data (invert p_T(bb) boost)**
- **V+jets: from data (invert b-tag)**
- **tt: from data (require extra jet)**
- **QCD: from data (require small Δϕ(MET,jet), …)**
- **W+Z(bb) and Z+Z(bb): from MC**

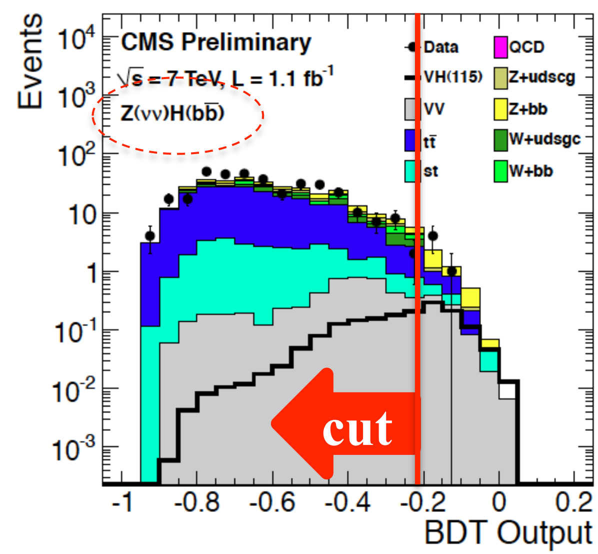
H->bb distributions (m_H=115 GeV)



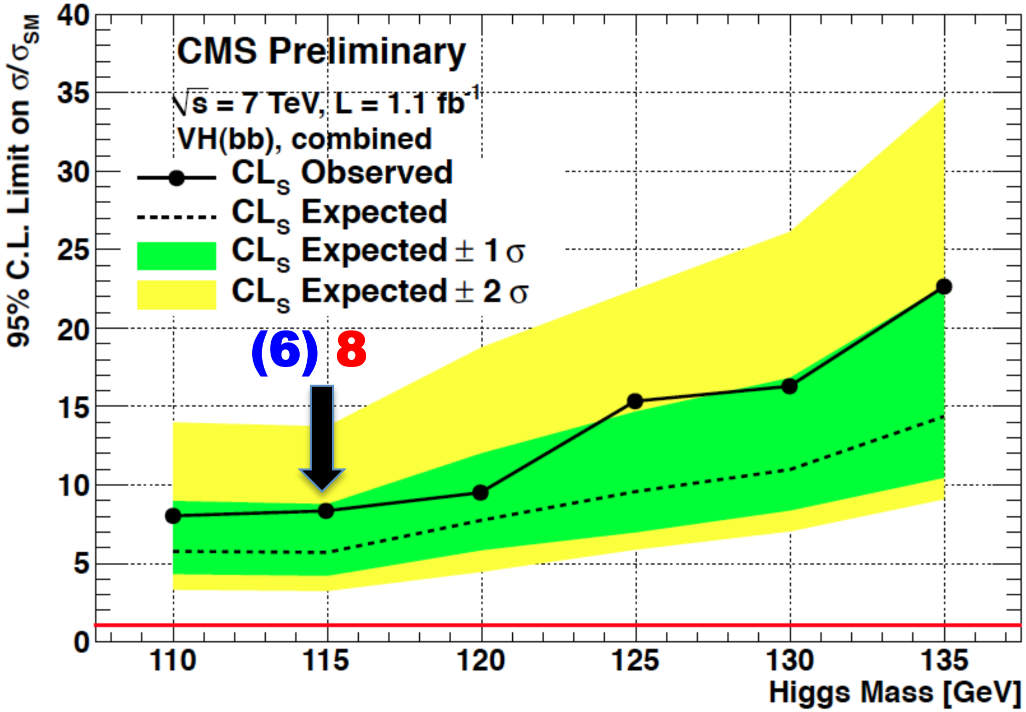








H->bb results



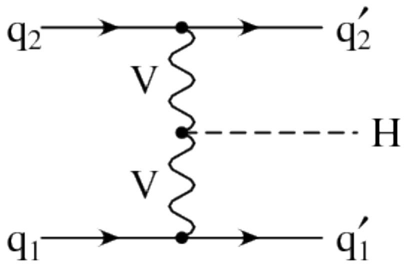
m_H=115 GeV

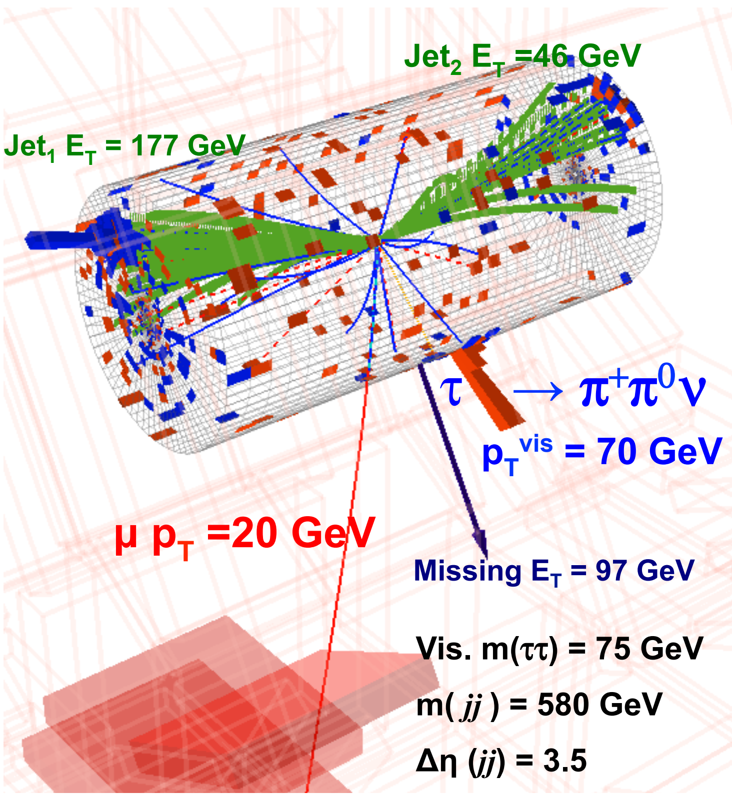
- Sensitivity 5.7
- Observed 8.3

Ratio of limits with/without systematic errors ~1.3

H -> $\tau\tau$

H->ττ signature





Selection:

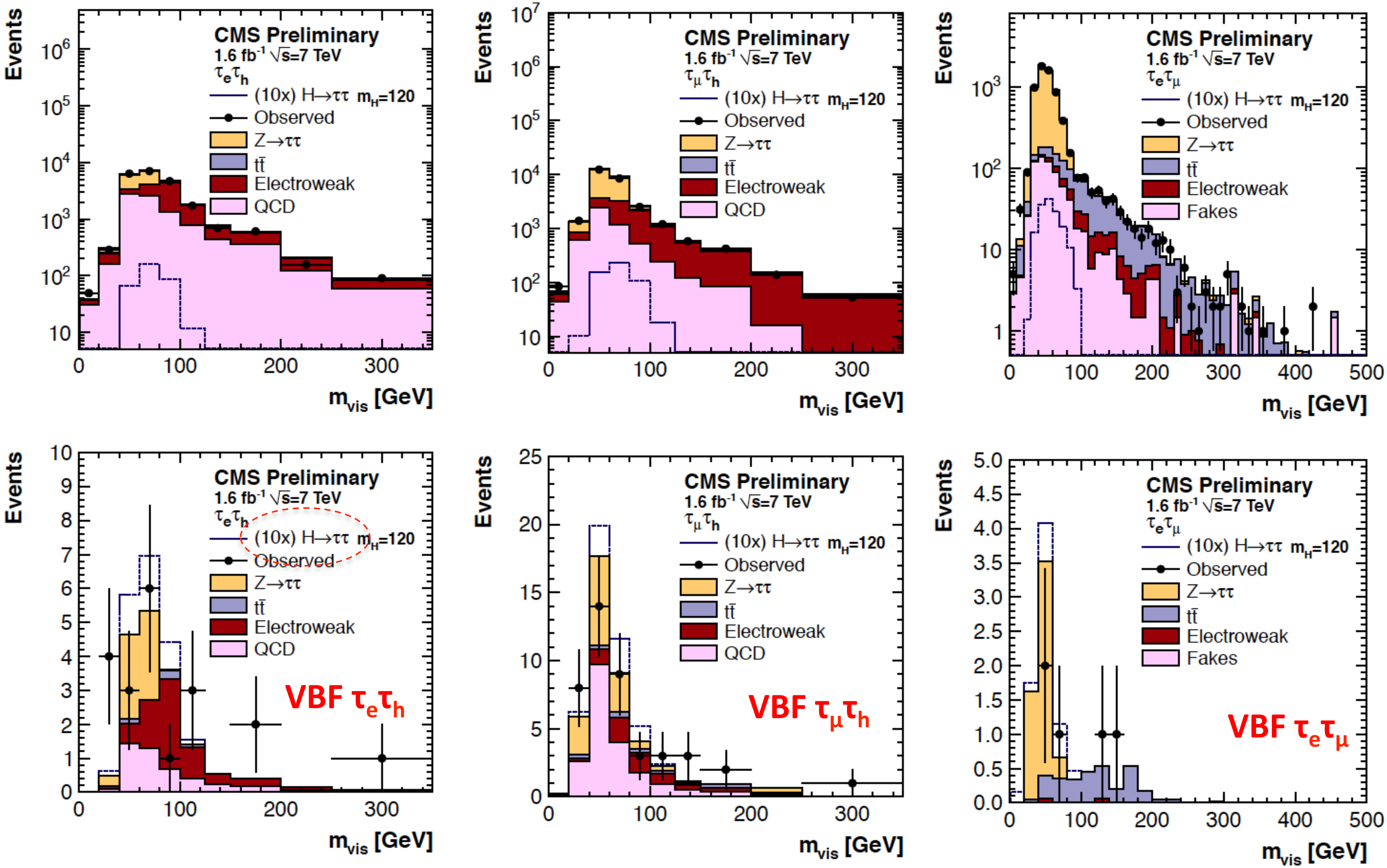
- 6 channels: $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_\mu$ (VBF, non-VBF)
- main sensitivity from VBF production: two forward jets with no jets in between
- isolated leptons
- CDF topological cut (p_{T1}, p_{T2}, MET)
- final discriminant: ττ-mass distribution

ττ mass resolution: 20%

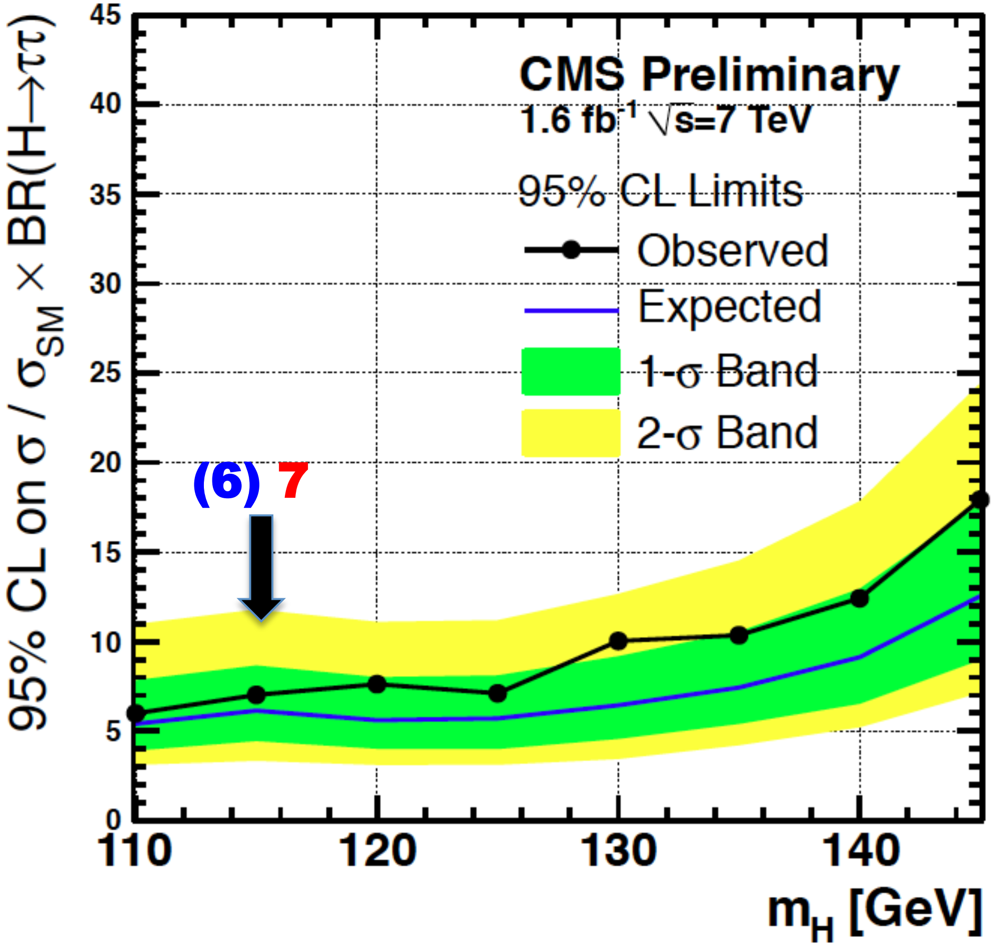
Main backgrounds:

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

H->ττ distributions



H->ττ results

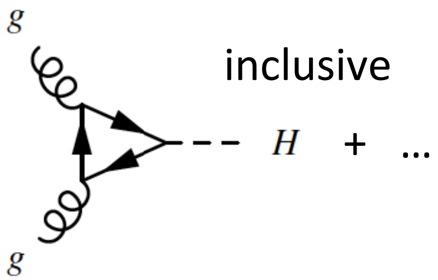


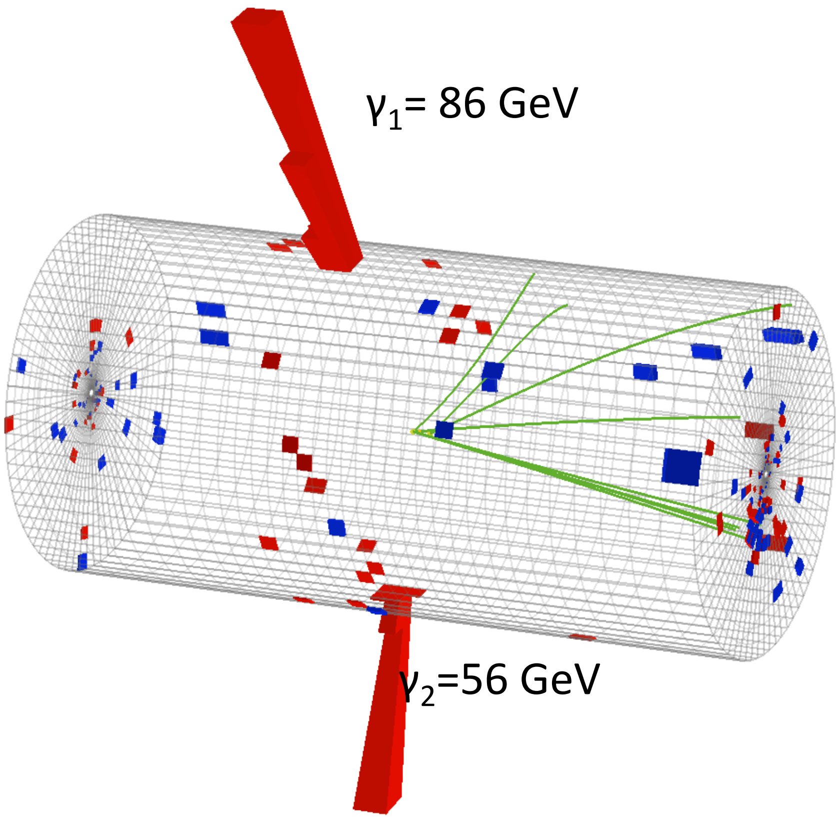
m_H=115 GeV

- Sensitivity 6.1
- Observed 7.0

H -> γγ

H->γγ signature



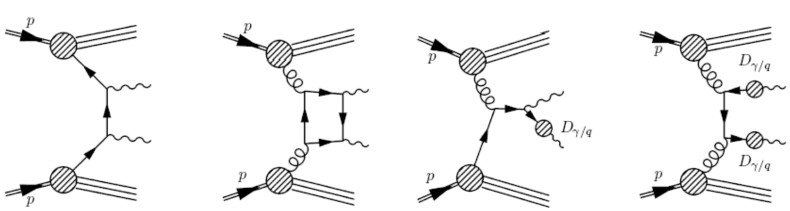


Selection:

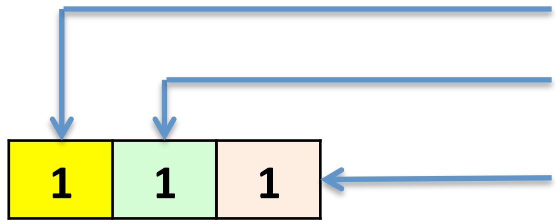
- inclusive production
- two isolated photons
- 4 event categories based on quality of photons and, hence, expected $m_{\gamma\gamma}$ resolution
- Events are also split based on $p_T(\gamma\gamma)$, but this helps only for fermiophobic higgs
- final discriminant: γγ-mass distributions

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

Main backgrounds: from sidebands



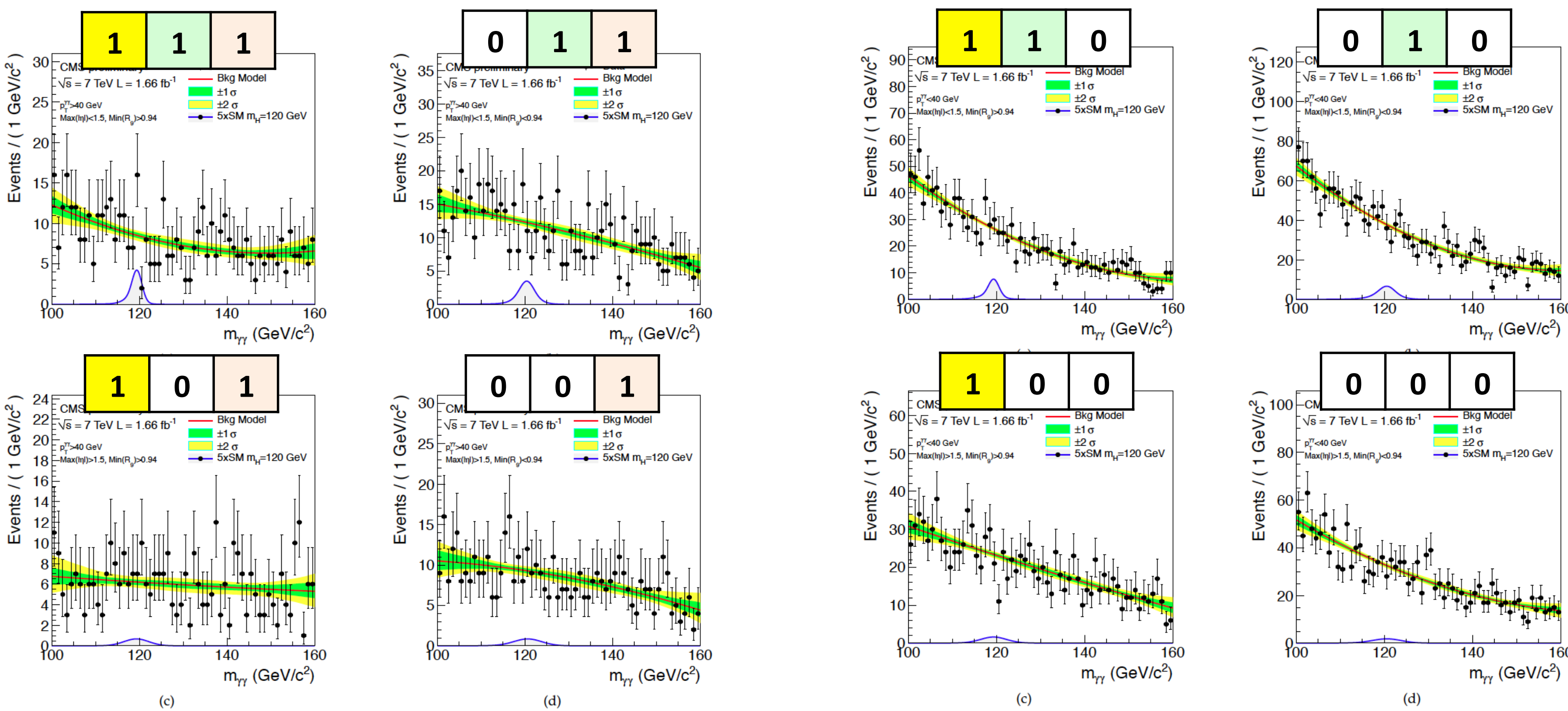
H->γγ distributions



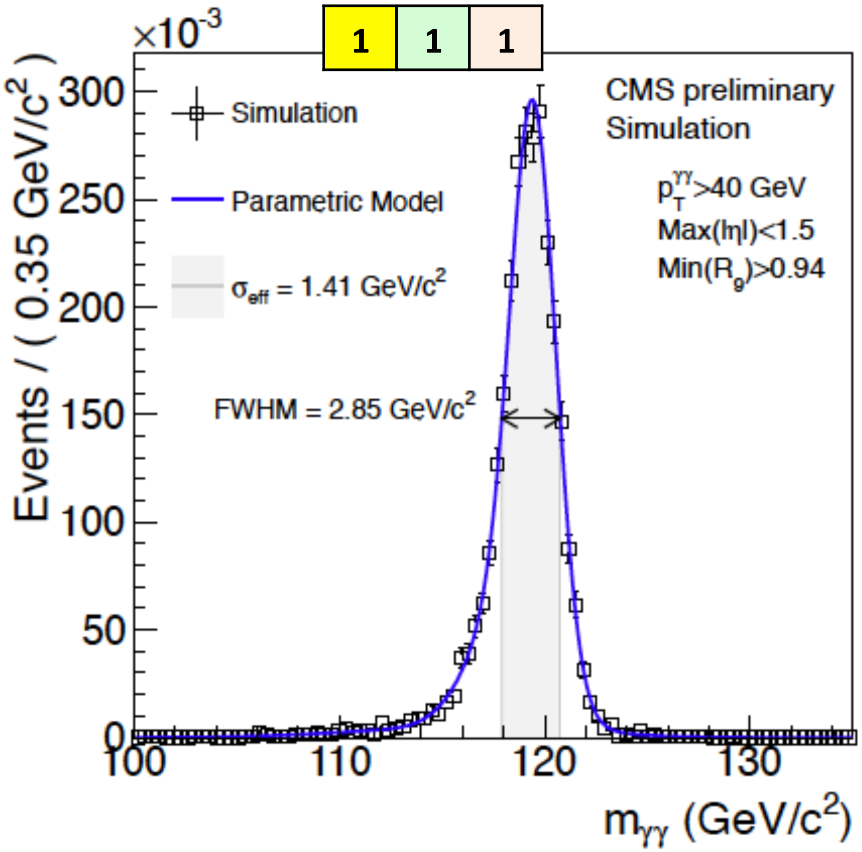
Both photons of high quality?

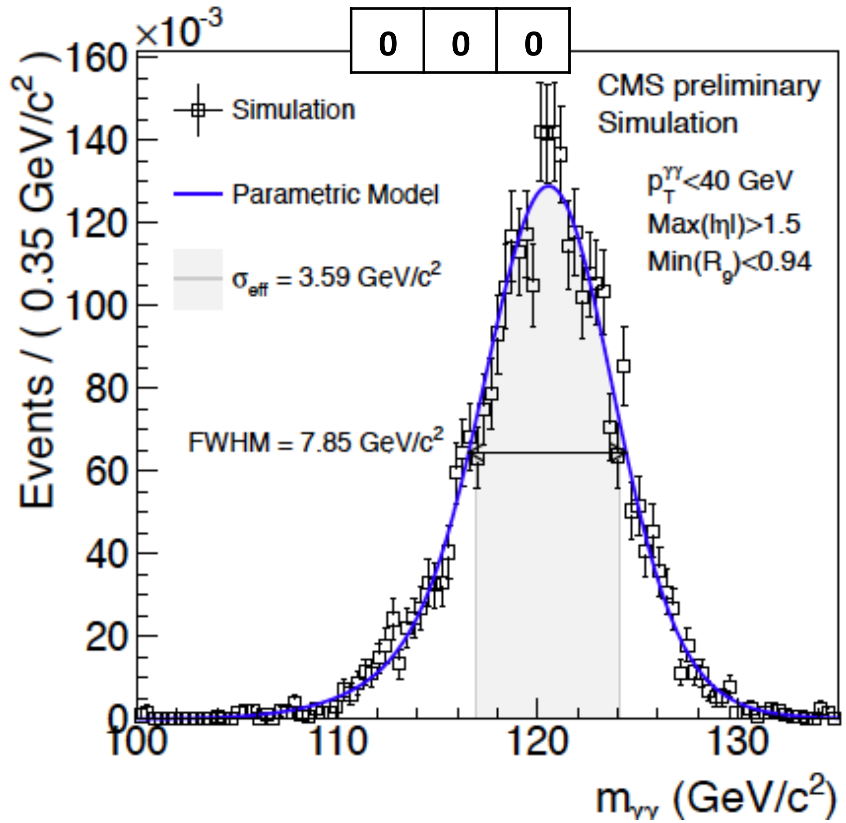
Both photons in barrel?

Di-photon p_T>40 GeV?
(this bit is useful for fermiophobic Higgs only)

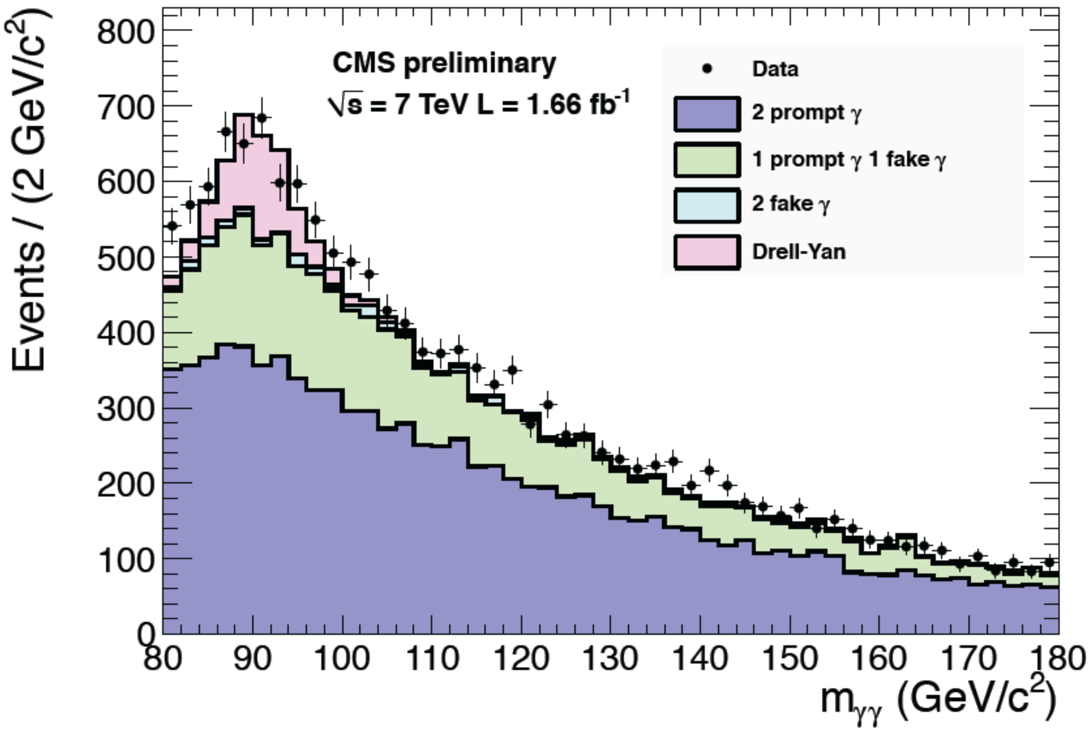


H->γγ mass resolutions

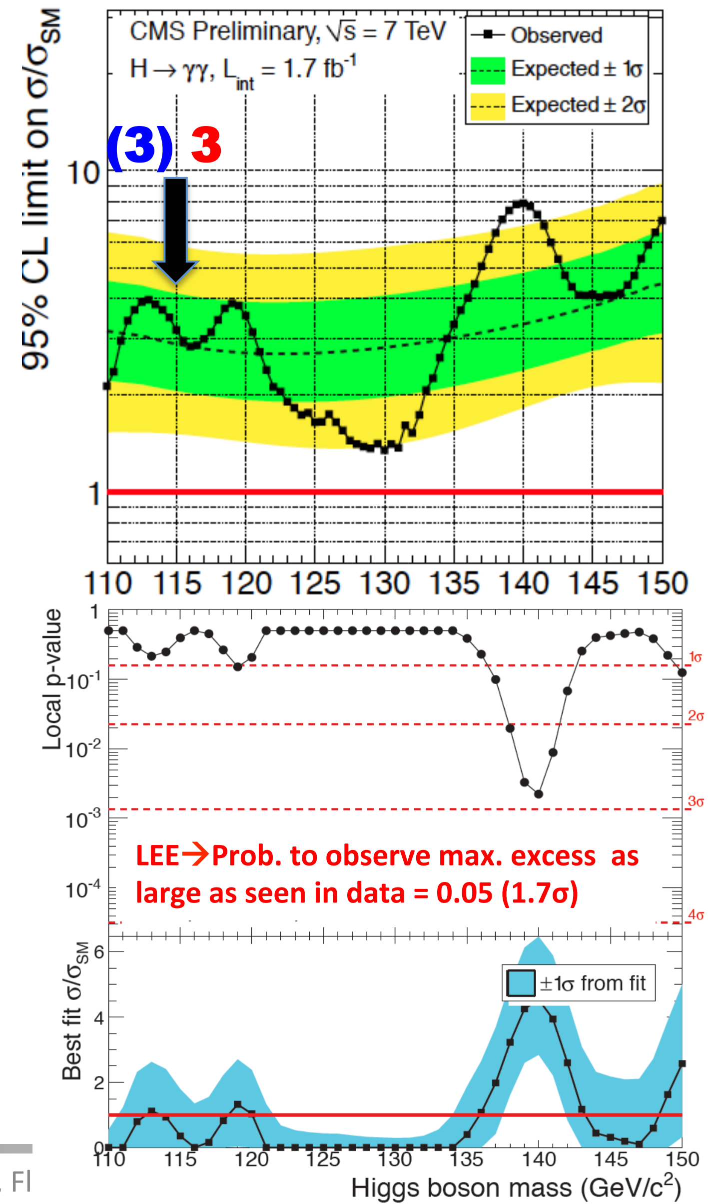




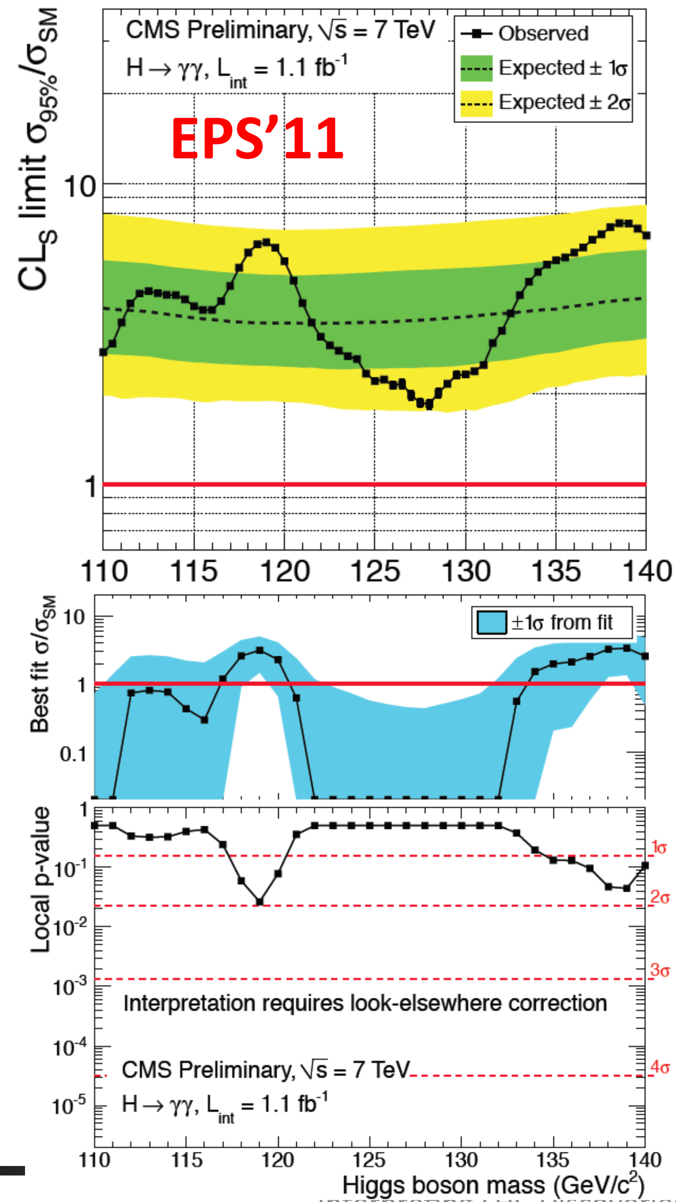
H->γγ results

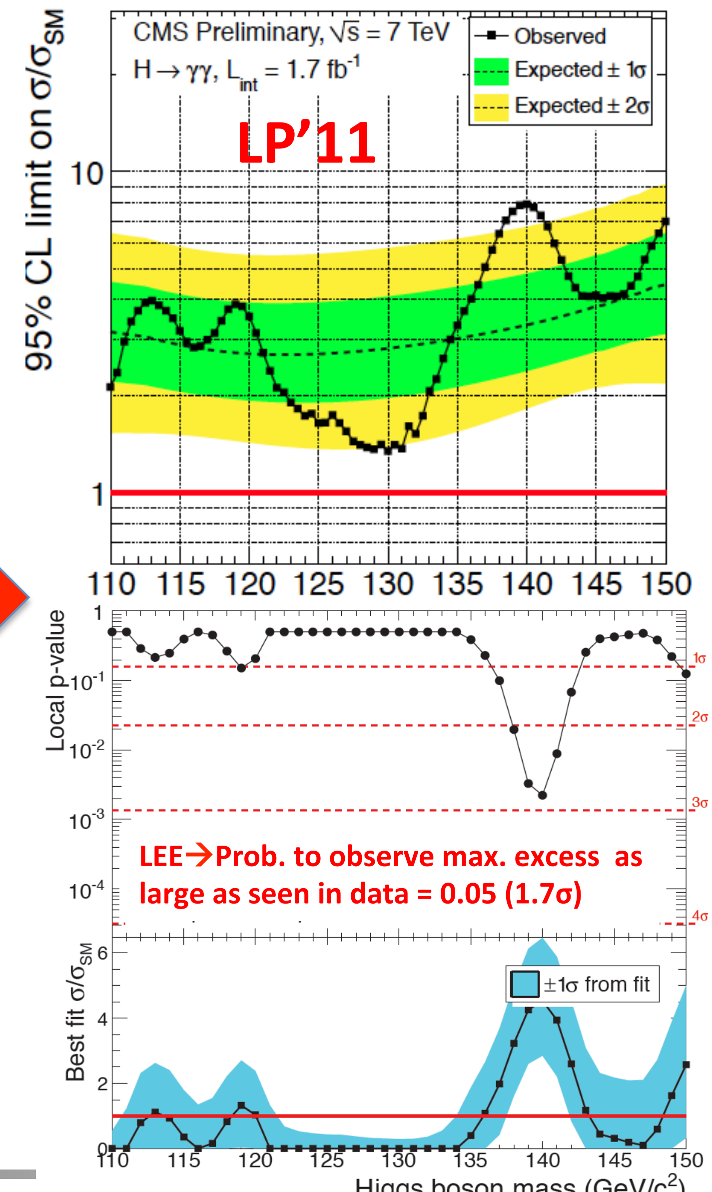


- **Bkgd MC predictions are not used in the analysis**
- **Mass distributions actually analyzed in 8 event categories**



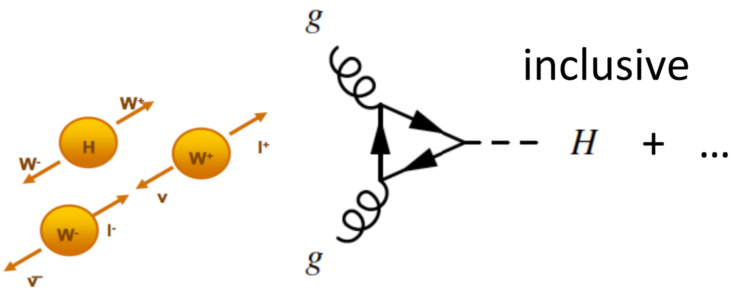
H->γγ results: from EPS and LP

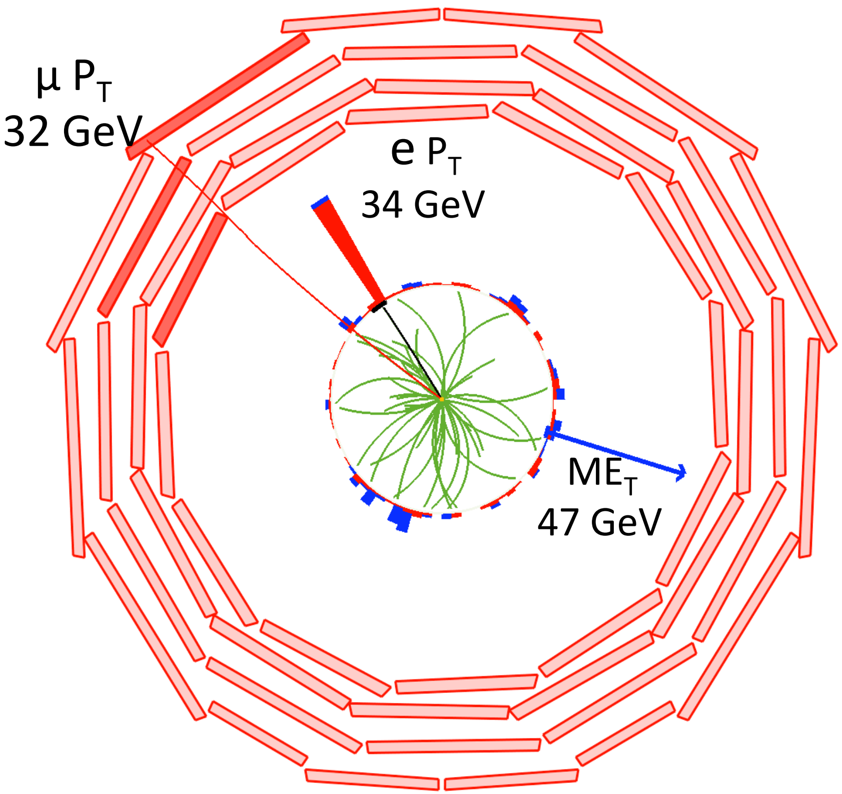




H -> WW

H->WW->lvlv signature





Selection:

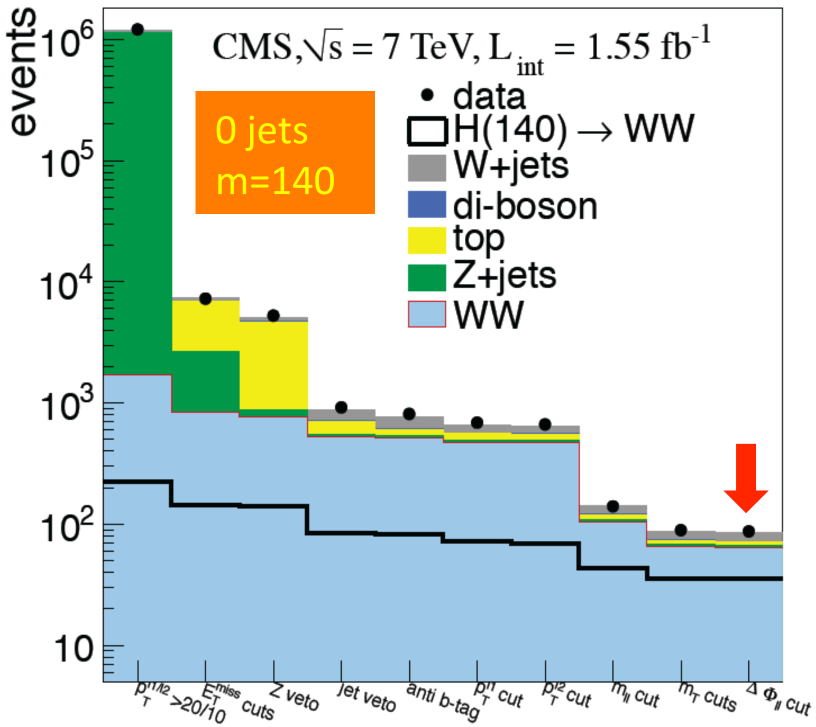
- **two isolated leptons, small Δϕ, small m_{ll}**
- **MET**
- **Transverse mass m_T**
- **cut-and-count in 5 categories:**
  - Same-Flavor di-leptons + 0 jets
  - Opposite-Flavor di-leptons + 0 jets
  - Same-Flavor di-leptons + 1 jet
  - Opposite-Flavor di-leptons + 1 jet
  - SF/OF di-leptons + 2 VBF-like jets

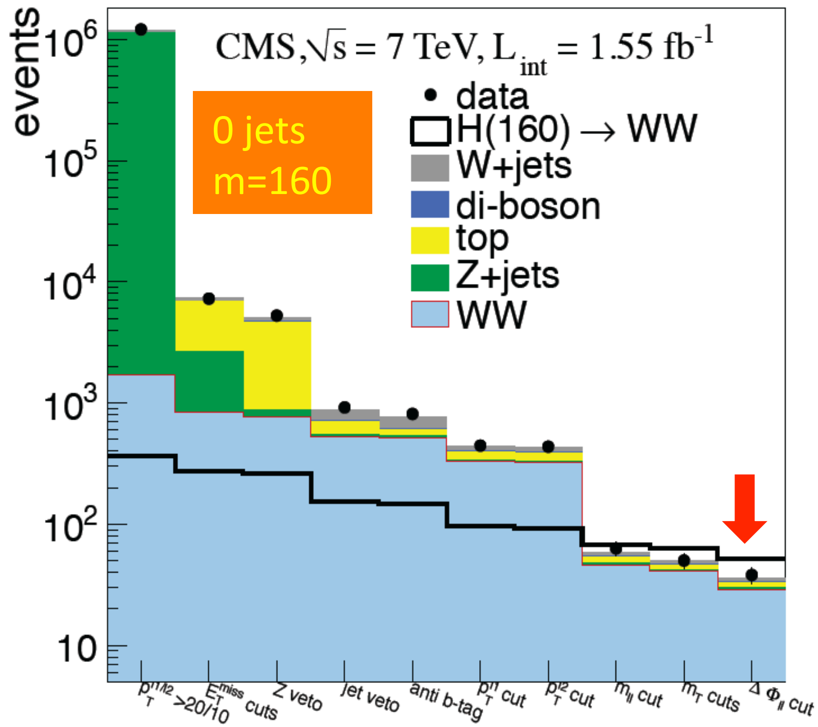
Mass resolution: 20%

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**

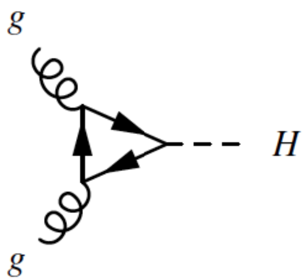
H->WW->lvlv: cut flow





- **Observations:**
  - **remarkable agreement of data and bkgd predictions cut by cut**
  - **for m=160, SM Higgs would give many more events than observed**

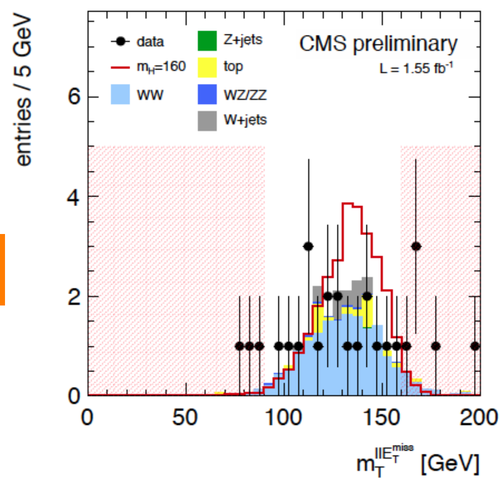
H->WW->lνlν distributions

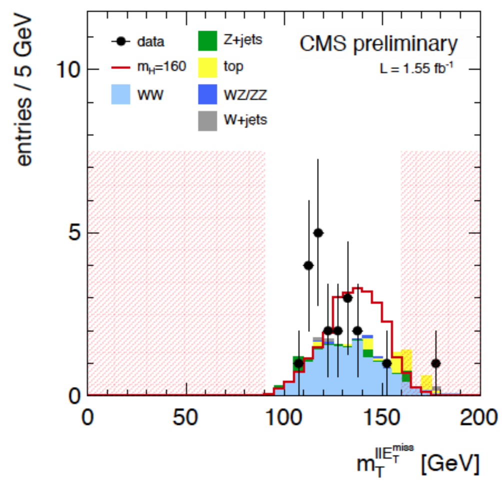


eμ

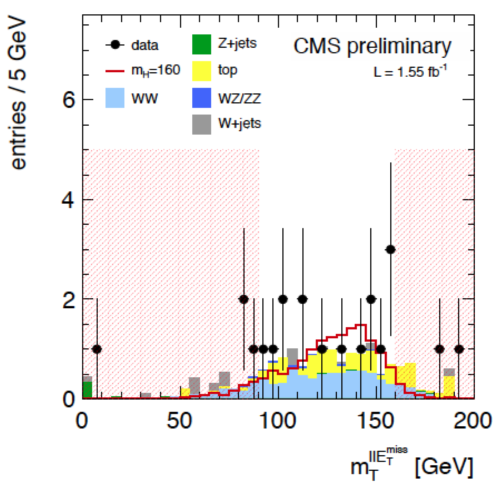
ee + μμ

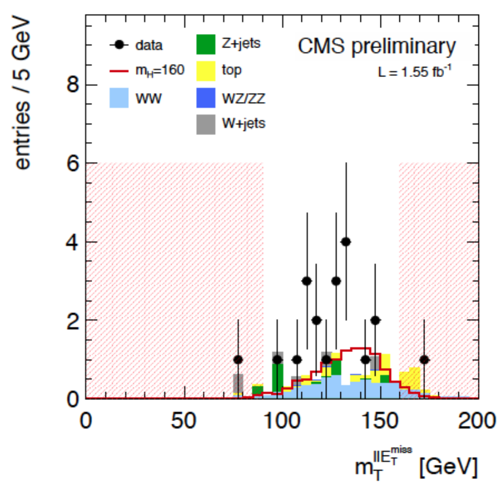
0 jets





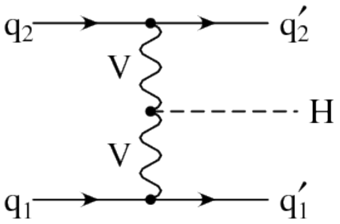
1 jet



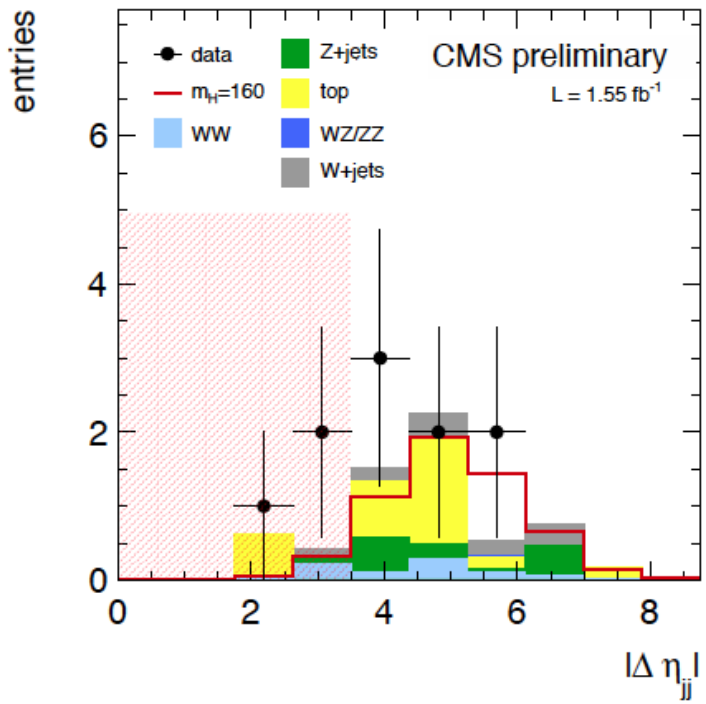


HWW signal is not stacked

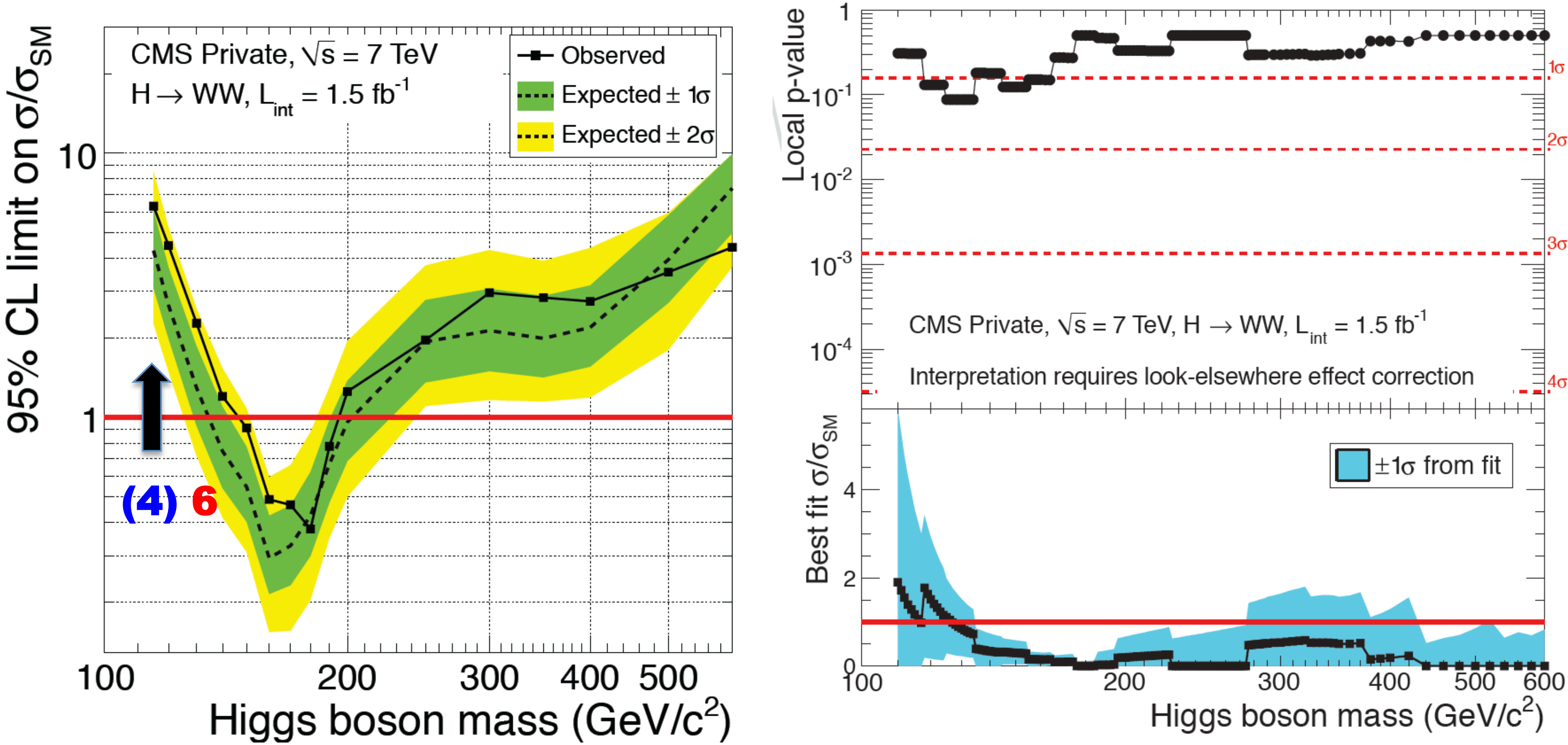
H->WW->lvlv distributions



2 jets

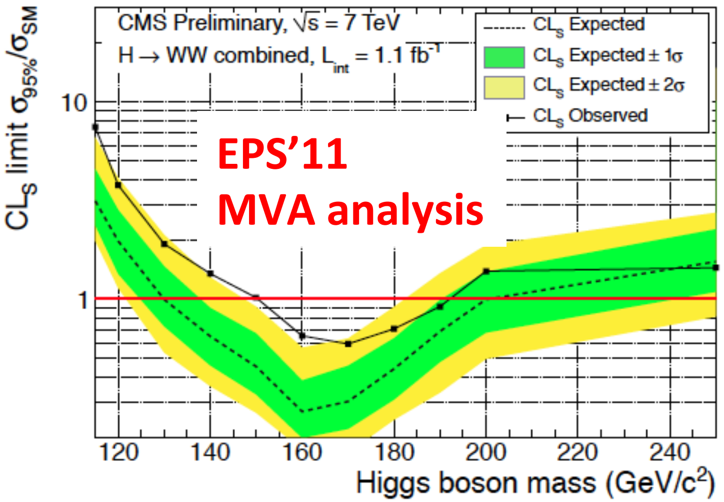


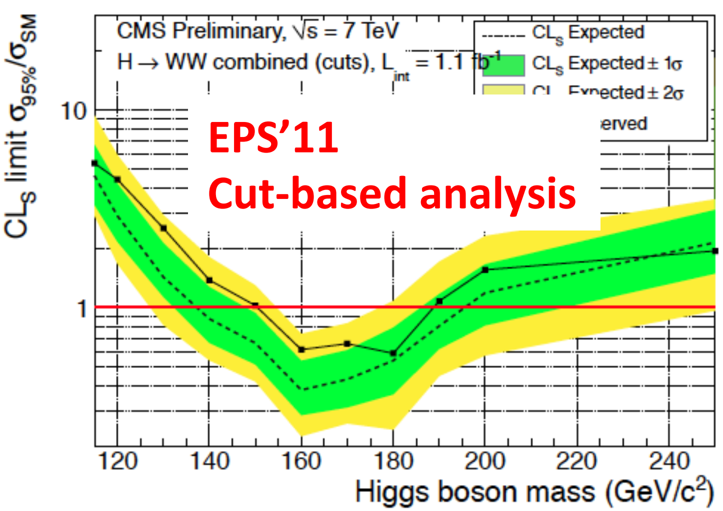
H->WW->lvlv results



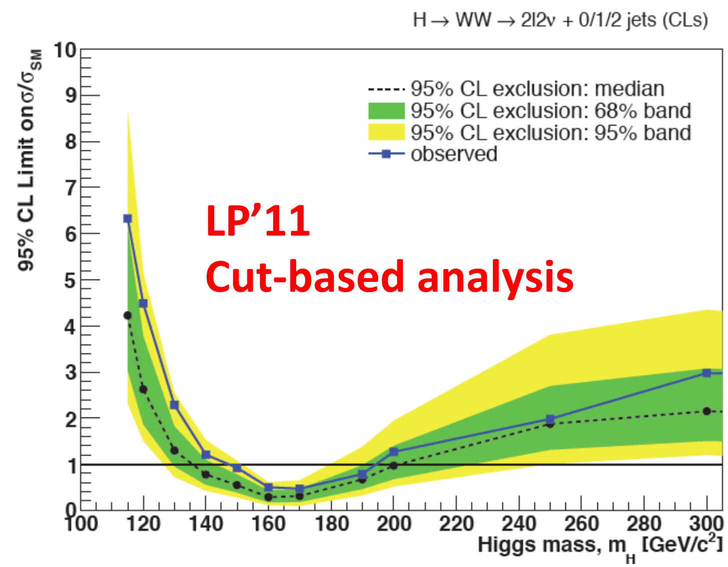
- **SM Higgs boson with mass 147 < M_H < 194 GeV ruled out at 95% CL**
- **SM Higgs boson <u>expected</u> sensitivity 136 < M_H < 200 GeV**
- Ratio of limits at m_H=130 with/without systematic errors ~1.5

H->WW->lνlν results: from EPS and LP



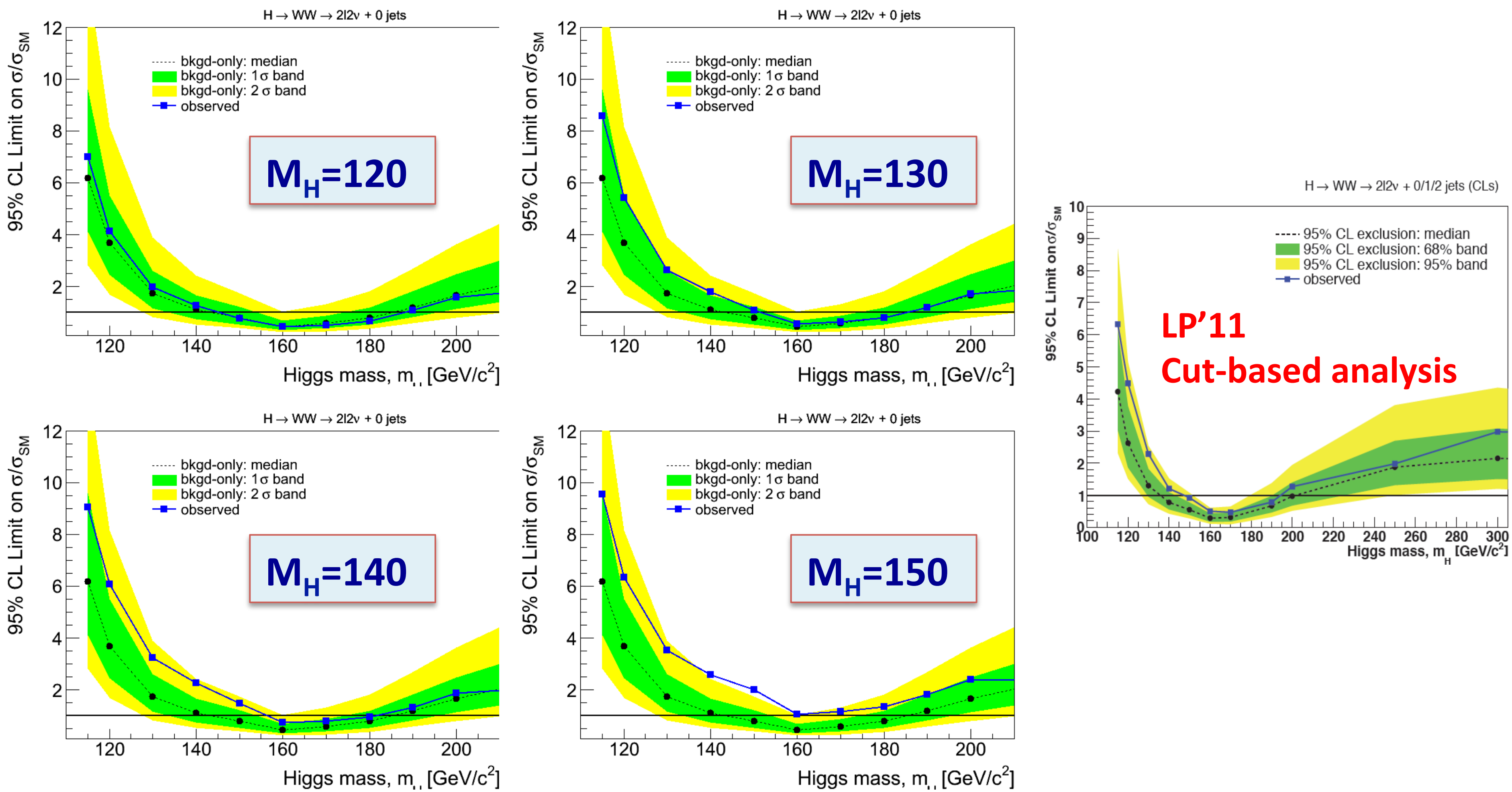


LP'11
MVA analysis not available



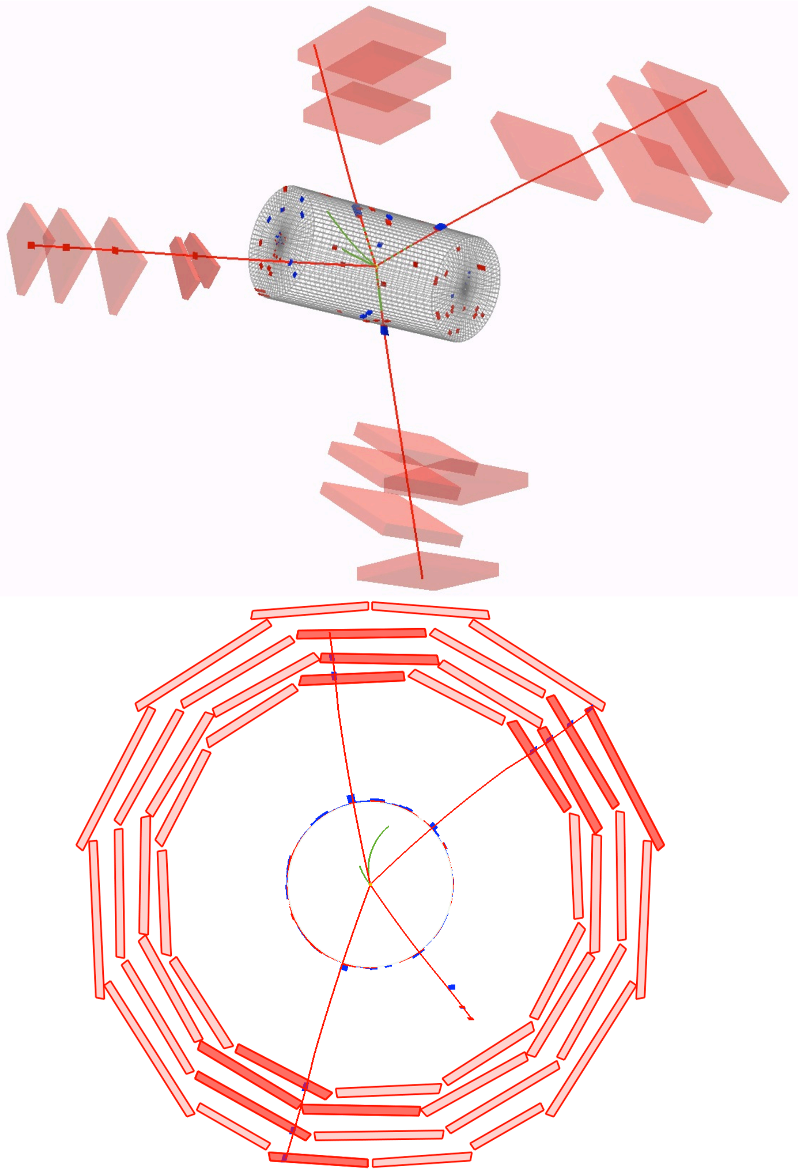
H->WW->2l2v: what to expect?

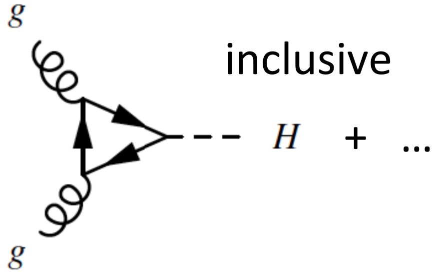
Injecting signal (Azimov dataset):
1.1 fb^{-1} exercise for cut-and-count analysis



H -> ZZ

H->ZZ->4l signature





Selection:

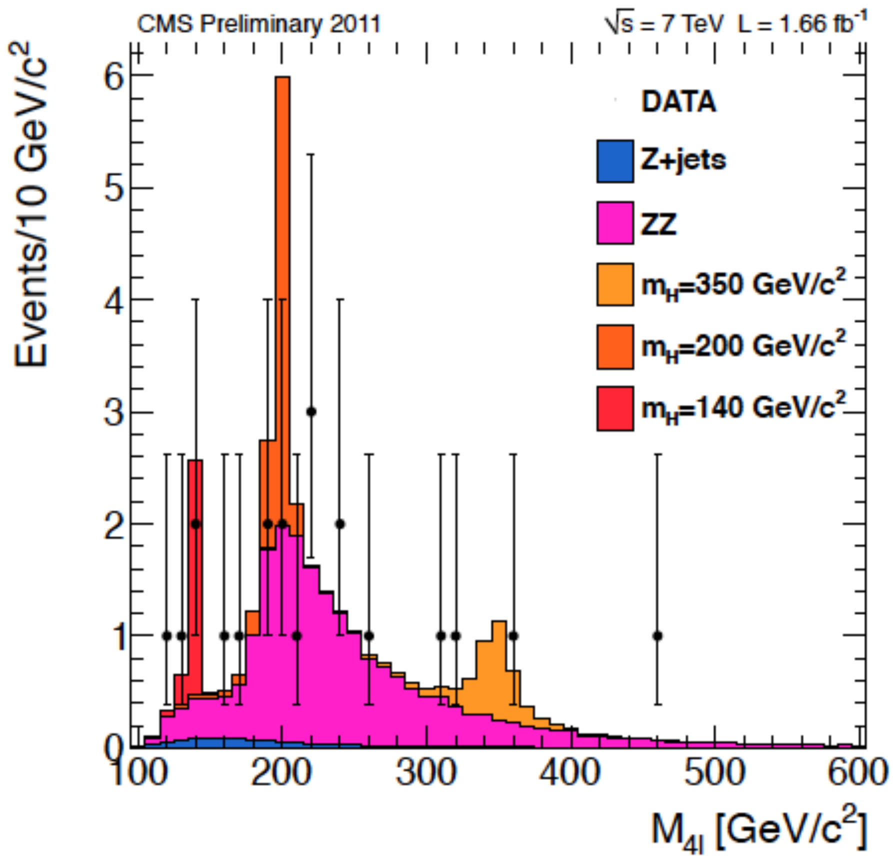
- **4 isolated leptons:** 4e, 4μ, 2e2μ
- **no impact parameter**
- **Final discriminant: m(4l) mass distribution**

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

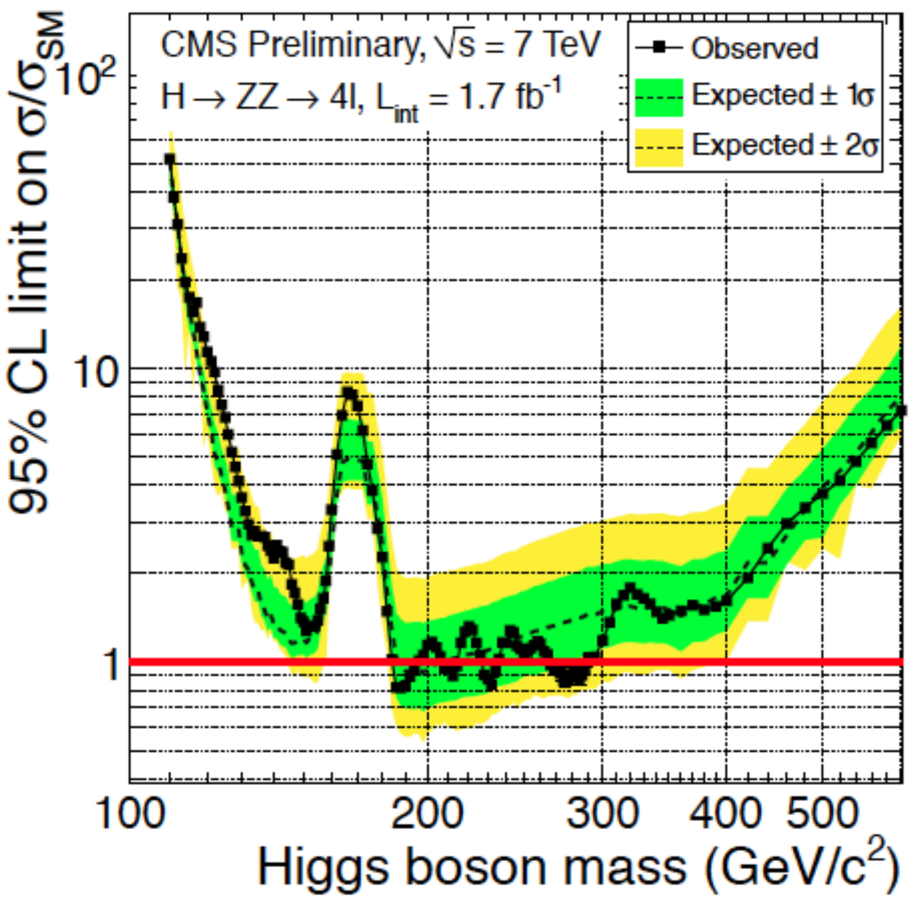


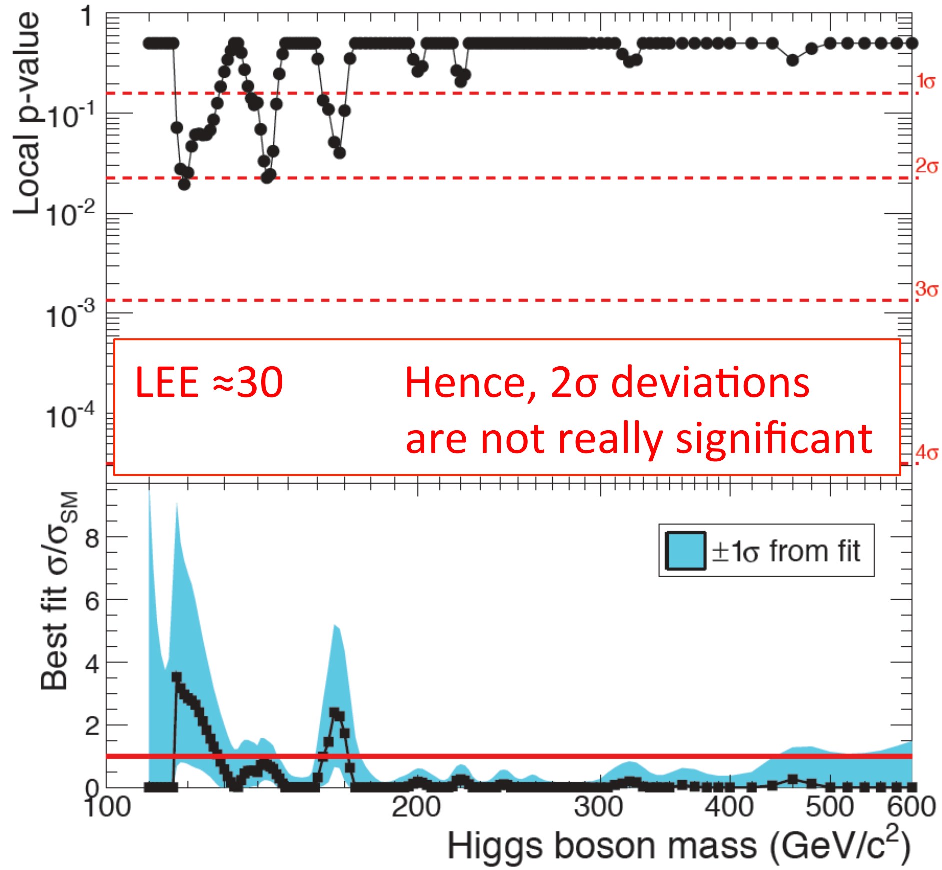
- Observed 21 events
- Expected 21.2 ± 0.8

Note:

- **each event with low m(4l) will appear very significant (low bkgd and narrow peak)**
- **update from EPS (1.1 fb^{-1}) to LP (1.7 fb^{-1}) did not bring new low mass events**

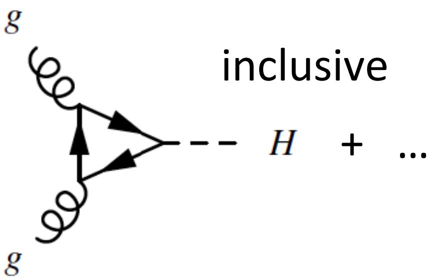
H->ZZ->4l results

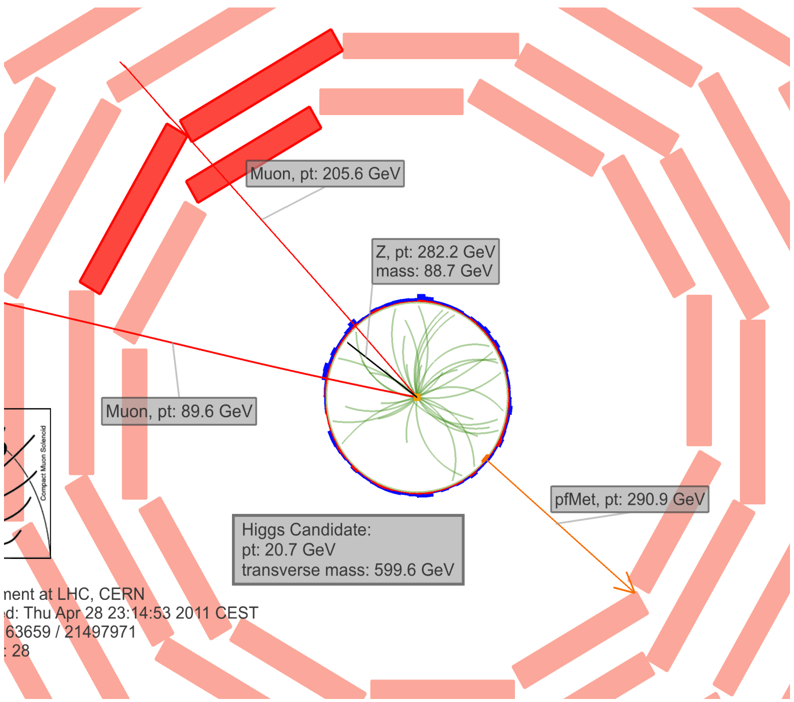




Ratio of limits with/without system errors ~1.06

H->ZZ->2l2ν signature





Selection:

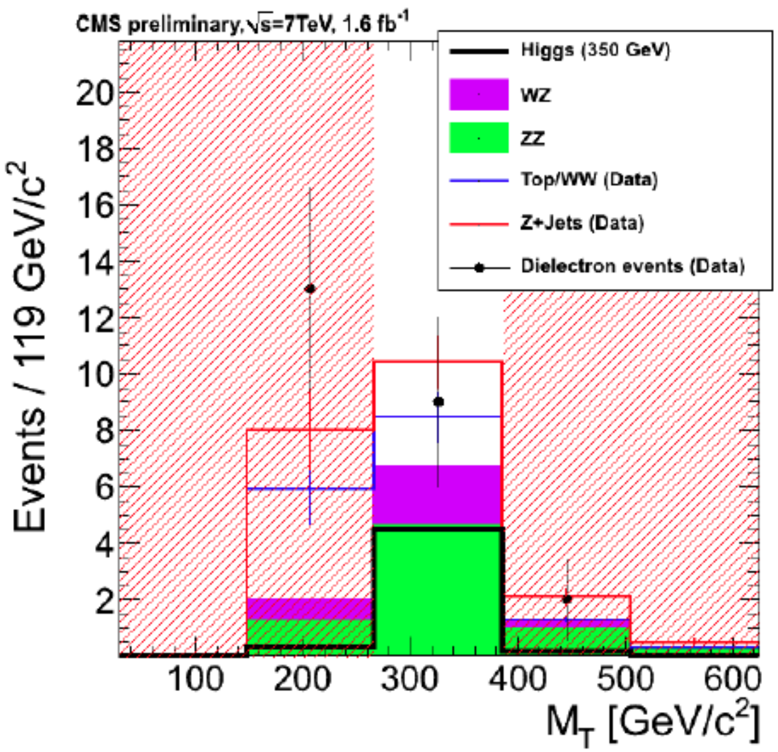
- 2 channels: 2 isolated leptons: Z(2e), Z(2μ)
- no impact parameter
- large $p_T(ll)$
- large MET, not aligned with jets or leptons
- m_T (sensitive to mass)
- cut-and-count

Mass resolution: 10%

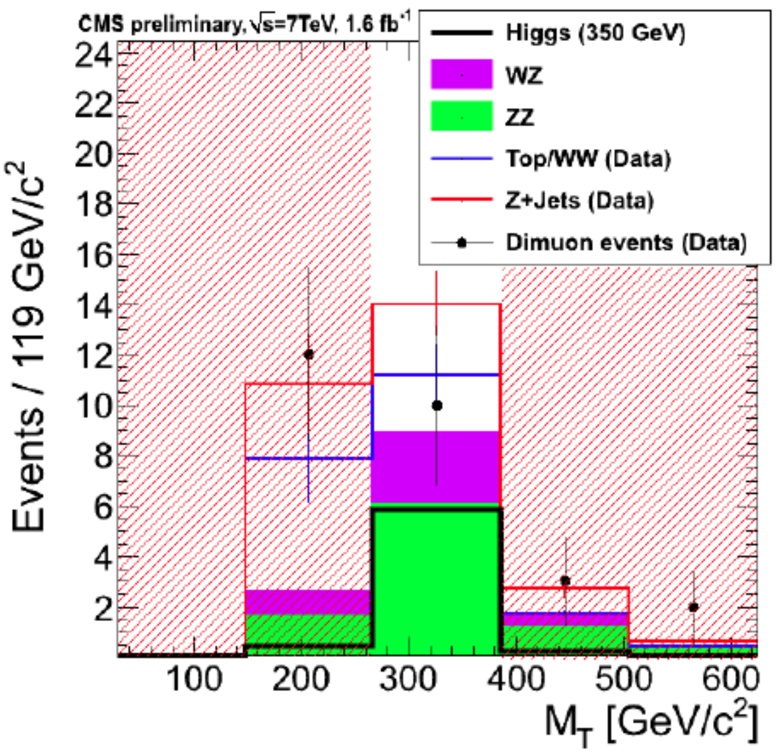
Main backgrounds:

- 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

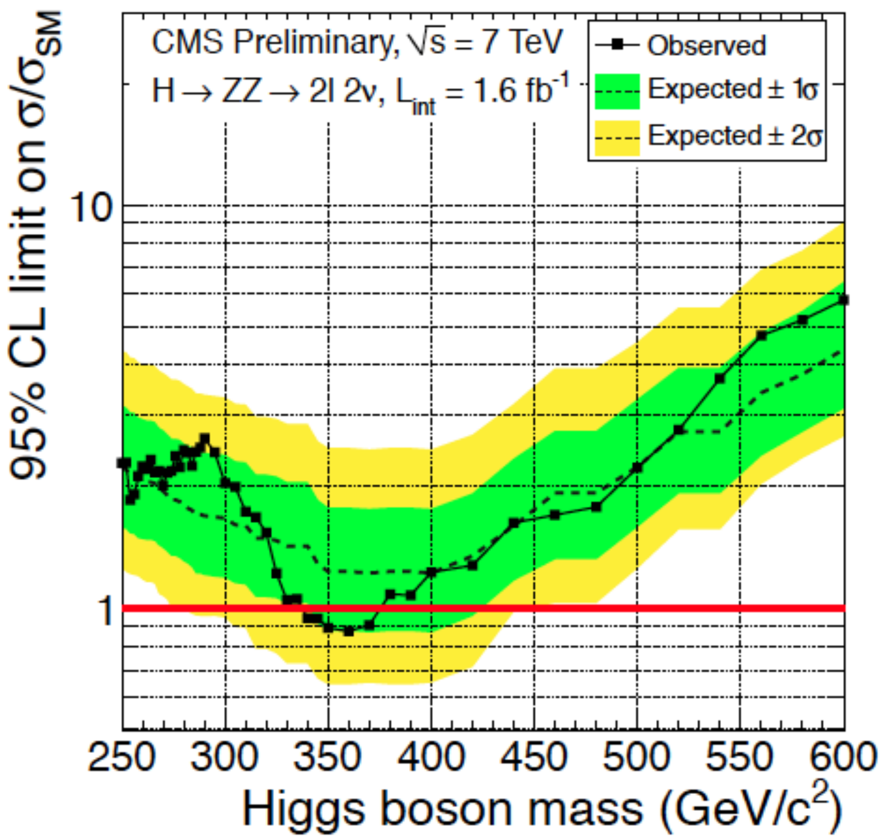


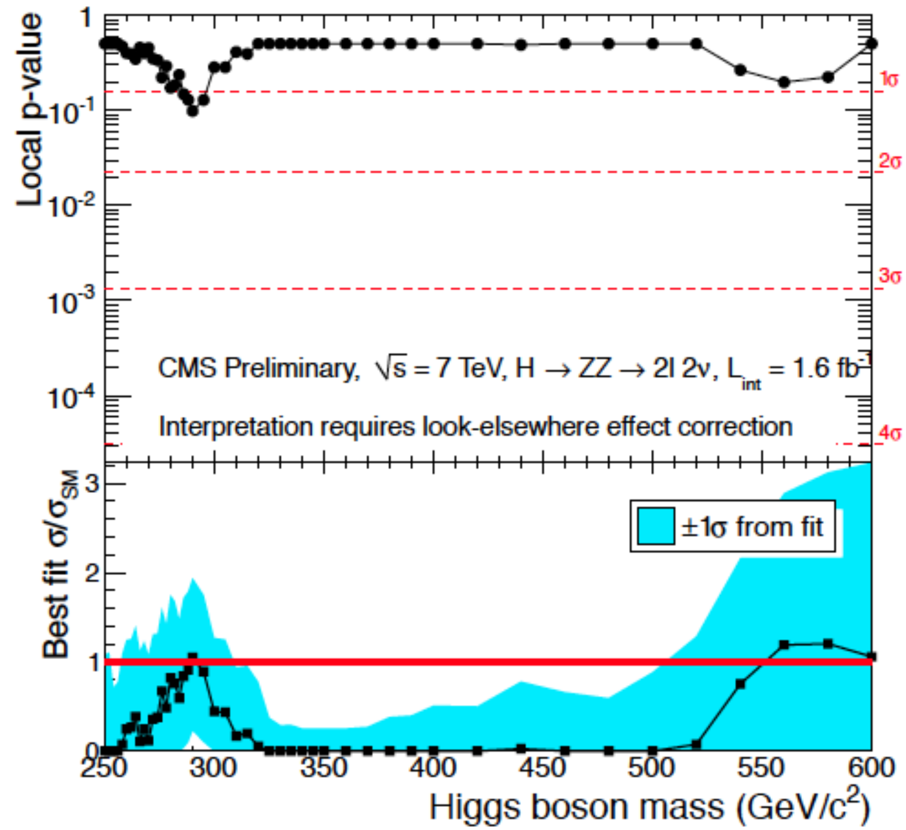
ee



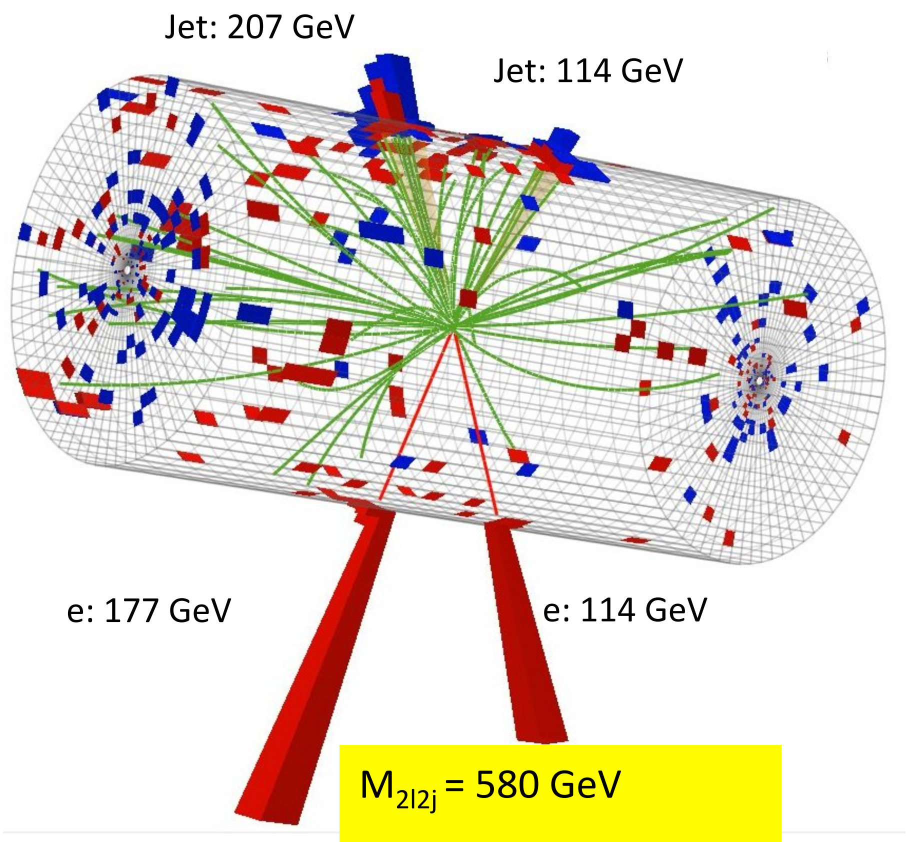
μμ

H->ZZ->2l2ν results





H->ZZ->2l2q signature



Selection:

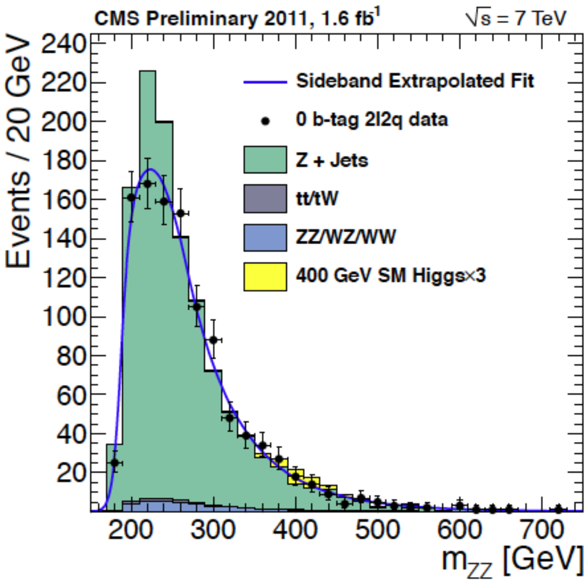
- 2 isolated leptons, Z(2e), Z(2μ), with no impact parameter
- two jets: Z(jj) with 0, 1, 2 b-tags
- most of sensitivity from 2 b-tag category
- no MET
- cut on angular topology (ME-based)
- m_{lljj} mass distribution

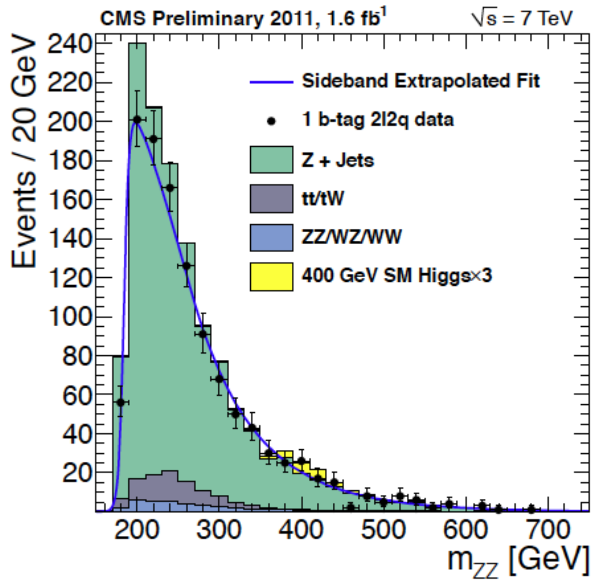
Mass resolution: 3%

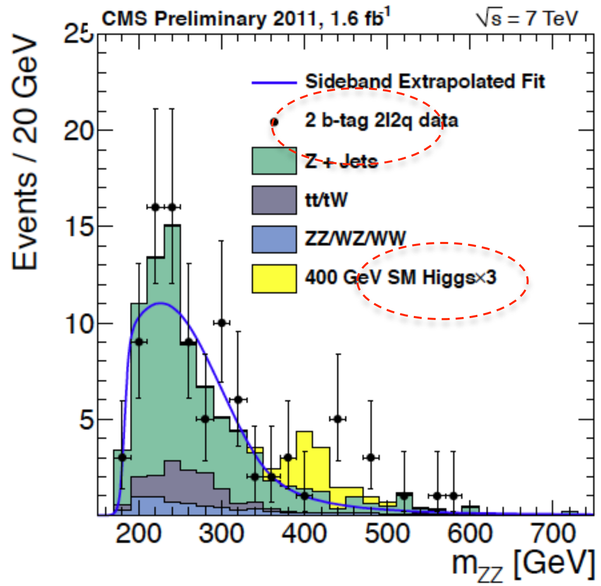
Main backgrounds: from sidebands

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

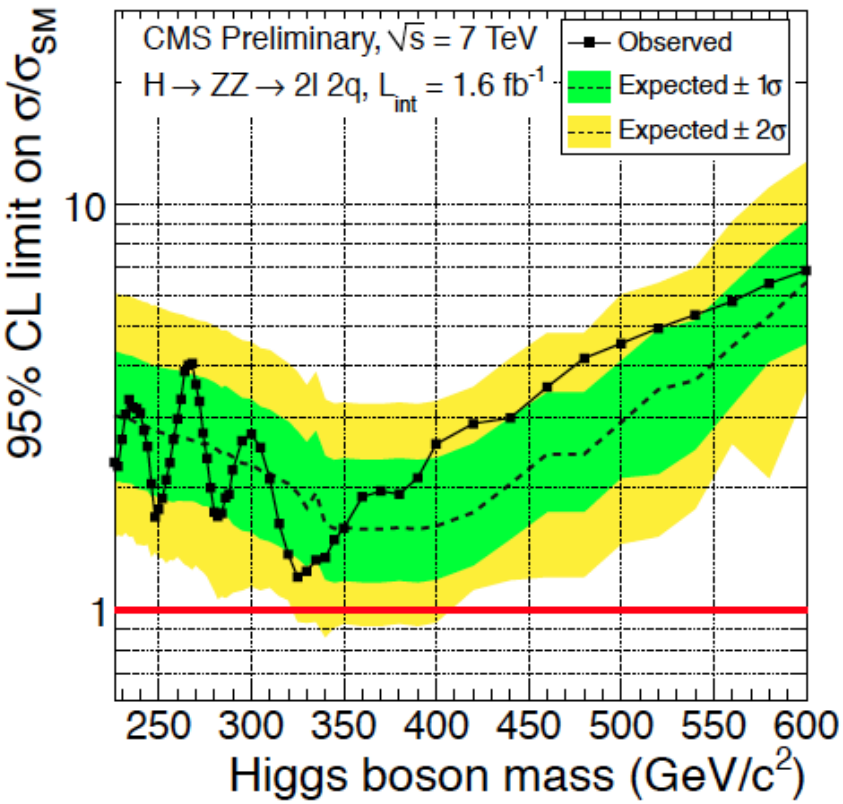
H->ZZ->2l2q distributions

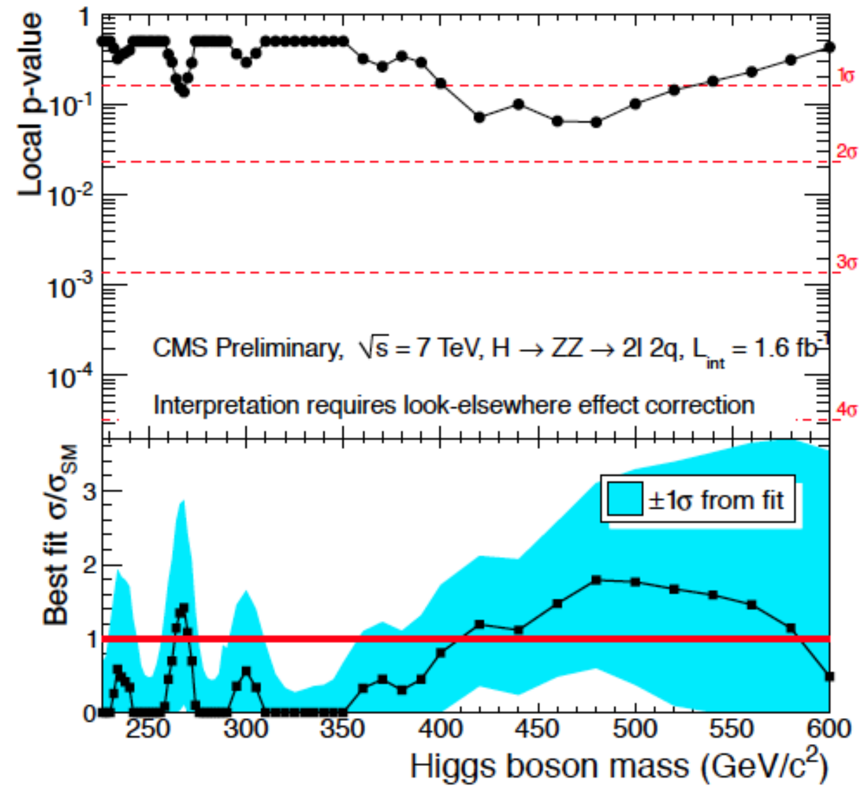






H->ZZ->2l2q results





Combination of searches

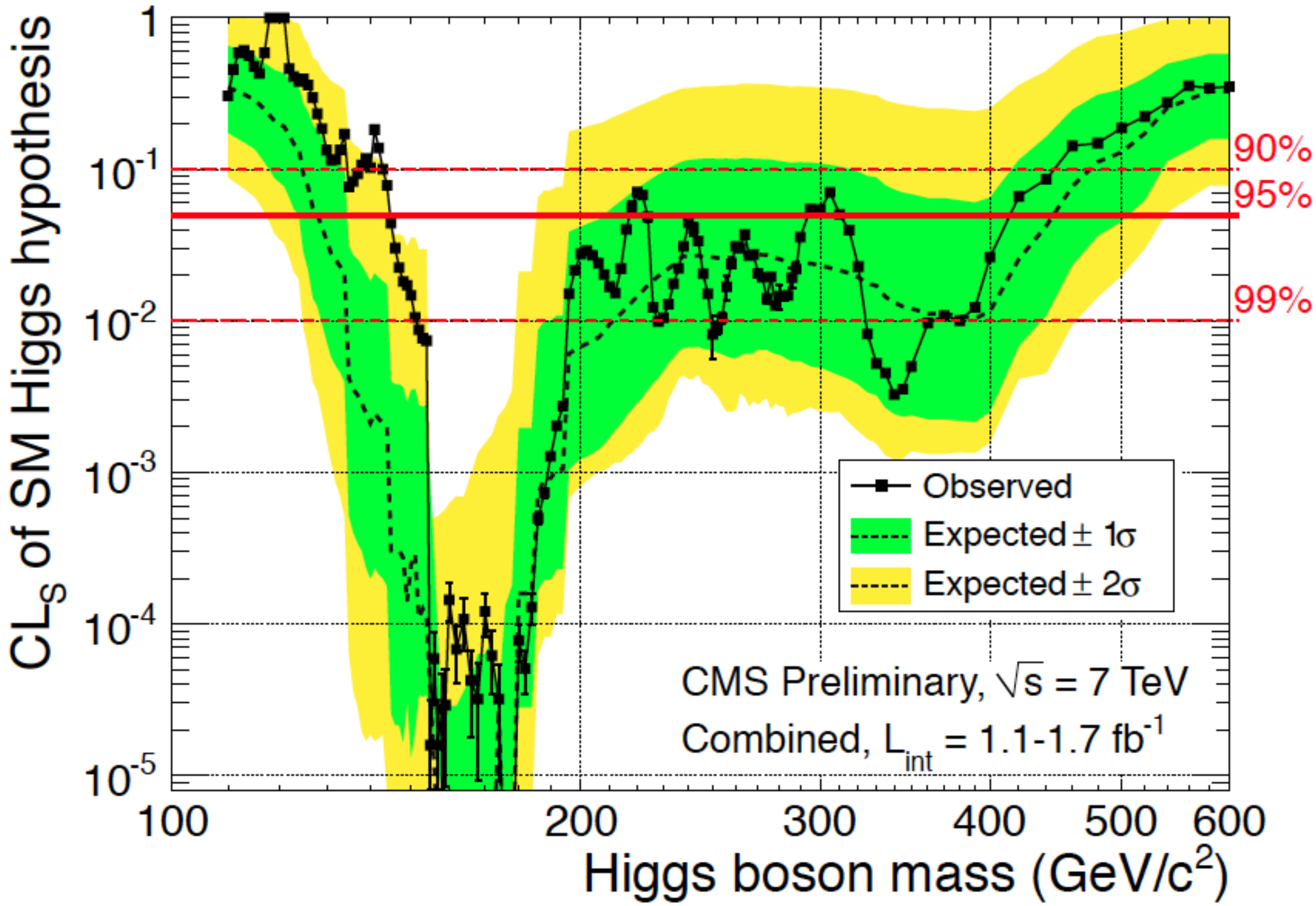
Combination scope

channel	mass range (GeV/c^2)	luminosity (fb^{-1})	number of sub-channels	type of analysis	number of nuisances
$H \to \gamma\gamma$	110-150	1.7	8	mass shape (unbinned)	3+40=43
$H \to \tau\tau$	110-140	1.1	6	mass shape (binned)	10+25=35
$H \to bb$	110-135	1.1	5	cut&count	10+59 = 69
$H \to WW \to 2\ell 2\nu$	110-600	1.5	5	cut&count	15 +79 =94
$H \to ZZ \to 4\ell$	110-600	1.7	3	mass shape (unbinned)	14+20=34
$H \to ZZ \to 2\ell 2\tau$	180-600	1.1	8	mass shape (unbinned)	13+10=23
$H \to ZZ \to 2\ell 2\nu$	250-600	1.6	2	cut&count	14+4=18
$H \to ZZ \to 2\ell 2q$	226-600	1.6	6	mass shape (unbinned)	12+15=27
TOTAL (8)	110-600	1.1-1.7	27 for low m_H 24 for high m_H		241 for low m_H 146 for high m_H

Uncertainties common to many channels

group	nuisance	comments
cross section (pdf)	gg qqbar	$gg \to H, t\bar{t}H, VQQ, t\bar{t}, tW, tb$ (s-channel), $gg \to VV$ VBF $H, VH, V, VV, \gamma\gamma$
cross section (QCD scales)	ggH ggH1in ggH2in qqH VH ttH VV ggVV	total inclusive $gg \to H$ inclusive $gg/qg \to H+ \geq 1$ jets inclusive $gg/qg \to H+ \geq 2$ jets VBF H associate VH $t\bar{t}H$ WW, WZ, and ZZ up to NLO $gg \to WW$ 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 electron tau b-tag	prompt muon efficiency (includes reconstruction, isolation) prompt electron efficiency (includes reconstruction, isolation) reconstruction efficiency of prompt hadronicly decaying tau b-tag efficiency for b-jets (anti-correlated with b-jet veto)
p_T scales	muon electron tau jets	prompt muon p_T-scale prompt electron p_T-scale p_T scale for prompt hadronicly decaying tau 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 electron	prompt muon efficiency (includes trigger, reconstruction, isolation) prompt electron efficiency (includes trigger, reconstruction, isolation)

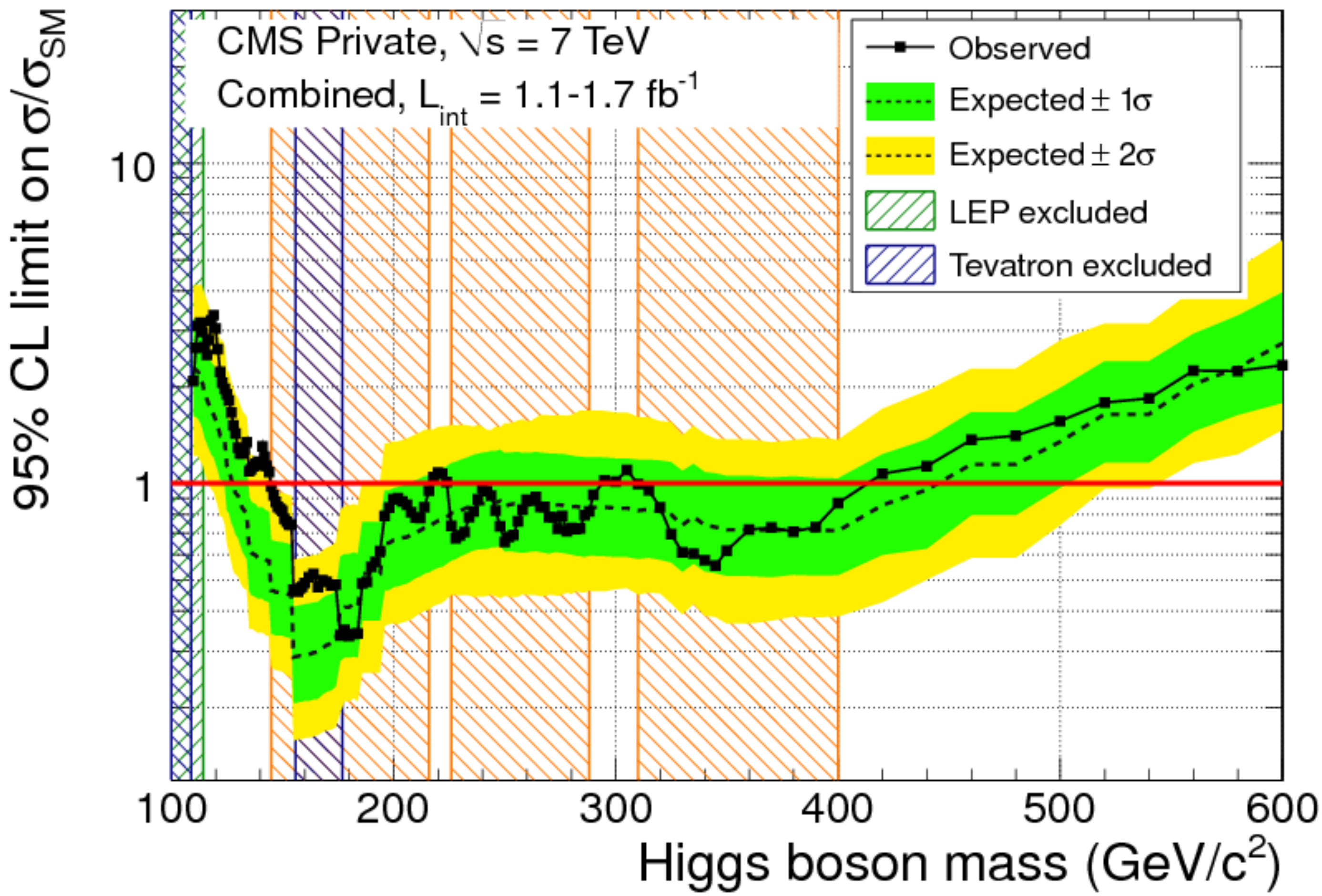
Exclusion CL for SM Higgs



SM Higgs boson: expected exclusion mass range: 130 – 440 GeV

Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

Exclusion limits on μ

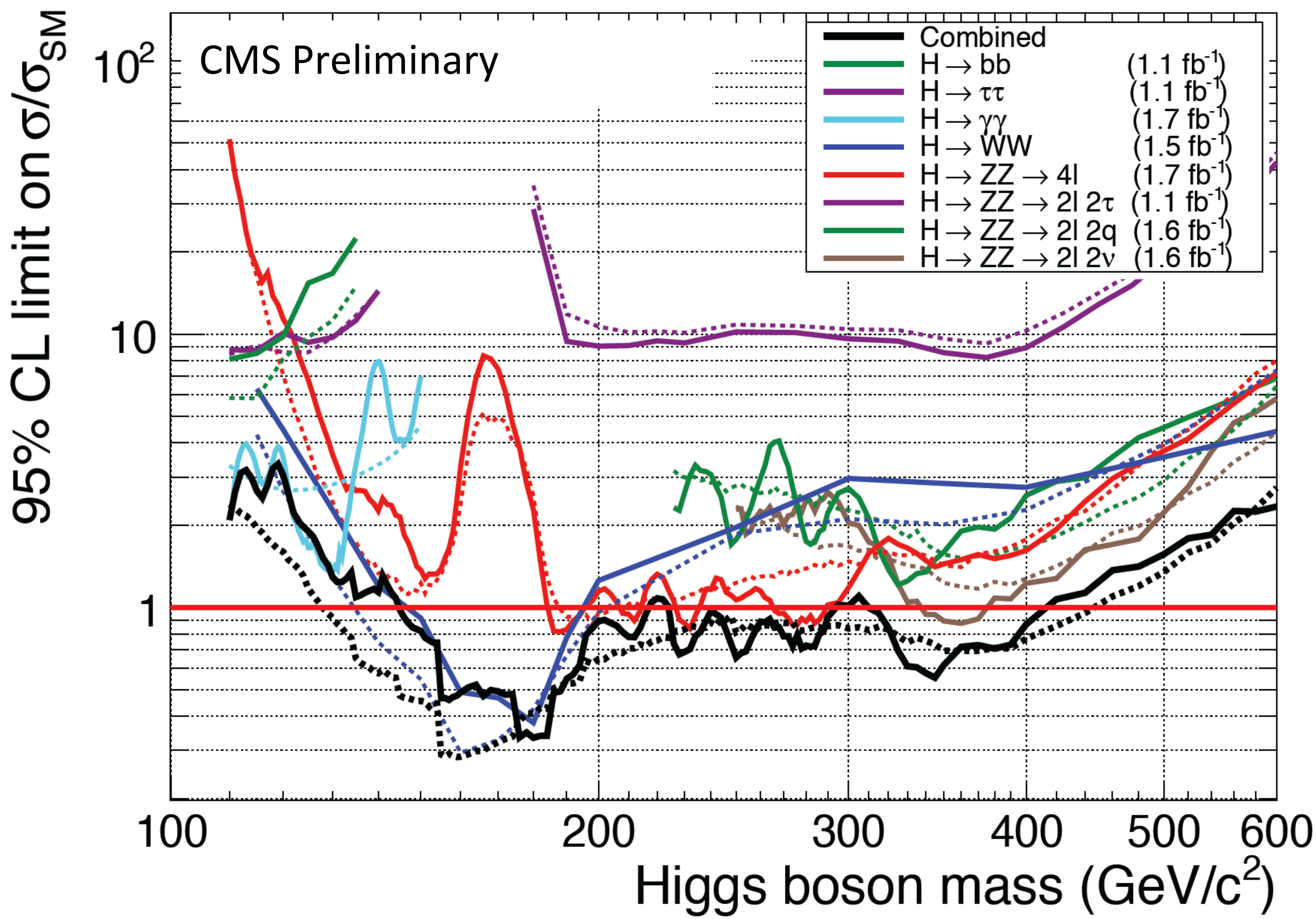


SM Higgs boson: expected exclusion mass range: 130 – 440 GeV

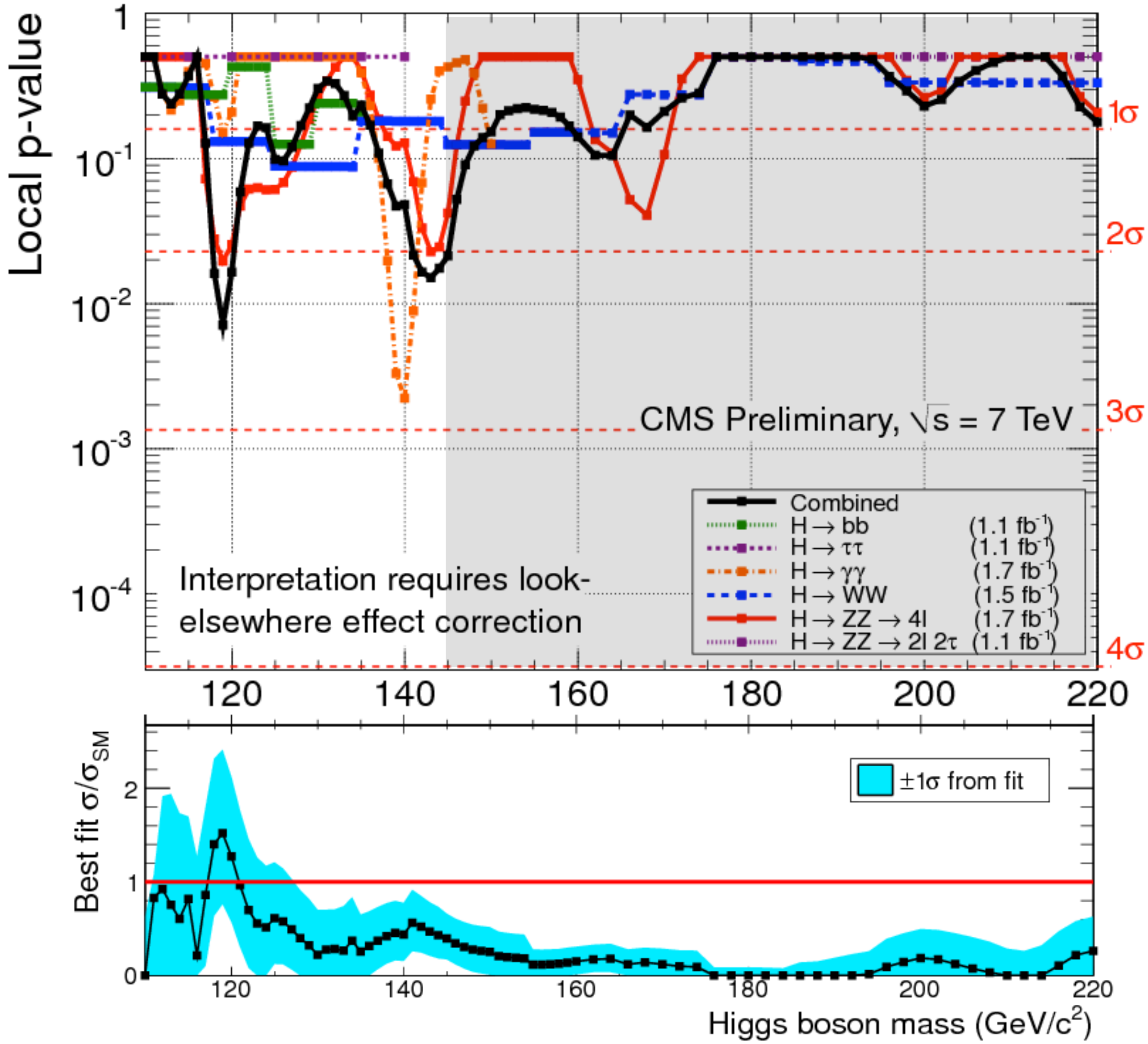
Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

Interplay of channels

Solid line – observed limit
Dashed line – median expected

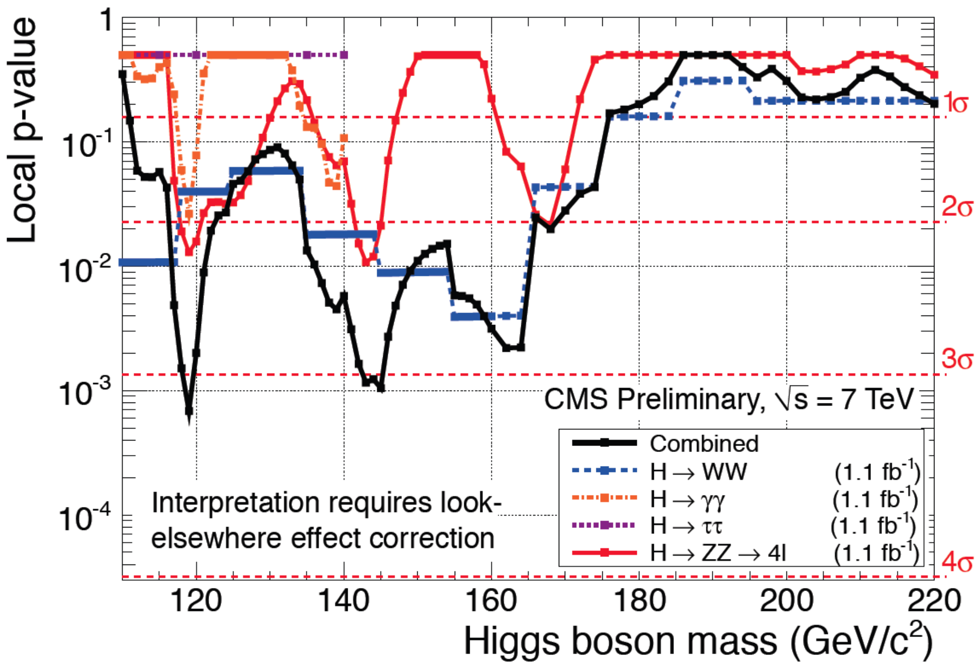


Quantifying excesses seen by CMS

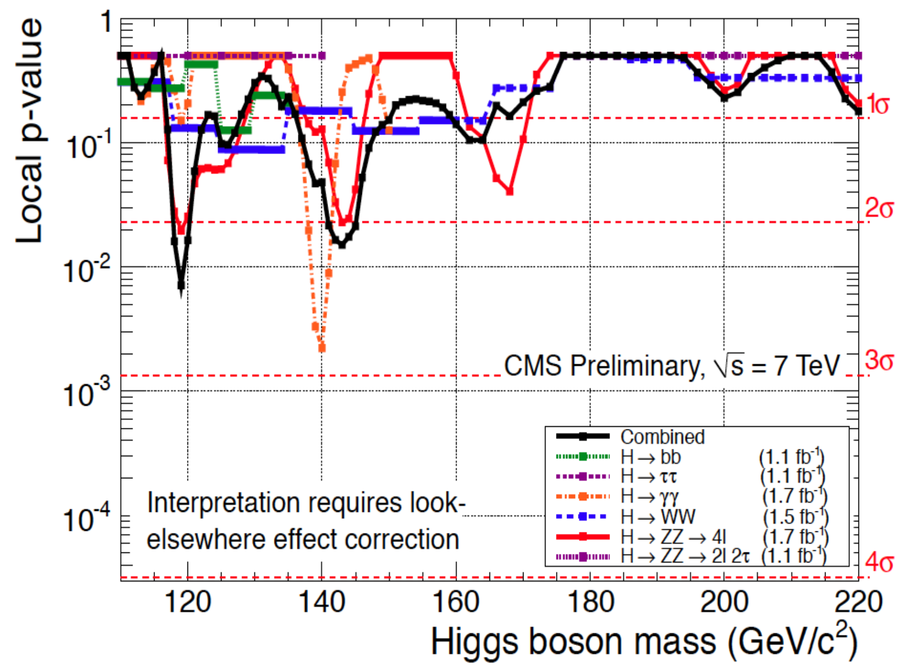


CMS excess: from EPS to LP

EPS results

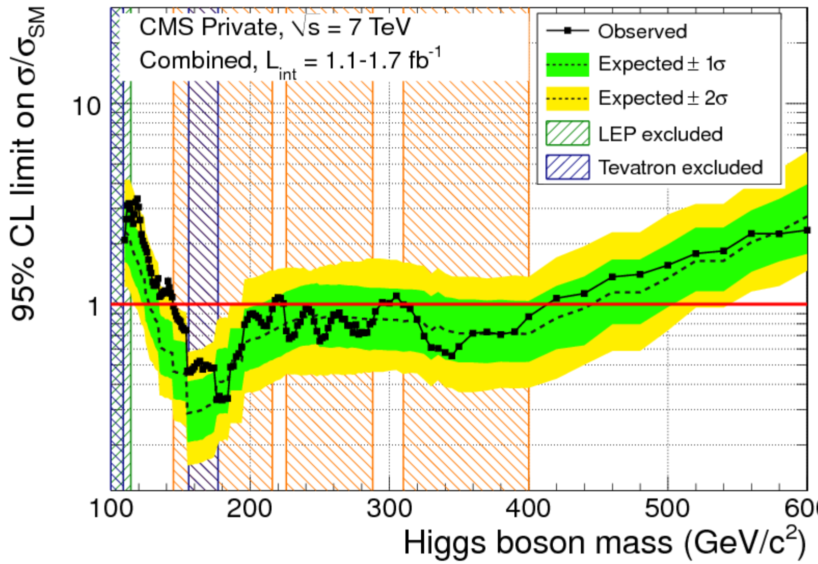


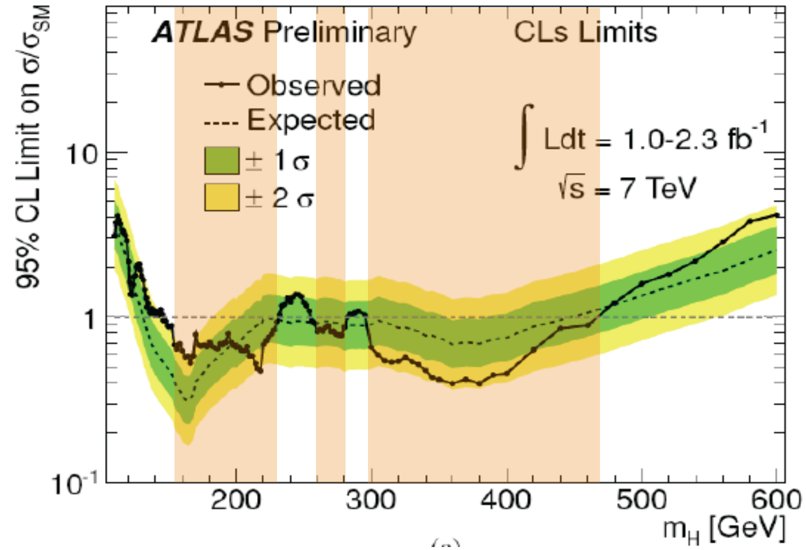
LP results

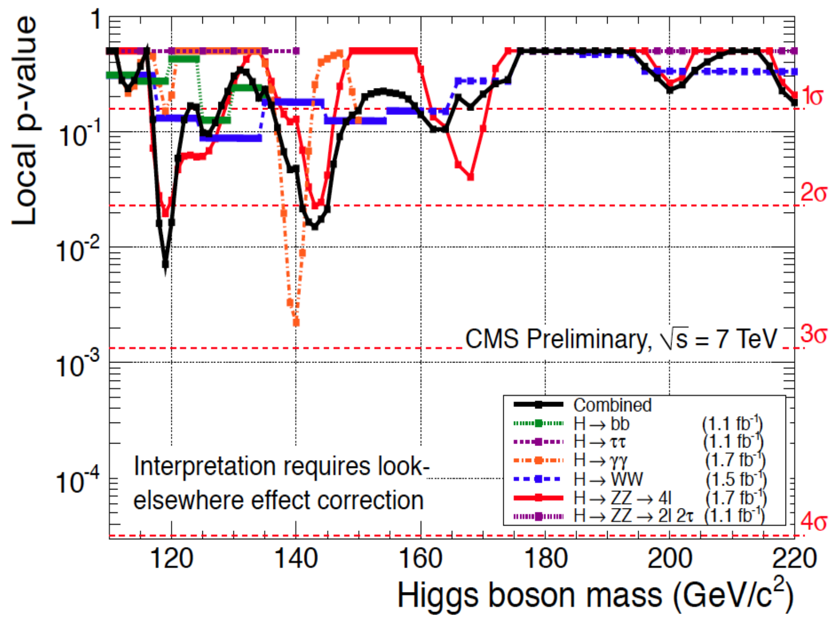


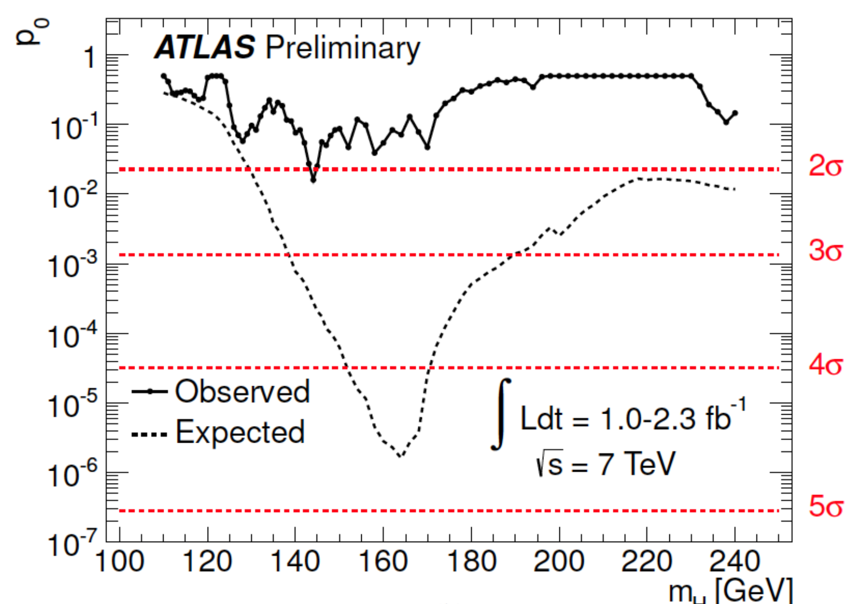
- **H→WW→lvlv recessed:** now more conservative analyses, new data has smaller excess
- **H→ZZ->4l:** no new low mass events (this is perfectly OK as we expected to add <1 event)
- **H→γγ:** m=120 excess recessed, m=140 excess grew

CMS – ATLAS

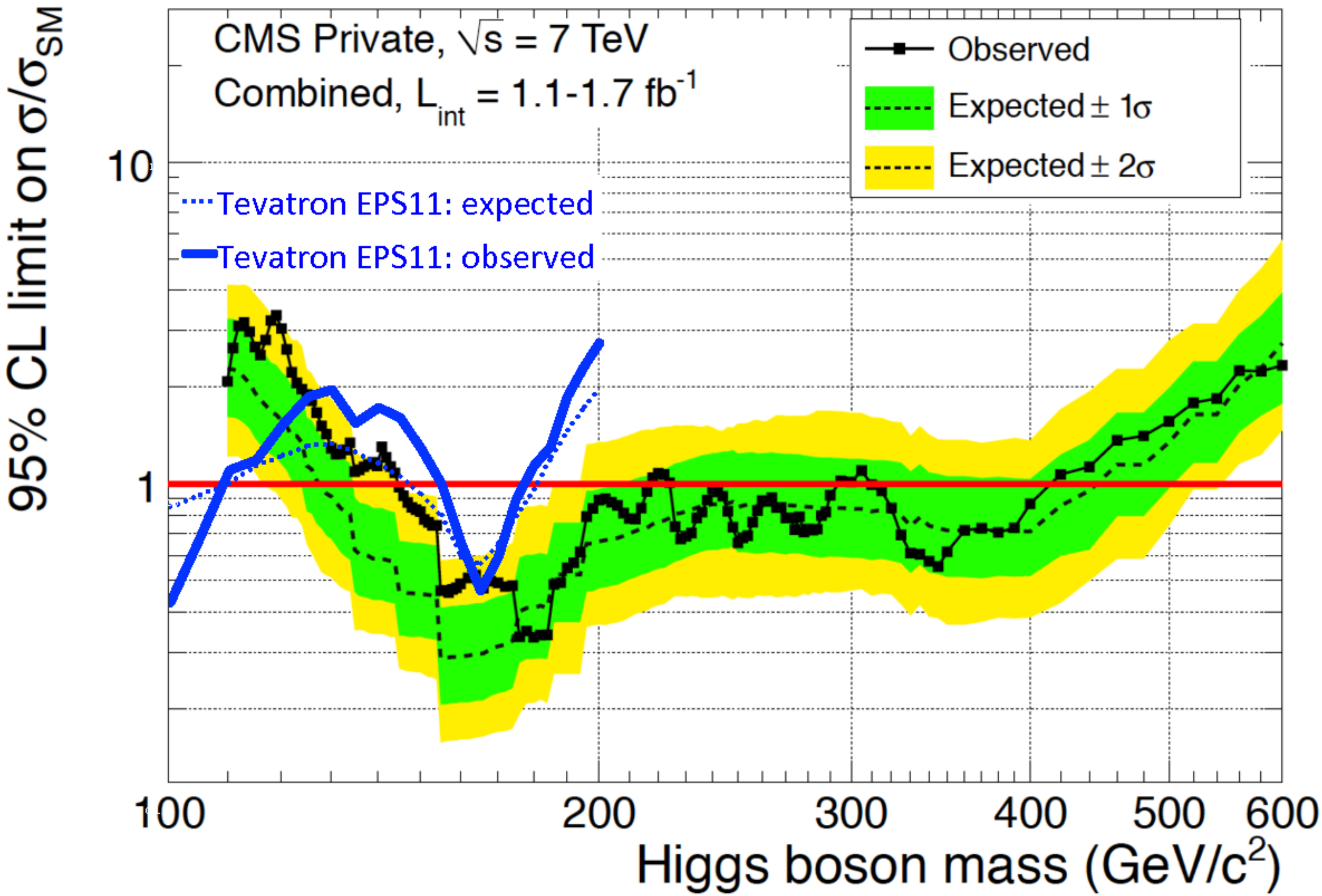

CMS Private, √s = 7 TeV
Combined, L_int = 1.1-1.7 fb-1
Observed
Expected ± 1σ
Expected ± 2σ
LEP excluded
Tevatron excluded
95% CL limit on σ/σSM
Higgs boson mass (GeV/c2)


ATLAS Preliminary
CLs Limits
Observed
Expected
± 1 σ
± 2 σ
∫ Ldt = 1.0-2.3 fb-1
√s = 7 TeV
95% CL Limit on σ/σSM
mH [GeV]


Local p-value
CMS Preliminary, √s = 7 TeV
Interpretation requires look-elsewhere effect correction
Combined
H → bb (1.1 fb-1)
H → ττ (1.1 fb-1)
H → γγ (1.7 fb-1)
H → WW (1.5 fb-1)
H → ZZ → 4l (1.7 fb-1)
H → ZZ → 2l 2τ (1.1 fb-1)
1σ
2σ
3σ
4σ
Higgs boson mass (GeV/c2)

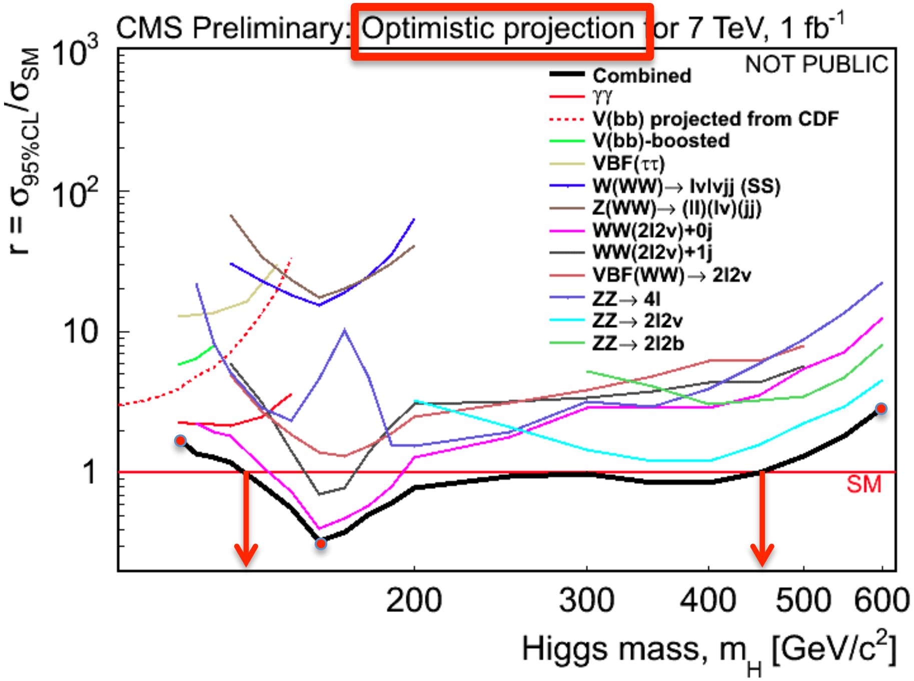

ATLAS Preliminary
Observed
Expected
∫ Ldt = 1.0-2.3 fb-1
√s = 7 TeV
2σ
3σ
4σ
5σ
p0
mH [GeV]

CMS – Tevatron

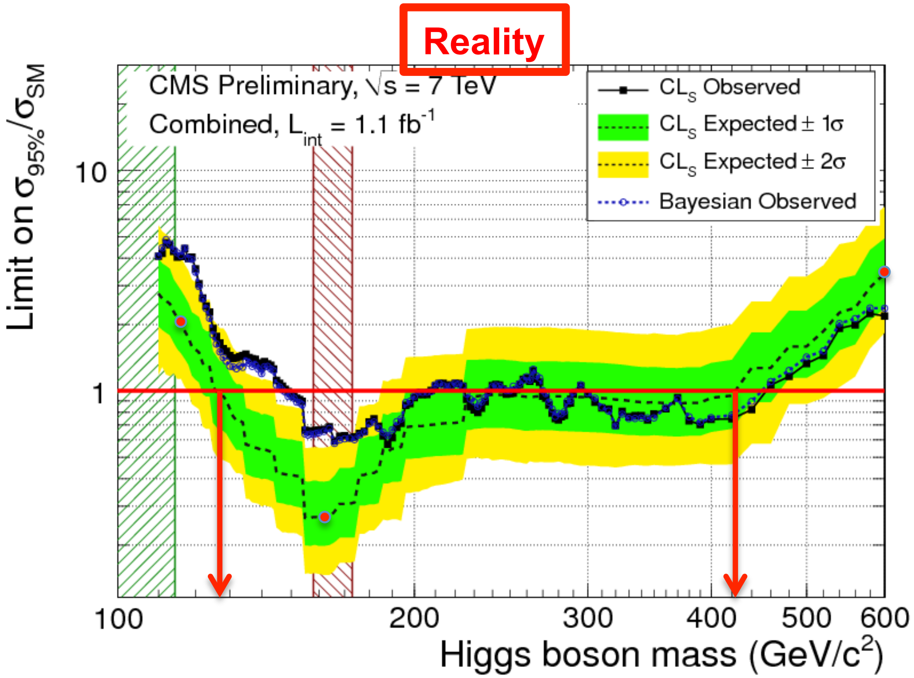


Outlook

How did we do so far?

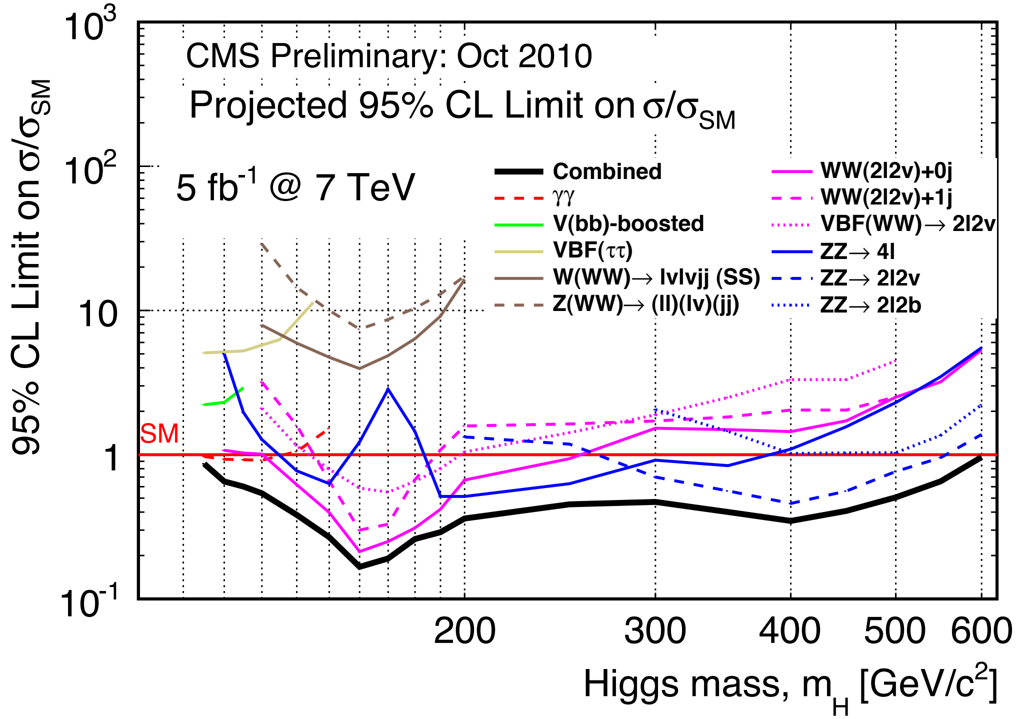


September 28, 2010 Projection: 135-450 GeV



Sensitivity reported at EPS: 127-420 GeV

Prospects for 2011



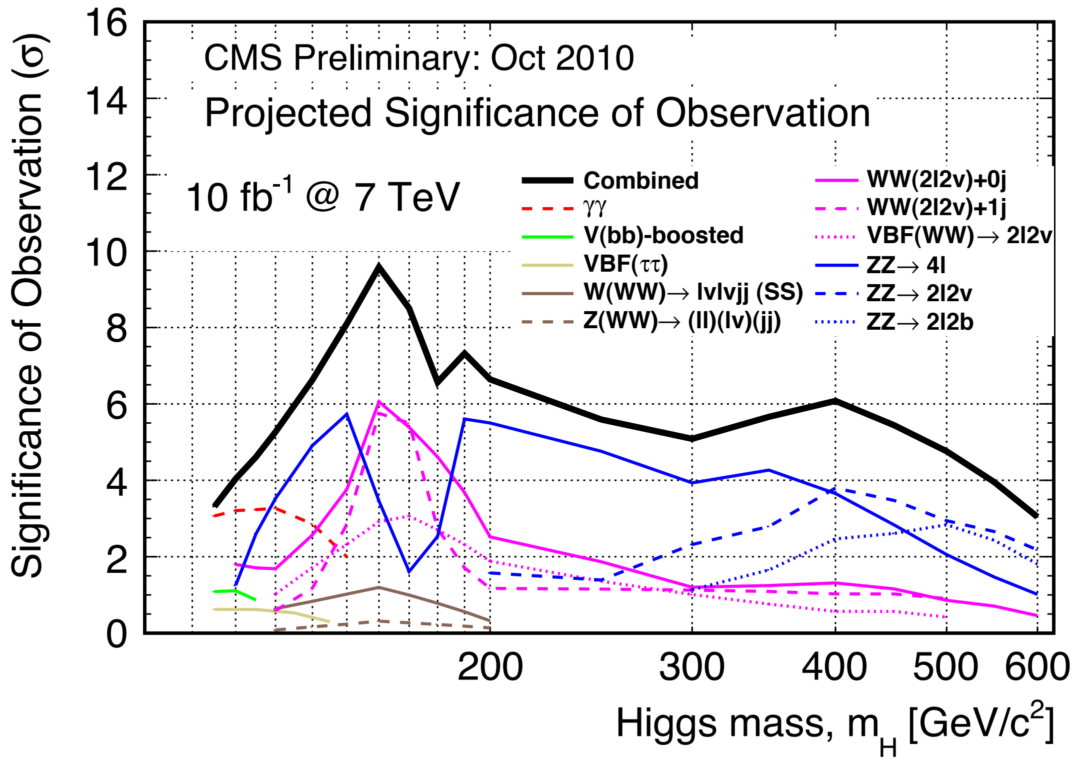
Full 2011 run integrated lumi (good data) = 4.7 fb^{-1}

If SM Higgs is not there at all,

one might expect to know that by the end of the year…

but, given we have an excess, it will now take a bit longer…

Prospects for 2012



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

If SM Higgs is there,

discovery is very likely next year

Summary

- SM Higgs boson excluded at 95% CL in the mass range from 145-400 GeV with two narrow gaps (gaps excluded at 90% CL)

- The excess at low masses remains. It is not inconsistent with SM Higgs, but its significance is way too low for any speculations.

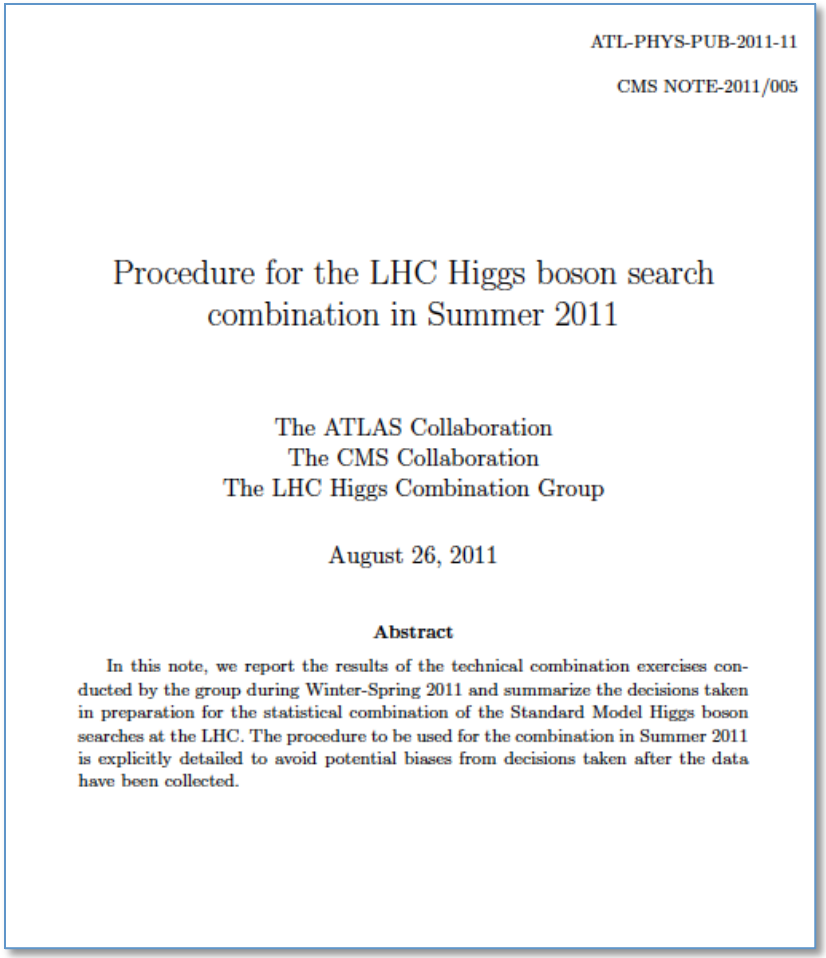
- 2011: with 5 fb^{-1} per experiment this year, we expect to reach exclusion sensitivity in the mass range from 115-600 GeV

- 2012: with 30 fb^{-1} per experiment next year, we expect to reach discovery sensitivity in the mass range from 115-600 GeV

Backup

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

Stat methods used: 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
- $CL_s = P(q \geq q^{obs} | b+\mu s) / P(q \geq q^{obs} | b)$

Stat methods used: 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**

Stat methods used: 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: $b = b_0 (1 + \varepsilon\theta)$

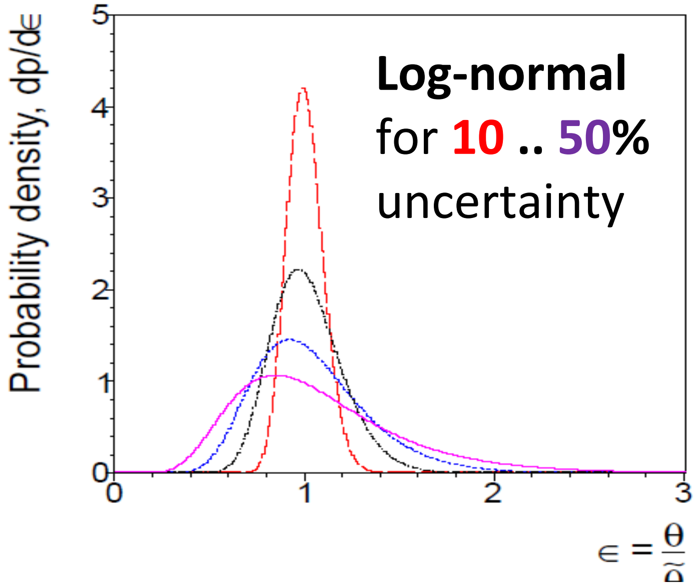
Lognormal: $b = b_0\, \kappa^\theta$

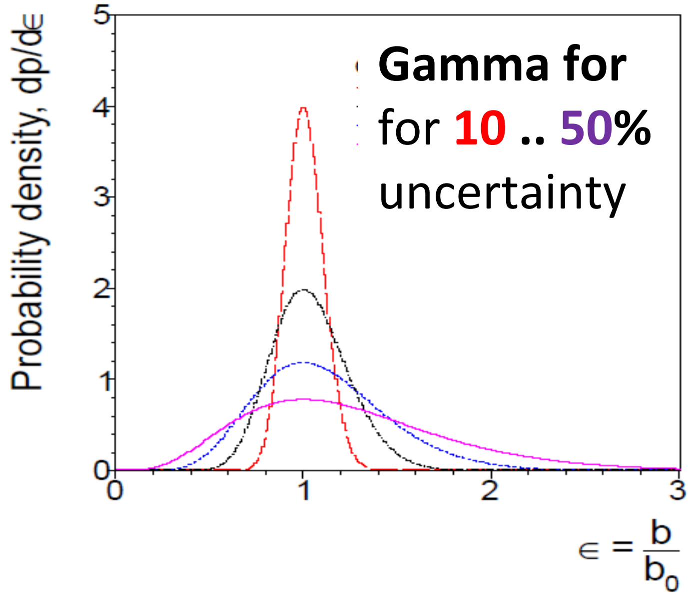
Statistical: $b = \alpha \times \theta$

Statistical analysis: modelling

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**





Statistical choices for setting limits

- **Two main paradigms**
  - **Frequentist**
    - classical
    - Feldman-Cousins
    - modified frequentist (a.k.a. CL_s)
  - **Bayesian**
    - which prior?

- **How do we deal with systematic uncertainties?**
  - this brings even more sub-sub-flavors for each of the above…

Stat methods used: limits

Pursue both frequentist and Bayesian paradigms, which allows us to validate robustness of results…

1. **CL_s (exact formulation as agreed with ATLAS)**
   - (a) assess probabilities using pseudo-experiments
   - (b) also, from asymptotic properties of the test statistic

2. **Bayesian (with flat prior on signal strength)**

Limits: Bayesian paradigm

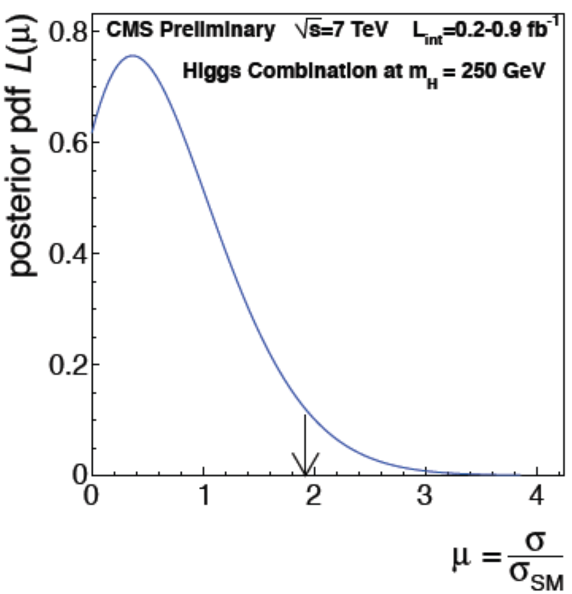
Posterior on signal strength μ

- using flat prior
- marginalization of nuisance parameters

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

Deriving limit on μ

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



Limits: modified frequentist CL_s

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

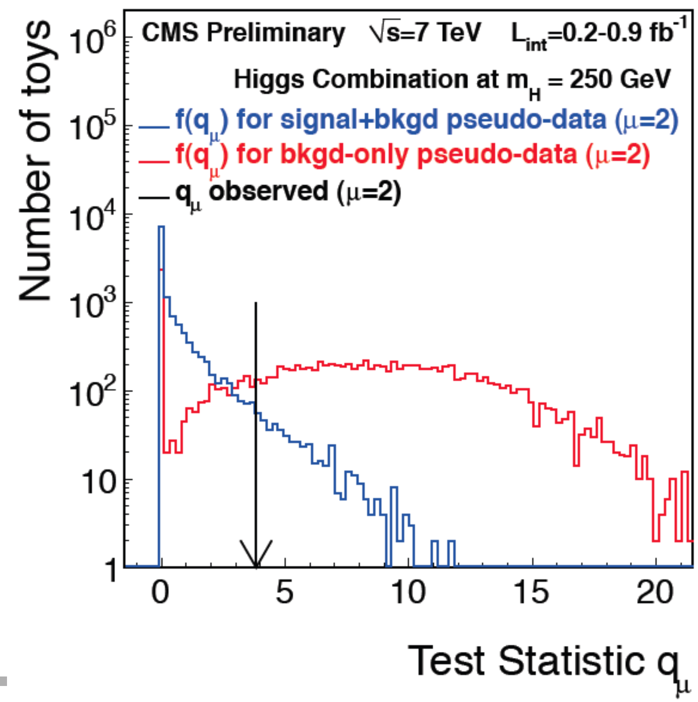
$$\tilde q_\mu \;=\; -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat\theta_\mu)}{\mathcal{L}(\text{data}|\hat\mu,\hat\theta)}, \qquad \text{with a constraint } 0\le\hat\mu\le\mu$$

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: modified frequentist CL_s

Likelihood

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

LEP did not use syst. error pdf's in Likelihood

TEV puts in $\rho(\theta|\tilde{\theta})$, = $p(\tilde{\theta} \mid \theta)$ for pdf's we use

Test statistics

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

LEP and TEV, fix μ=0 in the denominator

LEP does not profile nuisance (there aren't any)

TEV does profile for nuisances

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 $\mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})$

TEV/LEP use $\tilde{\theta}$ to generate θ and then generate pseudo-data using new s(θ) and b(θ), which is explicitly Bayesian

Define $$CL_s = \frac{P\left(q_\mu \geq q_\mu^{obs} \mid \mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \geq q_\mu^{obs} \mid b(\hat{\theta}_0^{obs})\right)}$$

Stat methods used: excess (p-value)

test statistic – profile likelihood

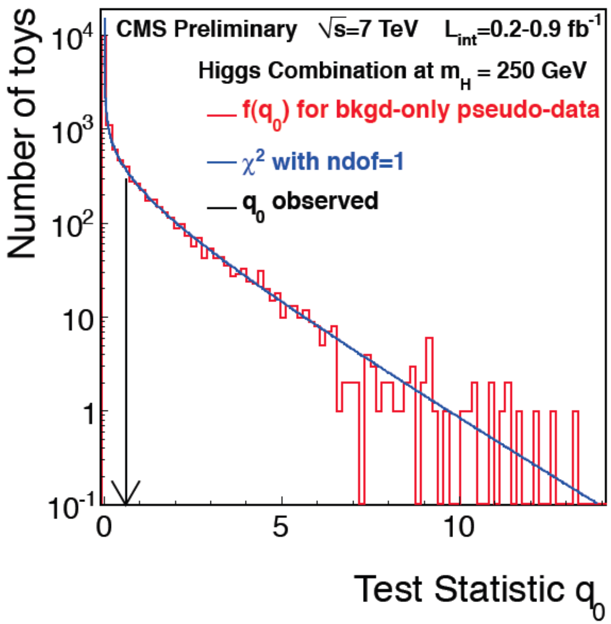
$$q_0 = -2\ln\frac{\mathcal{L}(\text{data}|0,\hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})} \quad \text{and } \hat{\mu} \geq 0$$

"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)**

Stat methods used: 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})

MORE THAN ONE WAY 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**

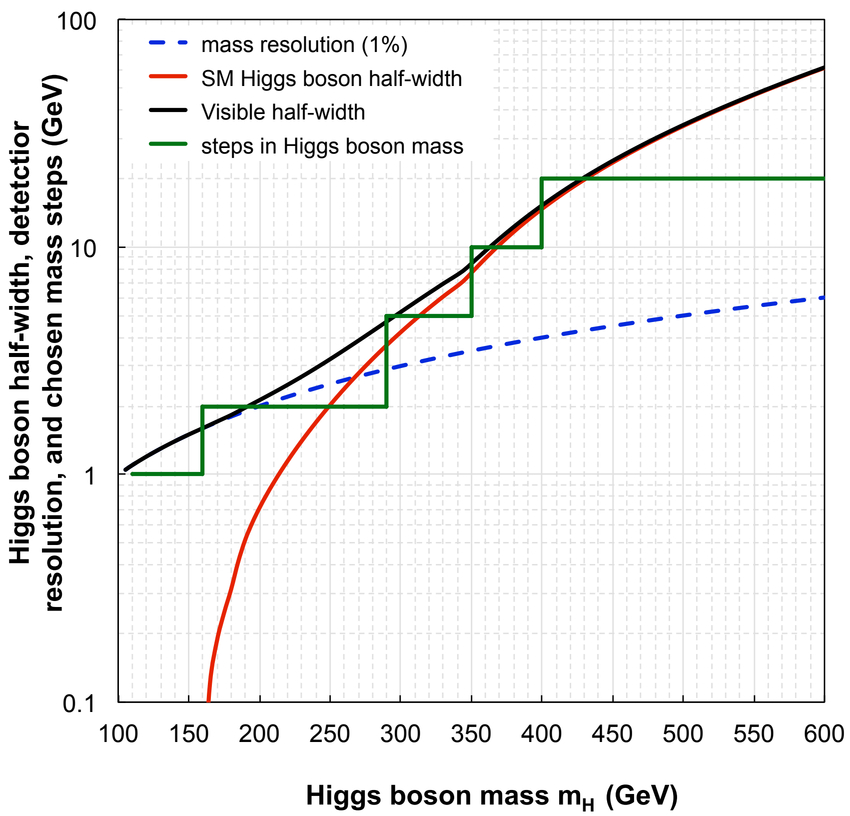
The last two have been used in the current combination

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



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 flat pdf for QCD scale uncertainties
    - use normal (or lognormal) pdf for PDF+α_s uncertainties
    - QCD scale PDF+α_s uncertainties are to be added linearly
- **LHC Higgs Combination group**
  - **takes all this input as is,
    except for the two underlined recommendations**

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 Higgs
- For example: gg→H→WW and gg→WW
  - **QCD scale errors** for these two are not correlated (so we are told)
  - **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