Higgs Searches at CMS

CRIMEA2011 – New Trends In High-Energy Physics

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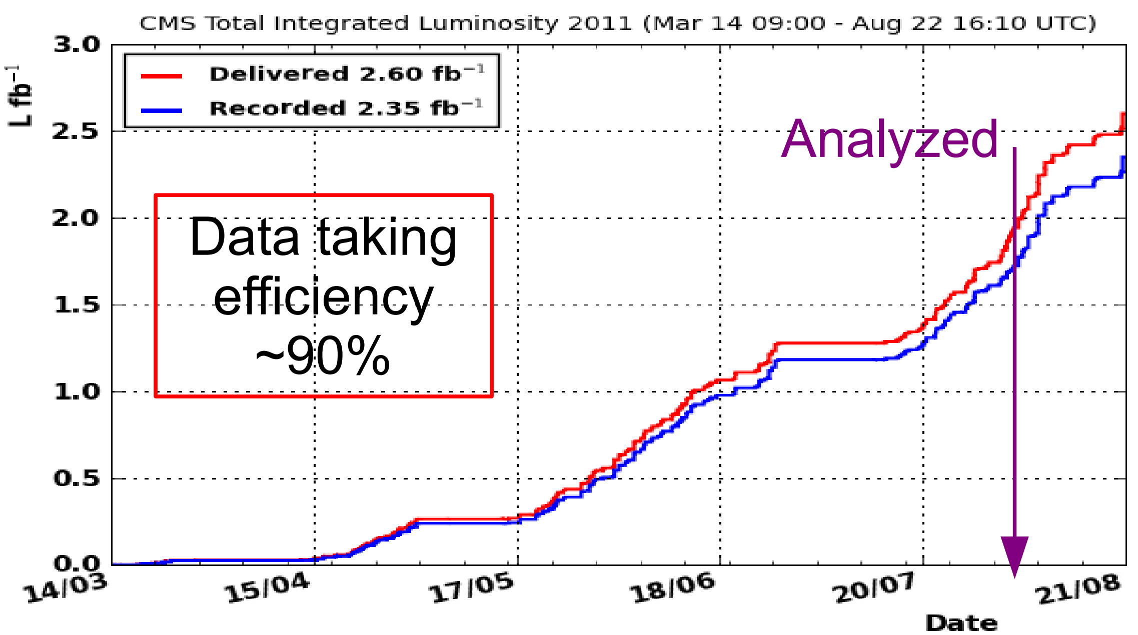
Outline

- SM Higgs Boson searches
  - Low, intermediate and high mass results
  - Combination
- MSSM Higgs Boson searches
  - neutral states in $\tau\tau$ channel
- Conclusions

CMS at 7 TeV and High Luminosity

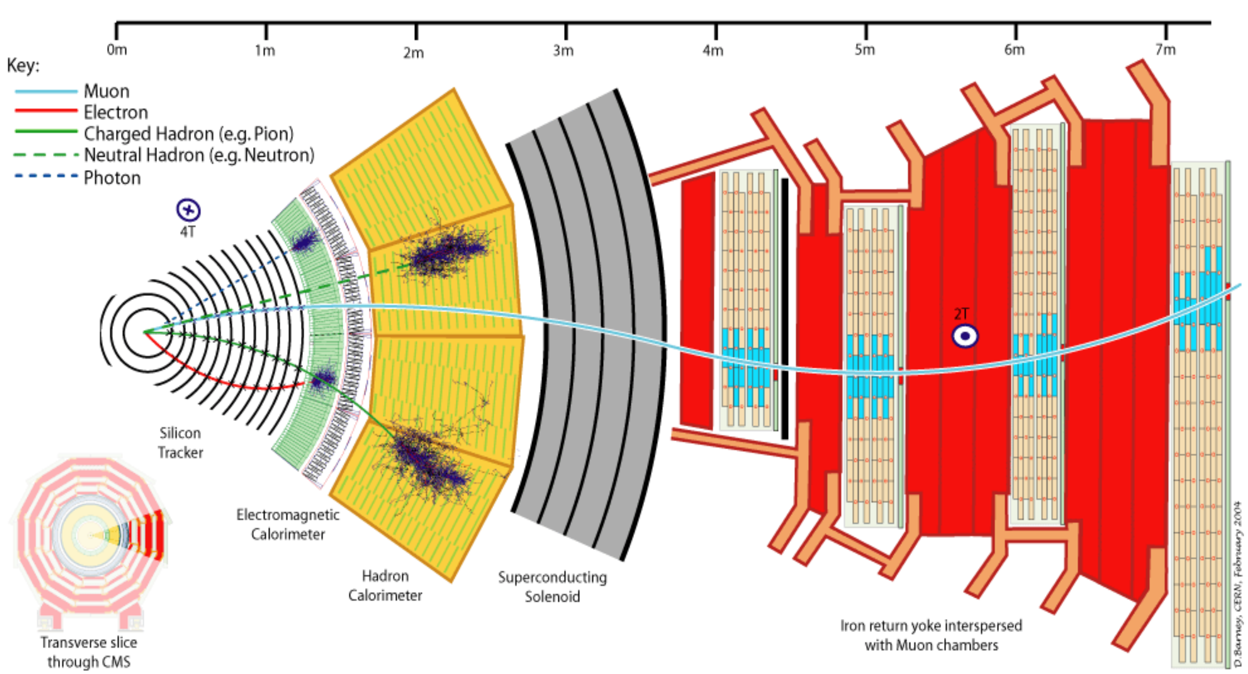


Instantaneous Lumi 2.4×10^{33} cm^{-2}s^{-1}

Multiple interactions in a single collision of 2 proton bunches (pileup) become relevant:

$<N_{PU}> \sim 6$

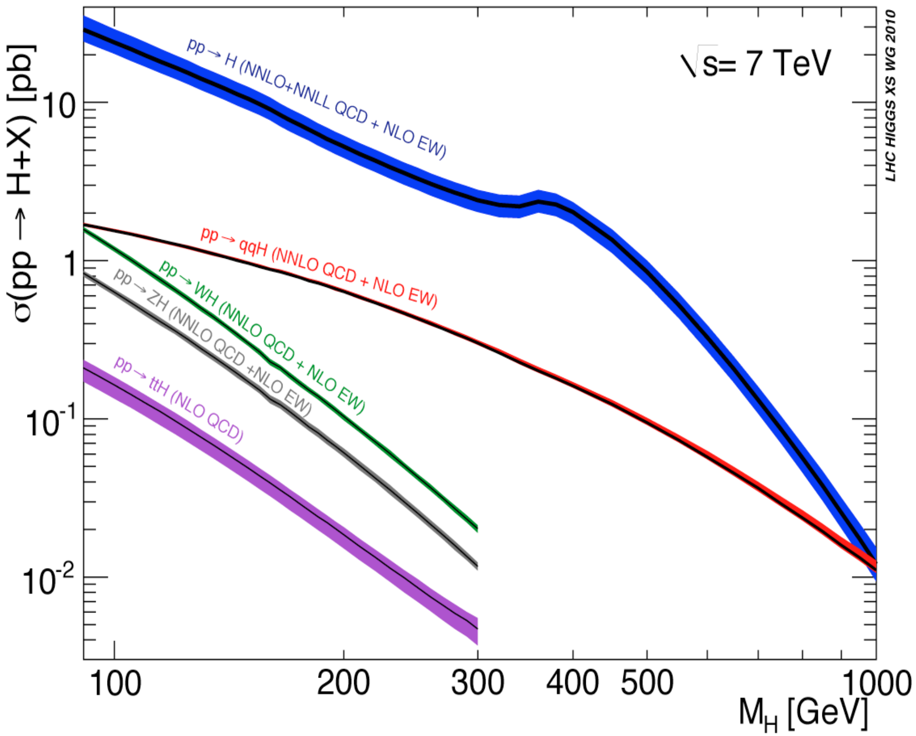
Effects on:

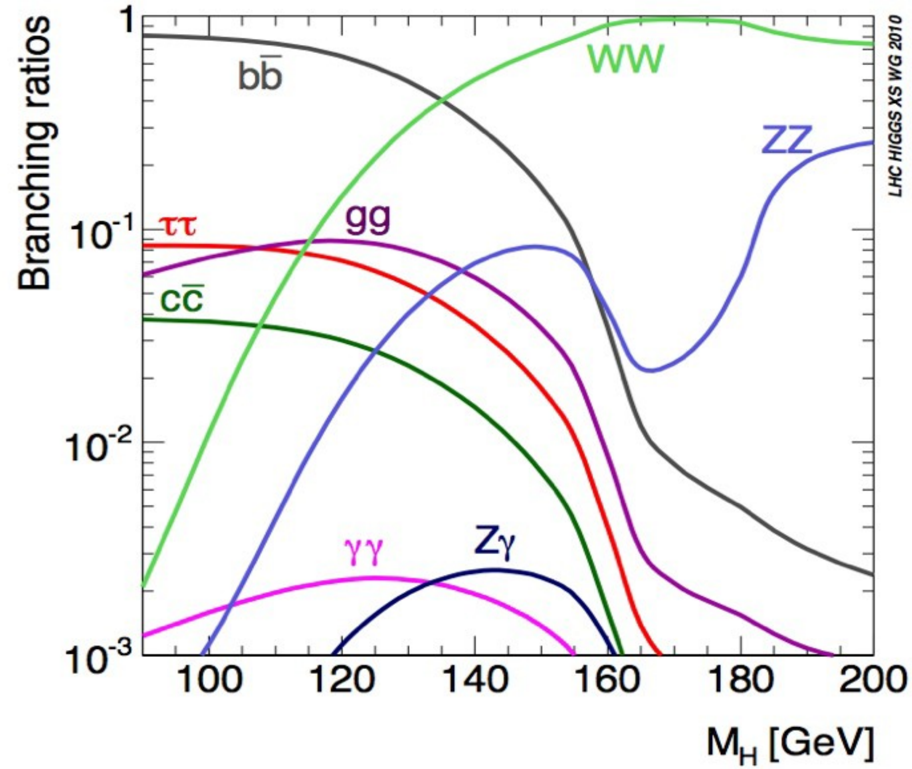


- jet momentum reconstruction
- missing transverse energy (MET)
- lepton isolation
- tagging of heavy flavor quarks

Algorithms developed to subtract activity not coming from primary interaction

SM Higgs Boson



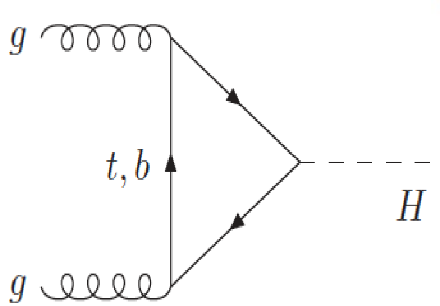


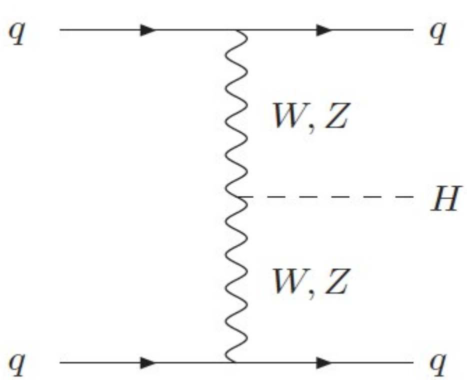
gluon-fusion

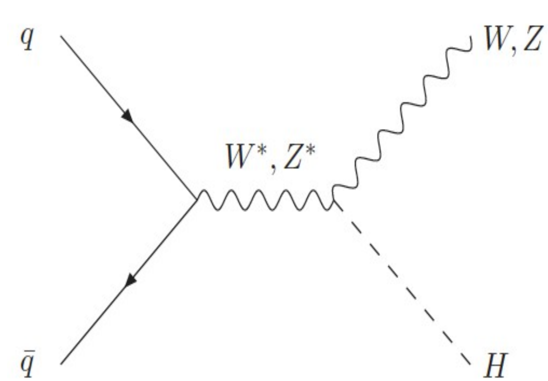
VBF

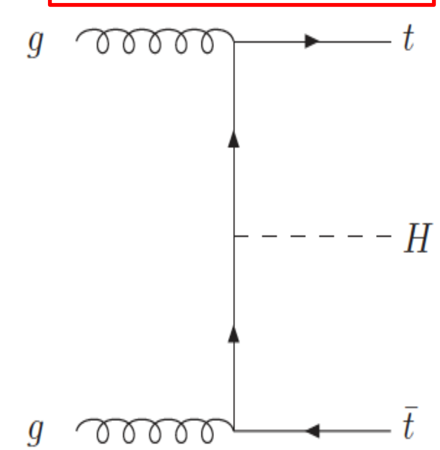
VH

ttH









$H \to \gamma\gamma$ HIG-11-021

Low Mass:
$110 < M_H < 150$ GeV

Higgs Signature:

- 2 well isolated, high energetic photons

High sensitivity at low masses, but small branching fraction.

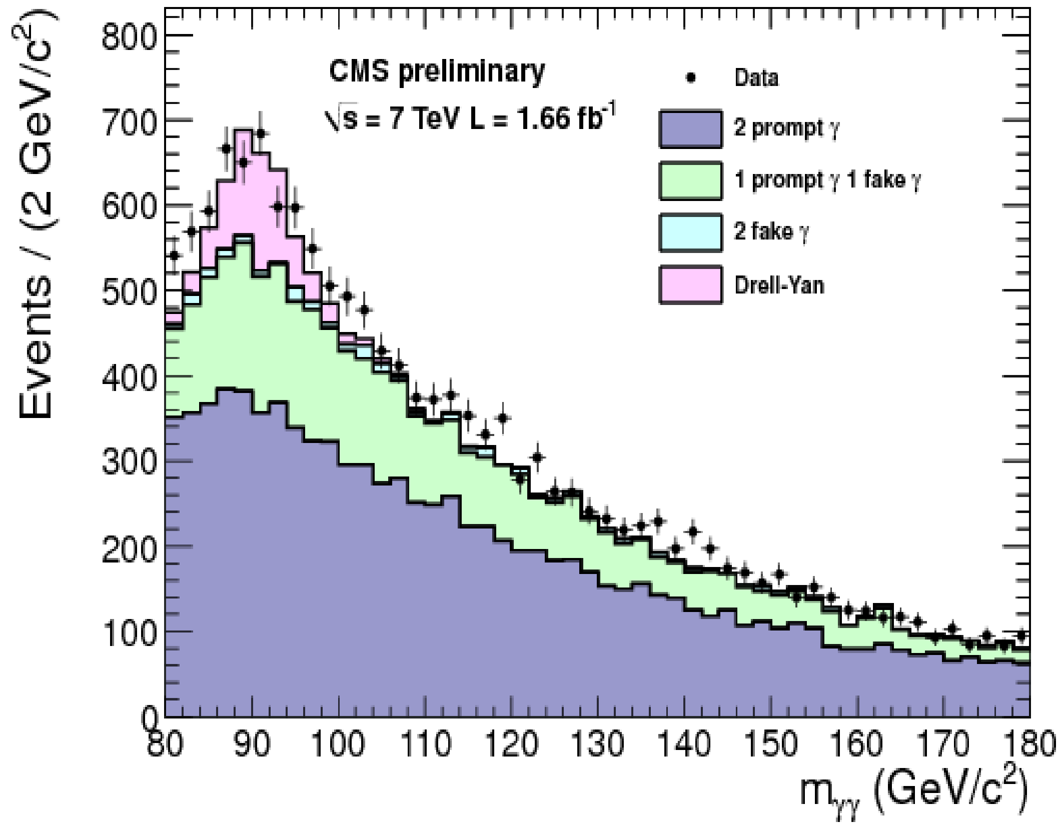
Backgrounds:

- irreducible: prompt di-photon
- reducible: γ + jet, jet + jet

Event Selection:

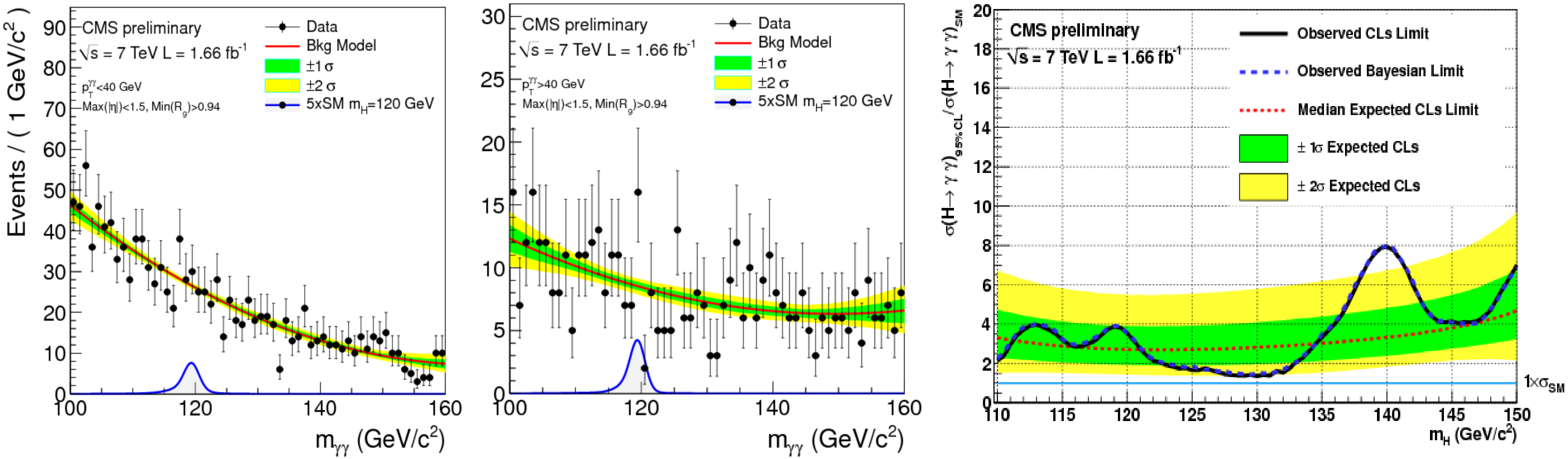
- 2 photons with high p_T
- photon isolation
- cluster shape in ECAL
- lepton veto

} Background suppression



Invariant mass for all the events used in the analysis. MC tracks the Data.

$H \to \gamma\gamma$



Events differently separated according to:

- mass resolution
- signal to background probability

Signal and background modeling:

- background derived from data (2nd order polynomial fit)
- signal shape from simulated events (with E_γ smearing from $Z \to ee$ data/MC comparison)

Expected limit (95% CL)
3XSM – 4XSM for $110 < M_H < 150$ GeV

Observed limit within 2σ from expected value

$H \rightarrow \tau\tau$

HIG-11-009

Low Mass: $110 < M_H < 140$ GeV

Selected Higgs decay channels:

- $\mu\mu$, $e\mu$, $e\tau_h$, $\mu\tau_h$

Background estimation:

- Data Driven

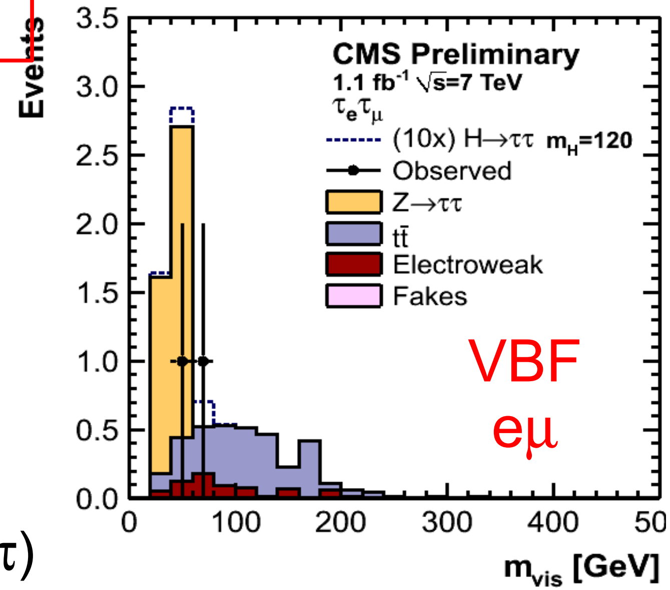
  QCD (μτ   eτ)
  Fake electrons bkg (eμ)
  $Z \rightarrow \mu\mu$ (μμ)

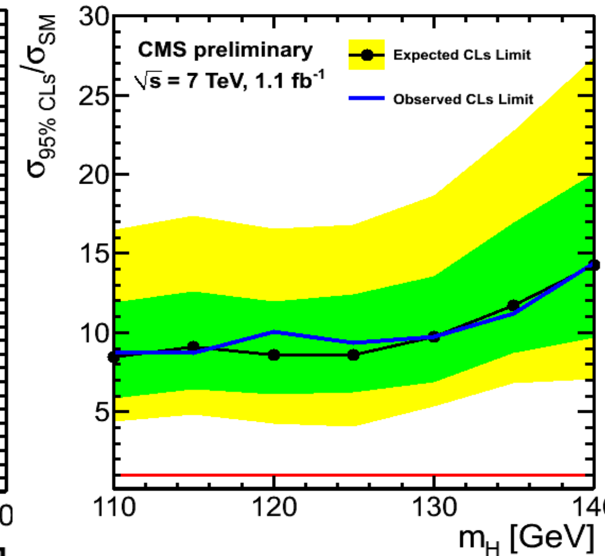
- MC shape and sidebands normalization

  ttbar, $Z \rightarrow \tau\tau$
  W + jets (μτ, eτ, eμ)

- MC

  WW/ZZ/WZ





Limit based on the fit of the visible mass distribution

- 2 events categories to increase sensitivity
  VBF (2 jet forward-backward)/NOT-VBF

Expected and observed limit (95% CL)
9XSM – 14XSM for $110 < M_H < 140$ GeV

MET cut to reject ttbar and W+jets.
Further suppression by topological cuts

$H \rightarrow b\bar{b}$

HIG-11-012

Low Mass: $110 < M_H < 135$ GeV

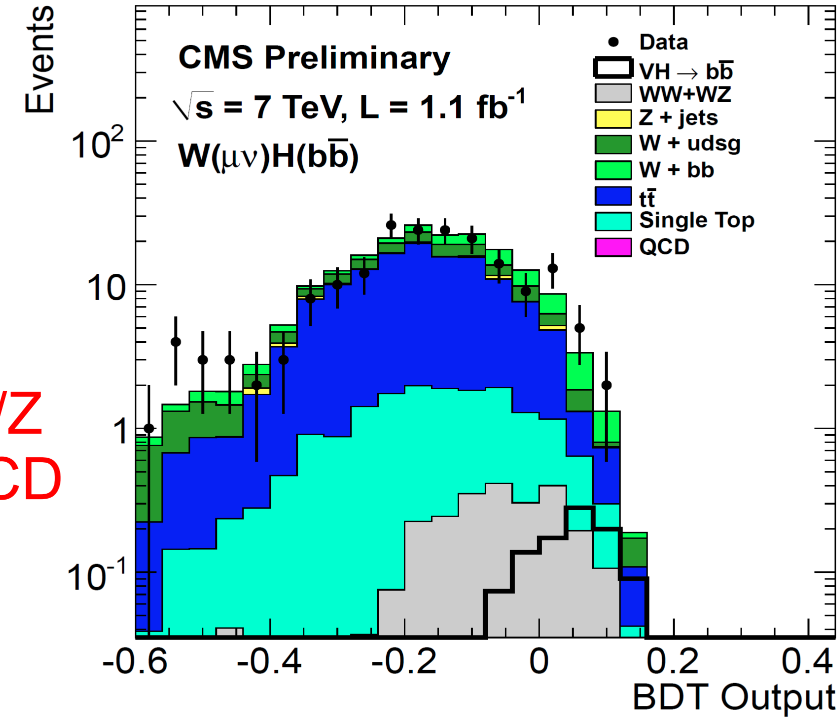
Production mode:

- gluon fusion
- vector-boson fusion

QCD is a big deal

- in association with a vector boson

leptonic decay of W/Z helps to suppress QCD

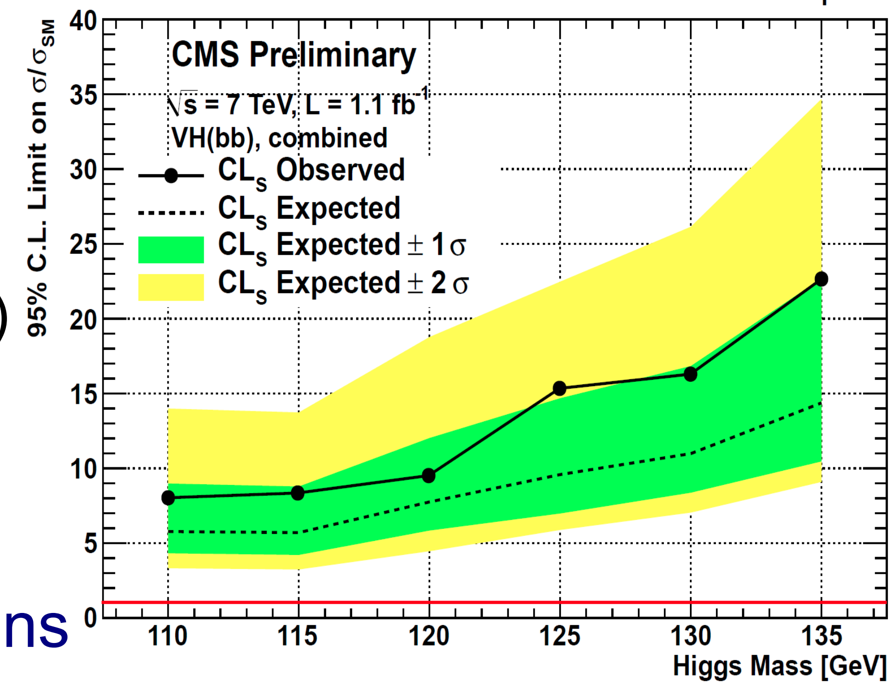


Backgrounds:

- Reducible: QCD, ttbar, V+udscg
- Irreducible: ZZ(bb), W(lν)Z(bb), V+bb

Discriminating variables:

- di-jet mass peak (VV)
- di-jet and V transverse momentum (V+jets)
- b-tagging (V+light, QCD)
- back to back topology (QCD)
- additional jets/leptons (tt)



Background estimation from control regions

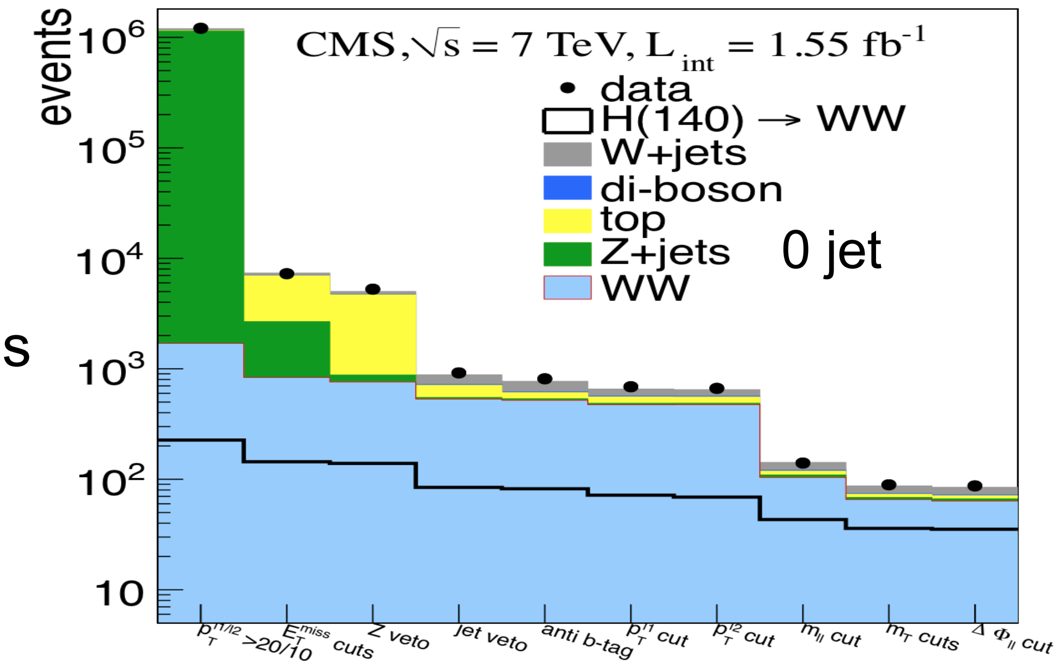
$H \rightarrow W^+W^- \rightarrow 2\ell\ 2\nu$ HIG-11-014

Intermediate Mass:
$130 < M_H < 200$ GeV

Higgs Signature:

- 2 opposite charge isolated leptons
- large MET

No invariant mass reconstruction.
Cut and counting approach.

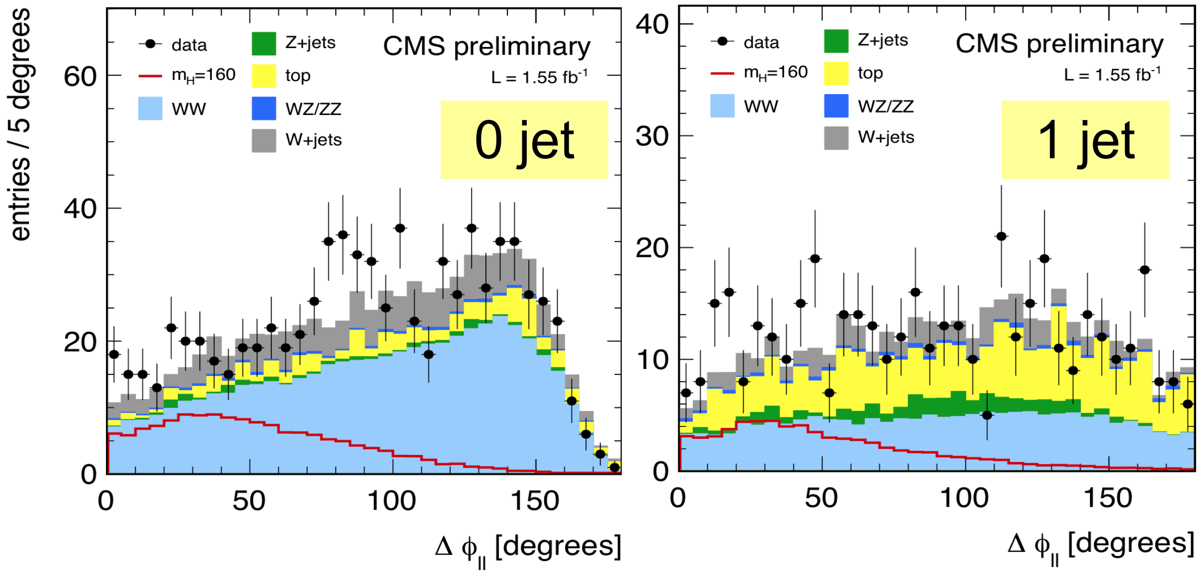


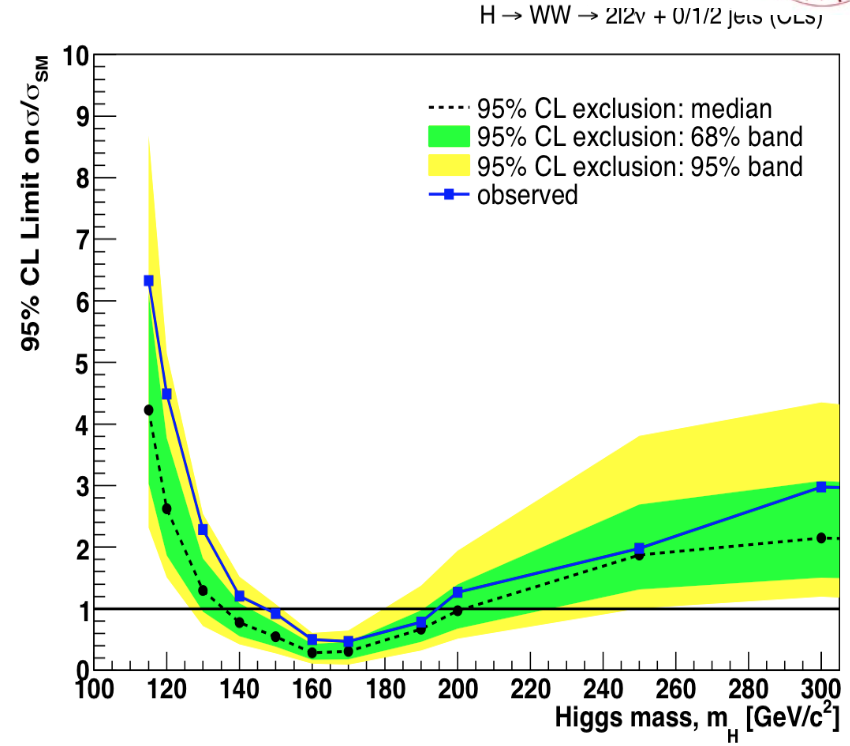
Backgrounds	major reduction from
• W^+W^-	kinematic variables cut
• W + Jets, QCD multijet	tight ID isolated lepton p_T > 10 GeV
• Drell-Yan $Z/\gamma^* \rightarrow \ell^+\ell^-$	MET and $Z \rightarrow \ell\ell$ veto
• ttbar, tW	b tagging veto
• $W\gamma$, WZ, ZZ	3 leptons and γ conversion events rejection

Three categories of events:

- 0 jets, 1 jet, 2 jets

Cut Based Analysis: limits





0-1 jet: cut on discriminating variables

2 jets: sensitive to the VBF production

- require 2 high p_T forward-backward jets

Backgrounds estimation:

- W + jets, Drell-Yan, WW from data after Higgs selection criteria
- Top from data after WW selection criteria and extrapolated into the signal region
- Wγ, WZ, ZZ from Monte Carlo

SM Higgs boson with mass $147 < M_H < 194$ GeV excluded at 95 % C.L.

Expected exclusion $136 < M_H < 200$ GeV

$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell'^+\ell'^-$ $\ell, \ell' = \mu, e$ HIG-11-015

GOLDEN CHANNEL

Higgs signature: 4 isolated leptons

Narrow resonance in 4 leptons invariant mass spectrum

Backgrounds:

- irreducible $ZZ^{(*)}$
- reducible ttbar, Zbb
- instrumental Z+jets,WZ+jets, QCD

Event Selection:

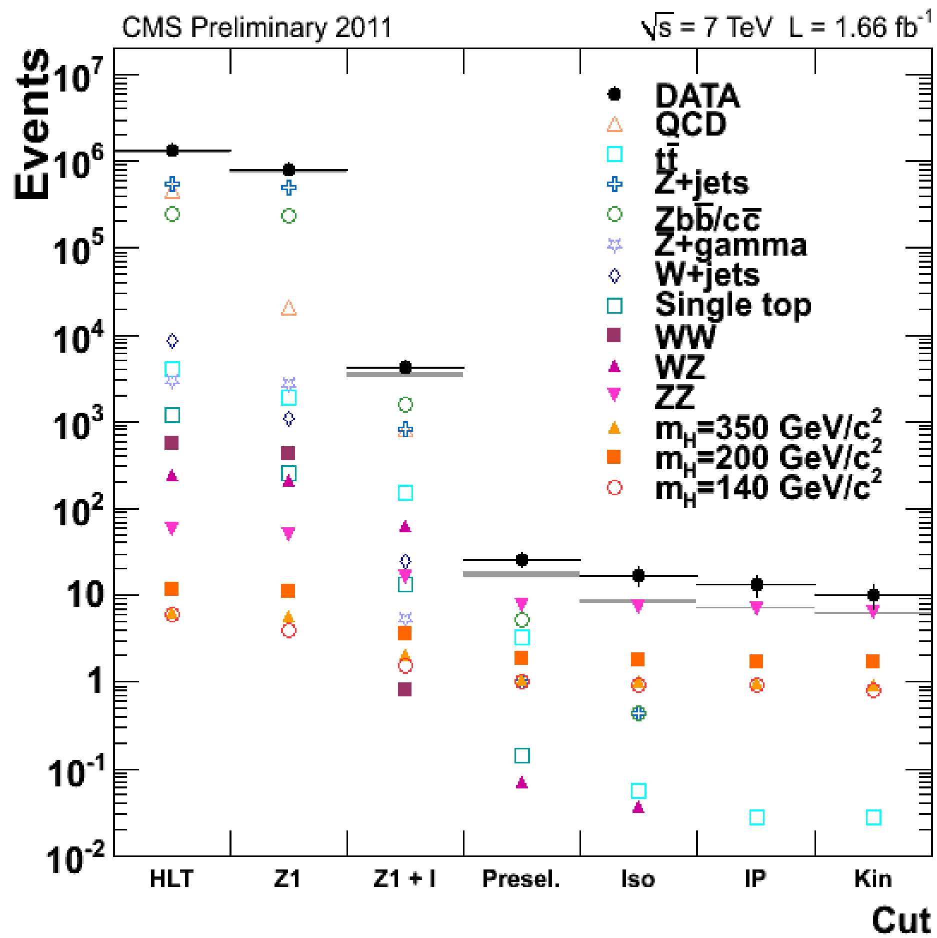
- 2 pair same flavor opposite charge leptons

  Z_1: $p_T^{1/2}$ > 20,10 GeV, 60<$M_{\ell\ell}$<120 GeV

  Z_2: 20< $M_{\ell\ell}$<120 GeV

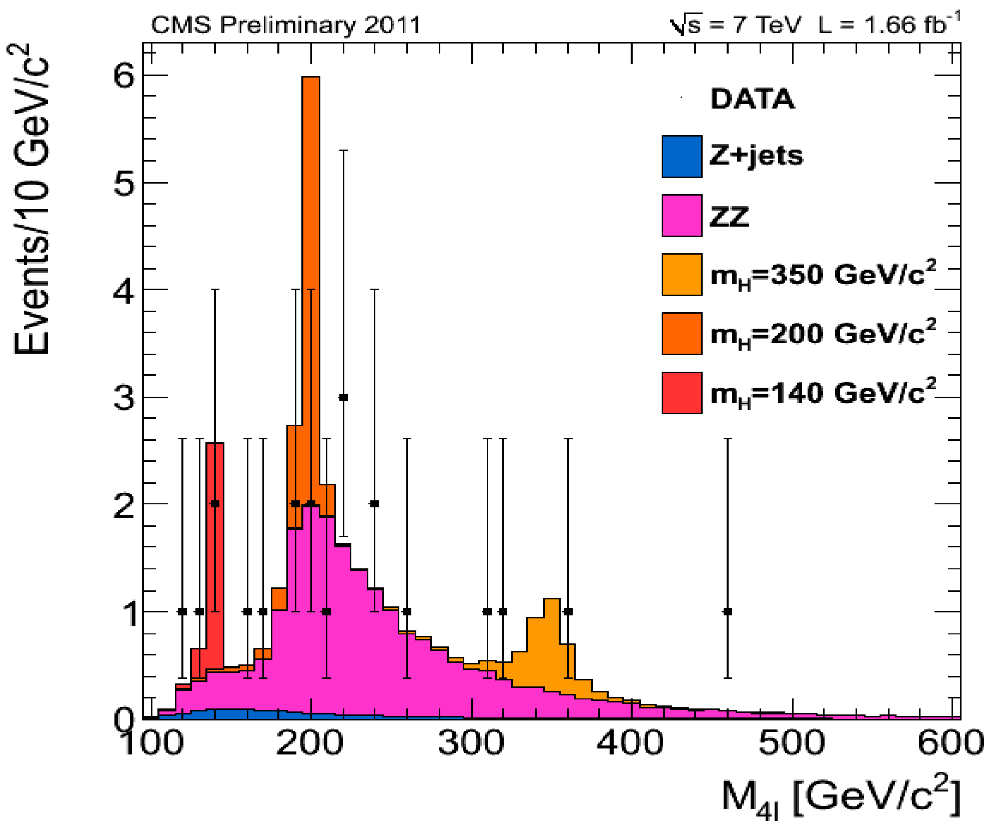
  $M_{4\ell}$ > 100 GeV

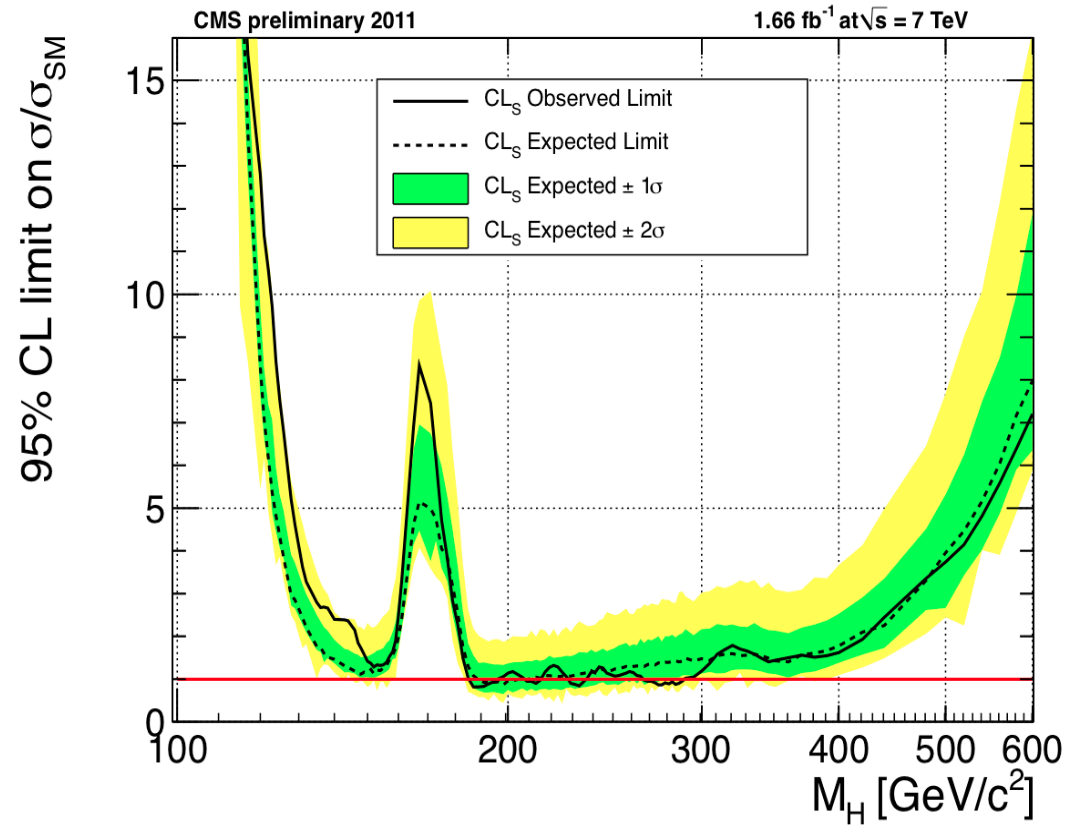
- Isolation and impact parameter requirements



Sensitive to whole mass range:
110 < M_H < 600 GeV

Upper Limits





Background estimated from data:

- ZZ: normalization to Z rate using theoretical cross sections
- Reducible: high impact parameter, relax charge, flavor and isolation
- Instrumental: fake rate measurements

Background shapes from MC

Sensitivity about 1XSM to 2XSM in the range $150 < M_H < 420$ GeV

Shape analysis. Parametrization:

- Signal: Breit-Wigner ⊗ Crystal-Ball
- Background: empirical PDF

$H \to ZZ \to 2\ell 2\nu$ HIG-11-016

High Mass:
$250 < M_H < 600$ GeV

Higgs Signature:

- 2 opposite charge isolated leptons
- large MET

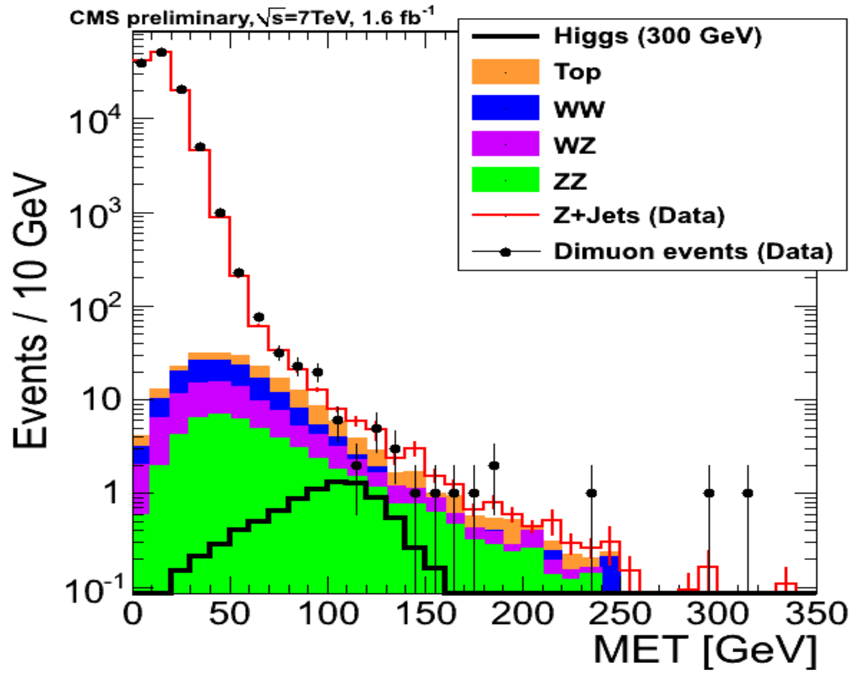
Backgrounds:

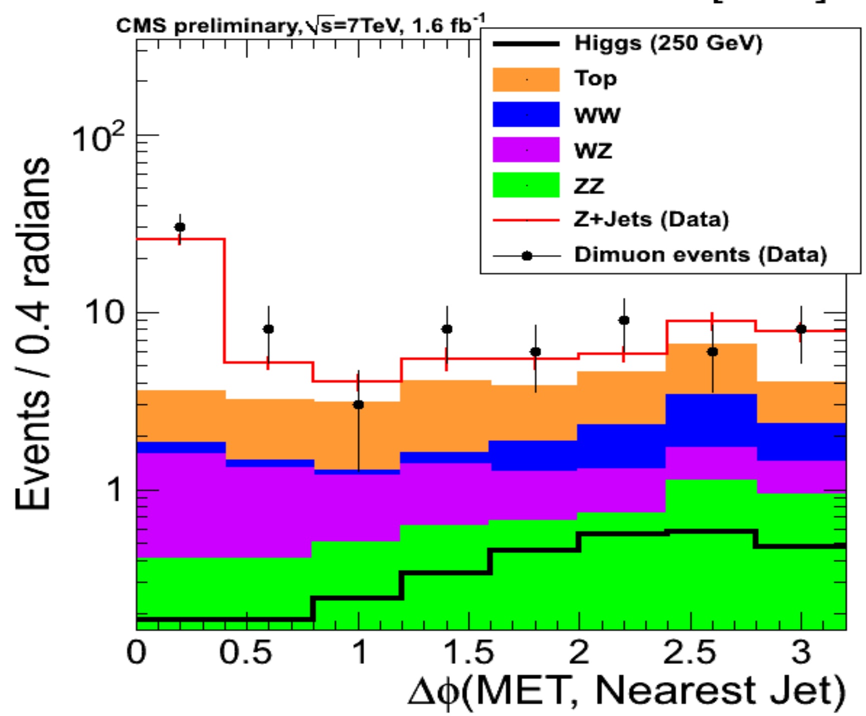
- Resonant: Z+jets
- Non resonant: ttbar, tW, WW, W+jets
- Irreducible: ZZ, WZ

Event Selection:

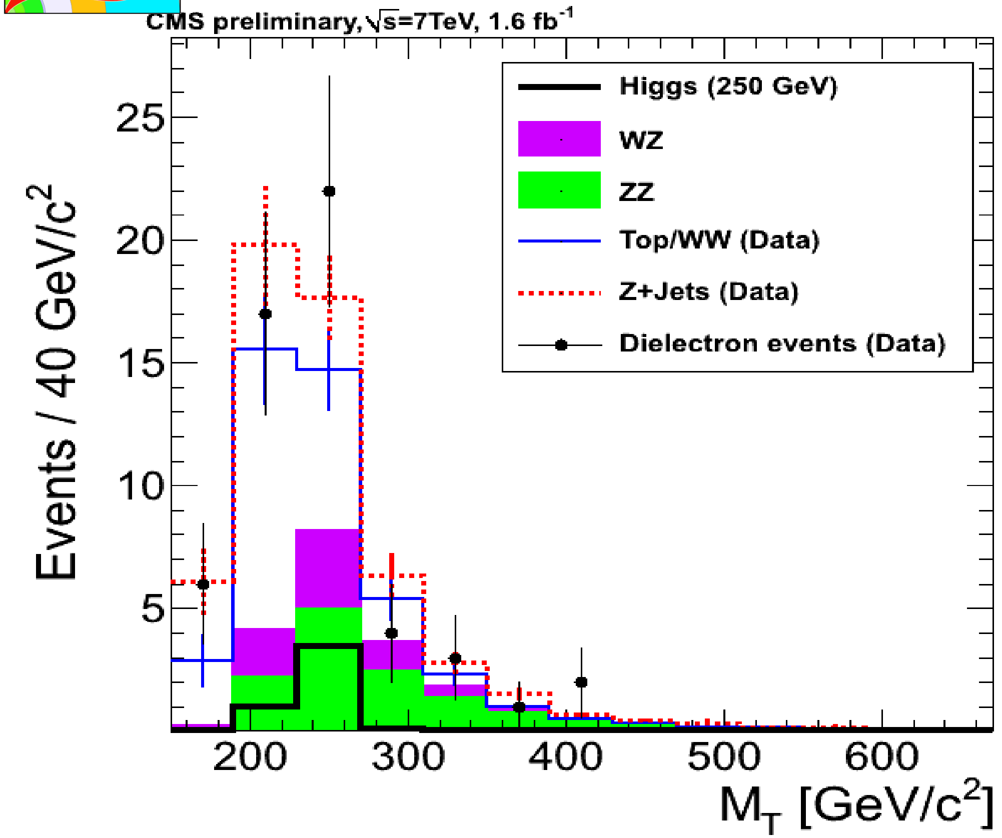
- 2 isolated, same flavor, opposite charge leptons around Z mass
- large MET
- b-jet/soft-muon veto
- 3rd leptons events veto
- MET-jet separation
- sideband cut on M_T

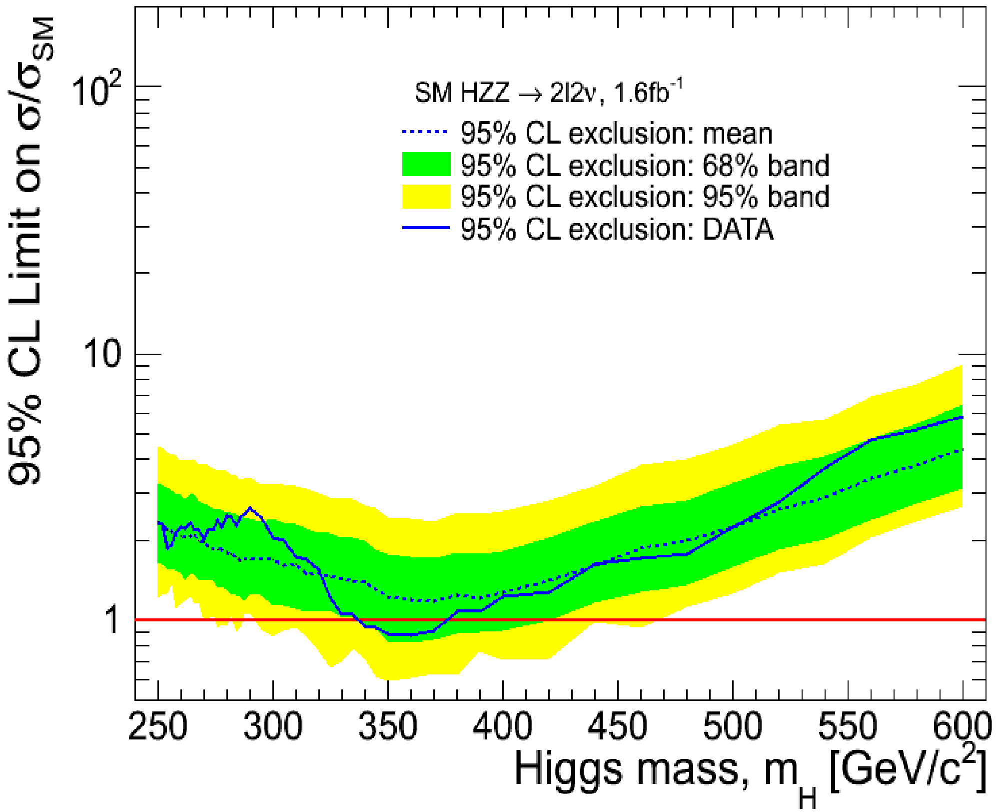
Background suppression





Upper Limits





Background estimation:

- Resonant: γ + jets events
- Non resonant: eμ events
- Irreducible: Monte Carlo

SM Higgs boson with mass $340 < M_H < 375$ GeV excluded at 95 % C.L.

Cut and Count analysis using M_T variable

$H \rightarrow ZZ \rightarrow 2\ell\ 2q$ HIG-11-017

High Mass: $200 < M_H < 600$ GeV

Large yield: $BR(Z \rightarrow qq) = 70\%$
Fully reconstructed decay chain

Higgs Signature:

- 2 opposite charge isolated leptons
- pair of jets

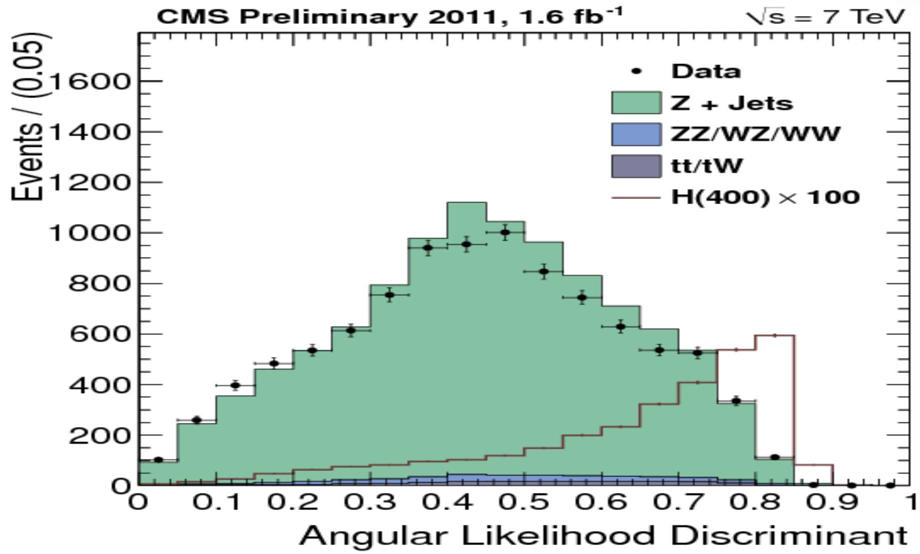
Backgrounds:

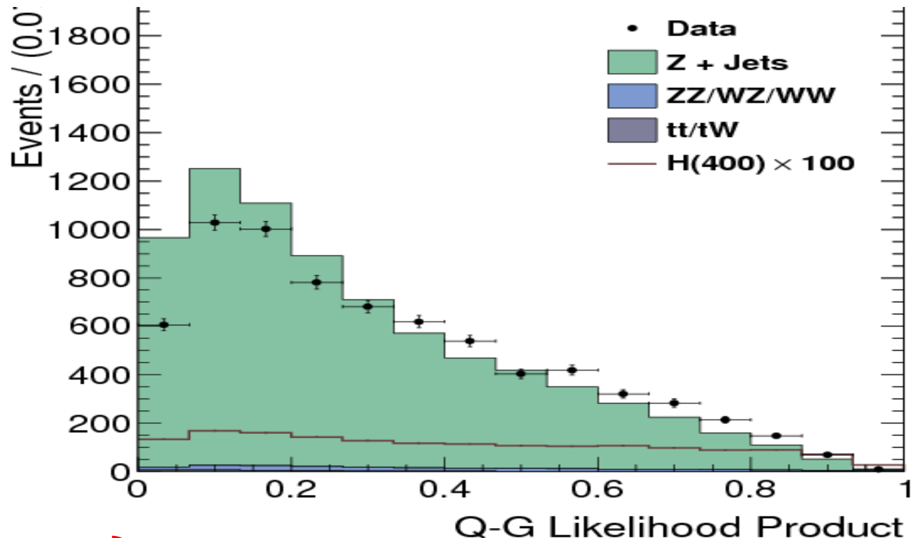
- Resonant: Z+jets
- Non resonant: ttbar, tW
- EWK: ZZ, WZ, WW

Event Selection:

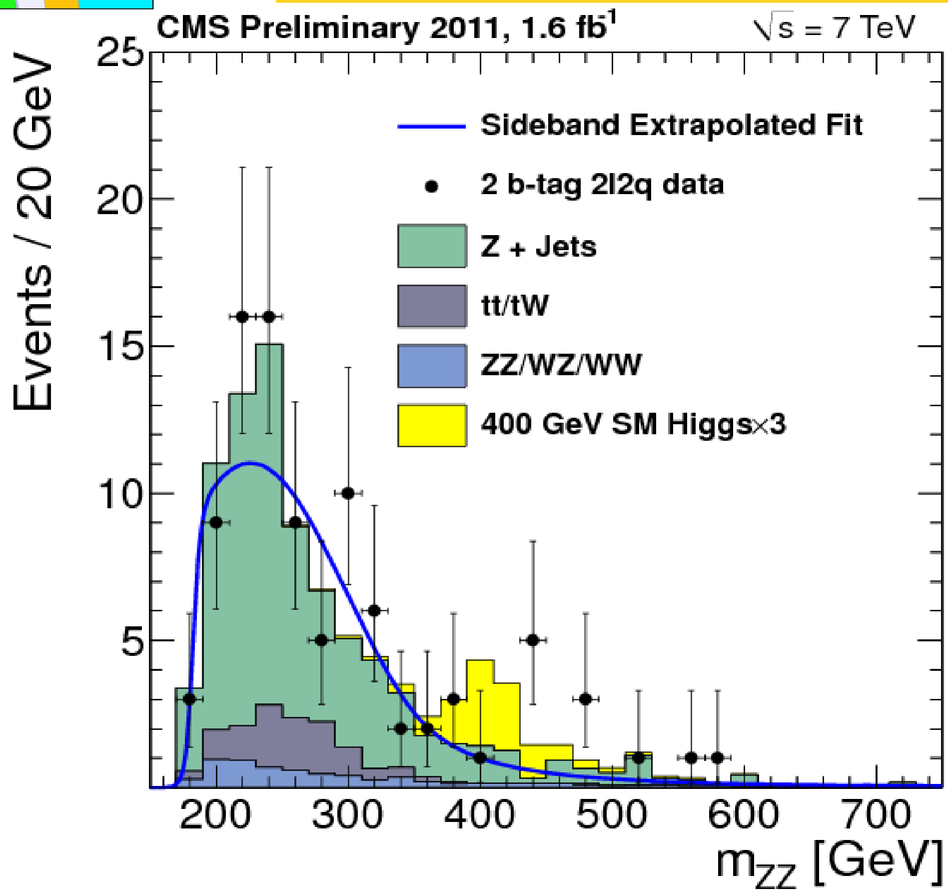
- 2 isolated, same flavor, opposite charge leptons
- at least 2 jets
- $M_{\ell\ell}$ and M_{jj} compatible with Z mass
- MET requirement
- angular Likelihood Discriminant cut
- quark-gluon Likelihood Discriminant cut

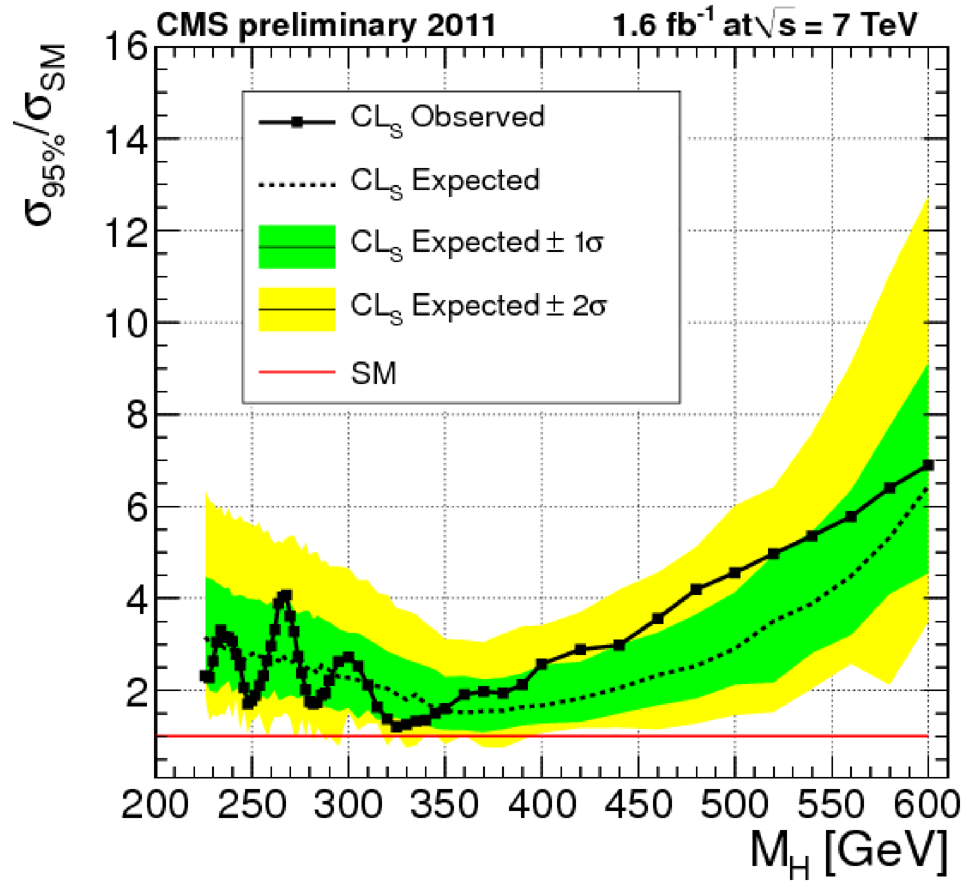
} Background suppression





Upper Limits





Background estimation:

- from M_{jj} sidebands
- additional information on ttbar from eμjj sample

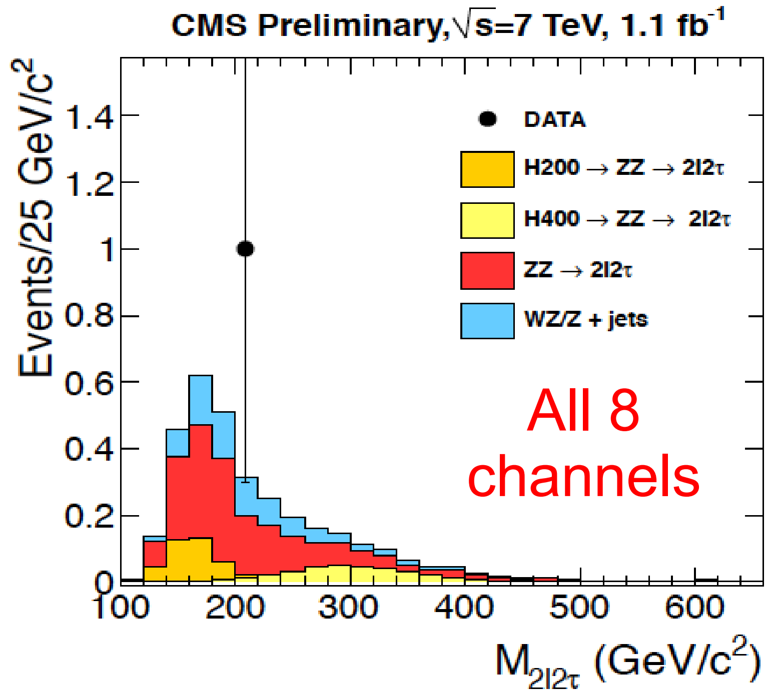
Exclusion limits approaching those of the SM expectation

Shape analysis. Parametrization:

- Signal: Breit-Wigner ⊗ Crystal-Ball
- background: empirical PDF

$H \to ZZ \to 2\ell\ 2\tau$ HIG-11-013

High Mass:
$200 < M_H < 600$ GeV



Event Selection:

- ee,μμ compatible with Z mass
- $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ with $30 < M_{\tau\tau} < 80$ GeV

Backgrounds:

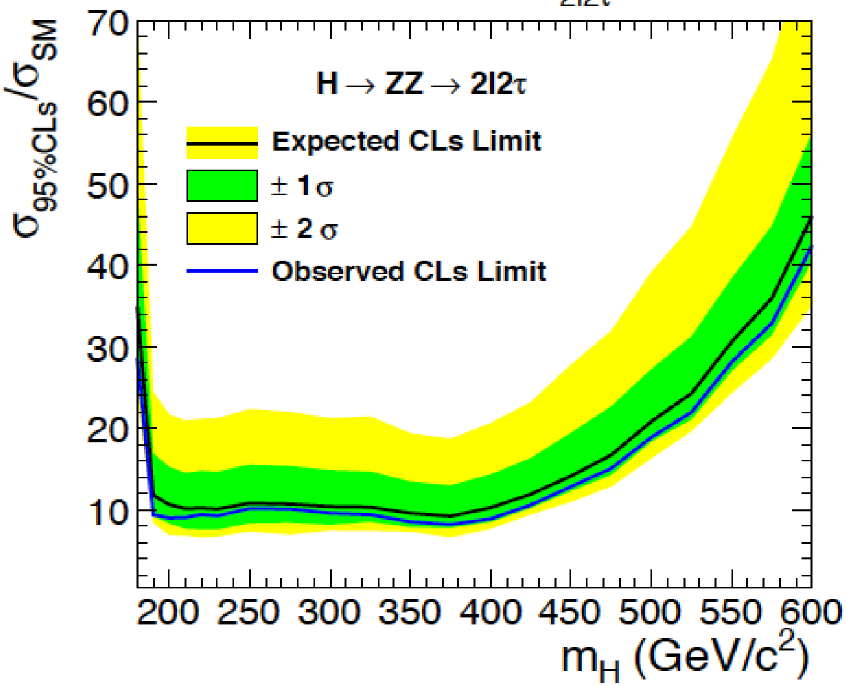
- Irreducible: ZZ
- Reducible: ttbar, WZ, Z+jets

Data driven background estimation:

- ZZ: normalization to Z rate using theoretical cross sections
- Reducible: fake rate measurements

Shape analysis:

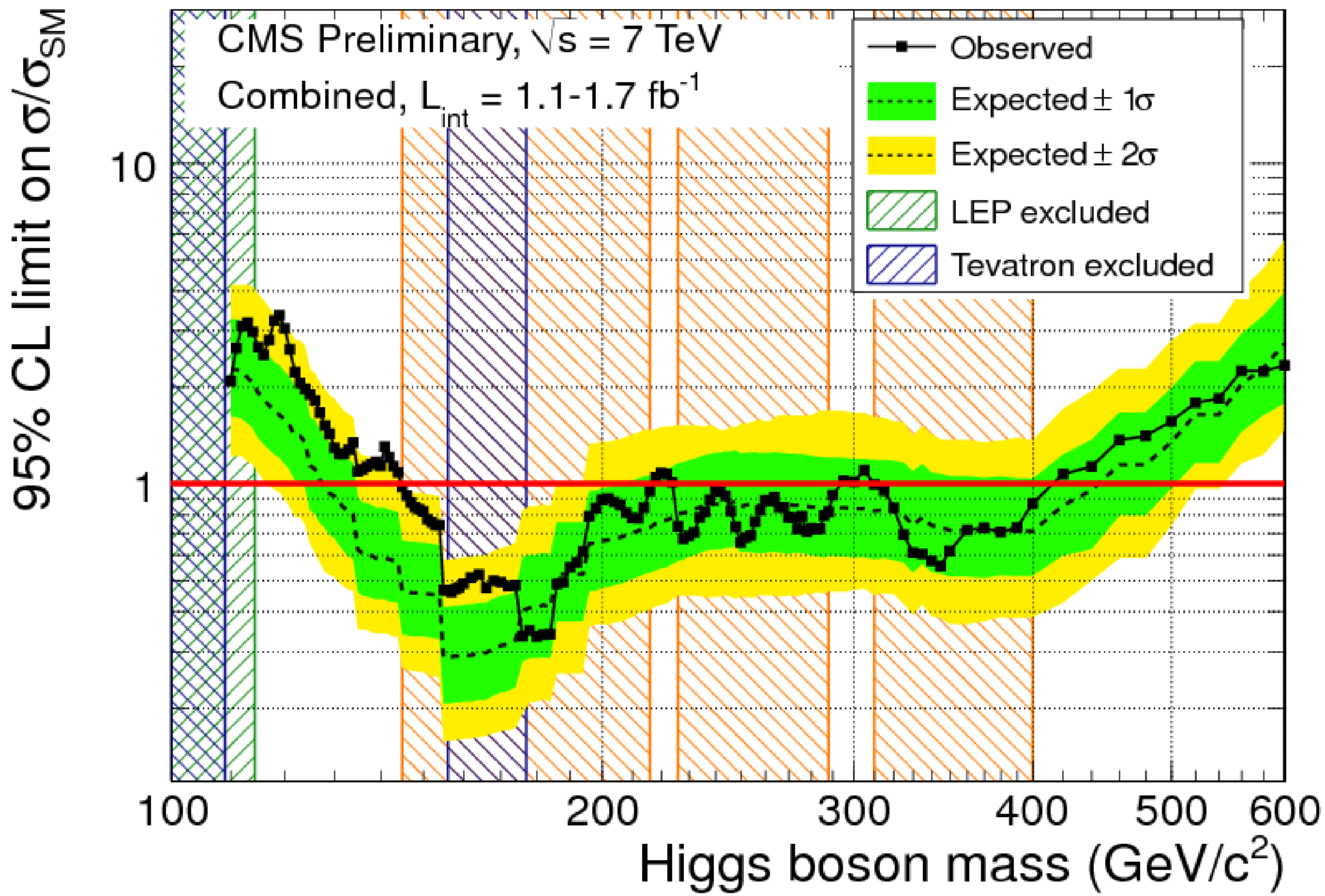
- signal and background from simulated data



expected and observed 95% CL limits:
10XSM to 12XSM for $200 < M_H < 400$ GeV

SM Higgs Combination Results: Limits

HIG-11-022



Three intervals in M_H excluded at 95% C.L.:

145-216, 226-288, 310-400 GeV

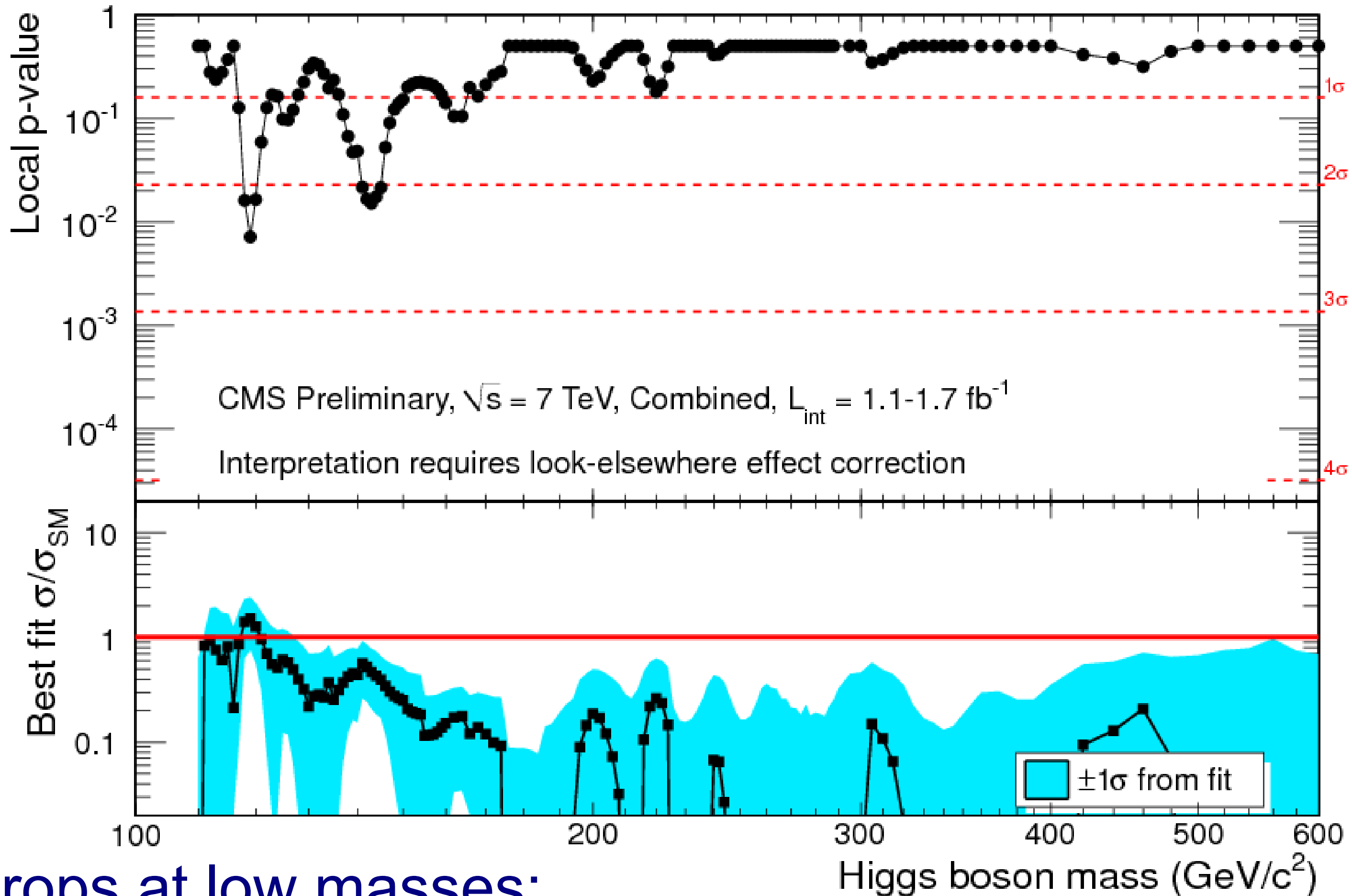
(expected exclusion 130-440 GeV)

Limits ~2σ larger than expectation for low masses:

- observed limits less sensitive than expected

SM Higgs Combination Results: p-value

HIG-11-022



p-value drops at low masses:

- from WW, ZZ and γγ analysis

p-value to observe a 2.3σ excess:

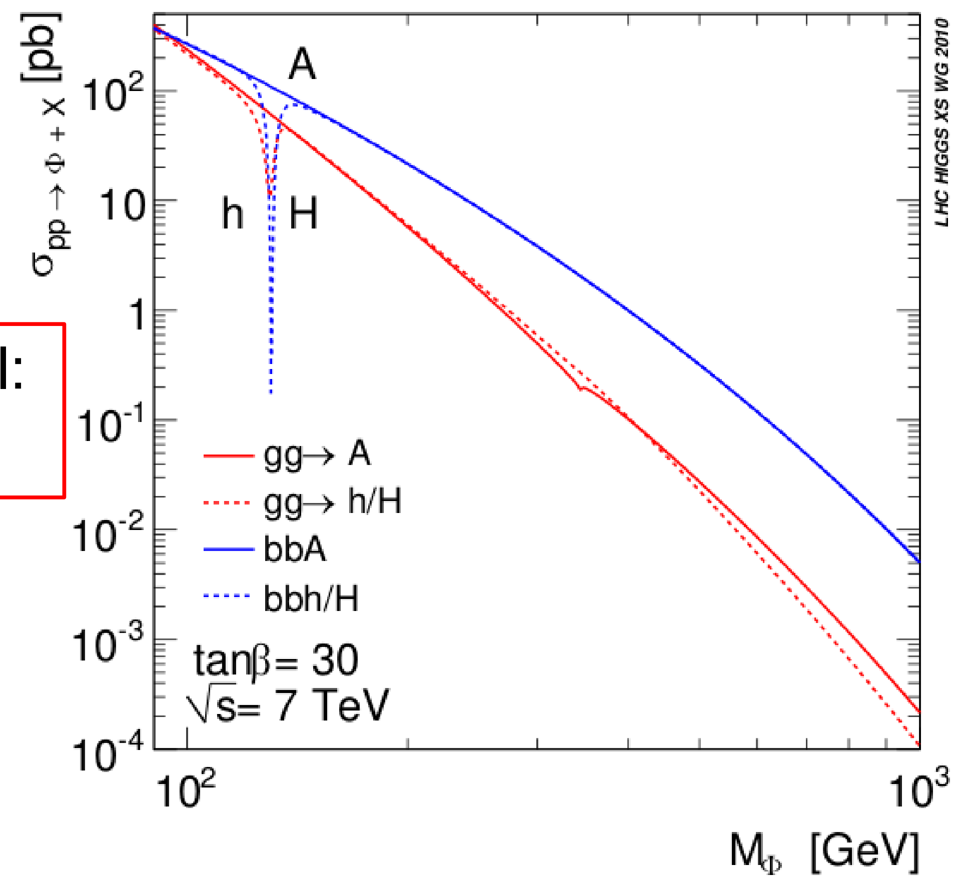
- ~ 0.4 taking into account the probability of observing the excess anywhere in the full search range (*look-elsewhere effects*)

Excess at low masses not significant with the current amount of data

Minimal Supersymmetric Standard model Higgs

Scalar sector more complicated:
5 massive Higgs Bosons

- 3 neutral states h, H, A
- 2 charged states $H^{\pm}$

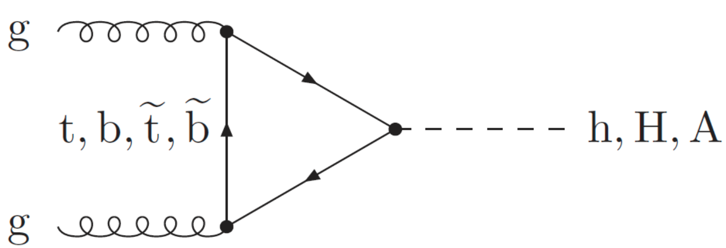


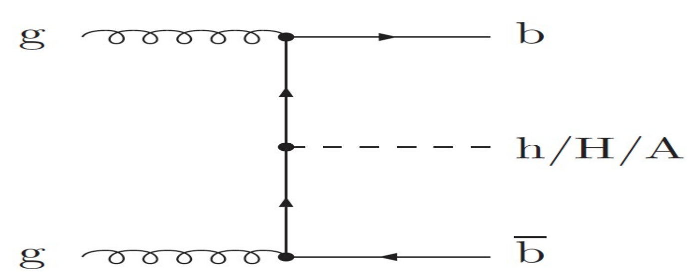
Described by 2 parameters at Tree-Level:
Tanβ, M_A

At large Tanβ:

- if $M_A \lesssim 130$ GeV: h, A nearly degenerate
  H ~ 130 GeV
- if $M_A \gtrsim 130$ GeV: A, H nearly degenerate
  h ~ 130 GeV

Scalar states: 2 main production channels



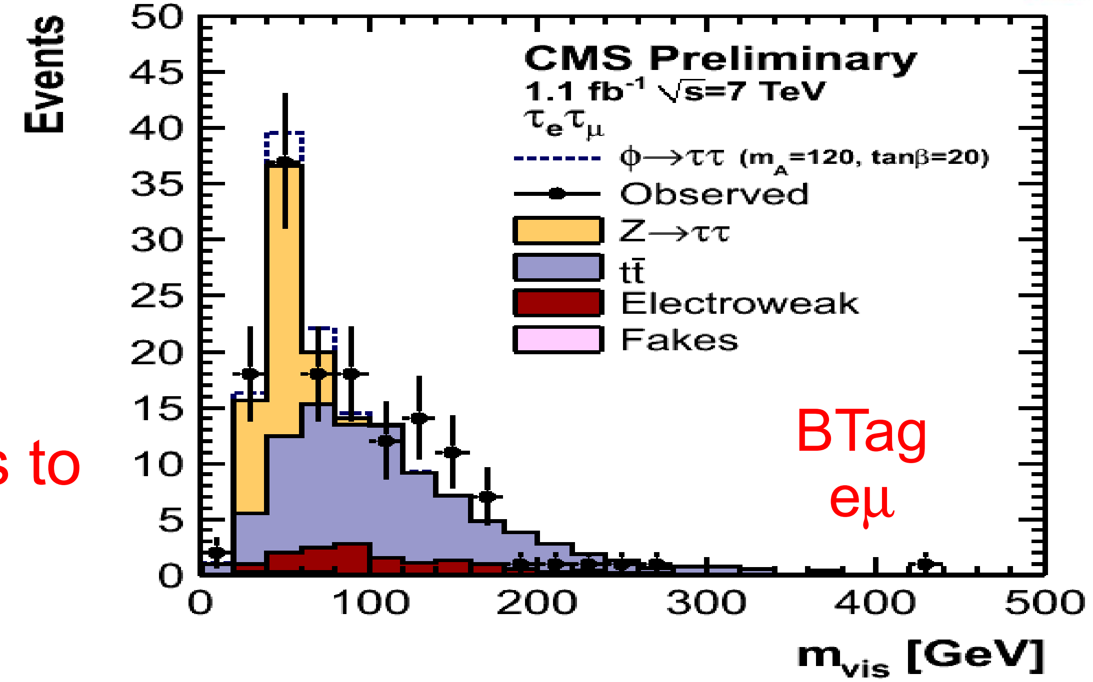


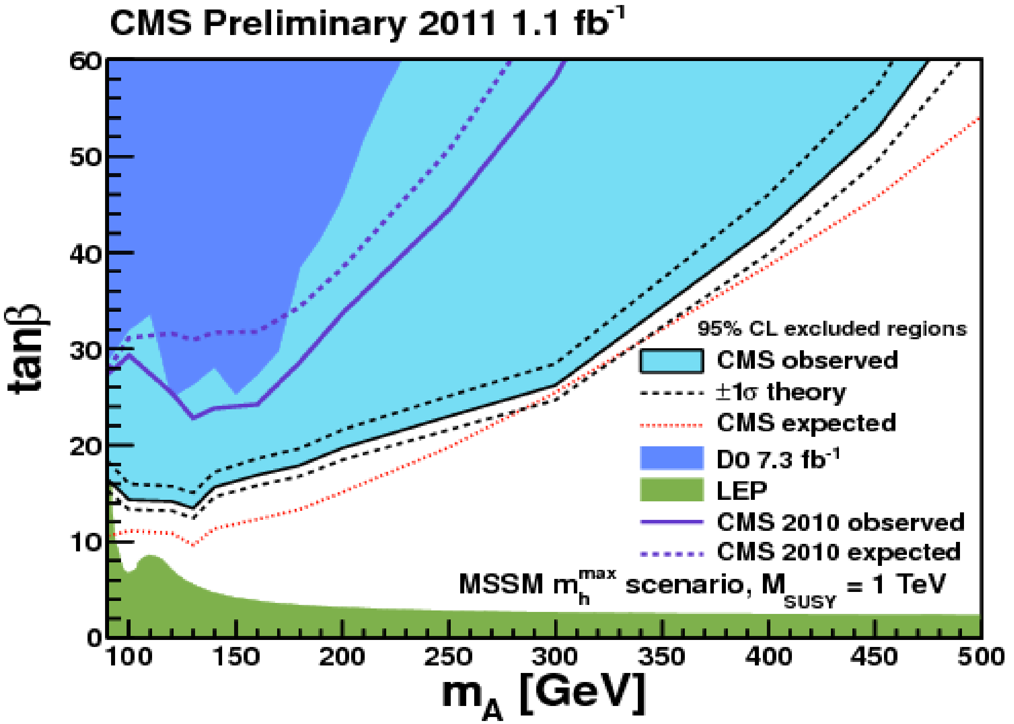
MSSM: $\phi \rightarrow \tau\tau$ HIG-11-009

As for the SM $H \rightarrow \tau\tau$:

- same Higgs channels selected
- same backgrounds, rejection-procedure and estimation
  - but different event categories to increase sensitivity:
    - less than 2 jet p_T>30 GeV at least 1 b-tagged jet p_T>20 GeV
    - less than 2 jets p_T>30 GeV no b-tagged jets p_T>20 GeV

Limit obtained from a fit to the visible mass distribution





Excluded large region of the MSSM parameters.
Good improvement w.r.t. 2010 data.

Conclusions

Results from the Higgs Boson searches performed with the CMS detector have been shown with 1.1-1.7 fb^{-1} of Integrated luminosity:

- exploiting 8 decay channels,
- no signal evidence found,
- three SM mass ranges excluded at 95% C.L.:

  145-216, 226-288, 310-400 GeV

- excess at low mass with a probability of 0.4,
- large ($\tan\beta$, M_A) area excluded in the MSSM context exploiting neutral Higgs in $\tau\tau$ channel.

BACKUP

Limits: modified frequentist CL_s

Systematic uncertainties

- introduced as nuisance parameters ϑ
- measured preferred value $\tilde{\vartheta}$ from control samples, theory, etc
- p.d.f. around the preferred value: Gamma, Lognormal, Uniform, Gaussian

Likelihood function:

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

$s(\vartheta)$, $b(\vartheta)$ signal and background expectation

$\mu = \sigma/\sigma_{SM}$ signal strength

$p(\tilde{\vartheta}|\vartheta)$ probability of measuring $\tilde{\vartheta}$ given ϑ (Frequentist)

Limits: modified frequentist CL$_s$

For each value of μ:

1) find the observed value $\tilde{q}_\mu^{obs}$ on data of the test statistic

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

2) find the values of the nuisance parameter ϑ that best fit the experimental data for the background-only and signal+background hypothesis

3) use these values to generate toy MC pseudo-data for background-only and signal+background to construct test statistic p.d.f. for a signal with strength μ and background only hypothesis:

$$f(\tilde{q}_\mu|\mu,\hat{\theta}_\mu^{\text{obs}}) \qquad f(\tilde{q}_\mu|0,\hat{\theta}_0^{\text{obs}})$$

4) from the p.d.f.s the p-values for background-only and signal+background hypothesis are found and the CL$_s$ as the ratio of the two p-values:

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

4) if CL$_s$ < 0.05, then the value of μ is excluded at 95% C.L.

Quantifying excess of events

Presence of signal quantified by the background-only p-value: probability of the background to fluctuate and give an excess as large or larger than the observed one.

1) use test statistic

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

2) use nuisance parameter that best fit data for background-only hypothesis to generate pseudo data and construct test statistic p.d.f. $f(q_0|0,\hat{\theta}_0^{\mathrm{obs}})$

3) obtain p-value from the p.d.f.

$$p_0 = P(q_0 \geq q_0^{obs}) = \int_{q_0^{obs}}^{\infty} f(q_0|0,\hat{\theta}_0^{\mathrm{obs}})\, dq_0$$

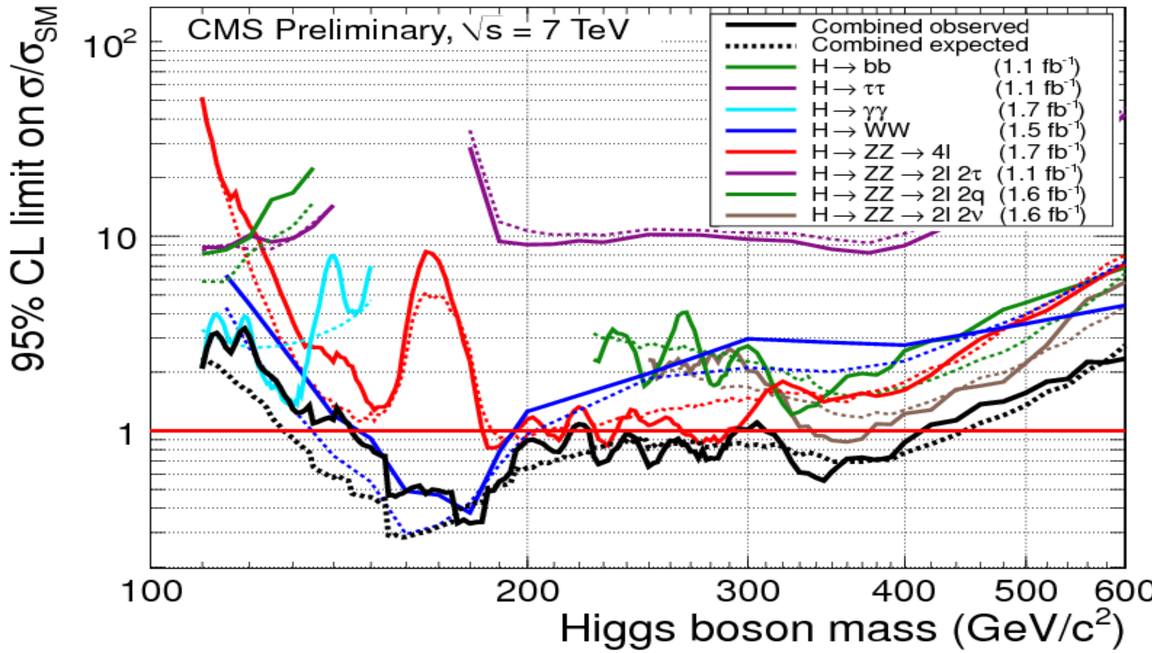
4) that can be approximated with "one-sided gaussian tail":

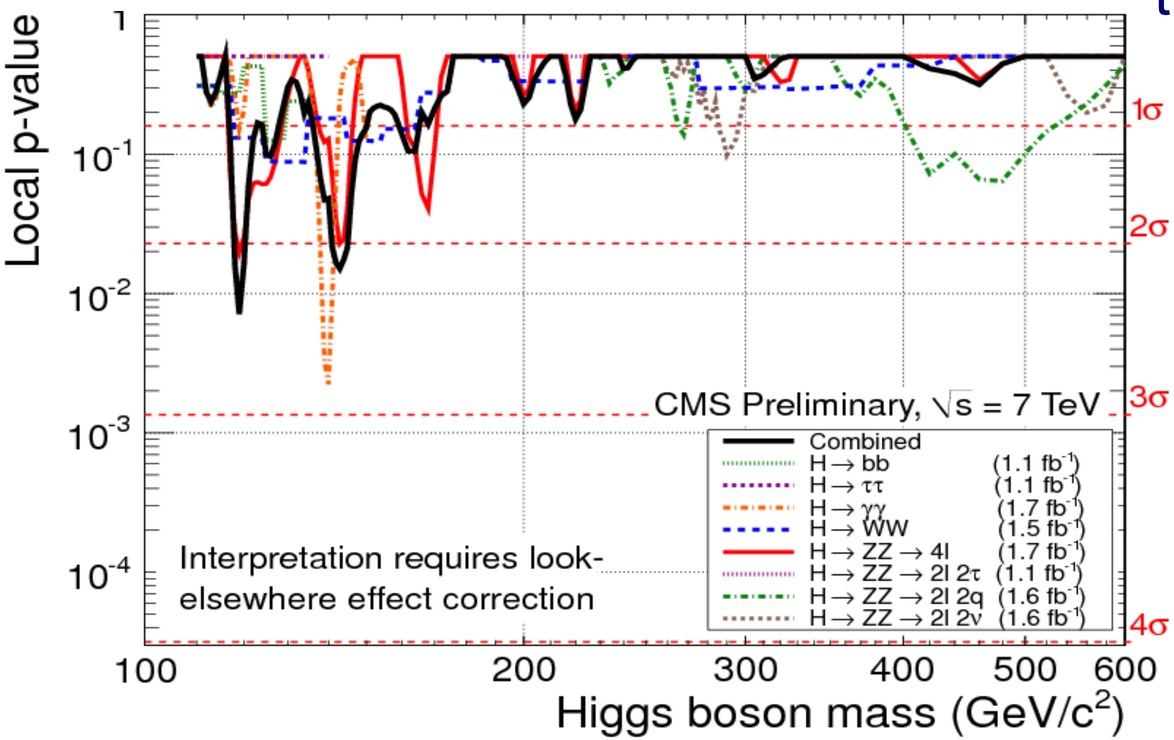
$$p_0 = P(q_0 \geq q_0^{\mathrm{obs}}) = \int_Z^{\infty} \frac{e^{-x^2/2}}{\sqrt{2\pi}}\,dx = \frac{1}{2}\left[1-\mathrm{erf}\left(Z/\sqrt{2}\right)\right]$$

with the significance:

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

SM Higgs Boson Combined Results





Combined limits sometimes not necessarily better than the best single channel limit:

- relative analyses sensitivities
- interplay of excesses and deficits in different channels

WW channel main contributor in the range 160-180 GeV

MSSM charged Higgs

HIG-11-008

For $M_{H+} < M_t$:

$t \rightarrow H^+ b$

For large value of tanβ (>20):

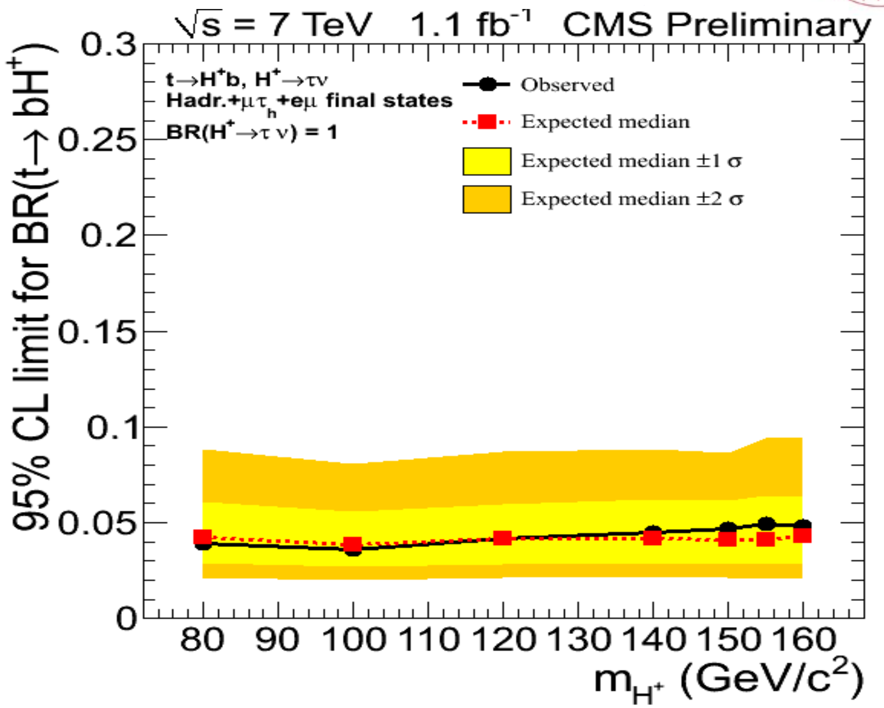
$H^+ \rightarrow \tau^+ \nu_\tau$ with BR~1

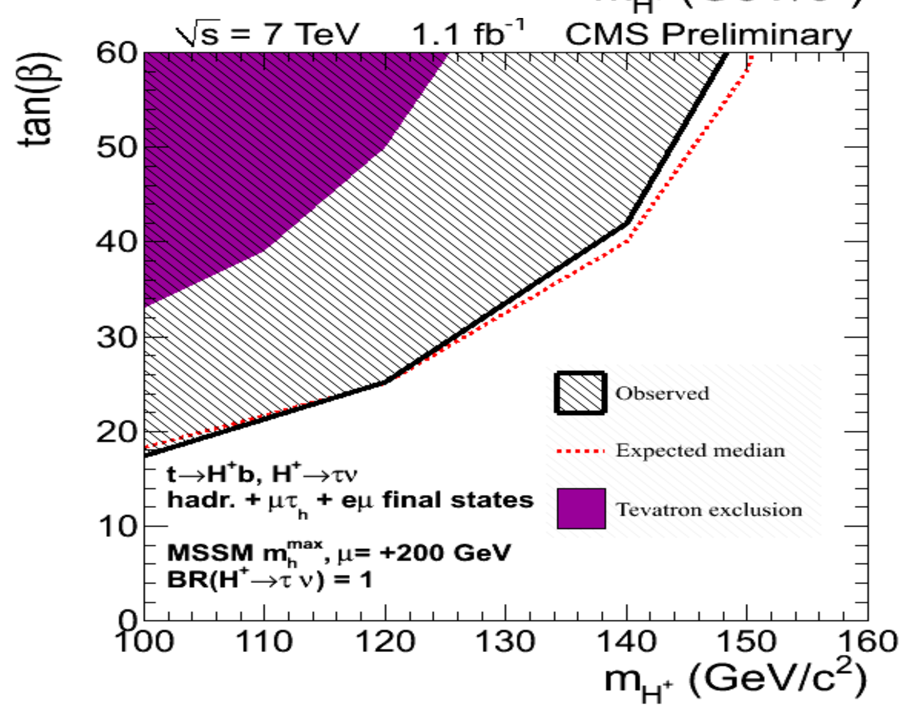
Search in decay products of ttbar:

$$pp \rightarrow t\bar{t} \rightarrow H^{\pm} b W^{\mp} \bar{b}$$

3 channels analyzed:

- τ_h + jets (QCD, ttbar, W+jets)
- $\mu\tau_h$ (ttbar, W+jets)
- μe (ttbar)





New world upper limit on BR($t \rightarrow H^+ b$):
4-5%

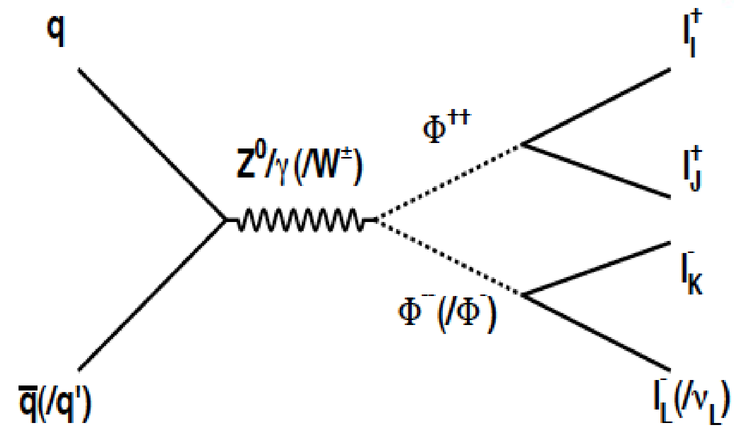
Doubly charged Higgs Boson

HIG-11-007

SM extension introducing a scalar triplet:

- 3 new particles

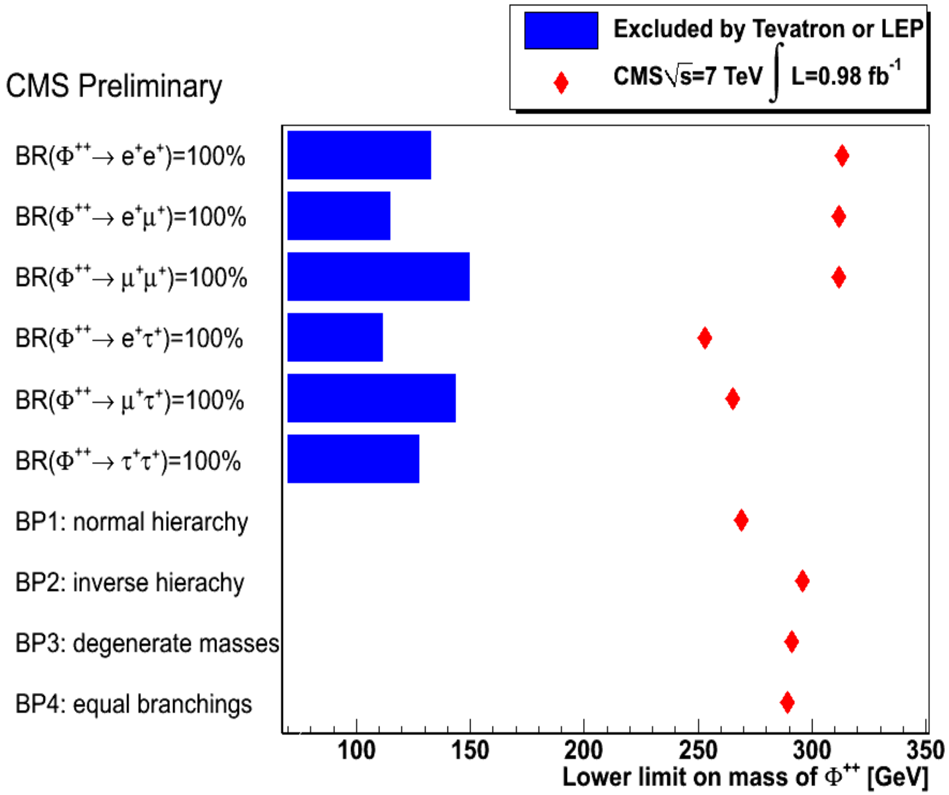
$$\Phi^{++} \quad \Phi^{+} \quad \Phi^{0}$$



Triplet responsible for neutrino masses:

- Yukawa coupling directly related to the mass matrix $M_{ij} = kY_{ij}$

Neutrino Mass Matrix not known: unknown branching ratio for Φ^{++}



Signature: 3 leptons, 4 leptons (ZZ, WZ, Z+jets, tt+jets)

1) Model independent search: set limits assuming BR($\Phi^{++} \rightarrow l^+l^+$) = 100%

2) Model dependent search: 4 benchmarks points (different ν-mass matrix structure)