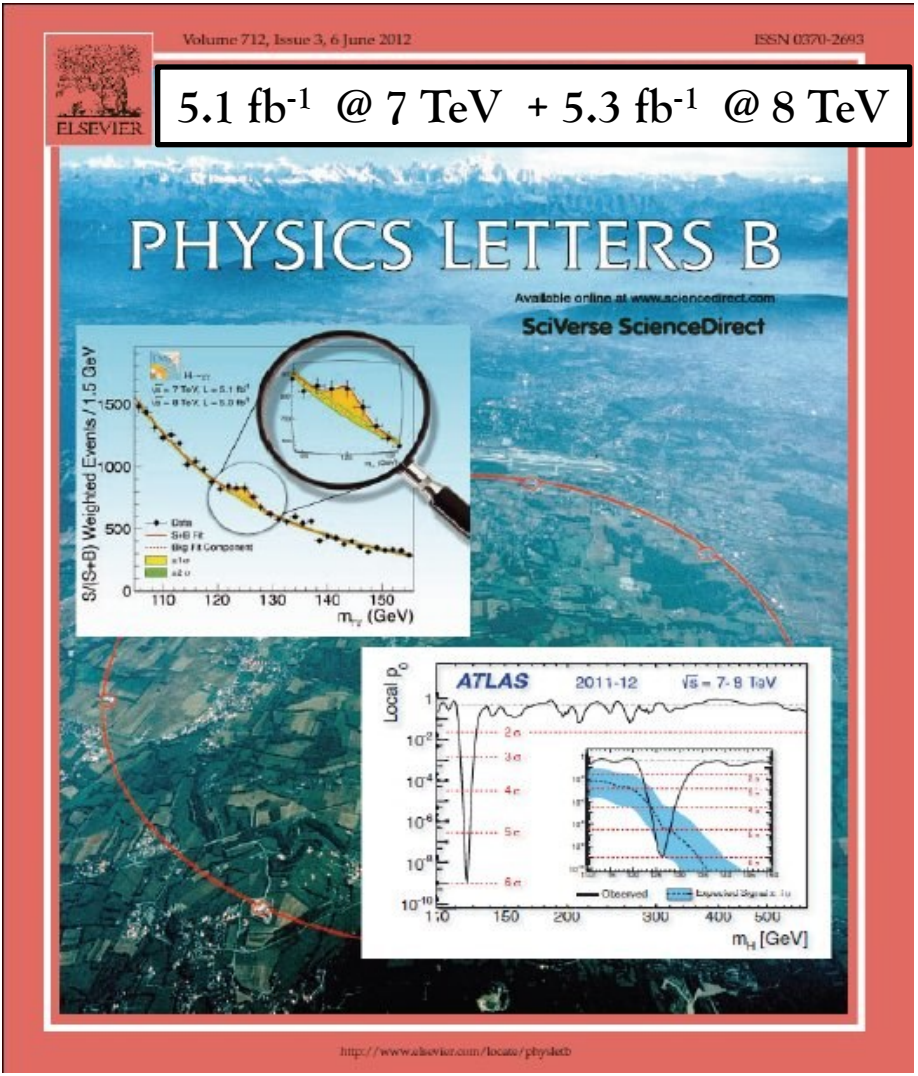
16th Lomonosov Conference on Elementary Particle Physics

22 – 28 August 2013, Moscow (Russia)

Higgs Boson at the CMS experiment

Somnath Choudhury

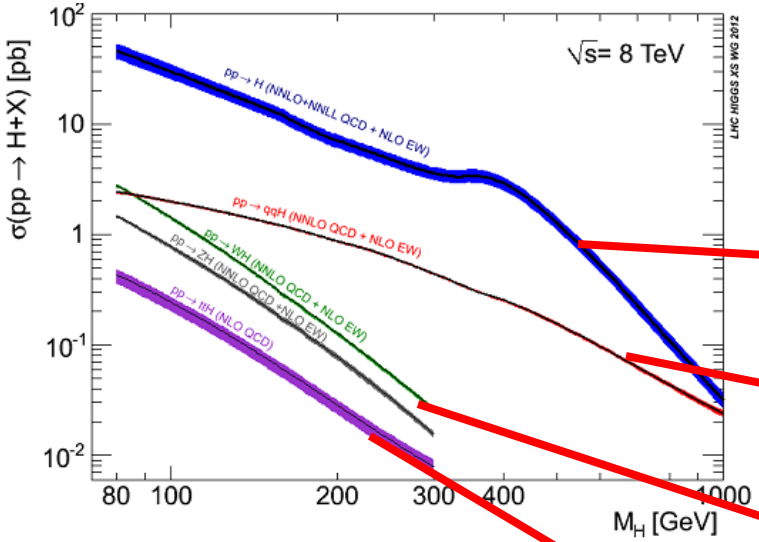
(for the CMS collaboration)

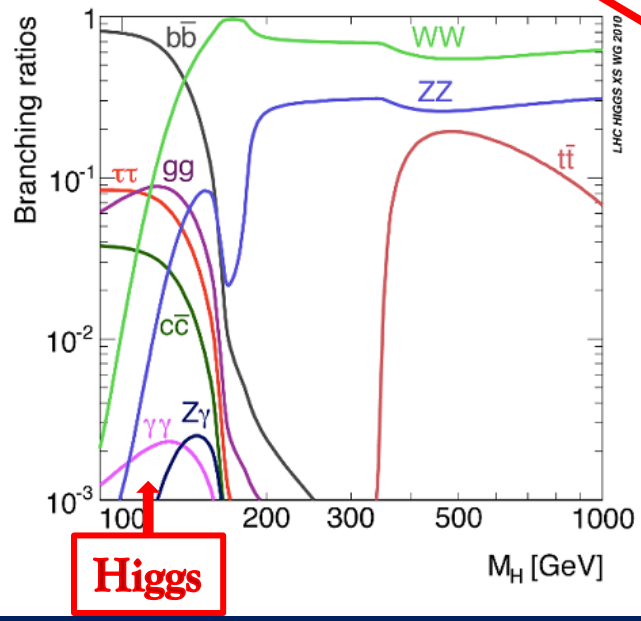


Outline –
Full 7 & 8 TeV dataset ~ 25 fb^{-1}

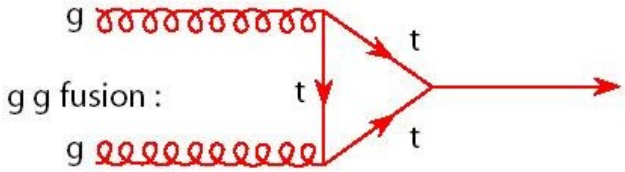
- LHC & CMS detector
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4\ell$
- $H \rightarrow WW \rightarrow 2\ell 2\nu$
- $H \rightarrow \tau\tau$
- $H \rightarrow b\bar{b}$
- Combination
- Summary & Outlook

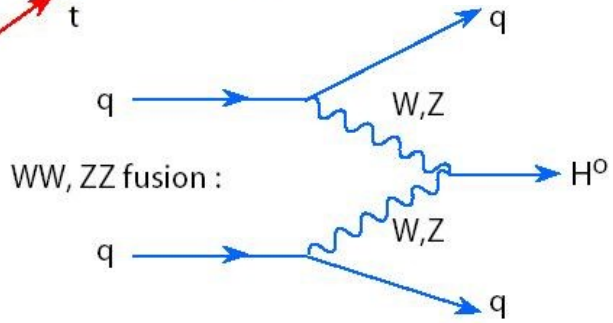
The quest for over 40 years has ended
The Higgs has been finally pinned down!

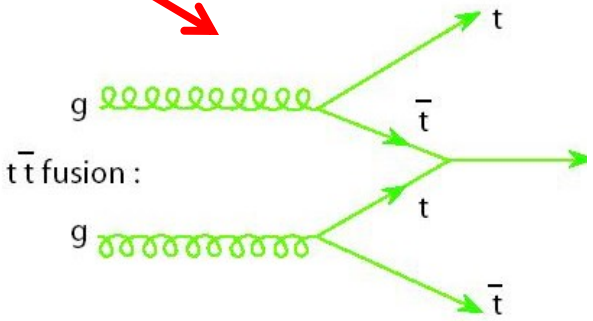


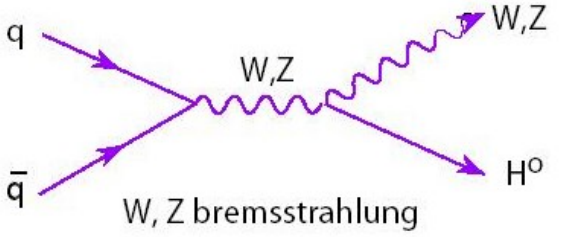


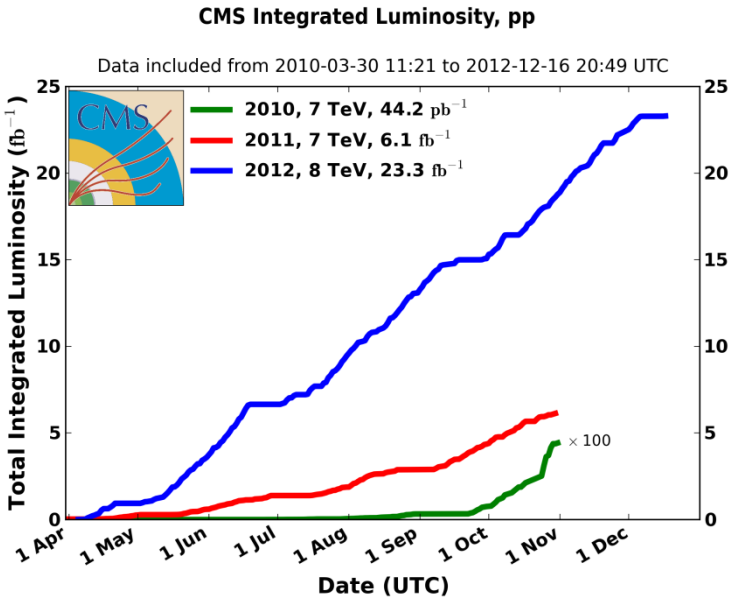
Higgs

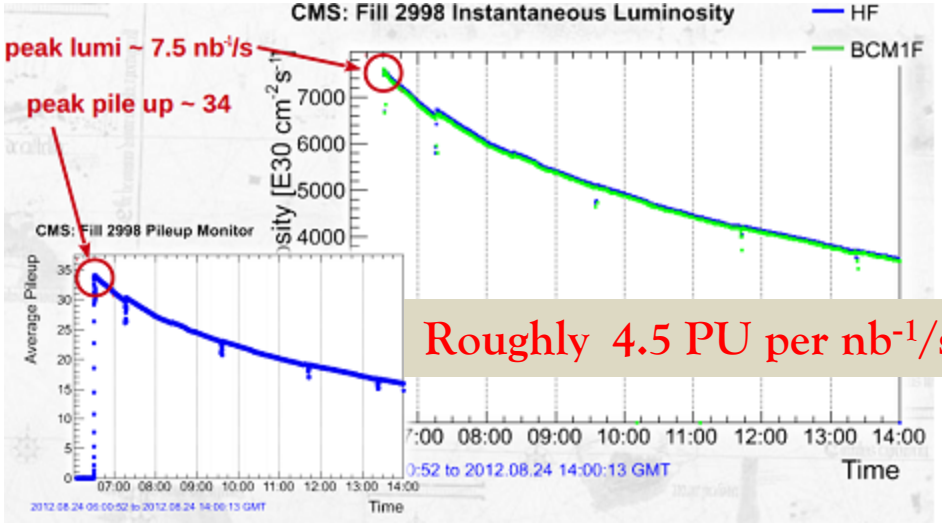


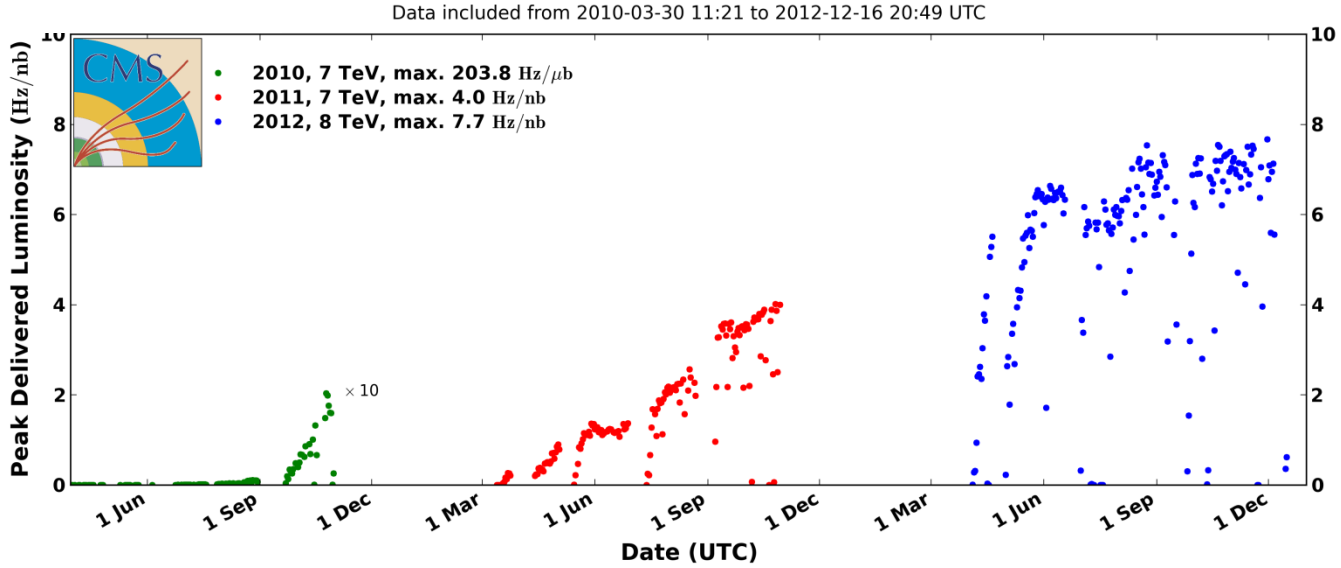












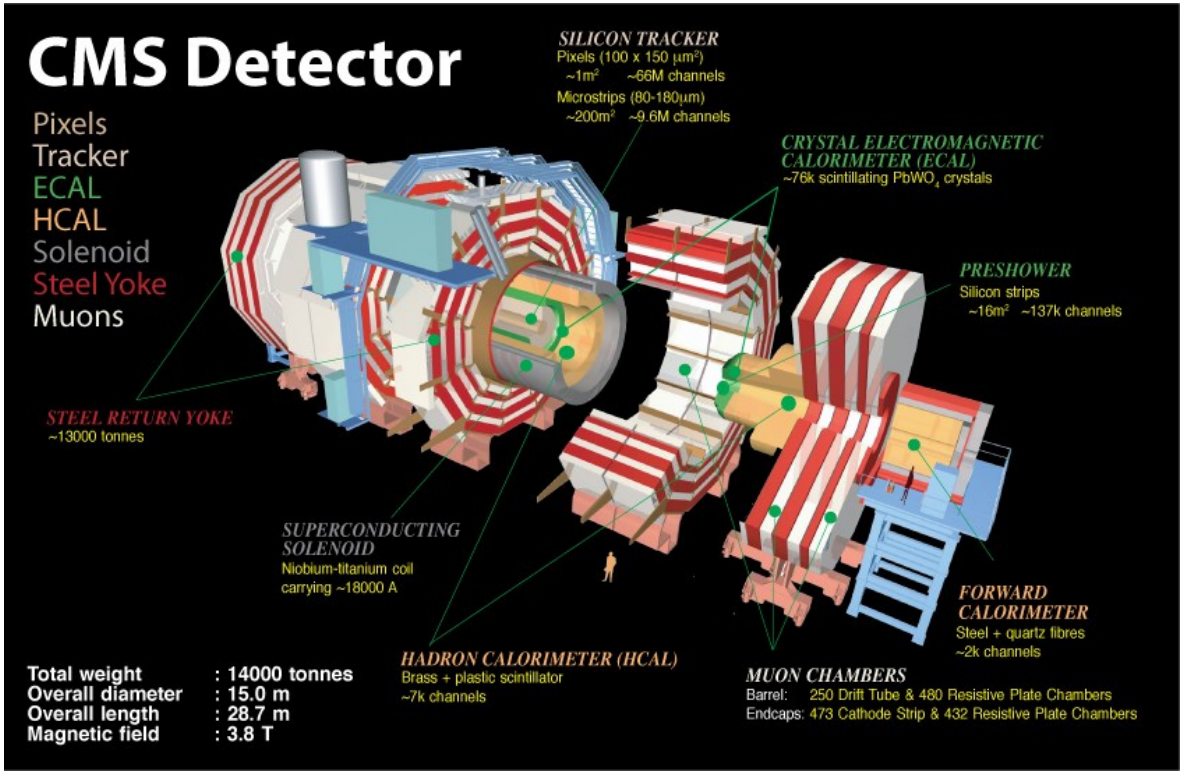
Overall data taking efficiency ~ 90%

3.8 T superconducting solenoid envelop:

- Tracker (silicon pixel and strip detectors) $|\eta| < 2.5$
- ECAL ($PbWO_4$ crystals)
- HCAL (brass/scintillator samplers)

  Barrel $|\eta| < 1.48$
  Endcap $1.48 < |\eta| < 3.0$

- Muon Chambers – gas ionization detectors embedded in steel return yoke outside the solenoid, $|\eta| < 2.4$
  Drift Tubes, Cathode Strips and Resistive Plate Chambers

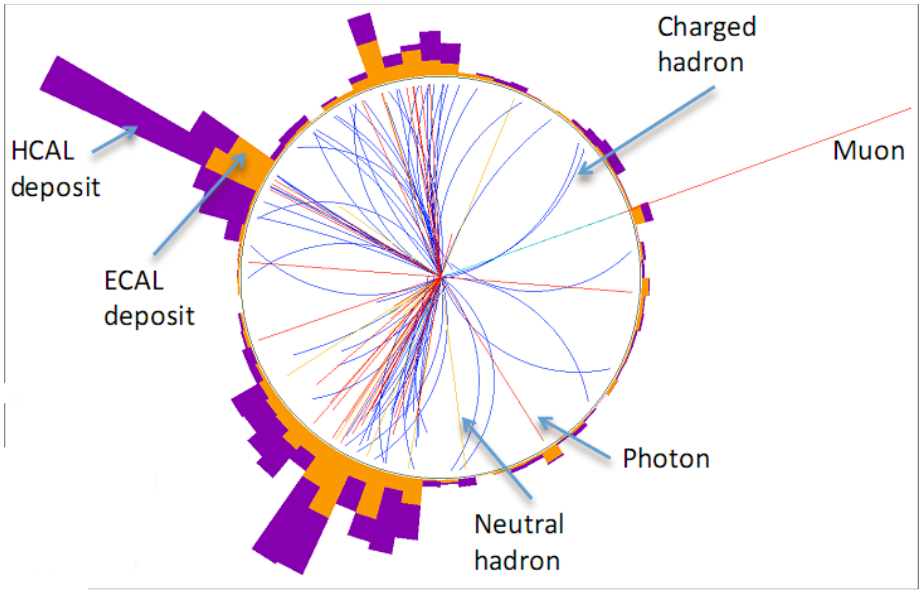


Particle Flow Technique @ CMS

⇒ Event description in form of mutually exclusive particles

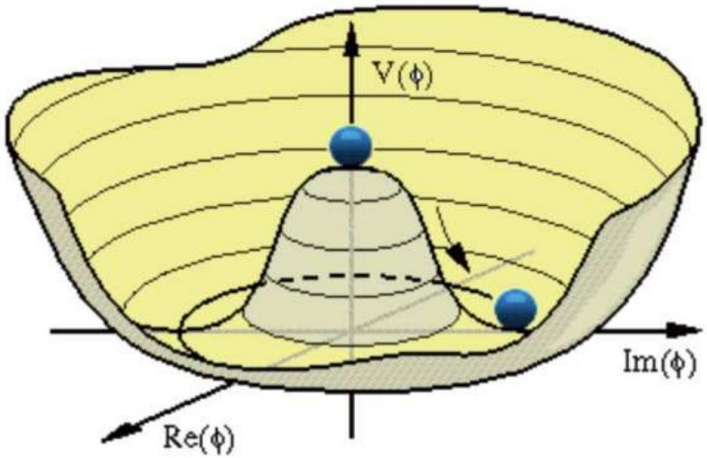
⇒ identification of all stable particles
produced in the event

⇒ combining capabilities of each sub-detector
most precise measurement
of the energy and direction for each particle

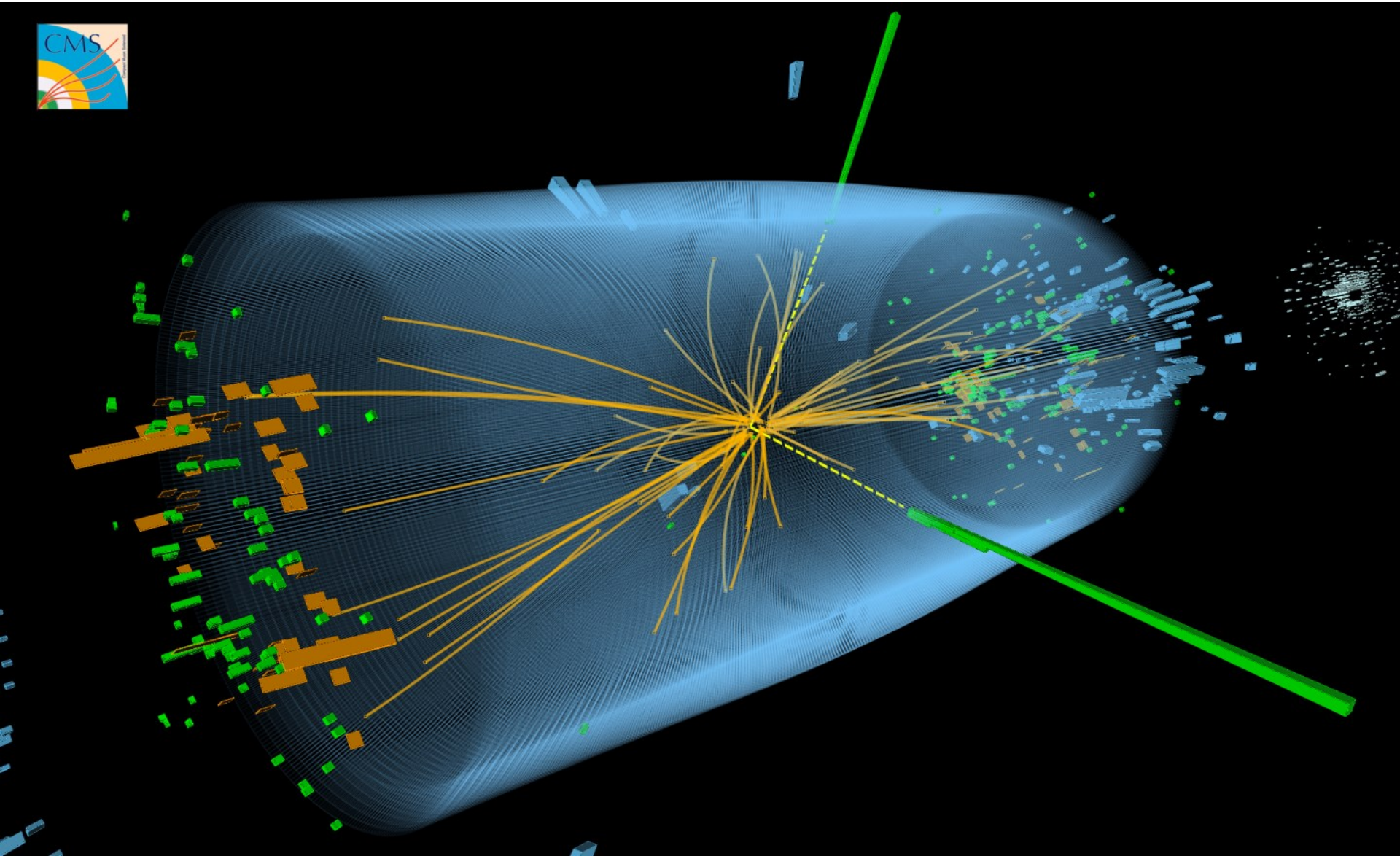


⇒ individual measurements combined
by a geometrical linking algorithm,
e.g. extrapolating a charged-particle track into ECAL and HCAL
particle ID on blocks of linked elements

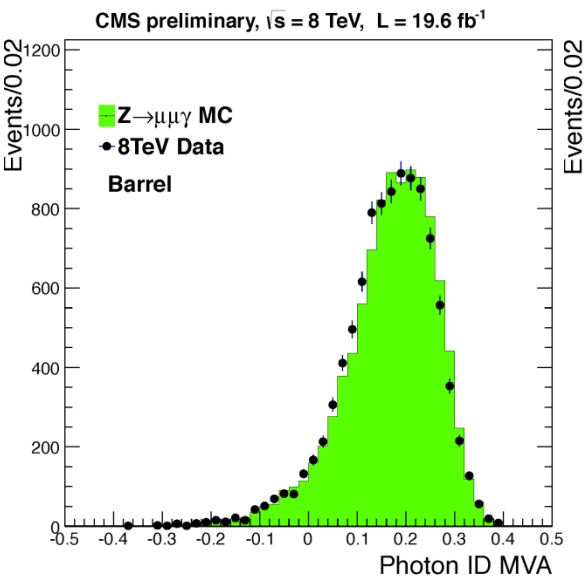
Higgs in Bosonic Decays

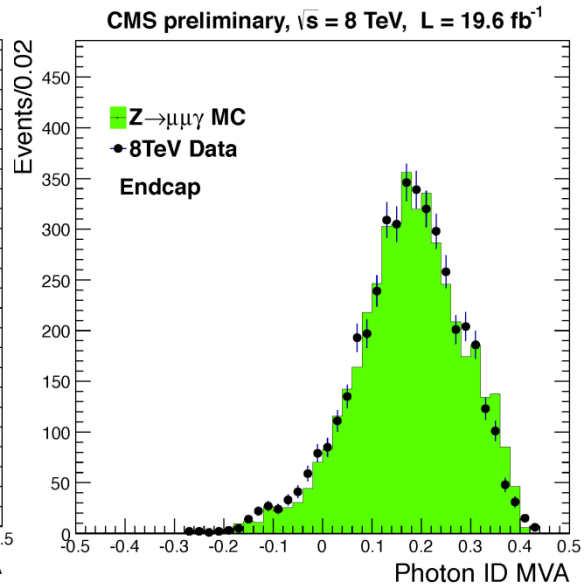


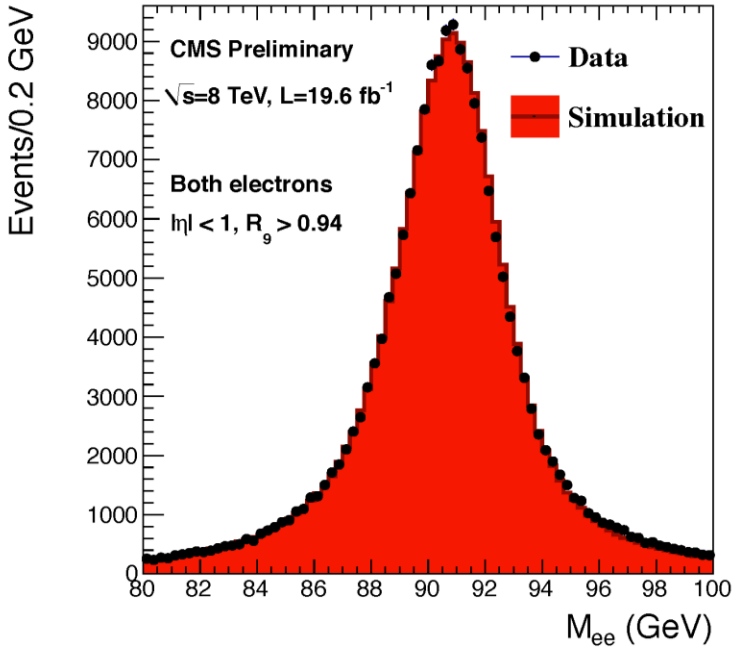
$H \rightarrow \gamma\gamma$



Photon ID MVA score for barrel and endcap photons from Z→μμγ evts in data/simulation

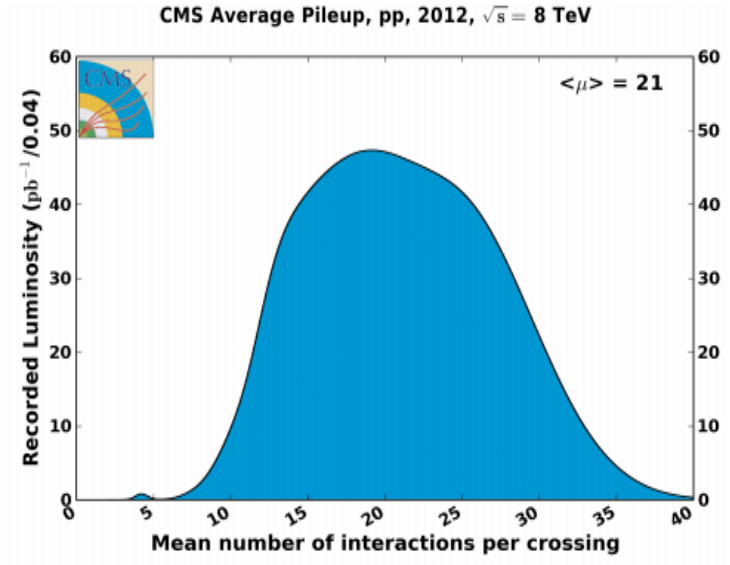




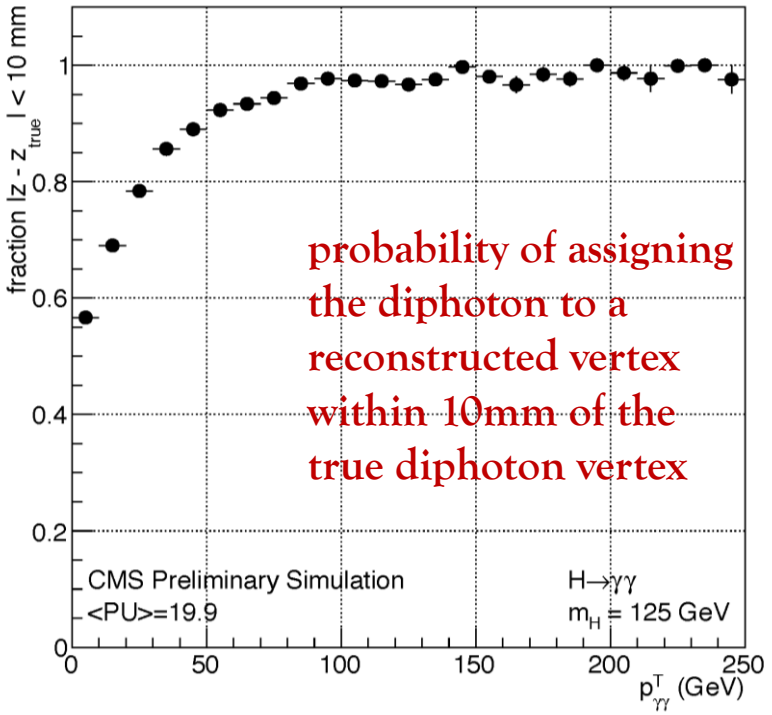


Z→ee events in data / simulation - Electron showers in ECAL reconstructed and corrected as photons

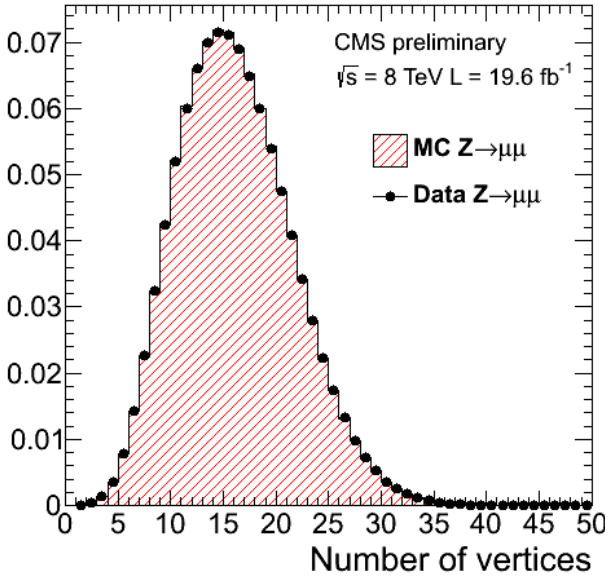
Pile-up & Vertex Reconstruction

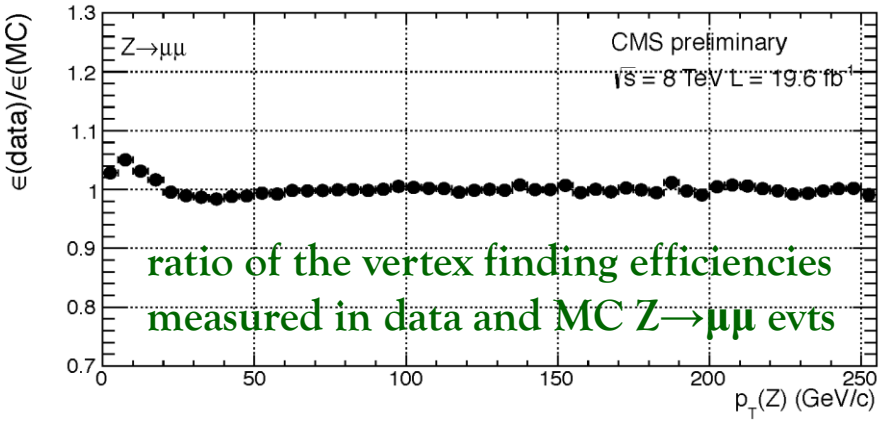


Primary Vertex identified using tracks from recoiling jets and underlying event + conversion



reconstructed vertices in Z→μμ events





Analysis Strategy

Signature: Narrow γγ mass peak
very good mass resolution 1 - 2%
Two isolated high E_T photons
over large smoothly decreasing background
Small Branching Ratio: ~ 2 x 10^{-3}

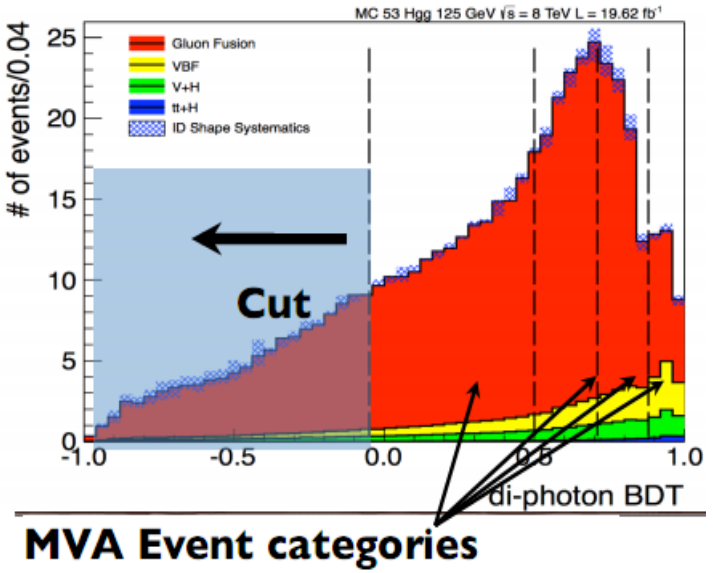
- Inclusive MVA Analysis

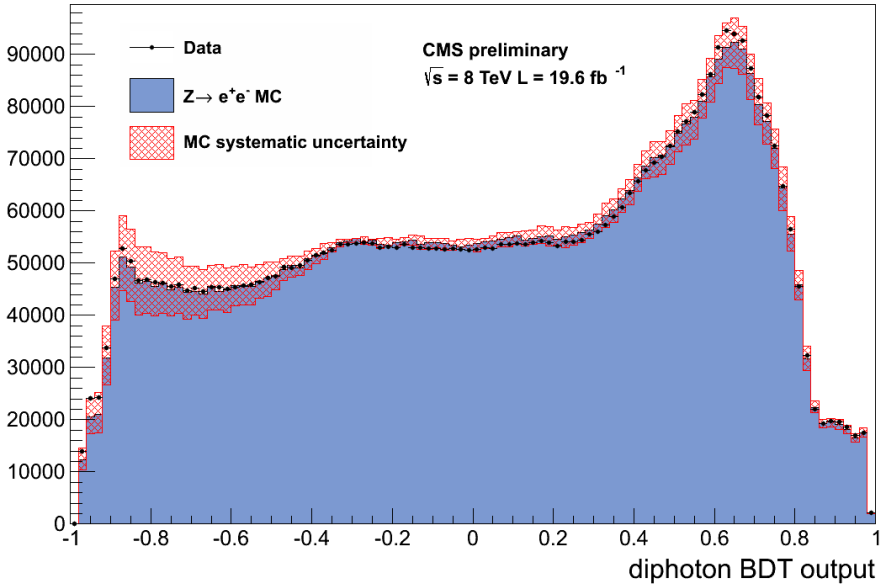
  photons selected with an MVA

  Variable in the MVA:
  photon kinematics,
  photon ID, electron rejection
  MVA score (shower shape, isolation)
  event-by-event $m_{\gamma\gamma}$ resolution

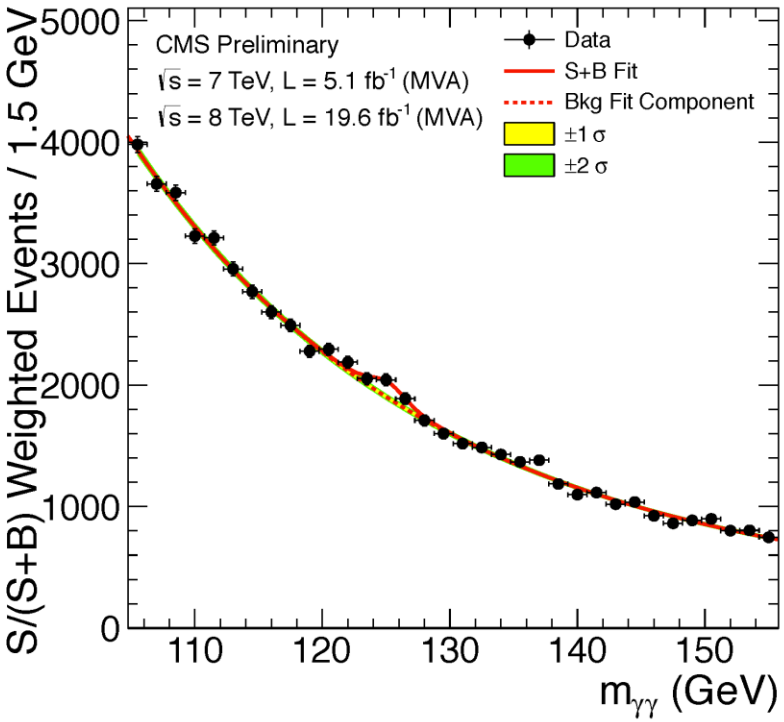
  4 MVA categories with different S/B

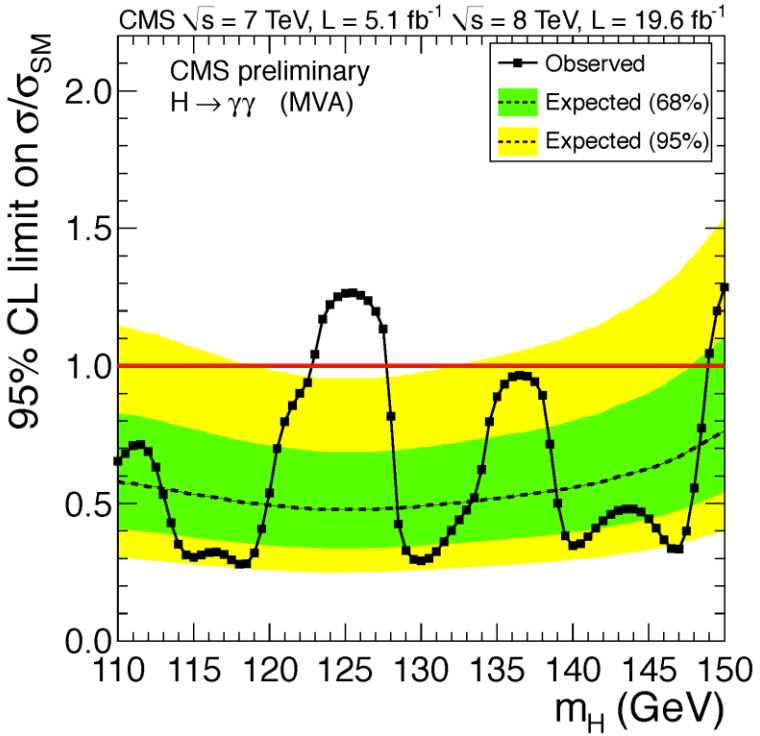
- 3 VH channels (e, μ and MET tag)
  VBF (2 dijet categories)





Di-photon invariant mass
each event weighted by S/(S+B)
of its category

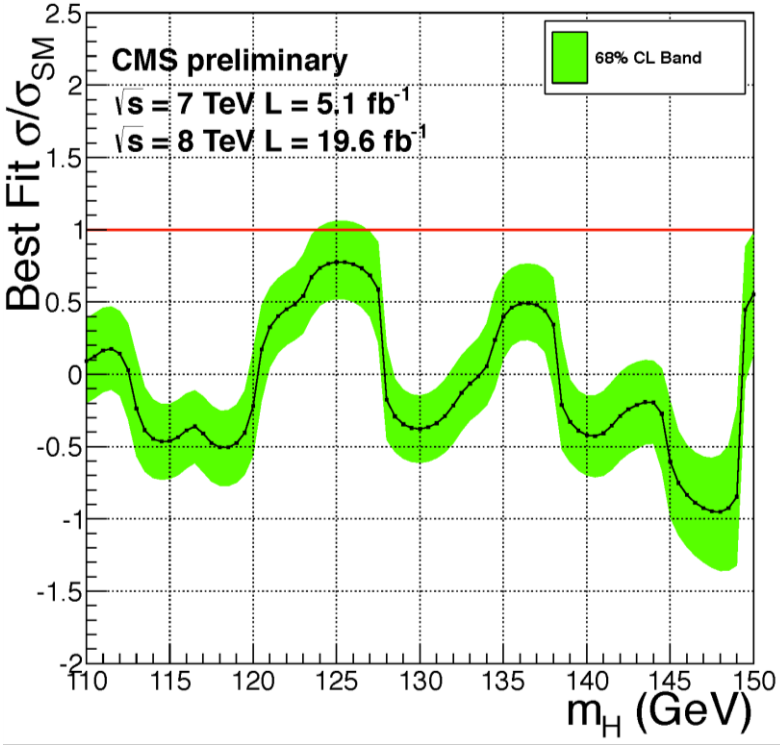




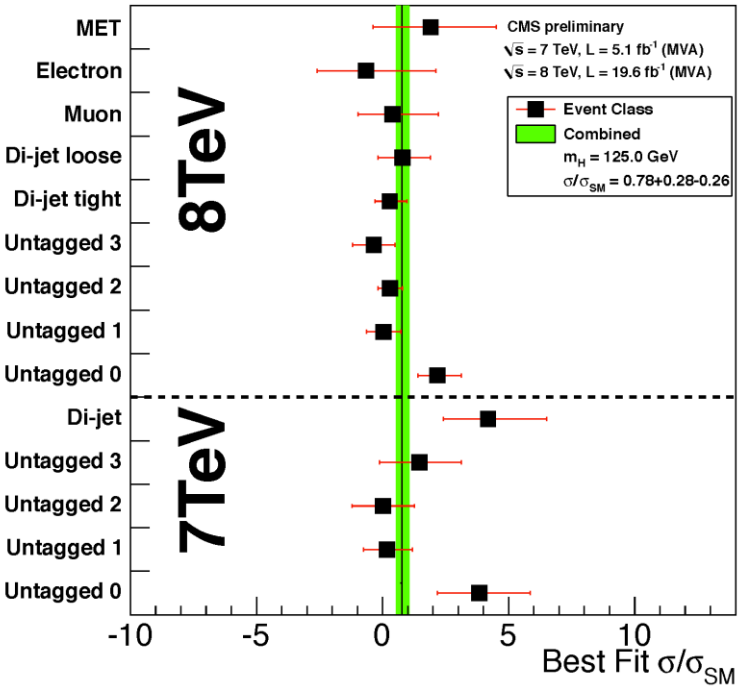
Excess around 125 GeV with
observed significance 3.2 **σ**

Results @ 7 + 8 TeV

CMS PAS HIG-13-001

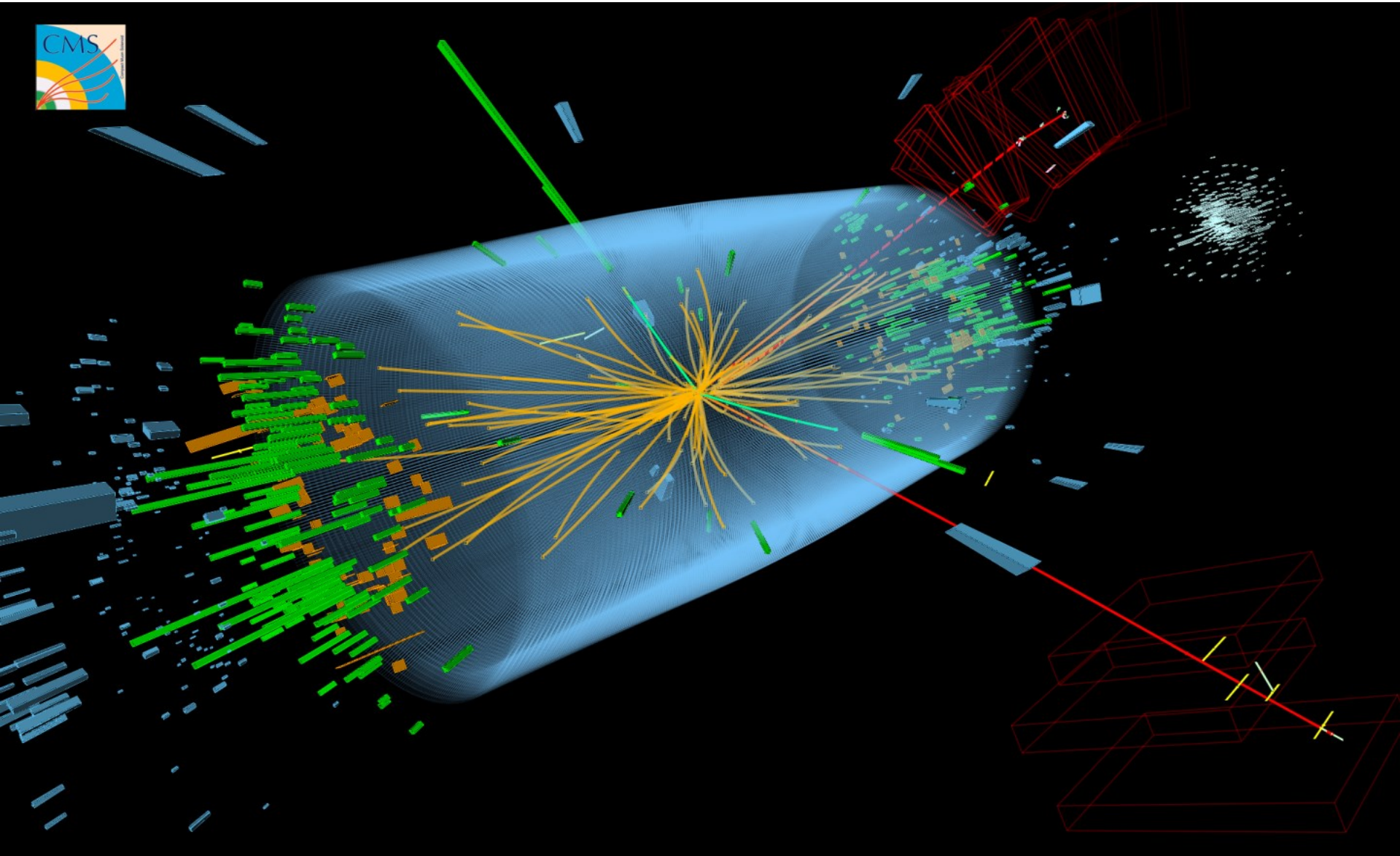


Observed best-fit signal strength in mass-fit-MVA analysis, as fn of SM Higgs boson mass

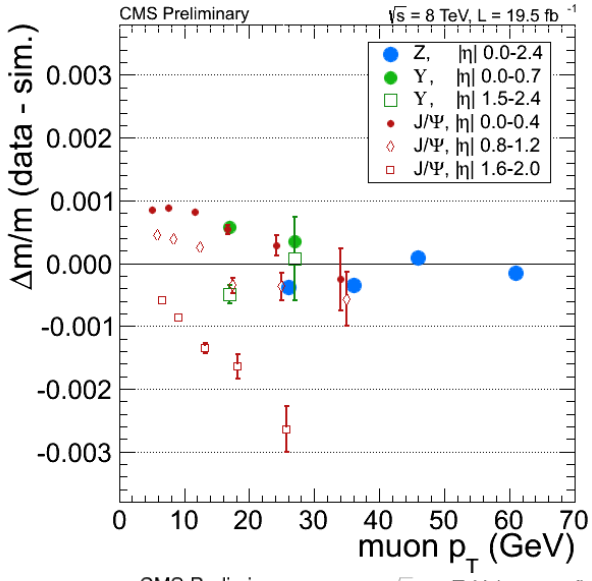


best fit signal strength, (σ/σ_{SM}) with mass-fit-MVA analysis for combined fit 5 classes @ 7 TeV & 9 classes @ 8 TeV

$H \rightarrow ZZ \rightarrow 4\ell$

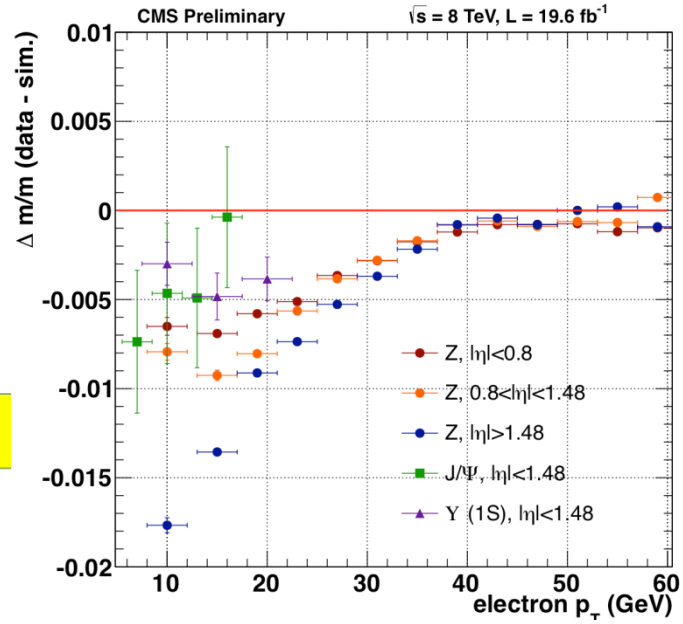


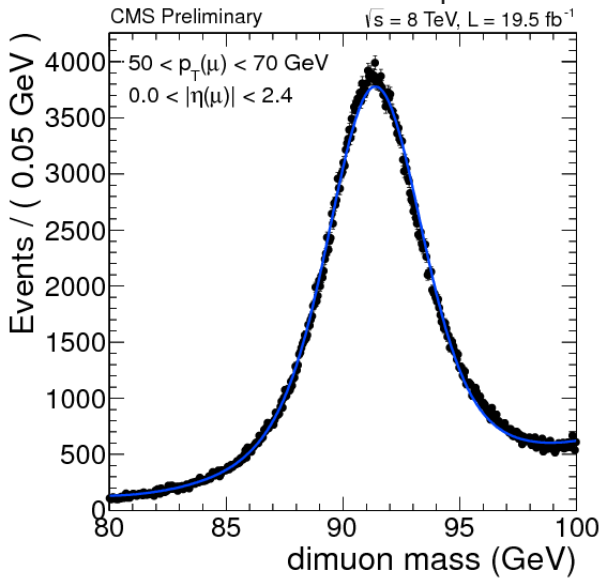
Leptons

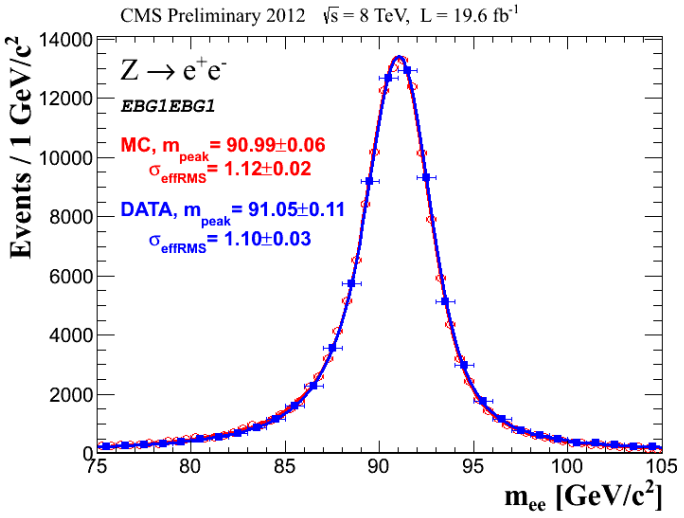


Muon momentum scale ~ 0.1%

Electron momentum scale ~ 0.2% for p_T > 35 GeV, else down to 1.5%



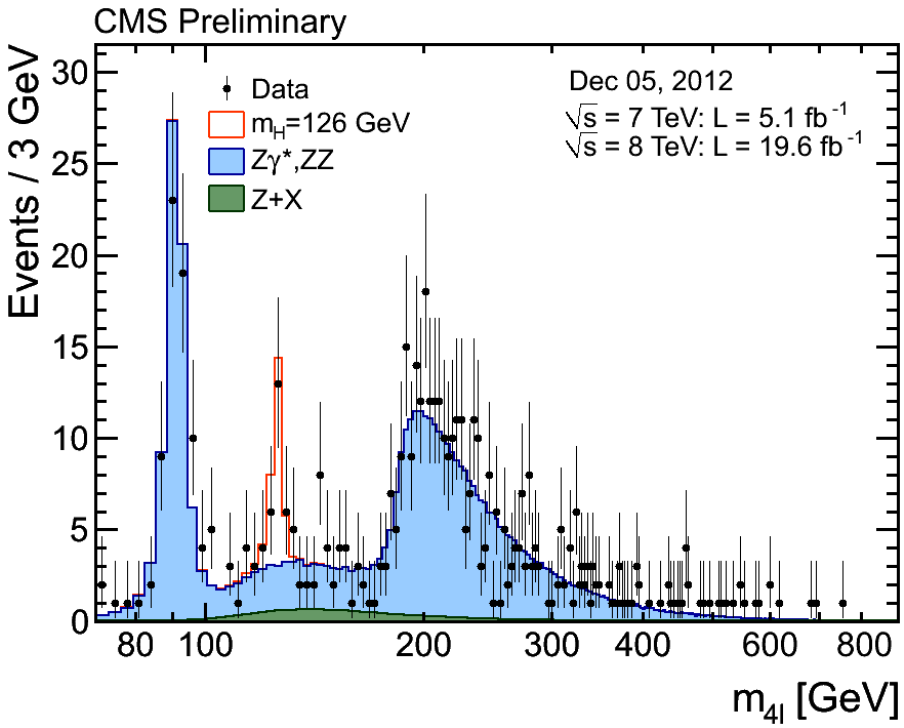


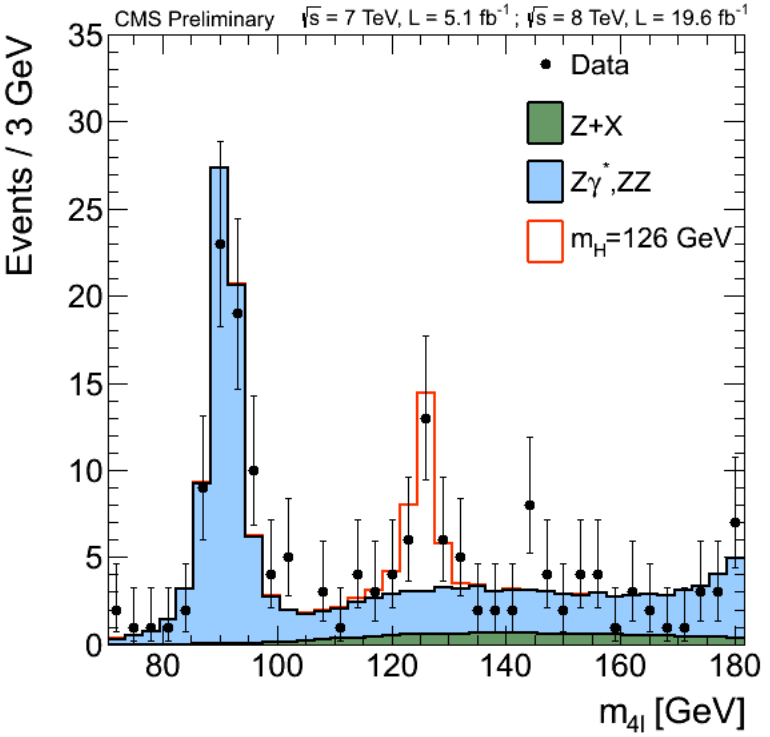


The 4-Lepton Analysis

Very Clean final state:
4 isolated leptons
from primary vertex

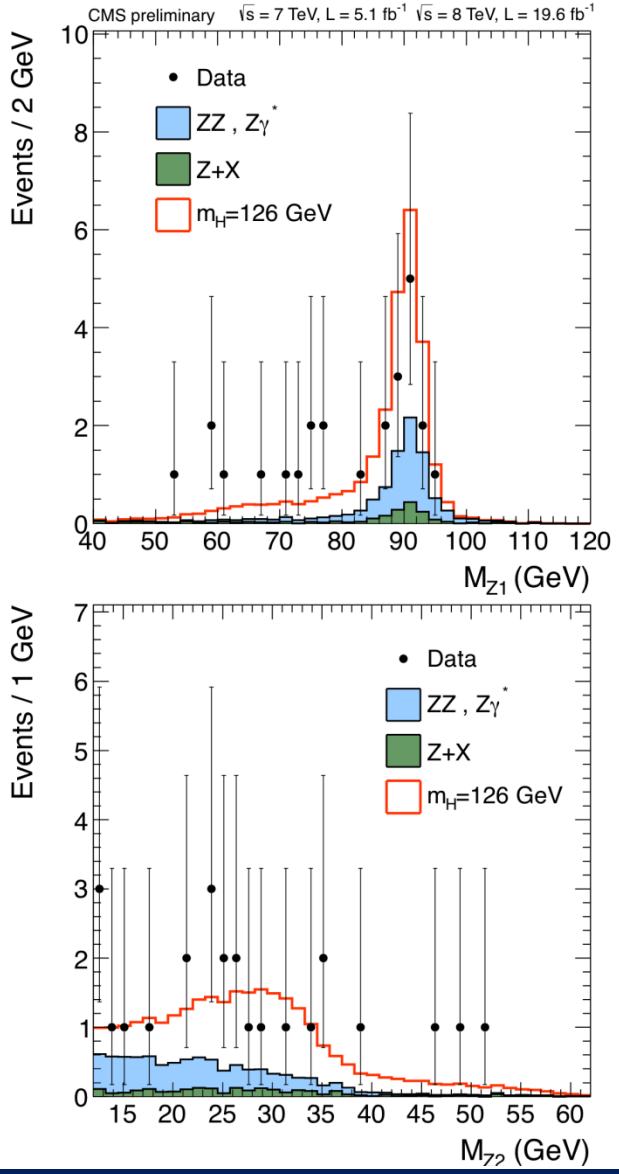
- measured four-lepton mass
- the mass uncertainty
- kinematic discriminants
- information sensitive to the production mechanism



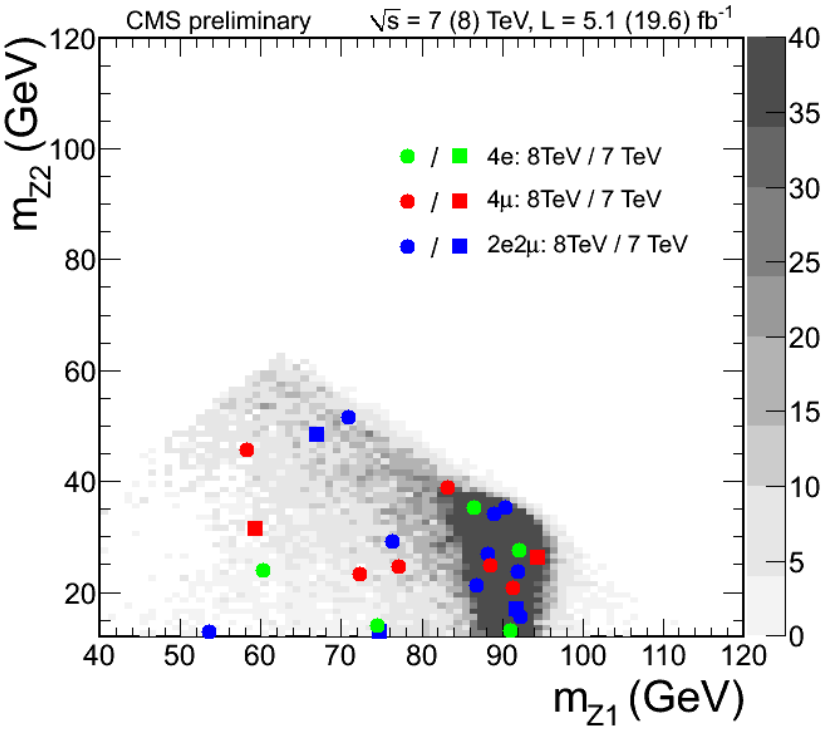


- Clean 4ℓ signal peak at ~ 126 GeV
- Very good control of the dominant ZZ background

M_{4l} distributions



Distributions with $121.5 < m_{4l} < 130.5$ GeV

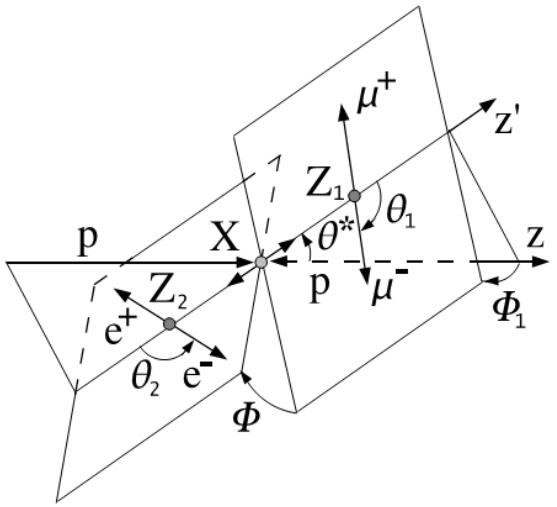


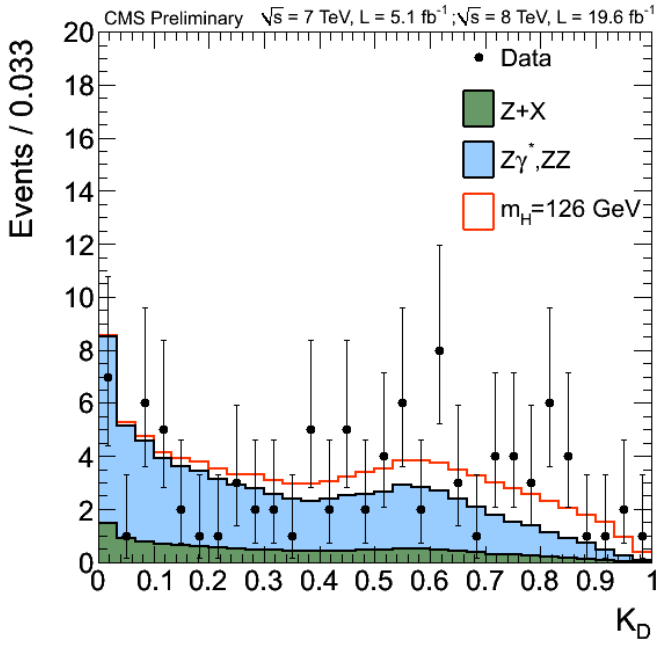
Shaded region represent expectations for a Higgs signal with m_H =126 GeV

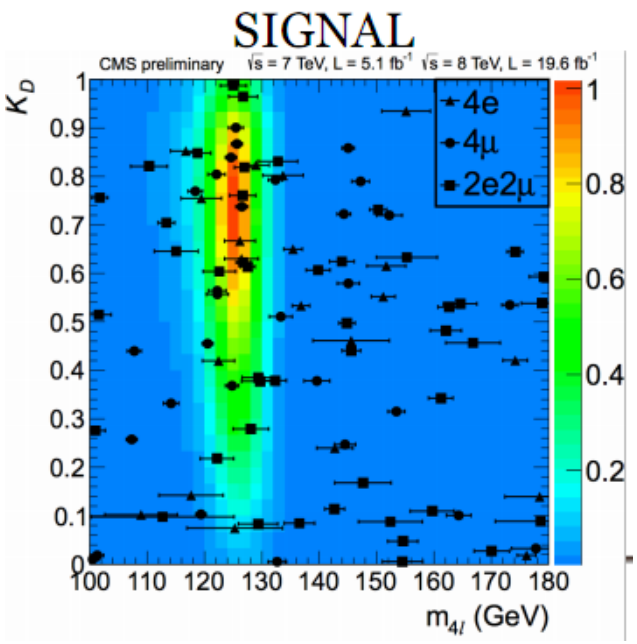
Matrix Element Likelihood Analysis (MELA)

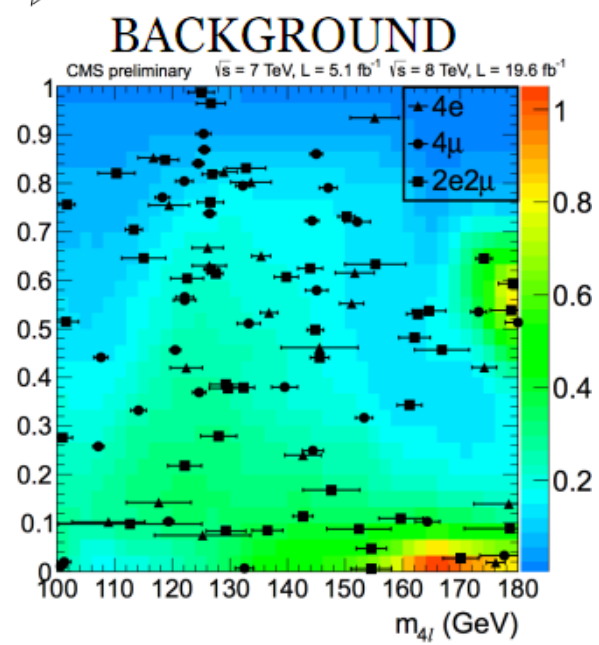
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

Masses of dilepton pairs and five angles fully defining a four-lepton configuration in their centre-of-mass frame







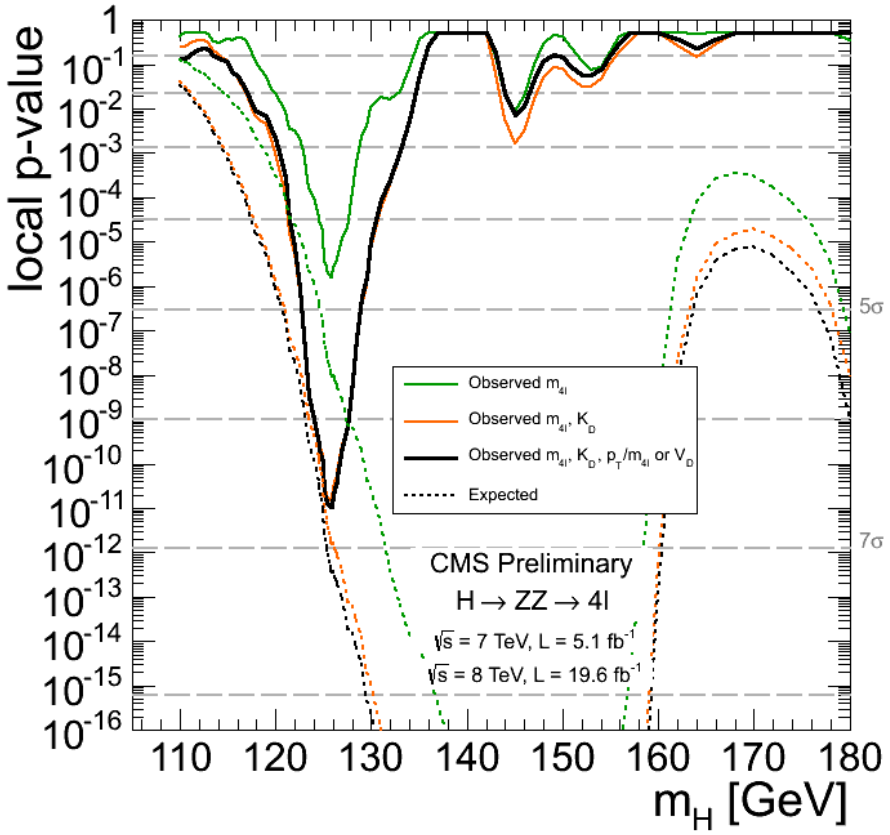


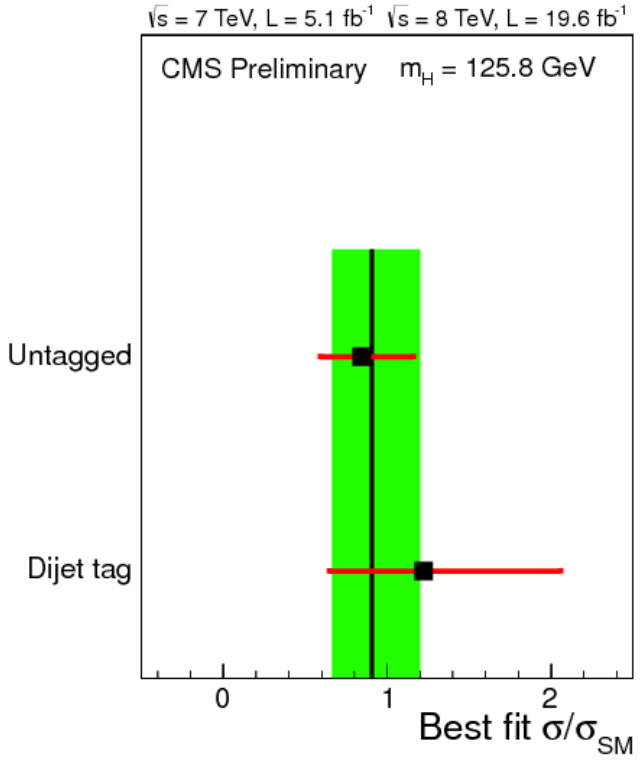
Results @ 7 + 8 TeV

CMS PAS HIG-13-002

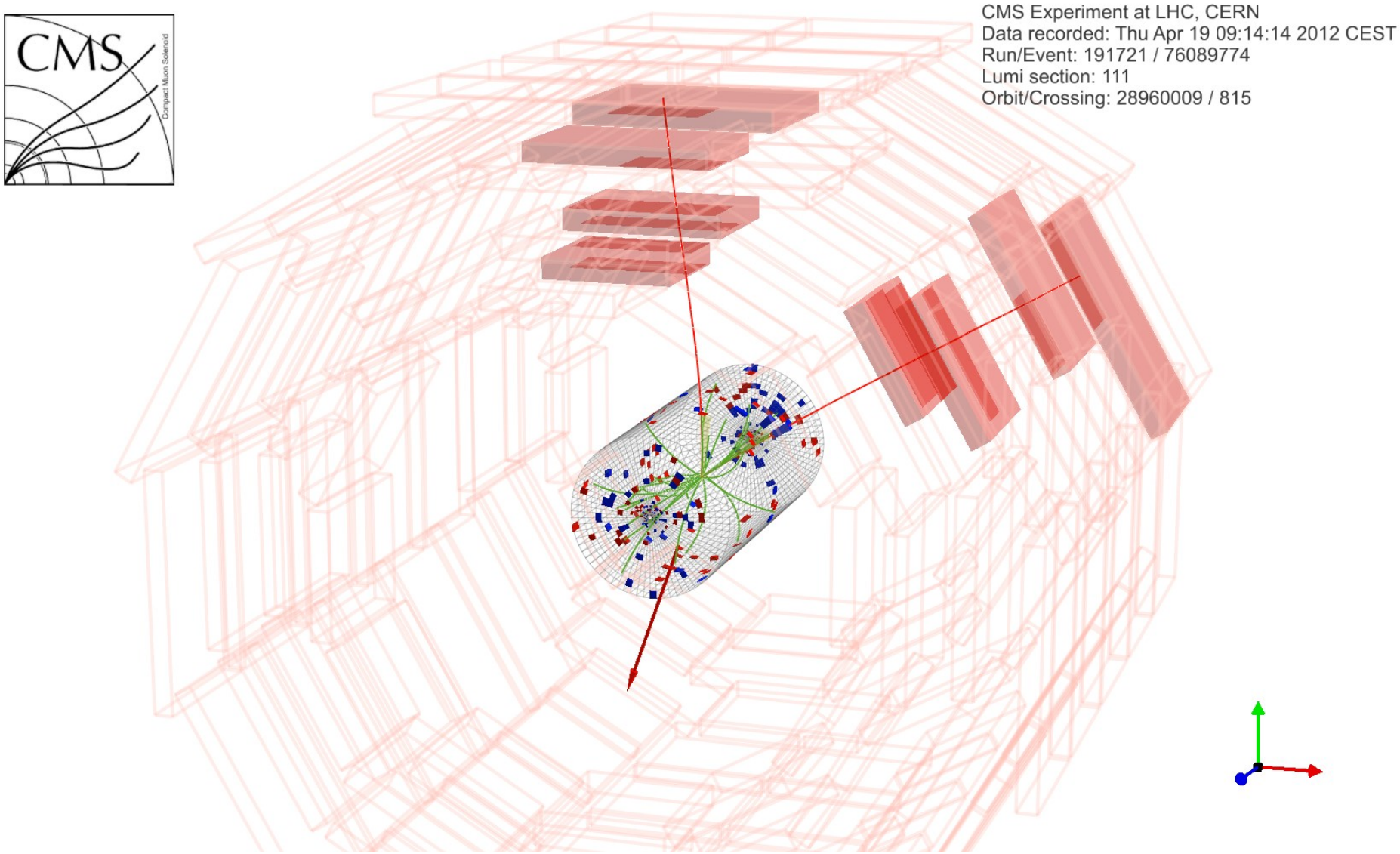
p-value Expected: 7.1σ
Observed: 6.7σ

Combined best-fit
$\mu = 0.92\ ^{+0.30}_{-0.24}$





$H \rightarrow WW \rightarrow 2\ell 2\nu$



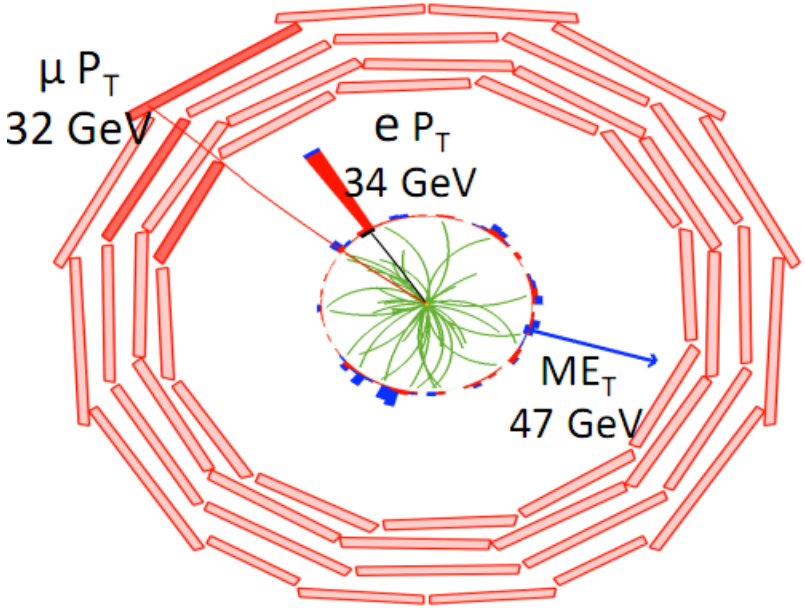
Analysis Strategy

- Channel with very high σ x BR
- No mass reconstruction, event counting for signal extraction
- Clean signature:
  2 isolated, high p_T leptons with small opening angle
  High MET

  Analysis performed on exclusive jet multiplicities (0, 1, 2-jet bins)
  Different Flavour, Same Flavour lep
- Discriminant Variables:
  p_T^l, M_{ll}, M_T, $\Delta\varphi$
  VBF selections for the 2-jets case

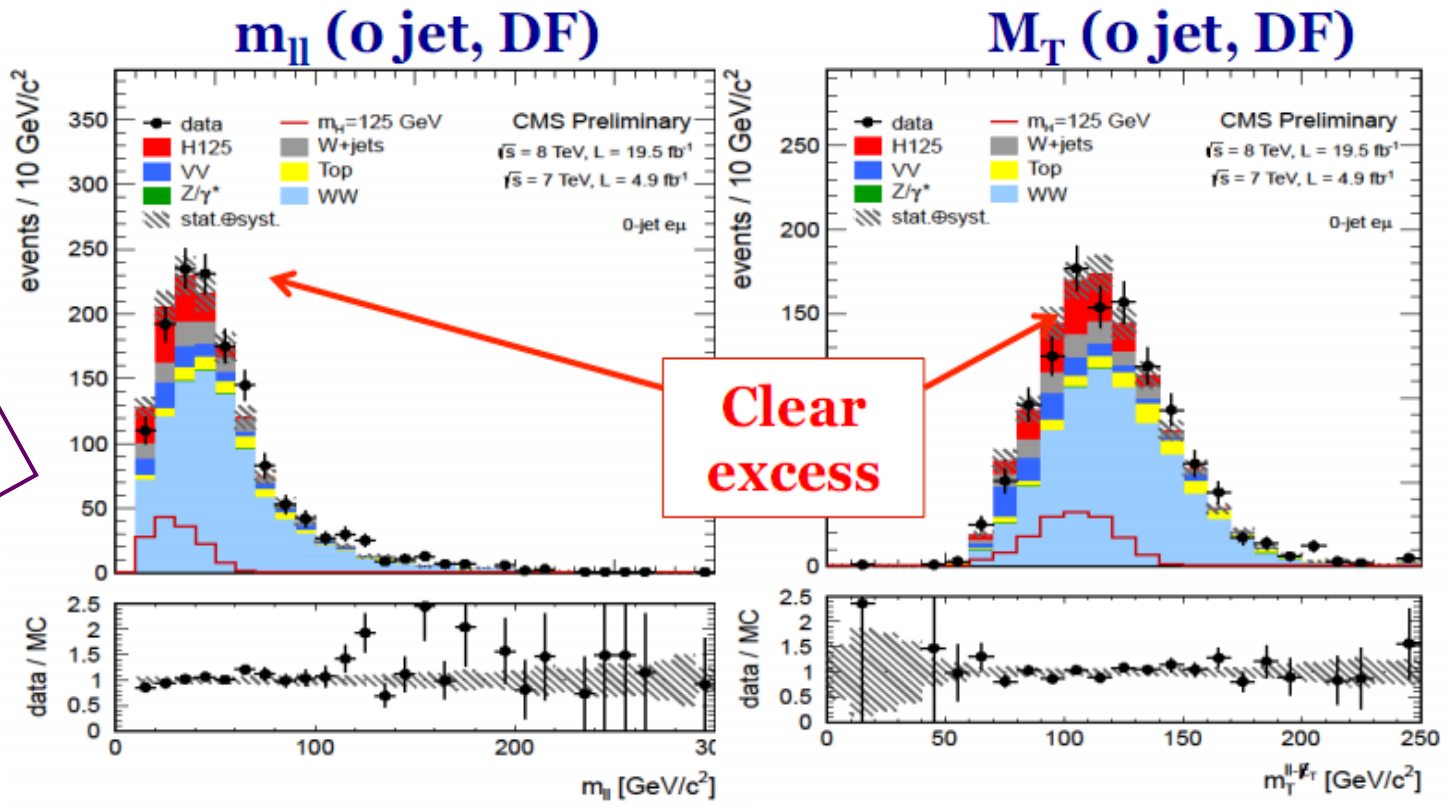
Cut based and 2D shape analysis

Vectors from decay of a scalar and V-A structure of W decay
➔ small opening angle between leptons
(especially true for on-shell W)



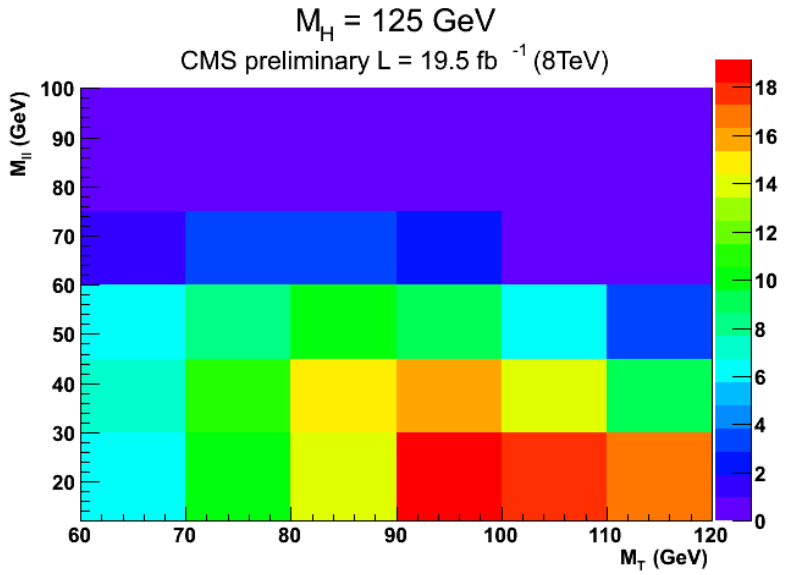
Cut-based analysis

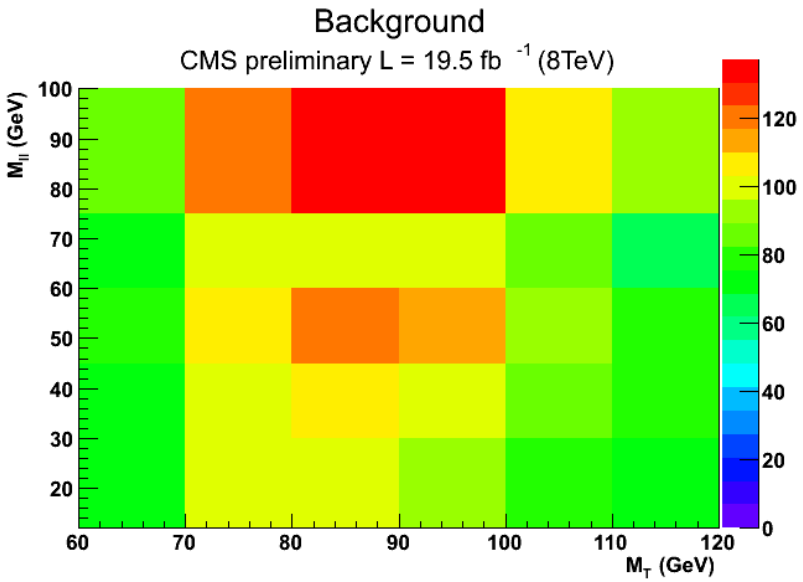
Backgrounds are estimated from data in "control regions"



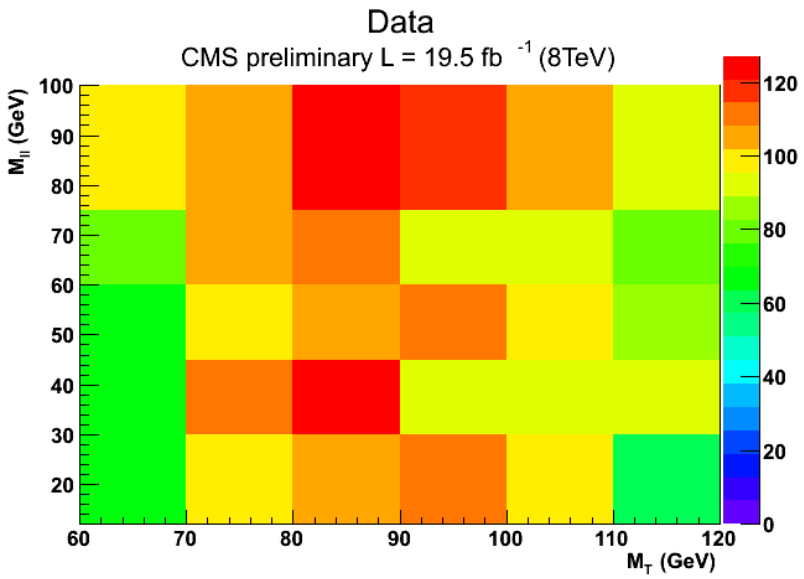
- Drell –Yan: Suppressed by M_{ll} and MET cuts
- W+jets (with one jet faking a lepton): lepton ID important
- Top (tt and single top): b-tag veto (or additional soft muon)
- WW: M(ll), M_T and $\Delta\varphi_{ll}$

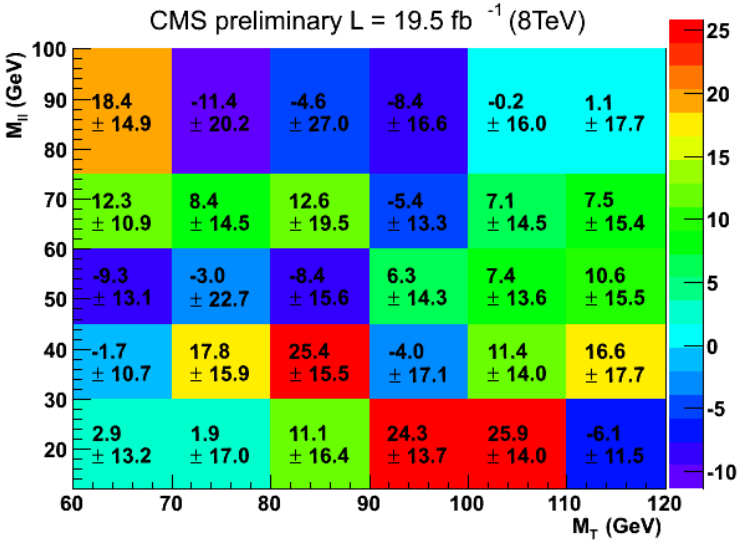
2-D shape analysis



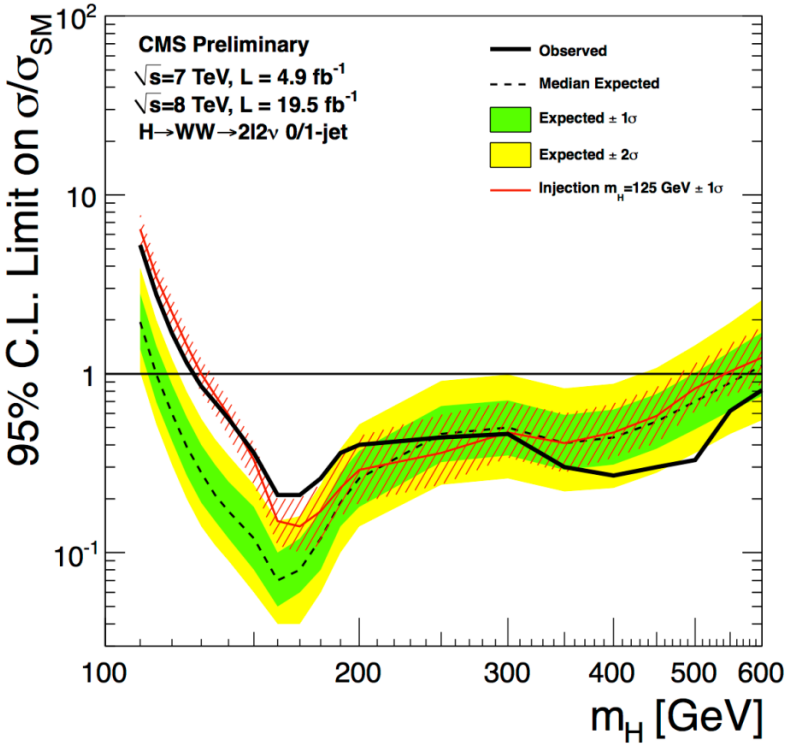


M_T - M_{ll} 2D distributions in 0-jet bin





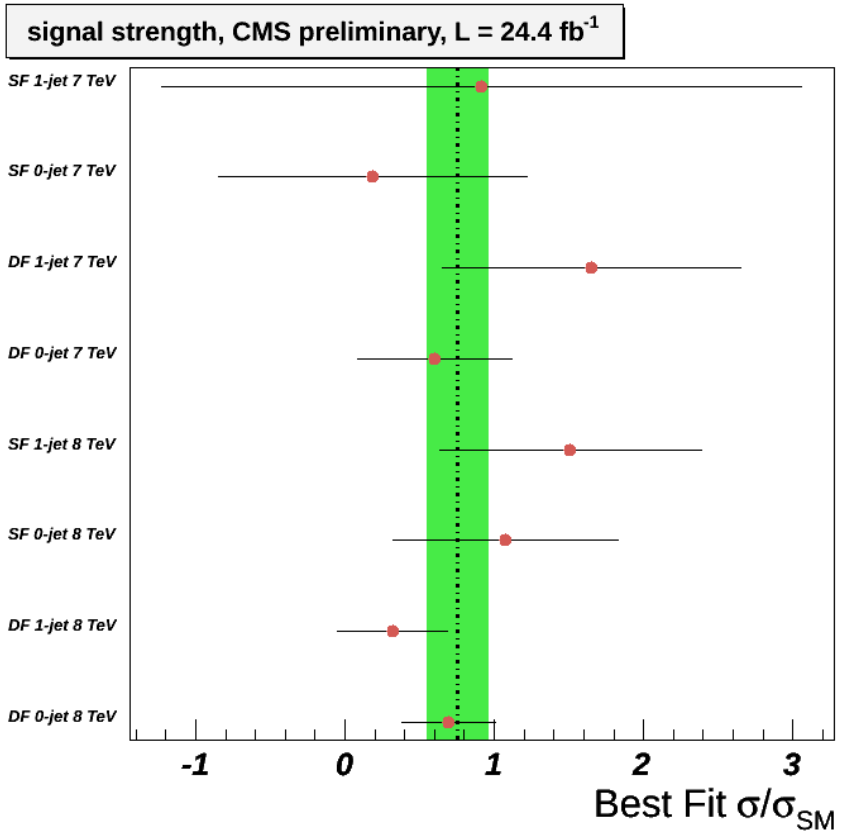
CMS PAS HIG-13-003



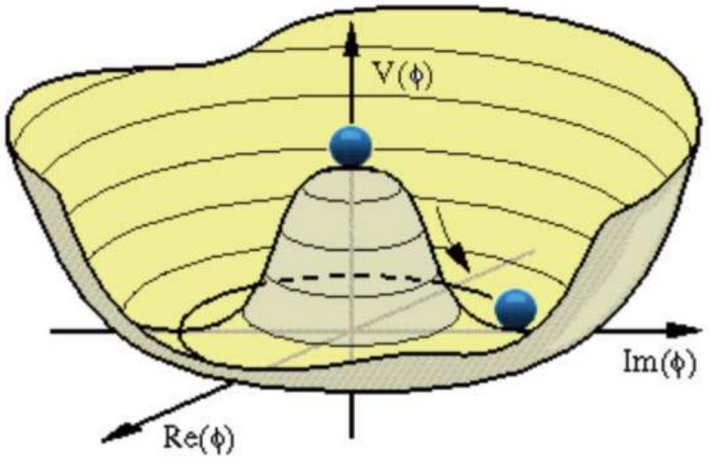
Large excess at low mass compatible with expected 125 GeV Higgs signal

σ/σ_{SM} signal strength μ: 0.76 ± 0.21

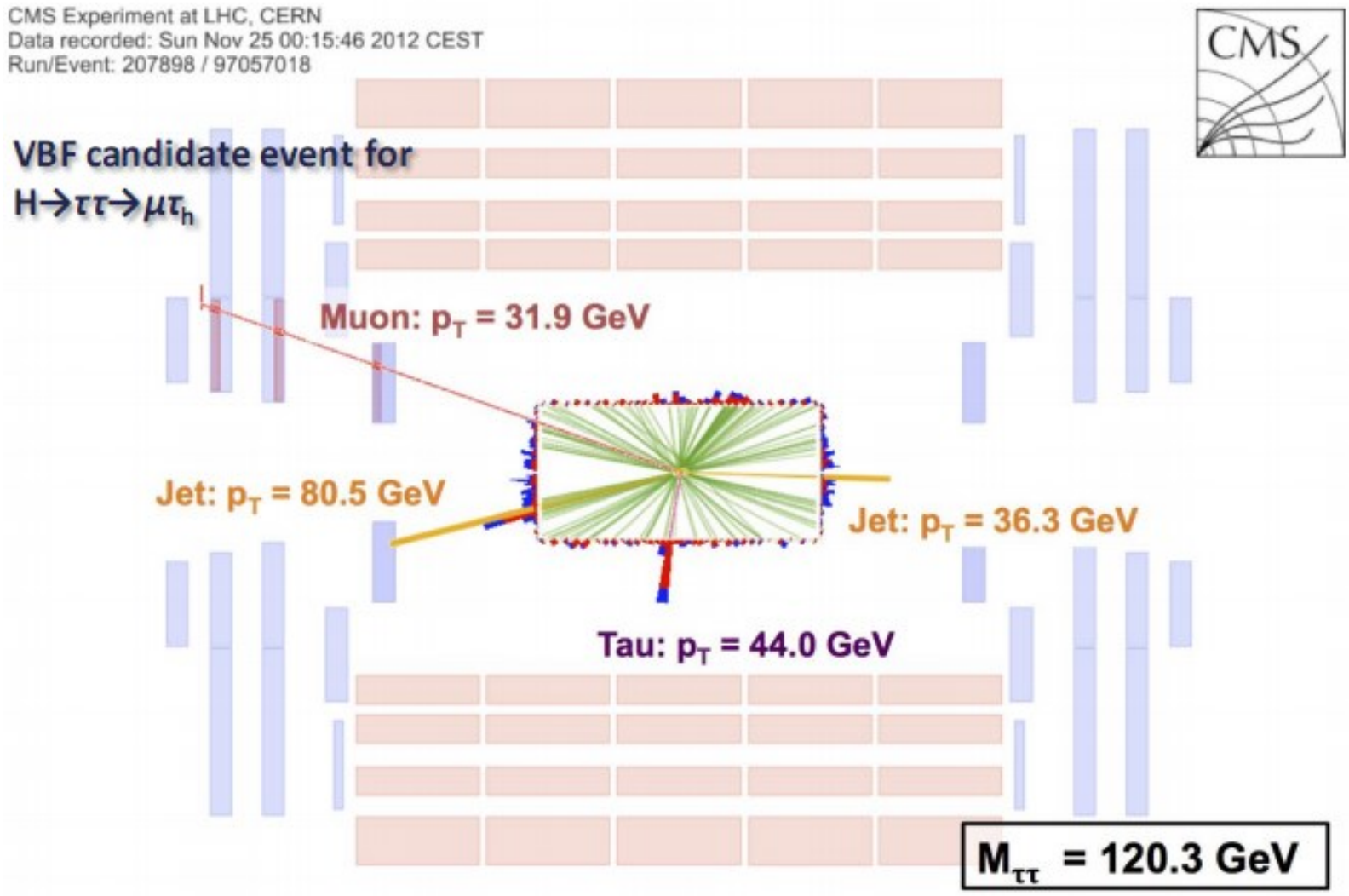
Results consistent across all categories

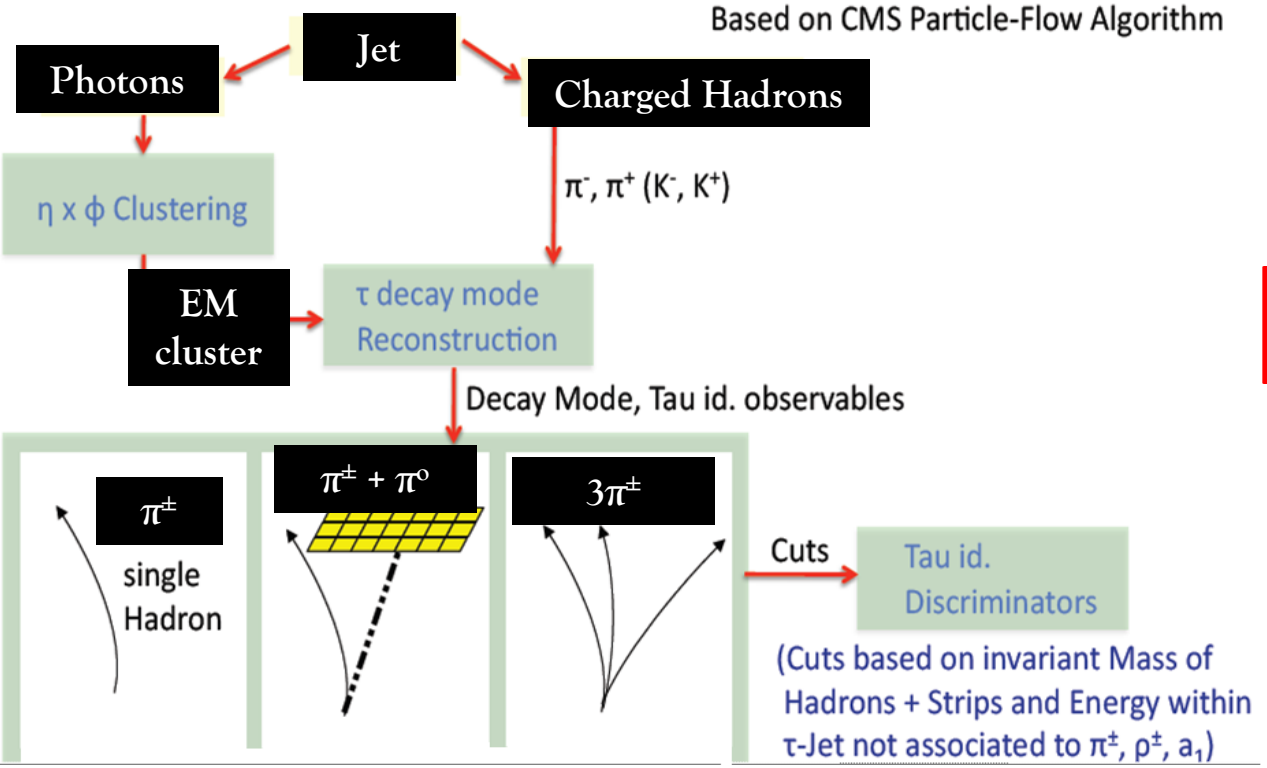


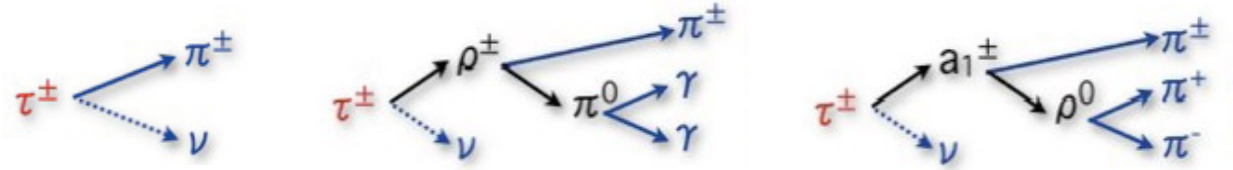
Higgs in Fermionic Decays



$H \rightarrow \tau\tau$

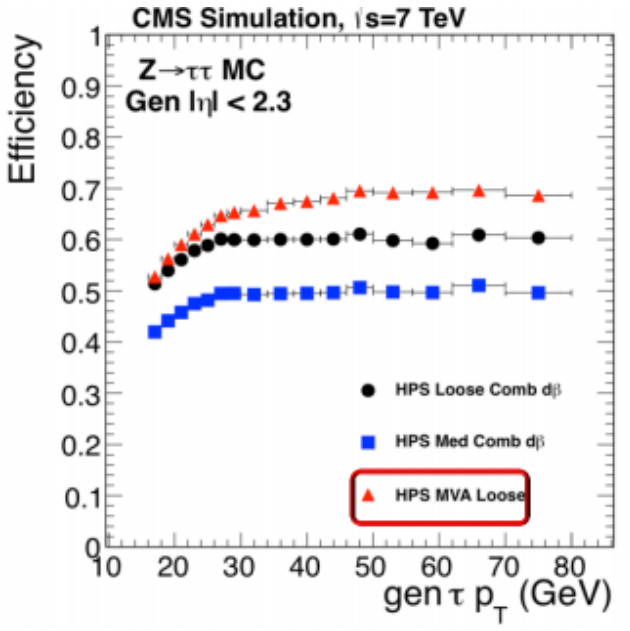






MVA based hadronic tau isolation in concentric rings Based on relative p_T of PF candidates in isolation rings

Fake Rate of jets→τ ~ 2%

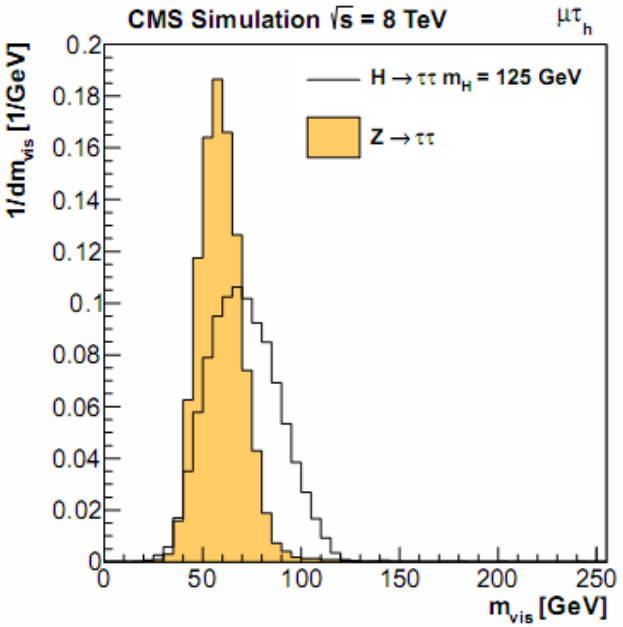


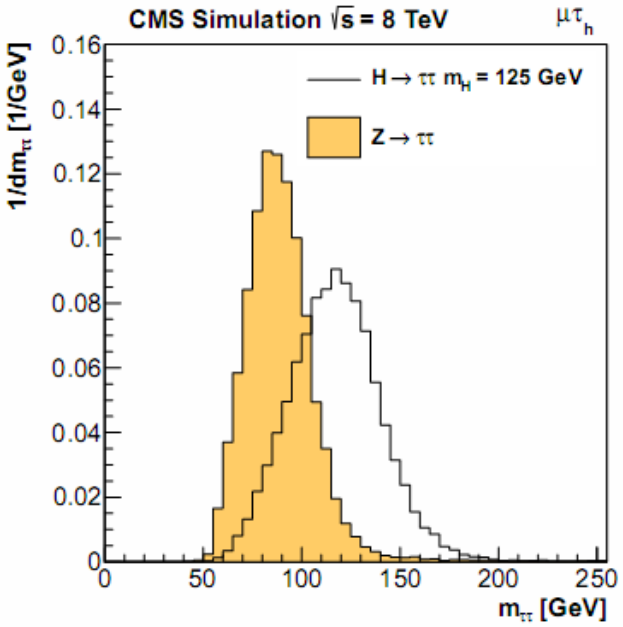
ττ mass reconstruction

Mass of τ lepton pair reconstructed via a **Likelihood technique**, based on:

- **τ decay kinematics**
- **Compatibility of reconstructed E_T^{miss} with neutrino hypotheses**

$m_{\tau\tau}$ - Obvious observable to discriminate Z boson from the Higgs signal

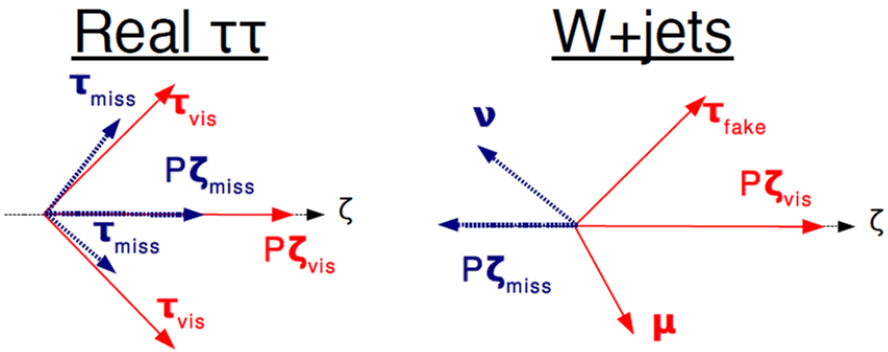




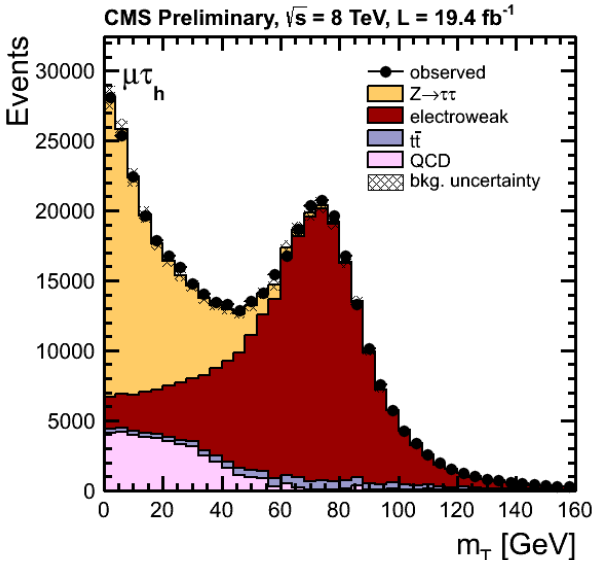
Decay final states : $\mu + \tau_h$, $e + \tau_h$, $\mu + e$, $\mu\mu$, $\tau_h\tau_h$

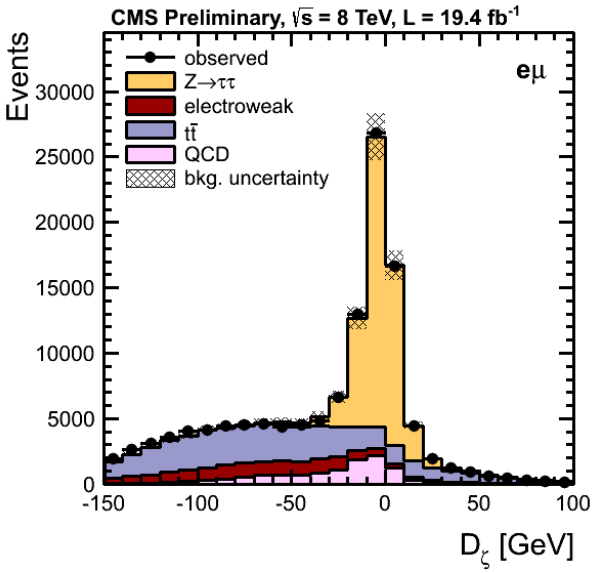
- Select isolated, well-identified leptons, τ_h
- Trigger
  $1 + \tau_h$ cross-trigger or lepton trigger or tau/jet trigger
- Lepton / τ_h Selection (p_T, η, isolation)
- Opposite Charge Lepton Pair
- Veto Events with additional isolated Leptons
- Topological cuts (based on azimuthal angle info)

$$M_T = \sqrt{2 p_T^{\ell} E_T (1 - \cos\Delta\phi)}$$

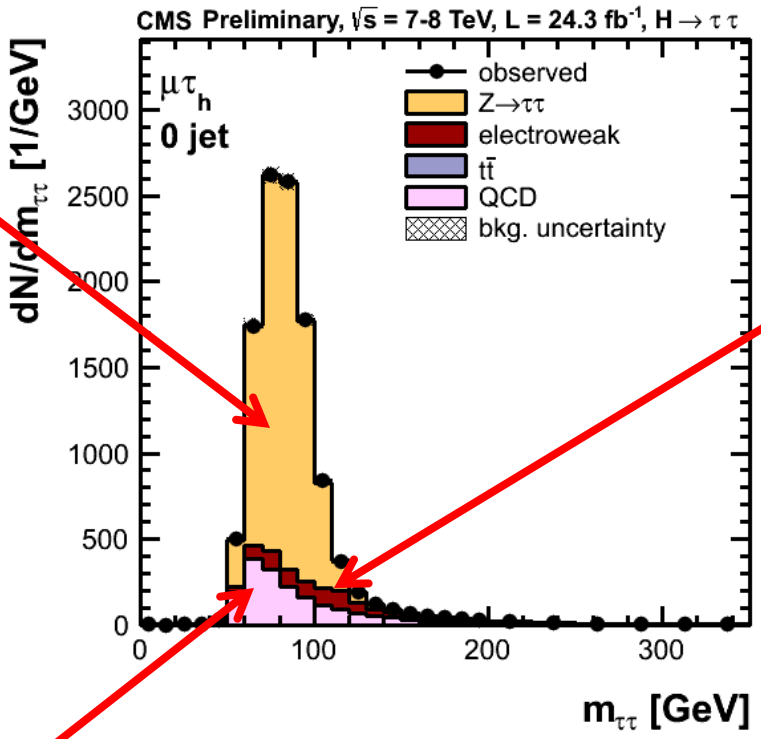


$$P_\zeta^{vis} = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta$$
$$P_\zeta = P_\zeta^{vis} + E_T^{miss} \cdot \zeta$$





$Z \rightarrow \tau\tau$: observed $Z \rightarrow \mu\mu$ sample and replace μ by simulated τ (embedding)



W + jets : Shape from simulation, normalization from m_T/P_ζ sideband

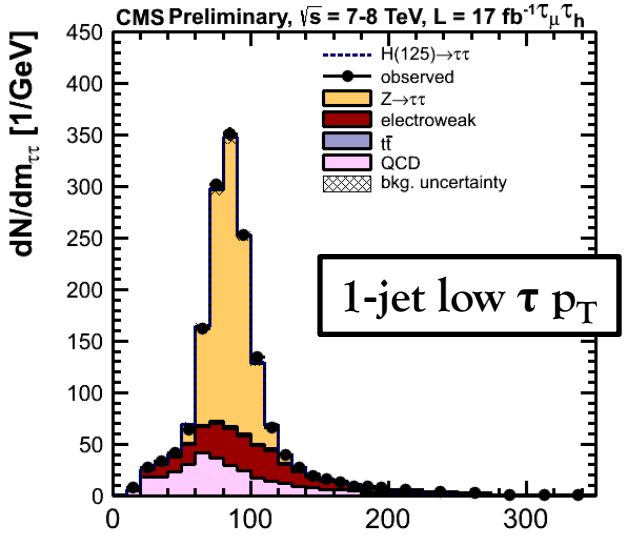
Z + jets : OS/SS ratio and lepton / jet faking hadronic τ with shape from simulation

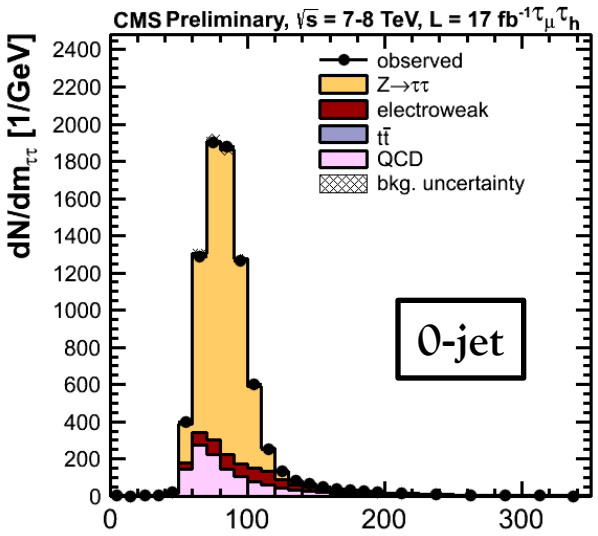
QCD : from SS data with OS/SS ratio

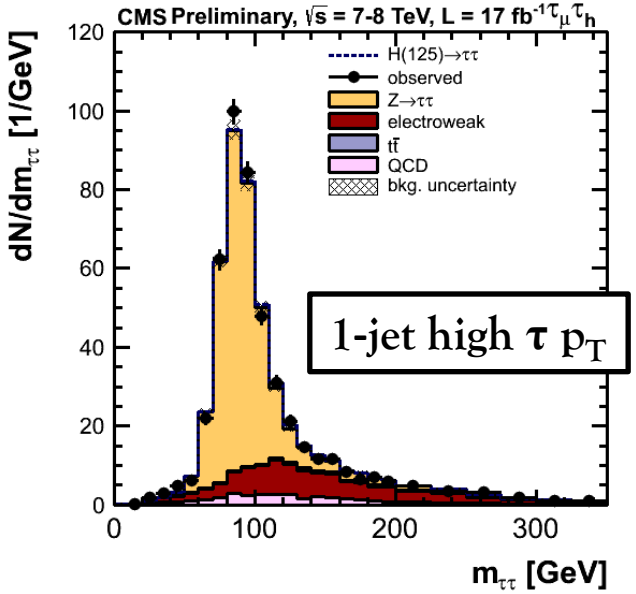
shape from SS data in relaxed lepton isolation

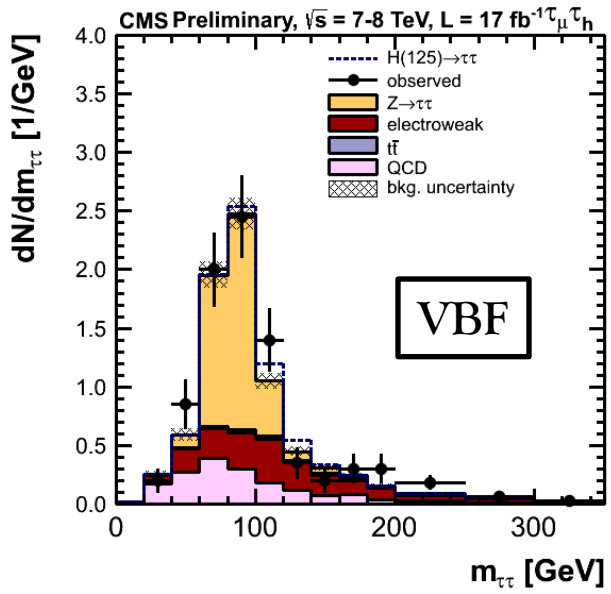
Top pair and Di-boson

Event Categories









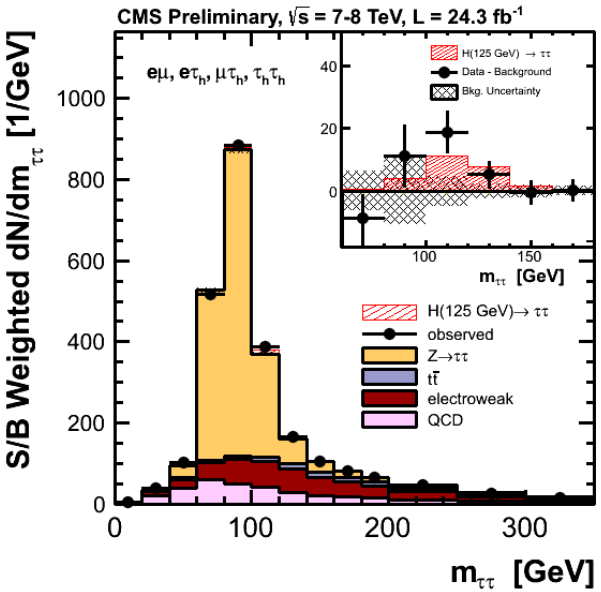
0 – jet category : constrains background, id efficiencies, energy scales

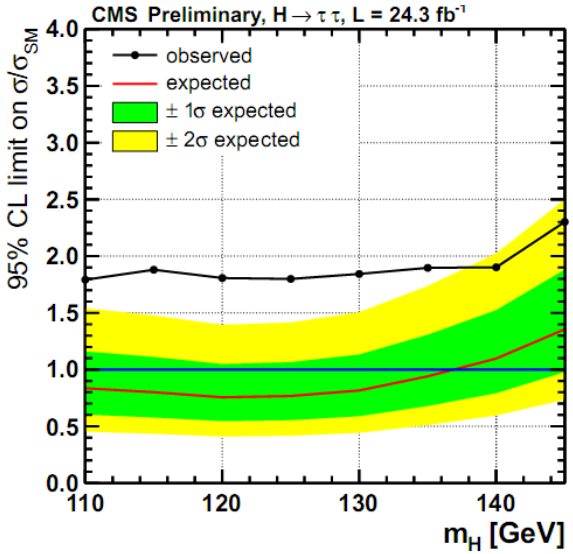
No signal fitted in the 0-jet category

1 – jet category : improves resolution of Higgs mass

2 – jet category : VBF process - high S/B ratio

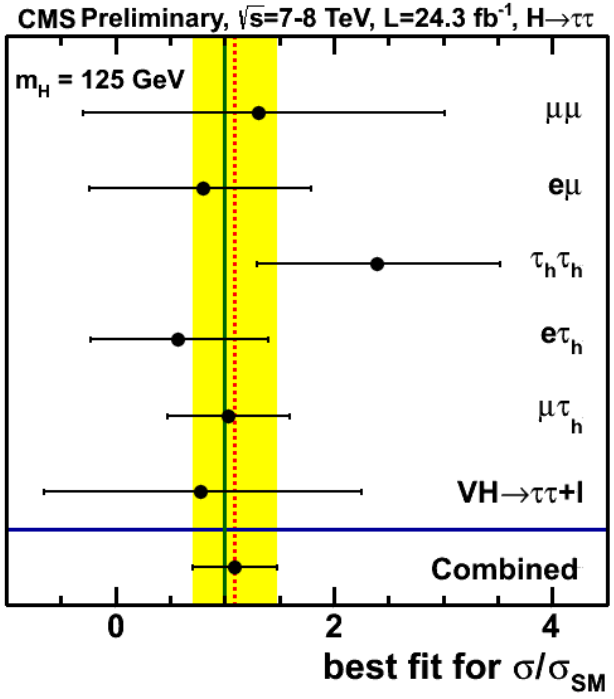
Results @ 7 + 8 TeV



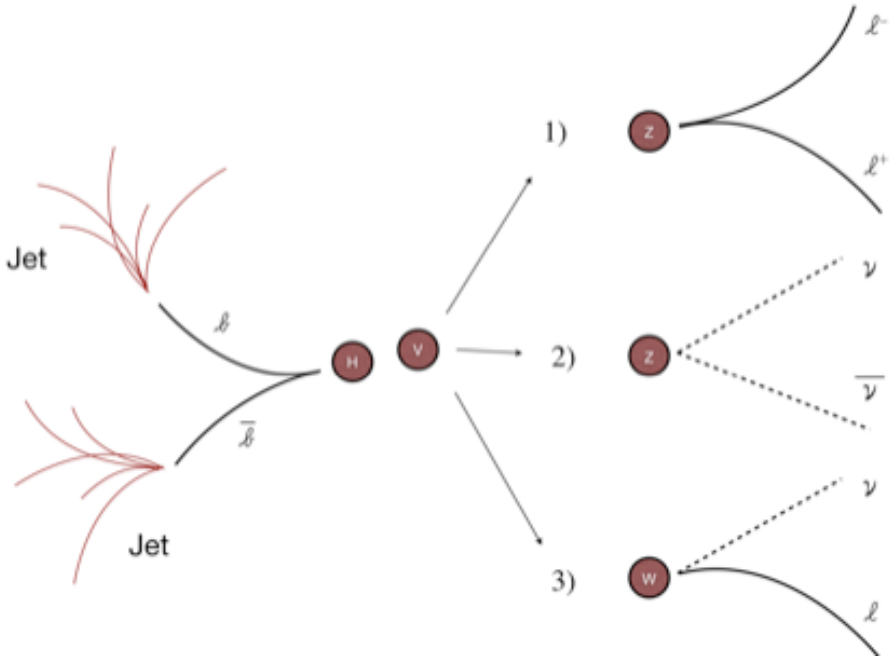


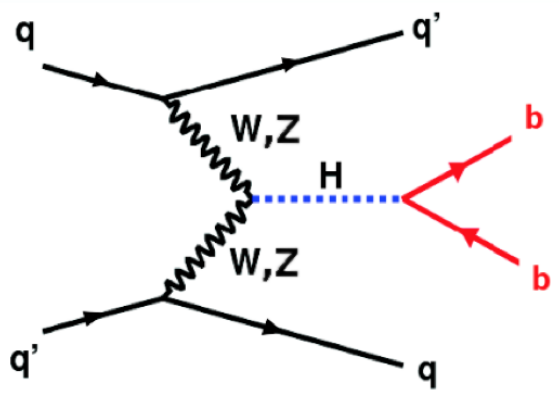
- Broad excess observed over range of m_H
- Max local significance 2.93σ at 120 GeV compatible with 125 GeV SM scalar boson
- Observed (expected) Signf 2.85σ (2.62σ) for m_H = 125 GeV
- Strong affirmation on Higgs-Fermion coupling, 1st Indication to Leptons

CMS PAS HIG-13-004

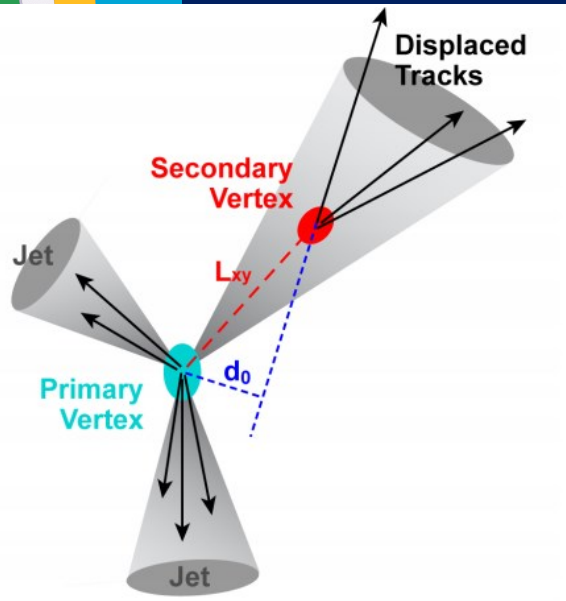


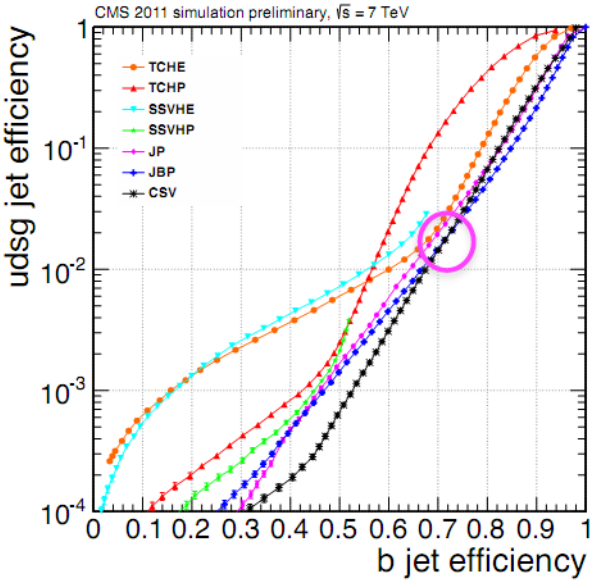
$H \to b\bar{b}$

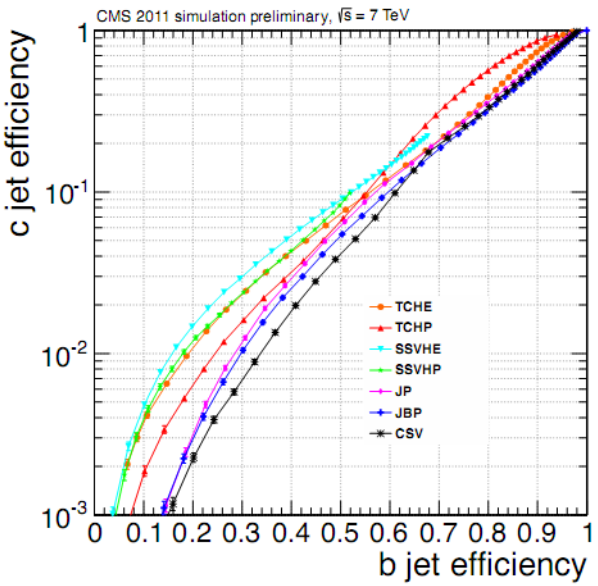




b – jets



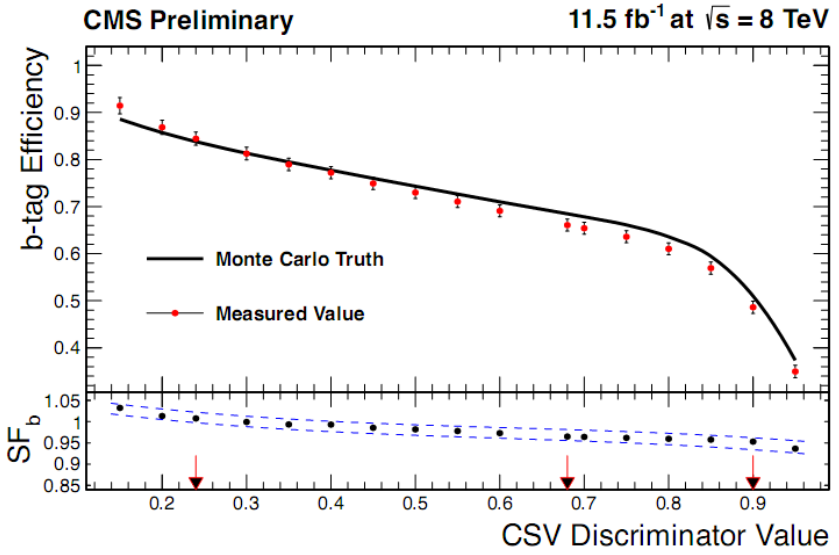




Separation from udsg and c jets

- Combined Secondary Vertex : track impact parameters and secondary vertex properties within jets in a likelihood discriminant
- Efficiency and fake-rate from top pair and muon + jets sample

Efficiency of ~70% for a fake-rate of ~ 2%



Analysis Strategy

$H \rightarrow b\bar{b}$ association with vector bosons

Multivariate technique – Boosted Decision Tree
- Trained with MC to discriminate bkg events

Most powerful discriminant –
dijet invariant mass M(jj)

– Combine M(jj) and other discriminating variables into one single discriminant
- p_T of the jets and the di-jet system
- CSV of the jets
- Angular information

– Correlations between variables encapsulated
- Such as M(jj) and ΔR(jj)

- V + jets – V + heavy flavor jets largest bkg after b-tagging (irreducible)

- V + light flavor jets – reducible – Falls more rapidly than signal with high boost

- top pair, single top

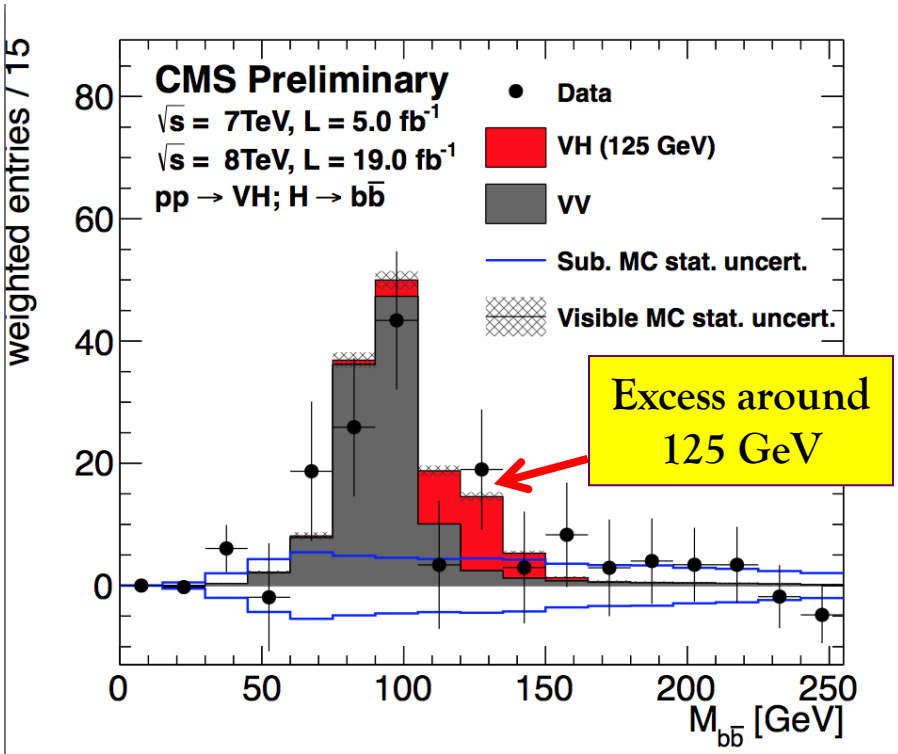
- VV
– Best discriminated by invariant mass

- – QCD fake leptons or jet energy mis-measurements

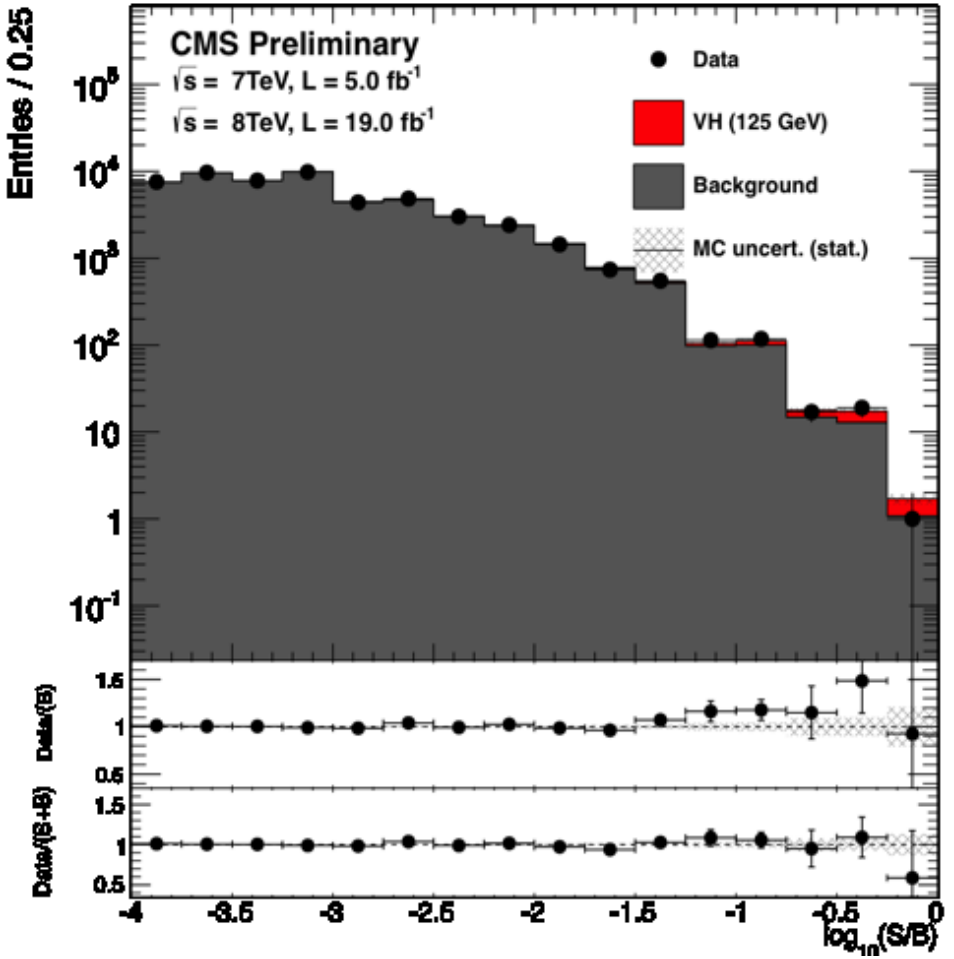
b-jet identification substantially reduces multi-jet background

Requires higher boost and VH back-to-back topology to enhance S/B
– Signal decreases more slowly than bkg

CMS PAS HIG-13-012

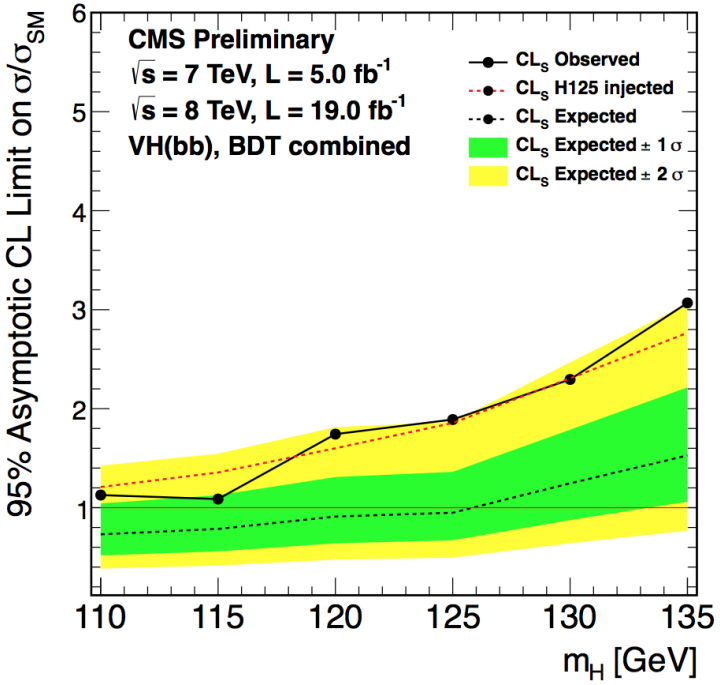


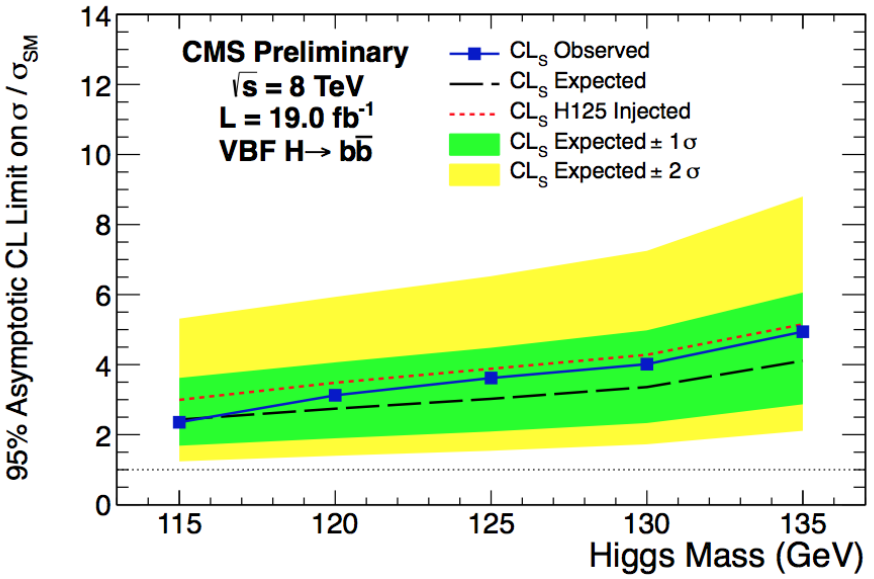
Di-jet Invariant Mass



in bins of similar expected S/B ratio, given by output of BDT discriminant

VH & VBF results





Observed (expected) limit 2.5 (1.2) x SM at 125 GeV

Observed (expected) signf 2.2σ (2.1σ) for m_H=125 GeV

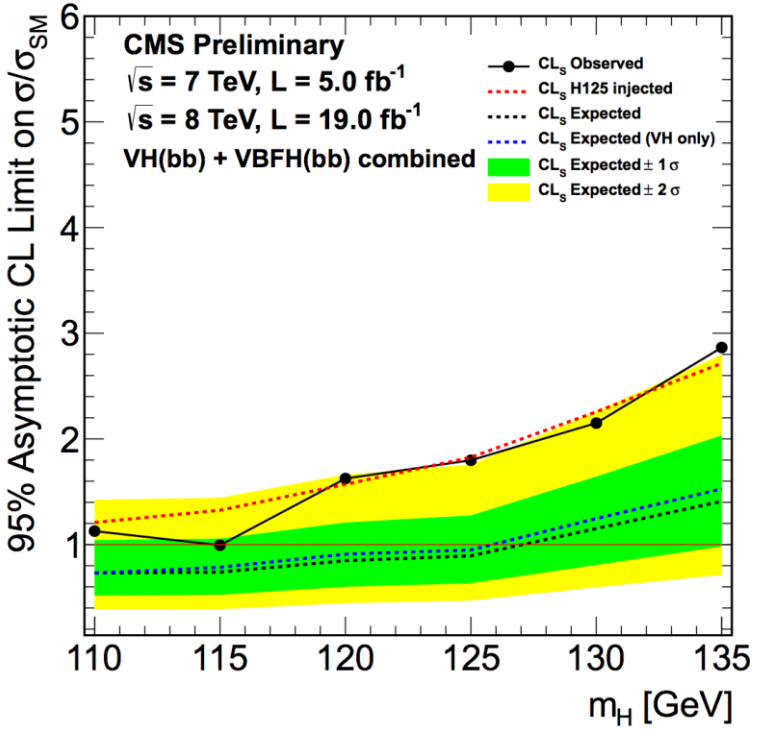
Mild excess observed in data compatible with 125 GeV Higgs boson

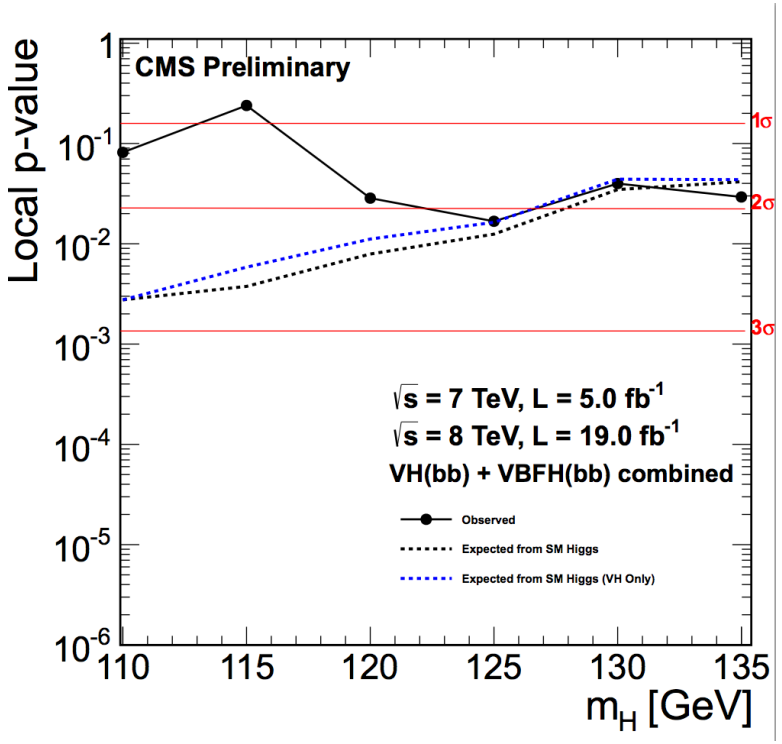
bb event + ≥ 2 non-b jets at large Δη

At 125 GeV the upper limit on σ x BR = 3.6 x SM (3.0 exp)

NEW

Combined results of the VBF and VH processes for H→bb





95% CL limit observed (expected): 1.79 (0.89)
Significance observed (expected): 2.1σ (2.2σ)
Signal strength: μ= 0.97± 0.48

Combination & Properties of the Higgs Boson

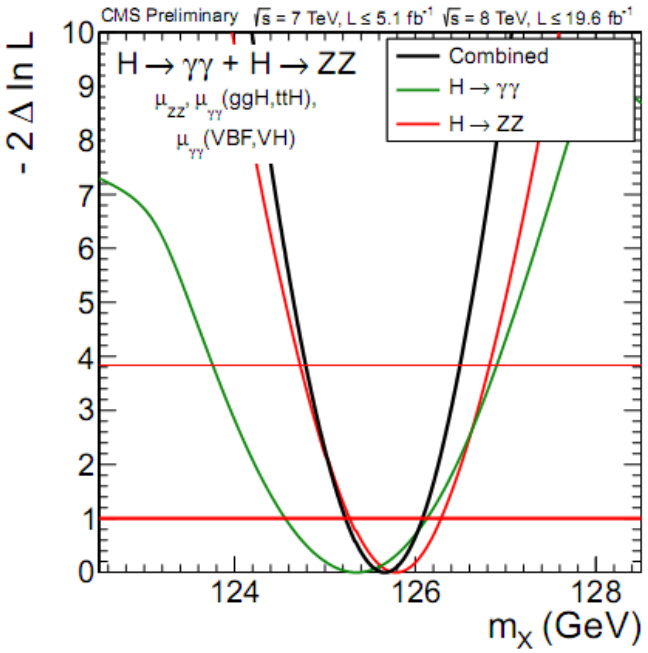
Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

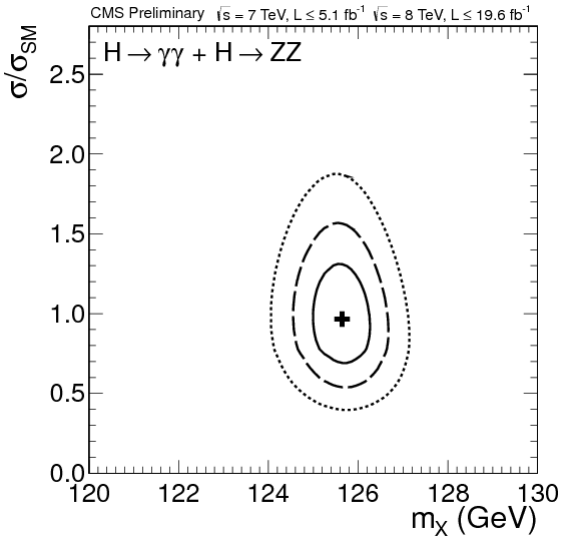
for Higgs mass $m_H = 125.7$ GeV

Combined Signal strength $\mu = 0.80 \pm 0.14$

Mass & Coupling

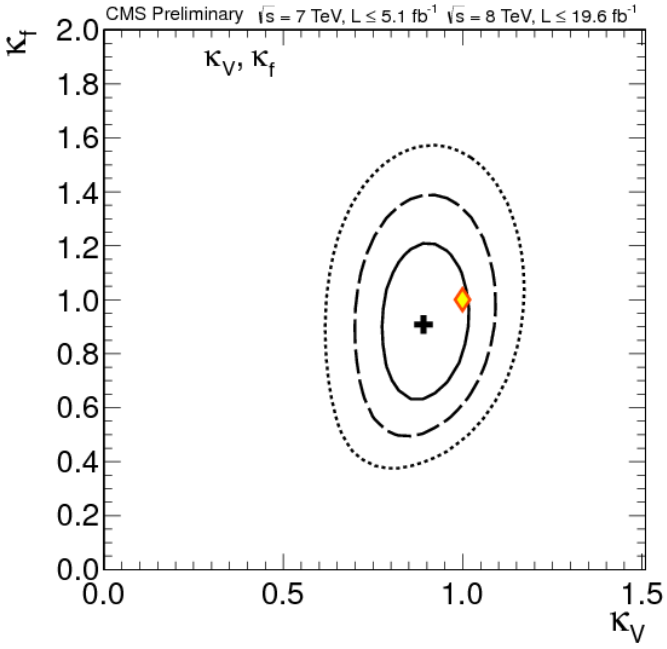
$$q_\mu = -2\,\Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(\text{data} \mid \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})}$$





Test of Fermion & Vector Boson Couplings : 2D test statistics $q(\kappa_V, \kappa_F)$ scan

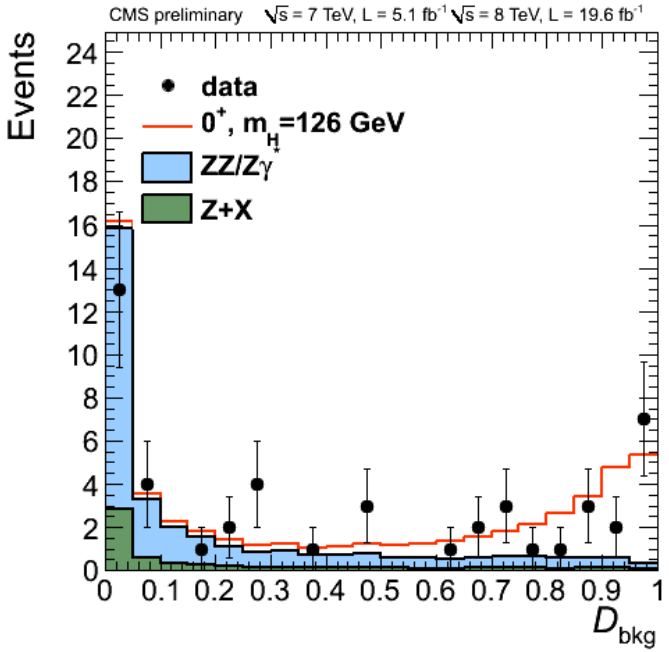
Consistent with SM Higgs boson expectation

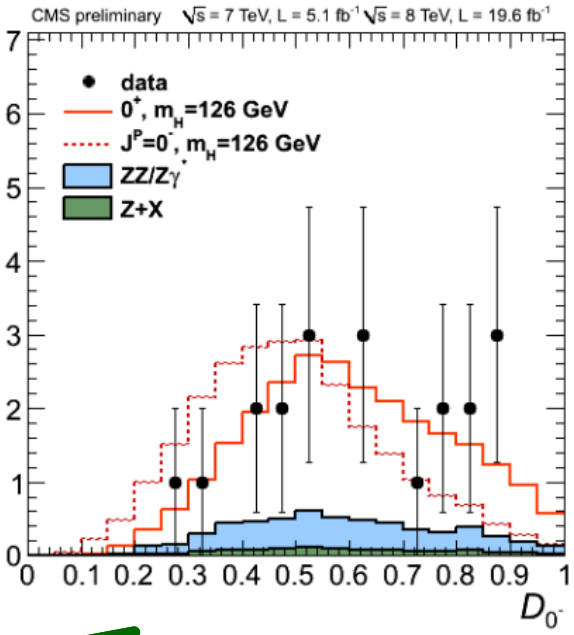


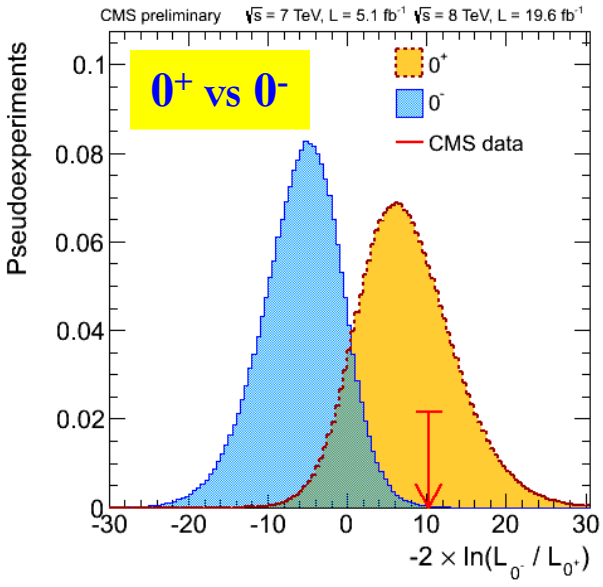
Mass = 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV

1D test statistics $q(m_H)$ scan vs hypothesized Higgs boson mass for combination of high resolution channels

Spin - Parity







$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{SM}}{\mathcal{P}_{SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

Kinematic discriminant describe kinematics of production and decay of different Higgs J^P state

Statistically equivalent to the 2D analysis of m_{4l} and K_D

$$\mathcal{D}_{bkg} = \mathcal{P}_{sig}/(\mathcal{P}_{sig} + \mathcal{P}_{bkg})$$

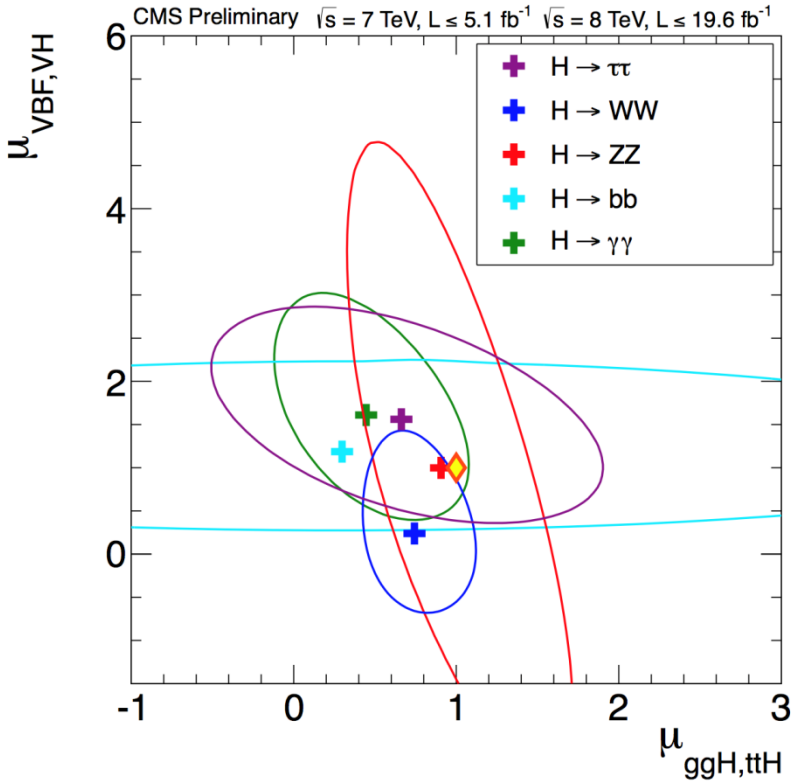
More J^P hypotheses have been tested in a similar way

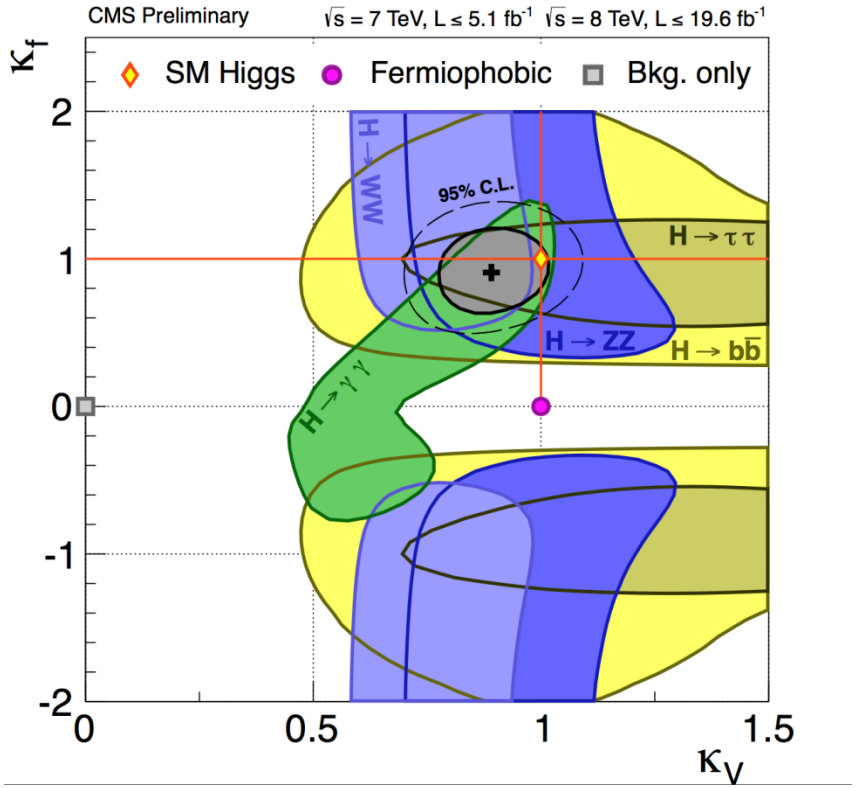
Consistency with the SM scalar boson

Consistency with SM hypothesis

2-dimensional view: test production modes in various decays

Vector Boson Couplings



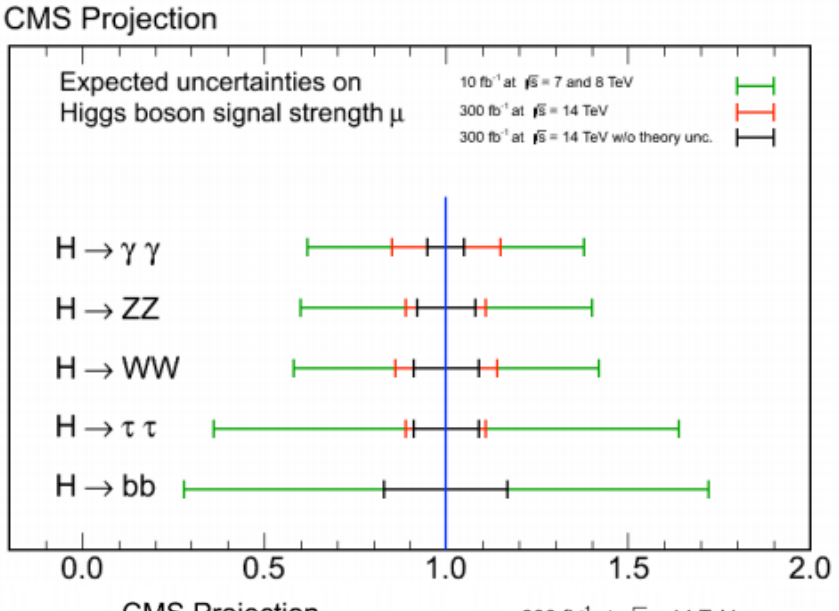


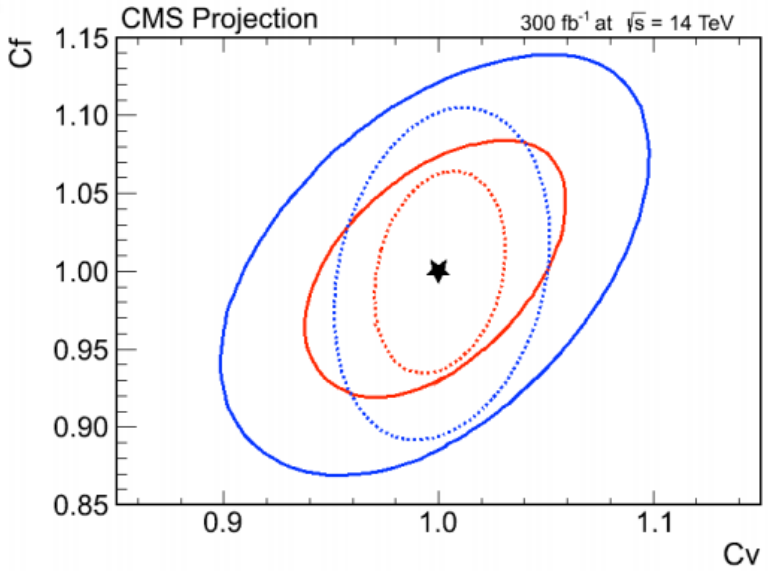
Fermion Couplings

Results within 1σ of SM prediction

Summary & Outlook

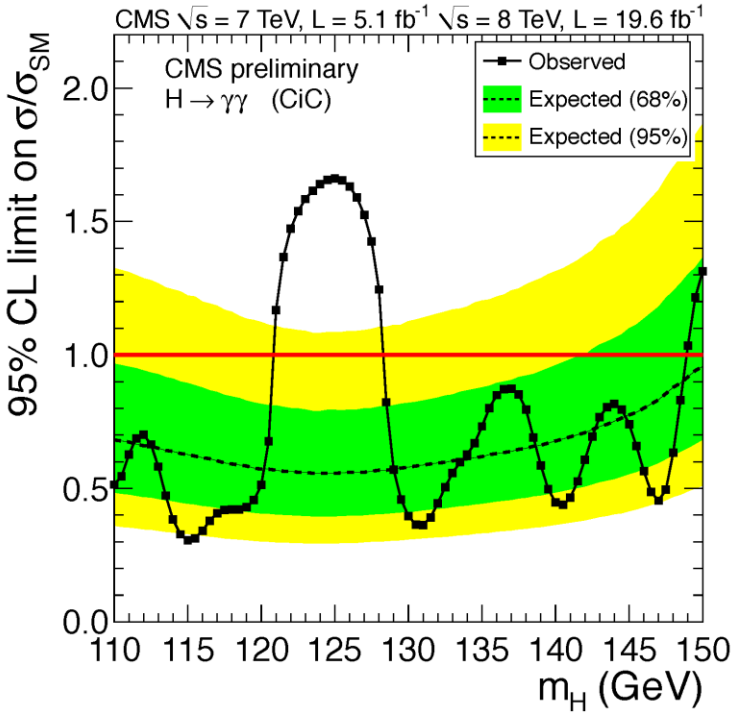
- Time for celebration: Discovery of new boson around 125 GeV !
- SM Higgs analysis in bosonic decay channels leads to the discovery
- Broad excess observed in ττ decay mode consistent with the new boson
- Di-Tau final state – First Indication of Higgs coupling to Leptons
- Mild excess observed in Higgs decay to b-jets, significance > 3σ combining ττ + bb channels
- Mass, Coupling and Spin-Parity properties measured show consistency with SM
- spin/parity is compatible with 0+ state, not with pseudoscalar or graviton states
- the present value of Higgs mass measured by CMS is 125.7 ± 0.4 GeV
- Starting 2015, a robust Higgs Physics program

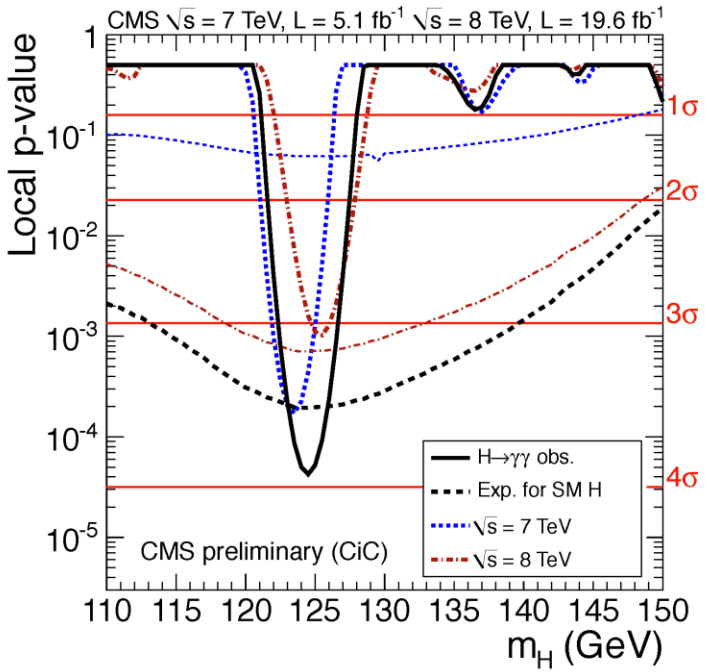




Back-up

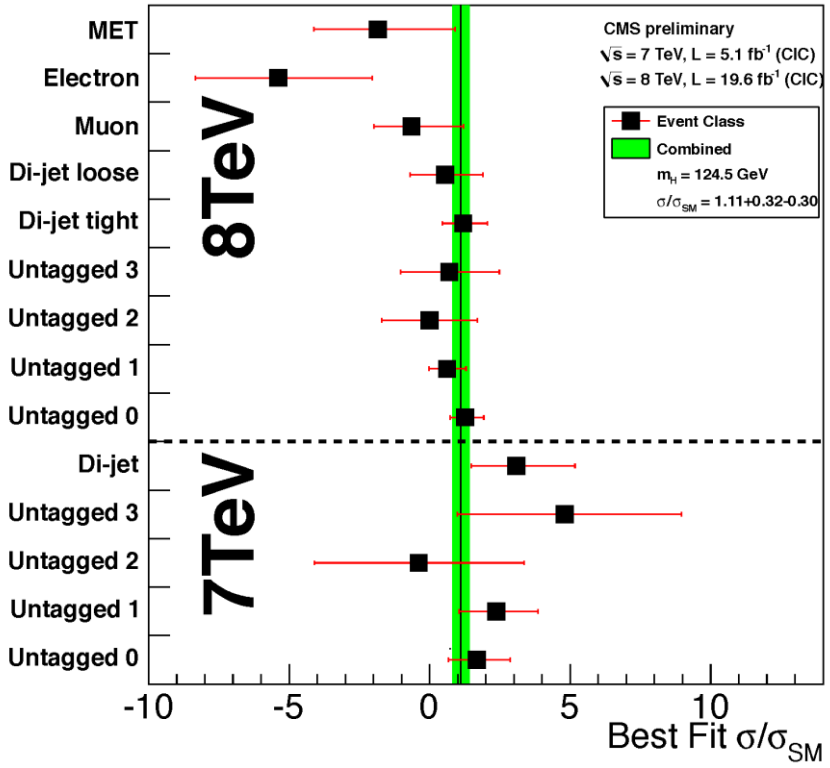
H→γγ cut-based

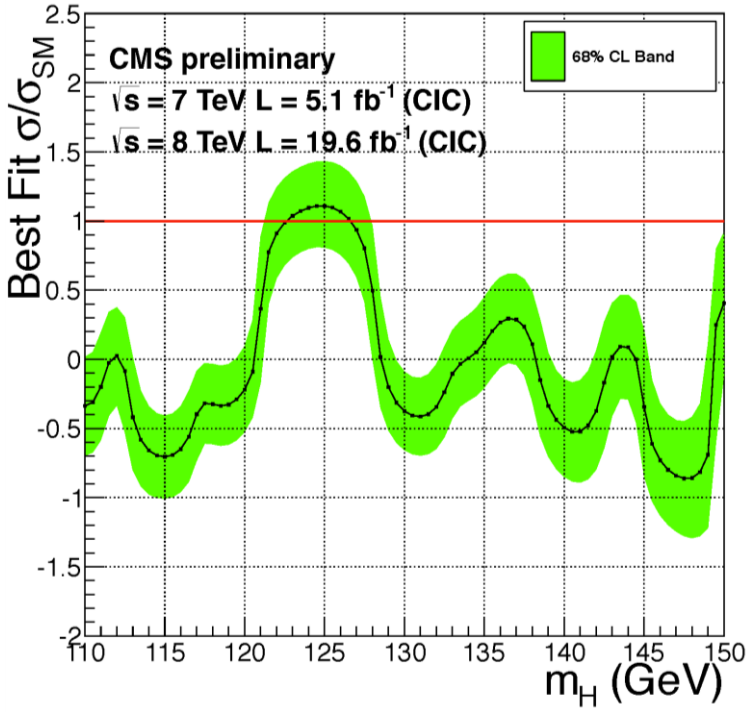




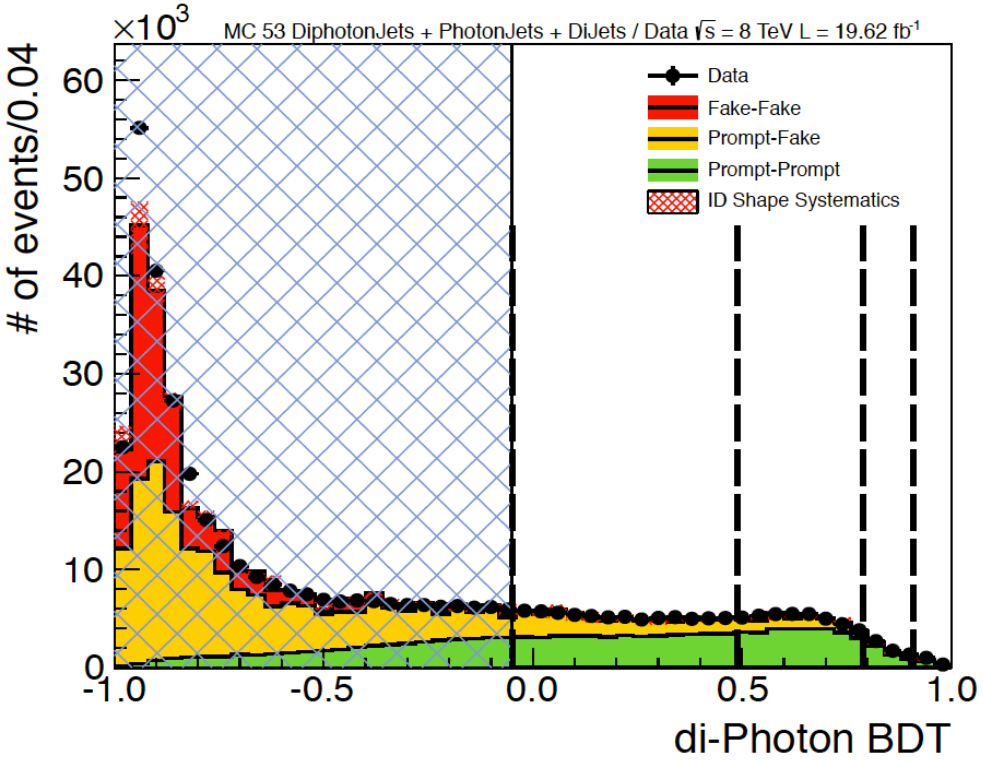
	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

H→γγ cut-based



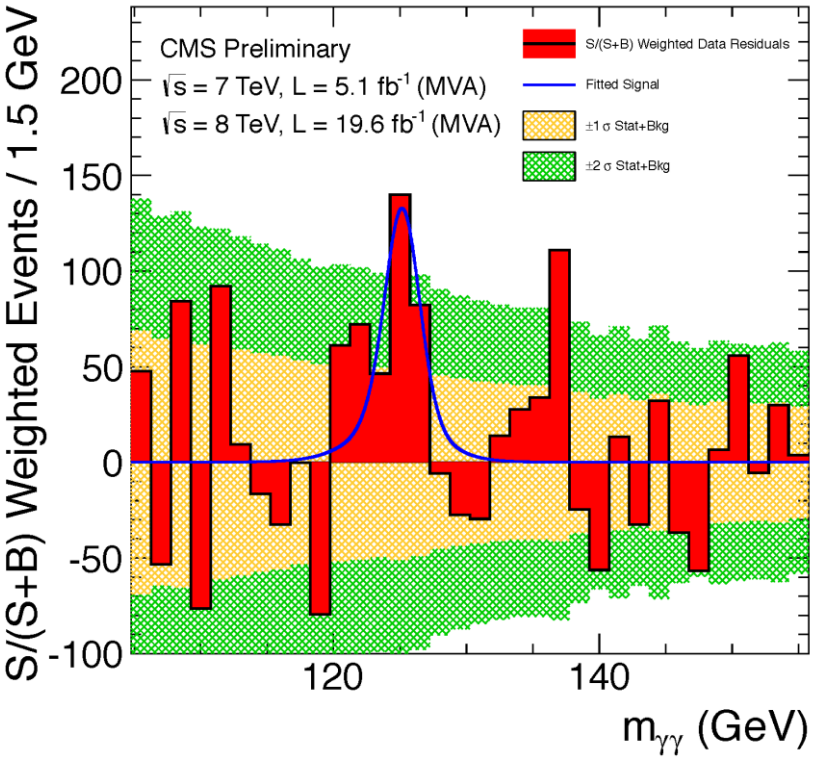


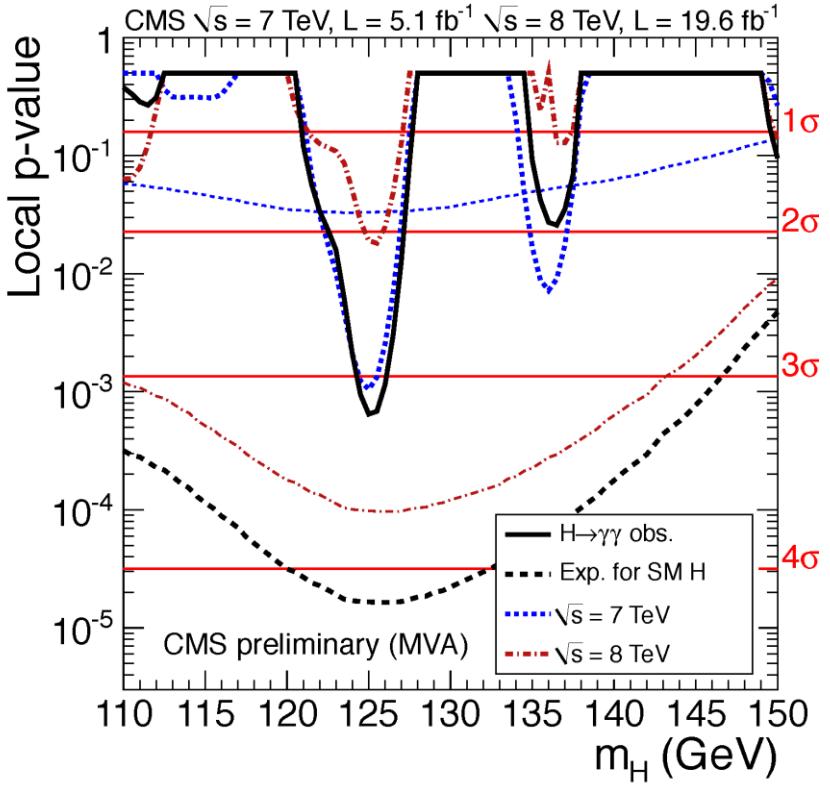
Di-Photon BDT



Di-photon MVA score for the background MC in the region $100 < m_{\gamma\gamma} < 180$ GeV and data

H→γγ MVA

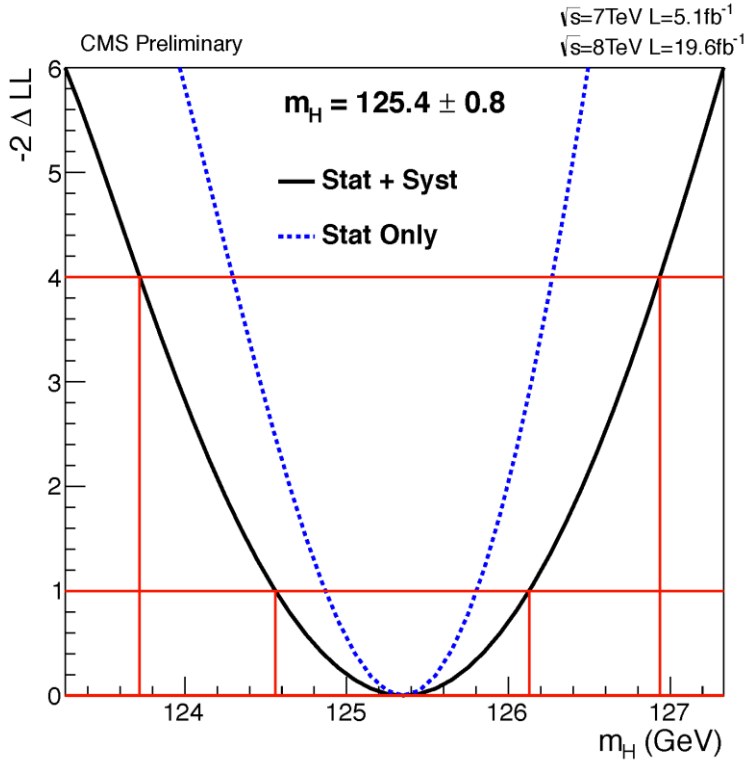




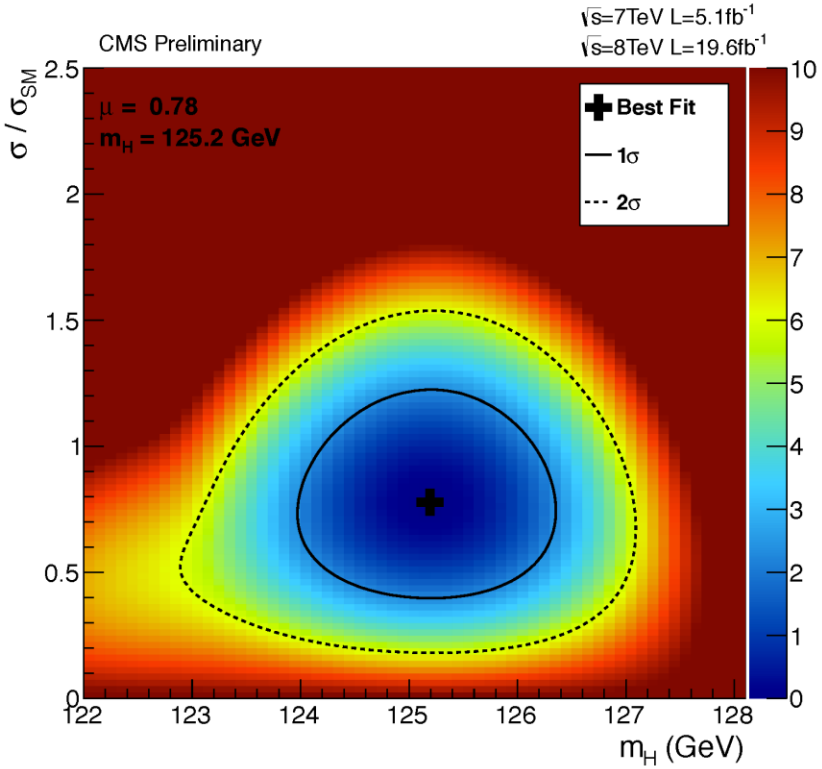
background subtracted diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category

Observed local p-values as a function of m_H obtained with mass fit MVA analysis

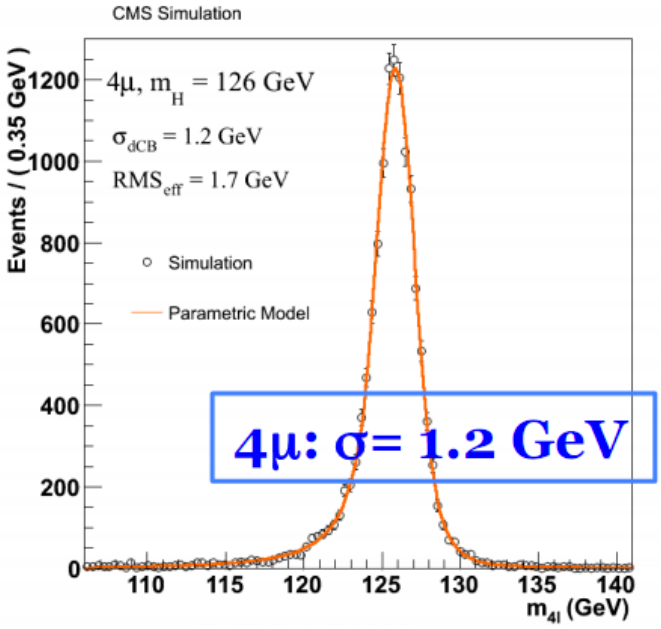
Mass (H→γγ)



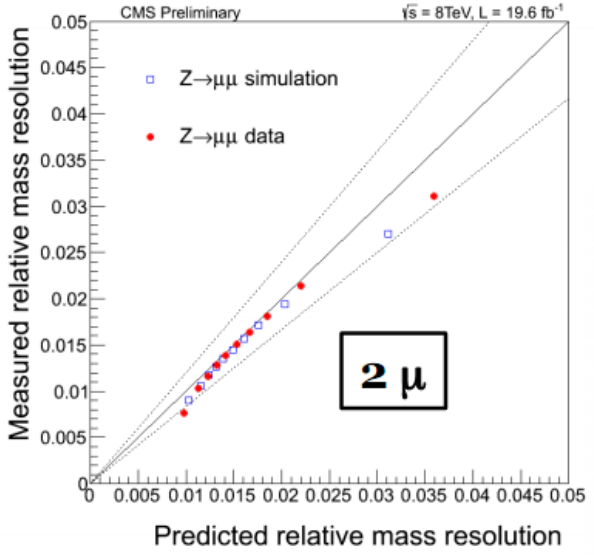
1D test statistic –2 ln Q vs Higgs boson mass hypothesis

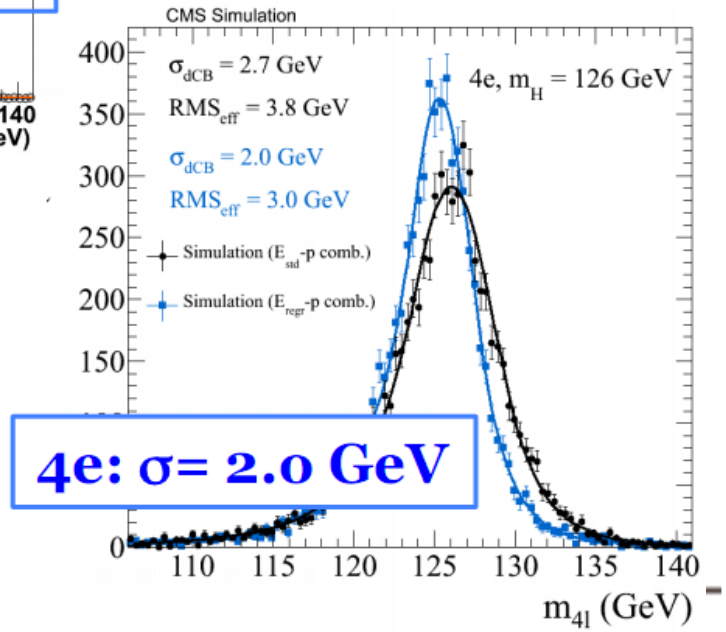


2D test statistic –2 ln Q for the signal strength, σ/σ_{SM}, vs Higgs mass hypothesis

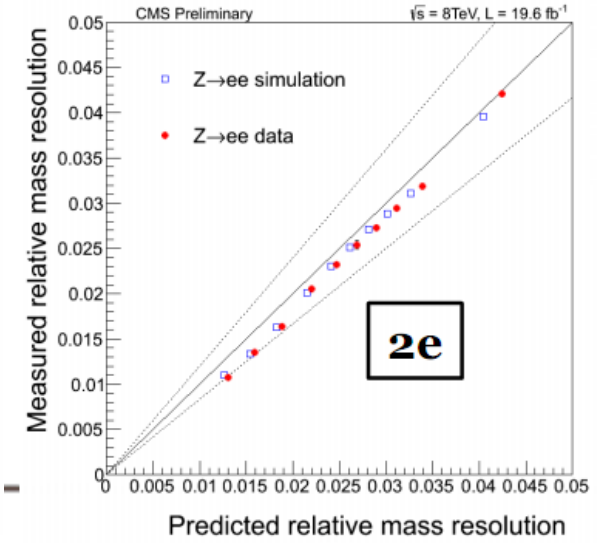


Good understanding of the lepton, dilepton and 4 lepton resolution



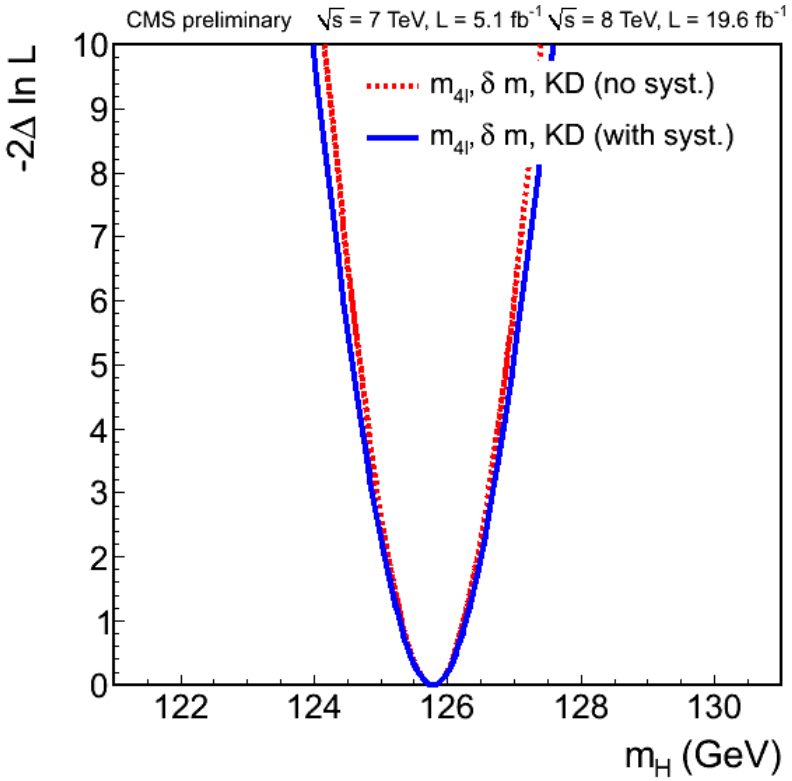


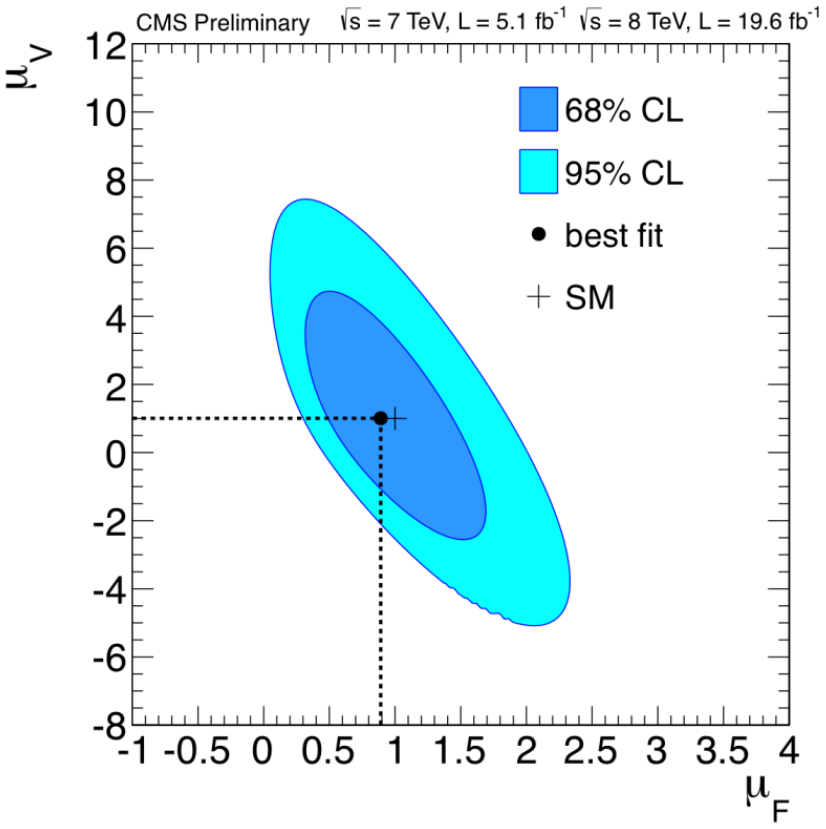
momentum scale uncertainty:
0.1% for muons
0.2% for electrons
of $35<p_T<50$ GeV
up to 1.5% at low p_T



Mass & Coupling (H→ZZ→4l)

Mass 125.8 +/- 0.5(stat.) +/- 0.2(syst.) GeV





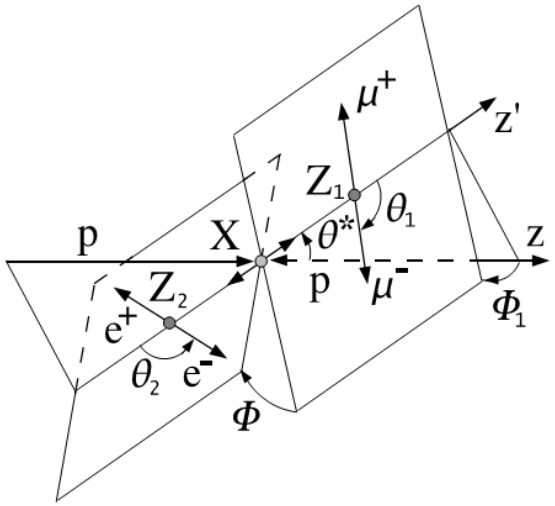
Coupling (to vector bosons and fermions) measurement in the 4-lepton channel

$$\mu_V = 1.0^{+2.4}_{-2.3} \qquad \mu_F = 0.9^{+0.5}_{-0.4}$$

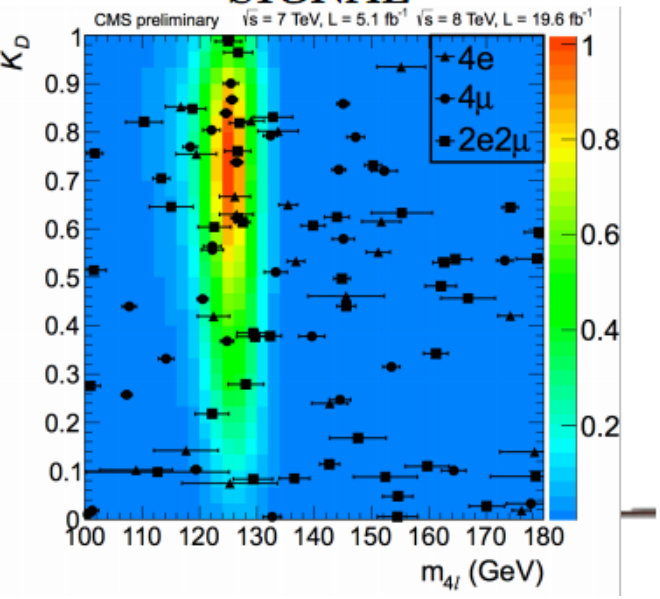
Matrix Element Likelihood Analysis

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

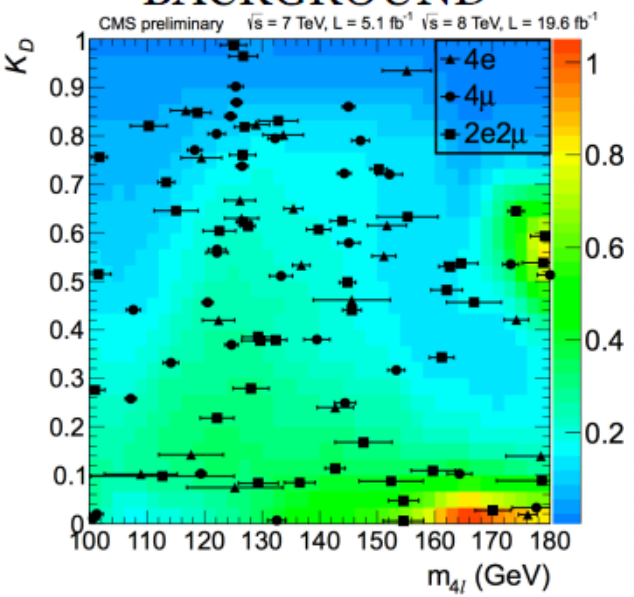
Masses of dilepton pairs and five angles fully defining a four-lepton configuration in their centre-of-mass frame

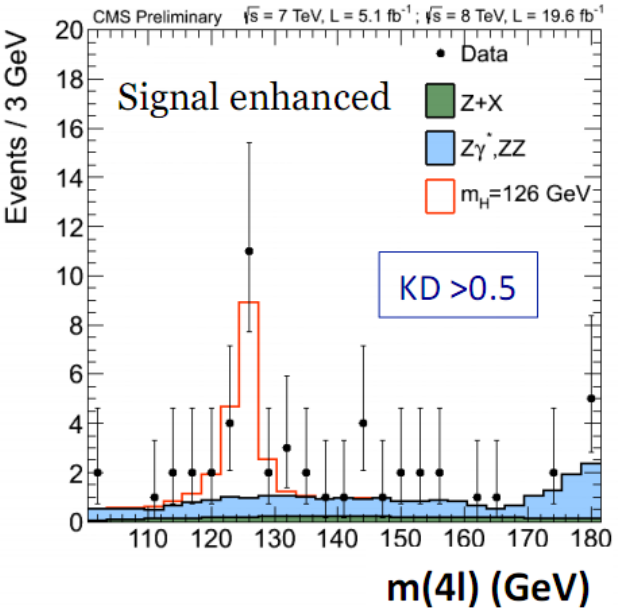


SIGNAL

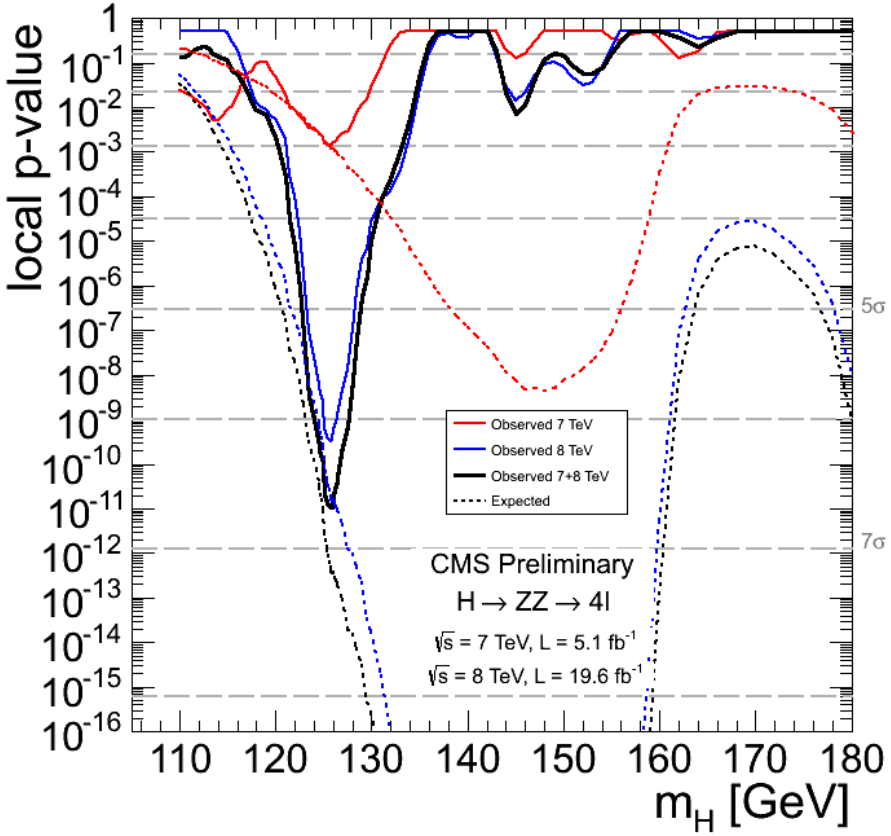


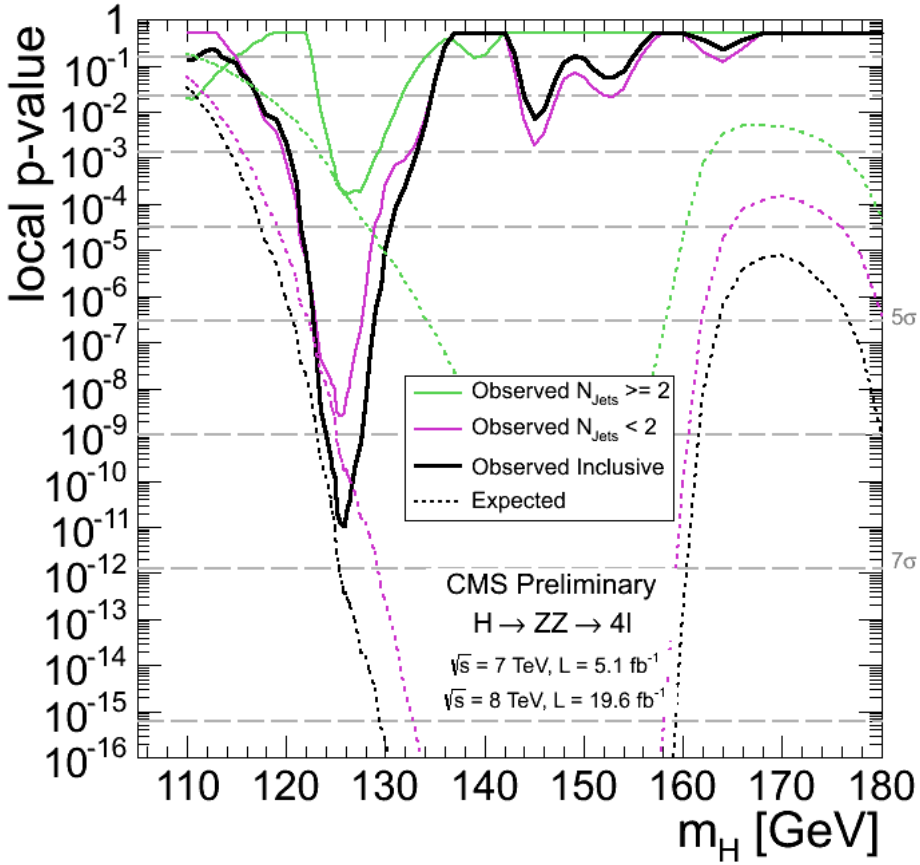
BACKGROUND



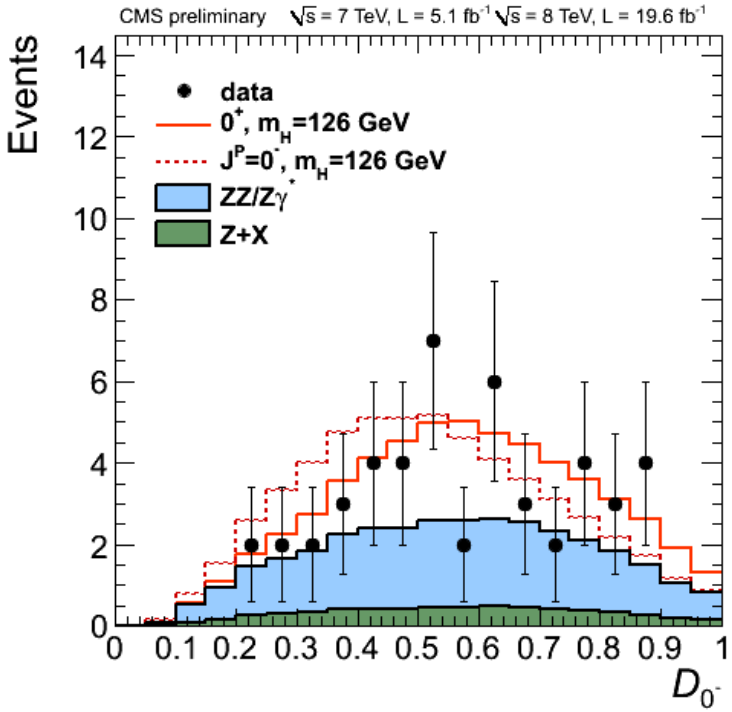


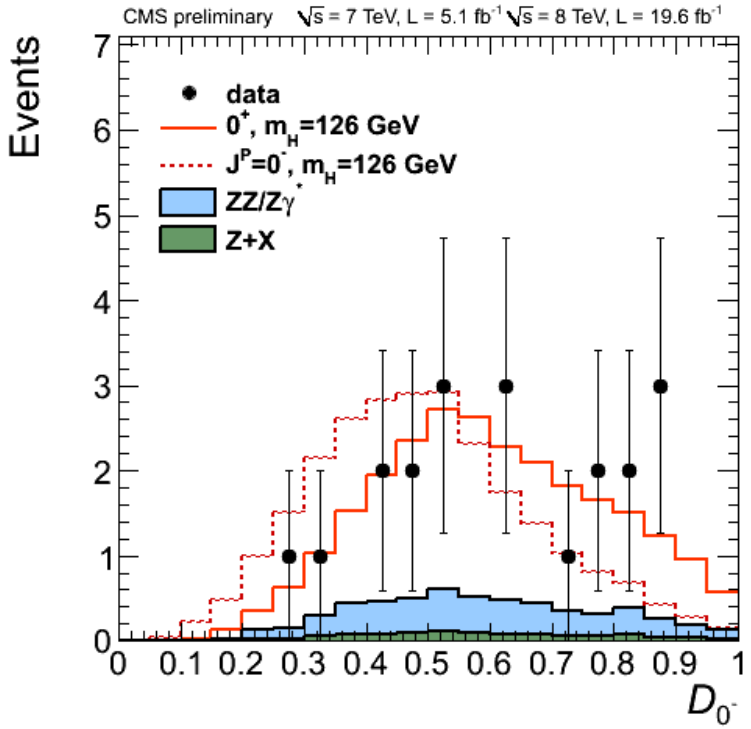
H→ZZ→4l excess





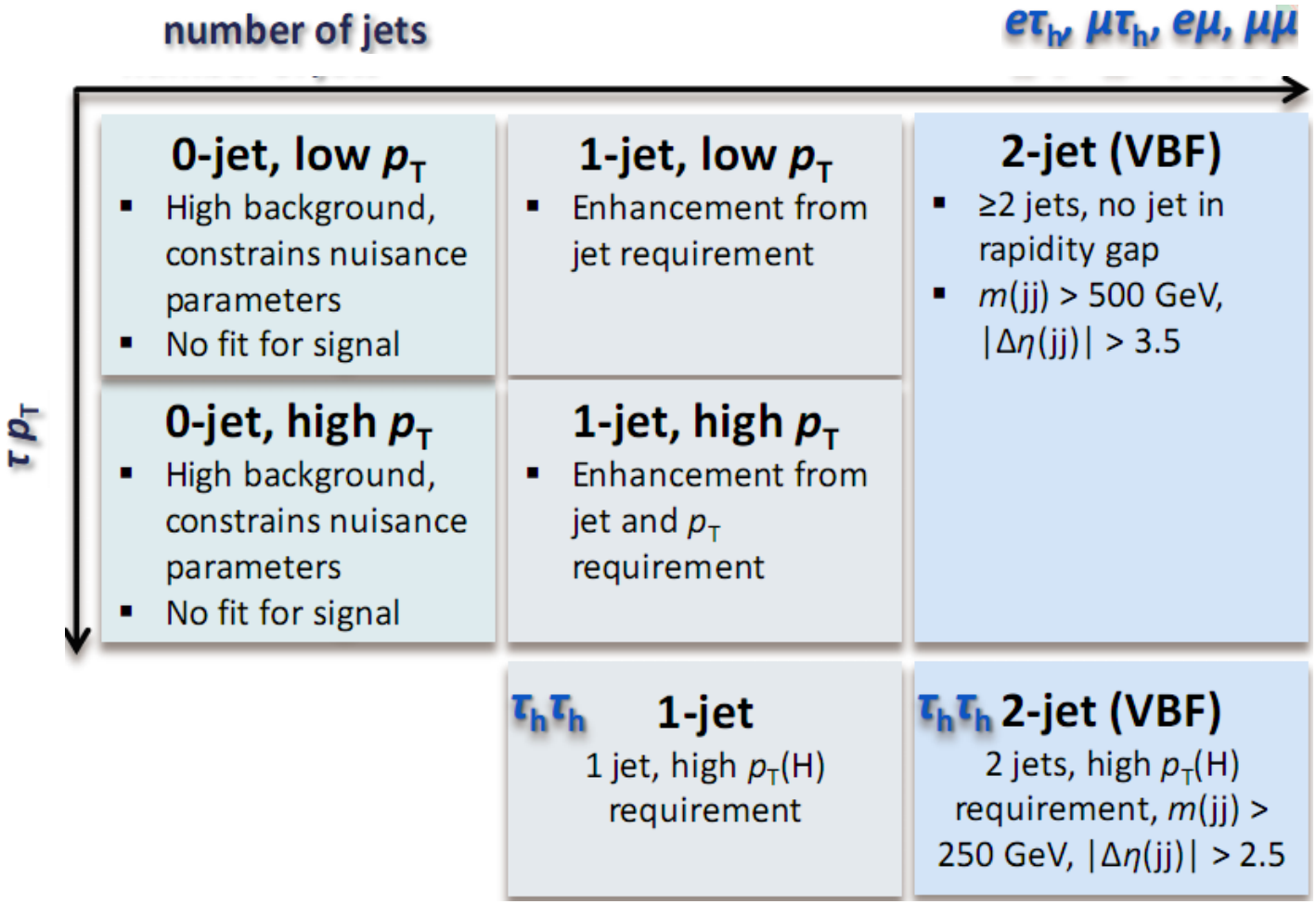
H→ZZ→4l (J^P)



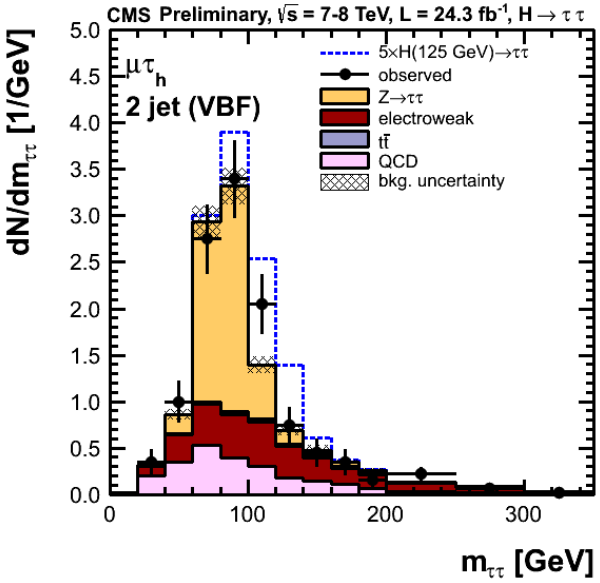


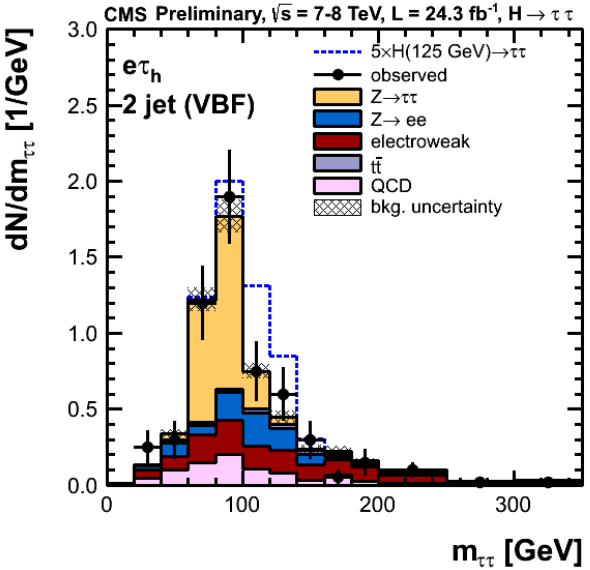
D_{JP} without (left) and with (right) a requirement $D_{bkg} > 0.5$

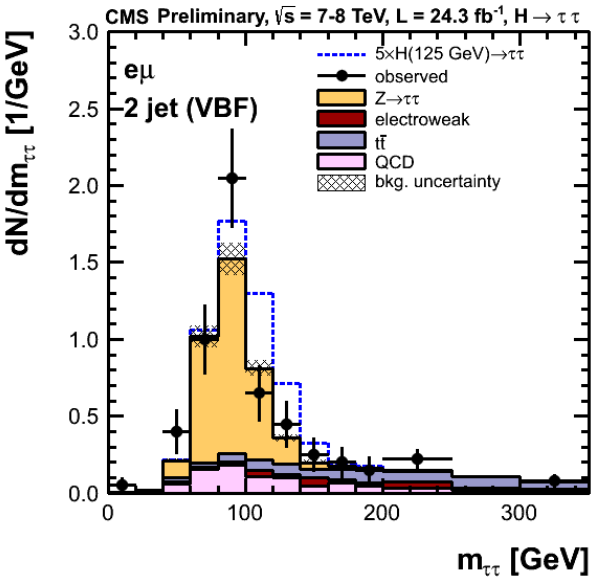
H→ττ
Event Categorization

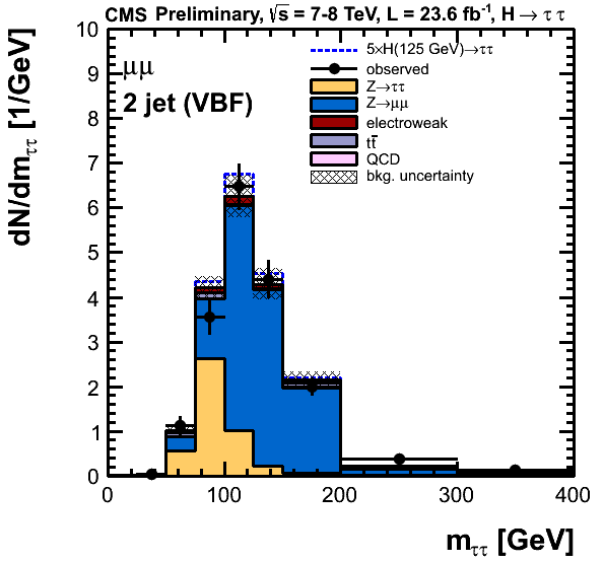


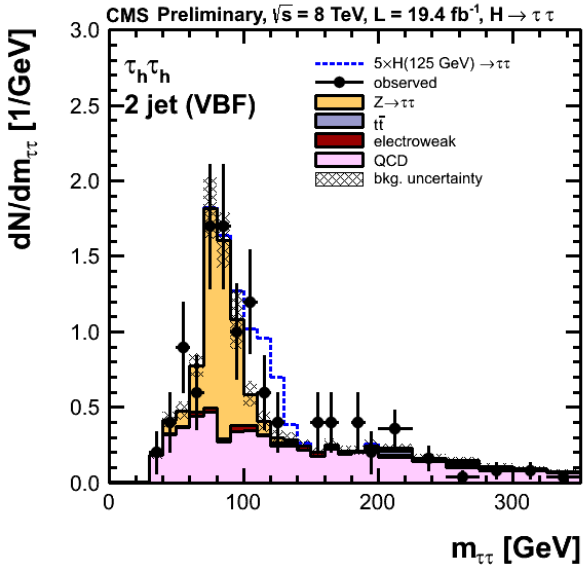
VBF H→ττ





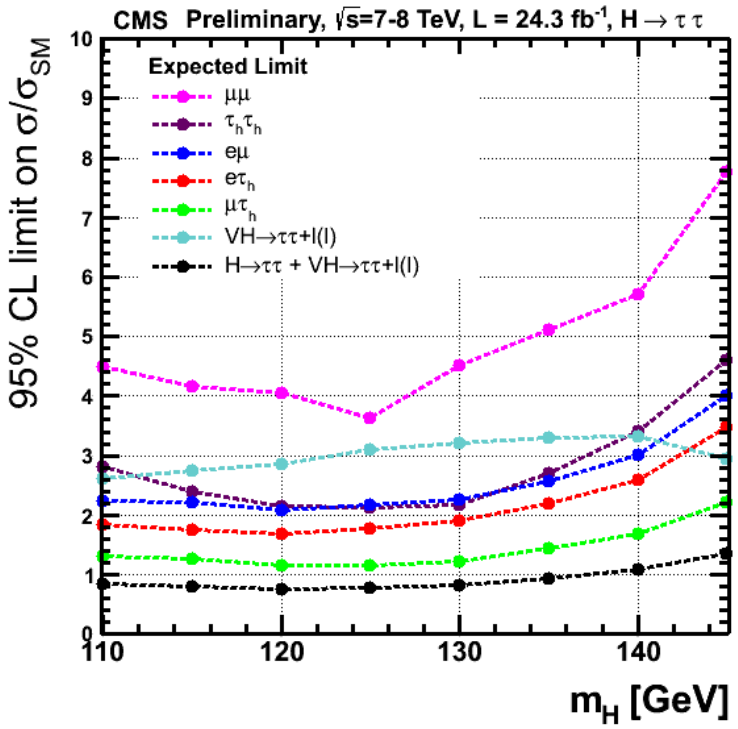




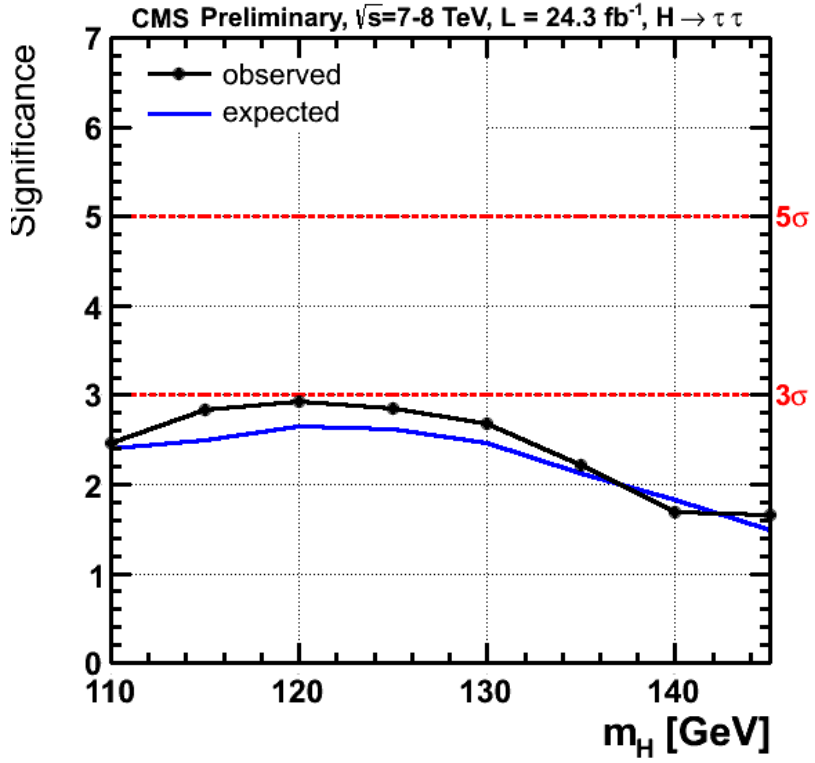


VBF category with S/B enhancement

Excess in H→ττ

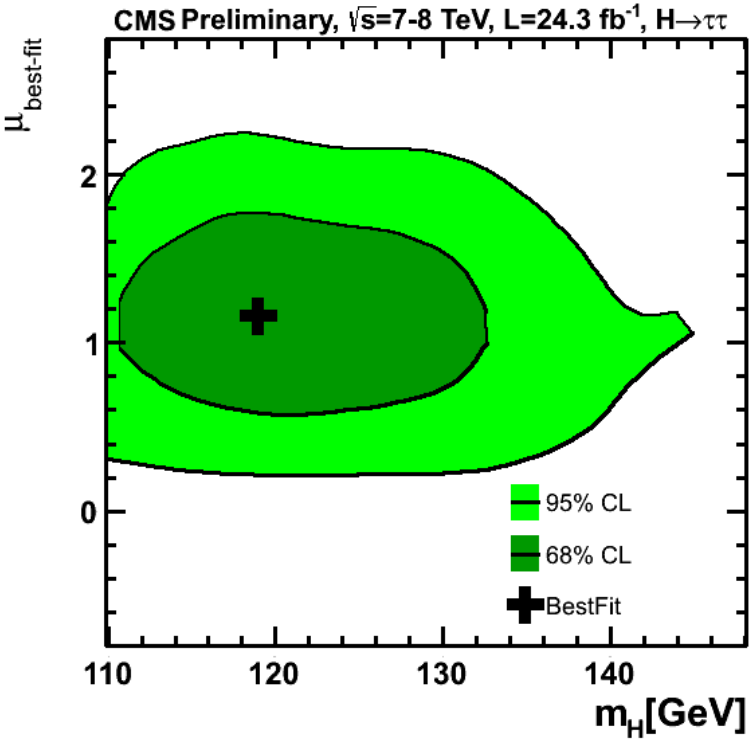


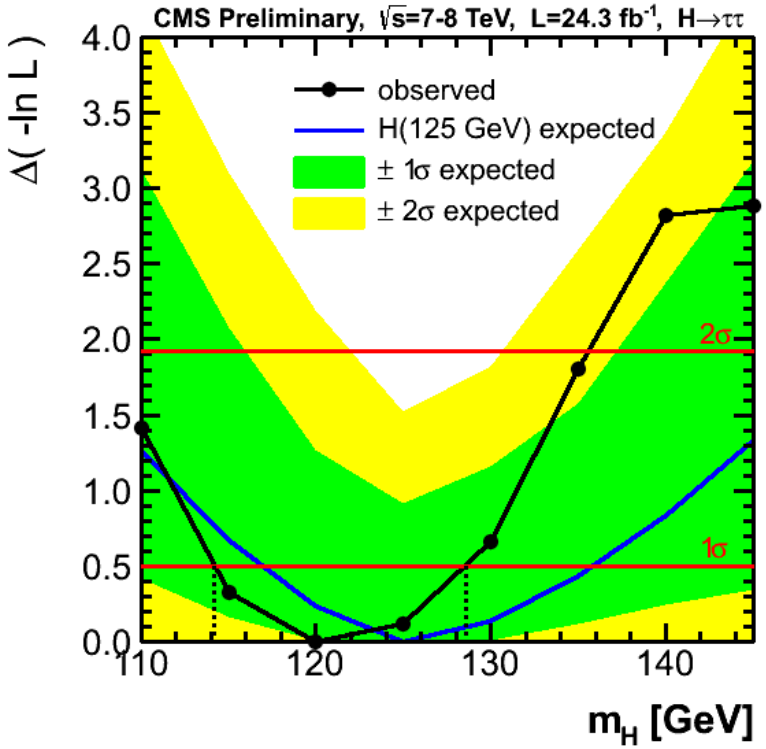
95% CL upper limits on SM Higgs production in different channels and its combination



Significance of excess observed

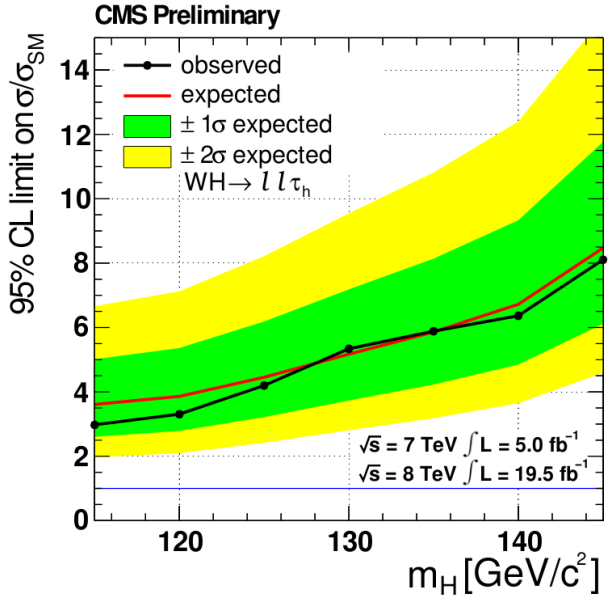
Mass measurement (H→ττ)

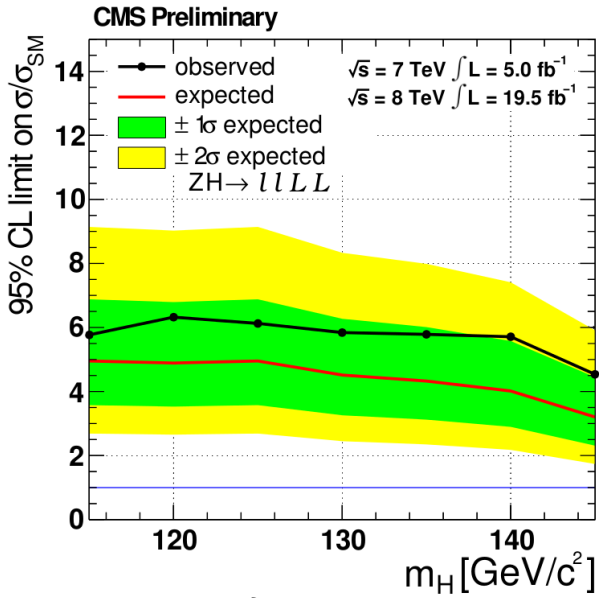


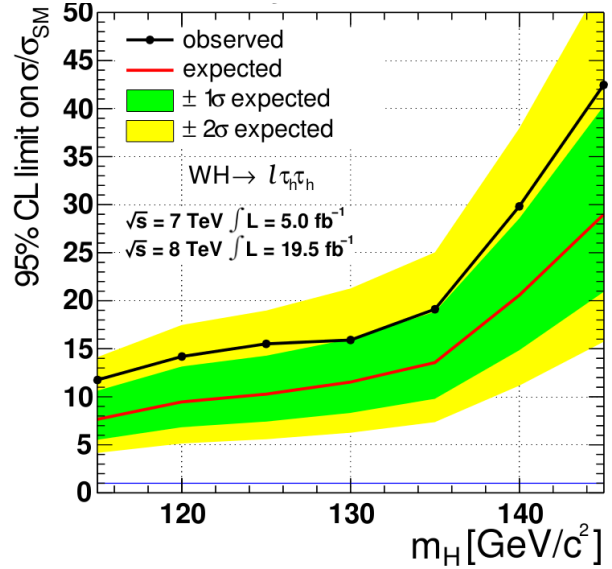


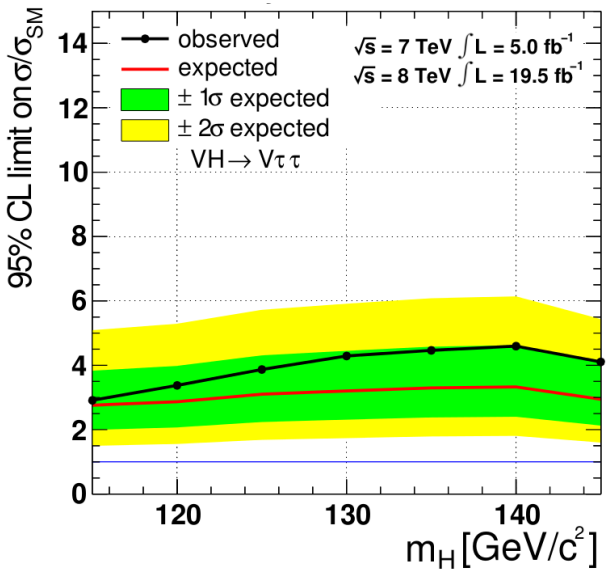
observed result gives a best fit
for the SM Higgs boson of
$m_H = 120\ ^{+9}_{-7}$ (stat + syst) GeV

VH with H→ττ









95% CL upper limits on SM Higgs production in VH channels and its combination

H→bb backgrounds

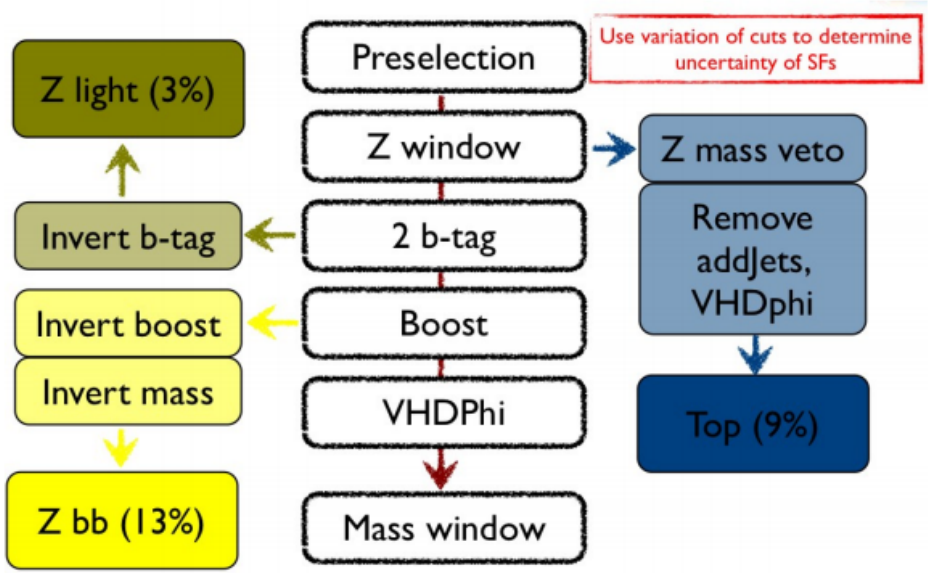
- V + jets
  - High cross section, non-resonant background
  - V + heavy flavor jets largest bkg after b-tagging (irreducible)

- V + light flavor jets - reducible
  - Falls more rapidly than signal with high boost

- top pair, single top

- VV
  - Smaller cross section, very similar to VH (irreducible)
  - Best discriminated by invariant mass

- Other reducible background:
  - QCD fake leptons or jet energy mis-measurements



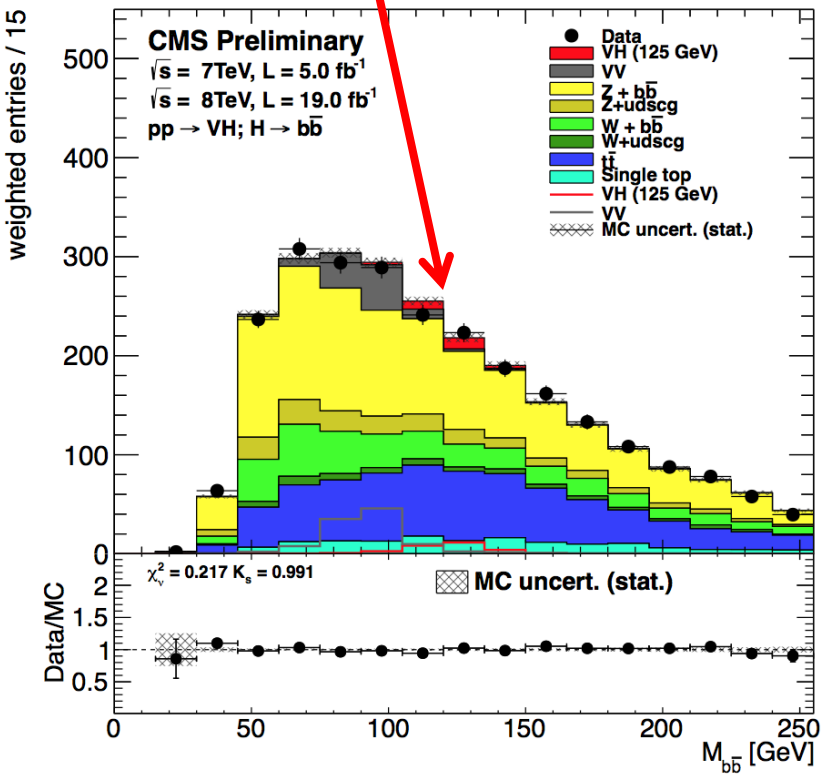
b-jet identification substantially reduces multi-jet background

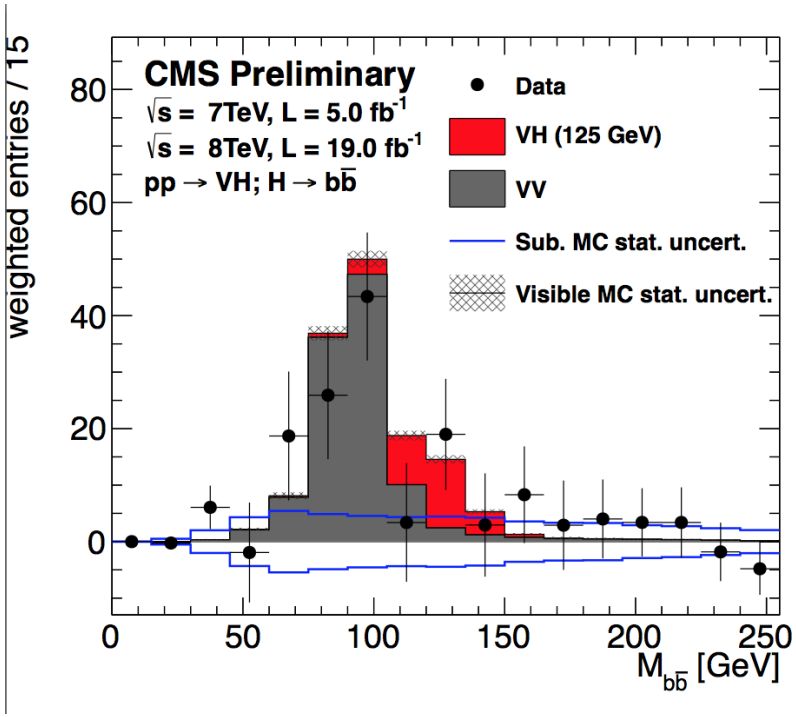
Requires higher boost and VH back-to-back topology to enhance S/B
- Signal decreases more slowly than bkg

M_{bb} Invariant Mass

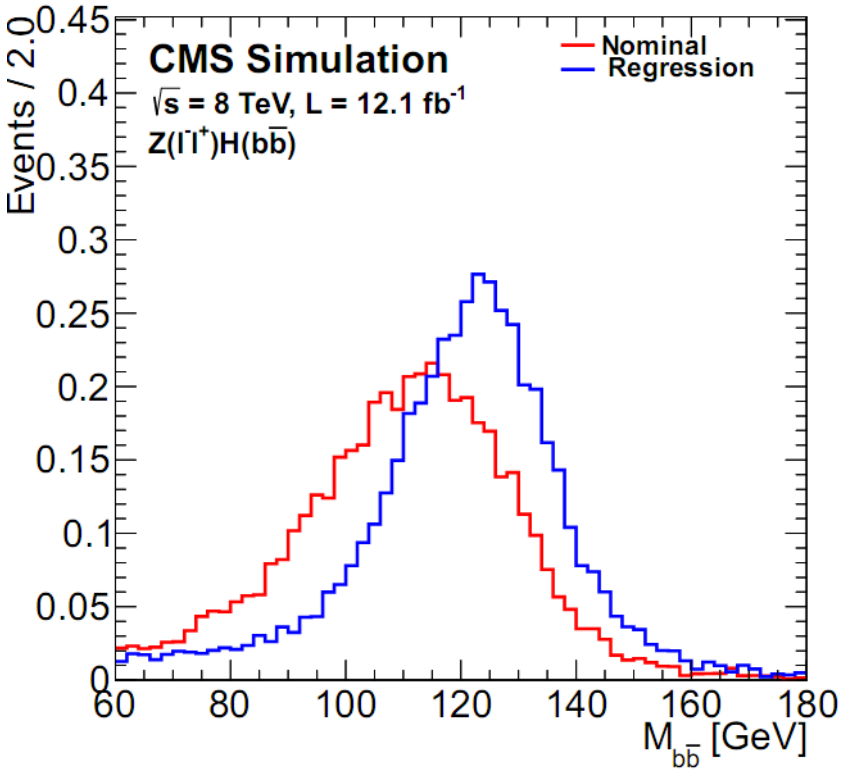
Excess around 125 GeV

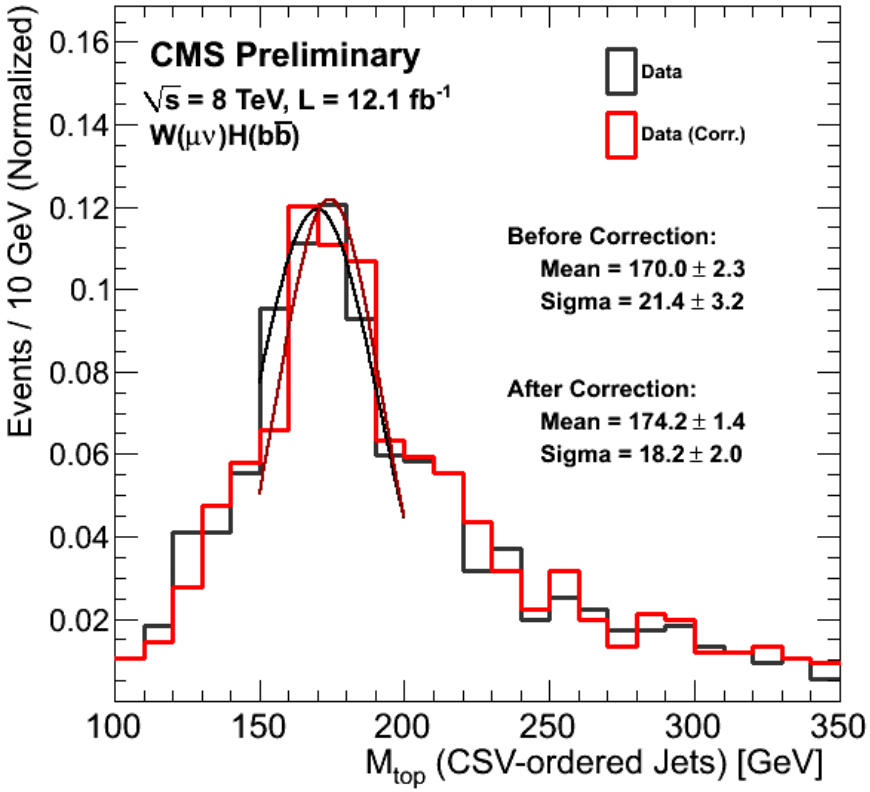
Di-jet Invariant Mass





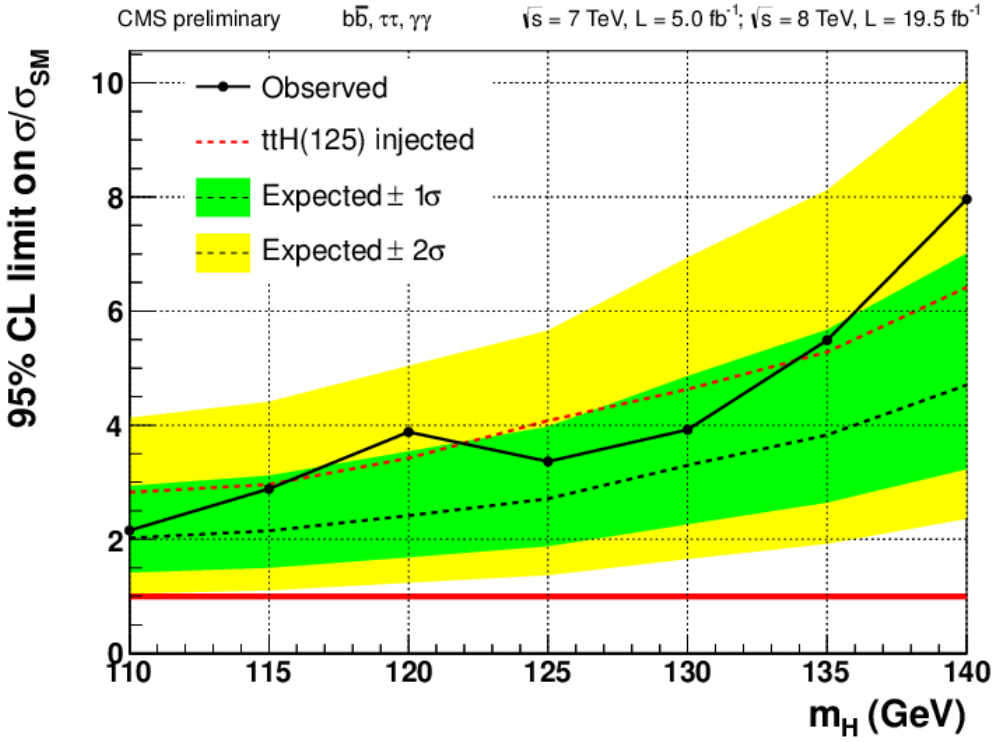
M_{bb} resolution

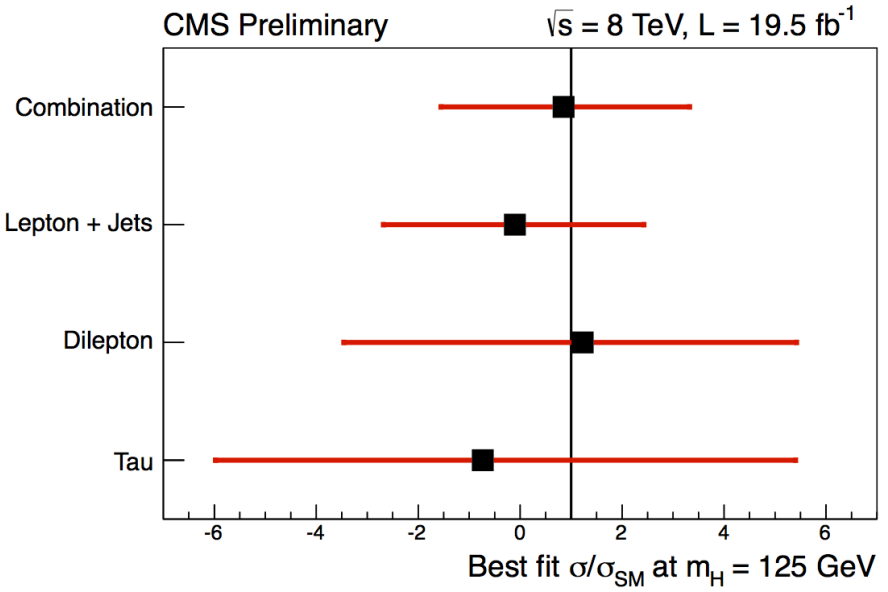




M_{bb} resolution improves – applying regression

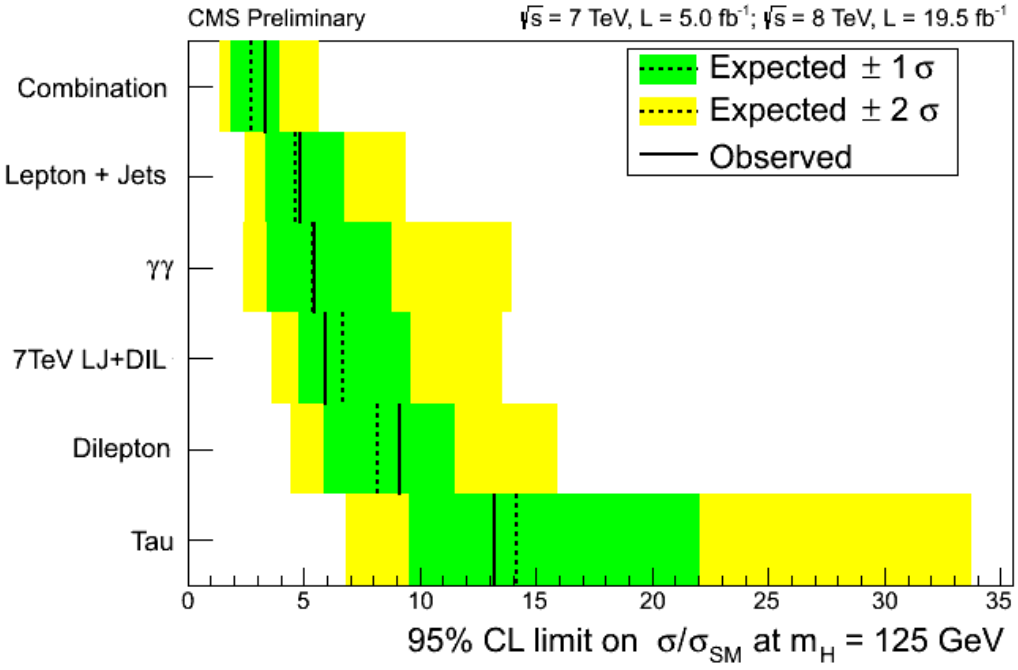
ttH production

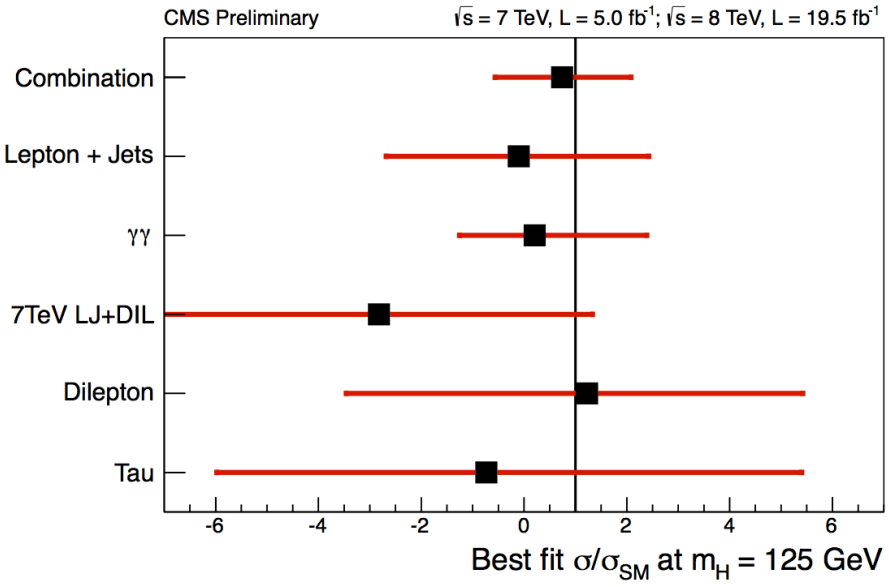




bb + ττ channels

ttH production





Combined γγ + bb + ττ channels

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

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:

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

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

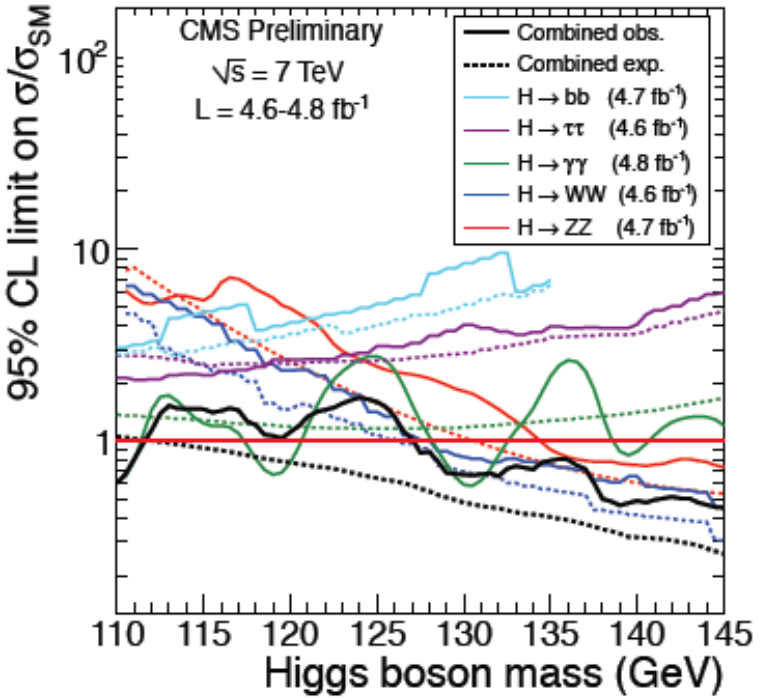
$$CL_s(\mu) = \frac{P\left(q_\mu \geq q_\mu^{obs} \,|\, \mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \geq q_\mu^{obs} \,|\, b(\hat{\theta}_0^{obs})\right)}$$

To set exclusion limits on a Higgs boson hypothesis:

$$q_\mu = -2\ln\frac{\mathcal{L}(\text{data}\,|\,\mu\cdot s(\hat{\theta}_\mu)+b(\hat{\theta}_\mu))}{\mathcal{L}(\text{data}\,|\,\hat{\mu}\cdot s(\hat{\theta})+b(\hat{\theta}))} \qquad 0 \leq \hat{\mu} < \mu$$

To quantify the statistical significance of an excess over the background-only expectation:

$$q_0 = -2\ln\frac{\mathcal{L}(\text{data}\,|\,b(\hat{\theta}_0))}{\mathcal{L}(\text{data}\,|\,\hat{\mu}\cdot s(\hat{\theta})+b(\hat{\theta}))} \qquad \hat{\mu} \geq 0$$



CMS PAS HIG-13-005

Quantify the presence of an excess over expected background

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{obs} \mid b, \hat{\theta}_0)}{\mathcal{L}(\text{obs} \mid \hat{\mu} \cdot s + b, \hat{\theta})}$$

Probability to obtain a value q_0 at least as large as the observation

$$p_0 = \mathrm{P}(q_0 \geq q_0^{obs} \mid \mathrm{b})$$

Scan of the profile likelihood ratio

parameters that maximize the likelihood – best fit set

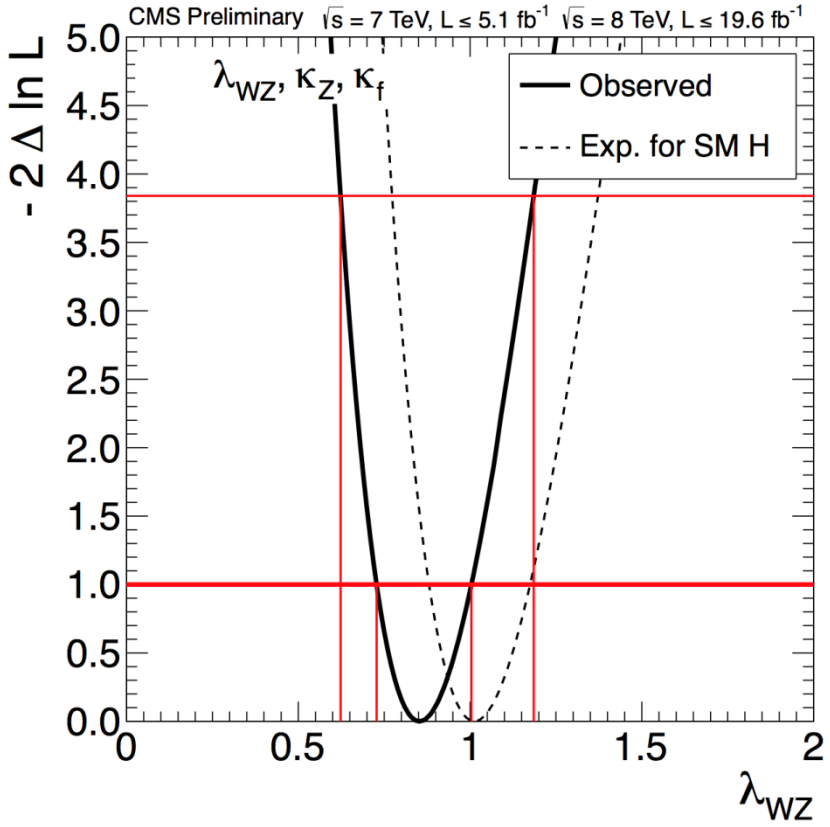
$$q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} \mid s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{obs} \mid s(\hat{a}) + b, \hat{\theta})}$$

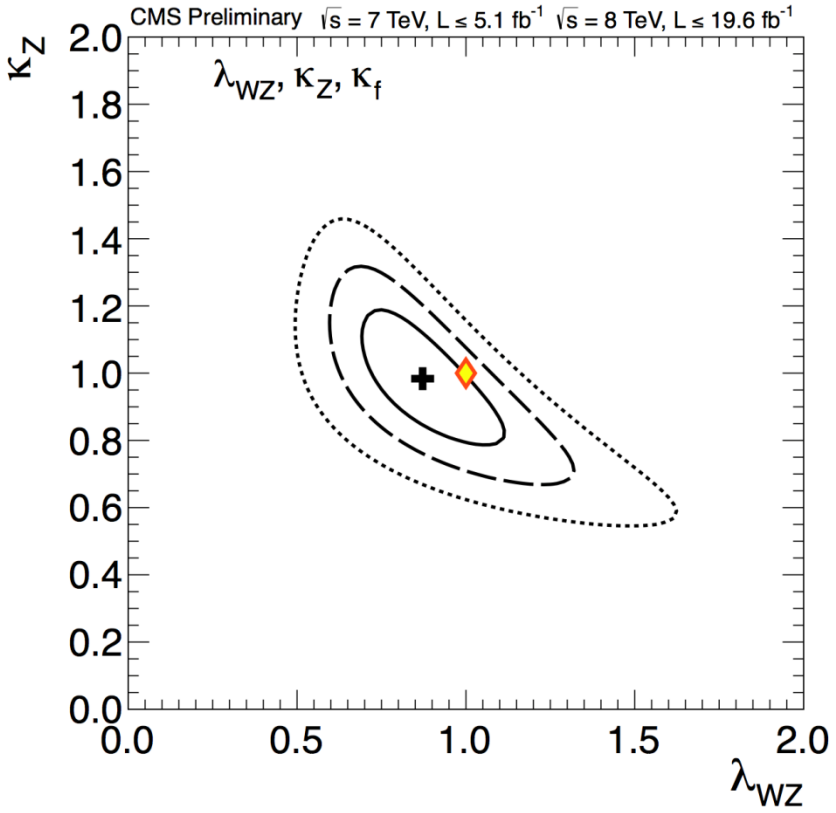
Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
bb	2.2	2.0
$\tau\tau$	2.6	2.8

Custodial Symmetry Test

Modify the SM Higgs boson couplings to the W and Z bosons introducing two scaling factors κ_W and κ_Z and perform two combinations to assess that

$\lambda_{WZ} = \kappa_W/\kappa_Z = 1$ for $m_H = 125.7$ GeV

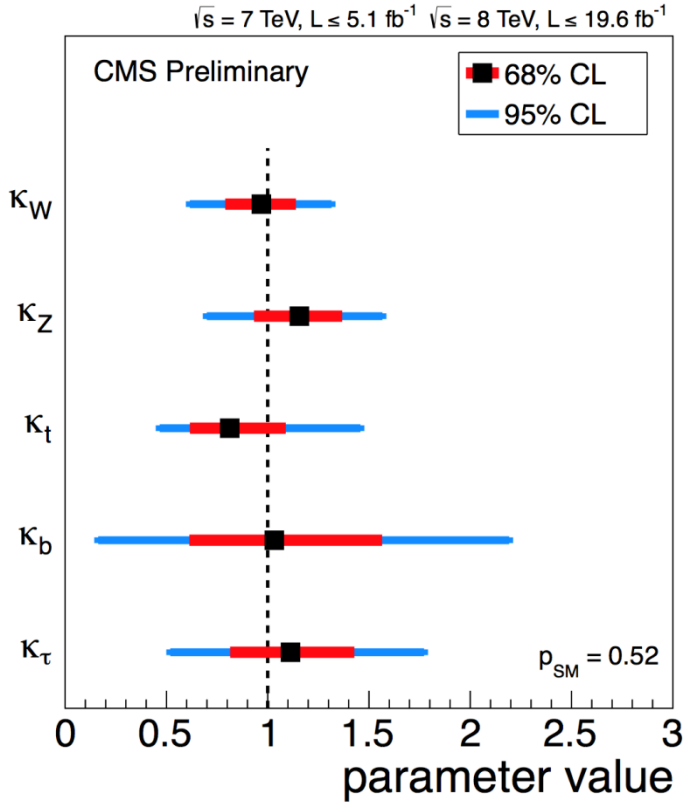




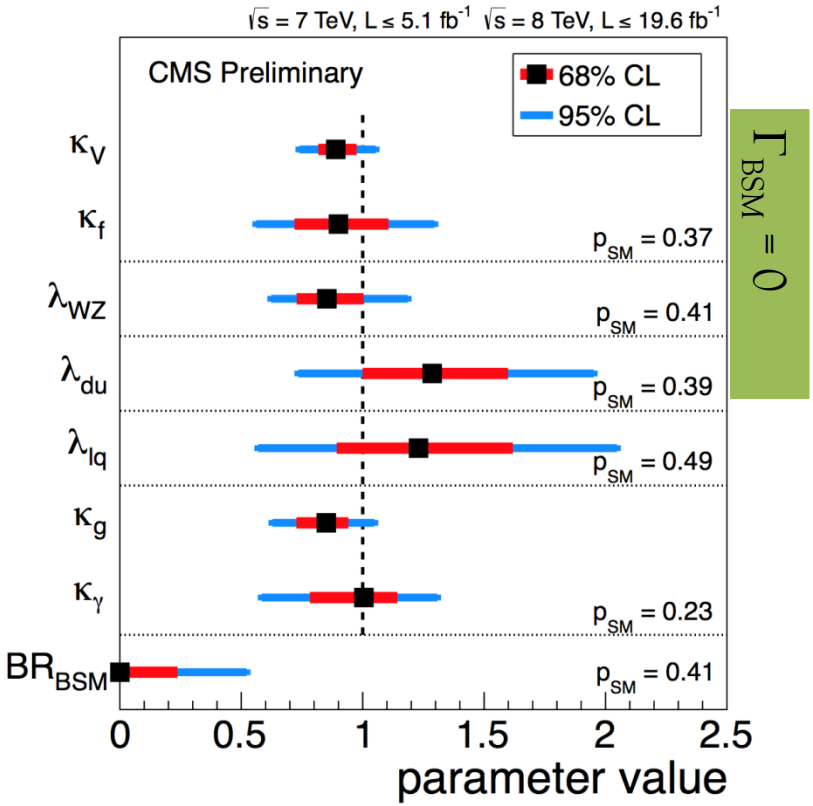
95% CL interval for λ_{WZ} : [0.62,1.19]

Summary of the fits for deviations in the couplings

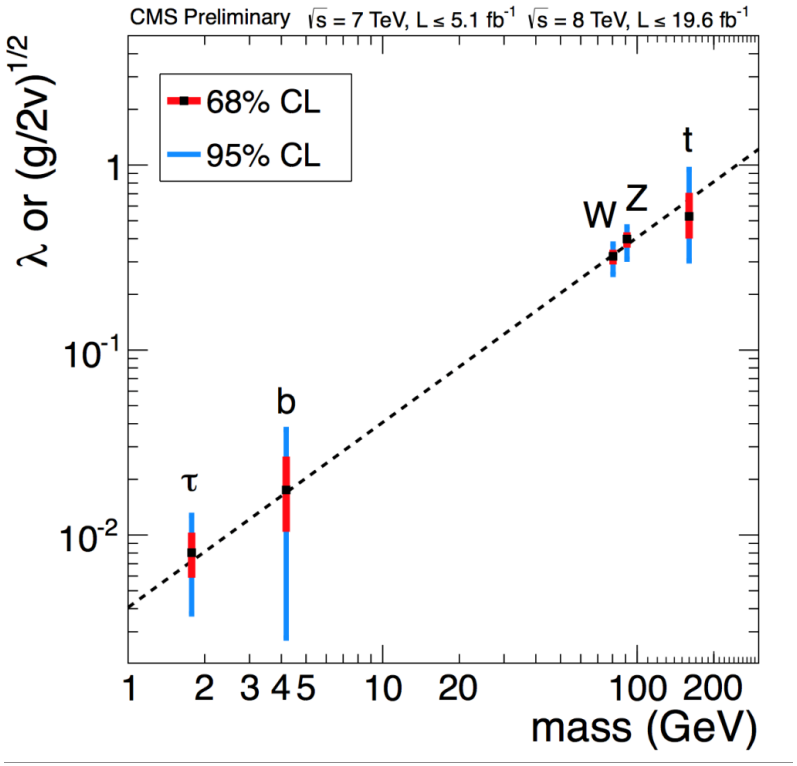
for a generic five parameter model (no eff. loop couplings)



for a LHC SX WG benchmark model (arXiv:1209.0040)



Summary of the Couplings Test



Fermions: fitted yukawa couplings

Vector bosons: square-root of the coupling for hVV vertex divided by twice the vev