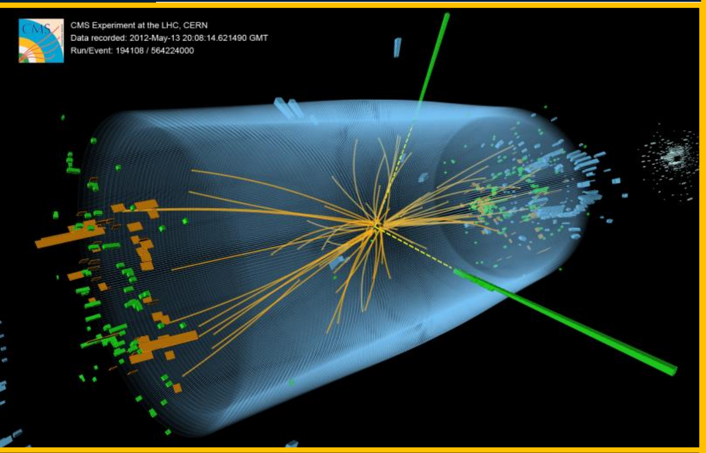
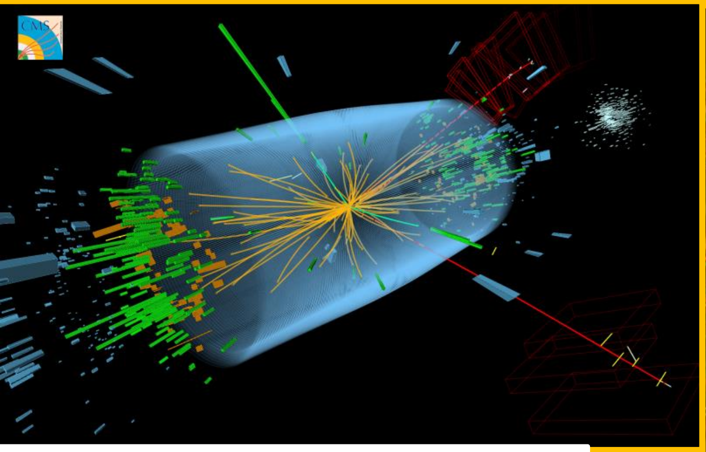
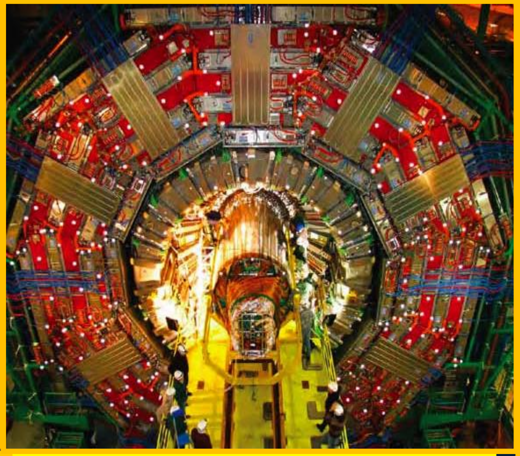
CMS Higgs Search: Discovery, Measurements and Prospects

INTERNATIONAL SCHOOL ON HIGH ENERGY PHYSICS



- ❒ *A 48 Year Search*
- ❒ *Observing a New Boson*
- ❒ *A Gateway*





Opening a New Era of Physics

~50 Vertices, 14 Jets, 2 TeV

Harvey B Newman

LISHEP 2013

March 22, 2013

On behalf of the CMS Collaboration

LISHEP
INTERNATIONAL SCHOOL ON HIGH ENERGY PHYSICS

CMS: A New Boson

Exploration in the Post-Discovery Era

- 2012 Data in CMS
- Post Discovery Progress
  - Is it the SM Higgs Boson ?
  - Is there just one ?
- Updates on Signals in Individual Channels
- Properties
  - The Mass
  - Couplings to Fermions as well as Vector Bosons
  - Spin/Parity
- BSM Higgs Searches:
- Outlook

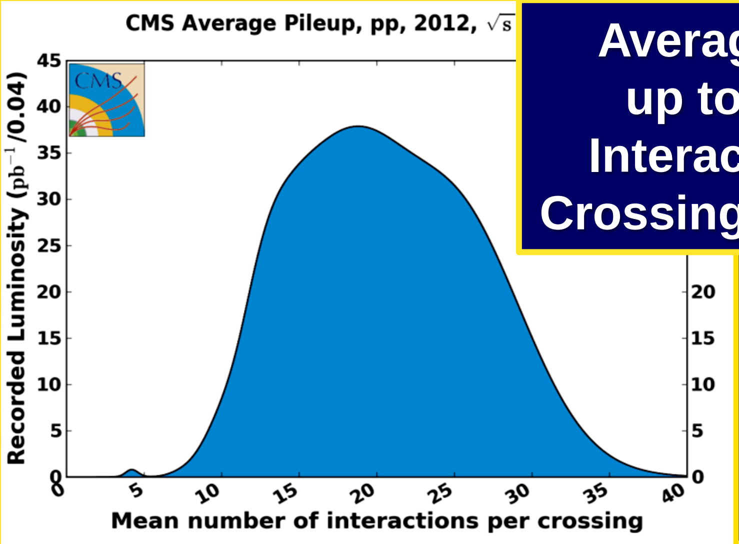
CMS Higgs Measurement

Talks at This Session

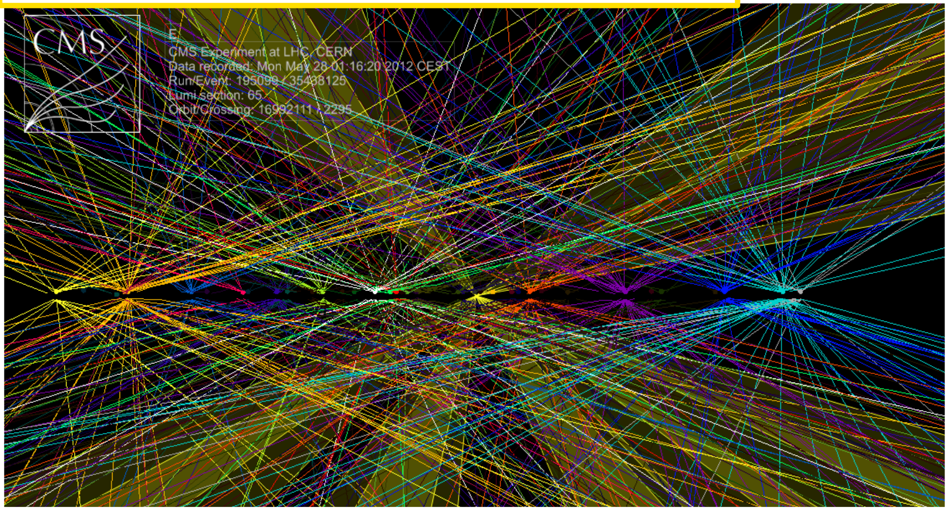
- A New Boson in the ZZ → 4 Lepton Channel
  Guenakh Mitselmaker (Florida)
- A New Boson in the $\gamma\gamma$ Channel
  Chris Palmer (UC San Diego)
- Measurements in the b-bar and $\tau^+\tau^-$ Channels
  Robertval Walsh (DESY)

The LHC: Spectacular Performance

To 7.7 X 10^{33}; The Challenge of Pileup



Average 19,
up to ~50
Interactions/
Crossing in 2012



~50 Vertices, 14 Jets, 2 TeV

$1.1 \times 10^{11} \rightarrow 1.5 \times 10^{11}$ ppb X 2

Emittance: ε 3.5→ 1.8 micron X 2

2012: 8 TeV X 50 nsec $\beta^* \rightarrow$ 0.6m

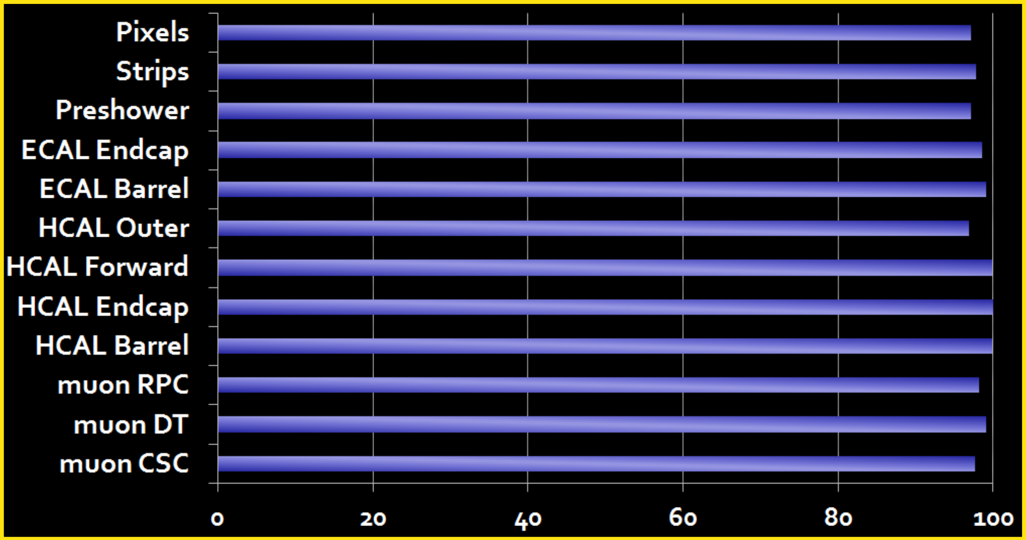
Modular 3.8 Tesla Design with H in Mind

Extending the State of the Art:

2.7 GJ Magnet, 200 m^2 Tracker, 76k Crystal ECAL

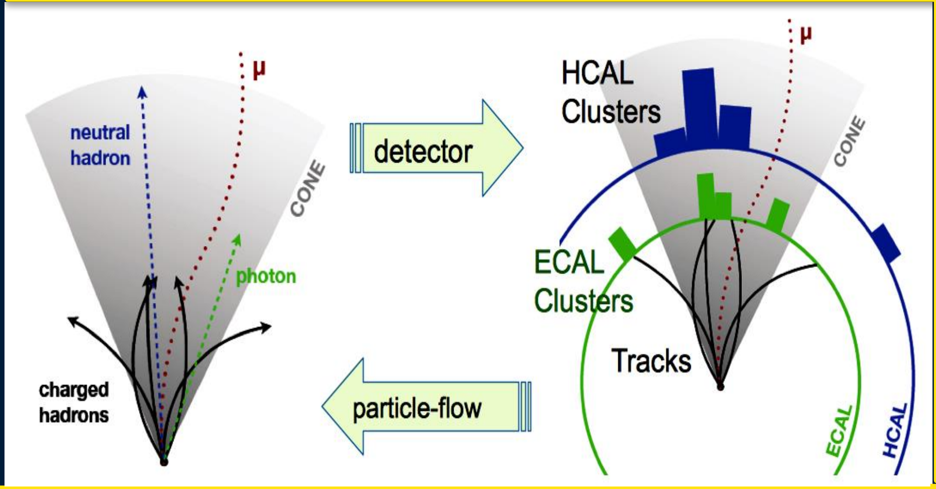
Global Muons 7% at 1 TeV, Software HLT

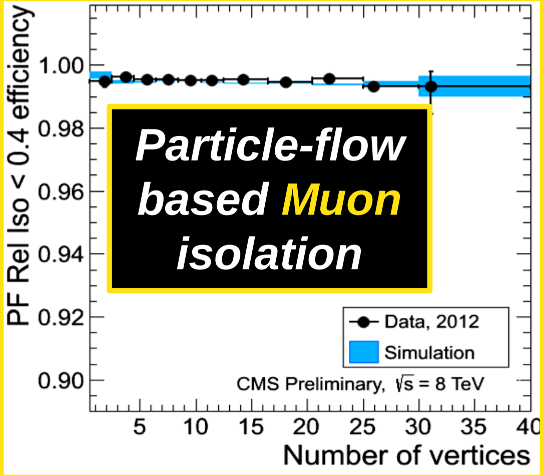
Works beautifully!



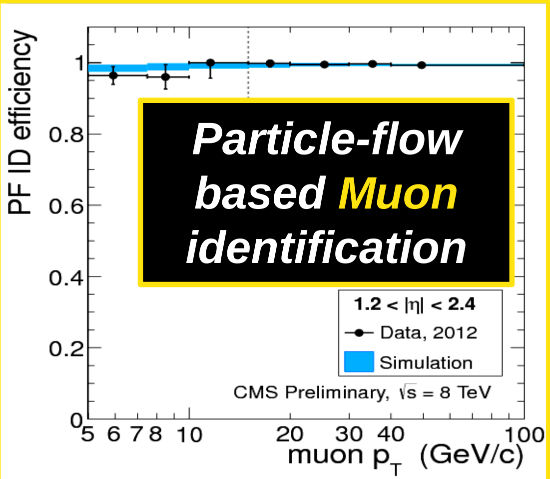
CMS Global Event Reconstruction

Made possible by CMS granularity and high magnetic field





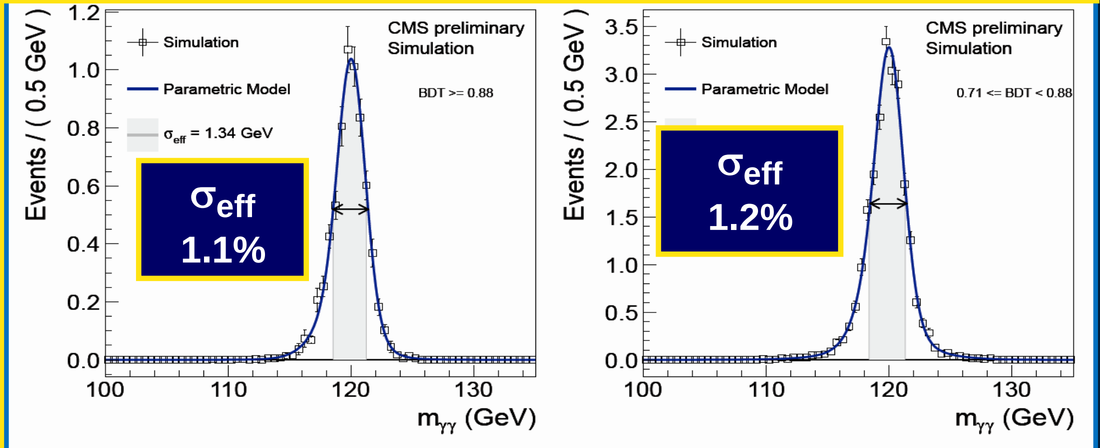
Particle-flow based Muon isolation



Particle-flow based Muon identification

- **Optimal combination of information from all subdetectors**
- **Returns reconstructed "particles": e, μ, γ, Charged & Neutral Hadrons**
- **Used as building blocks for jets, τs, Missing E_T, lepton isolation**
- **Tags charged particles from pile-up**
- **Minimized Pileup Impact on jet reco., lepton & photon ID, isolation**
- ***Restored 2011 performance***

Photon Resolution in ECAL Barrel



σ_{eff} 1.1%

σ_{eff} 1.2%

(a) BDT> 0.88

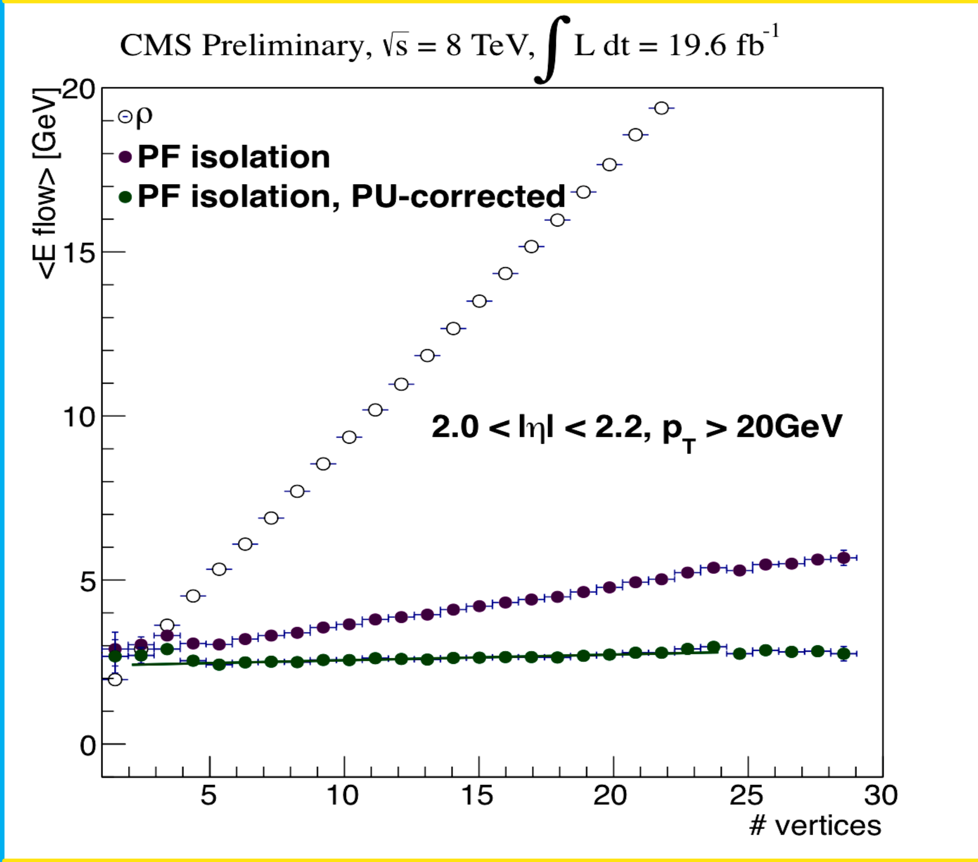
(b) 0.71 <BDT< 0.88

Using 8 TeV *Prompt Calibration*

Stability Against Pileup

Electron Isolation and Energy Scale

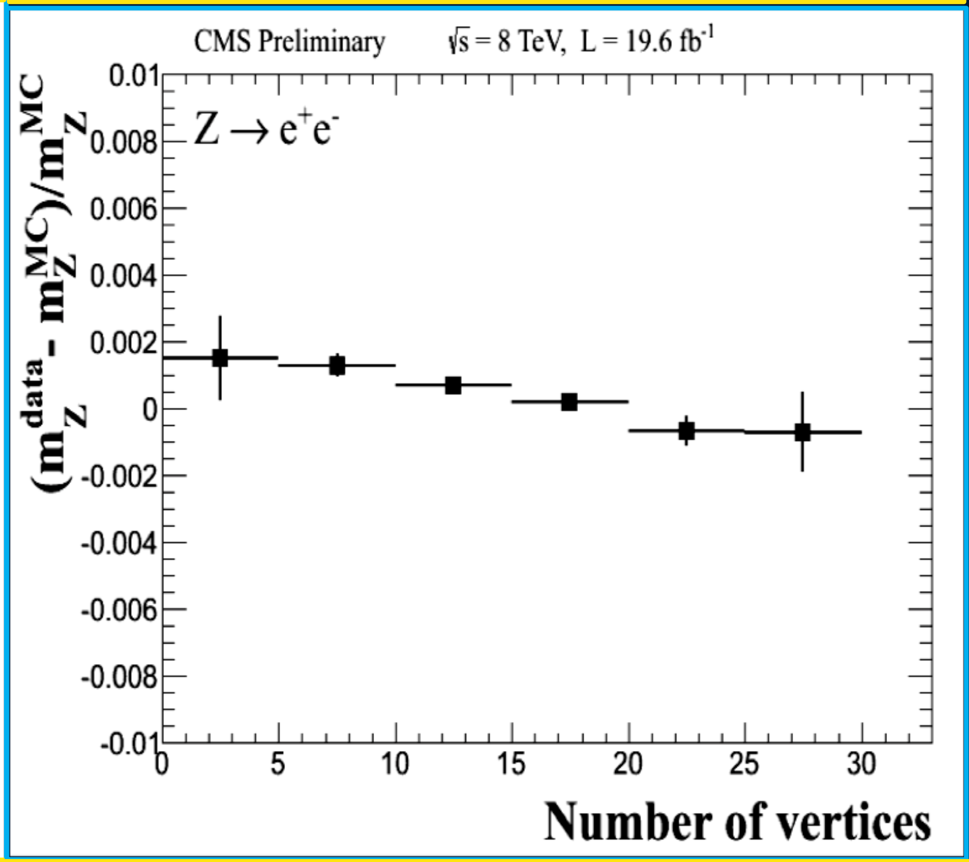
Electron isolation in data with $Z \rightarrow e^+e^-$ events



Charged: consistency with vertex

Neutrals: Average energy subtraction

Momentum scale in data with $Z \rightarrow e^+e^-$ events

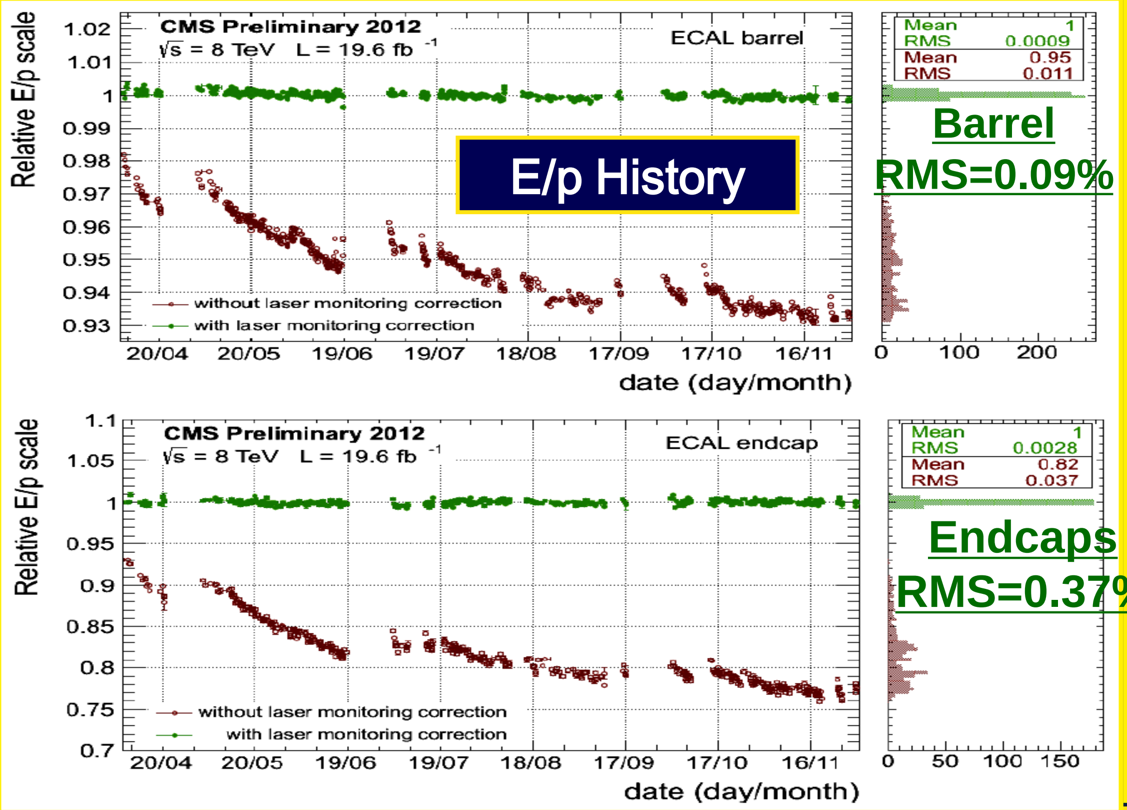


Effect within 0.2% in [0-30] reconstructed vertices in the event

Photon Energy Resolution

Comprehensive Monitoring and Calibration

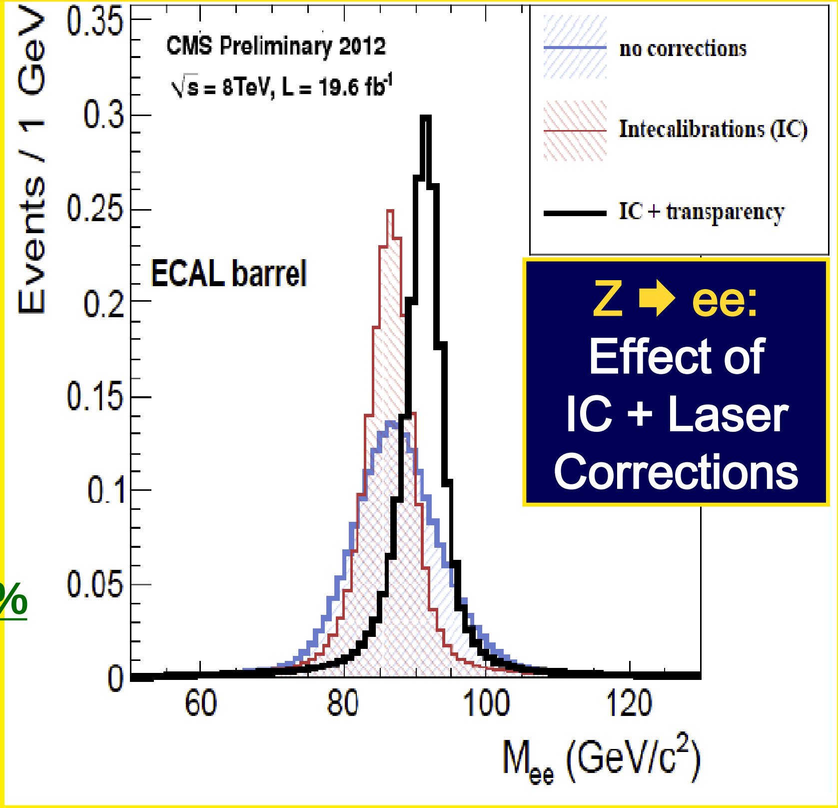
Laser runs every 40 minutes: crystal by crystal transparency corrections
With π^0,η Intercalibration + Z ➡ ee + W ➡ eν (E/p) scale corrections



E/p History

Barrel
RMS=0.09%

Endcaps
RMS=0.37%



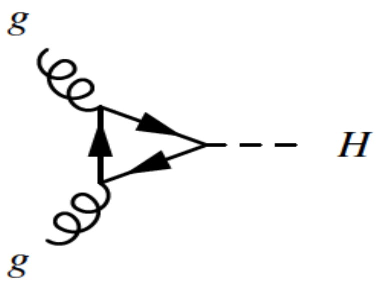
Z ➡ ee:
Effect of
IC + Laser
Corrections

<u>Excellent Stability with monitoring & calibration for 2012: 0.09 EB (0.37 EE) %</u>

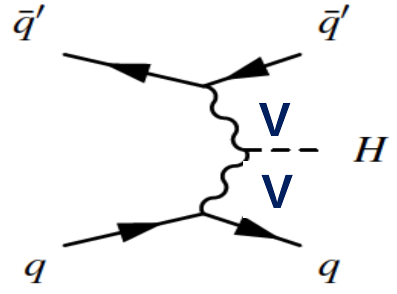
☞ Instrumental resolution: from Z → e+e- , W → eν with ECAL energies and electron track directions: 1% and Stable in ECAL Barrel

Higgs Production at the LHC

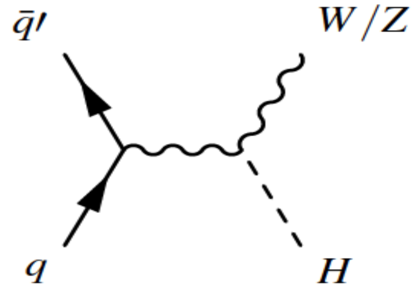
7-8 TeV pp CollIsions (8 TeV +25%)



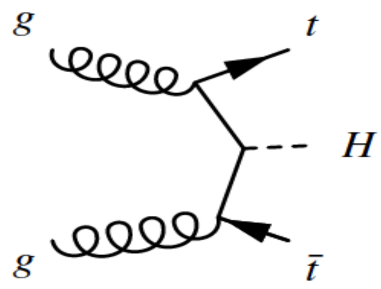
gg fusion gg→ H



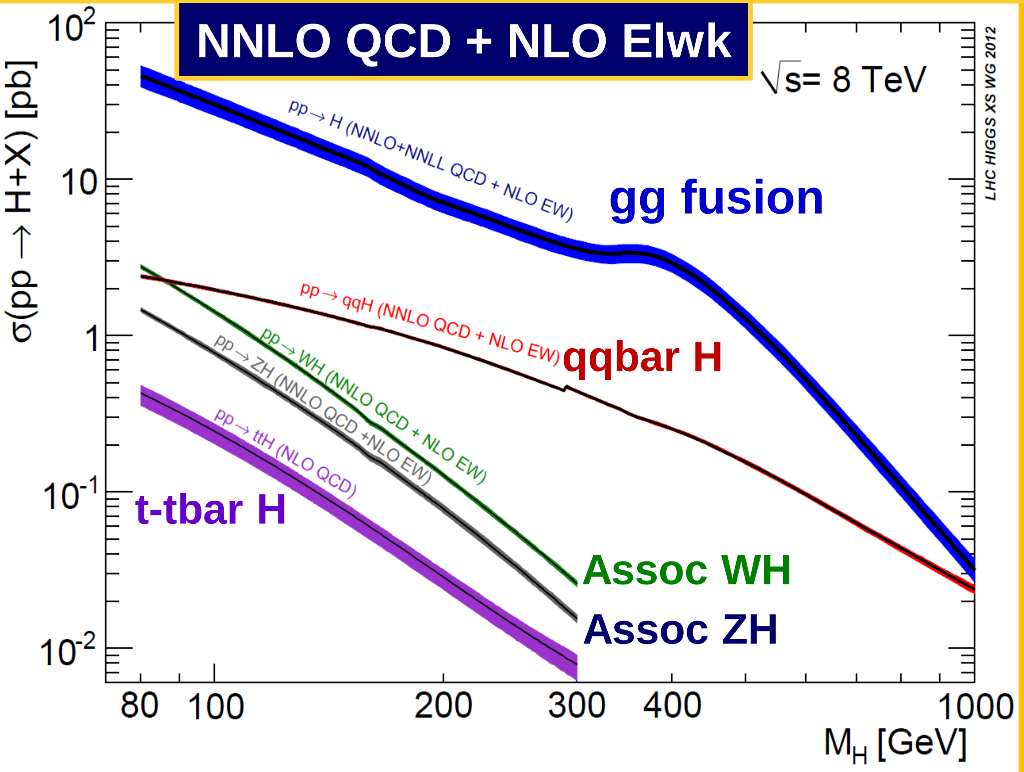
VB fusion (VBF)



Assoc Prod: WH, ZH



Assoc. Prod: t-tbar H



NNLO QCD + NLO Elwk

Dominant production at 125 GeV

gg→ H

Subdominant but with Larger S/B:

VBF: ~13X Less

WH + ZH: ~18X Less

ttH ~150X Less

CMS Higgs Search Channels

Updates on a New Boson

CMS-HIG-12-028 (HCP); 13-001 Through 009

Decay mode	Production tagging	No. of subchannels	m_H range (GeV)	Int. Lum. (fb^{-1})		m_H resolution
				7 TeV	8 TeV	
High Sensitivity ✸$\gamma\gamma$	untagged **Dijet, e, μ, MET**	4	110–150	5.1	**19.6**	**1-2%**
✸ZZ	untagged	**4l and *2l2τ***	**110-1000**	5.1	**19.6**	**1-2%**
✸WW	untagged dijet (VBF)	4 1 or 2	110–600	4.9	**19.5**	**20%**
$\tau\tau$	untagged dijet (VBF)	16 4	110–145	4.9	**19.4**	**15-20%**
bb	lepton, E_T^{miss} (VH)	10	110–135	5.0	**12**	**10%**

Other Modes Updated for *HCP* (11/12) and *Moriond* *(this month)*

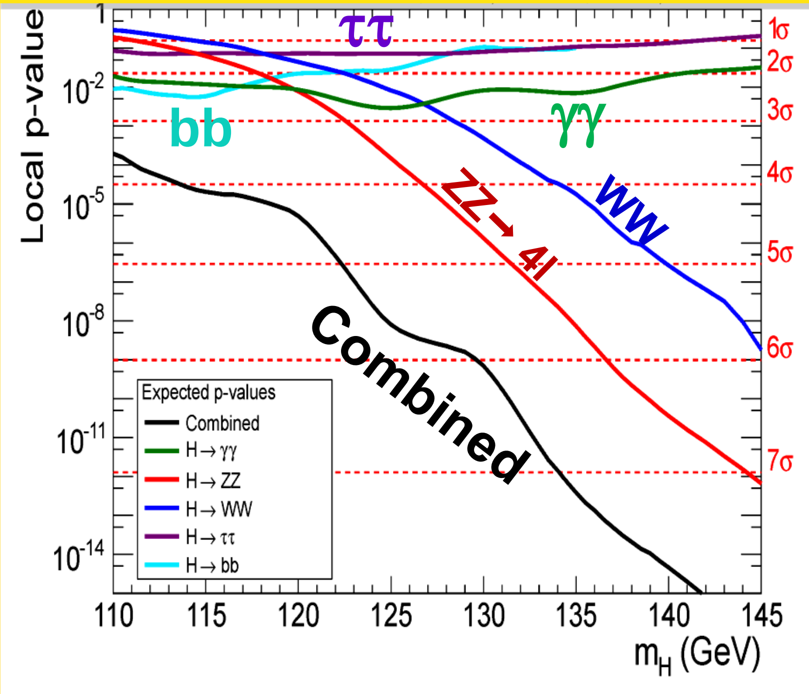
- ***New Updates (Low Mass):*** ***W/Z + H → WWW → 3l 3ν; H → Zγ***
- ***New Update (High Mass):*** ***H → ZZ →2l2τ (high sensitivity)***

High Mass Modes: ZZ → 2l 2ν; ZZ → qq′ 2l; WW → qq′ lν

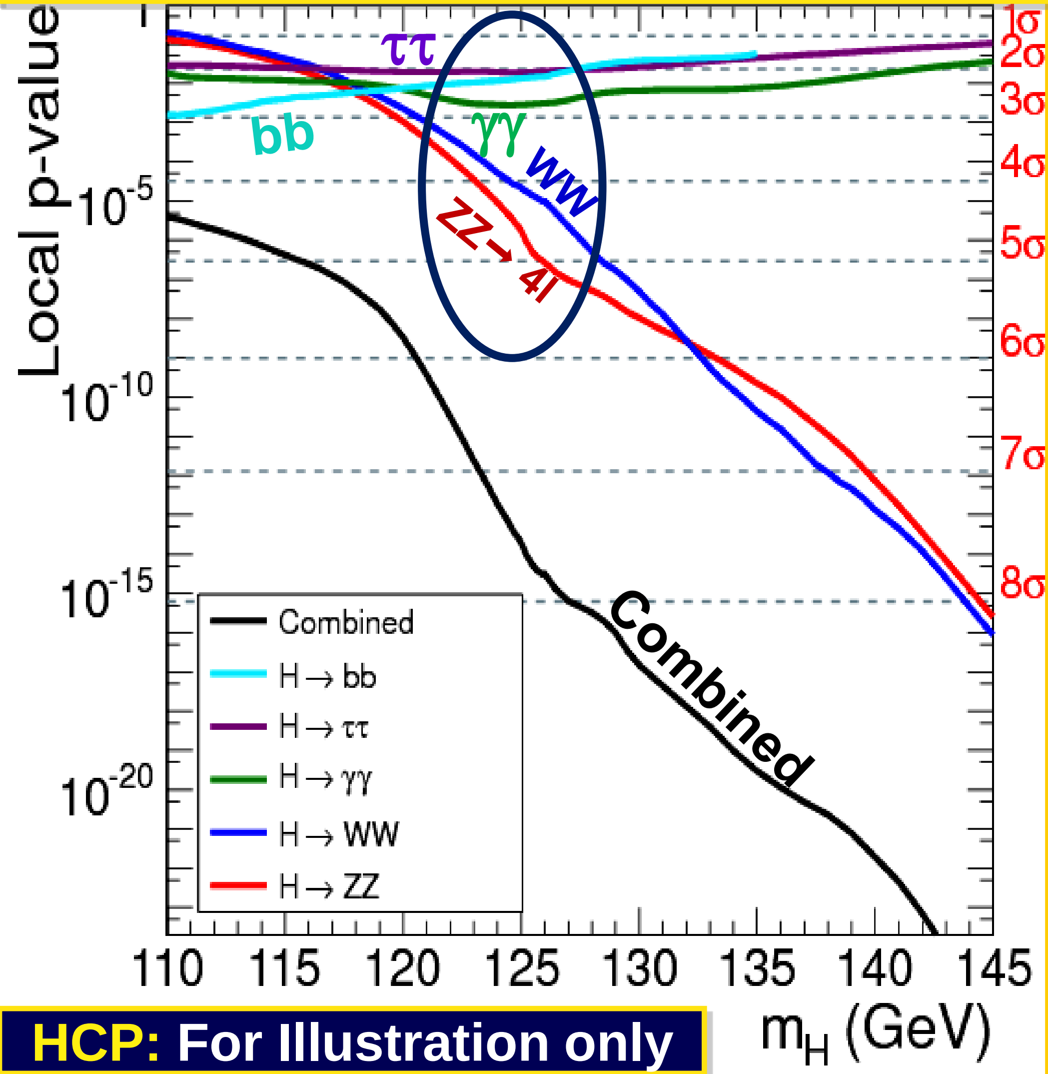
Other Low Mass Modes: WH + ZH → qq′ 2l 2ν

CMS Higgs Search Channels
Expected Sensitivity: p-values

ICHEP: 5 + 5 fb^{-1} at 7 and 8 TeV



HCP: 5 + 12 fb^{-1} at 7 and 8 TeV

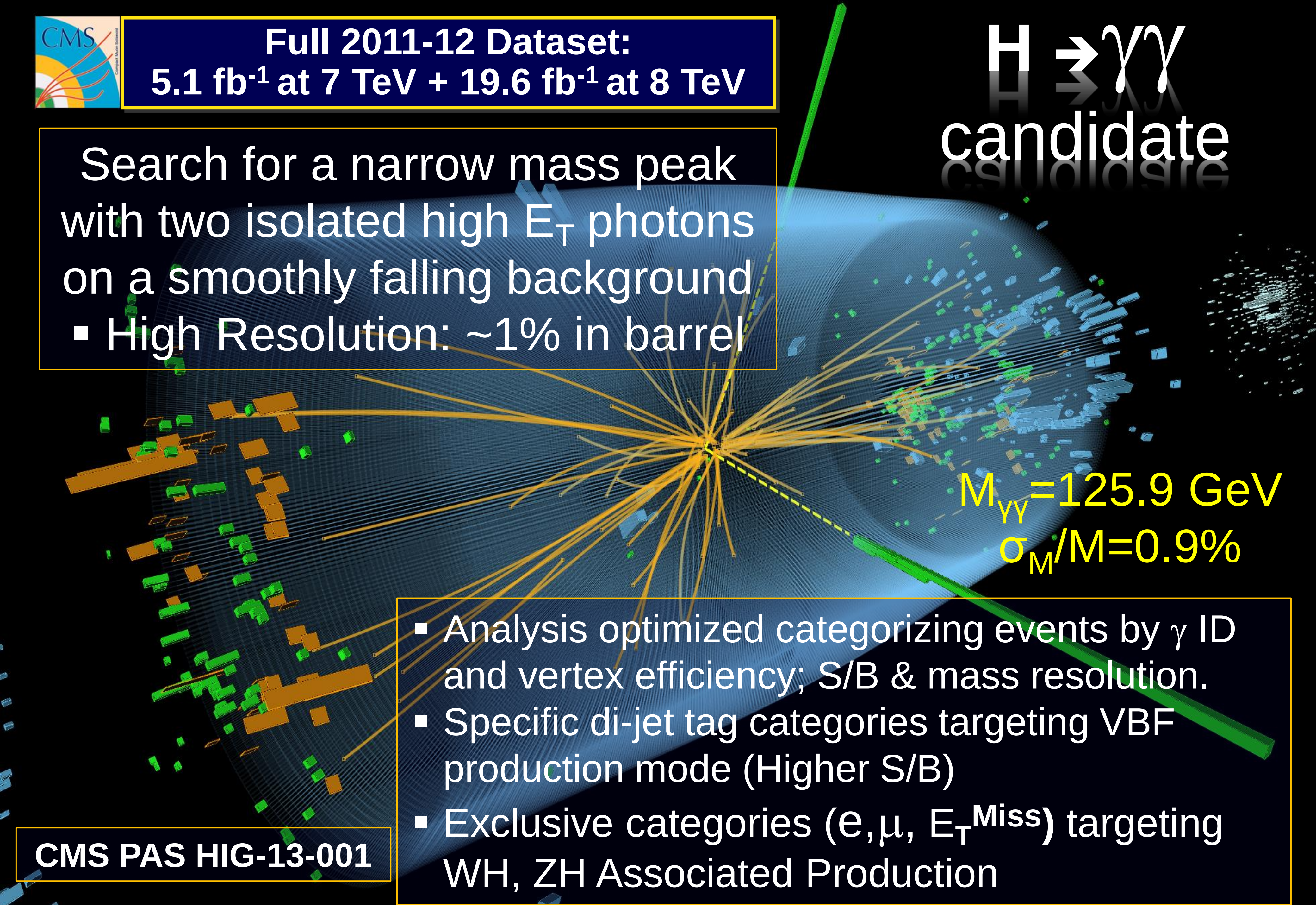


HCP: For Illustration only

ICHEP (July) to HCP (Nov.)

- Sensitivity Increase from 5.8 σ to 7.8 σ by HCP

Driven by ZZ (4l), WW, γγ; bb, ττ Important



Full 2011-12 Dataset:
5.1 fb^{-1} at 7 TeV + 19.6 fb^{-1} at 8 TeV

H → $\gamma\gamma$ candidate

Search for a narrow mass peak with two isolated high E$_T$ photons on a smoothly falling background

- High Resolution: ~1% in barrel

$M_{\gamma\gamma}$=125.9 GeV
σ_M/M=0.9%

- Analysis optimized categorizing events by γ ID and vertex efficiency; S/B & mass resolution.
- Specific di-jet tag categories targeting VBF production mode (Higher S/B)
- Exclusive categories (e,μ, E_T^{Miss}) targeting WH, ZH Associated Production

CMS PAS HIG-13-001

Di-jet Tagging

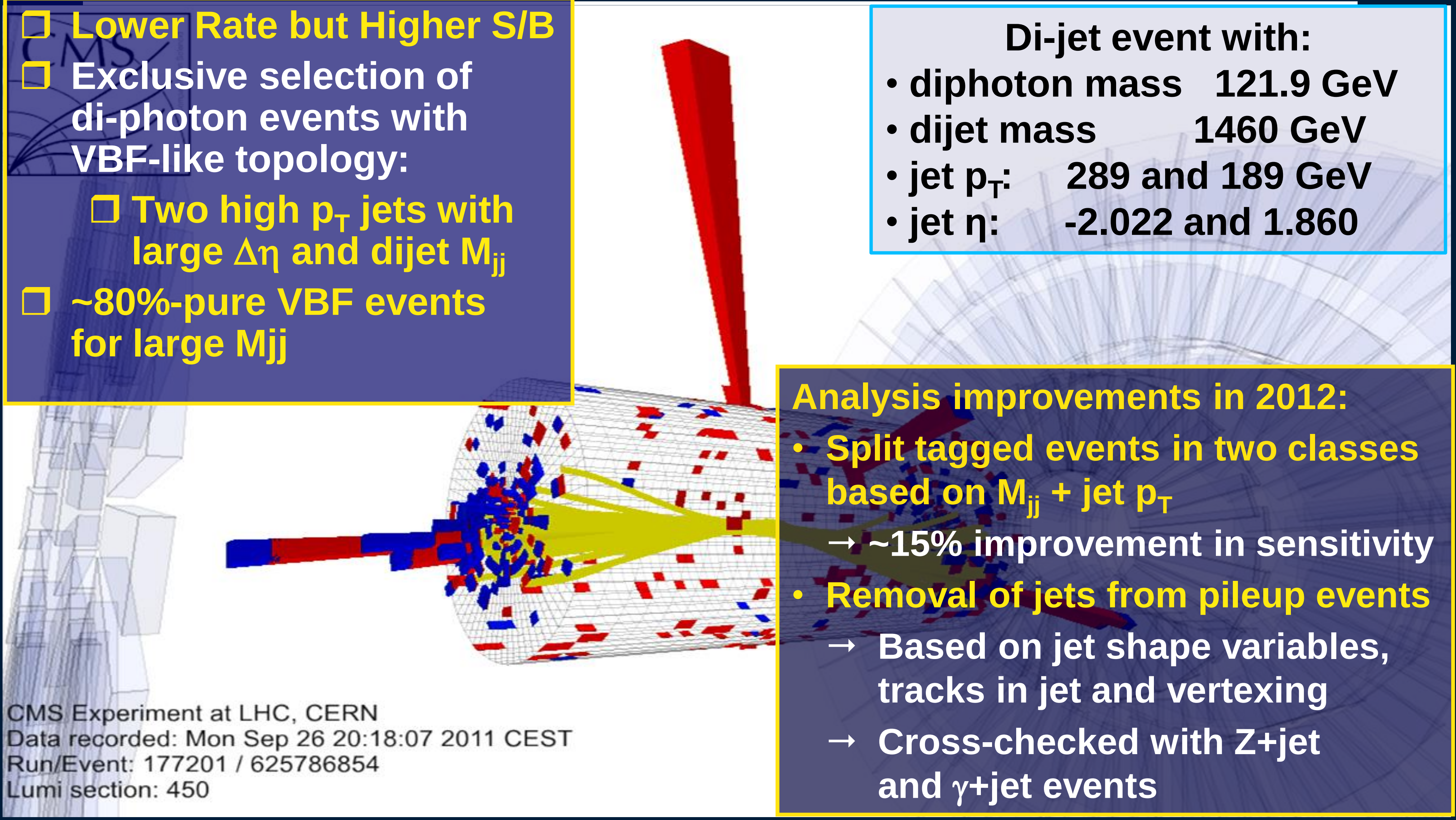
- ❒ Lower Rate but Higher S/B
- ❒ Exclusive selection of di-photon events with VBF-like topology:
  - ❒ Two high p_T jets with large $\Delta\eta$ and dijet M_{jj}
- ❒ ~80%-pure VBF events for large Mjj

Di-jet event with:

- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 289 and 189 GeV
- jet η: -2.022 and 1.860

Analysis improvements in 2012:

- Split tagged events in two classes based on M_{jj} + jet p_T
  - → ~15% improvement in sensitivity
- Removal of jets from pileup events
  - → Based on jet shape variables, tracks in jet and vertexing
  - → Cross-checked with Z+jet and γ+jet events



CMS Experiment at LHC, CERN
Data recorded: Mon Sep 26 20:18:07 2011 CEST
Run/Event: 177201 / 625786854
Lumi section: 450

$H \rightarrow \gamma\gamma$ Analysis Overview

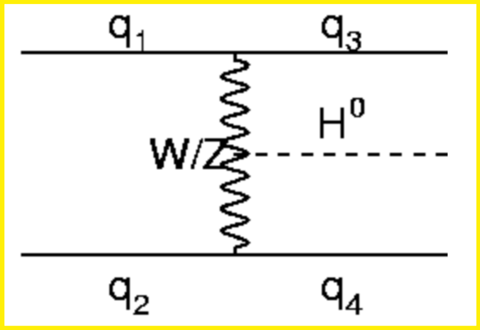
- **MVA Analysis: Fit to Diphoton mass $m_{\gamma\gamma}$ in event categories**
  - 4 event classes based on a Diphoton MVA output , 2 di-jet categories (VBF) + 3 Exclusive categories (VH,ttH): Electron, Muon, E_T^{Miss}
  - Diphoton MVA Score uses: Probability (correct vertex), per-event $m_{\gamma\gamma}$ resolution estimate, prompt photon ID score, + diphoton kinematics
- **Cross-checked with a cut based analysis**
  - **Simple and robust: photon ID & mass fit in categories**
    - 2 rapidity x 2 shower shape categories with different Signal/Background ratios; + 2 di-jet + 3 Exclusive Categories
- **Also cross-checked with alternative background model:**
    - **MVA combining diphoton ID and $m_{\gamma\gamma}$; fit data in mass sidebands to model background under the peak**
- **MVA analysis 15% more sensitive than cut-based analysis**

$H \rightarrow \gamma\gamma$ Exclusive Categories

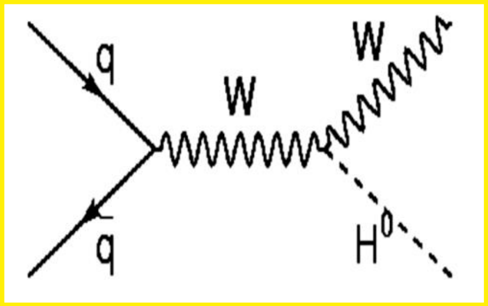
- In addition to the untagged categories, high S/B categories are defined using add'l objects in the event
  - **Di-jet:** 2 categories (loose/tight) with increasing VBF purity (loose ~50%, tight ~80%). MVA analysis uses a dijet BDT-based selection (validated using Z+jets events)
  - **VH:** Additional **Leptons** (electrons and muons with p_T>20 GeV) or **MET** (>70 GeV): lepton categories have negligible gg contamination, 20% for MET
- Significantly improves the sensitivity to measure the Higgs couplings
- Events are uniquely assigned to a category following the S/B ordering:

Muon Electron Dijet MET Untagged

VBF



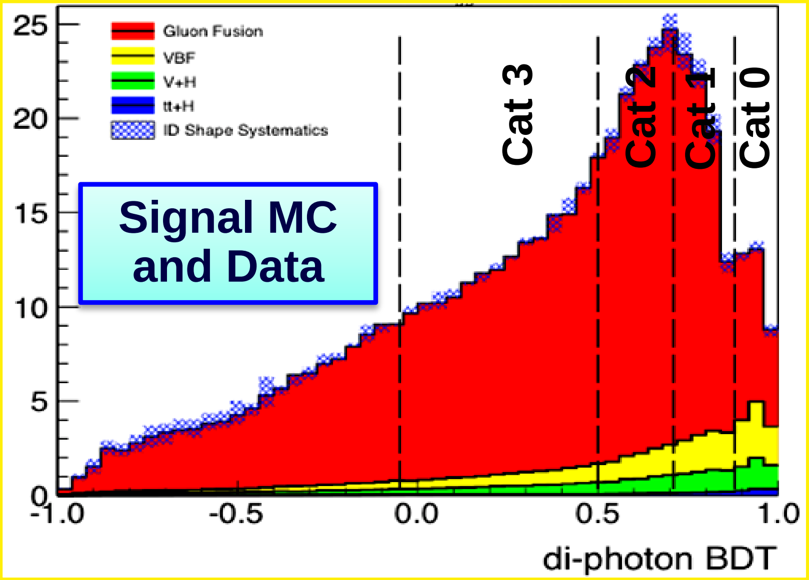
VH

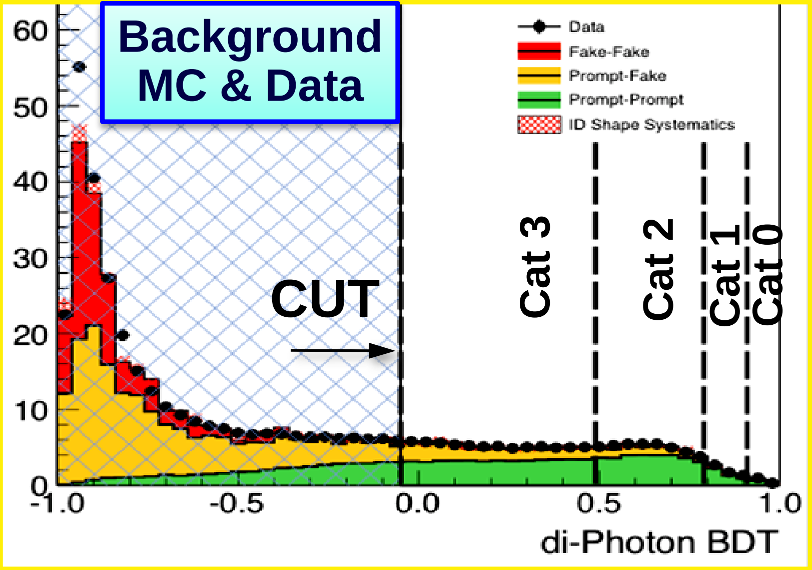


Diphoton MVA

Event Classification

- Encode all relevant information on S vs B (aside from $m_{\gamma\gamma}$ itself) into a single MVA diphoton discriminant, with input variables largely independent of $m_{\gamma\gamma}$
  - Photon ID MVA for each photon: based on isolation, shower shape, energy density per event
  - Kinematics and Topology: p_T and η of each photon, and cos $\Delta\phi$ between the two photons
  - Per-event mass resolution
  - Correct-vertex probability
- Validation of the inputs (photon ID, energy resolution): uses Z→ee, μμγ
- Validation of the output with Z→ee

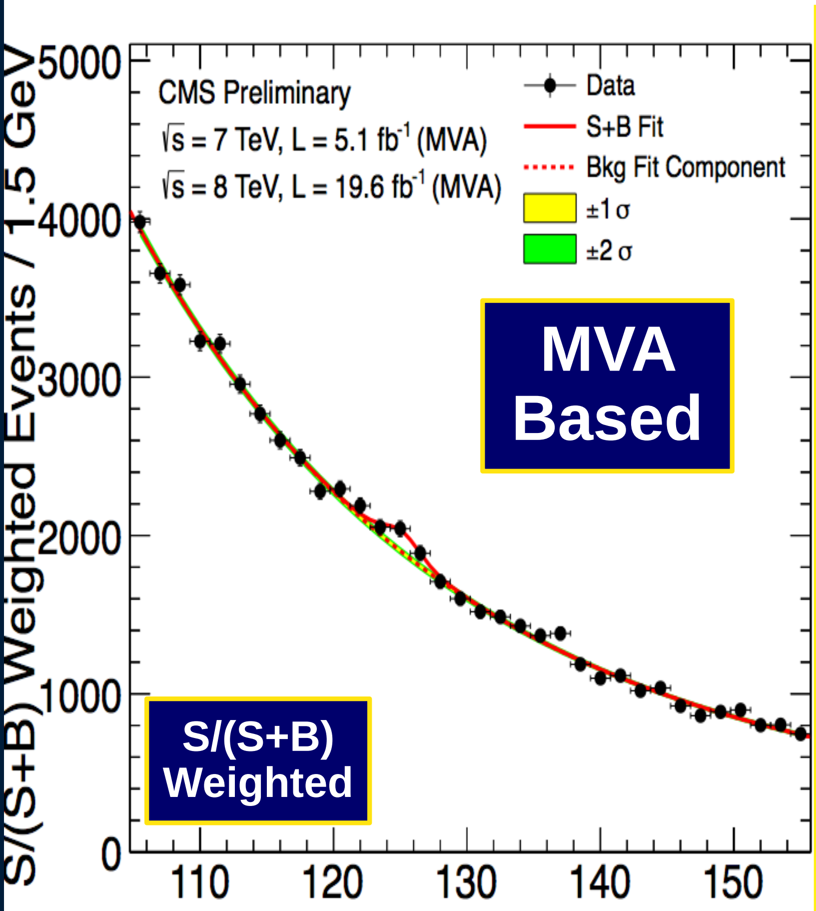




S/(S+B) Weighted Mass Distributions

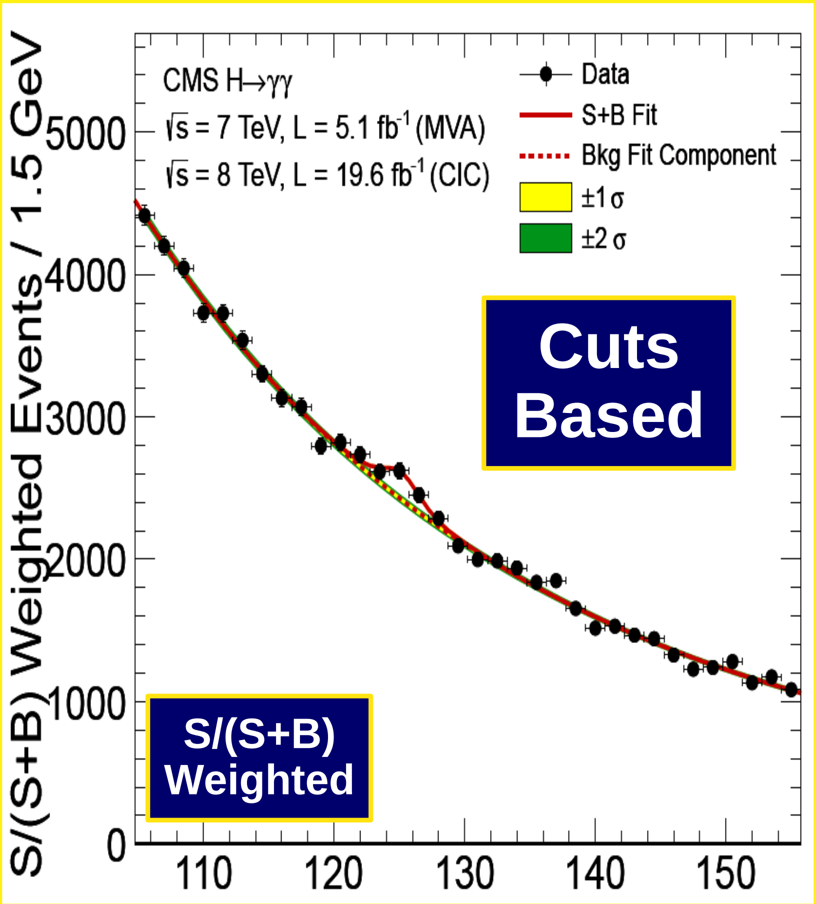
MVA and Cuts-Based Analysis Side by Side

- **Sum of mass distributions** for each event class, **weighted by S/(S+B)**
  - B is integral of background model over a constant signal fraction interval



MVA Based

S/(S+B) Weighted



Cuts Based

S/(S+B) Weighted

Weighting to Correctly Show S/(S+B)

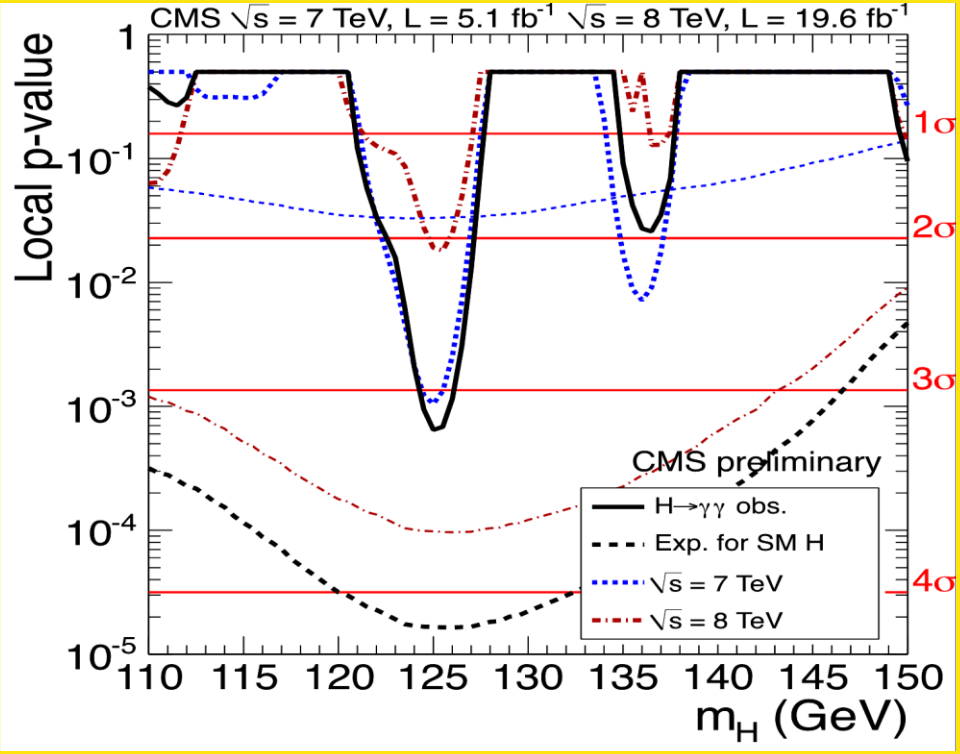
An illustration: Not used to derive the quantitative Results

R.J. Barlow, "Event Classification Using Weighting Methods", J. Comput. Phys. 72 (1987) 202

P-Values for SM Higgs

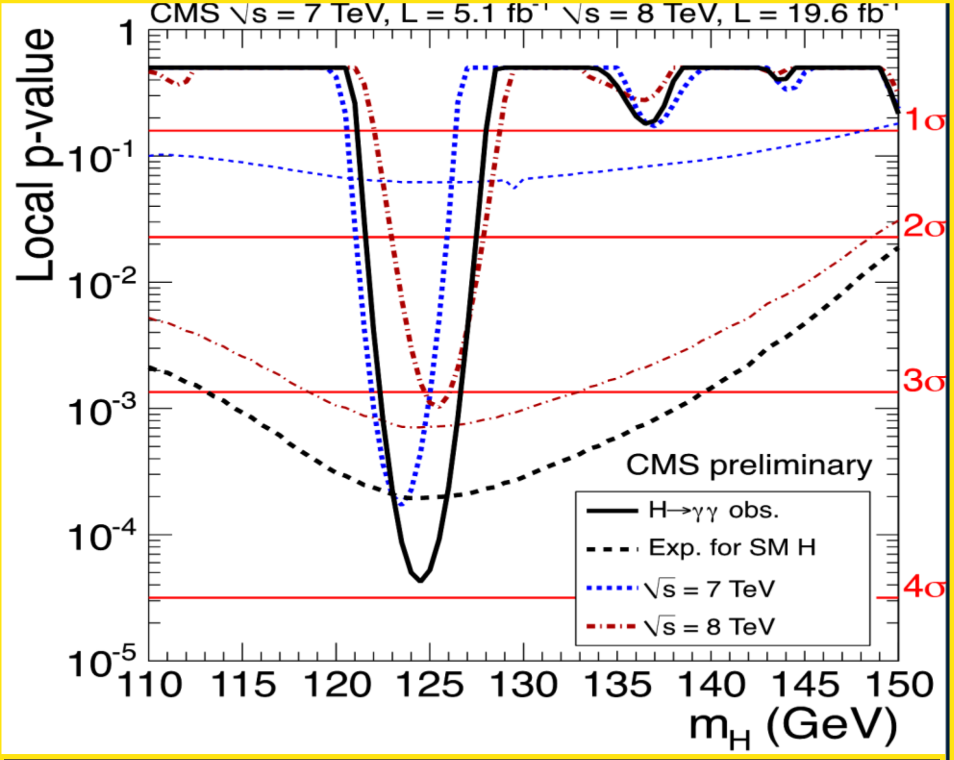
Full 7 + 8 TeV Dataset Side by Side

MVA Analysis



- **Minimum p-value at 125 GeV with local significance 3.2 σ**
  (Expected from SM Higgs: 4.2 σ)

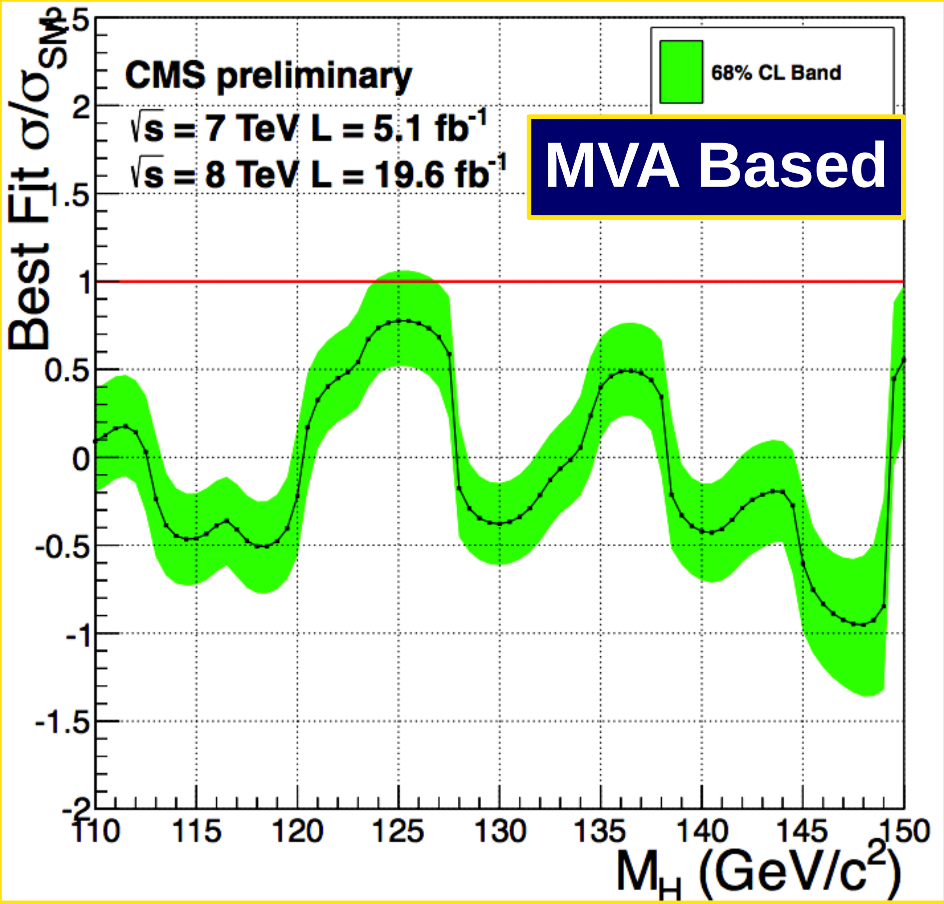
Cuts Based



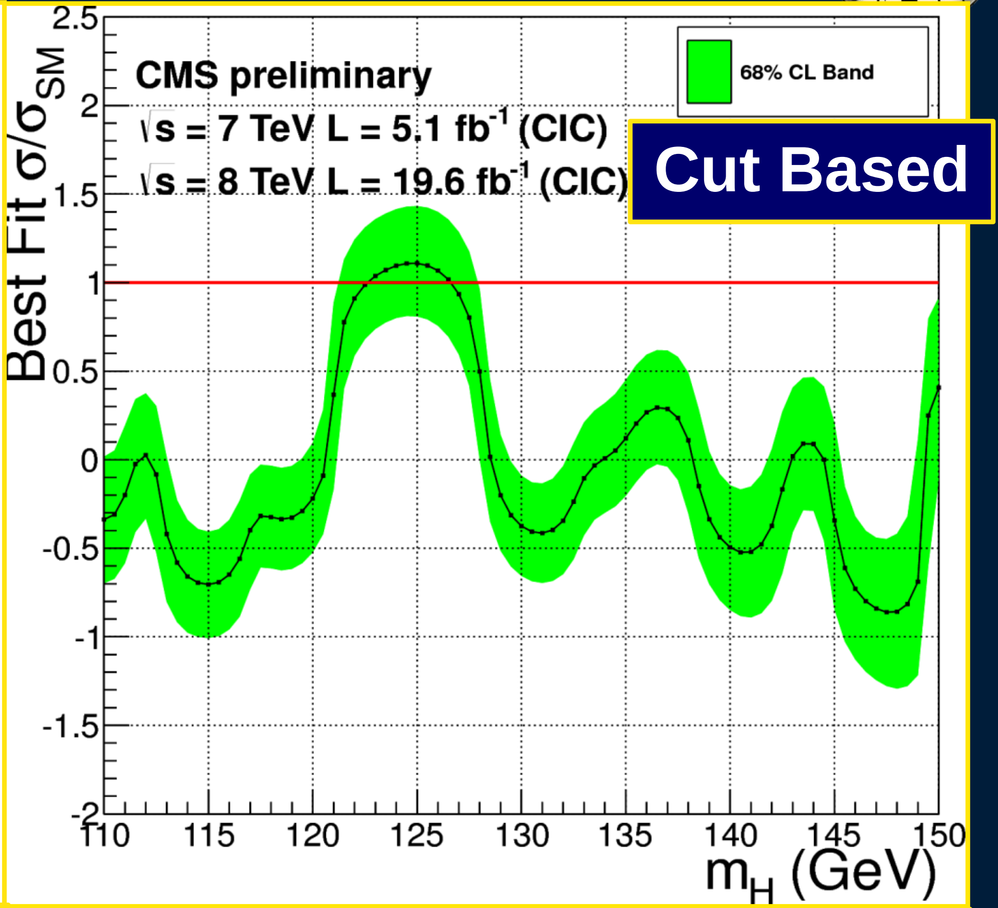
- **Minimum p-value at 124.5 GeV with local significance 3.9 σ**
  (Expected from SM Higgs: 3.5 σ)

Significance decreased a bit with more data and new analysis, compared to the published results

$H \rightarrow \gamma\gamma$ Fitted Signal Strength Vs M_H



MVA Based



Cut Based

Fitted Signal Strength

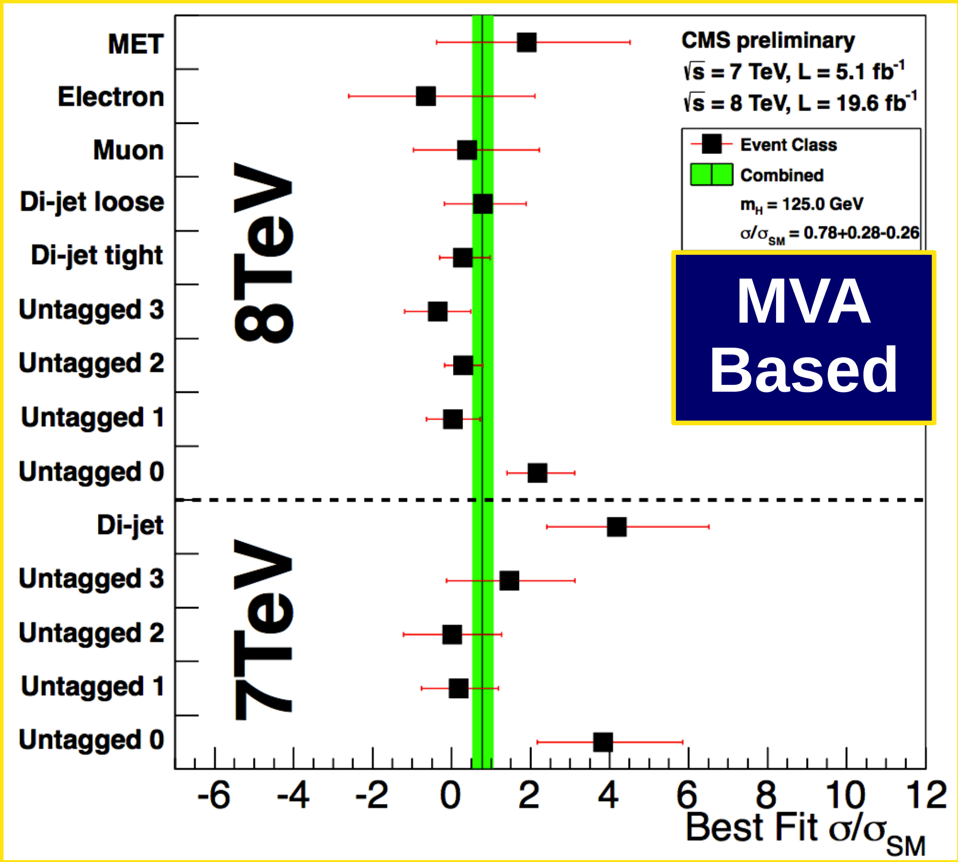
$\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$

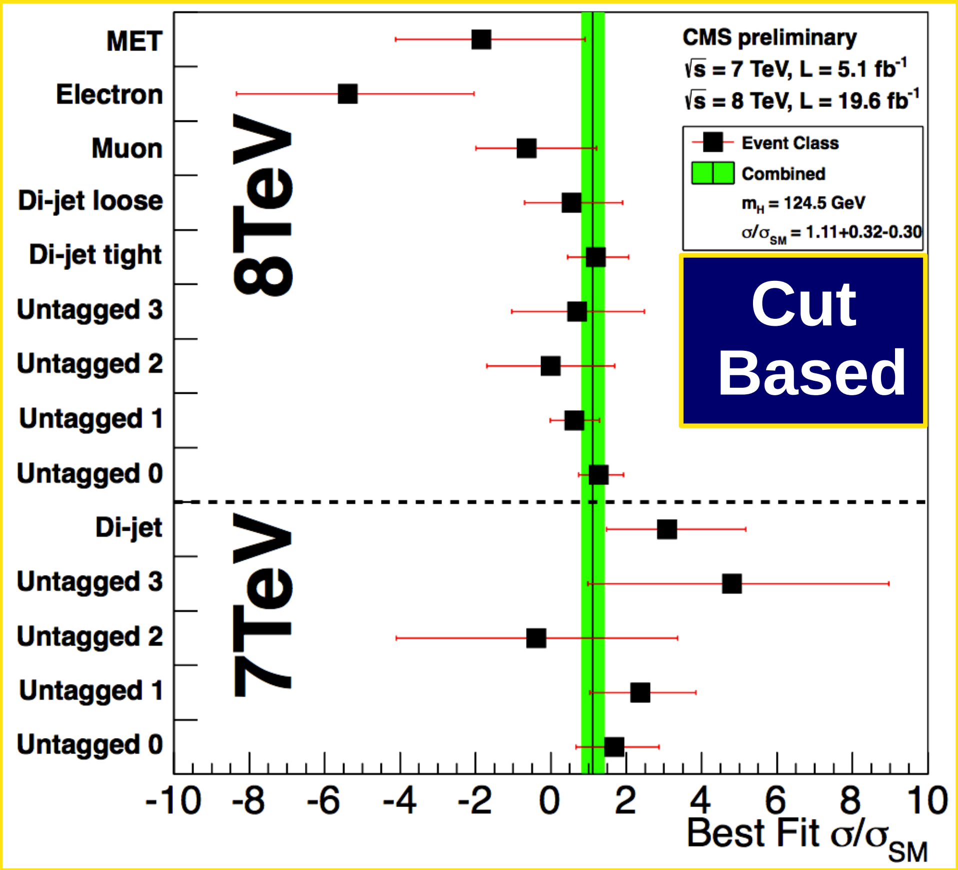
Fitted Signal Strength

$\sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$

Signal strength decreased a bit with more data and new analysis, compared to the published results

$H \rightarrow \gamma\gamma$ Best Fit Signal Strength
Compatibility Among the Classes

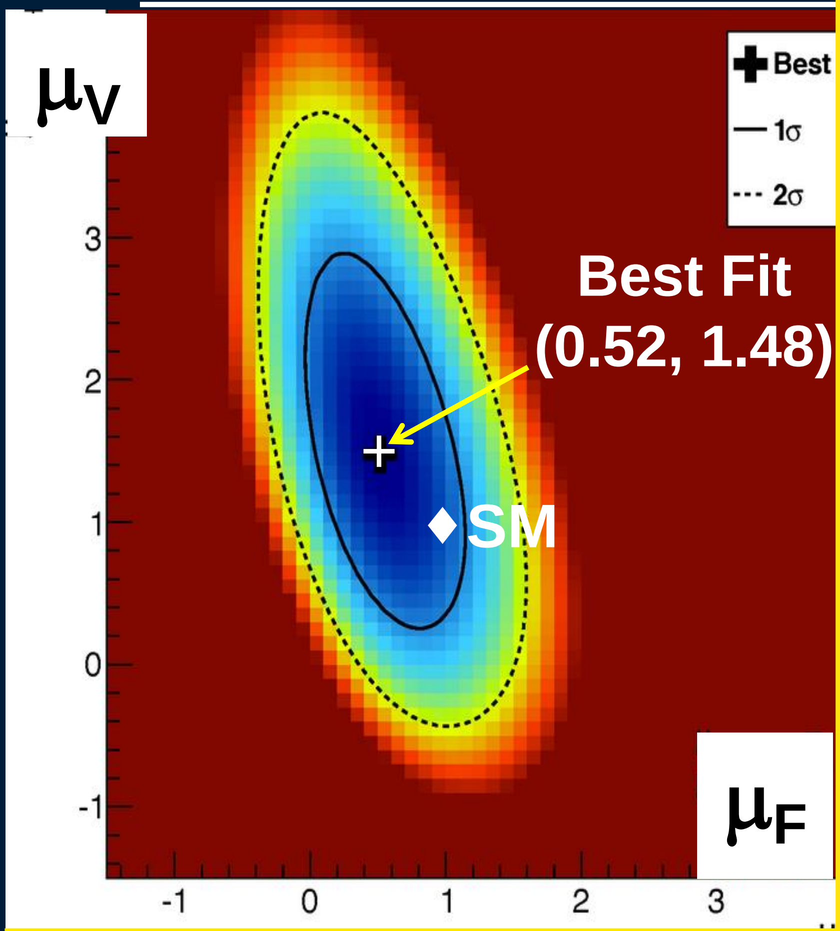




Best fit signal strength σ/σ_{SM} is consistent among different classes and with the SM, within errors

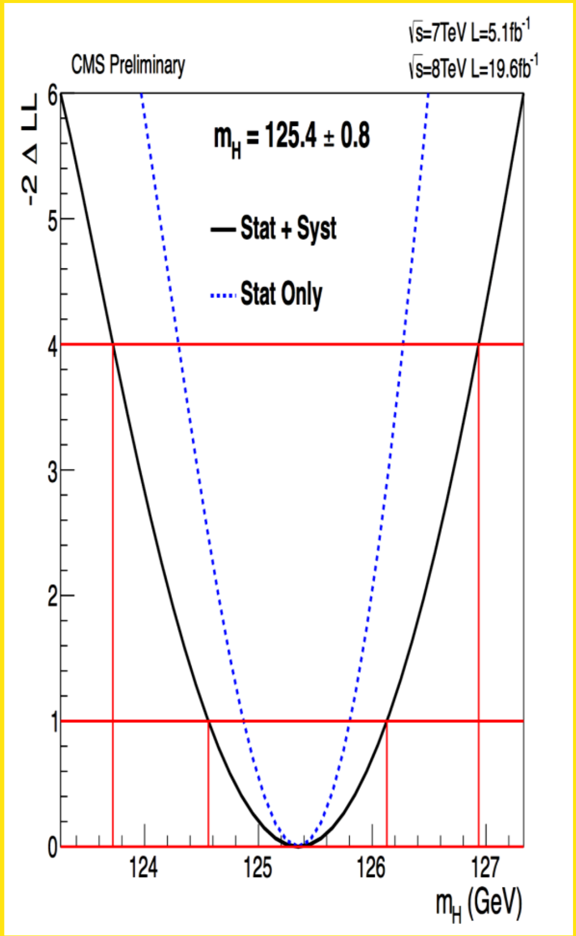
Note: in spite of the same names, untagged classes in the two analyses are different

H →γγ : Couplings μ_V (VBF+VH) vs μ_F (ggH+ttH) and Mass Determination



Best Fit (0.52, 1.48)

♦SM



Mass measured profiling μ_V, μ_F along with all other nuisances to reduce model dependence

Main Systematic: Energy Scale extrapolation from **M_Z to M_H ~125 GeV (0.47%)**

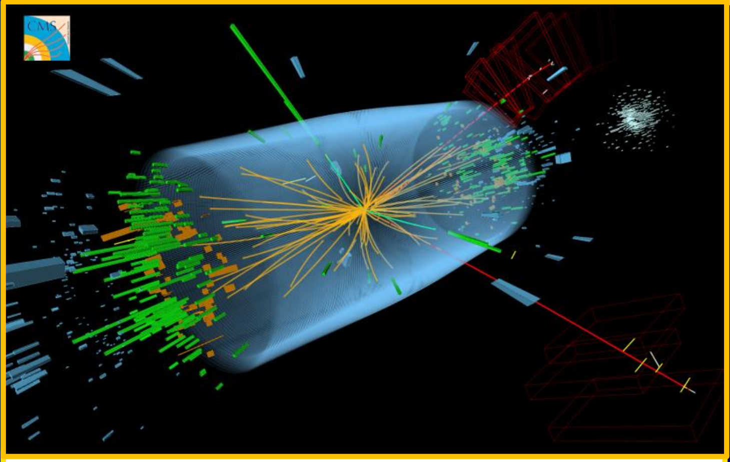
μ_V and μ_F are consistent, within 1 sigma, of SM prediction

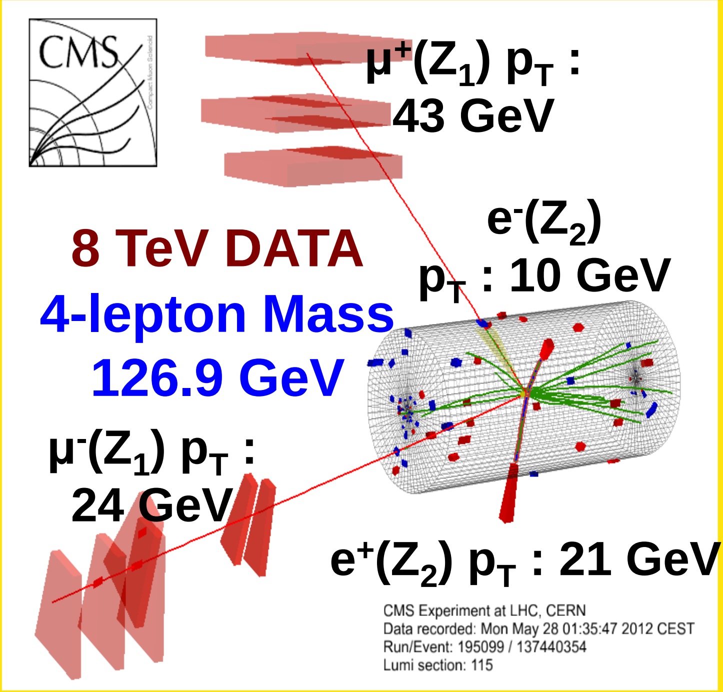
Best Fit: Mass = 125.4 GeV ± 0.5 (stat) ± 0.6 (syst.) GeV

H → ZZ(*) →4ℓ, 2ℓ2τ (ℓ = e,μ)

The Golden Channels

CMS HIG-13-002





CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

- **Signal:** 4 isolated lepton-pairs (SF, OS) from a common vtx; peak over small continuum BG
- **Fully reconstructed, Mass resolution ~ 1-2%**
- Kinematic info.➡ ideal for properties tests
- **Selection:** Same flavor, opposite charge pairs
  - Z_1: P_T^{min} (e) > 7, P_T^{min} (μ) >5, 40 < M_{ll} <120 GeV
  - Z_2: *12* < M_{ll}< 120 GeV
  - 3D IP to vtx < 4σ
  - Z p_T Thresholds; **Special selections for ττ**
- **Reducible Backgrounds:**
  - **t-tbar → 2l 2ν 2b ; Z + bb**: Removed by Isolation & Impact parameter requirements
- **Irreducible background: pp → ZZ Continuum**
  - Rate obtained from Z yield in data, + theory prediction for ratio of ZZ to Z cross sections
  - **BG shape corrected to NLO** w/ MCFM

H → ZZ(*) → 4 Leptons

Analysis Improvements in 2012-13

Improvements in 2012 (I)

Up to HCP:

- New lepton selection, extending the p_T range
- Muon reconstruction
- Recovery of photons from final state radiation

📪 Blind low mass “signal” region.

✓ Kinematic Discriminant Exploit angular information to discriminate signal from irreducible ZZ background

- ~20% gain in sensitivity with respect to 2011 analysis

✓ *Pure Scalar 0+ compared, favored over pure 0-*

Improvements in 2012 (II)

Since HCP:

📪 In 2l 2τ events: Constrain ττ mass to the nominal Z mass;

τ isolation requirements retuned

📪 Dijet categories: gg➡ H + 2Jets Also search for VBF

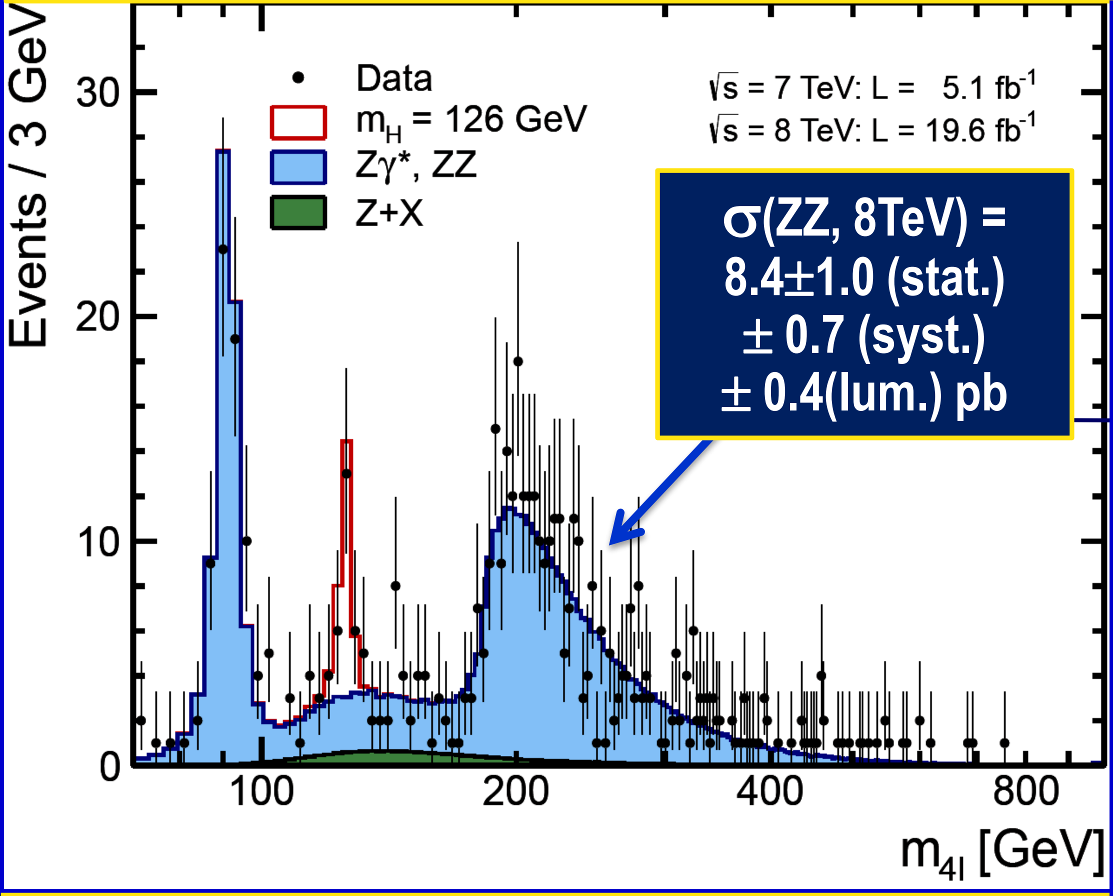
📪 Improved K_D: take interference among identical leptons fully into account

📪 Compare pure 0^+ hypothesis to more alternative J^P hypotheses

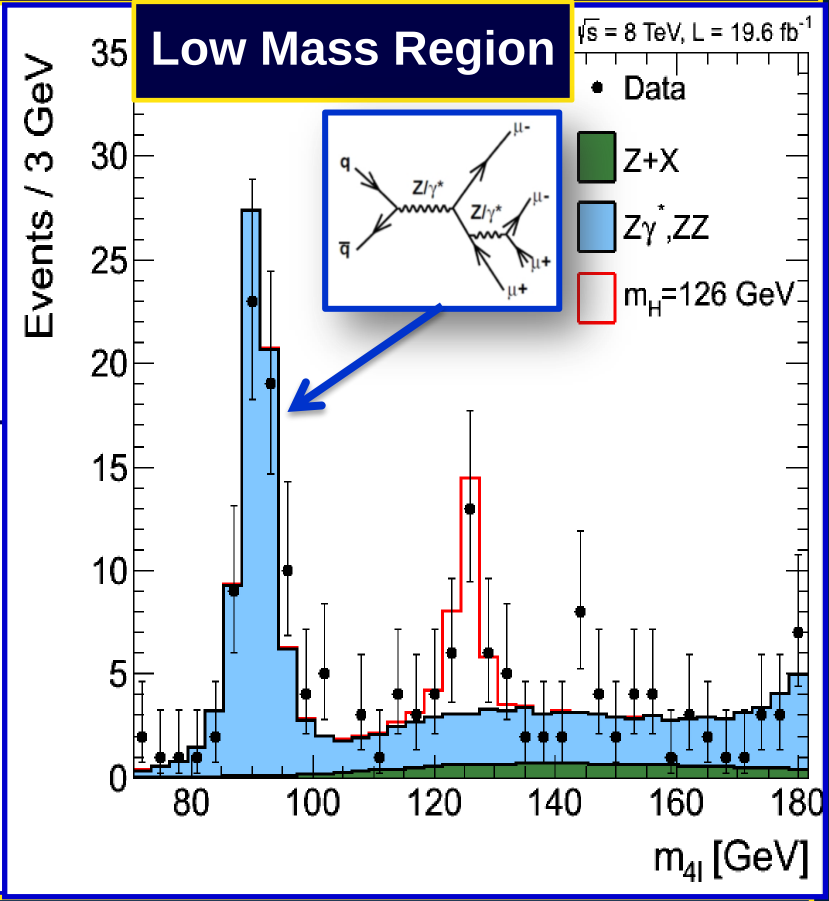
H ➡ ZZ(*) ➡ 4e, 4μ, 2e2μ Candidates

Mass Spectrum

Good description of Z →4L Peak, and ZZ continuum



σ(ZZ, 8TeV) = 8.4±1.0 (stat.) ± 0.7 (syst.) ± 0.4(lum.) pb



Low Mass Region

Clear Signal Peak Near 126 GeV

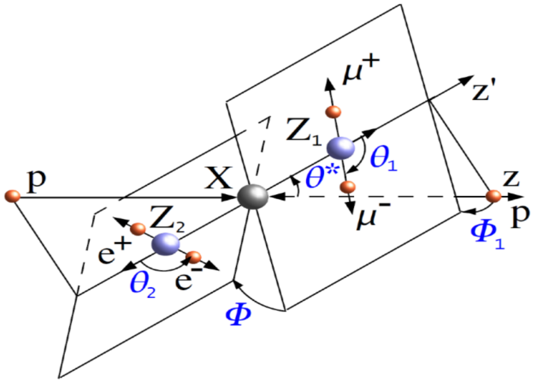
Z ➡4l Peak Provides Cross Check

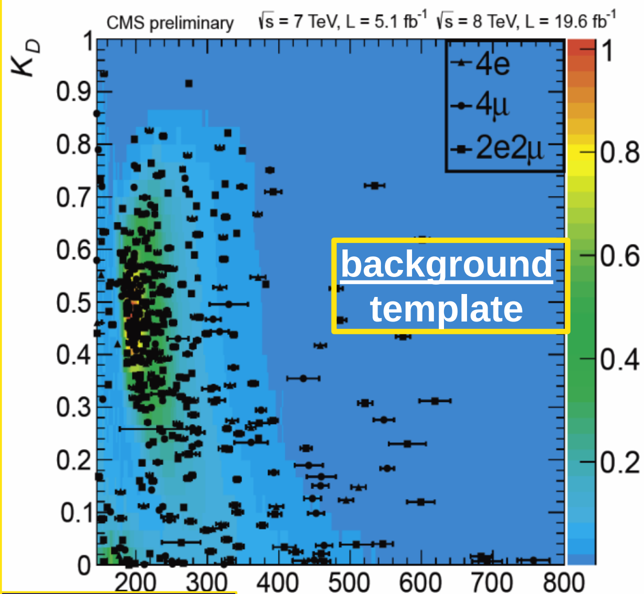
H → ZZ(*) → 4 Leptons

K_D: Matrix Element Kinematic Discriminant

To further improve S vs. B separation,
construct a discriminant based on the kinematic information (angles and masses)

$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + c \times \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{c \times \mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

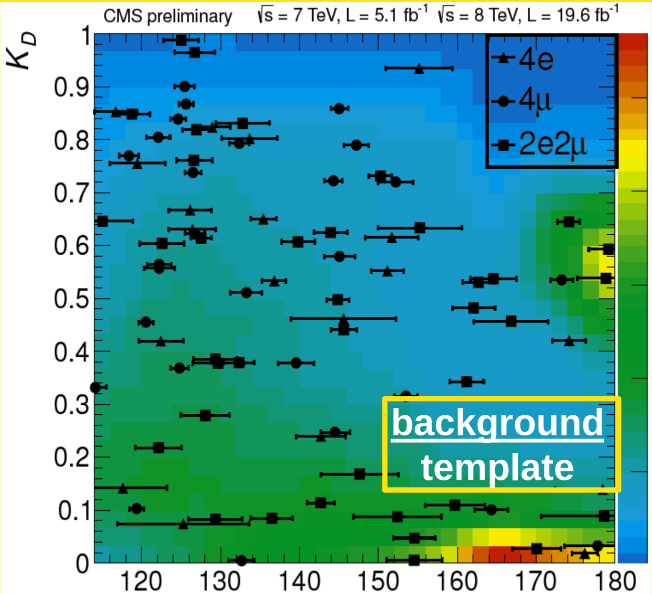




background template

K_D Vs M_{4l}

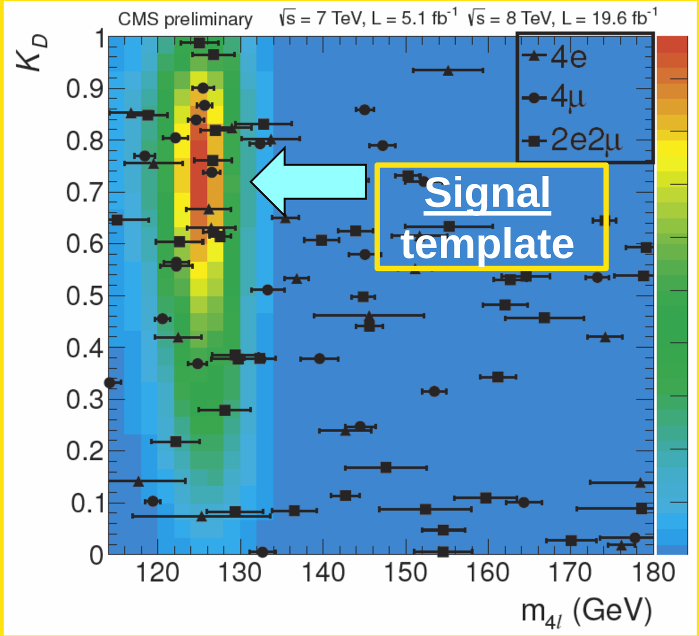
High mass data w/error bars
Superimposed on background



background template

K_D Vs M_{4l}

Low mass data with error bars
Superimposed on background



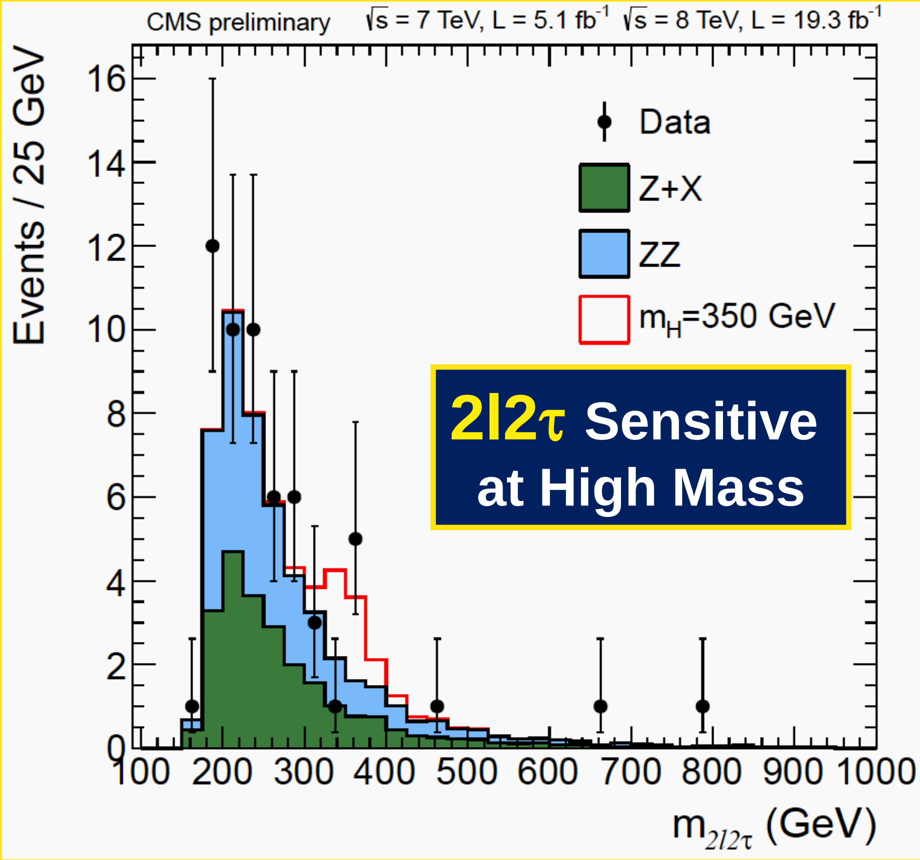
Signal template

Low mass data: ***Signal-like clustering near 126 GeV***

H → ZZ → 4l and 2l2τ (New)

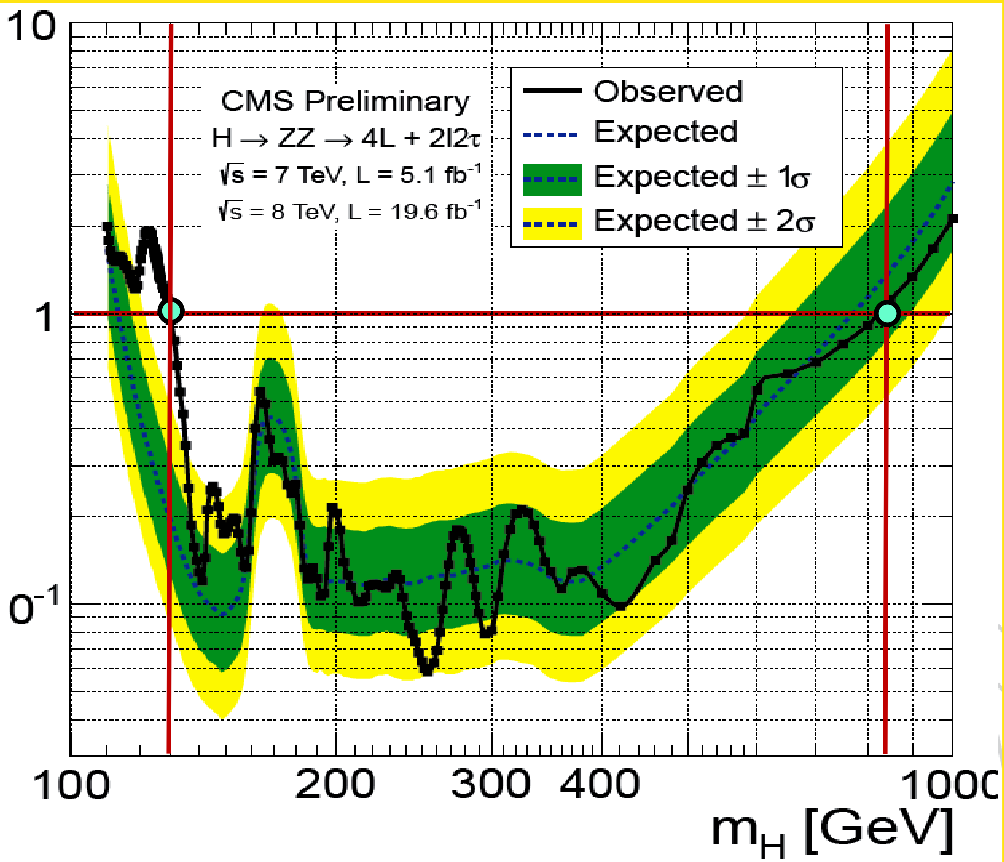
M (2l2τ) and Upper Limits Over the Full Range

M(2l2τ): No Excess at High Mass



2l2τ Sensitive at High Mass

95% CL on σ/σ_{SM}



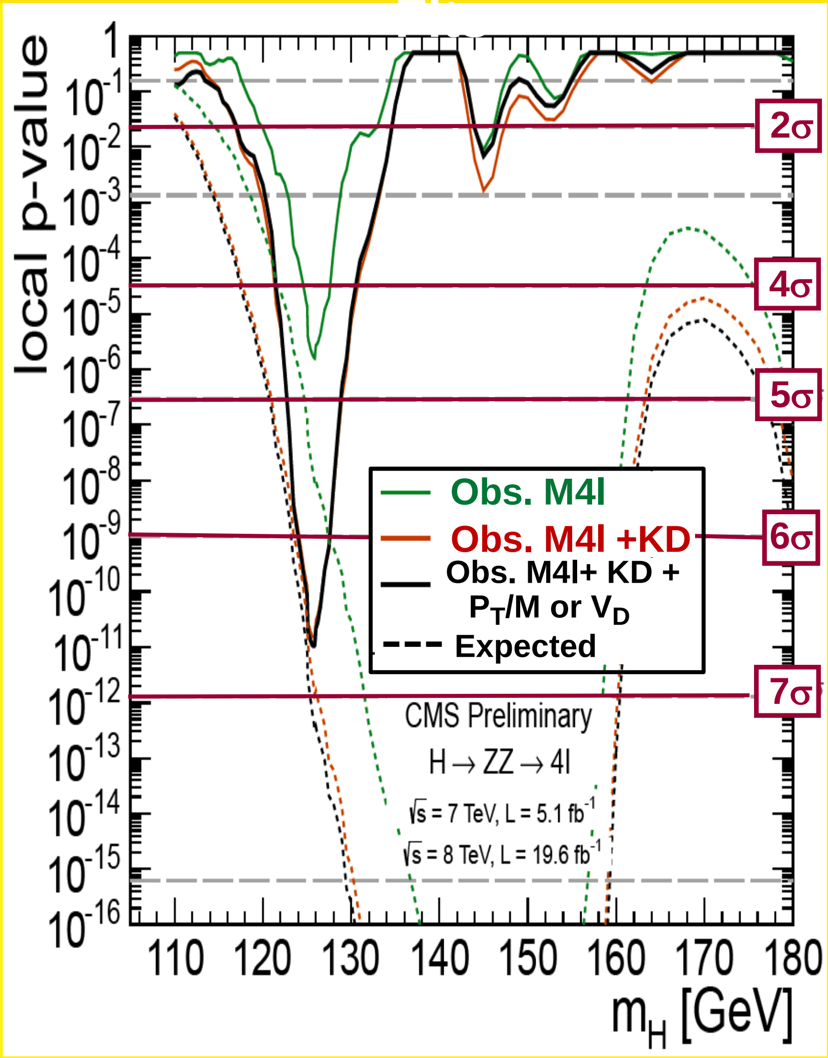
SM Higgs is excluded at 95% CL in the range 130 – 827 GeV

Expected exclusion 130 – 778 GeV

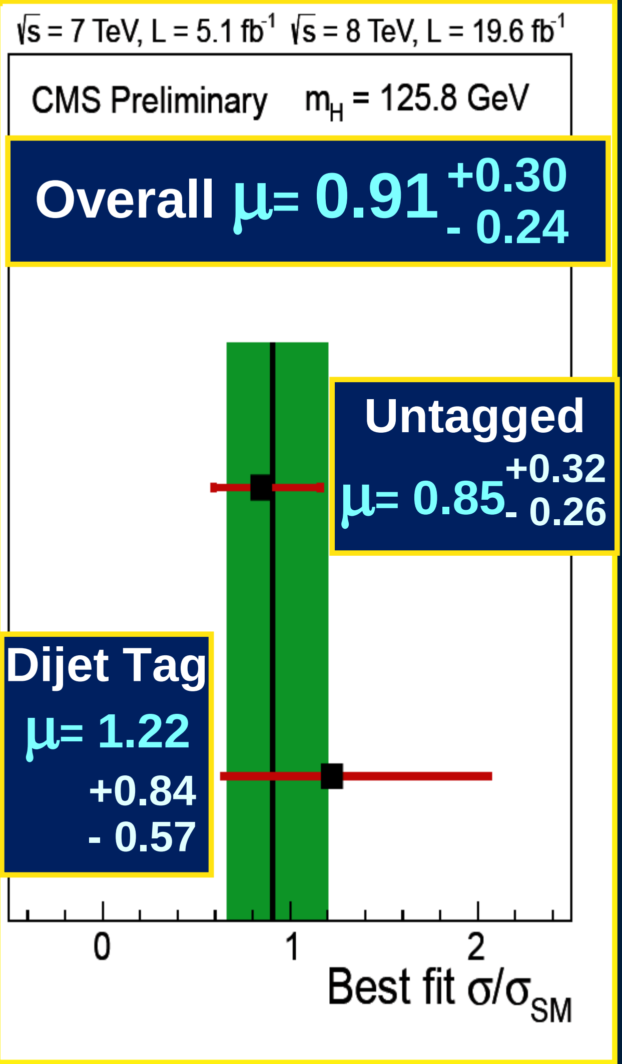
H → ZZ(*) → 4l Results

P-values (1D, 2D, 3D best fits) and signal strength

P Values (in σ) from 1D, 2D, 3D



Best Fit $\mu = \sigma/\sigma_{SM}$



Overall $\mu = 0.91^{+0.30}_{-0.24}$

Untagged

$\mu = 0.85^{+0.32}_{-0.26}$

Dijet Tag

$\mu = 1.22$ $^{+0.84}_{-0.57}$

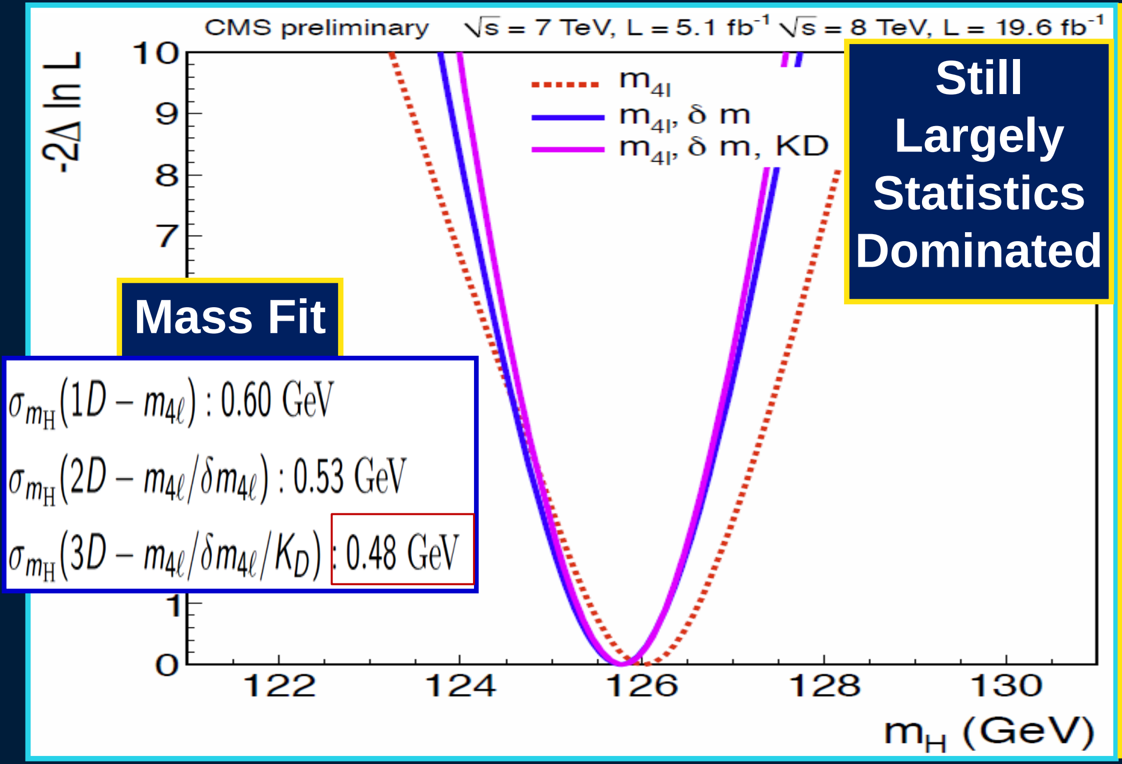
- 1D, 2D, 3D Fits: M_{4l}, K_D and P_T/M; or V_D for the dijet channel
- 3D Fit Significance 6.7σ at 126 GeV (expect 7.2σ for SM H)

  ➡ >5σ from this channel alone
- 2D Fit: 6.6σ (expect 6.9σ)
- 1D Fit: 4.7σ (expect 5.6σ)

$H \rightarrow ZZ \rightarrow 4l$

Mass Fit and Coupling Factors μ_V and μ_F

1. 3D Fit (M_{4l}, K_D, δM_{4l}) for mass: M = 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV
2. Momentum Scale, Resolution: Studied & tuned in dilepton control samples
3. In Dijet category: P_T spectrum, V_D : used to disentangle prod. Mechanisms: Scale factors for Couplings to Vector Bosons μ_V (from VBF, ZH, WH) and to Fermions μ_F (from gg via quark loops, ttH)



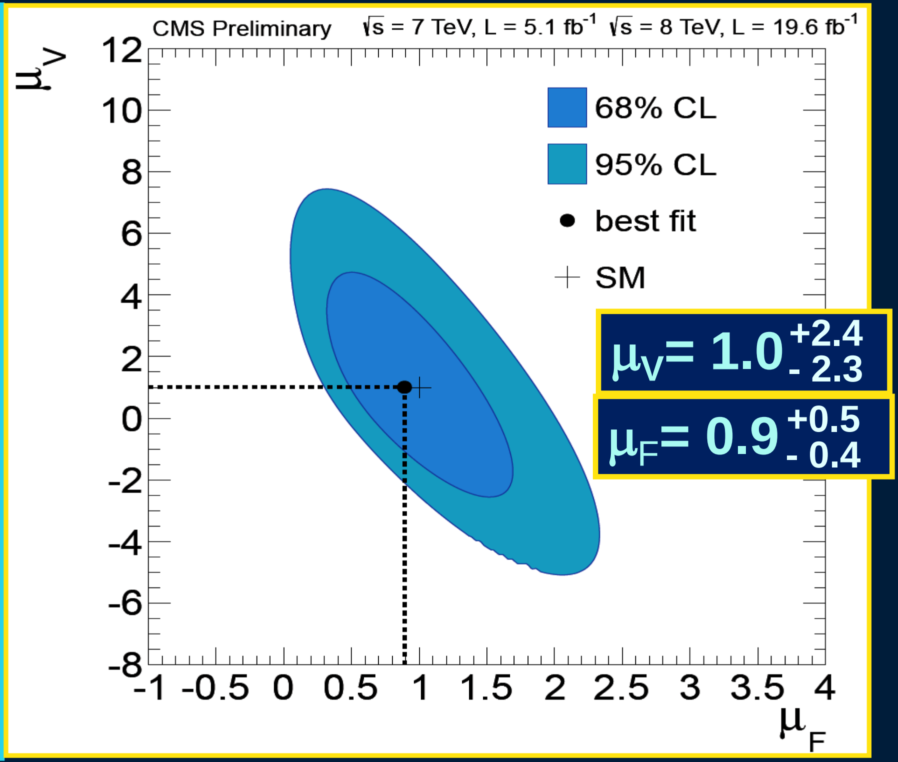
Still Largely Statistics Dominated

Mass Fit

$\sigma_{m_H}(1D - m_{4\ell})$: 0.60 GeV

$\sigma_{m_H}(2D - m_{4\ell}/\delta m_{4\ell})$: 0.53 GeV

$\sigma_{m_H}(3D - m_{4\ell}/\delta m_{4\ell}/K_D)$: 0.48 GeV



$\mu_V = 1.0^{+2.4}_{-2.3}$

$\mu_F = 0.9^{+0.5}_{-0.4}$

$H \rightarrow ZZ \rightarrow 4l$

Spin and Parity Measurements

- We know it is a boson, not Spin 1, not 100% 0- [PRL 110 081803 (2013)]
- To go further: build two discriminants based on the complete LO ME's

1. D_{bkg} to separate Signal from Background, combined with mass info.

$$D_{\mathrm{BKG}} = \left[1 + c_{\mathrm{bkg}} \cdot \frac{|\mathcal{M}_{\mathrm{BKG}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{BKG})}{|\mathcal{M}_{\mathrm{Higgs}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{Higgs})}\right]^{-1}$$

2. D_{JP} to Separate an SM Higgs from alternative J^P hypotheses

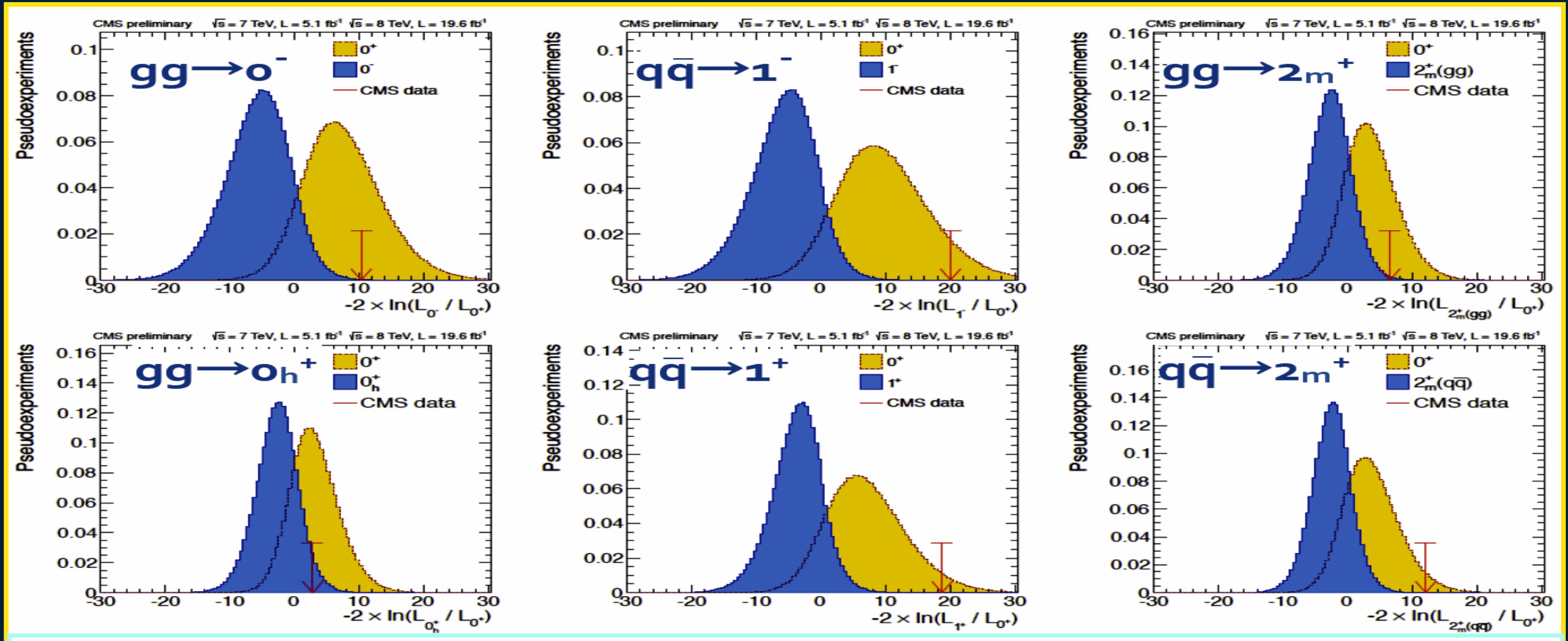
$$D_{\mathrm{J^P}} = \left[1 + c_{\mathrm{J^P}} \cdot \frac{|\mathcal{M}_{\mathrm{J^P}}(\vec{p}_i)|^2}{|\mathcal{M}_{\mathrm{Higgs}}(\vec{p}_i)|^2}\right]^{-1}$$

- Test (in ZZ and WW) several well-motivated alternatives using fully correlated information in the (D_{bkg} ,D_{JP}) plane: Pure States Only

0^+ : SM Higgs with minimal coupling
0^- : pure pseudoscalar
0^+_h : higher dimension operators (in decay amplitude)
1^- : vector
1^+ : axial vector
2^+_{gg} : graviton with minimal coupling
2^+_{qq} : graviton with minimal coupling

$H \rightarrow ZZ \rightarrow 4l$

Spin and Parity Test Statistics

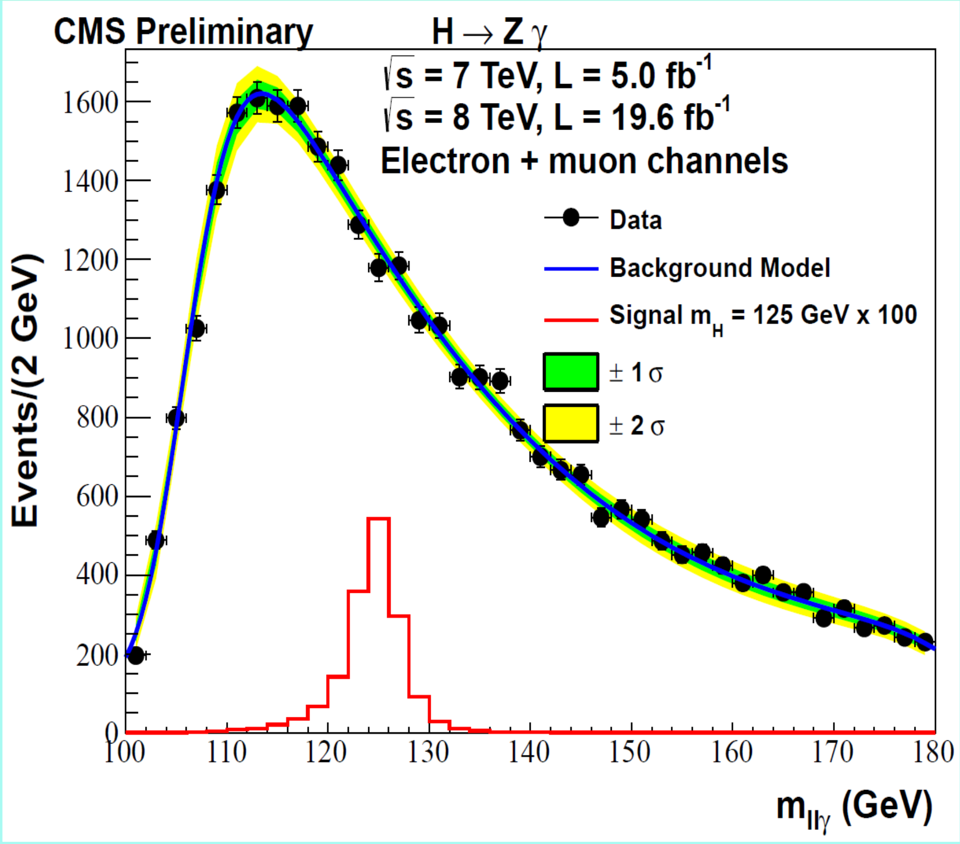


J^P	production	comment	expect	obs. J^P	obs. 0^+	CL_s
0^-	$gg \rightarrow X$	pseudoscalar	2.6σ	3.3σ	0.5σ	0.16%
0_h^+	$gg \rightarrow X$	higher dim operators	1.7σ	1.7σ	0.0σ	8.1%
2^+_{mgg}	$gg \rightarrow X$	minimal couplings	1.8σ	2.7σ	0.8σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \rightarrow X$	minimal couplings	1.7σ	4.0σ	1.8σ	<0.1%
1^-	$q\bar{q} \rightarrow X$	exotic vector	2.8σ	$>4.0\sigma$	1.4σ	<0.1%
1^+	$q\bar{q} \rightarrow X$	exotic pseudovector	2.3σ	$>4.0\sigma$	1.7σ	<0.1%

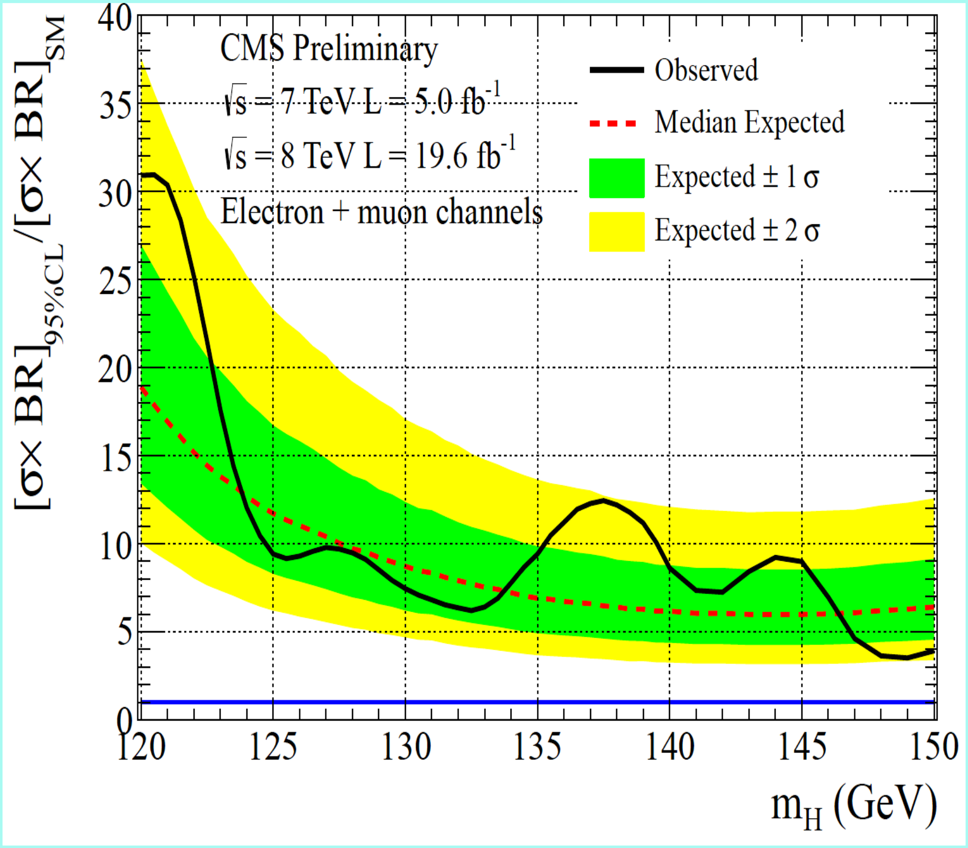
$H \rightarrow Z\gamma \rightarrow l+l-\gamma$ (l = e, μ): *New Rare Decay Channel with Good Resol'n*

CMS PAS-HIG-13-006

Combined m(eeγ), m(μμγ) Distribution



95% CL Limit on σ/σ_{SM} vs M_H

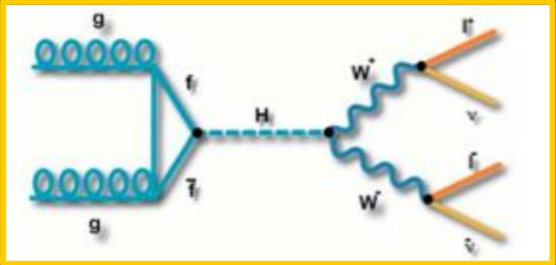


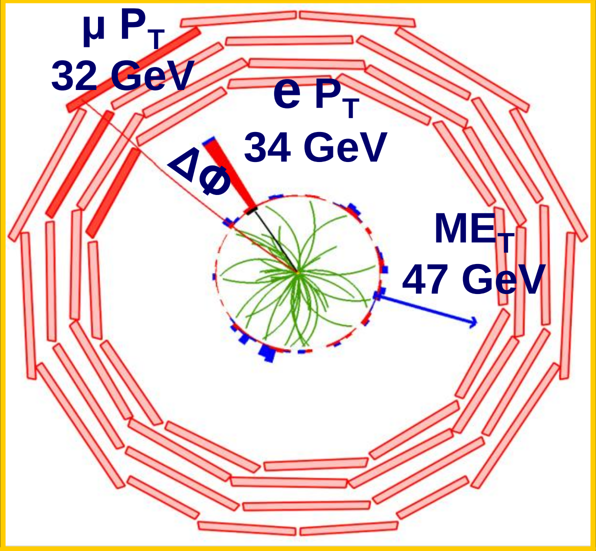
- Isolated leptons and photons
- Four classes each for eeγ, μμγ divided by S/B: shower shape and η
- Mass resolution (σ_{eff}) = 1.6 – 3.3 GeV

$H \rightarrow WW \rightarrow 2l\,2\nu$ (l = e, μ)

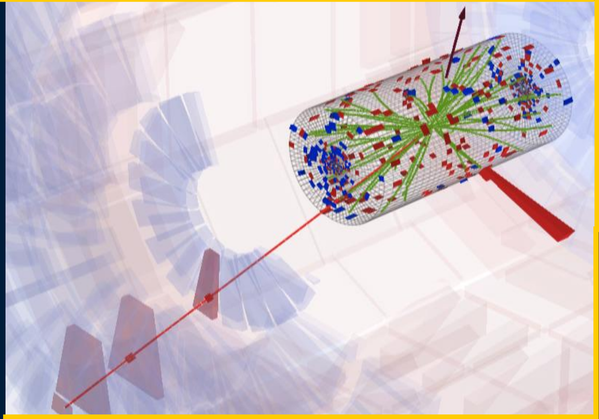
High Sensitivity, Low Resolution

CMS HIG-13-003; http://cds.cern.ch/record/1523673





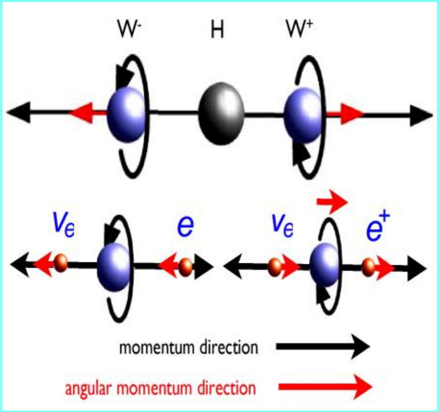
Lepton P_T > 20, 10 GeV



Main Backgrounds
W+Jets, Drell Yan, Top, WW

Signal characteristics

- 2 opposite sign, isolated leptons
- Significant E_T^{Miss} ➡ No Mass Peak
- Smaller ΔΦ (l^+l^-) and hence M_{ll} for low M_H: Higgs is a scalar



Analysis Strategies

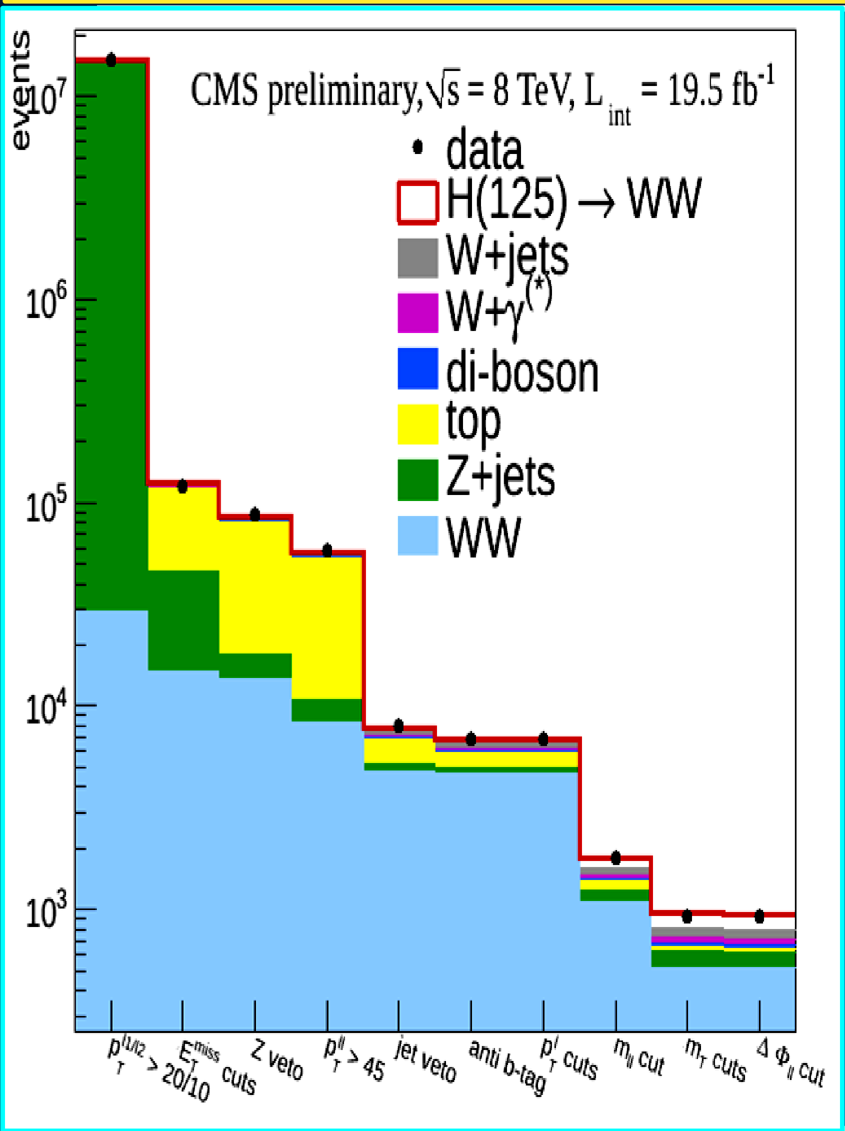
- Cuts Analysis (M_H Dependent) + 2D Shape Analysis
- *Separate categories with different S/B to optimize*
  (1) by lepton flavor; eμ (DF) events are purest
  (2) by 0, 1, 2 Particle-Flow Jets (VBF), P_T > 30 GeV
- No b-jets and no isolated 3rd lepton [suppress WZ]

Analysis Improvements

- New Lepton Selection, extending the p_T Range
- New electron E Determination, with MV regression
- M (126) Resol'n improved: 2.7 (3.8) to 2.0 (3.0) GeV

H ➡ WW Cut-and-Count: Cut Evolution

Cut-by-cut: at each step, background are normalized to the data



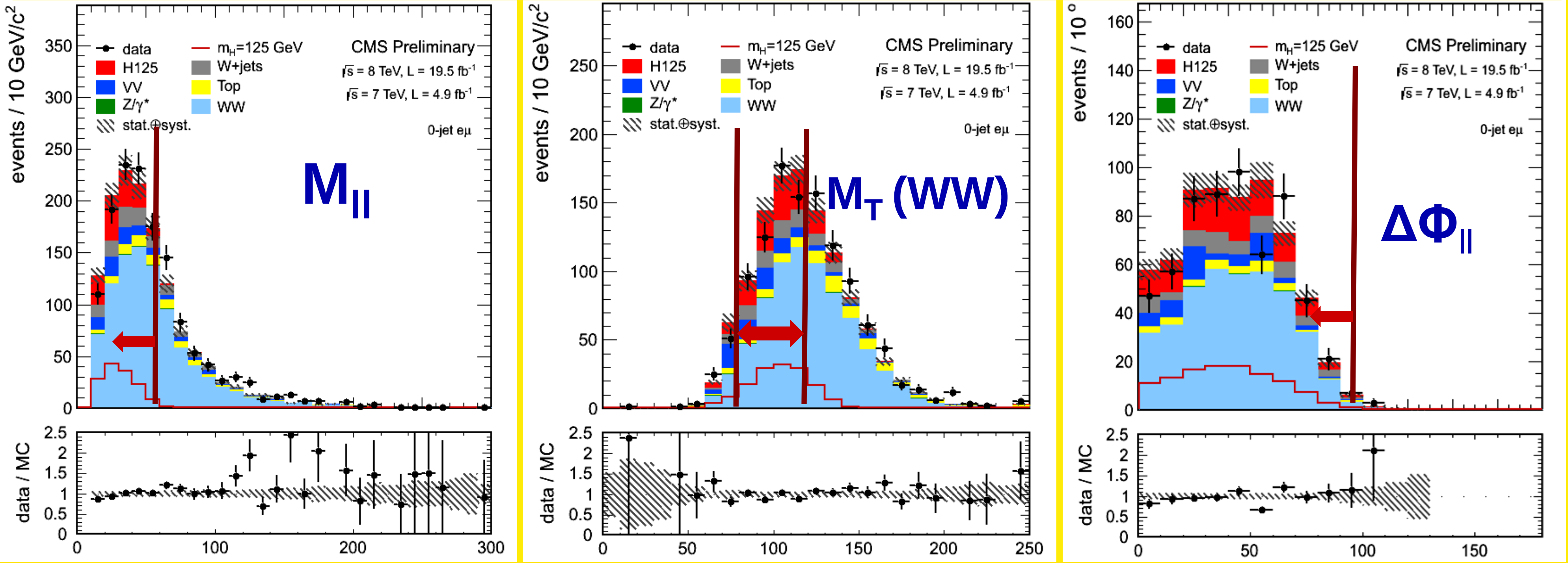
Major Requirements

- Lepton P_T > 10, 20 GeV, tight ID & Isolation
  - Removes QCD, W+jets contamination: Leaves Drell-Yan-dominated sample
- Missing E_T Discrimination; Veto Z → μμ, ee
  - Removes Drell-Yan contamination: Leaves a WW & top dominated sample
- Classification by N_{Jets} (P_T > 30 GeV), soft lepton & b-jet veto ["top tag"]
  - Removes Top contamination: Leaves a WW dominated sample
- Kinematic discriminants: M_{ll}, M_T (WW), $\Delta\Phi_{ll}$
  - Mitigate pp → WW background
- M_H – dependent cut optimization:
  - Leaves a WW+Higgs dominated sample; an excess is visible

H ➡ WW Cut-and-Count Analysis: DF 0 Jet

Optimized Selections per mass point are applied on leptons' p_T, M_{ll}, M_T (WW), $\Delta\Phi_{ll}$ to enhance a Higgs signal

Final Cuts: After backgrounds are fitted from the data in control regions



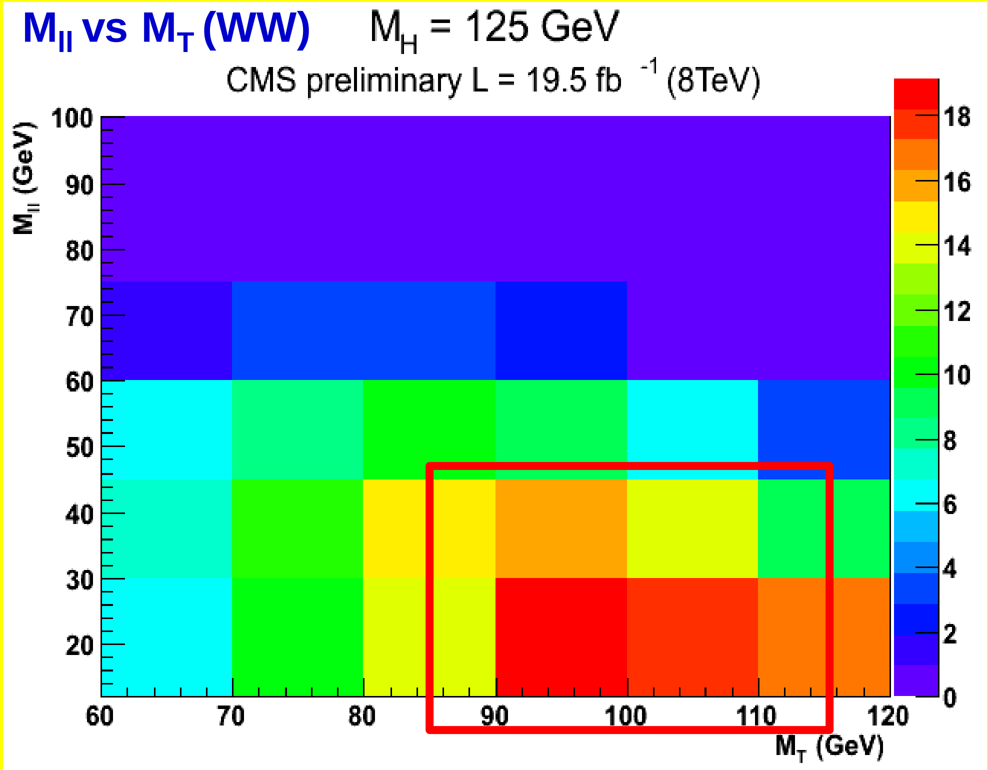
Observe excesses over background in the signal regions

MH	signal	WW	WZ+ZZ+ Z/γ*→ll	Top	W+jets	Wγ*	All bkg.	Data
125	90±19	310±29	11.4±1.1	20.0±4.3	48±13	40±13	429±34	505

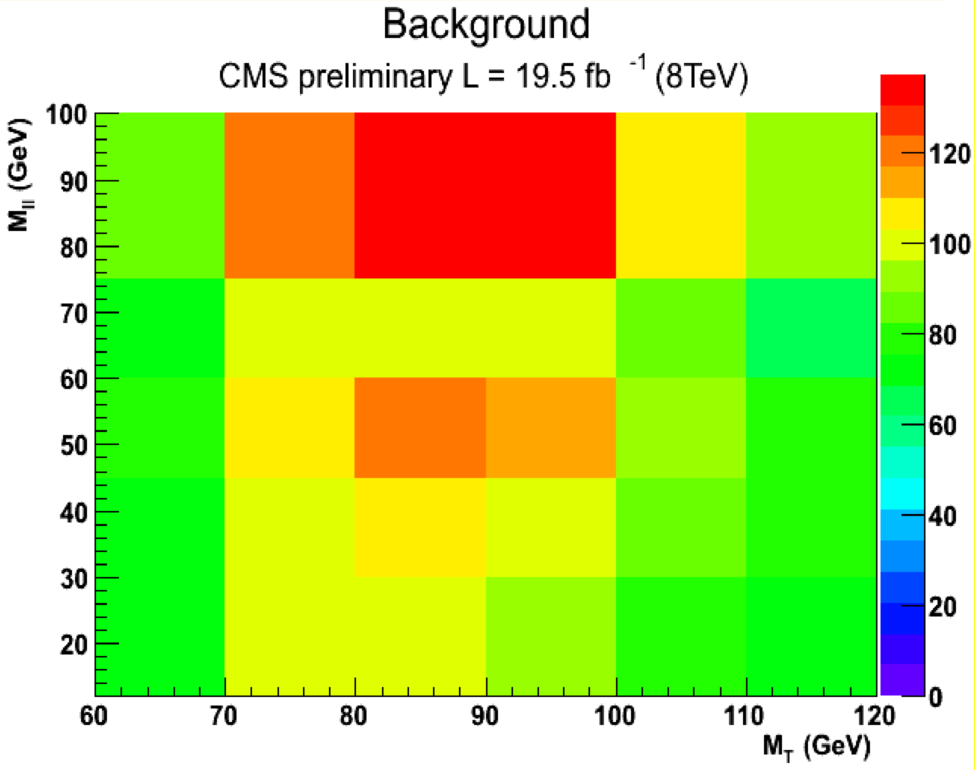
H ➡ WW 2D Shape Analysis eμ 0-Jet: PDFs

Relaxed Selections are applied on kinematic variables wrt cut-based. Performed a binned fit to M_{ll}, M_T (WW)

Signal, m_H=125 GeV. 0-jet eμ



Total background. 0-jet eμ



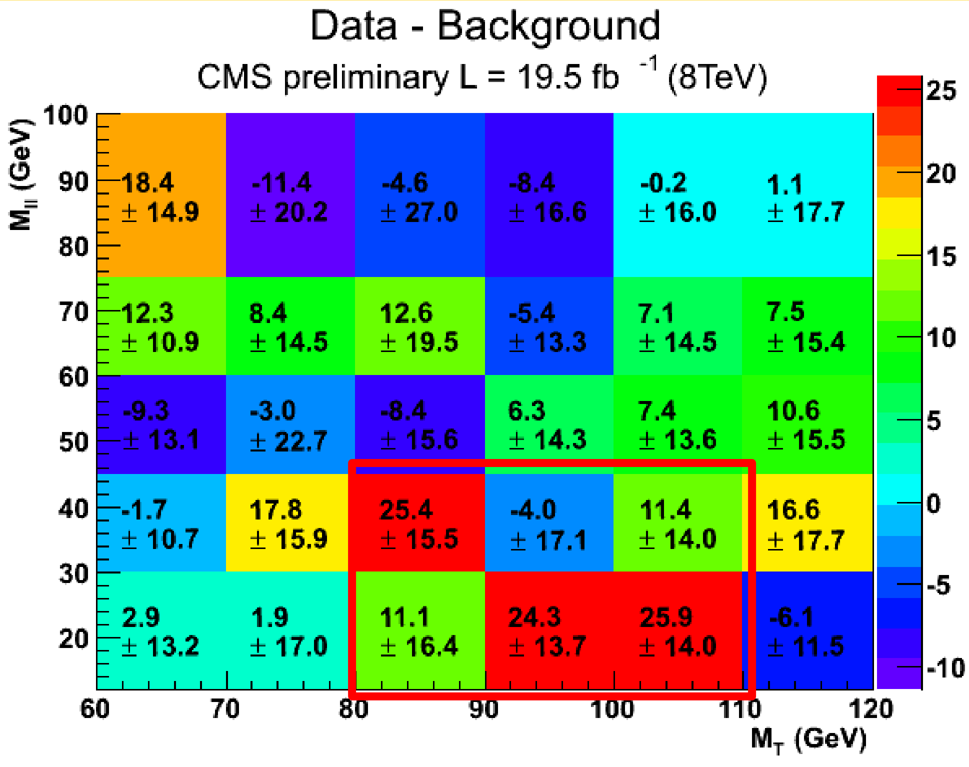
Clear region in 2D space dominated by the signal

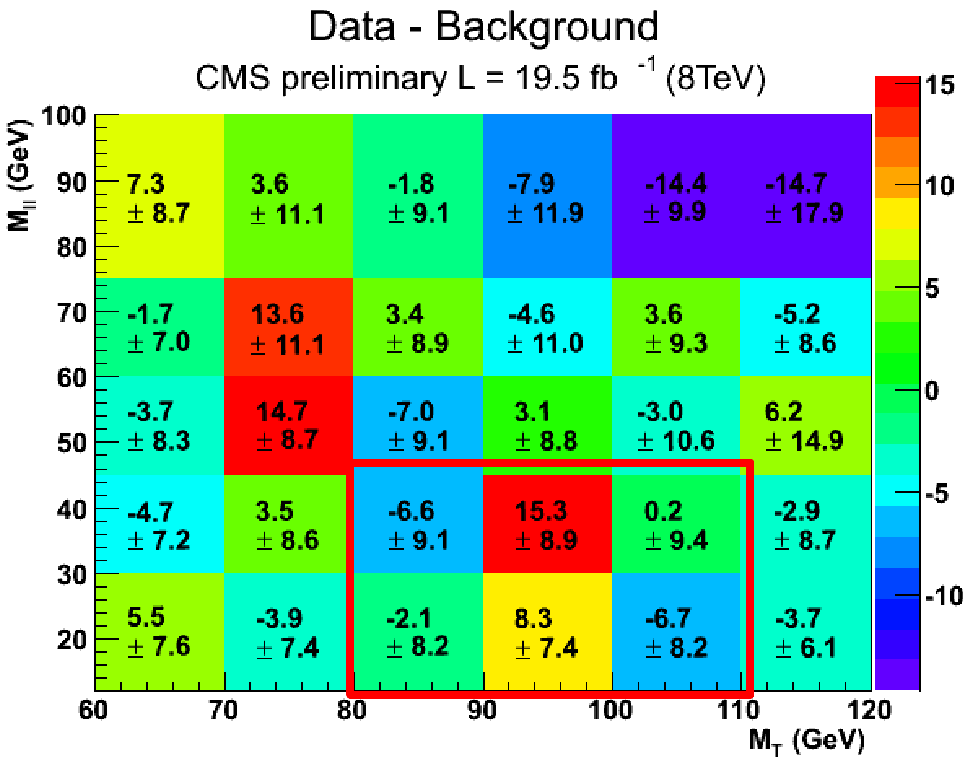
Gain wrt cut-based comes from use of kinematic distributions

H ➡ WW 2D Shape Analysis eμ 0 and 1 Jet: Data

Relaxed Selections are applied on kinematic variables wrt cut-based. Binned fit to M_{ll} vs M_T (WW)

8 TeV Data - Expected Background 0-Jet eμ	8 TeV Data - Expected Background 1-Jet eμ



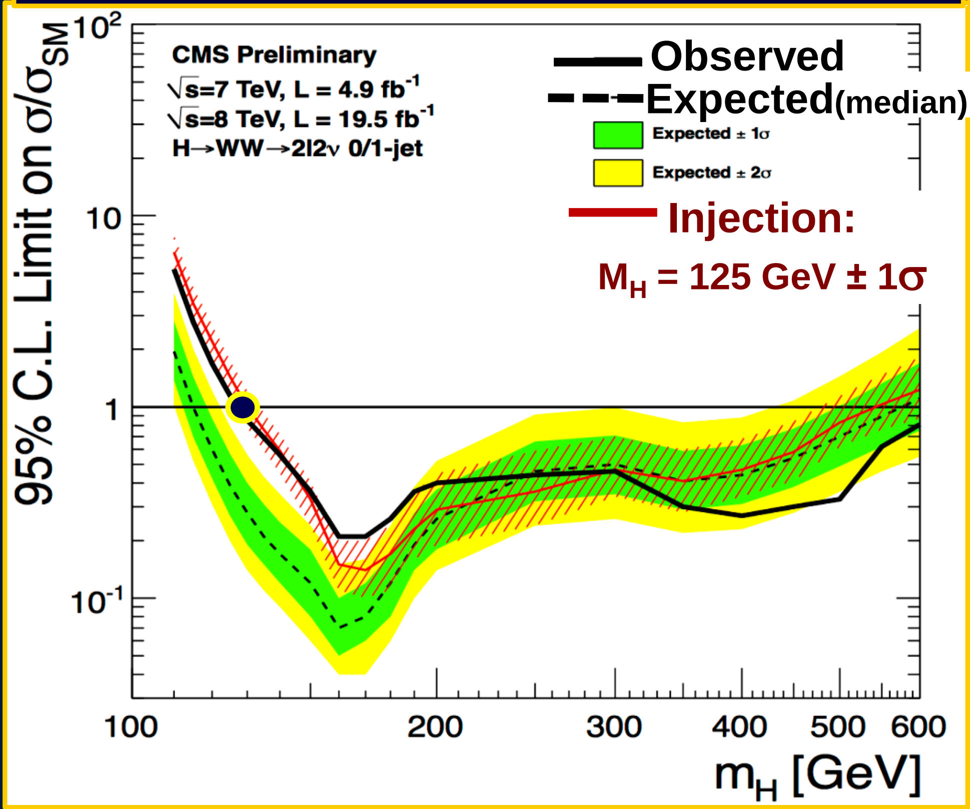


Clear excess observed in signal-enriched region (Low M_{ll}, M_T ~100 GeV)

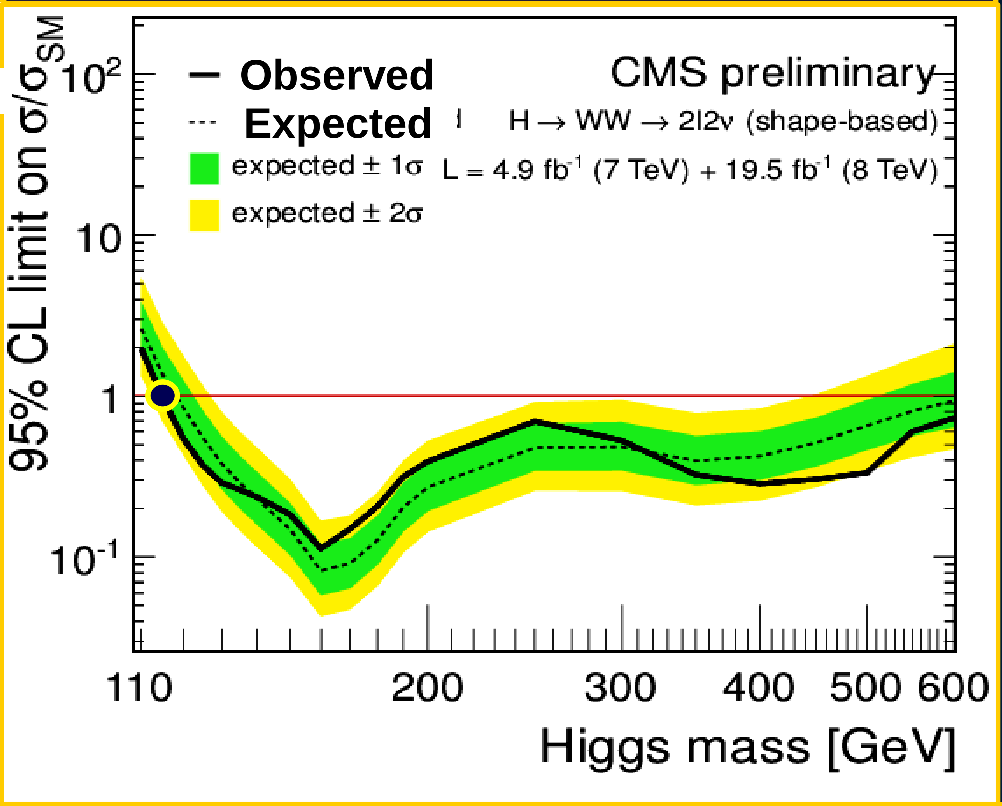
$H \rightarrow WW \rightarrow 2l\ 2\nu$ (l = e, μ) Results

Combined σ/σ_{SM} 95% CL Limits

7+8 TeV Limits (95% CL) on σ/σ_{SM}



σ/σ_{SM} with M_H=125 GeV) as background



Observed limit matches expected background + H(125) signal injection

✸ Masses of 128-600 GeV are excluded at 95% CL

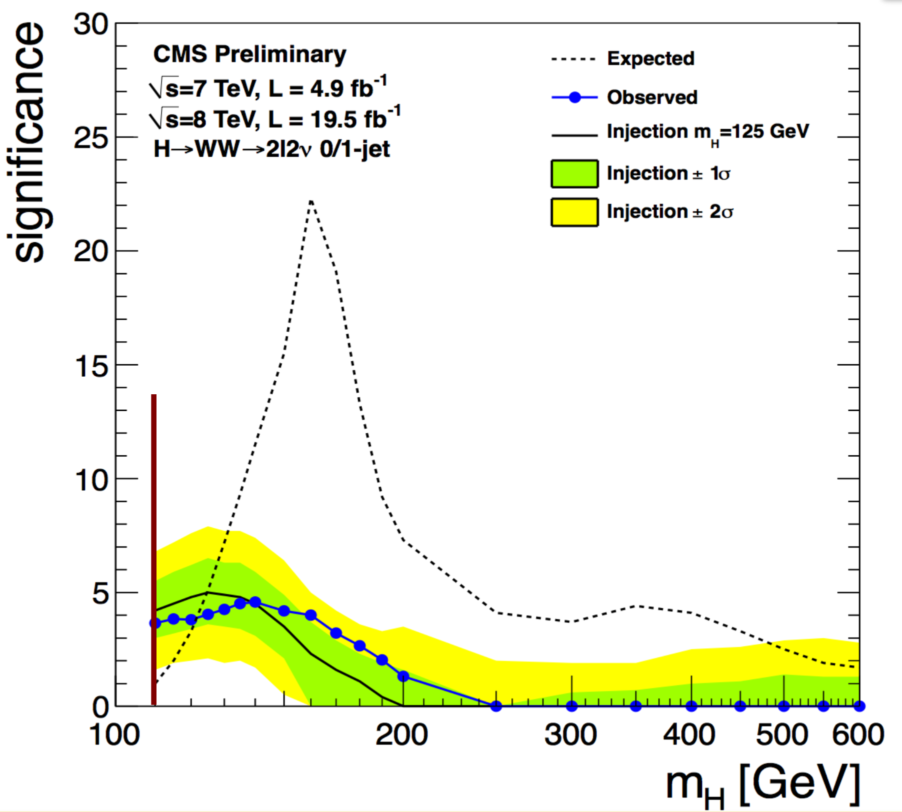
+ Limits on Additional Higgs-like bosons above 113 GeV

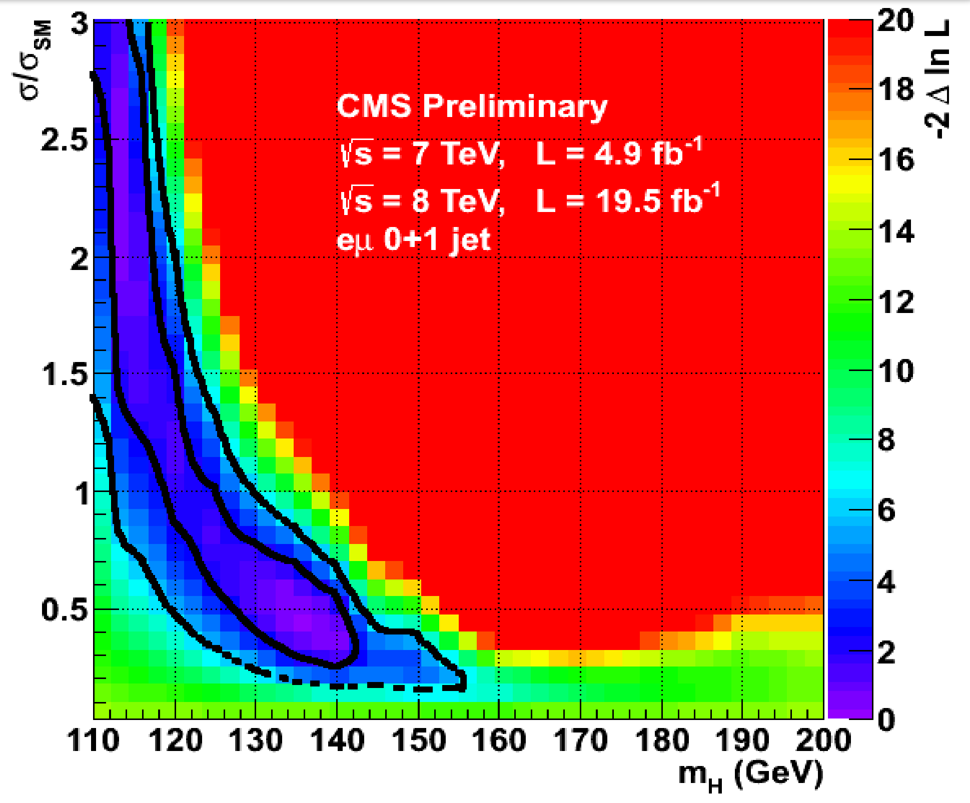
H → WW → 2*l* 2ν

Signal Significance

7+8 TeV: Signal Significance vs M_H

Signal strength $\mu=\sigma/\sigma_{SM}$ vs M_H





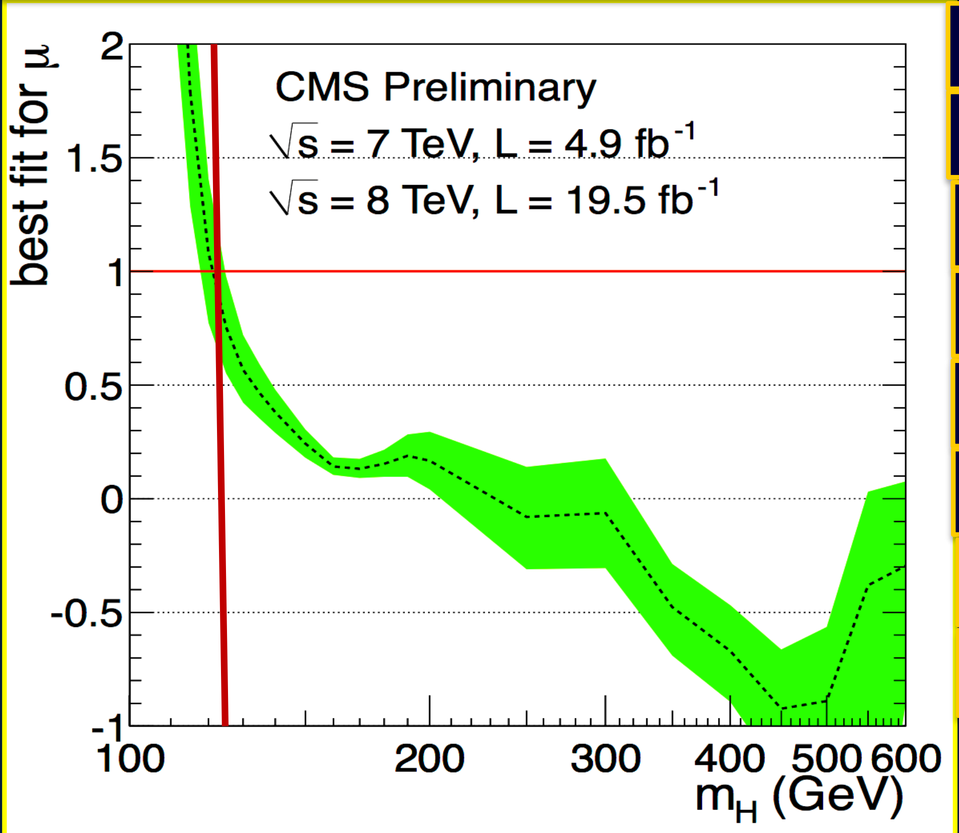
For M_H = 125 GeV:
Observed Significance = 4.0 σ
Expected Significance = 5.1 σ

Mass resolution of this channel (~30 GeV) gives a wide minimum in the Likelihood

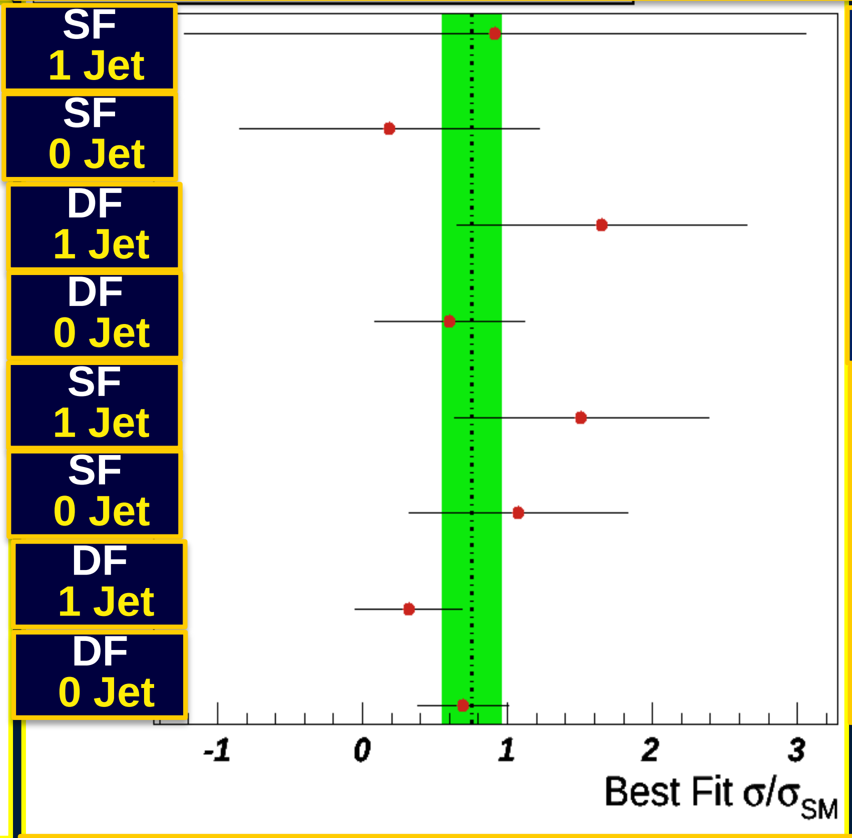
$H \rightarrow WW \rightarrow 2l\ 2\nu$

Signal Strength

Best Fit Signal Strength μ vs M_H



Best Fit Strength By Channel



7 TeV

8 TeV

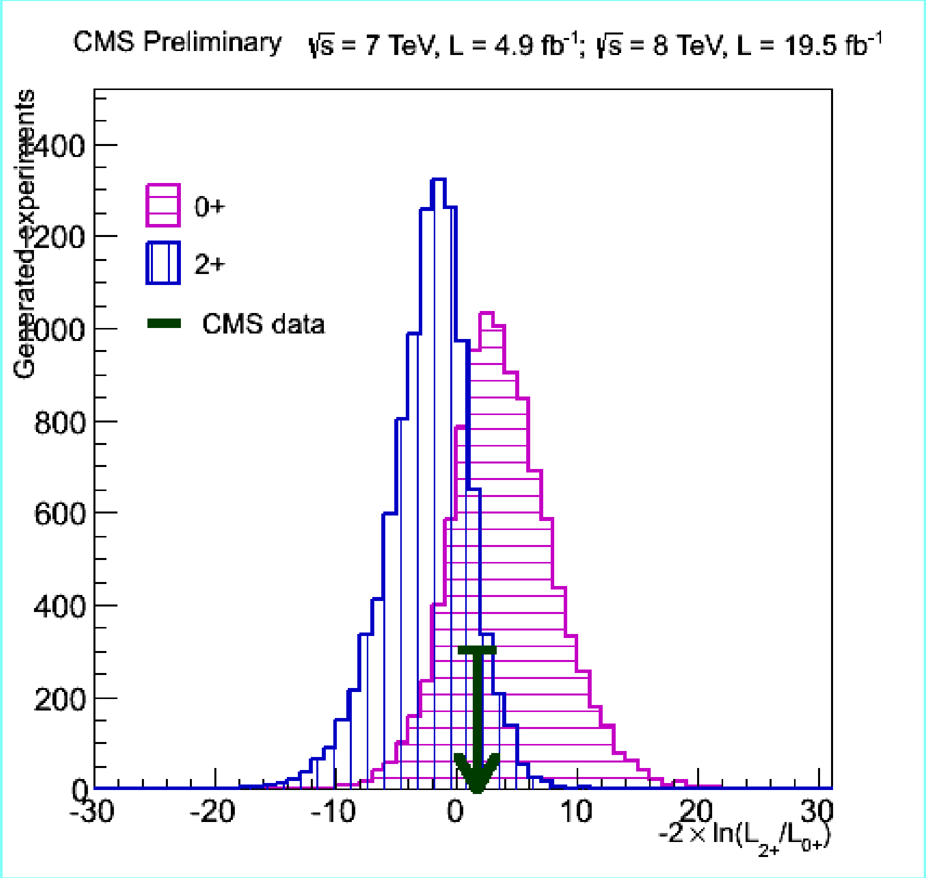
Best fit Signal Strength
for M_H = 125 GeV:
$\mu = \sigma/\sigma_{SM} = 0.76 \pm 0.21$

Best Fit $\mu = \sigma/\sigma_{SM}$ by channel
Consistent results
among the channels

$H \rightarrow WW \rightarrow 2l\ 2\nu$

Testing Spin Hypotheses: 0^+ vs 2^+

Discrimination based on Binned Fit to M_{ll} vs M_T (WW)



P-Value (in σ) of other hypothesis

Hypothesis	Expected	Observed
Assuming Signal Strength =1		
0^+	1.9 σ	0.9 σ
2^+_m	2.4 σ	1.3 σ
Assuming Prefit Strength on Data		
0^+	1.5 σ	0.5 σ
2^+_m	**1.8 σ**	**1.3 σ**

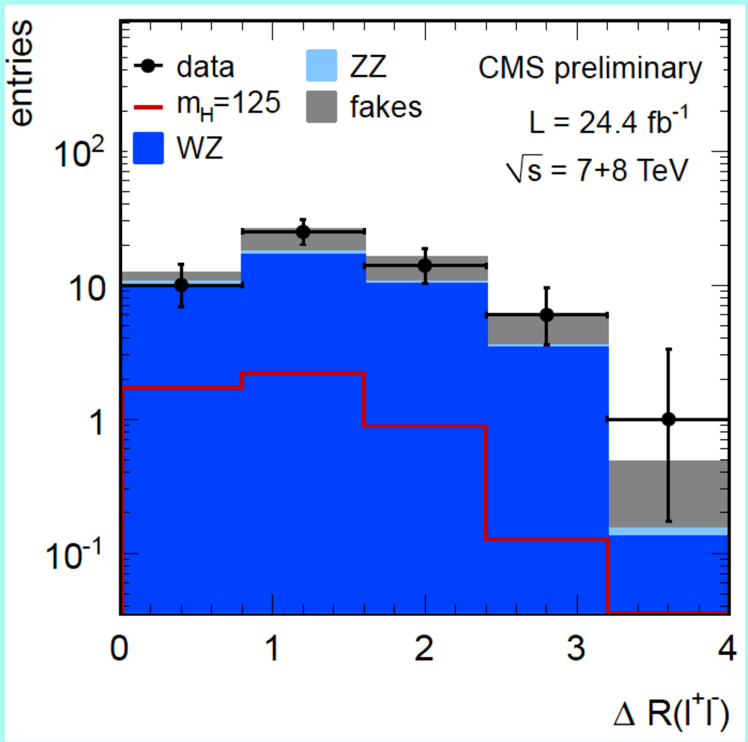
Expected separation between 0^+ & 2^+_m : 2 σ

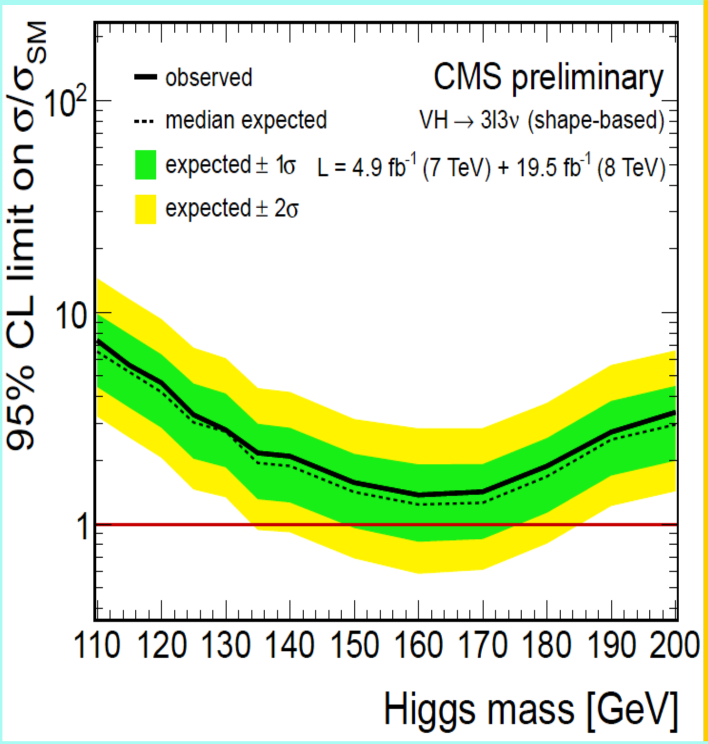
Data is consistent with both hypotheses [CL(2+) = 14%]

WH → WWW → $3l\ 3\nu$ ($l = e, \mu$)

New *Sensitive Channel*

CMS PAS-HIG-13-009





95% CL Limits on σ/σ_{SM}

3.3 Observed

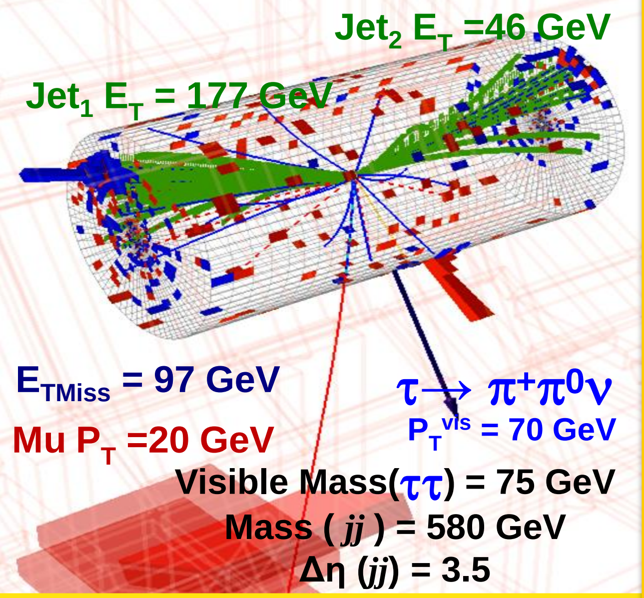
(3.0 Expected for M_H = 125 GeV)

- **Signature: Three high p_T isolated leptons with moderate E_T^{Miss}**
- **Two Approaches: Cut-Based and shape-based using ΔR (l+l-)**
  - **Shape-based has 20% better performance**
- **Z Veto and anti b-tagging to reject WZ and Top backgrounds**
- **Smallest m_{ll} < 100 GeV and smallest ΔR (l+l-) < 2**

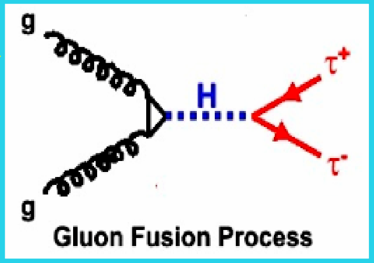
$H \rightarrow \tau\tau$

CMS PAS-HIG-13-004

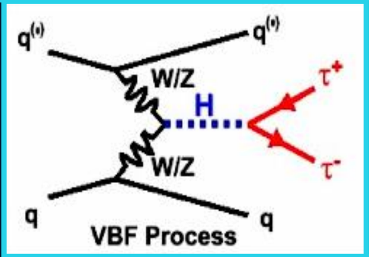
Signatures: $e\mu$ $\mu\tau_h$ $e\tau_h$ $\mu\mu$ $\tau_h\tau_h$



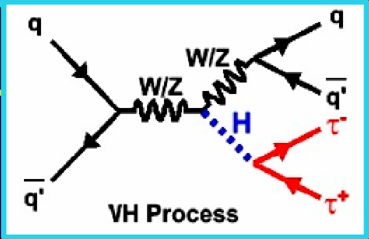
- Probes **coupling to leptons** ⇨
- Sensitive to **All** production modes: **gg fusion, VBF, VH**
- **High $\sigma \bullet$BR** at low mass
- Signature: **Broad excess in $m_{\tau\tau}$**
- Challenging backgrounds: **DY → ττ,ee,μμ, W+Jets,Top, QCD**



Gluon Fusion Process



VBF Process



VH Process

Analysis Strategy

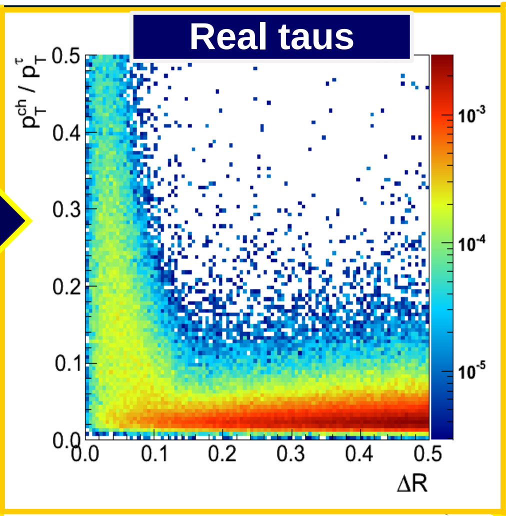
- ❑ **Select well-isolated leptons**
- ❑ **Topological cuts** to suppress background: **M_T** in $l\tau_h$, p_T(H) in $\tau_h\tau_{h,...}$
- ❑ Split events into Categories:
  - **1 Jet (GGF) or 2 Jets (VBF); and Low vs High P_T (τ_h or μ)**
  - **Dedicated categories for VH, with relatively hard leptons or MET**
- ❒ **Veto events with tagged b-jets with P_T > 20 GeV**
- ❒ **0 Jets:** Used to constrain backgd normalize, Tau ID Efficiency, E Scales

$H \rightarrow \tau\tau$: $\mu+\tau_{had}$, $e+\tau_{had,}$ $\mu+e$, $\mu\mu$, $\tau_h\tau_h$

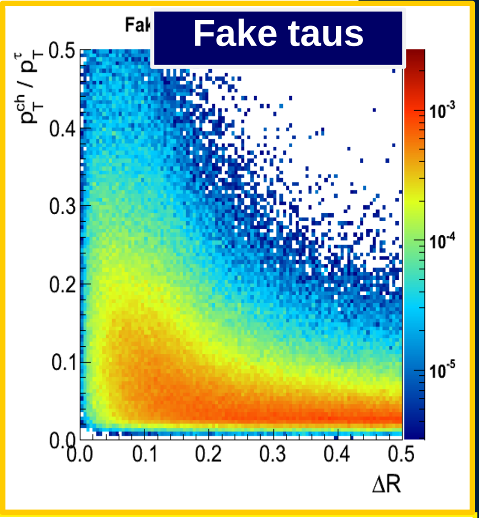
Many nalysis Improvements

Analysis Optimized:

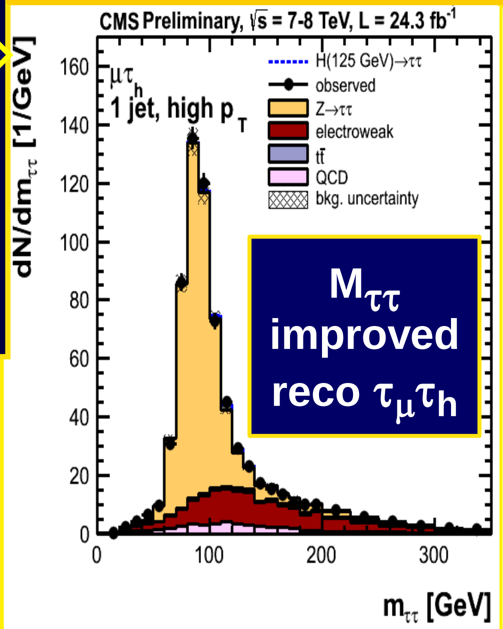
- ✓Improved lepton & (PF) τ_{had} ID: P_T^{ch}/P_T^{τ} in ΔR Rings about τ
- ✓BDT for improved (PF-based) E_T^{Miss}
- ✓Consistency of E_T^{Miss} from ν_τs
- ✓New $m_{\tau\tau}$ reconstruction with event-by-event likelihood 15-20% resolution
- ✓MVA selection for VBF tag



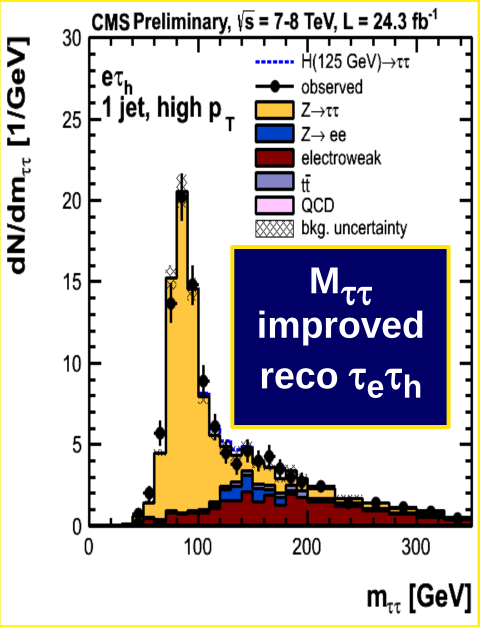
Real taus



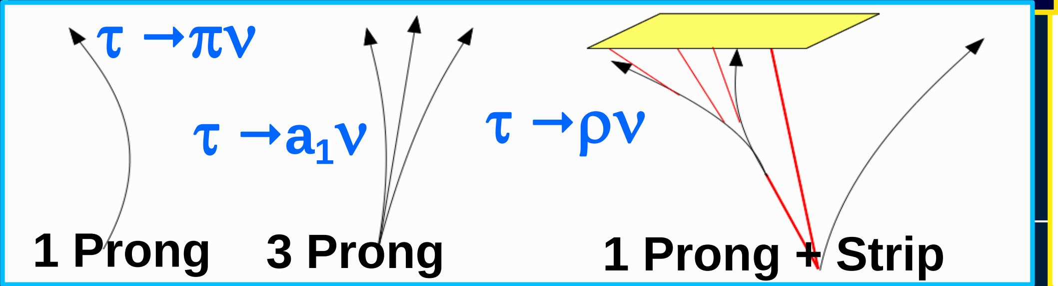
Fake taus



$M_{\tau\tau}$ improved reco $\tau_\mu\tau_h$



$M_{\tau\tau}$ improved reco $\tau_e\tau_h$



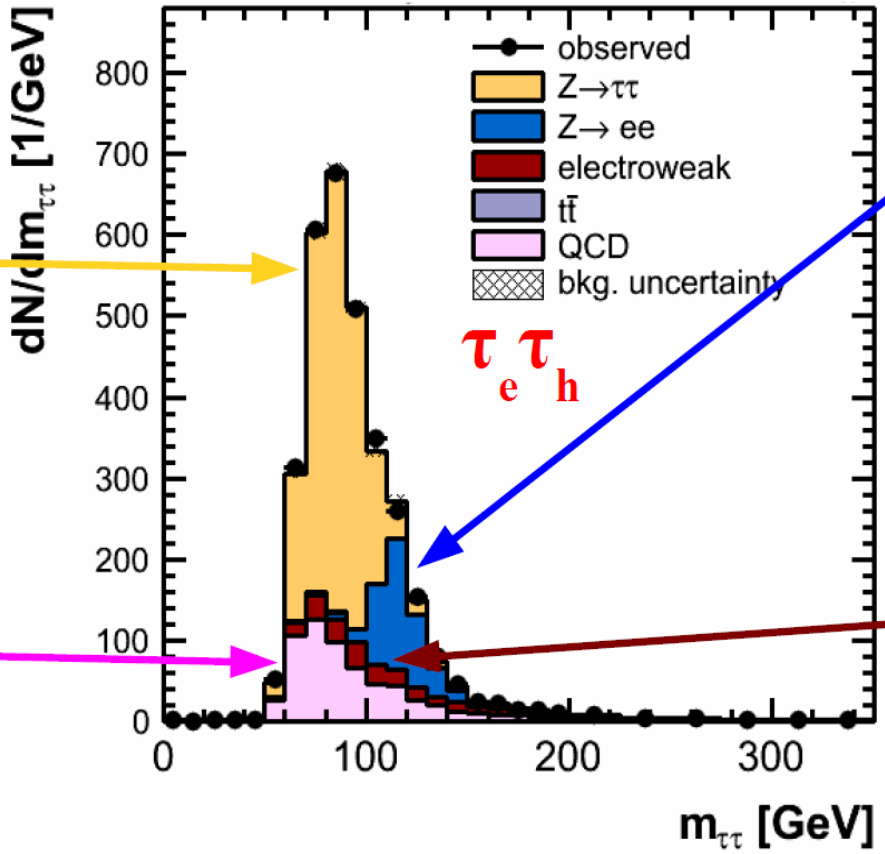
H ➡ ττ: Anatomy of the Analysis

Handling the Dominant Backgrounds

Z→ττ:
- Embedding: in Z→μμ, replace μ by sim. τ decay.
- Normalized from Z→μμ events.

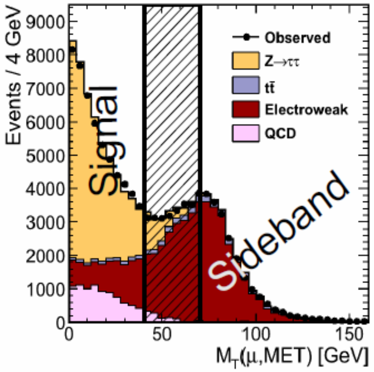
QCD:
- Normalization & shape taken from LS/OS or fakerate.

ttbar:
- From simulation.
- Normalization from sideband.



Z→ee(/μμ):
- From simulation.
- Corrected for jet→τ, e/μ→τ fakerate.

Diboson/W+jets:
- From simulation.
- Normalization from sideband.

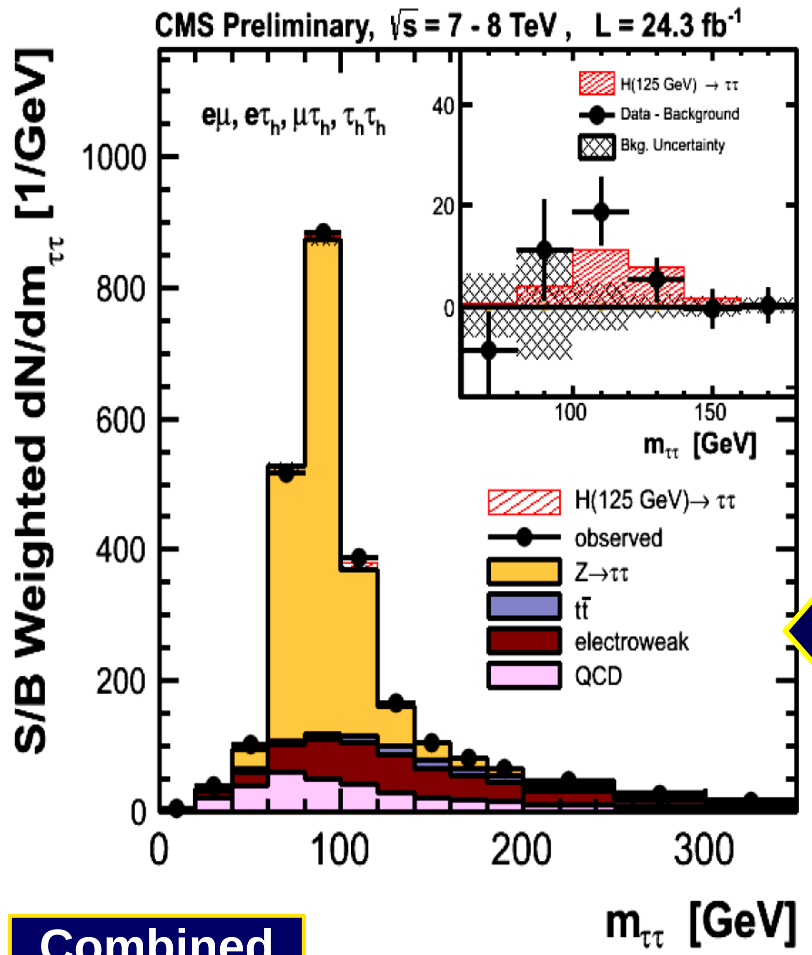


R. Wolf at HCP

H ➡ ττ: Signal Extraction

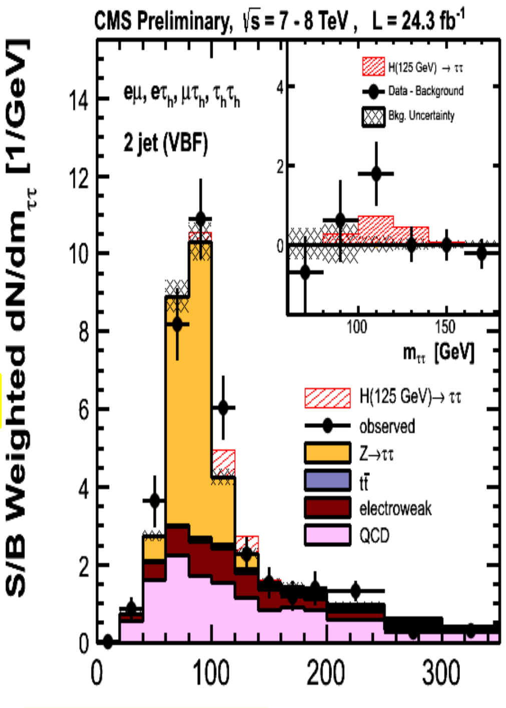
Combine 1-Jet and 2 Jet (VBF)

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

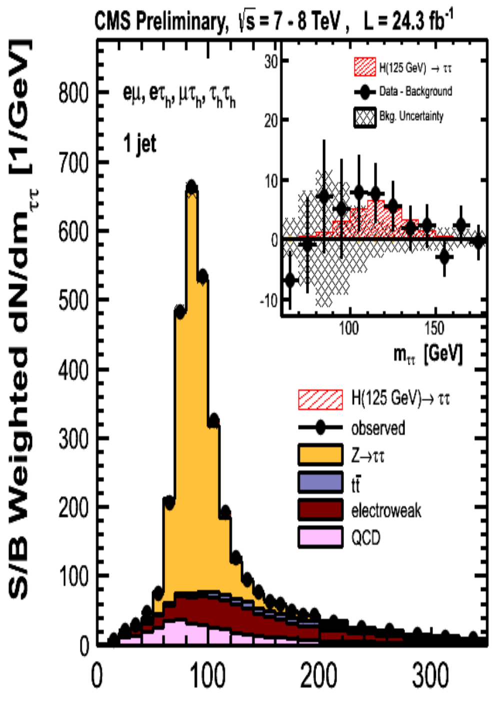


Combined

- ➡ Combine channels and categories
- ➡ Each channel in each category **weighted by its expected S/B**



2 Jet (VBF)

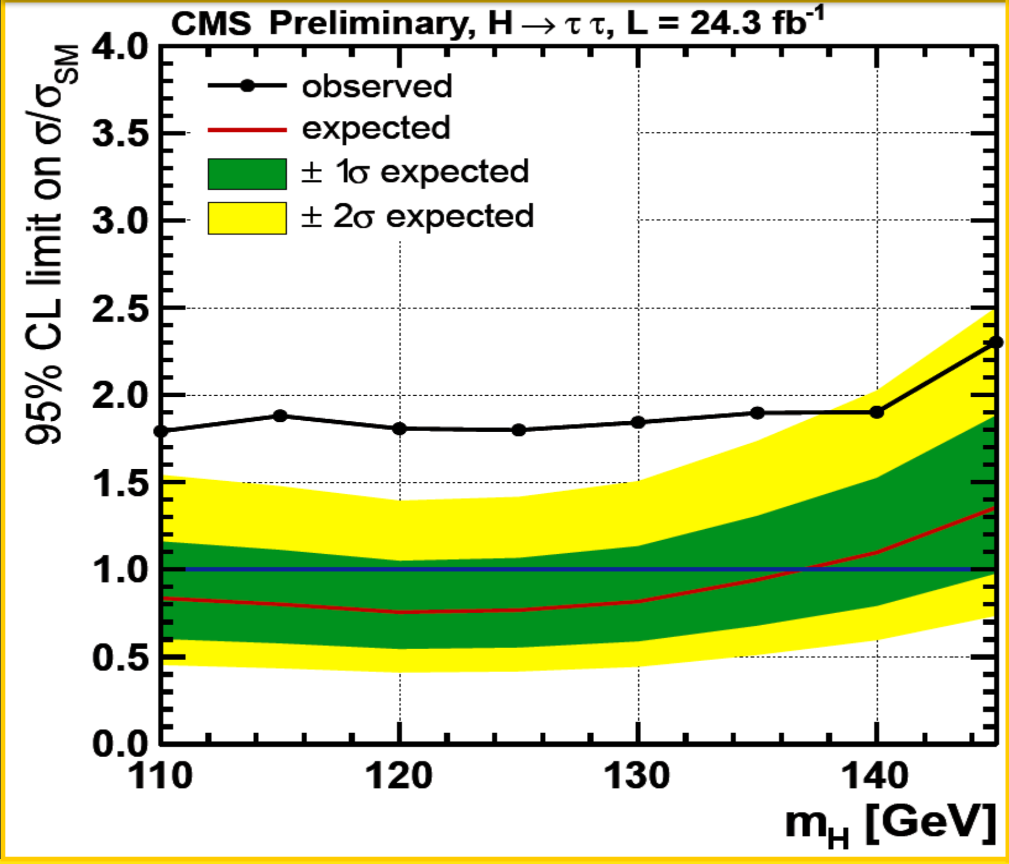


1 Jet

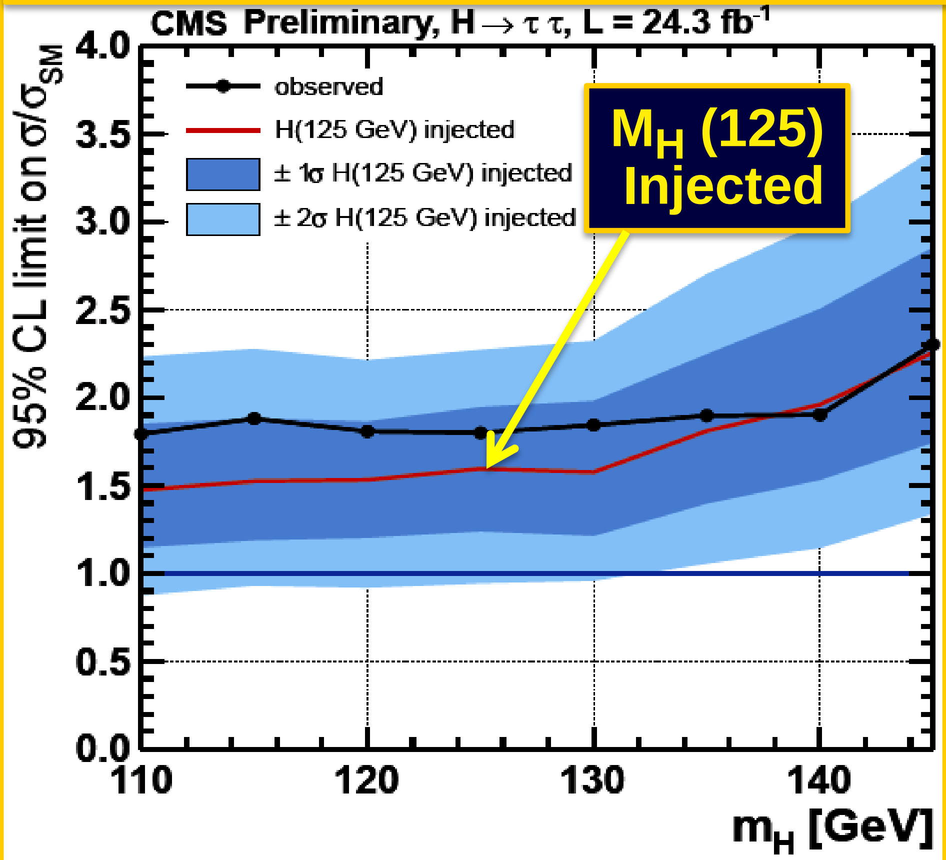
$H \rightarrow \tau\tau$: Statistical Interpretation

Limits and Signal Injection

95% CL Limits on σ/σ_{SM} vs M_H compared to background expectations



95% CL Limits on σ/σ_{SM} vs M_H compared to background + M_H (125)

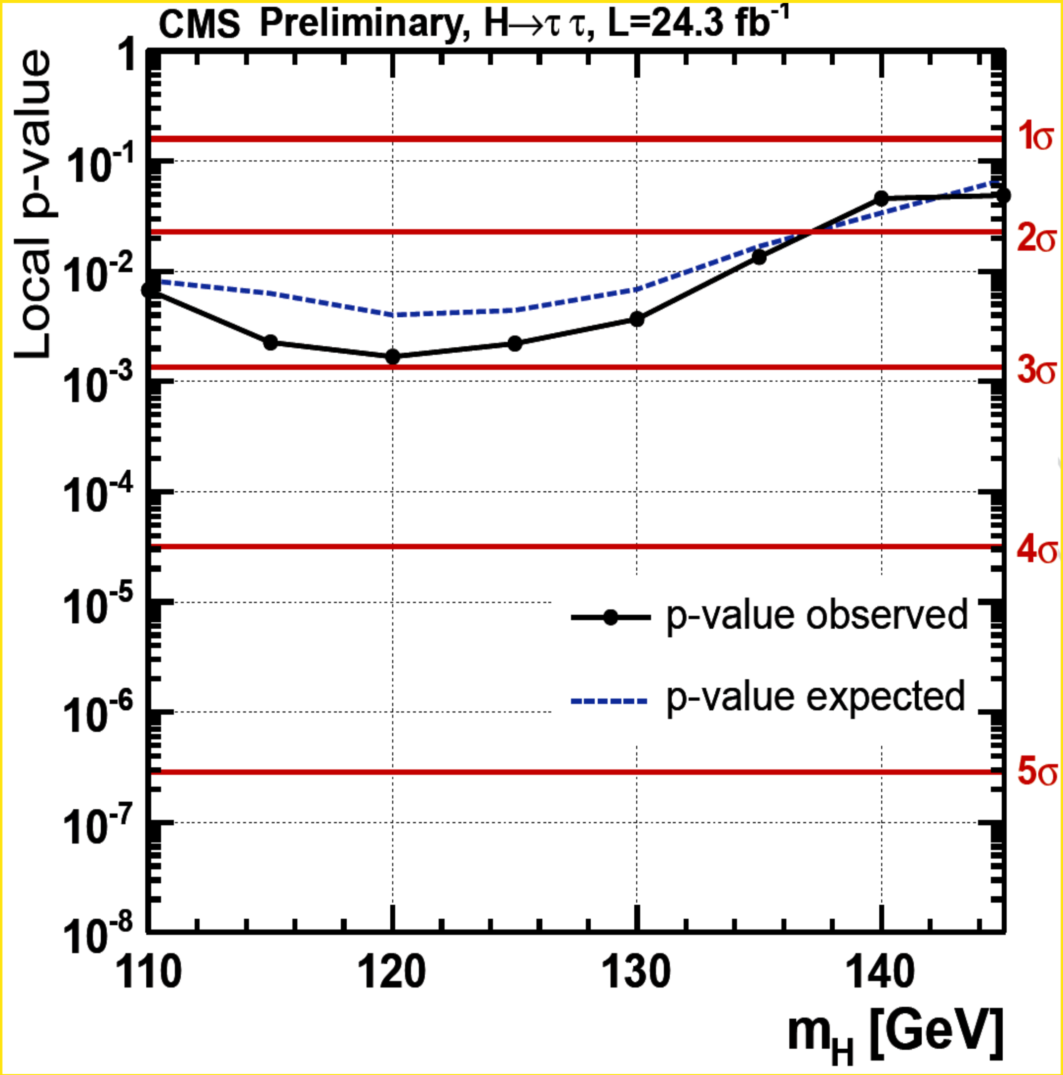


M_H (125) Injected

Results are consistent with the expectation for the presence of a SM boson at M_H = 125 GeV (within 1σ)

$H \to \tau\tau$

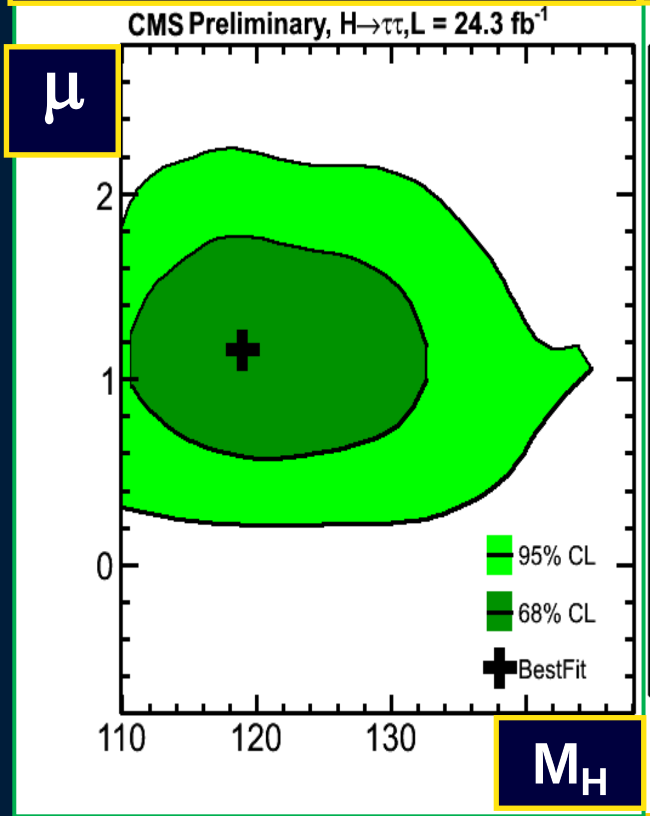
P-Values: Significance

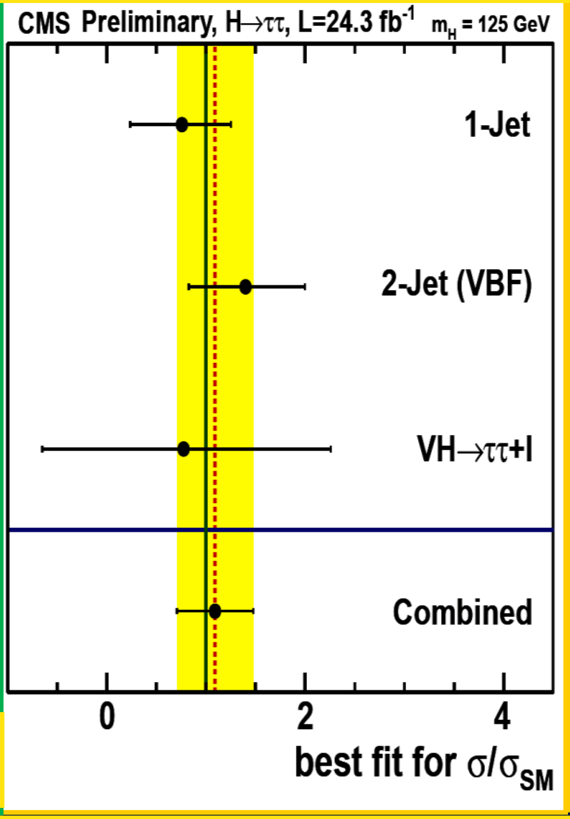


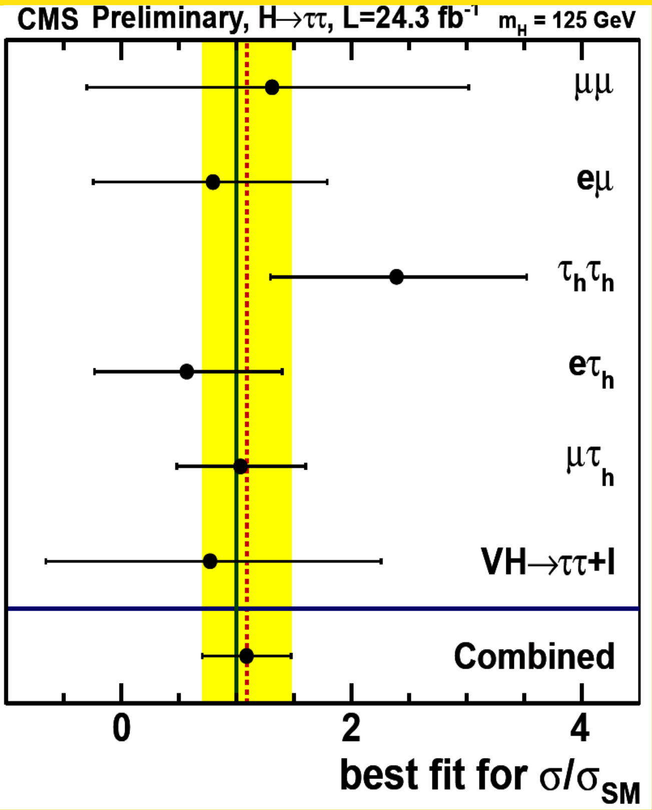
- **Broad excess is observed over the low mass M_H range**
- **Maximum local significance is 2.93σ at 120 GeV**
  - **Consistent with the presence of a 125 GeV SM scalar boson**
- **Observed significance is 2.85σ for M_H = 125.8 GeV**
  - **Expected: 2.6σ**
- **Strong Indication that the new particle decays to Taus**

H → ττ: Signal Strength vs Mass
and Compatibility Among Categories

Signal Strength vs M_H | **Prod. Categories** | **Decay Categories**







Combined Best Fit Strength $\mu = 1.1 \pm 0.4$ (M_H = 125 GeV)
Results consistent across categories, and with SM

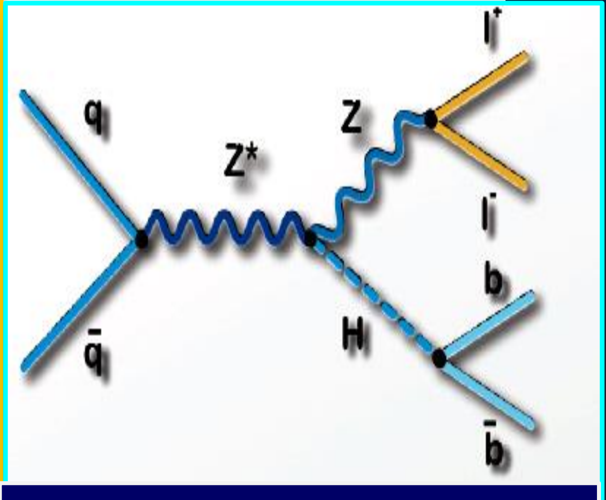
VH → Vb$\bar{b}$ Associated Production
W,Z + H ➡ l+l- , $l\nu$, $\nu\bar{\nu}$, l =e,μ + b$\bar{b}$

CMS PAS-HIG-12-046 (HCP)

- H →b$\bar{b}$: Largest σ•BR for M_H< 135 GeV
- *But very large QCD Background*
  ➡ *Use V+H Associated Production: Greater S/B*
- Signature: Leptons, 2 b-jets and E_T^{Miss}

5 Channels Z(ll)+H(bb), Z(νν)+H(bb), W(lν)+H(bb)

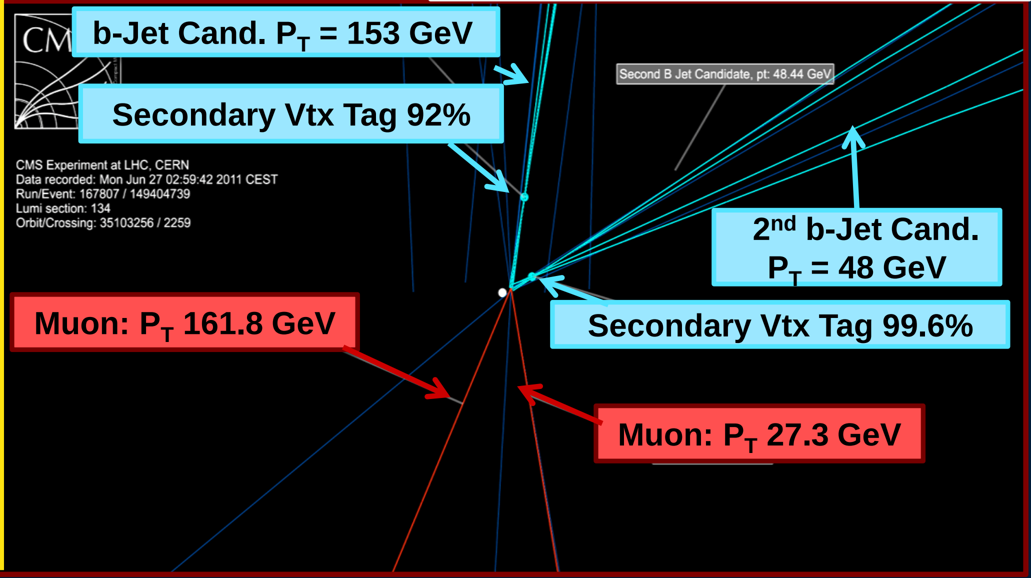
- Reducible Background: W, Z + Jets, Top



VH: Boosted Higgs Analysis

- ☐ Require high momentum (W or Z) and H; and 2 b-tagged jets
  - ☐ With back-to-back V and H
- ☐ Use MVA to Reconstruct M_{bb}, Classify Events: 8-9% Resolution
- ☐ Main backgrounds are estimated from data in control regions

Z (μμ) H (bb) Candidate



b-Jet Cand. P_T = 153 GeV

Secondary Vtx Tag 92%

2^{nd} b-Jet Cand. P_T = 48 GeV

Secondary Vtx Tag 99.6%

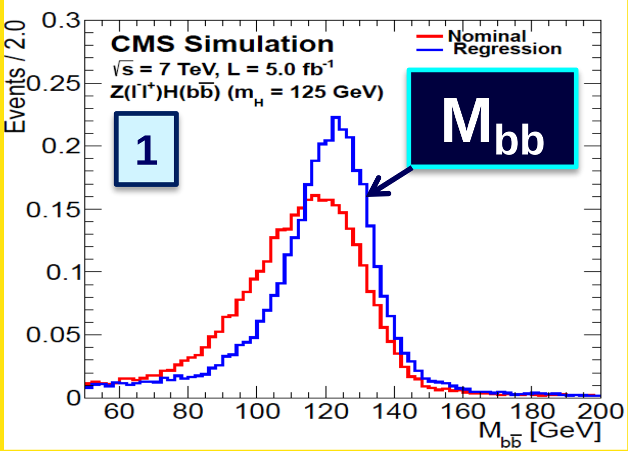
Muon: P_T 161.8 GeV

Muon: P_T 27.3 GeV

VH → V $b\bar{b}$ Associated Production
Many 2012 Analysis Improvements

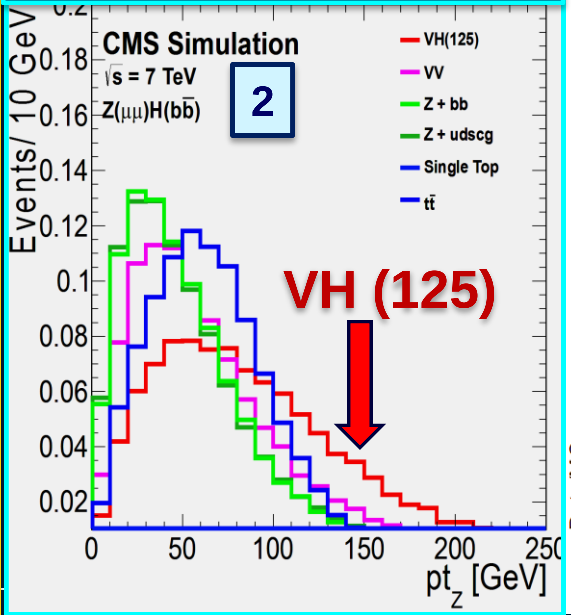
1. MVA for better b-jet P_T ➡ M_{bb} mass resolution ~10% for M_H = 125 GeV
2. Split events in medium and high boost: Based on $P_T(V)$
3. Reconstruct Jet Energy using BDT regression: 15-20% improvement
4. Use full shape of final MVA discriminant

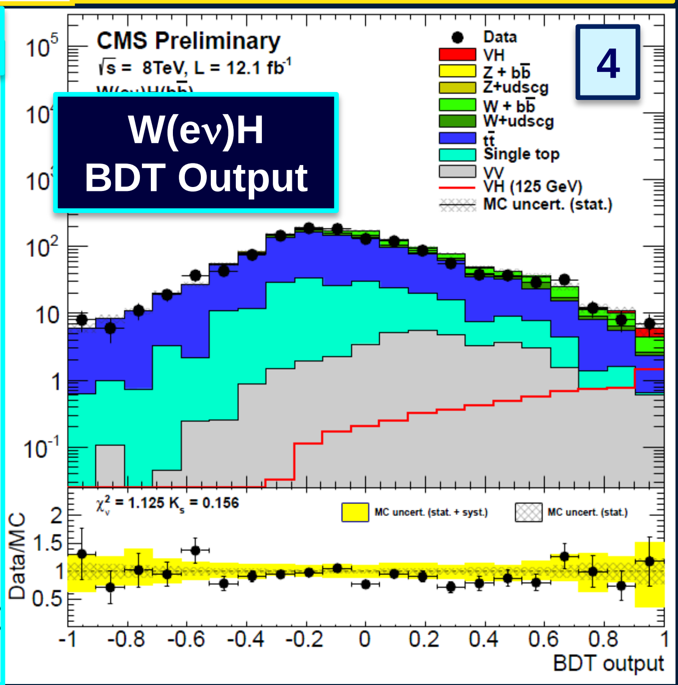
☞ Gain in sensitivity ~50% overall, already on 2011 dataset



Extensively validated in data using Z(ll) + bb, ttbar, and single top events

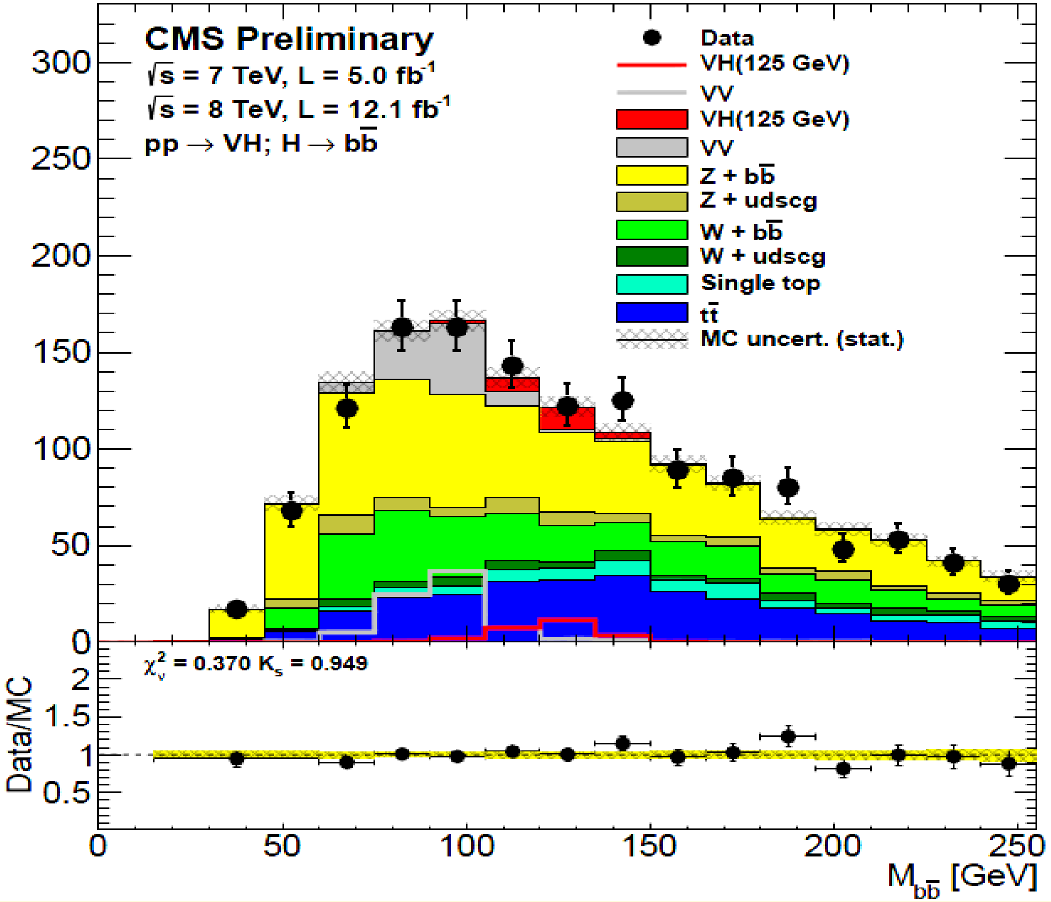
Large P_{TV} ➡ Larger S/B



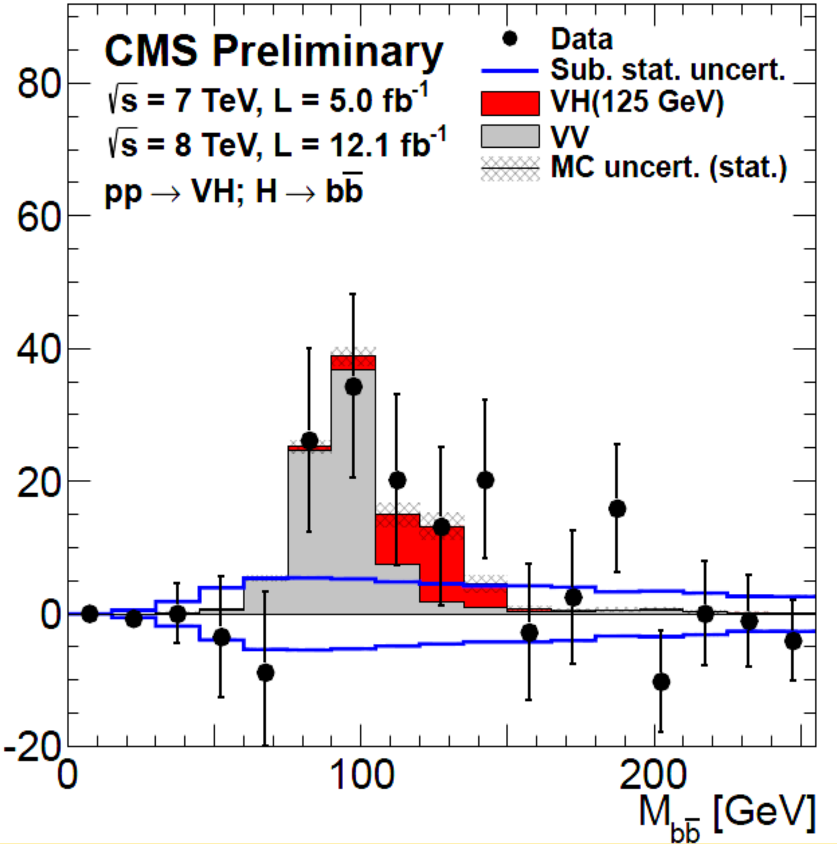


VH ➡ V $b\bar{b}$ Signal Extraction
Example: All Channels, High P_T(V) Bin

M($b\bar{b}$) Distribution After Selection



M($b\bar{b}$) After Background Subtraction (Except VV)



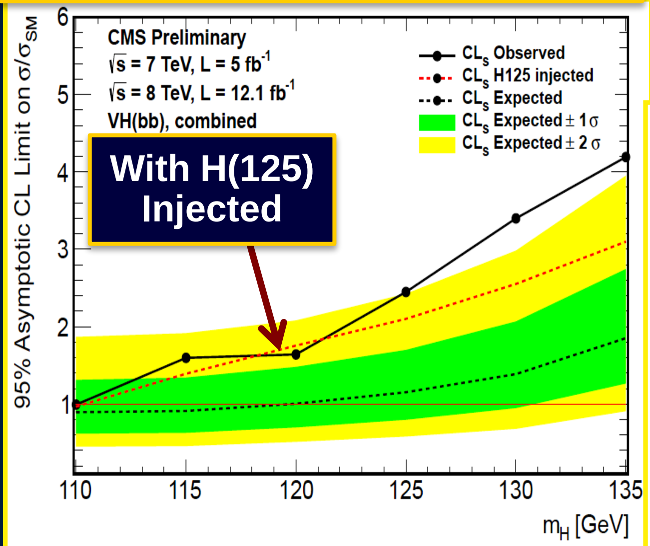
Consistent with Diboson Expectation plus a small excess in the Signal Region

VH → V$b\bar{b}$: Results

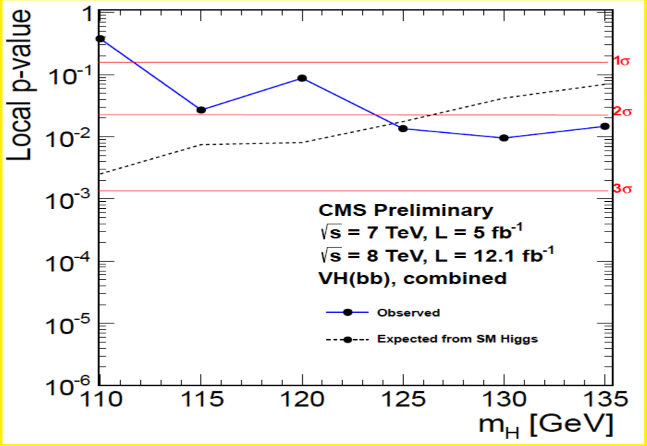
HCP

Local Significance and signal strength

95% CL Limits on σ/σ_{SM}

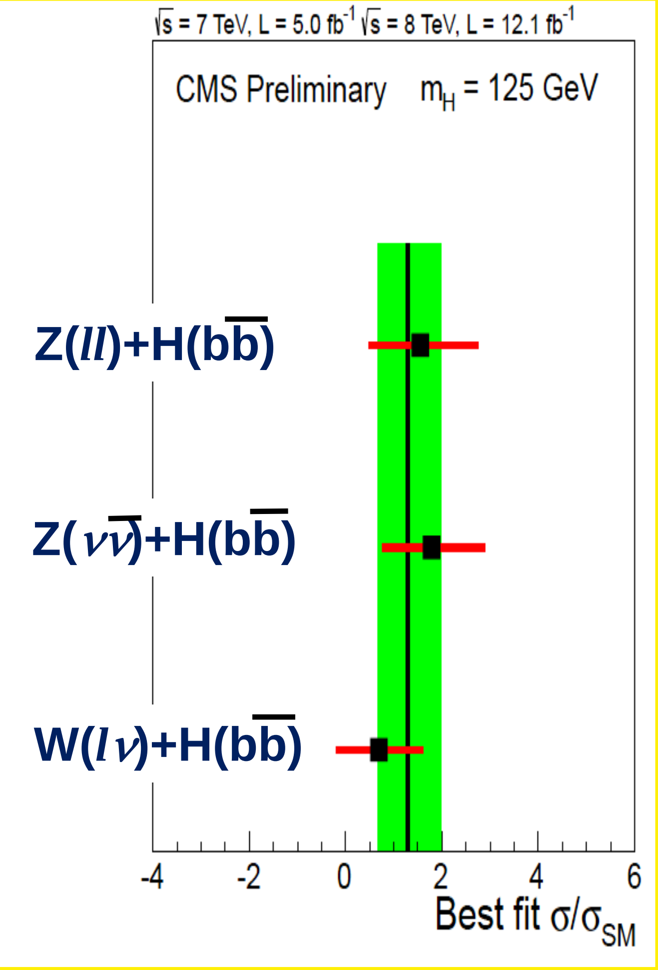


Local p-values Vs. M_H



Best Fit σ/σ_{SM}

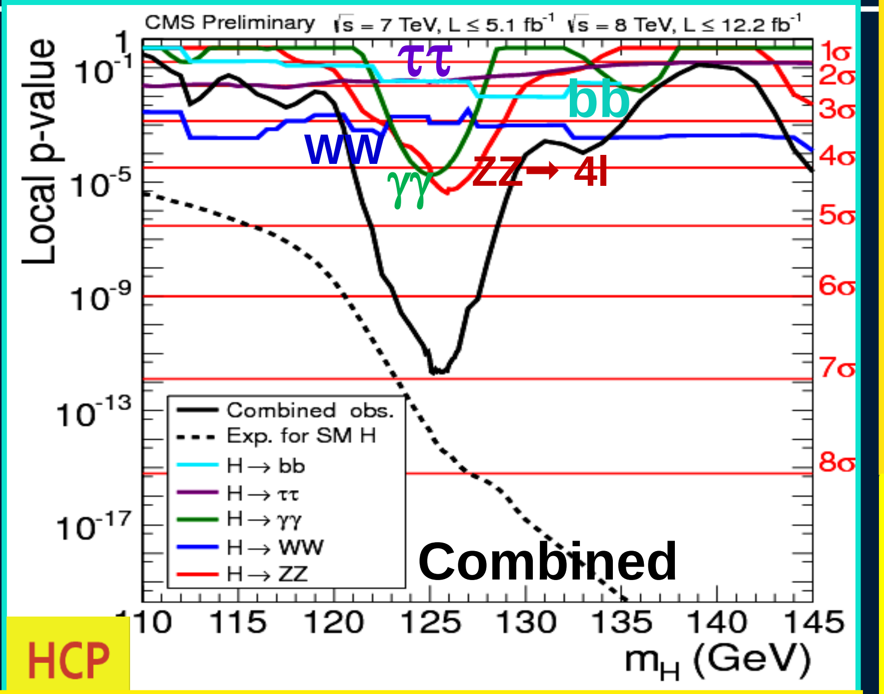
Channels are compatible within errors (M_H = 125 GeV)



- Observed σ/σ_{SM} limit is 2.5 at 125 GeV
  - Expected Limit with no SM Higgs is 1.2
- Observed local significance is 2.2σ
  - Expected Limit is 2.1σ with presence of SM H at 125 GeV
  - Compatible with SM
- Combined best fit signal strength σ/σ_{SM} is $\mu = 1.3^{+0.7}_{-0.6}$

Observation of a New Boson Near 125.8 GeV

p-values and Significance by Channel HCP



	un-tagged	VBF-tag	VH-tag	ttH-tag
γγ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	
WW(lvlv)	✔	✔	✔	
ZZ(4l)	✔			

CMS-HIG-12-045

Excess at ~125.8 GeV:

Combined Significance 6.9 σ

High sensitivity, high mass resolution channels: γγ + 4l

- **ZZ → 4l: 4.4 σ Excess**
- **γγ 4.0 σ Excess**

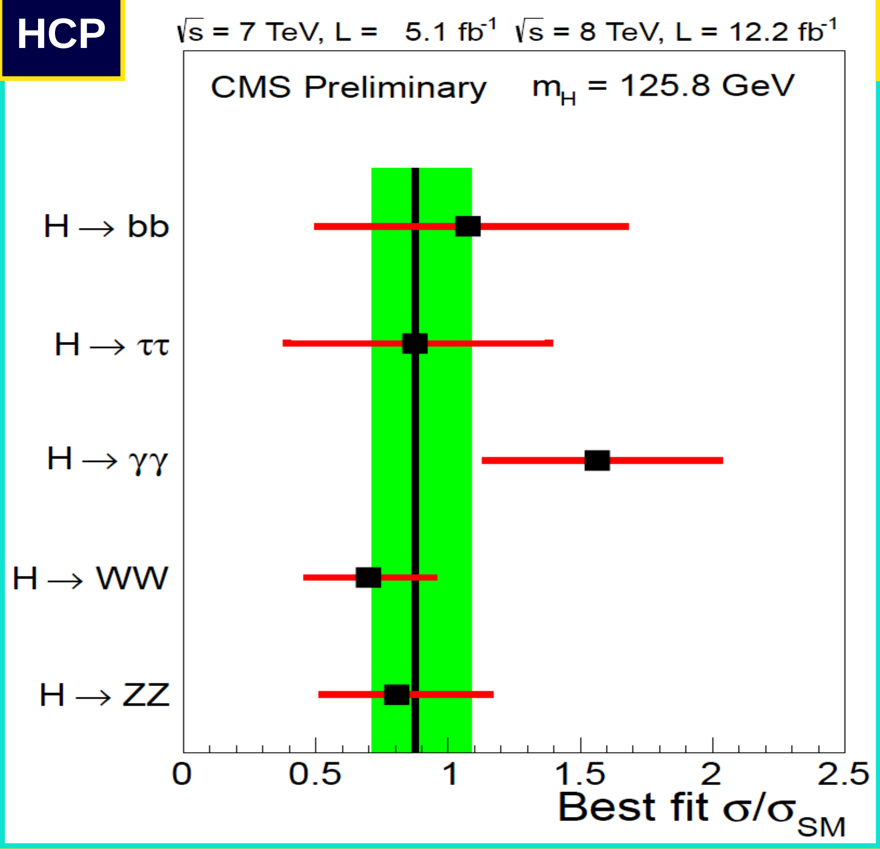
	Expected σ	Observed σ
H→ZZ	5.0	4.4
H→γγ	2.8	4.0
H→ WW	4.3	3.0
H→ bb	2.2	1.8
H → ττ	2.1	1.8
H → γγ+ZZ+WW + ττ + bb	7.8	6.9

Compatibility with SM Higgs boson

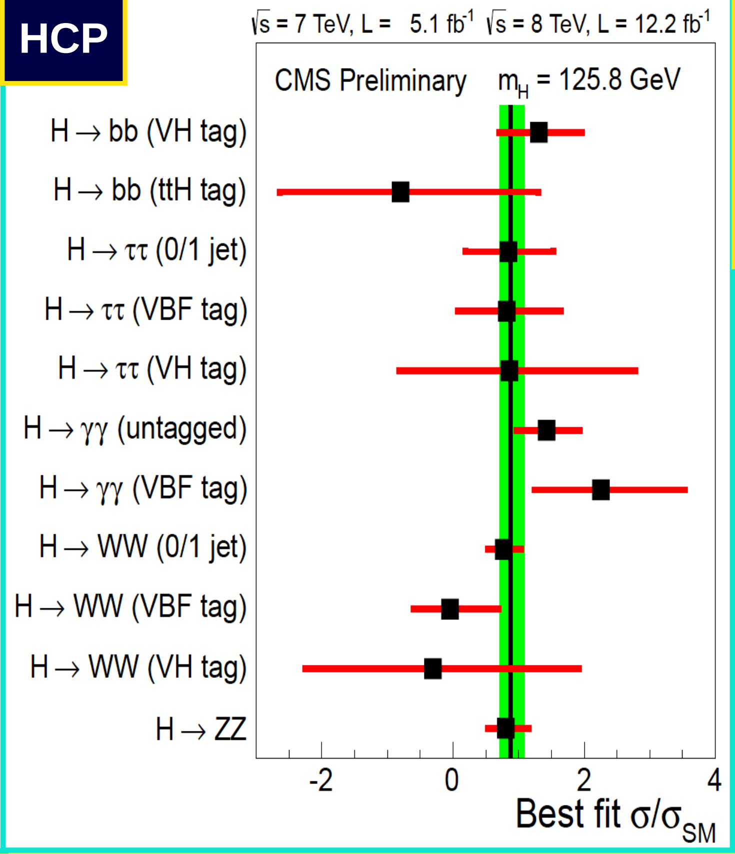
Best Fit σ/σ_{SM} grouped
by Decay Mode

σ/σ_{SM} grouped
by prod. and decay mode

HCP



HCP

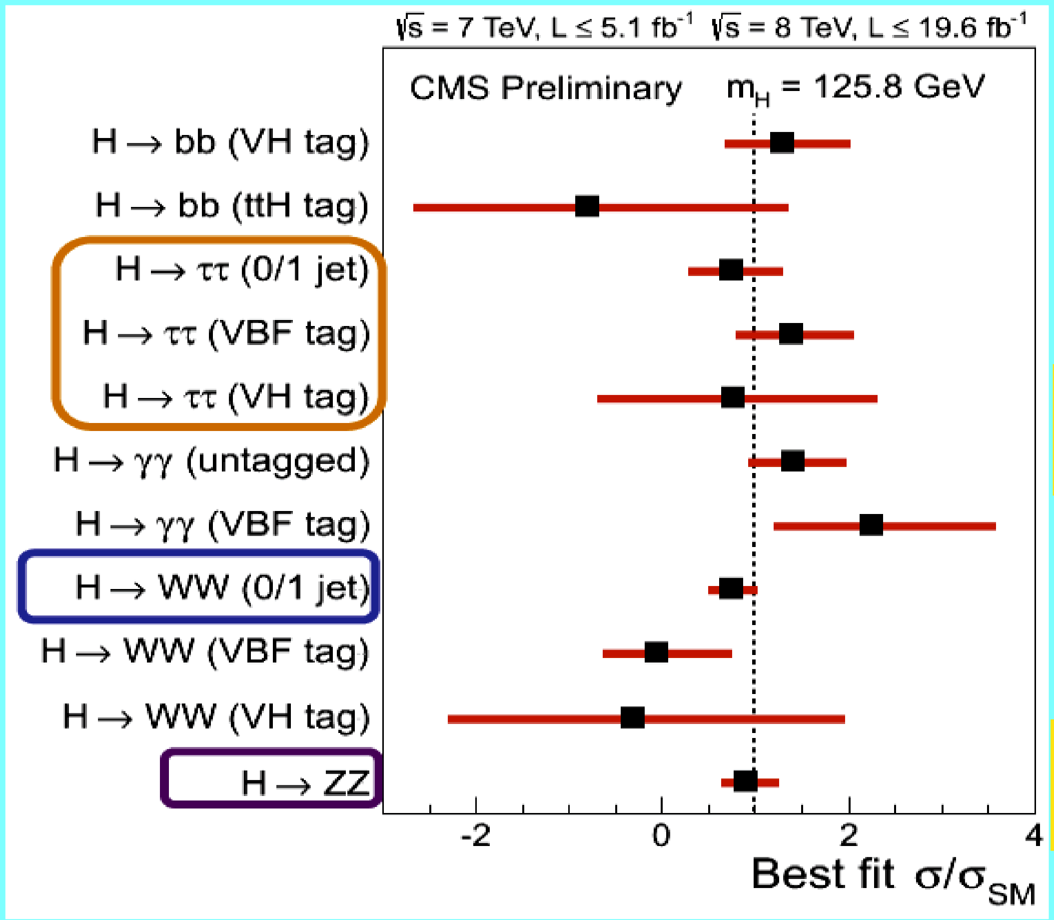


Compatible with SM:
χ^2/NDF = 8.7/11
Prob. = 0.65

HCP **Overall best-fit signal strength: σ/σ_{SM} = 0.88±0.21**

Signal strength σ/σ_{SM} in different modes is self-consistent, but some required more data to fully distinguish a SM signal from background

Compatibility: Among Channels and with SM Higgs boson



New updates on some modes using the full 2011-12 dataset:

ττ, WW, ZZ

H → ττ: $\mu = 1.1 \pm 0.4$

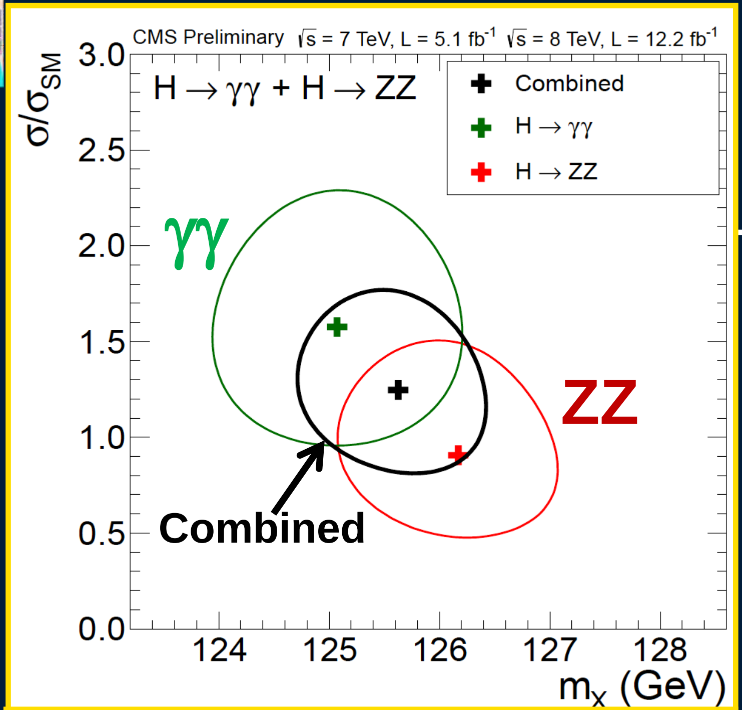
H → WW: $\mu = 0.76 \pm 0.21$

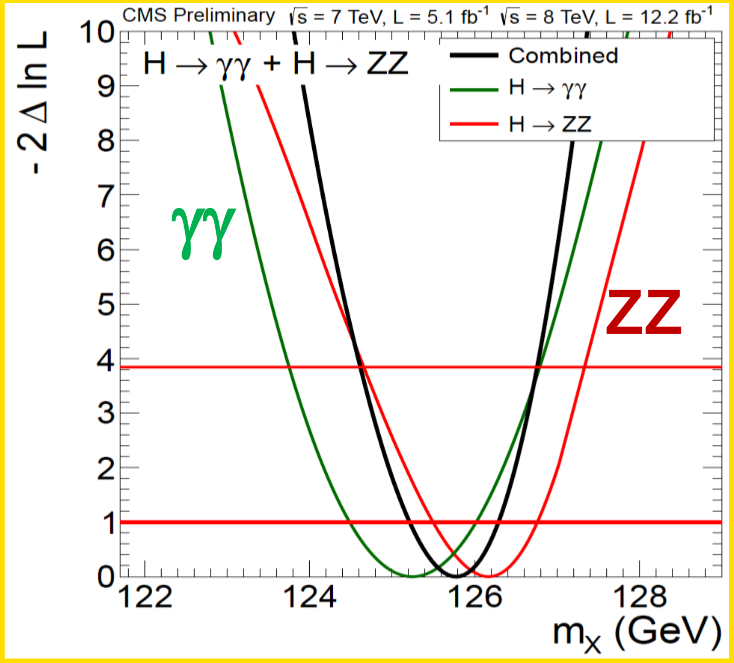
H → ZZ: $\mu = 0.91^{+0.30}_{-0.24}$

New (and older) results are compatible with the SM Higgs boson

Also Note Latest H → γγ Result on Full Dataset: $\mu = 0.78^{+0.28}_{-0.26}$

Characterization of the Boson: the Mass





- Assume one particle, use sub-channels with good mass resolution:

  γγ(untagged), γγ(VBF), ZZ(4l)

- Do a likelihood scan for the Mass & Signal Strength
- Results are self-consistent; can be combined
- To reduce model dependence, float cross sections in 3 channels; do 1D fit for a common mass:

m_X = 125.8 ±0.4(stat) ±0.4 (syst) GeV

Couplings Compatibility Tests

LHC Higgs Cross-Section WG: A. David et al, arXiv:1209.0040

- Assumptions: Single resonance, zero width, SM tensor structure
- There are 8 Independent parameters to describe all the currently relevant decays and production mechanisms:
- $\Gamma_{ZZ}, \Gamma_{WW}, \Gamma_{\tau\tau}, \Gamma_{bb}, \Gamma_{\gamma\gamma}, \Gamma_{gg}, \Gamma_{tt}$ and Γ_{TOT} which are given by:

$$N(xx \to \mathrm{H} \to yy) \sim \sigma(xx \to \mathrm{H}) \cdot B(\mathrm{H} \to yy) \sim \frac{\Gamma_{xx}\Gamma_{yy}}{\Gamma_{\mathrm{tot}}}$$

- We cannot extract all 8 parameters with the current data.
- So instead we do coupling compatibility tests in terms of scale factors relative to the SM: for the couplings κ, or ratios of the scale factors λ
- Example: For the gg → H → $\gamma\gamma$ process:

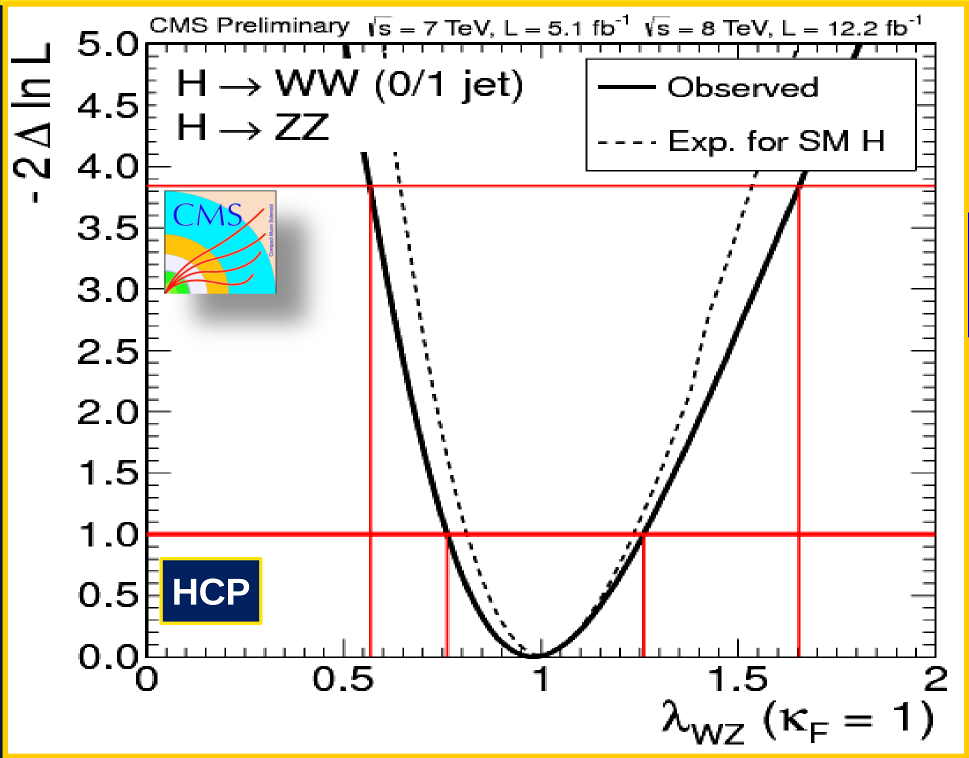
$(\sigma \times \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H)\, \mathrm{BR}(H \to \gamma\gamma) \bullet \kappa_g^2 \kappa_\gamma^2 / \kappa_H^2$

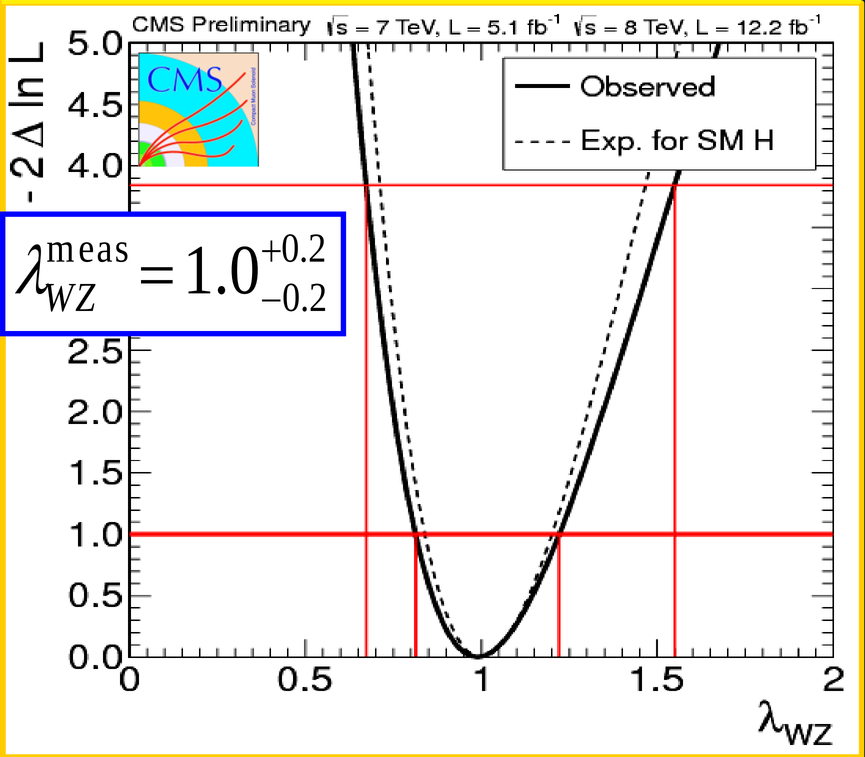
Custodial Symmetry

Test the Ratio of Couplings to the W and Z Bosons

- κ_Z, $\lambda_{WZ} = \kappa_W / \kappa_Z$ Profiled
- $\kappa_F = 1$ as in SM

- Full profiling of κ_Z, κ_F
- λ_{WZ} in [0.68 - 1.55] 95%CL





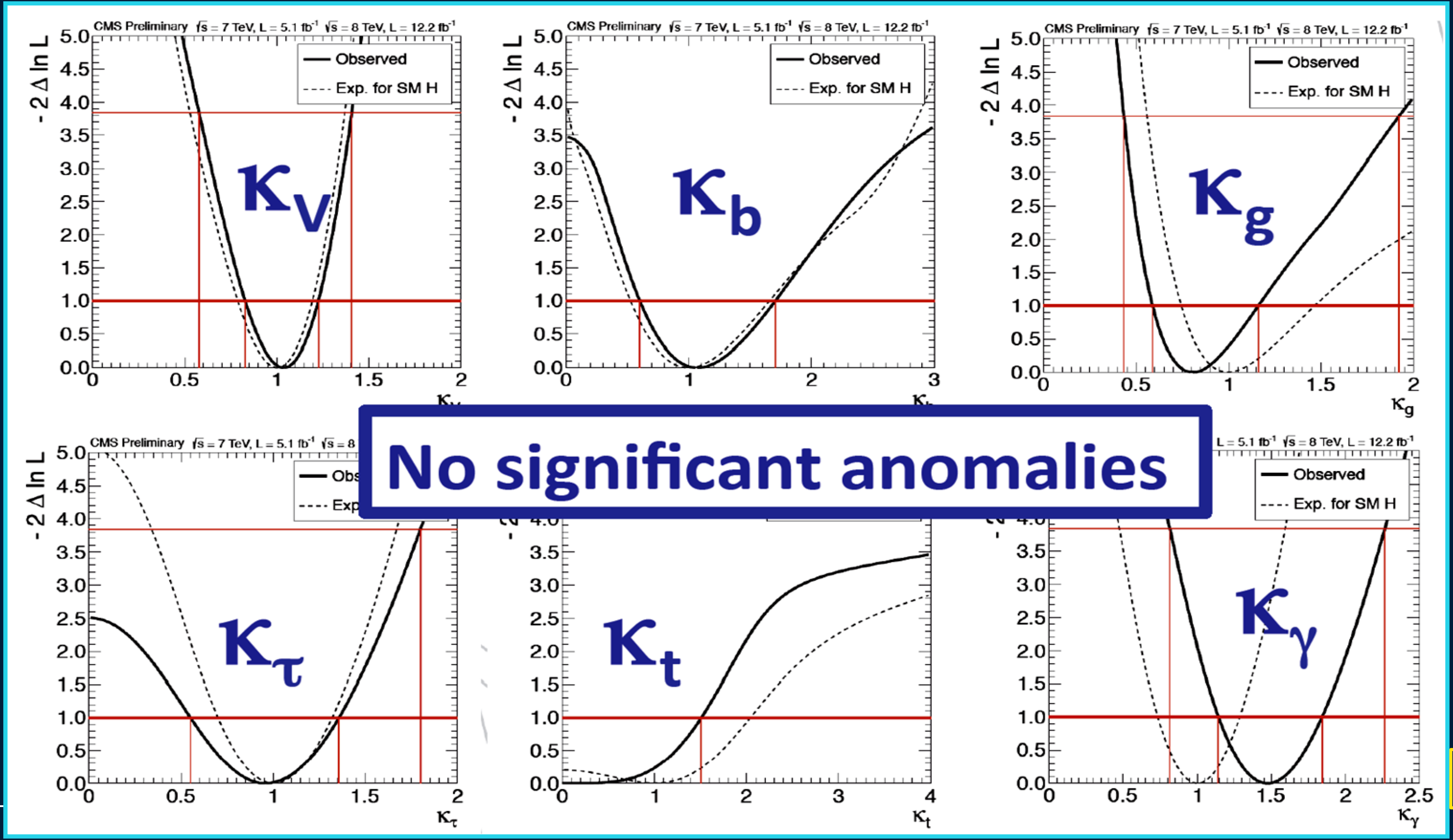
$$\lambda_{WZ}^{meas} = 1.0^{+0.2}_{-0.2}$$

$\lambda_{WZ} = \kappa_W / \kappa_Z$ is compatible with 1 (Custodial Symmetry) as in SM. Errors still relatively large

Six Coupling (C6) Model

Assume Custodial Symmetry $\kappa_Z = \kappa_W = \kappa_V$, $BR_{BSM}=0$

- End up with six scale factors: $\kappa_V, \kappa_t, \kappa_b, \kappa_\tau, \kappa_g, \kappa_\gamma$
- Fit each one of these while profiling the others

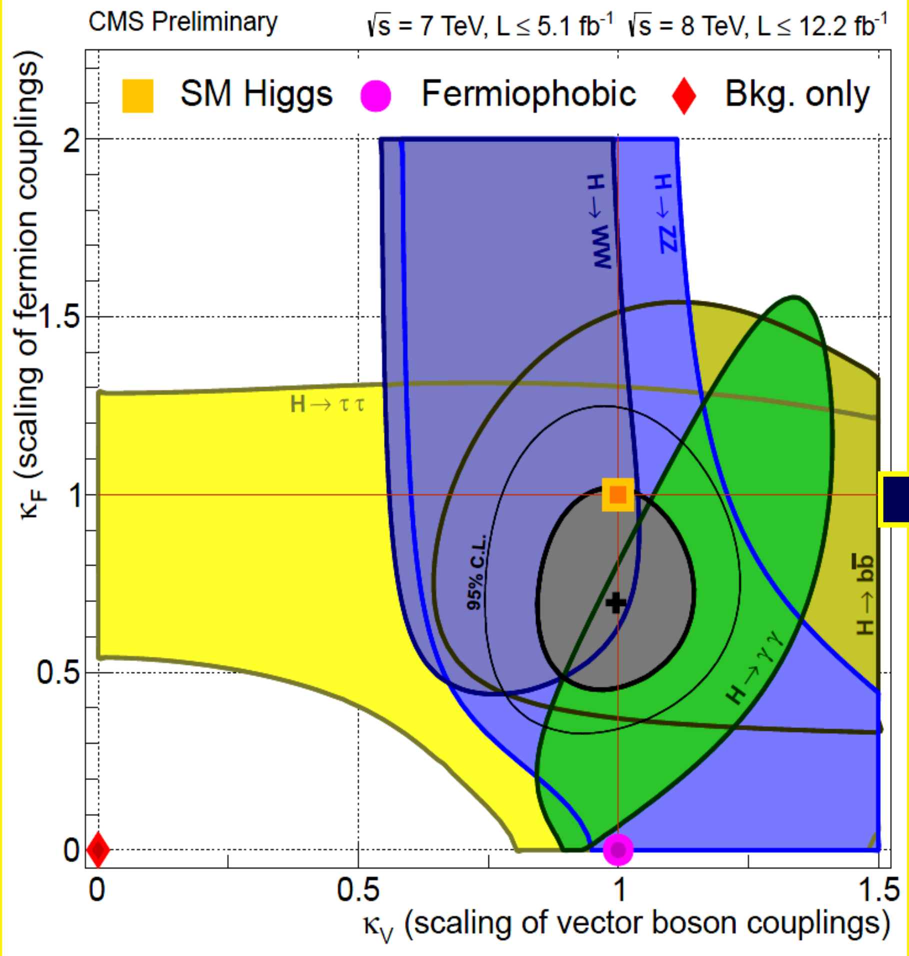


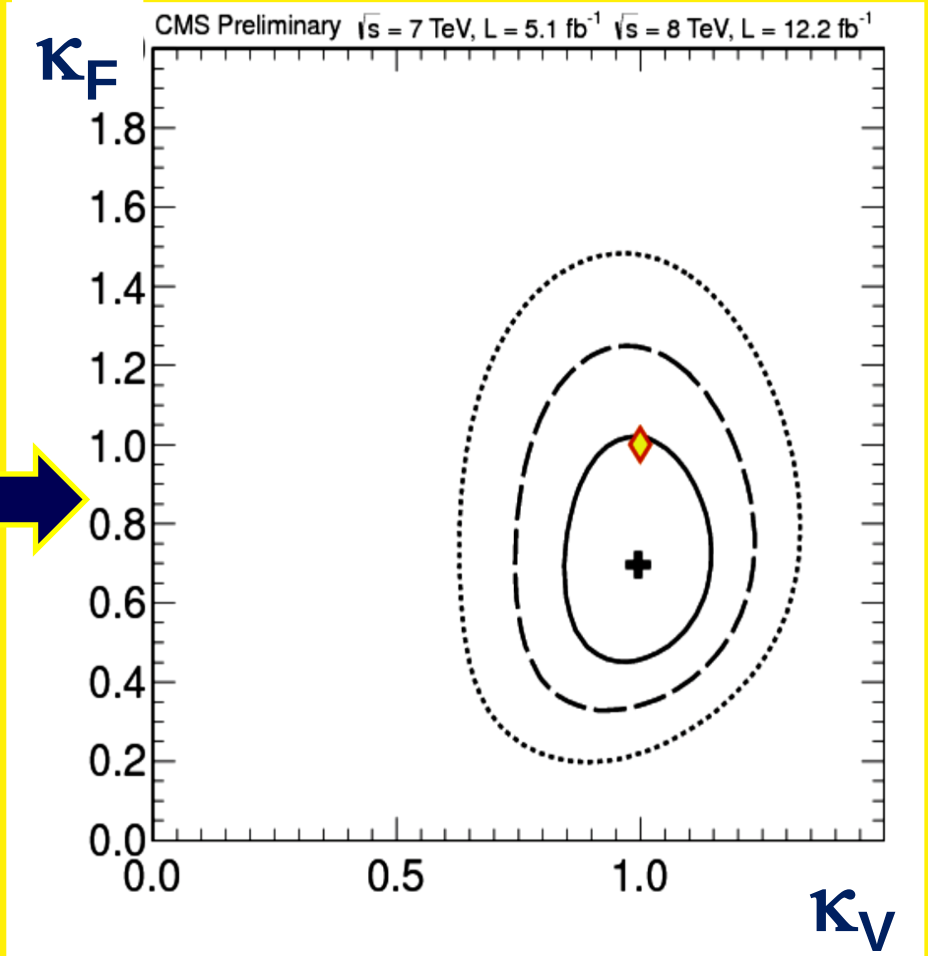
No significant anomalies

HCP

κ_V and κ_F: Map the Vector Boson and Fermion Couplings to Two Scale Factors

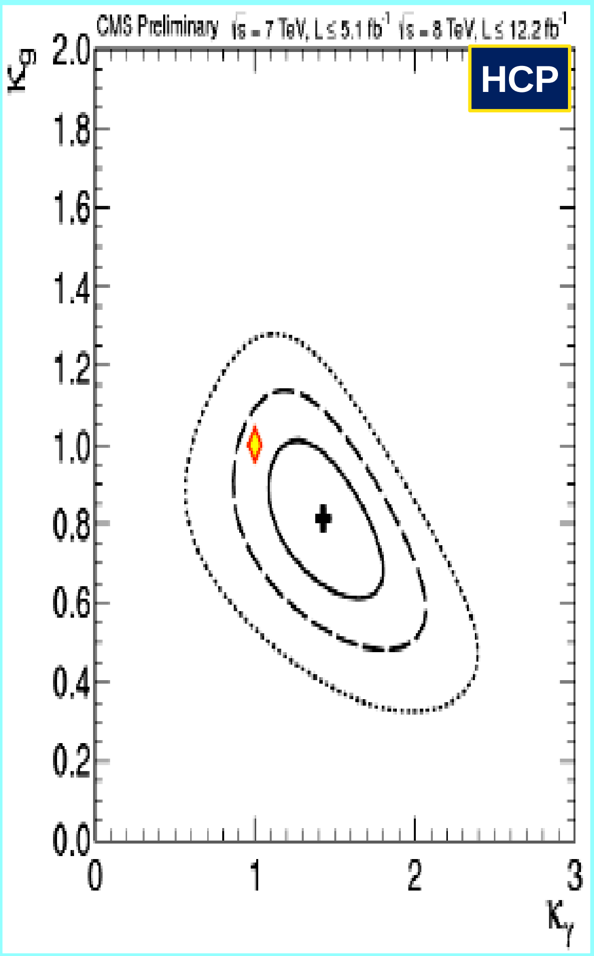
Assume custodial symmetry and fermion universality

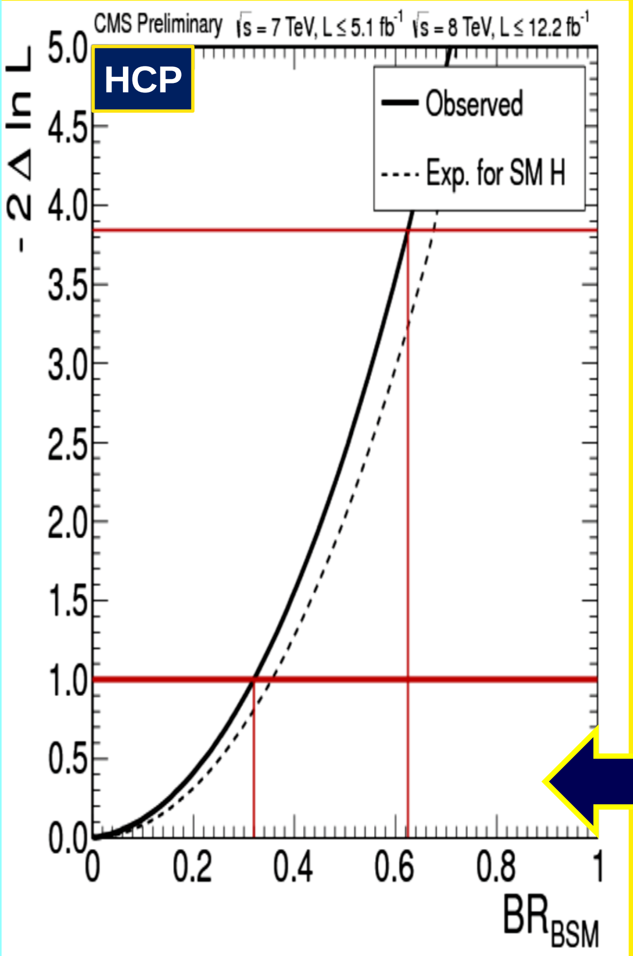




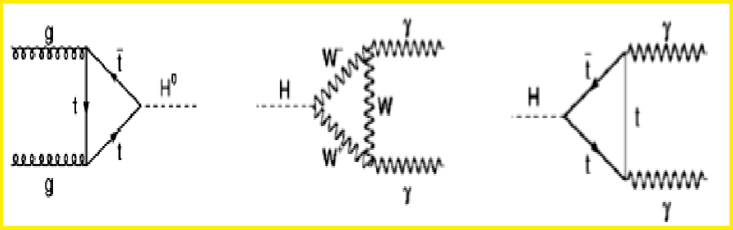
Data are consistent with the SM: κ_V =1; κ_F = 1

Searching for New Physics in the Boson's Total Width ➡ BR$_{BSM}$





- New Particles can hide in the loop-mediated couplings



- And contribute to the total width
- Affects κ_g, κ_γ, κ_H

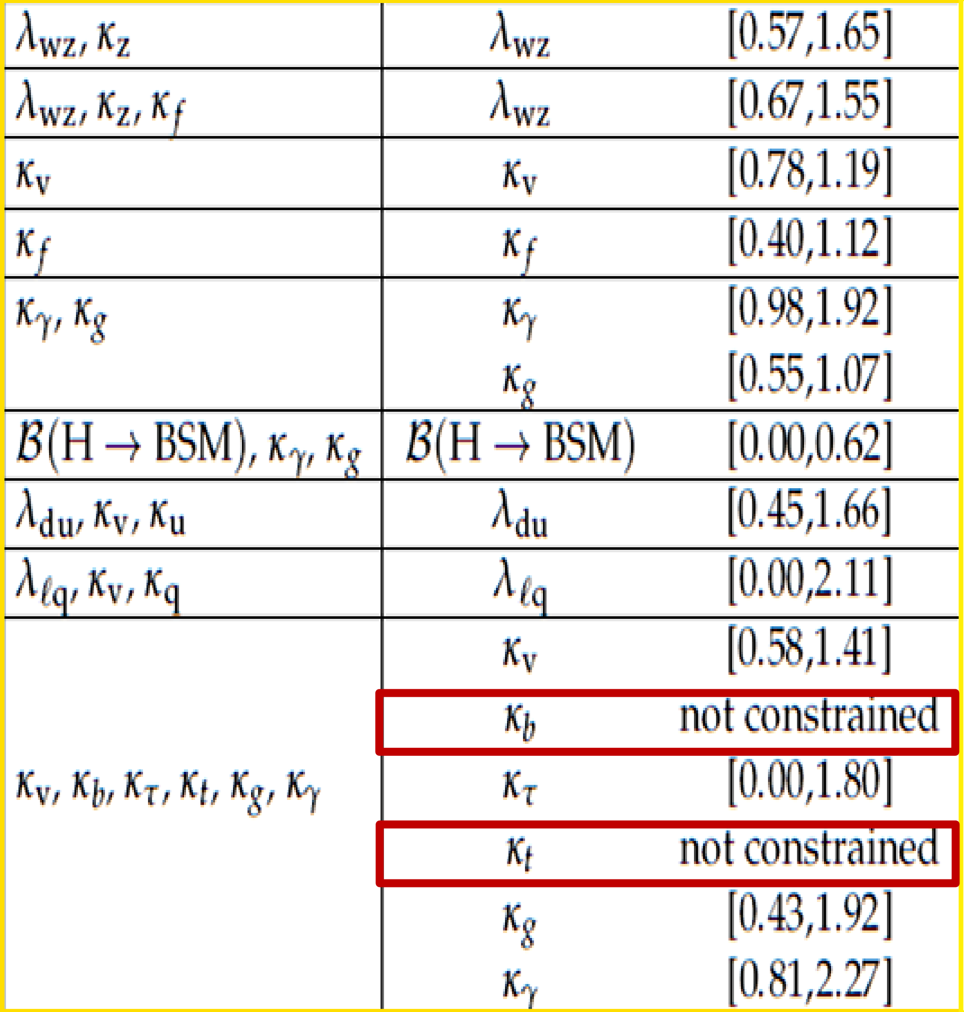
Allow the total width to scale as $1/(1 - BR_{BSM})$

Result: $BR_{BSM} < 0.62$ at 95% CL

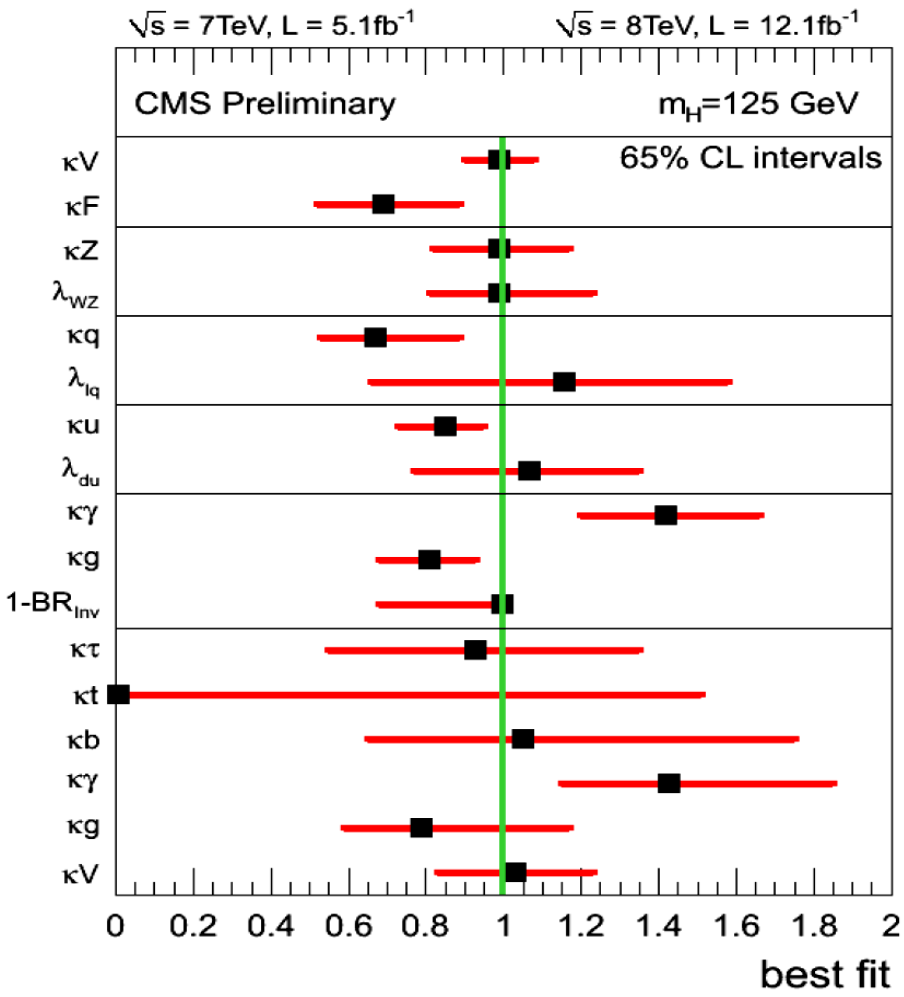
All the Boson Couplings and Ratios

Many Constrained at 95% CL

HCP



λ_{wz}, κ_Z	λ_{wz}	[0.57,1.65]
$\lambda_{wz}, \kappa_Z, \kappa_f$	λ_{wz}	[0.67,1.55]
κ_V	κ_V	[0.78,1.19]
κ_f	κ_f	[0.40,1.12]
κ_γ, κ_g	κ_γ	[0.98,1.92]
	κ_g	[0.55,1.07]
$\mathcal{B}(H \to BSM), \kappa_\gamma, \kappa_g$	$\mathcal{B}(H \to BSM)$	[0.00,0.62]
$\lambda_{du}, \kappa_V, \kappa_u$	λ_{du}	[0.45,1.66]
$\lambda_{\ell q}, \kappa_V, \kappa_q$	$\lambda_{\ell q}$	[0.00,2.11]
$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_V	[0.58,1.41]
	κ_b	not constrained
	κ_τ	[0.00,1.80]
	κ_t	not constrained
	κ_g	[0.43,1.92]
	κ_γ	[0.81,2.27]



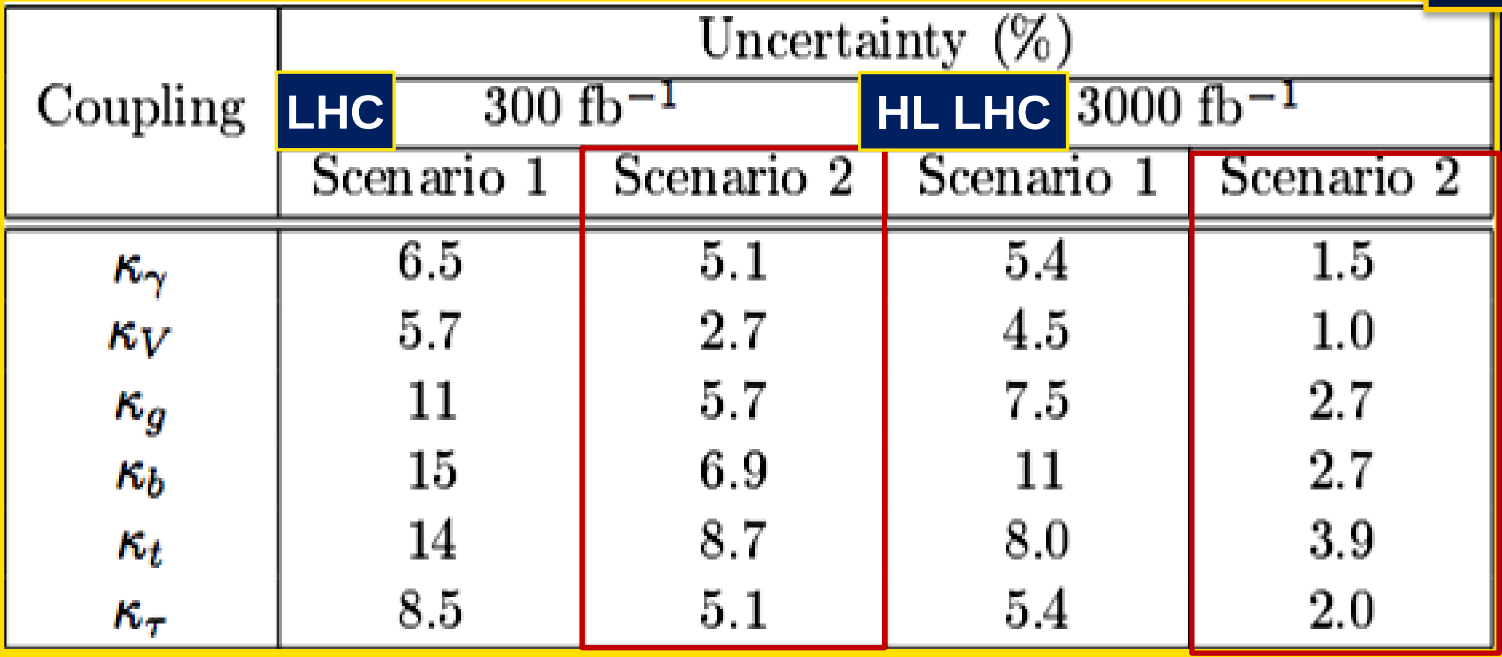
Bottom line: compatible with SM. **Some errors still large.**

Will improve with analysis on full dataset

CMS Coupling Determination Projections
At LHC (300 fb^{-1}) and HL-LHC (3000 fb^{-1})

Two scenarios

1. Experimental+theoretical systematics unchanged ⇐ **Pessimistic**
2. Scale experimental systematics with √L + *reduce theoretical uncertainties by 50%* ⇐ **Optimistic: + a challenge for theorists**



Coupling	Uncertainty (%)			
	LHC 300 fb^{-1}		**HL LHC** 3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Precision on the Couplings:

6-15 (3-9)% with 300/fb

5-11 (1-4)% with 3000/fb

H →μμ decay rate: preliminary studies indicate 5σ significance; between 25% and 10% precision on H to μμ coupling at HL LHC

BSM Higgs Overview

- Extensions to the SM
  - Fermiophobic Higgs sector
  - 4th generation of heavy fermions
- Supersymmetric
  - MSSM with two Higgs doublets:
    - ✓$H^0 \rightarrow$ bb, $\tau\tau$
    - ✓$H^\pm \rightarrow \tau\nu$
  - NMSSM with additional scalar field $a_1 \rightarrow \mu\mu$
- Triple your fun
  - Minimal Type II Seesaw Model: Relate to ν mass* + NP
  - Triplet scalar field → Doubly charged Higgs

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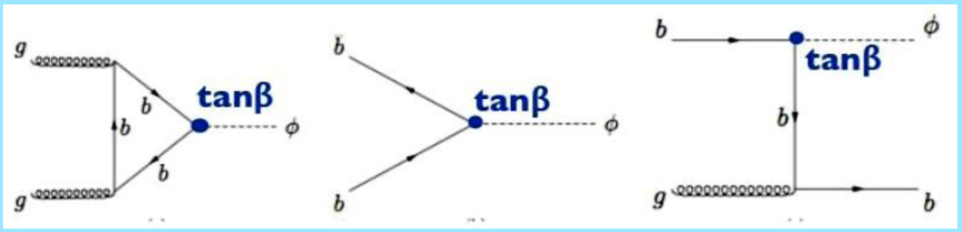
*Grimus et al http://arxiv.org/pdf/0902.2325v3.pdf

MSSM Higgs



- **Two Higgs doublets**
  - Five Higgs particles
    - Three neutral $\Phi = $ h, H, A
    - Two charged ($H^{\pm}$)
  - Two free parameters
    - Search in m_A – tan β plane
- **Production enhanced: $\tilde{b}$, $\tilde{t}$ loops**

Coupling ∝ $\tan^2\beta$ for tan β > ~7

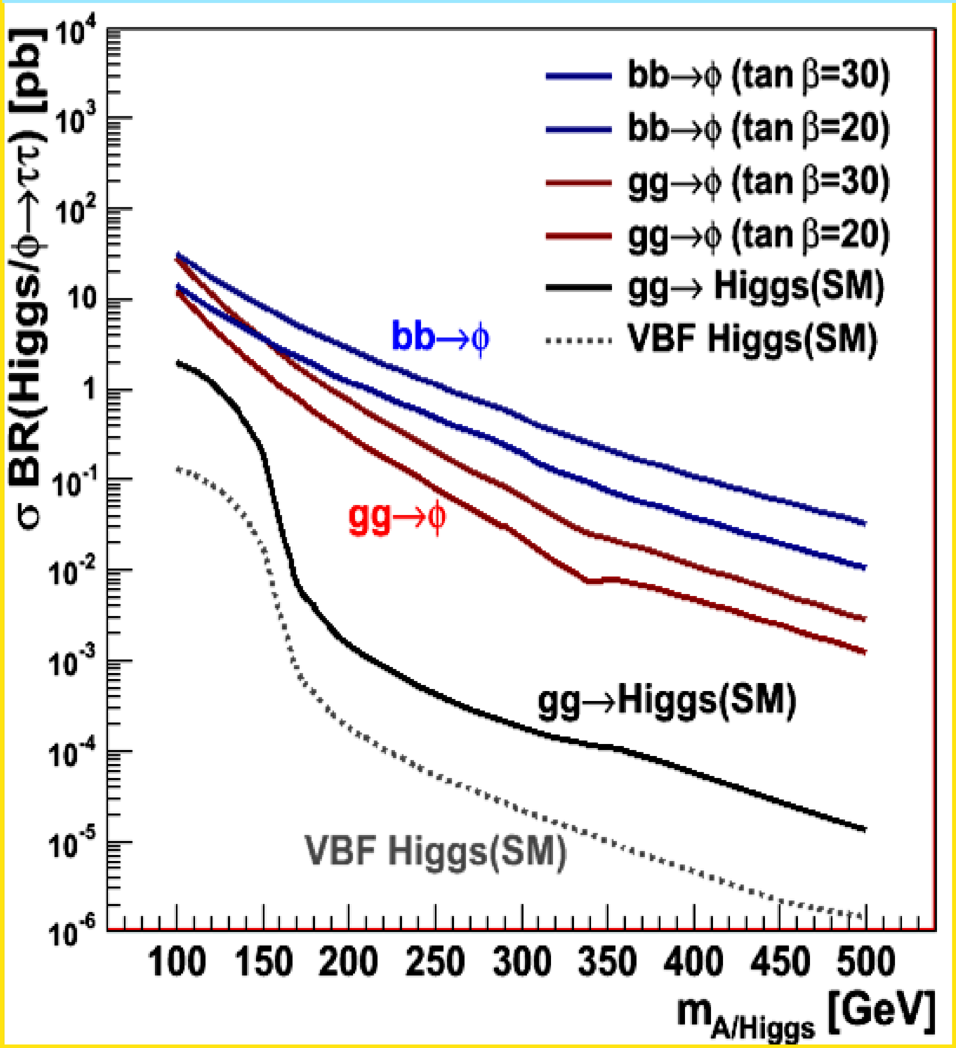
- **Searches @ CMS**

➡ **Neutral Φ: $\tau\tau$ (and bb,$\mu\mu$)**

$pp \rightarrow \Phi \rightarrow \tau\tau$; Φ b → bbb, with semileptonic, hadronic b-decays

➡ **Charged $H^{\pm}$: look in top decays:**

$t\bar{t} \rightarrow H^+W^-bb$ or H^+H^- bb with $H \rightarrow \tau\nu$



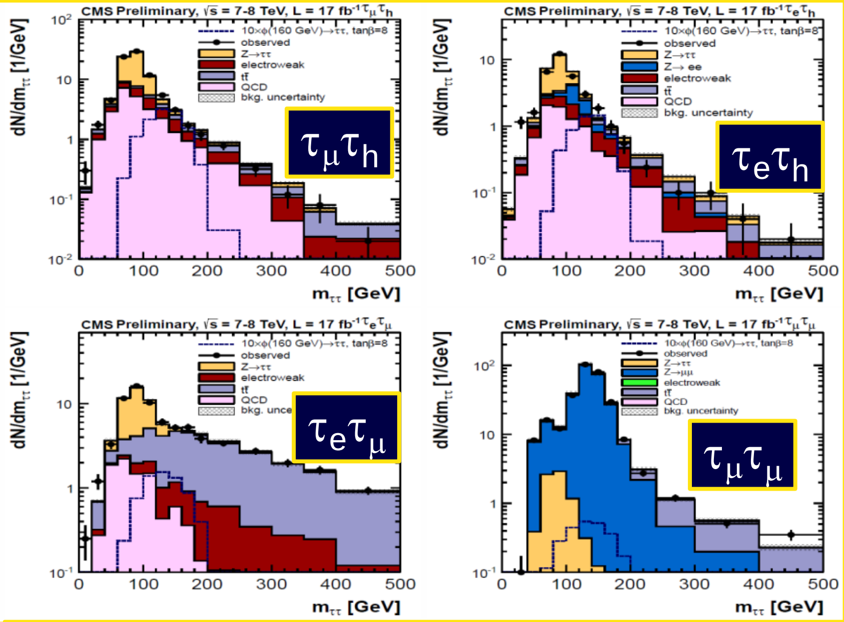
MSSM Φ(h, H, A) →ττ

Enhanced coupling to b quarks,
add associated production via b-tags

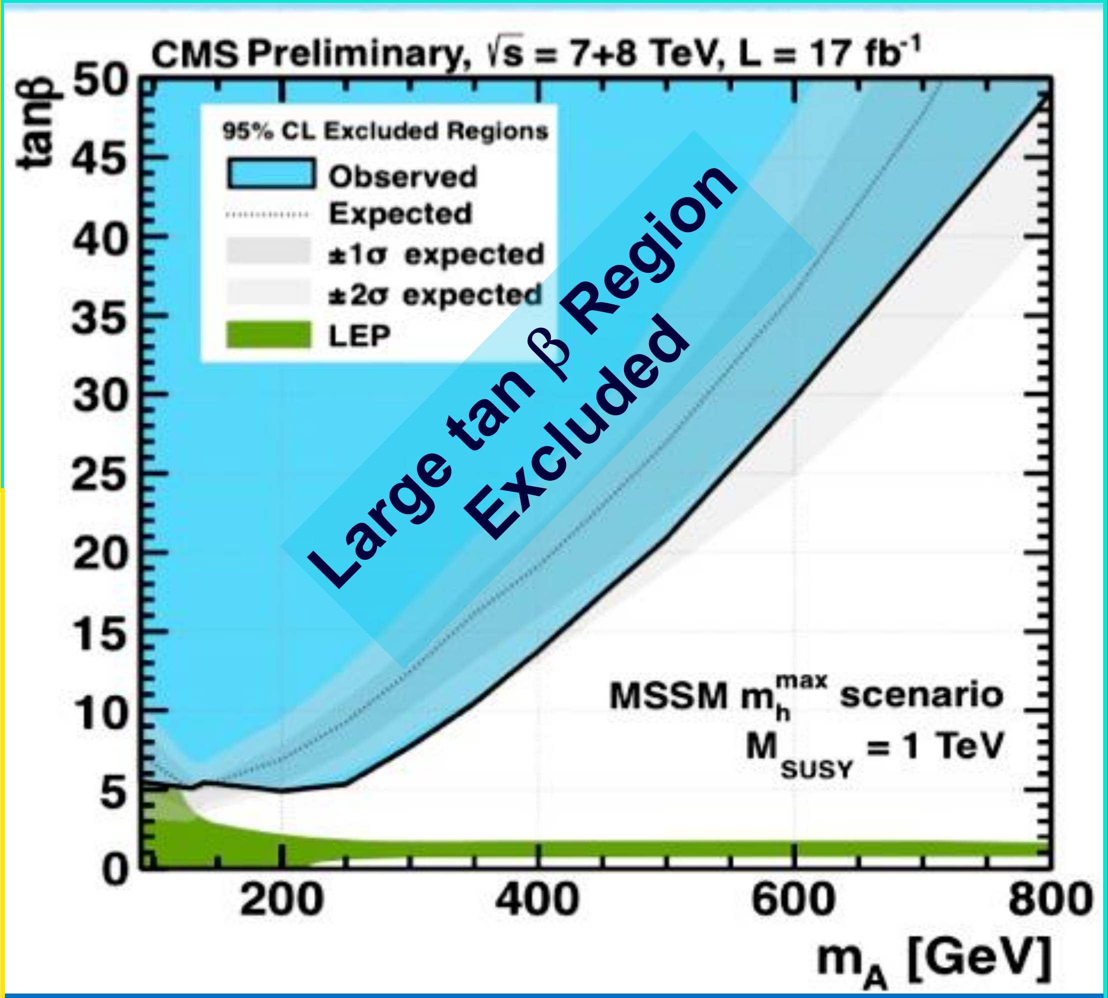
CMS PAS
HIG 12-050

- b-tag and no b-tag (ggF) classes
- ττ Mass constructed via Max. Likelihood technique using
  - τ decay kinematics
  - Compatibility of E_T^{Miss} with neutrino hypothesis

➡ Resulting $M_{\tau\tau}$ resolution is ~15-20% Almost Gaussian



$m_{\tau\tau}$ in the b-tag categories



Large tan β Region Excluded

Limit obtained by scanning tan(β) for each Mass hypothesis M_A:

m_h^{Max} scenario provides conservative limits

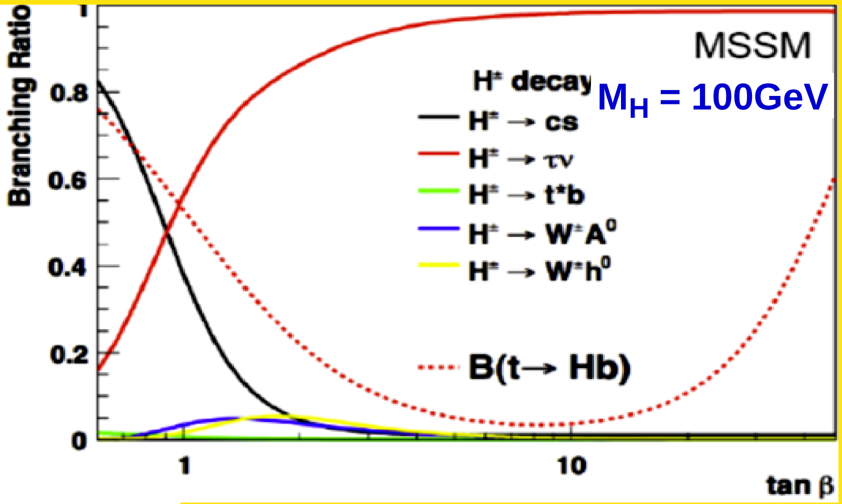
Charged Higgs in Top Quark Decays

Signatures: τ_h+Jets $\mu\tau_h$ $e\tau_h$ $e\mu$

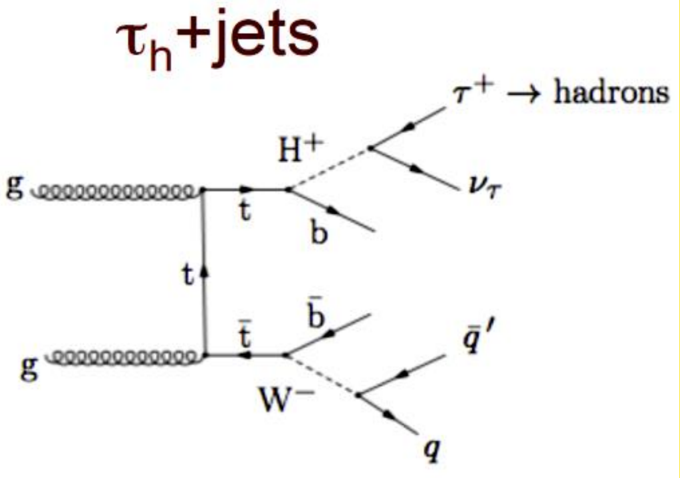
JHEP 07(2012)143
CMS-PAS-HIG-12-052

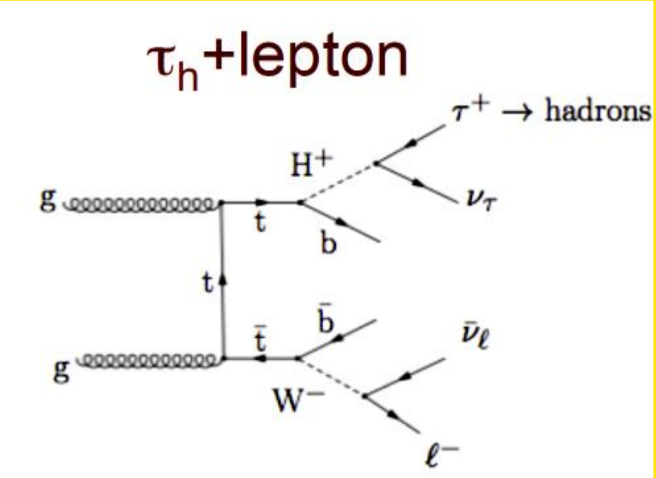
- **Strategy:**
  - **Look for $t\,\bar{t} \rightarrow (H^+b)\,(W^-b)$ or $(H^+b)\,(H^-\,b)$ with $H \rightarrow \tau\nu$**
  - **Three classes of events:**
    1. **All hadronic with jets + $\tau \rightarrow$ hadrons**
    2. **Lepton+jets with $\tau\rightarrow$ hadrons**
    3. **Dilepton in the $e\mu$ channel**

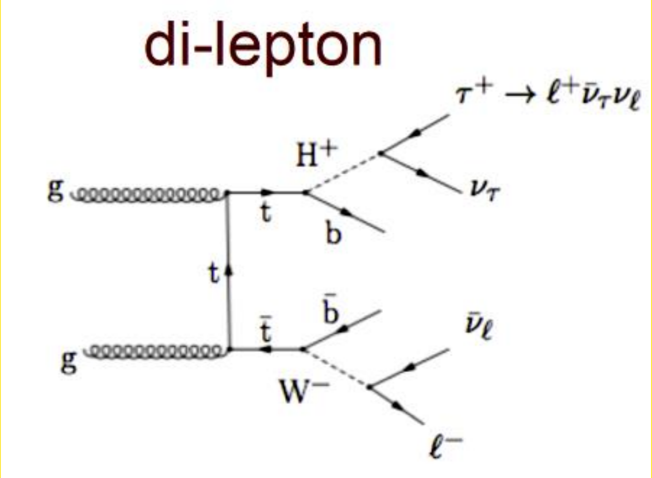
BR ($t \rightarrow Hb$) large for small or large tan β



M_H = 100GeV


τ_h+jets


τ_h+lepton


di-lepton

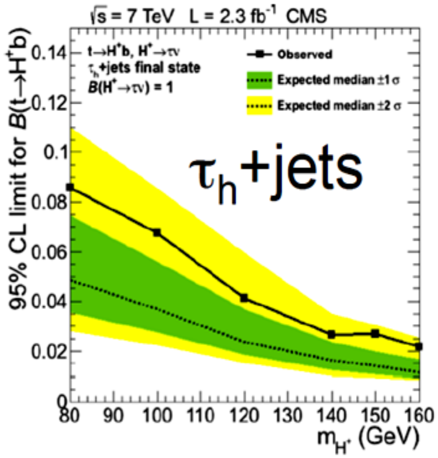
Studies assuming BR ($H \rightarrow \tau\nu$) = 1

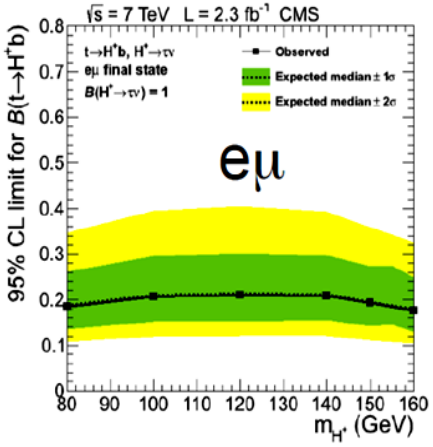
Charged Higgs Results

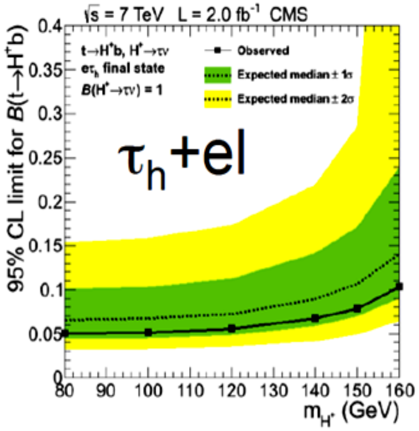
Limits in Each Channel and Combined

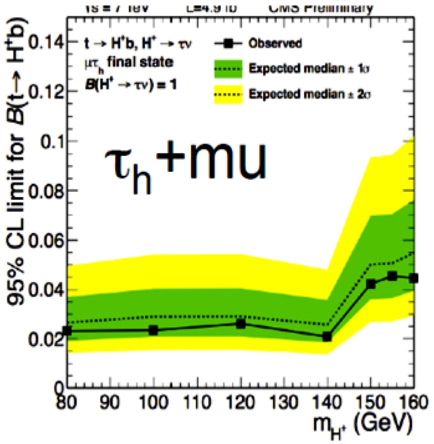
signal modeled as excess/deficit of event yields

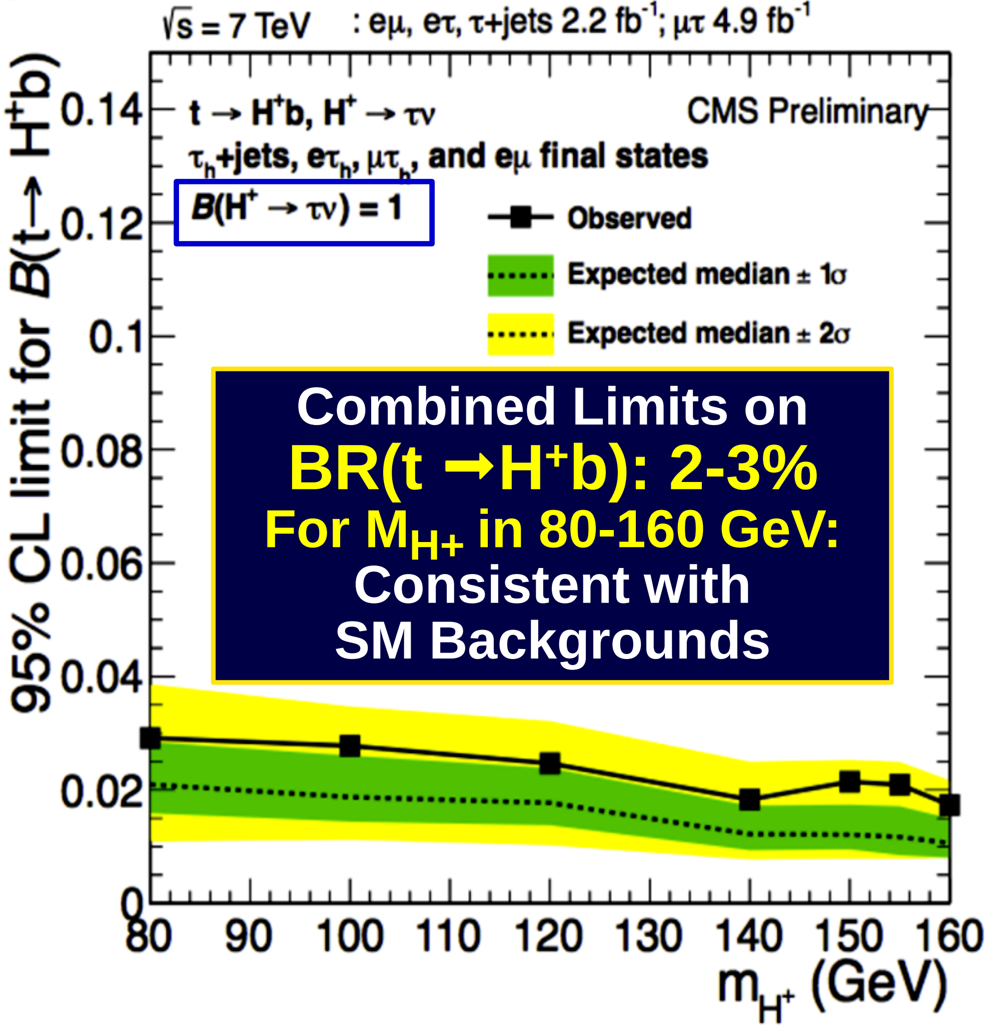
$$\Delta N = N_{t\bar{t}}^{\rm MSSM} - N_{t\bar{t}}^{\rm SM} = 2x(1-x)N_{\rm WH} + x^2 N_{\rm HH} + [(1-x)^2 - 1]N_{t\bar{t}}^{\rm SM}$$











Combined Limits on
BR(t →H⁺b): 2-3%
For M_{H+} in 80-160 GeV:
Consistent with
SM Backgrounds

Summary and Conclusion

- The examination of the new boson in CMS has advanced rapidly; many analyses have been improved; some new ones have begun
- We have made more accurate measurements of the boson’s mass
- We have set new limits on the production of add’l Higgs-like bosons
- We have made new measurements of its decays to bosons in WW and ZZ, and to fermions, especially in the $\tau\tau$ and bb final states
- The boson’s signal strength and couplings, measured in several channels, are compatible with SM expectations
  - But the uncertainties in some channels are still relatively large
- The boson’s spin and parity is compatible with 0+. Several other alternative pure J^P states are disfavored at 98% CL or greater
- We have found no sign of BSM physics in the Higgs width, nor in direct searches for MSSM, fermiphobic, or charged Higgs bosons
- Much has been learned; but these explorations have just begun; The greatest opportunities for discovery lie ahead of us

Many More
CMS Physics Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

For Further Information

- CMS Higgs Results twikipage
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- July 4 Seminar at CERN
  https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=6125
- CMS talks on Higgs searches at ICHEP 2012
  https://indico.cern.ch/conferenceProgram.py?confId=181298
- LHC Implications for TeV Scale Physics
  https://indico.cern.ch/conferenceDisplay.py?confId=173388
- CMS Observation of a New Boson at 125 GeV Paper
  http://cdsweb.cern.ch/record/1470975
- SUSY 2012 Conference Talks
  http://www.phy.pku.edu.cn/~susy2012/
- HCP (Kyoto) Conference Talks

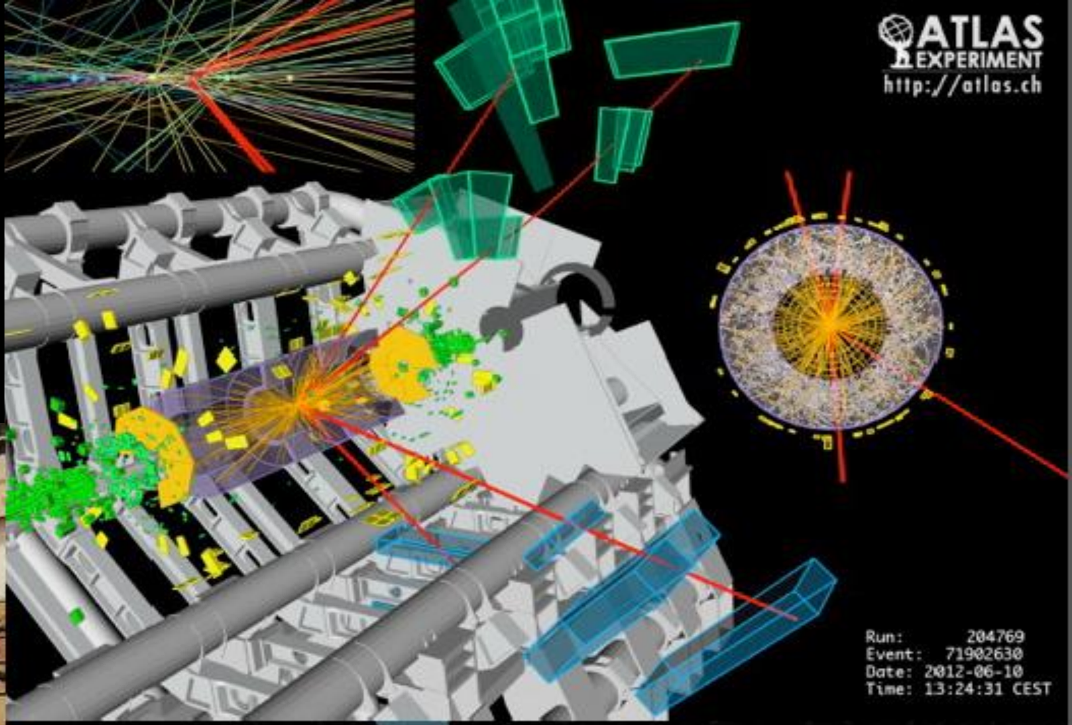
  http://www.icepp.s.u-tokyo.ac.jp/hcp2012/
- Moriond Conference Talks

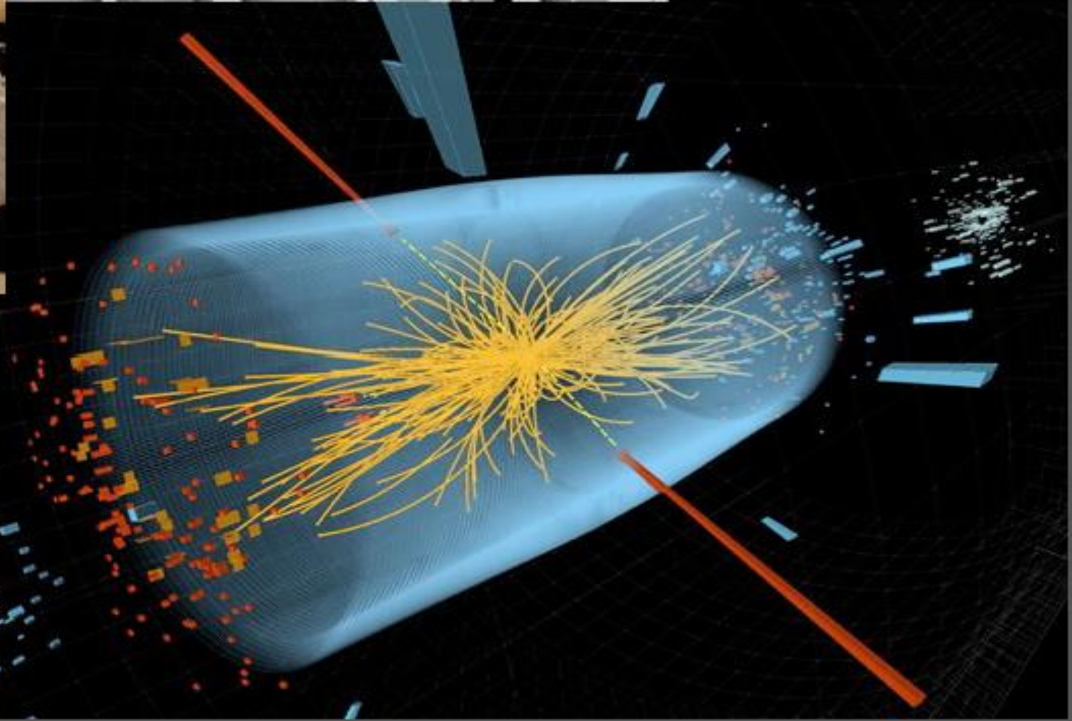
  http://moriond.in2p3.fr/

In the Discovery Era
The Outlook

2012.7.4

discovery of
Higgs-like boson





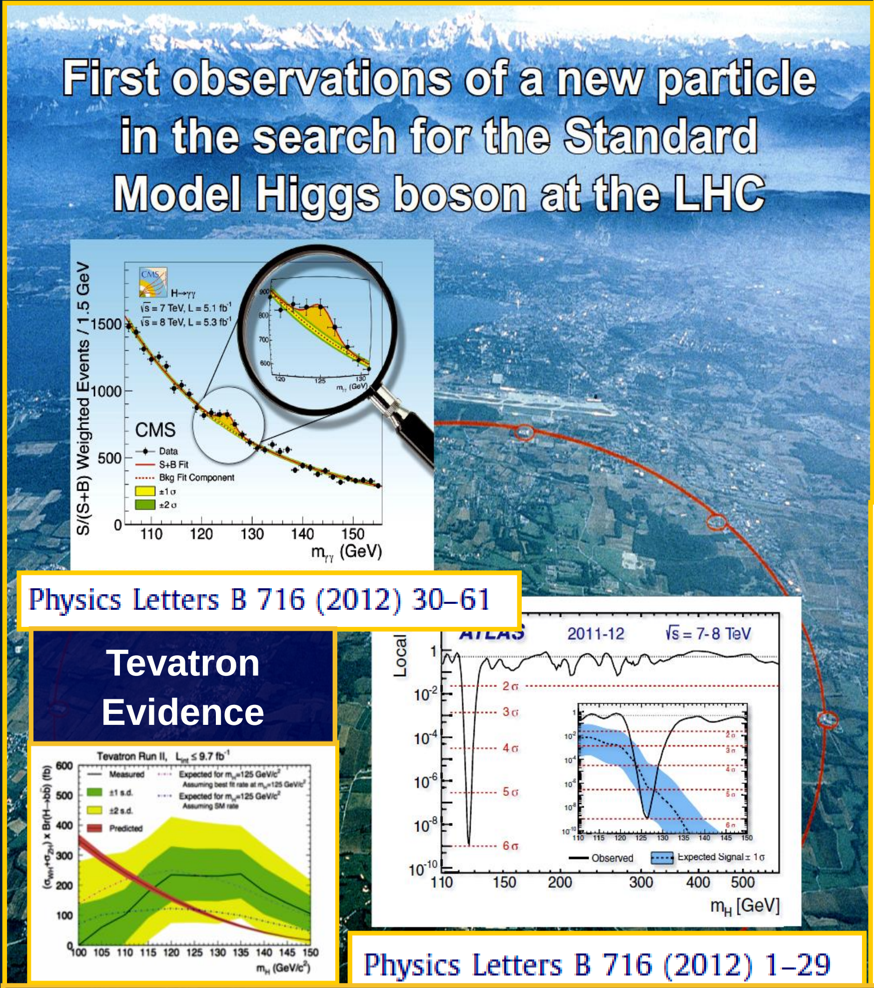
theory：1964

concept：1984

construction：2001

Observation of a New Boson Near 125 GeV

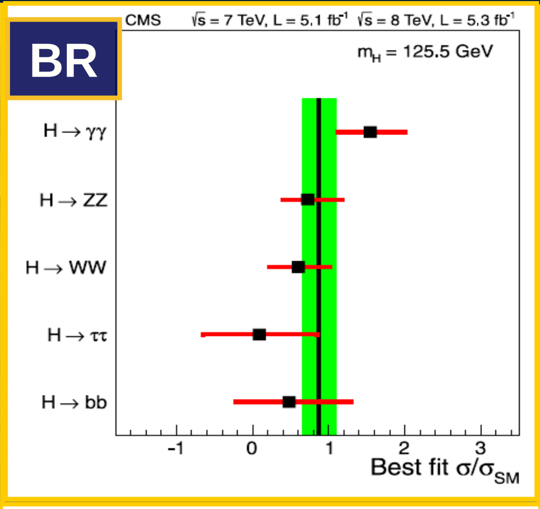
"The Discovery of the Century"

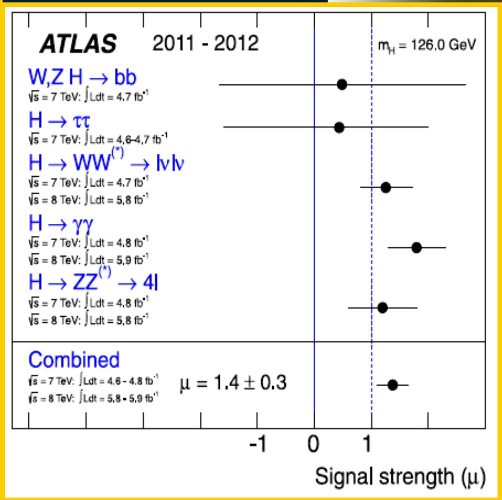


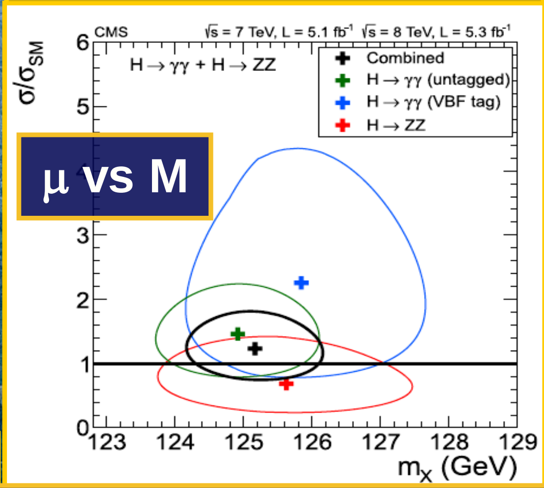
Physics Letters B 716 (2012) 30–61

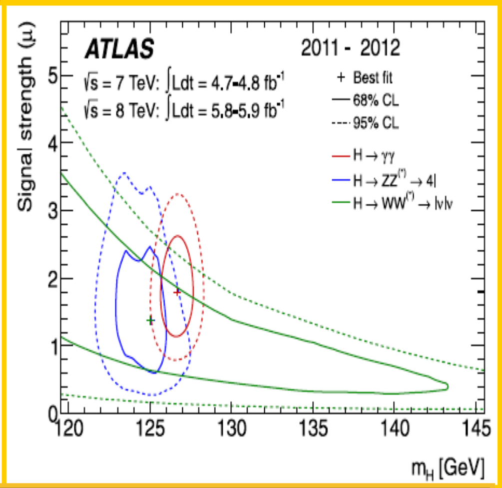
Tevatron Evidence

Physics Letters B 716 (2012) 1–29





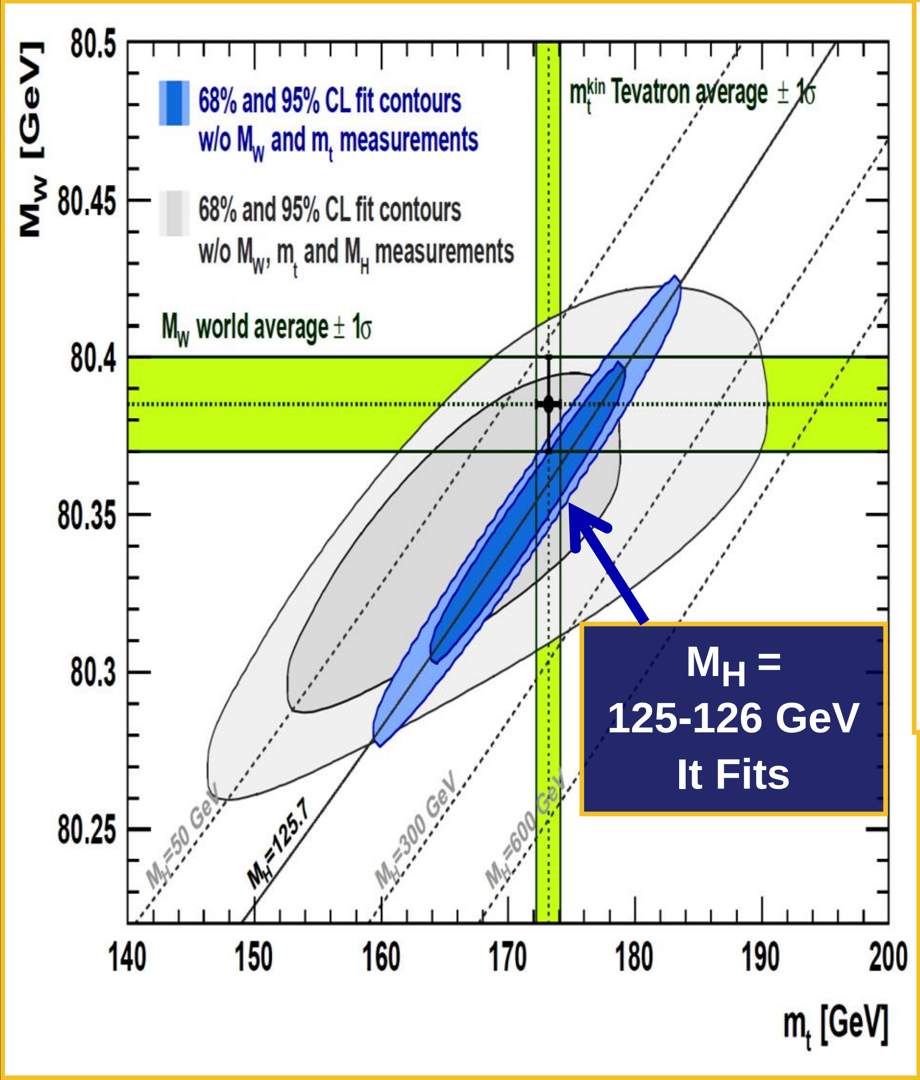




"Combined results of searches for the SM Higgs boson in pp collisions at s=7TeV" (http://www.sciencedirect.com/science/article/pii/S0370269312002055)
"Combined search for the SM Higgs boson with the ATLAS detector at the LHC" (http://www.sciencedirect.com/science/article/pii/S0370269312001852).

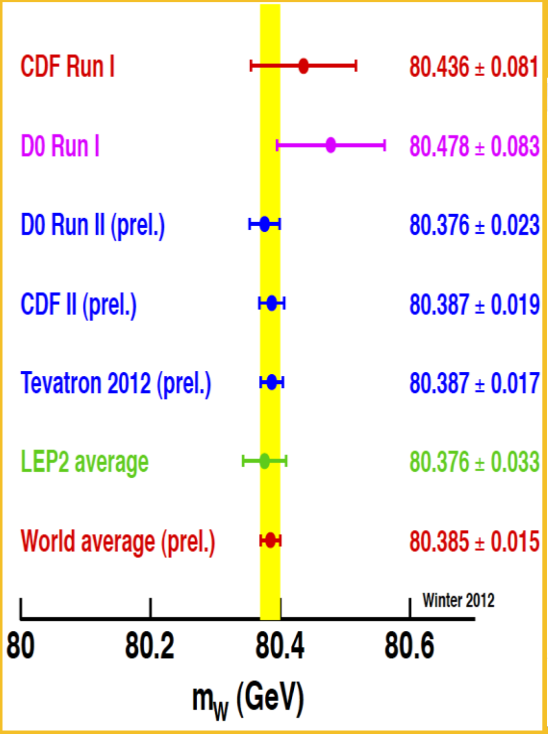
Precision Electroweak, Including the "SM Higgs": It Fits

Gfitter Post July 4 2012



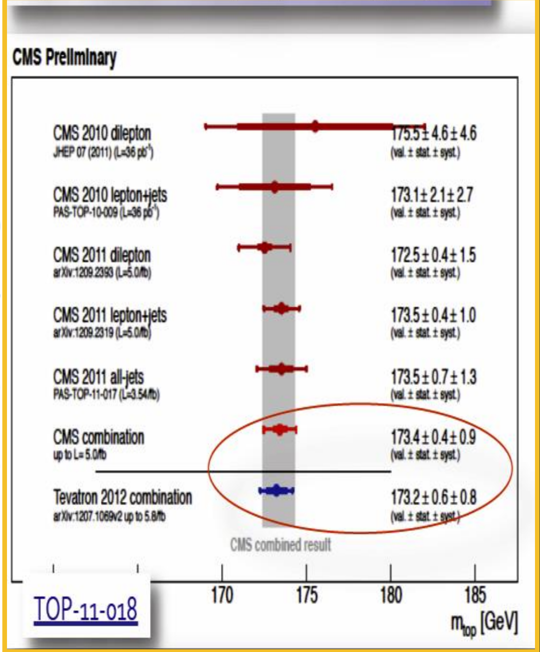
M_H =
125-126 GeV
It Fits

Precision W Mass



Precision Top Mass

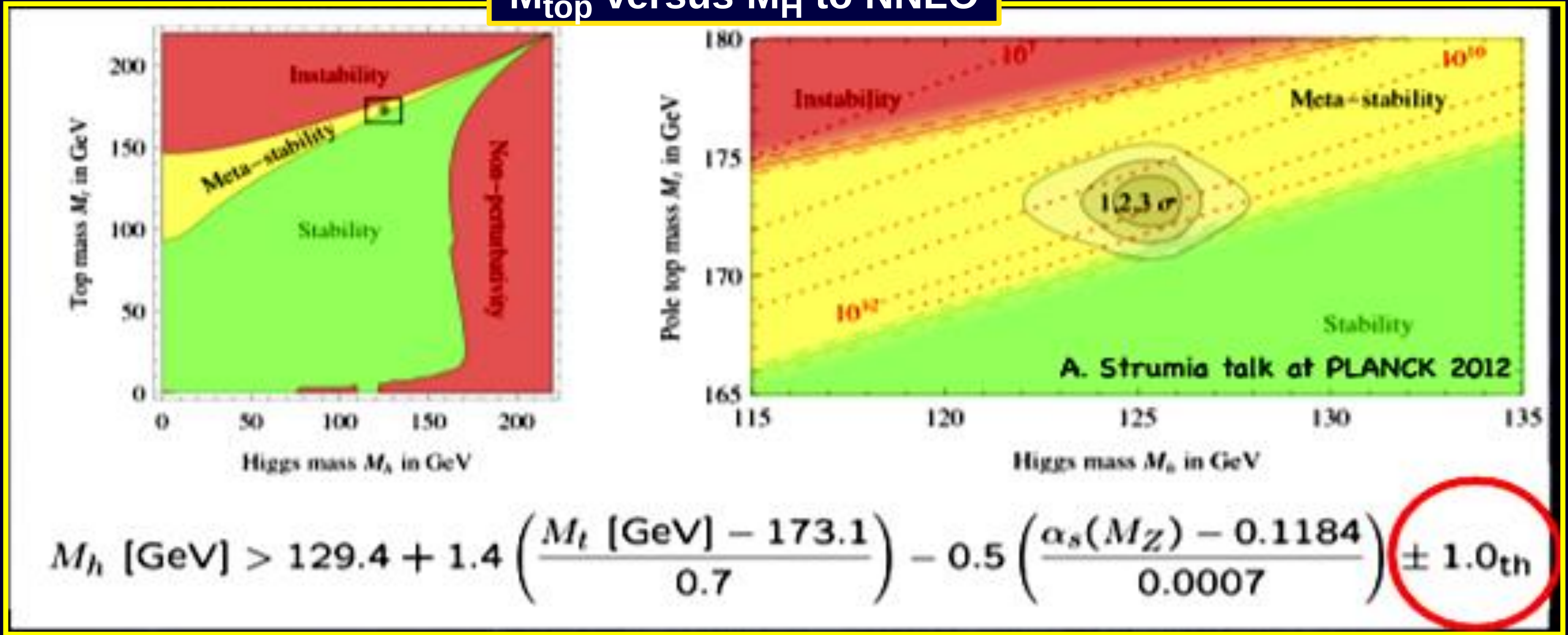
173.36 ± 0.38 ± 0.91 GeV



Higgs Mass and Vacuum Stability

- ✷ A 125.5 GeV Higgs mass means you are just on the wrong side of the Vacuum Stability bound
- ➡ We seem to be in a very particular *metastable region*
- ➡ OR –New physics exists at an intermediate mass scale ~10^{11} GeV

M_{top} versus M_H to NNLO

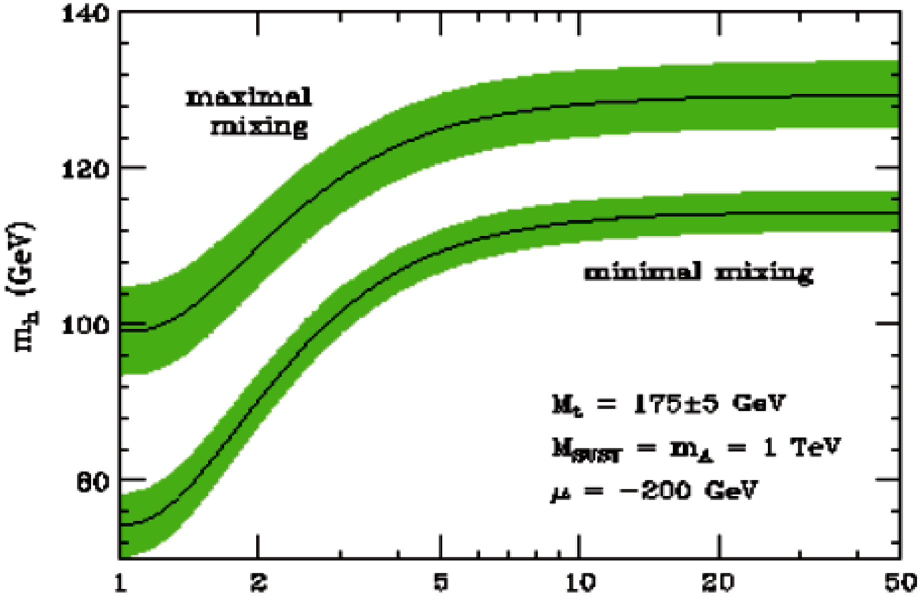


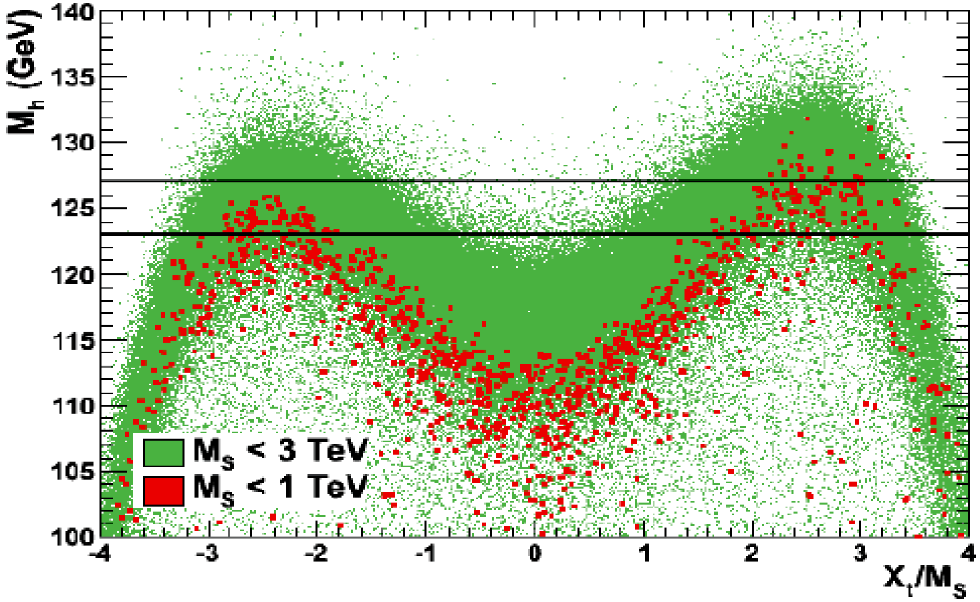
A. Strumia talk at PLANCK 2012

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

- We need to know both the Higgs mass and the top mass precisely, to know if the vacuum is stable [New role of ILC or CHF?]

SM-Like MSSM Higgs
and Beyond


M.C, Haber, Heinemeyer, Hollik,Weiglein,Wagner'00


Arbeya, Battaglia, Djouadi, Mahmoudi, Quevillon'11

- A 125.5 GeV Higgs needs tan β > ~5, and large mixing X_t
- Also favors large M_S especially for less than maximal mixing
- But M_S cannot be Too large, else theory is unstable at high scales

- M_H = 125.5 GeV and indications that BR(γγ) might be > BR(γγ) SM have led to many speculations, and *an industry of model-space profile likelihood studies, both within and beyond the MSSM*

Higgs and Supersymmetry

See Carena and Nath talks at SUSY2012

$$\tan\beta = v_2/v_1$$

$$\Rightarrow v = \sqrt{v_1^2 + v_2^2} = 246\ \text{GeV}$$

- ✸ MSSM has two Higgs Doublets, leading to:
  H, h (CP Even, Higgs-Like), A (CP Odd) and $H^{\pm}$
- ✸ H_u doublet couples only to up-quarks; H_d only to down-quarks; so SUSY is flavor diagonal if SUSY is unbroken
- ✸ Quartic Higgs couplings determined by SUSY gauge couplings
  - ➡ The lightest Higgs (h) mass is strongly correlated with the Z Mass, and is naturally light
  - ➡ Other Higges can be as heavy as the SUSY breaking scale M_S
- ✸ Important quantum corrections to the lightest Higgs mass due to incomplete cancellation of top and stop contributions in the loops
- ✸ A 125.5 GeV Higgs favors large LR Stop Mixing X_t and/or large M_S

$$\boxed{m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right) \qquad \underline{X_t = A_t - \mu/\tan\beta} \rightarrow \text{LR stop mixing}$$

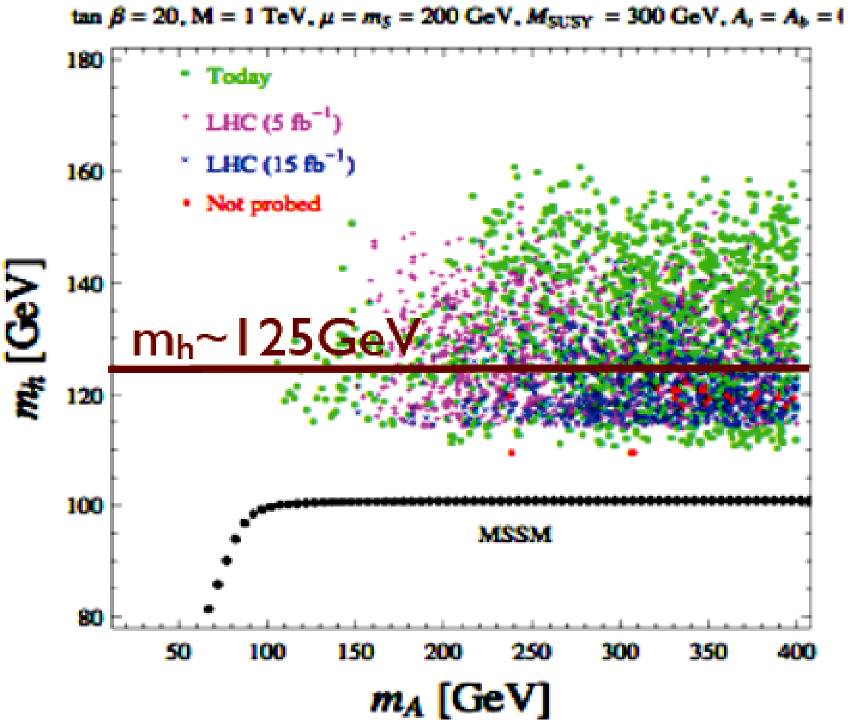
Beyond the MSSM Higgs

M. Carena at SUSY 2012

More general MSSM Higgs extensions: EFT approach

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2 \qquad W_X \supset \frac{\omega_1}{2M} X (H_u H_d)^2$$

Dine, Seiberg, Thomas;
Antoniadis, Dudas, Ghilencea, Tziveloglou
M.C, Kong, Ponton, Zurita



Scan over parameters including all possible dimension 5 and 6, SUSY Higgs operators

Higgs mass = 125 GeV easy to achieve for light stops, small mixing

Enhancement of h to di-photons due to bb suppression or light staus

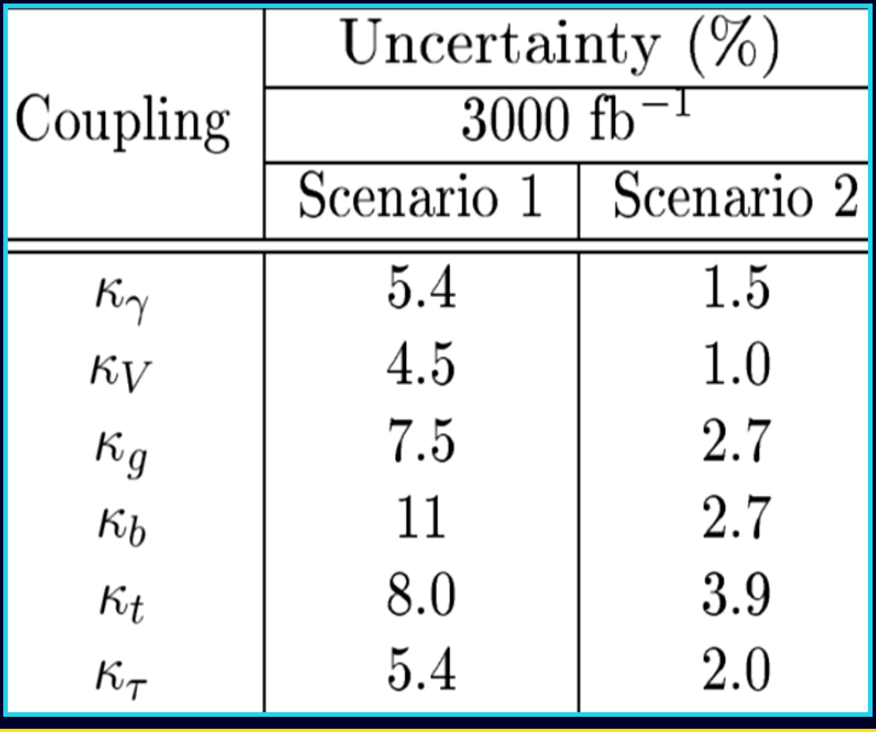
Higgs cascade decays from large splitting in masses : h/H to AA

If the new physics is seen only indirectly via deviations from the SM Higgs properties, it will be hard to disentangle among new singlets, triplets, extra Z’, W’, a given mixture of the above

CMS Phase 2 Upgrade at HL-LHC

Higgs Couplings with 3000 fb^{-1}

- **Extrapolation to higher luminosity by two orders of magnitude** is subject to large uncertainties: these are early projections
  - Scenarios 1 and 2 are likely to provide upper and lower bounds
- **Experience at LEP and the Tevatron indicates that scaling by 1/√L might not be unrealistic;** in spite of a more challenging environment
- **The Higgs couplings could possibly be** measured with high precision: 1-4% in Scenario 2
- **H → μμ decay could be measured** with 5σ significance
  - **And the H to μ coupling** could be determined to ~10%
- **Multiple Higgs production can be observed (σ = 33 fb), and**
  - **The self-coupling coefficient λ in the Higgs potential** could be measured



Coupling	Uncertainty (%)	
	3000 fb^{-1}	
	Scenario 1	Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

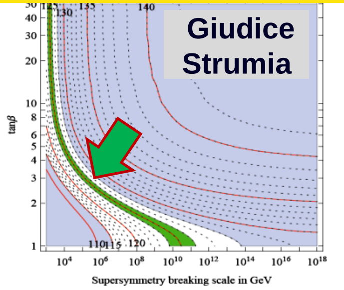
The Outlook

- SM or not: the 125-6 GeV “Higgs” boson has taken us to the **threshold of an era of new physics,** with a host of questions
- **Natural, Split** or **High Scale SUSY ?:**
  - **A nearby 3rd generation at ~0.5 TeV** ?
  - **Another nearby scale at** ~5-50 TeV ?
- *OR: new singlets, doublets, triplets; new scalars, vectors, composites, extra dim. ?…*
- Vacuum (meta)stability ➡ **Another new scale at ~$10^{10\text{-}12}$ GeV ?**
- Neutrino masses (via seesaws or RH ν): **A “similar” intermediate scale ?**
- ***The Discovery has Expanded our Vision***

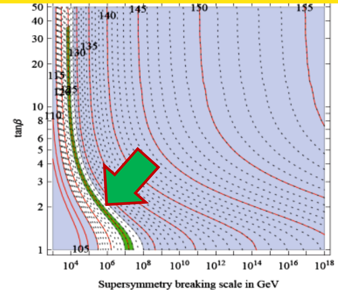
➡ **Exciting years ahead of results and (new) ideas: about EWSB and beyond**

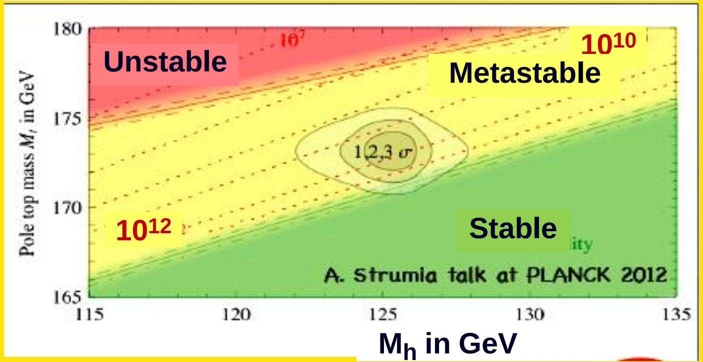
$$M_h^2 \overset{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

High Scale SUSY

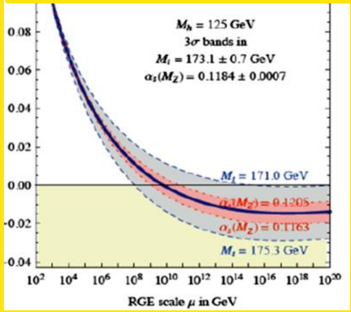


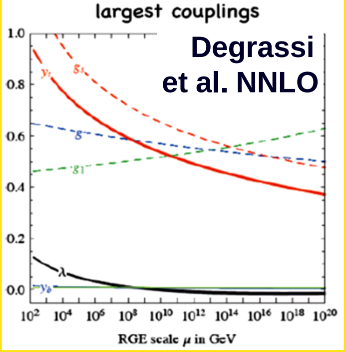
Split SUSY





λ at High Scales

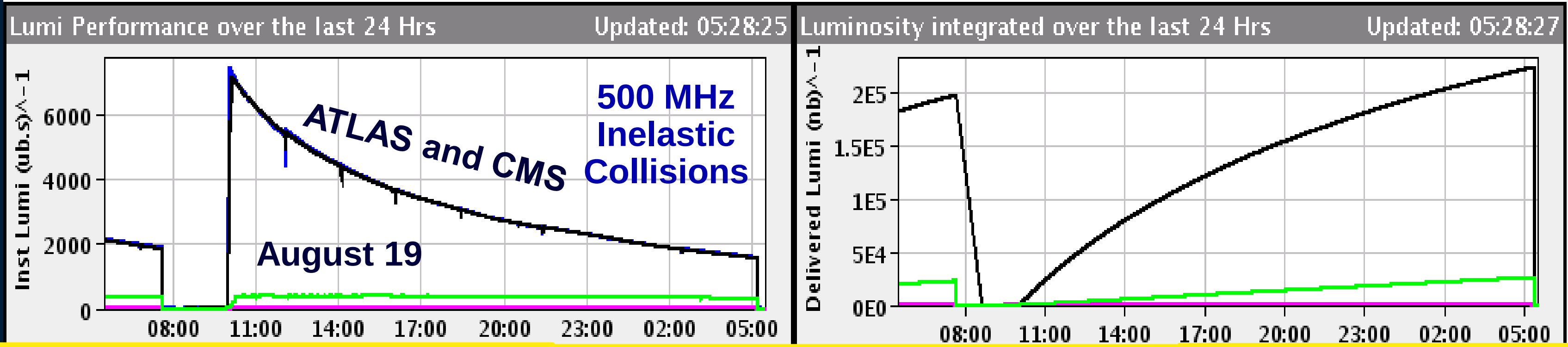




Backup Slides Follow

LHC: Remarkable Performance

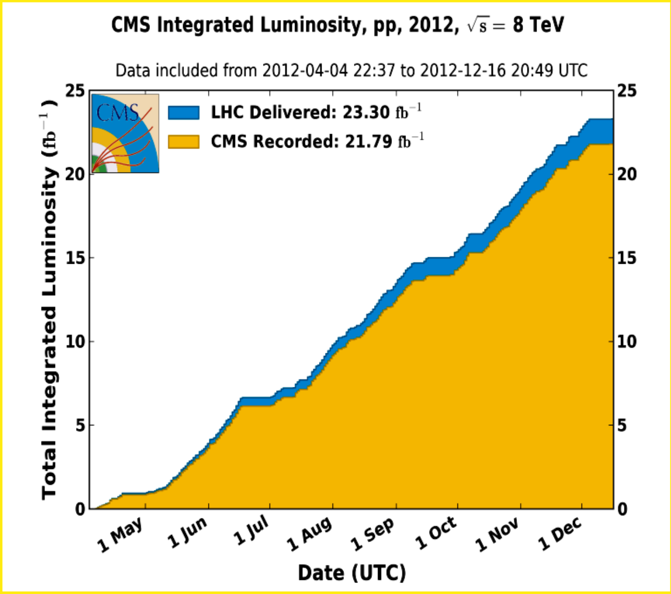
Peak luminosity: 7.7 X 10^{33}

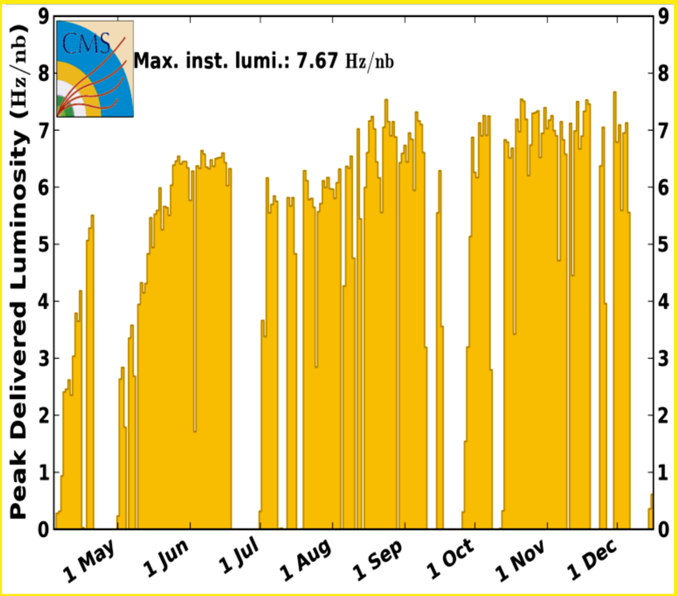


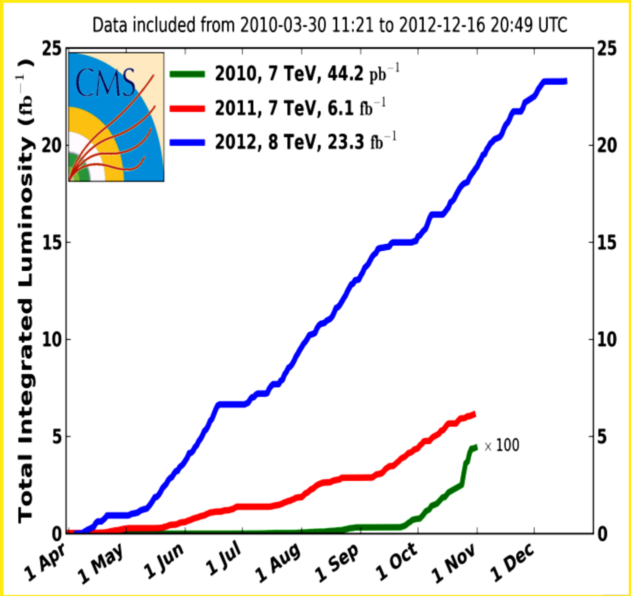
ATLAS and CMS

500 MHz Inelastic Collisions

August 19





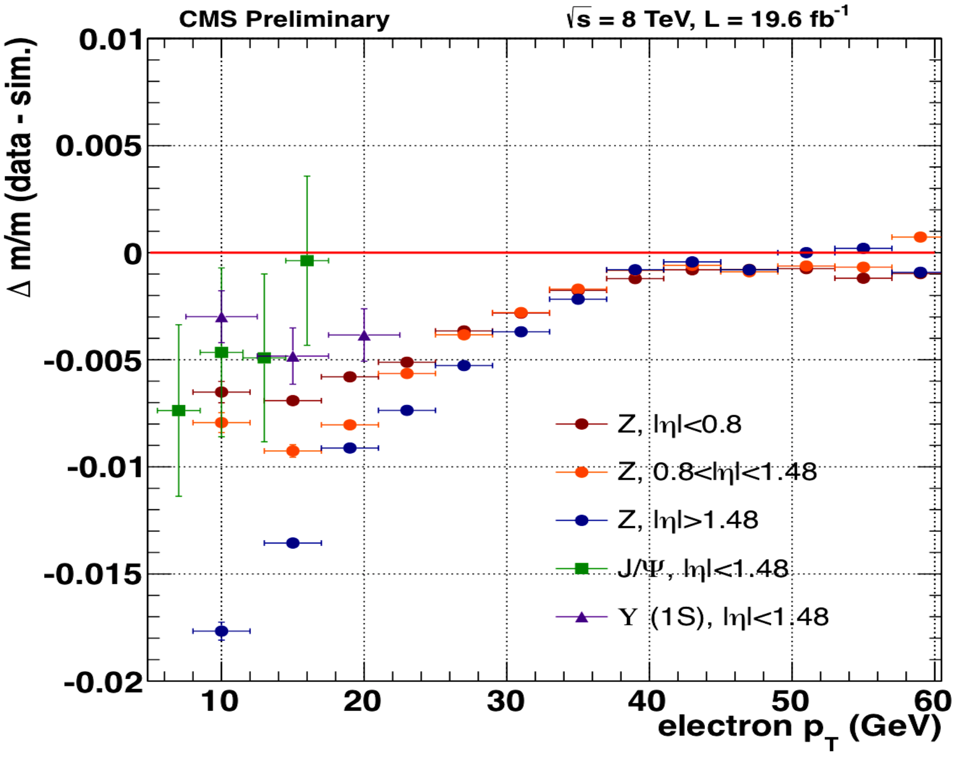


CMS Collected: 6 fb^{-1} by ICHEP. 23 fb^{-1} by December 6

Beyond the New Boson Discovery: New Physics Landscape in 2015 ?

Electron Scale and Resolution

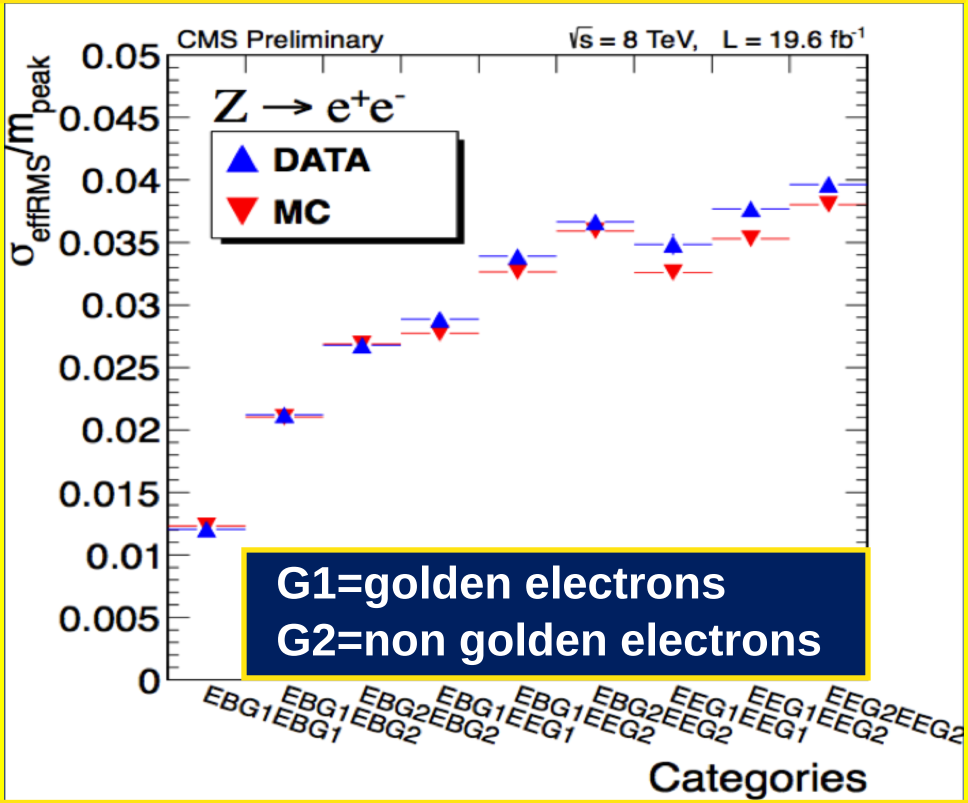
Electron scale linearity wrt MC with Z, J/Ψ, ϒ(1S)→e^+e^-



Better than 1% in barrel

Better than 2% in endcaps

Electron relative resolution in data with Z→e^+e^-



G1=golden electrons

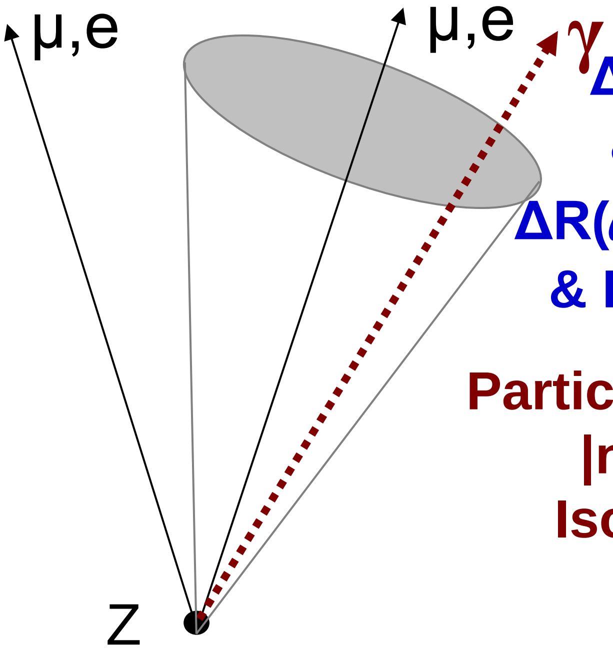
G2=non golden electrons

Best category: 1.2% resolution

Worst one: 4% resolution

Final State Radiation Recovery

- **Applied on each Z for photons near the leptons**



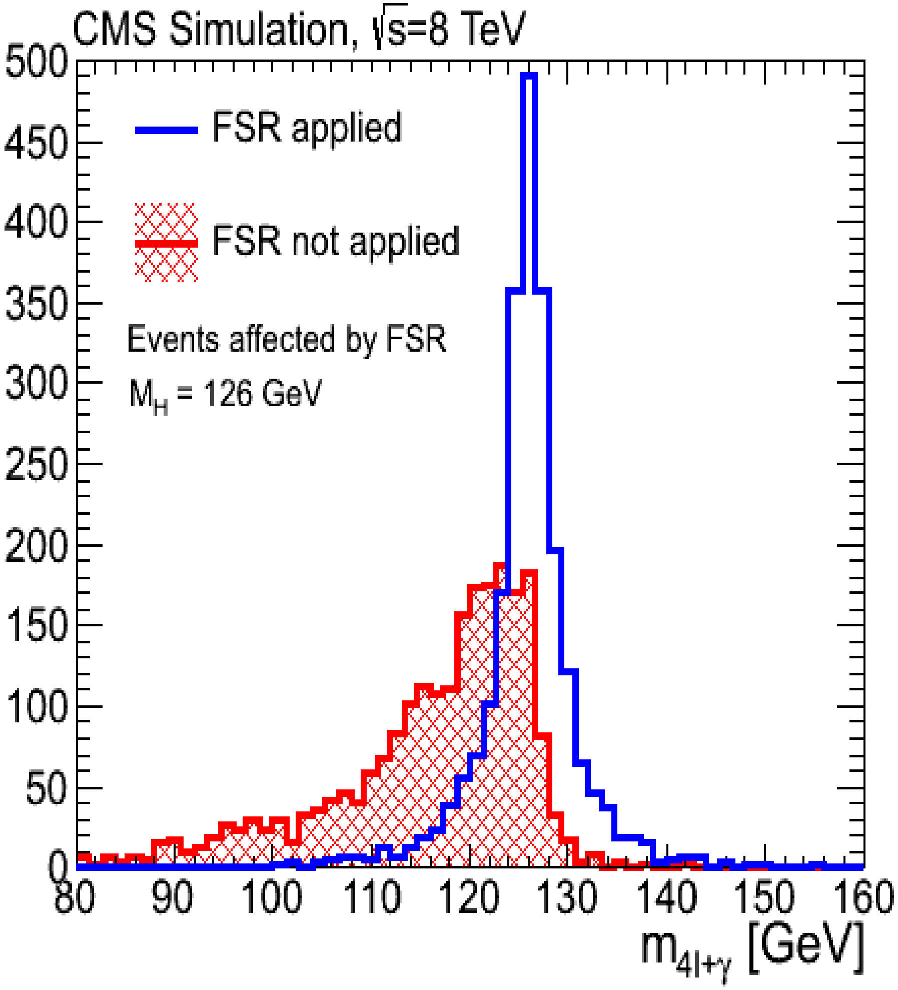
$\Delta R(\ell, \gamma)_{min} < 0.5$ & $E_T > 4$ GeV

$\Delta R(\ell, \gamma)_{min} < 0.07$ & $E_T > 2$ GeV

Particle Flow ID
$|\eta| < 2.4$
Isolation

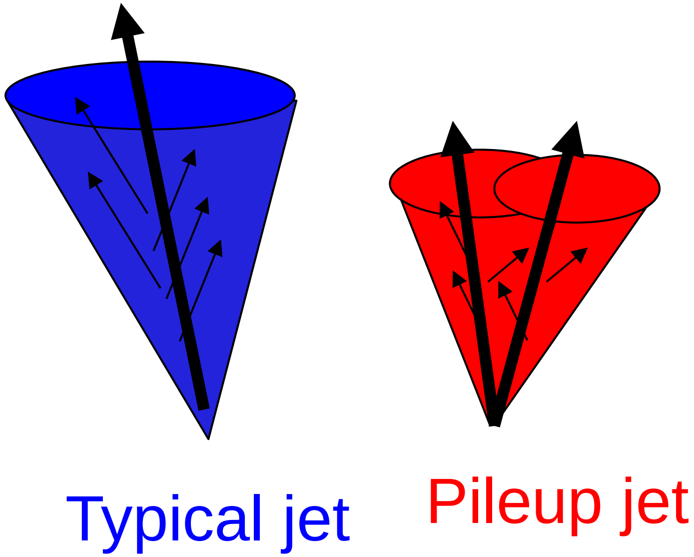
- **Associates photon with Z if:**
  - **$M(ll+\gamma) < 100$ GeV**
  - **$|M(ll+\gamma)-M_Z| < |M(ll)-M_Z|$**
- **Removes associated photons from lepton isolation calculation**

Expected Performance for M_H=126 GeV

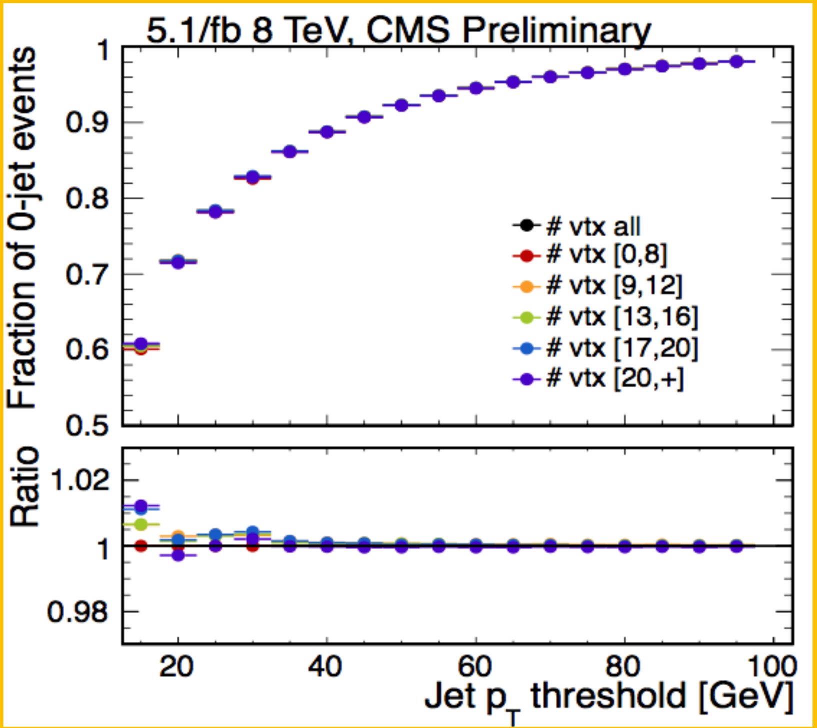


Pile-up Jet Tagging

Rejection of jets from PU, also outside the tracker coverage, relies on jet shape variables.



Important in VBF searches.



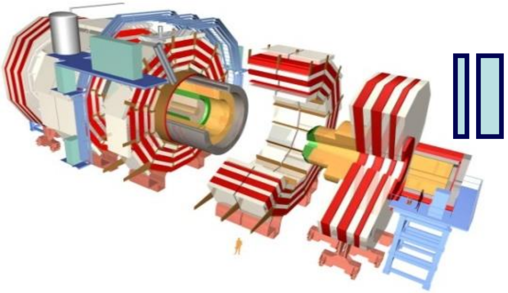
Validation on data: jet counting in $Z \rightarrow \mu\mu$ events vs vertex multiplicity.

Stable to <1% for jet p_T > 20 GeV

Result: jet thresholds and characteristics (well represented by MC) are Independent of Pileup

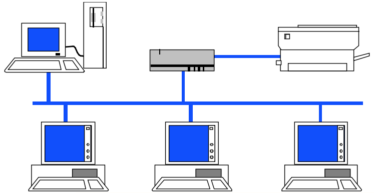
Precise π^0,η ➡ γγ Calibration Stream: 1st Time at a Hadron Collider

Data after L1 Trigger



~50 kHz

Online Farm

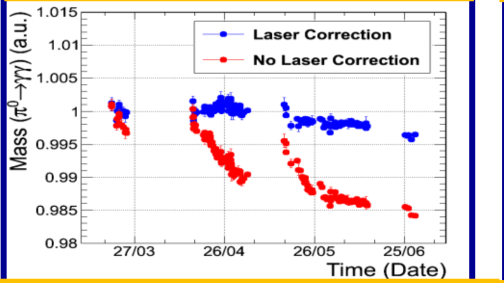


~1 - 10 kHz

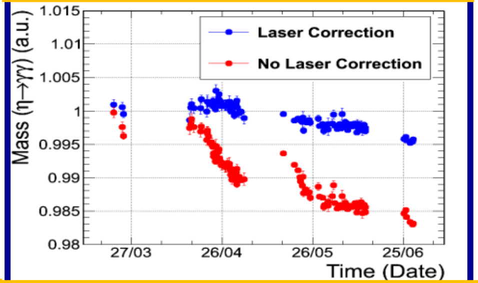
π^0 Calibration

- Level 1 trigger rate: several π^0's/event
- Advantage: high π^0 rate (use L1 not HLT triggers)
  - ➡ Use with laser crystal transparency monitor
- "Design" calibration → 0.5%: for optimized H→γγ detection
- June 2011 on: 5-10 kHz rate ➡ Bi-weekly calibration in central barrel to ~0.5%

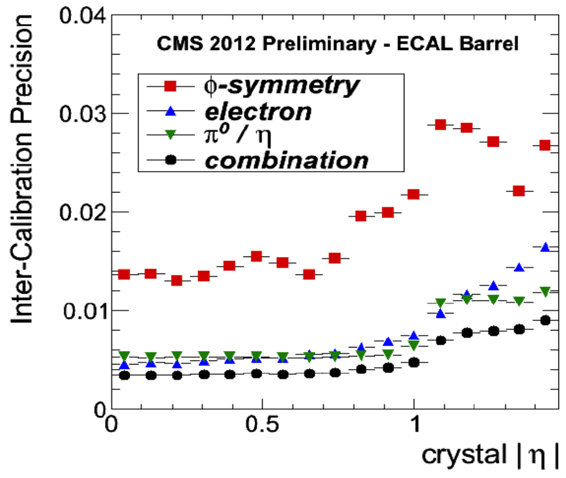
π^0 Mass History in EB Stable to 0.3%



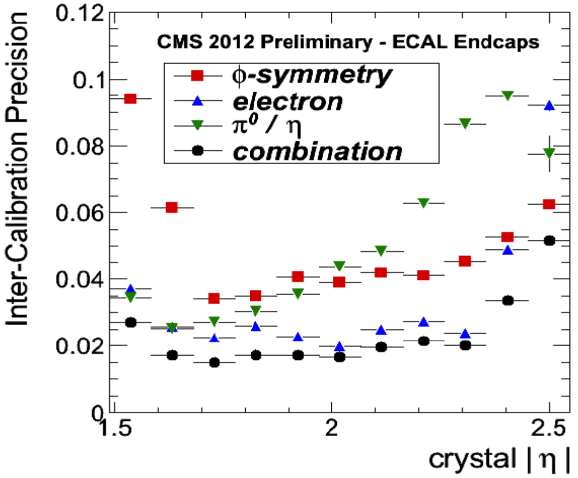
η^0 Mass History in EB Stable to 0.4%



2012 EB Crystal Calibration vs. |η|: Precision 0.4 – 0.9%

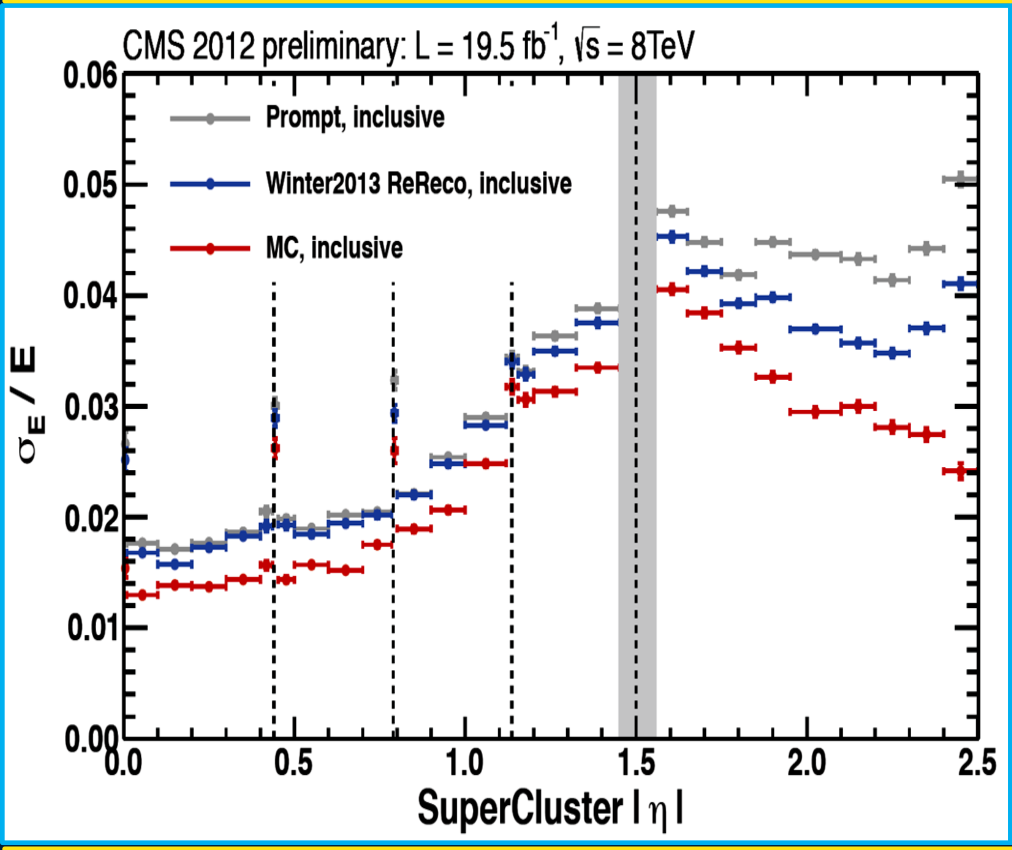


2012 EE Crystal Calibration vs. |η|: Precision 2%



Clusters: Energy Resolution

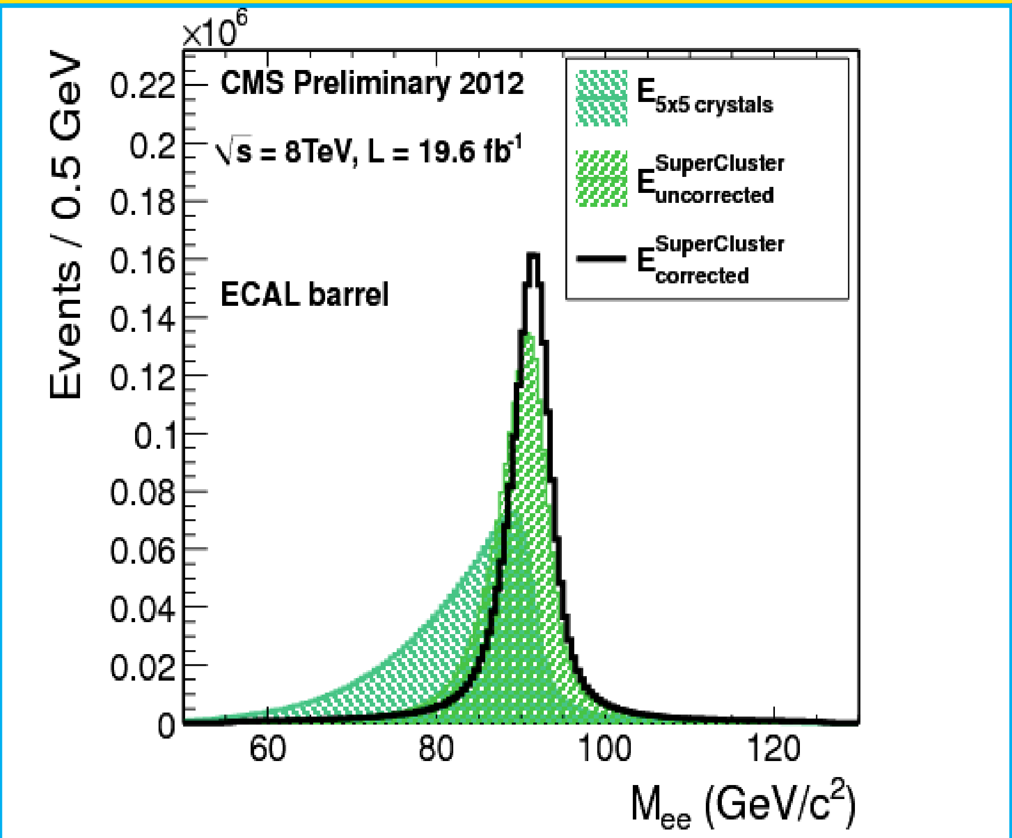
ECAL Relative Energy resolution with $Z \rightarrow e^+e^-$



Inclusive electrons

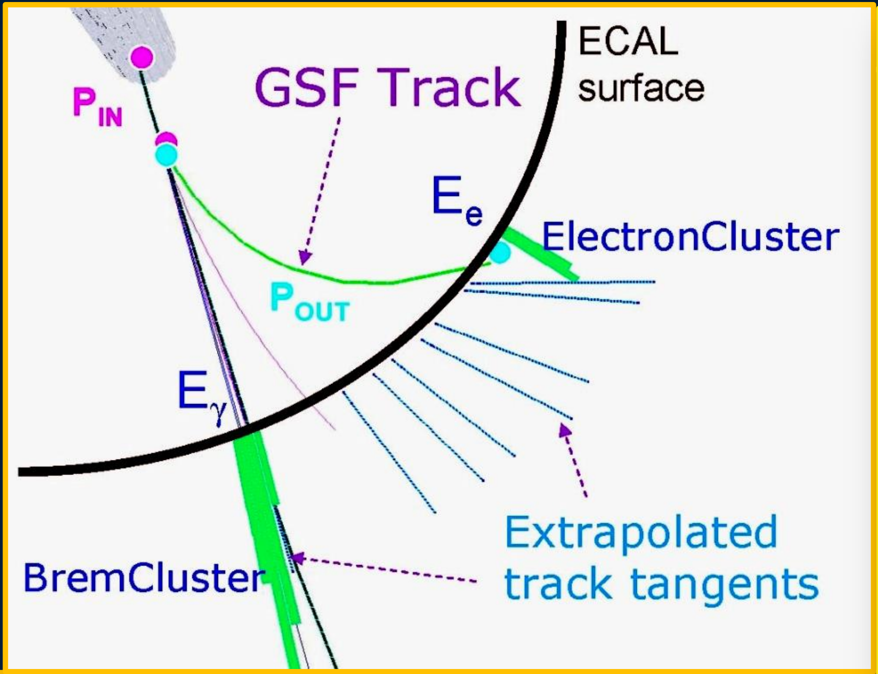
In the best categories, σ_E~1.5%

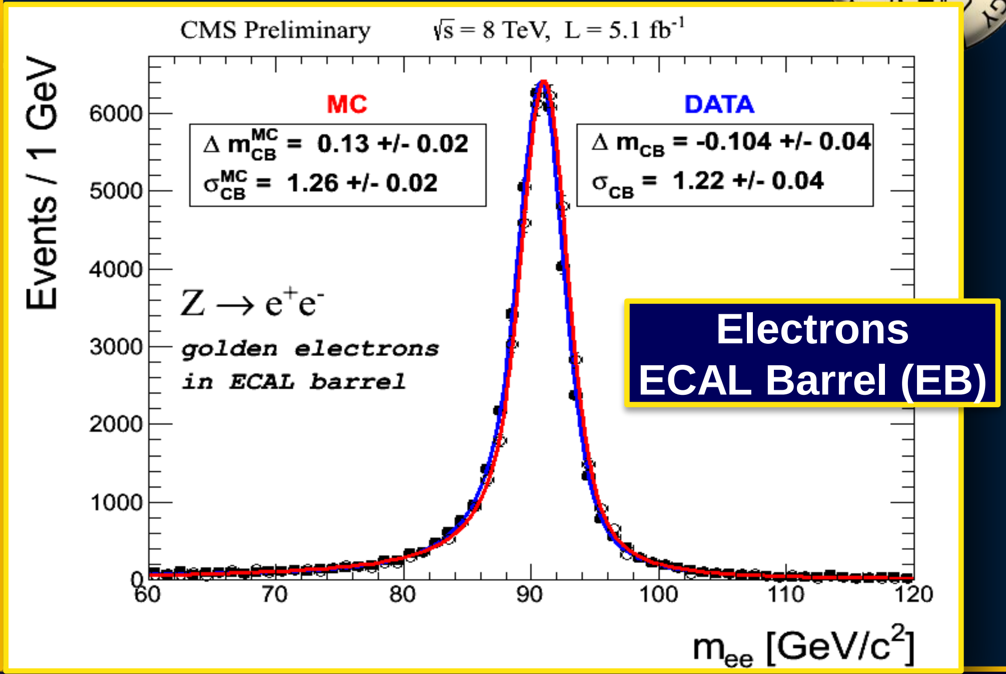
Effect of Energy Corrections on $Z \rightarrow e^+e^-$ mass



Significant improvements by including cluster corrections

Electron/Photon Reconstruction





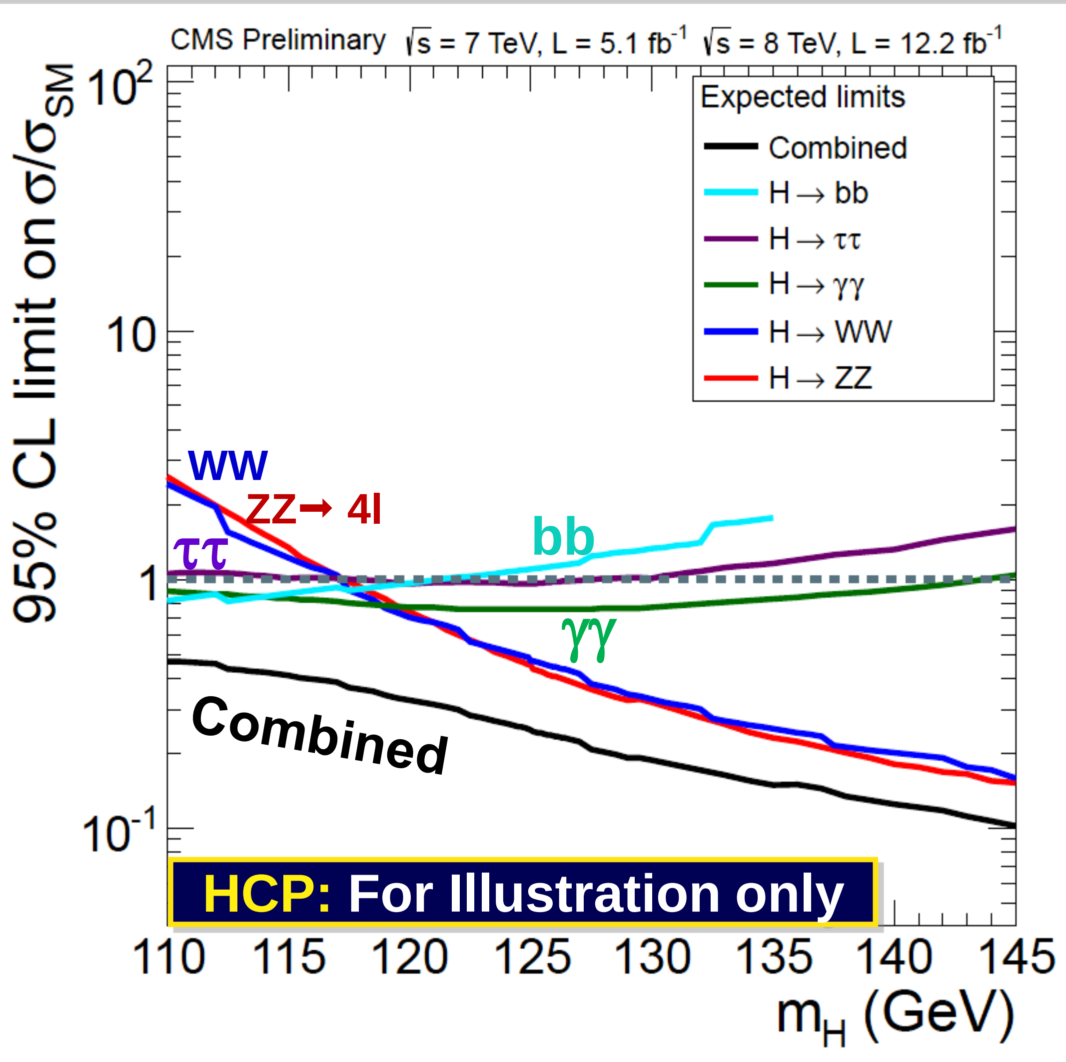
Electrons
ECAL Barrel (EB)

- **Cluster reconstruction in ECAL**
  - **Common for both electrons & photons (Electrons also reconstructed as photons)**
  - **Designed to collect bremsstrahlung and conversions in extended phi region**
- **Photon identification specific to H➔γγ**
- **Dedicated track reconstruction for electrons**
  - **Gaussian Sum Filter allows for tracks with large bremsstrahlung**
- **Energy scale and resolution**
  - **Extensive control with Z and J/ψ➔ee and Z for both electrons and photons**

CMS Higgs Search Channels

Expected Sensitivity in $\mu = \sigma/\sigma_{SM}$

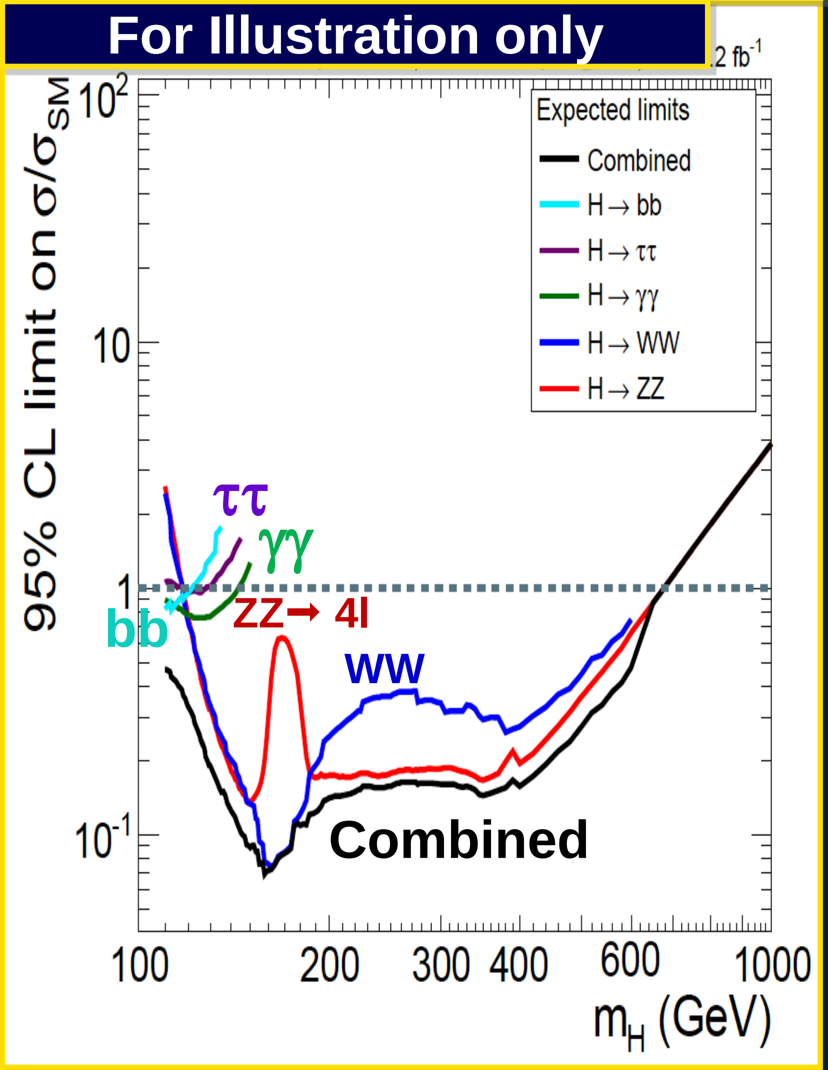
HCP: 110 – 145 GeV at 7 and 8 TeV



HCP: For Illustration only

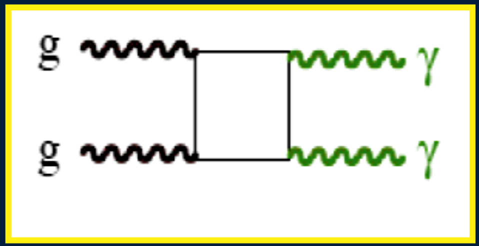
HCP: 110-1000 GeV at 7 and 8 TeV

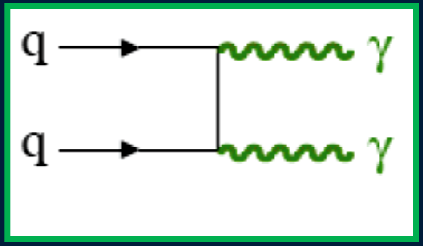
For Illustration only

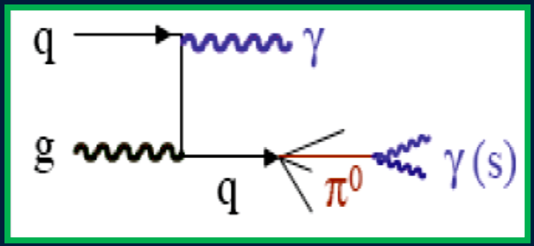


H → $\gamma\gamma$ Analysis Key Points

- **Diphoton Mass Resolution:** $M^2 = 2E_{\gamma1}E_{\gamma2}\,(1-\cos\theta)$
  - **Energy Resol'n:** ECAL Calibration & Energy Corrections
  - **Photon Directions:** Primary vertex determination
- **Photon Identification:** Separate prompt photons from reducible background from misidentified neutral mesons in QCD γ+Jet and multi-jet events
- **Event categorization:** (diphoton ID, inclusive/exclusive channels)
  - Probe different production processes (gg, VBF, VH) and exploit the different S/B and/or different resolution to maximize the sensitivity: Inclusive + Exclusive Dijet, e, μ, E_T^{Miss} Categories
    Background Modeling from the Data:
    Provides good description: background is ~70% QCD Di-Photon







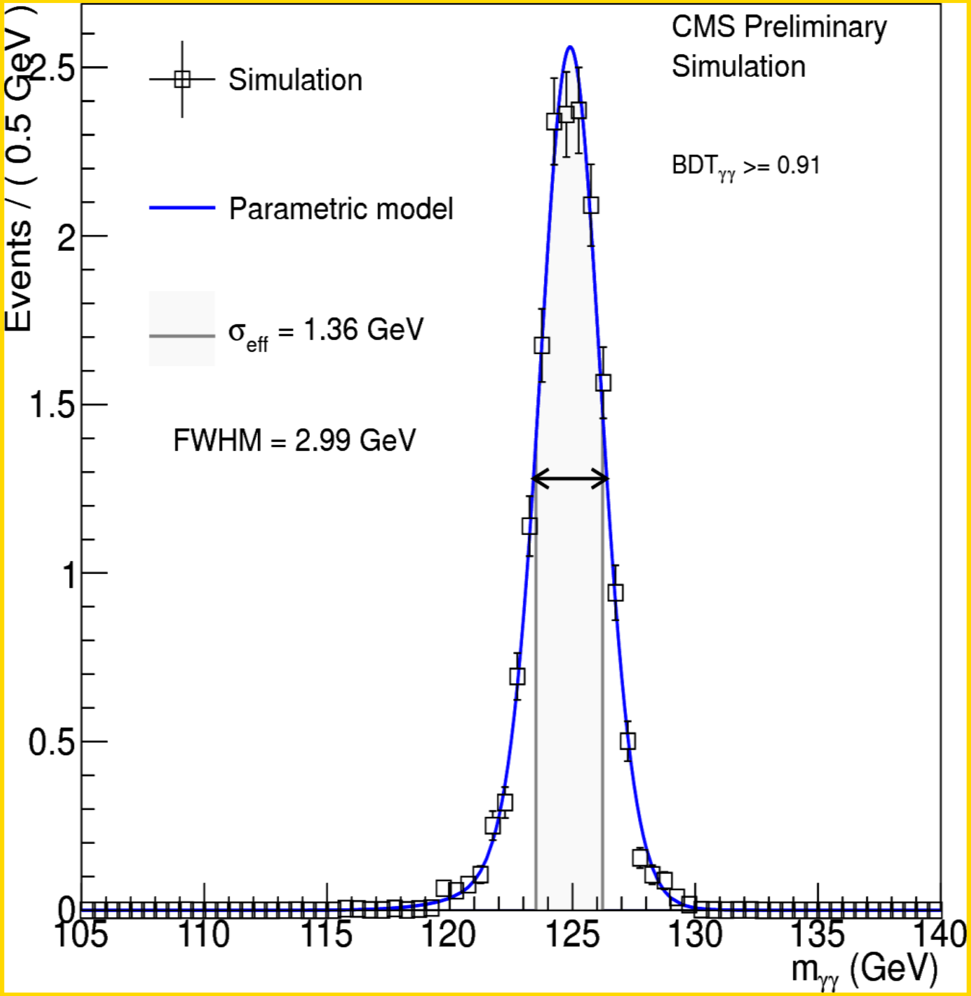
$H \rightarrow \gamma\gamma$ Analysis Improvements in 2012-13

- **Improved the energy calibration** on the first 5.3 fb^{-1} of 2012 data (after publication)
- **Added more exclusive channels** in 2012 analysis
- **Added MVA classification in dijet selection** for the MVA analysis

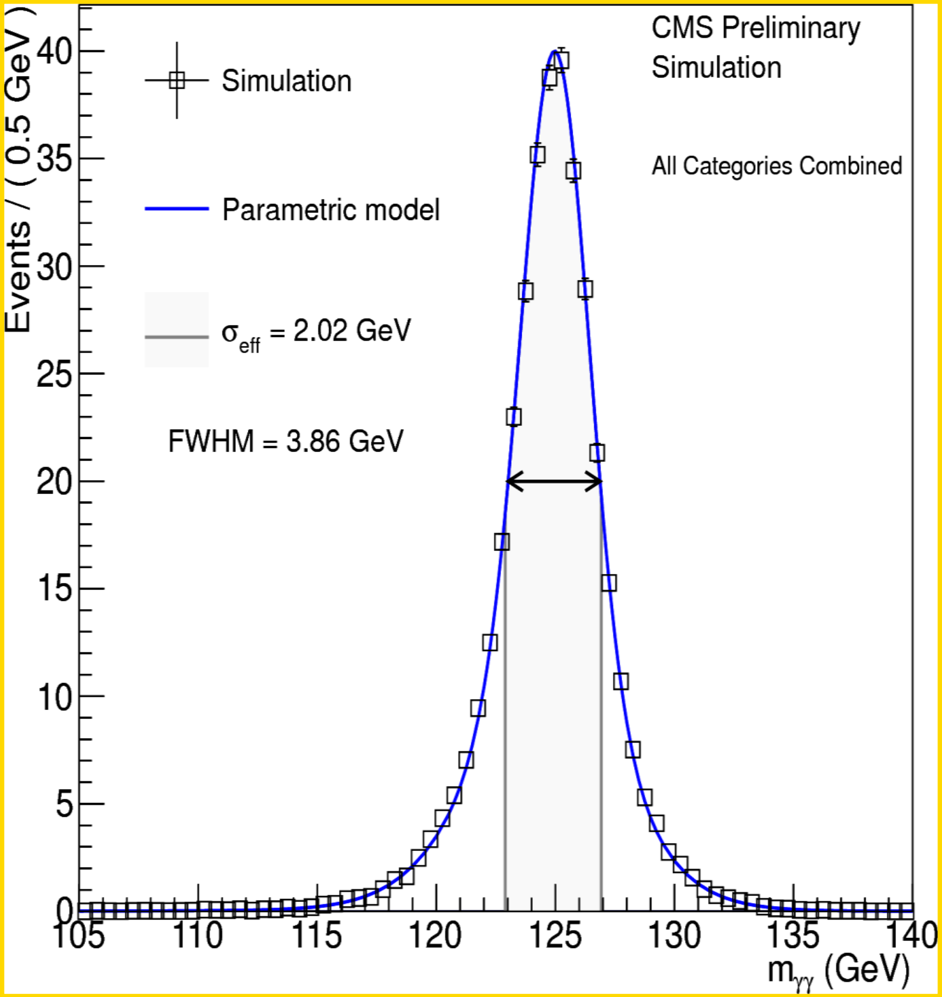
MVA Diphoton Analysis:

Signal Model Mass Resolution (8 TeV)

Untagged Category 0: σ_{eff} = 1.1%

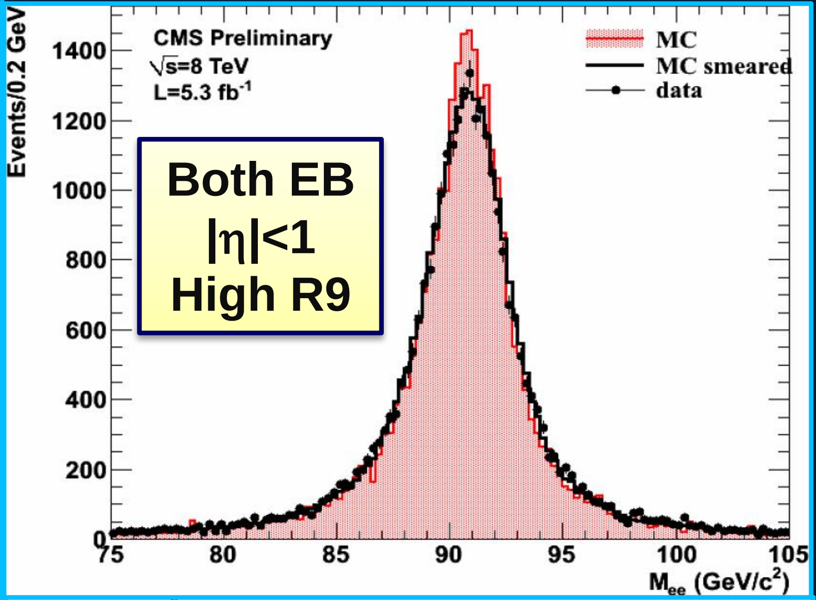


All Categories: σ_{eff} = 1.7%

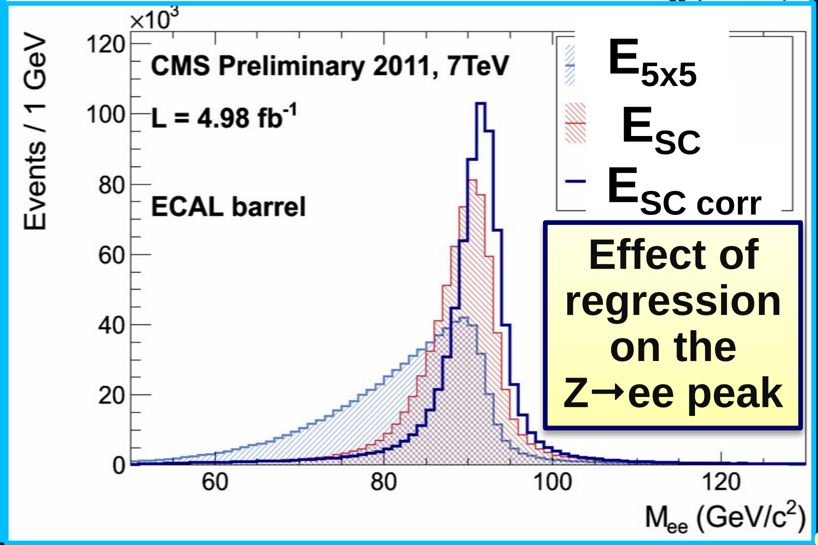


Photon Energy Scale and Resolution

- ECAL cluster energies corrected using a MC trained MVA regression
  - Improves resol'n and restores flat response of energy scale vs. pileup
  - Inputs: Raw cluster energies & positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry, pileup estimators
- Regression also used to provide a per photon energy resolution estimate
- After "best" individual crystal calibration and transparency corrections: measure Energy Scale & Resolution with $Z \rightarrow e^+e^-$
  - Also $Z \rightarrow \mu\mu\gamma$ for photon scale



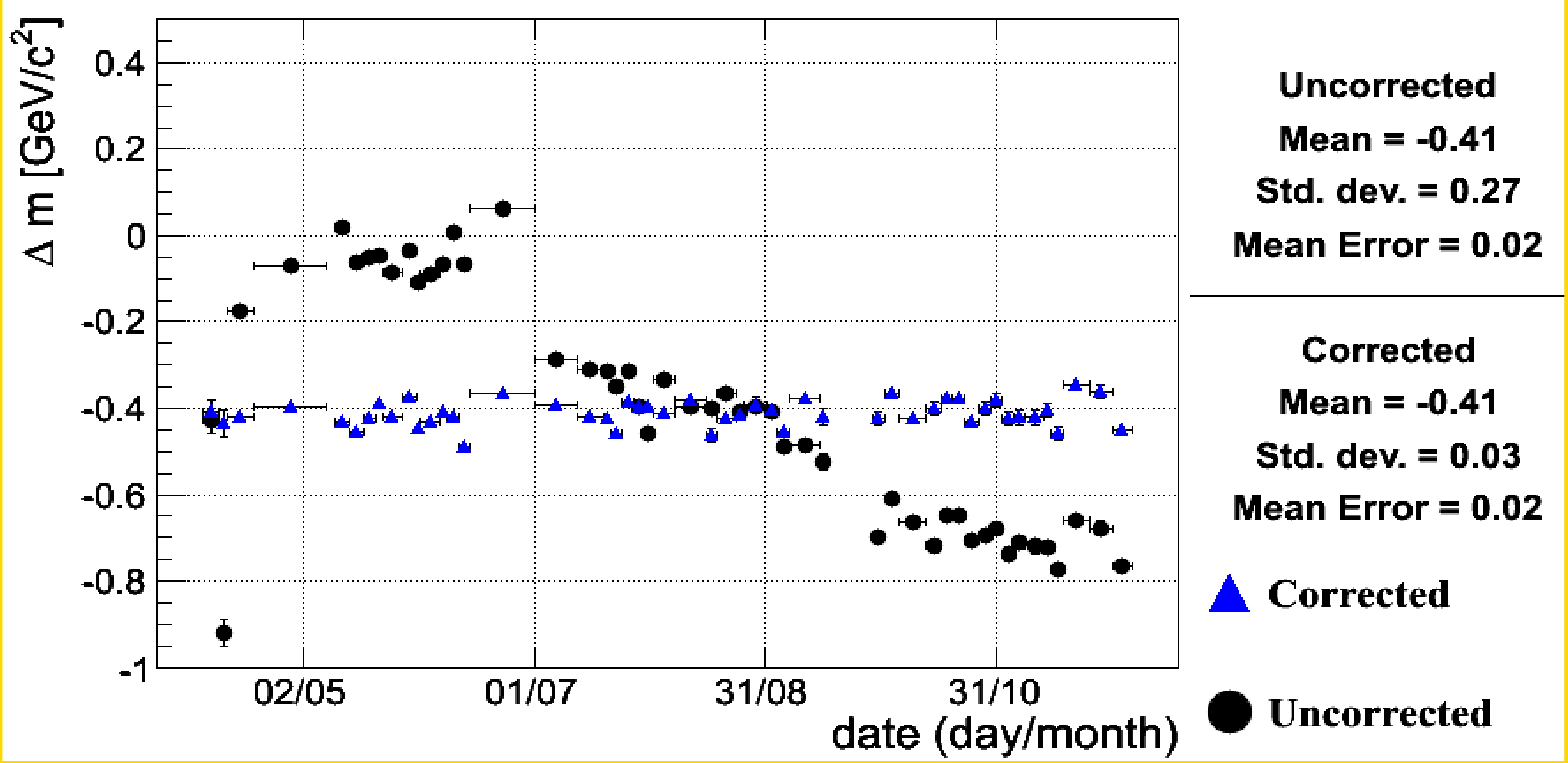
Both EB
|η|<1
High R9



Effect of regression on the Z→ee peak

Energy Scale vs Time (in Z →ee)

Stability at 0.3% level before application of analysis level corrections with prompt reconstructed data

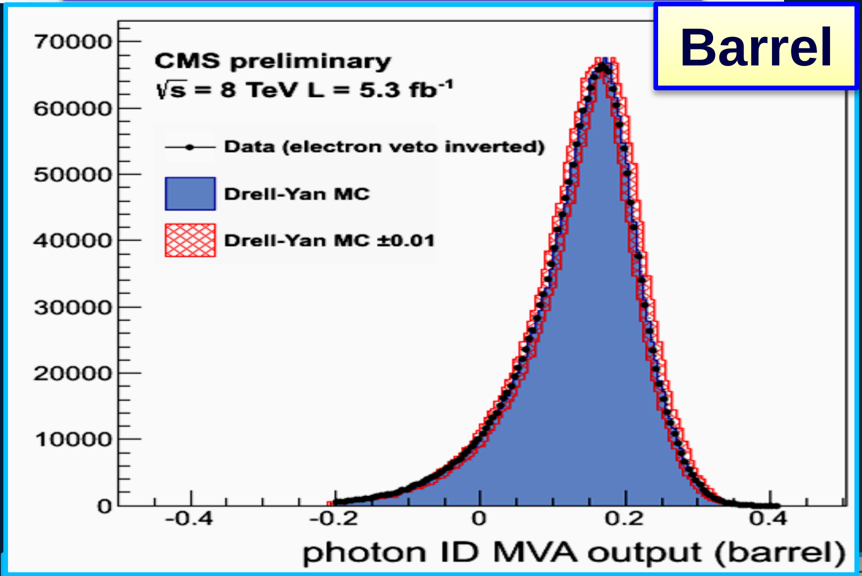


MVA Photon ID

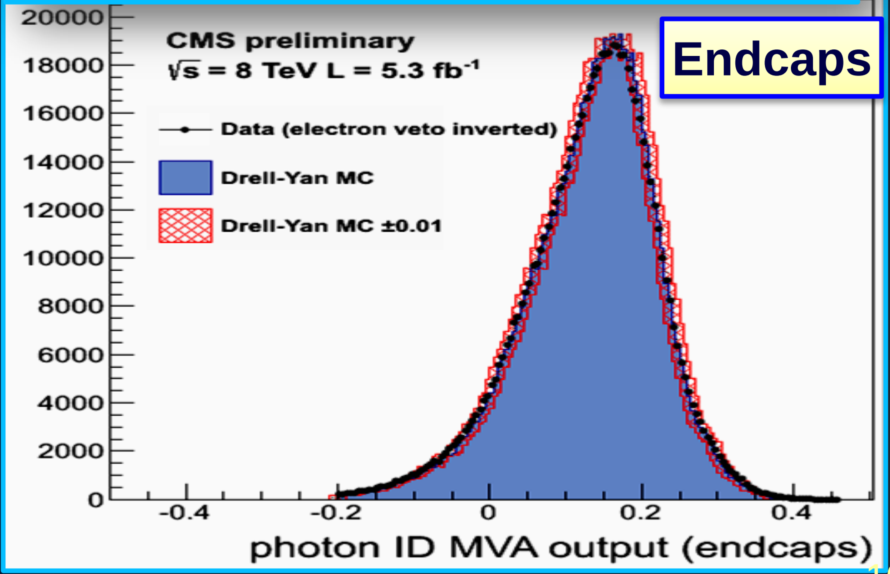
Validation with Z→ee (inverted electron veto)

- **Photon pre-selection:**
  - $E_{T\gamma 1}/m_{\gamma\gamma} > 1/3$, $E_{T\gamma 2}/m_{\gamma\gamma} > 1/4$
  - Photon ID a bit tighter than trigger selection and MC EM enrichment filters
  - Efficiency measured using tag and probe with Z→ee
  - Electron veto: Efficiency measured using tag and probe with $Z\to\mu\mu\gamma$
- **MVA based photon ID discriminates photons from fakes:**
  - Inputs: isolation, shower shape, per-event energy density, pseudorapidity

Barrel



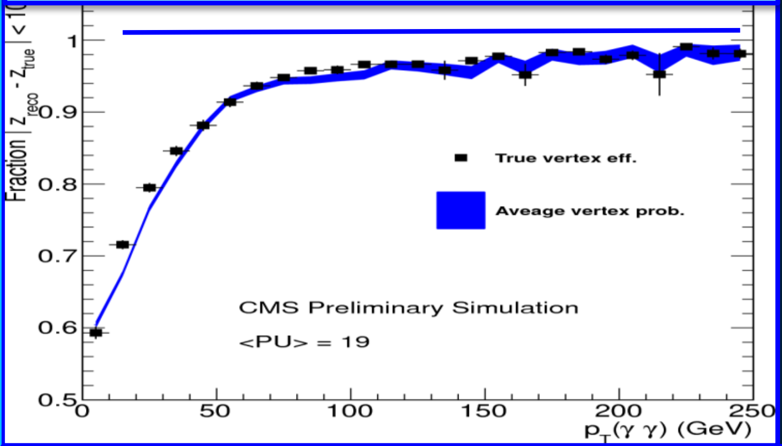
Endcaps



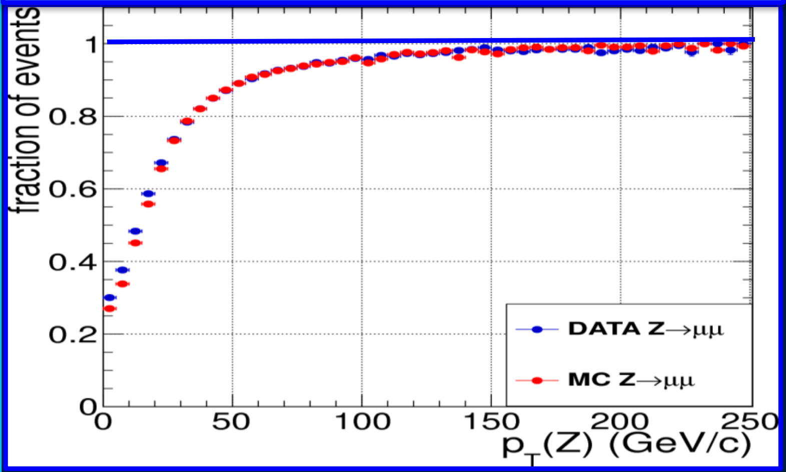
MVA $\gamma\gamma$ Vertex Choice

- **Mass reconstruction: Depends on correct position of the primary vertex**
- **Interaction vertex is identified using tracks from recoiling jets and the underlying event plus conversions**
    - **correct in 83% (79%) of cases for pileup in 2011 (2012)**
- **Vertex identification with a BDT**
    - Input variables: Σp_t^2, Σp_t projected onto the $\gamma\gamma$ transverse direction, p_t asymmetry and conversions
- **Correct vtx finding probability also estimated using a BDT**

Efficiency to ID correct vertex within 10 mm

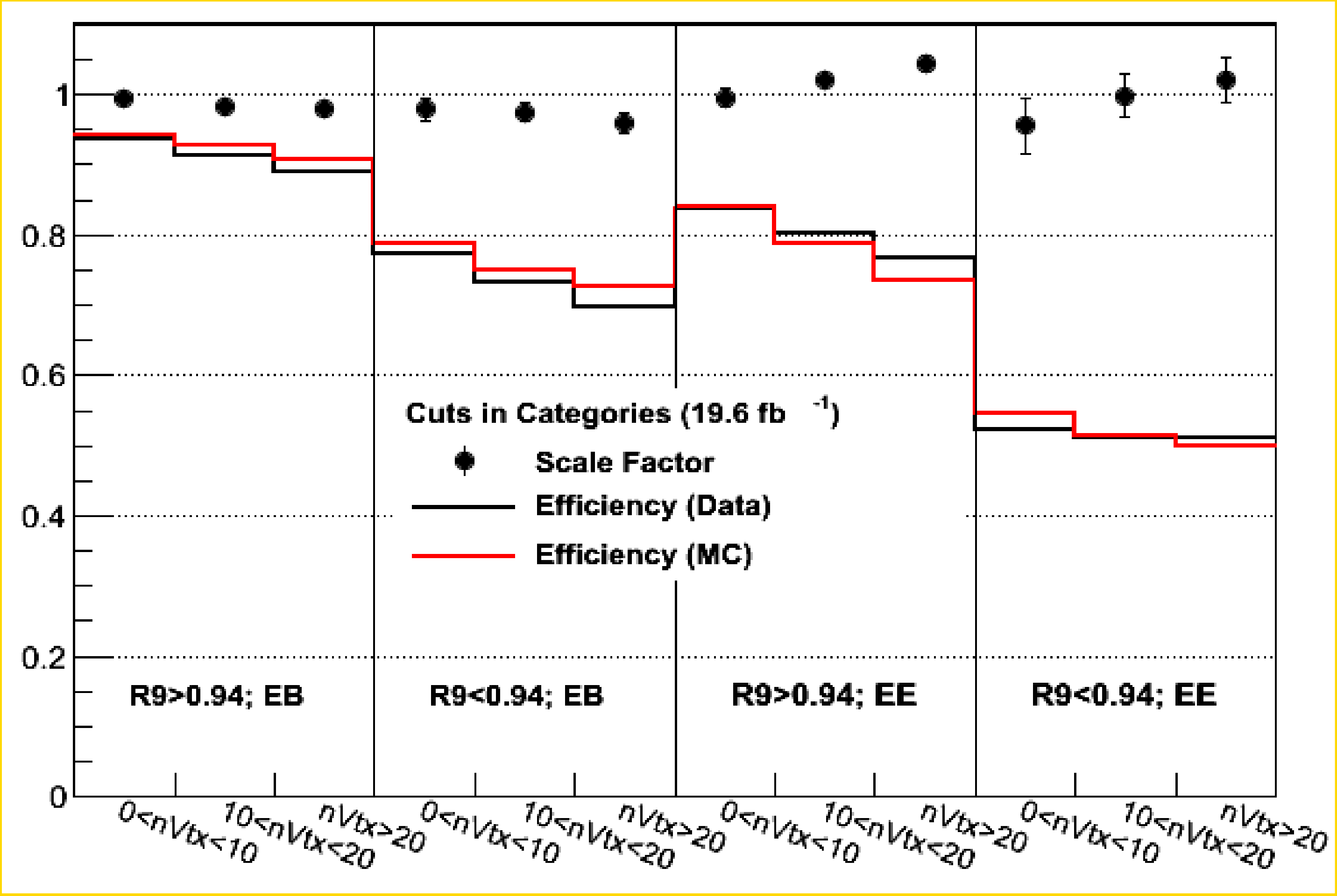


Data/MC efficiency for Z→μμ after removing the μ tracks



Pileup Robustness: Cut-based ID Efficiency

- **Cut-based Photon ID efficiency per event decreases with increasing pileup; well described by MC**

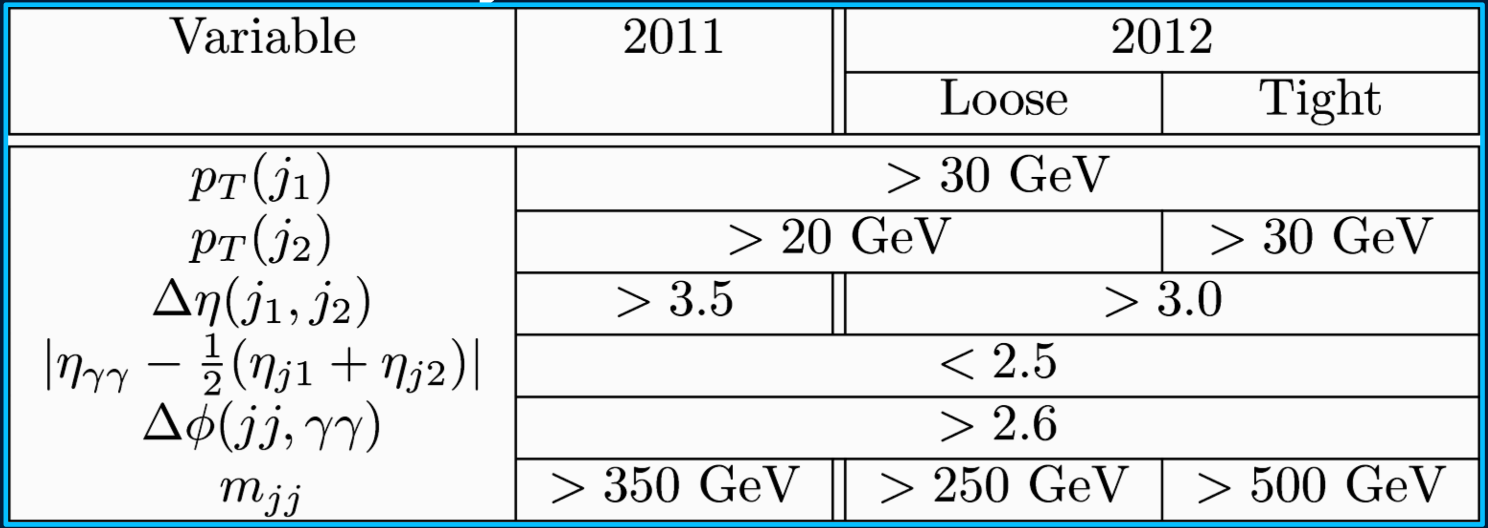


Di-jet Tagging: Selection

Analysis improvements in 2012:

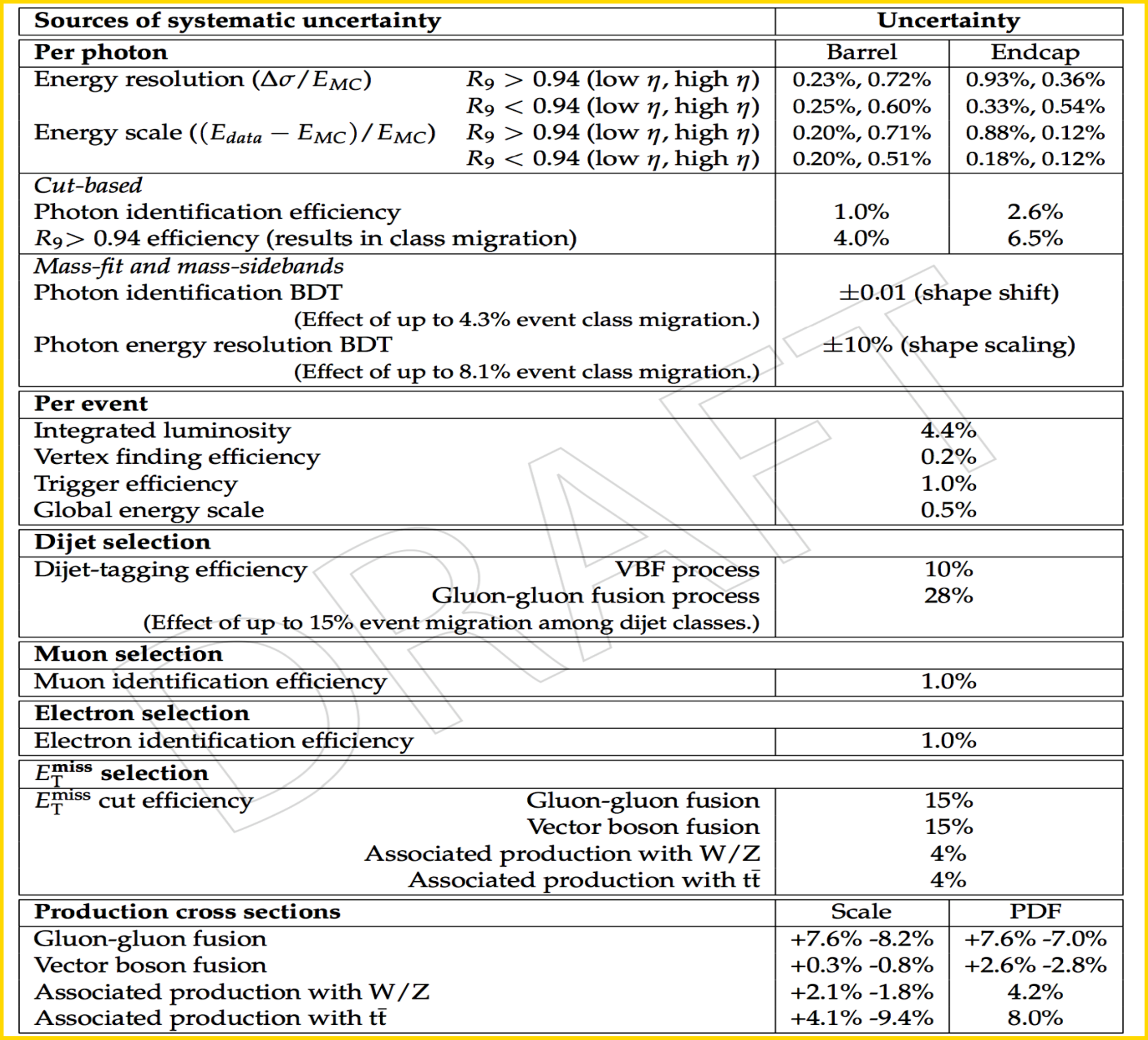
- Split di-jet tagged events in two categories based on M_{jj} and jet p_T
  - → ~15% improvement in sensitivity for dijet category
  - → Better sensitivity to separate different Higgs production modes
- Removal of jets from pileup events
  - → Based on the jet shape variables, tracks in jet and vertexing
  - → Cross-checked using Z+jet and γ+jet events

Dijet selection cuts



Variable	2011	2012	
		Loose	Tight
$p_T(j_1)$	> 30 GeV		
$p_T(j_2)$	> 20 GeV		> 30 GeV
$\Delta\eta(j_1, j_2)$	> 3.5	> 3.0	
$\|\eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2})\|$	< 2.5		
$\Delta\phi(jj, \gamma\gamma)$	> 2.6		
m_{jj}	> 350 GeV	> 250 GeV	> 500 GeV

H→ γγ MVA: Systematic Uncertainties
Per Photon, Per Event, Per Category



Sources of systematic uncertainty		**Uncertainty**	
Per photon		Barrel	Endcap
Energy resolution ($\Delta\sigma / E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.23%, 0.72%	0.93%, 0.36%
	$R_9 < 0.94$ (low η, high η)	0.25%, 0.60%	0.33%, 0.54%
Energy scale (($E_{data} - E_{MC}$)/E_{MC})	$R_9 > 0.94$ (low η, high η)	0.20%, 0.71%	0.88%, 0.12%
	$R_9 < 0.94$ (low η, high η)	0.20%, 0.51%	0.18%, 0.12%
Cut-based			
Photon identification efficiency		1.0%	2.6%
R_9> 0.94 efficiency (results in class migration)		4.0%	6.5%
Mass-fit and mass-sidebands			
Photon identification BDT		±0.01 (shape shift)	
	(Effect of up to 4.3% event class migration.)		
Photon energy resolution BDT		±10% (shape scaling)	
	(Effect of up to 8.1% event class migration.)		
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency		1.0%	
Global energy scale		0.5%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	28%	
	(Effect of up to 15% event migration among dijet classes.)		
Muon selection			
Muon identification efficiency		1.0%	
Electron selection			
Electron identification efficiency		1.0%	
E_T^{miss} **selection**			
E_T^{miss} cut efficiency	Gluon-gluon fusion	15%	
	Vector boson fusion	15%	
	Associated production with W/Z	4%	
	Associated production with $t\bar{t}$	4%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+7.6% -8.2%	+7.6% -7.0%
Vector boson fusion		+0.3% -0.8%	+2.6% -2.8%
Associated production with W/Z		+2.1% -1.8%	4.2%
Associated production with $t\bar{t}$		+4.1% -9.4%	8.0%

H → γγ Cut-based analysis

- Cut-based analysis uses a cut-based photon identification and a different definition of event classes
  - Photon identification data/MC efficiency scale factors computed from Z→ee and Z→μμγ.
- 4 categories are defined according to the photon characteristics
  - Barrel-endcap & converted/unconverted from shower shape
  - Different mass resolution and S/B among the 4 categories

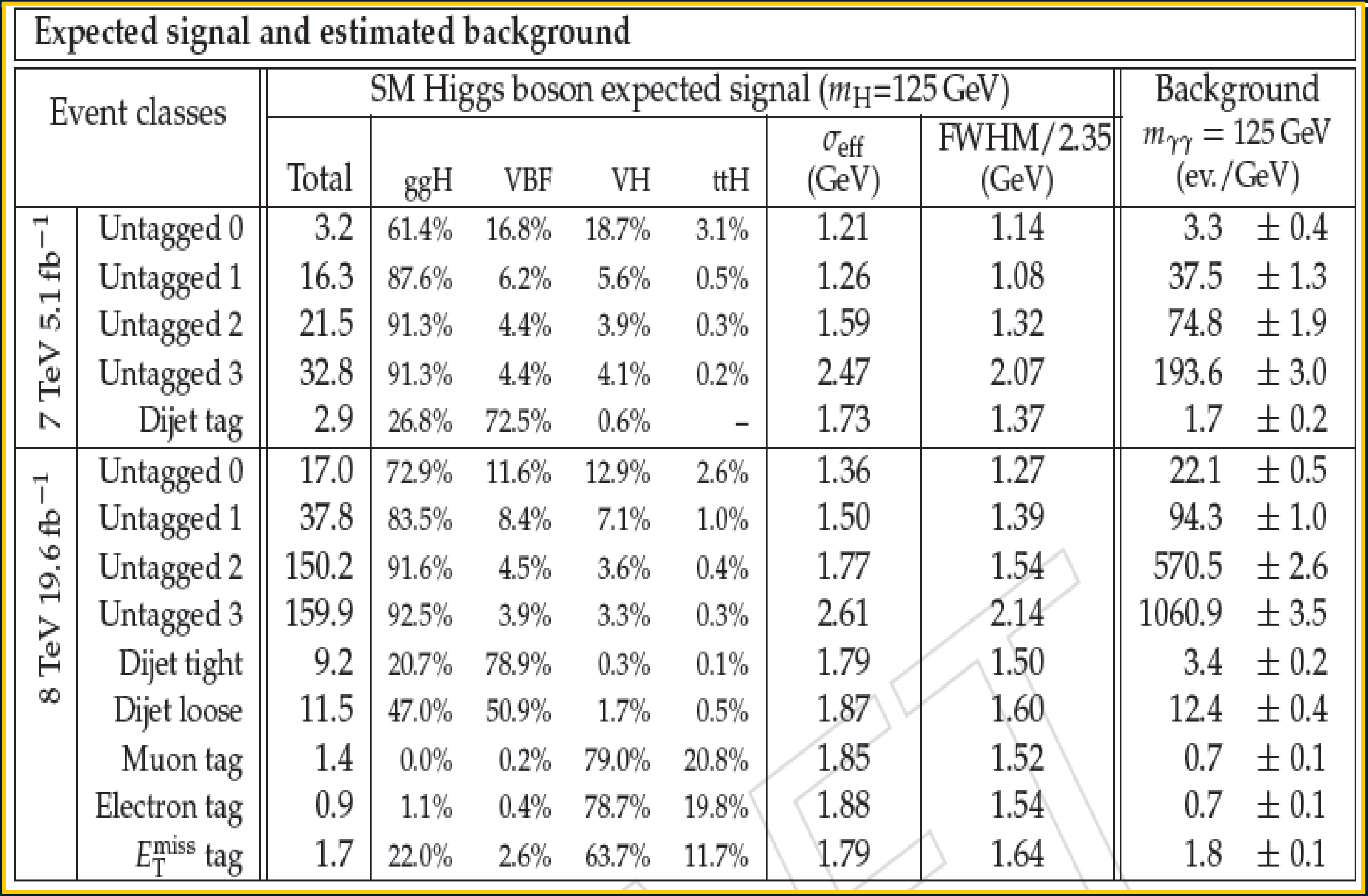
Cat 0	Both photons in barrel	Both photons $R_9 > 0.94$
Cat 1	Both photons in barrel	At least one photon with $R_9 < 0.94$
Cat 2	At least one photon in endcaps	Both photons $R_9 > 0.94$
Cat 3	At least one photon in endcaps	At least one photon with $R_9 < 0.94$

Photon ID: Cut Based

Validation with Z→ee (inverted electron veto)

- Four Categories: Barrel or Endcap;
  Shower Shape $R_9 < 0.94$, $R_9 > 0.94$
- Photon pre-selection:
  - $E_{T\gamma1}/m_{\gamma\gamma} > 1/3$, $E_{T\gamma2}/m_{\gamma\gamma} > 1/4$
  - H/E, shower shape, Isolation
  - Photon ID a bit tighter than trigger selection and MC EM enrichment filters
  - Efficiency measured using tag and probe with Z→ee
  - Electron veto: Efficiency measured using tag and probe with $Z \rightarrow \mu\mu\gamma$ (no electron veto)
- ID Selection in Each Category:
  - Shower shape, H/E, global event isolation, corrected by per-event energy density

H→ γγ Cuts Based Expected Event Yields, Resolution and Backgrounds in Each Category

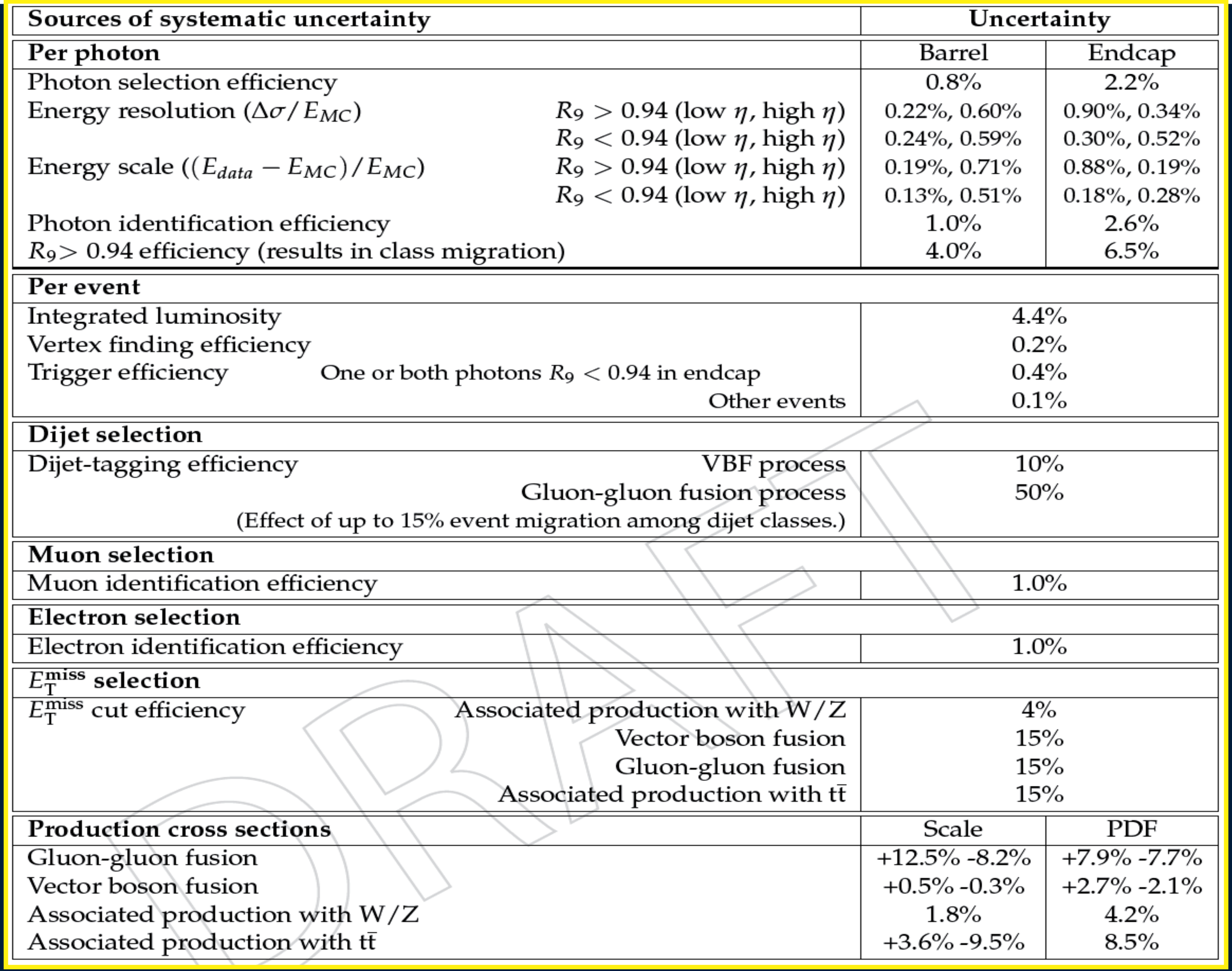


Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	$m_{\gamma\gamma} = 125$ GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1

H→ γγ Cuts Based: Systematic Uncertainties

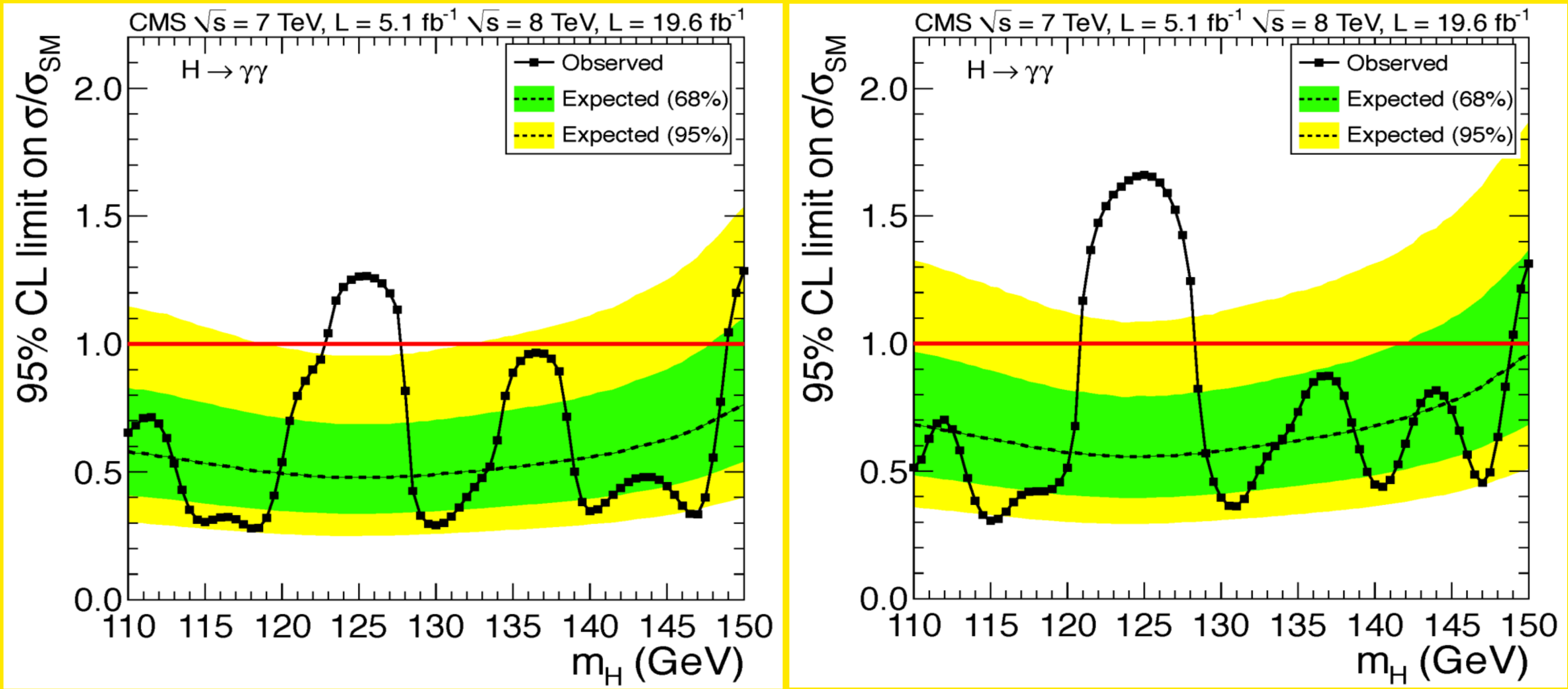
Per Photon, Per Event, Per Category



Sources of systematic uncertainty		**Uncertainty**	
Per photon		Barrel	Endcap
Photon selection efficiency		0.8%	2.2%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.60%	0.90%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.52%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Photon identification efficiency		1.0%	2.6%
$R_9 > 0.94$ efficiency (results in class migration)		4.0%	6.5%
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	50%	
	(Effect of up to 15% event migration among dijet classes.)		
Muon selection			
Muon identification efficiency		1.0%	
Electron selection			
Electron identification efficiency		1.0%	
E_T^{miss} selection			
E_T^{miss} cut efficiency	Associated production with W/Z	4%	
	Vector boson fusion	15%	
	Gluon-gluon fusion	15%	
	Associated production with $t\bar{t}$	15%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Associated production with $t\bar{t}$		+3.6% -9.5%	8.5%

H → γγ Results: 95% CL Limits

MVA mass-fit | **Cut-based**

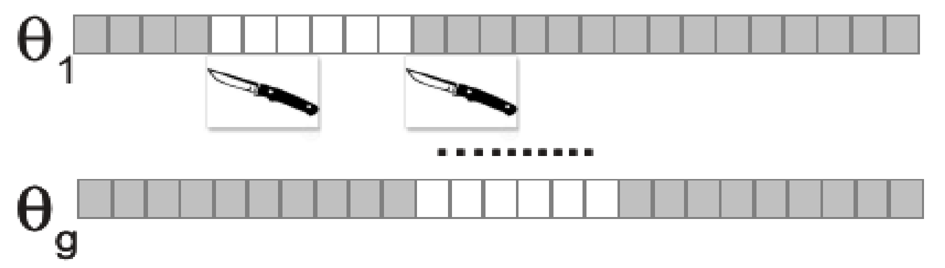


Exclude almost the full mass range at 95% CL

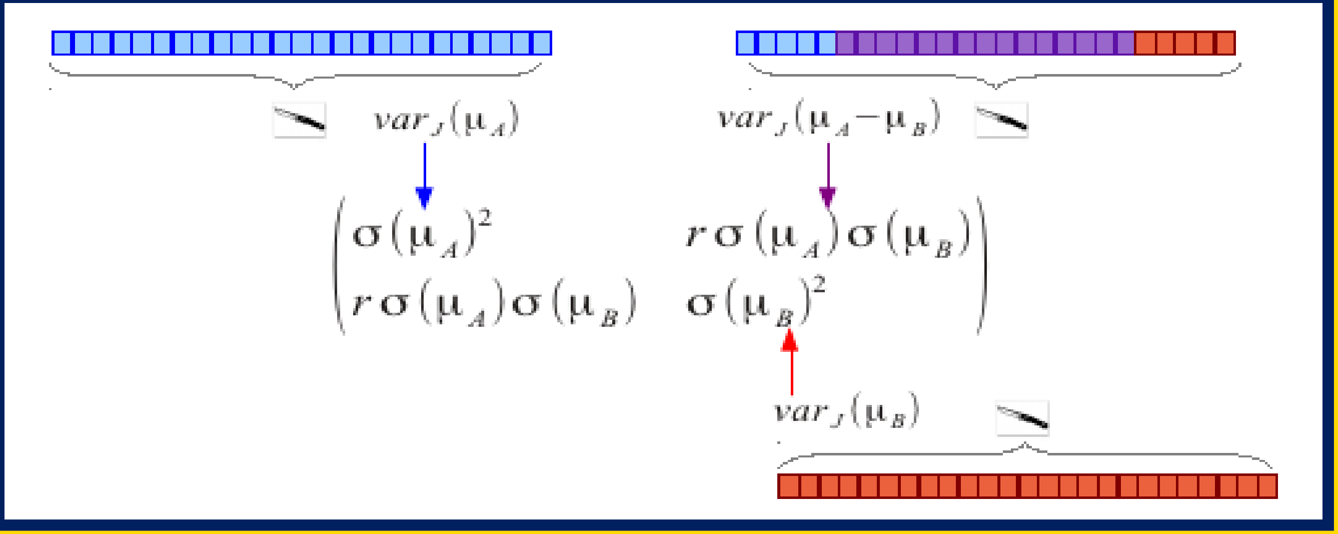
Except the region around 125 GeV

Jacknife Resampling

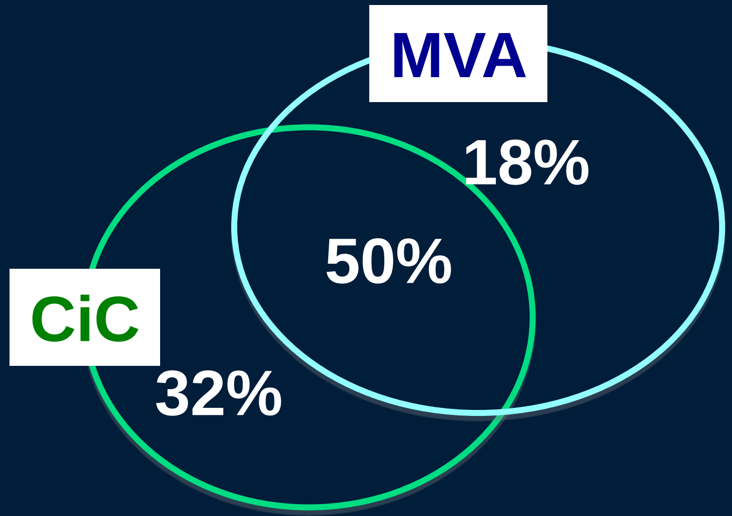
- Jackknife resampling can be used to estimate the variance of statistical estimators in a non parametric way.
  - Achieved evaluating the estimator on subsets of the statistical sample.



- Given analyses A and B, used to estimate the variance of μ_A-μ_B by applying the jackknife resampling method to the events selected by either analysis.

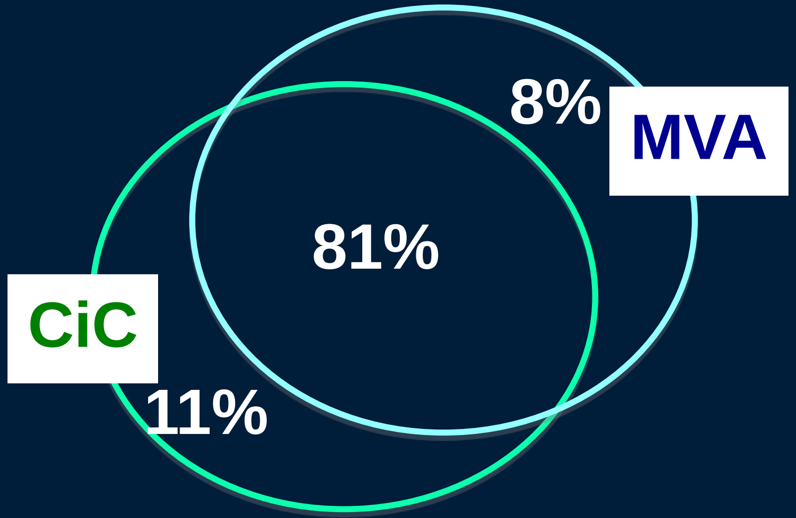


Overlap of Selected Events



Data

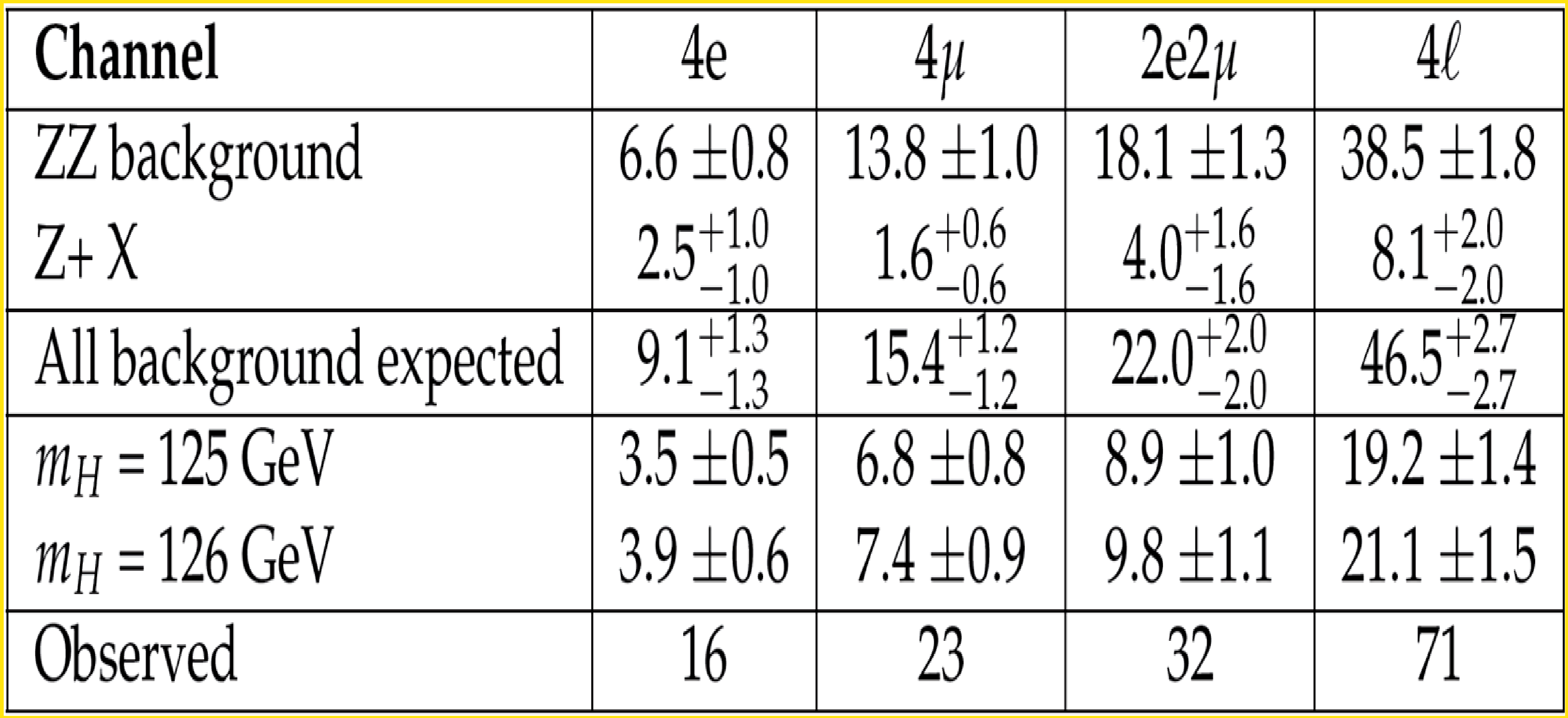
(Background MC agrees)



Signal MC

H → ZZ(*) Event Yields 110 – 160 GeV

Observed Vs. Expected Signal + Background Rates



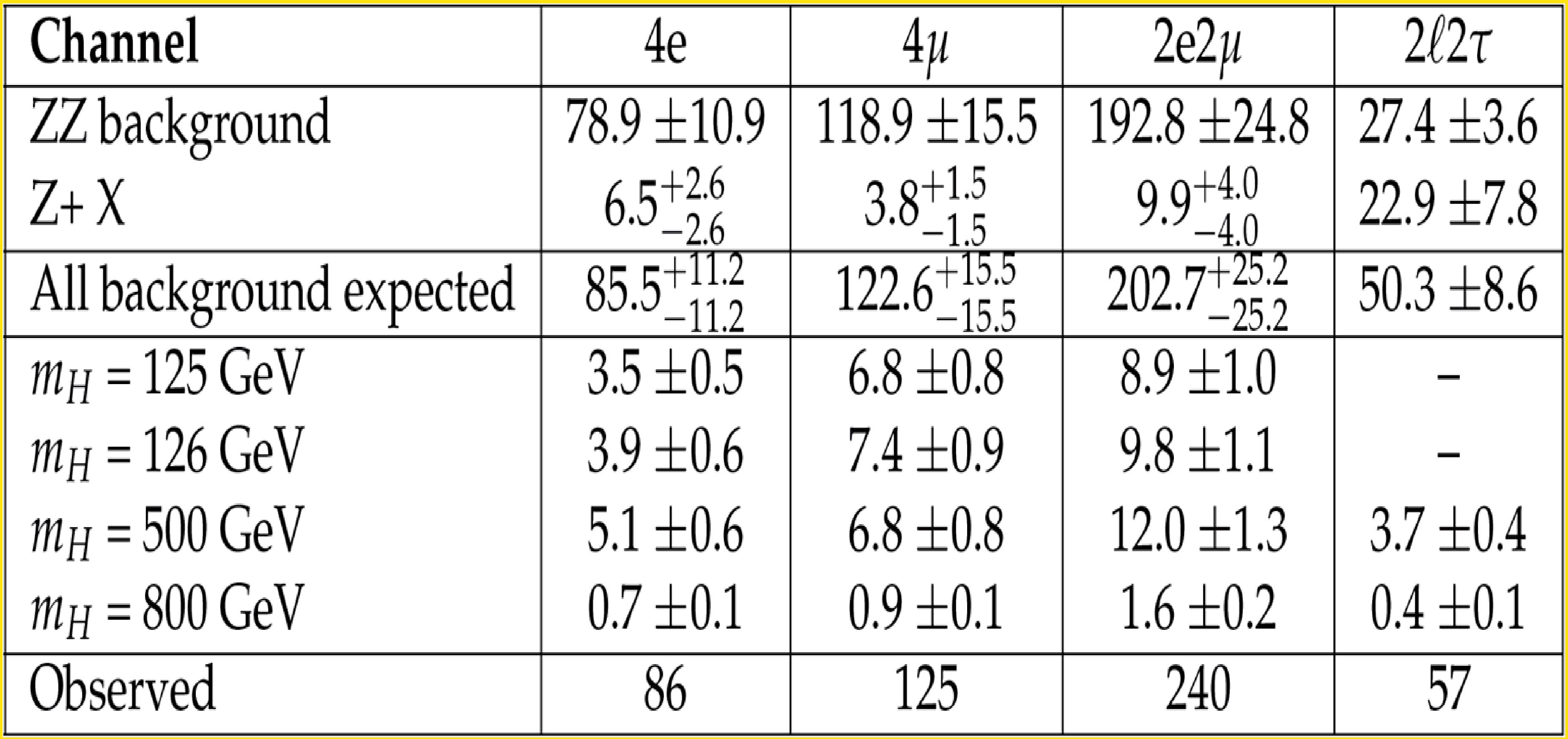
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ± 0.8	13.8 ± 1.0	18.1 ± 1.3	38.5 ± 1.8
Z+ X	$2.5^{+1.0}_{-1.0}$	$1.6^{+0.6}_{-0.6}$	$4.0^{+1.6}_{-1.6}$	$8.1^{+2.0}_{-2.0}$
All background expected	$9.1^{+1.3}_{-1.3}$	$15.4^{+1.2}_{-1.2}$	$22.0^{+2.0}_{-2.0}$	$46.5^{+2.7}_{-2.7}$
$m_H = 125$ GeV	3.5 ± 0.5	6.8 ± 0.8	8.9 ± 1.0	19.2 ± 1.4
$m_H = 126$ GeV	3.9 ± 0.6	7.4 ± 0.9	9.8 ± 1.1	21.1 ± 1.5
Observed	16	23	32	71

Z+X Background from data in control regions

ZZ background from Simulation

H ➡ ZZ(*) Event Yields 100 – 1000 GeV

Observed Vs. Expected Signal + Background Rates



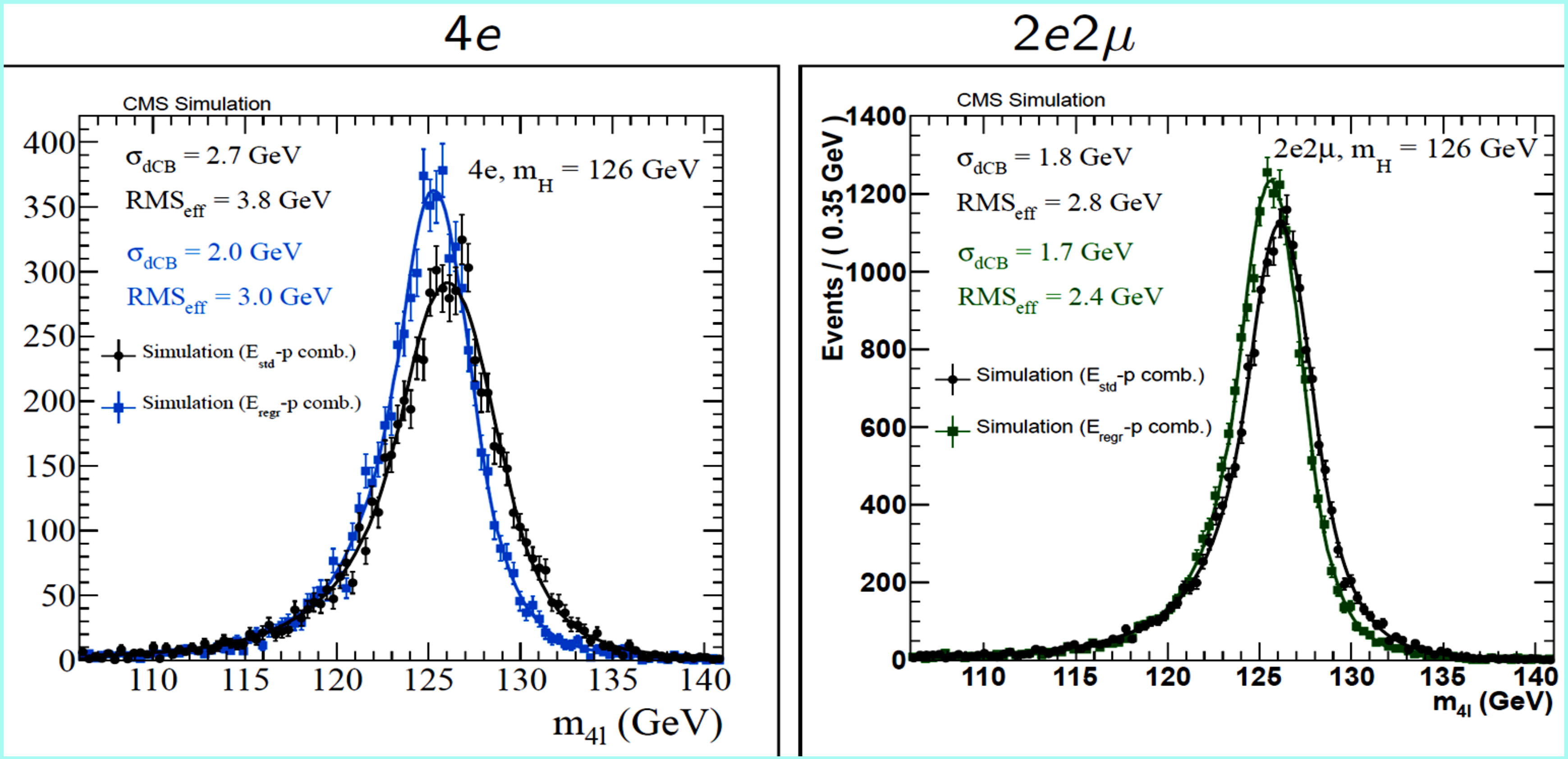
Channel	4e	4μ	$2e2\mu$	$2\ell2\tau$
ZZ background	78.9 ± 10.9	118.9 ± 15.5	192.8 ± 24.8	27.4 ± 3.6
Z+ X	$6.5^{+2.6}_{-2.6}$	$3.8^{+1.5}_{-1.5}$	$9.9^{+4.0}_{-4.0}$	22.9 ± 7.8
All background expected	$85.5^{+11.2}_{-11.2}$	$122.6^{+15.5}_{-15.5}$	$202.7^{+25.2}_{-25.2}$	50.3 ± 8.6
$m_H = 125$ GeV	3.5 ± 0.5	6.8 ± 0.8	8.9 ± 1.0	–
$m_H = 126$ GeV	3.9 ± 0.6	7.4 ± 0.9	9.8 ± 1.1	–
$m_H = 500$ GeV	5.1 ± 0.6	6.8 ± 0.8	12.0 ± 1.3	3.7 ± 0.4
$m_H = 800$ GeV	0.7 ± 0.1	0.9 ± 0.1	1.6 ± 0.2	0.4 ± 0.1
Observed	86	125	240	57

Z+X Background from data in control regions

ZZ background from Simulation

$H \to ZZ \to 2l_1\, 2l_2$ (l = e, μ)

Improved Electron Resolution in 2012

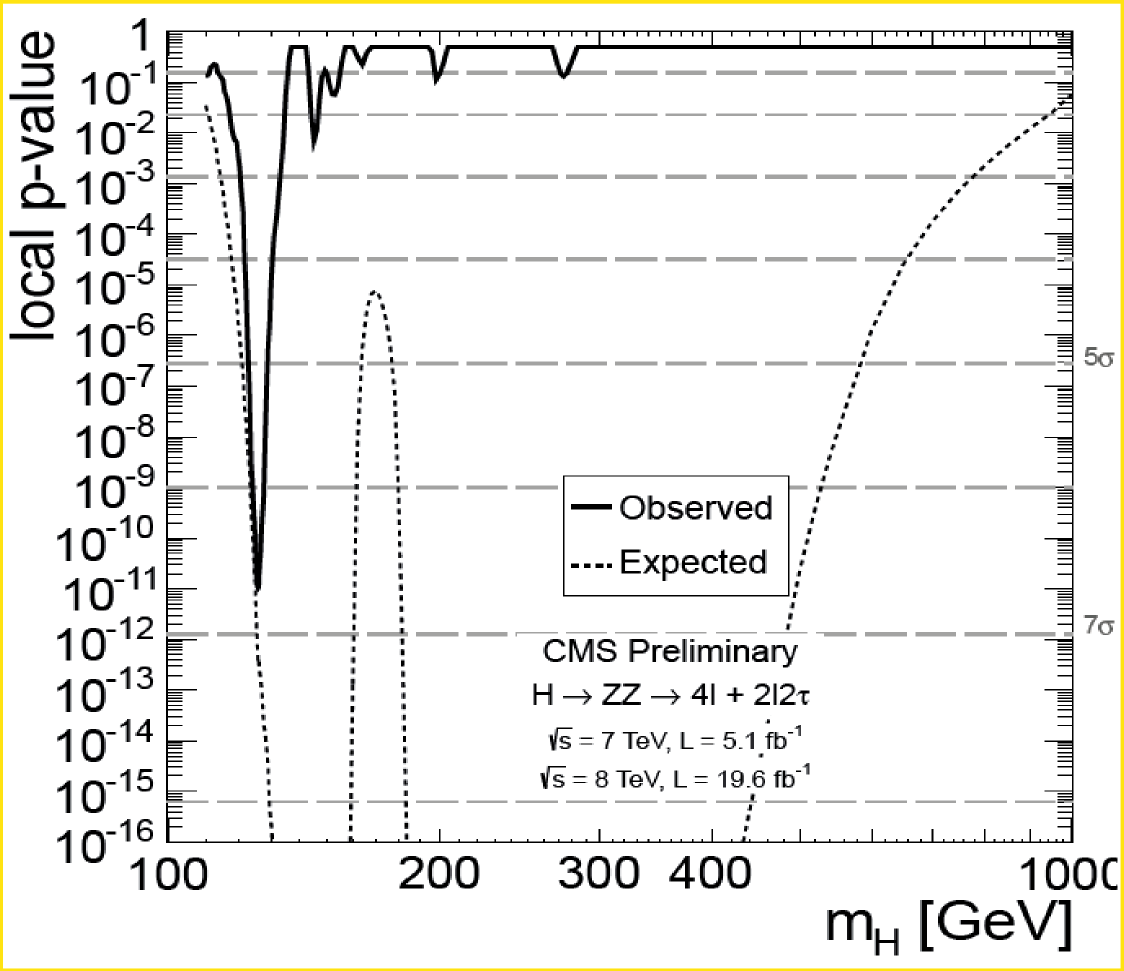


- ➡ **New electron Energy Determination** using regression
- ➡ M_H (126) **Resolution Improved**
  - ➡ σ_{CB} from **2.7** to **2.0 GeV**; σ_{eff} from **3.8** to **3.0 GeV (4e events)**
  - ➡ σ_{CB} from **1.8** to **1.7 GeV**; σ_{eff} from **2.8** to **2.4 GeV (2e2μ events)**

$H \rightarrow ZZ \rightarrow 4l$ and $2l2\tau$

Over the Full Range: P-Values

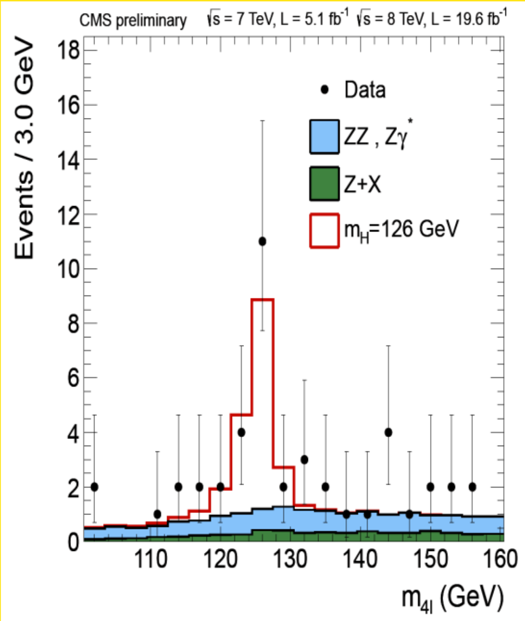
- SM Higgs is excluded at 95% CL in the range 130 – 827 GeV expected exclusion 130 – 778 GeV



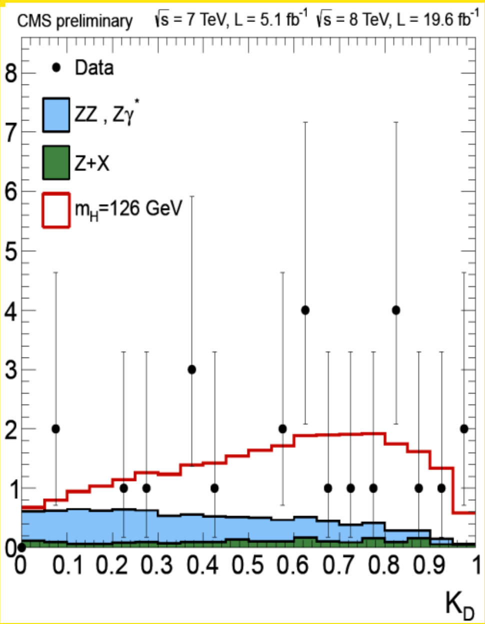
$H \rightarrow ZZ(^*) \rightarrow 4l$: Signal/Background Separation

Variables in 1D, 2D, 3D Fits: M_{4l}, K_D and (P_T/M or V_D)

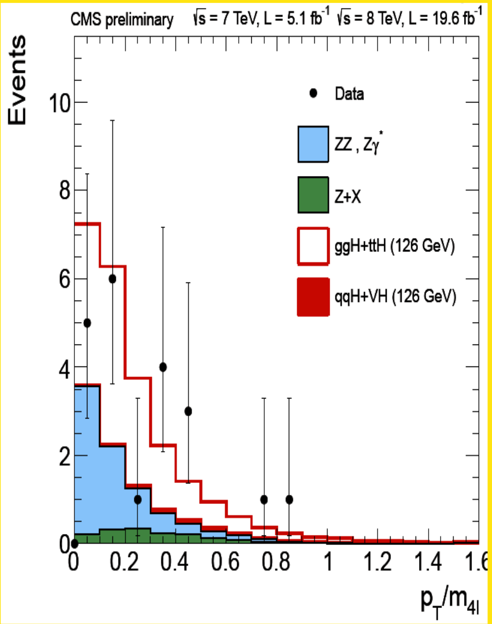
M_{4l} with $K_D > 0.5$



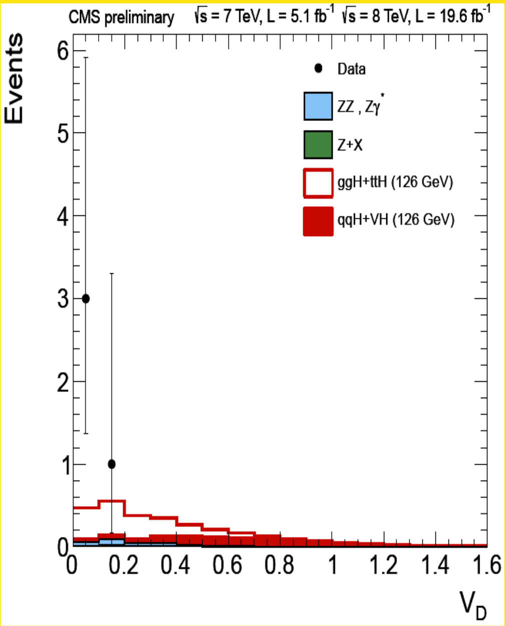
Kinematic Disc. K_D



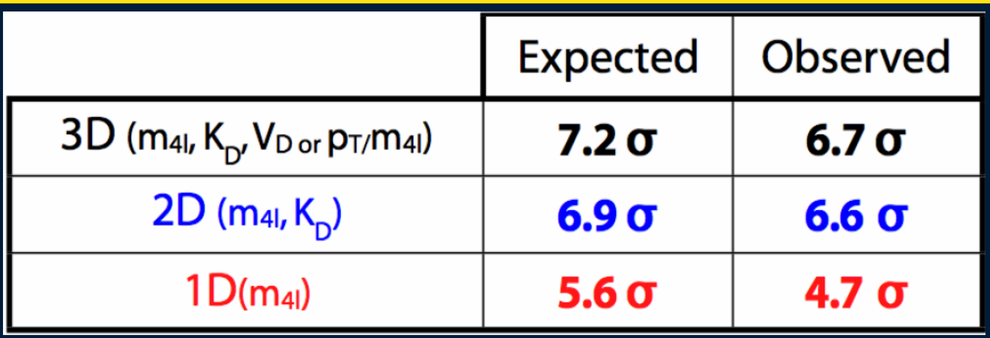
P_T/M_{4l}



DiJet Discriminant V_D



Events in the Peak Region: $121.5 < M_{4l} < 130.5$ GeV



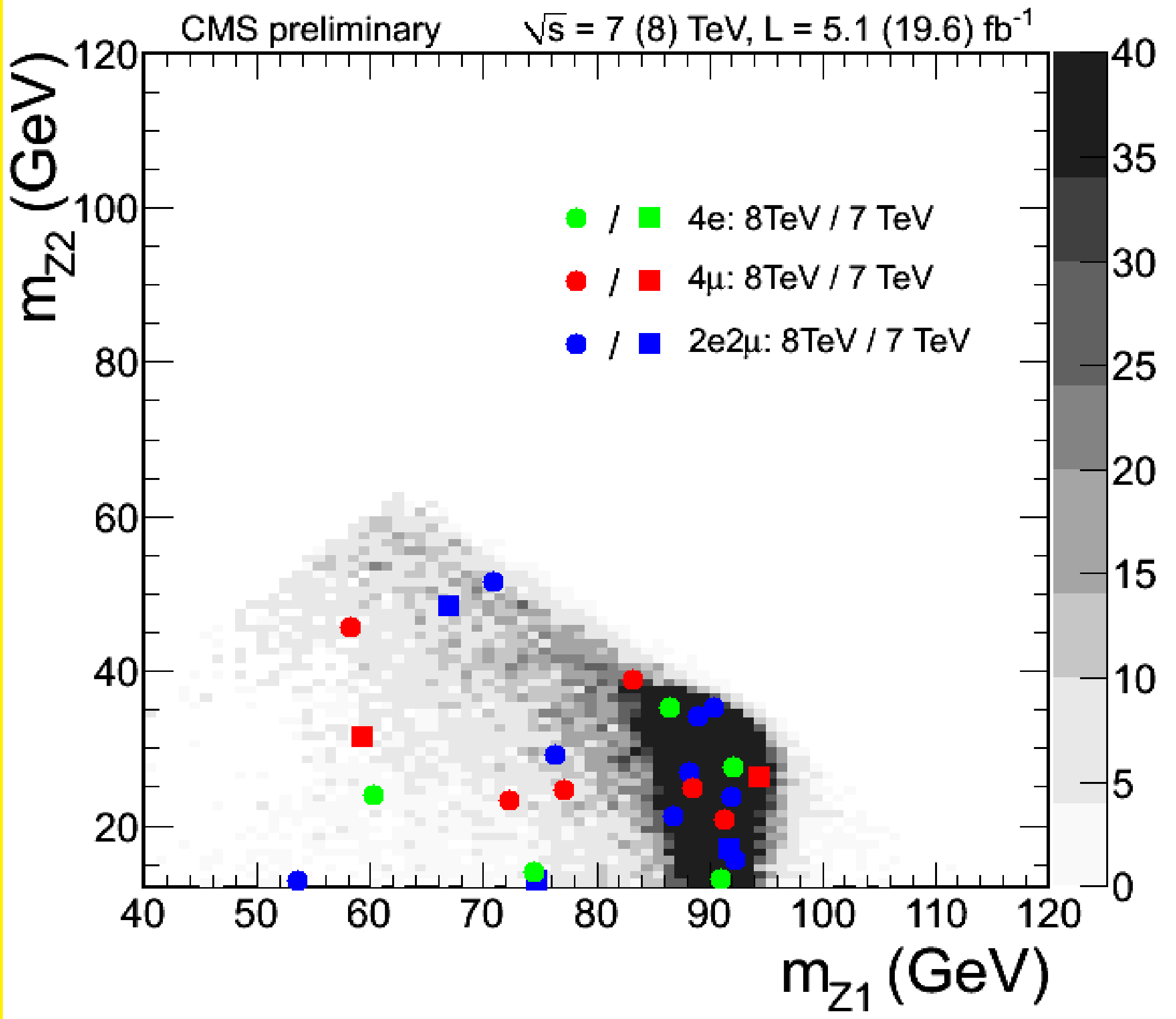
	Expected	Observed
3D (m_{4l}, K_D, V_D or p_T/m_{4l})	**7.2 σ**	**6.7 σ**
2D (m_{4l}, K_D)	**6.9 σ**	**6.6 σ**
1D(m_{4l})	**5.6 σ**	**4.7 σ**

V_D: A Fisher Discriminant for the Dijet-tagged Category using m_{jj} and $\Delta\eta_{jj}$ as inputs.

Events are mainly gg ➡ H + 2 jets; also targets VBF

$H \rightarrow ZZ \rightarrow 4l$

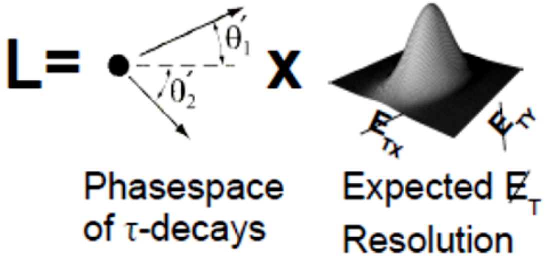
M_{Z1} Versus M_{Z2}

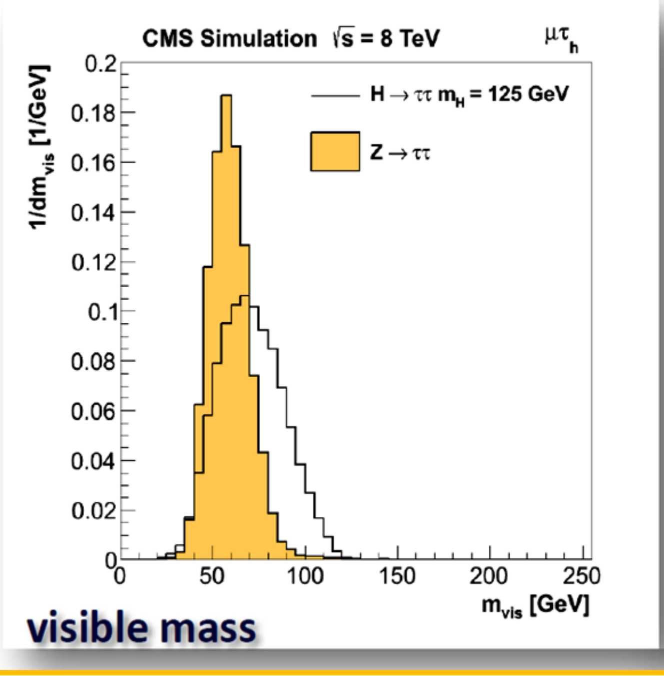


$M(\tau\tau)$

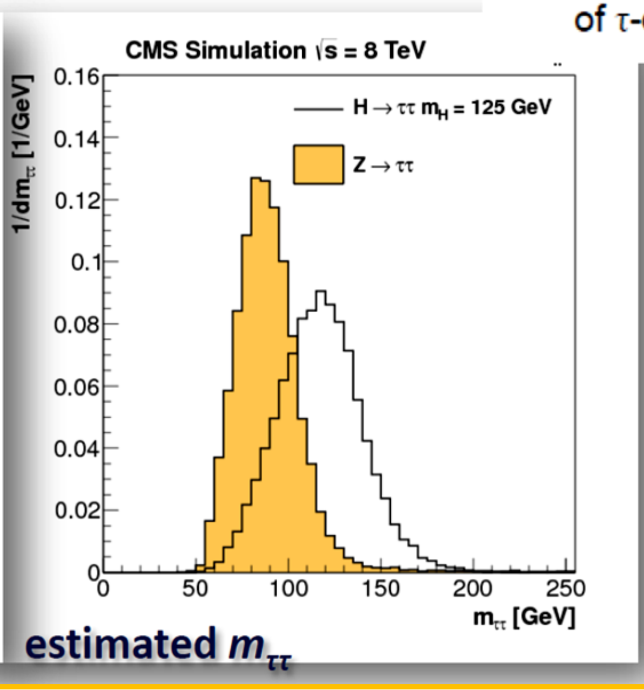
Improved Reconstruction

- Maximum likelihood method used
- Estimated on event-by-event basis using four-momenta of visible decay products, E_x^{miss}, E_y^{miss}, expected E_T^{miss} resolution
- Nuisance parameters integrated out
- 15-20% resolution on reconstructed $m_{\tau\tau}$

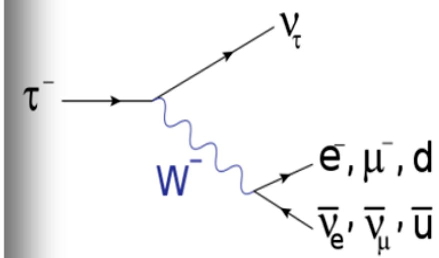




visible mass



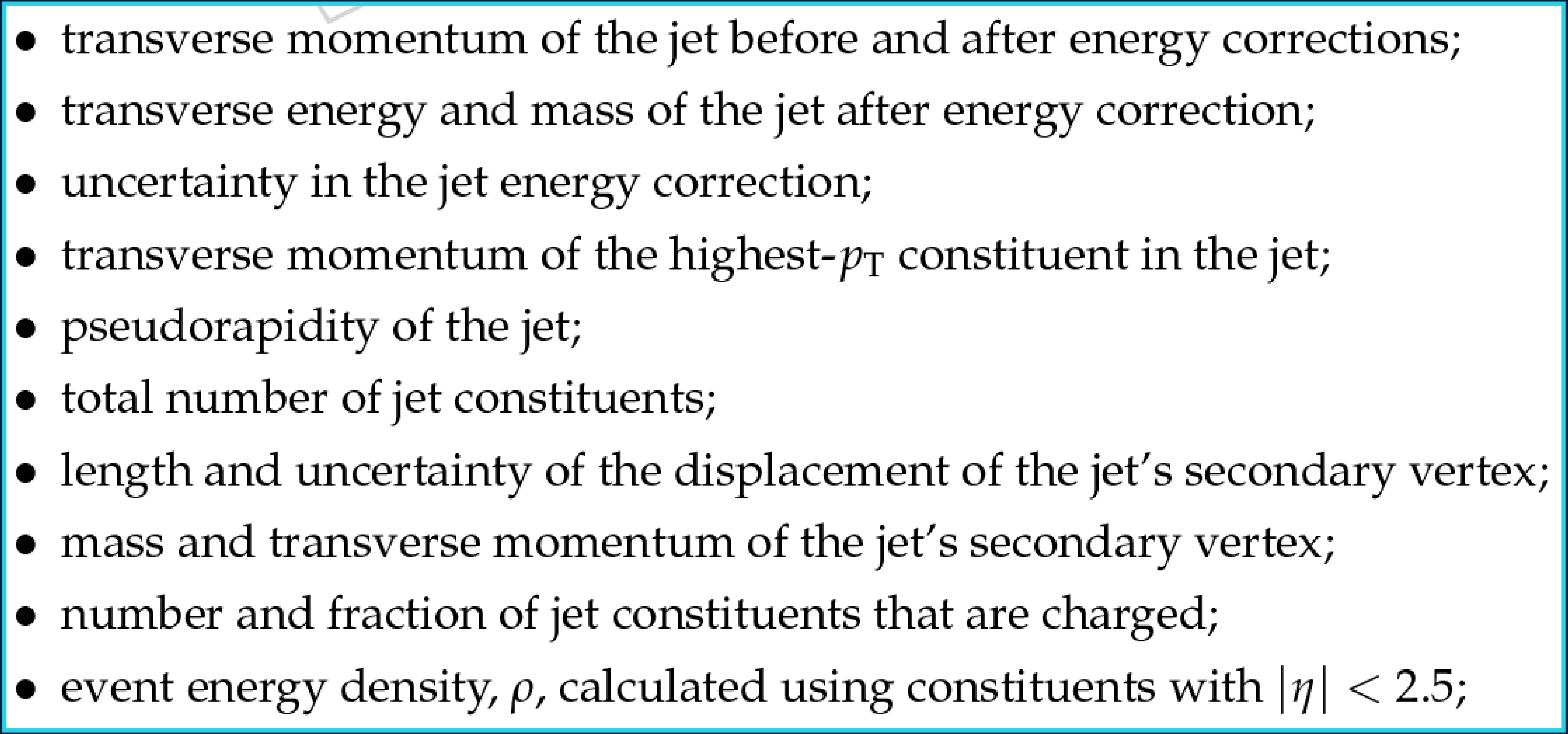
estimated $m_{\tau\tau}$



H → bb-bar Reconstruction

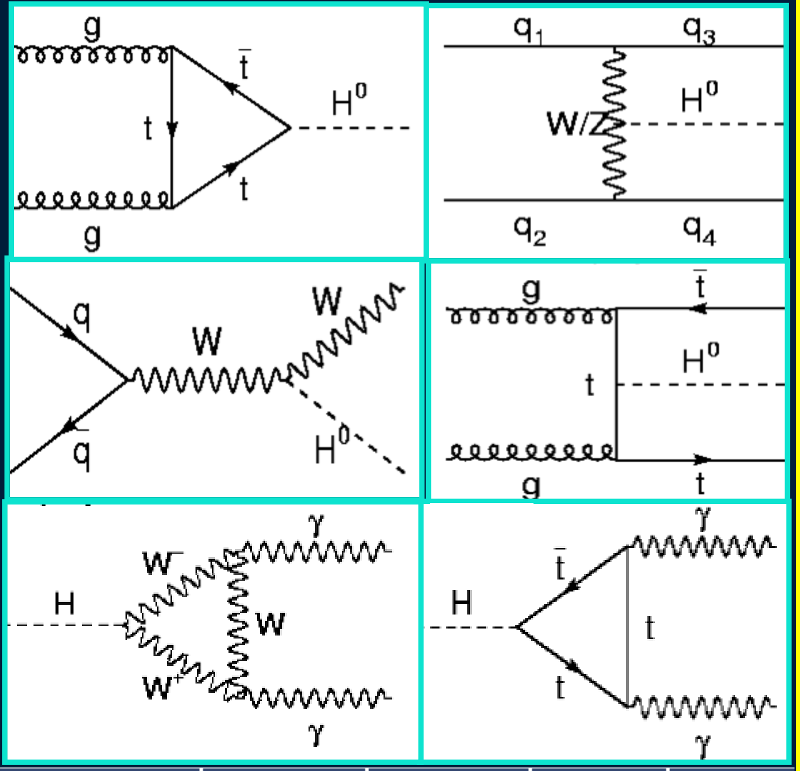
Regression Input Variables

- **15% Improvement in Resolution**
- **10-20% Increase in Analysis Sensitivity**



- transverse momentum of the jet before and after energy corrections;
- transverse energy and mass of the jet after energy correction;
- uncertainty in the jet energy correction;
- transverse momentum of the highest-p_{T} constituent in the jet;
- pseudorapidity of the jet;
- total number of jet constituents;
- length and uncertainty of the displacement of the jet's secondary vertex;
- mass and transverse momentum of the jet's secondary vertex;
- number and fraction of jet constituents that are charged;
- event energy density, ρ, calculated using constituents with $|\eta| < 2.5$;

Combining CMS
SM Higgs Searches



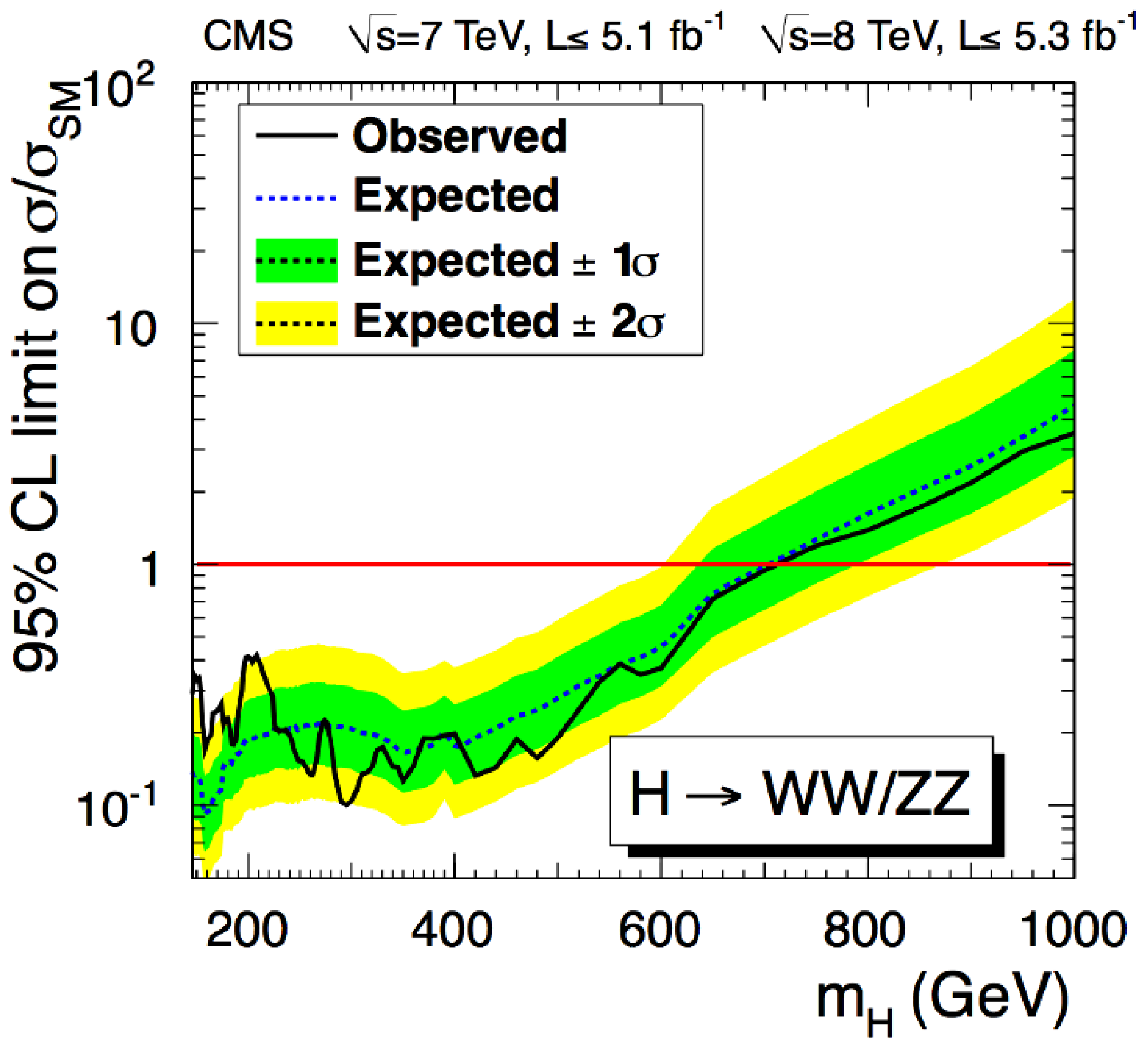
	un-tagged	VBF-tag	VH-tag	ttH-tag
γγ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	
WW(lvlv)	✔	✔	✔	
ZZ(4l)	✔	✓		

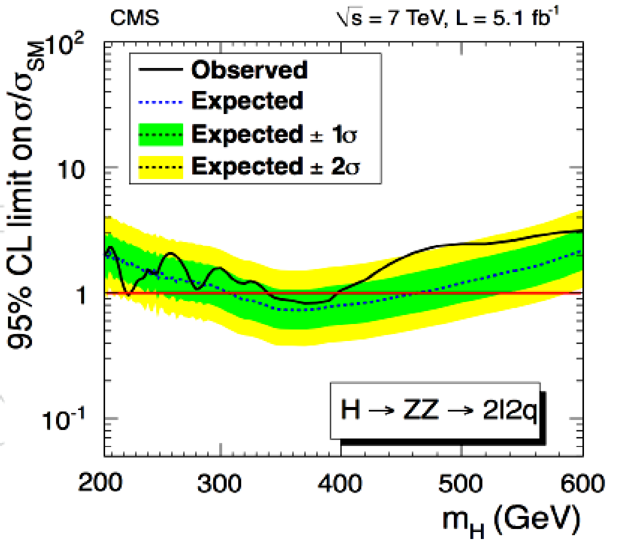
CMS HIG-12-045

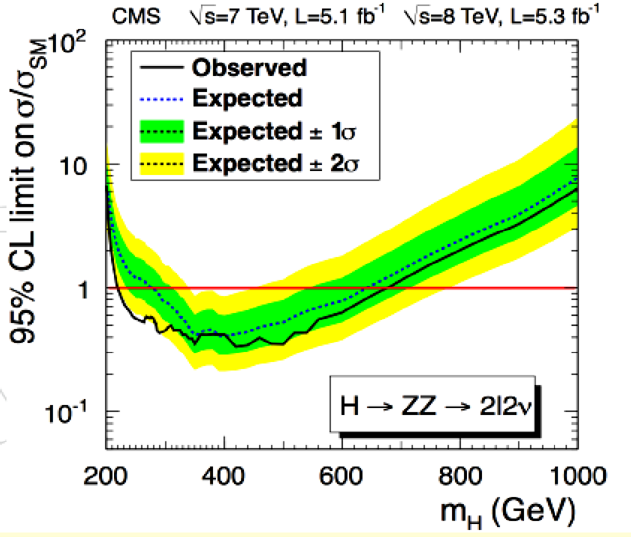
Decay	Prod. Topology	Luminosity
H→bb	VH + ttH	5+12 fb^{-1} at 7+8 TeV
H→ ττ	Inclusive + VBF + VH	5+12 fb^{-1} at 7+8 TeV
H → γγ	Inclusive + VBF	5+12 fb^{-1} at 7+8 TeV
H → WW	1 jet + VBF + VH	5+12 fb^{-1} at 7+8 TeV
H → ZZ	Inclusive [+ dijet tag at Moriond]	5+12 fb^{-1} at 7+8 TeV

H → ZZ → WW/ZZ, 2l2q, 2l2ν

Searches for Additional Bosons

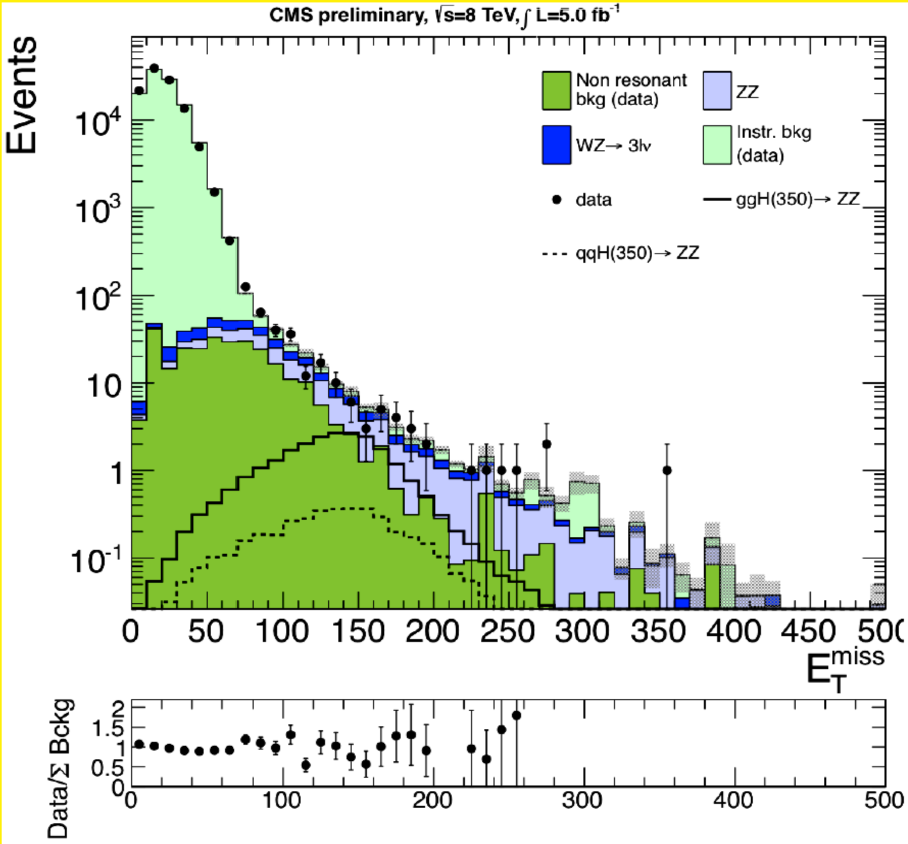




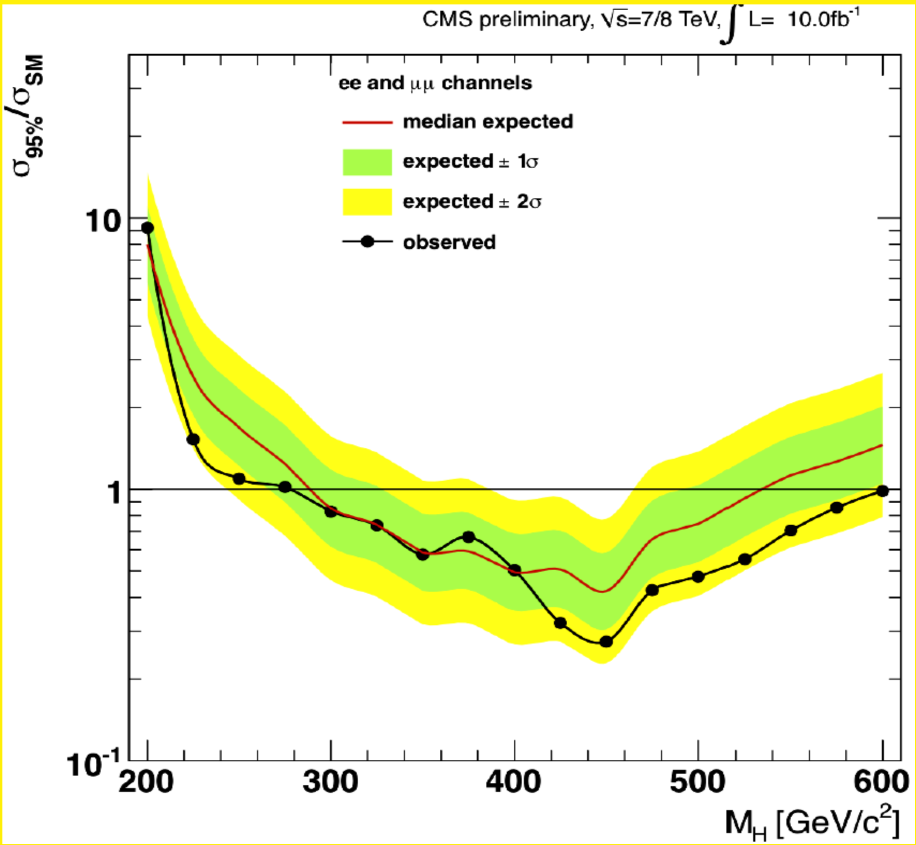


$H \rightarrow ZZ \rightarrow 2l2\nu$

E_T^{Miss}



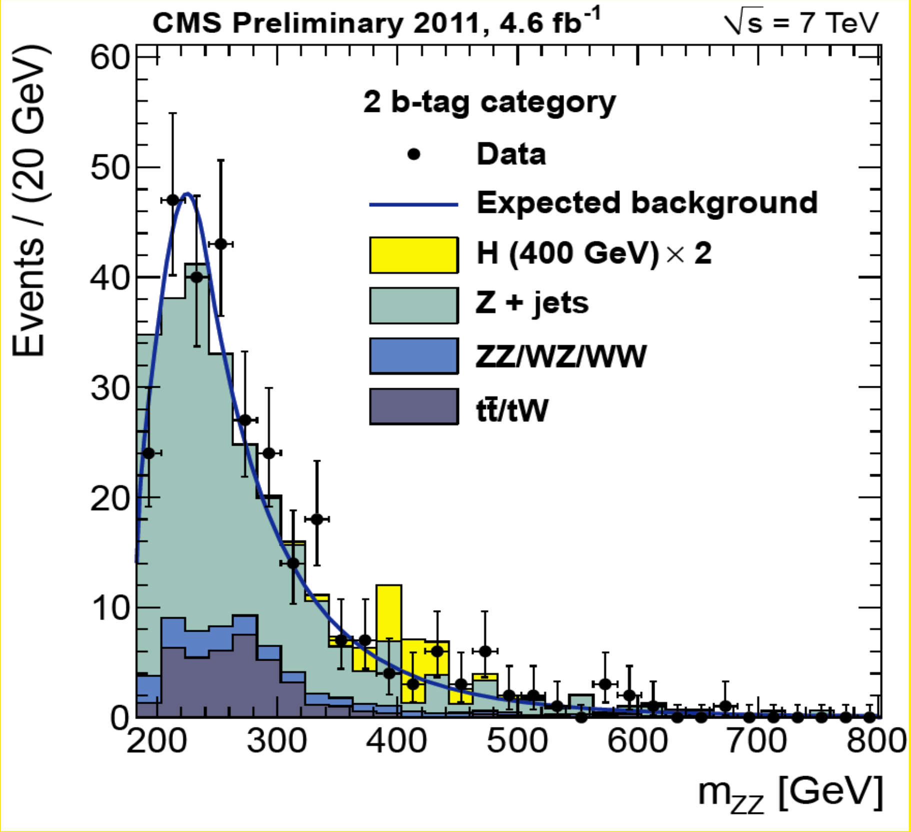
95% CL Limit on σ/σ_{SM} vs M_H



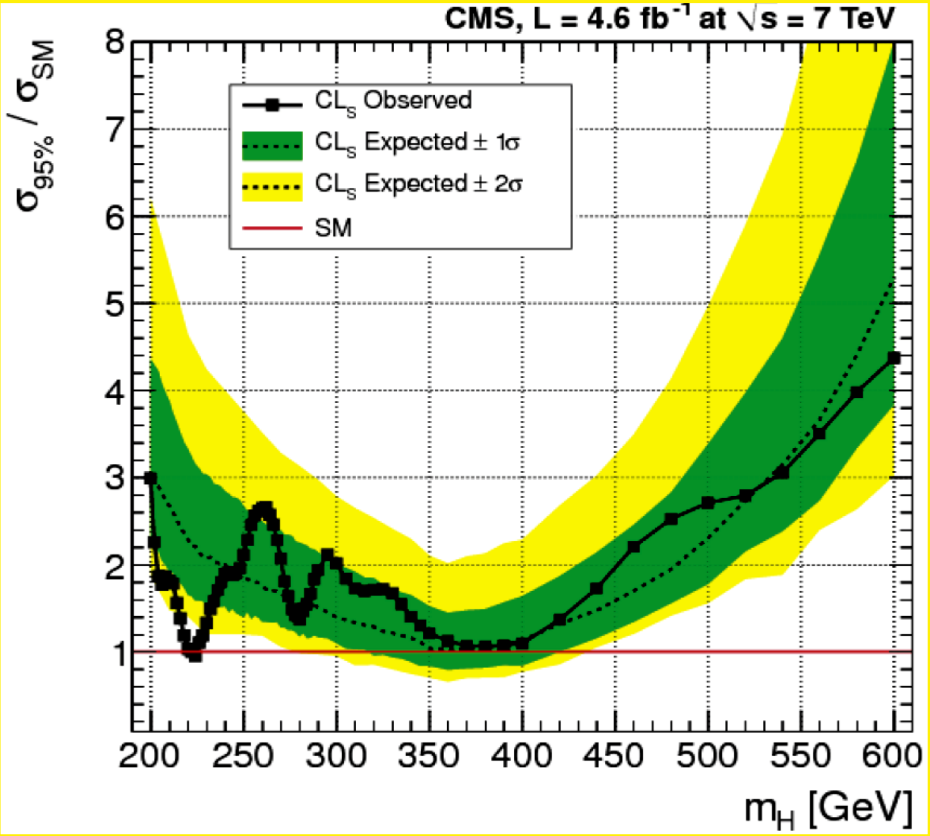
- Final State: **Dilepton from a Z, Large E_T^{Miss}**
- Split in Categories: **e, μ; 0,1,2 Jets**
- Use M_T as the Final Variable

H → ZZ → 2*l*2q

M_{ZZ}



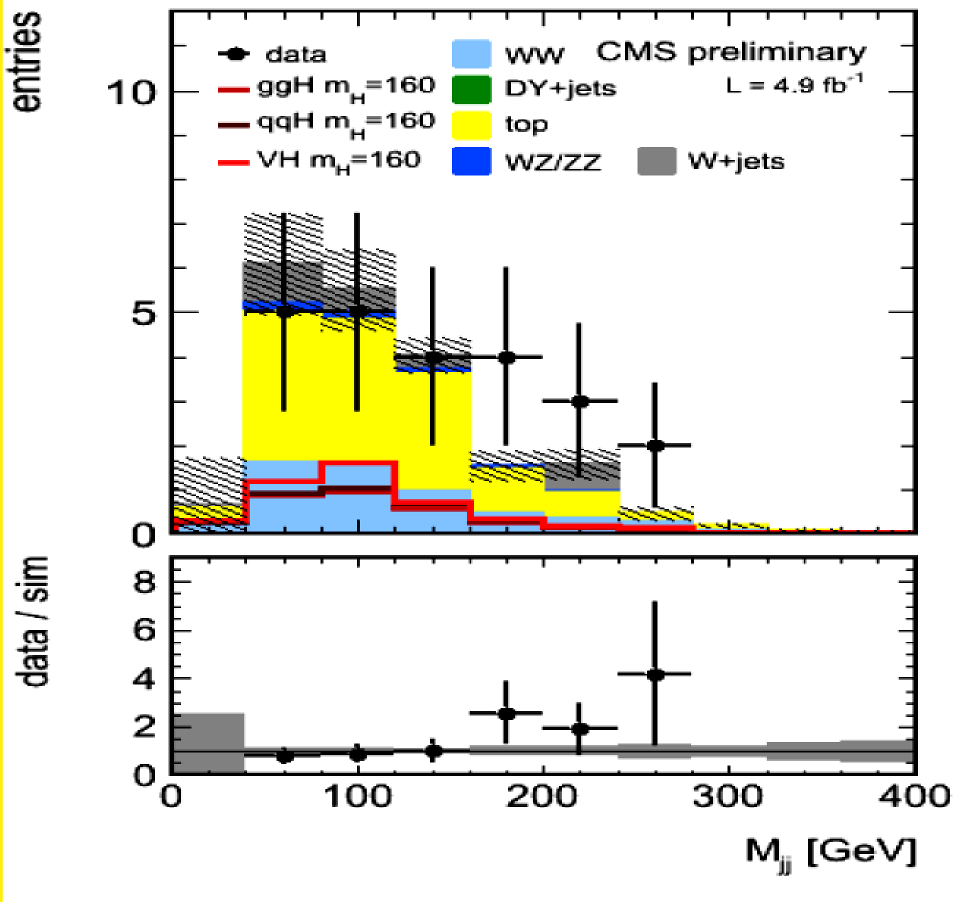
95% CL Limit on σ/σ_{SM} vs M_H



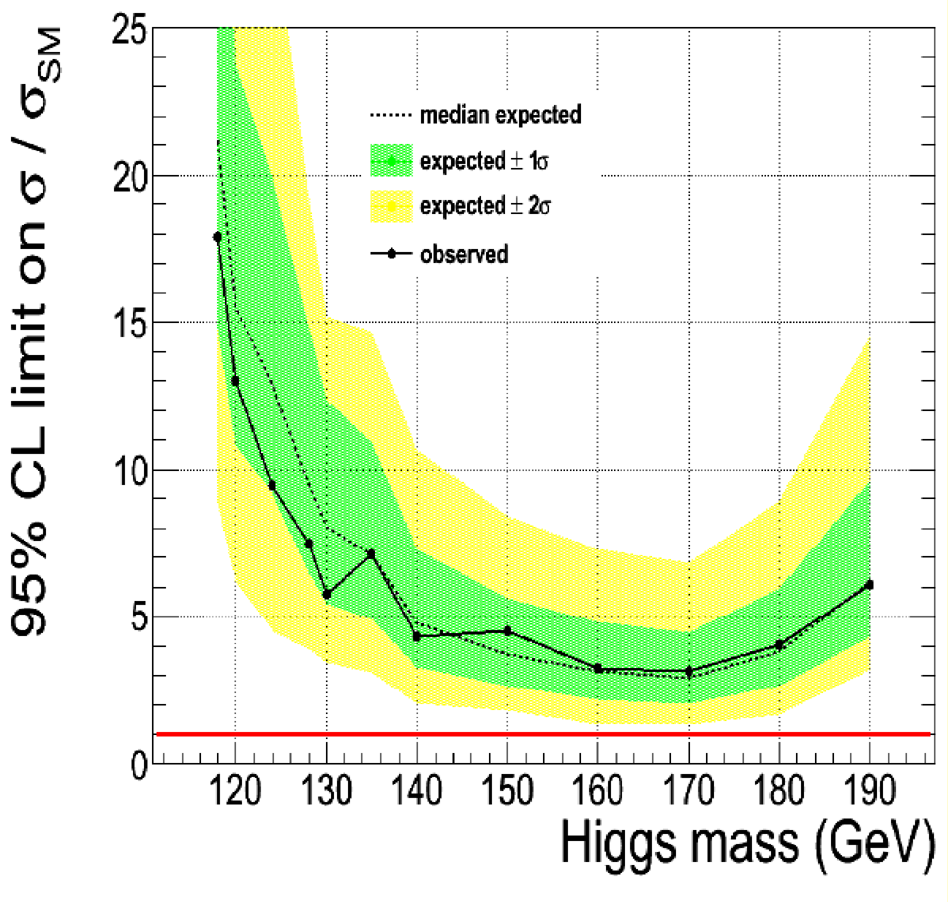
- Final State: Dilepton from a Z, DiJet from another Z
- Split in Categories: e, μ; 0,1,2 b-Jets
- Use M(2*l*2q) as the Final Variable

$WH \rightarrow qq'WW \rightarrow qq'2l2\nu$

M (Jet-Jet)



95% CL Limit on σ/σ_{SM} vs M_H

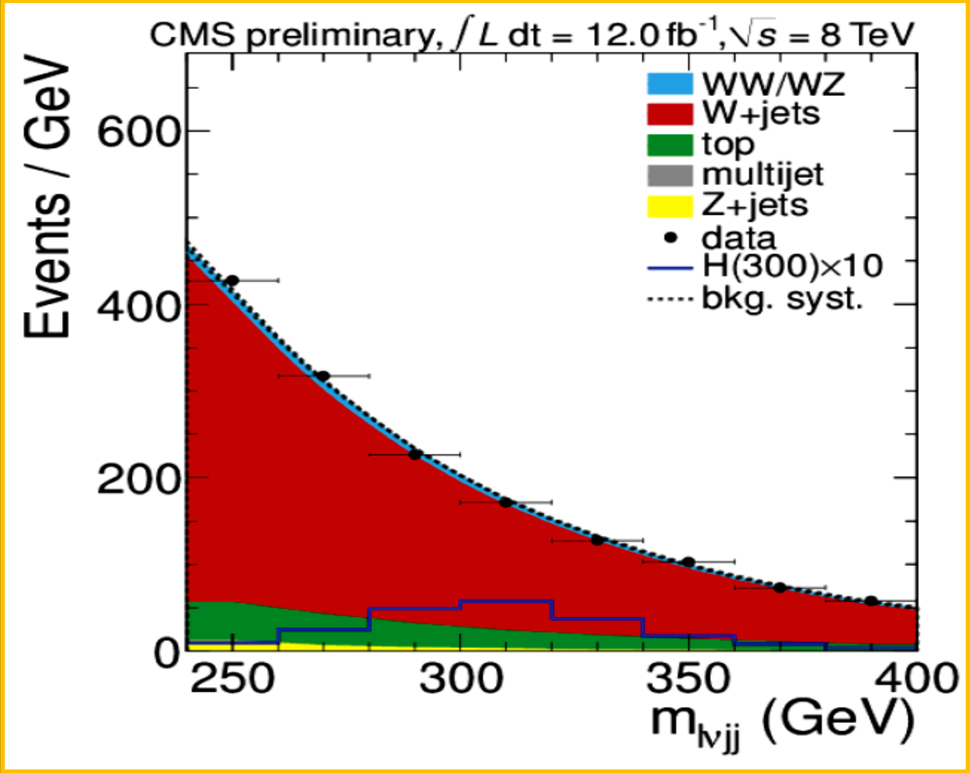


- Final State: **Two leptons, Two Jets and E_T^{Miss}**
- Use Methods from the main **$H \rightarrow WW \rightarrow 2l2\nu$** analysis

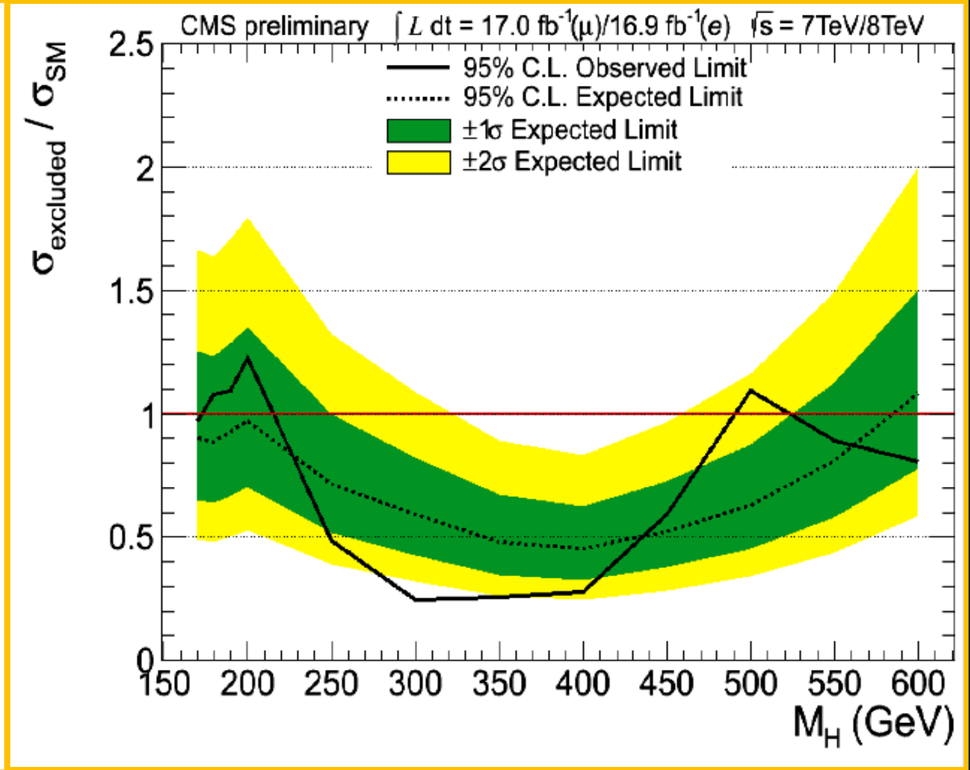
$H \to WW \to qq'l\nu$

CMS-PAS-HIG-12-046

$M(qq'l\nu)$



95% CL Limit on σ/σ_{SM} vs M_H



- Final State: One high pT isolated **lepton, two or more Jets, and large E_T^{Miss}**
- Use **$M(qq'l\nu)$** as the final variable
- **No significant excess observed**
- **Analysis in progress:** looking at higher masses

Statistics: Computing Limits
for the Higgs Search

CMS uses the CL_s method to set limits on $\mu = \sigma/\sigma_{SM}$

- Frequentist approach including systematic error evaluation

Likelihood function:

$$\mathcal{L}(data\,|\,\mu,\theta) = \text{Poisson}\left(\overbrace{data}^{\text{Observed}}\,\middle|\,\underbrace{\mu\cdot s(\theta)+b(\theta)}_{\text{Expected S+B}}\right)\cdot\overbrace{p(\tilde{\theta}|\theta)}^{\text{Systematics}}$$

Test statistics:

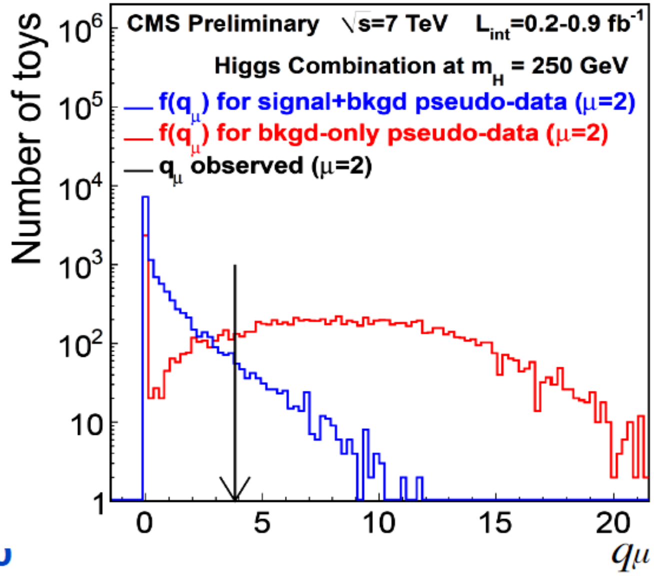
$$q_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)\leftarrow \text{fix } \mu\text{, vary } \hat{\theta}_\mu}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})\leftarrow \text{vary } \hat{\mu} \text{ and } \hat{\theta}}$$

$$0 \le \hat{\mu} \le \mu$$

Finally, calculate CL_s (toy MC):

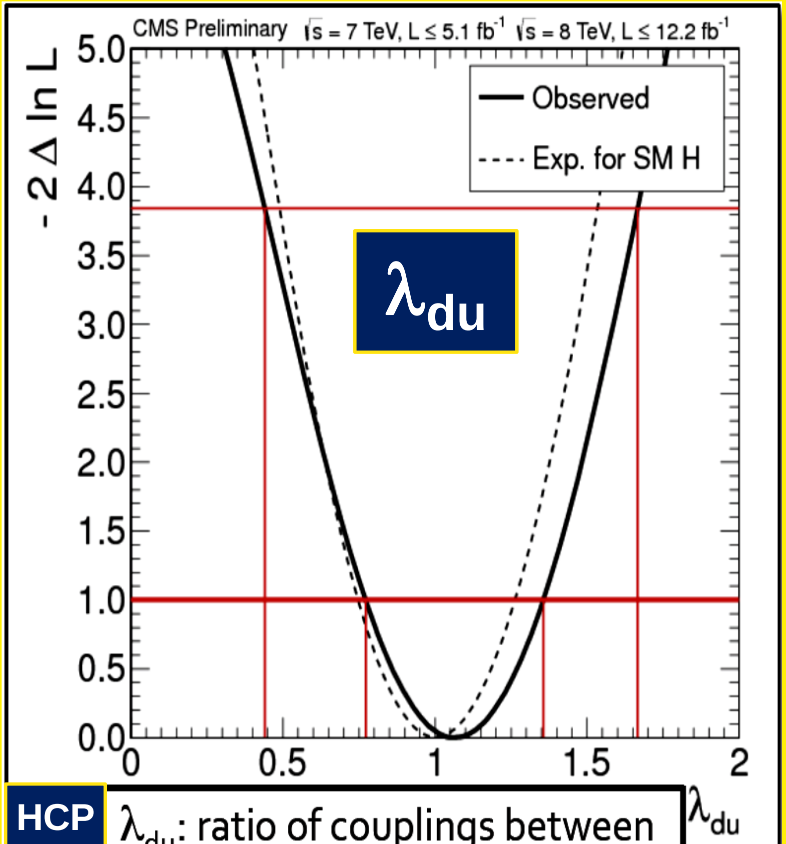
$$CL_s = \frac{P\left(q_\mu \geq q_\mu^{obs}\,|\,\mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \geq q_\mu^{obs}\,|\,b(\hat{\theta}_0^{obs})\right)}$$

95% C.L. is on μ value giving CL_s = 1 - 95%

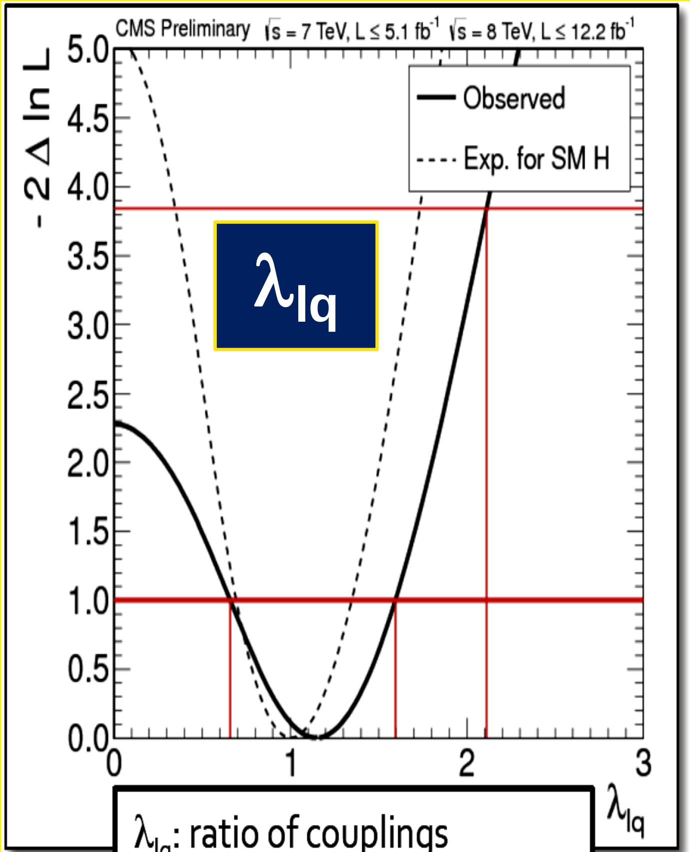


CERN-CMS Note-2011-005: Procedure for the LHC Higgs Boson Search Combination in Summer 2011

Searching for New Physics in the Relative Couplings to u and Quarks and to Leptons



λ_{du}: ratio of couplings between down- and up-fermions



λ_{lq}: ratio of couplings between leptons and quarks

- In the MSSM **the relative couplings to u and d quarks are modified**
- **The relative couplings to leptons and quarks** also can be modified in more general two Higgs doublet models

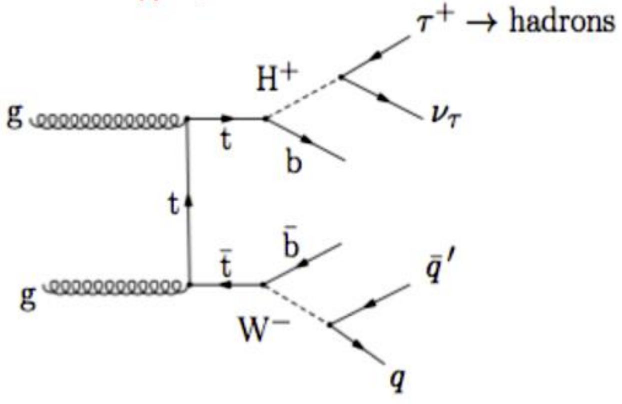
Result: the up/down and lepton/quark Coupling Ratios λ_{du} and λ_{lq} are both consistent with 1 ➡ **Consistent with the SM**

Charged Higgs in Top Quark Decays

Event Selections

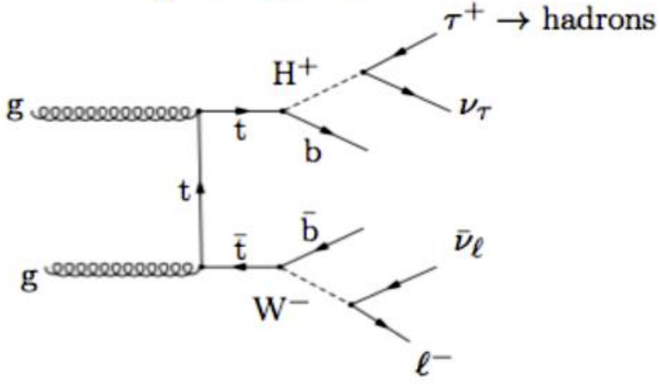
JHEP 07(2012)143
CMS-PAS-HIG-12-052

τ_h+jets



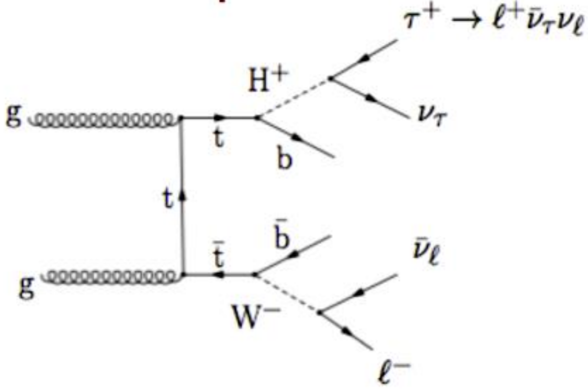
- Trigger: single tau+MET trigger
- Require one tau jet p_T>40 GeV
- MET>70 GeV
- At least 3 jets, p_T>30 GeV
- At least one b-tagged jet
- $\Delta\phi(\tau,MET)<160^o$
- Reconstruct $M_T(\tau,MET)$

τ_h+lepton



- Trigger: single muon (electron+jets) trigger
- One isolated electron/muon p_T>35(30) GeV
- At least 2 jets p_T>35(30) GeV
- MET>45(40) GeV
- One tau p_T>20 GeV
- Opposite-sign (tau,lepton)
- At least one b-tagged jet

di-lepton

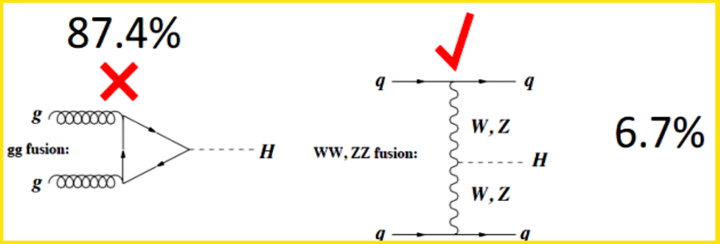


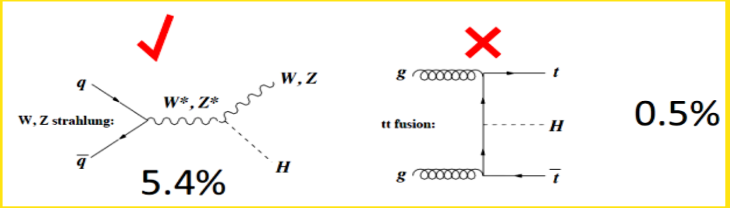
- eμ trigger: ele+mu (p_T>20 GeV)
- At least 2 jets (p_T>30 GeV)

Expect deficit of events (softer τ p_T)

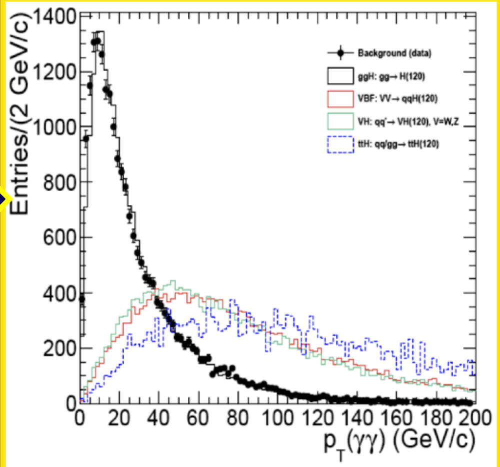
Fermiophobic Higgs: γγ, WW, ZZ

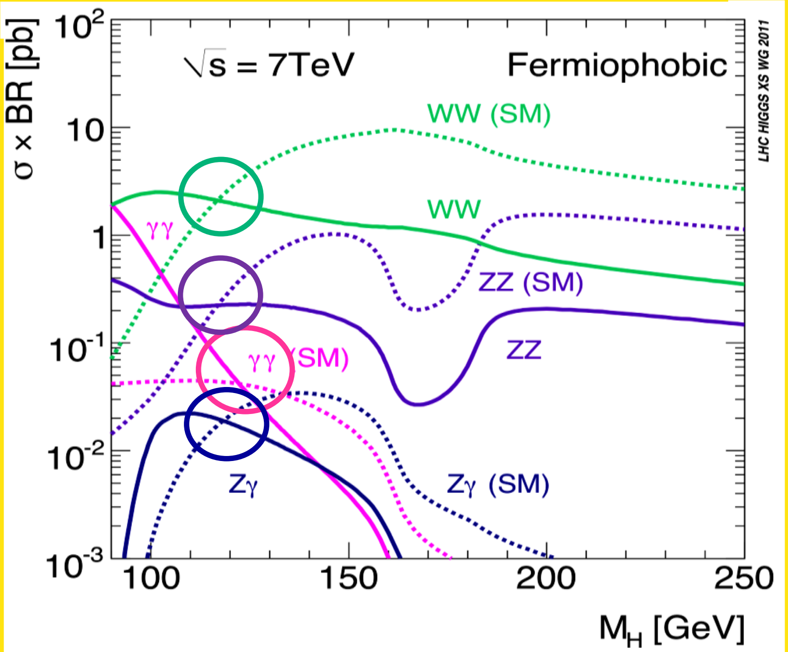
- **BSM Model with two Higgs doublets and no coupling to fermions**
  - Gluon fusion and ttH production forbidden; no change in VBF and VH
  - Big enhancement (10x) to γγ branching
  - Yields for FP Higgs at 125 GeV comparable to SM: γγ, ZZ, WW; also Zγ





- **Jets (VBF) and Leptons (VH) produced at LO:**
  - WW and γγ have both VBF and VH
  - Boosted Higgs
  - For ZZ: repurpose SM Analysis
  - 2012: 8 TeV γγ Update





Previous 95%CL limits: Tevatron 119 GeV [arXiv:1109:0576v1], ATLAS 121 GeV[arXiv:1205.0701v1]
CMS 110-194 GeV [arXiv1207.1130v1]

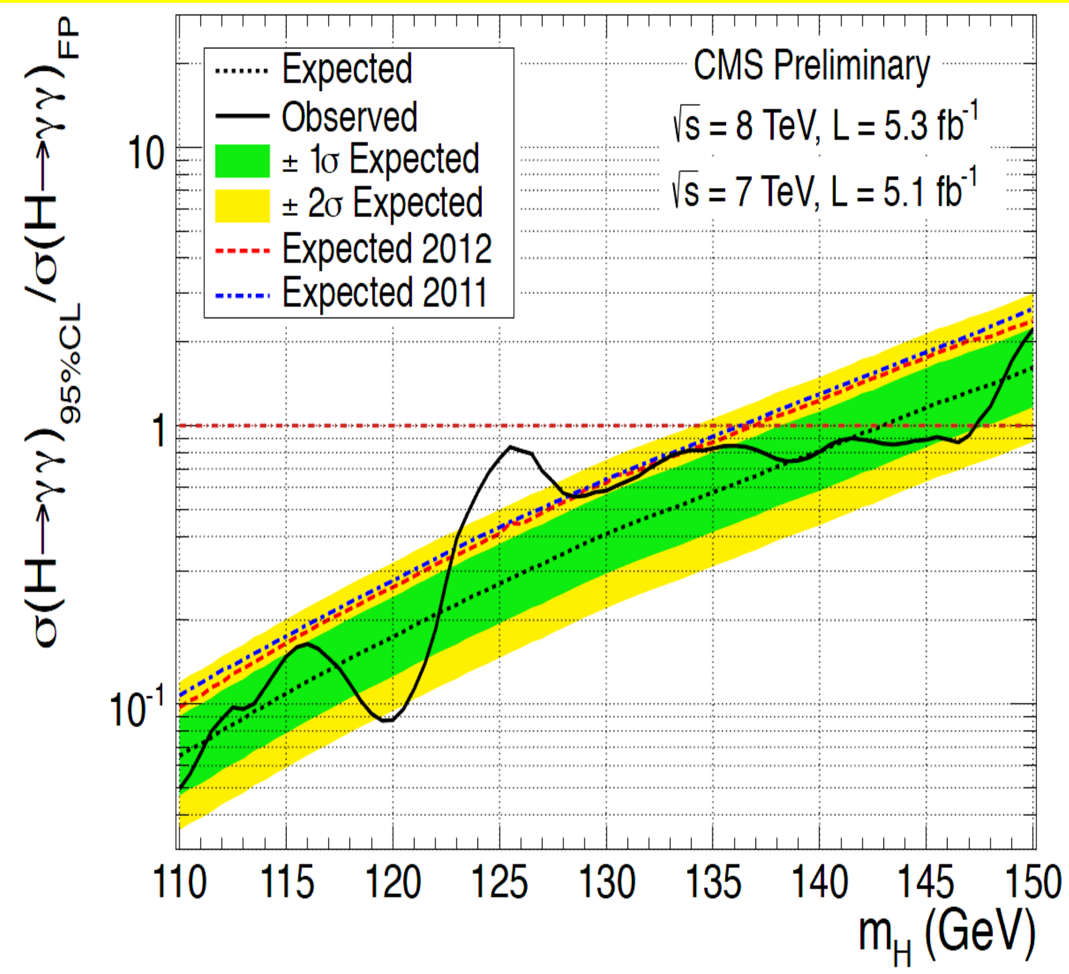
Fermiophobic Higgs

By Tag and Overall Combined Result

- **Dijet Tag: Most sensitive channel** 95% CL M_H Limit 131 GeV in 2012
- **Lepton Tag: Best S/B channel** 95% CL M_H Limit 121 GeV in 2012
- **MET Tag: High S/B;** complements lepton tag
- **Untagged: 70% of selected sample**
- **Exploit harder VBF, VH diphoton P_T spectrum** by using $\pi_T^{\gamma\gamma} = p_T^{\gamma\gamma}/m_{\gamma\gamma} > 0.1$
- **Constructed 2D model using $m_{\gamma\gamma}$, $\pi_T^{\gamma\gamma}$ for signal and background**

- **95% CL: Exclude** $110 \text{ GeV} < M_H < 147 \text{ GeV}$ (nearly the whole range)
- **99% CL: Exclude** $110 \text{ GeV} < M_H < 134 \text{ GeV}$

- **2012: 8 TeV Update in the $\gamma\gamma$ mode**

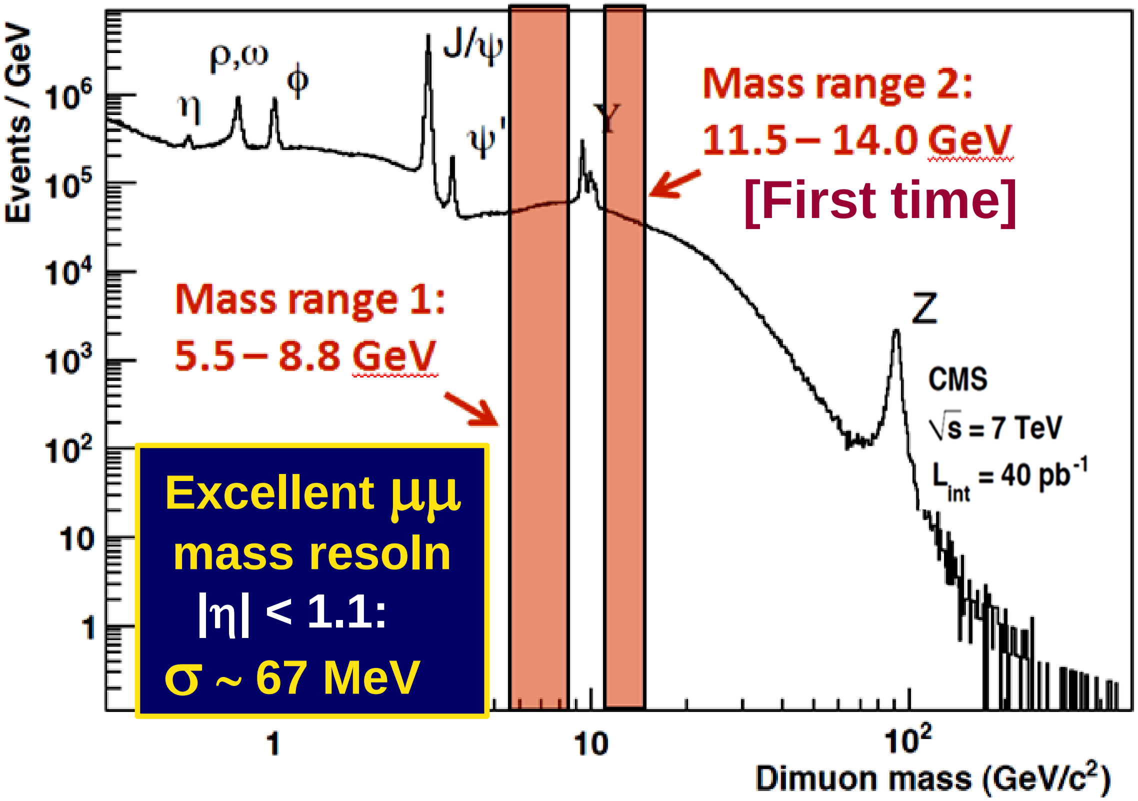


arXiv:1207.1130 ; CMS-HIG-12-009 ; CERN-PH-EP-2012-174

NMSSM: Light Pseudoscalar $a_1 \to \mu^+\mu^-$

Add a Scalar Singlet to the MSSM Higgs Family

- 3 CP even (h_1, h_2, h_3) , 2 CP odd (a_1, a_2), and $H^\pm$
- Out pops a potentially light pseudoscalar
  - $a_1 = a_{\mathrm{mssm}} \cdot \cos\theta_A + a_S \cdot \sin\theta_A$



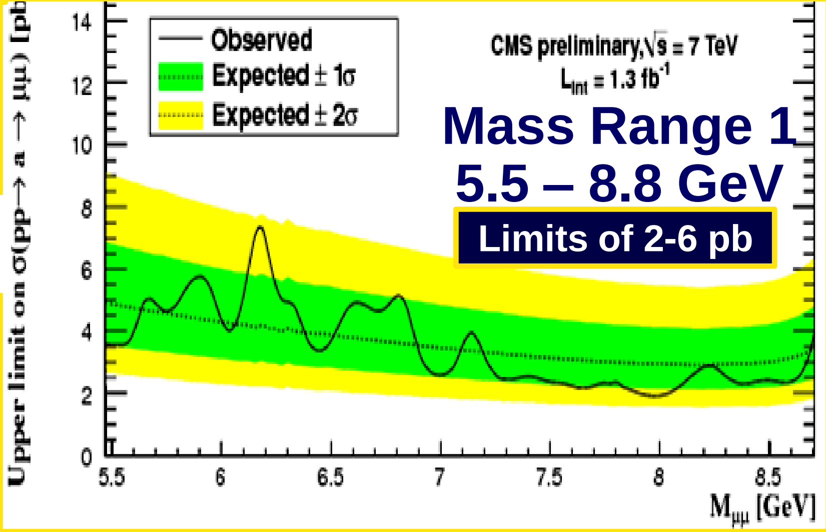
Mass range 2: 11.5 – 14.0 GeV

[First time]

Mass range 1: 5.5 – 8.8 GeV

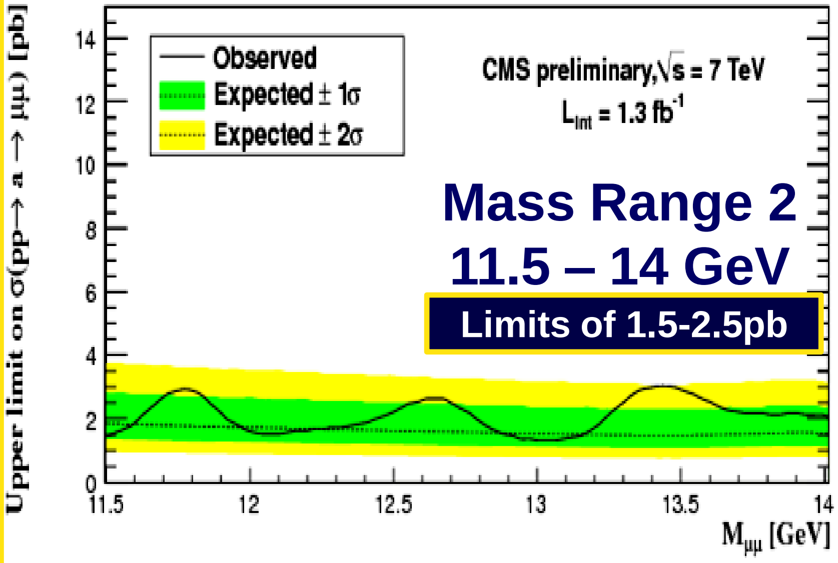
Excellent μμ mass resoln
|η| < 1.1:
σ ~ 67 MeV

Cross Section x BF Upper Limits



Mass Range 1
5.5 – 8.8 GeV

Limits of 2-6 pb

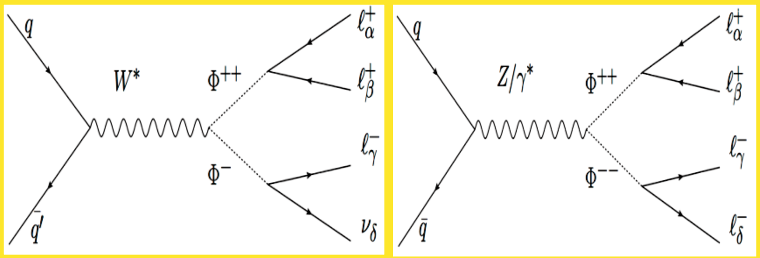


Mass Range 2
11.5 – 14 GeV

Limits of 1.5-2.5pb

arXiv:1206.6326 ; CMS-HIG-12-004 ; CERN-PH-EP-2012-176

Doubly Charged Higgs Φ^{++}

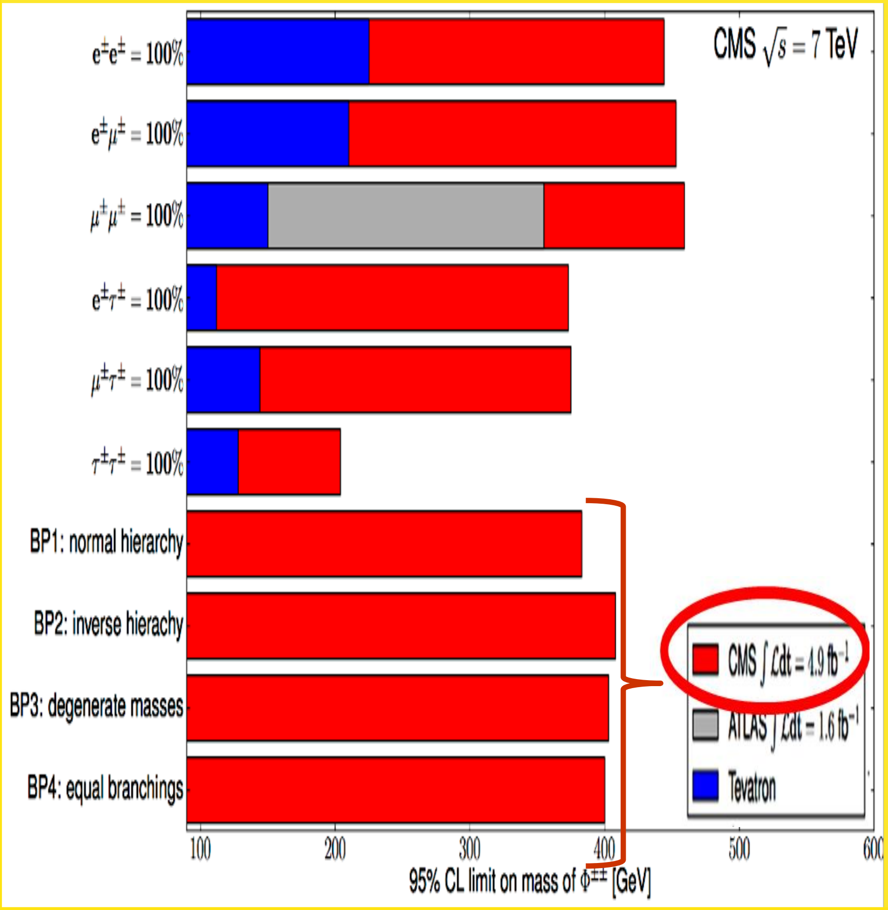


- **Minimal Type II See-Saw Models**
  - **An additional scalar field that is a triplet under $SU(2)_L$; motivated by ν masses**
  - **New Higgs-like particles: Φ^{++}, Φ^+, Φ^0**
  - **If observed would open a new window on neutrino physics at the LHC**
- **CMS search for Φ^{++} and Φ^+**
  - **Produced in pairs, or in association with singly charged Higgs (first time)**
  - **Unique experimental signatures**

$\ell\ell\ell$, $\ell\ell\tau_h$	$\ell\ell\ell\ell$, $\ell\ell\ell\tau_h$,$\ell\ell\tau_h\tau_h$

  - **Search in 7 TeV data using same-sign lepton combinations of all flavors**

7 TeV CMS Results: 0.036, 1, 4.9/fb



Φ^{++} and Φ^+ masses assumed degenerate

arXiv:1207.2666 ; CMS-HIG-12-005 ; CERN-PH-EP-2012-169

CMS Upgrade Program

LS1 Projects:

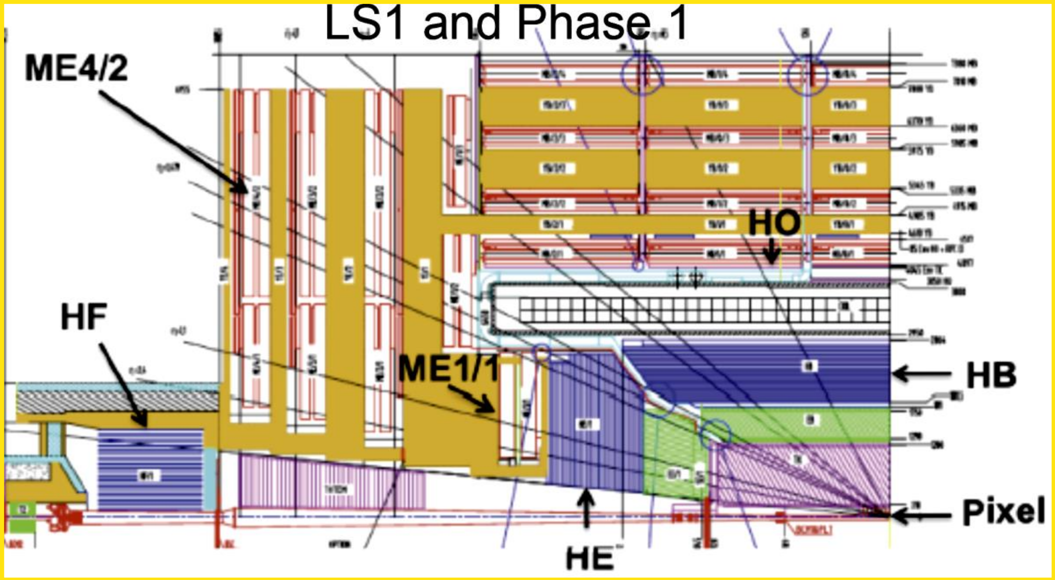
- •Completes muon coverage (ME4)
- •Improve muon trigger (ME1), DT electronics
- •Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD → SiPM)

Phase 1 Upgrades:

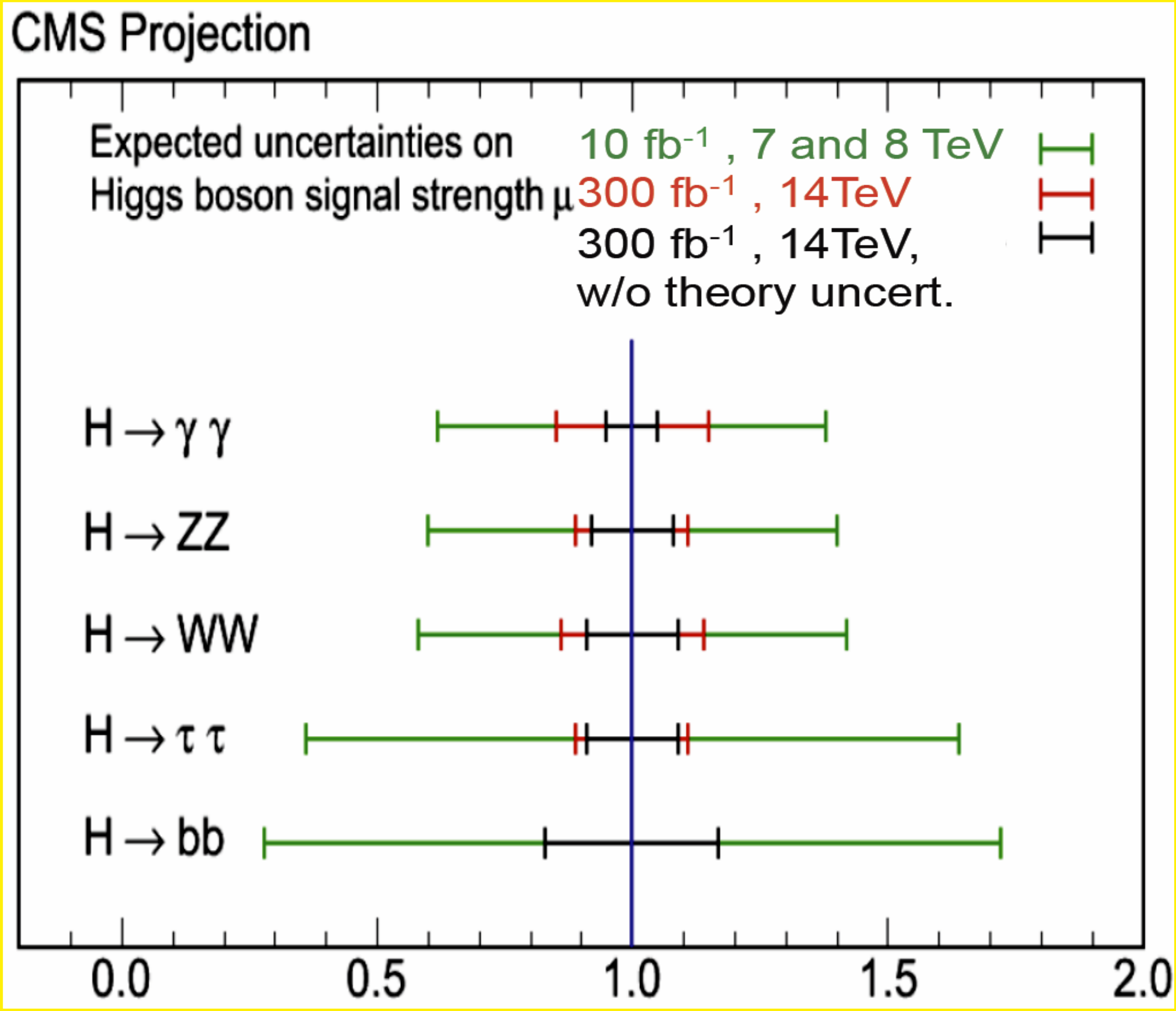
- New Pixels, HCAL SiPMs and electronics, and L1-Trigger
- Preparatory work during LS1:
  - new beam pipe
  - test slices of new systems

Phase 2 Upgrades: scope to be defined in Technical Proposal (2014)

- Tracker Replacement
- Forward Calorimetry and Muons
- Further Trigger upgrade: Track Trigger


LS1 and Phase 1

CMS Phase 1: Projected Precision of Higgs Signal Strength Measurements with **300 fb^{-1}** at 14 TeV



- ✸ Detector and trigger performance assumed to be **the same as the current detector**
- ✸ Assume the **same systematics as in the 2012 analysis (Scenario 1)**
- ✸ **Result:** Precision expected per channel is typically **10-15% with 300 fb^{-1}**

CMS Phase 1 Upgrade

Impact on H ➞ZZ ➞4l Analysis

Analysis as developed for 7-8 TeV, Average Pileup = 50

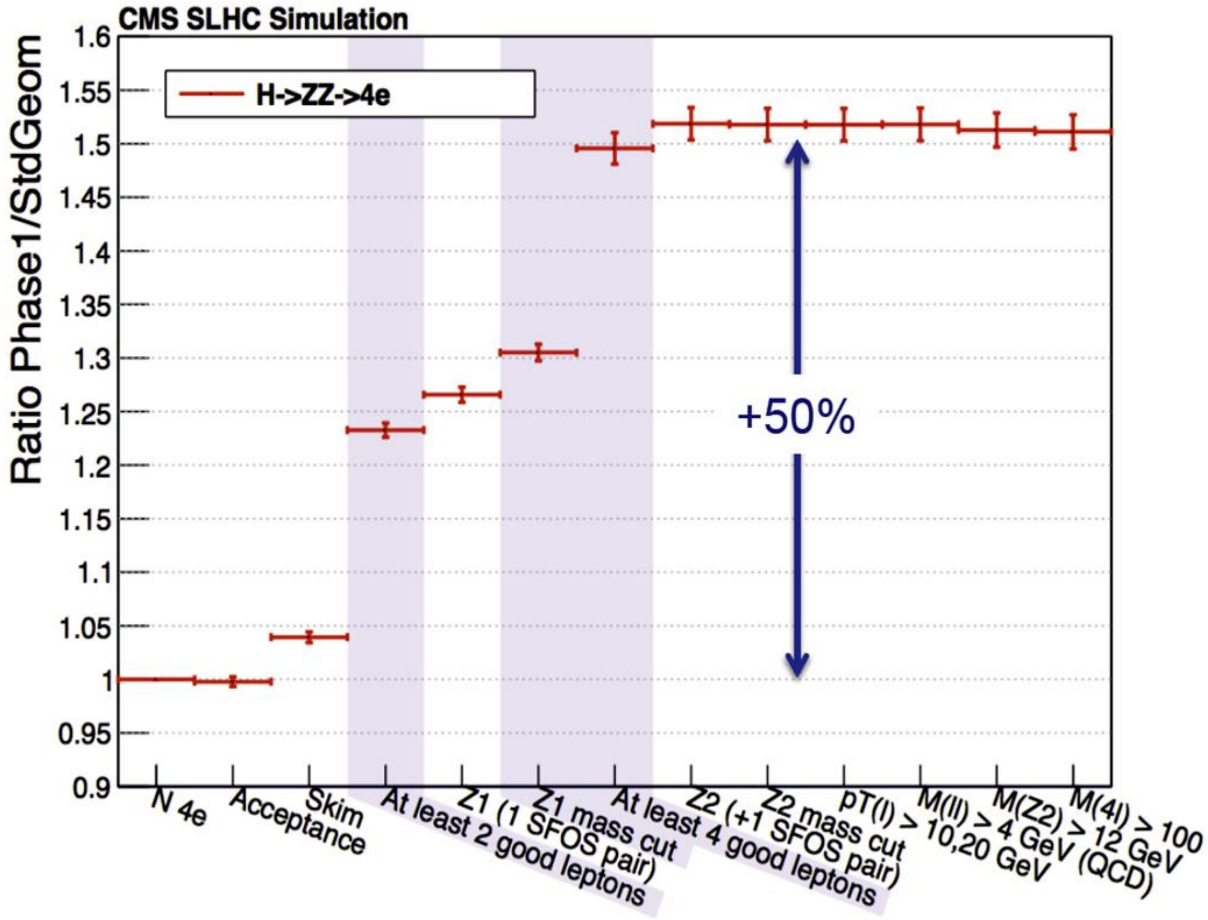
H → ZZ →4l

is sensitive to lepton tracking and isolation efficiency

Significant gain in signal reconstruction efficiency:

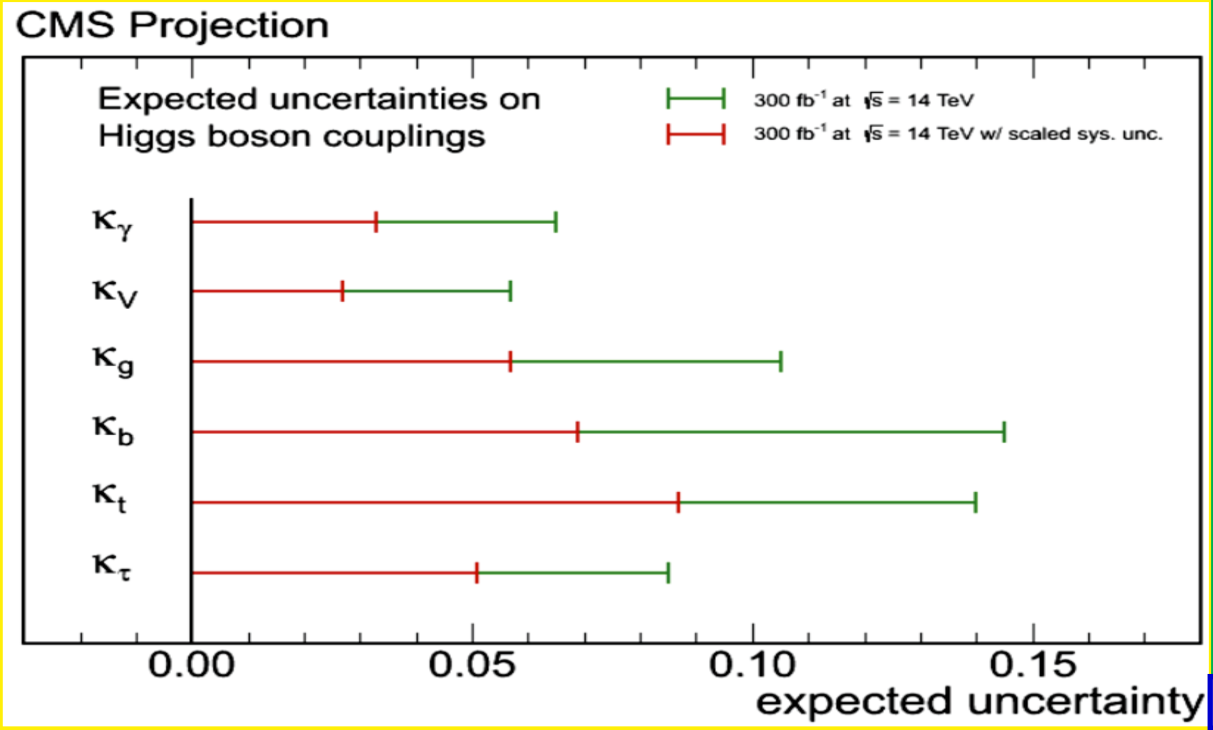
H→ 4μ	+41%
H→ 2μ2e	+48%
H→ 4e	+51%

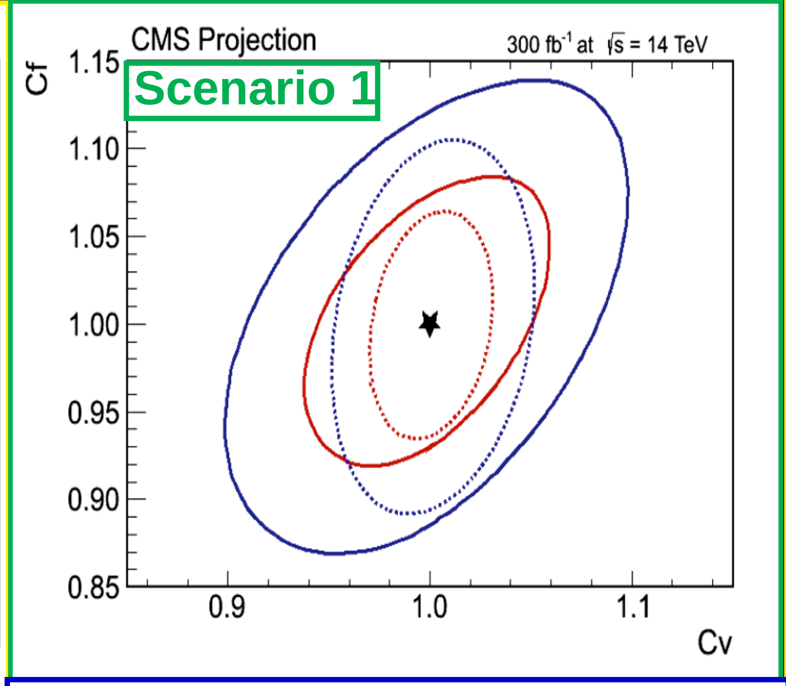
Improved signal yield (relative to current detector):



CMS Phase 1: Projected Precision on Higgs Couplings with 300 fb^{-1} at 14 TeV

- Two Scenarios
- Scenario 1: same systematics as in 2012
- Scenario 2: theory systematics halved,
  other systematics scaled by 1/ √L
- Result: With 300 fb^{-1} the uncertainties on the Higgs Couplings are expected to be in the range $\sigma(\kappa_V)$ = 3-6% to $\sigma(\kappa_b)$ = 7-15%





Dotted lines: no theory uncertainties