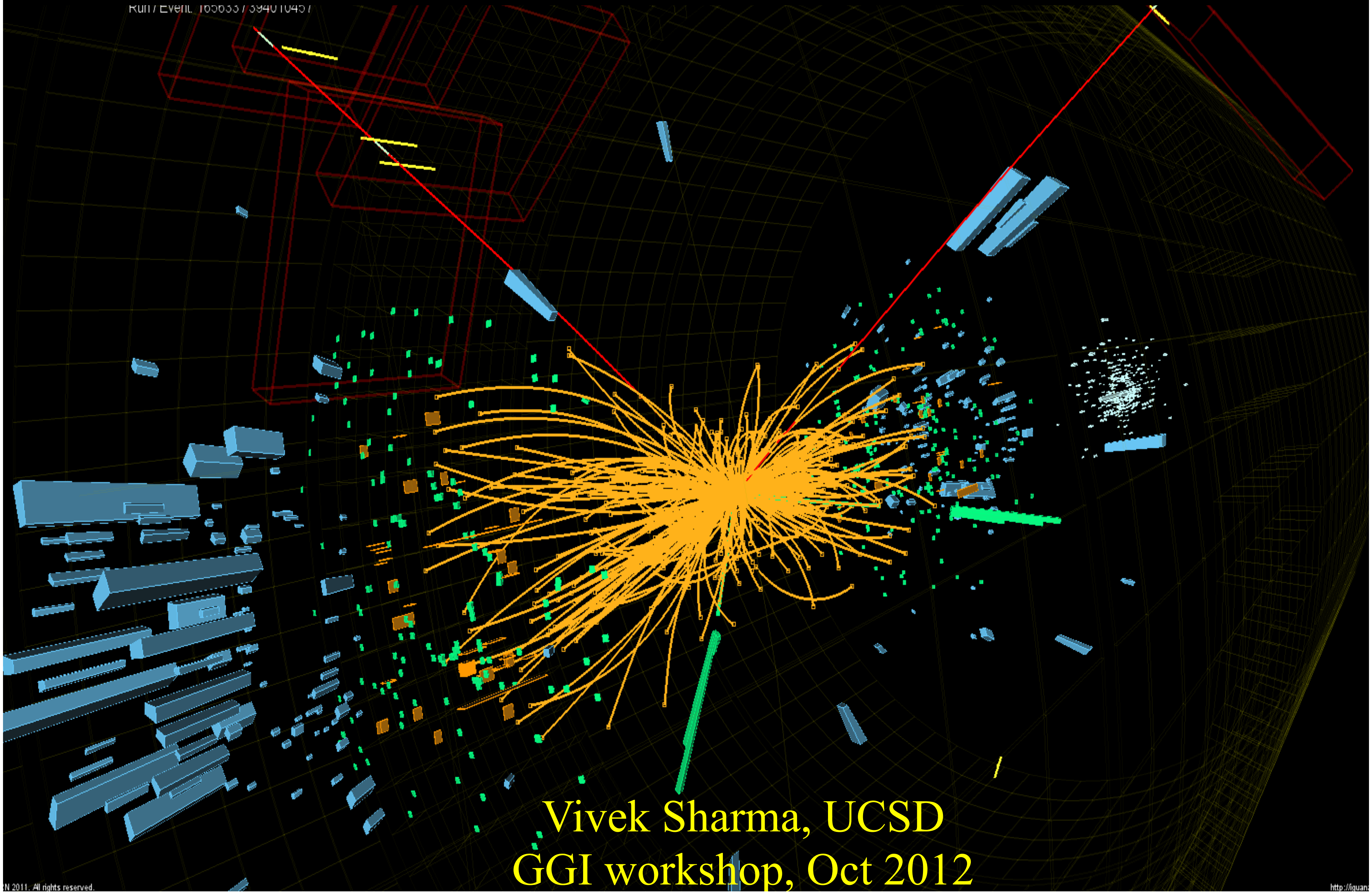
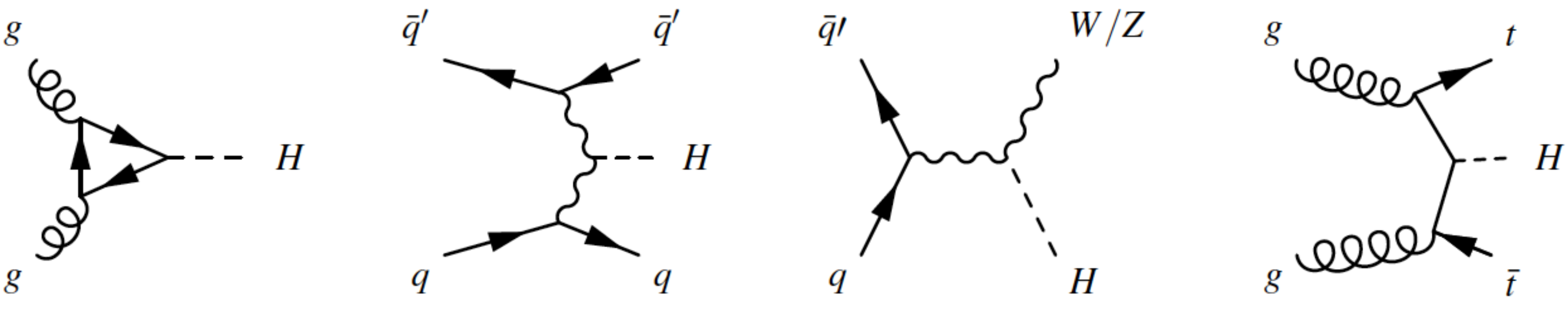
Searches for Higgs Boson with CMS



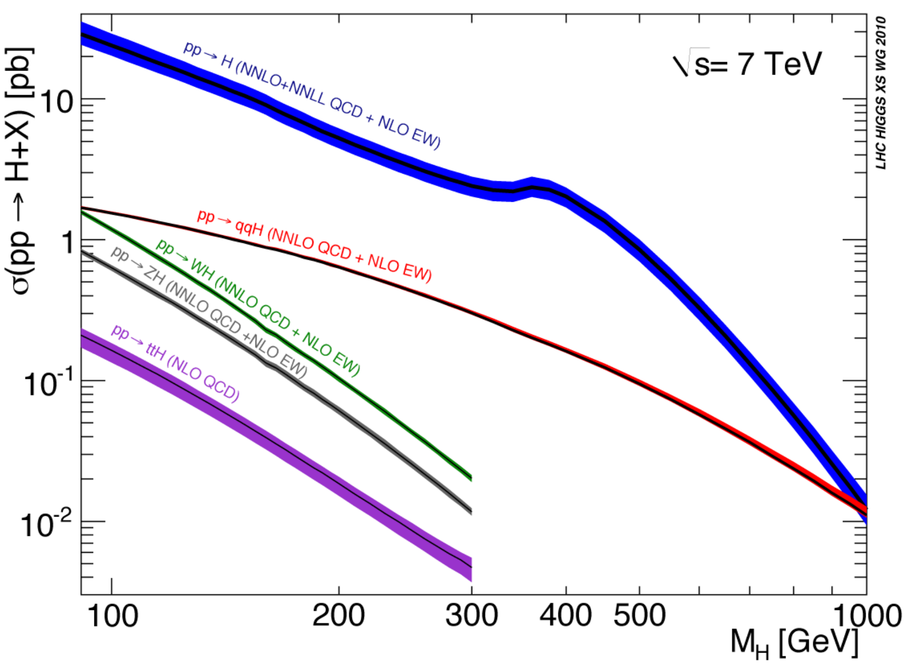
Vivek Sharma, UCSD

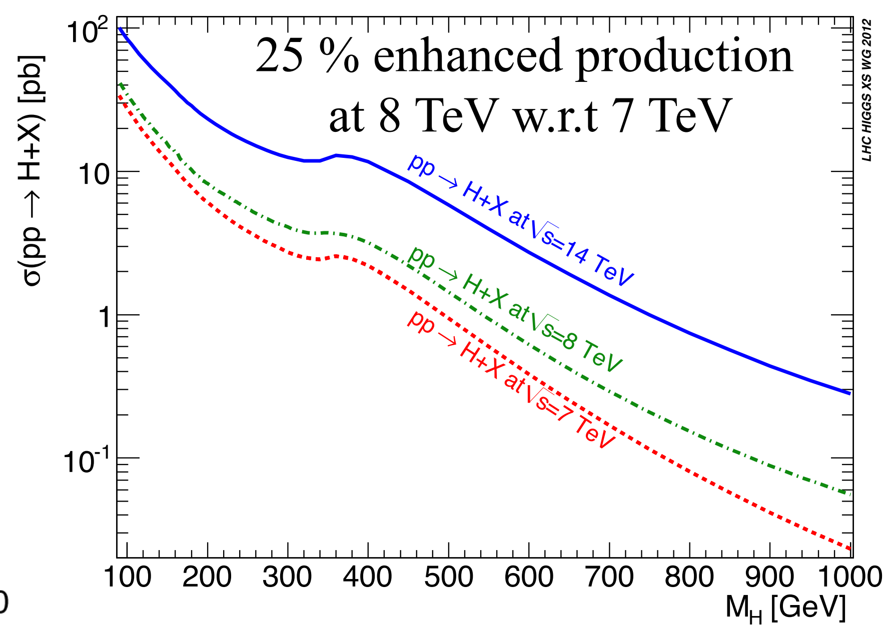
GGI workshop, Oct 2012

Higgs Production in pp Collsions

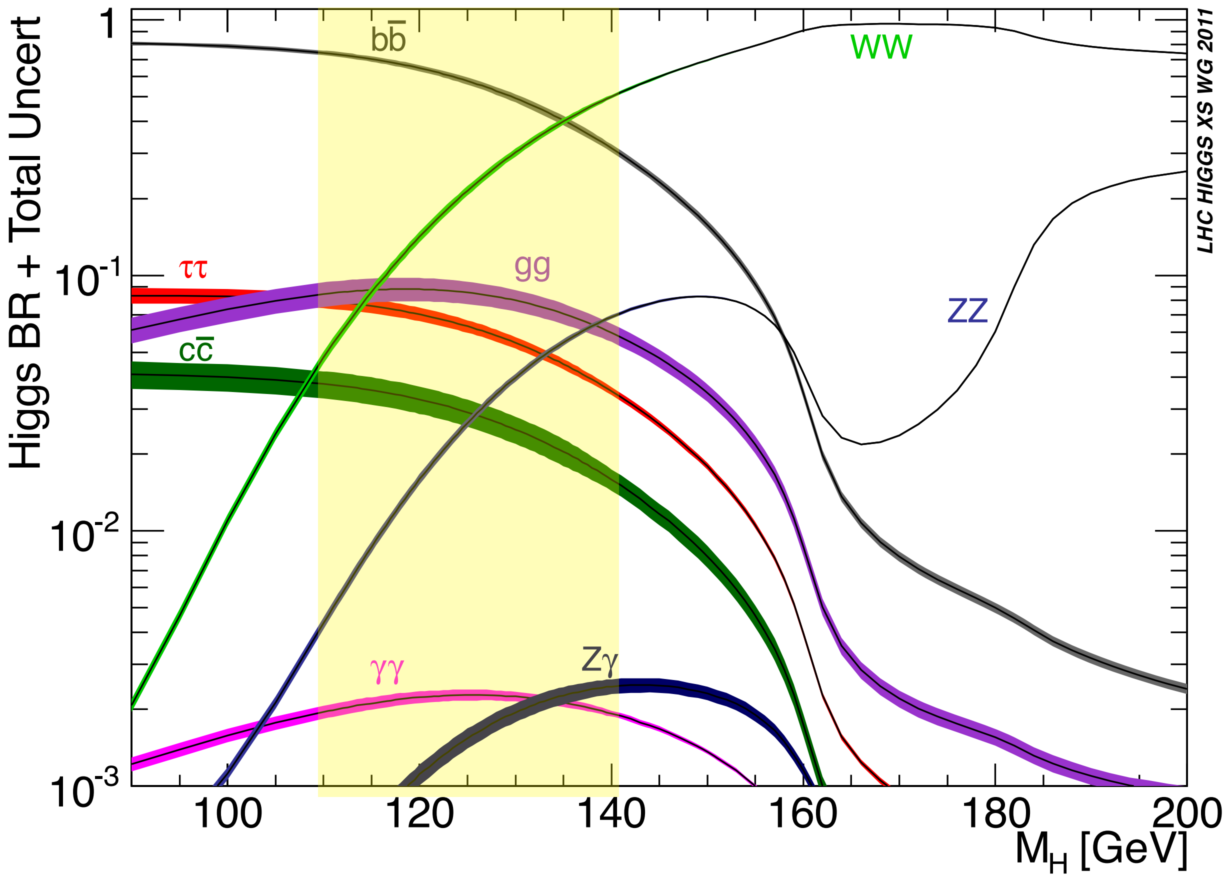


(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$





Higgs Branching Ratio



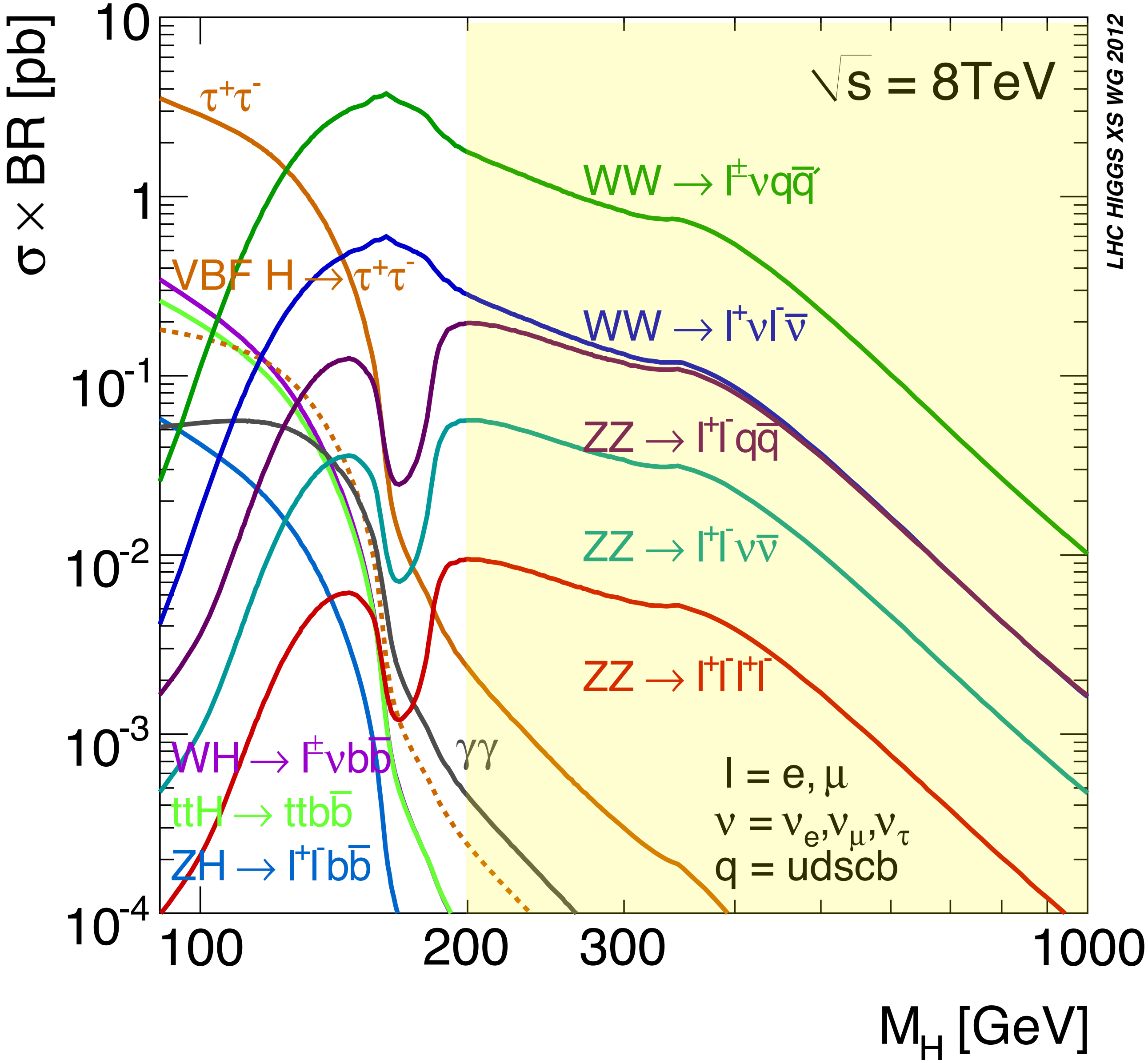
Bands indicate theoretical uncertainties

For $M_H > 200$ GeV Higgs decays mostly into WW and ZZ

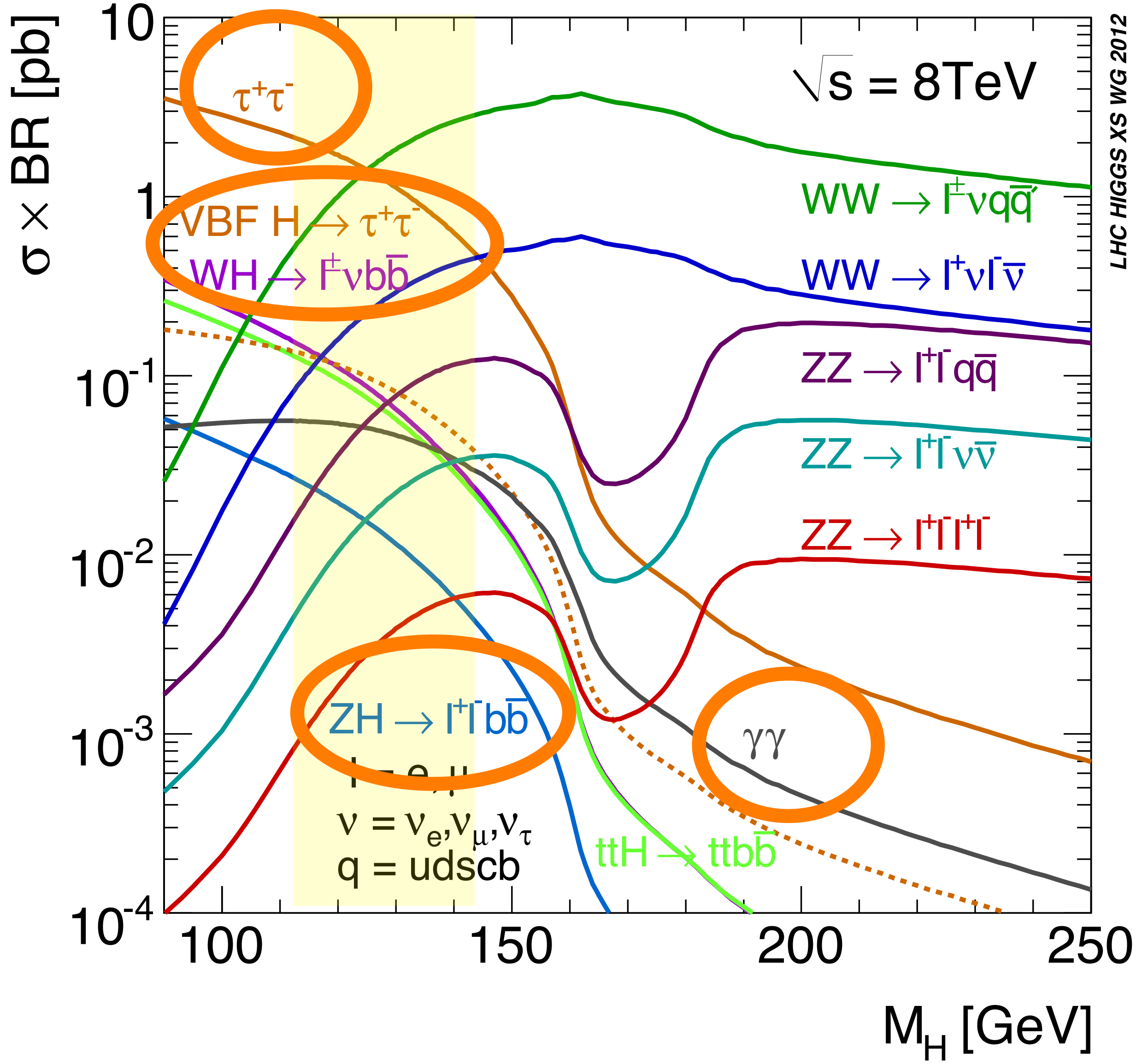
@ 125 GeV:

$\mathrm{BR}(h \to b\bar{b}) = 58\%$, $\mathrm{BR}(h \to WW^*) = 21.6\%$, $\mathrm{BR}(h \to \tau^+\tau^-) = 6.4\%$,
$\mathrm{BR}(h \to ZZ^*) = 2.7\%$, $\mathrm{BR}(h \to gg) = 8.5\%$, $\mathrm{BR}(h \to \gamma\gamma) = 0.22\%$,
$\mathrm{BR}(h \to c\bar{c}) = 2.7\%$

[Production Cross section × Decay Rate] Vs M_H



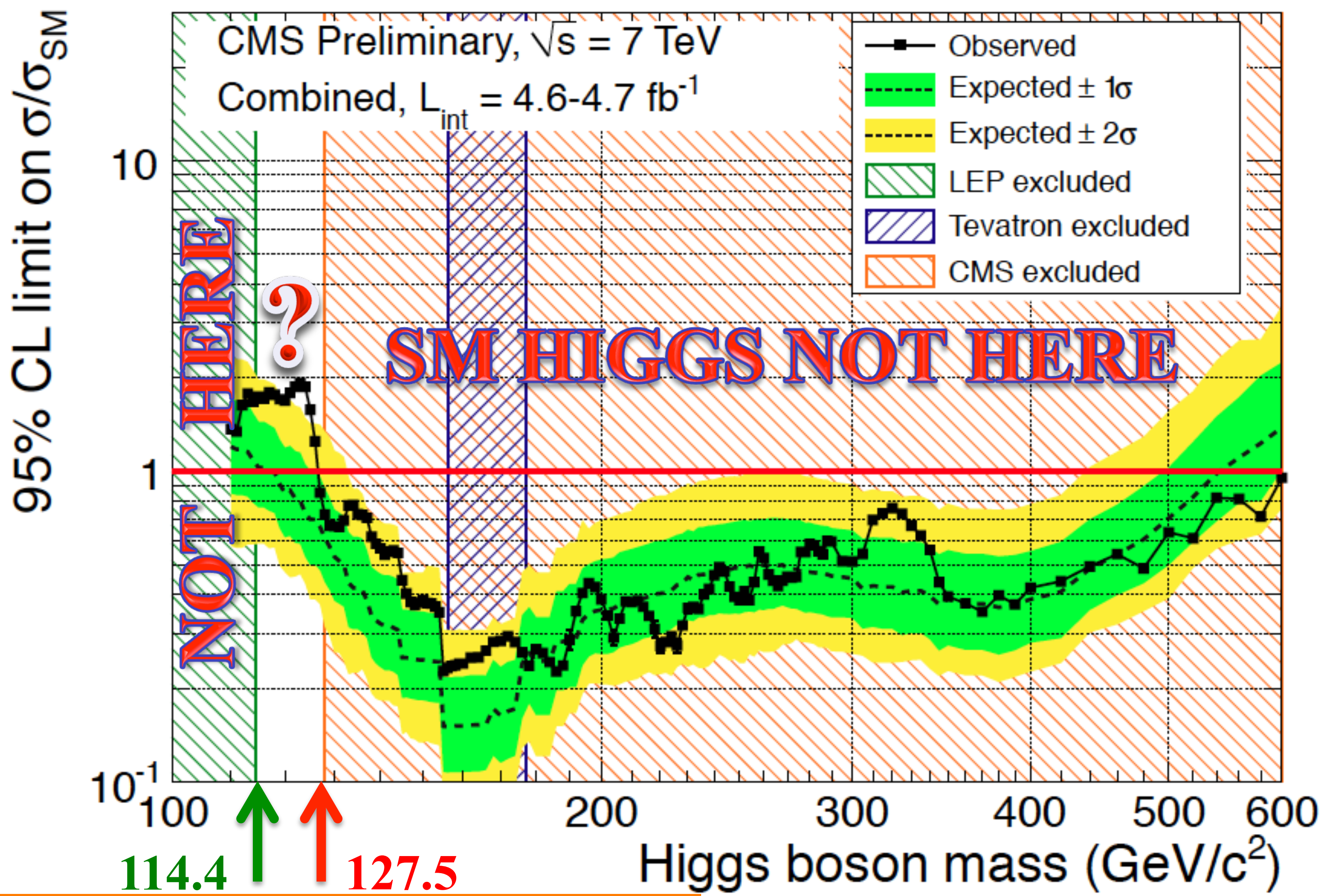
[Cross section × Decay Rate] Vs M_H : Low Mass



Higgs Search Sensitivity: By Mass & By Mode

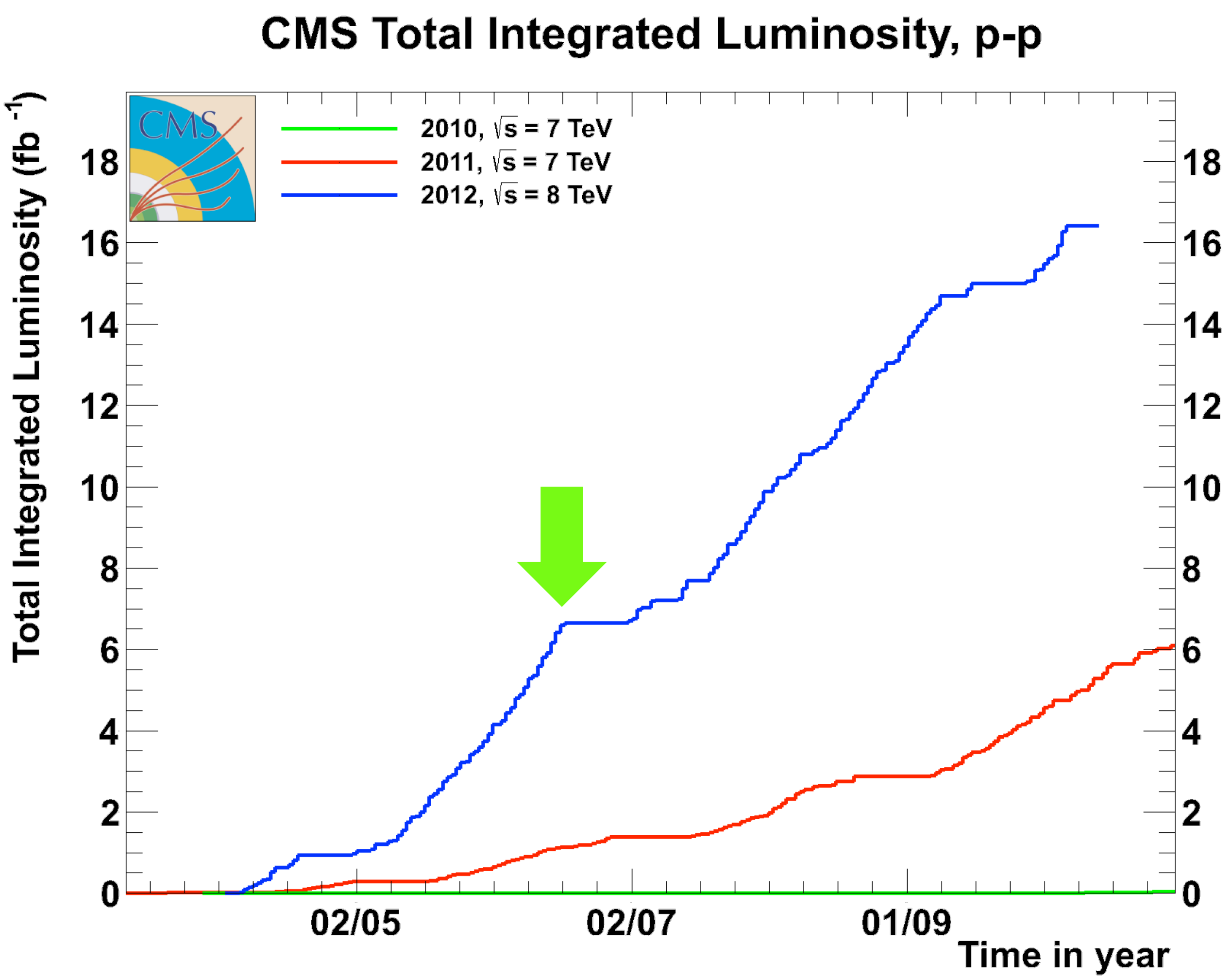
- For a given M_H, sensitivity of search channel depends on
  - Production cross section & decay branching fraction
  - Signal selection efficiency (including trigger)
  - Mass resolution (intrinsic and instrumental)
  - Level of SM background in the same or similar final states
- **In low mass range**:
  - $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ play a special role due to complete reconstruction & excellent photon/lepton reconstruction ($\Delta M \cong 2\%$)
  - $H \rightarrow WW \rightarrow (l\nu)(l\nu)$ provides high sensitivity but has poor mass resolution due to presence of neutrinos in the final state
  - Sensitivity in $H \rightarrow$ bbbar and $H \rightarrow \tau\tau$ channels is reduced due to large backgrounds and poor mass resolution (jets or neutrinos)
- **In high mass range**:
  - Sensitivity dominated by $H \rightarrow WW, ZZ$ in various sub-channels

The Story As Of Dec 13, 2011



Remaining corridor of uncertainty

ICHEP'12 Data Sample



Results shown today uses data recorded till June'12 :
~ 5 fb^{-1} each at $\sqrt{s}$ = 7 & 8 TeV

CMS Searches (ICHEP' 12)

H decay	H prod	Analyses Exclusive final states	No. of channels	m_H range (GeV)	m_H resolution	Lumi (fb^{-1}) 7 TeV	8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%	5.1	5.3
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%	5.1	5.3
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets)$\otimes$ (low or high p_T^V)	10	110–135	10%	5.0	5.1
	ttH-tag	(ℓ with 4,5,$\geq$6 jets) $\otimes$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140		5.0	-
H $\to \tau\tau$	0/1-jets	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)$\times$ (low or high $p_T^{\tau\tau}$) $\times$ (0 or 1 jets)	16	110–145	20%	4.9	5.1
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) + $(jj)_{VBF}$	4	110–145	20%	4.9	5.1
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160		5.0	-
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140		4.9	-
WW $\to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$)$\otimes$($(jj)_W$ with 0 or 1 jets)	4	170–600		5.0	5.1
WW $\to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\otimes$ (0 or 1 jets)	4	110–600	20%	4.9	5.1
WW $\to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%	4.9	5.1
WW $\to \ell\nu\ell\nu$	WH-tag	$3\ell 3\nu$	1	110–200		4.9	-
WW $\to \ell\nu\ell\nu$	VH-tag	$\ell\nu\ell\nu + (jj)_V$ (DF or SF dileptons)	2	118–190		4.9	-
ZZ $\to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–600	1-2%	5.0	5.3
ZZ $\to 2\ell 2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	200–600	10-15%	5.0	5.3
ZZ $\to 2\ell 2q$	inclusive	(ee, $\mu\mu$)$\times$($(jj)_Z$ with 0, 1, 2 b-tags)	6	{ 130–164 200–600	3%	4.9	-
ZZ $\to 2\ell 2\nu$	untagged	((ee, $\mu\mu$) with MET) $\otimes$ (0 or 1 or 2 non-VBF jets)	6	200–600	7%	4.9	5.1
ZZ $\to 2\ell 2\nu$	VBF-tag	(ee, $\mu\mu$) with MET and $(jj)_{VBF}$	2	200–600	7%	4.9	5.1

Most analyses updated with 8 TeV data

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

Today: Focus On the Low Mass Searches

- Low mass resolution modes:
  - H → $WW^{(*)}$ →(l ν) (l ν)
  - VH; H → bb
  - H →ττ
- High mass resolution modes
  - H → γγ
  - H → ZZ →4*l*

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

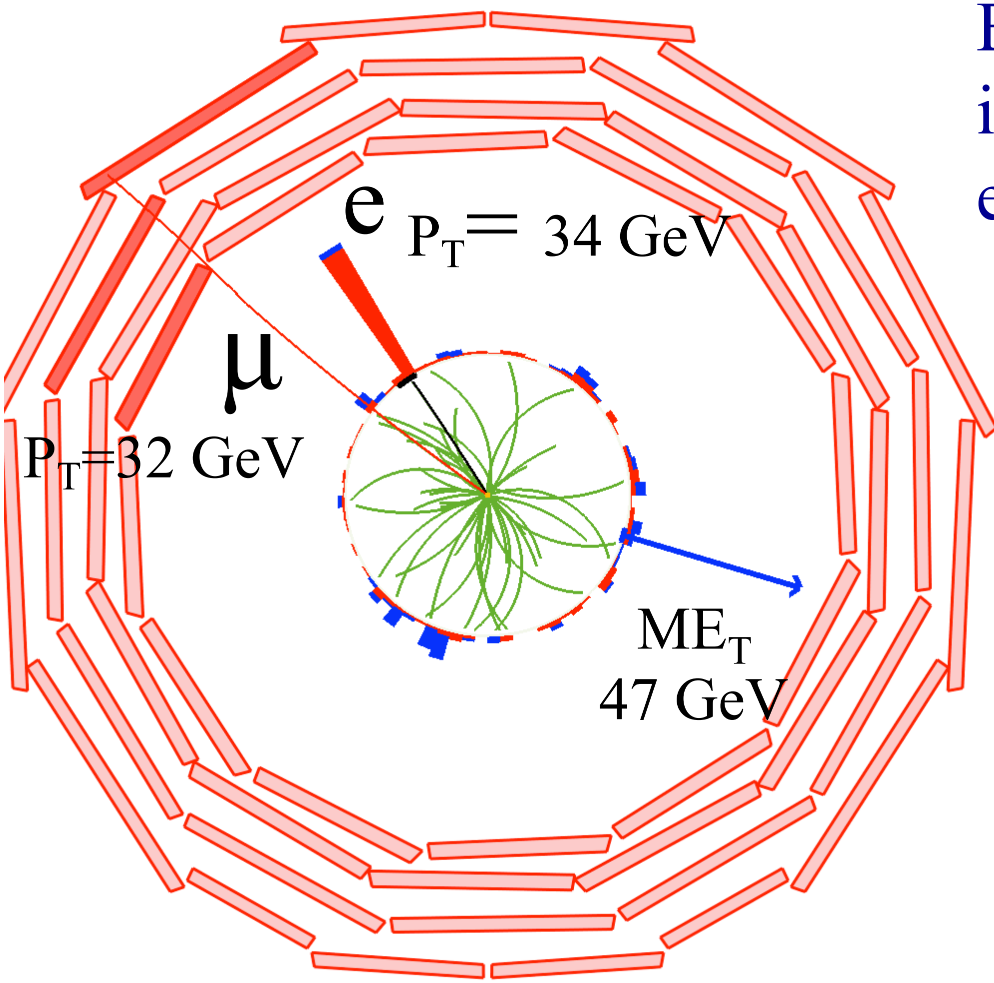
Physics Letters B, Vol. 716, Issue 1, 17 September 2012, Pages 30–61

arXiv:1207.7235

&

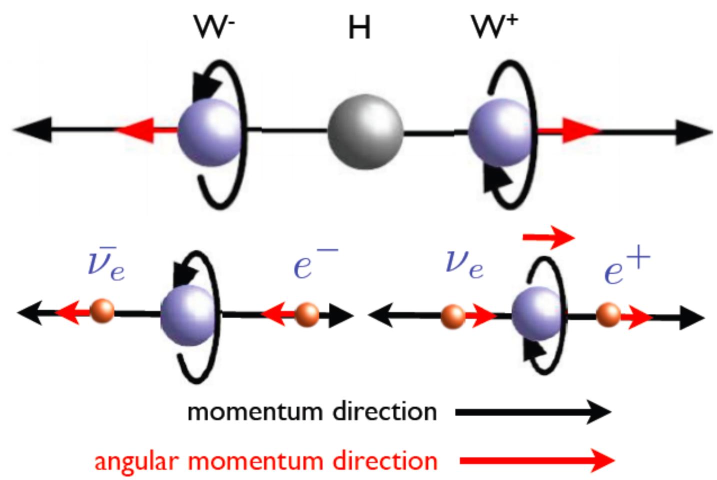
CMS PAS HIG-12-020 (Combination of All Higgs Searches, ICHEP'12)

$H \rightarrow WW^{(*)} \rightarrow (l\,\nu)\,(l\,\nu)$: The Workhorse



Events with two energetic & isolated leptons and missing energy (due to neutrinos)

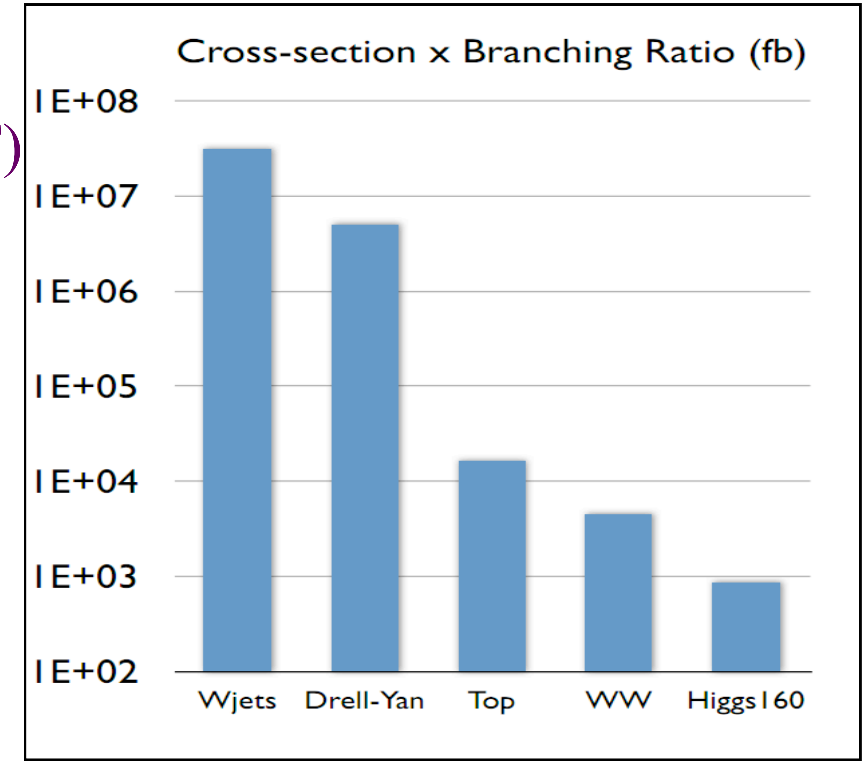
Higgs boson has spin = 0
➔ Leptons spatially aligned



Poor Higgs mass resolution (20%) due to escaping neutrinos
➔ Counting experiment, look for excess over backgrounds

Backgrounds In H → WW → (l ν) (l ν) Search

- Reducible backgrounds:
  - (DY) Z → ll + (jets faking MET)
  - W→ l ν + (jets faking lepton)
  - tW and ttbar production
  - W+ $\gamma^{(*)}$
  - WZ→ 3l + MET
- Irreducible background:
  - pp → WW → (l ν) (l ν)
    - **Non-resonant production**



- **Challenge is to kill off as much background & measure residual contributions using data-driven techniques and control samples**

Background Alleviation Strategy

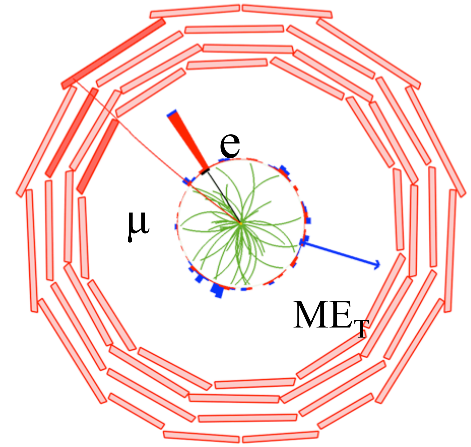
decreasing cross section (@7 TeV)

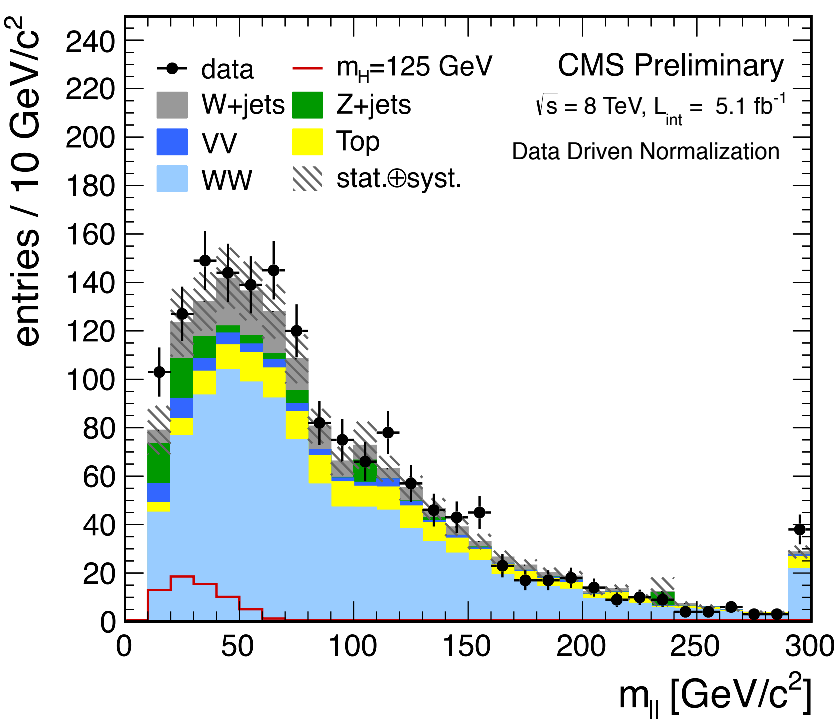
process	characteristic	rejection
W+jets (31000 pb)	lepton + fake lepton	2 well identified and isolated leptons
Z+jets (5000 pb)	Z peak, no real E_T^{miss}	• proj E^T_{miss} > 40 GeV(ee,μμ), 20 GeV (eμ) • $\lvert m_{ll}-m_Z \rvert<15$ GeV (ee, μμ), $m_{ll}>12$ GeV (eμ)
tt (158 pb), tW (11 pb)	additional (b-)jets	• classify events in 0-,1-jet • anti b-tagging
W,Z + γ (165 pb)	electron from γ coversion	• conversion veto
WW (43 pb)	non resonant	• small $\Delta\varphi_{ll}$
WZ (18 pb), ZZ (6 pb)	Z peak	• $\lvert m_{ll}-m_Z \rvert<15$ GeV (ee, μμ), $m_{ll}>12$ GeV (eμ)

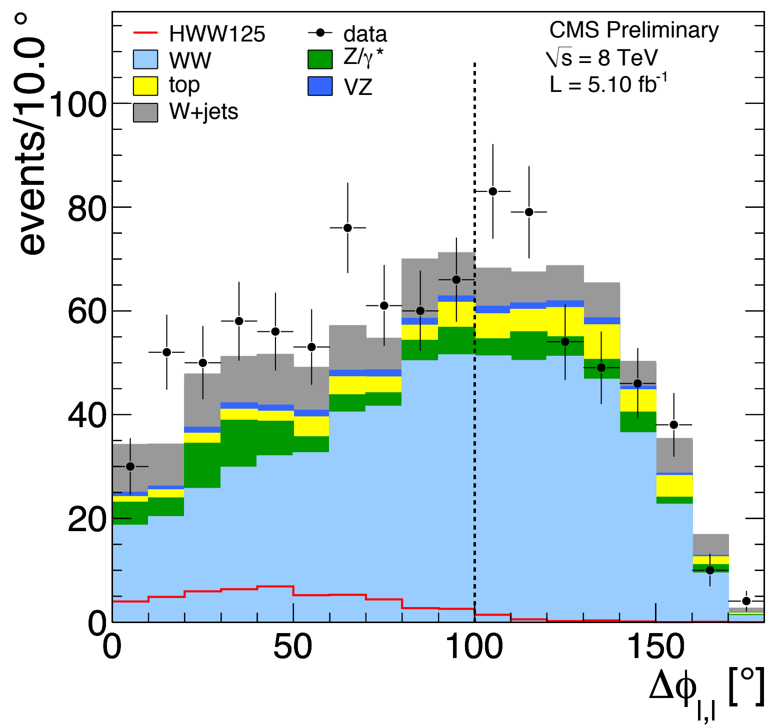
relative importance after selection depends on m_H

Key Kinematic Observables

- P_T of leading and sub-leading leptons
- Azimuthal angle difference ($\Delta\Phi_{ll}$)
- $P_T(ll)$
- Dilepton invariant mass (M_{ll})
- $M_T = \sqrt{2 p_T^{\ell\ell} E_T^{\text{miss}} (1 - \cos \Delta\phi_{E_T^{\text{miss}}\ell\ell})}$







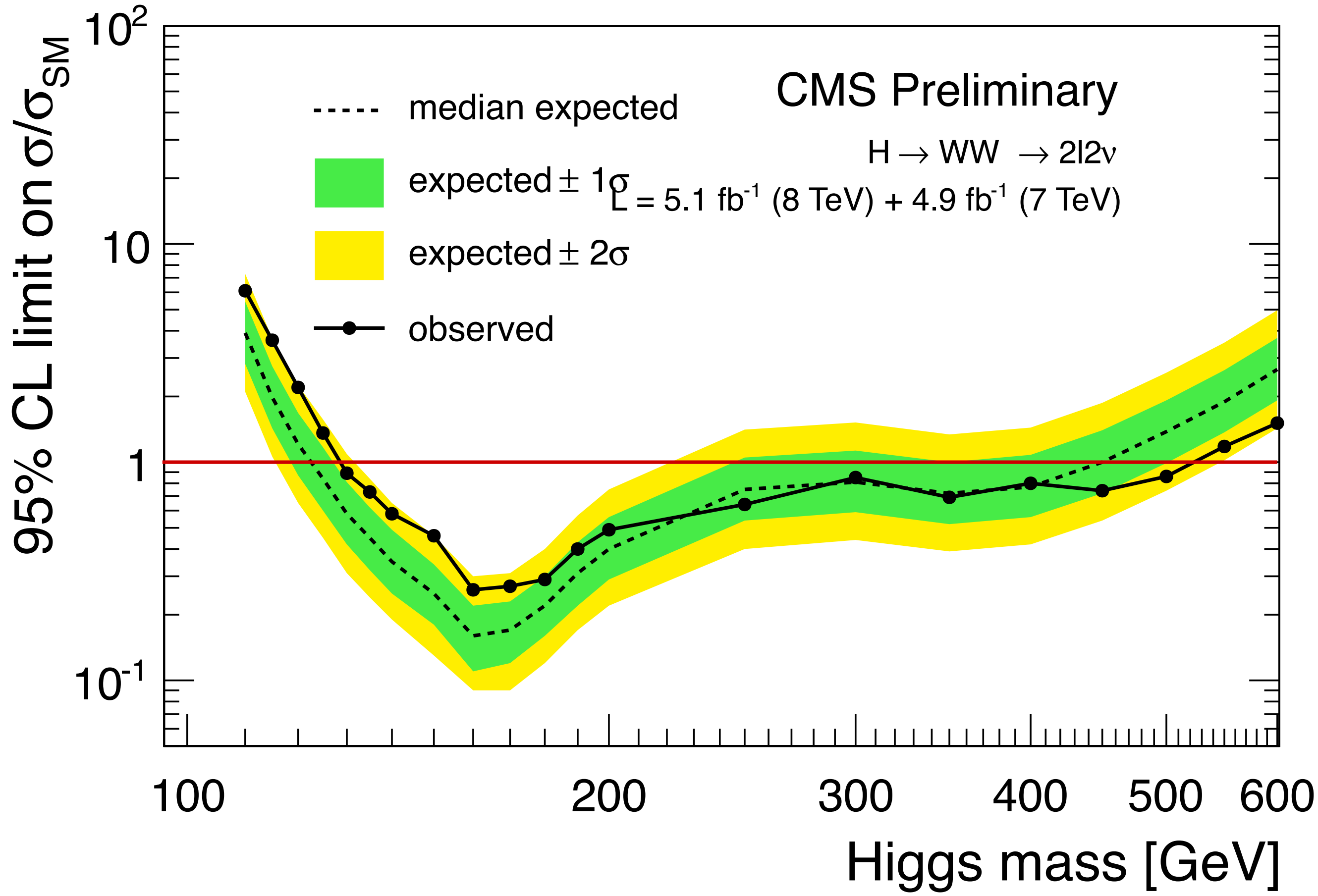
Background Prediction & Data Yields Vs M_H

2012 data : 5.1 fb^{-1} , Cut-based Analysis, 0-Jet category

m_H	H $\rightarrow W^+W^-$	pp $\rightarrow W^+W^-$	WZ + ZZ $+Z/\gamma^* \rightarrow \ell^+\ell^-$	Top	W + jets	$W\gamma^{(*)}$	all bkg.	data
		0-jet category $e\mu$ final state						
125	23.9 ± 5.2	87.6 ± 9.5	2.2 ± 0.2	9.3 ± 2.7	19.1 ± 7.2	6.0 ± 2.3	124.2 ± 12.4	158
130	35.3 ± 7.6	96.8 ± 10.5	2.5 ± 0.3	10.1 ± 2.8	20.7 ± 7.8	6.3 ± 2.4	136.3 ± 13.6	169
160	98.3 ± 21.2	53.6 ± 5.9	1.2 ± 0.1	6.3 ± 1.7	2.5 ± 1.3	0.2 ± 0.1	63.9 ± 6.3	79
400	16.6 ± 4.8	50.5 ± 5.8	1.5 ± 0.2	26.1 ± 5.7	4.5 ± 2.0	0.7 ± 0.5	83.3 ± 8.4	92
		0-jet category $ee/\mu\mu$ final state						
125	14.9 ± 3.3	60.4 ± 6.7	37.7 ± 12.5	1.9 ± 0.5	10.8 ± 4.3	4.6 ± 2.5	115.5 ± 15.0	123
130	23.5 ± 5.1	67.4 ± 7.5	41.3 ± 15.9	2.3 ± 0.6	11.0 ± 4.3	4.8 ± 2.5	126.8 ± 18.3	134
160	86.0 ± 18.7	44.5 ± 4.9	11.3 ± 13.4	3.8 ± 0.9	1.3 ± 1.1	0.4 ± 0.3	61.4 ± 14.4	92
400	12.3 ± 3.6	37.1 ± 4.3	5.7 ± 1.3	20.0 ± 4.7	3.4 ± 1.9	13.6 ± 4.8	79.9 ± 8.3	55

Mild excess over background is observed at low masses

$H \rightarrow WW^{(*)} \rightarrow (l\,\nu)\,(l\,\nu)$ Results



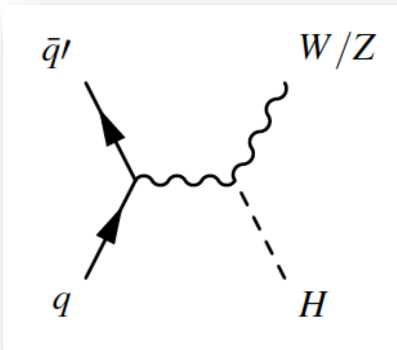
Expected Exclusion@ 95% CL: 122-450 GeV

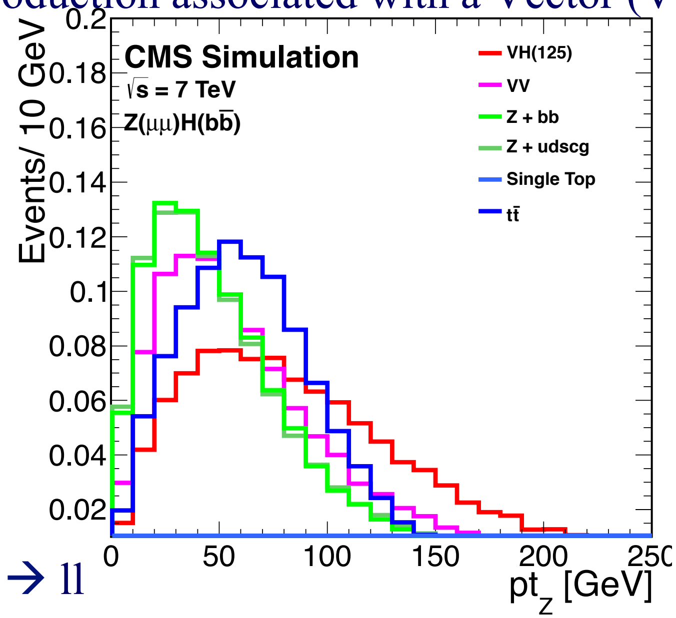
Observed Exclusion@95% CL: 129-520 GeV

A small excess makes limits weaker than expected

CMS H→ bb Search In a Nutshell

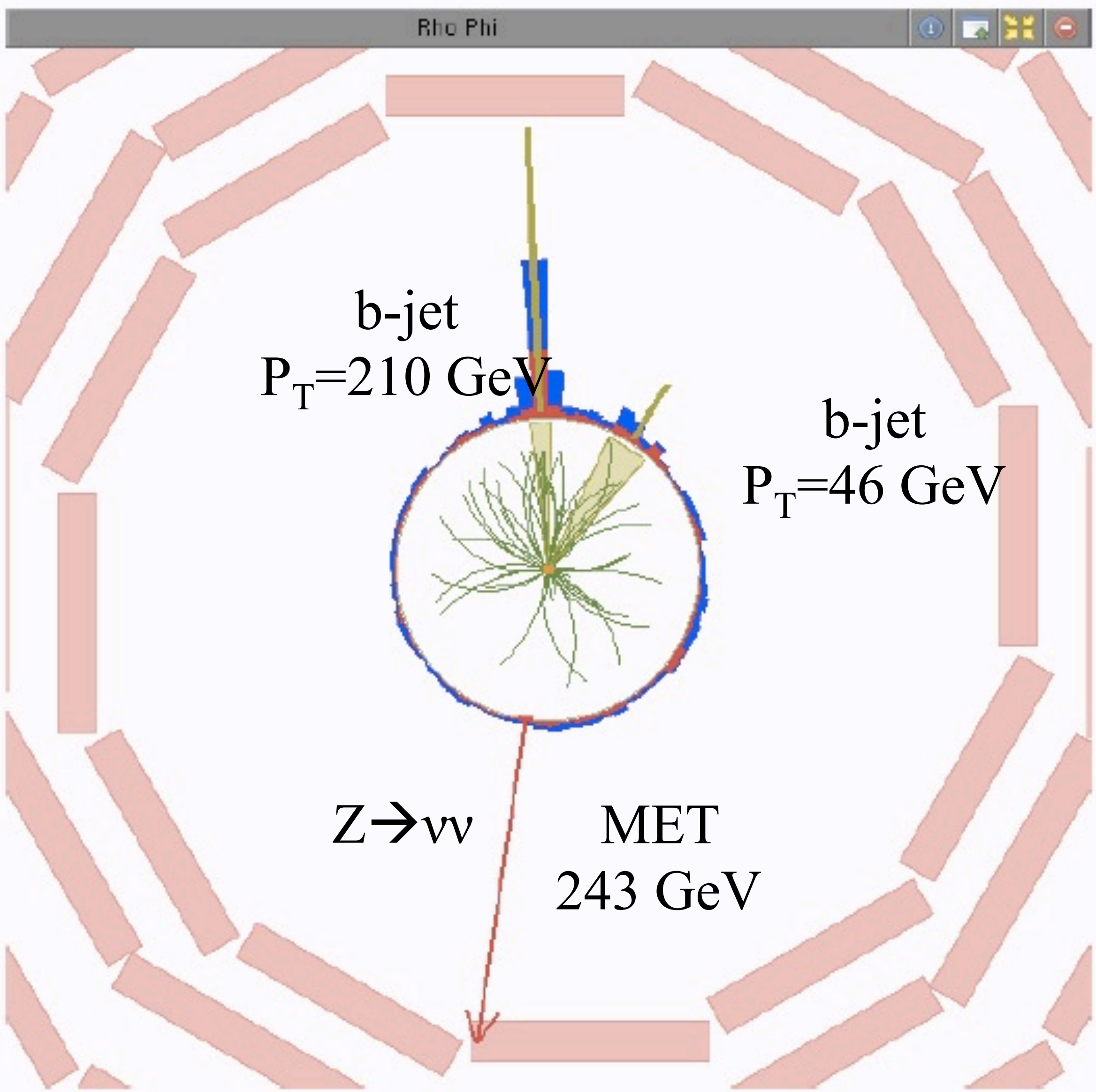
- H → bb production via gluon fusion and VBF are quite large but are buried (10^7) under QCD production of b bbar pairs
- Most promising channel is H → bb production associated with a Vector (V=W or Z) boson





- V reconstruction: W → l ν, Z→ νν, Z → ll
- H→ bb reconstructed as two b-tagged jets recoiling against a high P_T W/Z boson
  - Large W/Z P_T → smaller background & better di-jet mass resolution
  - Use b-jet energy regression → improved H → bb mass resolution
- Events separated into categories , based on S/N (5 channels x 2 P_T(V) bins = 10)
- Use data control regions to constrain major backgrounds (V + jets, ttbar etc)
- Use MVA methods to discriminate between signal & background.

$Z(\nu\bar{\nu})H(b\bar{b})$ candidate



Two clean b-jets

M_{bb} = 120 GeV

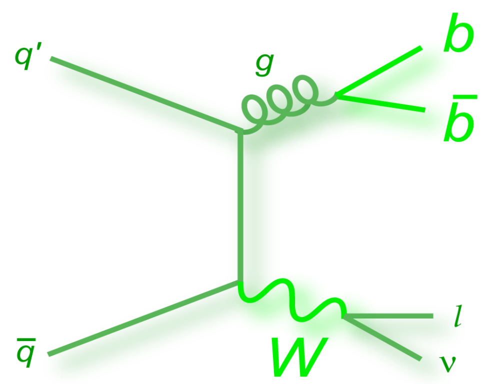
$P_{T,bb}$ = 248 GeV

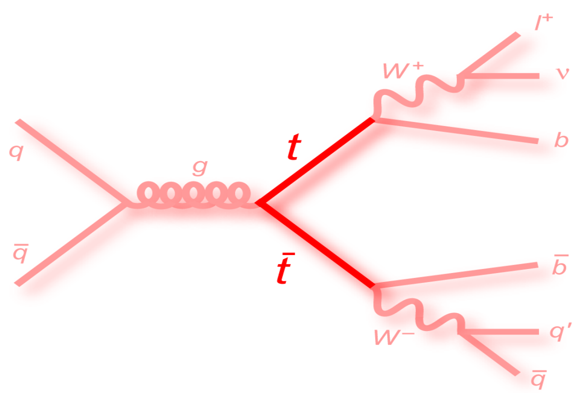
Recoiling against

$Z \rightarrow \nu\nu$

➔ Large MET

Backgrounds in H→ bb Search





Reducible backgrounds:

- QCD (strongly suppressed by lepton isolation and Pt)
- V+udscg,V+bb @ low p_T and mass
- W(lν)W(jj)
- ttbar and single top (→Wb)

Irreducible backgrounds:

- V+bb @ high p_T and mass
- ZZ(bb), W(lν)Z(bb)

Important discriminating variables

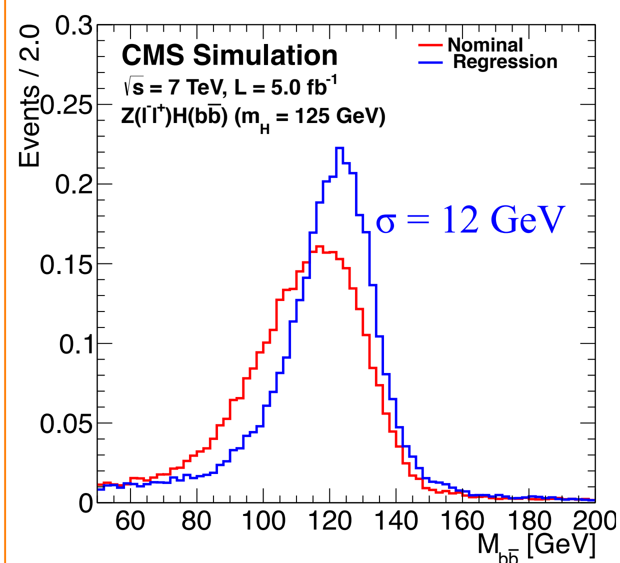
- Mass resolution (separation of VH from VV)
- b-tagging ➔ suppression of V+light quarks
- Back-to-back topology
- Additional jet activity in the event (ttbar)

Improved b-Jet Energy Measurement

Mass resolution and bias improved using algorithm developed at CDF for b-jet energy corrections http://arxiv.org/pdf/1107.3026.pdf

A Regression trained on VH signal events using several jet variables:

- raw p_T – transverse momentum of the jet before corrections;
- p_T – transverse momentum of the jet after corrections;
- E_T – transverse energy of the jet after corrections ($Z(\ell\ell)H$ uses E instead);
- M_T – transverse mass of the jet after corrections;
- η – pseudorapidity of the jet;
- ptLeadTrk – transverse momentum of the leading track in the jet;
- vtx3dL – 3-d flight length of the jet secondary vertex;
- vtx3deL – error on the 3-d flight length of the jet secondary vertex;
- vtxMass – mass of the jet secondary vertex;
- vtxPt – transverse momentum of the jet secondary vertex;
- Chf – fraction of jet constituents that are charged;
- Nch – number of jet constituents that are charged;
- Ntot – total number of jet constituents;
- $\rho 25$ – energy density calculated within $|\eta| < 2.5$;

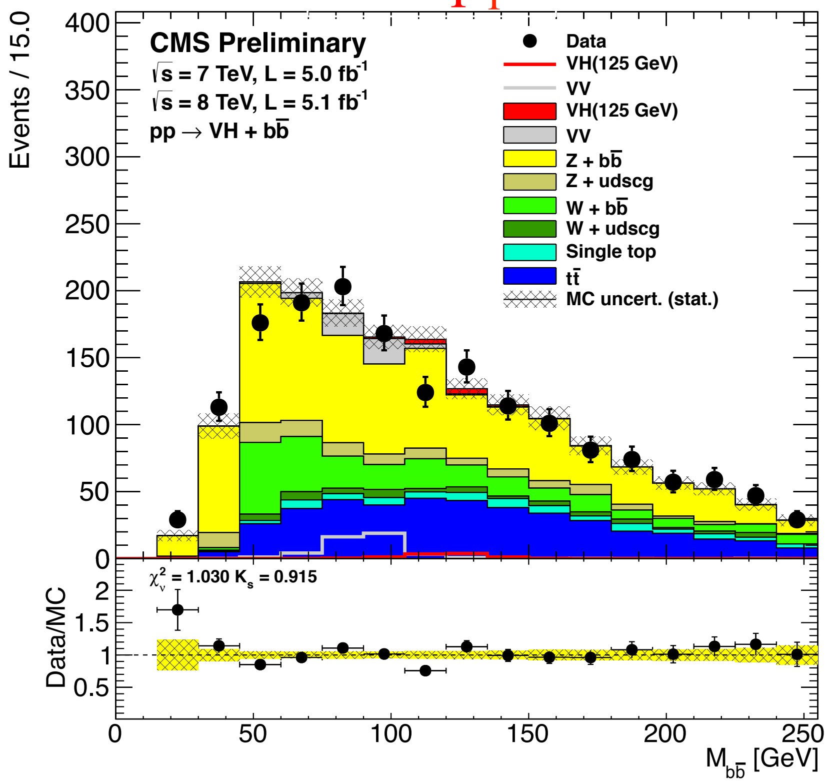


➔ Improvements in M_{bb} mass resolution of about 20% for Z(ll)H, 15% for W(lν)H and Z(νν)

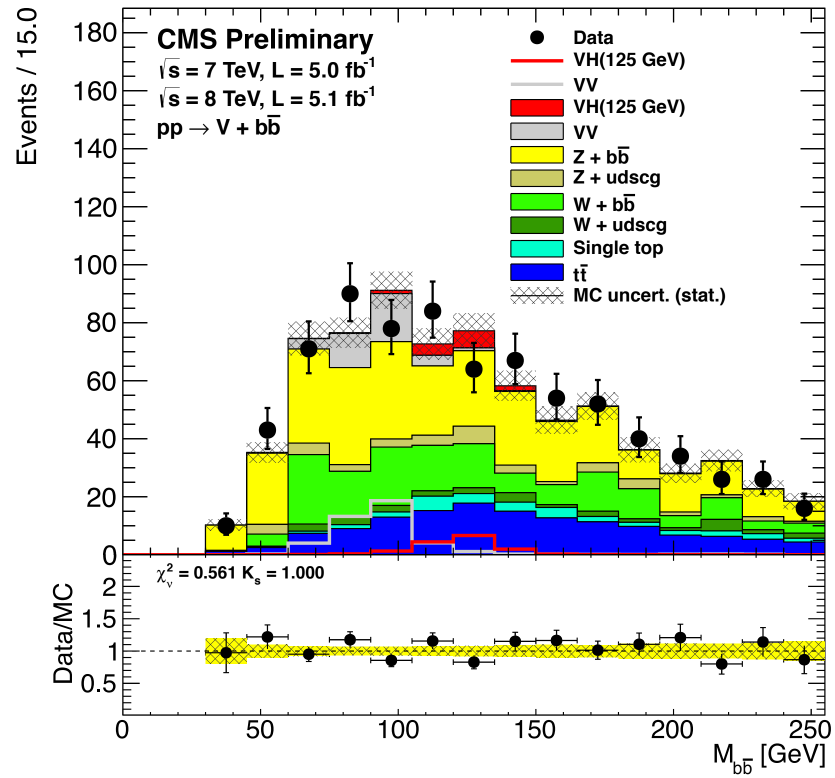
M_{bb} Mass Distribution : All Channels Combined

Distribution of events that pass a selection optimized for M_{bb} variable

Low p_T^V



High p_T^V



Good agreement between data and background prediction

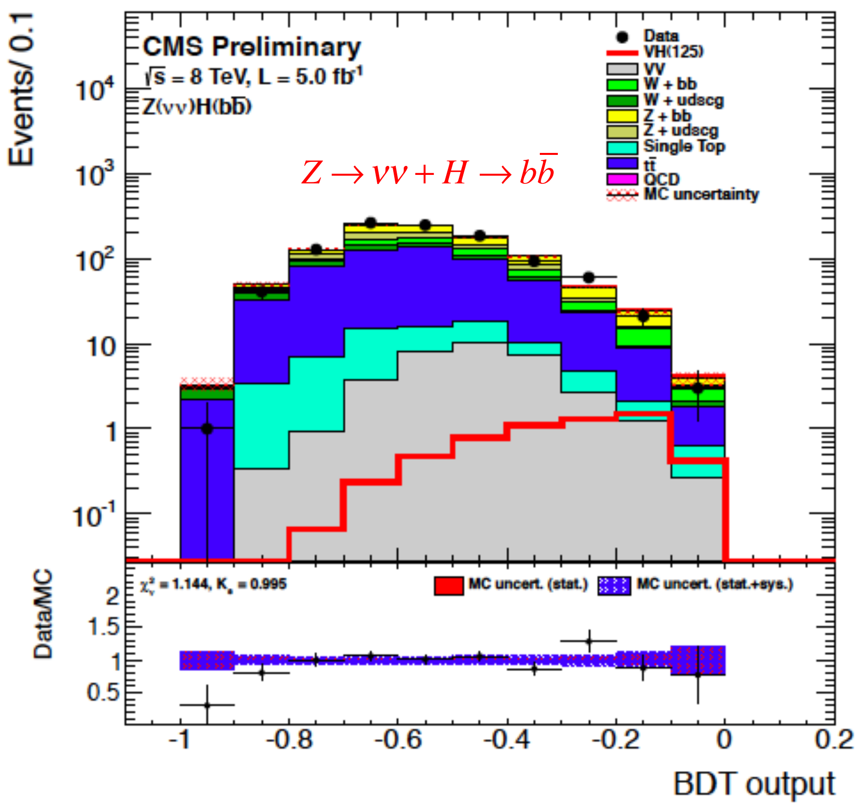
Further Separating Signal From Backgrounds

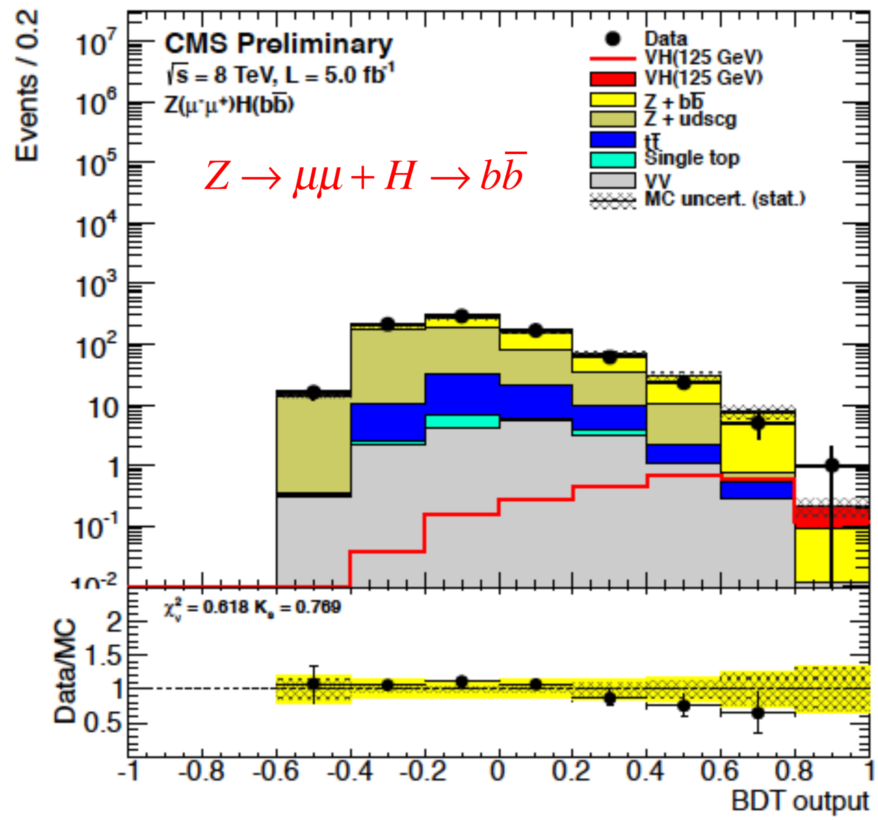
- A multivariate (BDT) algorithm trained at each Higgs mass hypothesis
- Several kinematic and topological variables used to separate signal from background

Variable
$p_{\mathrm{T}j}$: transverse momentum of each Higgs daughter
$m(\mathrm{jj})$: dijet invariant mass
$p_{\mathrm{T}}(\mathrm{jj})$: dijet transverse momentum
$p_{\mathrm{T}}(\mathrm{V})$: vector boson transverse momentum (or pfMET)
$\mathrm{CSV}_{\mathrm{max}}$: value of CSV for the b-tagged jet with largest CSV value
$\mathrm{CSV}_{\mathrm{min}}$: value of CSV for the b-tagged jet with second largest CSV value
$\Delta\phi(\mathrm{V},\mathrm{H})$: azimuthal angle between V (or $E_{\mathrm{T}}^{\mathrm{miss}}$) and dijet
$\|\Delta\eta(\mathrm{jj})\|$; difference in η between Higgs daughters
$\Delta R(\mathrm{j1},\mathrm{j2})$; distance in η–ϕ between Higgs daughters (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)
N_{aj}: number of additional jets ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\|\eta\| < 4.5$)
$\Delta\phi(\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet})$: azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest jet (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$)
$\Delta\theta_{\mathrm{pull}}$: color pull angle [62] (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)

Shapes of Signal & Background BDT Distributions

- A Higgs signal in the mass range [110-135] GeV is searched for as an excess in MVA classifier using predicted shapes for signal & bkgnd

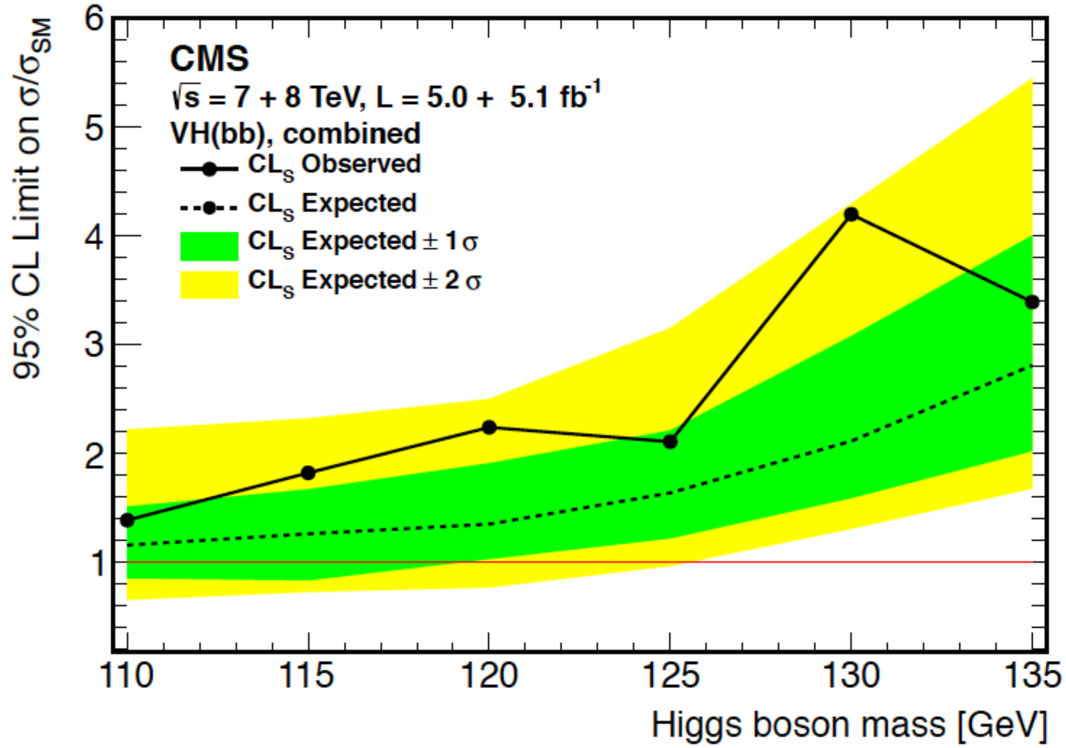




No significant excess seen over predicted background yields in these or other channels

CMS Limits: VH, H → bb Searches (10 fb^{-1})

Limit based on S & B shape analysis of BDT output

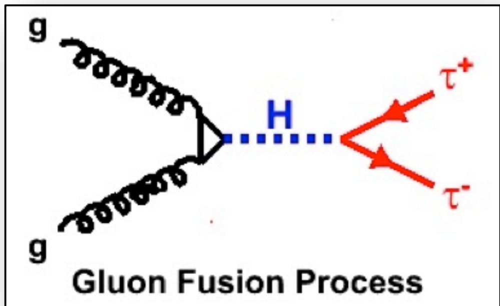


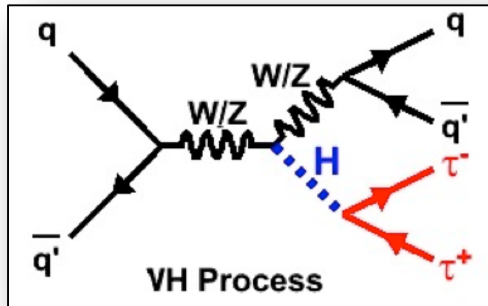
m_H(GeV)	110	115	120	125	130	135
Exp.	1.16	1.26	1.35	1.64	2.12	2.81
Obs.	1.39	1.82	2.24	2.11	4.20	3.39

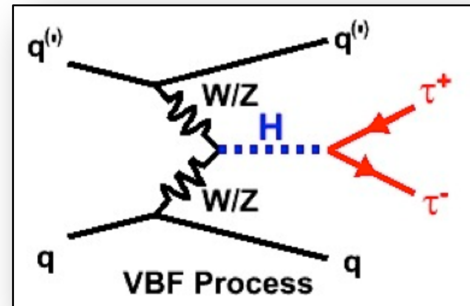
Approaching SM Higgs sensitivity, should hit < $1\times\sigma_{SM}$ with full data

H → ττ : Another Low Mass Specialist

- Most promising mode for measuring Higgs coupling to leptons
- Searched for in three Higgs production modes







- And subsequent decay of τ lepton
  - τ → eνν , τ → μνν, τ → hadrons
- Four signatures considered : eμ, μμ, $e\tau_h$, $\boldsymbol{\mu\tau_h}$
- Due to missing neutrinos, Higgs signal appears as a broad excess in reconstructed τ-pair mass (Mass resolution ≈ 20%)
- Major backgrounds arise from
  - ttbar
  - W & Z (+jets), dibosons

$H \rightarrow \tau\tau$ Search Strategy

- Search divided in 5 categories based on $H \rightarrow \tau\tau$ mass resolution & S/B

\# of Jets with p_T > 30 GeV

τ_h or μ p_T

0 Jet, Low p_T τ
High Background
Constrains fit

1 Jet, Low p_T τ
S/B enhancement
from Jet
Requirement

0 Jet, High p_T τ
Lepton p_T
spectrum harder
from H

1 Jet, High p_T τ
S/B enhancement
from p_T and Jet
requirement

VBF
2 Jets, Rapidity
Gap Veto, MVA
Selection

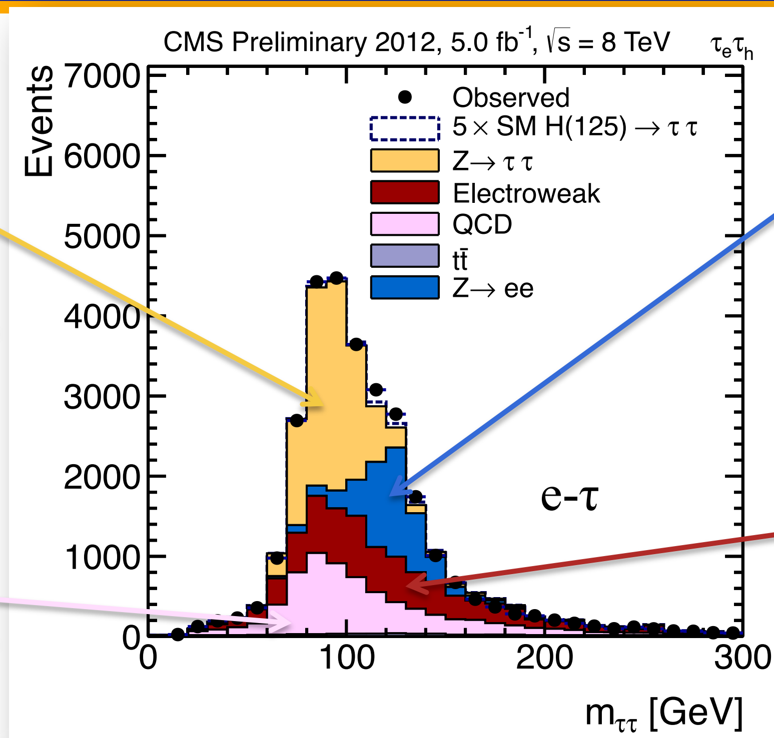
1) m_{jj}
2) $\Delta\eta_{jj}$
3) $\Delta\phi_{jj}$
4) $\Delta\phi_{Hjj}$
5) di-jet p_T
6) di-Tau p_T+ MET
7) visible di-tau p_T
8) $\Delta\eta$(di-tau, jet)

- All categories are fit simultaneously

Anatomy of the H→ ττ   Analysis

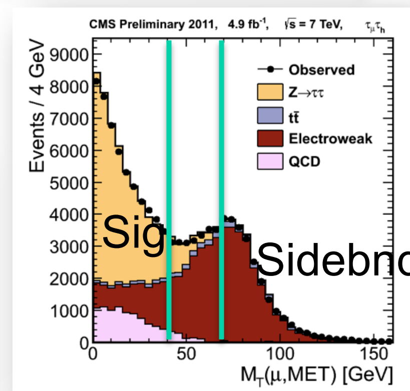
Z→ττ – Efficiency measured using τ embedded in Z→ μμ events

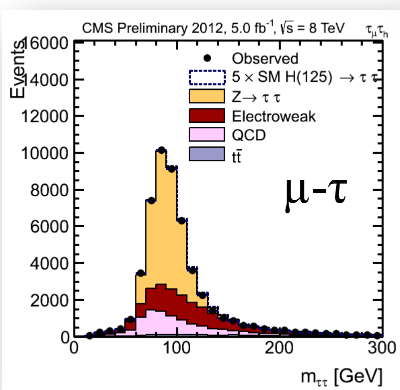
QCD – Estimated from same sign data

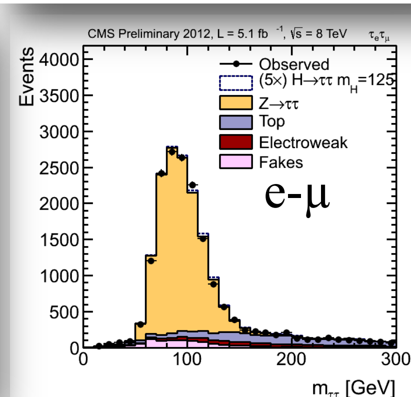


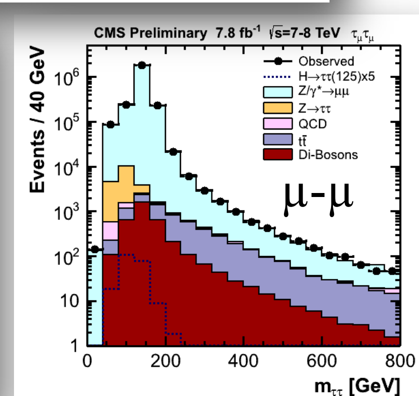
Z→ll – Taken from MC corrected for measured l→τ fake rates

EWK – Mostly W+Jets, measured from high M_T sideband



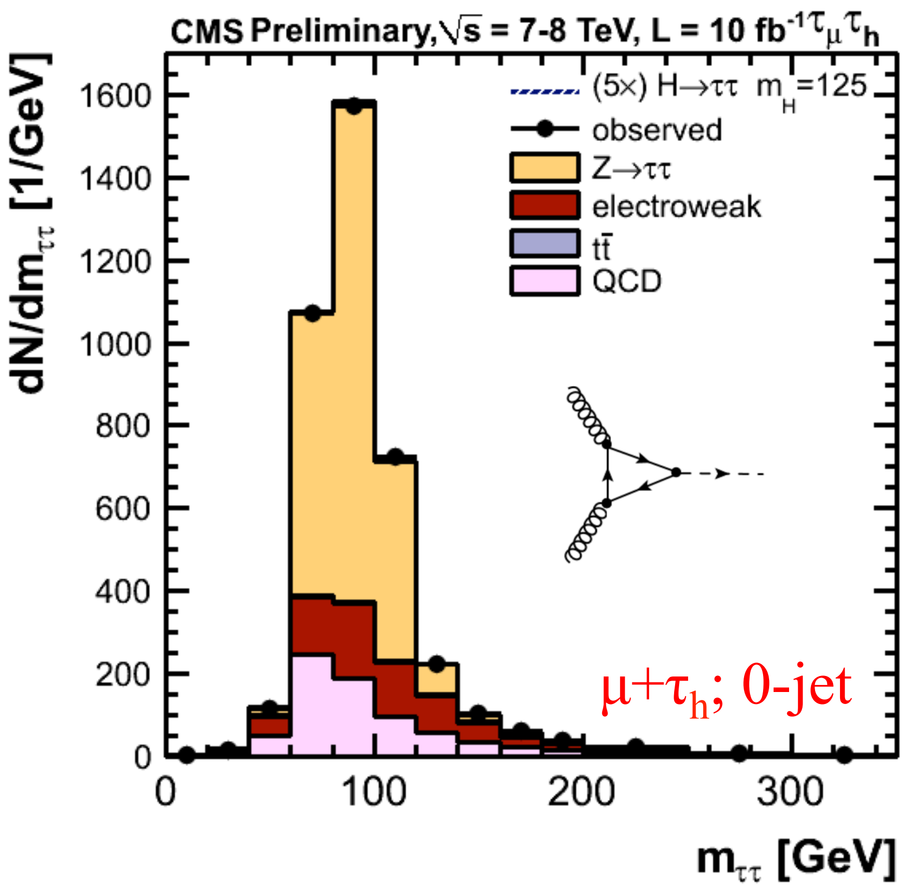


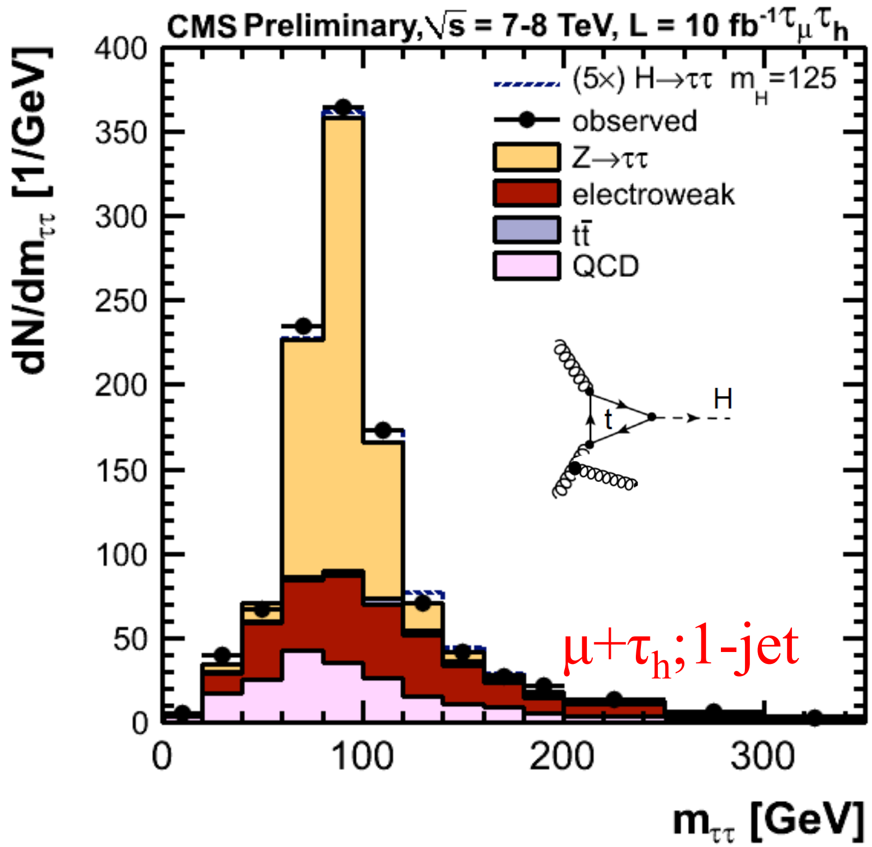




Plots are pre-fit

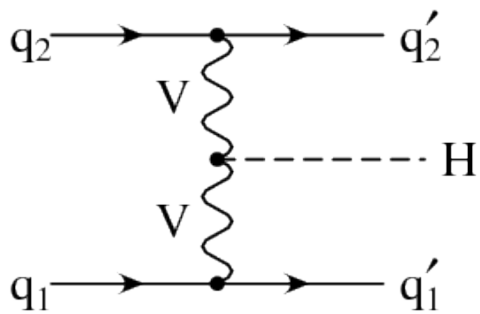
Tau-Pair Mass Distributions In 0 &1 Jet Catagories

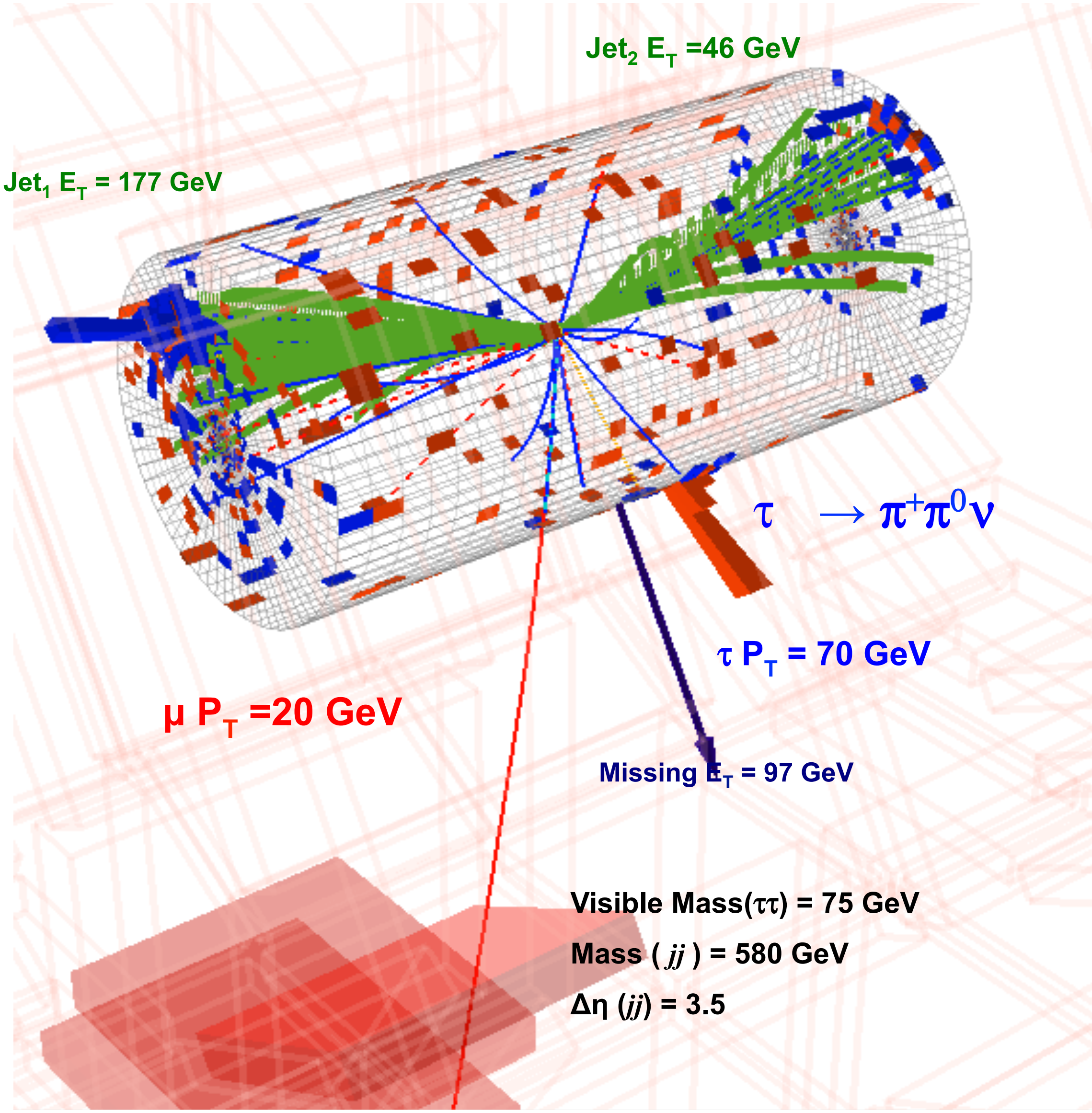




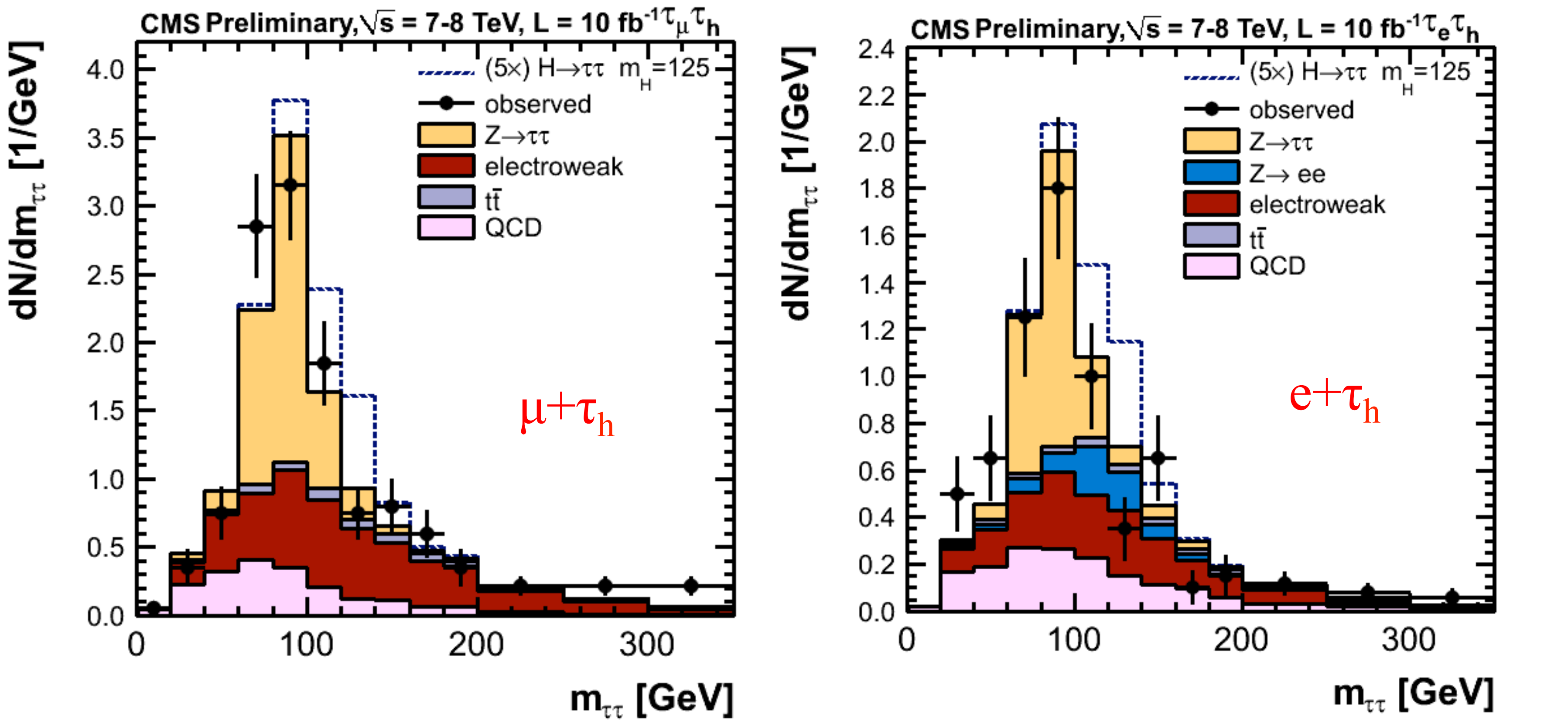
Possible Signal over large backgrounds !

VBF (ττ+2jets) Category Has Best S/N



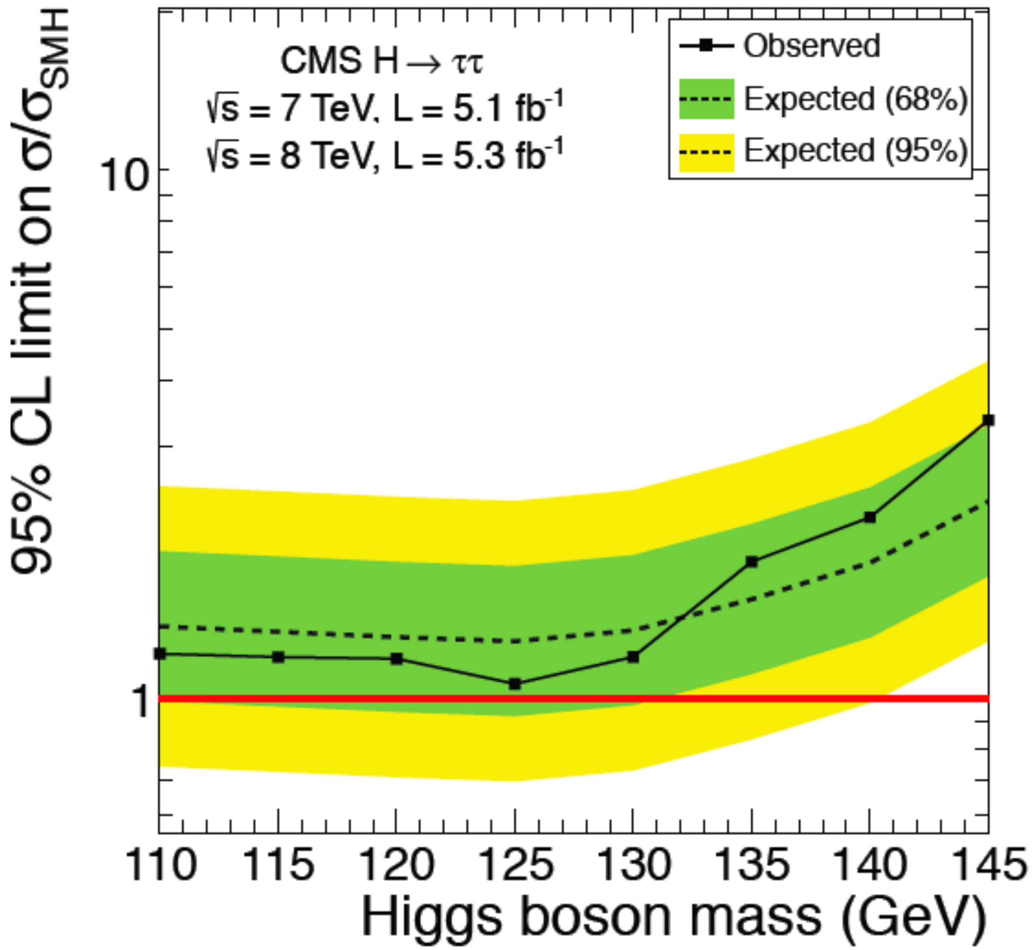


Yields & Expectations in VBF Catagory

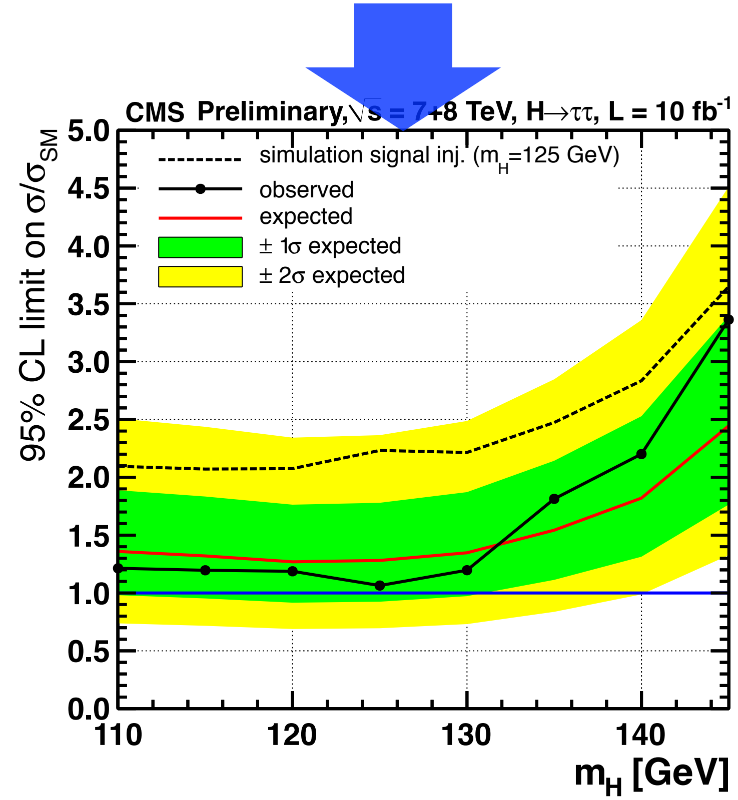


Much better signal to noise , but small signal

Limits From H → ττ Search



Median expectation (10 fb^{-1}) for SM H → ττ

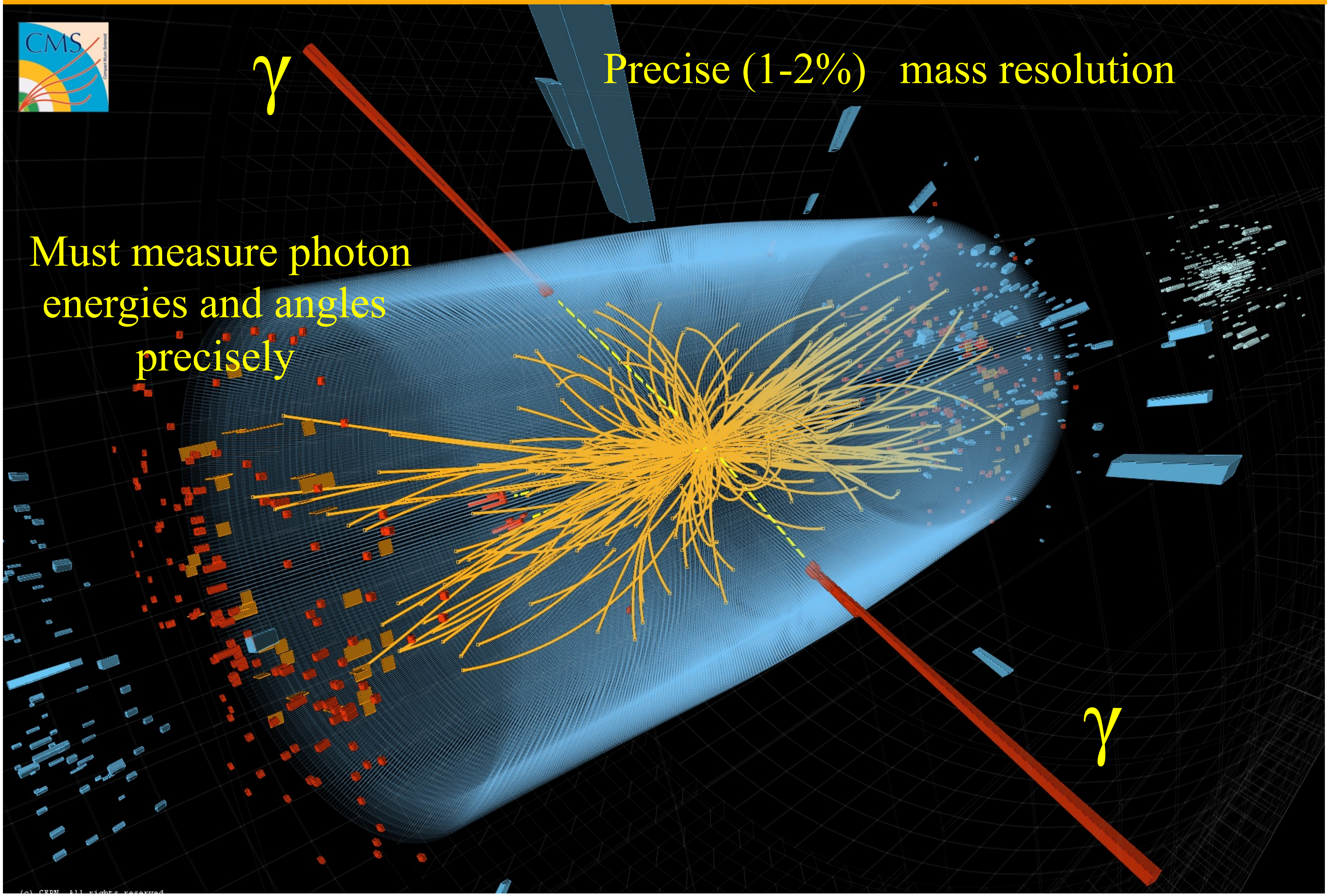


Expected exclusion @ M_H = 125 : 1.3 σ_{SM}

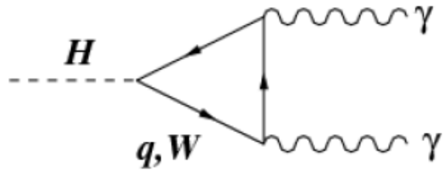
Observed exclusion @ M_H = 125 : 1.1 σ_{SM}

Sensitive to < 1×σ_{SM} with full 8 TeV data

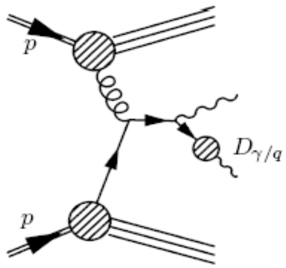
H → γγ : High Precision Mode

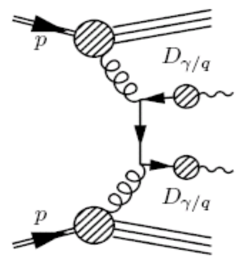


$H \rightarrow \gamma\gamma$

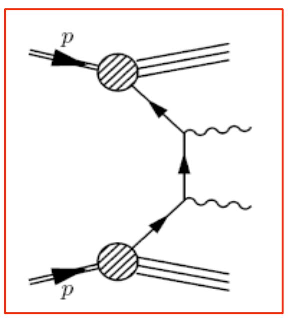


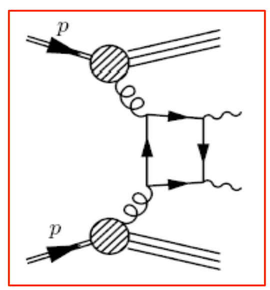
- A discovery channel in $110 < M_H < 150$ GeV
- Br $(H \rightarrow \gamma\gamma) \approx 10^{-3}$
- Search for a narrow peak with two isolated high E_T photons over a continuous diphoton background spectrum
- Background is large and composed of
  - Reducible: One or more misidentified (fake) photon (e.g. γ+jets)



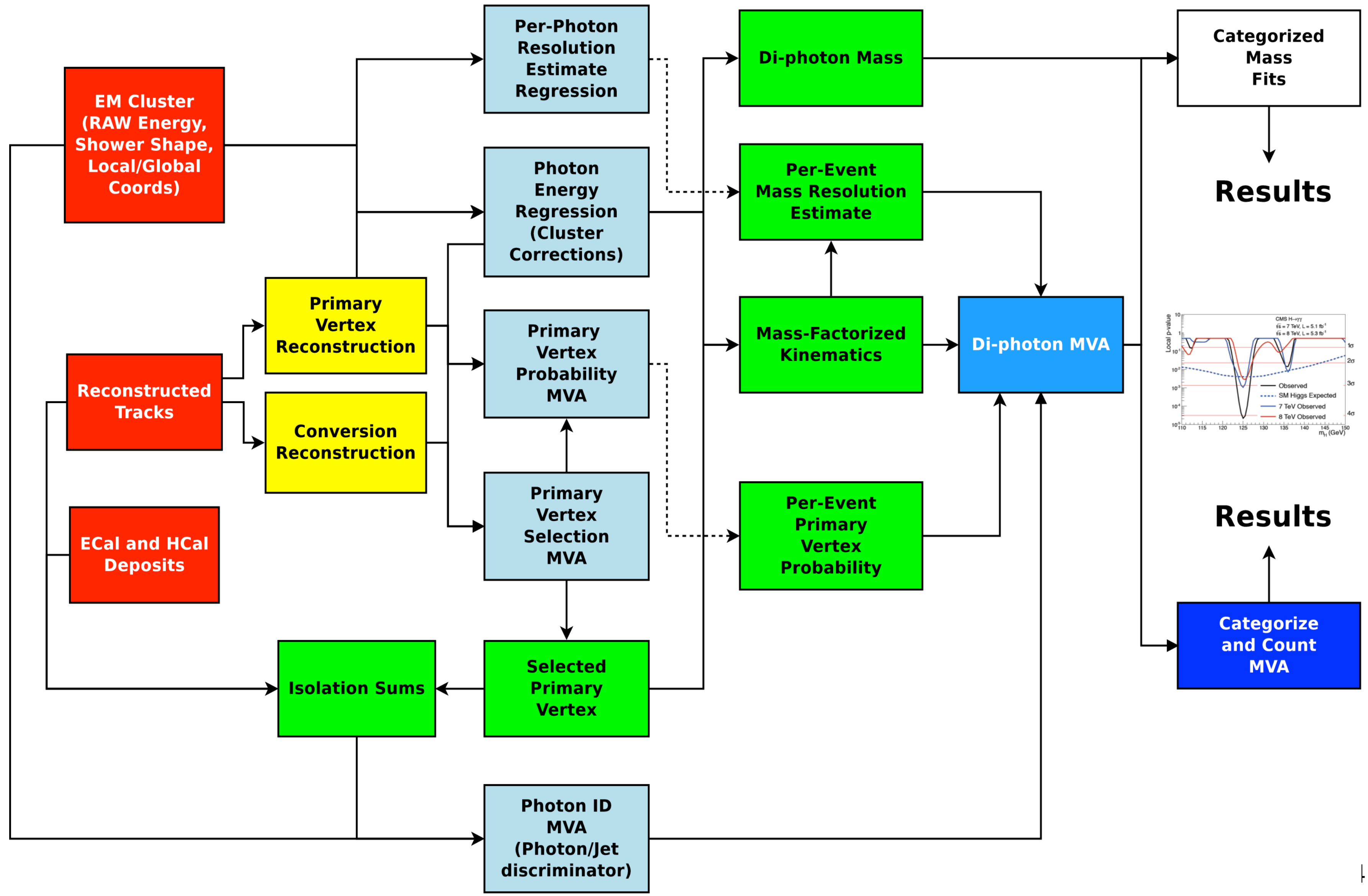


- Irreducible: both photons are real





Flowchart For $H \rightarrow \gamma\gamma$ Search



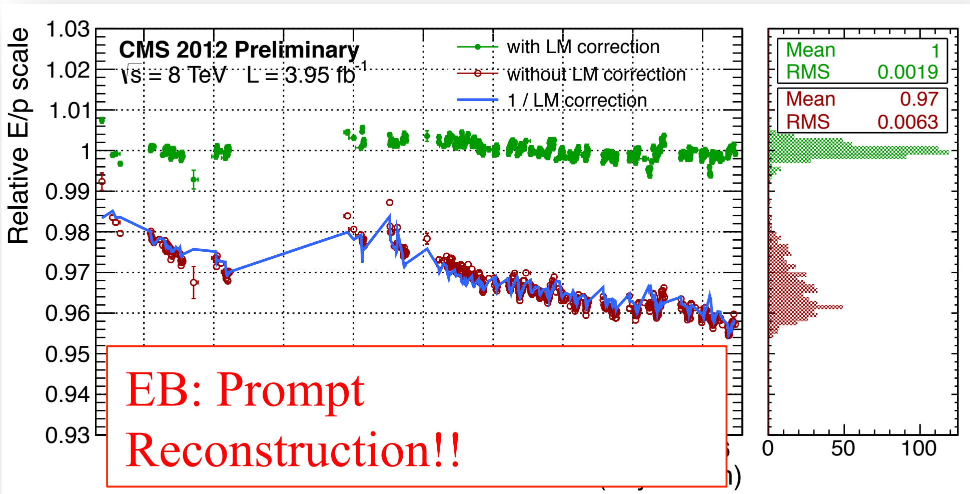
H → $\gamma\gamma$: Important Analysis Aspects

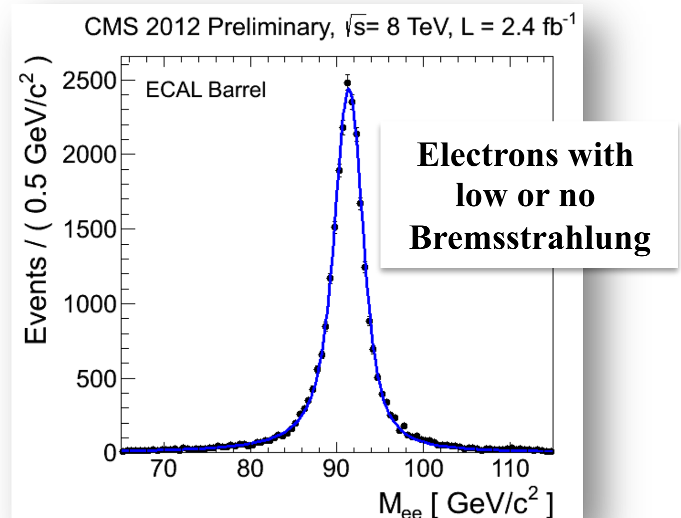
- $M^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha_{\gamma\gamma})$ →
  - ECAL Calibration for $M_{\gamma\gamma}$ energy scale & resolution
  - $\gamma\gamma$ vertex determination (angle $\alpha_{\gamma\gamma}$)
- Photon energy correction and energy resolution
- Prompt photon identification
- di-photon selection and S/B based catagorization(not all $\gamma\gamma$ pair are measured with same resolution)
  - 4 catagories for inclusive $\gamma\gamma$ analysis
  - + 1-2 exclusive VBF catagories
- Signal & background modeling

ECAL Calibration, 2012 Data

Single electron energy scale (E/p) stability in barrel measured with W →eν events

Z→ee invariant mass distribution for electrons measured in the barrel

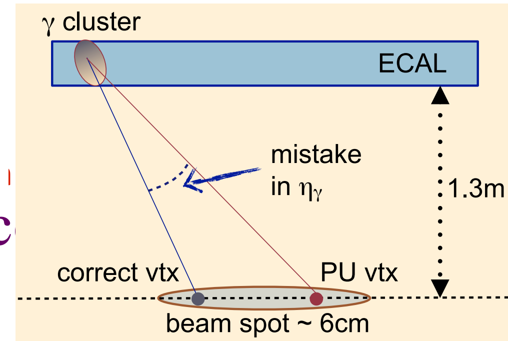




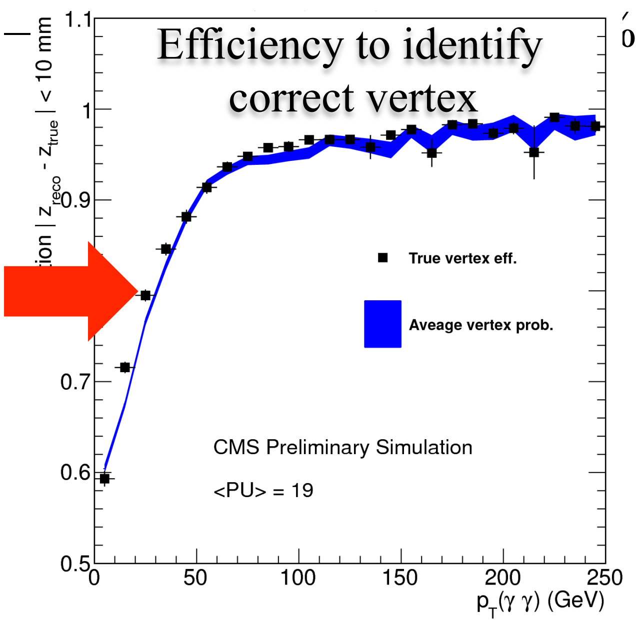
- **W→eν sample** E/p: Stable E scale during 2012 run after light monitoring (LM) corrections:
  - ECAL Barrel (EB): RMS stability after corrections 0.19%
- Z→ee: Good resolution with prelim. energy calibration for 2012:
  - Instrumental resolution: ≅1.0 GeV in ECAL Barrel

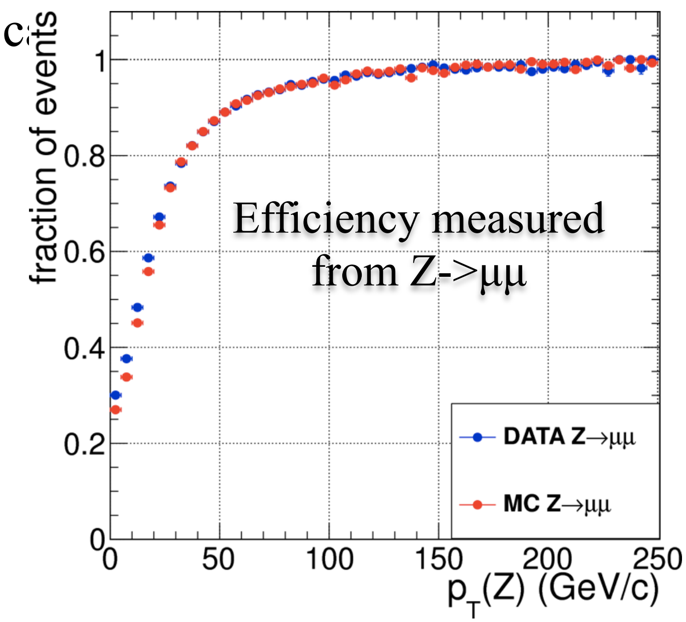
Selecting γγ Vertex (CMS)

- $M^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$,
  - $M_{\gamma\gamma}$ resolution depends on vertex selection
  - Important for high pileup events → many choic

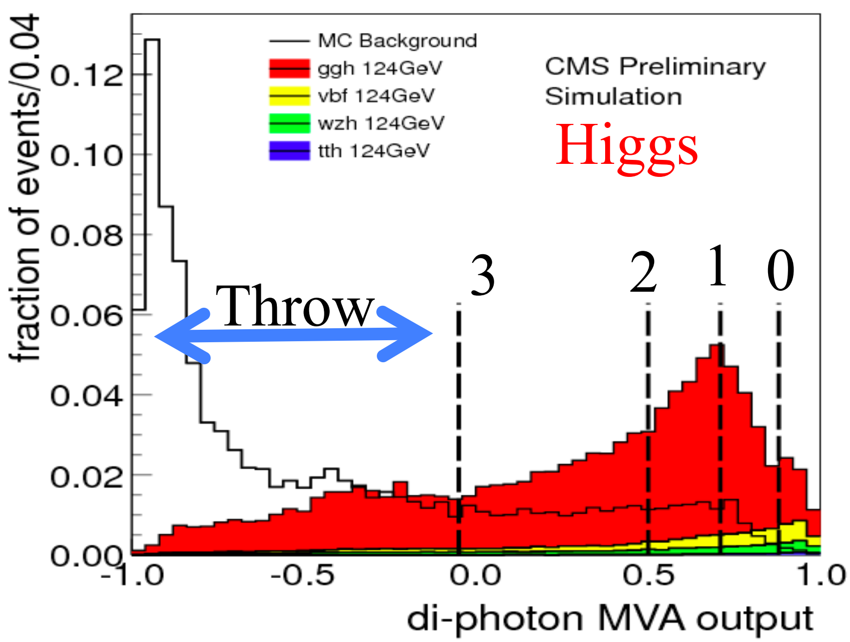


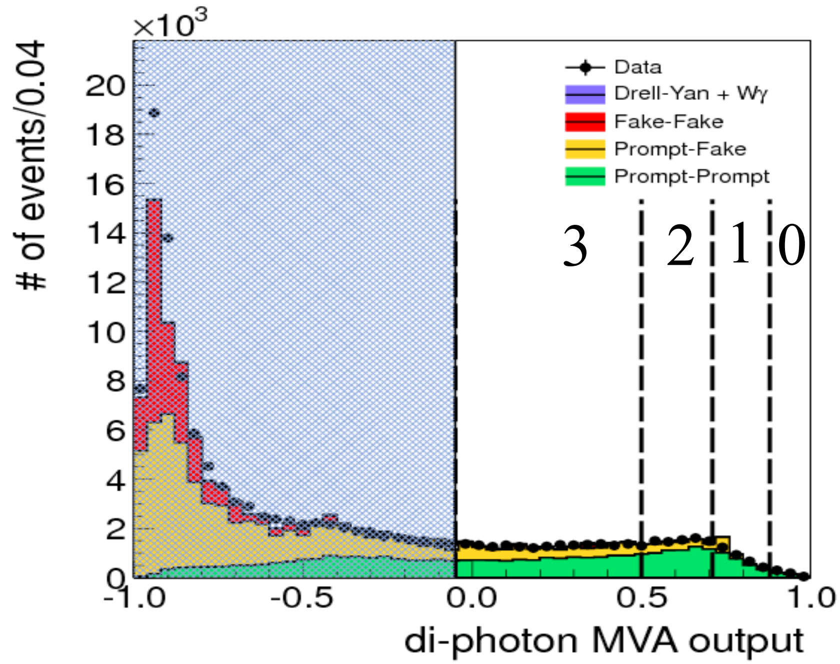
- No pointing → vertex identified using tracks from
  - recoiling jets and underlying event & γ→ee, Input variables: Σp_t^2, Σp_t projected onto the γγ transverse direction, p_t asymmetry and conversions





Inclusive γγ Event Catagorization (CMS)





Cat 0 : mostly $P_T^{\gamma\gamma} > 40$ GeV

Cat1 : unconverted γ in barrel

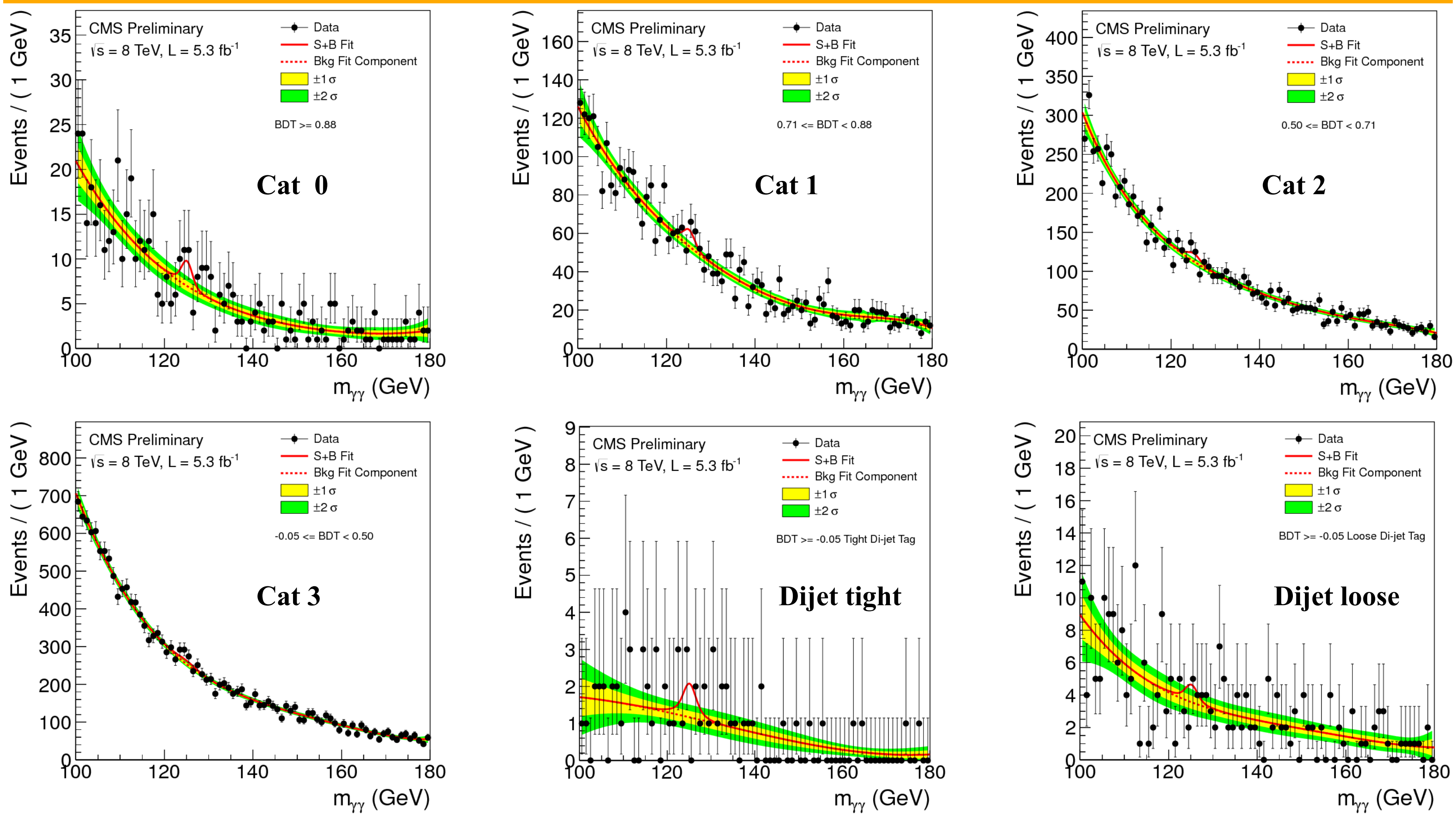
Performance By Catagory

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 ± 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

Category 3 diphotons have the worst $M_{\gamma\gamma}$ resolution & S/B

γγ Mass Distribution By Catagories (8 TeV)

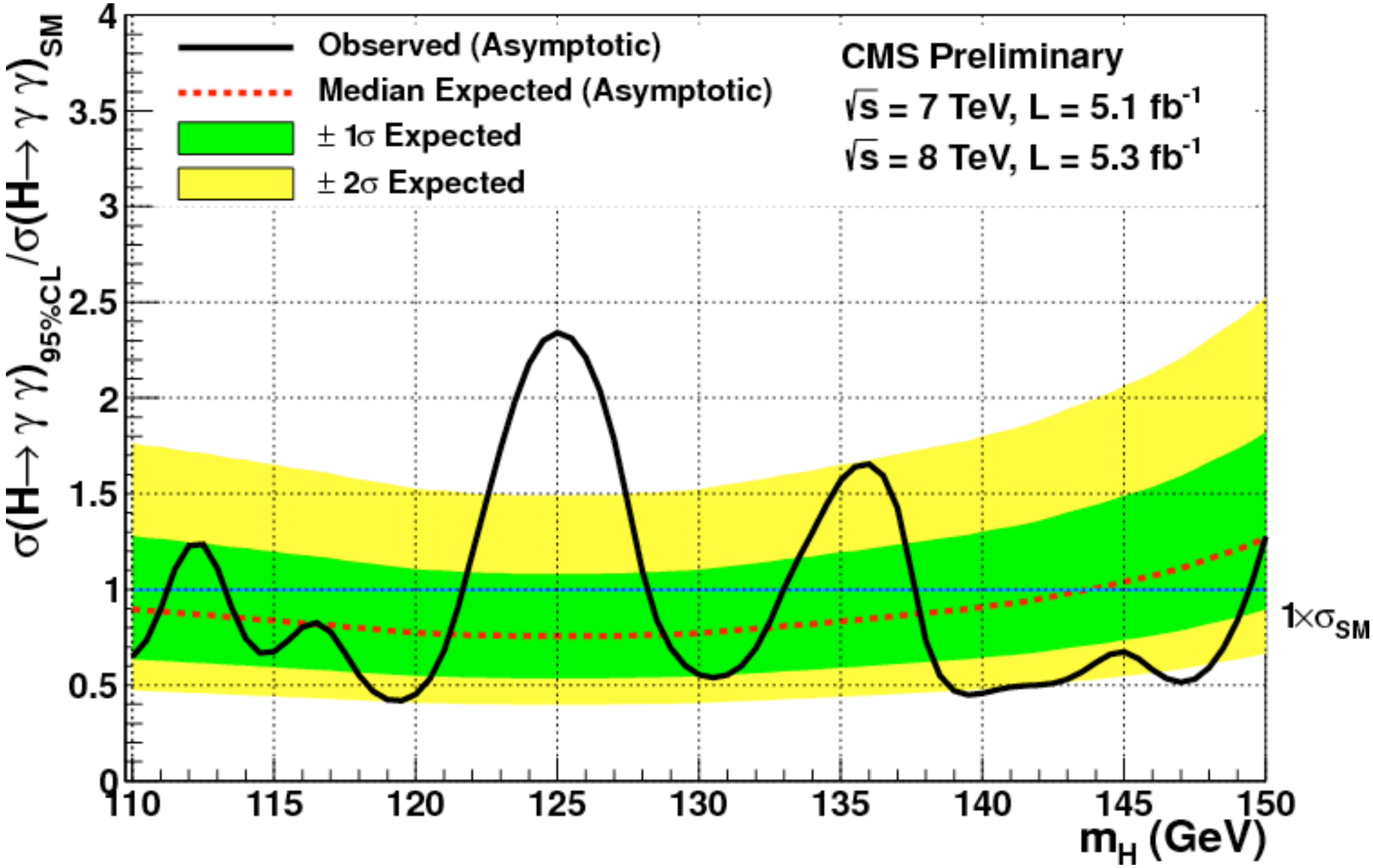


Catagories with good S/N show enhancement at ~125 GeV

but not obvious to naked eye !

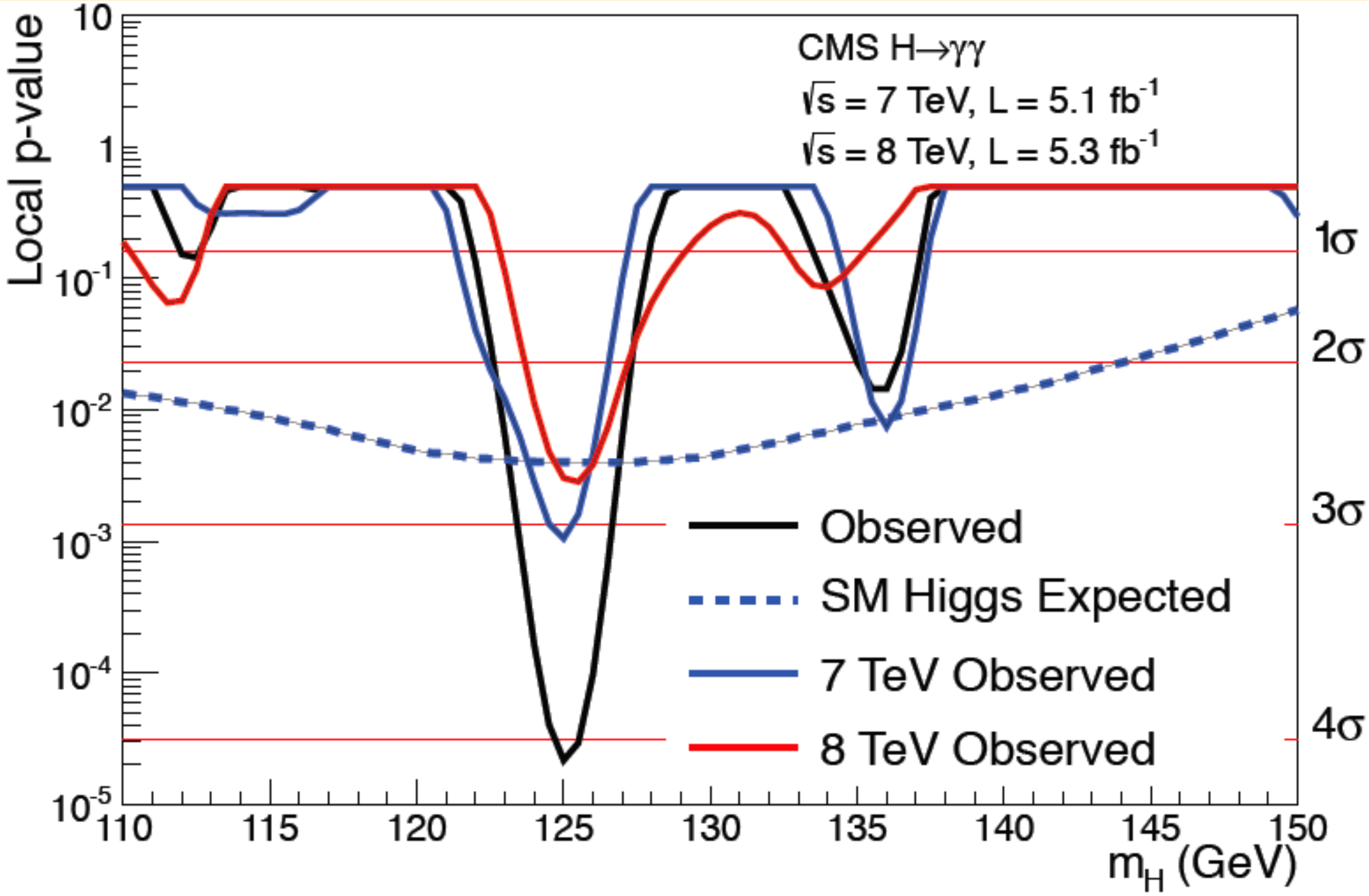
Fit all catagories simultaneously with a signal & background model

95% SM Higgs Exclusion Limit



- Expected 95% CL exclusion 0.76 x σ_{SM} at M = 125 GeV
- Large range with expected exclusion below σ_{SM}
- Largest excess at 125 GeV

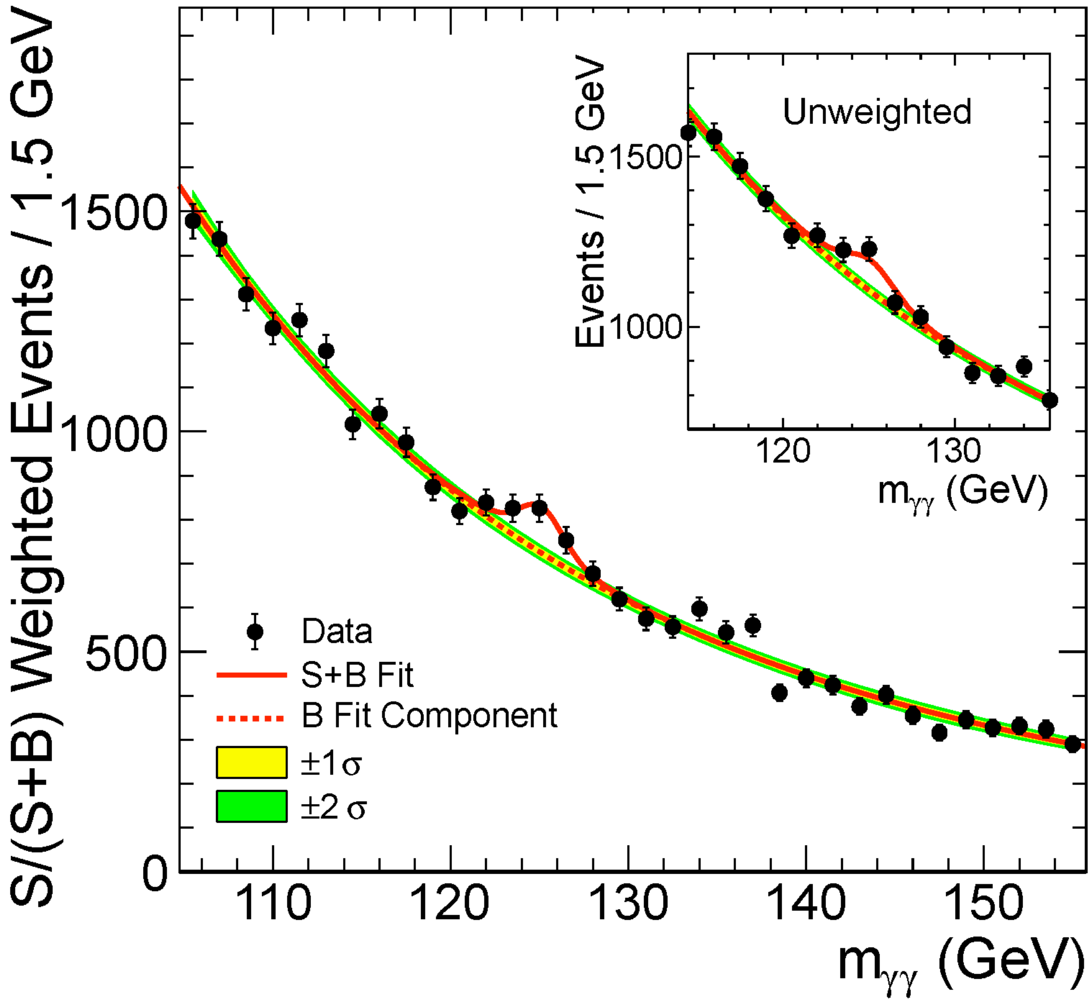
Scan Of p-value Vs Mass



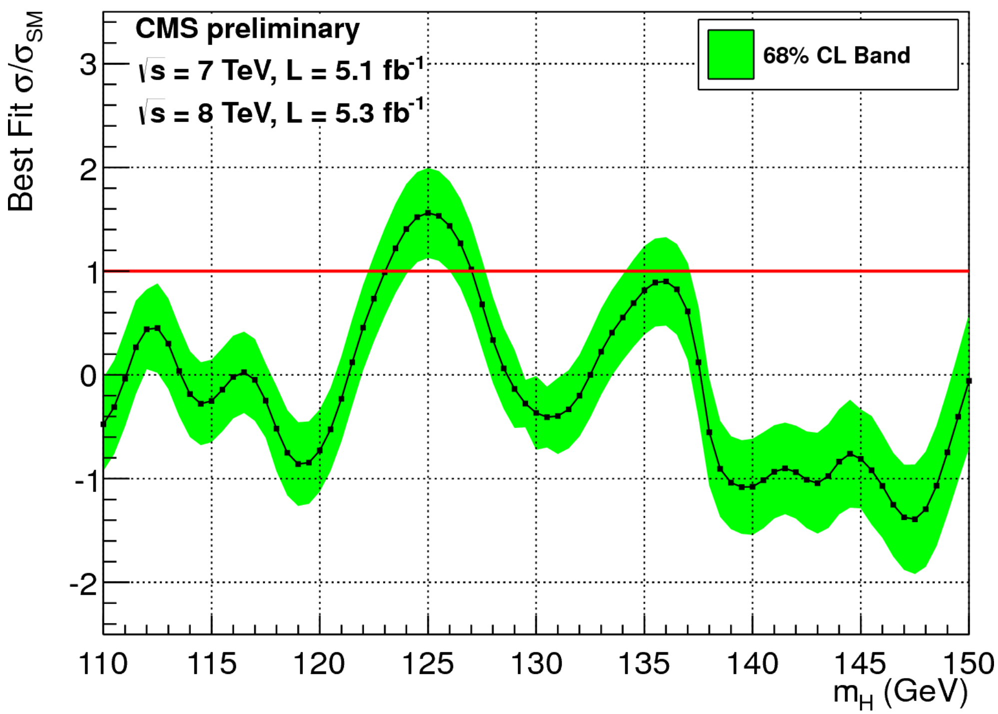
- Minimum p-value at 125 GeV with a local significance of 4.1 σ
- Similar excess at same mass in 2011 and 2012
- Global significance in the full search range (110-150 GeV): 3.2 σ

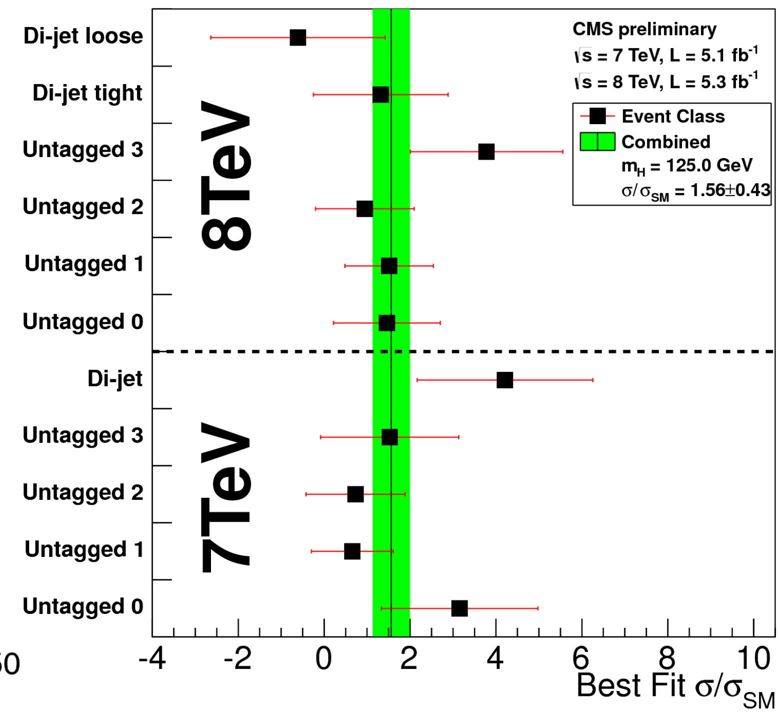
Combined Mass Distribution Weighted by S/B

- Sum of mass distributions for each catagory, weighted by S/B
- B is integral of background model over a constant signal fraction interval



Fitted Signal Strength σ/σ_{SM}



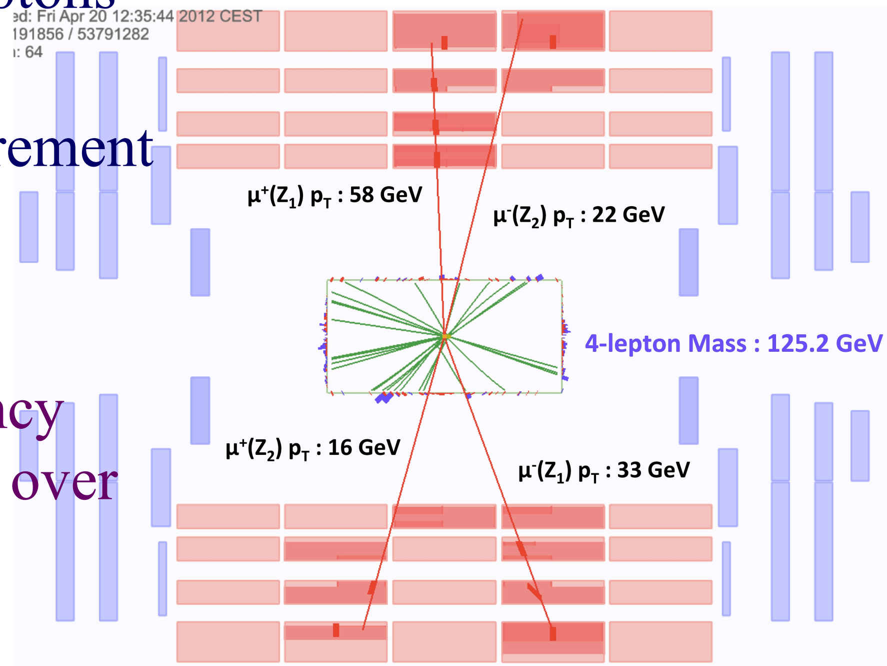


Combined best fit signal strength $\sigma/\sigma_{SM} = 1.56 \pm 0.43$ consistent with but larger than SM expectation

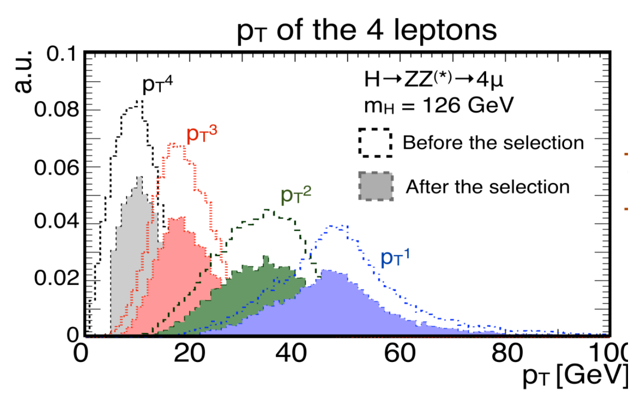
Best fit signal strength consistent between different classes and datasets

H → ZZ → 4*l*

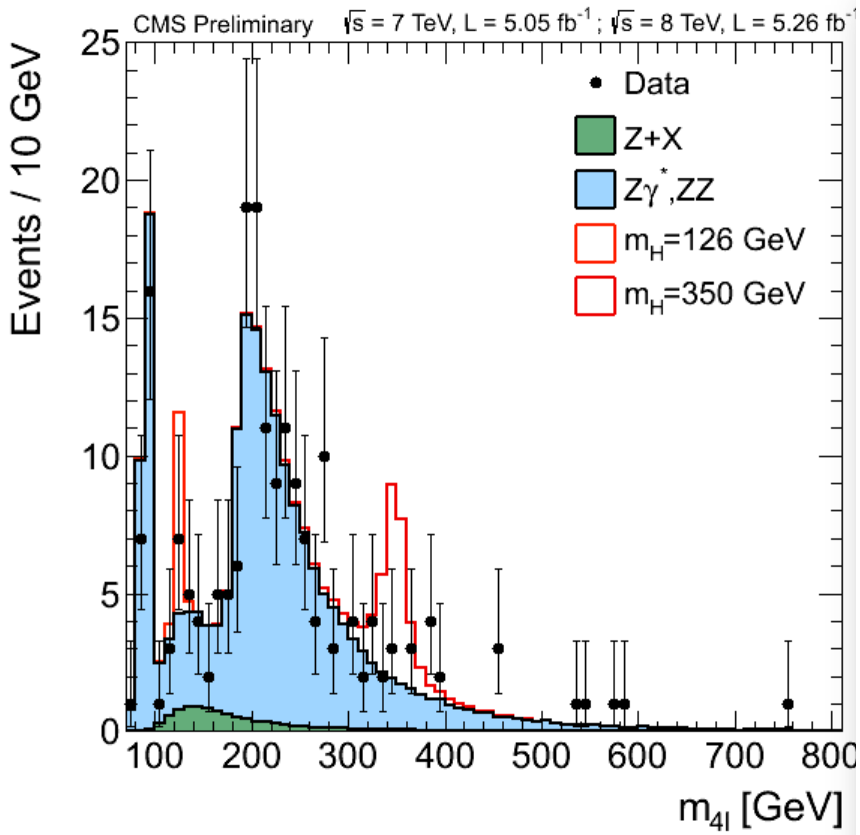
- **Golden channel** : Four isolated leptons from one point in 3D space
- Benefits from excellent e/μ measurement
  - M_{4l} mass resolution ≈ 1-2 %
- σ×Br(H→ ZZ→ 4l) quite small
  - Needs highest selection efficiency possible → Efficient lepton ID over broad P_t range

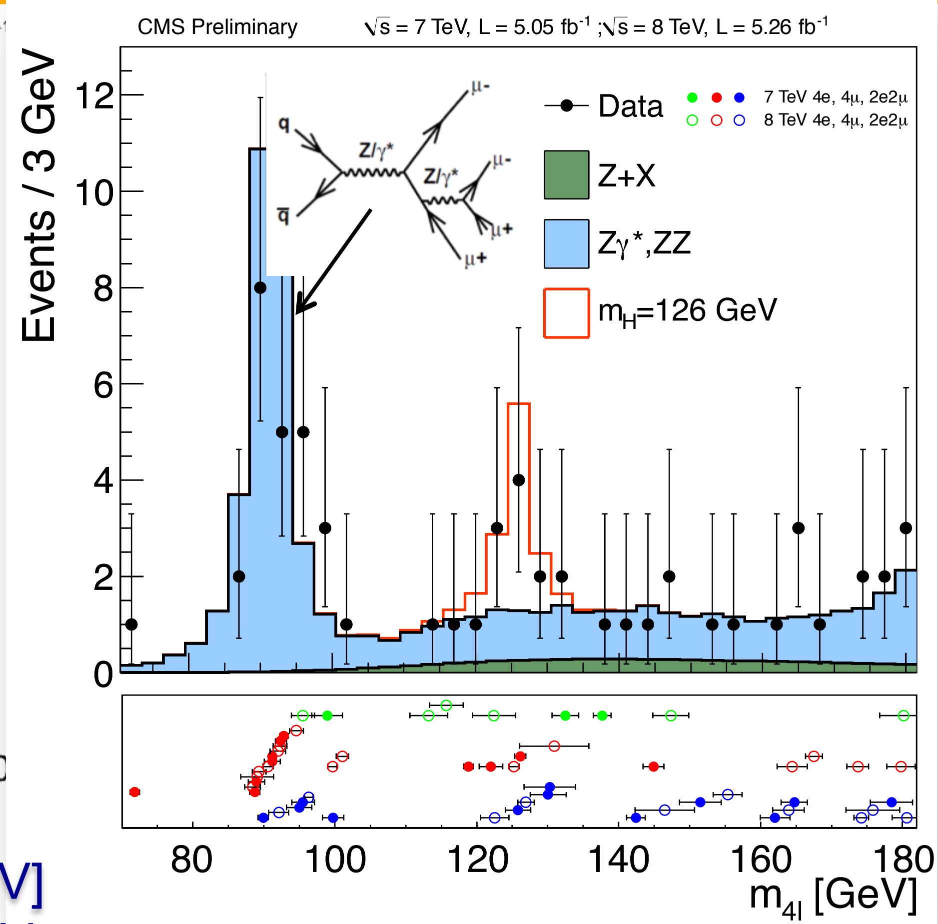


- Backgrounds
  - Non-resonant pp→ ZZ→4l is largest and irreducible, has same topological signature as H → 4l
    - **But no narrow peak as in H → ZZ**
  - Z+jets,ttbar, WZ…all reducible and important at low M_{4l}



4l Mass Spectrum In Data : CMS

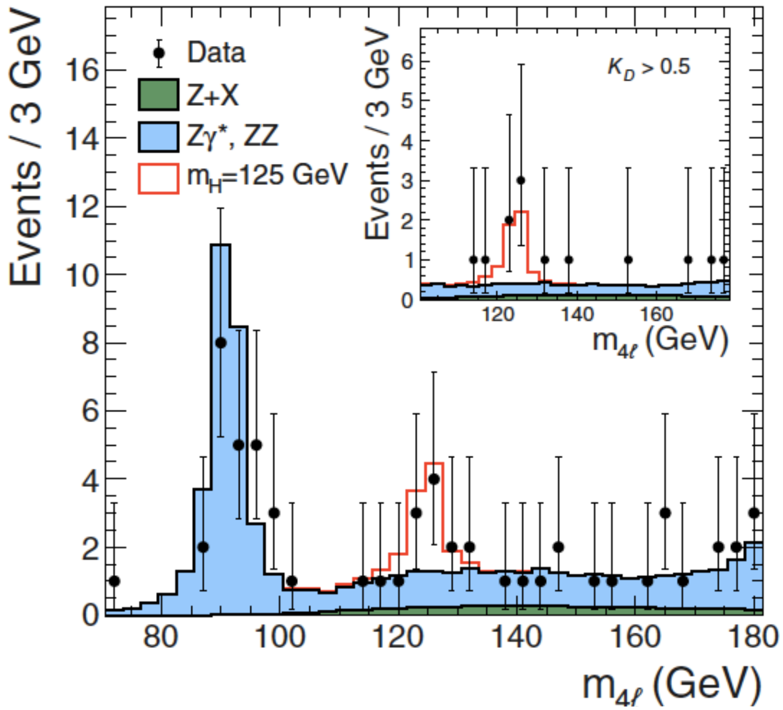




164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

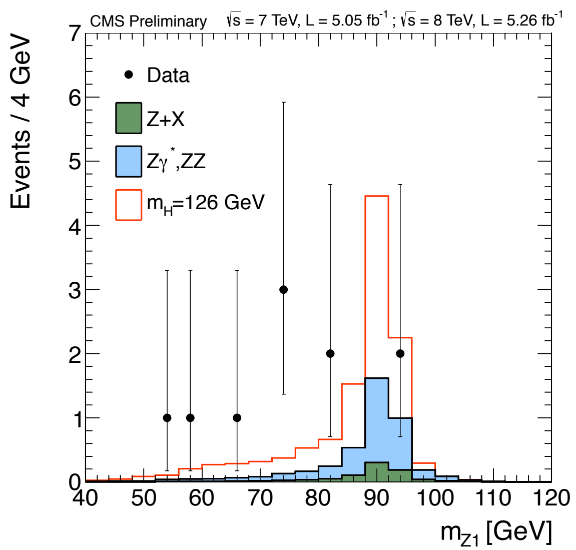
An excess observed near M = 126 GeV

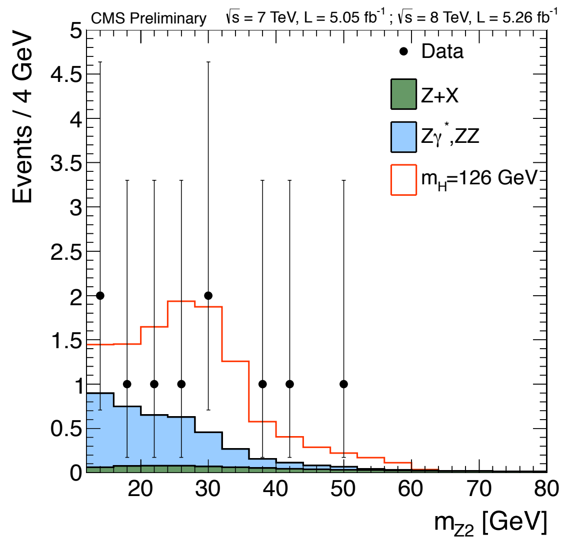
$H \rightarrow ZZ \rightarrow 4l$ Event yield : CMS

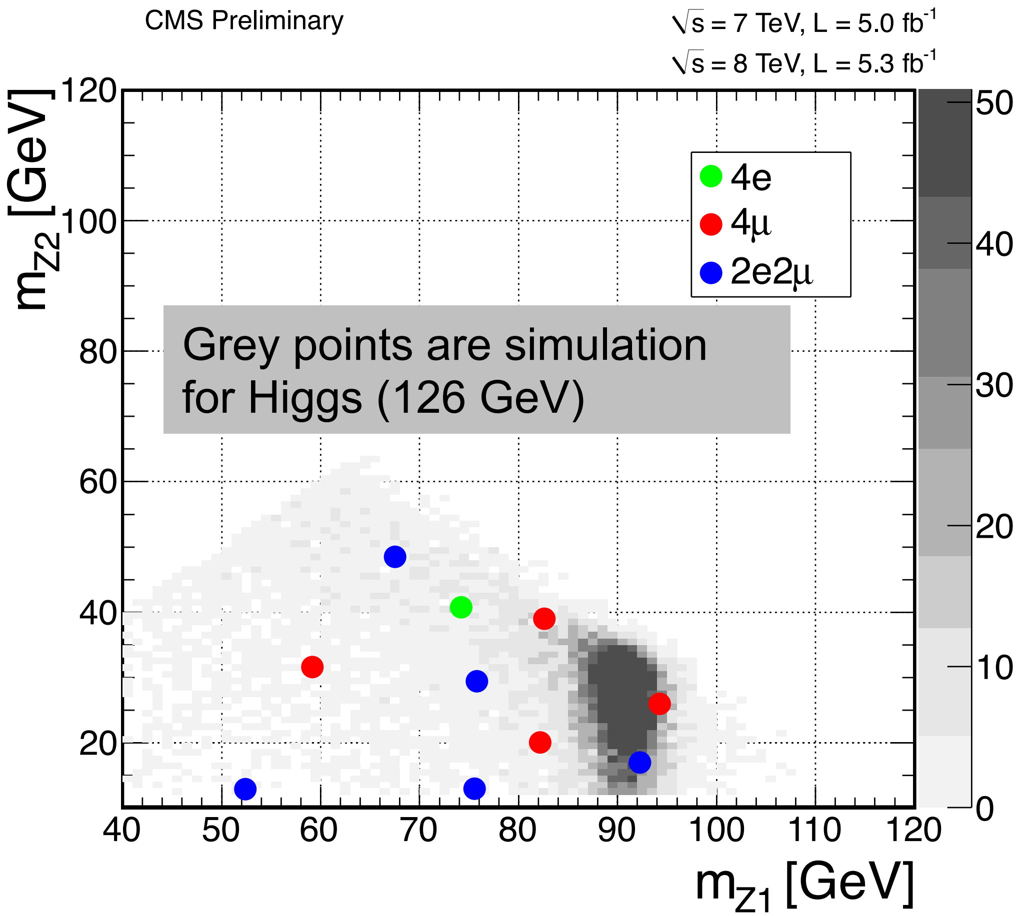


Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z + X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160\,\text{GeV}$)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160\,\text{GeV}$)	6	6	9	21
Signal ($m_{\text{H}} = 125\,\text{GeV}$)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9

An Odd Aspect: Z_1 Vs Z_2 Mass In H → ZZ







Probablity of observing such a fluctuation is ≈ 0.3-1%

Angular Analysis In H → ZZ → 4l (CMS)

- H → ZZ → 4l Decay kinematic fully described by 5 angles and the 2 Z masses
  - discriminates spin 0 particle from background
  - MELA: matrix element likelihood analysis

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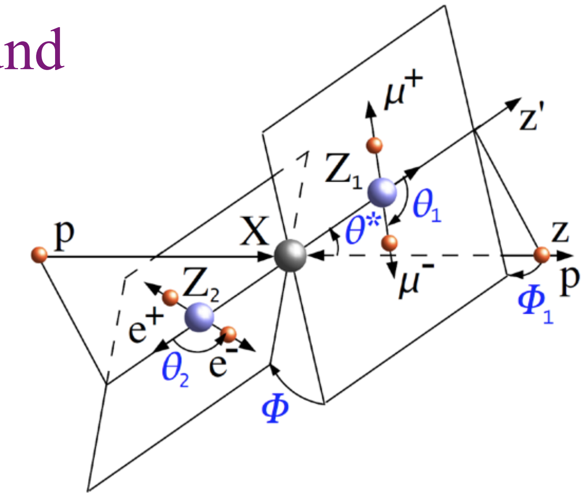
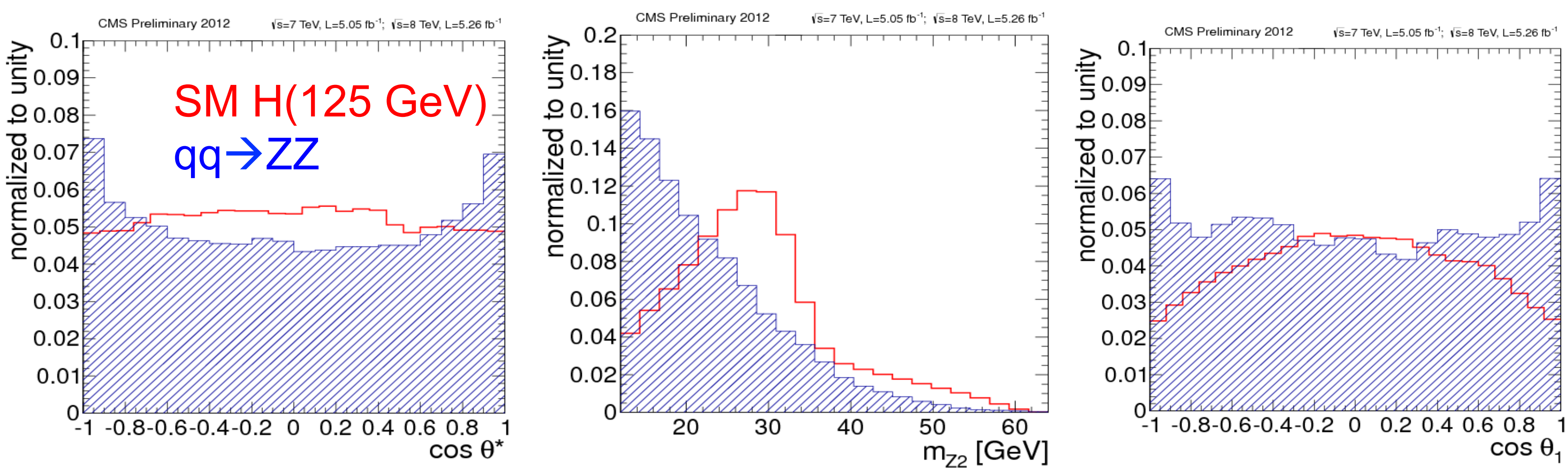
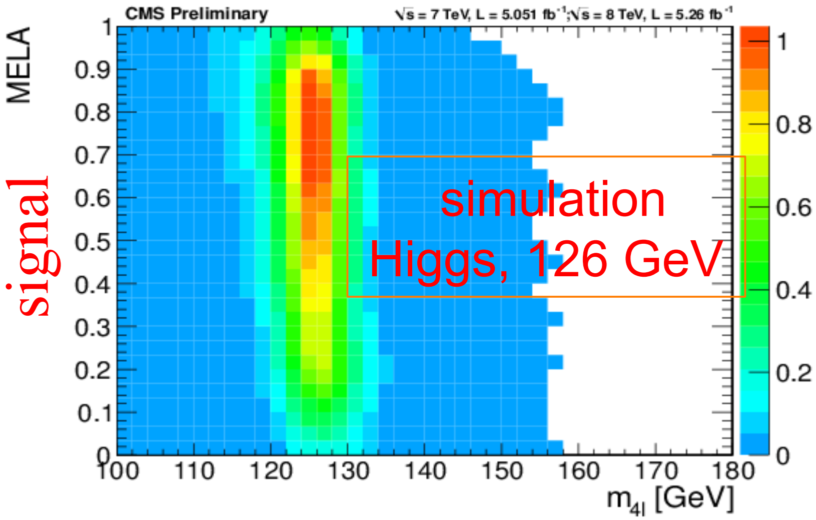


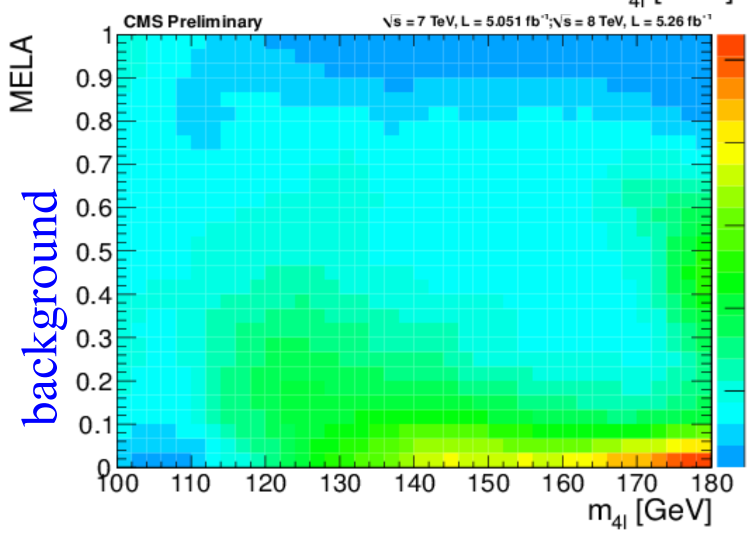
Some discriminating variables

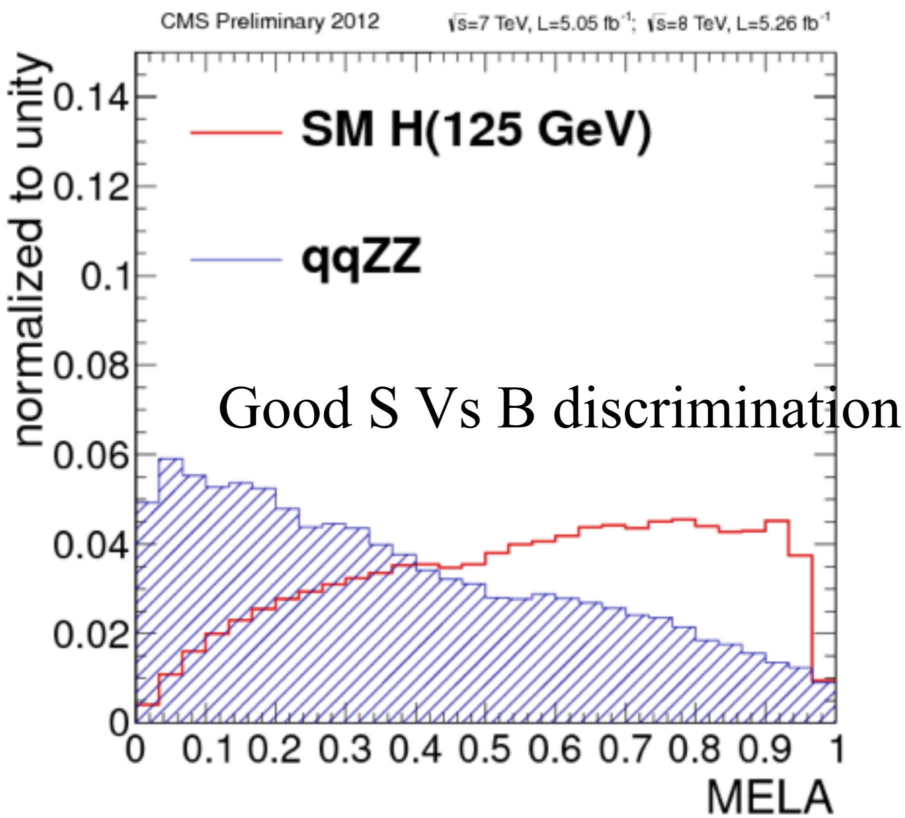


MELA Vs 4l Mass

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

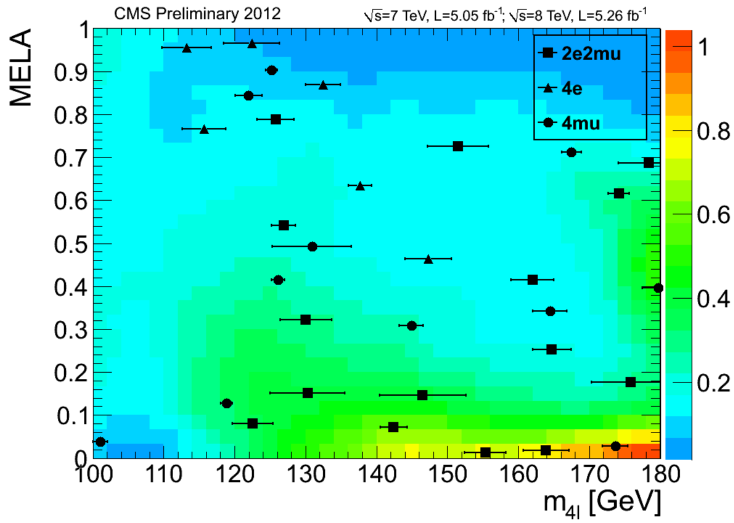




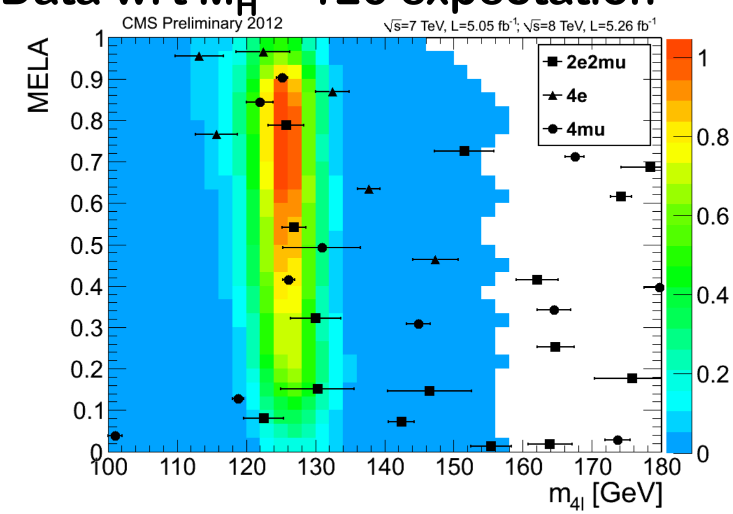


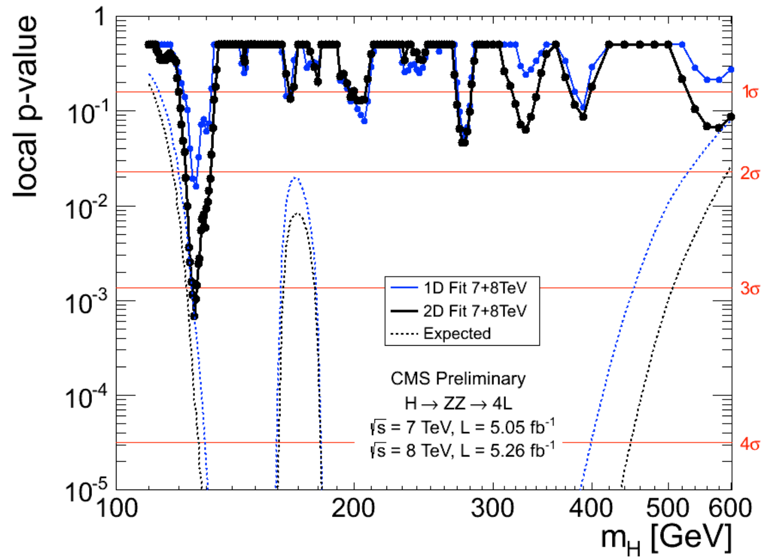
CMS : 2D Fit of MELA Vs 4l Mass

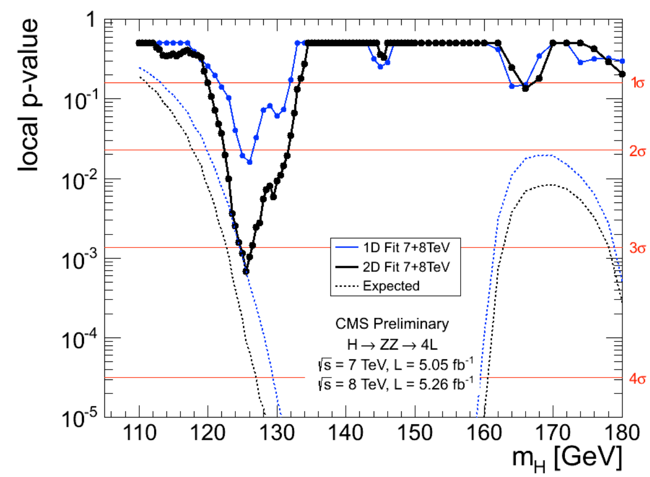
Data wrt background expectation



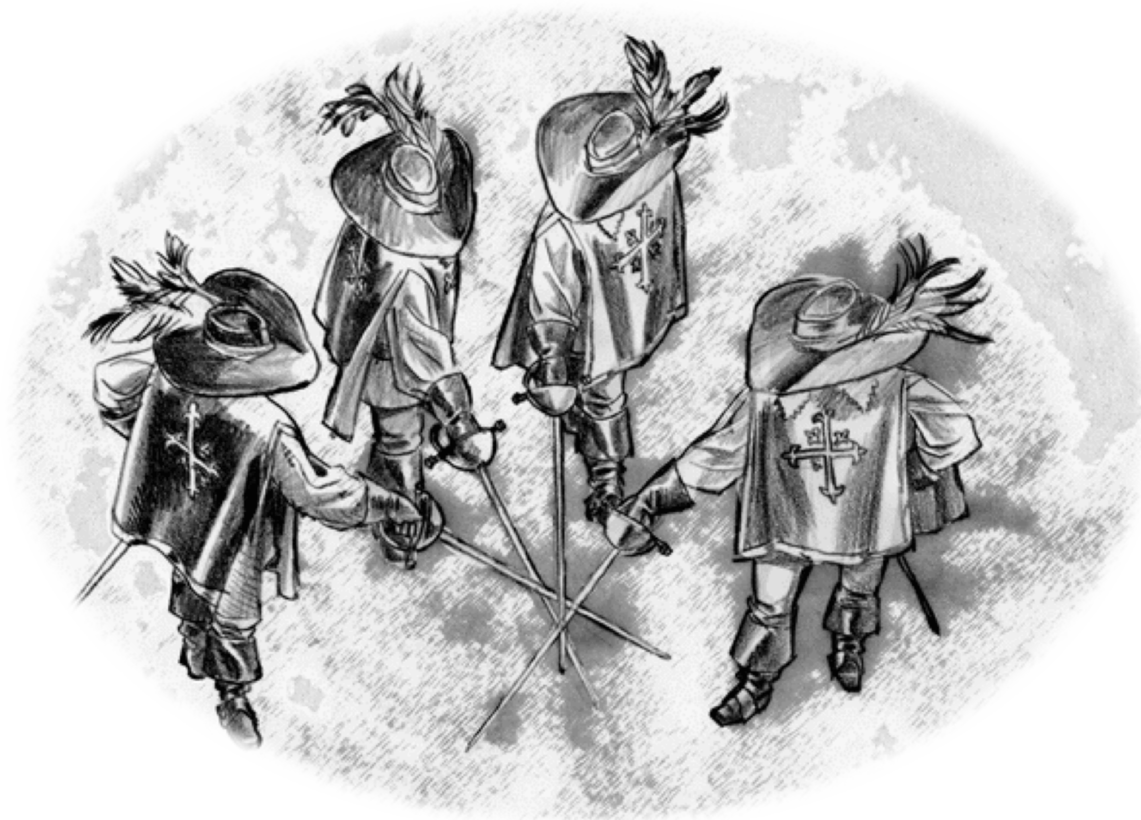
Data wrt M_H = 126 expectation





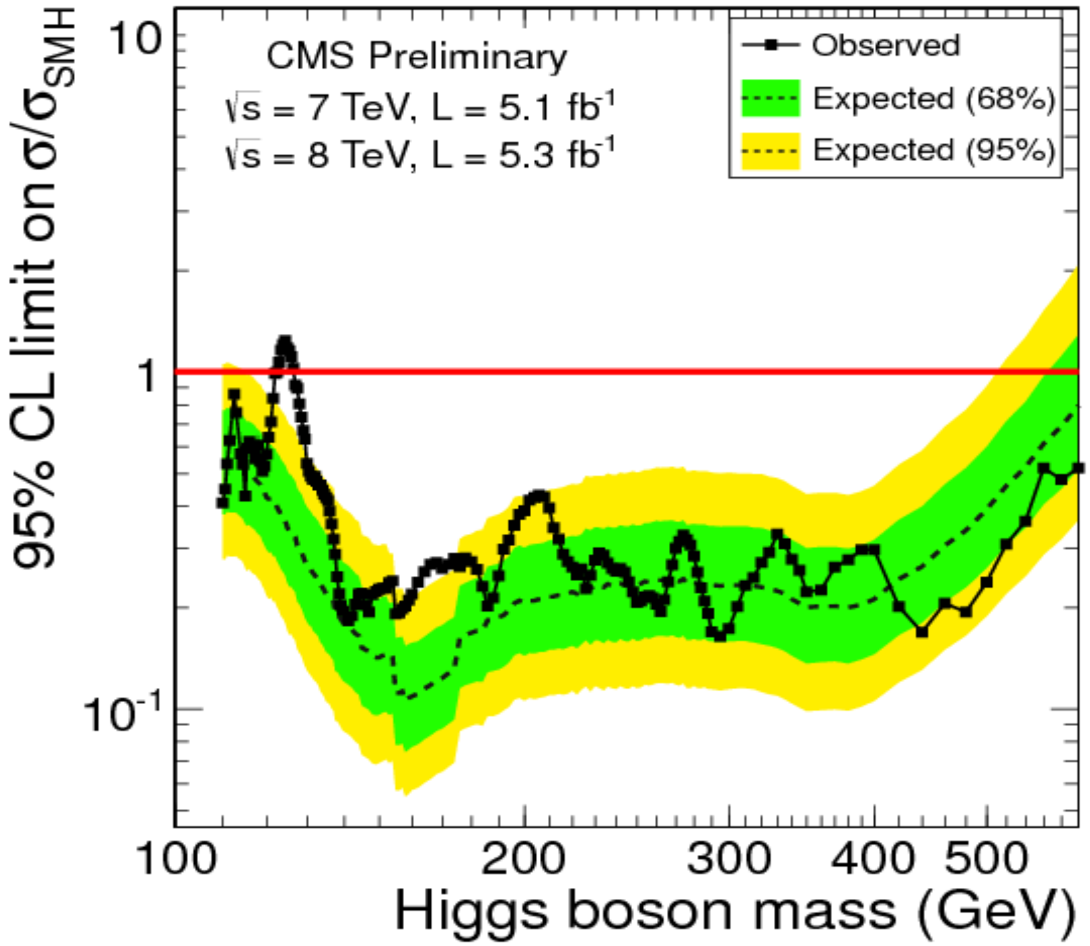


Expected local significance at 125.5 GeV: 3.8 σ
Observed local significance at 125.5 GeV: 3.2 σ



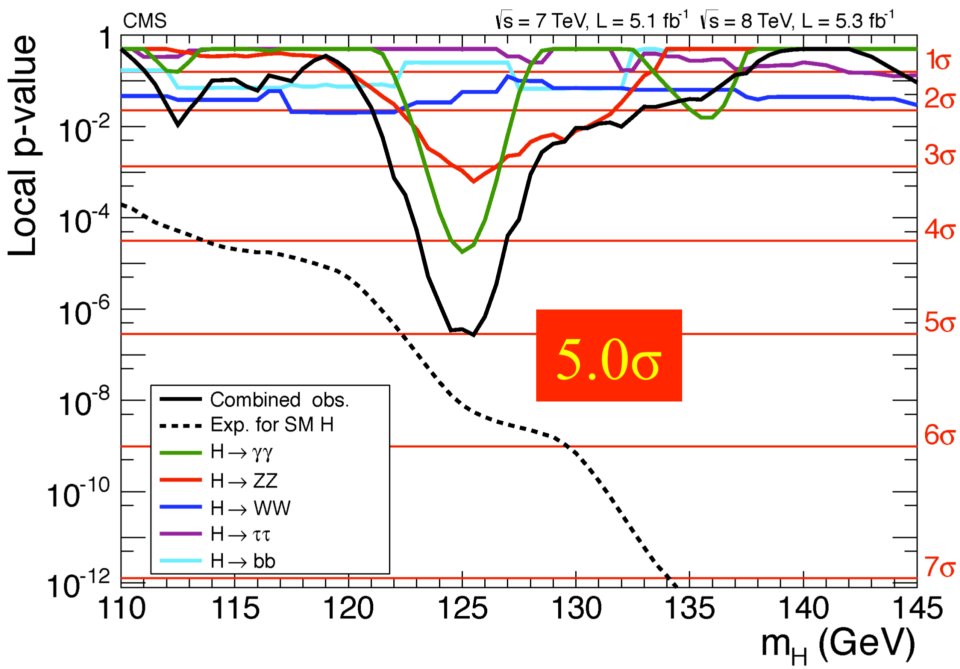
Combination Of SM Higgs Searches

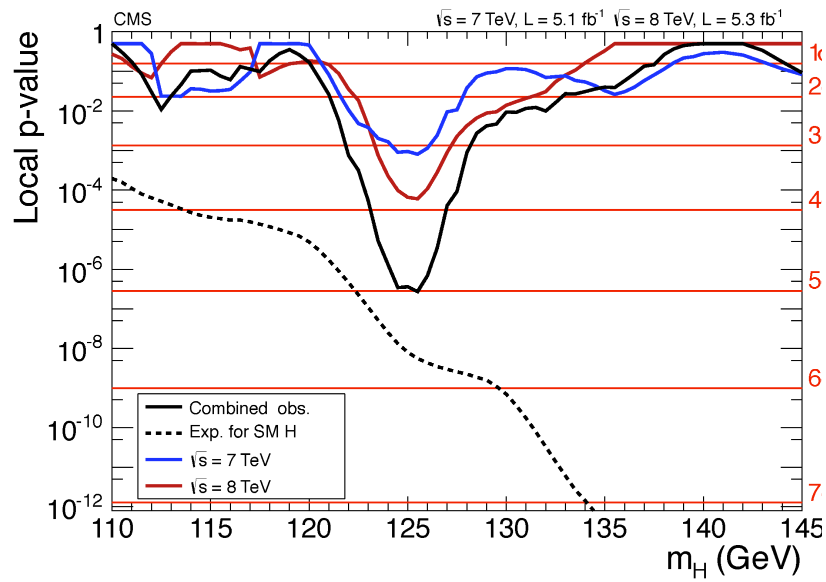
Exclusion Limits On The SM-like Higgs Boson



95% CL Exclusion: $110 < M_H < 122.5$, $127 < M_H < 600$ GeV

Observation Of A New Boson



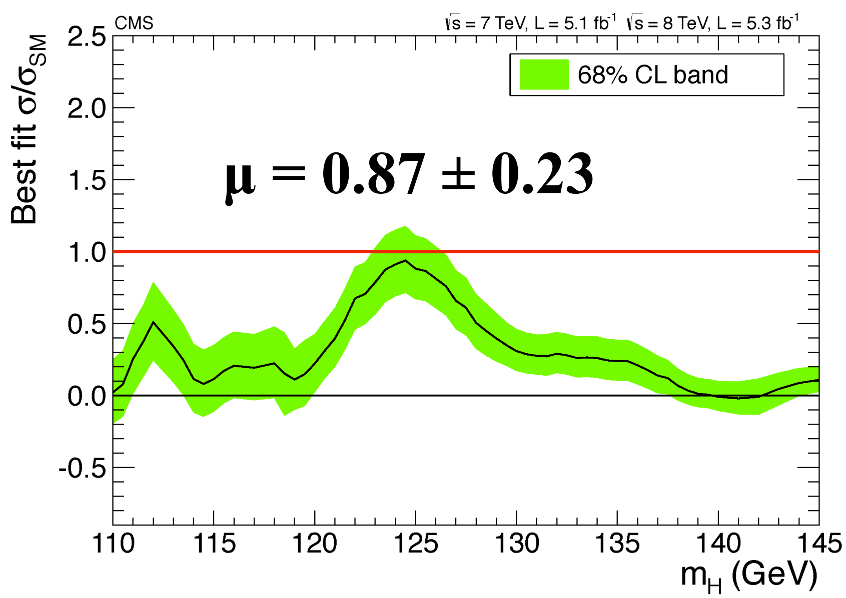


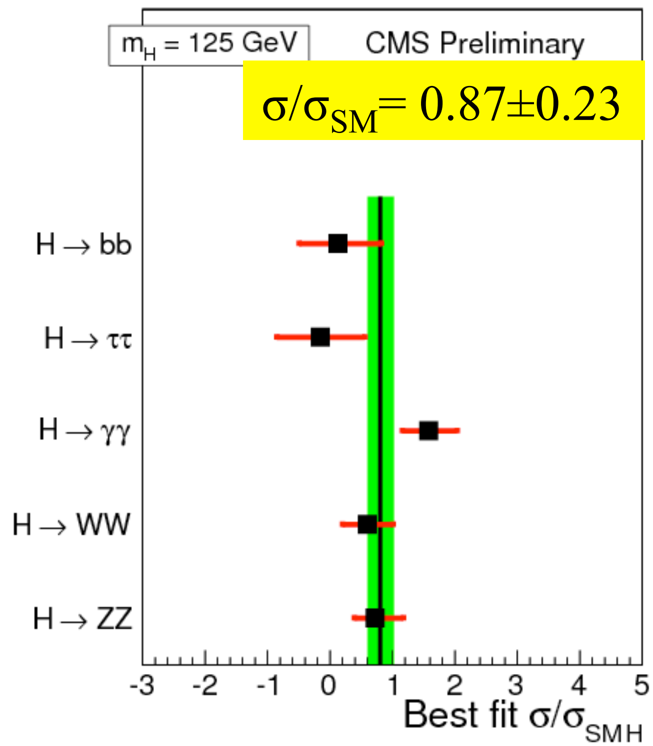
Decay mode or Combination	Expected (σ)	Observed (σ)
ZZ	3.8	3.2
$\gamma\gamma$	2.8	4.1
WW	2.5	1.6
bb	1.9	0.7
$\tau\tau$	1.4	–
$\gamma\gamma$ + ZZ	4.7	5.0
WW + $\tau\tau$ + bb	3.4	1.6
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

5.0σ at M_X = 125.3 GeV

Quantifying Observed Excess : Signal Strength μ

$\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$: Indicates by what factor SM Higgs cross section would have to be scaled to best match the observed data

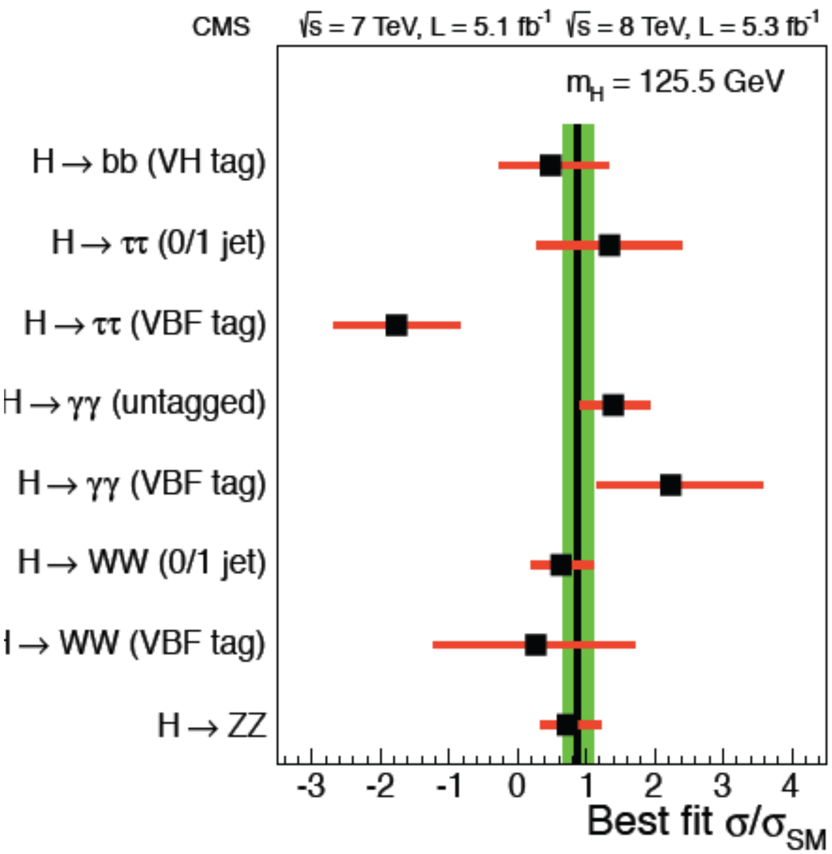


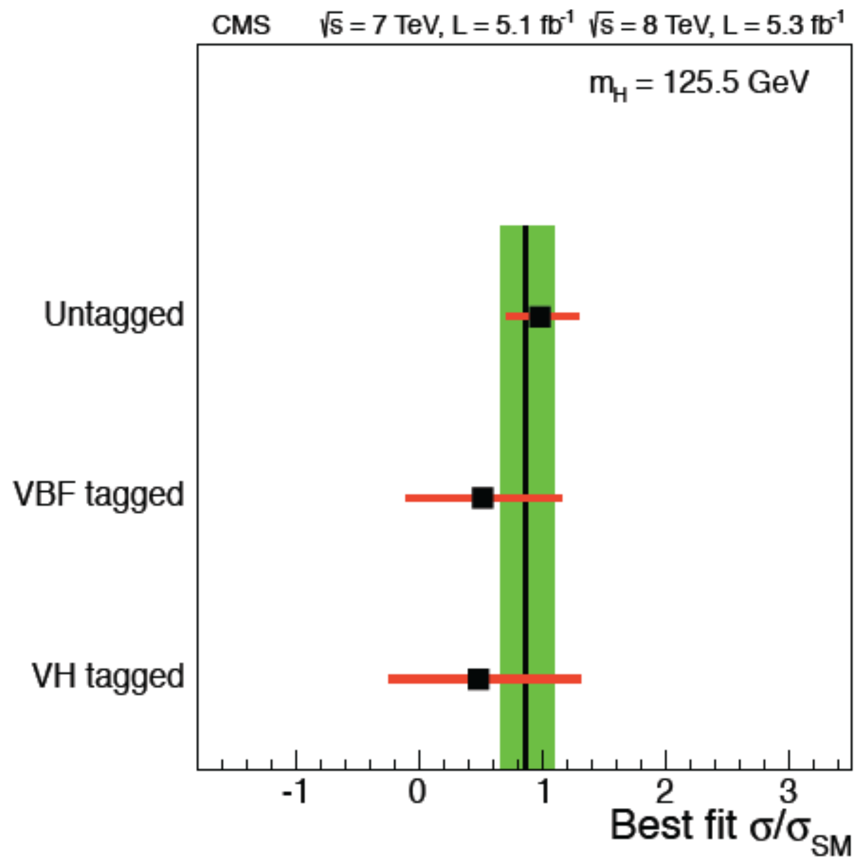


Observed rate consistent with SM Higgs expectations (μ = 1)

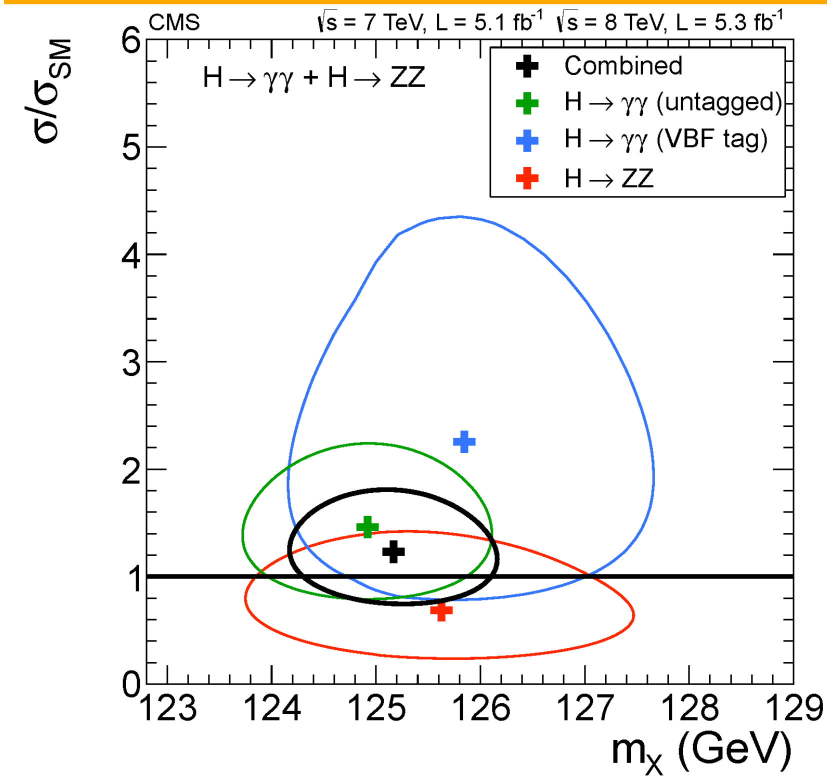
See a higher H→ $\gamma\gamma$ rate ($\mu_{\gamma\gamma}$= 1.6 ± 0.4)

Signal Strength By Sub Channel & Production Mode

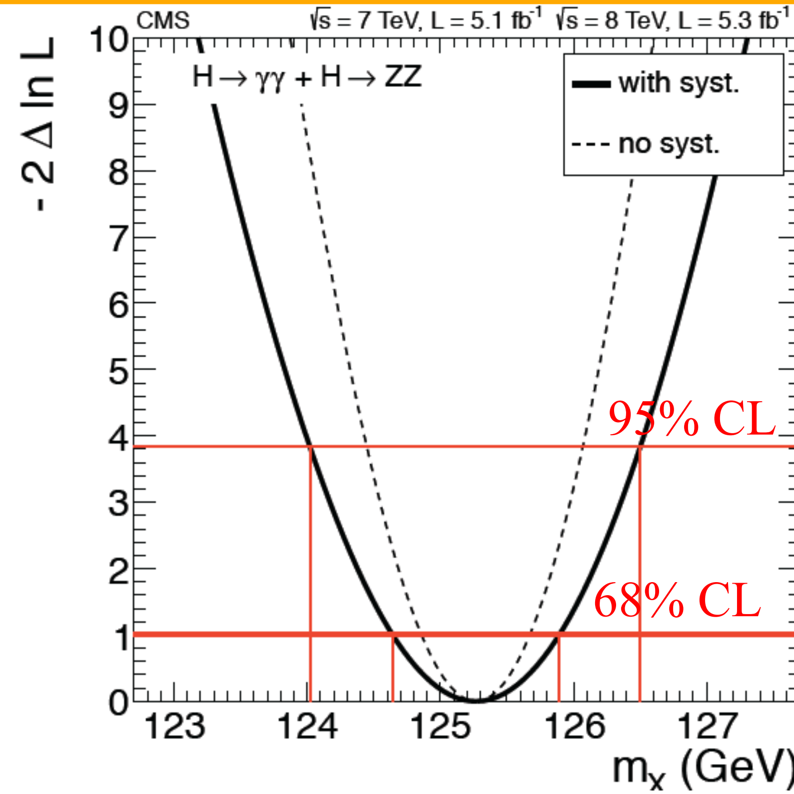




Mass Of The New Boson From High Precision Modes



68% CL contour after fixing relative signal strength to SM Higgs expectation (μ=1)



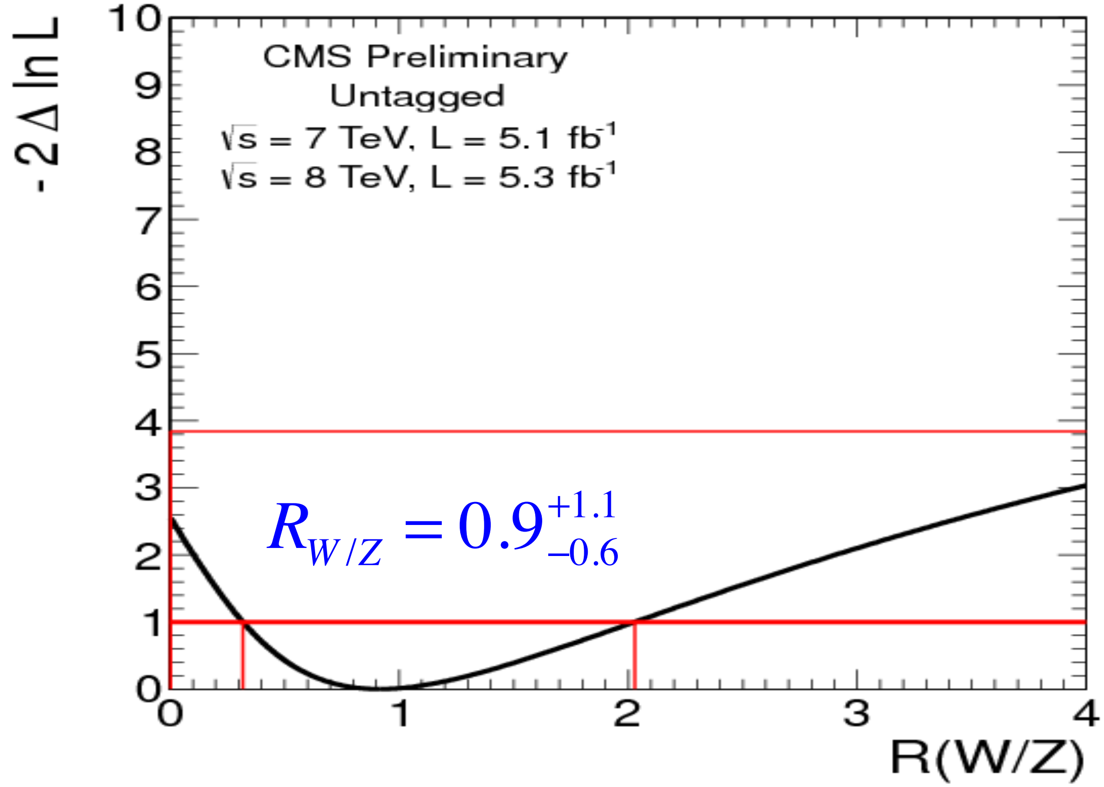
Model independent M_x scan with independent cross section but constraint of a unique mass

M_X= 125.3±0.4 (stat)±0.5 (syst), dominated by H → γγ

Dominant syst. uncertainty from extrapolation of energy scale from Z → ee to X(125) → γγ & control over energy resolution

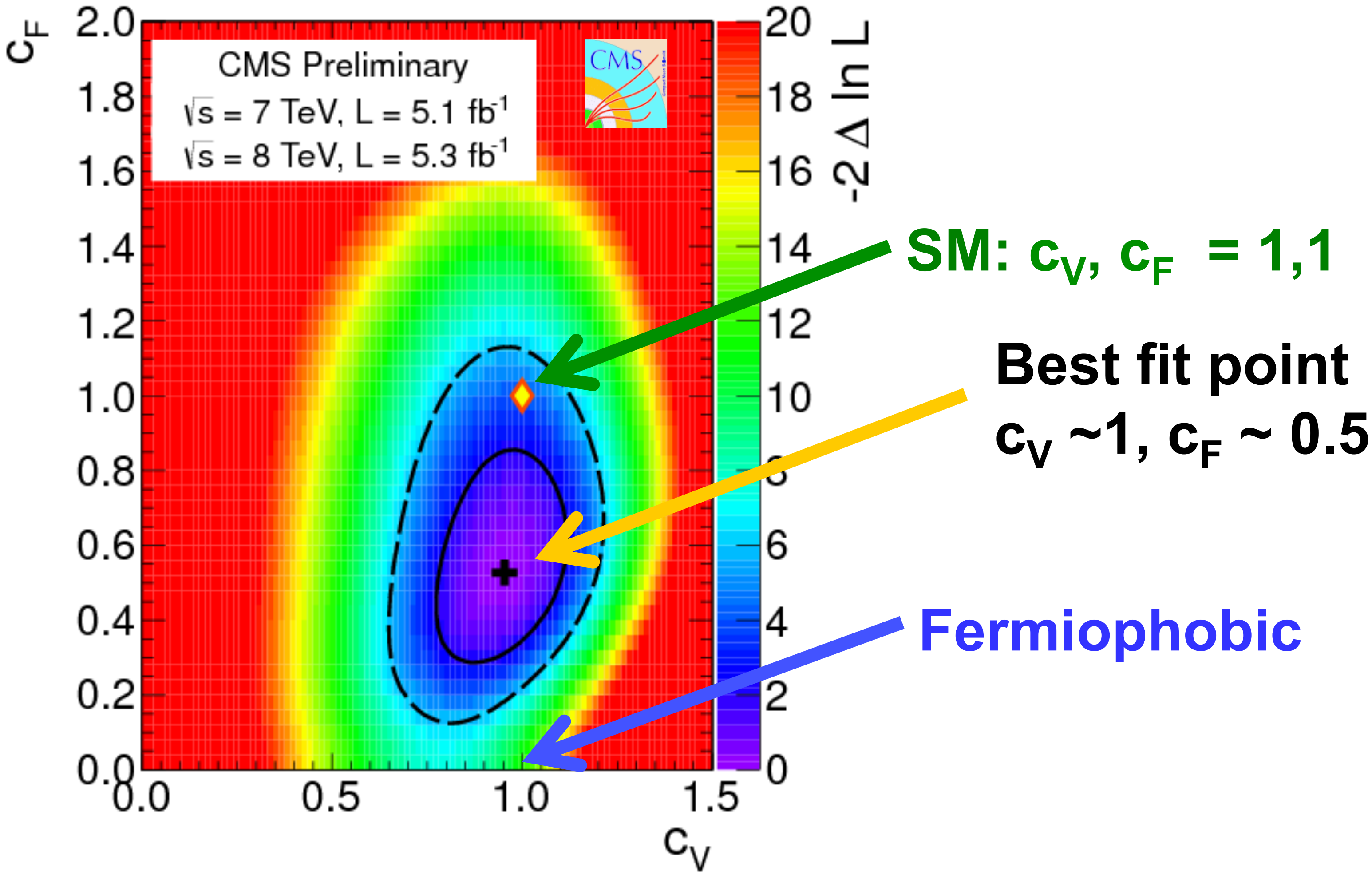
Test Of Custodial Symmetry

- Use inclusive H → ZZ sample & H → WW with 0,1 jets
- dominated by gg → H
  - small contamination from VH, VBF (mostly in H → ZZ)
- Scan ratio of event yields for $R_{W/Z}$



Test Of Coupling To Vector Bosons & Fermions

Rescale universally the Higgs boson couplings to fermion by $\mathbf{C_F}$ and couplings to vector boson by $\mathbf{C_V}$, compare with observed yields



Next Steps

- Establishing the properties of the new particle is just the first part of a long journey : **sprint is over, marathon has begun**
- LHC continues its excellent performance, CMS hopes to accumulate $\approx 25\ fb^{-1}$ by end of 2012
  - ➔ total $\approx 30\ fb^{-1}$ data
- Continue to investigate the observed resonance in a variety of channels
  - – Precise measurement of the boson mass
  - – Measure its coupling to Vector bosons and fermions
  - – Measure angular distribution in WW/ZZ modes to determine the spin and parity of the observed boson
- Exciting times ahead !