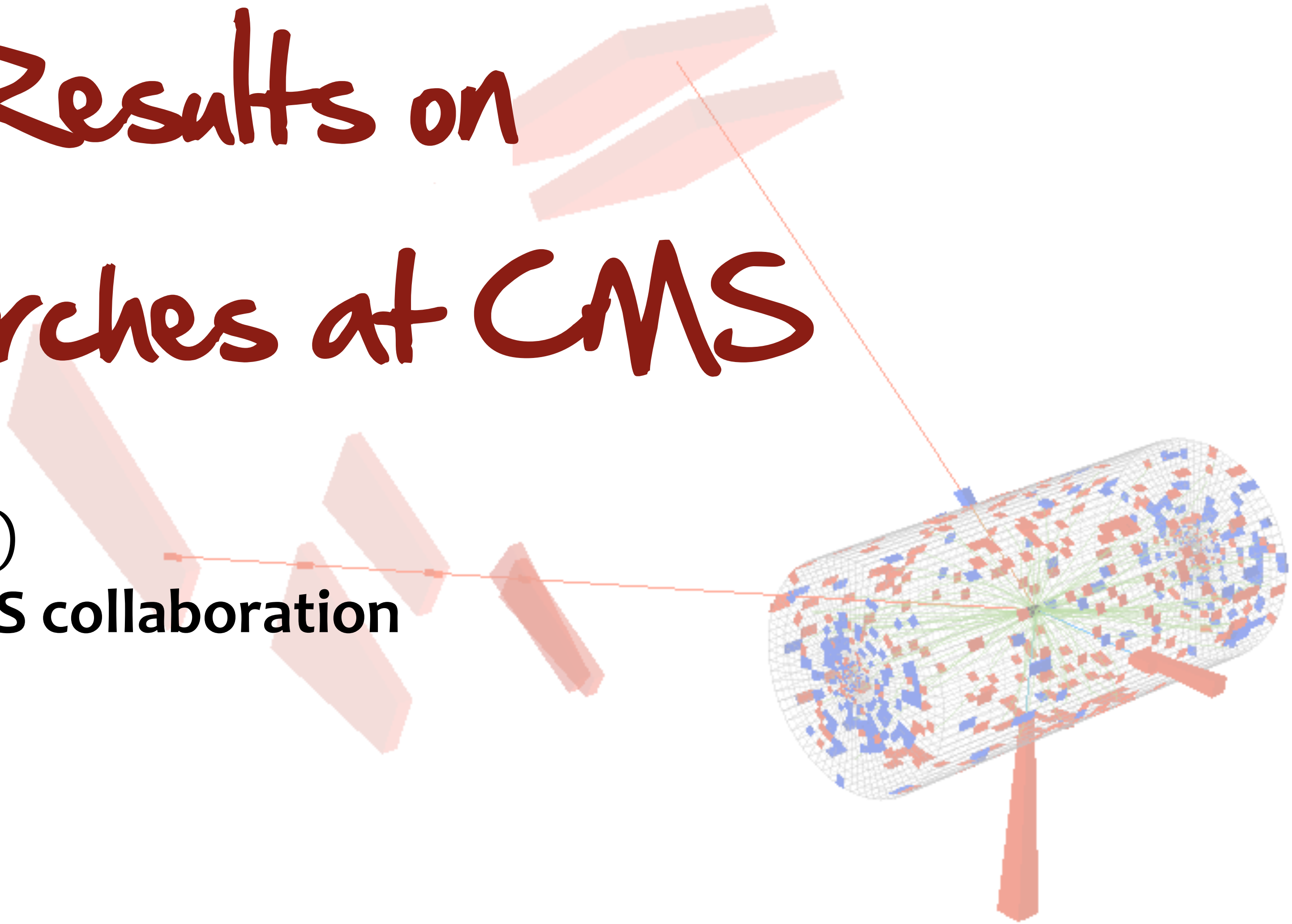
Updated Results on Higgs searches at CMS



Cristina Botta (CERN)
on behalf of the **CMS collaboration**

Understanding the TeV Scale Through LHC Data, Dark Matter, and Other Experiments- Workshop

The Galileo Galilei Institute for Theoretical Physics (GGI), Firenze

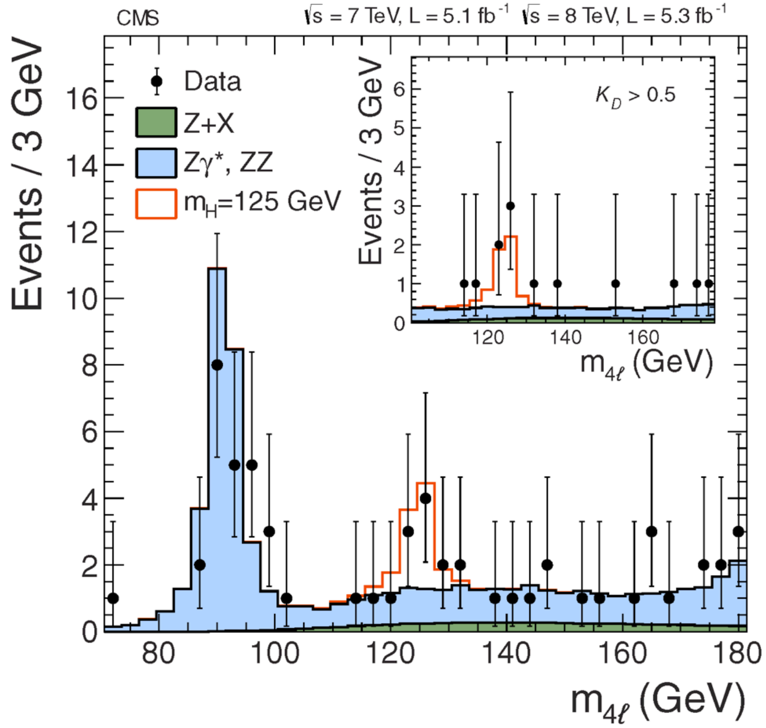
Outline

- The 2011-2012 CMS' Path to the "Higgs"
- The Search
  - The "big five" : $H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to bb$, $H\to\tau\tau$
  - Updated combined results
- The Measurements
  - Mass, Compatibilities with the SM, Spin&Parity

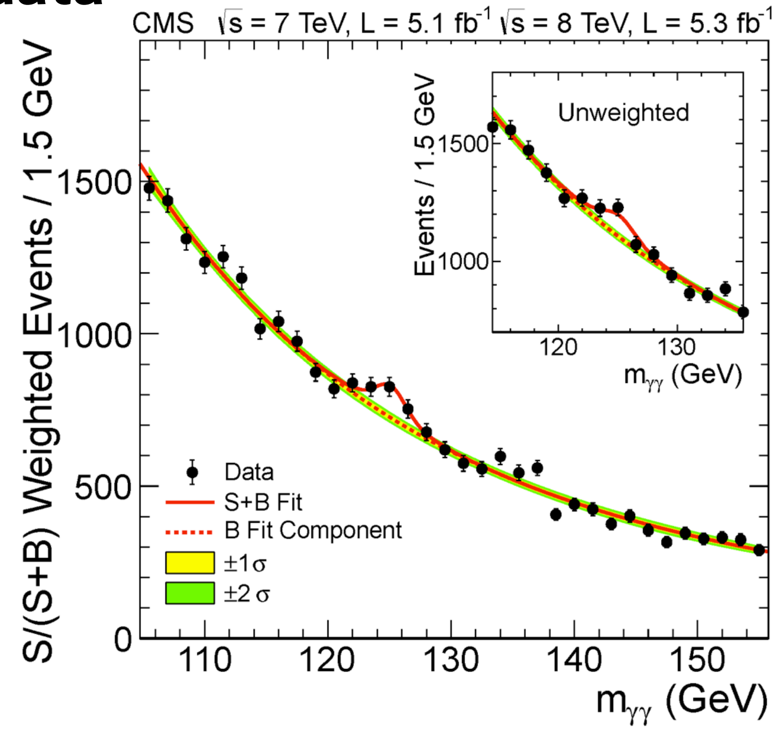
Where CMS stood at ICHEP

5.1 fb^{-1} 7TeV data +
5.3 fb^{-1} 8TeV data

H->ZZ->4l



H->γγ



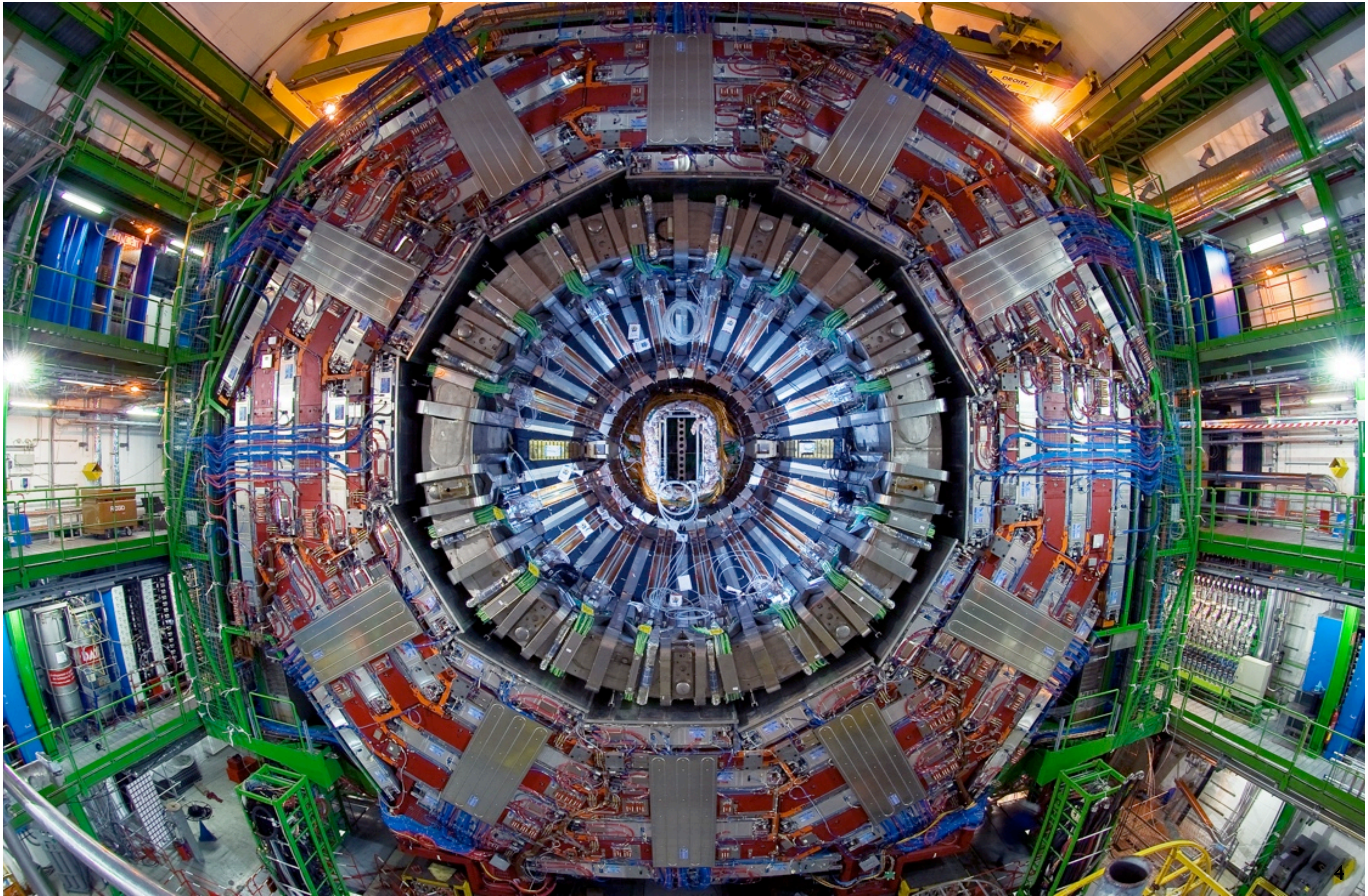
Observation of a new boson

Local significance of excess: 5.0 σ

[expected for a SM Higgs signal 6.0 σ]

M_X = 125.3 ± 0.4(stat) ± 0.5 (syst.)

The CMS Detector



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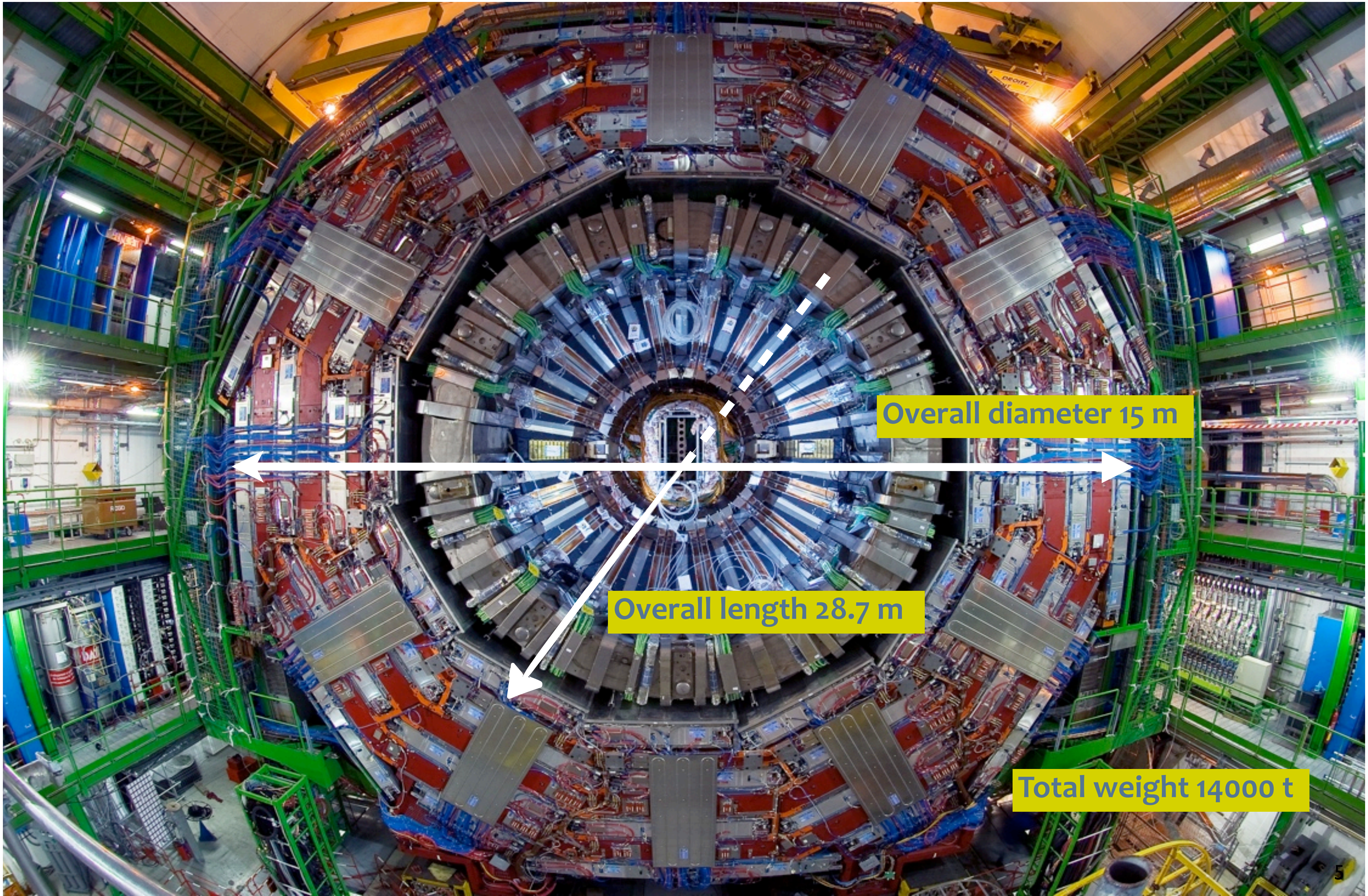

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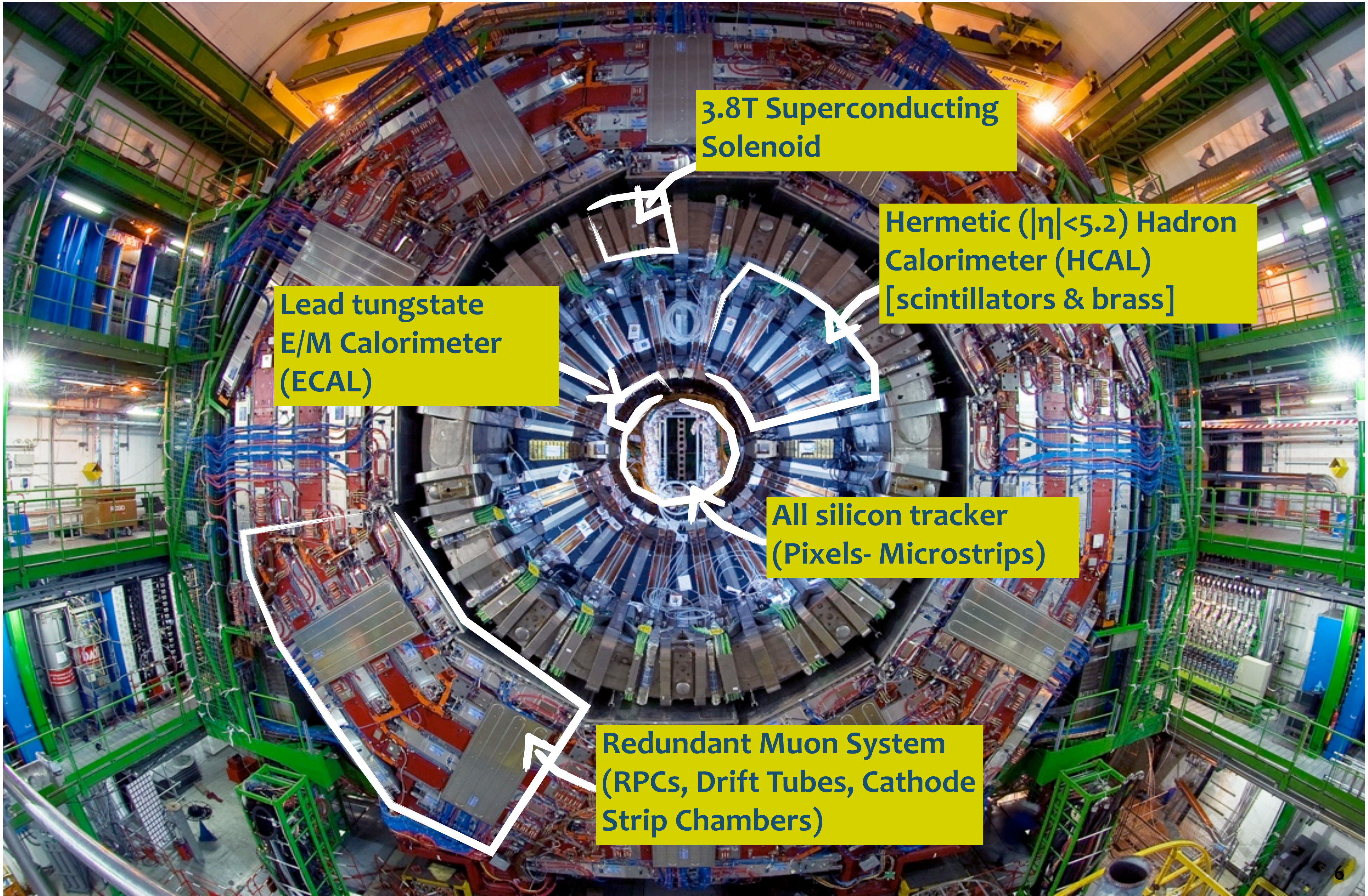
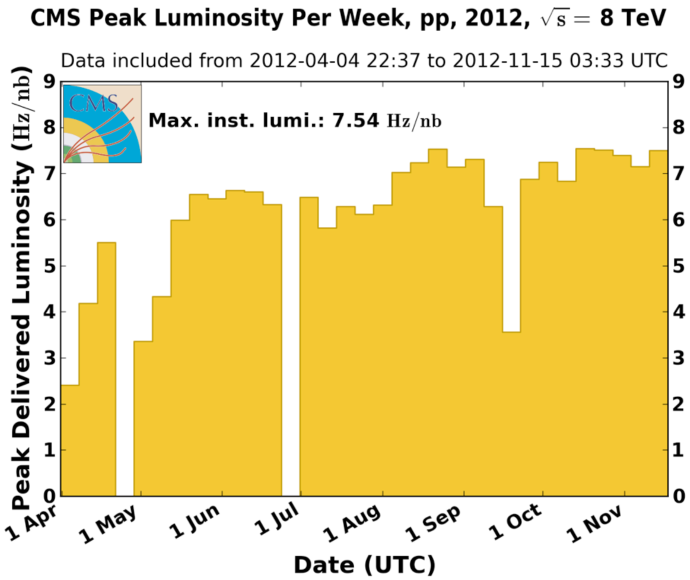
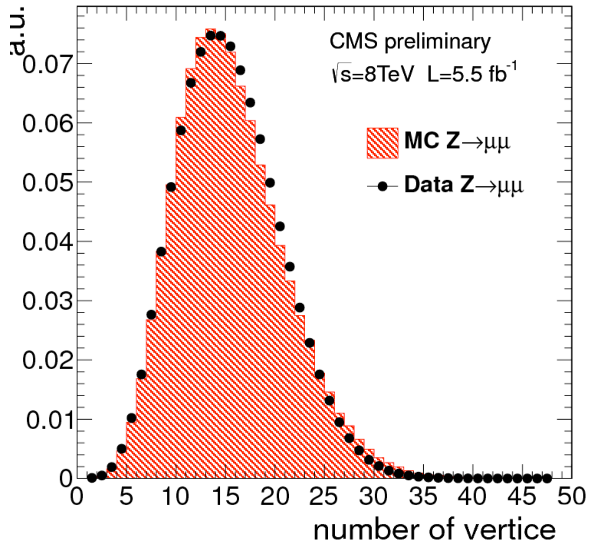


The Luminosity challenge

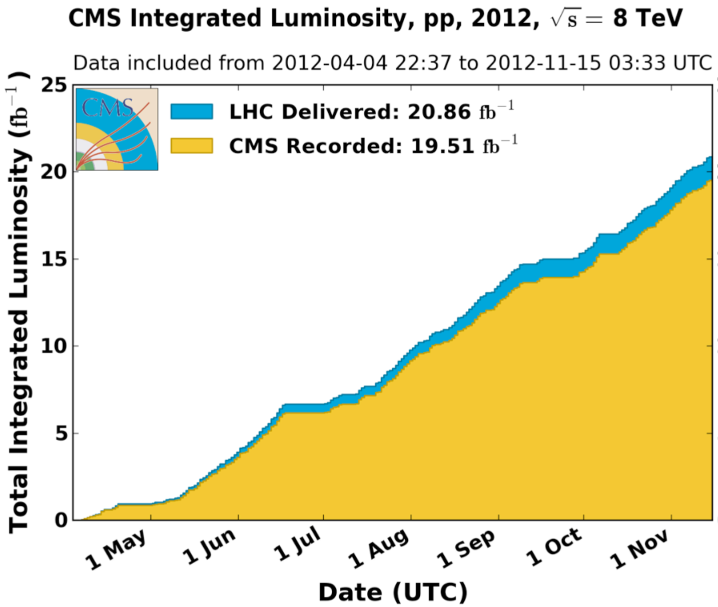
Instantaneous luminosity up to **~7·10³³**

20-30 pile-up interactions per bunch crossing





CMS Recorded luminosity as of today (8TeV): **20 fb-1**

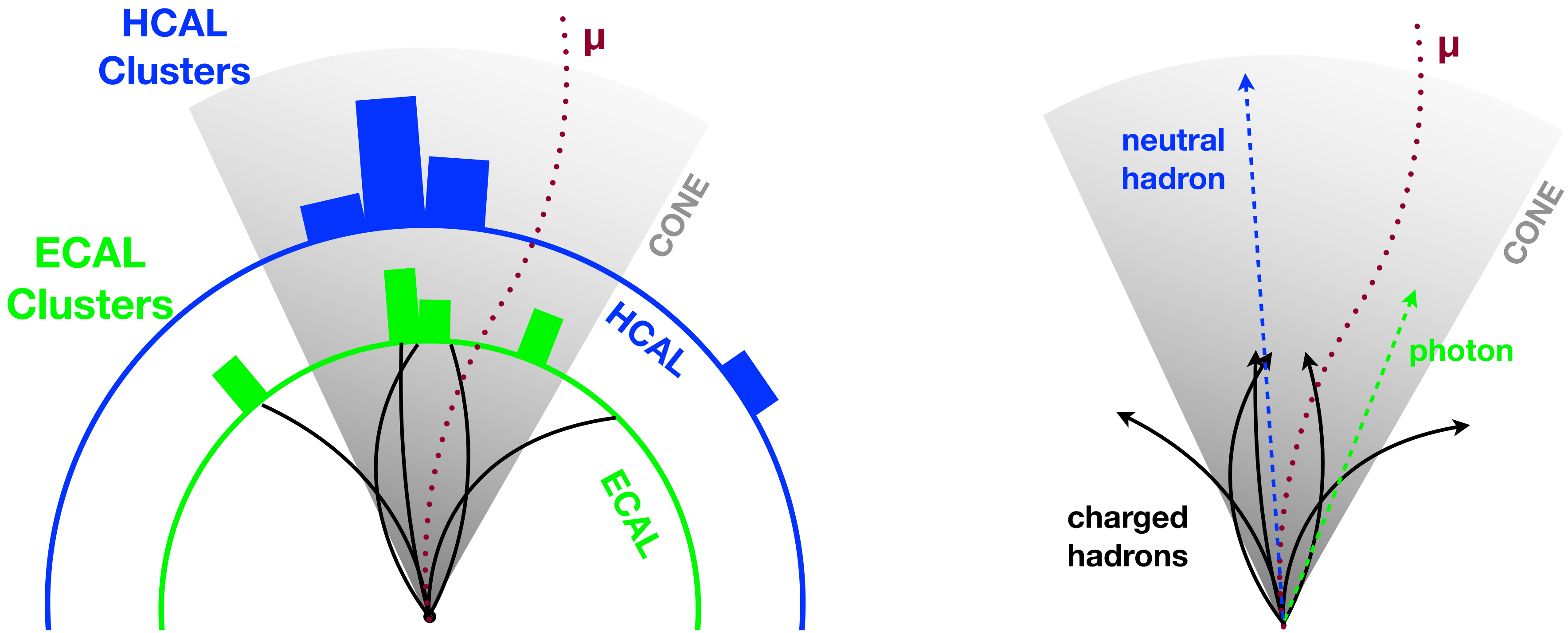


Data analyzed up to now:

5 fb-1 @ 7 TeV

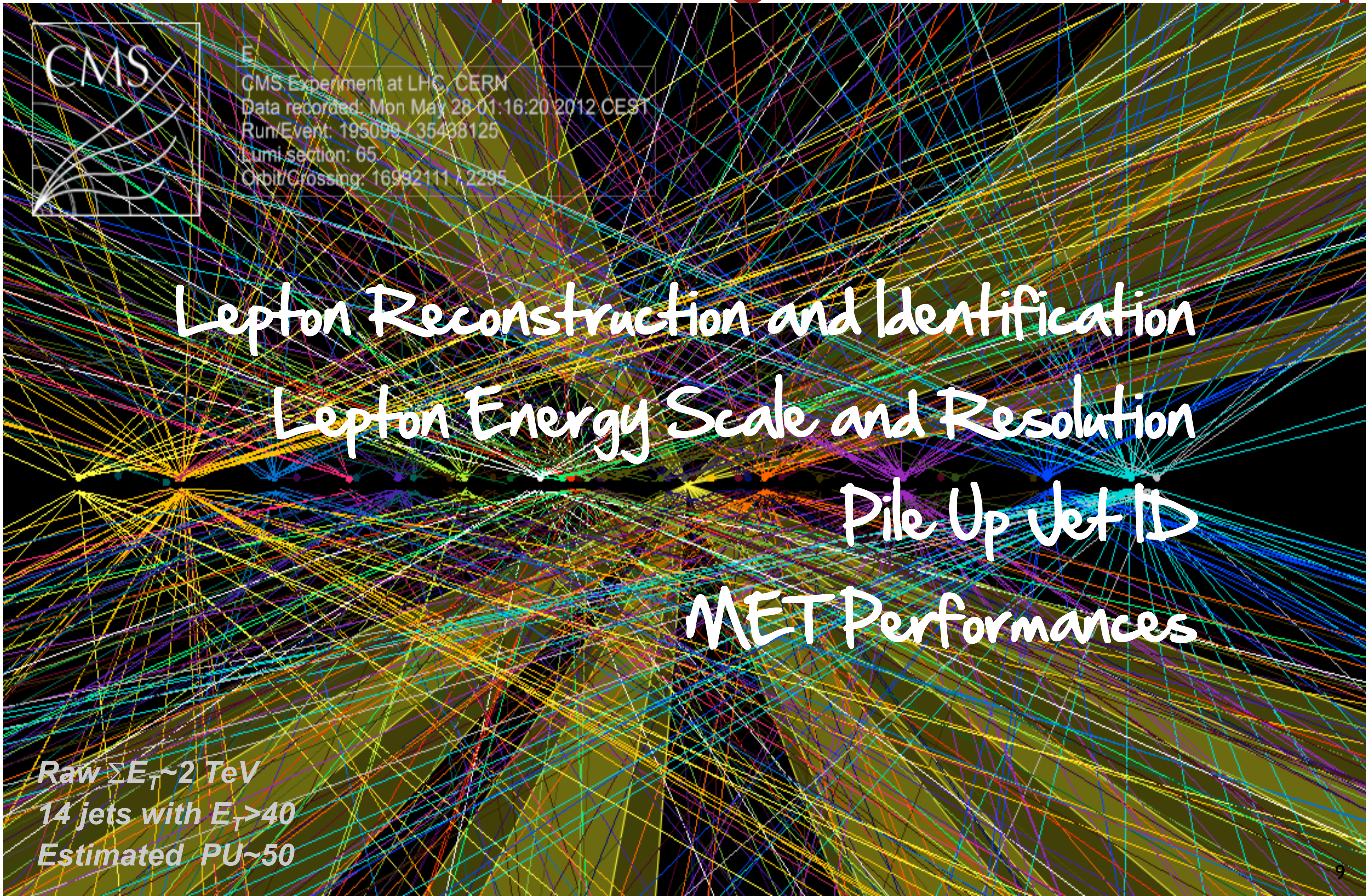
12 fb-1 @ 8 TeV

The CMS Global Event Description



- Rely on high granularity of CMS detector to identify and reconstruct each individual particle in the event: classified into mutually exclusive categories (charged hadrons, neutral hadrons, photons, muons, electrons)
- Allows tagging of charged particles from pile-up: minimize impact of PU on jet reconstruction, and lepton or photon isolation.

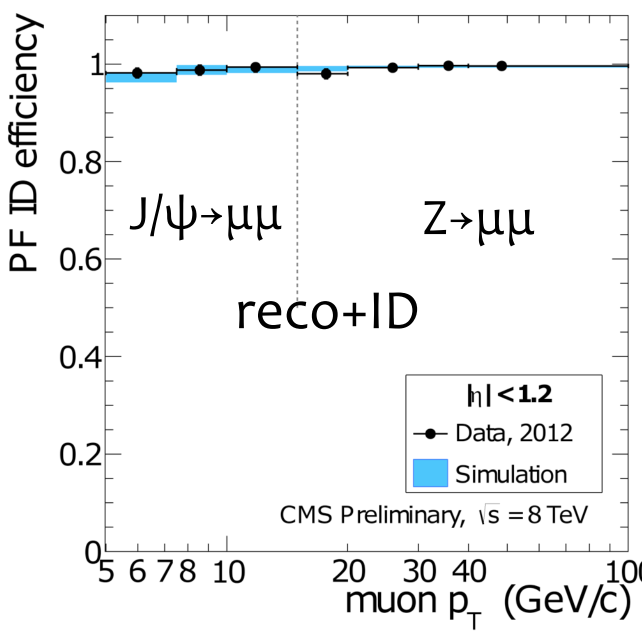
Objects: Grand Summary

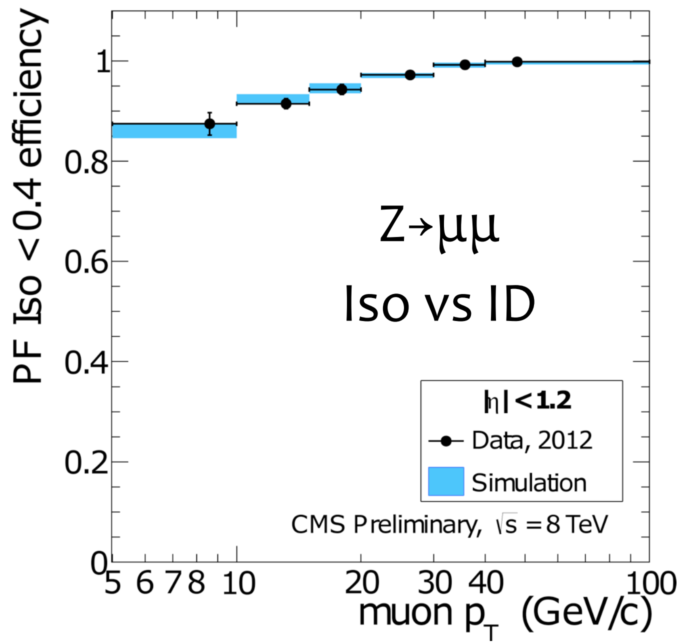


Leptons Identification

Efficiency to select prompt isolated leptons

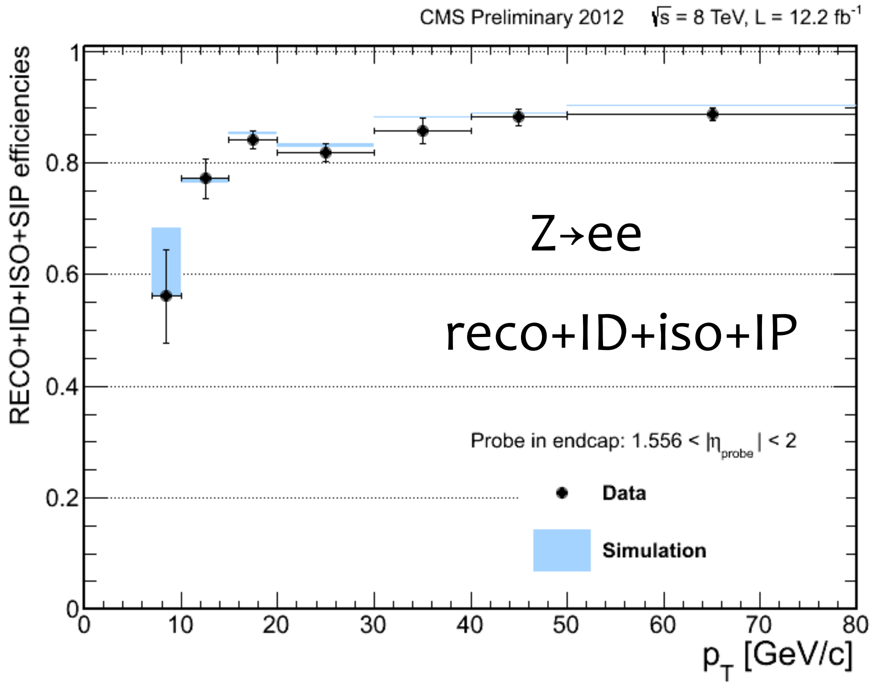
- reconstruction
- identification
- isolation
- IP requirement





Muons

computed with TnP techniques



Electrons

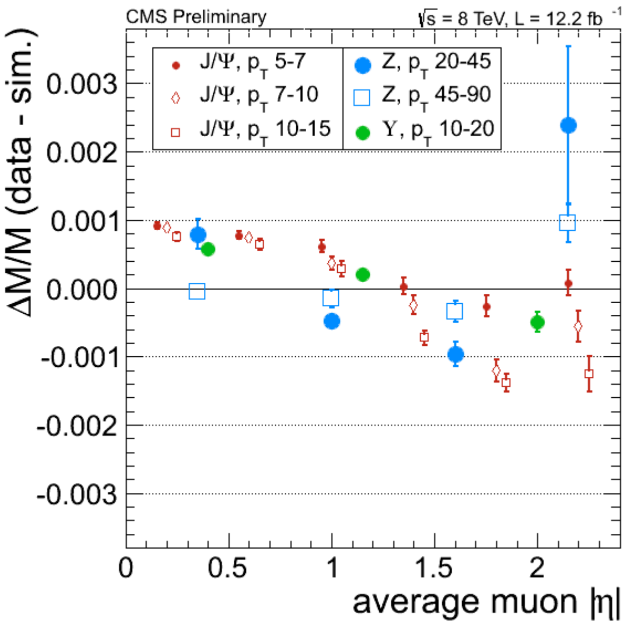
efficiency correction factor

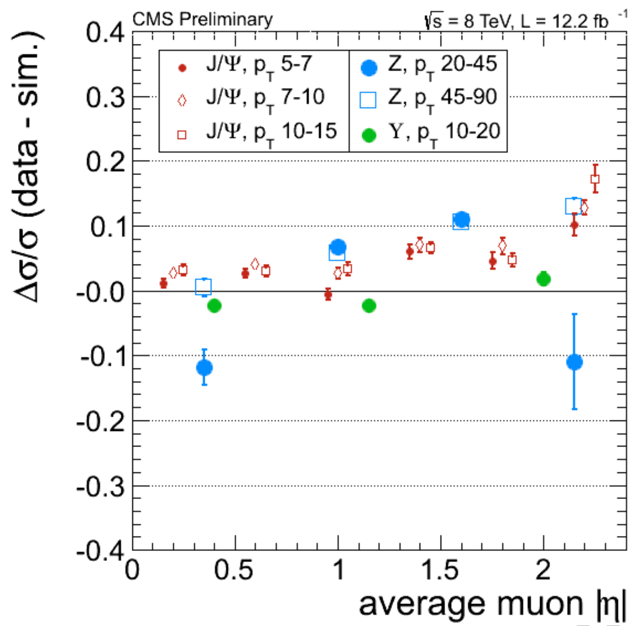
muons: 0.98 - 1.03

electrons: 0.84 - 1.01

Lepton Energy Scale and Resolution

Scale corrections on muon momentum obtained with a calibration procedure on Z->mm / J/psi -> mm events in data are applied MC is **smeared** to match the resolution in data NEW!





residual DATA/MC difference: ~ 0.1% in scale, 20% in resolution

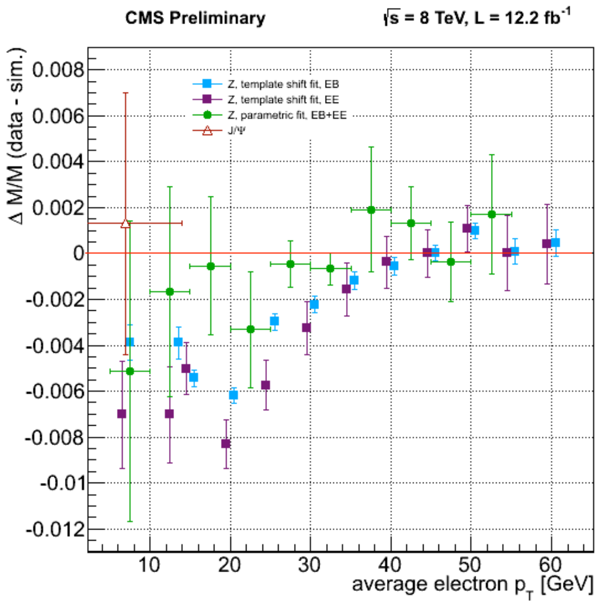
Muons

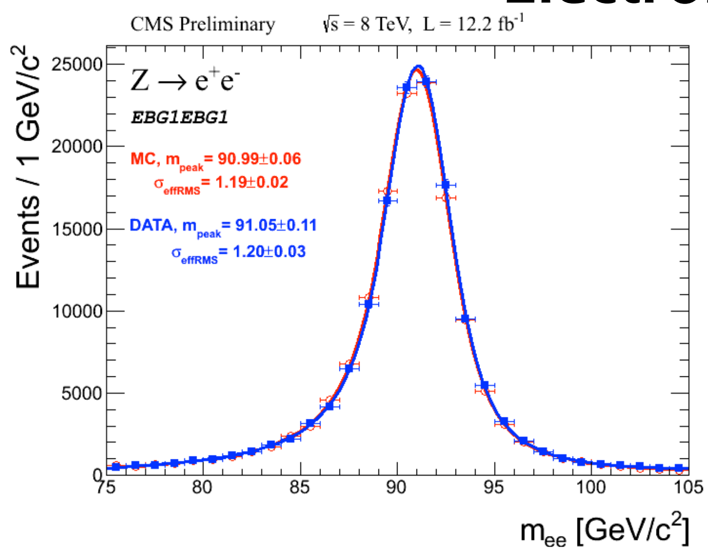
Electrons

The ECAL contribution to the electron momentum and its uncert is from an MVA regression approach: NEW!

- **10-15% improvements on resolution**

Energy scale and MC smearing obtained from calibration with Z->ee events are then applied



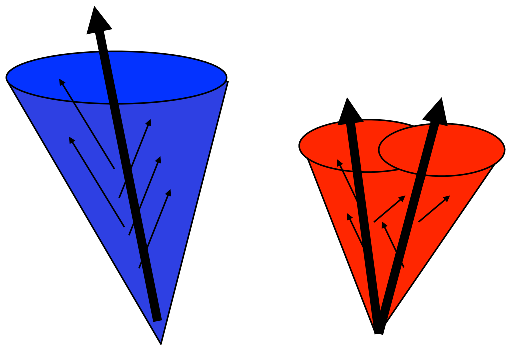


residual DATA/MC difference: ~ 0.4% in scale, 20% in resolution [conservative]

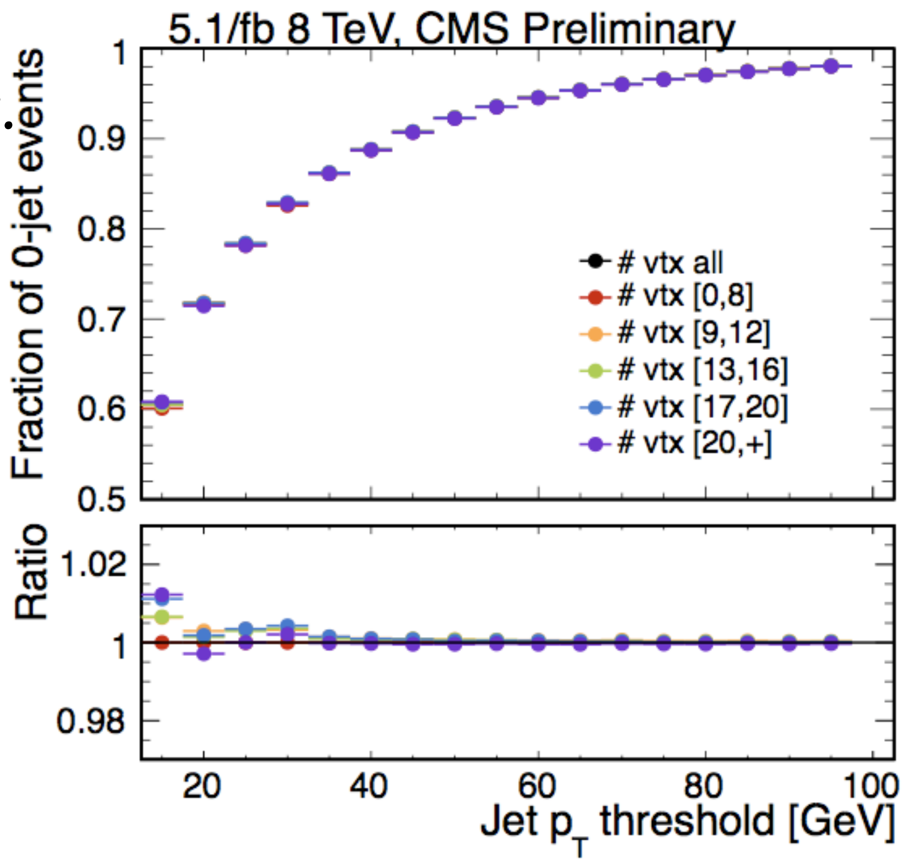
PileUP Jet tagging

PF reconstruction allows to **reject charged particles from PU** in jet building.

Additional: rejection of jets from PU also outside the tracker coverage, relying on jet shape variables.



Important in **VBF searches.**



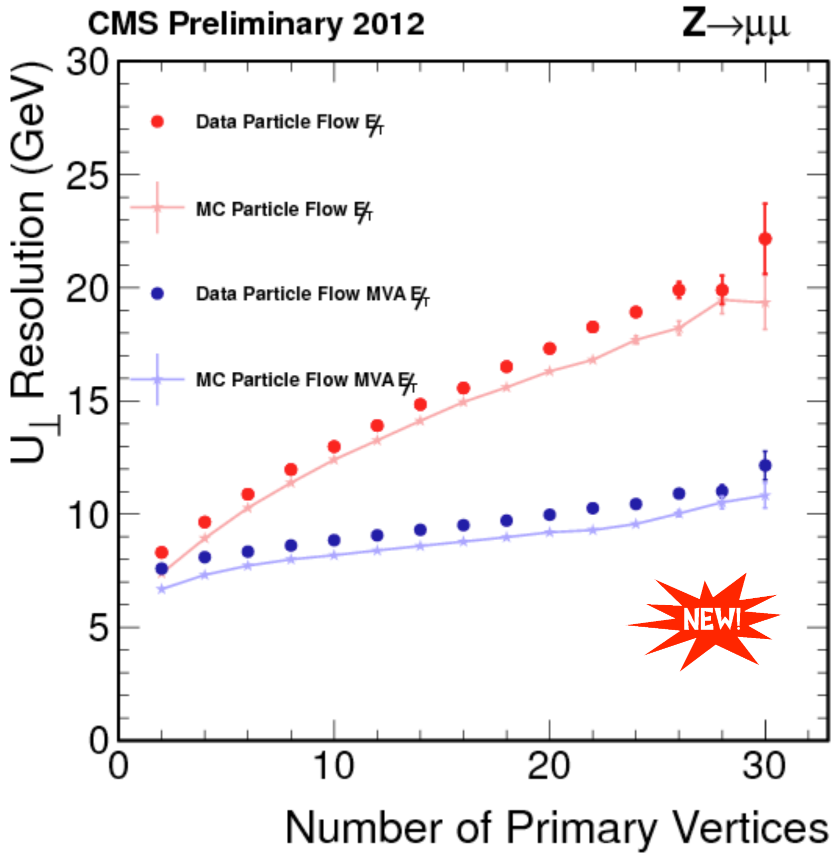
Validation on data:

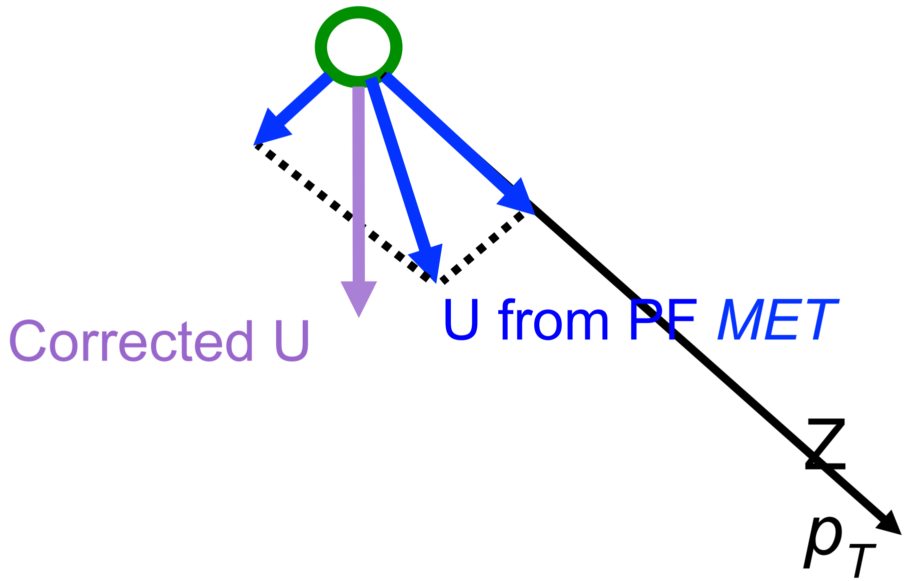
jet counting in

$Z \rightarrow \mu\mu$ events vs vertex multeplicity.

Stable to <1% for jet p_T > 20 GeV

MET Performances





- Instead of using PF MET (from all PF candidates) different flavour of MET variables (TK MET, NoPU MET, PU MET, PU corrected MET - in each one some component of the response of the event are removed) are included in a multivariate regression which is trained to measure a correction to the PF MET recoil
- MVA MET in output: better resolution

The Search

The Channels:

- High Resolution channels
  - $H \to \gamma\gamma$ [ICHEP results]
  - $H \to ZZ$ [minor changes in the analysis + LUMI UPDATE]
- Low Resolution channels
  - $H \to bb$ [analysis improved + LUMI UPDATE]
  - $H \to \tau\tau$ [analysis improved + LUMI UPDATE]
  - $H \to WW$ [analysis improved + LUMI UPDATE]

SM Higgs boson with M=125GeV an excellent mass for us

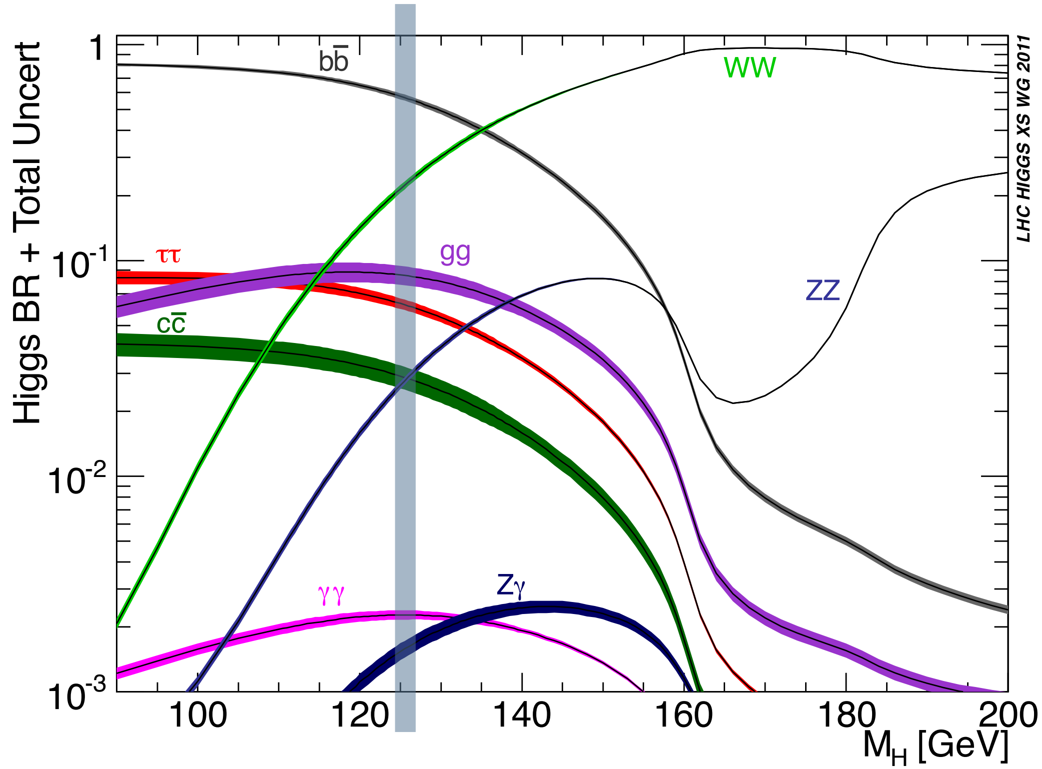
5 decay modes exploited:

γγ, bb, ττ, WW, ZZ
(High Mass: WW, ZZ)

bb, ττ favoured by BR but challenging channels in huge background environment (bb only from **WH,ZH,ttH**)

γγ, ZZ->4l provide very good mass resolution (1-2%)
- ZZ->4l no bkg but very low rate
- γγ low S/B

WW no good mass resolution but good S/B also in the low mass region with the leptonic final state



h125

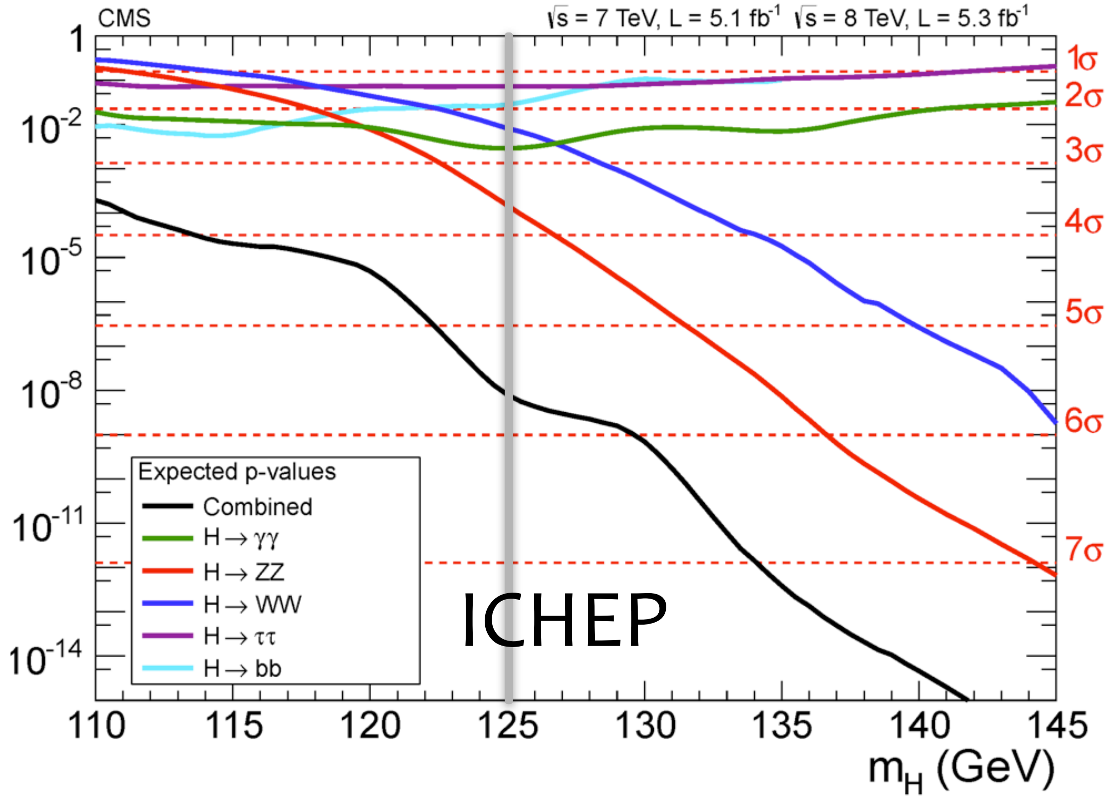
@8TeV >20K of h_{125} / fb

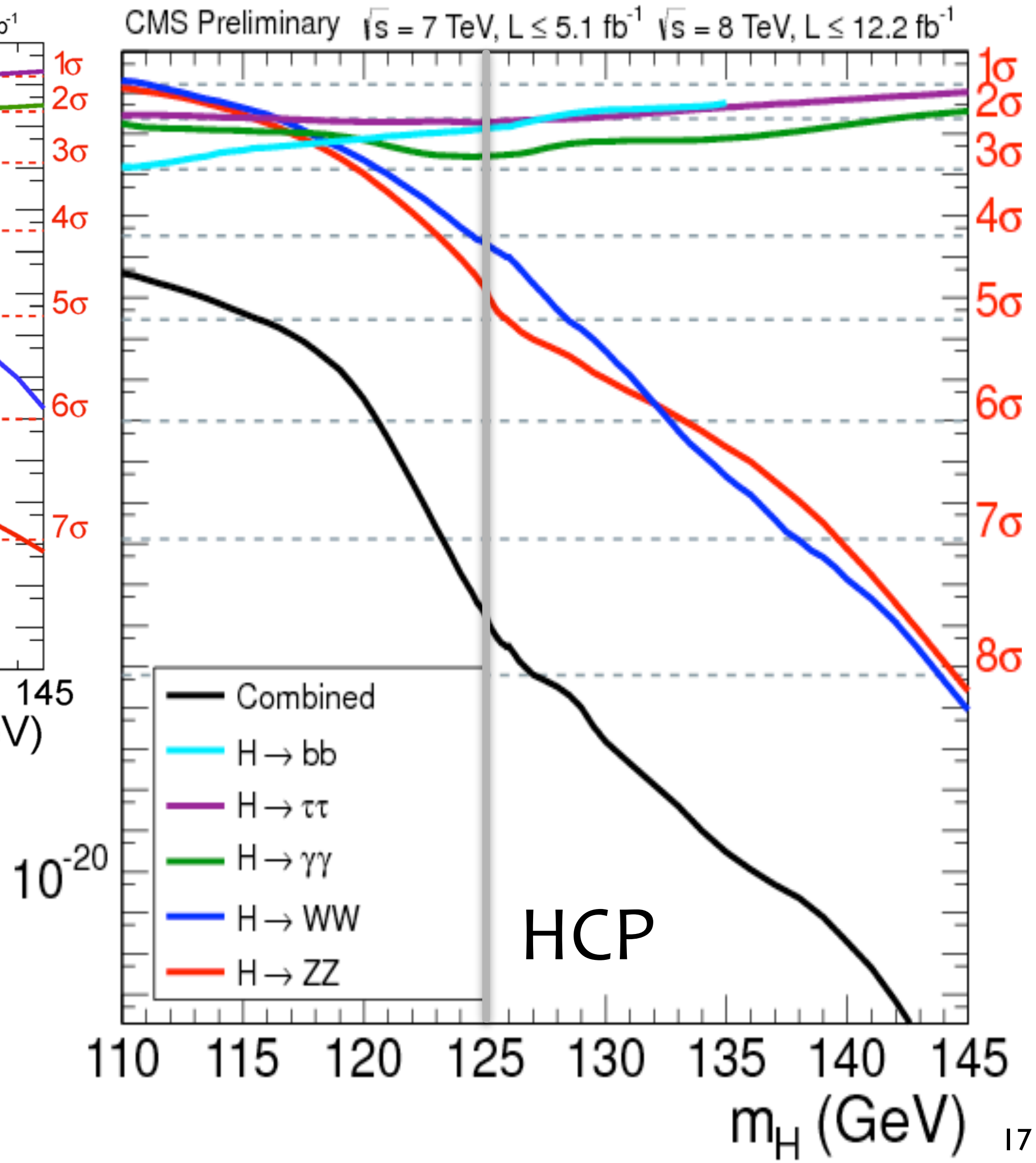
The Big Five: details

H decay	H prod	Exclusive Final States	No. of chan	m_H range [GeV]	m_H resolution	Lumi (fb^{-1}) [7/8 TeV]
H→γγ	untagged	γγ(4 diphoton classes)	4	110-150	1-2%	5.1 - 5.3
	VBF-tag	γγ + $(jj)_{VBF}$(low or high m_{jj} for 8TeV)	1 or 2	110-150	1-2%	5.1 - 5.3
H→bb	VH-tag	(υυ, ee, μμ, eυ, with 2-bjets) ⊗ (low or high p_T^V or low b-tag)	10 or 13	110-135	10%	5.0 - 12.1
	tt-H tag	(l with 4,5, ≥ 6 jets) ⊗ (3, ≥4 b-tags) (l with 6 jets with 2 b-tags) (ll with 2 or ≥3 b-tagged jets)	9	110-140		5.0 - 5.1
H→ττ	1-jets	($e\tau_h$, $\mu\tau_h$, eμ, μμ) × (low or high $p_T^{\tau\tau}$)	8	110-145	20%	4.9 - 12.1
	VBF-tag	(l with 4,5, ≥ 6 jets) ⊗ (3, ≥4 b-tags)	4	110-145	20%	4.9 - 12.1
	ZH-tag	(l with 6 jets with 2 b-tags)	8	110-160		5.0 - /
	WH-tag	(ll with 2 or ≥3 b-tagged jets)	3	110-140		4.9 - /
H→WW→lυqq	untagged	(eυ, μυ) ⊗ ($(jj)_W$ with 0 or 1 jets)	4	170-600	20%	5.0 - 12.1
H→WW→lυlυ	0/1-jets	(DF or SF dileptons) ⊗ (0 or 1jets)	4	110-600		4.9 - 12.1
H→WW→lυlυ	VBF-tag	lυlυ + $(jj)_{VBF}$ (DF or SF dileptons 8TeV)	1 or 2	110-600		4.9 - 12.1
H→WW→lυlυ	WH-tag	3l3υ	1	110-200		4.9 - 5.1
H→ZZ→4l	inclusive	4e, 4μ, 2e2μ	3	110-1000	1-2%	5.0-12.1
H→ZZ→2l2τ	inclusive	(ee, μμ) × ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, eμ)	8	180-1000	10-15%	5.0-12.1

Expected Discovery Potential

Local p-value: Probability for a background fluctuation to give an excess as large as the (average) signal size expected for a SM Higgs





> 7σ for m_H ~ 125

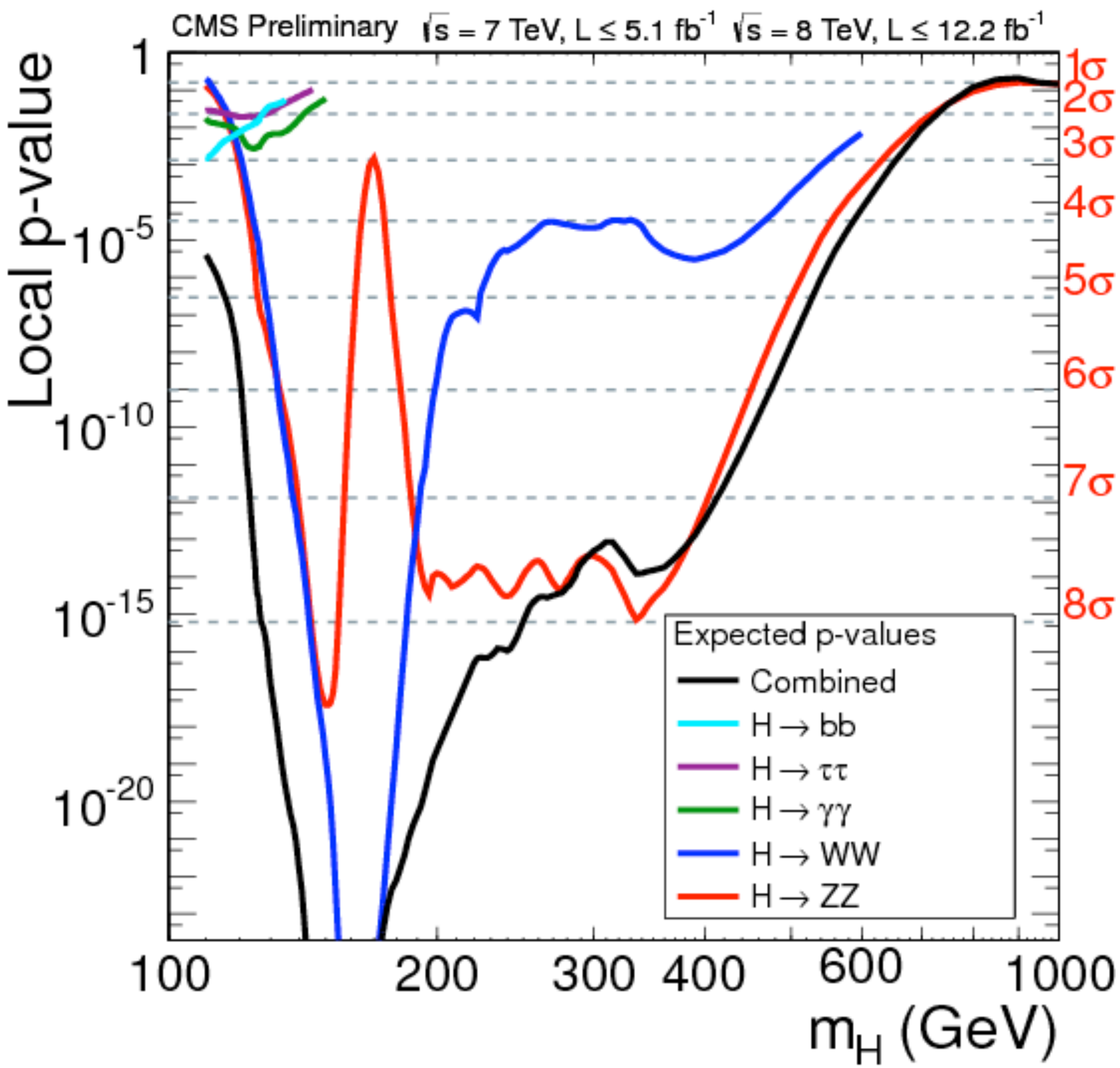
steeply falling

Expected Discovery Potential

Extended up to 1TeV

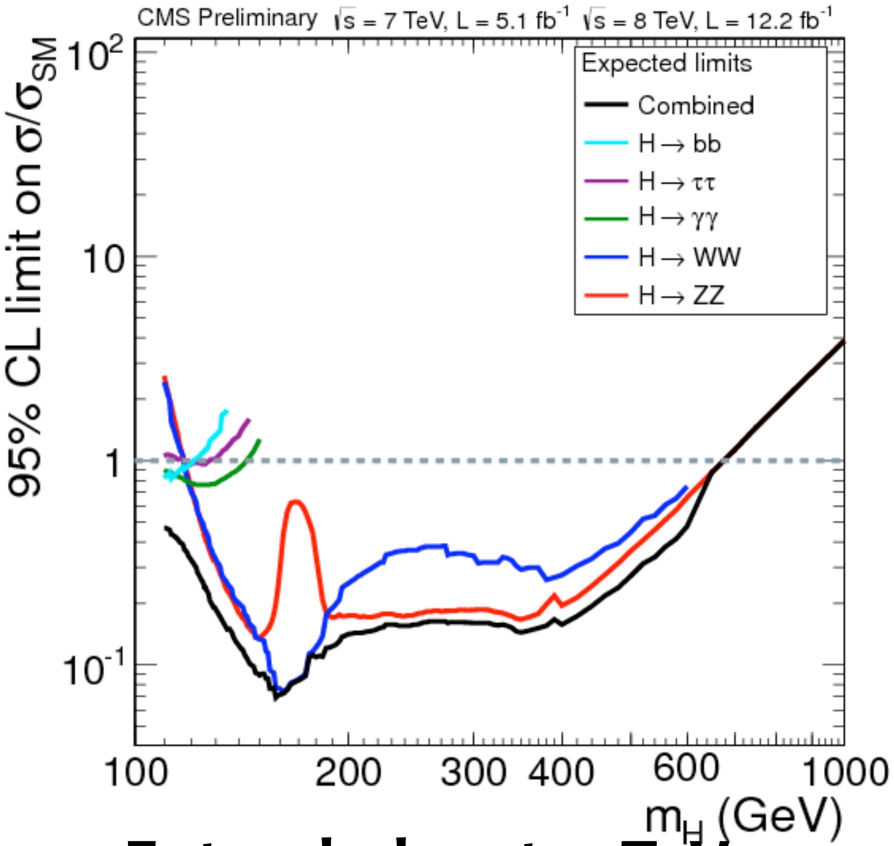
For m_H > 120 GeV driven by ZZ and WW

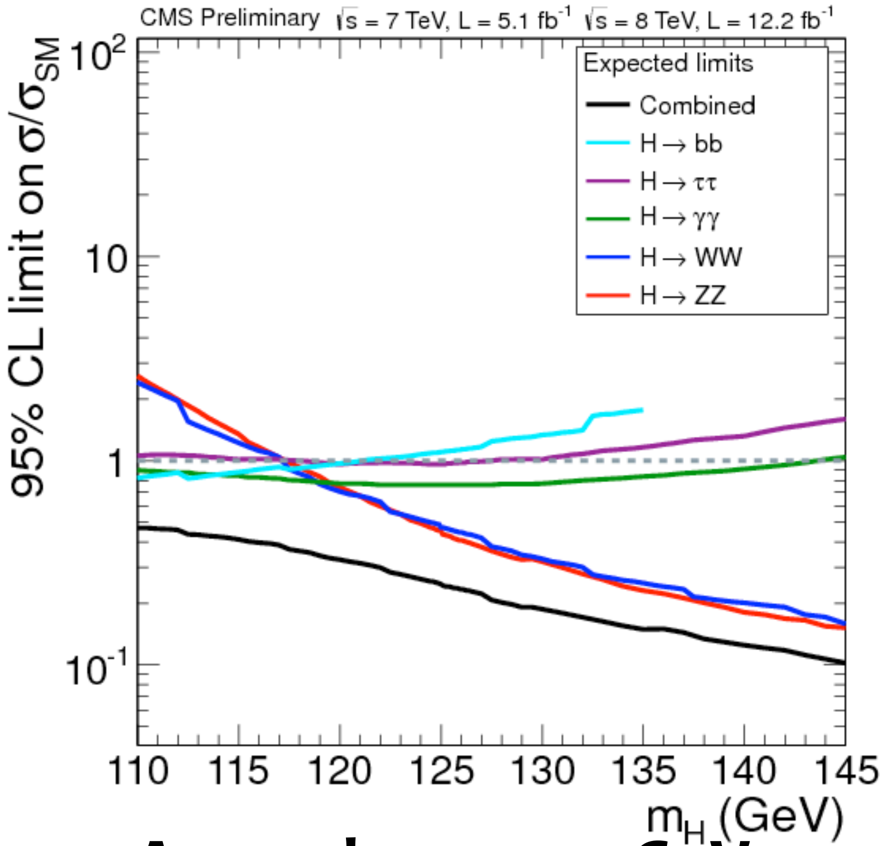
> 5σ up to 500 GeV



Expected Exclusion Potential

The 95% CL upper limits on the cross section ratio σ/σ_{SM} for the SM Higgs as function of mH





Extended up to 1TeV

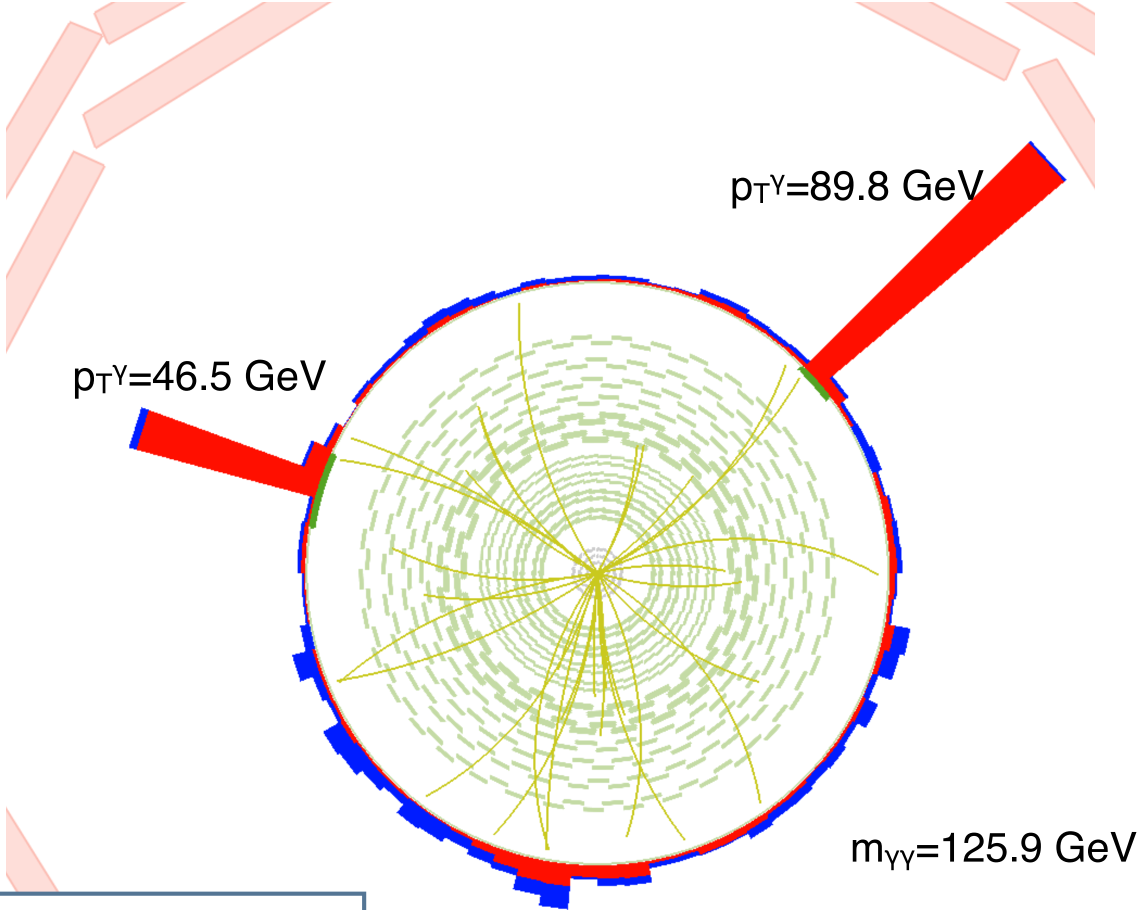
For m_H > 120 GeV
driven by ZZ and WW

< 0.3XSM up to ~500 GeV (1XSM up to ~700 GeV)

Around m_H ~ 125 GeV
driven by ZZ, WW, γγ

The Channels:

- High Resolution channels
  - H->γγ [ICHEP results]
  - H->ZZ [minor changes in the analysis + LUMI UPDATE]
- Low Resolution channels
  - H->bb [analysis improved + LUMI UPDATE]
  - H->ττ [analysis improved + LUMI UPDATE]
  - H->WW [analysis improved + LUMI UPDATE]



$H \rightarrow \gamma\gamma$ candidate

H->γγ analysis in a nut shell

Search for a narrow peak with two isolated high E_T photons on a smoothly falling background.

High resolution: ΔM/M ~ 1-2%

Analysis optimized categorizing events according to purity and mass resolution
specific **di-jet tag categories targeting VBF** production mode (Higher S/B)

Main analysis:
- uses MVA techniques for both photon identification and event classification
  background model derived from a fit to the data di-photon mass spectrum

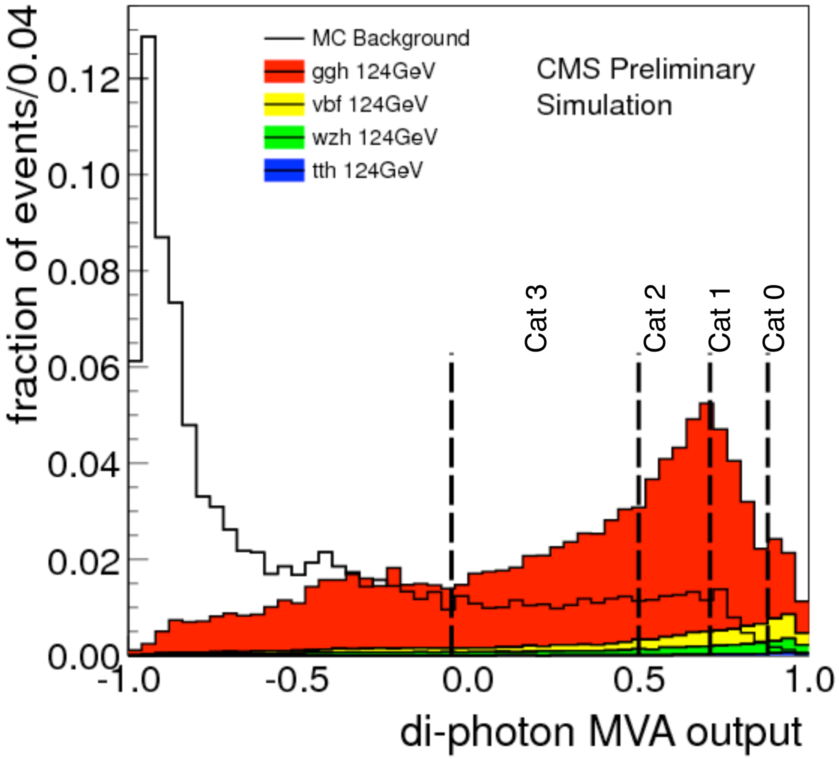
Independent cross checks analysis:
- cut-based analysis with same background model
- same MVA techniques but background estimated from side-band

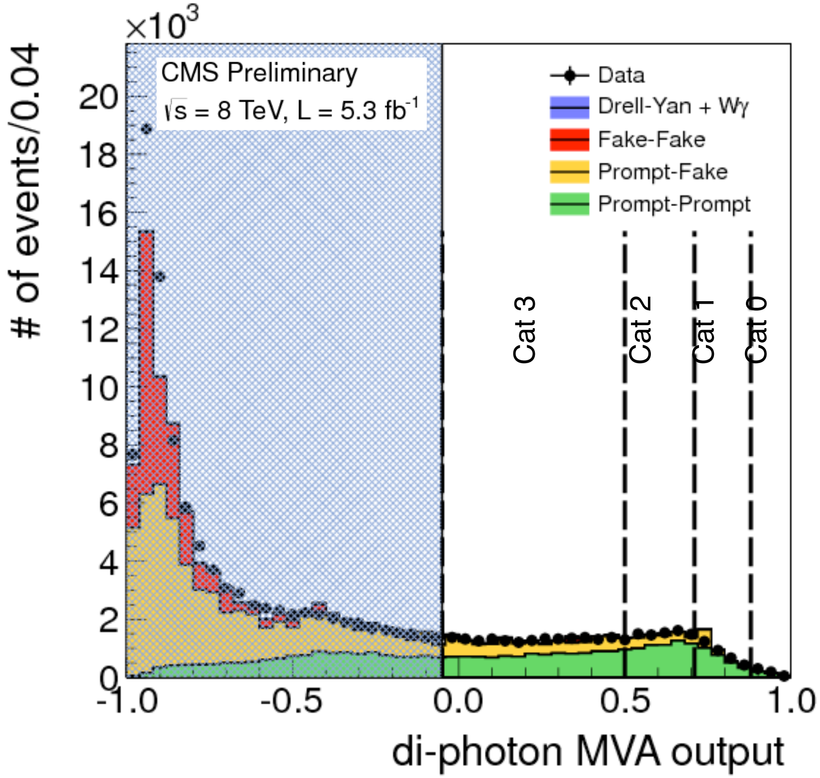
5.1 fb^{-1} @ 7 TeV (2011) + 5.3 fb^{-1} @ 8 TeV (2012): HIG-12-015
analysis not updated since ICHEP

Event Classification

The γγ MVA - Event classifier variable trained on signal and bkg MC with input variables:

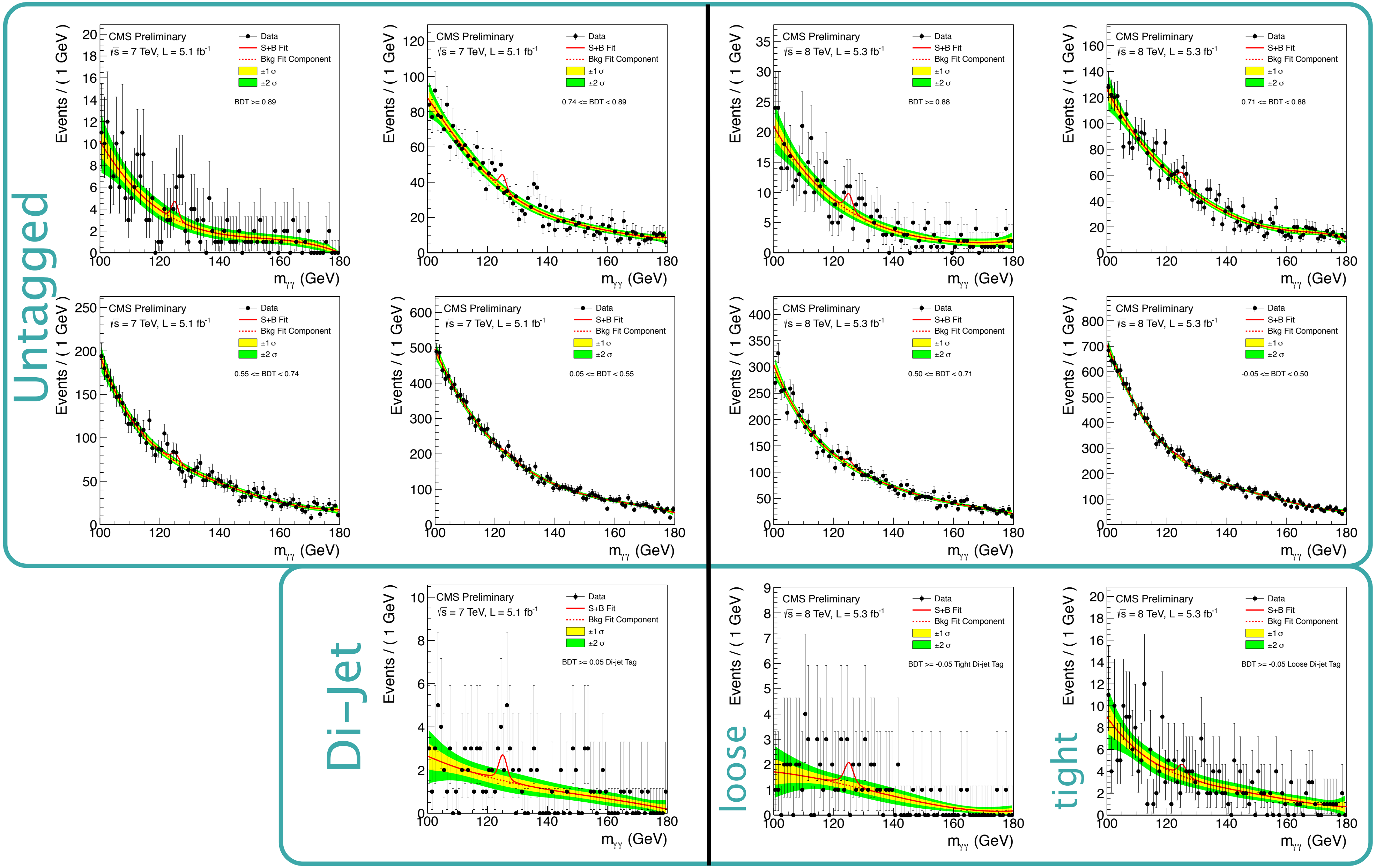
kinematic variables (pT and η of each γ, and cosΔφ between the 2Y)
photon ID MVA output for each Y
per-event mass resolution
vertex probability (from another MVA)





Mass distributions in categories

7 TeV (5 categories) — 8 TeV (6 categories)



Results

With a simultaneous maximum-likelihood fit of all the categories the statistical interpretation is obtained:

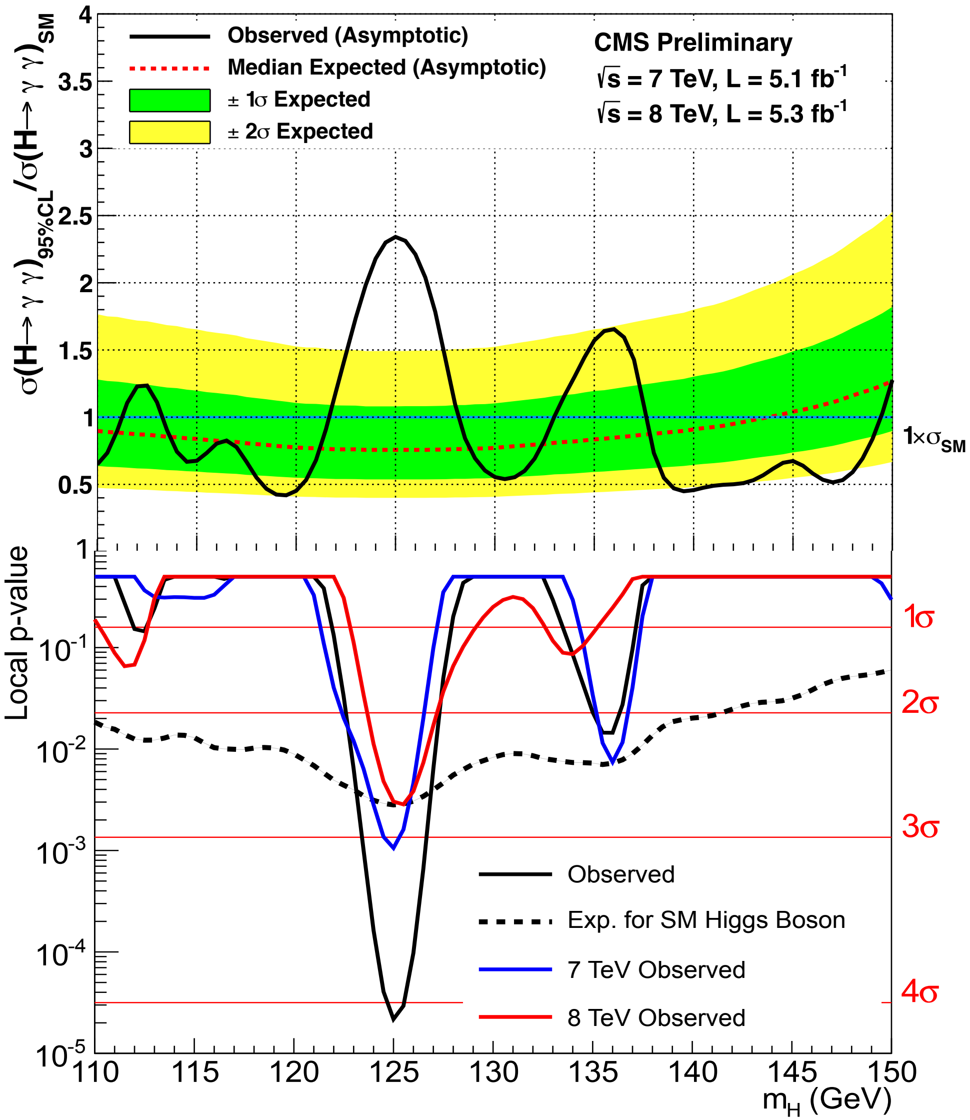
Largest excess at 125 GeV

- expected 95% CL exclusion 0.76xSM @ 125

Minimum p-value at 125 GeV with local significance 4.1 σ

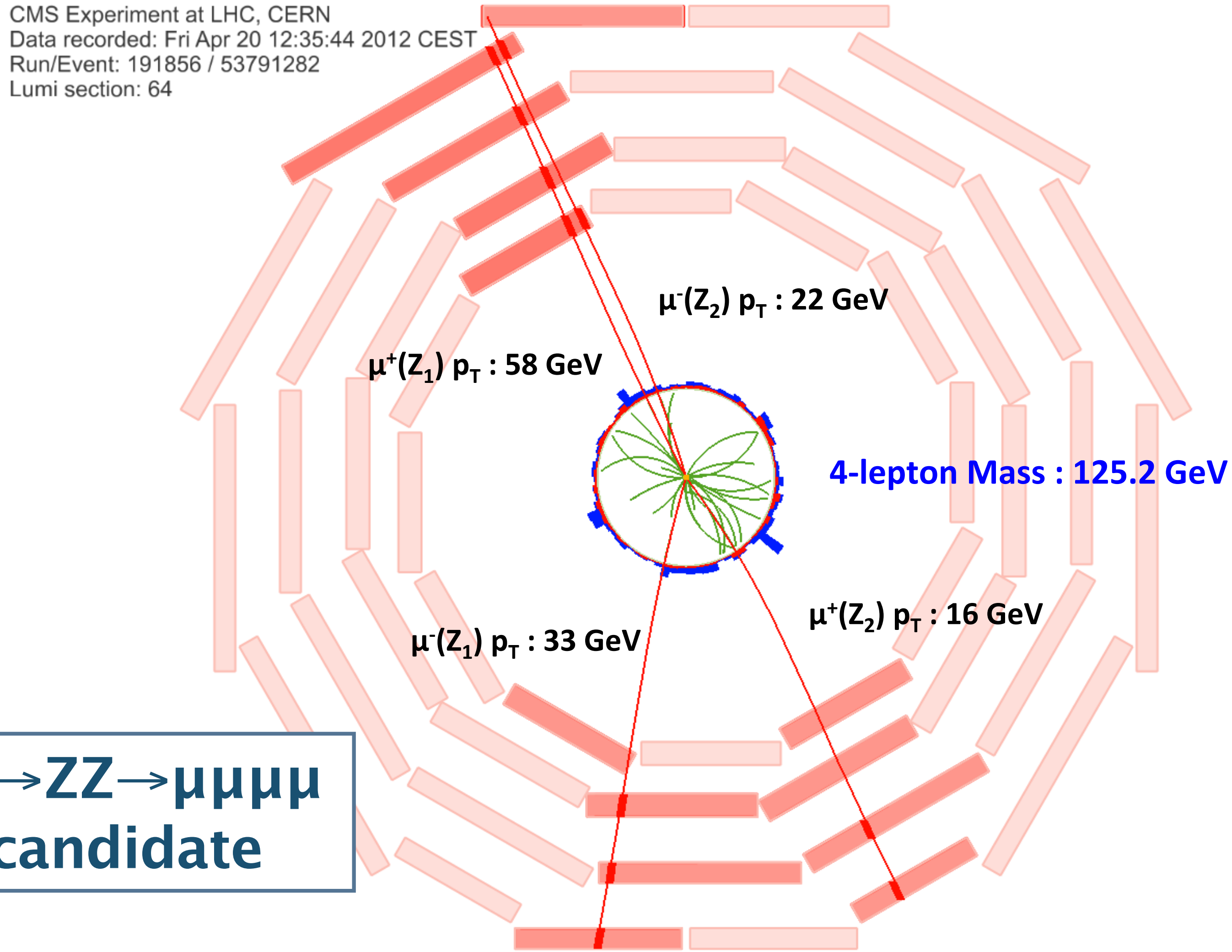
- global significance in full search range 110-150 GeV is 3.2 σ
- fitted signal strength μ(125)= 1.56±0.43

Similar excess in 2011 & 2012



The Channels:

- High Resolution channels
  - H->γγ [ICHEP results]
  - **H->ZZ** [minor changes in the analysis + LUMI UPDATE]
- Low Resolution channels
  - H->bb [analysis improved + LUMI UPDATE]
  - H->ττ [analysis improved + LUMI UPDATE]
  - H->WW [analysis improved + LUMI UPDATE]



H →ZZ→μμμμ candidate

HZZ4l analysis in a nut shell

Search for a narrow peak in the 4l mass spectrum on top of a flat and small bkg

Number of events small

Requires maximum signal efficiency: 4 isolated leptons from primary vertex

THE MUSTS: Excellent lepton reconstruction+identification and energy-momentum measurement

Inclusive search; signal yield dominated by gg->H

High resolution: ΔM/M ~ 1%

Backgrounds include

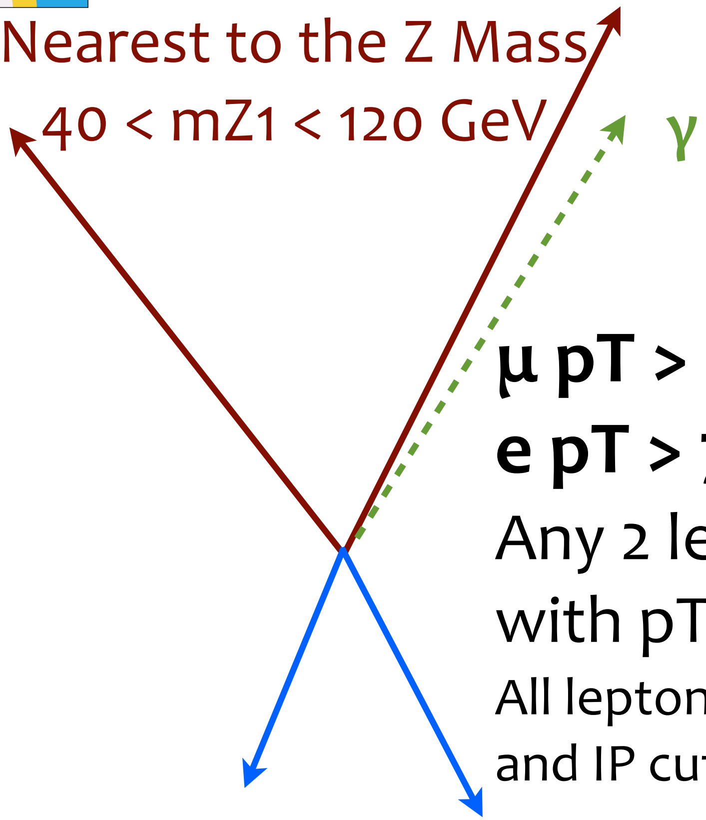
SM ZZ [irreducible]

Z/ tt + fake leptons or leptons from HF [reducible]

5.1 fb^{-1} @ 7 TeV (2011) + 12.2 fb^{-1} @ 8 TeV (2012): HIG-12-041
analysis updated since ICHEP: minimal changes
2/3% higher efficiency and lower systematic on energy scale

Event Selection

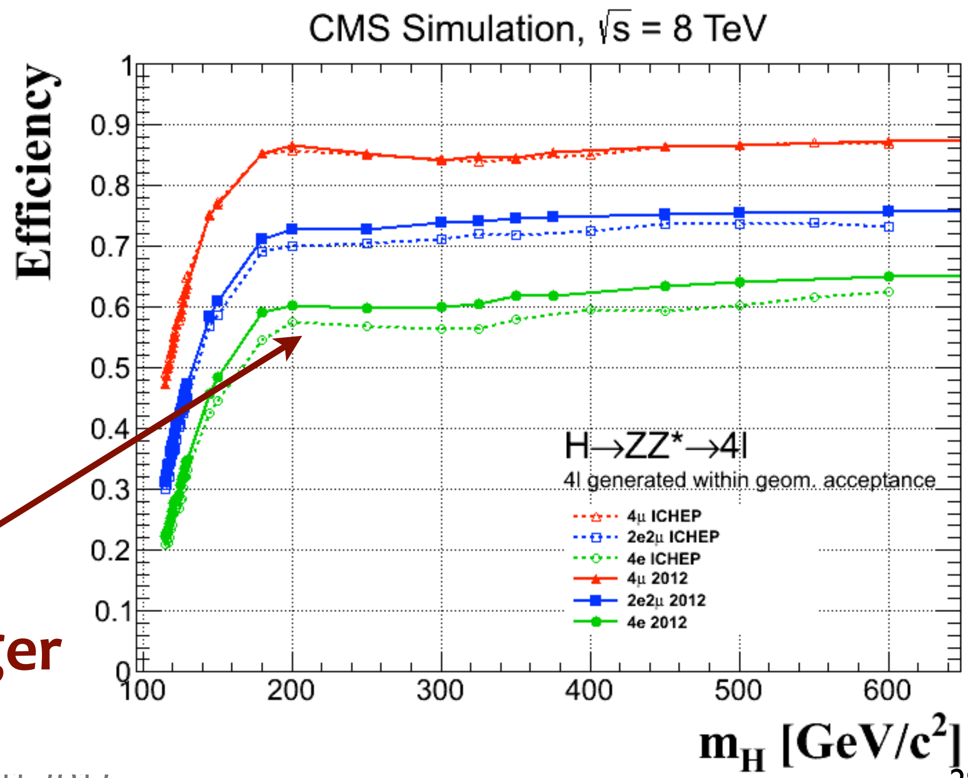
OS/SF
Nearest to the Z Mass
40 < mZ1 < 120 GeV



μ pT > 5, η<2.4
e pT > 7, η<2.5
Any 2 leptons
with pT>20,10 GeV
All leptons after isolatio
and IP cut

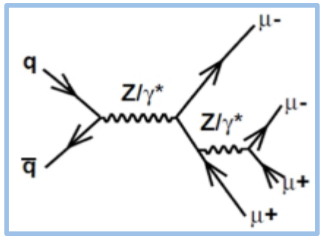
OS/SF
Highest Sum pT
12 < mZ1 < 120 GeV

- Any OS/SF lepton pair must have M_{ll}>4 GeV [to suppress QCD]
- FSR Recovery [photons added to the Z candidates before cuts]

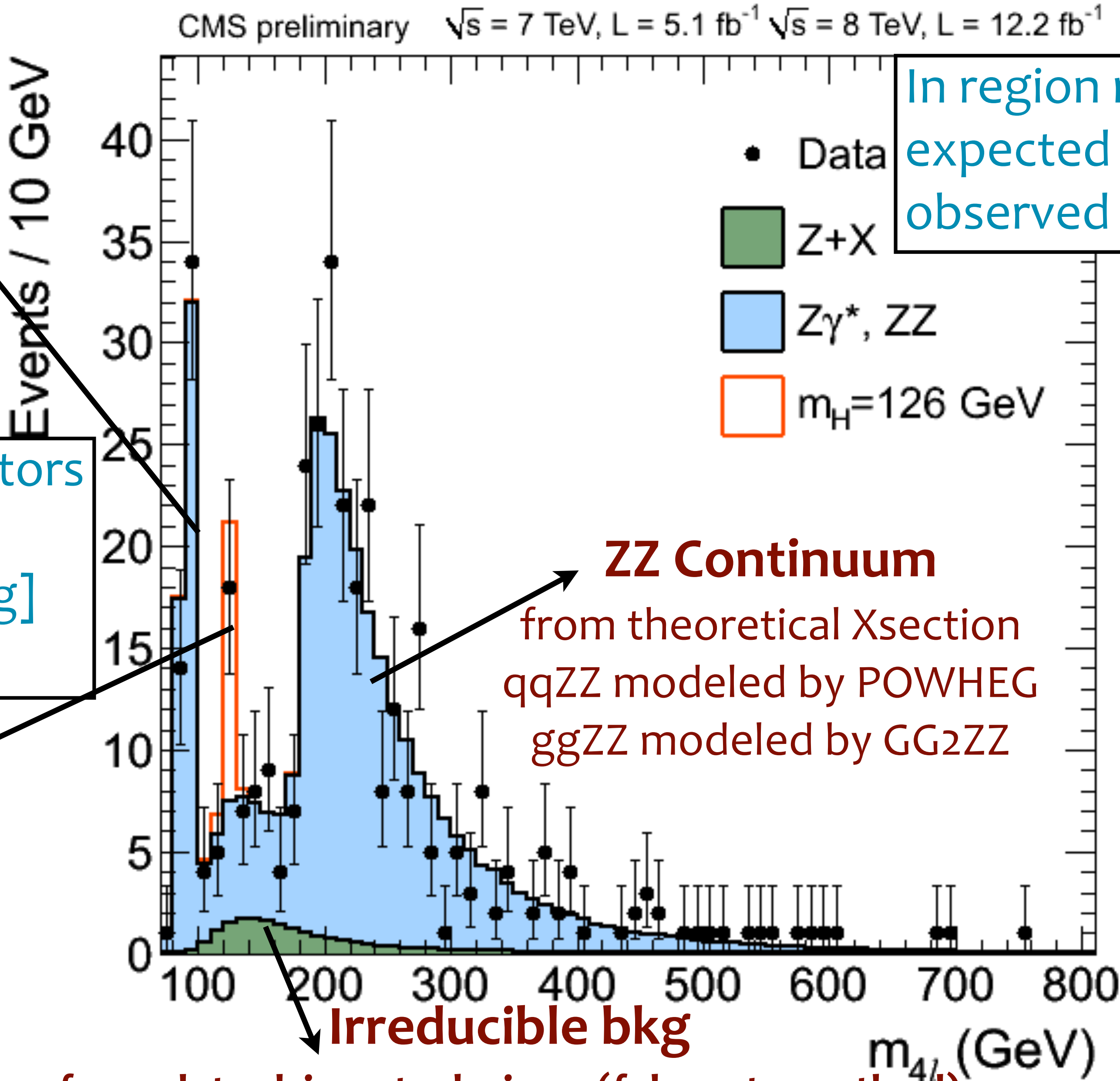


NEW! **Adding tri-lepton trigger**

M4l spectrum



Z->4l peak
good DATA/MC agreement
127 expec/115 obs



In region m4l [140-300]
expected 222 events
observed 224 events

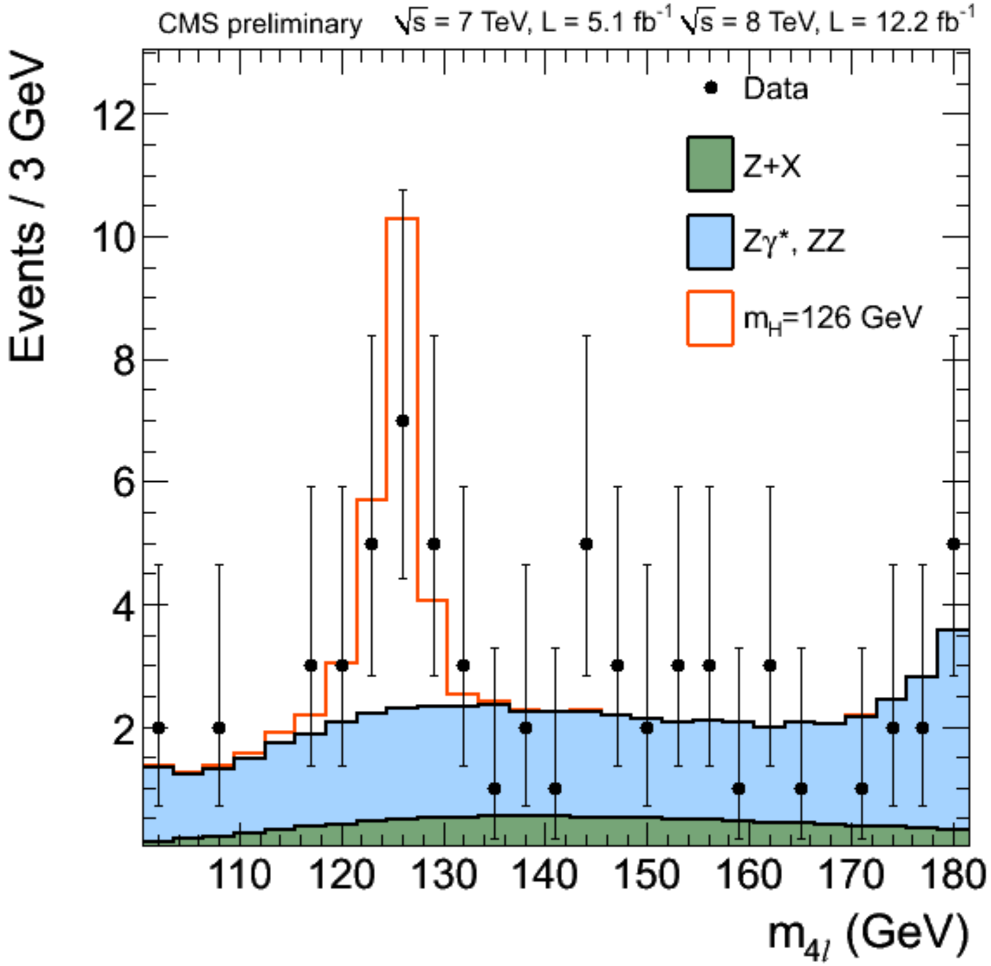
Data/MC scale factors [lepton reco/id/isolation/vertexing] applied

ZZ Continuum
from theoretical Xsection
qqZZ modeled by POWHEG
ggZZ modeled by GG2ZZ

h_{125} excess
still there!

Irreducible bkg
from data-driven technique (fake rate method)

M4l spectrum @ ~125



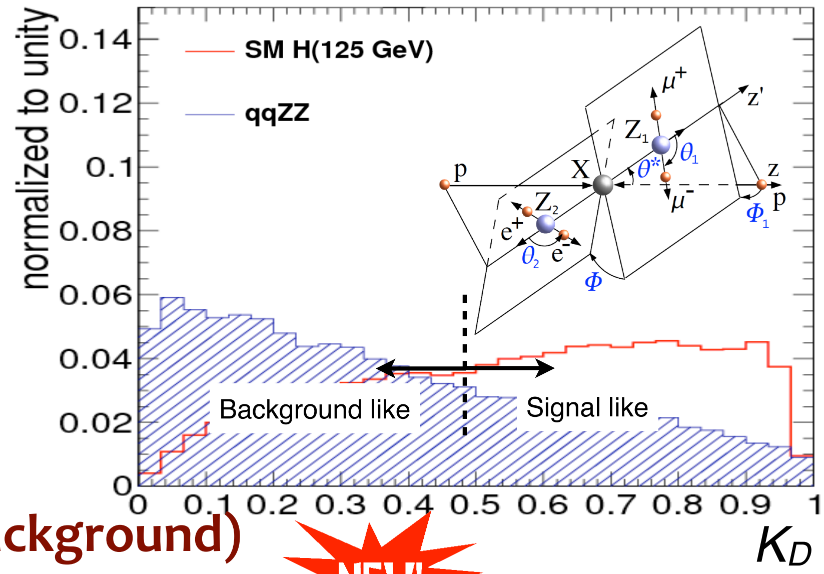
In region m4l [121.5-130.5]
expected **19** S+B events
observed **17**

	Exp. Bkg	mH=126	Obs
4e	1.25	2.20	3
4μ	2.09	4.26	6
2e2μ	3.14	5.97	8
TOT	6.48	12.43	17

Matrix Element Likelihood Approach

A kinematic discriminant (K_D *or MELA*) is constructed based on the probability ratio of the signal and background hypotheses

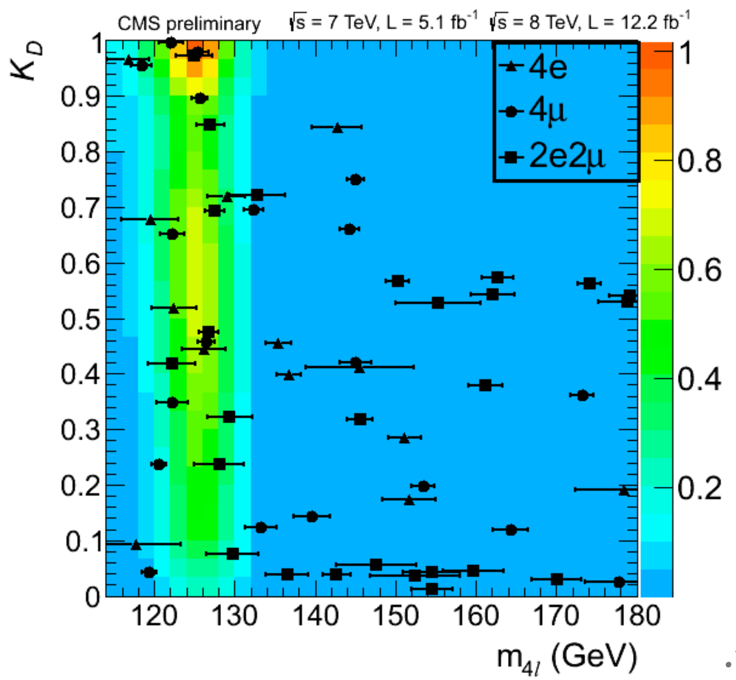
$$\left[1+\frac{\mathcal{P}_{\mathrm{bkg}}(m_1,m_2,\theta_1,\theta_2,\Phi,\theta^*,\Phi_1|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1,m_2,\theta_1,\theta_2,\Phi,\theta^*,\Phi_1|m_{4\ell})}\right]^{-1}$$

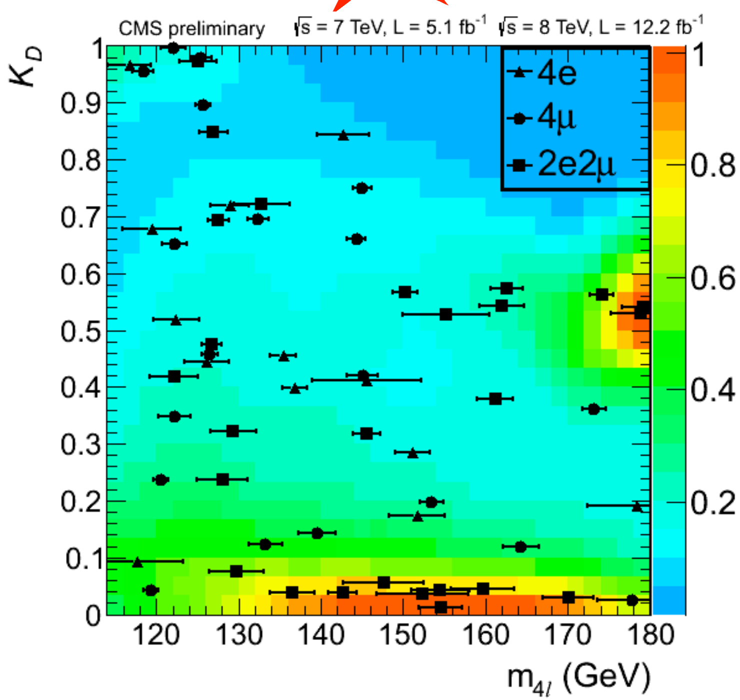


Moved to fully analytical approach (signal and background)

1% better significance @ 125 and 5% better limits at high mass

NEW!





2D Fit for the statistical analysis

The likelihood used in the test statistic to extract limits and p-values is for the 4l analysis a 2D PDF obtained as:

$$P(m_{4\ell}, K_D) = P(m_{4\ell}) \times P(K_D | m_{4\ell})$$

Unbinned mass model

Binned 2D model of KD in slices of m4l

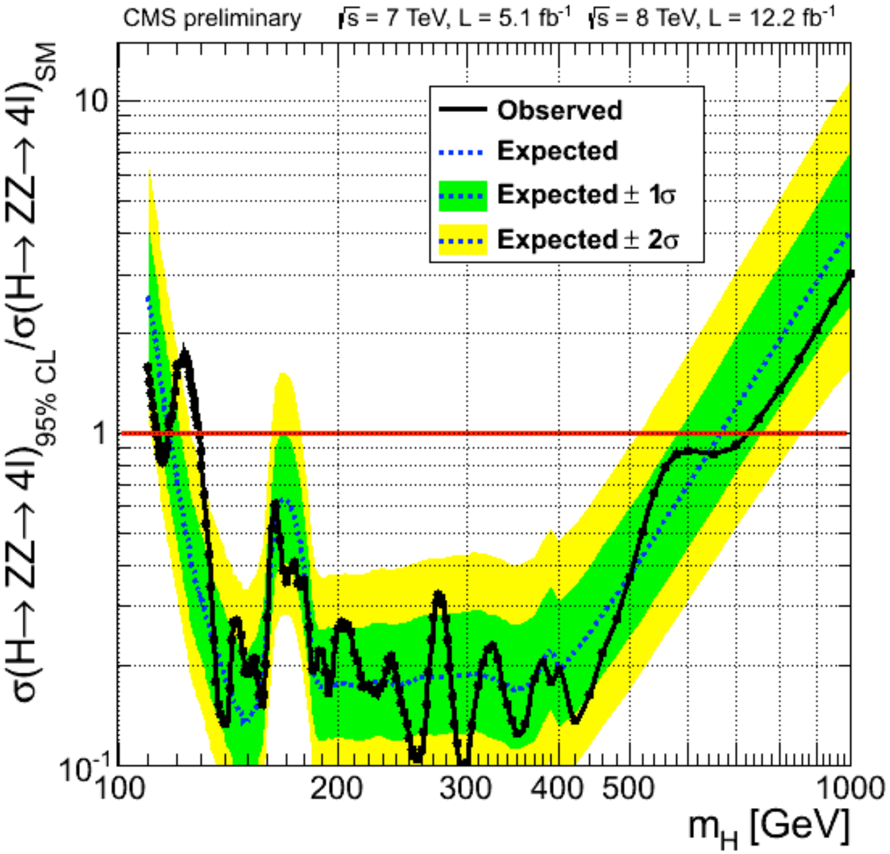
[all shape and normalization systematics are introduced as nuisance parameters]

Signal shape modeling: using convolution of double-sided crystal ball convoluted with Relativistic Breit Wigner NEW!

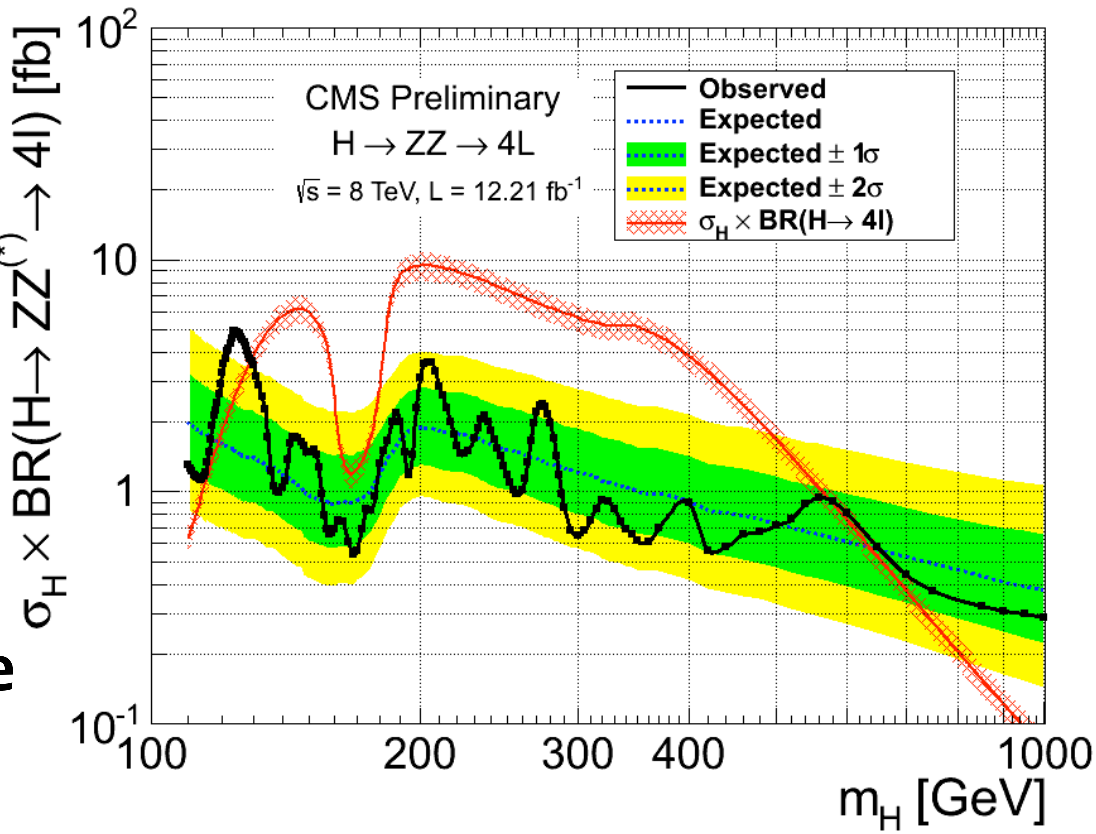
Background shape modeling: empirical parametrization distributions for qq->ZZ and gg->ZZ

limits

The 95% CL upper limits on the cross section ratio σ/σ_{SM} for the SM Higgs as function of mH



Excluding other "SM-Higgs" like bosons up to 700 GeV



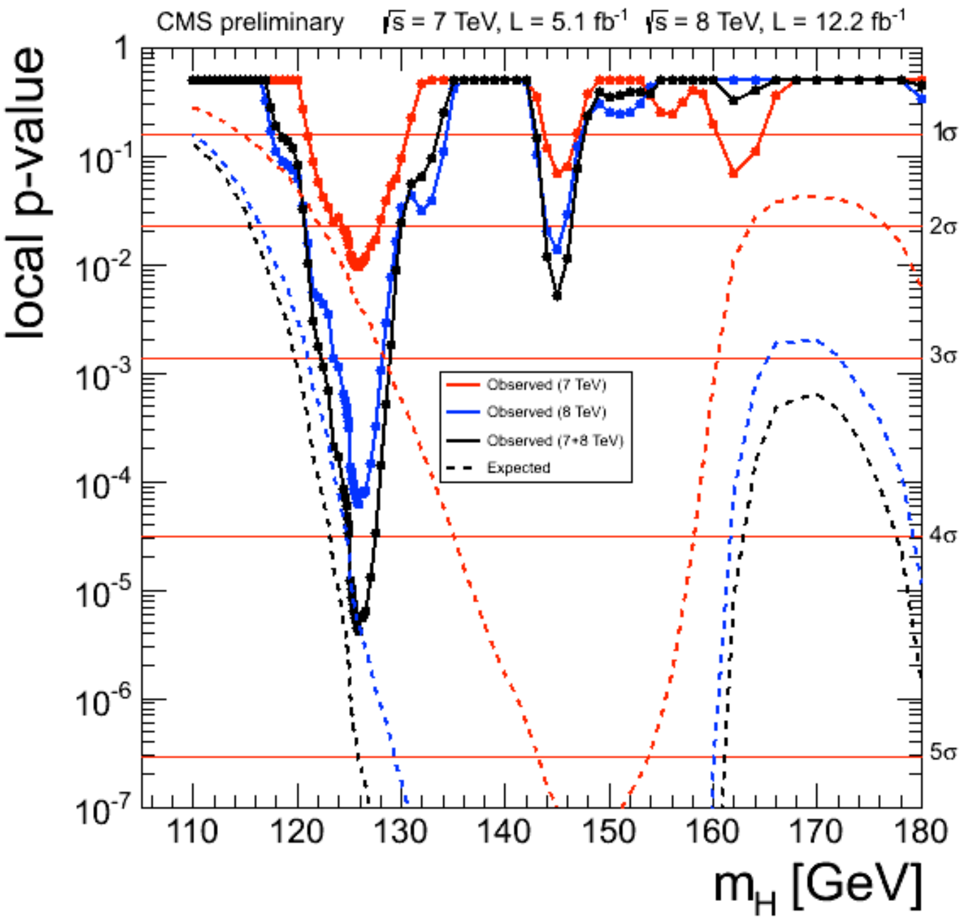
The 95% CL upper limits on the cross section σ·BR

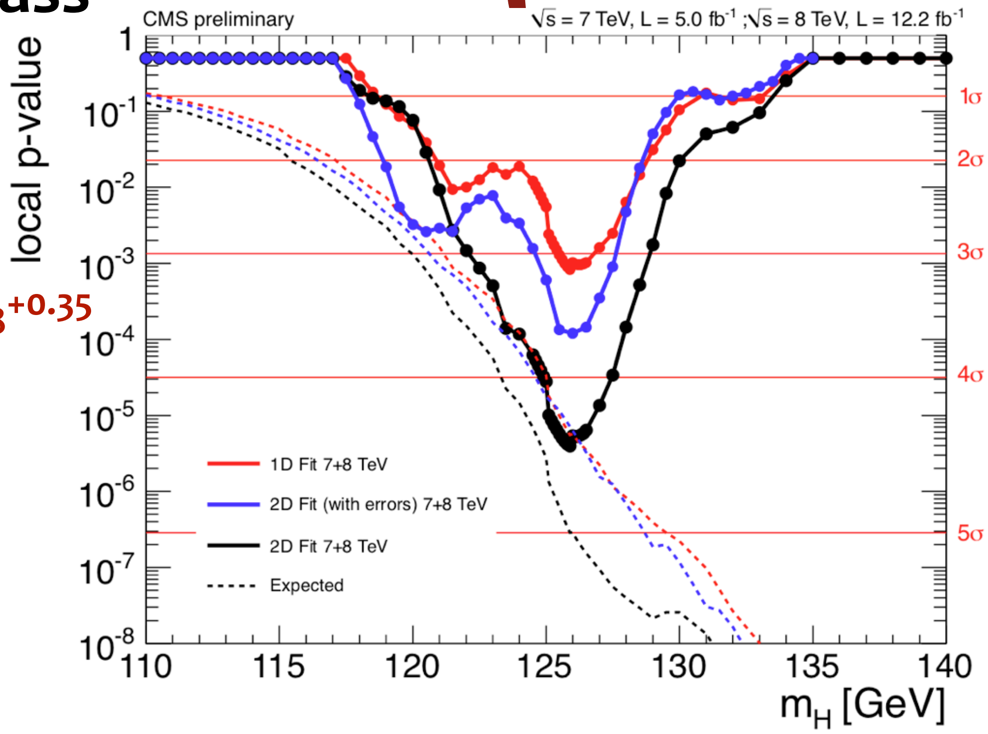
p-values

No sign of another signal at high mass

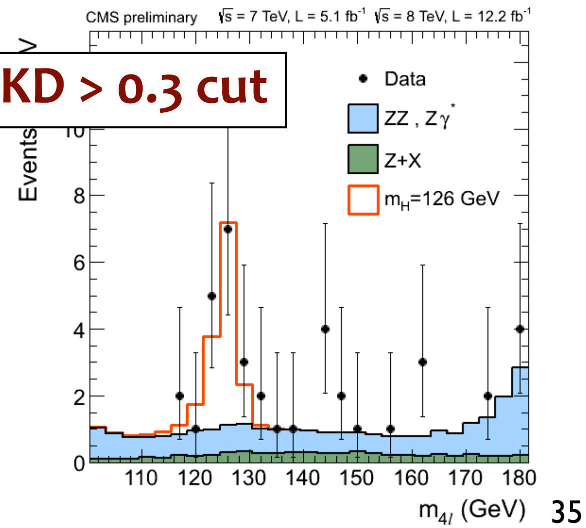
Minimum p-value at 125.9 GeV

- significance of 4.5 σ (5.0 expected)
- fitted signal strength $\mu(125.9) = 0.80^{+0.35}_{-0.28}$



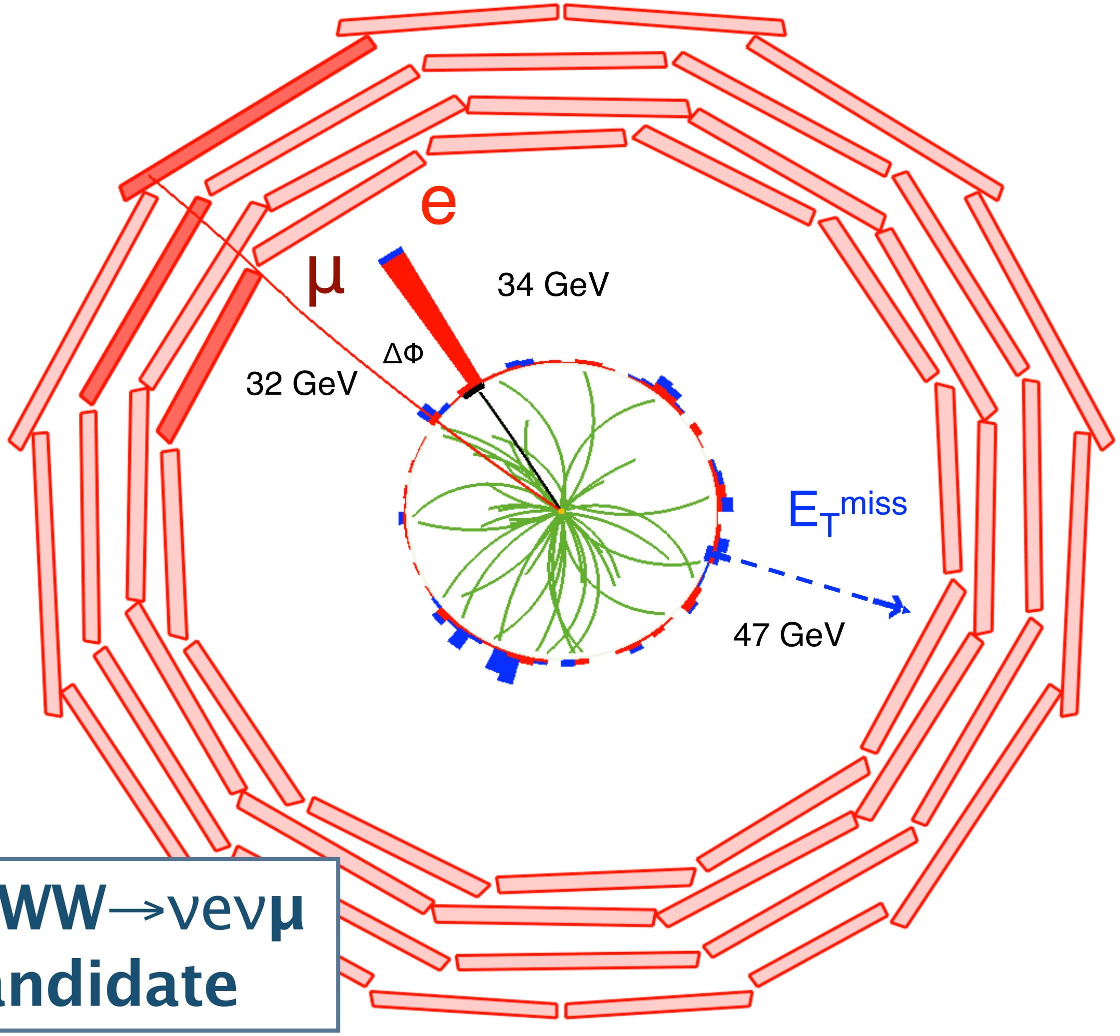


m4l after KD > 0.3 cut



The Channels:

- High Resolution channels
  - H->γγ [ICHEP results]
  - H->ZZ [minor changes in the analysis + LUMI UPDATE]
- Low Resolution channels
  - **H->WW [analysis improved + LUMI UPDATE]**
  - H-> bb [analysis improved + LUMI UPDATE]
  - H->ττ [analysis improved + LUMI UPDATE]



H →WW→νeνμ candidate

H->WW: Channels

Three decay channels that probe three different decay mechanisms:

- **Gluon Fusion:** WW->2l2v / WW-> 2l2q
- **VBF:** WW->2l2v
- **Associated production:** WH->3W->3l3v

	2l2v	2l2q	3l3v
Search range	120-600 GeV	170-600 GeV	110-200 GeV
Sensitive range	120-200 GeV (~$2M_W$)	200-400 GeV	150-180 GeV (~$2M_W$)

5.1 fb^{-1} @ 7 TeV (2011) + 12.2 fb^{-1} @ 8 TeV (2012): HIG-12-042
analysis updated since ICHEP, important changes:
- 2D shape analysis (M_{ll}, M_T) for most sensitive category
- VBF selection optimization

HWW analysis in a nut shell

Search for an excess of events with 2 opposite sign prompt isolated leptons (μ, e) and missing E_T

No mass peak, basically a counting analysis

Analysis challenge: understanding the backgrounds

DATA DRIVEN methods for reducible bkg: W+jets, tt/tW, Z/Y*->ll, Z/γ*->ττ

WZ/ZZ, V+γ$^{(*)}$ from MC

WW fit to data in sidebands after subtracting all other backgrounds

Events splitted in categories with different S/B and B composition

Dominant backgrounds

Most sensitive

	0-jet	1-jet	2-jet (VBF)
DF	WW W+jets, V+γ$^{(*)}$ (low m_H)	WW, Top	WW, Top
SF	WW Z/γ* (low m_H)	WW, Top	WW, Top Z/γ*

Almost common preselection for all the events based on background rejection cuts (inverted to define control regions): **mll cut, pT(ll), Z-peak veto, extra-lepton veto, B-veto, Z/Y* rejection MVA based on MET**

M_H dependent cut-and-count Analysis

Next step:

m_H dependent cuts common to 0, 1 jets

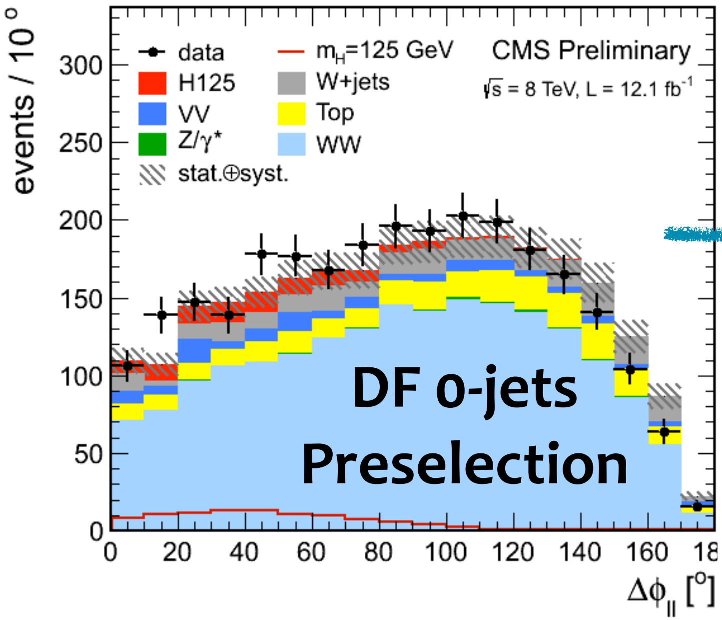
NEW! slightly different + VBF tags for the 2 jets

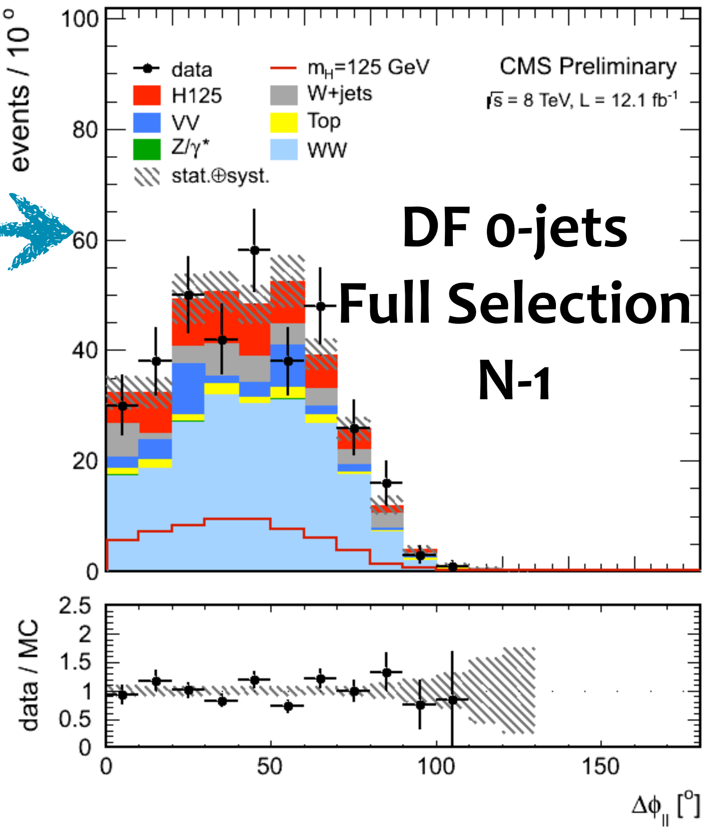
Variables:

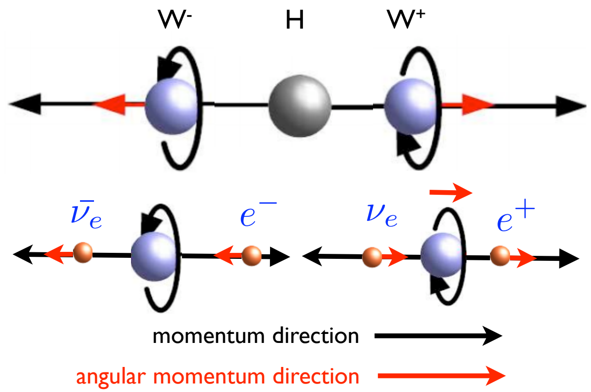
$\Delta\varphi(ll)$, $p_T(l_{max})$, $p_T(l_{min})$, m_{ll}, m_T

$$m_T = \sqrt{2 p_T^{\ell\ell} E_T^{\text{miss}} \left(1 - \cos \Delta\phi_{E_T^{\text{miss}}\ell\ell}\right)}$$

m_H [GeV]	$p_T^{\ell,max}$ [GeV]	$p_T^{\ell,min}$ [GeV]	$m_{\ell\ell}$ [GeV]	$\Delta\phi_{\ell\ell}$ [°]	m_T [GeV]
	>	>	<	<	[,]
120	20	10	40	115	[80,120]
125	23	10	43	100	[80,123]
130	25	10	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
[illegible]	[illegible]	25	200	175	[120,300]
[illegible]	[illegible]	25	300	175	[120,400]

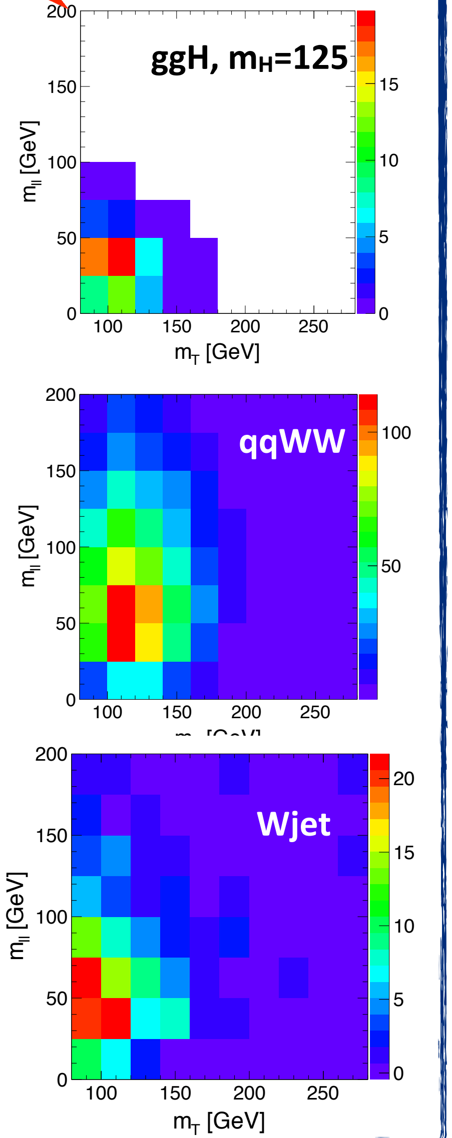






2D Shape Analysis M_{ll}:M_T

NEW!



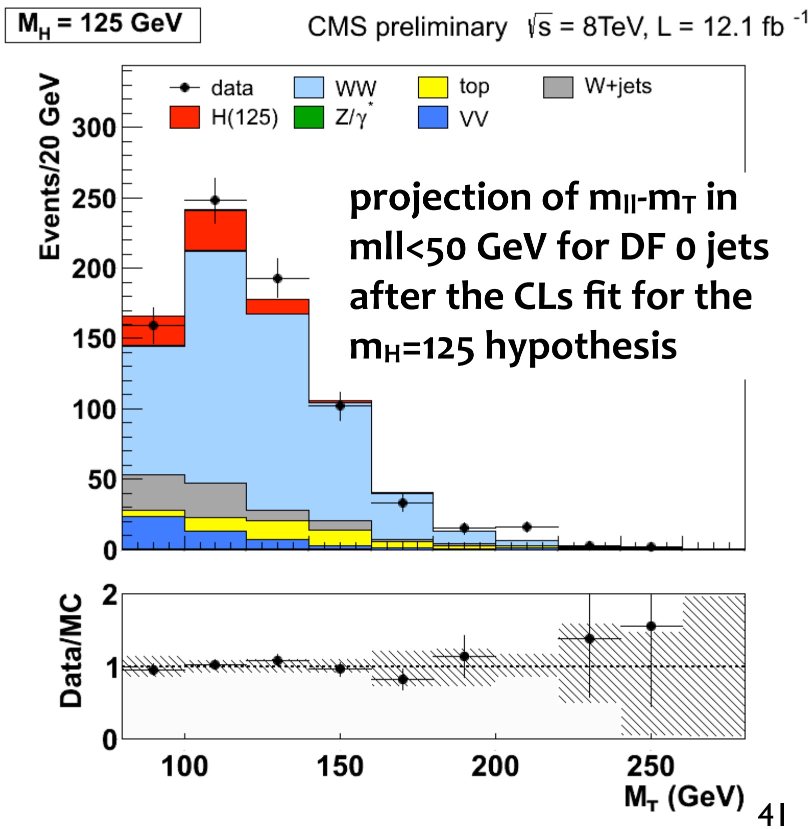
Exploit the correlation of two kinematic variables in 2D
- mass-like variables m_{ll} and m_T

Different background peaking at different location

Relaxed selection with respect to cut-based
- Exploit the full range of the variables
- Mass independent selection f

Applied only for **DF 0,1 jets** most sensitive categories

2D shape used as PDF in building the likelihood ratio

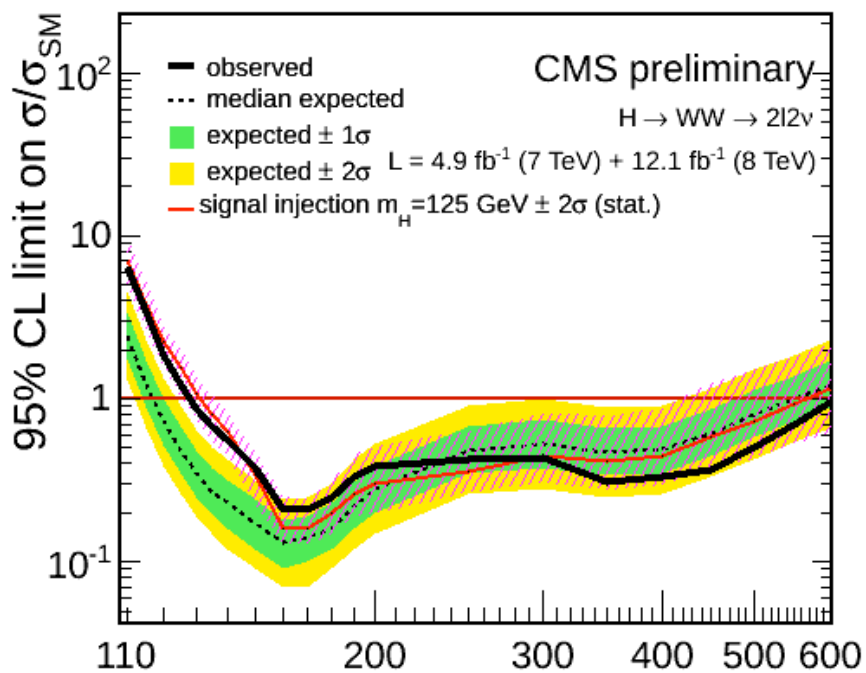


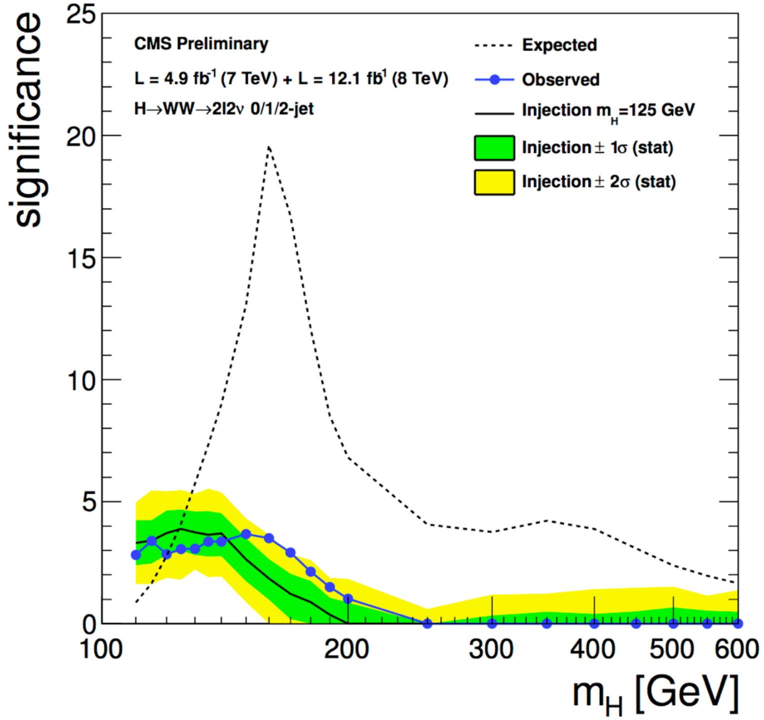
projection of m_{ll}-m_T in mll<50 GeV for DF 0 jets after the CLs fit for the m_H=125 hypothesis

Results

7+8TeV analyses result:

8TeV analysis with **shape based approach** (combine the analysis in DF 0,1 jets categories with the cut based analysis in other categories)





Excluding other "SM-Higgs" like bosons in range 128-600 GeV

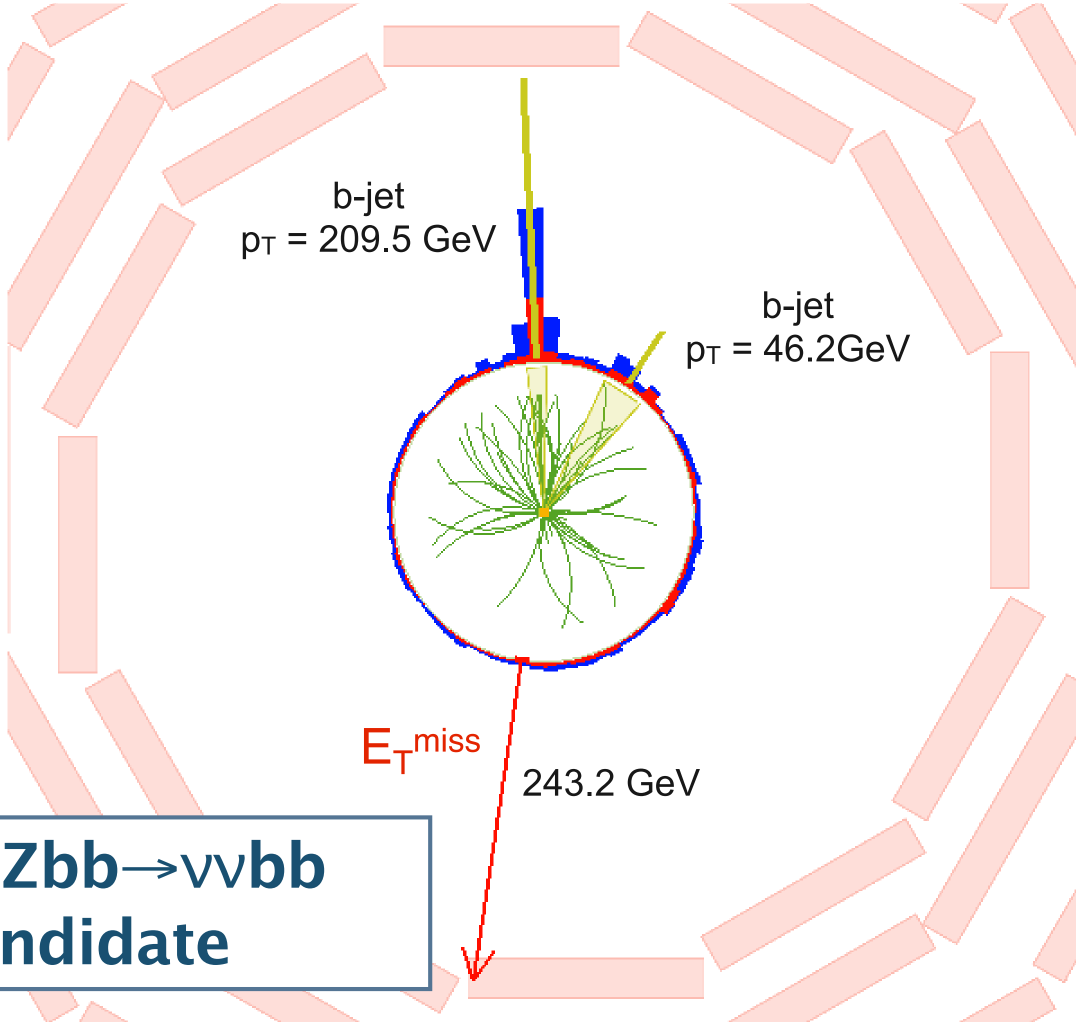
Broad excess at low mass [110-160] GeV compatible with a SM Higgs at m_H = 125GeV with statistical significance of 3.1σ

expected/observed significance		
8 TeV cut-based	8 TeV shape-based	7+8 TeV shape-based
2.4/1.7	3.7/2.9	4.1/3.1

best fit value		
8 TeV cut-based	8 TeV shape-based	7+8 TeV shape-based
0.80 ± 0.45	0.77 ± 0.28	0.74 ± 0.25

The Channels:

- High Resolution channels
  - H->γγ [ICHEP results]
  - H->ZZ [minor changes in the analysis + LUMI UPDATE]
- Low Resolution channels
  - H->WW [analysis improved + LUMI UPDATE]
  - **H-> bb [analysis improved + LUMI UPDATE]**
  - H->ττ [analysis improved + LUMI UPDATE]



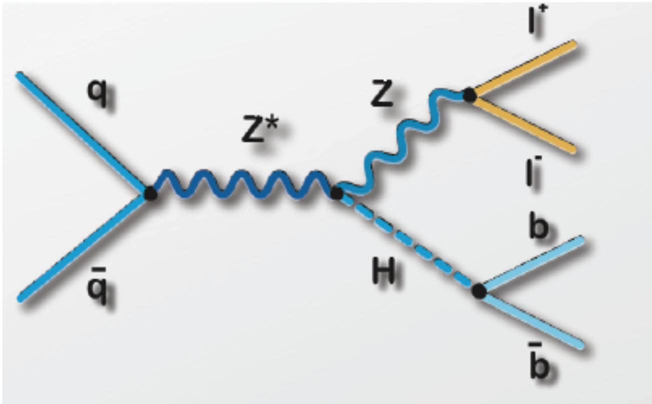
ZH →Zbb→ννbb candidate

H->bb analysis in a nut shell

The largest BR for m_H<130 GeV but σ_{bb}(QCD) ~ 10^7 x σ_H x BR(H→bb)

⇒Search in associated production with W or Z

final states with isolated leptons, MET, b-tagged jets



5 topologies

Z(ll)H(bb)

Z(νν)H(bb)

W(lν)H(bb)

l=e,μ

each mode splitted into high/low p_T(V) categories.

The high p_T(V) is splitted in low/high b-tag NEW!

General strategy:

High boosted vector boson and dijet back-to-back V & H

b-jet energy regression (15% improve in mass resolution m_{bb} - 10-20% in sensitivity)

BDT shape analysis (BDT output final discriminant for the fitting procedure)

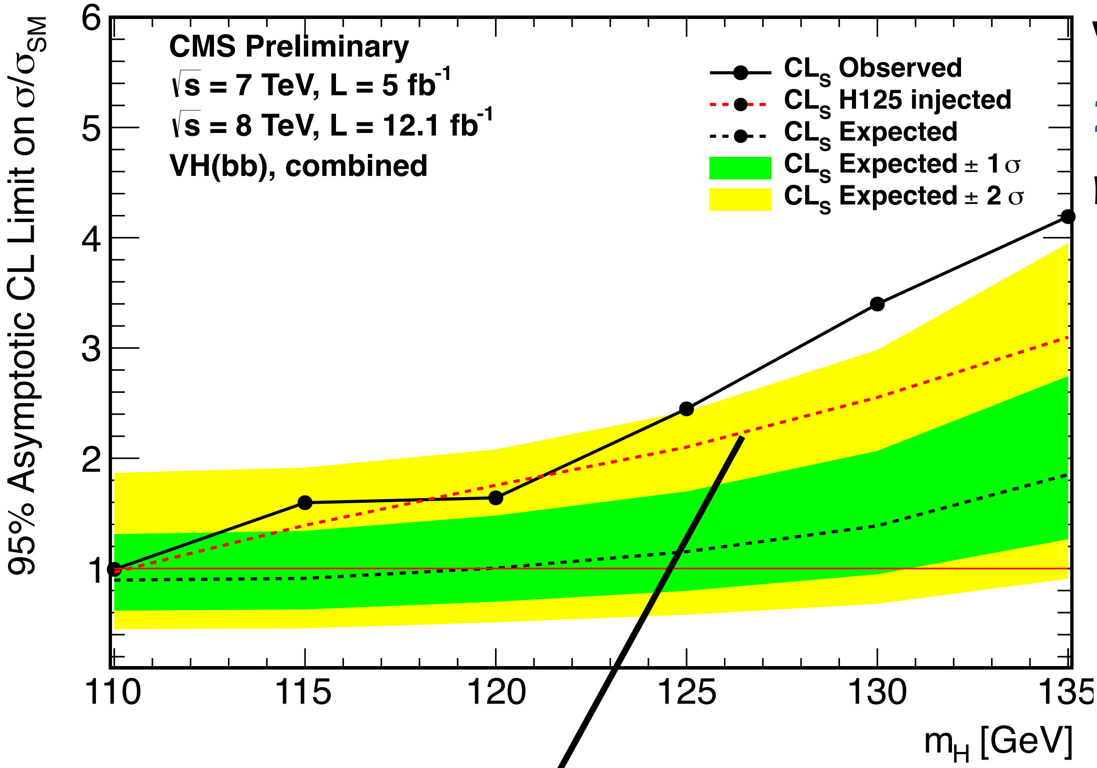
Main backgrounds → **V+jets, ttbar** estimated from data in control regions

5.1 fb^{-1} @ 7 TeV (2011) + 12.2 fb^{-1} @ 8 TeV (2012): HIG-12-044

analysis updated since ICHEP:

new categories + improved BDT regression for b-jet energy (new variables added)

Results



With more data and improvements 20-30% more sensitivity wrt ICHEP results

In the analyzed range [110-135]:
observed upper limits from **1.0 to 4.2**
expected upper limits from **0.9 to 1.9**

At m_H = 125GeV:
observed limit = **2.5** - expected = **1.2**
an excess of events is observed with a **local significance of 2.2σ**

All consistent with the expectation from the production of the standard model Higgs boson

---

The 7TeV data ICHEP **ttH,H->bb analysis** is also included in the combination
It directly probes the ttH vertex. Sensitivity in [110-140] is from 3-7 SM
No evidence of an excess.

5.1 fb^{-1} @ 7 TeV (2011): HIG-12-044

The Channels:

- High Resolution channels
  - H->γγ [ICHEP results]
  - H->ZZ [minor changes in the analysis + LUMI UPDATE]
- Low Resolution channels
  - H->WW [analysis improved + LUMI UPDATE]
  - H-> bb [analysis improved + LUMI UPDATE]
  - **H->ττ [analysis improved + LUMI UPDATE]**

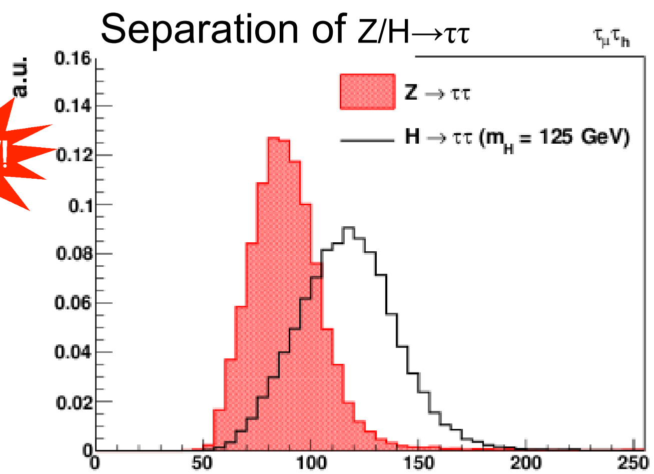
H->ττ analysis in a nut shell

The only handle we have to study Higgs coupling to leptons.
High σ·BR at low mass: sensitive to all production modes.
BUT:

- **taus decays hadronically 65% of the times: experimental challenge**
- **2-4 neutrinos in the tau decay**
  degrade mass resolution
- **dominated by Z->ττ decay**

General strategy:

- reconstruct hadronic τ decays with the hadron+strip algorithm
  channels included in the search: $\tau_e\tau_\mu$ $\tau_\mu\tau_h$ $\tau_\mu\tau_\mu$ $\tau_e\tau_h$ $\tau_h\tau_h$ NEW!
- likelihood method to reconstruct the $m_{\tau\tau}$ (SVFit)
- maximum likelihood fit to the $m_{\tau\tau}$ distributions in 5/2 categories with different S/B ratio [enhance specific higgs production mechanisms]



5.1 fb^{-1} @ 7 TeV (2011) + 12.2 fb^{-1} @ 8 TeV (2012): HIG-12-043
analysis updated since ICHEP, big improvements:
new categories + MVA MET + simplified VBF selection + 0jet category for bkg constrain only

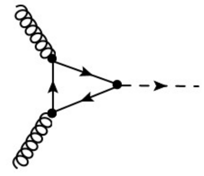
Event categorization

0-Jet
In situ calbration of backgrounds

0-Jet, p_T(lep.)≤30 GeV	0-Jet, p_T(lep.)>30 GeV

No attempt to extract signal from these categories.

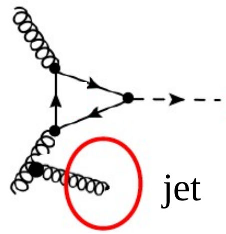
NEW!



Inclusive

1-Jet
Suppression of backgr. from $Z \rightarrow \tau\tau$

1-Jet, p_T(lep.)≤30 GeV • Large statistics.	1-Jet, p_T(lep.)>30 GeV • Improved resolution of $m_{\tau\tau}$. • Less background from $Z \rightarrow \tau\tau$.



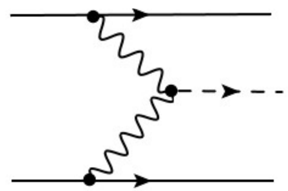
Boosted

2-Jet/VBF
Suppression of bkg from Z->ττ

2-Jet, VBF
- Cut based: mjj>XXX, |Δη|>XXX, central jet veto.

NEW!

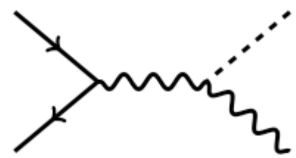
Increasing $p_T(\tau/\mu)$



VBF

+ VH, H->ττ analysis
less sensitive with respect to 1 and 2jets due to low cross section

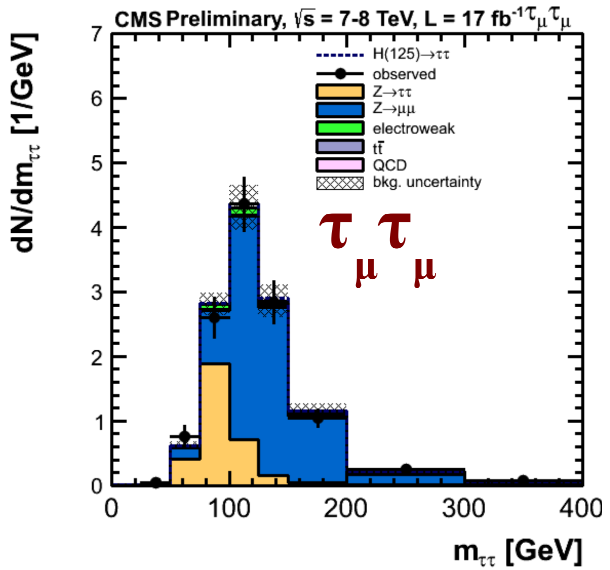
additional leptons from V decay
- less bkg from Z->ττ
- main background from dibosons

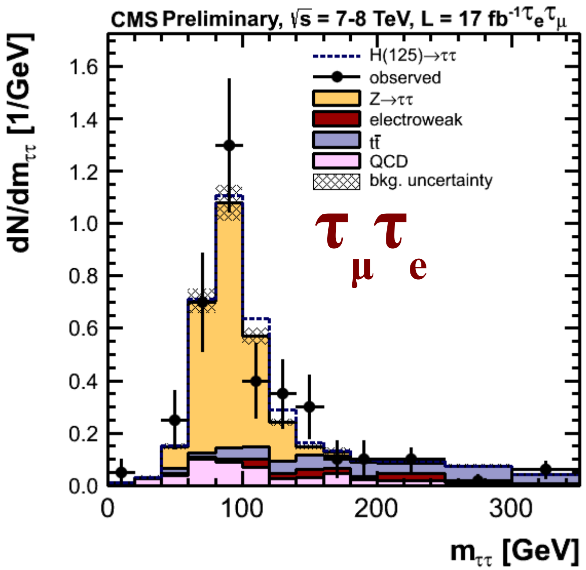


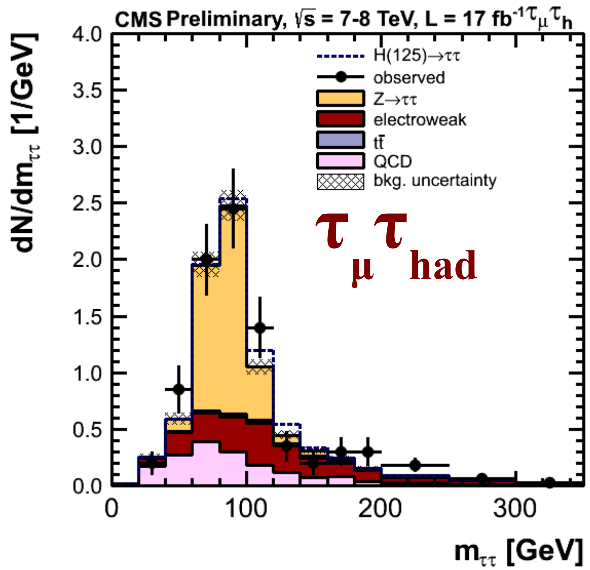
Associated

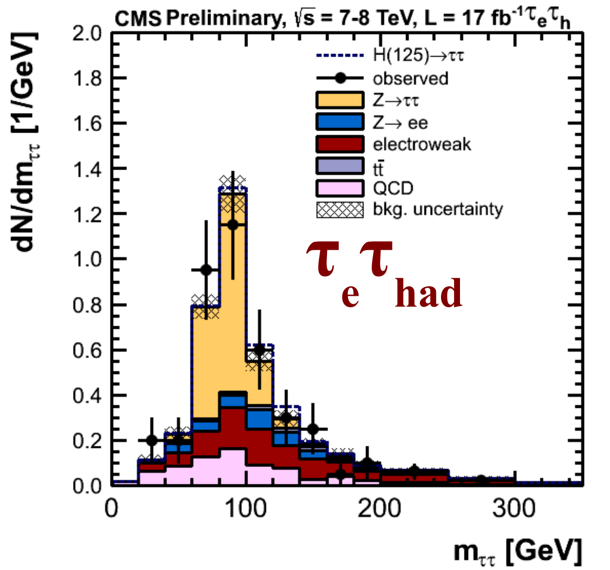
5.1 fb^{-1} @ 7 TeV (2011) + 12.2 fb^{-1} @ 8 TeV (2012): HIG-12-051

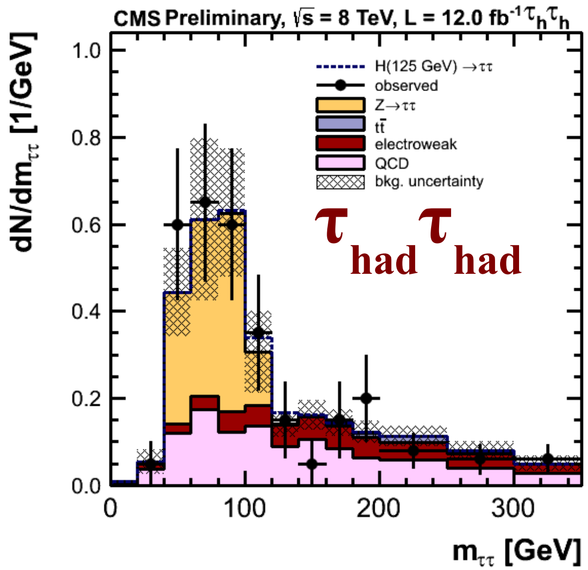
2jet VBF category







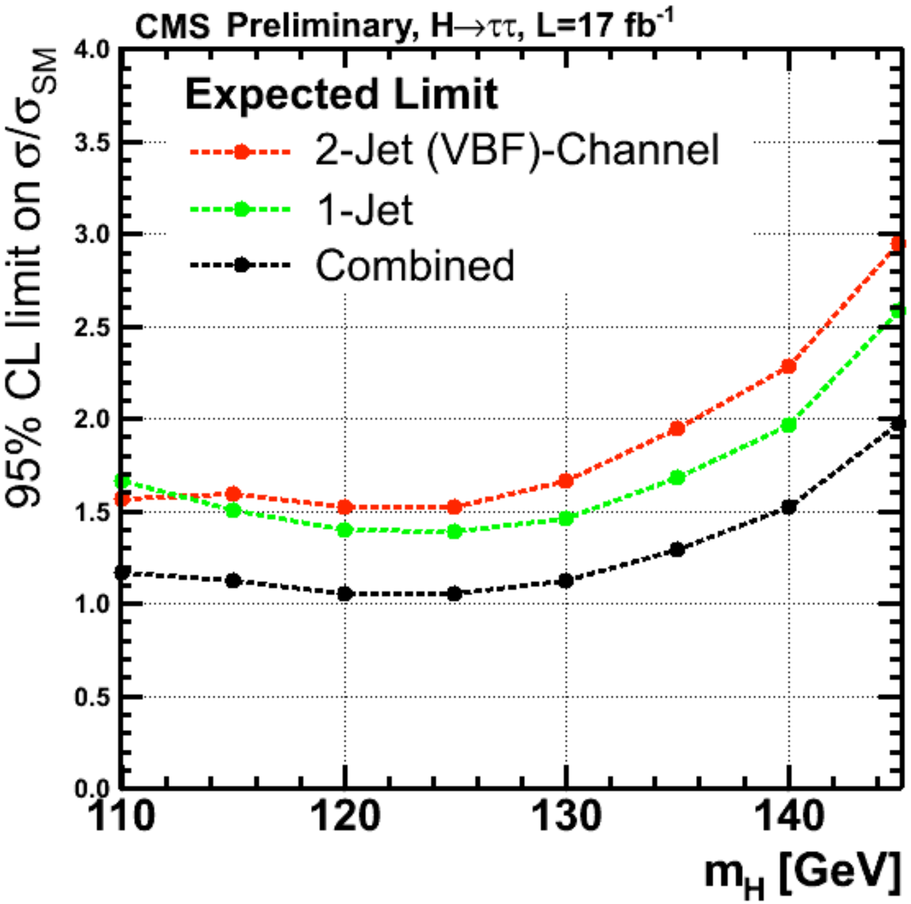


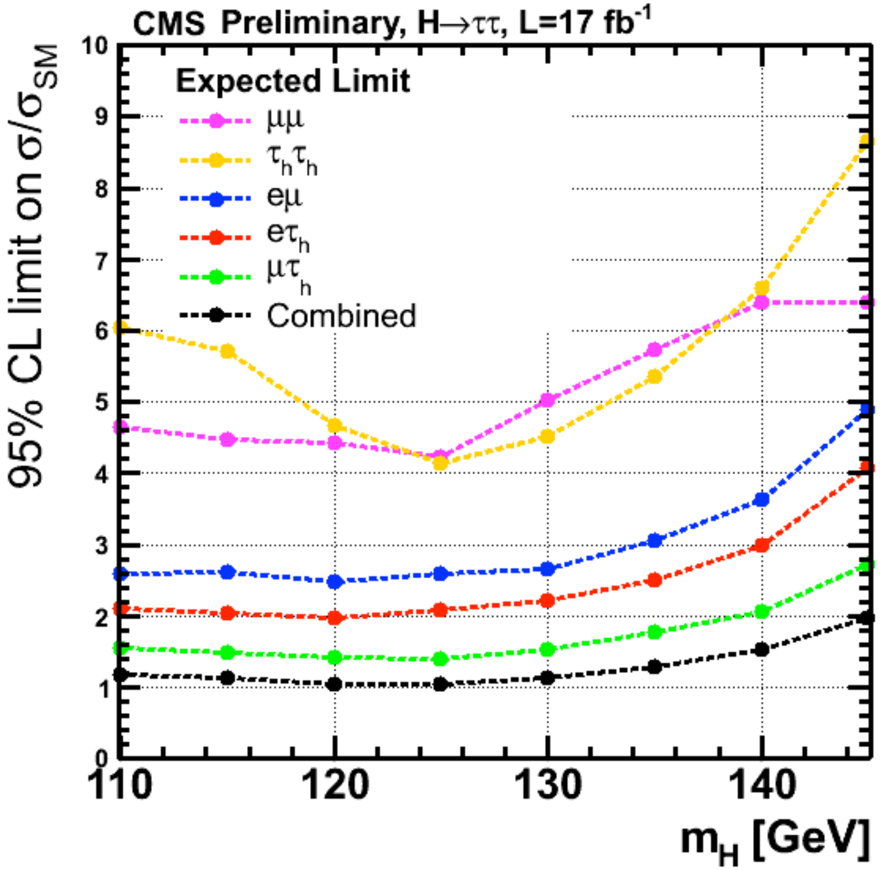


- After template fit has been applied (S+B hypothesis).
- Uncertainties after fit.

10

Sensitivity

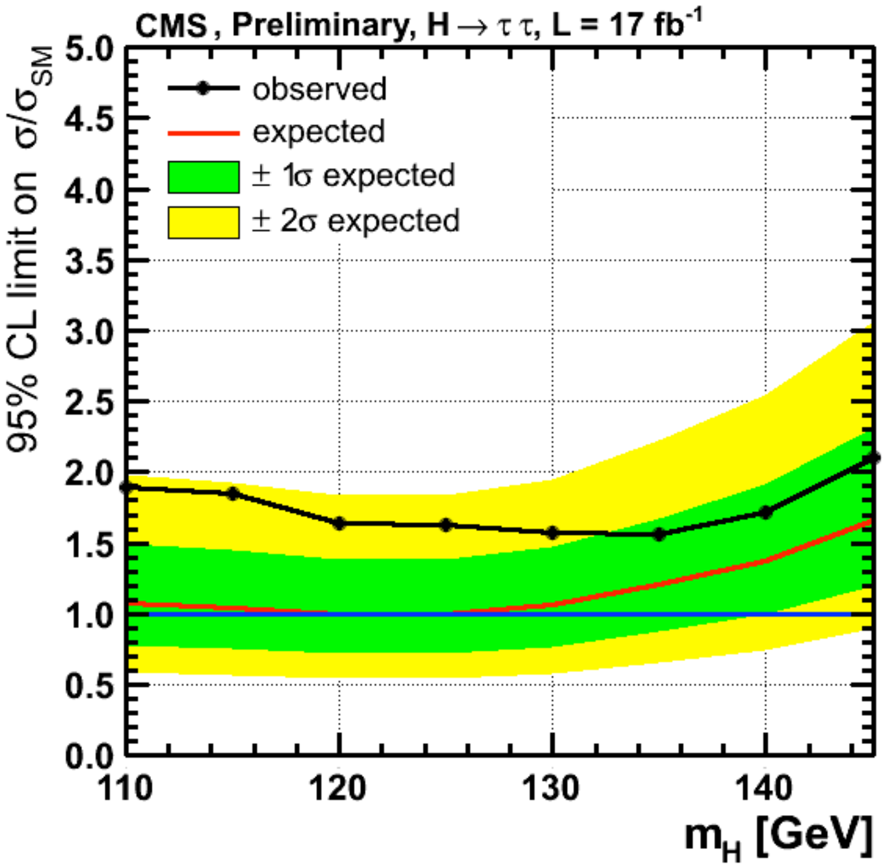


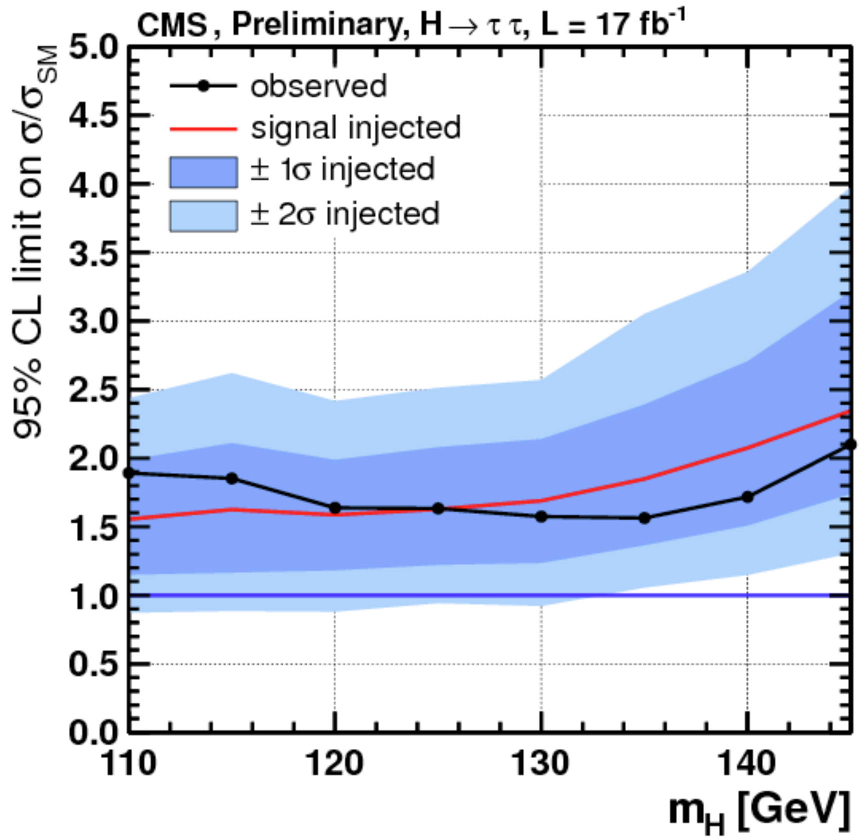


VBF and 1jet category roughly at equal strenght @ m_H=125 GeV

Strongest channel is μτ (eτ,eμ of equal strenght)

Results





With more data and improvements the SM sensitivity is reached

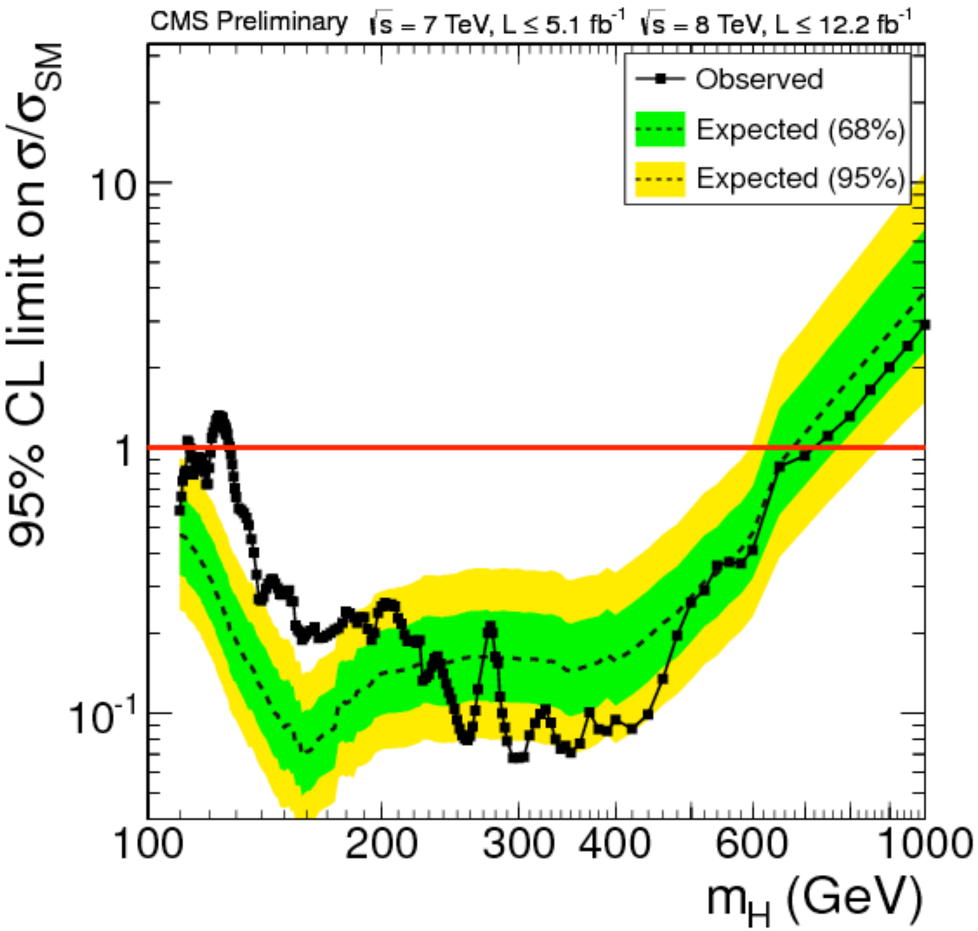
Observed 95% CL exclusion limit for mH=125 GeV = 1.63 (expected 1.00)

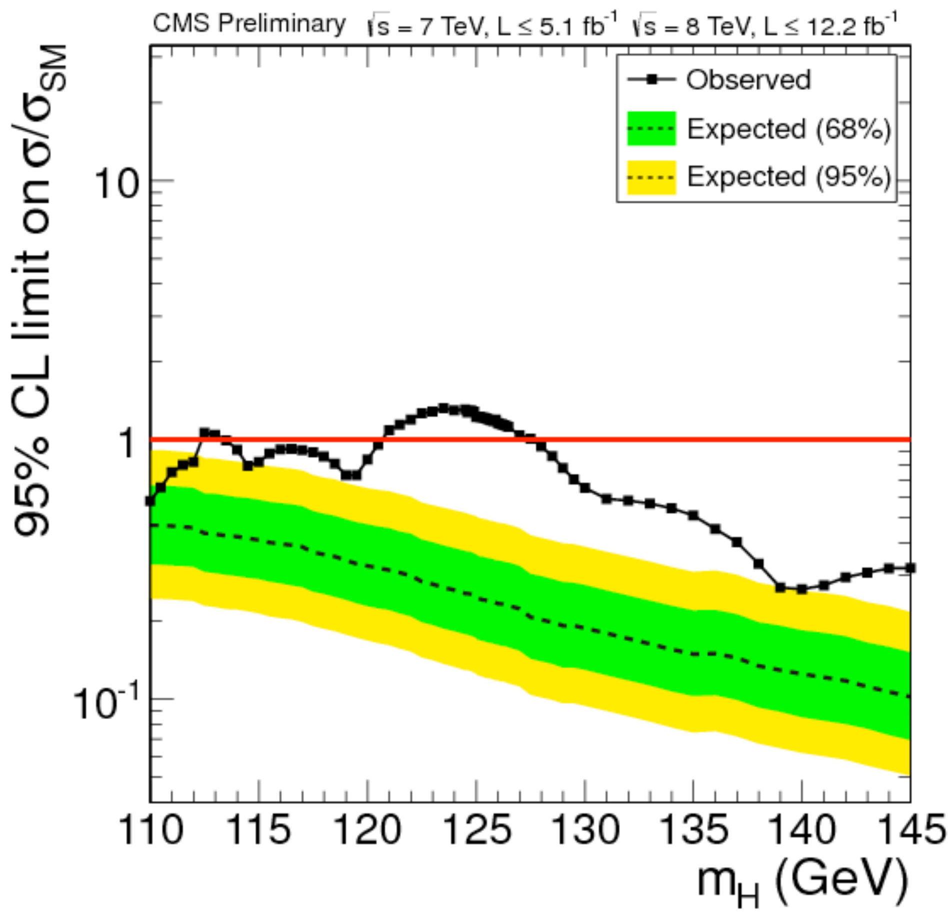
An mild excess is found, and it is compatible with the expectation from the production of the standard model Higgs boson

Combination

Combining the results: Limit on σ/σ_{SM}

The 95% CL upper limits on the cross section ratio σ/σ_{SM} for the SM Higgs as function of mH



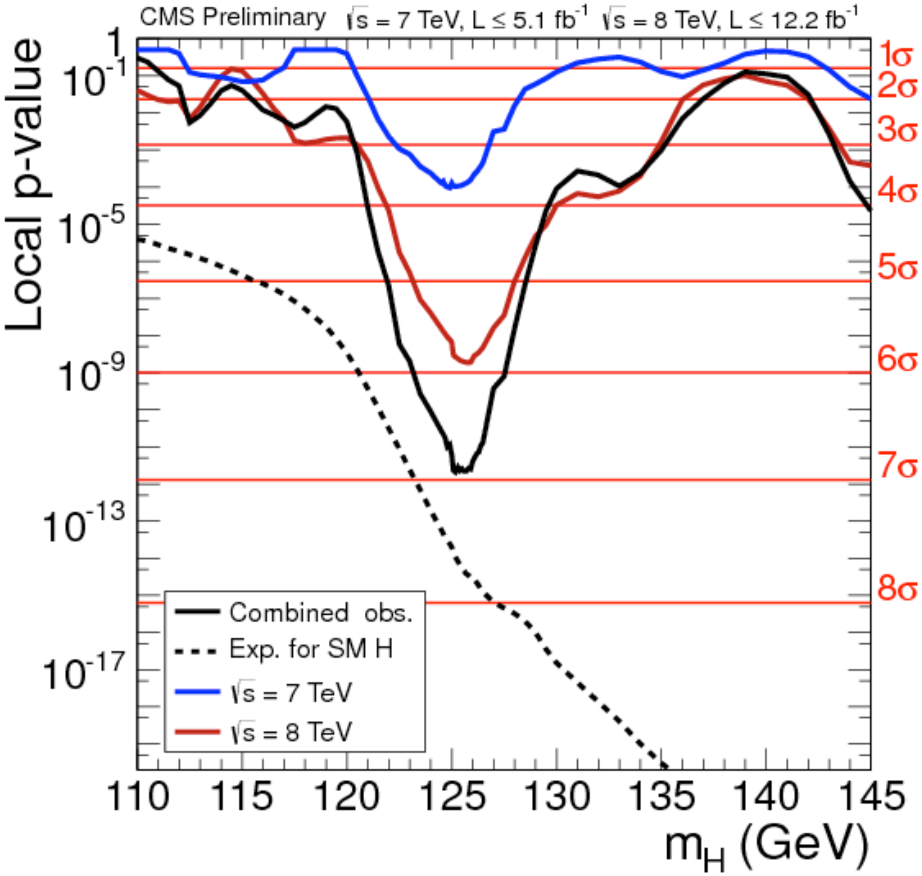


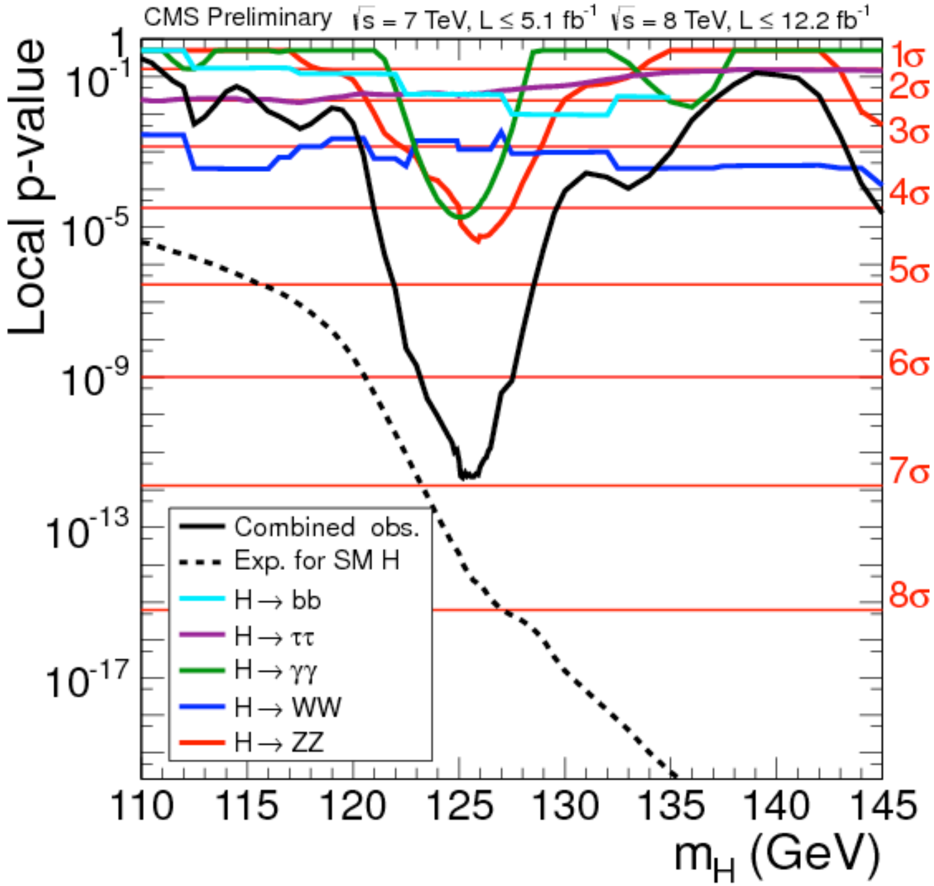
In absence of signal we expect to exclude the entire range from 110-650 GeV at 95% CL
For mH > 200 GeV the differences with obs and exp limits are consistent with statistical fluctuations

The broad excess for mH<200 GeV is attributed to the new boson with m~125GeV

Combining the results: significance of the excess

Local p-value: Probability for a background fluctuation to give an excess as large as the (average) signal size expected for a SM Higgs



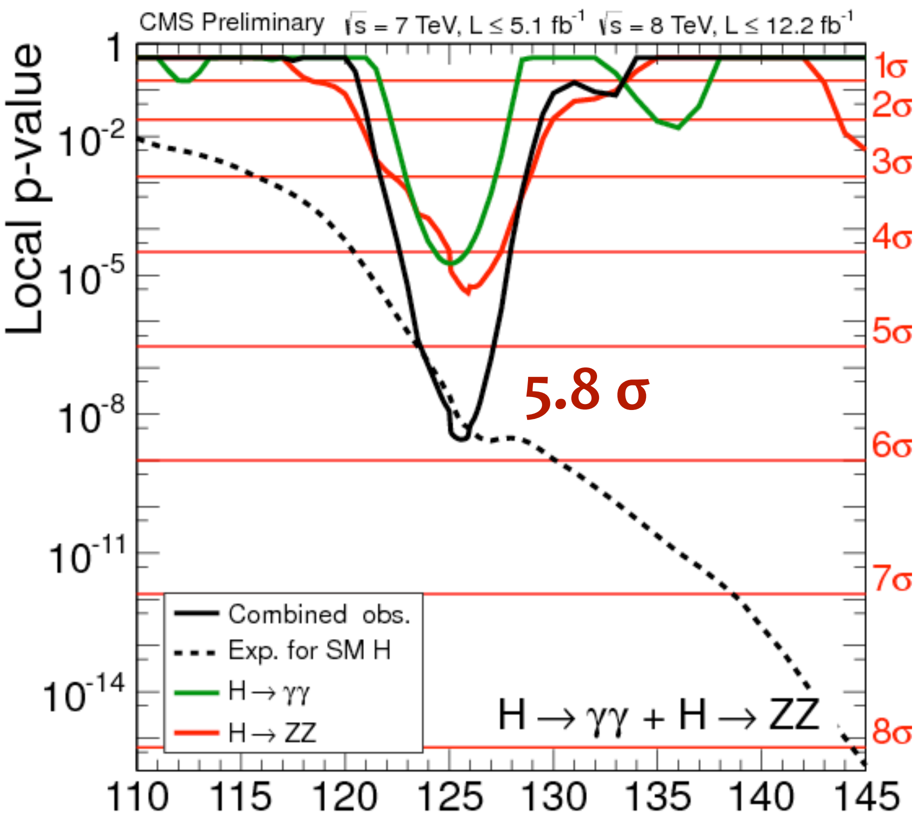


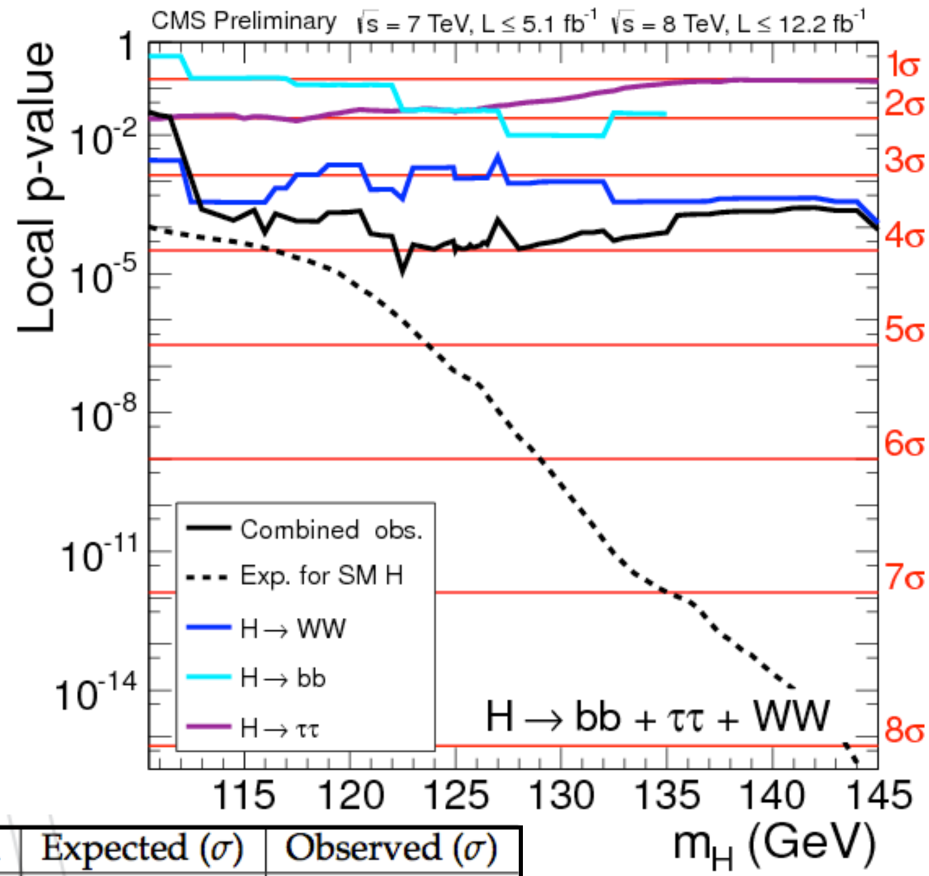
With the analyzed data the peak significance is 6.9 σ

Other than the '125-GeV boson', we see no evidence for a significant excess of events that could be attributed to either an additional particle or particles

Combining the results: significance of the excess

Local p-value: Probability that background fluctuates to give an excess as large as the (average) signal size expected for a SM Higgs





Decay mode or combination	Expected (σ)	Observed (σ)
ZZ	5.0 →	4.4
$\gamma\gamma$	2.8 ←	4.0
WW	4.3 →	3.0
bb	2.2 →	1.8
$\tau\tau$	2.1 →	1.8
$\gamma\gamma$ + ZZ	5.7	5.8
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	7.8	6.9

The Measurements

1. For the SM Higgs we expect 7.8σ significance
2. Something observed 6.9σ away from the BG only hypothesis

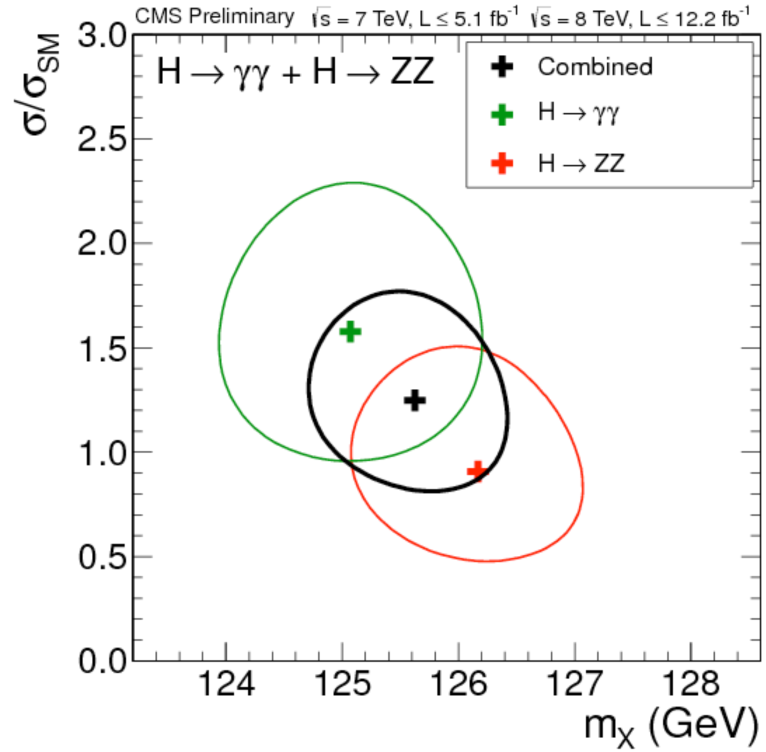
   maximum significance flat for mH in [125.1-125.9] GeV
3. Mass Measurements with the high resolution channels

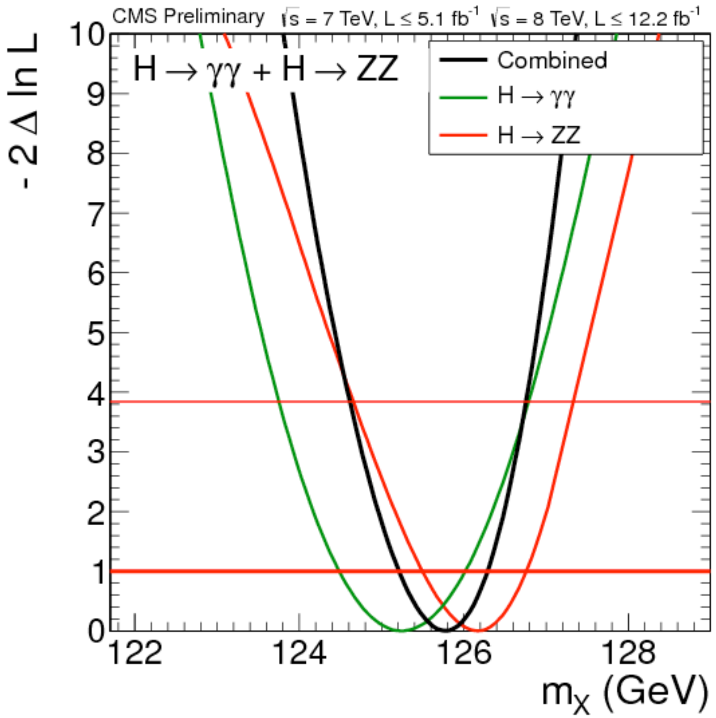
Mass of the observed state

2D 68% CL regions for the two parameters that are let free in the likelihood

- signal strenght modifier μ (σ/σ_{SM}) - mass m_X

for the 2 high-resolution channels → the channels give consistent results and thus can be combined





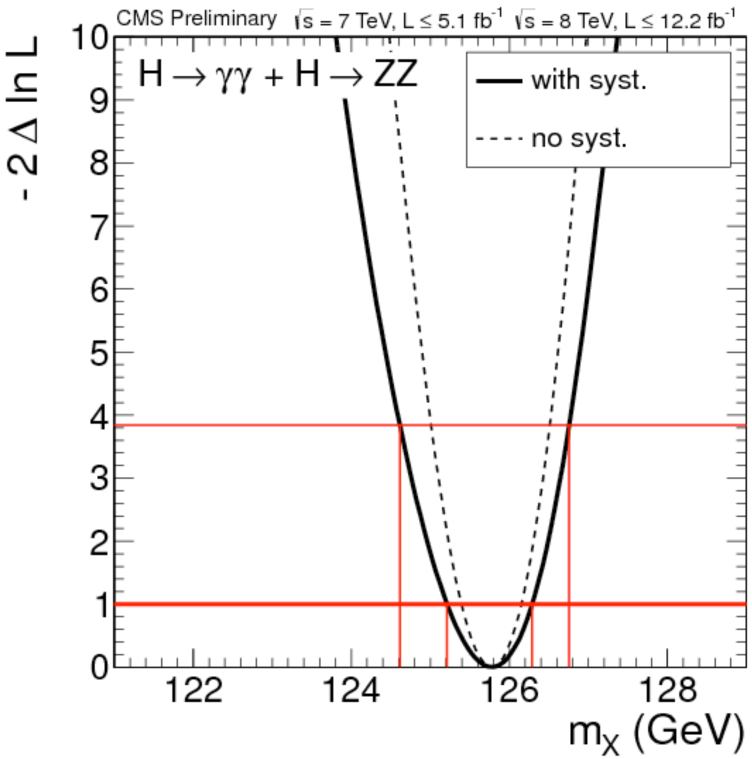
68% CL interval

m_X = 125.8± 0.5 GeV

Model-dependent 2D combination:
relative event yields between the two channels fixed to the SM

Model independent combination used for nominal result, with unconstrained normalization for HZZ, gg Hγγ, VBF Hγγ

Mass of the observed state



To evaluate the statistical component of the error: perform a scan of the test statistic with all nuisance parameters fixed to their best-fit values

68% CL interval:

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

Systematic part obtained subtracting in quadrature stat. uncert. from the total one

Systematic uncertainty :

As coming from [H->γγ and H->ZZ], dominant contribution is from the knowledge of the energy scales for photons and leptons:

- extrapolation from the standard candles (J/ψ→μμ, Z→μμ/ee) to the kinematic of a H125 signal (p_T, η)
- extrapolation from electrons to photons

The control of the energy resolution on data is also important

The Measurements

1. For the SM Higgs we expect 7.8σ significance
2. Something observed 6.9σ away from the BG only hypothesis

   maximum significance flat for mH in [125.1-125.9] GeV

3. Mass Measurements with the high resolution channels

   ZZ and γγ measures m_X = 125.8 ± 0.4(stat) ± 0.4(syst)

   This mass is used to fix m_H for the measurement of properties

4. Compatibility of the observed state with the SM Higgs

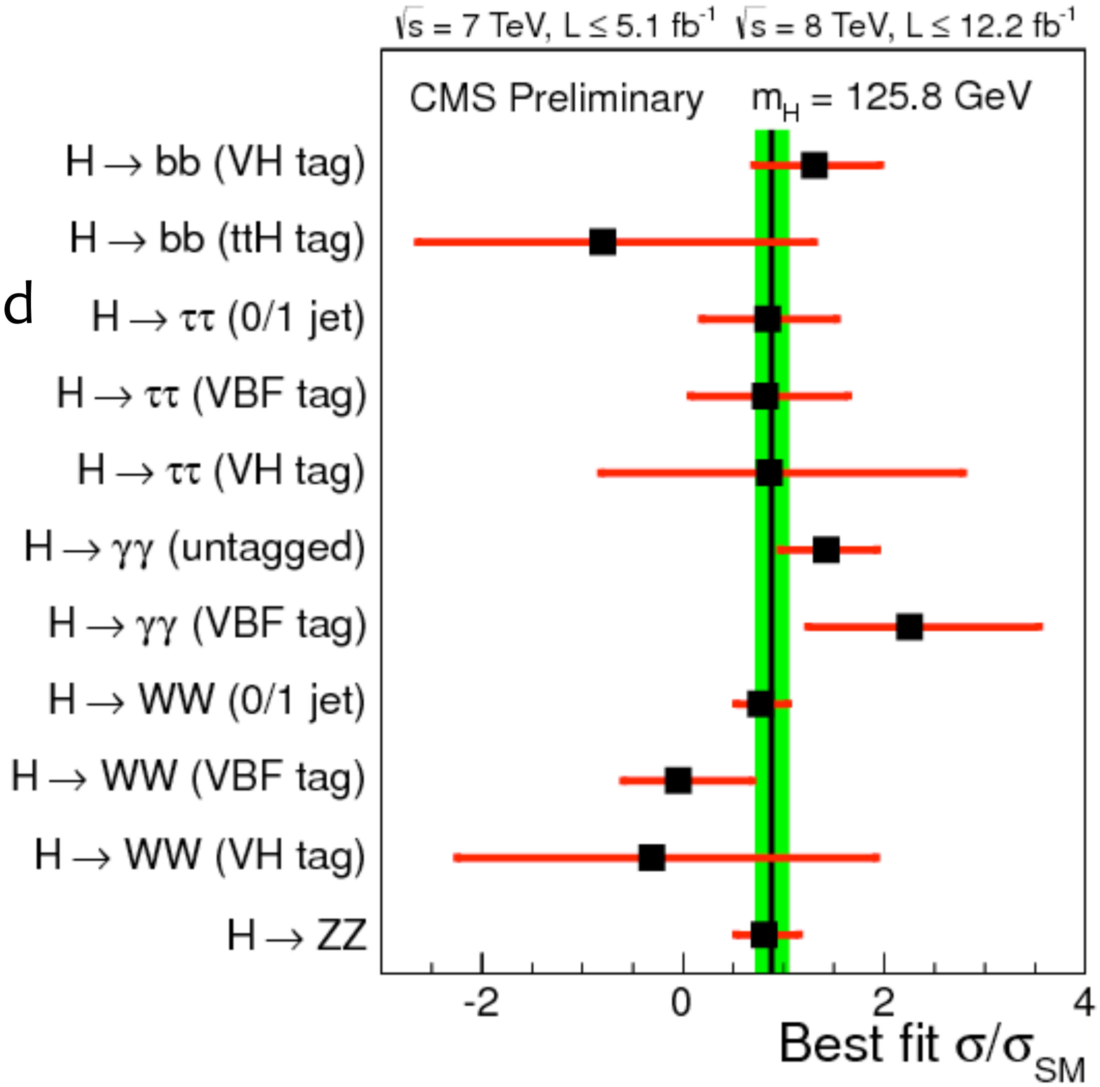
   Signal strenght in channel combinations and sub-combinations

Signal Strenght at m_H=125.8 GeV

First compatibility test:
best fit value for the common μ (signal strength modifier) obtained in the combination of all channels

The observed μ for m_H = 125.8 is consistent within 1σ with SM:
0.88 ± 0.21

The sum q(μ=1) for any of the N sub-combinations can be used as X^2 (with ndof =N) to test the compatibility of each sub-combination to the SM

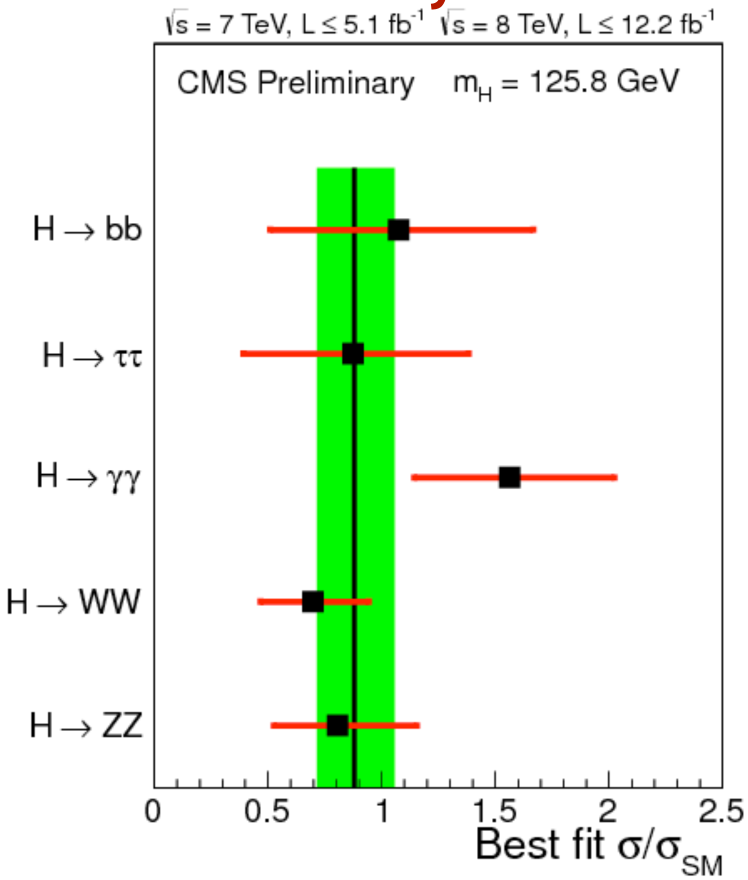


X^2/n.d.f. = 8.7/11
- asymptotic p-value = 0.65%
[from toys = 0.46%]

Signal Strenght at m_H=125.8 GeV

μ values obtained in different sub-combinations of search channels organized by

decay mode

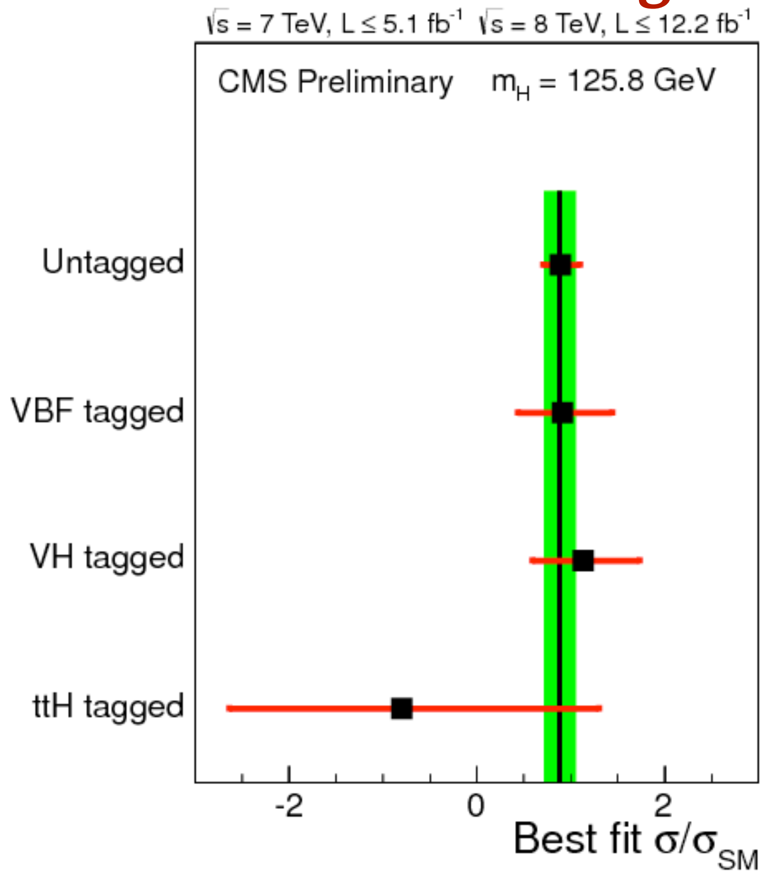


X^2/n.d.f. = 4.3/5

- asymptotic p-value = 0.51%

[from toys = 0.54%]

additional tags



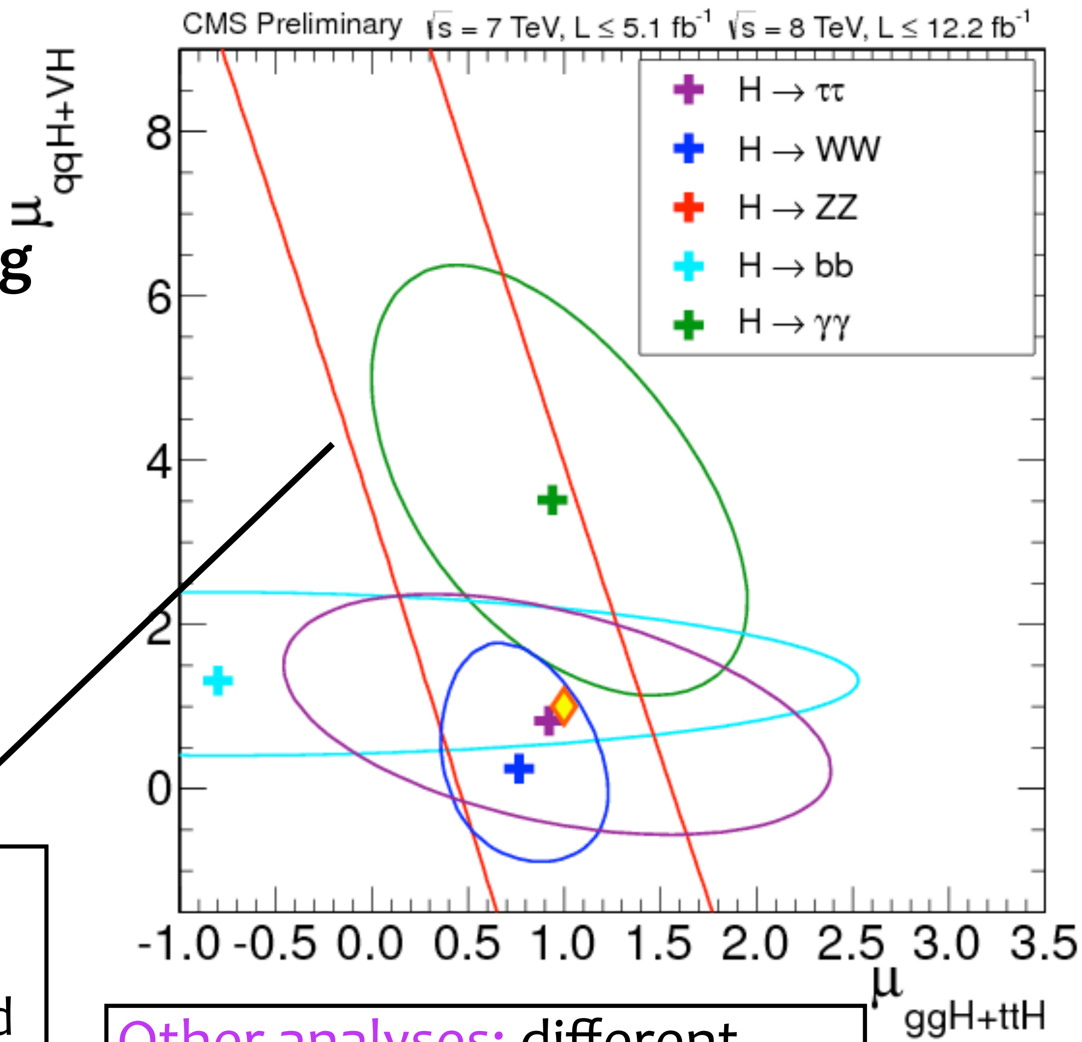
X^2/n.d.f. = 1.3/4

- asymptotic p-value = 0.86%

[from toys = 0.87%]

Signal Strenght at m_H=125.8 GeV

A combination of channels associated with a particular decay mode and explicitly targeting different production mechanisms can be used to test the relative strengths of the couplings to the vector bosons [μ_{qqH+VH}] and top quarks [$\mu_{ggH+ttH}$]



ZZ analysis: the different production mechanisms are not yet explicitely separated [diagonal band corresponding to same values of total cross section]

Other analyses: different production mechanisms are explicitely exploited [elliptical allowed regions]

The Measurements

1. For the SM Higgs we expect 7.8σ significance
2. Something observed 6.9σ away from the BG only hypothesis

   maximum significance flat for mH in [125.1-125.9] GeV
3. Mass Measurements with the high resolution channels

   ZZ and γγ measures m_X = 125.8 ± 0.4(stat) ± 0.4(syst)

   This mass is used to fix mH for the properties measurements
4. Compatibility of the observed state with the SM Higgs

   Signal strenght in channel combinations and sub-combinations

   - at mH = 125.8 combined σ_x/σ_{SM} = 0.88 ± 0.21 (different ways of splitting contributions fully compatible, with min(pValue) ~ 45%)

Test of the Couplings

The Coupling scaling factors

1. **The event yield in any mode is related to partial and total Higgs boson decay widths**

$$N(xx \to H \to yy) \sim \sigma(xx \to H)*B(H \to yy) \sim \Gamma_{xx}\ \Gamma_{yy}\ /\ \Gamma_{tot}$$

2. **Eight parameters ($\Gamma_{WW}\Gamma_{tt}\Gamma_{ZZ}\Gamma_{bb}\Gamma_{\tau\tau}\Gamma_{gg}\Gamma_{\gamma\gamma}\Gamma_{tot}$) are relevant for the following**
   - $\Gamma_{gg}\Gamma_{\gamma\gamma}$ are generated by loop diagrams and are directly sensitive to the presence of new physics
   - Γ_{tot} is kept as an independent parameter to accommodate the possibility of a Γ_{BSM}
3. **Current limited dataset allows only to fit for a few of them at a time**

4. **The Γ_i are proportional to the square of the Higgs boson couplings. To test for possible deviations in the data from the SM rates, modified couplings [denoted by scale factors k_i] are introduced according to the LHC HXSWG prescriptions** arxiv:1209.0040

5. **We fit the data and the allowed regions of $\{k_i\}$, or the allowed region for one k, allowing all the others k's to take arbitrary values**

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   Test of the Couplings

   ✓ Test fermions vs vector boson couplings

Universal vector and fermion couplings

Rescale universally the Higgs boson couplings to fermions by k_F and coupling to vector bosons by k_V

- σ_{VBF}, σ_{VH}, Γ_{WW}, Γ_{ZZ} scale as $(k_v)^2$

- σ_{ttH}, Γ_{ff}, scale as $(k_F)^2$

- σ_{ggH}, Γ_{gg}, scale as $(k_F)^2$

[assume they're just the SM quarks in the loop]

- $\Gamma_{\gamma\gamma}$, scale as $|\alpha \cdot k_v + \beta \cdot k_F|^2$

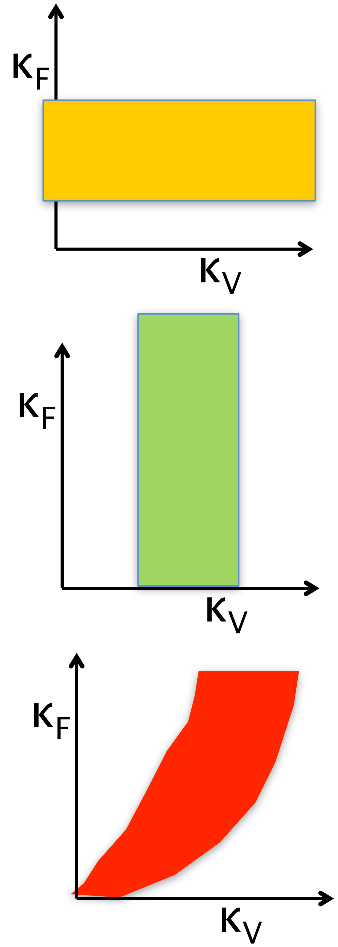
[assume W, t, b in the loop, as in the SM]

- $\Gamma_{tot} = \sum \Gamma_X$ for all X decays in SM

[assume no other BSM decay mode]

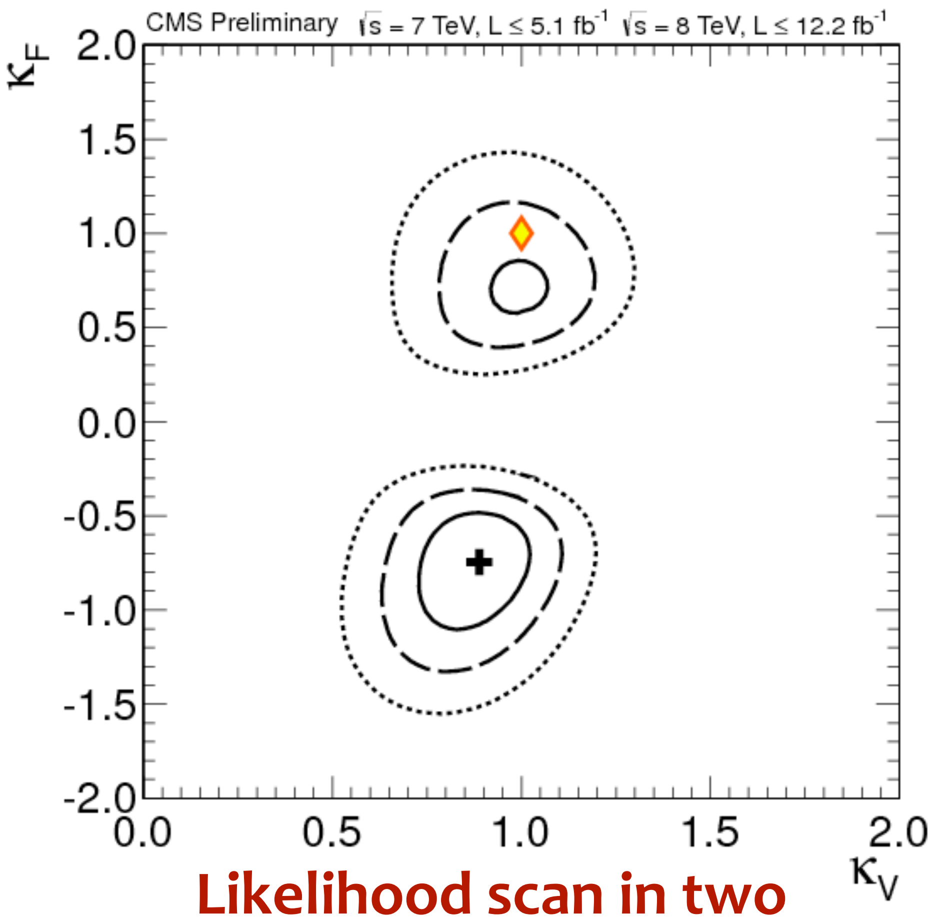
Universal vector and fermion couplings

Prod.	Decay	Signal yield scale	Approx
VH	bb	$\kappa_V^2\ \kappa_F^2\ /\ [¾\ \kappa_F^2 + ¼\ \kappa_V^2]$	κ_V^2
ttH	bb	$\kappa_F^2\ \kappa_F^2\ /\ [¾\ \kappa_F^2 + ¼\ \kappa_V^2]$	κ_F^2
VBF	ττ	$\kappa_V^2\ \kappa_F^2\ /\ [¾\ \kappa_F^2 + ¼\ \kappa_V^2]$	κ_V^2
ggH	ττ	$\kappa_F^2\ \kappa_F^2\ /\ [¾\ \kappa_F^2 + ¼\ \kappa_V^2]$	κ_F^2
ggH	WW, ZZ	$\kappa_F^2\ \kappa_V^2\ /\ [¾\ \kappa_F^2 + ¼\ \kappa_V^2]$	κ_V^2
VBF	WW	$\kappa_V^2\ \kappa_V^2\ /\ [¾\ \kappa_F^2 + ¼\ \kappa_V^2]$	$\kappa_V^4\ /\ \kappa_F^2$
ggH	γγ	$\kappa_F^2\ \ \lvert\kappa_V - 0.21\ \kappa_F\rvert^2\ /\ [...]$	κ_V^2
VBF	γγ	$\kappa_V^2\ \ \lvert\kappa_V - 0.21\ \kappa_F\rvert^2\ /\ [...]$	$\kappa_V^4\ /\ \kappa_F^2$

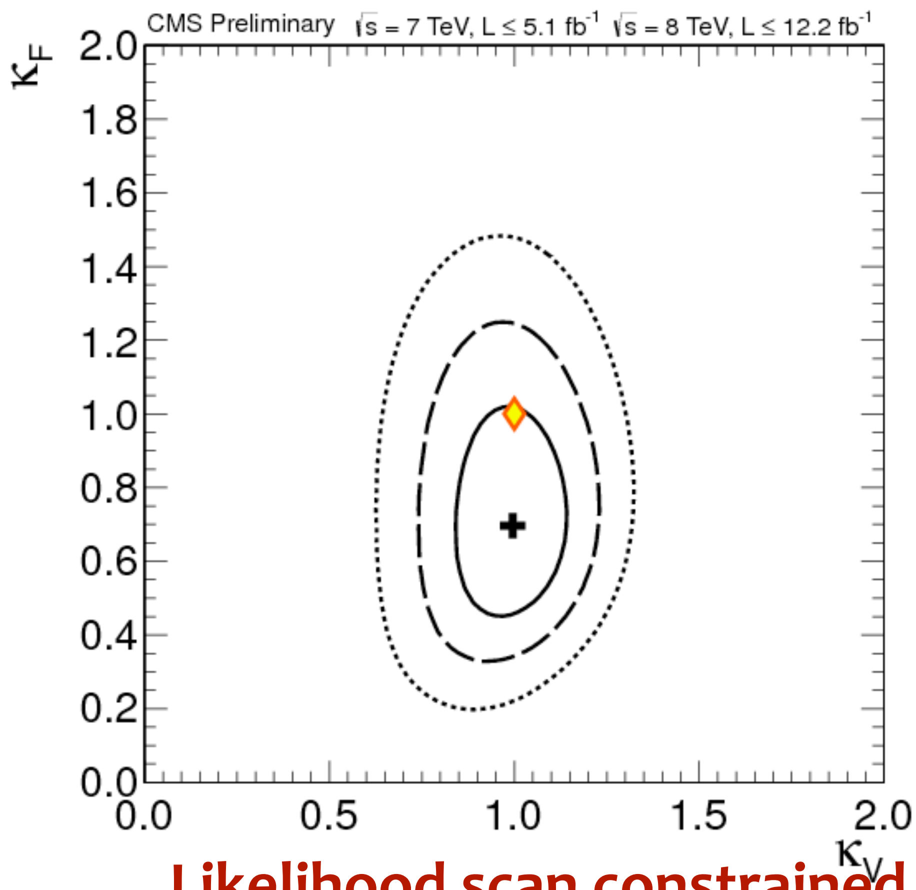


Universal vector and fermion couplings

2D likelihood scan of the test statistic $q(k_v, k_f)$ vs the (k_v, k_f) parameters



Likelihood scan in two quadrants (++), (+-)

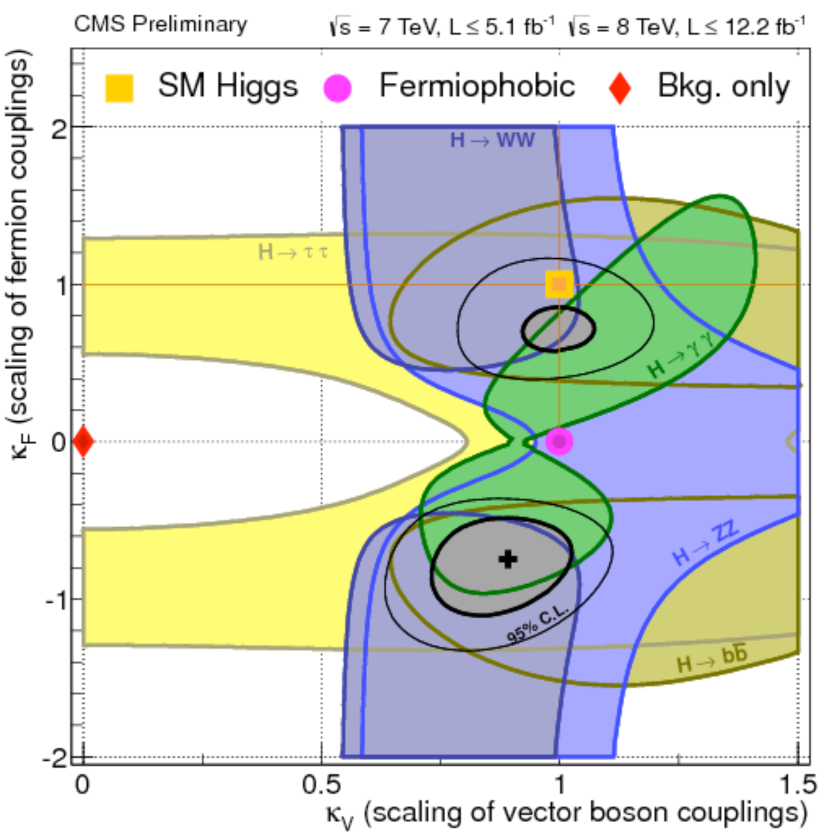


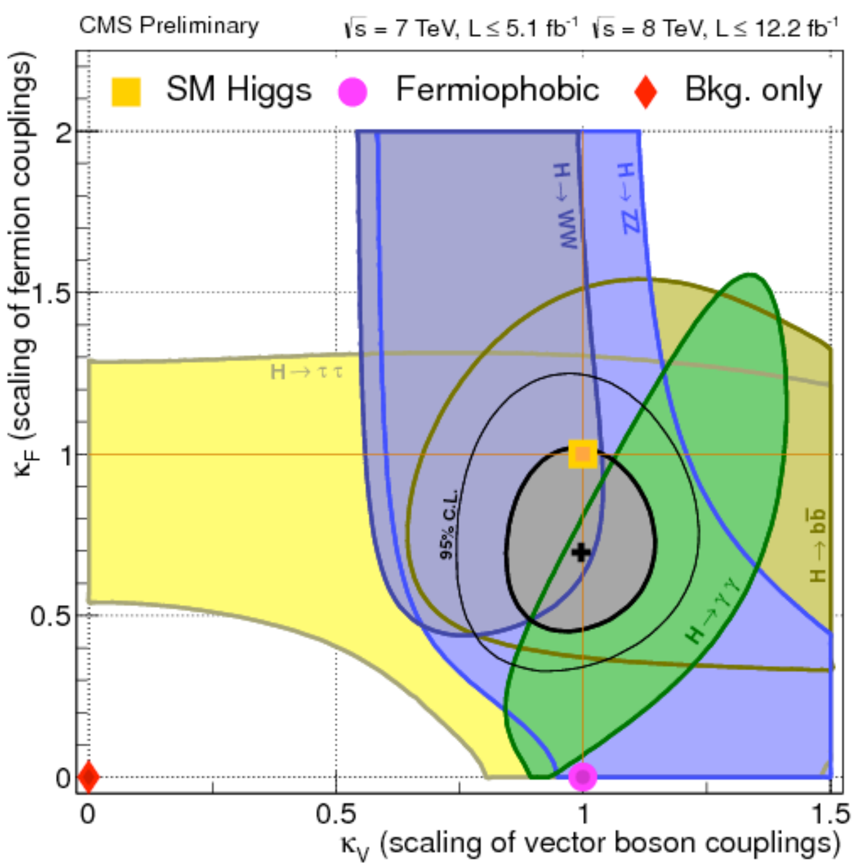
Likelihood scan constrained to the (++) quadrant

Solid, dotted, dashed contours show the 68%, 95%, 99.7% CL ranges
Yellow diamond shows the SM point (kv, kf) = (1,1)

Universal vector and fermion couplings

2D likelihood scan of the test statistic $q(k_v, k_f)$ vs the (k_v, k_f) parameters: interplay of different decay modes





The 1D 95% confidence level intervals for kv and kf while the other parameter is fixed to unity, are obtained from a 1D-scans and are:

k_v [0.78 - 1.19] k_f [0.40 - 1.12] **The data agree with the SM expectations**

The Measurements

1. For the SM Higgs we expect 7.8σ significance
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   maximum significance flat for mH in [125.1–125.9] GeV
3. Mass Measurements with the high resolution channels

   ZZ and $\gamma\gamma$ measures mx = 125.8 ± 0.4(stat) ± 0.4(syst)

   This mass is used to set mH (no profiling) for the properties measurements
4. Compatibility of the observed state with the SM Higgs

   Signal strenght in combination and sub-combination

   – at mH = 125.8 combined σ_x/σ_{SM} = 0.88 ± 0.21 (different ways of splitting contributions fully compatible with min(pValue) ~ 45%)

   Test of the Couplings

   ✓ Test fermions vs vector boson couplings

   ✓ **Test Castodial simmetry**

Testing Castodial Simmetry

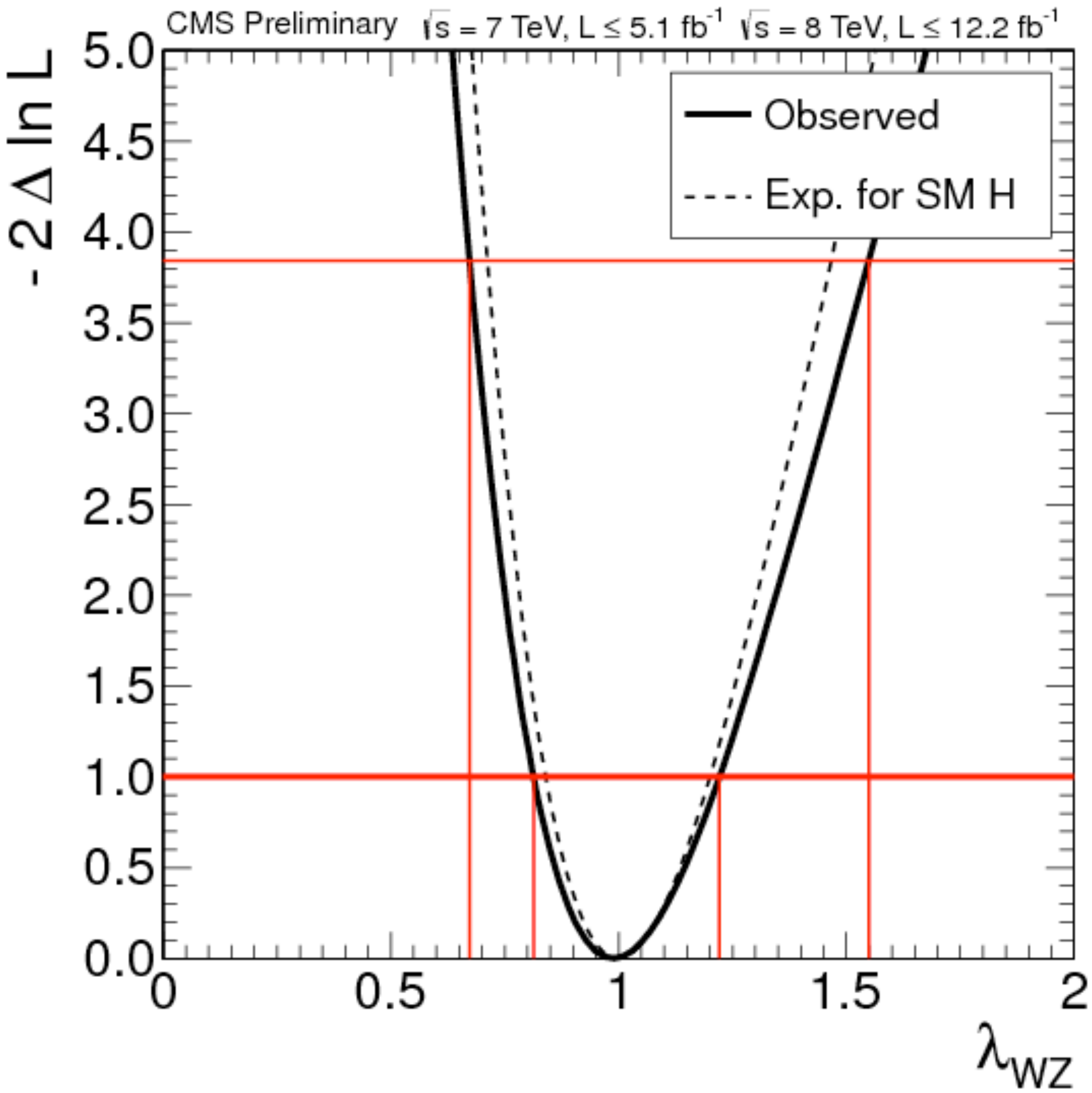
Test that the coupling to W and Z bosons scale together from a fit to the full dataset, as in (kv, kf) but with independent parameters for W and Z

Parametrization: $k_{F}, k_{Z}, \lambda_{WZ} = k_{W}/k_{Z}$

[assume no other BSM decay mode]

Testing Castodial Simmetry

1D likelihood scan vs λ_{WZ} when k_F, k_Z are profiled together with all the other nuisance parameters



λ_{WZ} **is in the interval [0.67 - 1.55] at 95% CL.**

The data agree with the SM expectations

The Measurements

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   Signal strenght in combination and sub-combination

   - at mH = 125.8 combined σ_x/σ_{SM} = 0.88 ± 0.21 (different ways of splitting contributions fully compatible with min(pValue) ~ 45%)

   Test of the Couplings

   ✓ Test Castodial simmetry

   ✓ Test fermions vs vector boson couplings

   ✓ **Test no BSM physics in Loops or Total Width**

BSM Physics in loops

Processes induced by loop diagrams ($H \rightarrow \gamma\gamma$, $gg \rightarrow H$) can be particularly susceptible to the presence of new particles

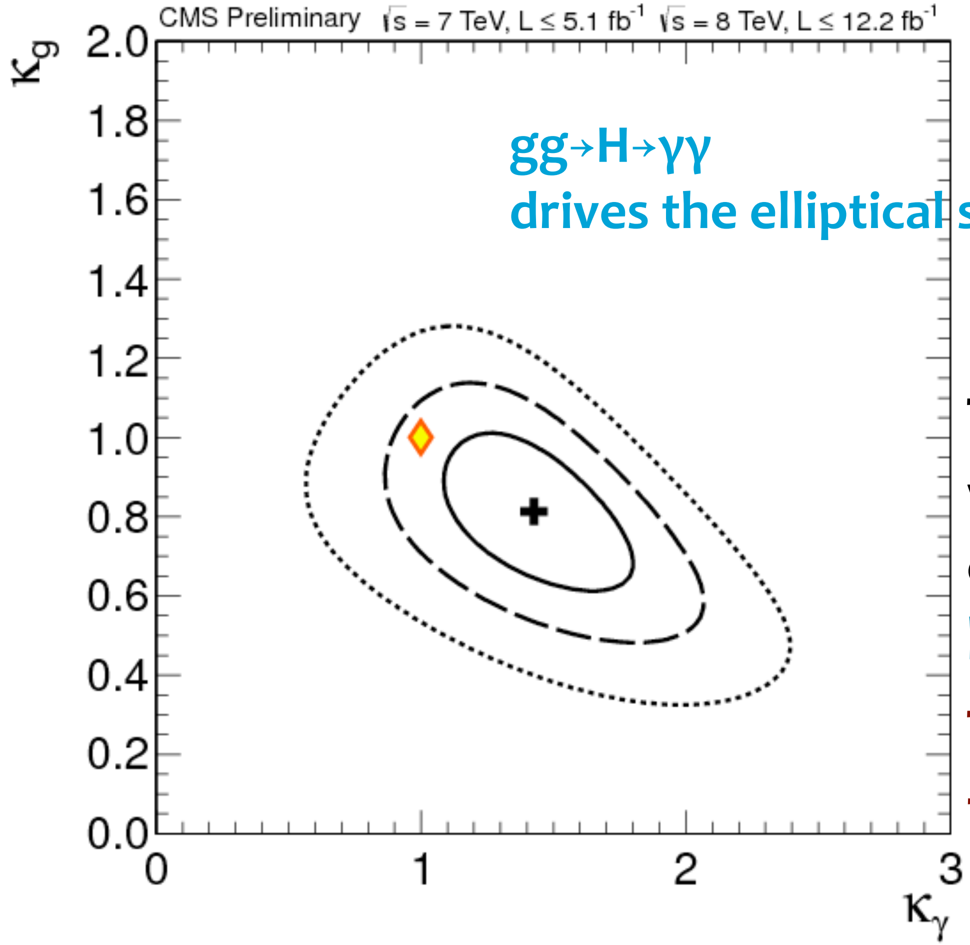
Combine and fit data for scaling factors k_γ and k_g for these two processes

$$\sigma_{ggH} \sim \kappa_g^2 \quad \Gamma_{gg} \sim \kappa_g^2 \quad \Gamma_{\gamma\gamma} \sim \kappa_\gamma^2$$

(assume the tree-level couplings between Higgs and the other particles as they are in the SM)

BSM Physics in loops

2D likelihood scan of the test statistic $q(k_\gamma, k_g)$ vs the (k_γ, k_g) parameters: interplay of different decay modes



The best fit value is $(k_\gamma, k_g) = (1.43, 0.81)$, while the 95% CL intervals for these coupling separately are:

k_γ [0.98 - 1.92] k_g [0.55 - 1.07]

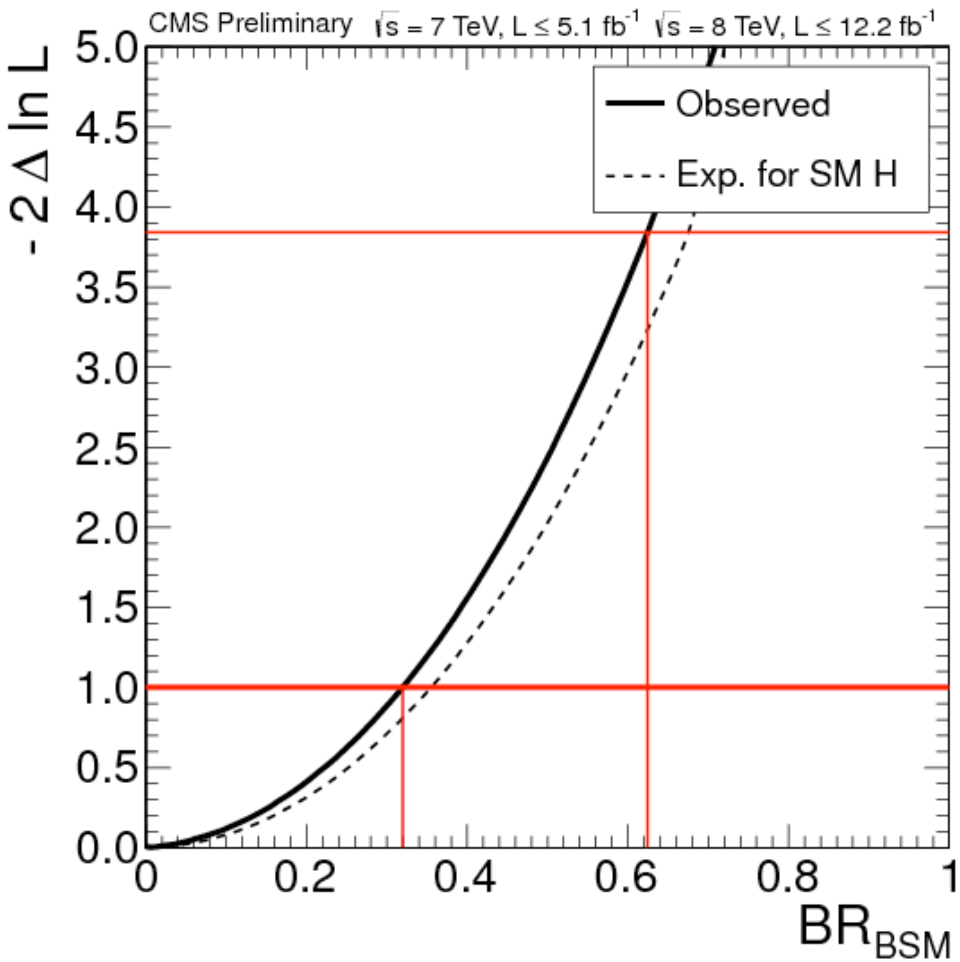
The data agree with the SM expectations

Solid, dotted, dashed contours show the 68%, 95%, 99.7% CL ranges

Yellow diamond shows the SM point $(k_\gamma, k_g) = (1,1)$

BSM Physics in Γ_{tot}

1D likelihood scan vs $BR_{BSM} = \Gamma_{BSM} / \Gamma_{tot}$ when k_γ, k_g are profiled together with all the other nuisance parameters



BR_{BSM} is in the interval [0.00 - 0.62] at 95% CL.

The data agree with the SM expectations

The Measurements

1. For the SM Higgs we expect 7.8σ significance
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   maximum significance flat for mH in [125.1-125.9] GeV

3. Mass Measurements with the high resolution channels

   ZZ and γγ measures $m_X = 125.8 \pm 0.4(stat) \pm 0.4(syst)$

   This mass is used to set mH (no profiling) for the properties measurements

4. Compatibility of the observed state with the SM Higgs

   Signal strenght in combination and sub-combination

   - at mH = 125.8 combined $\sigma_x/\sigma_{SM} = 0.88 \pm 0.21$ (different ways of splitting contributions fully compatible with min(pValue) ~ 45%)

   Test of the Couplings

   ✓ Test Castodial simmetry

   ✓ Test fermions vs vector boson couplings

   ✓ Test no BSM physics in Loops or Total Width

   ✓ **Test of fermion universality**

Fermion Universality

Several BSM models predict different couplings for the Higgs to different fermion kinds

Two benchmark models devised to probe this:

- allow separate couplings for up-type and down-type fermions: separate **t** from **b**, **τ**
- allow separate couplings for quarks and leptons

In particular define:

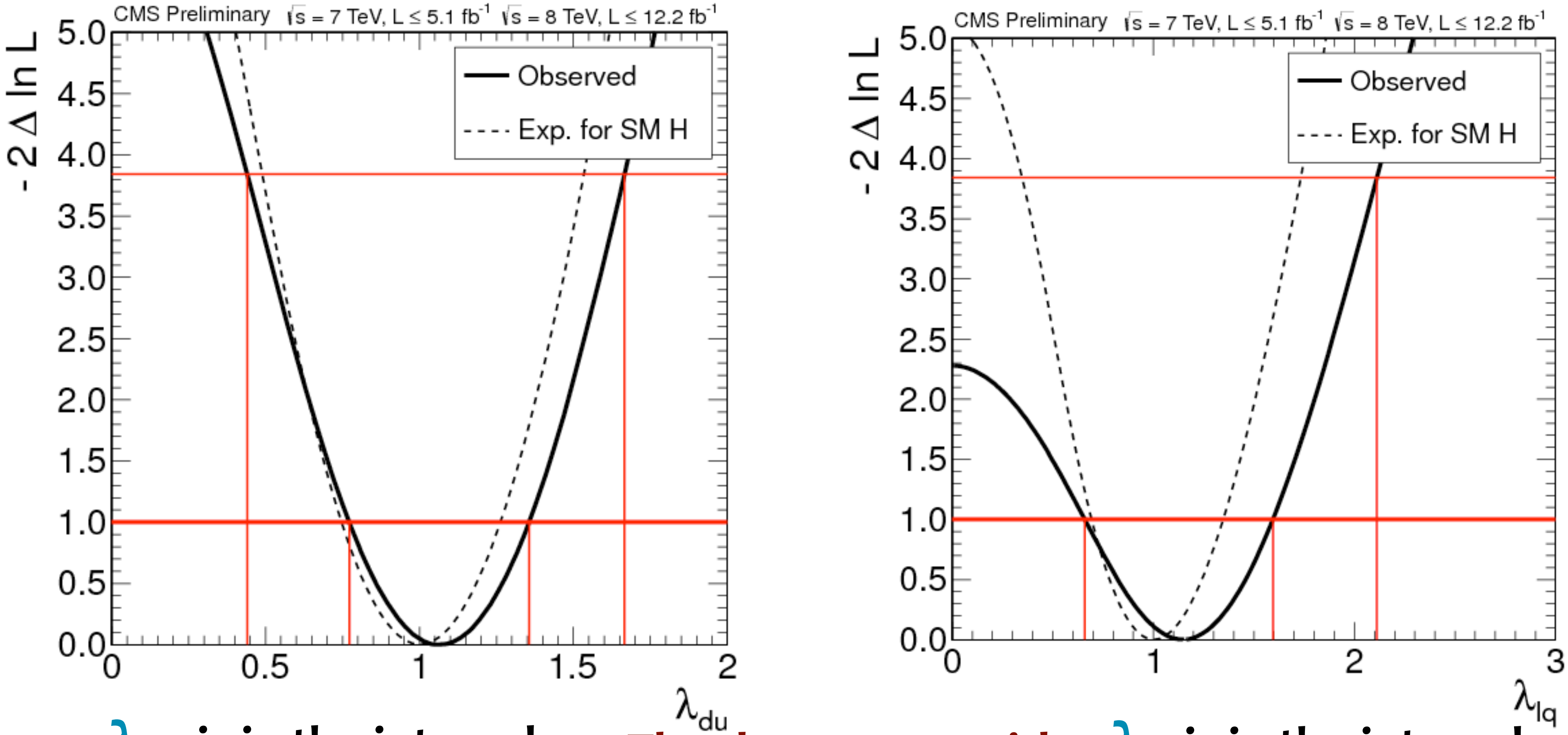
$\lambda_{du} = k_d/k_u$ (ratio of the coupling to down/up fermions)

$\lambda_{lq} = k_l/k_q$ (ratio of the coupling to leptons and quarks)

[assume no other BSM decay mode]

Fermion Universality

1D likelihood scan vs λ_{du} and λ_{lq}
(while the other free coupling modifiers (kv,ku)/(kv,kq)
are profiled together with the other nuisance paramenters)



λ_{du} is in the interval [0.45 - 1.66] at 95% CL.

The data agree with the SM expectations

λ_{lq} is in the interval [0.00 - 2.11] at 95% CL.

The Measurements

1. For the SM Higgs we expect 7.8σ significance
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   Signal strenght in combination and sub-combination

   - at mH = 125.8 combined σ_x/σ_{SM} = 0.88 ± 0.21 (different ways of splitting contributions fully compatible with min(pValue) ~ 45%)

   Test of the Couplings

   - all coupling tests within one sigma from SMH (2 sigma when H->γγ drives)

5. Spin and parity

Spin and Parity

The new state decays in γγ -> **SPIN 1 Hypothesis ruled out**

The **H->ZZ->4l** channel can exploit the angular information using the "MELA" methodology to test the hypothesis **$J^P = 0^+$ vs $J^P = 0^-$**

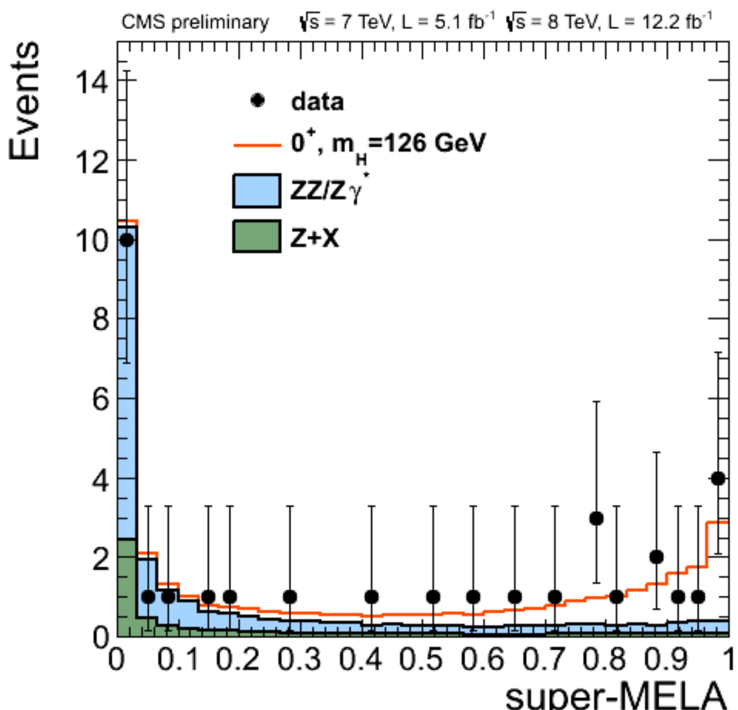
"MELA" methodology: $$\left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

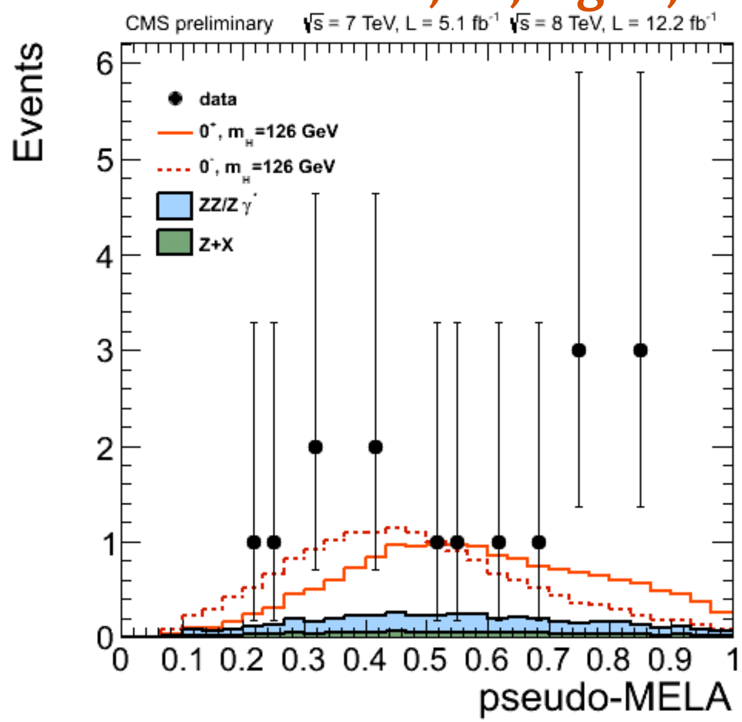
(2D PFD (MELA, m4l)) ---> (2D PFD (pseudoMELA, superMELA))

Signal to Bkg prob ratio as a function of m1,m2,angles

Signal(0^+) to Signal(0^-) prob ratio as a function of m1,m2,angles

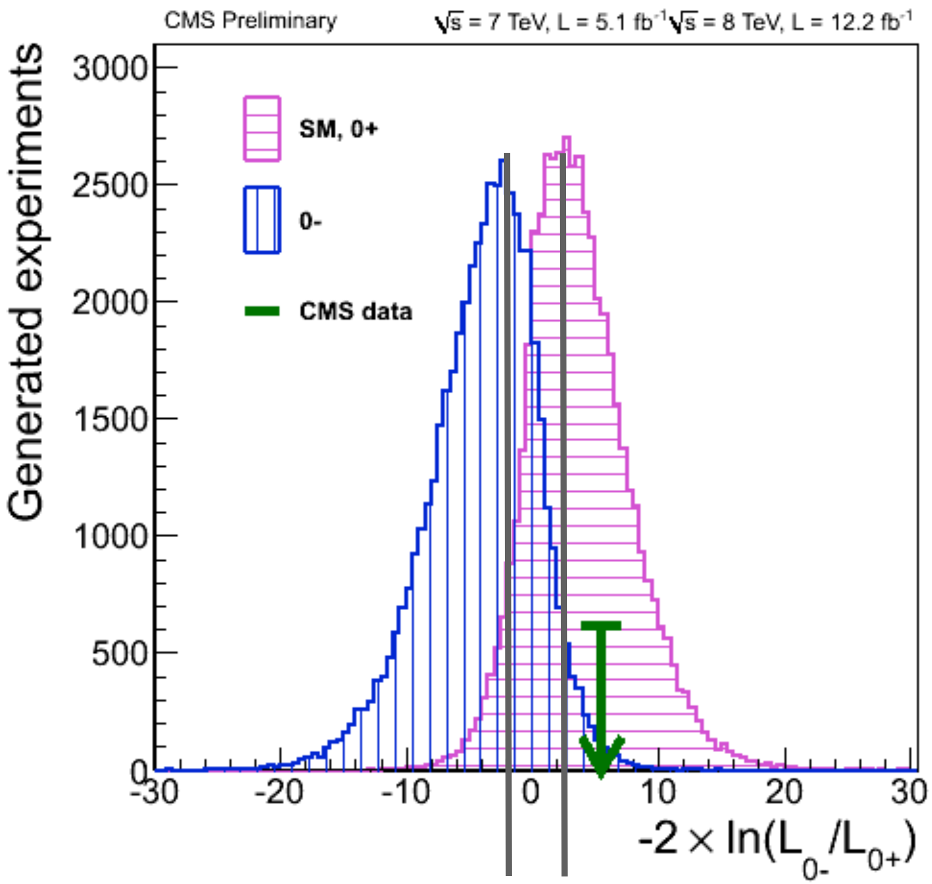
Signal to Bkg prob ratio as a function of m1,m2,angles, m4l





Spin and Parity

Distribution of the test statistic (likelihood ratio) built with the 2D PDF:
(pseudoMELA, superMELA) with generated bkg and signal of two types, for mH=126
Expected distributions are obtained with cross section equal to SM for both signal hypothesis



1.99σ from 0^+ 1.93σ from 0^-

assuming $J^P = 0^-$
the observed value of q is consistent with expectation within 2.5 standard deviations

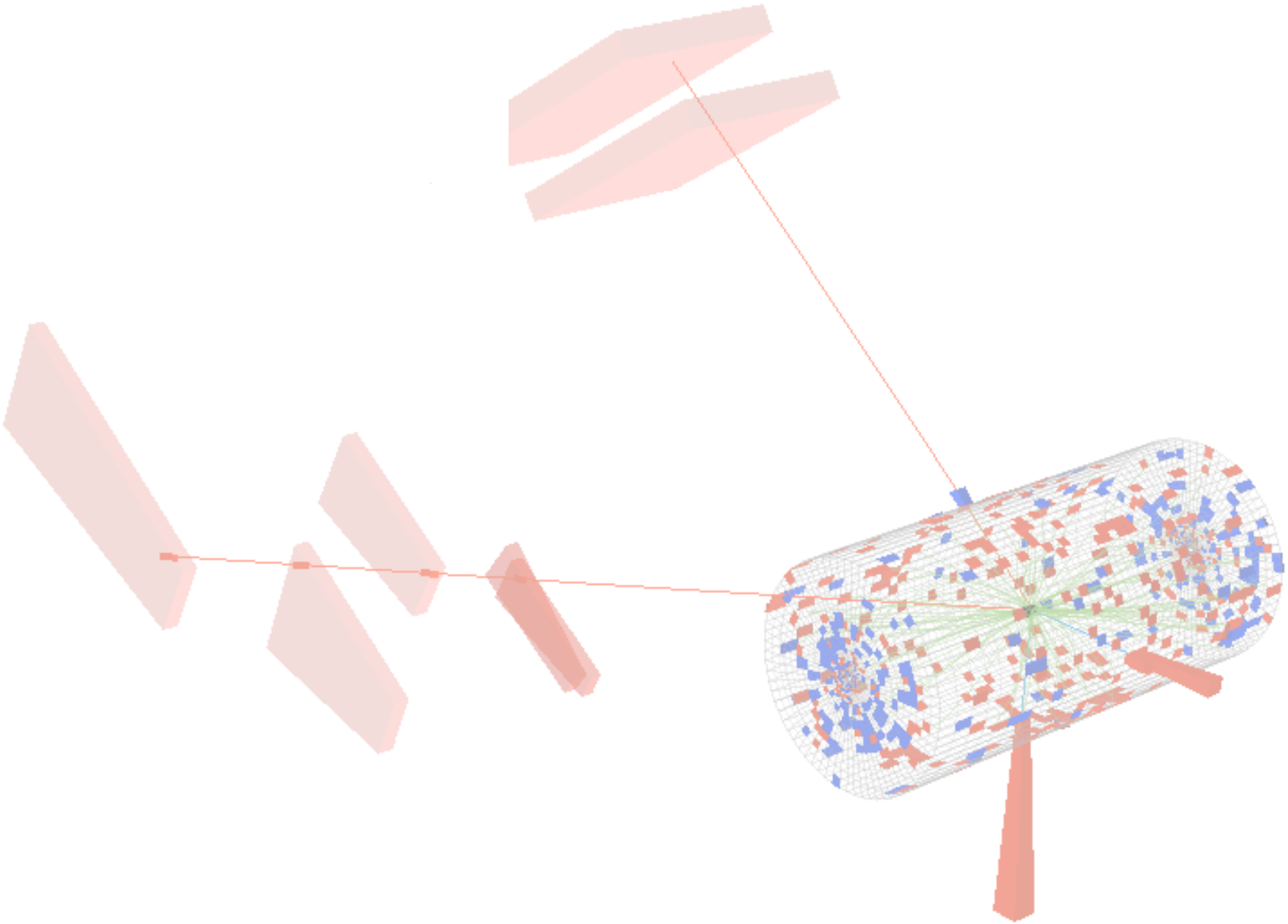
assuming $J^P = 0^+$
the observed value of q is consistent with expectation within 0.53 standard deviations

CLs criterion: ~ 3% disfavouring $J^P = 0^-$

Conclusions

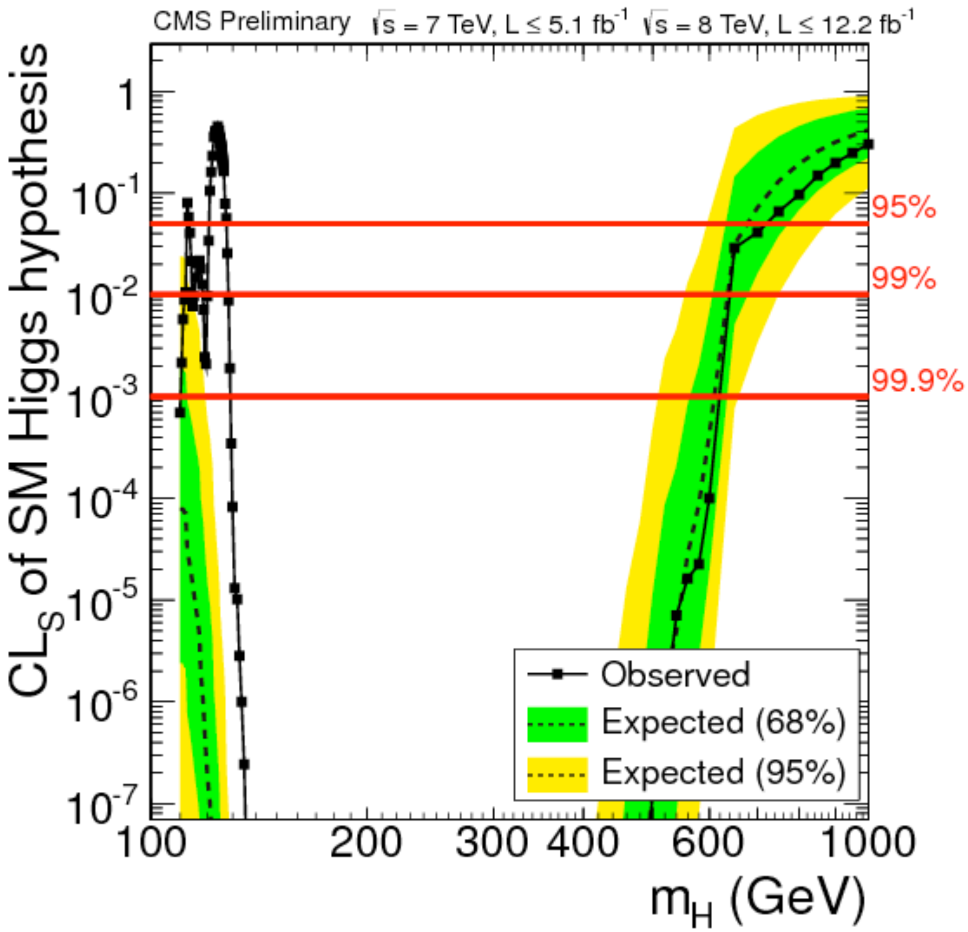
- New results consistent with publications
  - significance of the signal now at 6.8 standard deviations
  - mass of the particle: $m_X = 125.8 \pm 0.4\ (\mathrm{stat}) \pm 0.4\ (\mathrm{syst})$
- Particle behave even more like the Higgs compared to ICHEP
  - fermionic final states starting to build up excess
  - 2.5 standard deviations disfavoring particle to be pseudoscalar
  - couplings are well within 2 standard deviations of SM

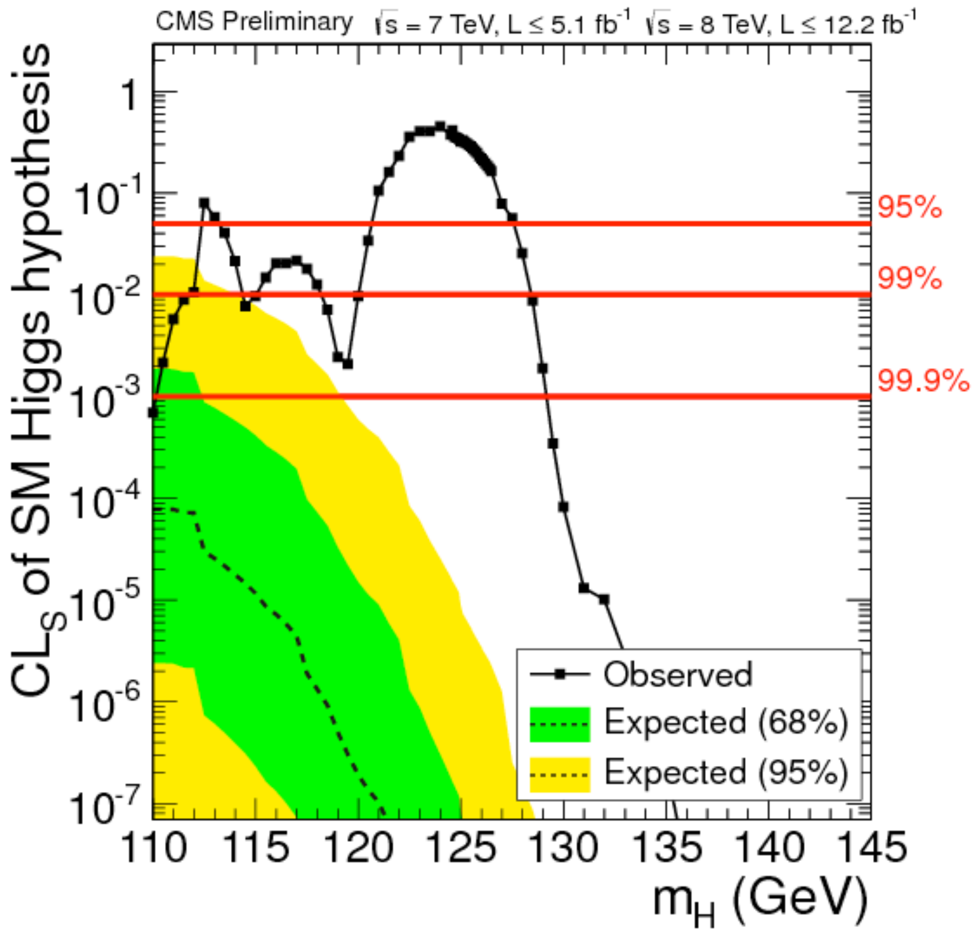
Backup



Combining the results: Exclusion CLs

The CLs value for the SM Higgs boson hypothesis as a function of mH

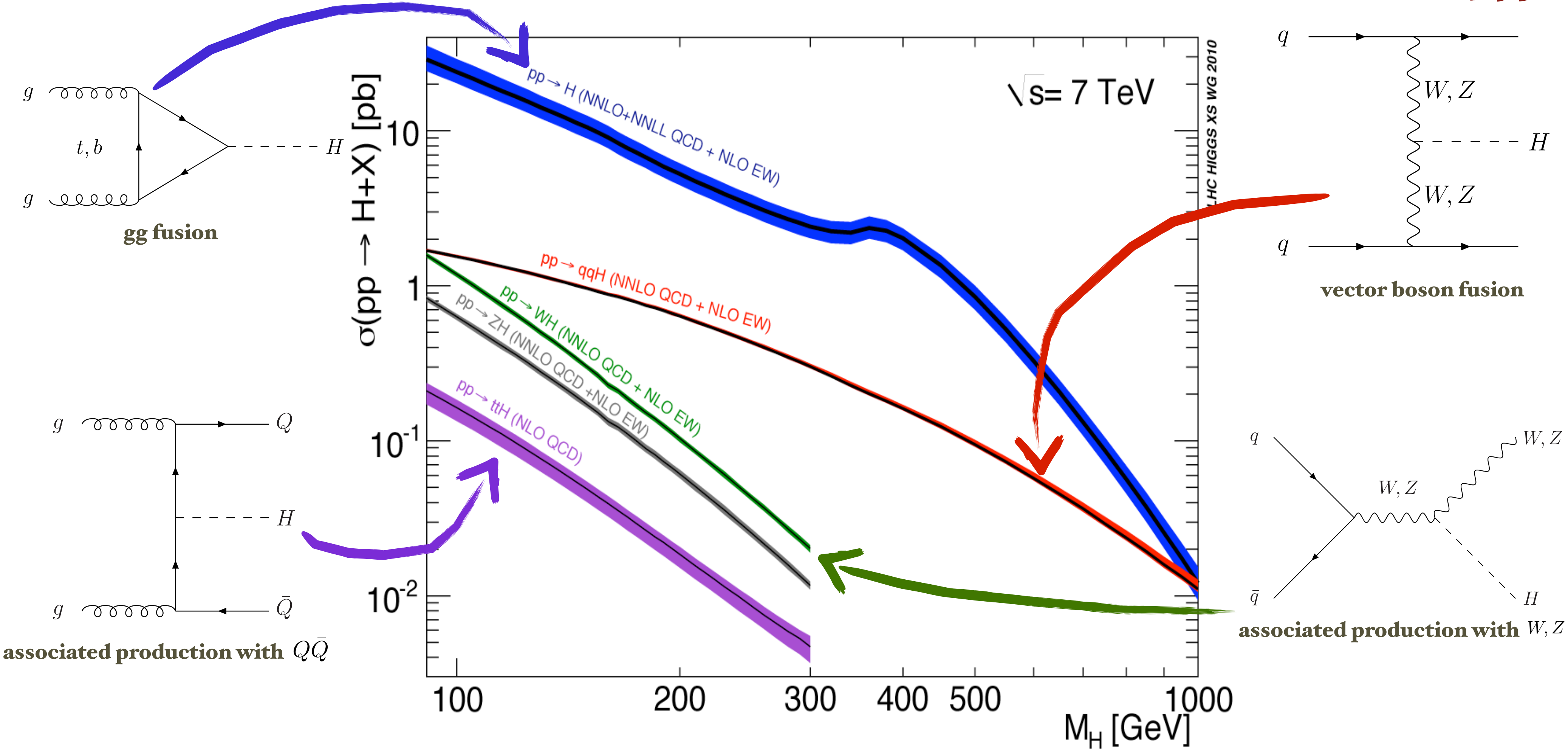




Higgs Production

The LHC H XS WG

CERN-2011-002 arXiv:1101.0593



Higgs Production

The LHC H XS WG

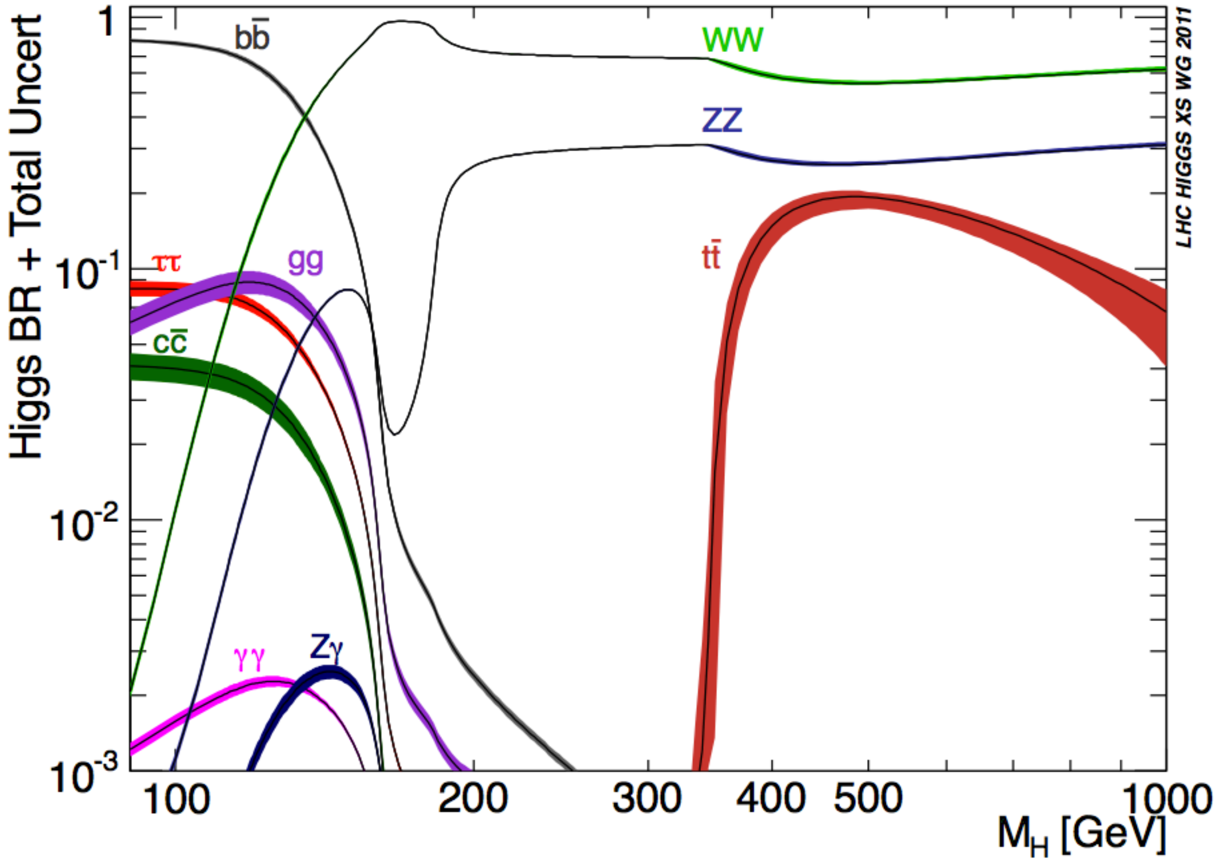
CERN-2011-002 arXiv:1101.0593

	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+a_S	Total error
ggF	+25% (+100%)	+12% -7%	±8%	+20 -15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% -10%	±8%	+12 -18%

Higgs Decay

The LHC H XS WG

$$\Gamma_H = \Gamma^{HD} - \Gamma^{HD}_{ZZ} - \Gamma^{HD}_{WW} + \Gamma^{Proph.}_{4f} + \Gamma^{HD}_{\gamma\gamma}\delta^{QED}_{\gamma ff}$$



MH	Decay	THU	PU	Total
120 GeV	H→γγ	±2.9%	±2.5%	±5.4%
	H→bb	±1.3%	±1.5%	±2.8%
	H→ττ	±3.6%	±2.5%	±6.1%
150 GeV	H→WW	±0.3%	±0.6%	±0.9%
	H→ZZ	±0.3%	±0.6%	±0.9%

HD=HDecay NLO QCD +NLO EW
Proph = Prophecy4f NLO QCD+NLO EW

HZZ4l systematics

HZZ4l blobs

To remember tags

	untagged	VBF-tag	VH-tag	$t\bar{t}$H-tag
$H \to \gamma\gamma$	✓	✓		
$H \to bb$			✓	✓
$H \to \tau\tau$	✓	✓	✓	
$H \to WW$	✓	✓	✓	
$H \to ZZ$	✓			

H->gg Event Selection

γ Preselection: **$E_{T\gamma1}/m_{\gamma\gamma} > 3$ and $E_{T\gamma2}/m_{\gamma\gamma} > 4$**
electron veto, isolation and shower width criteria

[preselection efficiency [no ele veto] from 93-100% from Z->ee tnp]

[ele veto efficiency 97-100% from Z->μμγ events]

γ ID MVA (BDT) BASED: to separate prompt-γ from π^0 emerging from jets

requirement on γ ID BDT output 99% on preselected signal events, removing 27% of data-event in 100-180 GeV region.

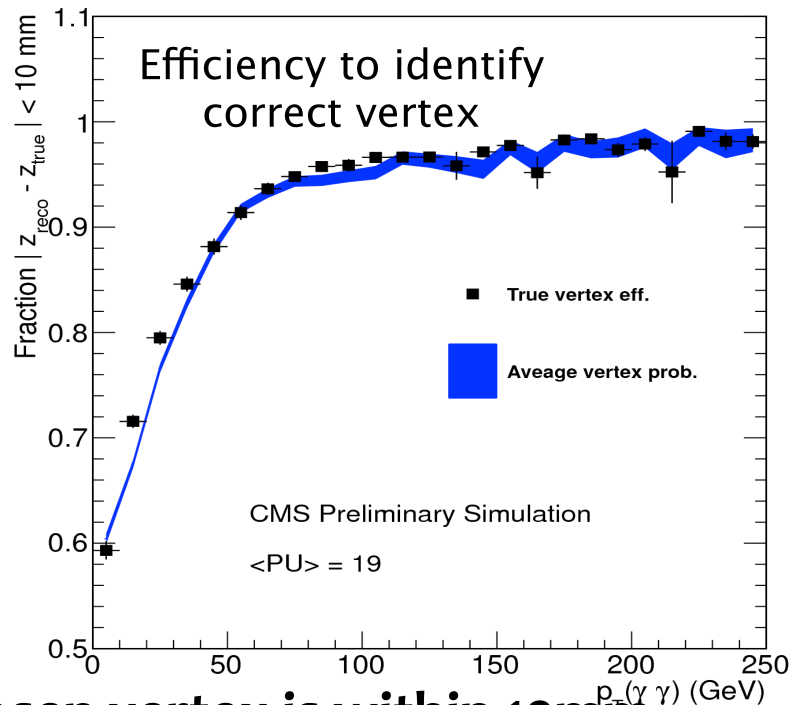
Inputs variables: isolation, shower shape, pre- shower energy, per event energy density, and pseudorapidity

VERTEX ID MVA (BDT) BASED:

- if the vertex is within ~10 mm from the nominal interaction point mass resolution is not degraded
- choose the vertex among the reconstructed ones

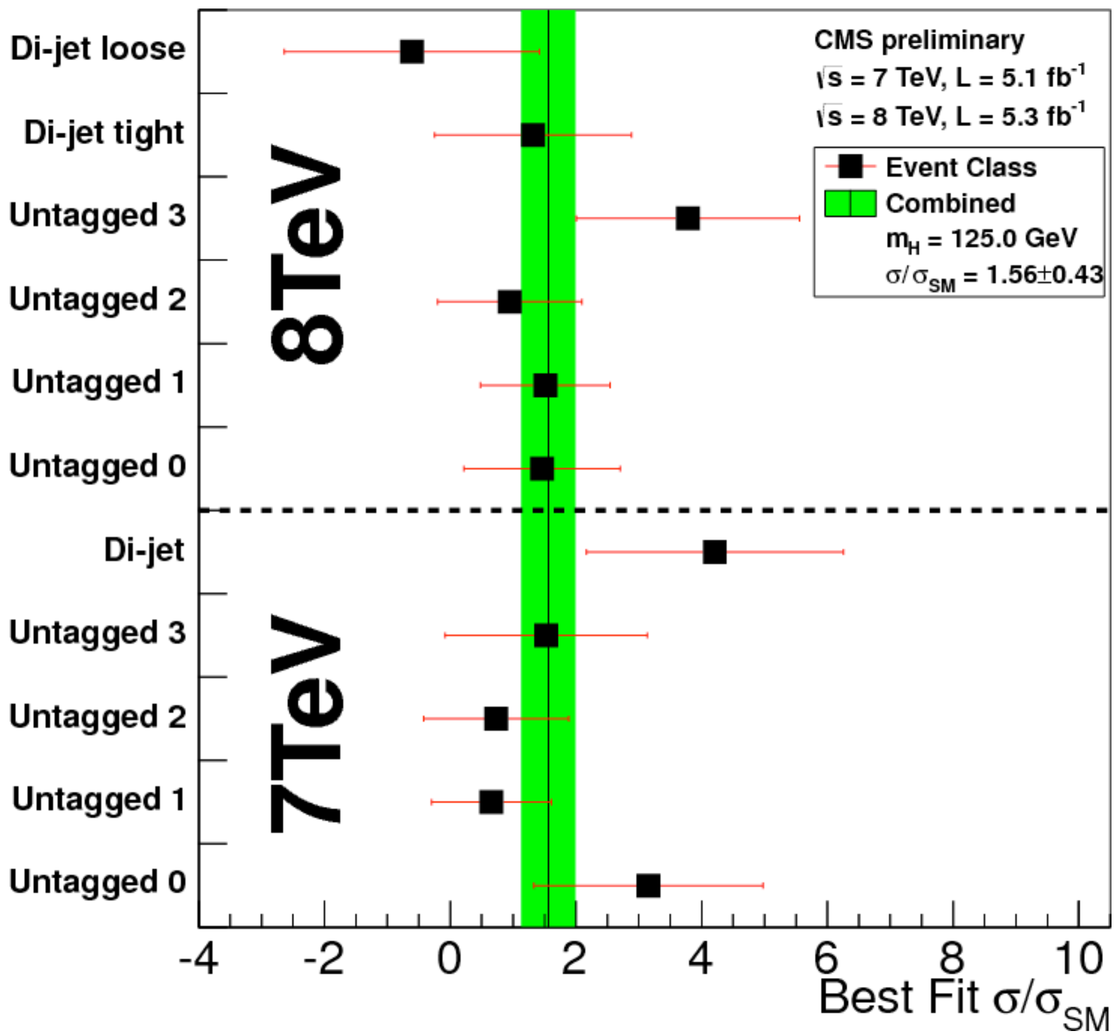
BDT variable to select the right vertex

Inputs variables: Σp_t^2, Σp_t projected onto the **γγ** transverse direction, p_t asymmetry, and conversions



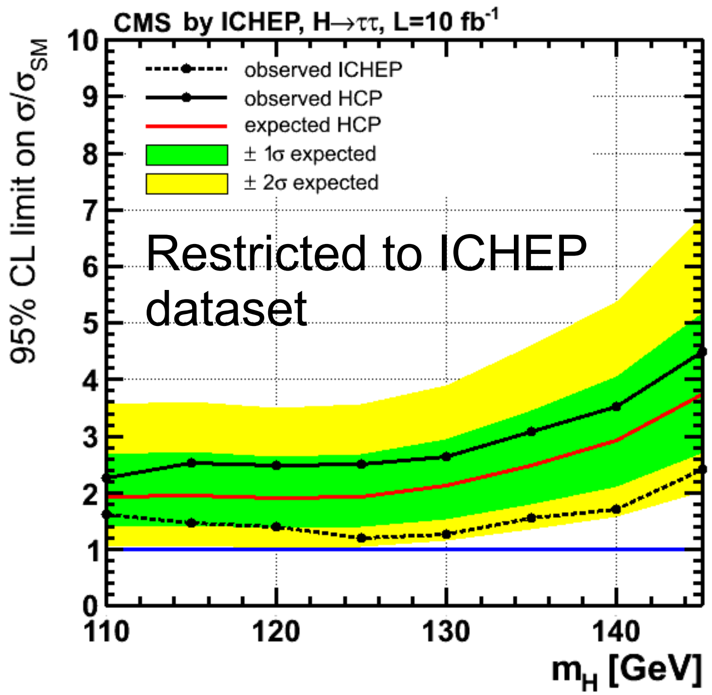
BDT variable to define the EBE probability the choosen vertex is within 10mm from the nominal interaction **[used with energy resolution, to estimate mass resolution]**

H->gg categories



H->ττ @ ICHEP

Compatibility with ICHEP Result



- Underfluctuation by ICHEP driven by VBF category.
- Since ICHEP several changes applied to improve and simplfy analysis:
  - Re-reconstruction of 2012 dataset.
  - Improved $\not{E}_T$ reconstruction.
  - Simplification of VBF selection (unification across all channels).
- Due to these changes the event overlap in this event category is O(20%).
- Estimated compatibility of the two observed limits after re-analysis ~12%

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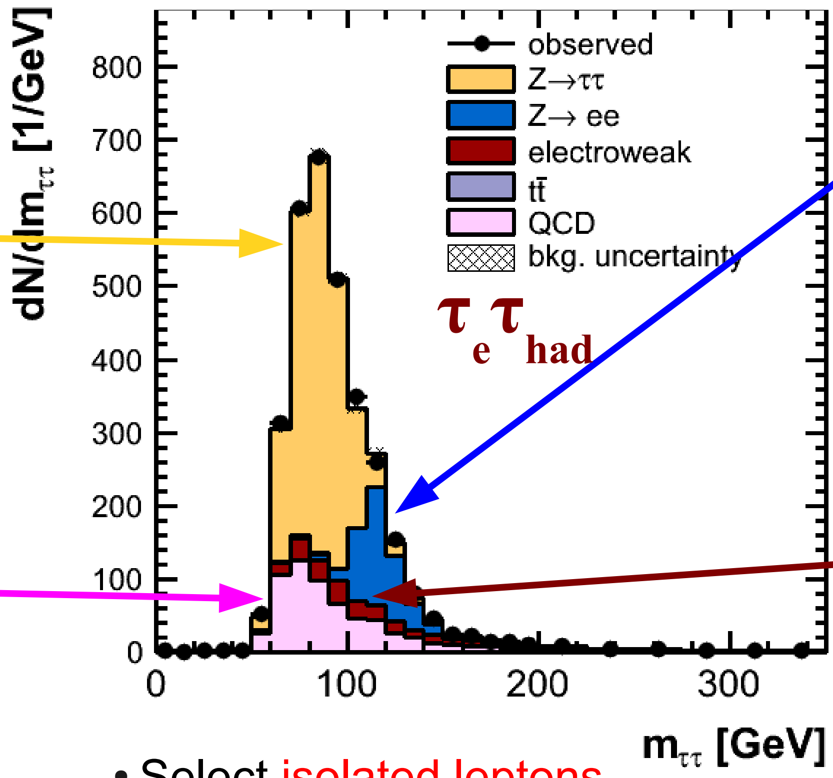
H->ττ Background

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.

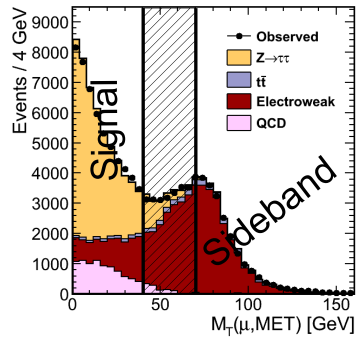
ttbar:
- From madgraph.
- Normalization from sideband.



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

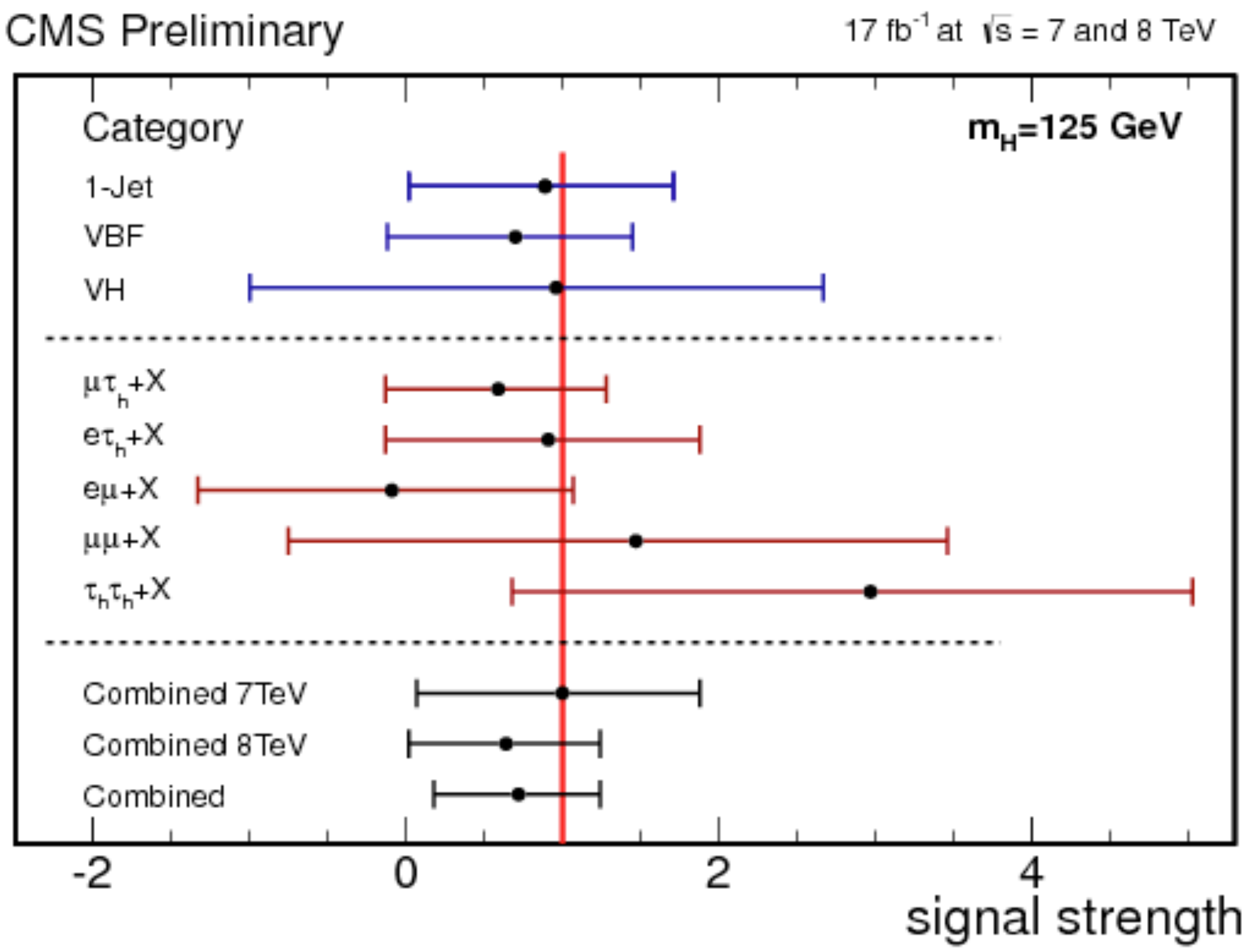
Diboson/W+jets:
- From madgraph.
- Normalization from sideband.

- Select isolated leptons.
- Restrict $\not{E}_T$ (supp. W+jets, ttbar).
- Discriminate signal from background based on $m_{\tau\tau}$.

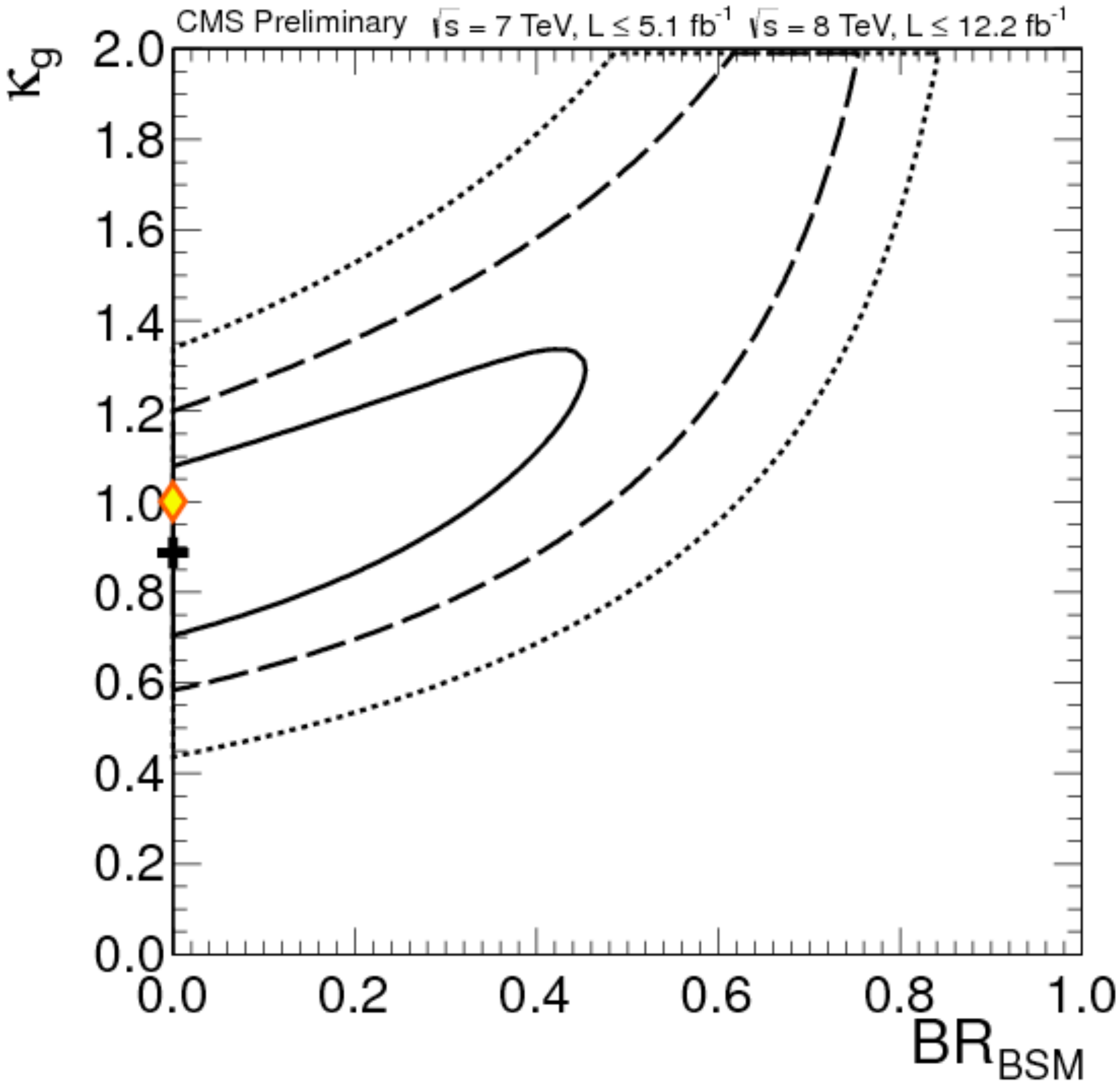


8

H->ττ Signal Strength



BSM Physics in Γ_{tot}



Summary Coupling

Model parameters	Assessed scaling factors (95% CL intervals)		Comments
$\lambda_{\mathrm{WZ}}, \kappa_{\mathrm{Z}}$	λ_{WZ}	[0.57–1.65]	Ratio of couplings to W and Z; ZZ and WW(0/1jet) channels only
$\lambda_{\mathrm{WZ}}, \kappa_{\mathrm{Z}}, \kappa_f$	λ_{WZ}	[0.67–1.55]	Ratio of couplings to W and Z
κ_{V}	κ_{V}	[0.78–1.19]	Couplings to W/Z-bosons (V); $\kappa_f = 1$
κ_f	κ_f	[0.40–1.12]	Couplings to fermions (f); $\kappa_{\mathrm{V}} = 1$
κ_γ, κ_g	κ_γ	[0.98–1.92]	Couplings to photons (γ) and gluons (g)
	κ_g	[0.55–1.07]	(loop-induced couplings)
$\mathcal{B}(\mathrm{H} \to \mathrm{BSM}), \kappa_\gamma, \kappa_g$	$\mathcal{B}(\mathrm{H} \to \mathrm{BSM})$	[0.00–0.62]	Branching ratio for decays to BSM particles
$\lambda_{\mathrm{du}}, \kappa_{\mathrm{V}}, \kappa_{\mathrm{u}}$	λ_{du}	[0.45–1.66]	Ratio of couplings to down and up-type fermions
$\lambda_{\ell\mathrm{q}}, \kappa_{\mathrm{V}}, \kappa_{\mathrm{q}}$	$\lambda_{\ell\mathrm{q}}$	[0.00–2.11]	Ratio of couplings to leptons and quarks
$\kappa_{\mathrm{V}}, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_{V}	[0.58–1.41]	Couplings to W/Z-bosons (V)
	κ_b	[not constrained]	Couplings to down-type quarks (b)
	κ_τ	[0.00–1.80]	Couplings to charged leptons (τ)
	κ_t	[not constrained]	Couplings to top-type quarks (t)
	κ_g	[0.43–1.92]	Effective couplings to gluons (g)
	κ_γ	[0.81–2.27]	Effective couplings to photons (γ)