Recent results on Higgs studies at CMS

15 April 2013, CERN

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Outline

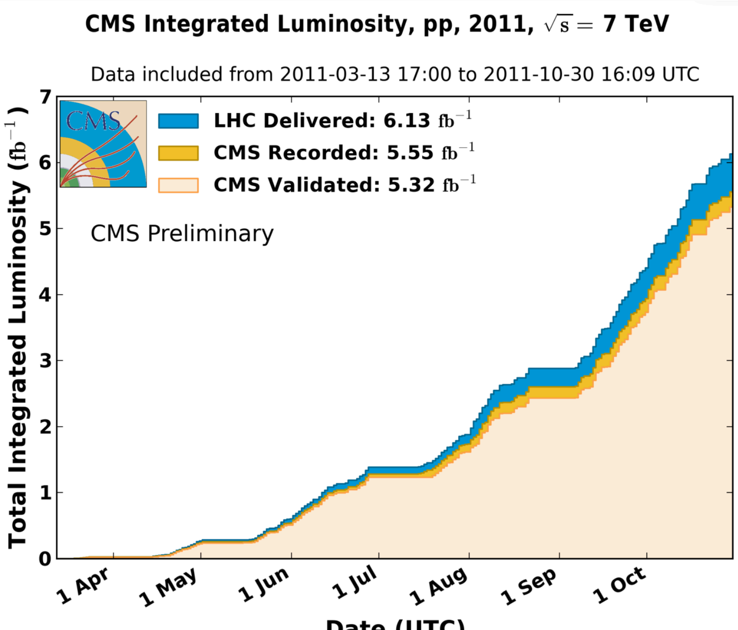
- The data taking
- Pile-up
- Channels + objects
- Combination & properties

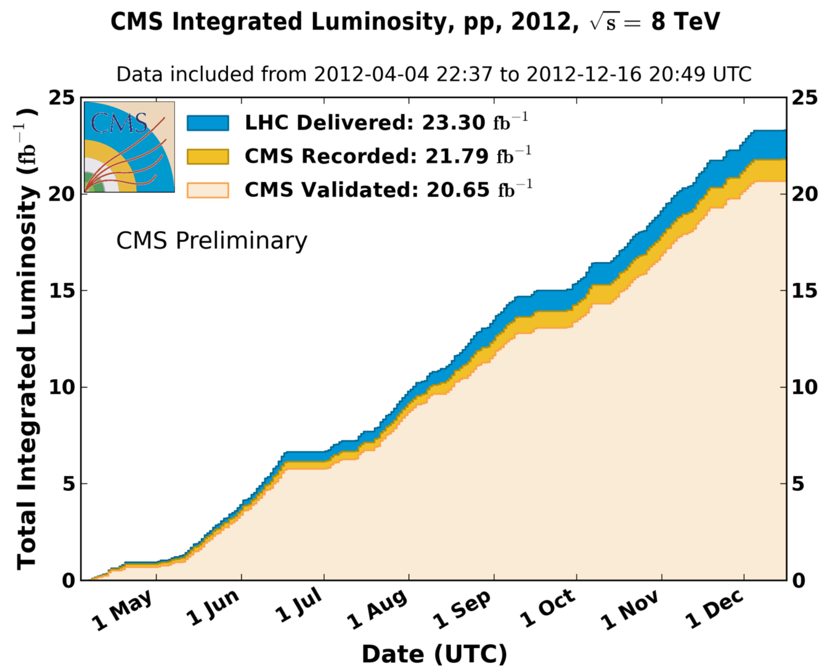
Data taking

Fraction of delivered data used for physics

pp 2011: 87%

pp 2012: 89%





Analyses presented in this talk:

$L < 5.1 fb^{-1}$ at 7 TeV

$L < 19.6 fb^{-1}$ at 8 TeV

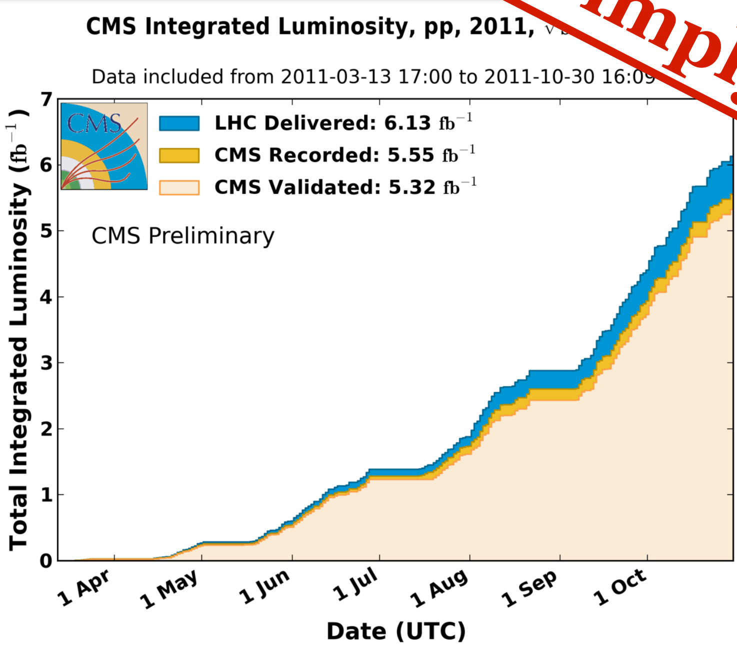
Data taking

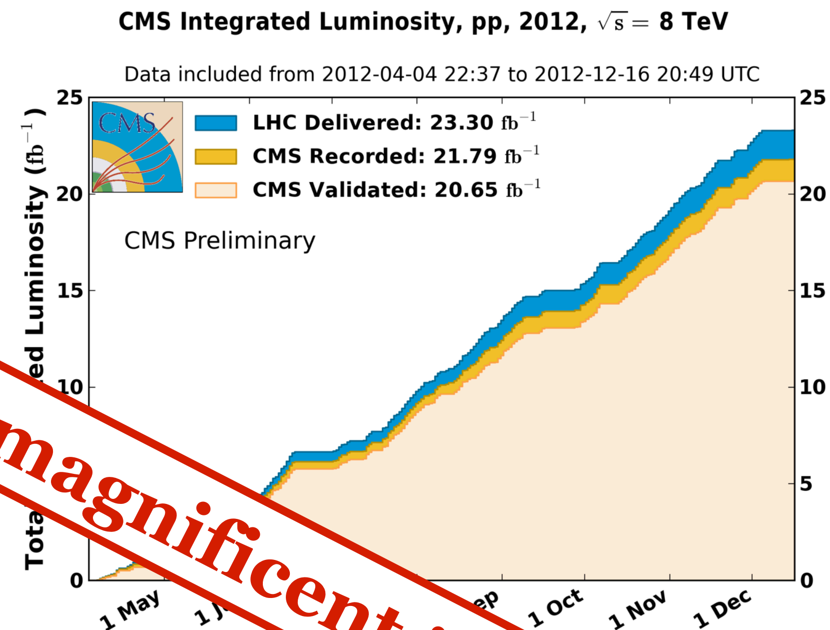
Fraction of delivered data used for physics

pp 201

pp 2012: 8

LHC: Simply magnificent !!!





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L < 5.1fb^{-1} at 7 TeV
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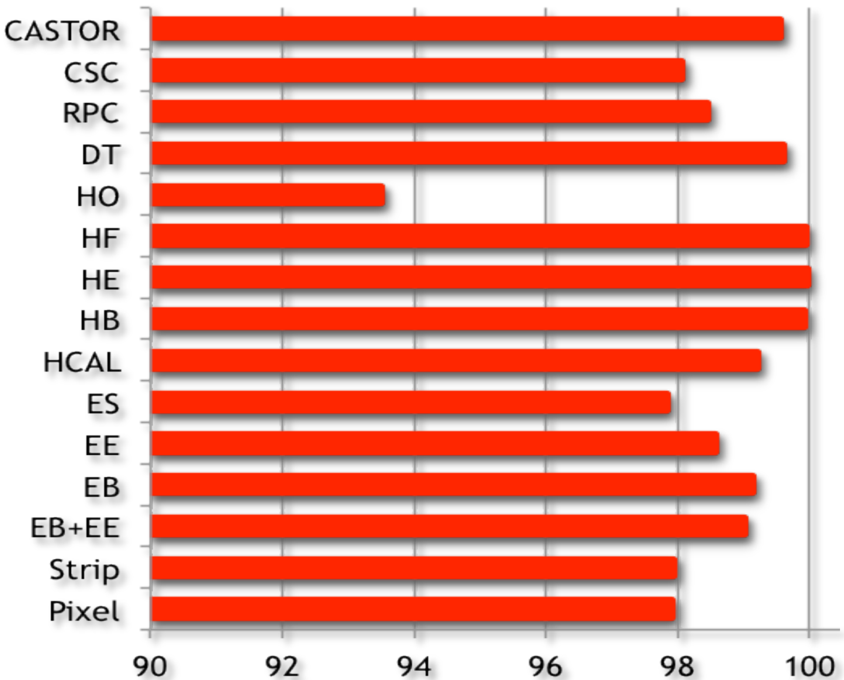
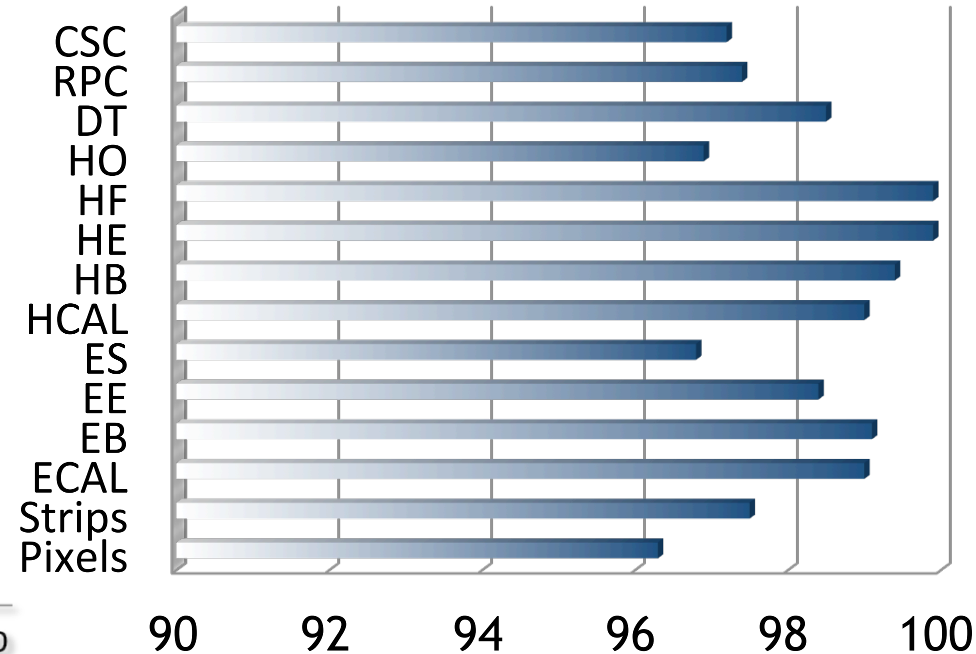
Detector status

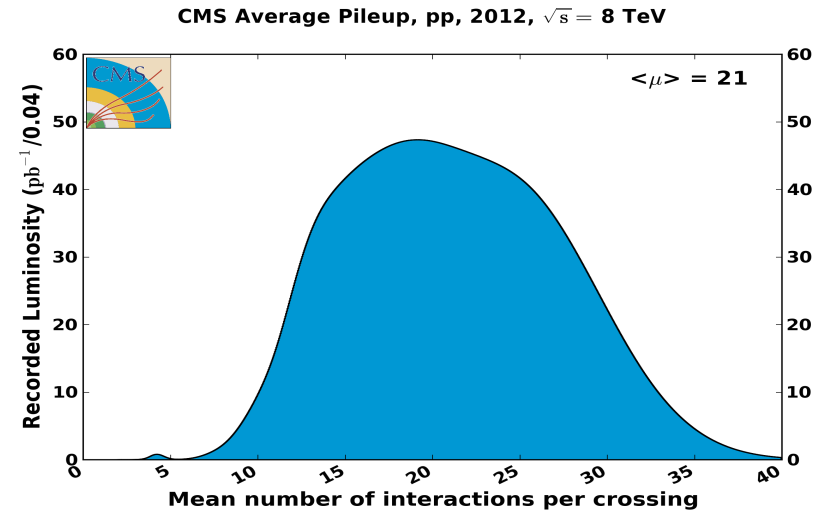


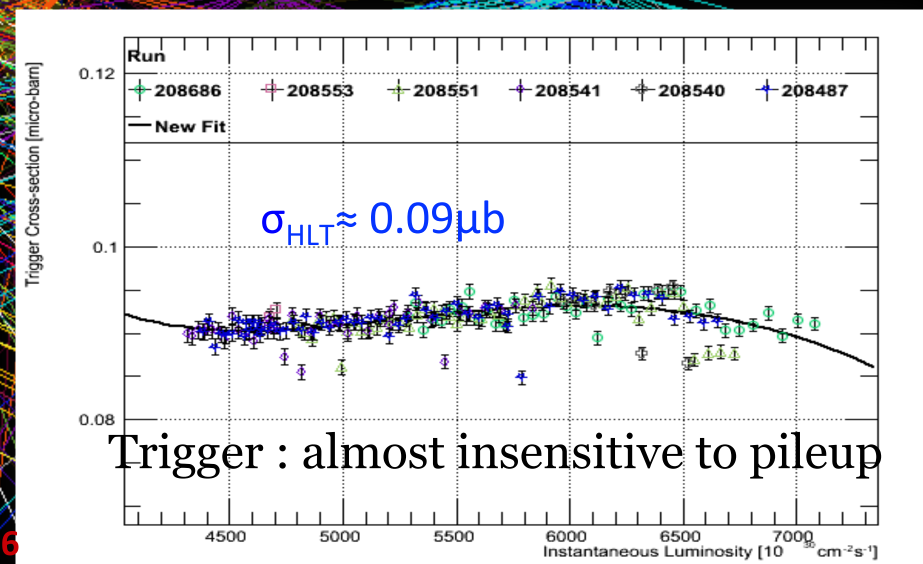
the first runs in 2010



the last runs in 2013

Pileup

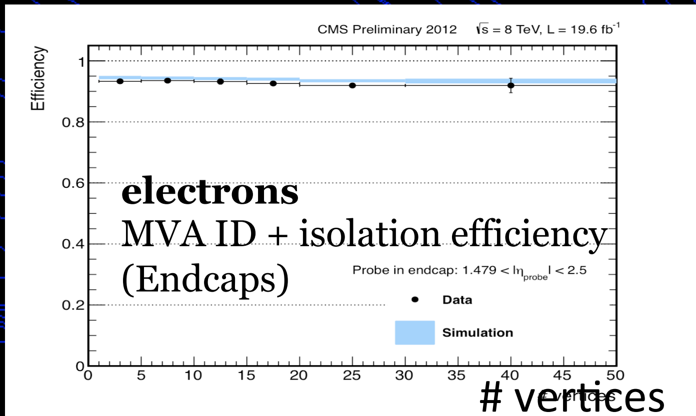


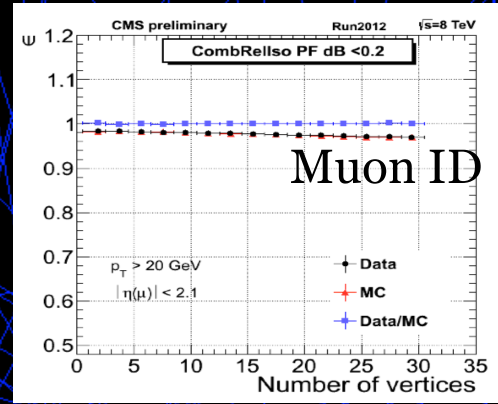


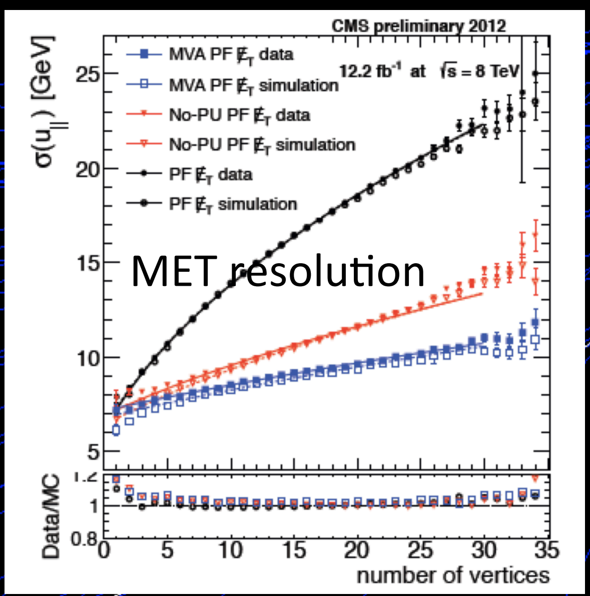
$\sigma_{HLT} \approx 0.09 \mu b$

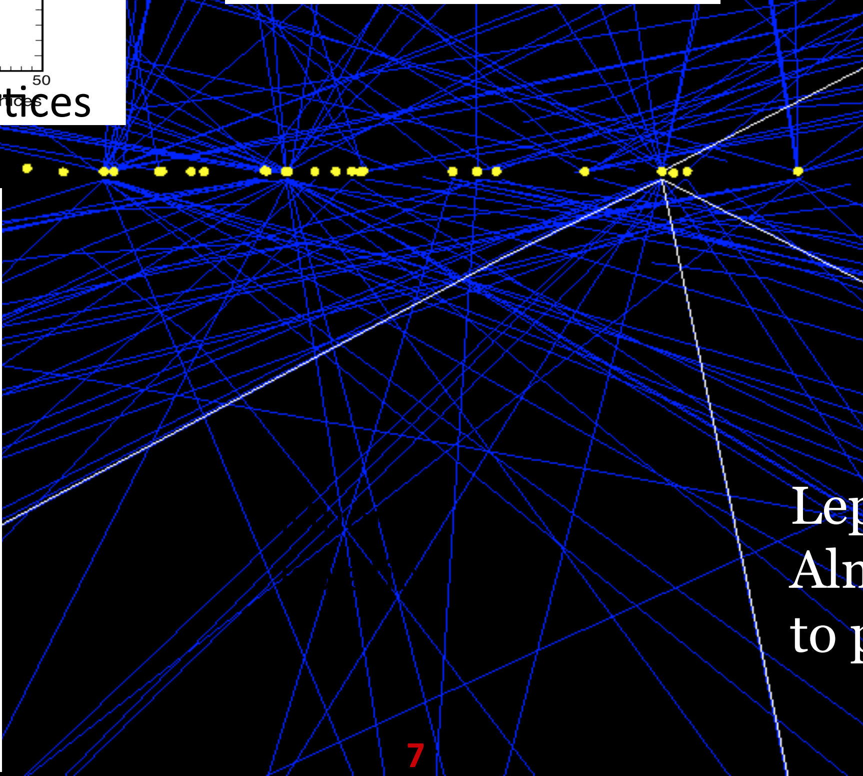
Trigger : almost insensitive to pileup

PU control





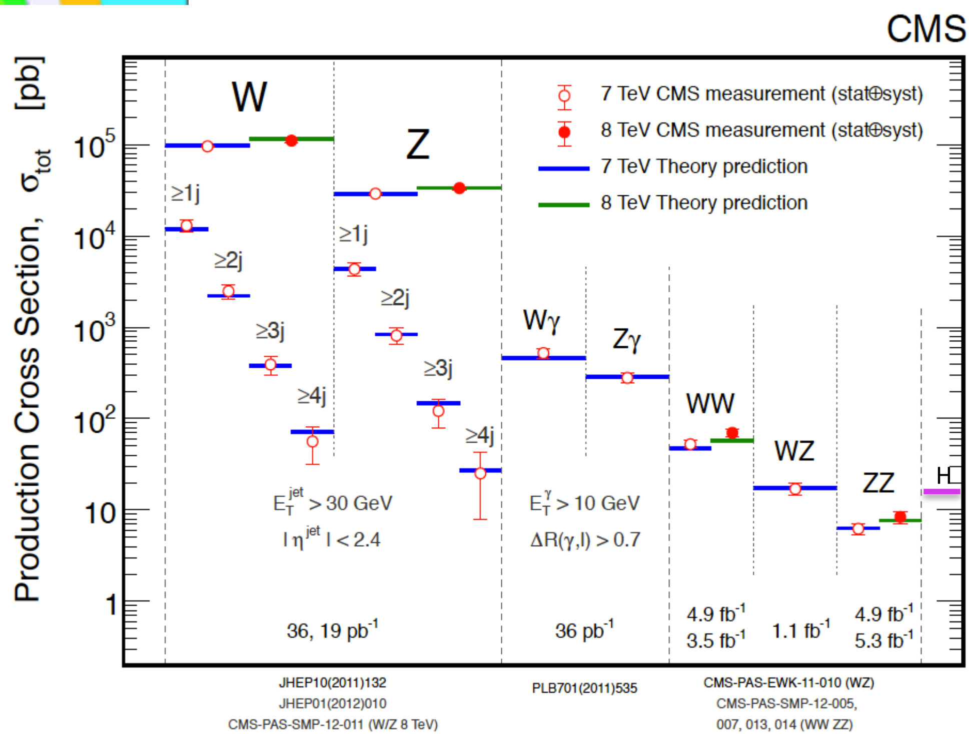




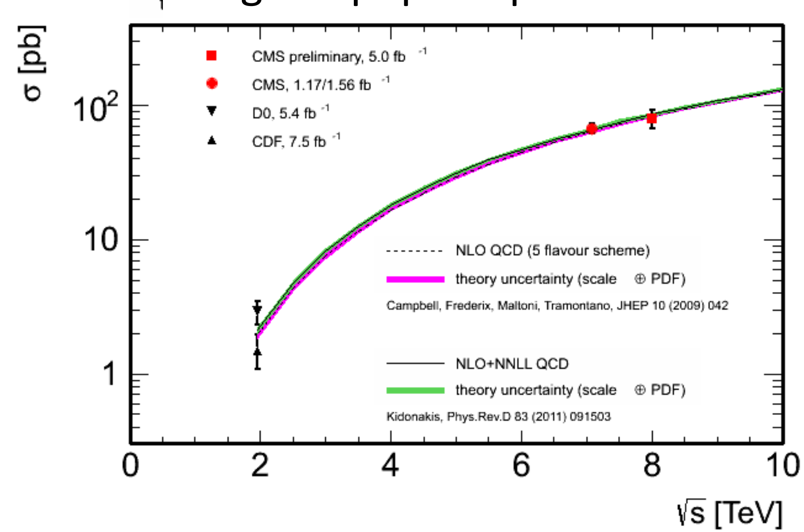
H→ ZZ →4l candidate
24 vertices

Leptons and MET
Almost insensitive
to pileup

Precise SM measurements



Single top quark production



Good understanding of the detector + accurate theory predictions

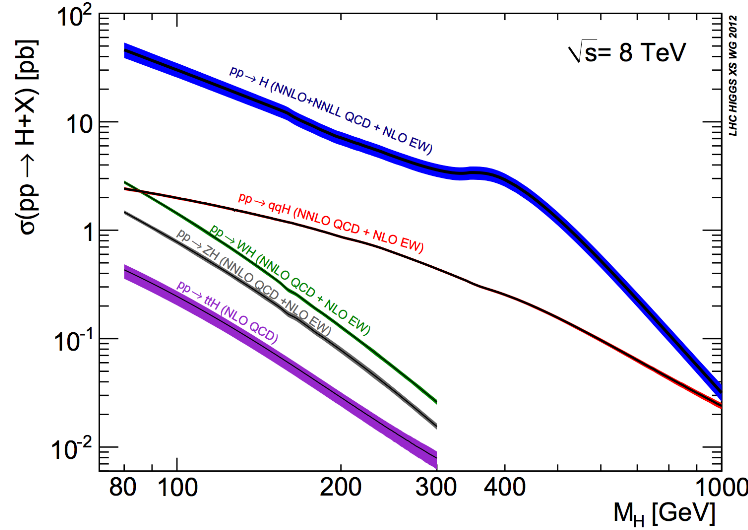
→ Precise measurements of the SM processes over many orders of magnitude

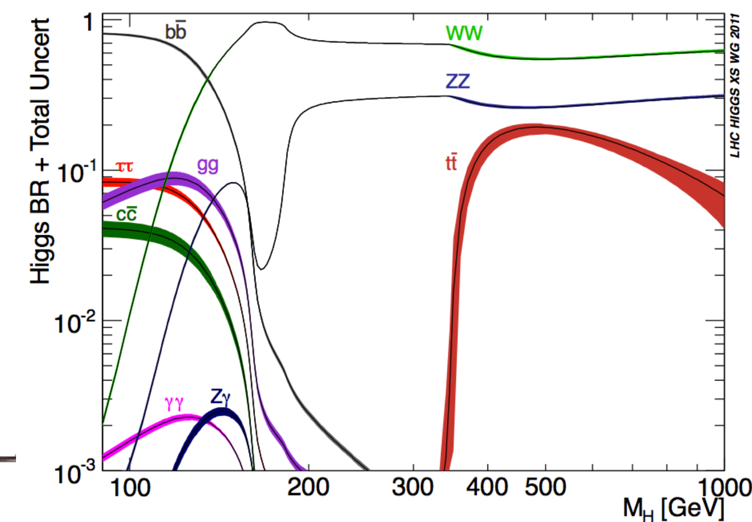
→ Good knowledge of the background to Higgs analyses

The LHC Higgs Cross Section WG

- Created at the end of 2009, the exact day the LHC delivered the first pp interactions has provided from "day 0" the best theory predictions on XS, BR and their uncertainties

- Experiments are coherently using the **COMMON INPUTS** based on the interaction with the TH community. This facilitates the comparison and the combination of the individual results





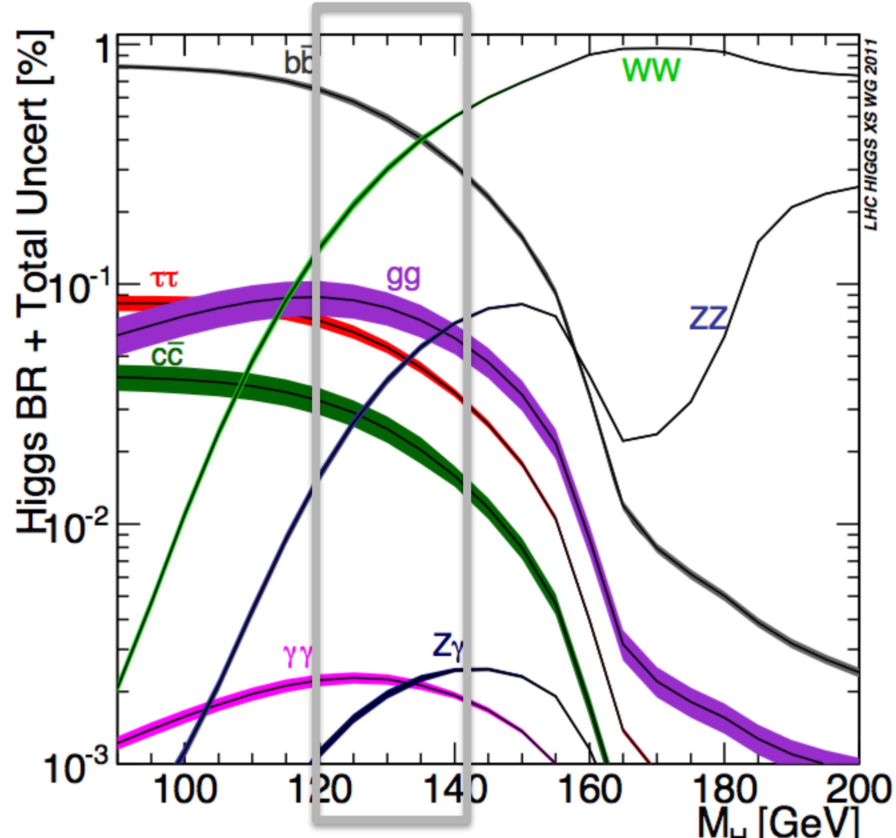
"Yellow Reports": YR1 (inclusive XS), YR2 (differential XS) and soon YR3 (properties)

The channels in CMS

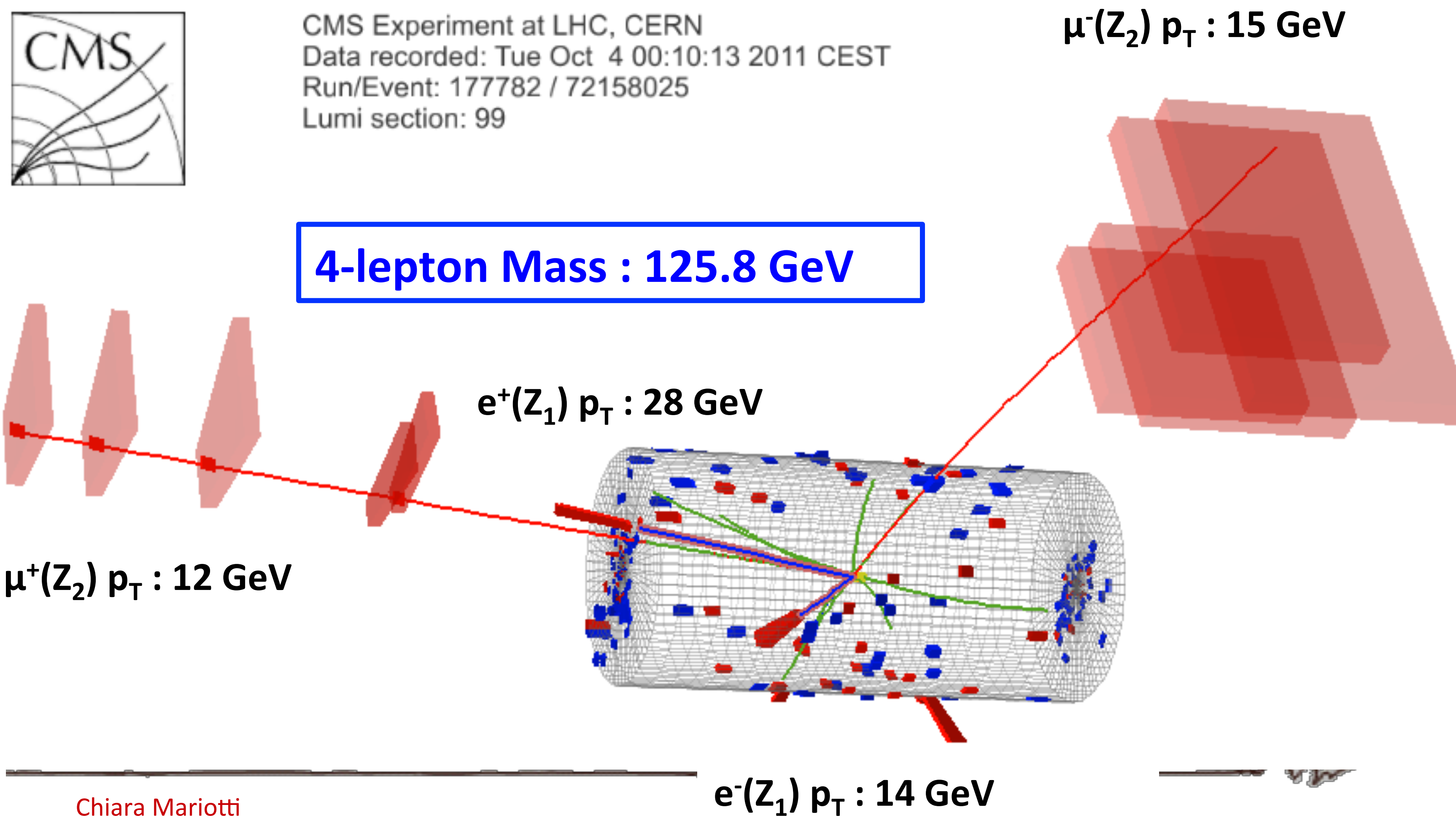
5 decay modes exploited

	Exp Sig @125.7	σ_M/M
• bb	2.2σ	10%
• ττ	2.6σ	10%
• WW	5.3σ	20%
• ZZ	7.1σ	1-2%
• γγ	3.9σ	1-2%

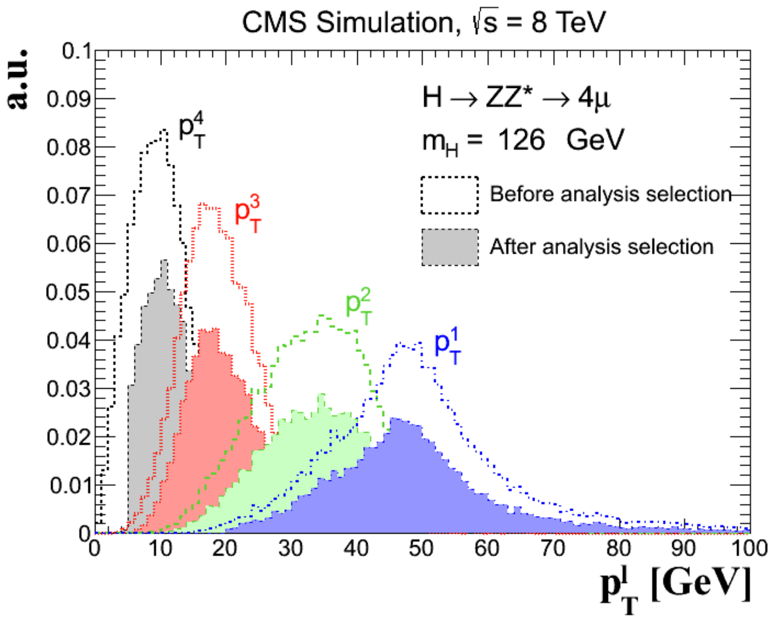
- and searches in Zγ

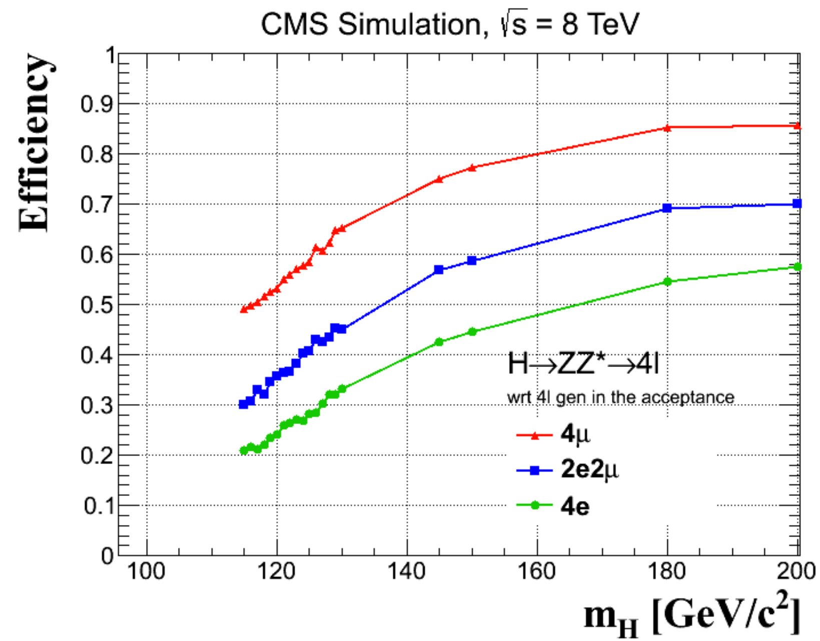


The golden channel



H → ZZ → 4l (l=e,μ)



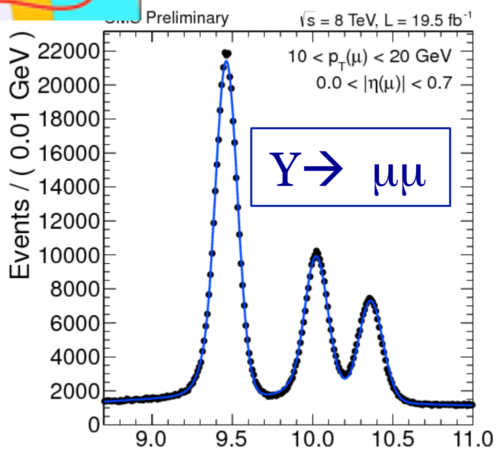


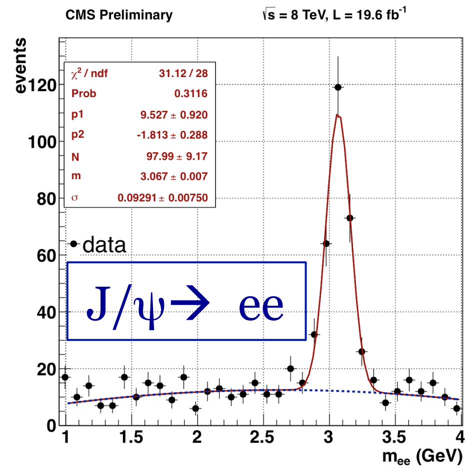
Very clean final state: - 4 leptons - isolated - coming from the primary vertex

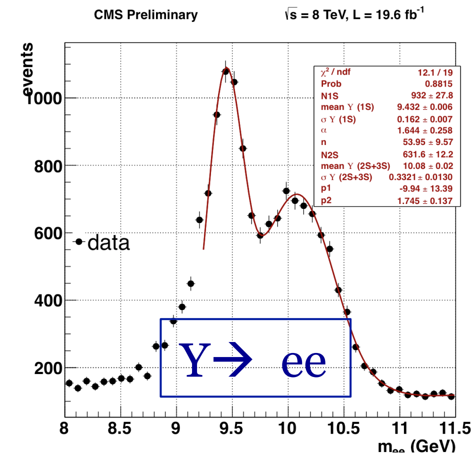
Very tiny cross section, thus highest efficiency must be conserved

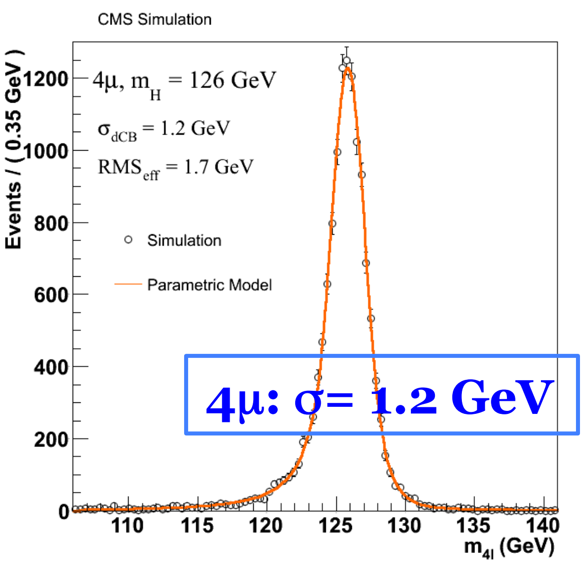
huge effort on lepton ID and efficiency, 2l / 4l mass resolution

Electrons and Muons





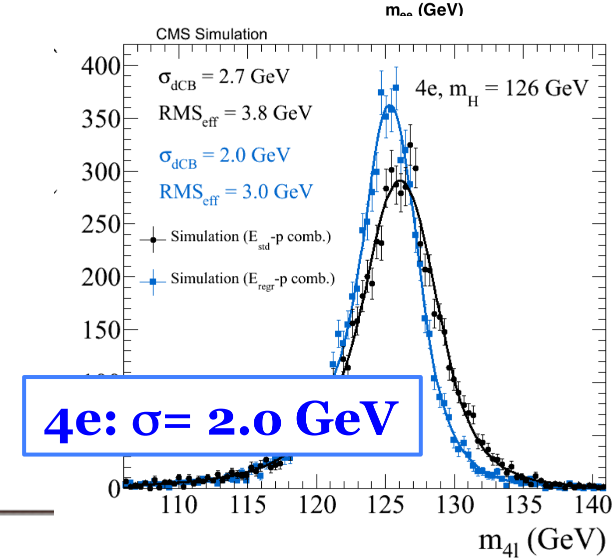




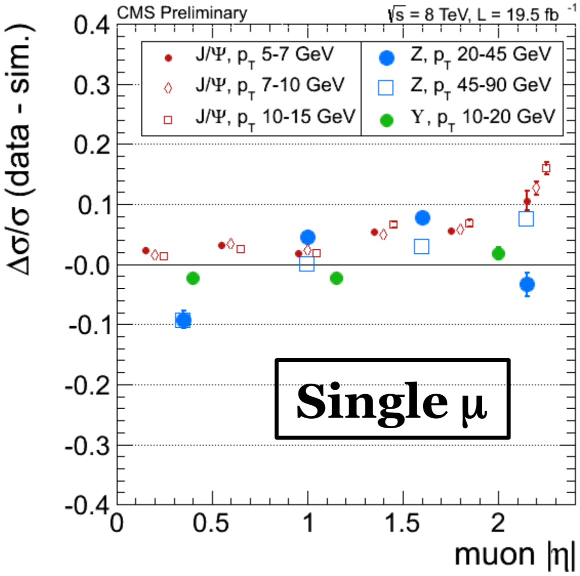
momentum scale:

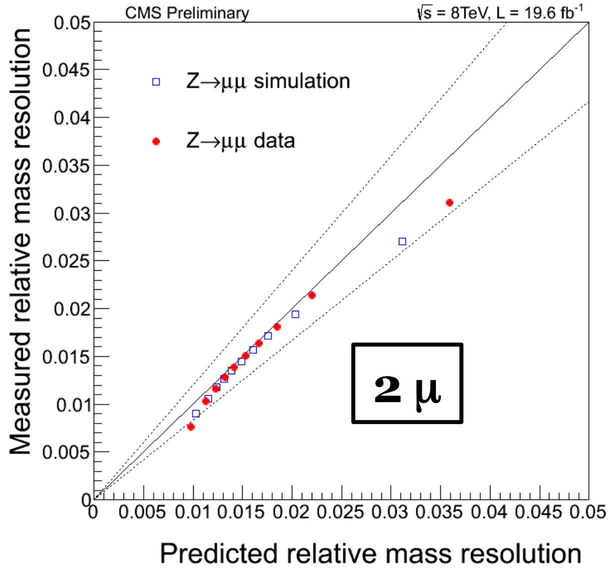
0.1% for muons

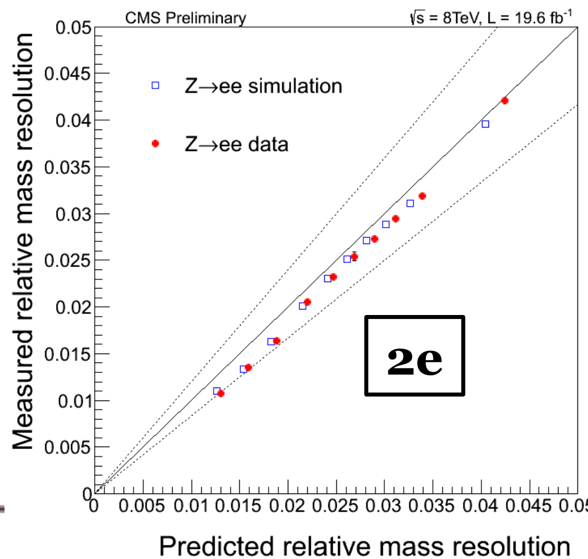
0.2% for electrons
of 35<pT<50
up to 1.5% at low pT

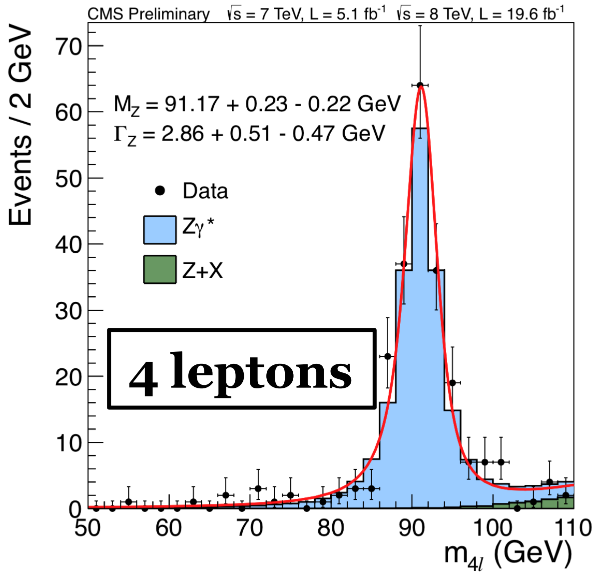


Resolution









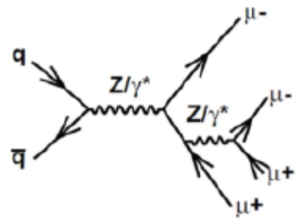
Good understanding of the lepton, dilepton and 4 lepton resolution

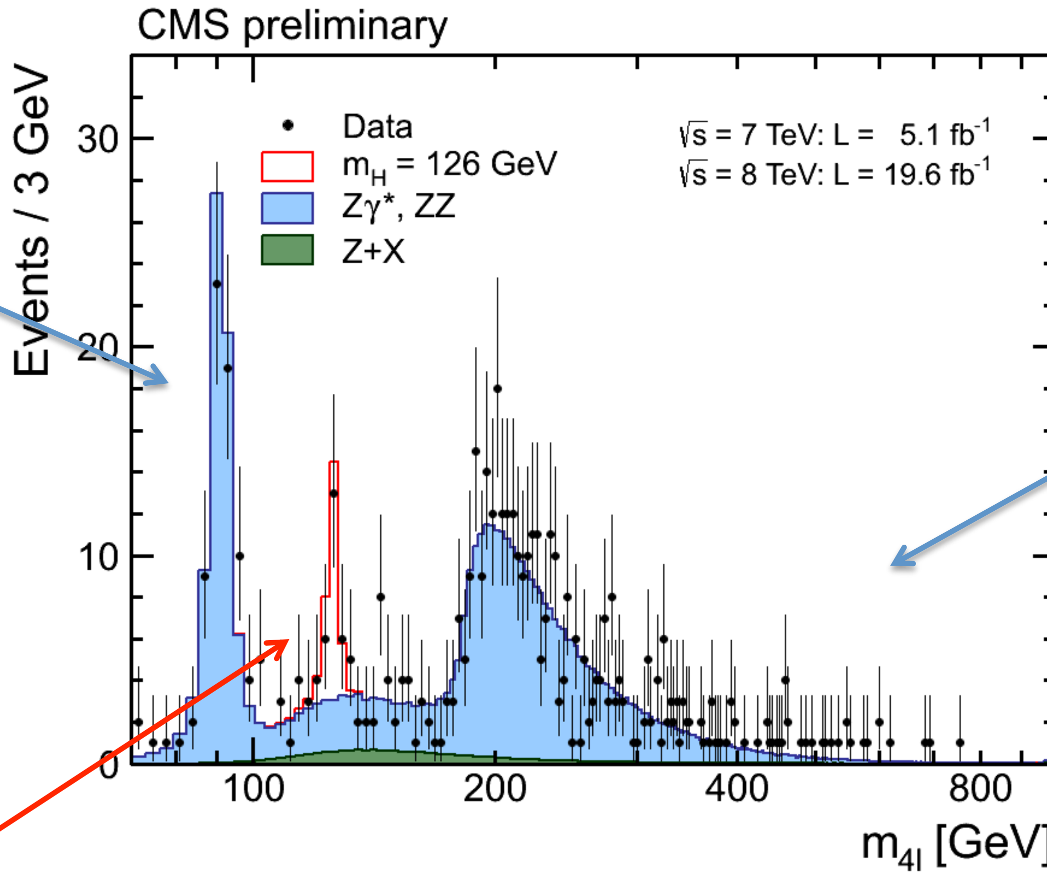
Lepton resolution= 1 - 2%
uncertainty: 20%

Validated in situ with Z(4l)

Chiara Mariotti

pp → 4l





Very good control of the dominant ZZ background

M(4l)>160 GeV
Data 380
MC 364.5

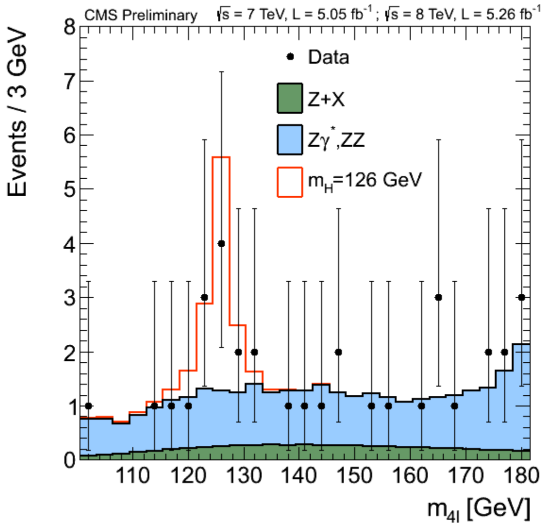
Clean signal peak at ~126 GeV

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

σ_{SM}(th) = 7.8 ± 0.6 pb

A beautiful peak

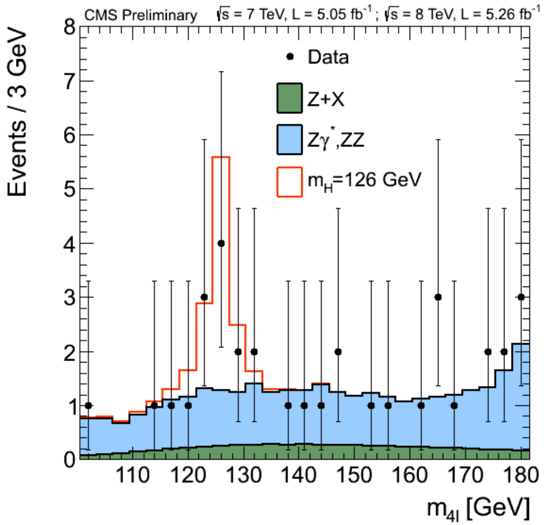
4 July



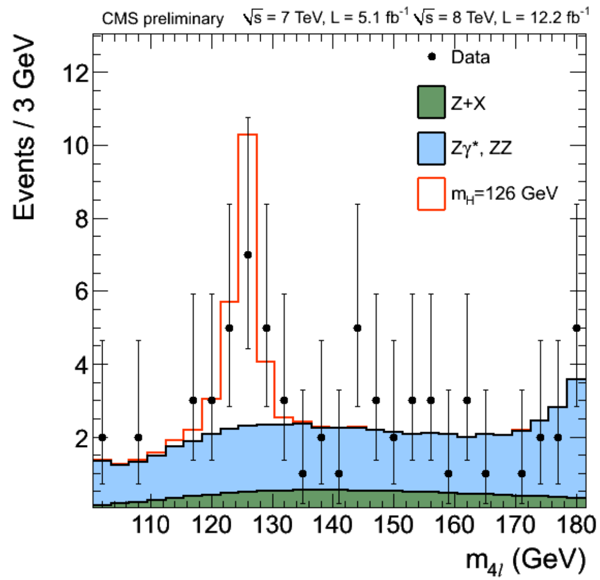
The beauty of an equation is more important than its correctness, in the sense that if an equation is beautiful, sooner or later it will be demonstrated to be correct. Paul Dirac

A beautiful peak

4 July



HCP



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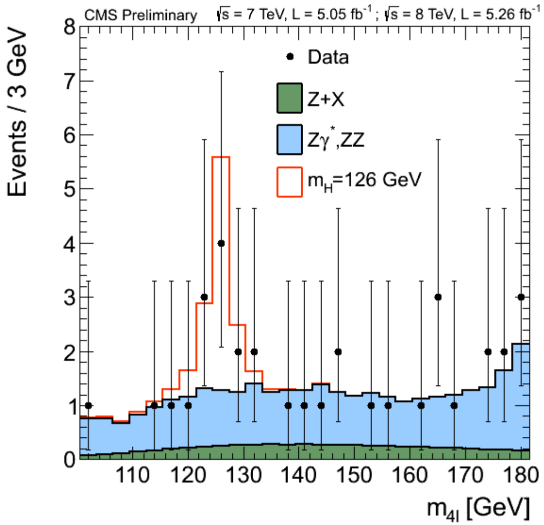
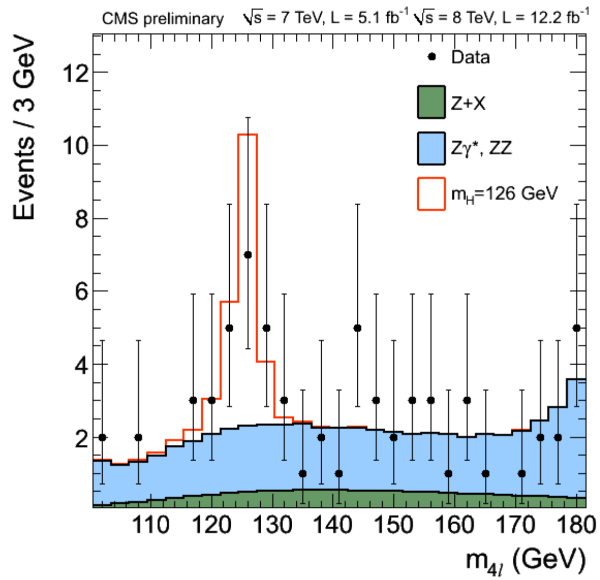
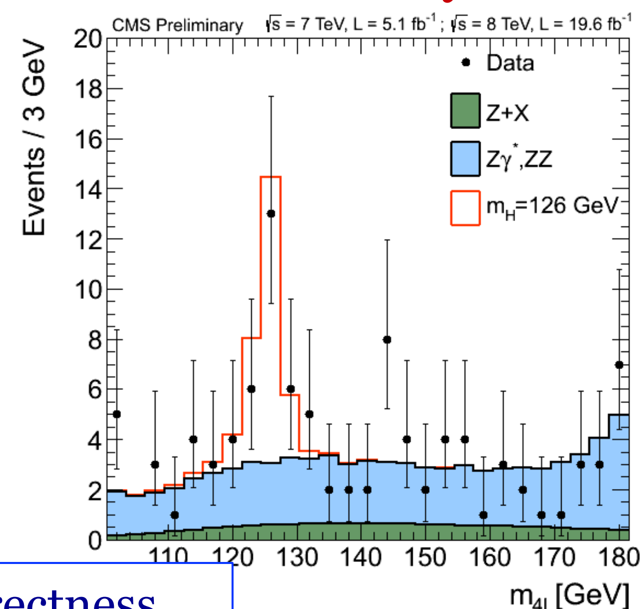


HCP



Today



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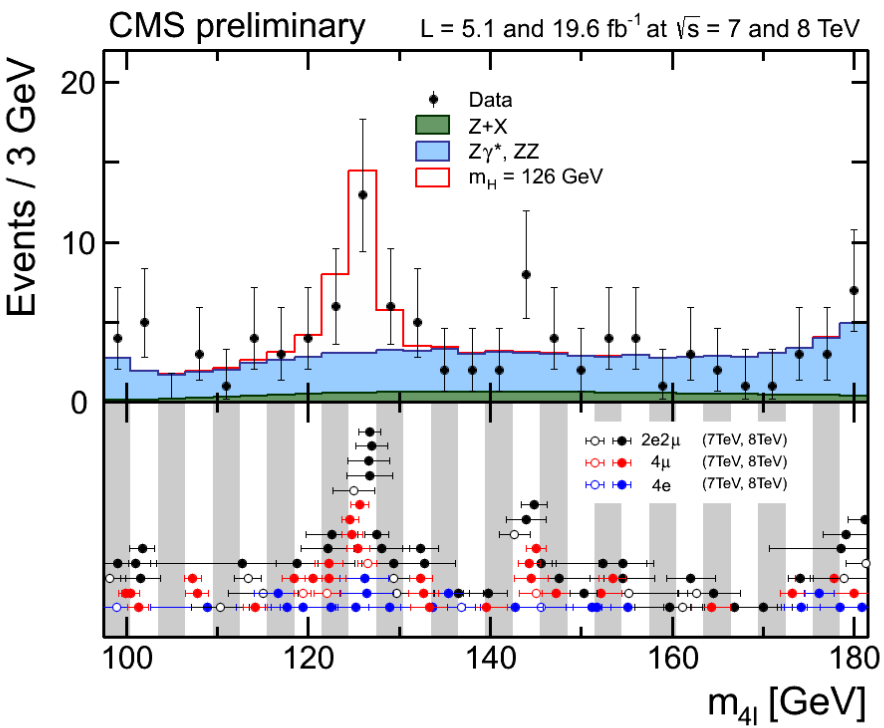
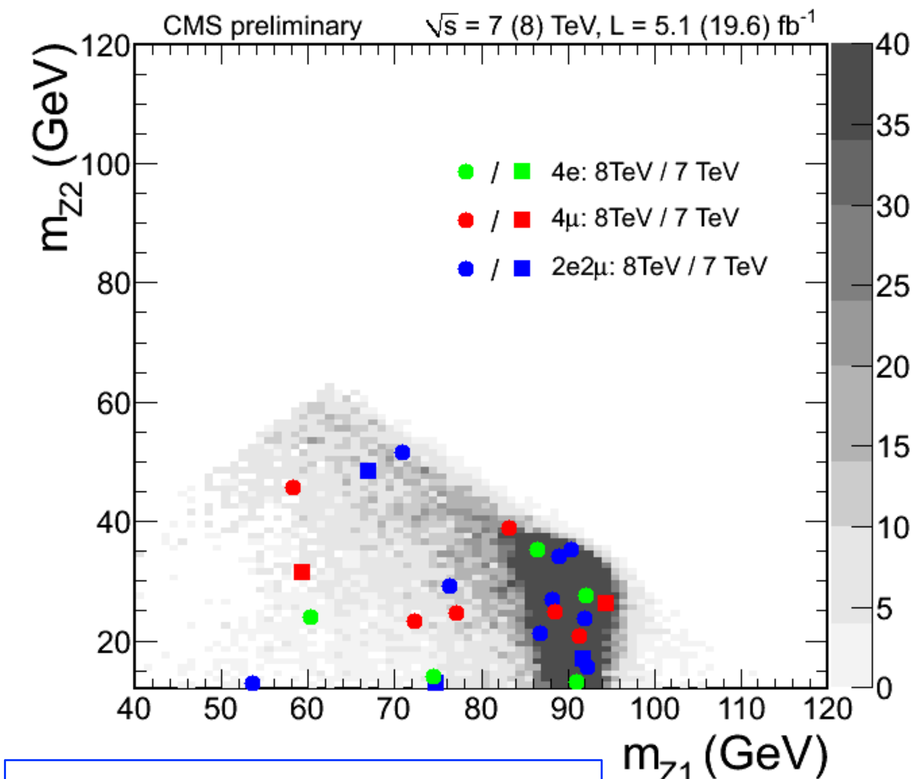
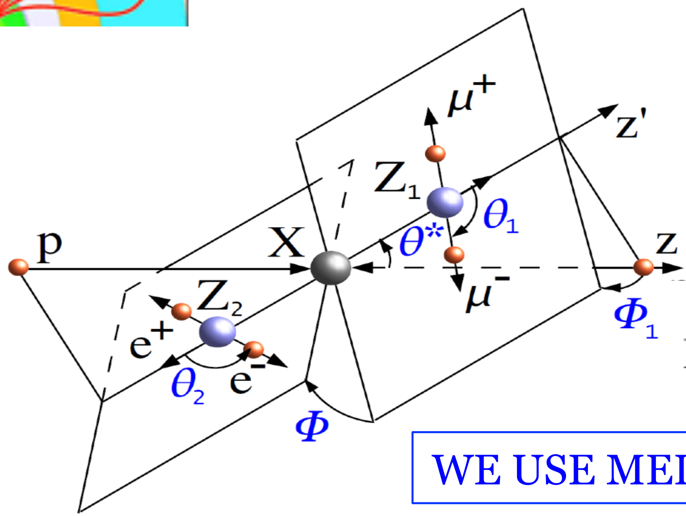
The candidates





$121.5 < M(4l) < 130.5$ GeV

Kinematic Discriminant

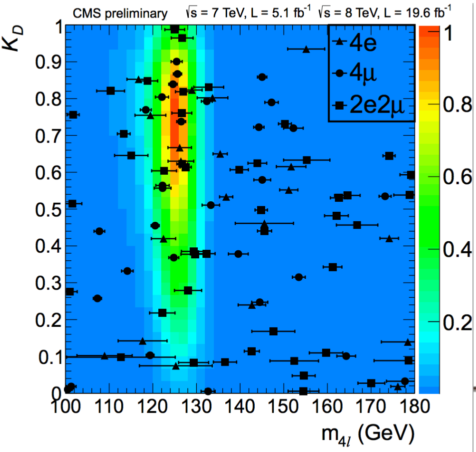


Matrix **E**lement **L**ikelihood **A**nalysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1,m_2,\theta_1,\theta_2,\theta^*,\Phi,\Phi_1\}$

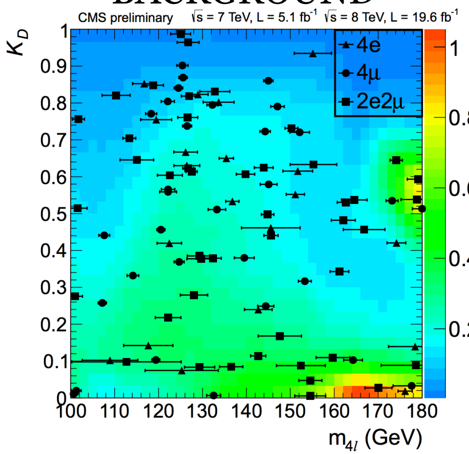
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})}\right]^{-1}$$

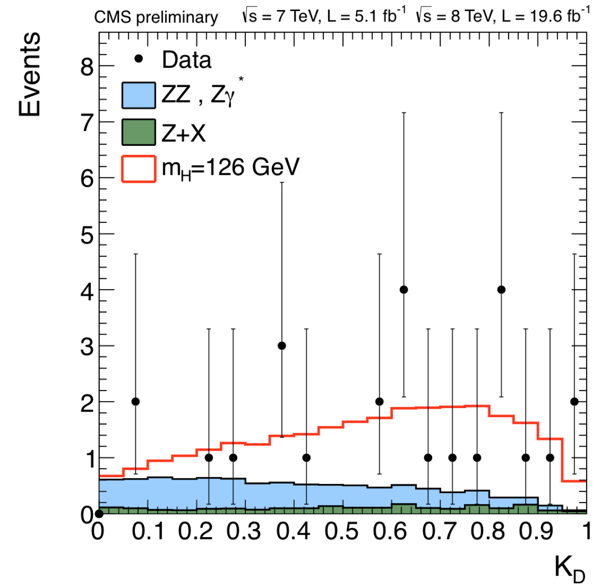
WE USE MELA IN THE FIT

SIGNAL

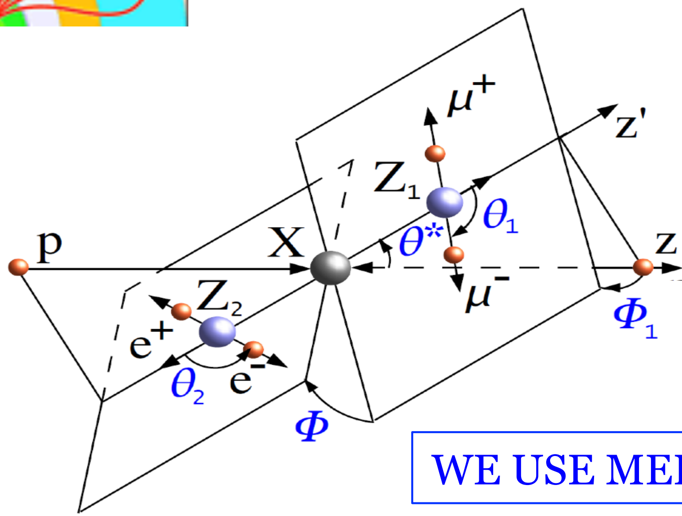


BACKGROUND





Kinematic Discriminant



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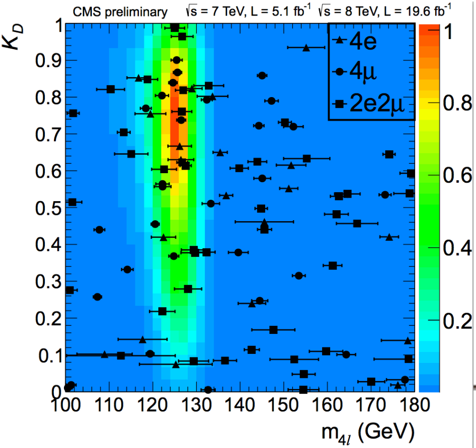
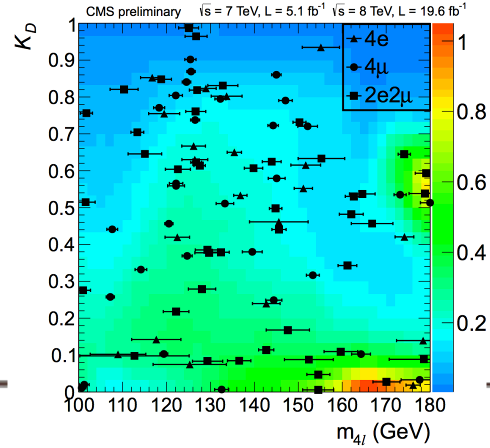
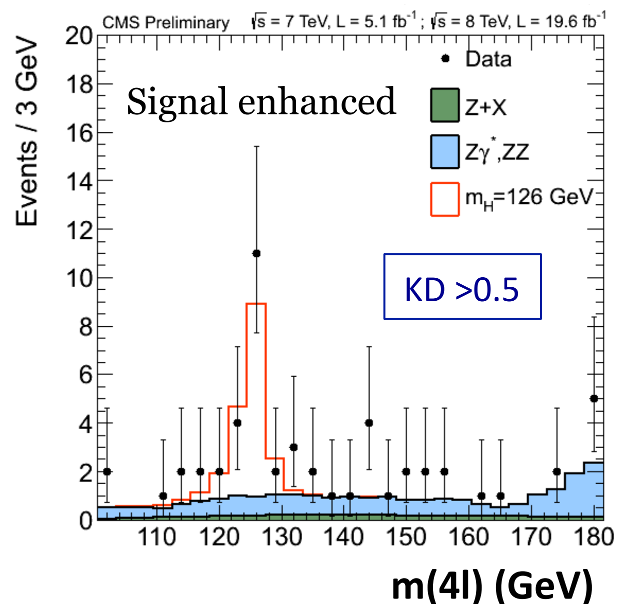
WE USE MELA IN THE FIT

SIGNAL

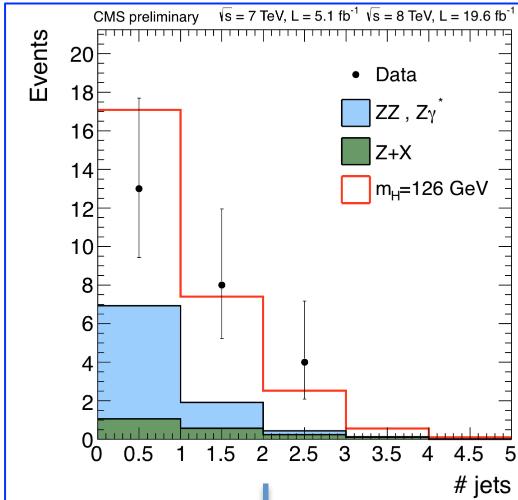


BACKGROUND





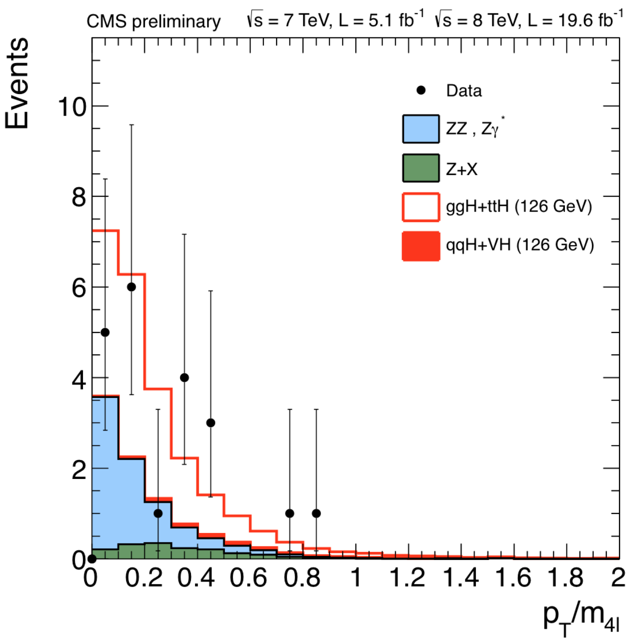
Jet categories



Un-tagged (0/1 jet)

Use pT_{m4l}/m_{4l}

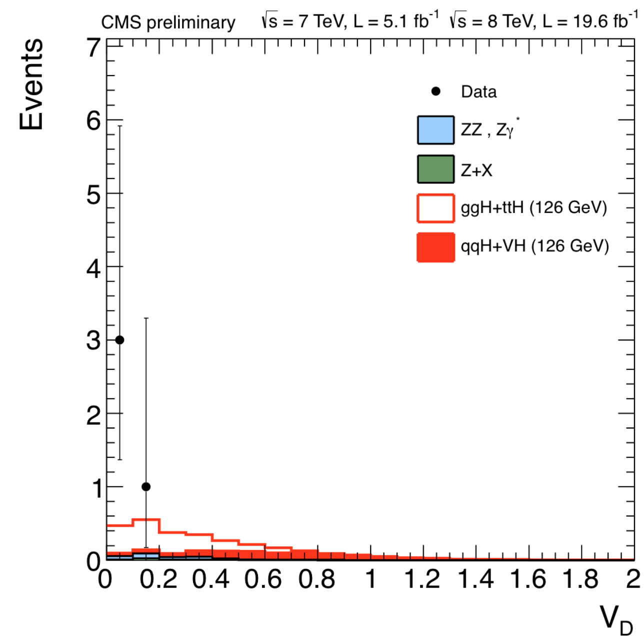
(VBF fraction~5%)



Di-jet Tagged (>=2 jets)

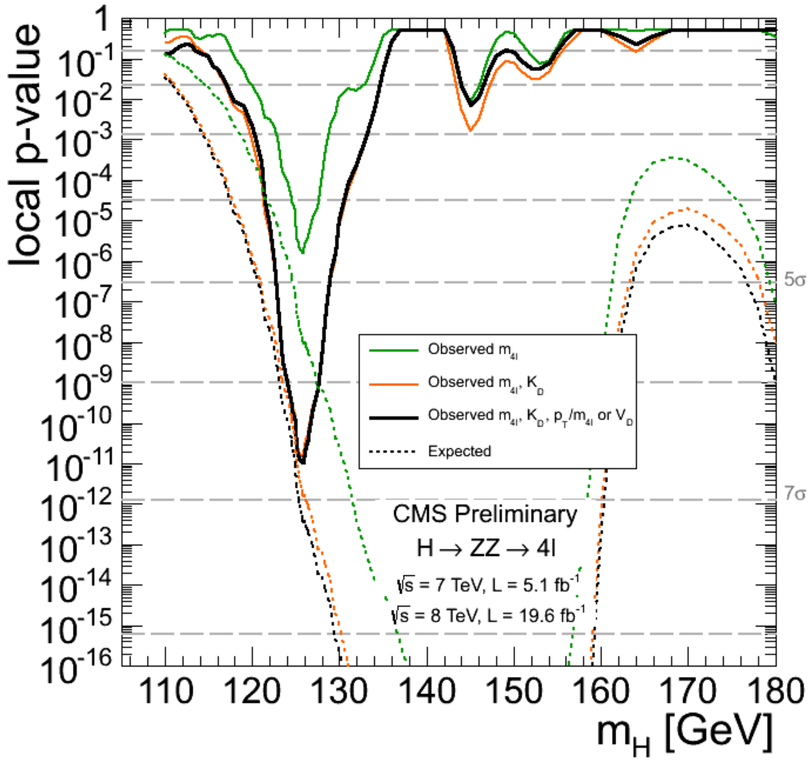
Use Fisher Discriminant (m_{jj}, $\Delta\eta_{jj}$)

(VBF fraction~20%)

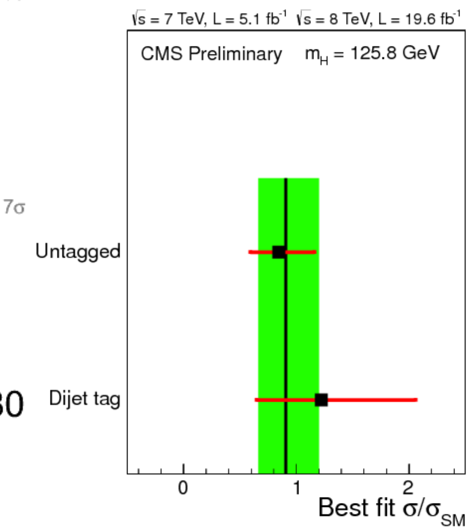


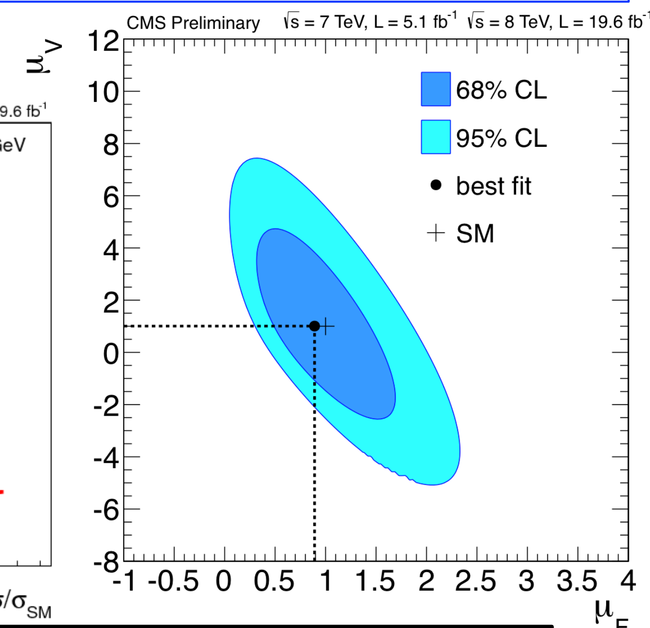
121.5 < M(4l) < 130.5 GeV

Results



Jet categories to measure couplings



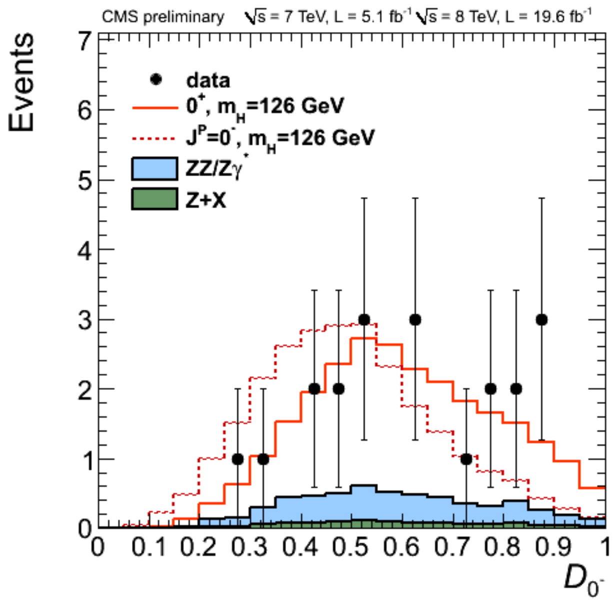


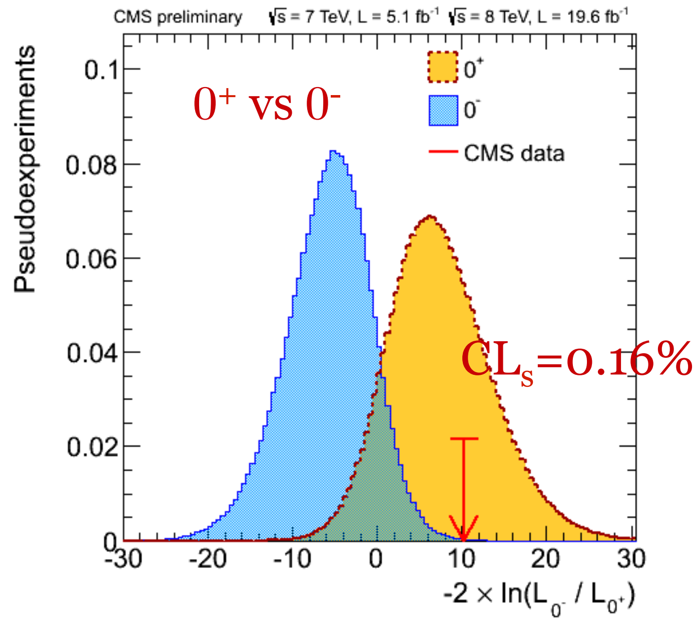
p-value **Expected: 7.1 σ**
Observed: 6.7 σ

σ/σ_{SM} @ 125.7 GeV = 0.92 ± 0.28

J^P

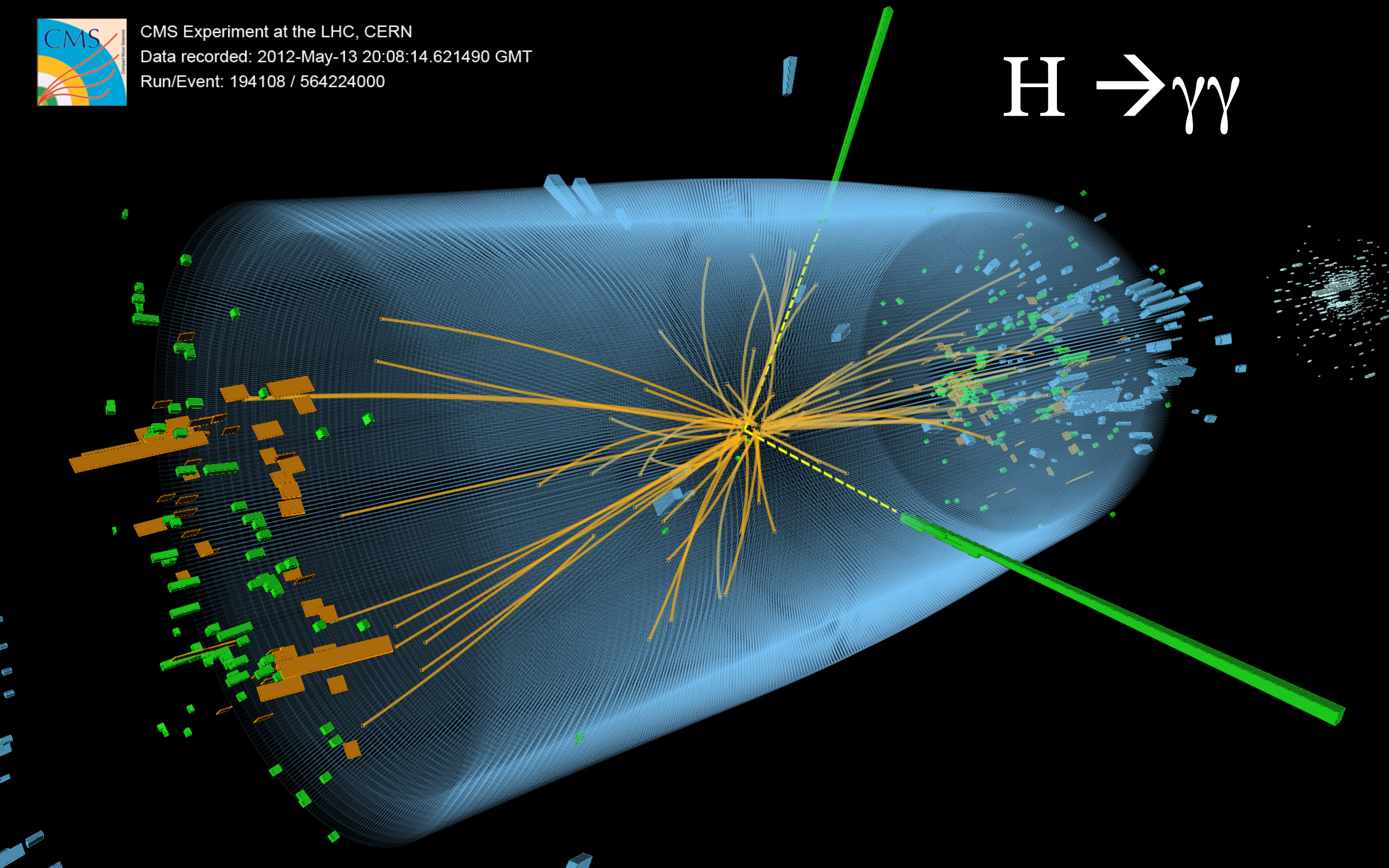
Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of "Higgs"



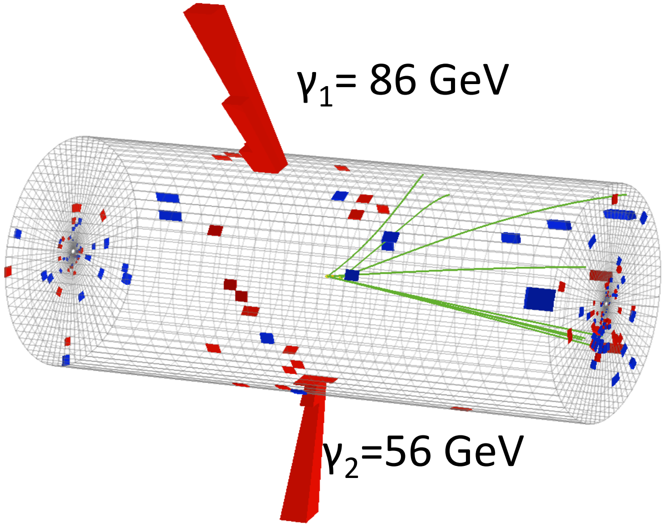


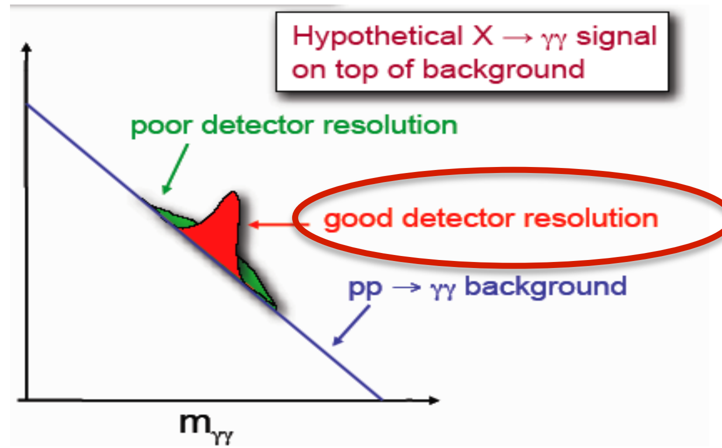
More J^P hypotheses have been tested in a similar way →

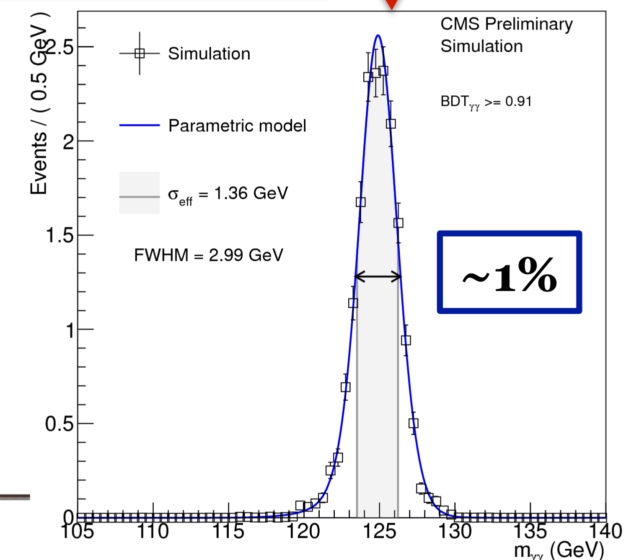
J^P	CL_s
0^-	0.16%
0_h^+	8.1%
2_{mgg}^+	1.5%
$2_{mq\bar{q}}^+$	<0.1%
1^-	<0.1%
1^+	<0.1%


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ

H → γγ







Signature: 2 energetic, isolated γ, in a narrow mass peak on top of a large steeply falling background

Relevant aspects:

- Photon identification/ background rejection
- Di-photon mass spectrum
- Background estimation
- Primary vertex determination (pile-up!)

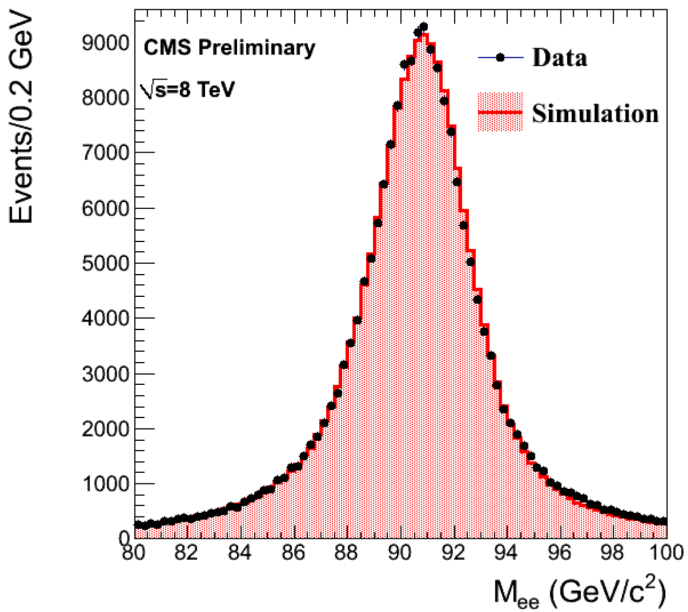
Ecal performance

$$m^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)$$

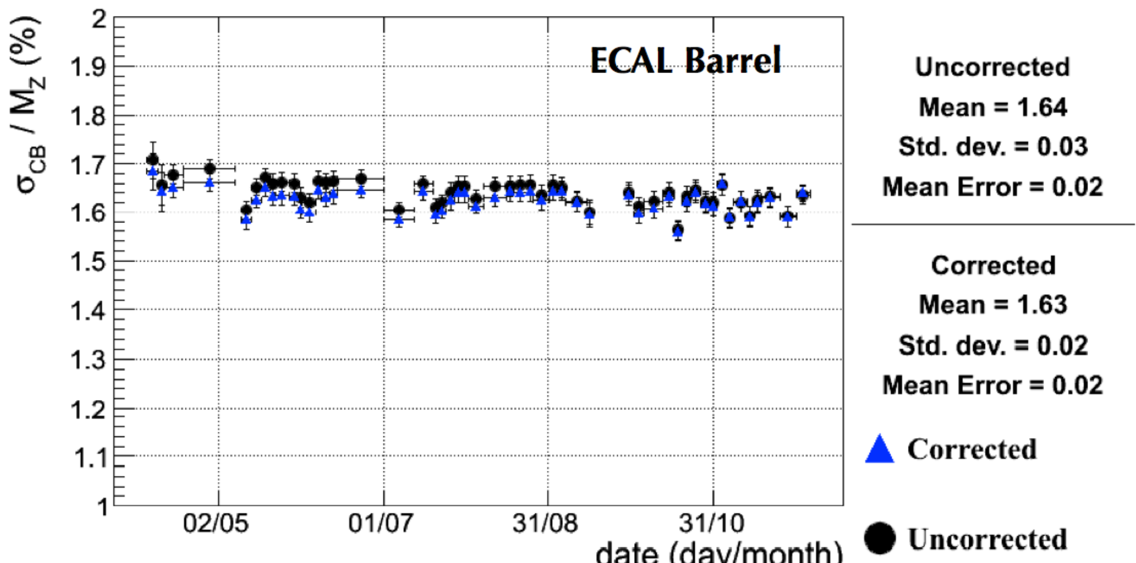
Energy resolution

- **Very good ECAL performance in 2012**
  Z→ee mass resolution better than 1.2% for electrons with low bremsstrahlung in the barrel.
- **Stable performance** already using promptly reconstructed data

Z→ee lineshape:
good agreement between data/MC



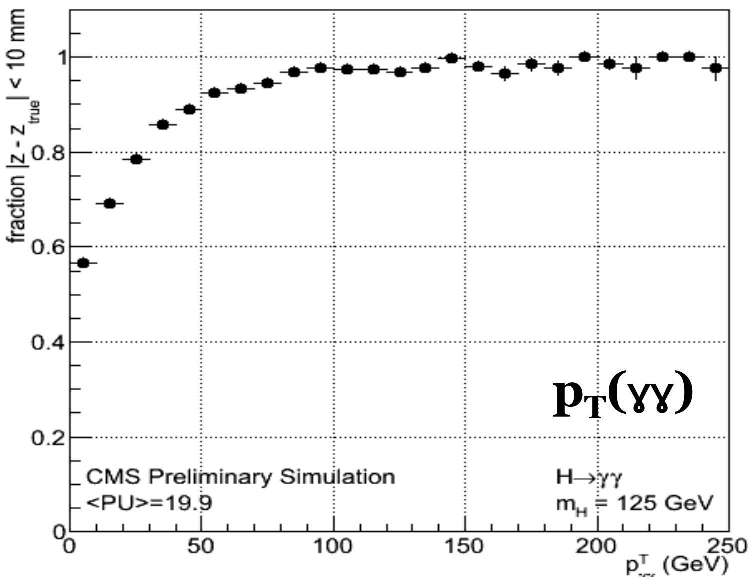
Z mass **resolution** as a function of time after application of analysis level corrections (energy scale)

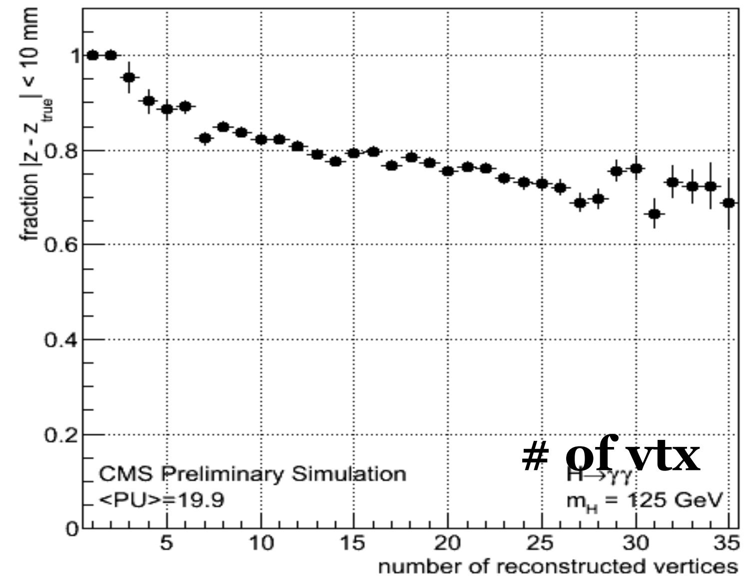


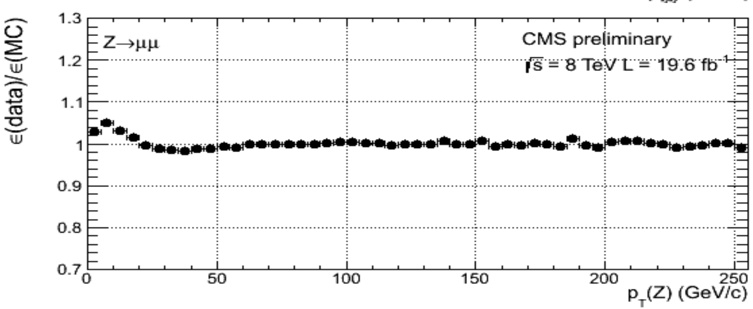
$H\to\gamma\gamma$: Vertex selection with a BDT

$$m^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)$$

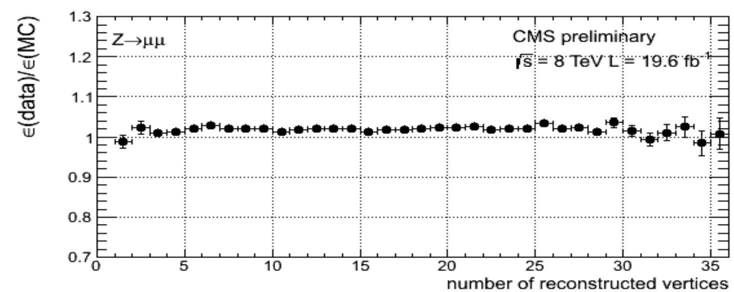
Primary vertex





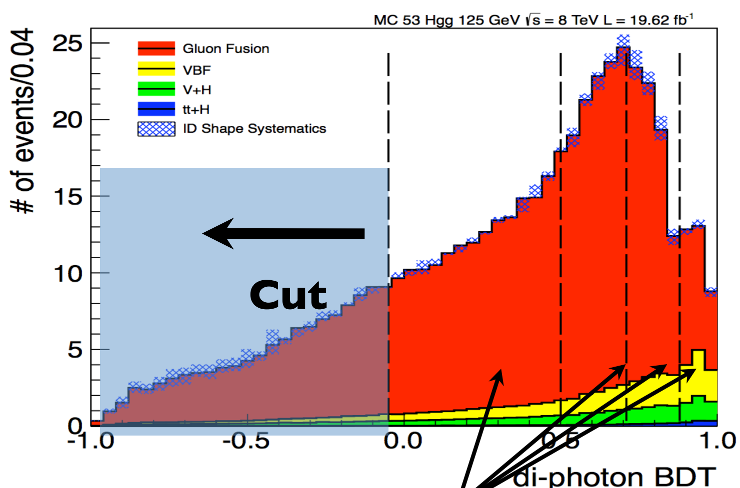


Data/MC ratio using $Z\to\mu\mu$ with μ track removed



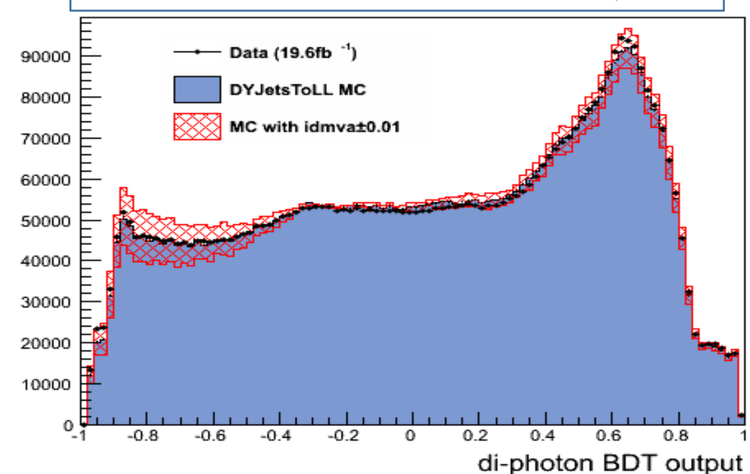
H→γγ

- Two inclusive analyses:
  - PRIMARY — MVA: photons selected with an MVA. Variable in the MVA: photon kinematics, photon ID MVA score (shower shape, isolation), di-photon mass resolution. 4 MVA categories with different S/B
  - CROSS-CHECK — Cut-based: photons selected with cuts. 4 categories based on: γ in Barrel/Endcap, (un)converted γ. Each category has different mass resolution and S/B
- 3 VH channels (e, μ and MET tag) + VBF (2 dijet categories)



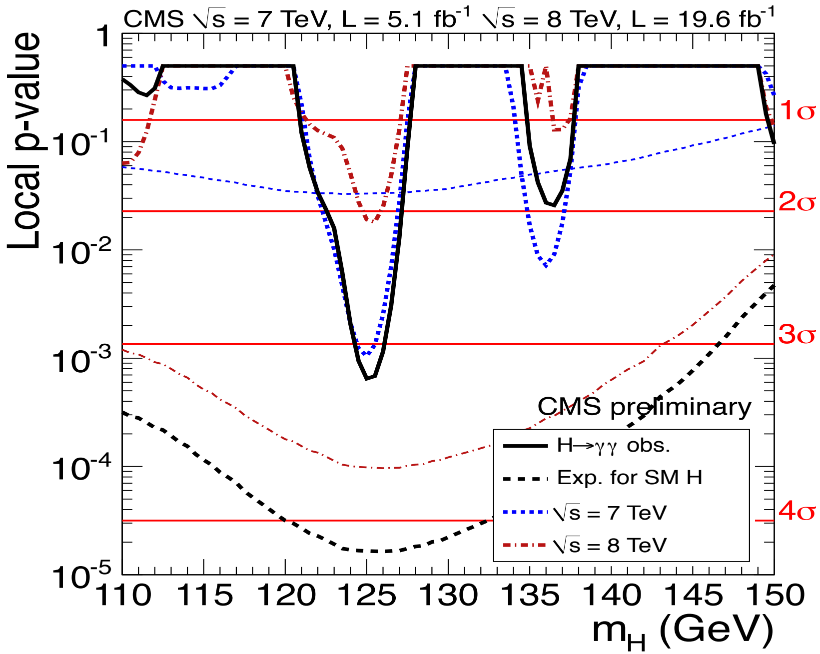
MVA Event categories

Output of the MVA validated using Z→ee (where e are reconstructed as γ)



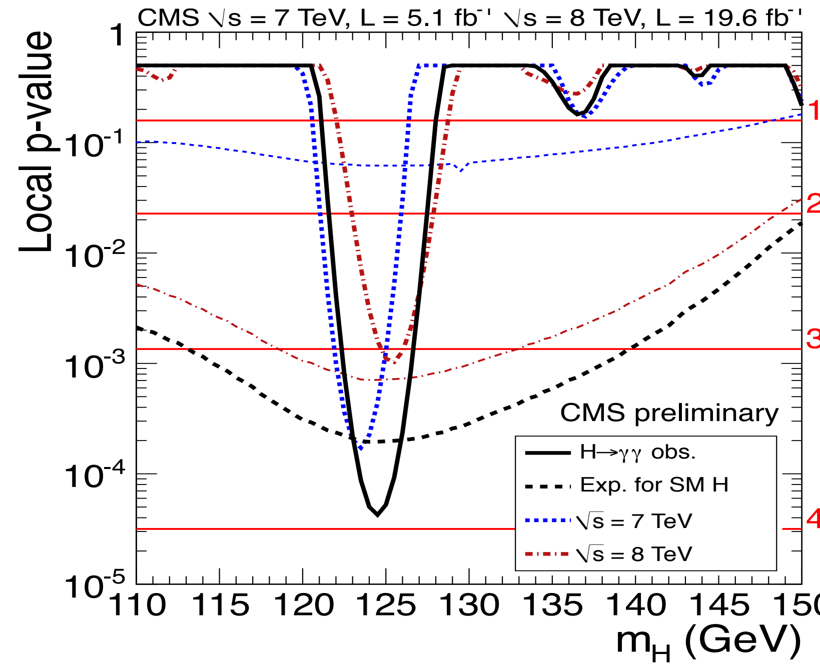
H→γγ: Results (p-values)

MVA mass-factorized



Significance @ 125.0 GeV: 3.2 σ (4.2 exp.)

Cut-based

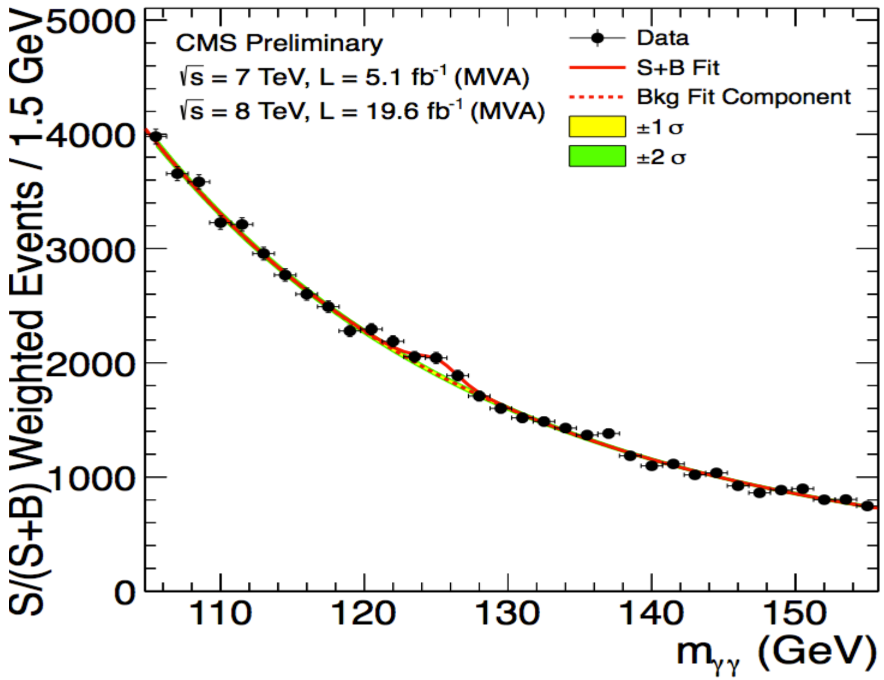


Significance @ 124.5 GeV: 3.9 σ (3.5 exp.)

With additional data and new analysis: significance decreased compared to the published results

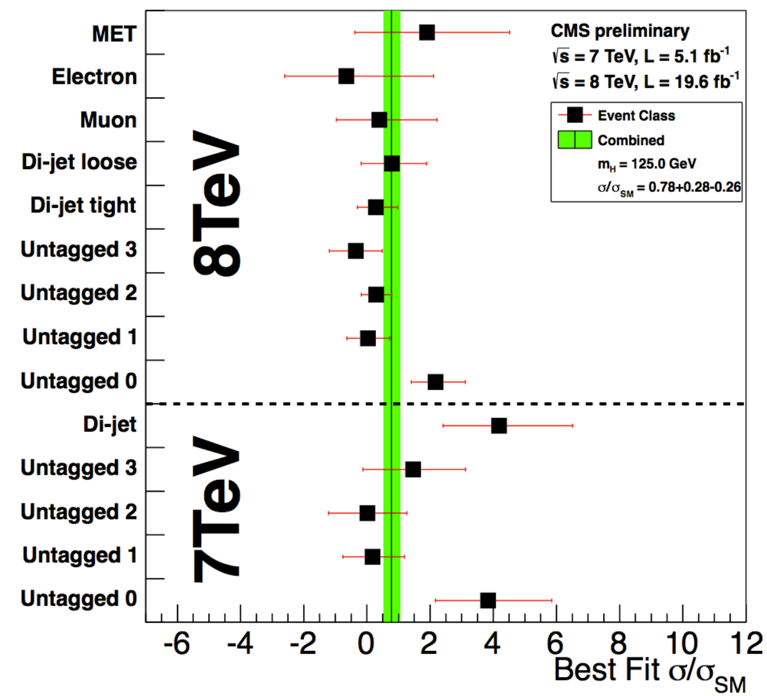
H→γγ: Combined mass plot: 7+8 TeV

MVA mass-factorized



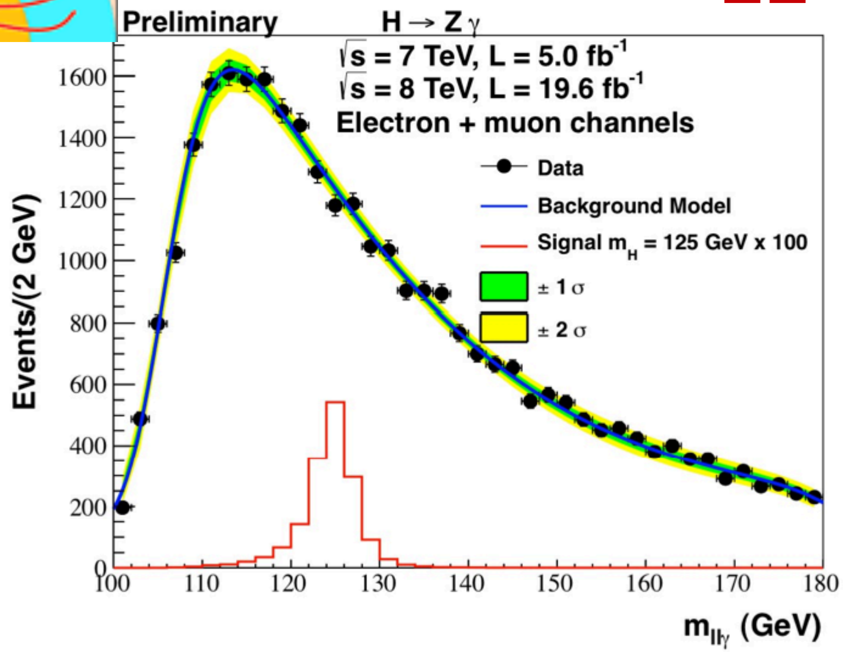
Each event category is **weighted by its S/(S+B)** only for visualization purposes

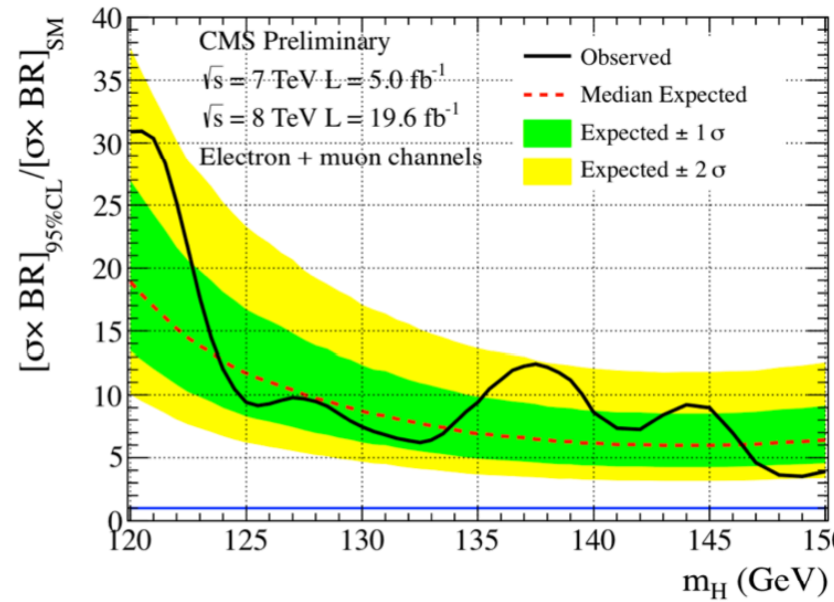
MVA mass-factorized



7+8 TeV: σ/σ_{SM} @ 125.0 GeV = 0.78 $^{+0.28}_{-0.26}$

H → Zγ



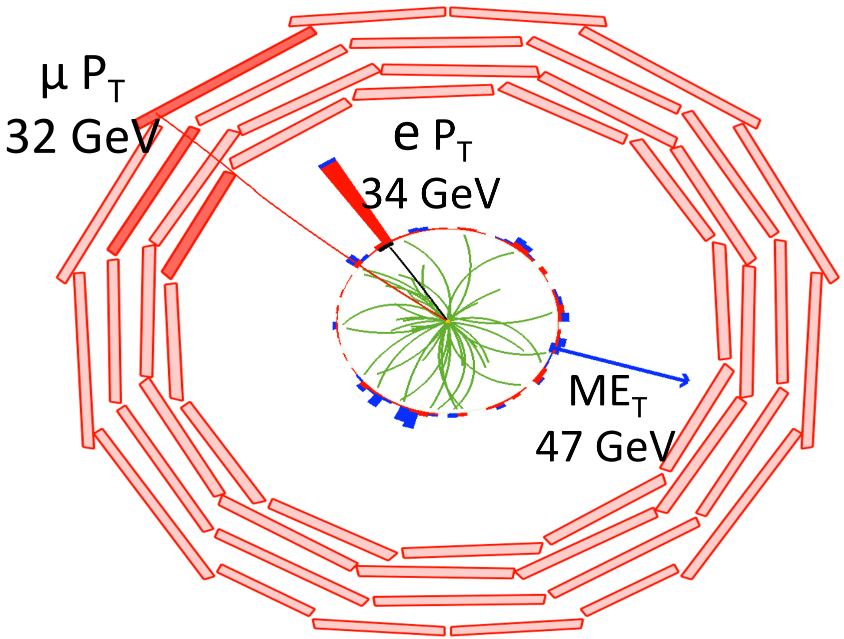


BR (H → Zγ) comparable to BR(H → γγ) , but BR (Z → ll) suppresses signal by ~ 20

Search for a narrow llγ peak on top of a falling background " a la H → γγ "

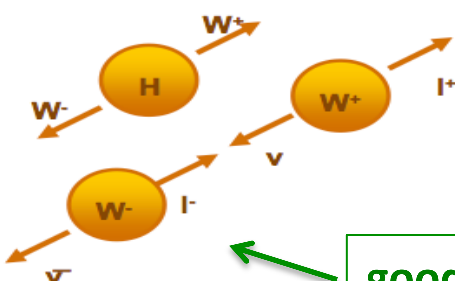
Events are divided in 4 classes, depending on the S/B and mass resolution

H →WW→lνlν



- Channel with very high σxBR
- No mass reconstruction, signal extraction from event counting
- Clean signature:
  - 2 isolated, high p_T leptons with small opening angle
  - High ME_T
  - Analysis performed on exclusive jet multiplicities (0, 1, 2-jet bins)
  - Different Flavour, Same Flavour lept
- Discriminant Variables:
  - p_T^l, M_{ll}, M_T, $\Delta\phi$
  - VBF selections for the 2-jets case

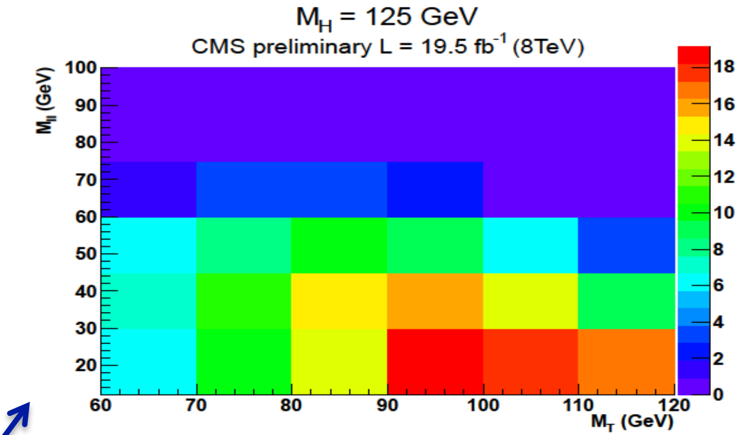
Vectors from the decay of a scalar and V-A structure of W decay lead to a small opening angle between leptons (especially true for on-shell Ws)

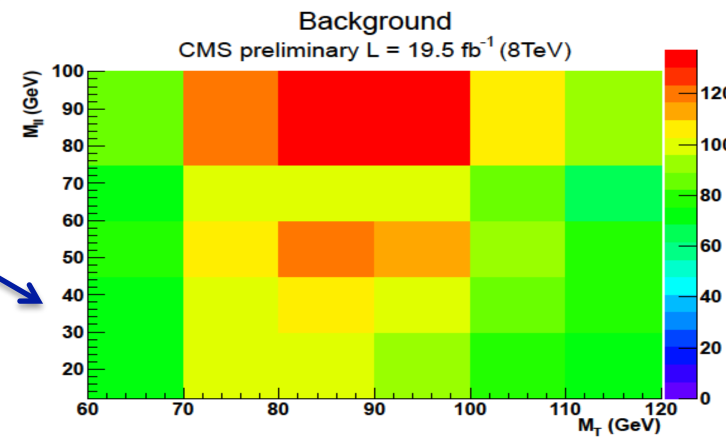


good sensitivity to Spin

$H \rightarrow WW \rightarrow 2l2\nu$: strategy

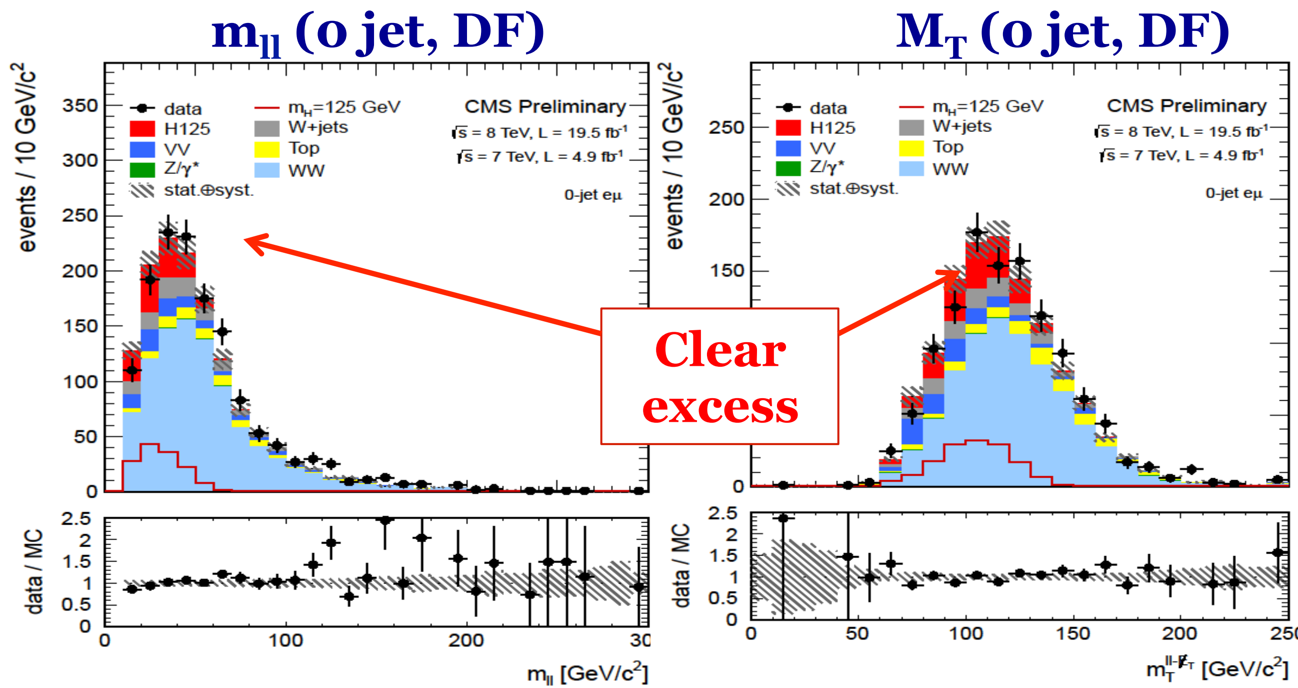
- Pre-selection cuts:
  (on lepton p_T, MET, anti-b-tag..)
- Jet categories: 0 Jet
  1 Jet
  2 Jets with VBF topology
- 0 & 1 jet category subdivided in:
  - Different Flavour (DF)
    2D (M_T, m_{ll}) shape analysis
  - Same Flavour (SF)
    Cut-based analysis





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

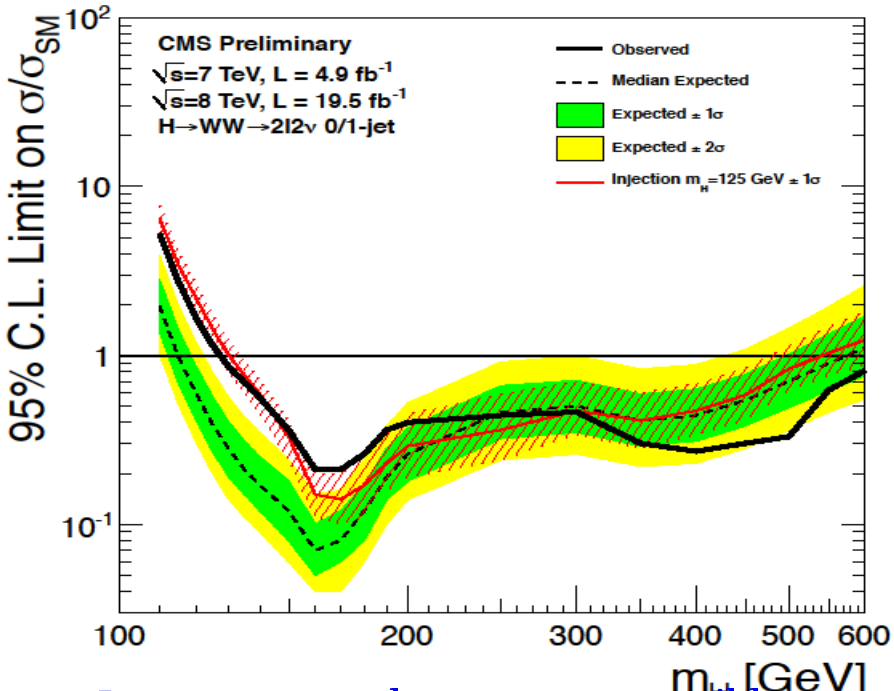
H →WW→2l2ν: results

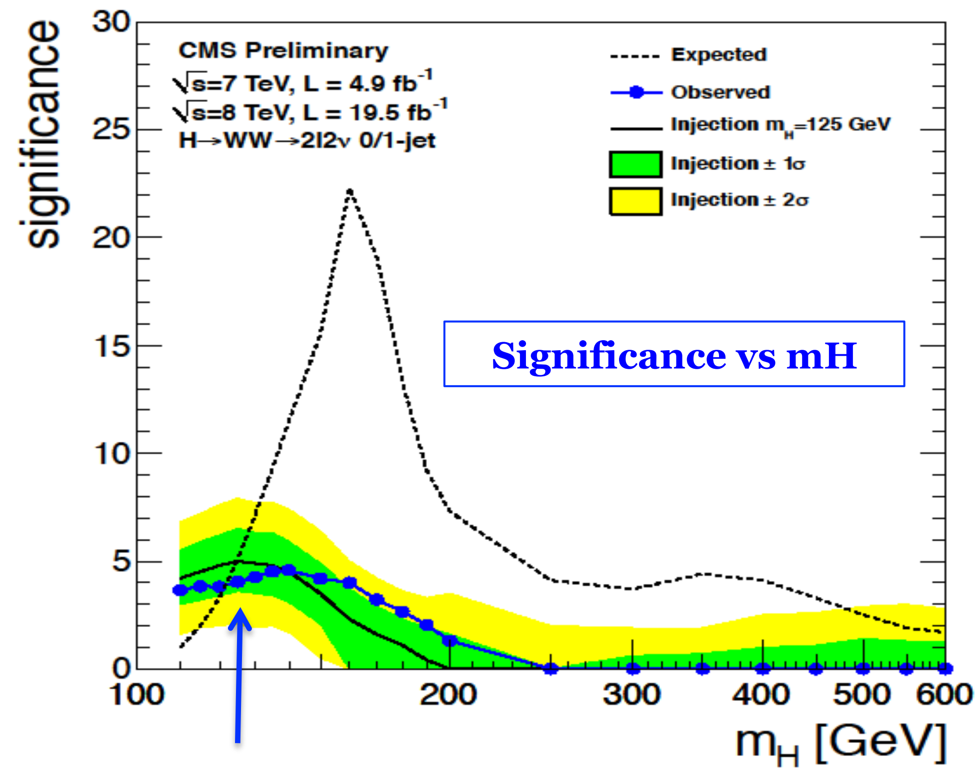


All the background are estimated from DATA in "control regions"

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

H →WW→2l2ν: Results



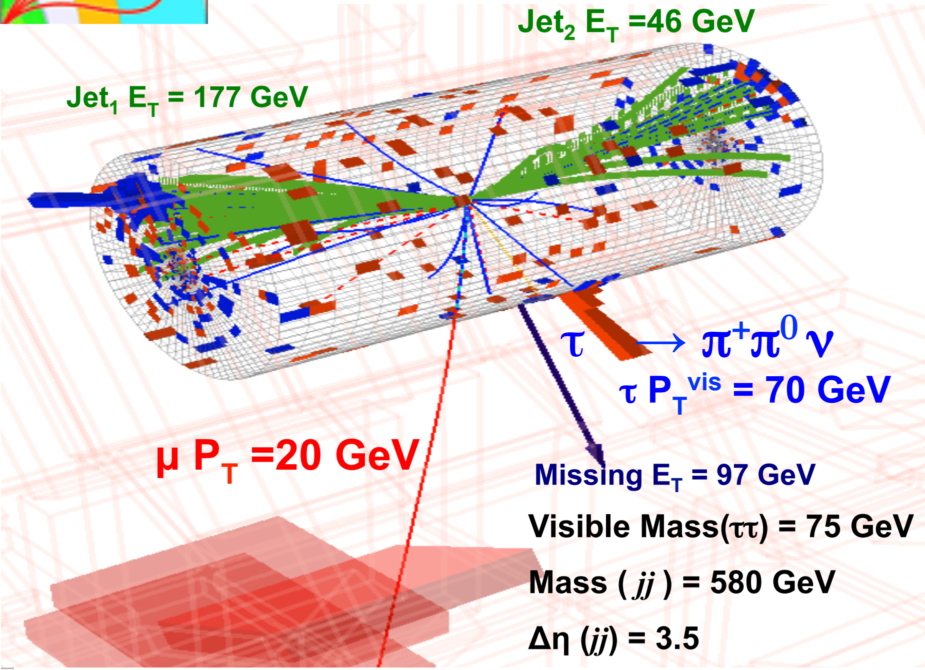


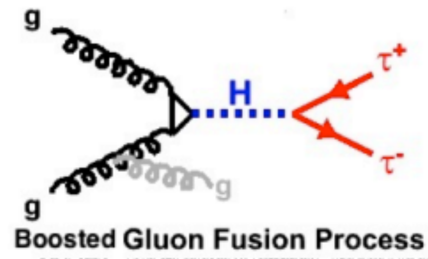
Large excess at low mass compatible with the expected Higgs signal

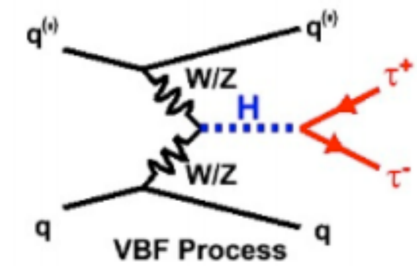
Significance @ 125 GeV: 4.0 σ (5.1 expected)

σ/σ_{SM} @ 125 GeV = 0.76 ± 0.21

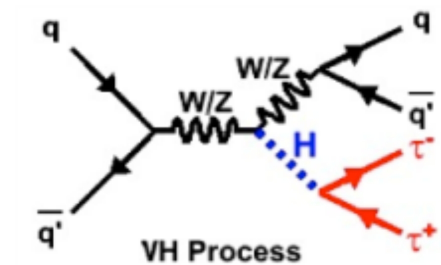
$H \rightarrow \tau\tau$







ggF, VBF production: $\mu\mu, e\mu, \tau_h\tau_h, e\tau, \mu\tau_h$



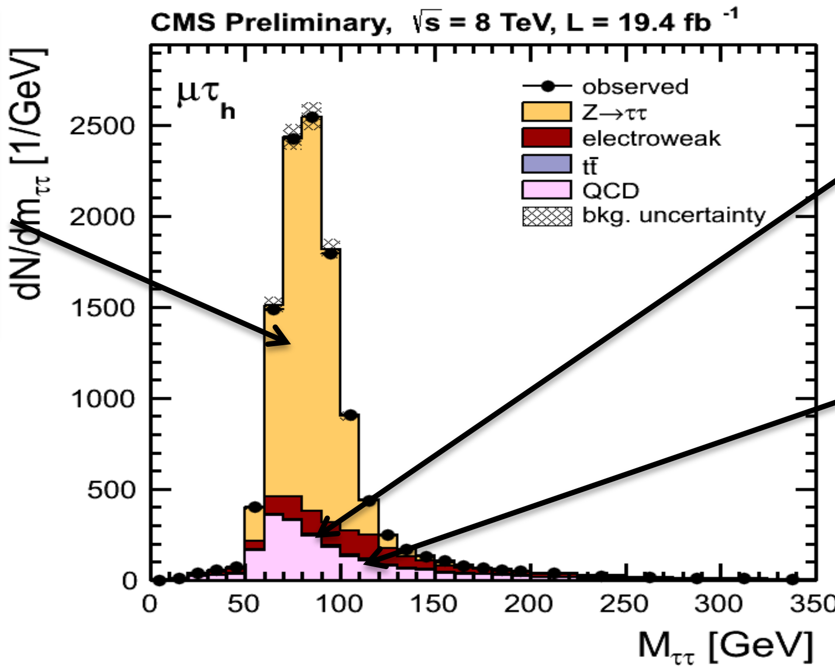
VH production: $l\tau_h\tau_h, ll\tau_h\tau_h, ll\tau_h$

jet categories:

0-jet: used only to constrain the background
1-jet: low pT / high pT
2-jets (VBF).

Anatomy of the analysis

Z→ττ Embedding:
Z→$\mu\mu$ data, replace μ with simulated τ decay
Normalization from Z→$\mu\mu$ data
Syst: 5%

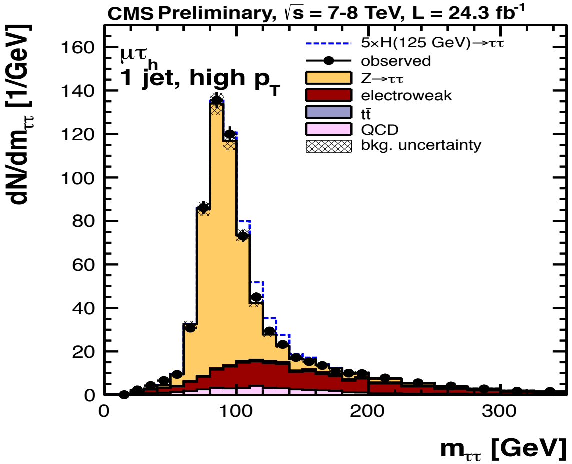


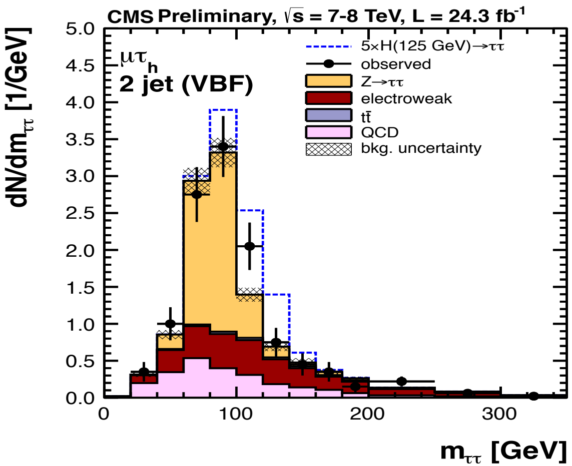
W+jets
Shape from simulation
Normalization from control region
Syst: 10-20%

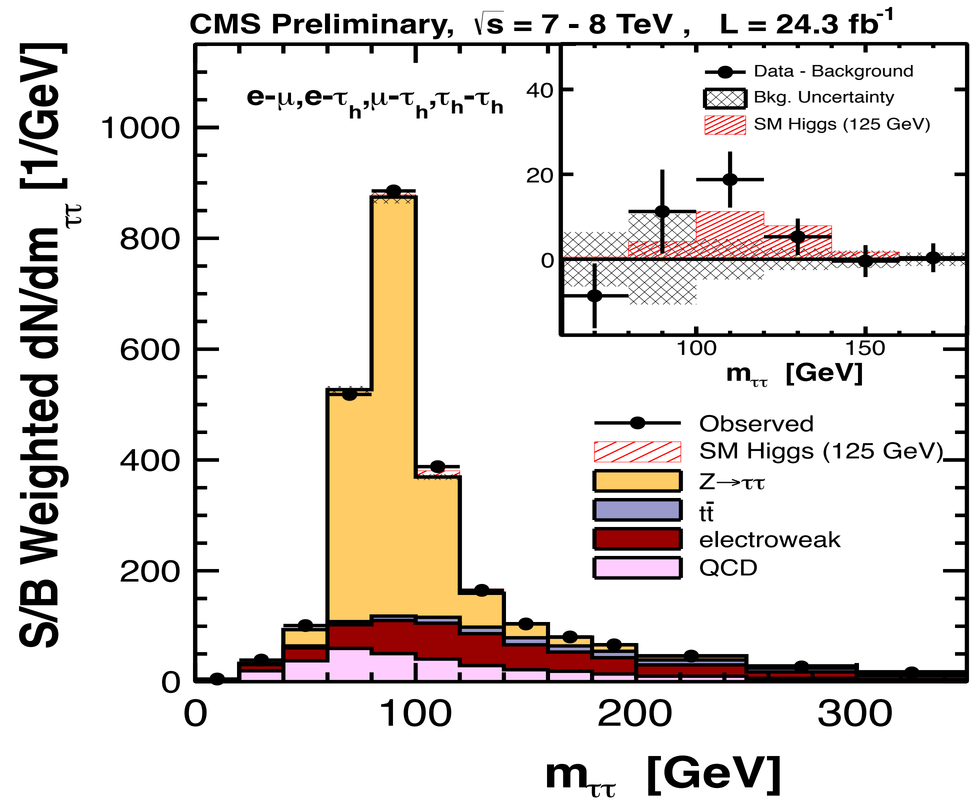
QCD
SS data, corrected for SS/OS ratio
Syst: 10%

Strategy:
- Select isolated, well-identified **leptons**, $\boldsymbol{\tau_h}$
- Topological cuts (e.g. m_T in $\boldsymbol{l\tau_h}$) to suppress backgrounds
- Categorize events based on number of jets, τ p_T
- Template fit to $m_{\tau\tau}$ shape

H → ττ

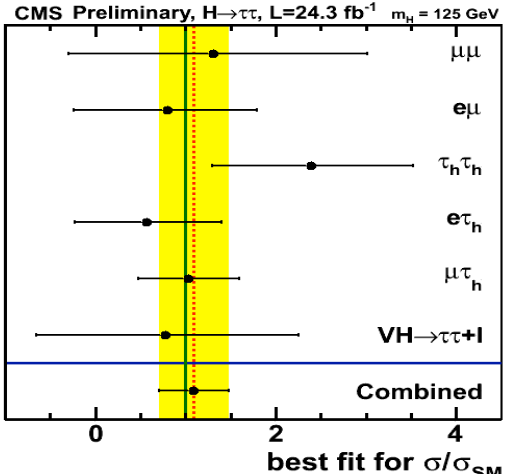






Combine the sensitive categories of all channels with a S/B weight

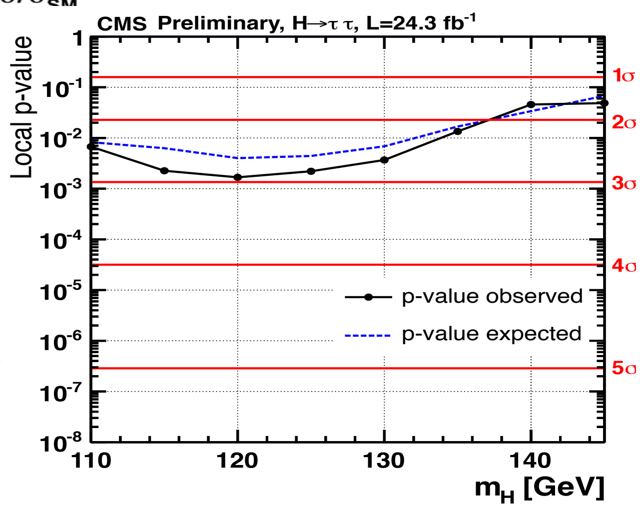
H → ττ : Results

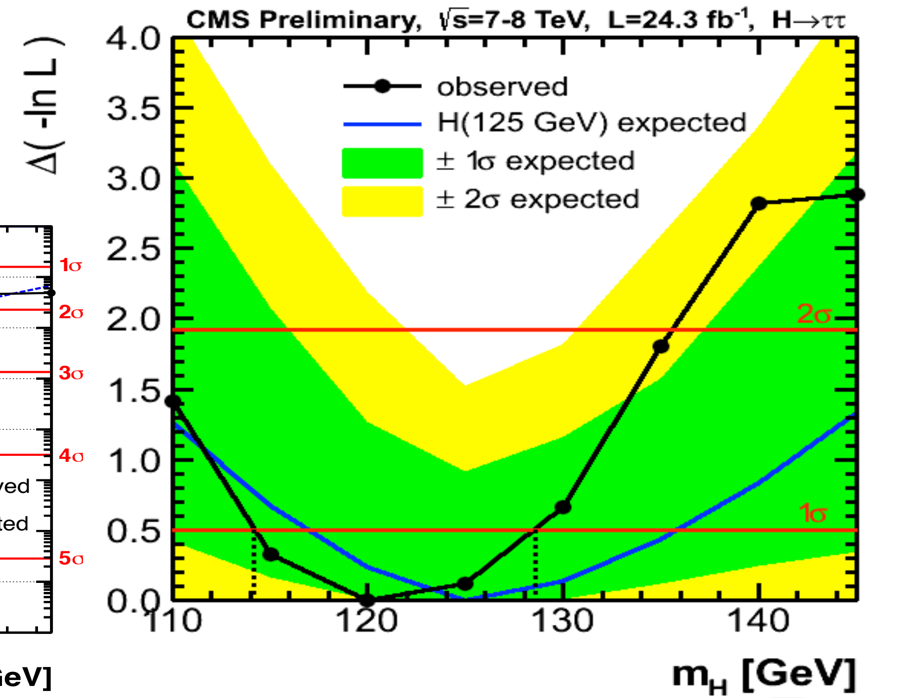


$\mu = 1.1 \pm 0.4$

Mass: all ττ channels combined:

$m_H = 120^{+9}_{-7}$ (stat+syst) GeV



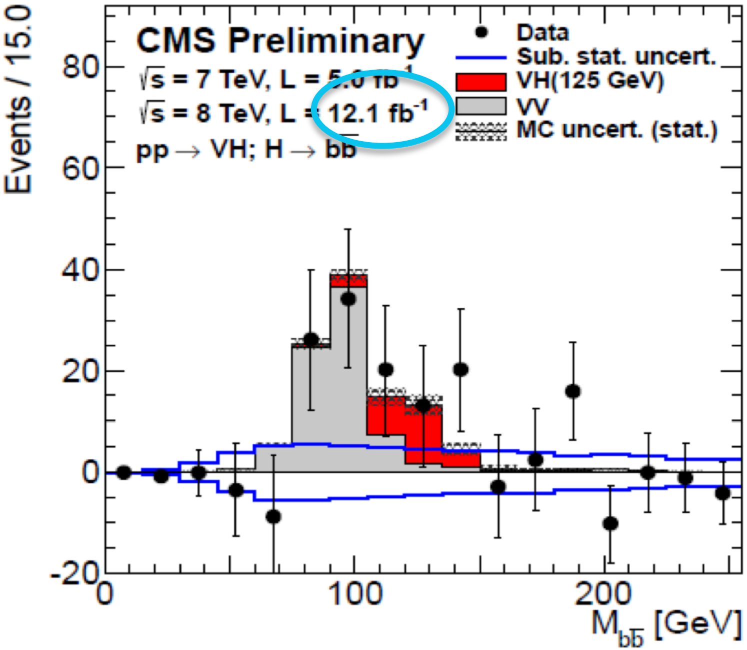


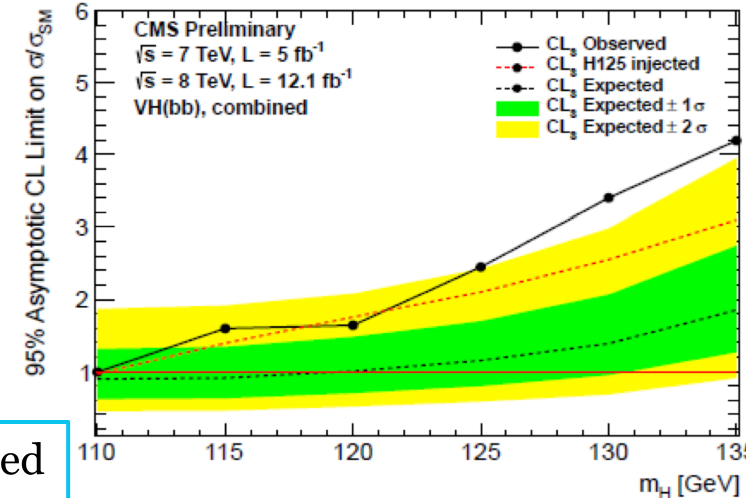
Significance:

2.93 σ @ mH = 120 GeV

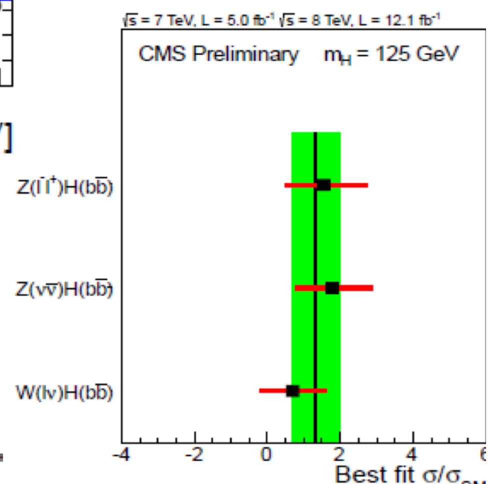
2.85 σ @ mH = 125 GeV

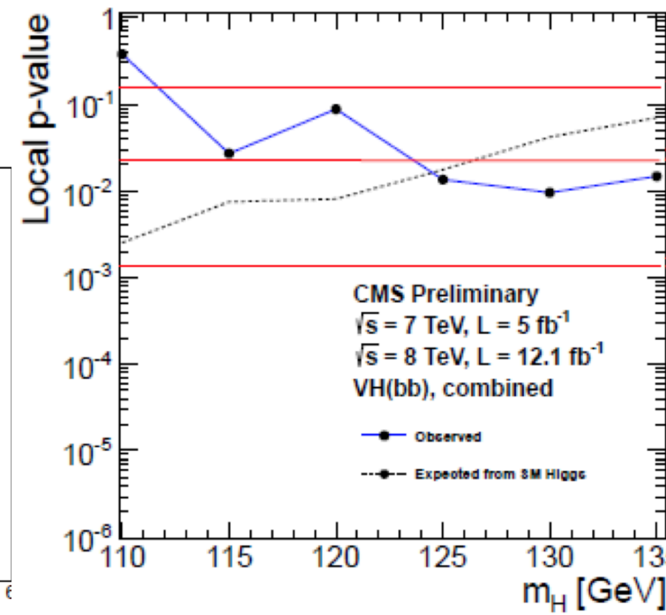
VH →bb: results





Soon will be updated with full statistics



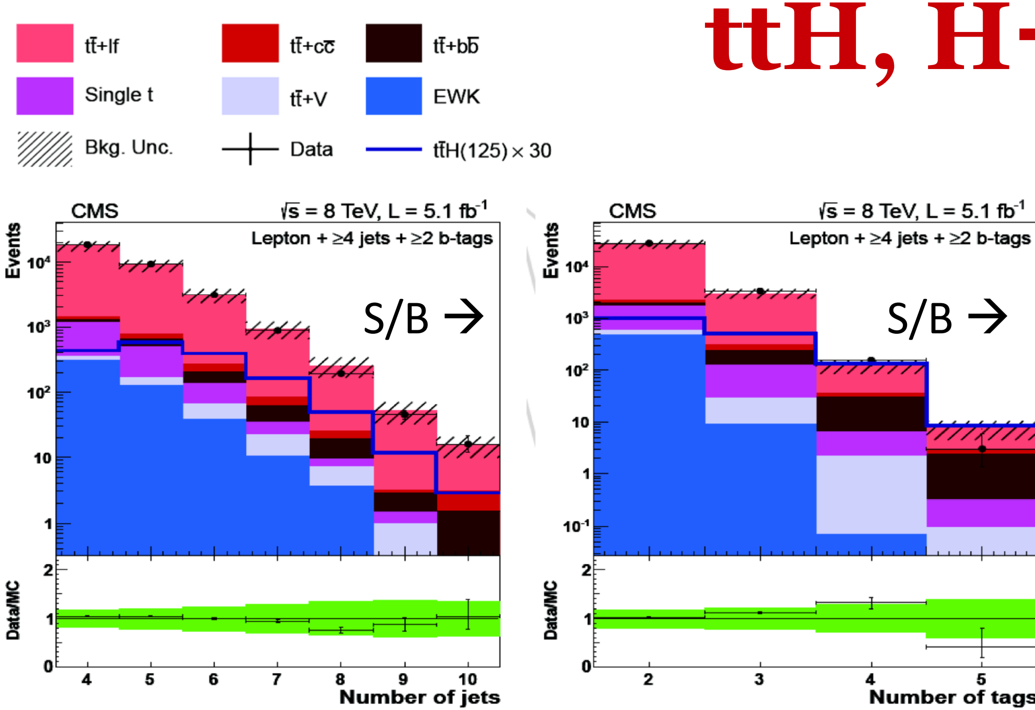


at 125 GeV

sig= 2.2σ

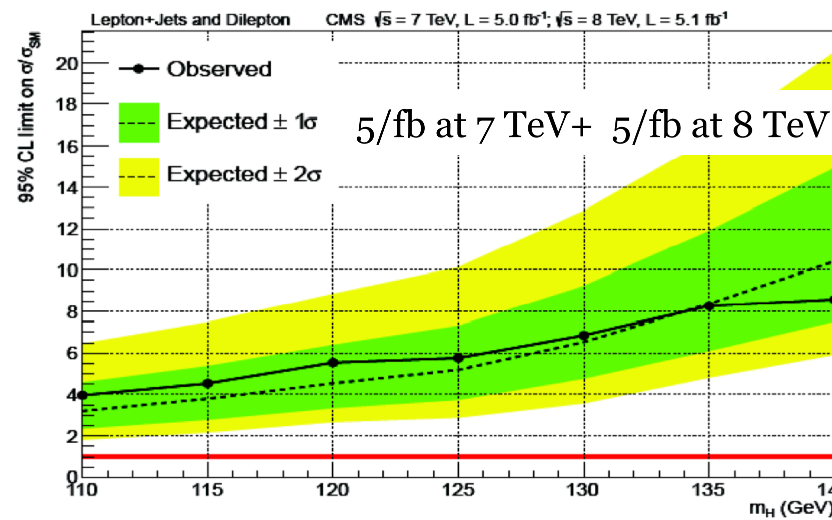
$\mu = 1.3^{+0.7}_{-0.67}$

ttH, H→bb



Data compatible with background expectations

@125 GeV: Exp:5.2,
Obs:5.8



Limits extracted with shape analysis on NN:

- B-tagging of jets
- Kinematic of jets
- M_{bb} (only for 6j,4t)

Summary of the five main channels

@m_H = 125.7 GeV

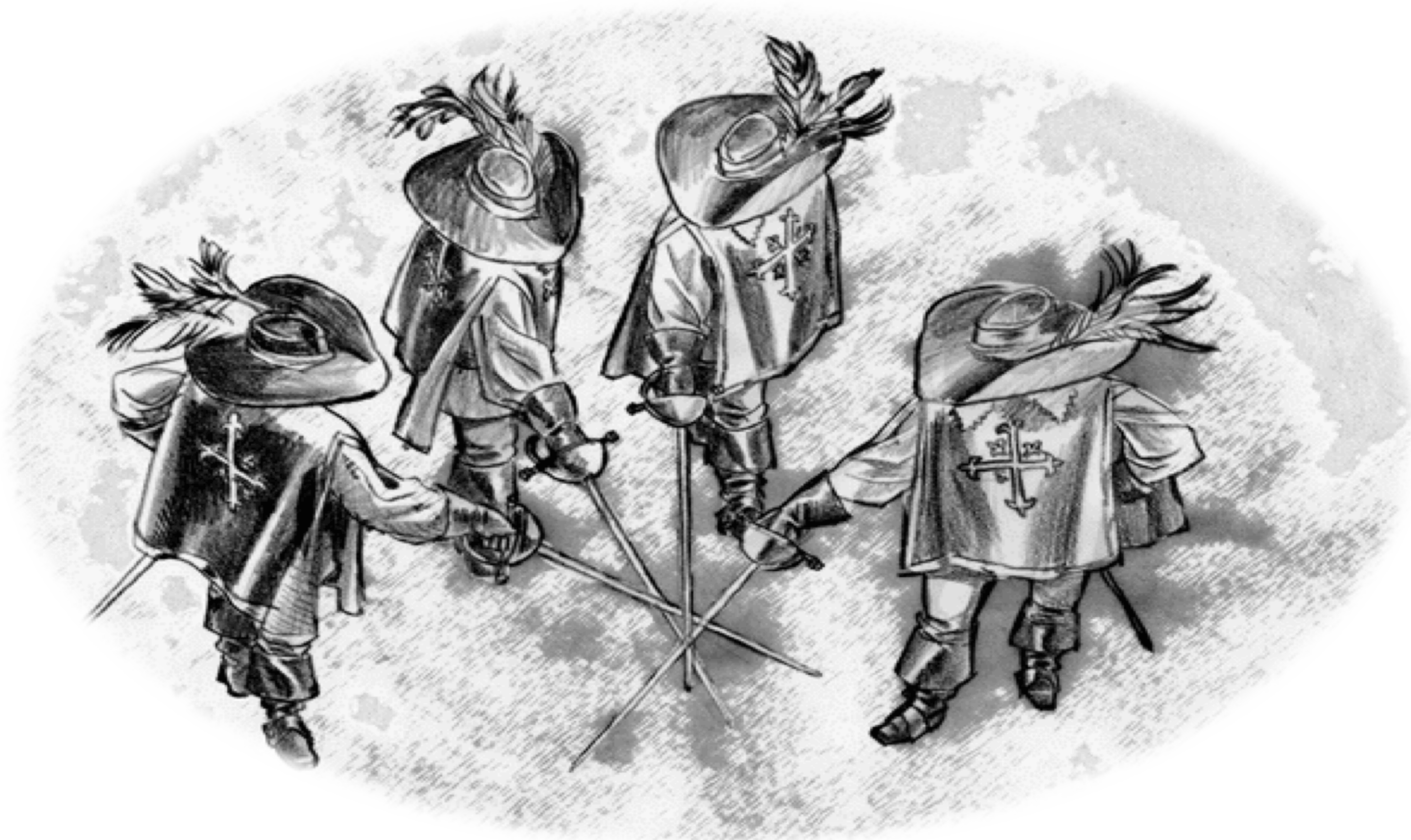
Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.0 σ
ττ	2.6 σ	2.8 σ

ggF, VBF, VH

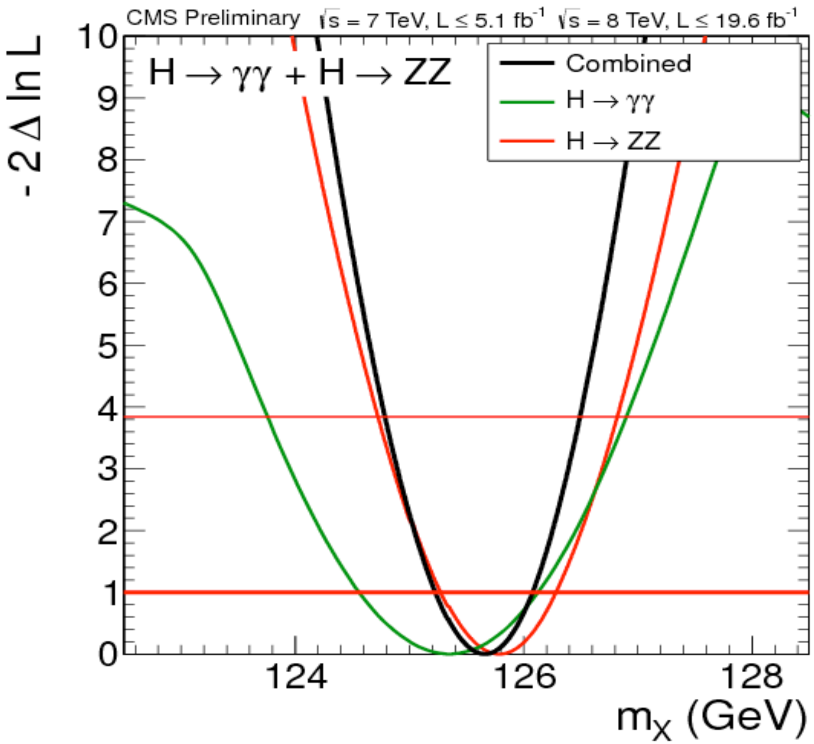
3.4 σ combined

Soon will be updated with full statistics

Combination



The Mass



H → ZZ → 4l:

Mass estimation with m_{4l}, KD and $\sigma(m_{4l})$

Very small systematics due the very good control of the leptons scale and resolution:

m_H = 125.8 ± 0.5 (stat.) ±0.2 (syst.) GeV.

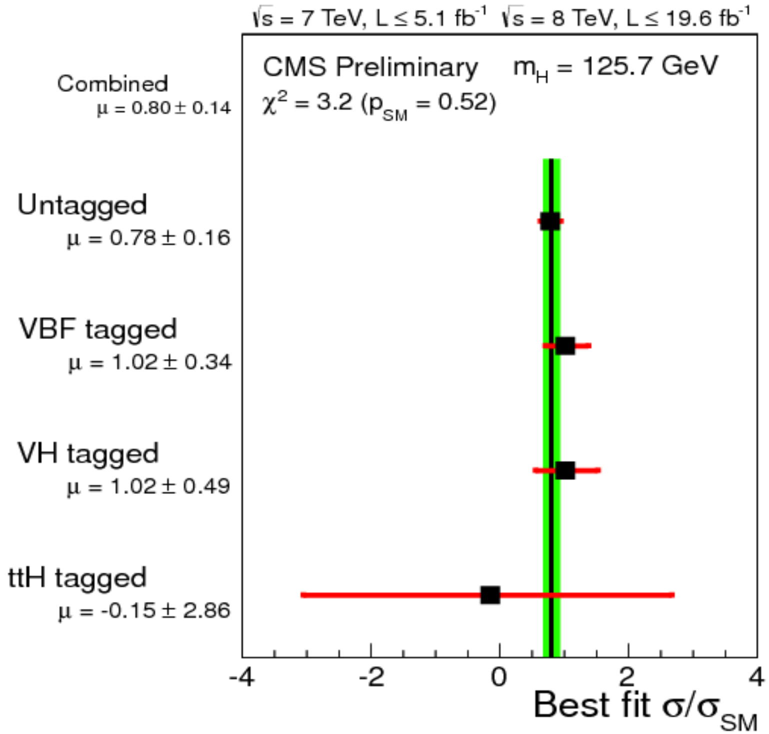
H → γγ:

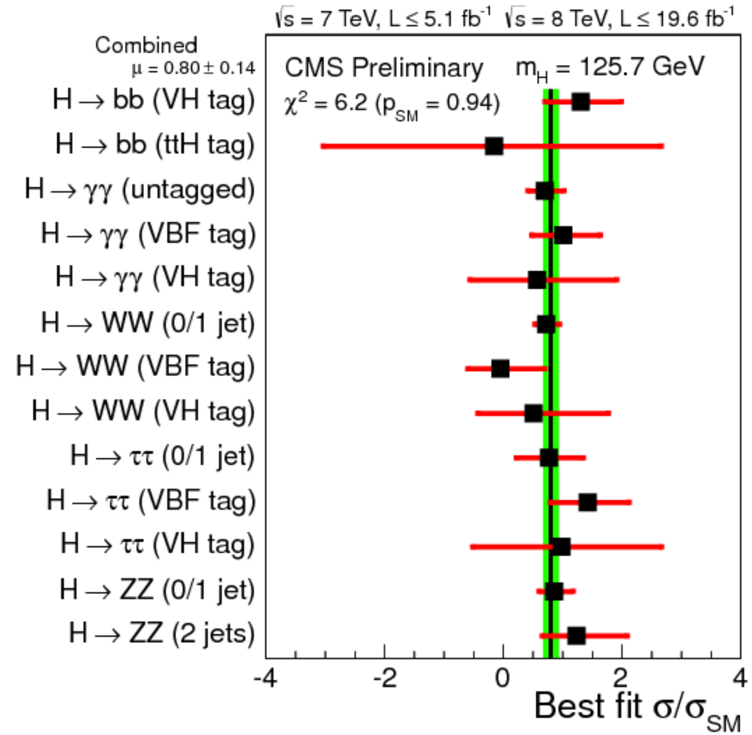
Systematics on the extrapolation from the Z→ee to H→γγ (0.25% from e to γ, 0.4% from Z to H)

m_H = 125.4 ± 0.5 (stat.) ±0.6 (syst.) GeV

$$m_X = 125.7 \pm 0.3^{(stat)} \pm 0.3^{(syst)}\ \text{GeV}$$
$$= 125.7 \pm 0.4\ \text{GeV}$$

Consistency with SM hypothesis





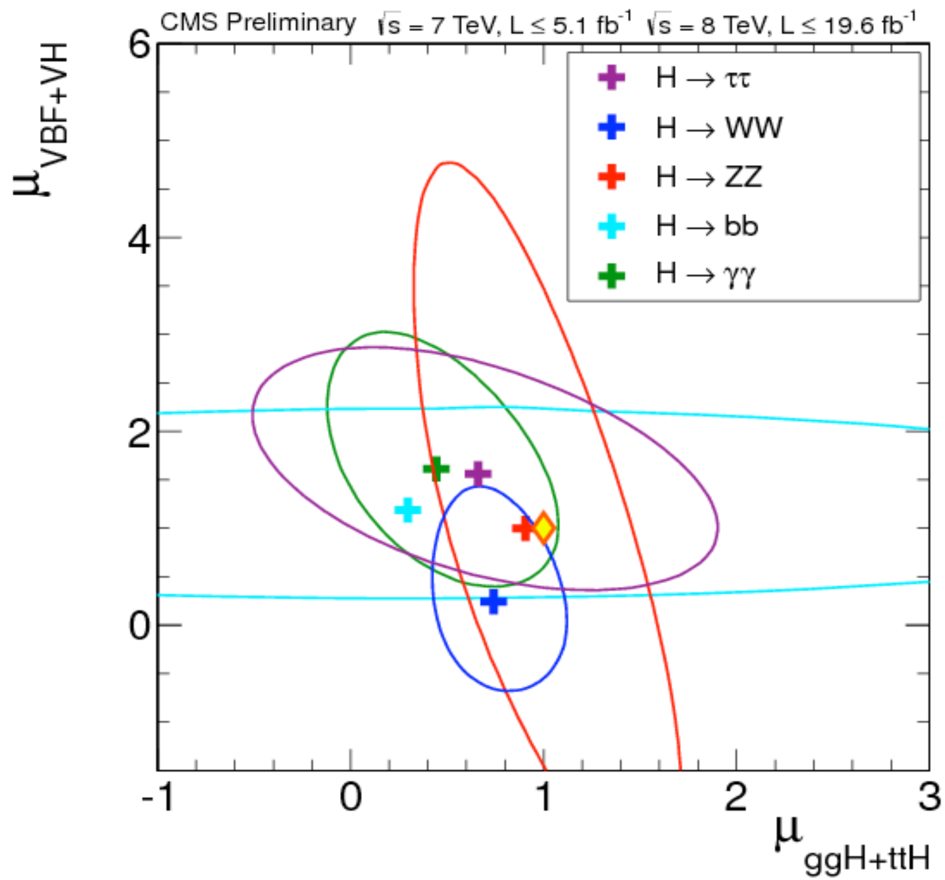
p-value= 0.52 w.r.t. μ=1

μ=0.80±0.14

p-value= 0.94 w.r.t. μ=1

Consistency in 2D

- Test production modes in the various decay modes.
- Properly accounts for contamination in the tagged categories and their uncertainty.



The couplings

They can be extracted from the different final states at the LO EW and NLO QCD approximation:

$$\sigma(H) \text{ x BR(ii} \rightarrow H \rightarrow \text{xx)} = \sigma_{ii} \text{ x } \Gamma_{xx} / \Gamma_H$$

We can measure deviations from the SM couplings, by measuring ratios w.r.t. to the SM prediction.

As an example for the gg→ H → γγ process:

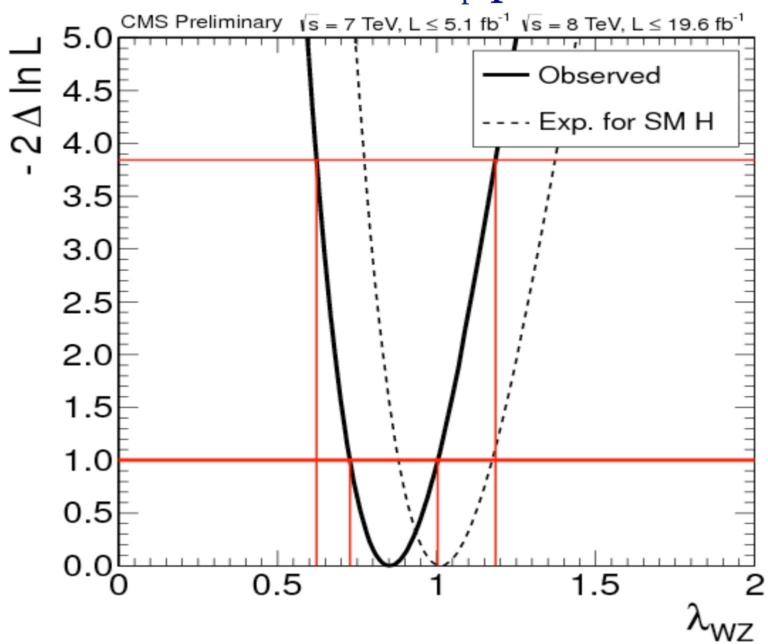
$$(\sigma \text{ x BR) (gg} \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \text{ BR}(H \rightarrow \gamma\gamma) \bullet \kappa_g^2 \ \kappa_\gamma^2 / \kappa_H^2$$

- LHC XS WG benchmark models (arxiv:1209.0040):
  - Fermionic vs bosonic couplings: $\kappa_V \kappa_f$
  - Search for asymmetries: λ_{WZ}, λ_{du}, λ_{lq}
  - Search for new physics in loops: $\kappa_g \kappa_\gamma \text{BR}_{BSM}$

Custodial symmetry

Testing custodial symmetry (measuring HWW/HZZ couplings) will tell us if the the object produced is Higgs-like.

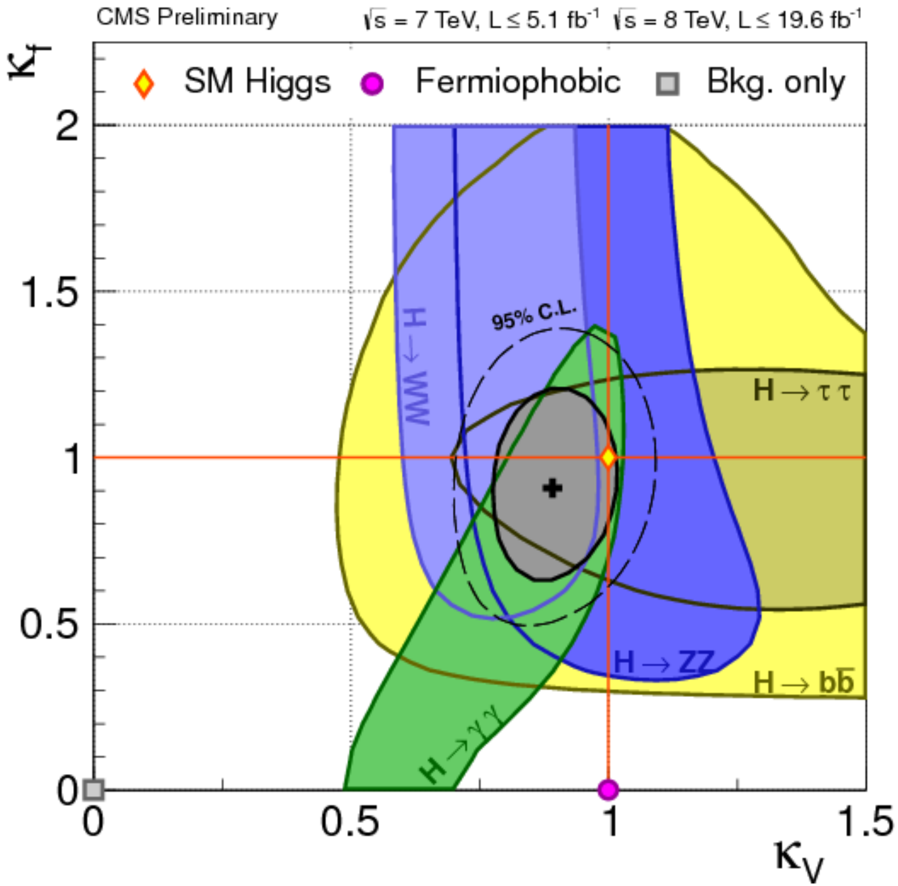
All channels. κ_f profiled.

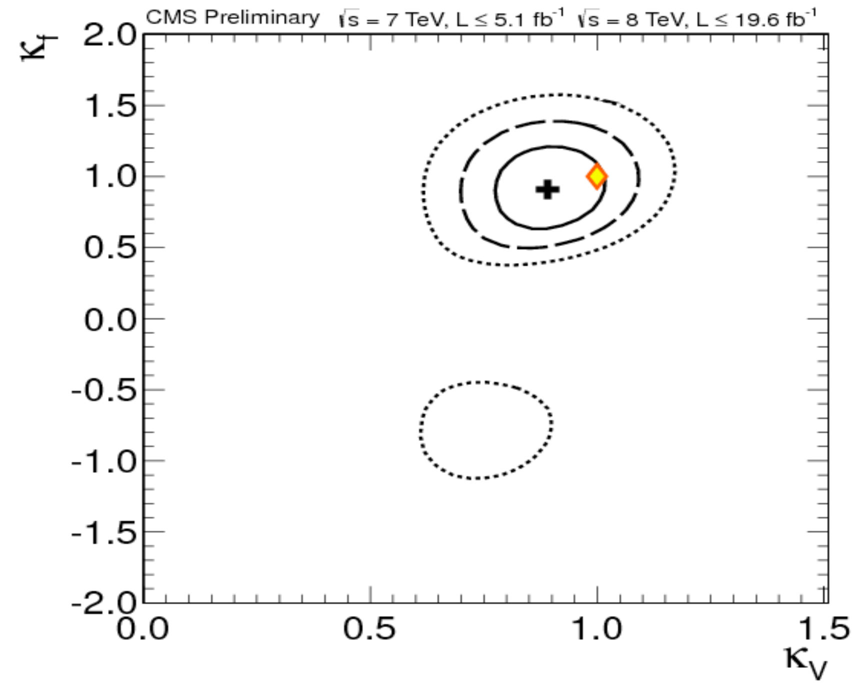


three degrees of freedom:
λ_{WZ}, κ_Z, and κ_f.
$\Gamma_{BSM} = 0$.
$m_H = 125.7$

[0.73,1.00] @ 68% CL

Couplings: κ_V, κ_f



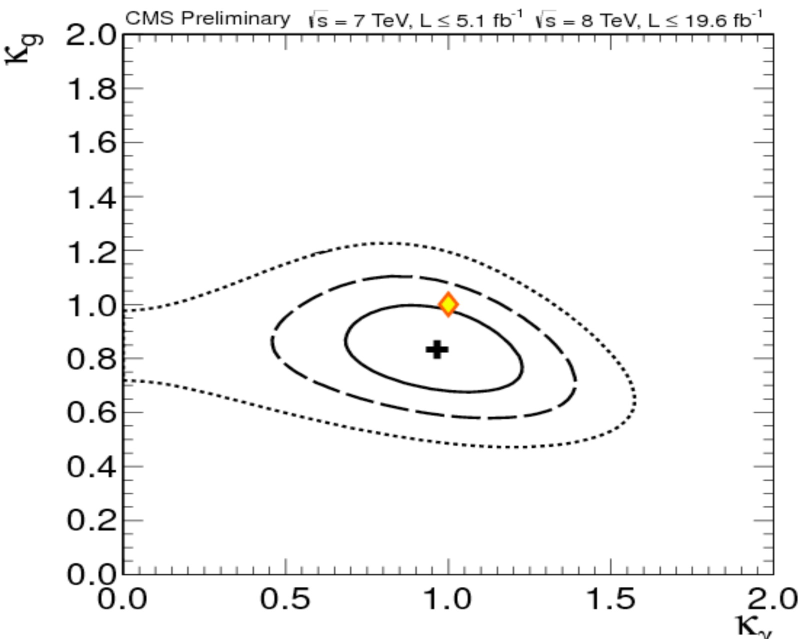


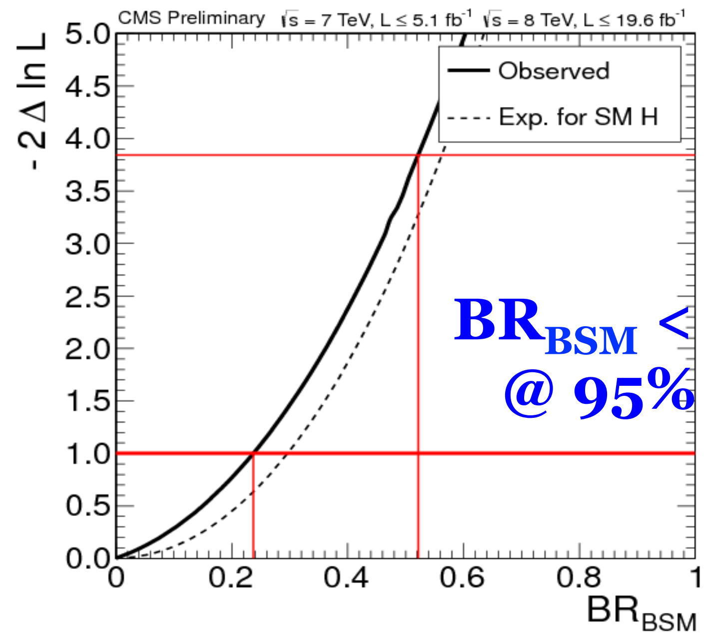
@ $m_H = 125.7$

$\Gamma(H \rightarrow \gamma\gamma) \sim |\alpha\,\kappa_V + \beta\,\kappa_f|^2$, $\alpha/\beta = -0.2$

$\Gamma_{BSM} = 0$

Search for new physics in loops and decays

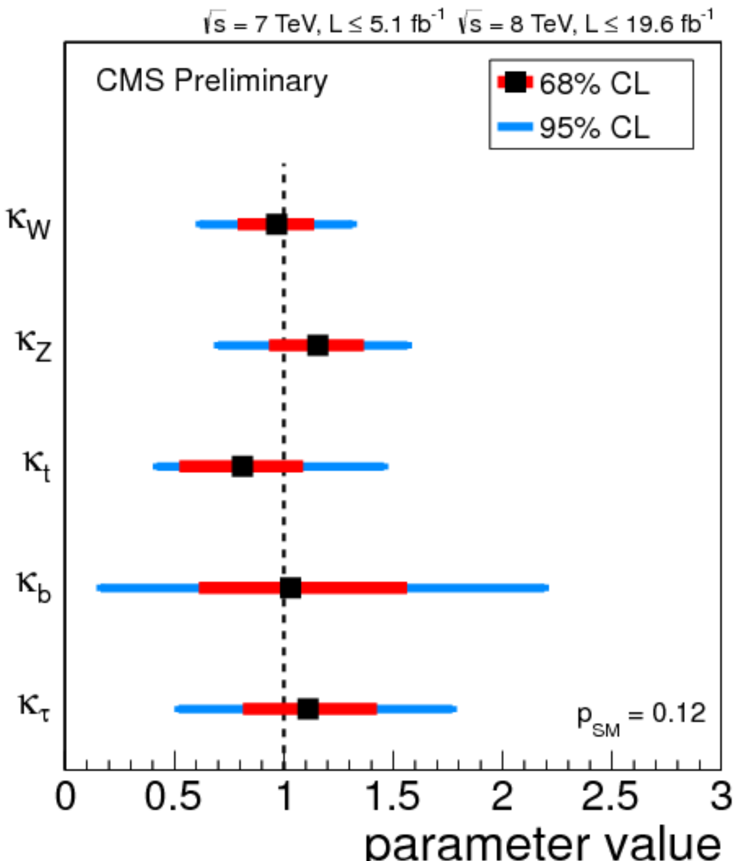


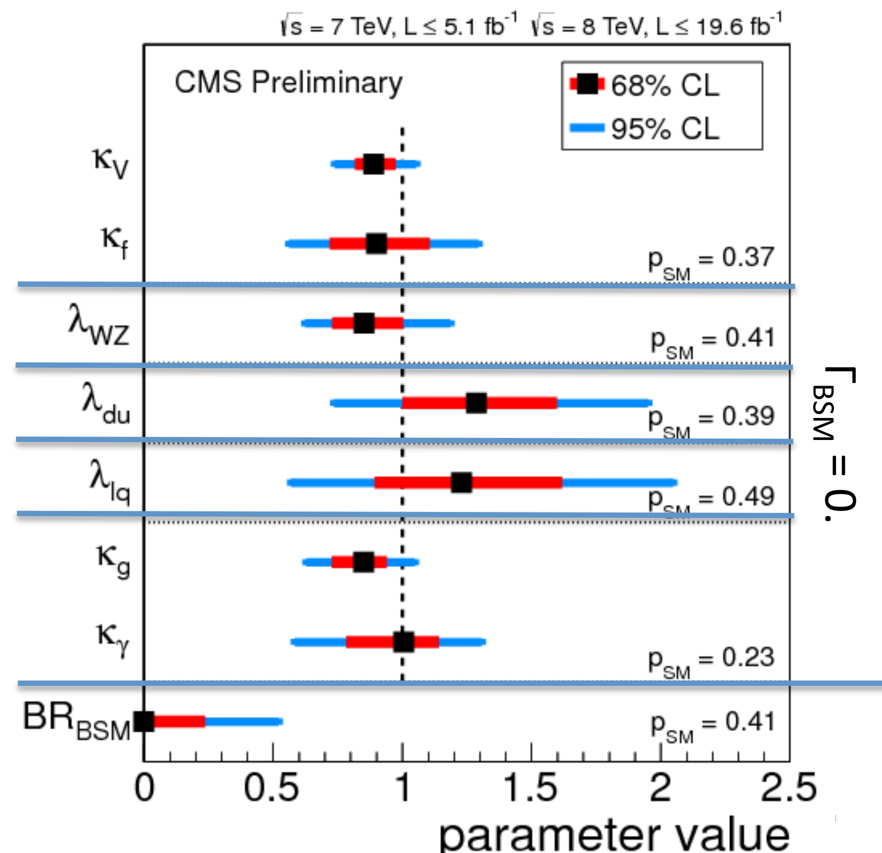


Effective couplings to gluons and photons.
Note best fit $\kappa_\gamma \sim 1$, with $\kappa_g < 1$ in line with $\mu < 1$ in VV modes as well.
$\Gamma_{BSM} = 0$.

Loop-induced couplings free (κ_γ, κ_g profiled). Allowed for extra particles in loop, i.e. extra width.

Summary of all searches for coupling deviations





Spin 2 combination: results

CLs values for $2^+_m(gg)$

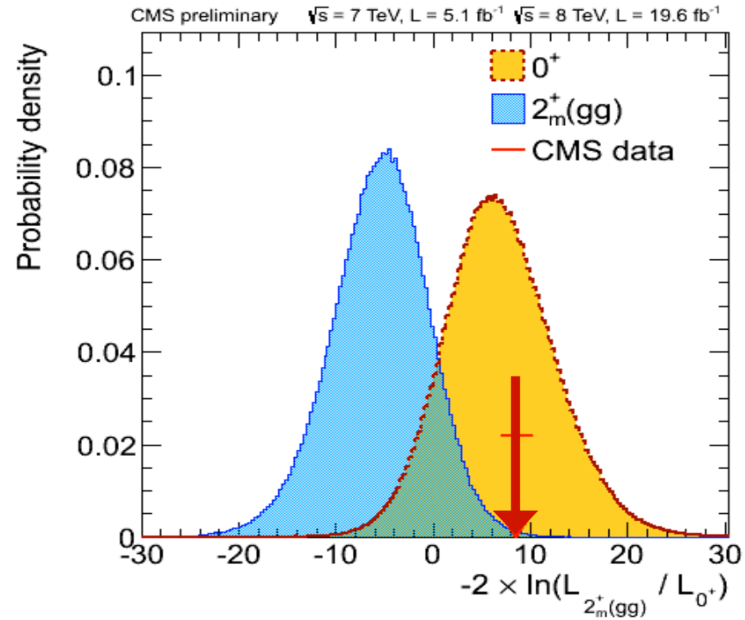
- Expected results with μ=1"

ZZ	WW	Comb
6.8%	1.4%	0.2%

- Observed results at measured μ

ZZ	WW	Comb
1.4%	14%	0.6%

- Observed results weaker than expected especially for WW due to best fit μ < 1 (like having less luminosity)
- Observed better than expected for ZZ due to a fluctuation

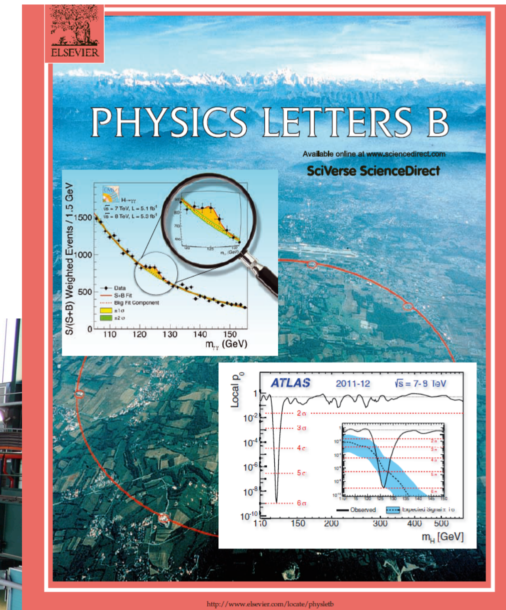


The observation is well compatible with SM Higgs expectations (0^+).

The data disfavours the the $2^+_m(gg)$ hypothesis with a CLs value of 0.6%

An incredible collaboration of many thousands people made it possible


Recycling brass artillery shells for the HCAL



Conclusions

- Fantastic 3 years of physics: from the very first $\pi \rightarrow \gamma\gamma$ reconstructed with the first LHC interactions, to precise SM measurements, to the discovery of a Higgs boson of m~125 GeV
- Already quite precise measurements of properties, all consistent with SM predictions within uncertainties

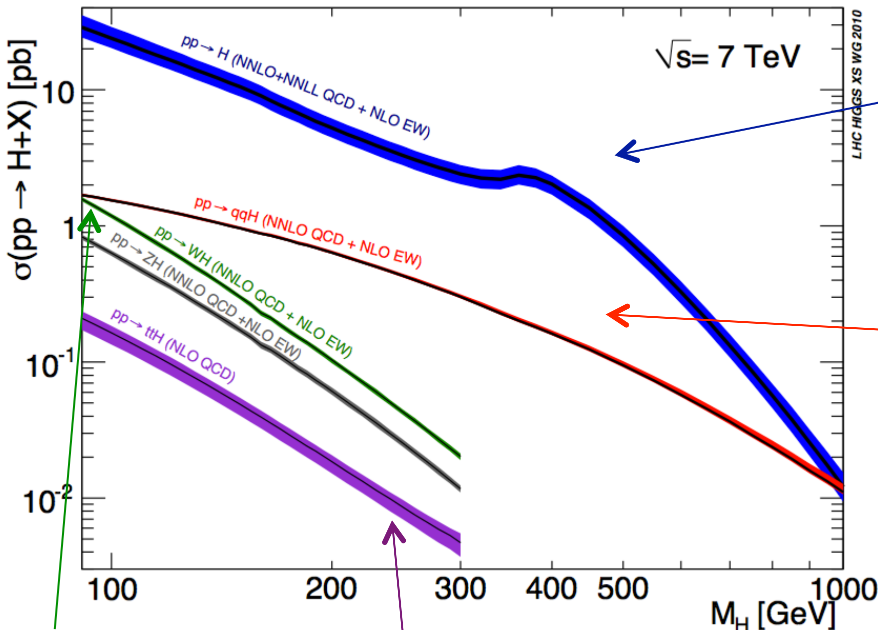
A new era is beginning

- Precise measurements of properties
- Keep searching for BSM particles
- Ultimately VV-scattering

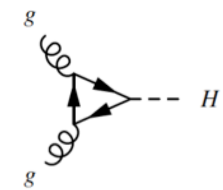
Is there anything beyond the Standard Model?

backup

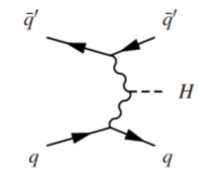
Higgs production at LHC



ggF: NNLO+NNLL QCD + NLO EW



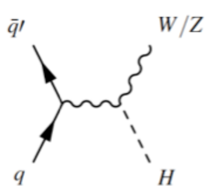
qqH: NNLO QCD + NLO EW

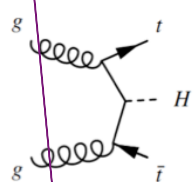


the
LHC H XS WG

WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW

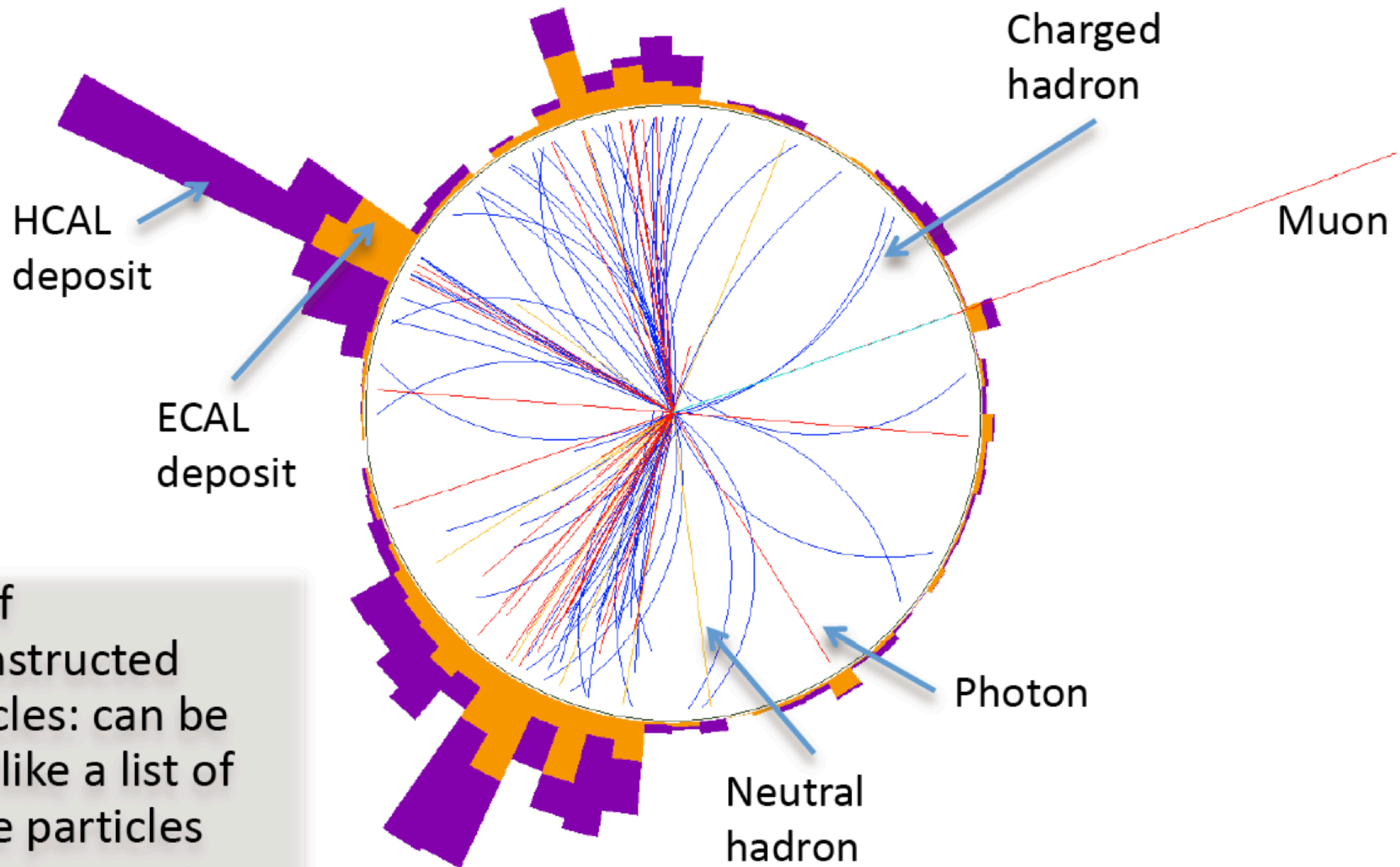




ttH: NLO QCD

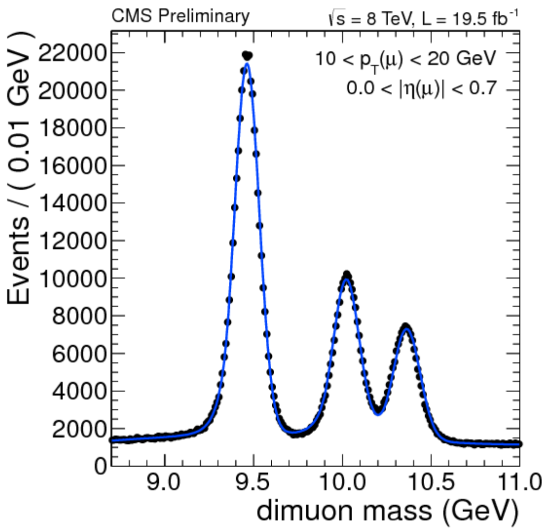
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+a_s	Total error
ggF	+25% (+100%)	+12% -7%	±8%	+20 -15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% -10%	±8%	+12 -18%

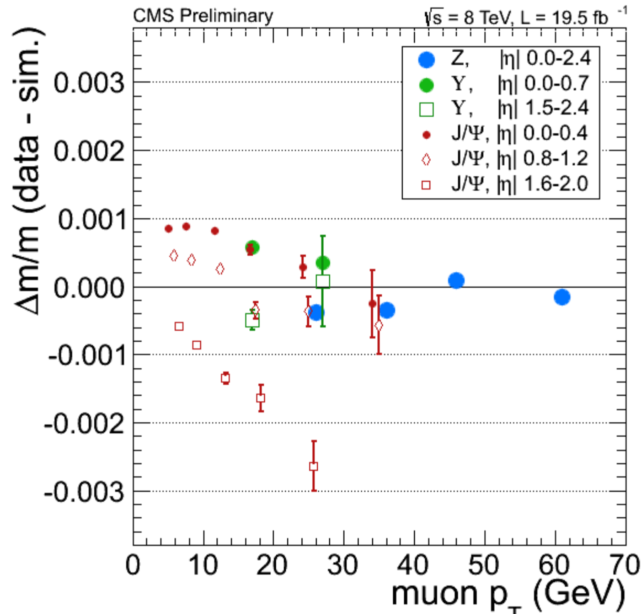
Global Event Description (Particle Flow)

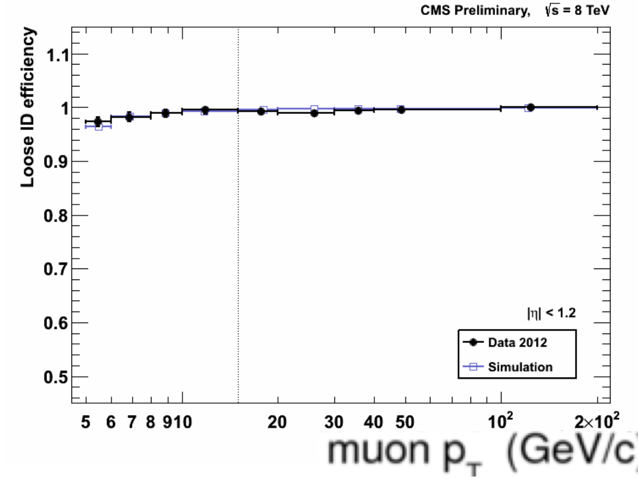


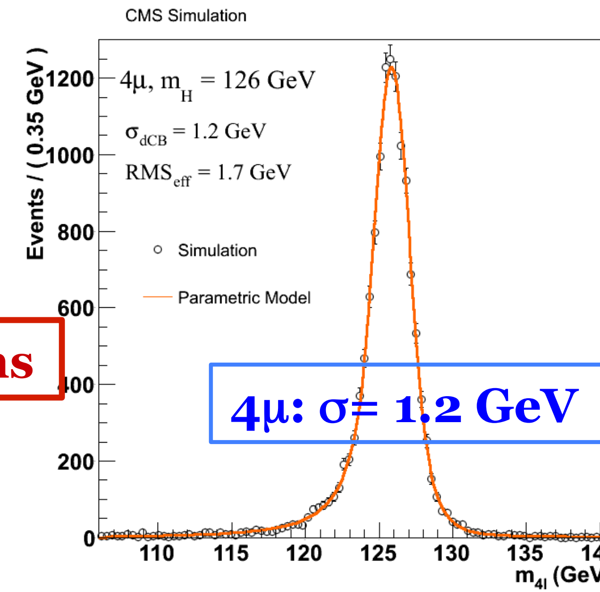
List of reconstructed particles: can be used like a list of stable particles from a generator

Muons



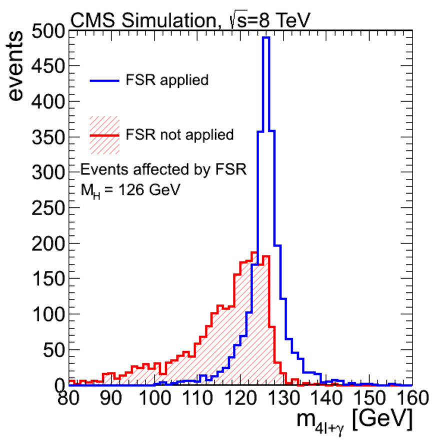






momentum scale: 0.1% for muons

4μ: σ= 1.2 GeV



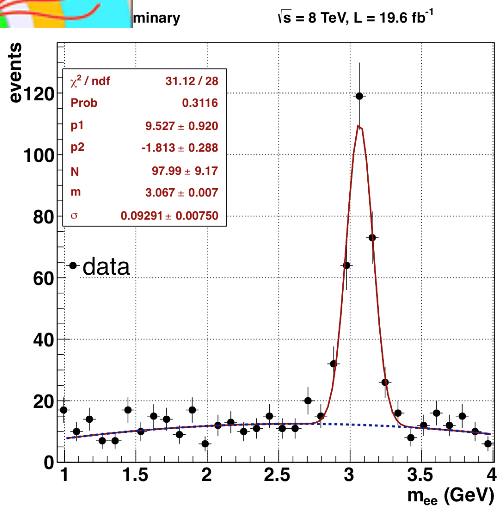
Final State Radiation (FSR) Recovery

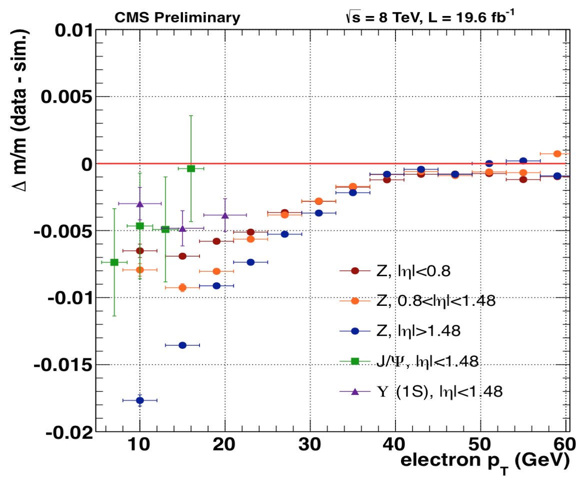
6% of events affected

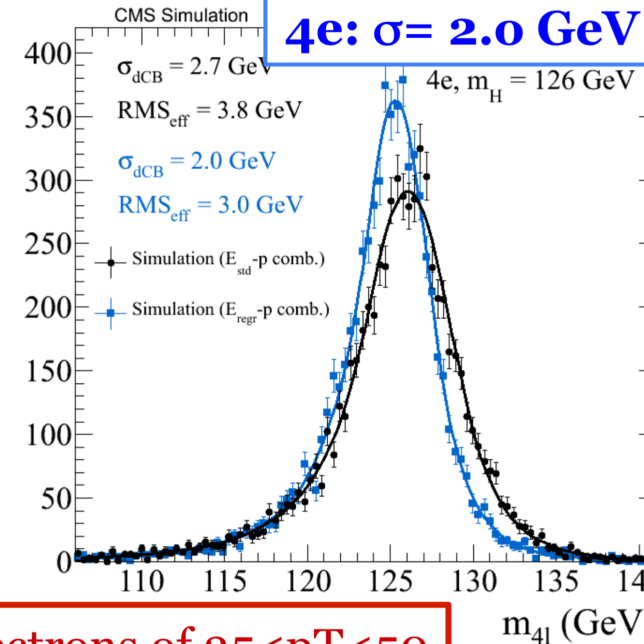
Chiara Mariotti

Electrons

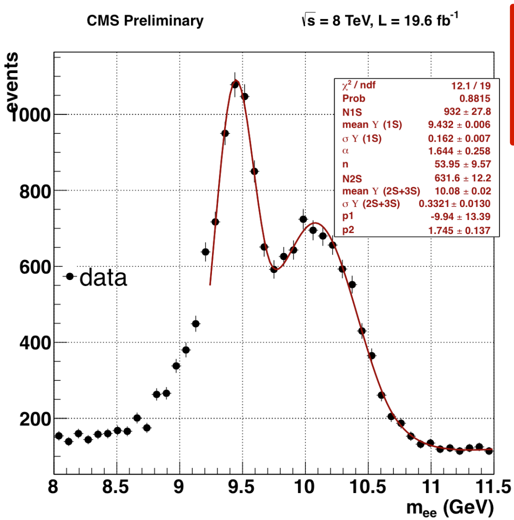
4e: σ= 2.0 GeV

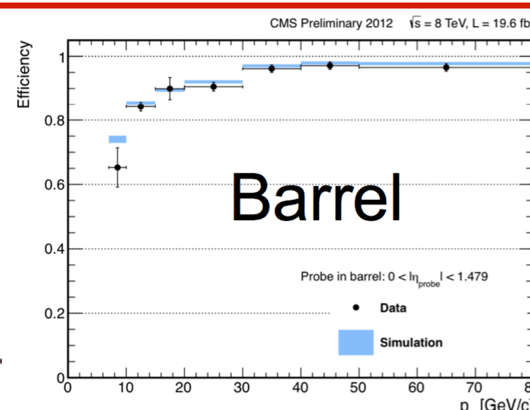


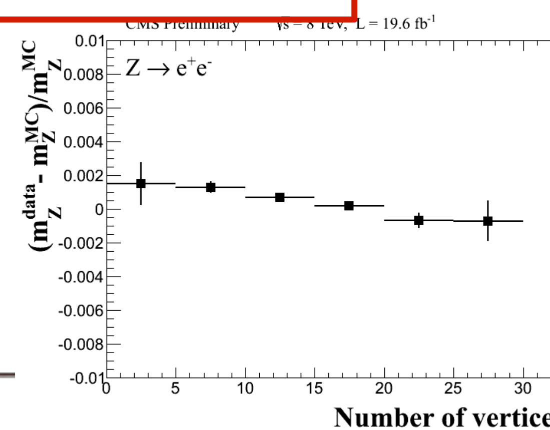




Momentum scale: 0.2% for electrons of 35<pT<50 up to 1.5% at low pT



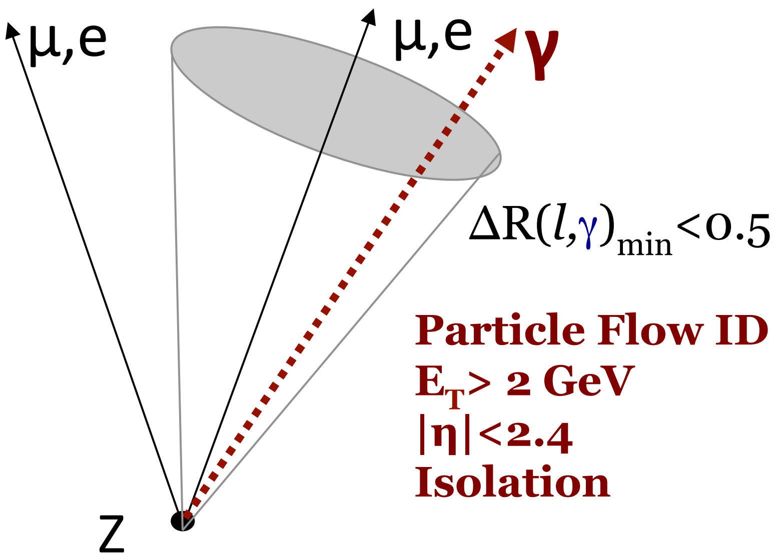




Chiara Mariotti

ZZ 4l: FSR recovery algorithm

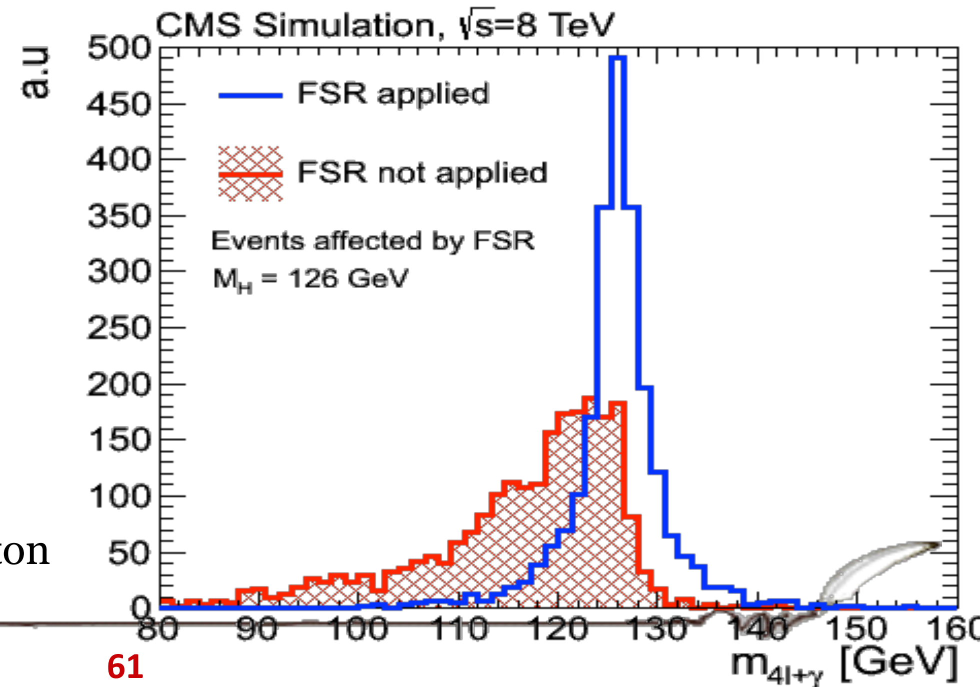
- **Applied on each Z for photons near the leptons**



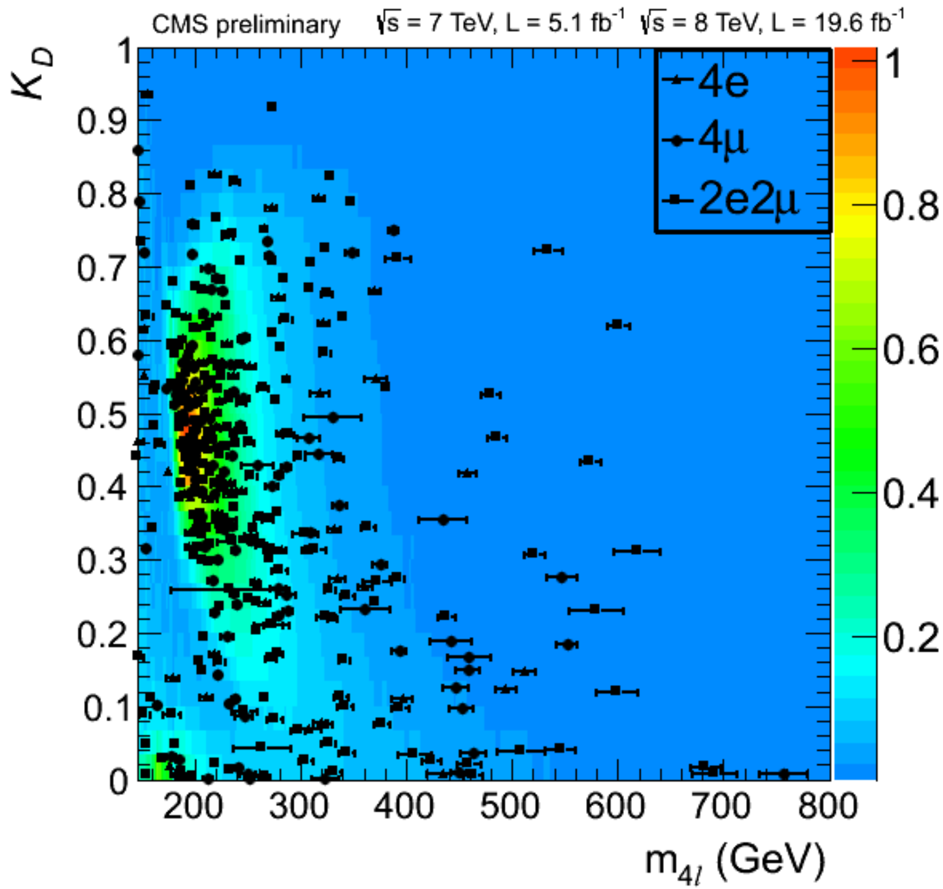
- Associates photon with Z if:
  - $M(ll+\gamma) < 100$ GeV
  - $|M(ll+\gamma) - M_Z| < |M(ll) - M_Z|$
- Removes associated photons from lepton isolation calculation

Expected Performance for $M_H = 126$ GeV

- 6% of events affected
- Average purity of 80%
- 2% added in analysis



MELA – Background high mass



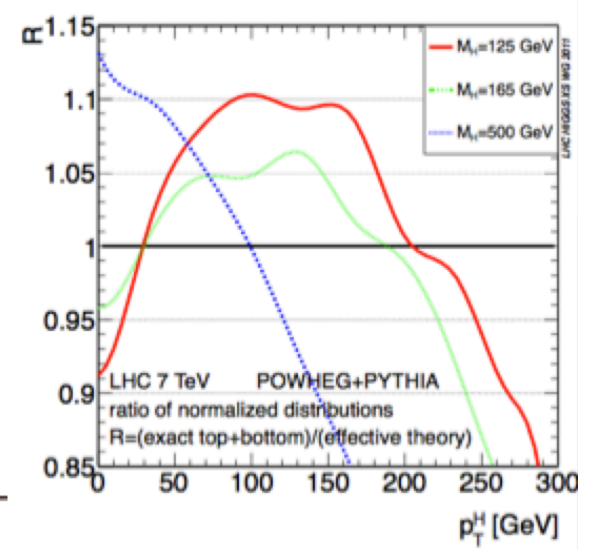
Jet categories systematics

Large theoretical uncertainties:

- 2 jets category
  gg→H+2jets has 30% uncertainty on the XS from QCD scale (process known at NLO)
  Intense study in the LHC H XS WG: Powheg MINLO, Powheg NLO, aMC@NLO, madgraph, Sherpa, GoSam

→ soon in LHCHXSWG YellowReport 3

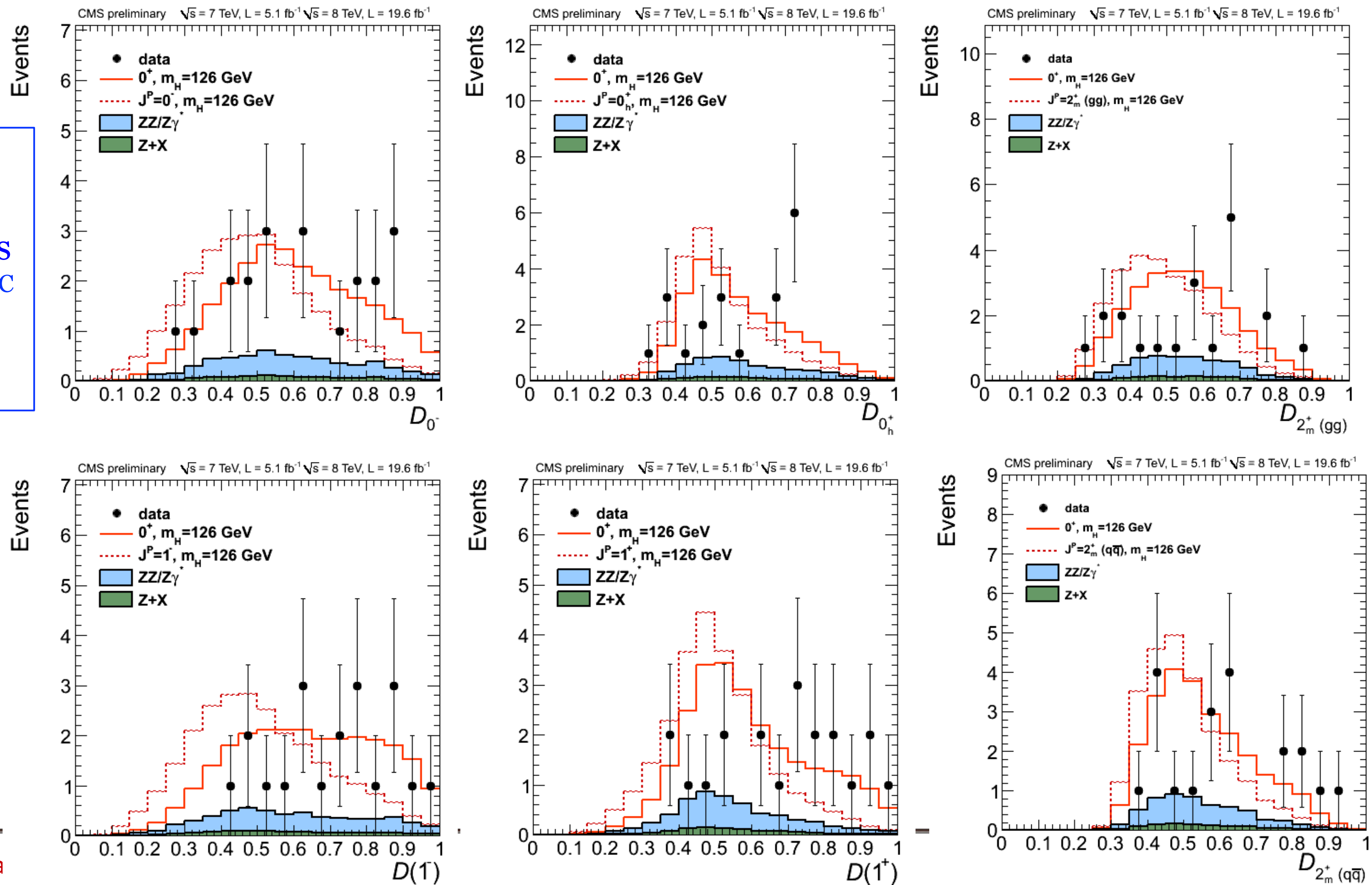
- Higgs p_T spectrum:
  scale uncertainty from HRes and 100% from HQ
  residual discrepancy between MC at NLO and resummed calculation
  Effect of finite top and bottom mass ~ 10 %
  (Now in Powheg , soon in HRes)



J^{PC}

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

MELA:
can describe the kinematics of different J^{PC} boson decay

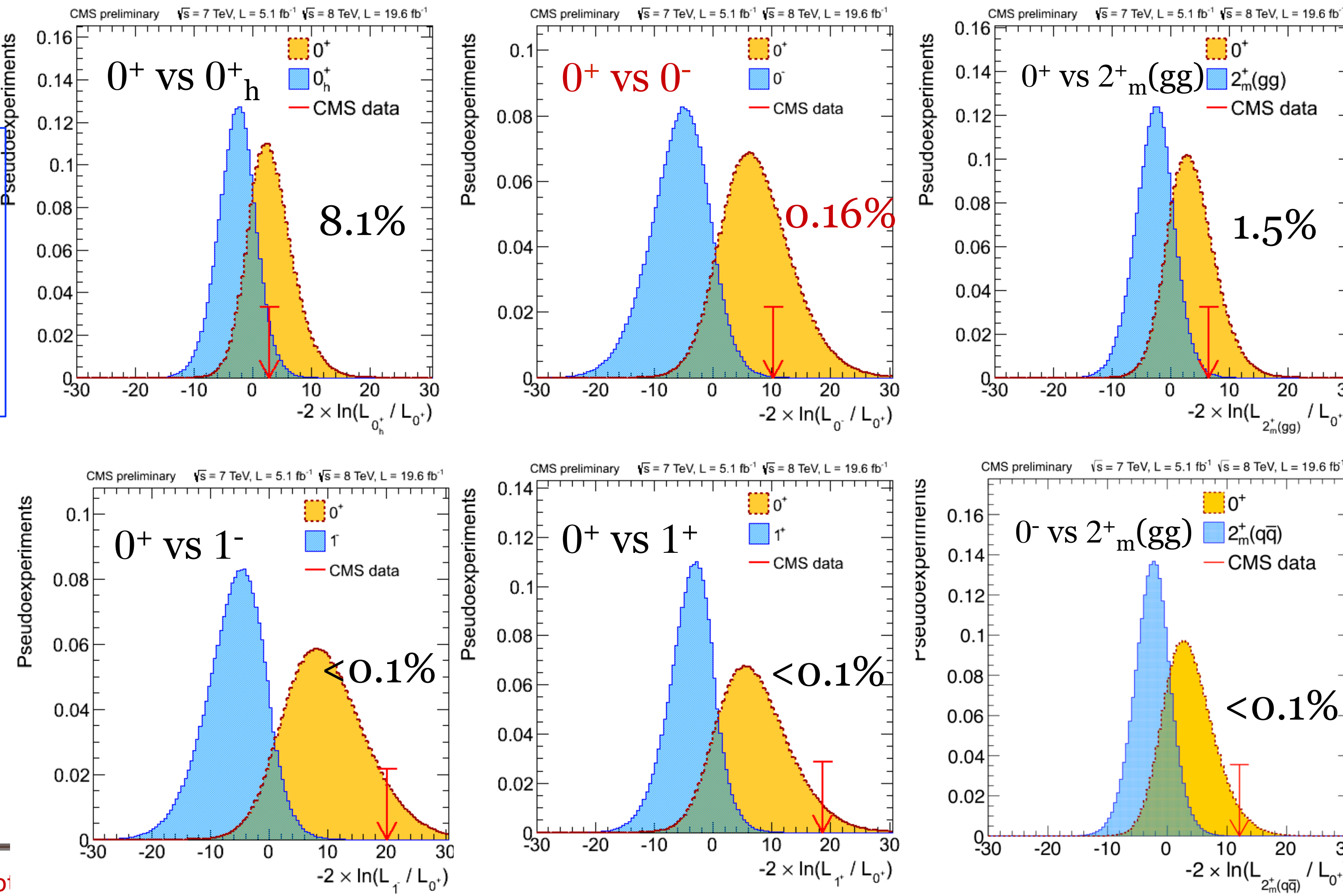


J^{PC}

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

MELA:
can describe the kinematics of different J^{PC} boson decay

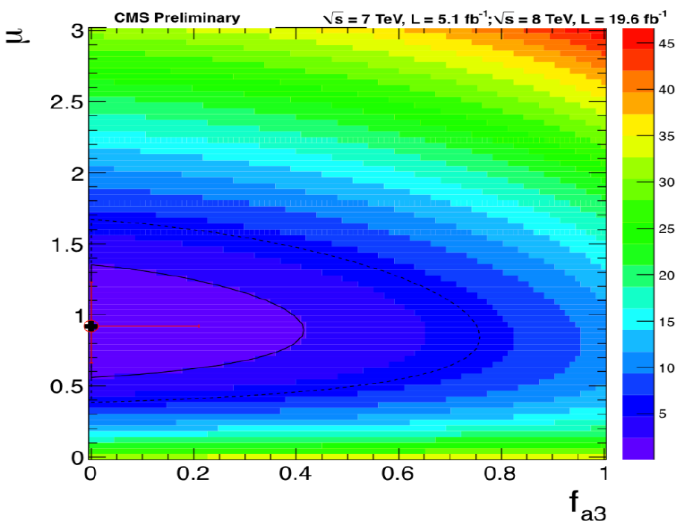
CLs values

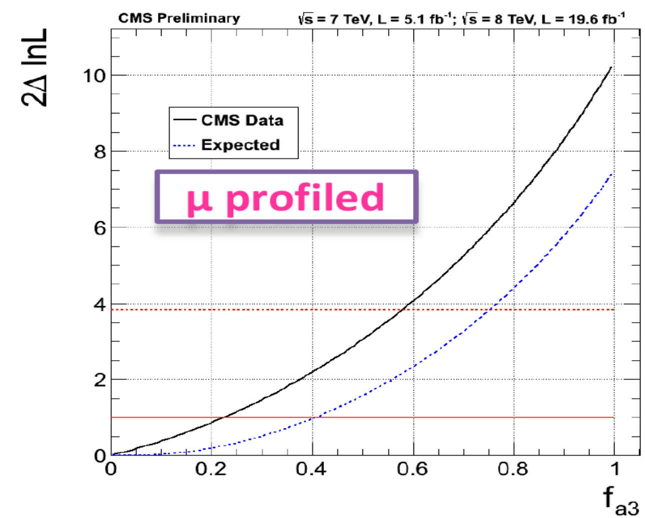


H→ZZ →4l: Mixed parity

$$A(X \rightarrow V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

$$f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$$





$f_{a3} = 0.00^{+0.23}_{-0.00}$
$f_{a3} < 0.58$ @ 95% C.L.

- SM 0+ decay dominated by A1
- 0- decay dominated by A3

H→γγ: Analysis strategy

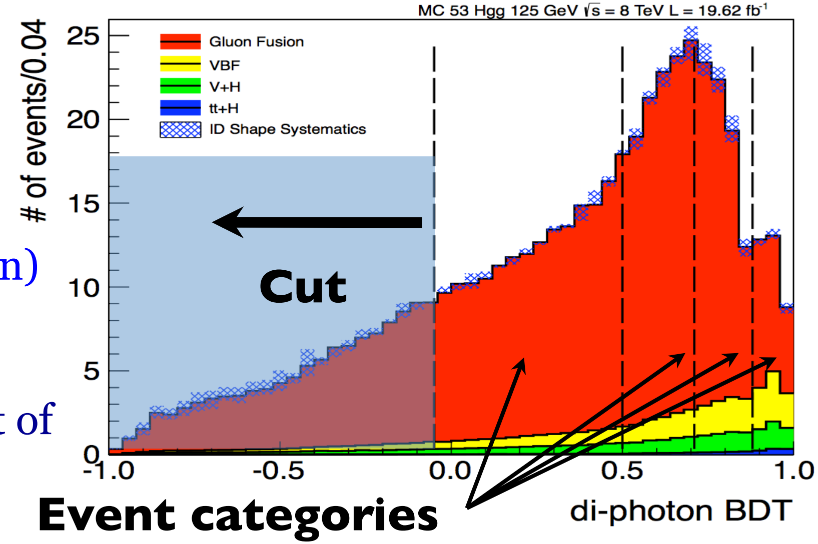
- Events are separated in exclusive categories with different S/B and resolution.
- Special "tagged" categories enriched in VBF and VH signal production.
  - Improve the sensitivity of the analysis for the coupling measurements.
- Background directly estimated from data
  - Fit the γγ invariant mass in categories using polynomials (3rd-5th order)

- **Two different analysis**
  - **Cut-based (CiC)**
  - **Multivariate (MVA):** select and categorize events using a BDT
- **Baseline result: MVA approach** (~15% better expected sensitivity)

H→γγ: Di-photon MVA selection

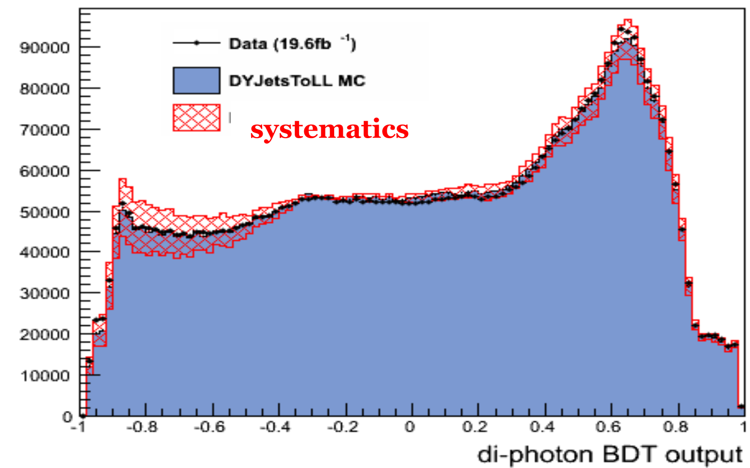
A single discriminant (BDT) trained on MC signal and background using

- photon kinematics
- photon ID MVA score (shower shape, isolation)
- di-photon mass resolution



4 untagged categories are defined on the output of the di-photon BDT, ordered by S/B

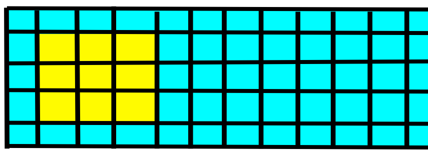
Output of the MVA validated using Z→ee (where e are reconstructed as γ)



$H \to \gamma\gamma$: Cut-based analysis

- **Cut-based analysis uses**
  - cut-based photon identification
  - a different definition of event categories
    - Photon identification data/MC efficiency scale factors computed from $Z \to ee$ and $Z \to \mu\mu\gamma$.

$R_9 = E_{3\times3}/E_{SC}$



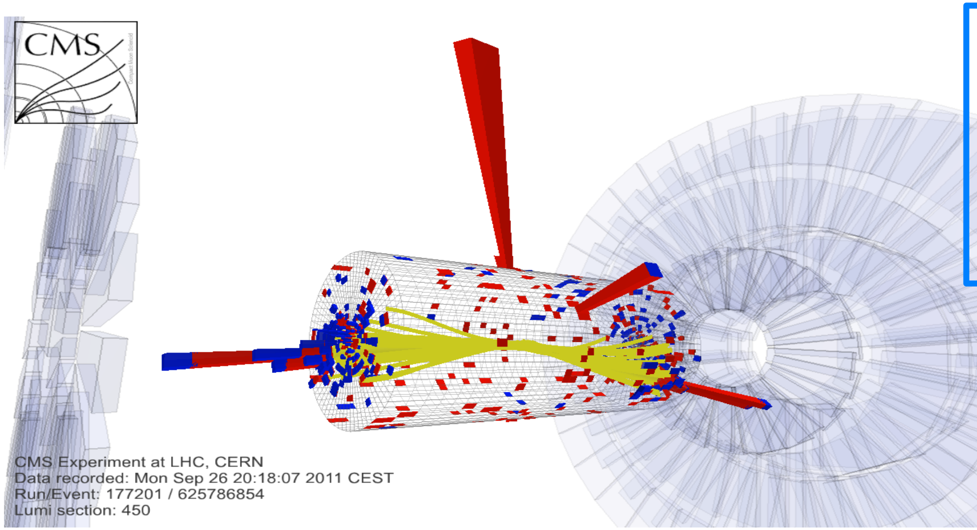
- **4 untagged categories** defined according to the γ characteristics**:**
  - Barrel-endcap and converted/unconverted from shower shape R9
  - Different mass resolution and S/B among the 4 categories

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

H→γγ: Exclusive categories

In addition to the untagged categories, high S/B categories are defined using additional objects in the event

- **Improve significantly the reach to measure Higgs couplings**



Di-jet:

- 2 categories (loose/tight) with increasing VBF purity (loose ~50%, tight ~80%).
- MVA analysis uses a dijet BDT-based selection (validated using Z+jets events)

- Additional **leptons** (e or μ p_T>20 GeV)
- **MET** (>70 GeV): lepton categories have negligible gg contamination, 20% for MET

Events are assigned exclusively to a category following the S/B ordering:

Muon → Electron → Dijet → MET → Untagged

Compatibility among the two analysis

- **Low signal to background ratio a fundamental feature of this channel**
  - Uncertainty on signal strength driven by statistical fluctuations of the background
  - Analysis changes can lead to statistical changes due to fluctuations in selected events and their mass

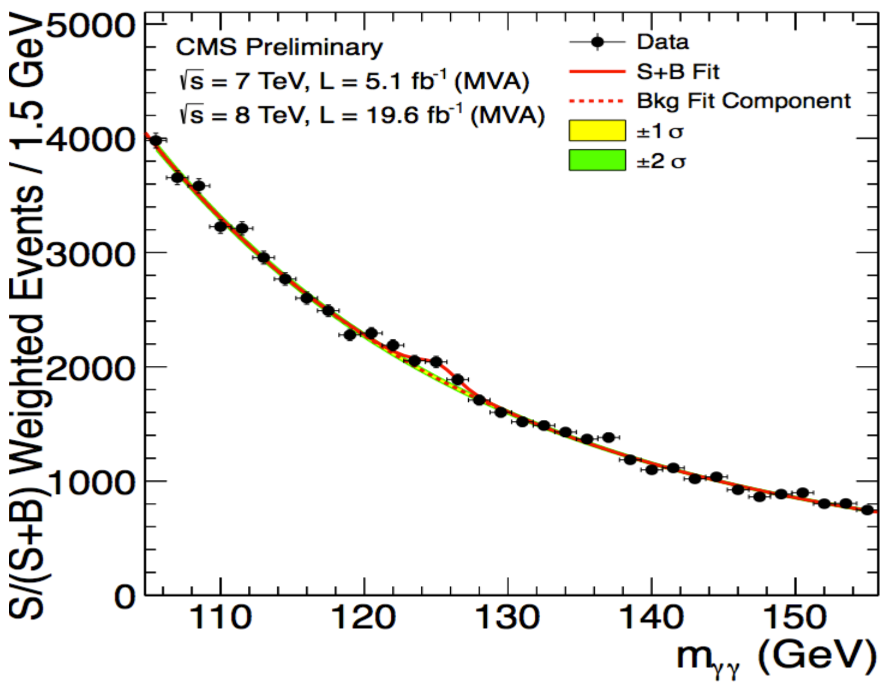
- The correlation coefficient between the MVA and cut-based signal strength measurements is found to be **r=0.76** (estimated using jackknife techniques)

	Signal strength compatibility (including correlation)
MVA vs CiC 7+8 TeV	1.5 σ
MVA vs CiC 8 TeV only	1.8 σ
Updated MVA vs published (5.3/fb 8TeV)	1.6 σ
Updated CiC vs published (5.3/fb 8TeV)	0.5 σ

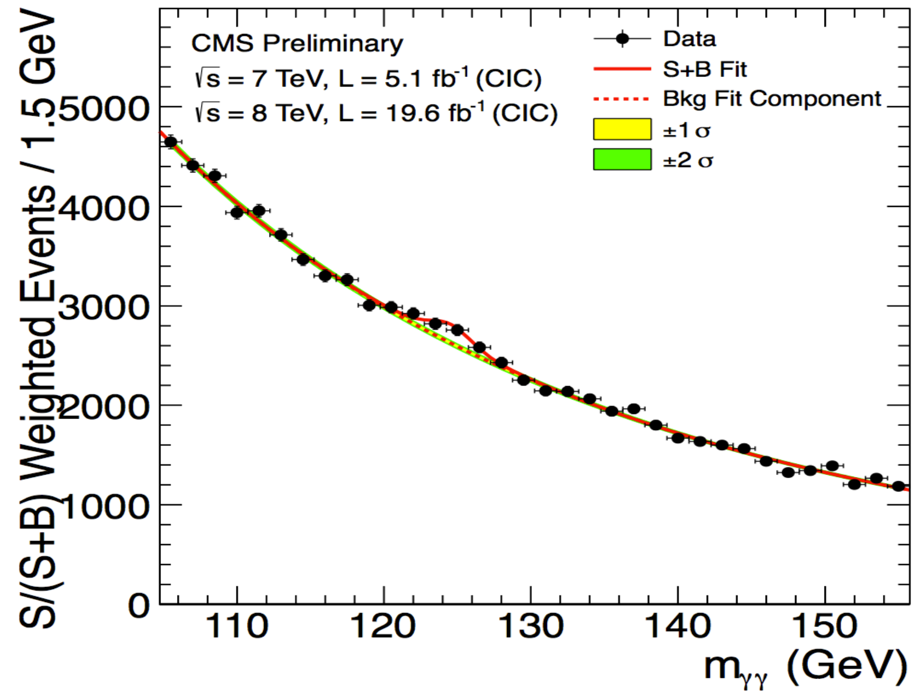
- Observed changes in results and differences between analyses are all **statistically compatible at less than 2σ**

H→γγ: Combined mass plot: 7+8 TeV

MVA mass-factorized



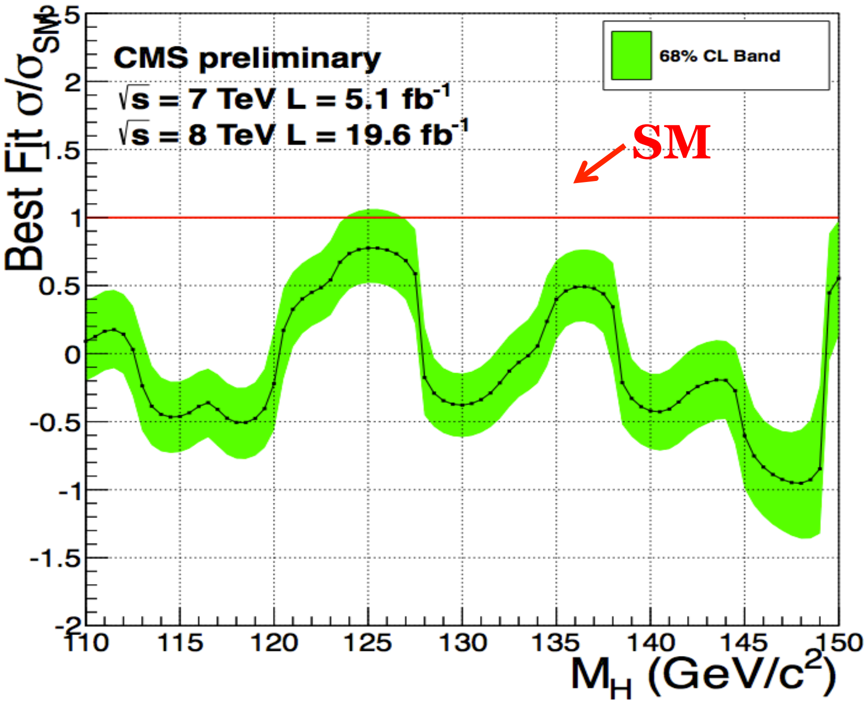
Cut-based



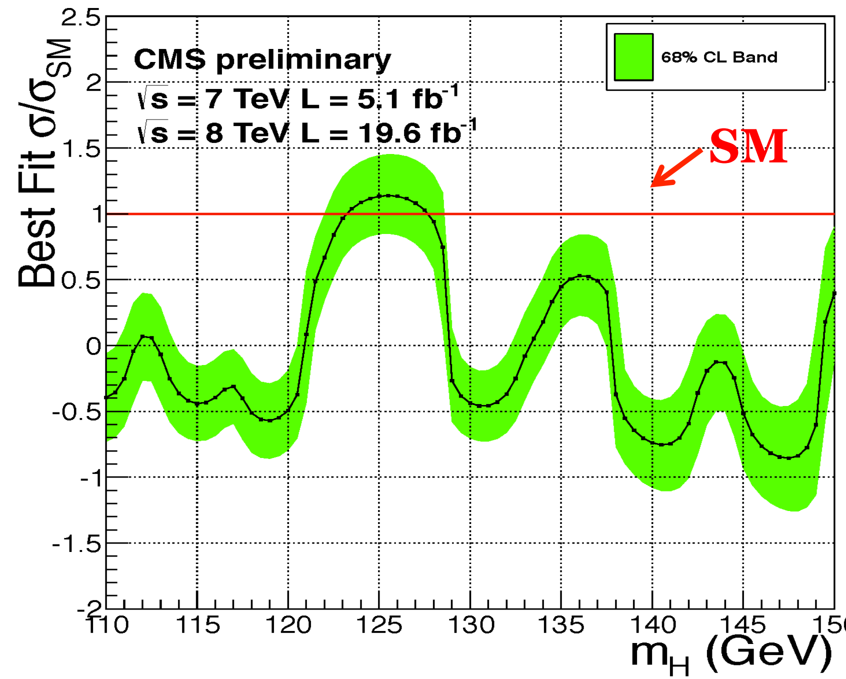
Each event category is **weighted by its S/(S+B)**
only for visualization purpose

H→γγ: Results (signal strength)

MVA mass-factorized



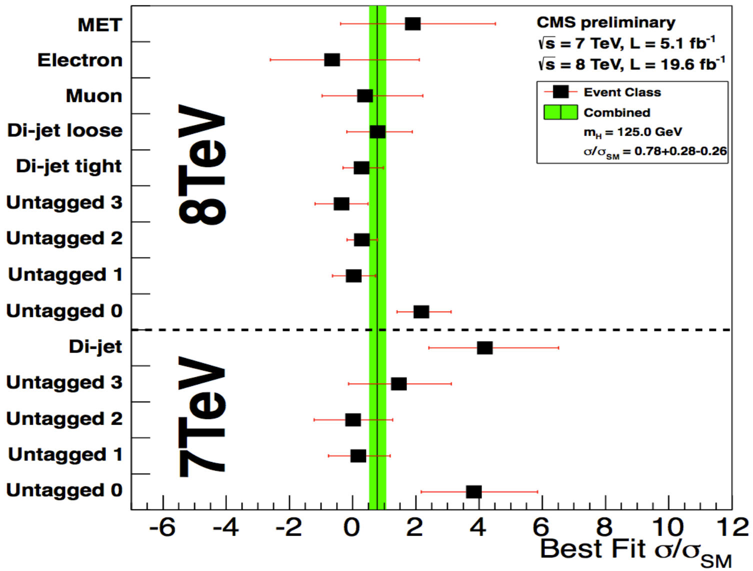
Cut-based



Compared to the published results, the measured σ/σ_{SM} decreased.

H→γγ: Results (channel consistency)

MVA mass-factorized

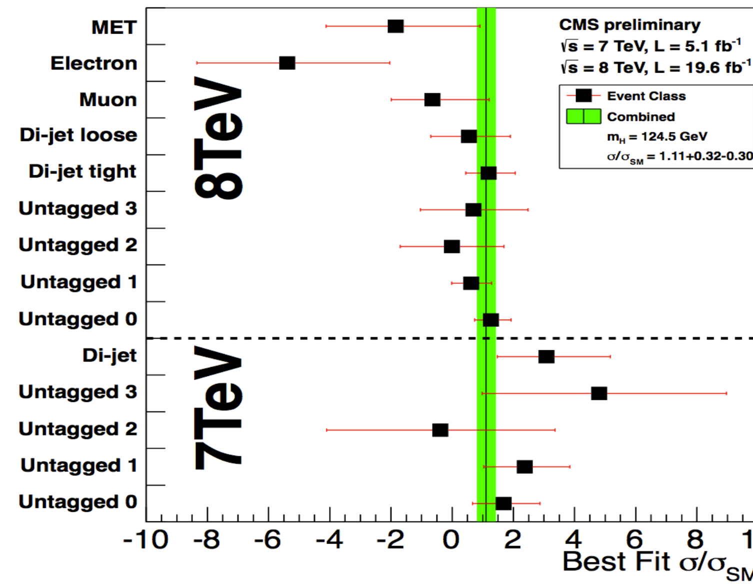


$7+8$ TeV: σ/σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

7 TeV: σ/σ_{SM} @ 125.0 GeV = $1.69^{+0.65}_{-0.59}$

8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.55^{+0.29}_{-0.27}$

Cut-based



$7+8$ TeV: σ/σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

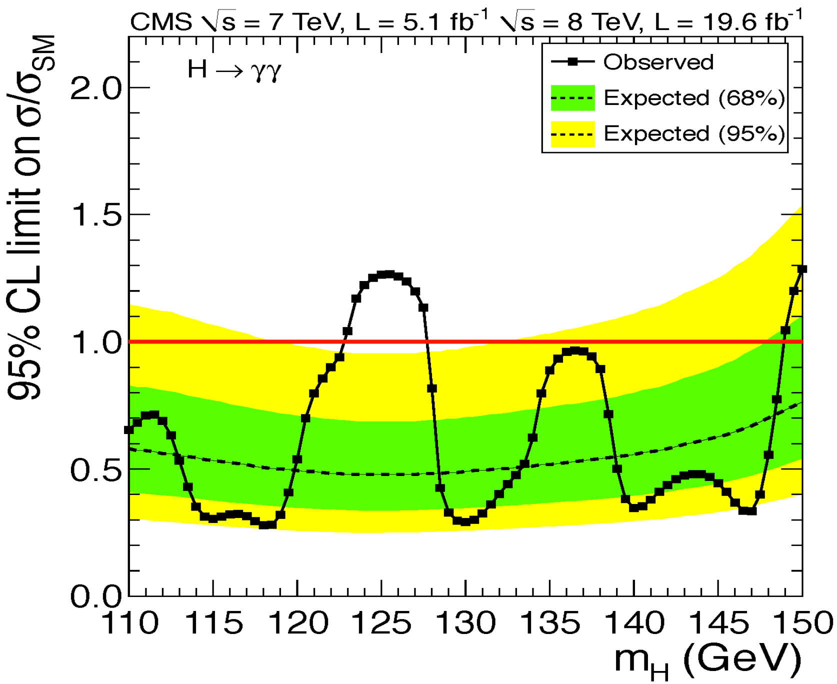
7 TeV: σ/σ_{SM} @ 124.5 GeV = $2.27^{+0.80}_{-0.74}$

8 TeV: σ/σ_{SM} @ 124.5 GeV = $0.93^{+0.34}_{-0.32}$

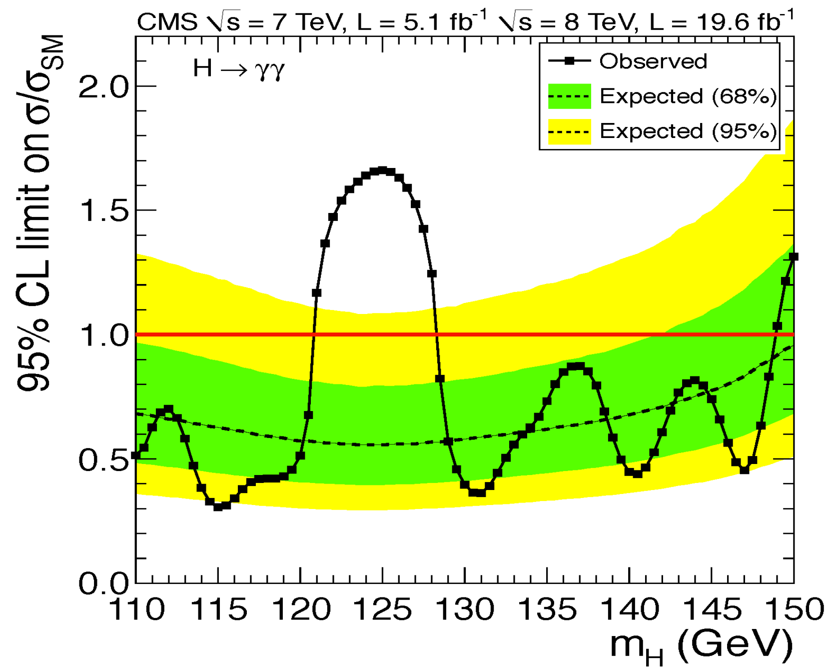
Despite the same names, the untagged categories in MVA and Cut-basd are not equivalent

Results: limits

MVA mass-factorized

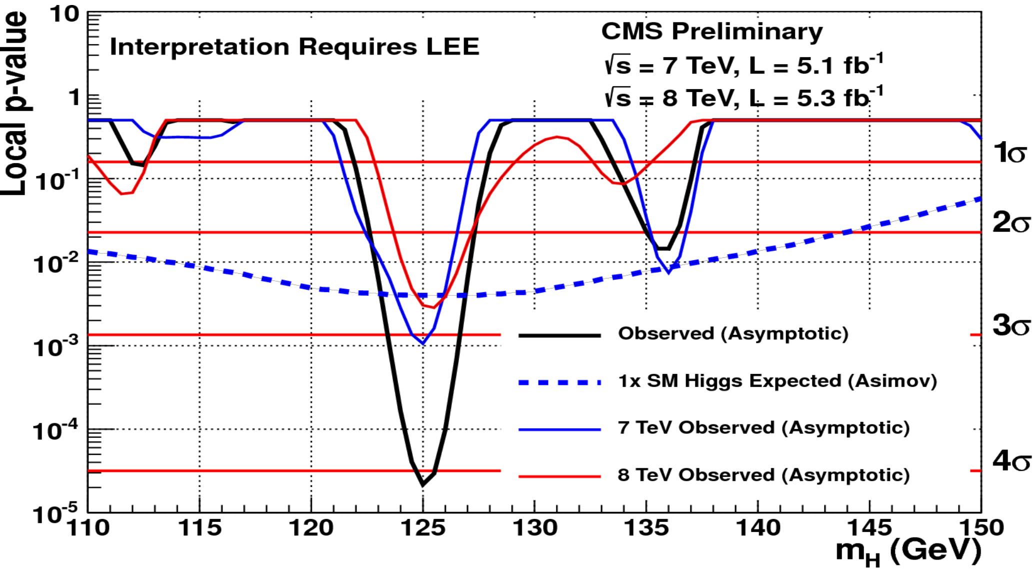


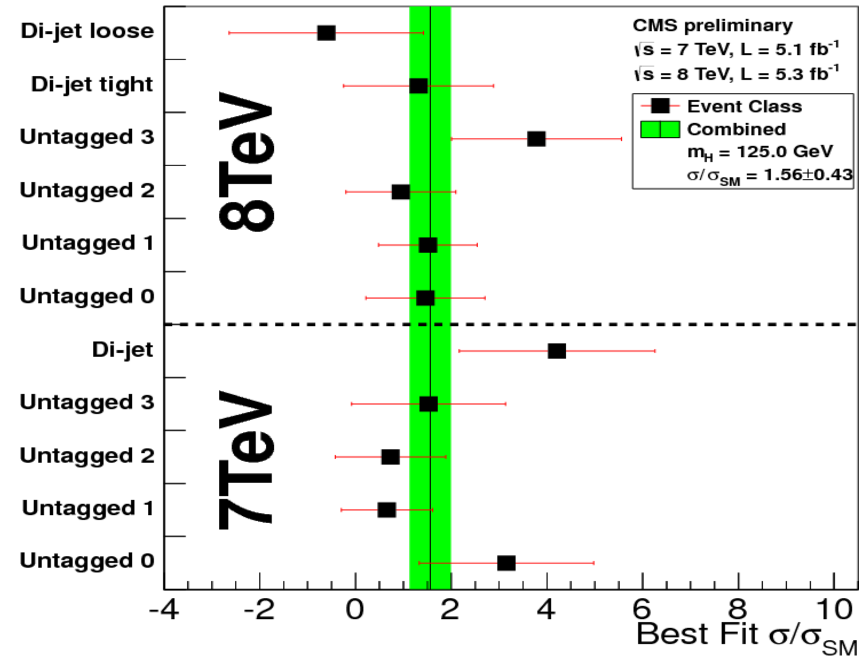
Cut-based



Exclude at 95% CL almost the full mass range except the region around 125 GeV

H→γγ: published results





- Maximum significance 4.1 σ at 125 GeV

- Sum of mass distributions for each event class, weighted by S/(S+B)
- Weighed data events and BG model parametrizations

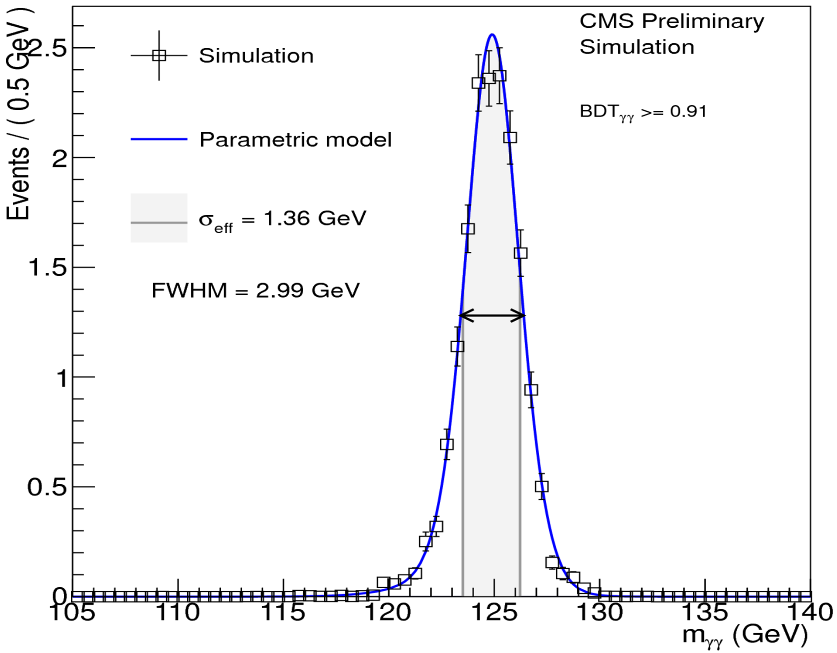
H→γγ: MVA categories

Expected signal and estimated background

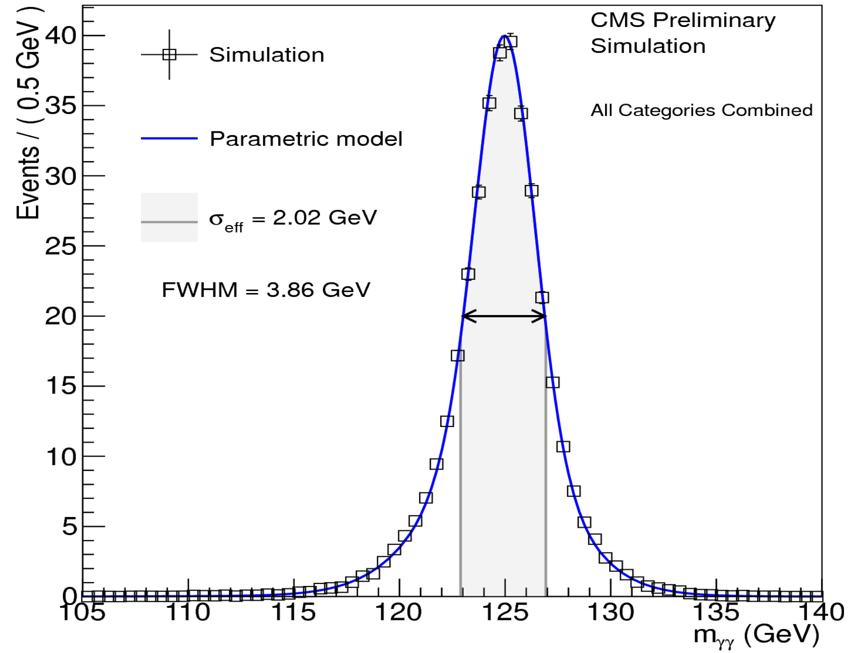
Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.6	72.9%	11.6%	13.0%	2.6%	1.38	1.31	21.9 ± 0.5
	Untagged 1	39.4	83.5%	8.4%	7.1%	1.0%	1.51	1.38	93.0 ± 1.0
	Untagged 2	155.3	91.7%	4.4%	3.5%	0.4%	1.78	1.52	559.6 ± 2.5
	Untagged 3	162.1	92.5%	3.9%	3.3%	0.2%	2.63	2.18	1021.3 ± 3.4
	Dijet tight	9.3	20.7%	78.9%	0.3%	0.1%	1.81	1.43	3.3 ± 0.2
	Dijet loose	11.6	46.8%	51.1%	1.7%	0.5%	1.87	1.60	12.0 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.1%	20.8%	1.87	1.55	0.7 ± 0.1
	Electron tag	1.0	1.1%	0.4%	78.9%	19.7%	1.91	1.55	0.6 ± 0.1
	E_T^{miss} tag	1.6	21.1%	2.5%	64.5%	11.8%	1.81	1.66	1.7 ± 0.1

H→γγ: Signal Model: MVA categories

8TeV Untagged cat 0



8TeV: All categories combined

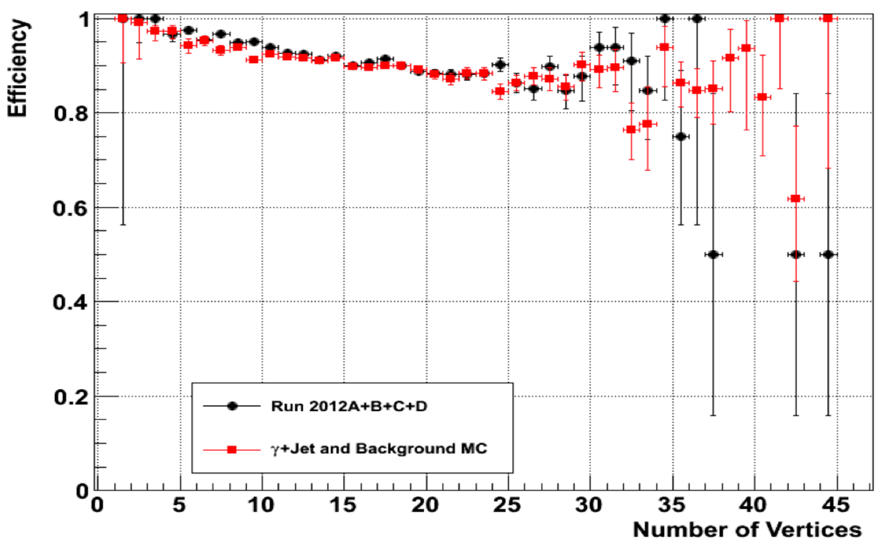


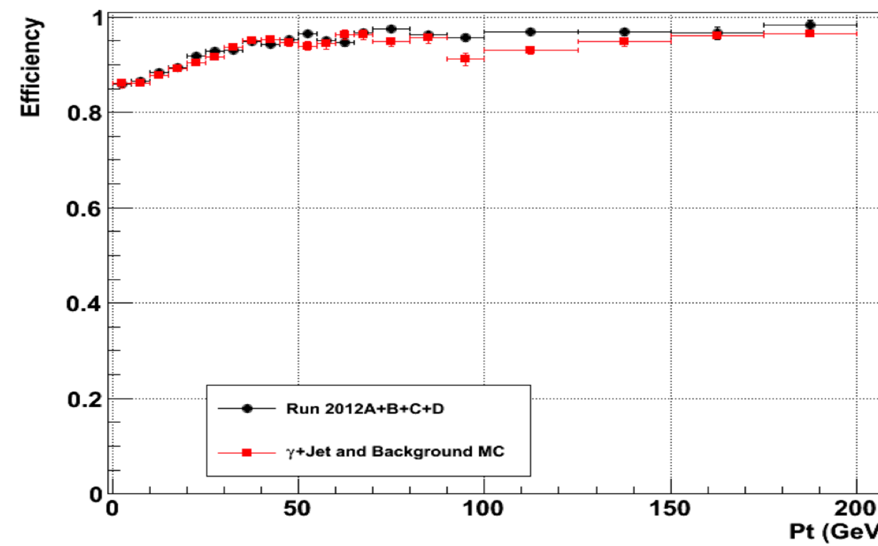
H→γγ: Systematic errors

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

H→γγ: Vertex from converted photons: gam+jet

Vertex pointing from converted photons is validated with g+jet

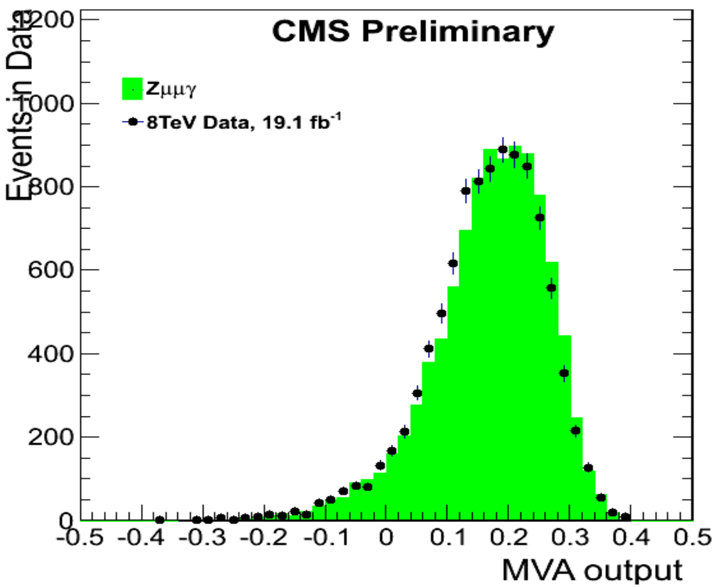




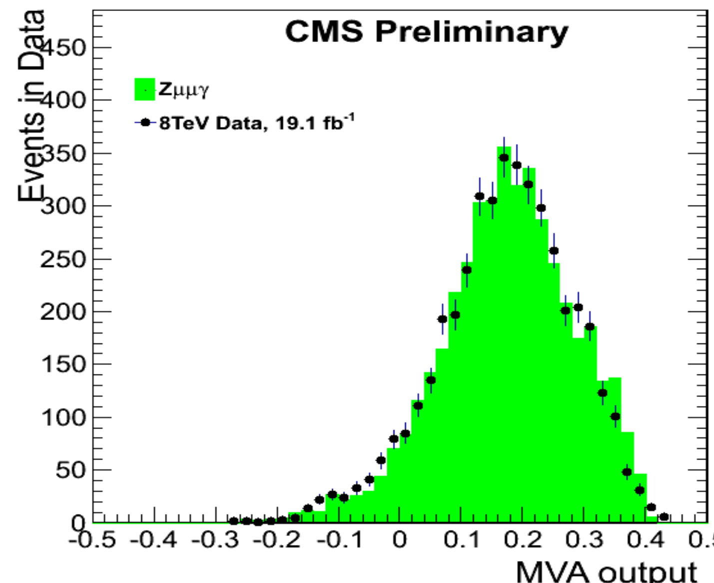
H→γγ: PhotonID MVA

- PhotonID MVA is checked with Z→ee and Z→μμγ

Barrel

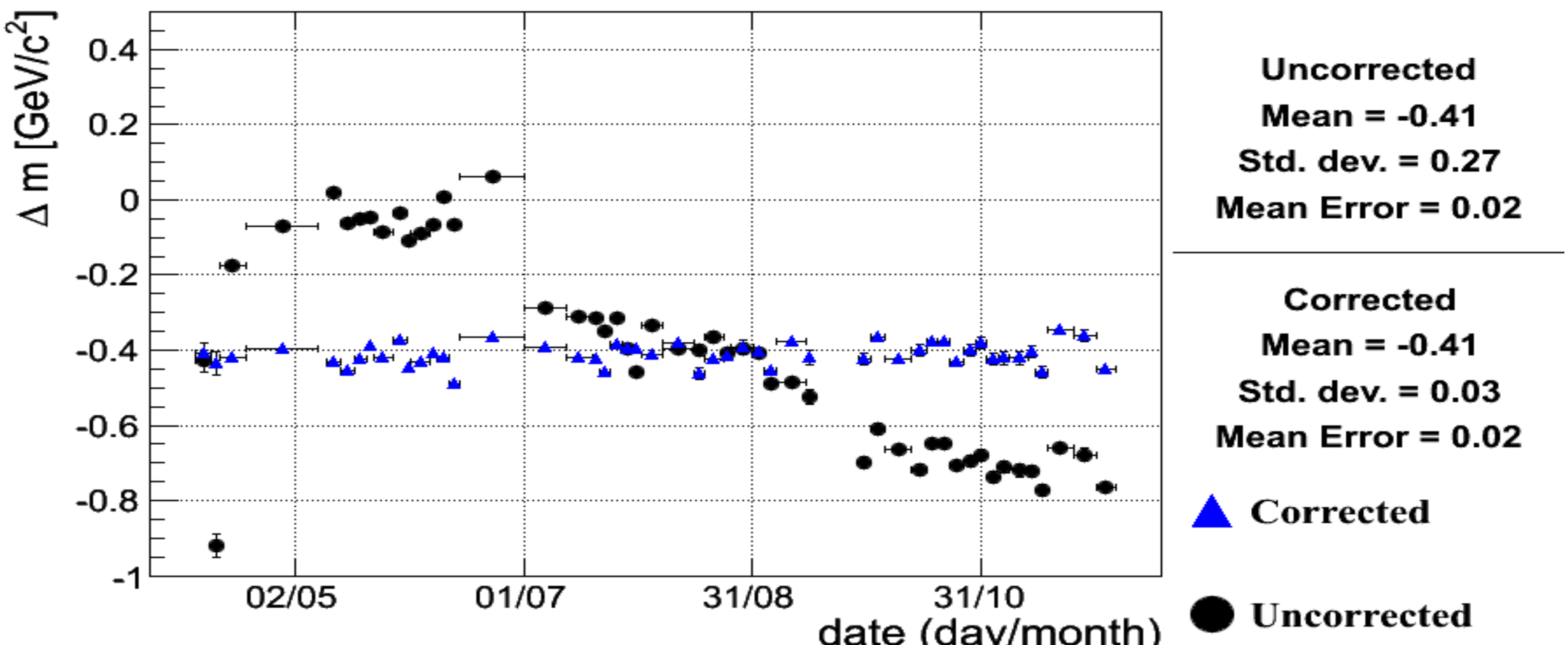


Endcap

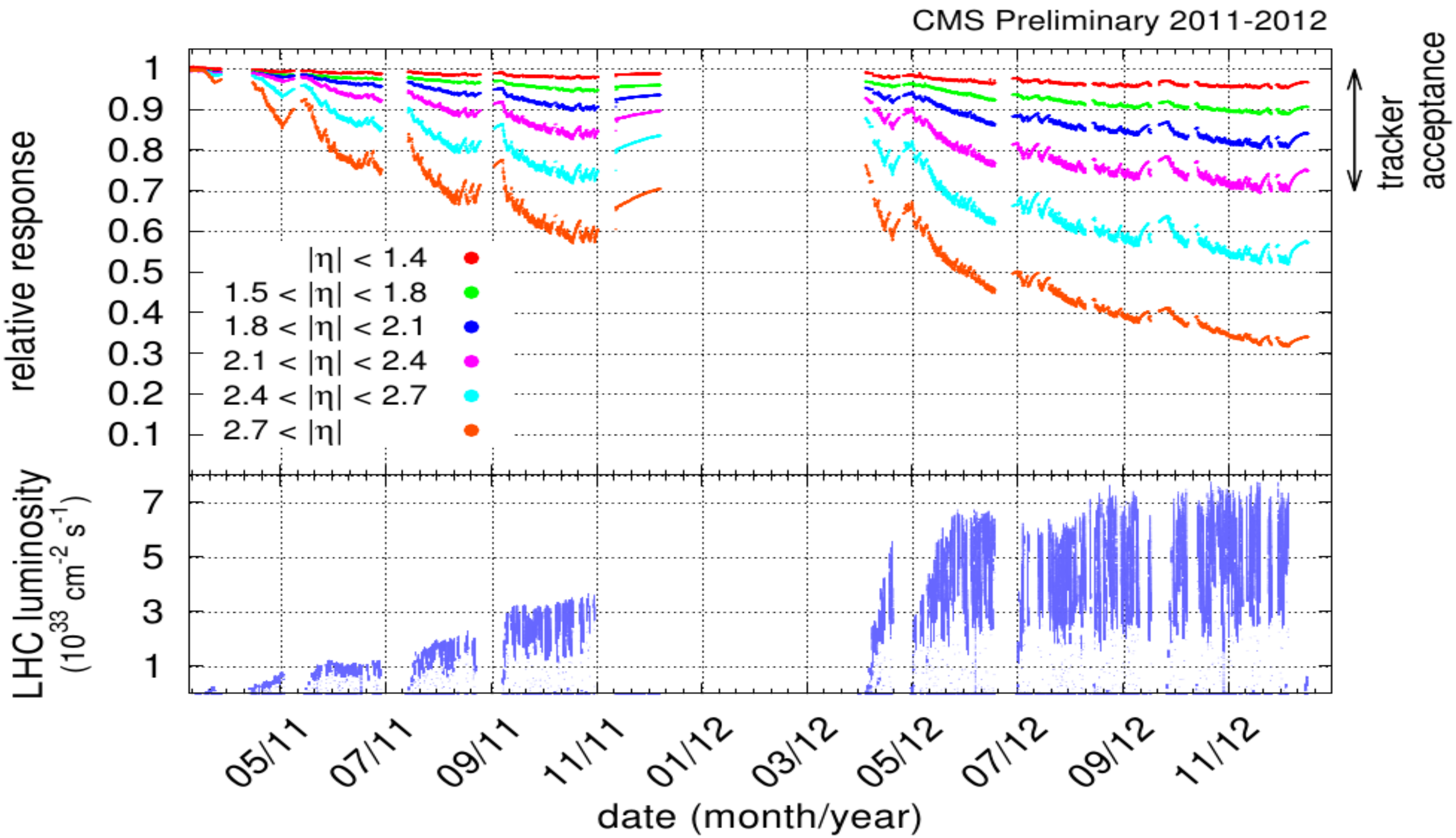


H→γγ: Energy scale vs time

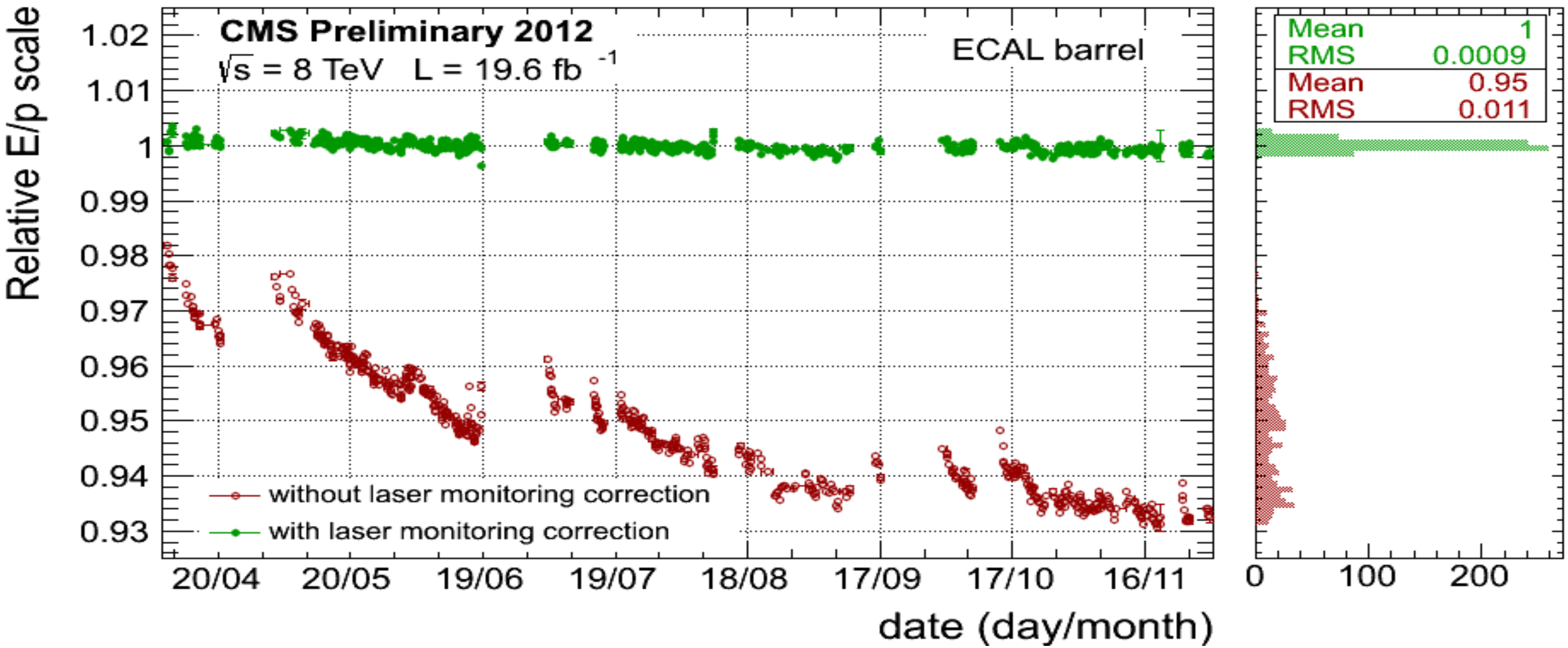
Stability at 0.3% level before application of analysis level corrections with prompt reconstructed data



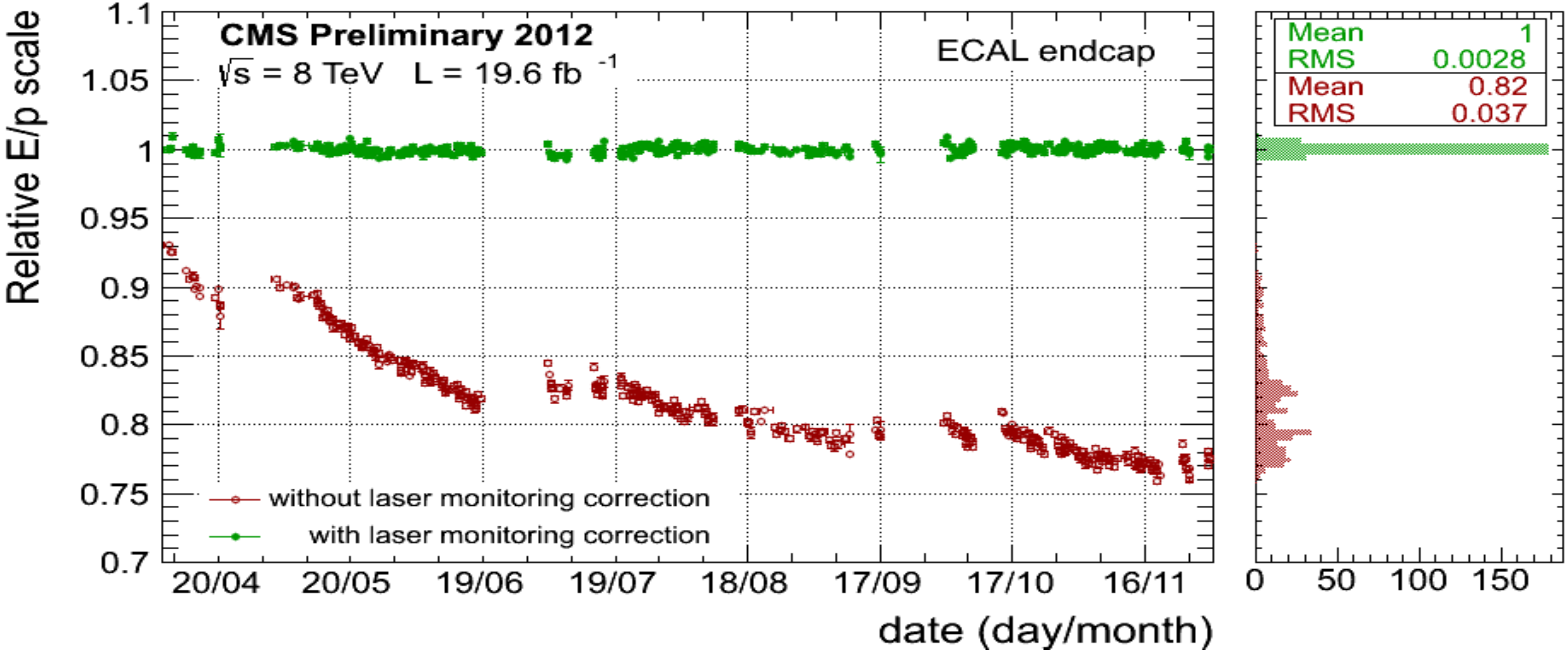
ECAL: response variation



ECAL: response correction (barrel)

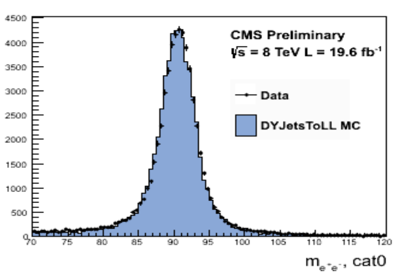


ECAL: response correction (endcap)

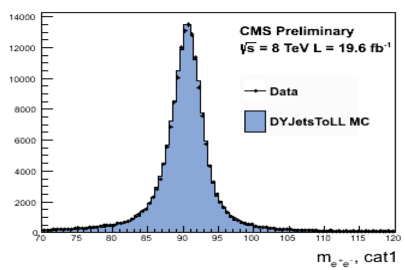


H→γγ: Di-photon MVA validation

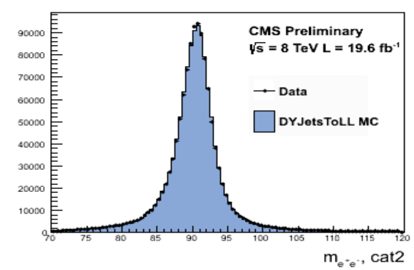
- Z→ee lineshape in MVA untagged categories



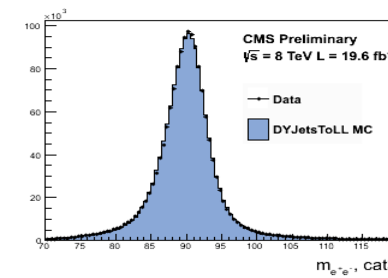
Untag cat0



Untag cat1



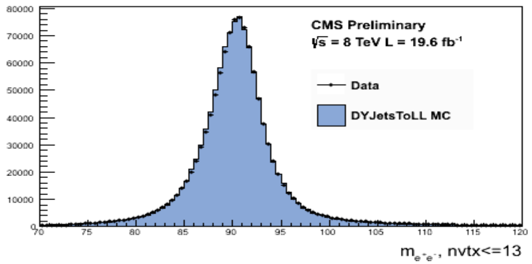
Untag cat2



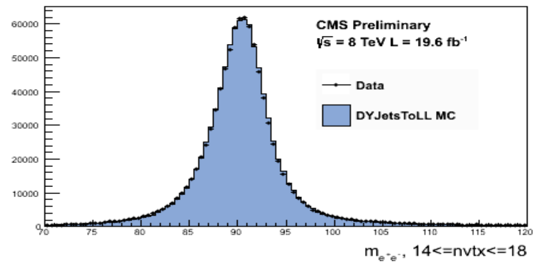
Untag cat3

H→γγ: Pileup Robustness - Energy Scale/ Resolution

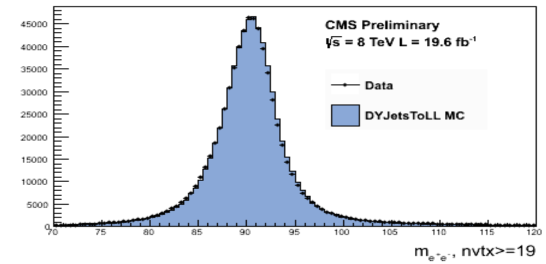
- Data-MC agreement in Z→ee validation maintained across nvtx bins:



nvtx<=13



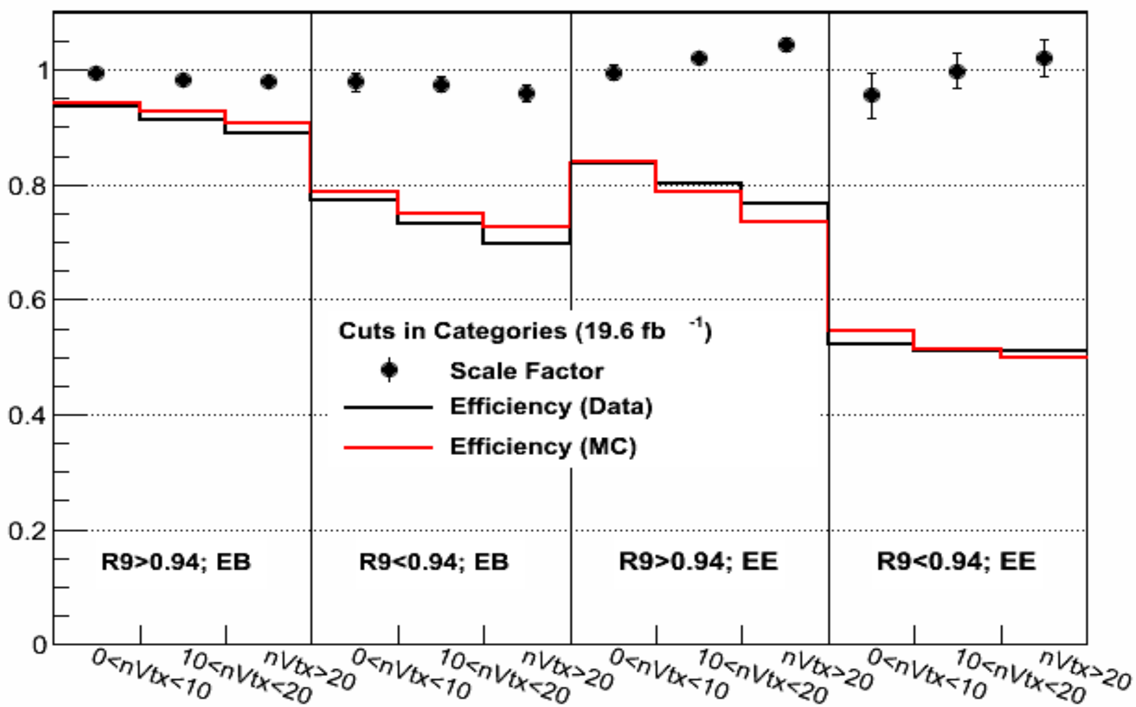
14<=nvtx<=18



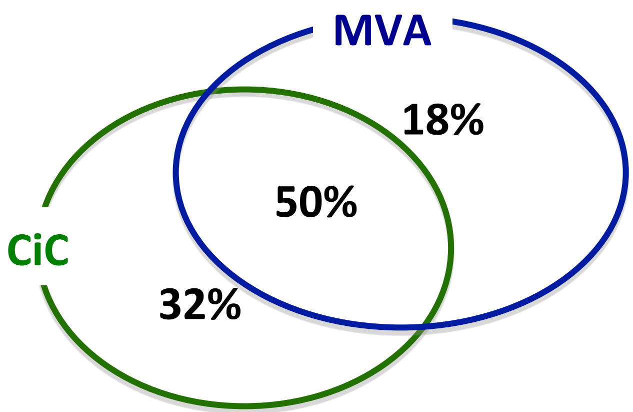
nvtx>=19

H→γγ: Pileup Robustness: Cut-based ID Efficiency

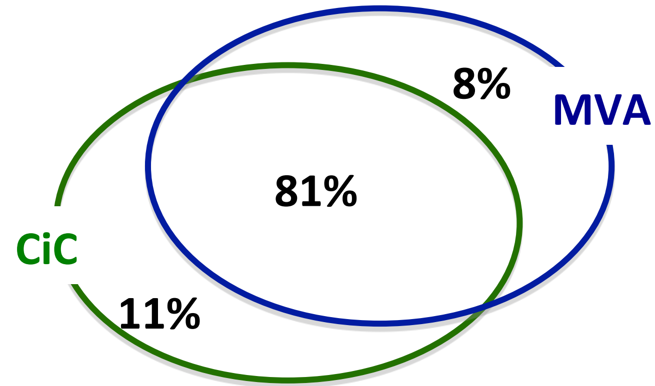
- Cut-based Photon ID efficiency decreases with respect to pileup, well described by MC



$H \rightarrow \gamma\gamma$: Overlap of selected events



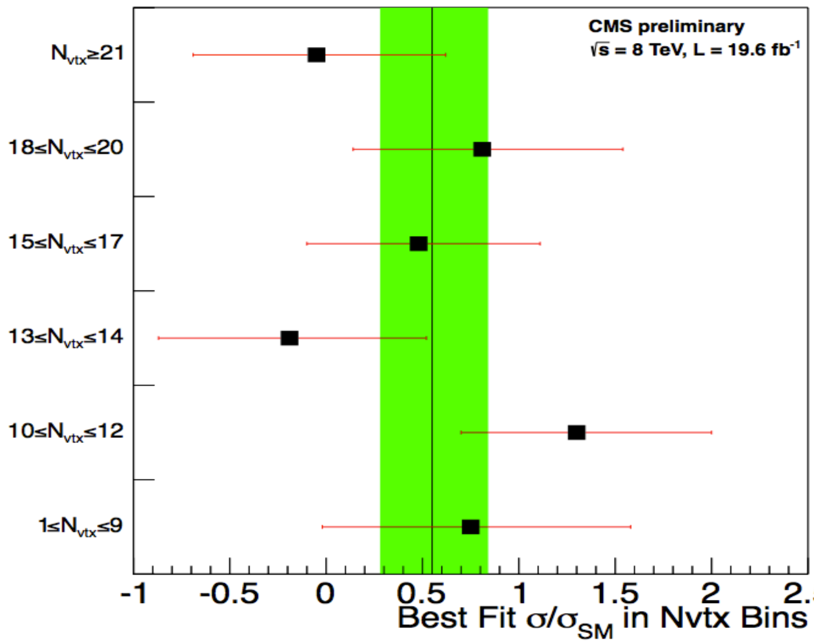
Data
(Background MC agrees)



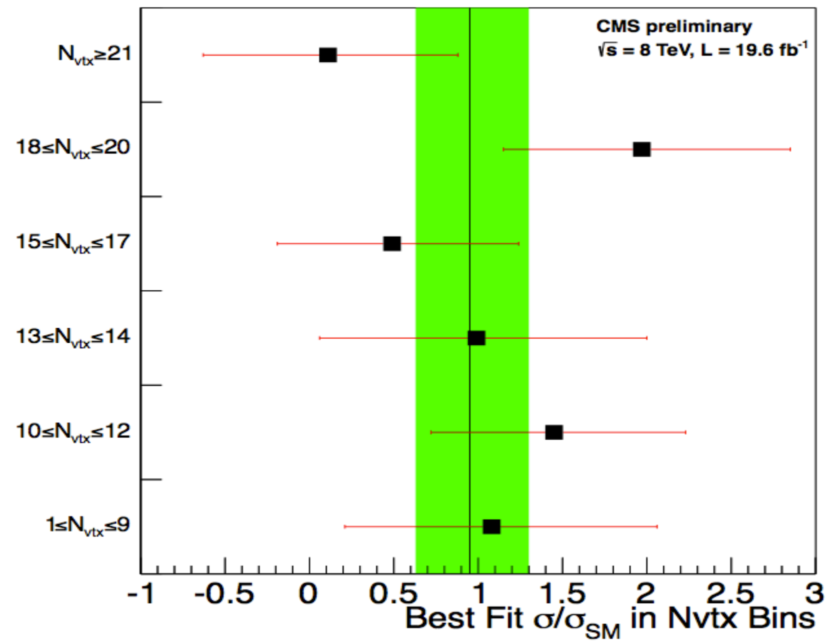
Signal MC

Observed μ in nvtx bins

MVA

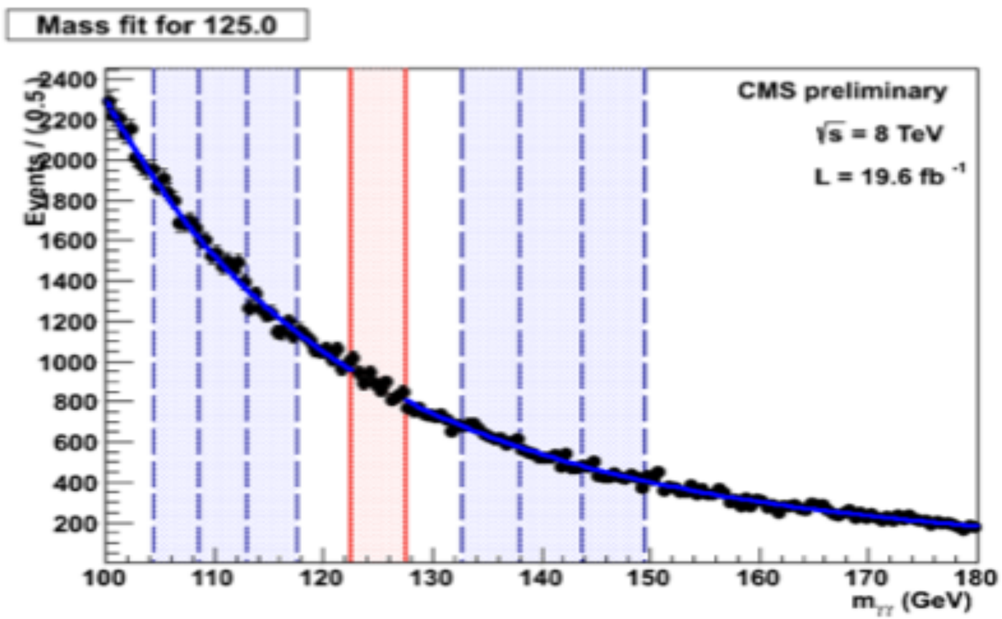


Cut Based



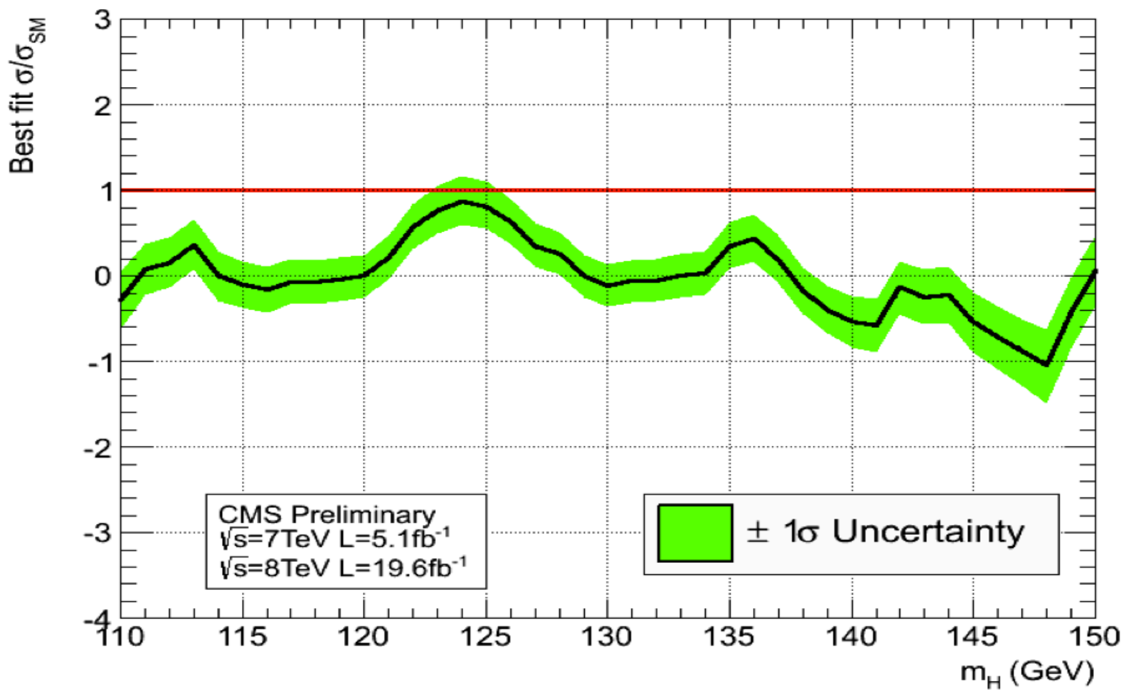
Mass sideband analysis

- Different background estimation method



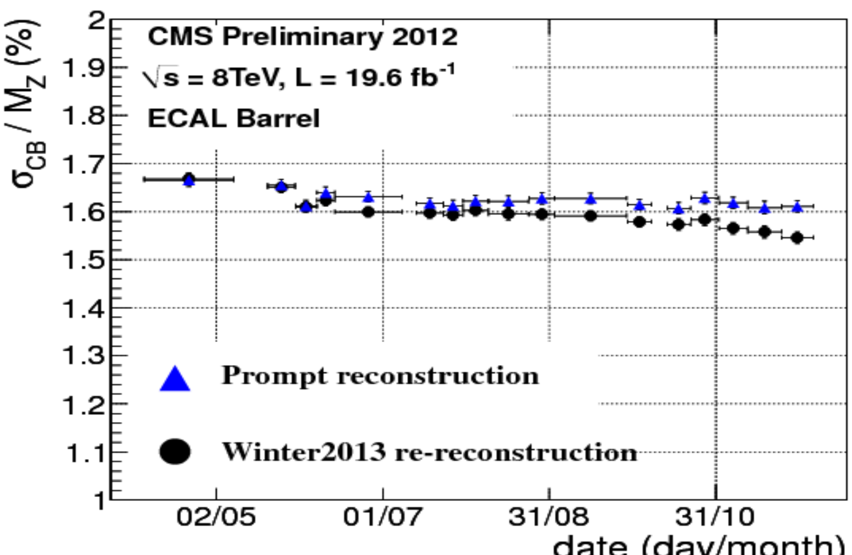
Mass sideband analysis II

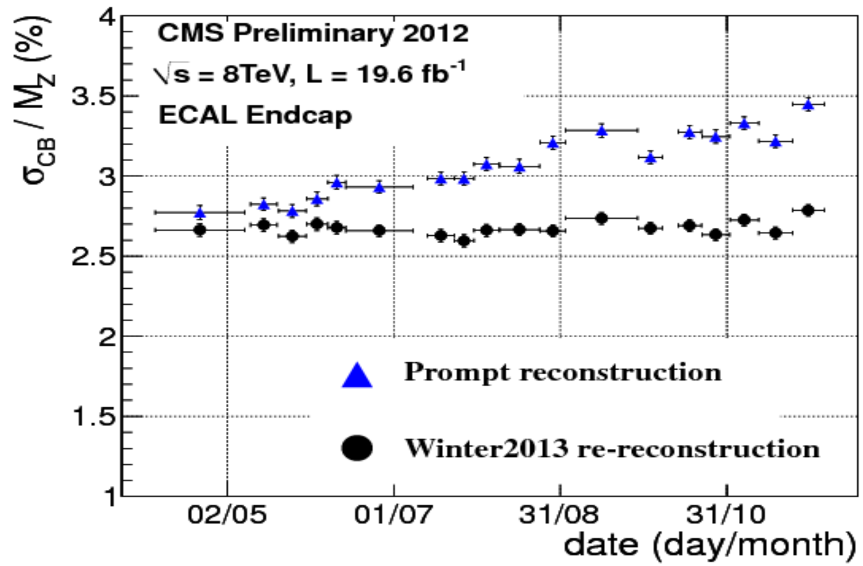
- Consistent results with the mass factorized analysis



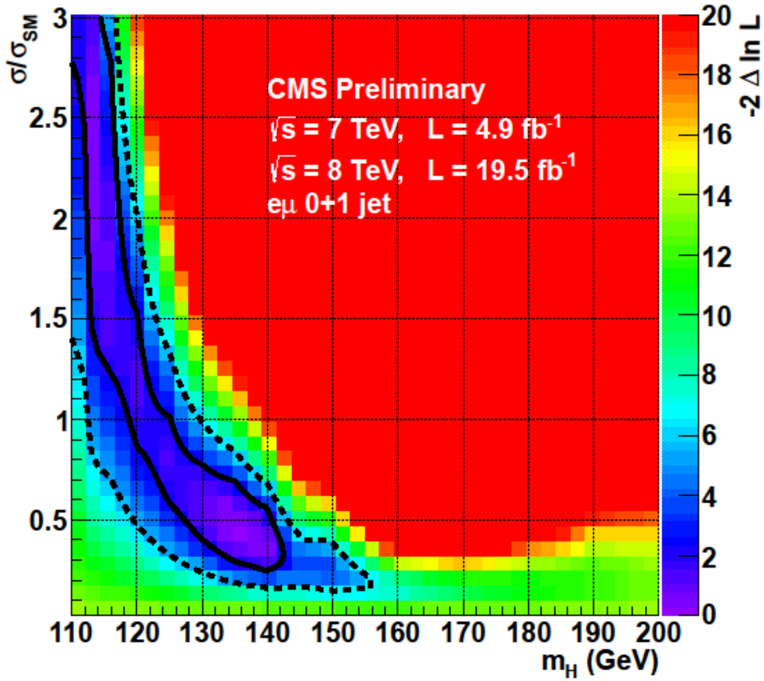
ECAL improved calibration

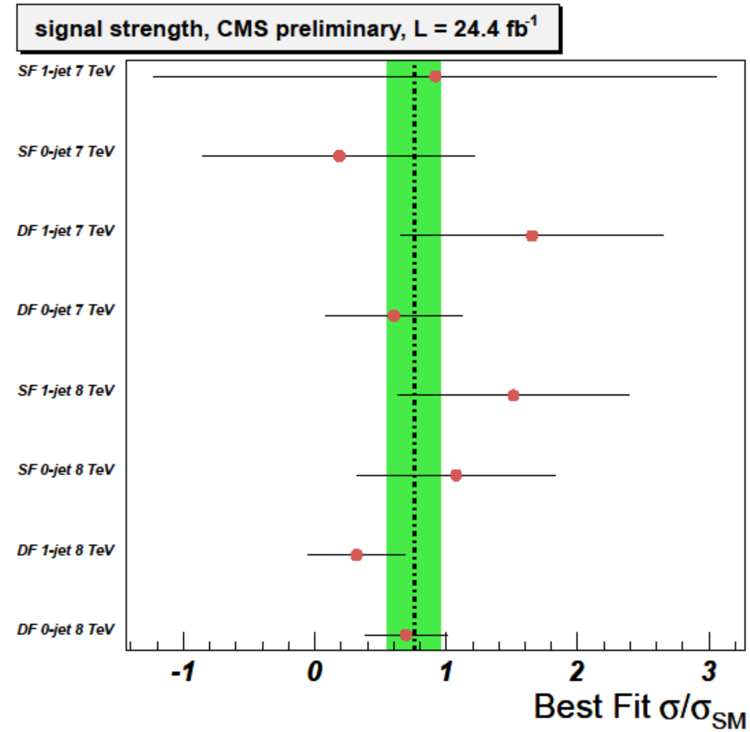
Comparison of the prompt reconstruction (used for Moriond13 result) with improved available ECAL calibrations





Mass and signal strength





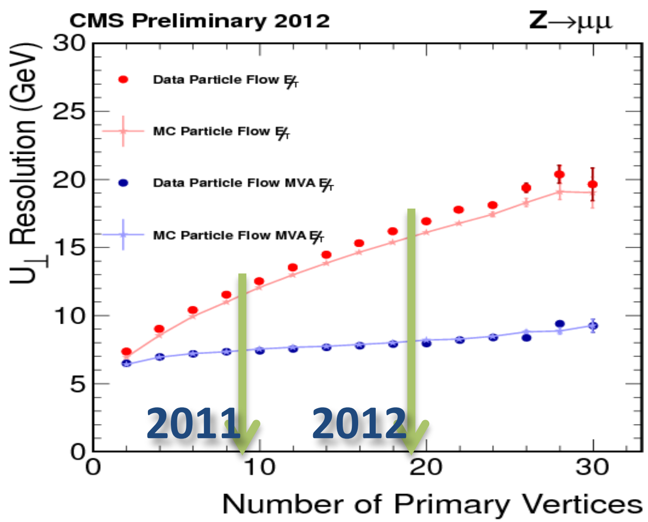
$\mu = 0.76 \pm 0.21$ @ 125 GeV

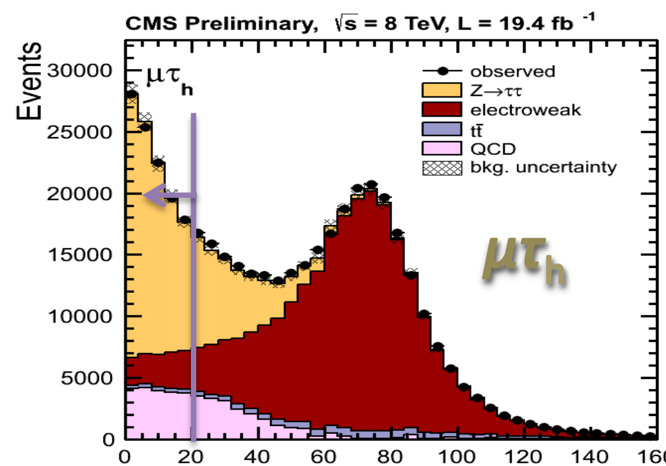
Broad mass profile due to low resolution

High contribution to μ precision when combined to ZZ,γγ

Object: MET

- Problem: Pileup degrades resolution
  - Bulk resolution critical
- Solution: MVA regression which chooses best *MET*
  - Constructed out 5 different *MET*s (recoils really)





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

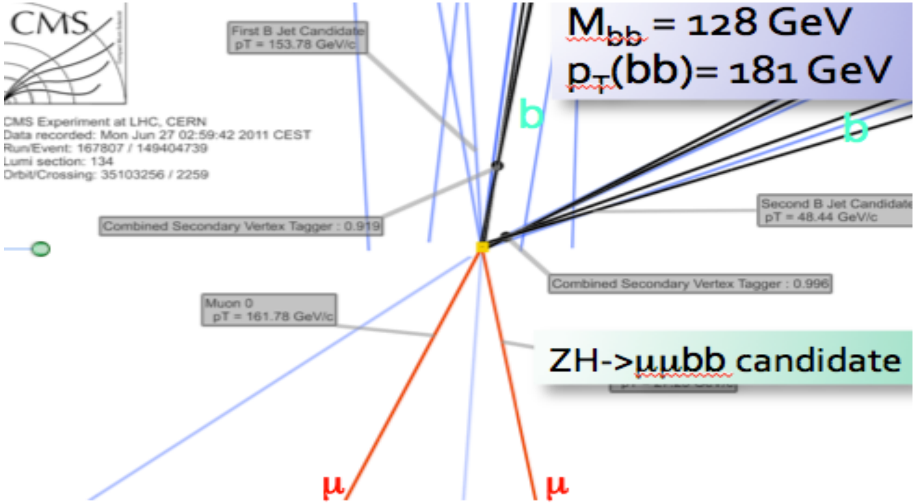
- Crucial for **H→ττ** analysis: $m_{\tau\tau}$ reconstruction, separation of signal from W+jets background using m_T

VH → bb

- Several final states considered:
  - *lνbb, llbb, ννbb*
  - Δϕ(V,H), tight b-tagging
- Boosted Higgs to increase S/B

  (σ_{bb}(QCD) ~ 10^7 σxBR(H-> bb))

  Two pT(H) categories: require p_T^{bb}>100 (150) GeV for ZH (WH)

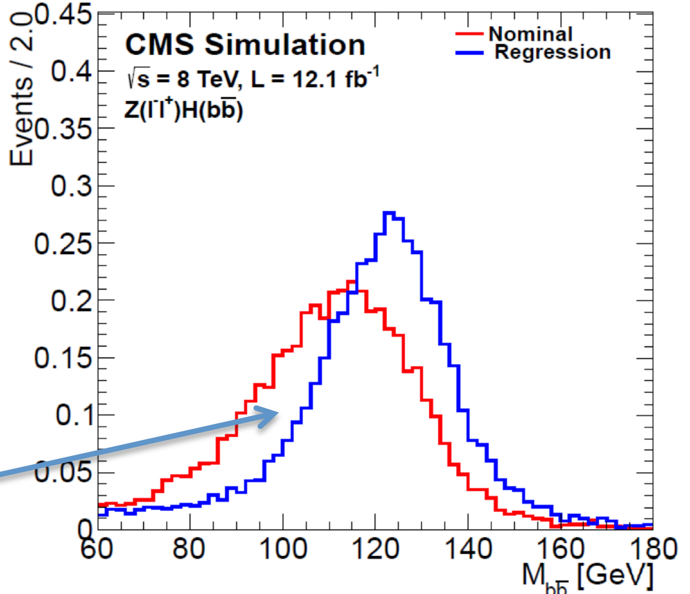


The dijet mass is the most discriminating variable

Presence of leptons and neutrinos in b-jets

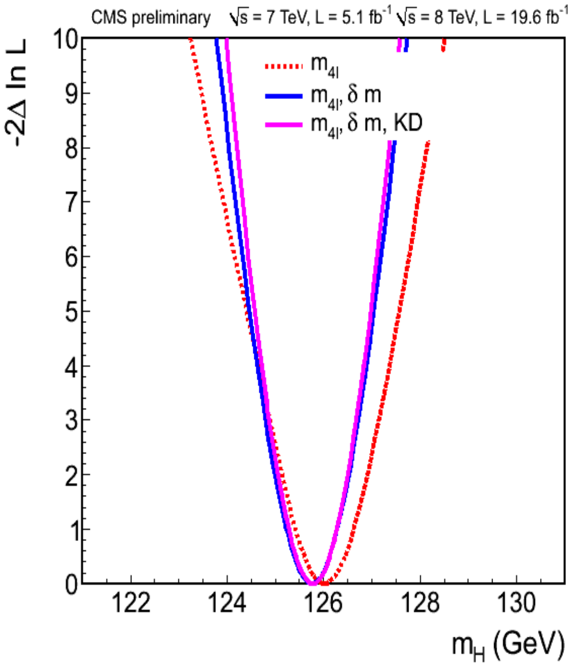
Use a BDT regression in order to correct the jet energy exploiting jet and b-tag variables

~ 15% improvement in mass resolution

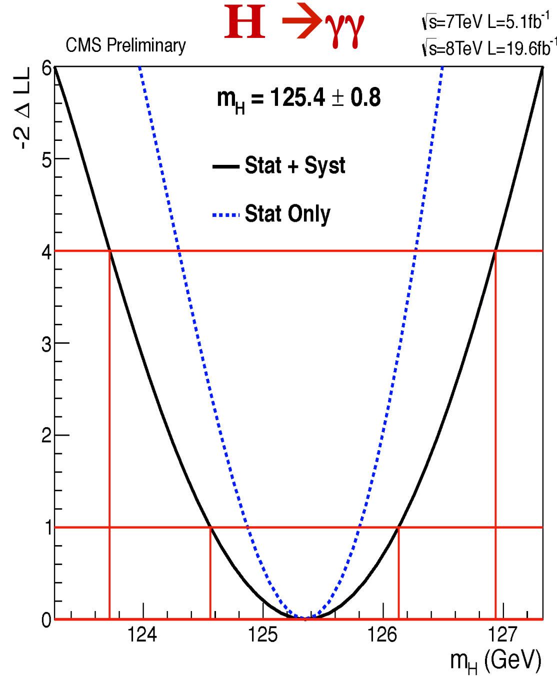


The Mass

H →ZZ→4l



H →γγ



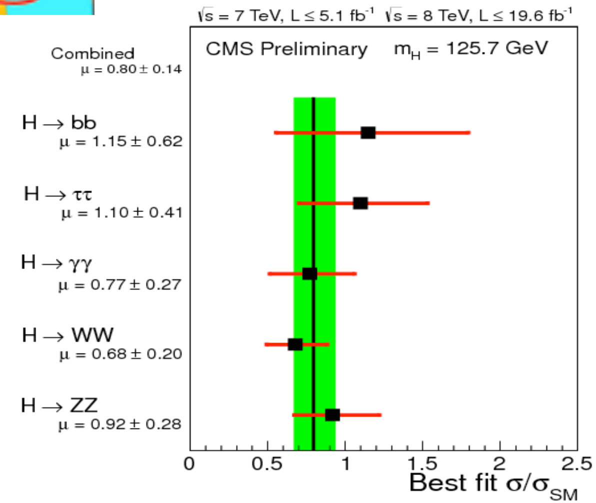
H →γγ: Systematical uncertainty on the mass:

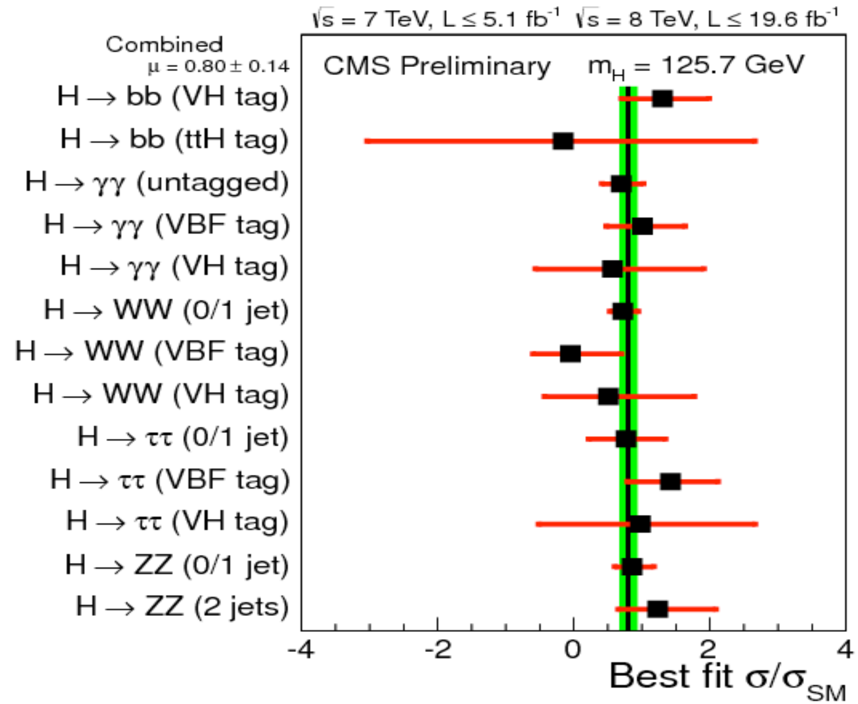
- Statistical fluctuation of the large background below the signal peak
- Systematics on the extrapolation from the Z→ee to H→γγ (0.25% from e to γ, 0.4% from Z to H)

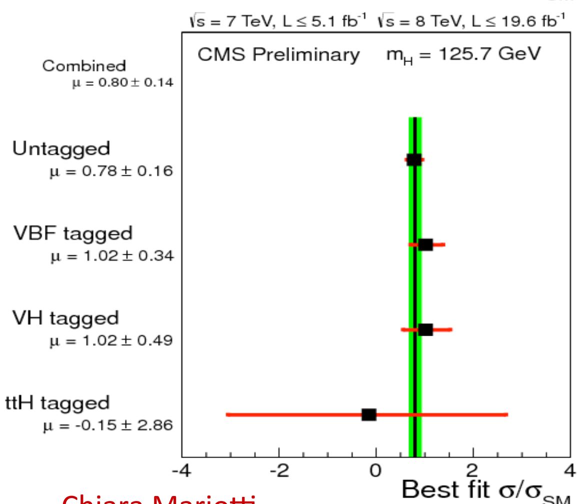
Conservative estimate ~0.5%, will improve in the future.

H →ZZ→4l: Very small systematics due the very good control of the leptons scale and resolution:
m_H = 125.8 ± 0.5 (stat.) ±0.2 (syst.) GeV.

Is it a SM Higgs boson ?







Signal strength consistency with SM hypothesis

Custodial symmetry

- $\rho = M^2_W / M^2_Z \cos^2\theta_W = 1$ at tree level

- LEP experiments have measured

  $\rho = 1.005 \pm 0.001$

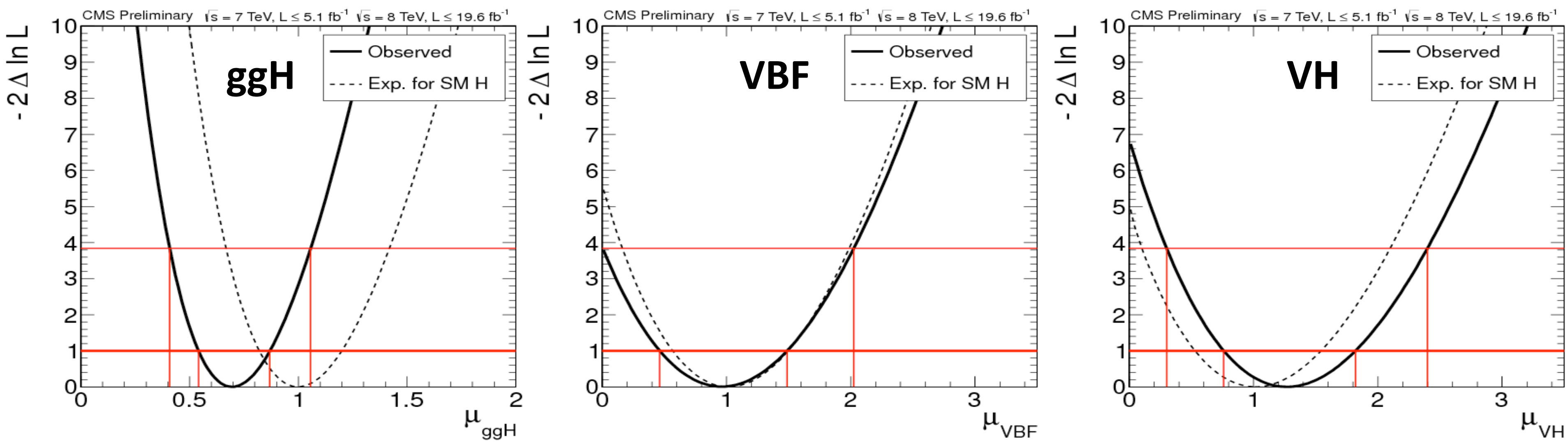
  i.e. 5 sigma away from 1 !
  BUT in perfect agreement with the theoretical value of $\rho' = 1 + \Delta\rho$, when radiative corrections are correctly taken into account $\Delta\rho = 3\, G_F\, m_t^2/(8\sqrt{2})\, \pi^2)$

- The radiative corrections affect ρ mildly, because of a symmetry of the Higgs Potential, called SU(2) "Custodial Symmetry"

- **Thus measuring the W, Z coupling ratio from H decays, means measuring the ratio between boson masses, thus ρ. It will tell us if the object produced is Higgs like.**

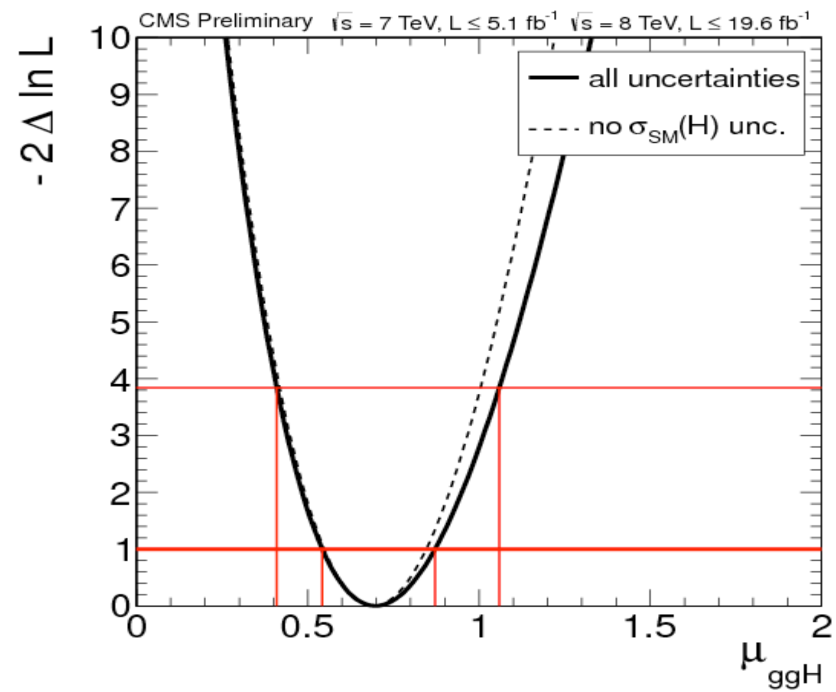
Testing production modes

- Simultaneous fit for the production cross sections, normalized to SM, in all modes.
  Decay BR's assumed to be the SM ones.



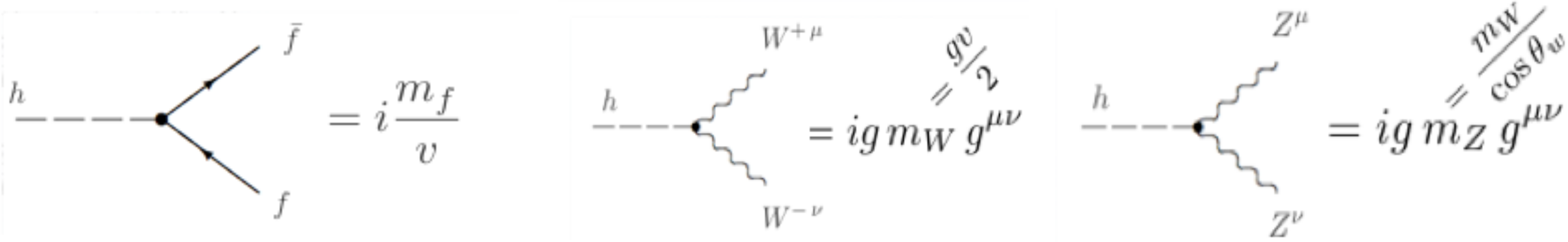
Production modes: theory uncertainties

- Repeated extraction of μ(ggH) also w/o the theoretical uncertainty on the cross section. (kept PDF, jet-bin and UE/PS uncertainties)
- Theory uncertainties contribute to ~10%.
- Negligible contribution for μ(VBF) and μ(VH)

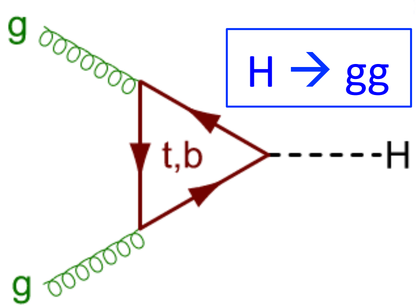


$$\mu_{ggH} = 0.69 \,^{+0.15}_{-0.14} \,^{+0.09}_{-0.05}$$

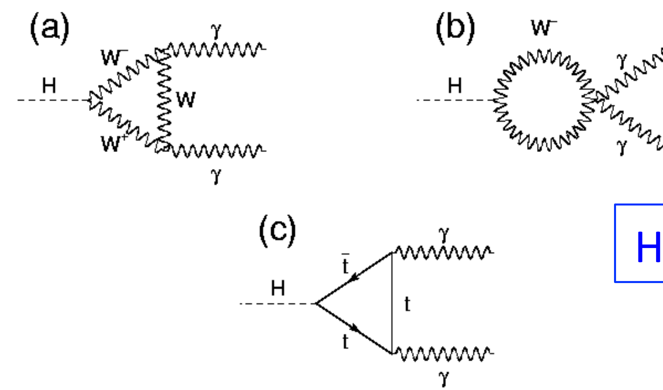
Higgs couplings



No direct coupling to massless particles



Top is dominating



H → γγ

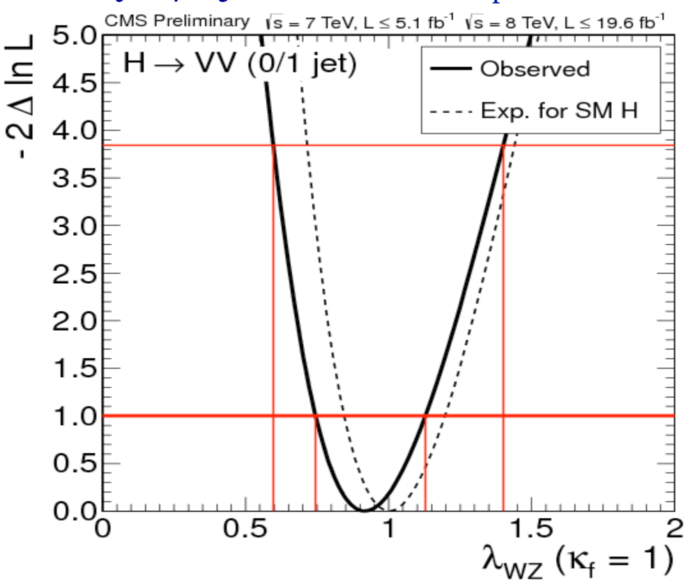
$|\alpha\, \kappa_V + \beta\, \kappa_f|^2$, $\alpha/\beta = -0.2$

destructive interference between W and top

Custodial symmetry

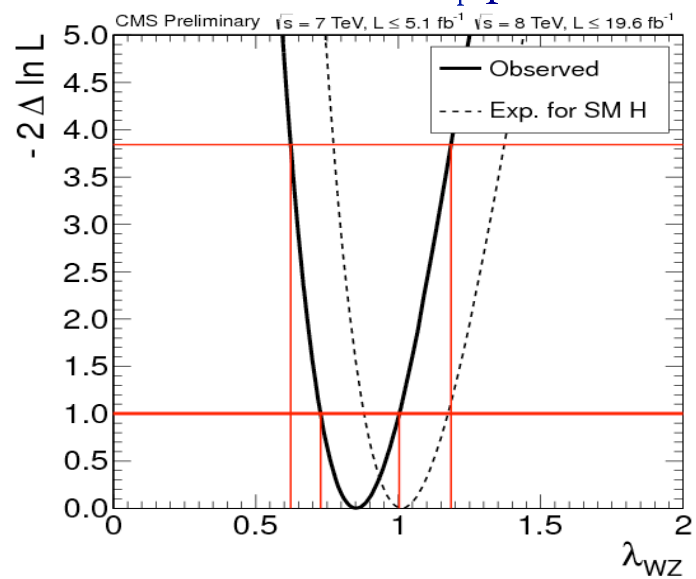
Testing custodial symmetry (measuring HW/HZ couplings) will tell us if the the object produced is Higgs-like.

Only 0/1 jet ZZ, WW. κ_f fixed to SM



[0.75,1.13] @ 68% CL

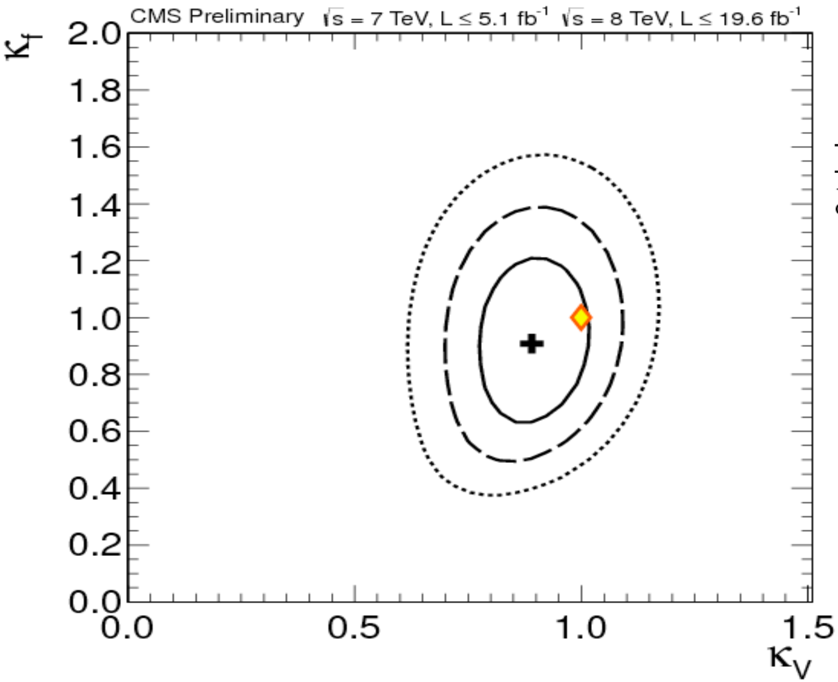
All channels. κ_f profiled.



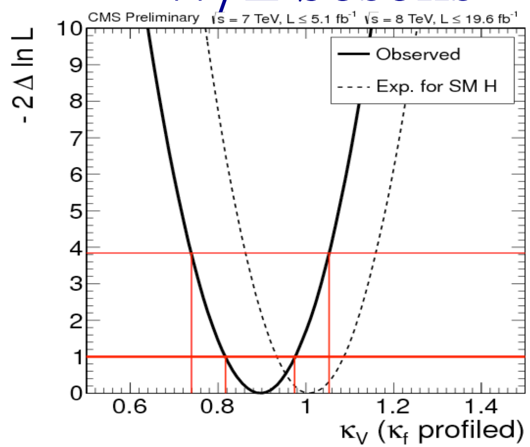
[0.73,1.00] @ 68% CL

Consistent results with the two approaches.

Couplings: κ_V, κ_f

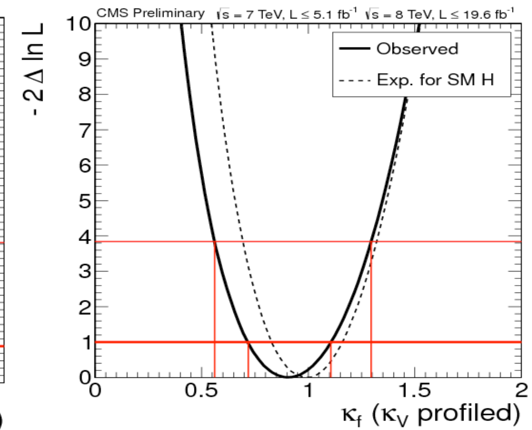


W/Z bosons



[0.81, 0.97] @ 1σ
[0.73, 1.05] @ 95%

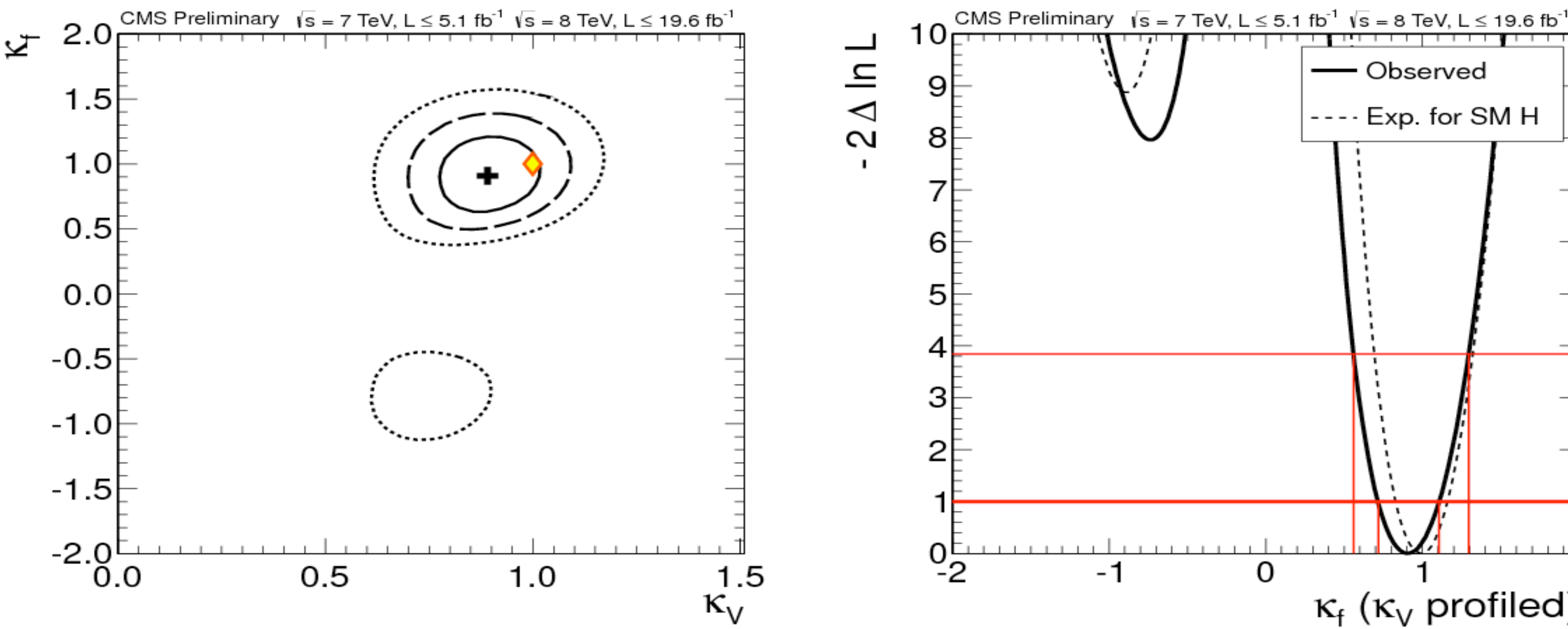
Fermions



[0.71, 1.11] @ 1σ
[0.55, 1.31] @ 95%

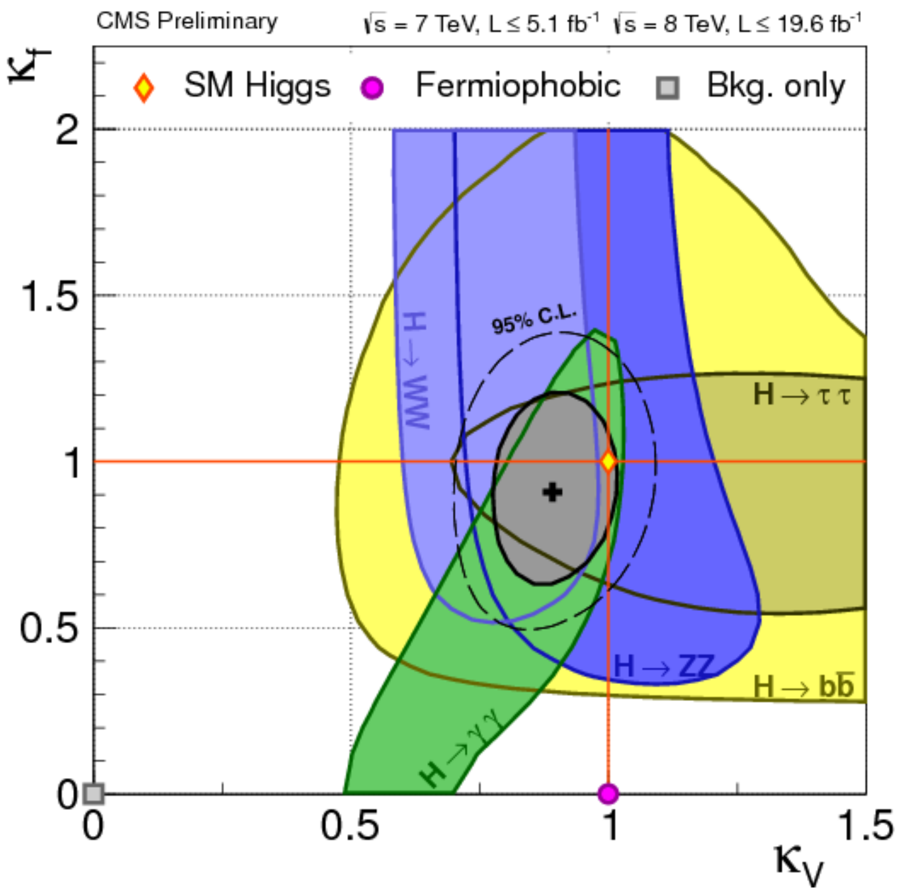
- Good consistency with SM hypothesis.

Couplings: κ_V, κ_f

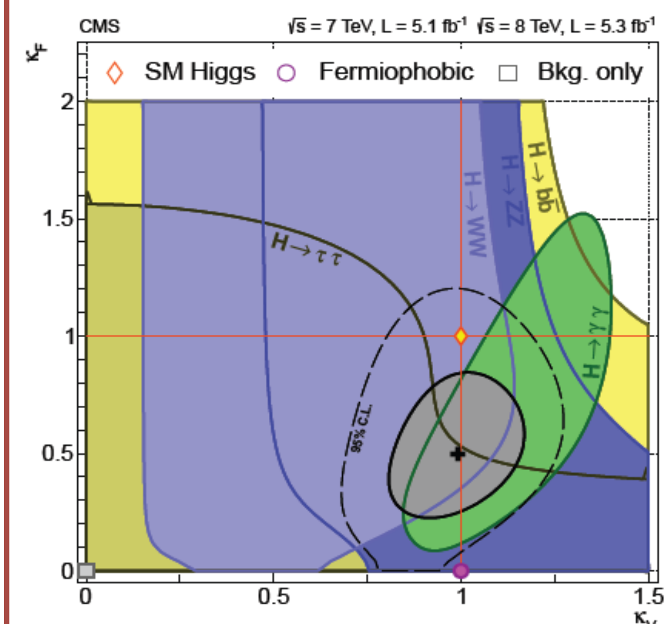


- Anomalous $\kappa_f < 0$ disfavoured at about 2.7σ for κ_V profiled (and even more strongly if assuming $\kappa_V = 1$)

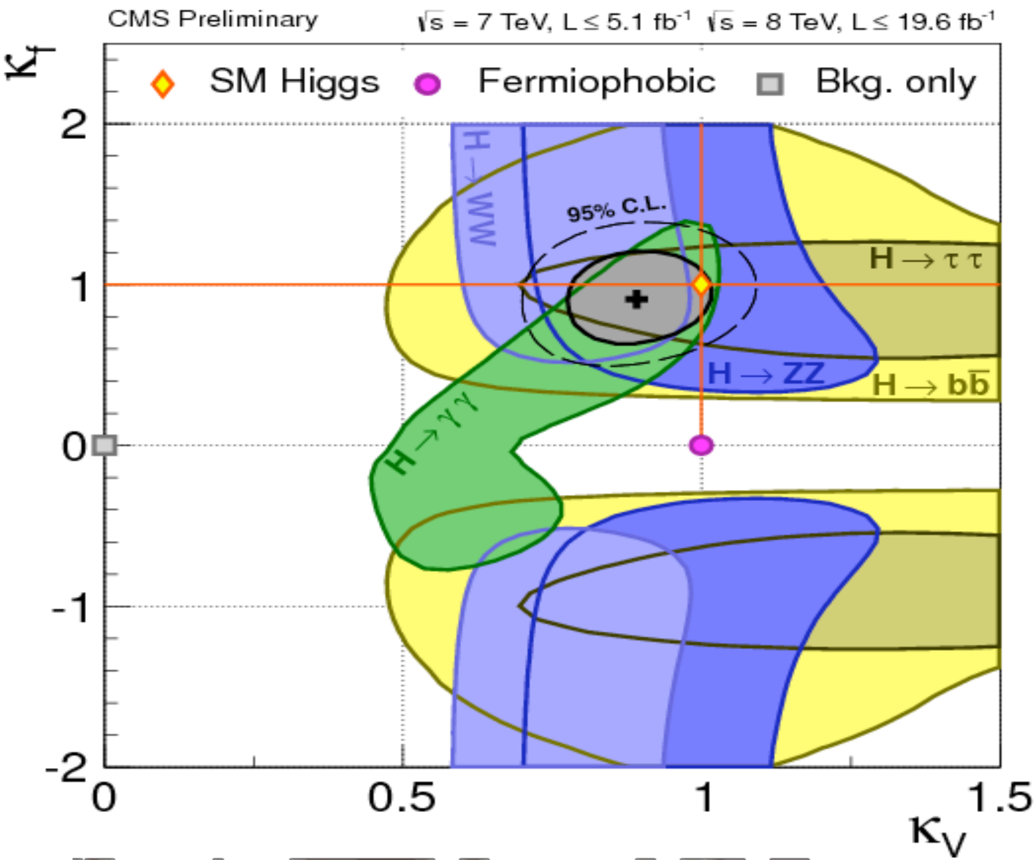
Couplings: κ_V, κ_f



ICHEP



Couplings: κ_V, κ_f teamwork

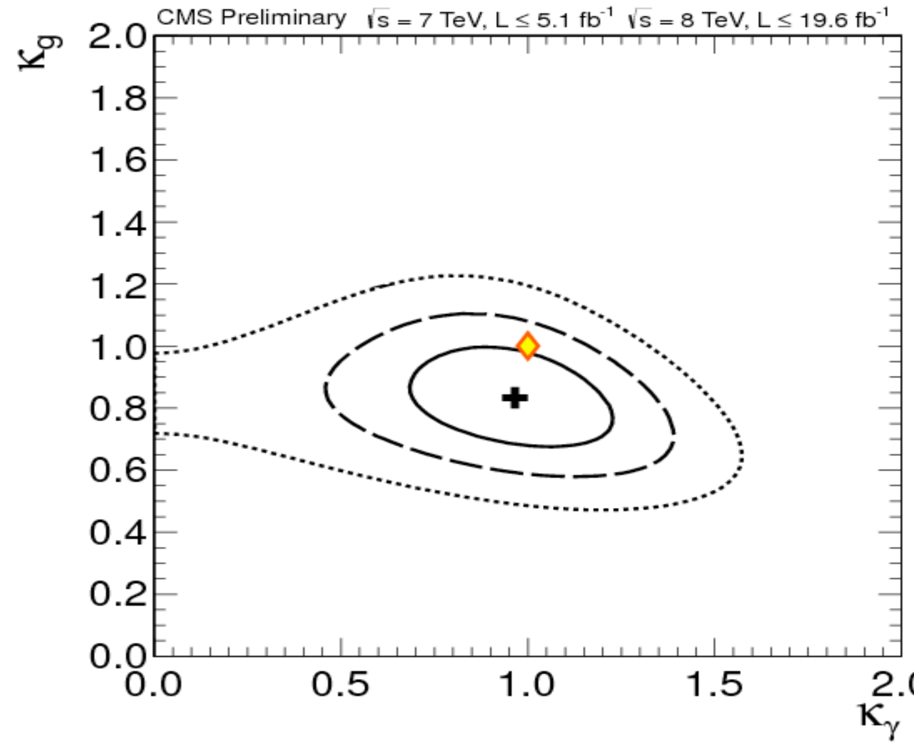


Exclusion of $\kappa_f < 0$ from combination of:

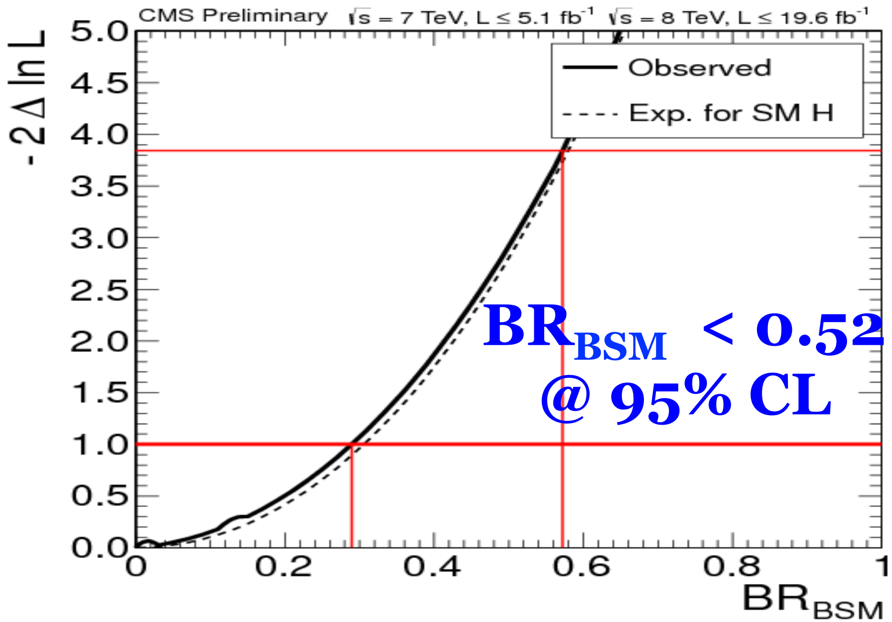
- VV modes: $\kappa_V > 0.7$
- ττ boosted: $|\kappa_f| \sim 1$
  (ττ VBF sensitive to κ_V)
- γγ: $\kappa_f = -1$, $\kappa_V = 1$ would require BR(γγ) ~2.3*SM

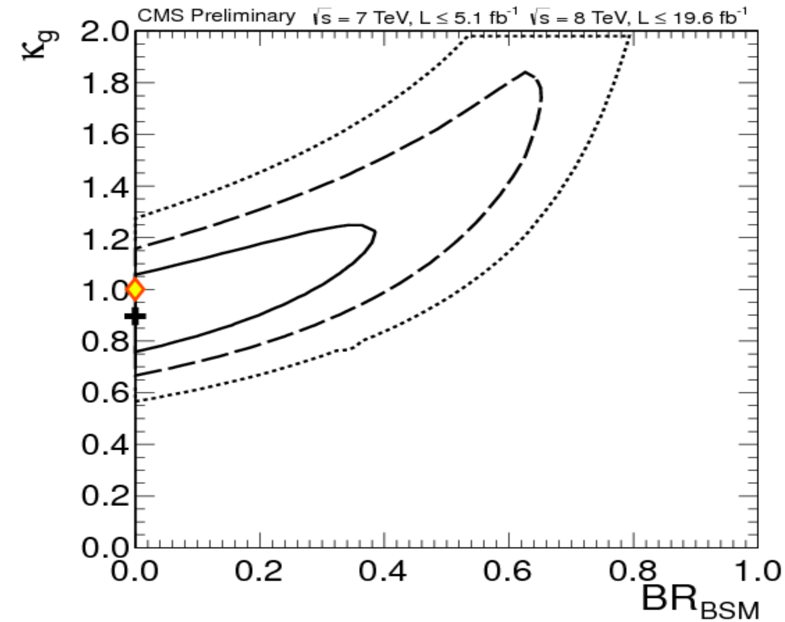
Search for new physics in loops and decays

- Effective couplings to gluons and photons in good agreement with SM predictions.
- Note best fit $\kappa_\gamma \sim 1$, with $\kappa_g < 1$ in line with $\mu < 1$ in VV modes as well.



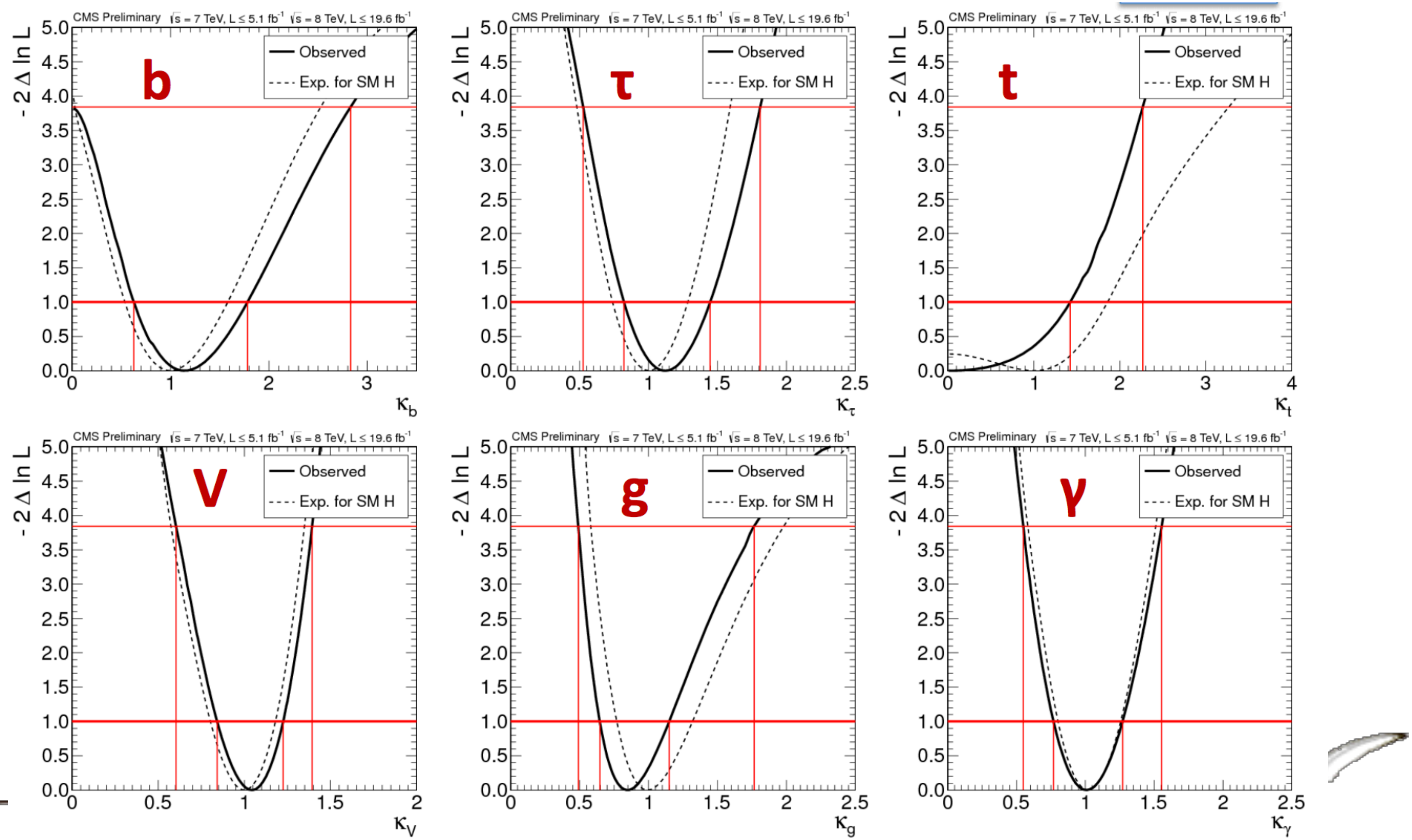
Search for new physics in decays





- Constrain total width from observed σ·BR's assuming SM tree-level couplings, but loop-induced couplings free.
- Degeneracy of BR_{BSM} with gluon coupling from σ(gg→H)

Fit all couplings at once



Total width with free couplings

- If no assumption is made, all couplings are degenerate with the total width:

  All σ·BR scale as $\kappa^4 / (\kappa^2 \Gamma_{SM} + \Gamma_{BSM})$

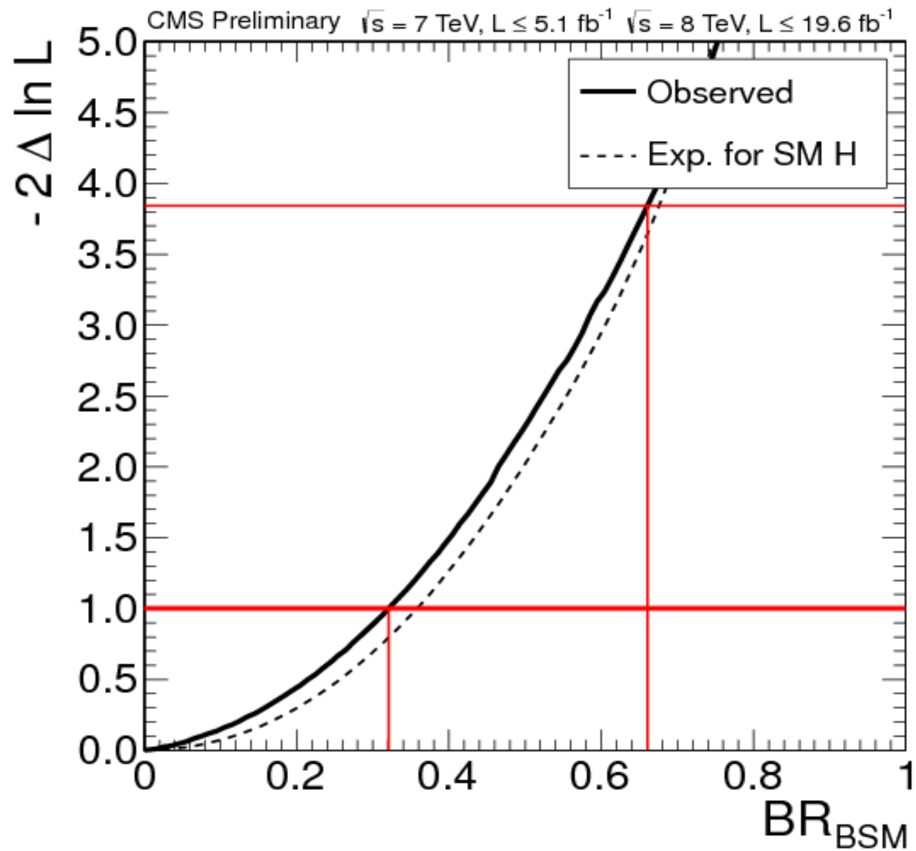
- However, in most EWSB models

  $\kappa_V \leq 1$

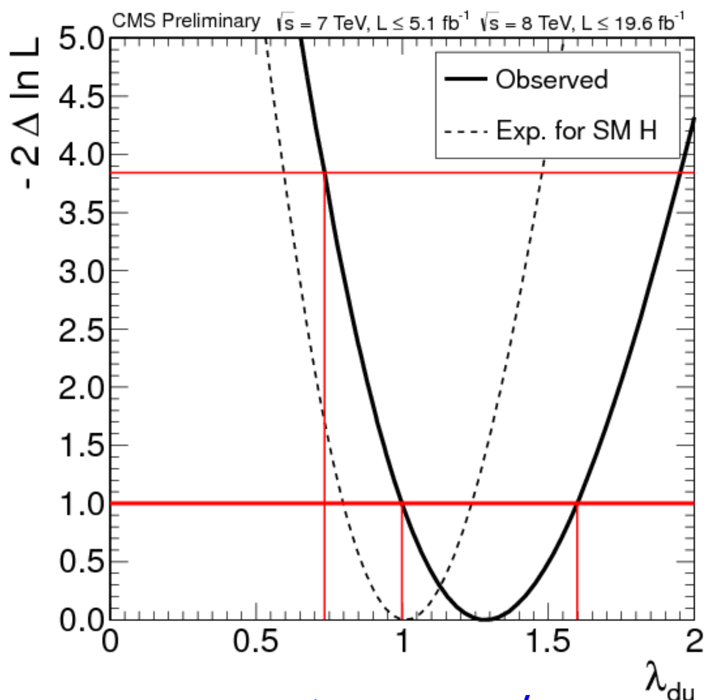
- If that constraint is imposed, one can put an upper limit on the total width with no other assumption on the other couplings.

- Upper limit to BSM decays imposing $\kappa_V \leq 1$:

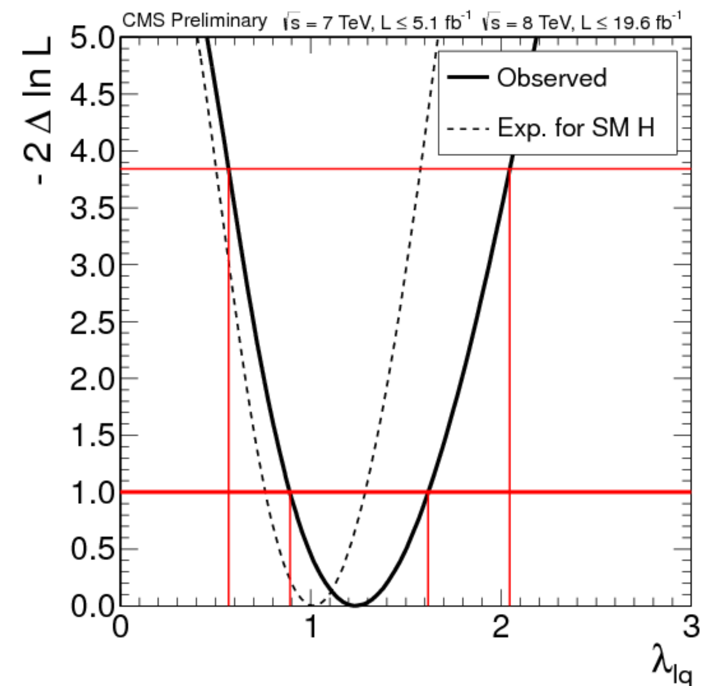
  $BR_{BSM} < 0.64$
  @ 95% CL



Fermion universality



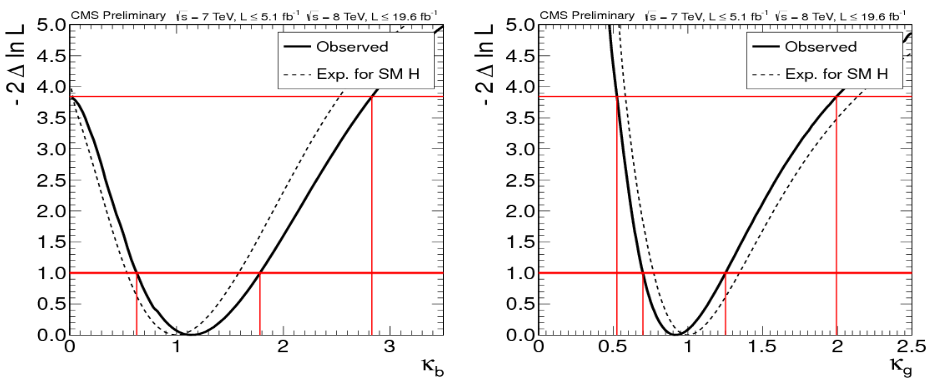
$\Lambda_{du} = \kappa_d/\kappa_u$

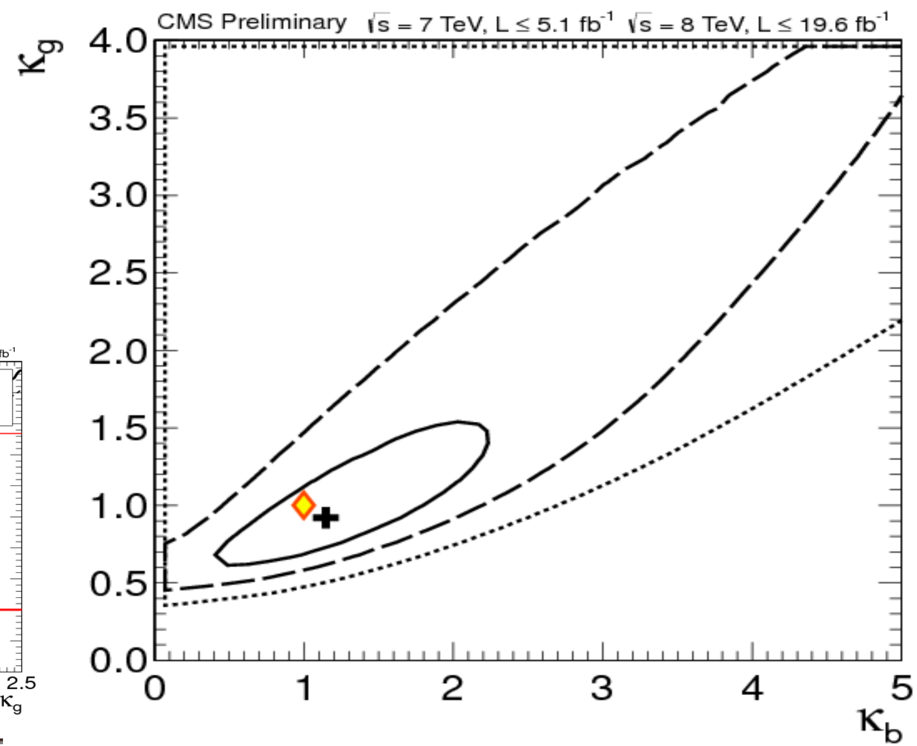


$\Lambda_{lu} = \kappa_l/\kappa_u$

Fit all couplings at once

κ_b - κ_g degeneracy: scaling both does not change $\sigma \cdot BR$ of $gg \rightarrow VV, \gamma\gamma, \tau\tau$ (and BR of $H \rightarrow bb$ also unaffected by larger κ_b's)

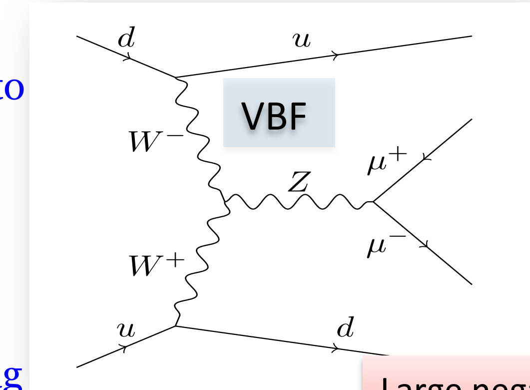


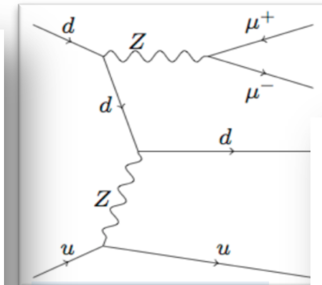


Vector Boson Fusion Z-production (1)

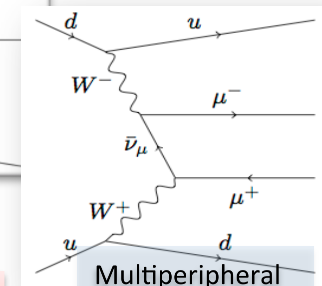
FSQ-12-019

- Important benchmark
  - Comparable σ and topology to SM Higgs
  - Use it to refine forward jet selection and central jet veto



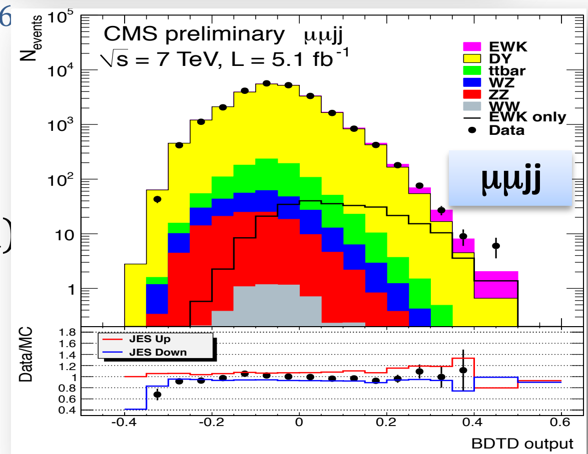


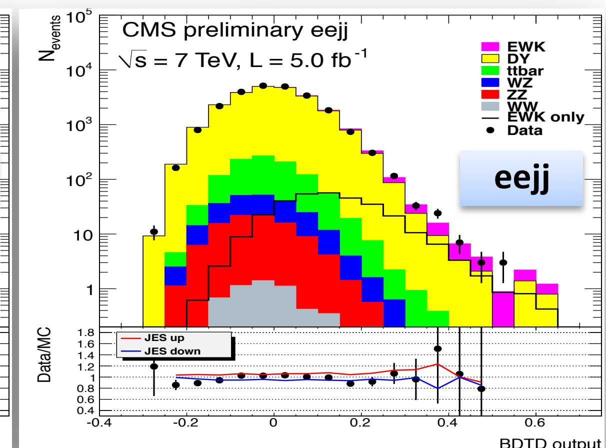
Bremsstrahlung



Large negative interference

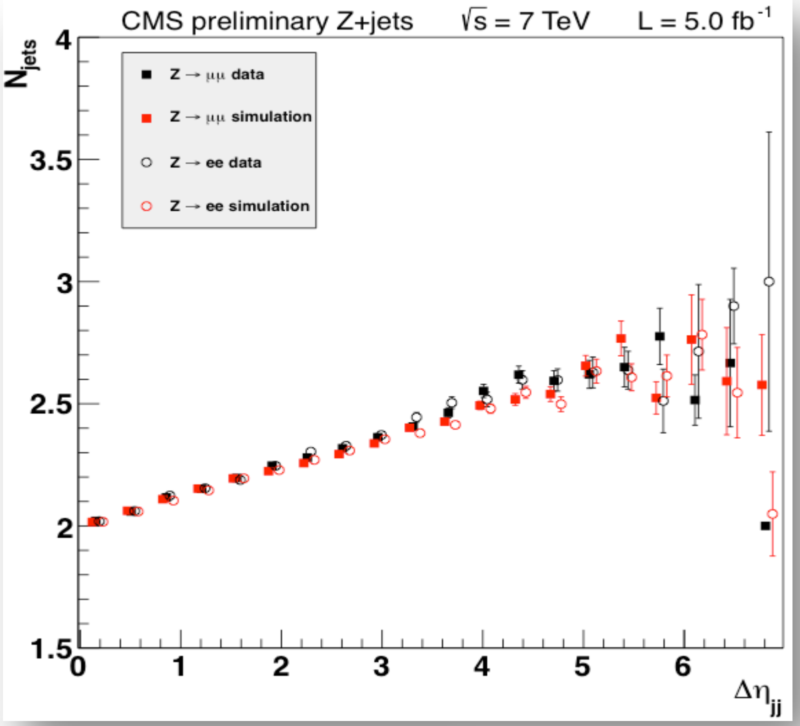
- Signal extraction
  - large rapidity gap between tag jets, BDT used to extract signal
    - $p_T(j1)>65$, $p_T(j2)>40$, $|\eta^j|<3.6$
    - $|y^*|=|y_Z-0.5(y_{j1}+y_{j2})|<1.2$
    - $M_{jj} > 600$
  - Measured σ using μμ+ee:
  - 154±24±46(sys)±27(th)±3(lum) fb
  - Theoretical:
    - 166 fb (NLO)
    - 157 fb (LO)





Forward Physics: VBF Z-production (2)

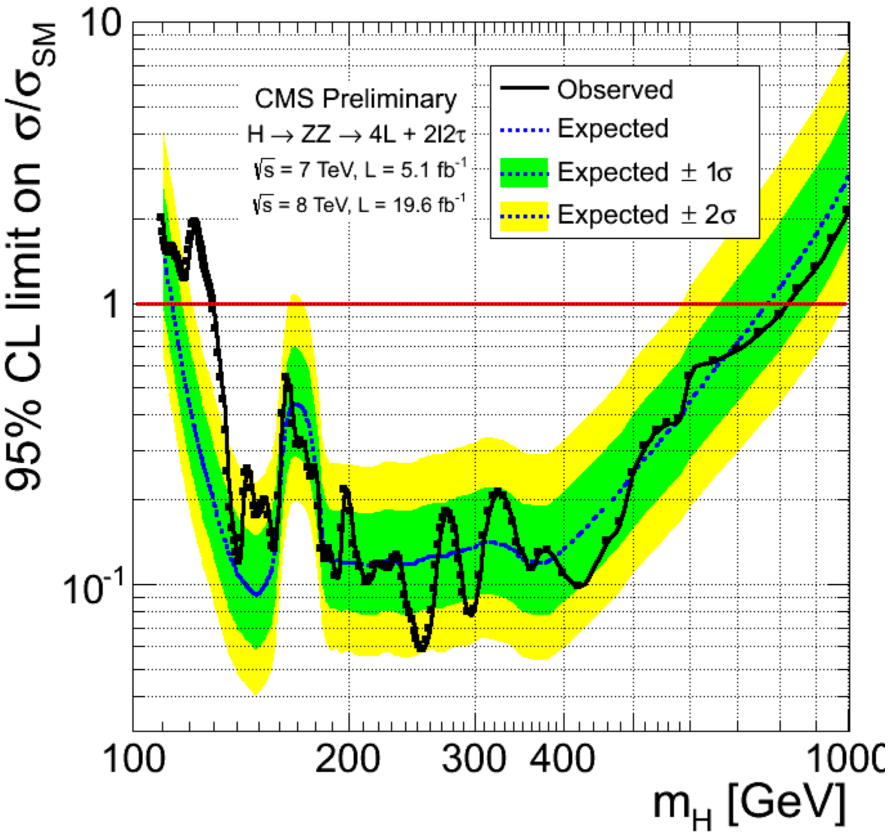
- VBF selection criteria
  - MADGRAPH vs Data
    - Plot shows data-MC comparison for N_{jets} vs $|\Delta\eta_{jj}|$
    - Table: Efficiency of the central jet veto for various $|\Delta\eta_{jj}|$ cuts



data, simulation	$\lvert\Delta\eta_{j1j2}\rvert > 2.5$	$\lvert\Delta\eta_{j1j2}\rvert > 3.5$	$\lvert\Delta\eta_{j1j2}\rvert > 4.5$
data	0.56±0.03	0.58±0.03	0.62±0.04
simulation	0.56	0.57	0.58

http://cds.cern.ch/record/1493475?ln=en

High Mass search



- H to ZZ to 4l up to 1 TeV
- Exclusion of M_H<800 GeV

Complex Pole Scheme used for the H lineshape (XS coherently calculated in CPS) and interference between Signal and ggZZ background (from LHC H XSWG)

Other channels are following:

H→ZZ→llqq, llvv

H→WW→lvlv

VBF H, H→WW→lvqq

Is it a SM Higgs Boson ?

- J^{PC} and couplings are consistent with the SM predictions
- Beside improving the measurements, we should look for new physics:
  - other H boson at higher mass ?
- Ultimately VV scattering: it will tell us if the object at 125 GeV is capable alone to restore unitarity

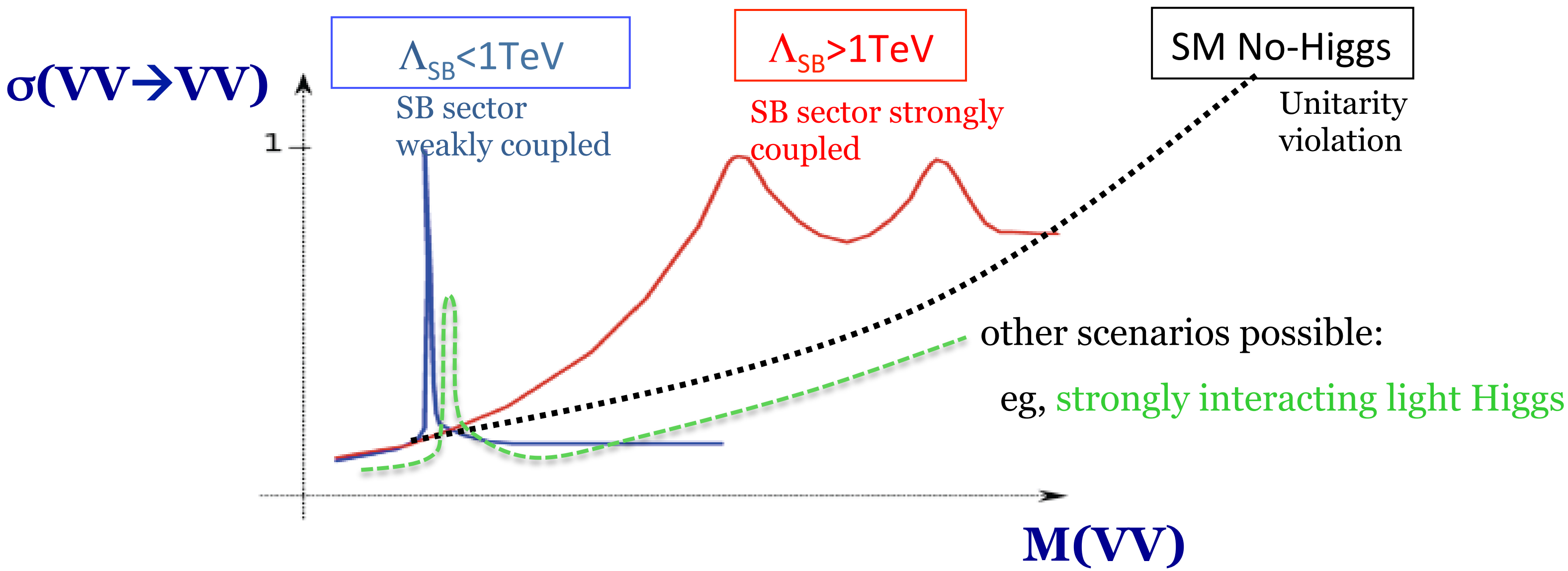
BSM H

- More models will be studied following the prescriptions of the LHC H XS WG:
  - Additional EW singlet
  - 2HDM
  - MSSM

Interference and width of the resonance will be varied accordingly.

VV scattering as a probe of EWSB

The identity of the Higgs comes from **its role in EWSB: unitarisation of $V_L V_L \rightarrow V_L V_L$**



More the 125 boson will be constrained to be similar to SM
→ more the XS of the second heavy resonance will be suppressed
→ more the VV strong interaction scale will move to high energy