[towards a] Full Combination

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Disclaimer: in these slides, the merit of any correct results goes to the experimental collaborations, while the responsibility of any wrong statement is just mine.

Un-outline

What I won't describe in this talk:

- Results of an official LHC(+Tevatron?) combination: it doesn't exist yet, and won't come before this LHC shutdown.
- Results of the global fits done within the phenomenology community:
  topic of this afternoon's session.

So, what's left?

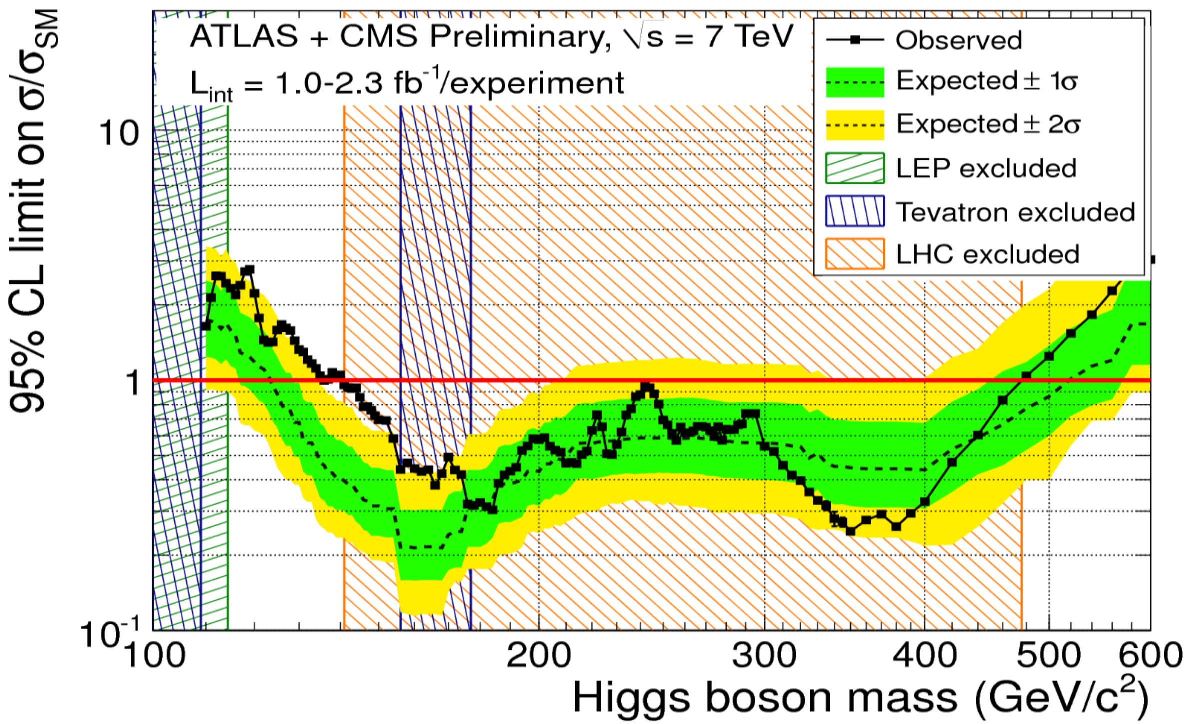
Outline

An experimentalists prespective on how LHC (and Tevatron) results compare and combine.

- What we can learn from past combinations in view of the future ones.
- Similarities, differences and common issues in a few of the key searches: $\gamma\gamma$, ZZ, bb
- Mass measurements and energy scales

Learning from the past

- Back in fall 2011, ATLAS and CMS have combined their summer data to compute exclusion limits on SM Higgs.



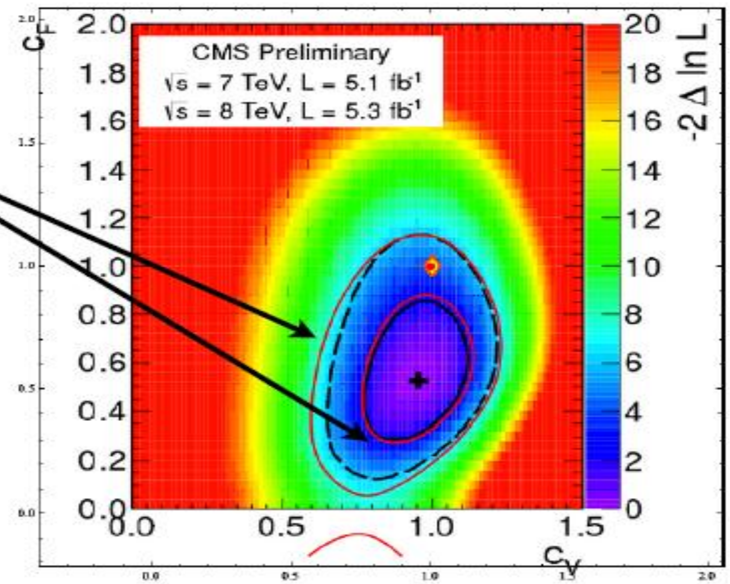
Learning from the past: tools

- Back in fall 2011, ATLAS and CMS have combined their summer data to compute exclusion limits on SM Higgs.
- Combination done using the full likelihood function: tracking individual signal and backgrounds, systematics and correlations.
- From the technical point of view, there should be no obstacles to doing it for any kind of measurement extracted from the likelihood (not just limits and p-values)

Combining the full likelihoods

- Do we really care, given how well the a-posteriori combinations of results reproduce the ones computed from the full likelihood?

Our contours



[C. Grojean, LHC2TPS workshop, https://indico.cern.ch/event/173388]

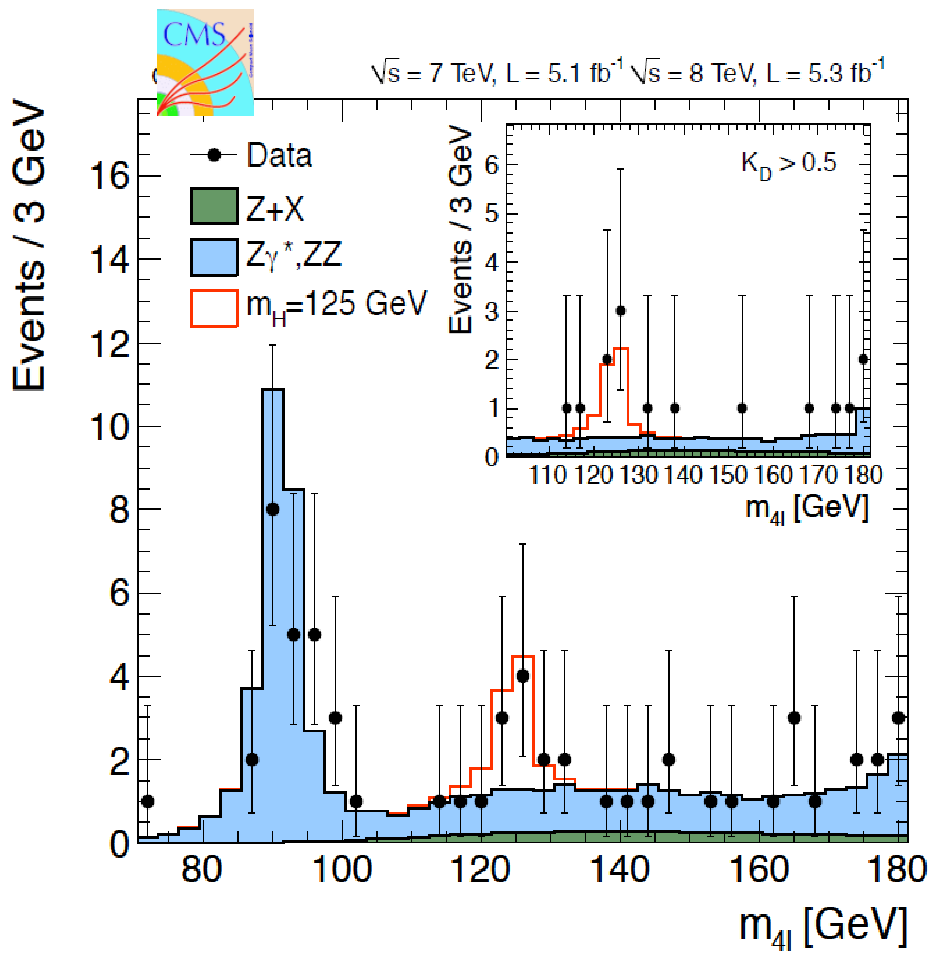
Combining the full likelihoods

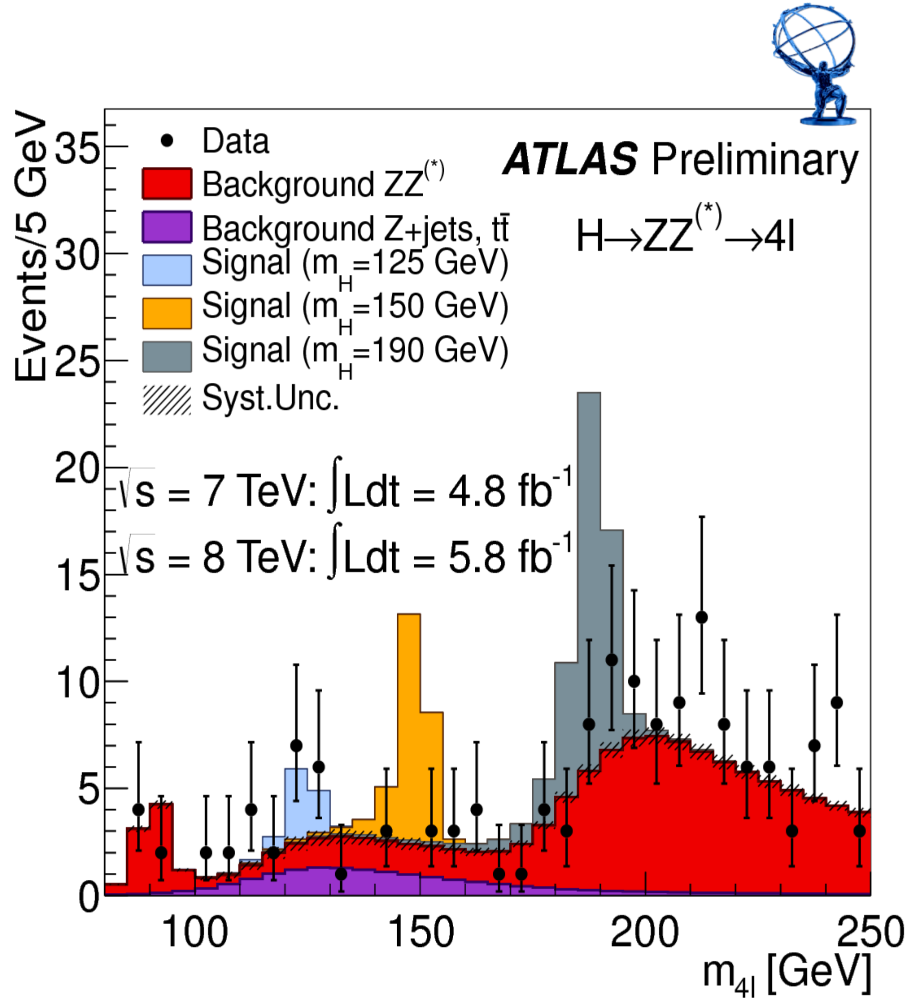
- Do we really care, given how well the a-posteriori combinations of results reproduce the ones computed from the full likelihood?
- Uncorrelated, statistical uncertainties will decrease with time, and the importance of systematics and correlations will increase.
- E.g. the current best fit σ/σ_{SM} from ATLAS, CMS have already uncertainties of ~25%, comparable with the correlated uncertainty on the gluon fusion production cross section!
- Handling of theoretical uncertainties in the measurements also to be discussed.

Learning from the past

- For the HCP'11 combination, all ATLAS and CMS analyses were reviewed together to assess possible correlations of systematical uncertainties.
- Pragmatic approach used:
  - In nominal result, correlate only what seems more likely to be correlated.
  - Assess separately how results change if things that might be correlated are considered correlated or uncorrelated.

$H \rightarrow ZZ \rightarrow 4l$





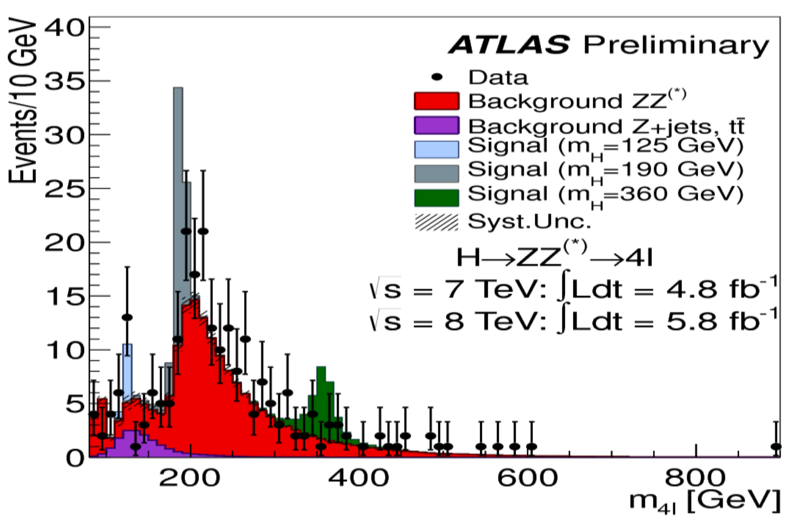
$H \rightarrow ZZ \rightarrow 4l$

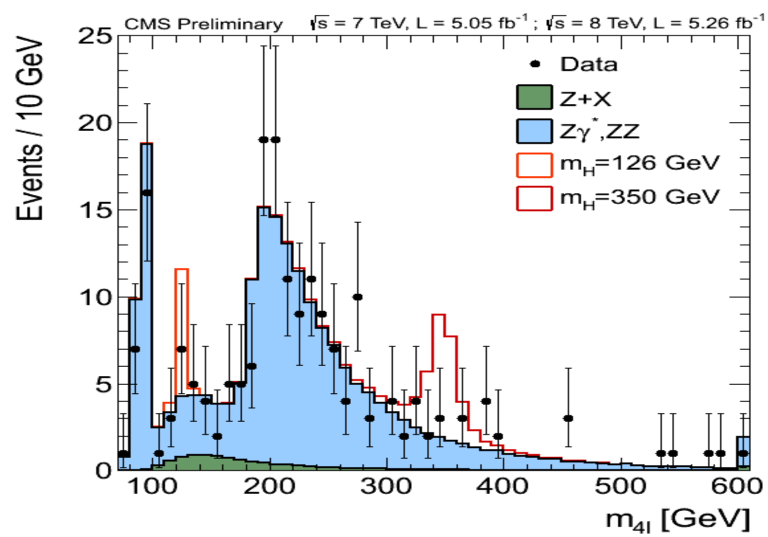
Significant differences here:

- CMS uses angular likelihood to discriminate against continuum ZZ.
- ATLAS applies a kinematic fit using a Z mass constraint to dilepton pairs compatible with being on-shell.
- CMS applies FSR recovery.
- ATLAS sees ~30% more ZZ events at high mass compared to the SM predictions. CMS sees only ~6%

H → ZZ → 4l: event yields

	Expected bkg. Low mass	Observed Low mass	Expected bkg. High mass	Observed High mass
ATLAS, 7 TeV	14.1	17	75.2	71
ATLAS, 8 TeV	20.0	22	89.5	120
ATLAS, 7+8	34.1	39	146.7	191
CMS, 7+8	19.9	21	142.5	150





$H \to ZZ \to 4l$: high mass yields

Yields for m(4l) >160	Expected background	Observed events
ATLAS, 7 TeV	75.2	71
ATLAS, 8 TeV	89.5	120
ATLAS, 7+8	146.7	191
CMS, 7+8	141.0	150

- Reducible background negligible at high mass.
- Theoretical uncertainty on $qq \to ZZ$ production is small, and $gg \to ZZ$ contribution should be small
- Most differences between ATLAS and CMS analysis don't matter here (e.g. angular discrim.)
- However, the discrepancy is not that significant: **191/146.7 − 150/142.5 = 0.24 ± 0.14 (stat. only)**

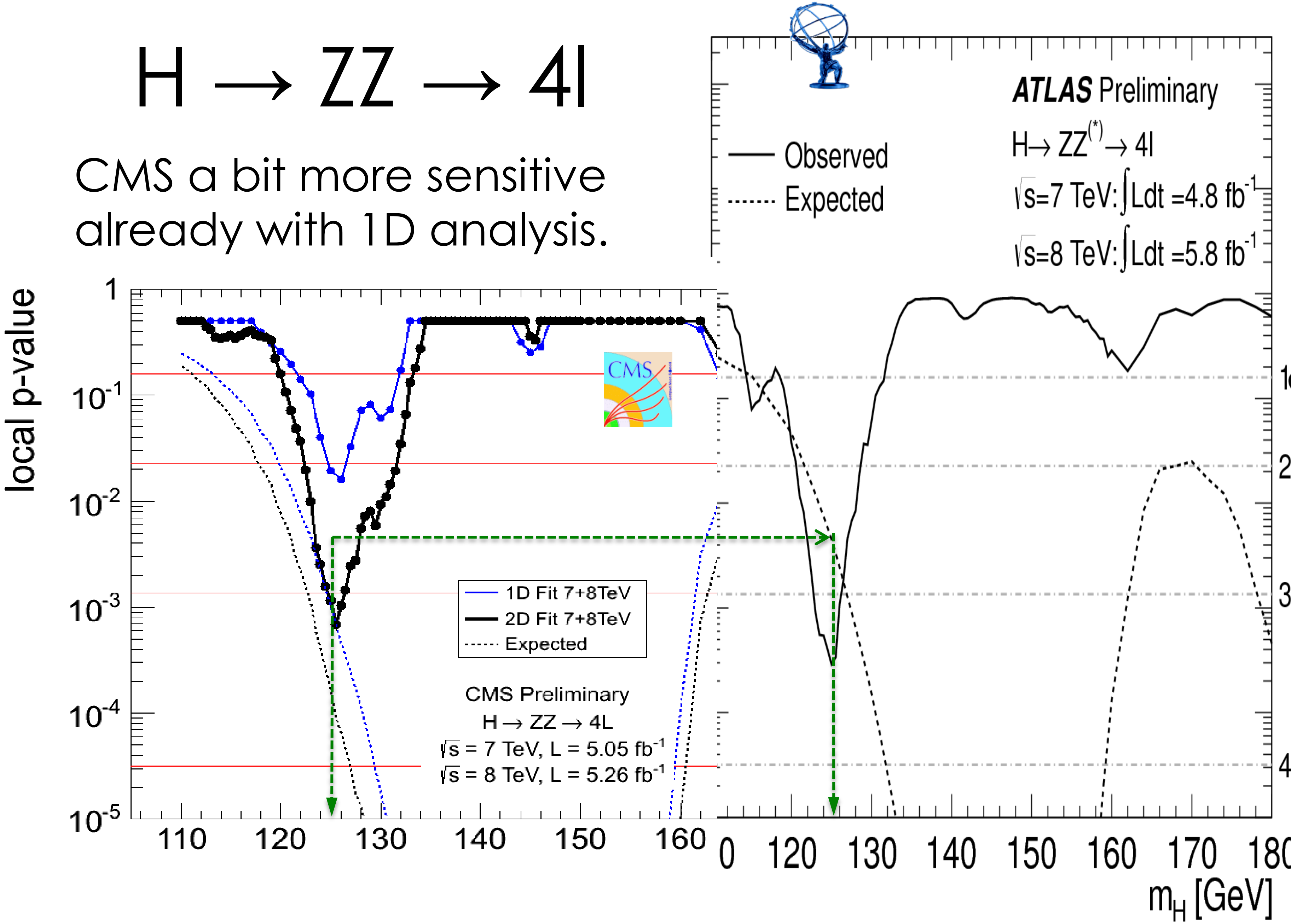
$H \rightarrow ZZ \rightarrow 4l$: low mass yields

Yields for m(4l) < 160	Expected background	Observed Events	Exp. signal (1xSM, 125 GeV)
ATLAS, 7 TeV	14.1	17	2.4
ATLAS, 8 TeV	20.0	22	3.9
ATLAS, 7+8	34.1	39	6.3
CMS, 7+8	19.9	21	7.6

- Yield depends strongly on kinematic cuts on lepton p_T's and dilepton masses
- Beware also different mass ranges: CMS 110-160, ATLAS <160 (no explicit lower cut)
- Note: the 8.3 in the CMS PAS is for 126 GeV. The $\sigma \times BR(H \rightarrow 4l)$ changes very quickly with M_H!

$H \to ZZ \to 4l$

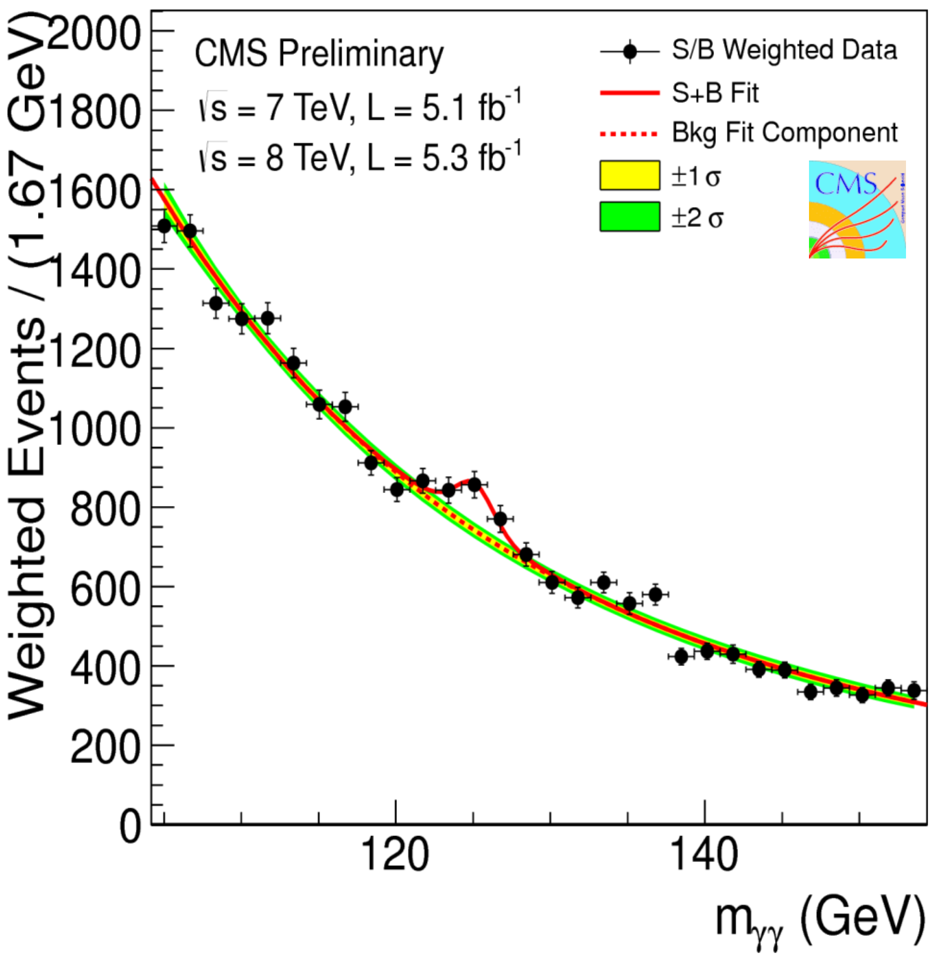
CMS a bit more sensitive already with 1D analysis.



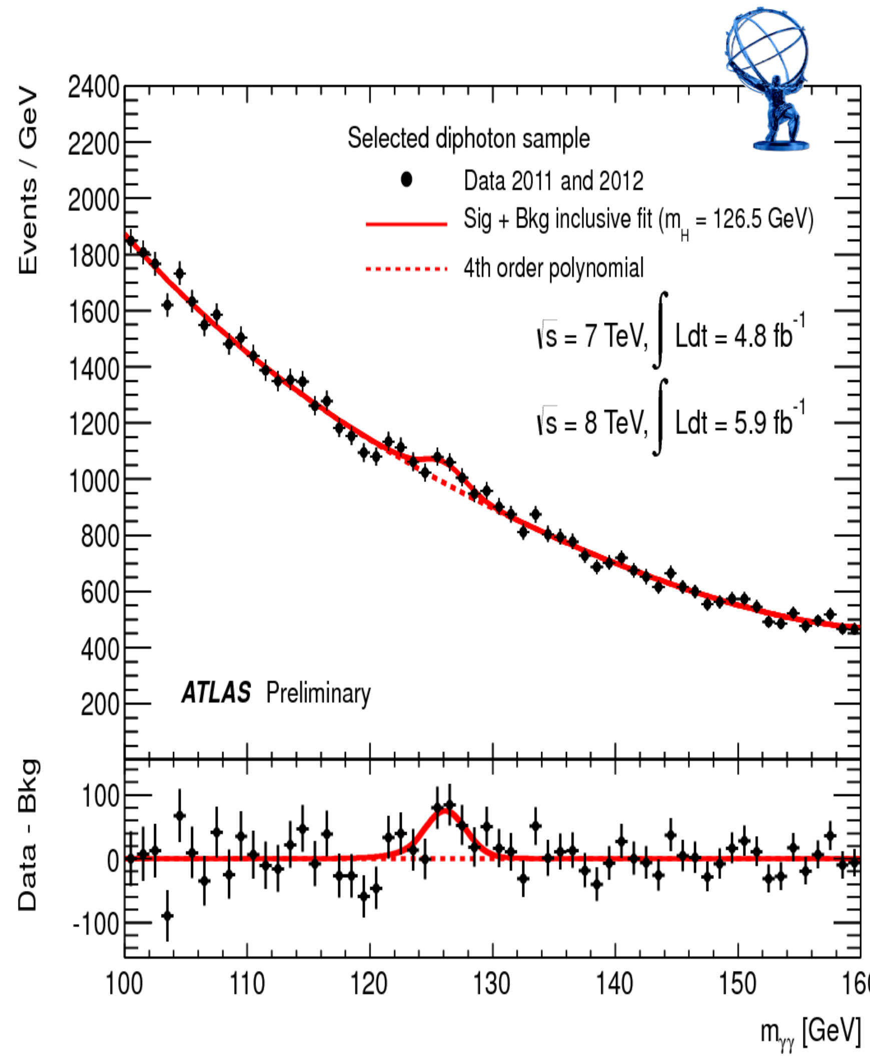
$H \rightarrow ZZ \rightarrow 4l$

- The 4l analysis, driven by statistical uncertainties, would obviously benefit from a combination of the results.
- Background estimates have however a fairly high degree of correlation:
  - ZZ / Zγ* is theory-driven
  - Extrapolations used to estimate reducible background can have common issues (e.g. flavour composition of fake leptons)
- Actual impact of these might however still be small even with $2 \times 30\ \mathrm{fb}^{-1}$

H → γγ



CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
CMS
Weighted Events / (1.67 GeV)
$m_{\gamma\gamma}$ (GeV)



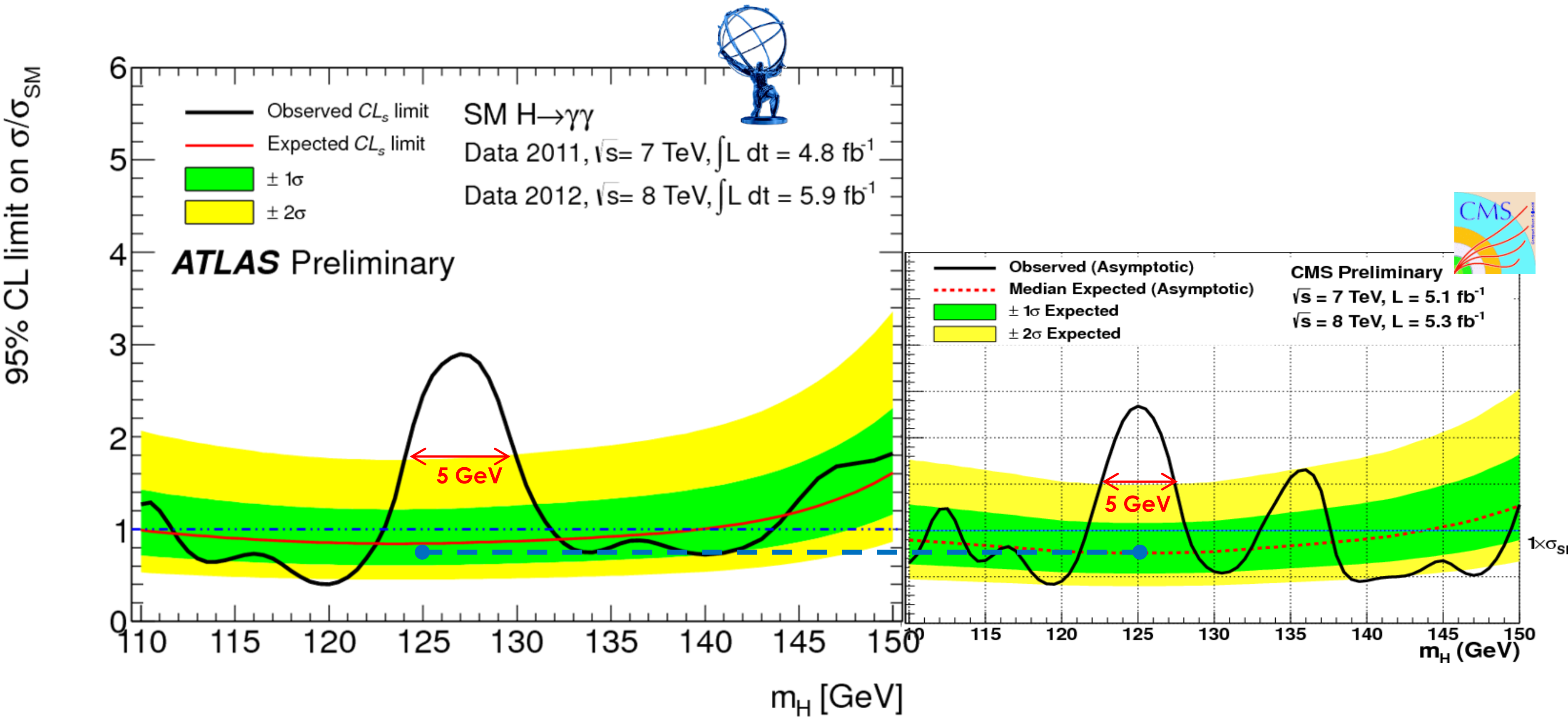
Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb⁻¹
√s = 8 TeV, ∫ Ldt = 5.9 fb⁻¹
ATLAS Preliminary
Events / GeV
Data - Bkg
$m_{\gamma\gamma}$ [GeV]

$H \to \gamma\gamma$

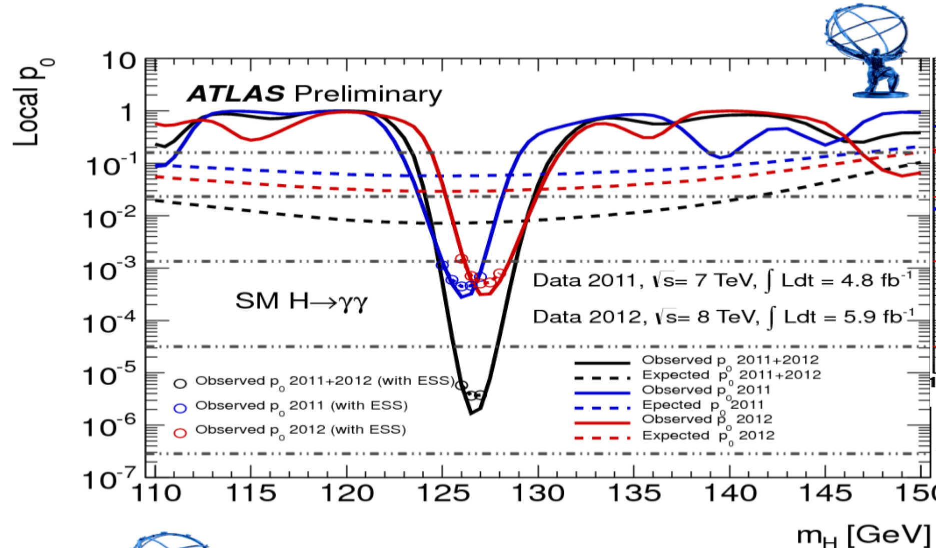
- High level analysis very, very similar:
  - Categorization by S/B, resolution and p_T (ATLAS using cuts, CMS using a BDT)
  - Similar di-jet categories with O(70%) purity
  - Mass fit with polynomial background chosen minimizing the bias on the signal
- Different basic building blocks (photon reconstruction, isolation, vertexing)

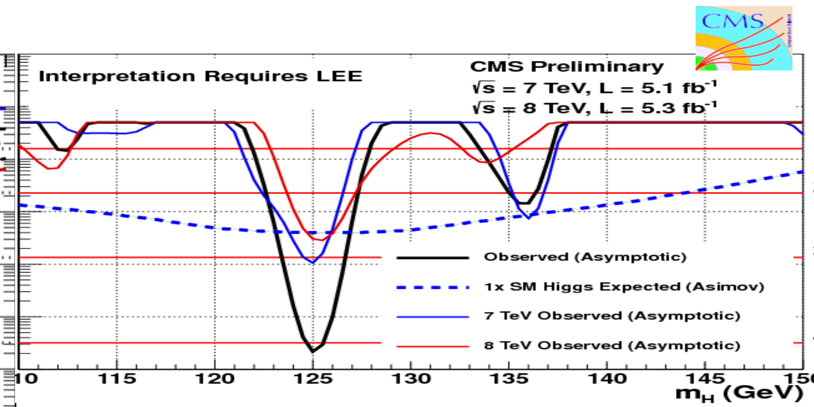
$H \to \gamma\gamma$

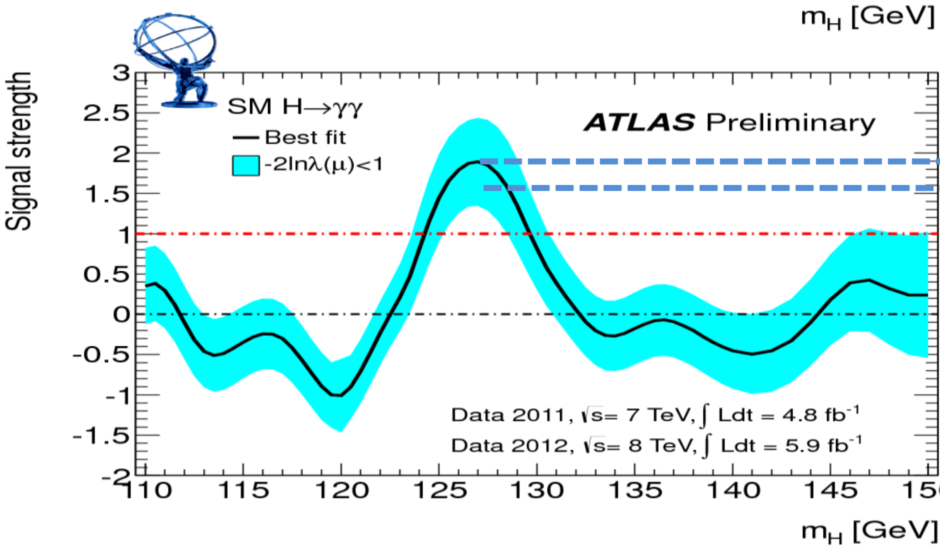
Similar sensitivity, and similar mass resolution.

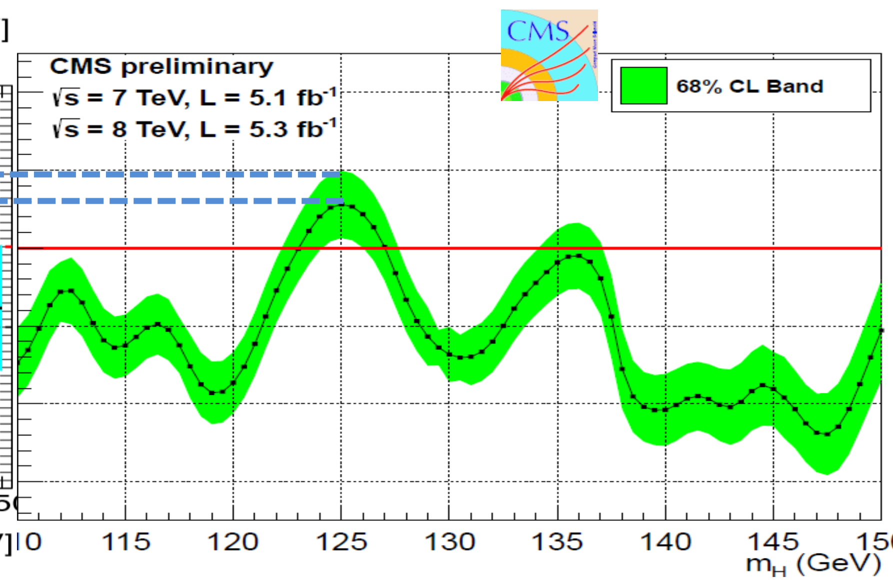


$H \rightarrow \gamma\gamma$









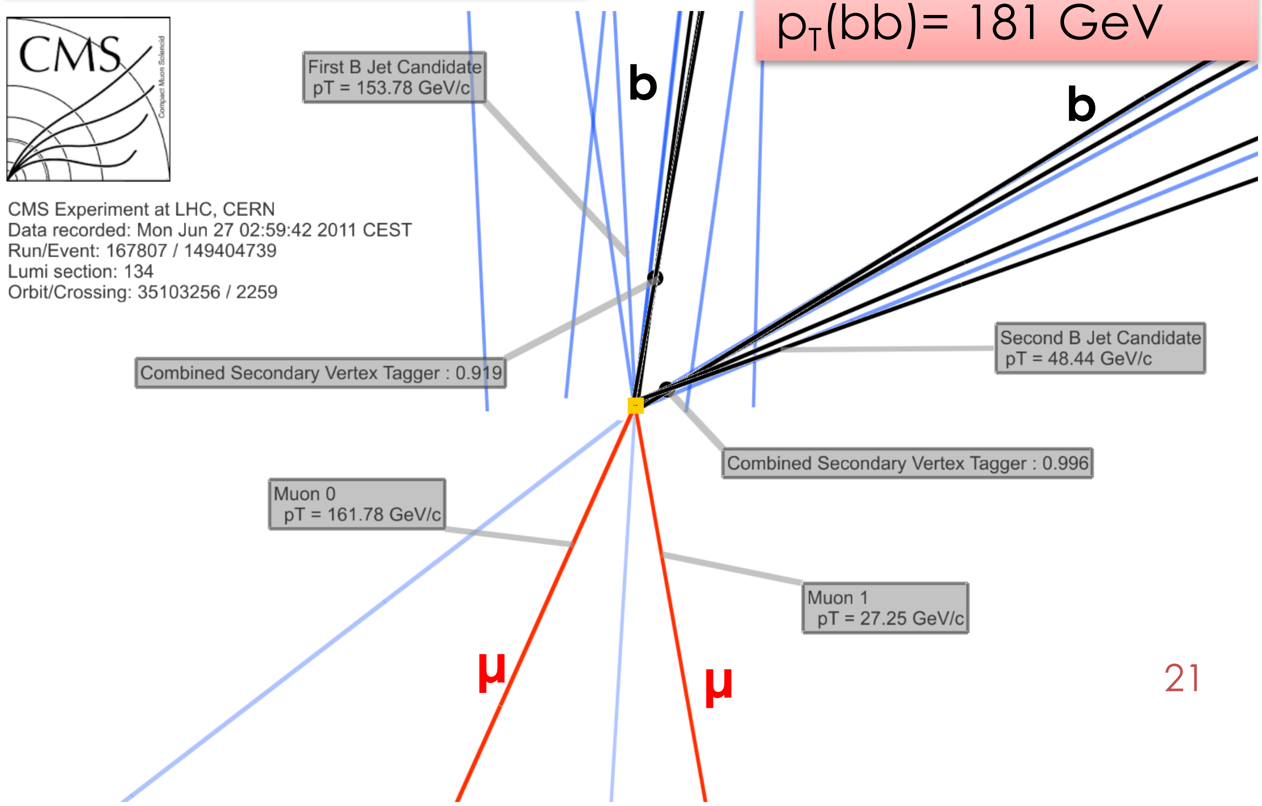
$H \rightarrow \gamma\gamma$ issues for combination

- Large theoretical uncertainties on signal composition (especially in di-jet category)
- Possible biases on signal strength fit:
  - from the choice of the background pdf: potentially the same for ATLAS & CMS?
  - from using the mass giving largest excess: decreases with increasing sensitivity, so it is reduced when combining the two.
- Energy scale calibration (more on this later)

V+H, H → bb

ZH->μμbb candidate

M_{bb} = 128 GeV
$p_T(bb)$ = 181 GeV



V+H, H $\rightarrow$ bb

- Search performed both at Tevatron and at LHC (with boosted W/Z bosons)
- Systematical uncertainties play a major role in this analysis, challenging the scaling of the sensitivity with the integrated luminosity
- However:
  - Many systematics are of experimental origin: they improve combining e.g. ATLAS with CMS.
  - Theoretical uncertainties from boost could also be reduced combining with Tevatron
  - Accuracy of background cross sections (e.g. single top) will increase with luminosity, and can potentially also benefit from combinations (esp. at LHC)
  - Analyses get better with time (has always been so)

V+H, H → bb

- Example figures from CMS (ICHEP'12)

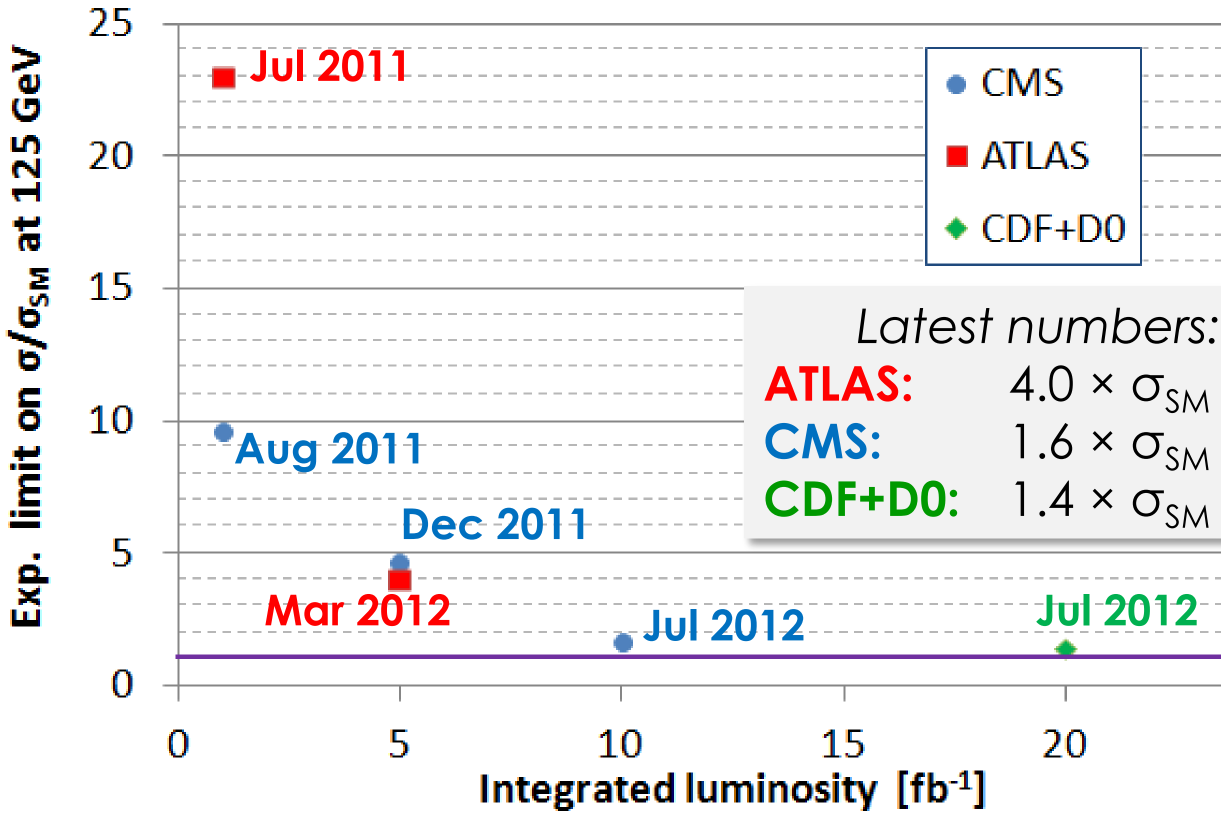
Source	Range
Luminosity	2.2-4.4%
Lepton efficiency and trigger (per lepton)	3%
Z($\nu\nu$)H triggers	2%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section (p_T boost, EWK/QCD)	5–10% / 10%
Signal Monte Carlo statistics	1-5%
Backgrounds (data estimate)	$\approx$ 10%
Diboson and single-top (simulation estimate)	30%

Experimental: uncorrelated with ATLAS

boost: uncorrelated with Tevatron?

background cross sections: improves with lumi & time.

the VH → bb race



Latest numbers:

ATLAS: $4.0 \times \sigma_{SM}$ (~5 fb^{-1})

CMS: $1.6 \times \sigma_{SM}$ (~5+5 fb^{-1})

CDF+D0: $1.4 \times \sigma_{SM}$ (~10+10 fb^{-1})

Mass measurement

"The" 1kg, sitting just ~20km away from this lab...

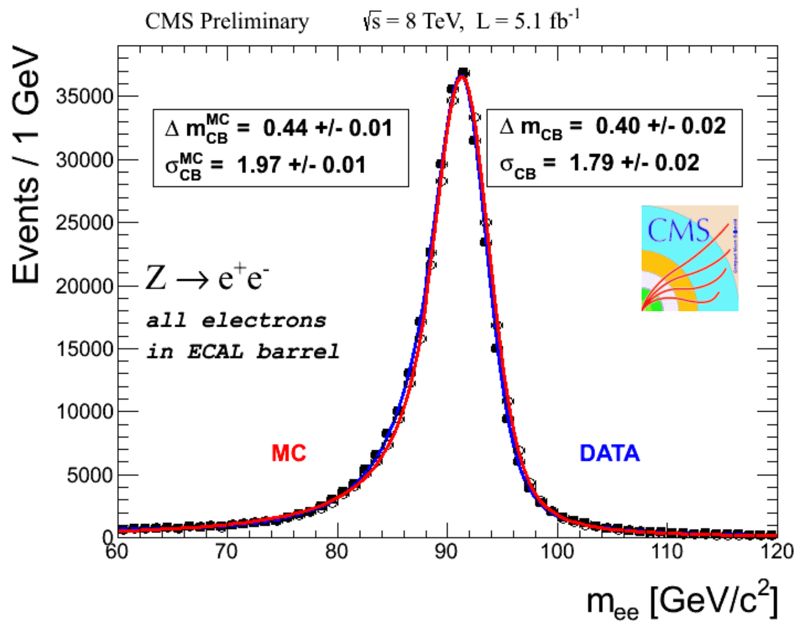
Mass measurements

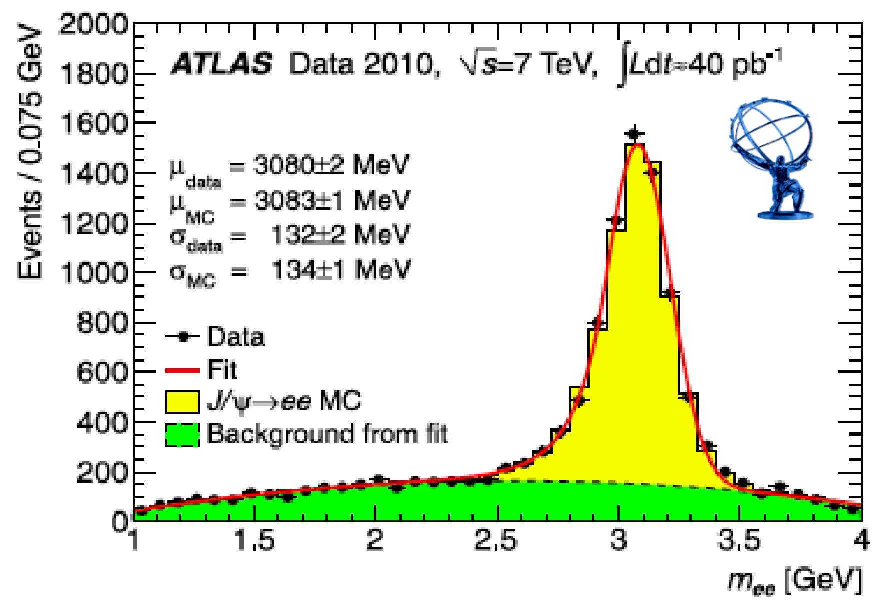
- Most basic property of the new state.
- Directly accessible experimentally in the diphoton and four-lepton modes.
- Well defined theoretically since the natural width is much narrower than the experimental resolution.
- Results from individual channels are the more straightforward to interpret.

note: this topic is quite new, and only little information is yet publicly available.

Mass from H→ ZZ → 4l

- Lepton energy scales from Z and J/Ψ.

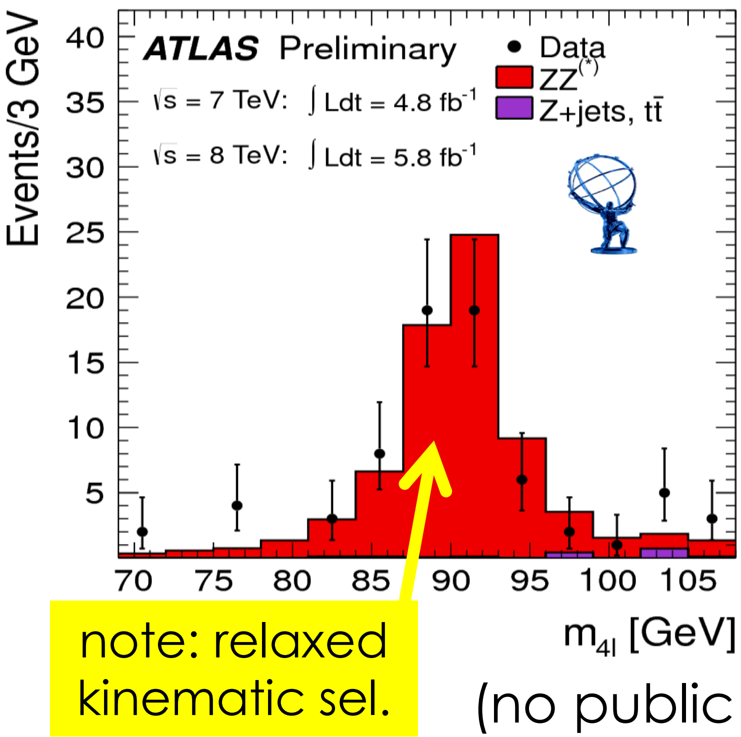


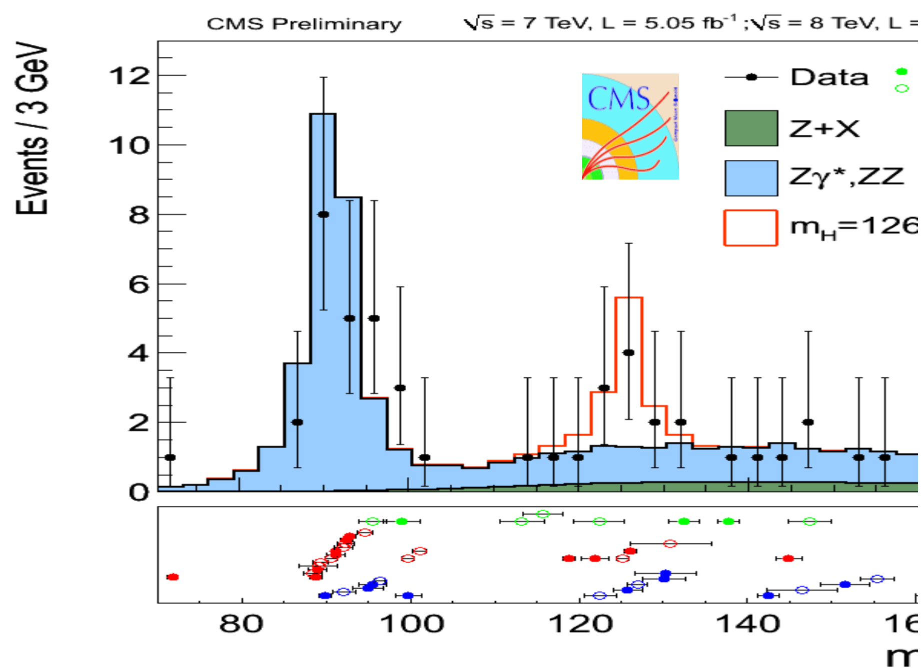


	Muons	Electrons
ATLAS	"negligible"	0.7% (4e), 0.4% (2e2μ)
CMS	0.4% (conservative)	~ 0.2%

Mass from H → ZZ → 4l

- Z → 4l provides a useful crosscheck of linearity since $M_Z/4 < M_H/4 < M_Z/2$



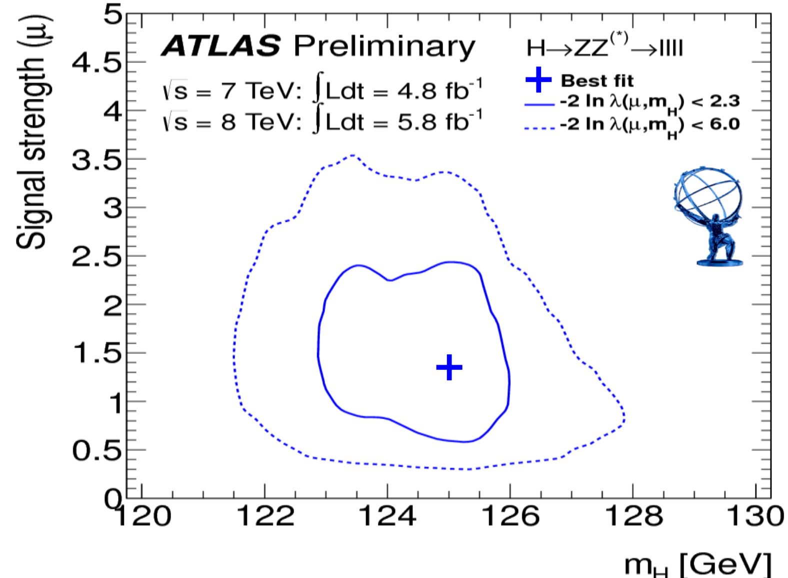


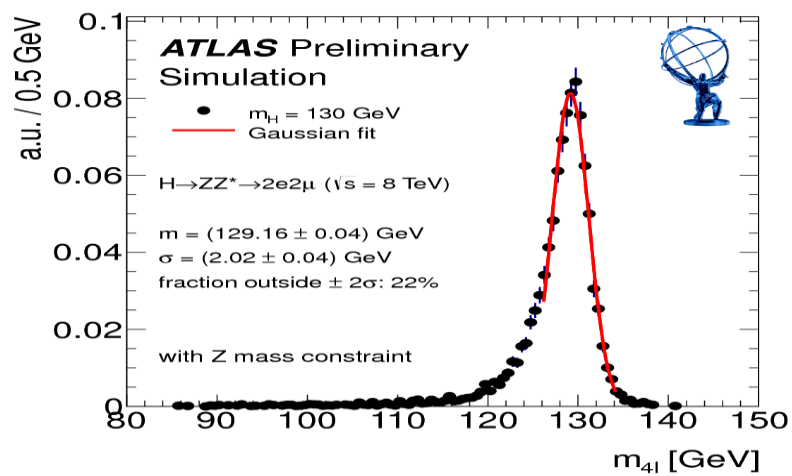
(no public quantitative comparison available yet)

$H \to ZZ \to 4l$ non-trivial issues

- Low event yields: individual events have big weight in the mass fit. Non-gaussian results

- Not all events in a given final state have the same mass resolution.
  Both ATLAS and CMS fits only account for this on average, not by event.



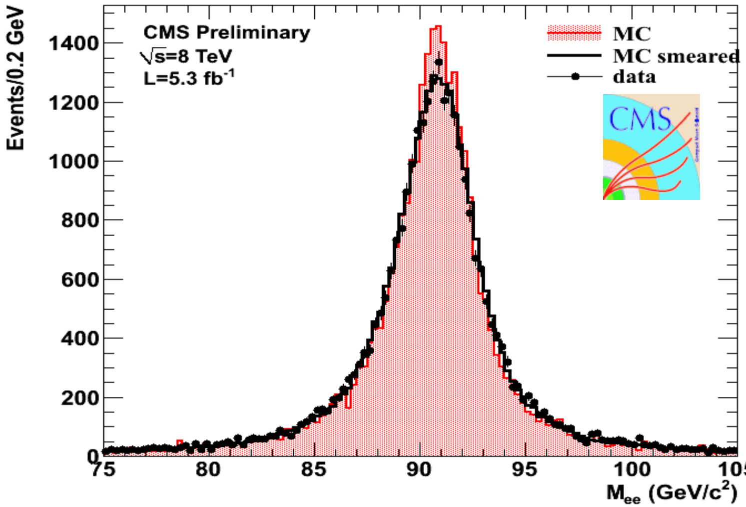


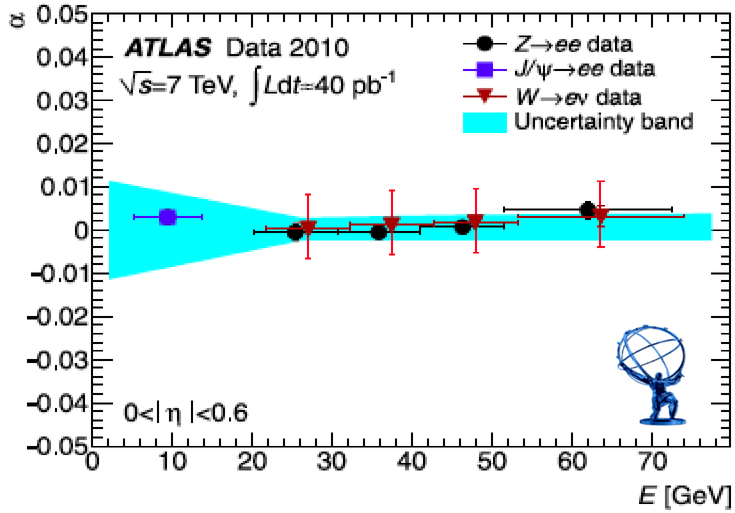
Mass from H → $\gamma\gamma$

- Compared to the 4l channel, the $\gamma\gamma$offers a much larger signal yield, and events categorized by resolution.
- The main sources of uncertainty are:
  - The statistical fluctuations of the large background below the signal peak
  - The systematics on the extrapolation from the Z→ee calibration candle to H→ $\gamma\gamma$ (electrons to photons, 91 to 126 GeV)

di-photon mass scale

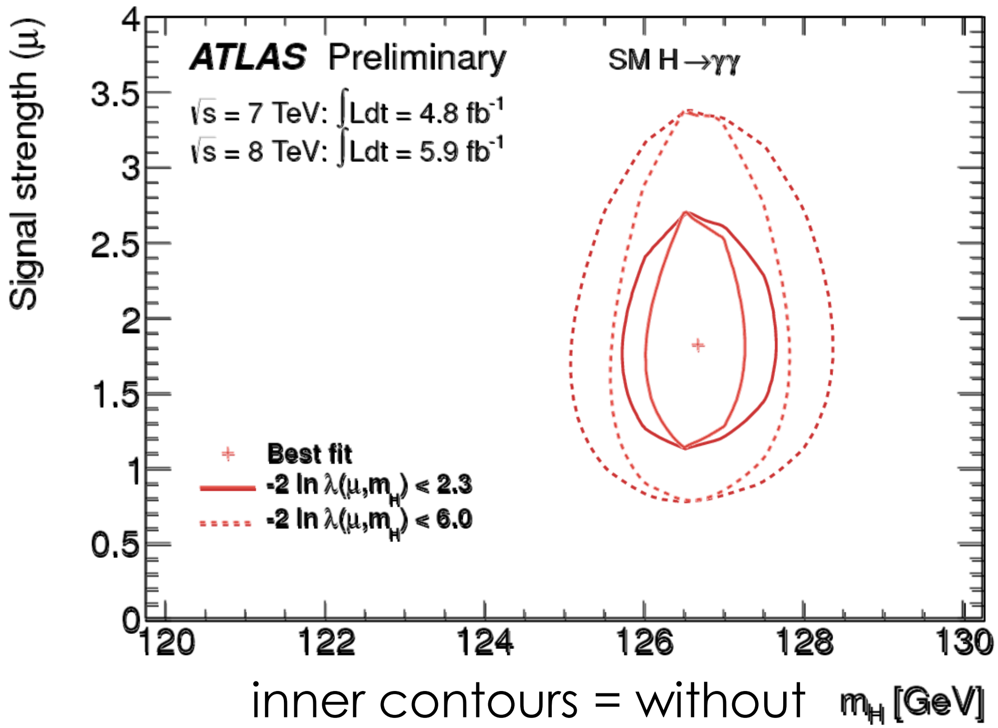
- With the current data, the statistical uncertainty on the Z→ee lineshape is tiny.
- Main uncertainties are:
  - Extrapolation from electrons to photons (~0.25% for CMS)
  - Extrapolation in energy from m_Z to m_H (~0.4% for CMS)
- Detector effects, no ATLAS-CMS correlation expected.
- Only overall scale matters, inter-category scales have small effect on the result.





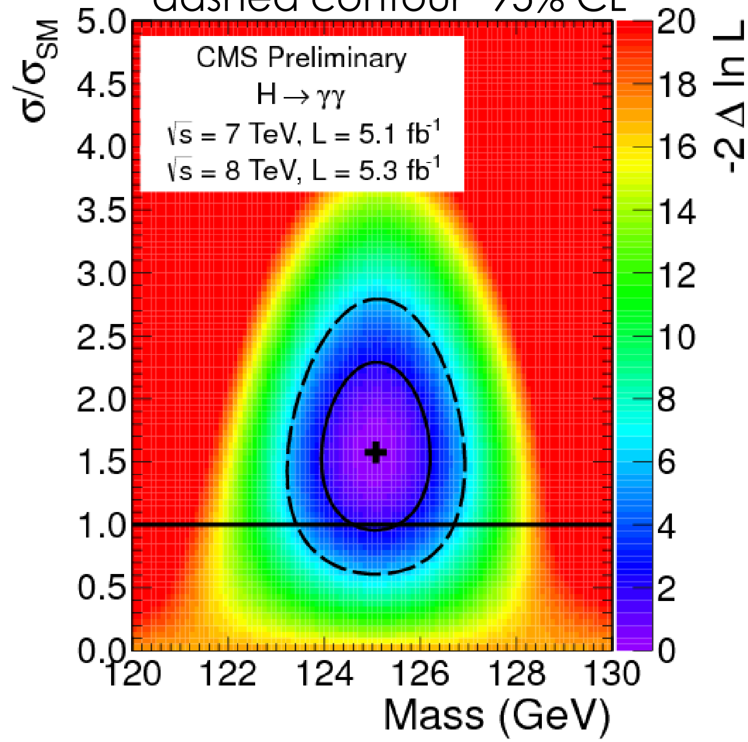
di-photon mass results

solid contours 68% CL dashed contours 95% CL



inner contours = without energy scale systematic

solid contour 68% CL
dashed contour 95% CL



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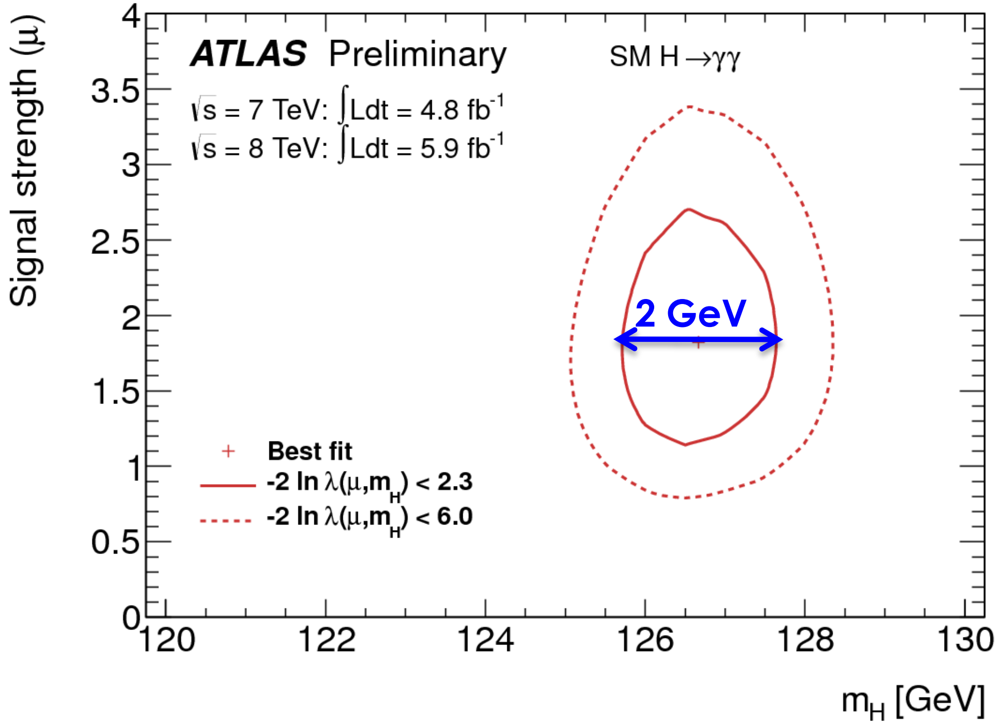

solid contour 68% CL
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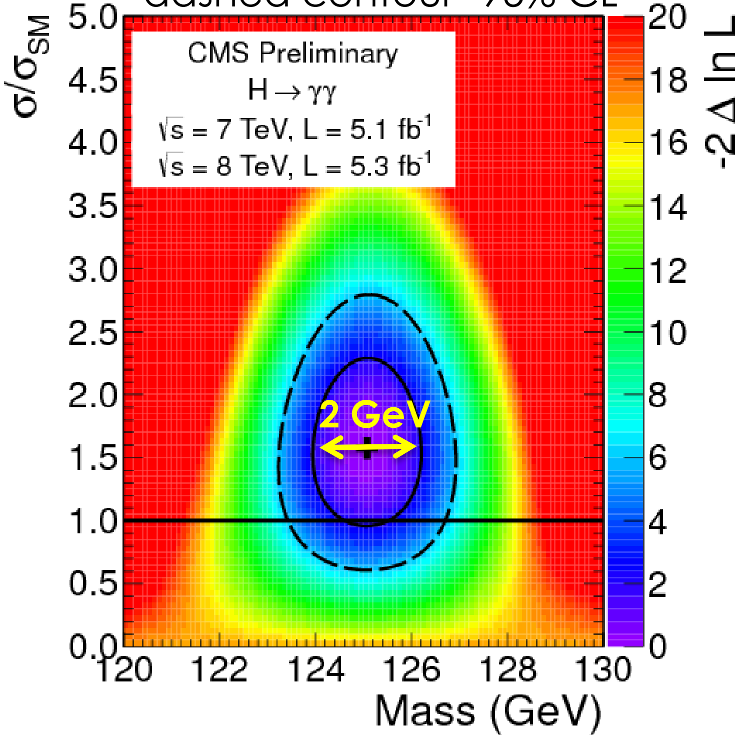
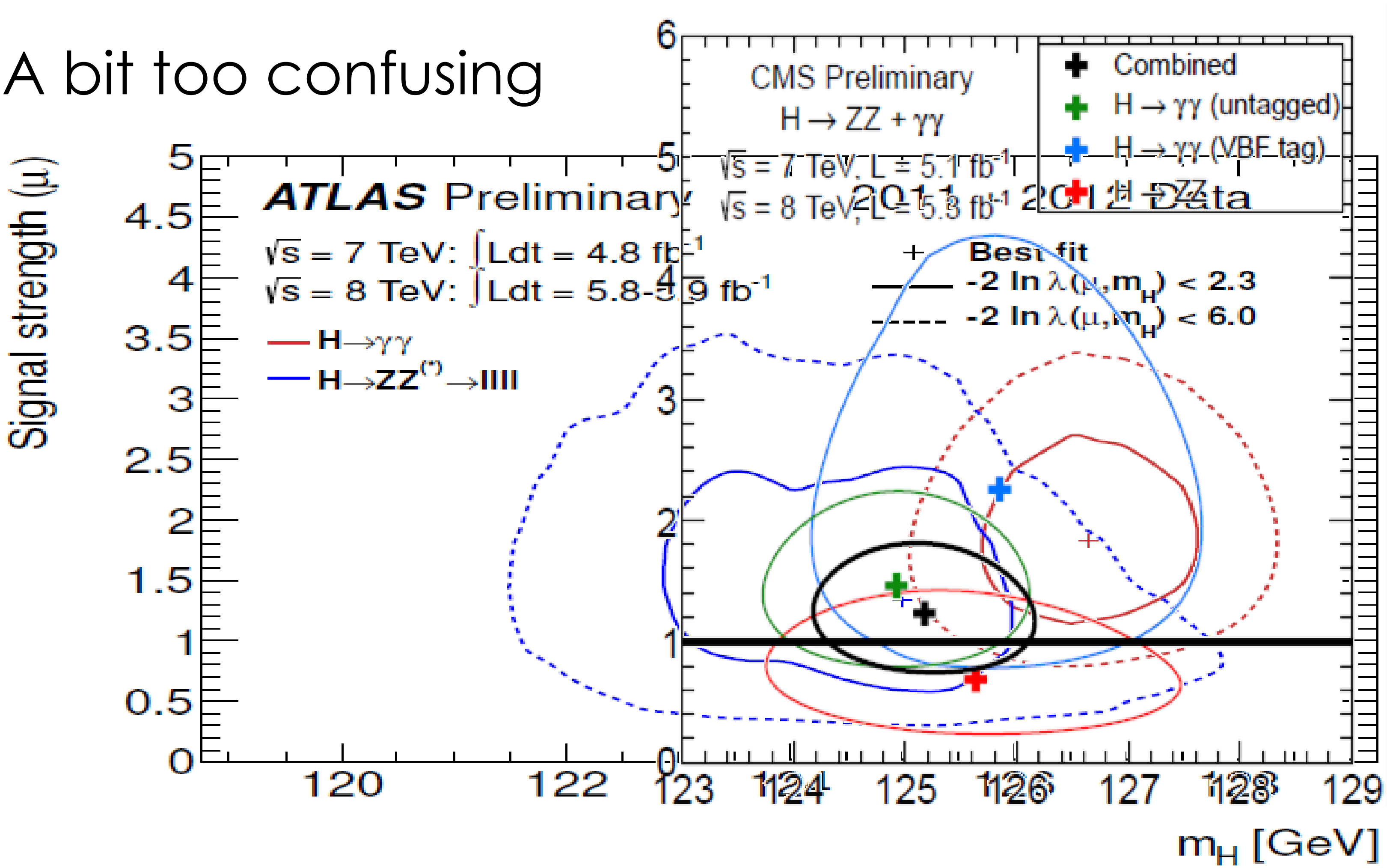


Comparable diphoton mass resolution between the two

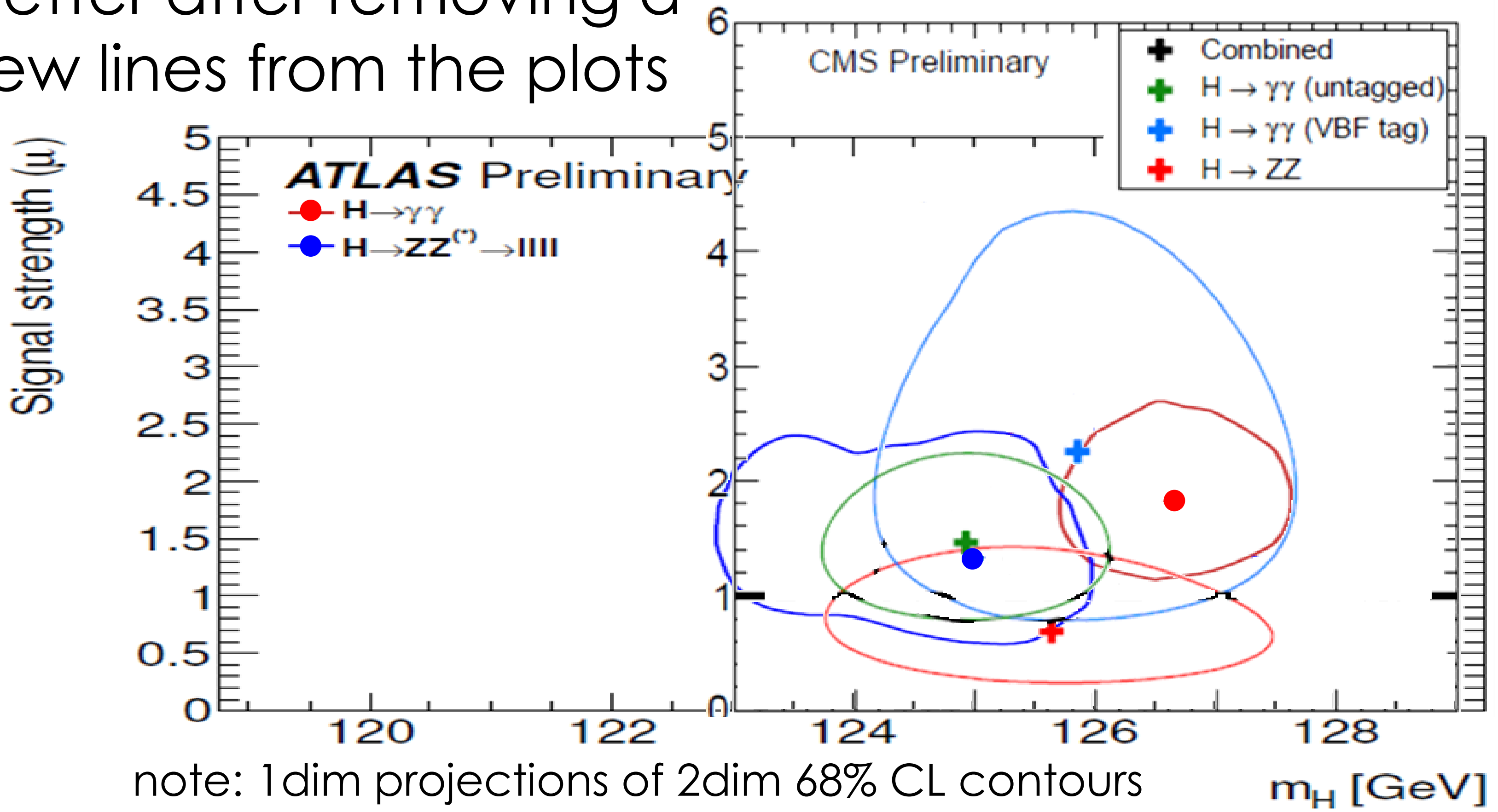
Mass: the big picture

A bit too confusing



Mass: slightly cleaner big picture

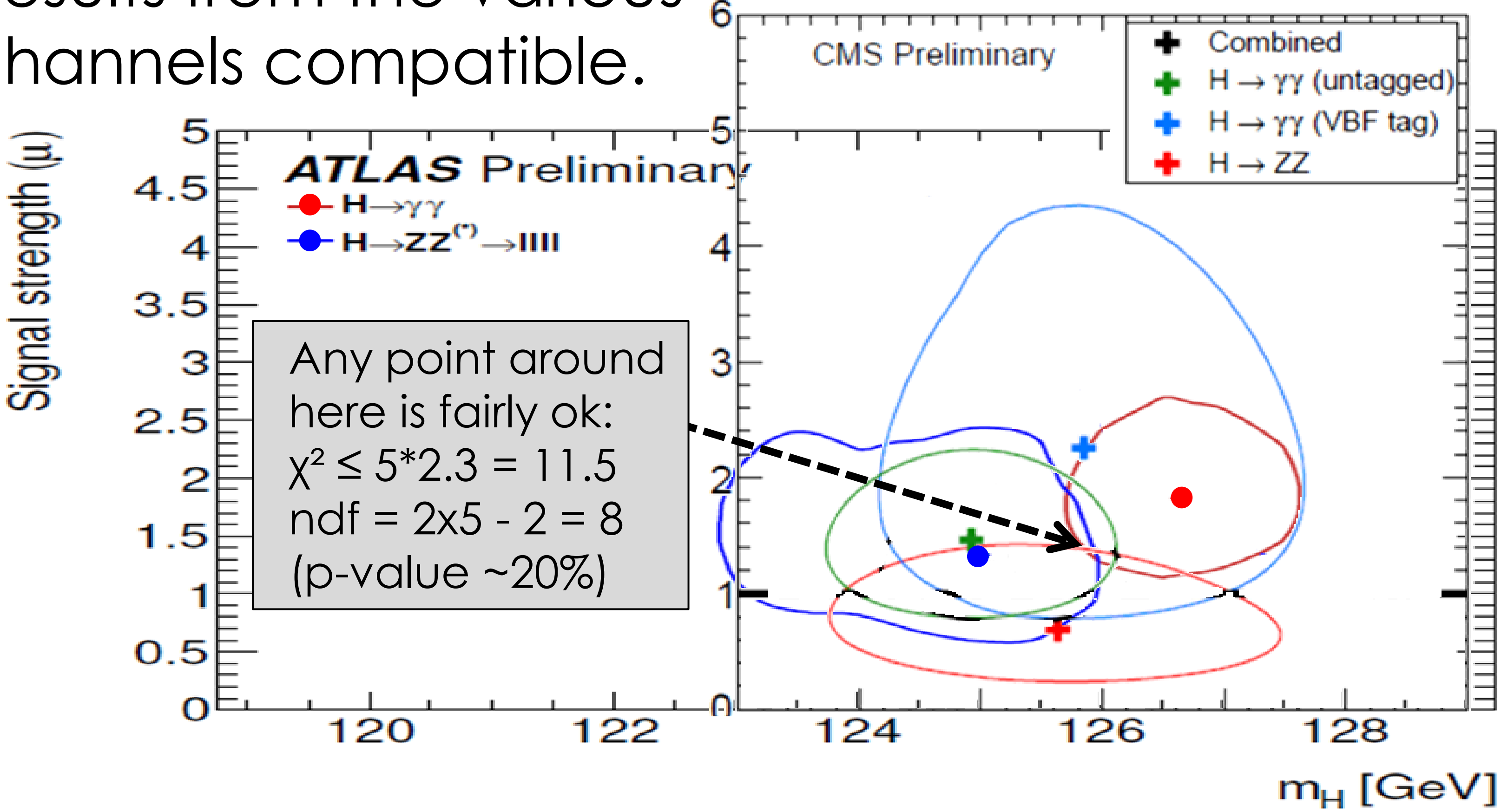
Better after removing a few lines from the plots



note: 1dim projections of 2dim 68% CL contours are not 1dim 68% CL intervals.

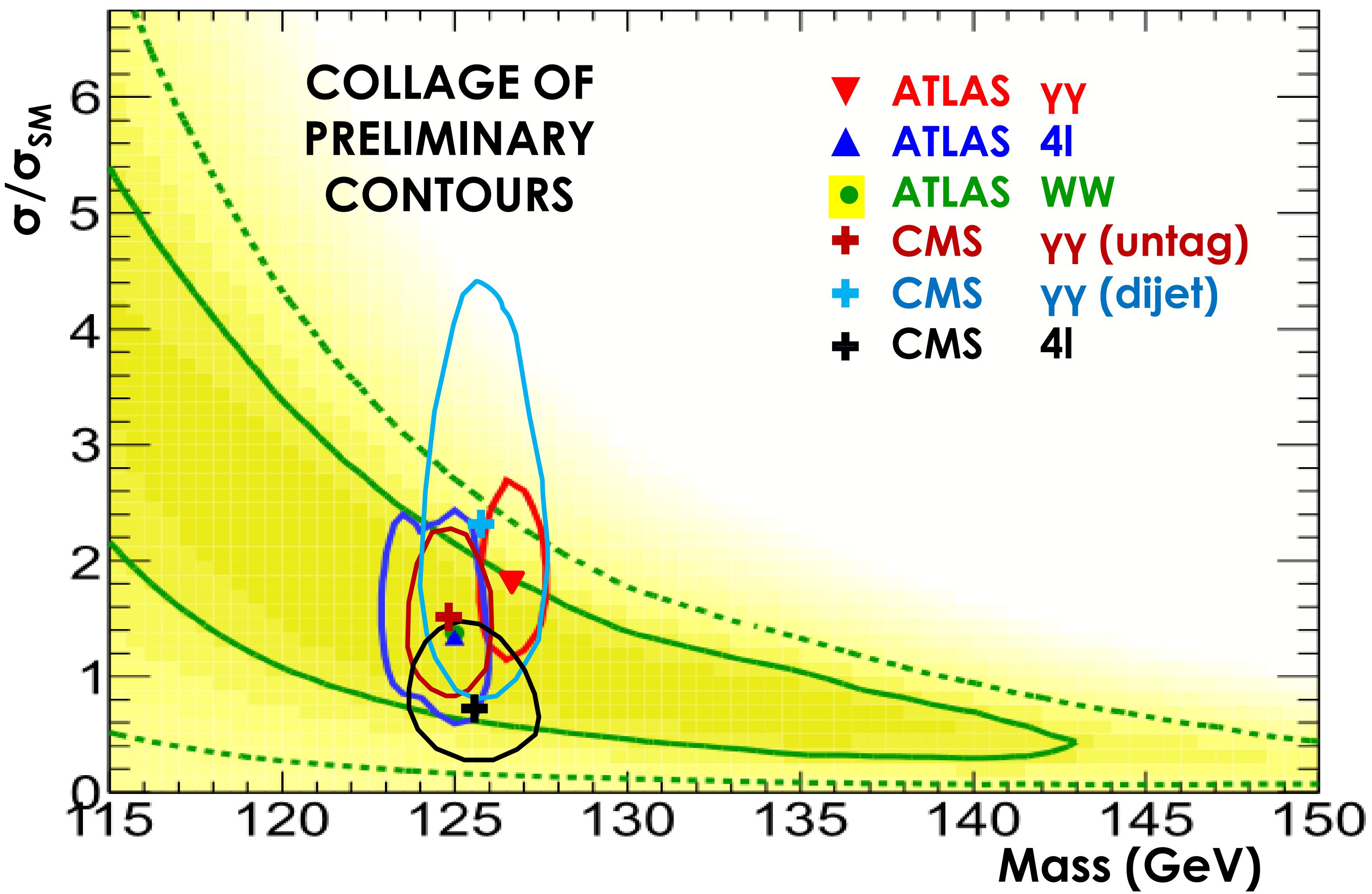
Mass: slightly cleaner big picture

Results from the various channels compatible.



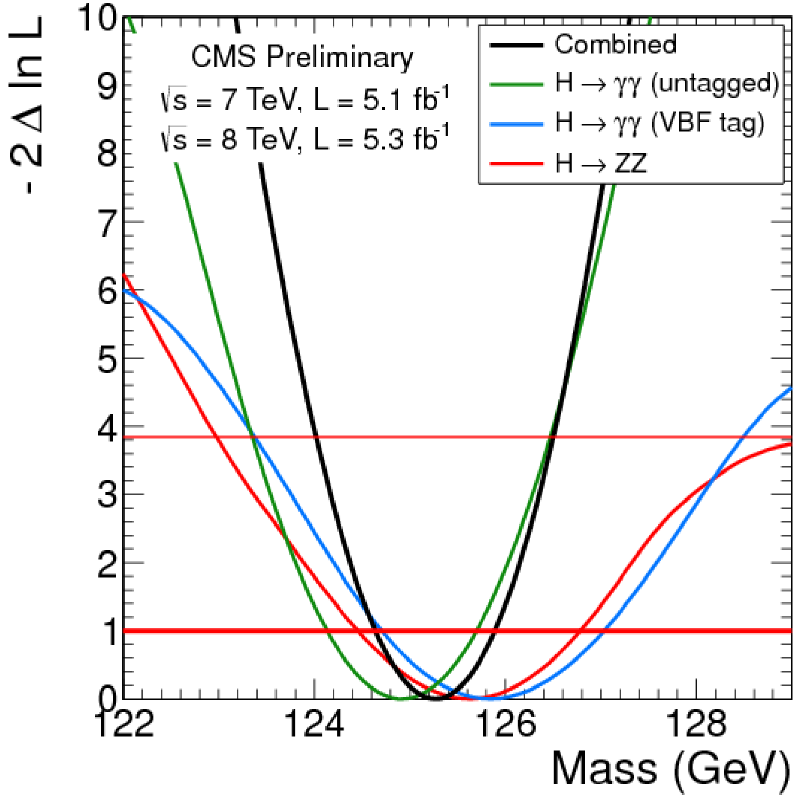
Any point around here is fairly ok:
$\chi^2 \leq 5*2.3 = 11.5$
ndf = 2x5 - 2 = 8
(p-value ~20%)

Adding new ATLAS H→WW



Combining mass measurements

- When combining multiple channels, result has some model dependency:
  - events with different S/B contribute have different weights in the fit
  - S/B depends on relative scale of cross sections and branching ratios.
- In CMS, a slightly less model dependent fit is done with freely floating signal strengths for ZZ, γγ untagged, γγ di-jet.



Combining mass measurements

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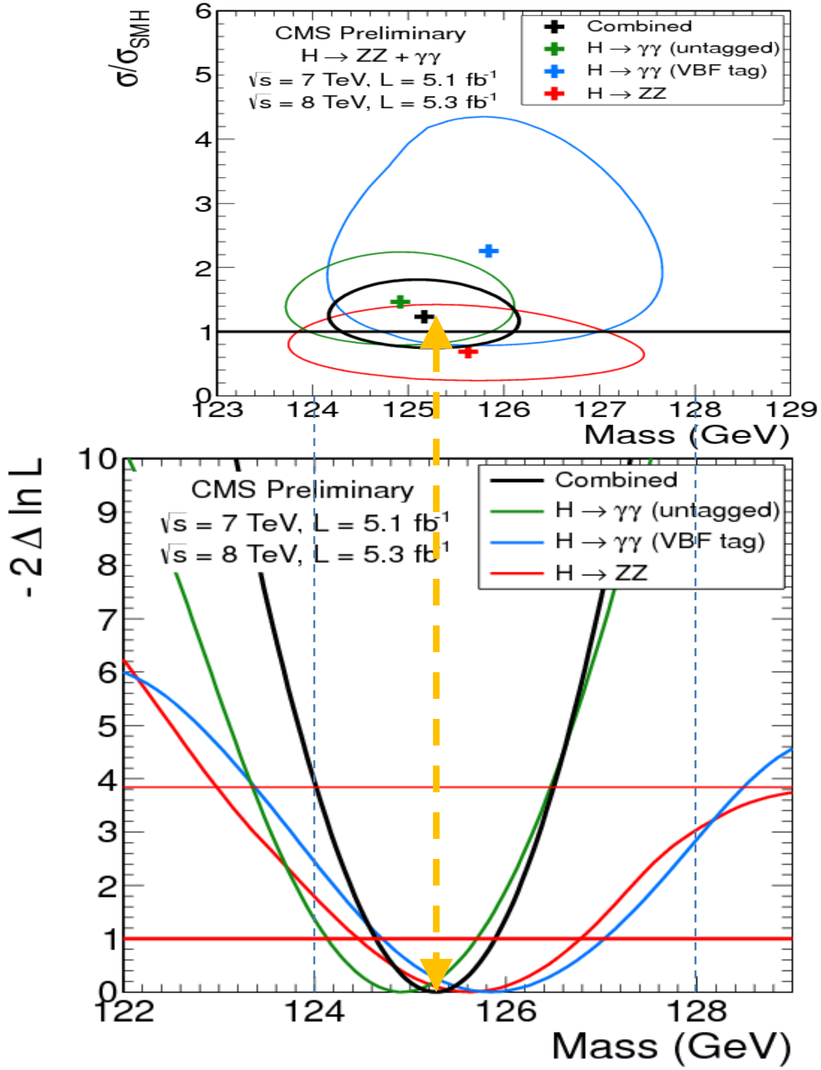
- Result not that different.



Combining mass measurements

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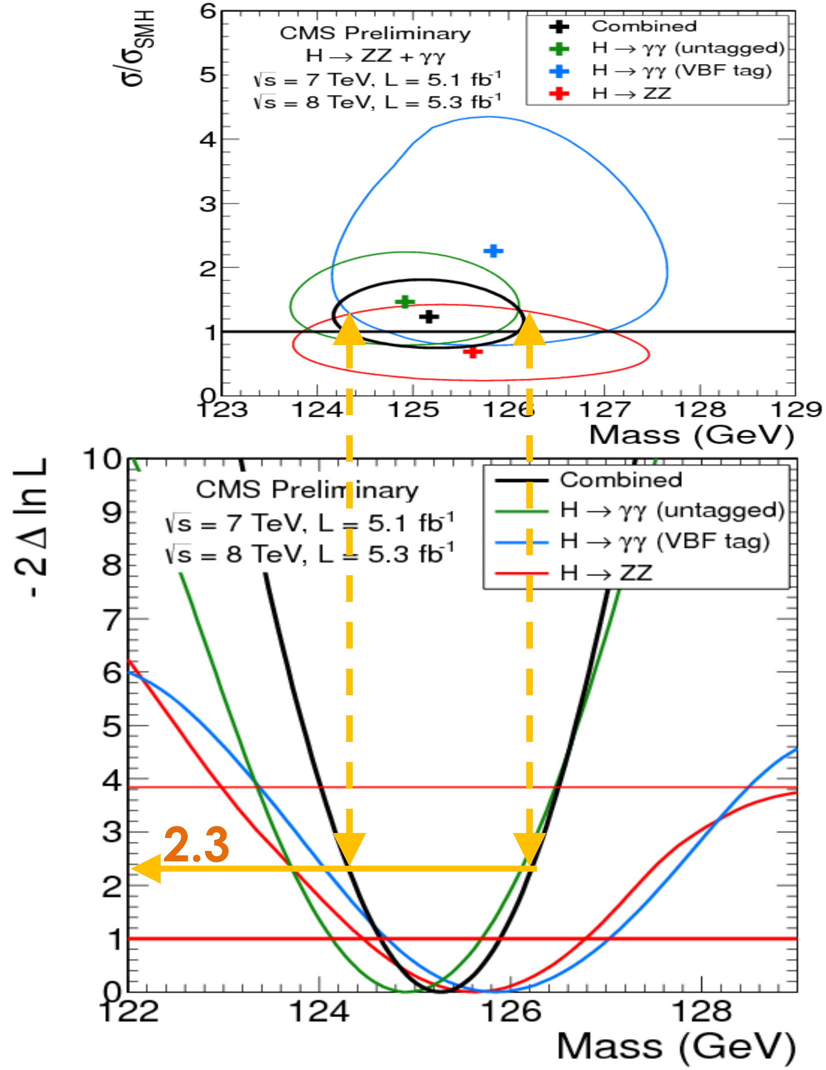
  - S/B depends on relative scale of cross sections and branching ratios.
- In CMS, a slightly less model dependent fit is done with freely floating signal strengths for ZZ, γγ untagged, γγ di-jet.
- Result not that different. Uncertainties too, when using same χ^2 threshold.

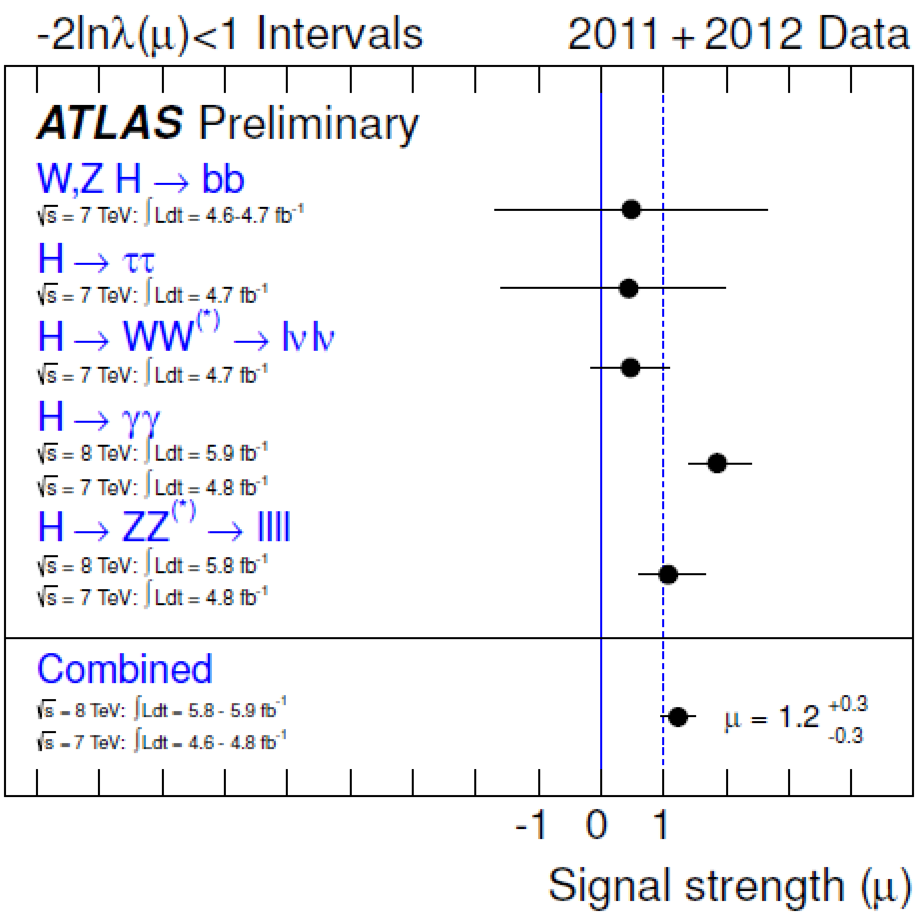


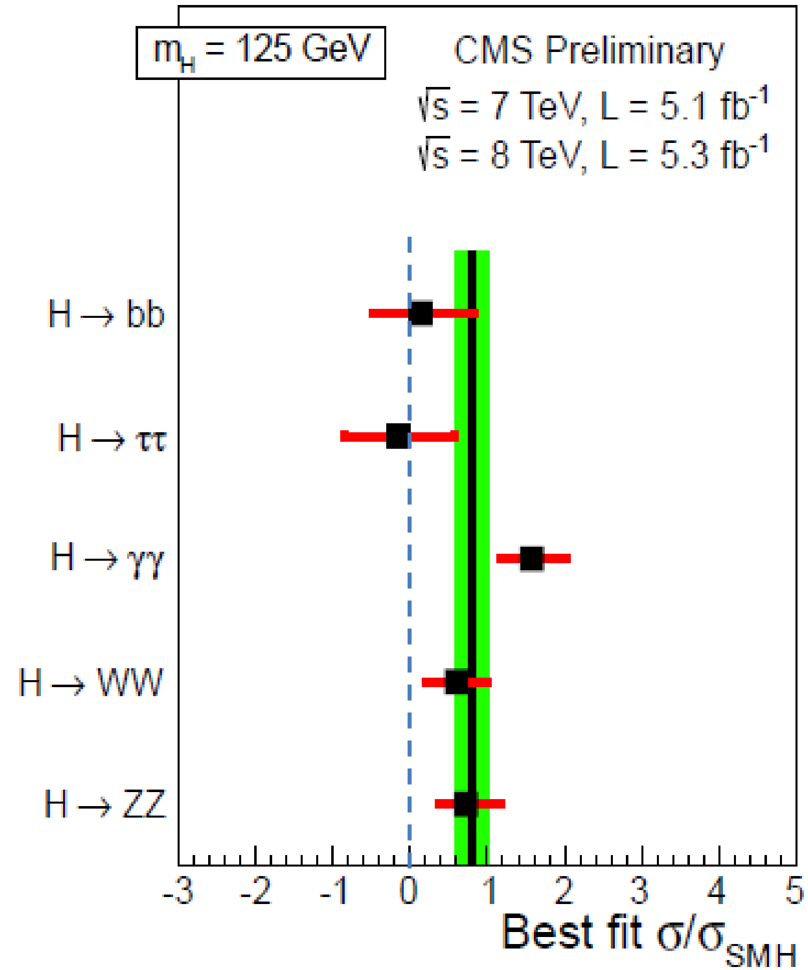
Mass measurements conclusions

- ATLAS and CMS delivering first mass measurements for the new boson.
- Main sources of uncertainties have been described, to the extent of the little public information available yet.
- Current results are fairly compatible.
- CMS results suggest ther is little model dependency in the mass extraction.

Summary

- The natural scope of combinations is now the measurement of properties, no longer the limits and significances.
- In this talk, thoughts about a few issues that could matter for a combination in the future have been presented.
- Past experience shows full combinations of experimental likelihoods are possible. These will become more important when the statistical uncertainties will decrease, making correlations more important.


-2lnλ(μ)<1 Intervals
2011 + 2012 Data
ATLAS Preliminary
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
H → γγ
√s = 8 TeV: ∫Ldt = 5.9 fb⁻¹
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
H → ZZ(*) → llll
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
Combined
√s = 8 TeV: ∫Ldt = 5.8 - 5.9 fb⁻¹
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
μ = 1.2 +0.3 -0.3
-1
0
1
Signal strength (μ)


mH = 125 GeV
CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
-3
-2
-1
0
1
2
3
4
5
Best fit σ/σSM H