H-> $ZZ^{(*)}$ -> 4lep - Mass and Width Measurements with the ATLAS Detector

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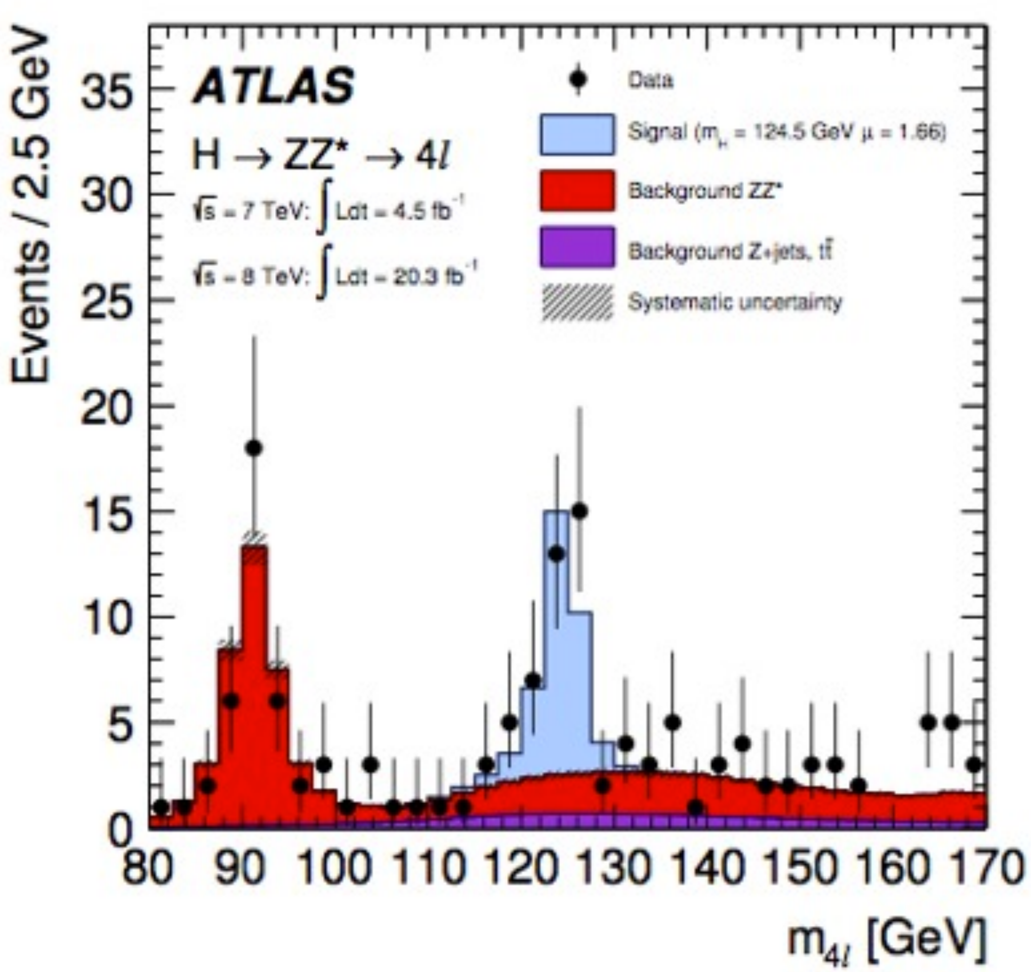
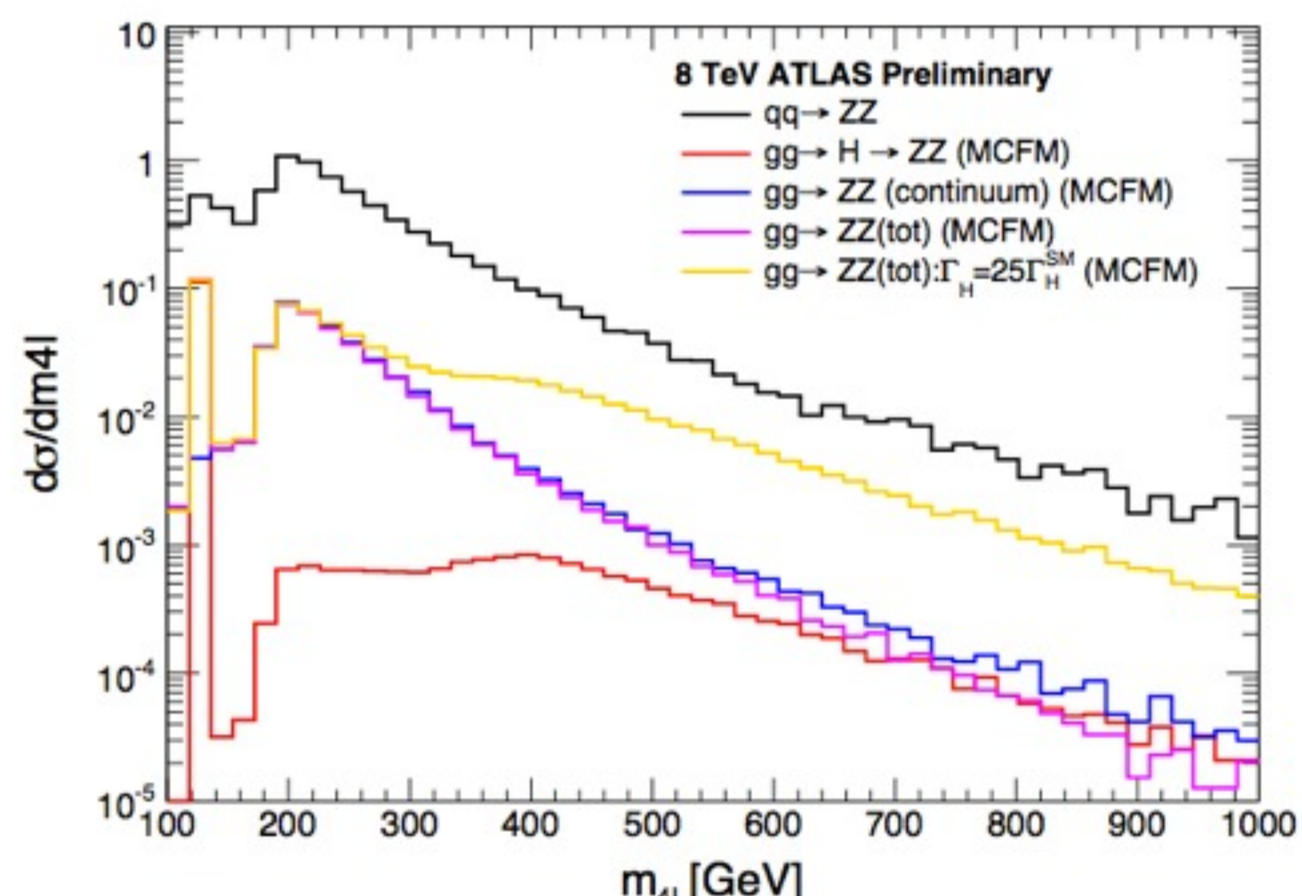
CEA - Saclay, IRFU/SPP

DDays (Journées des Doctorants IRFU) - July 2nd, 3rd 2014

- Alessandro Calandri
- ED 517 (Université Paris Sud) - PhD starting date: October 1st, 2012
- Motivations: exploring the frontiers of the high energy physics at LHC

- Propriétés du Boson de Higgs se disintegrant dans le mode 4 leptons à LHC: masse, limite sur la contribution à haute masse et sur la largeur
- Standard Model, ATLAS detector, LHC, Higgs mechanism, Higgs mass measurement, Electrons, Higgs width measurement



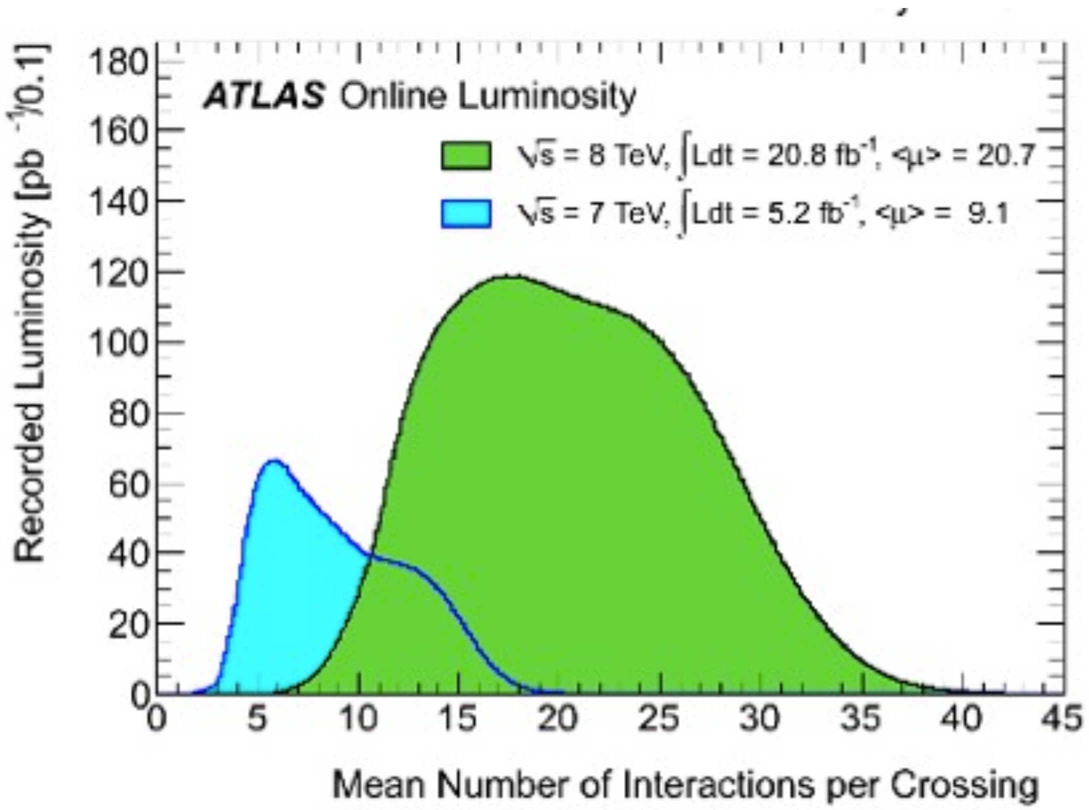


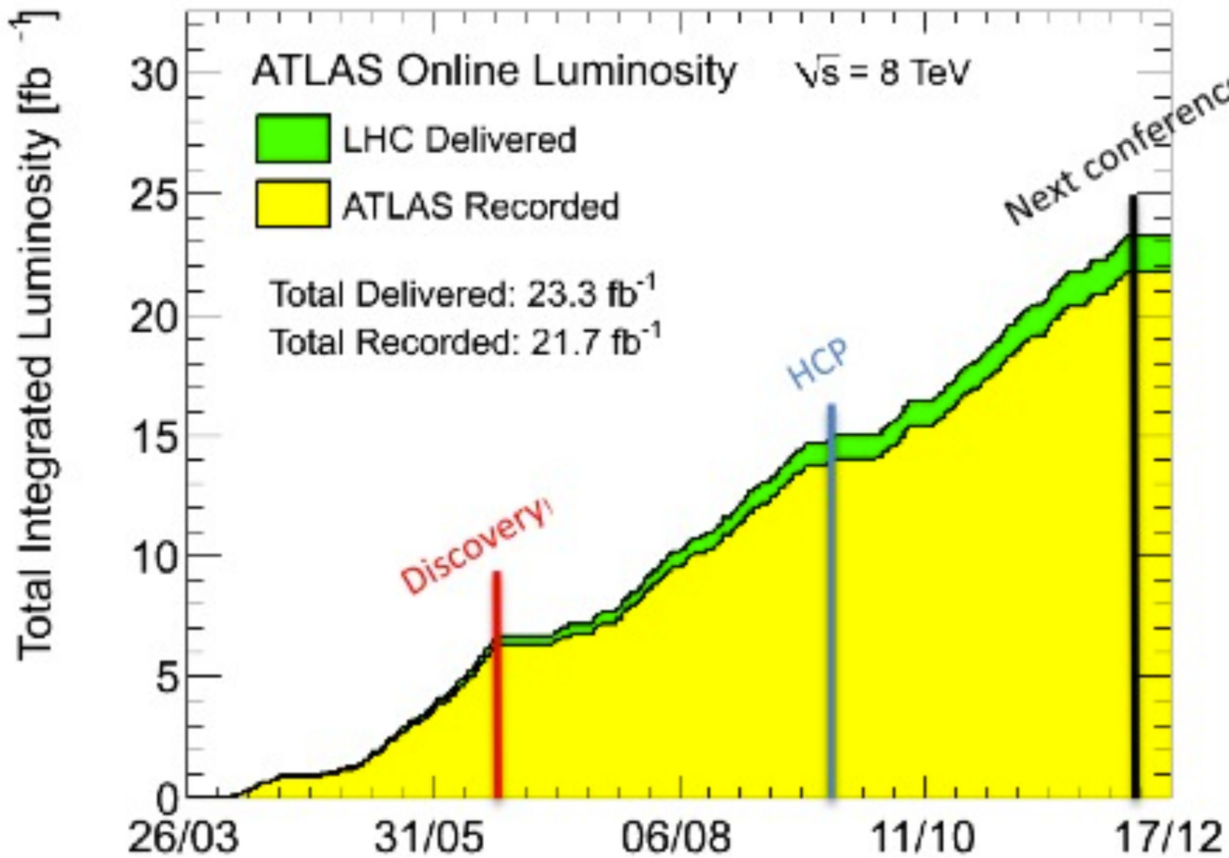
Outline of the talk

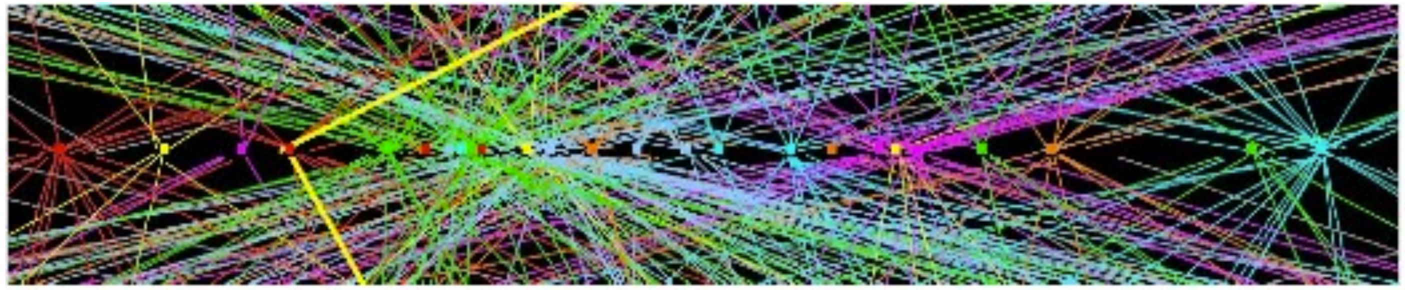
- Performance of the LHC and the ATLAS detector
- The Higgs boson mass measurement
    - track and cluster combination for the electrons
- The Higgs boson indirect width measurement and the constraint on the off-shell couplings

Performance of LHC

- Proton-proton collider @ $\sqrt{s}$= 7 TeV (2011) and 8 TeV (2012)
- Peak luminosity: $7.7*10^{33}$ $cm^{-2}s^{-1}$
- Integrated luminosity delivered: ~23 fb^{-1} (8 TeV) and 5 fb^{-1} (7 TeV)
- Bunch crossing 50 ns

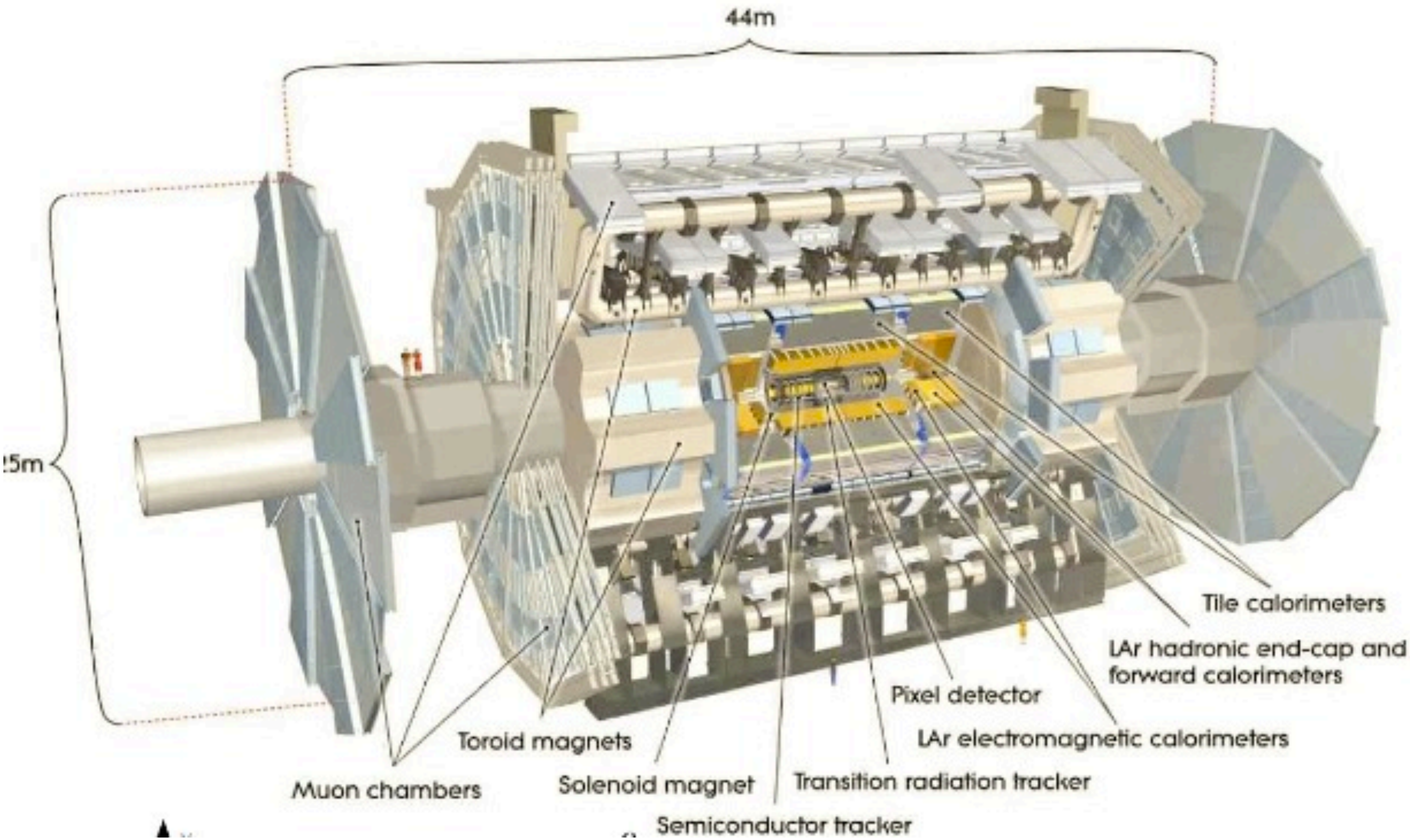






A candidate Z boson event in the dimuon decay with 25 reconstructed vertices

The ATLAS Detector

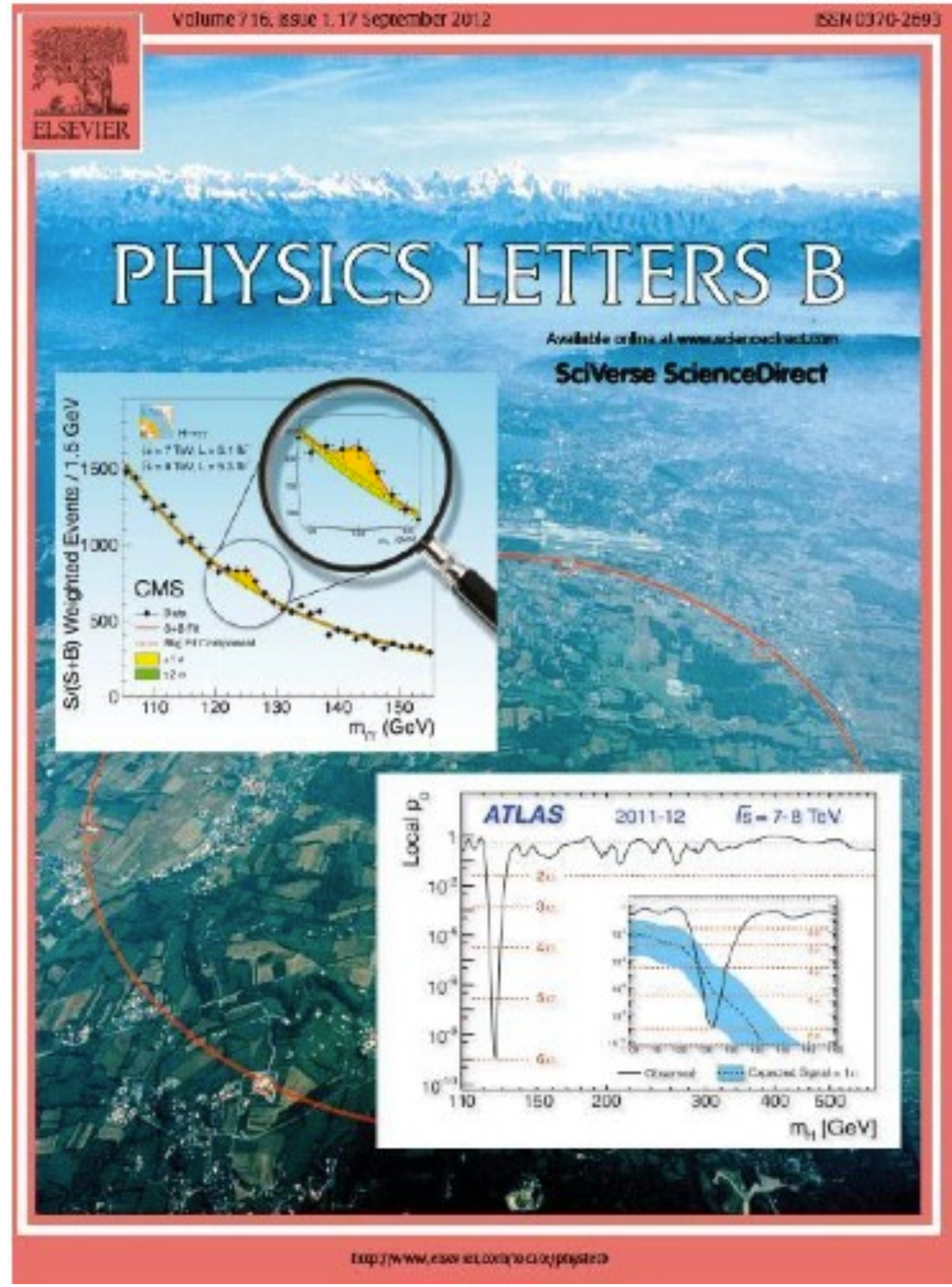


Higgs Boson Mass Measurement

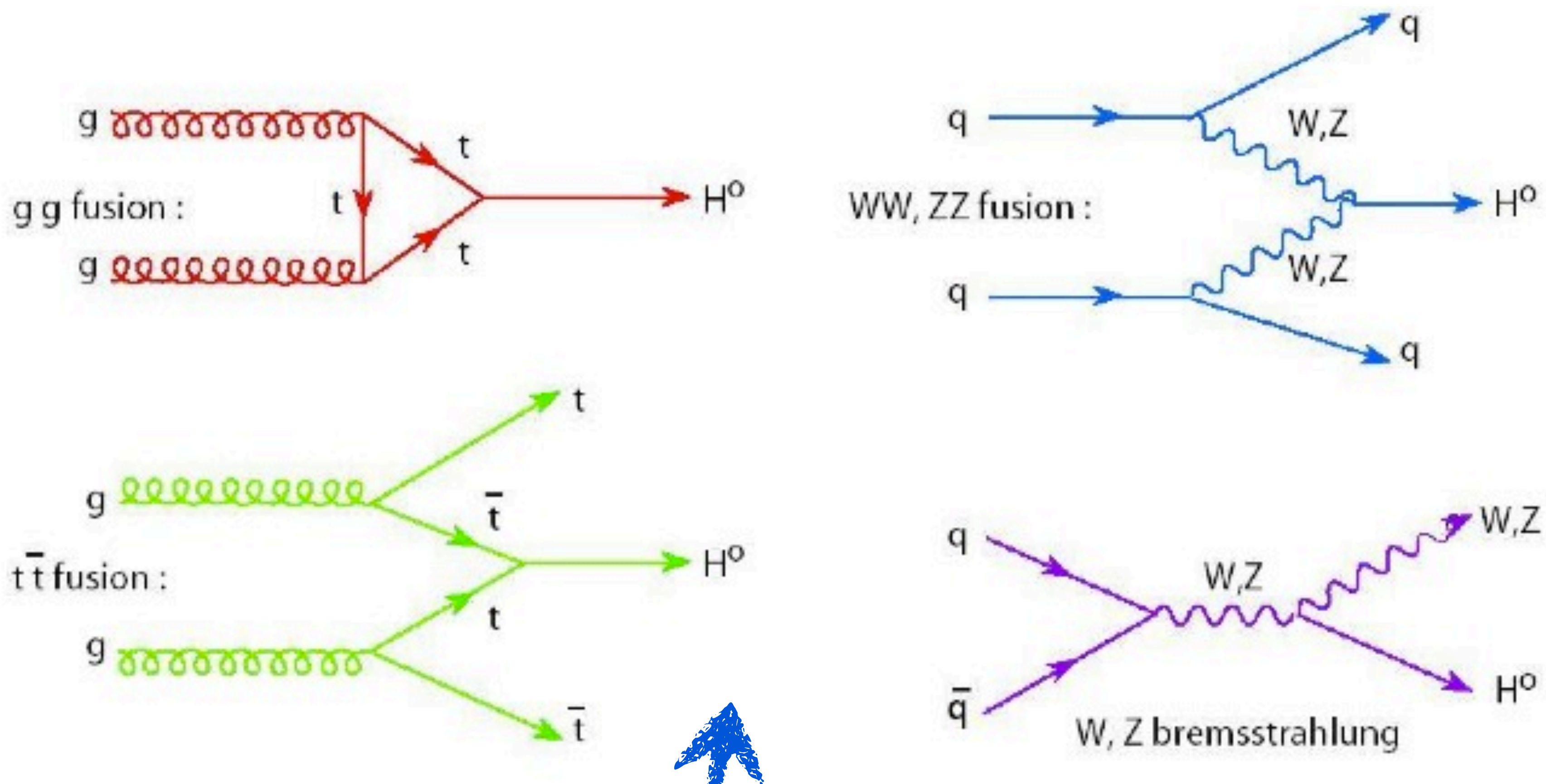
Higgs Boson Discovery

- 4th July, 2012, the ATLAS and CMS collaborations announced the observation of a new particle
- ATLAS channels (7 TeV and 8 TeV)
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4l$
  - $H \rightarrow WW \rightarrow l\nu l\nu$

arXiv: 1207.7214, 1207.7235



Higgs @ LHC


g g fusion :
g
g
t
t
t
H°
WW, ZZ fusion :
q
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W,Z
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W,Z
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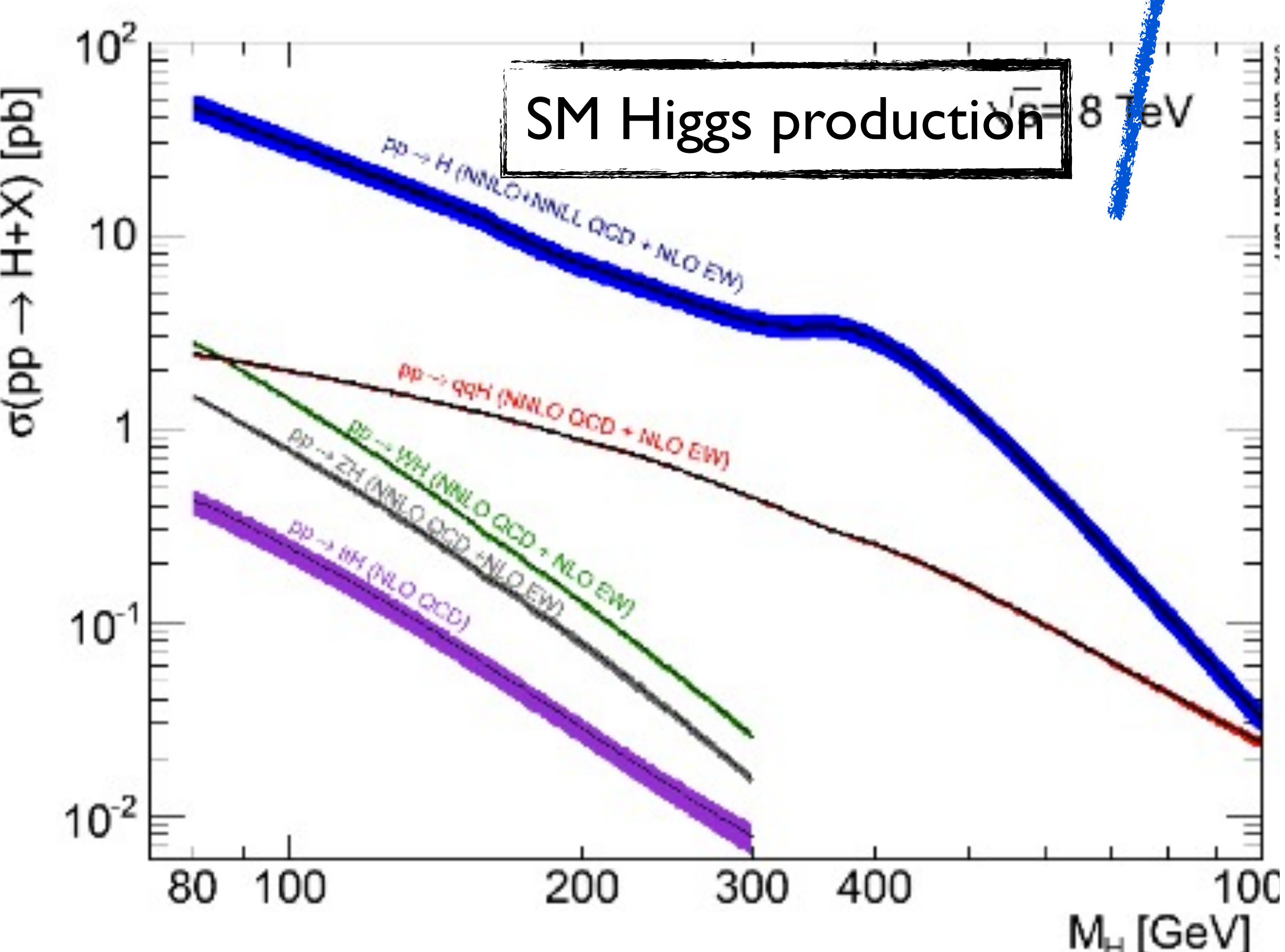
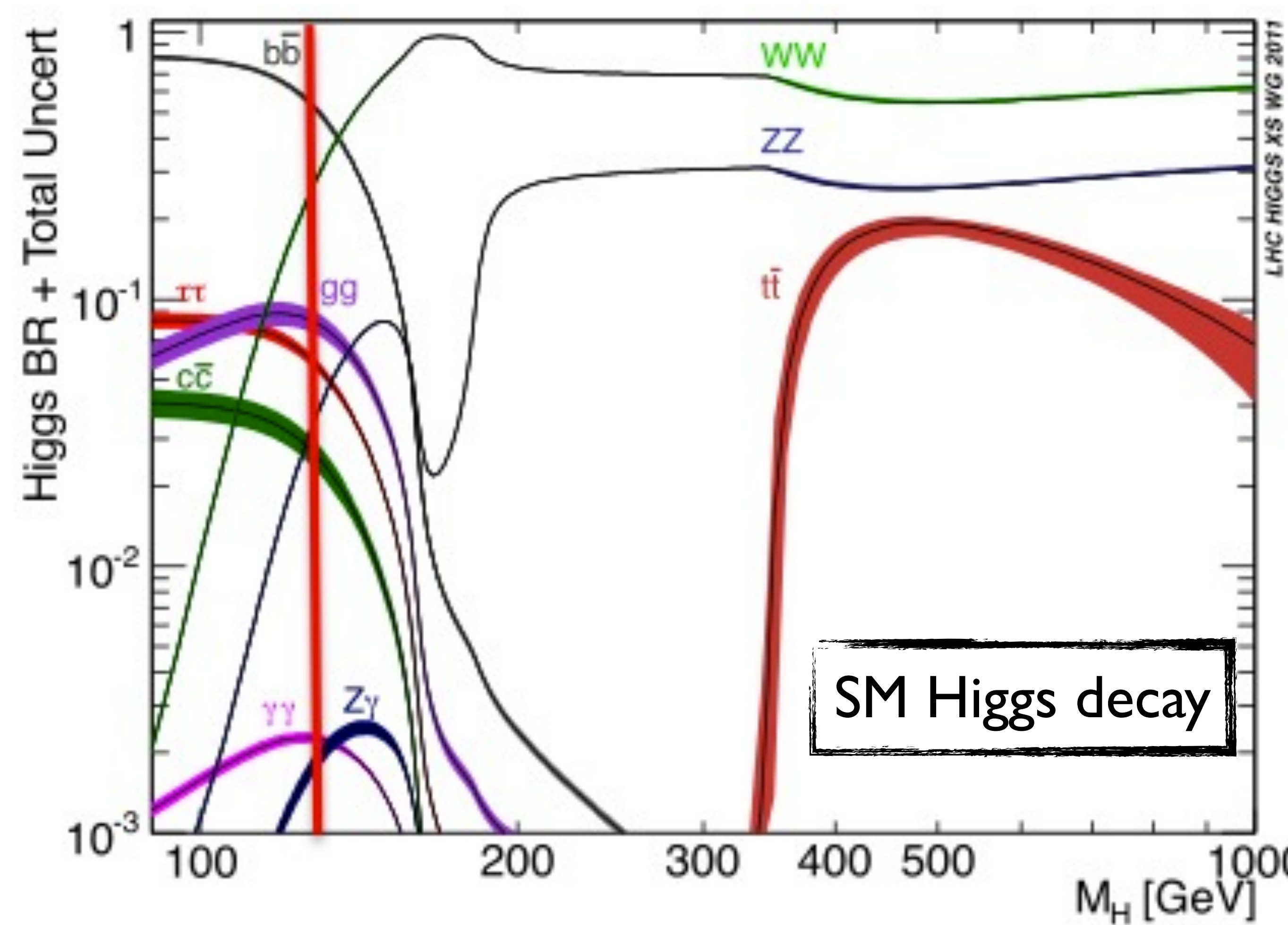
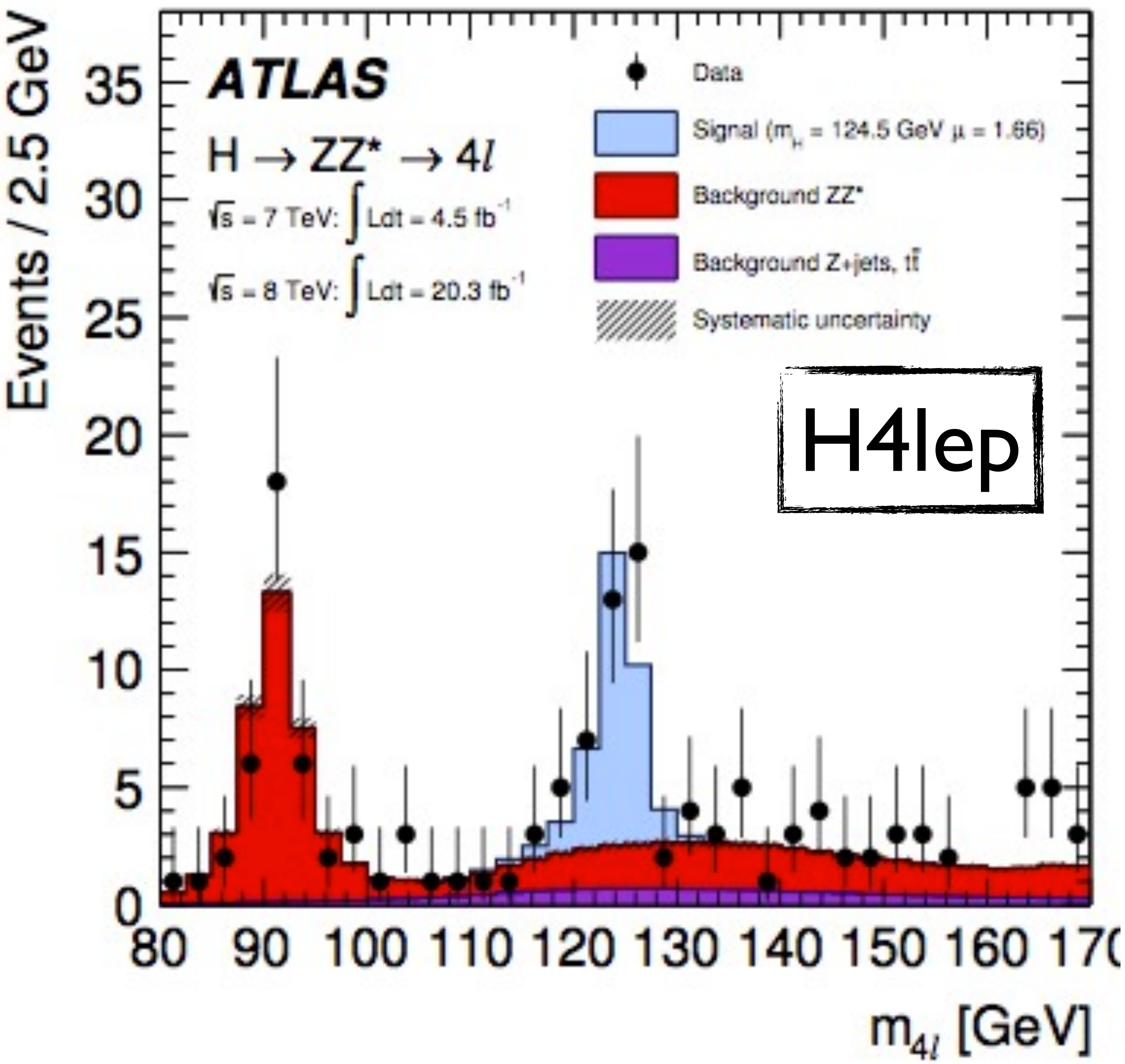
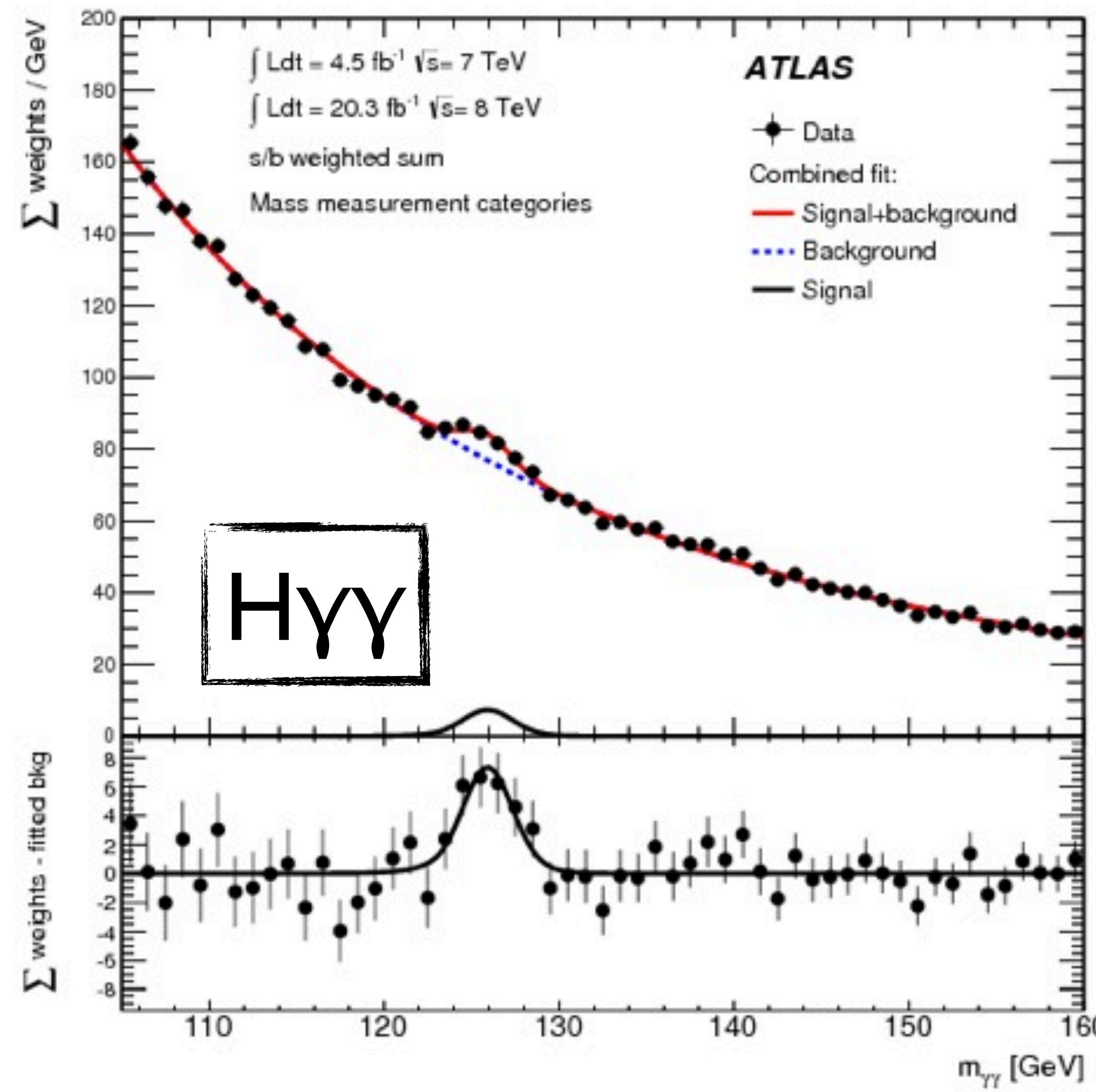
W, Z bremsstrahlung


SM Higgs production
8 TeV
σ(pp → H+X) [pb]
10^2
10
1
10^{-1}
10^{-2}
80
100
200
300
400
M$_H$ [GeV]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)


SM Higgs decay
Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
100
200
300
400
500
M$_H$ [GeV]
bb̄
WW
ZZ
tt̄
ττ
gg
cc̄
γγ
Zγ
LHC HIGGS XS WG 2011

Higgs - Results





124.51 ± 0.52 (stat) ± 0.04 (sys) GeV

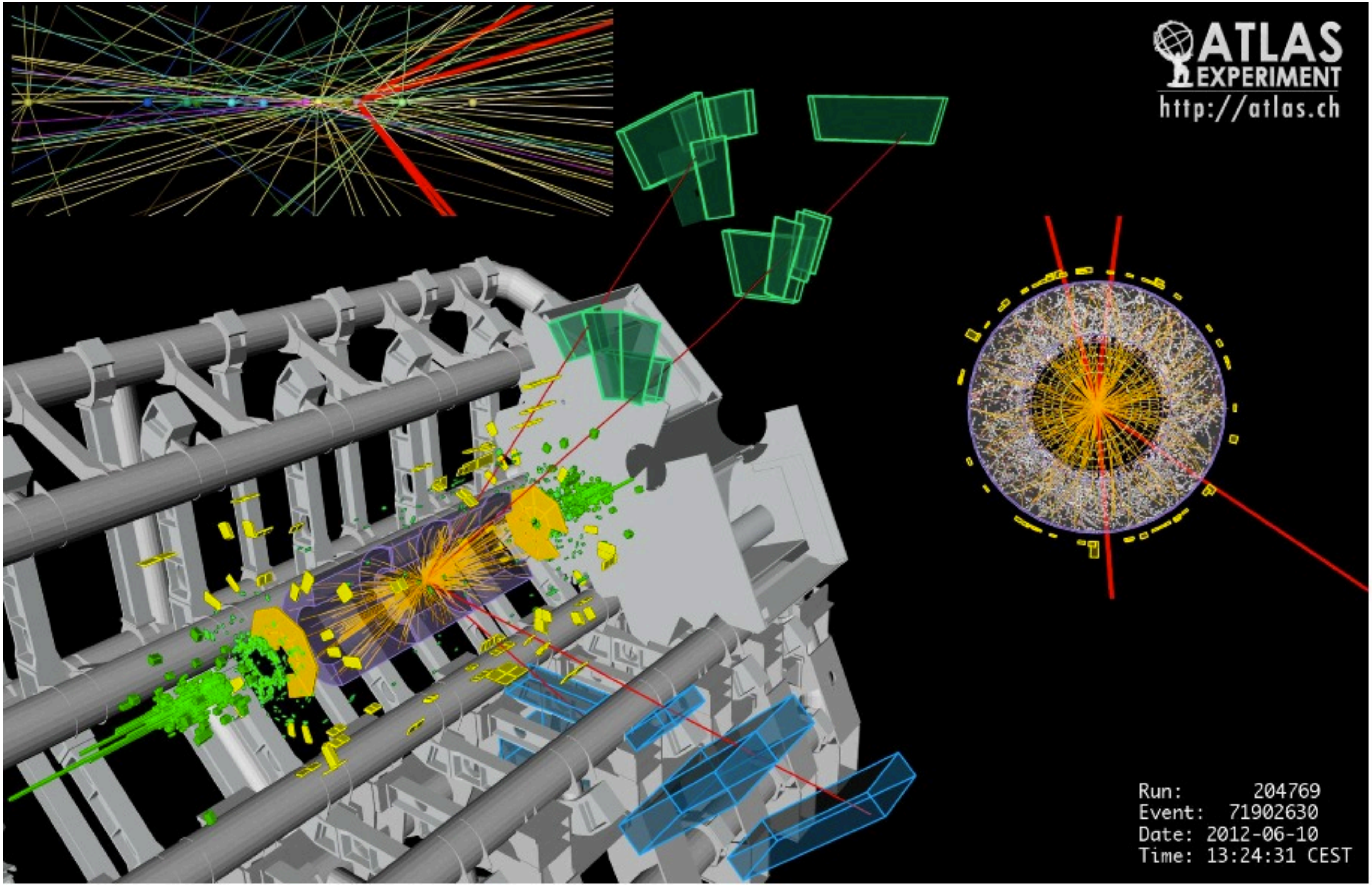
125.98 ± 0.42 (stat) ±0.28 (sys) GeV

Combined mass →

$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$
$$= 125.36 \pm 0.41\ \text{GeV}$$

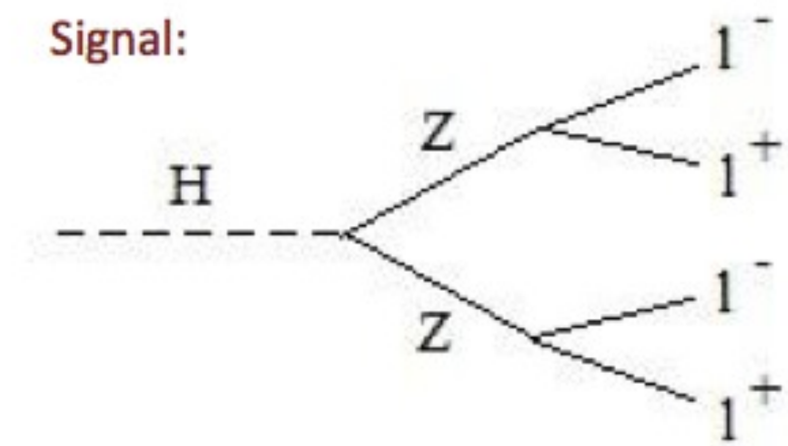
1.98σ compatibility between the two channel measurements

H→ZZ→4lep - Event display

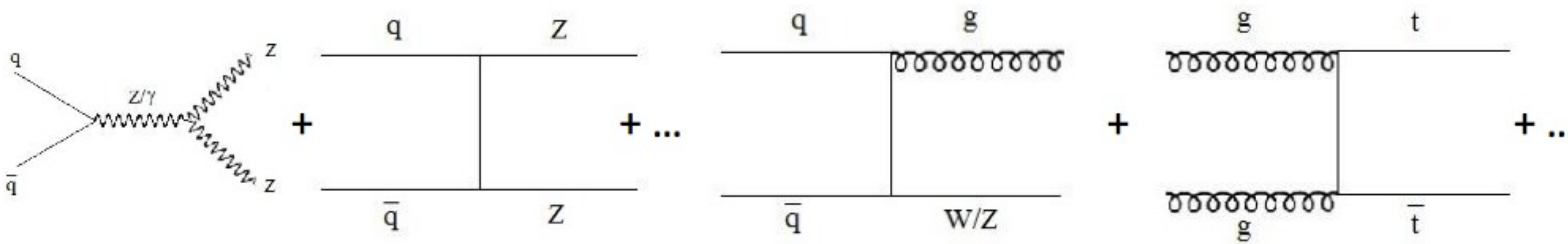


H→ZZ→4lep - The Golden Channel

- Small BR, but very clear 4-lepton final state
- → high signal purity
- 4e, 4μ and mixed final channel (2e2μ and 2μ2e)
- Analysis background: ZZ, Z+jets, top



- Irreducible background: pp → ZZ - reduction driven by kinematic cuts. Shape and normalization from MC → analysis discriminant deployed to remove ZZ bkg (BDT) (pt and η of the 4lepton system, as well as other kinematic variables used in this discriminant).
- Reducible background: Z+jets, tt - kinematic cuts - Z+jets from signal-free region, Zbb shape from MC and normalization from data.



- More information on the H4lep (number of the events in the sub-channnel) in the backup slides

Energy - Momentum Combination for Electrons

Why combining track and cluster information

- 3/4 decay channels contain electrons in the final state (4e, 2e2μ, 2μ2e)
- Electron energy is measured using the cluster deposit at the calorimeter level.
- Track information of the particle may be used too - not trivial to treat because of the bremsstrahlung.
- We can gain acceptance (number of events in a rare decay mode) by lowering the transverse momentum (pT) cut at the analysis level

↓

  - ... but the calorimeter resolution decreases when E decreases; on the contrary, the track resolution increases

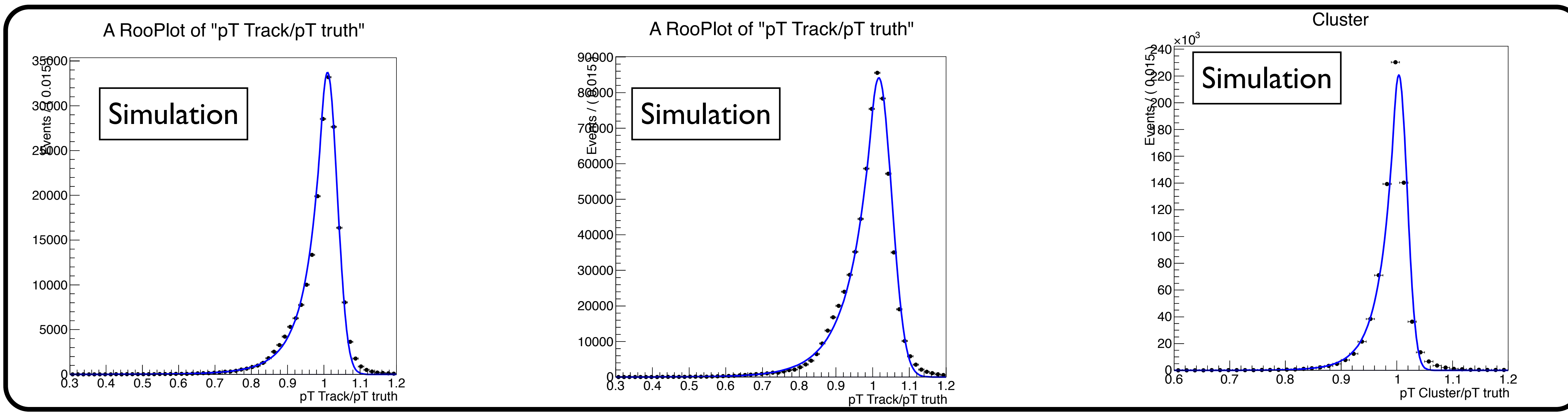
- Exploited an algorithm that combines track and cluster information and built a "combined" momentum for electrons.

→ Usage of track and cluster information holds potential for significant improvement in energy resolution → Statistical combination of E and p (maximum likelihood fit) using the full expected statistical distributions of each electron, parametrized for all pT, region of the detector (η) and bremsstrahlung emission.

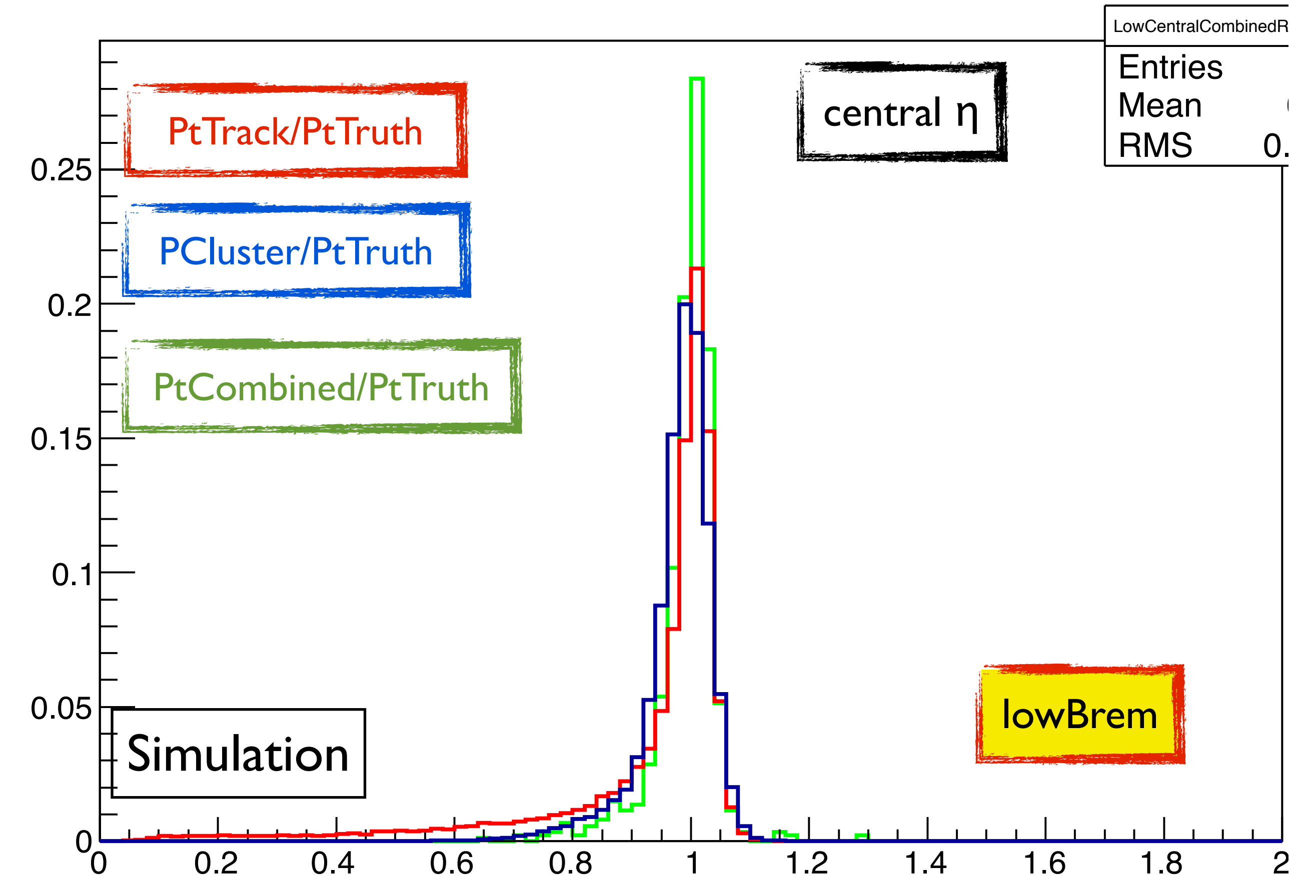
Track and cluster - The combination algorithm

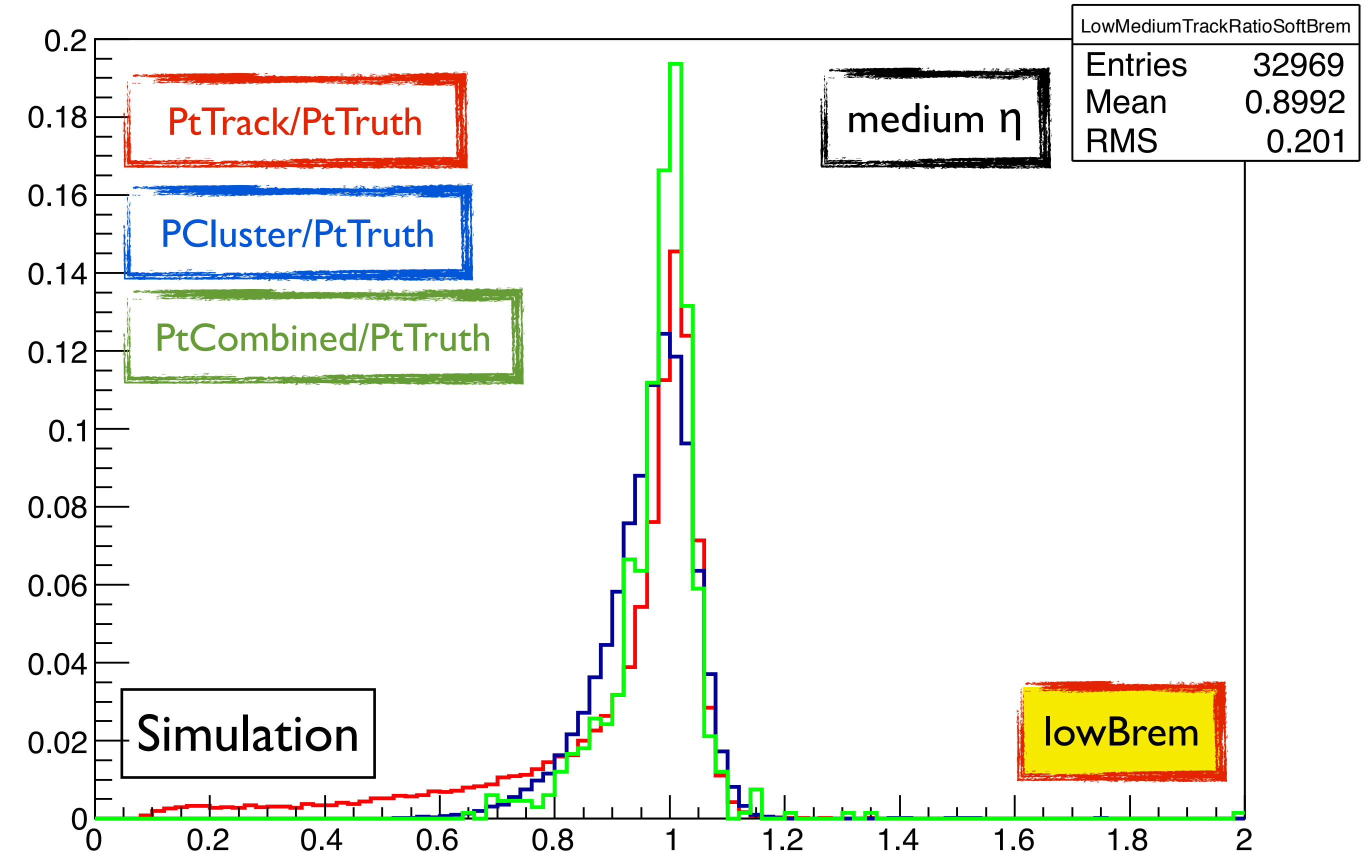
- Maximum-likelihood fit:
  - combination of track and cluster information.
- Extracted some parameters (from simulation) of the distributions (mean value, σ etc.) of p_T track/p_T truth and p_T cluster/p_T truth (fitted with a CrystalBall function)

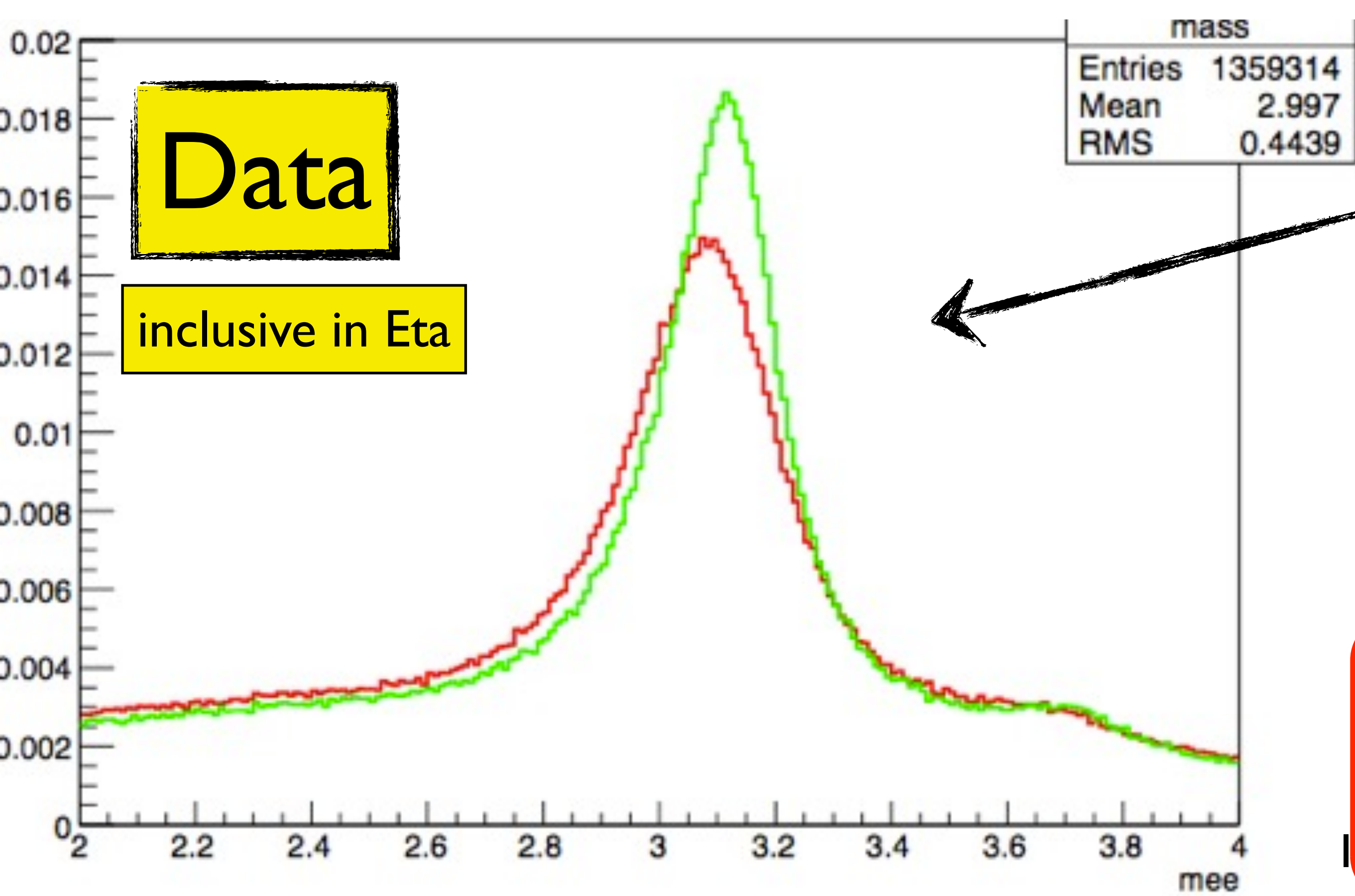
Some examples of the input distributions



Combination - results on single electron and J/Ψ



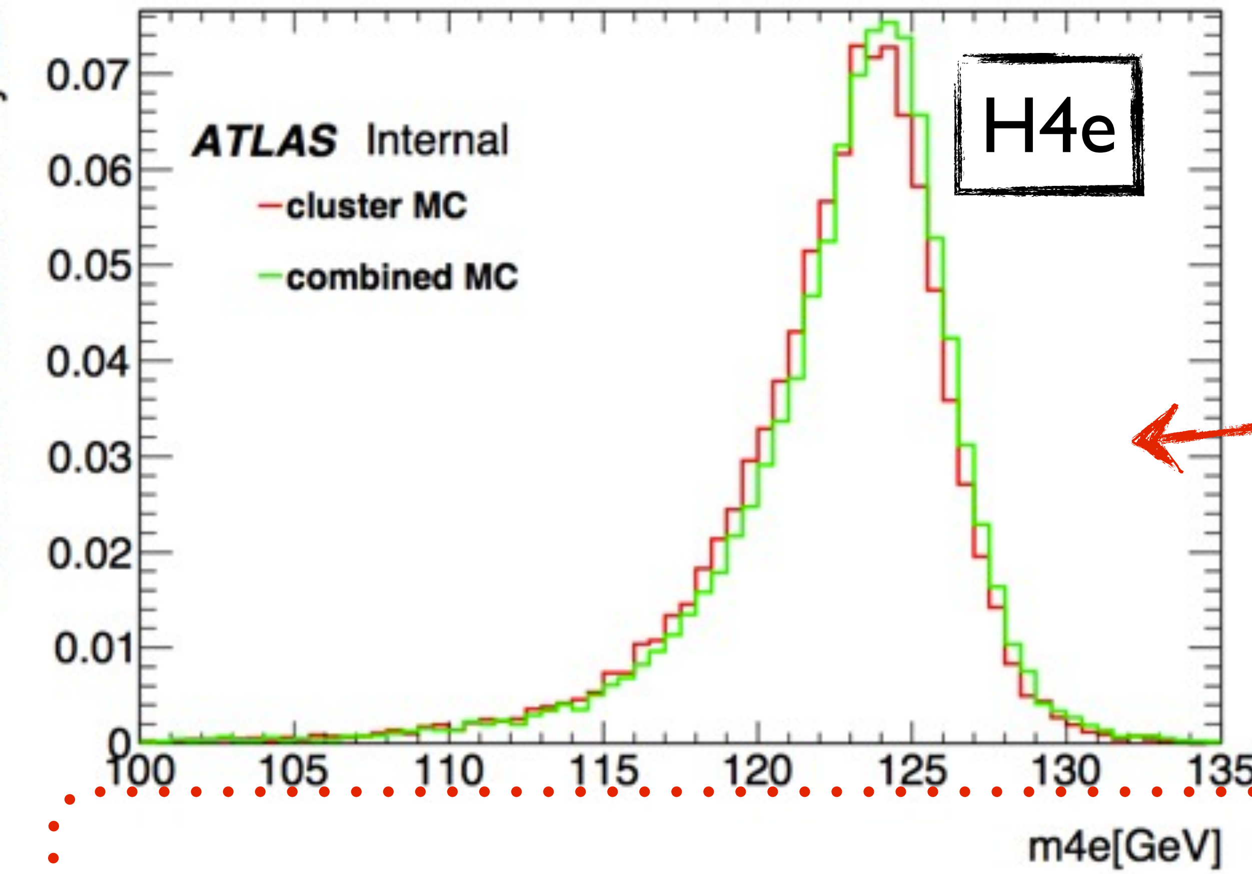




J/Ψ- very well known particle with negligible intrinsic width and low mass. It is very useful to check the performance of the algorithm for low momentum electrons (electron pt spectrum for Z decays is too hard, hence the combination is not often applied)

The dielectron mass resolution in the barrel improves from 0.12 to 0.09 GeV (both for data and MC) ⇒ ~ -30 %

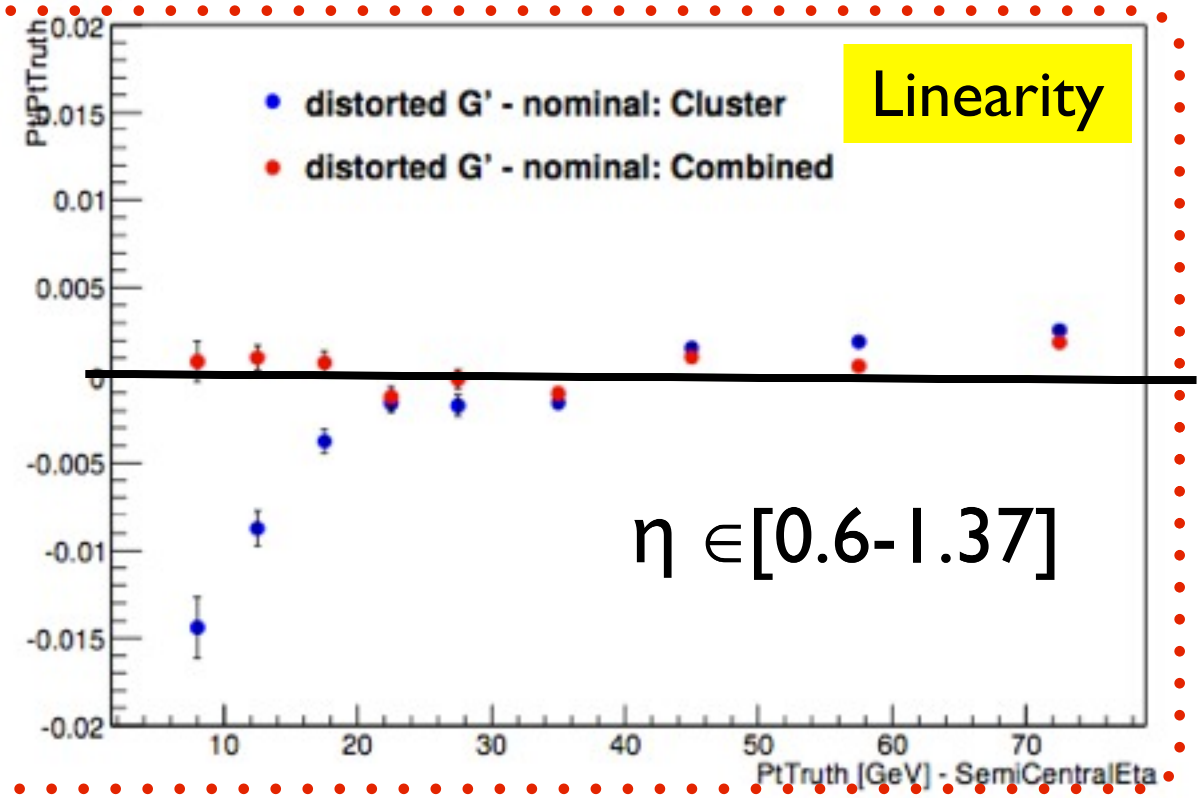
Higgs Mass (H4lep) and systematic uncertainties



3-6% improvement on resolution on the Higgs mass in the channel with electrons in the final states

Check on the systematic uncertainties for the cluster and combined-based momenta.

The combined momentum is less prone to material uncertainties.



The algorithm has been adopted by ATLAS → Extraction of the final 4l mass (arXiv - 1406.3827 June 15th, 2014)

$$m_H = 124.51 \pm 0.52\ \text{(stat)}\ \pm 0.06\ \text{(syst)}\ \text{GeV}$$
$$= 124.51 \pm 0.52\ \text{GeV}$$

Indirect Higgs Boson Width Measurement

The present analysis is currently under approval and internal circulation (the goal is to release a conf note for the summer conferences) → Limited selection of material for this section (overall procedures and public results)

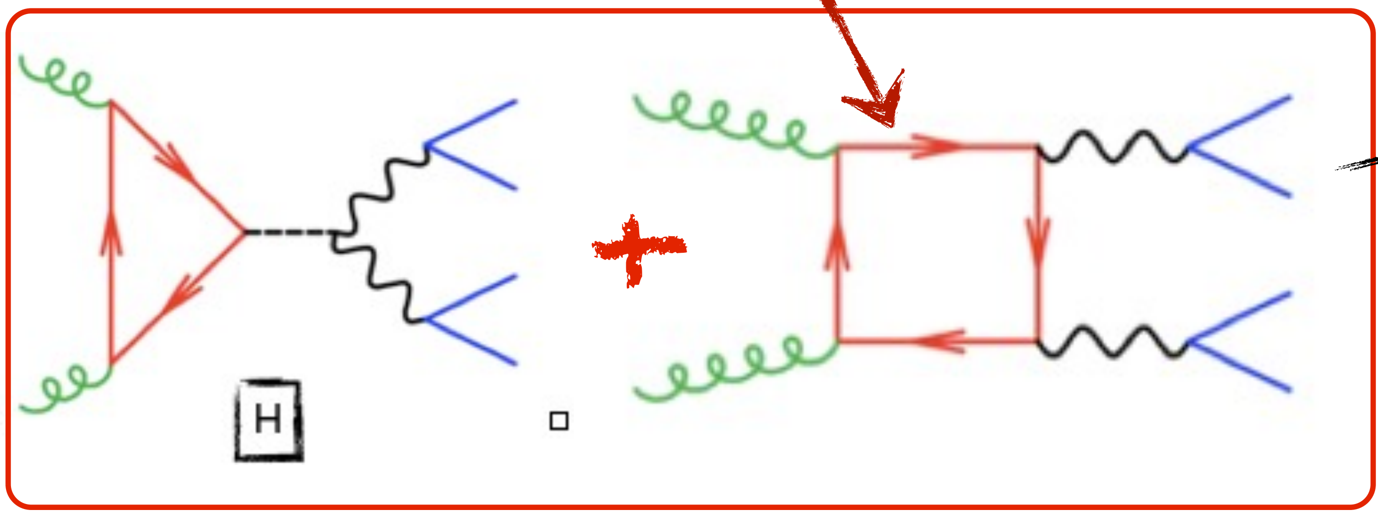
Off-peak Contribution (1)

- We used to search the Higgs as a new on-shell particle (peak on the final state invariant mass spectrum) - refer to slide 11
- Recently, N. Kauer and G. Passarino explained the possible inadequacy of the zero-width approximation → Higgs has also contributions as a virtual particle (propagator) and can be therefore measured in the high mass region.
- In the 0-width approximation (no off-peak contribution), the integrated cross section is given by:
  - $\sigma_{\text{on-peak}} \sim g^2_{ggH}\, g^2_{HZZ} / \Gamma^2_H$
  - it depends on the couplings to the initial and final state particles as well as on the Higgs width.
  - The total cross section is unchanged if the product of the coupling (*BR) and the total width are scaled by a common constant
- In the off-shell regions (where the Higgs acts as a propagator), the cross section is:
  - $\sigma_{\text{off-peak}} \sim g^2_{ggH}\, g^2_{HZZ}$
  - the cross section is independent of the total width and it may provide extra information about possible non-SM Higgs nature
- It is evident that the ratio of off-shell and on-shell production will lead to a direct measurement of the μ_offShell and consequently the Higgs width, as long as the ratio of the coupling remains constant
  - We'll present a limit on the off-shell couplings (μ_offshell) in the high mass region
  - We'll interpret this off-shell limit as a limit on gammaH (gammaH_SM=4.2 MeV) when combining with the on shell measurement.

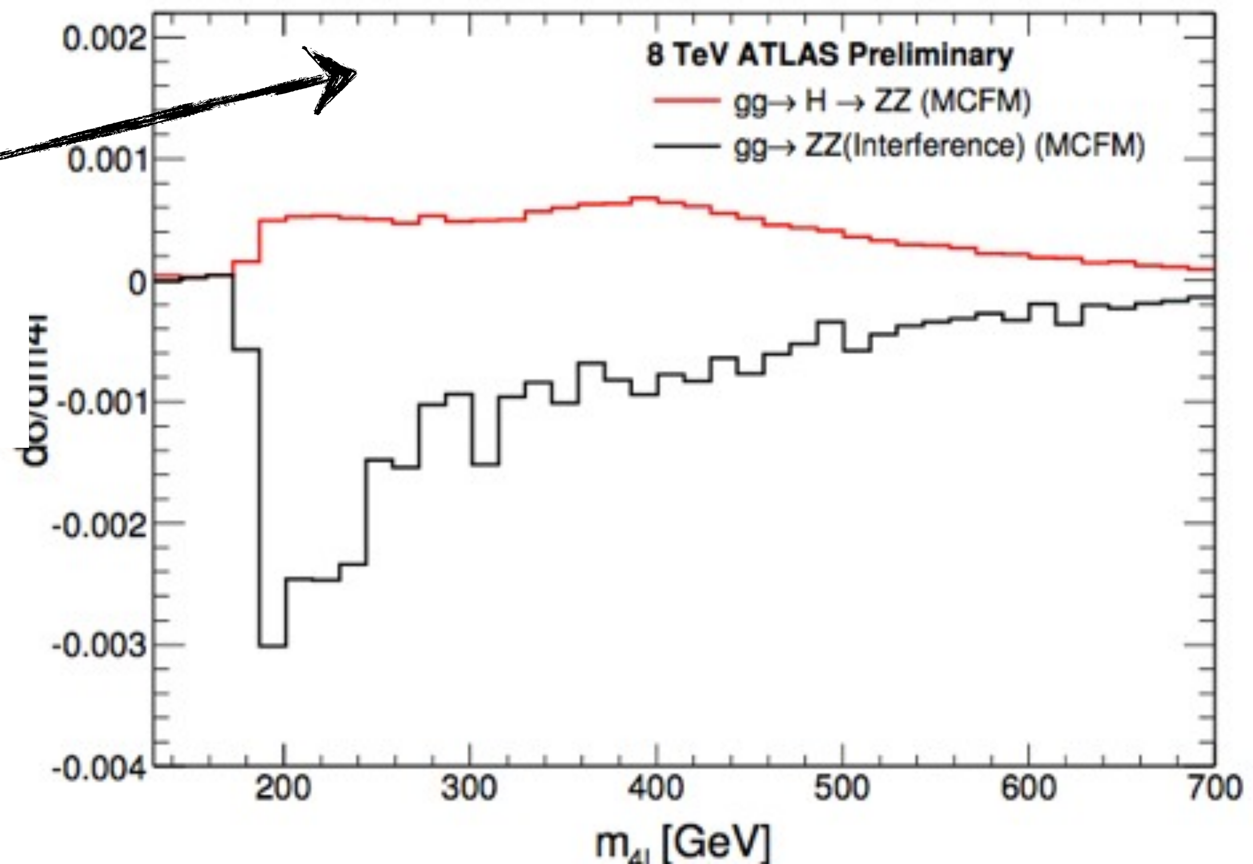
Off-peak contribution (2)

- It is important to have a good theory prediction to properly model the analysis:
  - quantum interference effects (between HZZ and continuum ggZZ, featured by the same initial state) is included in the simulation
  - perturbative corrections are also added in order to better model the kinematic distributions.
  - higher order Monte Carlo predictions and effects are to be taken into account too.

The higher order calculations for QCD-related gluon emissions on the background ggZZ do not exist → we have to rely on phenomenological models

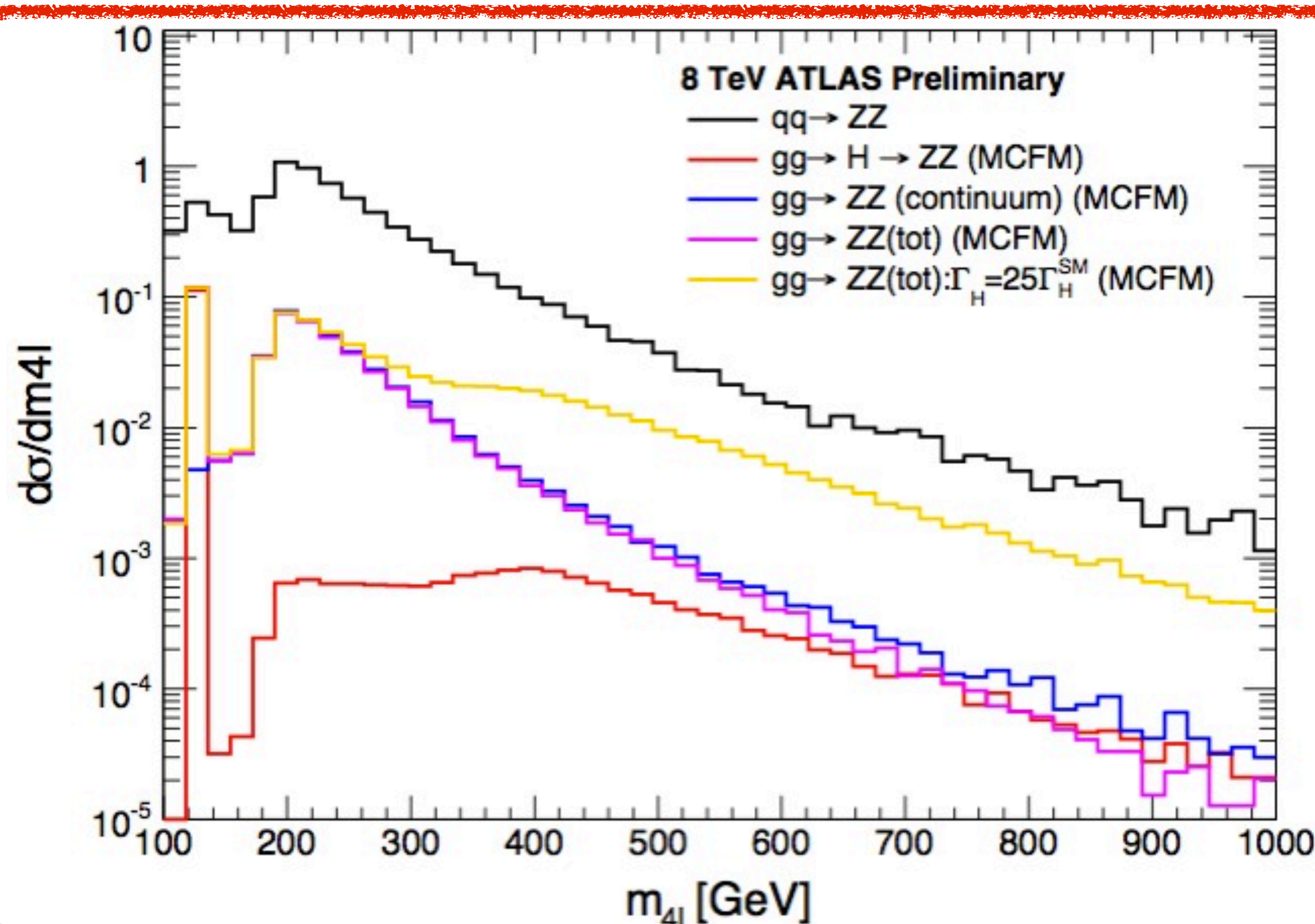


Quantum interference due to same initial state (signal and background)



Analysis Strategy

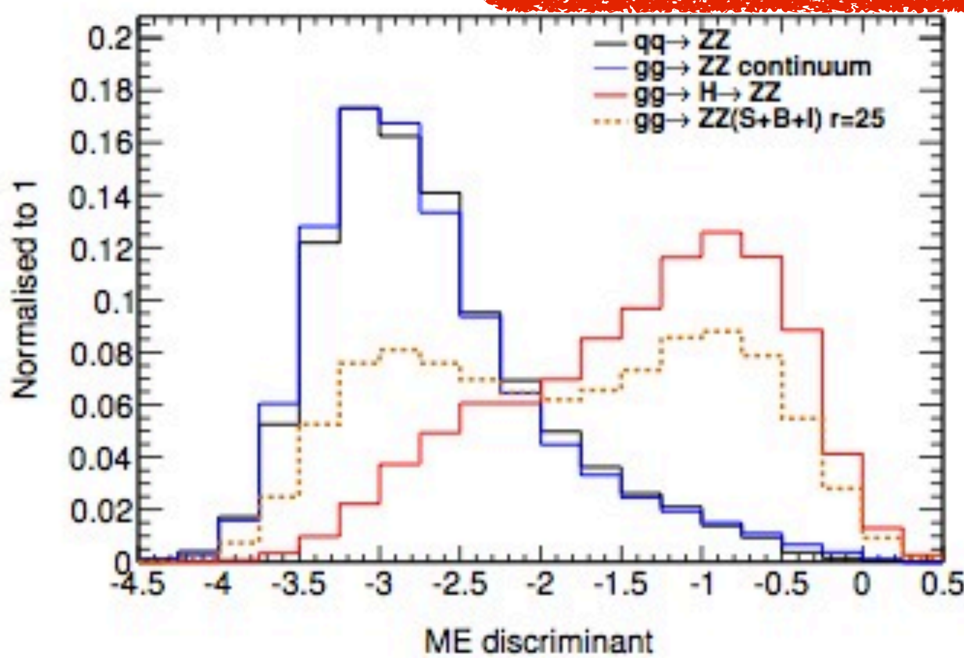
- The analysis is performed in the off-shell ZZ region (m4l>220 GeV):
  - the ZZ final state contribution is produced by signal (ggHZZ), continuum-background (ggZZ) and interference between signal and background
- We try to reject the qqZZ background using simple (cut-based) or more sophisticated methods (multivariate analysis deploying several kinematic variables that fully exploit the ZZ kinematics)



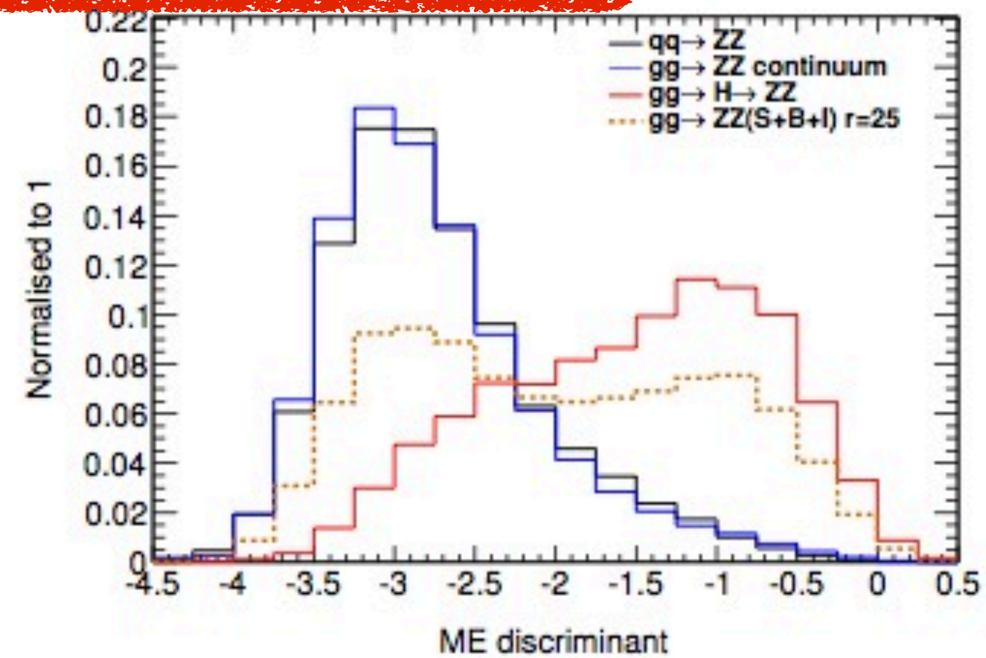
Rejecting the ZZ background

Definition of the discriminant

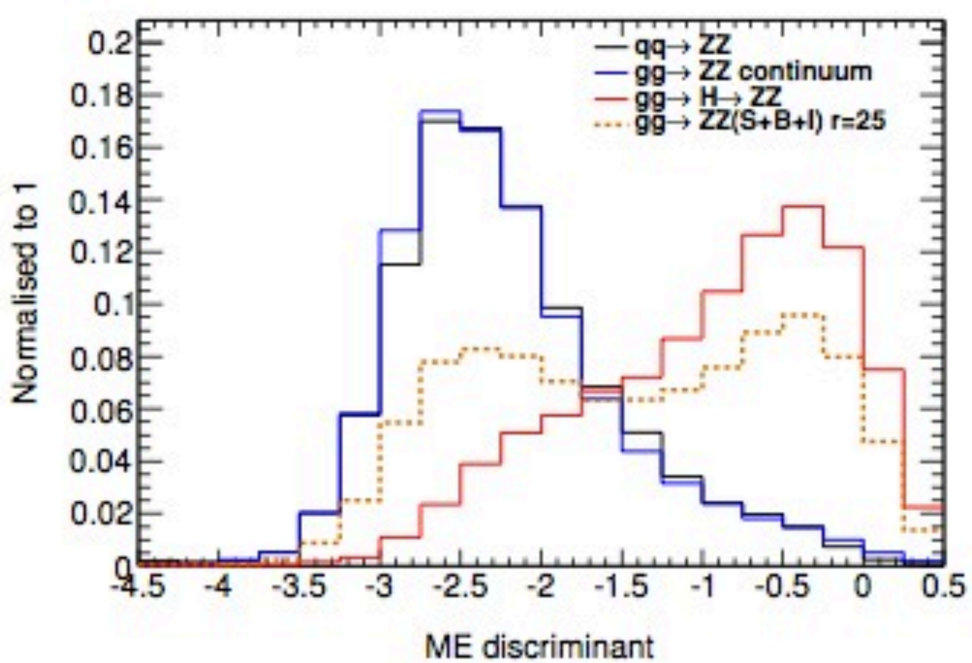
$$K_D = \log_{10}\left(\frac{P_{H\to ZZ}}{P^{\mathrm{tot}}_{gg\to ZZ} + c\cdot P_{q\bar{q}\to ZZ}}\right)$$

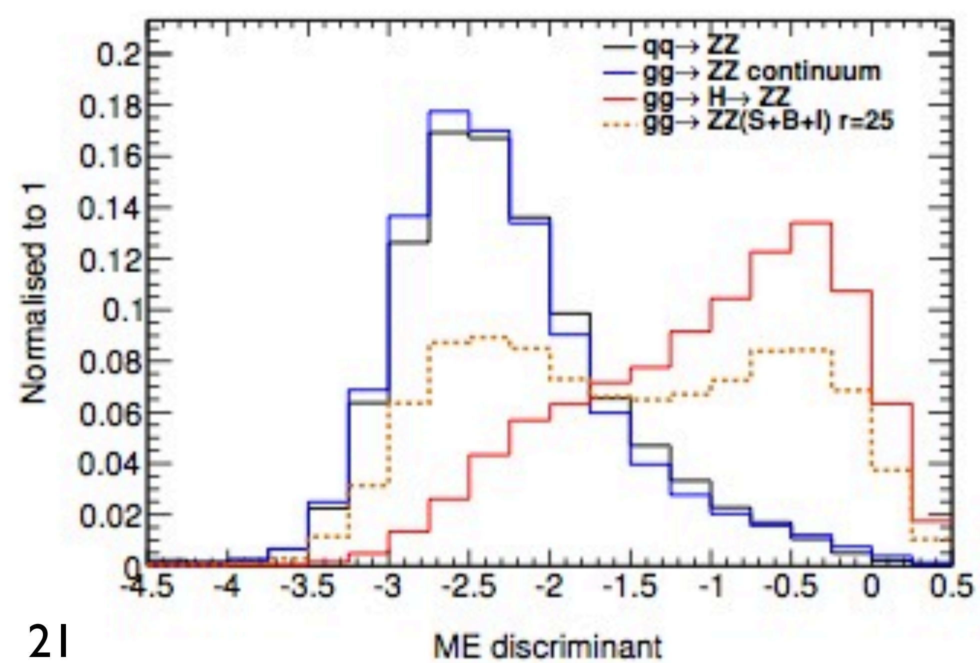


(a) $2e2\mu$



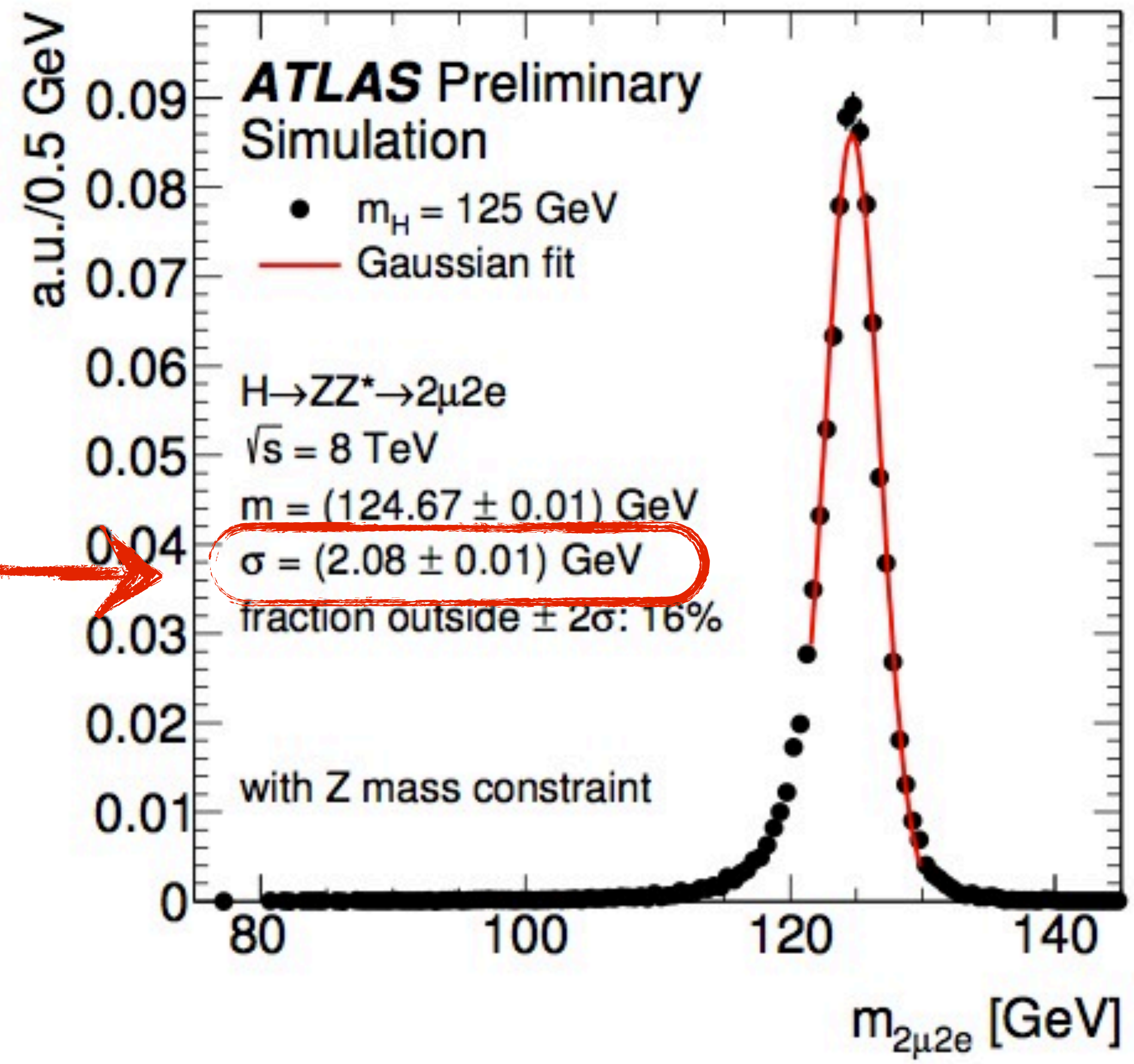
(b) $2\mu 2e$





Wrapping up

The direct limit on the Higgs width (predicted to be 4.2 MeV) is performed by a fit on the lineshape of the Higgs resonance → convolution of the intrinsic Breit-Wigner distribution of the resonance and the resolution of the detector (dominant contribution)
⇒ the indirect measurement is way more sensitive (order of MeV) than the simple fit on the mass peak (~GeV).



- The primary result is a limit on μ_offShell as this is independent on the width and the hypotheses in the analysis
- Through the hypothesis μ_offShell = μ_onShell, the above-defined limit is converted into a limit on the Higgs width (CMS showed an observed limit of approximately 20 MeV in the ZZ→4l and ZZ→2l2ν channels).
- ATLAS will publish results on the indirect limits on the width very soon (summer conferences).

Conclusions

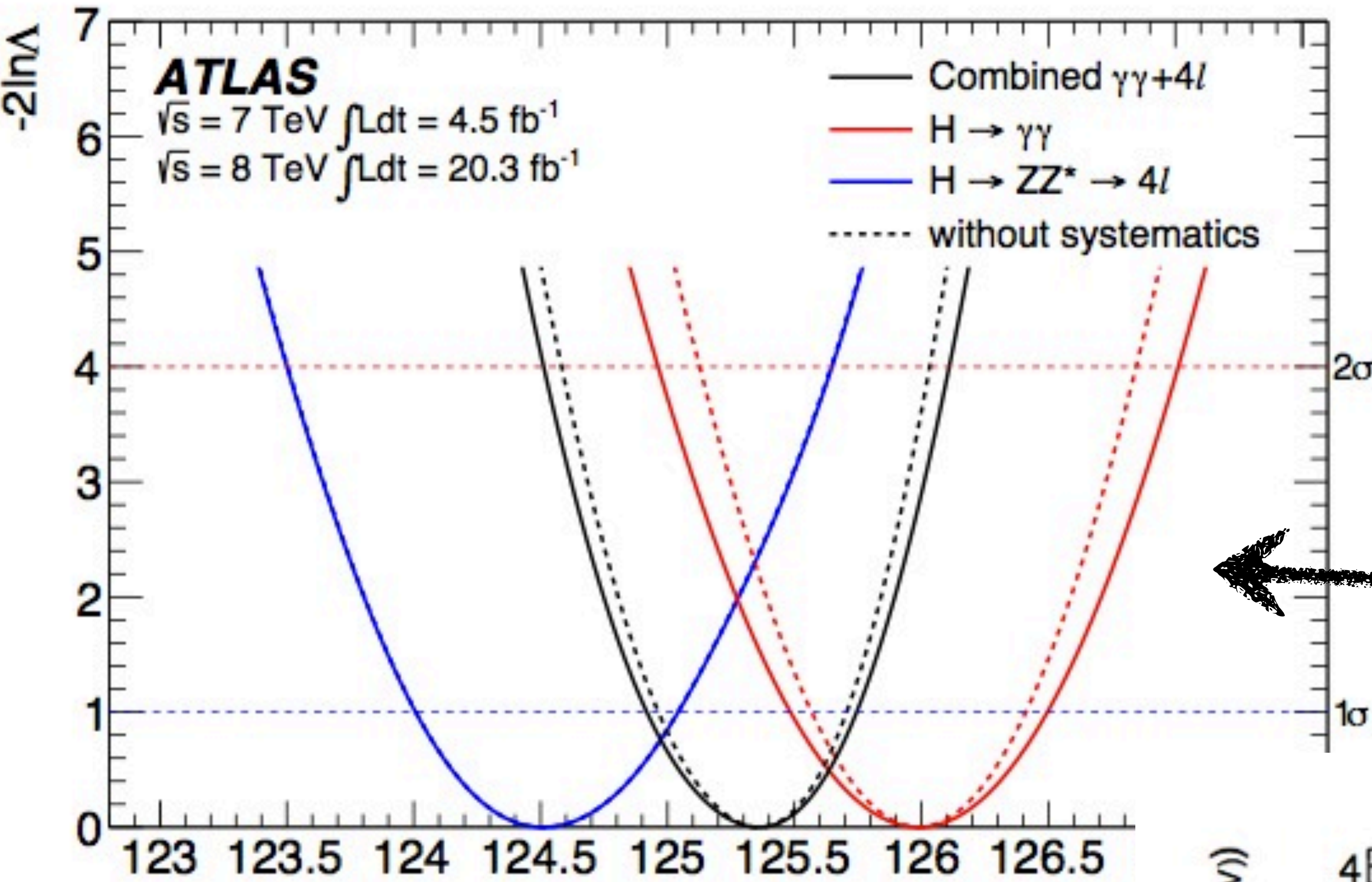
- The final paper on the Higgs mass measured by ATLAS has now been published (http://inspirehep.net/record/1300650)
    - main contribution to the mass extraction
    - E-p combination algorithm (qualification task) now fully developed, validated and released to the ATLAS collaboration
    - EGamma paper including the Ep combination produced (Supporting note too)
- Higgs Indirect Width measurement
    - the analysis note is now going through the approval process- ready for the summer conferences.
    - Personal contribution to the analysis: production and validation of the Monte Carlo simulations, development of the BDT and cut-based approaches, extraction of the final limit on the width, studies on the systematic uncertainties, supporting note redaction
- Future prospects/plans
    - Paper on the Indirect Higgs Boson Width measurement likely to be scheduled by next fall
    - Studies on prospects for run2 (re-calibration of the EP combination, other possible H4lep-related topics,...)
    - ...looking forward to new data by April 2015!

Backup slides

H→ZZ→4lep - Wrapping up

Final state	Signal full mass range	Signal	ZZ^*	$Z + \text{jets}, t\bar{t}$	s/b	Expected	Observed
			$\sqrt{s} = 7$ TeV				
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu 2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s} = 8$ TeV				
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu 2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
			$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu 2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

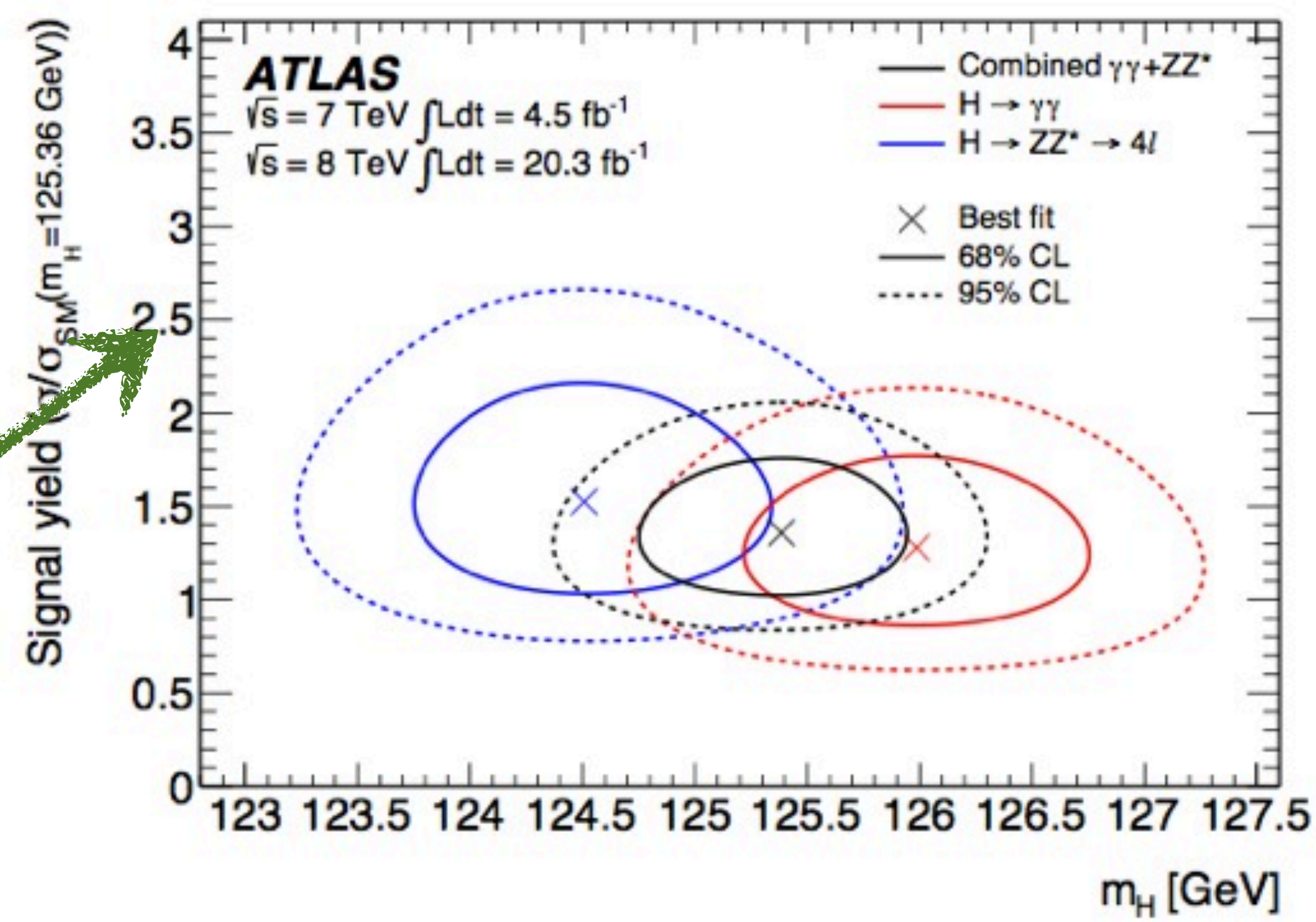
Higgs Combination



$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$
$$= 125.36 \pm 0.41\ \text{GeV}$$

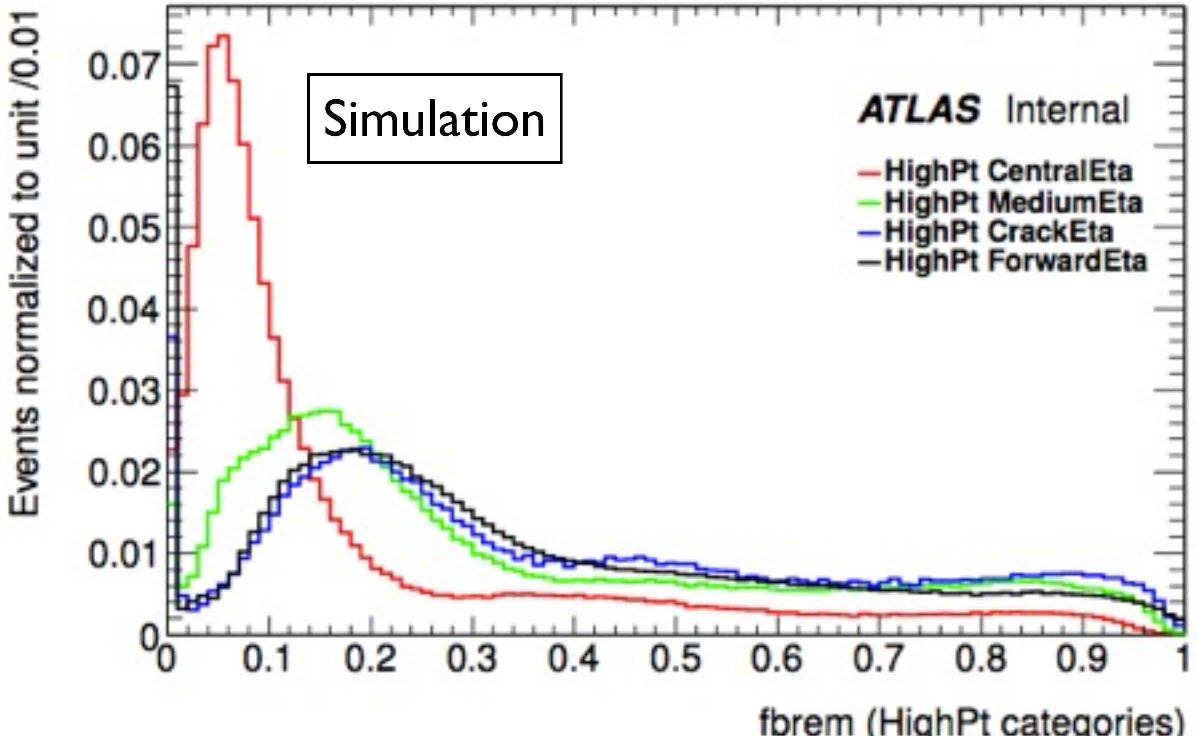
Likelihood scan for H→γγ and H→ZZ→4lep. The dashed line shows the statistical component of the mass measurement

Likelihood contours as a function of the normalized signal yield μ and the Higgs mass for ZZ and γγ as well as their combination.



Electron categories for the combination

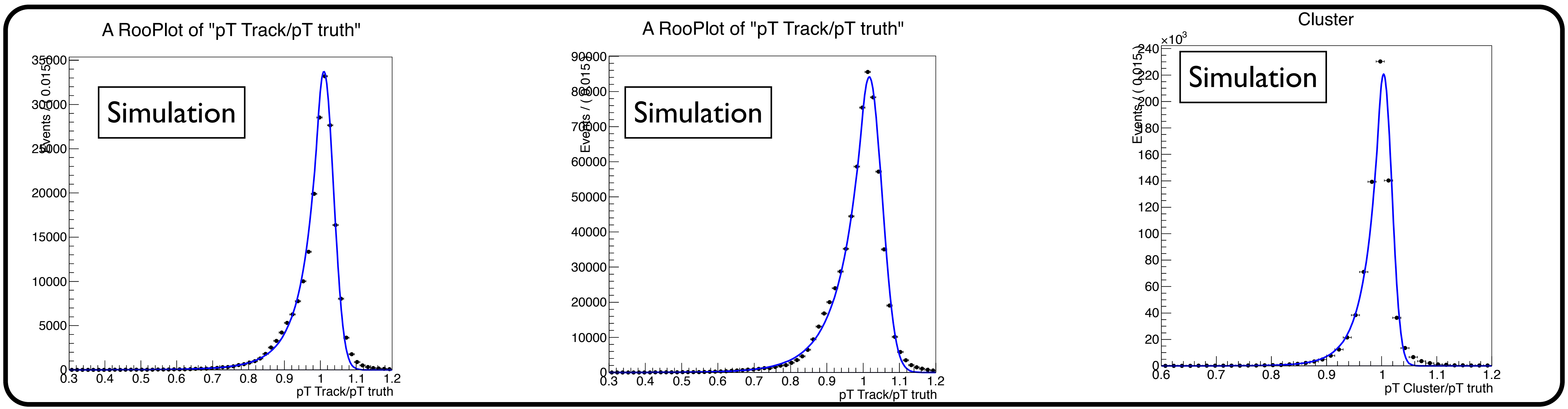
- Electrons are placed in categories according to their transverse momentum and pseudorapidity values:
  - LowPt ($7 < pT < 15$ GeV), mediumPt ($15<pT<30$ GeV) and highPt ($pT>30$ GeV) regions;
  - CentralEta ($0<|\eta|<0.7$), MediumEta($0.7<|\eta|<1.37$), CrackEta ($1.37<|\eta|<1.52$) and ForwardEta ($1.52<|\eta|<2.5$) regions.
- Another categorization is exploited using fbrem variable:
  - this variable takes into account the amount of bremsstrahlung the track has experienced in the Inner Detector.
  - fbrem= $((q/p)_{Fin}-(q/p)_{In}) / (q/p)_{Fin}$



Track and cluster - The combination algorithm

- Maximum-likelihood fit:
  - combination of track and cluster information.
- Extracted some parameters (from simulation) of the distributions (mean value, σ etc.) of p_T track/p_T truth and p_T cluster/p_T truth (fitted with a CrystalBall function)

Some examples of the input distributions

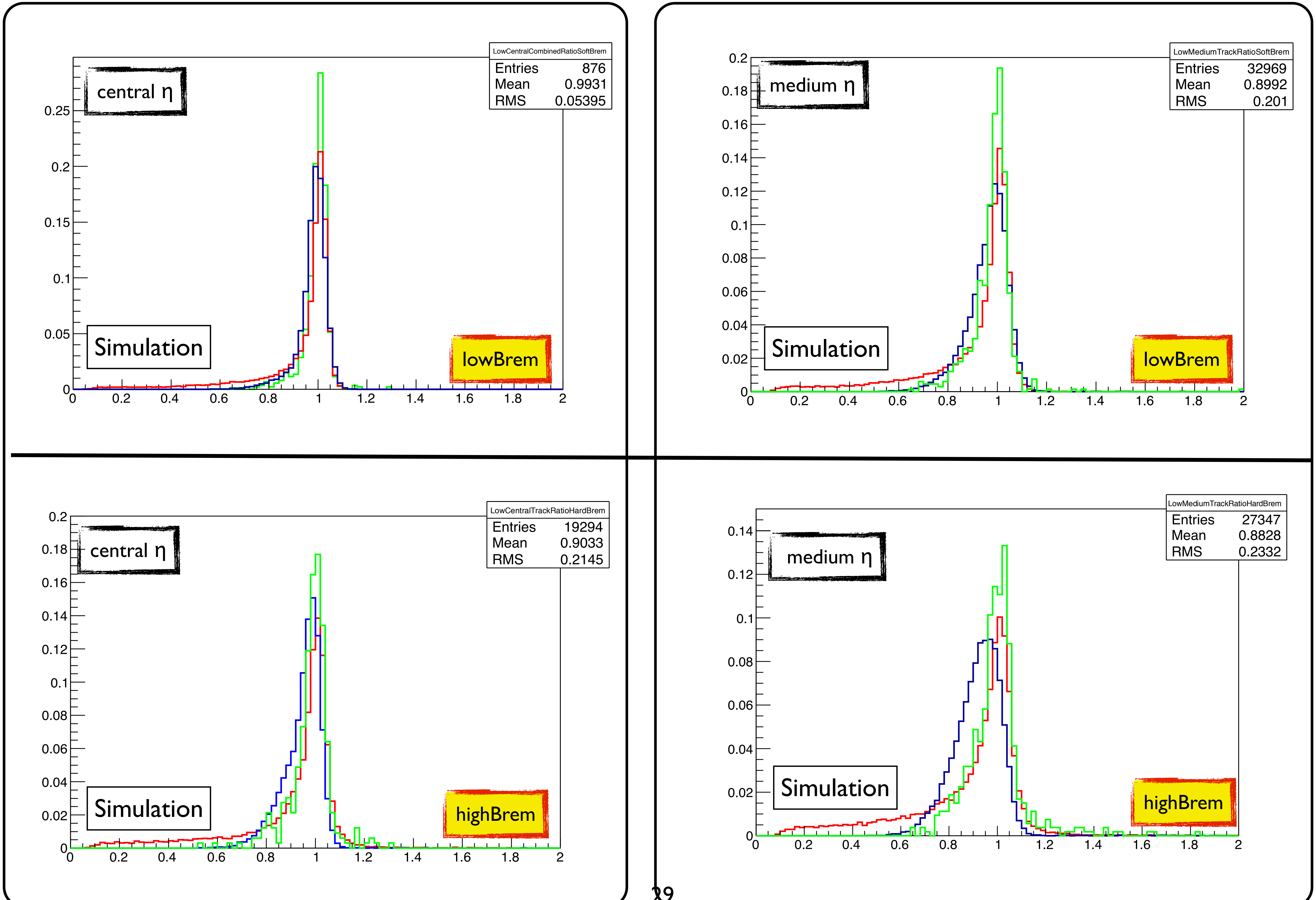


PtTrack/PtTruth

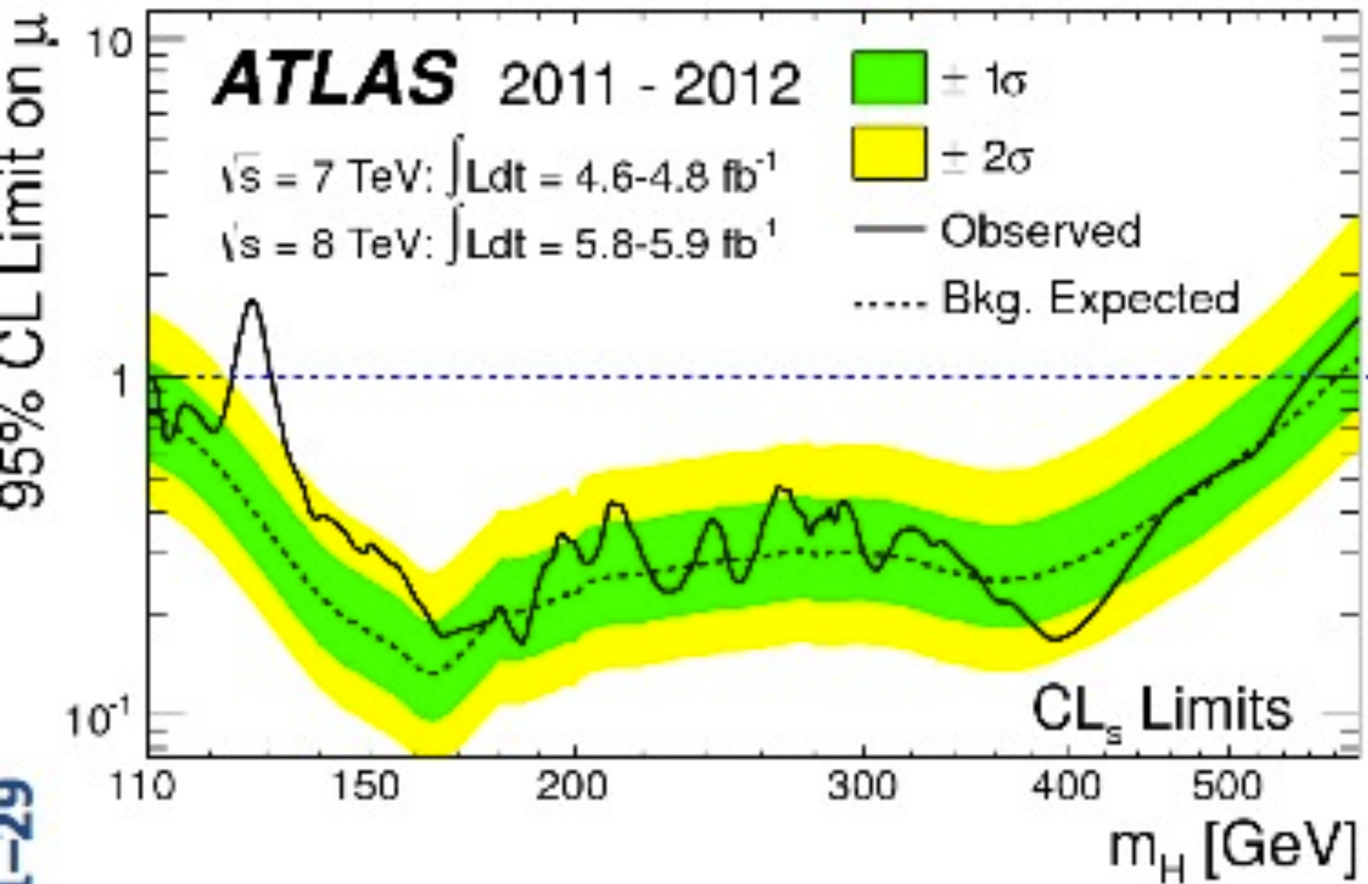
PCluster/PtTruth

Single Electron (LowPt)

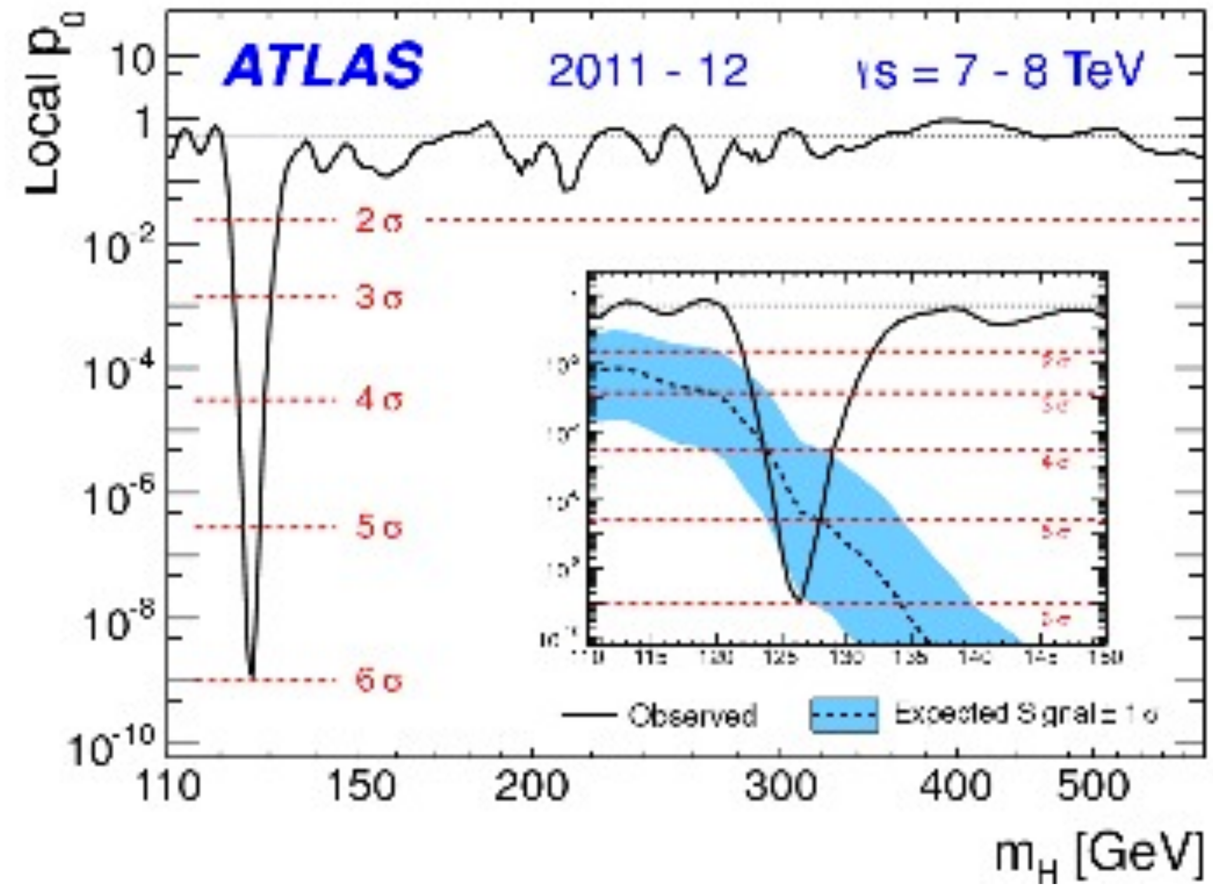
PtCombined/PtTruth



H→ZZ→4lep - 2012



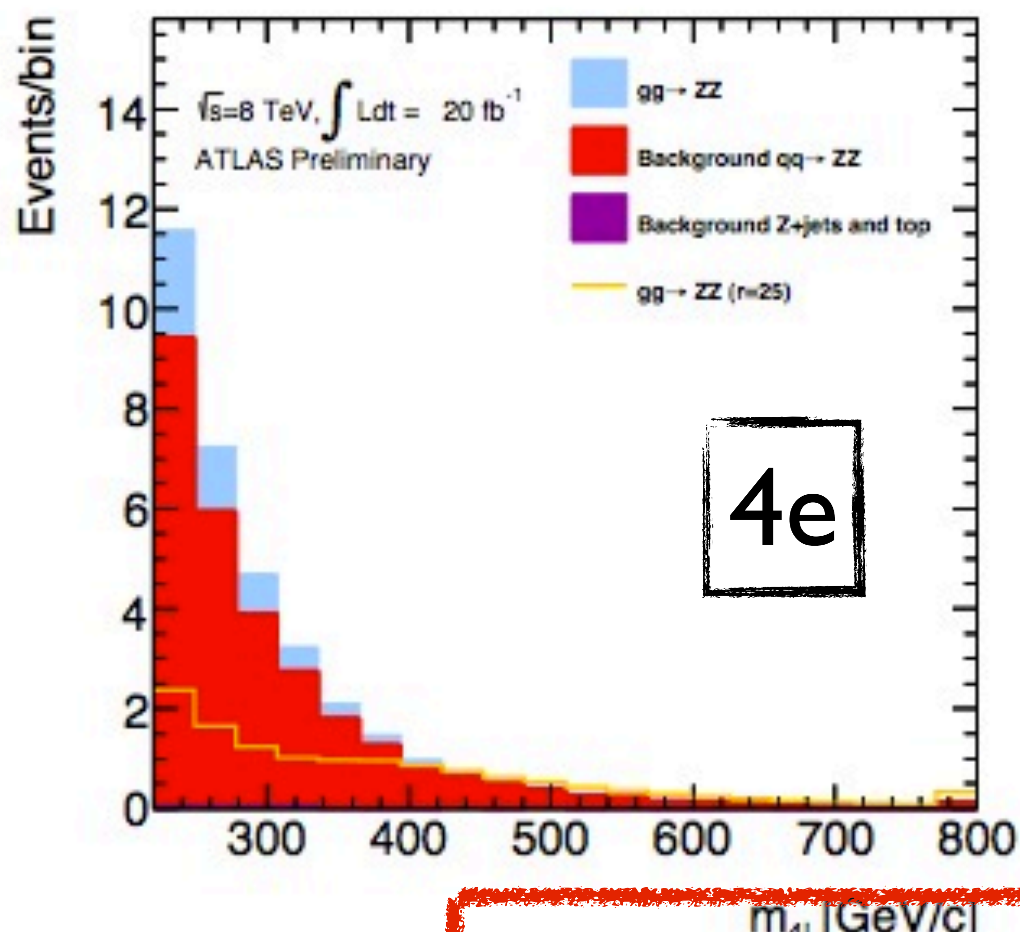
Observed and expected CLs limit on the normalized signal strenght vs Higgs mass

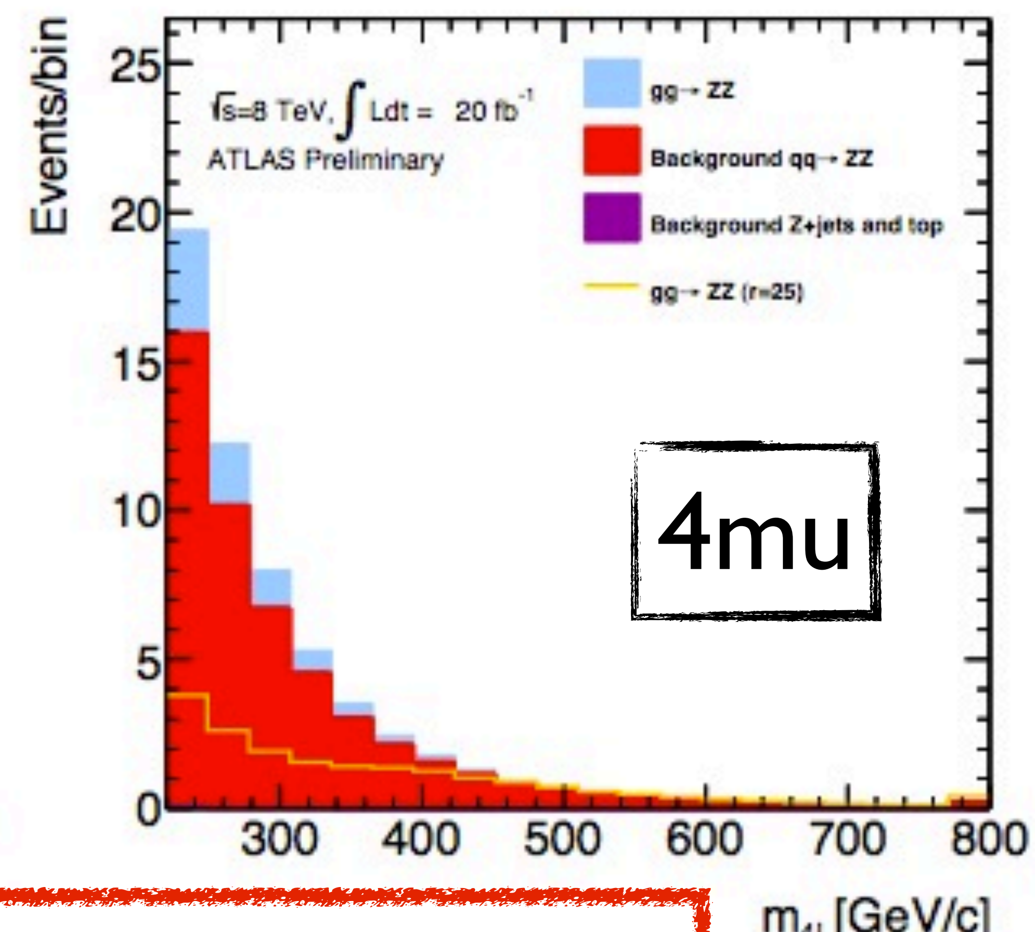


Observed and expected pvalue vs Higgs Mass

Analysis Strategy (3)

sample	$2\mu 2e$	$2e2\mu$	4μ	$4e$	TOTAL
$gg \to H \to ZZ$	0.48 ± 0.00	0.60 ± 0.01	0.62 ± 0.00	0.45 ± 0.00	2.15 ± 0.01
$gg \to ZZ$ (S+B+I)	7.28 ± 0.04	7.14 ± 0.04	9.01 ± 0.03	5.67 ± 0.02	29.10 ± 0.06
$gg \to ZZ$ (Int)	-0.81 ± 0.05	-1.00 ± 0.05	-1.06 ± 0.04	-0.70 ± 0.03	-3.57 ± 0.08
$qq \to ZZ$	38.14 ± 0.27	37.00 ± 0.27	48.87 ± 0.26	28.52 ± 0.19	152.53 ± 0.50
$gg \to ZZ)$ (B)	7.61 ± 0.03	7.54 ± 0.03	9.45 ± 0.03	5.93 ± 0.02	30.52 ± 0.06
Reducible	0.24 ± 0.05	0.07 ± 0.01	0.09 ± 0.01	0.21 ± 0.05	0.61 ± 0.07
Total Backgrounds	45.98 ± 0.28	44.61 ± 0.27	58.41 ± 0.26	34.66 ± 0.20	183.66 ± 0.51
$gg \to ZZ$ (S+B+I, $25\Gamma_H^{SM}$)	15.46 ± 0.06	17.37 ± 0.06	19.55 ± 0.05	13.27 ± 0.04	65.65 ± 0.11

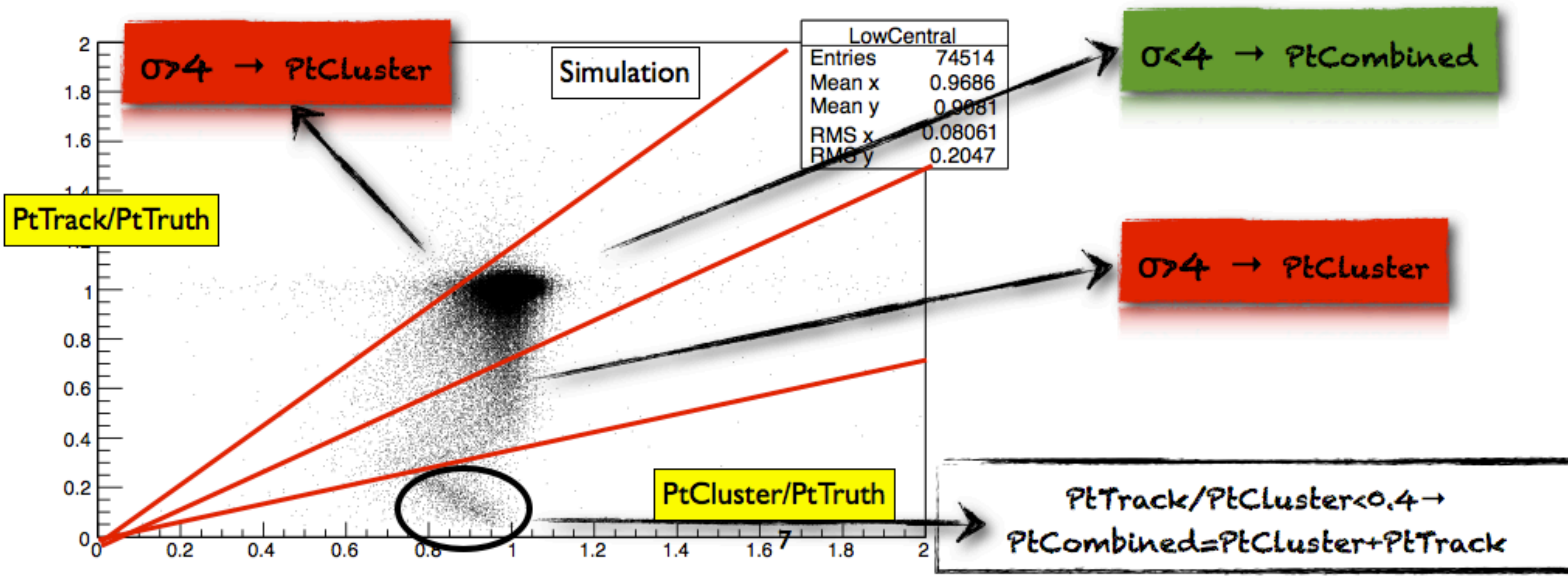




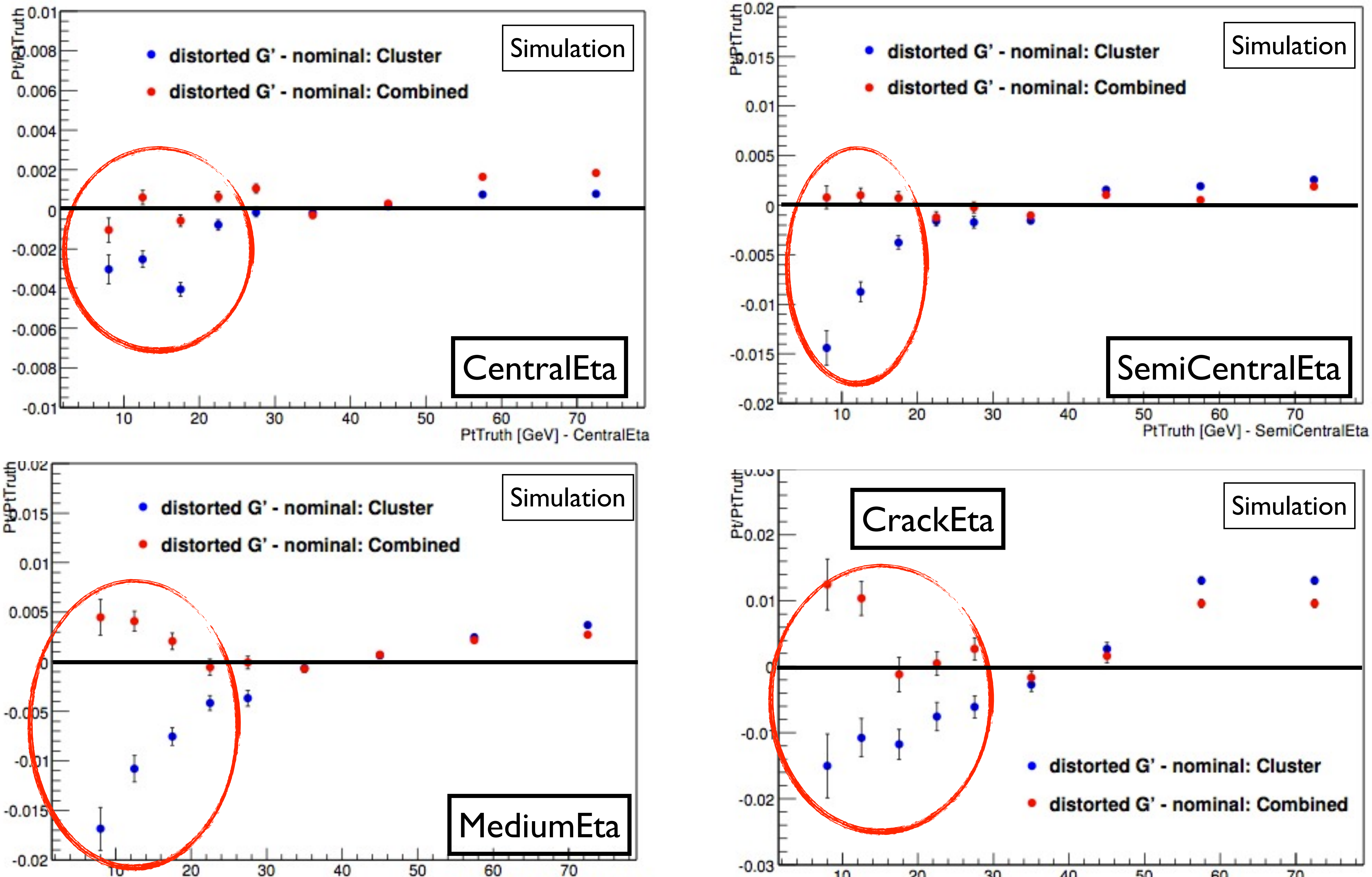
Stack plot of the various contributions

Summary of the algorithm

- A detailed study was pursued in order to define under which conditions/assumptions the Ep combination is to be applied.
- if → $\sigma = |ECluster - pTrack| / \sqrt{(\sigma^2_{ECluster} + \sigma^2_{pTrack})} < 4$ → PtCombined
- else → PtCluster
- if PtTrack/PtCluster<"0.4" (depends on the η- pt category)
  - →PtCombined=PtCluster+PtTrack



Linearity



The combined momentum (mostly in the low pt region) is less prone to material uncertainties.