Search for the Higgs boson in the channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$ with the ATLAS detector

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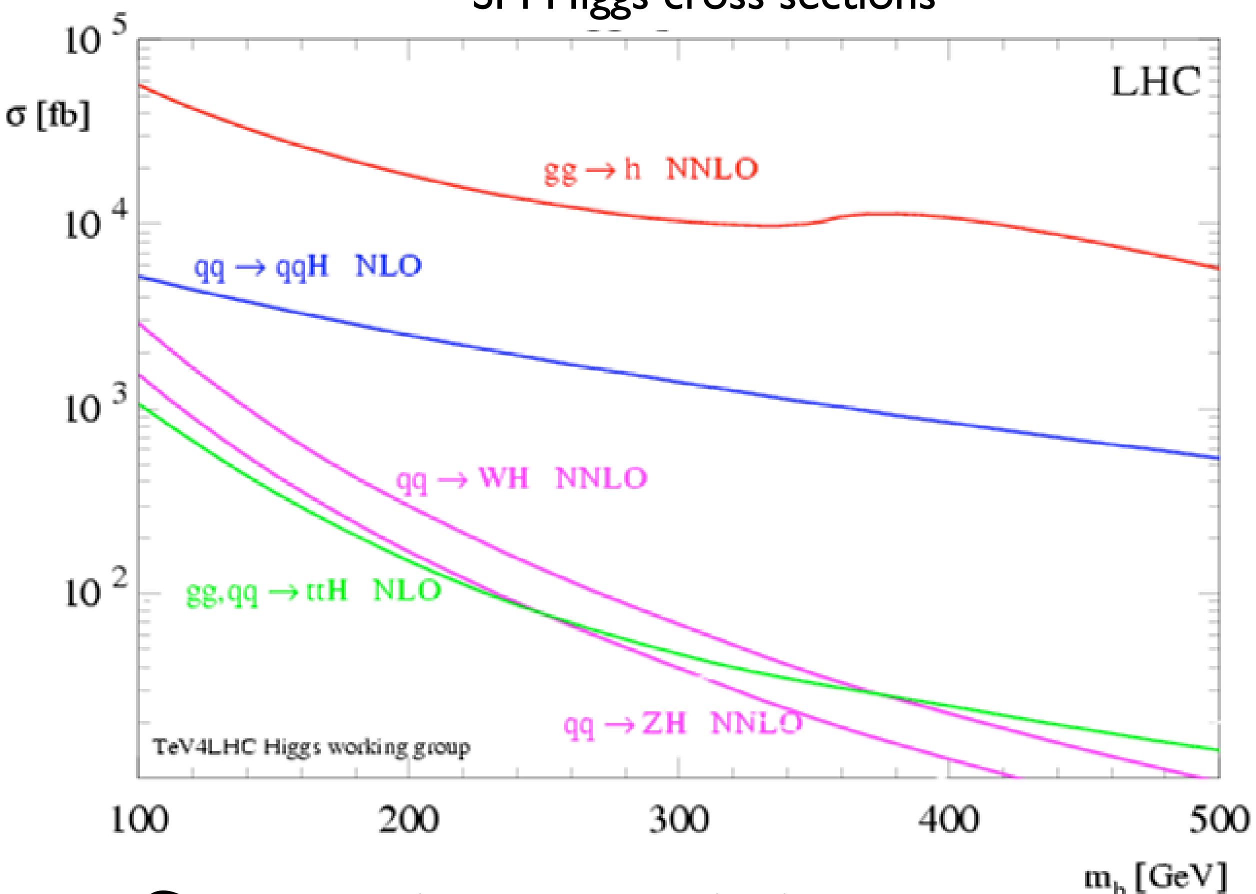
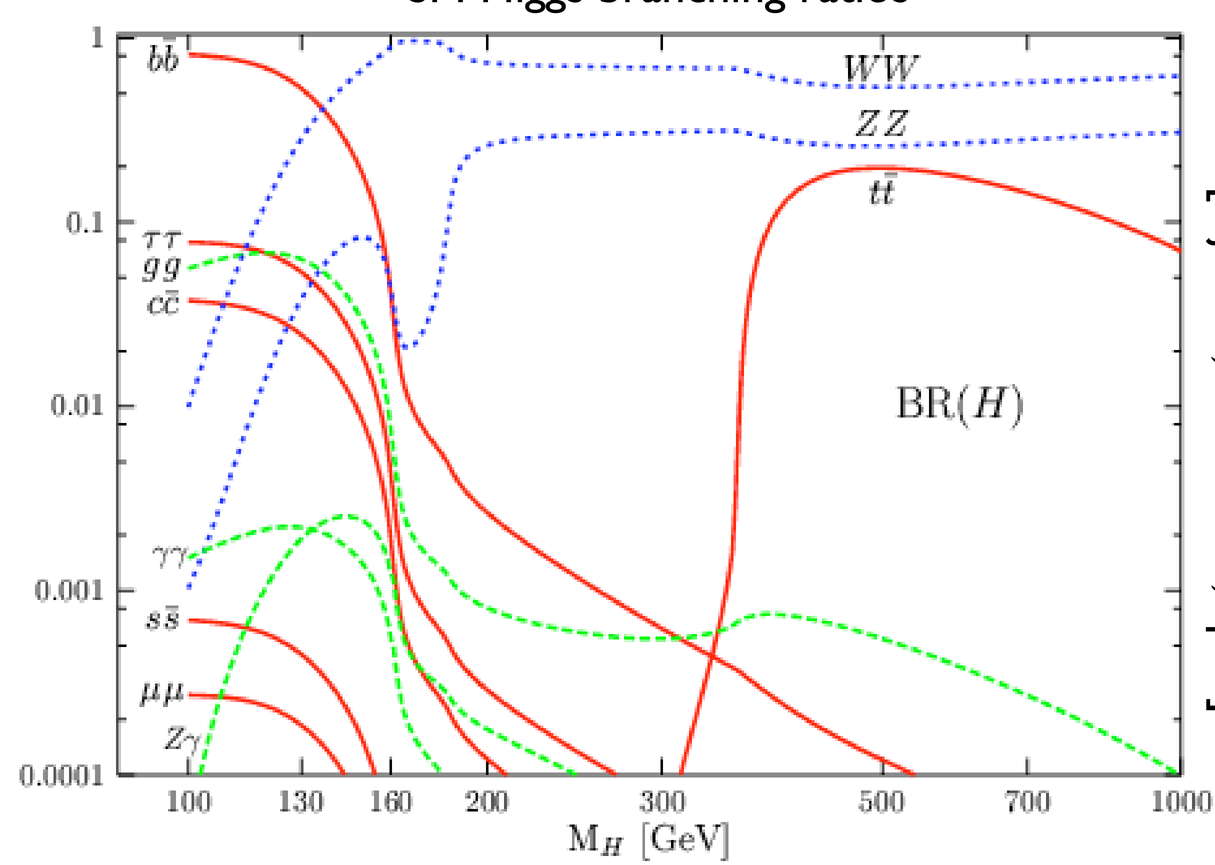
SM Higgs at LHC

- *Standard Model fit* : M_H < 182 GeV/c^2 @ 95% CL (including the LEP-2 direct limit)
- *Direct searches* at LEP-2 : SM Higgs lighter than 114.4 GeV/c^2 *excluded* at 95% CL

SM Higgs cross sections



SM Higgs branching ratios



[Djouadi, Kalinowski, Spira]

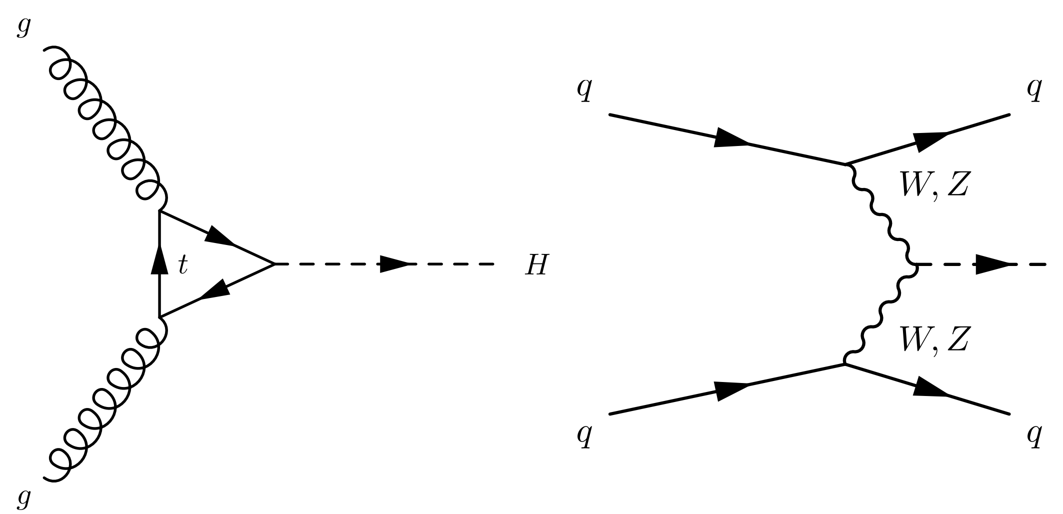
Cross section uncertainties:

gg fusion 10-20% (NNLO) tt fusion 10% (NLO)

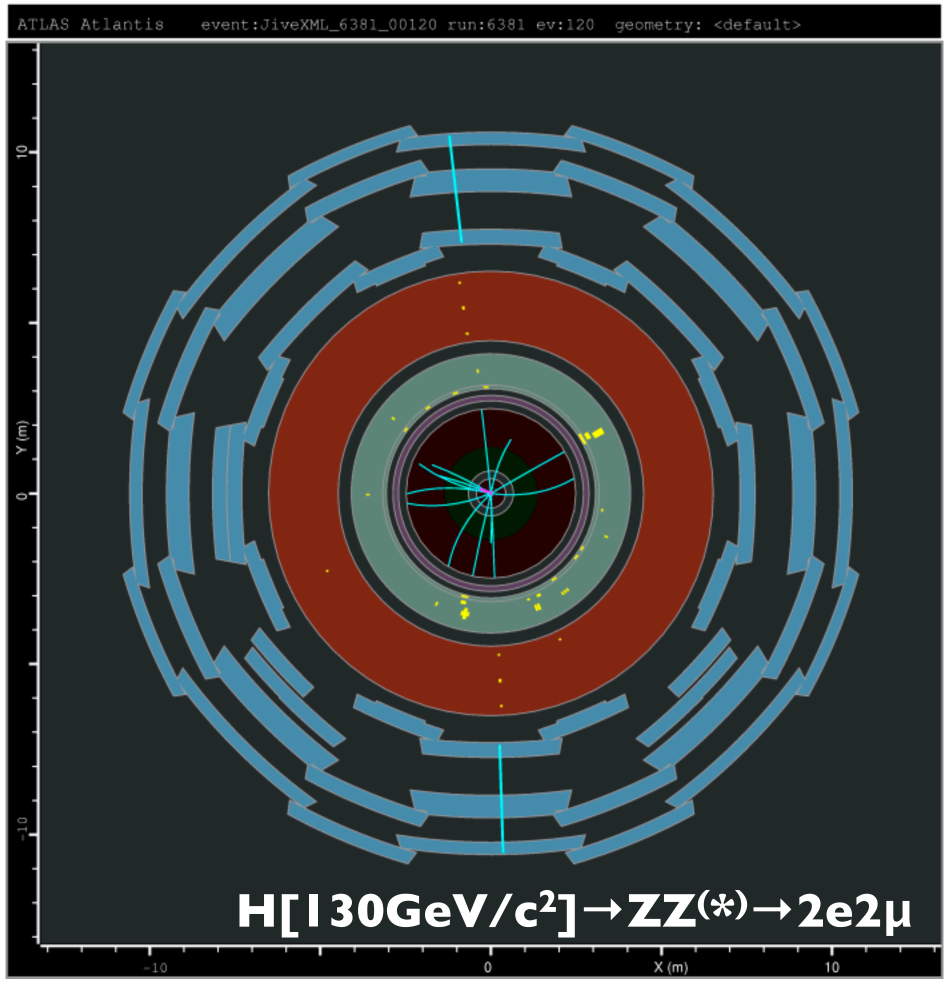
W, Z bremss <5% (NNLO) WW, ZZ fusion <10% (NLO)

Branching ratios known to NLO ⇒ few % uncertainty

H→4l Channel



main two productions channels considered (but no dedicated analysis for WW, ZZ fusion)



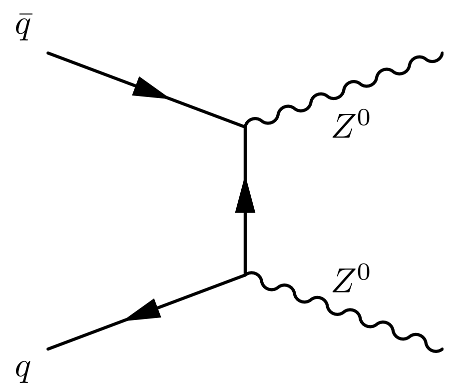
- H→ZZ$^{(*)}$→4l (l = e, μ) *clean channel at LHC*
- low signal cross section × BR but *narrow mass peak* and *low background*
- PYTHIA used to generate events - cross sections and BR known at NLO (HIGLU, HQQ,V2HV, VV2H, HDECAY)

Process	$\sigma_{LO} \cdot$ BR [fb]	$\sigma_{NLO} \cdot$ BR [fb]
H[120]	1.68	2.81
H[130]	3.76	6.25
H[180]	3.25	5.38
H[200]	12.39	20.53
H[300]	7.65	13.32
H[600]	1.53	2.53

- H→ZZ$^{(*)}$→4l analysis: *three selections* 4e - 4μ - 2e2μ
- 12 mass points evaluated, from 120 to 600 GeV/c^2
- full detector simulation for signal (and backgrounds)

H→4l Backgrounds

irreducible background



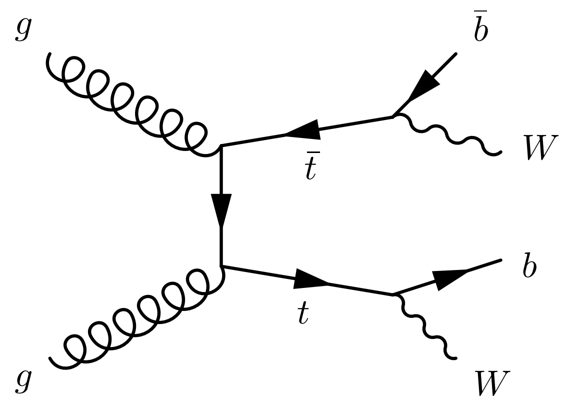
ZZ*/γ* →4l

PYTHIA rescaled to NLO (MCFM)

+30% for quark box diagram

σ_{NLO} × BR = 34.8 (K[M_{ZZ}] + 0.3) fb

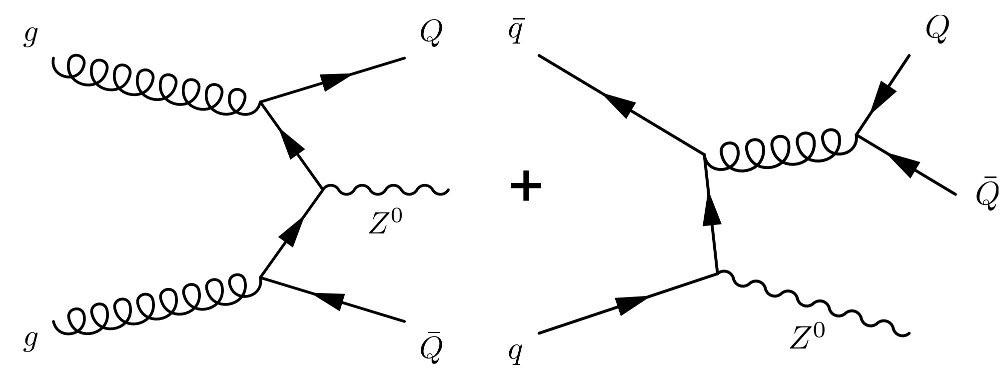
reducible backgrounds



tt →4l

MC@NLO

σ_{NLO} × BR = 6.1 pb



Zbb →4l

AcerMC rescaled to NLO (MCFM)

Kfactor = 1.42

σ_{NLO} × BR = 812.1 fb

- Additional backgrounds, especially in case of *pileup* (i.e. minimum bias events and of cavern background overlapped to hard collisions): **WZ→3l, Zbb→3l, Z+jets**
- cross sections including 4 lepton filter efficiency (p_T > 5 GeV/c and $|\eta|$ < 2.7)
- QCD scale and pdf uncertainties evaluated

σ_{NLO} for Background Processes

- all MC generators used to produce background samples are *LO* (apart from MC@NLO) and not always including all the diagrams
- CSC exercise: *aim for NLO evaluation of physics potential* (improvement w.r.t. the TDR) ⇒ need to evaluate NLO cross sections for all backgrounds

Technique: once selected the phase space, use MCFM program for the NLO cross section calculation and apply corrections to take into account missing sub-processes (e.g. gg→ZZ, and qq→Zbb)

Overall parameter choice:

- pdf set CTEQ6 (CTEQ6L1 for the LO and CTEQ6M for the NLO)
- uncertainties from the choice of renormalization and factorization scales estimated by increasing and decreasing the central scale value by a factor 2 - uncertainties on the pdf evaluated by making use of 40 sets of CTEQ6M (20 plus and 20 minus)
- EW corrections not included

Common background cross section reference: "*Cross sections for the Standard Model processes to be used in the ATLAS CSC Notes*", ATL-COM-PHYS-2008-077
editors: D. Rebuzzi, M. Schumacher

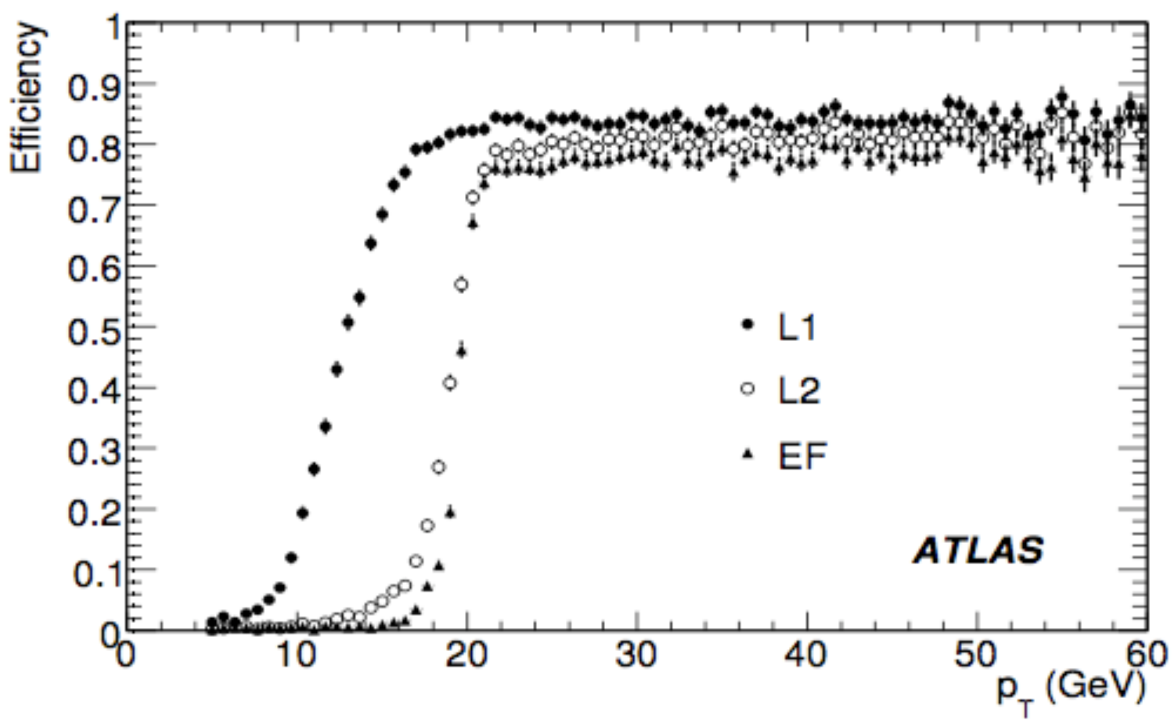
Trigger Selection

- impact of the three-level ATLAS trigger chain on H→4l search evaluated
- just events fulfilling a given trigger selection are kept (only electron and muon trigger slices)

- **Trigger Menus for H4l:** *single or dilepton triggers*
  - single lepton triggers suited for low luminosity (10^{33} $cm^{-2}s^{-1}$)

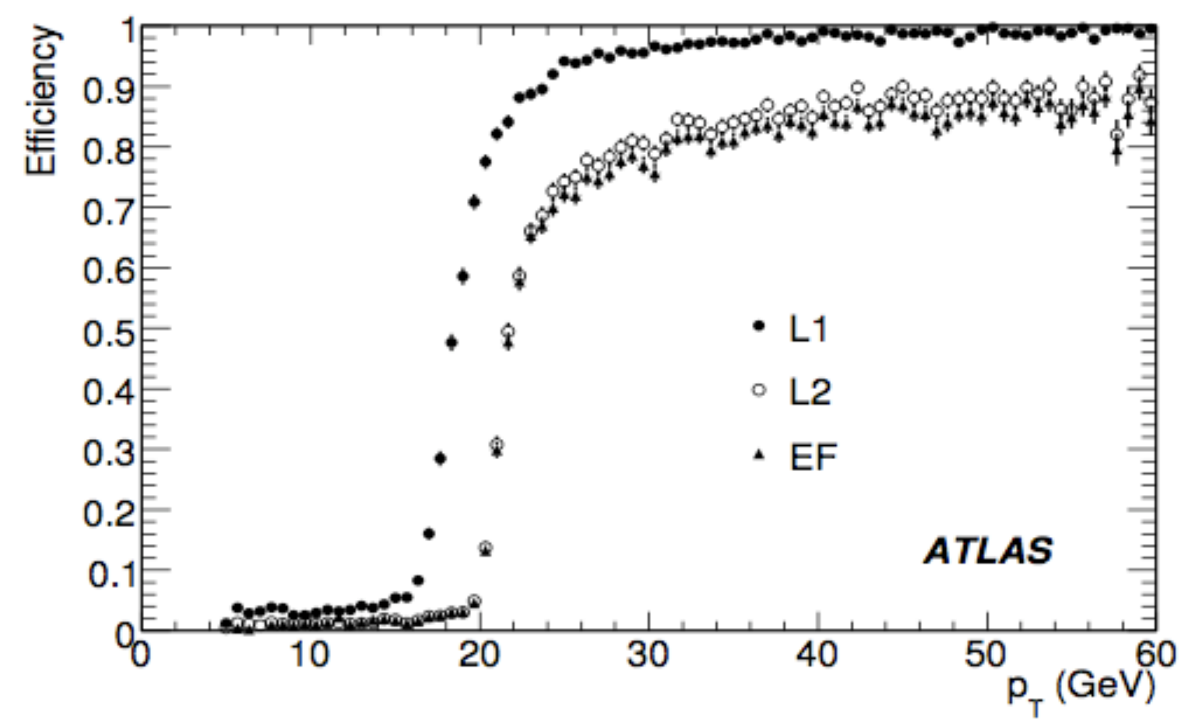
Muon Trigger

selection efficiencies for p_T^{thres} = 20 GeV/c



Electron Trigger

selection efficiencies for E_T^{thres} = 22 GeV/c^2



- *single lepton trigger (1µ20 or 1e22i, default in H→4l analysis) efficiency on H→4l decays > 98%*
- *a di-lepton trigger (2µ10 or 2e15i or 1µ10 and 1e15i) with 10 GeV/c for the muons and 15 GeV/c^2 for the electrons (isolated) selects H→4l decays with efficiency higher than 97%*

Lepton Reconstruction

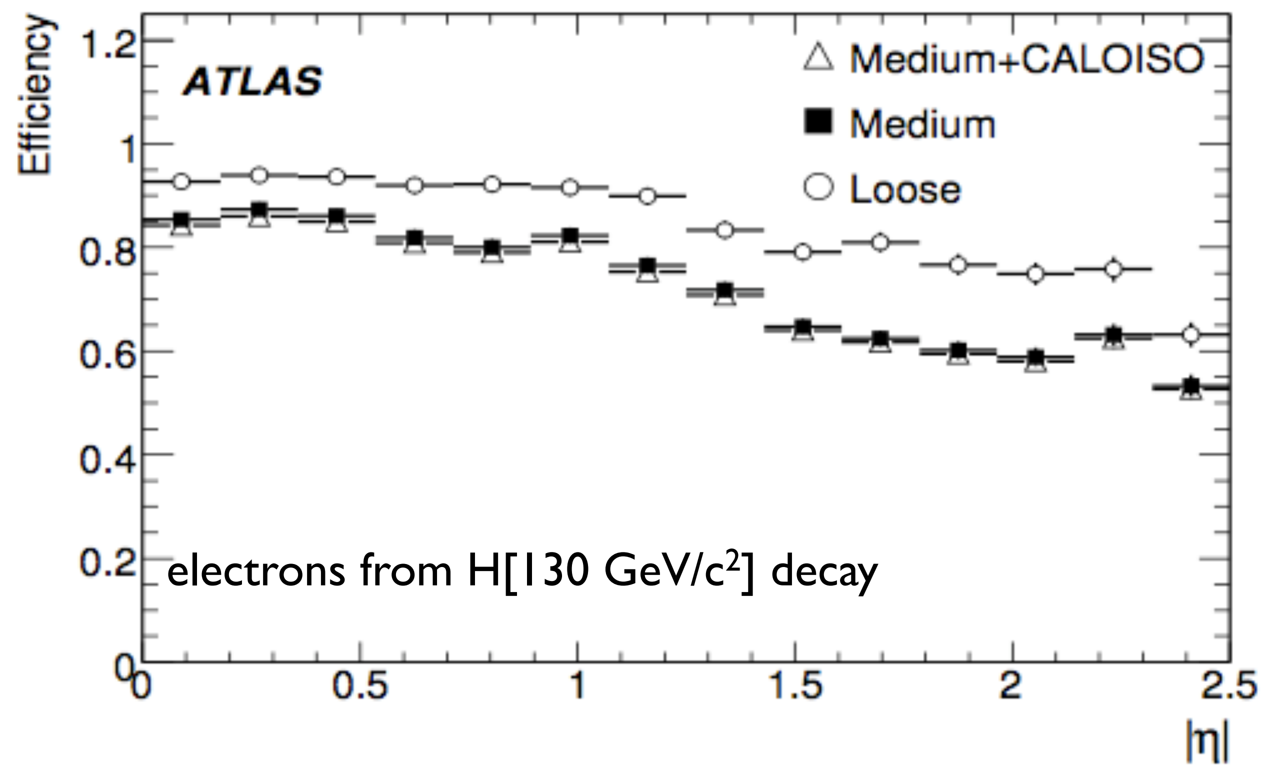
Electrons: ID and EM Calo information

LooseElectron = isolated and contained LAr EM cluster matched to an ID track

MediumElectron = additional LAr EM Calo strip information + ID track quality requirements

Calo-Iso = calorimetric isolation using EM and hadronic cells inside a $\Delta R = 0.4$ cone

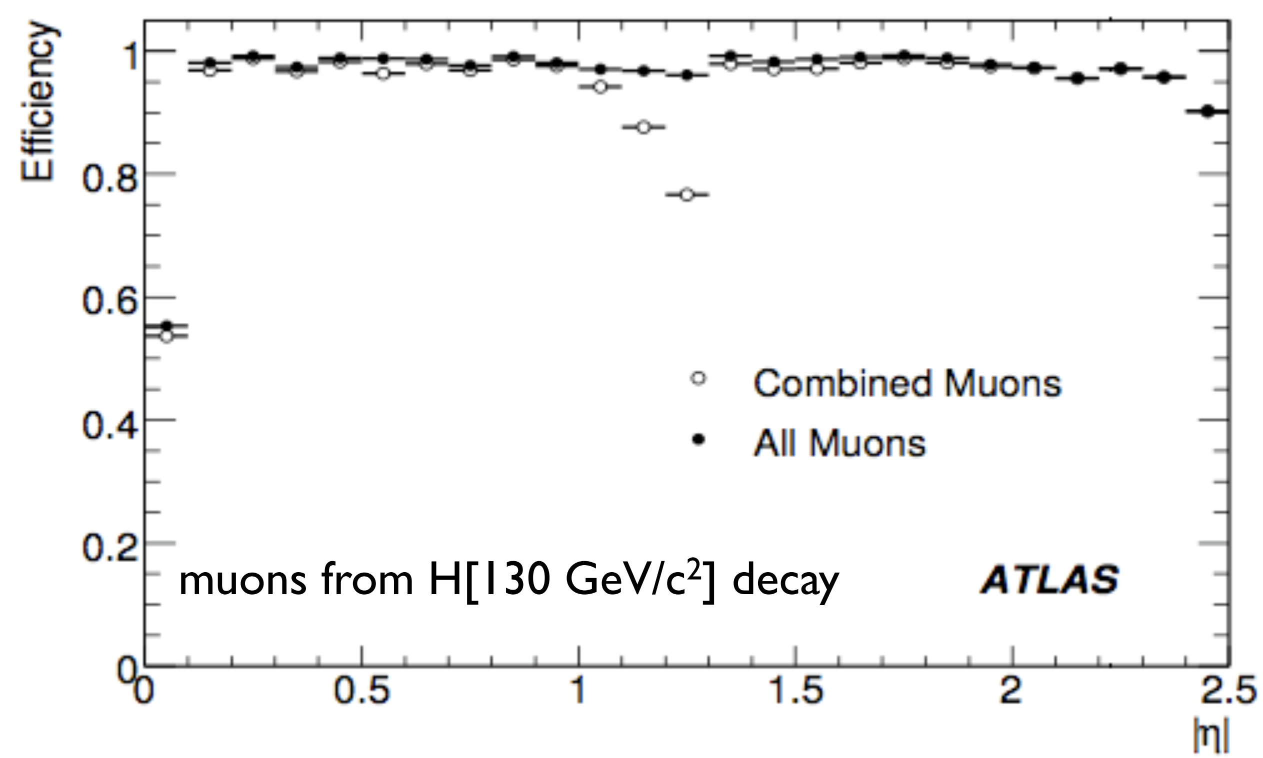
non-Z e^+/e^- 1% - fakes 8% for $p_T < 15$ GeV/c



Muons: combination of Muon Spectrometer and ID tracks

CombinedMuon = Muon Spectrometer track matched to an ID one

low-pTMuon = ID track extrapolated to a Inner (or Middle) Station muon track segment



Selecting Higgs Events

a) Event Preselection

1. lepton quality and kinematical cuts

Muons
combined or low-p_T
$p_T > 5$ GeV/c and $\lvert\eta\rvert < 2.5$

Electrons
at least *LooseElectrons*
$E_T > 5$ GeV/c^2 and $\lvert\eta\rvert < 2.5$

2. creation of lepton pairs

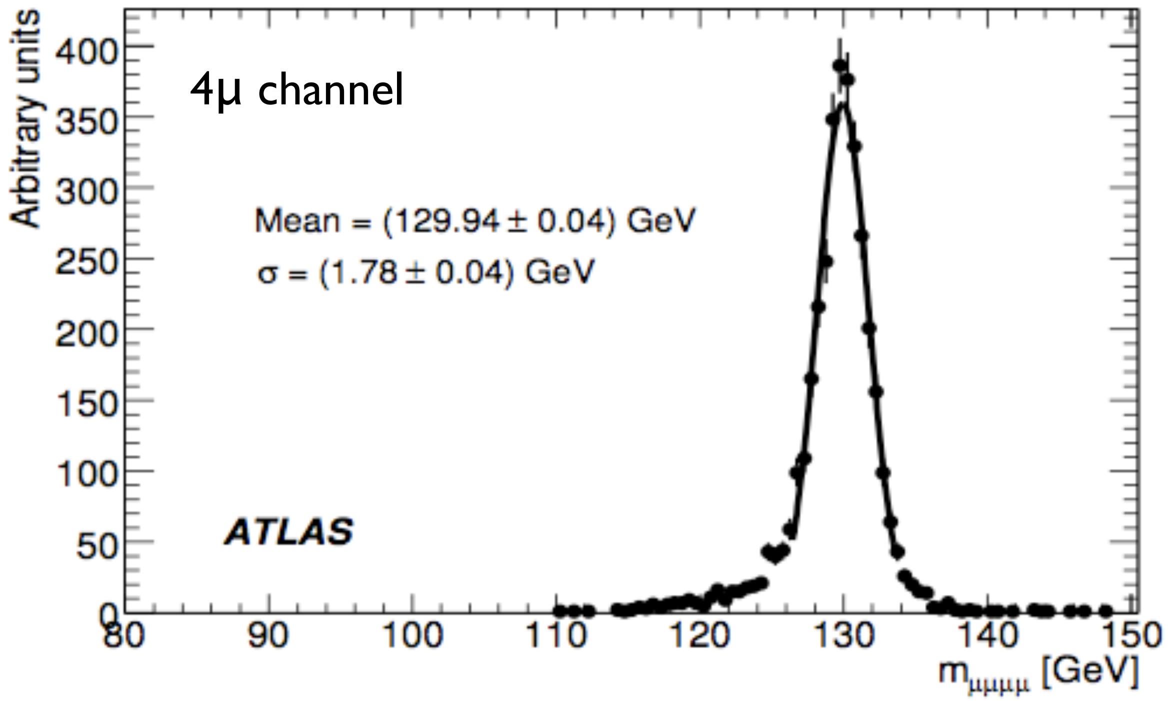
- p_T (E_T) > 7 GeV (GeV/c^2) and $|\eta| < 2.5$
- at least two leptons with p_T (E_T) > 20 GeV/c (GeV/c^2)

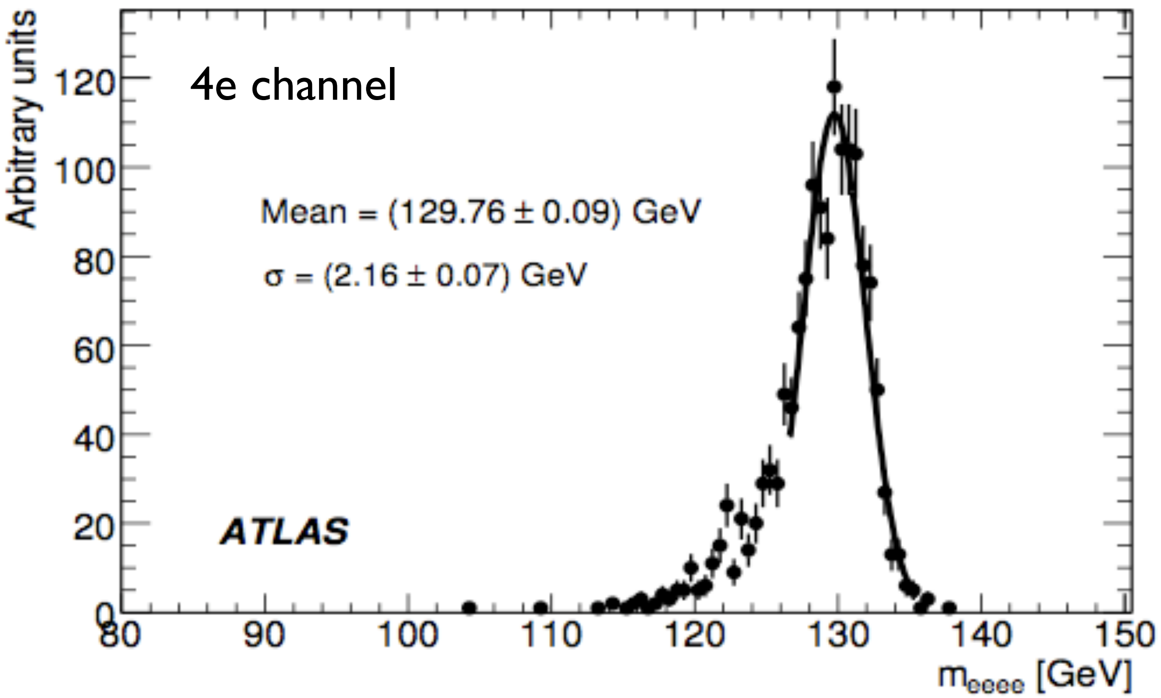
b) Event Selection

1. *four leptons (e,μ) in pairs of opposite charge and same flavor*
2. electrons: *additional lepton pair quality*
   for $M_H < 200$ GeV/c^2 : *MediumElectrons* + *CaloIsol*
   for $M_H > 200$ GeV/c^2 : *LooseElectrons*
3. *Z mass constraint* (i.e. Breit-Wigner + Gaussian distribution, with σ equal to Z experimental resolution) - applied to both Z's if $M_H > 200$ GeV
4. *Kinematic cuts on Z objects*
5. *Higgs mass window* $M_H \pm 2\sigma_{MH}$

Higgs Mass Reconstruction

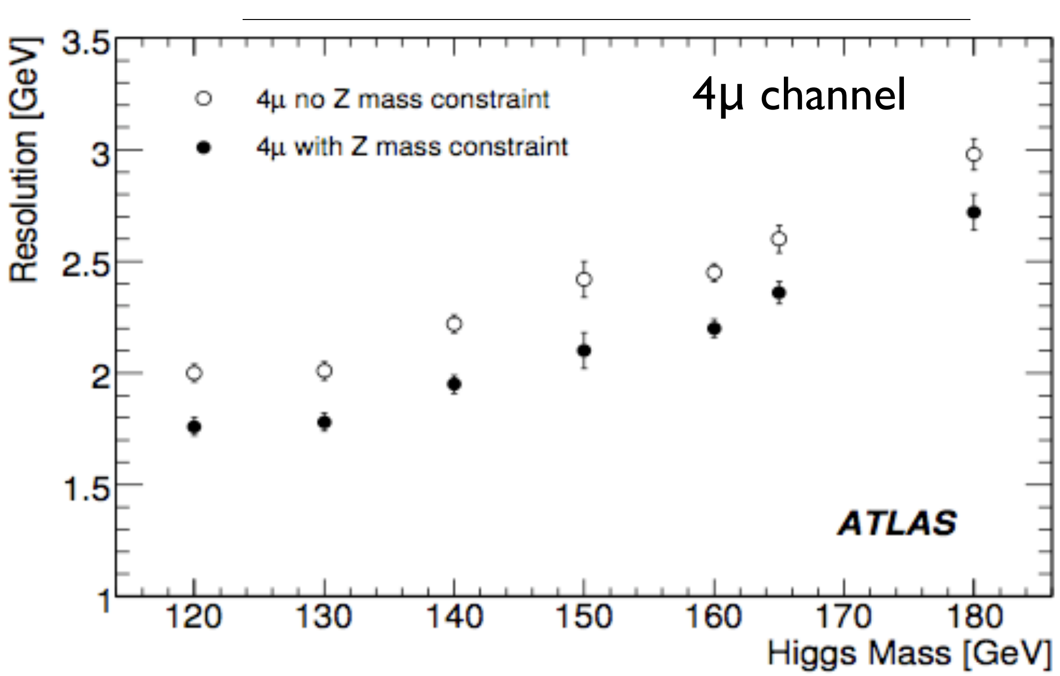
M_H=130 GeV/c^2 - Z mass constraint applied





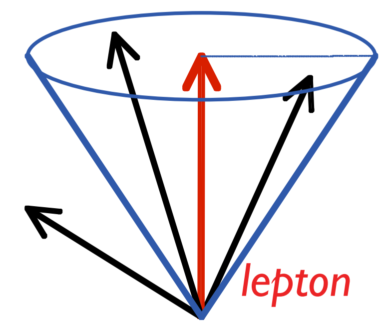
- Z mass constraint *improves mass resolution by 10-17% for M_H < 200 GeV/c^2*
- for low Higgs masses (intrinsic Higgs width < 1GeV/c^2) *experimental resolution is crucial for discovery*
- *for electrons, a +1% energy scale correction is also needed*

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel: detector performance benchmark



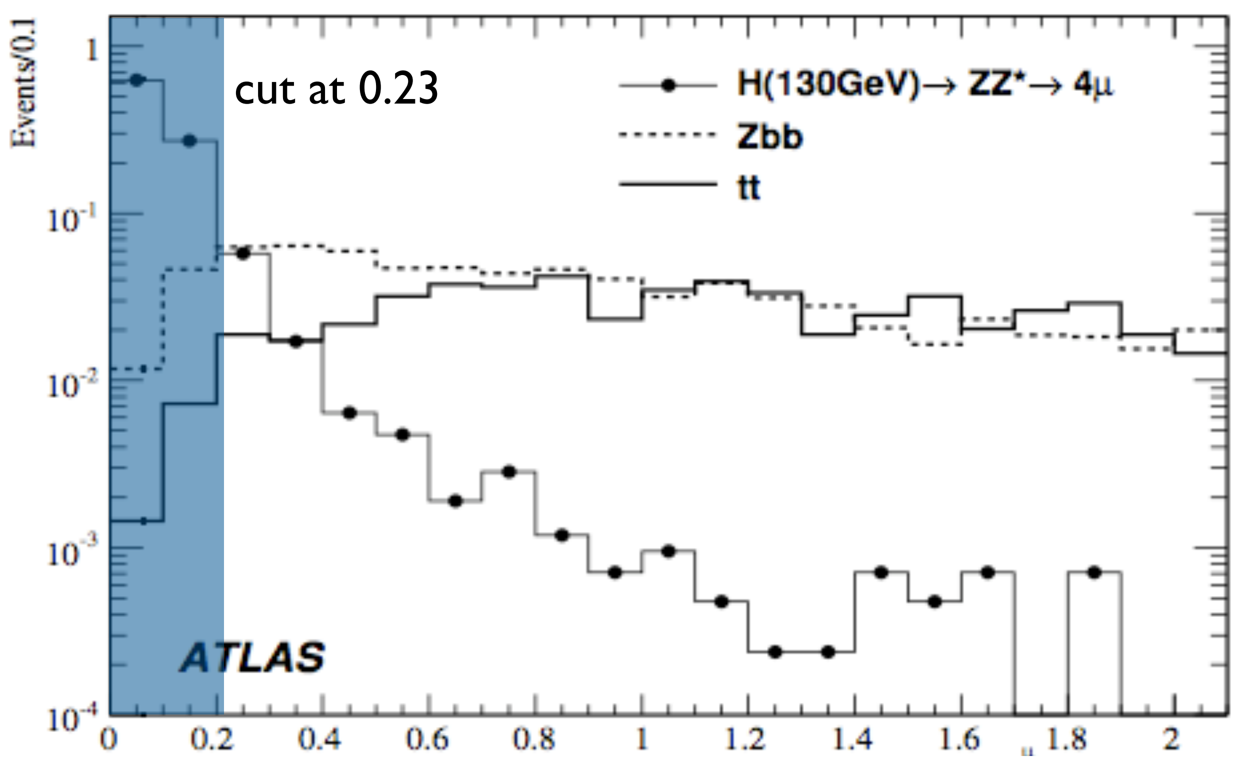
Background rejection: Lepton Isolation

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



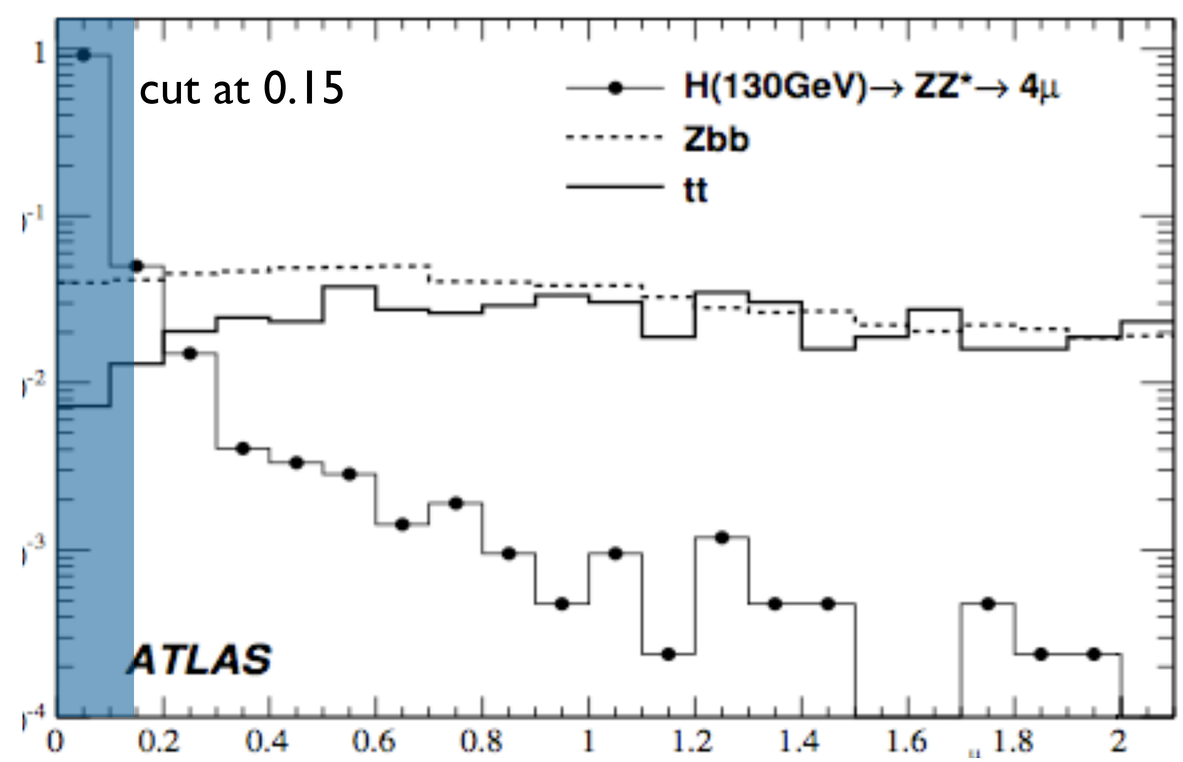
- Zbb and tt backgrounds: leptons from *b*-hadron decays ⇒ additional activity in calorimeters and the tracker
- **isolation variables**: *sum of p_T (or E_T)* in cone of ΔR / p_T (or E_T) of the lepton

calorimeter isolation - 4μ channel



maximum $\sum E_T/p_T$ - ΔR = 0.2

tracker isolation - 4μ channel

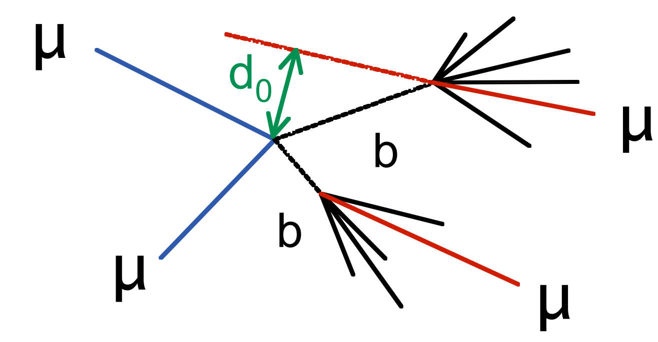


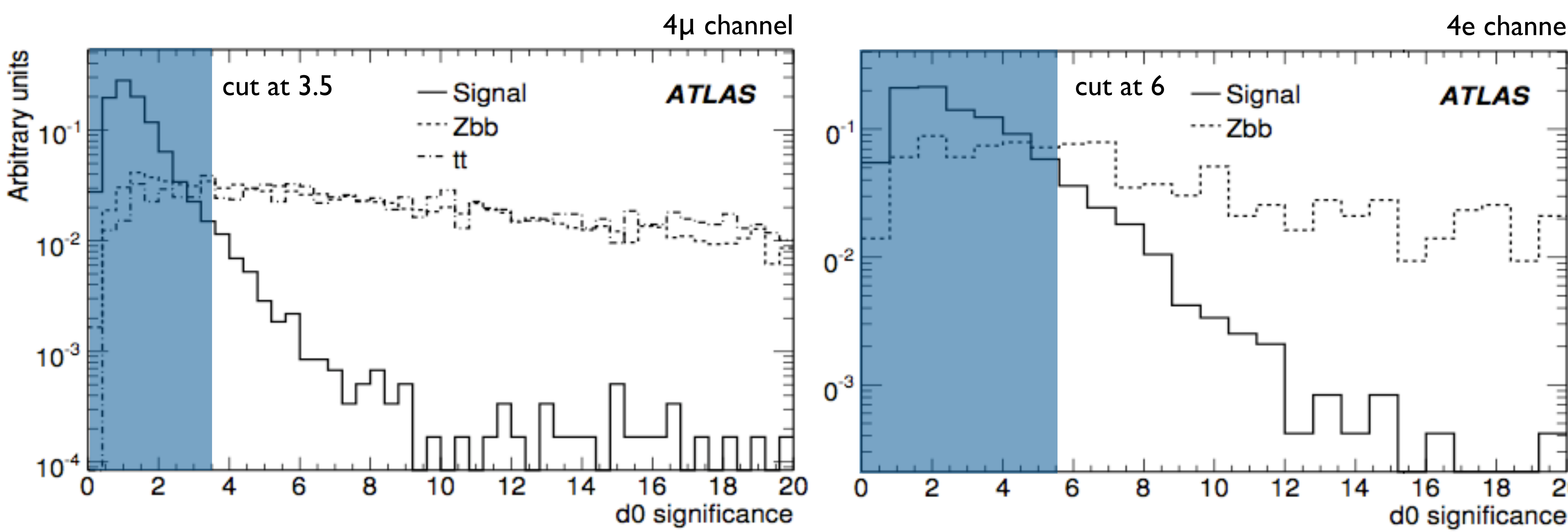
maximum $\sum p_T/p_T$ - ΔR = 0.2

signal efficiency 90% - background rejection ≈ 20

Background rejection: Impact Parameter

- *leptons from b, c*-hadrons not point to primary vertex
- **impact parameter variable**: *maximum impact parameter significance* d_0/σ_{d0} (d_0 = track distance of closest approach to the event vertex on the transverse plane)

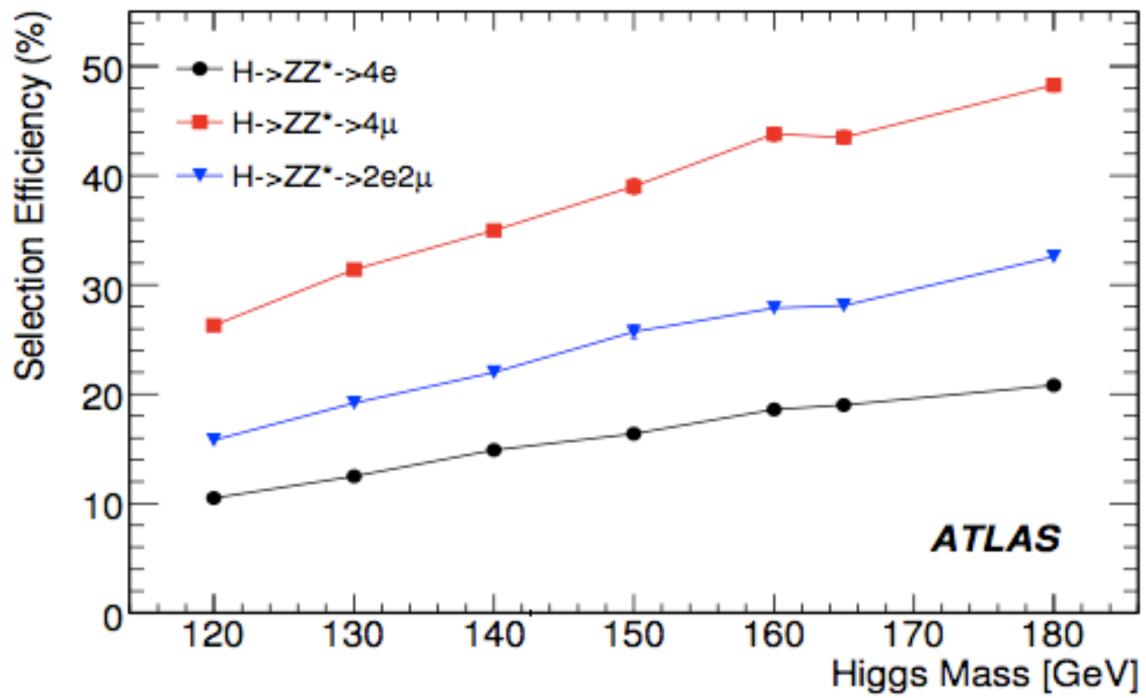


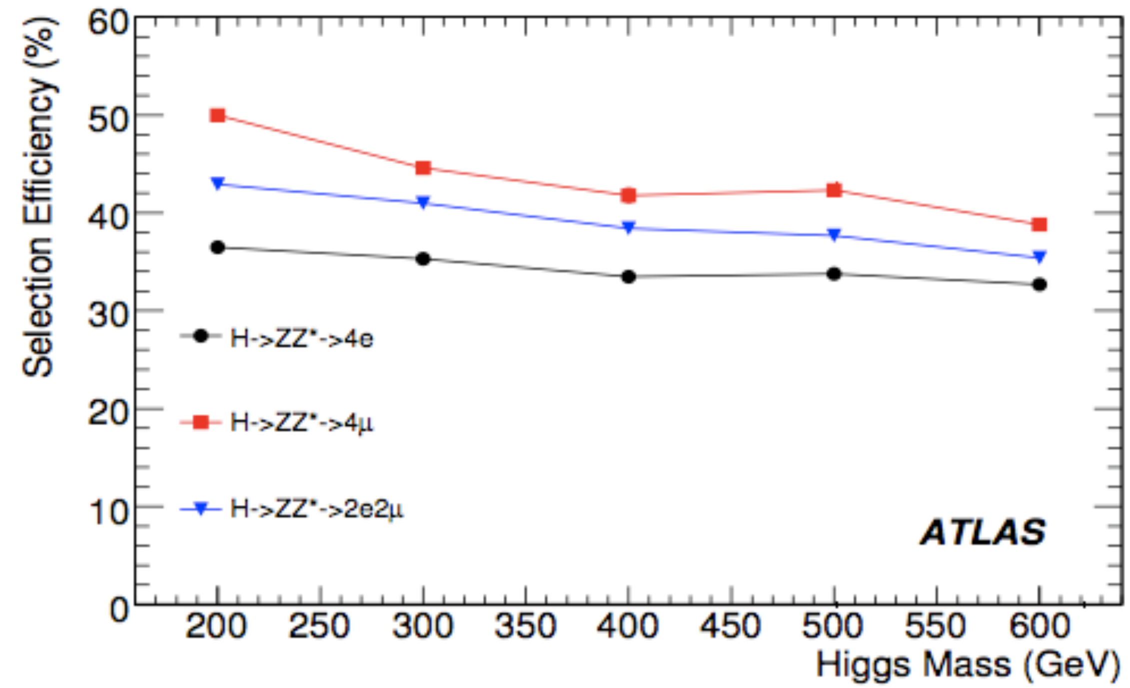


isolation + impact parameter cuts:
signal efficiency 80% - O(10^2) rejection for Zbb and O(10^3) rejection for tt

Selection Efficiencies

Selection efficiencies (%) on signal



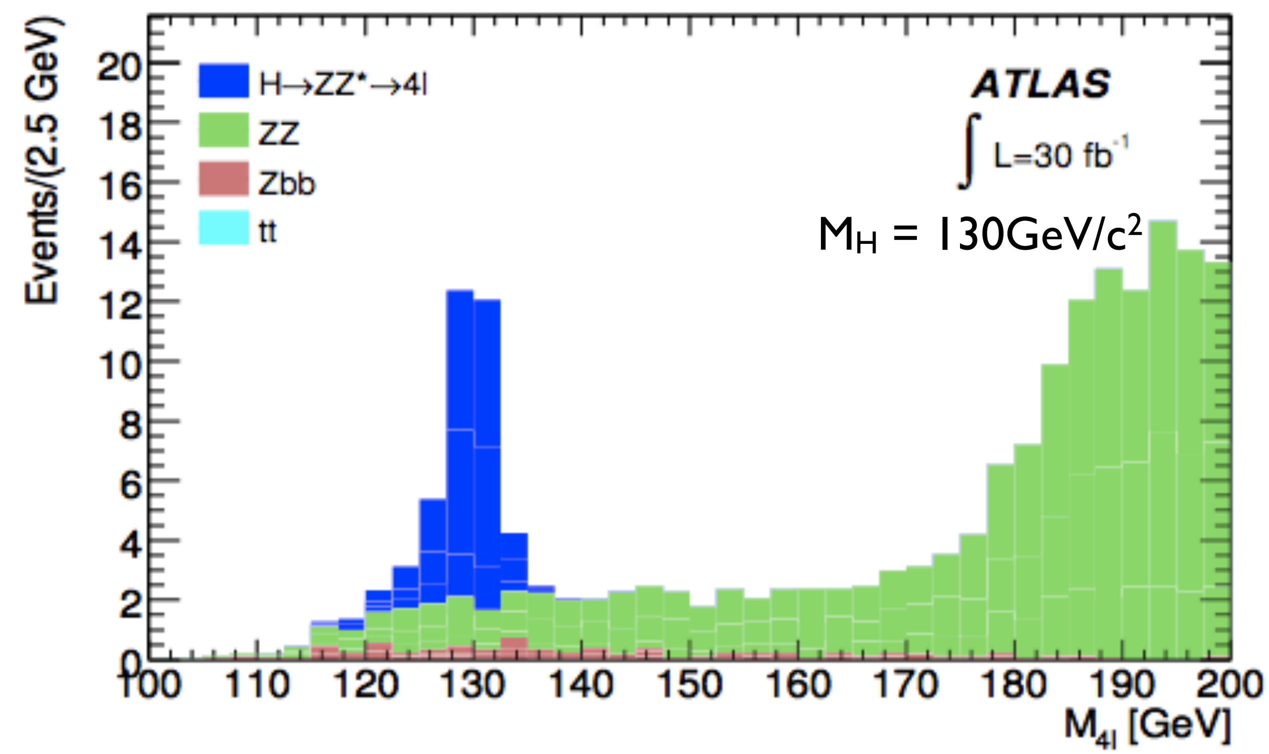


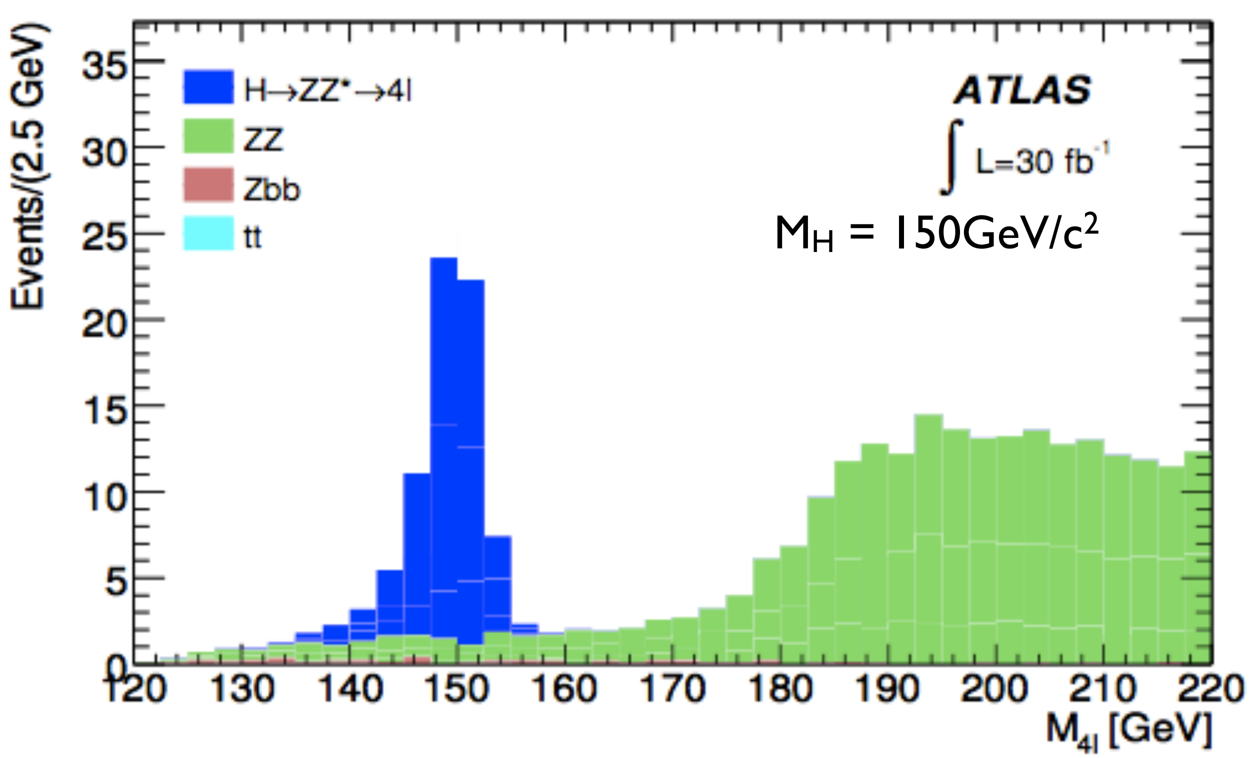
Selection efficiencies (%) on backgrounds - selections for M_H = 130 GeV/c^2

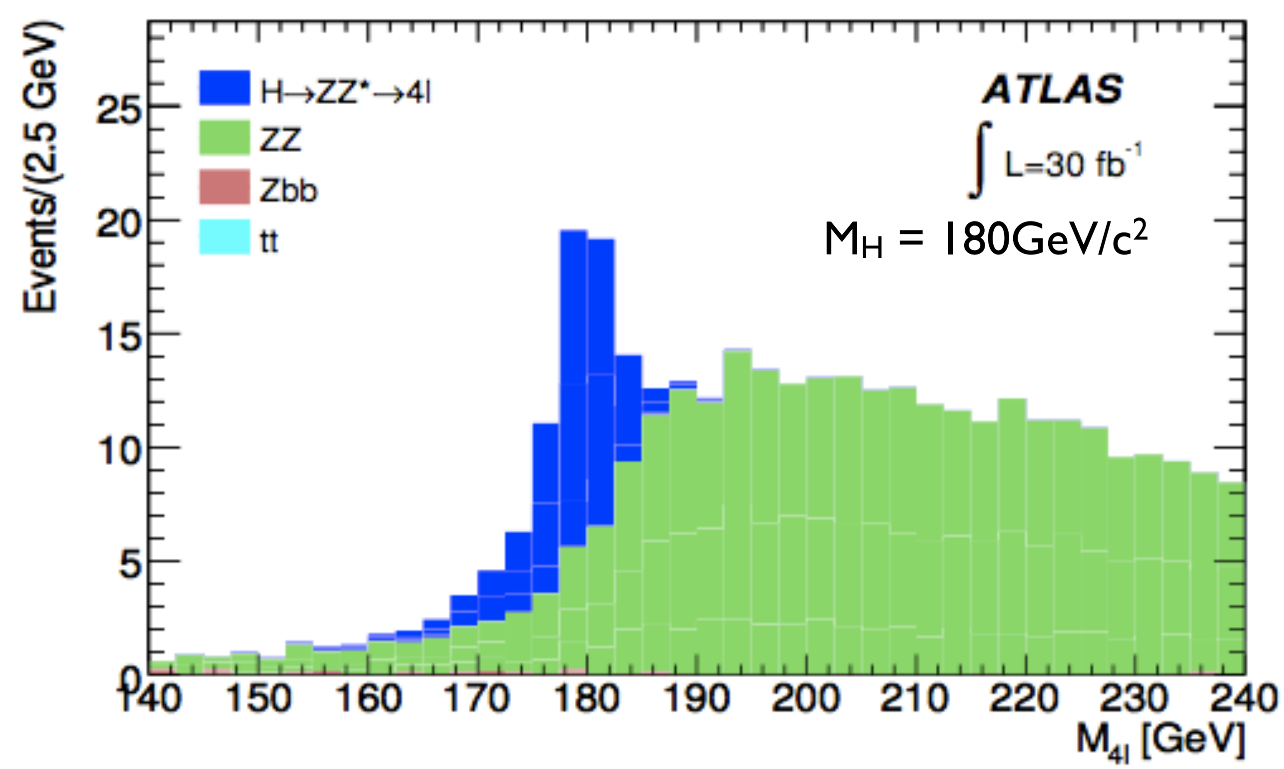
Selection cut	ZZ			Zbb			tt		
	4e	4μ	2e2μ	4e	4μ	2e2μ	4e	4μ	2e2μ
Trigger	96.6	96.6	96.6	91.4	91.4	91.4	75.1	75.1	75.1
Lepton presel	13.8	17.6	31.4	2.6	9.4	12.0	1.0	4.7	10.1
Lepton quality + p_T	7.3	16.0	21.9	$1.1\cdot10^{-1}$	2.1	1.7	$6.8\cdot10^{-3}$	$7.3\cdot10^{-1}$	$5.8\cdot10^{-1}$
Z's mass cut	6.9	14.8	20.2	$4.7\cdot10^{-2}$	1.1	$8.4\cdot10^{-2}$	$1.6\cdot10^{-3}$	$2.0\cdot10^{-1}$	$1.0\cdot10^{-1}$
Calo Isolation	6.9	13.9	19.5	$4.7\cdot10^{-2}$	$8.5\cdot10^{-2}$	$1.2\cdot10^{-1}$	$1.6\cdot10^{-3}$	$1.6\cdot10^{-3}$	$5.4\cdot10^{-3}$
Tracker Isolation	6.8	13.6	19.2	$1.3\cdot10^{-2}$	$3.3\cdot10^{-2}$	$4.4\cdot10^{-2}$	$2.6\cdot10^{-4}$	$2.5\cdot10^{-4}$	$1.0\cdot10^{-3}$
IP cut	6.2	13.0	17.8	$5.6\cdot10^{-3}$	$1.1\cdot10^{-2}$	$1.8\cdot10^{-2}$	$2.6\cdot10^{-4}$	$< 6\cdot10^{-4}$	$2.6\cdot10^{-4}$
H mass cut	**$5.2\cdot10^{-2}$**	**$11.3\cdot10^{-2}$**	**$12.0\cdot10^{-2}$**	**$1.6\cdot10^{-3}$**	**$1.2\cdot10^{-3}$**	**$3.0\cdot10^{-3}$**	**$< 6\cdot10^{-4}$**	**$< 6\cdot10^{-4}$**	**$< 6\cdot10^{-4}$**

Mass Distributions - low mass region

- reconstructed 4-lepton mass after full event selection - all three selections included
- no pileup, no systematics
- *Signal clearly observable above backgrounds*

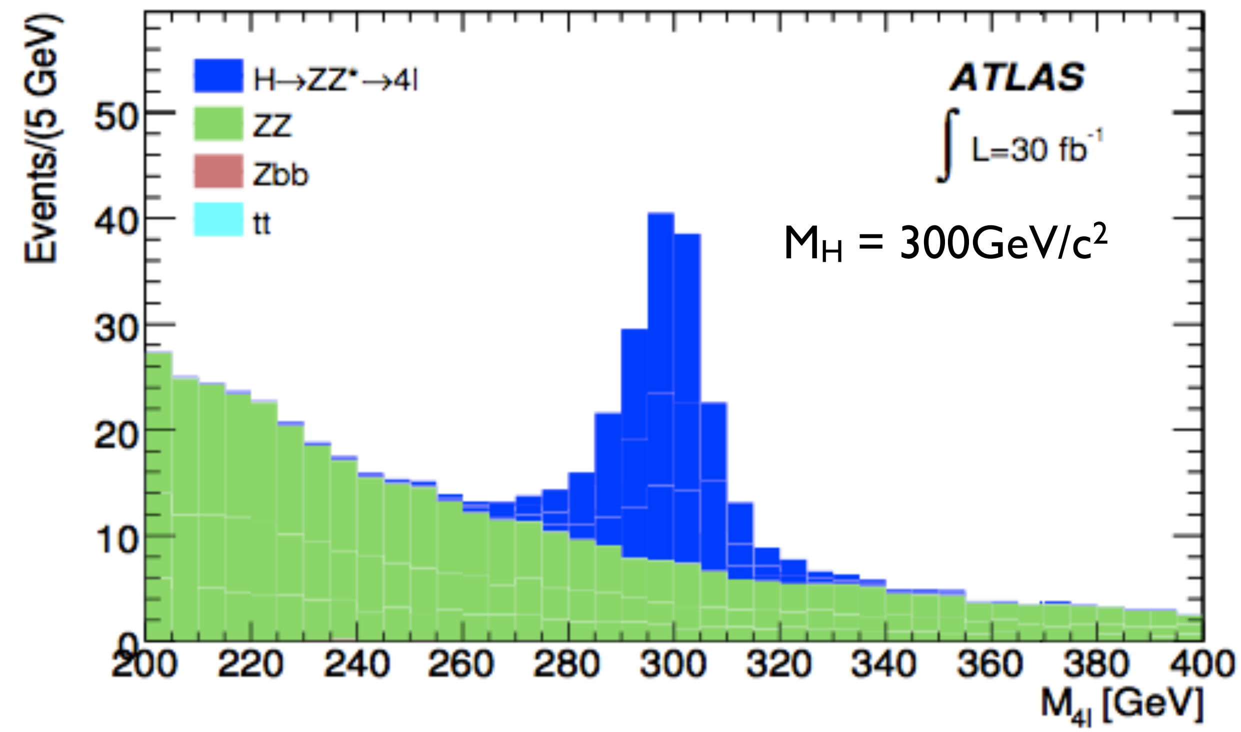


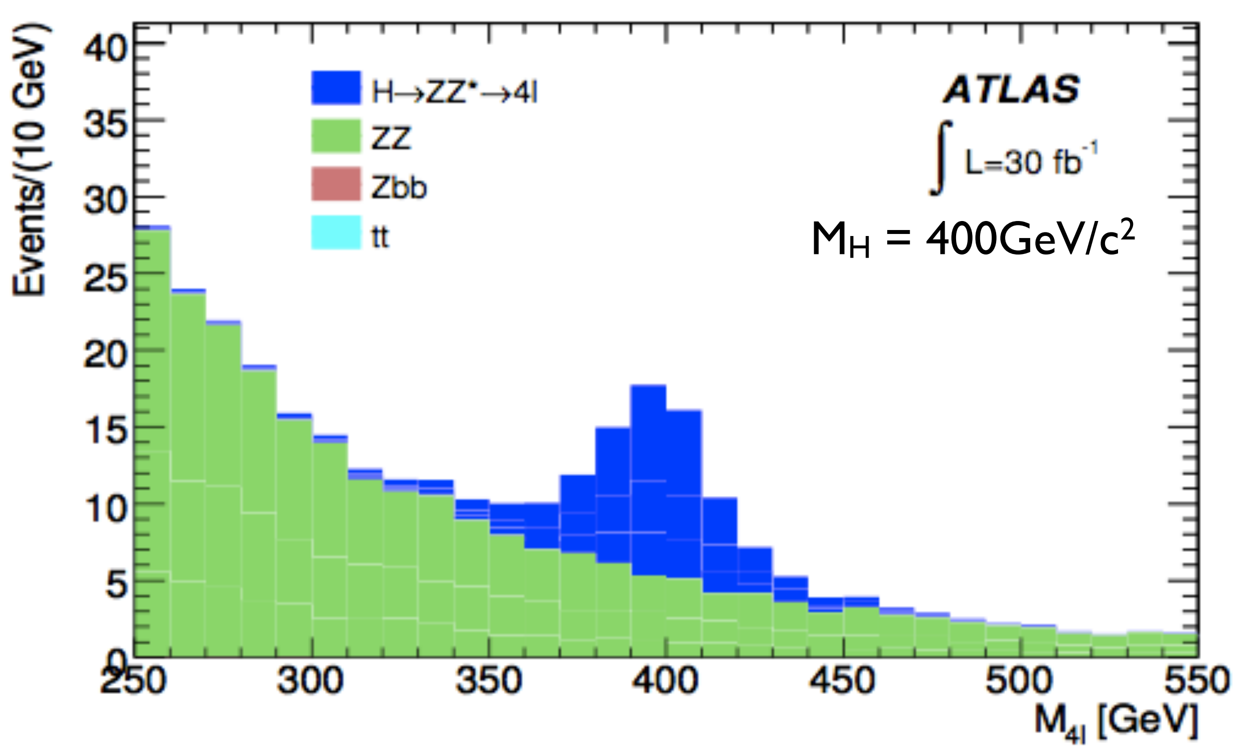


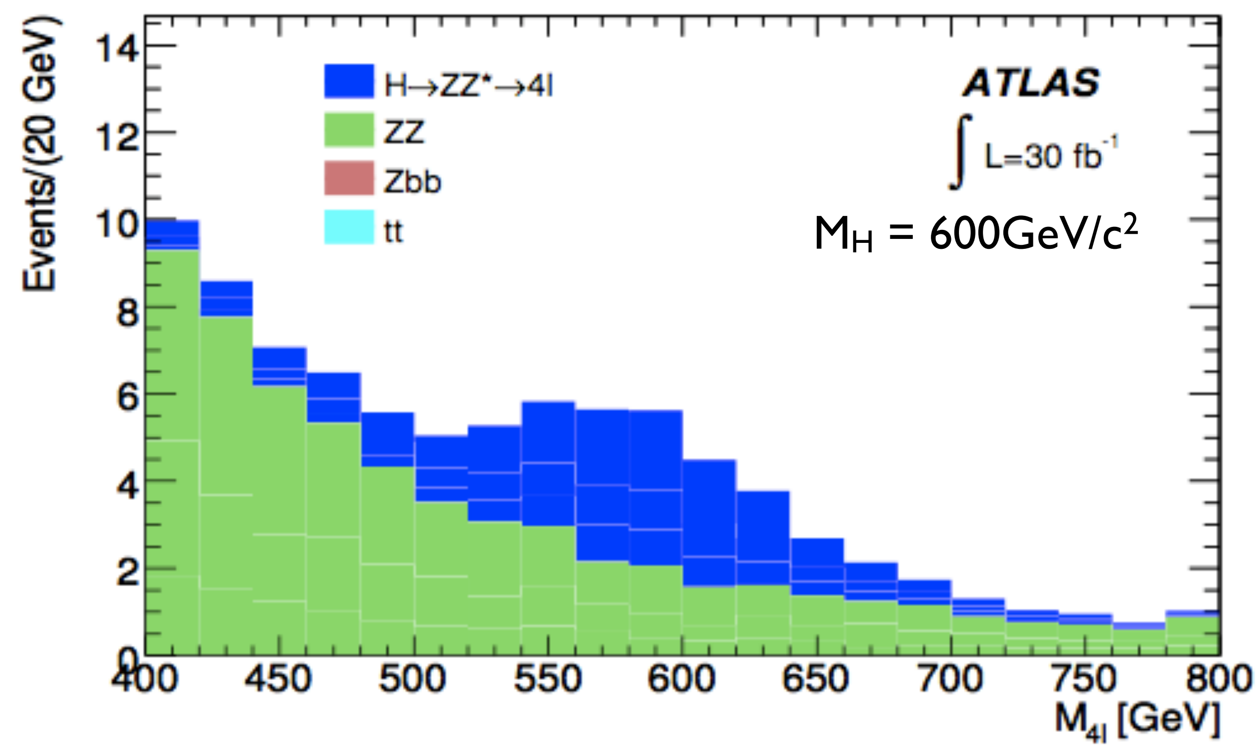


Mass Distributions - high mass region

- reconstructed 4-lepton mass after full event selection - all three selections included
- no pileup, no systematics
- *Signal clearly observable above backgrounds*



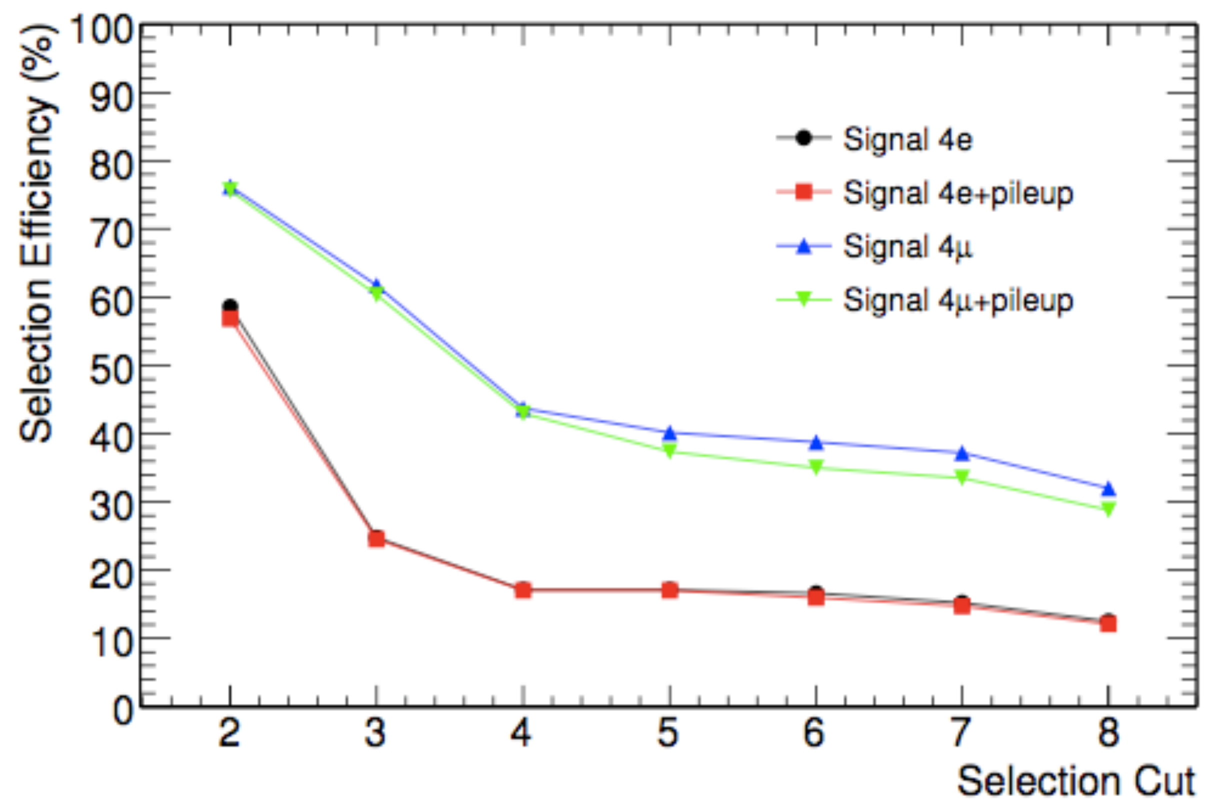




Pileup Effect

- how much is the presence of minimum bias interactions and cavern background (CB) affecting the selection efficiencies?
- study done for M_H =130 GeV/c^2, pileup at 10^{33} $cm^{-2}s^{-1}$, CB safety factor 5

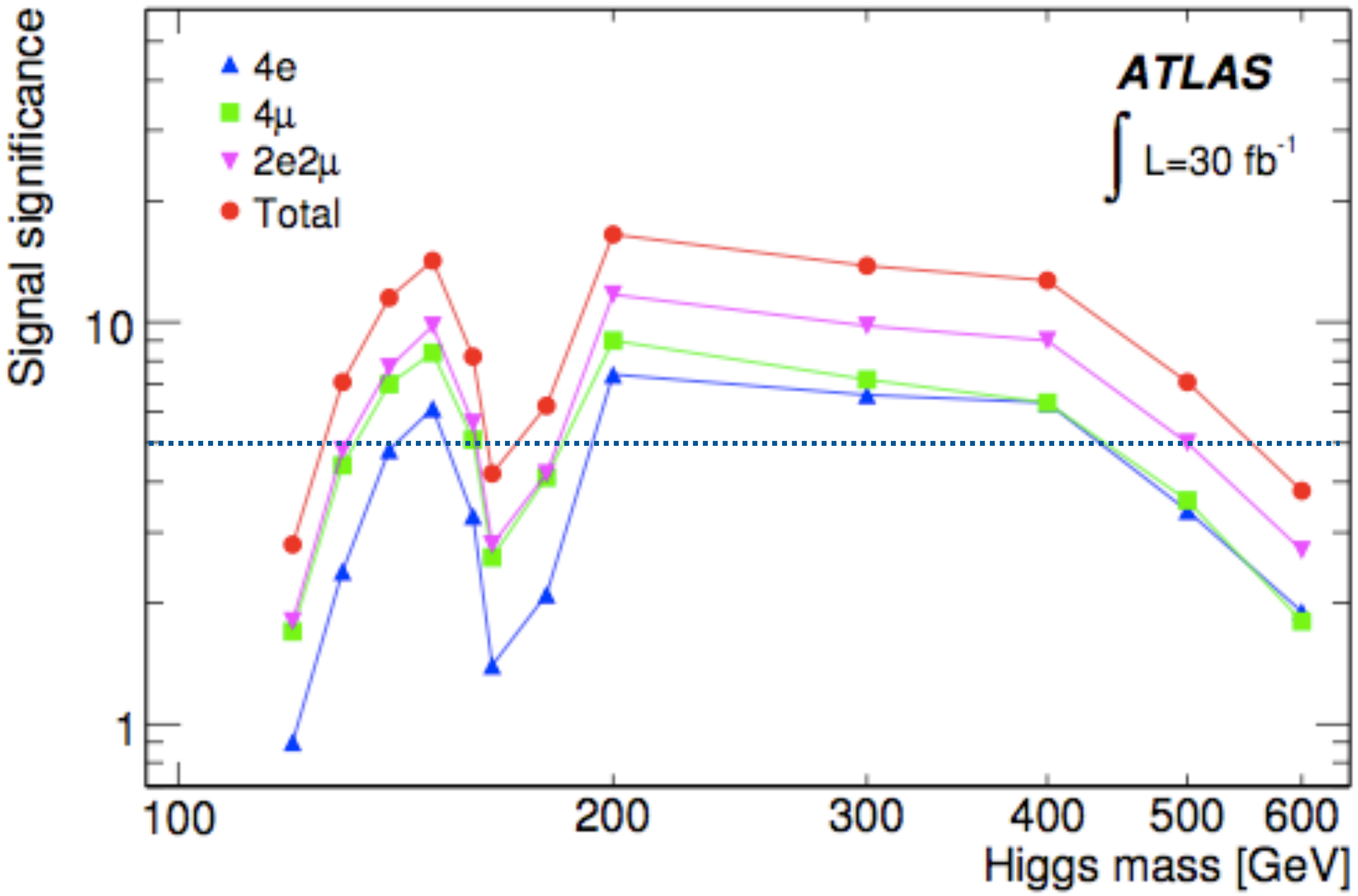
Selection cut	Step
Trigger	1
Lepton presel	2
Lepton quality + p_T	3
Z's mass cut	4
Calo Isolation	5
Tracker Isolation	6
IP cut	7
H mass cut	8



- *decrease of the signal selection efficiency by 10%*
  - reduced trigger efficiency and tracker and calorimeter isolation rejection
- similar effect on the ZZ background
- no analysis optimization for pileup (so far)

Signal Significance

- Signal event selected within a $\pm 2\sigma_{MH}$ mass window
- Results for integrated luminosity = 30 fb^{-1} - not including systematics and pileup (only statistical fluctuation)
- Significance calculated with Poisson statistics



Progresses w.r.t the ATLAS TDR:

- *NLO cross sections*
- *trigger performance*
- *as-installed detector geometry*

Effect of pileup (preliminary!):
~5% significance degradation
(no optimized cuts)

Systematics Uncertainties

1. **theoretical uncertainties**: PDF, QCD scales
   - accounted in the effective NLO cross section evaluation

2. **experimental uncertainties**: related to lepton reconstruction

provided by the ATLAS performance WGs

   - *lepton energy scale*: uncertainty of ±1% on muon p_T and of ±0.5% on electron E_T
   - *lepton energy resolution*: Gaussian smearing with $\sigma_{ET} = 0.0073\ E_T$ (energy) or $\sigma_{1/pT[GeV]} = 0.011/p_{T[GeV]} \oplus 0.00017$ (momentum)
   - *lepton reconstruction efficiency*: discarded 0.2% of reconstructed electrons and 1% of reconstructed muons
   - *material effects* in electron efficiency: < 2% overall (can be measured using data)

3. **uncertainty on LHC luminosity** of 3%

Overall impact on the selection efficiencies of 2. and 3. : *from 3.2% to 6.0% on the signal* and *from 3.1% to 5.4% on ZZ and Zbb backgrounds* (tt contribution negligible)

Significance Extraction from Data

- evaluation of background uncertainties for M_{4l} from 120 GeV/c^2 to 600 GeV/c^2 - uncertainties in rejection should be folded to uncertainties in their rates from direct measurements

- four fit-based approaches for background and significance extraction adopted

1. *full range fit using signal hypothesis at fixed mass and profile likelihood method to extract significance*

2. *background-only sideband fit in a restricted mass range using a number counting with frequentist treatment of background uncertainty*

3. *background-only sideband fit using the full M_{4l} range and assuming knowledge of the M_{ZZ^*} distribution*

4. *a 2D (M_{4l}, M_{Z^*}) fitting method with floating Higgs mass and signal hypothesis*

1. Profile Likelihood Ratio Method

- *method used to provide H→4l input to the combination of all ATLAS SM Higgs searches*
- four lepton mass used as discriminant variable to construct the likelihood function

likelihood ratio method

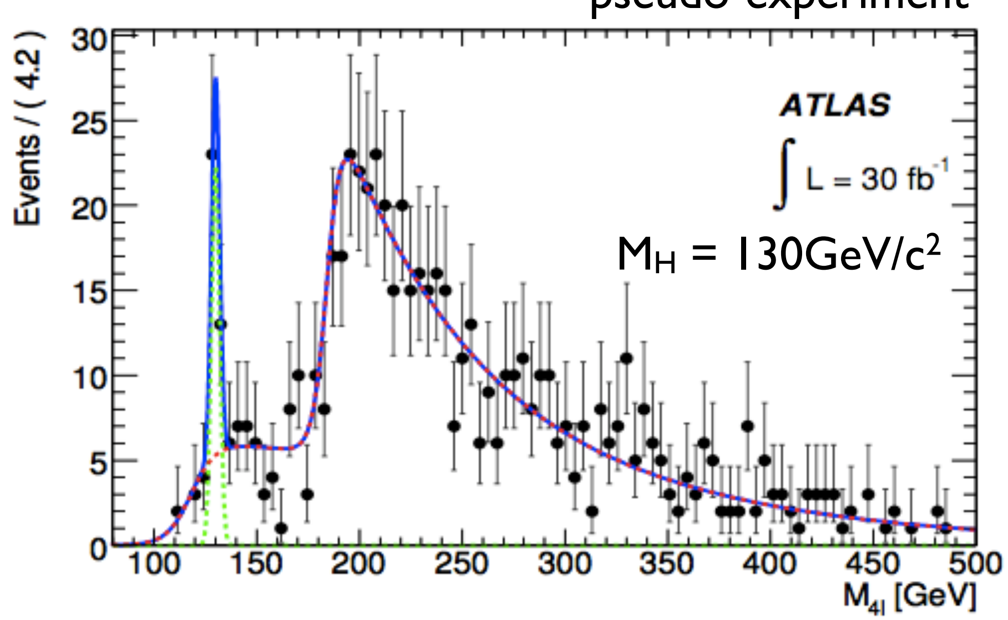
$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\vec{p}}})}{L(\hat{\mu}, \hat{\vec{p}})}$$

$\hat{\hat{\vec{p}}}$ = pdf parameters which maximize the likelihood L for a given μ
$\vec{p}$ = pdf parameters
μ = ratio of the signal cross section to the SM expectation
$(\hat{\mu}, \hat{\vec{p}})$ = values of μ and $\vec{p}$ that maximize the L function

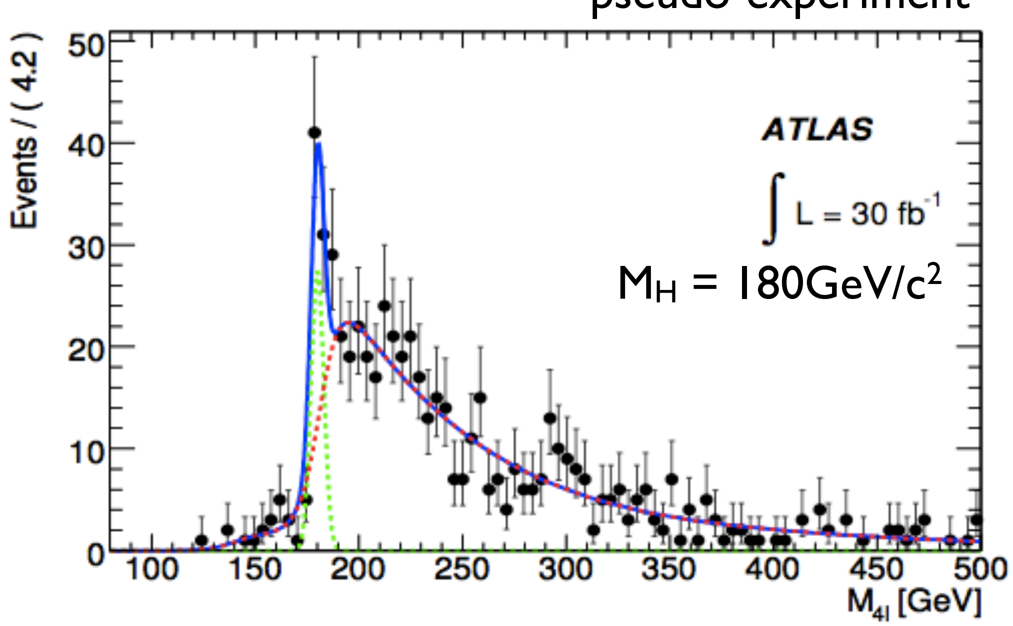
discovery = *backgr-only hyp rejection* (μ = 0) - exclusion = *backgr+signal hyp rejection* (μ = 1)

- signal and background probability density functions (pdf) determined from the MC
  - ZZ (and Zbb) background modeled using a combination of Fermi functions
  - signal modeled by a Gaussian for M_H < 300 GeV/c^2, relativistic Breit-Wigner for higher masses

pseudo-experiment



pseudo-experiment

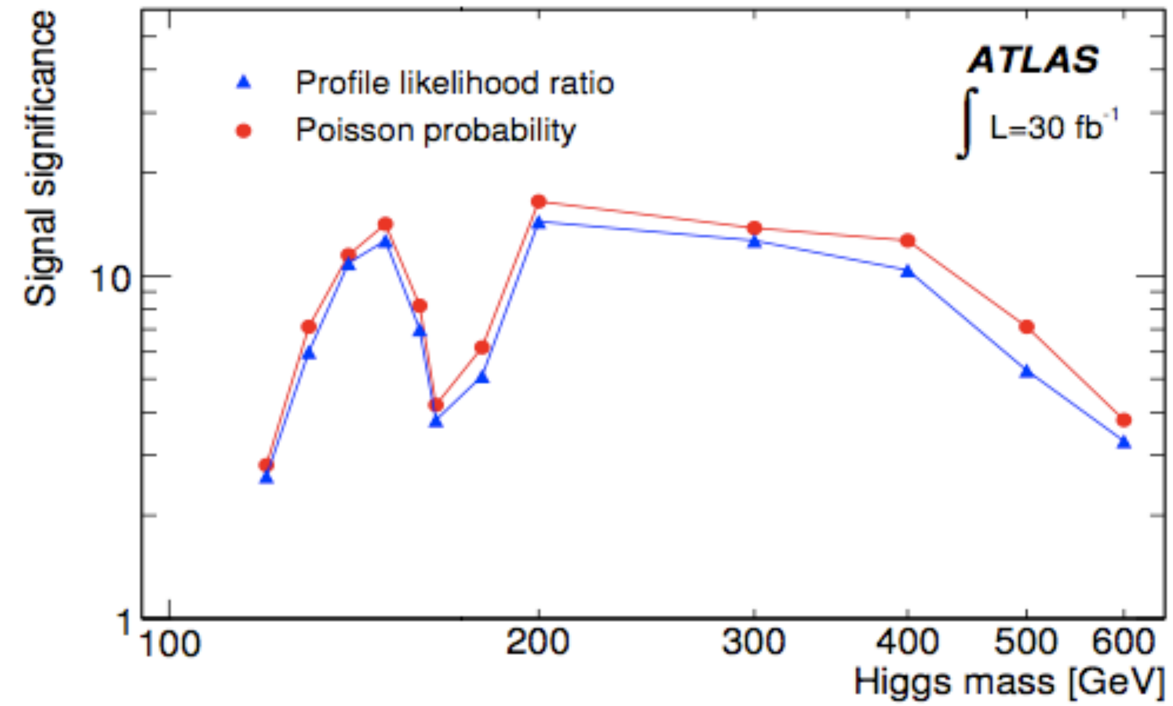


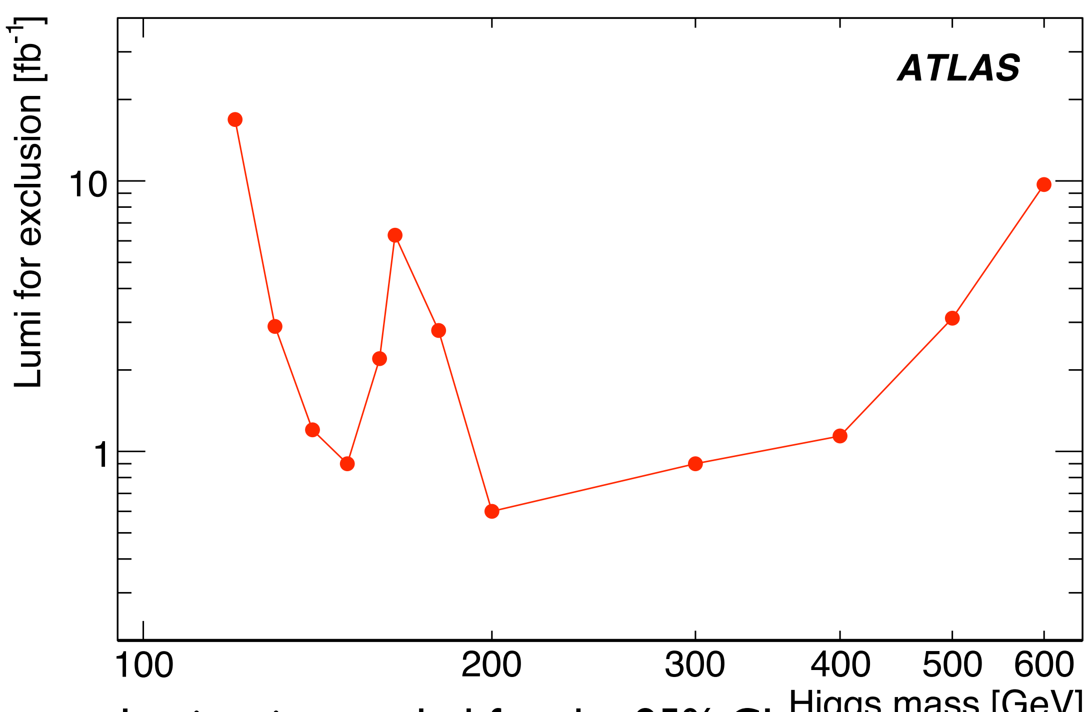
I. Profile Likelihood Ratio Method

- statistic test used $q_\mu = -2\ln\lambda(\mu)$
- validation using a toy MC: good agreement of with the expected chisquare distribution
  ⇒ significance approximated to

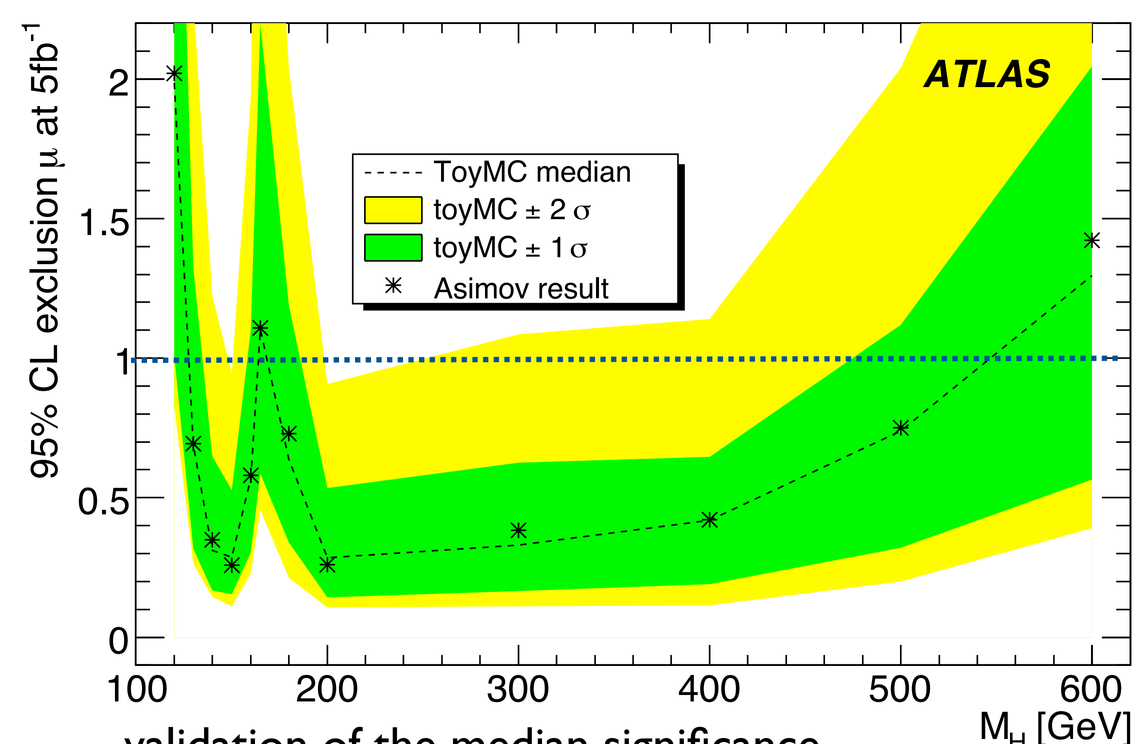
$$\sqrt{-2\ln\lambda(\mu)}$$

- *exclusion*: median profile likelihood ratios calculated under background-only hypothesis
- significance estimation validated with toy MC - 3000 background-only pseudo-experiments





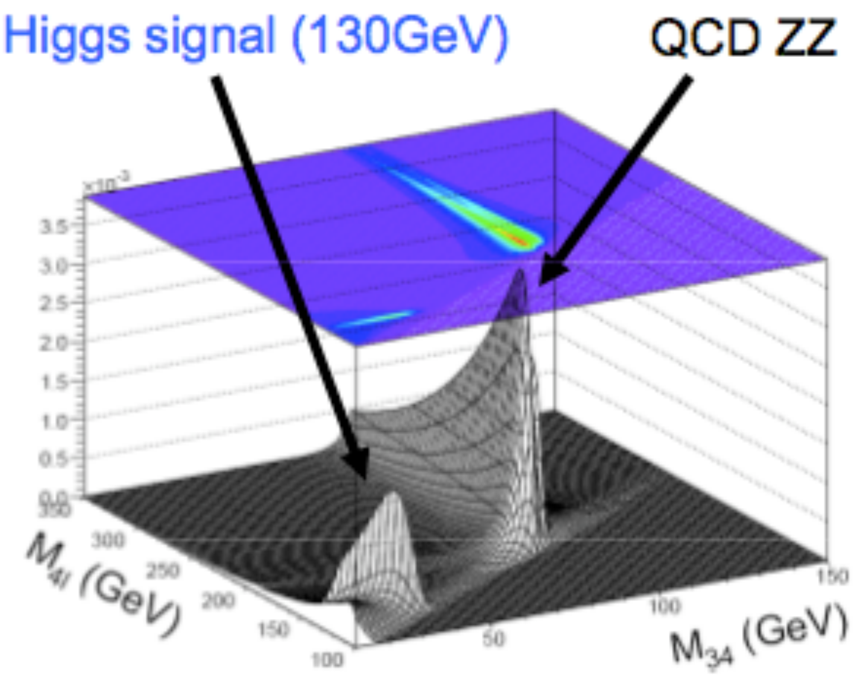
luminosity needed for the 95% CL exclusion of SM Higgs

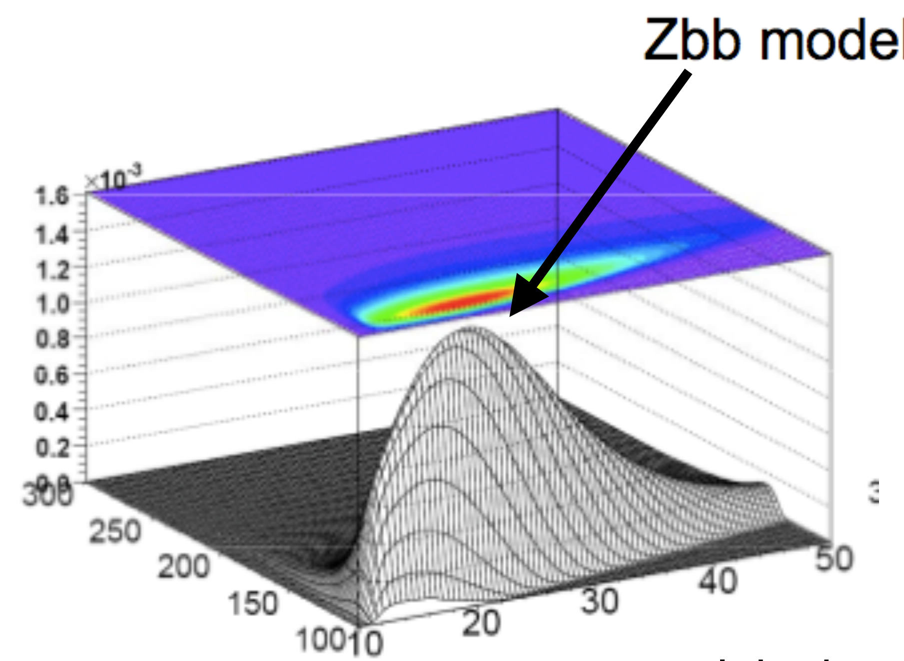


validation of the median significance estimation with toy MC

4. Two Dimensional Fit

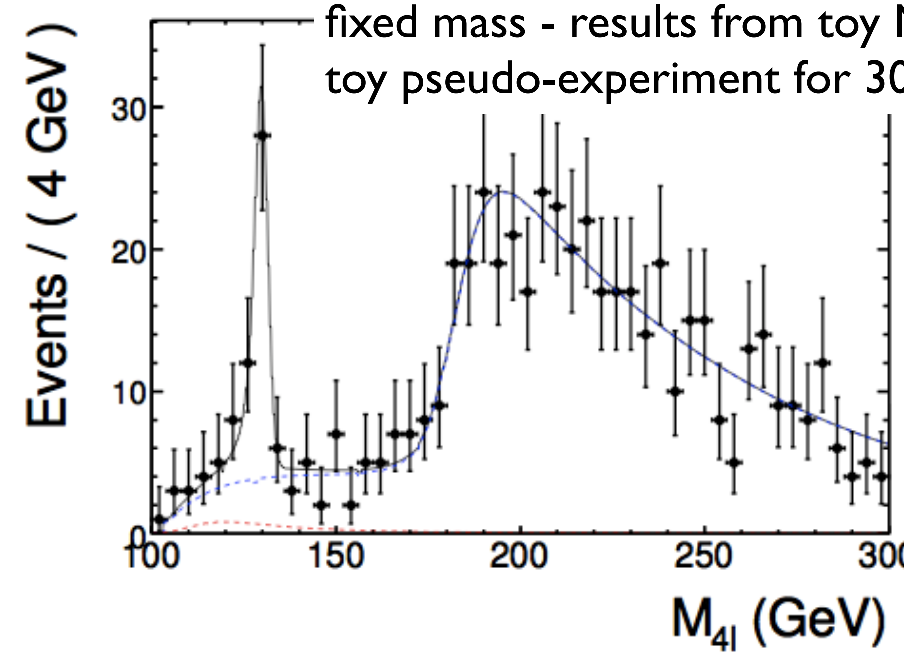
- model signal+background in the (M_{4l}, M_{Z^*}) plane and extract signal from an unbinned maximum likelihood global fit





- one single set of cuts for all Higgs masses - *both fixed and floating H mass fits*
- 2D models for ZZ and Zbb backgrounds from full simulation - signal samples (from 115 to 600 GeV/c^2) define one-parameter family of surfaces
  - background fitted (slices in M_{34}) with inverted Gaussian multiplying an exponential decay
  - signal fitted with a *bifurcated Crystal Ball* in M_{34} and a *double Crystal Ball* in M_{4l}

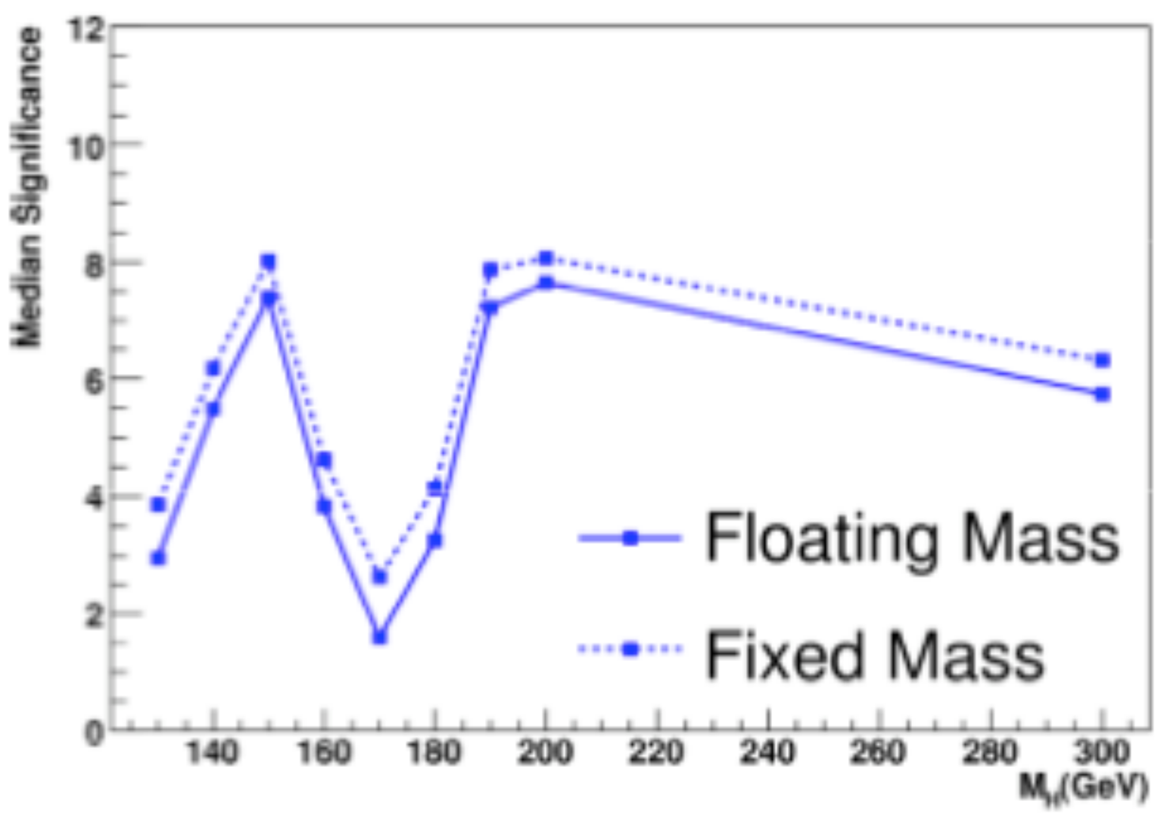
signal+background model and fixed mass - results from toy MC toy pseudo-experiment for 30 fb^{-1}



4. Two Dimensional Fit

$$\frac{\text{\# of candidates in the global-fit region}}{\text{\# of candidates accepted by the sliding cuts}}$$

M_H [GeV/c²]	4e	4μ	2e2μ
130	1.65	1.40	1.49
150	1.70	1.41	1.51
180	1.33	1.20	1.21



- *median significance* = median of the likelihood ratio for the S+B toy MC
- (shapes and) cross sections from full simulation
- Zbb background included, with floating normalization

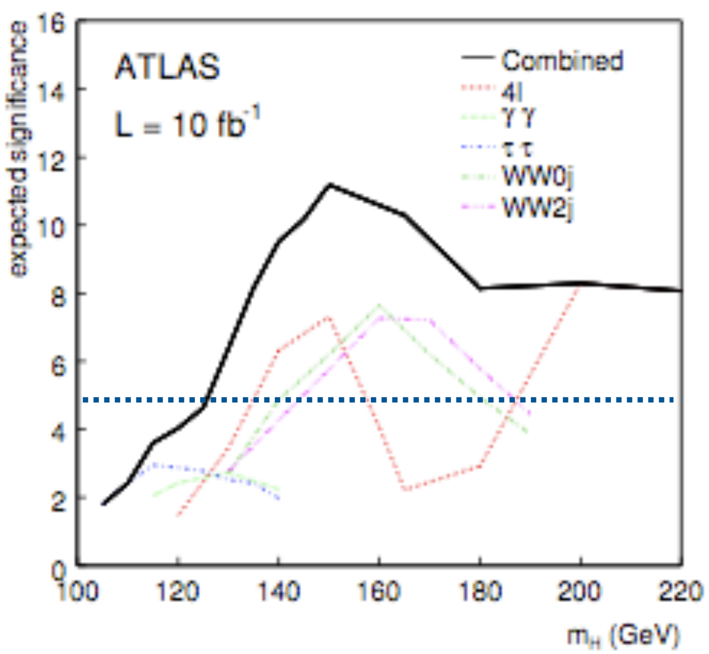
median significances calculated for 10 fb^{-1}

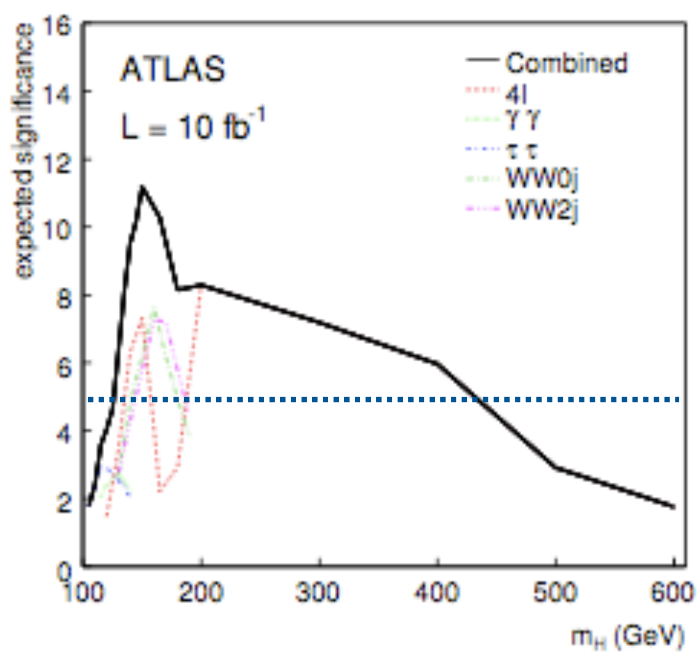
M_H [GeV/c²]	130	140	150	180
Number counting	4.0	6.6	8.1	3.6
2D fit fixed mass	3.9	6.2	8.0	4.1
2D fit floating mass	2.8	5.5	7.4	3.3
Likelihood Ratio	3.46	6.31	7.31	2.92

- *fixed-mass fit results in good agreement with number-counting results and O(10%) enhancement w.r.t. Likelihood Ratio*
- *floating-mass fits lower than the fixed-mass ones*
  - degradation from 0.6 to 1.1 sigma

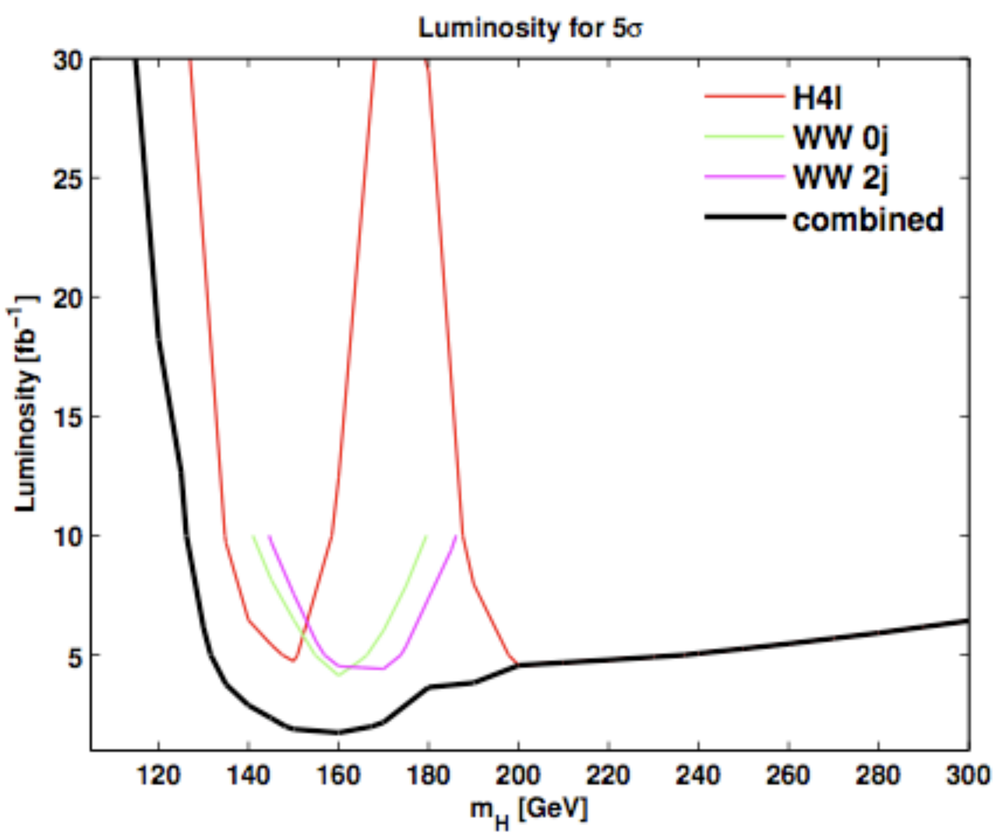
Combination of Higgs Search Channels

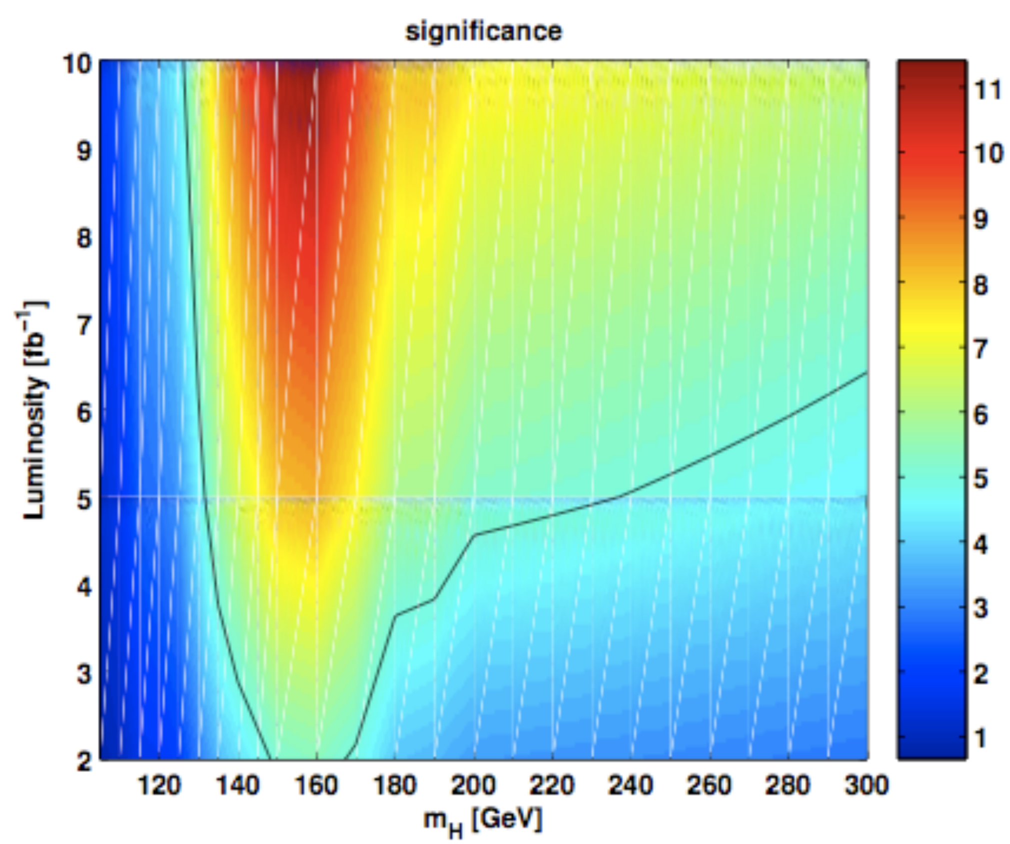
- *ATLAS combined discovery sensitivity*





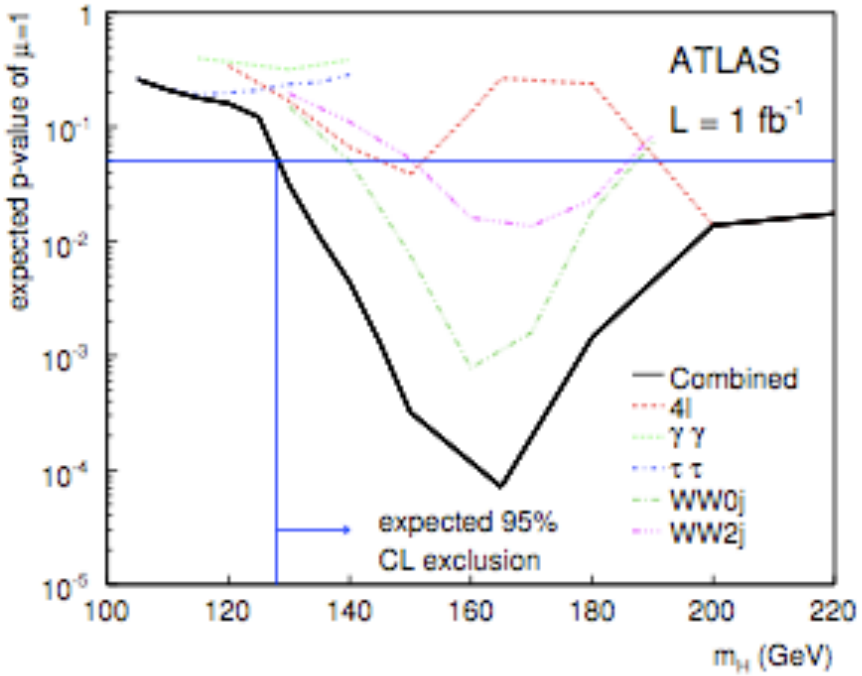
- discovery significance calculated using $Z \approx \sqrt{-2 \ln \lambda(0)}$ ($\lambda(0)$ = combined median likelihood ratio)
- *at 10 fb^{-1} ATLAS has a sensitivity to discover Higgs boson heavier than 124 GeV/c^2*
- *only 2 fb^{-1} needed for the discovery at 160 GeV/c^2*

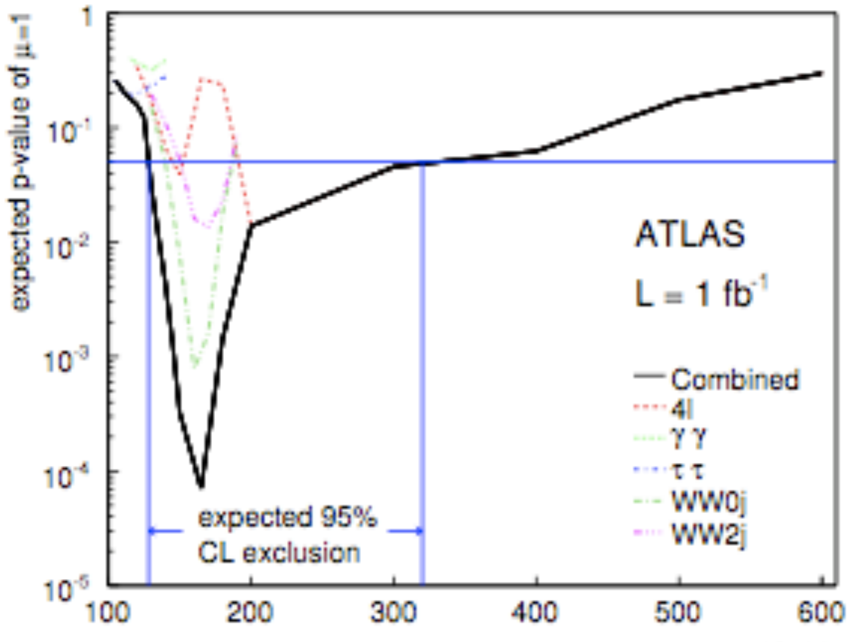




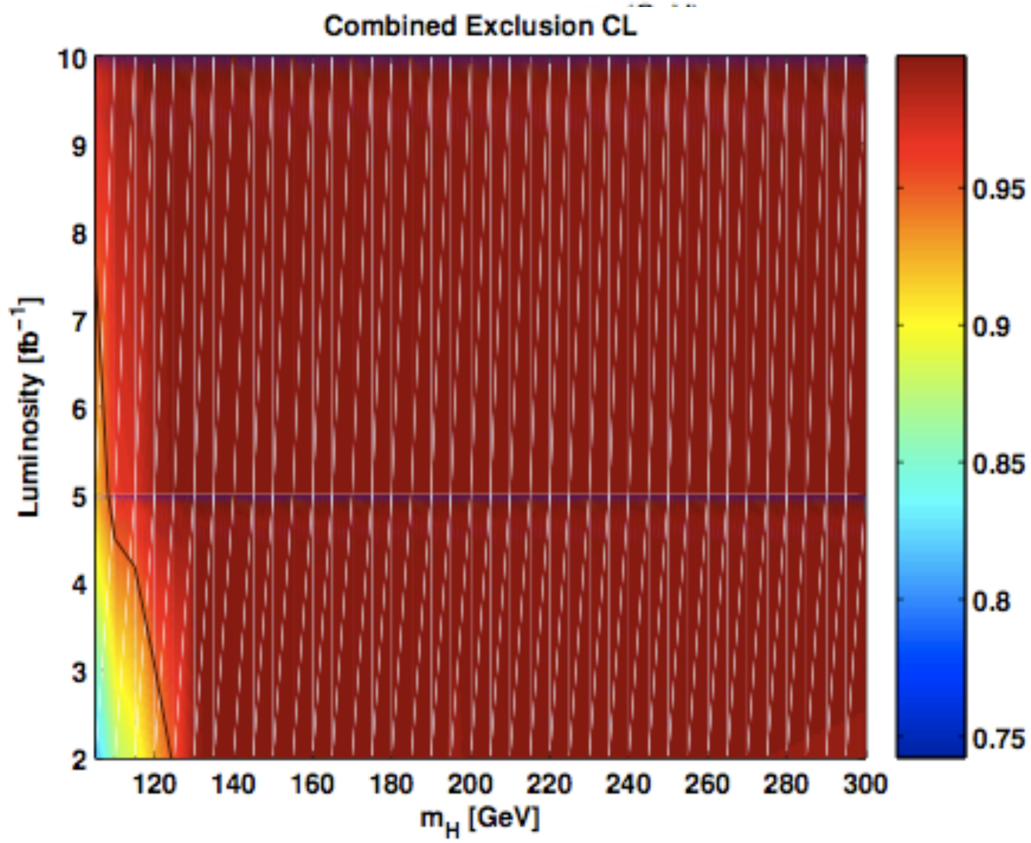
Combination of Higgs Search Channels

- *ATLAS combined exclusion sensitivity*





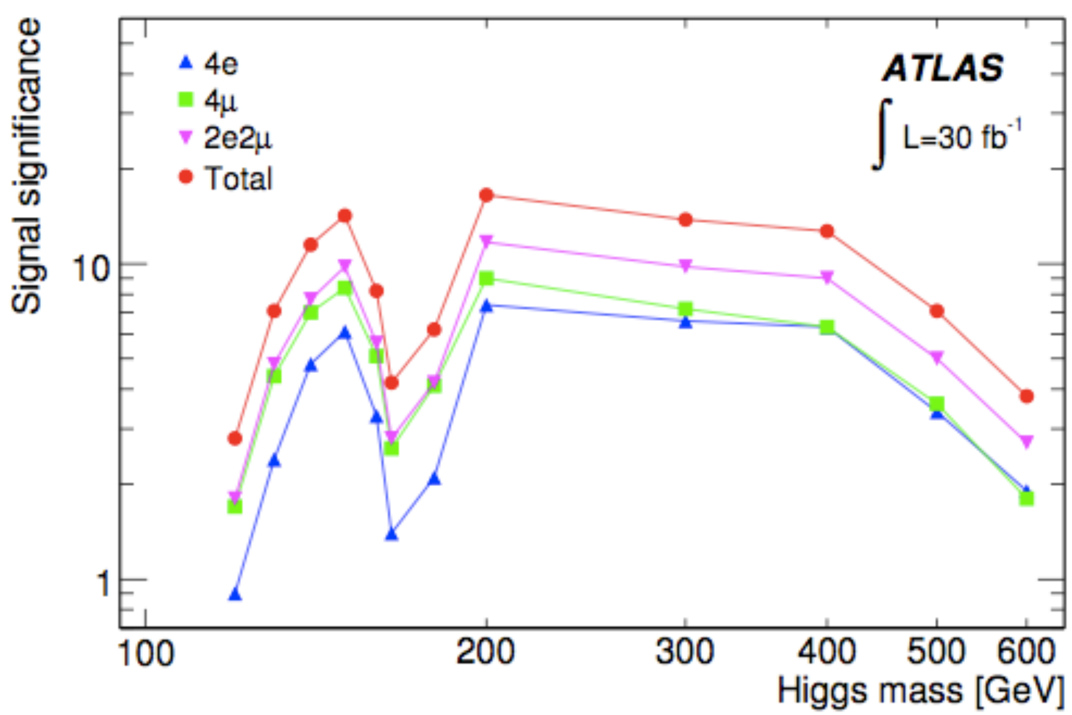
- any p-value below 0.05 in the plots above indicates an exclusion
- *with 2 fb^{-1} ATLAS has the median sensitivity to exclude a SM Higgs boson heavier than 124 GeV/c^2 at 95% CL*
- *a 115 GeV/c^2 SM Higgs boson is excluded at almost 90%*

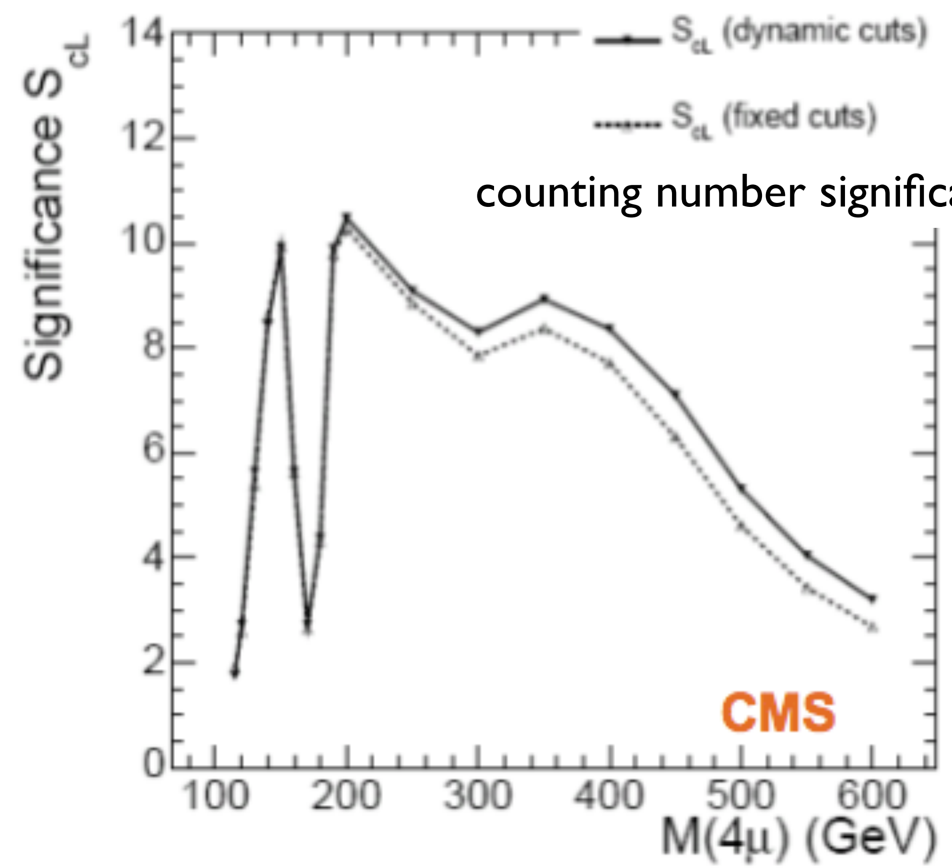


Comparisons with CMS - 4μ

CMS : no impact parameter cut, absolute calorimeter ($\Delta R = 0.24$) and track isolation ($\Delta R = 0.20$) isolation - fixed and mass dependent analyses → differences more pronounced for high masses

ATLAS: impact parameter significance cut, normalized calorimeter ($\Delta R = 0.2$) and track isolation ($\Delta R = 0.2$)





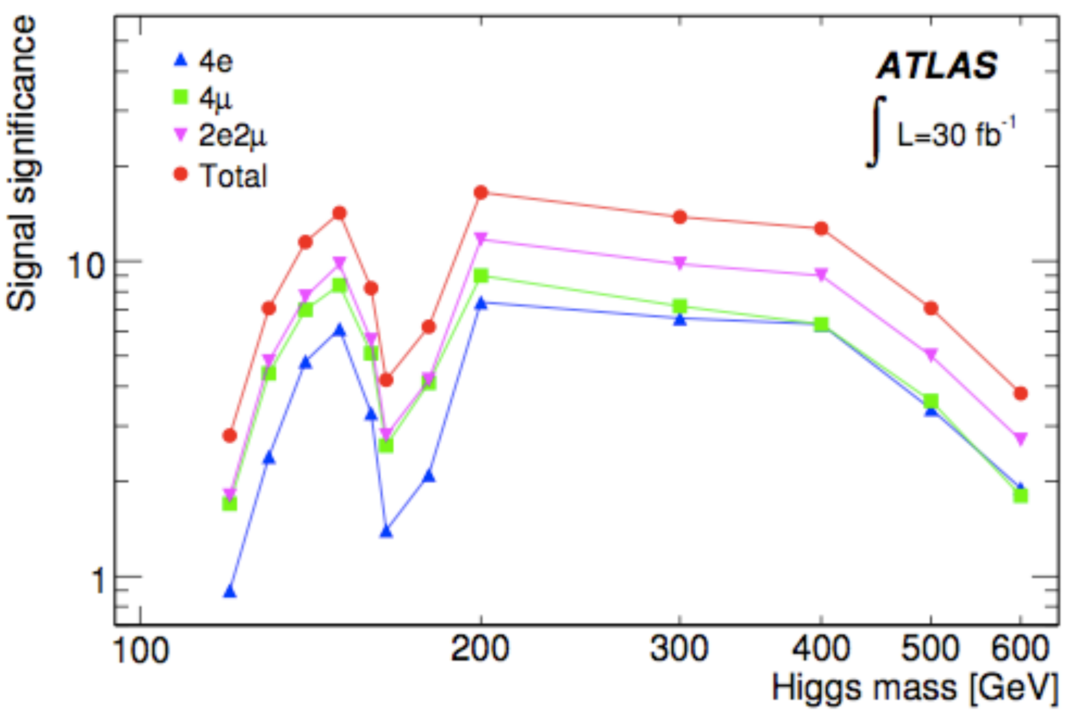
M_H [GeV/c²]	ATLAS	CMS
130	4.4	~5.4 - 5.6
200	9.0	~10.4 - 10.6

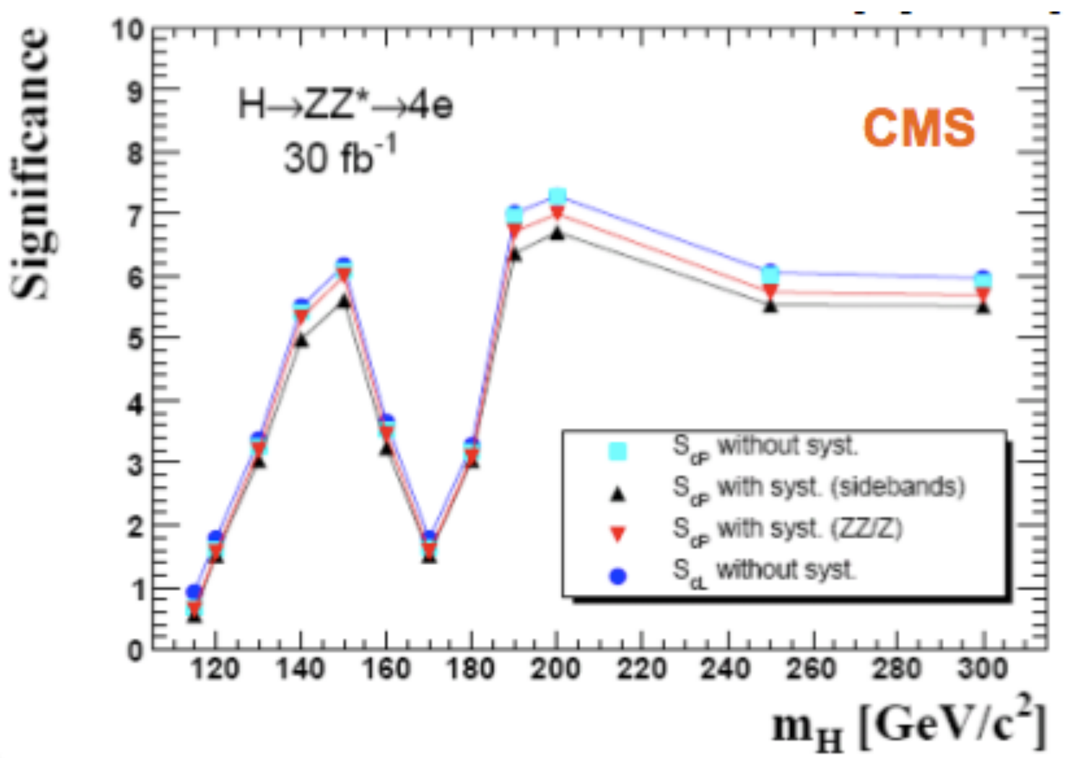
significances calculated for 30 fb⁻¹ with the same methods, no systematics

Comparisons with CMS - 4e

CMS : normalized hadronic isolation ($\Delta R = 0.2$) and normalized track isolation ($\Delta R = 0.2$) - tracks from the same vertex with $p_T > 1.5$ GeV/c - longitudinal and transverse impact parameter used, mass dependent analyses

ATLAS: impact parameter significance cut, calorimeter and normalized track isolation





M_H [GeV/c^2]	ATLAS	CMS
130	2.4	3.4
200	7.4	7.3

significances calculated for 30 fb^{-1} with the same methods, no systematics

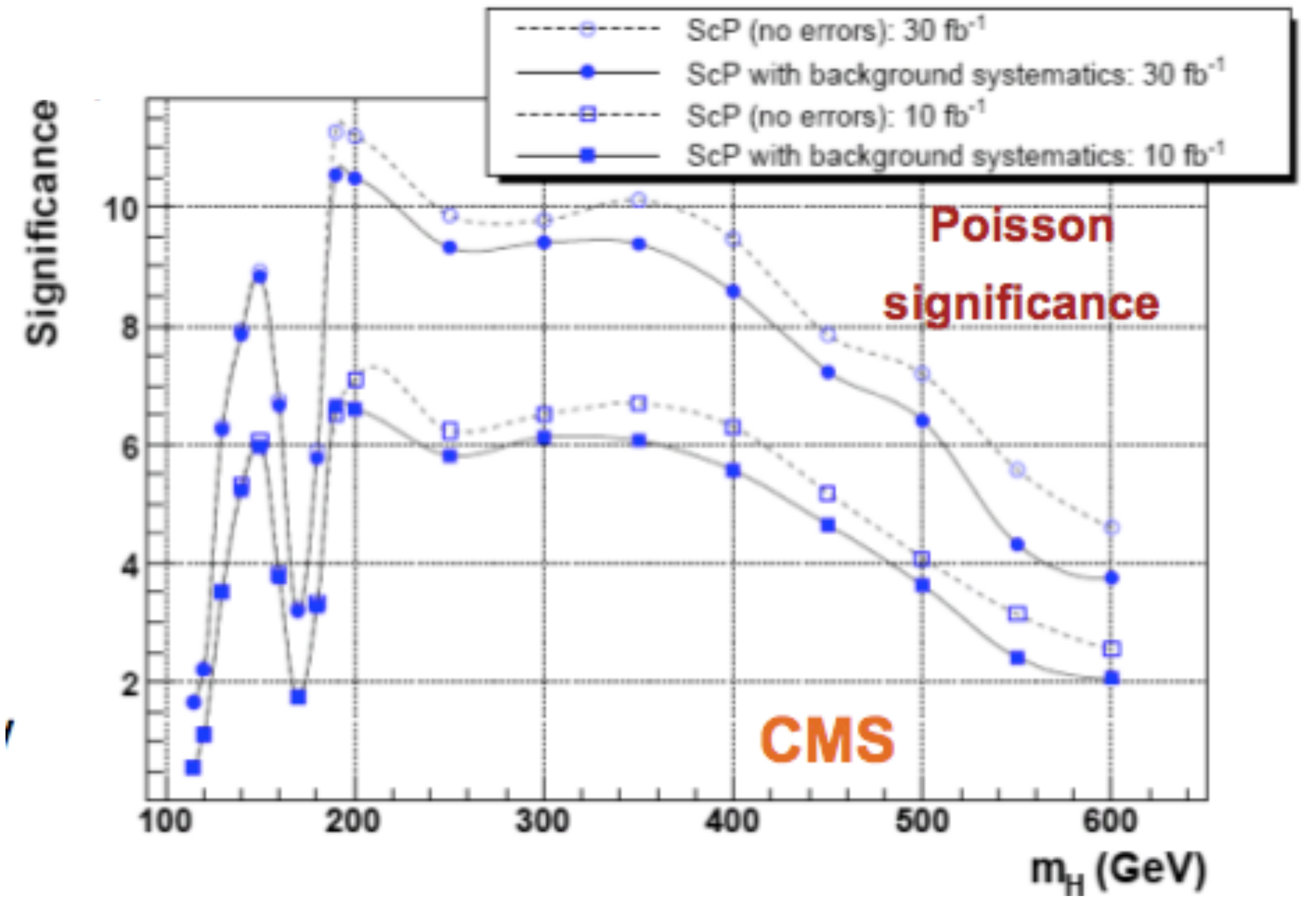
- ATLAS has lower electron efficiency
- and narrower mass window (6 GeV/c^2 vs 8.8 GeV/c^2: O(45%) more ZZ background)
- high M_H, loosened e-id cuts: efficiency recovered + mass resolution less important

Comparisons with CMS - 2e2μ

CMS : vertex and impact parameter cuts - track isolation - kinematic cuts, dilepton and Higgs mass windows selected to optimize the significance (using MINUIT)

M_H [GeV/c²]	M_{Z1} [GeV/c²]	M_{Z2}[GeV/c²]
130	< 97	> 22
200	< 105	> 60

no lower M_{Z1} threshold applied



significances calculated for 30 fb^{-1} with the same methods, no systematics

M_H [GeV/c²]	ATLAS	CMS
130	4.8	6.3
200	11.7	12.4

as in the case of 4e, electron efficiency and Higgs mass window explain most of the observed difference

Conclusions

- ATLAS has an *high capability of lepton identification and measurements*
  - it will be crucial to first understand the detector!
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$ covers a *wide mass range* (from 120 GeV/c^2 to 600 GeV/c^2) with a *large discovery potential* in ATLAS
  - *gold-plated channel* when the Higgs is heavier that 200 GeV/c^2
- Studies on systematic uncertainties on the signal extraction
- Updated results in the ATLAS CSC Note "Search for the Standard Model $H \rightarrow ZZ^{(*)} \rightarrow 4l$ with the ATLAS Detector"

Higgs discovery possible in this channel with few fb^{-1}, if M_H = 150 GeV/c^2 or M_H > 200 GeV/c^2

Exclusion limit for Higgs boson heavier than 124 GeV/c^2 at 95% CL with 2 fb^{-1}

Larger integrated luminosity needed to *measure the Higgs properties* (width, spin, CP parity)

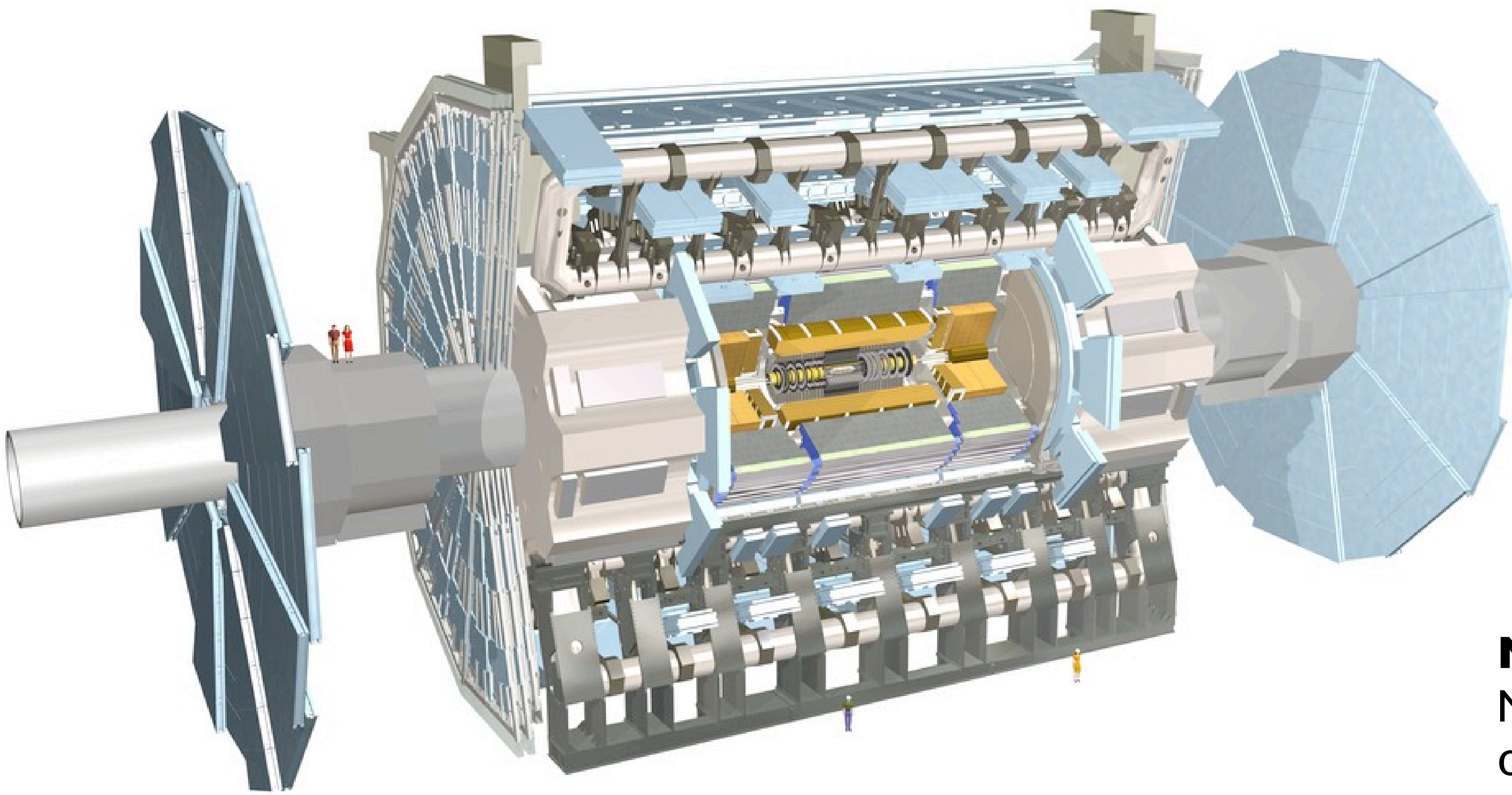
- *Comparison with CMS:* ATLAS more conservative in e-id efficiency (safety against Z + jets) - differences in Higgs mass resolution crucial in low mass region - di-lepton mass cuts loose in CMS, ATLAS more conservative

Many thanks to A. D'Orazio, S. Horvat, O. Kortner, K. Nikolopoulos, L. Flores Castillo

Backup Slides

H→4l studies at ATLAS

ATLAS Detector



TRACKER (ID)
Si pixels + strips TRT → particle identification
$\sigma/p_T = 5\times10^{-4}\, p_T \oplus 0.01$
$|\eta| < 2.5$

EM CALO
Pb-liquid argon - uniform longitudinal segmentation
$\sigma/E = 10\%/\sqrt{E} \oplus 0.07$
$|\eta| < 3.2$

HAD CALO
Fe-scint. + Cu-liquid argon
($\geq 10\ \lambda$)
$\sigma/E = 50\%/\sqrt{E} \oplus 0.03$ $|\eta| < 3.2$
$\sigma/E = 100\%/\sqrt{E} \oplus 0.1$ $3.1 < |\eta| < 4.9$

MUON SYSTEM
MDT, CSC, RPC, TGC
$\sigma/p_T = 10\%/p_T$ at $p_T = 1$ TeV/c
$|\eta| < 2.7$

H→4l (l = e, μ) channel
electrons and muon involved only ⇒ *very good lepton trigger and identification* needed
full event reconstruction - mass peak

lepton-only final states are the cleanest at LHC

Cross Sections for Background

Process	Generator	$\sigma \cdot BR$ [fb]	Corrections	FA	Events (K)
$qq \to ZZ \to 4l$	PYTHIA6.3	158.8	+47.64	[4l] 0.219	100
$gg \to Zbb \to 2lbb$	AcerMC/PYTHIA6.3	52030	+8640 ($qq \to Zbb$)	[4l] 0.00942	430
$gg \to Zbb \to 2lbb$	AcerMC/PYTHIA6.3	52030	+8640 ($qq \to Zbb$)	[3l] 0.147	200
$gg, qq \to tt$	MC@NLO/Jimmy	833000		[4l] 0.00728	400
$qq \to WZ$	HERWIG/Jimmy	26500		[3l] 0.0143	70

$qq \to ZZ^{(*)}$

$\sigma_{eff} = \sigma_{LO} \cdot [BR(Z \to ee, \mu\mu, \tau\tau)]^2 \cdot EF \cdot (K + 0.3) = 34.82 \cdot [K(M_{ZZ}) + 0.3]$ fb

$gg \to Zbb$

K = 1.42

$\sigma_{eff} = \sigma_{LO} \cdot [BR(Z \to ee, \mu\mu)]^2 \cdot EF \cdot K = 812.1$ fb

$qq \to WZ$

$\sigma_{eff} = \sigma_{NLO}(W^+Z + W^-Z) \cdot EF = 807$ fb

M_{ZZ} [GeV/c^2]	K factor
[115, 125]	1.15
[125, 135]	1.21
[135, 145]	1.25
[155, 165]	1.34
[175, 185]	1.31
[195, 205]	1.32
[295, 305]	1.40
[395, 405]	1.52
[495, 505]	1.84
[595, 605]	1.81

Trigger selection

- **Trigger Menus for H4l:** *single or dilepton triggers*
  - single lepton triggers suited for low luminosity ($2 \cdot 10^{33}$ $cm^{-2}s^{-1}$)

Trigger Menu	Unbiased sample			After Event Selection		
	4e	**4μ**	**2e2μ**	**4e**	**4μ**	**2e2μ**
1μ20	0.1	95.3	71.3	0.4	98.2	72.7
1e22i	94.7	0.4	68.6	99.8	0.1	78.1
2e15i	76.3	< 0.2	33.2	98.9	< 0.2	60.2
1μ20 or 1e22i	94.7	95.3	95.7	99.8	98.2	98.9
2μ10 or 2e15i or 1μ20 and 1e15i	76.4	93.3	87.8	98.9	97.6	96.9

full trigger (LVL1 + HLT) selection efficiencies (in %) for H[130 GeV/c^2]

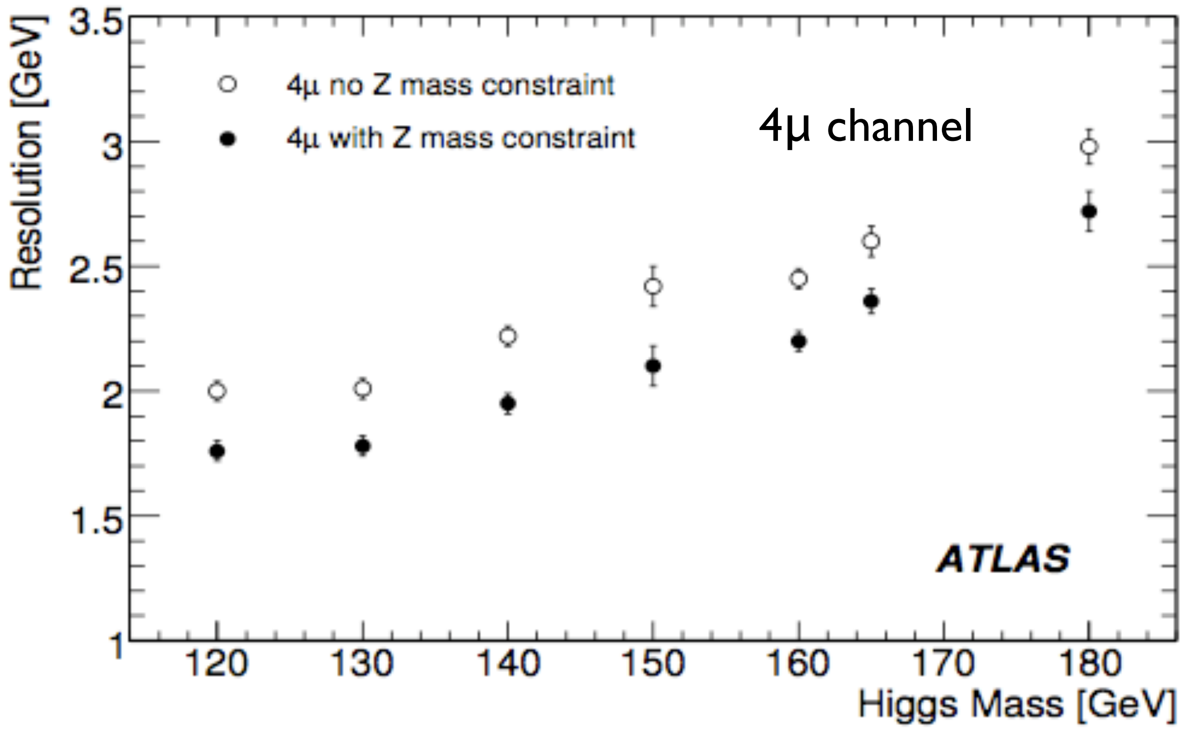
- absolute error on the efficiencies: 0.4 % for unbiased sample - 0.2 % for event passing the offline selections
- similar results on ZZ background

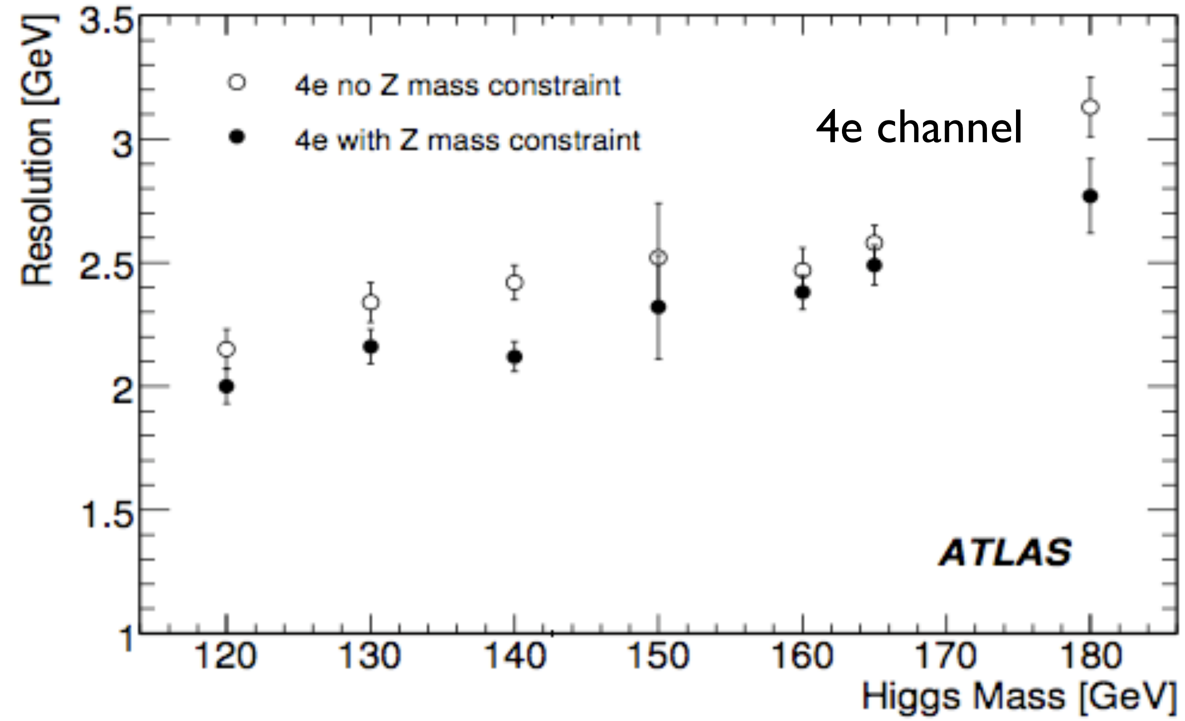
Z and H kinematical selections

- Cuts applied to the reconstructed leading and subleading Z masses, and width of the reconstructed Higgs mass window (used to define the signal region)
- optimized using the expected distributions for signal and backgrounds and the expected dilepton resolution
- for significance estimation, events in ±2σ mass window are selected

H Mass [GeV/c²]	Z1 Mass Window [GeV/c²]	Z2 Mass Window [GeV/c²]	H Mass Resolution [GeV/c²]		
			4e	4μ	2e2μ
120	± 15	> 15	2.0	1.8	1.9
130	± 15	> 20	2.2	1.8	1.9
140	± 15	> 30	2.2	2.0	2.1
150	± 15	> 30	2.3	2.1	2.2
160	± 15	> 30	2.4	2.2	2.3
165	± 15	> 35	2.5	2.4	2.4
180	± 12	> 40	2.8	2.7	2.8
200	± 12	> 60	3.9	3.7	3.8
300	± 12	± 12	8.4	8.4	8.4
400	± 12	± 12	16.5	17.3	17.2
500	± 12	± 12	33.8	34.4	32.8
600	± 12	± 12	52.2	57.2	53.2

Higgs Mass Resolution





Z mass constraint :

- convolution between the nominal Z Breit-Wigner distribution and a Gaussian distribution centered at the measured Z value with σ equal to the experimental resolution
- for Higgs masses above 200 GeV/c^2, applied to both lepton pairs

- improvement of mass resolution of 10-17% ⇒ *for low Higgs masses (intrinsic H width < 1GeV/c^2) experimental resolution is crucial*

Systematics Uncertainties

- impact of the systematic on signal and background samples with the hypothesis of M_H = 130 GeV/c^2

	Zbb	ZZ	H	Zbb	ZZ	H	Zbb	ZZ	H
		4e			4μ			2e2μ	
Scale +0.5% (+1%)	+1.5	+0.1	+0.9	+2.4	+0.4	+1.3	+1.9	+0.1	+0.9
Scale -0.5% (-1%)	-1.1	-0.2	-0.5	-2.3	-0.3	-2.5	-1.7	-0.2	-1.4
Resolution	-0.5	-0.1	-0.4	+0.1	-0.1	-2.6	-0.2	-0.1	-0.5
Rec efficiency	-1.0	-0.7	-0.5	-3.8	-4.0	-3.8	-2.0	-2.1	-1.7
Luminosity		3			3			3	
Total	3.6	3.1	3.2	5.4	5.0	6.0	4.1	3.7	3.8

1. Profile Likelihood Ratio Method: pdfs

- MC distributions after event selection (*Asimov data*) fitted to derive pdf parameters
  - M_H fixed to its true value, σ_H floating in a ±20% range
  - background parameters floating within sensible ranges
- ZZ modeled using a combination of Fermi functions

$$f(M_{ZZ}) = \frac{p0}{(1+e^{\frac{p6-M_{ZZ}}{p7}})(1+e^{\frac{M_{ZZ}-p8}{p9}})} + \frac{p1}{(1+e^{\frac{p2-M_{ZZ}}{p3}})(1+e^{\frac{p4-M_{ZZ}}{p5}})}$$

- Zbb contribution modeled by a Fermi contribution similar to the second term above

significance obtained from the median profile likelihood ratios for discovery $-2\ln\lambda(\mu=0)$

L [fb-1]	M_H[GeV/c²]											
	120	130	140	150	160	165	180	200	300	400	500	600
1	0.47	1.10	2.0	2.31	1.29	0.70	0.93	2.62	2.28	1.88	0.94	0.56
2	0.66	1.55	2.82	3.27	1.82	0.99	1.31	3.71	3.23	2.77	1.32	0.79
5	1.02	2.44	4.46	5.17	2.87	1.57	2.07	5.86	5.08	4.21	2.08	1.24
10	1.48	3.46	6.31	7.31	4.07	2.22	2.92	8.29	7.19	5.96	2.91	1.76
30	2.56	5.98	10.9	12.7	6.99	3.84	5.06	14.4	12.7	10.4	5.28	3.31