Discovery Potential for the Standard Model Higgs at ATLAS

Les Rencontres de Physique de la Vallée d'Aoste

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Representing the ATLAS Collaboration

Outline

Introduction

Standard Model Higgs @ LHC/ATLAS

Standard Model Higgs channels considered here:

$H \rightarrow \gamma\gamma$

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$

$H \rightarrow ZZ^{(*)} \rightarrow 4l \quad (l = e, \mu)$

$H \rightarrow \tau^{+}\tau^{-} \rightarrow ll, lh$

Statistical combination of channels

Results

Conclusions and outlook

Emphasis of this talk

Status of Higgs search recently published in:

Expected Performance of the ATLAS Experiment: Detector, Trigger and Physics, arXiv:0901.0512, CERN-OPEN-2008-20.

Updated since previous studies: improved detector description and MC generators, higher order QCD and EW corrections included.

Statistical procedure for combination of channels.

Systematics included via profile likelihood

In this talk, concentrate on "discovery modes":

$H \to \gamma\gamma$ $\quad$ $H \to WW^{(*)} \to e\nu\mu\nu$

$H \to ZZ^{(*)} \to 4l \;\; (l = e, \mu)$ $\quad$ $H \to \tau^+\tau^- \to ll, lh$

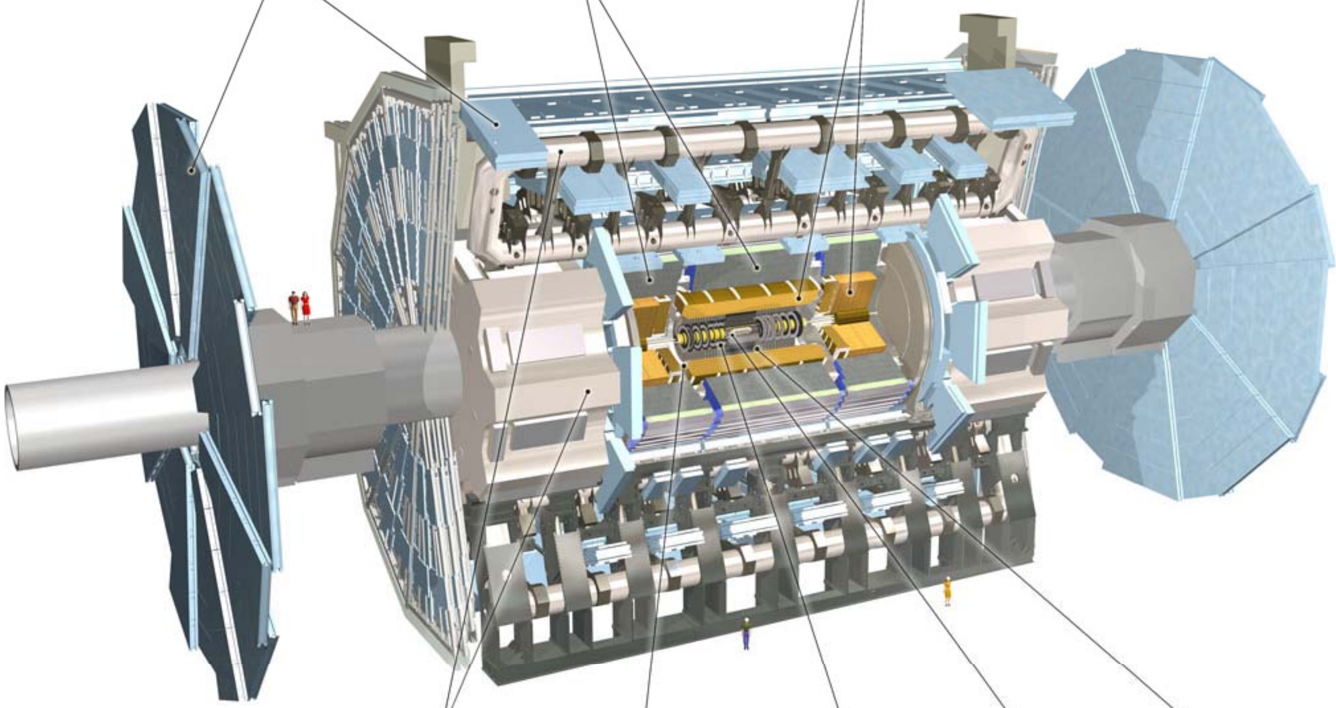
Some modes not yet included, e.g., $WW \to e\nu e\nu$, $\mu\nu\mu\nu$, $l\nu qq$;

$\to$ sensitivity will improve

The Large Hadron Collider

CM energy	14 TeV (design)
Luminosity ($cm^{-2}s^{-1}$)	Low: 2×10^{33} High: 10^{34}
Bunch crossing	24.95 ns
Particles/bunch	1.15×10^{11}
Beam radius	16.7 μm
Overlaid events	23 @ 10^{34} $cm^{-2}s^{-1}$
Dipole field	8.33 Tesla
Stored energy	360 MJ/beam

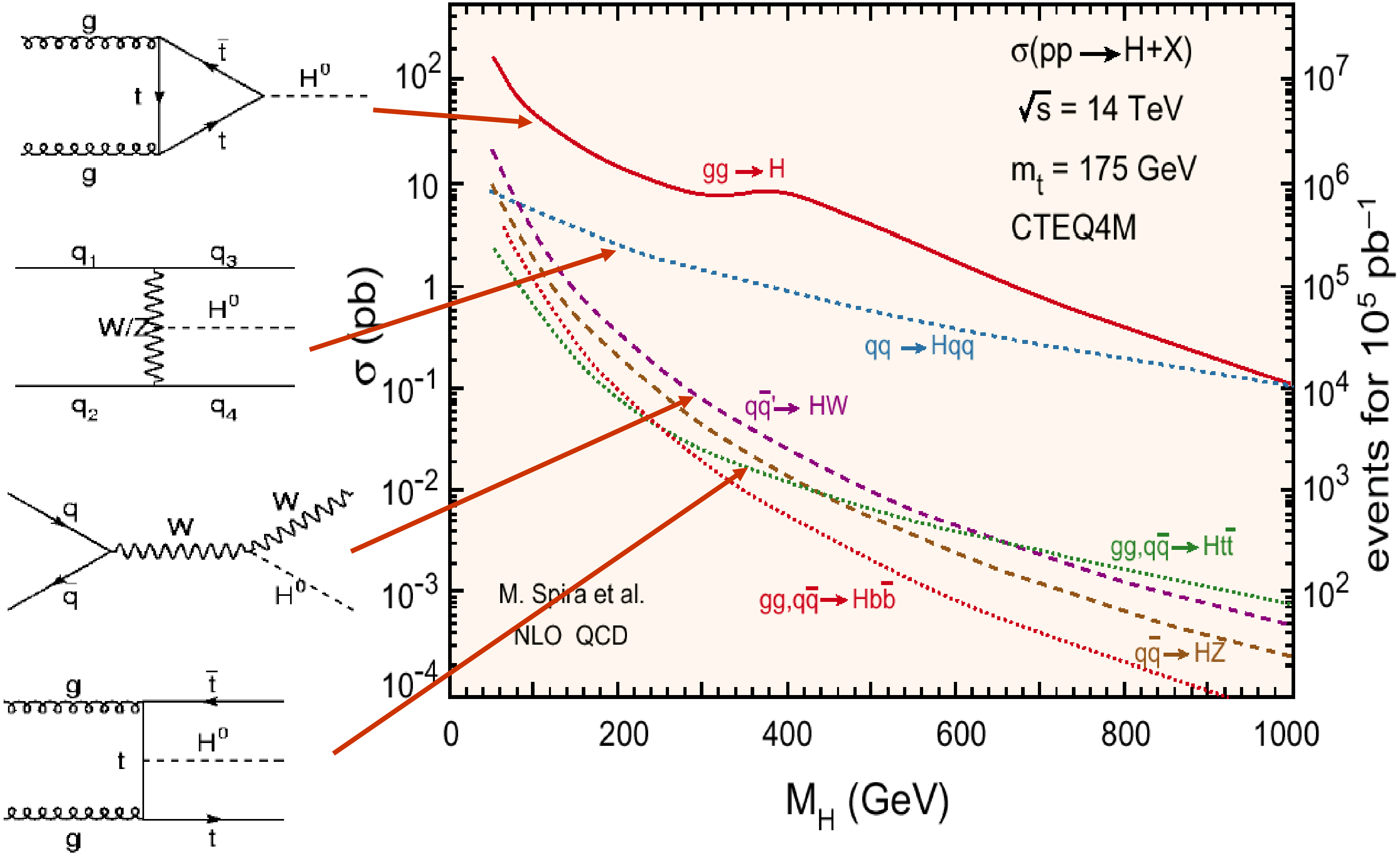
The ATLAS Detector



Magnet: 2 T solenoid + toroids (0.5 T barrel, 1 T endcap)
Tracker: Si pixels, strips + TRT, $\sigma(p_T)/p_T \approx 5\text{x}10^{-4} p_T + 0.01$
ECAL: Pb+LAr, $\sigma(E)/E \approx 10\%/\sqrt{E} + 0.007$
HCAL: Fe+scint. / Cu+LAr (10λ), $\sigma(E)/E \approx 50\%/\sqrt{E} + 0.03$ GeV
Muon: $\sigma(p_T)/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)
Trigger: L1 + RoI-based HLT (L2+EF)

G. Aad *et al*., (The ATLAS Collaboration) *J. Instrum.* 3 (2008) S08003

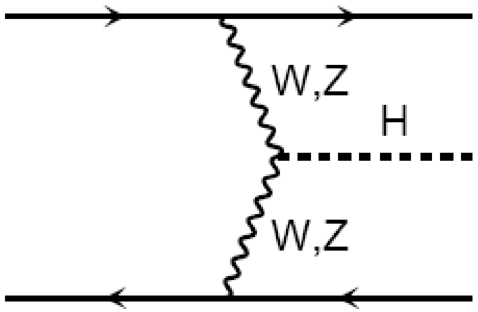
Higgs production at the LHC

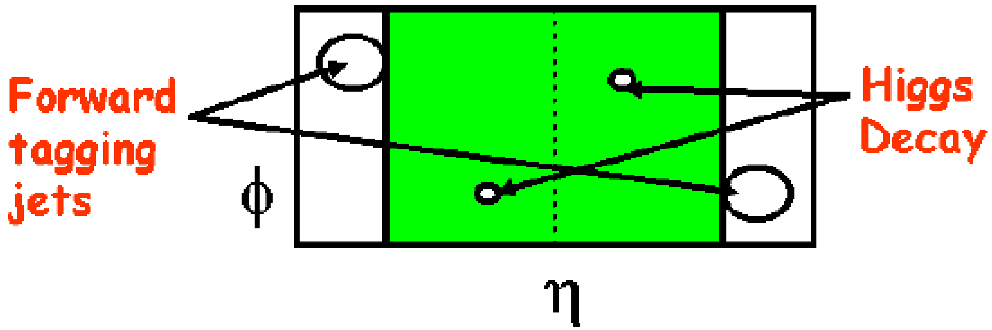


Vector Boson Fusion

VBF ($qq \rightarrow qqH$) gives two forward jets,

no colour connection → large rapidity gap





Additional kinematic properties give background suppression

studied in ATLAS for: $H \rightarrow WW, \tau\tau, \gamma\gamma$

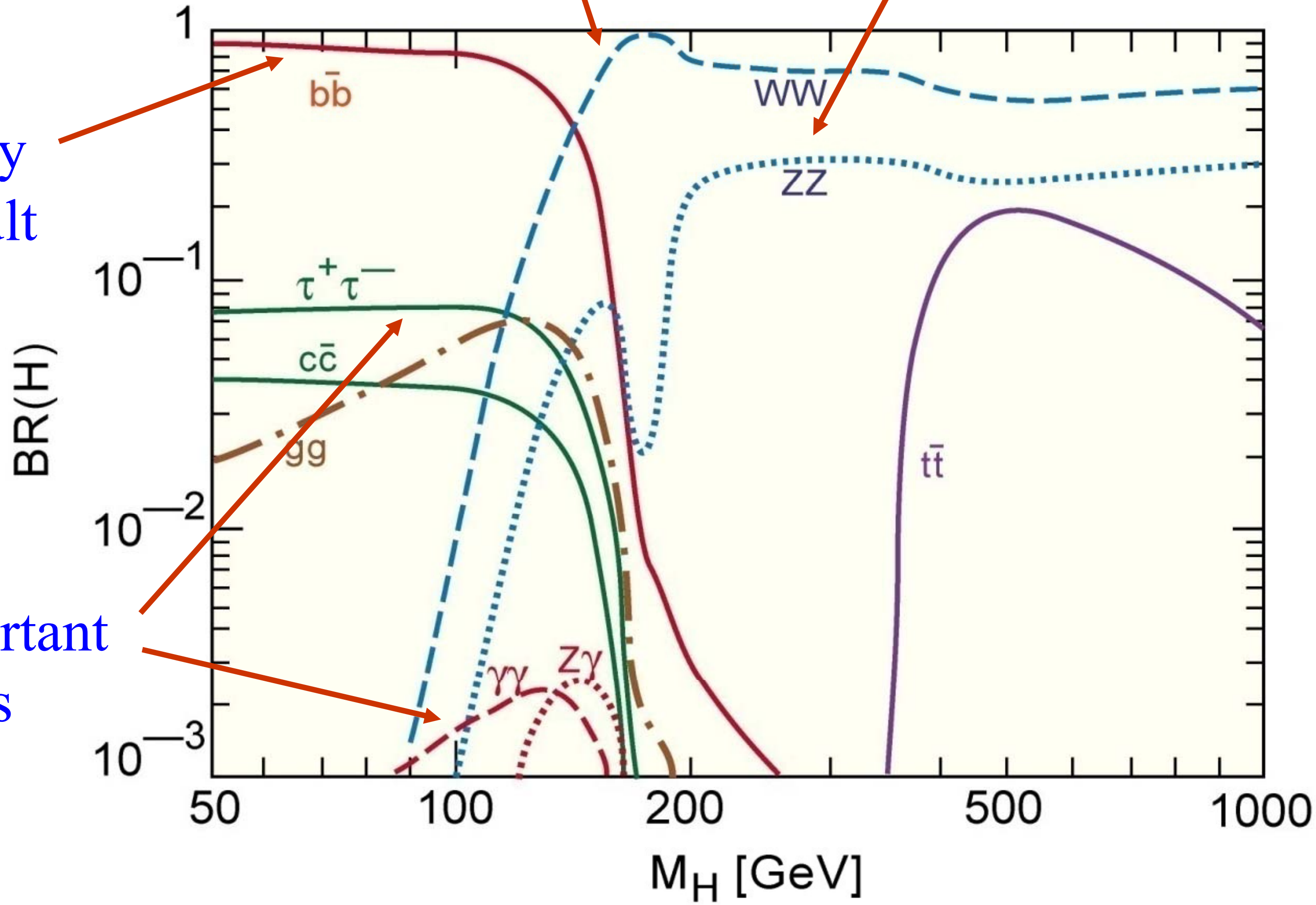
Higgs decay modes

WW dominates for
$2M_W < m_H < 2M_Z$

ZZ "golden mode"

bb very difficult

$\tau\tau$, $\gamma\gamma$ important at low mass



$H \rightarrow ZZ^{(*)} \rightarrow 4l \quad (l = e,\mu)$

Effective in a broad mass range for $m_H > 130$ GeV (except small gap between $2M_W$ and $2M_Z$).

Lepton efficiency crucial: $\varepsilon_{4l} \sim \varepsilon_l^4$

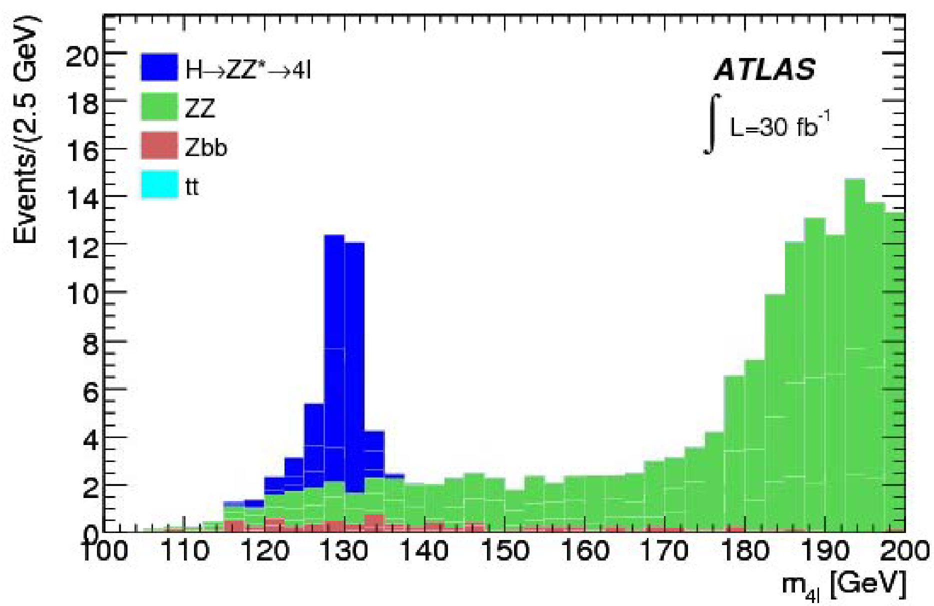
Require at least one Z on shell.

Main triggers: $p_T(e) > 22$ GeV or $p_T(\mu) > 20$ GeV

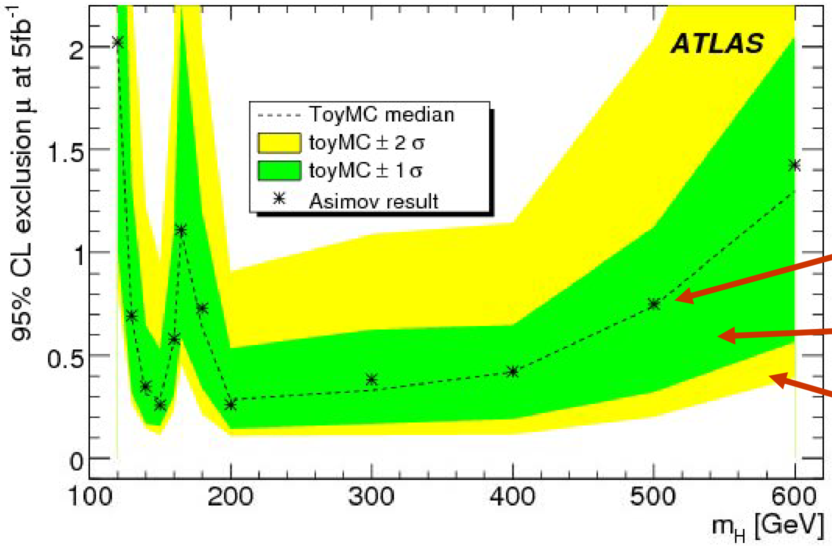
Main background: $ZZ^{(*)}$

also (reducible) Zbb, tt, suppress with isolation, impact parameter, vertex constraints

Fit remaining background from sidebands of m_{4l}.



$H \to ZZ^{(*)} \to 4l$ sensitivity

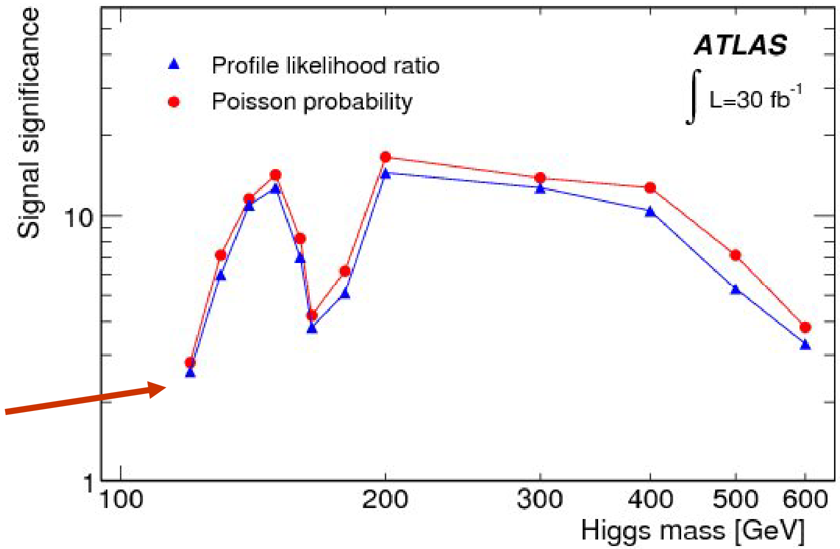


Expected 95% CL upper limit on $\mu = \sigma / \sigma_{SM}$ for 5 fb^{-1} if no Higgs.

median

$\pm 1\sigma$

$\pm 2\sigma$



Expected discovery significance (# of σ) of SM Higgs for 30 fb^{-1}

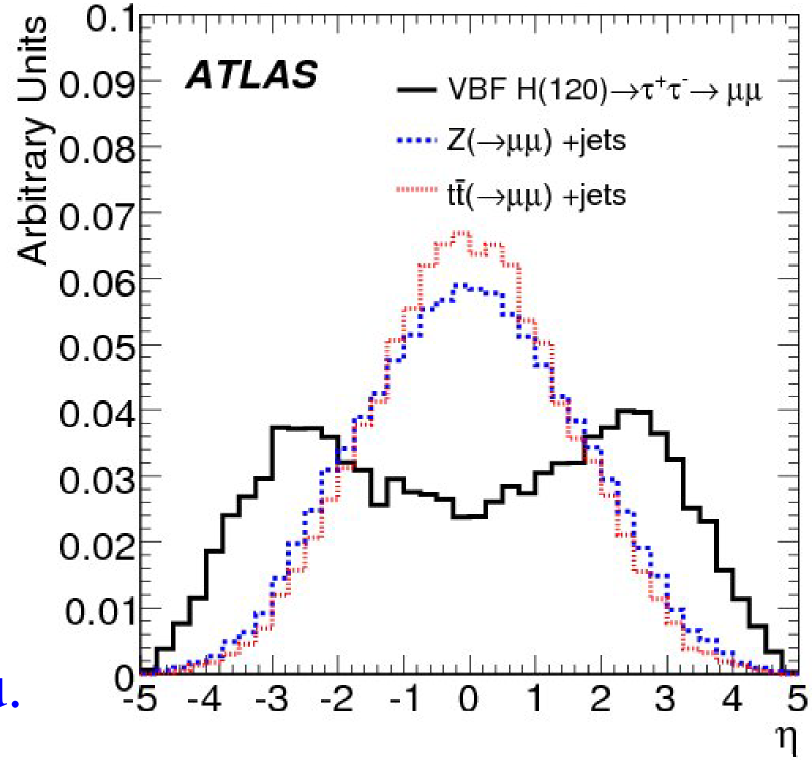
Lower points include systematics

$H \to \tau^+\tau^-$ with 2 jets

Exploit VBF kinematics to suppress Z+jets, tt back-grounds (Central Jet Veto).

Use $\tau\tau \to ll$, lh (also study $\tau\tau \to hh$).

Higgs mass reconstructed using missing E_T and by assuming tau decay products collinear with tau.



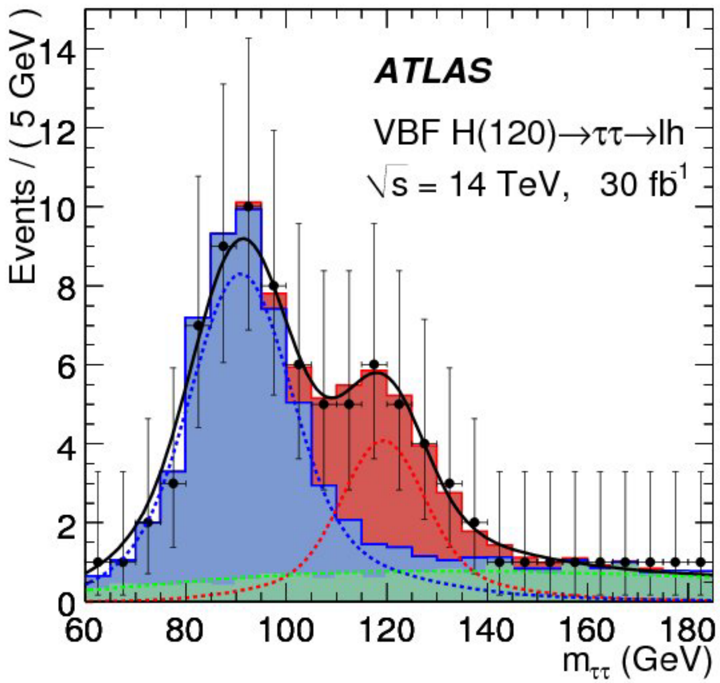
Main triggers: $p_T(e) > 22$ GeV or $p_T(\mu) > 20$ GeV

Important backgrounds: Z + jets, tt

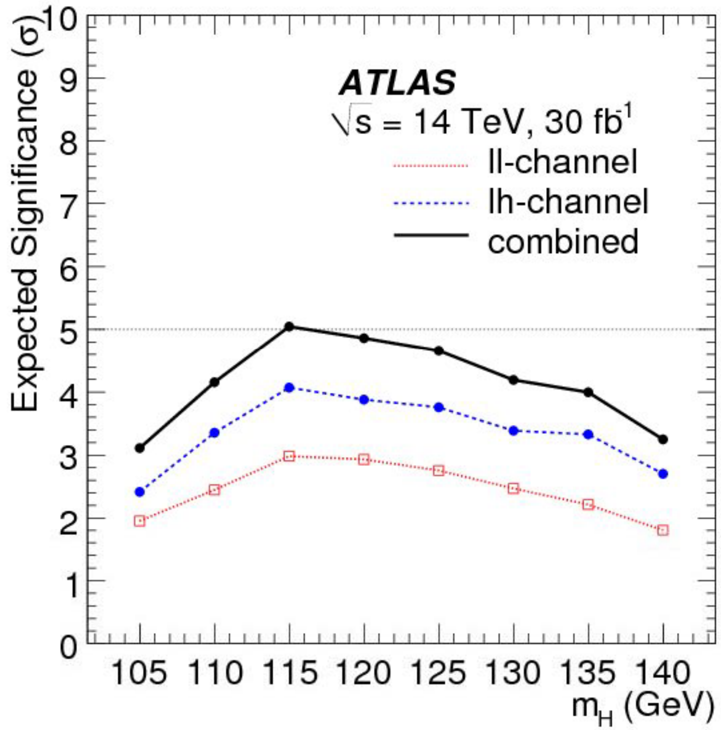
Z + jets background control: select $Z \to \mu\mu$, replace μ by (MC) τ

$H \to \tau^+\tau^-$ with 2 jets

Simultaneous fit of signal and QCD, Z+jets control samples:



$\tau\tau \to lh$ gives most sensitivity:



$H \to \gamma\gamma$

For $115 < m_H < 140$ GeV, BR ~ 0.002, but distinct signature.

Inclusive analysis based on $m_{\gamma\gamma}$

Exclusive analyses (H + 0,1,2 jets) also use other variables (event topology, $p_{T,\gamma\gamma}$, $\cos\theta_{\gamma\gamma}{}^*$); combined in simultaneous fit.

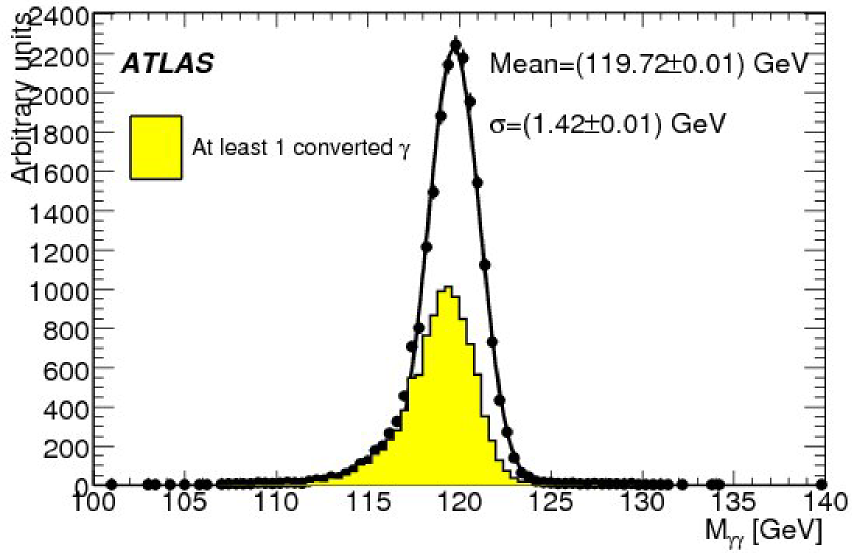
Main triggers: 2 photons, each $p_T > 20$ GeV

Main backrounds: $\gamma\gamma$, γ+jet, jet+jet

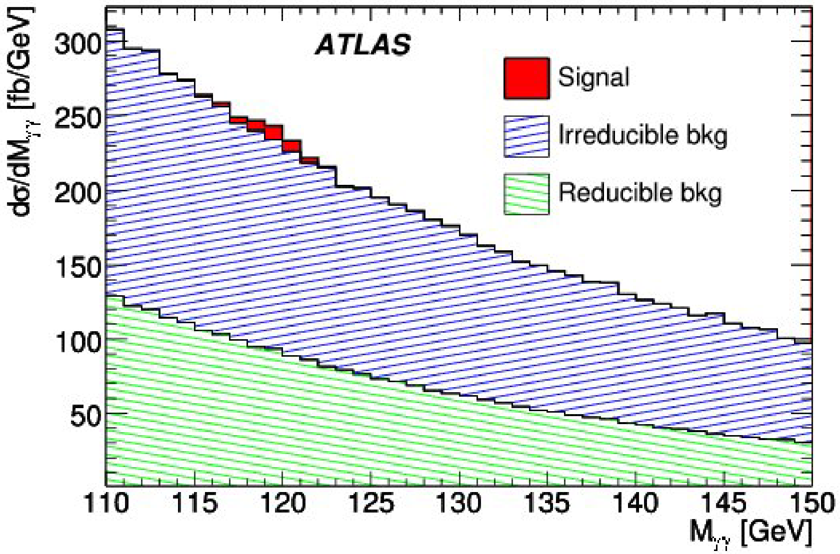
57% of $H\to\gamma\gamma$ events have at least one photon convert ($|\eta|<2.5$)

Conversion reconstruction efficiency 66.4% ($r < 40$ cm)

$\gamma\gamma$ vertex from ECAL pointing and tracker.



$H \rightarrow \gamma\gamma$

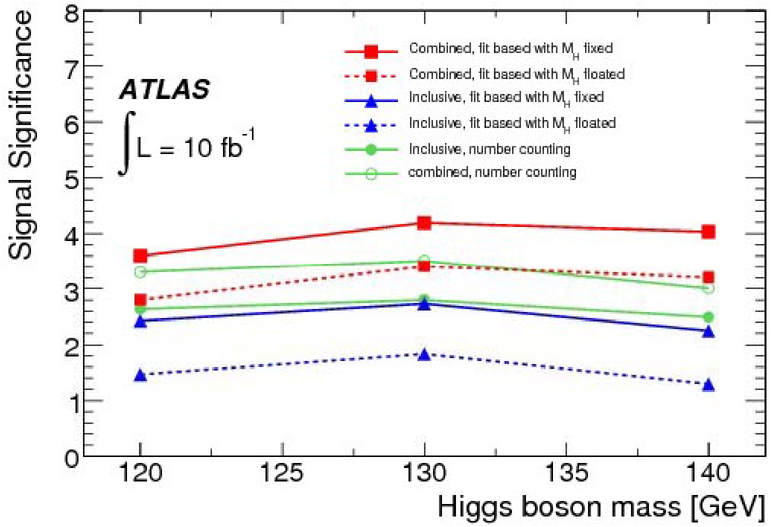


$m_{\gamma\gamma}$ resolution crucial.

Note number of entries here for 1 $\mathrm{fb}^{-1} \sim 250 \rightarrow 6\%$ stat. error per bin.

Expected discovery significance for inclusive and combination of exclusive channels (H + 0,1,2 jets), here both fixed and floating m_{H}.

Inclusive analysis used in current combination with other channels.



$H \to WW^{(*)}$

Most important for $2M_W < m_H < 2M_Z$

Two cases: no jets (mainly gg fusion) and 2 jets (mainly VBF)

For now only WW → eνμν (eνeν, μνμν lνqq under study)

No mass peak because of neutrinos → use transverse mass:

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T,miss}} + E_{\mathrm{T},ll})^2 - (\vec{p}_{\mathrm{T,miss}} + \vec{p}_{\mathrm{T},ll})^2}$$

where

$$E_{\mathrm{T},ll} = \sqrt{p^2_{\mathrm{T},ll} + m^2_{ll}}$$

$$E_{\mathrm{T,miss}} = \sqrt{p^2_{\mathrm{T,miss}} + m^2_{ll}}$$

H → WW with 0 jets

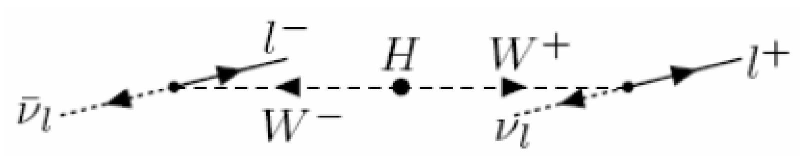
Main triggers: $p_T(e) > 22$ GeV or $p_T(\mu) > 20$ GeV

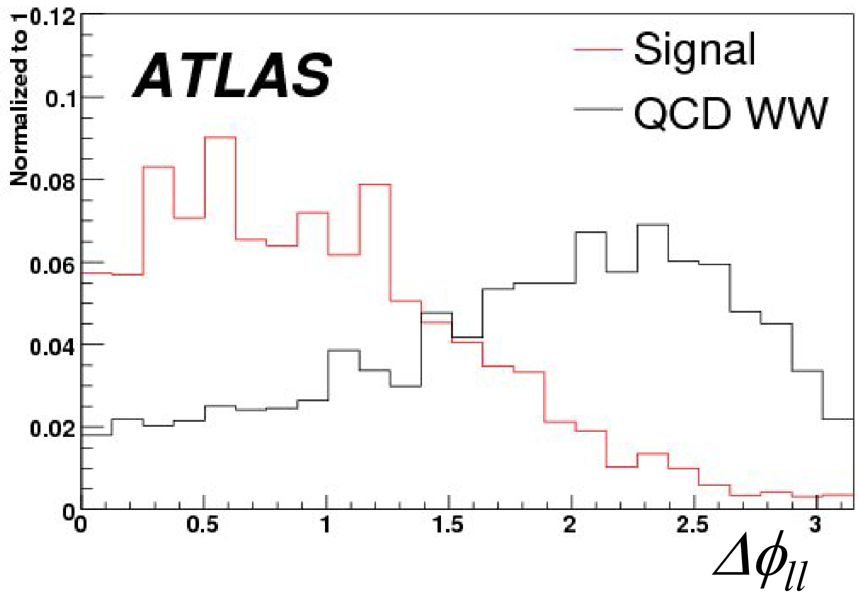
Main background: QCD WW

Simultaneous fit of:

transverse mass,
p_T of WW,
$\Delta\phi_{ll}$ (angle between ll in transverse plane)

Correlated W spins cause leptons to go preferentially in same direction:





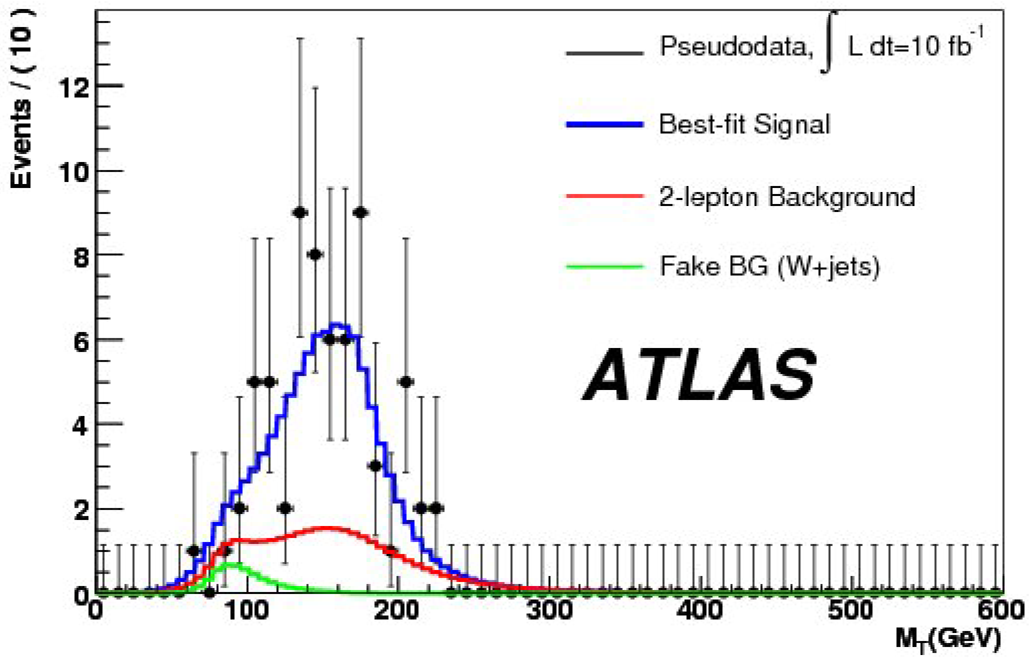
$H \rightarrow WW$ with 2 jets

Main triggers: $p_T(e) > 22$ GeV or $p_T(\mu) > 20$ GeV

Main background: tt

Select signal region in $\Delta\eta_{ll}$, $\Delta\phi_{ll}$

Simultaneous fit of transverse mass and neural net output based on jet activity



Statistical combination of channels

Treat systematics by means of profile likelihood method.

Considers fixed-mass hypothesis; "look-elsewhere-effect" must be studied separately.

Studies for individual channels also use floating-mass fits.

Approximate methods for discovery/exclusion significance.

Valid for $L > 2\ \mathrm{fb}^{-1}$. For lower L need MC methods.

Does not represent final word on methods -- other developments ongoing (Bayesian, $\mathrm{CL_s}$, look-elsewhere-effect,...)

In following describe method for binned distributions; some channels also use unbinned fits.

Statistical model

Bin i of a given channel has n_i events, expectation value is

$$E[n_i] = \mu L \varepsilon_i \sigma_i \mathcal{B} + b_i \equiv \mu s_i + b_i$$

μ is global strength parameter, common to all channels.
$\mu = 0$ means background only, $\mu = 1$ is SM hypothesis.

Expected signal and background are:

$$s_i = s_{\mathrm{tot}} \int_{\mathrm{bin}\, i} f_s(x; \boldsymbol{\theta}_s)\, dx \,,$$

$$b_i = b_{\mathrm{tot}} \int_{\mathrm{bin}\, i} f_b(x; \boldsymbol{\theta}_b)\, dx$$

b_{tot}, $\boldsymbol{\theta}_s$, $\boldsymbol{\theta}_b$ are nuisance parameters

The likelihood function

The single-channel likelihood function uses Poisson model for events in signal and control histograms:

data in signal histogram

data in control histogram

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k}$$

here signal rate is only parameter of interest

$\boldsymbol{\theta}$ represents all nuisance parameters, e.g., background rate, shapes

There is a likelihood $L_i(\mu,\boldsymbol{\theta}_i)$ for each channel, $i = 1, \ldots, N$.

The full likelihood function is $L(\mu, \boldsymbol{\theta}) = \prod_i L_i(\mu, \boldsymbol{\theta}_i)$

Profile likelihood ratio

To test hypothesized value of μ, construct profile likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

Maximized L for given μ

Maximized L

Equivalently use $q_\mu = -2 \ln \lambda(\mu)$:

data agree well with hypothesized $\mu \rightarrow q_\mu$ small

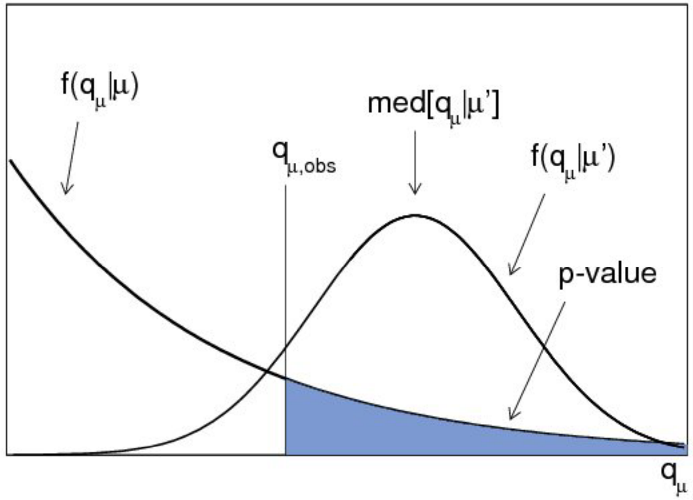
data disagree with hypothesized $\mu \rightarrow q_\mu$ large

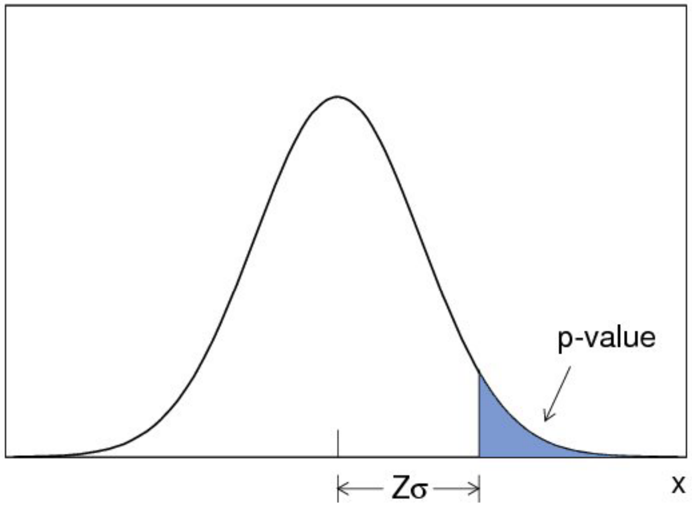
Distribution of q_μ under assumption of μ related to chi-square (Wilks' theorem, approximation valid for roughly $L > 2$ fb^{-1}):

$$f(q_\mu|\mu) \approx \frac{1}{2} f_{\chi^2_1}(q_\mu) + \frac{1}{2}\delta(q_\mu)$$

p-value / significance of hypothesized μ

Test hypothesized μ by giving p-value, probability to see data with $\leq$ compatibility with μ compared to data observed:





Equivalently use significance, Z, defined as equivalent number of sigmas for a Gaussian fluctuation in one direction:

$$Z = \Phi^{-1}(1-p)$$

Sensitivity

Discovery:

Generate data under $s+b$ ($\mu = 1$) hypothesis;

Test hypothesis $\mu = 0 \rightarrow p$-value $\rightarrow Z$.

Exclusion:

Generate data under background-only ($\mu = 0$) hypothesis;

Test hypothesis $\mu = 1$.

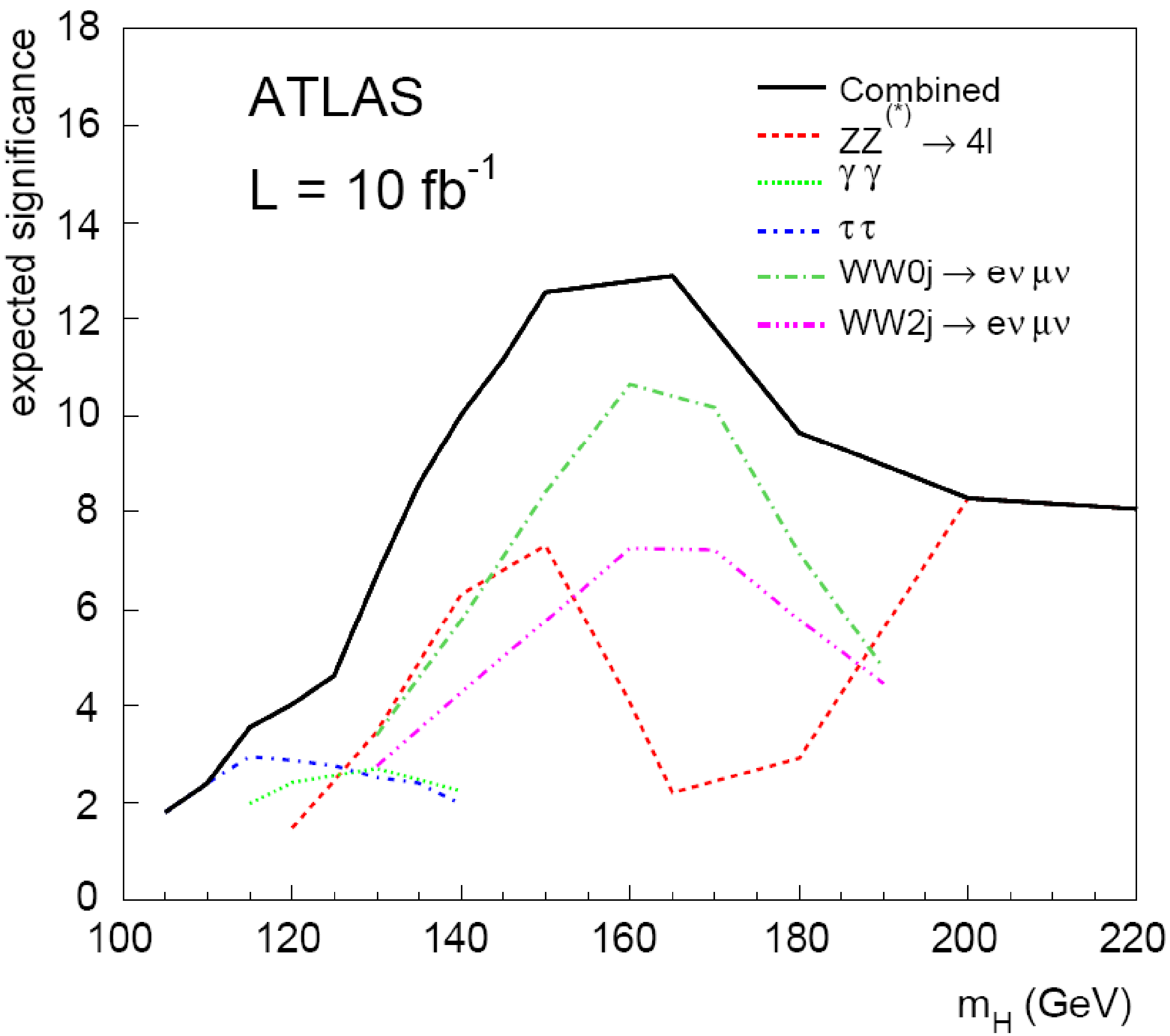
If $\mu = 1$ has p-value < 0.05 exclude m_{H} at 95% CL.

Estimate median significance by setting data equal to expectation values or by using MC.

For median, can combine significances of individual channels.

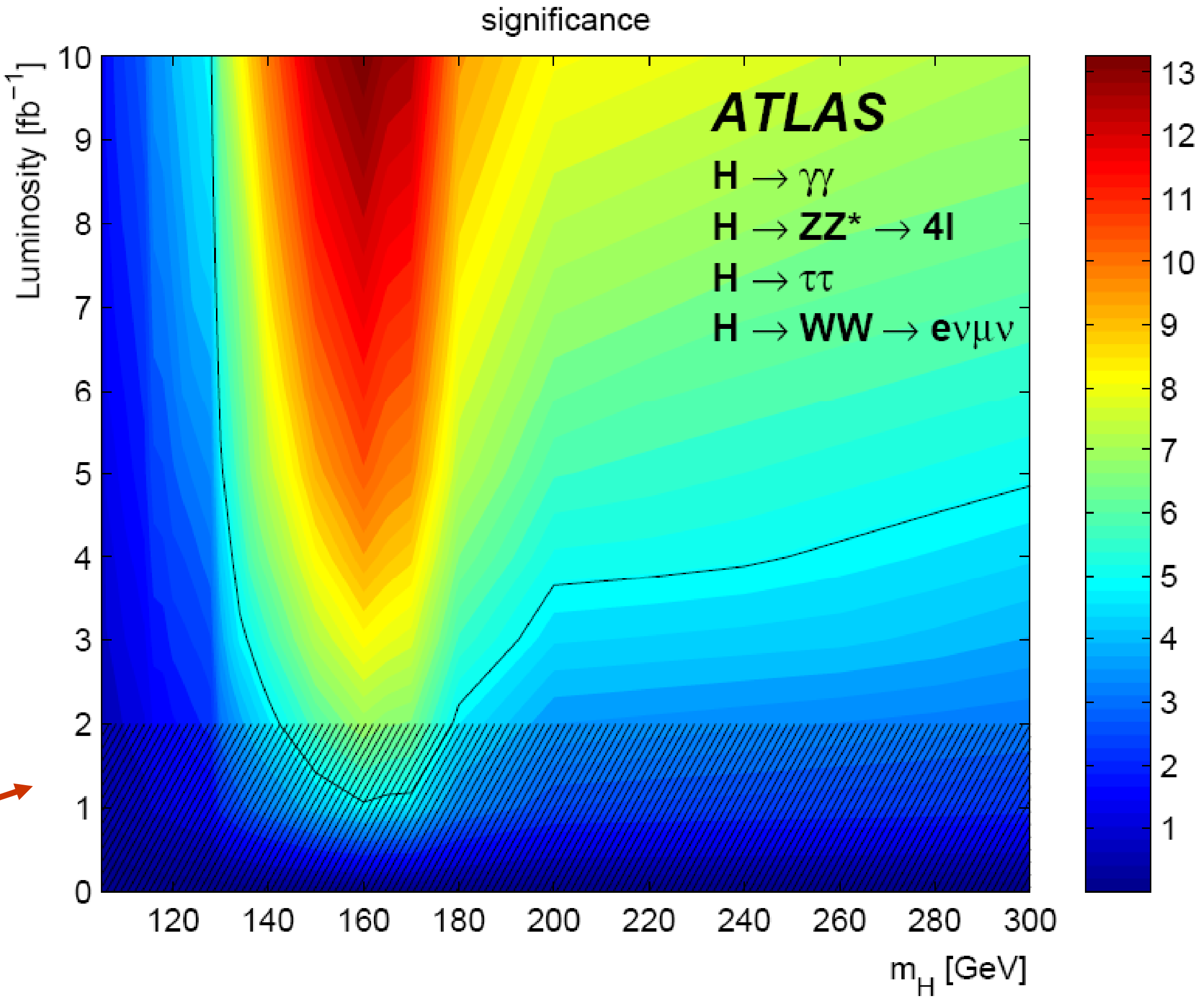
For significance of e.g. a real data set, need global fit.

Combined discovery significance



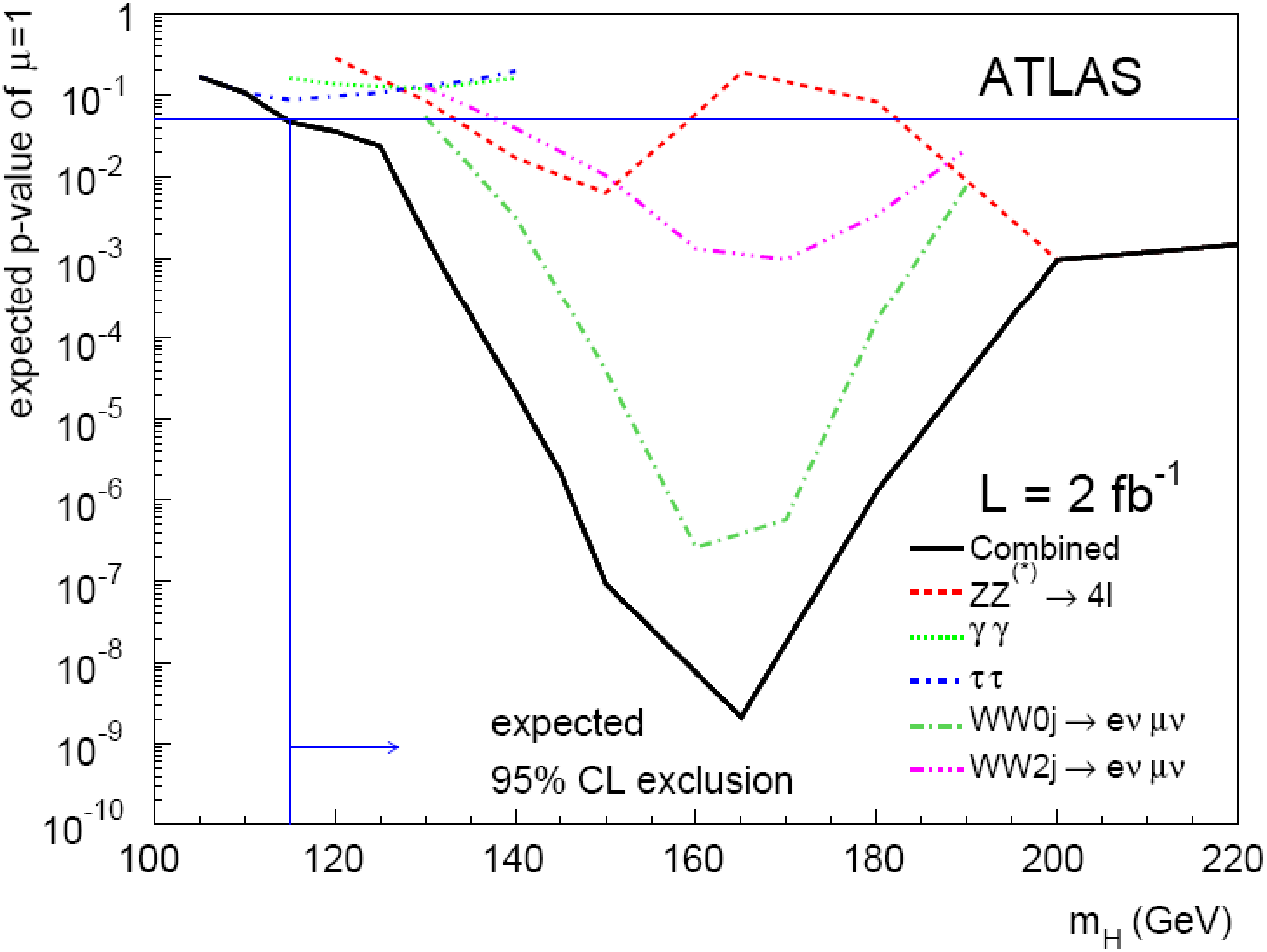
Combined discovery significance

Discovery signficance (in colour) vs. L, m_H:



Approximations in combination not always accurate for $L < 2$ fb^{-1} but in most cases conservative.

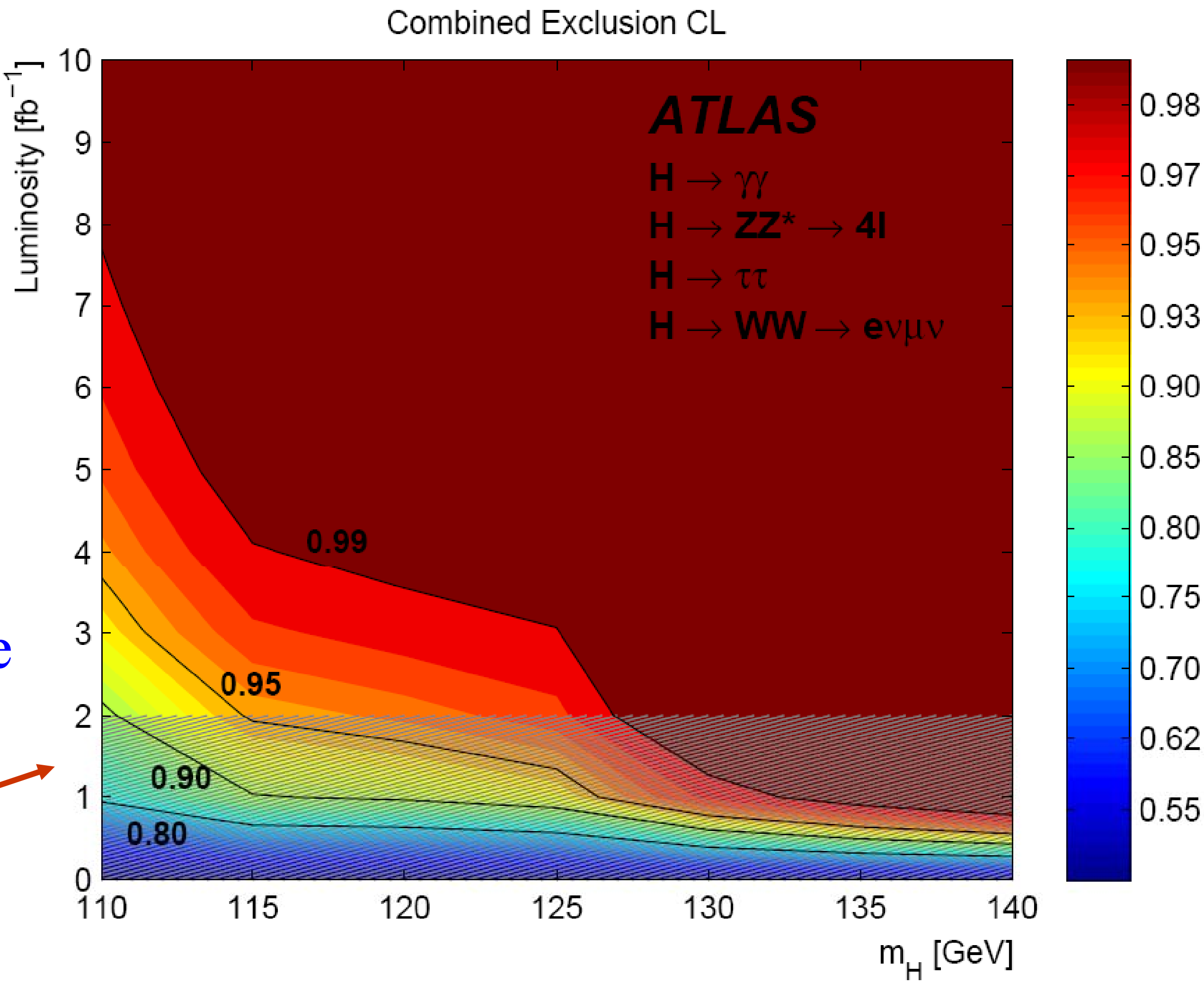
Combined 95% CL exclusion limits



For 2 fb^{-1}, expected 95% CL upper limit on m_H is 115 GeV.

Combined 95% CL exclusion limits

$1 - p$-value of m_{H} (in colour) vs. L, m_{H}:



Approximations in combination not always accurate for $L < 2\ \mathrm{fb}^{-1}$ but in most cases conservative.

Summary and conclusions

Studies here only cover Standard Model Higgs channels most relevant to discovery

some modes not yet included → sensitivity will improve

Studies use NLO cross sections, improved MC generators, detailed detector simulation, improved statistical treatment.

Systematic uncertainties treated using profile likelihood.

Due to approximations used, combined results valid for $L > 2\ \mathrm{fb}^{-1}$

For $L = 2\ \mathrm{fb}^{-1}$:

expected discovery 5σ or more in $143 < m_{\mathrm{H}} < 179$ GeV,
expected upper limit on m_{H} at 95% CL is 115 GeV

Special thanks to

my ATLAS colleagues, especially:

Eilam Gross, Aleandro Nisati, Ketevi Assamagan, Bill Quayle, Yaquan Fang, Ricardo Goncalo, Tom LeCompte, Bruce Mellado, Marumi Kado,...

Extra slides

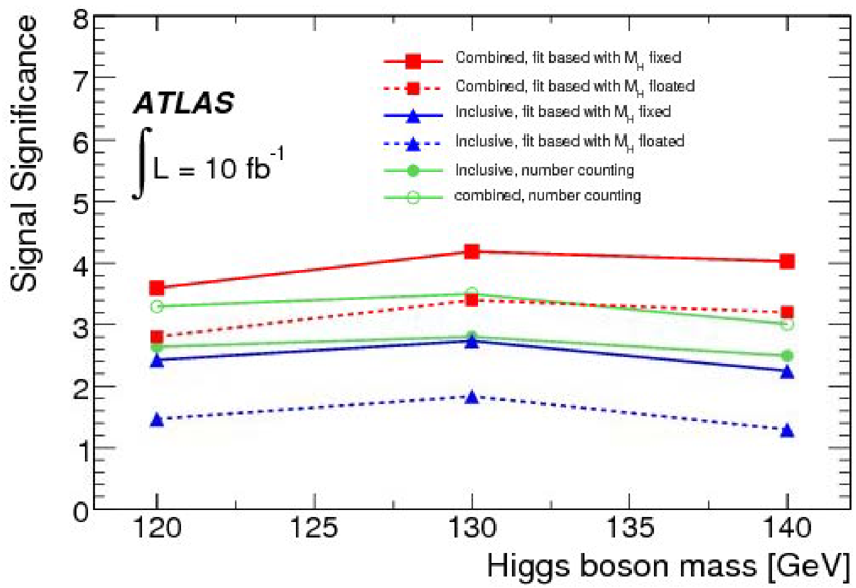
The "look-elsewhere effect"

Look for Higgs at many m_H values -- probability of seeing a large fluctuation for *some* m_H increased.

Combined significance shown here relates to fixed m_H.

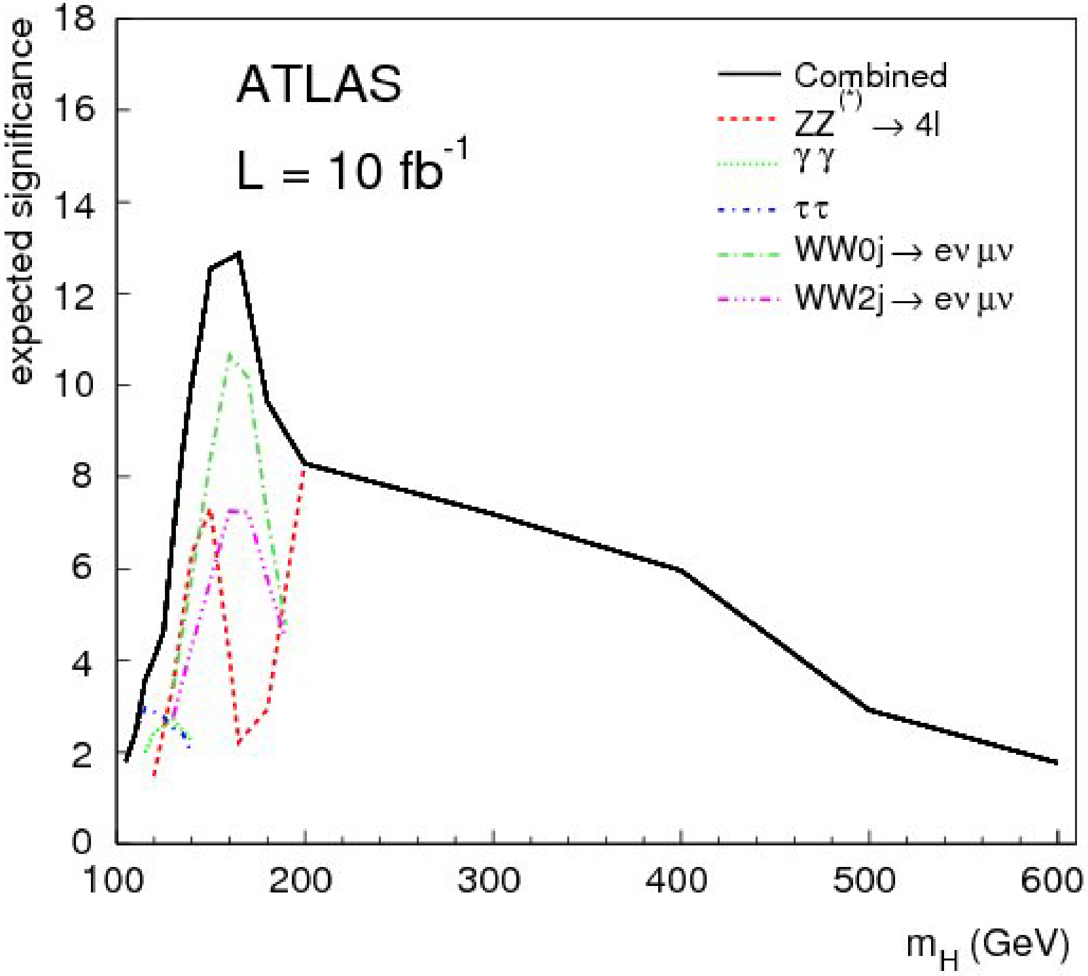
False discovery prob enhanced by ~ mass region explored / σ_m

For $H \to \gamma\gamma$ and $H \to WW$, studied by allowing m_H to float in fit:

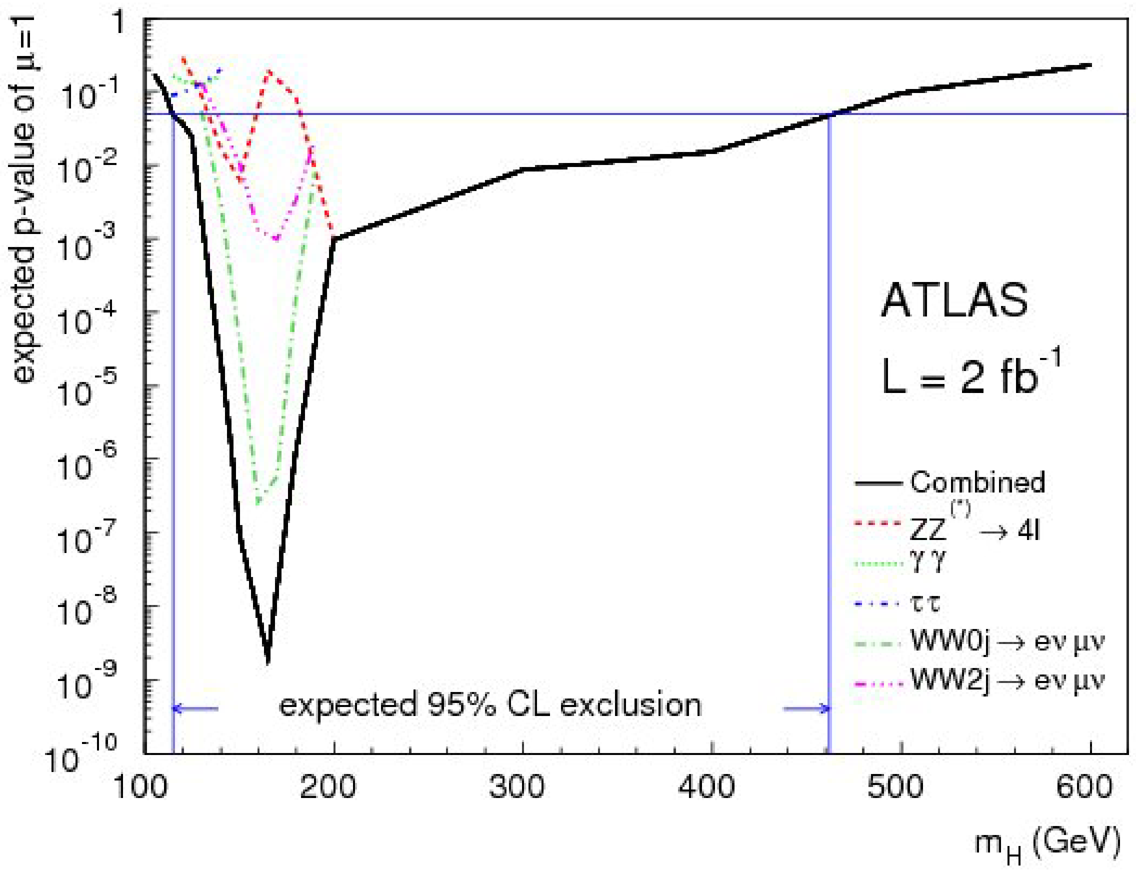


$H \to \gamma\gamma$

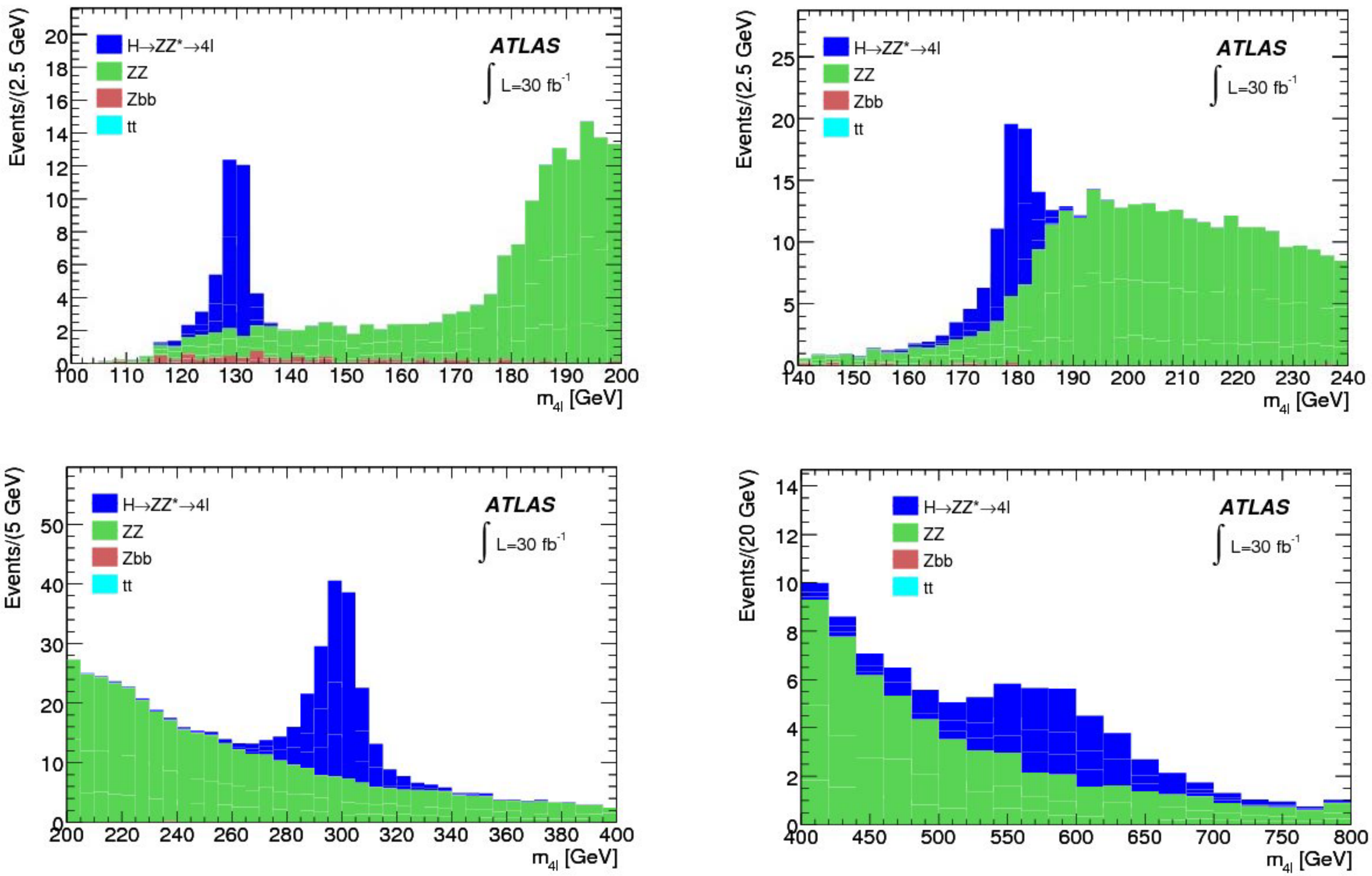
Expected discovery significance



Expected p-value of SM vs m_H

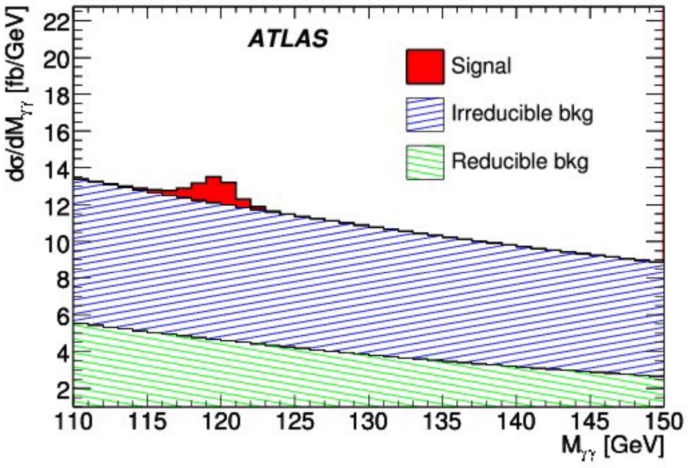


H → 4l at different m_H

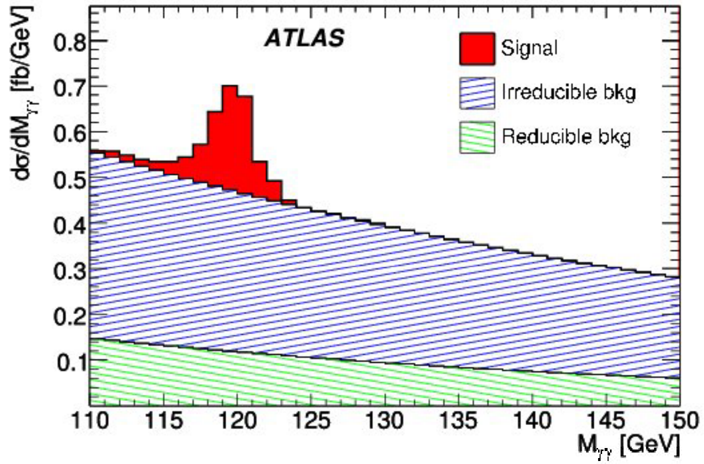


$H \rightarrow \gamma\gamma$ for exclusive channels

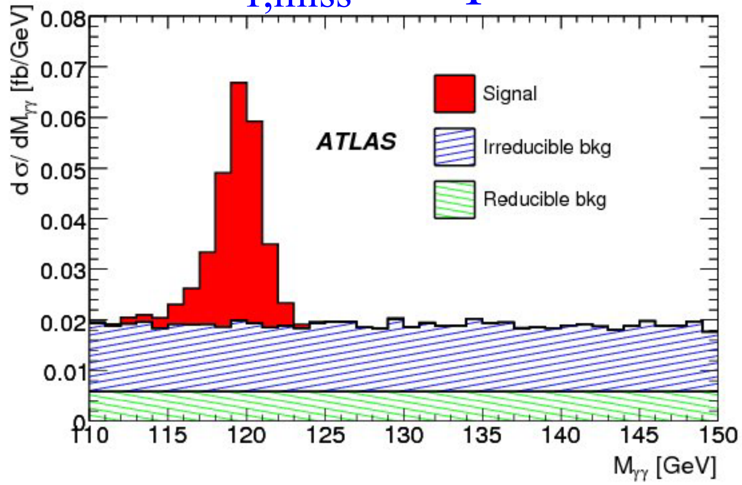
H + 1 jet



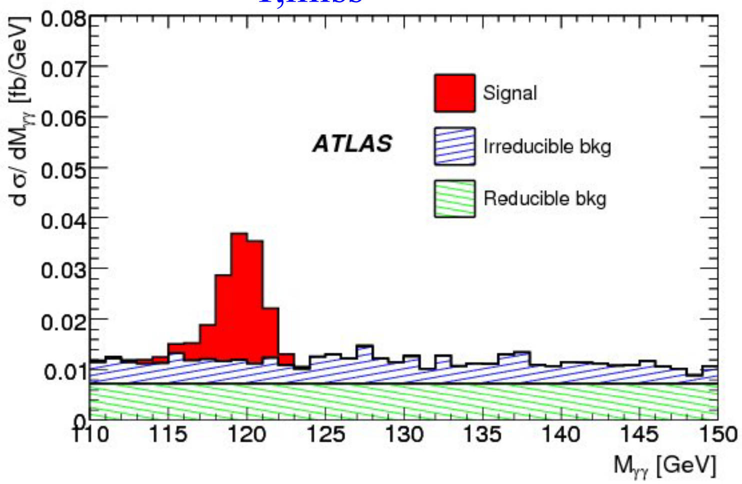
H + 2 jets



H + $E_{T,miss}$ + lepton

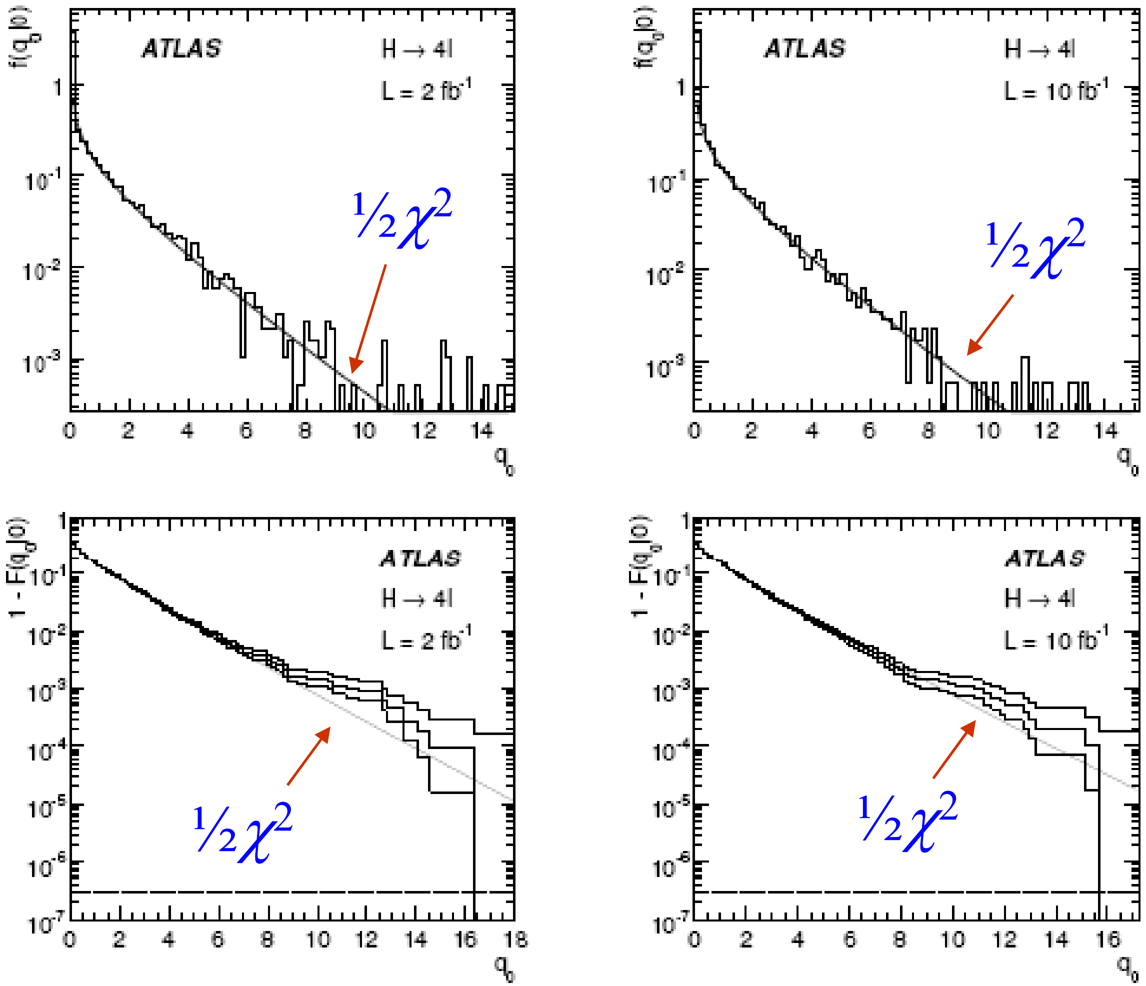


H + $E_{T,miss}$



Example from validation exercise: $ZZ^{(*)} \rightarrow 4l$

Distributions of q_0 for 2, 10 fb^{-1} from MC compared to $\frac{1}{2}\chi^2$



(One minus) cumulative distributions.
Band gives 68% CL limits.

5σ level