Low Mass Standard Model Higgs Searches at the LHC

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On behalf of the ATLAS and CMS Collaborations

MCTP Spring Symposium on Higgs Boson Physics

University of Michigan, Ann Arbor

May 12-15th 2010

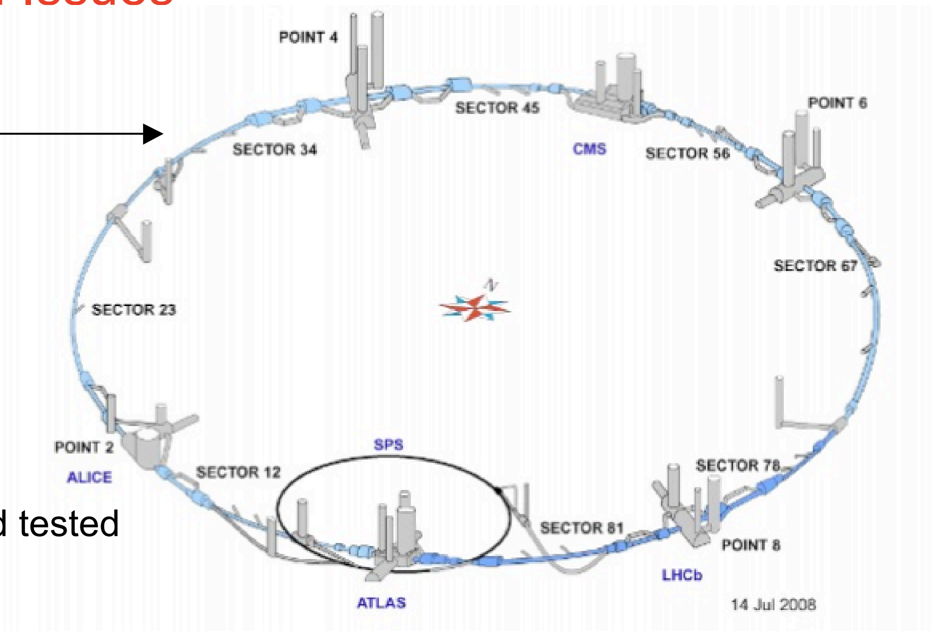
The LHC Status and Schedule

Very Brief Review

Brief Recap of the LHC Situation

The Main Issues

September 19, 2008
Incident in sector 3-4



- Aftermath of the Incident
  - All the damages were repaired
  - New Quench Protection System deployed and tested
  - All magnet circuits qualified for 3.5 TeV

However…

- Splice issues not solved : Consolidation needed
- Energy limited to 3.5 TeV (per beam) until the end of 2011

run in 2010-2011 to collect ~1 fb^{-1} at 7 TeV followed by a long shutdown to consolidate and prepare for higher energies and luminosity

After a short run at 900 GeV december 2009, since march running at 7 TeV with nominal optics and safe beams (2 bunches, few 10^{10} ppb)

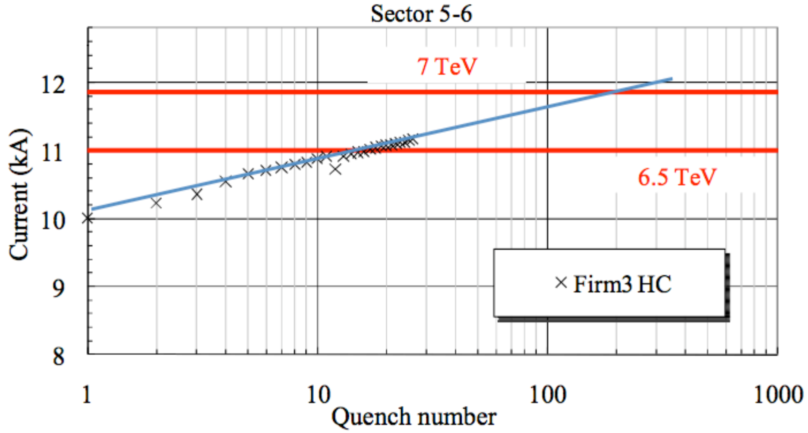
Next learn how to operate with destructive beams…

- Towards higher energies

  - To eradicate the problem need complete warm up and consolidation of most splices
  - Still not obvious which centre-of-mass energy can be reached (training quenches)…

However the difference between 13 and 14 TeV is not really relevant

C. Lorin and E. Todesco, Chamonix 2010



- Towards Higher Luminosities

  - Absolutely critical is the MPS : Machine Protection System

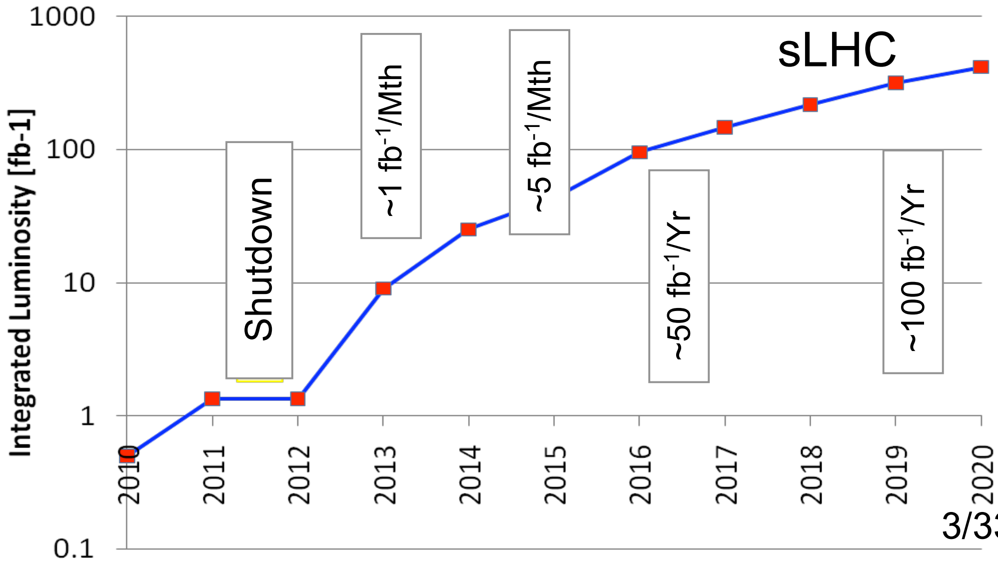
…be able to dump the beam (nominal 350 MJ) in three turns !

  - The collimation system

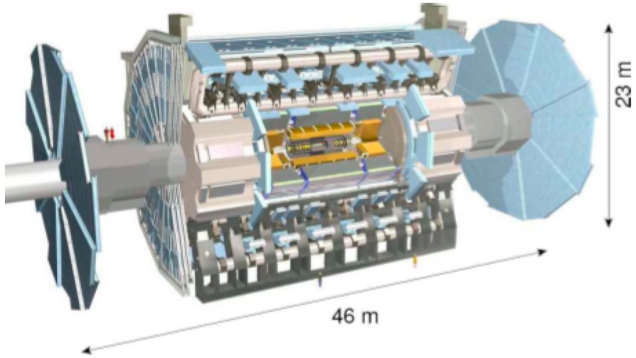
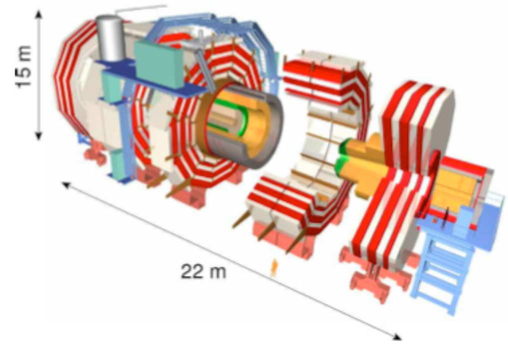
Cold collimation will require to move some of the magnets

Long Term Plan

After the long shutdown in 2012 probably at least one additional long shutdown for the installation of the collimators



The ATLAS and CMS Detectors Synopsis

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4}p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4}p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

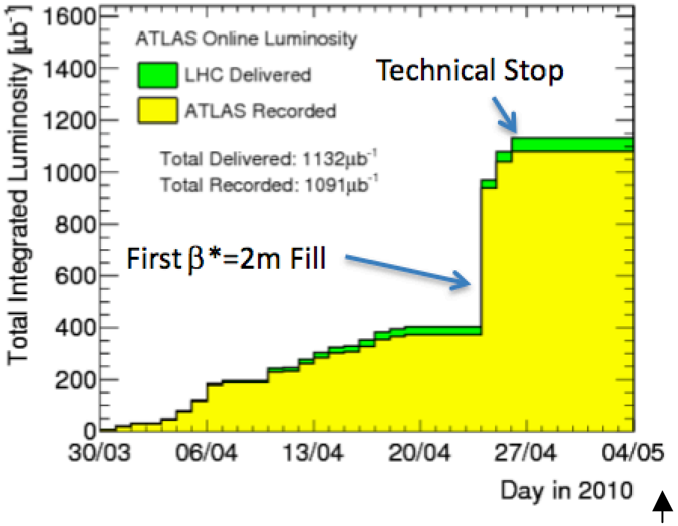
The ATLAS Detectors Overall Readiness

The CMS detector will be discussed by S. Nahn

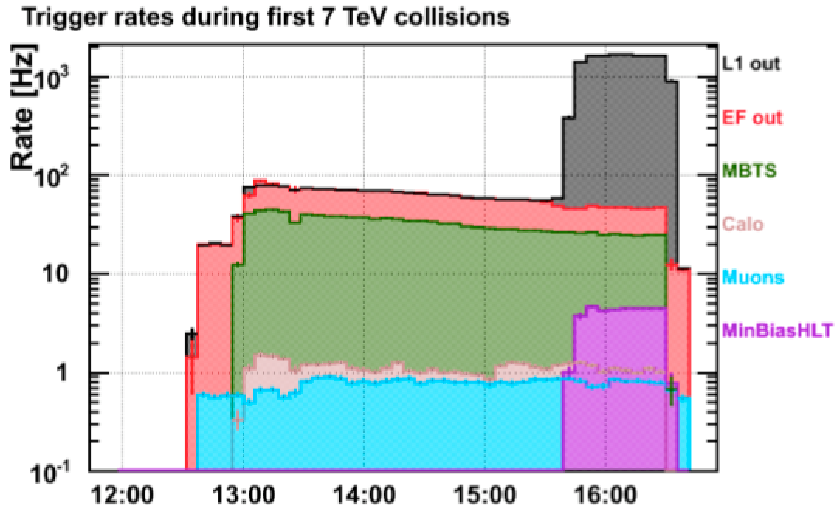
- Commissioning in situ is ongoing since more than two years, started with cosmics and beam dump data

- Since the beginning of collision data ATLAS has been working very well collecting more than 96% of the stable beams delivered luminosity

- The peak luminosity has reached ~2.10^{28} cm^{-2}s^{-1} about 3 nb^{-1} of data has been collected.



About a week ago



- Triggering is a critical issue at LHC : Commissioning well advanced

- Another critical issue is the data processing (and reprocessing) which has also been working very well

- Data quality is excellent so far

A non exhaustive number of preliminary results will be shown to illustrate the readiness of the ATLAS detector

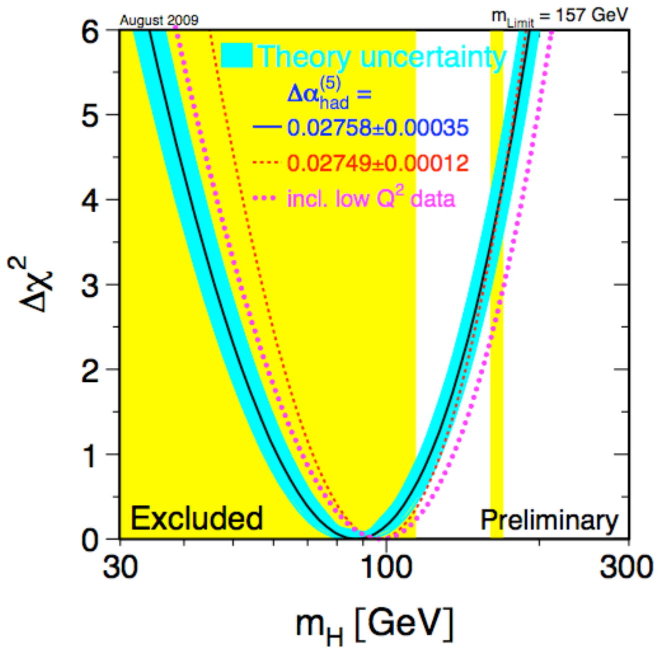
Low Mass Higgs Hunting at LHC

Only rather long term results will be shown (~2 fb^{-1} or more at 14 TeV), results with 1 fb^{-1} of data at a centre-of-mass energy of 7 TeV will be given by V. Sharma

MSSM Higgs searches : B. Lenzi

B-SM-MSSM Higgs searches : D. Rebuzzi

What Makes the Low Mass Range so Special?



- Electroweak fit yields an upper limit at ~160 GeV/c^2
- From GFitter $116^{+15.6}_{-1.3}$ GeV/c^2 (M. Baak et al.)
- LEP 2 direct search limit 114.4 GeV/c^2 at 95% CL

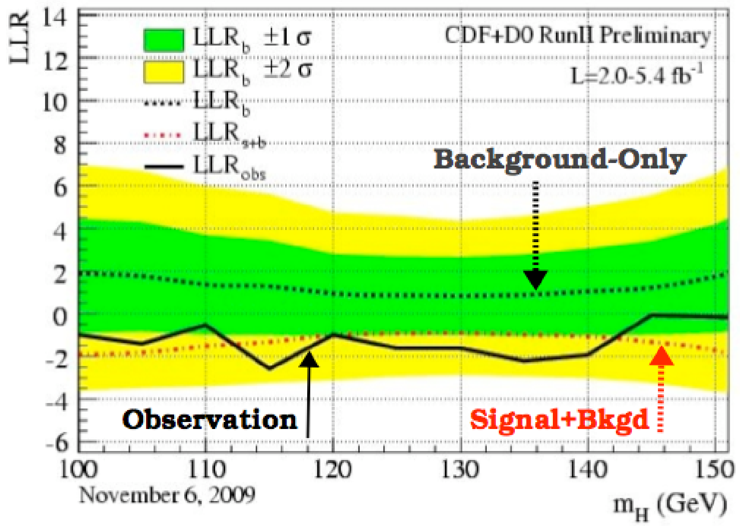
Very sharp limit… In fact :

The expected limit was 115.3 GeV/c^2 at 95% CL

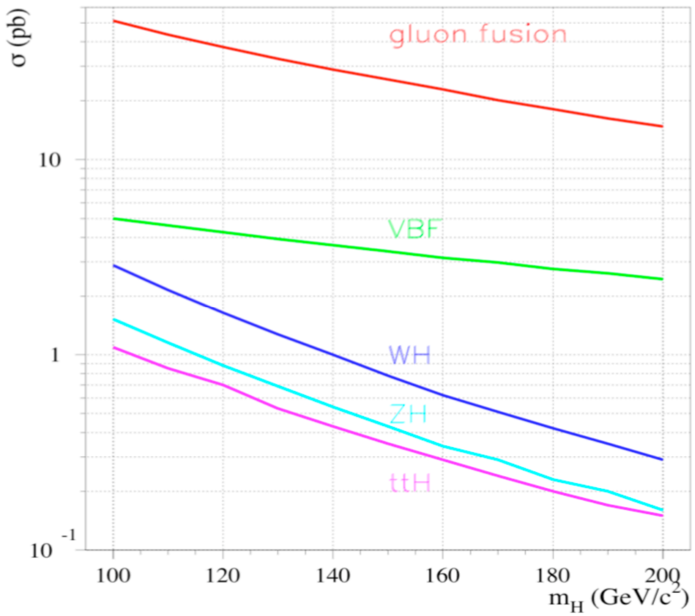
Difference due to an excess of ~1.7σ at ~115 GeV/c^2

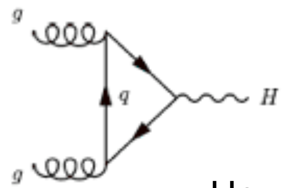
- TeVatron is closing in from above the low mass region (see Sergo Jindariani's talk)

From Taka Yasuda's talk, TeVatron is also seeing an excess compatible with the standard model signal expectation (not significant but certainly to follow closely)



Main Production Modes

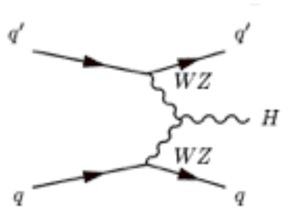




- Gluon fusion process :

Dominant process known at NNnLO

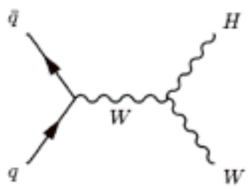
However rather large TH uncertainty* ~O(10%) due to the large corrections for gluon initiated process

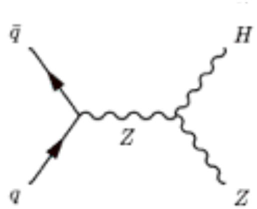


- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Rather distinctive features with two conspicuous forward jets and a rapidity gap

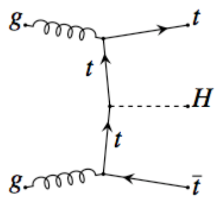




- Associated Production with W and Z :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically



- Associated Production with top pair :

known at NLO TH uncertainty ~O(15%)

Quite distinctive but also quite crowded

* TH uncertainty mostly from scale variation, $\delta\sigma_{PDF}$~ 2-3% and $\delta\sigma_{\alpha s}$~ 4-5% More on this by Joey Huston

Decay Modes

The three "Low Mass" Higgs channels

- The dominant b-decay channel

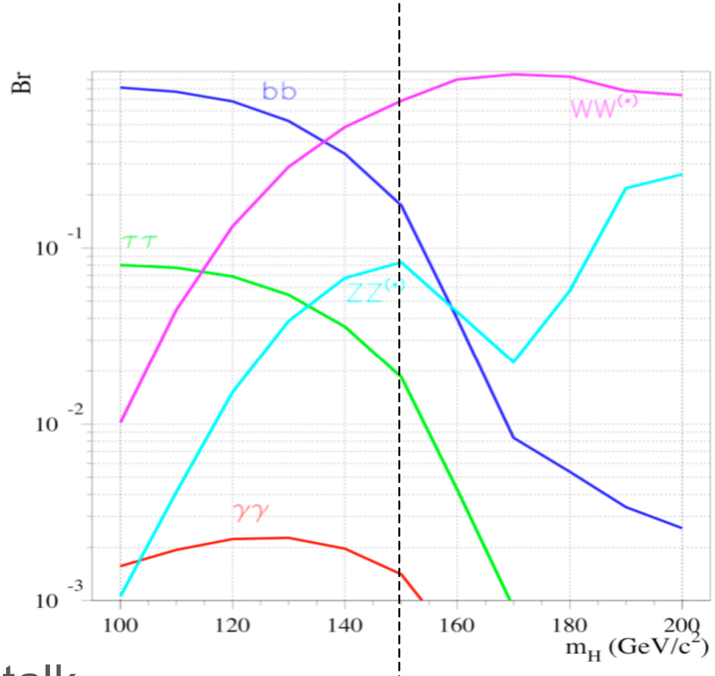
Huge backgrounds, needs distinctive features at production level and beyond…

- The $\tau\tau$ channel

Also needs distinctive production features, typically VBF

- The $\gamma\gamma$ channel

Small branching but very distinctive signature on its own



WW and ZZ will be covered in Steve Nahn's talk

Common effort LHC-wide to compute cross sections and branching ratios and…

- Use common standard model input parameters

- Use a common strategy on the estimation of uncertainties some of which are highly correlated (scale variation, PDFs, α_S, etc…)

- Inauguration workshop in Freiburg April 2010

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

See Jianming and Daniela for more details

The Mainstream Low Mass Higgs Search Channels

$H \to \gamma\gamma$ and VBF $H \to \tau\tau$

Mainstream channels event yields for 1 fb^{-1} (with trigger and reconstruction efficiencies) :

$\gamma\gamma$ (120 GeV/c^2)	$\tau\tau$ (120 GeV/c^2)	ZZ (130 GeV/c^2)	WW (170 GeV/c^2)
25	1 (ll and lh)	1 (4e,4μ,2e2μ)	20 (no jets) and 13 (2jets)

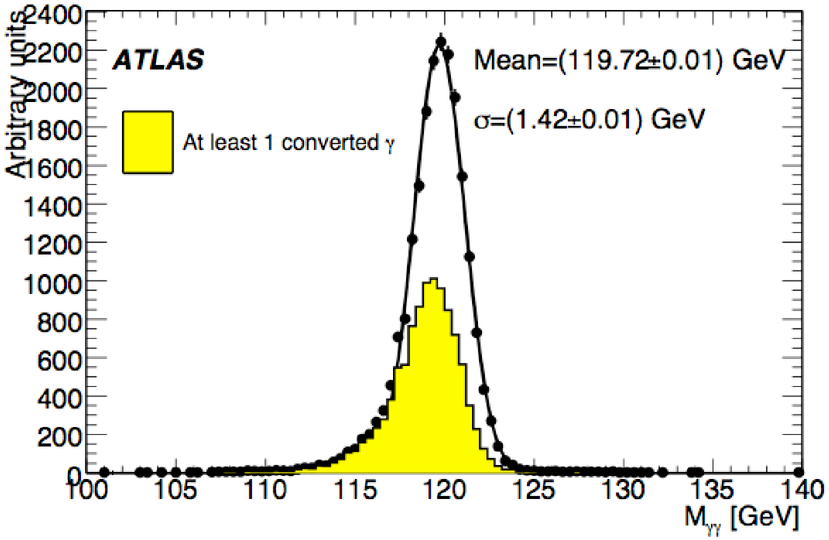
Small branching but large event yield

ATLAS numbers (similar for CMS)

The channels with subsequent decay of the Higgs in bb will be discussed later but for comparison in the ttH channel ~ 1 event is expected.

The H→γγ Channel(s)

- All inclusive and very robust signal (in particular robust against pile-up)
- Despite the low branching (~0.2%) it has the large event yield!
- If observed implies that the Higgs is not spin 1 from Landau-Yang theorem
- Excellent mass resolution : ~1.4 GeV (ATLAS) and ~0.9 GeV (CMS)



Main differences (ATLAS vs. CMS) :

- CMS better sampling term (homogenous crystals)
- CMS Does not have a magnet in front

- ATLAS has a longitudinal segmentation
- ATLAS has a very granular first compartment

→ Allow for an improved identification…

- Note the very large fraction of converted photons… require a very thorough calibration!

(CMS has ~same number of conversions)

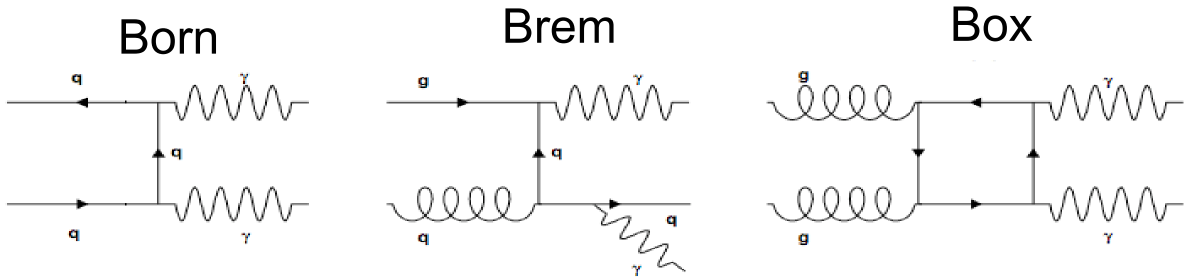
- Primary vertex reconstruction is also crucial (photon pointing, recoil tracks and conversion tracks)

(5.6 cm beam spot adds ~1.4 GeV mass resolution!)

This is not the whole story…

- Backgrounds !

Irreducible backgrounds



- Not much can be done against Born and box.

Best estimate by parton-level resummed NLO ResBos (See Talk by C.P. Yuan)

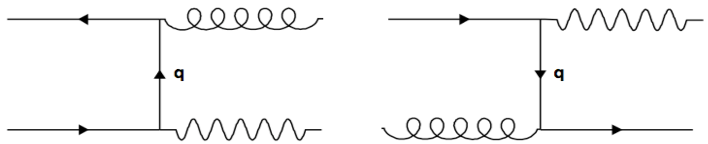
- The brem in principle reducible in practice not, and it is a process difficult to simulate

Best estimate by parton-level NLO fixed order Diphox (T. Binoth,J.Ph. Guillet et al.)

Now SHERPA (Gleisberg and S. Hoeche et al.)

- The Reducible backgrounds : Critical to reach jet rejections O(5000)

Not at all exhaustive list…



Final state parton(s) fragments into a leading π^0

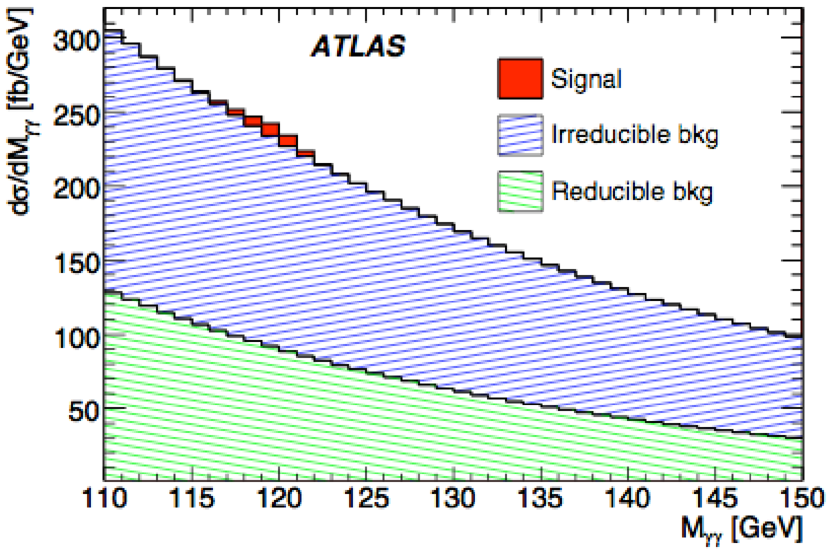
Best estimate by parton-level fixed order NLO JetPhox (S. Catani, M. Fontannaz et al.)

High granularity of ATLAS comes to play.

Also note : large difference Pythia vs. Herwig in the leading $\pi 0$ fragmentation

The H→γγ Inclusive Channel

80% gg, 10% VBF and 10% AP*



To illustrates the importance of background rejection : s/b ~ 2.6%

Sensitivity for 10 fb^{-1} (14TeV): $s/\sqrt{b} \sim 2.6$

s ~ 25 and b ~ 950** (m_H=120 GeV/c^2 for 1 fb^{-1})

**In a mass window 1.4σ

Robustness also stems from background estimate in side bands

How to improve the statistical power ?

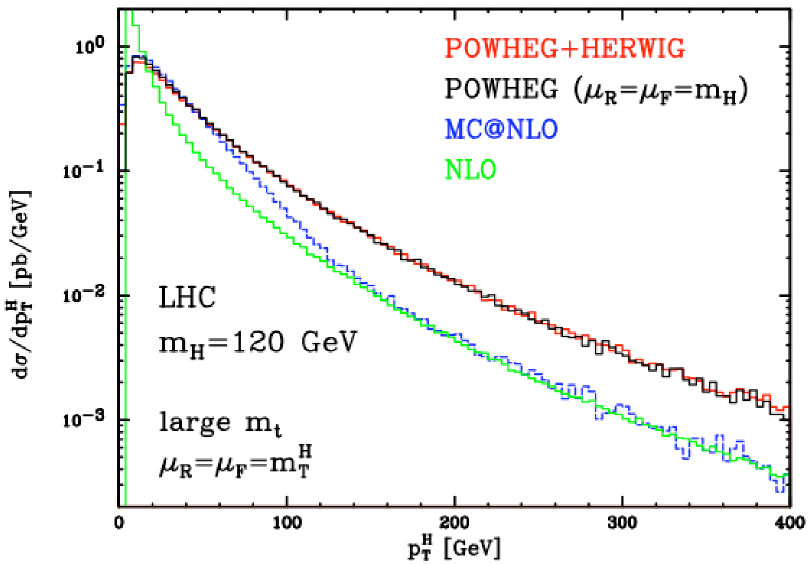
Further discrimination…

- Also using the scalar nature of the Higgs (cos θ^*)
- The system transverse momentum

  Still large differences between generators while it is an important input to sensitivity

- Critical to have an accurate signal simulation

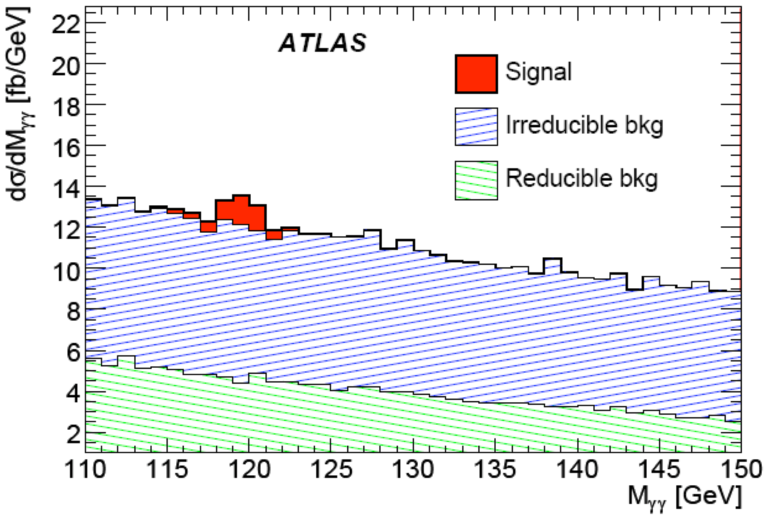
(no known control process, could tt production teach us something?)



* AP : All Associated production modes

The H→γγ Exclusive Channels

60% gg and 35% VBF



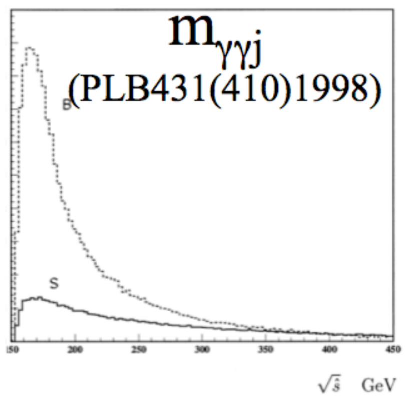
Exclusive H+1jet Analysis : s/b ~ 8%

Additional discrimination from $M_{\gamma\gamma j}$

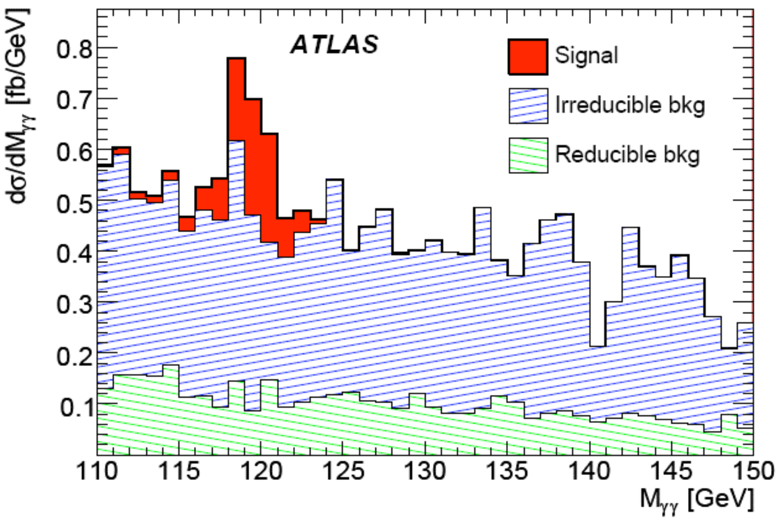
Sensitivity for 10 fb^{-1} $s/\sqrt{b} \sim 1.8$

s ~ 4 and b ~ 50

(m_H=120 GeV/c^2 for 1 fb^{-1})



20% gg and 80% VBF



Exclusive H+2jet Analysis : s/b ~ 50%

Additional discrimination VBF topology with two forward jets

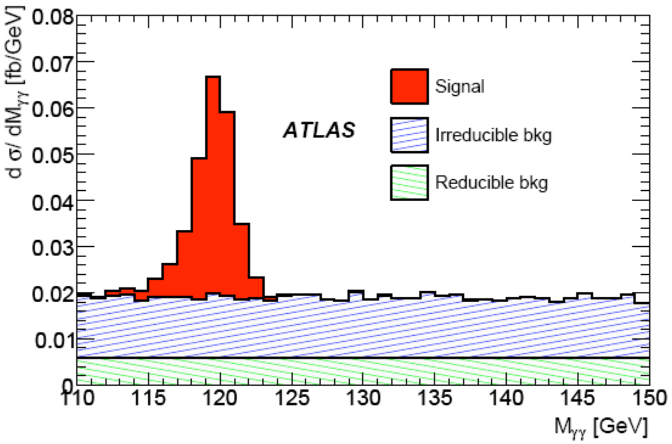
(no CJV not applied neither ATLAS nor CMS)

Sensitivity for 10 fb^{-1} $s/\sqrt{b} \sim 2.2$

s ~ 1 and b ~ 2 (m_H=120 GeV/c^2 for 1 fb^{-1})

The Associated Production Channels

The search is performed in two fairly inclusive… and pure channels



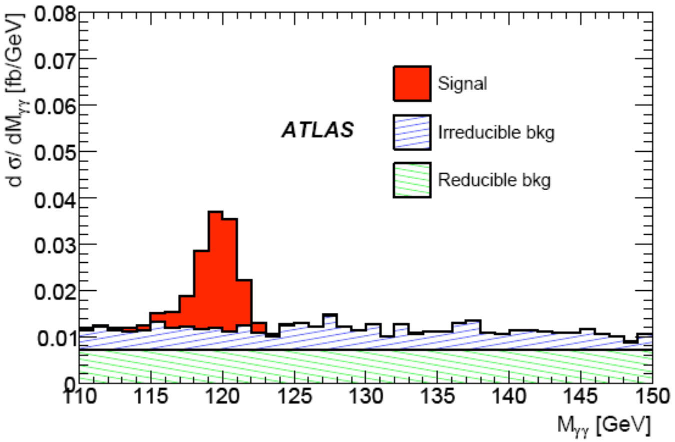
- The two photons, missing energy and isolated leptons (ATLAS and CMS)

(Inclusive of W,ZH and ttH)

s/b ~ 1.8

s ~ 12.6 and b ~7.5 (m_H=120 GeV/c^2 for 100 fb^{-1})

Note that ttH not singled out!



- The two photons and missing energy

(ATLAS only) (Inclusive of ZH and WH)

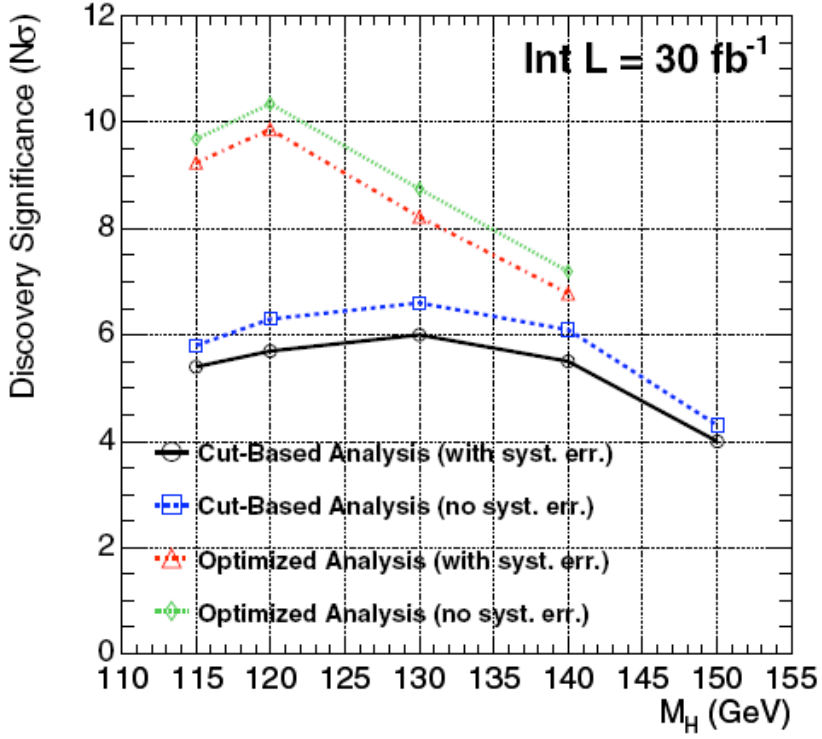
s/b ~ 2.7

s ~ 7.3 and b ~ 2.7 (m_H=120 GeV/c^2 for 100 fb^{-1})

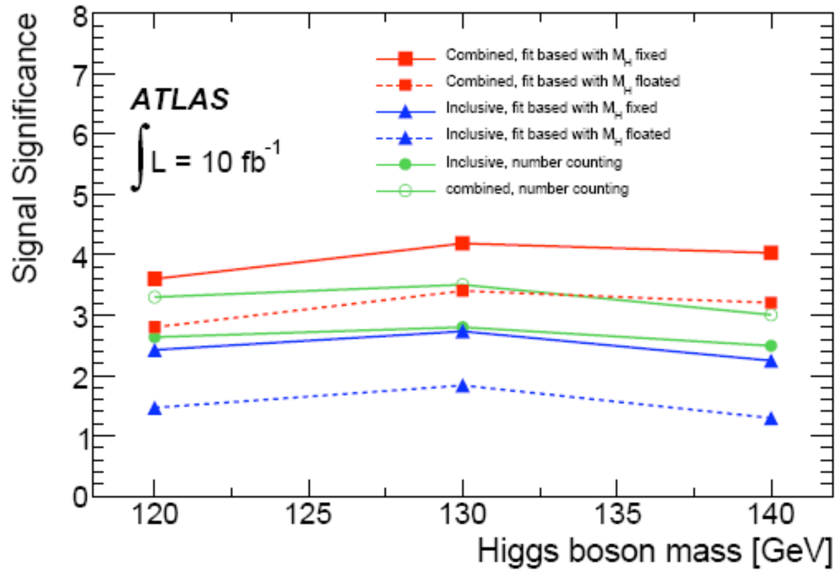
To be taken *cum granu salis* due to very large uncertainties on the backgrounds such as $tt\gamma\gamma$, $W\gamma(\gamma)$ …

The H→γγ Results

Early data expectations at 7 TeV and 1 fb^{-1} will be given by V. Sharma



CMS result uses a Neural Network with kinematic variables as discriminating, a NN for isolation and event categories in η, shower shape variable*



ATLAS Best result uses a combined fit using categories in η, number of jets (exclusive channels) and p_T and cos θ^* as discriminating variables

CMS and ATLAS use rather different techniques… baseline has similar performance

The difference in performance is very large between various analyses !

* Shower shape variable is the ratio of the max. energy crystal to that of the 3x3 cluster

ATLAS Readiness in the H→γγ Search Context

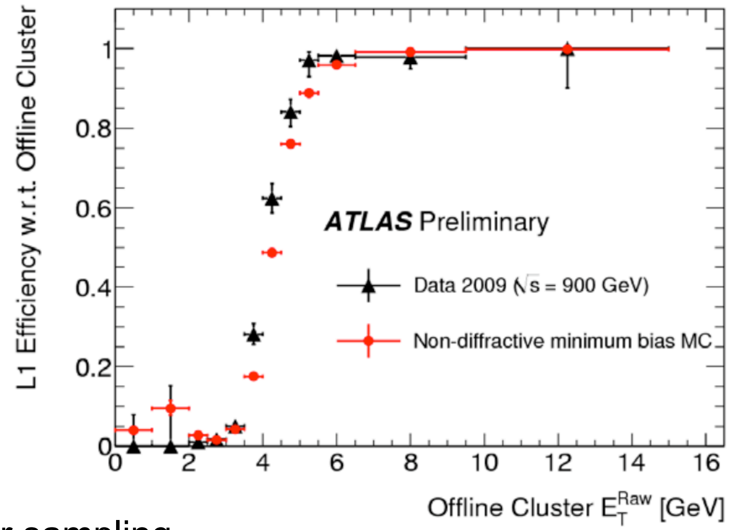
CMS details will be given by S. Nahn

Since its installation was completed in 2008 and collisions in 2009 ATLAS has collected a large number of cosmic data…

…Allowing to align to a good precision the tracking devices and perform calorimeter checks

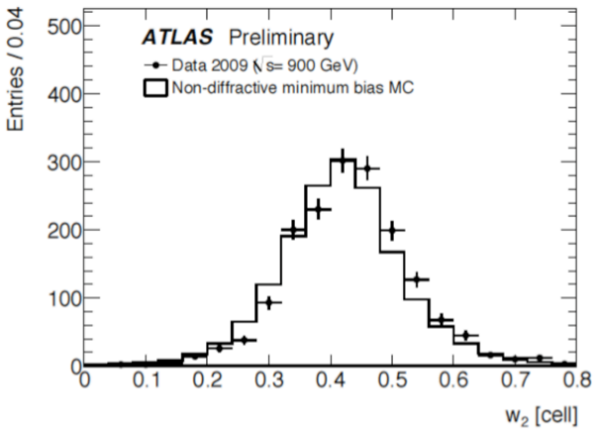
In collision data using minbias events…

L1 low threshold trigger as measured from minibias data (note the good agreement with MC)

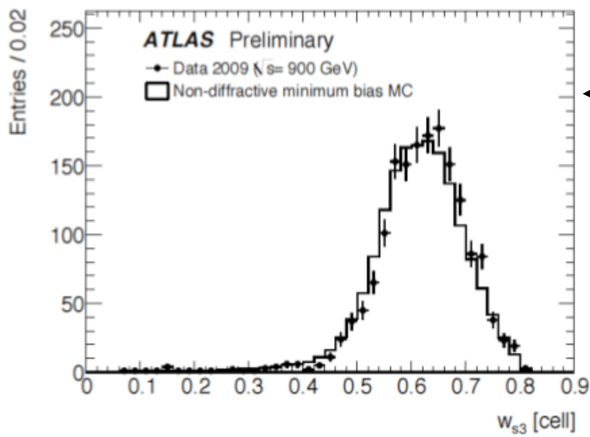


Reconstructed photons from minbias events are mostly background (from π^0) still allows to check the shower shapes…

Second calorimeter sampling



First calorimeter sampling



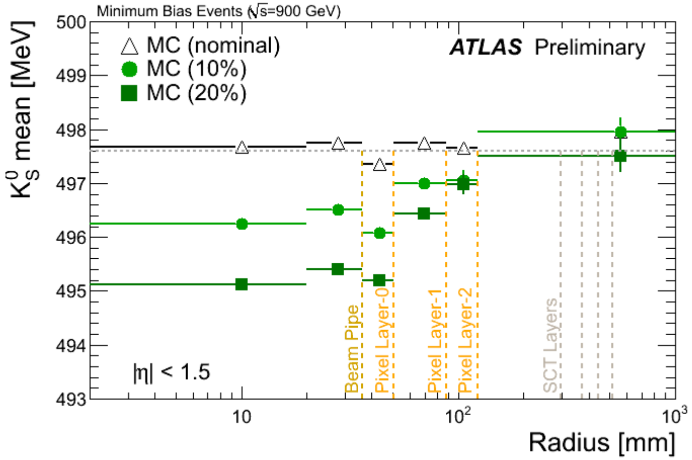
Very important for π^0/γ discrimination

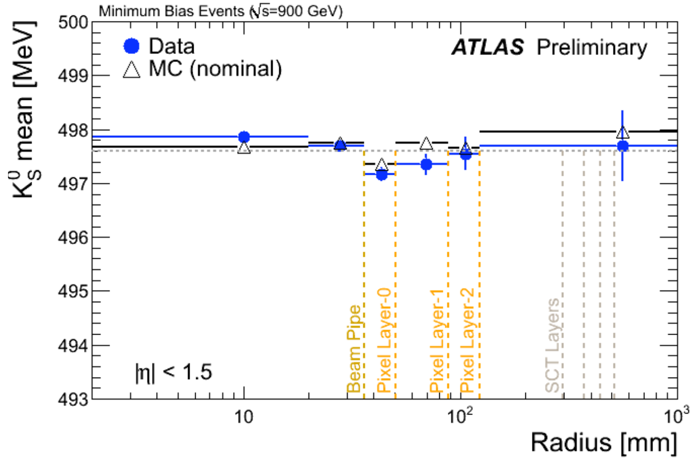
Very nice agreement observed between data and MC

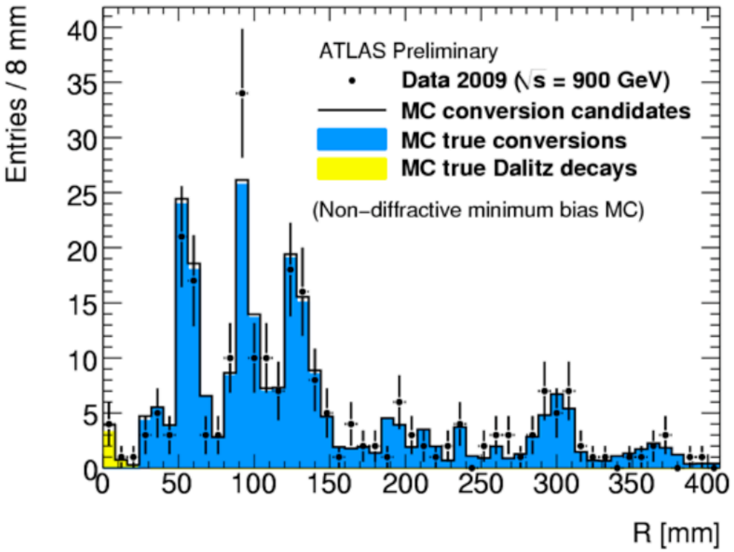
Another crucial issue for the photon energy calibration is the verification of the material upstream of the calorimeter…

K^0_S decays to $\pi^+\pi^-$ mass reconstruction as a function of the reconstructed radius…

Momentum calibration of π is quite sensitive to the amount of material traversed





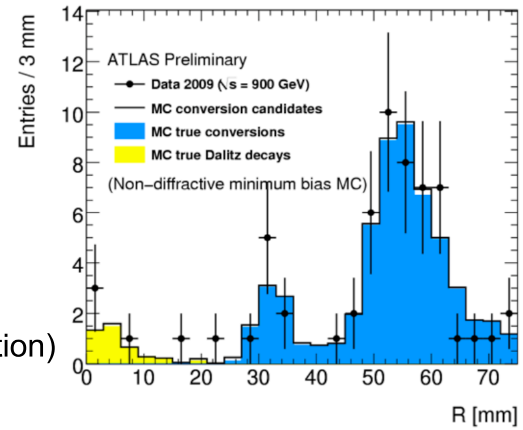


Conversion rates measure the Inner Detector material

- Three layers of the pixel are clearly visible

- The Beam pipe and Dalitz decays are also clearly separated

(Could be used for absolute normalisation)



The knowledge and simulation of the detectors are already at a very advanced stage!

The H→ττ VBF Channel

The tau decay channel requires a distinctive production process : VBF.

Why it is a more challenging channel :

- Triggering events is an issue
- Hadronic tau reconstruction is delicate
- Requires a good missing ET for mass reconstruction
- Central Jet Veto and jet tagging prone to be affected by pile-up and cannot easily be controlled

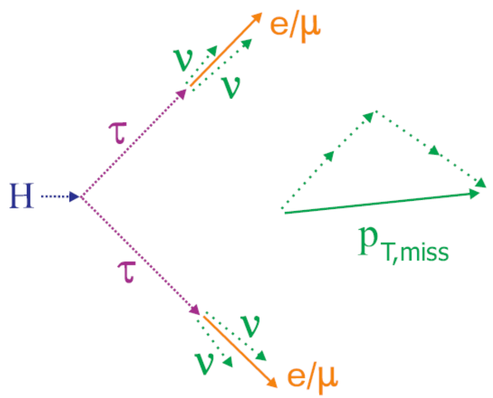
Three possible subsequent tau decay channels : ll, lh and hh

Use lepton trigger, but the lepton p_T is low

Hard to trigger and has a large QCD background (TBD in data)

Very low overall efficiency ~O(few per mil)

See ATLAS CERN-OPEN-2008-020

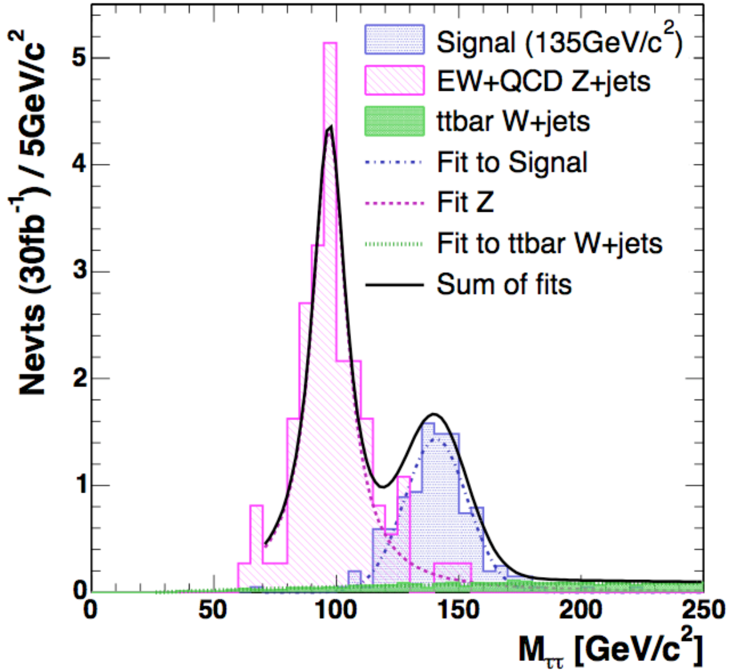


Mass reconstruction uses collinear approximation…

Relying on the transverse missing energy resolution, to reach a reconstructed mass resolution of 8-10 GeV/c^2 (depends also on pile-up)

…for Higgs masses above 115 GeV/c^2 a peak is clearly visible above a reasonable background…

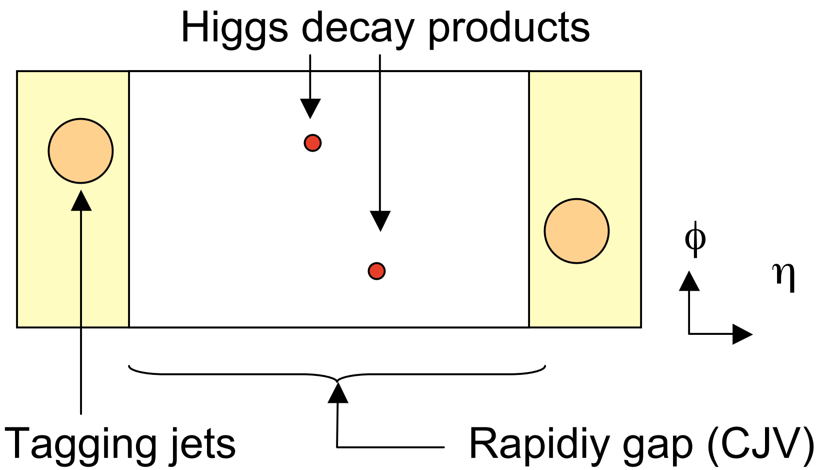
Dominated at ~70% by QCD Z+jets
(tt background rejected also using b-veto)

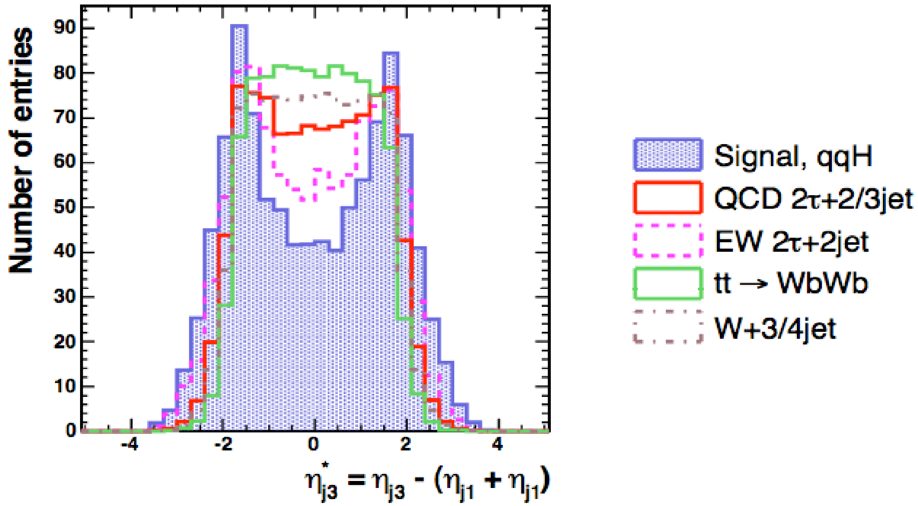


Can be estimated by data-driven methods

Jet tagging and Central Jet Veto…

To reduce the effect of pile-up use tracks related to the jet and check that it originates from the primary vertex

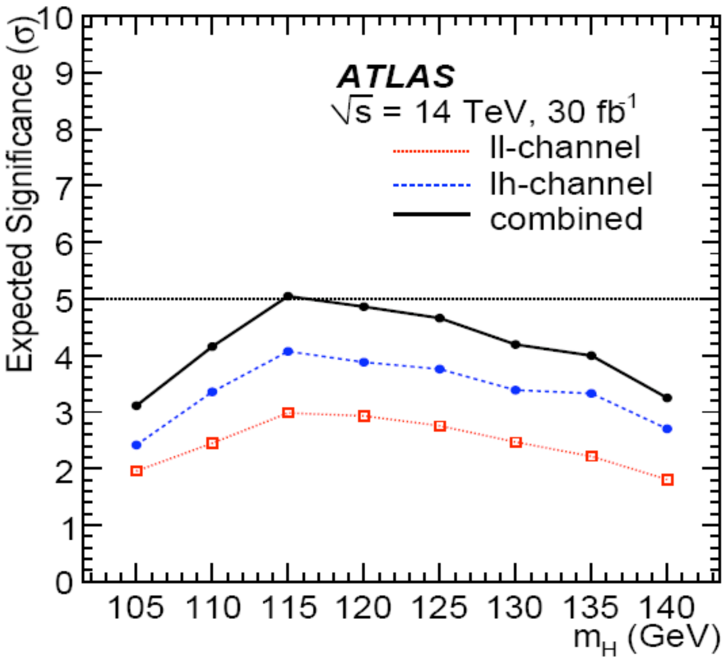




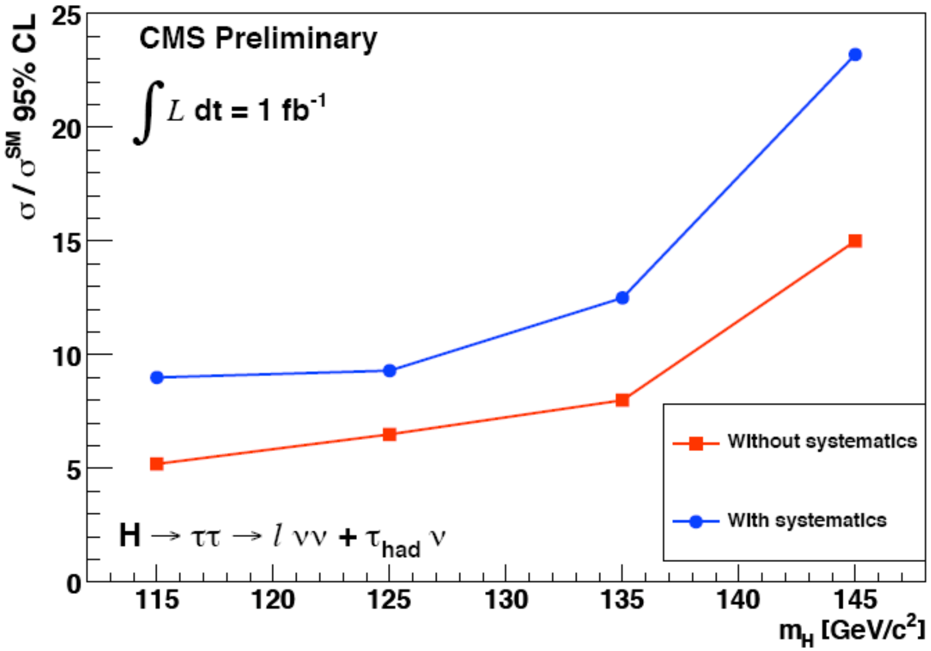
Jet tag & CJV : How to control their efficiency on signal ?

Experimental studies succeeding in separating the color-singlet production of Z have not yet been shown…

The VBF H→ττ Results



The ATLAS exclusion (without pile-up)



Note the large impact of systematics (here are those mostly due to Jet Energy scale and tau identification

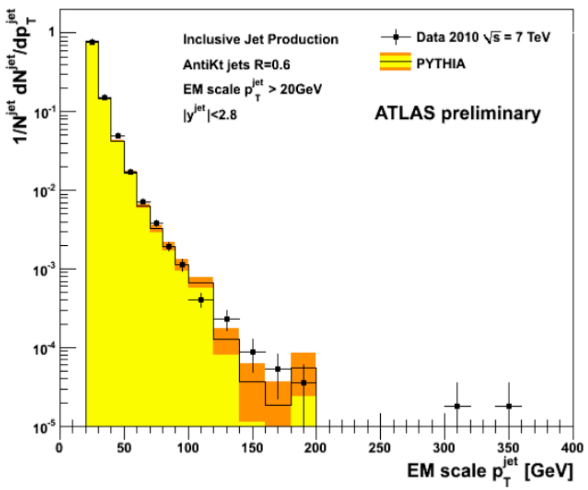
(with pile-up)

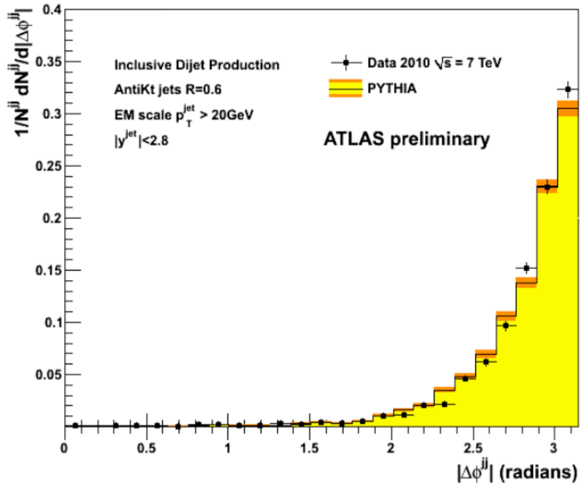
CMS results in terms of observation are very close to those of ATLAS

ATLAS Readiness in the VBF H→ττ Search Context

CMS details will be given by S. Nahn

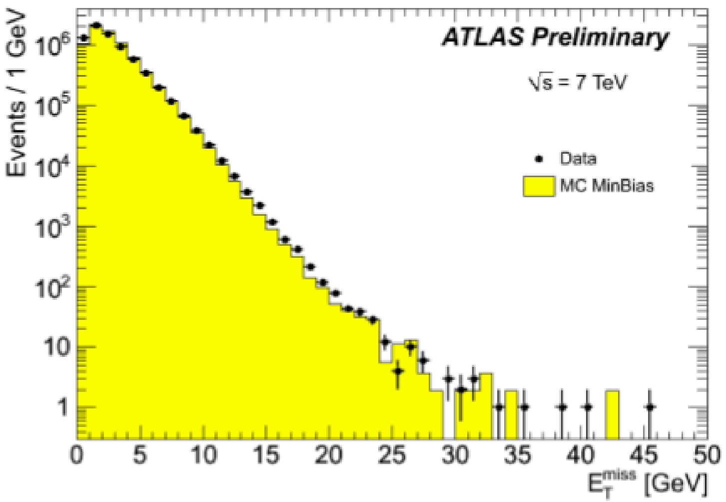
Jets are being observed in minbias events





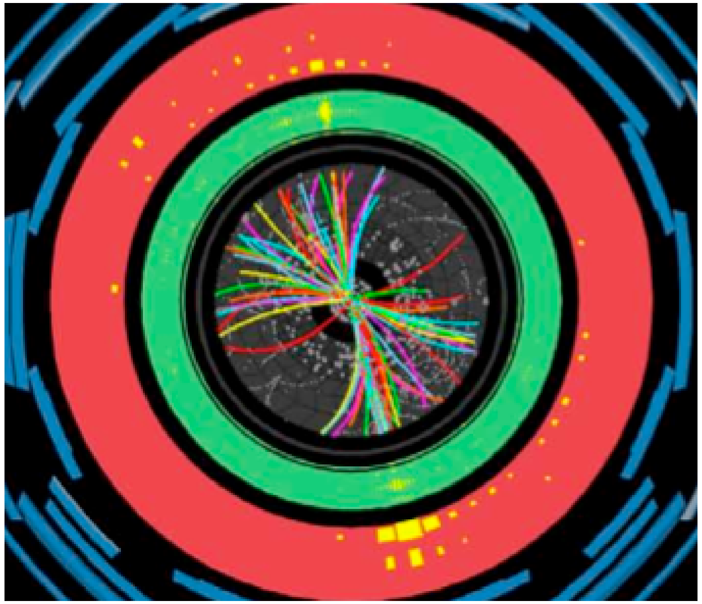
Distributions normalized to unity, Jet energy defined at EM scale and p_T>20 GeV/c (two high p_T events incompatible with Pythia)

MET in un-crowded minbias events



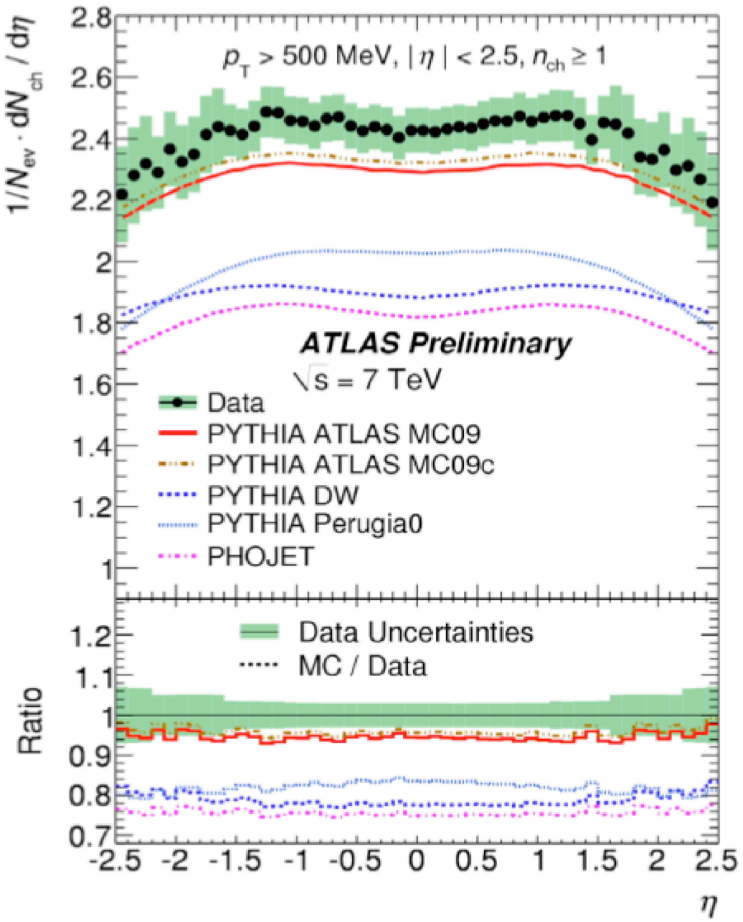
Dijet event

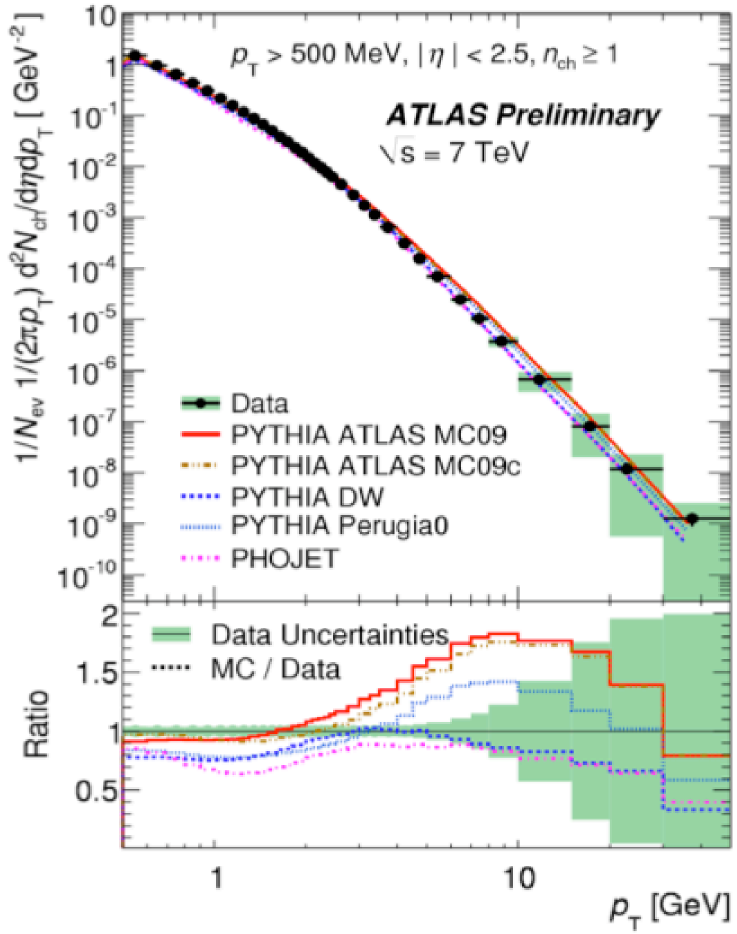
(with both jets above 300 GeV)



Tune the underlying event model using charged particle multiplicities

- Kinematic range $|\eta|<2.5$ and $p_T>500$ MeV/c
- Unfold detector effect to correct reconstructed track distributions to hadron level
- Results are compared to varios Pythia tunes and Phojet

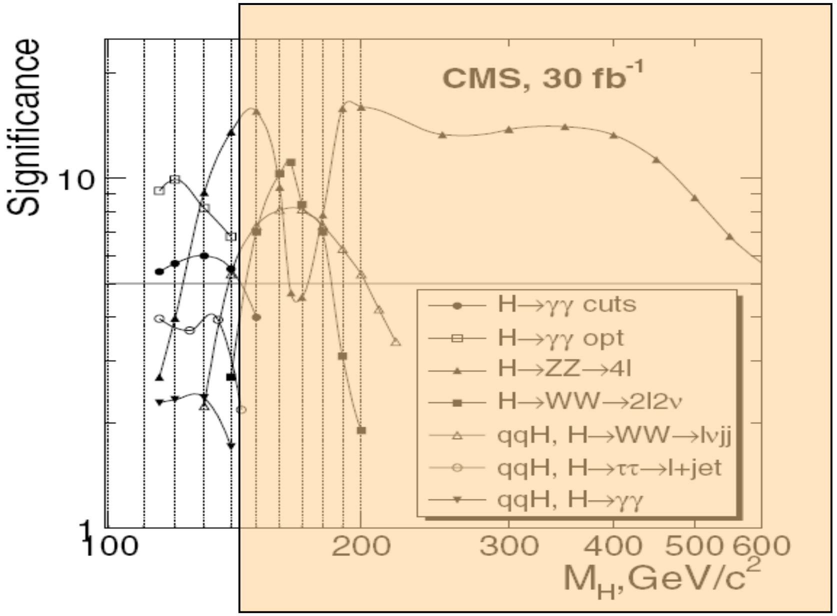


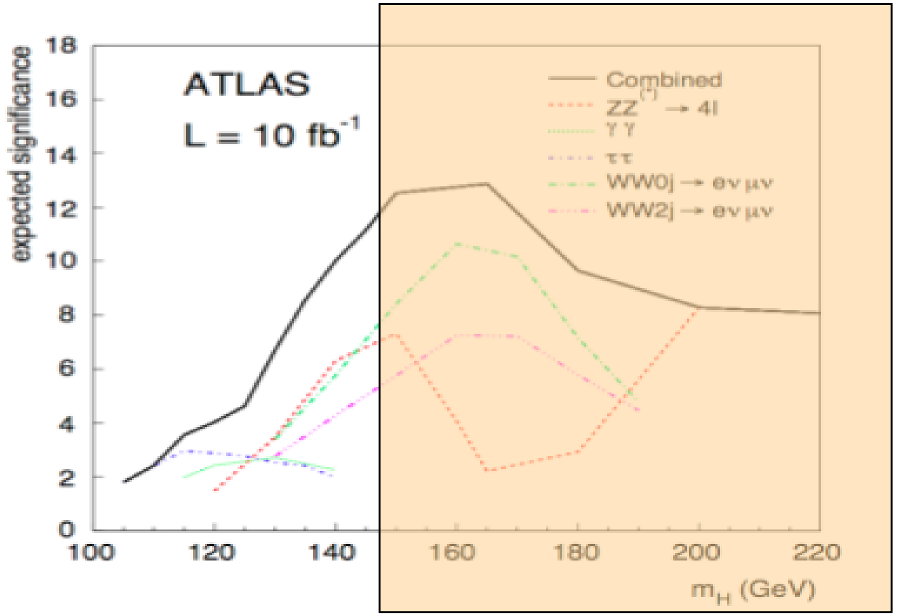


Significant differences observed… More studies/tuning needed

The Mainstream Low Mass Channels Combination

- To exclude a low mass Higgs boson at LHC need ~2 fb^{-1} of data at 14 TeV
  (Using mainstream channels only)
- For a 3σ observation need ~3 fb^{-1} of data at 14 TeV
- A 5σ discovery will require ~7-10 fb^{-1} of data at 14 TeV





For the high mass see S. Nahn's talk

Note that the WW and ZZ channels also contribute in the low mass range
(they are important for the measurement of couplings at low mass)

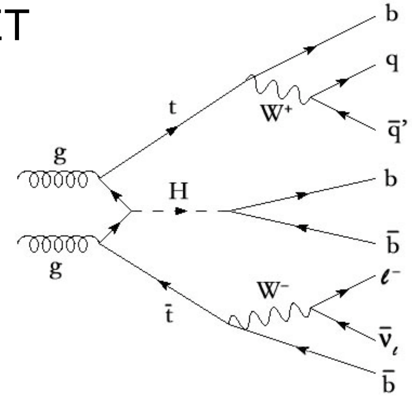
The mainstream channels are not the whole story…

The Revival of the H→bb Channels

An overview of the searches in the b-decay mode

Why the ttH→bb Channel Disappeared from Radar Screens (Sensitivity Plots)?

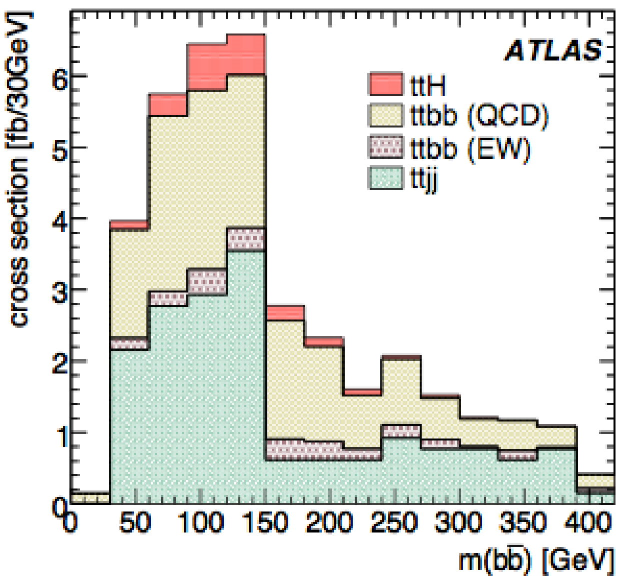
- Very important to check the Yukawa nature of the Higgs-fermion coupling
- Originally very promising channel ~O(H→γγ) in the low luminosity scenario…
- However a very intricate final state… 6 jets (4b), one lepton and MET
    - Very large combinatorial background
    - Very large and uncertain ttbb and ttjj (no obvious control samples)



Very dilute channel at 120 GeV/c^2 : s/b ~ 10%

but no definite mass peak

Sensitivity for 30 fb^{-1} (14TeV): s/√b ~ 2

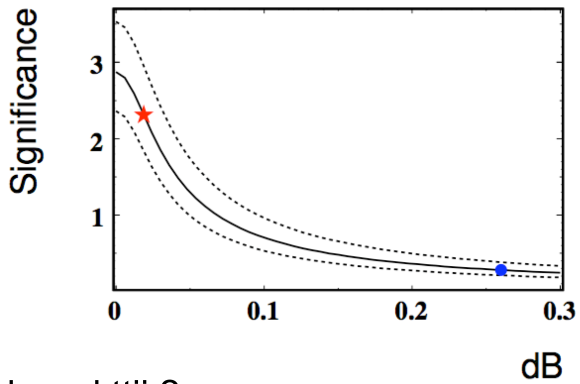


Without systematic uncertainties… None with systematics

What could be done ?

Perhaps experimentally use multivariate techniques or improved b-tagging, but…

Mostly needs guidance from theory :



-Simulation to higher orders of ttbb and ttjj ?

-Overlaps treatment ?

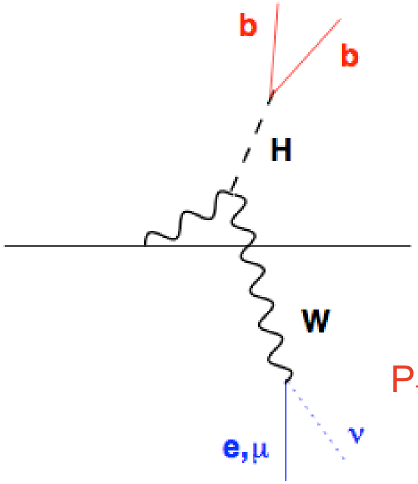
… or new ideas …

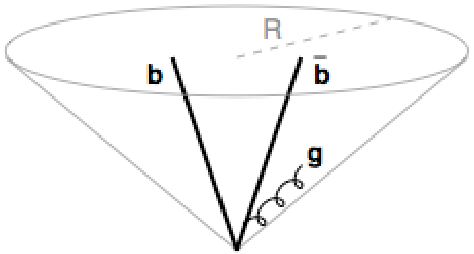
The Associated Production W/ZH→bb Channels Never Really Made it to the Radar Screen… Until Recently

Idea : - Use Higgs only at high p_T to improve acceptance and reduce bkg.

- The Higgs would be a single jet, then investigate the jet structure

Butterworth, Davison, Salam, Rubin





P_T> 200 GeV/c

Fat jet
With mass m

- Use the Cambridge-Aachen jet algorithm Dokshitzer et al. 97'
  (Clustering based on the R-distances between objects, iterate until $\Delta R>1.2$)

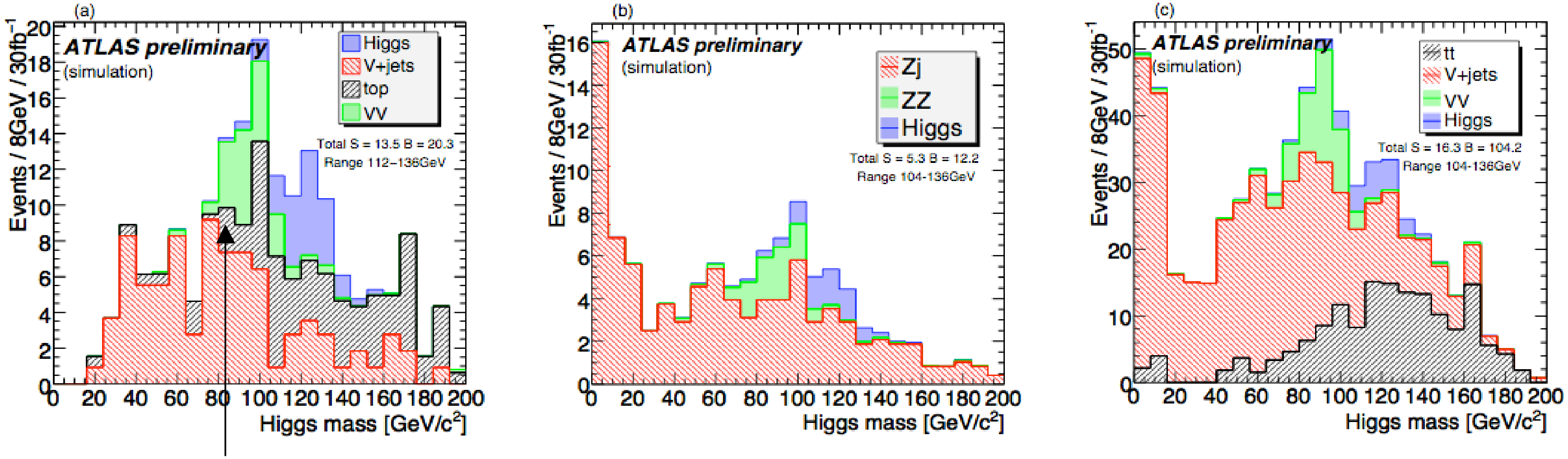
- Undo the last stage of clustering defining J_1 and J_2
  If $\max(m_1,m_2) < 2m/3$ then there is a "mass drop"

- If there is a mass drop apply b-tagging

- Then recluster using a $R_{filt} = \min(0.3, R_{J1,J2})$

ATLAS has performed this search with full Monte Carlo simulation in three channels…

lνbb llbb ννbb



Z mass peak clearly visible!

A combined significance of ~3.0 - 3.7σ is expected for 30 fb^{-1}
(depending on the systematic uncertainties on main backgrounds)

- Very promising/discovery channel
- bb branching is critical to assess Higgs properties (See talk by T. Plehn)

Revival of the ttH channel also foreseen using a similar technique…

T. Plehn, G. Salam, m. Spannovsky, KA-TP-12-2009

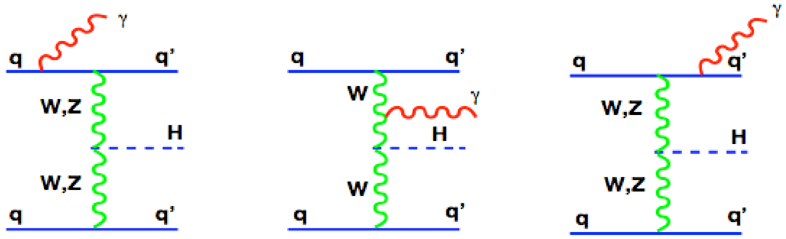
- A similar technique applied requiring at least two fat jets and a lepton (2 or 3 b-tags)
- Combinatorial background not a problem
- Sensitive only at around 100 fb^{-1} (4-5σ sensitivity)

Analyses still need to be performed by experiments with full simulation

Another idea waiting for a word from experiments…

The VBF with an additional photon

E. Gabrielli, F. Maltoni, B. Mele, M. Moretti, F. Piccinini and R. Pittau, Nucl. Phys. B **781**, 64 (2007)



Idea : -The extra photon will improve trigger efficiency

- Large gluonic bbjj(γ) background is suppressed

- Destructive interference reduces the irreducible background when requiring a high p_T photon

Signal reduction by ~α while

background is far more more reduced by ~1/3000 overall

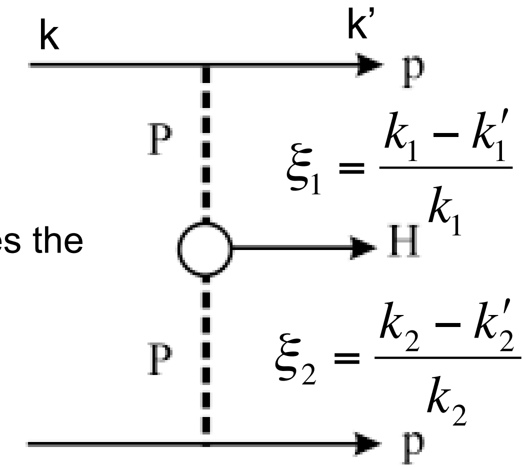
Interesting but will still need large amounts of luminosity :

About 3σ at 100 fb^{-1} and m_H = 120 GeV/c^2 studies are underway in experiments

Two Additional (and more Marginal) Cases

1.- The diffractive Higgs search :

Color singlet exchange between protons where the two protons are at very large rapidity



Completely constrained kinematics : $M = \sqrt{\xi_1 \xi_2 s}$

Pros
- M measured from the protons (in roman pots) ΔM ~1-2 GeV
- Constraining M_{bb} (ΔM_{bb} ~ 10 GeV) to be near M strongly decreases the background.

…but - Very large uncertainty on signal cross section

Two projects considered at 220 m (ATLAS) and 420 m (CMS)

2.- The search for the Higgs at LHCb :

Search possible in the associated production mode (~30% are produced in 1.8-4.9 pseudo rapidity range)… but no significant signal (~1.5σ in the highest luminosity scenario)

CERN-THESIS-2008-101

CERN-THESIS-2007-73

Low Mass Higgs Boson Properties

An overview in a nutshell…

Details in talks by I. Low, T. Plehn, T. Han, A. Gristan and S. Dawson

Properties accessible with low mass channels alone and with rather low luminosity

Higgs Mass : - $\gamma\gamma$ best mass resolution (~1.1%) and the dominant systematic uncertainty is EM scale

~1%. Systematic limit should be reached fo ~30 fb^{-1}

~0.1%. Systematic limit should be reached fo ~100 fb^{-1}

Higgs Spin : - $\gamma\gamma$ decay forbids a spin-1 nature (Landau-Yang theorem)

- Otherwise need angular correlations in higher mass channels (See S. Nahn's talk)

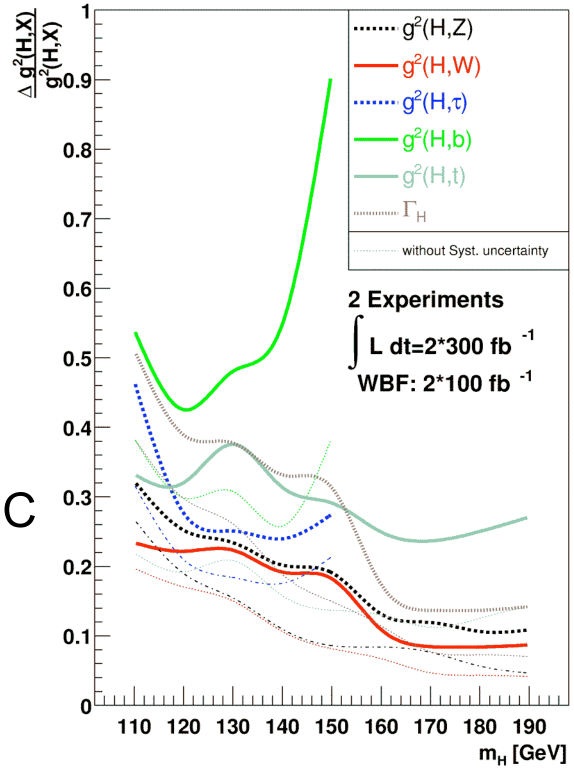
Properties that will require more luminosity and all channels together

Higgs CP : - Angular correlations in tagging jets in VBF channels

- Angular correlations in ttH
- Otherwise also need angular distributions in ZZ channel

Couplings : - The total width not directly measurable below 200 GeV/c^2

- Larger variety of decay modes access to more couplings



Properties that will require additional analyses and s(uper)LHC amounts of data (thousands of fb^{-1}) if possible at all…

Higgs self couplings

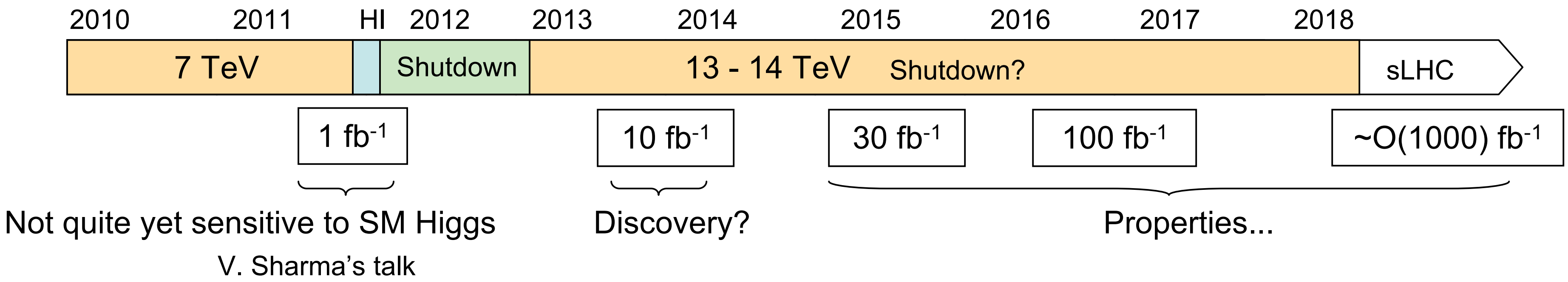
Conclusions

ATLAS and CMS have similar sensitivities to a Standard Model low mass Higgs boson

New methods have revived the searches for the Higgs decay into bb

Essential for coupling measurements but also helpful for discovery - see T. Plehn's talk

The LHC has started taking data and experiments are ready to perform these searches



According to plans it could be a quite rapid transition…

Efforts towards a combination of ATLAS and CMS have already started (signal cross sections, statistical methods, systematic uncertainties…)

Backup Slides

Higgs Cross Sections

Gluon fusion process (nNNLO) : S.Moch and A.Vogt Phys Lett B631,48,2005

Gluon fusion process (NNLO) : HNNLO, M. Grazzini et al. and FeHip, C. Anastasiou et al.

Gluon fusion process (NLO) : HiGlu, M. Spira and Hpro, C. Anastasiou et al.

Vector Boson fusion process (NLO) : VV2H, M. Spira from

T.Han,G.Valencia and S.Willenbrock Phys Rev Lett 69,3274,1992

And VBF@NLO, K. Arnold et al.

W,Z associated production process (NLO) : V2HV, M. Spira from

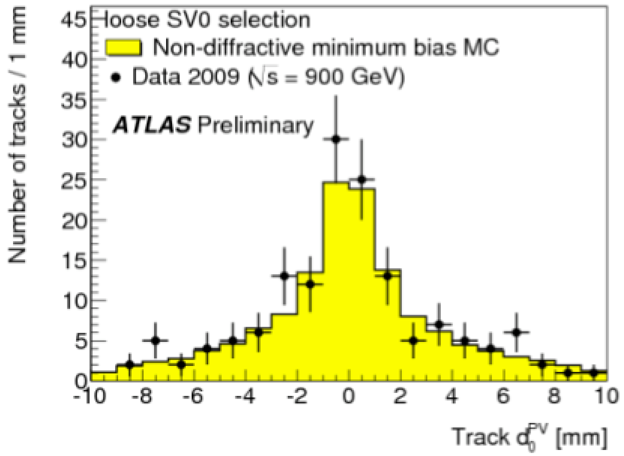
T.Han and S.Willenbrock Phys Rev B 273 1991

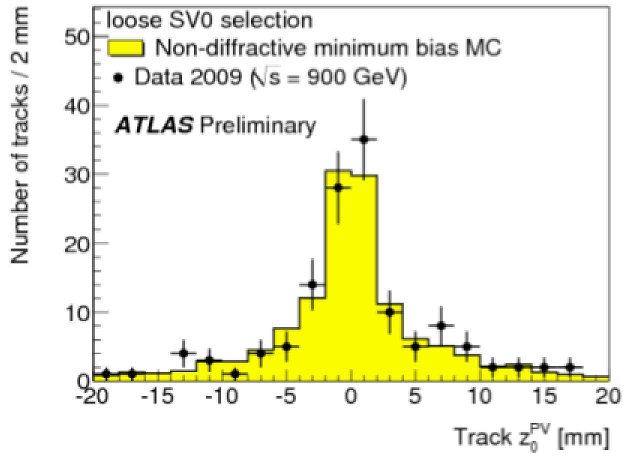
And O.Brein,A.Djouadi and R.Harlander
Phys.Lett.B579:149-156,2004

tt associated production process (NLO) :

W.Beenaker,S.Dittmaier,M.Kramer,B.Plumper,M.Spira and P.Zerwas Phys Rev Lett 87,201805,2001
S.Dawson,C.Jackson,L.Orr,L.Reina and D.Wackeroth Phys.Rev.D68:034022,200

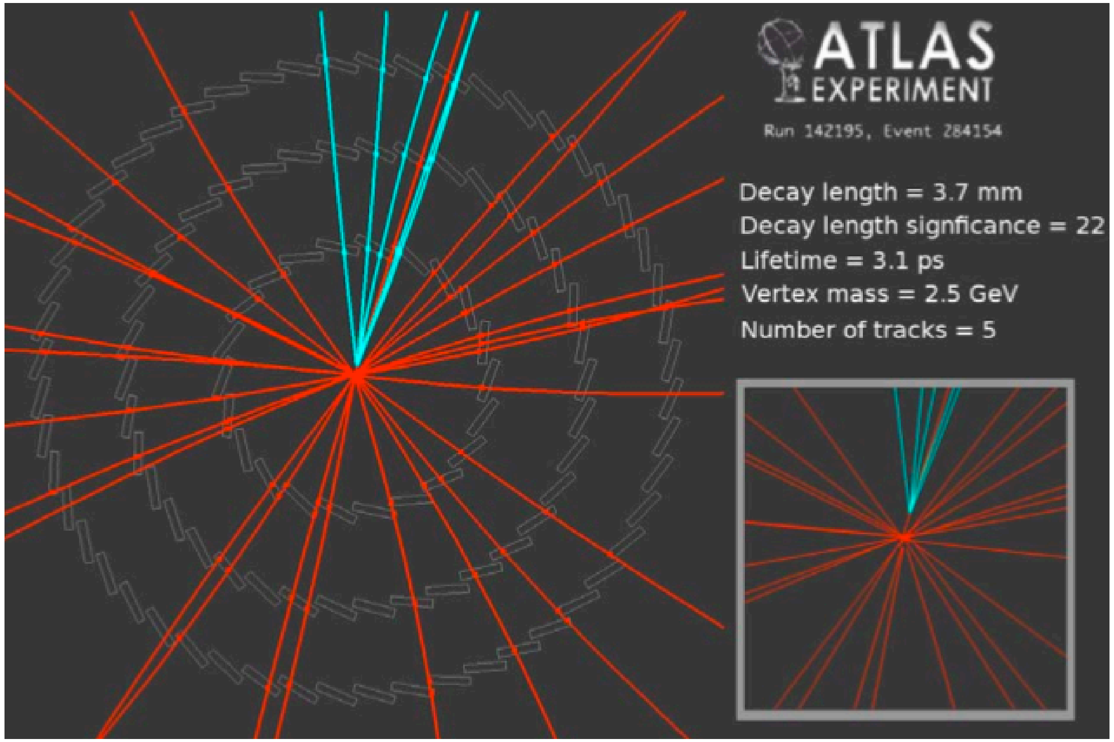
ATLAS Readiness in Heavy Flavor Tagging



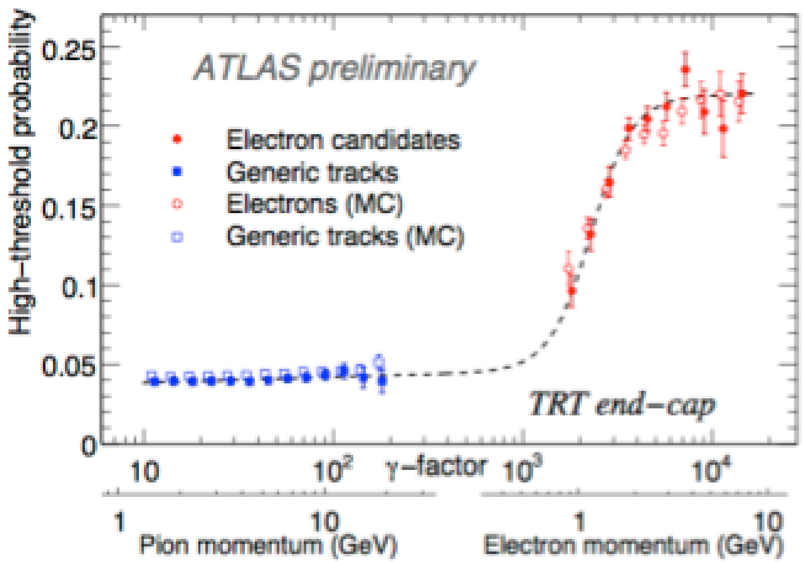


In 900 GeV minbias events most high impact parameter tags are from K_s

Few nice candidates such as the following →



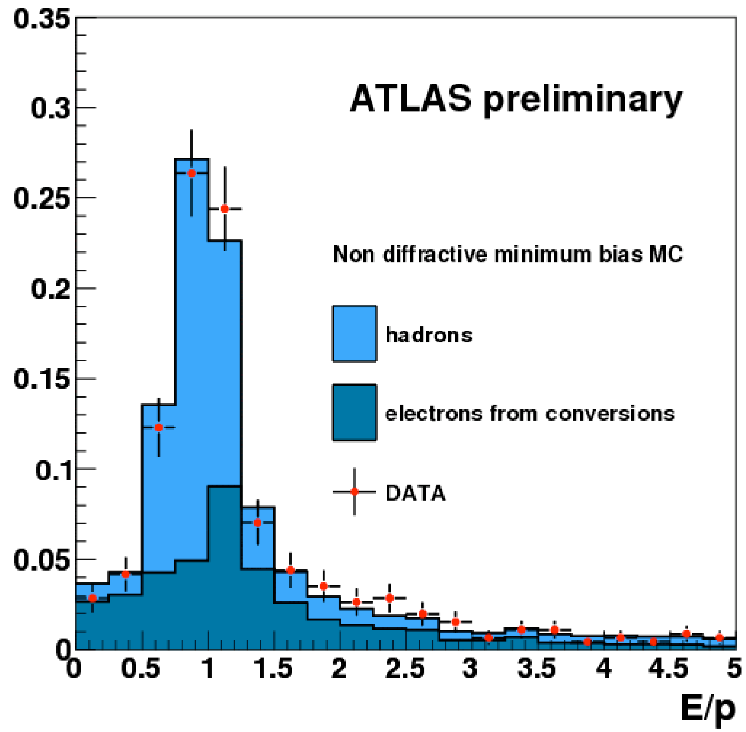
ATLAS Readiness in Electron ID



Using TRT transition radiation, select electrons from high threshold hits

Most electrons we have originate from photon conversions

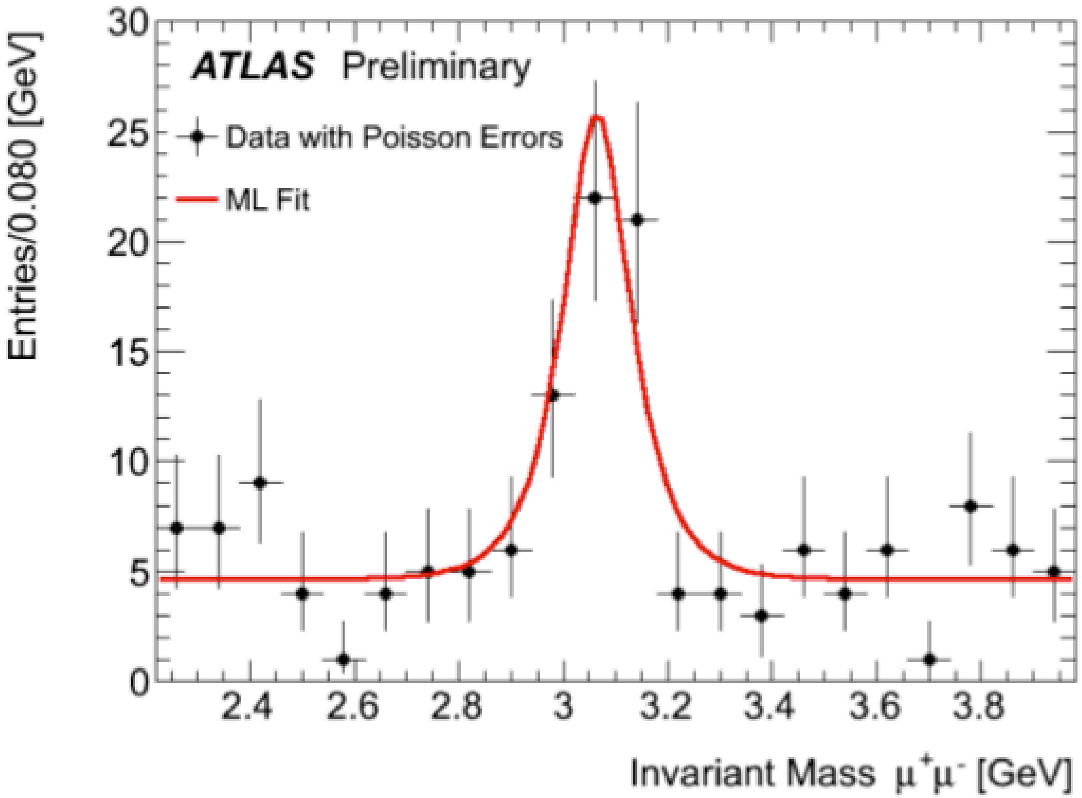
Good agreement in shape variables between data and Monte Carlo



ATLAS Readiness for Muons

Observation of the J/ψ in the dimuon channel

Opposite signs and one muon combined



Gaussian mean mass : 3.06±0.02 GeV/c^2

Gaussian resolution : 0.08±0.02 GeV/c^2

49±12 signal vs. 28±4 background