What can we learn about the Higgs with 10 fb^{-1} at the LHC?

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BNL

Outline

With 10 fb^{-1}:

- Which channels could be visible?
- What kind of deviation from the SM could we expect?
- Which mass and property measurements could we achieve? With which precision?

But I will discuss early physics first …

Twenty-five years…

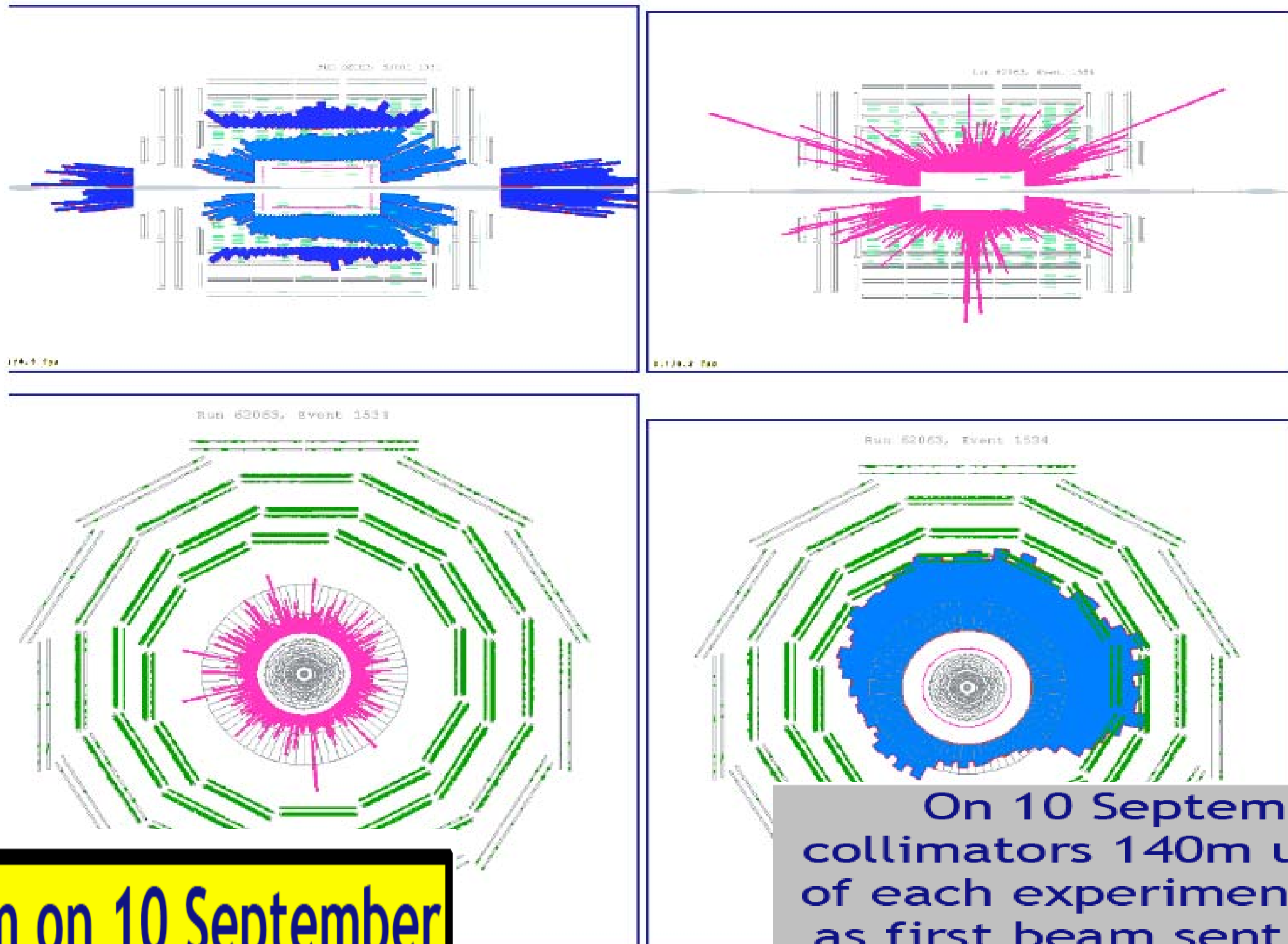
- 1984: First LHC workshop (Lausanne)
  - Use LEP tunnel for protons
- 1992: First ‘expressions of interest’ for experiments
- 1996: First exp'ts approved
- 1998: First full-size magnet test
- 2003: End of civil engineering
- 2006: Last magnet produced
- 2008: First beam
- 2009: First collisions
- Some vital statistics
  - Tunnel circumference 27 km
  - 1232 main magnets, 8 T field
  - Another 7000 smaller magnets
  - Operating temperature 1.9K
  - Cost: ~4700 MCHF (incl. manpower)
  - Experiment cost: ~500 MCHF each for ATLAS & CMS (excl. manpower)


16 June 2008: Last piece of LHC ring being put in place

First Events: Collimators Closed

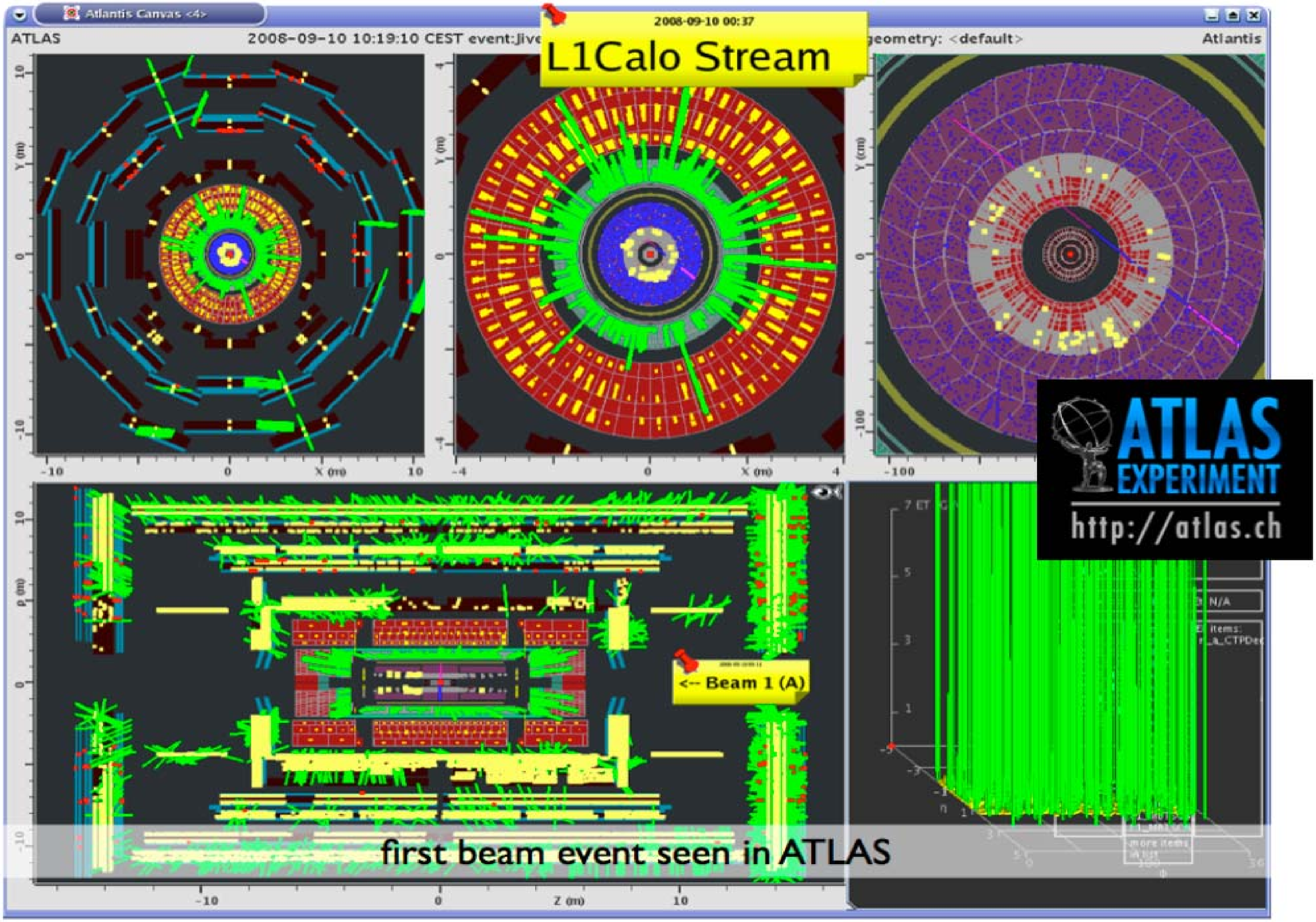
~2.10^9 protons on collimator ~150 m upstream of CMS

ECAL- pink; HB,HE - light blue; HO,HF - dark blue; Muon DT - green; Tracker Off



First Beam on 10 September

On 10 September, collimators 140m upstream of each experiment closed, as first beam sent around: "beam splash" events

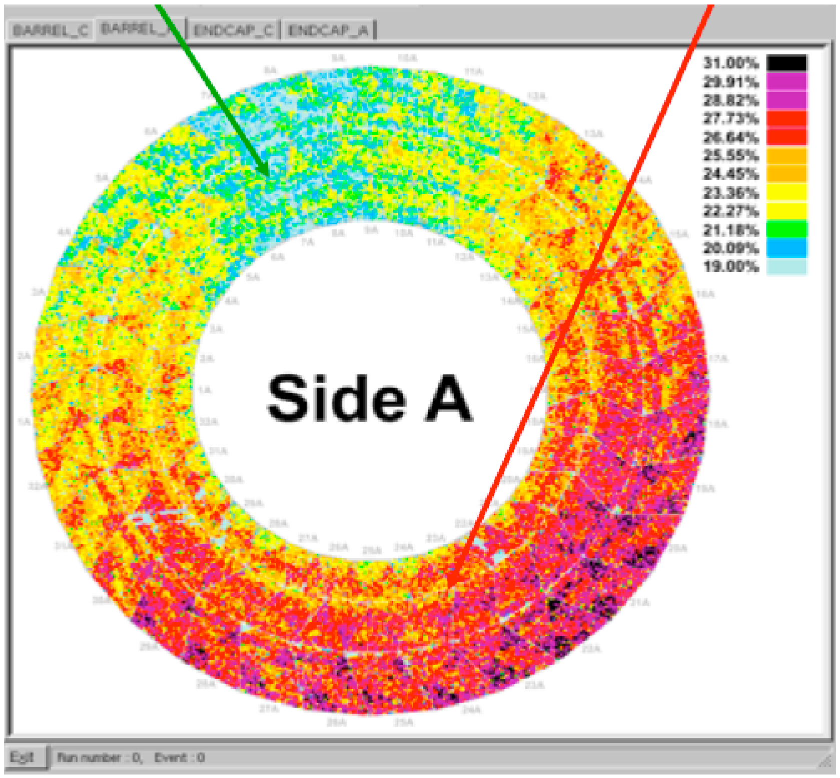

Atlantis Canvas <4>
ATLAS
2008-09-10 10:19:10 CEST
2008-09-10 00:37
L1Calo Stream
Atlantis
<-- Beam 1 (A)
ATLAS EXPERIMENT
http://atlas.ch
first beam event seen in ATLAS

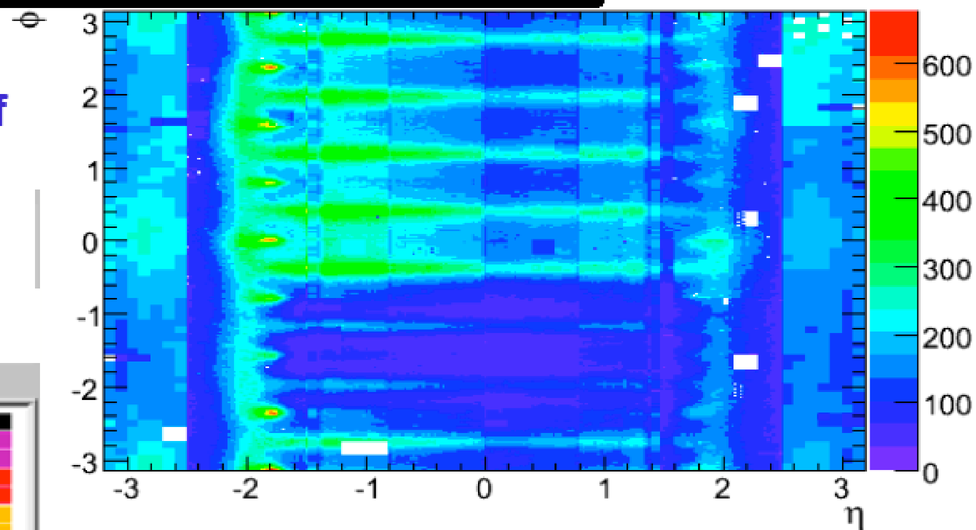
Splash event in ATLAS

D Froidevaux

Timing of all TRT readout channels could be performed with accuracy of ~ 1 ns per event! Differences in colour due to cosmic timing:

Top: early **Bottom: late**





2D display in $\eta-\phi$ of energy deposited in LAr EM calorimeter per cell (layer 2):

- **structures seen are due to material between collimators and calorimeter (mostly 8-fold structure of end-cap toroid coils)**
- **energy seen per event is huge!**

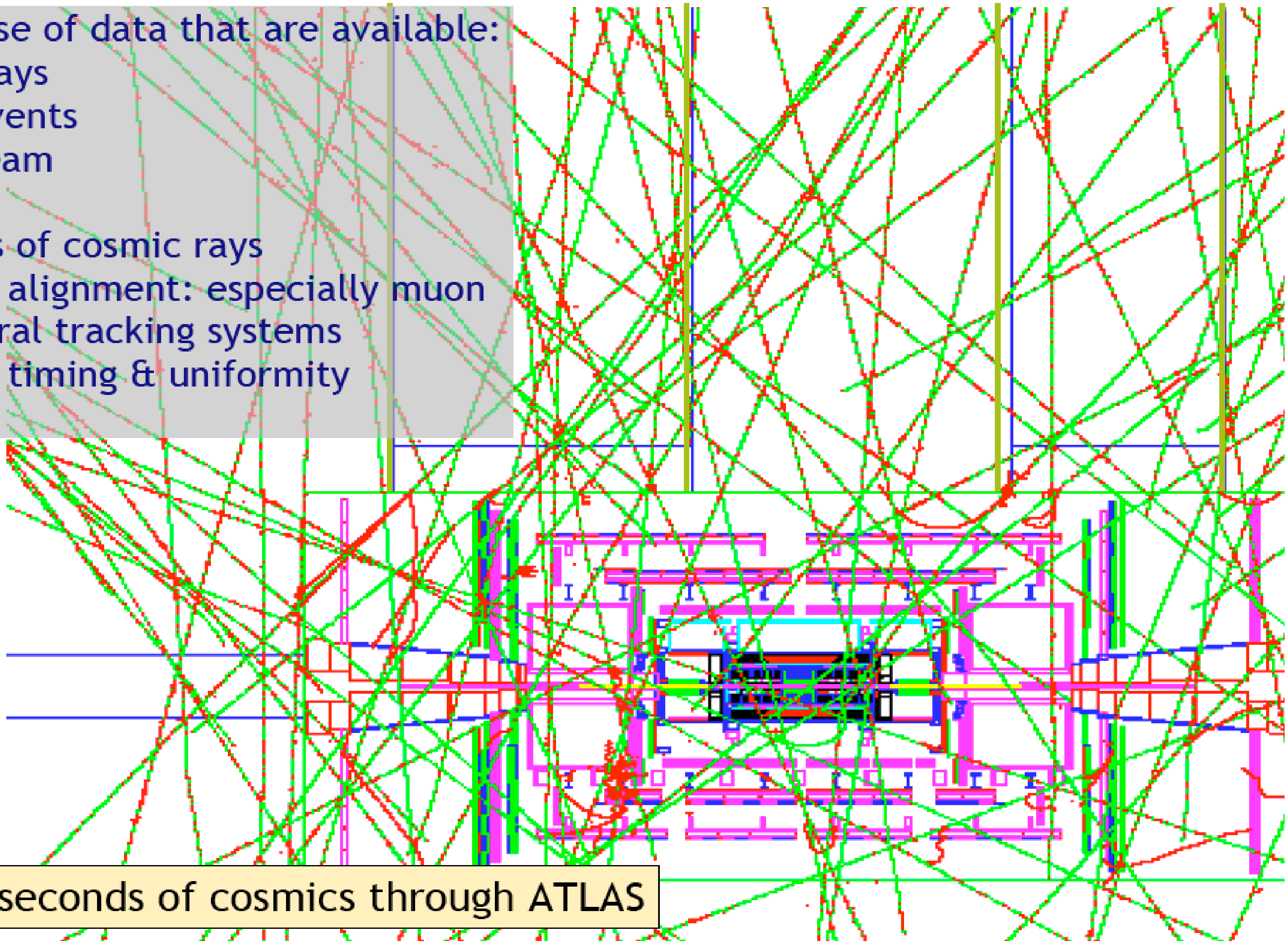
Commissioning with 2008 Data

Very much use of data that are available:

- Cosmic rays
- Splash events
- Single beam

Many months of cosmic rays

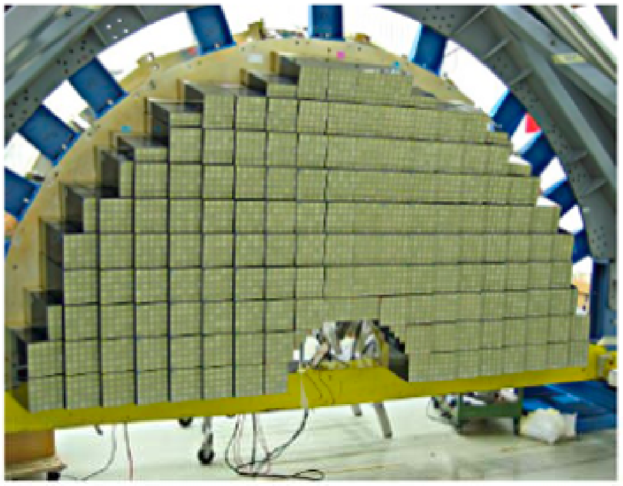
- Detector alignment: especially muon and central tracking systems
- Detector timing & uniformity
- ...



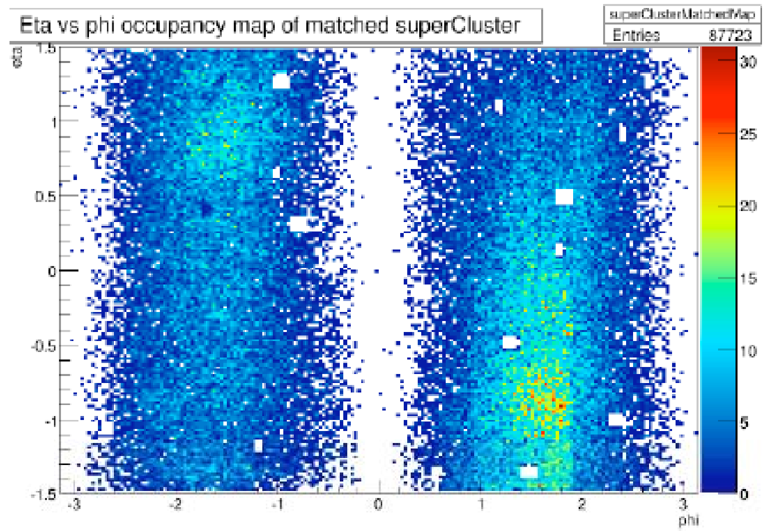
13 10 milliseconds of cosmics through ATLAS

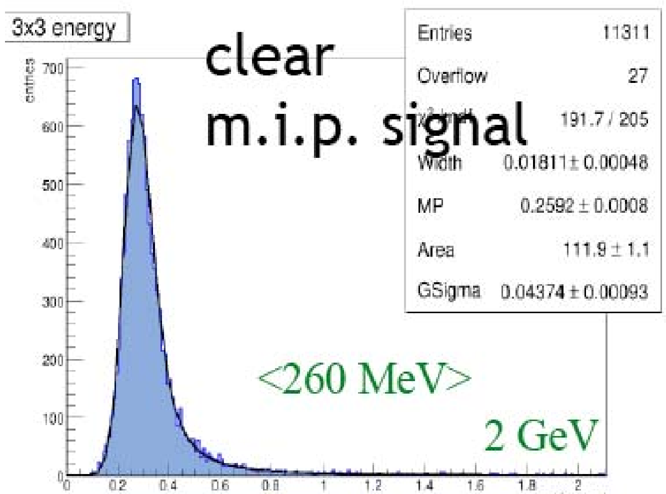
Example: CMS Electromagnetic Calorimeter

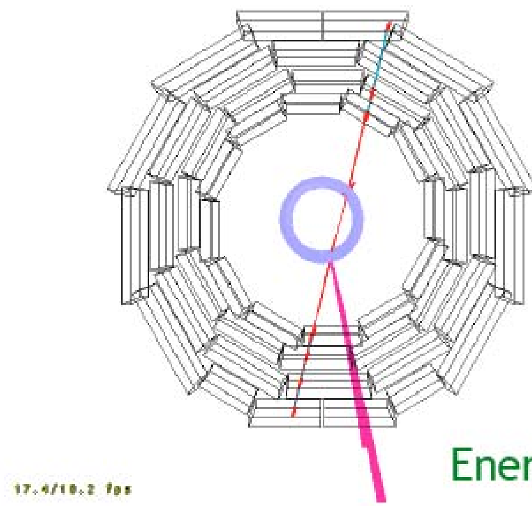
A “Dee” of endcap ECAL



Barrel ECAL clusters matching muon tracks







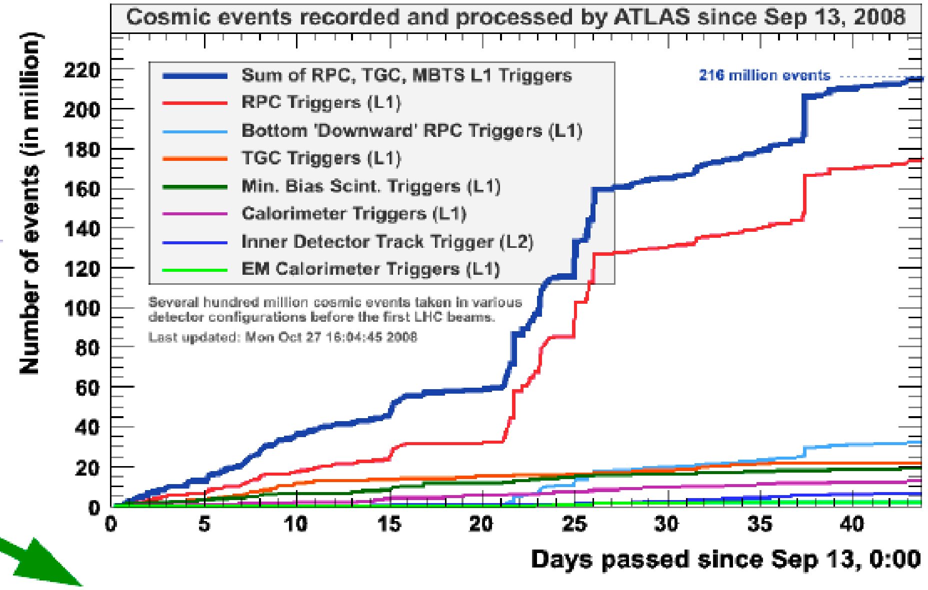
sometimes:

huge energy deposition from cosmic muon in ECAL

Energy: 250 GeV

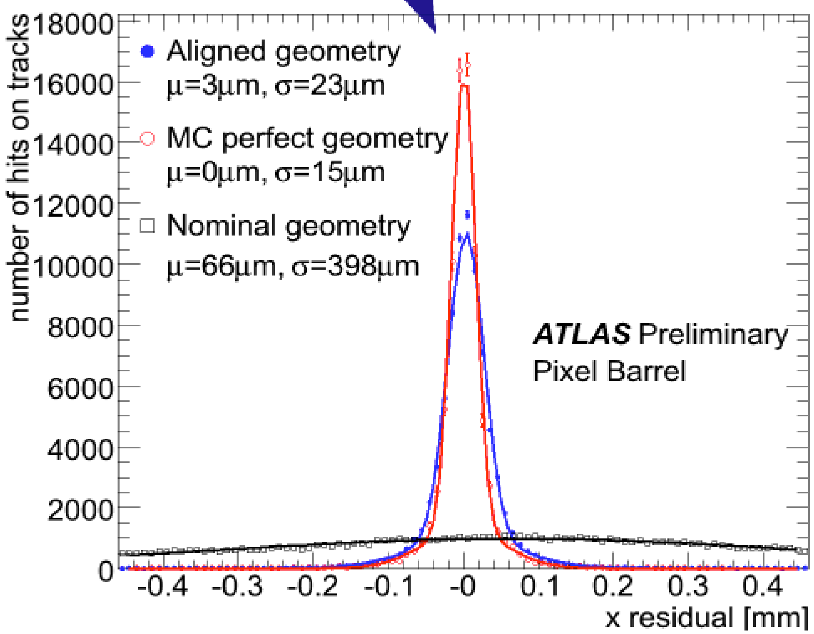
Using Cosmics

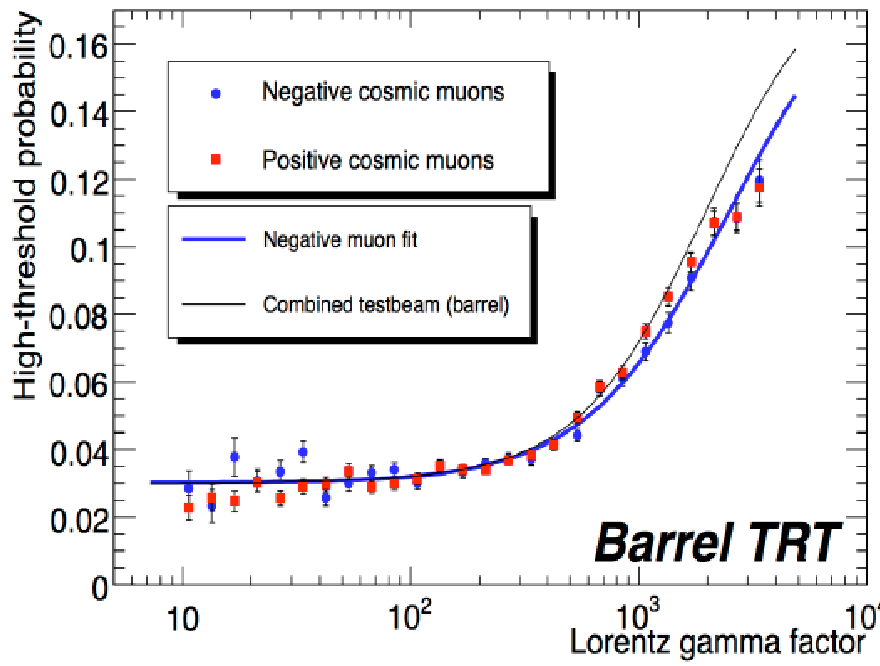
>200 million cosmic ray events since Sept



See transition radiation turn-on with μ !

Pixel detector alignment





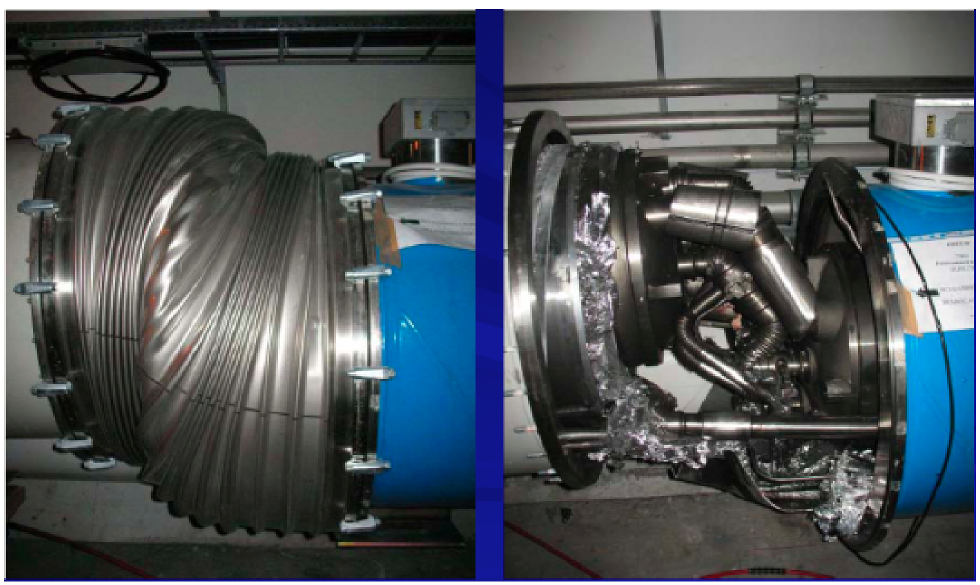
LHC Incident

Interconnect busbar between superconducting magnets developed a significant resistance at a splice

No quench protection system covering the busbar splices

Heating, followed by rapid loss of helium into vacuum

- Soot in the beam-pipe
- Collateral mechanical damage to more distant magnet interconnects
- Around 50 magnets being repaired/replaced



Next Beams in the LHC?

Chamonix 2009 LHC workshop 2-6 February

Ongoing work to protect against problems from small splice resistances

"Since the incident, enormous progress has been made in developing techniques to detect any small anomaly. These will be used in order to get a complete picture of the resistance in the splices of all magnets installed in the machine. This will allow improved early warning of any additional suspicious splices during operation. The early warning systems will be in place and fully tested before restarting the LHC." - Rolf Heuer

Full quench protection system will be installed before next LHC operation

Additional measures taken to vent He rapidly to avoid collateral damage in the case of an incident

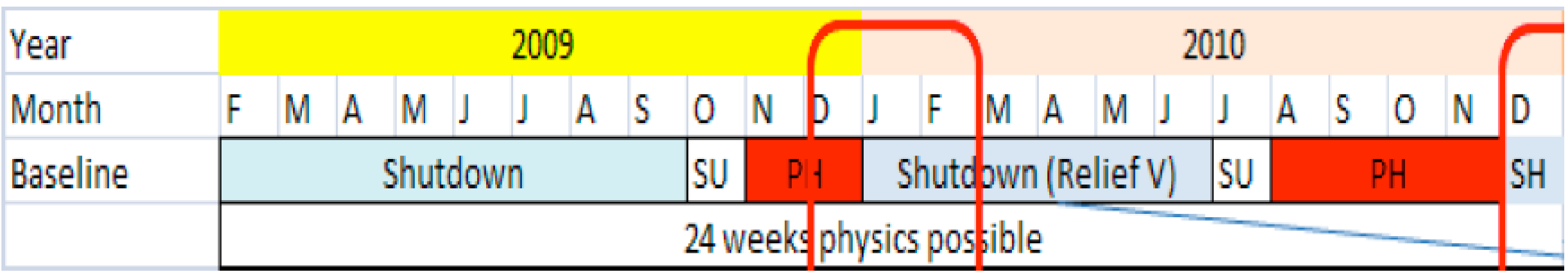
- Two different levels of protection in different sectors of the machine, equip full machine before going to 14 TeV

Decided not to warm up the whole machine now - should ensure operation with beam in 2009 - but only from the autumn

A 2009/10 Shutdown?

Repair and protection work allows first beam injection at end of September according to current schedule

Baseline schedule if no running over the winter...



- Allows very limited physics in 2009/2010 (24 weeks)
- Any slip of >1 month in the repair will delay first LHC physics till August/September 2010!!
- Repair schedule has no contingency (some suggestion for 4 extra weeks)

Alternative plan developed now, to run through the winter months

The 2009/10 LHC Run

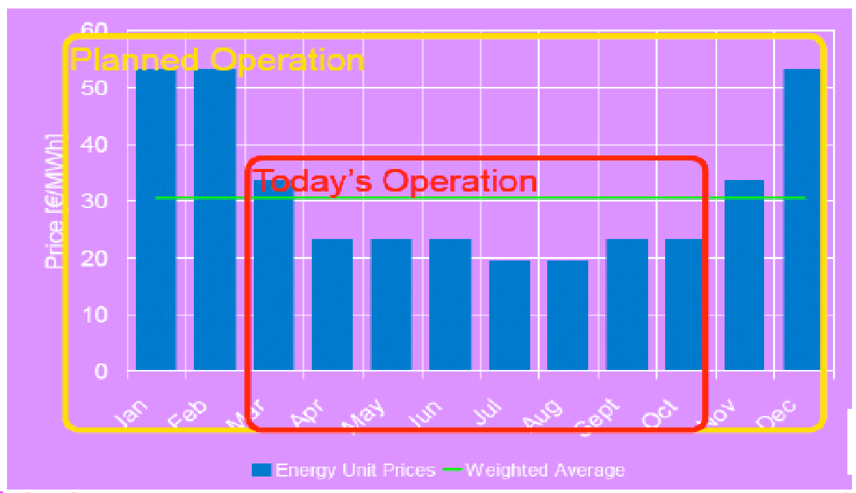
Year	2009											2010														
Month	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Baseline	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH		SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	SH	SH	SH	SH
	24 weeks physics possible																									
Base '	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH	SH	SH
	44 weeks physics possible																									
Delay (4W)	SH	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH	SH
Delay (8W)	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH

Gain 20 weeks of physics in 2010 by running during winter months

HIGH price Electricity

Further delays (eg 4 or even 8 weeks, above), would have a relatively minor impact

Annual maintenance (infra-structure, injectors), electricity cost



The 2009/10 Data Sample

Energy:

- 5 TeV per beam for physics
- 4 TeV "on the way" to 5 TeV
- Small data samples at 0.9 TeV (injection energy) and perhaps 2 TeV
  (mainly for earlier timing-in/commissioning of detectors)

Luminosity:

- 5 x 10^{31} $cm^{-2}s^{-1}$ to 2x10^{32} $cm^{-2}s^{-1}$ peak
- With 200 days and 10% efficiency ~200-300 pb^{-1}
- Quite a large uncertainty...

In the range 100-500 pb^{-1} ?

LHC Commissioning

Note - pre-Chamonix plan (July 2008) - LHC-OP-ES-0011

Stage A	**Pilot physics run**	Physics aim 43x43 bunches; maximum 156x156 bunches; no crossing angle	→ 5×10^{31}
Stage B	**Intermediate physics run**	Physics aim 75 ns bunch spacing; possible initial physics aim 96x96 bunches (bunch intensity 1×10^{10} protons); maximum aim 936x936 bunches (maximum 9×10^{10} protons per bunch). 250 µrad crossing angle.	→ 10^{32}
Stage C	**25 ns run I**	Intensity per bunch 5×10^{10} protons (initial 1×10^{10}); physics aim 2808 x 2808 bunches. 285 µrad crossing angle.	
Stage D	**25 ns run II**	Push towards nominal performance	

Chamonix favoured 50 ns operation in Stage B

Physics Commissioning

First collisions: work to establish detector and trigger performance, measure Standard Model processes

- Min bias - timing in, tracking & calorimeter uniformity & performance
- Dijets - calorimeter uniformity, jet uniformity and inter-calibration
- γ-jet - photon ID, jet energy scale
- J/ψ - μ ID, tracking performance (e ID)
- bb - lifetime-based b-tagging
- W/Z - e/μ ID, resolutions, efficiencies, τ ID (in time), missing E_t
- Z+jets - jet energy scale
- Top - many things, once we have statistics...

You will need to be patient - this will take some time...

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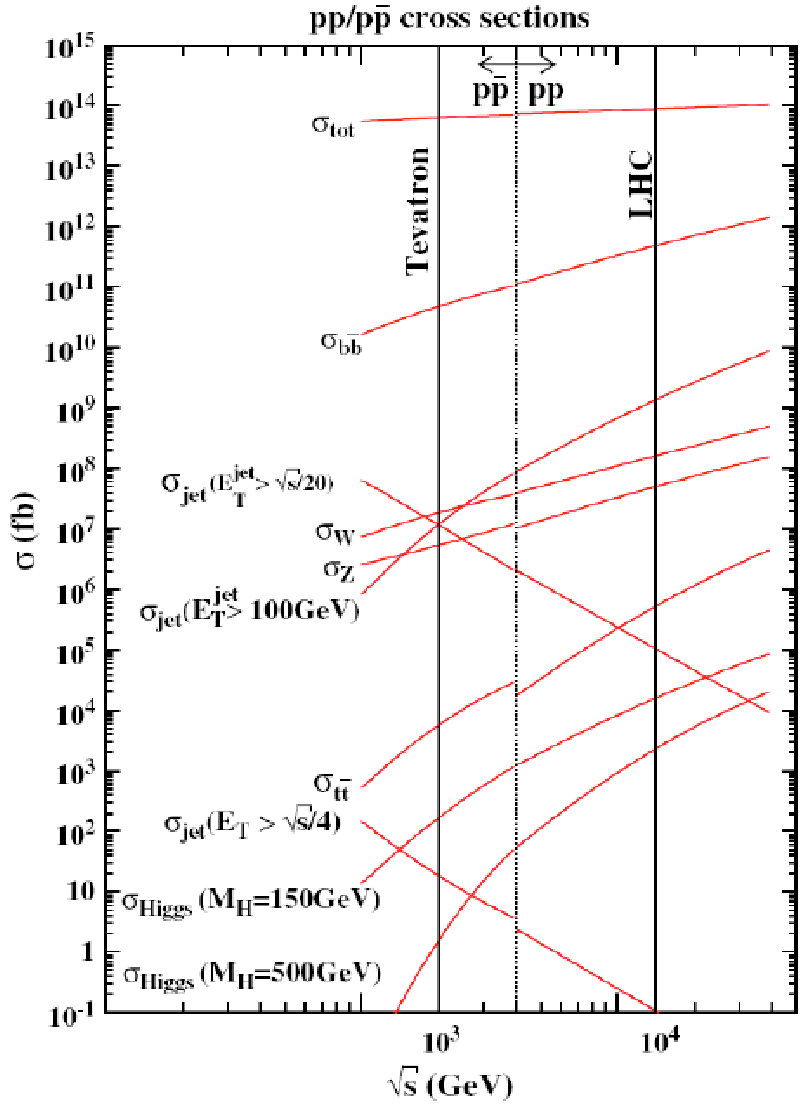


Calibration and Alignment

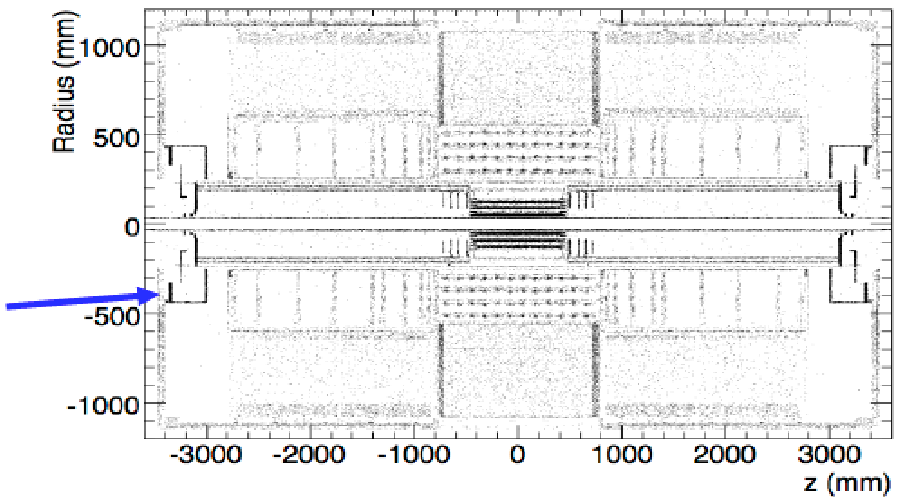
Much work to be done before physics, building on:

- test-beam
- calibration and alignment systems
- cosmics being taken now

	Initial	Ultimate	Samples
e/γ E scale	~2%	0.1%	$Z \to ee$, J/ψ, π^0
e/γ uniformity	1-4%	0.5%	$Z \to ee$
jet E scale	5-10%	~1-2%	$W \to jj$ in tt, γ/Z+jets
tracking alignment	10-100μm	<10 μm	tracks, $Z \to \mu\mu$
muon alignment	?	30 μm	inclusive μ, $Z \to \mu\mu$

Early data very important:

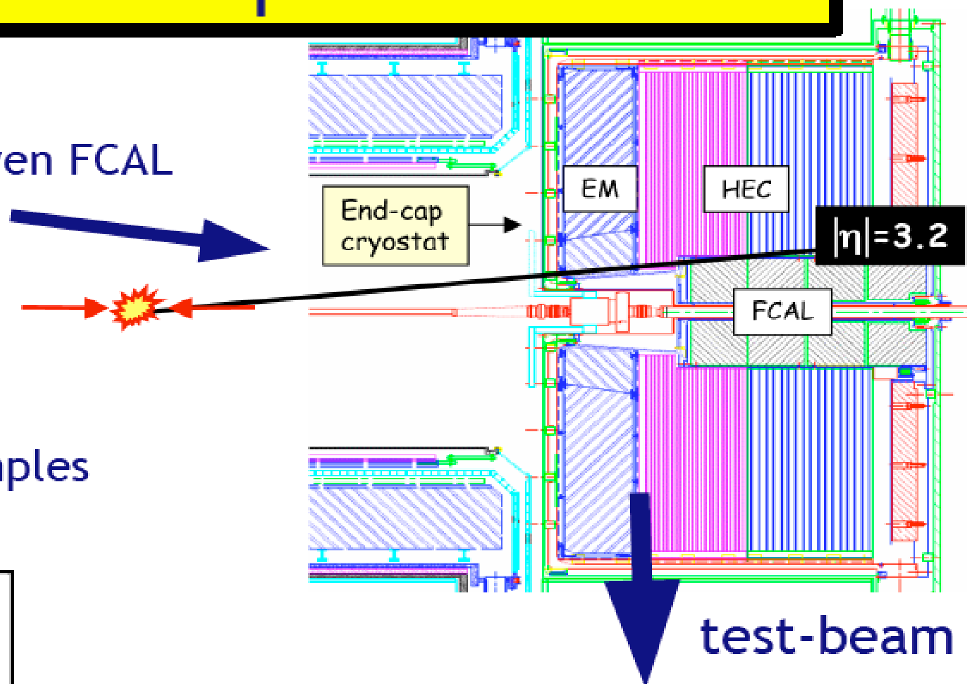
- tracks for alignment
- azimuthal asymmetry for calo. uniformity
- conversions for material assay
- ...



Missing-E_T

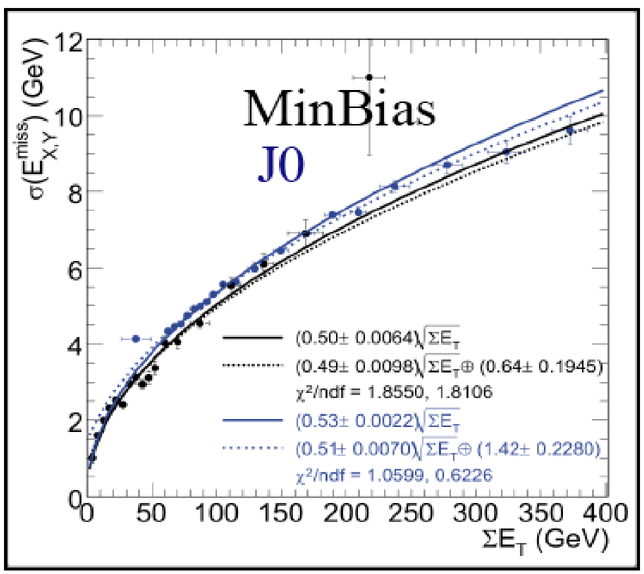
Challenging to commission:

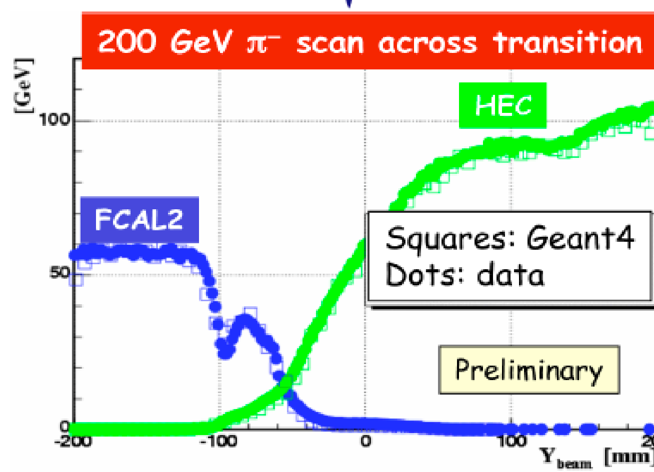
- dependence on all calorimetry, even FCAL
- modelling of crack regions, eg
- machine backgrounds, etc



ATLAS studies shown here

Detailed studies ready for control samples of data…



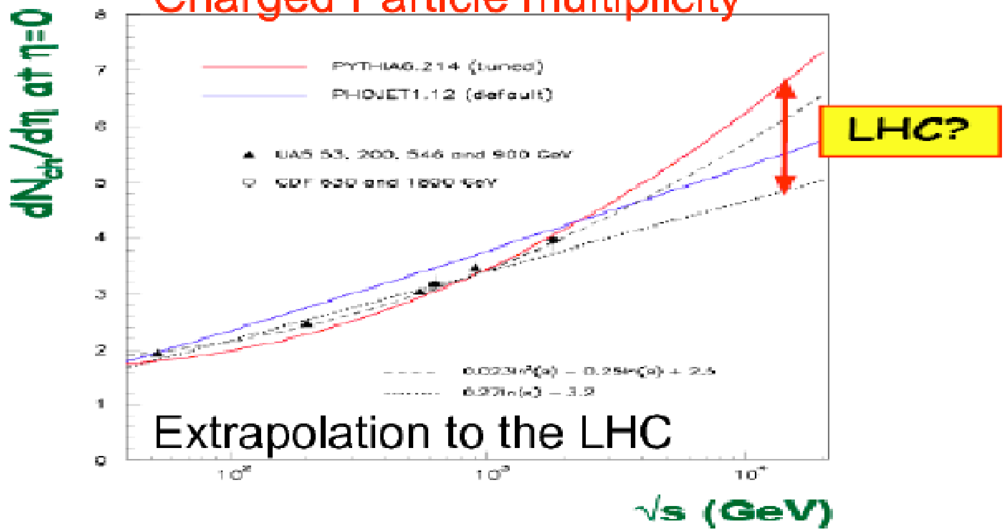


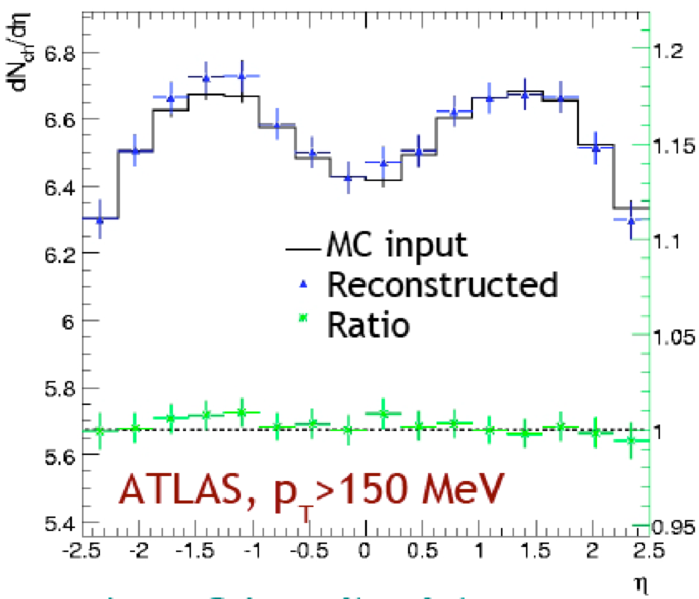
Minimum Bias

Early measurements - need tracker alignment, efficiency and material, to be understood

Challenge to extend tracking to low p_T (high B-fields at LHC!)

Charged Particle multiplicity

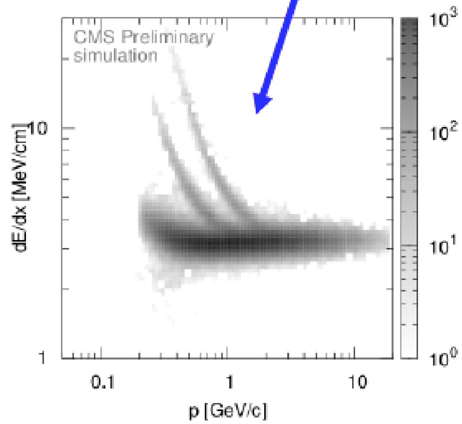


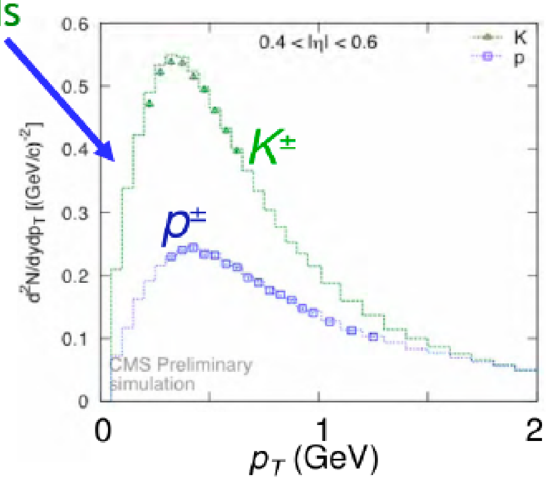


1 minute @ L=10^{31}cm^{-2}s^{-1} 14 TeV

CMS tracker: dE/dx (digitised readout of Si)

Individual particle yields

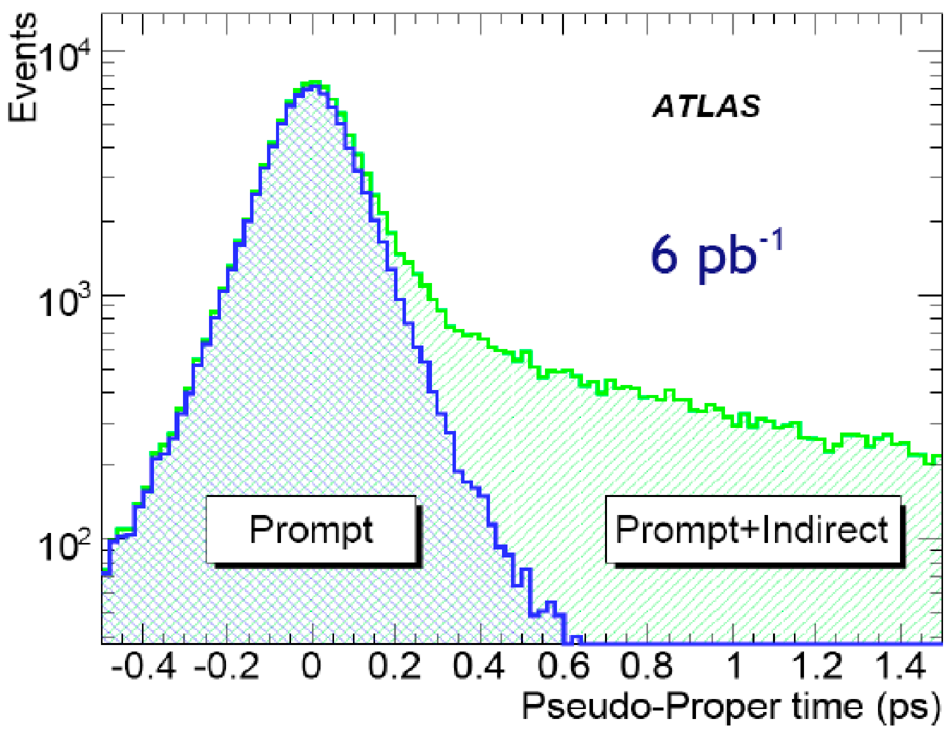


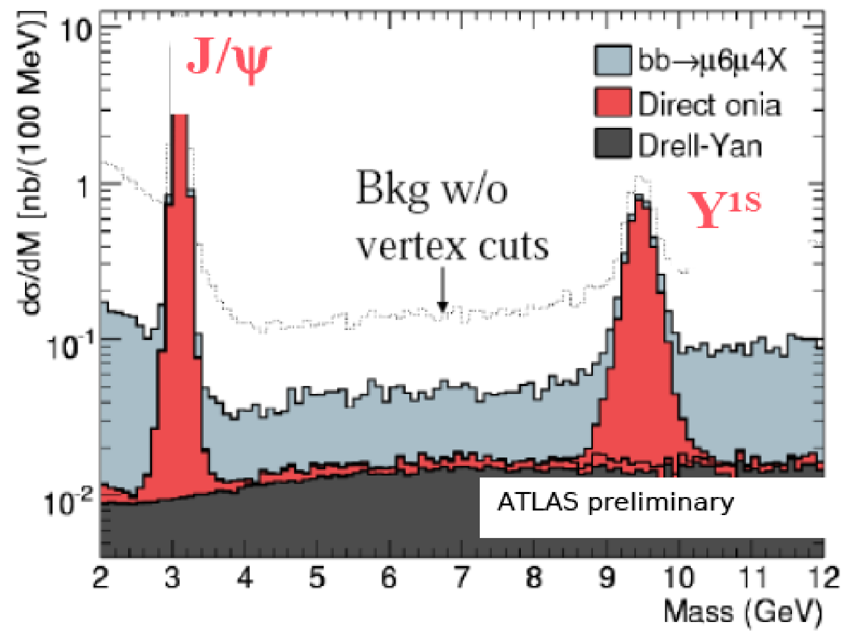


J/ψ

Huge statistics very fast, especially in μμ channel

- important standard candle for commissioning





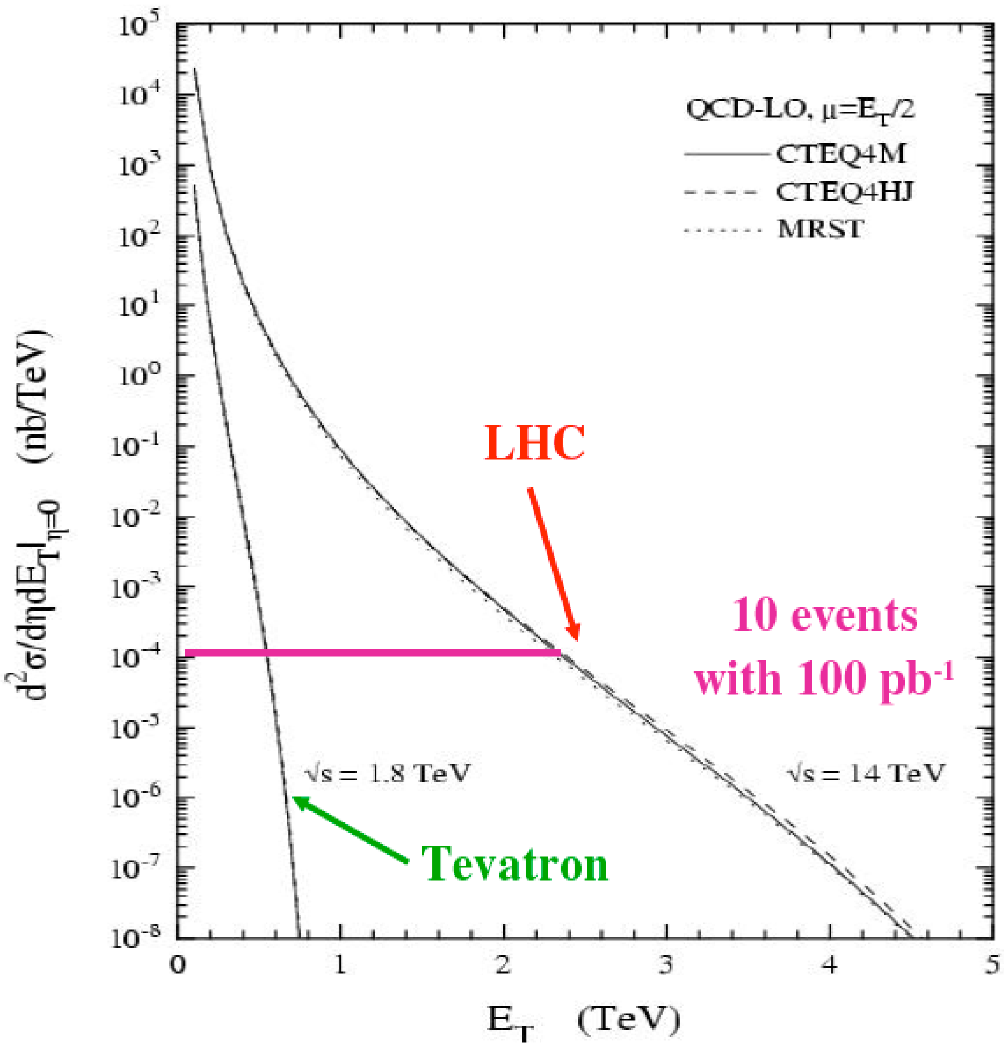
With 1 pb^{-1} could already measure

R = σ(bb->J/ψ)/σ(pp->J/ψ)

with <5% statistical precision

provided: muon trigger working; tracking understood well enough

Jets



Huge cross-sections

Very rapidly sensitive beyond Tevatron at 10 or 14 TeV

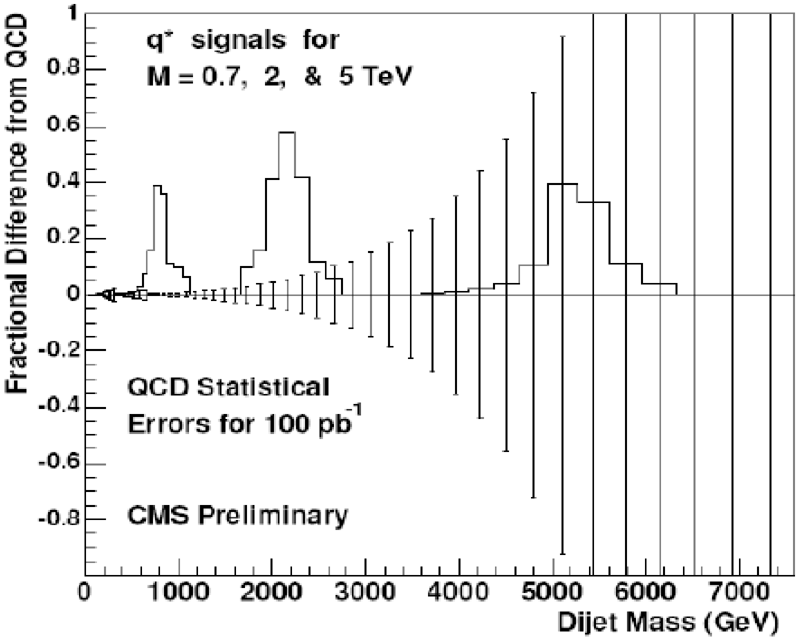
Main experimental challenge: jet energy scale uncertainty

- γ-jet, Z-jet events
- E_T-balance in dijet and multijet events

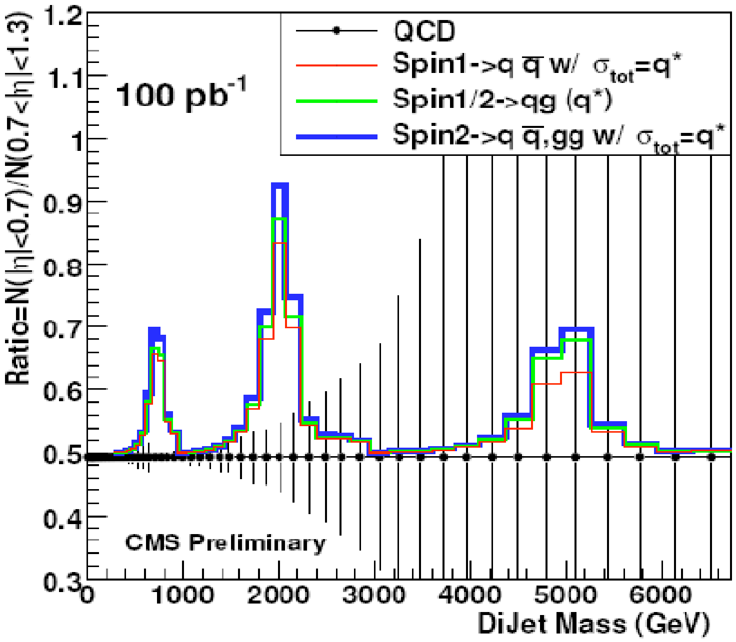
New Physics in Dijets

Other sensitive distributions, such as:

- dijet mass
- dijet ratios, e.g. N(|η|<0.7)/N(0.7<|η|<1.3)



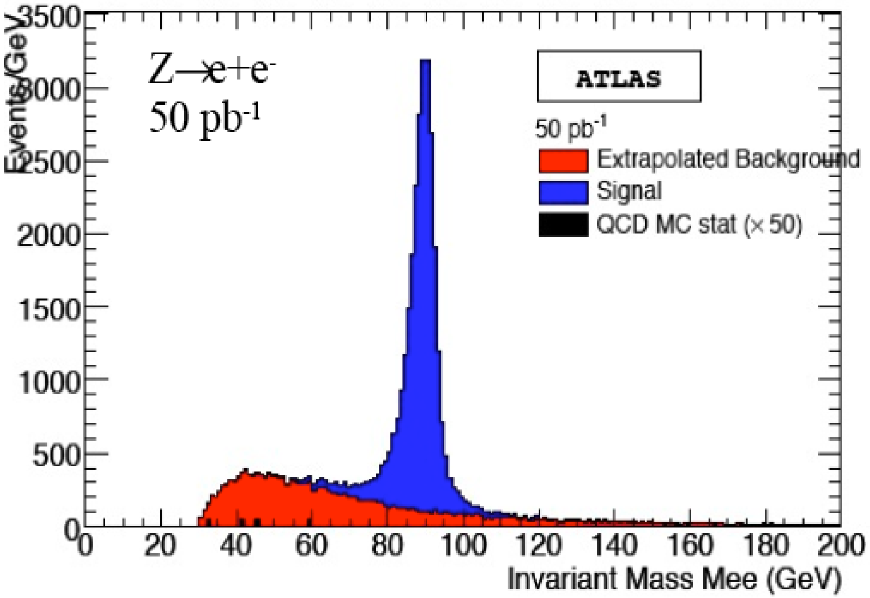
100 pb^{-1} at 14 TeV: sensitive well beyond Tevatron limit at 0.8 TeV

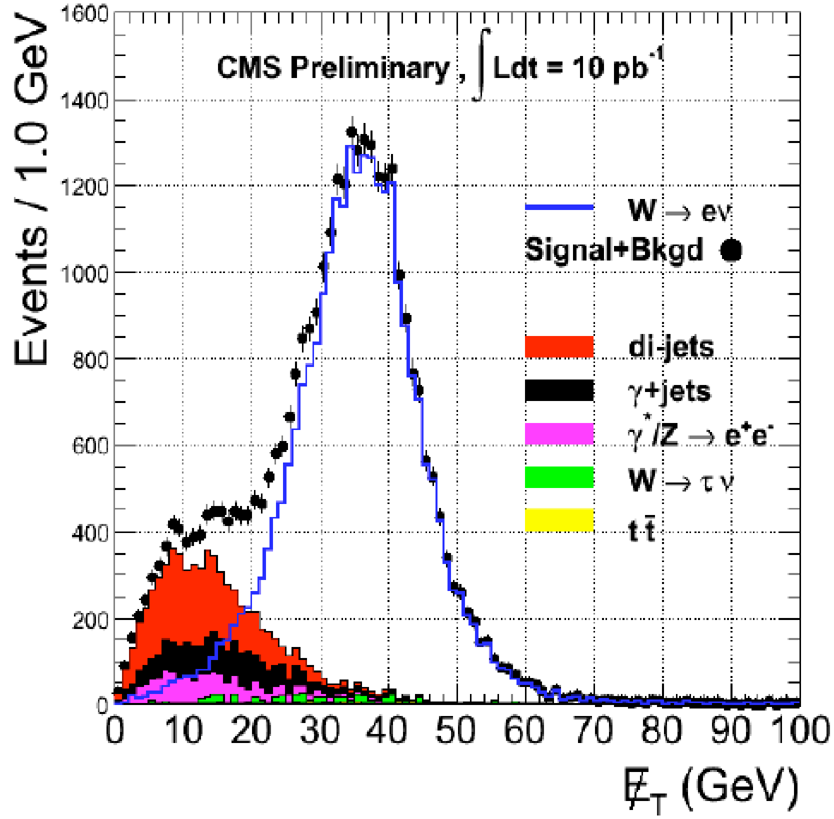


Sensitive to spin of a high-mass resonance observed

W and Z

Clean selections anticipated: excellent lepton ID





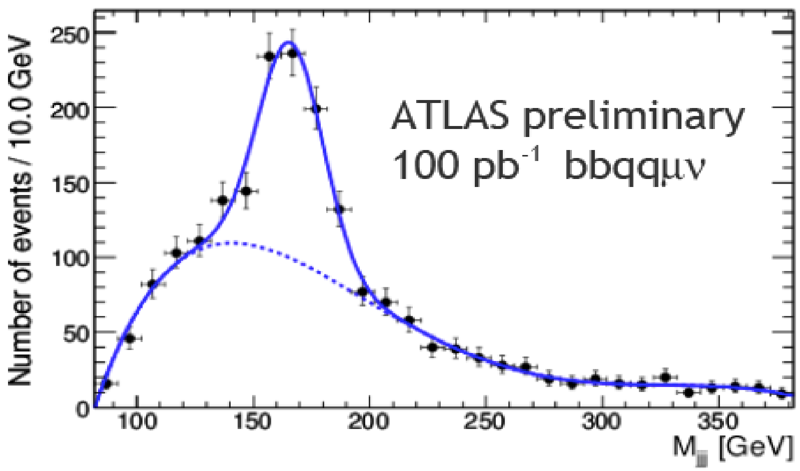
25k Z→ee for 50 pb^{-1} at 14 TeV

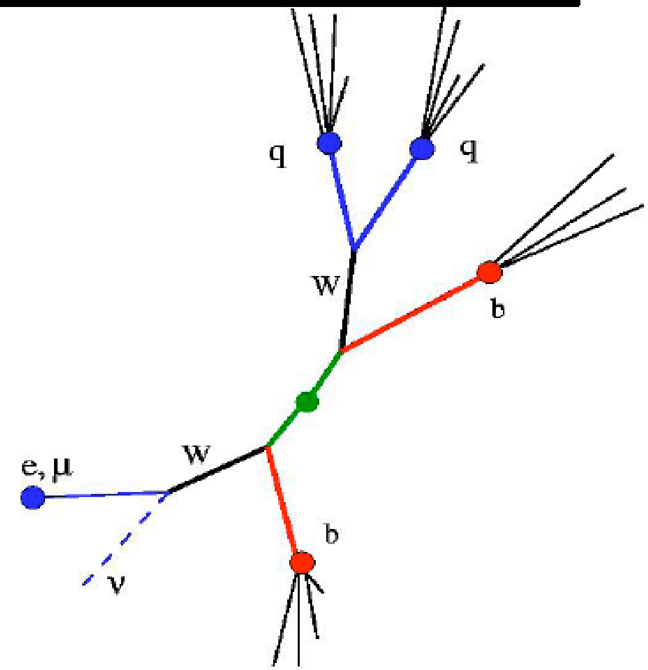
Quickly dominated by systematics

Initial precision of W/Z cross sections 4-5%

Top Physics

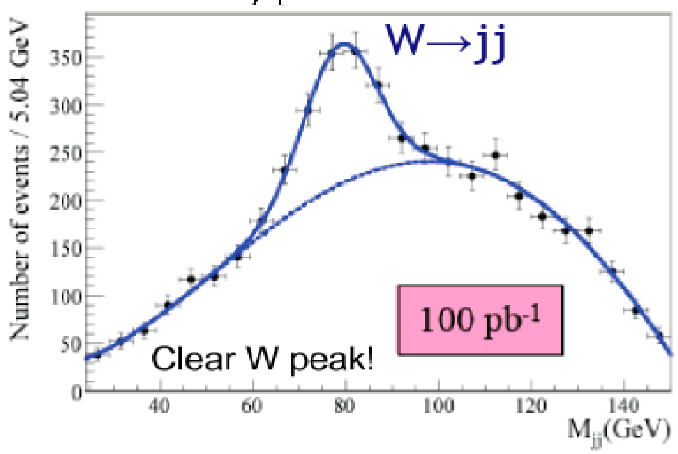
Top ($t\bar{t}$) cross-section at 14 TeV ~ 850 pb
Cf Tevatron ~ 7 pb NLO + corrections





Invaluable channel for data-driven calibration

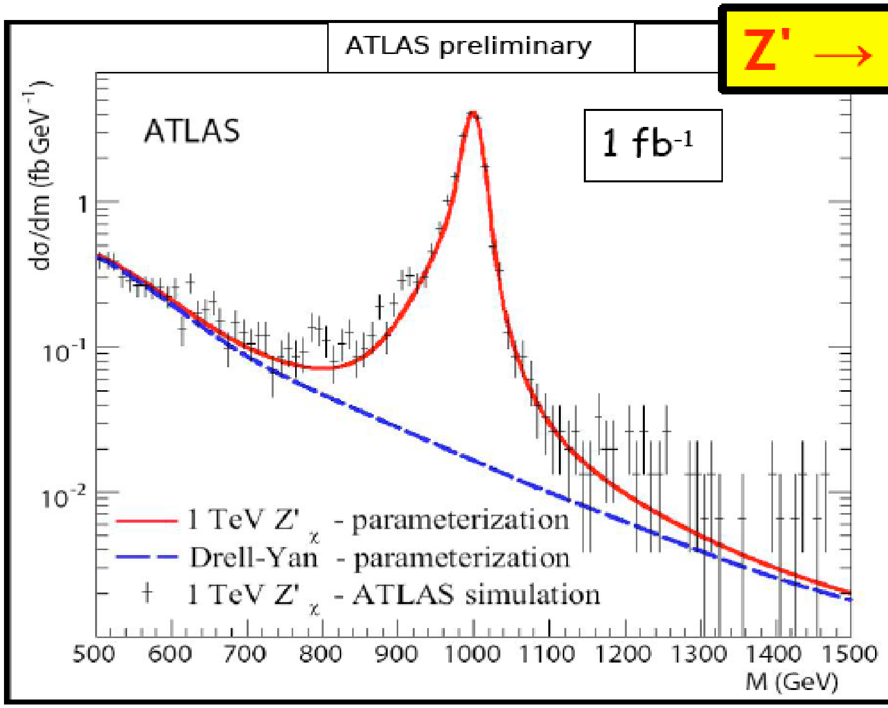
- can select without b-tags
- commission b tagging
- general performance
- calibrate the light jet energy scale with W→jj

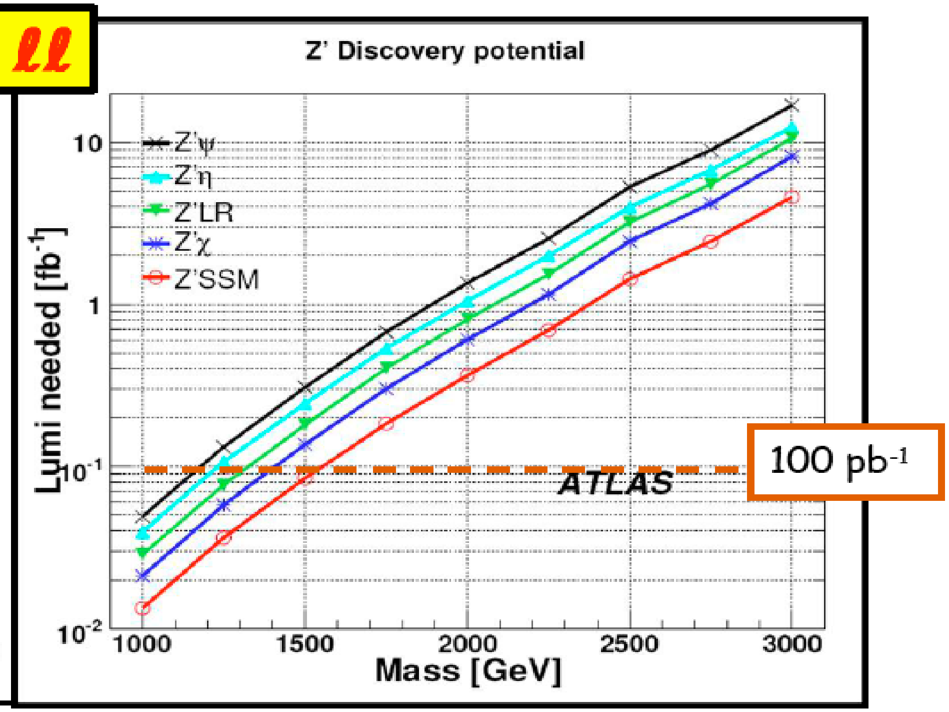


Cross-section about half at 10 TeV

Simplest New Physics Signature?

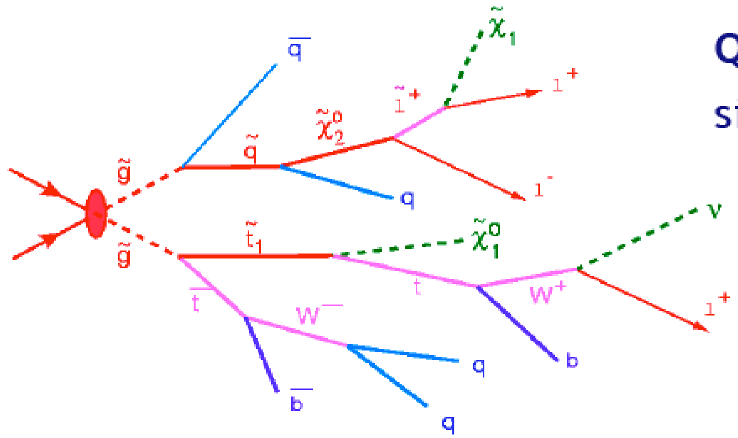
$Z' \rightarrow \ell\ell$



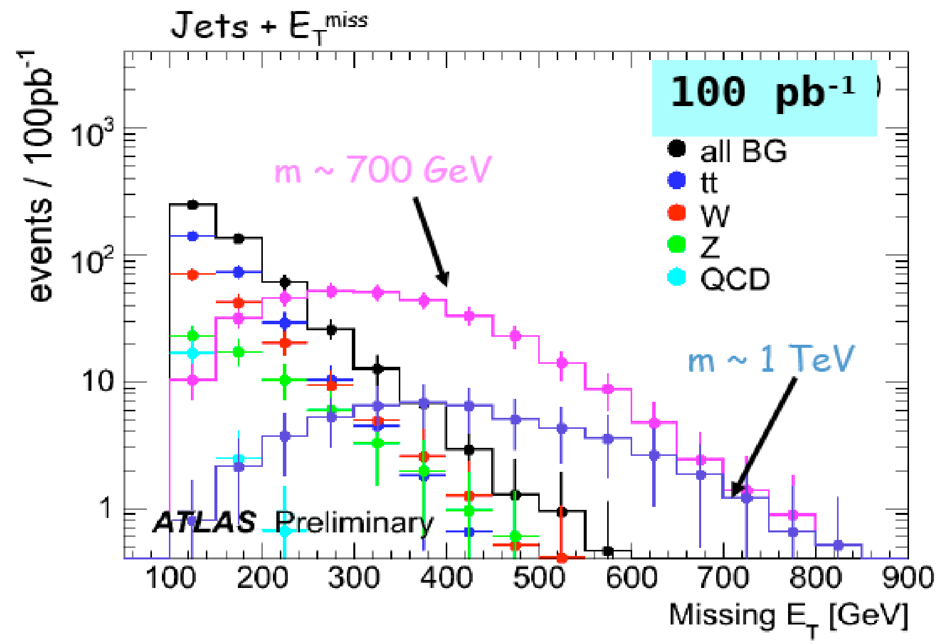


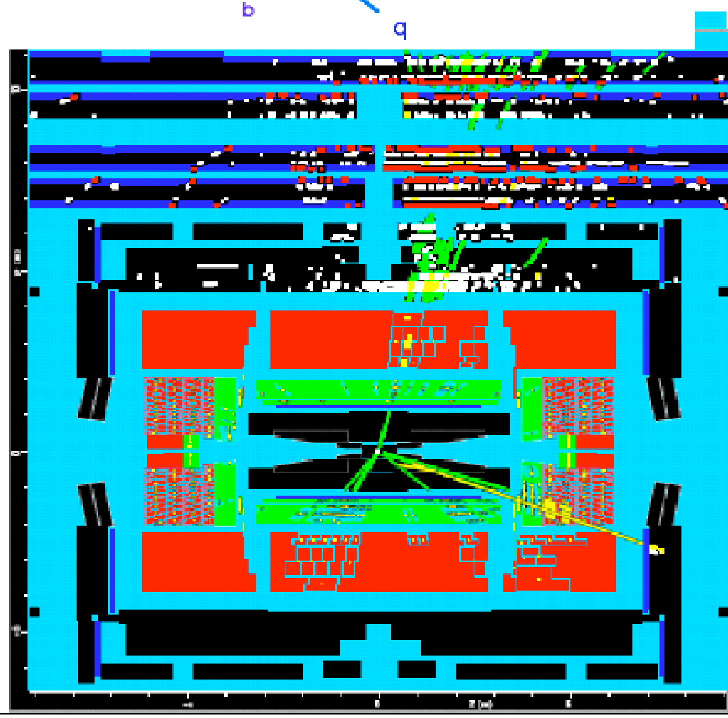
- Z' mass peak on top of small Drell-Yan background
- with 100 pb^{-1} large enough signal for discovery up to m ~ 1.5 TeV in sequential SM σ(10 TeV) ~ ½ σ(14 TeV)
- current Tevatron 95% CL limit ~ 1 TeV
- ultimate calorimeter performance not needed
- ultimate reach (300 fb^{-1}) ~ 5 TeV

SUSY - mSUGRA



QCD production of squarks, gluinos - E_T^{miss} signatures





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Need to understand whole detector well to rely on E_T^{miss}

→ problem will be to know if an excess is real, and what it is…

Improvement in Higgs Studies at the LHC

- Many studies have meanwhile been performed using detailed GEANT simulations of the detectors
  - Physics Performance Technical Design Report from the CMS collaboration, TDR, J. Phys. G 34 (2006) 995
  - "Expected Performance of the ATLAS Experiment" , Dec 2008, arxiv:09010512

- New (N)NLO Monte Carlos (also for backgrounds)
  - MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
  - MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/
  - T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
  - E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
  - C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130
  - .....

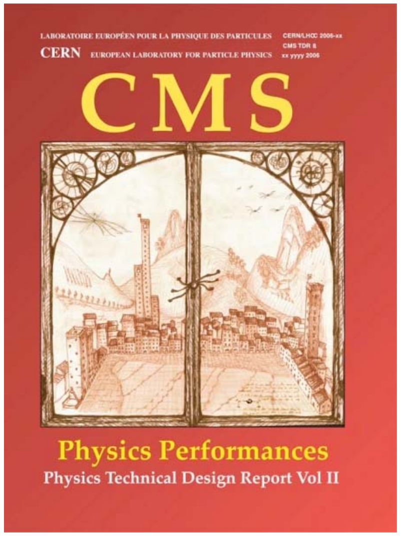
- New approaches to match parton showers and matrix elements
  - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
  - SHERPA Monte Carlo, F. Krauss et al.
  - ...

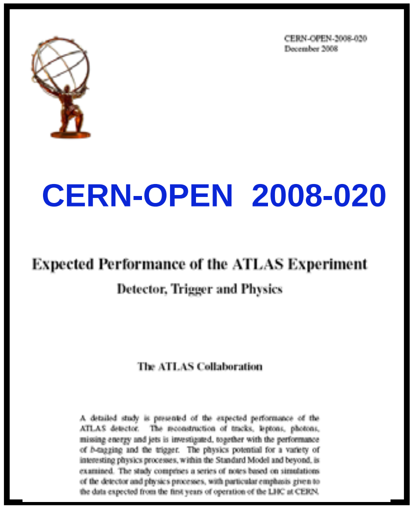
  Tevatron data are extremely valuable for validation, work has started

- More detailed, better understood reconstruction methods
  (partially based on test beam results,…)

- Further studies of new Higgs boson scenarios
  (Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)

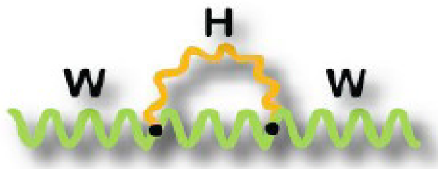
CERN / LHCC 2006-021



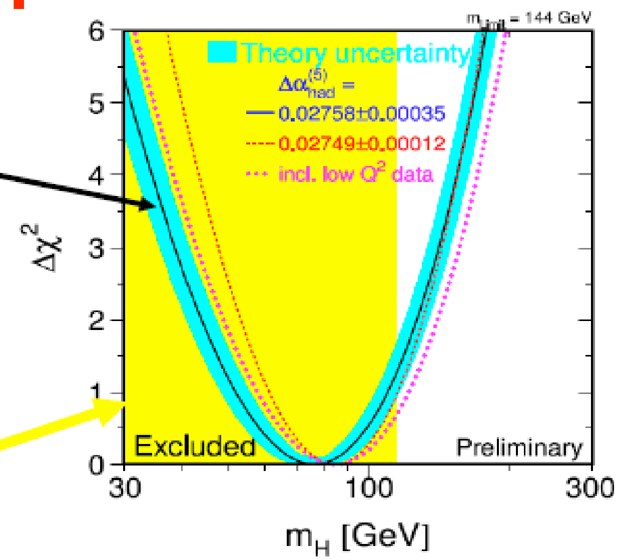


Higgs Searches: present limits

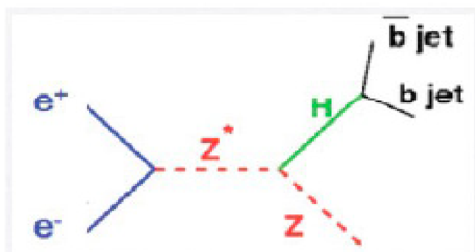
- **The electroweak measurements are sensitive to m_H through radiative corrections:**



$$\log \frac{m_H}{m_Z}$$



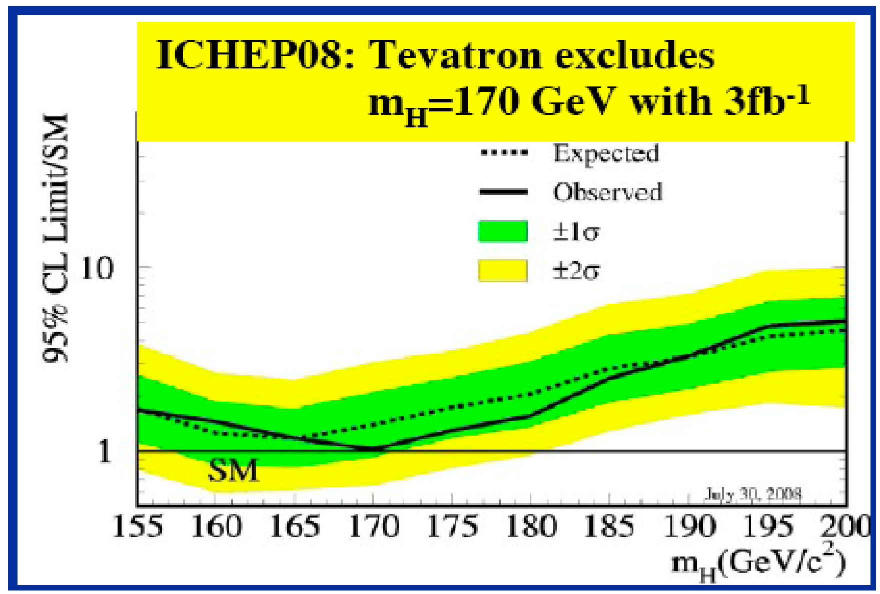
- **Direct search at LEP2:**



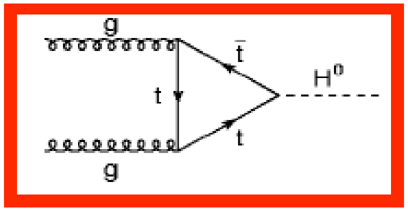
LEP limits:

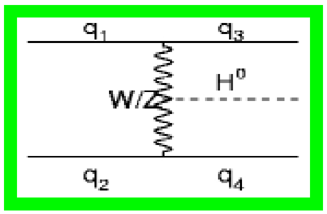
$114.4 < m_H \lesssim 182$ GeV/c^2

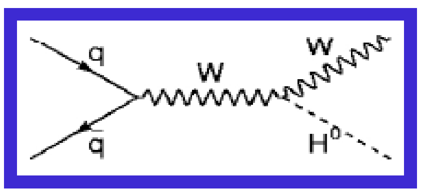
Directe *Indirecte*

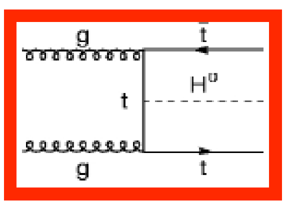


Higgs Production at the LHC

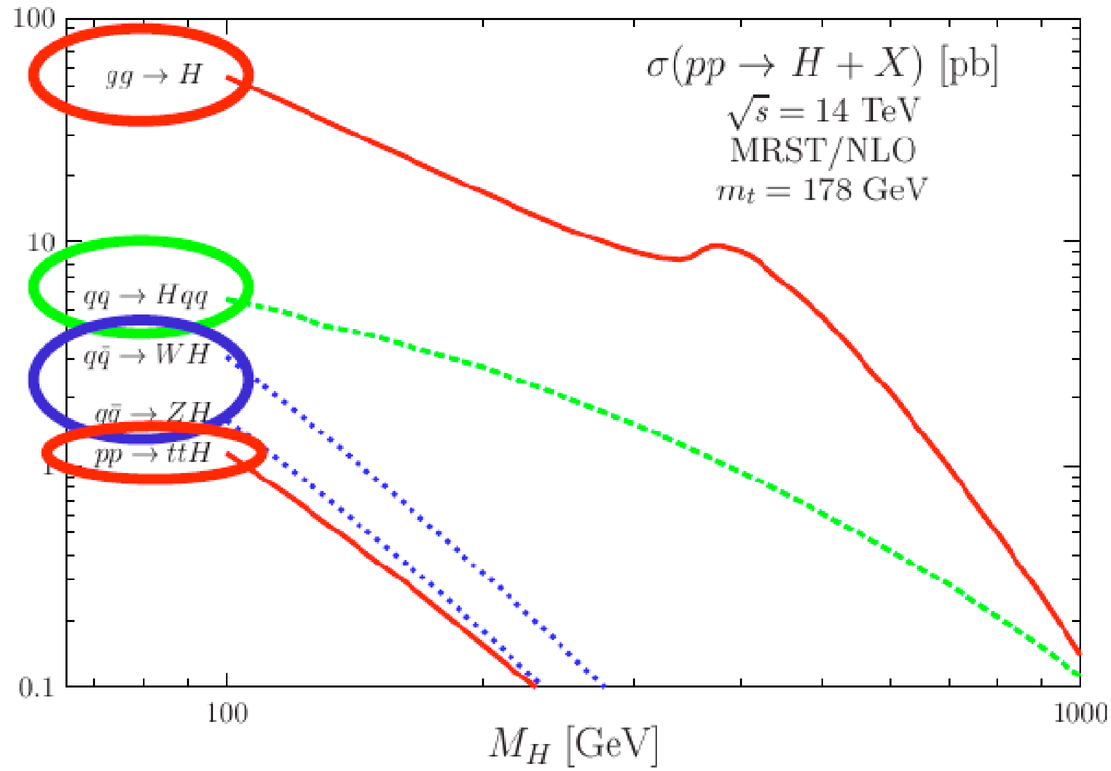








A.Djouadi Phys.Rept.457:1-216

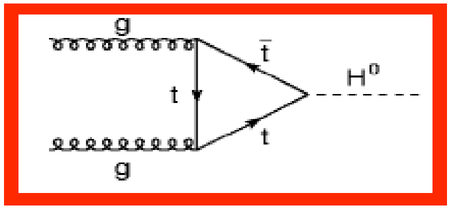


***gg fusion* process is the more abundant, followed by the *Vector Boson Fusion* process.**

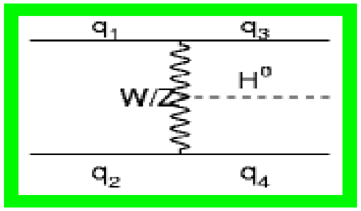
Typical uncertainties on cross-section

gg	10 %	NNnLO
VBF	5%	NLO
WH,ZH	5%	NNLO
ttH	15%	NLO

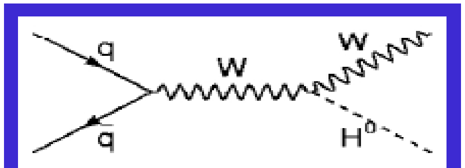
SM Higgs Decays at the LHC



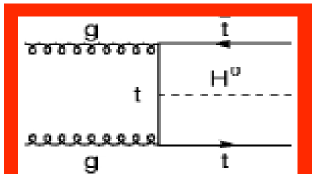
GF H → WW, ZZ , γγ



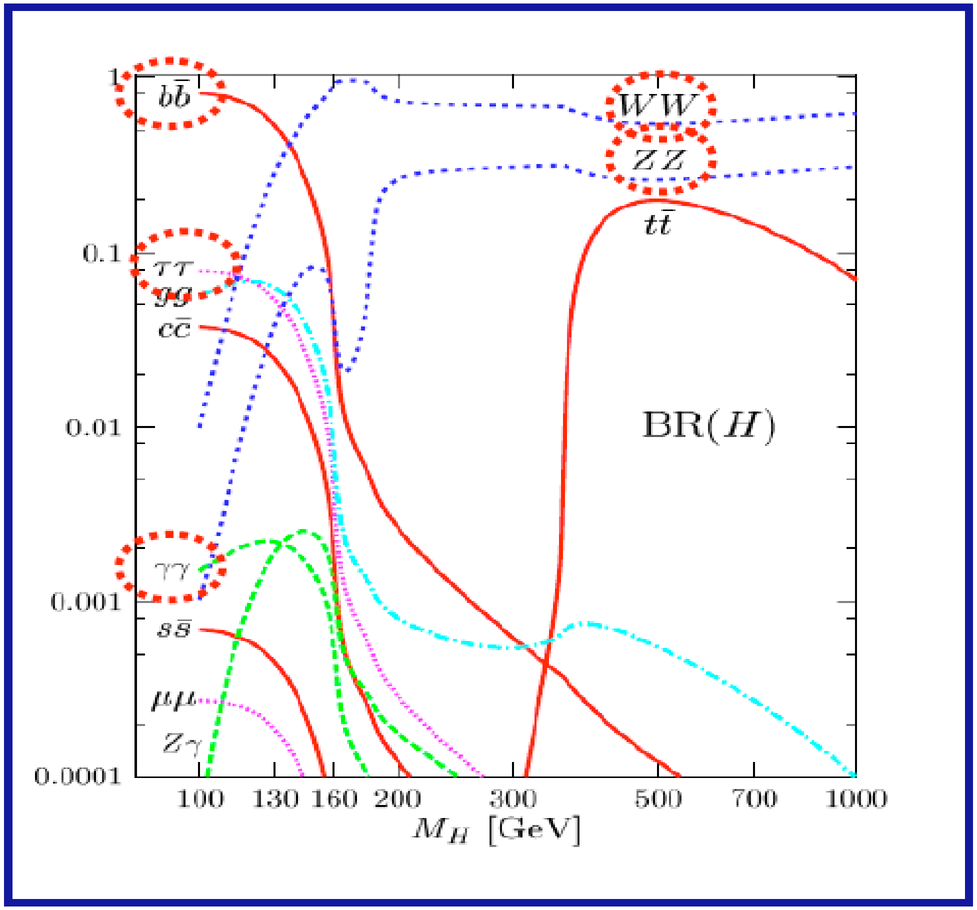
VBF H → WW , γγ , ττ



H → WW, γγ

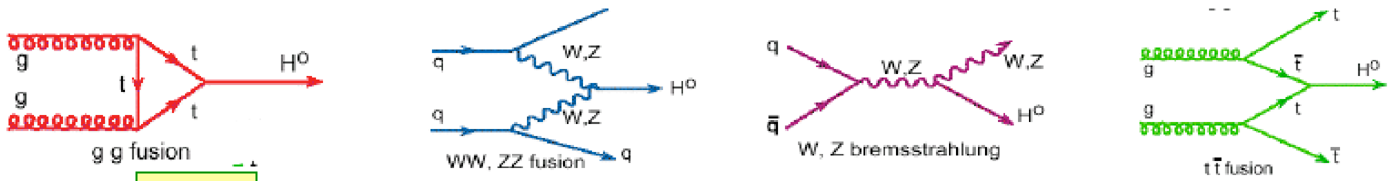


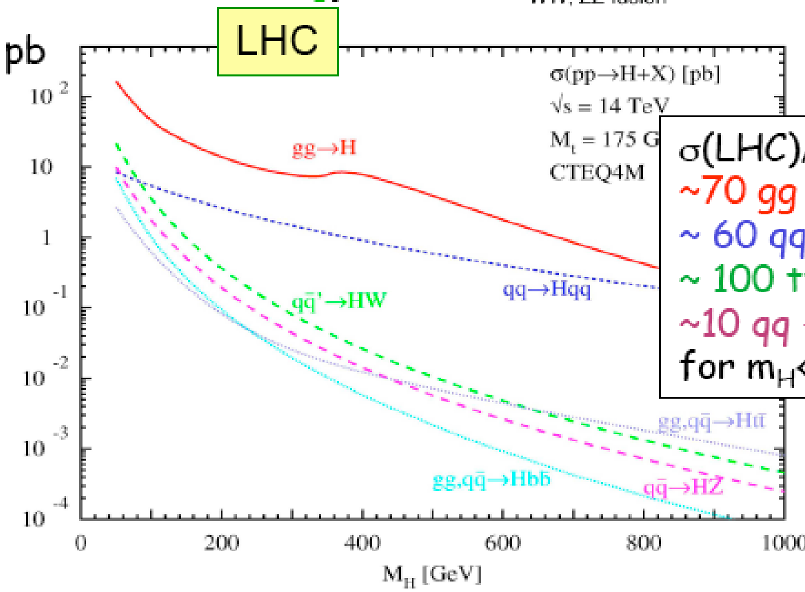
H → WW, γγ, bb



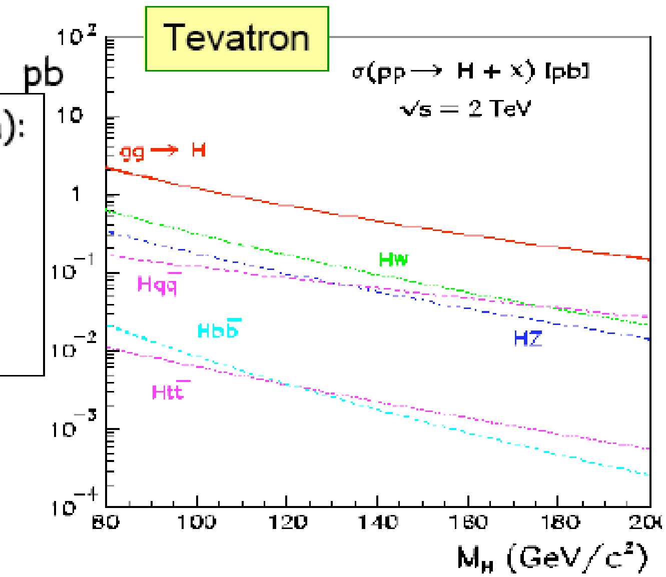
Many channels explored!
All the mass range is covered!

Light Higgs Boson …





σ(LHC)/σ(Tevatron):
~70 gg → H
~ 60 qqH → qqH
~ 100 ttH
~10 qq →WH/ZH
for m_H<200 GeV



	Tevatron Main Search Channels	LHC Main Search Channels
m_H ~115 GeV	WH→ lνbb ZH → ννbb, llbb	H → γγ, qqH → qqττ ttH→ lνbbX
m_H ~ 160 GeV	H →WW → lνlν	H → WW→ lνlν,H→ZZ*→4l, qqH→ qqWW→ qqlνlν

Large backgrounds at the LHC

Cross-sections too small at the Tevatron

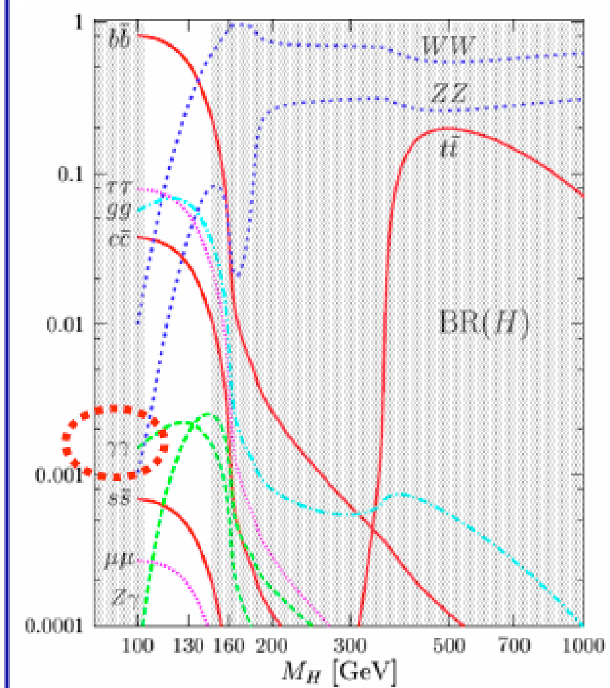
Higgs → γγ

- ***Important channel in the low mass region.***
- ***It gives the best mass resolution thanks to excellent electromagnetic energy resolution***

ATLAS **SELECTION**

- **Trigger**: at least 2 isolated photons, with $p_T > 20\ GeV/c$ each
  → ε (respect to offline) = $(93.6 \pm 0.4)\%$
- **Identification cut** exploiting the shower shape.
- **Fiducial cut**: $0 < |\eta| < 1.37$ & $1.52 < |\eta| < 2.37$.
- **Isolation cut**: $\Sigma p_T < 4\ GeV/c$, considering all tracks with $p_T > 1 GeV/c$ in a $\Delta R = 0.3$ cone around the electromagnetic cluster.
- **Momentum cut**: $p_T > 25 GeV/c$ and $p_T > 40 GeV/c$ for the two most energetic photons.

Selection efficiency:
$\varepsilon = 36.0\ \%$ (32.2% with pileup $10^{33} cm^{-2} s^{-1}$)



In a mass window M_H +/- 1.4σ GeV:

Signal Process	Cross-section (fb)
$gg \to H$	21
VBF H	2.7
ttH	0.35
VH	1.3

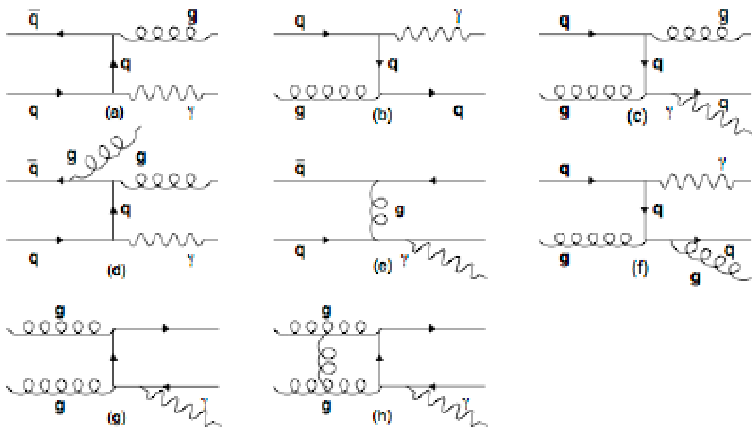
Higgs → γγ backgrounds

ATLAS

Within a mass window M_H +/- 1.4σ *GeV*:

Background Process	Cross-section (fb)
$\gamma\gamma$	562
Reducible γj	318
Reducible jj	49
Drell Yan	18

Example: γ-jet processes



- Background is evaluated with *NLO* simulations.
- ***It will be measured from data sidebands.***

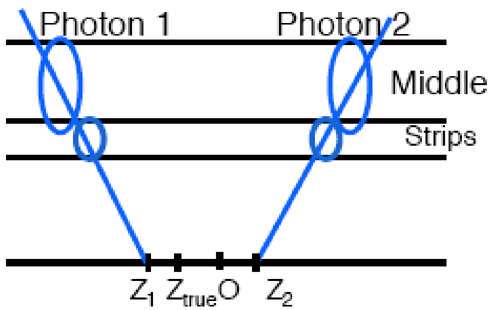
Strategy for jet rejection:

- *Longitudinal segmentation* of the calorimeter.
- Fine segmentation of the first layer (*η-strips*) => good π^0 rejection.
- *Isolation* of the *electromagnetic* cluster.
- *Isolation based on tracks* reconstructed by the inner detector.

Higgs → γγ reconstruction

PRIMARY VERTEX

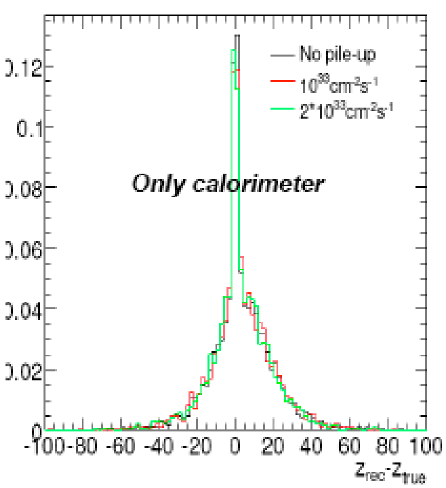
If the vertex is unknown, add 1.4 GeV to the mass resolution.
Combine calorimeter and tracker informations!

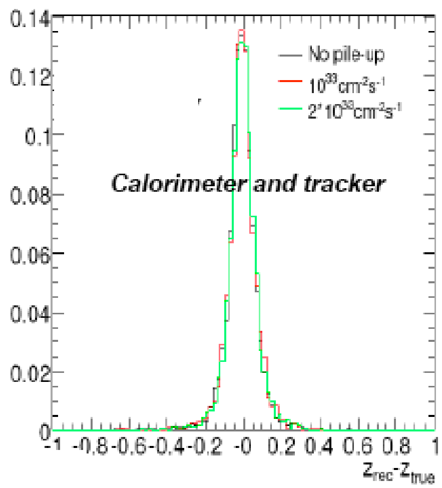


ATLAS

- Calorimeter → vertex position accuracy of *19 mm*
- Combining with the tracker information → *~0.1 mm*

Calorimeter information is useful in case of pile-up or events with low tracks multiplicity.

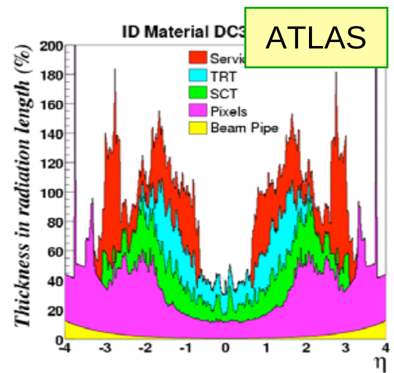


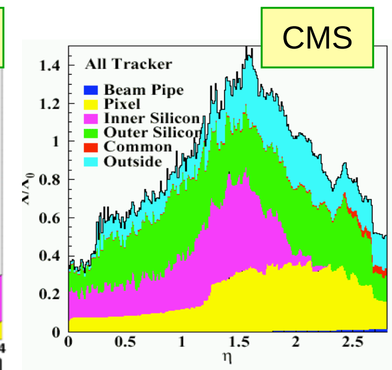


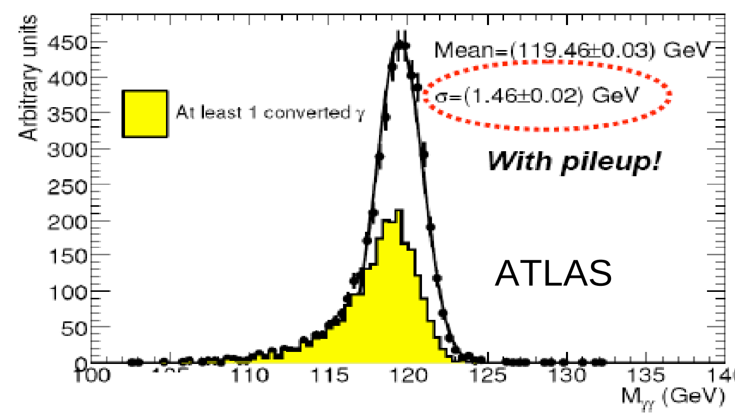
CONVERSIONS

~50% of the events with at least one converted γ !

- ad hoc energy calibration required in late conversions;
- conversion vertex used in computation of the direction;
- used for gamma-jet background estimation.







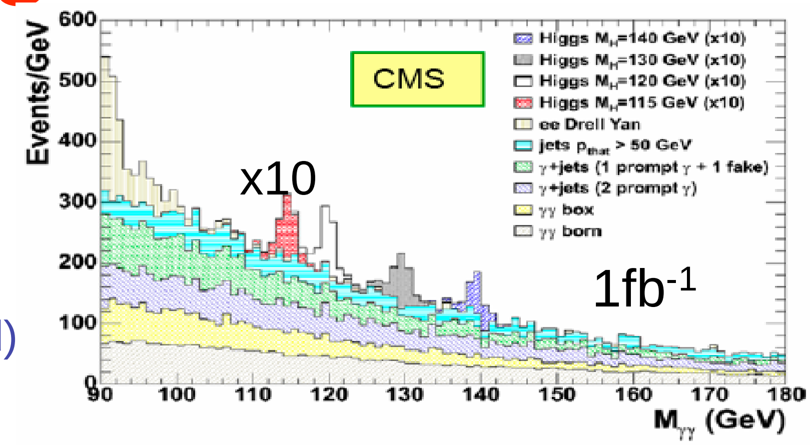
CMS: fraction of converted γs

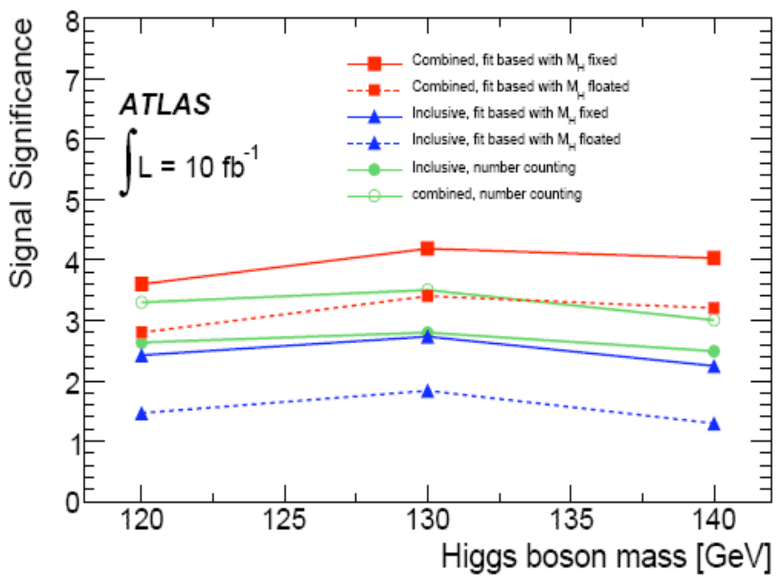
Barrel region:	42.0 %
Endcap region:	59.5 %

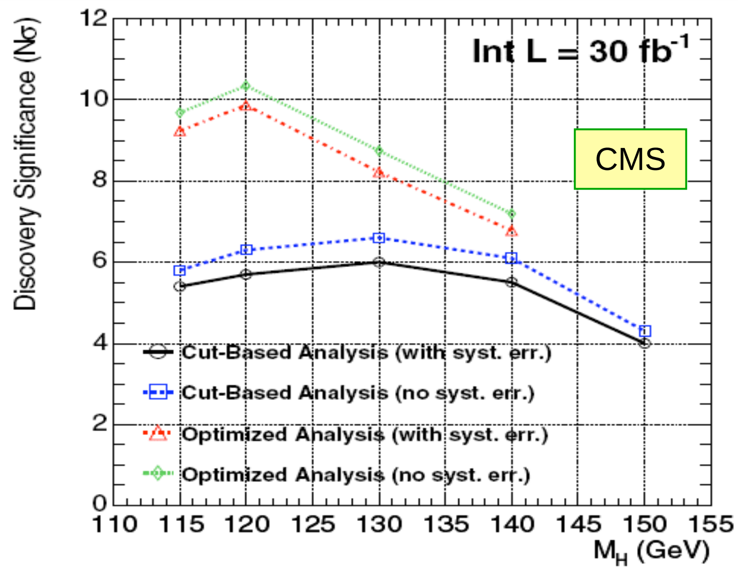
Higgs → γγ significance

<u>New elements of the analyses</u>:

- NLO calculations available
  (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Divide signal sample acc. to resolution functions

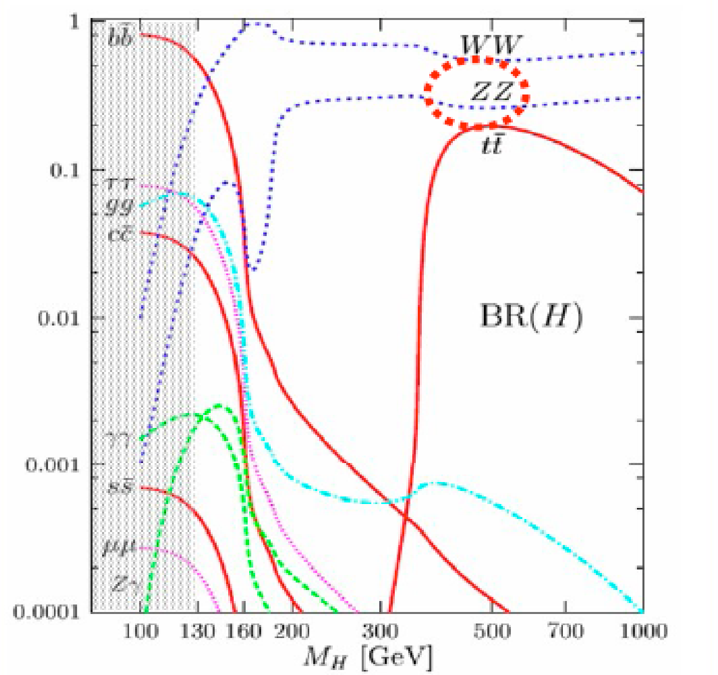






- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive γγ + jet topologies

Higgs → ZZ* → 4l



ATLAS **SELECTION**

- **Trigger**: - single isolated μ (e) with p_T>20 (25) GeV/c;
  - two μ (e) with p_T>10 (15) GeV/c.
- **Kinematic**: - 2 pairs of same flavor opposite charge lept.
  - p_T>7GeV (at least two with p_T>20GeV)
  - calorimeter identification
  - $|M_{ll1}-M_Z|<\Delta M_{12}$ and $M_{ll2}>M_{34}$
- **Fiducial cut**: $|\eta| < 2.5$
- **Isolation cut**: - Calorimeter: $\Sigma E_T/p_T < 0.23$ (ΔR<0.2)
  - tracker: $\Sigma p_T/p_T < 0.15$
- **Vertexing cut** on maximum lepton *impact parameter*:

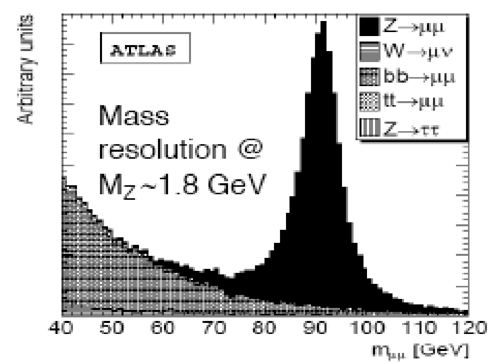
  $d_0/\sigma_{d0}<3.5\ (6.0)$ for $\mu\ (e)$

It is the "golden channel"!

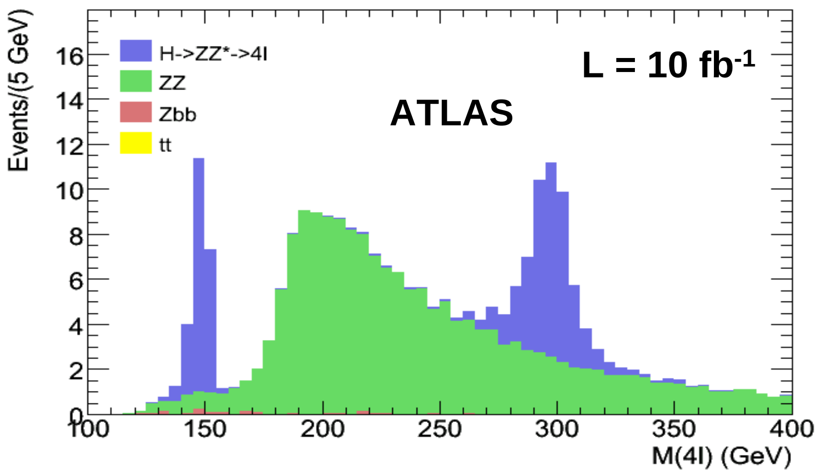
- ***Observation of a clear peak on top of a smooth background!***
- ***Wide range of masses explored***

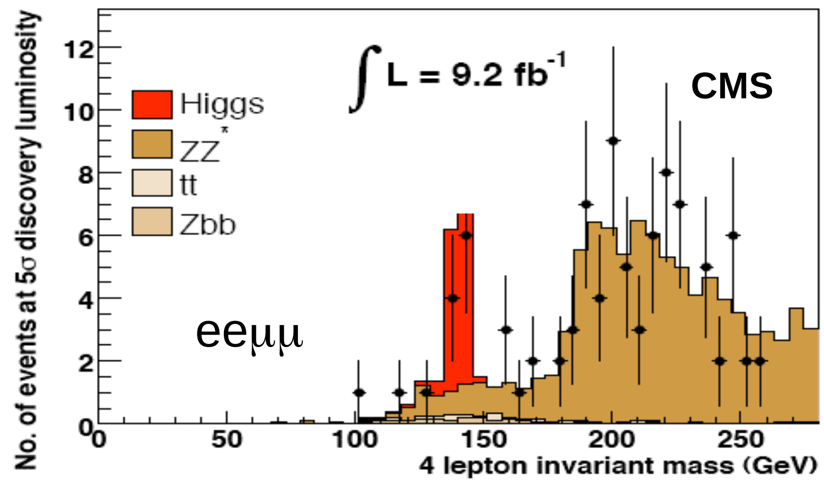
Background will be estimated in sidebands → low systematic uncertainties

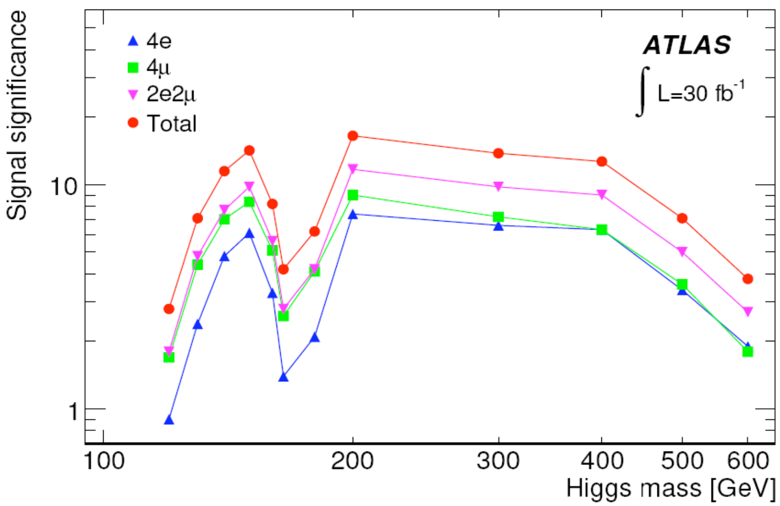
- Look to the *Z* with first data to understand lepton reconstruction and detectors response.
- *Z*→*ee* mass peak is affected by electron bremsstrahlung.

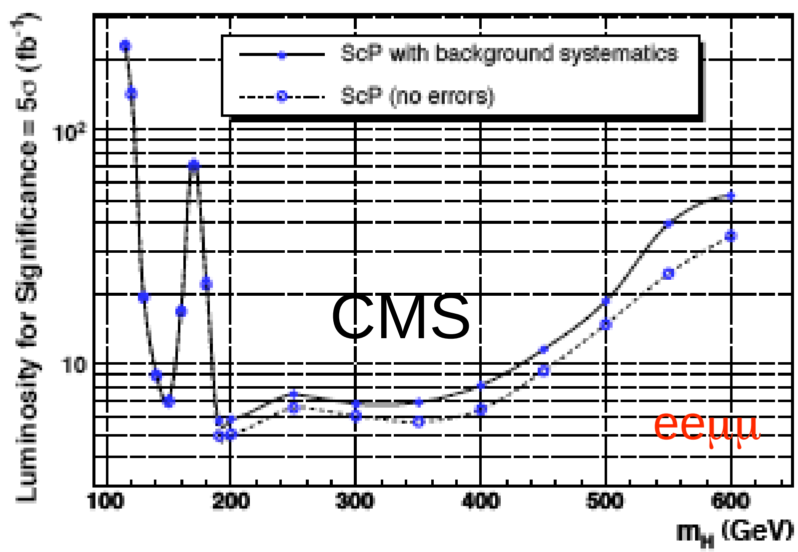


Higgs → ZZ* → 4l







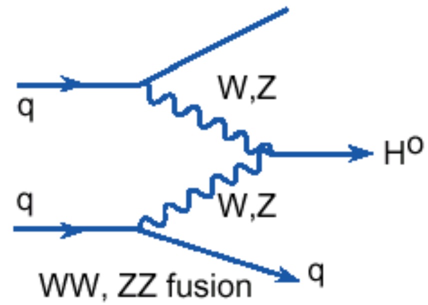


5 fb^{-1} to claim discovery ~ m_H=150 GeV or 200<m_H(GeV)<400

Vector Boson Fusion qq H

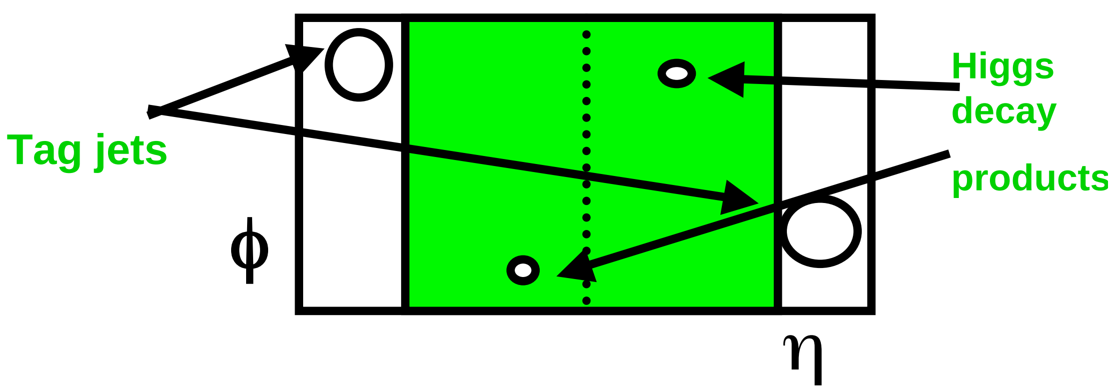
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

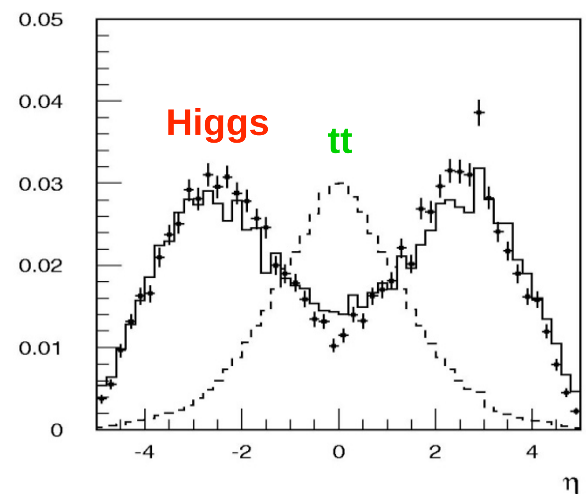


Distinctive Signature of:

- two high P_T forward tag jets
- little jet activity in the central region
  $\Rightarrow$ central jet Veto



Rapidity distribution of jets in tt and Higgs signal events:

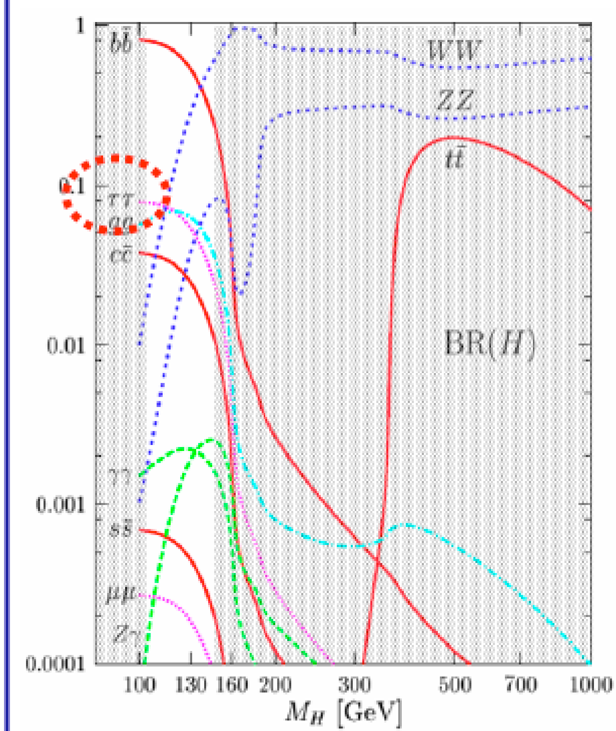


Vector Boson Fusion qq H(→ ττ)

- ***High BR in the low mass region.***
- ***3 channels: ll, lh, hh (65% of τ gives hadrons)***

SELECTION

- **Trigger**: isolated electrons (μ) with p_T>22 (20)GeV/c (ε~10%)
  $\tau + E_T^{miss}$ (ε~3.7%) for the *hh* channel
- **Isolation cut**
- **Likelihood** exploiting the shower shape and the track quality to separate τ and jet.
- **b-jet veto** to kill *tt(+jets)→lvb lvb (+jets)* (background for the ll channel)
- select highest E_T jets in opposite hemispheres
- **Central jet veto**



BACKGROUNDS

- $Z \rightarrow \tau\tau + jets$
- $W \rightarrow \tau\nu + jets$
- *tt+jets*
- *QCD* multi-jets for the *hh* channel

MAIN ISSUES:

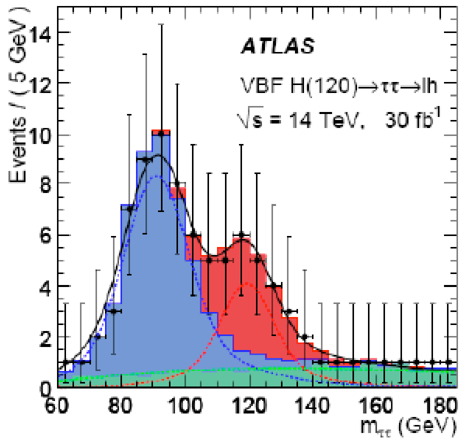
- Discrepancies in Monte Carlo generator → impact on veto efficiency
- Pileup → impact on E_T^{miss} and jet veto
- Estimation of QCD multi-jet → no sensitivity yet on *hh* channel

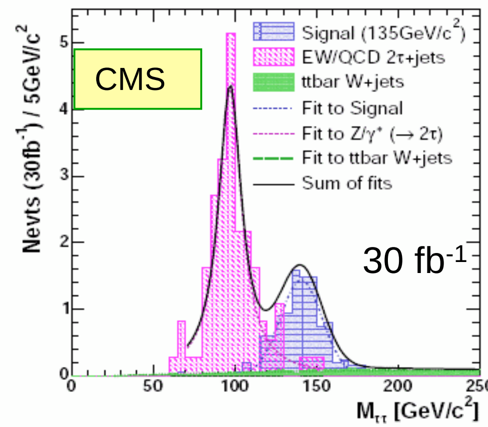
VBF qq H($\to \tau\tau$)

qq H $\to$ qq $\tau\,\tau$
$\to$ qq $\ell\nu\nu$ $\ell\nu\nu$
$\to$ qq $\ell\nu\nu$ hν

Experimental challenges:

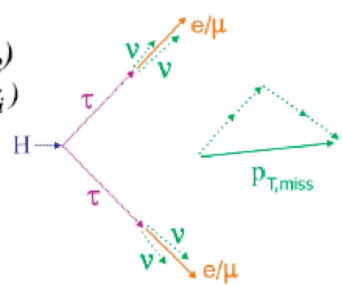
- In-time pileup, out-of-time pileup, underlying event.
  - test simulations & use vertexing for the jet
  - calorimeter timing
  - early data underlying event measurement
- Identification of hadronic τ
- Good E_T^{miss} resolution (since there are neutrinos…)
- Knowledge of the $Z \to \tau\tau$ background shape in the high mass region: use data $Z \to \mu\mu$ to emulate it!

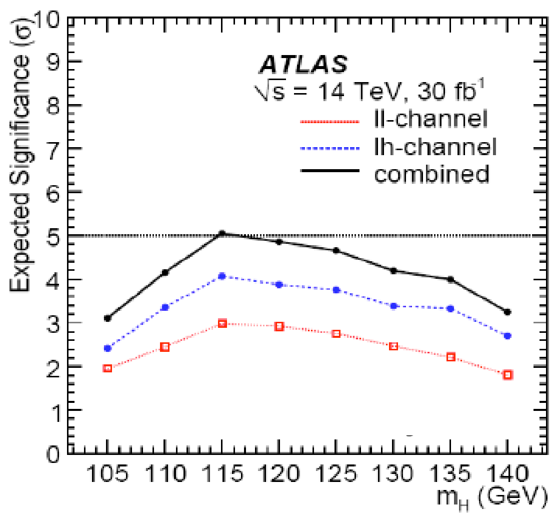




Higgs mass reconstructed using the angle between the two τ and the **collinear approximation:**

$m_{\tau\tau} = m_{ll} / sqrt(X_1 X_2)$
with $X_i = P_T(l_i)/P_T(\tau_i)$





~5σ combining ll and lh channels in the low mass region with 30 fb^{-1}

$H \to WW(*)$

Interesting for $2M_W < M_H < 2M_Z$ *where all other decay modes are suppressed.*

Signature is $e\mu$ *(or lqq)* $+ E_T^{miss}$.

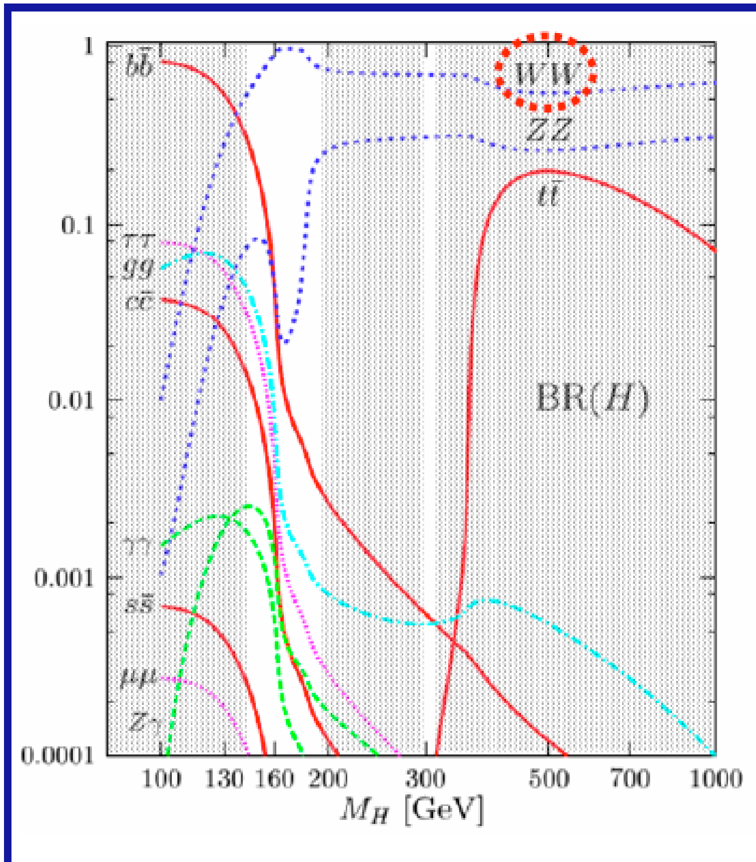
ATLAS

Three channels:

- $- H \to WW \to e\,\nu\,\mu\,\nu$ *(H+0jet)*
- $- H \to WW \to e\,\nu\,\mu\,\nu$
- $- H \to WW \to l\,\nu\,q\,q$
- *(only for* M_H*=300 GeV)*

(the last three lines: *VBF (H+2jet)*)

Measure of spin and CP properties possible for heavy $H \to WW \to lvqq$



Comments:

- No mass peak ➔ use transverse mass. $M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$

- **High backgrounds**: *WW, Wt, ttbar, Z➔2l, bb,cc,QCD multijet*

CMS: ee, μμ, eμ final states have been analyzed
ATLAS: ee, μμ analysis in preparation

$H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

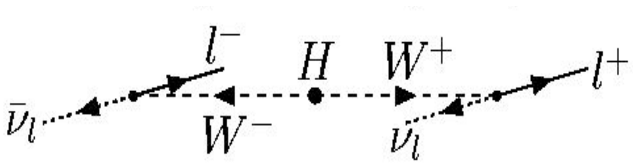
gg → H → W W*
→ ℓν ℓν

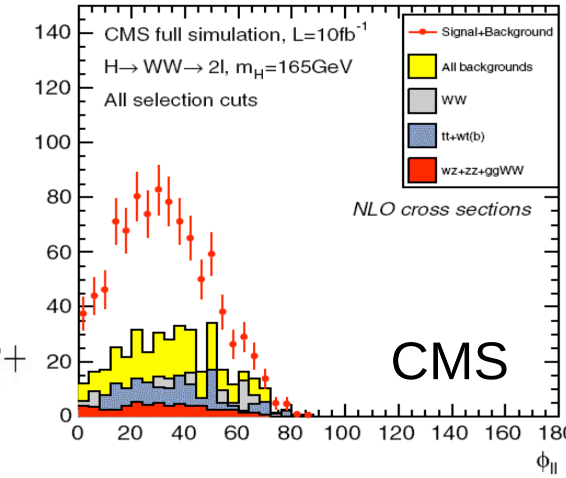
M. Dittmar and H. Dreiner
arXiv:hep-ph/9608317v1

qq H → qq W W*
→ qq ℓν ℓν

- Large H → WW BR for m_H ~ 160 GeV/c^2
- Neutrinos → no mass peak,
- Large backgrounds: WW, Wt, tt
- Two main discriminants:

(i) Lepton angular correlation



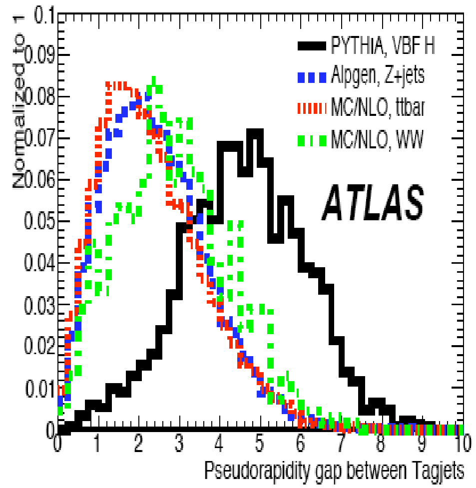


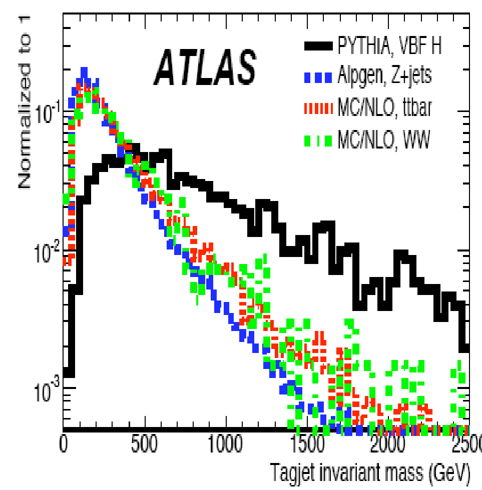
Selection criteria:
- Lepton P_T cuts and tag jet requirements ($\Delta\eta$, P_T)
- Require large mass of tag jet system
- Jet veto (important)
- Lepton angular and mass cuts

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$

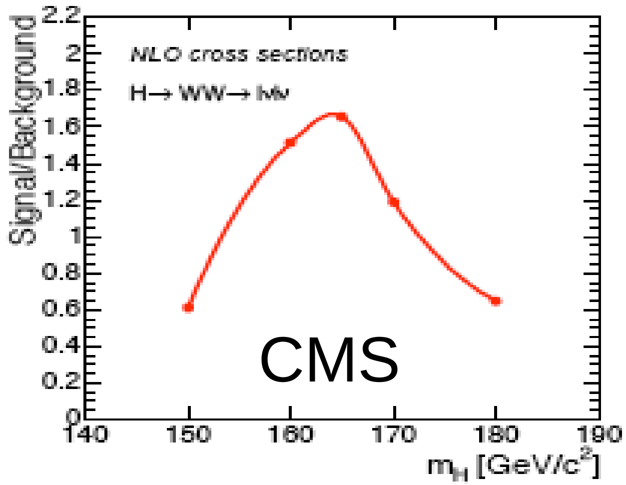
(ii) Jet veto: no jet activity in central detector region

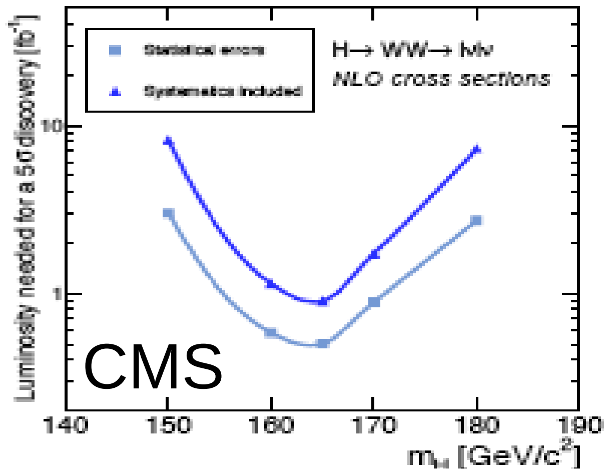
Difficulties:
(i) need precise knowledge of the backgrounds
Strategy: use control region(s) in data, extrapolation in signal region
(ii) jet veto efficiencies need to be understood for signal and background events
→ reliable Monte Carlo generators, data driven-background normalizations

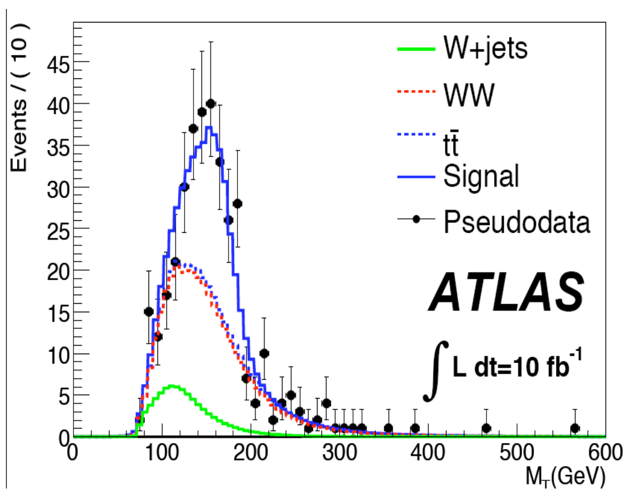


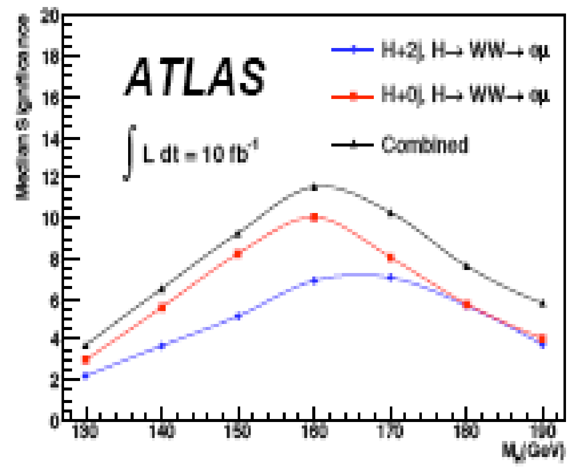


$H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$





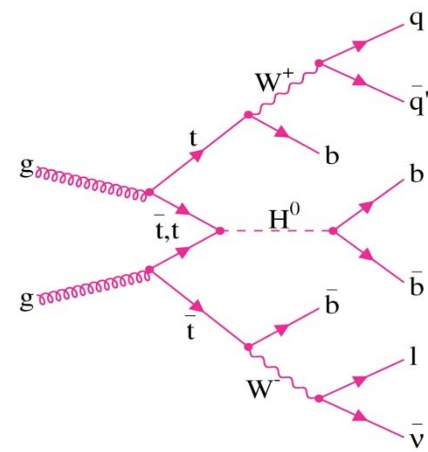




Significance > 5σ @ 10 fb^{-1}

ttH → ttbb

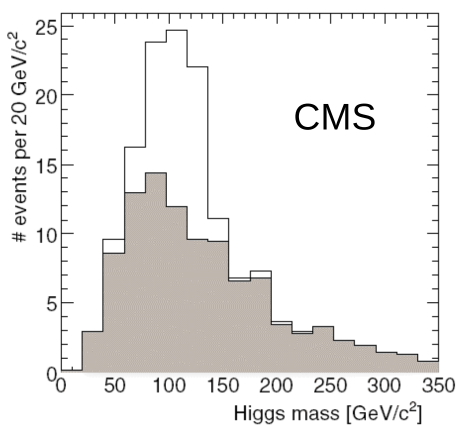
Complex final states: $H \to bb$, $t \to bjj$, $t \to b\ell\nu$
$t \to b\ell\nu$, $t \to b\ell\nu$
$t \to bjj$, $t \to bjj$



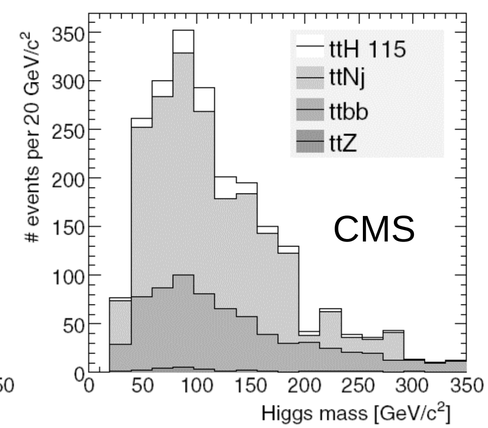
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds → larger backgrounds (ttjj dominant), experimental + theoretical uncertainties, e.g. ttbb, exp. norm. difficul. Maybe some hope in the highly boosted regime …

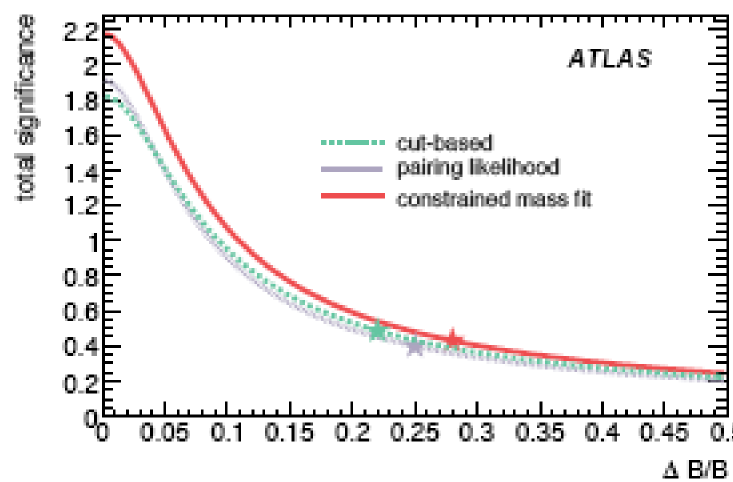
M (bb) after final cuts, 60 fb^{-1}



Signal events only

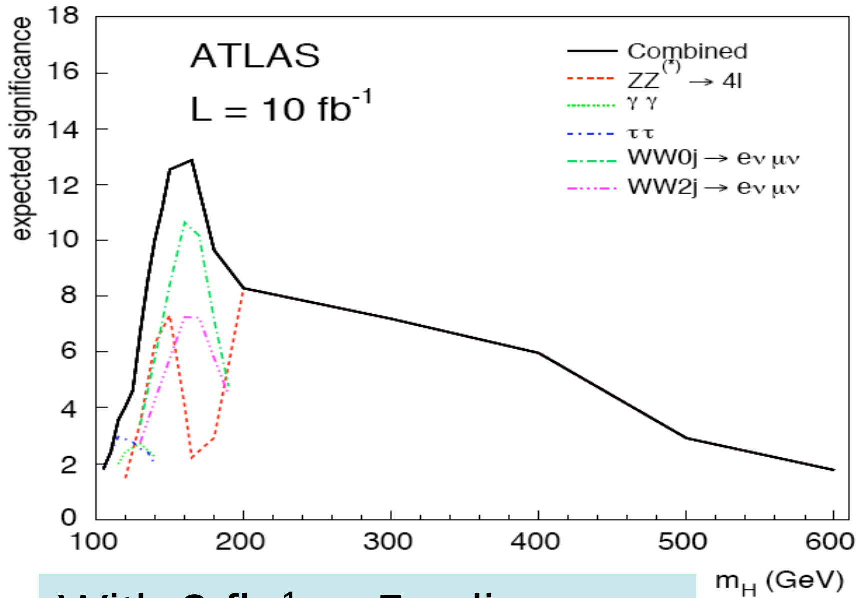


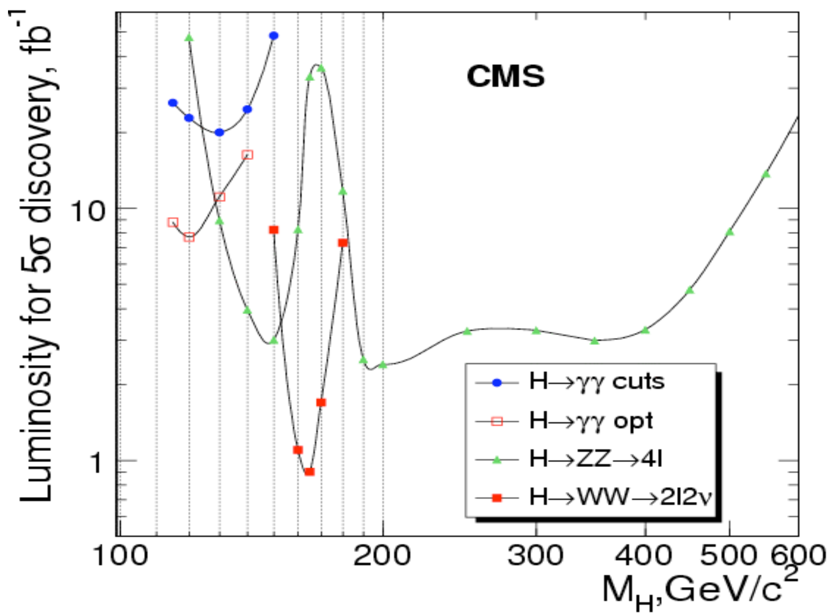
…. backgrounds added



Signal significance as function of background uncertainty

LHC discovery potential





With 2 fb^{-1}, > 5σ discovery in 143 < m_H(GeV) < 179

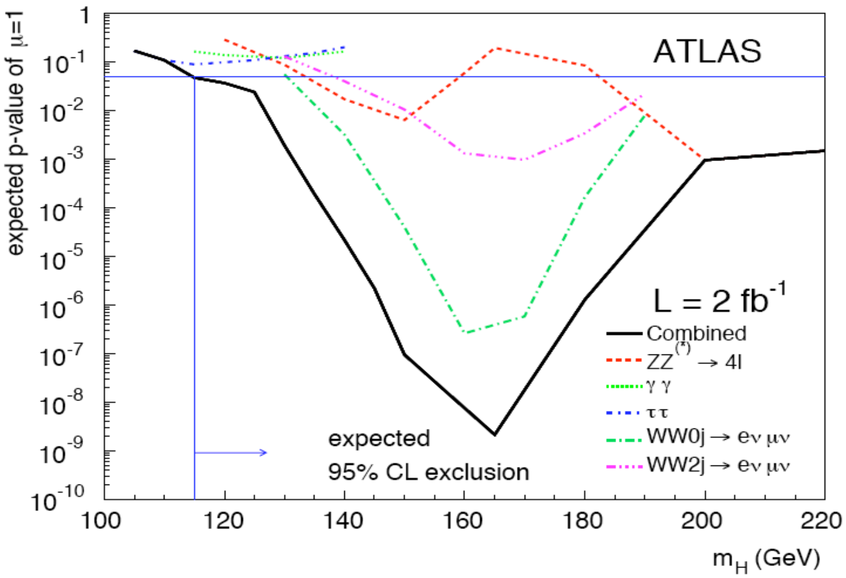
- Full mass range can already be covered after a few years at low luminosity
- Similar performance in ATLAS
- Several channels available over a large range of masses

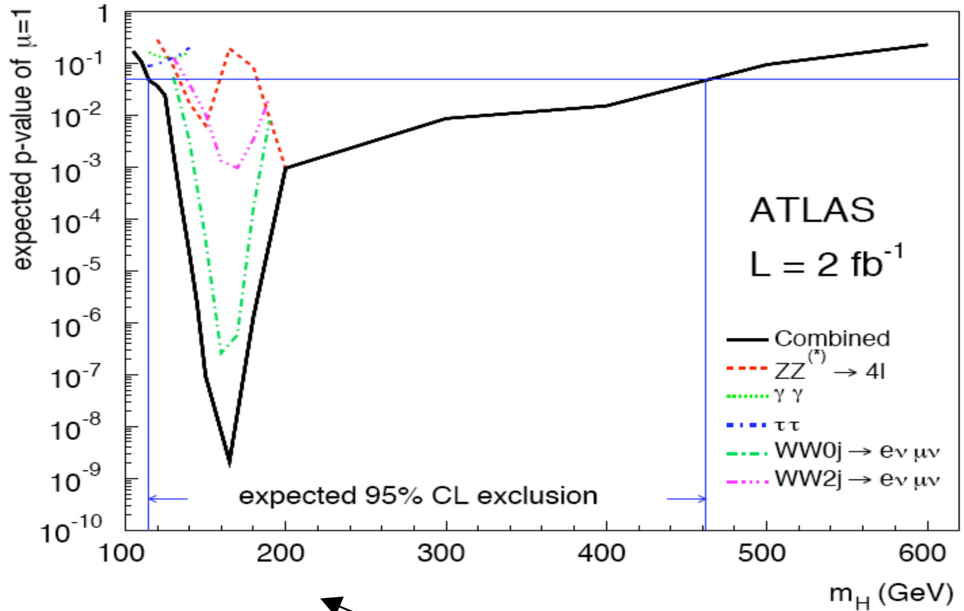
Vector boson fusion channels play an important role at low mass !

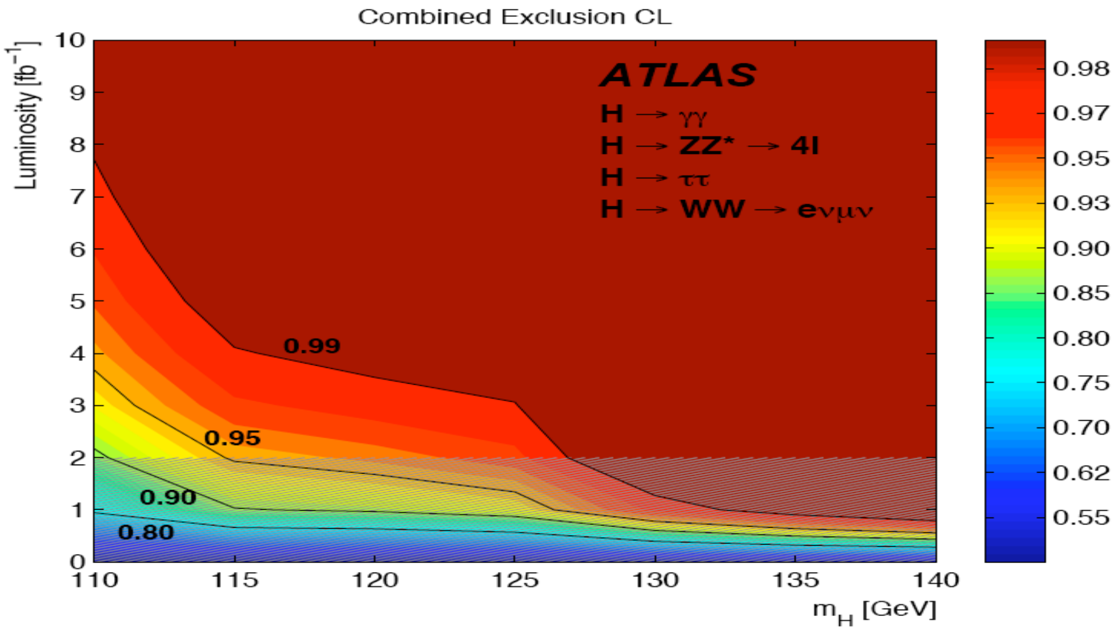
Important changes w.r.t. previous studies:

- **H $\rightarrow \gamma\gamma$** sensitivity of ATLAS and CMS comparable
- **ttH $\rightarrow$ tt bb** disappeared in both ATLAS and CMS studies

Combined Exclusion Limit



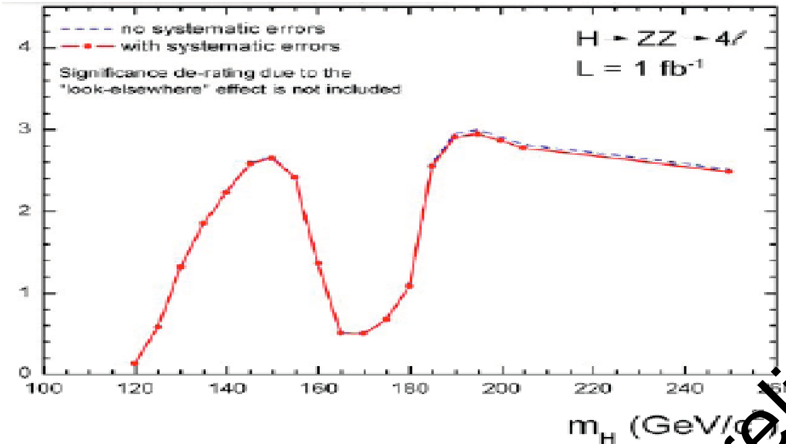


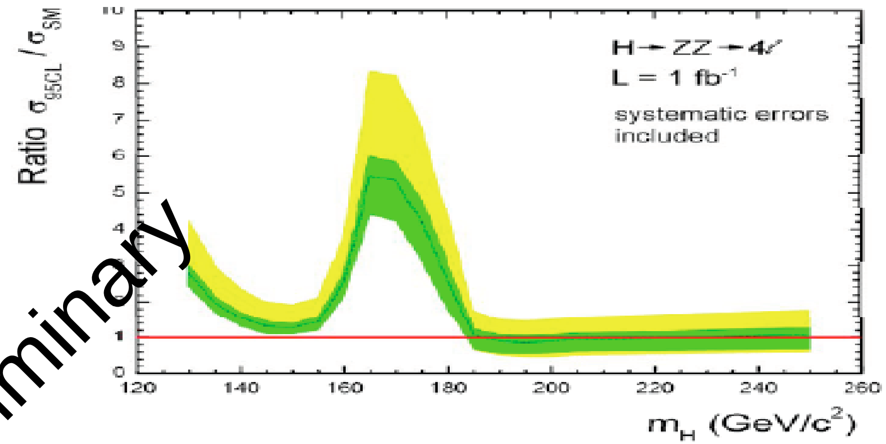


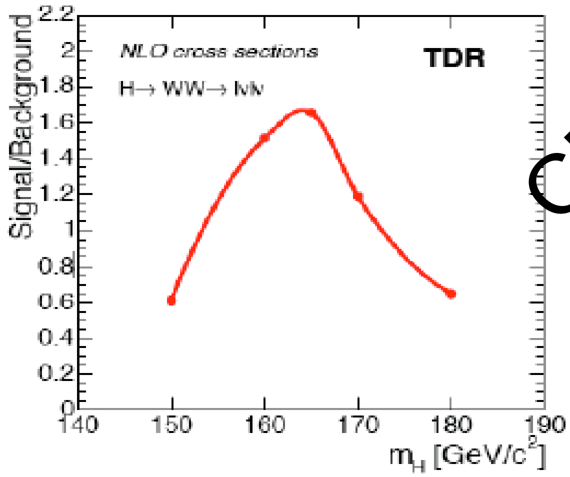
$m_H > 115$ GeV at 95% CL with 2 fb^{-1}

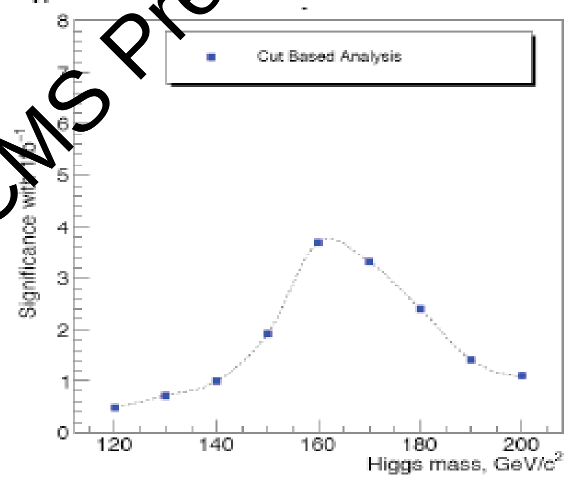
Luminosity required for exclusion as function of m_H

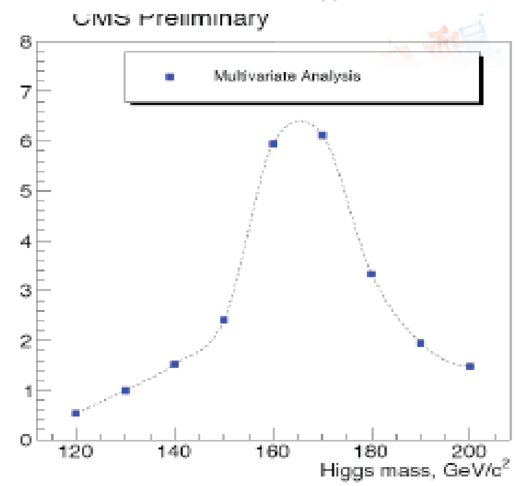
Update







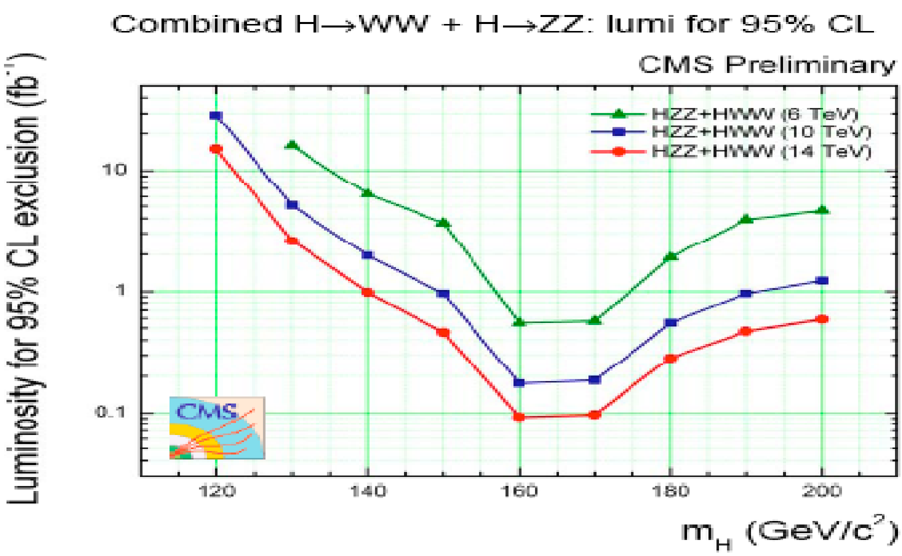




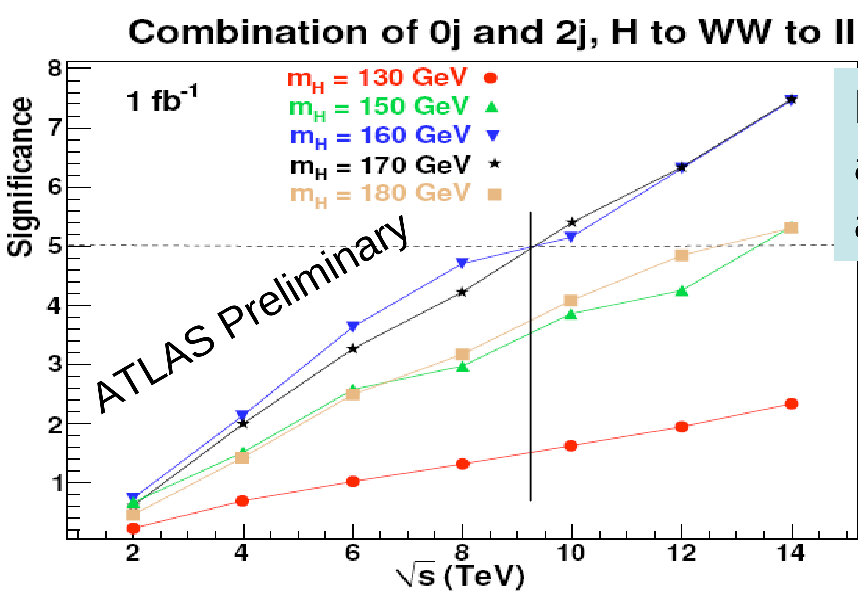
With 1 fb^{-1}, exclude SM-like Higgs with m_H>185 GeV in the 4l channel

With 1 fb^{-1}, 5σ discovery around m_H=160 GeV in $H \to WW \to ll\nu\nu$ channel

Input to Charmonix Workshop



Luminosity needed for 95% CL exclusion at 10 TeV (m_H~160 GeV): 0.2 fb^{-1}



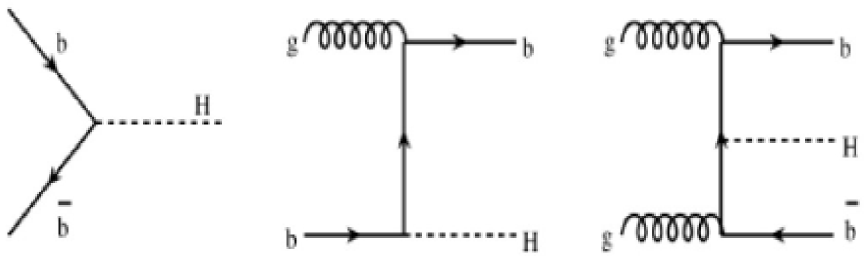
Fast Simulation and simplified analysis

> 5σ possible for m_H~160 GeV at 10 TeV and ~1fb^{-1} good data

Extended Higgs Sector

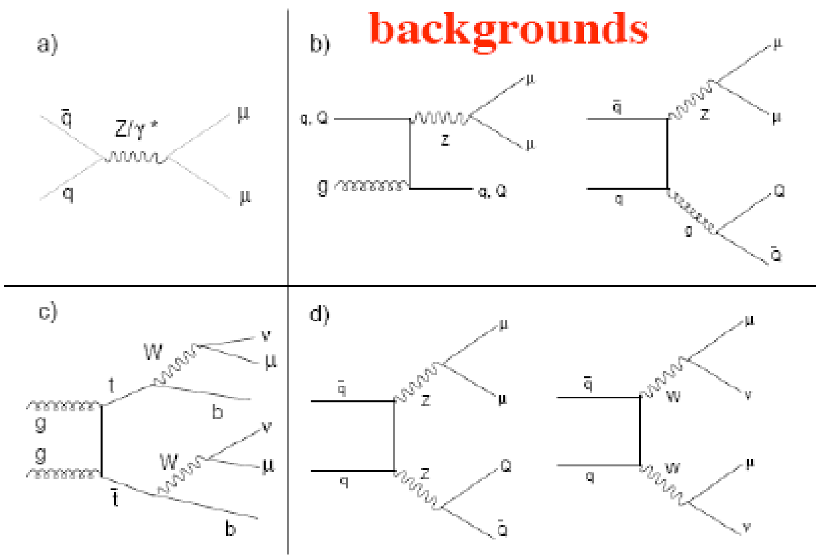
A/H → μμ

At high tanβ the associated production with a *b* quark is enhanced respect to gluon gluon fusion



- Decay prohibited in *SM*
- Enhanced in *MSSM*
- Clear signature!
- Direct mass measurement (no E_T^{miss})!

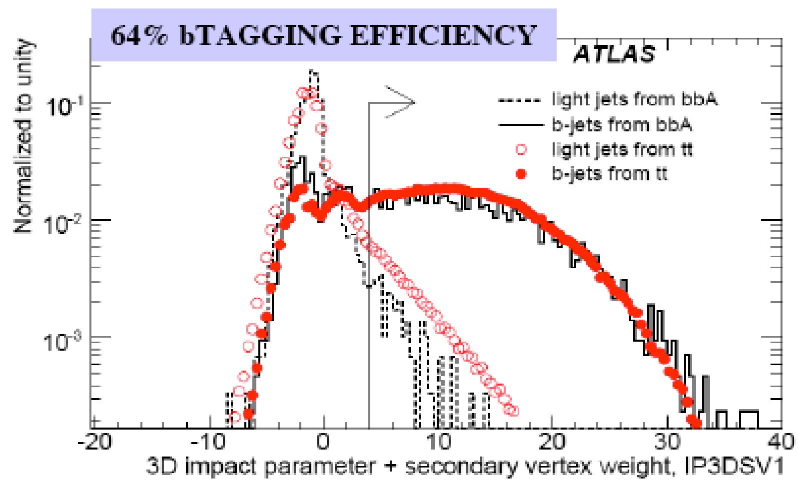
backgrounds



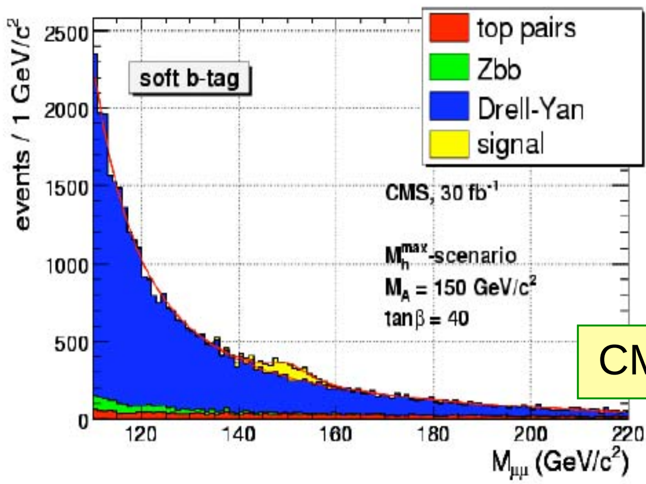
WW and ZZ backgrounds are expected small.

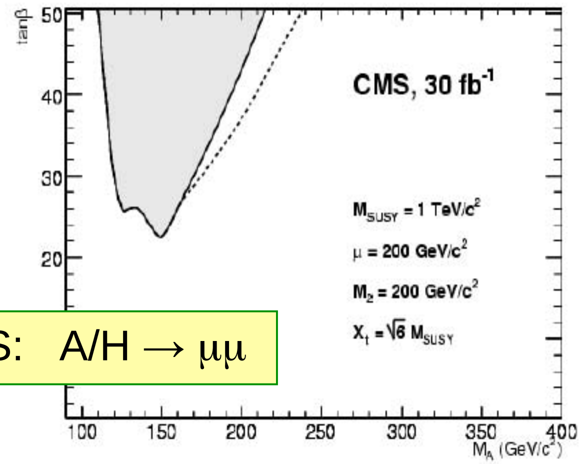
Background rejection:

- Additional jet required => kill Drell-Yan
- muon isolation
- b tagging (based on longitudinal impact parameter and secondary vertex)
- reject large E_T^{miss} (against ttbar)
- jet vetos



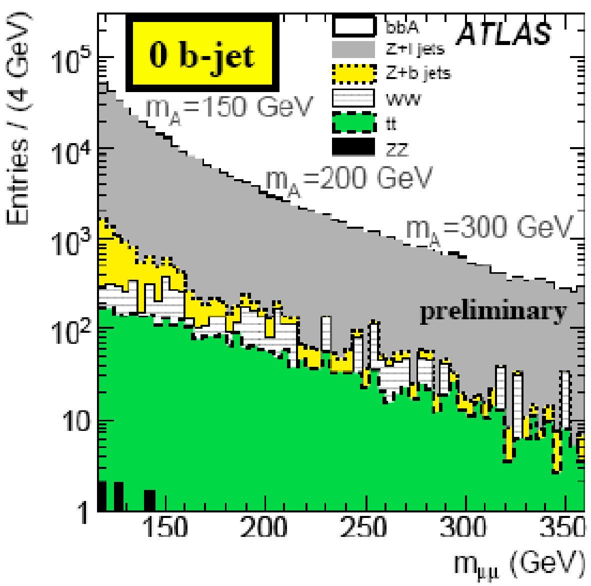
A/H → μμ



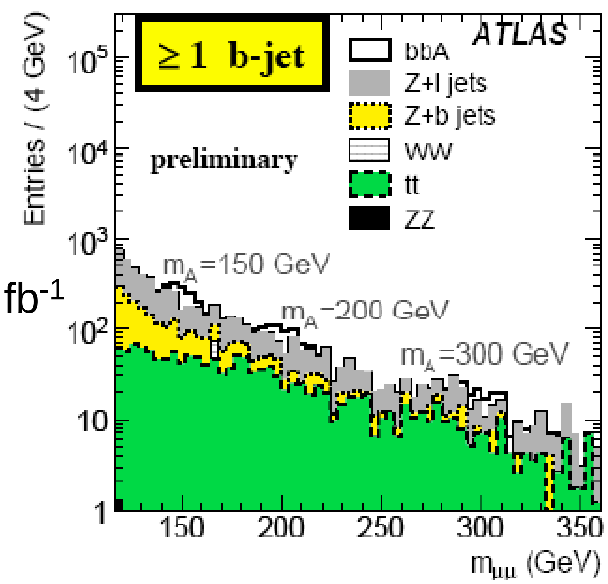


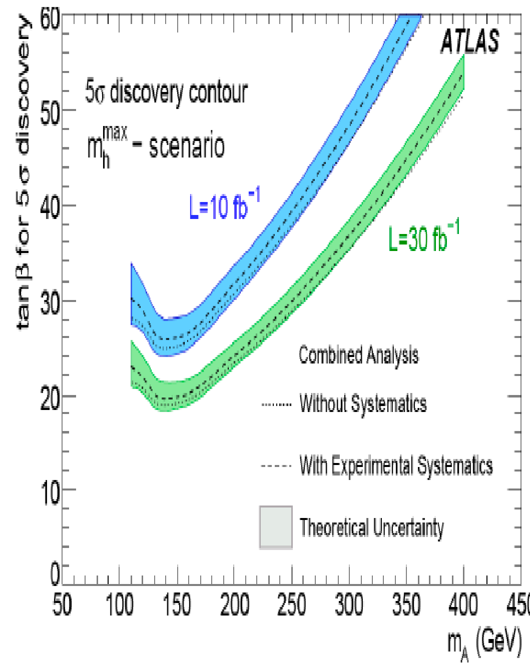
CMS: A/H → μμ

Excellent dimuon mass resolution essential. Measure width and tan(beta)



30 fb^{-1}





H →ττ (→ ll)

SELECTION.

•**Trigger**: isolated *μ(e)* with p_T>20 (25)GeV || two isolated *e* || or one *e* & one *μ*

• **b-tagging** on at least one jet to suppress light jets

• Cuts on *missing E_T , b momentum , lepton momentum, number of jets* (<3) to reject *Z* and *tt* backgrounds

• **Collinear approximation**

BACKGROUNDS:

•*Drell-Yan*

•*Z→ee*

•*Z→ττ*

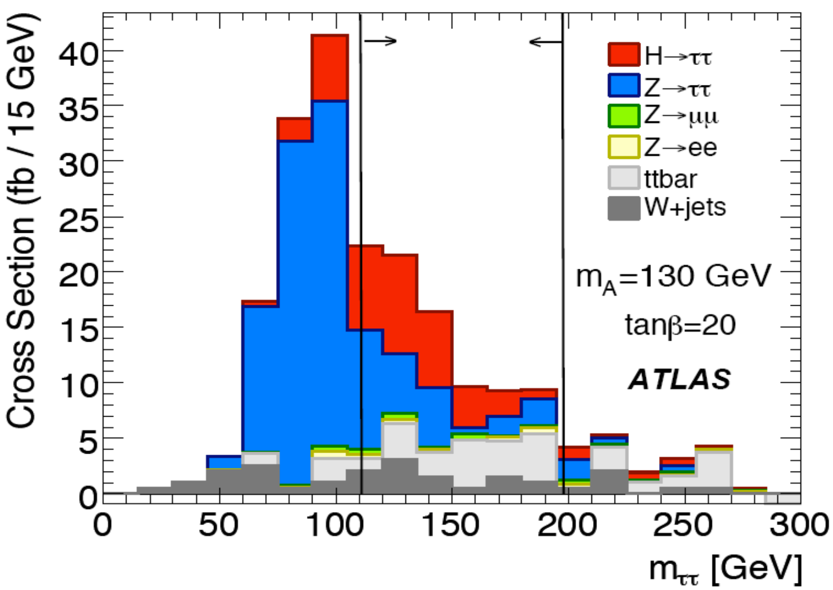
•*tt*

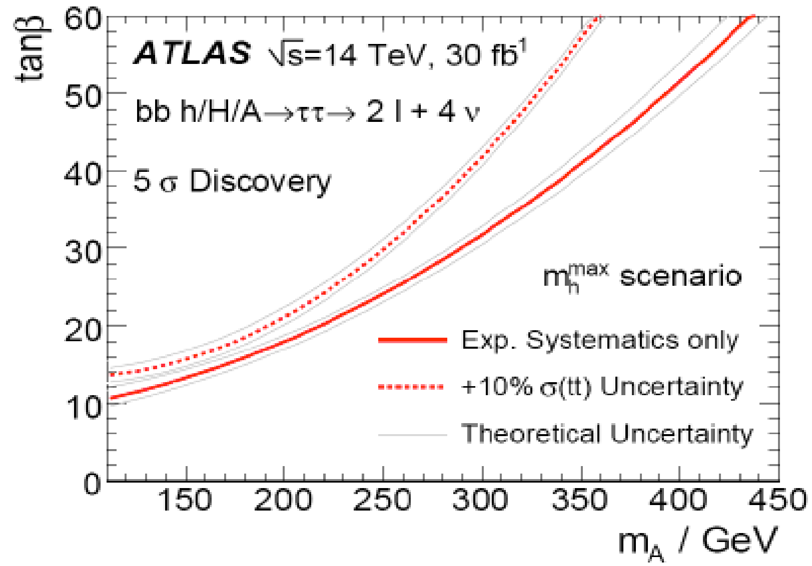
•*W jets*

Z estimated from data!

• **Studies ongoing on hadronic τ decay mode**

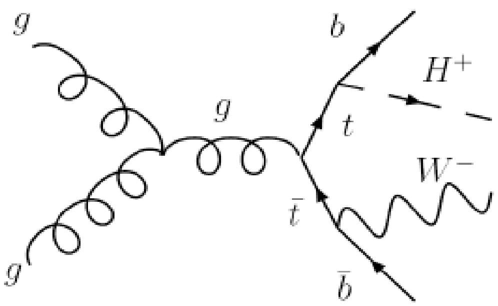
• **Mass reconstruction as for *SM VBF H→ ττ***





Charged Higgs

m(H⁺) < m(top)



$t\bar{t} \rightarrow bH^{+}bW \rightarrow b\tau(had)\nu b\ell\nu$

$t\bar{t} \rightarrow bH^{+}bW \rightarrow b\tau(lep)\nu bqq$

$t\bar{t} \rightarrow bH^{+}bW \rightarrow b\tau(had)\nu bqq$

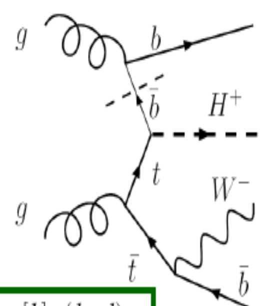
DECAY MODES:

$H^{+} \rightarrow \tau\nu$

$H^{+} \rightarrow tb$

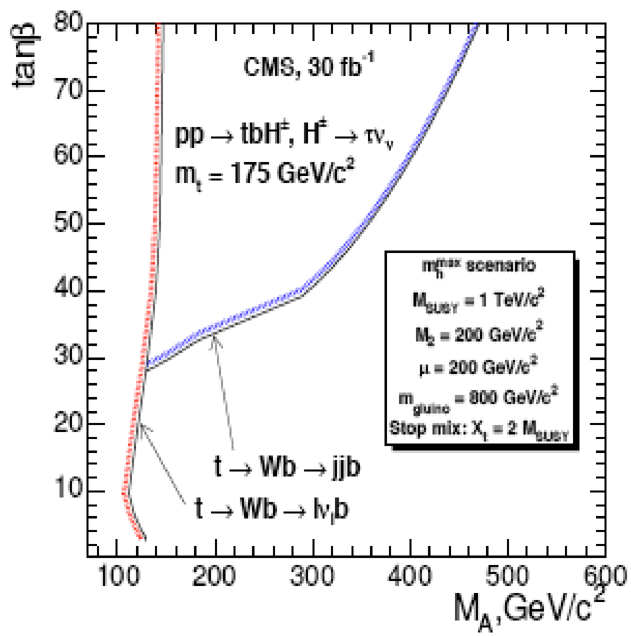
- High tanβ well covered already with 10 *fb*$^{-1}$
- Intermediate region hard to reach (only exclusion)

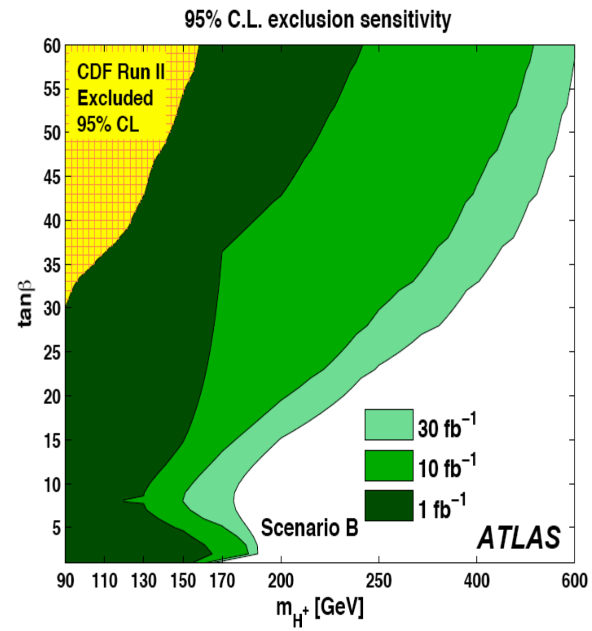
m(H⁺) > m(top)



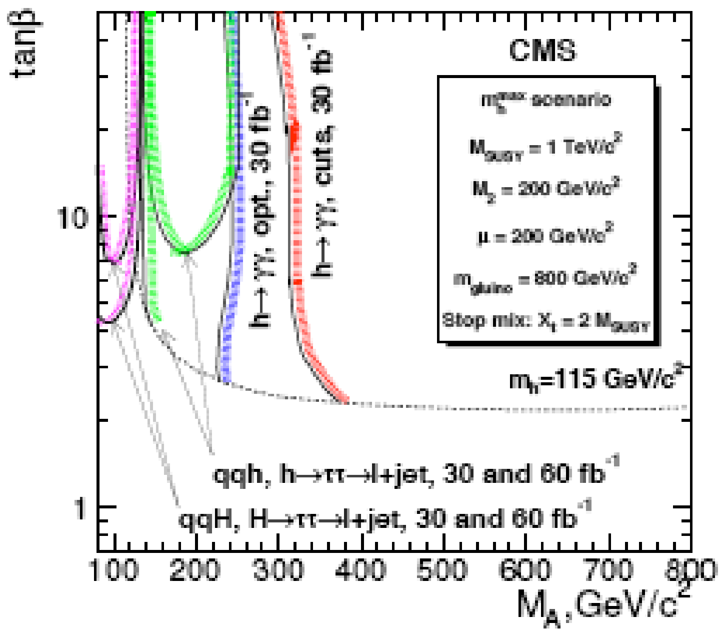
$gg/gb \rightarrow t[b]H^{+} \rightarrow bqq[b]\tau(had)\nu$

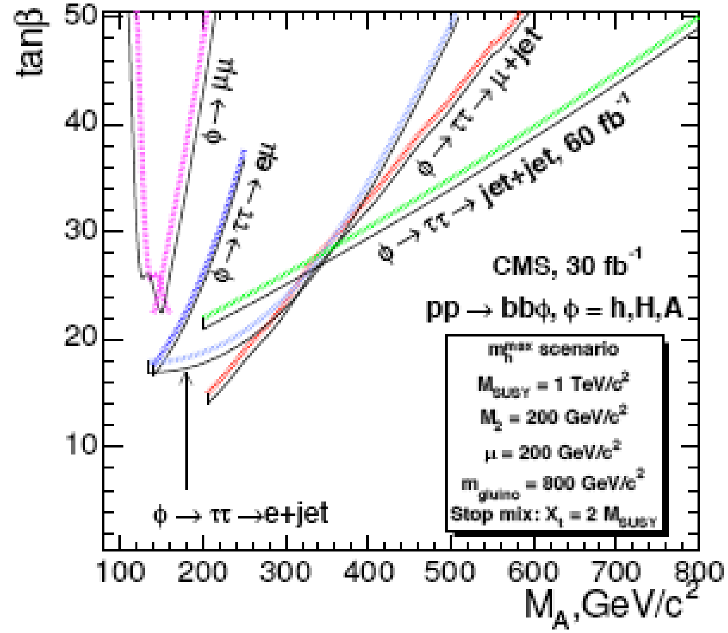
$gg/gb \rightarrow t[b]H^{+} \rightarrow t[b]tb \rightarrow bW[b]bWb \rightarrow b\ell\nu[b]bqqb$

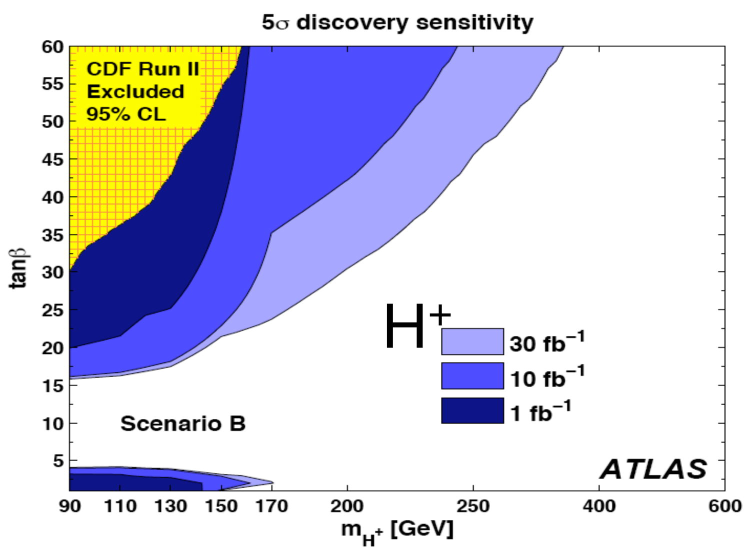




MSSM discovery potential

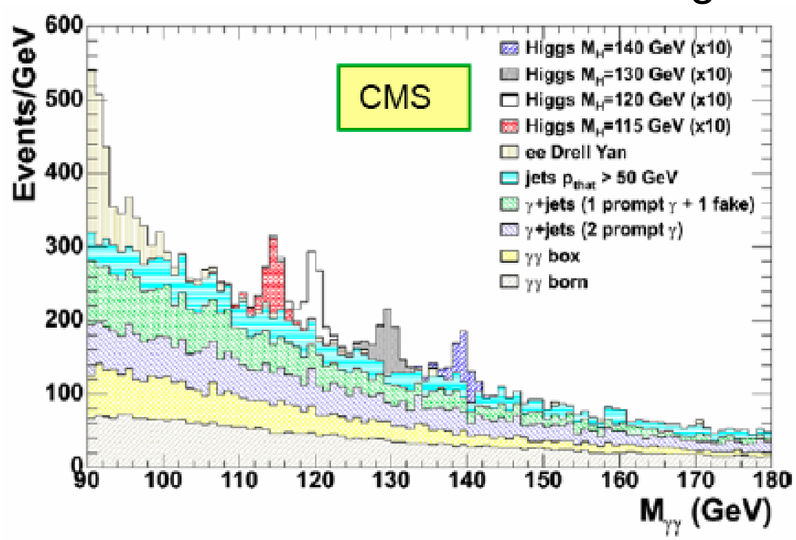


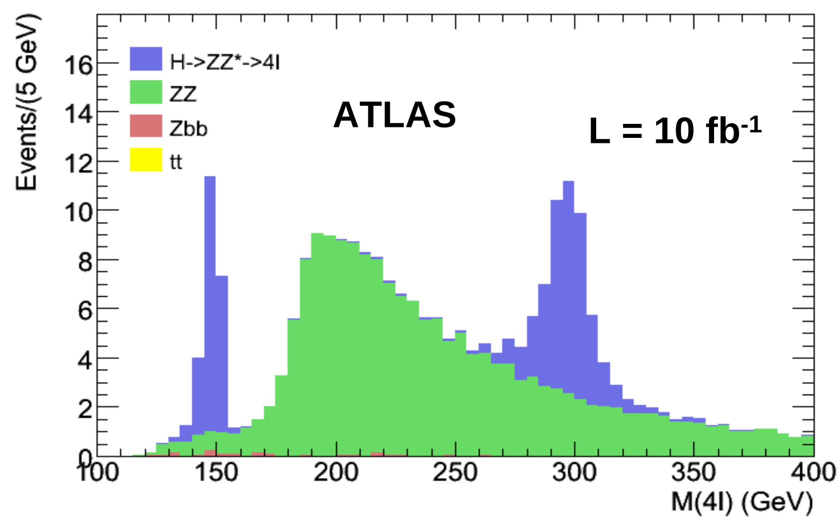




Higgs mass measurements

- The mass value itself is important for precision tests of the Standard Model, but moderate precision seems to be adequate; (as compared to the anticipated m_t and m_W uncertainties)
- In addition: the Higgs mass value is important for the extraction of ratios of couplings)
- Higgs boson mass measurement dominated ZZ→4l and γγ resonances
  – Well identifiable with good resolution

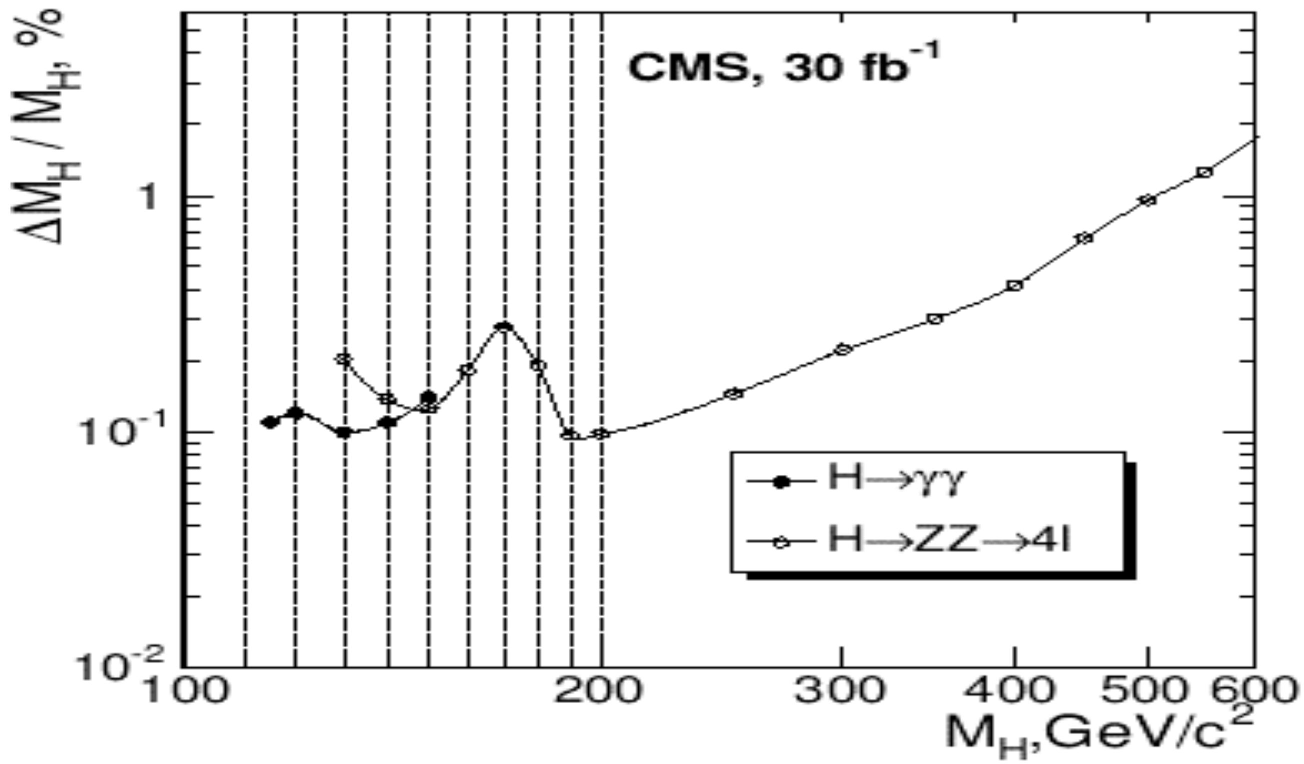




γ/lepton energy scale - assume 1‰ (ultimately 0.2‰)

– Lepton energy scale from Z→ll (close the light Higgs)

Higgs mass measurements



Precision below 1% can be achieved over a large mass range for 30 fb^{-1};
syst. limit can be reached for higher integrated luminosities → 100 fb^{-1}
Note: no theoretical errors, e.g. mass shift for large Γ_H (interference resonant/non-resonant production) taken into account

Higgs mass measurements

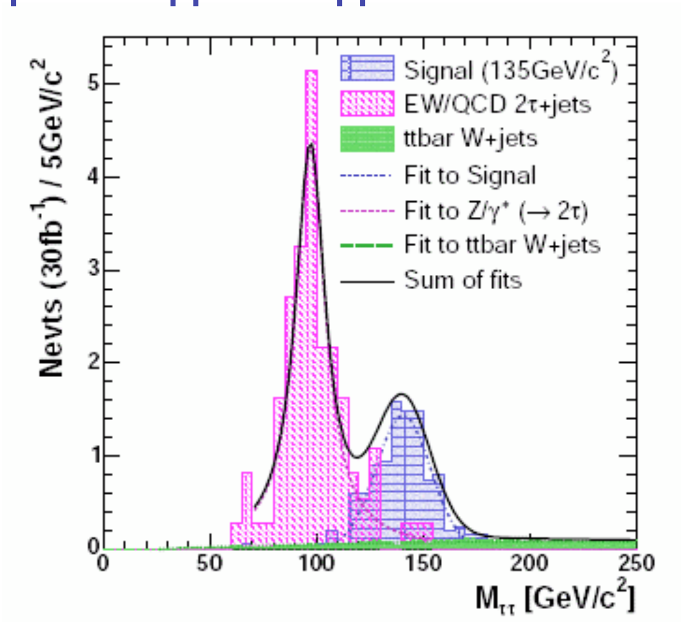
In case of exotic Higgs boson couplings (e.g. suppressed $H \rightarrow WW / ZZ$ couplings) the situation is more difficult

(even the $\gamma\gamma$ decay mode would be affected, since the WW loop contribution is dominant)

Remaining channels at low mass: $H \rightarrow \tau\tau$

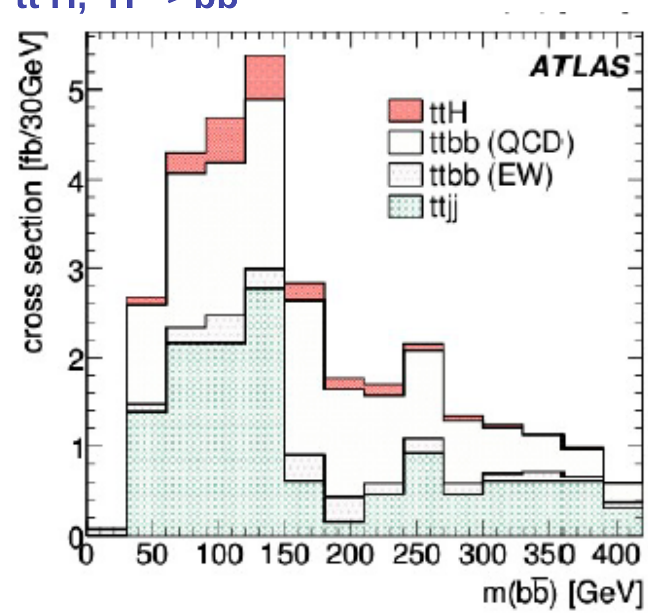
$H \rightarrow bb$ (difficult S:B situation, difficult as a discovery channel;
mass value is most likely needed to extract a signal,
if background and mass known, it might be useful and
add to coupling measurements)

qq H → qq ττ → qq ℓνν had ν

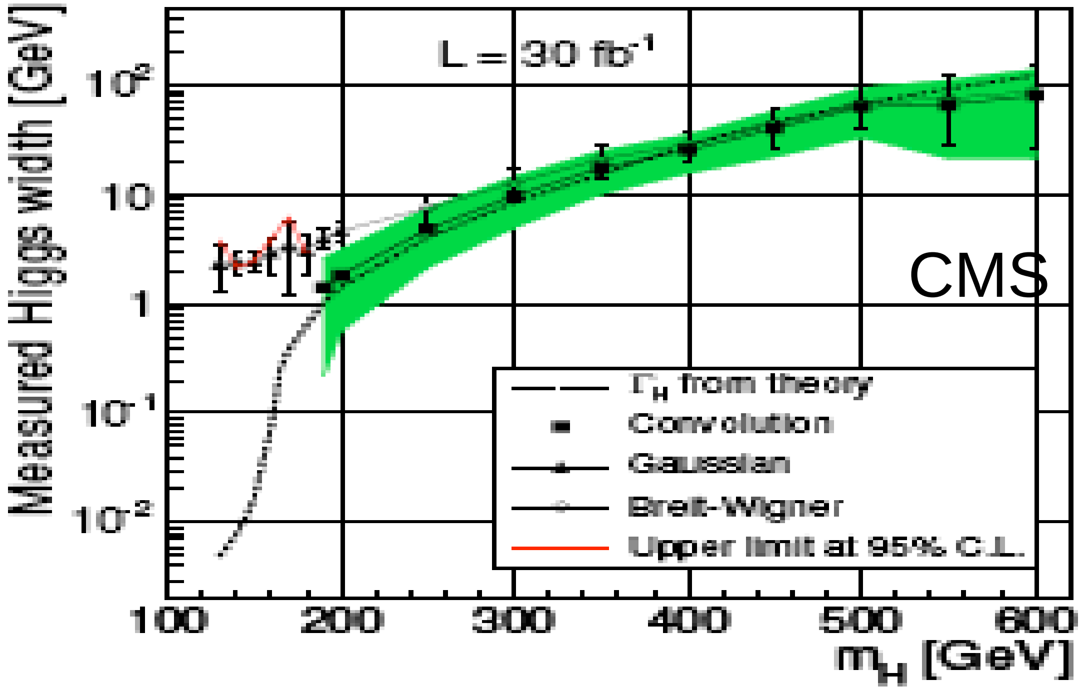


Requires good understanding of
the detector (τ, E_T^{miss}), resolution limited

tt H, H → bb



Higgs Width measurements



Total width, Γ_H, cannot be measured below ~ 200 GeV - detector resolution; An upper limit of a few GeV could be set.

Above ~200 GeV intrinsic width could be measured with a precision of ~35% with 30 fb^{-1} (one experiment)

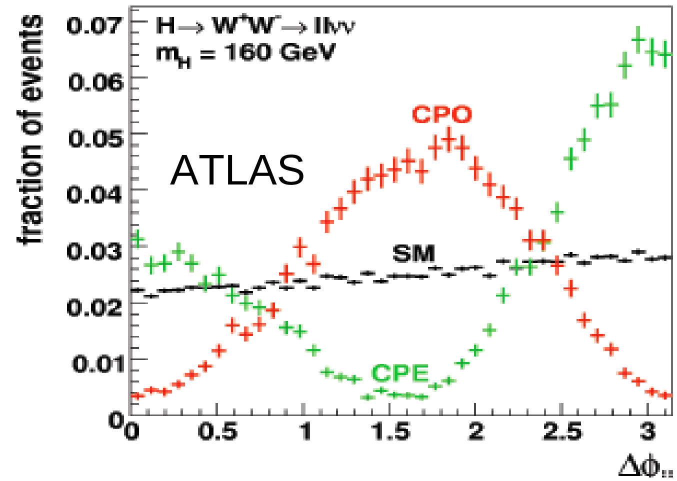
Spin/CP measurements

- General parametrization of the coupling of a scalar to vector bosons:

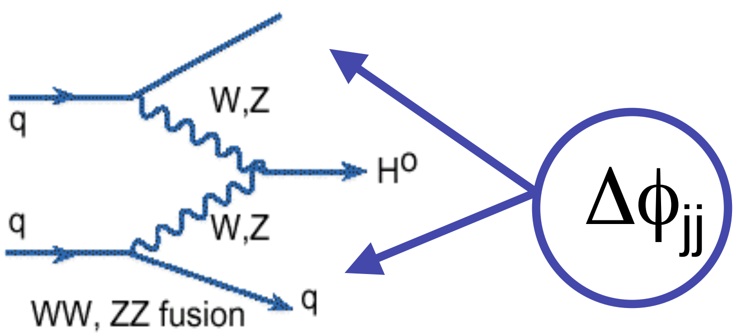
T.Plehn,D.Rainwater and D.Zeppenfeld Phys Rev Lett 88,051801,2002
T.Figy and D.Zeppenfeld Physics Letters B 591 (2004) 297-303
V.Hankele,G.Klamke,D.Zeppenfeld and T.Figy Phys.Rev.D74:095001,2006
C.Ruwiedel,M.Schumacher and N.Wermes Eur.Phys.J.C51:385-414,2007

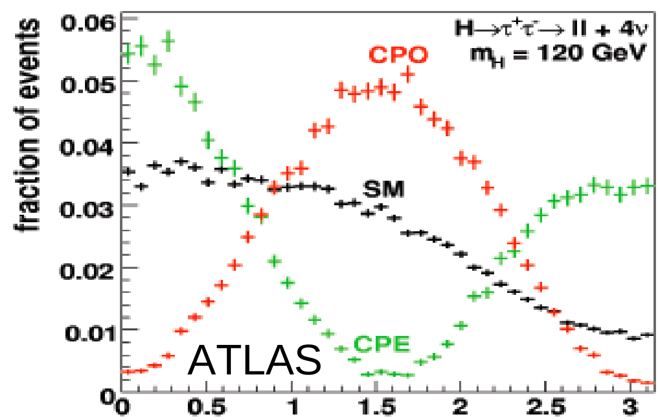
$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)g^{\mu\nu} + a_2(q_1,q_2)[q_1\cdot q_2 g^{\mu\nu} - q_2^{\mu}q_1^{\nu}] + a_3(q_1,q_2)\varepsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}.$$

SM (a_1 term), CPE (a_2 term), CPO (a_3 term)



- Contributions and admixtures can be determined in VBF using the $\Delta\phi$ distribution between the two tag jets





Eur. Phys. J. C51:385-414

Spin/CP measurements

Anomalous CP-even and CP-odd couplings in VBF

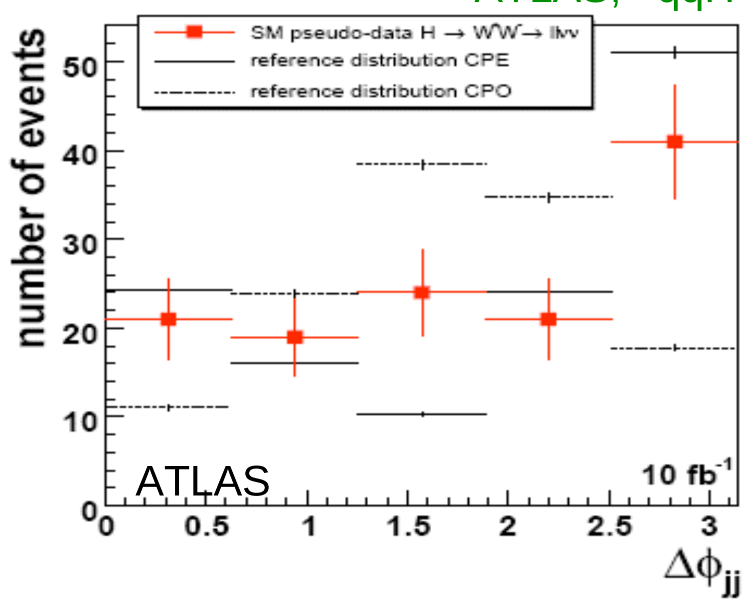
- ATLAS study using the qqH → qqWW and qqH → qq ττ channels:

  C.Ruwiedel, M.Schumacher and N.Wermes, Eur. Phys. J. C51 (2007) 385

- Apply typical VBF selection cuts: central leptons
  two tag jets: M_{jj}, P_T

After (fast) detector simulation

ATLAS, qqH → qqWW, L = 10 fb^{-1}



Expectations:

CPE* and *CPO anomalous couplings:

- with *10 fb^{-1}* can be excluded at 5σ in $H \to WW \to ll\nu\nu$ for m_H=*160 GeV* .
- with *30 fb^{-1}* can be excluded at 2σ in $H \to \tau\tau$ for m_H=*120 GeV*.

Summary

- **Exclusion**
  - With 2 fb^{-1} (one experiment), exclude SM-like Higgs with m_H>115 GeV, if it does not exist
- **Higgs Searches**
  - ATLAS and CMS are well-prepared to discover Higgs bosons. The SM mass range and the MSSM parameter space are well covered
  - With 1-2 fb^{-1}, discovery possible in $H \to WW \to ll\nu\nu$ depending on m_H. > 5σ discovery possible in 143 < m_H(GeV) < 179
  - With 10 fb^{-1}, normally 1 year of low luminosity operation, discovery possible for $m_H \in$ [120, 500] GeV
- **Higgs Mass Measurement - needs more than 10 fb^{-1}**
  - Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and $ZZ \to 4\ell$ resonances
- **Spin and CP**
  - Angular correlations in $H \to ZZ(*) \to 4\ \ell$ and $\Delta\phi_{jj}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

BACKUP

Summary (cont.)

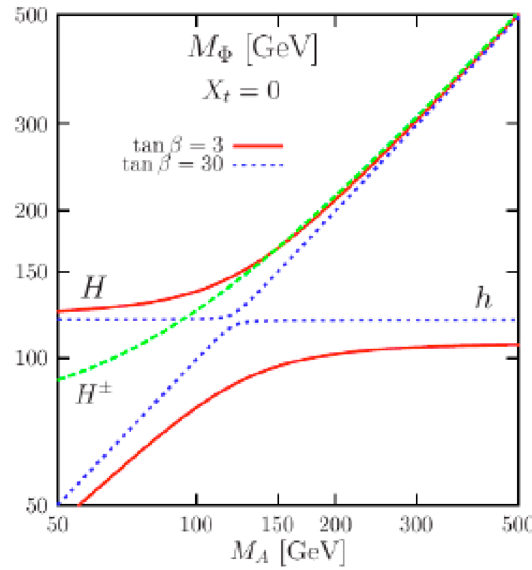
- **Couplings to bosons and fermions - need more than 10 fb^{-1}**
  - Ratios of major couplings can be measured with reasonable precision;
  - Absolute coupling measurements need further theory assumptions (Methods established, exp. updates are needed, in particular for VBF channels at high luminosity)
- **Higgs self coupling**
  - No measurement possible at the LHC; Very difficult at the sLHC, there might be sensitivity in HH → WW WW for m_H ~ 160 GeV. Situation needs to be re-assessed with more realistic simulations, timescale unknown

MSSM Higgs

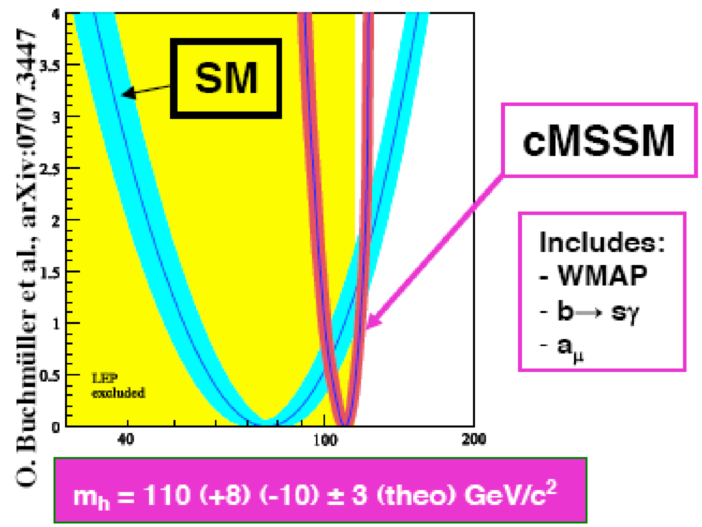
- **One doublet of Higgs pseudo-scalar fields is replaced with two:**
  - **One couples to up-fermions and has $vev=v_u$**
  - **One couples to down fermions and has $vev=v_d$**

- **2X4-3=5 physical scalar fields/particles: $h, H, A, H^{\pm}$**

- **Properties at tree level:**
  - **fully defined by 2 free parameters: m_A, $\tan\beta=v_u/v_d$**
  - **CP-odd A:**
    never couples to Z or W;
    decays to bb, $\tau\tau$ (and additionally tt for small $\tan\beta$).
  - **CP-even h and H:**
    SM-like near their mass limits vs m_A;
    at large $\tan\beta$ enhanced coupling with down fermions,
    suppressed couplings to W and Z.
  - **$H^{\pm}$ "strongly" couples to tb and $\tau\nu$**
  - **All Higgs bosons are narrow (Γ<10GeV)**



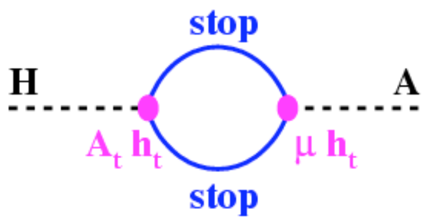
We choose the benchmark scenario m_h^{max} corresponding to maximal theoretically allowed region for m_h.

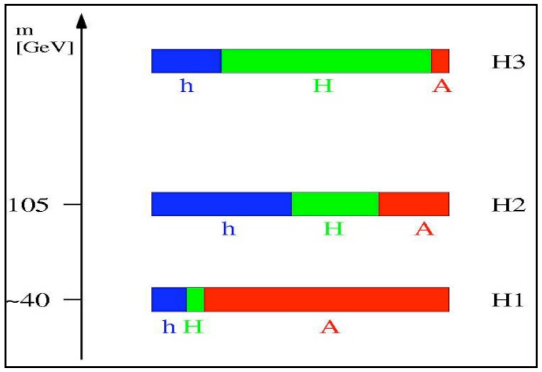


….watch the low mass region !

Higgs search at the LHC in CP-violating scenarios

- Tree level CP of Higgs Potential in MSSM may be violated sizably at higher orders by loop effects involving CP-violating interactions of Higgs to stop and sbottom





- CP eigenstates h, A, H mix to mass eigenstates H_1, H_2, H_3

- Effect maximized in a defined benchmark scenario (CPX)

(M. Carena et al., Phys.Lett. B 495 155 (2000))

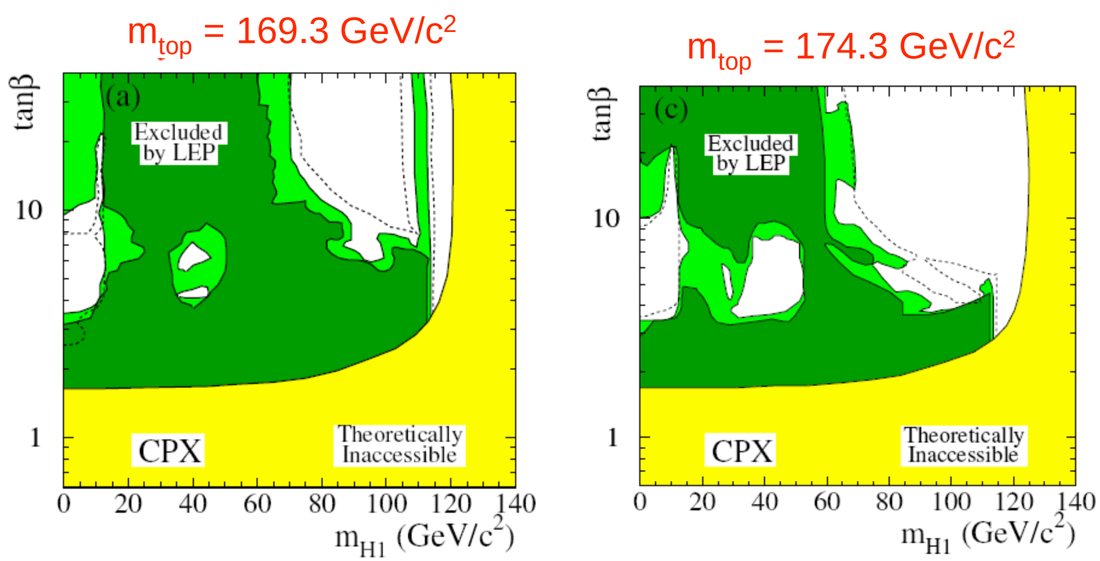
$\arg(A_t) = \arg(A_b) = \arg(M_{gluino}) = 90^o$

- No lower mass limit for H_1 from LEP !

(decoupling from the Z)

details depend on m_{top} and on theory model

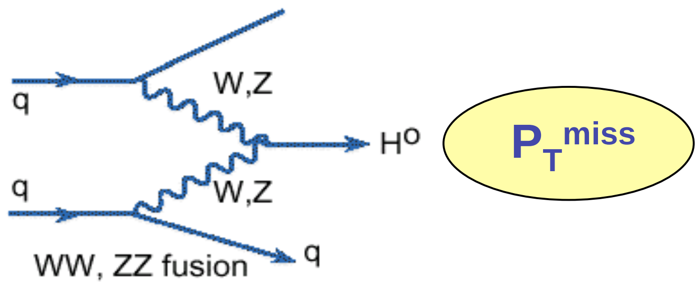
(FeynHiggs vs. CPsuperH)



Invisible Higgs decays ?

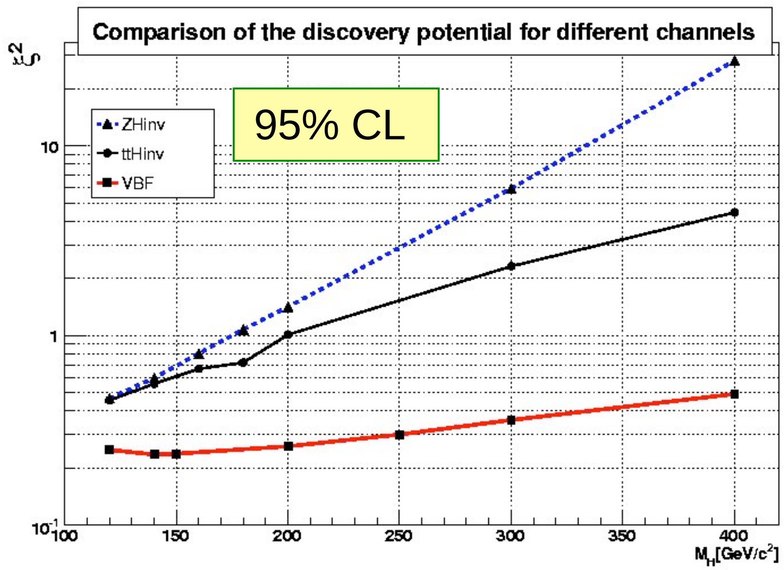
Possible searches: tt H → ℓνb qqb + P_T^{miss}
Z H → ℓℓ + P_T^{miss}
qq H → qq + P_T^{miss}

- J.F. Gunion, Phys. Rev. Lett. 72 (1994)
- D. Choudhury and D.P. Roy, Phys. Lett. B322 (1994)
- O. Eboli and D. Zeppenfeld, Phys. Lett. B495 (2000)



All three channels have been studied:
key signature: excess of events above SM backgrounds with large P_T^{miss} (> 100 GeV/c)

Sensitivity: $$\xi^2 = Br(H \rightarrow Inv.)\frac{\sigma_{qq\rightarrow qqH}}{\sigma_{qq\rightarrow qqH}|_{SM}}$$



ATLAS preliminary

Problems / ongoing work:

- ttH and ZH channels have low rates
- More difficult trigger situation for qqH
- backgrounds need to be precisely known (partially normalization using ref. channels possible)
- non SM scenarios are being studied at present
  first example: SUSY scenario

Invisible Higgs decays ?

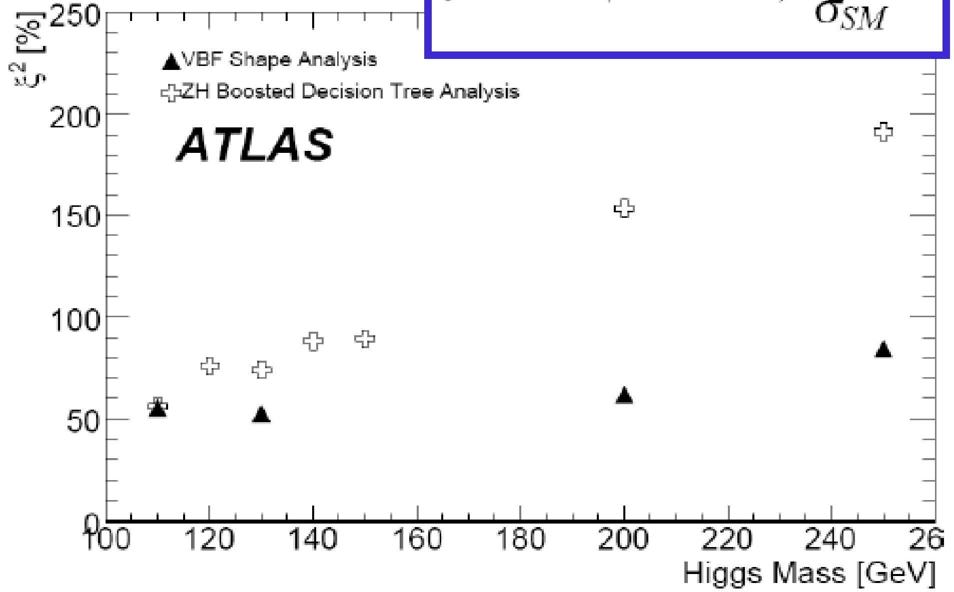
Higgs→Lightest Susy Particle

Two production modes analyzed:

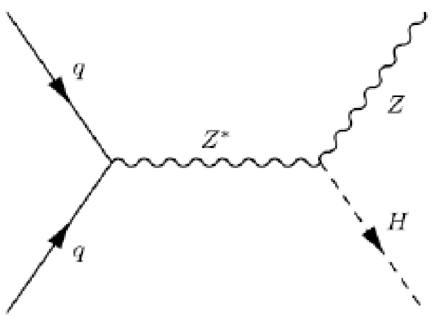
- **Associated production** *ZH*.
  - Background from $ZZ \to ll\nu\nu$.
  - Too much background to analyze *WH*.
- **VBF**.
  - Backgrounds from *QCD-dijets*, *W+jets* and *Z+jets*, when leptons are outside the detector acceptance or $Z \to \nu\nu$.

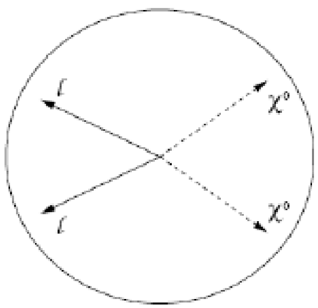
Caution: there could be nonSM backgrounds…
Missing energy is crucial

$$\xi^2 = BR(H \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$



Associated production:
$H \to \chi^0\chi^0$ **recoiling against** $Z \to ll$



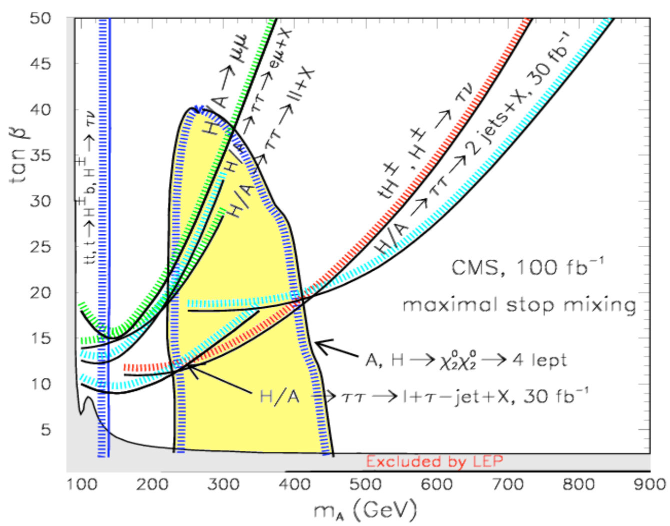


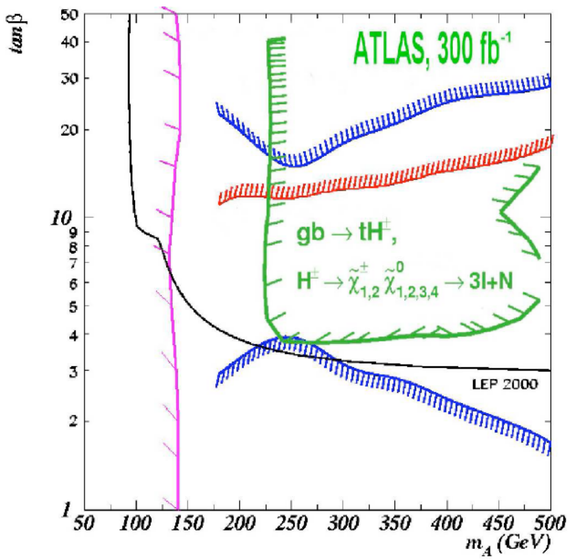
Higgs decays via SUSY particles

If SUSY exists : search for

$H/A \rightarrow \chi^0_2\chi^0_2 \rightarrow \ell\ell\chi^0_1 \; \ell\ell\chi^0_1$

$gb \rightarrow tH^+, \; H^\pm \rightarrow \chi_{2,3}^0 \, \chi_{1,2}^\pm \rightarrow 3\ell + E_T^{miss}$





CMS: special choice in MSSM (no scan)

M_1 = 60 GeV/c^2

M_2 = 110 GeV/c^2

μ = -500 GeV/c^2

ATLAS: special choice in MSSM (no scan)

M_1 = 60 GeV/c^2

M_2 = 210 GeV/c^2

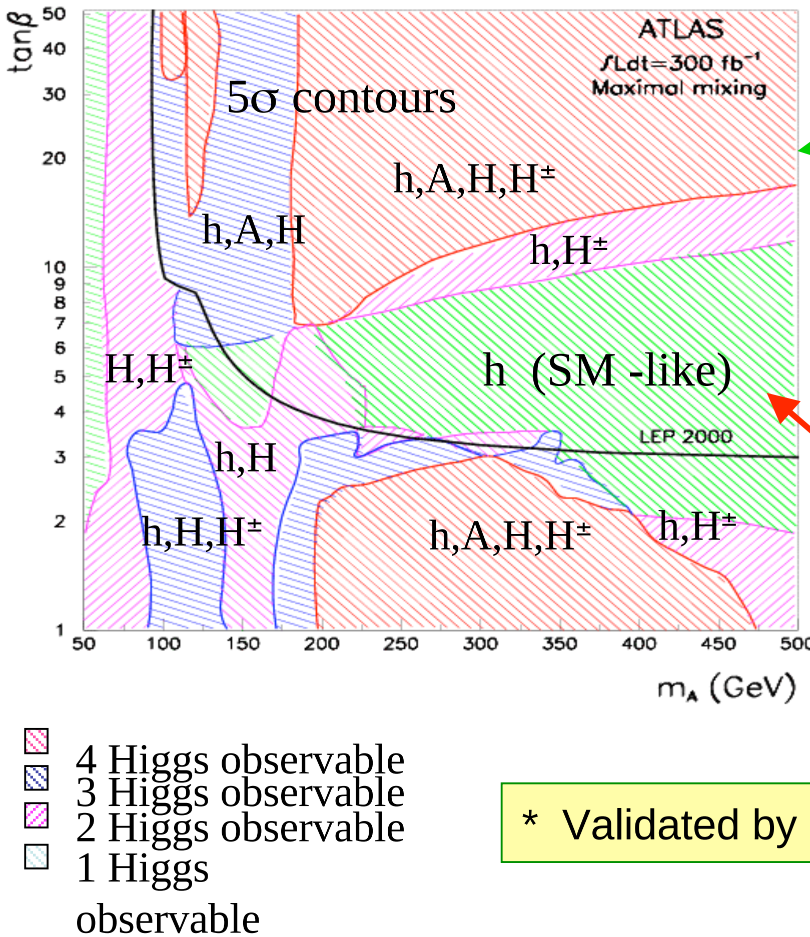
μ = 135 GeV/c^2

m(s-ℓ_R) = 110 GeV/c^2

m(s-τ_R) = 210 GeV/c^2

- Exclusions depend on MSSM parameters (slepton masses, m)
- More systematic studies are needed (initiated by A. Djouadi et al., also started in ATLAS)

Discovery potential for SUSY Higgs bosons



A, H, H± cross-sections ~ $\tan^2\beta$

- best sensitivity from A/H → ττ, H± → τν
  (not easy the first year ....)

- A/H → μμ experimentally easier
  (esp. at the beginning)

Here only SM-like h observable if SUSY particles neglected.

* Validated by recent ATLAS and CMS full simulation studies *

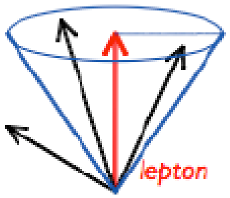
Coverage in the large m_A wedge region can be improved (slightly) by:

- Higher luminosity: sLHC
- Additional SUSY decay modes (is however model dependent)

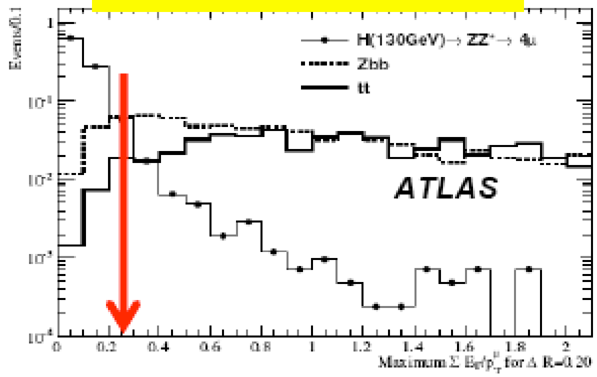
Higgs → ZZ* → 4l

Reducible backgrounds have activity around leptons from b-decay

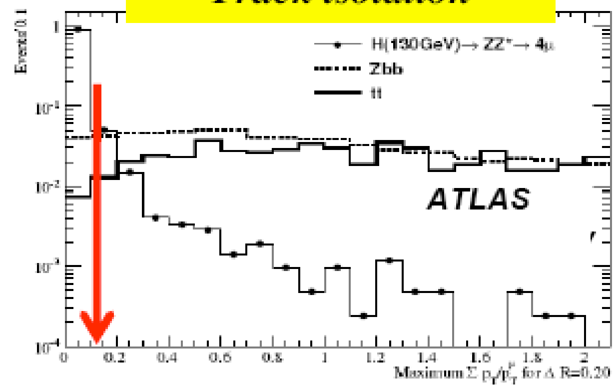
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Calorimetric isolation

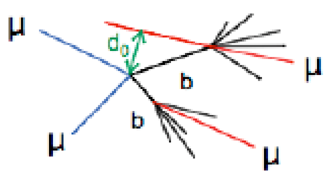


Track isolation

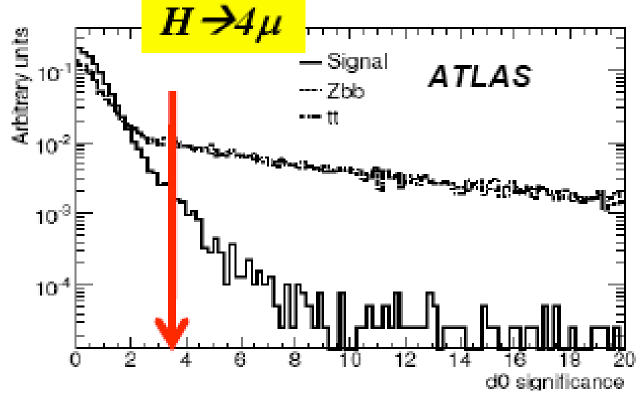


Normalized calorimetric and track isolation (ΔR=0.2) for the signal (m_H = 130) and the *Zbb* and tt backgrounds in the 4μ channel.

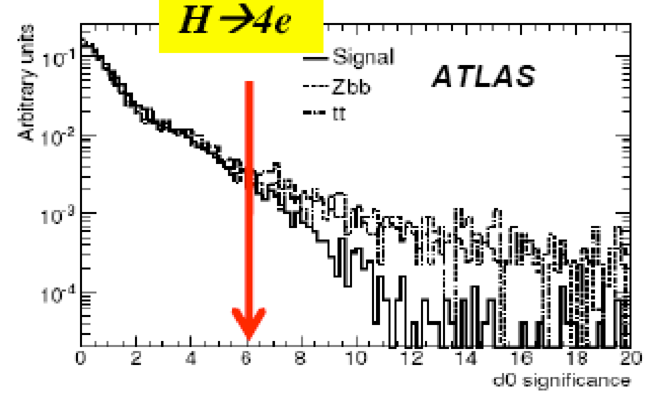
Lepton from b-quark decay do not point towards primary vertex



H→4μ



H→4e

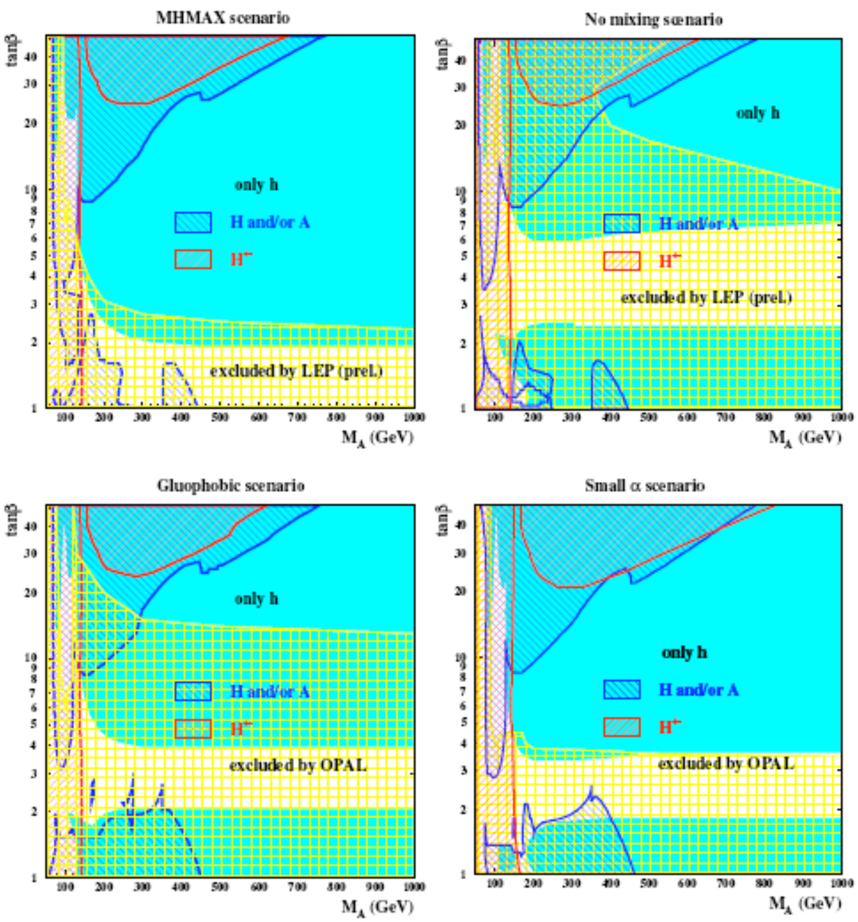


Transverse impact parameter significance in signal and reducible background events.

MSSM scan

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,   30 fb^{-1},   5σ discovery



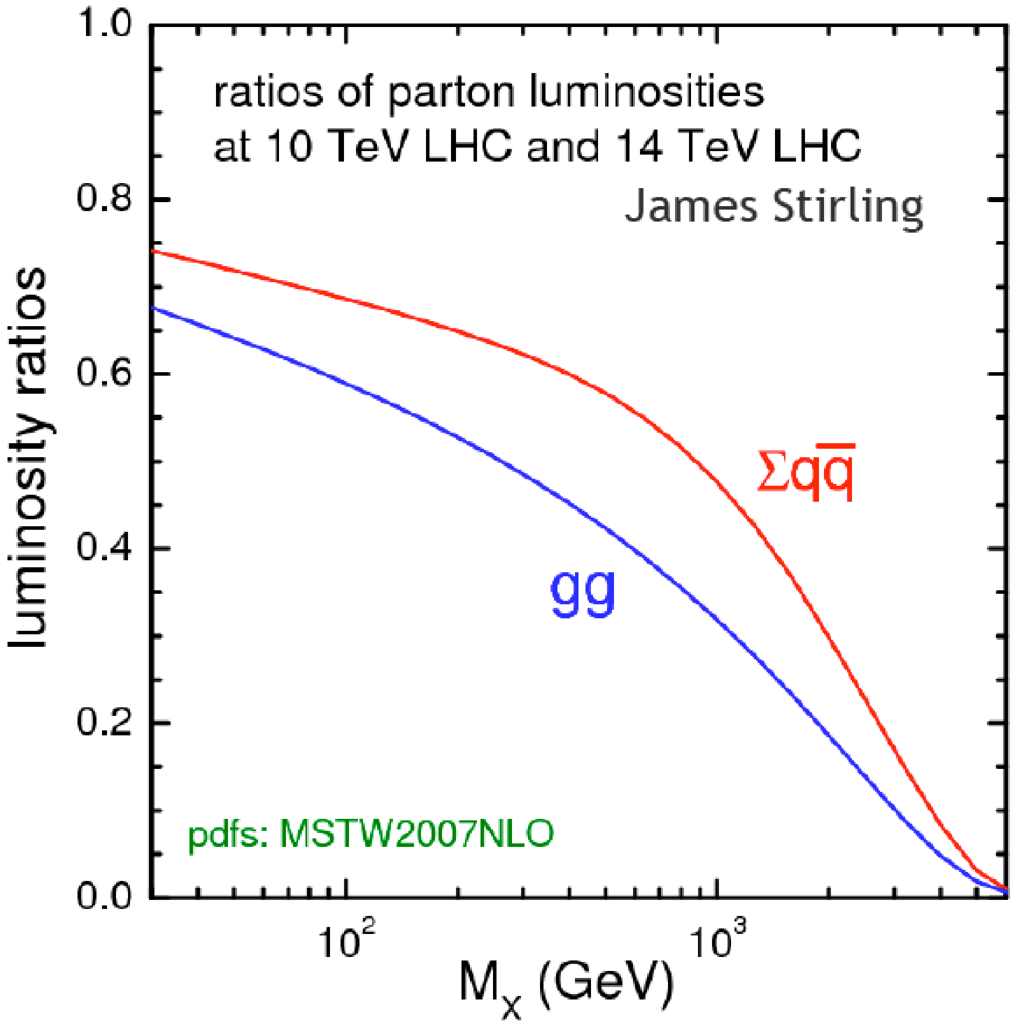
MHMAX scenario (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV/c^2

10 vs 14 TeV?



At 10 TeV, lower cross-section for high mass objects due to lower parton luminosities...

Below about 200 GeV, the suppression is <50% (process dependent)

- e.g. $t\bar{t}$ ~ factor 2 lower cross-section (still 50x Tevatron)

Above ~2-3 TeV the effect is more marked

Vast majority of studies done on $\sqrt{s}$=14 TeV capabilities