Higgs boson searches at hadron colliders

Part 3

- Higgs Bosons at the LHC
- Higgs boson parameters

The first Higgs has already been seen

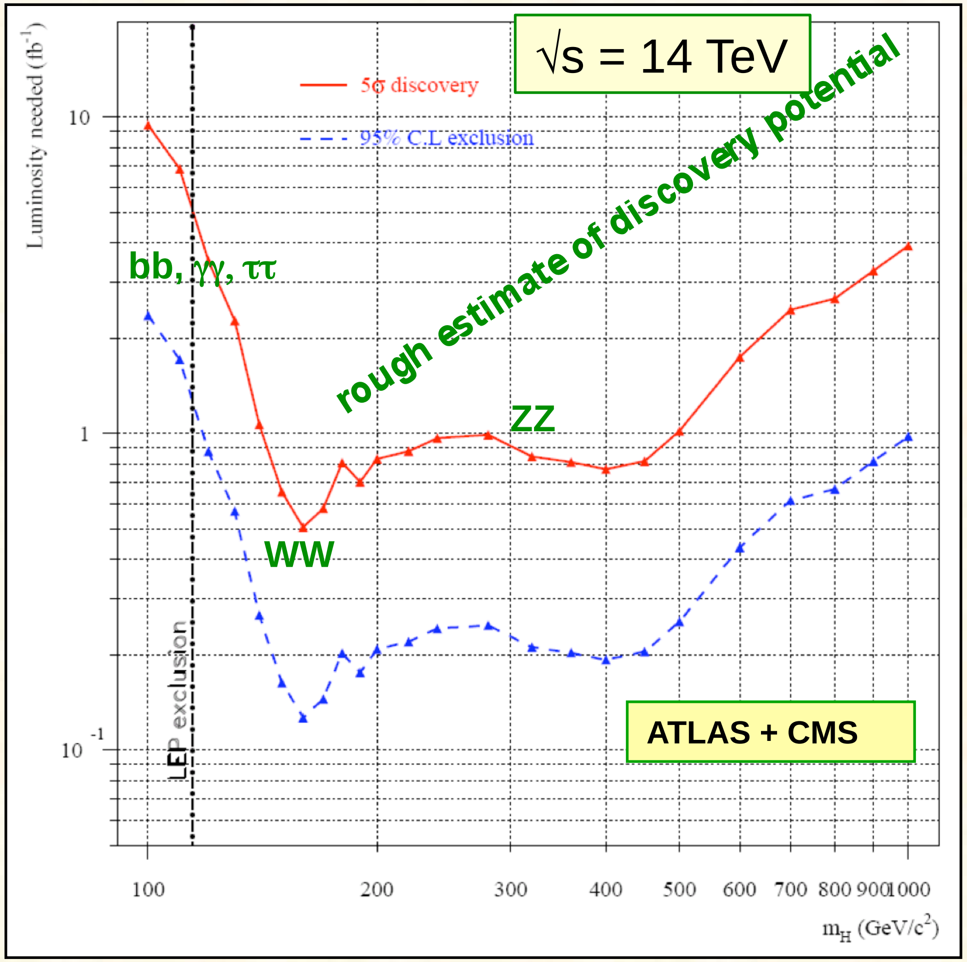
.. jointly by ATLAS

....and CMS

....and even confirmed by ALICE

…. also the prospects for the discovery of the Higgs particle are good

- Luminosity required for a 5σ discovery or for a 95% CL limit – (< 2006 estimates)



J.J. Blaising, A. De Roeck, J. Ellis, F. Gianotti, P. Janot, G. Rolandi and D. Schlatter,
Eur. Strategy workshop (2006)

~ < 1 fb^{-1} needed to set a 95% CL limit in most of the mass range
(low mass ~ 115 GeV/c^2 more difficult)

comments:
- these curves are optimistic on the ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent (no simple scaling, σ ~ √L, possible)

What is new on LHC Higgs studies ?

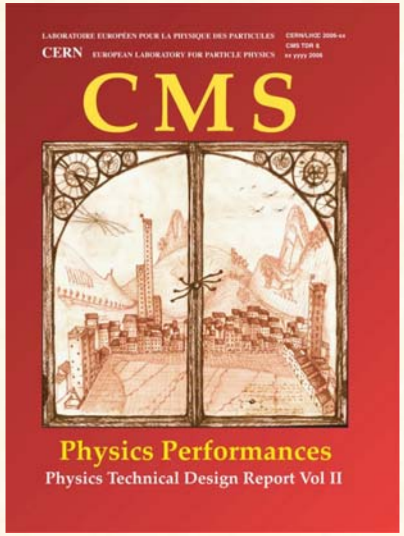
- Many studies have been performed using detailed GEANT simulations of the detectors
  - Physics Performance Technical Design Report from the CMS collaboration
  - ATLAS CSC book (Computing System Commissioning)

- New (N)NLO Monte Carlos (also for backgrounds)
  - as already discussed (see 1^{st} lecture)

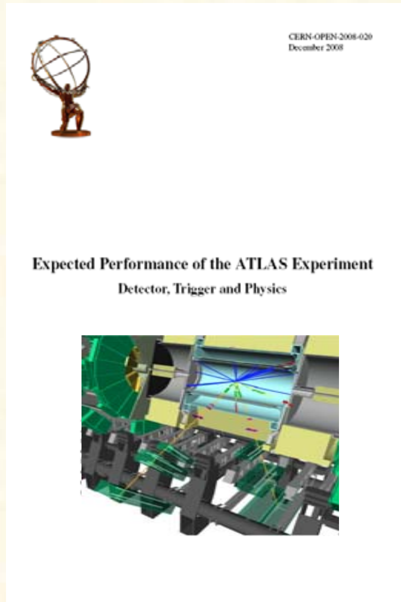
- More detailed, better understood reconstruction methods
  (partially based on test beam results, and first LHC data)

- and: we have first LHC DATA at $\sqrt{s}$ = 7 TeV

Important note: most LHC studies are based on $\sqrt{s}$ = 14 TeV;
Results presented here are from these studies, however,
preliminary sensitivities for $\sqrt{s}$ = 7 TeV will be presented,
if available

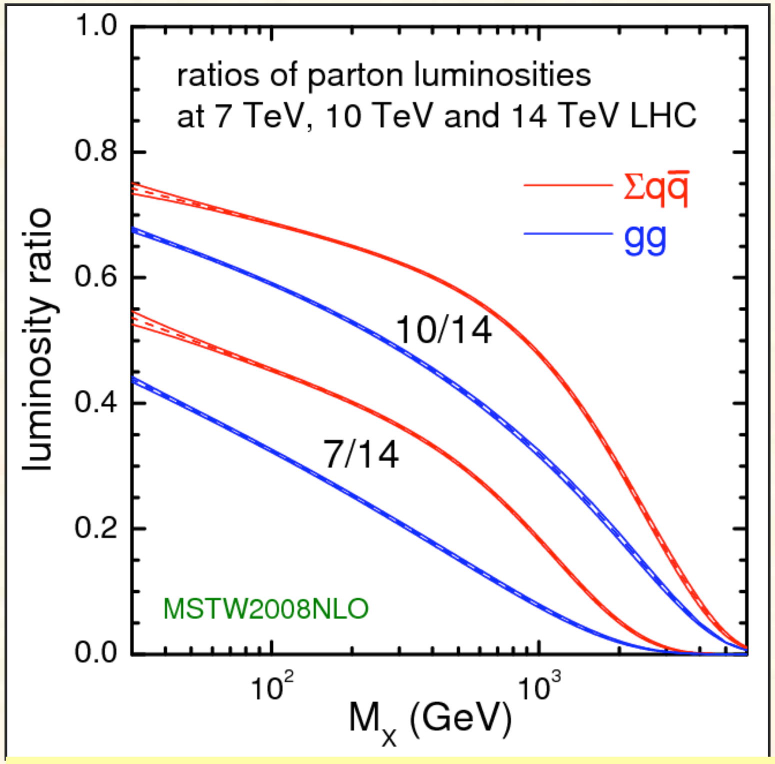


CMS: CERN / LHCC 2006-021
ATLAS: CERN-OPEN 2008-020

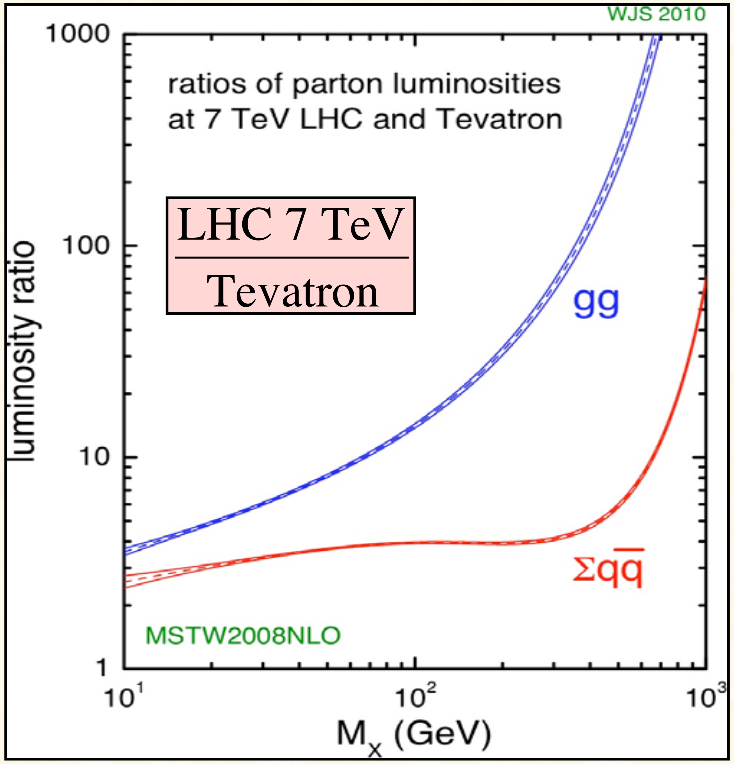


Impact of reduced LHC beam energy

- Ratio of parton luminosities for 7/14 and 10/14 TeV …



J.Stirling
http://projects.hepforge.org/mstwpdf/plots/plots.html



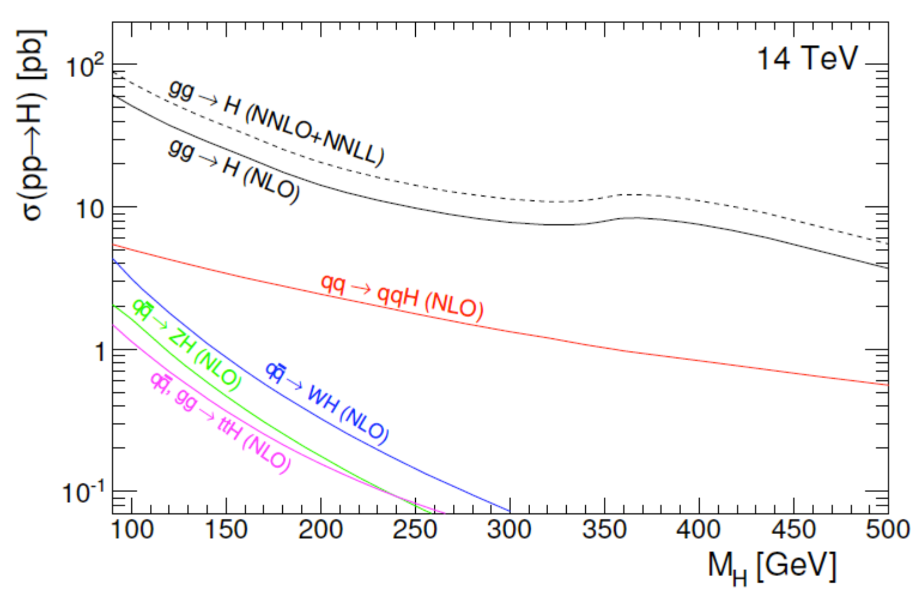
tt:
7/14 = 0.2

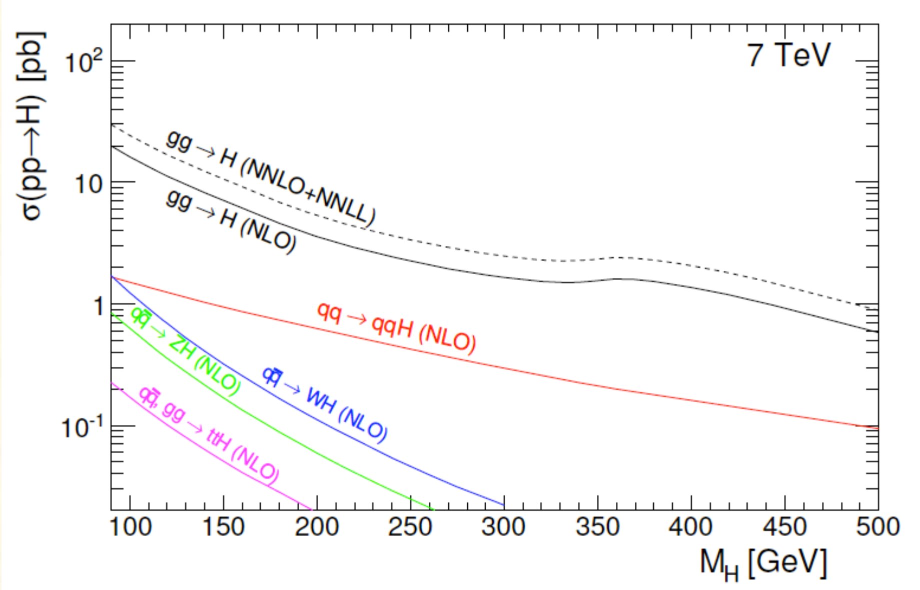
W' (1.5 TeV):
7/14 = 0.1

W' (1 TeV):
7(pp) / 2(ppbar) ~ 60

...but still large factor compared to the Tevatron ($\sqrt{s}$ =1.96 TeV)

Higgs cross sections: 14 TeV vs. 7 TeV



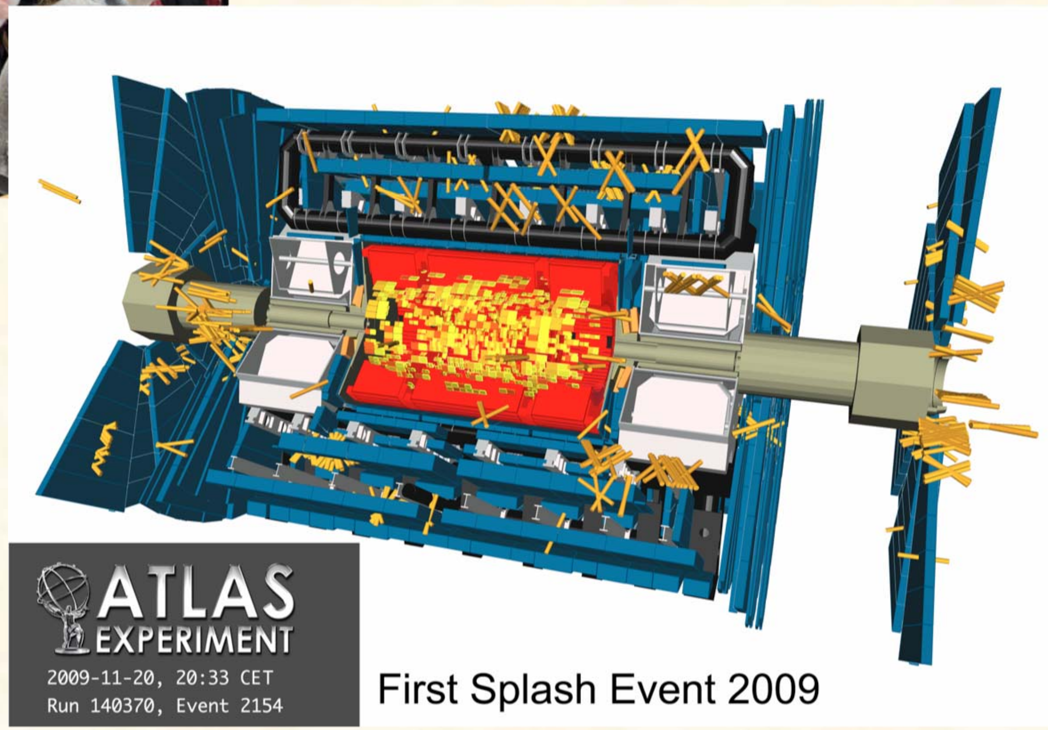


For a Higgs boson of 160 GeV: reduction by a factor of ~3.6 for gg → H
and ~3.7 for qq → qqH

LHC re-start as seen from the experiments

Praying for beam

First beam splash events in ATLAS, 20th Nov 2009



First Splash Event 2009

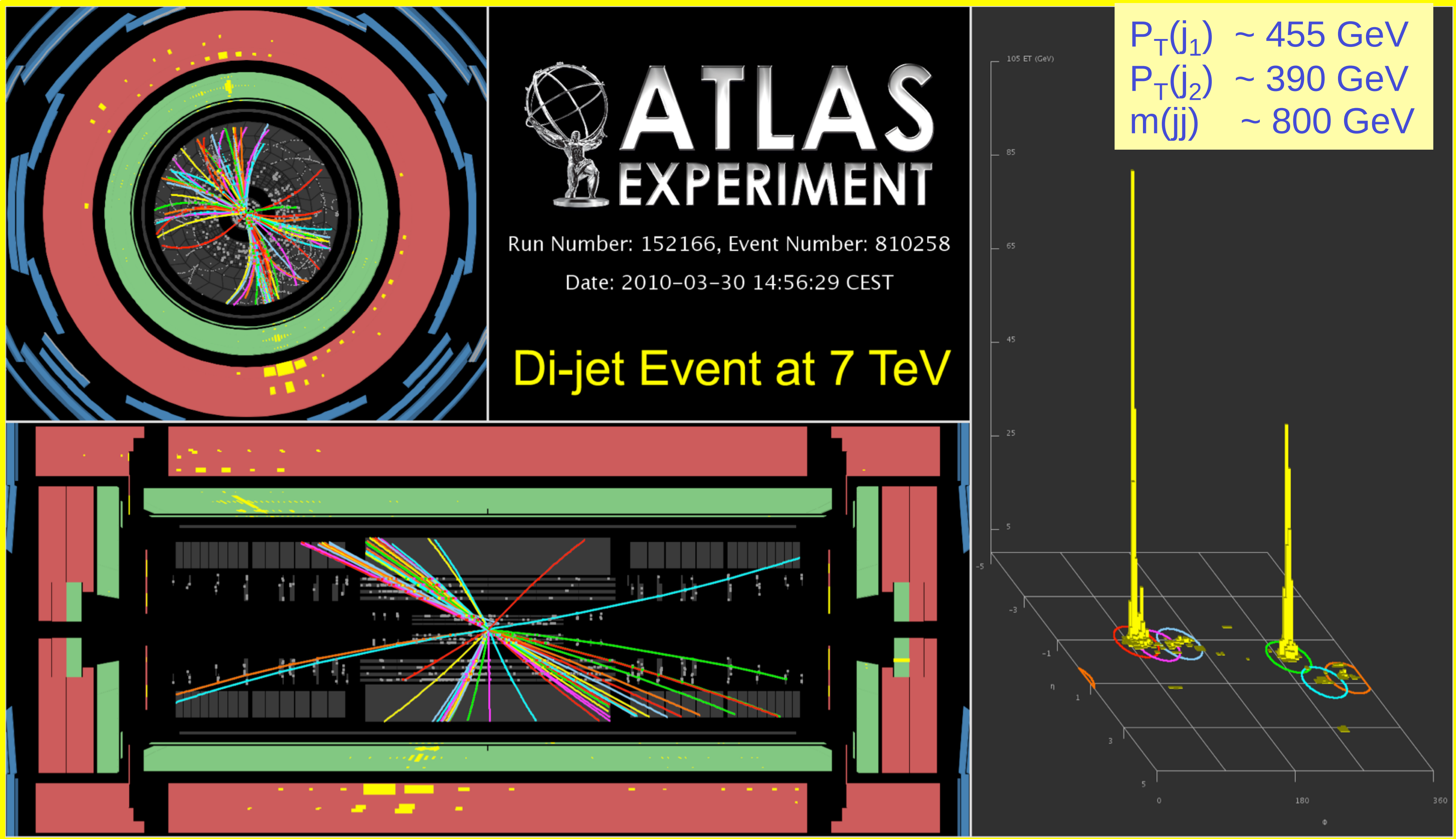
CMS re-start in BBC News

November 21, 2009

BBC NEWS

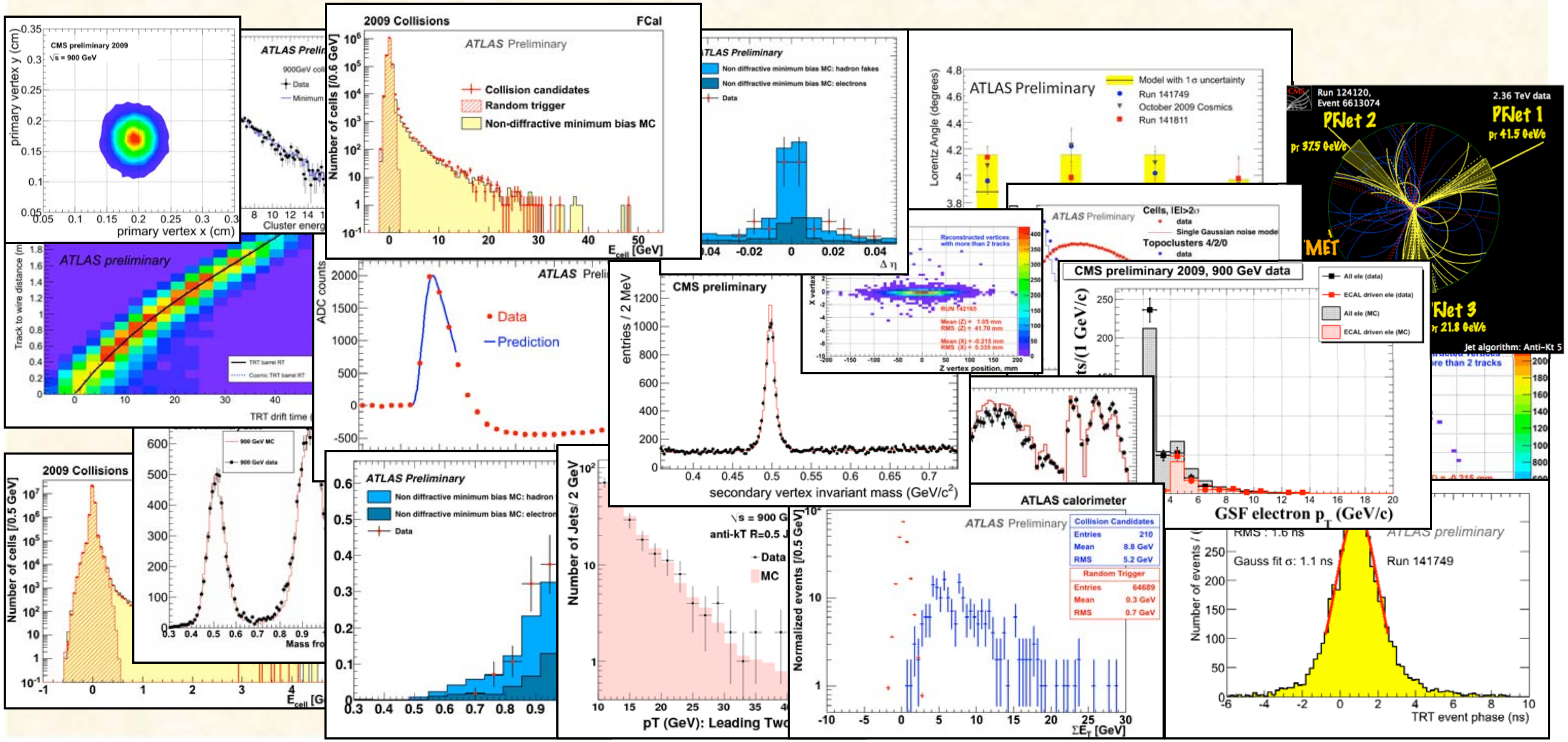
Scientists at Cern in Geneva have restarted the Large Hadron Collider (LHC) experiment, which hopes to shed light on the origins of the universe.

Since 30. March 2010: collisions at $\sqrt{s}$ = 7 TeV
(.... first interesting events)



First results on
Detector performance

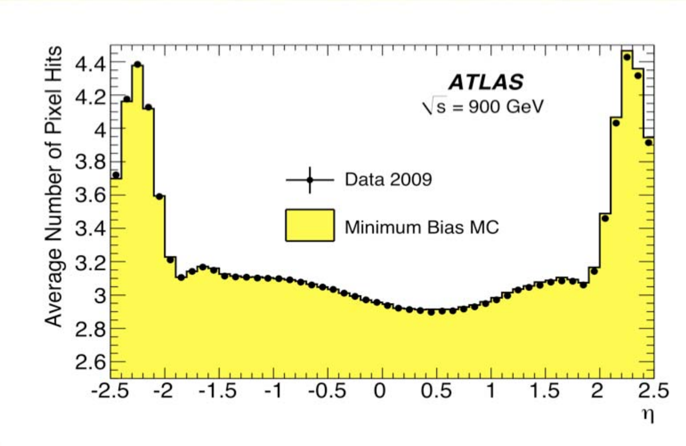
(already published)

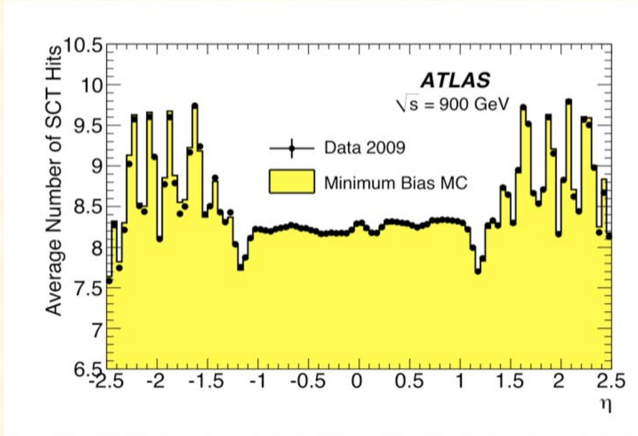


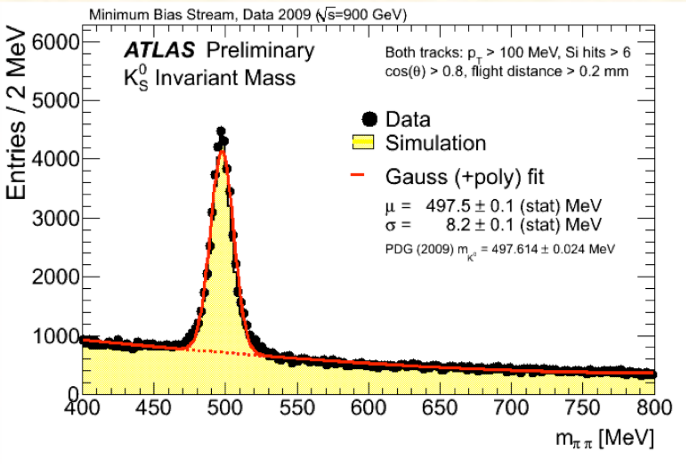
Inner Detector performance: hits, tracks, resonances,...

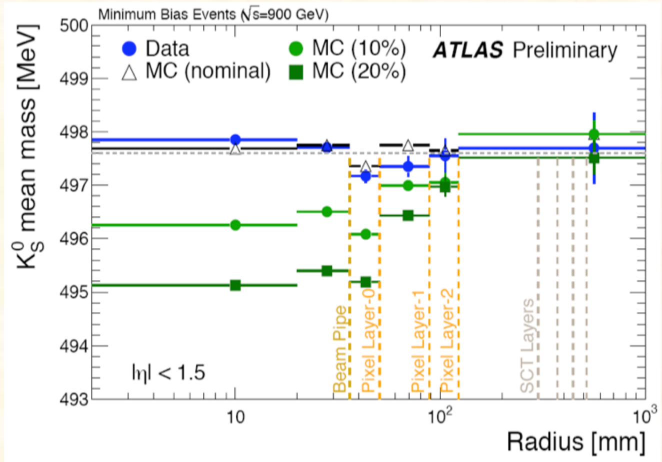
- Very good agreement for the average number of hits on tracks in the silicon pixel and strip detectors

- Material distribution in the inner detector is well described in Monte Carlo (nice cross-check with K^0-mass dependence on radius in the Monte Carlo)

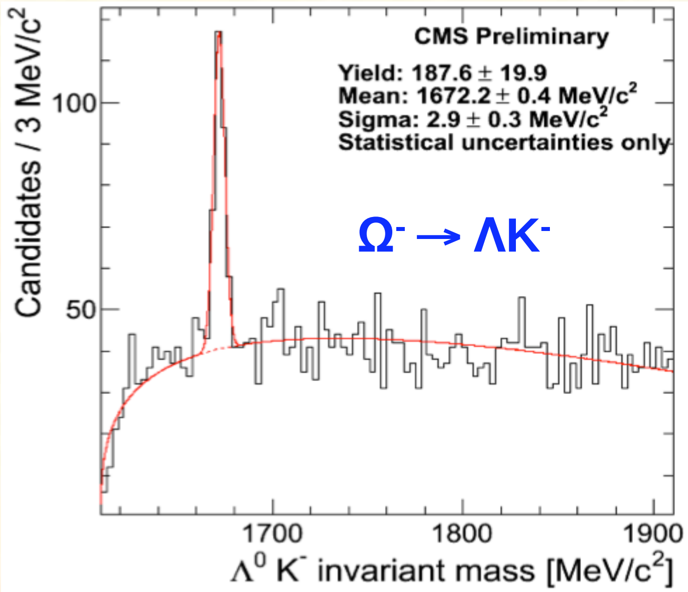


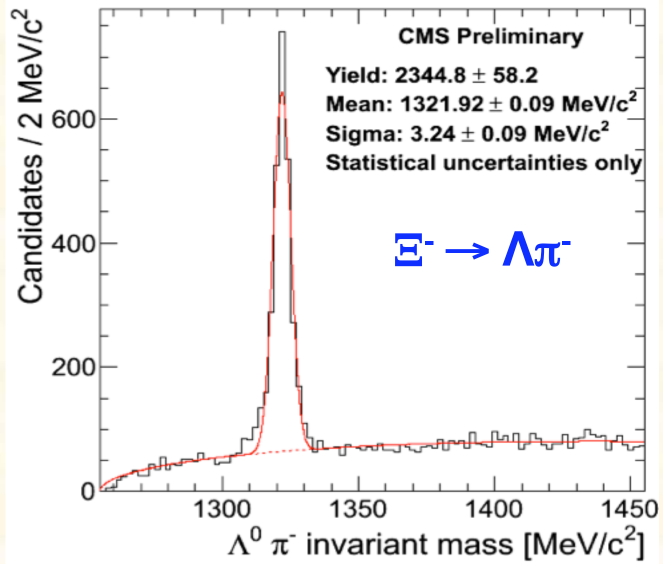


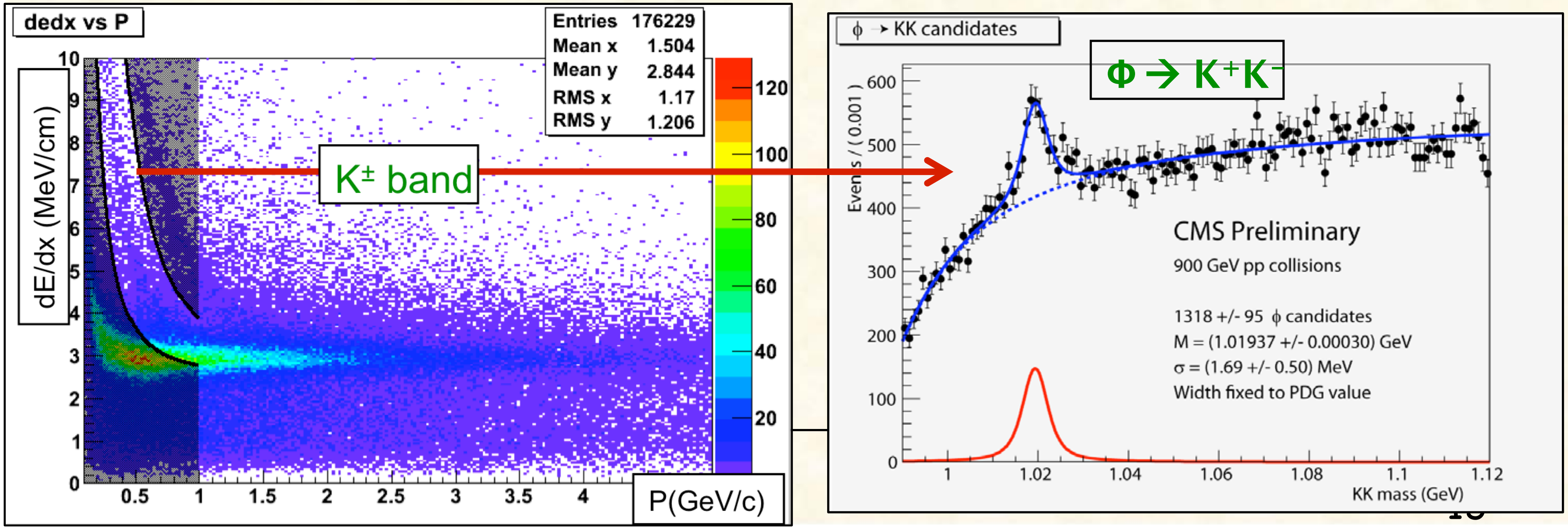




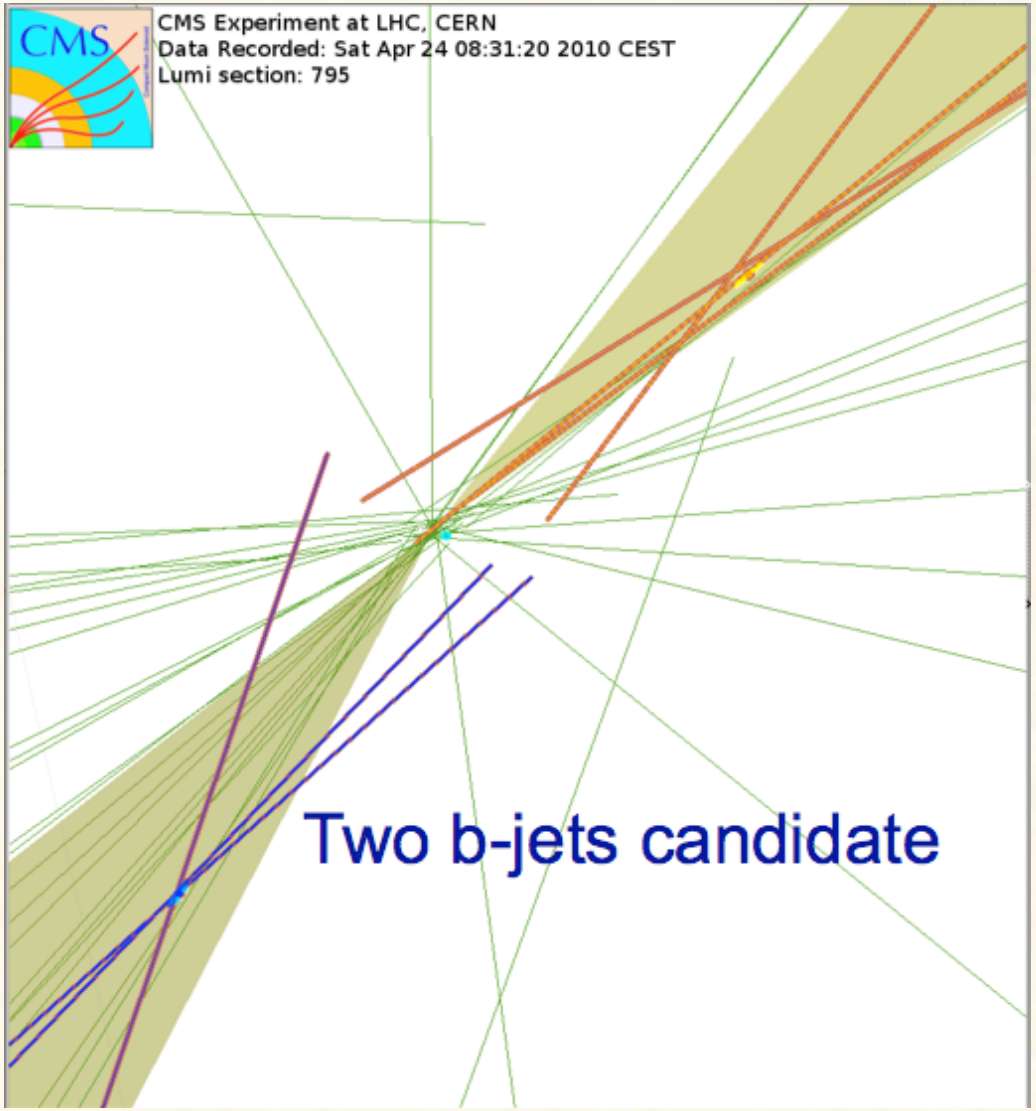
Resonances: CMS tracking detector

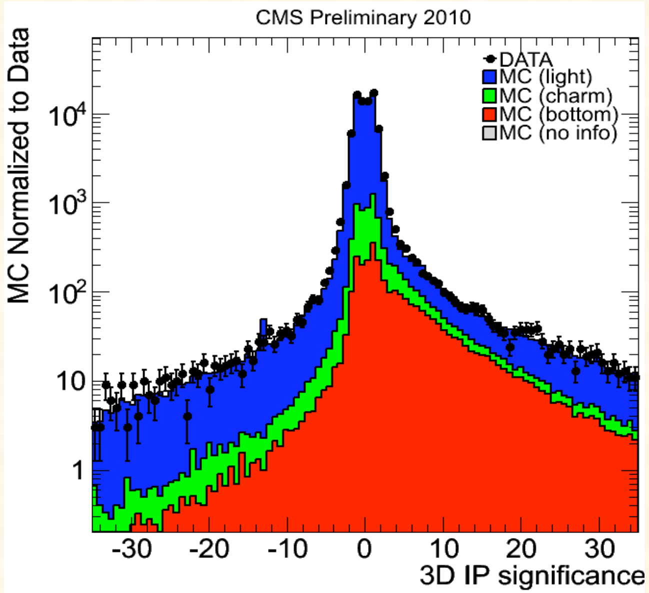


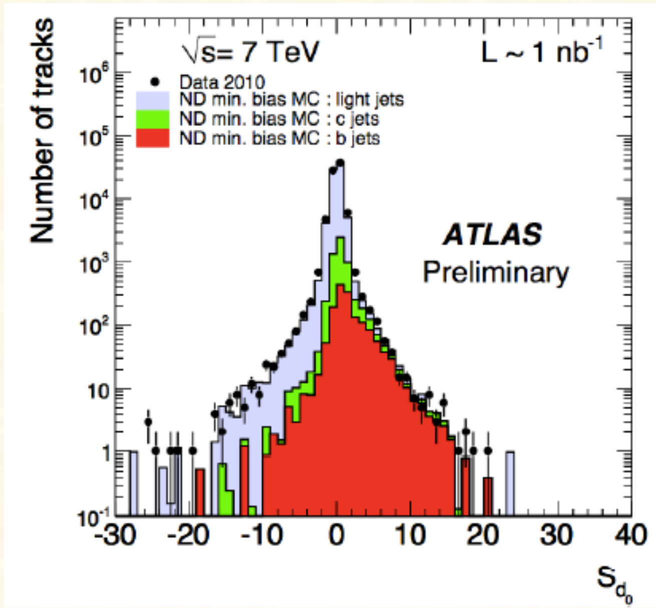




...towards b-tagging

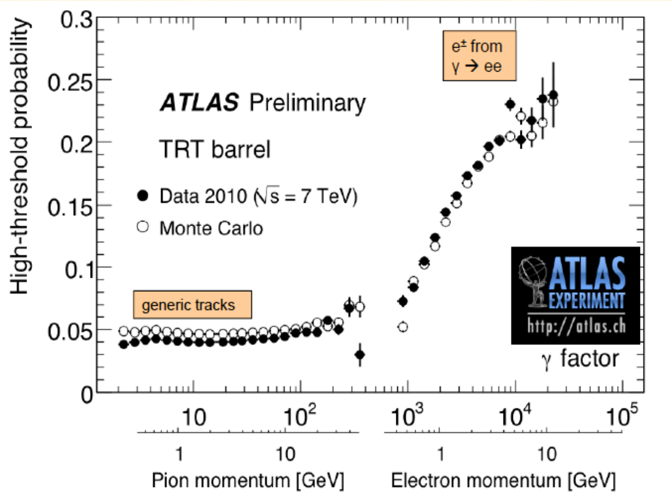


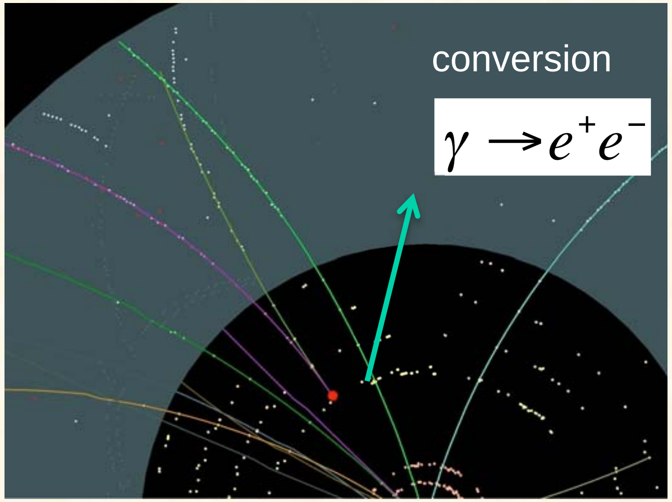


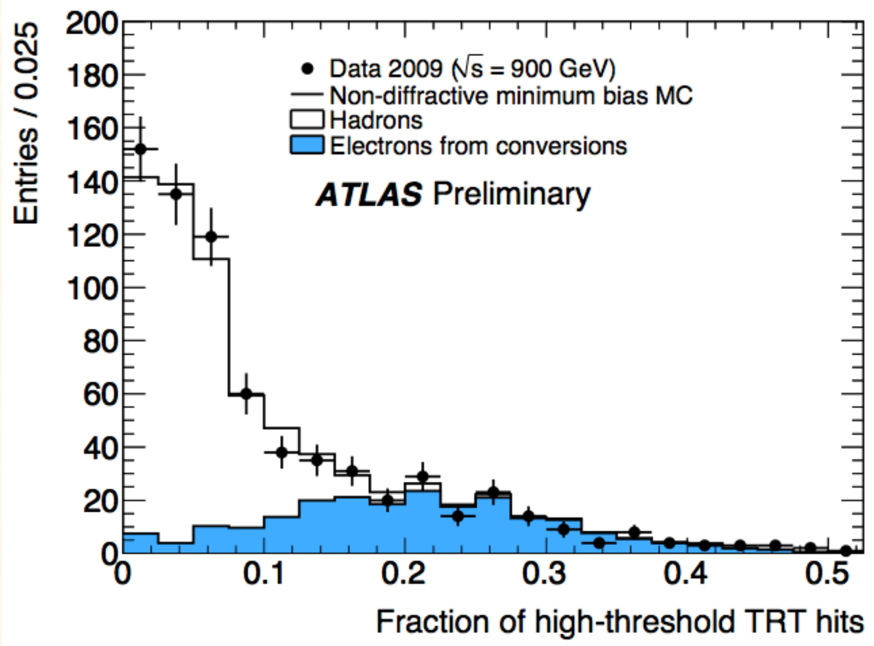


TRT and electron identification

The intensity of the transition radiation in the TRT is proportional to the Lorentz Factor $\gamma = E/mc^2$ of the traversing particle.
Number of high threshold hits is used to separate electrons and pions

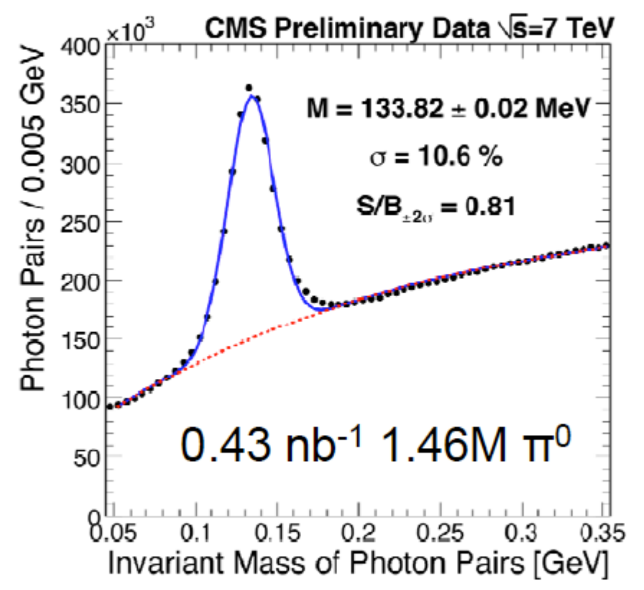




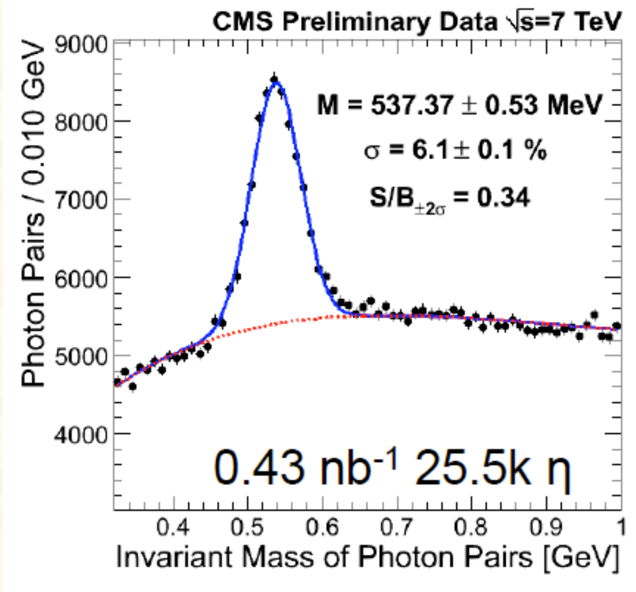


"Tail" towards high-threshold hits is due to electrons from conversion candidates

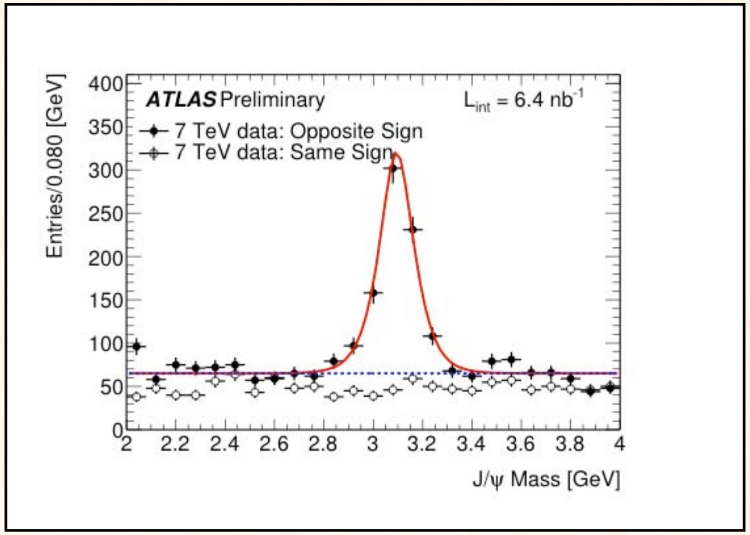
Calorimeters: resonances in the el.magn. calorimeters



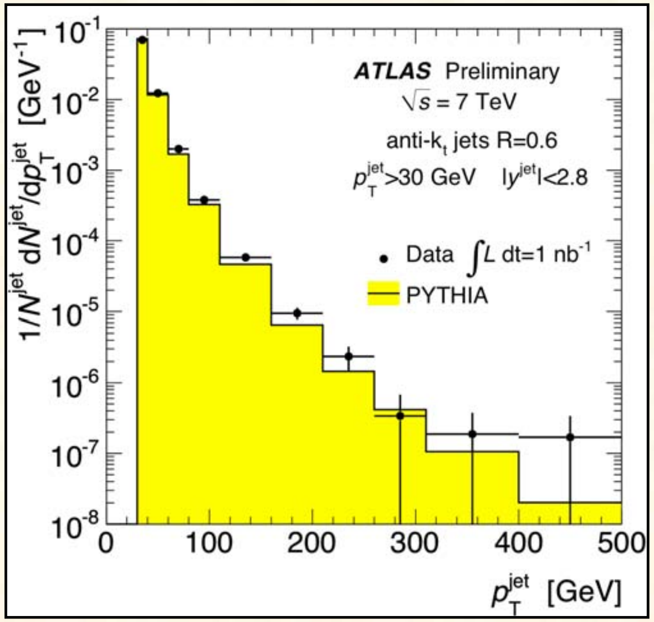
π^0 , $\eta \rightarrow \gamma\gamma$

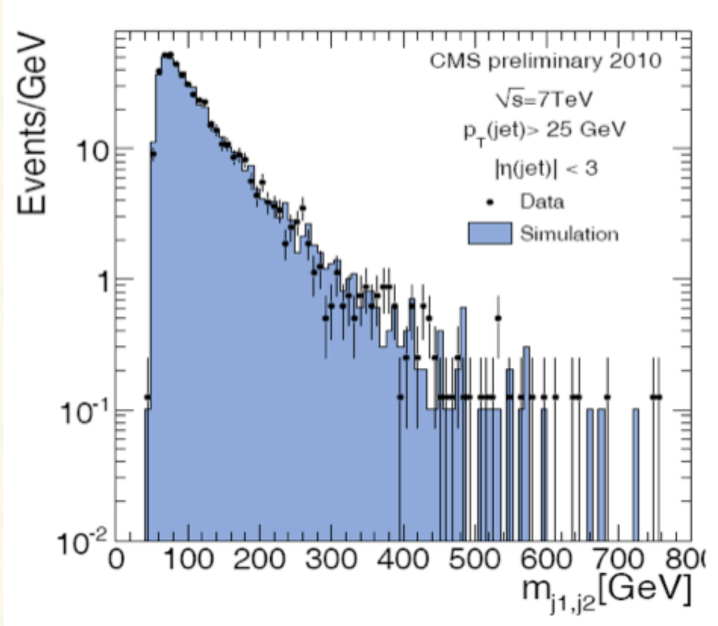


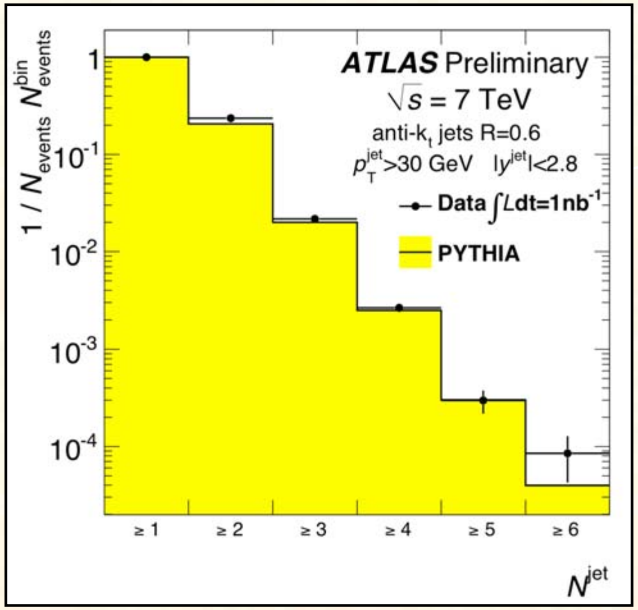
First muon signals:
$J/\Psi \rightarrow \mu^+ \mu^-$



Jets and missing transverse energy







<u>Particle-Flow algorithm:</u>

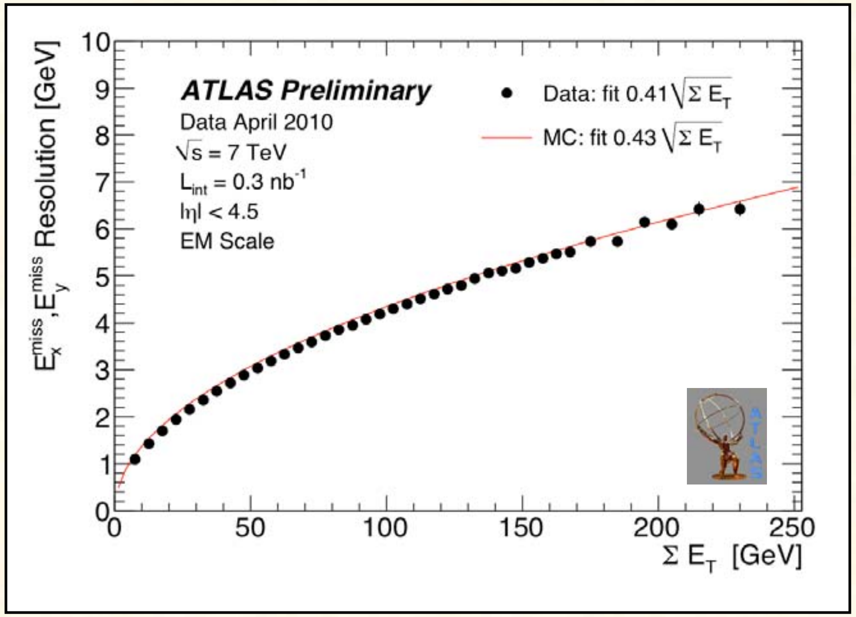
- Identify all type of particles:
- Photons (ECAL only)
- Charged Hadrons (Tracker only)
- Electrons (ECAL+Tracker)
- Neutral Hadrons (CALO only)
- Muons (muon chambers + Tracker)
- And then τ, π^0, …

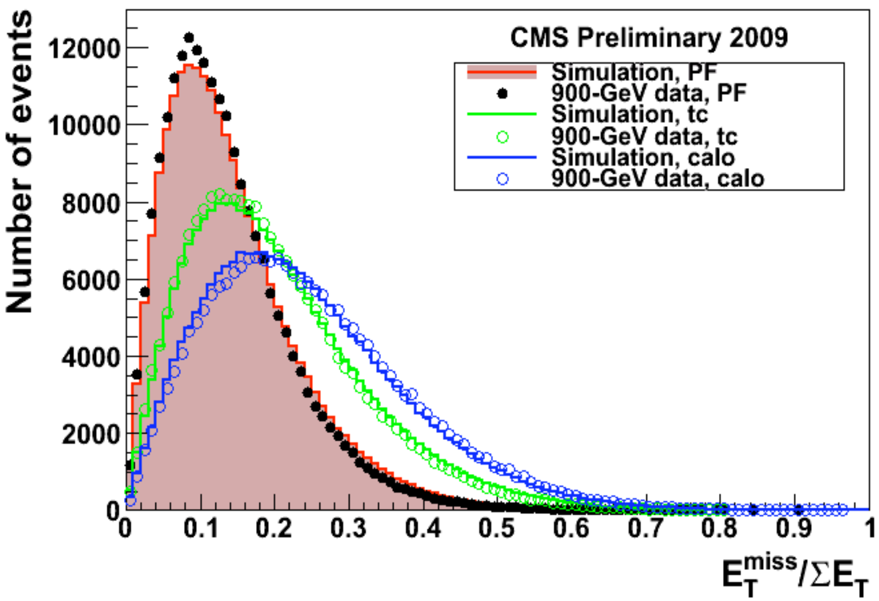
- Obtain the best energy estimate for each type of particle

Missing transverse energy, E_T^{miss}

Sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks, etc.) and backgrounds from cosmics, beams, …

Even at this early stage, the missing E_T is well described in simulation !



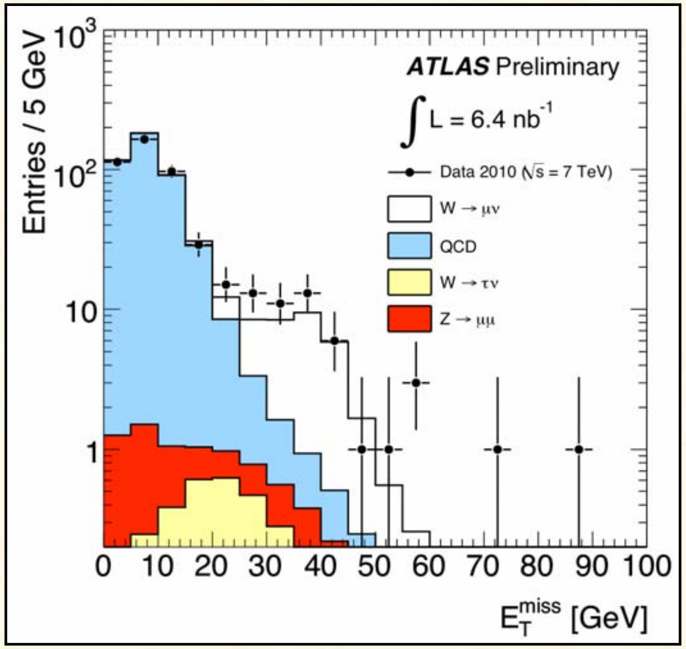


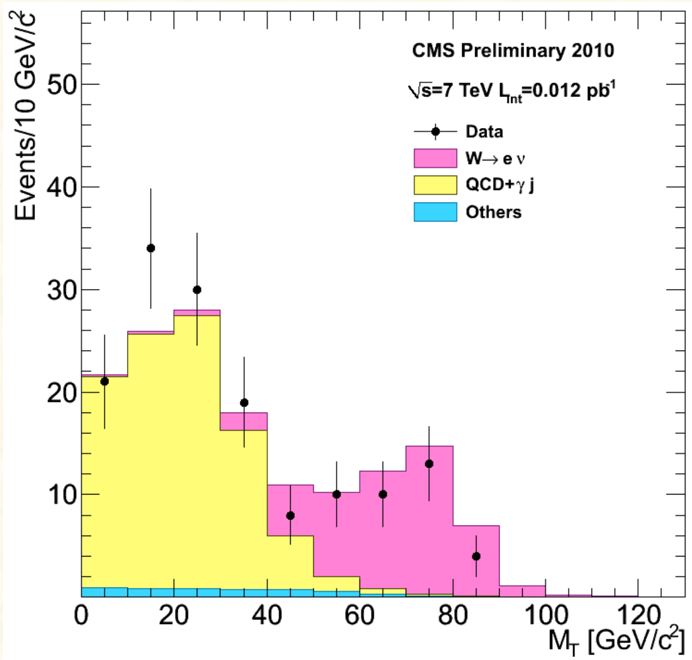
$$\sigma(E_{x,y}^{\mathrm{miss}}) = a \oplus b\sqrt{\sum E_{\mathrm{T}}}$$

Particle-flow based MET:
a = 0.55 GeV, b = 45%

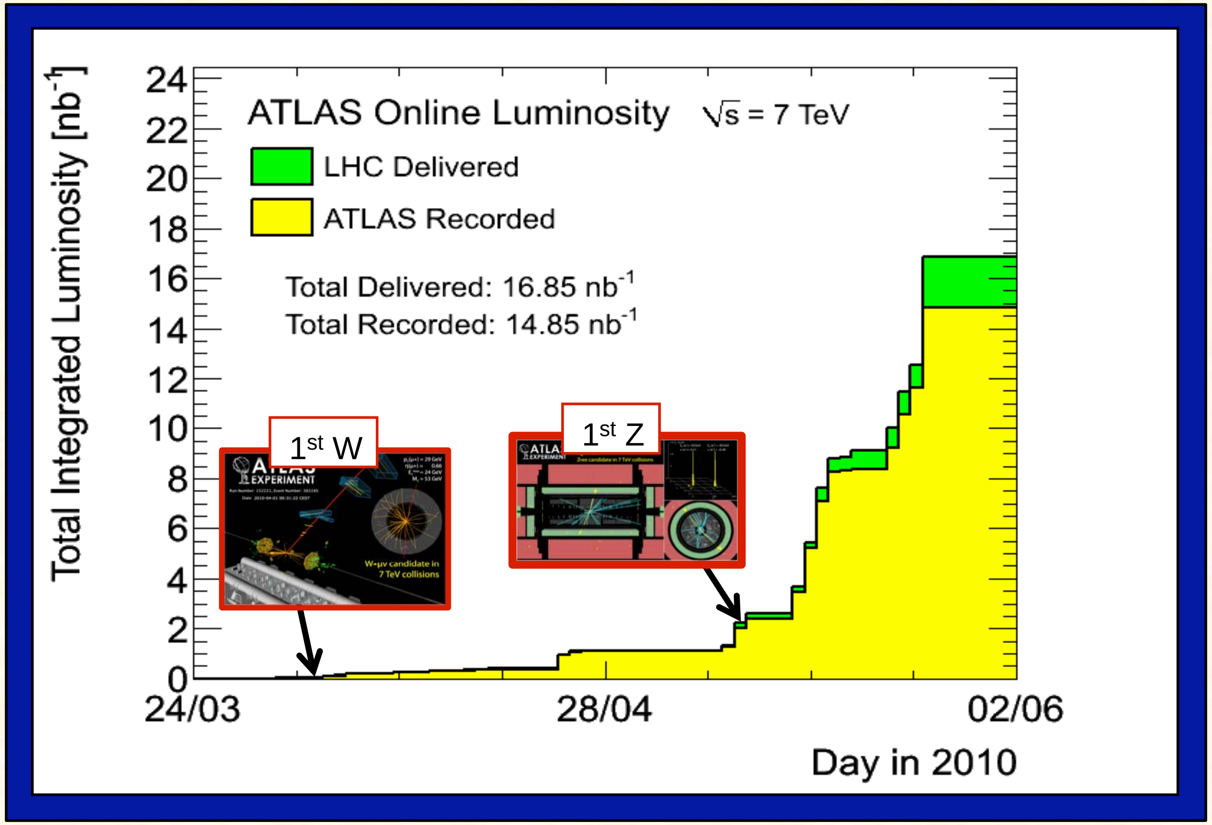
Particle-flow based E_T^{miss} relative resolution is significantly better than calorimeter based E_T^{miss}

The first W signals



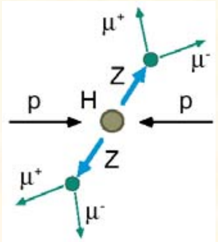


.....however, still lacking luminosity



$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m$_H$ = 100 GeV)



$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

Background: Top production

$tt \rightarrow Wb\ Wb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$

σ BR ≈ 1300 fb

Associated production Z bb

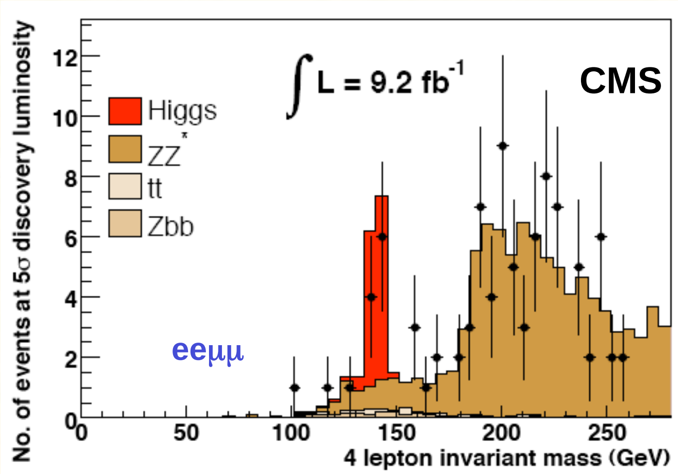
$Z\ bb \rightarrow \ell\ell\ c\ell\nu\ c\ell\nu$

Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum

$H \rightarrow ZZ^* \rightarrow \ell\ell\;\ell\ell$

$\sqrt{s}$ = 14 TeV

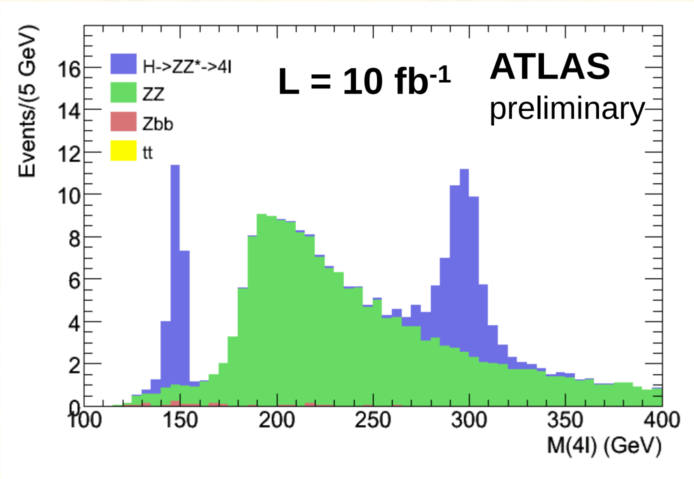


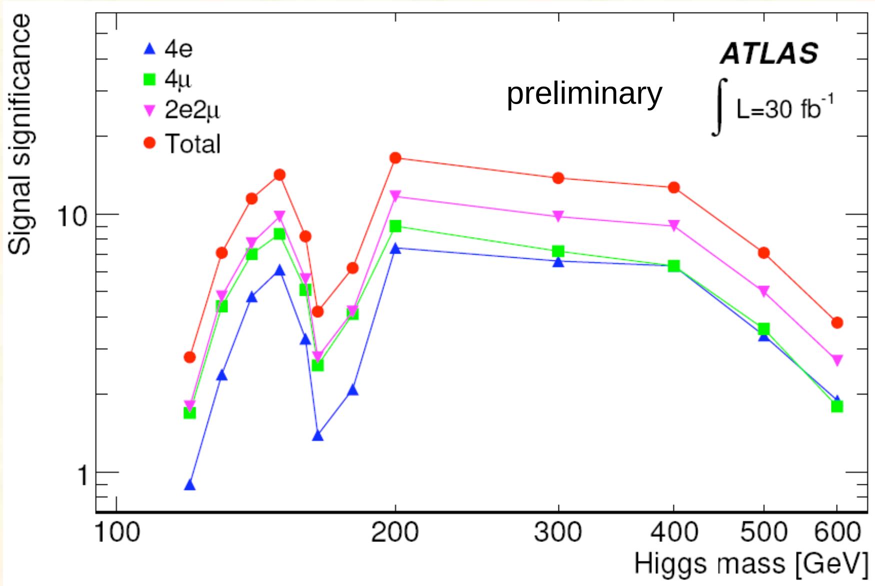
Main backgrounds: ZZ (irreducible),
tt, Zbb (reducible)

Updated ATLAS and CMS studies:

- ZZ background: NLO K factor used
- background from side bands

(gg->ZZ is added as 20% of the LO qq->ZZ)

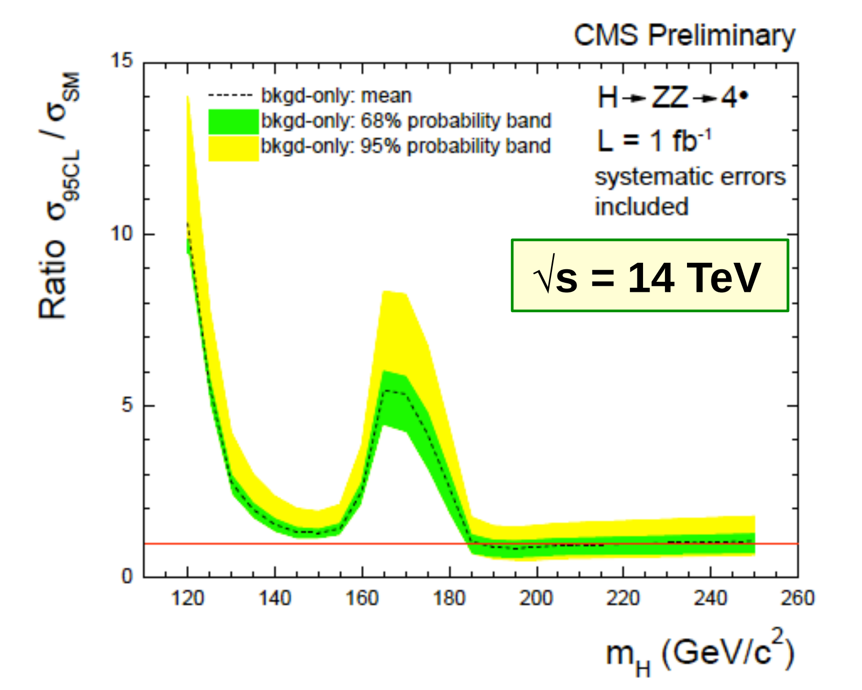


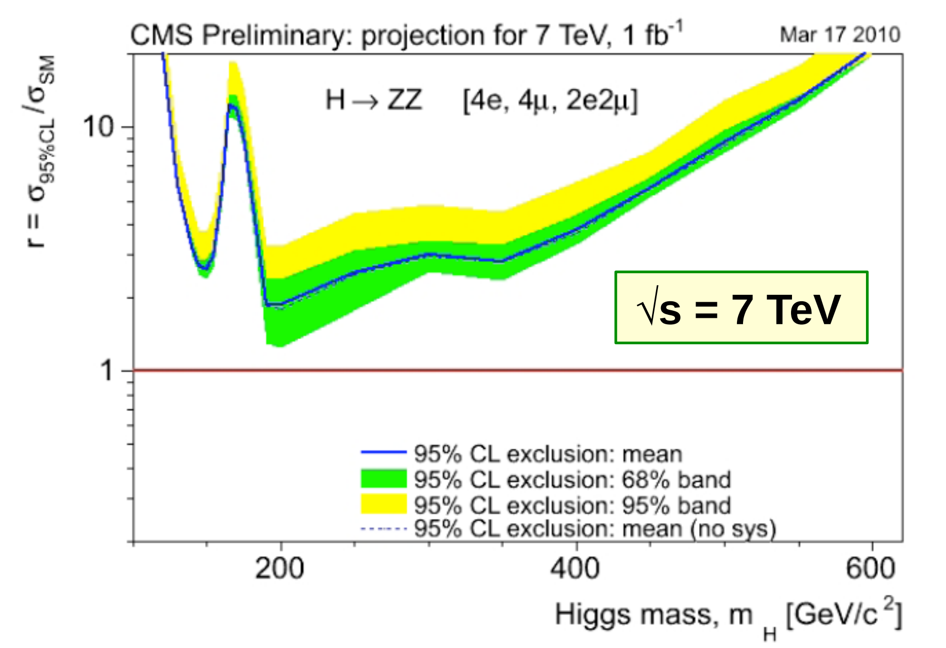


$H \rightarrow ZZ^{*} \rightarrow \ell\ell\ \ell\ell$

What can be done with 1 fb^{-1}?

95% C.L. excluded cross sections normalized to Standard Model cross section

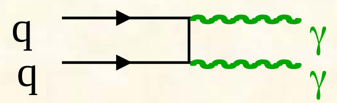




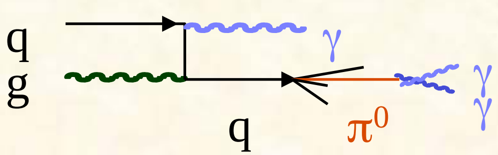
$H \rightarrow \gamma\gamma$

Main backgrounds:

$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



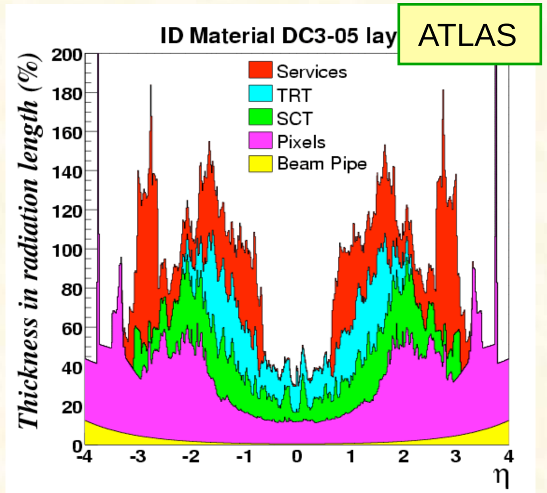
$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

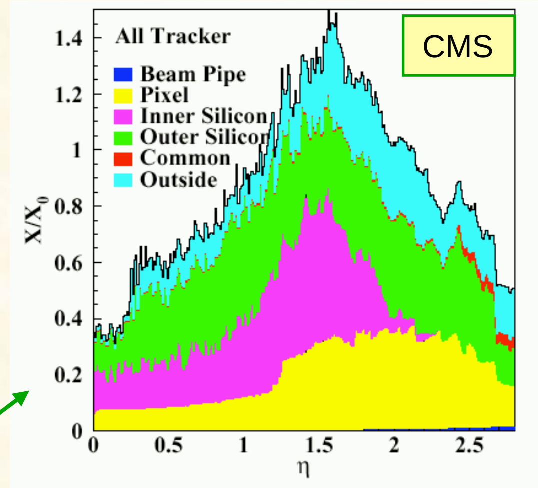
$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

- Main exp. tools for background suppression:
  - photon identification
  - γ / jet separation (calorimeter + tracker)

  - note: also converted photons need to be reconstructed
    (large material in LHC silicon trackers)



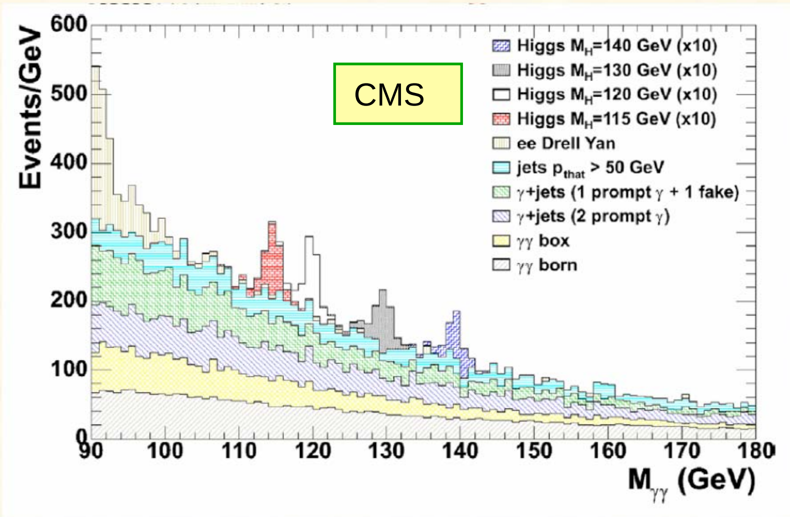


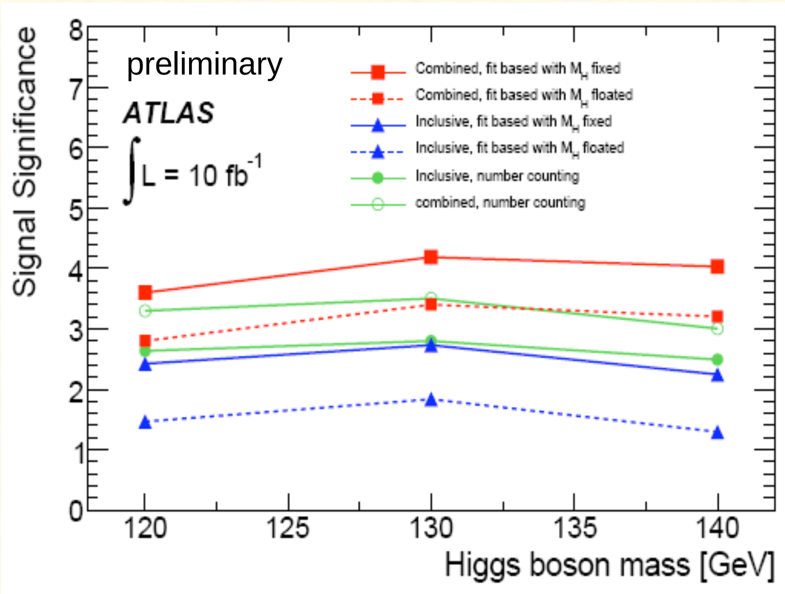
CMS: fraction of converted γs

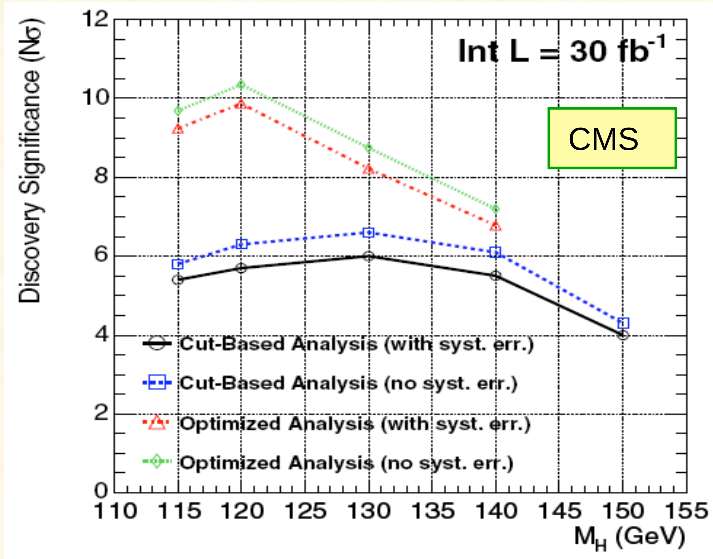
Barrel region:	42.0 %
Endcap region:	59.5 %

<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)
- Split signal sample acc. to resolution functions





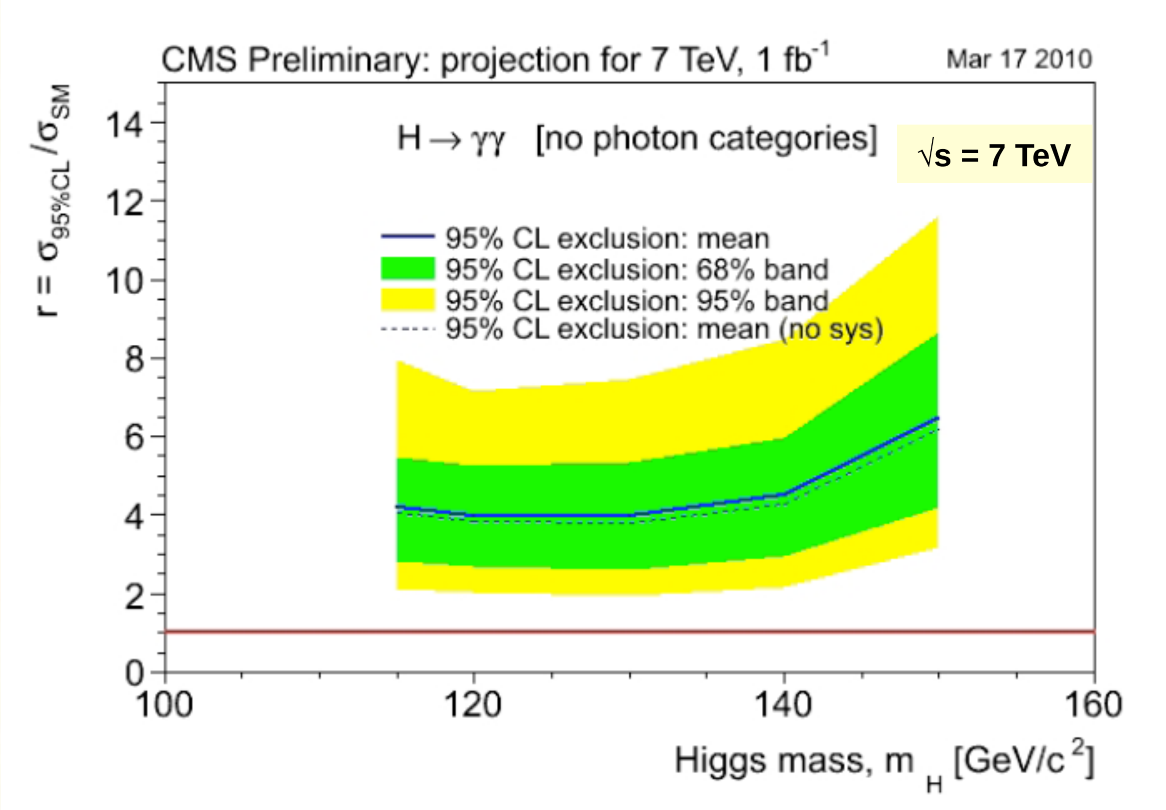


- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

$H \rightarrow \gamma\gamma$

What can be done with 1 fb^{-1} at $\sqrt{s}$ = 7 TeV ?

95% C.L. excluded cross sections normalized to the Standard Model cross section

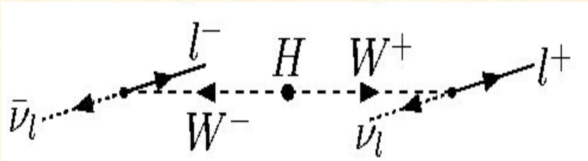


$H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

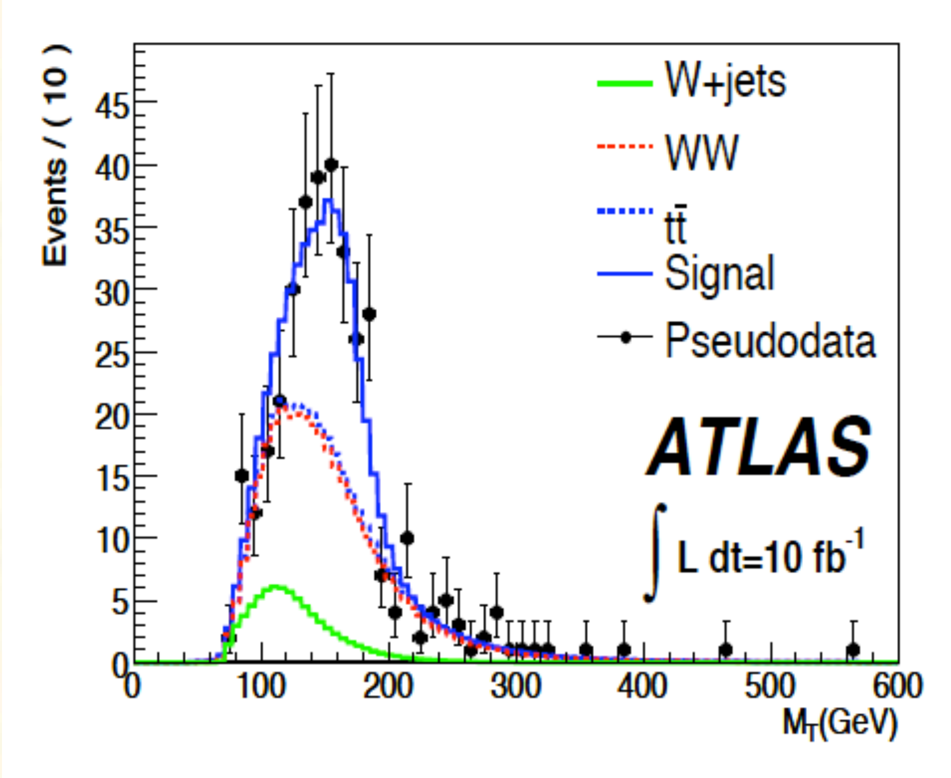
- Large $H \rightarrow WW$ BR for $m_H \sim 160$ GeV/c^2
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt

- Two main discriminants:

  (i) Lepton angular correlation



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

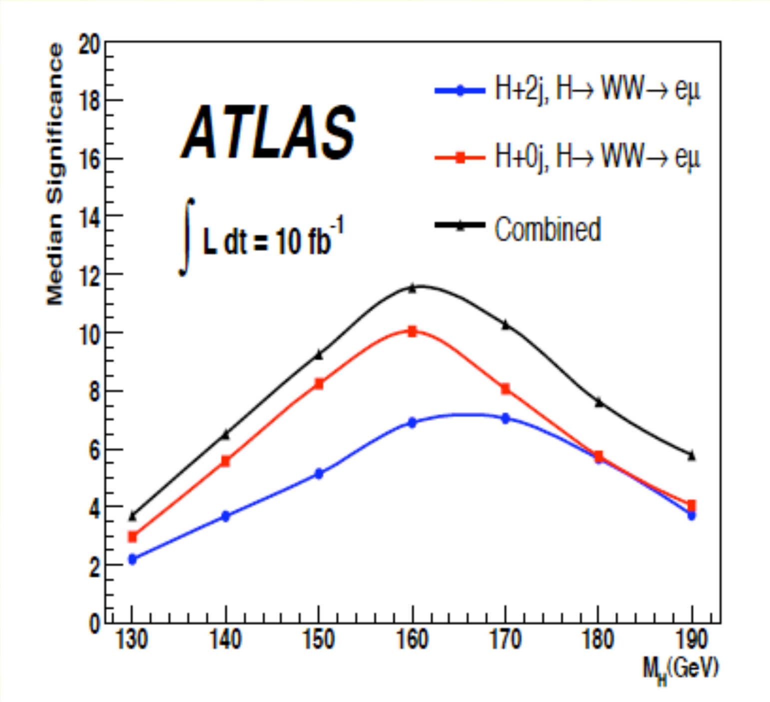


Difficulties:
(i) need precise knowledge of the backgrounds
Strategy: use control region(s) in data, extrapolation in signal region
(ii) jet veto efficiencies need to be understood for signal and background events

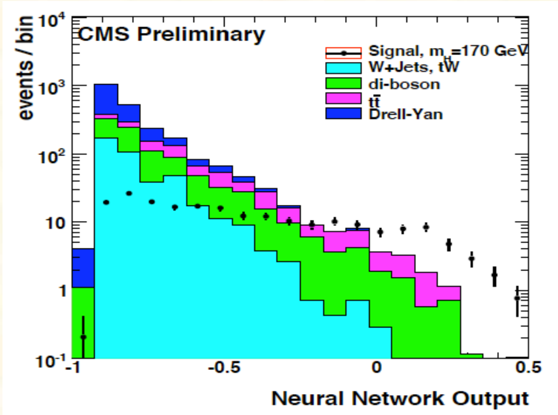
Discovery reach in H → WW → ℓν ℓν

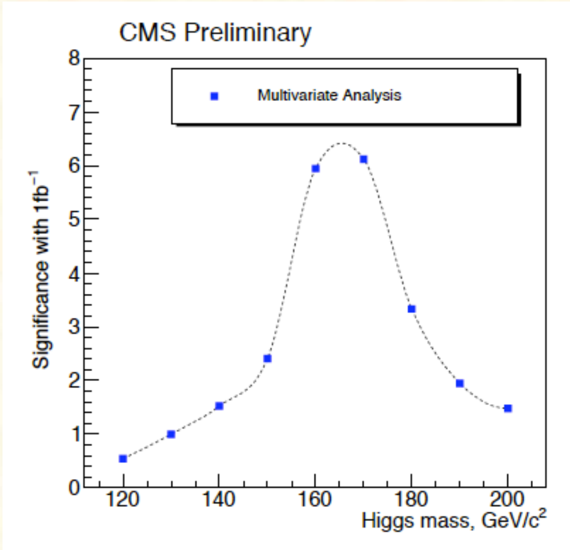
Expected ATLAS discovery reach at √s = 14 TeV for 10 fb^{-1}

Separated in:
- H + 0 jet (gluon fusion)
- H + 2 jets (vector boson fusion)

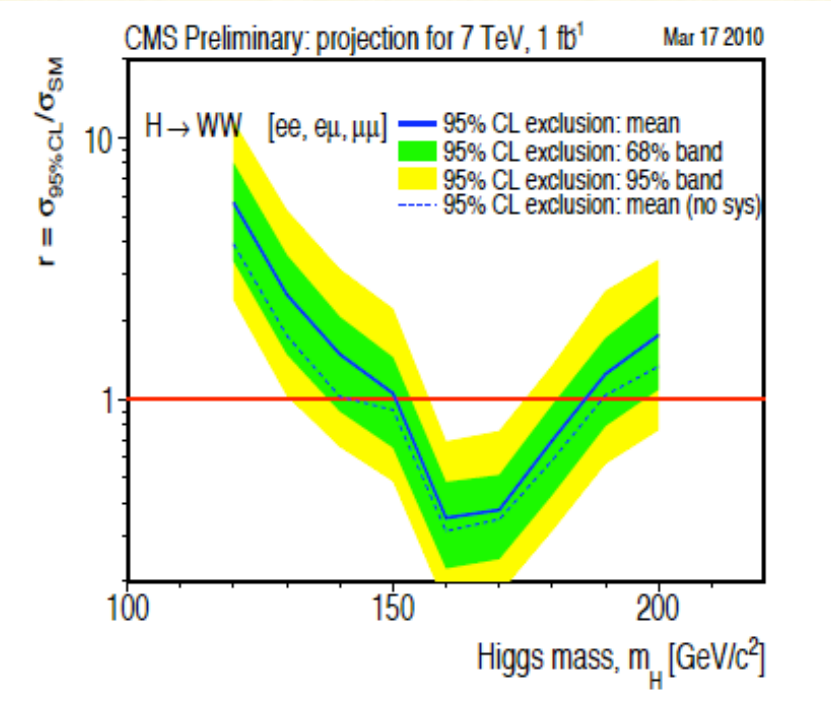


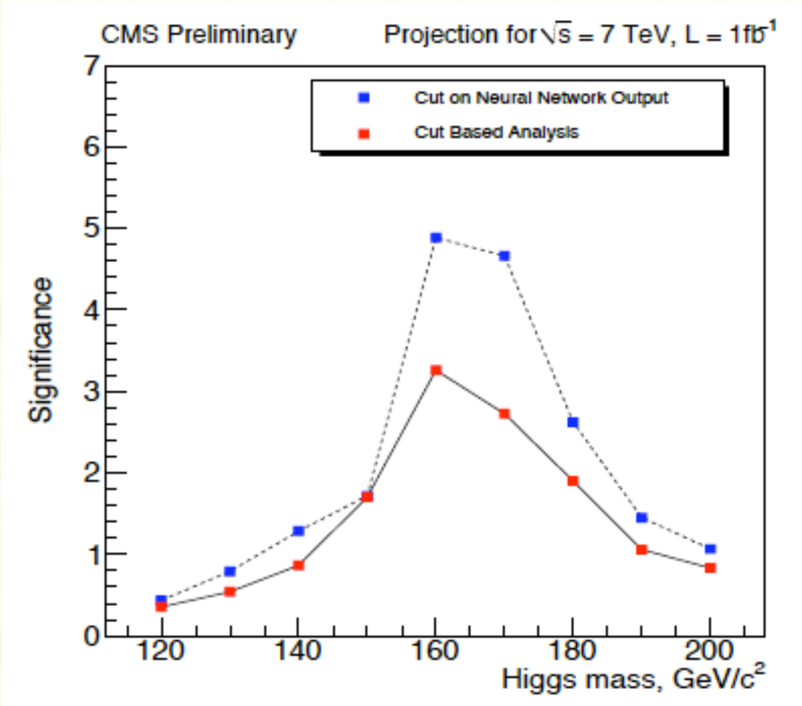
CMS Neural Net approach for √s=14 TeV:
(gluon fusion + vector boson fusion)





Discovery reach in H → WW → ℓν ℓν at √s = 7 TeV



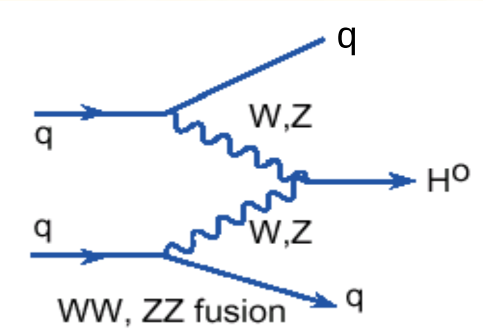


- Looks promising, provided backgrounds (systematic uncertainties) can be controlled
- Exclusion reach is comparable to Tevatron reach (nominal performance) (note that a single experiment is quoted above)

Vector Boson Fusion qq H

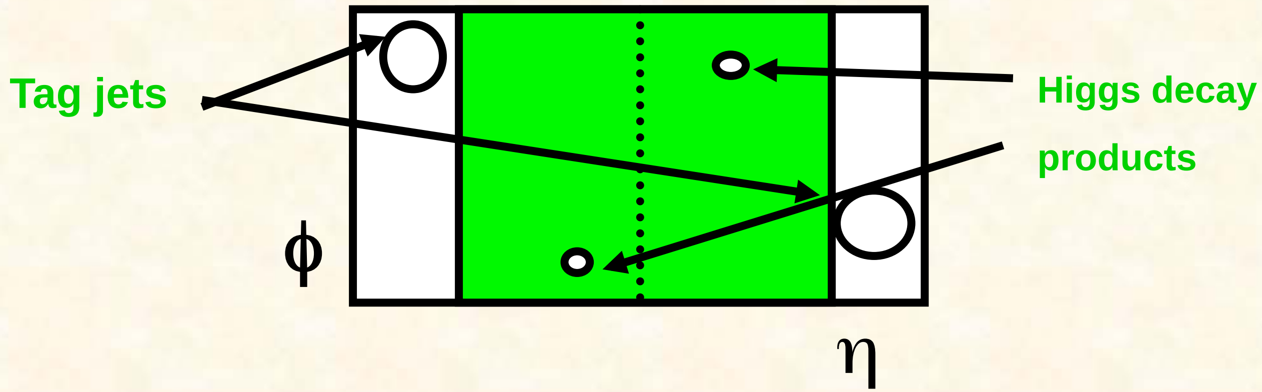
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

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.

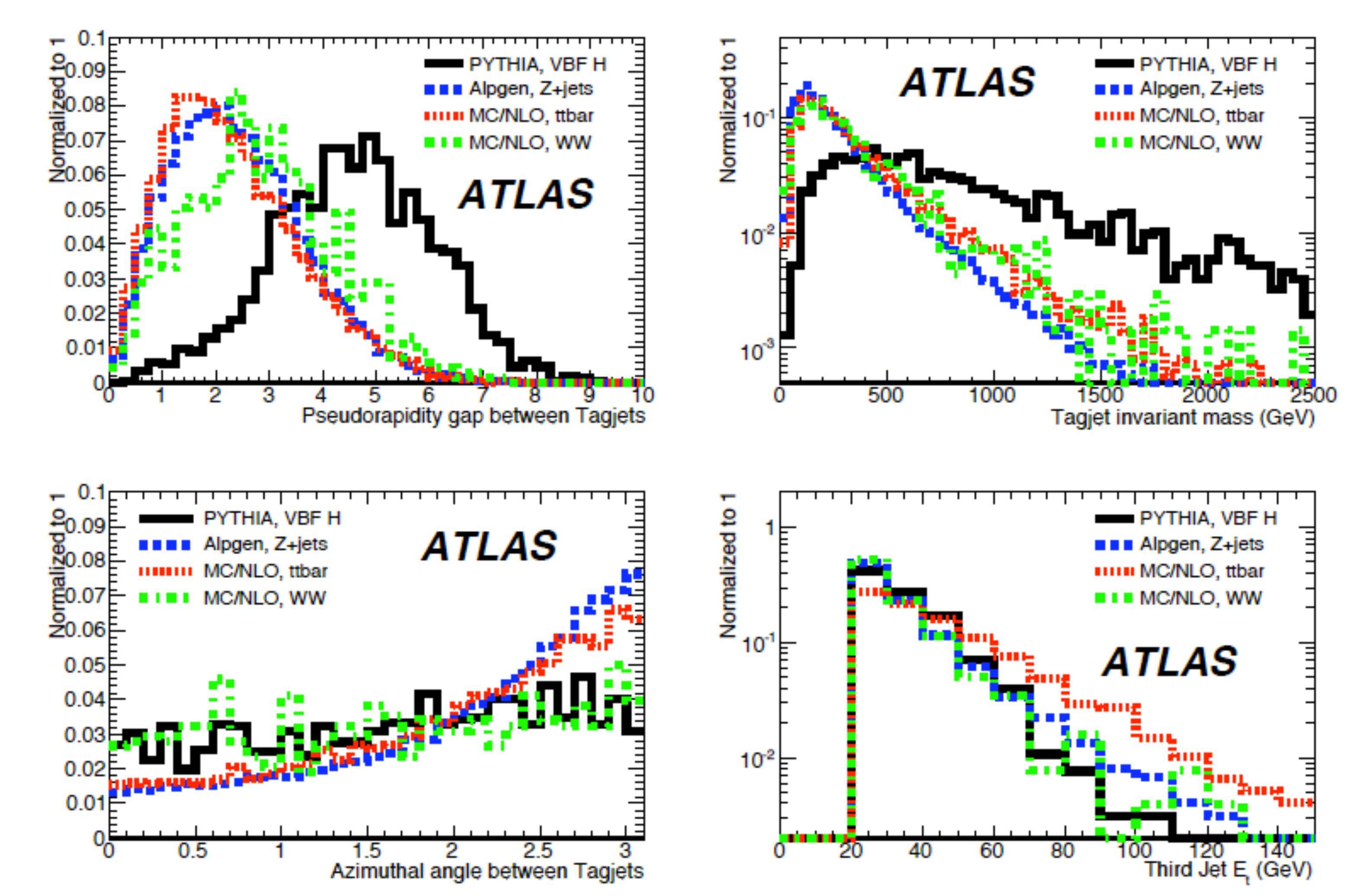


Distinctive Signature of:

- two high p_T forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  $\Rightarrow$ central jet Veto



Forward jet tagging



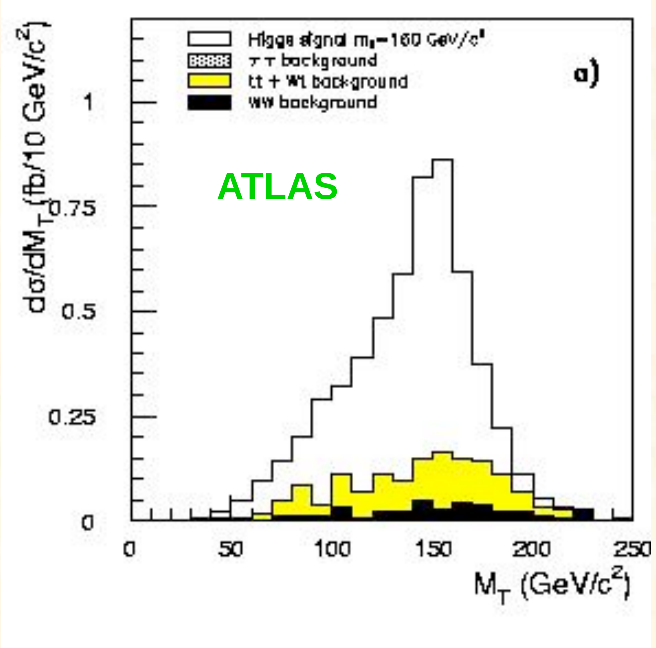
ATLAS full simulation

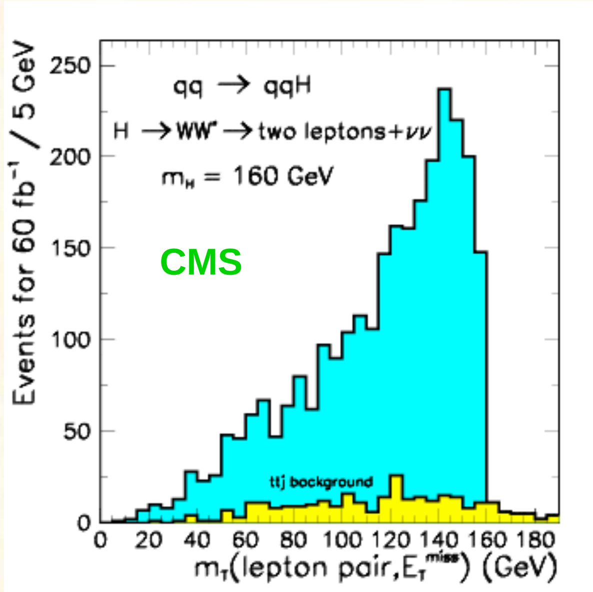
qq H → qq W W*

→ qq ℓν ℓν

<u>Selection criteria:</u>
- Lepton P_T cuts and
- Tag jet requirements ($\Delta\eta$, P_T, large mass)
- Jet veto (important)
- Lepton angular and mass cuts

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

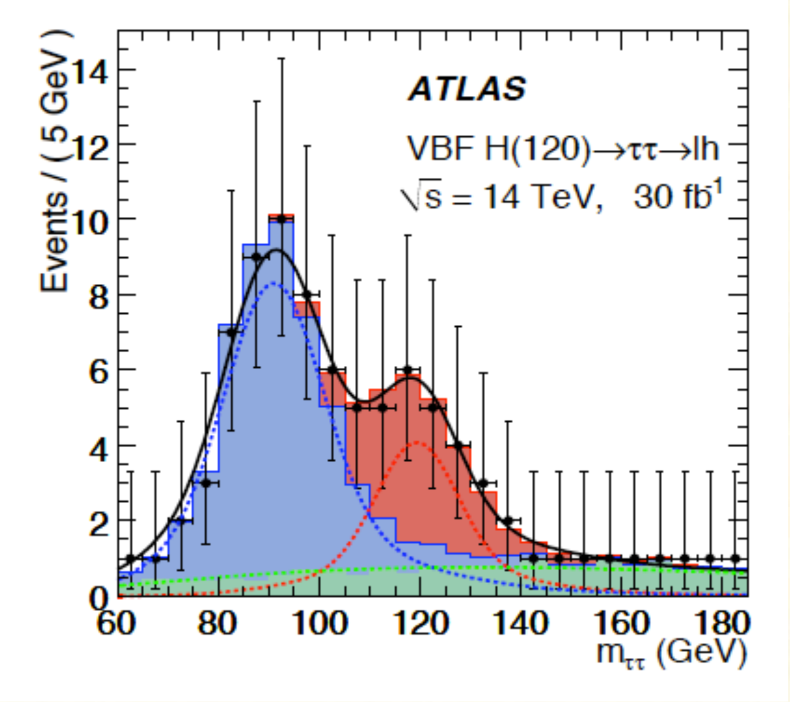




Transverse mass distributions: clear excess of events above the background from tt-production

$H \rightarrow \tau\tau$ decay modes visible for a SM Higgs boson in vector boson fusion

$qq\,H \rightarrow qq\,\tau\,\tau$
$\rightarrow qq\ \ell\nu\nu\ \ \ell\nu\nu$
$\rightarrow qq\ \ell\nu\nu\ \ h\nu$



Experimental challenge:

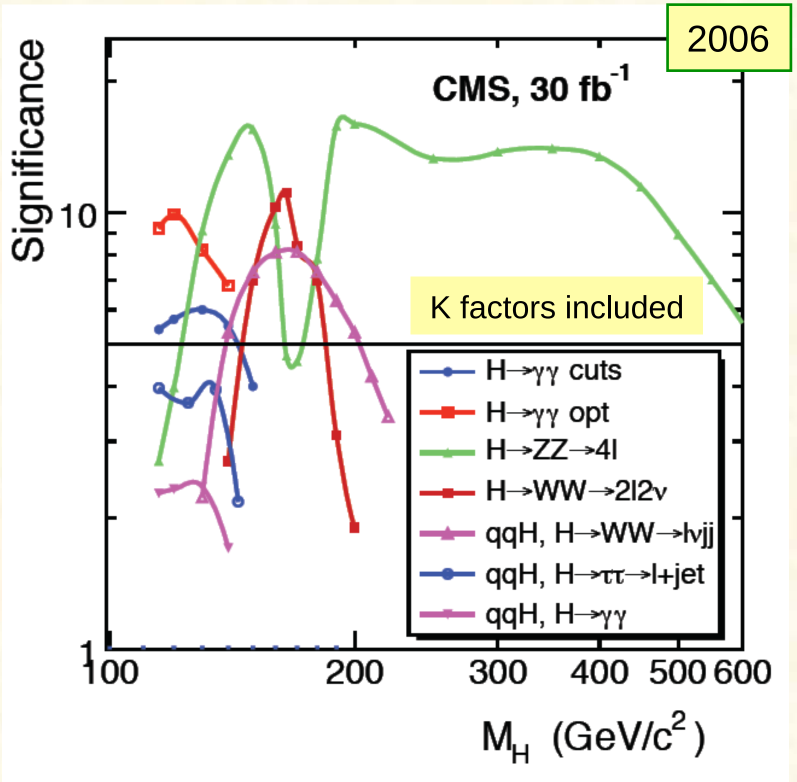
- Identification of hadronic taus
- Good E_T^{miss} resolution
  (ττ mass reconstruction in collinear approximation,
  i.e. assume that the neutrinos go in the direction of the visible decay products,
  good approximation for highly boosted taus)

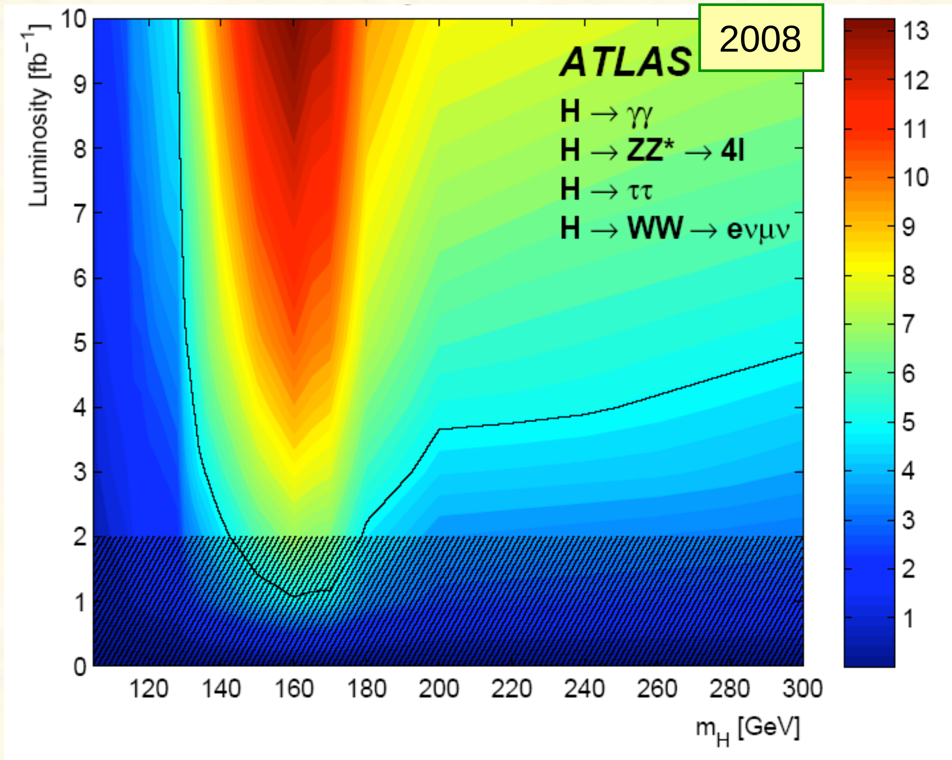
  → Higgs mass can be reconstructed

- Dominant background: $Z \rightarrow \tau\tau$

  the shape of this background must be controlled in the high mass region
  → use data ($Z \rightarrow \mu\mu$) to constrain it

LHC Higgs boson discovery potential for √s = 14 TeV

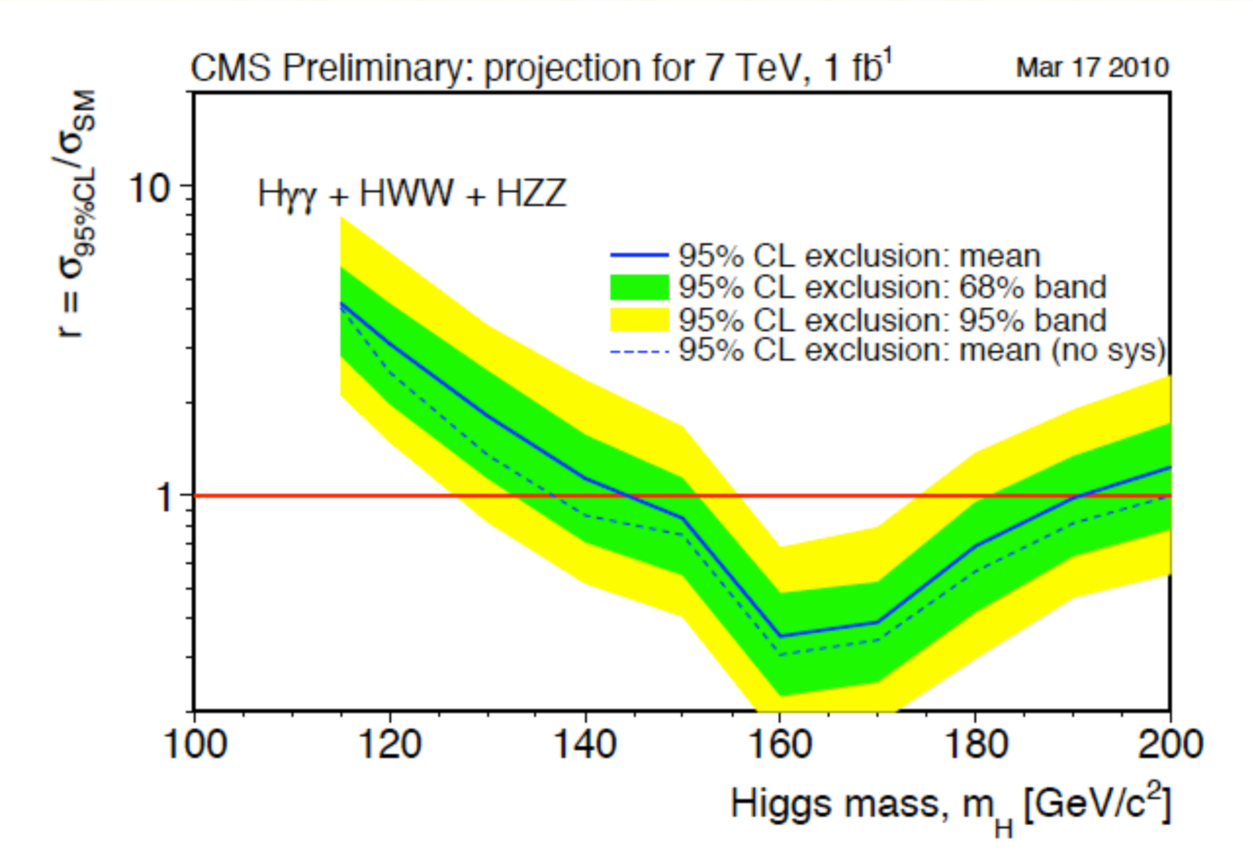




- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]

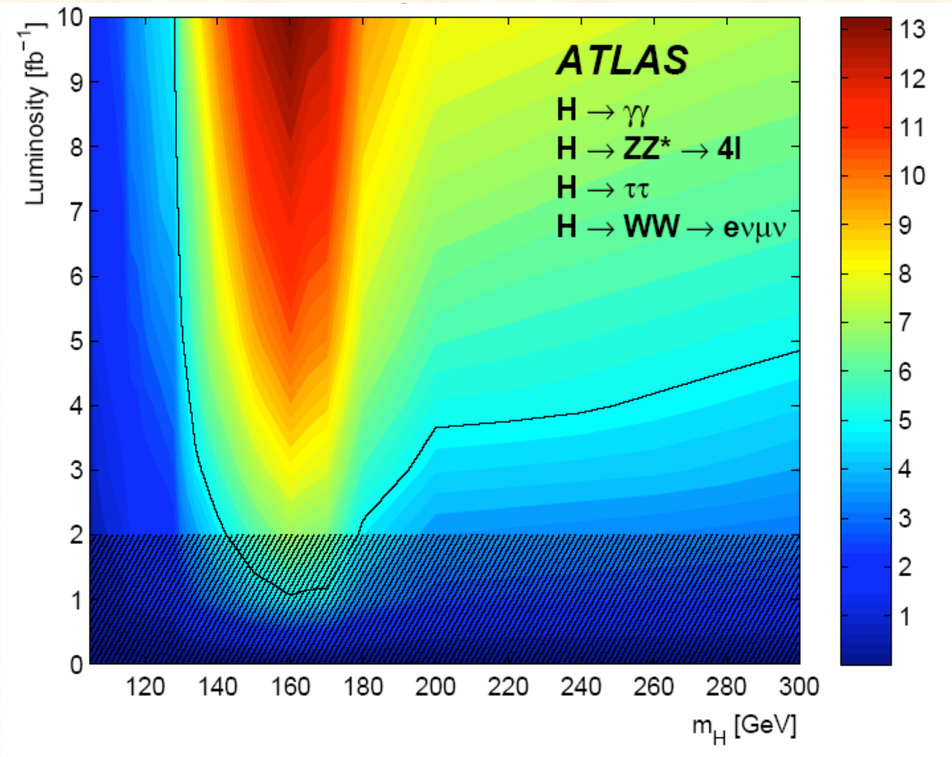
- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)

What can be achieved with 1 fb^{-1} at $\sqrt{s}$ = 7 TeV ?



- Combination of the WW, γγ and ZZ decay channels
  (CMS study, preliminary, numbers from 14 TeV scaled down)

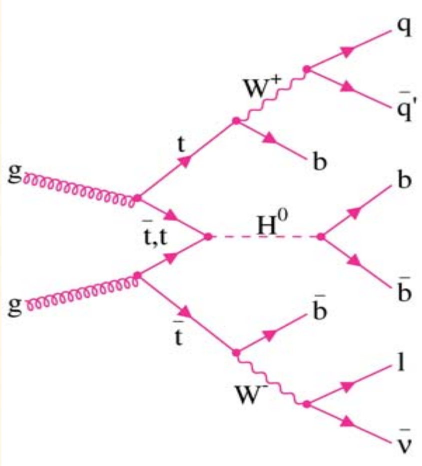
- Mass range in the region between 145 and 190 GeV can be excluded within one experiment



Can the situation at low mass be improved by detecting the bb decay mode ?

(needs higher luminosity and energy)

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

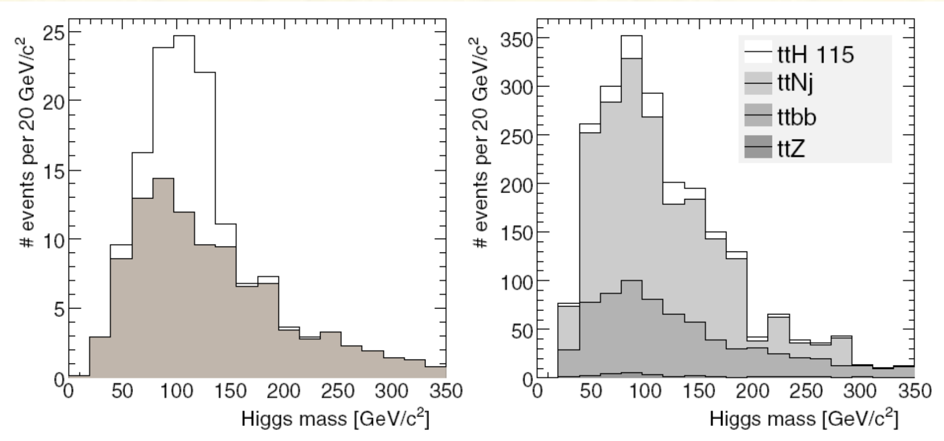


Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

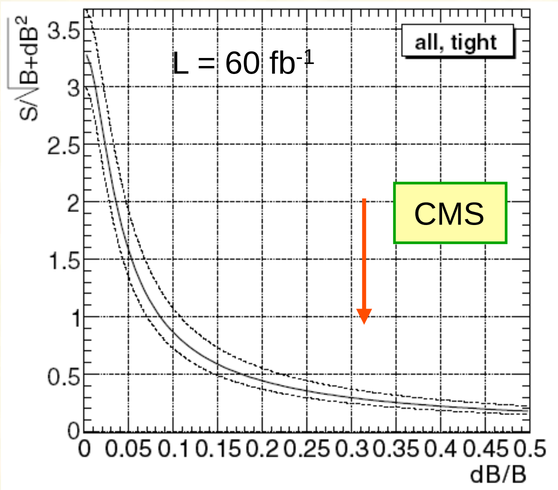
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds
→ larger backgrounds (ttjj dominant), experimental + theoretical uncertainties, e.g. ttbb, exp. norm. difficult…..

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



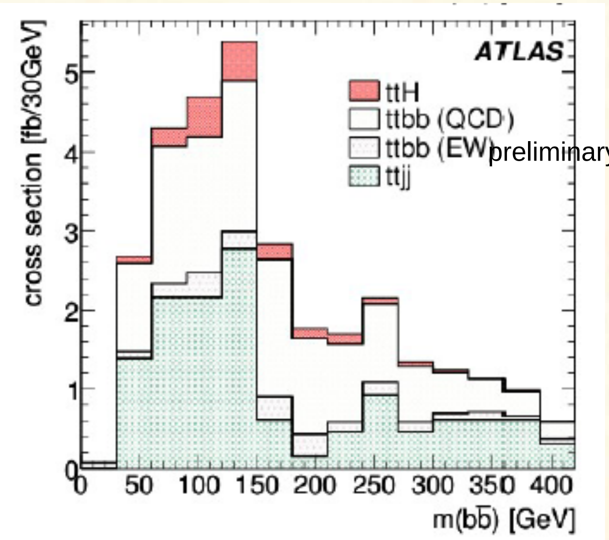
Signal events only …. backgrounds added

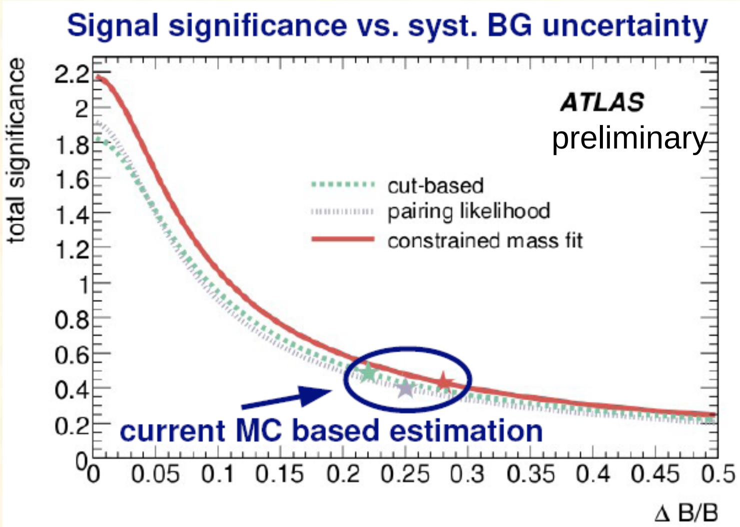


Signal significance as function of background uncertainty

…..comparable situation in ATLAS (ttH cont.)

Preselection cut	$t\bar{t}H$(fb)	$t\bar{t}b\bar{b}$(EW) (fb)	$t\bar{t}b\bar{b}$(QCD) (fb)	$t\bar{t}X$ (fb)
lepton cuts (ID + p_T)	$57. \pm 0.2$	141 ± 1.0	1356 ± 6	63710 ± 99
+ $\geq$ 6 jets	36 ± 0.2	77 ± 0.9	665 ± 4	26214 ± 64
+ $\geq$ 4 loose b-tags	16.2 ± 0.2	23 ± 0.7	198 ± 3	2589 ± 25
+ $\geq$ 4 tight b-tags	3.8 ± 0.06	4.2 ± 0.2	30 ± 0.8	51 ± 2
	LO	LO	LO	NLO





estimated uncertainty on the background: ± 25% (theory, + exp (b-tagging))

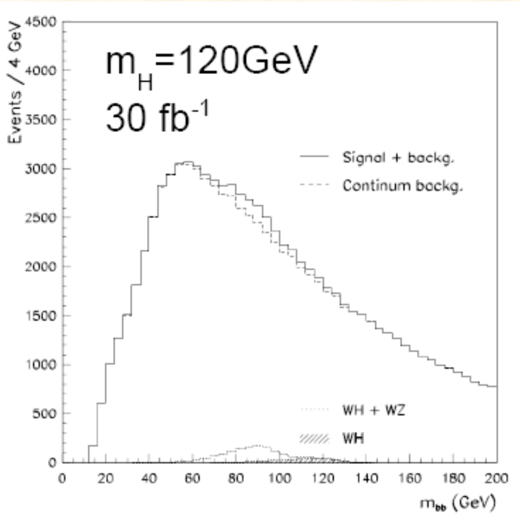
⇒ Normalization from data needed to reduce this (non trivial,…)

New hope for H→ bb decays at the LHC: W/Z H, H → bb

NEW!

The most important channels at the TEVATRON at low mass!

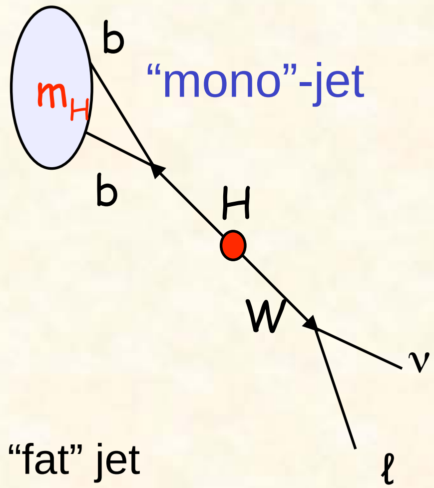
But: signal-to-background ratio less favourable at the LHC



$S/\sqrt{B}$	2.1
S/B	1.3%

Follow idea of J. Butterworth, et al.
[PRL 100 (2008) 242001]

Select events (≈5% of cross section), in which H und W bosons have large transverse momenta: p_T > 200 GeV



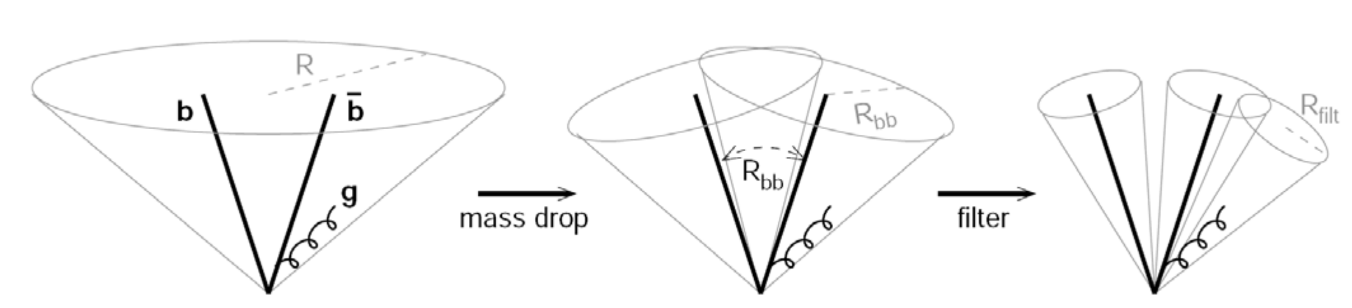
→ b-quarks in one “fat” jet

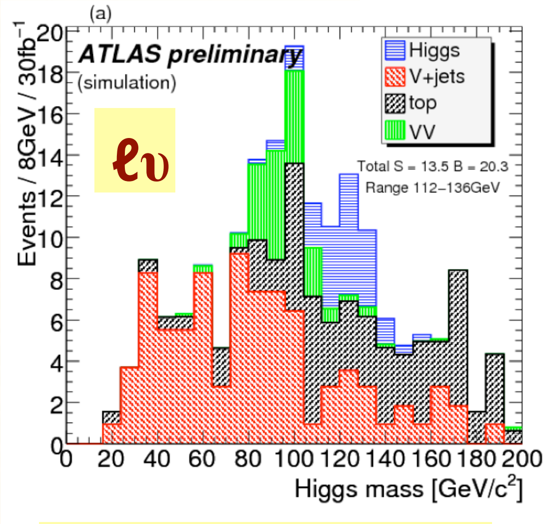
+ Acceptance (more central in detector)
+ Lepton identification, b-tagging

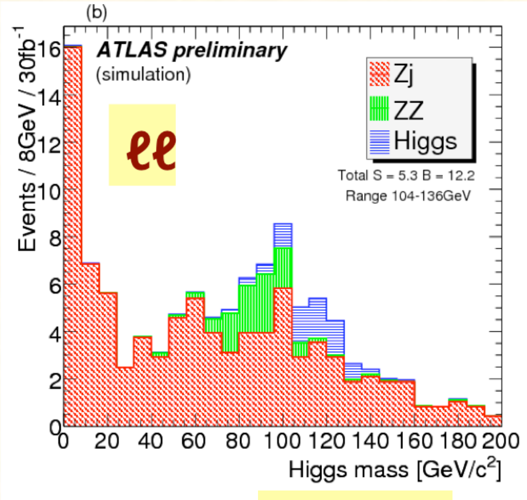
High p_T W/Z H, H → bb

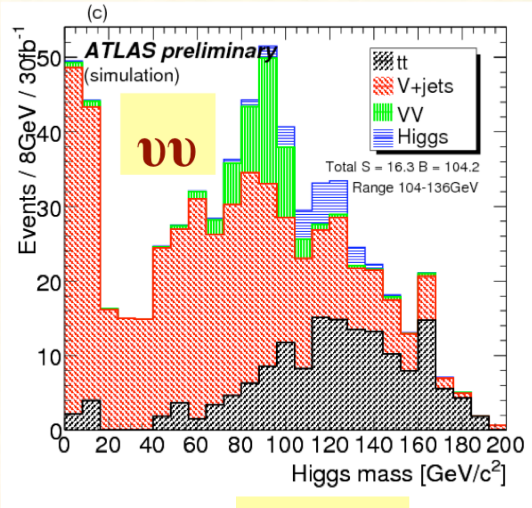
ATL-PHYS-PUB-2009-088

Analyze jet structure:









$L^{int.} = 30\, fb^{-1} : \frac{S}{\sqrt{B}} = 3.0$

M_H = 120 GeV

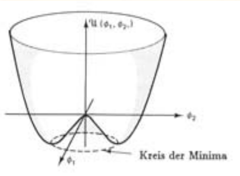
$\frac{S}{\sqrt{B}} = 1.5$

$\frac{S}{\sqrt{B}} = 1.6$

Combined: $\frac{S}{\sqrt{B}} = 3.7$

(Pileup not yet included)

- S/B much better than for ttH
- Different backgrounds for different channels
- Still good sensitivity including systematics
  (e.g. S/√B = 3.0 for 15% uncertainty on all backgrounds)



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

- Mass
- Couplings to bosons and fermions
- Spin and CP
- Higgs self coupling

Motivation:

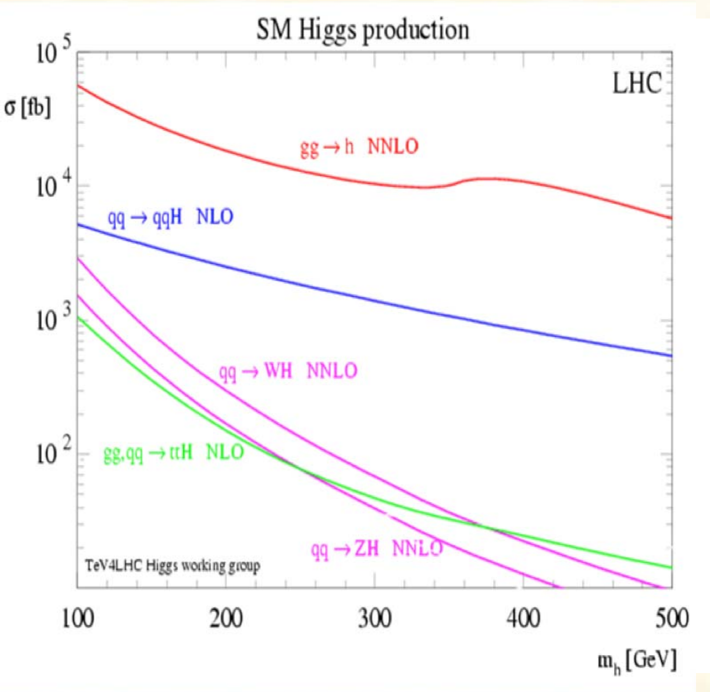
- After a discovery of a “Higgs-like” resonance at the LHC one has to measure its parameters and consolidate the evidence for a Higgs boson
- As many parameters as possible have to be measured in as many different production and decay channels as possible ! (global fit, see later)
- Discriminate between: SM Higgs boson,
  MSSM like Higgs boson,
  Composite Higgs boson, ….

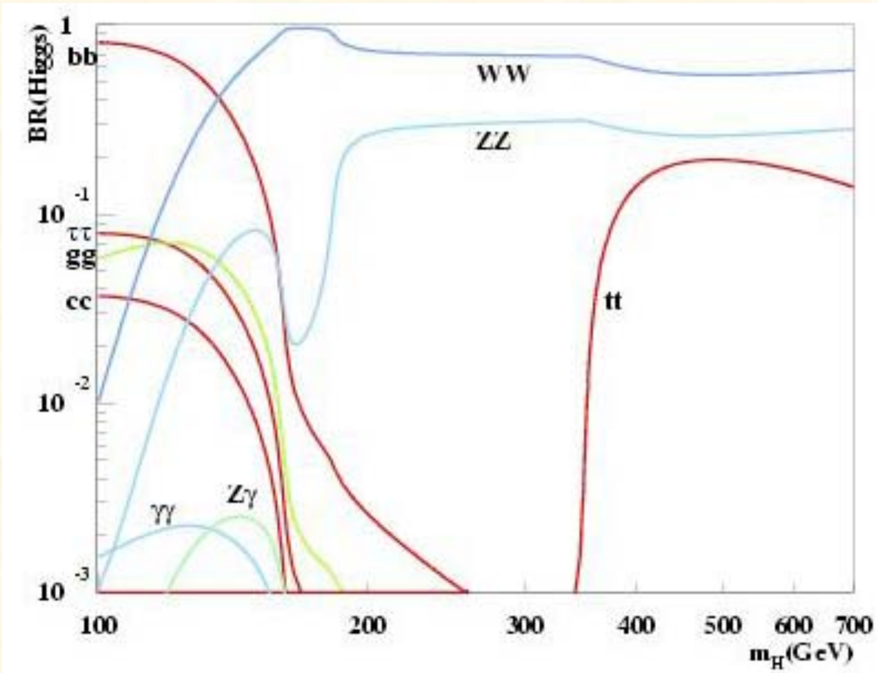
(i) Measurement of the Higgs boson mass

- 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)

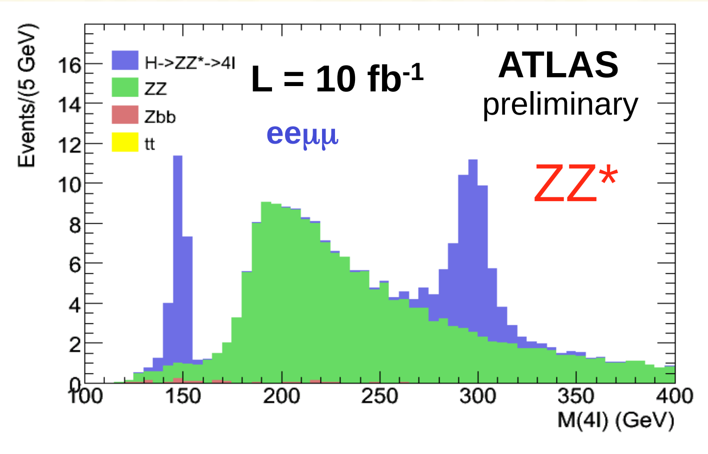
- In addition: the Higgs mass value is important for the parameter measurements (in particular for the extraction of ratios of couplings) …..

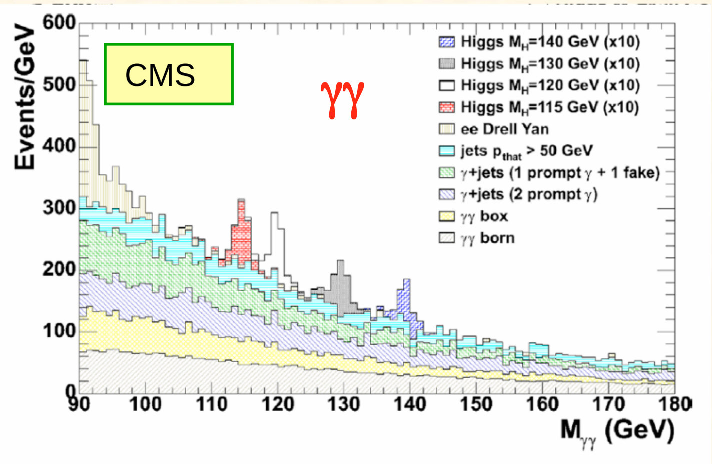
… as many experimental observables / input values need to be compared to the theoretical predictions, which in turn depend -sometimes rather strongly- on m_H



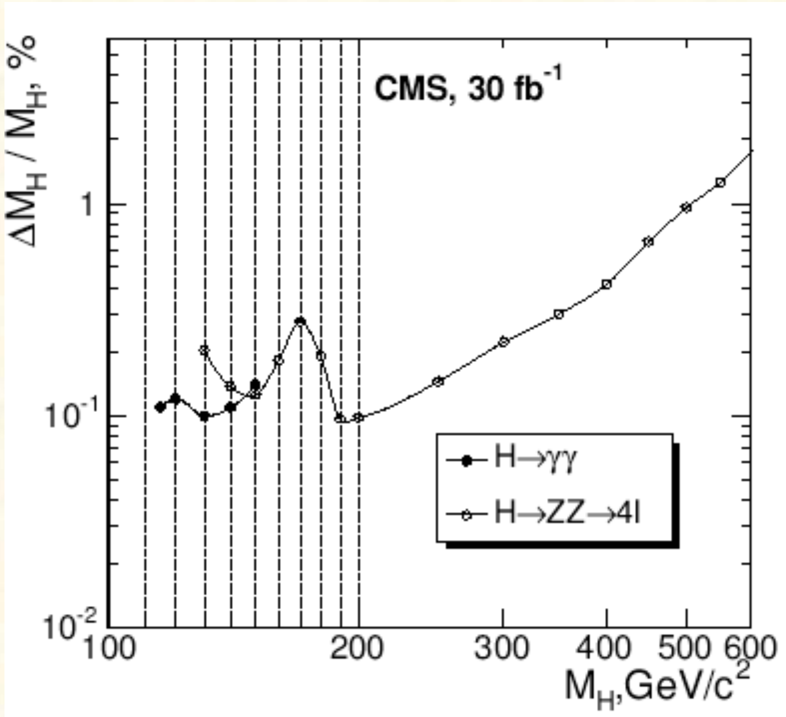


Precision on mass is achieved in el.magn. final states





Dominant systematic uncertainty:
γ / ℓ energy scale.
assumed: 1‰ (goal 0.2‰)
Scale from Z → ℓℓ (close to light Higgs)



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 boson mass (cont.)

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

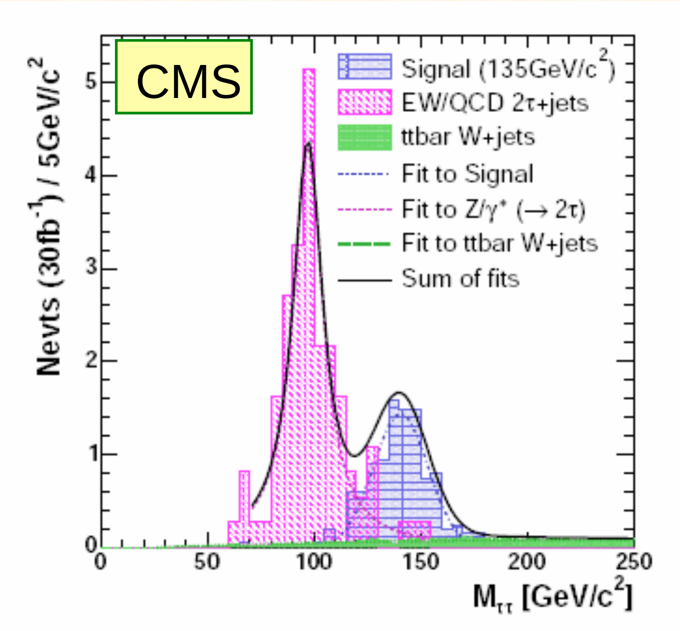
(even the $\gamma\gamma$ decay mode would be affected, since the WW loop contribution is dominant)

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

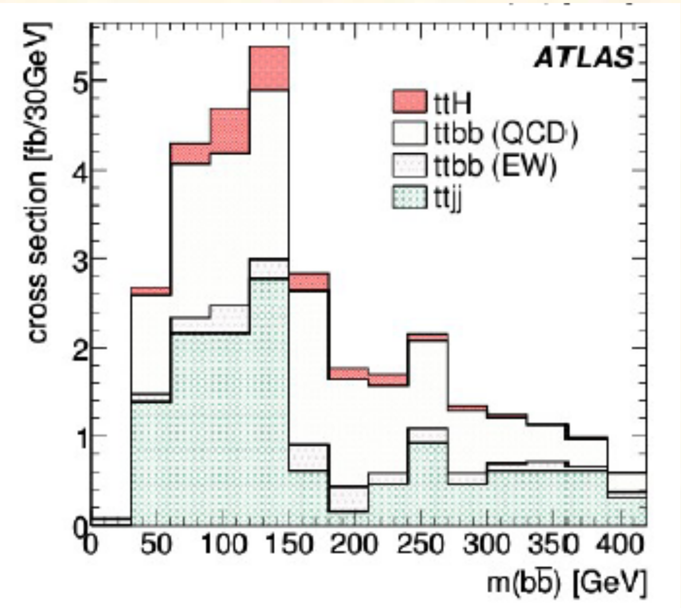
$H \to bb$

(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

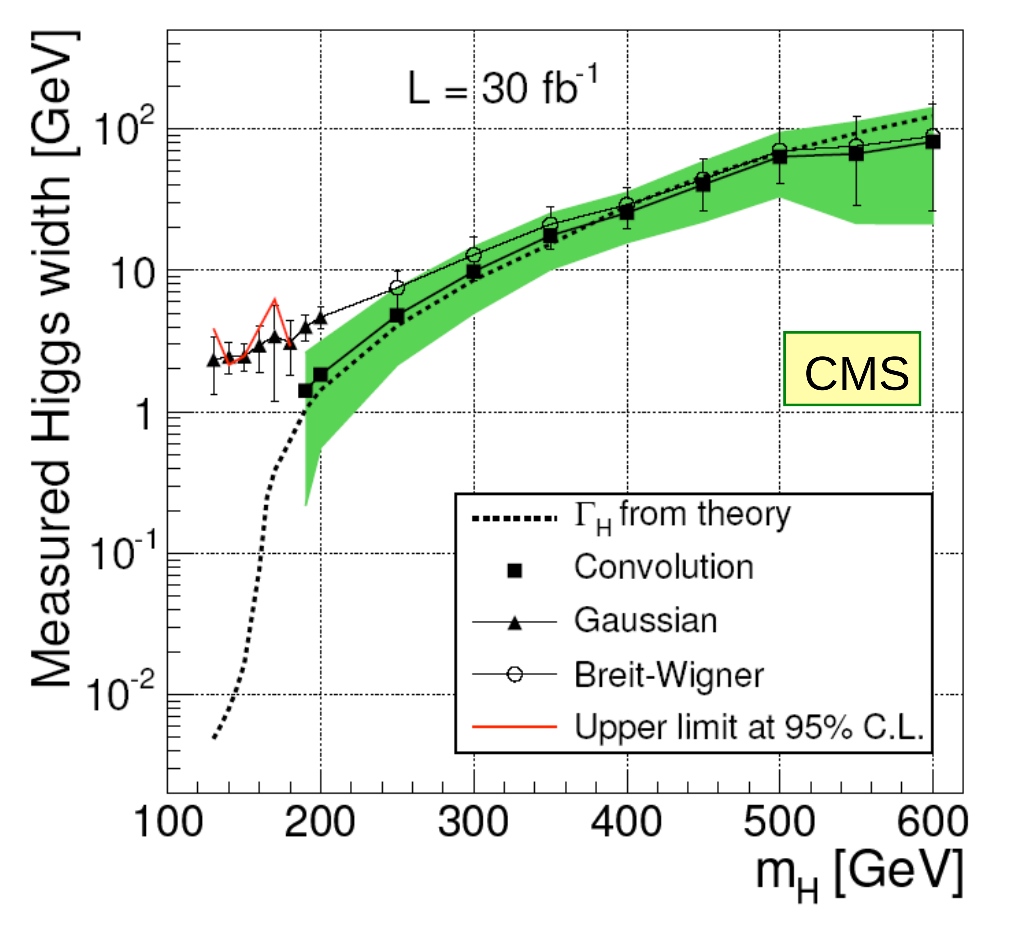


tt H, H → bb



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

Direct extraction of the Higgs boson width:



(ii) Higgs boson couplings to fermions and bosons

The Higgs boson couplings can in principle be extracted from rate measurements,

$$\sigma_{yy \to H} \cdot BR(H \to xx) \sim \Gamma_y \cdot \Gamma_x / \Gamma_H$$

however, Γ_H is needed, which cannot be directly measured at the LHC for $m_H < 200$ GeV.

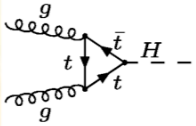
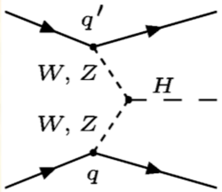
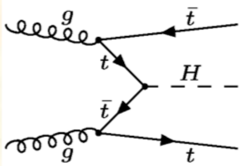
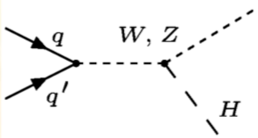
Two options:

(i) Measure ratios of couplings
Systematic uncertainties taken into account;
M. Dührssen, ATLAS-PHYS-2003-030.

(ii) Include more theoretical assumptions and measure absolute couplings
M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld, Phys. Rev. D70 (2004) 113009.

For both options, the information from all visible Higgs boson production and decay modes can be combined into one global maximum likelihood fit

Experimental input:

Production		Decay	mass range	
	Gluon-Fusion $(gg \to H)$	$H \to ZZ \to 4l$	110 GeV - 200 GeV	
		$H \to WW \to l\nu\, l\nu$	110 GeV - 200 GeV	
		$H \to \gamma\gamma$	110 GeV - 150 GeV	
	WBF $(qq\,H)$	$H \to ZZ \to 4l$	110 GeV - 200 GeV	
		$H \to WW \to l\nu\, l\nu$	110 GeV - 190 GeV	
		$H \to \tau\tau \to l\nu\nu\, l\nu\nu$	110 GeV - 150 GeV	
		$H \to \tau\tau \to l\nu\nu\, \mathrm{had}\nu$	110 GeV - 150 GeV	
		$H \to \gamma\gamma$	110 GeV - 150 GeV	
	$t\bar{t}H$	$H \to WW \to l\nu\, l\nu\, (l\nu)$	120 GeV - 200 GeV	optimistic assumptions
		$H \to b\bar{b}$	110 GeV - 140 GeV	optimistic assumptions
		$H \to \gamma\gamma$	110 GeV - 120 GeV	
	WH	$H \to WW \to l\nu\, l\nu\, (l\nu)$	150 GeV - 190 GeV	optimistic assumptions
		$H \to \gamma\gamma$	110 GeV - 120 GeV	
	ZH	$H \to \gamma\gamma$	110 GeV - 120 GeV	

Mass range is restricted to m_H < 200 GeV
Based on „old ATLAS studies“
Most significant differences: ttH channels with H → bb and H → WW
Updates in preparation, T. Plehn, M. Dührssen et al.

Higgs-Boson Couplings (cont.)

Global fit

(all channels at a given mass point)

Analysis is done with increasing level of theoretical assumptions

Fit parameters:

$$\frac{g_Z^2}{g_W^2} \quad \frac{g_\tau^2}{g_W^2} \quad \frac{g_b^2}{g_W^2} \quad \frac{g_t^2}{g_W^2} \quad \frac{g_W^2}{\sqrt{\Gamma_H}}$$

Production cross-sections

$$\sigma_{ggH} = \alpha_{ggH} \bullet g_t^2$$
$$\sigma_{VBF} = \alpha_{WF} \bullet g_W^2 + \alpha_{ZF} \bullet g_Z^2$$
$$\sigma_{ttH} = \alpha_{ttH} \bullet g_t^2$$
$$\sigma_{WH} = \alpha_{WH} \bullet g_W^2$$
$$\sigma_{ZH} = \alpha_{ZH} \bullet g_Z^2$$

(b loop neglected so far in ggH)

Branching ratios

$$BR(H \to WW) = \beta_W \frac{g_W^2}{\Gamma_H}$$
$$BR(H \to ZZ) = \beta_Z \frac{g_Z^2}{\Gamma_H}$$
$$BR(H \to \gamma\gamma) = \frac{(\beta_{\gamma(W)} g_W - \beta_{\gamma(t)} g_t)^2}{\Gamma_H}$$
$$BR(H \to \tau\tau) = \beta_\tau \frac{g_\tau^2}{\Gamma_H}$$
$$BR(H \to bb) = \beta_b \frac{g_b^2}{\Gamma_H}$$

α,β from theory with assumed Uncertainties:

$\Delta\alpha_{ggH} = 20\%$

$\Delta\alpha_{WF} = \alpha_{ZF} = 4\%$

$\Delta\alpha_{ttH} = 15\%$

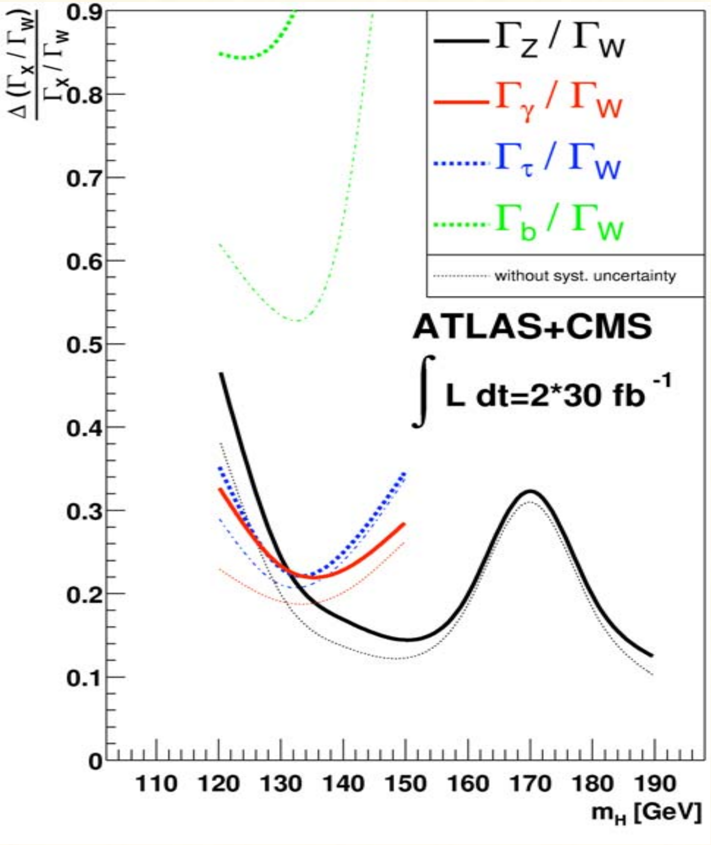
$\Delta\alpha_{WH} = \Delta\alpha_{ZH} = 7\%$

$\Delta\beta = 1\%$

Step 1: measurement of ratios of partial decay width:

Assumption: only one light Higgs boson

To cancel Γ_H, normalization to Γ_W is made
(suitable channel, measurable over a large mass range ~120–200 GeV)

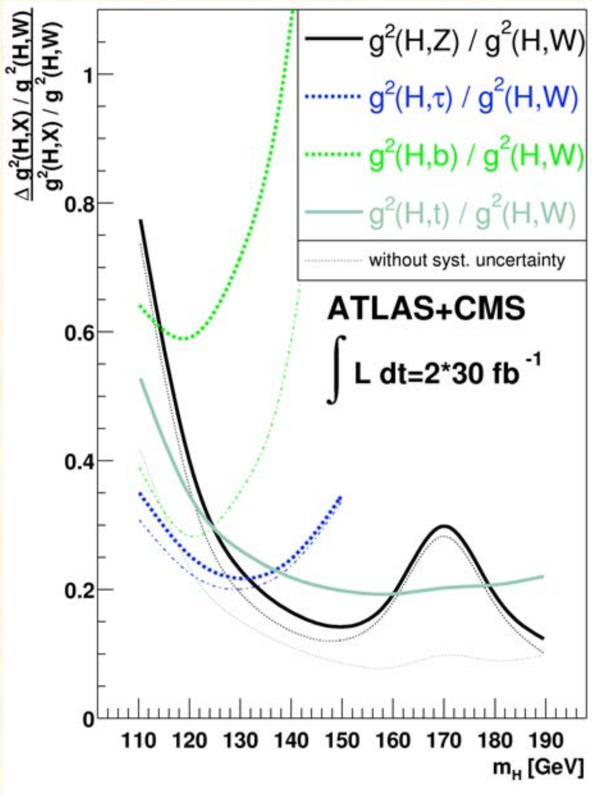


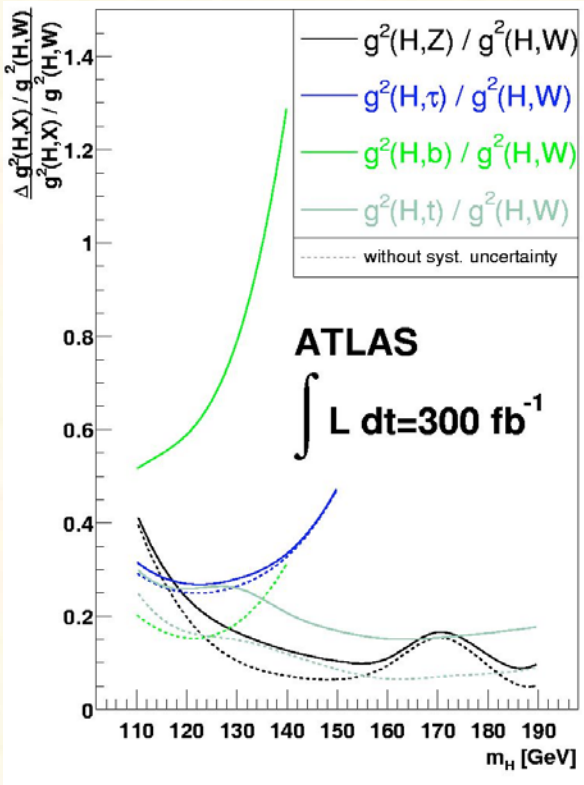
Note: optimistic assumptions for H → bb (based on old studies)

Step 2: measurement of ratios of couplings:

Additional assumption: particle content in the gg- and $\gamma\gamma$-loops are known;

Information from Higgs production is now used as well;
Important for the determination of the top-Yukawa coupling



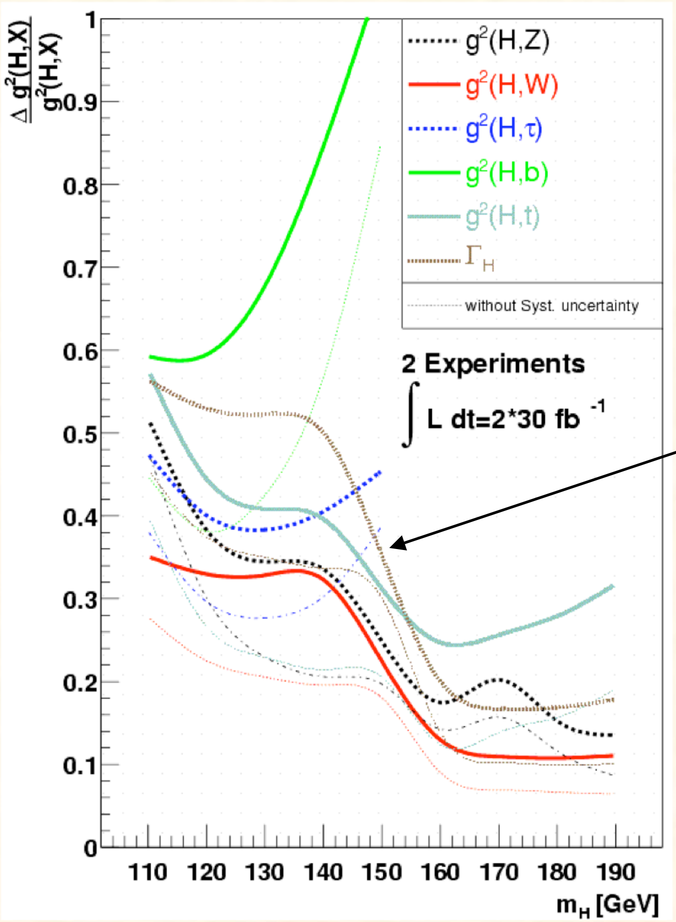


Step 3: measurement of couplings (absolute values):

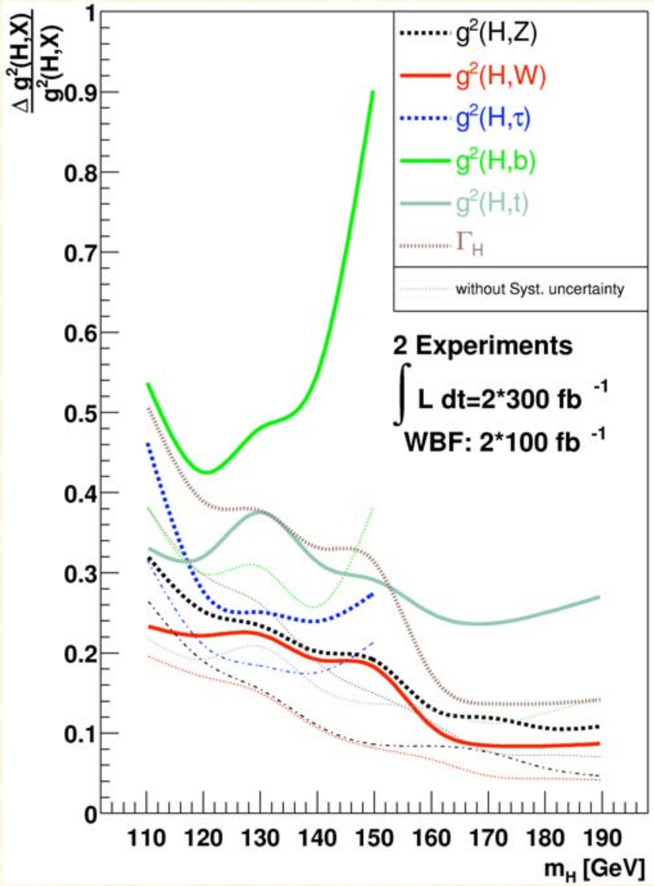
Needs additional *("mild")* theoretical assumptions:

- use lower limit on Γ_H from visible decay modes
- assume that g (H,W) are bound from above by the Standard Model value:

  $g^2(H,W) \leq g^2(H,W,SM)$; (valid for any model that contains only Higgs doublets and singlets)
  (upper value is motivated from WW scattering unitarity arguments)



Total width is "measured" as well

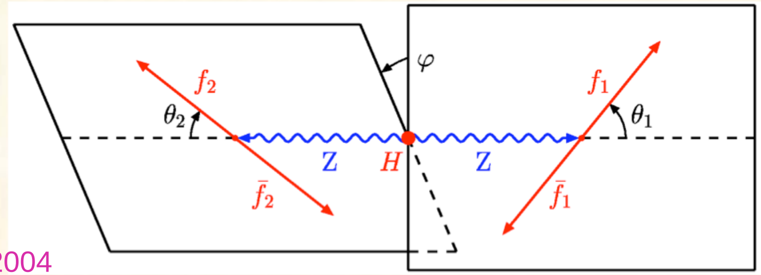


(iii) Spin and CP quantum numbers

Spin:

- Spin 0: angular correlations in H → WW → ℓν ℓν decays
- More general: Angular distributions in the decay channel H → ZZ$^{(*)}$ → 4 ℓ are sensitive to spin and CP eigenvalues

  - Azimuthal angle φ
  - Polar angle θ



J.R. Dell'Aquila and C.A. Nelson Phys.Rev.D33:101,1986
S.Choi,D.Miller,M.Mühlleitner and P.Zerwas Phys.Lett.B553 (2003)
C.P.Buszello,I.Fleck,P.Marquard and J.J. van der Bij, Eur Phys J C32,209,2004
C.P. Buszello, P. Marquard, J. van der Bij, hep-ph/0406181.
CMS TDR - M.Bluj CMS NOTE 2006/094
R.Godbole,D.Miller and M.Mühlleitner JHEP 0712:031,2007

CP information:

- Angular distributions in the decay channel H → ZZ(*) → 4 ℓ
- Angular correlation of tagging jets in vector boson fusion production
- Angular correlations in ttH decays

J. Gunion and X.G. He, Phys. Rev. Lett. 76 (1996) 4468.
T. Plehn, D.Rainwater and D.Zeppenfeld Phys Rev Lett 88,051801, 2002
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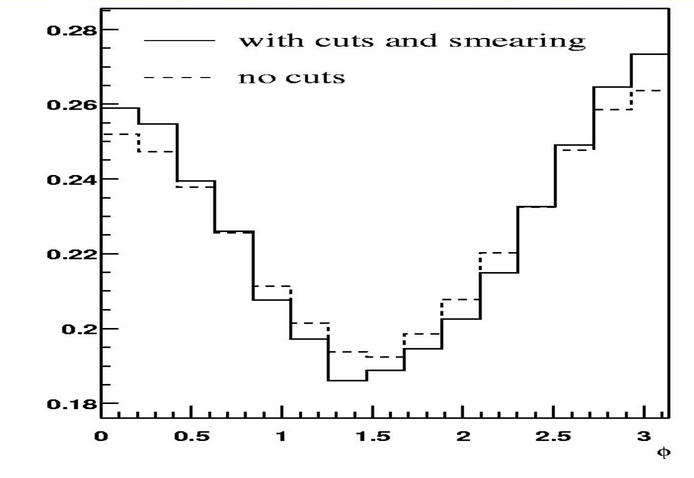
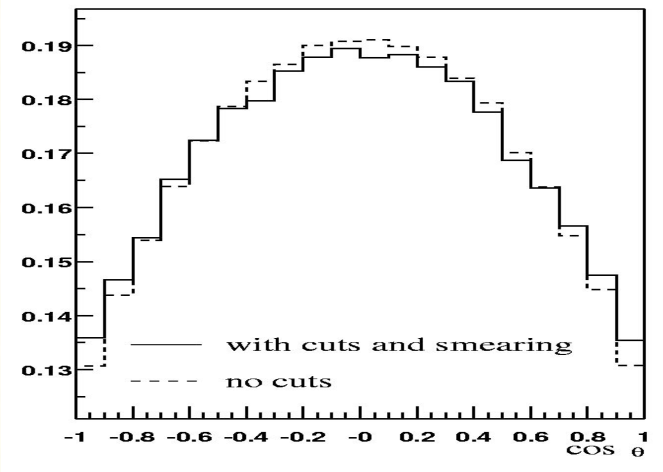
V. Hankele,G. Klamke,D. Zeppenfeld and T. Figy, Phys.Rev.D74:095001,2006
C. Ruwiedel,M. Schumacher and N. Wermes, Eur.Phys.J.C51:385-414,2007

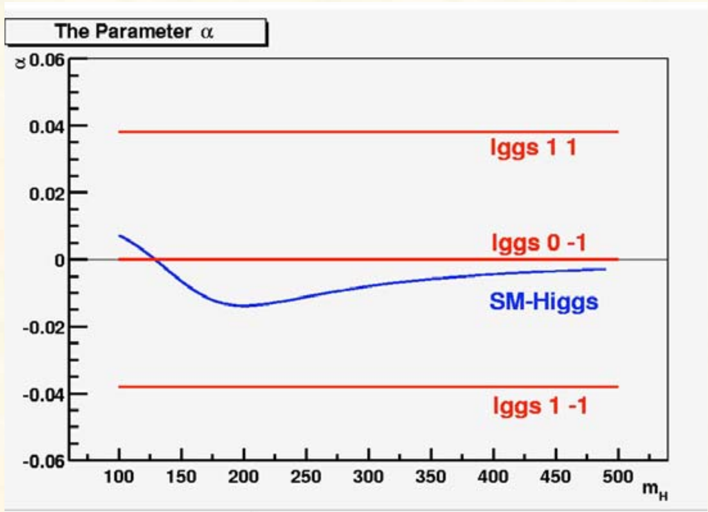
Exploiting angular correlations in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ decays:

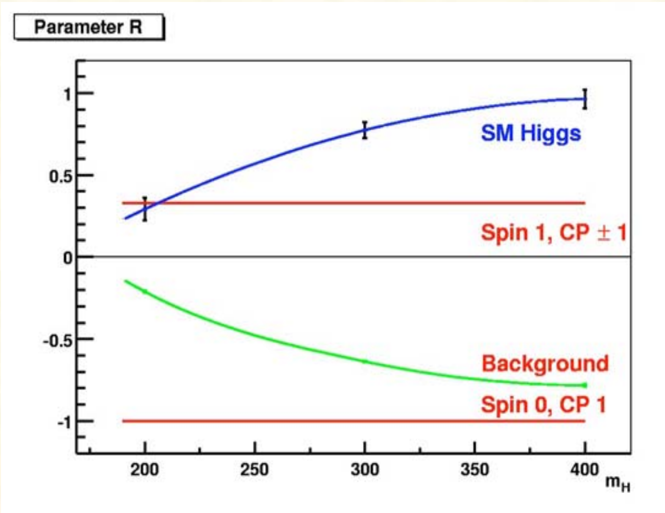




Fit to $F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$

$F(\theta) = T(1+\cos^2\theta) + L \sin^2\theta$ $\qquad R = (L-T)/(L+T)$

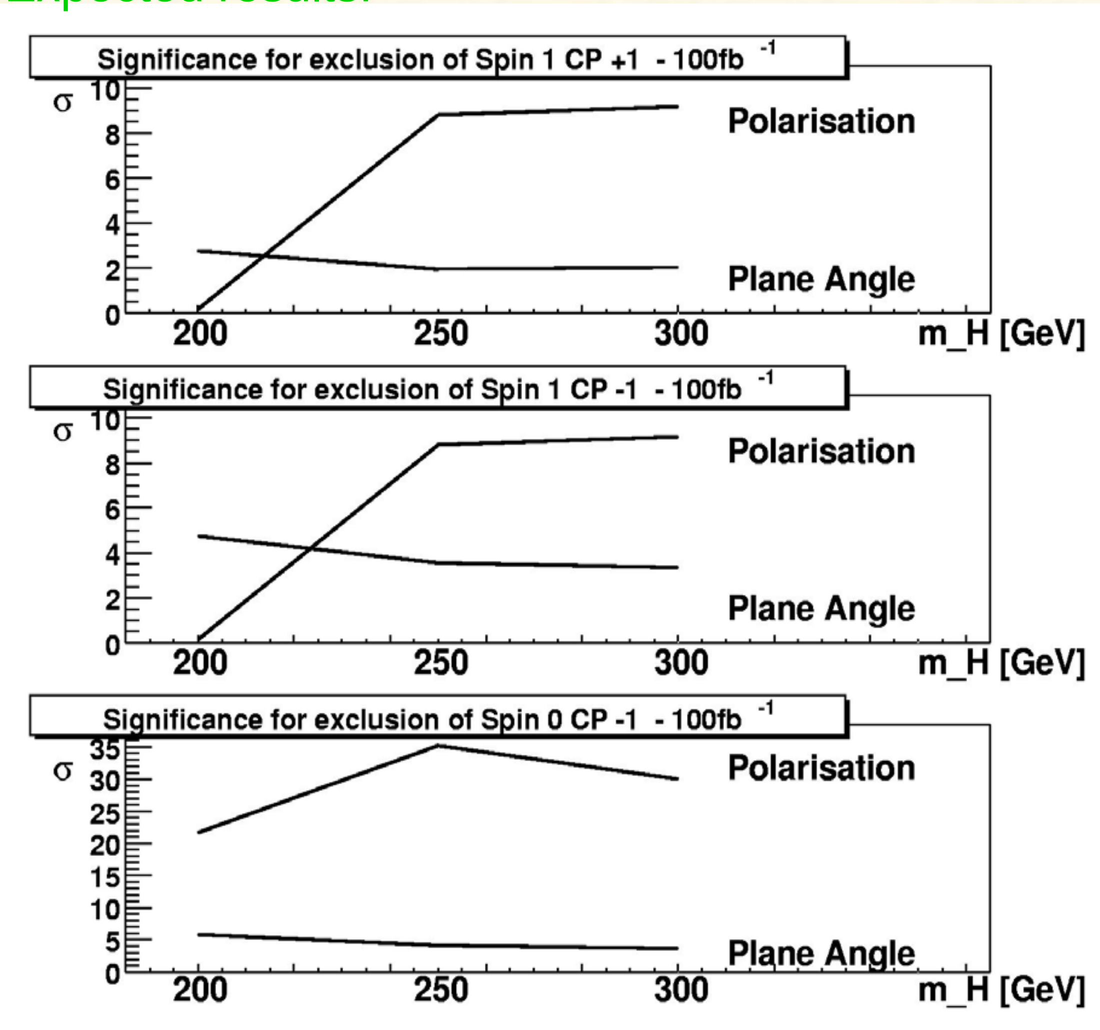




J.R. Dell´Aquila and C.A. Nelson, Phys. Rev. D33 (1986) 101

Exploiting angular correlations in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ decays:

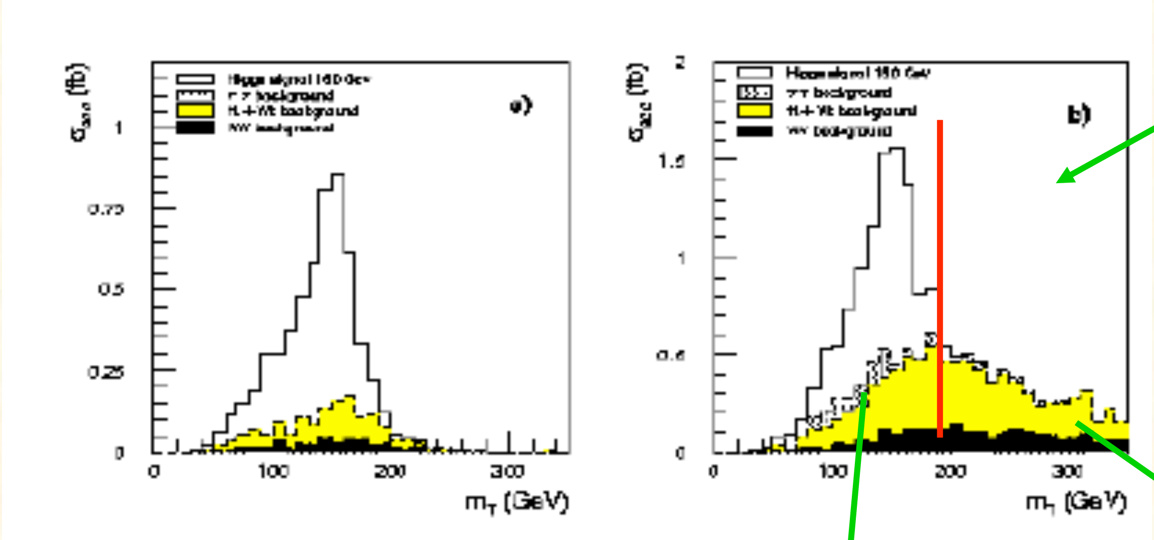
Expected results:



C.P. Buszello, P. Marquard, J. van der Bij et al., SN-ATLAS-2003-025 and Eur. Phys. J C32 (2004) 209.
method extended in: C.P. Buszello, P. Marquard, J. van der Bij, hep-ph/0406181.

Evidence for spin-0 in H → WW → ℓν ℓν

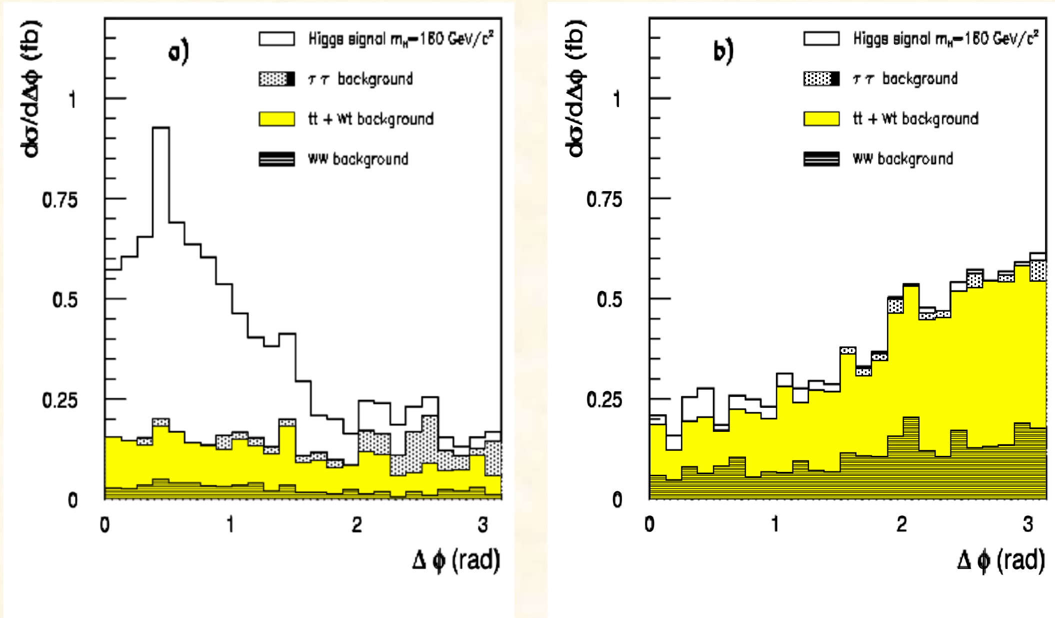
- Cuts can be relaxed, to get background shape from the data + Monte Carlo:



No kinematical cuts on leptons applied: (ATLAS study)

Evidence for spin-0 of the Higgs boson, Δφ distribution

Spin-0 → WW → ℓνℓν expect leptons to be close by in space



S. Asai et al., Eur. Phys. J. C32, (2003) 209.

Tensor structure of Higgs couplings in VBF events

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

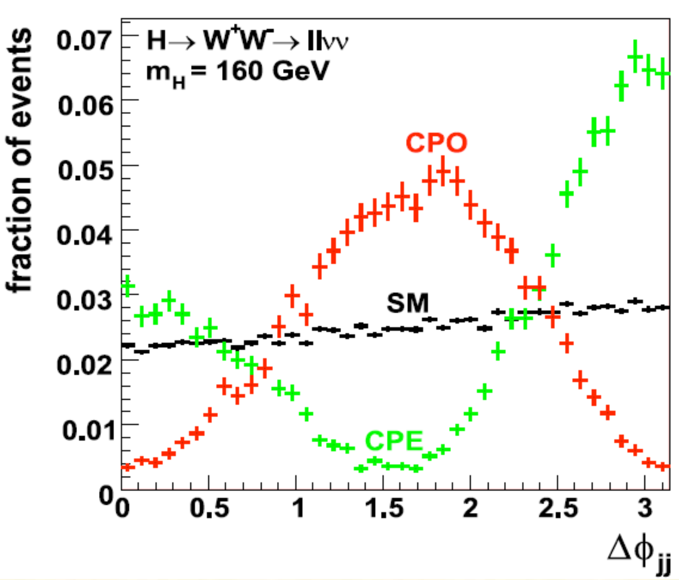
$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)g^{\mu\nu} + a_2(q_1,q_2)\left[q_1\cdot q_2 g^{\mu\nu} - q_2^{\mu}q_1^{\nu}\right] + a_3(q_1,q_2)\varepsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}.$$

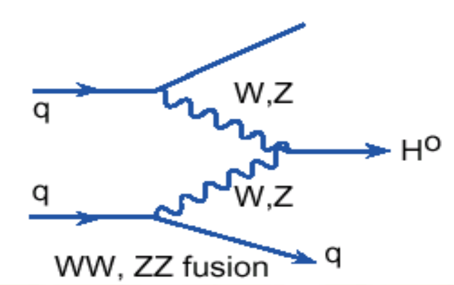
CP even Standard Model term

anomalous CPE term

anomalous CPO term

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





Shapes of $\Delta\phi$ distributions
(no backgrounds, large statistics)

T. Plehn, D.Rainwater and D.Zeppenfeld, Phys. Rev. Lett. 88, (2002) 051801

Tensor structure of Higgs couplings in VBF events (cont.)

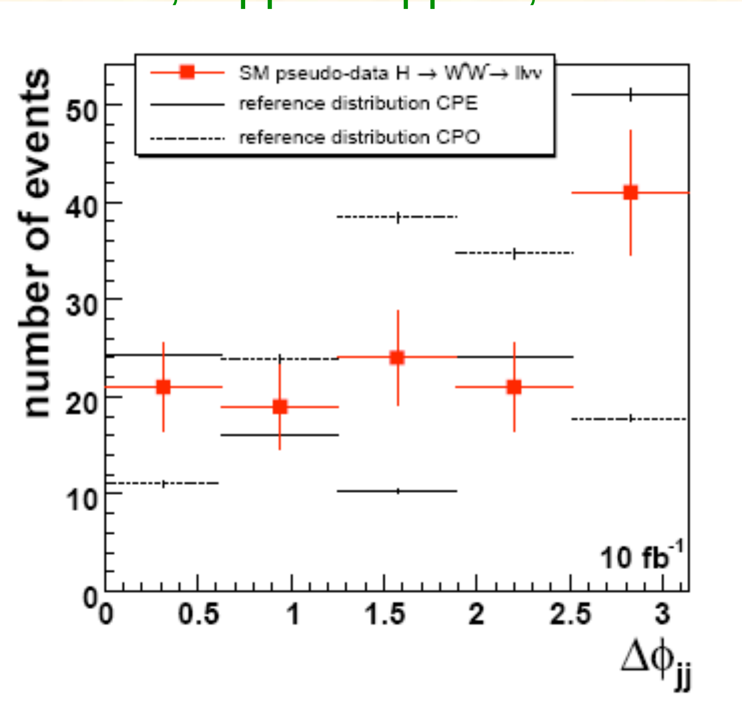
- ATLAS study using the qqH $\rightarrow$ qqWW and qqH $\rightarrow$ qq $\tau\tau$ channels:

  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 $\rightarrow$ qqWW, $L = 10\ fb^{-1}$



Expectations:

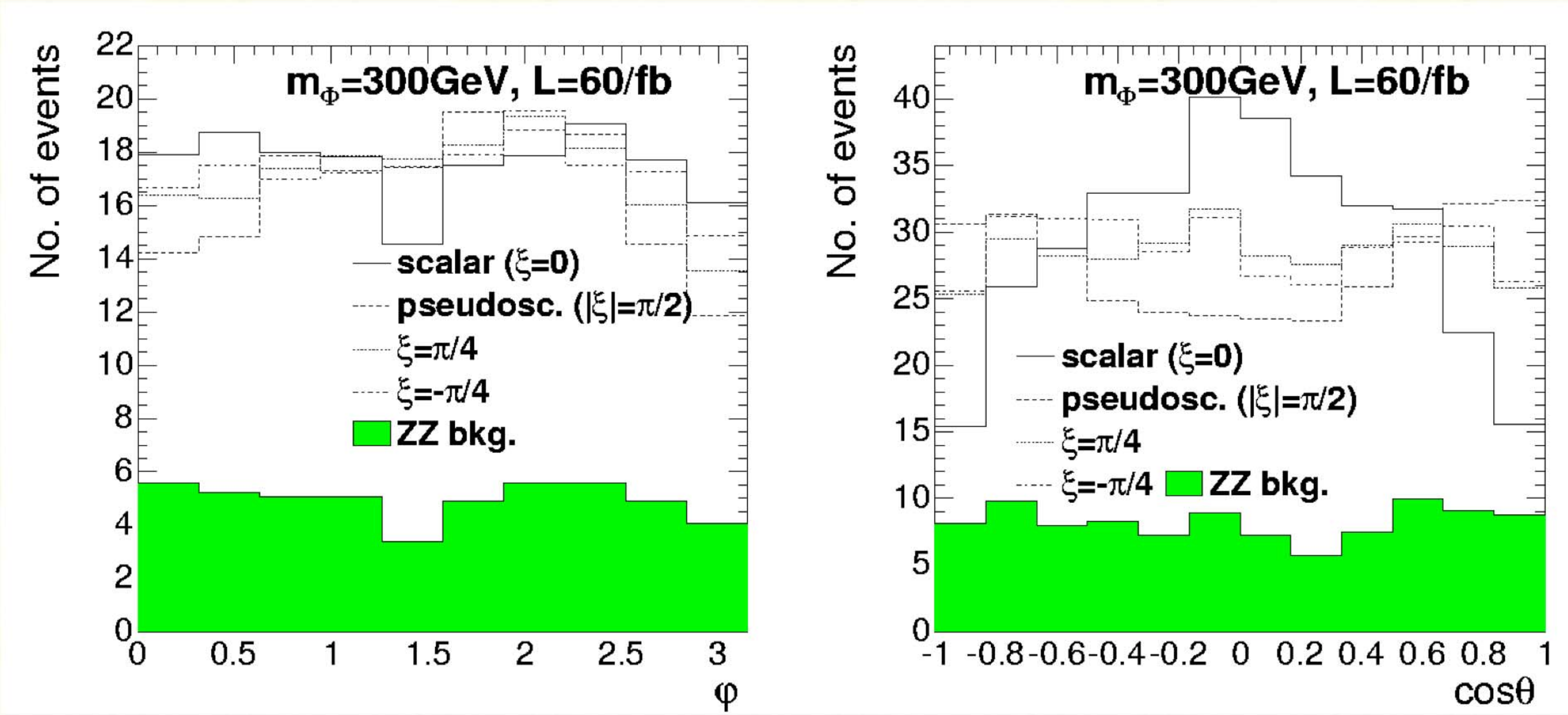
<u>WW decay mode: m_H = 160 GeV</u>
Anomalous CP-even and CP-odd couplings can be excluded with 5σ, for $10\ fb^{-1}$

<u>$\tau\tau$ decay mode: m_H = 120 GeV</u>
Exclusion with a 2σ significance requires $30\ fb^{-1}$

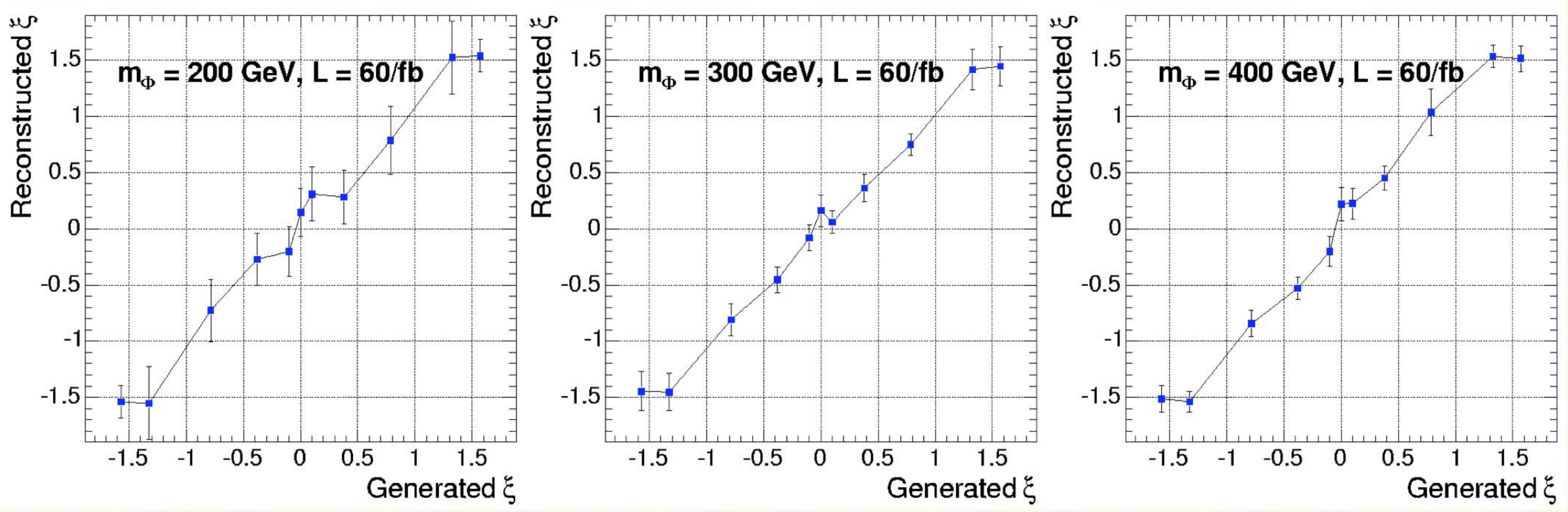
CMS analysis: search for a pseudoscalar admixture

- Use again the angular correlations in $H \rightarrow ZZ \rightarrow 4\ell$ decays
- Assume Spin-0 Higgs boson and allow for a pseudoscalar admixture $\phi = H + \xi A$

(Standard Model (scalar) case: $\xi = 0$)



Results from Monte Carlo experiments for a maximum likelihood fit to the angular distributions and the 4-lepton invariant mass (including signal and background)



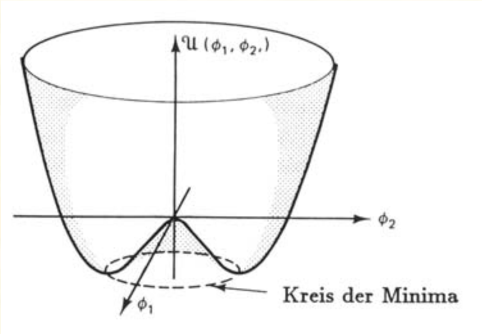
Allows precise measurement of pseudoscalar admixture for 60 fb^{-1}

CMS Collaboration, J. Phys. G 34 (2006) 995

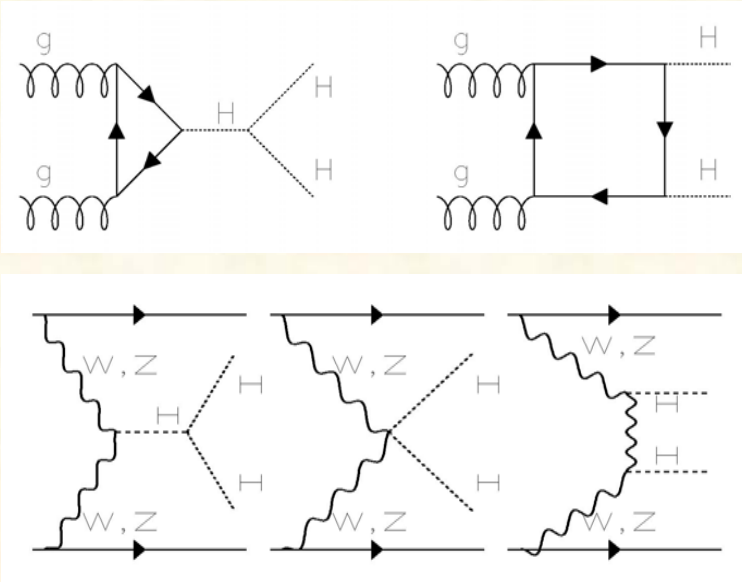
(iv) Higgs boson self-coupling ?

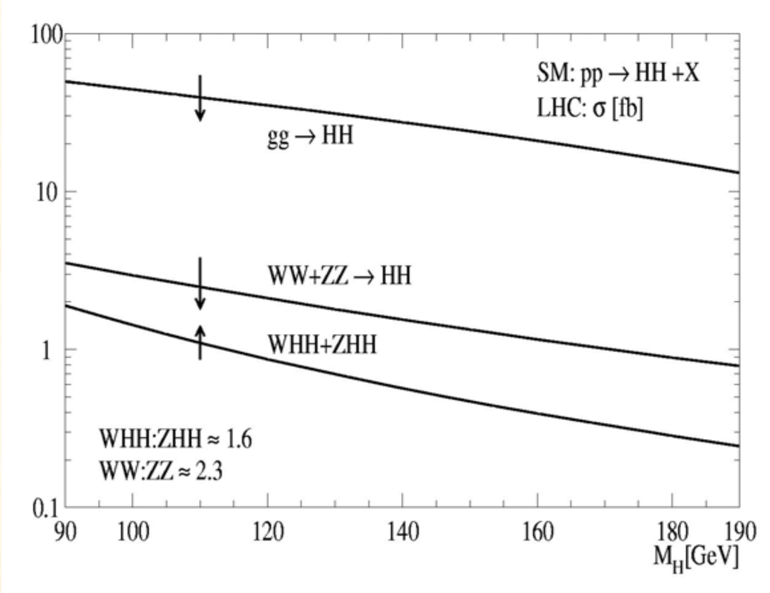
To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

$$\lambda_{HHH}^{SM} = 3\,\frac{m_H^2}{v}\,, \qquad \lambda_{HHHH}^{SM} = 3\,\frac{m_H^2}{v^2}$$



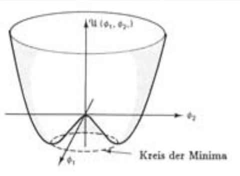
Cross sections for HH production:





small signal cross-sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
need Super LHC $L = 10^{35}$ cm^{-2} sec^{-1}, 6000 fb^{-1}
even there: a measurement is very difficult, needs more studies.



Summary: Is it a Higgs Boson ?

1. Mass

Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and ZZ→ 4ℓ resonances

2. Couplings to bosons and fermions

- 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)

3. Spin and CP

Angular correlations in H → ZZ(*) → 4 ℓ and $\Delta\phi_{jj}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. 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