Physics at LHC and the recent progress toward the first collision

1/11/2007 @ KEK seminar

Katsuo Tokushuku (KEK)

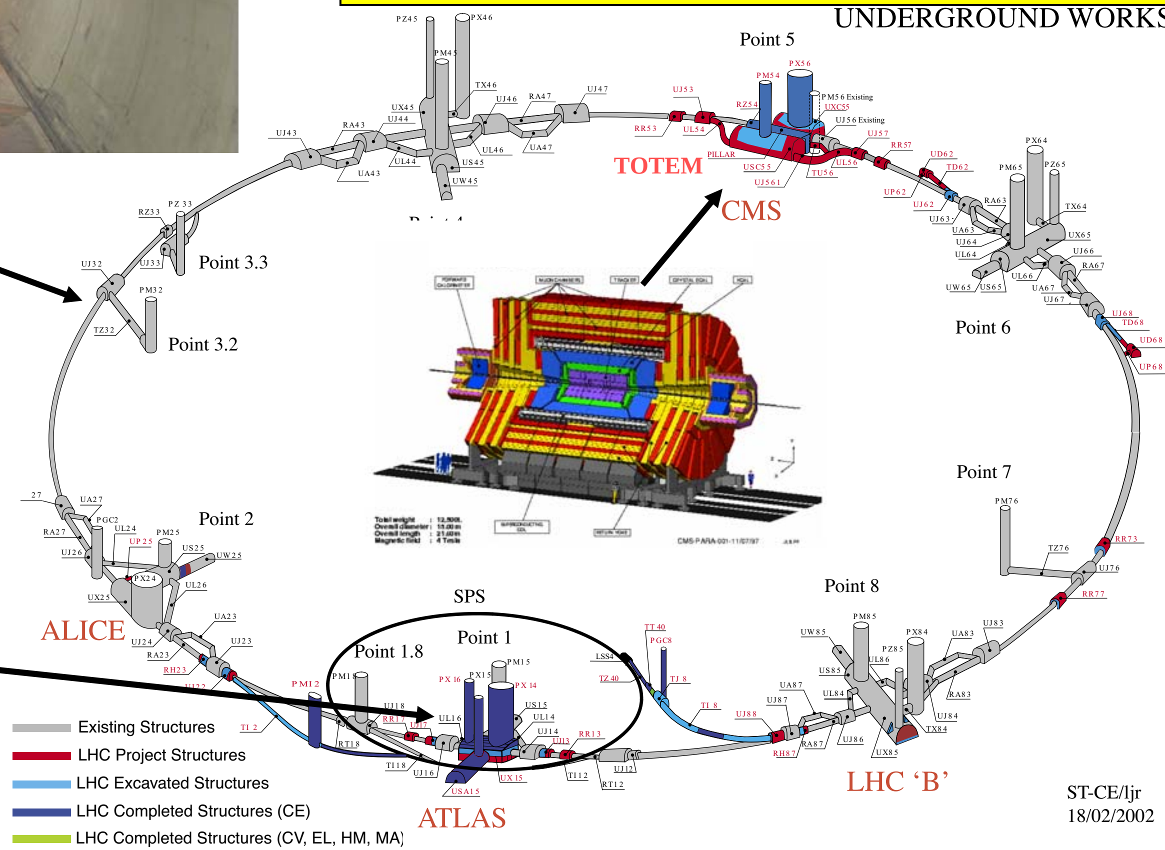
Contents

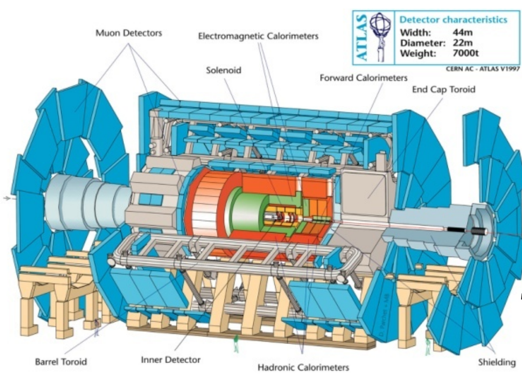
- LHC status
  - (ref. Nakamoto-san's talk tomorrow (kincha-kai))
- ATLAS/CMS status (photo gallery)
- Physics at LHC
  - Introduction
  - Higgs
  - SUSY

LHC (Large Hadron Collider)

Circumference : 27km
1232 superconducting dipoles
with magnetic field B=8.3 T

pp collider $\sqrt{s}$=14TeV
Design L=10^{34}cm^{-2}s^{-1} (100fb^{-1}/year)
10^{33} for the early stage

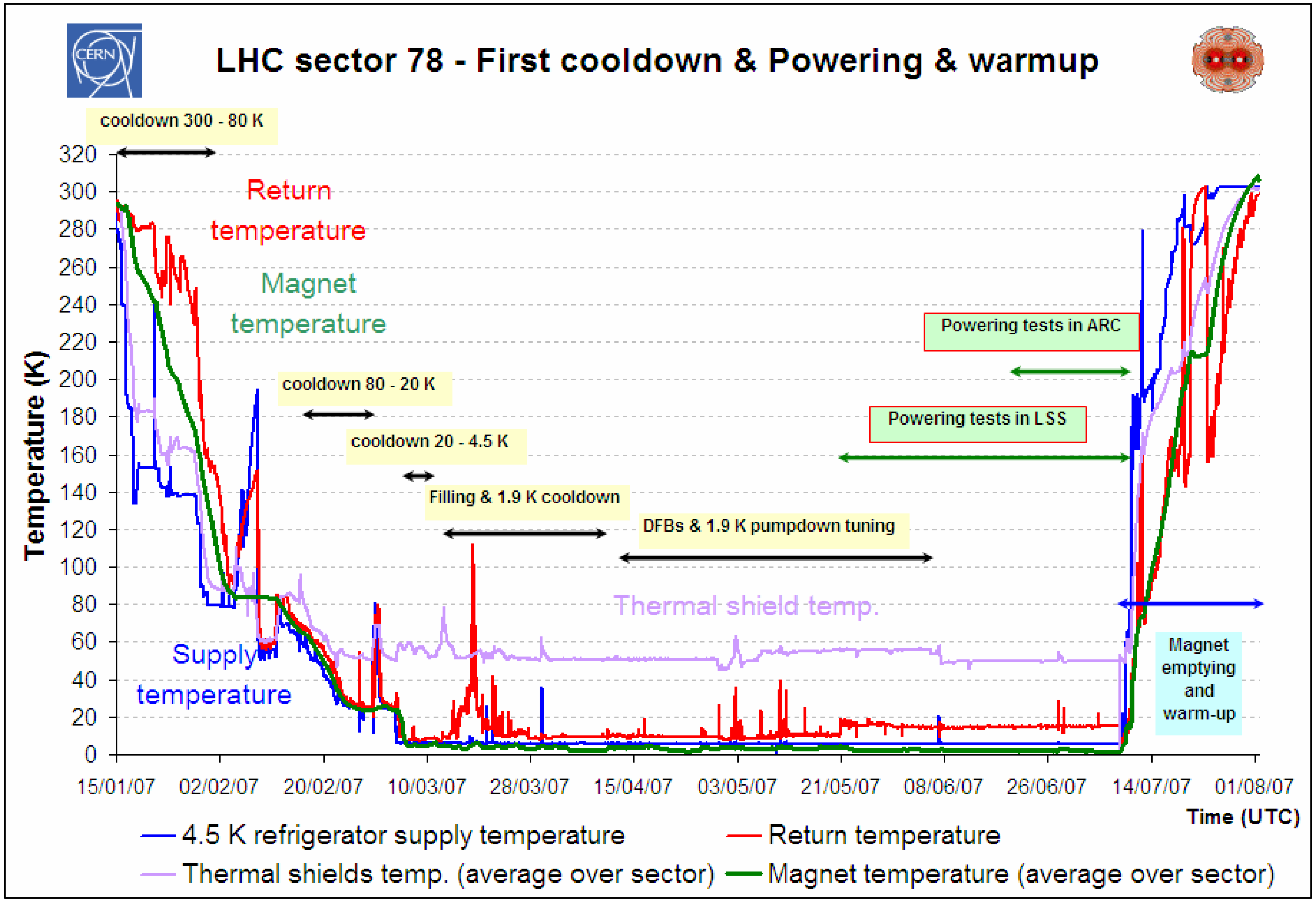




Two General purpose Detectors: ATLAS and CSM

Descent of the last magnet, 26 April 2007

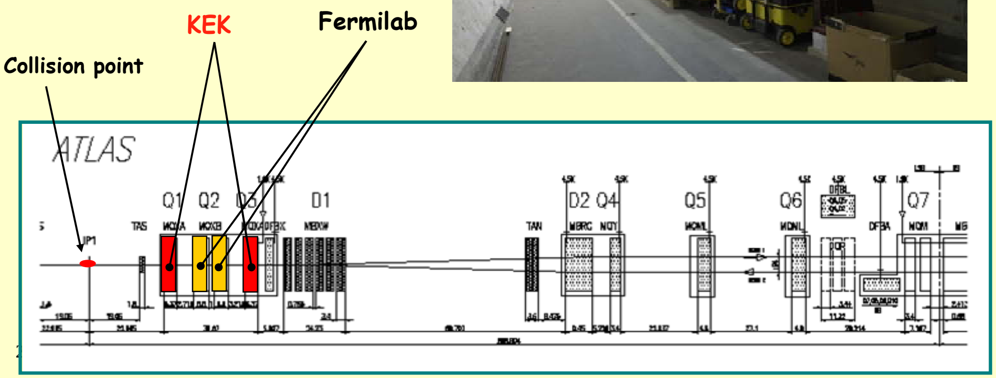
First cool down and warm up of Sector 7-8



LHC Contstruction : ITQ successfully repaired

Inner Triplet Quadrupoles

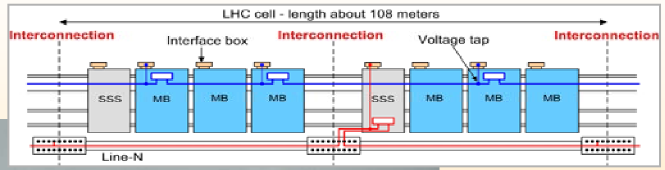
Near the interaction points, triplet quadrupole magnets focus the beam. Two types of superconducting magnets are separately developed and manufactured at KEK and Fermilab. Both magnets were assembled with common cryostat at Fermilab and then shipped to CERN.

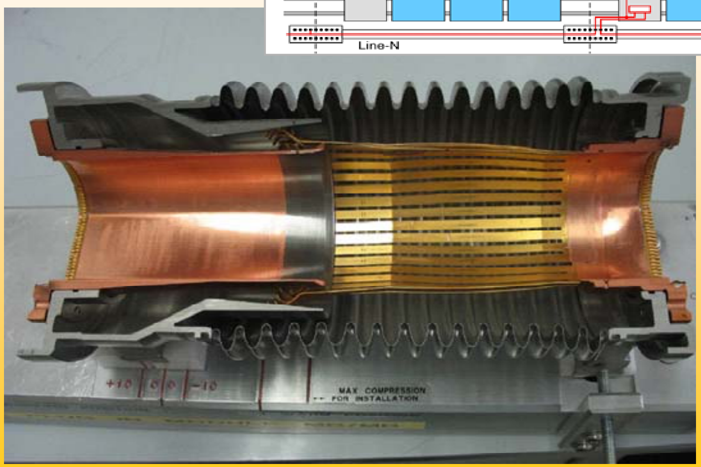


ITQ: Repaired in situ

LHC Construction : “Pingpong ball”

RF bellows in the 1700 interconnections





L. Evans – EDMS Document 872652

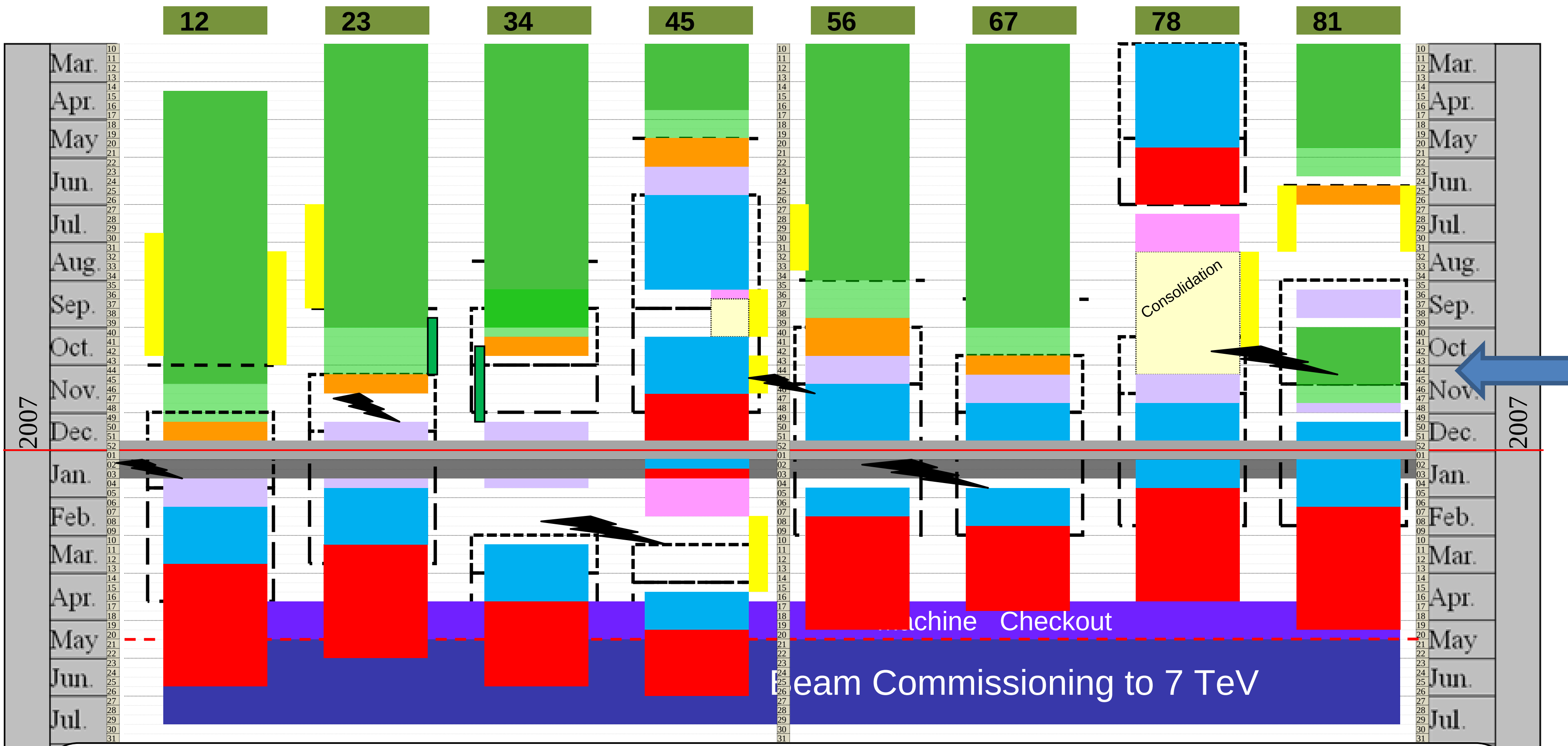
Transmitter prototype

… First, the 6.3km long beam pipe turned out to have obstruction, … The desperate machine-builders even tried employing a ferret, named Felicia, to help in pulling magnets on wires through the pipe in an attempt to clear it!

F. Close “The particle Odyssey”
on the construction of FNAL MR.

L. Evans – EDMS Document 872652

Updated General Schedule - 08.10.07



General schedule Baseline rev. 4.0

Global pressure test &Consolidation

Cool-down

Powering Tests

Interconnection of the continuous cryostat

Leak tests of the last sub-sectors

Inner Triplets repairs & interconnections

Global pressure test &Consolidation

Flushing

Cool-down

Warm up

Powering Tests

Beam Parameter Evolution at 7 TeV/beam

accelerator policy : just one change per each stage

Parameters			Beam levels		Rates in 1 and 5	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	2	$1.1\ 10^{30}$	<< 1
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76
936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72
2808	$5\ 10^{10}$	2	$1.4\ 10^{14}$	157	$5.9\ 10^{32}$	1.1
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1

Considered to be an all-out maximum with the hardware as installed

2007.7.23

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From T.Kondo's talk in July

Schedule

- In March 2008, the beam pipes at ATLAS area will be closed.
- Beam commissioning will start in May 2008.
- First collisions (14TeV) in July 2008.
- Official inauguration of the LHC on 21/Oct/2008
- Expected Luminosity

  (with large uncertainties)

  - $6 \times 10^{30} \sim 10^{32}$ in 2008 -> $\sim 100 pb^{-1}$
  - 10^{32}-10^{33} in 2009 -> a few fb^{-1}
  - 10^{33} till ~2011? LHC low lumi phase

    Int. L ~ 30 fb^{-1}
  - Then 10^{34} LHC low high phase

    Int. L ~ 300 fb^{-1}
  - 10^{35} LHC upgrade

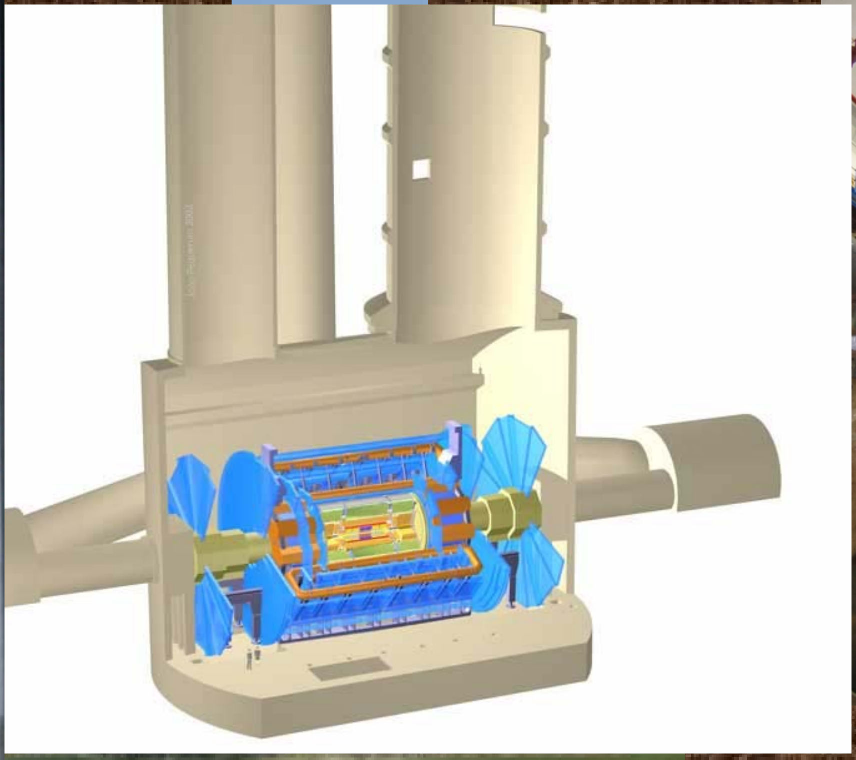
    (~2015)

The ATLAS Detector

Dimensions :~25x25x46m

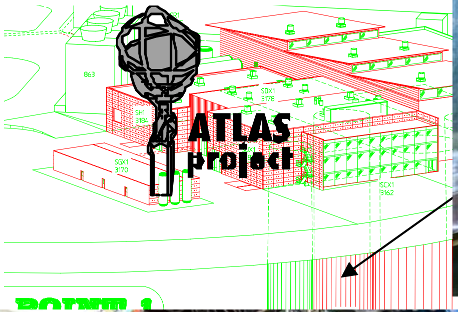
Weight:7000 ton

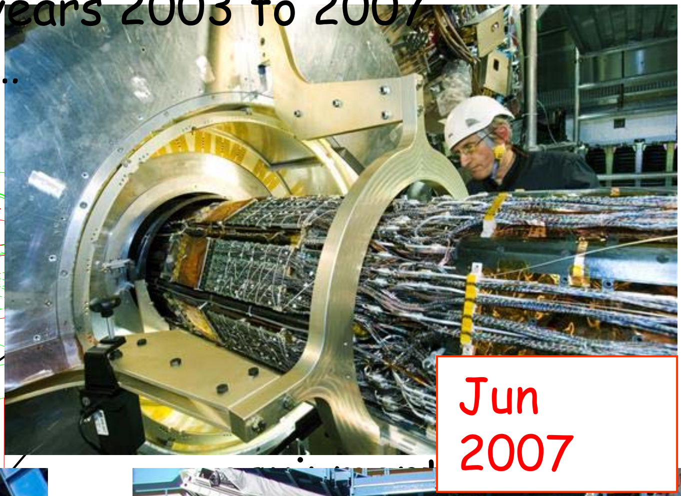
⇒ density $0.31 g/cm^3$

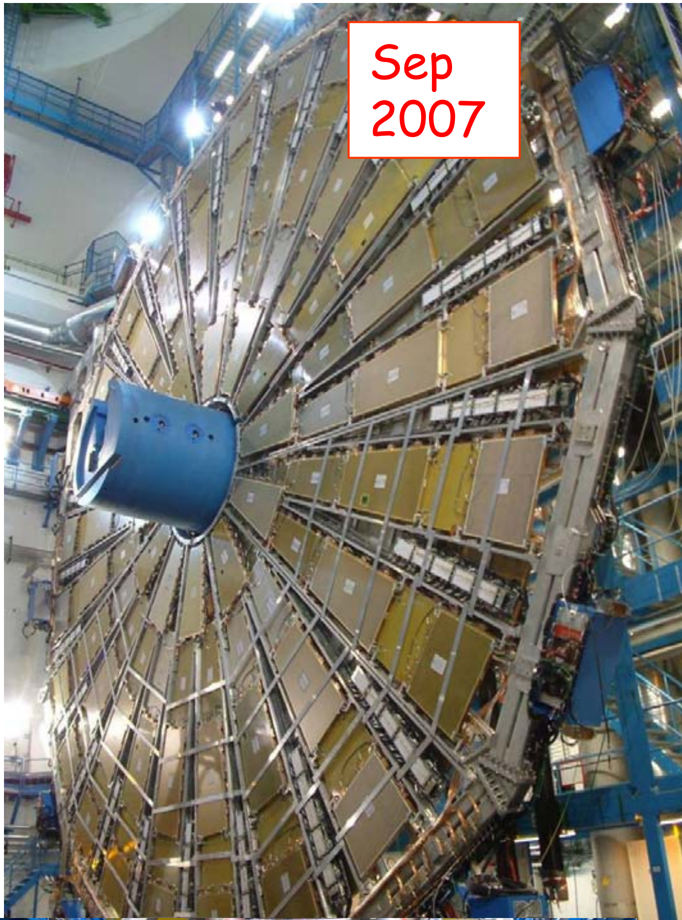


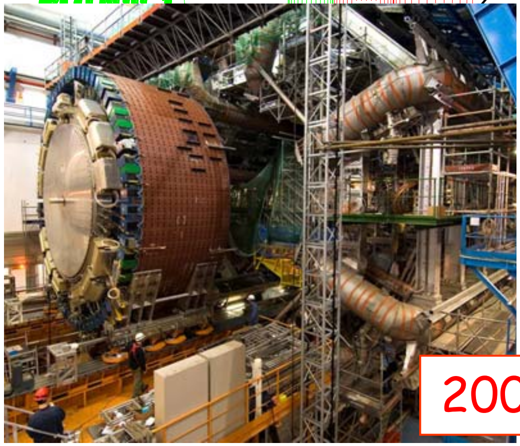
Installation – the years 2003 to 2007

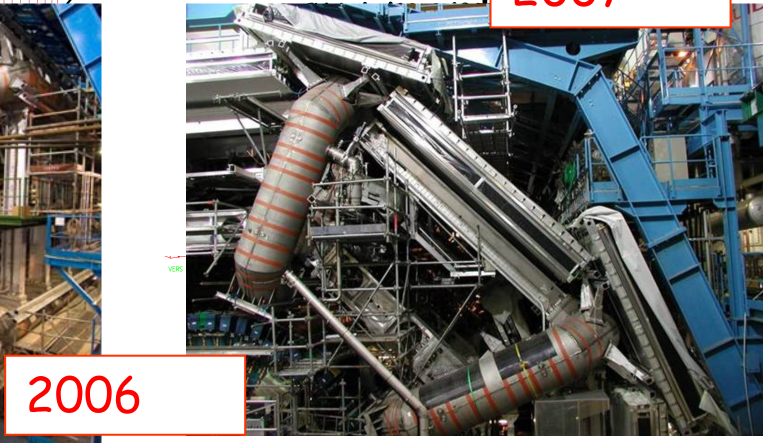
…

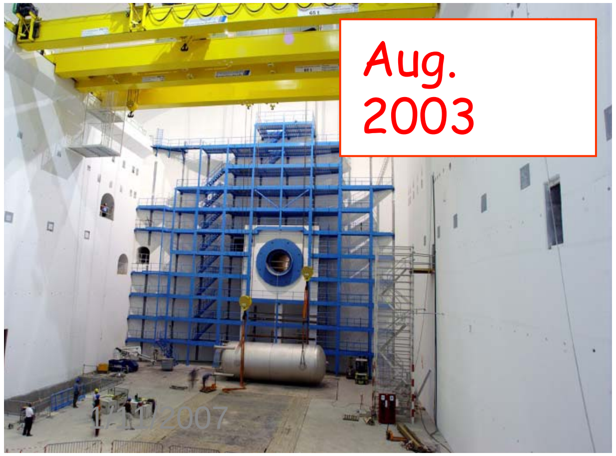


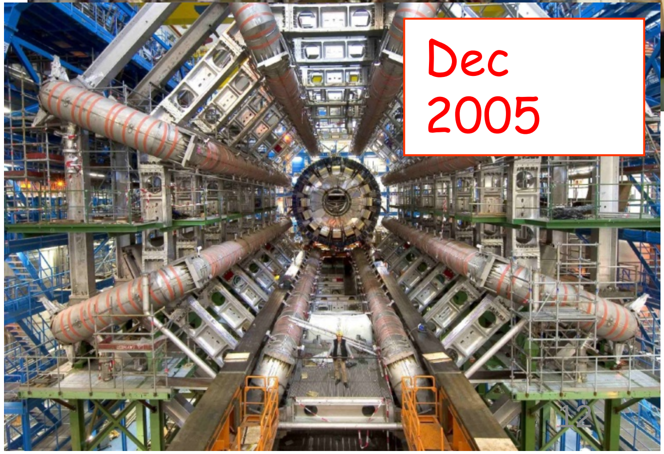




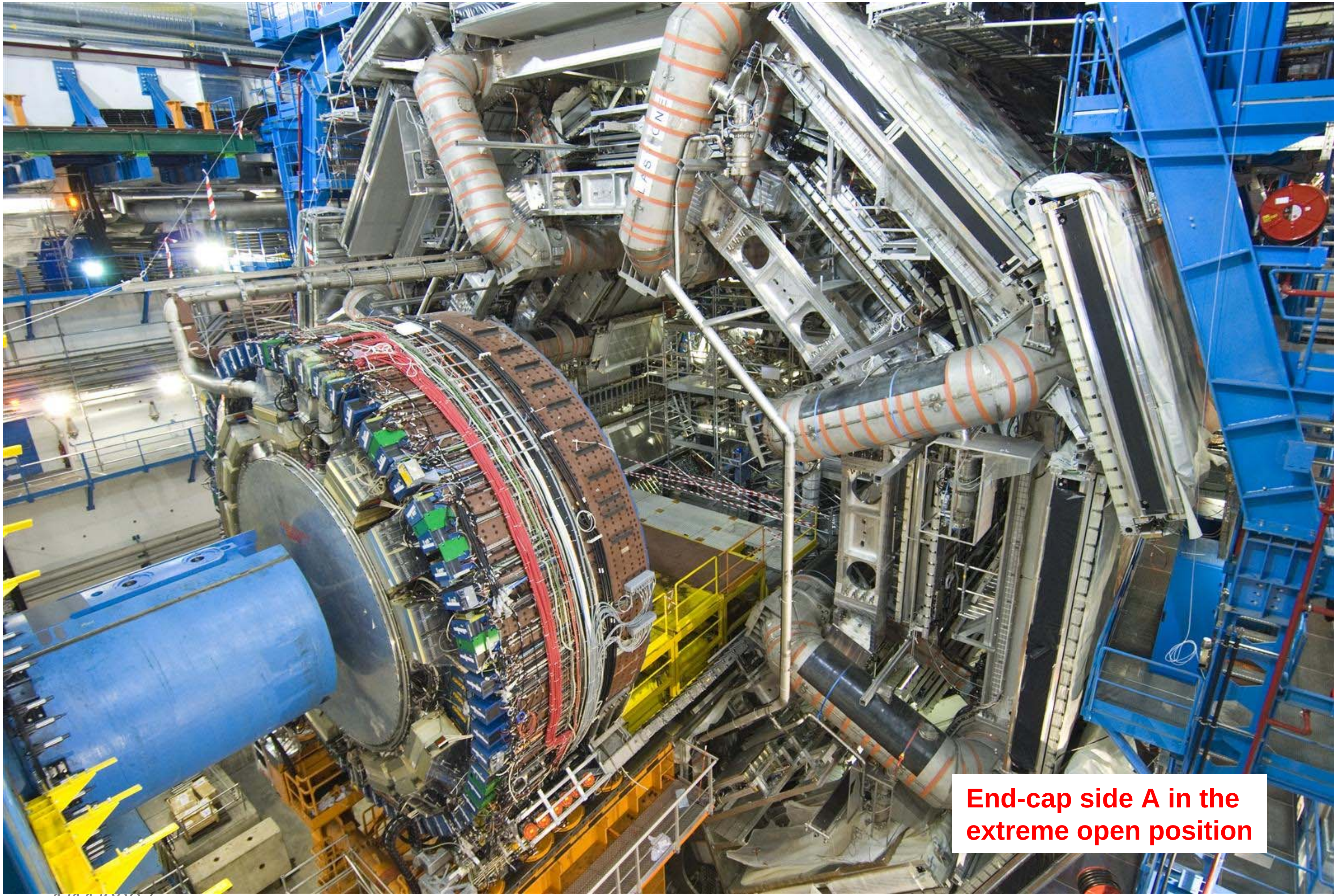








All calorimeters are installed, and the three LAr cryostats are cold and filled with LAr



End-cap side A in the extreme open position

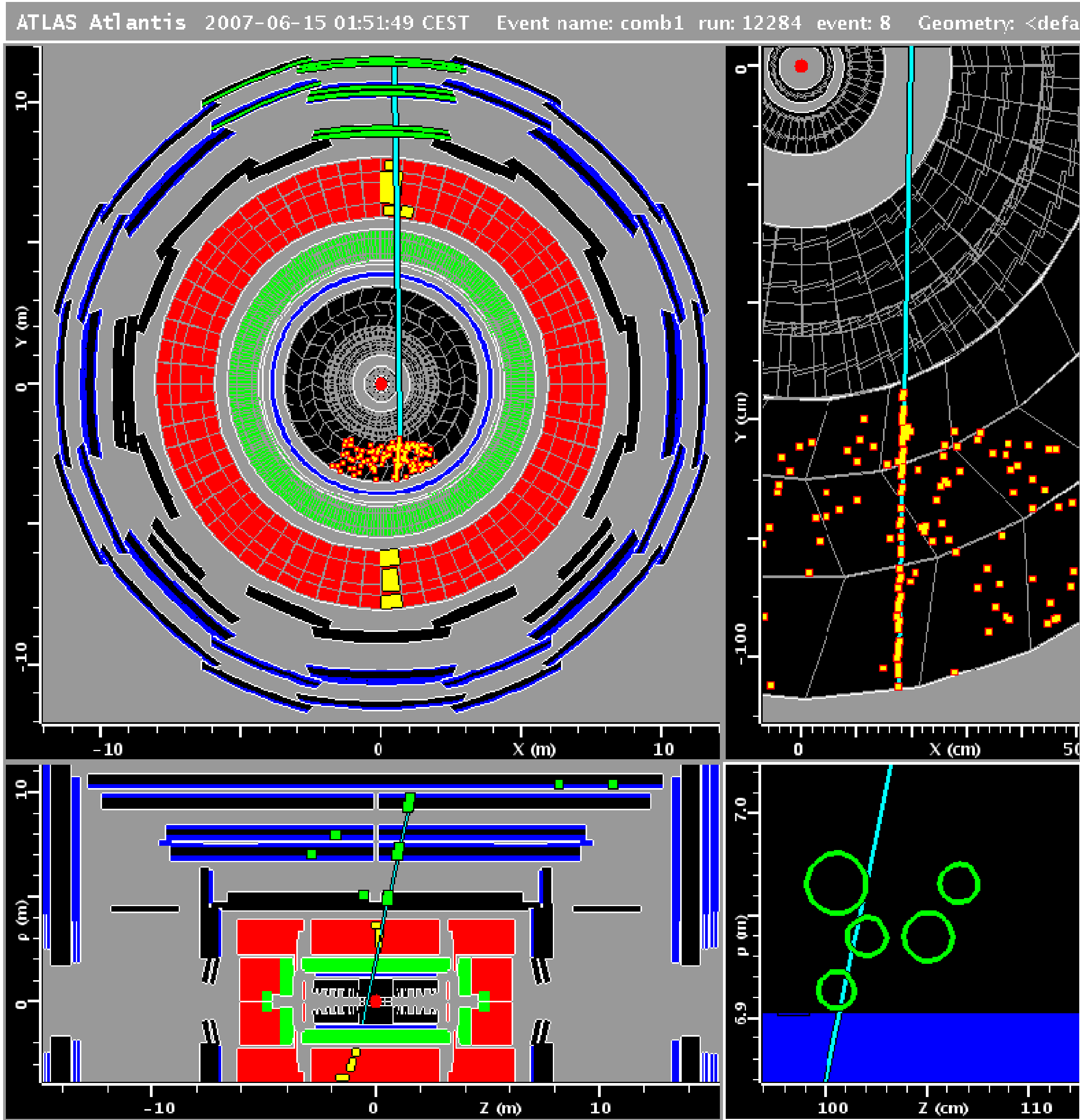
End-Cap Toroid C

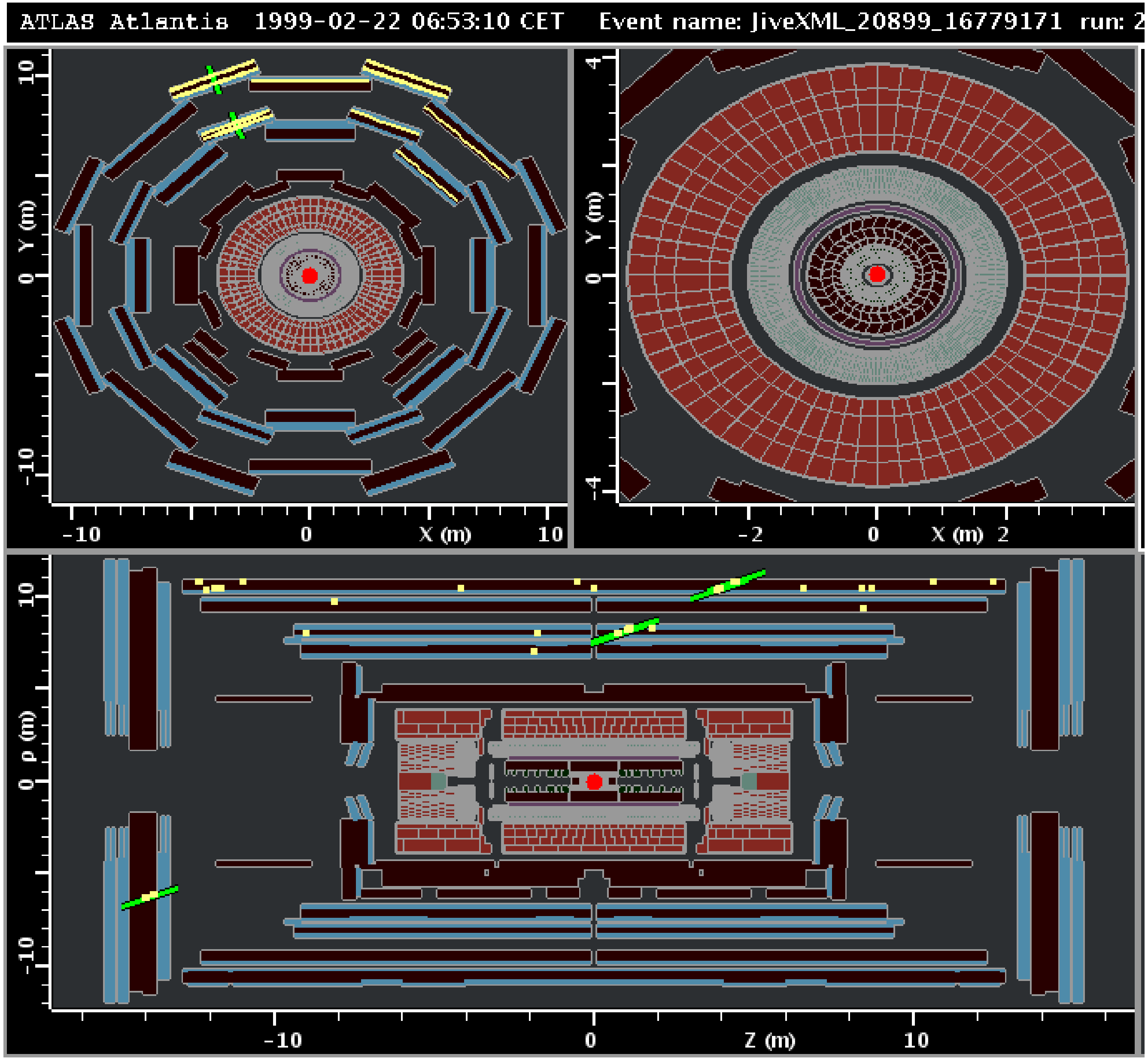
2007.7.2

ATLAS Control Room (ACR)

The control room is located on surface.
Cosmic ray commissioning runs are being taken now.

Cosmics through MDTs, Calorimeters, and TRT during M3

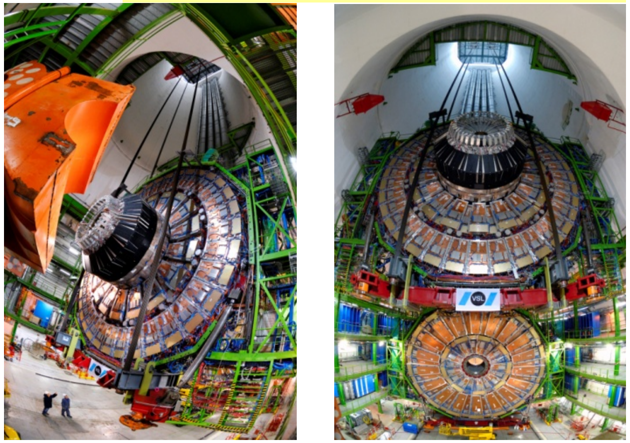



ATLAS Atlantis 1999-02-22 06:53:10 CET Event name: JiveXML_20899_16779171 run: 2
Y (m)
X (m)
Y (m)
X (m)
ρ (m)
Z (m)

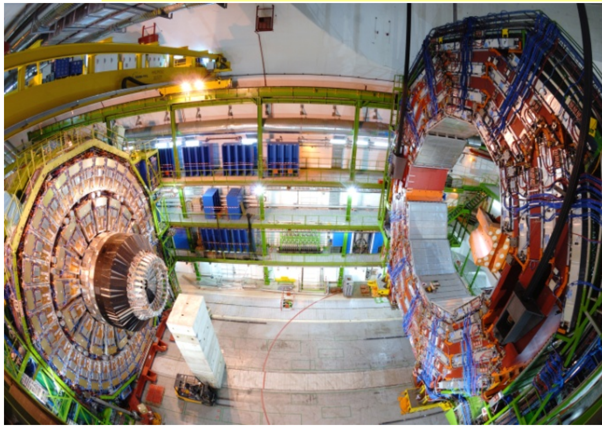
CMS Installation

Underground UXC Cavern
May06

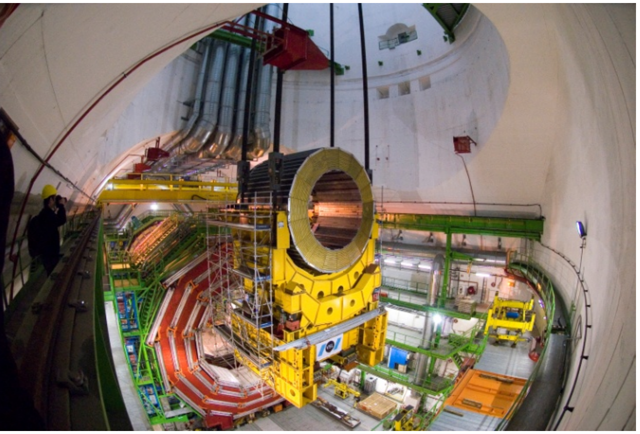
Heavy Lowering YE+1 (9 Jan07)



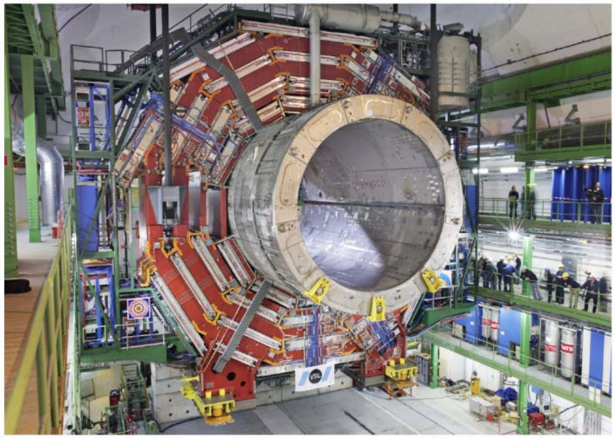
Heavy Lowering YE+2(19 Jan07)



Heavy Lowering (HB+, 13 Feb)

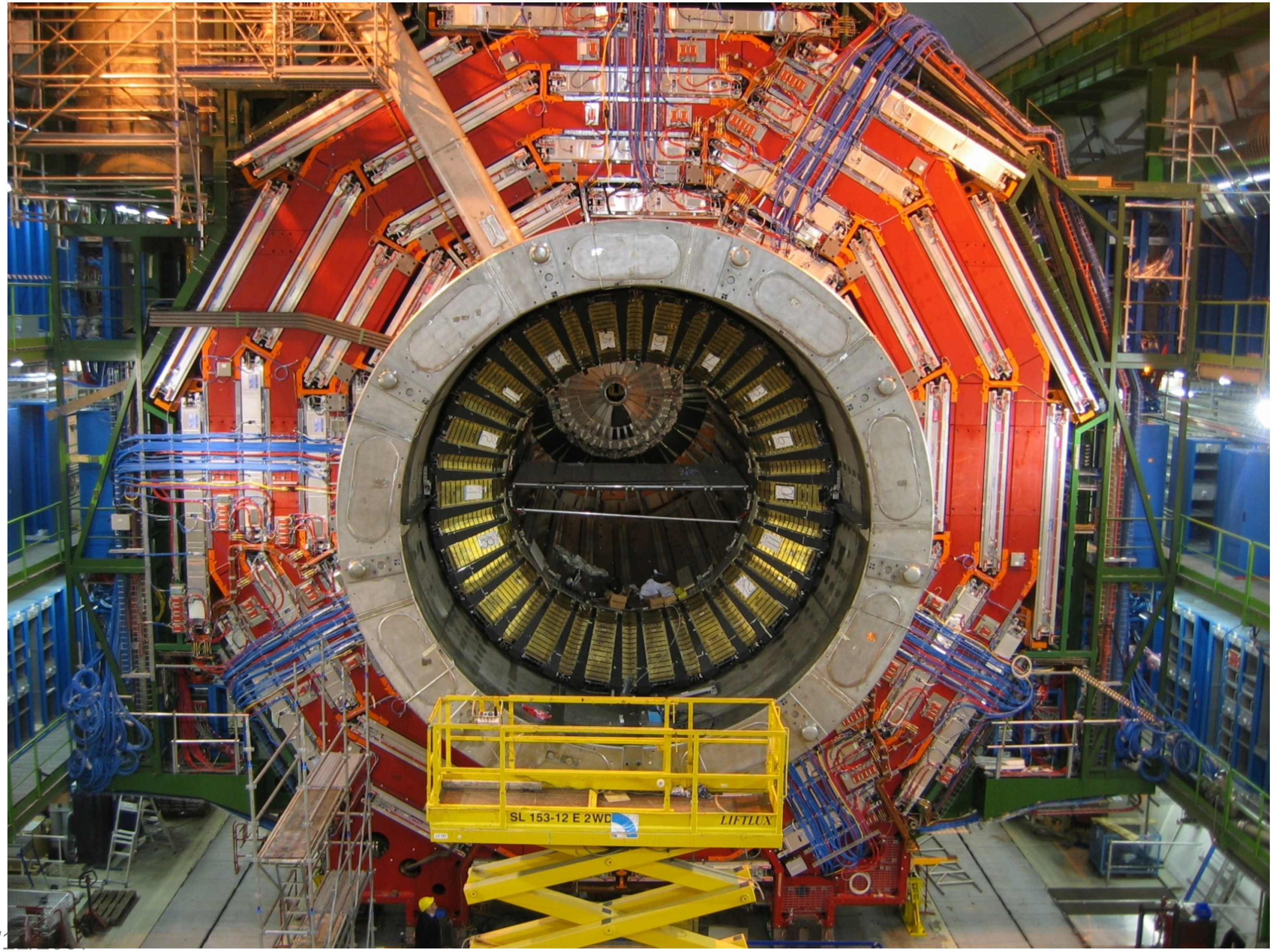


Heavy Lowering (YB0, 28 Feb)



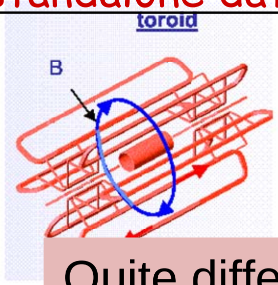
YB0 landing in the CMS experiment hall

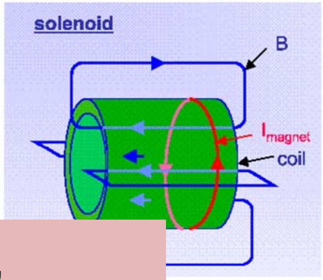
Situation in Experiment Cavern (9 Apr)



Detector performance

	ATLAS (A Toroidal LHC ApparatuS)	CMS (Compact Muon Solenoid)
INNER TRACKER	Silicon pixels+ strips TRT $\rightarrow$ particle ID (e/π) B=2T $\sigma/p_T \sim 4\mathrm{x}10^{-4}\, p_T \oplus 0.01$	Silicon pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\mathrm{x}10^{-4}\, p_T \oplus 0.005$
EM CAL.	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CAL.	Fe-scint. + Cu-liquid argon $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 l +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air-core toroids $B=4T_{peak}$ $\sigma/p_T \sim 7$ % at 1 TeV for standalone data	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker



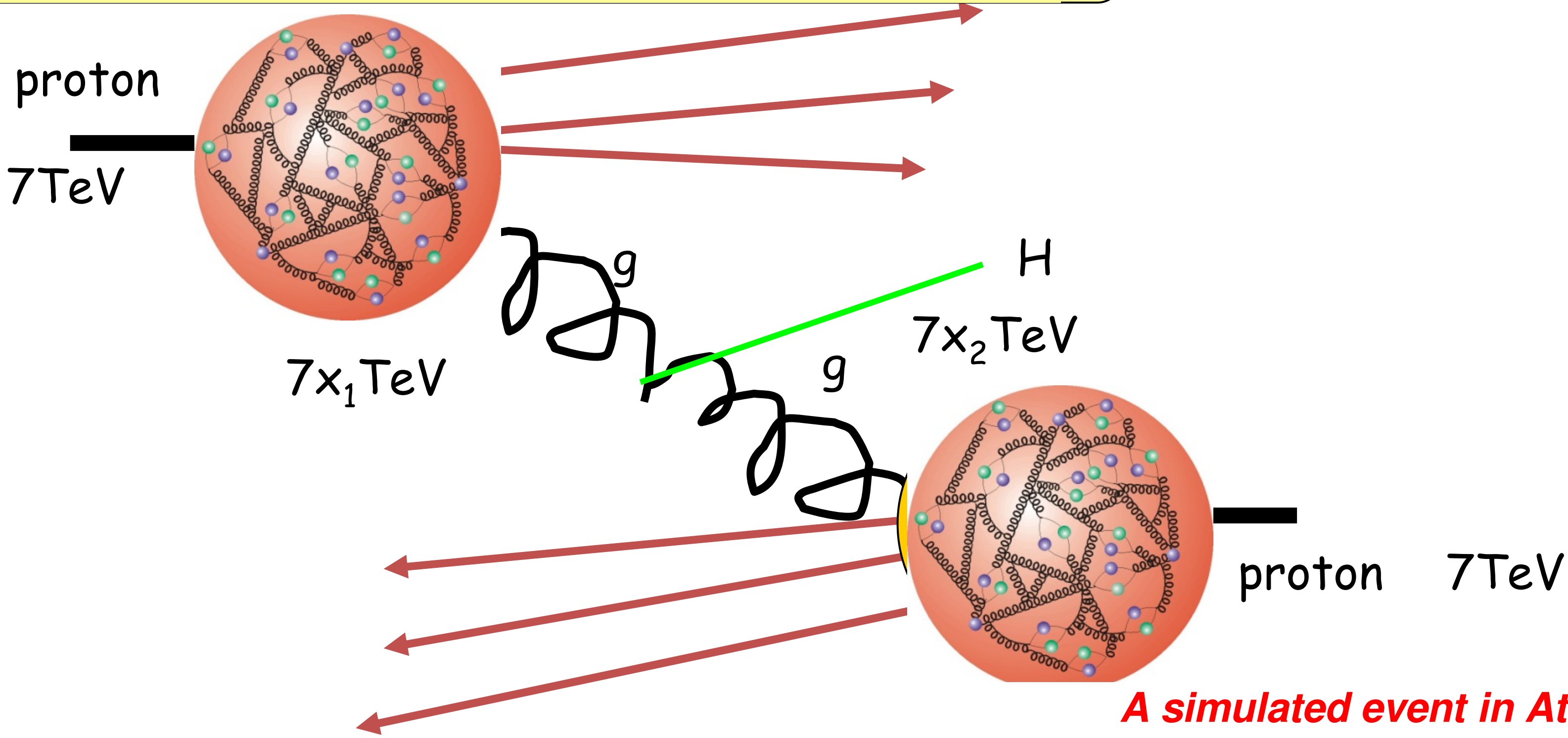


Quite different detector concept,
but the physics performance is similar

Physics at LHC

- Introduction
- Higgs search
- SUSY
- Extra-Dim.
- Standard model
- Proton structure
-

LHC: parton-parton collider



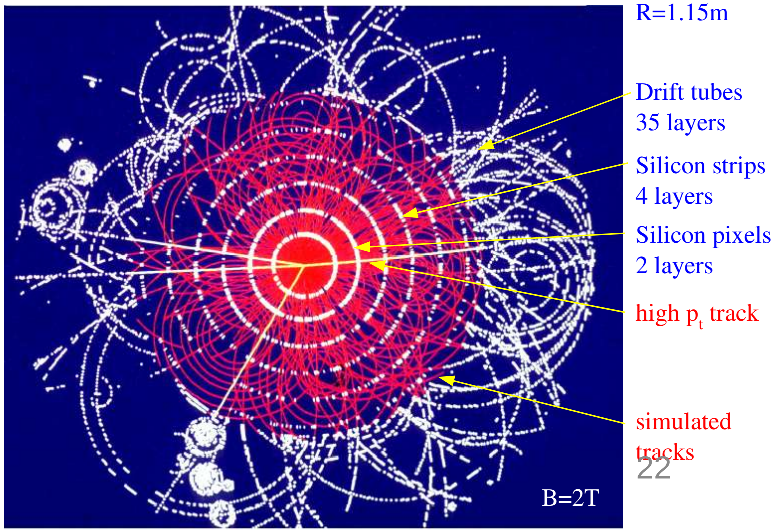
$M_H^2=4\,(x_1E_p)(x_2E_p)$

If Higgs is 140GeV,

$$\sqrt{x_1x_2}=1/100$$

$$x_1\approx x_2\approx 0.01$$

A simulated event in Atlas



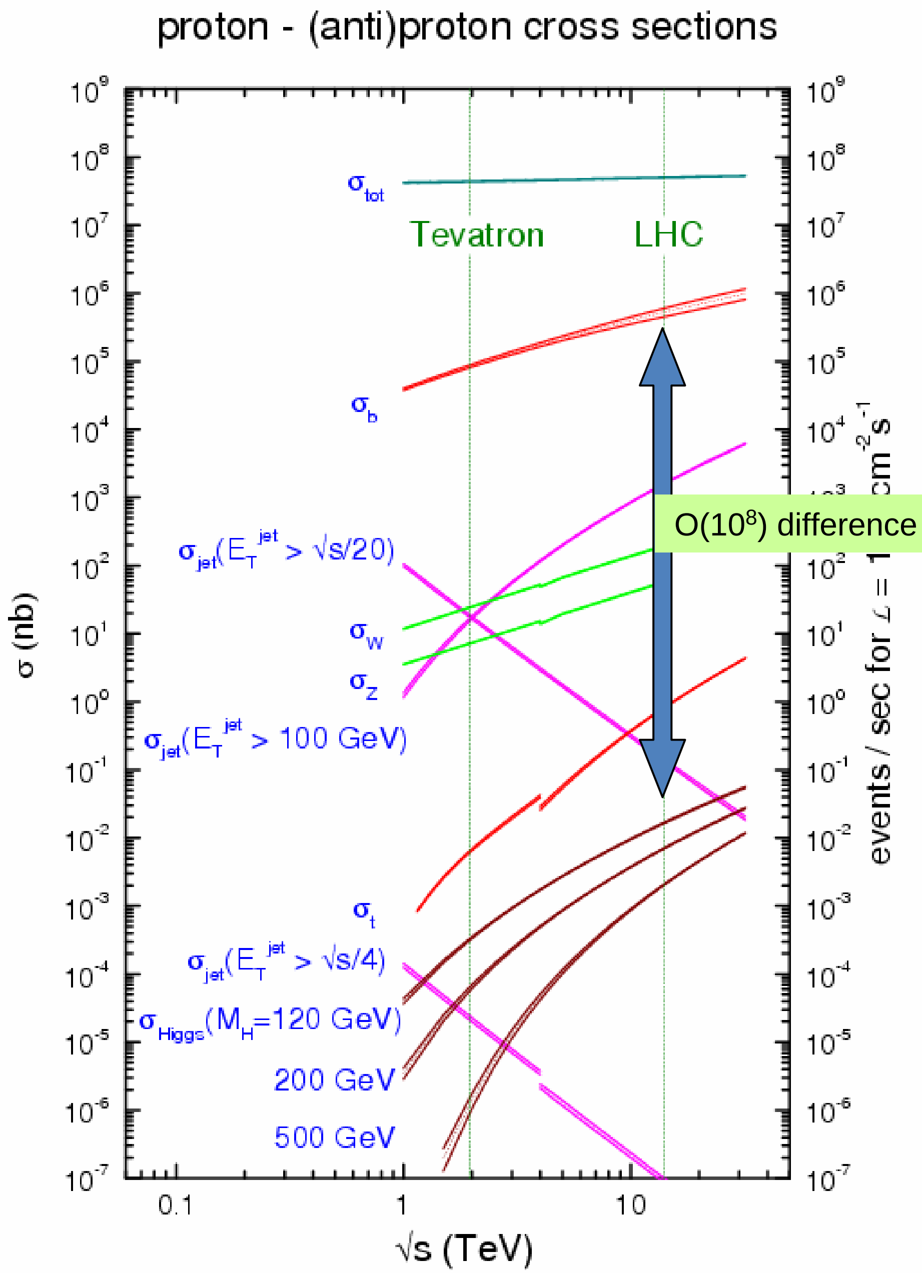
Event rates at LHC

- Huge event rates: (@L=10^{33})
  B production : ~ 1 MHz
  W,Z ~ O(100) Hz
  Higgs: 0.1~0.01 Hz

  -> Background rejection is very important
  -> highly sophisticated event selection are needed.

- $\sigma_{pp(inelastic)} \times (L_{/bunch}) > 1$
  -> Pile-up:
  ATLAS expects ~2 (low-lumi) or 20 (high-lumi) p-p minimum bias interactions per bunch crossing (25 ns)

  -> Some physics analysis requires the low luminosity condition.



Trigger Menu for $L=2x10^{33}\ cm^{-2}s^{-1}$

Selection	$2 \times 10^{33}\ cm^{-2}s^{-1}$	Rates (Hz)
Electron	e25i, 2e15i	~40
Photon	γ60i, 2γ20i	~40
Muon	μ20i, 2μ10	~40
Jets	j400, 3j165, 4j110	~25
Jet & E_T^{miss}	j70 + xE70	~20
tau & E_T^{miss}	τ35 + xE45	~5
b-physics	2μ6 with $m_B / m_{J/\psi}$	~10
Others	pre-scales, calibration,	~20
Total		~200

Menus for the initial runs are under discussions

- To have the event recorded, it has to contain a (local) significant object. (i.e. an electron or a muon…)
- Jet Trigger : Et threshold is very high.
- Missing Et : Need extensive commissioning
- B-tagging: only at HLT

SM Higgs

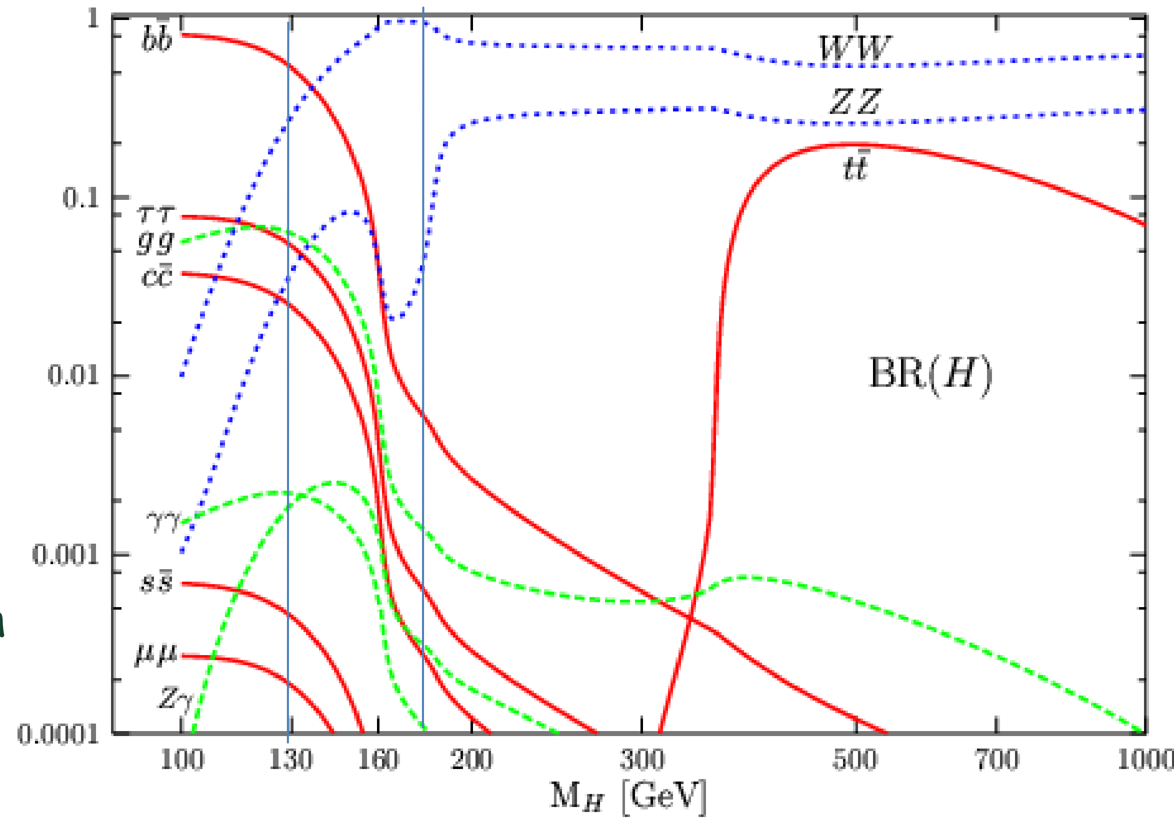
SM Higgs Decay

Higgs fermion coupling ~ Mass

-> BR is prop. to M_f^2

- Light Higgs

  ($110 < m_H(\text{GeV}) < 130$)
  - Dominant mode is $H \rightarrow bb$ (75-50%)
  - $H \rightarrow \tau\tau$ and cc with 3-7%
  - Higgs decay to $\gamma\gamma$ through loop of massive particle ~ few permil
  - $H \rightarrow VV^{(*)}$ rises close to 130 GeV

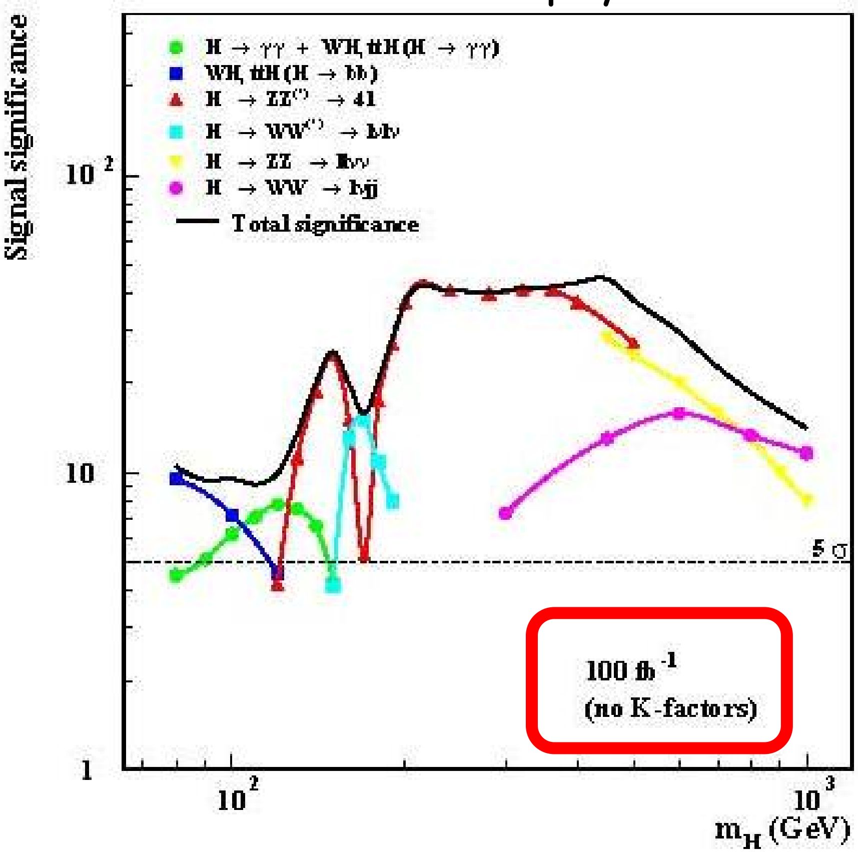


- Intermediate Higgs

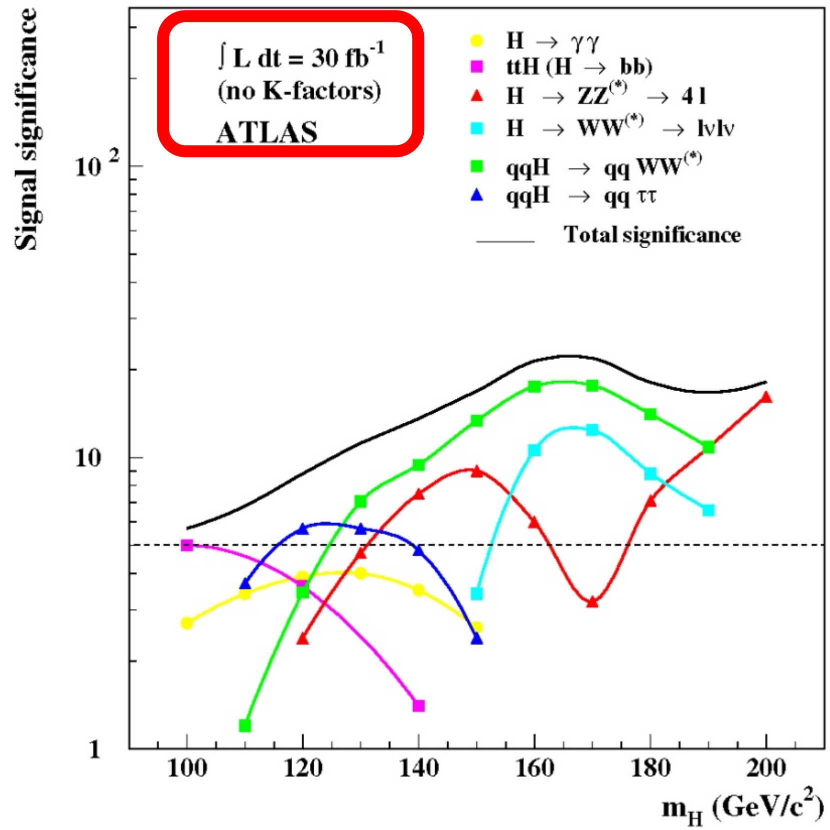
  ($130 < m_H(\text{GeV}) < 180$)
  - $H \rightarrow VV^{(*)}$ most important decay mode
- Heavy Higgs ($180 < m_H(\text{GeV}) < 1000$)
  - $H \rightarrow VV$
  - For $m_H \sim 400$ GeV the decay in two top quarks also plays a role

Higgs sensitivity

Yr1999 ATLAS physics TDR



ATLAS now

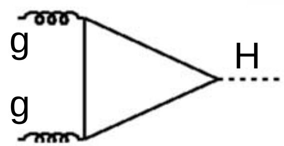


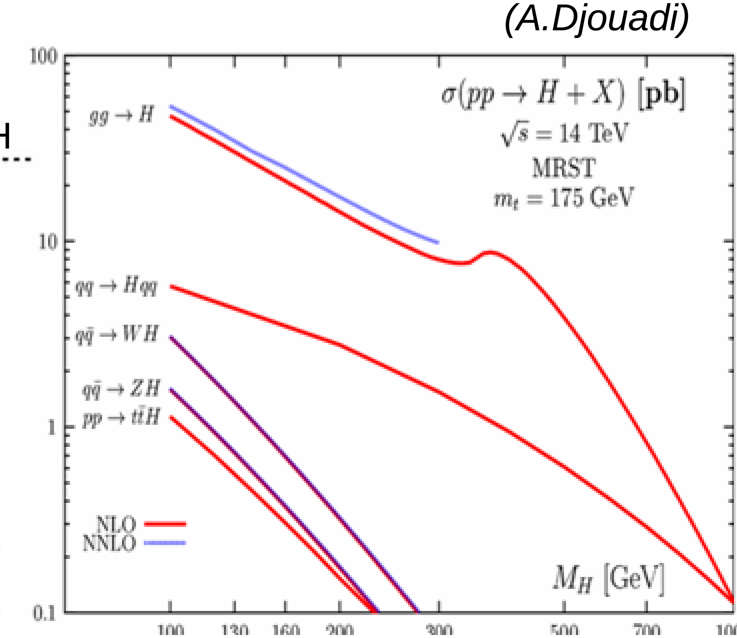
- More emphasis on lighter mass region. = difficult region
- More various channels : A big improvement with VBF fusion processes

SM Higgs production

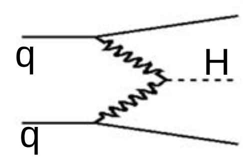
(A.Djouadi)

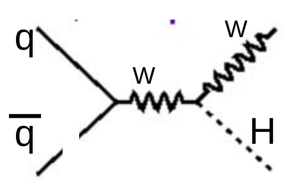
- Gluon Gluon fusion:
  - Dominant production mode
  - NLO correction important
    - K = 1.7
    - Main contribution is gluon radiation
      - many events with at least one jet
  - NNLO cross section known
    - Sig(NNLO)/Sig(NLO) = 1.3





- Vector Boson Fusion:
  - small K factor ~ 1.1
    - Small jet multiplicity in final state
  - No color exchange between quarks
    - large energetic jets at FWD
    - Low hadronic activity in central region from hard event
      - *apart from Higgs decay*

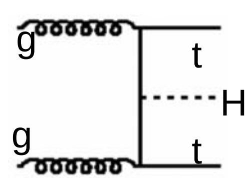




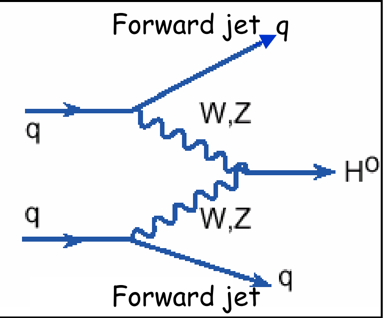
Typical uncertainties on cross-sections

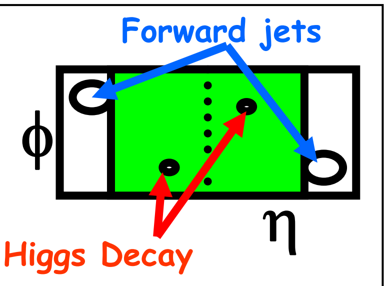
- gg 10-20 % (NNLO)
- VBF ~ 5% (NLO)
- WH,ZH ~< 5% (NNLO)
- ttH 10-20 % (NLO)

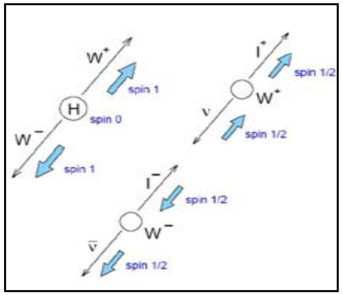
- Production with Gauge boson:
  - Known NNLO for QCD and EW corrections
- Production with heavy quarks:
  - More complicated final state
  - More than 10 diagrams, known at NLO



Vector Boson Fusion





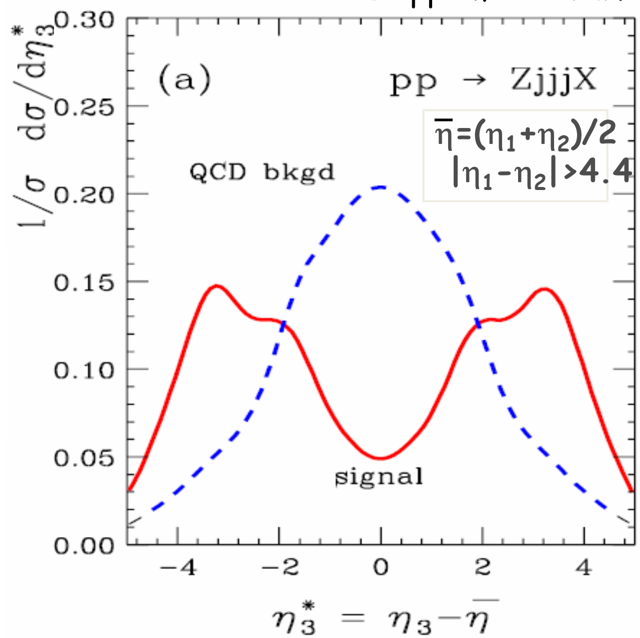


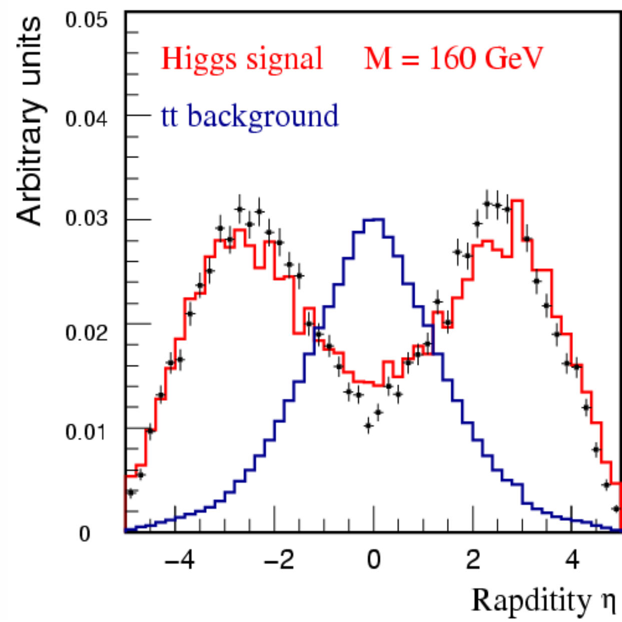
Features:

- 2nd most important production process (σ~10-20% of gg fusion)
- H decay products between two forward tag-jets.
- No central jets (no q-q colour exchange).
- WW Leptonic final state: leptons are spin correlated
  → for $l\nu l\nu$ final state, l^+,l^- in same direction.

- Look for:
  - $H \rightarrow \tau\tau$, WW
- Event selection:
  - $\eta_{j1} \cdot \eta_{j2} < 0$
  - $|\Delta\eta_{jj}| > 3.5 - 4$
  - $M_{jj} > 500\text{–}700$ GeV
- Pile-up may give fake central jets, also harder to identify tag-jets.
- VBF may not be viable at high luminosity.

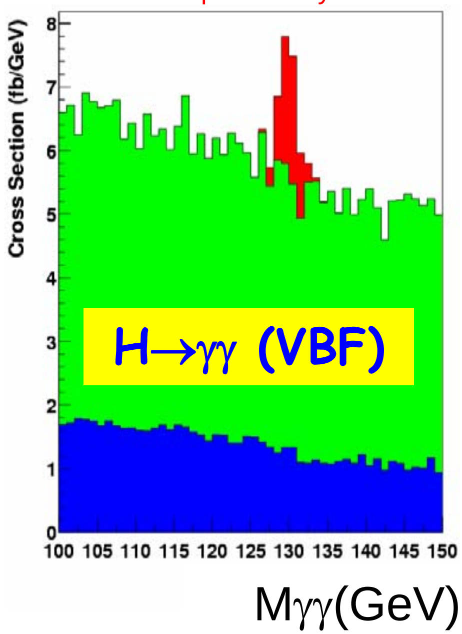
Zeppenfeld et al.

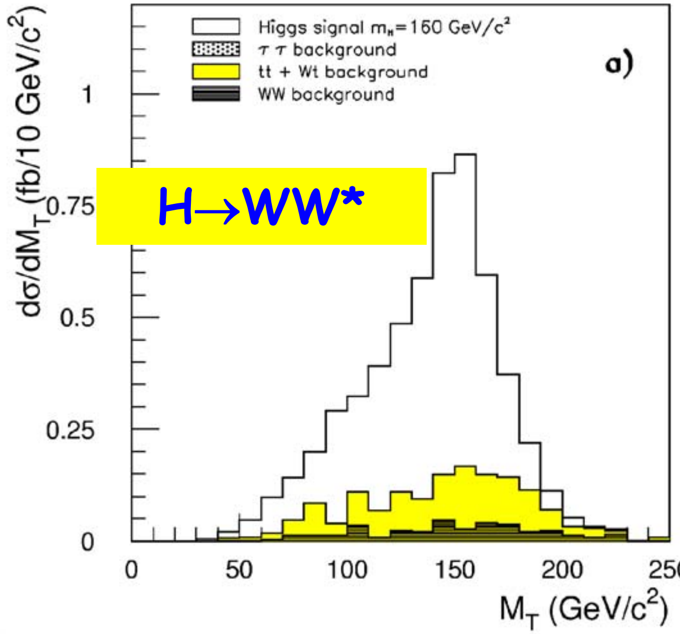


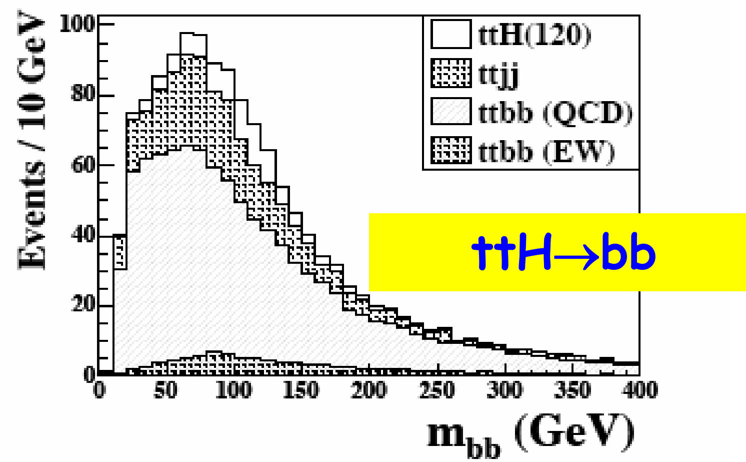


SM Higgs Signatures

ATLAS preliminary

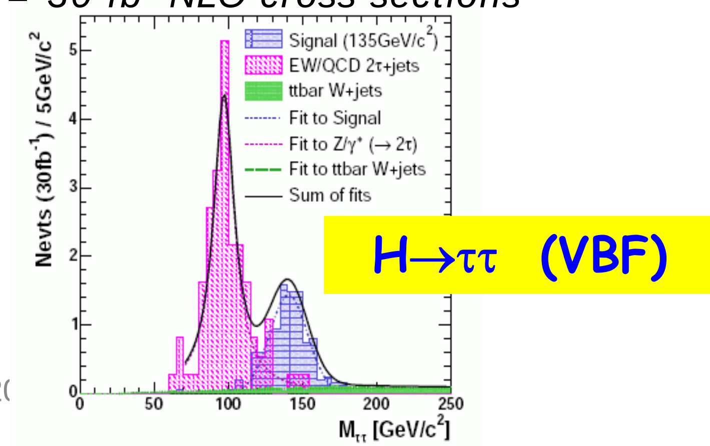






CMS note 2006 88

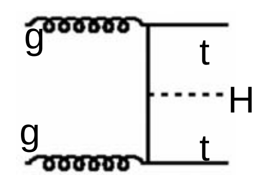
L = 30 fb⁻¹NLO cross sections



m_H = 120 GeV, L = 30 fb^{-1}

$S/\sqrt{B}$ = 2.8

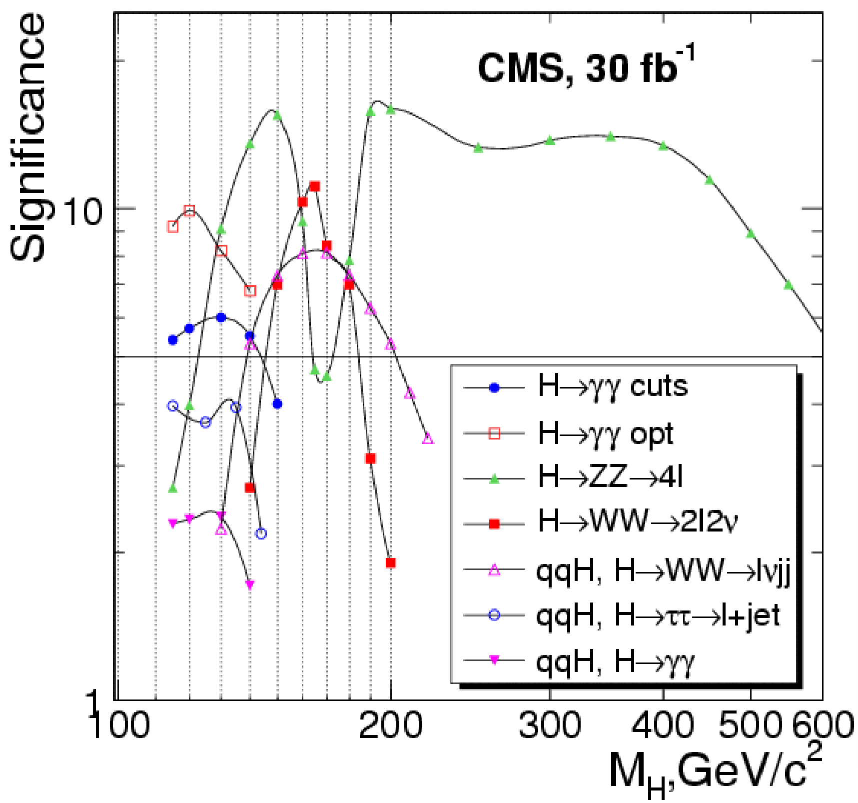
LO cross sections



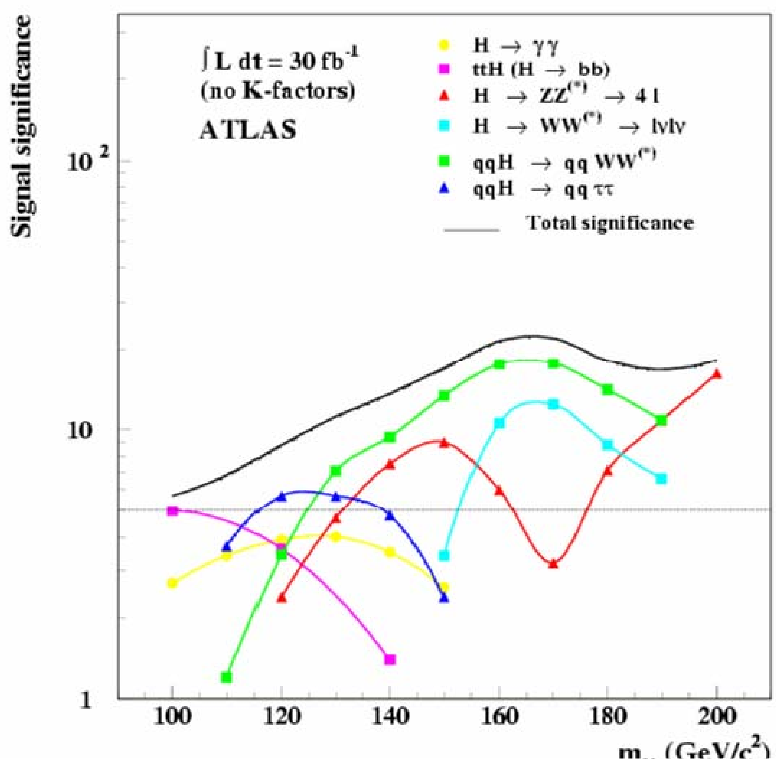
Higgs searches in early period

CMS-ATLAS comparison

NLO calculation

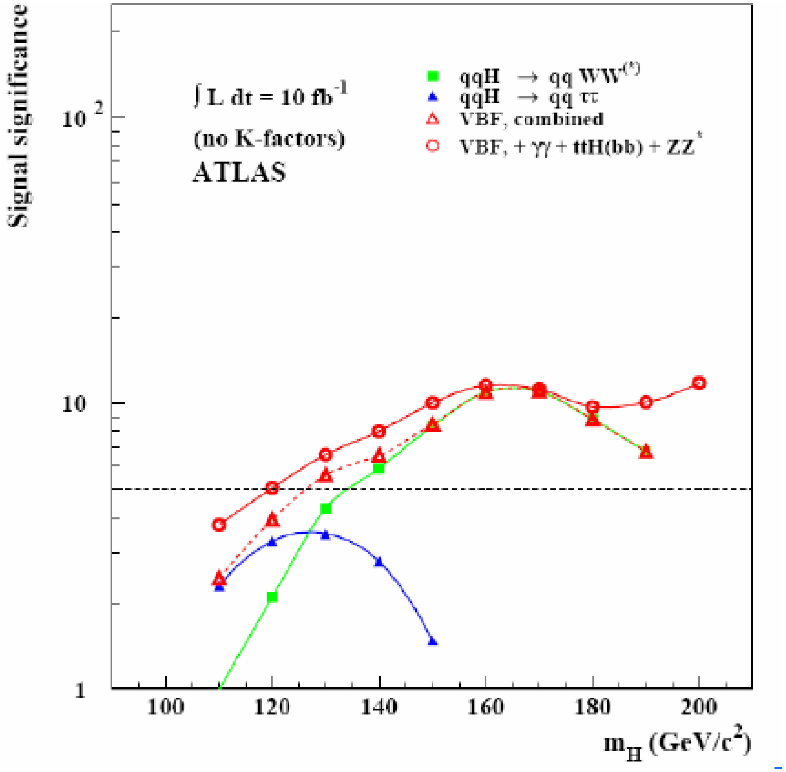


LO calculation



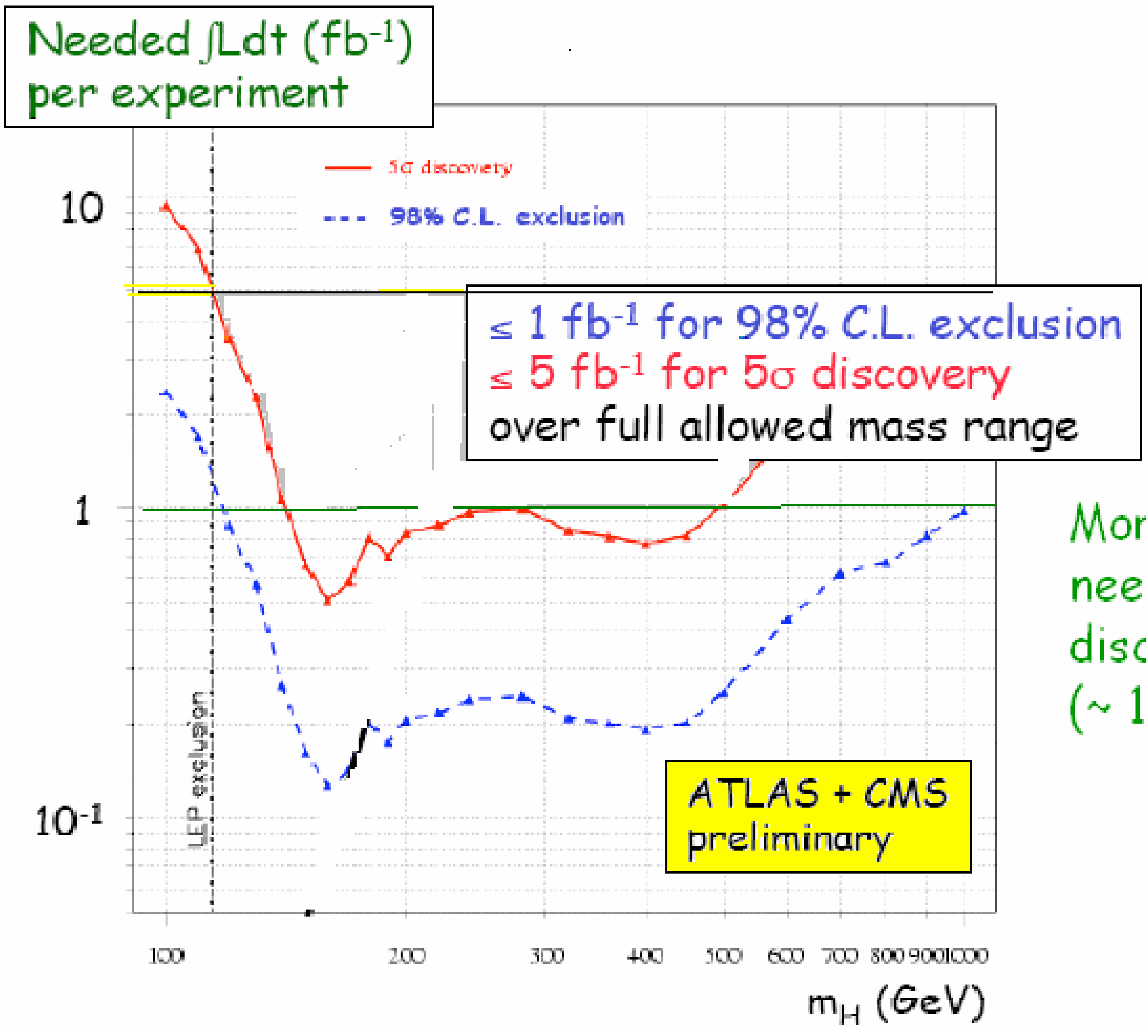
Note: CMS uses NLO cross sections. K-factor for gg->H is high (~1.8)

Higgs searches in initial period



Higgs searches in initial period

ATLAS+CMS on the discovery of the SM Higgs

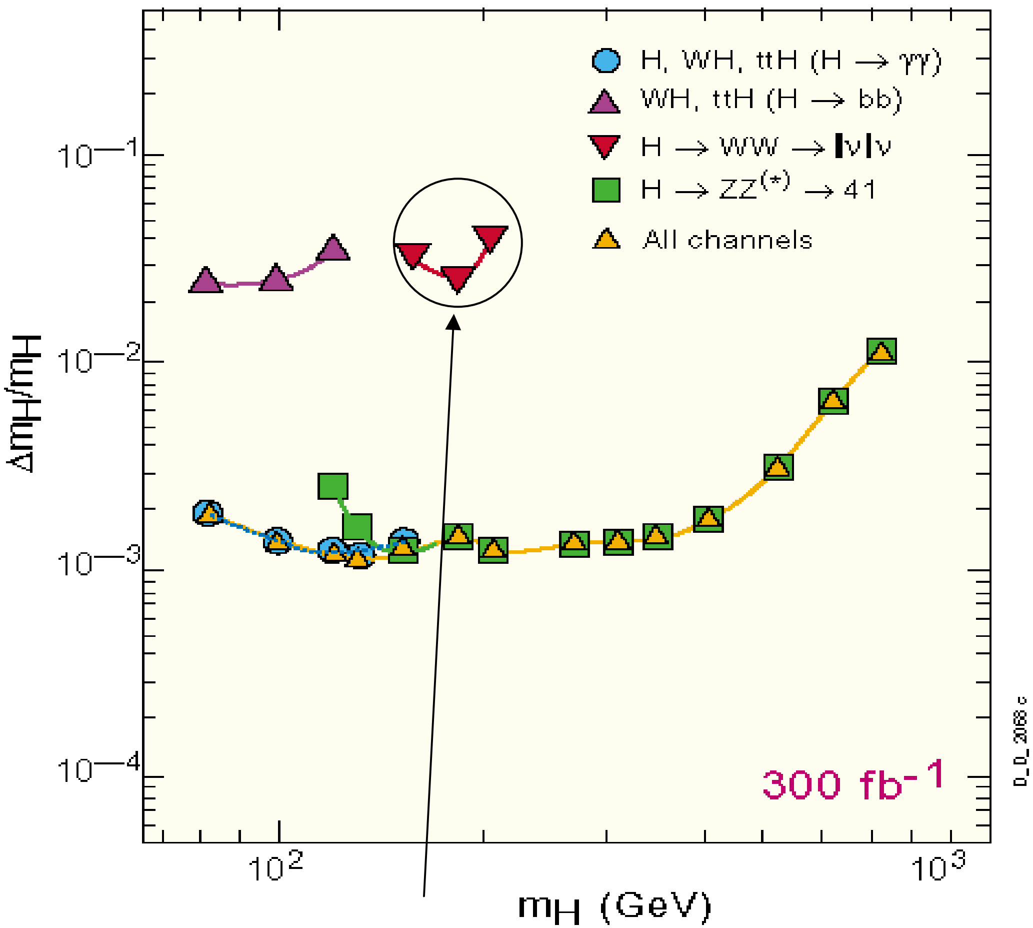


More than one channel needed for early discovery of light Higgs (~ 115 GeV)

F.Gianotti, ICHEP06

Higgs mass measurement

Precision on SM Higgs mass



<u>H→WW no mass peak</u>

mil-level precision measurement with $H\to\gamma\gamma$ or 4 leptons.

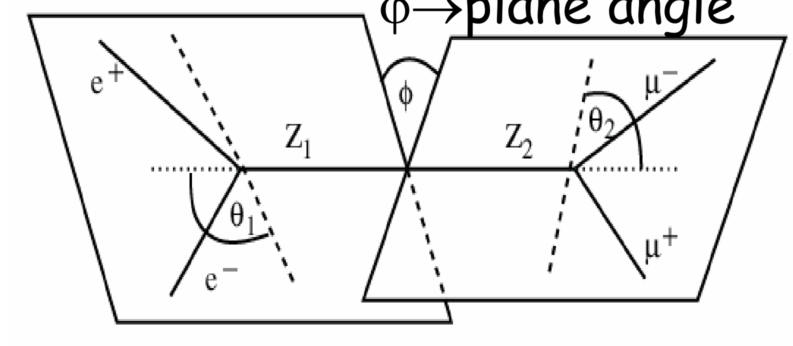
The channel $H\to\tau\tau$ can also contribute at low luminosity

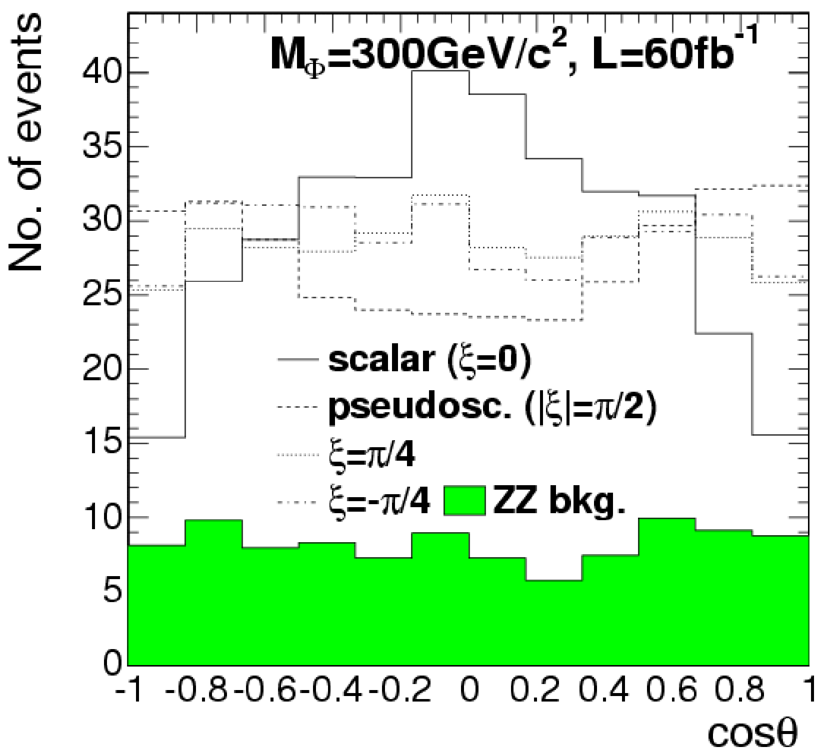
~%-precision with Jacobian peak (i.e. H-> WW)

Higgs spin, CP (High mass)

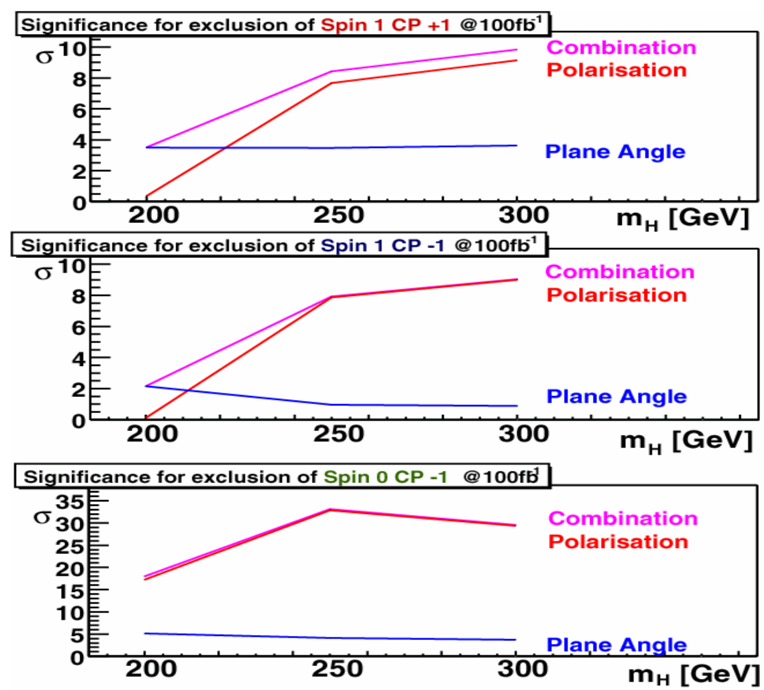
- Observation of $gg \to H$ or $H \to \gamma\gamma$ excludes spin 1
- For M_H>200 GeV, study spin/CP from $H \to ZZ \to 4l$
- Exclusion can be deduced from θ and φ distributions

$\Theta \to$ Z polarization
$\varphi \to$ plane angle

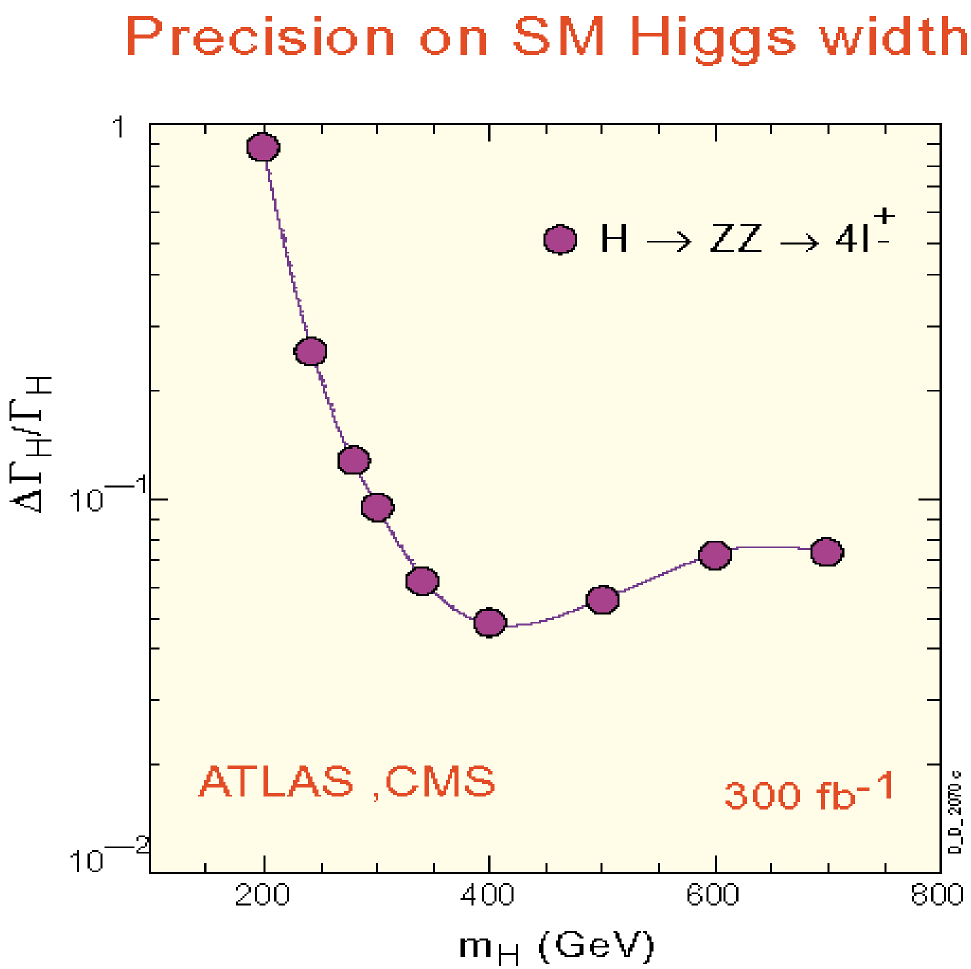




Atlas-sn-2003-025



Couplings (high M_H)



For m_H>200 GeV, Γ(H) is directly measurable at <10% level with the 4-lepton channel.

Couplings (low M_H)

Atlas note phys-2003-030

- Assume spin 0:
  - allow to use angular distribution on $H \to WW$ (most precise measure)
  - measure σ.BR in different channels:

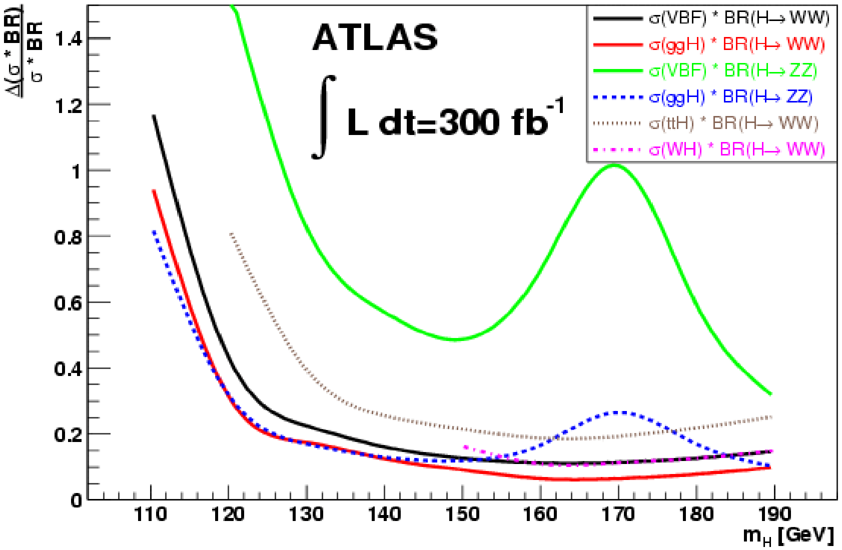
    $\Rightarrow \sigma.BR = (N_{S+B} - \langle N_B \rangle)/\varepsilon L$
    - Uncertainties:

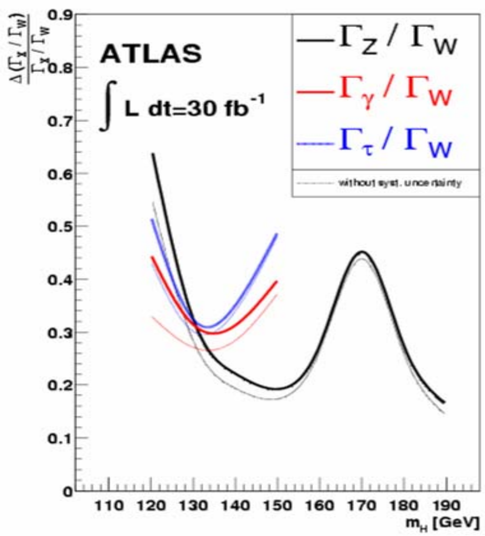
      $\Rightarrow$ Selection efficiencies

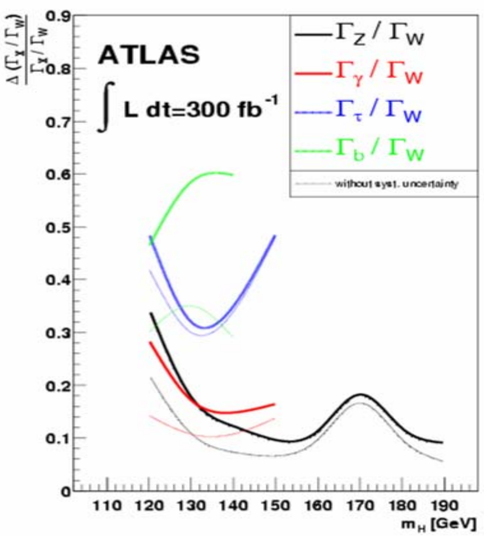
      $\Rightarrow$ Background subtraction

      $\Rightarrow$ Luminosity
- Assume only one Higgs boson
  - $BR(H \to x)/BR(H \to WW) = \Gamma_x/\Gamma_W$
  - Reduced number of fitted parameters

    $\Rightarrow$ smaller errors



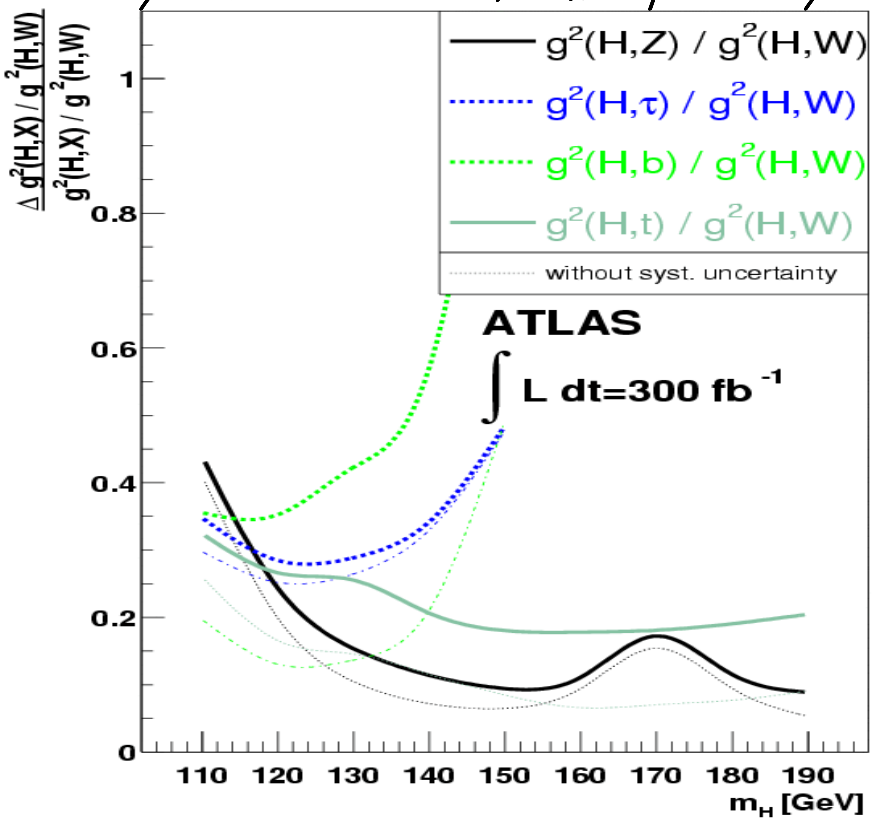




Couplings (low M_H)

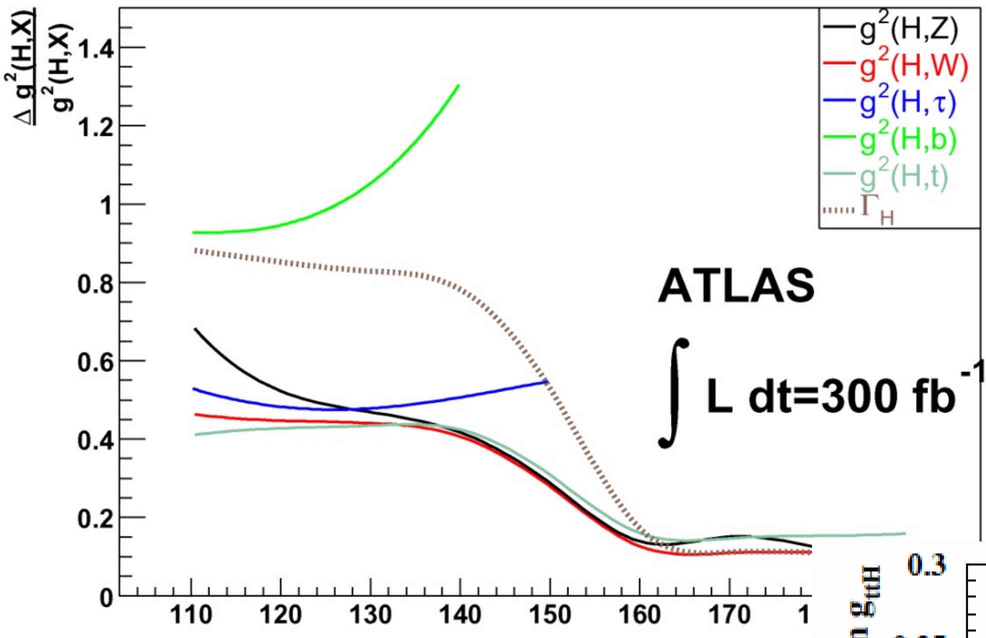
- Express all rates and BR as a function of 5 couplings:
  - $g_W, g_Z, g_{top}, g_b, g_\tau$
  - Examples:
    - $\Rightarrow \sigma(\text{VBF})$: $a_{WF} \cdot g_W^2 + a_{ZF} \cdot g_Z^2$
    - $\Rightarrow \text{BR}(\gamma\gamma)$: $(b_1 \cdot g_W^2 - b_2 \cdot g_{top}^2)/\Gamma_H$

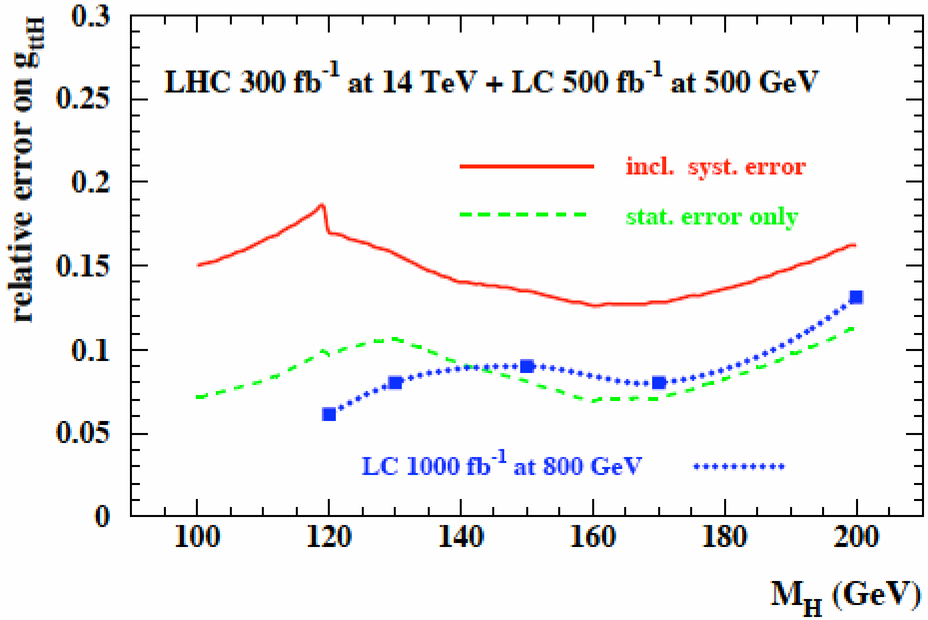
Syst uncertainties from exp+theory



Relative coupling error : ~ 5-20 %

Higgs couplings (absolute)

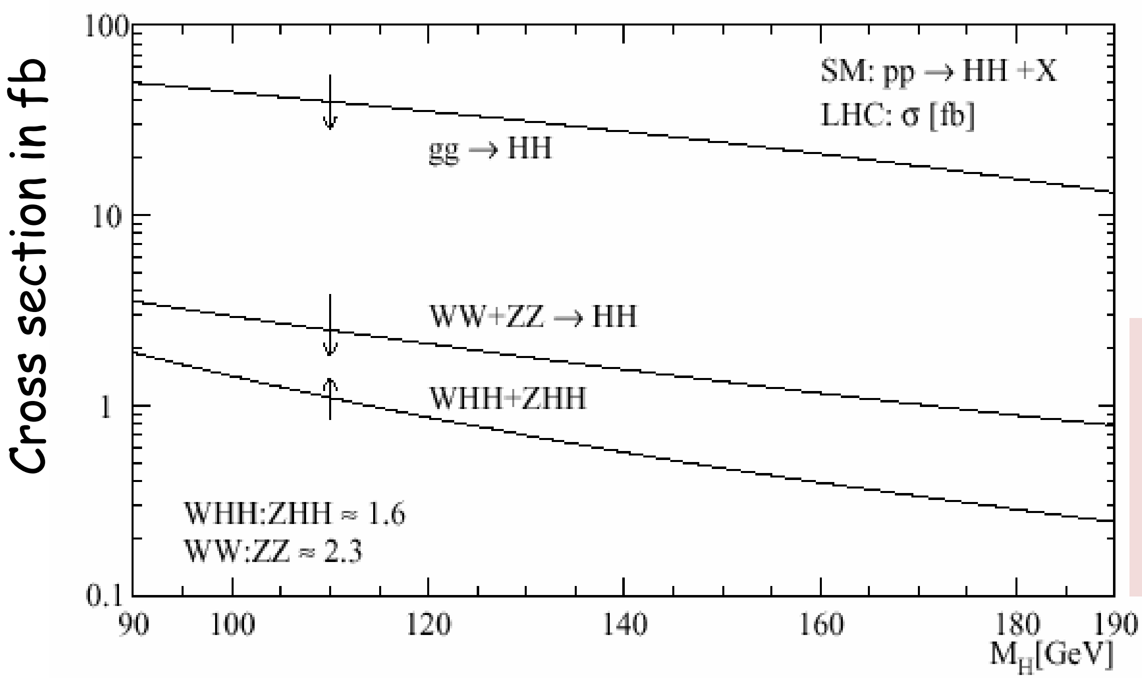




Absolute coupling error at low mass : 20~ 50 %

Higgs self coupling

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



Important to determinne the shape of Higgs potential

Luminosity required
= 6000 fb^{-1}

-> after LHC upgrade

$$gg \rightarrow HH \rightarrow W^+W^-\,W^+W^- \rightarrow \ell^\pm \nu jj \ell^\pm \nu jj$$

Table 8: Expected numbers of signal and background events after all cuts for the $gg \rightarrow HH \rightarrow 4W \rightarrow \ell^+\ell'^+4j$ final state, for $\int \mathcal{L} = 6000$ fb^{-1}.

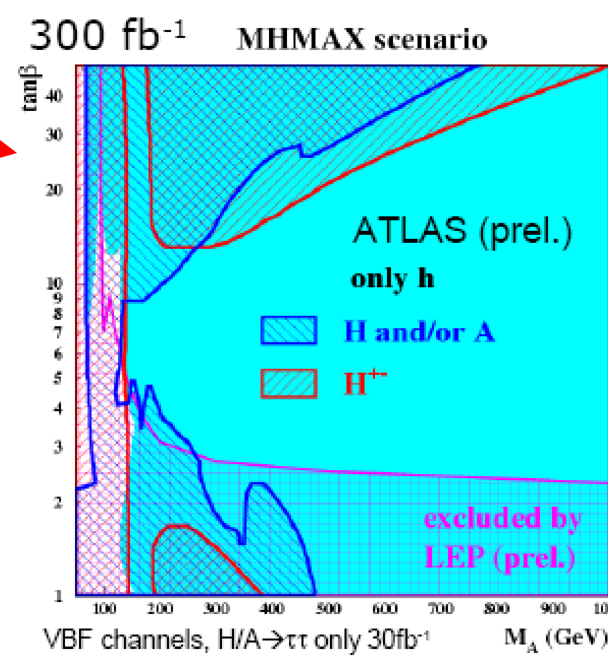
m_H	Signal	$t\bar{t}$	$W^\pm Z$	$W^\pm W^+ W^-$	$t\bar{t}W^\pm$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8

SUSY Higgs

- MSSM theory predicts 5 physical Higgs bosons: h^0, H^0, A^0, H^+, H^- from two Higgs doublets.
- Higgs masses (to first order) are defined by two parameters:
  - ***tanβ*** ratio of 'vev' of 2 Higgs doublets
  - ***m_A*** mass of cp-odd Higgs A^0.
- Four points chosen in parameter space (M.Carena et al. EPJ C26 601 (2004))
- An example

Mhmax scenario: maximal M_h when Higgs-stop mixing large
No mixing scenario: stop mixing set to 0
Gluophobic scenario: coupling of h to gluons suppressed designed for gg→h, h→γγ, h→ZZ→4l
Small α scenario: coupling of h to b(τ) suppressed designed for VBF, h→ττ and tth,h→bb

Name	M_{SUSY} (GeV)	μ (GeV)	M_2 (GeV)	X_t (GeV)	M_{gluino} (GeV)
m_h-max	1000	200	200	2000	800
no mixing	2000	200	200	0	800
gluophobic	350	300	300	-750	500
small α	800	2000	500	-1100	500



Strategy:

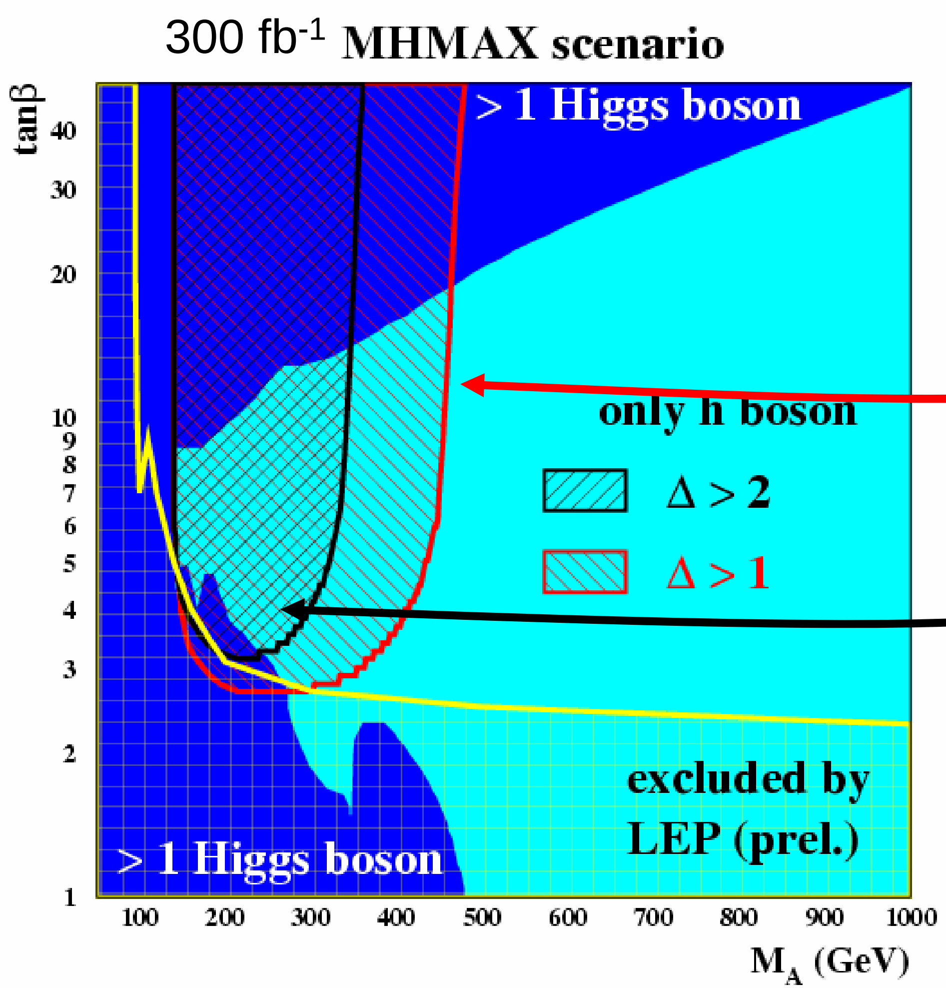
- At least one Higgs should be found.

(this is the case in all 4 CP conserving scenarios. A small hole in CPX senario)

- Extend the region with >1 Higgs observation

(Important to have H searches with the various modes
gluon fusion : coupling to gluon.
VBF: coupling to VB
ttH: coupling to top quark)

Precision measurements of Higgs coupling help distinguishing SM-Higgs and SUSY-Higgs

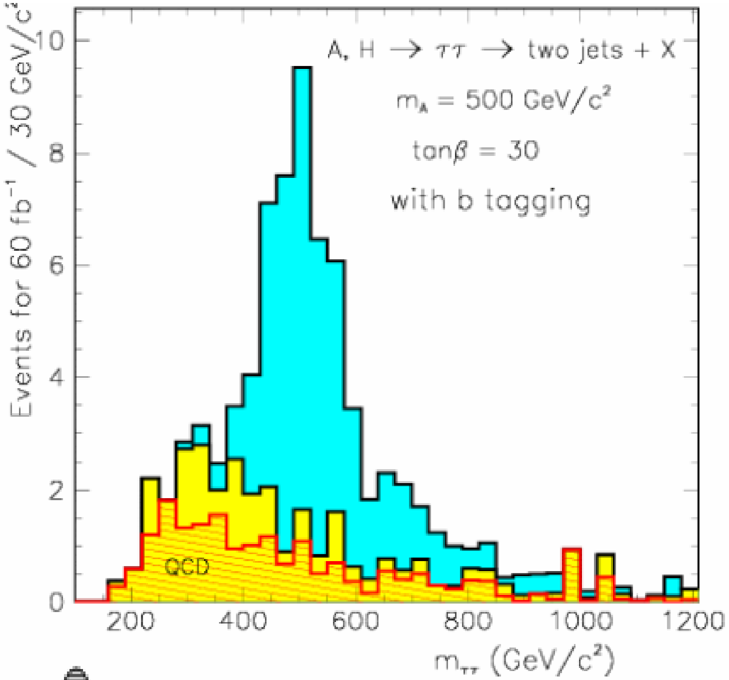


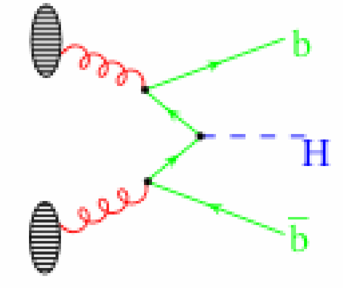
$$\frac{BR(h \to \tau\tau)}{BR(h \to WW)}$$

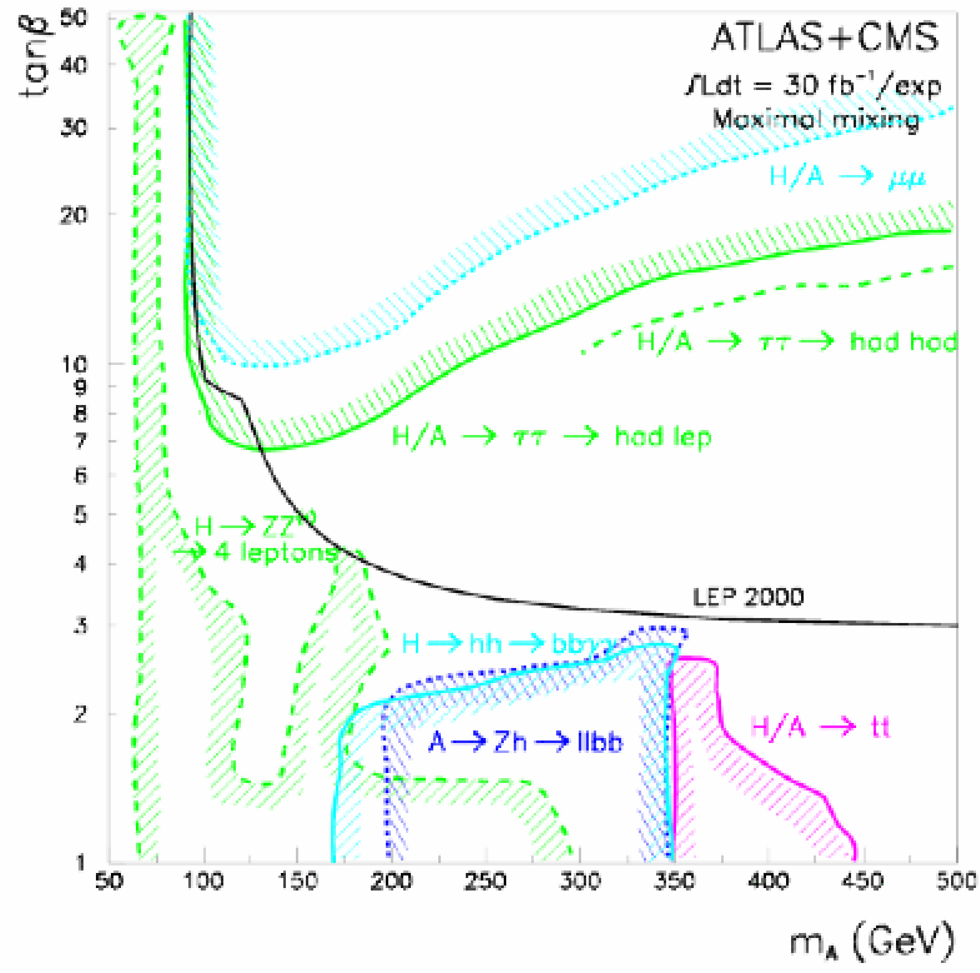
1σ deviation from SM

2σ deviation from SM

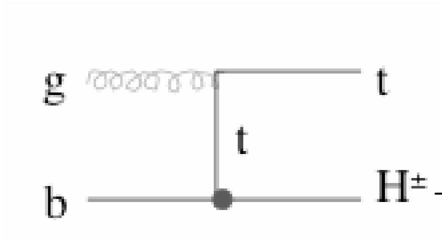
SUSY Higgs (A/H)



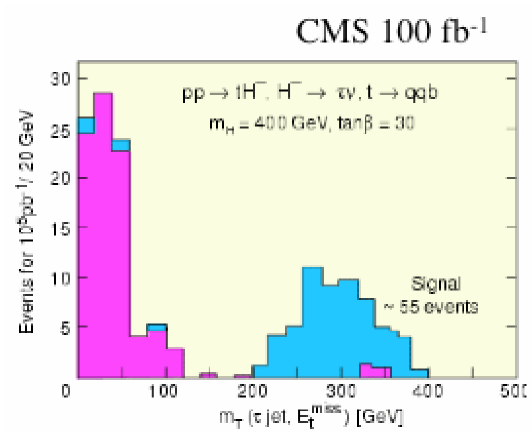


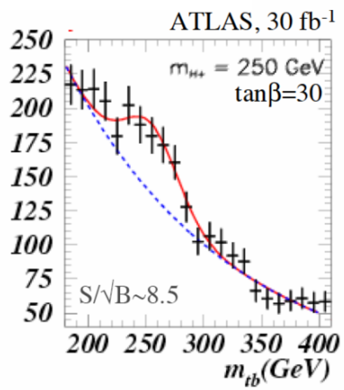


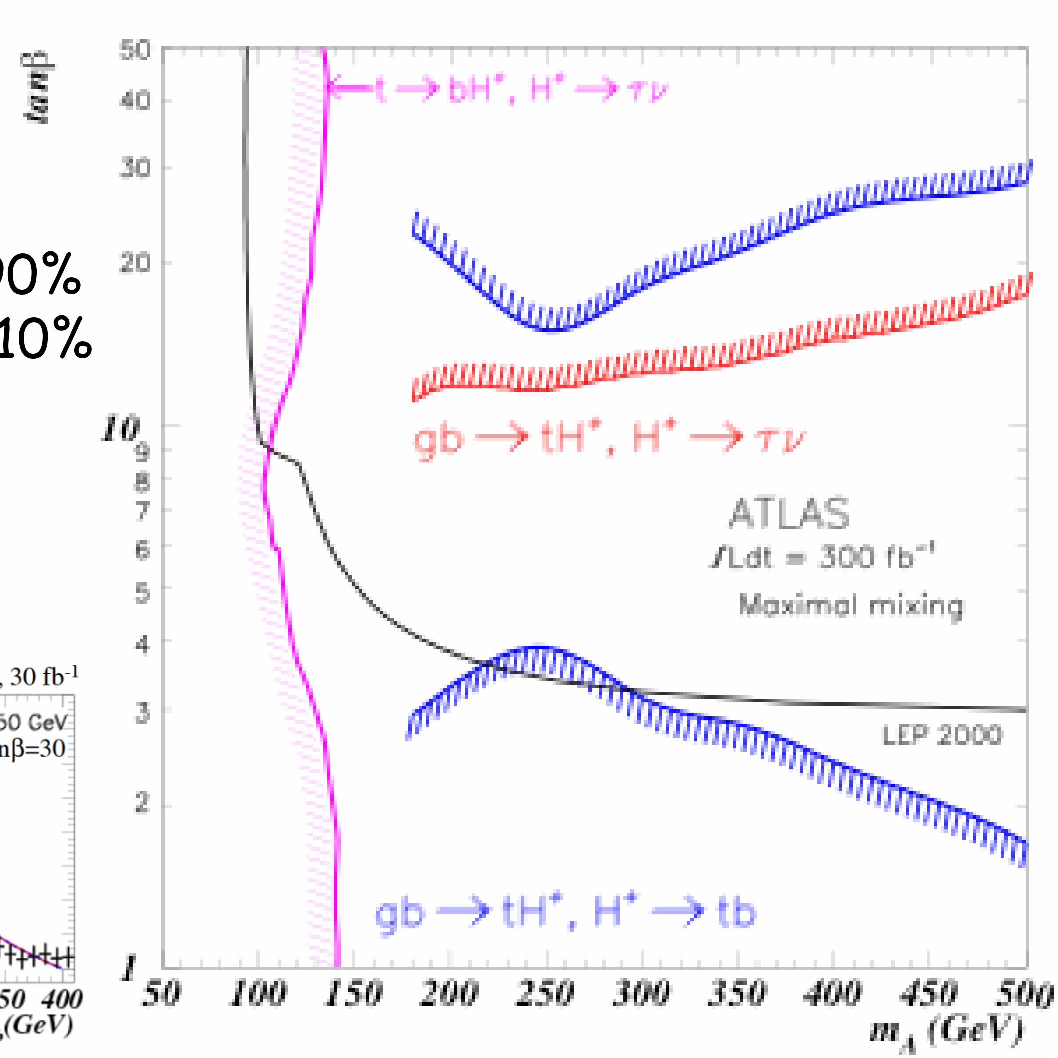
SUSY Higgs (H^+)



$\rightarrow$ (tb) Br=90%
(τν) 10%



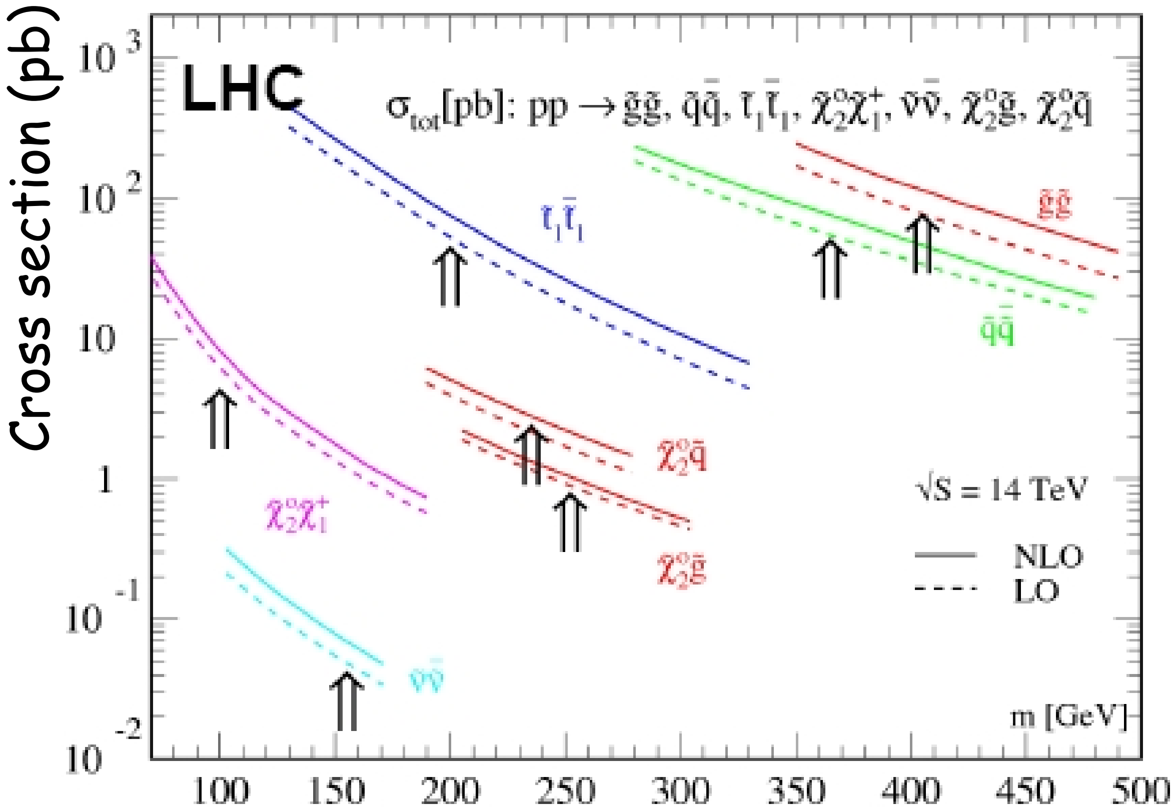


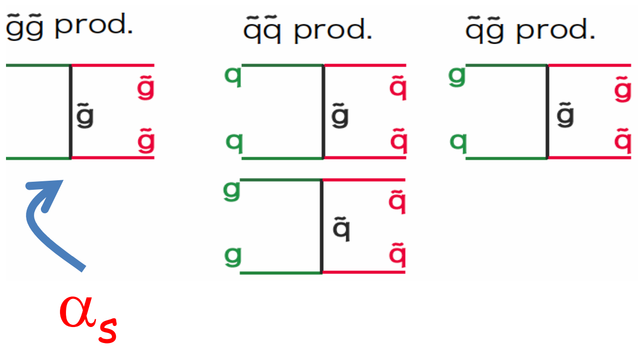


SUSY

SUSY production

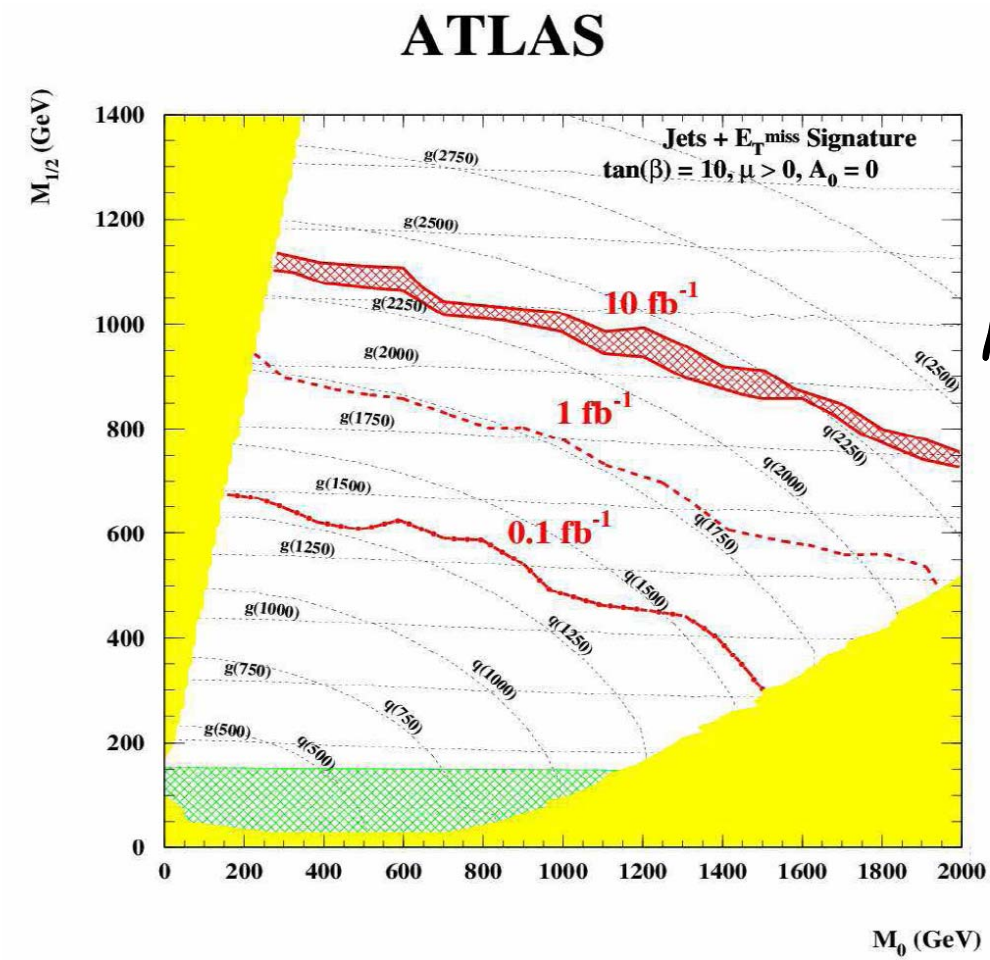
- SUSY particles are created as a pair.
- Production cross sections mainly depend on masses of the sparticles and EW/strong coupling.
- Mass depends on SUSY model.





mSUGRA

- MSSM : 105 parameters (in addition to SM)
- mSUGRA : 5 free parameters M_0, $M_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$
- Squark and gluino masses are mainly determined by M_0 and $M_{1/2}$

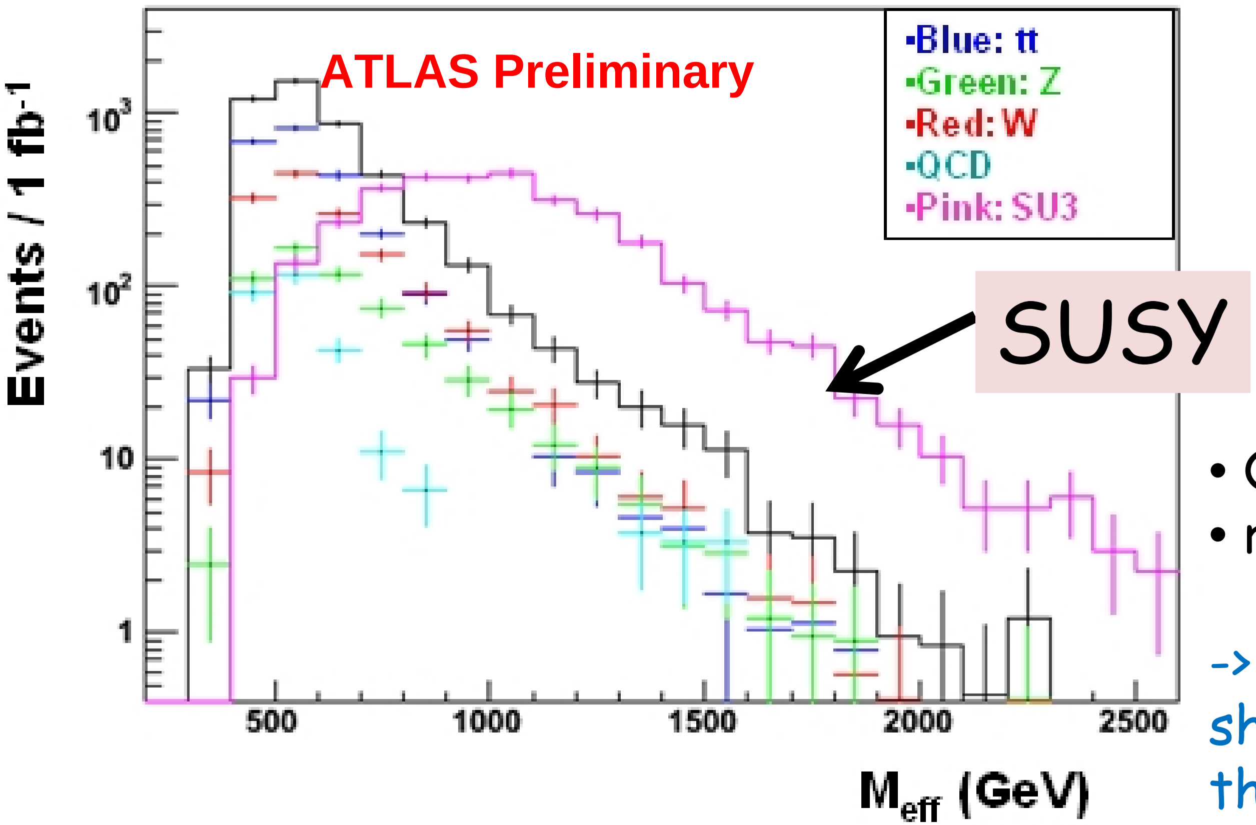


Mass reach: With $L=10^{33}$
~1300 GeV in "one week"
-> by end of 2008
~1800 GeV in "one month"
-> by end of 2009

SUSY signature

Event topology strongly depends on SUSY parameters:
-> Try to keep selections as inclusive as possible.

Effective mass : $M_{eff} = MET + P_{T,1} + P_{T,2} + P_{T,3} + P_{T,4}$



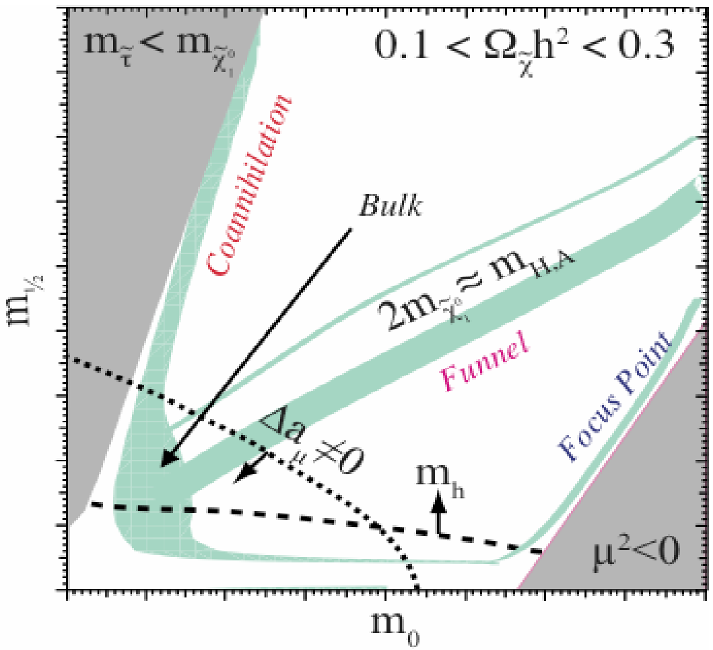
- QCD model dependence?
- reliability of detector simulation?

-> Background distribution should be determined with the real data.

SUSY parameter determination

Set several points in mSUGRA plane
with the WMAP constraint $\Omega_\chi h^2=0.14$

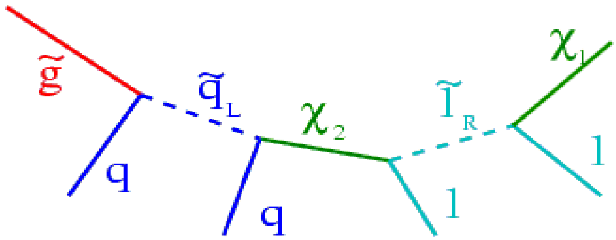
qualitative picture – no mass scale



Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	tan(β)	sign(μ)	σ (pb)
Coannihilation - SU1	70	350	0	10	+	7.43
Focus Point - SU2	3550	300	0	10	+	4.86
Bulk - SU3	100	300	-300	6	+	18.59
Low Mass - SU4	200	160	-400	10	+	262
Funnel - SU6	320	375	0	50	+	4.48
Coannihilation - SU8.1	210	360	0	40	+	6.44
Coannihilation - SU8.2	215	360	0	40	+	6.40
Coannihilation - SU8.3	225	360	0	40	+	6.32

Benchmark tests with these points are on-going.

Decay chain anaylsis

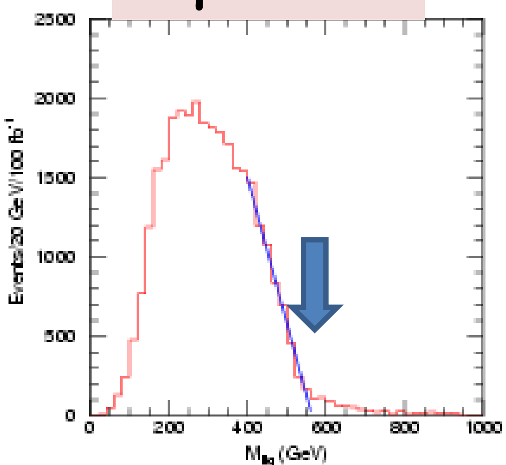


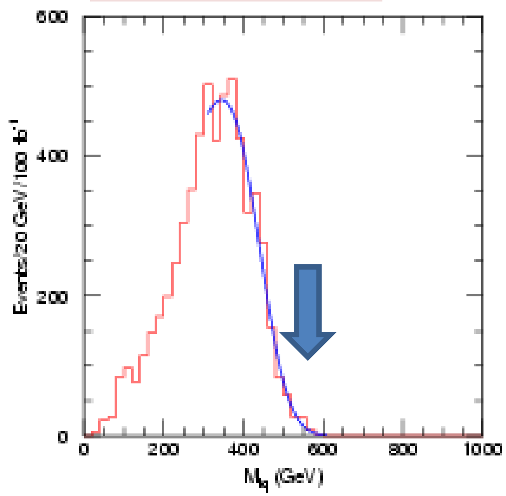
$$\tilde{q}_L \rightarrow q\, \tilde{\chi}_2^0 \rightarrow q\, \tilde{l}_R\, l^{\pm} \rightarrow q l^{\pm} l^{\mp} \tilde{\chi}_1^0$$

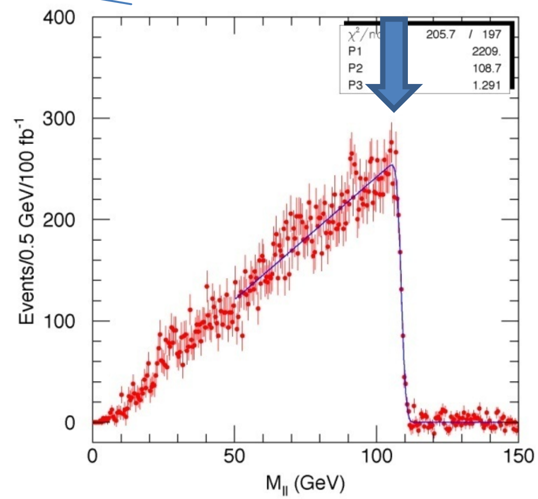
llq mass

lq mass

l^+l^- mass



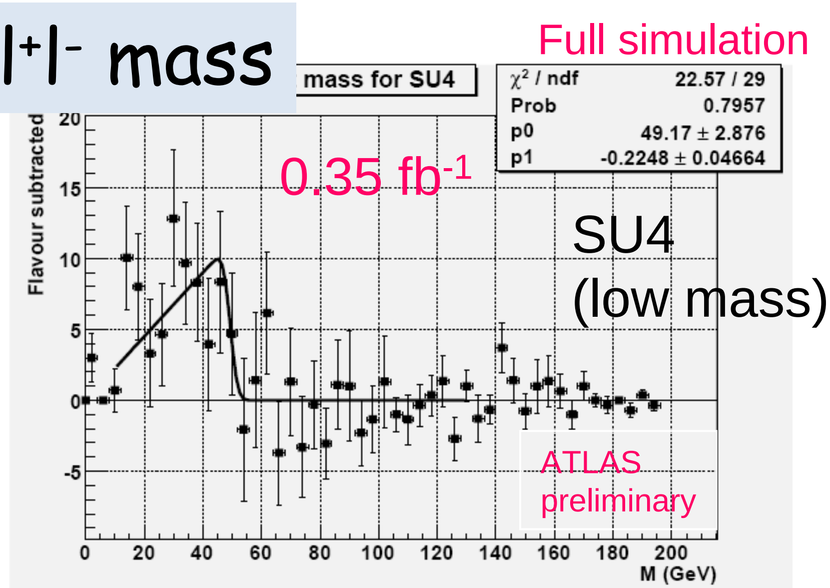




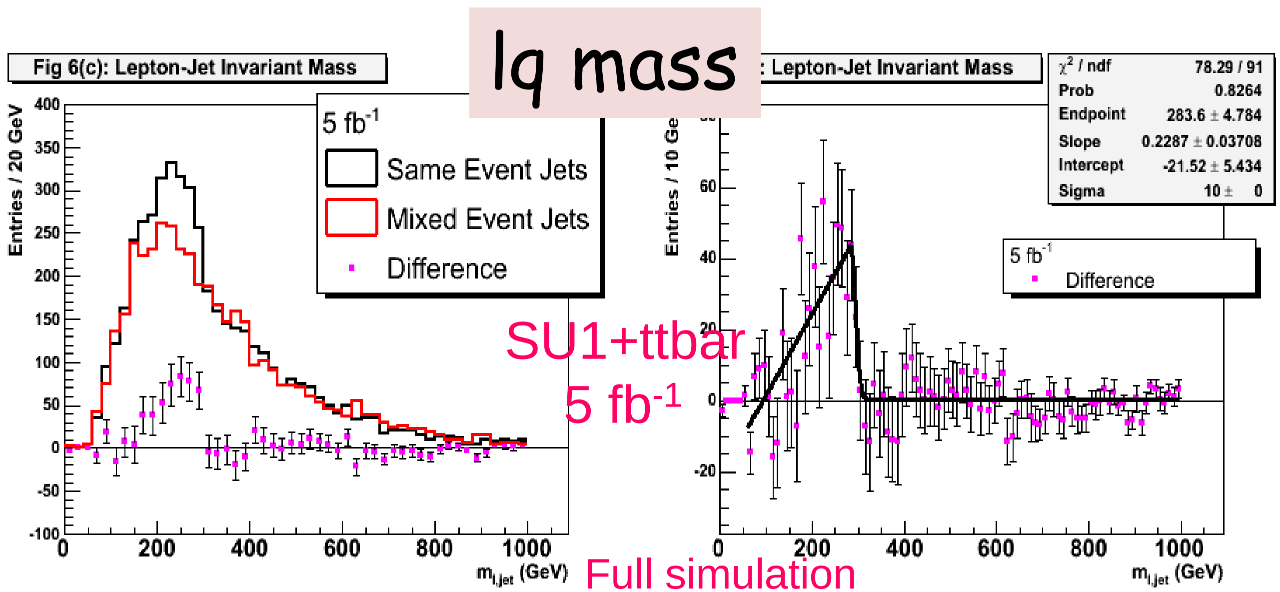
$100fb^{-1}$

End point -> Mass difference

Decay chain anaylsis with initial data



Co-annihilation Region $\tilde{\tau} \sim \tilde{\chi}^0$

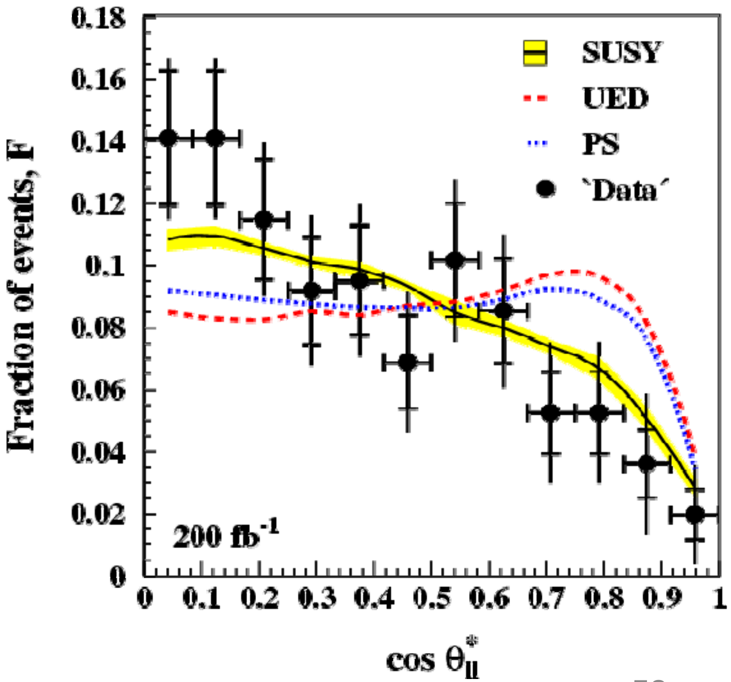


Spin determination

J. Barr JHEP 02 (2006) 042

$$q\bar{q} \rightarrow Z^0/\gamma \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow \tilde{\chi}_1^0 l^+ \tilde{\chi}_1^0 l^-$$

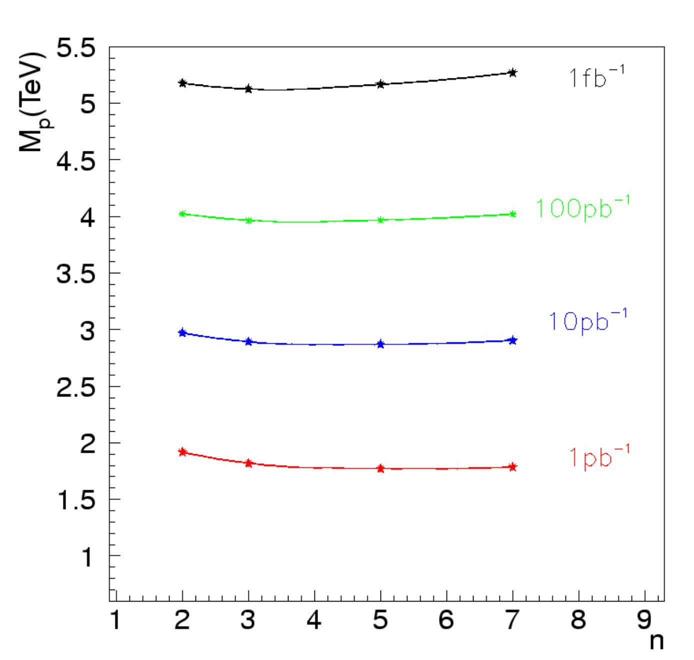
$$\cos\theta_{ll}^* = \cos(2\tan^{-1} e^{-\frac{1}{2}\Delta\eta}) = \tanh(\tfrac{1}{2}\Delta\eta)$$



Extra dimension

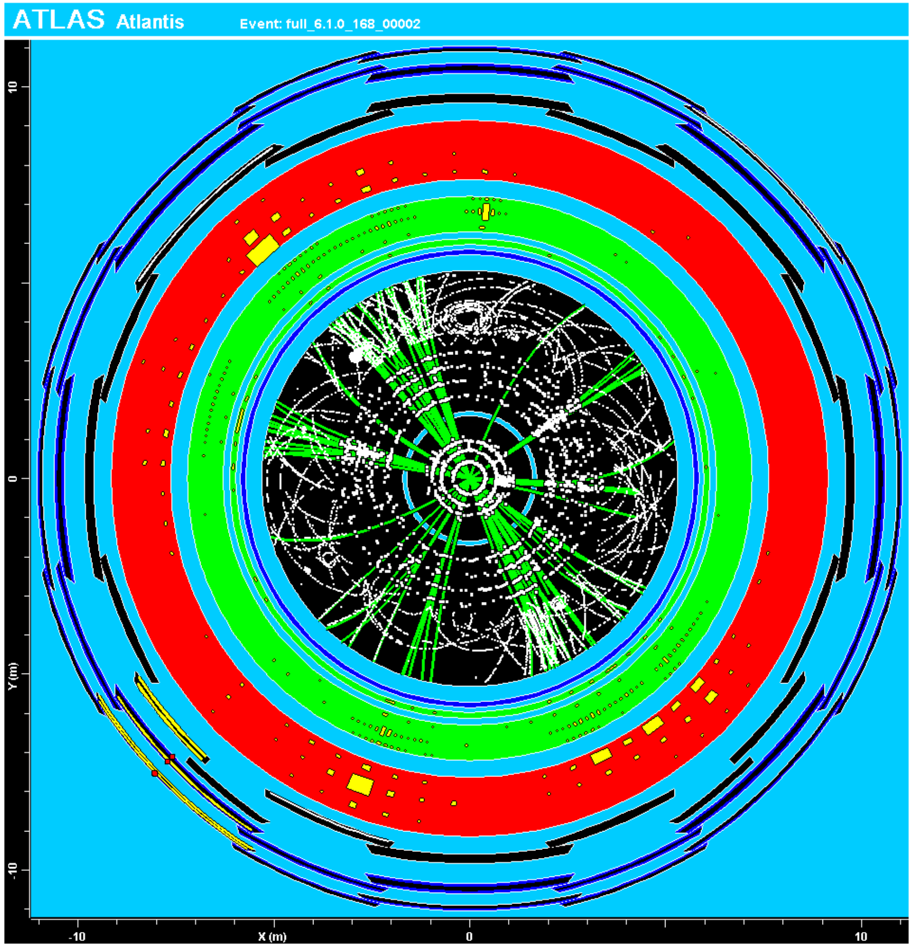
Black-holes

May mini black holes will be produced for low Planck scale in Extra-D Models.



Tanaka, Yamamura, Asai, Kanzaki
Eur. Phys. J. C 41 (2005) s19-s33

BH evaporates with Hawking Radiation:
Many energitic "flavor democratic" particles are emitted:



M_{Pl}=1TeV, n=2 M_{BH}=6.3TeV

Summary

- LHC machine integration is on going, aiming for the first collision in summer 2008.
- ATLAS and CMS detectors are becoming in shape. “Real” cosmic data are collected.
- Early discovery ($\sim 5 fb^{-1}$) of Higgs is possible. Searches are set up in multiple decay channels. Decent Higgs properties can be studied at LHC.
- The first SUSY signature may come rather quickly. Determining the SUSY parameters will take long.
- LHC is the energy frontier machine. We like to expect many unexpected events.