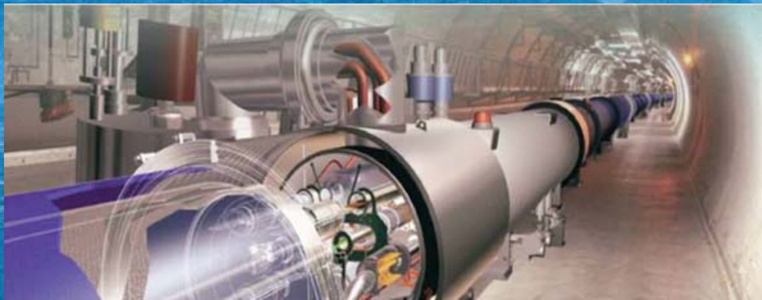
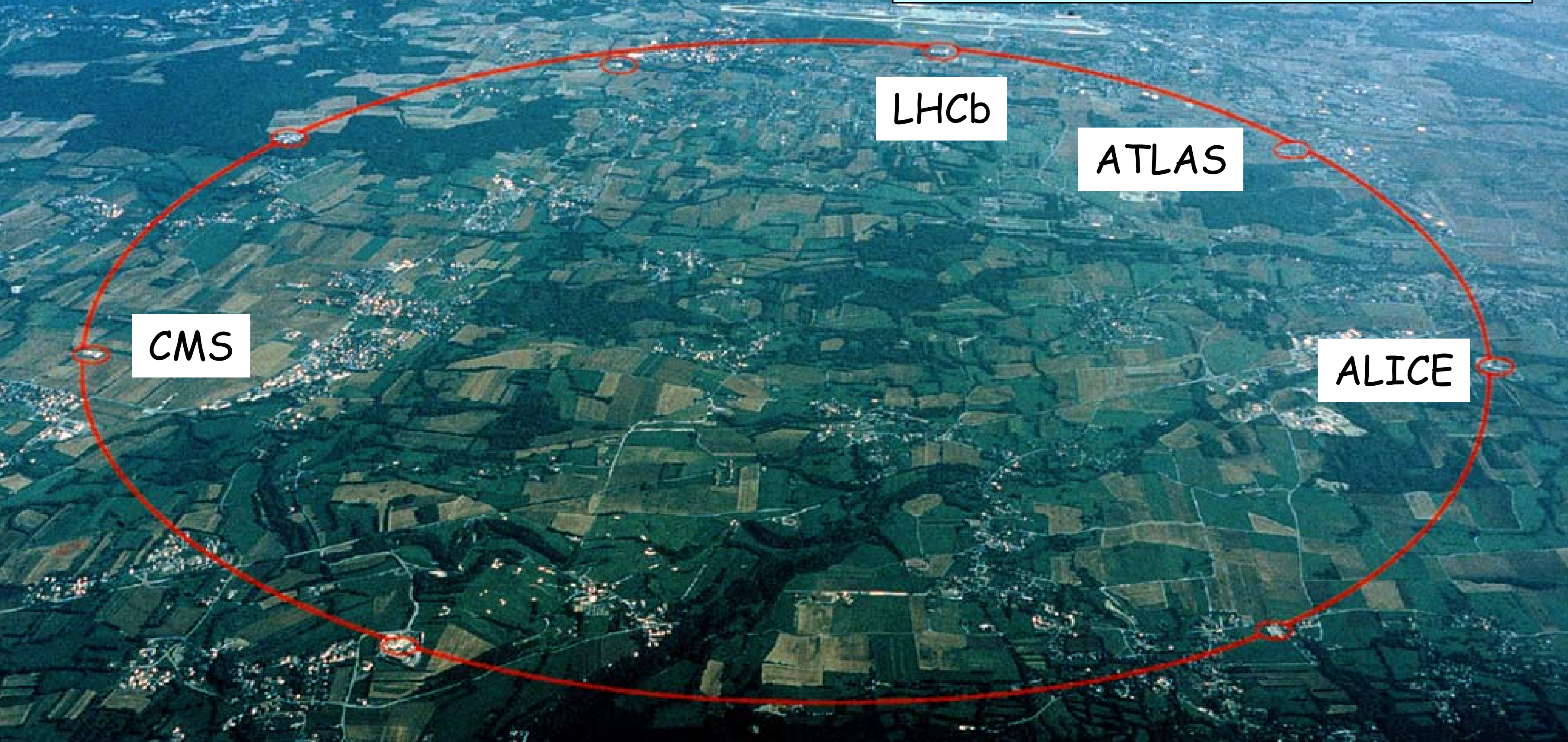
LHC Physics
What can be done in the first years

Klaus Desch
University of Freiburg
Matter To The Deepest
Ustron, 12/09/2005

The Large Hadron Collider

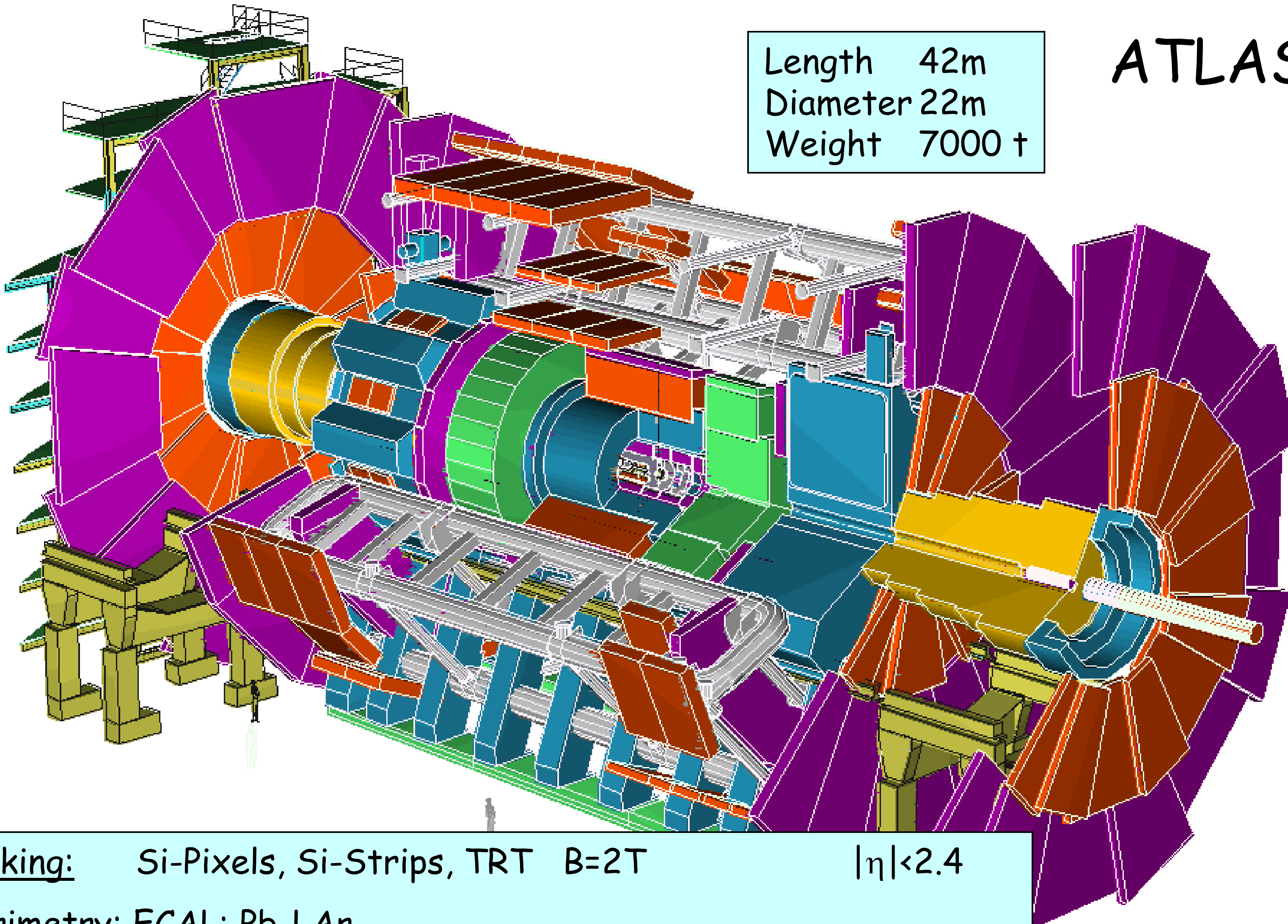


Beam energy	7 TeV
Luminosity	10^{34} cm^{-2}s^{-1}
Bunch spacing	25 ns
Particles/Bunch	10^{11}
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	350 MJ/Beam



ATLAS

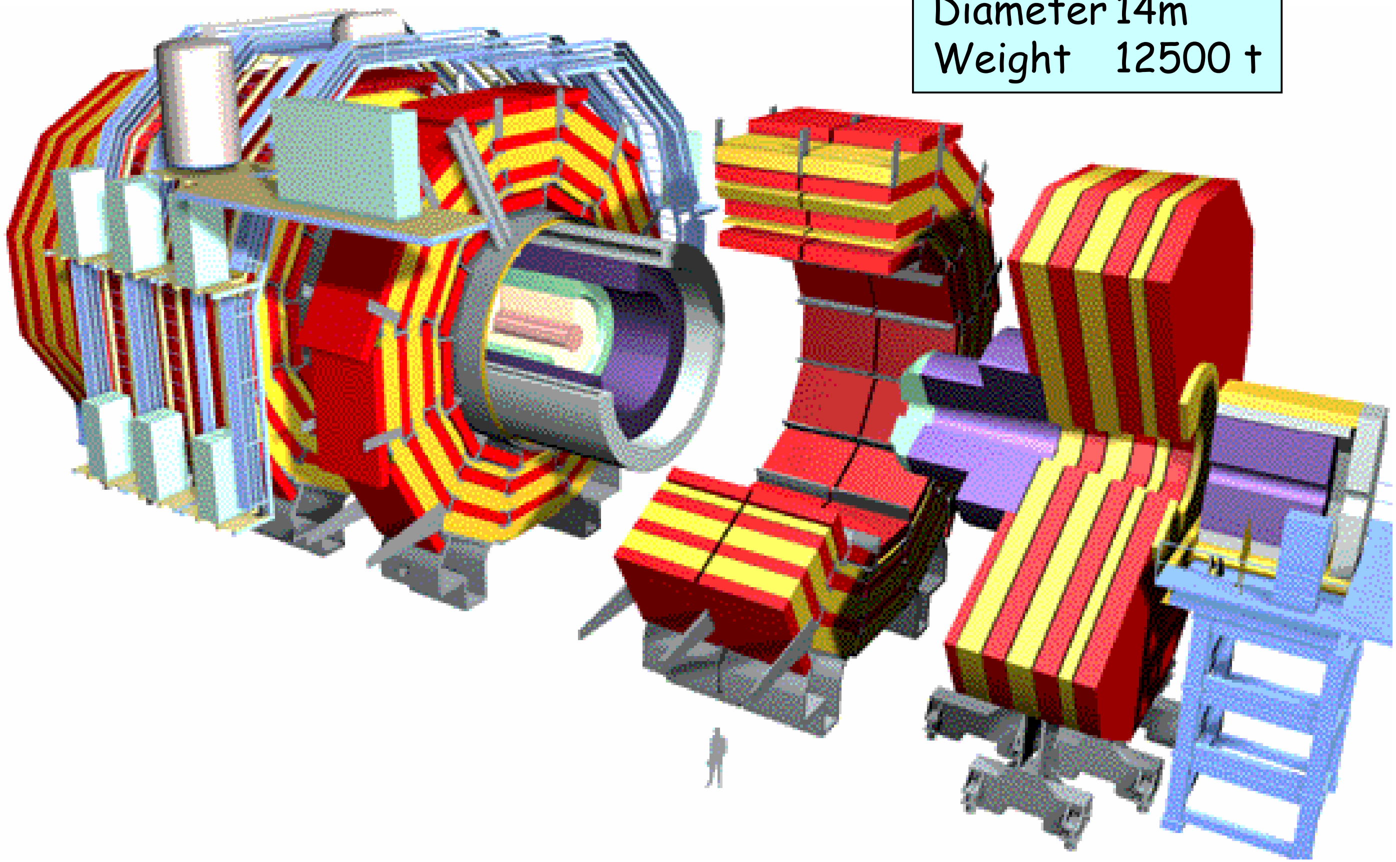
Length	42m
Diameter	22m
Weight	7000 t



Tracking:	Si-Pixels, Si-Strips, TRT B=2T	$\|\eta\|<2.4$
Calorimetry:	ECAL: Pb-LAr	
	HCAL: Fe-Sc (central) , Cu-LAr (fwd)	$\|\eta\|<5$
Muons:	MDTs, RPCs(Trigger), CSCs(fwd), air-core toroid	$\|\eta\|<2.7$

CMS

Length	22m
Diameter	14m
Weight	12500 t



Tracking:	Si-Pixels, Si-Strips, B=4T	$\lvert\eta\rvert<2.4$
Calorimetry:	ECAL: 76.000 $PbWO_4$ Crystals	
	HCAL: Brass-Sc	$\lvert\eta\rvert<5$
Muons:	MDTs, RPCs(Trigger), CSCs(fwd),	$\lvert\eta\rvert<2.7$

+ TOTEM=

forward spectrometer using Roman Pots+ CSCs

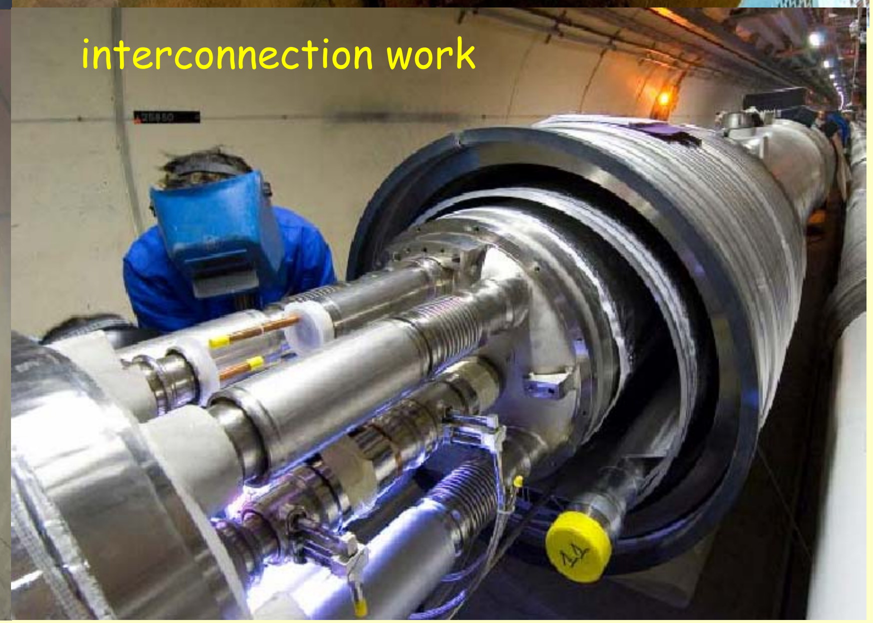
Status: Where are we?

Status: LHC – in pictures

Upstream transport line T12
ready and under vacuum

First cryodipole lowered 07/03/05

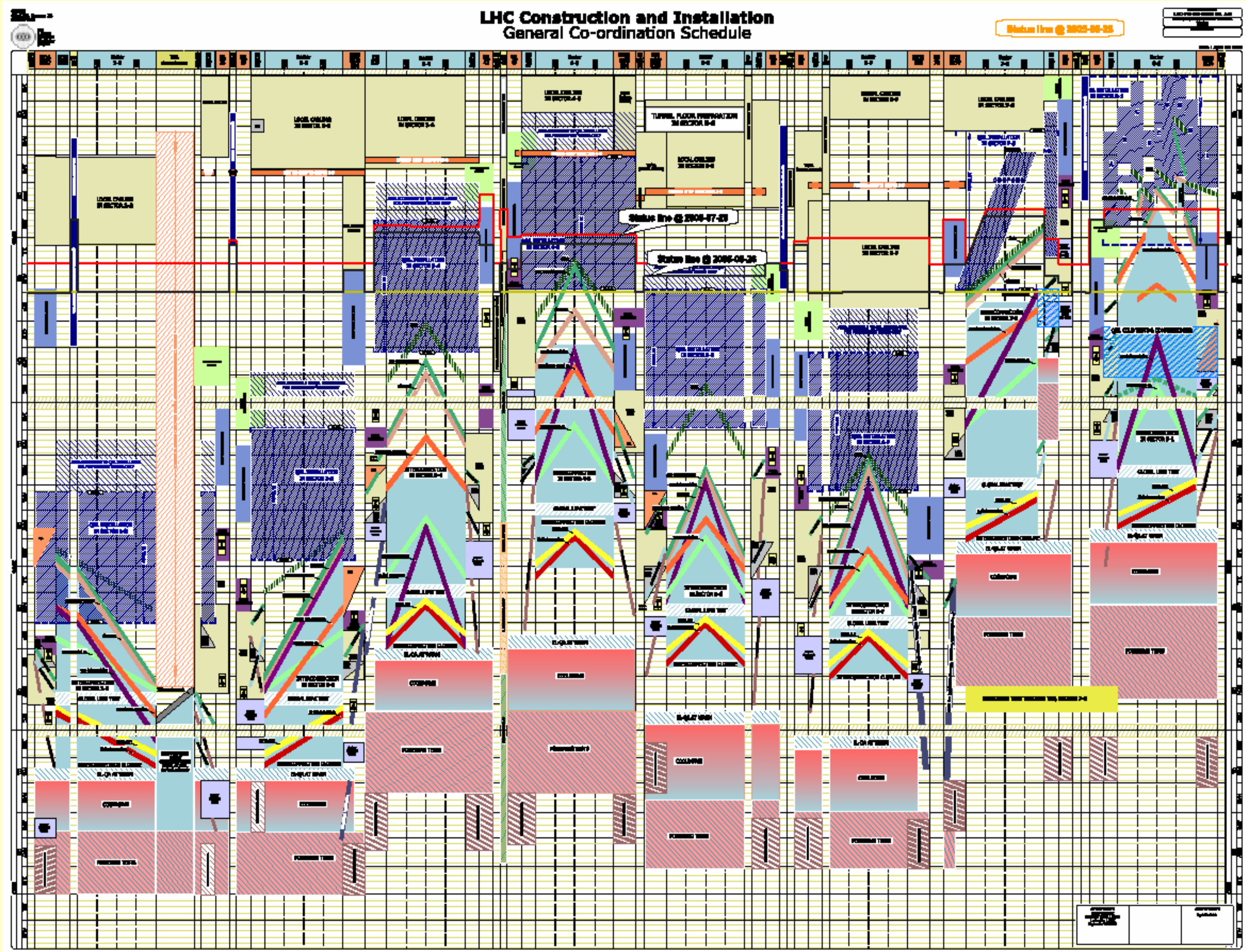
more than 80 dipoles installed in tunnel



interconnection work

Official LHC installation schedule – a piece of art

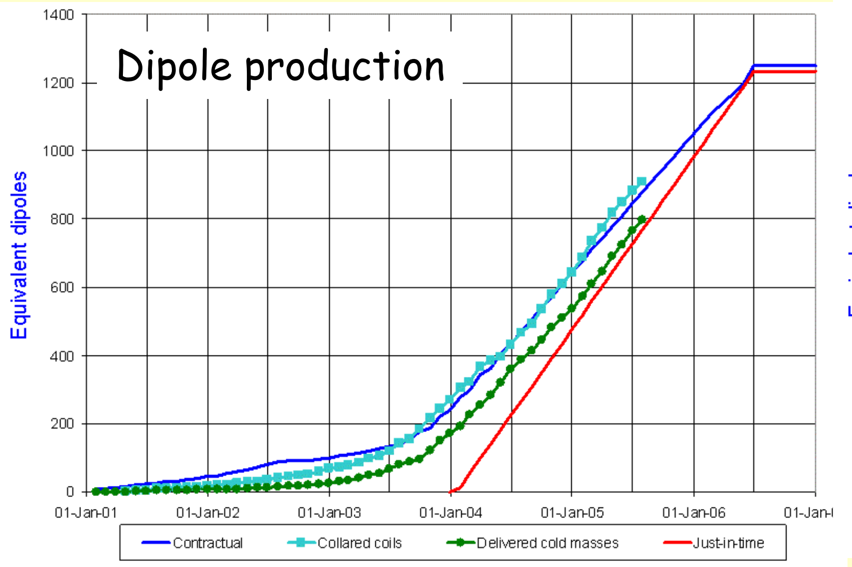
we are here

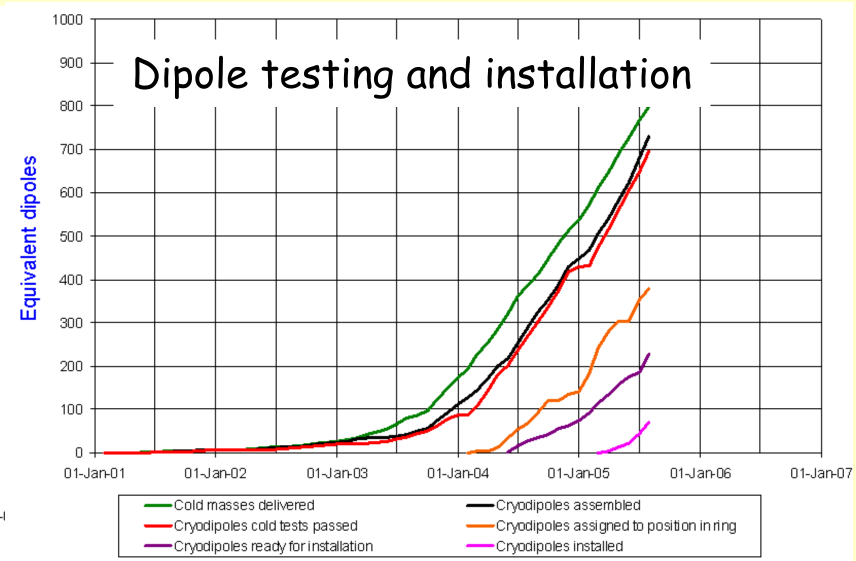


June 07

Status: LHC – in words

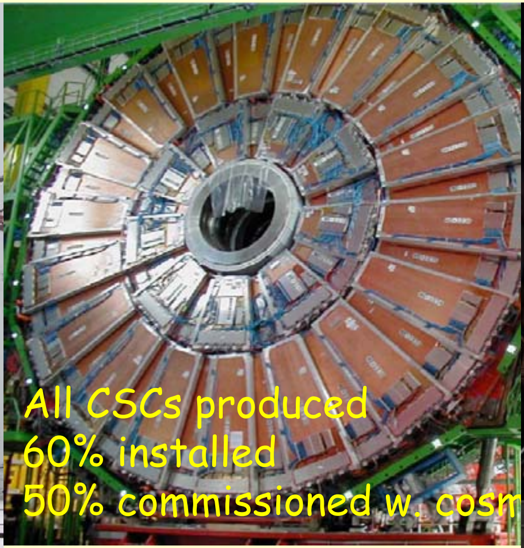
- 75% of dipoles produced, very good quality
- ~ 80 dipoles installed in tunnel
- cryogenics problem solved – revised installation plan implemented
- plan: terminate installation in February 2007
- cryogenics + dipole installation on critical path
  to be ready for beam in Summer 2007



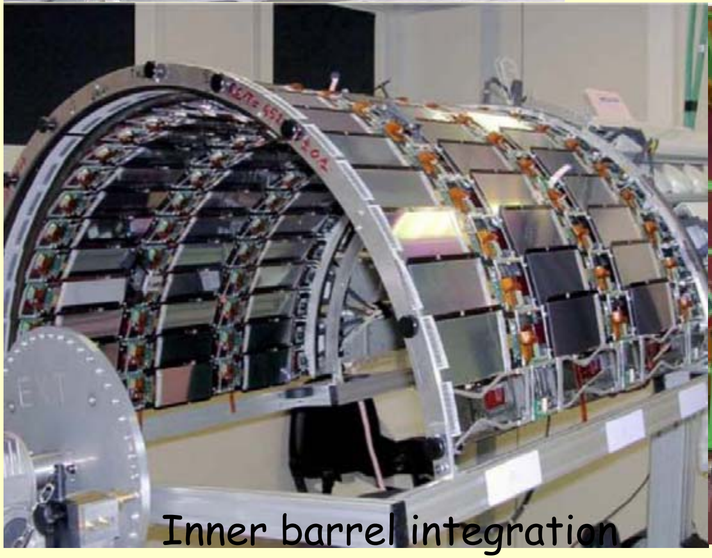


Status: CMS


Civil enginieering of
CMS Cavern finished

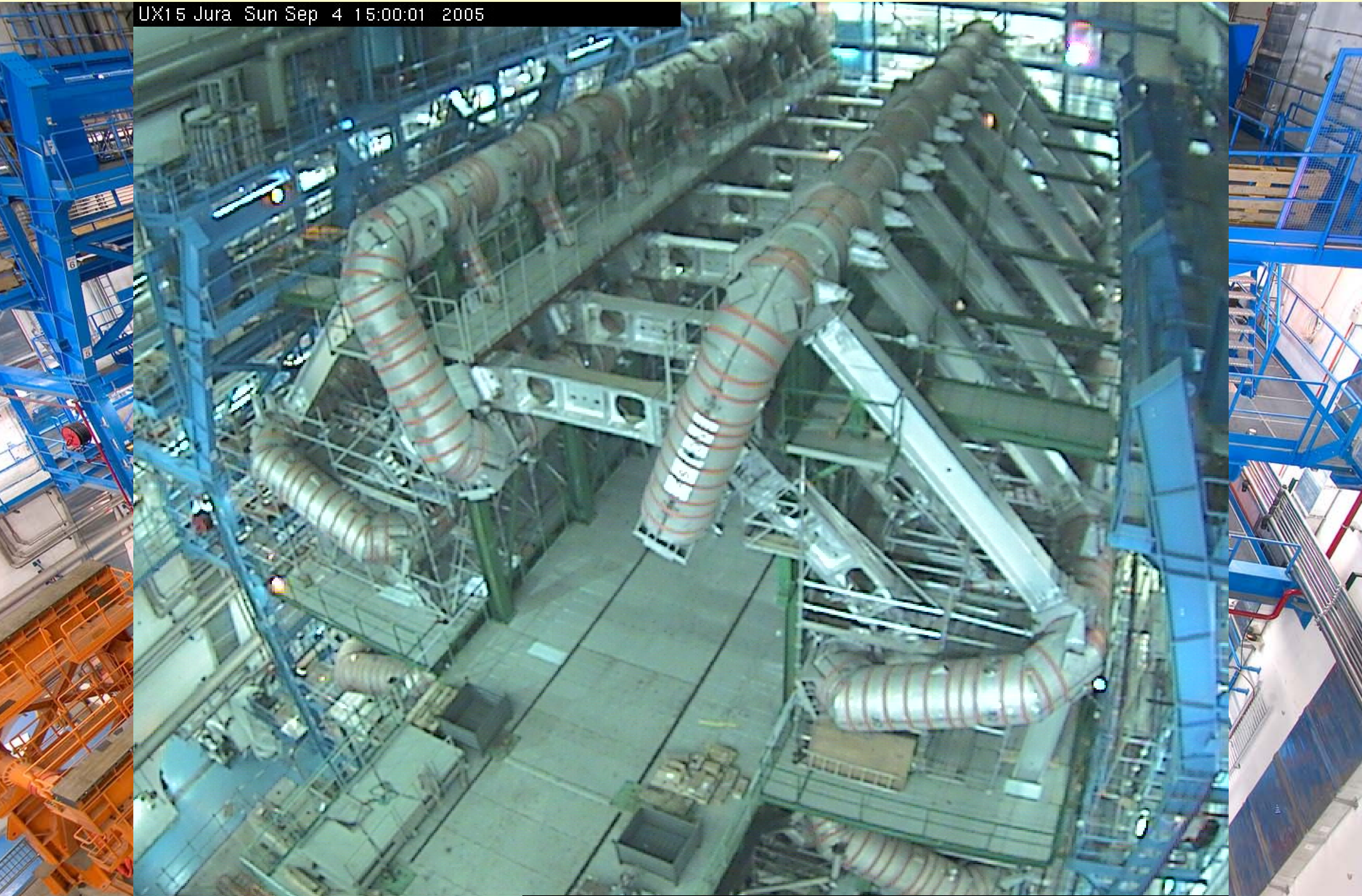

All CSCs produced
60% installed
50% commissioned w. cosm


4T magnet inauguration

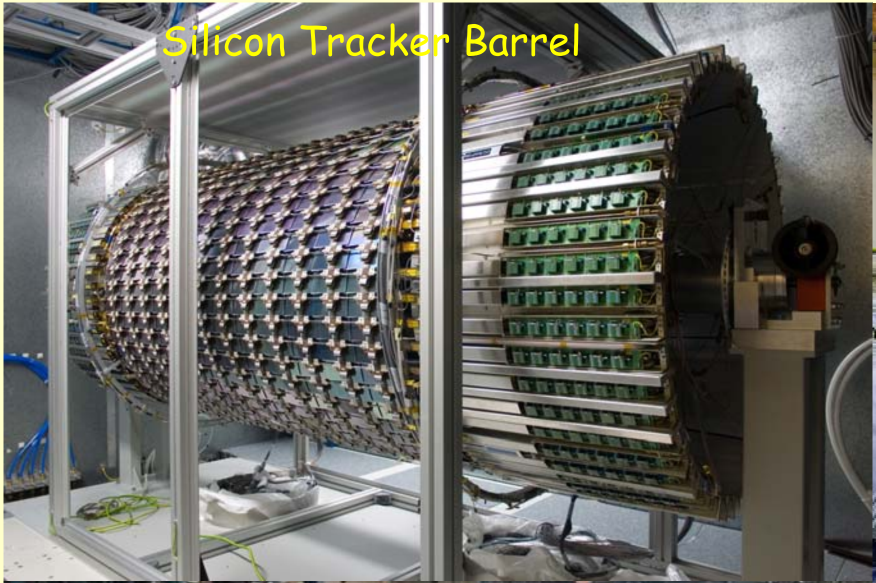

Inner barrel integration

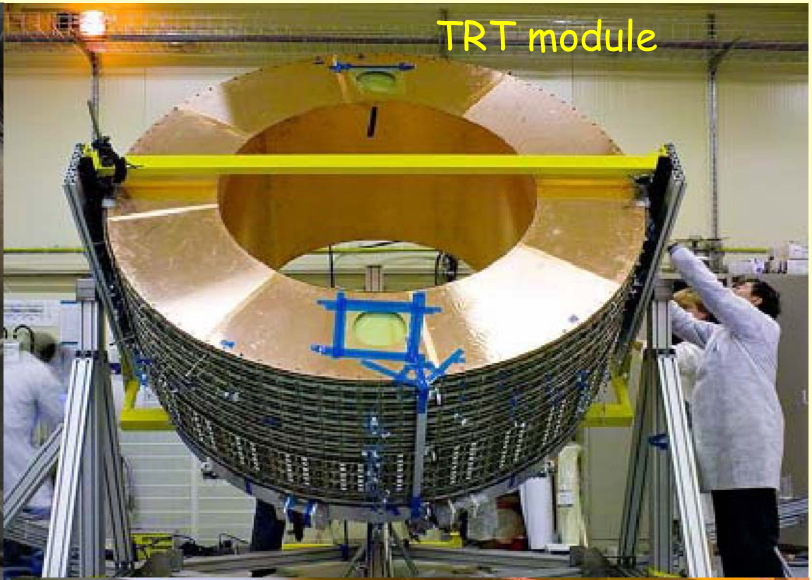

70% of Drift tubes assembled,
15% installed

Status: ATLAS



Status: ATLAS





Status: Summary

LHC construction advancing well
cryogenics problem overcome
tight installation schedule
plan to be ready for beam in June 07

ATLAS construction of components (almost) finished
installation in pit advancing very well

CMS civil engineering in pit finished
HCAL and Muon systems well advanced
Magnet assembled
Crystal production and tracker integration on critical path

Endcap ECAL and Pixels will be installed in first shutdown (2007-08)

Comissioning

<u>Machine:</u> What luminosity may we expect when?

<u>Detectors:</u>

GOAL: Best possible "day 1" performance

<u>Challenges:</u>

- Alignment of tracking devices (Pixels, Strips, TRT, Muon Chambers)
- Calibration of Calorimeters
- Trigger/DAQ
- Software comissioning
- Computing comissioning – The GRID

<u>Stages:</u>

1. Fabrication control
2. Test beam programs
3. Cosmics
4. Single Beam
5. Physics Comissioning (colliding beams)

LHC startup

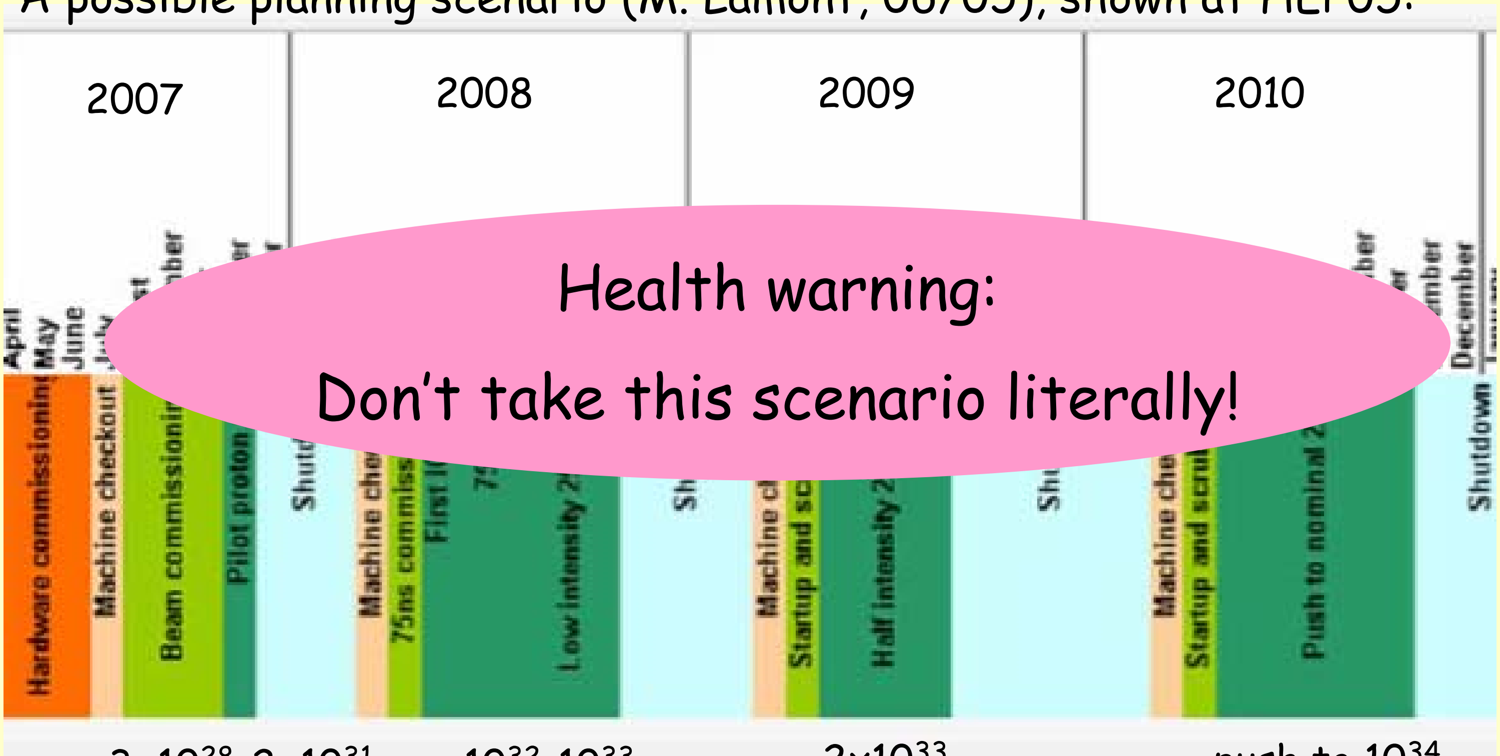
No really 'official' statements

Achieve luminosity as fast as possible with most careful protection of machine and detectors

Lyn Evans:

"Difficult to speculate further on what the performance might be in the first year. As always CERN departments will do their best."

A possible planning scenario (M. Lamont, 06/05), shown at HEP05:



???

Health warning:

Don't take this scenario literally!

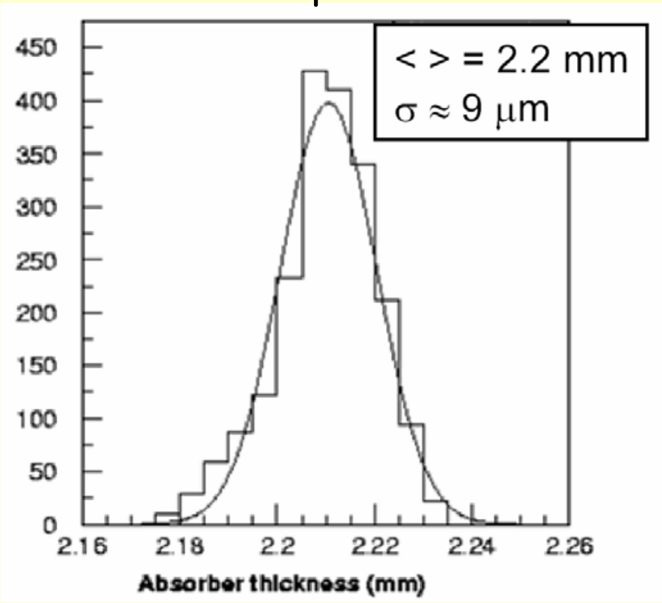
1 fb^{-1} = 6 months at 10^{32}

Comissioning

Phase 1: Hardware fabrication control

Achieve best possible uniformity of detector response by very tight fabrication tolerances

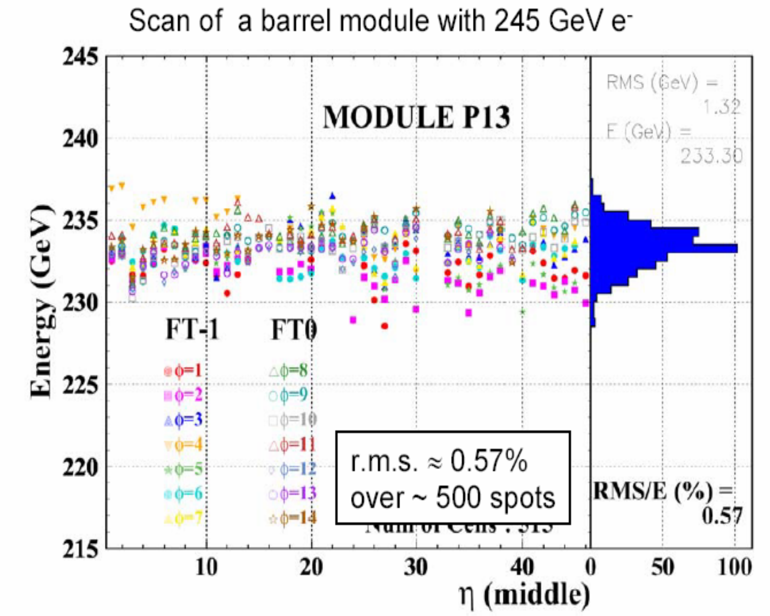
Example: absorber thickness in ATLAS Endcap ECAL:



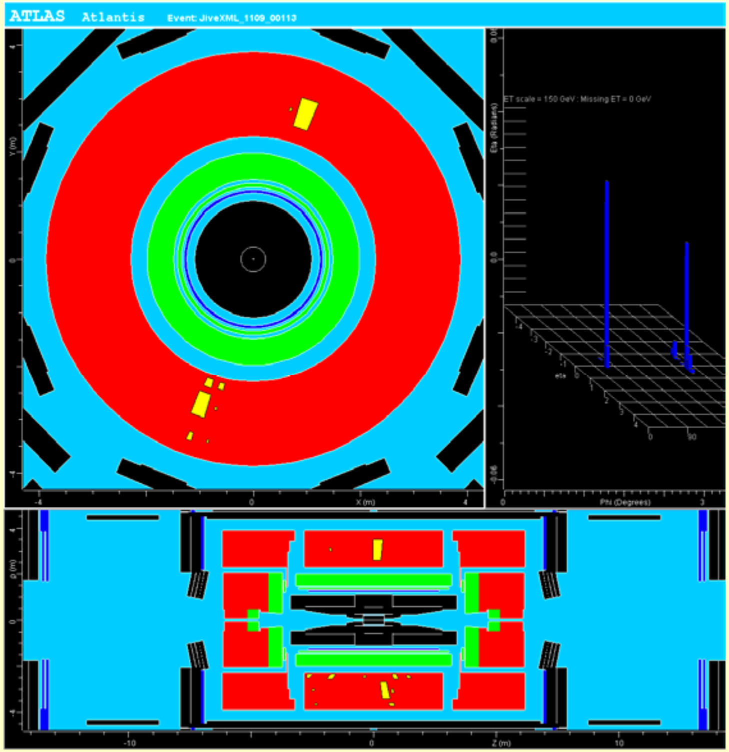
Phase 2: Testbeam

ATLAS example: combined test beam of modules of all detector components

Example: response of ECAL:



Phase3: Comissioning with Cosmics

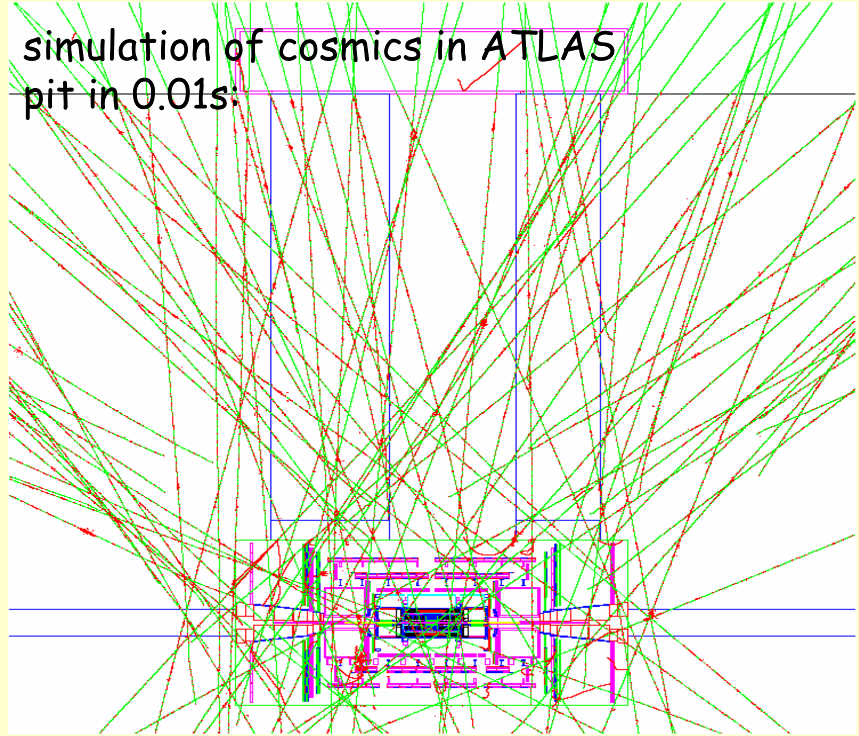


First cosmic event in UX15!!

Barrel TileCal is complete in the cavern.

Single tower trigger

First cosmic events observed



Need ~3 months of cosmics running (during cooldown of machine)

→ 100 muons/cell in ECAL
- check ECAL timing to 1ns
- check alignment w.r.t other comp.: <1mm
- check response uniformity vs η: 0.5%

Comissioning

Expected day 1 performance — to be improved by

ECAL uniformity e/γ scale	~1%(ATLAS),4%(CMS) 1-2%	min bias, $Z\rightarrow ee$, $W\rightarrow e\nu$ $Z\rightarrow ee$
HCAL uniformity jet energy scale	2-3% <10%	single π, QCD jets Z+jets, $W\rightarrow qq$ in top
Tracking alignment	20-500 μm	tracks, isol.μ, $Z\rightarrow\mu\mu$

(F. Gianotti)

Early Physics

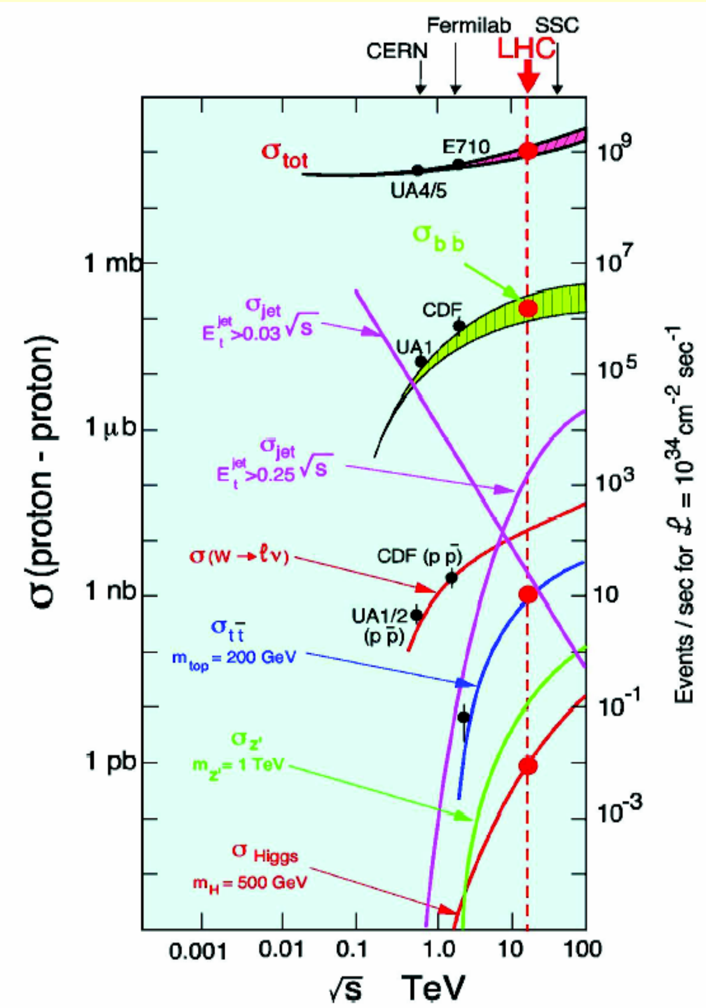
Establish signals from “known” SM processes to

- calibrate the detector

- estimate backgrounds for new physics from data

Early Physics

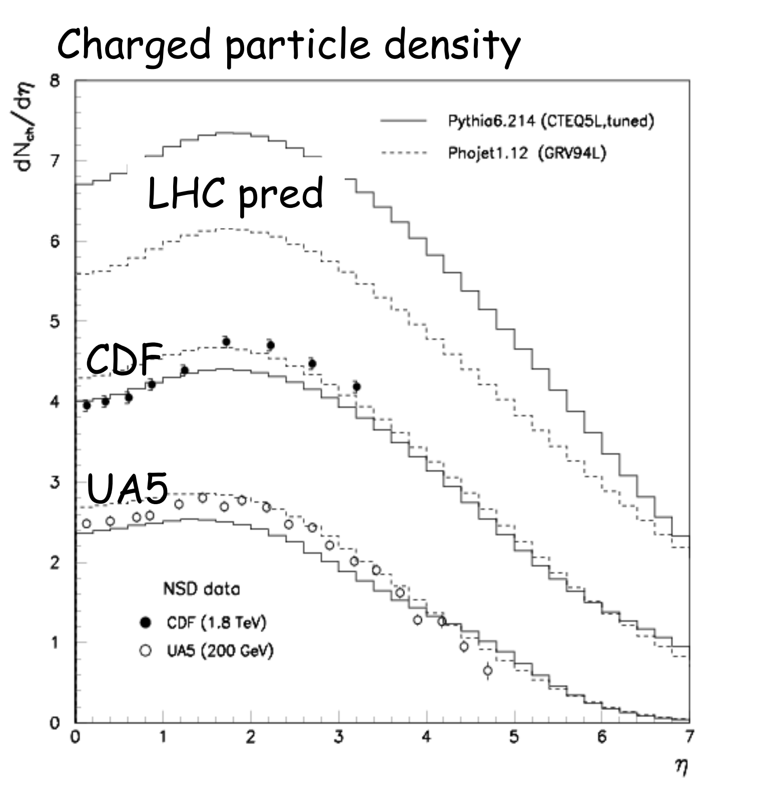
Process	Rate [Hz] at $L=10^{33}$	Events on tape ($10fb^{-1}$)
$W \rightarrow e\nu$	15	10^8
$Z \rightarrow ee$	1	10^7
tt	1	10^6
minimum bias	10^8	10^7
QCD jets p_T>150 GeV	10^2	10^7
bb	10^3	10^7
gluinos, m=1TeV	0.001	10^3
Higgs, m=130 GeV	0.02	10^4

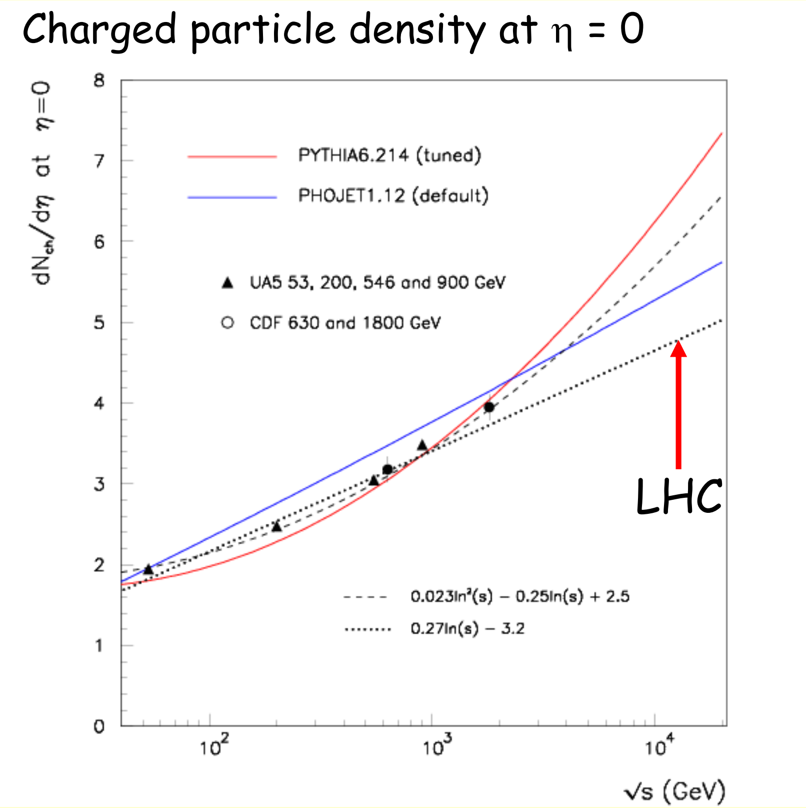


Statistical errors negligible in most cases after few days
Focus on systematics: understand detector, luminosity, theory

Examples →

Very Early Physics: the first three minutes…





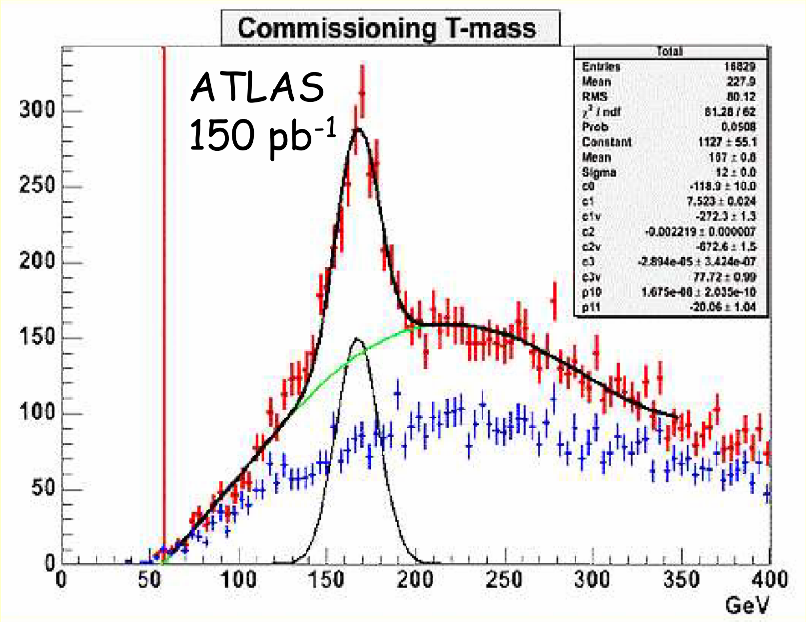
Energy dependence of $dN/d\eta$?
Vital for tuning Underlying Event model
Important of Jet-Energy, Etmiss
Only requires a few thousand events.

- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a ln(s) dependence.

Early Physics: Top quark without b-tag

Extremely simple selection:

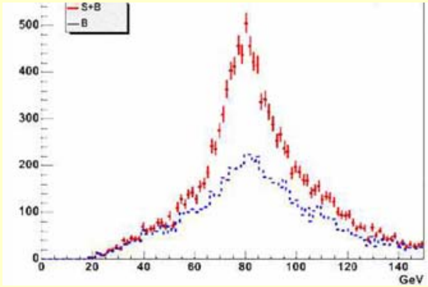
- Use goldplated semileptonic events: $tt \to bWbW \to bl\nu bqq$
- Require 1 isolated lepton (p_T>20 GeV)
- Exactly 4 jets (p_T>40 GeV)
- no kinematic fit, no b-tagging (!)
- plot invariant mass of 3 highest p_T jets



Signal visible after few days at 10^{33}

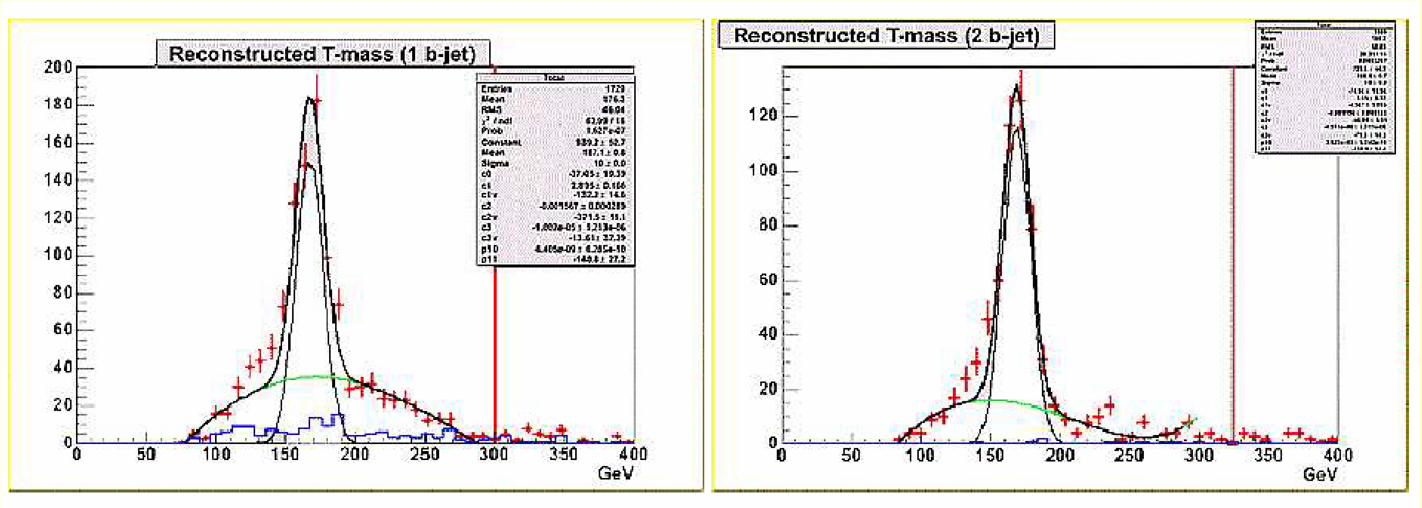
- stat. error on m_{top} ~ 400 MeV after one week
- Δm_{top} = 7 GeV (assuming 10% b-jet-scale error)
- use for jet energy calibration
- ideal to commission b-tagging!
- study most important BG to searches

also: hadronic W-mass peak ($\to$jet E-scale)



Early Physics: Top quark with b-tag

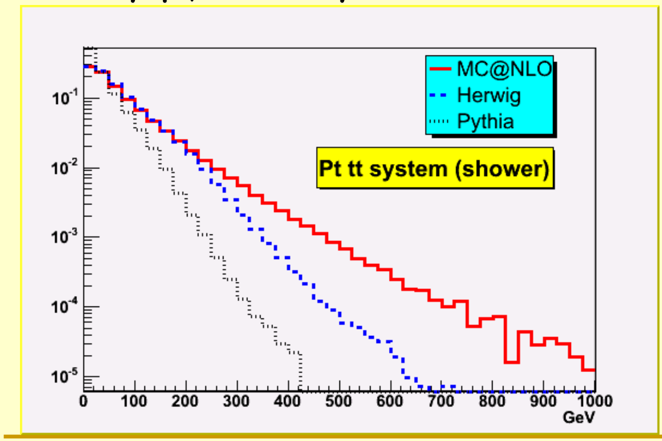
Once b-tagging is established, very clean tt samples can be obtained
Ratio of single/double b-tags to obtained b-tag efficiency from data



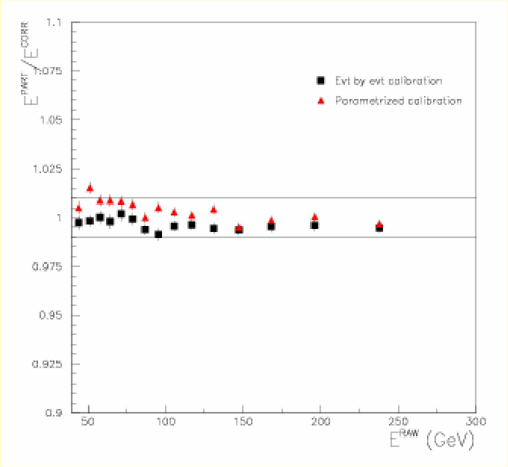
ATLAS

150 pb^{-1}

Study p_T of tt system

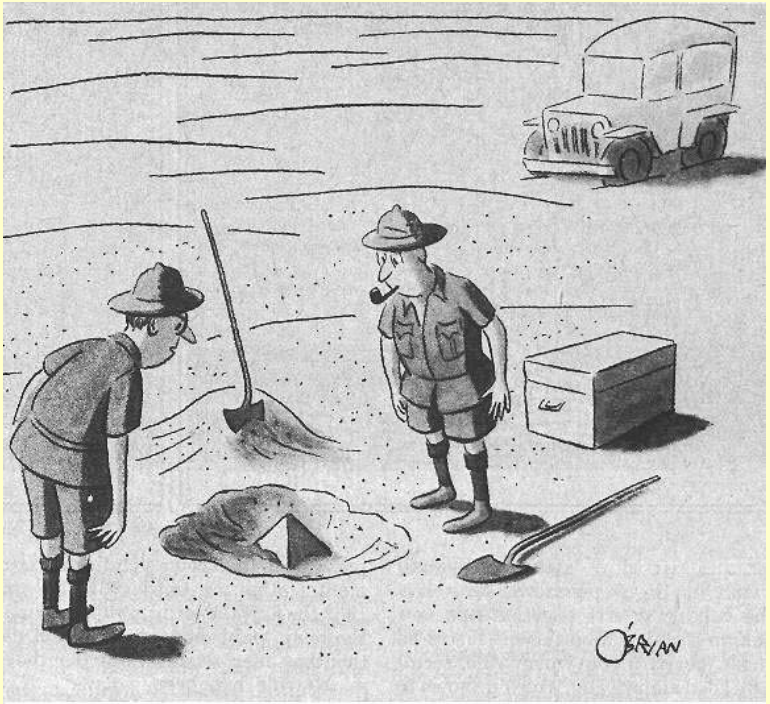


Calibrate jet energy scale



The Road To Discovery

What can be done
with the first 10-30 fb^{-1} ?

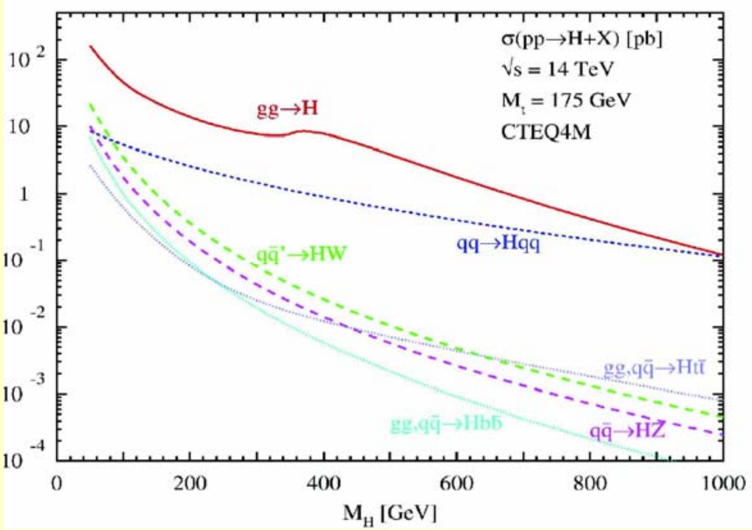


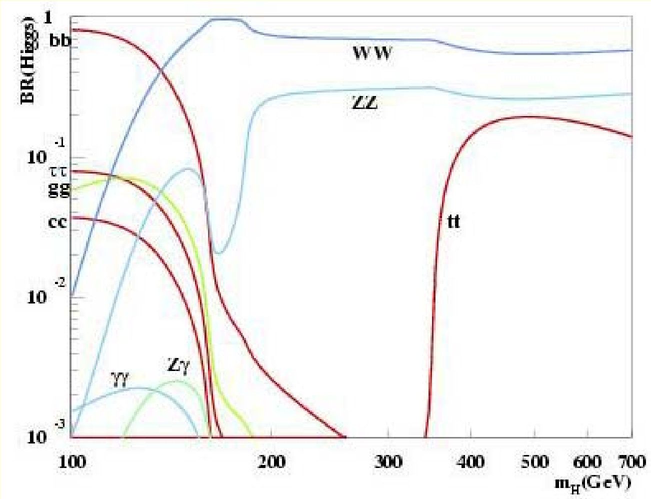
"This could be the discovery of the century. Depending, of course, on how far down it goes."

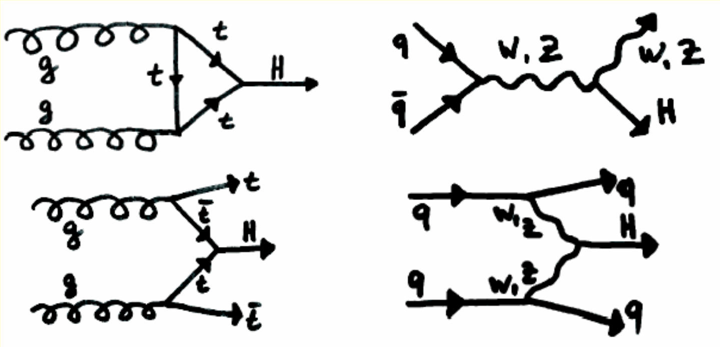
SM Higgs

SM Higgs discovery is guaranteed over the whole theoretically possible mass range.

Multitude of production mechanisms: and decay modes:







main sensitivity from lepton/photon modes

H→bb only in association with tt,W,Z

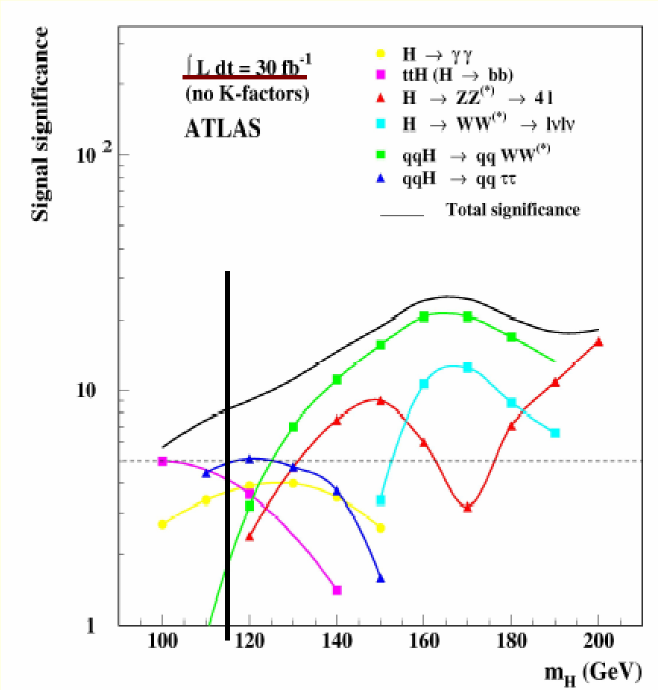
Discovery channels:

$\gamma\gamma$, qq$\tau\tau$, ttbb for light Higgs

ZZ→4l for heavier Higgs

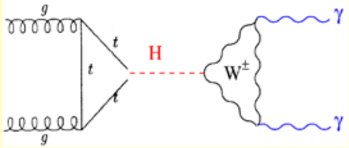
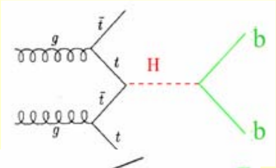
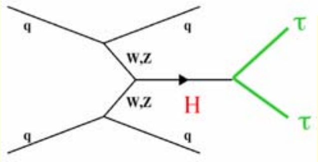
Light SM-Higgs: Challenge and Opportunity

For "early" discovery need
3 complementary channels



m_H=115 GeV

Singnificance for $10fb^{-1}$:

	S	B	S/√B
	130	4300	2.0
	15	45	2.7
	10	10	2.7

Combined Significance ~ 4σ

Involves full understanding of detector and backg.

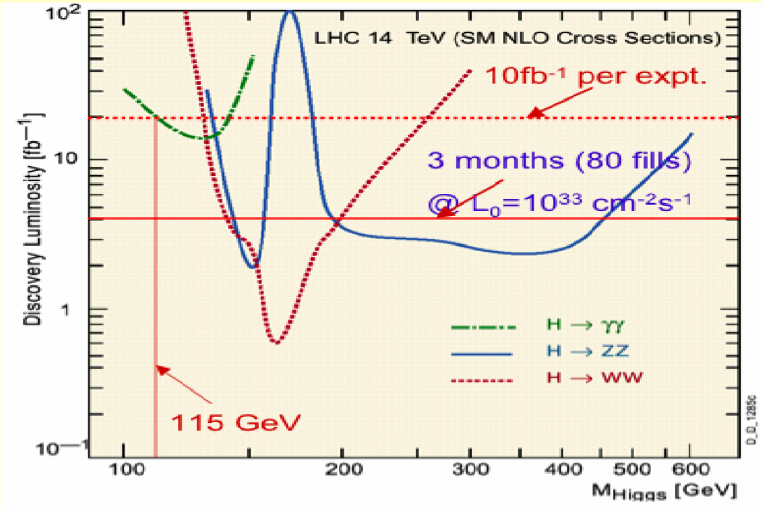
photons, leptons, b-tag, tau-ID, UE, …

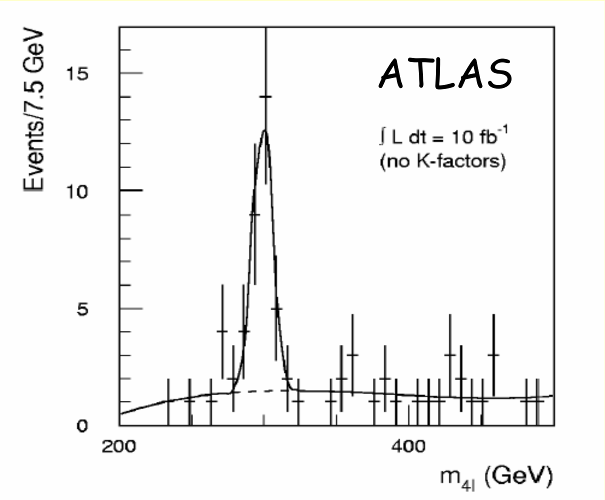
Later, this turns into an advantage: 3 different channels provide robustness of signal and allow for extraction of Higgs properties (→ D. Zeppenfeld)

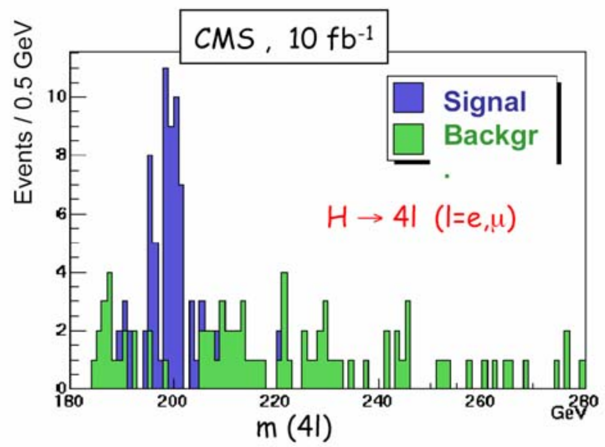
Main current activities: improve on detector simulation, study backgrounds (MC@NLO, SHERPA), strategies to get background from data

Heavy SM Higgs

For m_H > 180 GeV, early discovery relatively easy in H→4l channel







- very moderate backgrounds
- width soon dominated by natural width of Higgs (→ measure Γ_{tot})
- H→WW→lνlν has higher rate but no mass peak (not ideal for discovery)

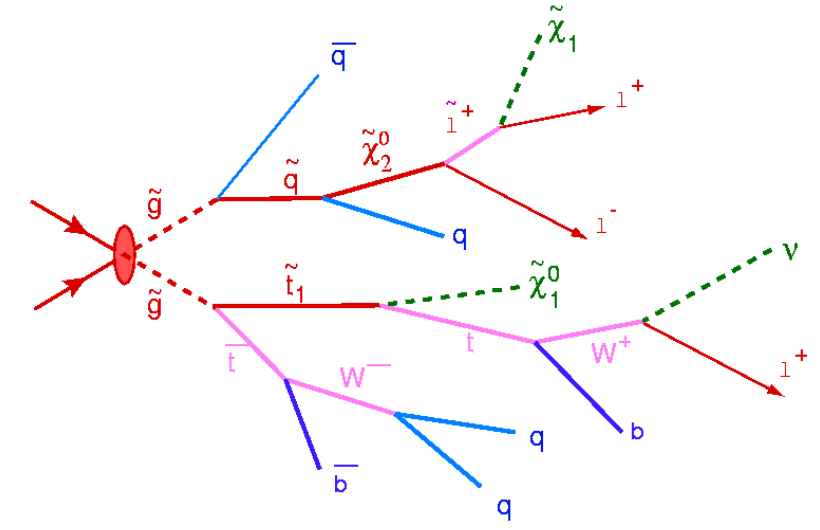
Supersymmetry

no need to repeat, why SUSY is good for us – let's see if it is out there…

LHC: sensitive to all known SSB scenarios within MSSM (mSugra, GMSB, AMSB, RPV)
Dominant production modes in MSSM with R-Parity conservation:
strong production of gluinos and squarks: $gg, q\bar{q}, qq, qg \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$
cross sections comparable to QCD at same scale

Production of EW-interacting sparticles through Drell-Yan,
but typically too low cross-sections/ too large BG from W/Z

Normally: gluinos, squarks = heaviest sparticles
→ long decay chains, quite complex final states



- jets
- leptons
- LSPs

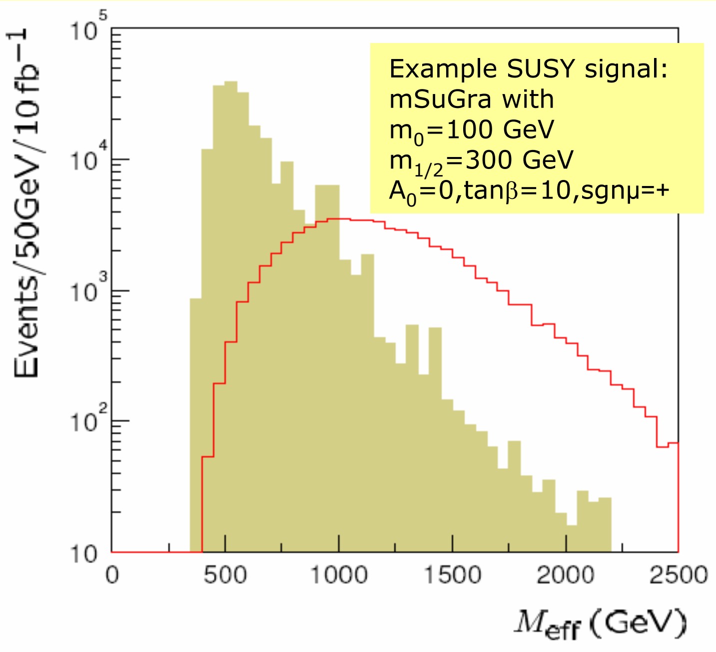
With R-parity converved,
large missing transverse energy
is the inclusive signature for SUSY

- establish signal there first (?)
- then look for more exclusive features
- then try to extract parameters

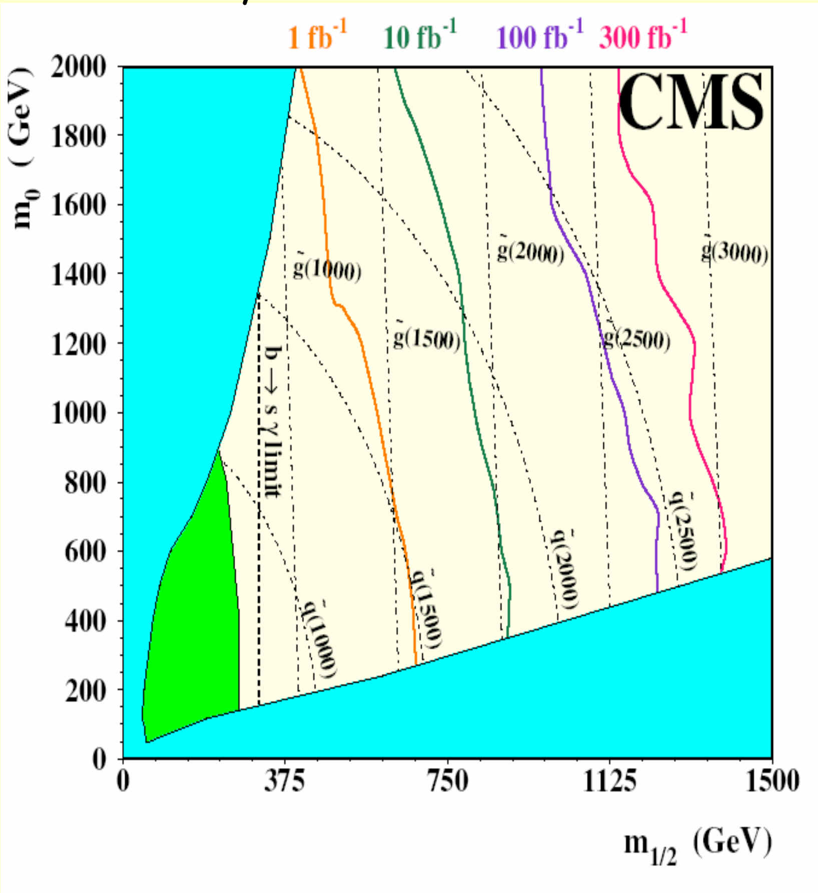
Supersymmetry: inclusive E_T^{miss} signature

Well-known simple approach: require (e.g.) $\not{E}_T > 100\,\text{GeV}$, $\geq 4\,\text{jets with } E_T^i > 100,50,50,50\,\text{GeV}$

and plot $M_{eff} := \not{E}_T + \sum^{4} E_T^{jet=i}$



5σ discovery mass reach

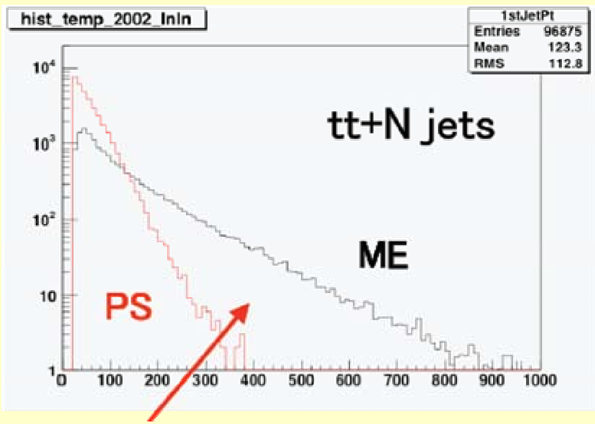


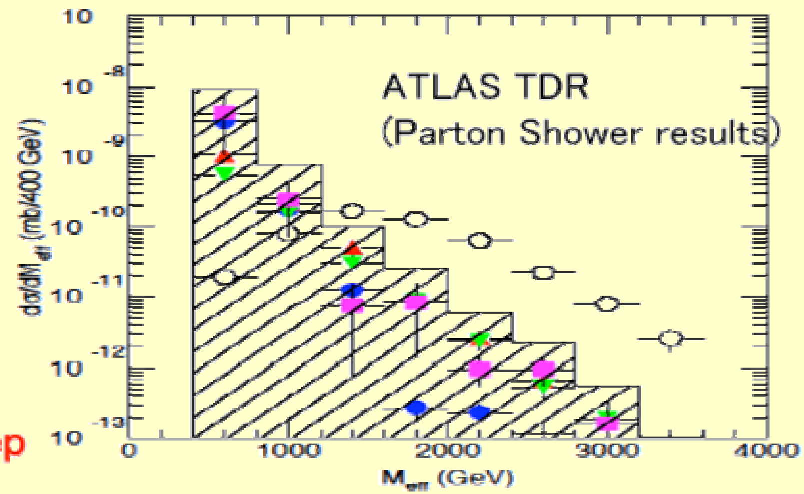
Lumi	Mass reach
1 fb^{-1}	~1 TeV
10 fb^{-1}	~2 TeV
300 fb^{-1}	~2.5-3 TeV

Supersymmetry: inclusive E_T^{miss} signature

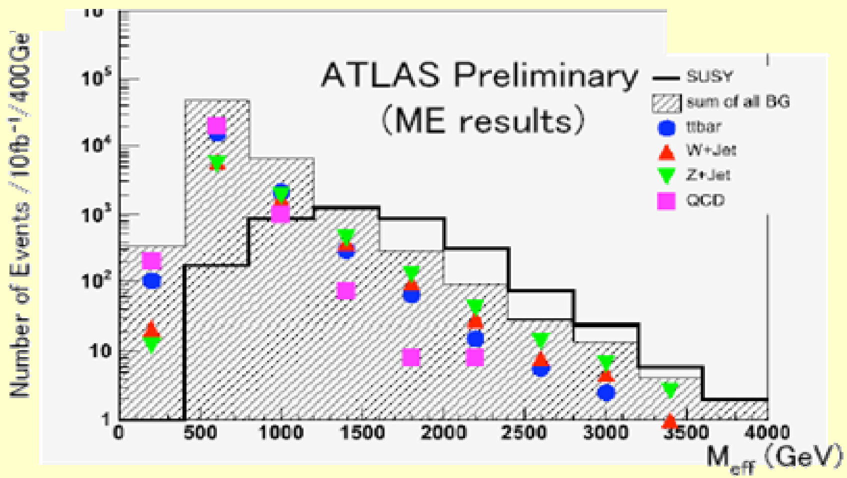
But watch out...

it is well known that parton showers underestimate the high PT region





Currently complete background estimation is redone



Using ME approach where possible

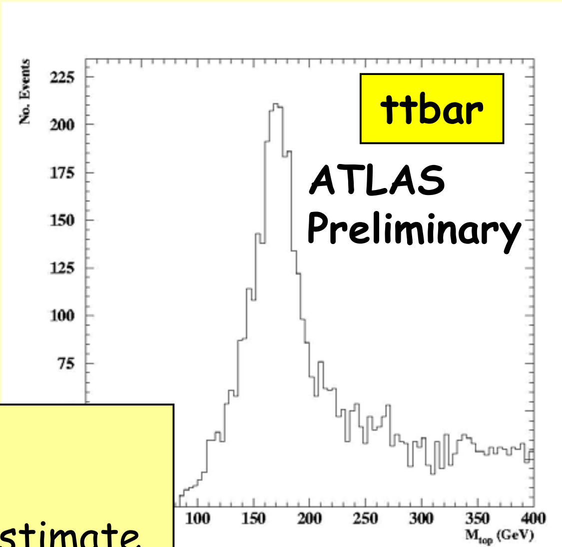
inclusive SUSY signal less clear in this channel

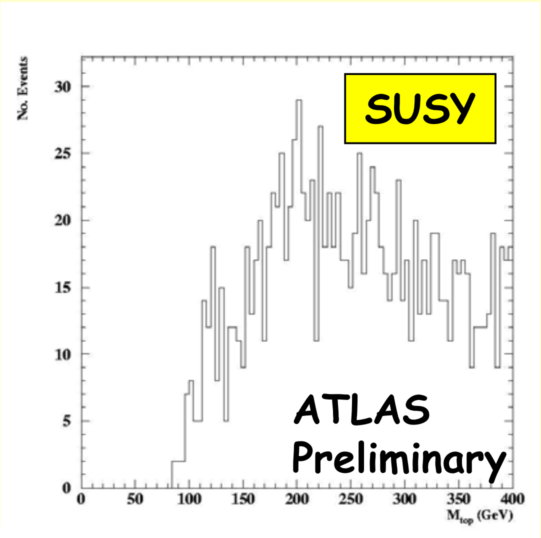
May lower reach slightly

Lepton channels much more robust

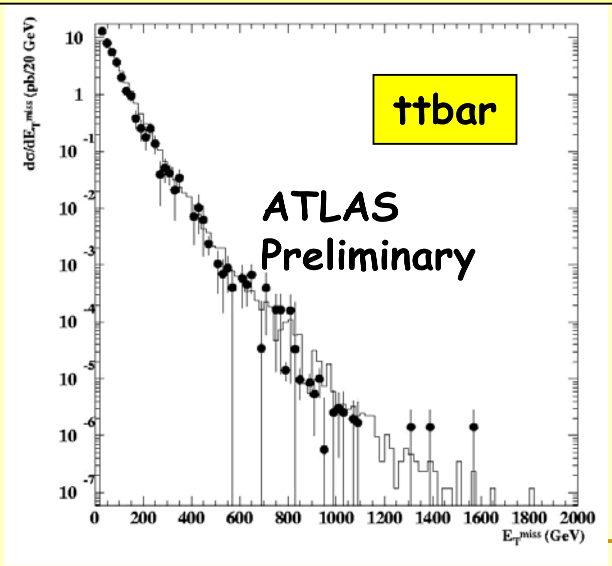
Get the background from data

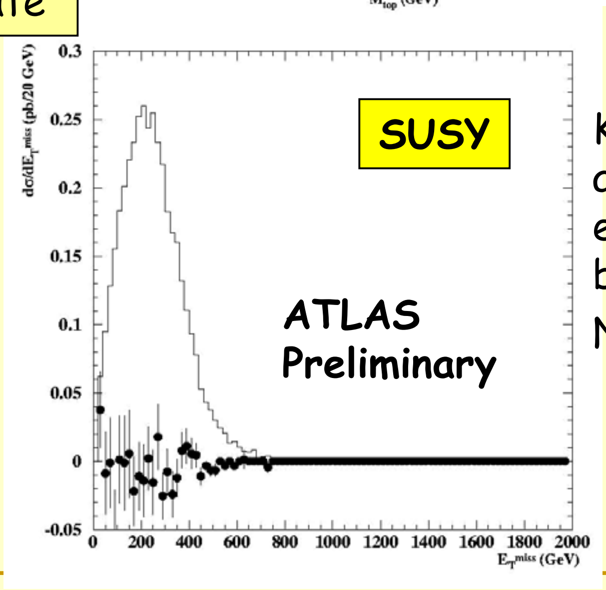
1 lepton top selection, reconstructed leptonic top mass peak:





Histogram – 1 lepton
SUSY selection (no b-tag)
Data points – background estimate



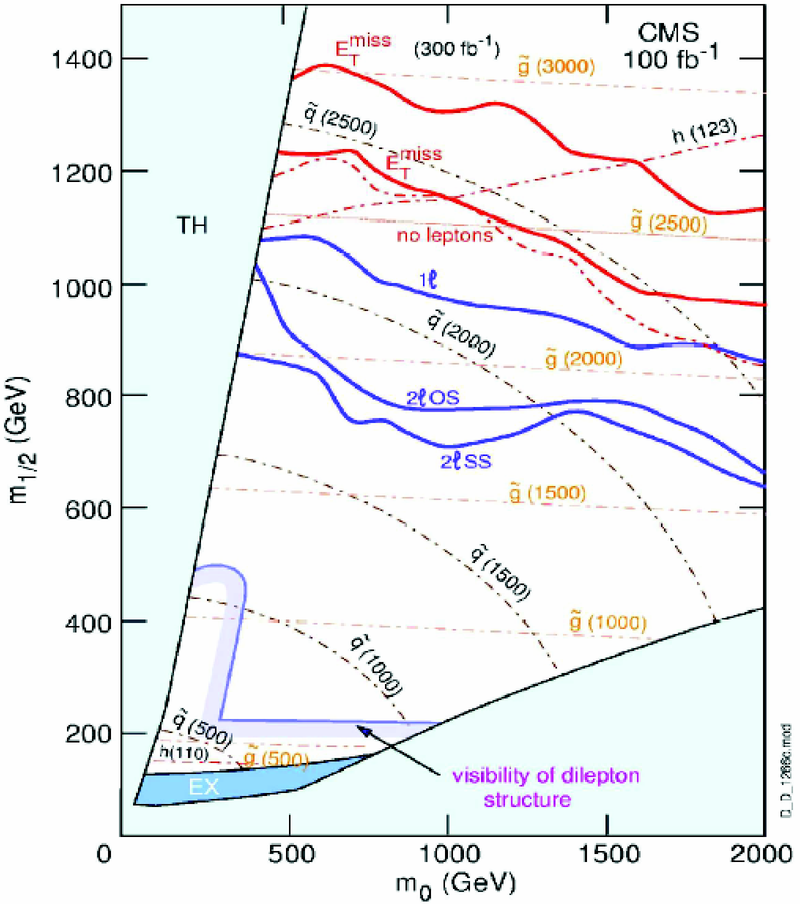


Key question: does this approach select SUSY events (hence introduce bias)?

No evidence for this

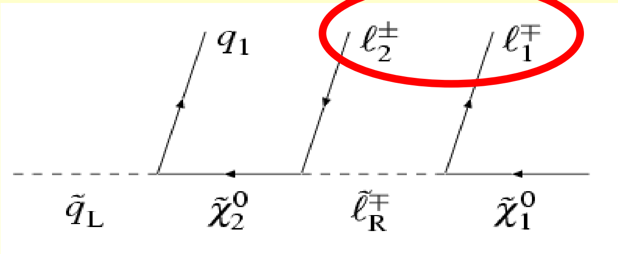
SUSY: leptonic signatures

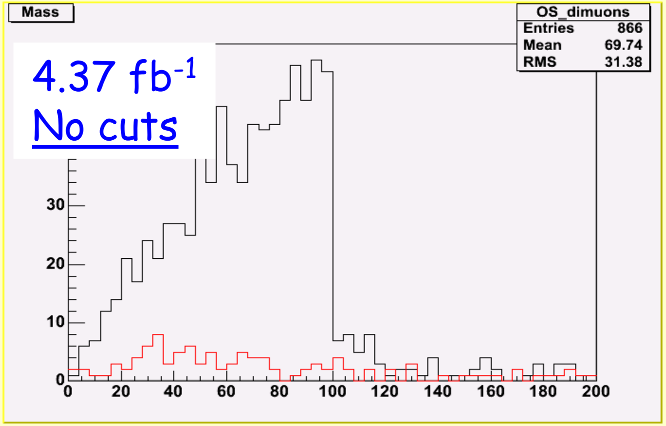
SUSY cascade decays give also rise to many other inclusive signatures: **leptons, b-jets, τ's**



less vulnerable to
- SM backgrounds
- ETmiss calibration

very robust discovery channel
mass reach somewhat lower





If strong diplepton edge present this an "early discovery" channel!

Supersymmetry

current activities:

- use multi-jet ME and MC@NLO Monte Carlos to refine background estimates
- develop strategies to obtain backgrounds from data
- exploit further channels (tau's and b's)
- strategies to calibrate and understand Etmiss
- control QCD background – fake Etmiss (filter strategies)

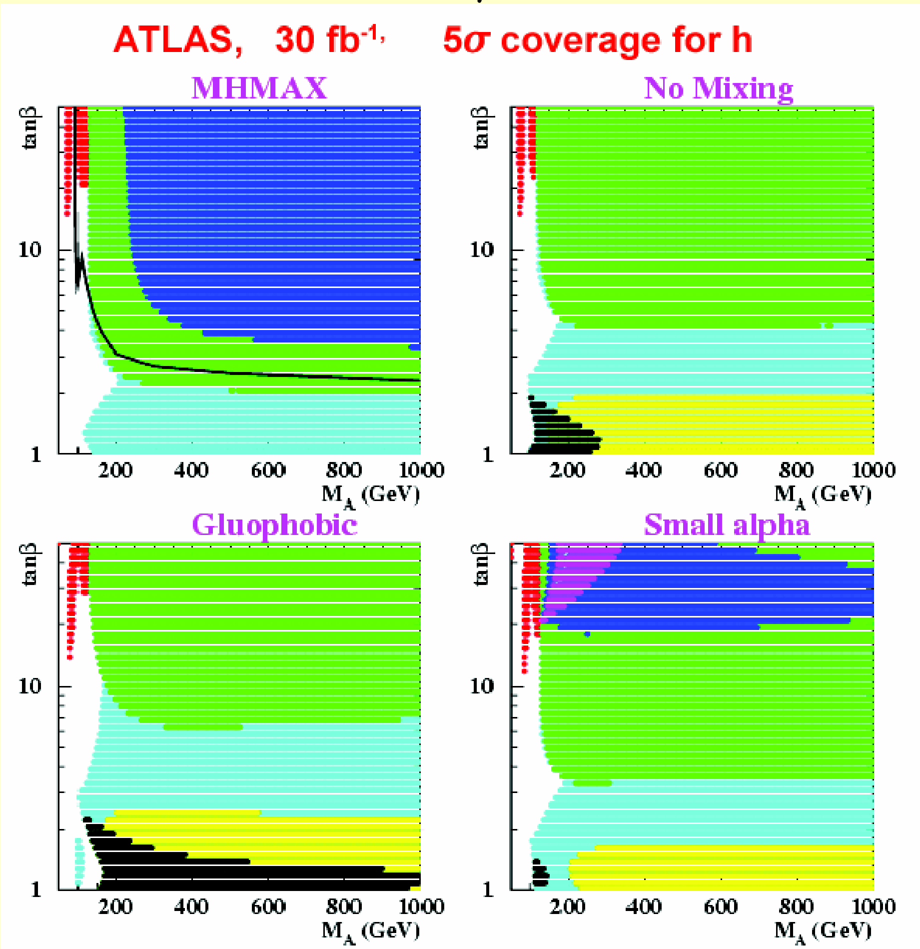
Note:

sensitivity studies and parameter scans less important than

optimal preparation for day 1!

SUSY Higgs

- VBF channels provide full coverage for lightest SUSY-Higgs h with 30 fb^{-1}
- like in SM, not an easy task



bbh→μμ
VBF, h→ττ
VBF, h→ττ+WW
tth→bb
W→Wh→lνbb
VBF,h→WW
combined

VBF channels cover a large part of the MSSM plane

SUSY Higgs: heavy Higgs bosons

Additional (heavy) SUSY Higgs bosons:

production~$\tan^2\beta$

<u>Neutral H/A:</u>

$H/A \rightarrow \tau\tau$, $\mu\mu$ at large $\tan\beta$

Intermediate $\tan\beta$ region not accessible except if SUSY decays ($H/A \rightarrow \chi_2^0\ \chi_2^2$) open

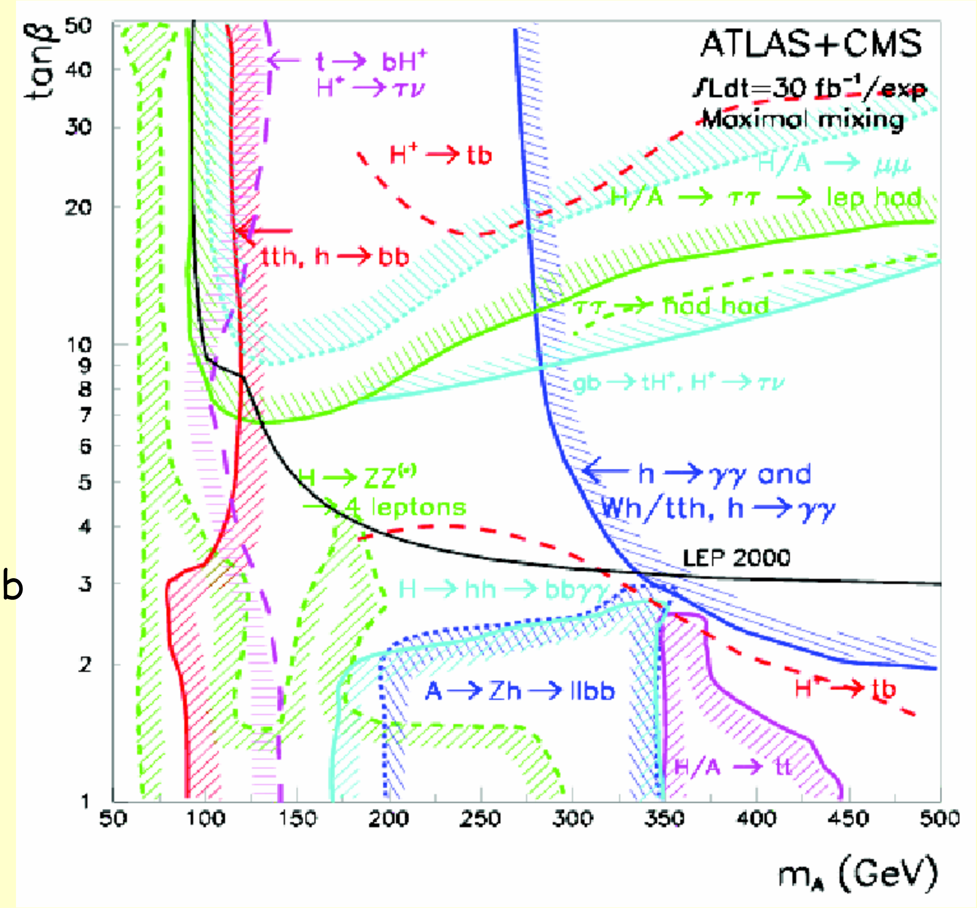
<u>Charged Higgs:</u>

Production $gb \rightarrow H^+t$, $gg \rightarrow H^+tb$, $t \rightarrow H^+b$

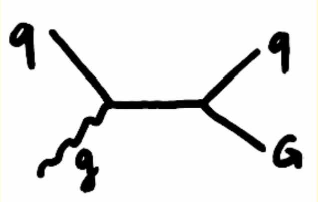
Decays: tb, $\tau\nu$, SUSY, H^0W

Intermediate $\tan\beta$ region not accessible except if SUSY decays

Need high luminosity, no "early" physics unless $\tan\beta$ very large (getting constrained from Tevatron)



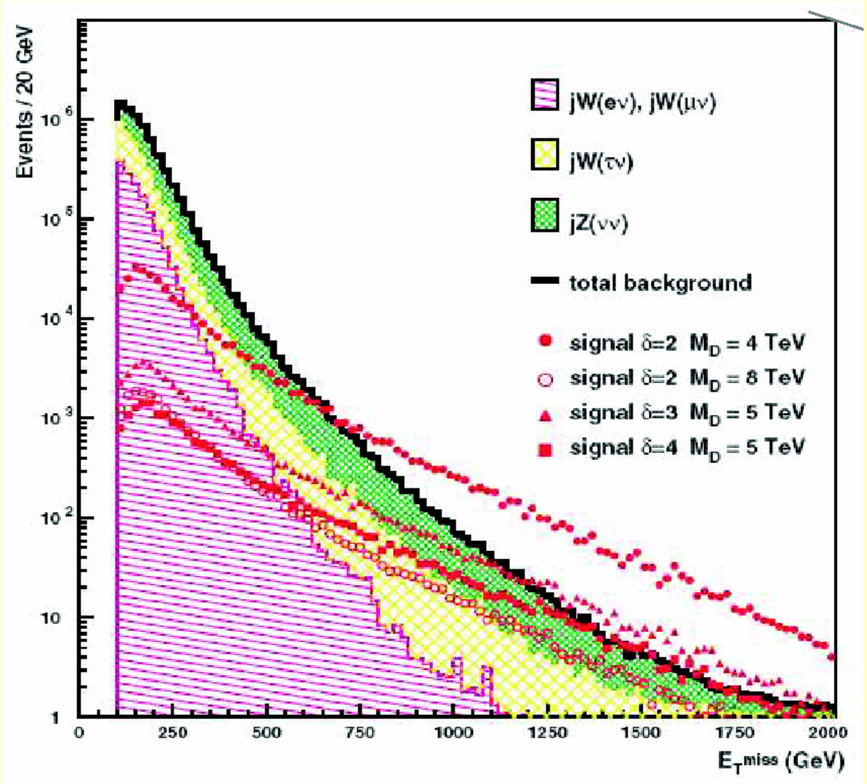
Extra space dimensions: large



ADD model of large compactified ED's

Quasi-continous tower of Gravitons

Singature: Missing transverse energy from real Gravitons emission



Very challening:

- structureless excess of Etmiss
- only visible as tail in Etmiss distr.
- huge W+jets, Z+jets backgrounds

Probably no "early" physics

Reach in M_D (true scale of grav.) for 100 fb^{-1} for δ extra dimensions:

δ= 2	9 TeV
δ= 3	7 TeV
δ= 4	6 TeV

Extra space dimensions: warped

Randall-Sundrum model

Discrete, narrow Graviton resonances

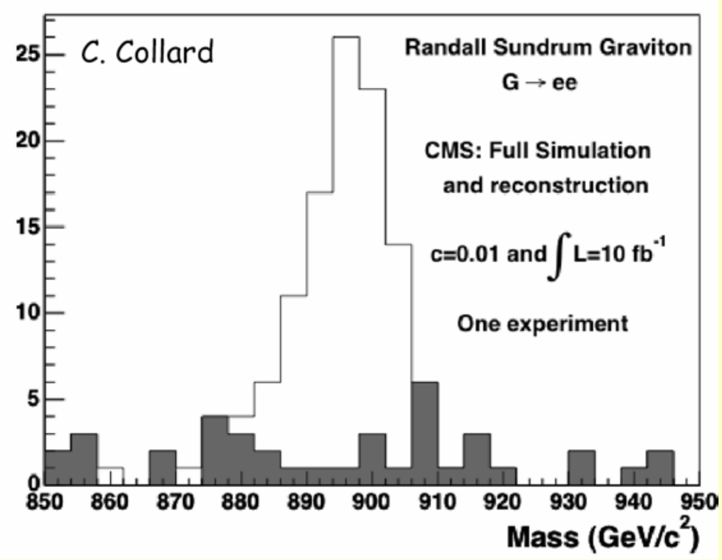
Singature: e.g. G→ll

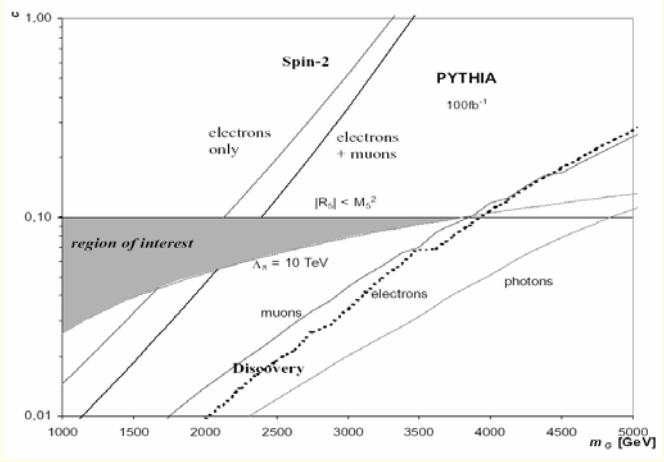
May be an "early surprise"

With BR(G→ee)=2%, c=0.01 discovery reach

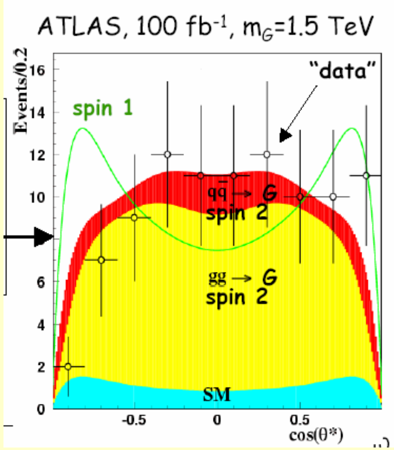
0.9 – 1.25 TeV for $1.2 - 8\ fb^{-1}$

Later: cover all of interesting parameter space





and distinuish from e.g. Z':



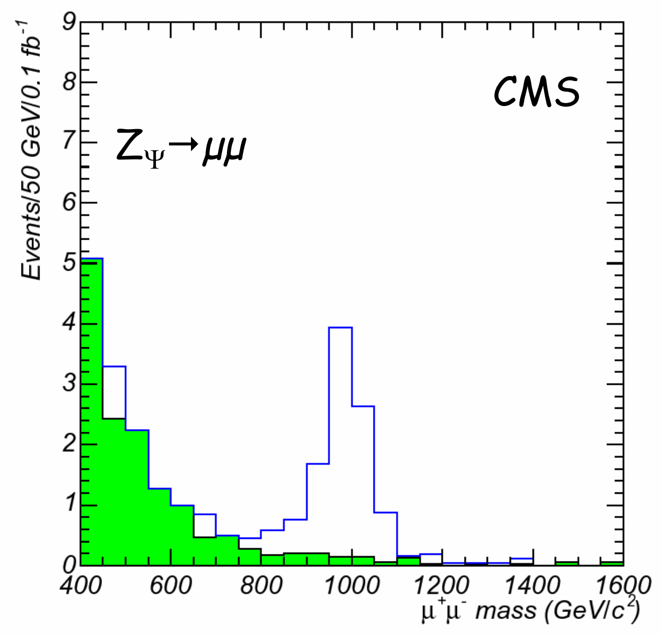
Early surprises: Di-Lepton resonances

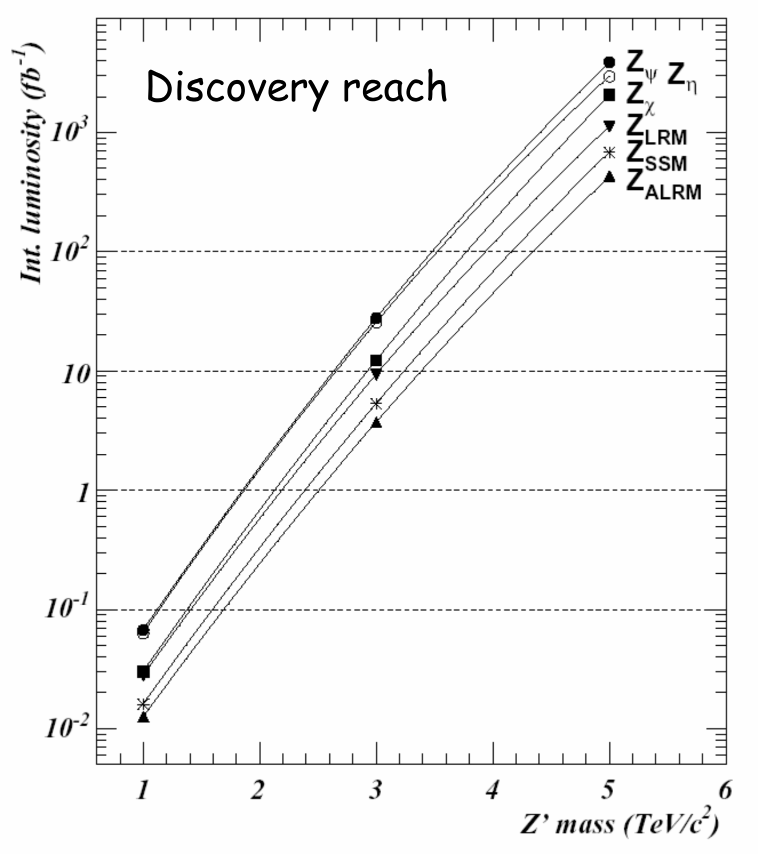
Di-Lepton resonances appear in many extensions of the SM
(GUT models, Graviton-Resonances in RS model, Z_H in Little Higgs, …)

Isolated leptons (e,μ) can be nicely indetified – small SM background at high masses

Example: sequential Z' (SM-like couplings):

Need 1.5 fb^{-1} for discovery up to 2 TeV

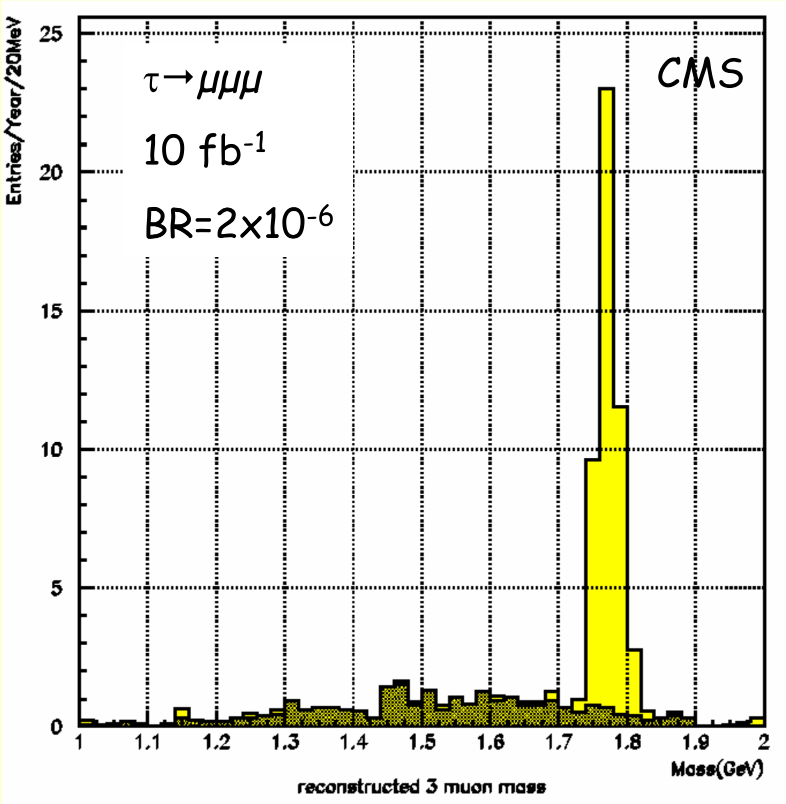




Early Surprises: LFV

Example: search for lepton flavour violation in $\tau \to \mu\mu\mu$ decay

Huge number of clean τ's from $W \to \tau\nu$



With 30 fb^{-1} : BR<4×10^{-8}

BaBar: BR<2×10^{-7}

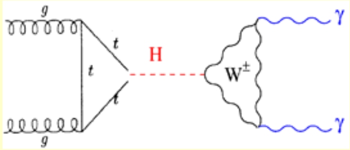
Summary and Outlook

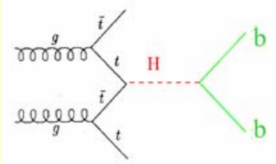
- Construction of LHC, ATLAS, CMS is advancing very well
- First collisions in only 2 years from today
- Understanding the detectors and backgrounds has the highest priority
- Already with 10-30 fb^{-1} great discovery potential!
- My personal guess: winter conferences 2009 may be beginning of a new revolution in physics!

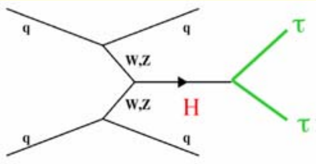
Thanks to all colleagues from the LHC machine, ATLAS,CMS who provided me with information,

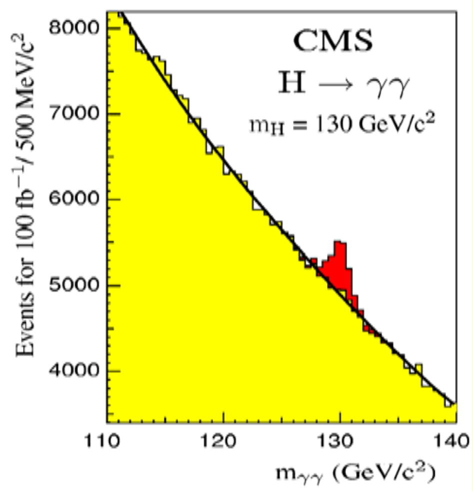
in particular M. Heldmann, M. Hauschild, K. Jakobs, G. Polesello

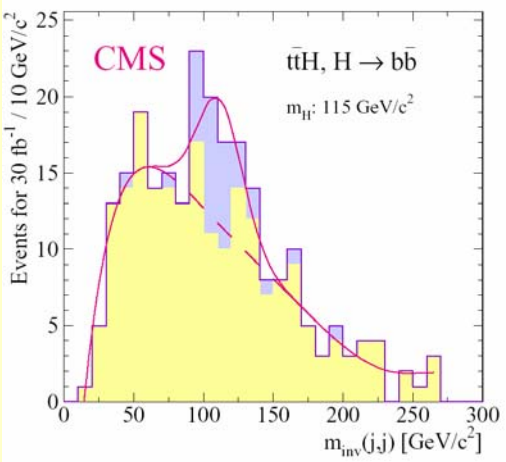
Light SM-Higgs: (Backup)

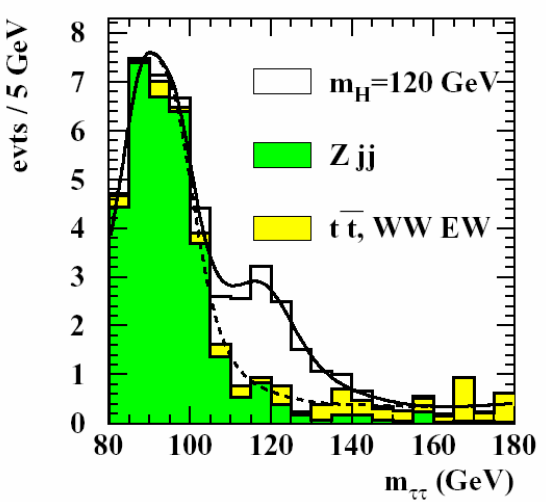






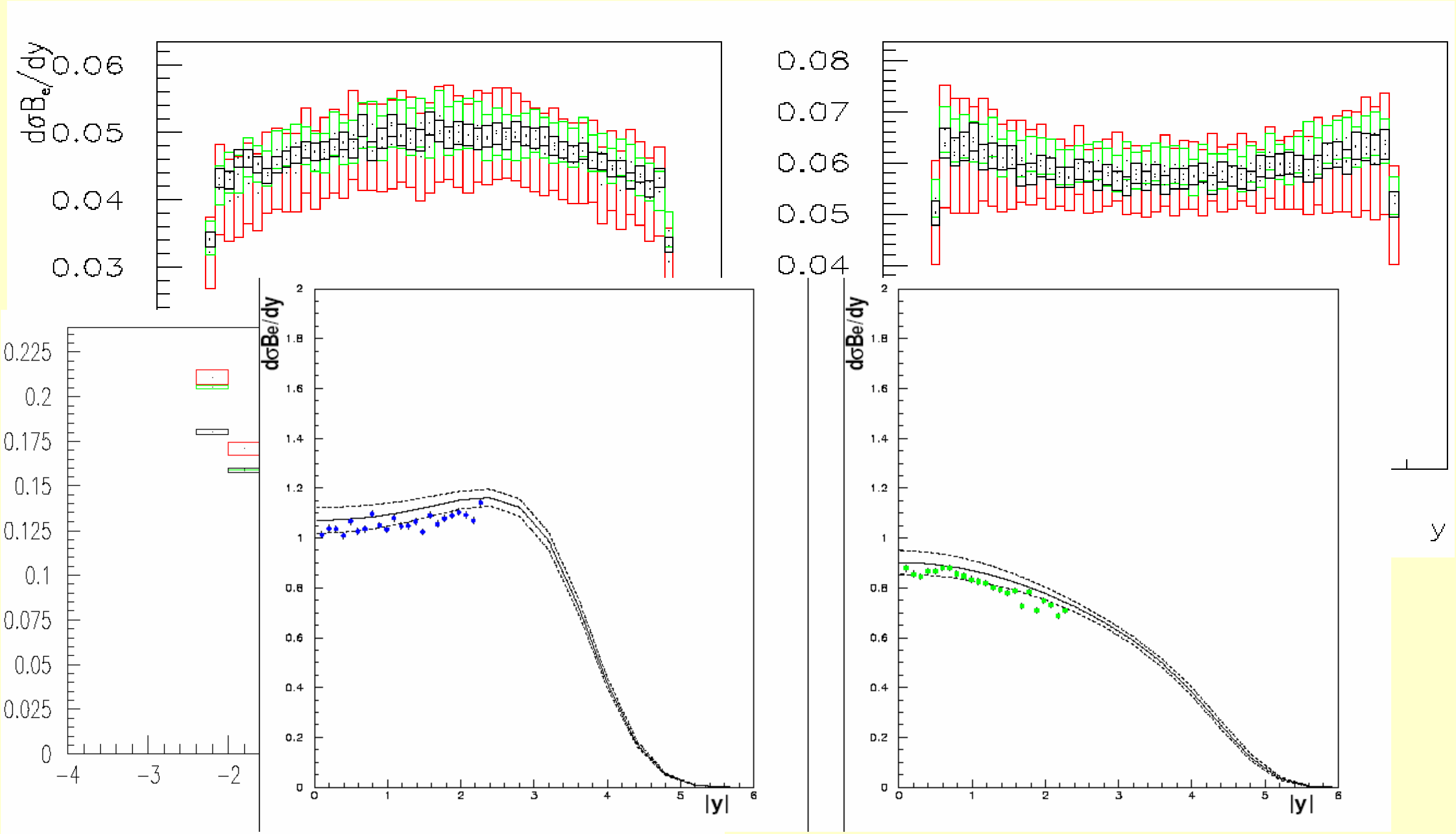






Early Physics: p.d.f.s from W-bosons

Structure Functions from W charge asymmetry



Early Physics: Calibrating ECAL with Z→ee

Constant term $c_{tot} = c_L + c_{LR}$ composed of two terms:

- c_L: local term. $c_L \simeq 0.5\%$ demonstrated at the test-beam over units of $\Delta\eta \times \Delta\phi = 0.2 \times 0.4$
- c_{LR} long-range response non-uniformities from unit to unit (400 in total): from module-to-module variations, different upstream material, etc.

Use $Z \to ee$ and Z mass constraint to correct for long-range uniformities

From full simulation: $\sim 250\ e^{\pm}$ per unit to achieve $c_{LR} \leq 0.4\%$

$\Rightarrow \sim 10^5\ Z \to ee$ events, few days of data-taking at 10^{33}

Worst case scenario: no corrections applied

$c_L = 1.3\%$ "on-line" non uniformity of individual modules

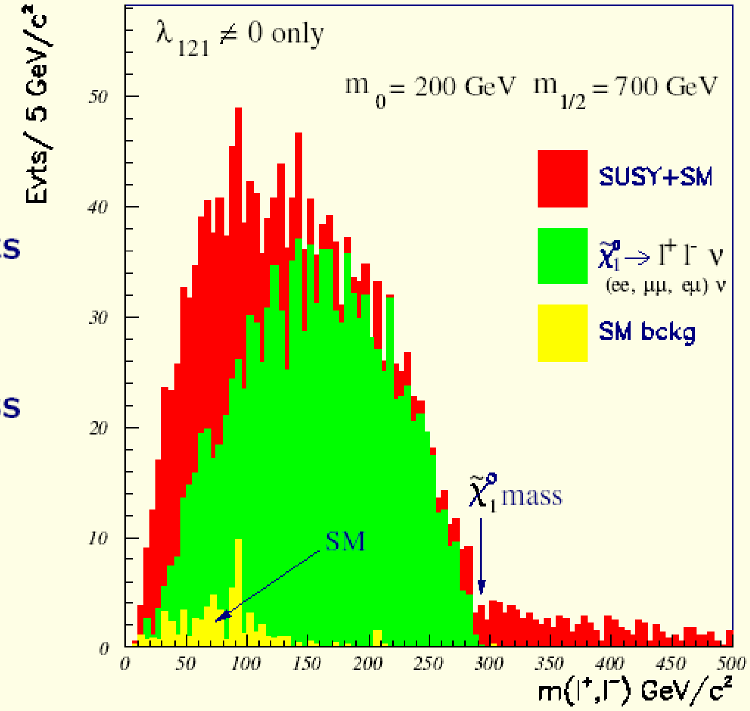
$c_{LR} = 1.5\%$ no $Z \to ee$ corrections, poor knowledge of upstream material

G. Polesello

Odd Ball:R parity broken?

Note that missing energy is not needed

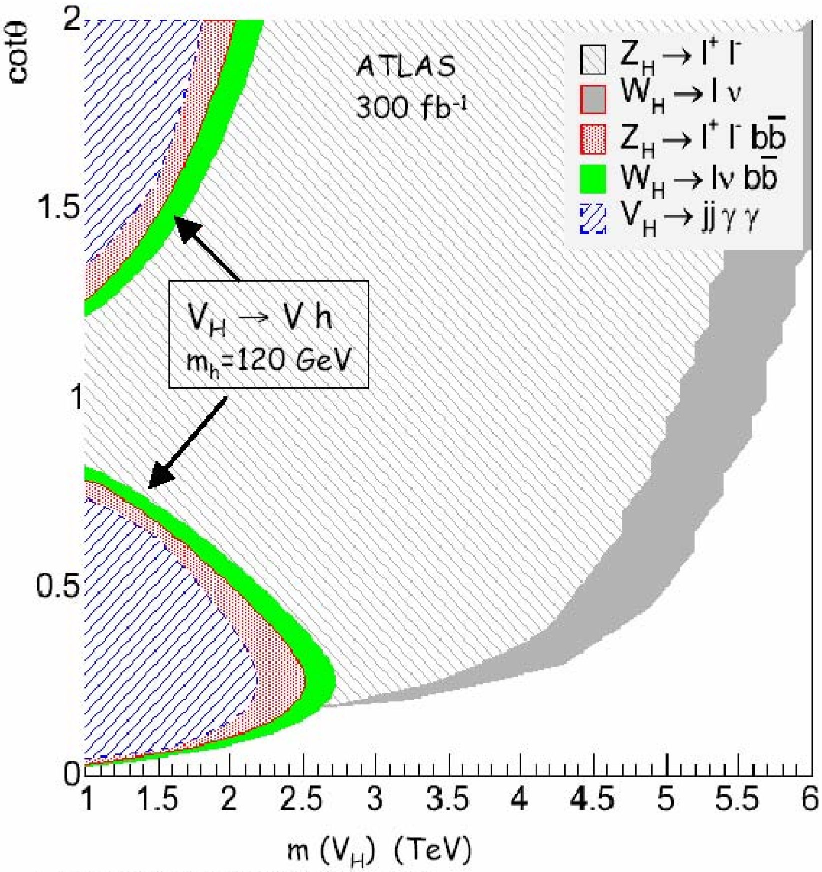
LSP unstable: can decay either to jets or leptons
Jet case has no missing E_T
Lepton case (shown) has much less missing E_T



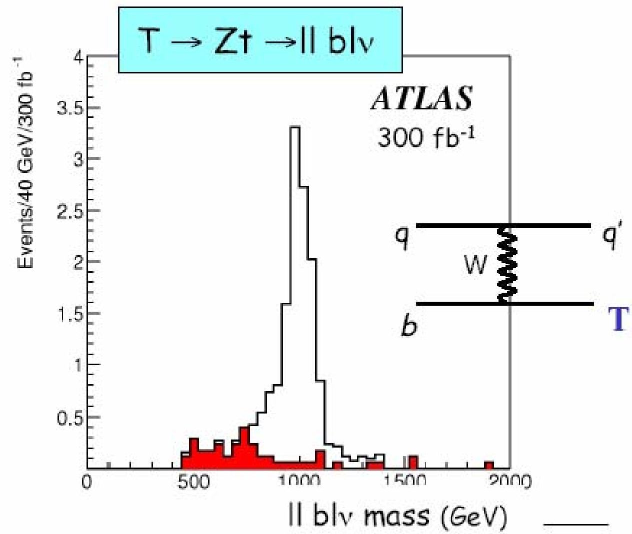
I Hinchliffe

Little Higgs  models

Alternative approach to the hierarchy problem predicting heavy top T (EW singlet), new gauge bosons W_H, Z_H, A_H and Higgs triplet Φ^0, Φ^+, Φ^{++}



Observation of T → Zt, Wb discriminates from 4[th] family quarks
Observation of $V_H \to Vh$ discriminates from W′, Z′



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F. Gianotti