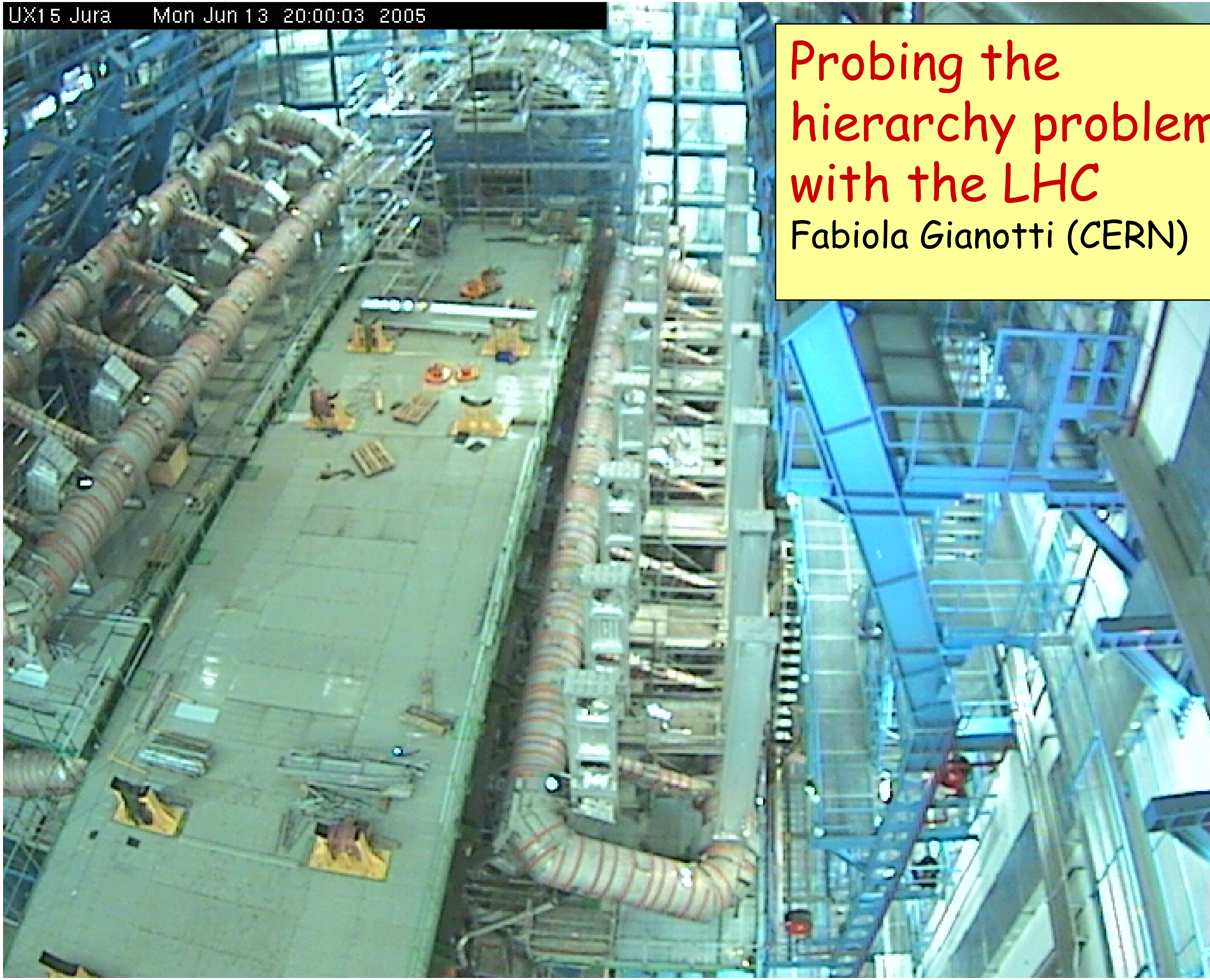
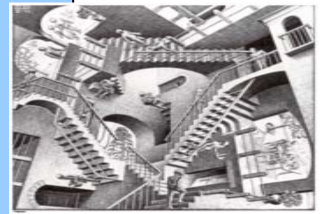


Probing the hierarchy problem with the LHC

Fabiola Gianotti (CERN)

SUSY

New particles at TeV scale stabilize m_H



Extra-dimensions

Additional dimensions

$\rightarrow M_{gravity} \sim M_{EW}$

New states at TeV scale

Little Higgs

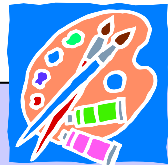
SM embedded in larger gauge group

New particles at TeV scale, stable m_H

$M_{EW} / M_{Planck} \sim 10^{-17}$

$\delta m_H \sim \Lambda$ (scale up to which SM is valid)

$\Rightarrow$ New Physics at TeV scale to stabilize m_H

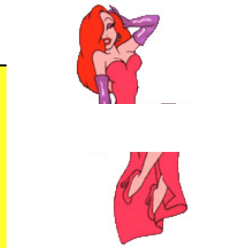


Technicolour

New strong interactions break EW symmetry

$\rightarrow$ Higgs (elementary scalar) removed

New particles at TeV scale



Split SUSY

Accept fine-tuning of m_H

(and of cosm. constant)

by anthropic arguments

Part of SUSY spectrum at TeV scale

(for couplings unification and dark matter)

LHC potential for ~all these scenarios demonstrated since long time. Here:

➊ What can be done at the beginning ?

➋ Signal interpretation and constraints of underlying theory ?

➊ What can be done at the beginning ?

The first LHC data : from Summer 2007...

$1\ fb^{-1}$ ($10\ fb^{-1}$) ≡ 6 months at 10^{32} (10^{33}) $cm^{-2}s^{-1}$ at 50% efficiency → may collect several fb^{-1} per experiment by end 2008

Channels (examples ...)	Events to tape for $1\ fb^{-1}$ (per expt: ATLAS, CMS)	Total statistics from previous Colliders
$W \to \mu\nu$	7×10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \to \mu\mu$	~ 10^6	~ 10^6 LEP, ~ 10^5 Tevatron
$tt \to WbWb \to \mu\nu + X$	~ 10^5	~ 10^4 Tevatron
$\tilde{g}\tilde{g}$ m = 1 TeV	10^2 - 10^3	———

With these data:

- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \to bl\nu\ bjj$ jet scale from $W \to jj$, b-tag performance, etc.

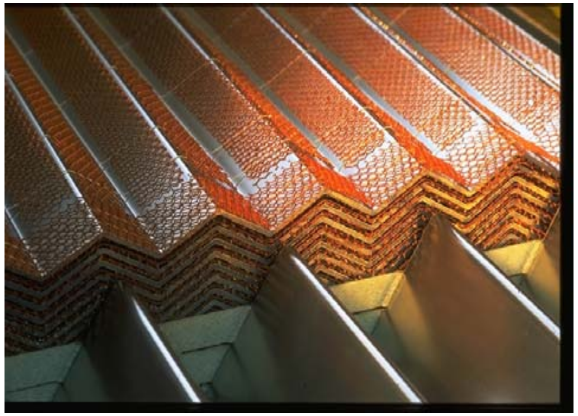
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets ... (omnipresent backgrounds to New Physics)

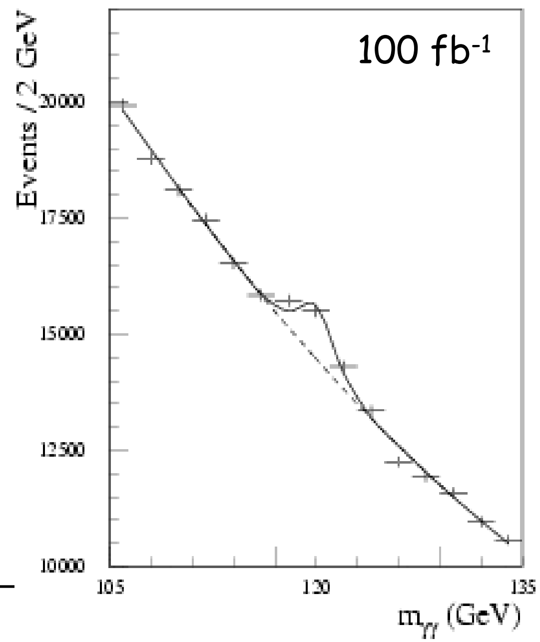
→ prepare the road to discovery .... it will take a lot of time ...

Preparing the detectors to explore the hierarchy problem …

Example : the ATLAS electromagnetic calorimeter

Pb-liquid argon sampling calorimeter with Accordion shape, covering $|\eta| < 2.5$

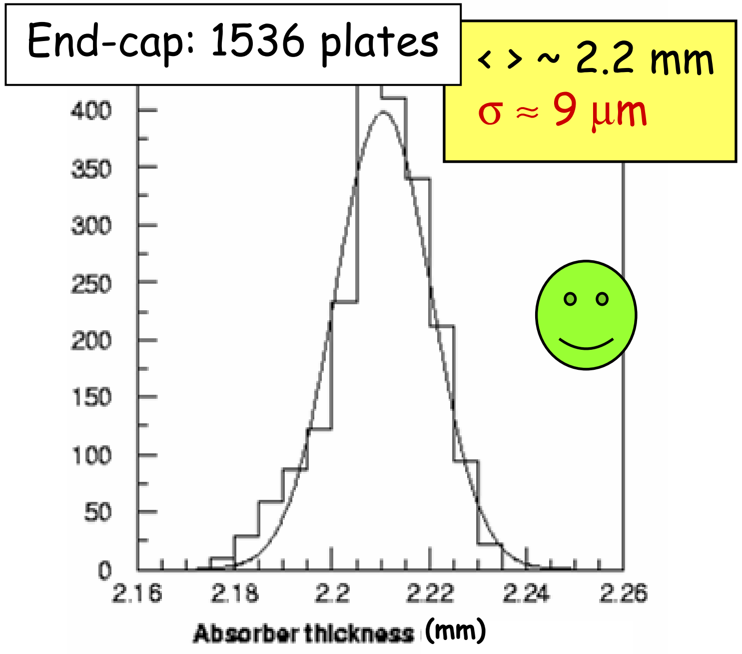




$H \rightarrow \gamma\gamma$: to observe signal peak on top of huge $\gamma\gamma$ background need mass resolution of ~ 1% → response uniformity (i.e. total constant term of E-resolution) $\leq 0.7\%$ over $|\eta| < 2.5$

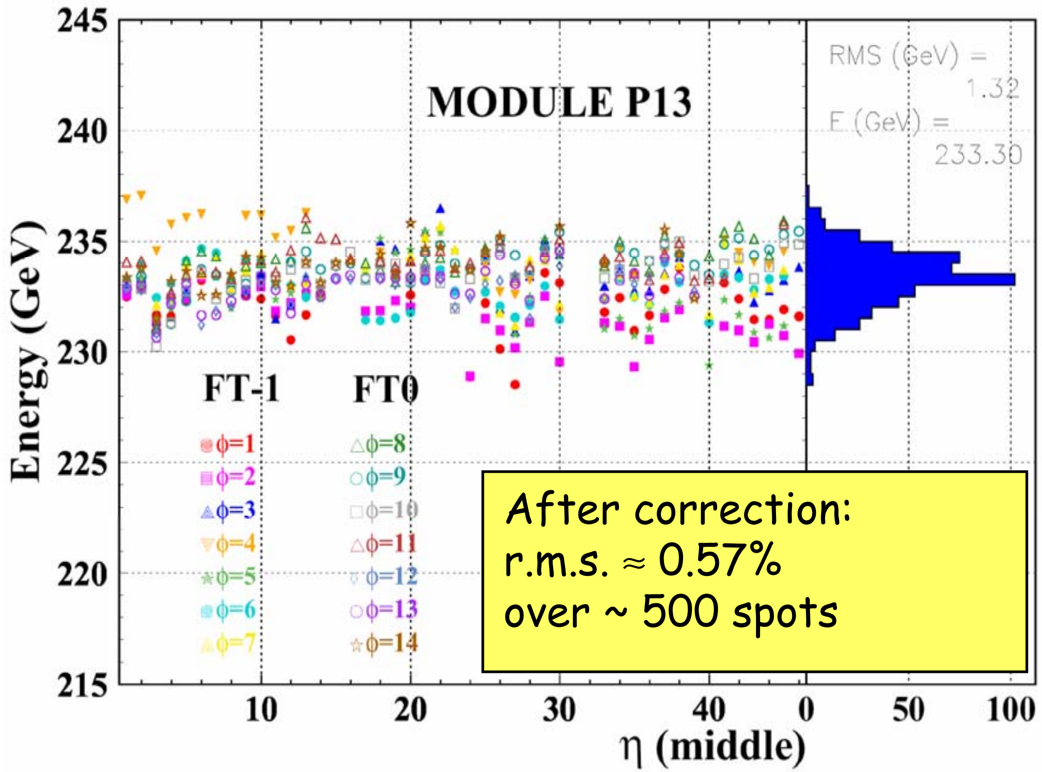
❶ Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)



❷ Test-beam measurements

Scan of a barrel module (Δφ×Δη=0.4×1.4) with high-E electrons



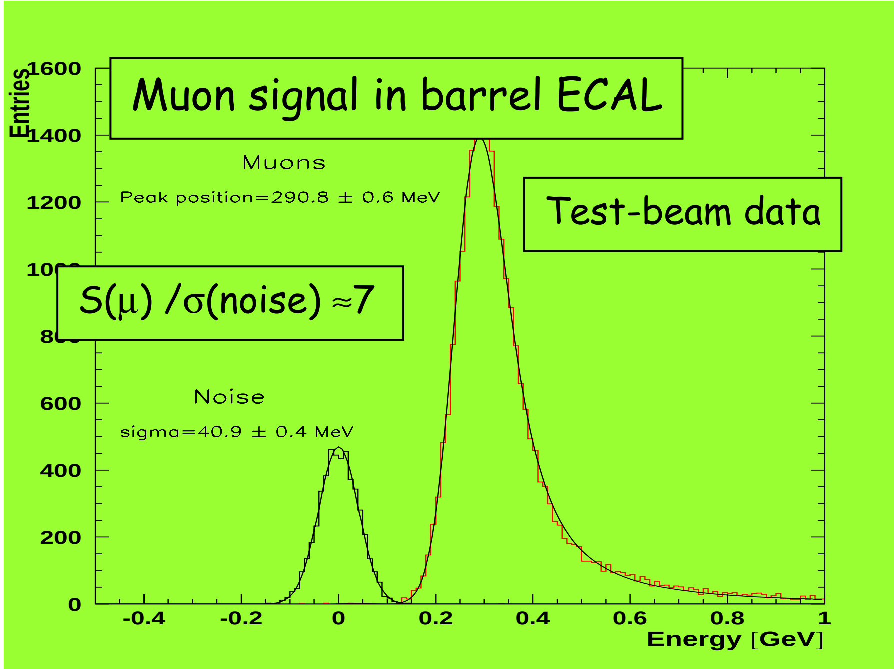
❸ Cosmics runs:

Measured cosmic μ rate in ATLAS pit : few Hz

→ ~ 10^6 events in ~ 3 months of cosmics runs beginning 2007

→ enough for initial detector shake-down

→ ECAL : check calibration vs η to 0.5%



❹ First collisions : calibration with $Z \to ee$ events (rate ≈ 1 Hz at 10^{33})

Use Z-mass constraint to correct long-range non-uniformities
(module-to-module variations, effect of upstream material, etc.)

~ 10^5 $Z \to ee$ events (few days data taking at 10^{33}) enough to achieve constant term $c \leq 0.7\%$

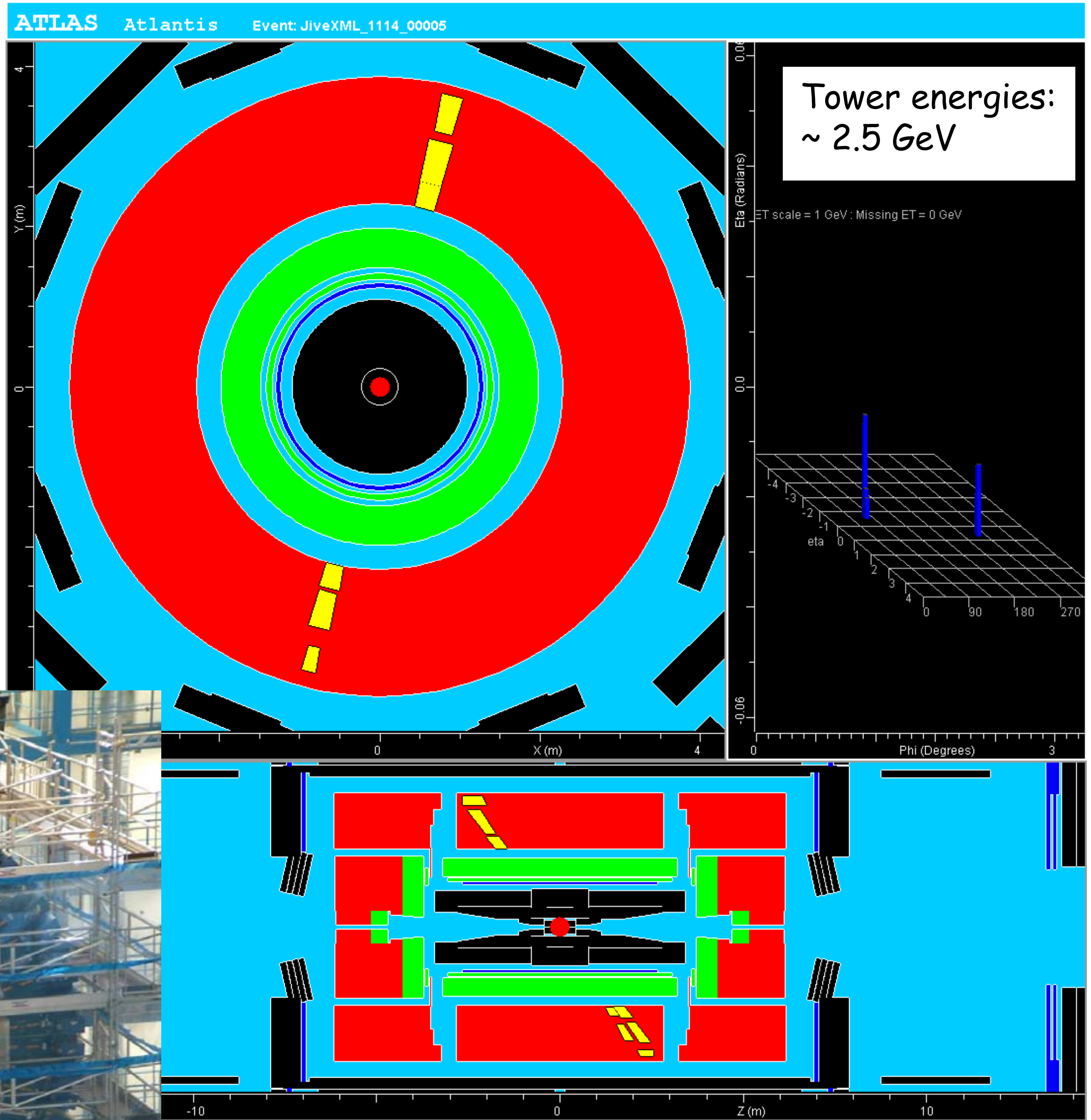
Nevertheless, let's consider the worst (unrealistic ?) scenario : no corrections applied

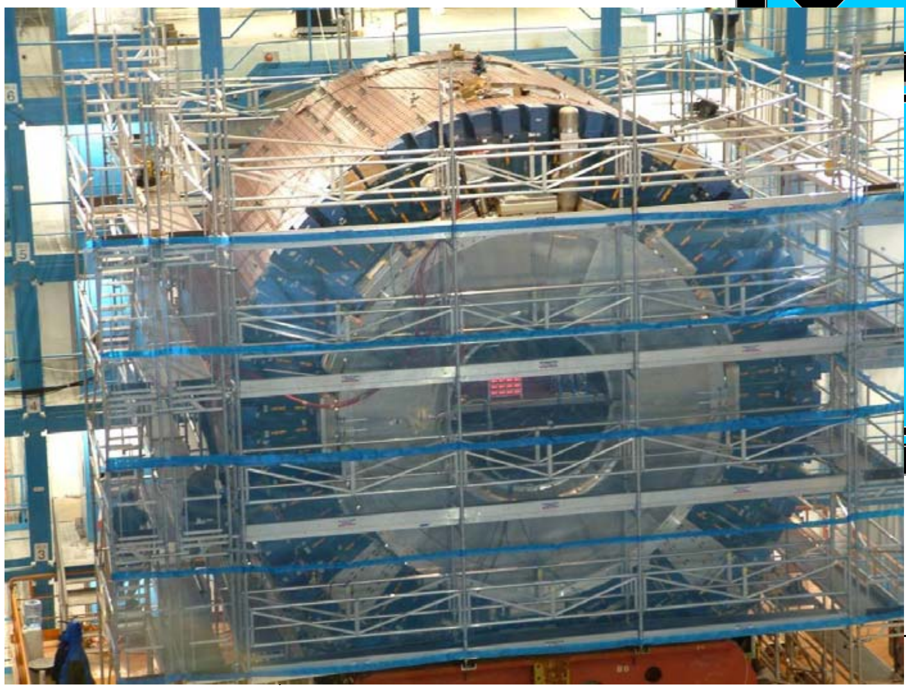
ECAL non-uniformity at construction level, i.e.:
-- no test-beam corrections
-- no calibration with $Z \to ee$

→ $c \approx 2\%$

$H \to \gamma\gamma$ significance m_H~ 115 GeV degraded by ~ 25%
→ need 50% more L for discovery

First cosmic muons observed by ATLAS in the pit on June 20th (recorded by hadron Tilecal calorimeter)

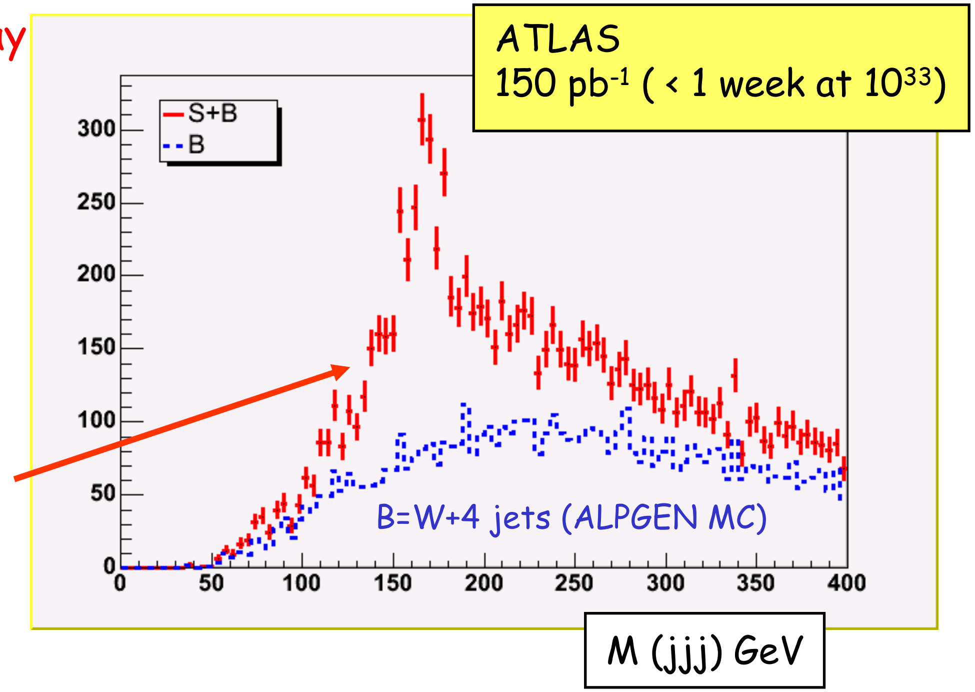




Example of initial SM measurement : top signal and top mass
(relevant to New Physics …..)

Bentvelsen et al.

- Use gold-plated $t\bar{t} \rightarrow bW\,bW \rightarrow bl\nu\,bjj$ decay
- Very simple selection:
  - -- isolated lepton (e, μ) $p_T > 20$ GeV
  - -- exactly 4 jets $p_T > 40$ GeV
  - -- no kinematic fit
  - -- no b-tagging required (pessimistic, assumes trackers not yet understood)
- Plot invariant mass of 3 jets with highest p_T



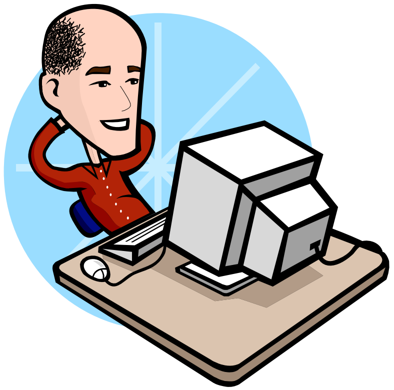
Time	Events at 10^{33}	Stat. error δM_{top}(GeV)	Stat. error $\delta\sigma/\sigma$
1 year	3×10^5	0.1	0.2%
1 month	7×10^4	0.2	0.4%
1 week	2×10^3	0.4	2.5%

- top signal visible in few days also with simple selection and no b-tagging
- cross-section to ~ 20%
- top mass to ~7 GeV (assuming b-jet scale to 10%)
- get feedback on detector performance :
  m_{top} wrong → jet scale ?
  gold-plated sample to commission b-tagging
- $t\bar{t}$ is background to many searches

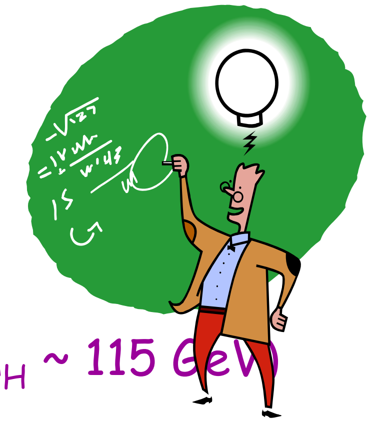
What about early discoveries ?
Three examples relevant to the hierarchy problem …

An easy case : a new (narrow) resonance of mass ~ 1 TeV decaying into e^+e^-,

e.g. a Z' or a Graviton $\rightarrow e^+e^-$ of mass ~ 1 TeV



An intermediate case : SUSY



A difficult case : a light Higgs (m_H ~ 115 GeV)

An "easy case" : $G \to e^+e^-$ resonance with m ~ 1 TeV

predicted in Randall-Sundrum Extra-dimensions

BR ($G \to ee \approx 2\%$), c = 0.01 (small/conservative coupling to SM particles)

Mass (TeV)	Events for 10 fb^{-1} (after all cuts)	$\int L\,dt$ for discovery ($\geq$ 10 observed events)
0.9	~ 80	~ 1.2 fb^{-1}
1.1	~ 25	~ 4 fb^{-1}
1.25	~ 13	~ 8 fb^{-1}

CMS

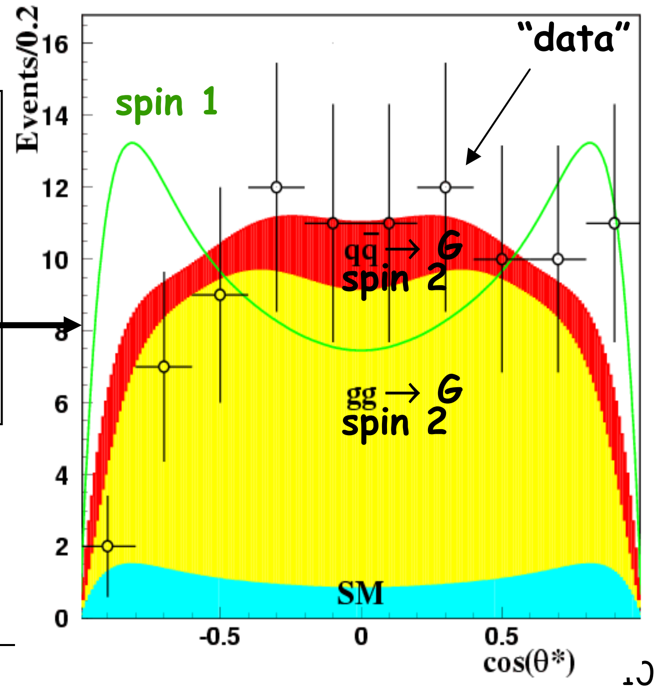
- large enough signal for discovery with $\int L dt$ < 10 fb^{-1} for m < 1.3 TeV
- dominant Drell-Yan background small
- signal is <u>mass peak</u> above background

C. Collard

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Graviton (s=2) or Z' (s=1) ?
$\to$ look at $e^\pm$ angular distributions

ATLAS, 100 fb^{-1}, m_G=1.5 TeV

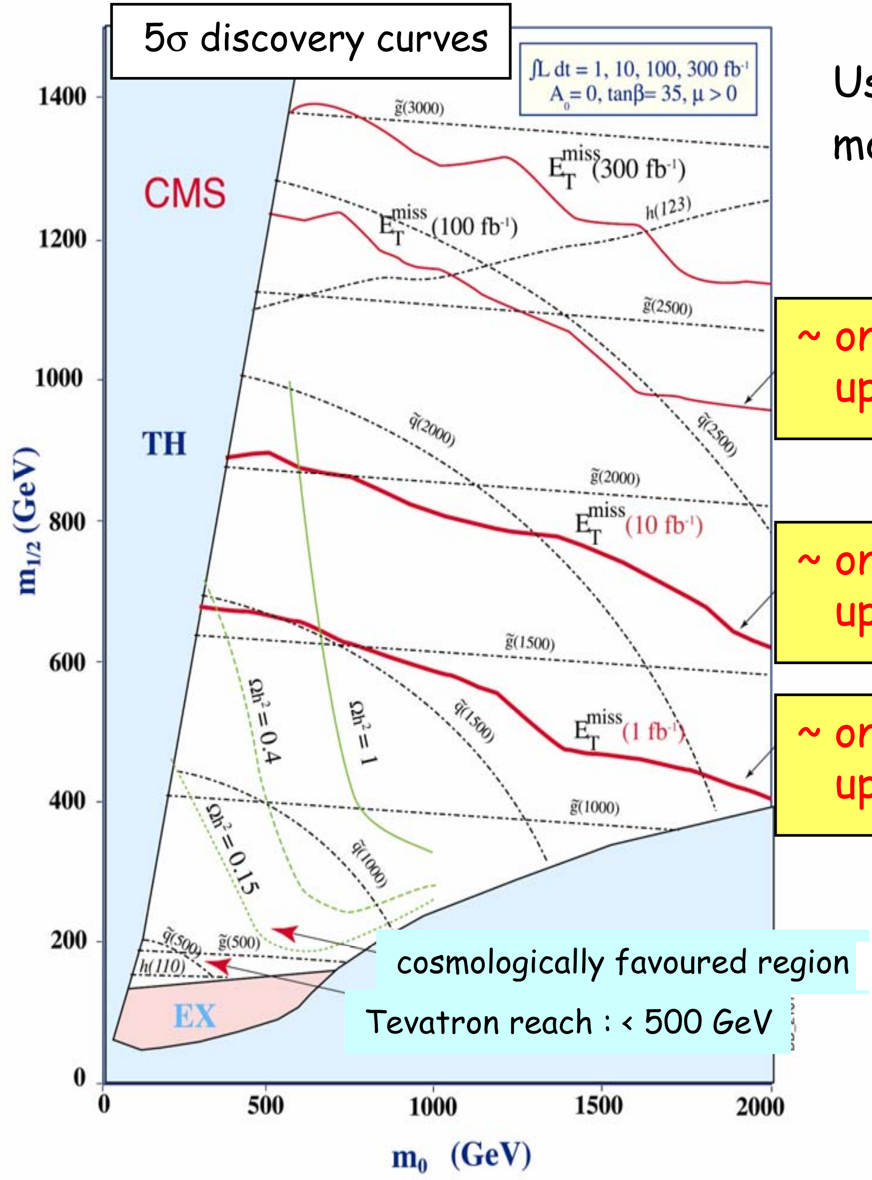


An "intermediate case" : SUPERSYMMETRY

If SUSY stabilizes m_H → is at TeV scale → could be found quickly .... thanks to:

- large $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ cross-section → ≈ 100 events/day at 10^{33} for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV
- spectacular signatures

5σ discovery curves

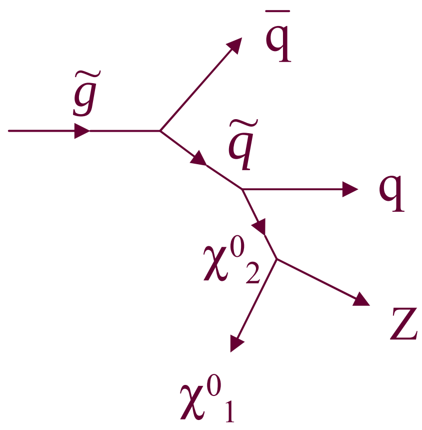


Using multijet + E_T^{miss} (most powerful and model-independent signature if R-parity conserved)

~ one year at 10^{34}: up to ~2.5 TeV

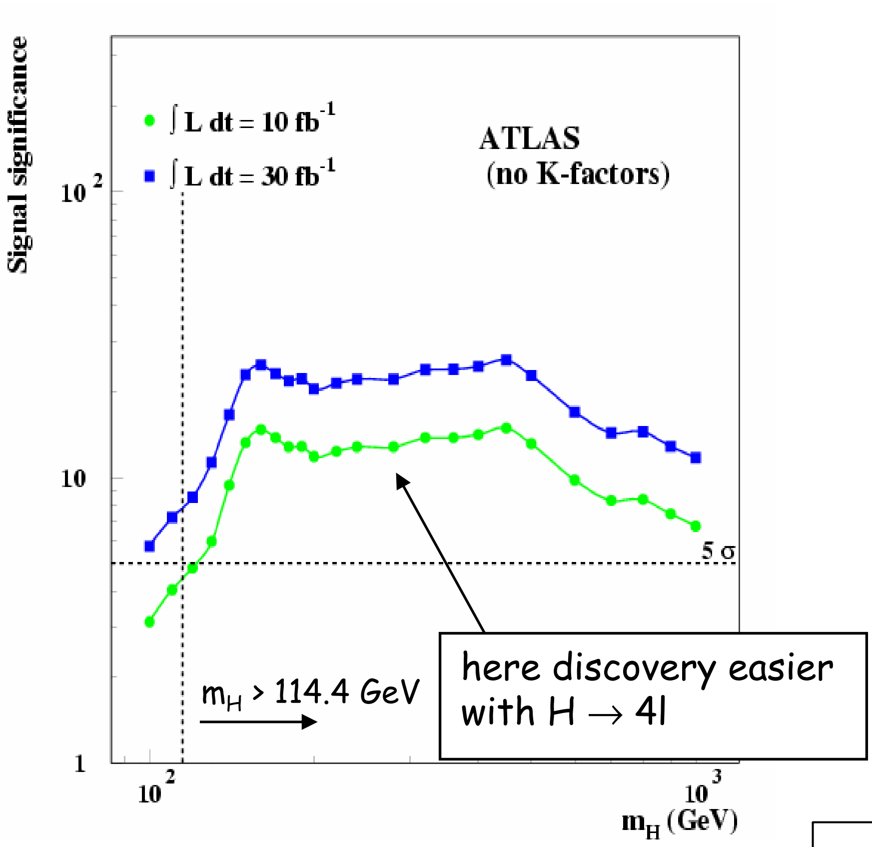
~ one year at 10^{33} : up to ~2 TeV

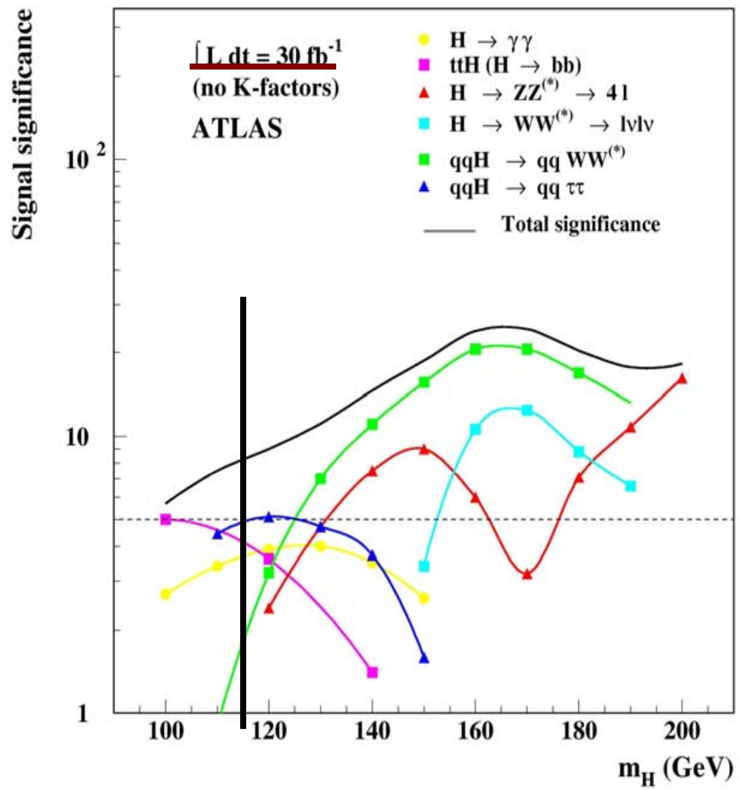
~ one month at 10^{33} : up to ~1.5 TeV



First/fast determination of SUSY (squark, gluino) mass scale from distribution of $E_T^{miss} + \Sigma\, p_T$(jets)

A difficult case: a light Higgs ($m_H \sim 115$ GeV) …





$m_H \sim 115$ GeV   10 fb^{-1}

total $S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$

ATLAS	$H \to \gamma\gamma$	$ttH \to ttbb$	$qqH \to qq\tau\tau$ (ll + l-had)
S	130	15	~ 10
B	4300	45	~ 10
$S/\sqrt{B}$	2.0	2.2	~ 2.7

K-factors ≡ σ(NLO)/σ(LO) ≈ 2 not included

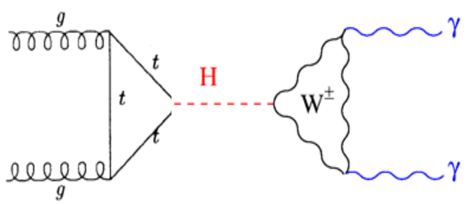
Full GEANT simulation, simple cut-based analyses

Remarks:

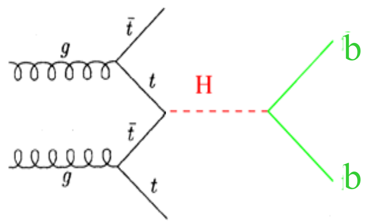
Each channel contributes ~ 2σ to total significance $\rightarrow$ observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary $\rightarrow$ robustness:

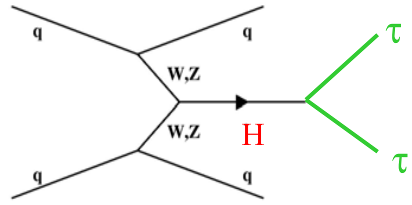
$H \rightarrow \gamma\gamma$



$ttH \rightarrow tt\ bb \rightarrow bl\nu\ bjj\ bb$



$qqH \rightarrow qq\tau\tau$



- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \rightarrow \gamma\gamma$ (in particular response uniformity) : $\sigma/m \sim 1\%$ needed
  - -- b-tagging crucial for ttH : 4 b-tagged jets needed to reduce combinatorics
  - -- efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \rightarrow qq\tau\tau$: forward jet tag and central jet veto needed against background

Note : -- all require "low" trigger thresholds

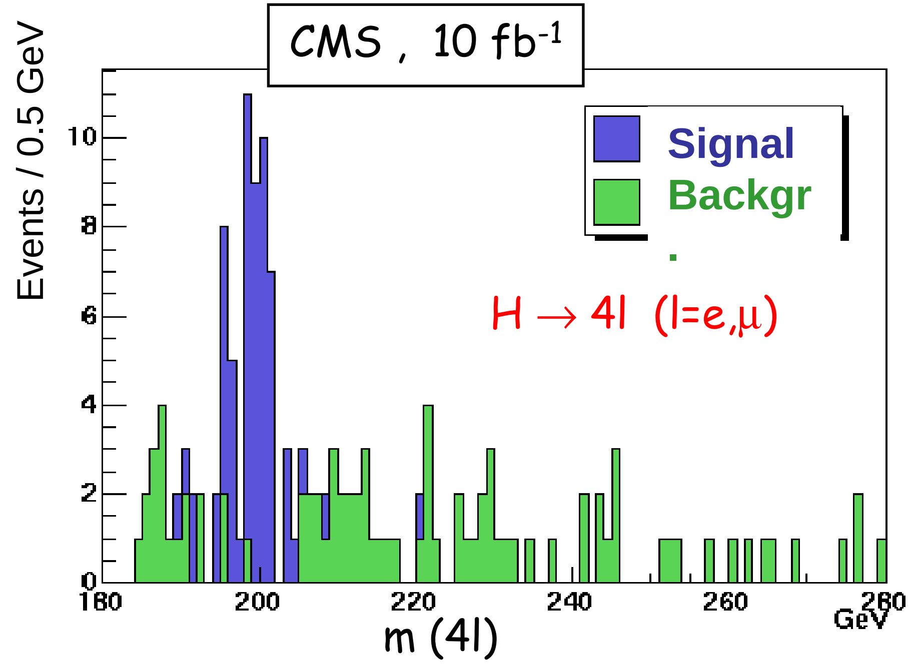
E.g. ttH analysis cuts : p_T (l) > 20 GeV, p_T (jets) > 15-30 GeV

-- all require very good understanding (1-10%) of backgrounds

If m_H > 180 GeV : early discovery may be easier with H → 4l channel

Luminosity needed for 5σ discovery (ATLAS+CMS)

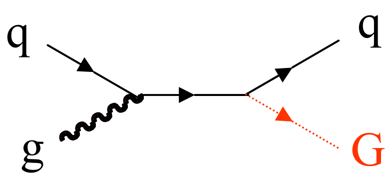
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



- H → WW → lν lν : high rate (~ 100 evts/expt) but no mass peak
  → not ideal for early discovery …
- H → 4l : low-rate but very clean : narrow mass peak, small background

Extra-dimensions (ADD models)

Look for a continuum of Graviton KK states :



→ topology is jet(s) + missing E_T

Cross-section $\approx \dfrac{1}{M_D^{\ \delta+2}}$

M_D = gravity scale
δ = number of extra-dimensions

ATLAS, 100 fb^{-1}

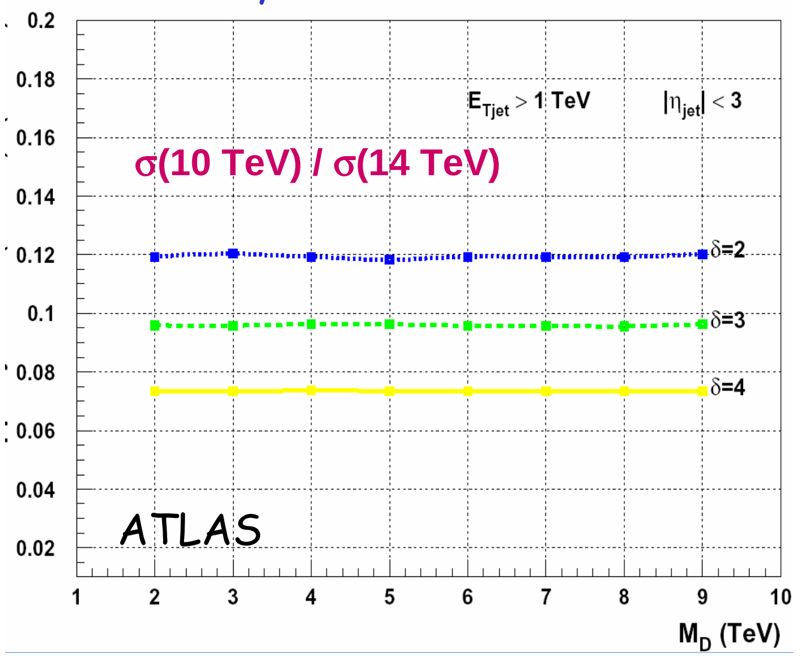
	$\delta = 2$	$\delta = 3$	$\delta = 4$
M_D^{max}	9 TeV	7 TeV	6 TeV

Discriminating between models:
-- SUSY : multijets plus E_T^{miss} (+ leptons, …)
-- ADD : monojet plus E_T^{miss}

To characterize the model need to measure M_D and δ

Measurement of cross-section gives ambiguous results: e.g. δ=2, M_D= 5 TeV very similar to δ=4, M_D= 4 TeV

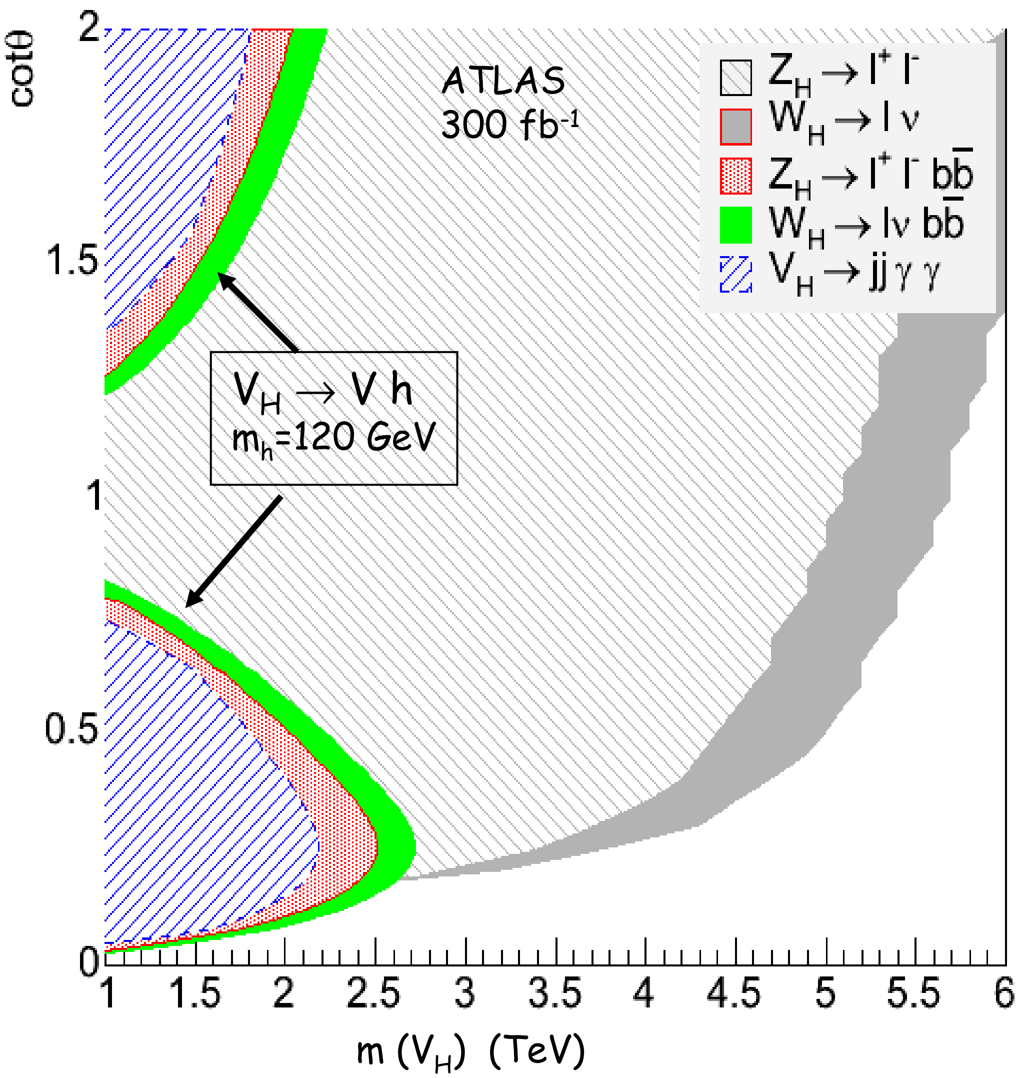
Solution may be to run at different √s :



Good discrimination between various solutions possible with expected <5% accuracy on σ(10)/σ(14) for 50 fb^{-1}

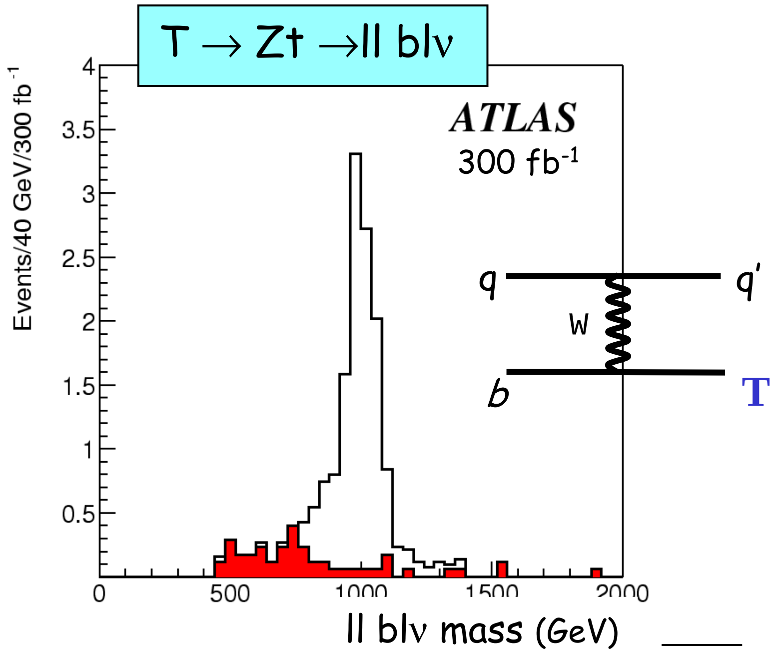
Little Higgs  models

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^{++}



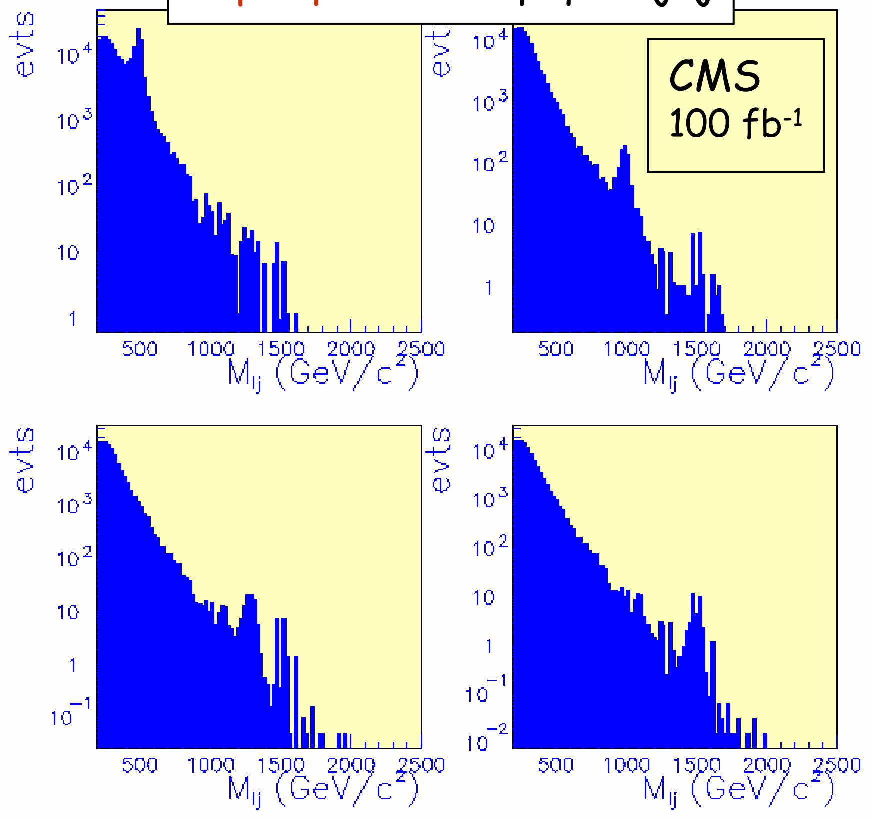
Observation of $T \to Zt$, Wb discriminates from 4th family quarks

Observation of $V_H \to Vh$ discriminates from W′, Z′

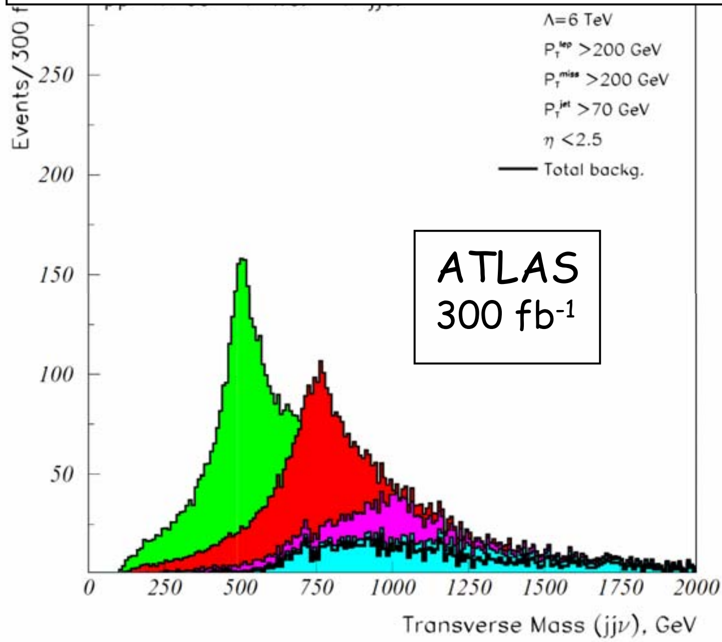


Other scenarios …..

Leptoquarks : lq lq → lj lj



Excited leptons ; e*e, e* → Wν →jj ν



LFV: W → τν, τ→ 3μ

CMS, 10 fb^{-1}
BR=1.9 x 10^{-6}

Reach (30 fb^{-1}):
BR < 4 x 10^{-8}

Large number of scenarios studied:

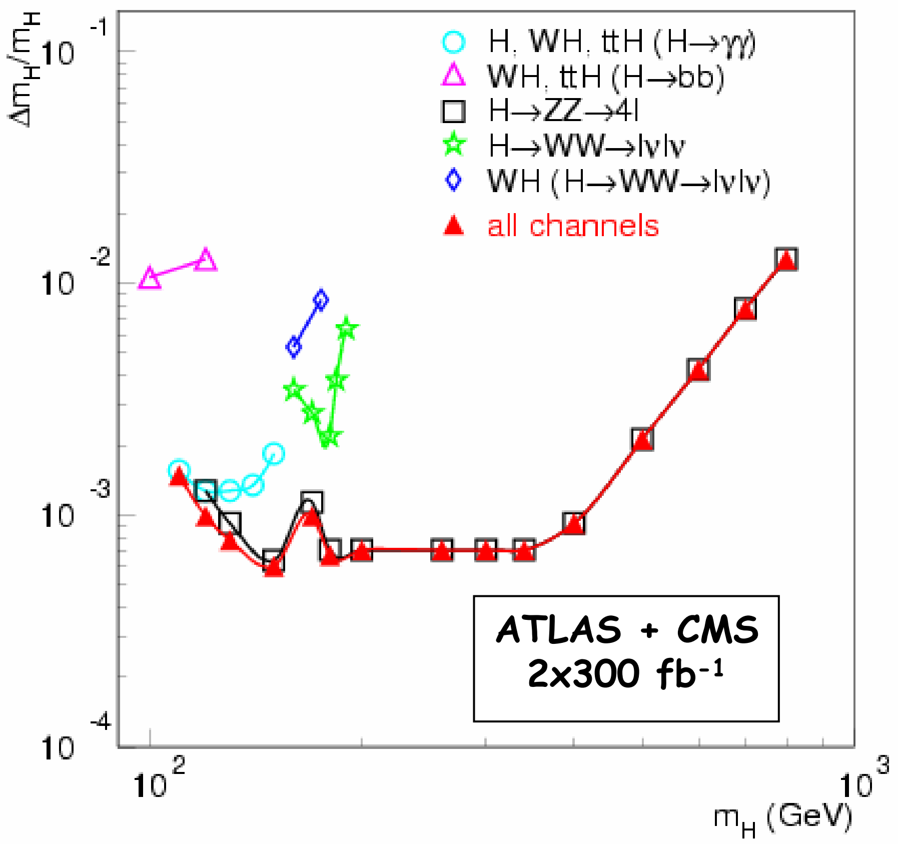
⇒ demonstrated detector sensitivity to many signatures
→ robustness, ability to cope with unexpected scenarios

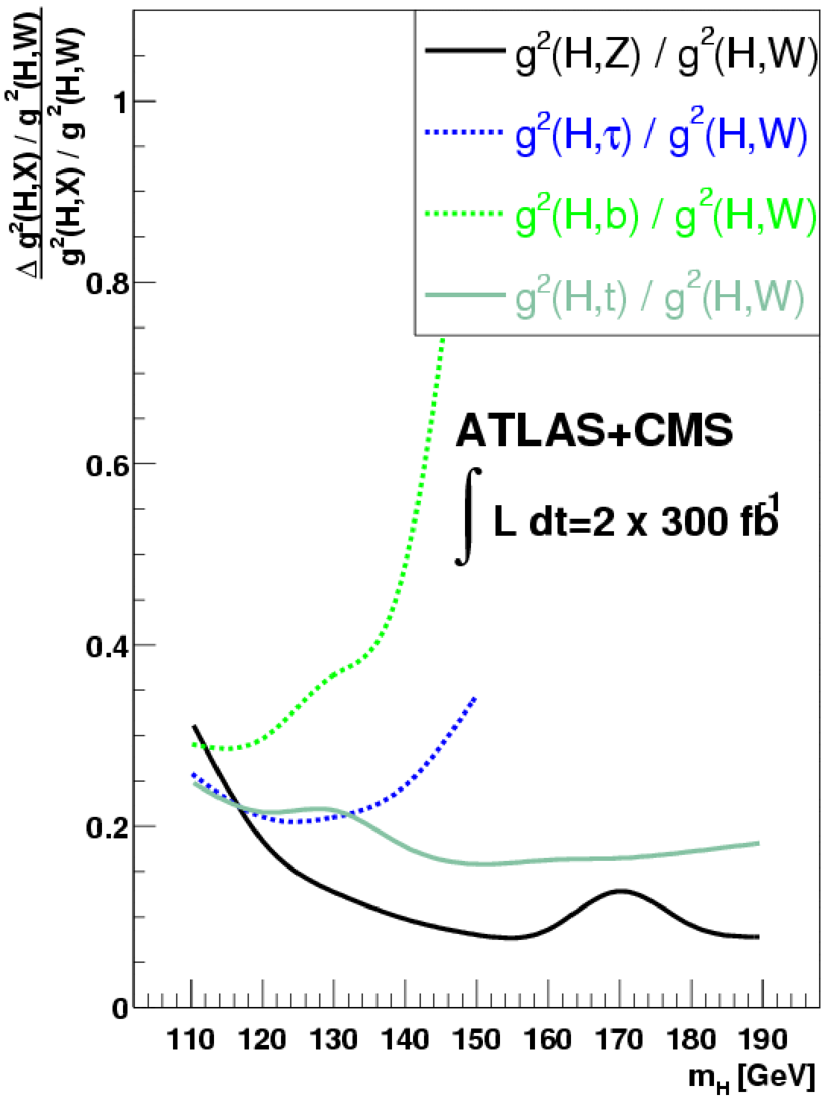
⇒ LHC direct discovery reach (hence exploration of hierarchy problem …) up to m ≈ 5-6 TeV

❷ Constraining the underlying theory …

Courtesy M. Duehrssen

Measurements of the SM Higgs parameters

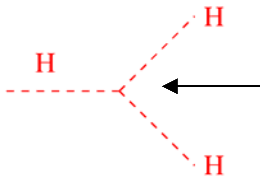




Lot of useful information to constrain the theory
(though not competitive with LC precision of e.g. ≈ % on couplings)

Higgs self-coupling λ

- not accessible at LHC
- may be constrained to ≈ 20% at Super-LHC ($L=10^{35}$)



$\sim \lambda v$

$m_H^2 = 2\,\lambda\, v^2$

Buszello et al. SN-ATLAS-2003-025

Higgs spin and CP

Promising for m_H > 180 GeV ($H \to ZZ \to 4l$), difficult at lower masses

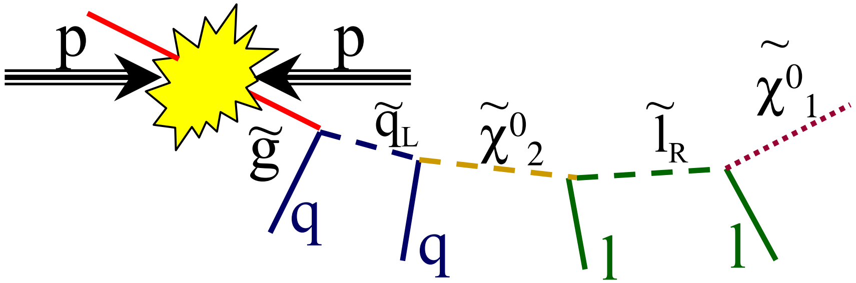
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Significance for exclusion of $J^{CP}=0^+$

ATLAS + CMS, 2 x 300 fb^{-1}

m_H (GeV)	$J^{CP} = 1^+$	$J^{CP} = 1^-$	$J^{CP}=0^-$
200	6.5 σ	4.8 σ	40 σ
250	20 σ	19 σ	80 σ
300	23 σ	22 σ	70 σ

Precise SUSY measurements

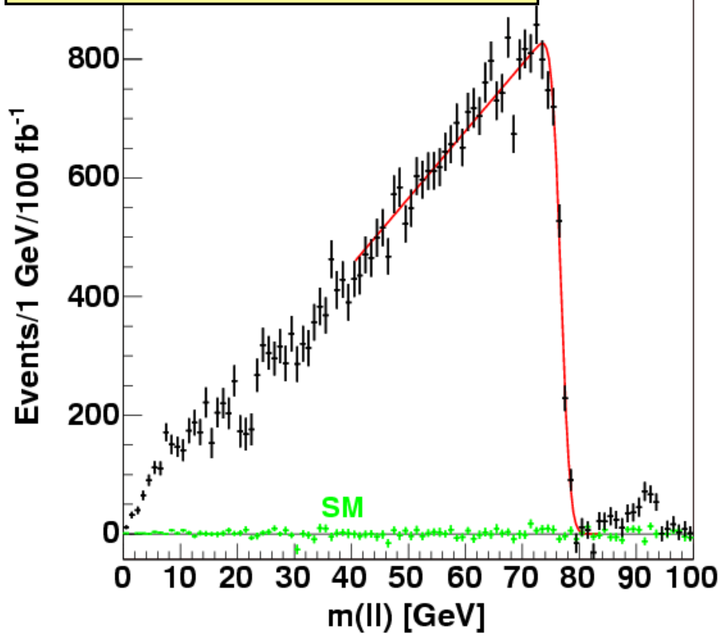


Mass peaks cannot be directly reconstructed (χ^0_1 undetectable) → measure invariant mass spectra (end-points, edges,..) of visible particles
→ deduce constraints on combinations of sparticle masses

m (l^+l^-) spectrum
end-point : 77 GeV
experim. precision ~0.1%

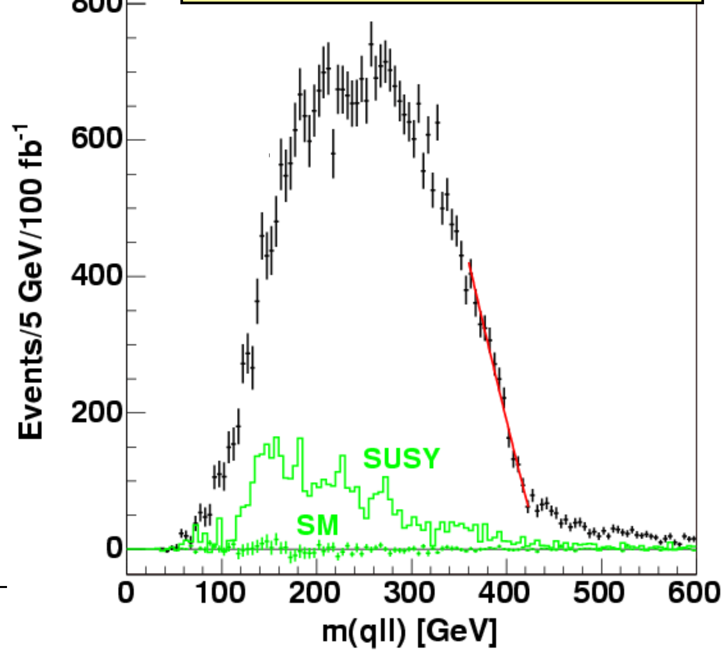
$m(\tilde{q}_L \;\; \chi^0_2 \;\; \tilde{\ell}_R \;\; \chi^0_1) =$ 540, 177,143,96 GeV

m $(llj)^{min}$ spectrum
end-point: 431 GeV
experim. precision ~1 %



ATLAS, 100 fb^{-1}

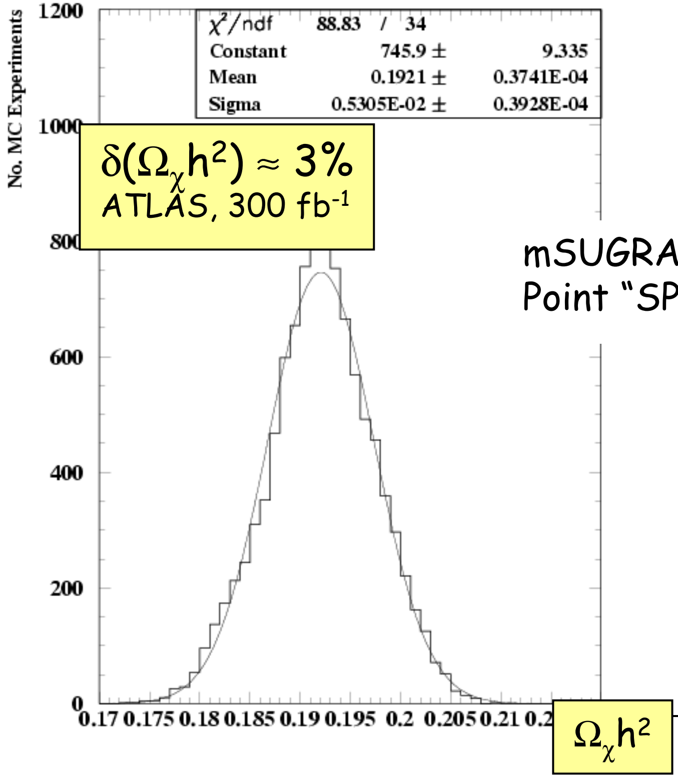
mSUGRA Point "SPS1A"
Courtesy B. Gjelsten



Putting all measurements together:

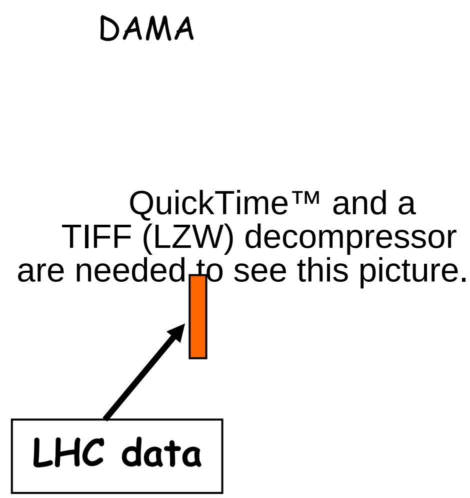
- deduce several sparticle masses: typical precision 1%-20%
  Model-indep. (just kinematics), but interpretation is model-dep.
- from fit of model to all experimental measurements derive
  -- sparticle masses with higher accuracy
  -- fundamental parameters of theory to 1-30%
  -- dark matter (χ^0_1) relic density and σ (χ^0_1 - nucleon)

demonstrated so far in mSUGRA (5 param.) and in more general MSSM (14 param.)



mSUGRA, Point "SPS1A"

Direct Dark Matter searches



Zepelin, CDMS, Edelweiss
___ present limit
--- projected

General strategy toward understanding the underlying theory

(SUSY as an example …)

Discovery phase: inclusive searches … as model-independent as possible

First characterization of model: from general features: Large E_T^{miss} ? Many leptons ?
Exotic signatures (heavy stable charged particles, many γ's, etc.) ? Excess of b-jets or τ's ? …

Interpretation phase:

- reconstruct/look for semi-inclusive topologies, eg.:
  - -- h $\rightarrow$ bb peaks (can be abundantly produced in sparticle decays)
  - -- di-lepton edges
  - -- Higgs sector: e.g. A/H $\rightarrow \mu\mu$, $\tau\tau \Rightarrow$ indication about tanβ, measure masses
  - -- tt pairs and their spectra $\Rightarrow$ stop or sbottom production, gluino $\rightarrow$ stop-top
- determine (combinations of) masses from kinematic measurements (e.g. edges …)
- measure observables sensitive to parameters of theory (e.g. mass hierarchy)

At each step narrow landscape of possible models and get guidance to go on:

- lot of information from LHC data (masses, cross-sections, topologies, etc.)
- consistency with other data (astrophysics, rare decays, etc.)
- joint effort theorists/experimentalists will be crucial

What the LHC can do and cannot do ….

SUSY as an example …

In general the LHC can (examples …):

- discover SUSY up to m ($\tilde{q},\tilde{g}$) ~ 2.5 TeV
- measure lightest Higgs h mass to ~ 0.1%
- derive sparticle masses (typically $\tilde{q},\tilde{g}$, χ^0_2) from kinematic measurements
- constrain underlying theory by fitting a model to the data

More difficult or impossible (examples …):

- disentangle squarks of first two generations
- observe / measure sleptons if m > 350 GeV
- measure full gaugino spectrum
- measure sparticle spin-parity and all couplings
- constrain underlying theory in model-indep. way

➡ complementarity with LC

GeV^{-1} **EW-scale → RGE → GUT-scale**

SPS1A: courtesy W.Porod
(based on hep-ph/0403133)

$1/M_1$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

$1/M_2$

$1/M_3 = m(\tilde{g})$

Colour bands : LHC
Black lines : LHC+ LC

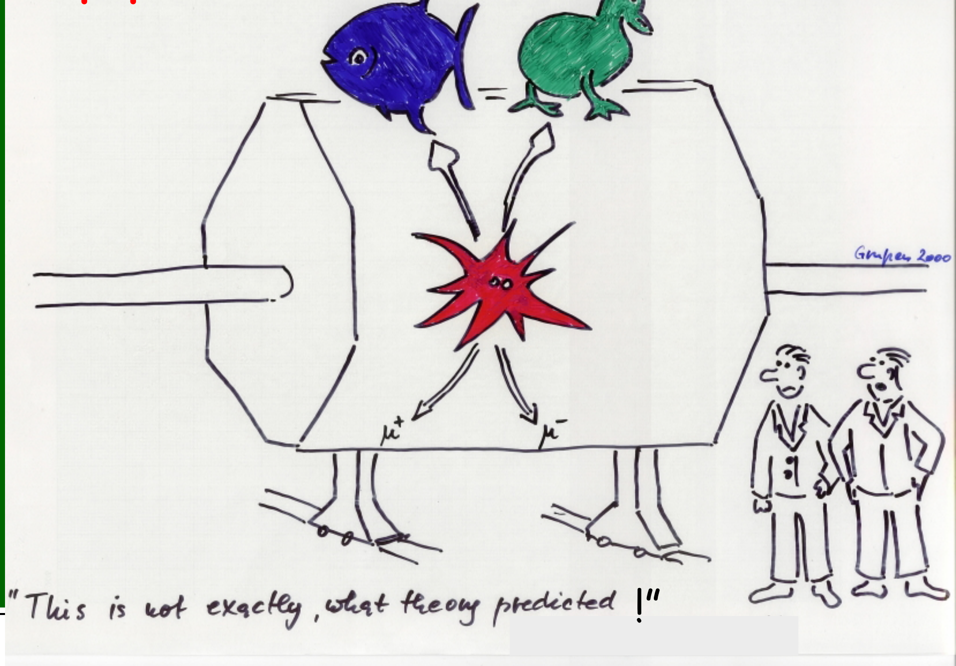
Q (GeV)

Ultimate goal : from precise measurements of e.g. gaugino masses at the TeV scale reconstruct high-E theory

Conclusions

- In 2 years from now, particle physics will enter a new epoch, hopefully the most glorious and fruitful of its history.
- Indeed, the hierarchy problem motivates strongly New Physics at the TeV scale
- The LHC will explore this scale in detail with direct discovery potential up to m ≈ 5-6 TeV
  → if New Physics is there, the LHC will find it
  → it will say final word about many TeV-scale predictions
  → it will tell us which are the right questions to ask, and how to go on

hep-ph/070701



Has Nature prepared a "pleasant" welcome to the TeV-scale (striking signals with limited luminosity and non-ultimate detector performance) or shall we have to sweat through years of data taking and hard work before we can claim a discovery ?

Early determination of scale of New Physics would be crucial for planning of future facilities (ILC ? CLIC ? Underground Dark Matter searches ? ….)
The future of our discipline will benefit from a quick feedback on SUSY and the rest .. !

Next challenge: efficient and as-fast-as-possible commissioning of machine and detectors of unprecedented complexity, technology and performance

From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ? "
given to the American Physical Society, NY, Jan. 29th 1954

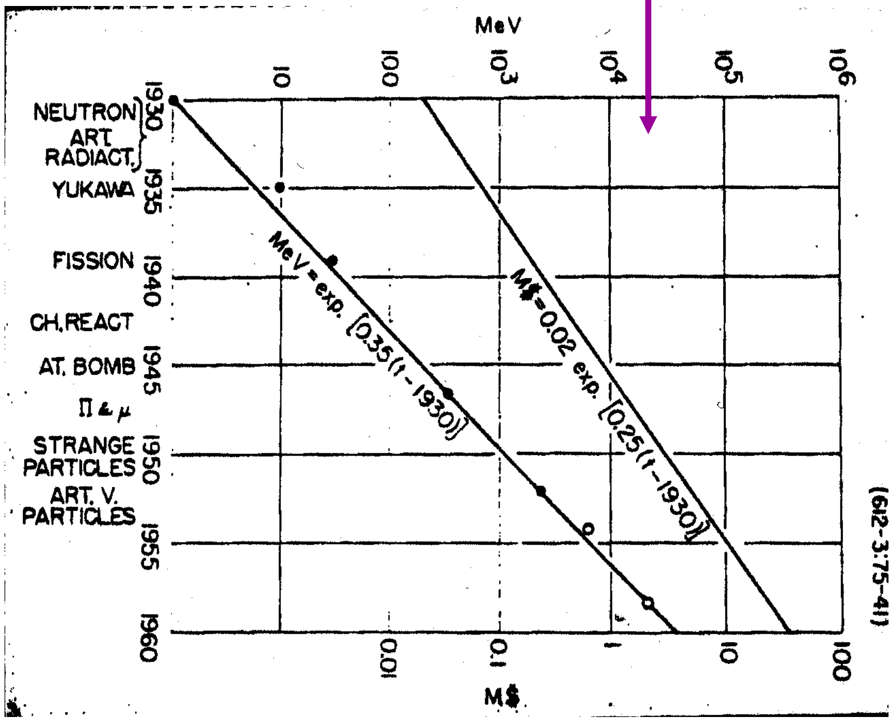
For these reasons....clamoring for higher and higher....

Slide 1 - MeV - M$ versus time.

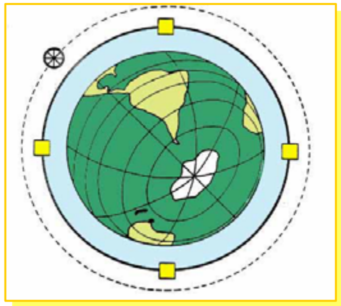
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss

Slide 2 - 5 hi 15 ev machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening knowledge.....~~spin and symmetry~~....certainly look for multiple production...



Fermi's extrapolation to year 1994:
2T magnets, R=8000 Km machine
E_{beam} ~ 5×10^3 TeV , cost 170 B$



University of Chicago library
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