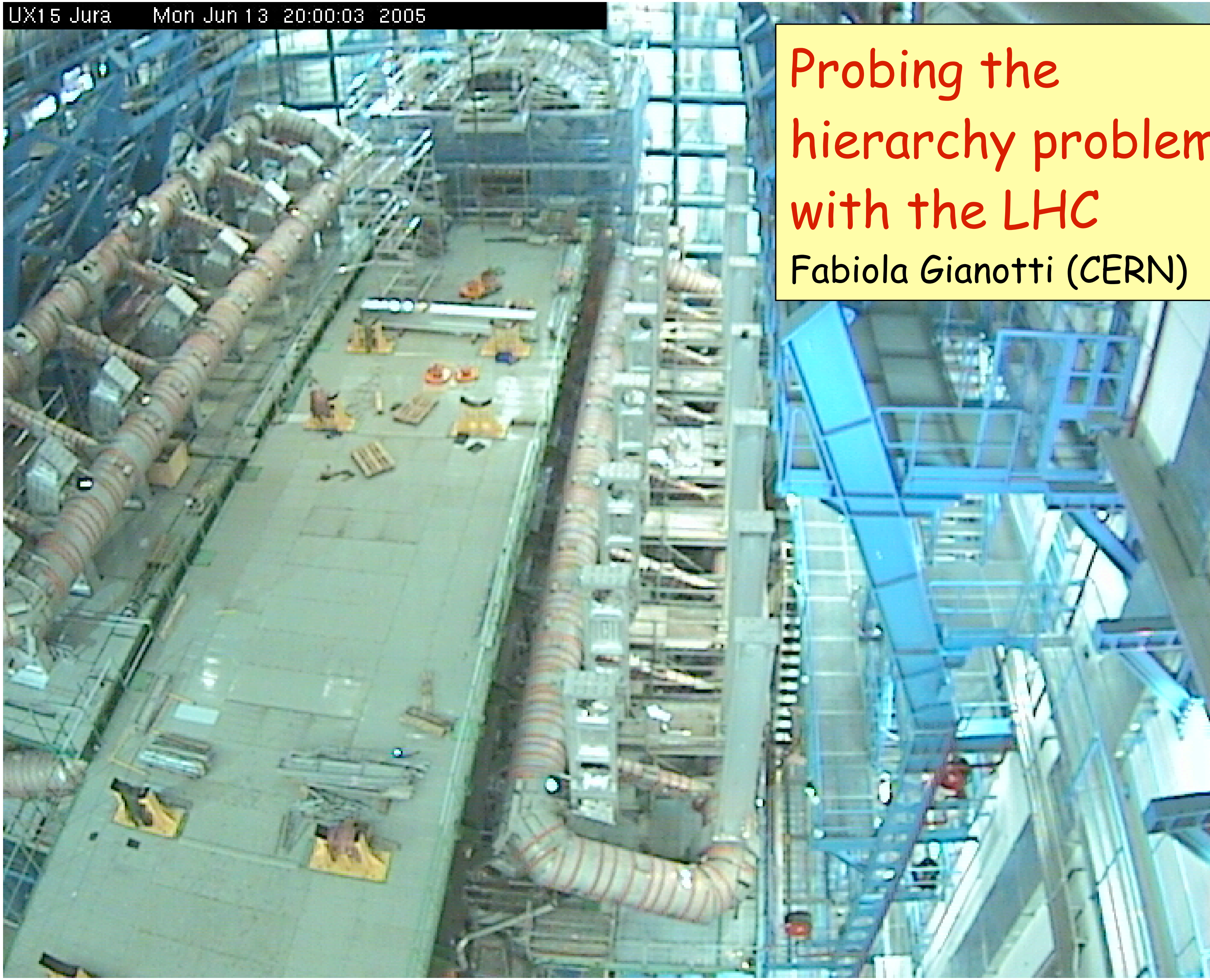
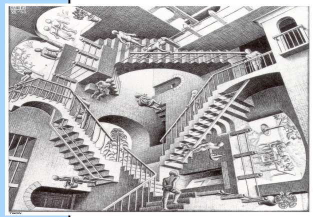
Probing the hierarchy problem with the LHC

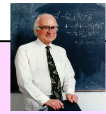
Fabiola Gianotti (CERN)



SUSY
New particles at TeV scale stabilize m_H

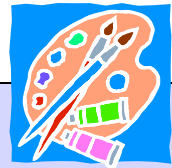
Extra-dimensions
Additional dimensions
$\rightarrow M_{gravity} \sim M_{EW}$
New states at TeV scale



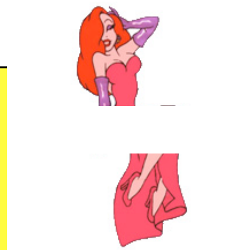


Little Higgs
SM embedded in larger gauge group
New particles at TeV scale, stable m_H

$M_{EW} / M_{Planck} \sim 10^{-17}$
$\delta m_H \sim \Lambda$ (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:

❶ **What can be done at the beginning ?**

❷ **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:

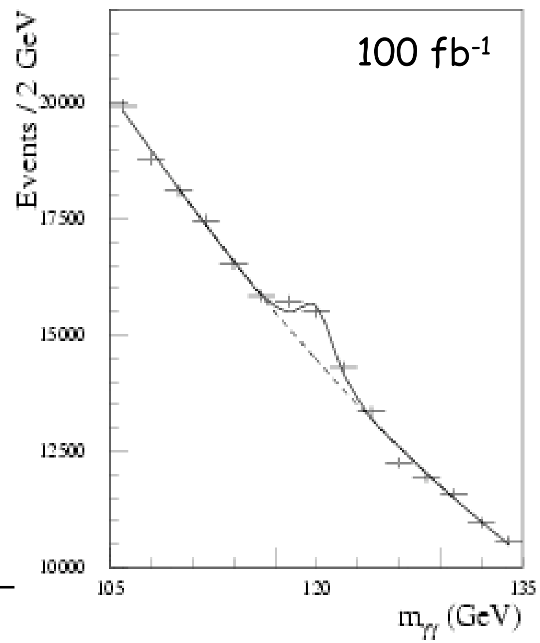
- Understand and calibrate detectors *in situ* using well-known physics samples
  - e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - - $tt \to bl\nu\ bjj$ jet scale from $W \to jj$, b-tag performance, etc.
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, 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

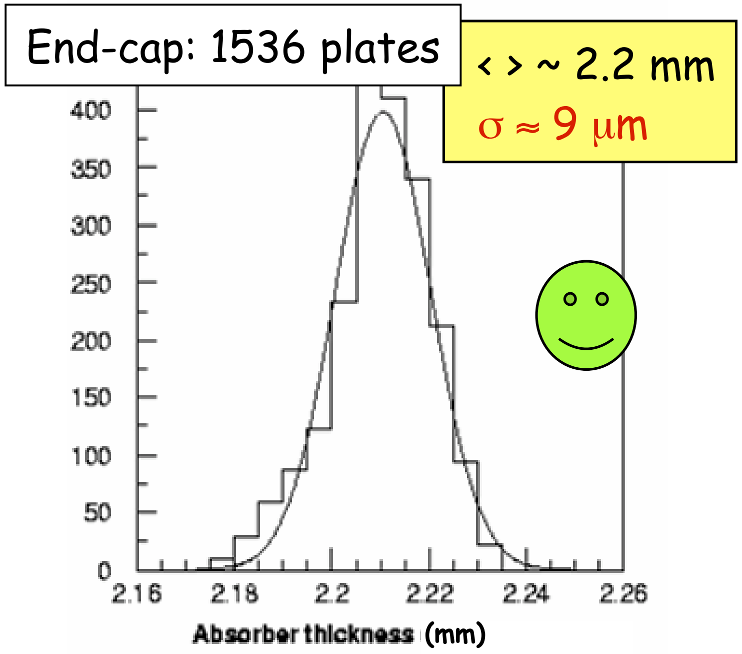
Pb-liquid argon sampling calorimeter with Accordion shape, covering $|\eta| < 2.5$



$H \rightarrow \gamma\gamma$: 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 $|\eta| < 2.5$

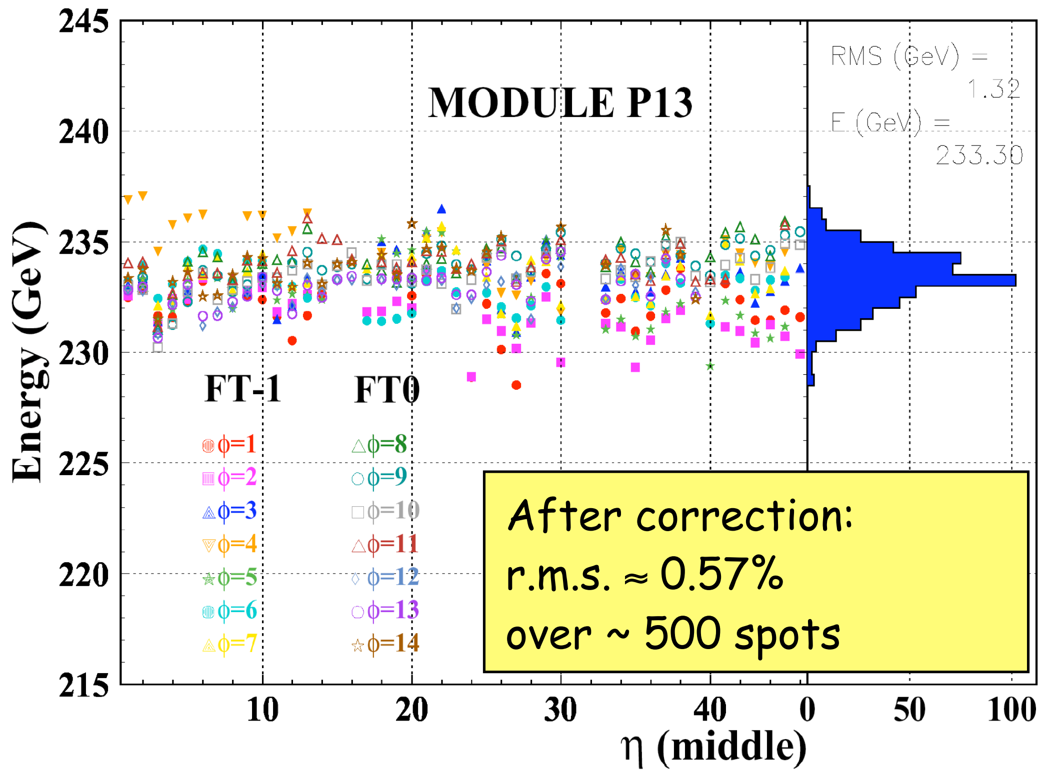
❶ Construction quality

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



❷ Test-beam measurements

Scan of a barrel module (Δφ×Δη=0.4X1.4) with high-E electrons



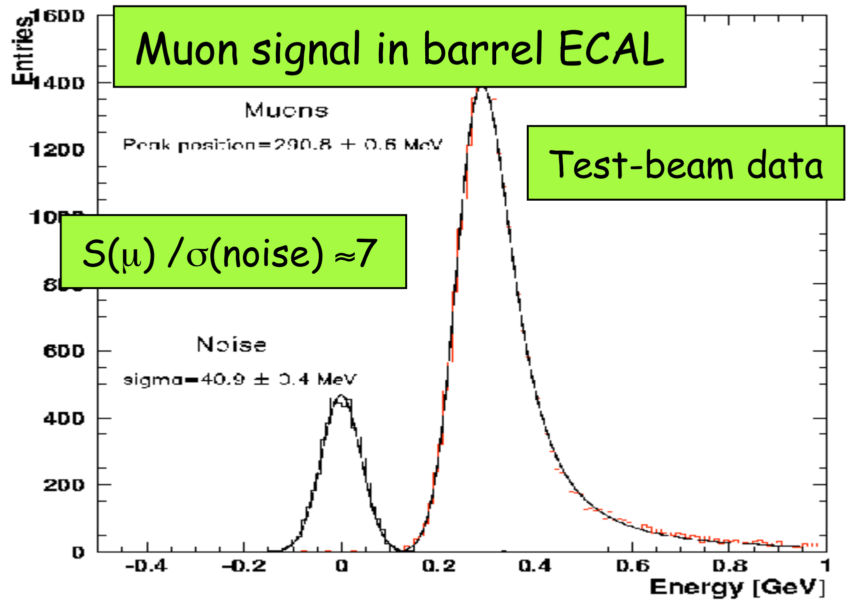
❸ Cosmics runs:

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

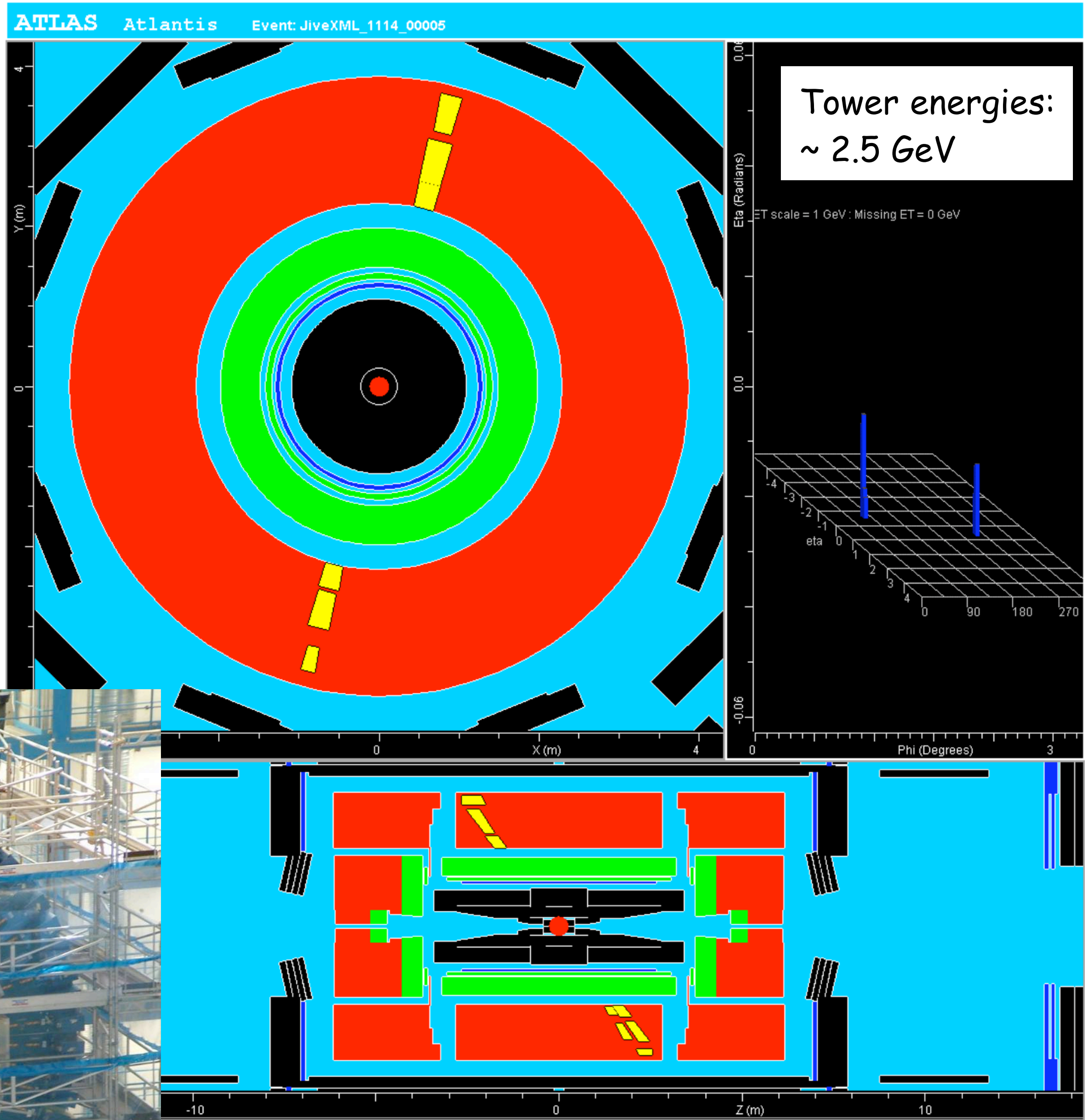
ECAL non-uniformity at construction level, i.e.:
-- no test-beam corrections
-- no calibration with $Z \to ee$

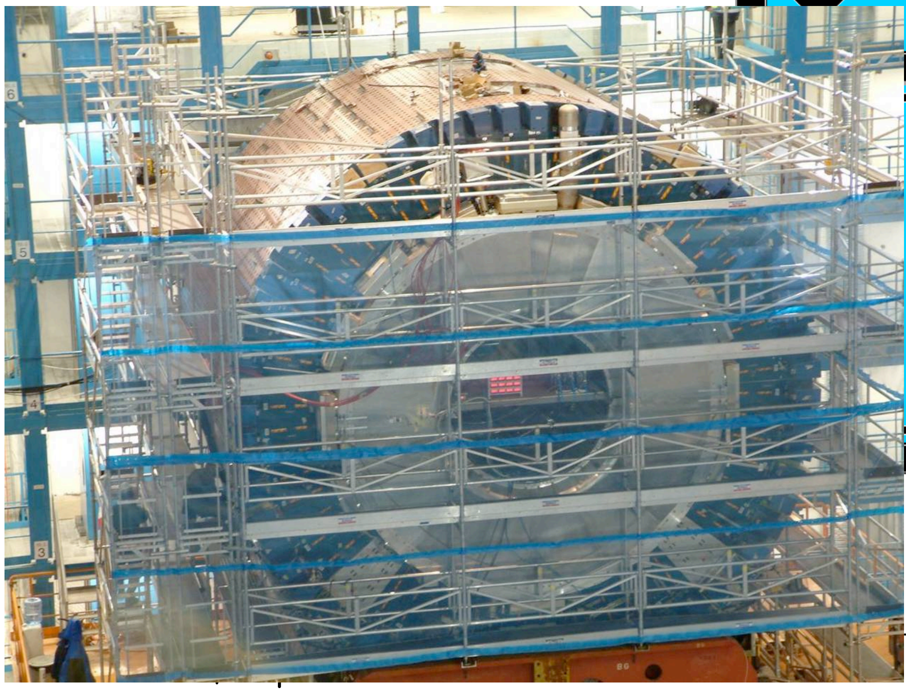
} → $c \approx 2\%$

↓

$H \to \gamma\gamma$ 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)



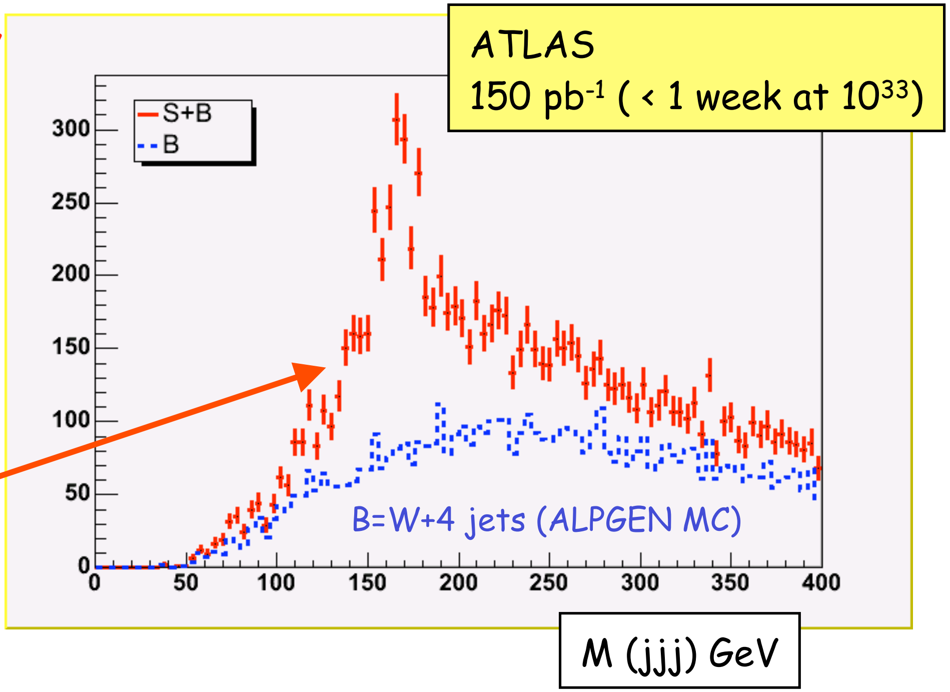


Example of initial SM measurement : top signal and top mass

(relevant to New Physics .....)

Bentvelsen et al.

- Use gold-plated $t\bar{t} \to bW\, bW \to bl\nu\, bjj$ 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



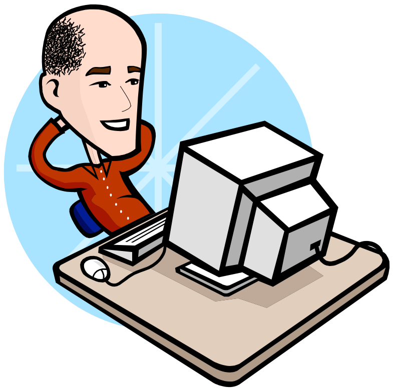
Time	Events at 10^{33}	Stat. error δM_{top}(GeV)	Stat. error $\delta\sigma/\sigma$
1 year	3×10^5	0.1	0.2%
1 month	7×10^4	0.2	0.4%
1 week	2×10^3	0.4	2.5%

- 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

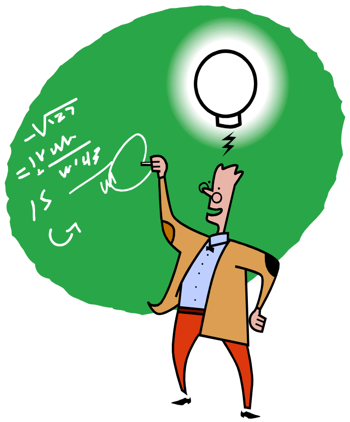
What about early discoveries ?
Three examples relevant to the hierarchy problem …

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 → e+e- resonance with m ~ 1 TeV

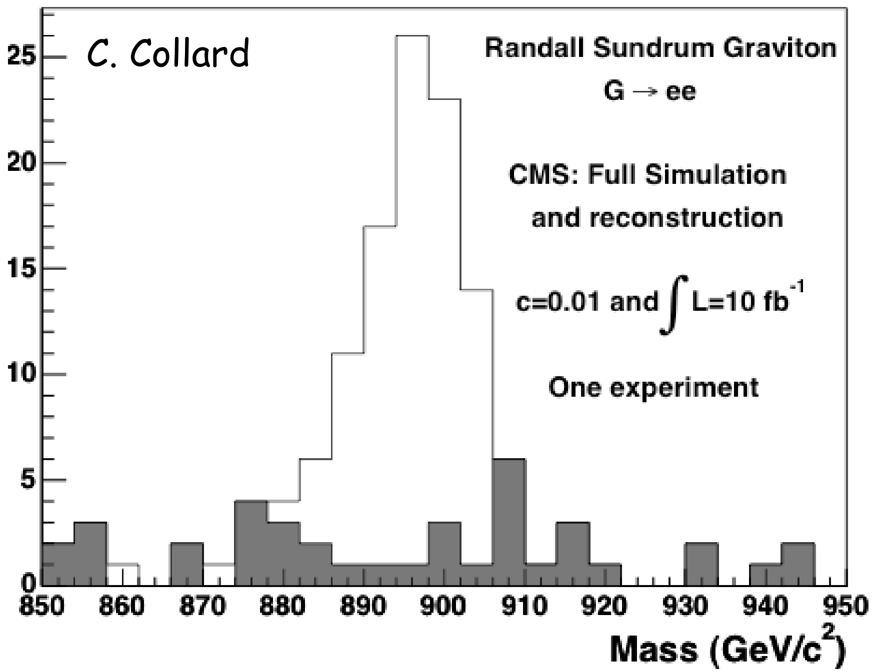
predicted in Randall-Sundrum Extra-dimensions

BR ($G \rightarrow ee \approx 2\%$), 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}

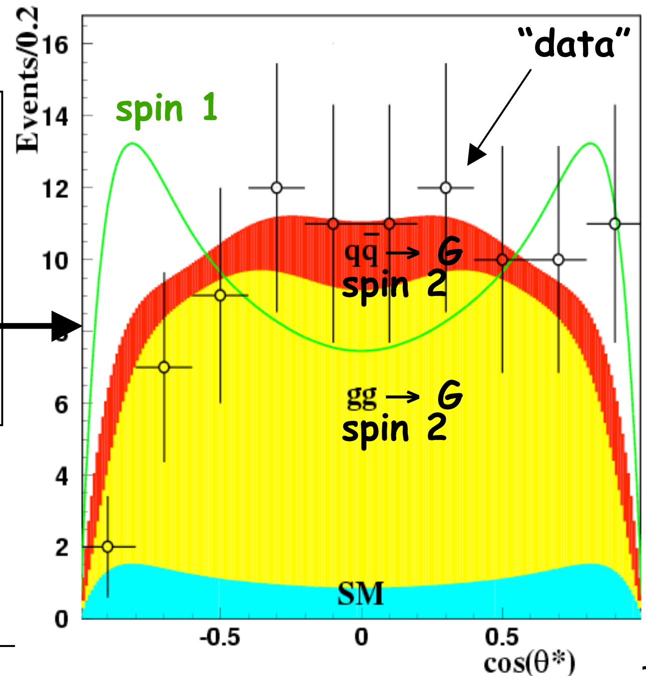
CMS

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



Graviton (s=2) or Z′ (s=1) ?
→ look at $e^{\pm}$ angular distributions

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

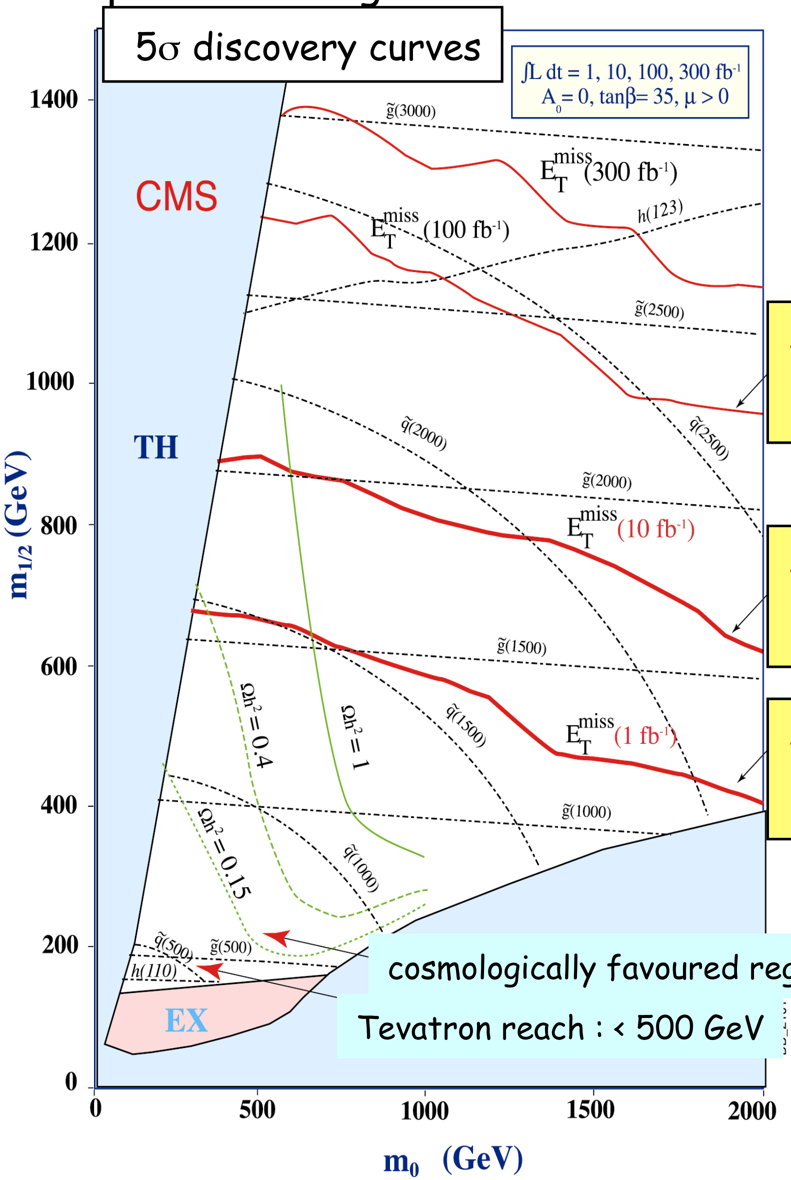


An "intermediate case" : SUPERSYMMETRY

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

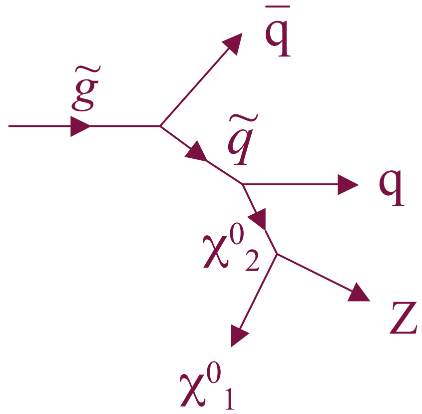


Using multijet + E_T^{miss} (most powerful and model-independent signature if R-parity conserved)

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

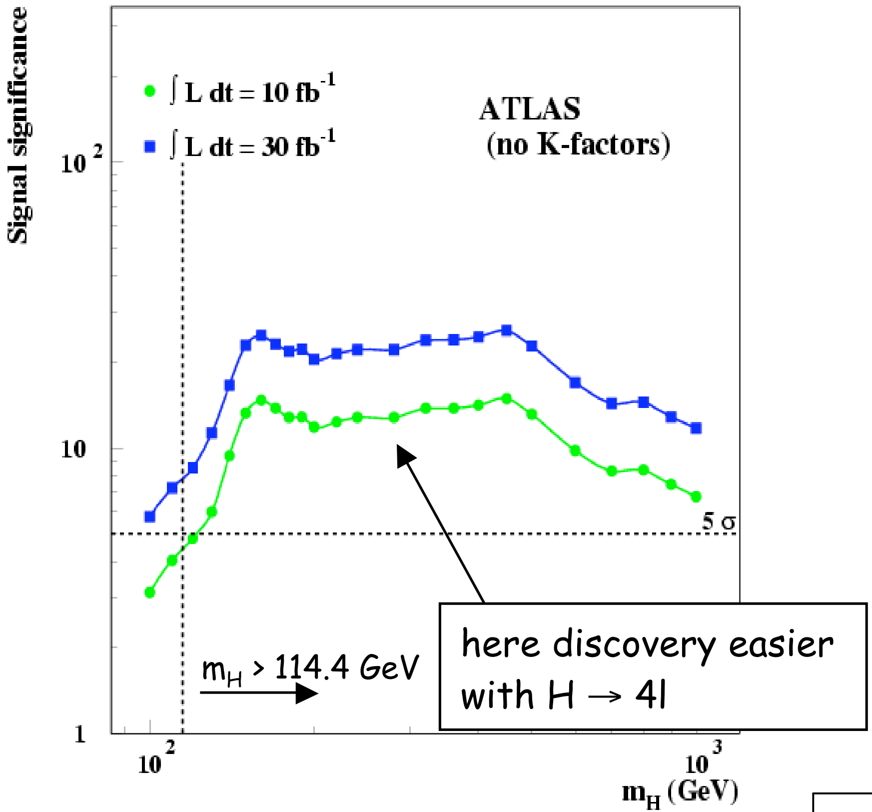
~ one year at 10^{33} : up to ~2 TeV

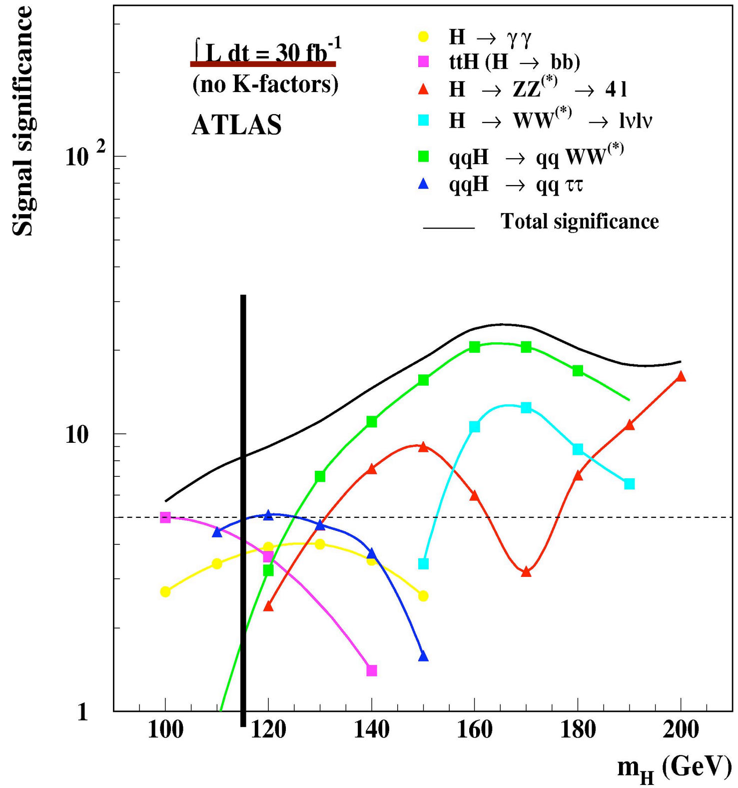
~ one month at 10^{33} : up to ~1.5 TeV



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 ~ 115 GeV) …





m_H ~ 115 GeV	10 fb^{-1}

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

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

Full GEANT simulation, simple cut-based analyses

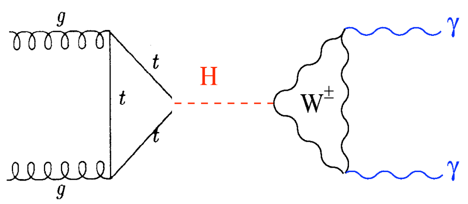
K-factors ≡ σ(NLO)/σ(LO) ≈ 2 not included

Remarks:

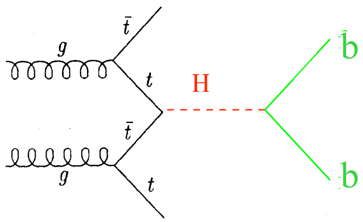
Each channel contributes ~ 2σ to total significance → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:

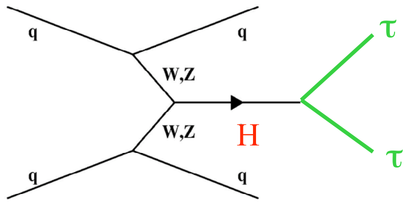
$H \rightarrow \gamma\gamma$



ttH → tt bb → blν bjj bb



qqH → qqττ



- 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 → qqττ : forward jet tag and central jet veto needed against background

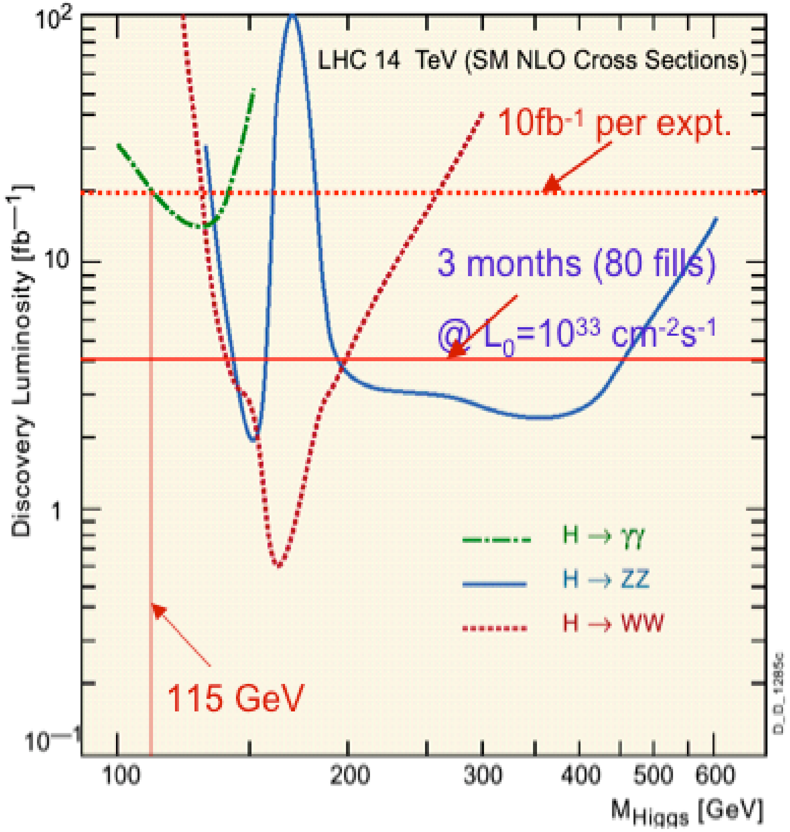
Note : -- all require "low" trigger thresholds

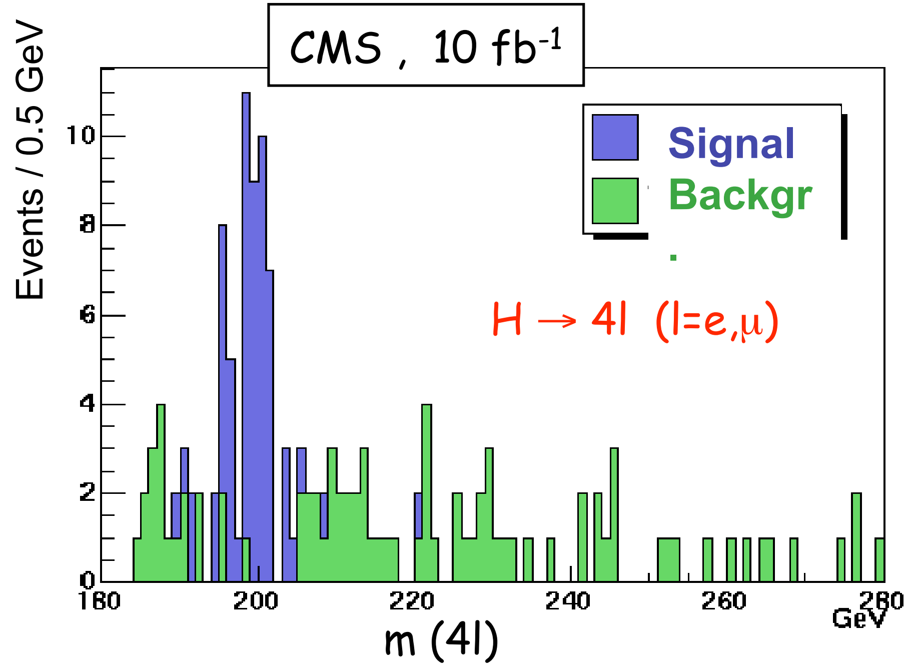
E.g. ttH analysis cuts : p_T (l) > 20 GeV, p_T (jets) > 15-30 GeV

-- 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)

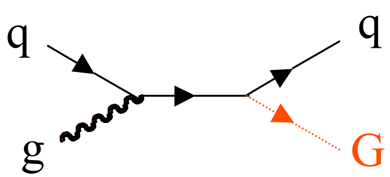




- H → WW → lν lν : high rate (~ 100 evts/expt) but no mass peak
  → not ideal for early discovery …
- H → 4l : low-rate but very clean : narrow mass peak, small background

Extra-dimensions (ADD models)

Look for a continuum of Graviton KK states :



→ topology is jet(s) + missing E_T

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

M_D = gravity scale
δ = number of extra-dimensions

ATLAS, 100 fb^{-1}

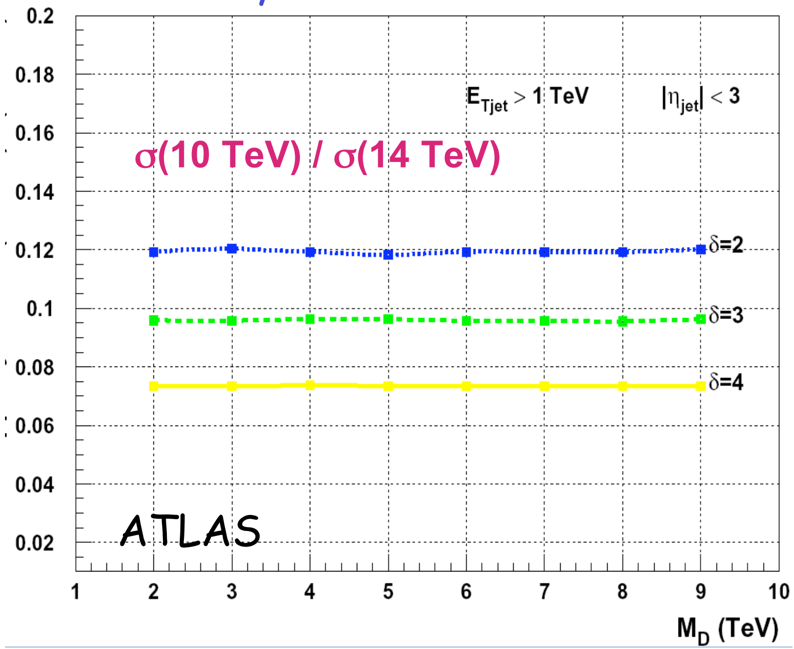
	$\delta = 2$	$\delta = 3$	$\delta = 4$
M_D^{max}	9 TeV	7 TeV	6 TeV

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

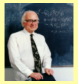
To characterize the model need to measure M_D and δ

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

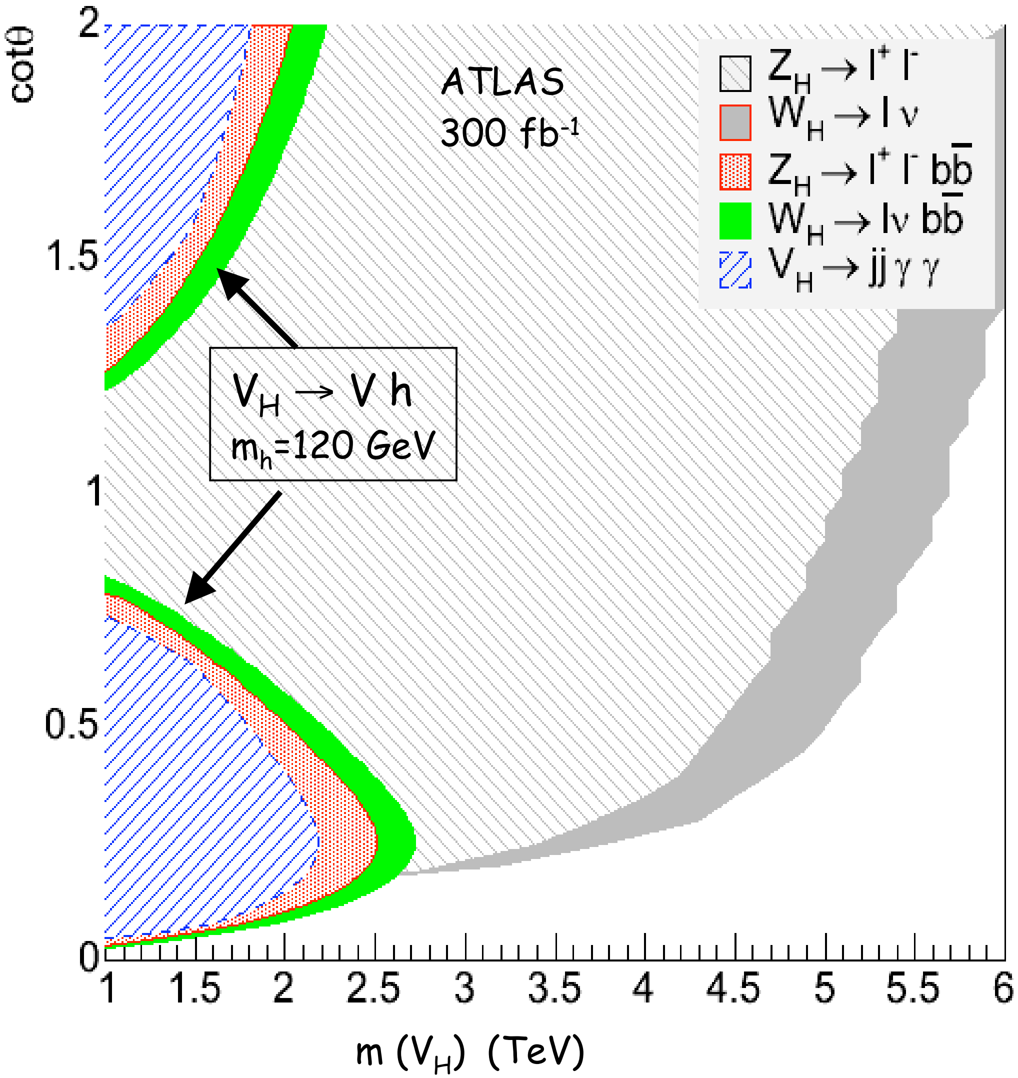
Solution may be to run at different $\sqrt{s}$:



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

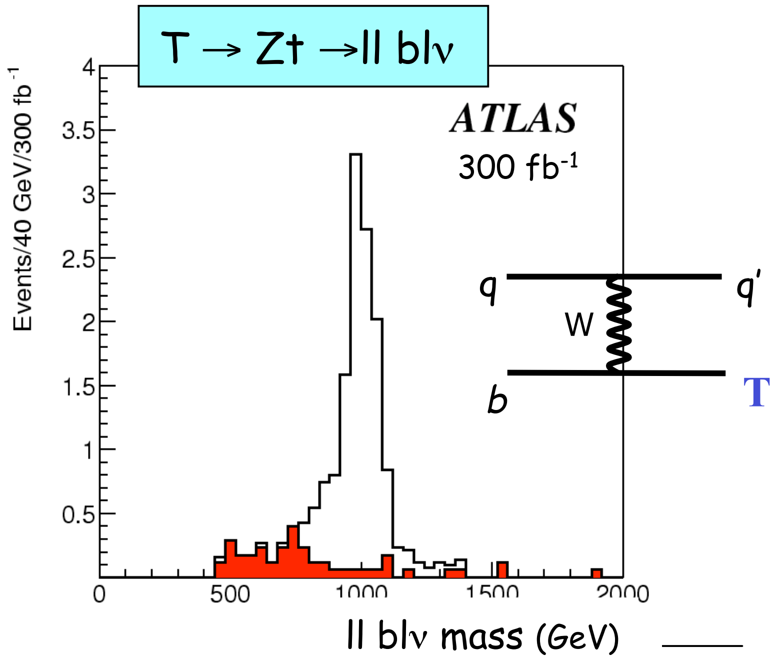
Little Higgs  models

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^{++}



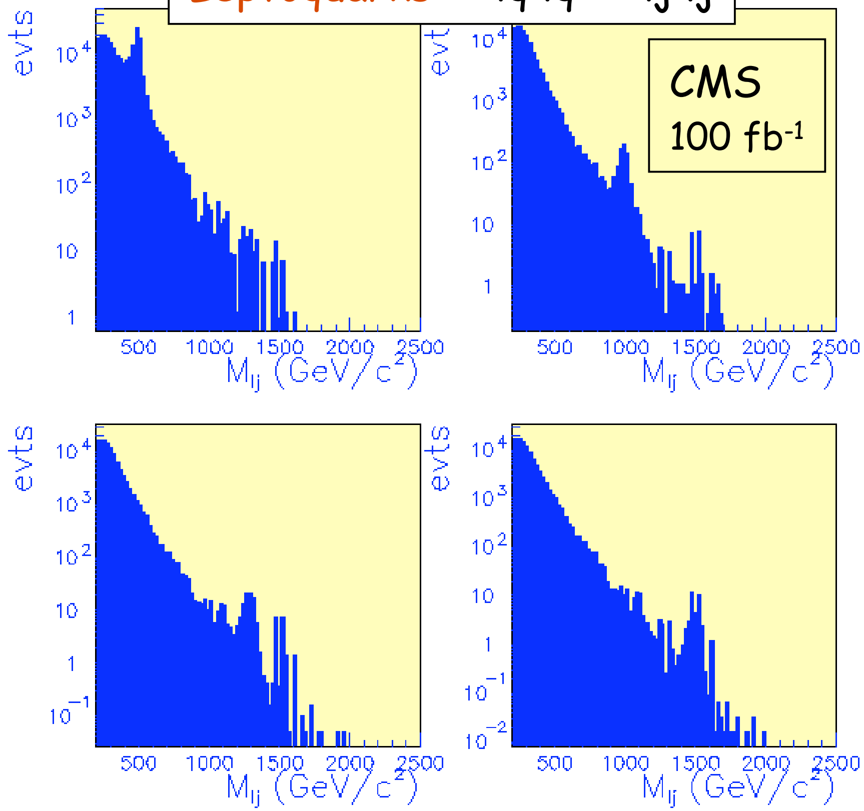
Observation of $T \to Zt$, Wb discriminates from 4th family quarks

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

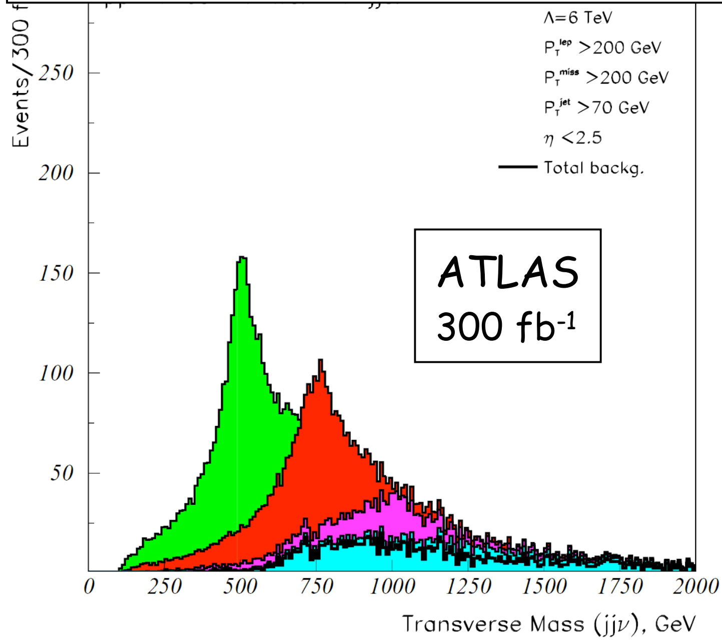


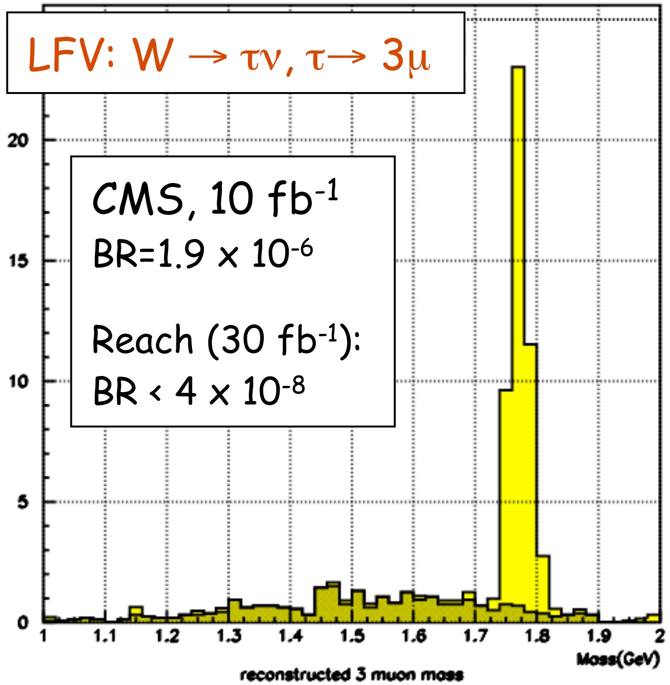
Other scenarios .....

Leptoquarks : lq lq → lj lj



Excited leptons ; e*e, e* → Wν →jj ν





Large number of scenarios studied:

⇒ demonstrated detector sensitivity to many signatures

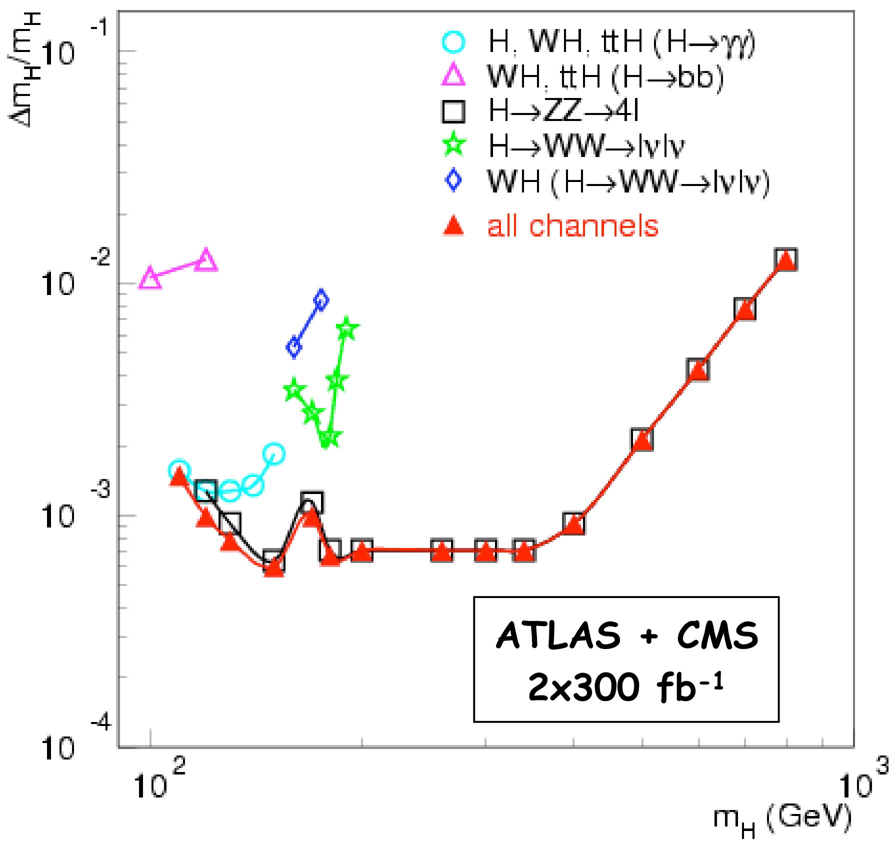
→ robustness, ability to cope with unexpected scenarios

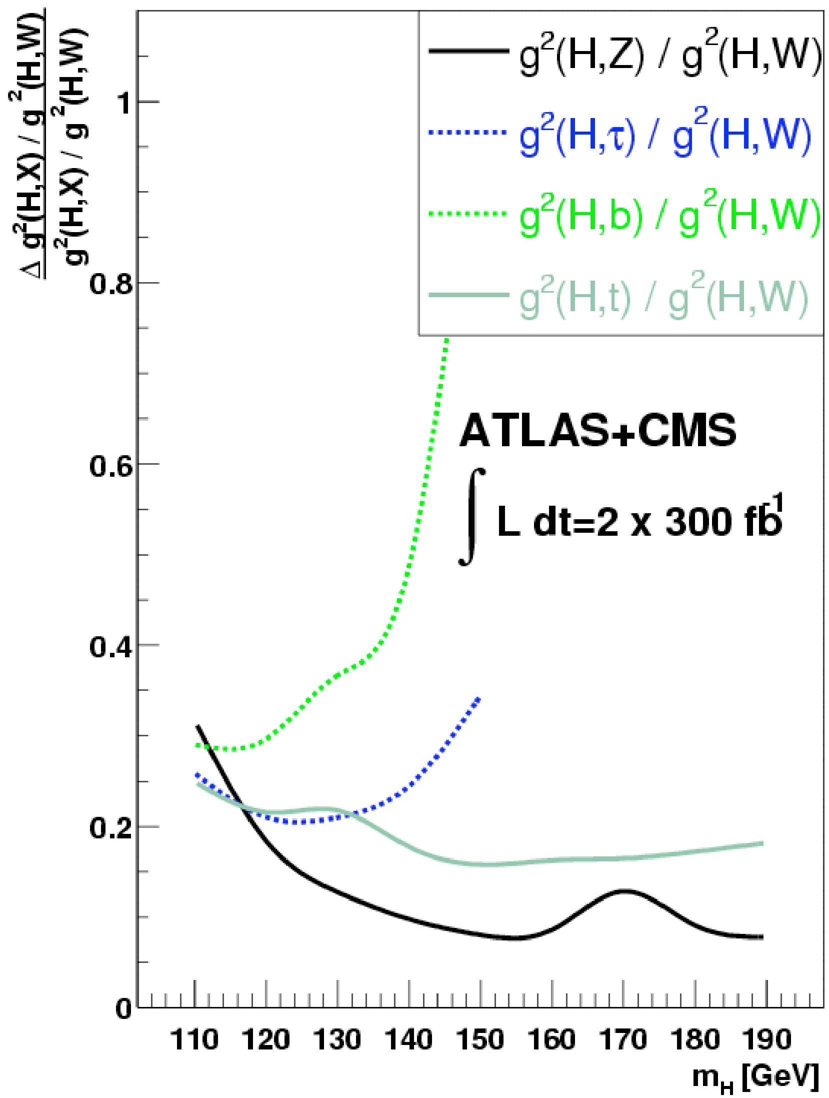
⇒ LHC direct discovery reach (hence exploration of hierarchy problem ...) up to m ≈ 5-6 TeV

❷ Constraining the underlying theory …

Courtesy M. Duehrssen

Measurements of the SM Higgs parameters

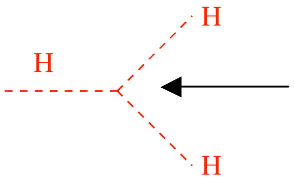




Lot of useful information to constrain the theory
(though not competitive with LC precision of e.g. ≈ % on couplings)

Higgs self-coupling λ

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



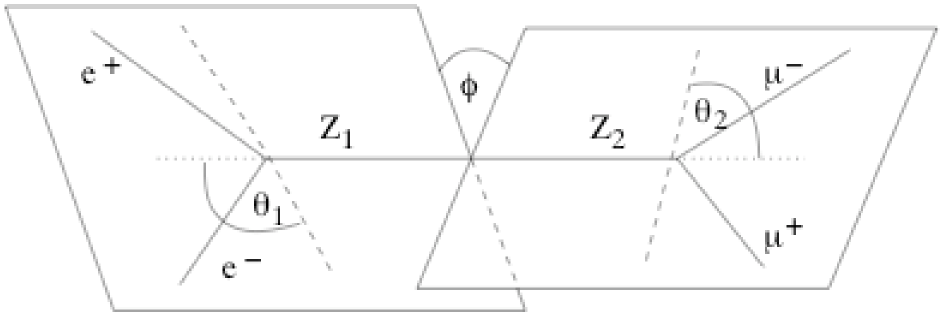
~ λv

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

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

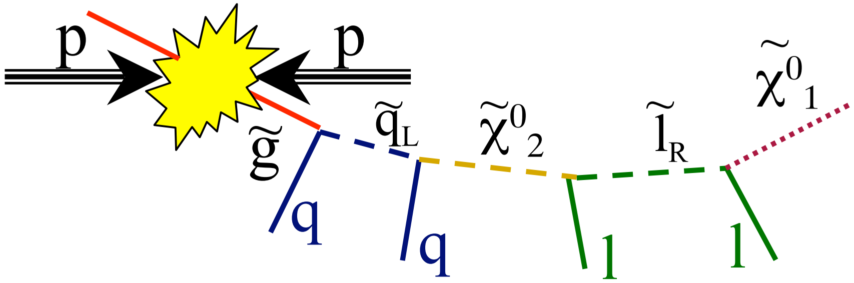


Significance for exclusion of $J^{CP}=0^+$

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



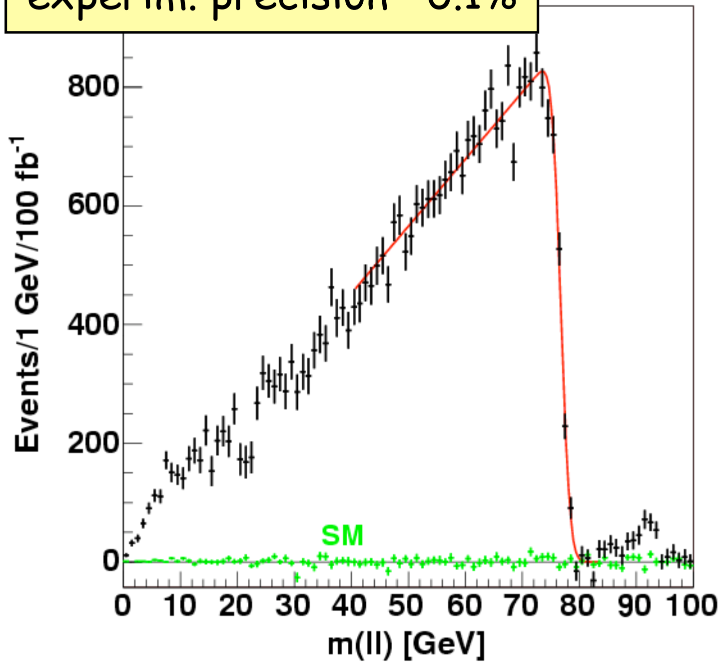
Mass peaks cannot be directly reconstructed (χ^0_1 undetectable) → measure invariant mass spectra (end-points, edges,..) of visible particles

→ deduce constraints on combinations of sparticle masses

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

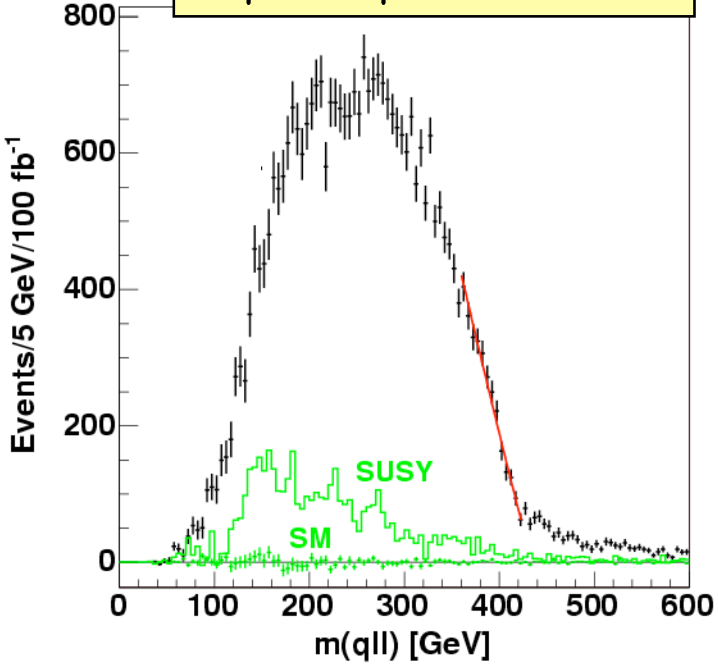
$m(\tilde{q}_L\ \chi^0_2\ \tilde{l}_R\ \chi^0_1) =$ 540, 177,143,96 GeV

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



ATLAS, 100 fb^{-1}

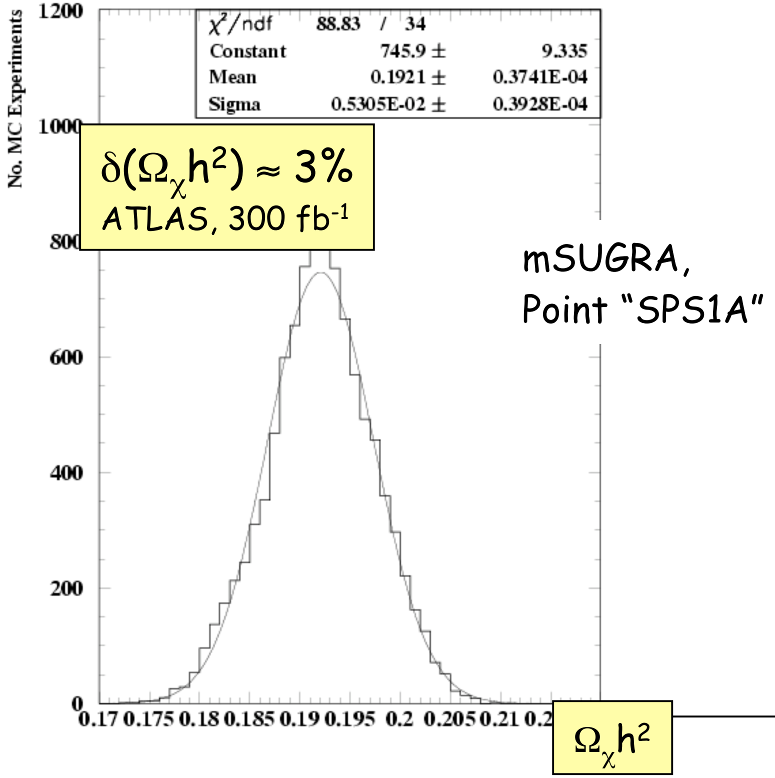
mSUGRA Point "SPS1A"
Courtesy B. Gjelsten

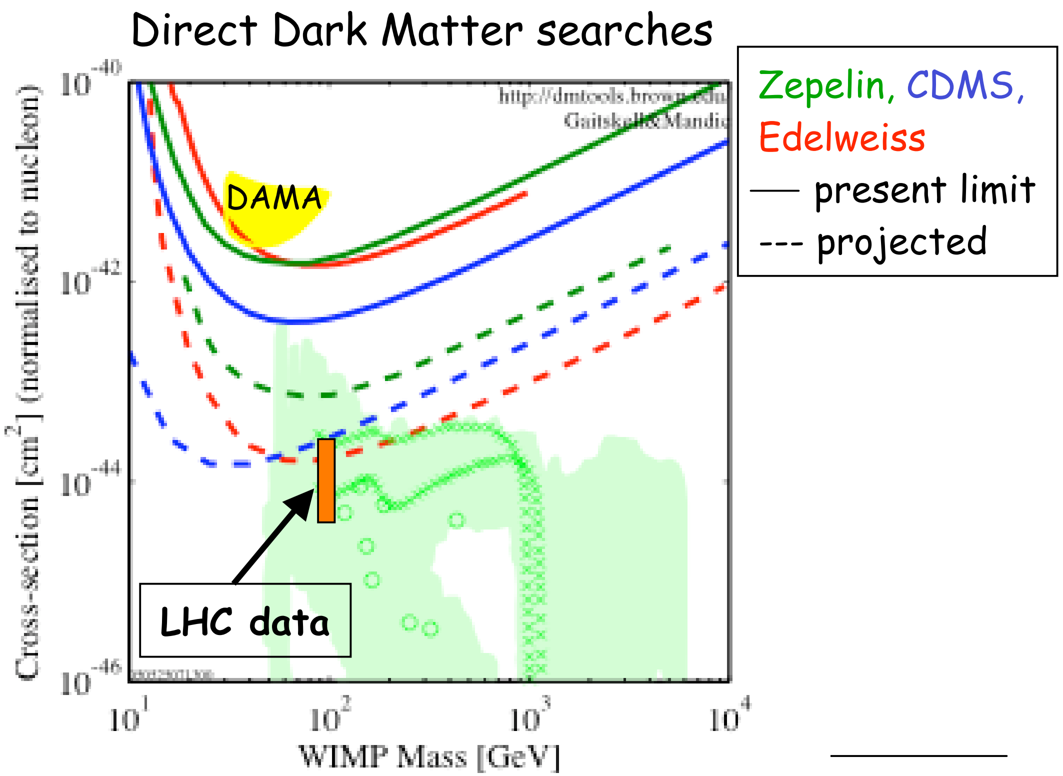


Putting all measurements together:

- 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.)





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.:
  - -- $h \to bb$ peaks (can be abundantly produced in sparticle decays)
  - -- di-lepton edges
  - -- Higgs sector: e.g. $A/H \to \mu\mu, \tau\tau \Rightarrow$ indication about tanβ, measure masses
  - -- tt pairs and their spectra $\Rightarrow$ stop or sbottom production, gluino $\to$ 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 ...

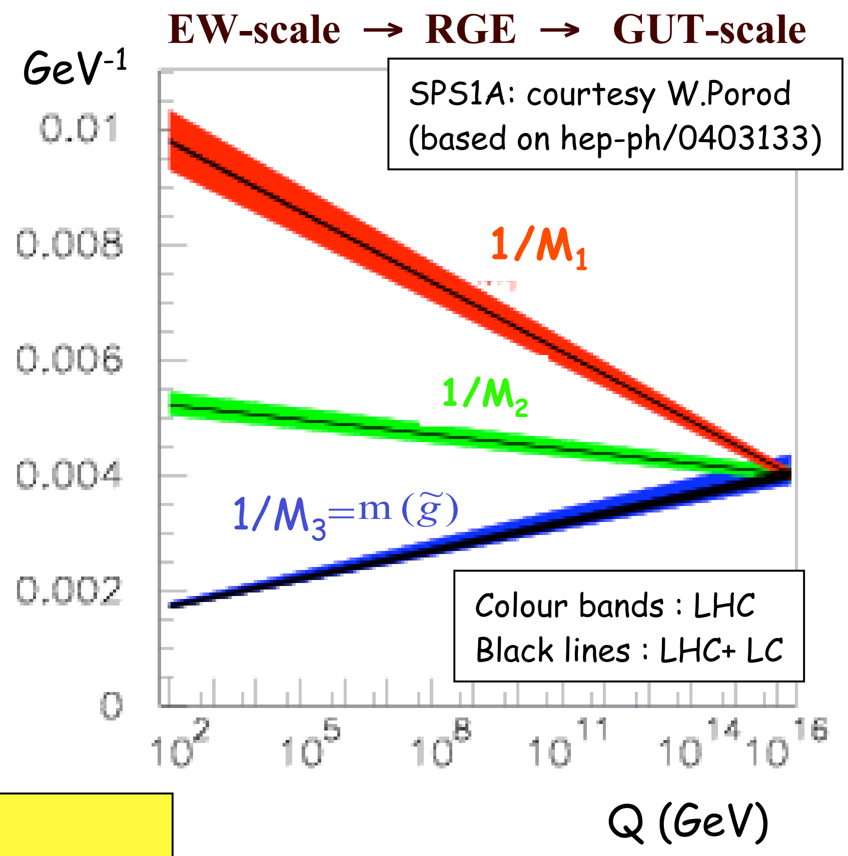
In general the LHC can (examples ...):

- 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

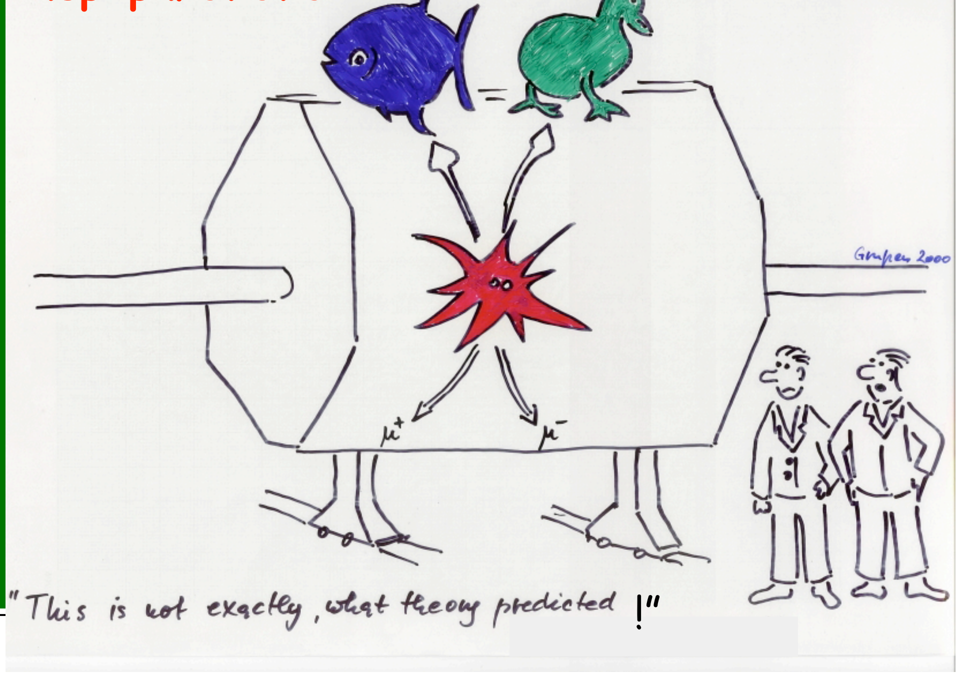


Ultimate goal : from precise measurements of e.g. gaugino masses at the TeV scale reconstruct high-E theory

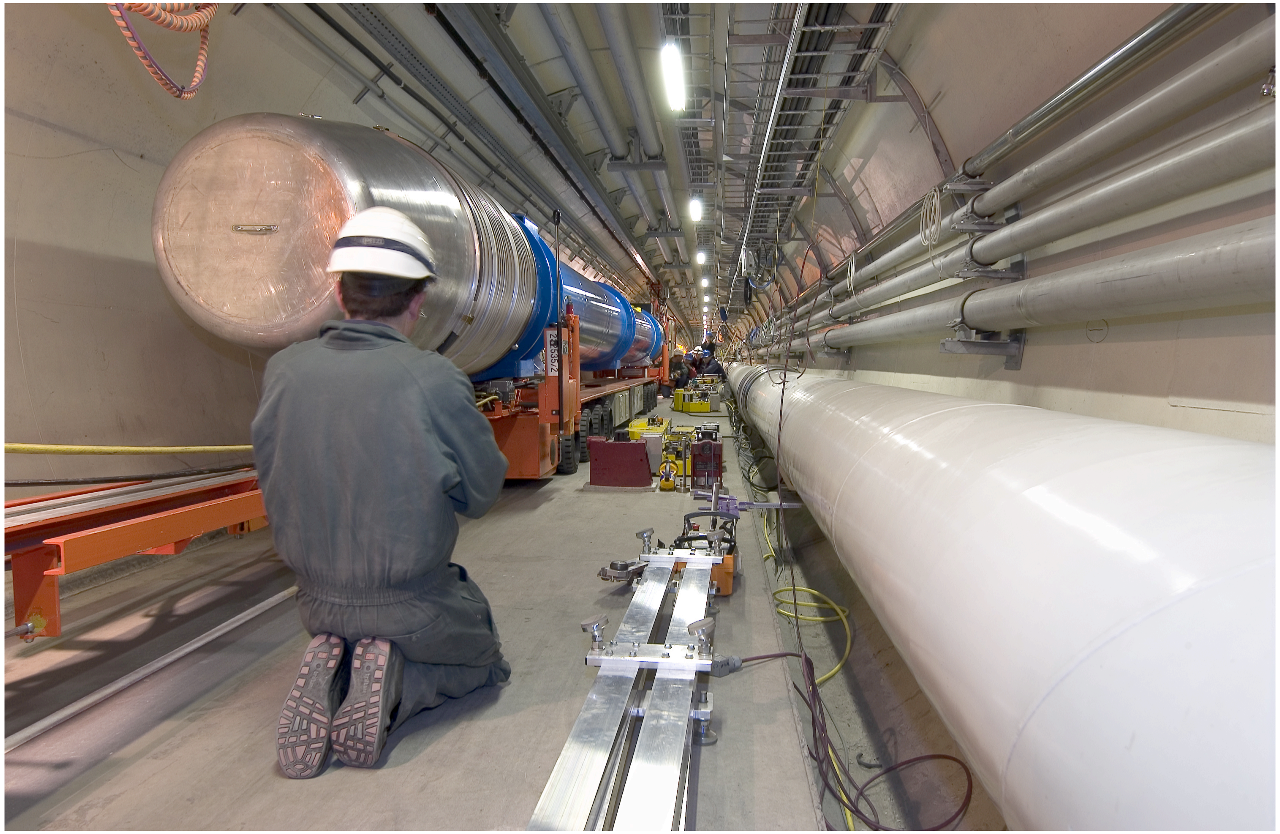
Conclusions

- 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

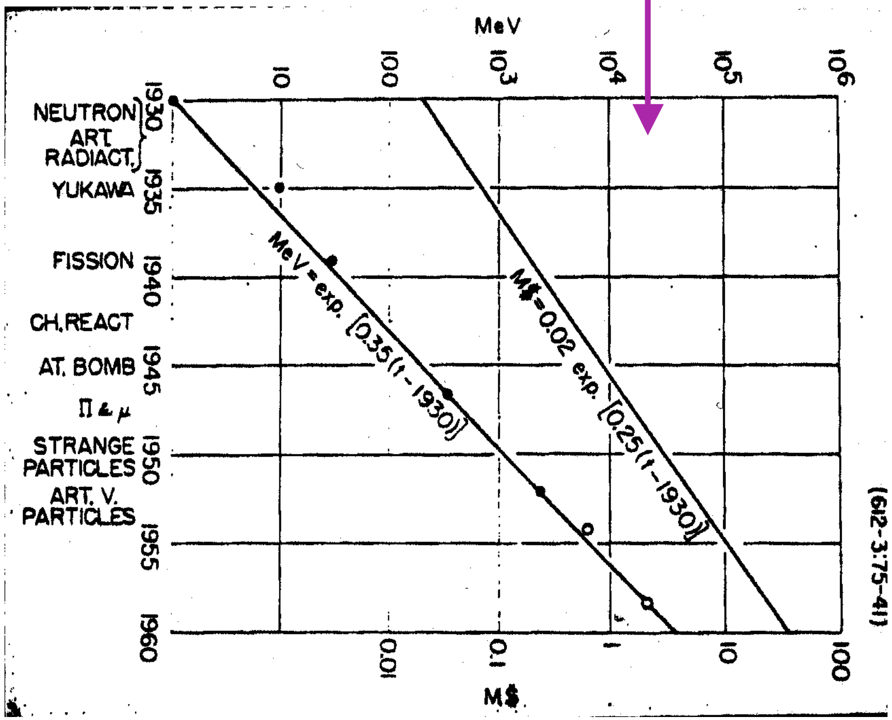
For these reasons....clamoring for higher and higher....

Slide 1 - MeV - M$ versus time.

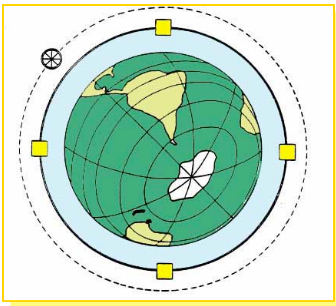
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss

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.....certainly look for multiple production...



Fermi's extrapolation to year 1994:
2T magnets, R=8000 Km machine
E_{beam} ~ $5x10^3$ TeV , cost 170 B$



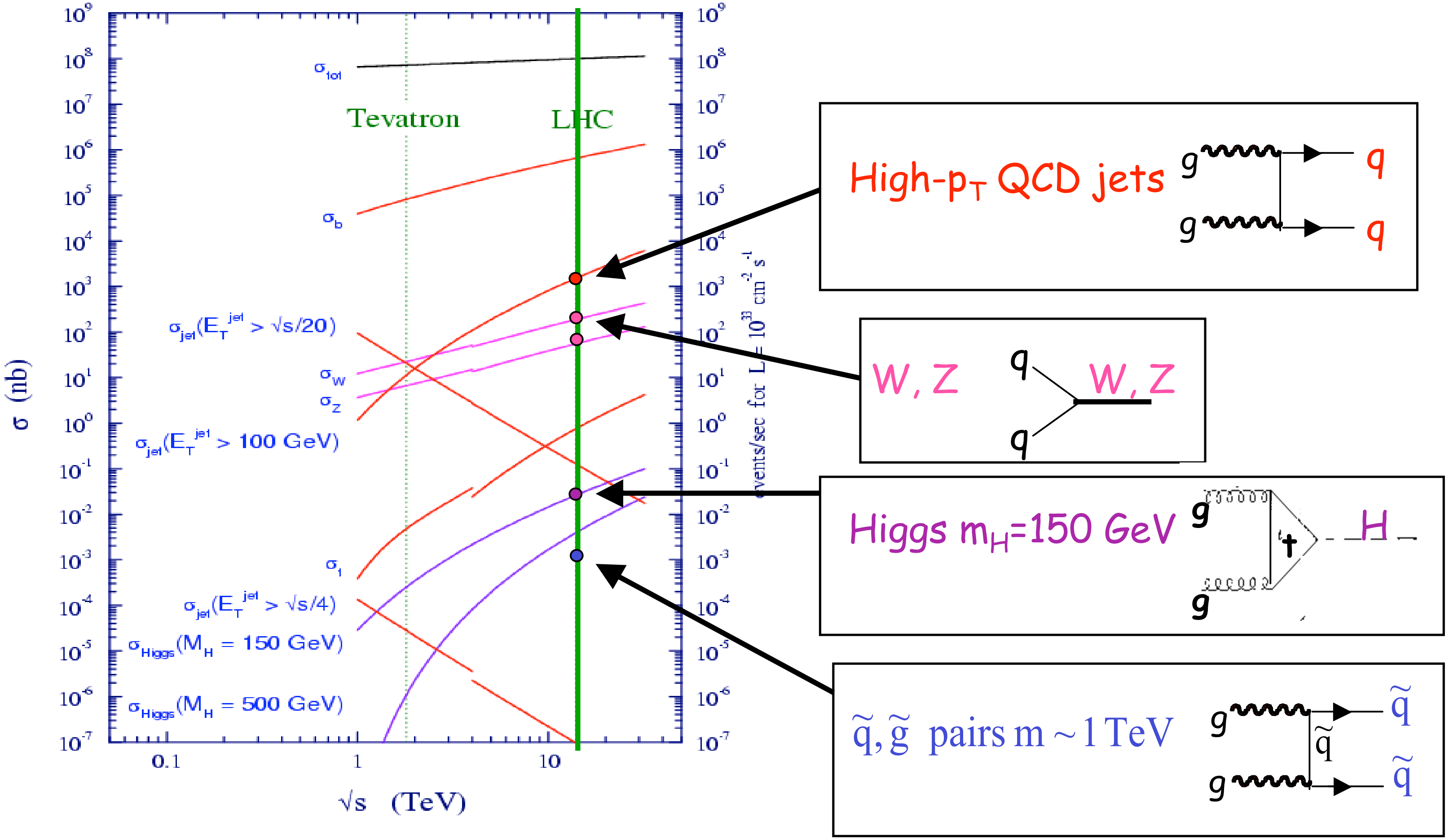
University of Chicago library
(thanks to M.Oreglia)

Many thanks to:

C. Collard, A. De Roeck, B. Gjelsten, K. Moening,
L. Pape, G. Polesello, W. Porod, D. Tovey

Back-up slides

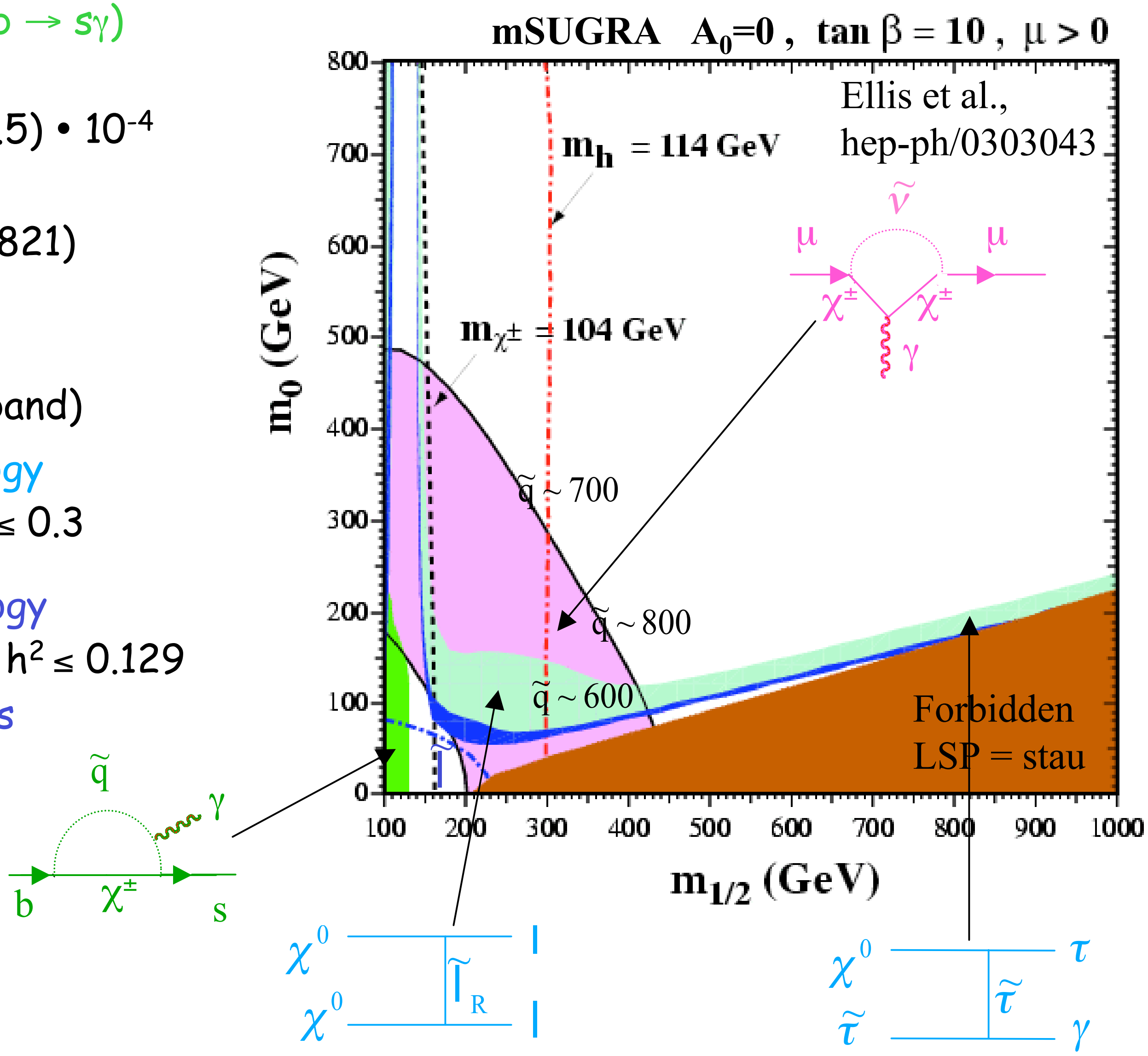
❸ Huge (QCD) backgrounds (consequence of high energy ..)



- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Fully-hadronic final states (e.g. q* → qg) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
- Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds
- Excellent particle identification: e.g. e/jet separation

Combining Collider searches with other constraints (cosmology, …)

- Disfavoured by BR ($b \rightarrow s\gamma$) from CLEO, BELLE $BR(b \rightarrow s\gamma) = (3.2 \pm 0.5) \cdot 10^{-4}$ used here
- Favoured by g_μ-2 (E821) assuming that $\delta\alpha_\mu = (26 \pm 10) \cdot 10^{-10}$ is from SUSY ($\pm$ 2 σ band)
- Favoured by cosmology assuming $0.1 \leq \Omega_\chi h^2 \leq 0.3$
- Favoured by cosmology assuming $0.094 \leq \Omega_\chi h^2 \leq 0.129$ i.e. new WMAP results



"bulk region"

"co-annihilation region"

Expected precision on mSUGRA parameters for six "LHC Points"

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	tgβ
1	400 ± 100 (25%)	400 ± 8 (2%)	2 ± 0.02 (1%)
2	400 ± 100 (25%)	400 ± 8 (2%)	10 ± 1.2 (12%)
3	200 ± 5 (2.5%)	100 ± 1 (1%)	2 ± 0.02 (1%)
4	800 ± 35 (4%)	200 ± 1.5 (0.8%)	10 ± 0.6 (6%)
5	100 ± 1.3 (1.3%)	300 ± 1.5 (0.5%)	2 ± 0.05 (2.5%)
6 tanβ = 45	218 ± 30, 242 ± 25 (~ 10%)	196± 8, 194 ± 6 (3.5%)	44 ± 1.1, 45± 1.7 (~ 3%)

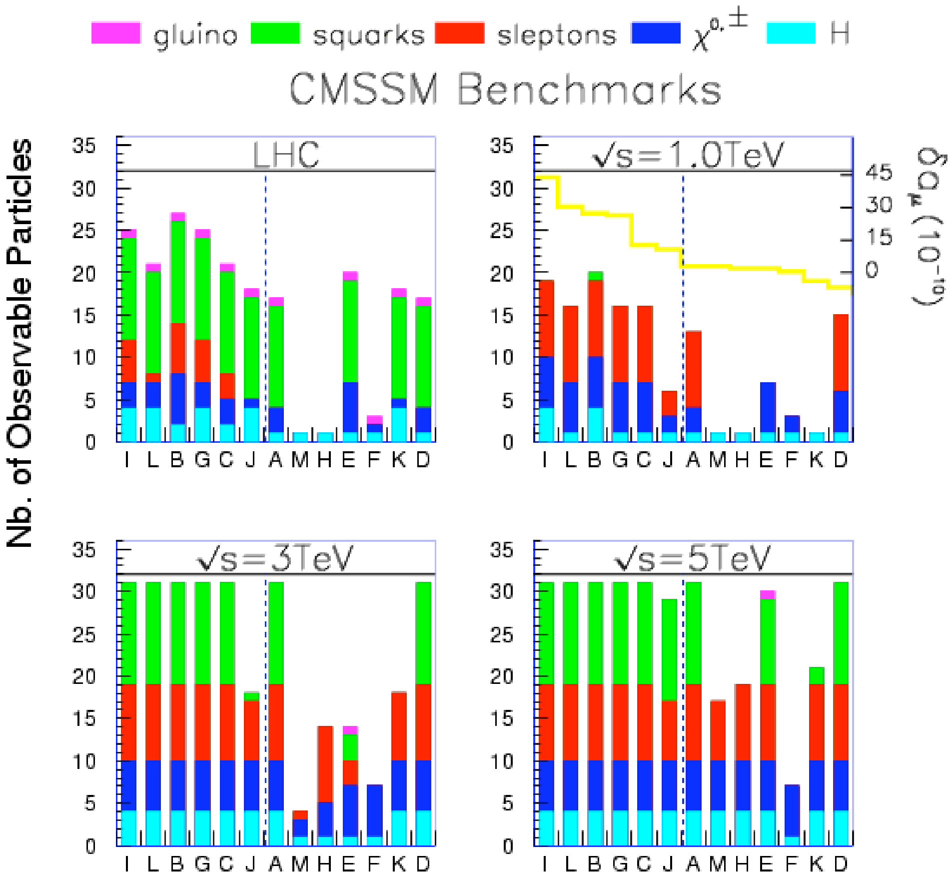
ATLAS
300 fb^{-1}

sign μ determined except Point 6

A_0 ~ unconstrained except Point 6

μ = +, -

Complementarity between LHC and future e^+e^- Colliders



In general :

- LHC most powerful for $\tilde{q}$ and $\tilde{g}$ (strongly interacting) but can miss some EW sparticles (gauginos, sleptons) and Higgs bosons

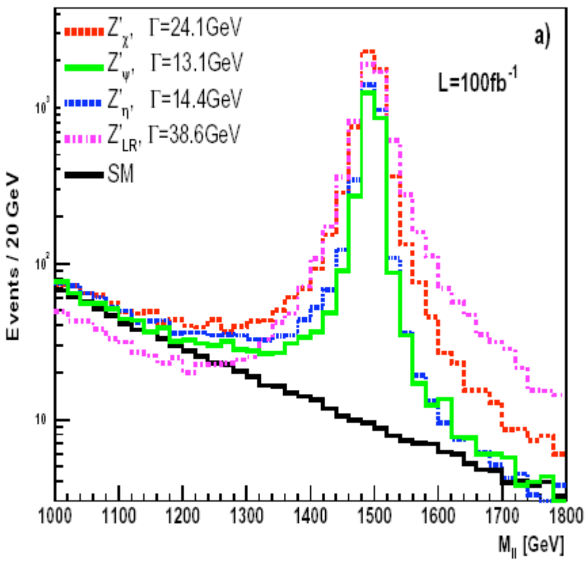
- Depending on √s, LC should cover part/all EW spectrum (usually lighter than squarks/gluinos) → should fill holes in LHC spectrum. Squarks could also be accessible if √s large enough.

LC can perform precise measurements of masses (to ~ 0.1%), couplings, field content of sparticles with mass up to ~ √s/2, disentangle squark flavour, etc. (see lectures by M. Battaglia)

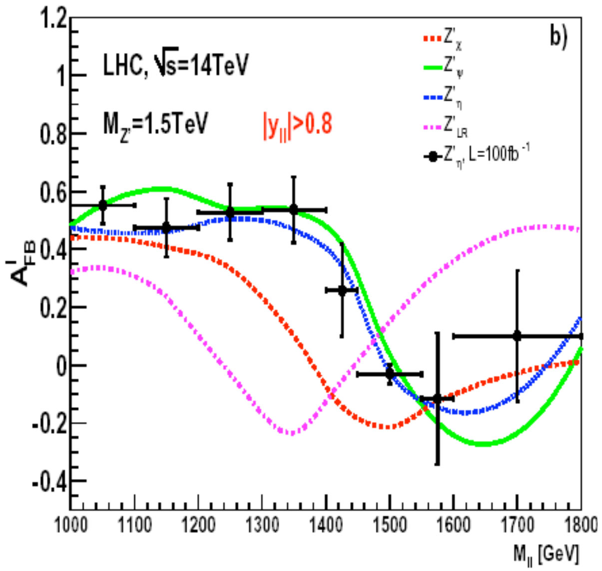
Extended gauge groups : Z' → l^+l^-

CMS

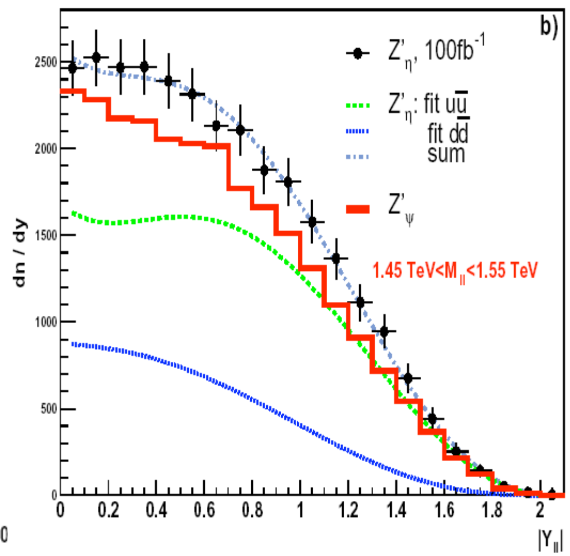
Dilepton invariant mass spectrum



Forward backward asymmetry measurement



Rapidity distribution



- Reach in 1 year at 10^{34} : 4-5 TeV
- Discriminating between models possible up to m ~ 2.5 TeV by measuring:
  - -- $\sigma \times \Gamma$ of resonance
  - -- lepton F-B asymmetry
  - -- Z' rapidity

-- HLT/DAQ deferrals limit available networking and computing for HLT → limit LVL1 output rate

-- Large uncertainties on LVL1 affordable rate vs money (component cost, software performance, etc.)

Selections (examples ...) Real thresholds set for 95% efficiency at these E_T	LVL1 rate (kHz) L= 1 x 10^{33} no deferrals	LVL1 rate (kHz) L= 2 x 10^{33} no deferrals	LVL1 rate (kHz) L= 2 x 10^{33} with deferrals An example for illustration...
MU6,8,20	23	→ 19	→ 0.8
2MU6	---	0.2	0.2
EM20i,25,25	11	→ 12	→ 12
2EM15i,15,15	2	4	4
J180,200,200	0.2	0.2	0.2
3J75,90,90	0.2	0.2	0.2
4J55,65,65	0.2	0.2	0.2
J50+xE50,60,60	0.4	0.4	0.4
TAU20,25,25 +xE30	2	2	2
MU10+EM15i	---	0.1	0.1
Others (pre-scaled, etc.)	5	5	5
Total	~ 44	~ 43	~ 25

LVL1 designed for 75 kHz
→ room for factor ~ 2 safety

Likely max affordable rate,
no room for safety factor

❸ Which data samples ?

Total trigger rate to storage at 2 x 10^{33} reduced from ~ 540 Hz (HLT/DAQ TP, 2000) to ~ 200 Hz (now)

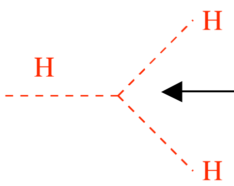
High-Level-Trigger output

⬇

Selection (examples …)	Rate to storage at 2×10^{33} (Hz)	Physics motivations (example
e25i, 2e15i μ20i, 2μ10	~ 40 (55% W/b/c → eX) ~ 40 (85% W/b/c → μX)	Low-mass Higgs (ttH, H→ 4λ, qc W, Z, top, New Physics ?
γ60i, 2γ20i	~ 40 (57% prompt γ)	H → γγ, New Physics (e.g. X → γ yy m_X~ 500 GeV
j400, 3j165, 4j110	~ 25	Overlap with Tevatron for new X → jj in danger …
j70 + xE70	~ 20	SUSY : ~ 400 GeV squarks/glu
τ35 + xE45	~ 5	MSSM Higgs, New Physics (3rd family !) ? More difficult
2μ6 (+ m_B)	~ 10	Rare decays B → μμX
Others (pre-scaled, exclusive, …)	~ 20	Only 10% of total !
Total	~ 200	No safety factor included. "Signal" (W, γ, etc.) : ~ 100 H

Best use of spare capacity when L < 2 x 10^{33} being investigated

Can the LHC measure the Higgs self-coupling λ ?

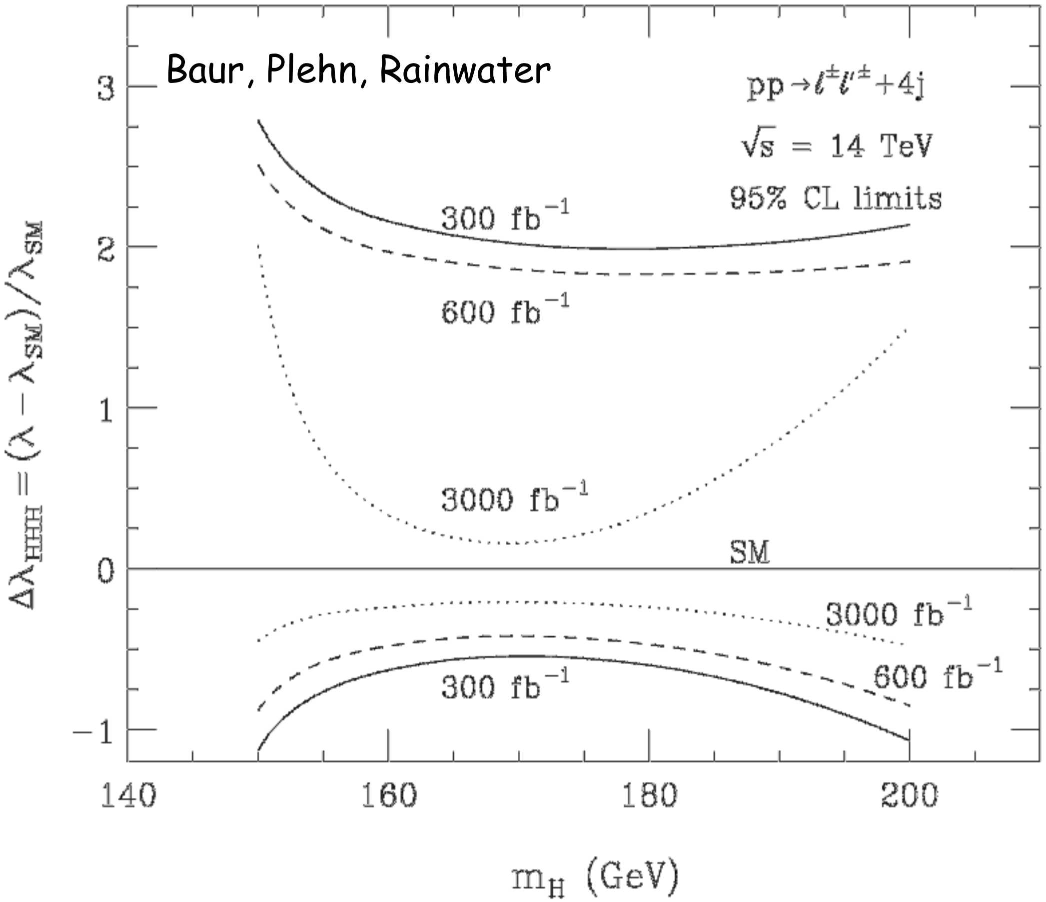


$\sim \lambda v$

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

$HH \rightarrow W^+ W^- W^+ W^- \rightarrow l^\pm \nu \; jj \; l^\pm \nu \; jj$

Higgs pair production is rate-limited at the LHC, but should be accessible with a luminosity upgrade to 10^{35} (expected in ~ 2013)

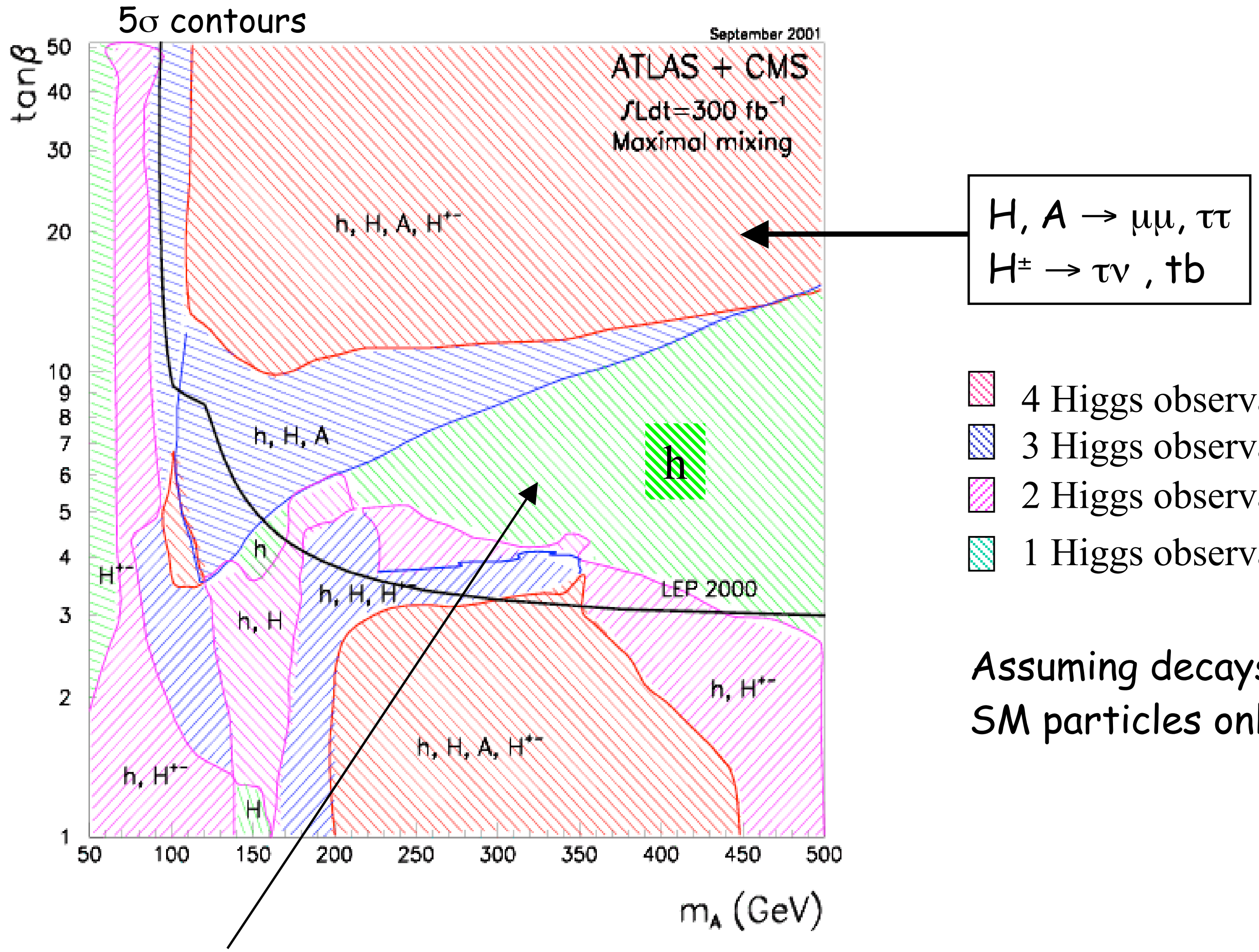


LHC: $\lambda = 0$ may be excluded at 95% CL.

SLHC: λ may be determined to 20-30% (95% CL)

SUSY Higgs sector : h, H, A, $H^\pm$

$m_h < 135$ GeV , $m_A \approx m_H \approx m_{H\pm}$



- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

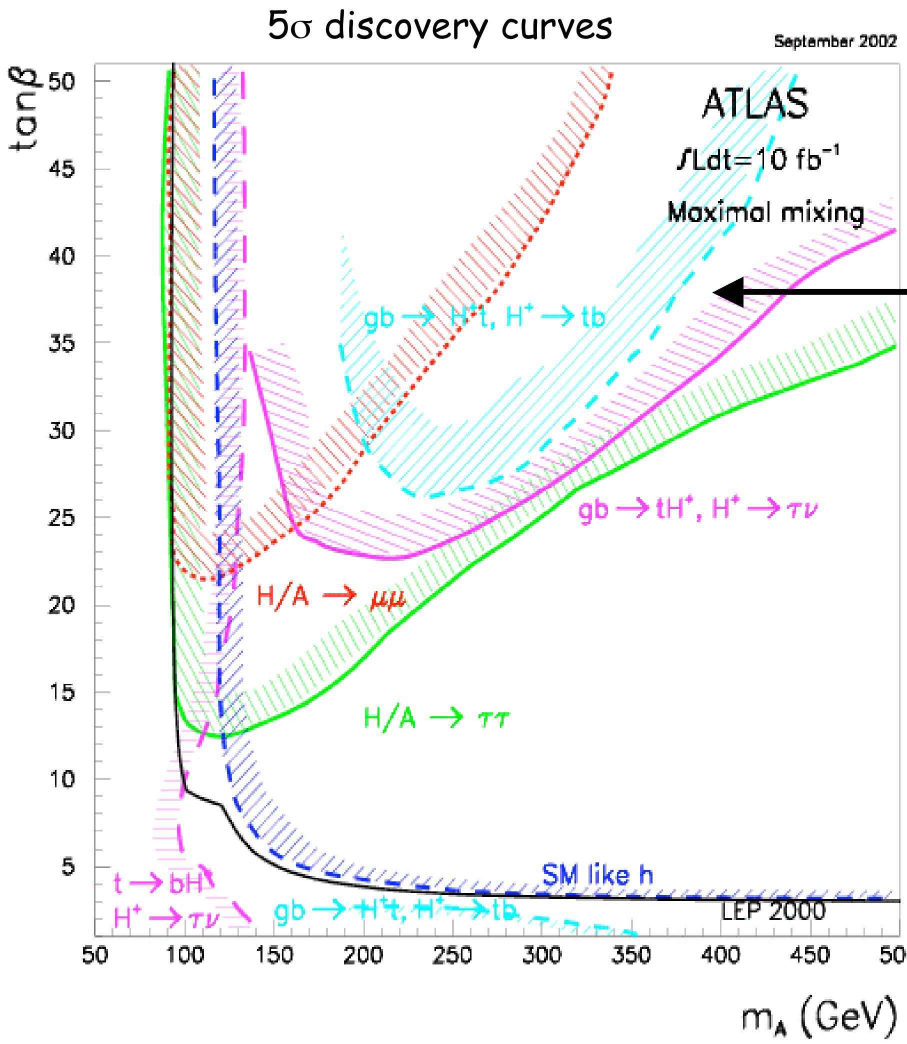
Assuming decays to SM particles only

Here only h (SM - like) observable at LHC, unless A, H, $H^\pm \rightarrow$ SUSY

$\rightarrow$ LHC may miss part of the MSSM Higgs spectrum

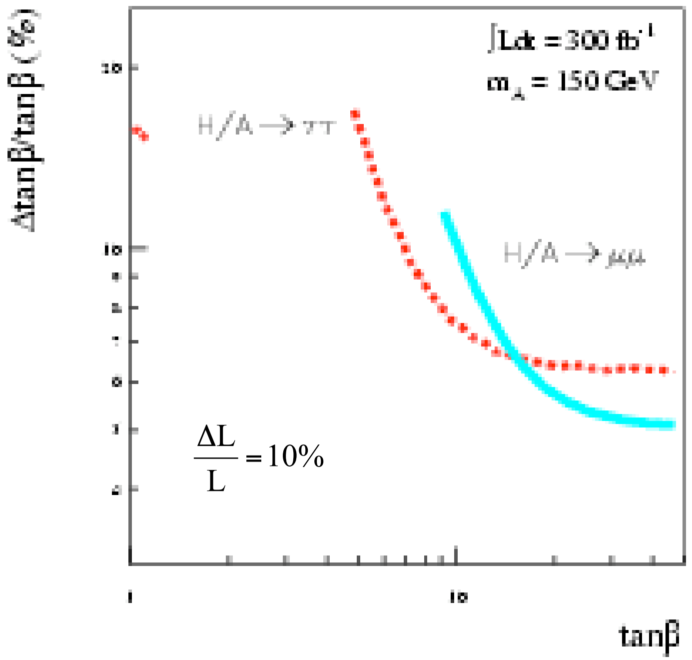
Observation of full spectrum may require high-E ($\sqrt{s} \approx 2$ TeV) Lepton Collider

Most of MSSM Higgs plane already covered after 1 year of data taking …

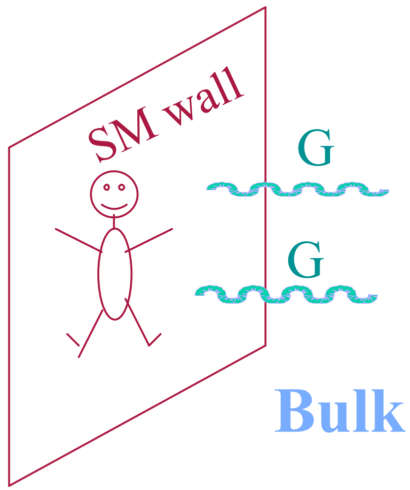


A, H, H± cross-section ~ $tg^2\beta$

Measurement of tg β



Large variety of channels and signatures accessible



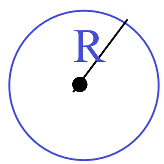
Arkani-Hamed, Dimopoulos, Dvali

If gravity propagates
in $4 + \delta$ dimensions,
a gravity scale **$M_D \approx 1$ TeV** is possible

$$\left.\begin{aligned} V_4(r) &\sim \frac{1}{M_{Pl}^2}\frac{1}{r} \\ V_{4+\delta}(r) &\sim \frac{1}{M_D^{\delta+2} R^\delta}\frac{1}{r} \end{aligned}\right\} \text{ at large distance} \Rightarrow \boxed{M_{Pl}^2 \approx M_D^{\delta+2} R^\delta}$$

- If $M_D \approx 1$ TeV :
  $\delta = 1 \quad R \approx 10^{13}$ m $\rightarrow$ excluded by macroscopic gravity
  $\delta = 2 \quad R \approx 0.7$ mm $\rightarrow$ limit of small- scale gravity experiments
  ....
  $\delta = 7 \quad R \approx 1$ Fm

$\Rightarrow$ Extra-dimensions are compactified over $R <$ mm

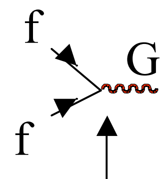


- Gravitons in Extra-dimensions get quantised mass:

$$m_k \sim \frac{k}{R} \qquad k = 1, \ldots \infty$$

$$\Delta m \sim \frac{1}{R} \qquad \text{e.g. } \Delta m \approx 400 \text{ eV} \quad \delta = 3$$

→ continuous tower of massive gravitons (Kaluza - Klein excitations)

$$\sigma \Bigg[$$


$$\Bigg] \approx \frac{1}{M_{Pl}^2} N_{kk} \approx \frac{1}{M_{Pl}^2}\left(\frac{\sqrt{s}}{\Delta m}\right)^{\delta} \approx \frac{1}{M_{Pl}^2}\sqrt{s}^{\,\delta} R^{\delta} \approx \boxed{\frac{\sqrt{s}^{\,\delta}}{M_D^{\delta+2}}}$$

Due to the large number of G_{kk}, the coupling SM particles - Gravitons becomes of EW strength

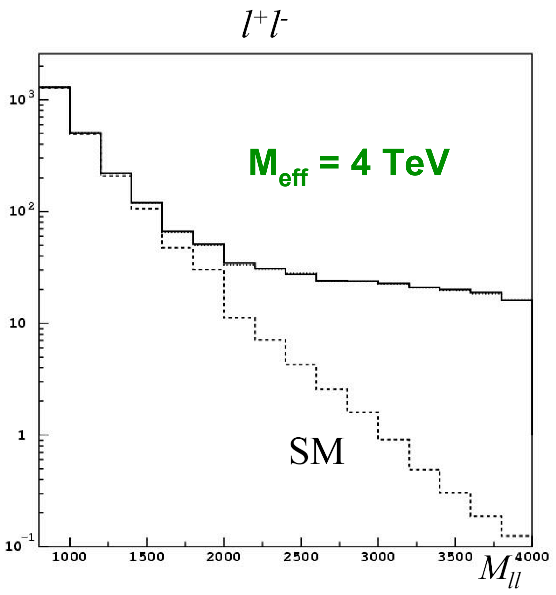
➡
- Only one scale in particle physics : EW scale
- Can test geometry of universe and quantum gravity in the lab

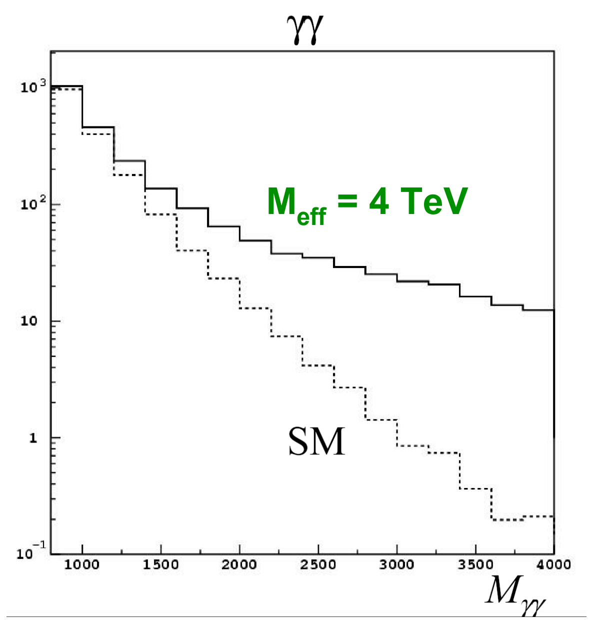
Large Extra Dimensions

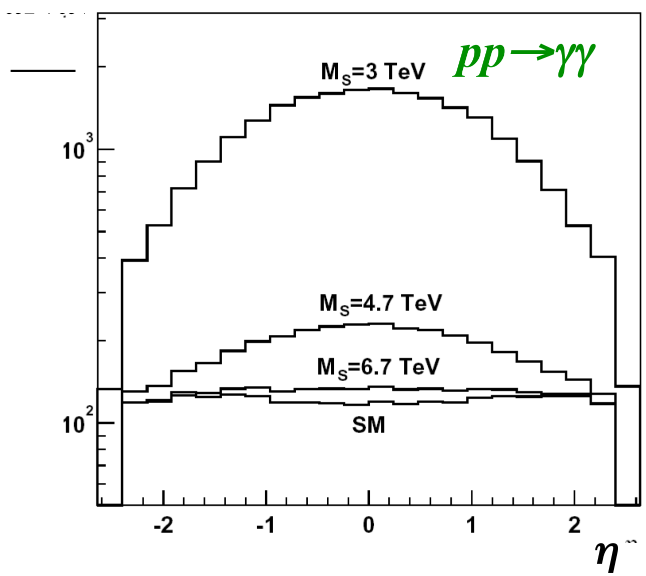
Virtual Exchange of Kaluza-Klein Gravitons

Signatures: qq,gg → γγ, ll, (WW, tt, …)

- excess over DY events in di-lepton, di-photon mass distributions
- some s-channel processes not present at tree-level in SM:
  - ➔ more central production for γγ





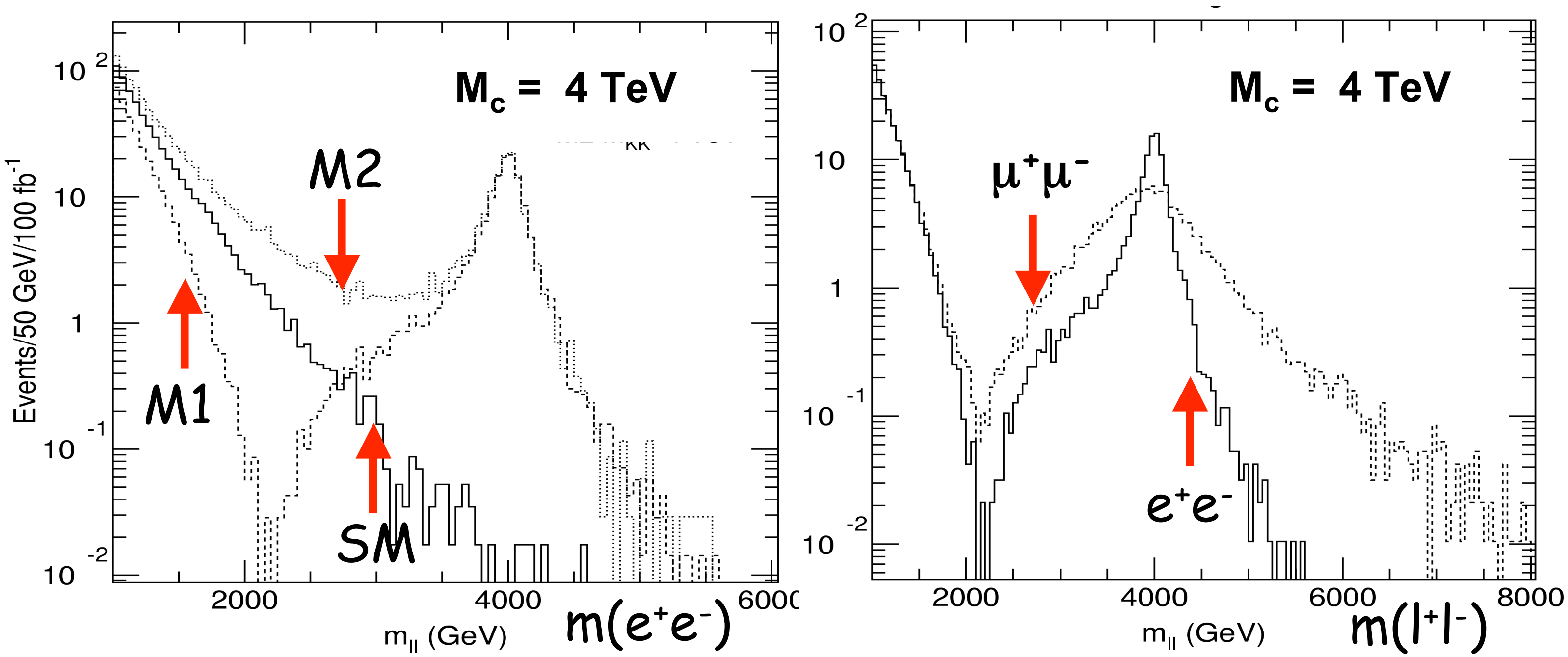


TeV^{-1}-sized Extra Dimensions

$\gamma^{(1)}/Z^{(1)}$ Kaluza-Klein Gauge Bosons

Signatures: $\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^-, \mu^+\mu^-$

- 2 TeV electron in ATLAS: $\Delta E/E \sim 0.7$ % (~20 % for a muon)
- acceptance for leptons: $|\eta| < 2.5$

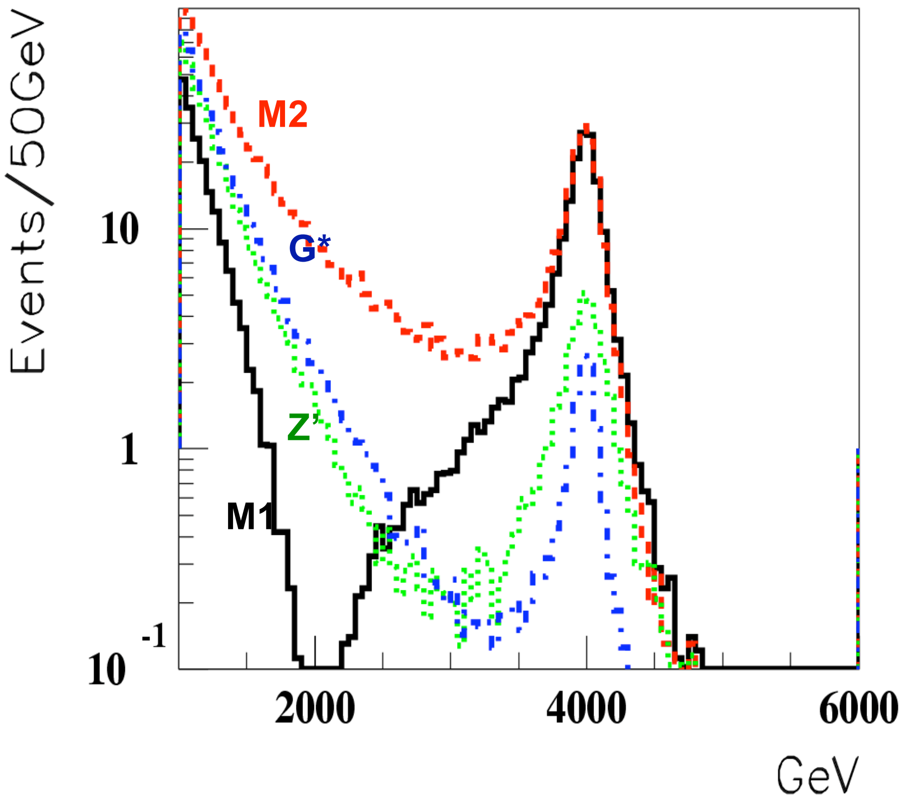


TeV^{-1}-sized Extra Dimensions

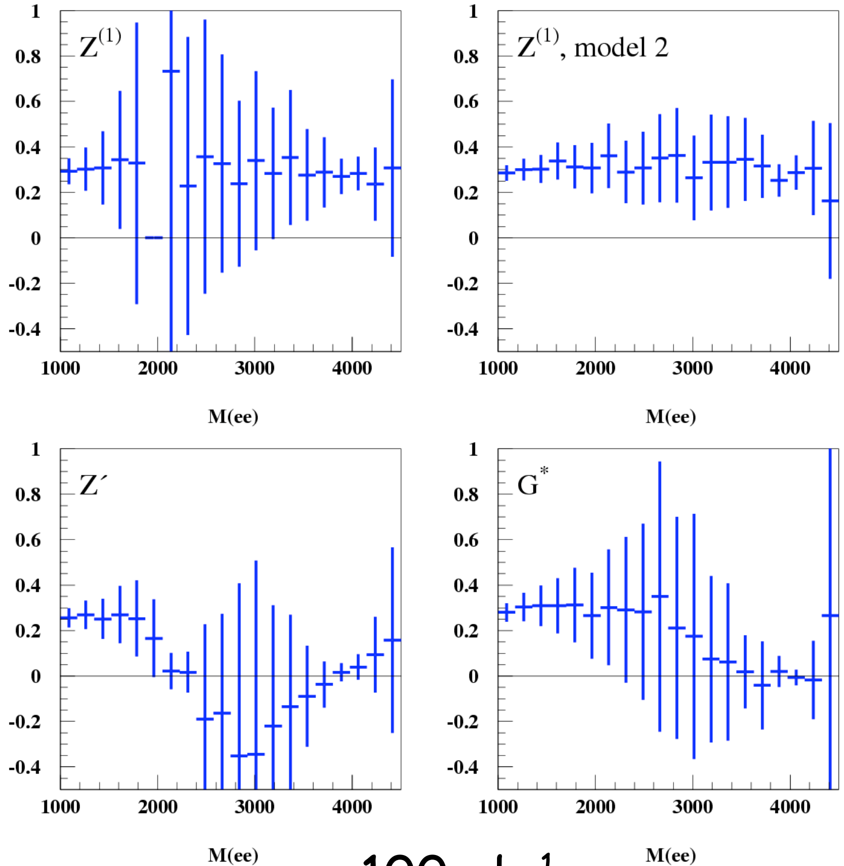
$\gamma^{(1)}/Z^{(1)}$ Kaluza-Klein Gauge Bosons

Characterization of the model:

$Z^{(1)}$ or Z ' or RS graviton ??



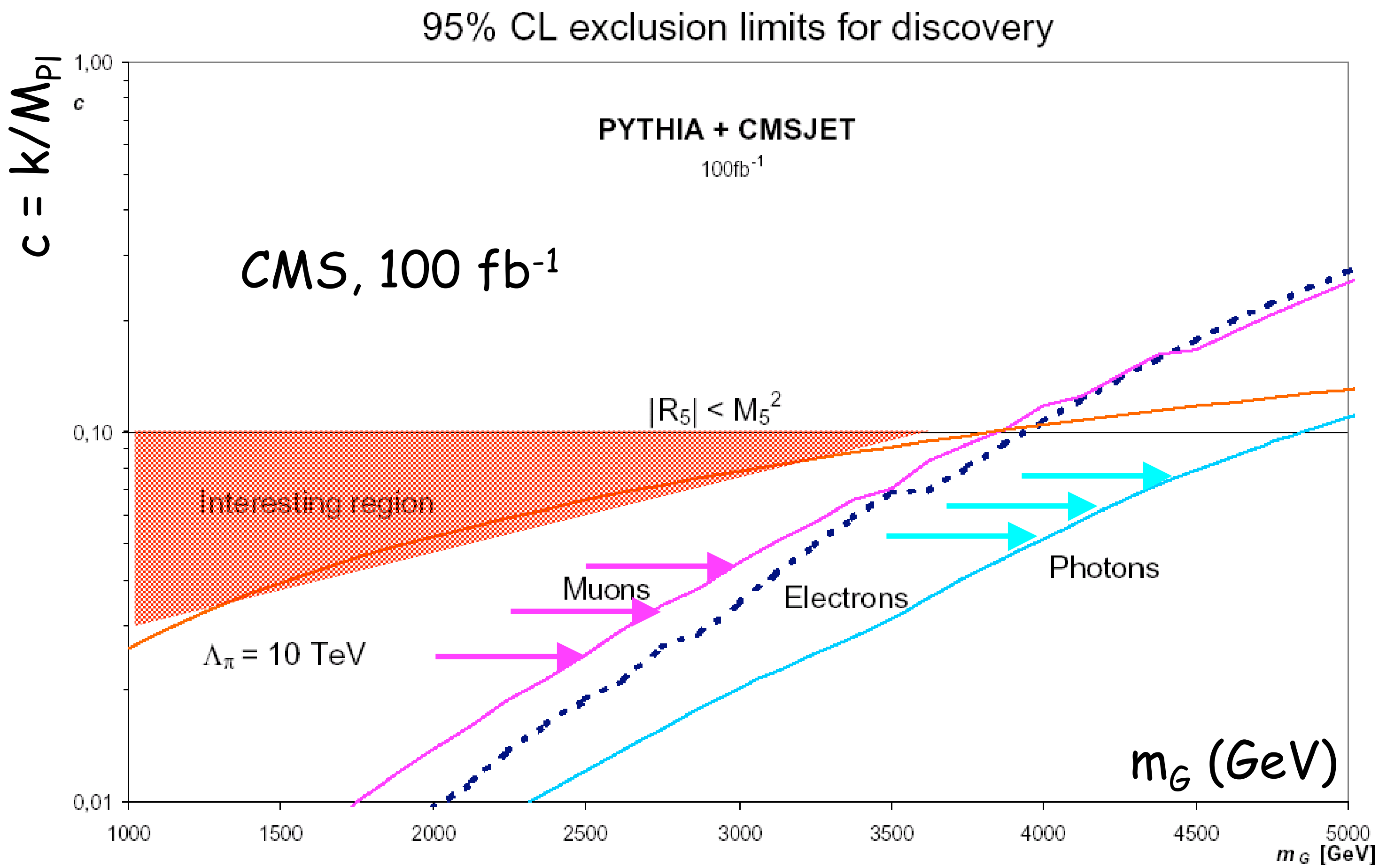
Forward-backward asymetries:



100 pb^{-1}

Warped Extra Dimension

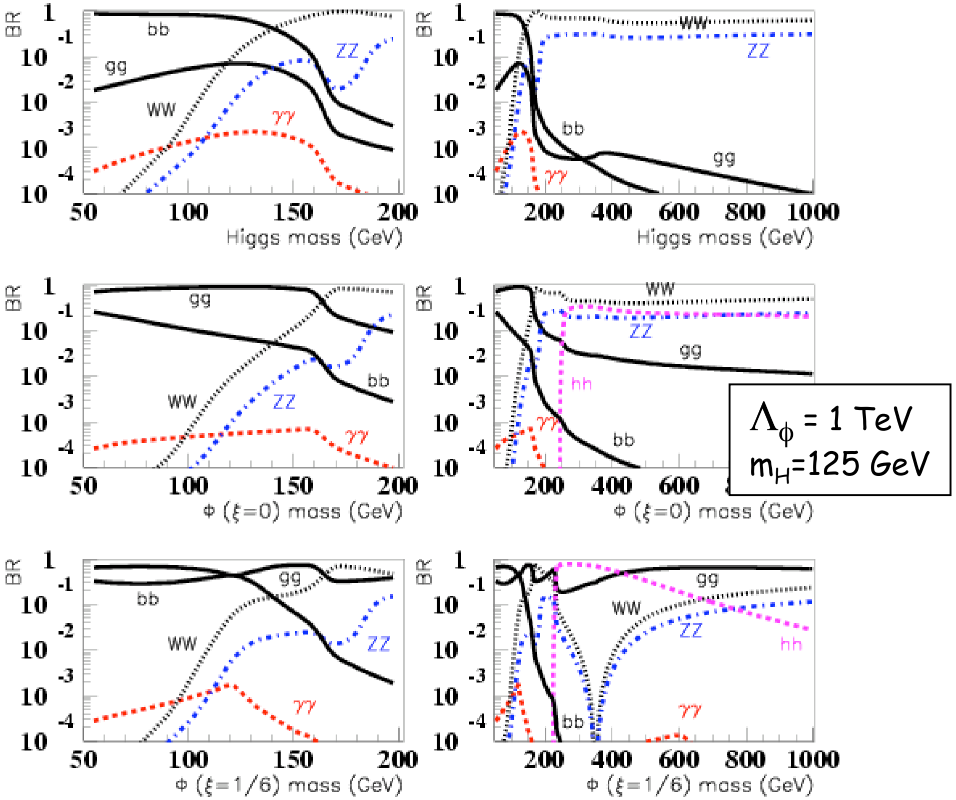
Randall-Sundrum model: KK graviton narrow resonance



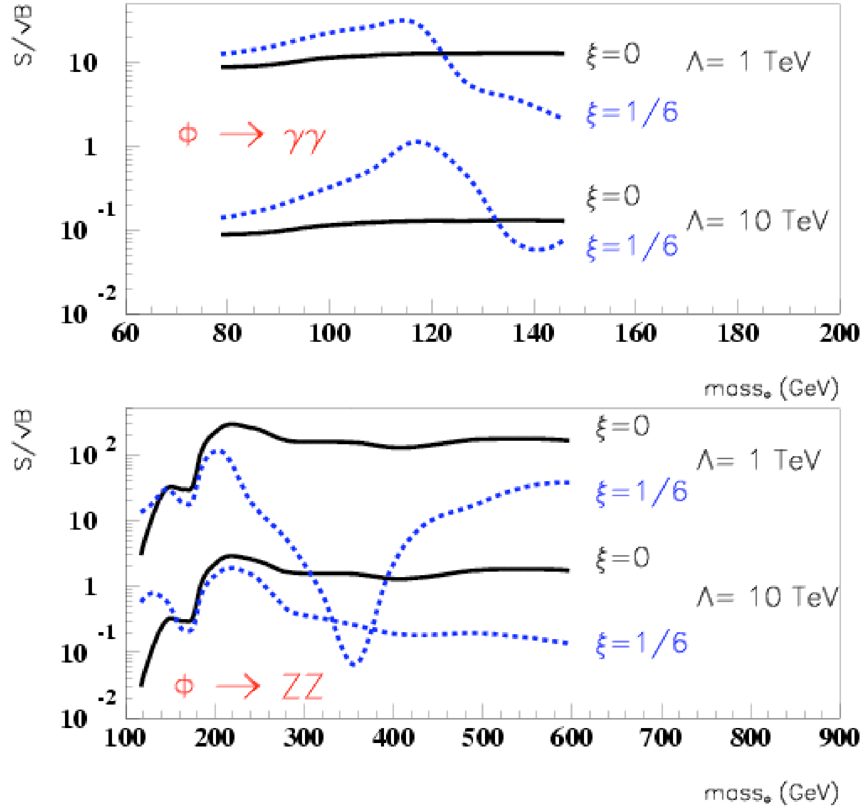
➔ LHC covers completely the interesting region

Search for the Radion

- Scalar field which stabilises the size of the extra-dimension
- Parameters : radion mass (m_ϕ), radion vev (Λ_ϕ), h-ϕ mixing (ξ)



Azuelos et al.



- Similar couplings as SM Higgs but with different strenghts (ϕgg enhanced, ϕWW/ZZ suppressed in some cases); $\phi \rightarrow$ hh important if open. $\Gamma_\phi \ll \Gamma_H$
- Precise measurements of couplings needed to disentangle ϕ / H. LHC : 10-20%. More work needed here …
- Impact on cosmological constant ? $\rho_{radion} \sim M_D^8/M_P^4 \approx \rho_\Lambda$

Mini black holes production at LHC ?

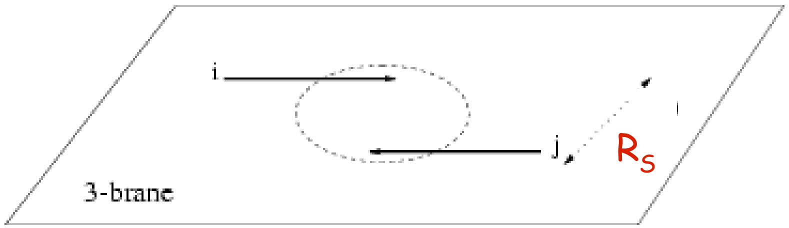
… quite speculative for the time being … many big theoretical uncertainties

- Schwarzschild radius (i.e. within which nothing escapes gravitational force):

4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2} \frac{M_{BH}}{c^2}$

4 + δ-dim., $M_{gravity} = M_D \sim$ TeV : $R_S \sim \frac{1}{M_D} \left(\frac{M_{BH}}{M_D} \right)^{\frac{1}{\delta+1}}$

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S

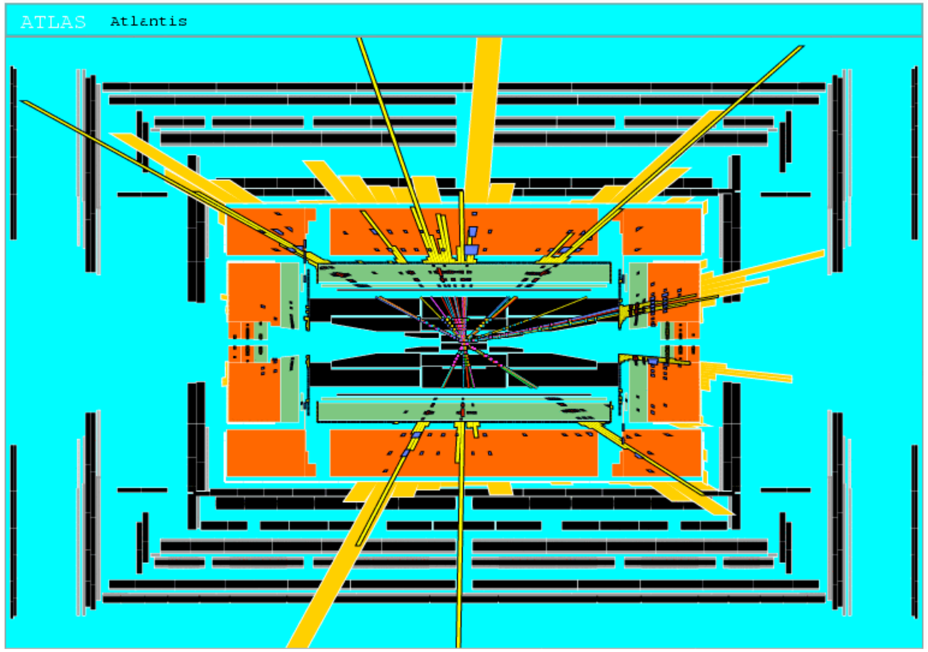


- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S^2$

e.g. for $M_D \sim 1$ TeV expected rate is ~ 1 Hz !

- Black holes decay immediately ($\tau \sim 10^{-26}$ s) by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

  } expected signature (quite spectacular …)



A black hole event with $M_{BH} \sim 8$ TeV in ATLAS

From preliminary studies : reach is $M_D \sim 4$ TeV for any δ in one year at high luminosity.

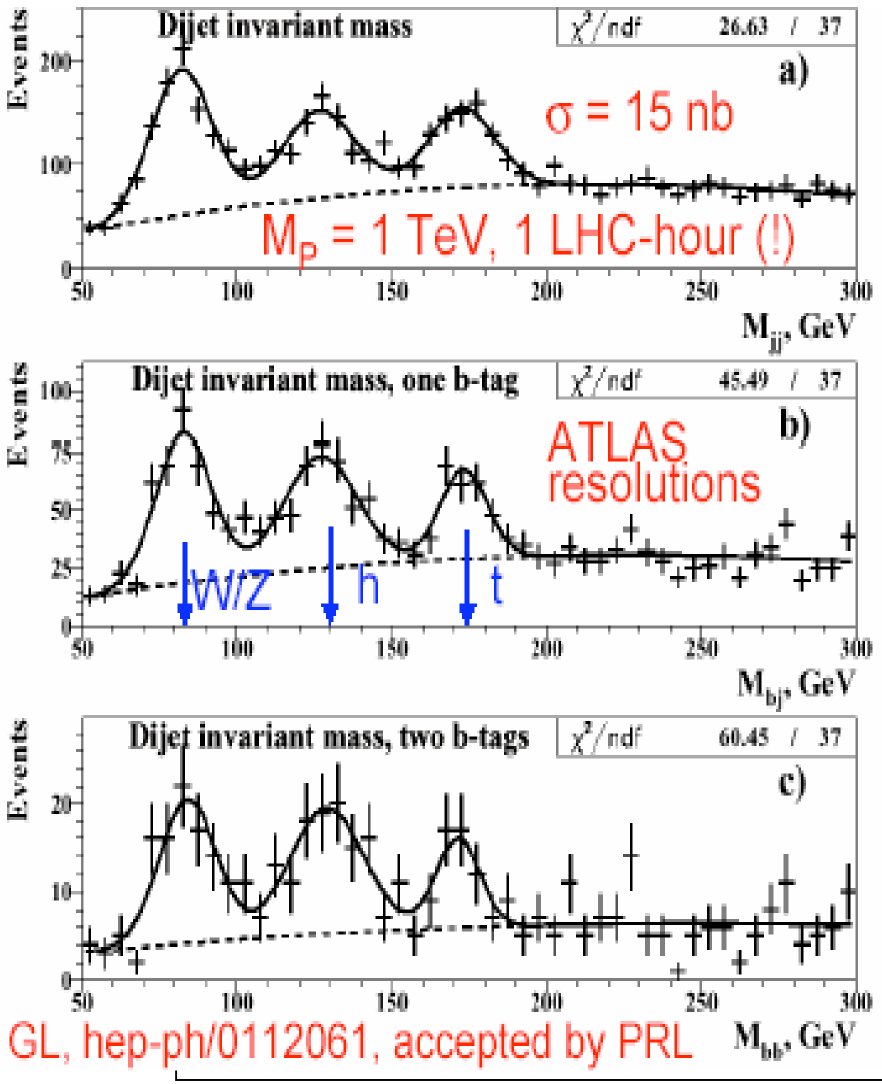
By testing Hawking formula → proof that it is BH + measurement of δ

$$\log T_H = -\frac{1}{\delta+1}\log M_{BH} + f(M_D, \delta)$$

precise measurements of M_{BH} and T_H needed
(T_H from lepton and photon spectra)
M_D from cross-section

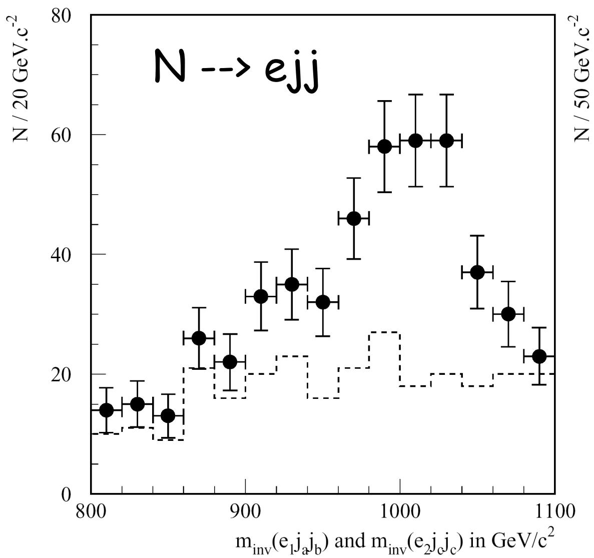
Note: mini-BH should also be produced by ultra-high-energy cosmic neutrinos and observed by Auger (Feng and Shapere, hep-ph/0109106)

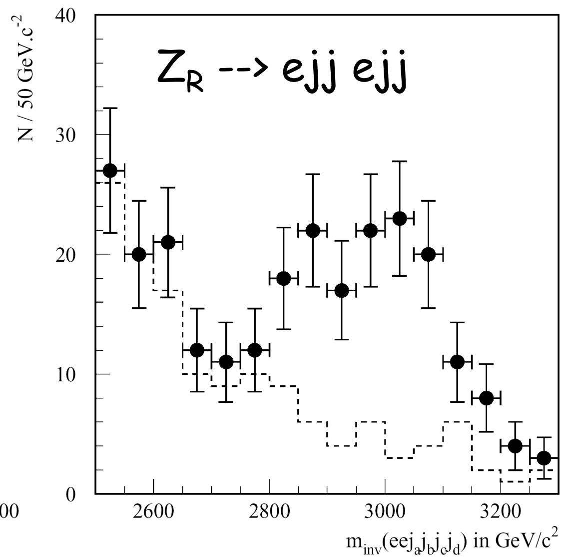
Higgs production in black hole decays



Higgs of mass 130 GeV may be discovered in
one hour (M_P= 1 TeV)
one day (M_P= 2 TeV)
one month (M_P= 3 TeV)
one year (M_P= 4 TeV)
at 10^{34}

pp--> Z_R --> N_l N_l --> ljj ljj





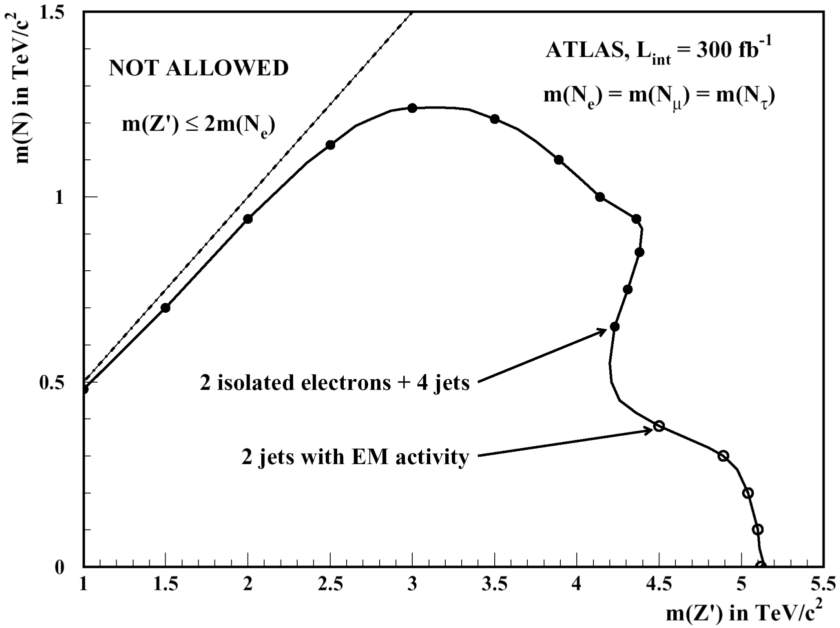
backgrounds:

t tbar

DY, WW, ZW, ZZ

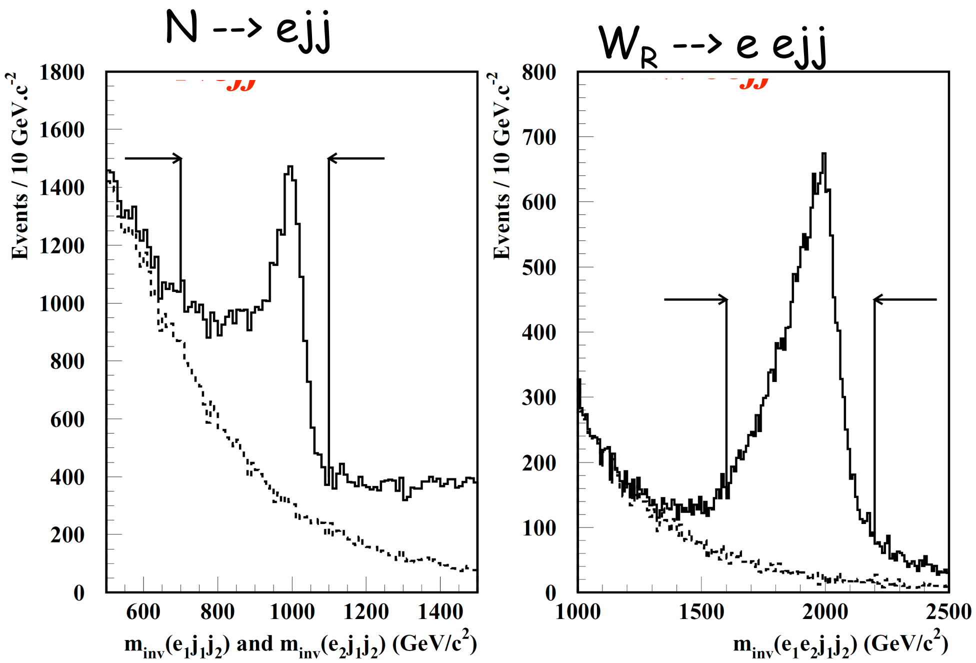
LRSM bckg: W_R,…

⇒ cuts on m_{ee}, pT(jets)



FB asymmetry gives a measure of $\kappa = g_R/g_L$

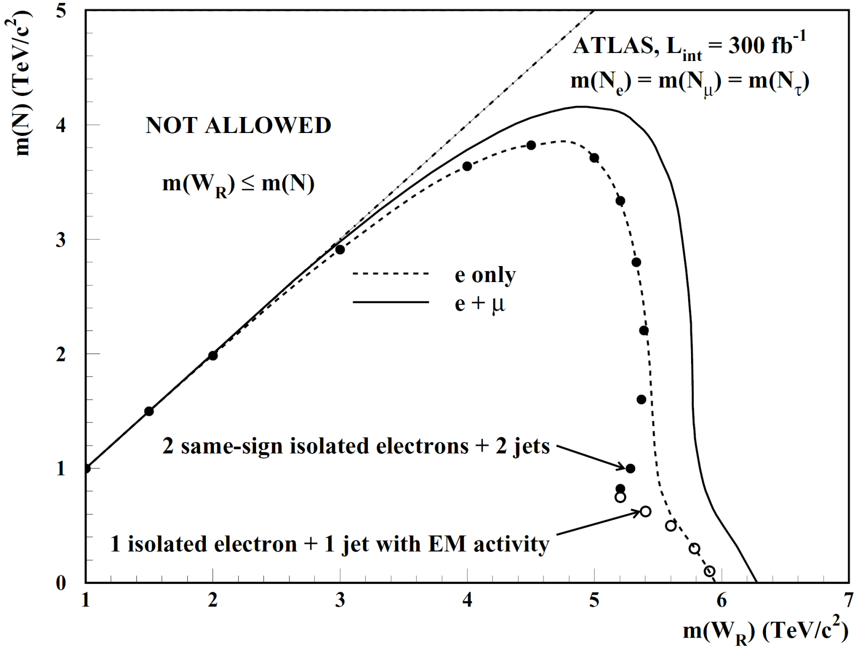
pp--> W_R --> l N_l --> l ljj



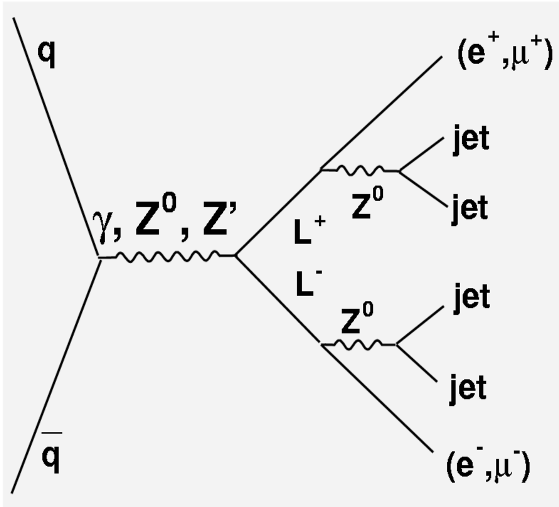
backgrounds:

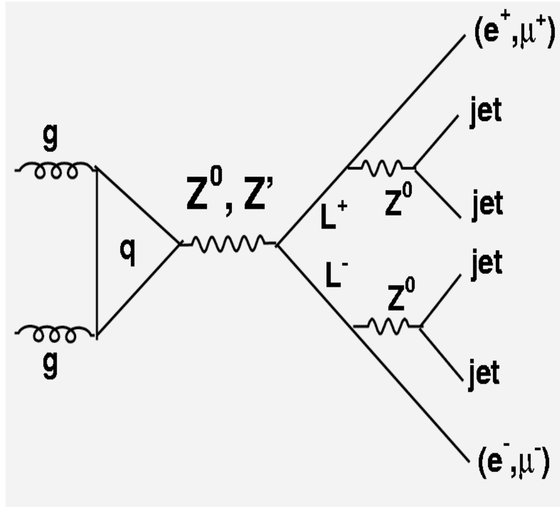
t tbar

DY, WW, ZW, ZZ



Heavy leptons





backgrounds:
ttbar, WW, WZ, ZZ

also:
6-lepton channel

Experimental considerations:
- **high energy leptons, jets**

Systematics:
- **large NLO corrections**

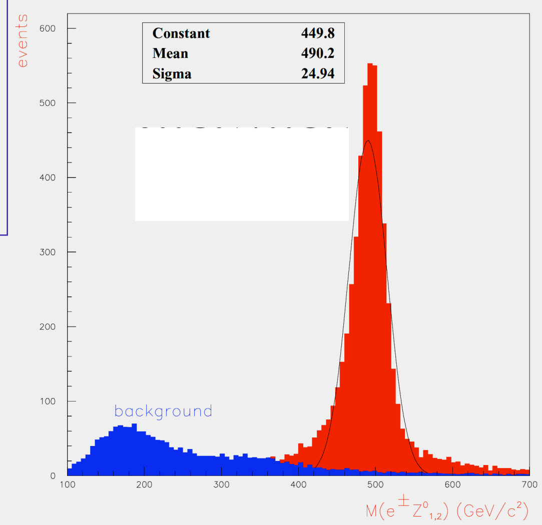
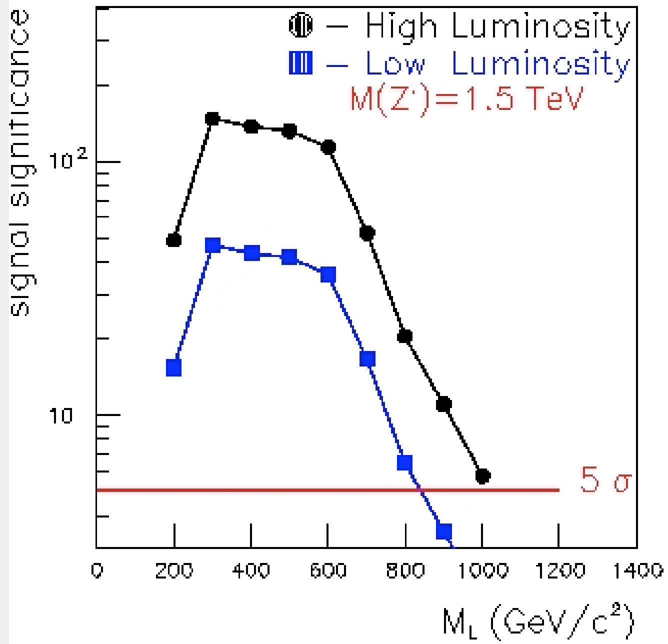


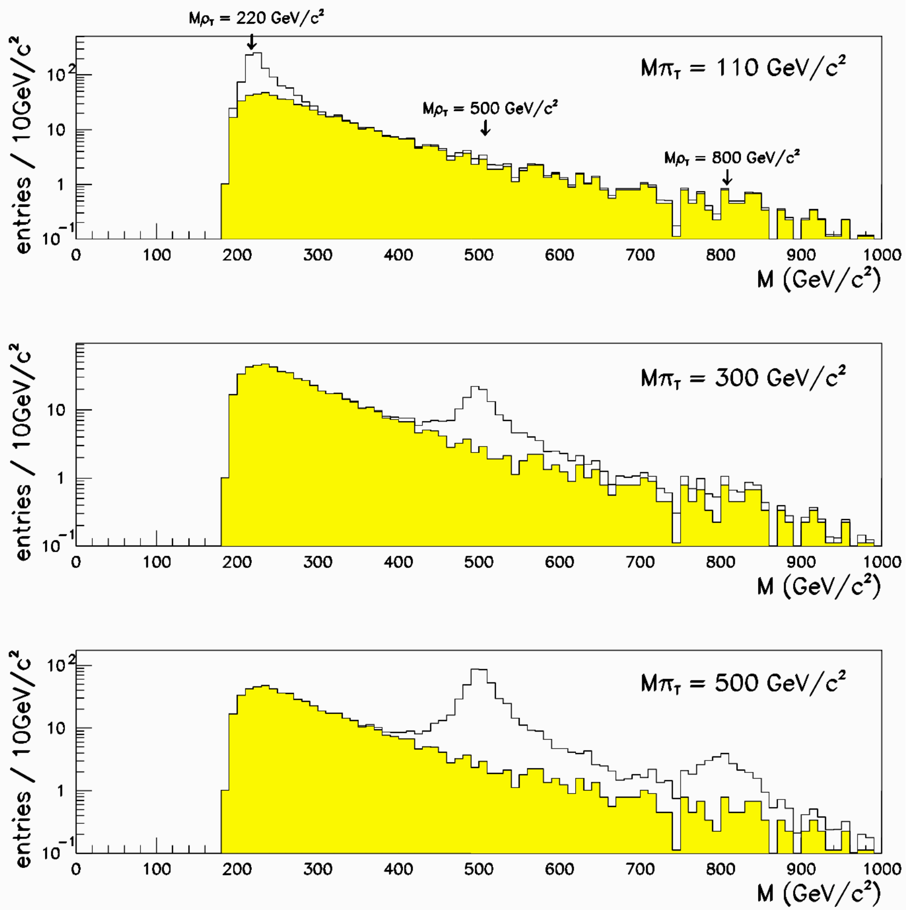
Figure 13: Signal to background comparison for $M_L = 0.5\ TeV/c^2$ and $M_{Z'} = 0.7\ TeV/c^2$, for $L \to e + Z^0$ channel.

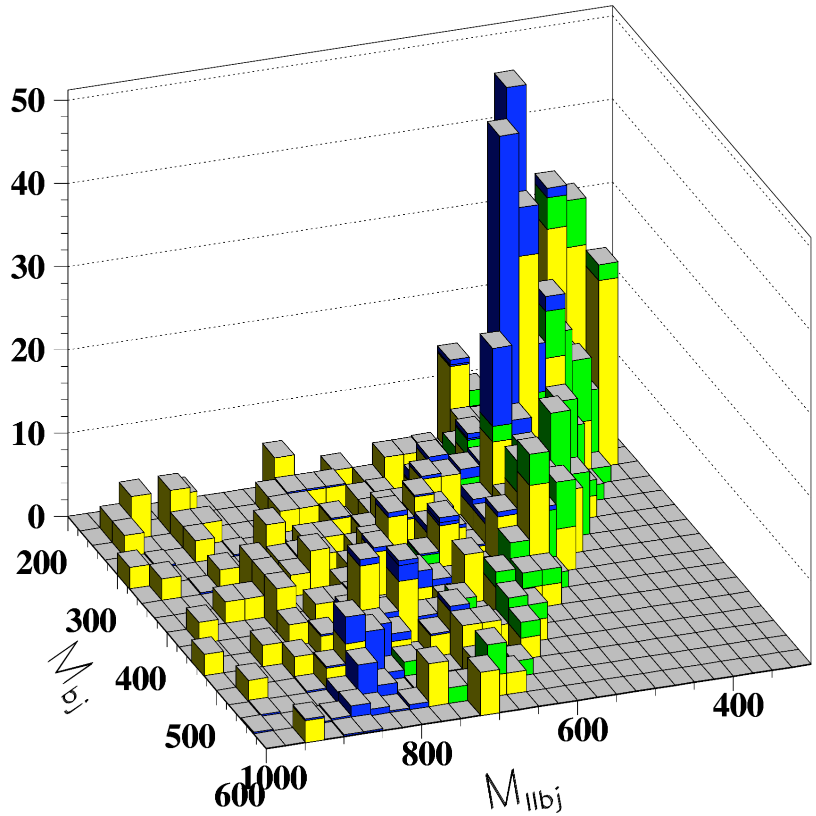


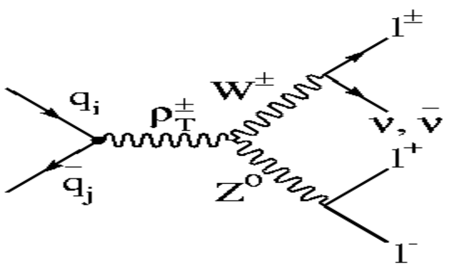
conclusion:

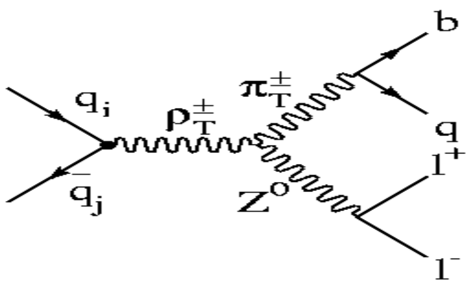
ATLAS can discover this sequential charged heavy leptons up to M_L = 0.9 / 1.0 TeV (low/high luminosity)

Technicolour



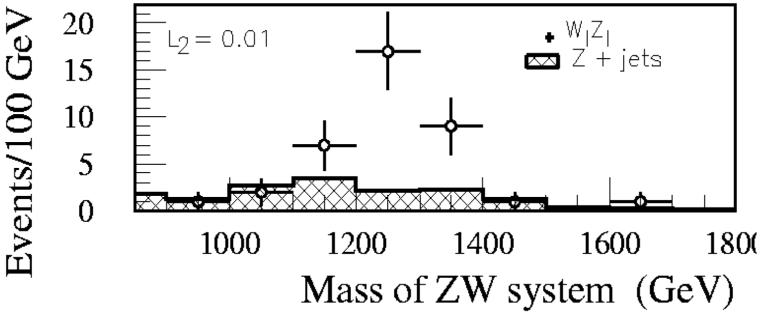


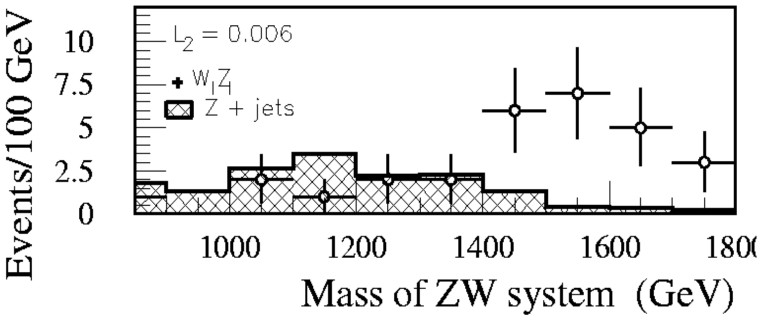




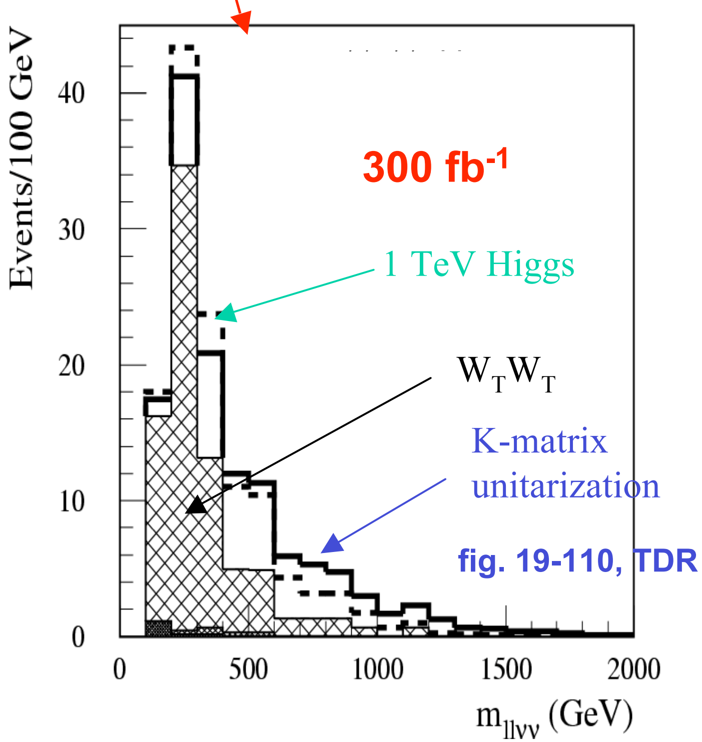
Strong symmetry breaking : V_L V_L scattering

Resonant scattering
qq --> qq WZ --> qq jj ll





Non-resonant VV scattering:
needs high luminosity, good understanding of backgrounds

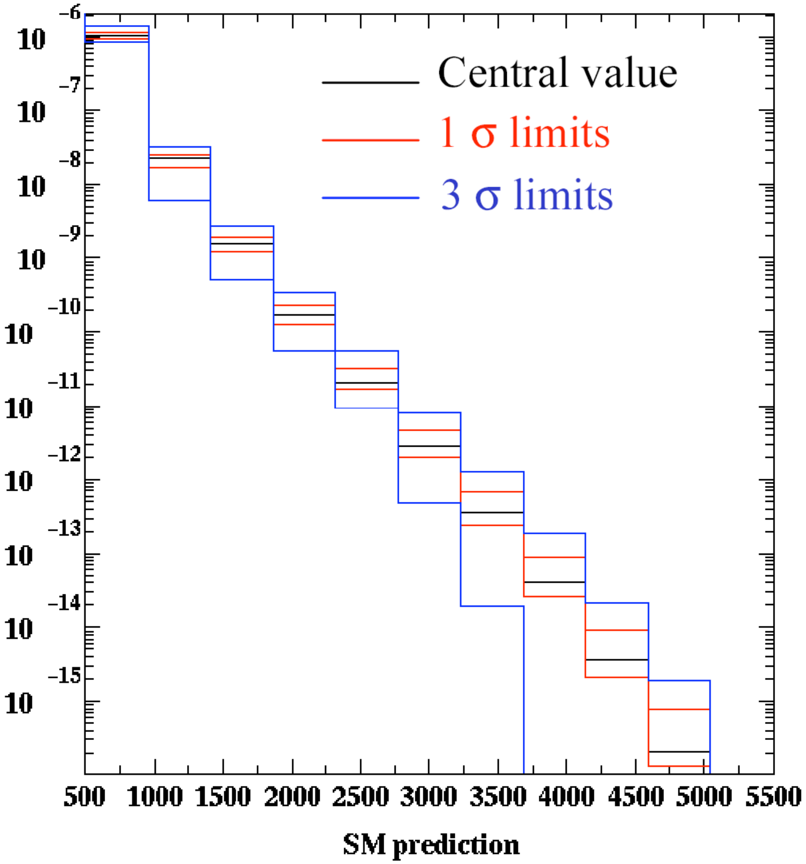


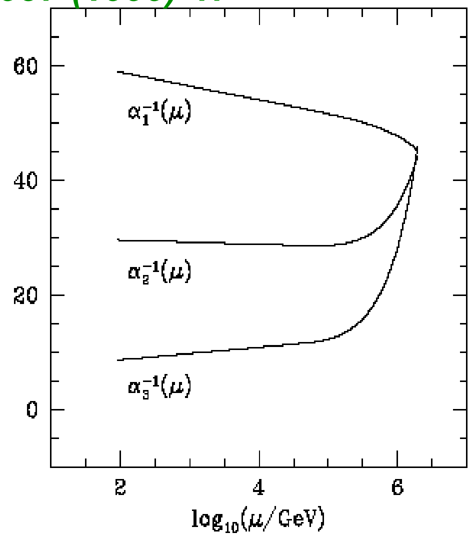
Coupling Unification at TeV

- KK states affect running of gauge couplings
- Dijet cross-section

K.R. Dienes, E. Dudas and T. Gherghetta, *Nucl.Phys. B537 (1999) 47*

SM prediction zones



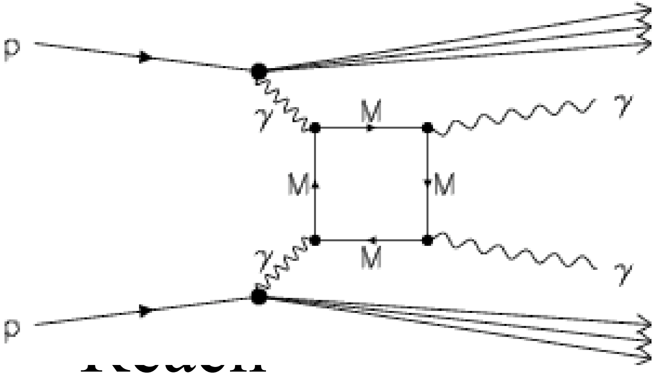


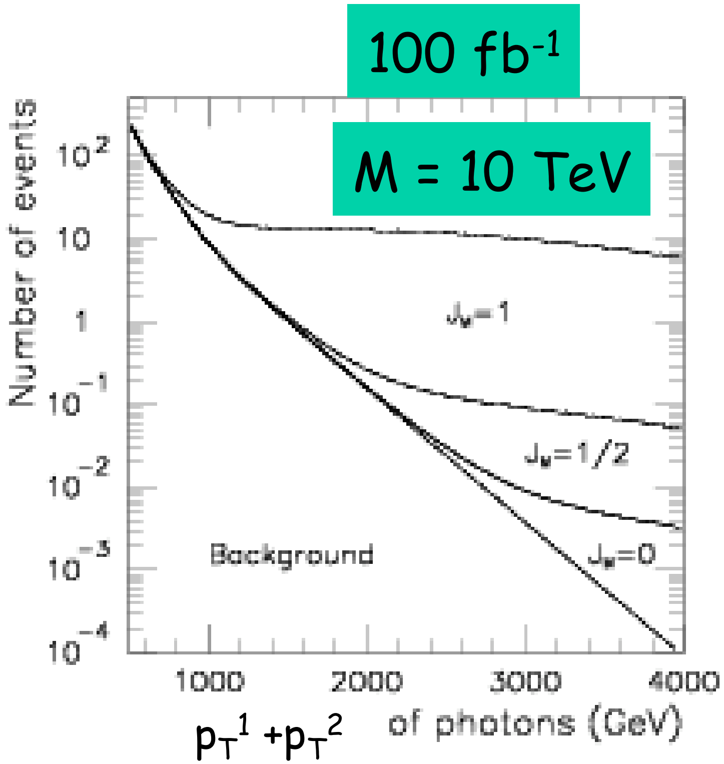
-Sensitivity of deficit in jet cross section, ~ 10 TeV, at parton level

-PDF uncertainties limit reach to 1 TeV

Monopoles

- Motivation
  - Restores Maxwell's equ'ns symmetry & explains charge quantization





  - 10-20 TeV
    (spin dependent)

	LHC	LC	LHC+LC	SPS1a
$\tan\beta$	10.22±9.1	10.26±0.3	10.06±0.2	10
M_1	102.45±5.3	102.32±0.1	102.23±0.1	102.2
M_2	191.8±7.3	192.52±0.7	191.79±0.2	191.8
M_3	578.67±15	fixed 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fixed 500	197.68±1.2	199.25±1.1	197.8
$M_{\tilde{\tau}_R}$	129.03±6.9	135.66±0.3	133.35±0.6	135.5
$M_{\tilde{\mu}_L}$	198.7±5.1	198.7±0.5	198.7±0.5	198.7
$M_{\tilde{\mu}_R}$	138.2±5.0	138.2±0.2	138.2±0.2	138.2
$M_{\tilde{e}_L}$	198.7±5.1	198.7±0.2	198.7±0.2	198.7
$M_{\tilde{e}_R}$	138.2±5.0	138.2±0.05	138.2±0.05	138.2
$M_{\tilde{q}3_L}$	498.3±110	497.6±4.4	521.9±39	501.3
$M_{\tilde{t}_R}$	fixed 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fixed 500	504.35±61	525.6
$M_{\tilde{q}2_L}$	550.72±13	fixed 500	553.31±5.5	553.7
$M_{\tilde{c}_R}$	529.02±20	fixed 500	531.70±15	532.1
$M_{\tilde{s}_R}$	526.21±20	fixed 500	528.90±15	529.3
$M_{\tilde{q}1_L}$	550.72±13	fixed 500	553.32±6.5	553.7
$M_{\tilde{u}_R}$	528.91±20	fixed 500	531.70±15	532.1
$M_{\tilde{d}_R}$	526.2±20	fixed 500	528.90±15	529.3
A_τ	fixed 0	-202.4±89.5	352.1±171	-253.5
A_t	-507.8±91	-501.95±2.7	-505.24±3.3	-504.9
A_b	-784.7±35603	fixed 0	-977±12467	-799.4
m_A	fixed 500	399.1±0.9	399.1±0.8	399.1
μ	345.21±7.3	344.34±2.3	344.36±1.0	344.3

Table 5.29: Result for the general MSSM parameter determination in SPS1a using the mass measurements given in Tab. 5.25. Shown are the nominal parameter values and the result after fits to the different data sets. All masses are given in GeV.