Physics beyond the Standard Model at LHC

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- Introduction (main parameters, machine, experiments …)
- Experimental challenges and techniques
- Examples of potential for physics beyond SM

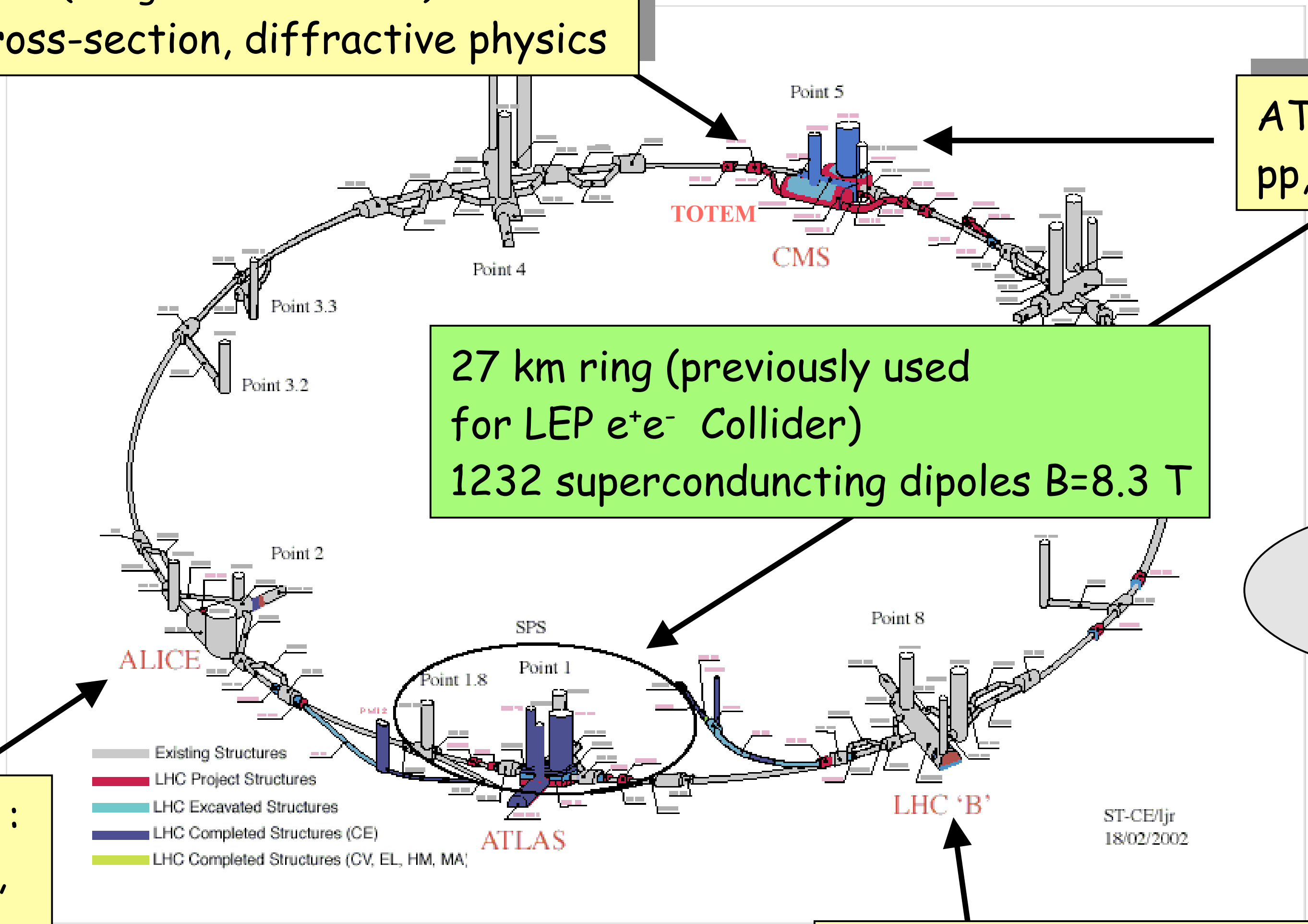
LHC

- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$
  $\sqrt{s}$ is 7 times higher and L is ~ 100 times higher than Tevatron
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

Start : summer 2007

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
pp, general purpose



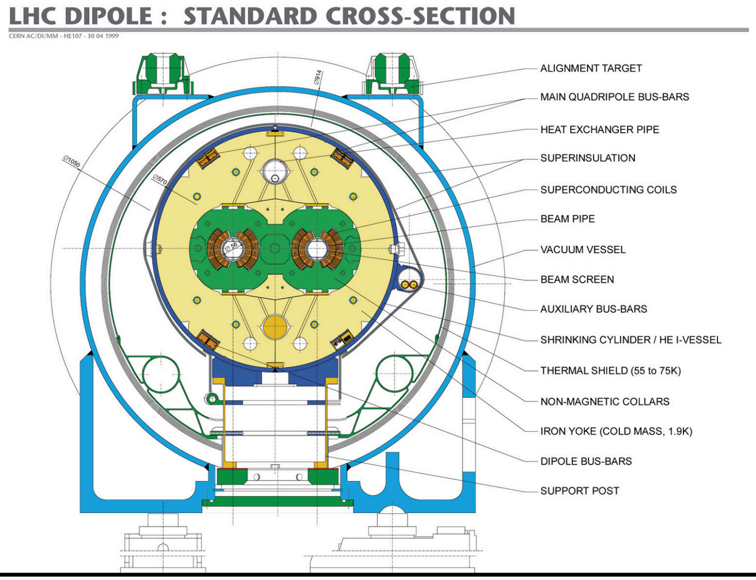
27 km ring (previously used
for LEP e^+e^- Collider)
1232 superconducting dipoles B=8.3 T

Here: mainly
ATLAS, CMS

ALICE :
ion-ion,
p-ion

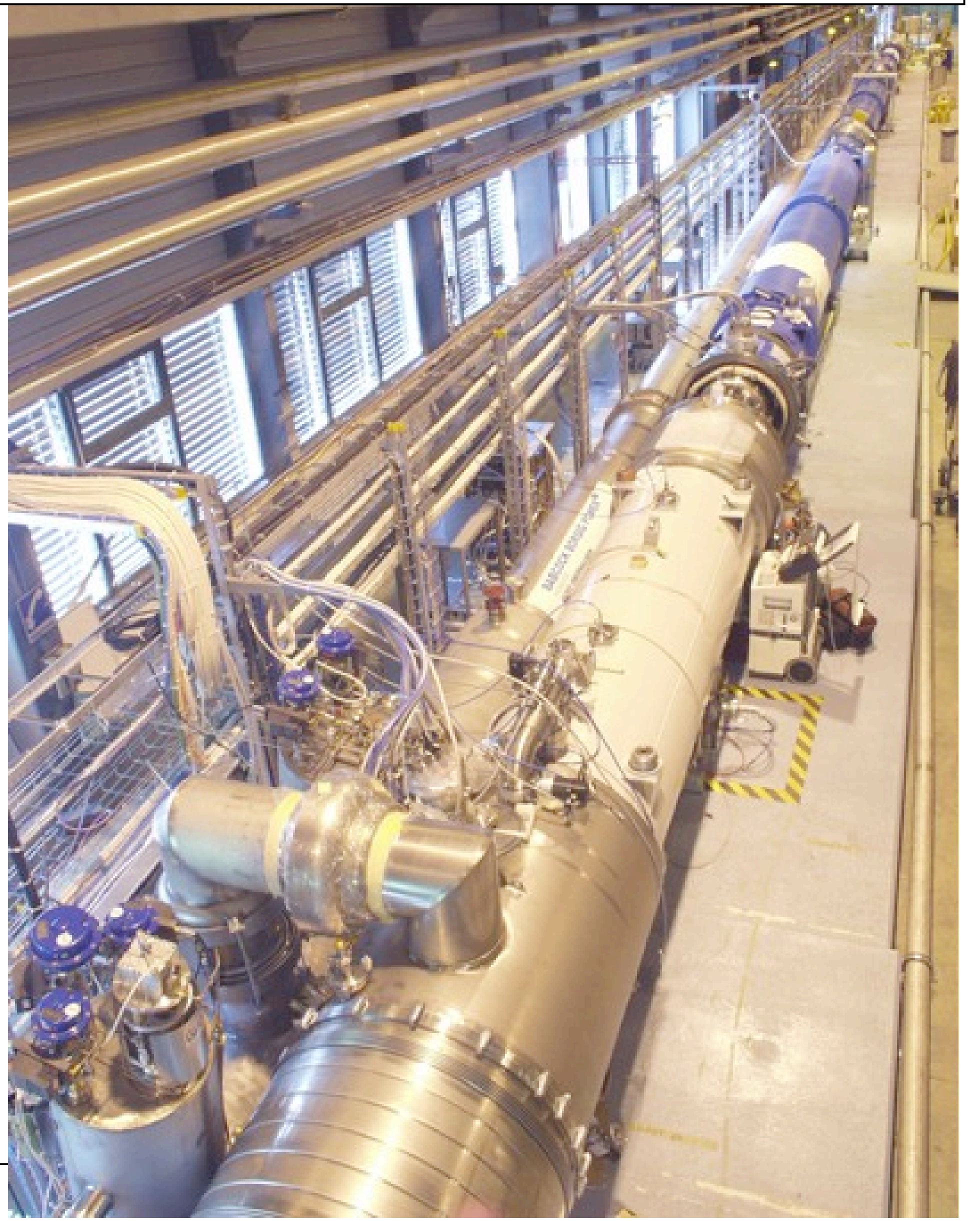
LHCb :
pp, B-physics, CP-violation

The machine



~ 300 dipoles delivered

First full LHC cell (~ 120 m long) :
6 dipoles + 4 quads
Successfully tested at nominal current (12 kA)



A few numbers .....

Rate of pp interactions at 10^{34} : 10^9 events per second
Weight of the CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)
Amount of cables used in ATLAS : ~ 3000 km
Data volume collected by CMS in 1 second: equivalent to 10000 Encyclopedia Britannica
Machine temperature : 1.9 K (largest cryogenic system in the world)
Total cost of machine + experiments : ~ 5000 MCHF
Total number of involved physicists : ~ 4000
Etc. etc.

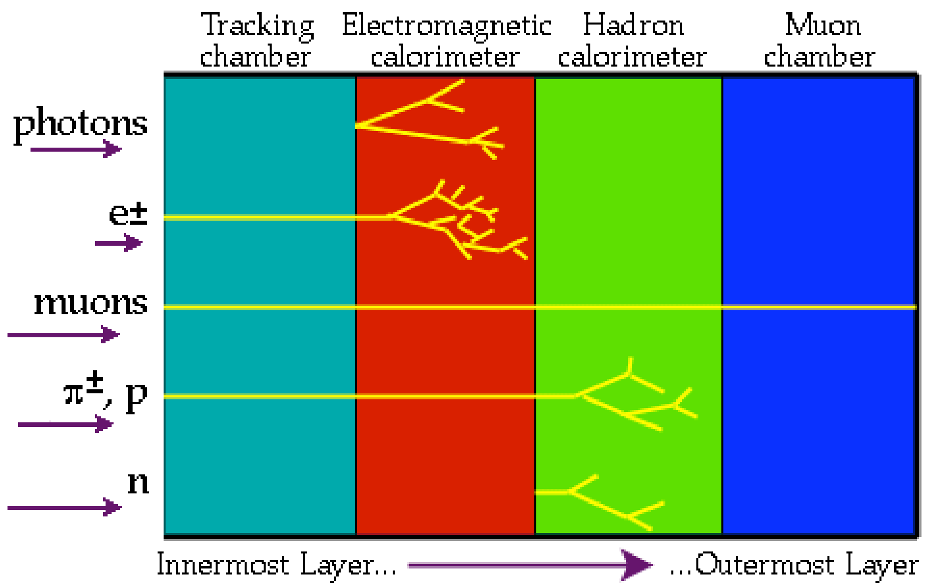
WHY ???

To explore in detail and directly the highly-motivated TeV-scale and say the final word about the SM Higgs mechanism and various TeV-scale predictions

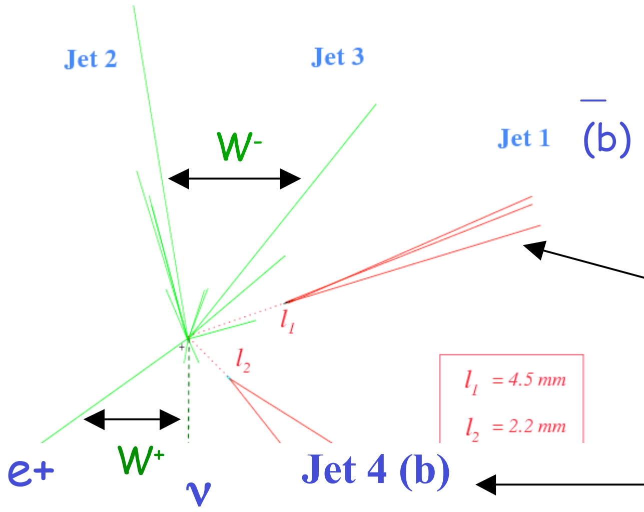
The environment and the experimental challenges

❶ Don' t know how New Physics will manifest → detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….
→ ATLAS and CMS are general-purpose experiments.

Excellent performance over unprecedented energy range :
few GeV → few TeV

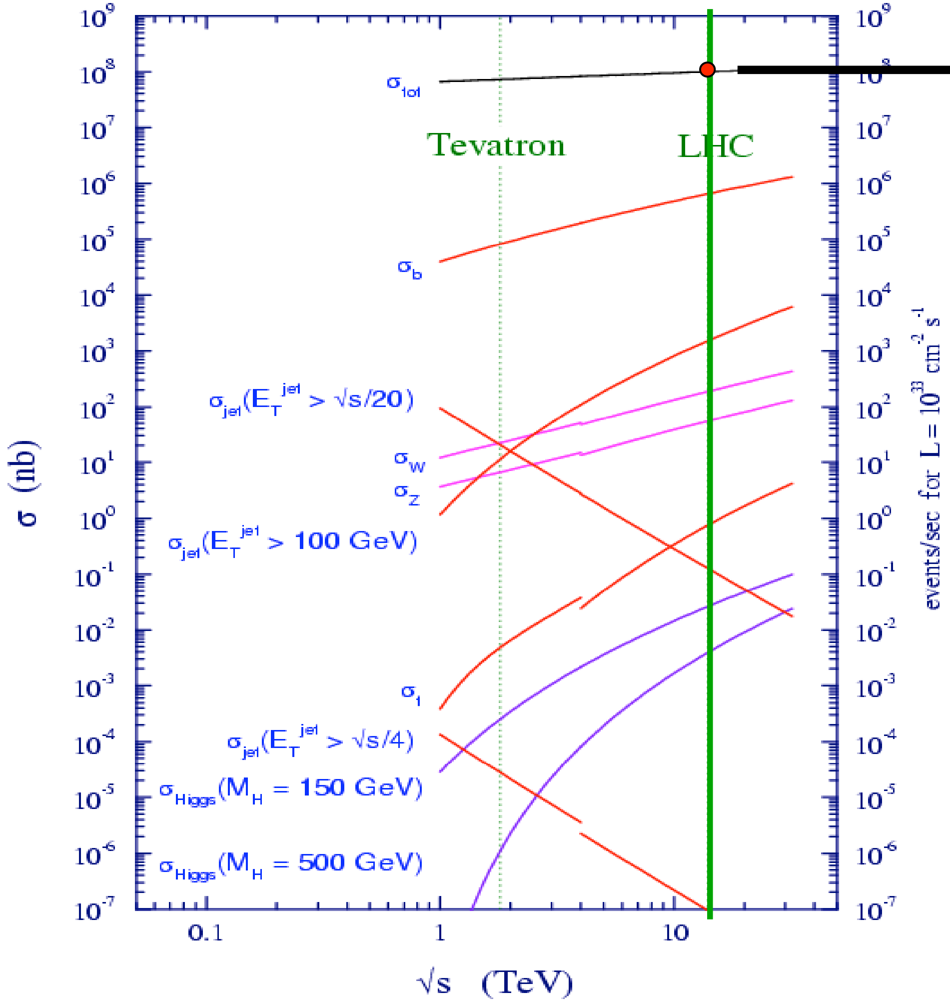


$t\bar{t} \rightarrow bW\bar{b}W \rightarrow bl\nu\bar{b}jj$ event from CDF data



b-tagging (secondary vetices)
τ(b-hadrons) ~ 1.5 ps
→ decay at few mm from primary vertex → detected with high-granularity Si detectors

❷ Event pile-up (consequence of high luminosity …)

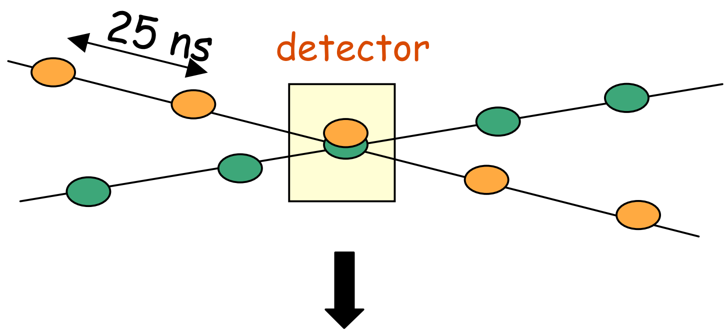


Event rate in ATLAS, CMS :

$N = L \times \sigma_{inelastic}(pp) \approx 10^{34}$ cm^{-2} s^{-1} x 70 mb

$\approx 10^9$ interactions/s

Proton bunch spacing : 25 ns



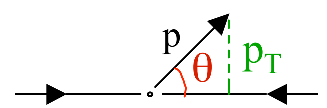
~ 25 inelastic (low-p_T) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing → pile-up

Simulation of CMS tracking detector

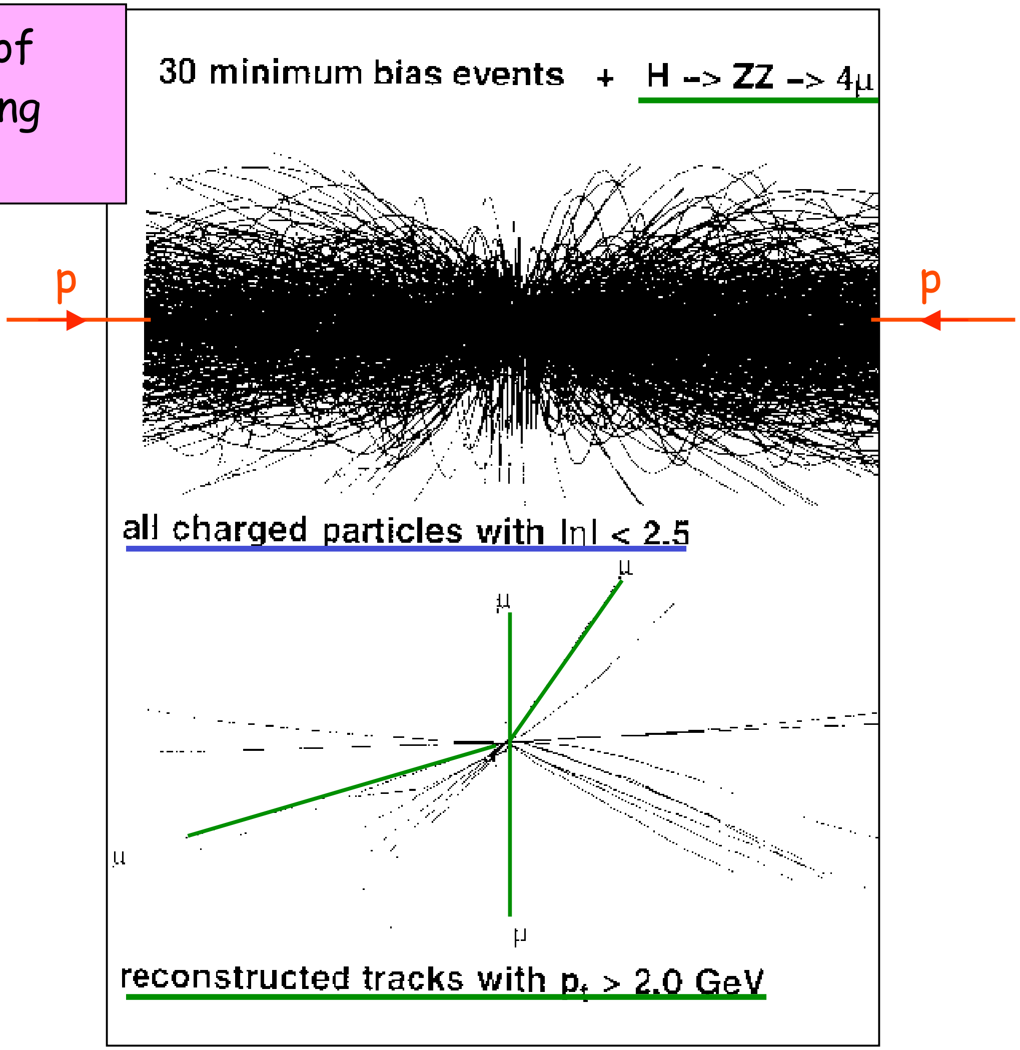
At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$ ($10^0 < \theta < 170^0$)

However : $\langle p_T \rangle \approx 500$ MeV

→ applying p_T cut allows extraction of interesting events



$\eta = -\ln \mathrm{tg}\, \theta/2$



Impact of pile-up on detector requirements and performance:

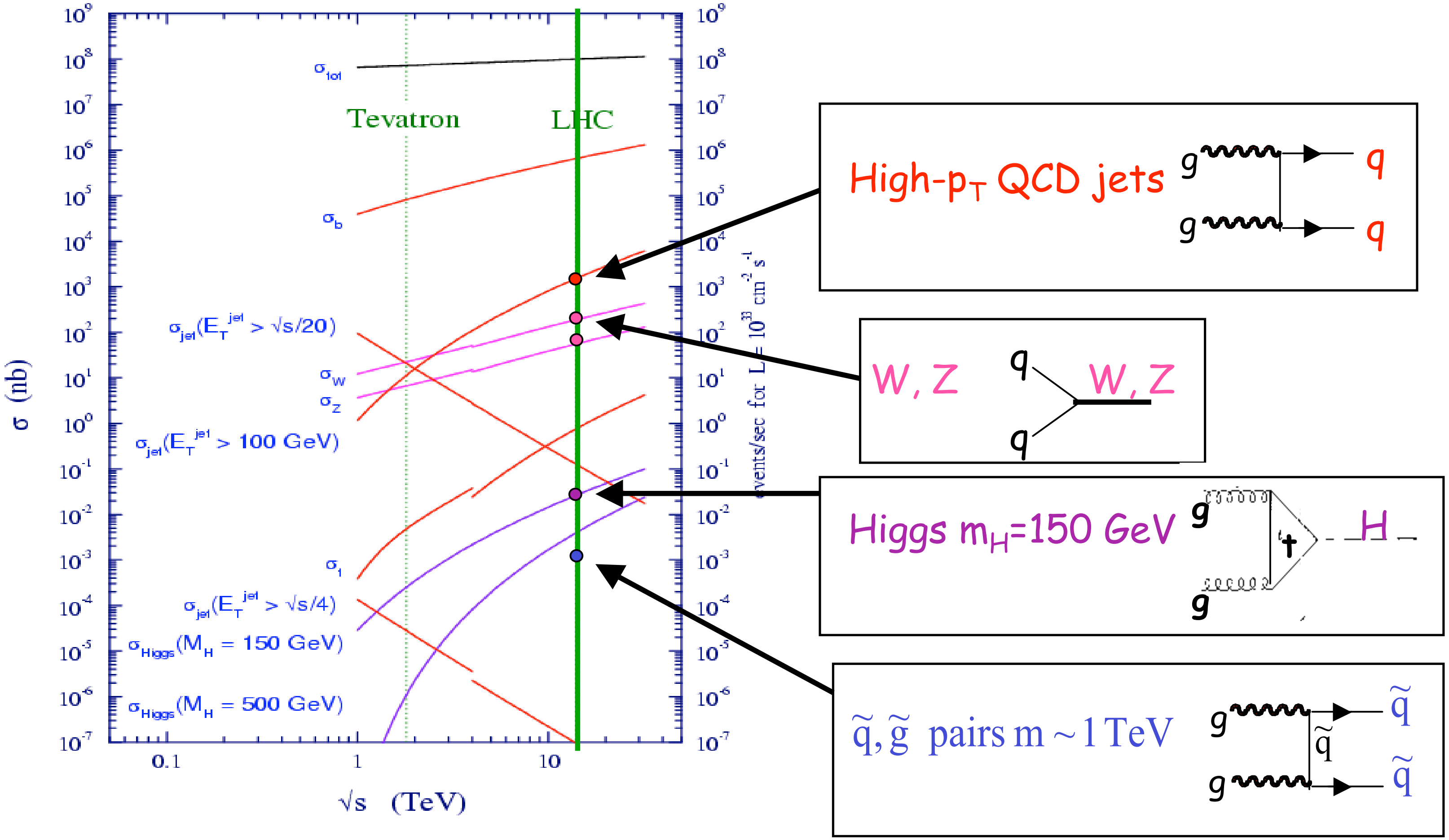
-- fast response : ~ 50 ns

-- granularity : > 10^8 channels

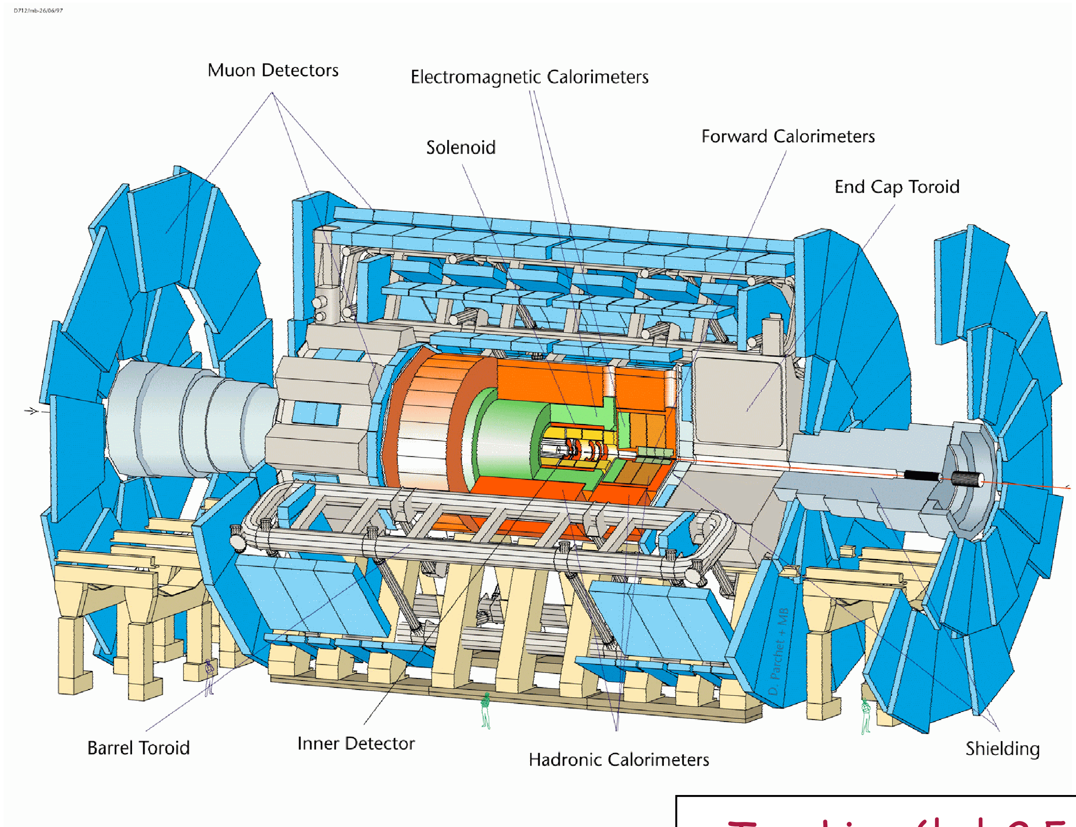
-- radiation resistance (up to 10^{16} n/cm^2/year in forward calorimeters)

-- event reconstruction much more challenging than at previous colliders

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



ATLAS

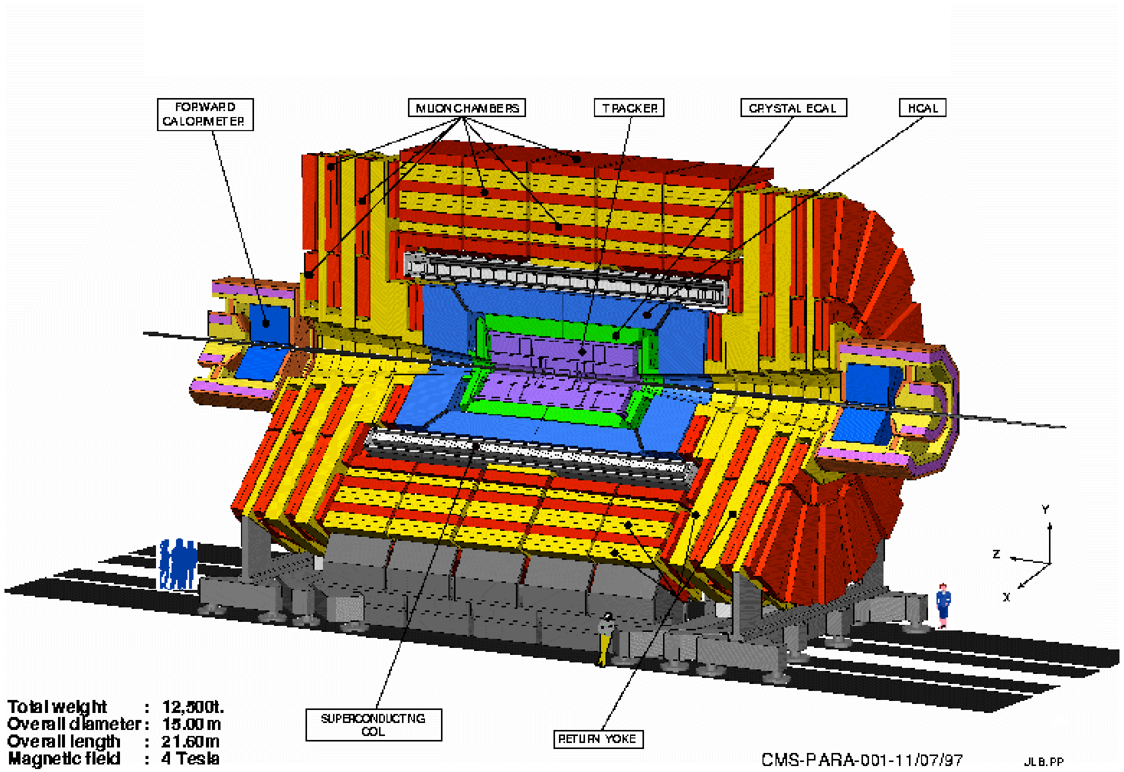
Length : ~45 m
Radius : ~12 m
Weight : ~ 7000 tons
Electronic channels : ~ 10^8

… and 3000 km of cables …

- Tracking ($|\eta|<2.5$, B=2T) :
  -- Si pixels and strips
  -- Transition Radiation Detector (e/π separation)

- Calorimetry ($|\eta|<5$) :
  -- EM : Pb-LAr
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

- Muon Spectrometer ($|\eta|<2.7$) :
  air-core toroids with muon chambers



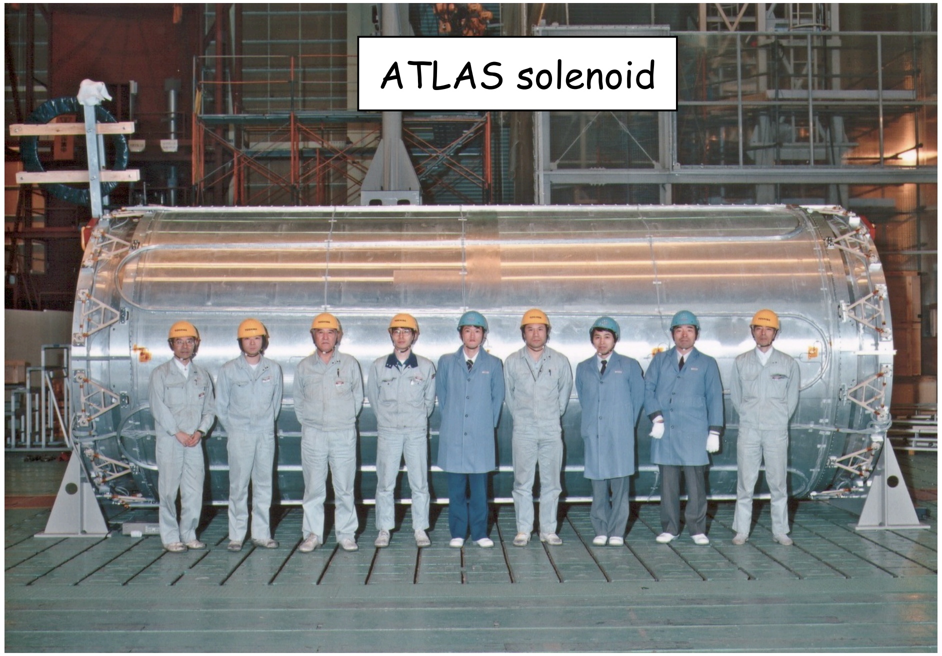
CMS

Length : ~22 m
Radius : ~7 m
Weight : ~ 12500 tons

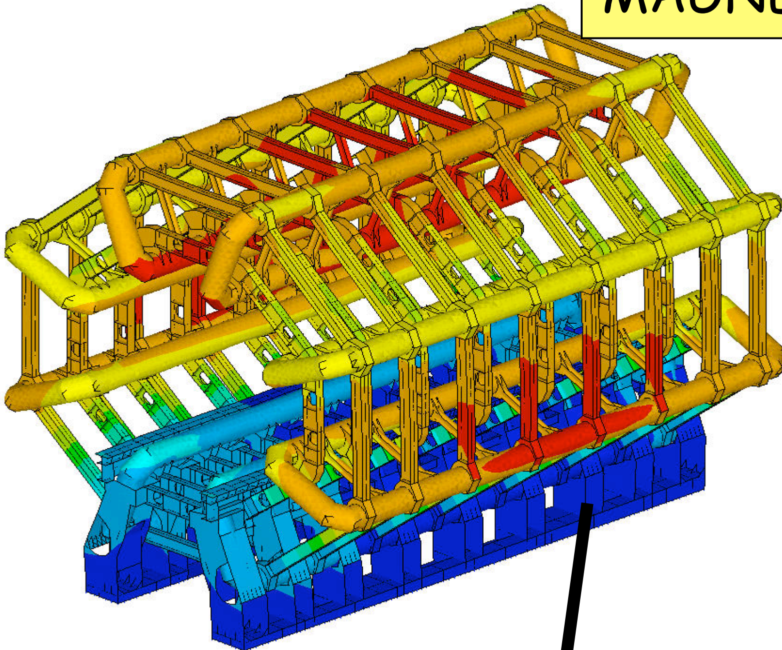
- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass/scintillator (central+ end-cap), Fe/Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

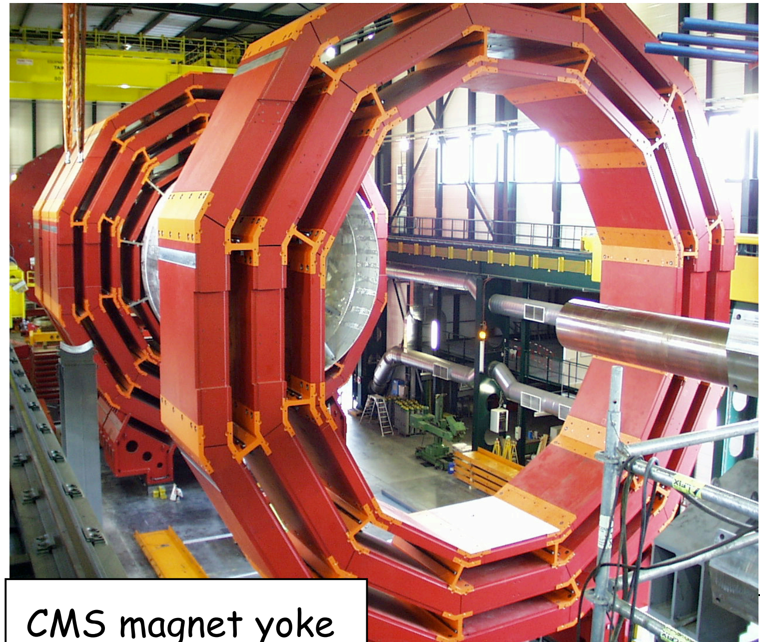
Detector construction and performance : a few examples .....

MAGNETS



ATLAS solenoid

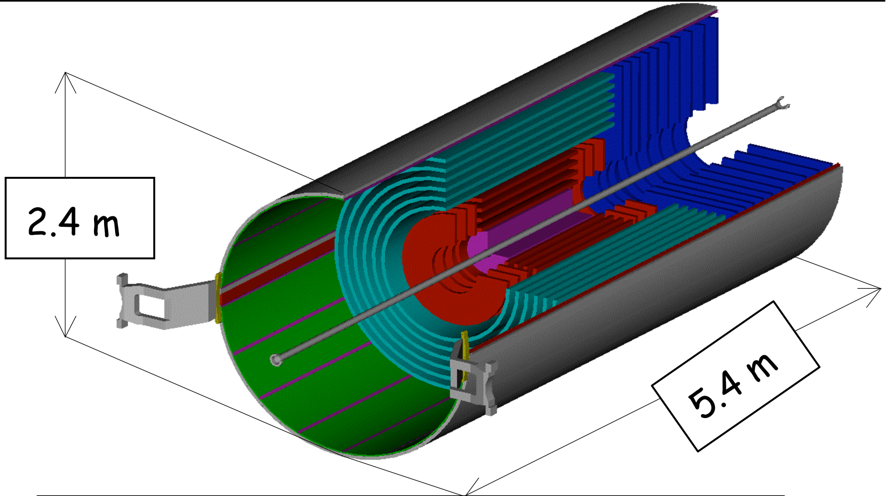




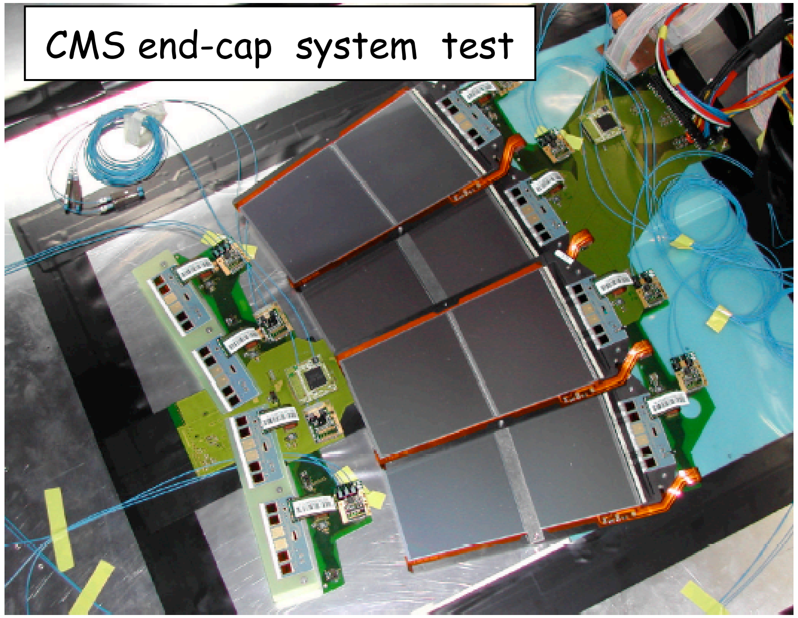
CMS magnet yoke

ATLAS : coil components delivered, assembly started

Tracking and muon spectrometers

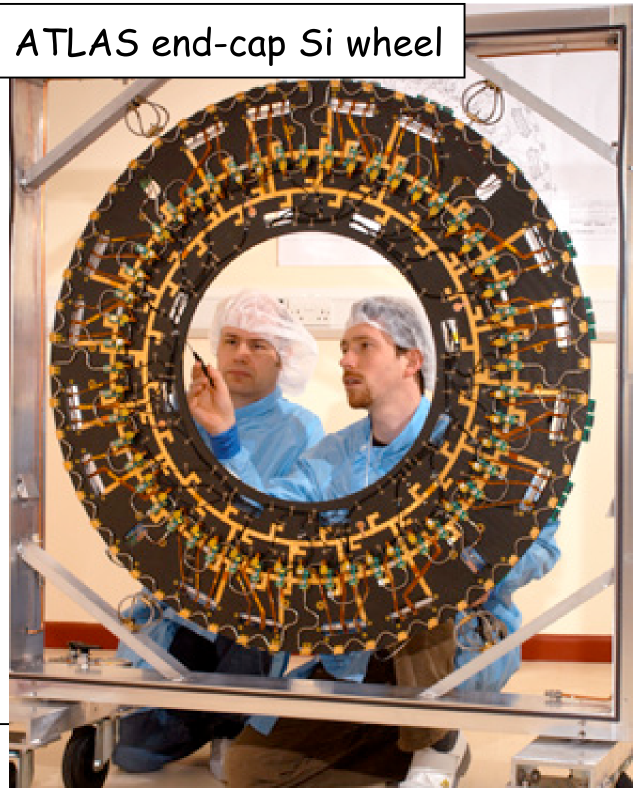


CMS tracker : 210 m^2 of Si sensors



CMS end-cap system test

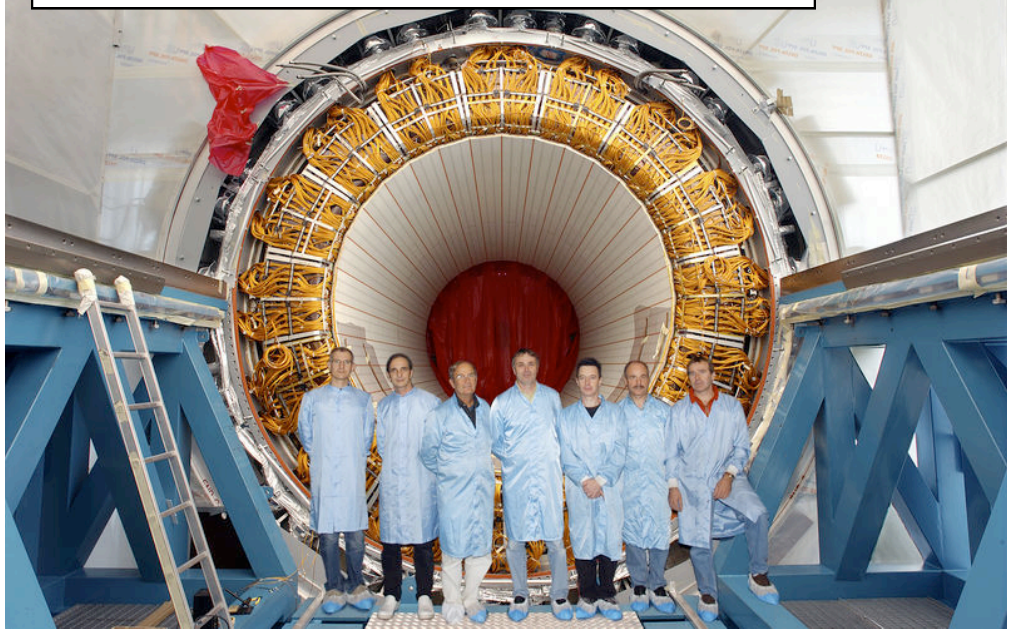
Installation of CMS muon chambers



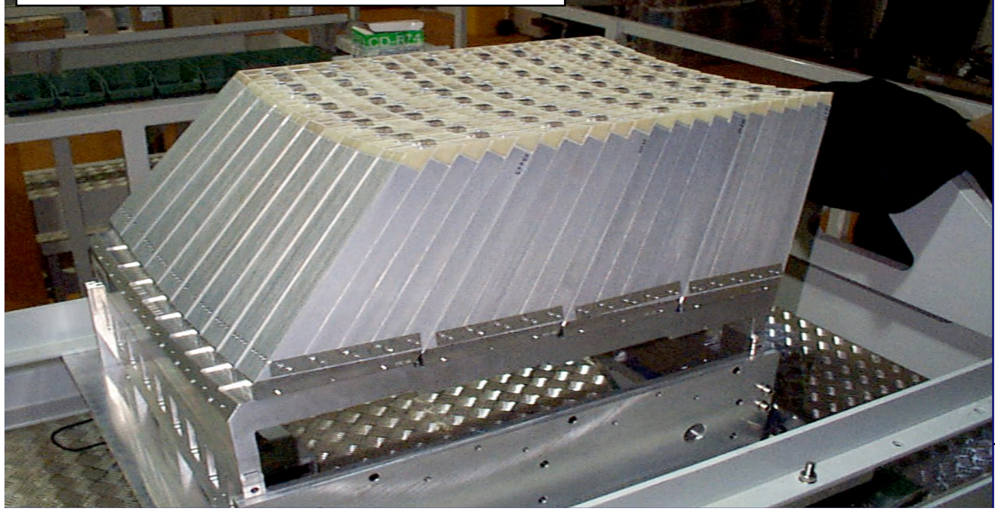
ATLAS end-cap Si wheel

Electromagnetic calorimeters

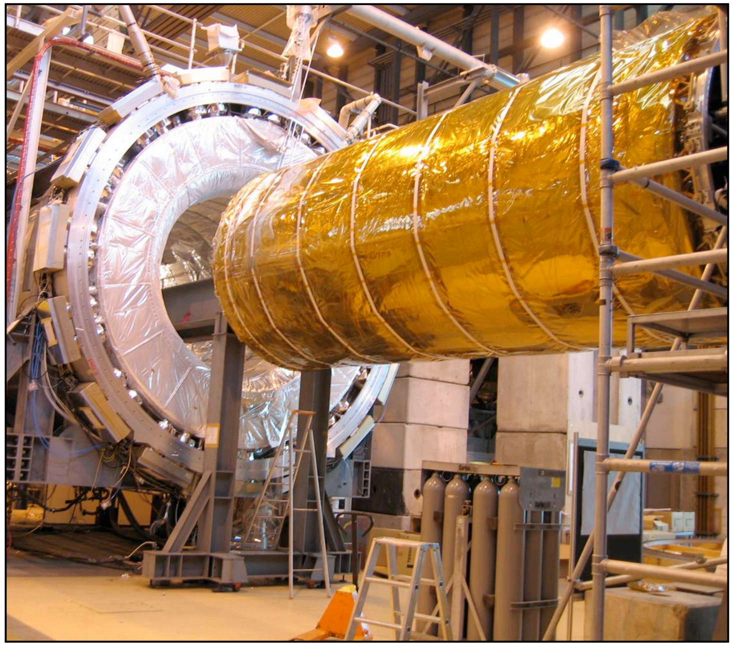
ATLAS barrel calorimeter inside cryostat



Module of 200 CMS crystals



ATLAS solenoid before insertion inside the cryostat



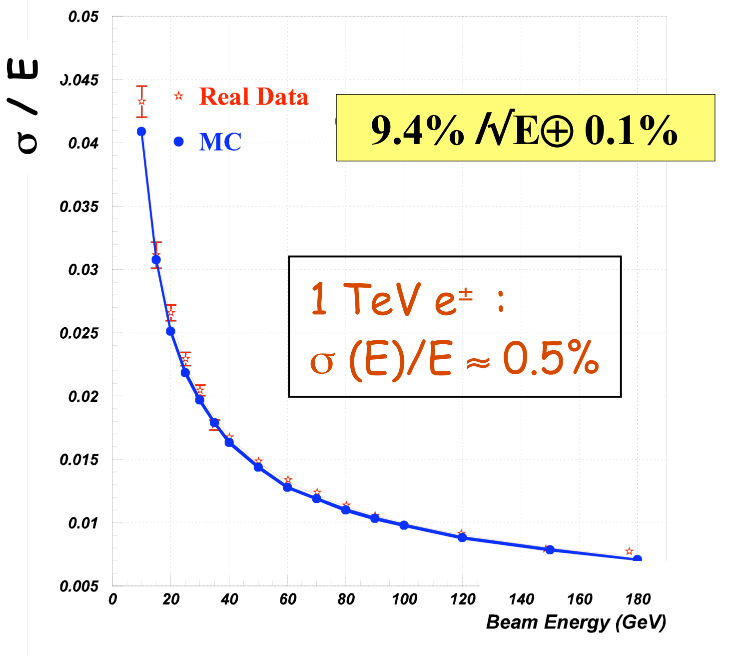
Hadronic calorimeters

Modules of ATLAS barrel calorimeter being lowered in the pit

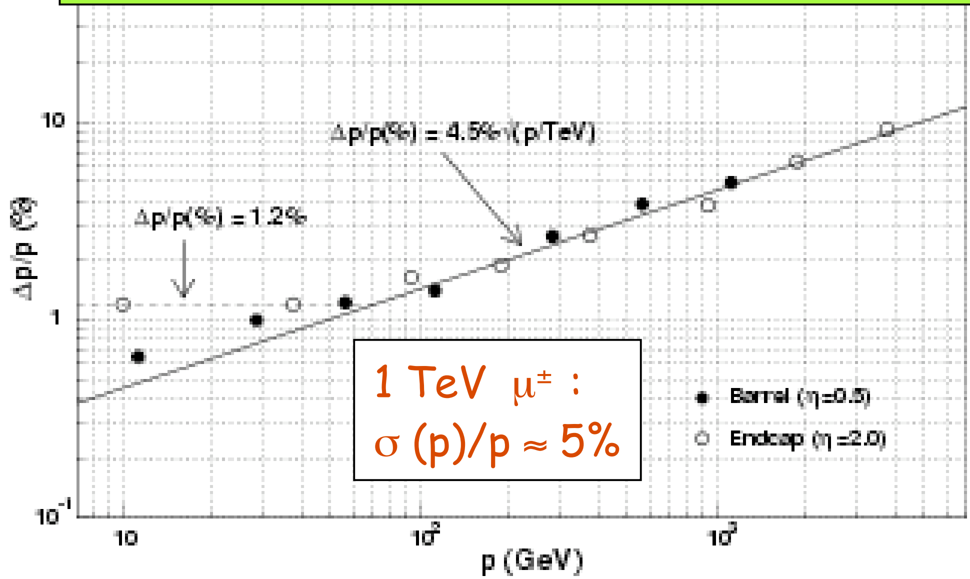
CMS end-cap calorimeter assembled

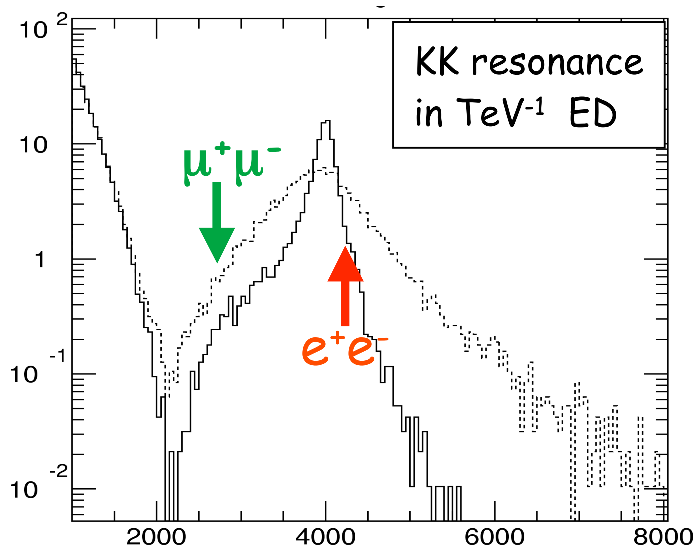
Examples of expected performance

Electron E-resolution measured in beam tests of ATLAS EM calorimeter



Muon momentum resolution expected in CMS





Heavy narrow resonances will likely be discovered in the X → ee channel (muon decay useful for couplings, asymmetry, etc.)

Main asset of LHC physics potential: huge event statistics thanks to high √s and L

Expected event production rates in ATLAS or CMS for representative (known and new) physics processes at the initial "low" luminosity of $L = 10^{33}\ cm^{-2}\ s^{-1}$

Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / $\sim 10^6$ Tevatron
$Z \to ee$	1.5	10^7	10^6 LEP
$t\bar{t}$	1	10^7	$\sim 10^4$ Tevatron
$b\bar{b}$	10^6	$10^{12} - 10^{13}$	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

→ LHC is a top factory, W/Z factory, Higgs factory, SUSY factory, etc….

→ mass reach for direct discovery of new particles up to m ~ 6 TeV

Very broad physics programme, including :

-- precise measurements of SM particles (e.g. W mass, top sector) and CP-violation
-- SM Higgs searches
-- Physics beyond the SM

Many scenarios studied by the experiments

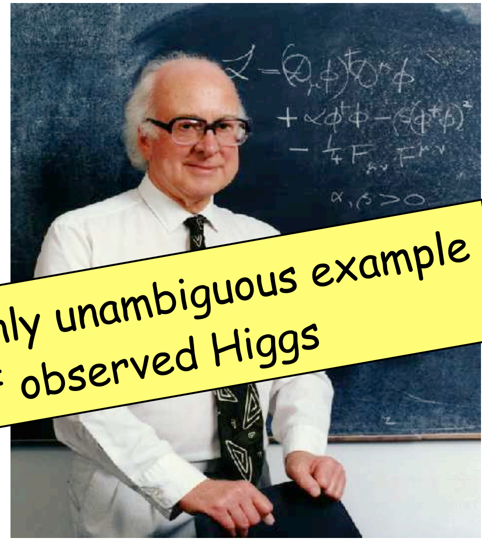
-- Supersymmetry
-- Extra-dimensions
-- Little Higgs
-- Technicolour and strong EWSB
-- Compositeness
-- Additional bosons and fermions
-- etc.

Goals:

- make sure that we don't miss any relevant topology → detector robustness/flexibility, ability to cope with the unexpected
- go beyond assessment of discovery potential → attempt to characterize underlying model (fundamental parameters) through precise measurements

Here : a few examples (Higgs, SUSY, Extra-dimensions ....) to illustrate physics potential and experimental techniques

Where is the Higgs boson ?



Only unambiguous example of observed Higgs

- Higgs mass :

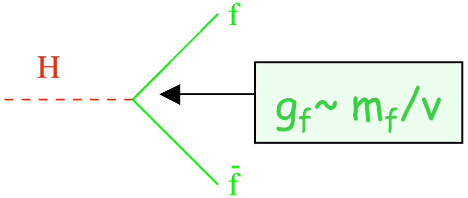
-- 114.4 GeV < m_H < 1000 GeV ← from theory

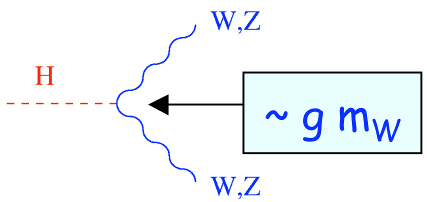
↑ from direct searches at LEP

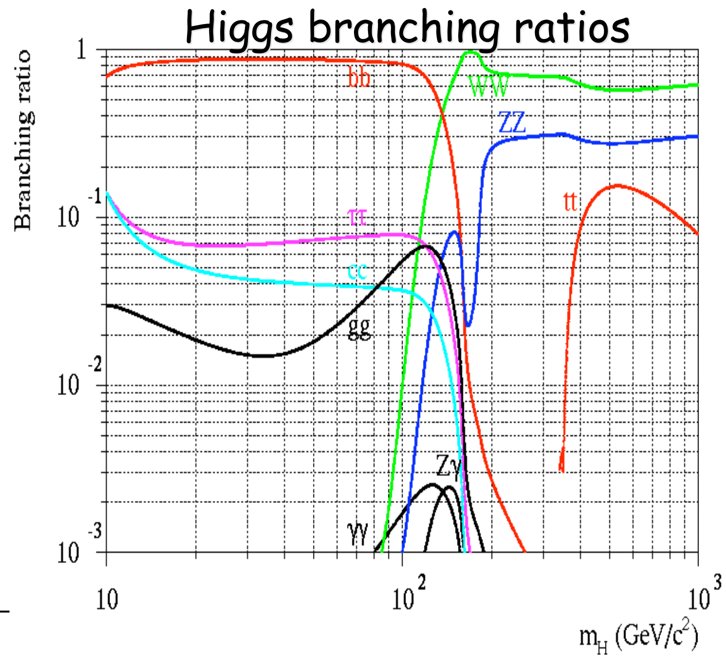
-- from fit to the electroweak data (LEP, Tevatron, SLC, etc.):
indirect limit m_H < 251 GeV at 95% C.L. → present data favour a light Higgs

-- LEP " hint " (~ 2σ excess) for m_H ~ 115 GeV ?

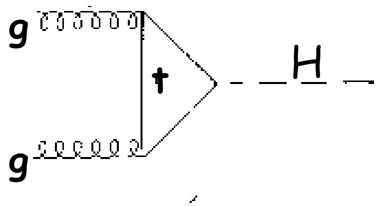
- Higgs decay modes :

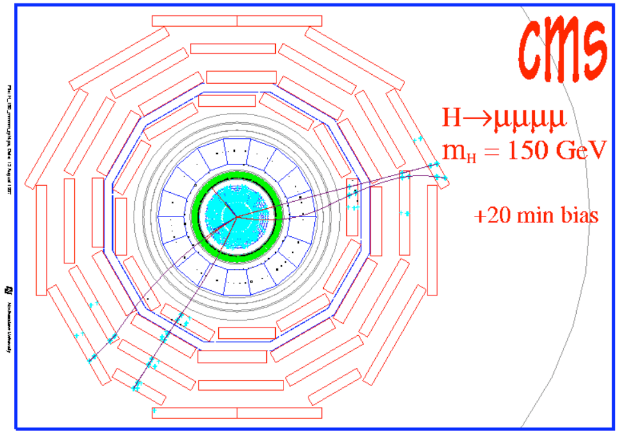




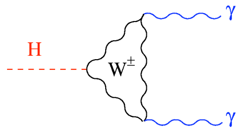


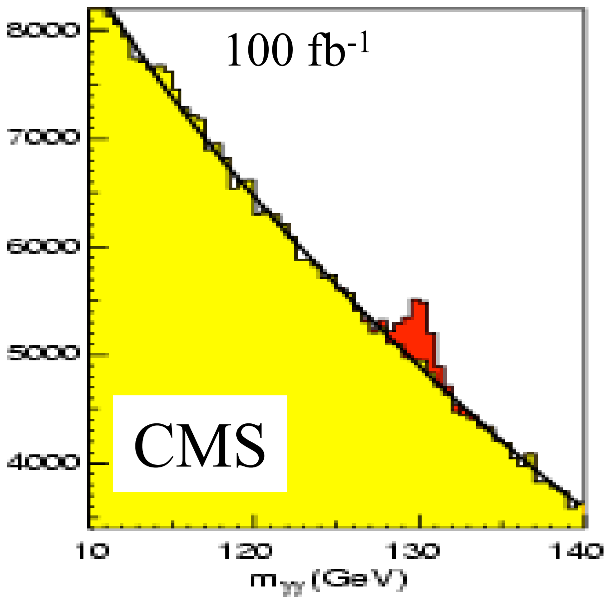
Best channels at LHC :





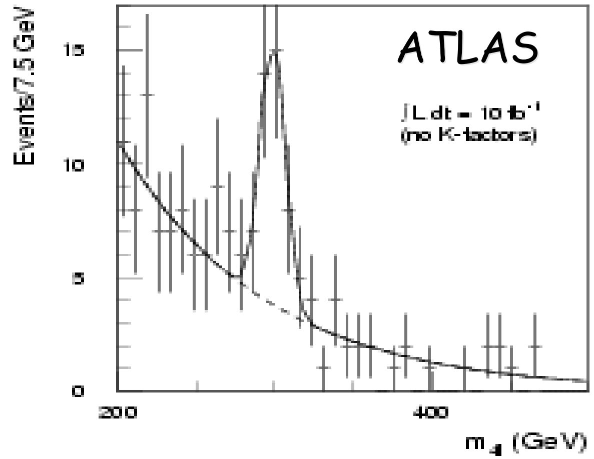
m_H < 150 GeV : $H \rightarrow \gamma\gamma$





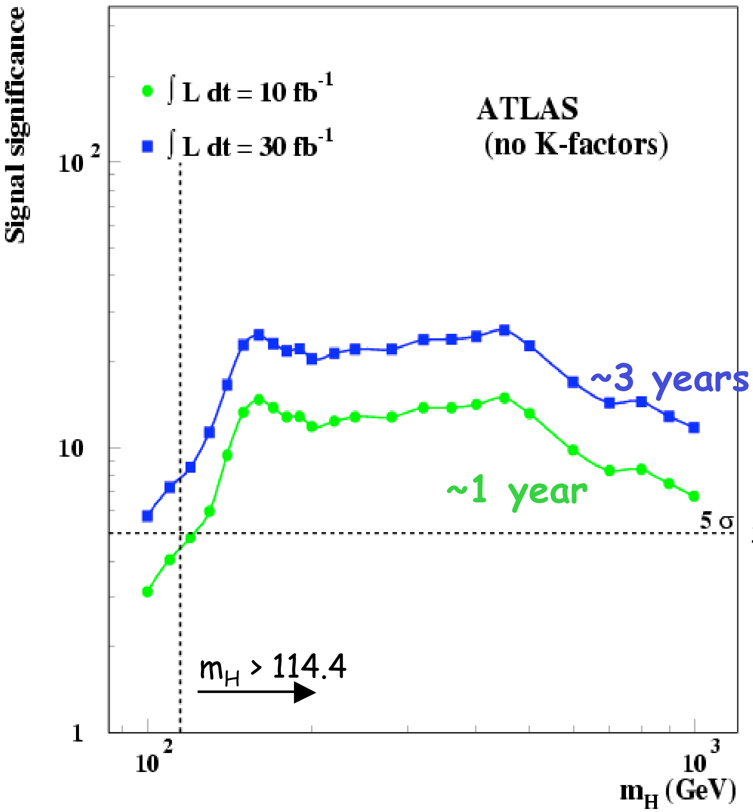
Requires excellent EM calorimetry (E-resolution, γ/π^0 separation)

m_H > 130 GeV : $H \rightarrow ZZ^{(*)} \rightarrow 4e, 4\mu$

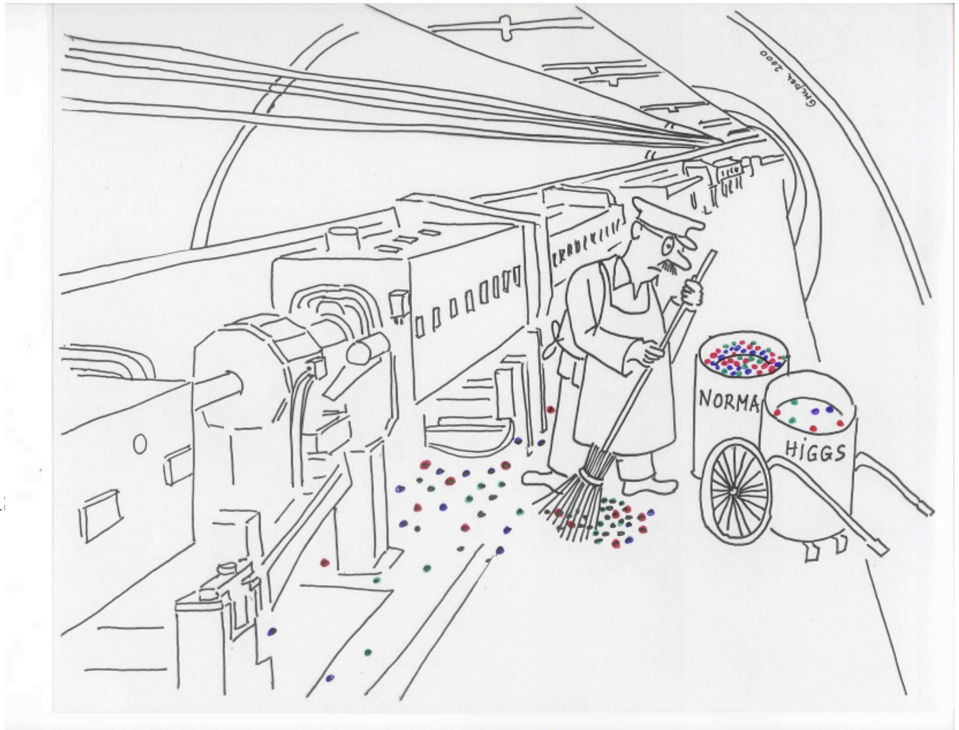


Requires good lepton E, p resolution and identification. Gold-plated channel at LHC (~ background free ...)

Expected Higgs signal significance (S/√B) at the LHC



5σ ≡ di



- Higgs can be discovered over full allowed mass range in 1 year of LHC operation
  → final word about SM Higgs mechanism
- However: it will take time to understand and calibrate ATLAS and CMS …
- In most difficult region m_H < 130 GeV ≥3 different channels observable → robustness
- If Higgs found, mass can be meaured to 0.1% up to m_H~ 500 GeV

SUPERSYMMETRY

Present status … from an experimentalist's point of view :

$m(\tilde{q}, \tilde{g}) > 200-300$ GeV	from Tevatron Run 1
$m(\tilde{l}, \chi^{\pm}) > 90-100$ GeV	from LEP
$m(\chi^0_1) > 46$ GeV	from LEP

➡ Sparticles (if exist …) are heavy

BUT : to stabilize the Higgs mass need $m(\tilde{p}) <\sim$ TeV ➡ **LHC**

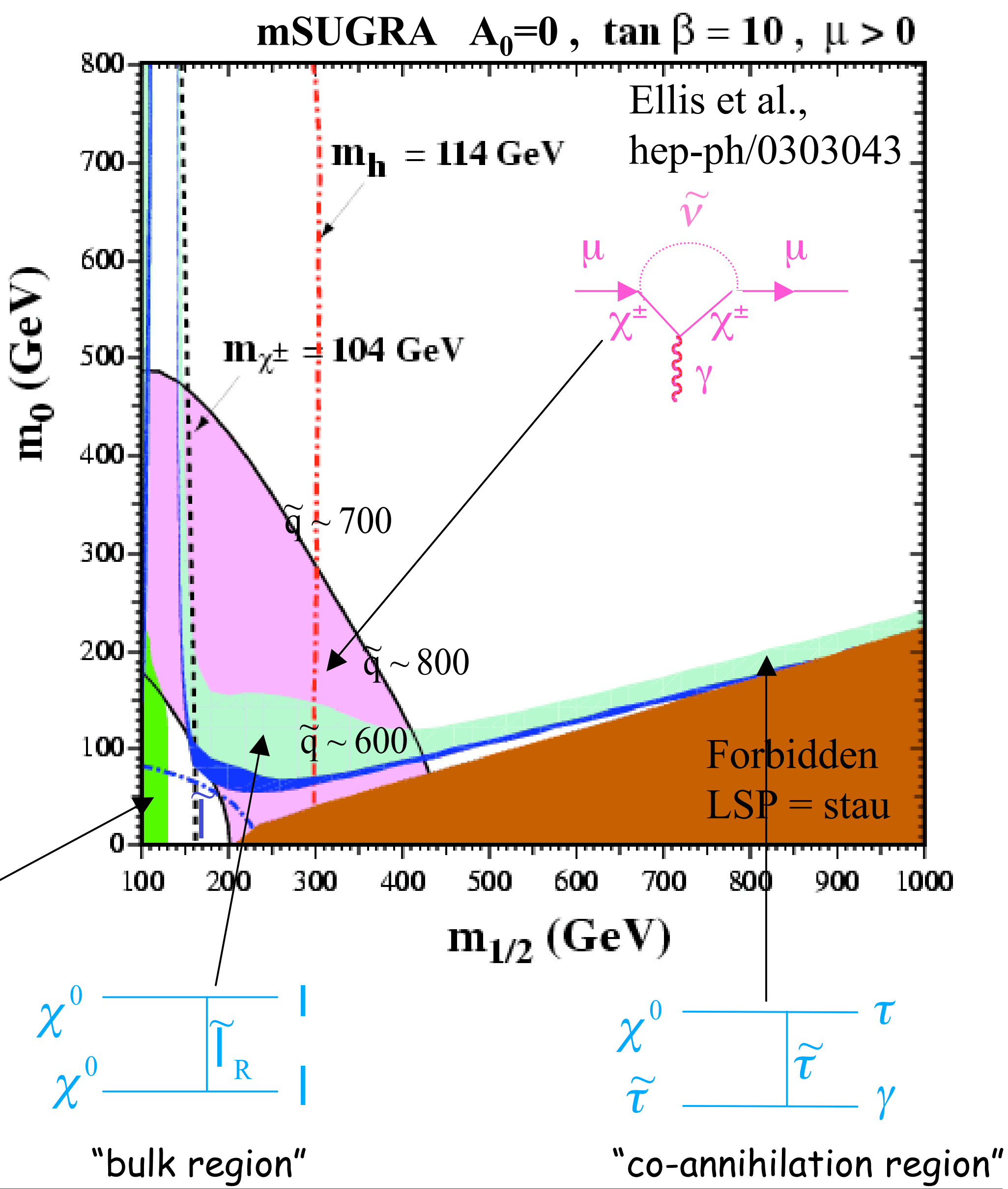
Combining Collider searches with other constraints (cosmology, …)

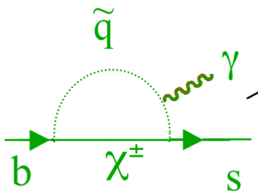
Disfavoured by BR ($b \rightarrow s\gamma$)
from CLEO, BELLE
BR ($b \rightarrow s\gamma$) = $(3.2 \pm 0.5) \cdot 10^{-4}$
used here

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





SUSY searches at LHC

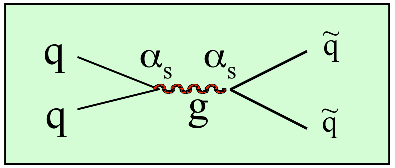
R-parity conservation assumed

- Dominant processes : $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ production

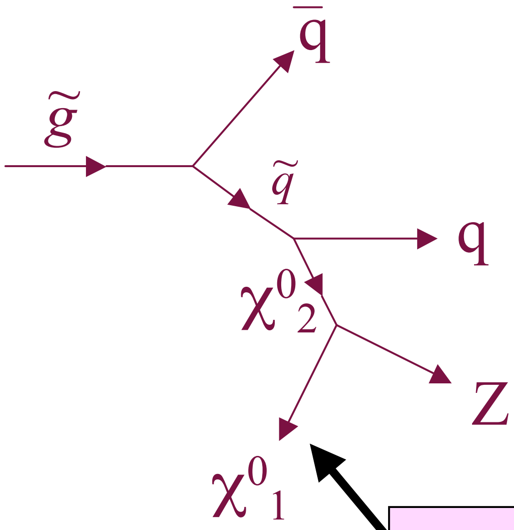
  strong production → huge cross-section

  e.g. for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV ~ 10^4 events produced in one year at low L

e.g.



- $\tilde{q}, \tilde{g}$ heavy → cascade decays



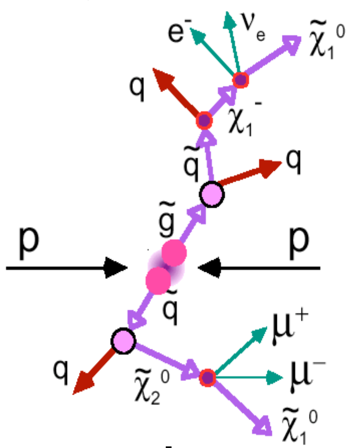
→ spectacular signatures with many jets, leptons + missing E

→ easy to extract SUSY signal from SM backgrounds at LHC

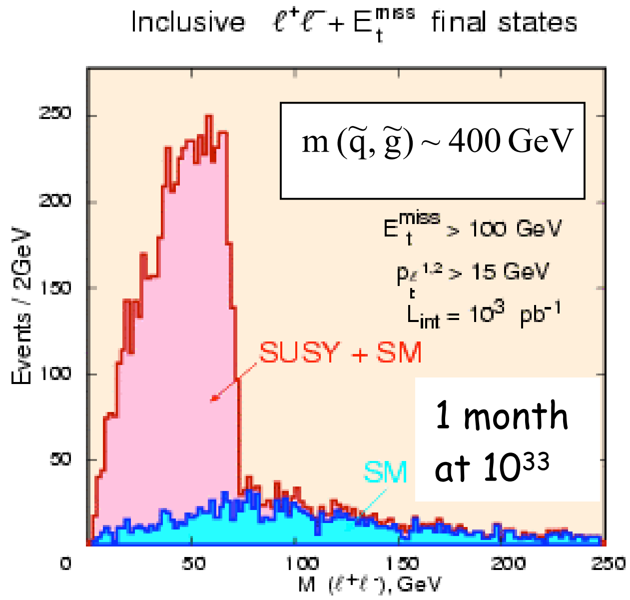
Lightest Susy Particle (LSP)
weakly interacting → not detected
→ missing energy in final state

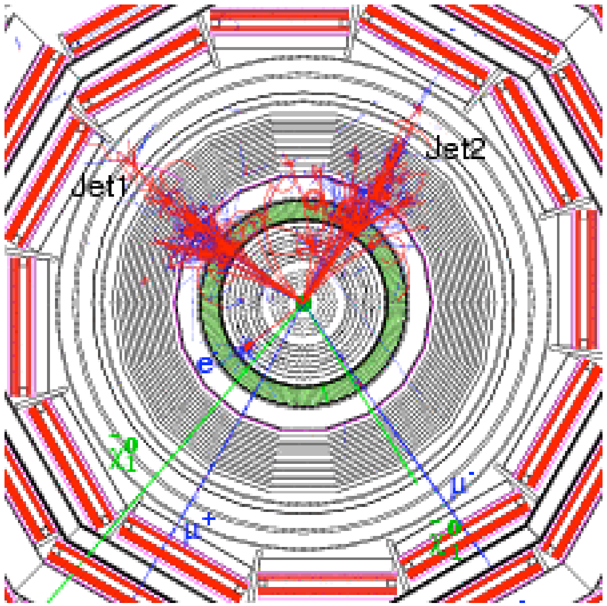
Requires good measurements of jets and of missing E_T (calorimeter resolution)

Example :



CMS



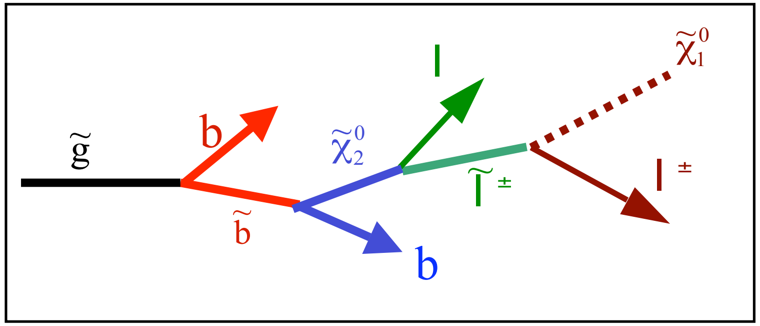


LHC discovery reach

Time	reach in squark/gluino mass
1 month at 10^{33}	~ 1.3 TeV
1 year at 10^{33}	~ 1.8 TeV
1 year at 10^{34}	~ 2.5 TeV
ultimate (300 fb^{-1})	up to ~ 3 TeV

if nothing found at LHC, (low-E) SUSY is likely dead
→ need another explanation for e.g. dark matter …

If SUSY is there ....

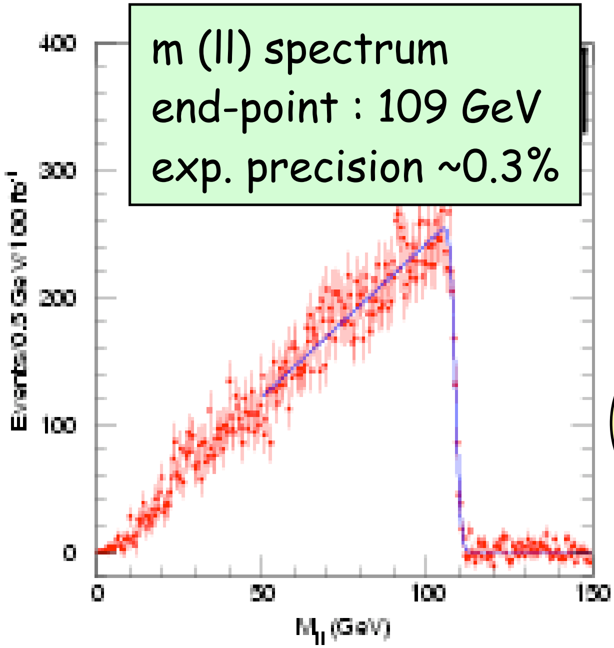


- ATLAS and CMS should be able to perform precise measurements of SUSY final states → determine sparticle masses and fundamental parameters of theory with precision ≈ 10% or better in many cases (studied in minimal models like mSUGRA)
- Method: measure end-points of reconstructed mass spectra at each step of (long) squark/gluino decay chains. End-points depend on involved masses → deduce constraints on combinations of masses
- LSP is not directly observable but its mass can be constrained indirectly from other measurements in final state → constraints on cold dark matter

Ex. : LHC "Point 5" : m_0 = 100 GeV, $m_{1/2}$ = 300 GeV, A_0 = 300 GeV, tanβ = 2, μ > 0

$m(\tilde{q}) \sim 700$ GeV
$m(\tilde{g}) \sim 800$ GeV
$m(\chi^0{}_1) \sim 120$ GeV

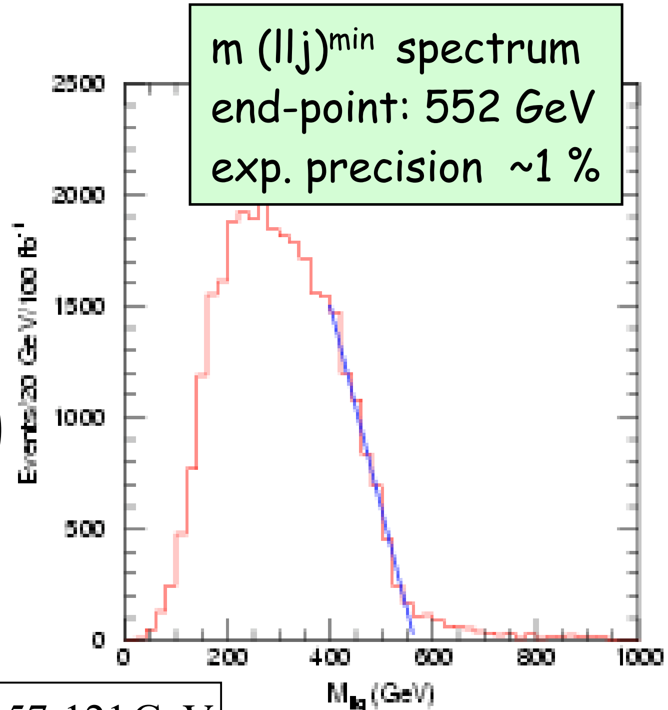
m (ll) spectrum
end-point : 109 GeV
exp. precision ~0.3%



Example of
a typical chain:

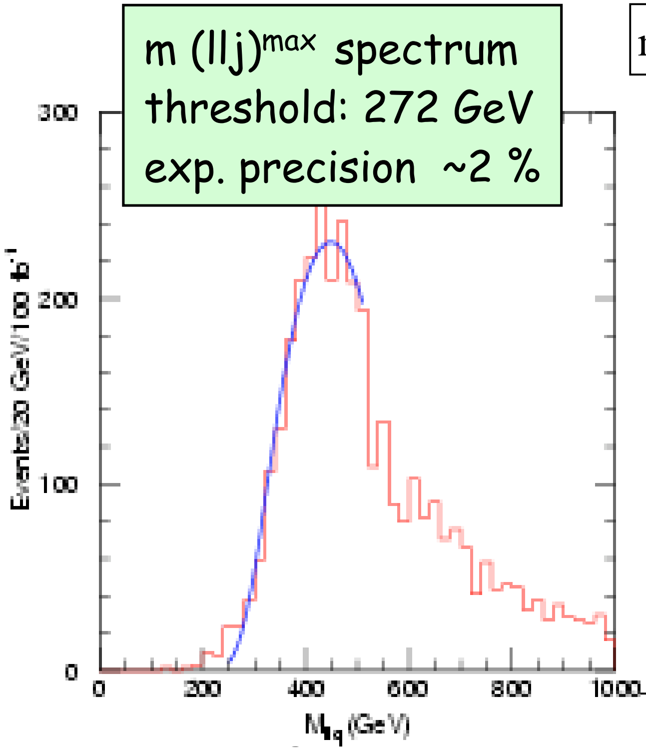
$\tilde{q}_L \rightarrow q\, \chi^0_2$
$\hookrightarrow \tilde{l}\; l$
$\hookrightarrow l\, \chi^0_1$

m (llj)^{min} spectrum
end-point: 552 GeV
exp. precision ~1 %



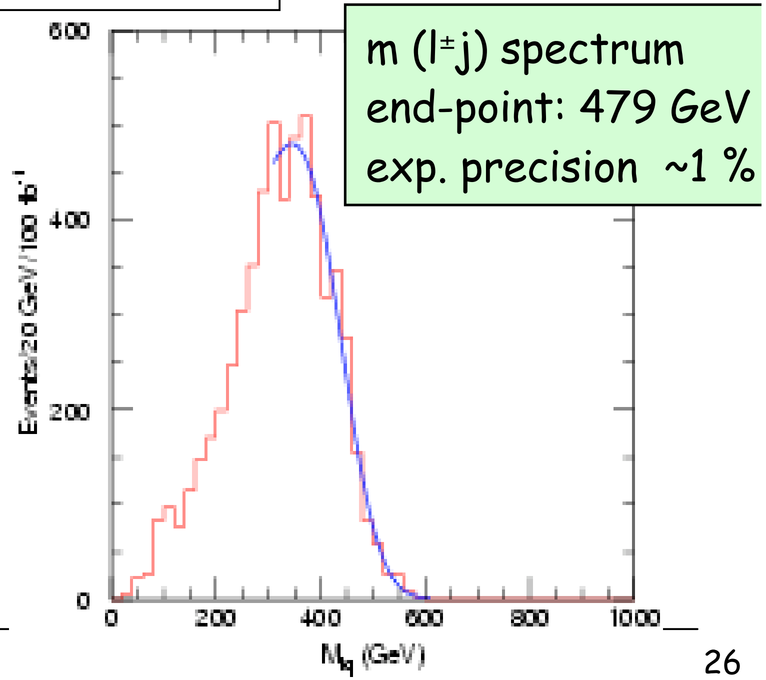
$$m(\tilde{q}_L\ \chi^0_2\ \tilde{l}_R\ \chi^0_1) = 690, 232, 157, 121\,\mathrm{GeV}$$

m (llj)^{max} spectrum
threshold: 272 GeV
exp. precision ~2 %

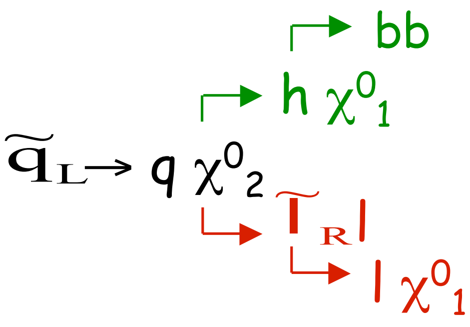


ATLAS
100 fb^{-1}
LHC Point 5

m (l$^{\pm}$j) spectrum
end-point: 479 GeV
exp. precision ~1 %



Putting all constraints together: m (bbj), m(ll), m(llj)^{max}, m(llj)^{min}, m(lj)



Sparticle mass	Expected precision 100 fb^{-1}
squark left	± 3%
χ^0_2	± 6%
slepton mass	± 9%
χ^0_1	± 12%

Particles directly observable at Point 5:

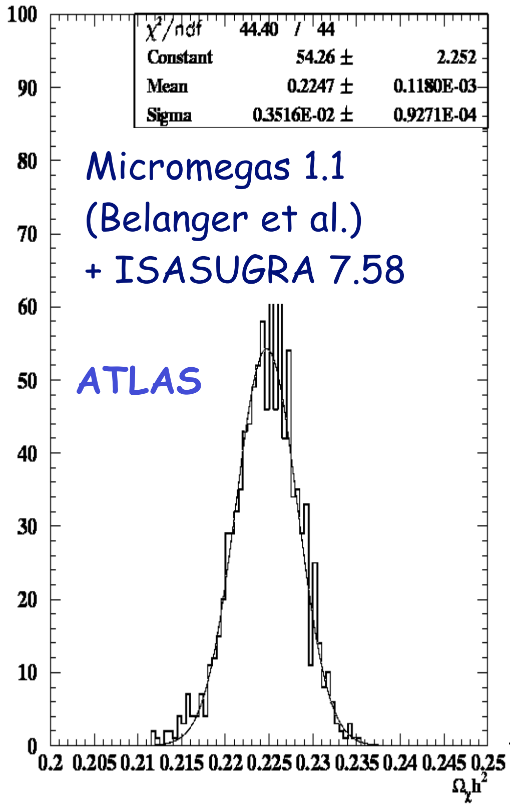
$\tilde{q}_L, \tilde{q}_R, \tilde{g}, \tilde{t}_1, \tilde{l}_R, \tilde{l}_L, h, \chi^0_2$

From fit of mSUGRA to all experimental measurements can deduce :

-- fundamental parameters of theory

-- cold dark matter relic density:

$\Omega_\chi h^2 = 0.2247 \pm 0.0035$ at Point 5



Expected precision on mSUGRA parameters for six "LHC Points"

ATLAS
300 fb^{-1}

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%)

μ = +, -

sign μ determined except Point 6

A_0 ~ unconstrained except Point 6

Remarks :

- These results are conservative because :
  only mass distributions used. Much more information will be available in the data:
  cross-sections, branching ratios, several distributions → will use everything
  → many more constraints.

- These results are optimistic because :
  constrained models like mSUGRA can artificially improve expected precision
  on model parameters because of high correlations between masses, etc. However :
  - impossible in practice to work in general MSSM (~ 100 parameters, not predictive enough) without experimental data to provide guidance
  - constrained models nevertheless provide useful benchmarks for study of LHC potential, detector performance, main analysis strategies

Experimental strategy towards understanding the underlying theory

❶ Inclusive searches → SUSY discovery (must be as model-independent as possible …)

❷ First characterization of the model, e.g.:

-- First estimate of SUSY mass scale and cross-section (to 10-20%)

-- Measure h mass to 0.1%-1%

-- Look for general features : Is there large missing E_T (R_p violation ?) ? Are there many leptons ? Are there "exotic" signatures (many γ's, heavy stable charged particles, etc.) ? Are there many b-jets and taus (could indicate large tanβ) ? Is there an excess of top-quarks ?

-- Look for / reconstruct semi-inclusive topologies, e.g. :

-- h → bb peaks

-- l^+l^- peaks, edges, …

-- tt pairs and their spectra → may indicate stop, sbottom in final state

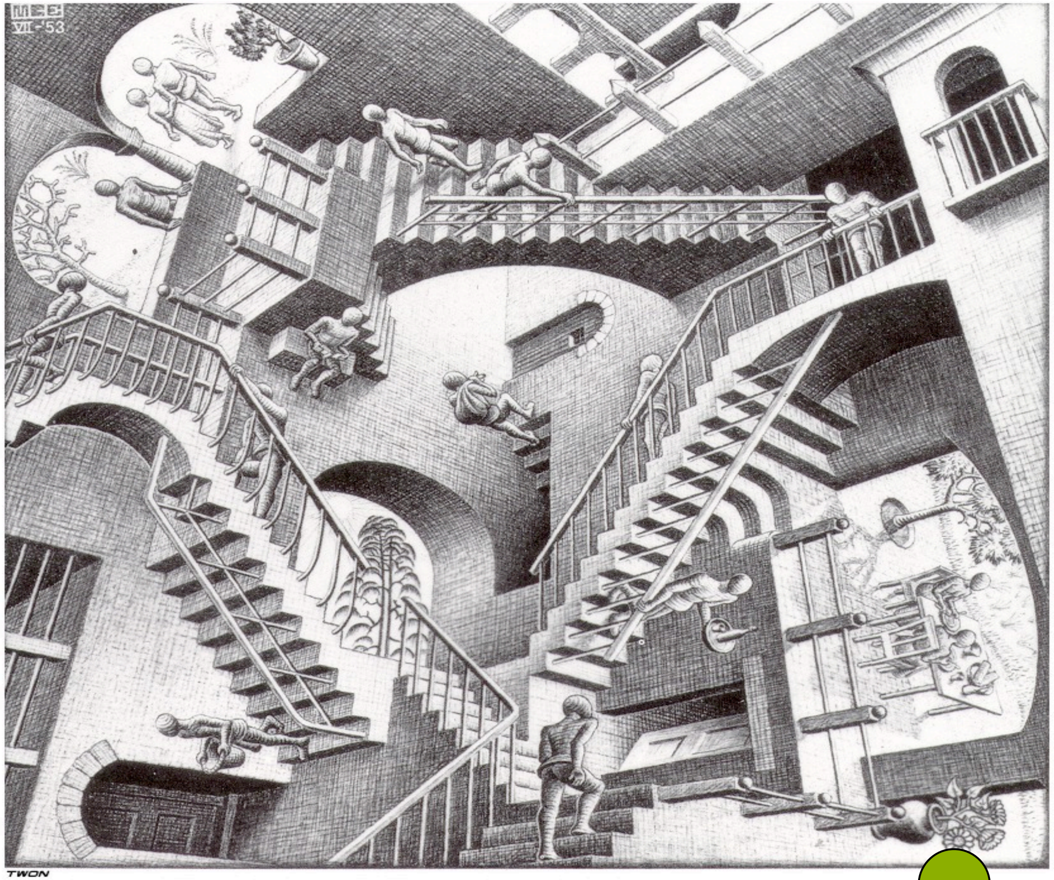
-- Explore Higgs sector: e.g. look for $\mu\mu$ and $\tau\tau$ peaks (from A/H decays)

-- More complicated signatures (e.g. involving combinations of jets) require more work …

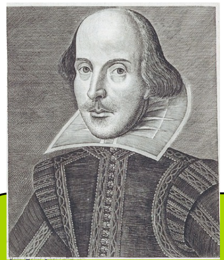
❸ Measure exclusive chains (masses, couplings, etc.) → try to determine theory parameters

At each step we should narrow spectrum of possible models and get guidance to go on …
Joint effort theory/experiments will be essential !

Theories with Extra-dimensions



A few examples
of the expected reach …

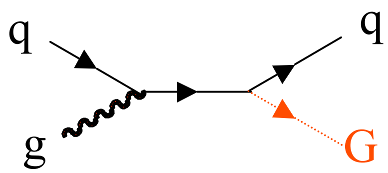


"Why bastard ? Wherefore base ? When my dimensions are as well compact,
my mind as generous, and my shape as true as honest madam's issue ? "

W. Shakespeare, King Lear, Act 1, Scene 2 (Edmund bastard son to Gloucester)

Large Extra-dimensions (ADD models) : direct graviton production

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

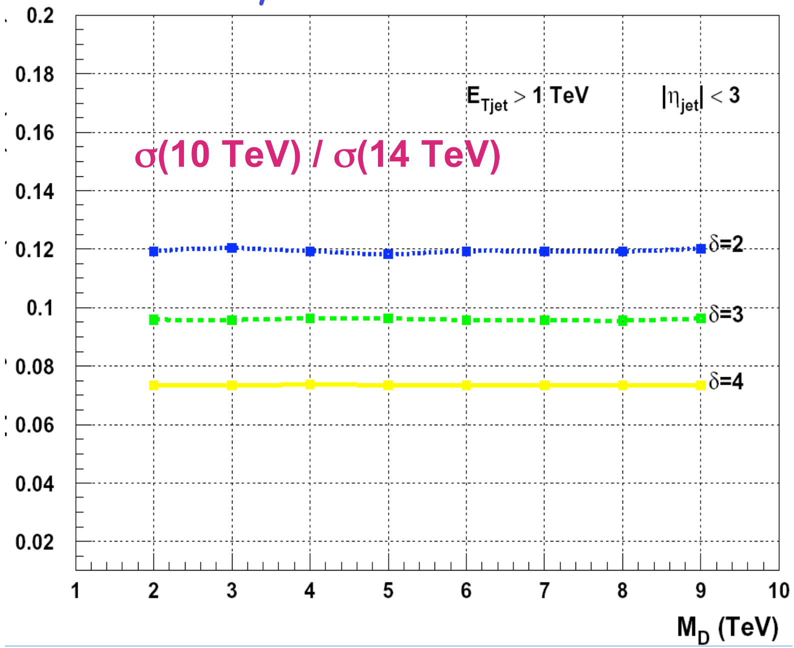
	δ = 2	δ = 3	δ = 4
M_D^{max}	9 TeV	7 TeV	6 TeV
$R_{compact}$	8 μm	2 Å	1 pm

Effective theory, valid only for
$\sqrt{\hat{s}} < M_D$ ➔ M_d^{min} ~ 5 TeV

To characterize the model need
to measure M_D and δ

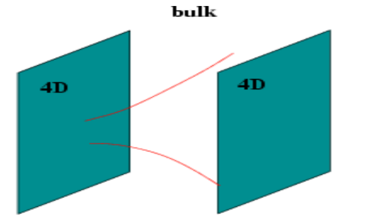
Measurement of cross-section gives ambiguous results: e.g. δ=2, M_D= 5 TeV very similar to δ=4, M_D= 4 TeV

Solution may be to run at different √s :



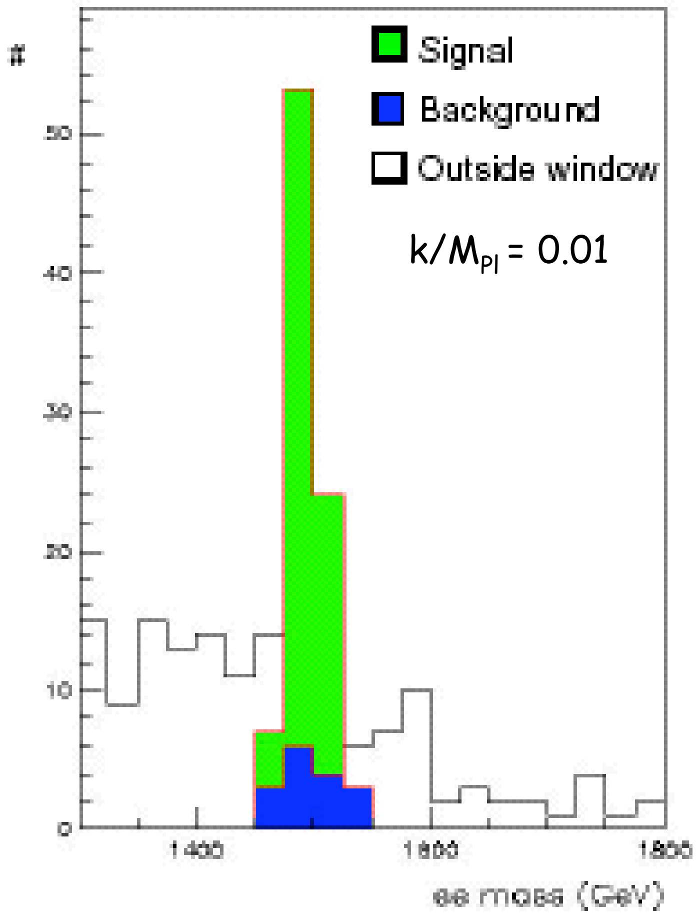
Good discrimination between various solutions possible with expected <5% accuracy on σ(10)/σ(14)

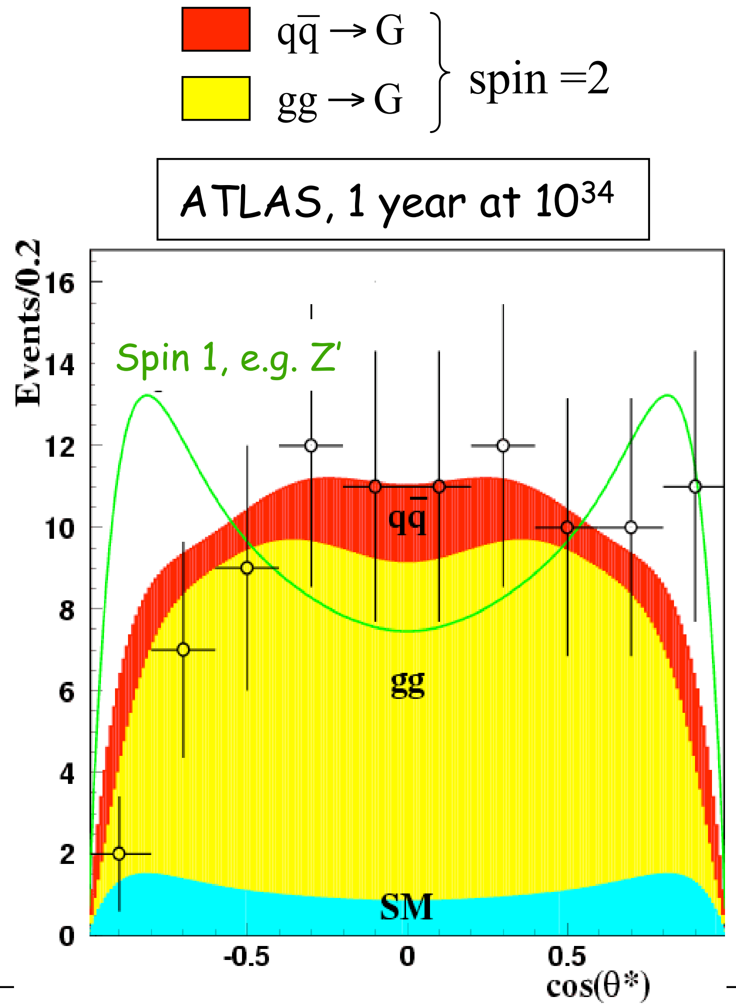
Warped Extra-dimensions (Randall Sundrum models) : production of narrow Graviton resonances



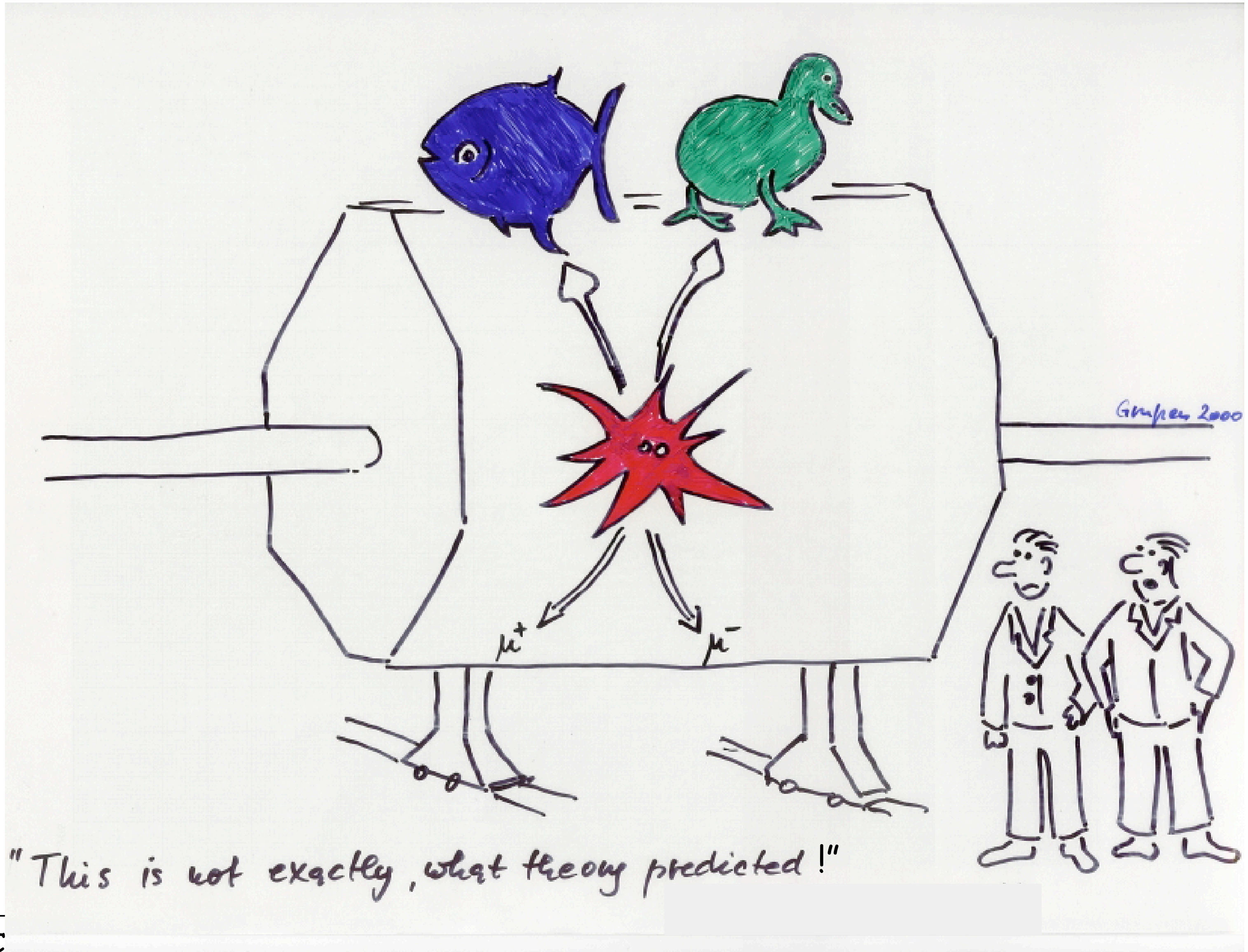
Best discovery channel : $qq, gg \to G \to e^+e^-$

CMS, 1 year at 10^{34}



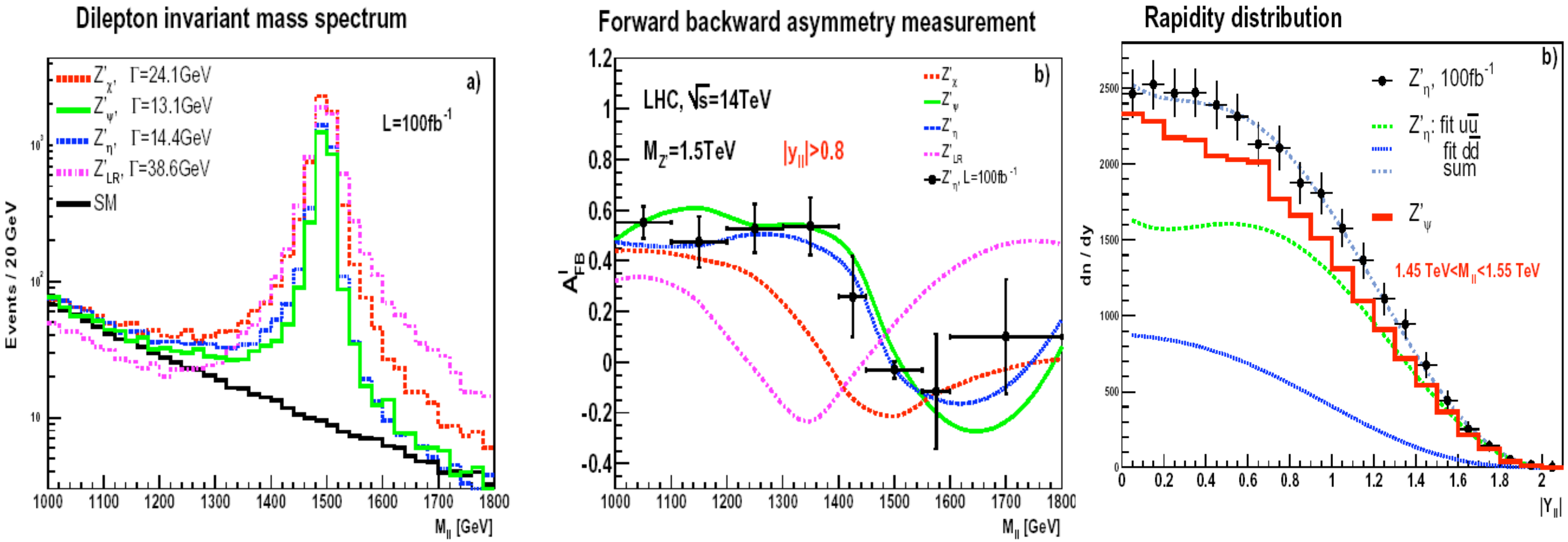


Many other scenarios and topologies are accessible ....



Extended gauge groups : $Z' \rightarrow l^+l^-$

CMS

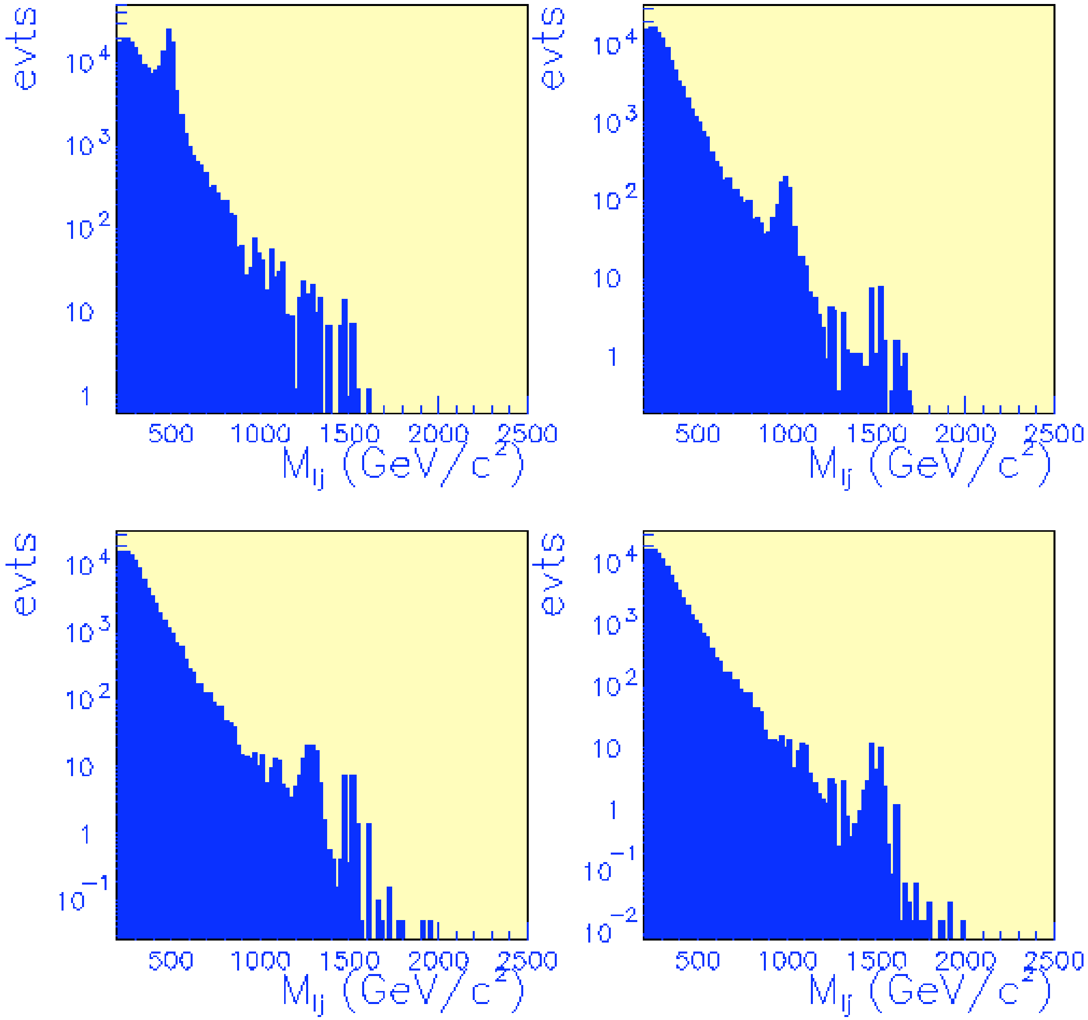


- Reach in 1 year at 10^{34} : 4-5 TeV
- Discriminating between models possible up to m ~ 2.5 TeV by measuring:
  - -- $\sigma x \Gamma$ of resonance
  - -- lepton F-B asymmetry
  - -- Z' rapidity

Extended groups (l-q symmetry): leptoquarks

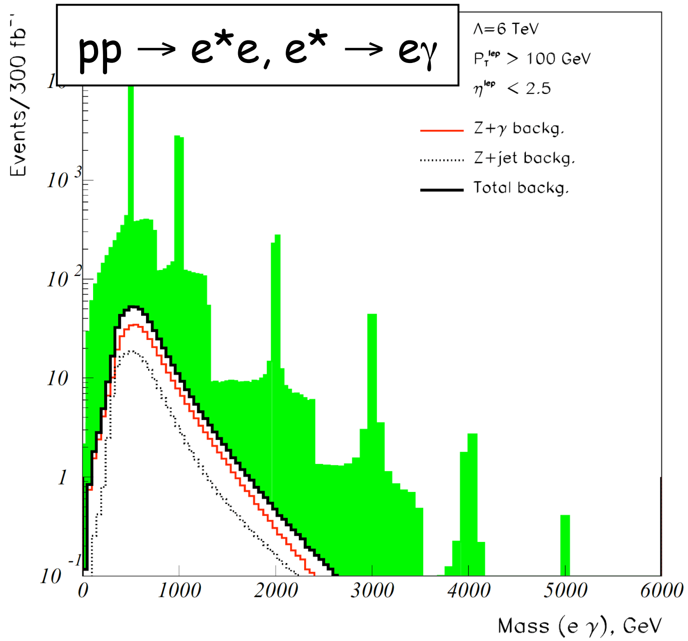
CMS

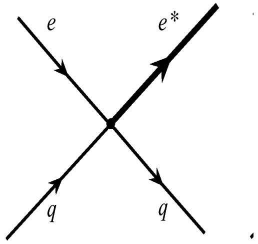
Production of pairs of scalar leptoquarks LQ LQ → lq lq → lj lj

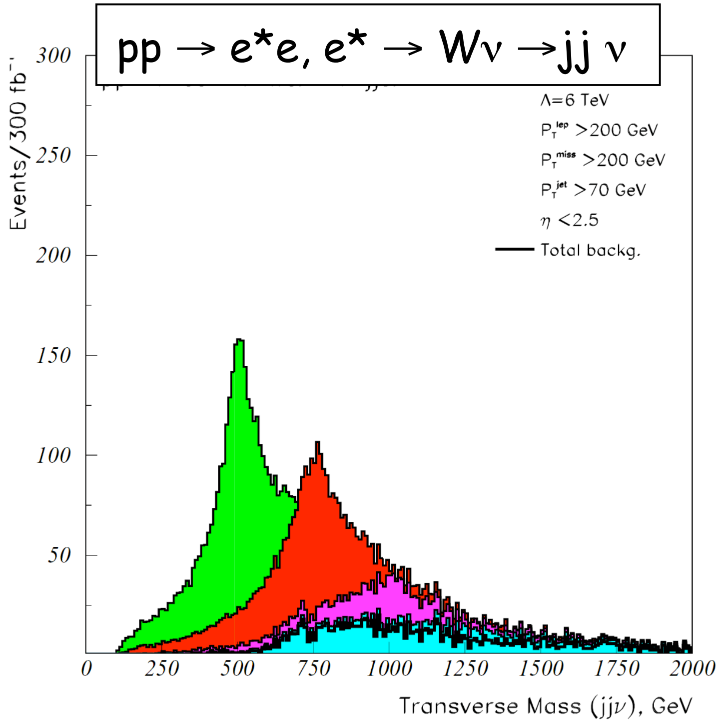


Reach up to ~ 1.5 TeV
Mass resolution ~ 3%

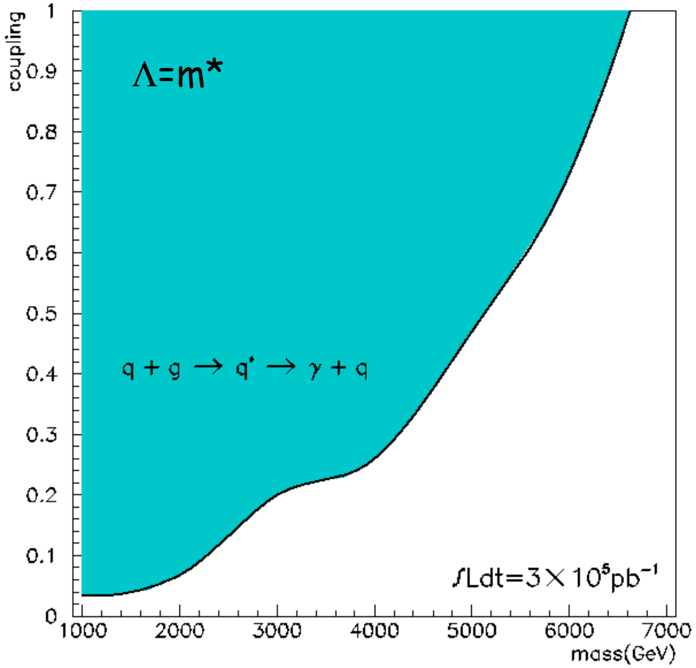
Compositeness : excited quarks and leptons



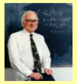




ATLAS



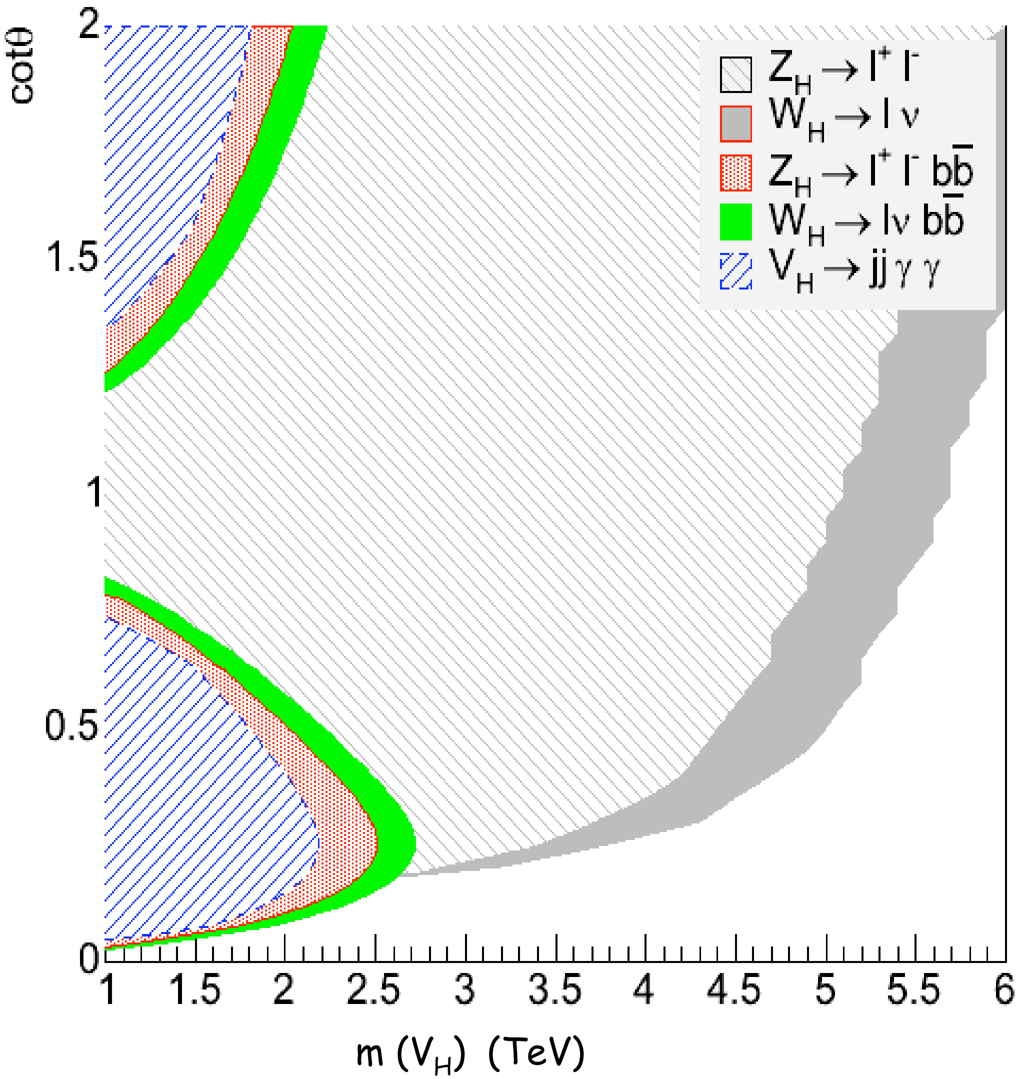
Reach : up to m ~ 6.5 TeV for q* Λ= m*
up to m ~ 4 TeV for e* Λ=6 TeV

Little Higgs  models

Arkani-Hamed et al., JHEP 207 (2002) 34

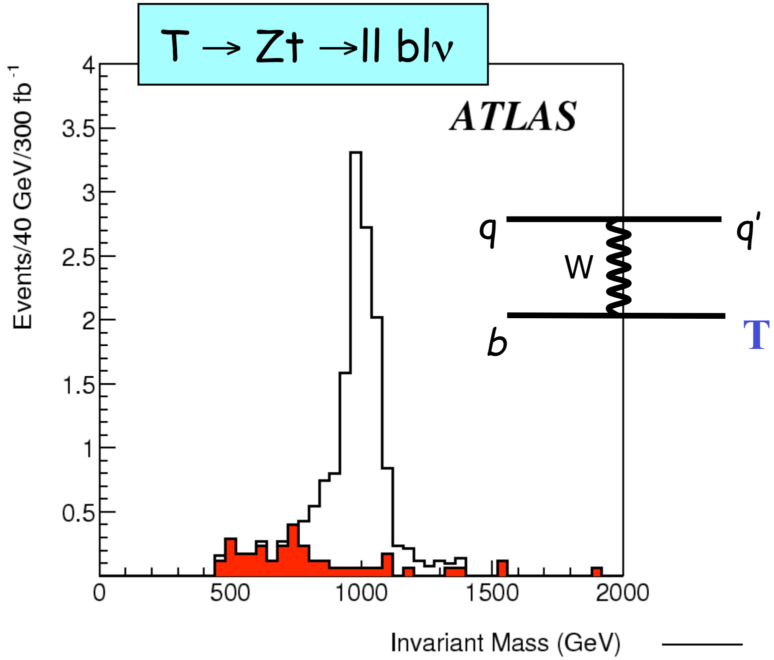
Han et al., Phys. Rev. D67 (2003) 95004

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

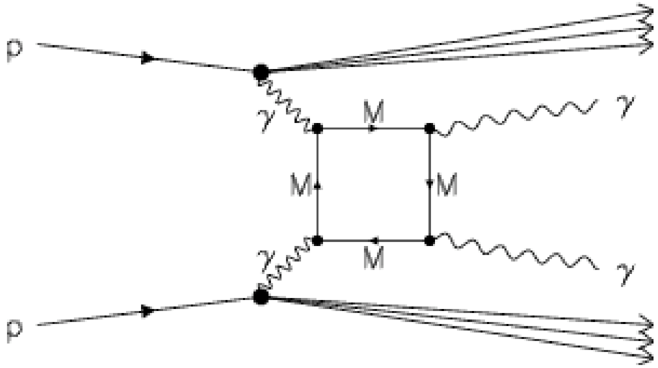


$V_H \rightarrow V\ h$

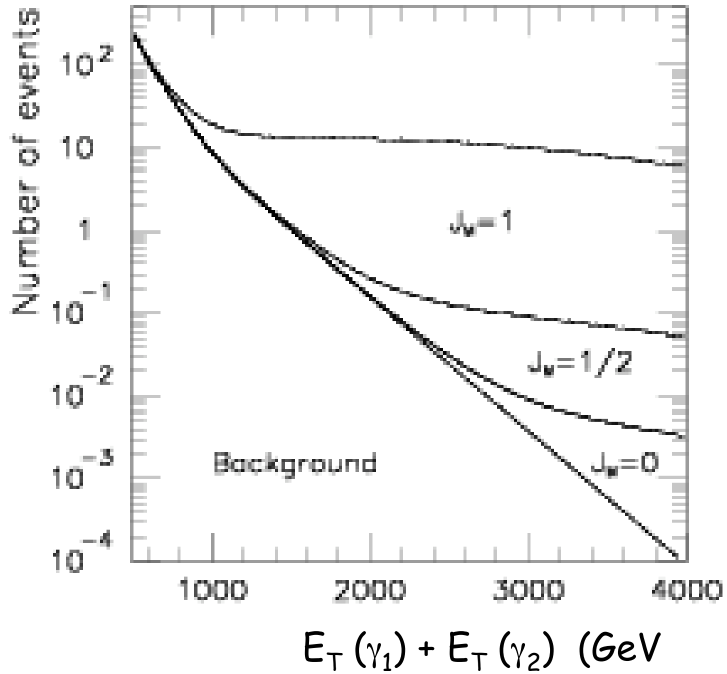
m_h=120 GeV

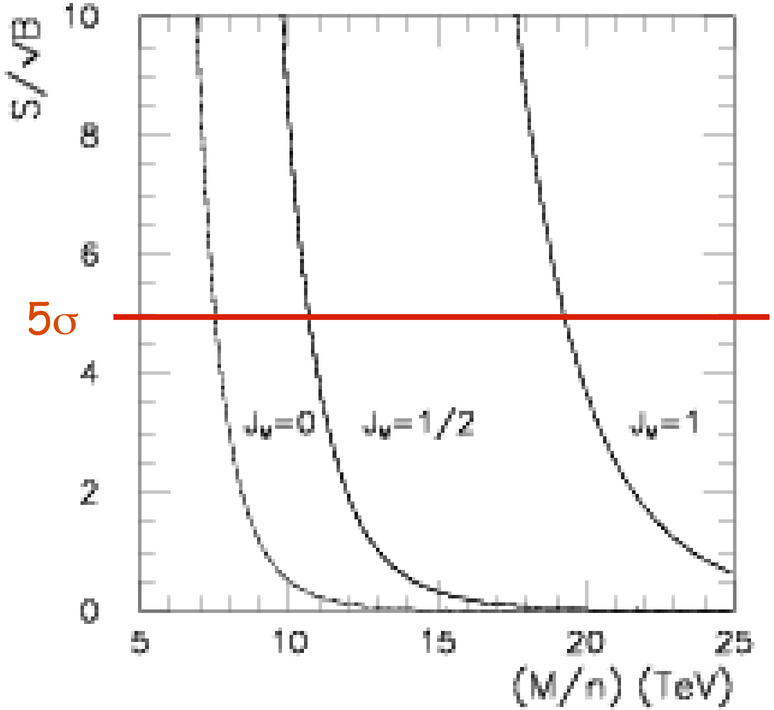


Dirac Monopoles



ATLAS, 100 fb^{-1} ≡ 1 year at 10^{34}

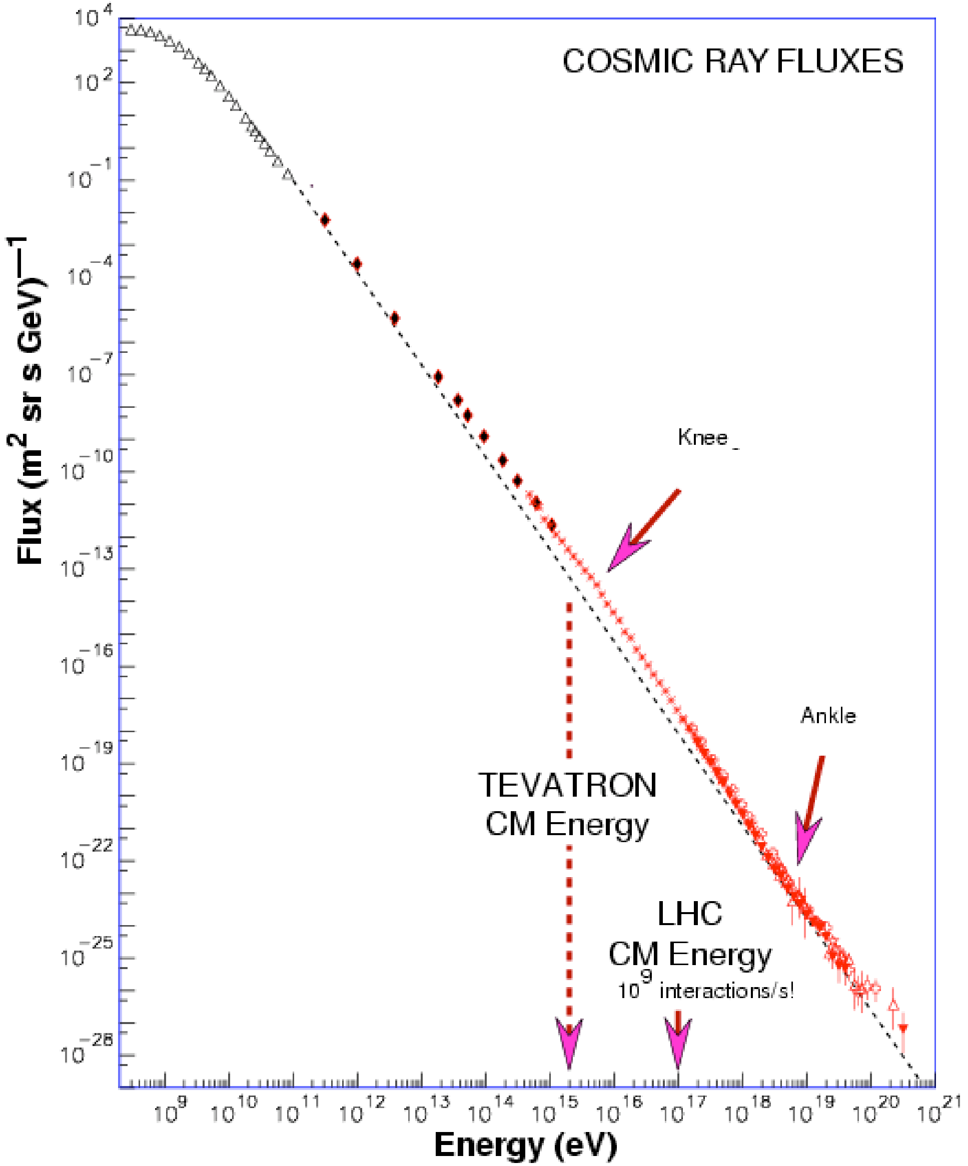




Discovery reach up to ~ 20 TeV

The LHC and high-energy cosmic rays

$\sqrt{s}$ = 14 TeV → corresponds to E ~ 100 PeV fixed target proton beam



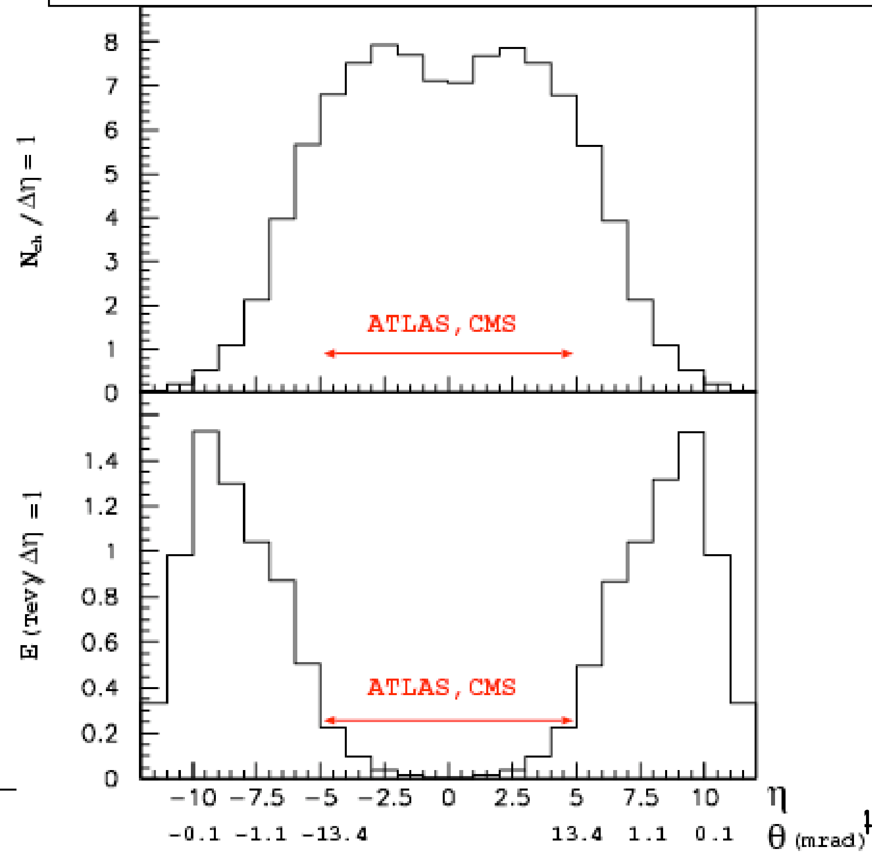
LHC studies most relevant to HECR:

-- most energetic particles from the collisions

-- pp (and pA, AA) cross-sections

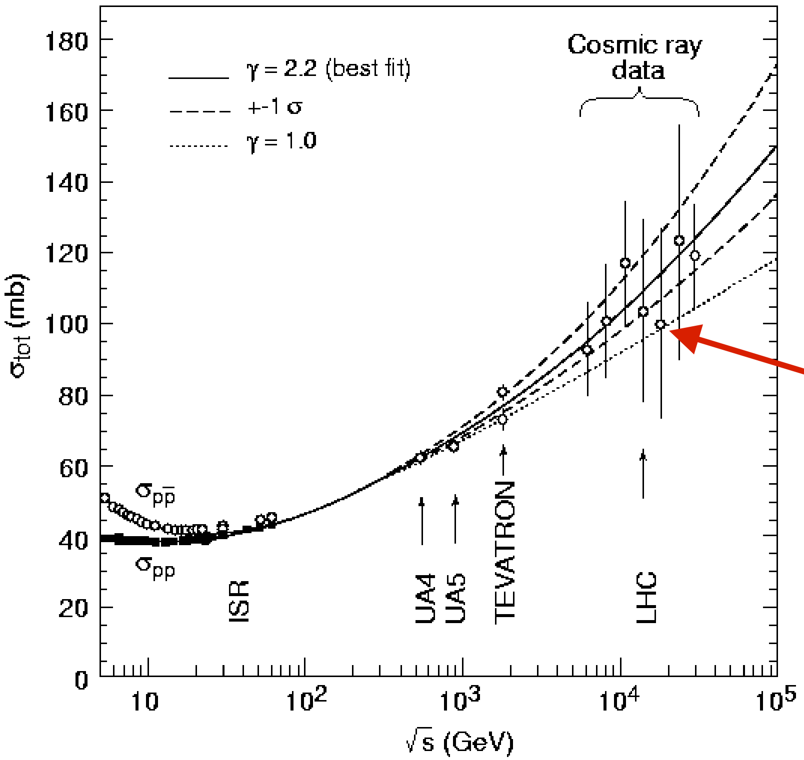
both require detection in the forward region

Charged particle multiplicity and energy in pp inelastic events at $\sqrt{s}$ = 14 TeV



F. Gianotti, Strings at CERN, 5/7/2004

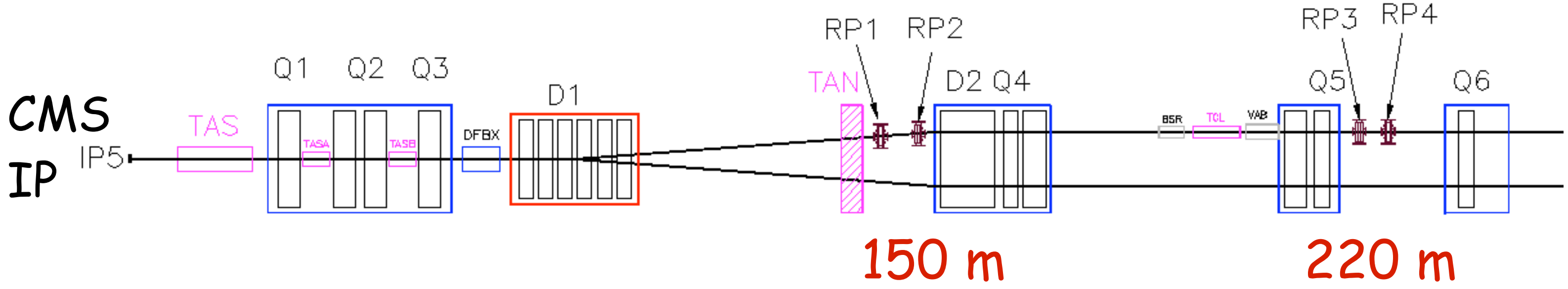
Measurement of σ_{tot} (pp)



Curves are ~ $(\log s)^{\gamma}$

Goal of TOTEM: ~ 1 % precision

TOTEM : 3 stations of detectors ("Roman Pots" RP1, RP2, RP3) at both sides of IP5 (integrated with beam pipe) to measure scattered proton in elastic interactions down to $\theta_{scat} \approx 20\ \mu rad$



Conclusions

LHC has very compelling and ambitious physics goals :

- Explore the highly-motivated TeV scale with direct discovery potential up to m ≈ 6 TeV
- Say the final word about several TeV-scale predictions:
  SM Higgs mechanism → origin of particle masses ?, SUSY → dark matter ?, etc.
- Perform several measurements with unprecedented precision : e.g. W mass, top mass, CP-violation (→ matter/anti-matter asymmetry, baryogenesis)
- Study heavy-ion collisions → quark-gluon plasma
- Measure σ_{tot} (pp, pA and AA) and study very high energy products of pp collisions
  → relevant to high-energy cosmic rays

To achieve these goals, we are building challenging machine and detectors , of unprecedented performance and complexity

Note : sensitivity of experiments to a huge number of signatures demonstrates their ability to cope with unexpected scenarios …

⬇

LHC should add many crucial pieces to our knowledge of fundamental physics
→ huge impact also on astroparticle physics and cosmology ?
→ in ~ 3 years particle physics may enter the most glorious epoch of its history …