Mass determination of Supersymmetric particles in ATLAS

Dr. scient. thesis by Borge Kile Gjelsten

Fabiola Gianotti (CERN), opponent

The Standard Model of the elementary particles and their interactions

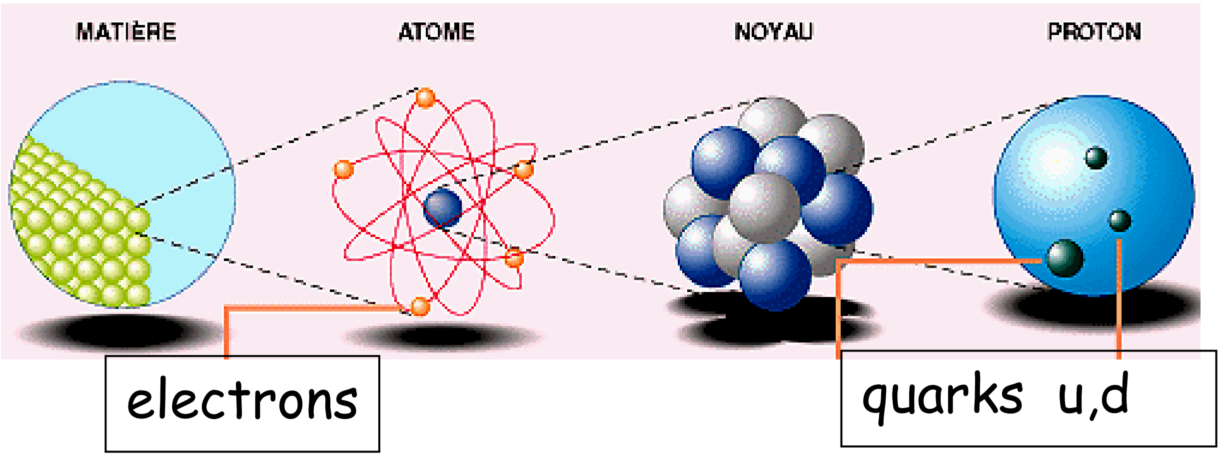
Predicts 3 families of elementary "matter" particles

Matter particles : fermions, spin =1/2

e	μ	τ	q= -1
ν_e	ν_μ	ν_τ	q= 0

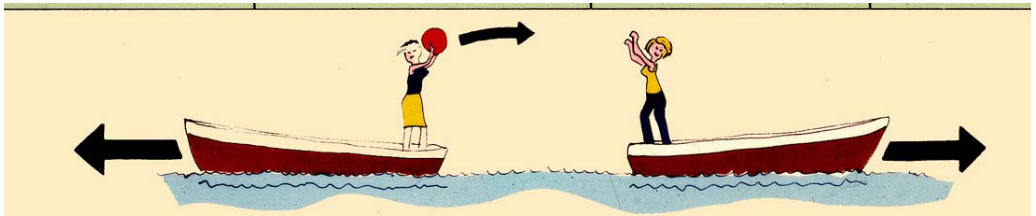
u	c	t	q= +2/3
d	s	b	q= -1/3

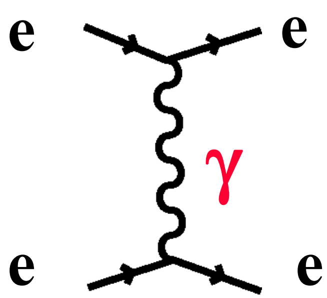
+ anti-particles

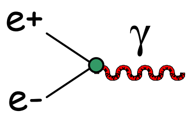
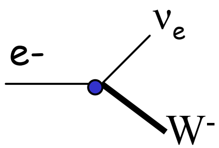
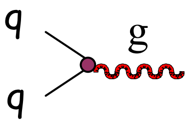


Note :
-- our world is made mainly of 1st family …
-- m(e-) ~ 0.5 MeV, m(top)~ 175 GeV !

These "matter" particles interact via the EM, strong and weak forces.
These forces are transmitted through the exchange of other elementary particles





Force carriers : bosons, spin=1				
Particle	Force	Coupling (E~100 GeV)	Mass	Intensity
γ	EM (charged particles) 	$\alpha_{EM} = \frac{e^2}{4\pi} \approx 0.008$	0	~ 10^{-1}
$W^{\pm}$, Z	weak (q, l, $W^{\pm}$, Z) 	$\alpha_W = \frac{g^2}{4\pi} \approx 0.03$	~ 100 GeV	~ 10^{-5}
8 g	strong (q, g) 	$\alpha_s = \frac{g_s^2}{4\pi} \approx 0.12$	0	1

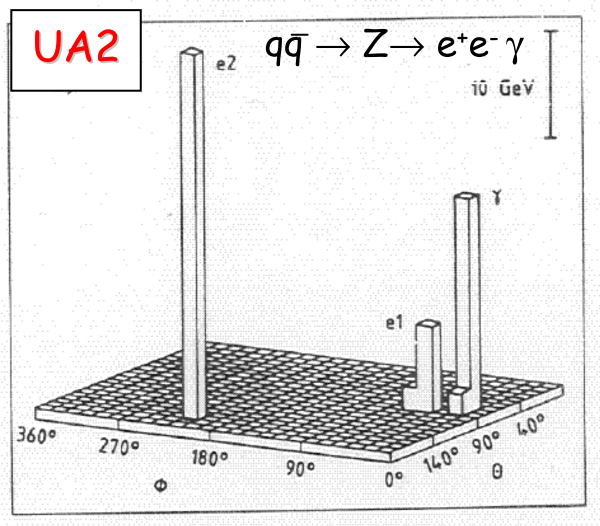
Intensity: relative to strong

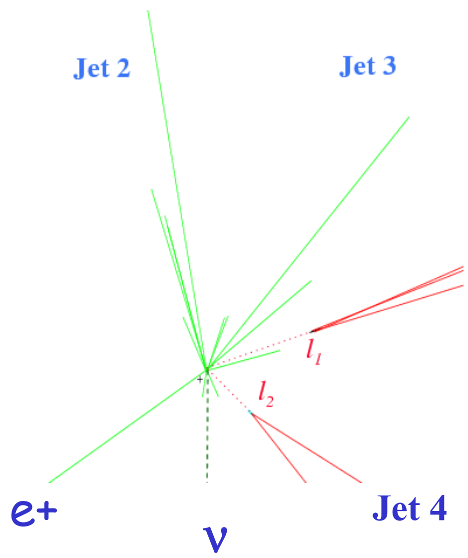
Why do we like the Standard Model ?

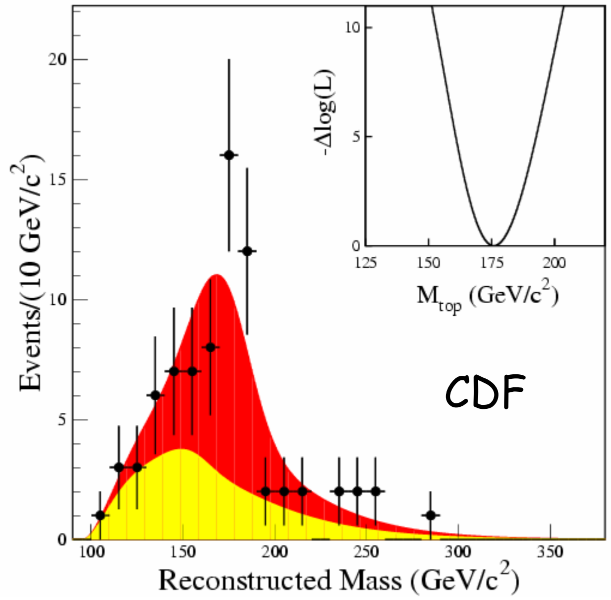
All the SM predictions (but one ...), in terms of particles and features of their interactions, have been verified by many experiments at many machines

1983 : Discovery of W,Z at CERN $p\bar{p}$ Collider ($\sqrt{s}$ ~ 600 GeV)
m ~ 100 GeV as predicted (UA1,UA2)

1994 : top quark discovered at Fermilab $p\bar{p}$ Collider ($\sqrt{s}$ ~ 2 TeV)
m ~ 175 GeV (CDF, D0)





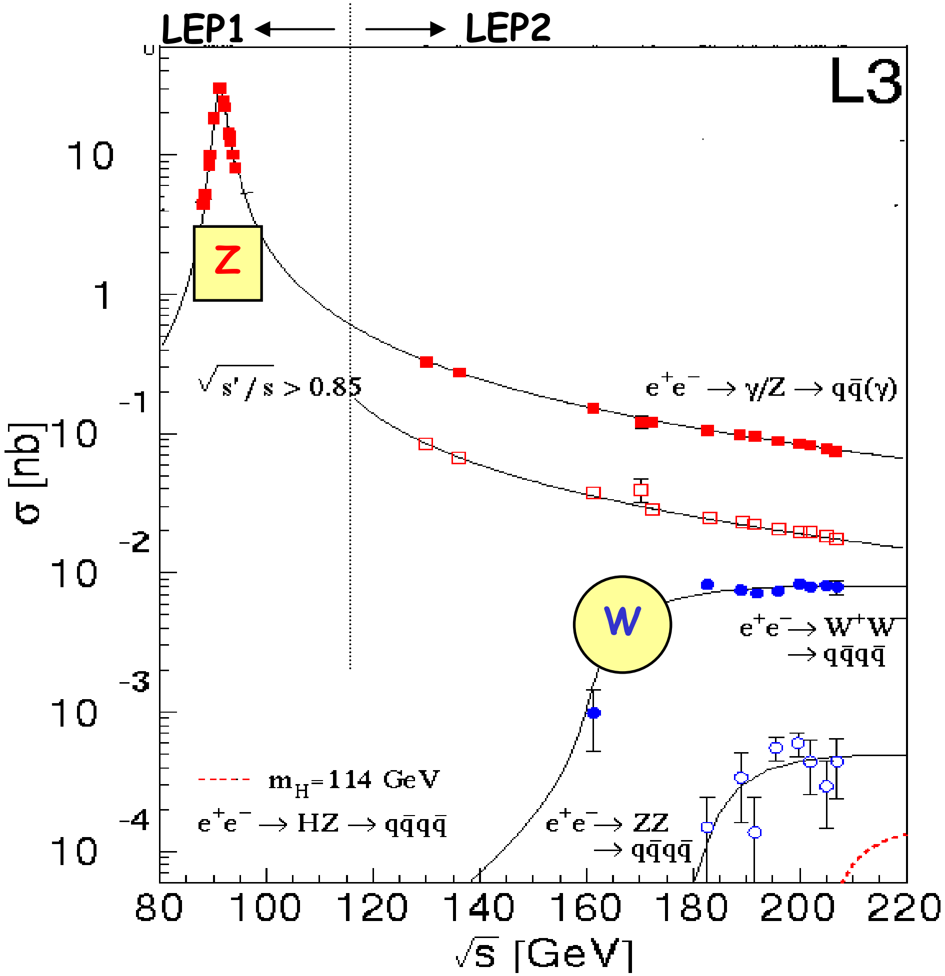


$t\bar{t} \to bW\,\bar{b}W \to bl\nu\,\bar{b}jj$ event from CDF data

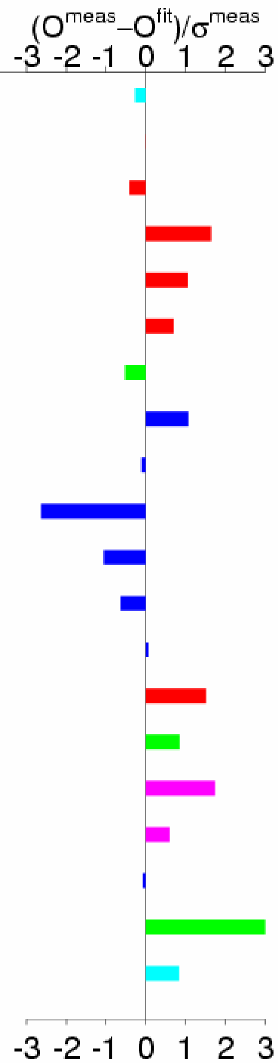
The LEP e+e- Collider at CERN

1989-2000 : $\sqrt{s} \approx m_Z \rightarrow 209$ GeV

Precise measurements of Z particle and of m_W, and search for new particles (Higgs !)



	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.39 ± 0.59	.84



Many spectacular measurements: agreement theory-data at the permil level !

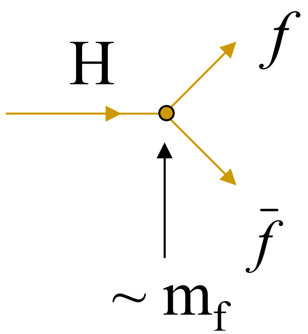
Why we don't like the Standard Model ?

Unable to answer in a satisfactory way to (too) many questions of fundamental importance …

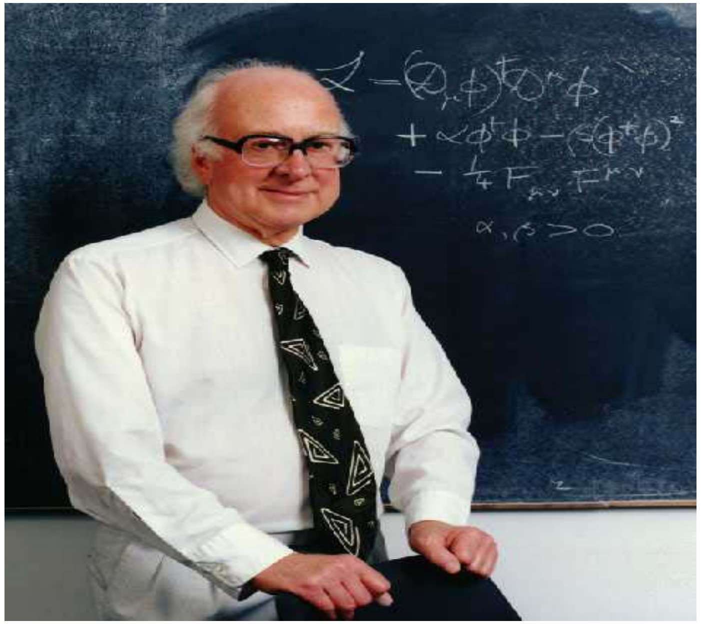
1) What is the origin of the particle masses ?

E.g. why $m_\gamma = 0$, $m_{W,Z} \approx 100$ GeV ?

SM : Higgs mechanism gives mass to particles



$m_H < 1$ TeV from theory



P.W. Higgs, Phys. Lett. 12 (1964) 132

Only unambiguous example of observed Higgs

However:
- -- Higgs not found yet: only missing (and essential !) piece of SM
  Present limit : $m_H > 114.4$ GeV (from LEP)
- -- Higgs mass increases (diverges !) with scale Λ up to which SM is valid $\rightarrow$ unphysical

2) Many other open questions

-- Why 3 lepton/quark families ? Why is the first family privileged ?
-- Are there additional (heavy) leptons and bosons ?
-- Are quarks and leptons really elementary ?
-- What is the origin of matter / anti-matter asymmetry in the universe ?
-- Why $M_{EW}/M_{Planck} \sim 10^{-17}$ ("hierarchy" problem) ?

-- What is the nature of the Universe Dark Matter ?

Recent astrophysical measurements (e.g. WMAP satellite) indicate that The Universe is made of:
-- 5% of known matter
-- 25 % of "Dark Matter" (no SM particle can explain it)
-- 70% of "Dark Energy"
→ today we understand only 5% of the Universe composition

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

All this calls for

A more fundamental theory
of which SM is low-E approximation → New Physics

Best candidates : Supersymmetry (SUSY)
Extra-dimensions
Technicolour

← to solve SM problems,
all predict New Physics
at ≈ **TeV scale**

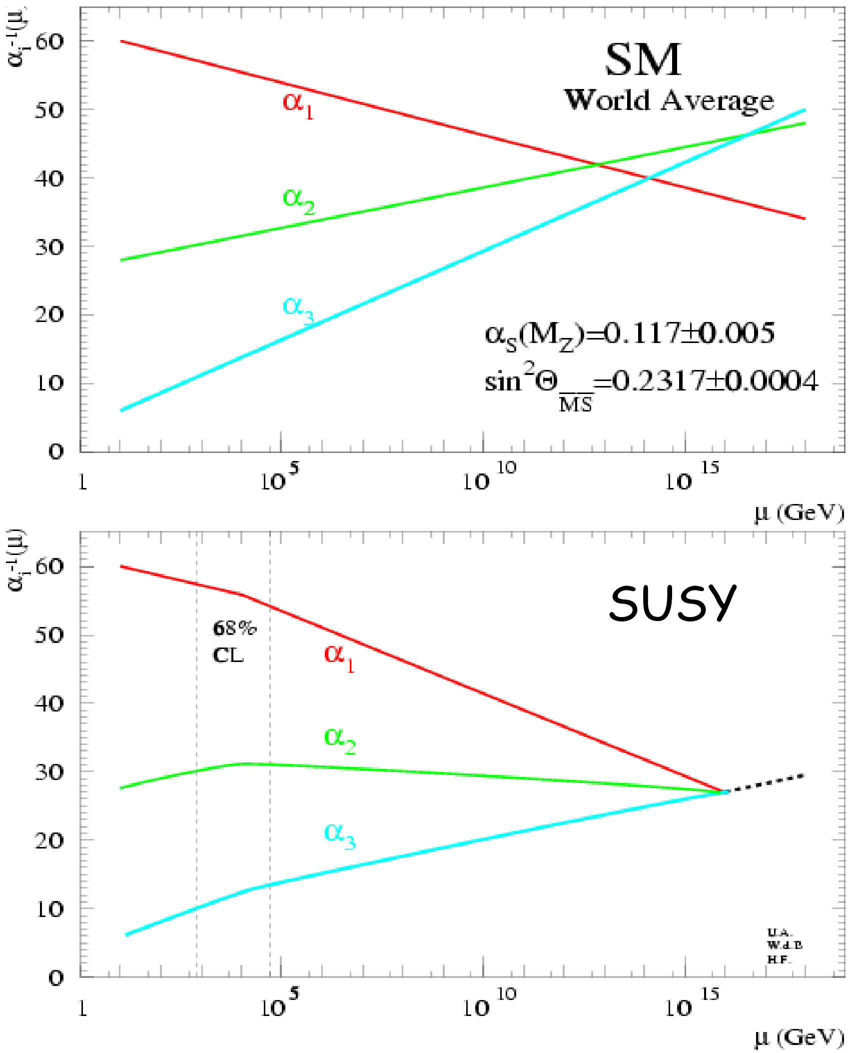
→ **need a machine to explore the ~ TeV energy range**

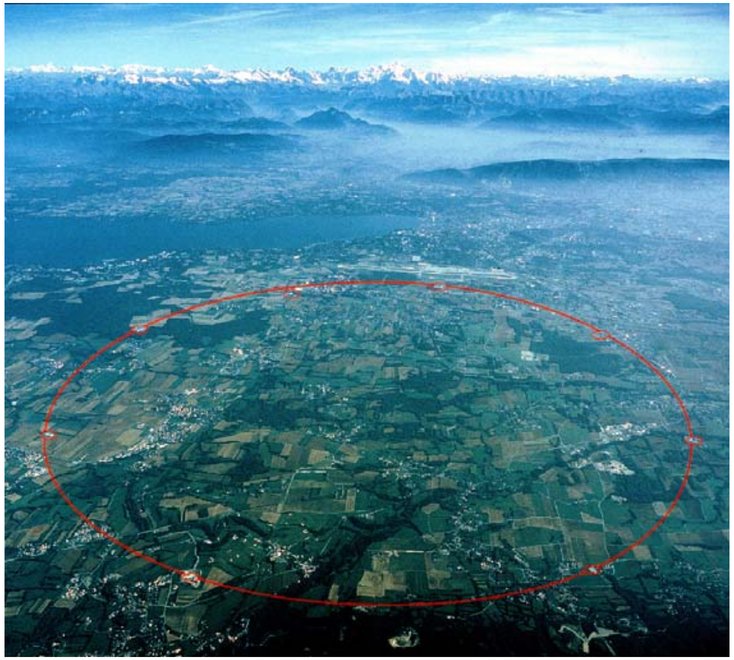
→ **CERN Large Hadron Collider (LHC)**

Borge's thesis is on Supersymmetry at LHC

One of the main indications in favour of SUSY : unification of coupling constants of EM, weak and strong forces at high energy scale

$\alpha_{EM} = 1/\alpha_1$
$\alpha_W = 1/\alpha_2$
$\alpha_S = 1/\alpha_3$

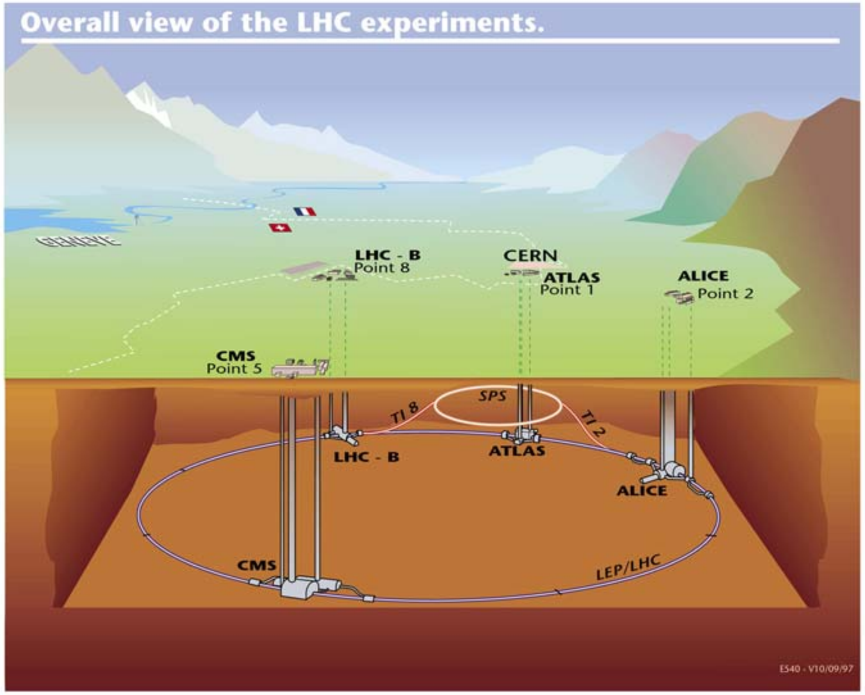




Large Hadron Collider

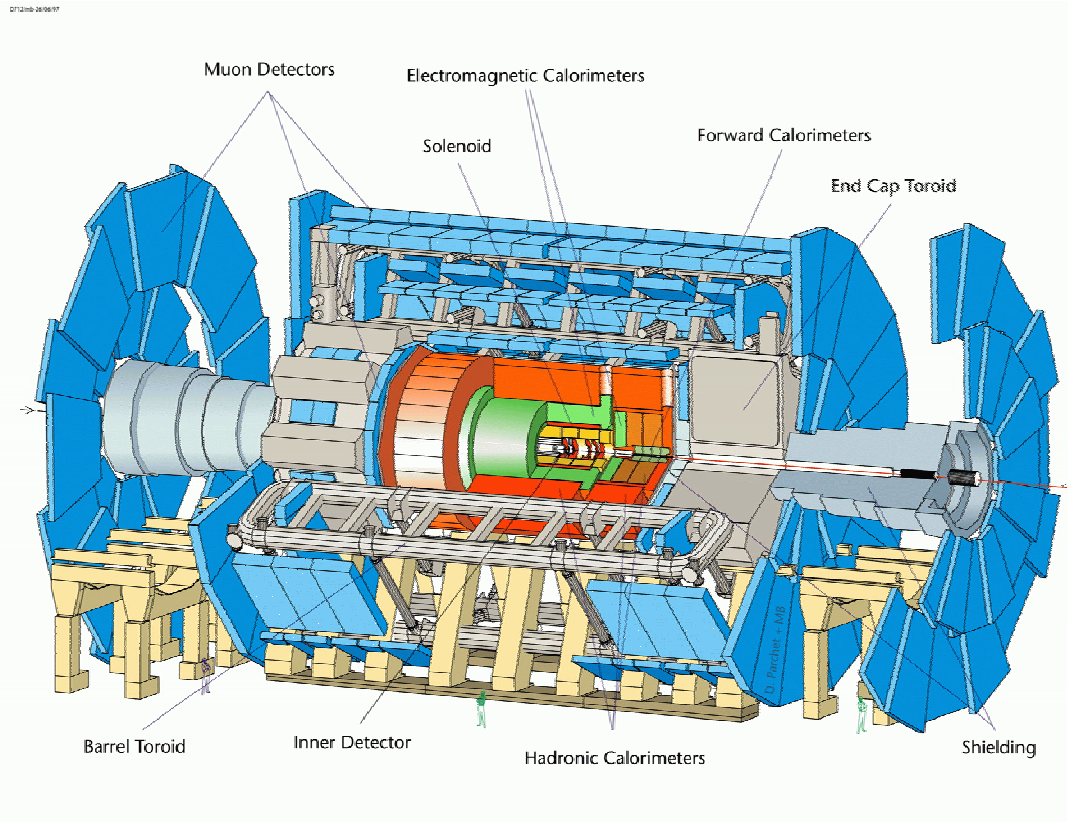
pp collisions at $\sqrt{s}$= 14 TeV
in 27 km ring

Data taking starts in Summer 2007



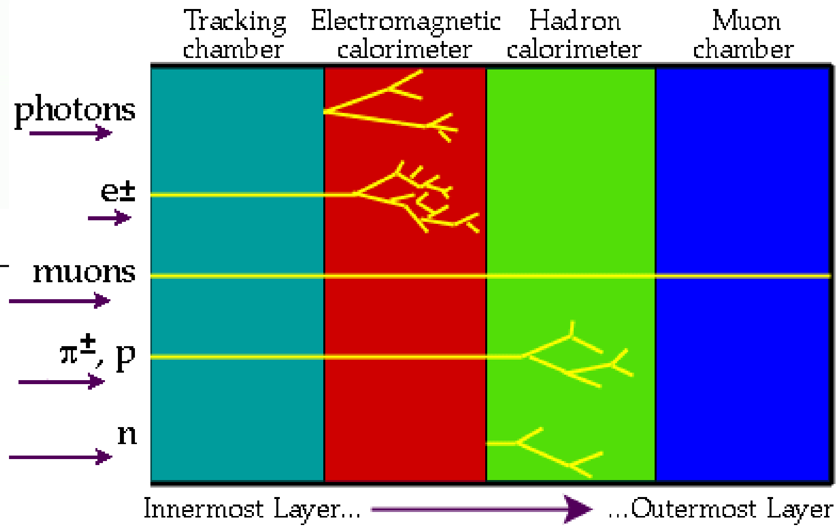
LHC, pp, $\sqrt{s}$= 14 TeV , L= 10^{33} cm^{-2} s^{-1}

	LHC events in 1 yr	Previous machines total data samples
Z	10^7	LEP: 10^7 in ~ 10 yrs
W	10^8	FNAL: 10^7 in ~7 yrs
top	10^7	FNAL: 10^5 in ~7 yrs
1 TeV Susy	10^4	----



ATLAS

Length : ~46 m
Radius : ~12 m
Weight : ~ 7000 tons
~10^8 electronic channels
~ 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

SUPERSYMMETRY (SUSY) ≡ symmetry between fermions (matter) and bosons (forces)

- All SM particles p have SUSY partner $\tilde{p}$ with same couplings and quantum numbers except $\text{spin}(\tilde{p}) = \text{spin}(p) - 1/2$

SM particle	SUSY partner	spin
l	sleptons $\tilde{\ell}$	0
q	squarks $\tilde{q}$	0
g	gluino $\tilde{g}$	1/2
$W^{\pm}$ (+Higgs)	charginos $\chi^{\pm}_{1,2}$	1/2
γ, Z (+Higgs)	neutralinos $\chi^{0}_{1,2,3,4}$	1/2

Particle spectrum in minimal models (MSSM)

+ 5 Higgs : h, H, A, $H^{\pm}$

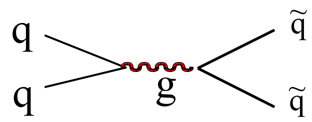
$m_h < 130$ GeV

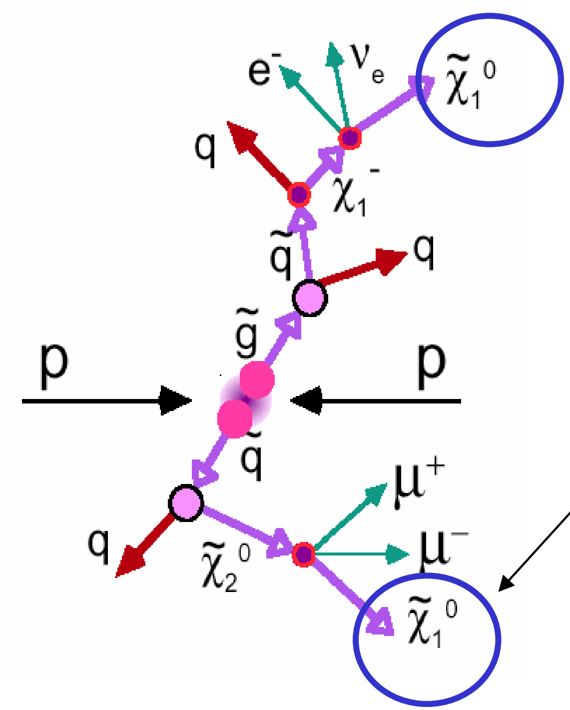
- No experimental evidence for SUSY → sparticles are heavy

However : to solve SM Higgs mass problem need : $m(\tilde{p}) < \sim 1$ TeV

- In most popular/motivated models:
  - -- SUSY particles produced in pairs
  - -- Lightest Supersymmetric Particle (LSP) is stable
    LSP ≡ χ^0_1 weakly interacting ⟷ dark matter candidate
  - -- all SUSY particles decay to LSP

SUSY production at LHC





This particle (neutralino) is neutral and weakly interacting → escapes detection (like neutrinos)

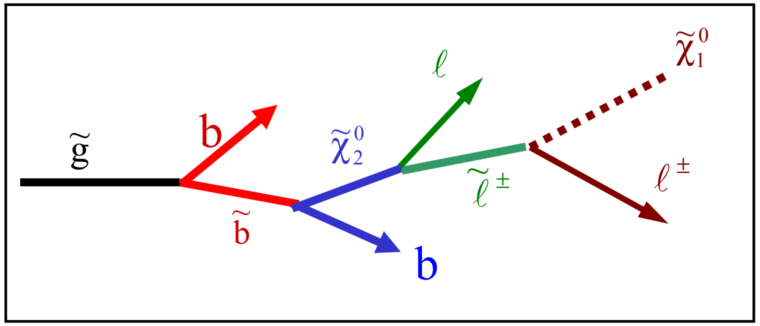
LHC discovery reach

Time	reach in squark/gluino mass
1 month	~ 1.3 TeV
1 year	~ 1.8 TeV
3 years	~ 2.5 TeV
ultimate	up to ~ 3 TeV

Discovery is not enough to understand and constrain the NEW theory (and also to be sure that χ^0_1 is indeed the Dark Matter particle): for this we need to measure the sparticle masses.

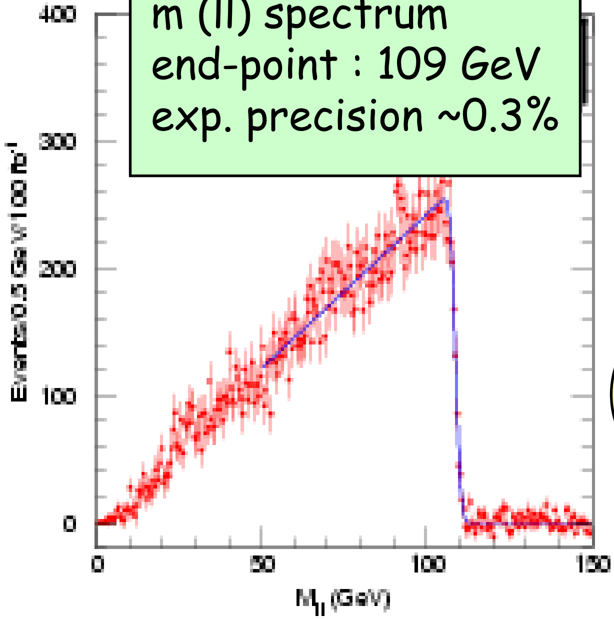
This is the subject of Borge's thesis

However, this is not so simple …



- Because of the escaping neutralinos, mass peaks cannot be directly reconstructed
- Method: measure end-points of reconstructed mass spectra of visible particles 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 → information on and consistency with Dark Matter

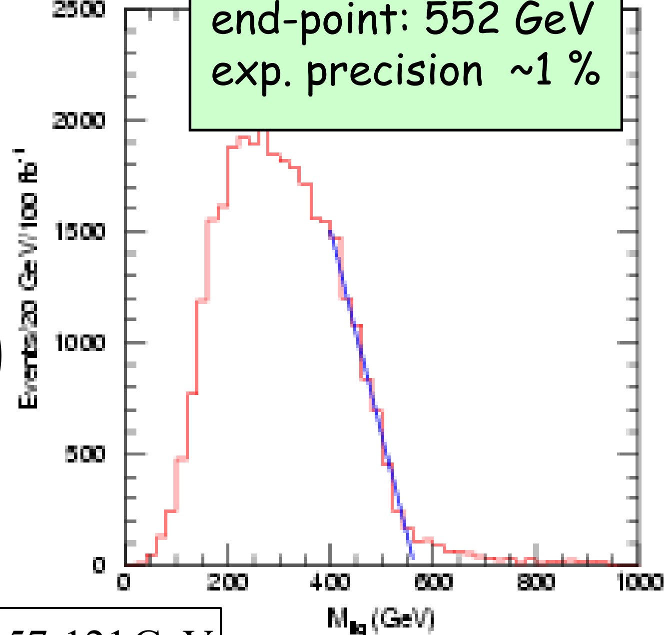
m (ll) spectrum
end-point : 109 GeV
exp. precision ~0.3%



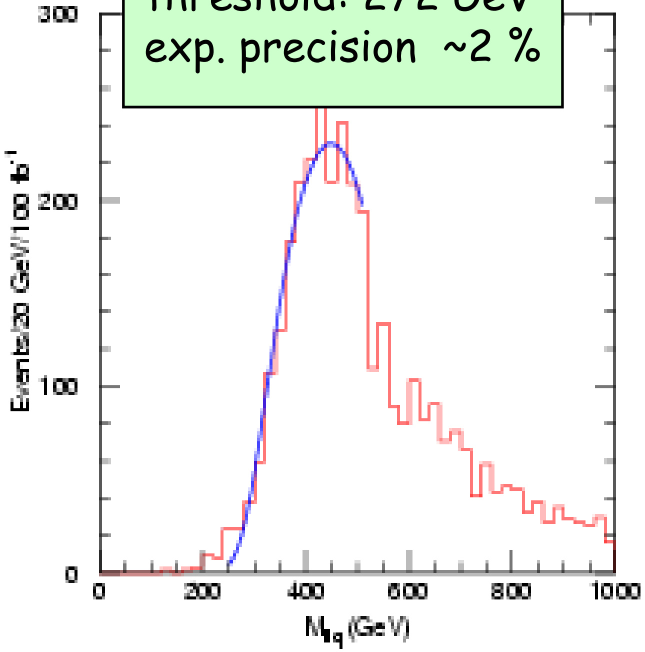
Example of a typical chain (studied by Borge):

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

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



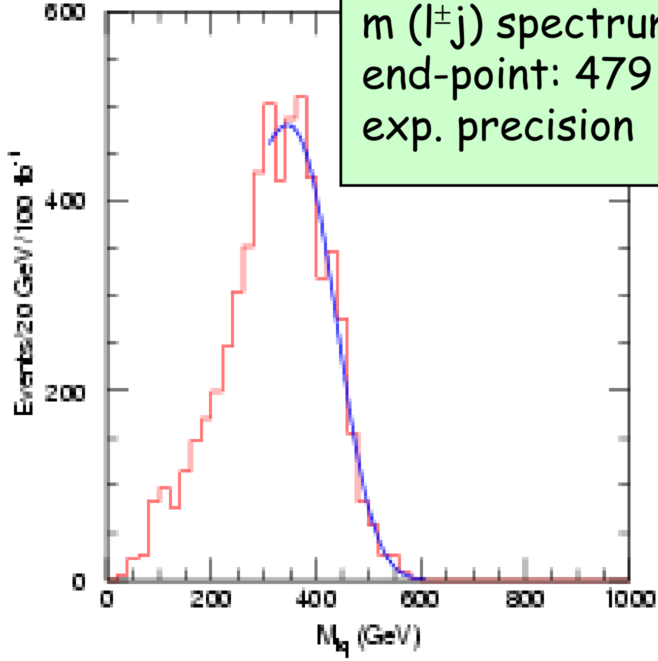
m (llj)^{max} spectrum
threshold: 272 GeV
exp. precision ~2 %



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

ATLAS
100 fb^{-1}

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

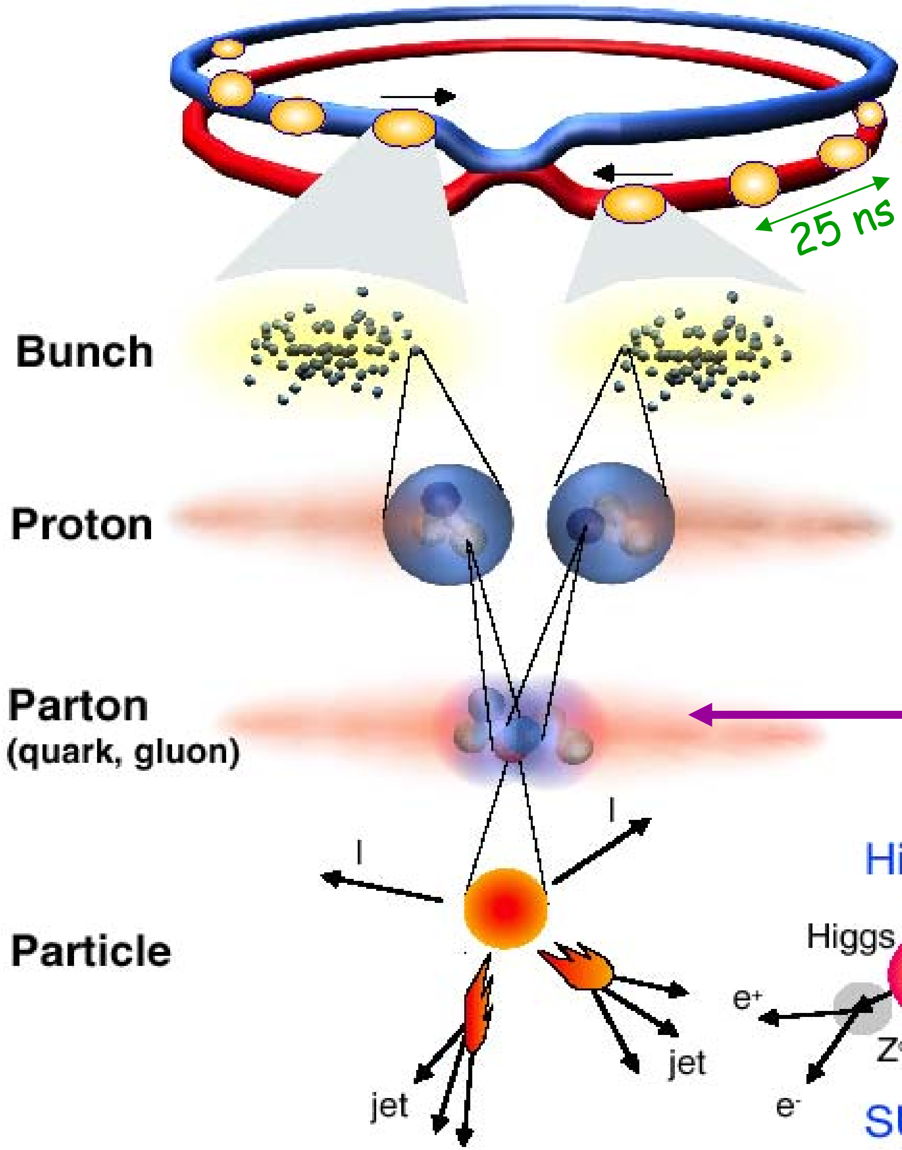


Borge's thesis

- Detailed studies on how to determine SUSY particle masses from end-point measurements
- For the first time, the complexity of such measurements (coming e.g. from the *a priori* unknown SUSY phenomenology) has been addressed in detail
- Pioneering work of scientific significance because this technique will be the standard method used at the LHC
- For the reasons outlined before the thesis subject is original and well motivated
- The work level meets international standards, as demonstrated also by the two published papers based on this thesis
- The thesis is written in a clear way, and indicates that Borge masters both experimental and theoretical/phenomenological issues

Back-up slides

Collisions at LHC



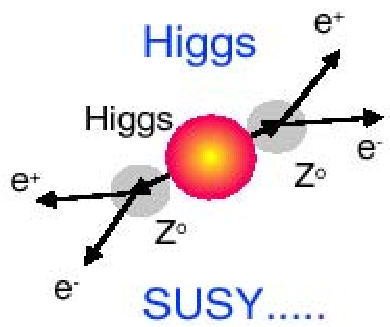
Proton-Proton	
Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**

Event rate in ATLAS :

$N = L \times \sigma\,(pp) \approx$ 10^9 interactions/s

Mostly soft (low p_T) events

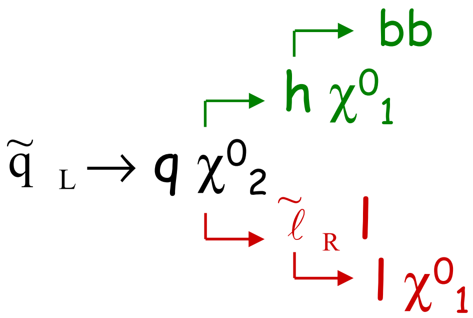
Interesting hard (high-p_T) events are rare



Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

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:

$\tilde{q}_L$, $\tilde{q}_R$, $\tilde{g}$, $\tilde{t}_1$, $\tilde{\ell}_R$, $\tilde{\ell}_L$, h, χ^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