Pomeriggi Tematici della

Sezione INFN di Roma 2011

Prospettive di fisica oltre il Modello Standard a LHC

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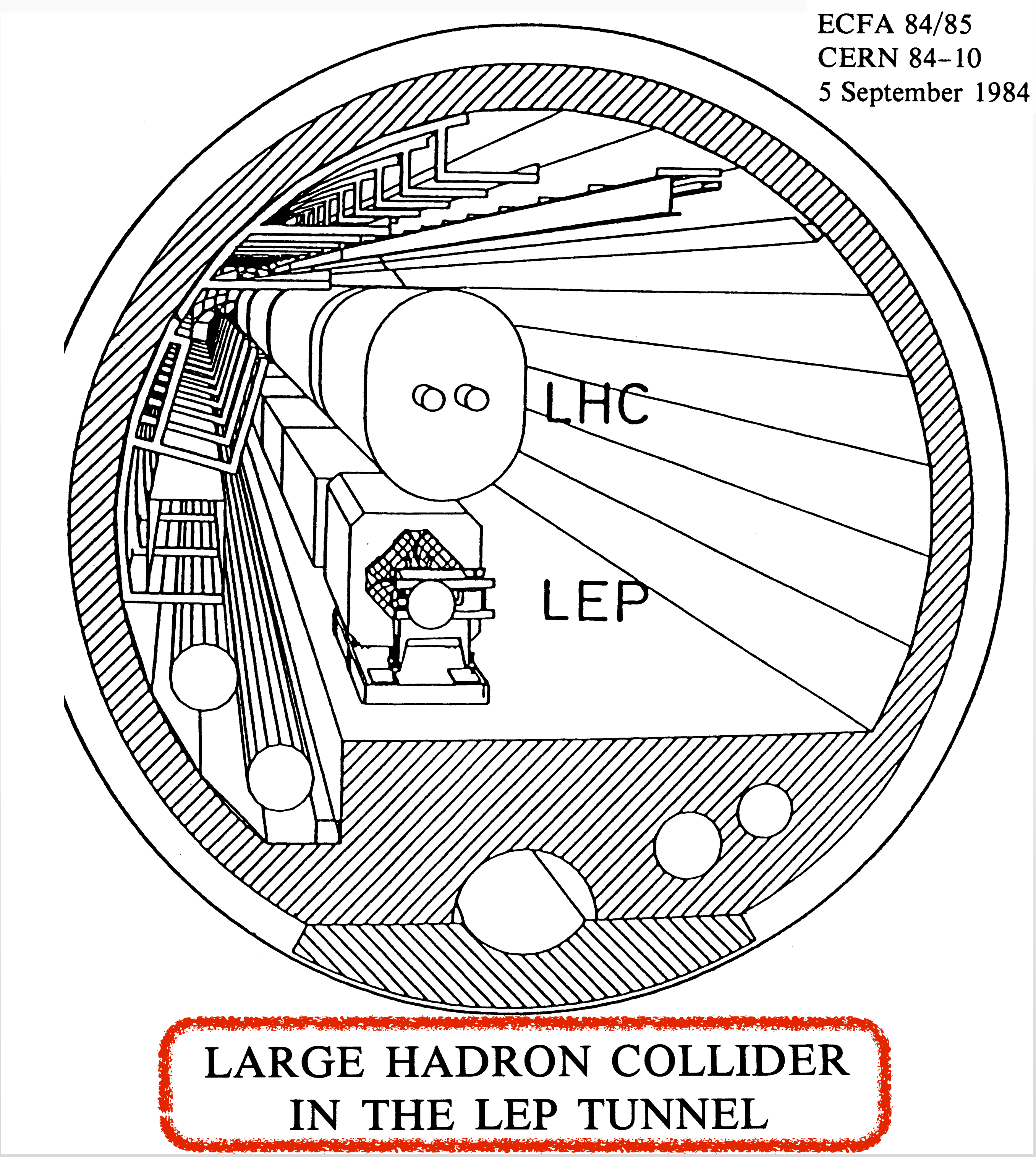
Outline

- **Why "Today" is so special for HEP:**
  - Historical Prologue
  - Theoretical Expectations
  - hot LHC results just about to come
    (well-deep into the yet-unexplored regime)

Historical Prologue

- Lausanne-Geneva Workshop (21-27 March 1984)



first public discussion on the LHC project (27 years ago ...)

*Note :
LEP approved in 1981;
W discovery at CERN ppbar collider in 1983

pp (ppbar) Collider
with $\sqrt{S}$ ~ 10-20 TeV
and L~ $10^{33(31)}$ $cm^{-2}s^{-1}$

probes interactions at
$\sqrt{S'}$~ o(TeV)→ 10^{-17} cm

LHC Physics Case in '84

- Exp's in 70's and early 80's beautifully confirmed the gauge theory picture of fundamental interact's based on

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

that solved problems arised in 30's to 60's related to :

what is the nature of the weak force?

what is the nature of the strong force?

what is the structure of hadrons?

- "not the end of the story but the opening of a new chapter"

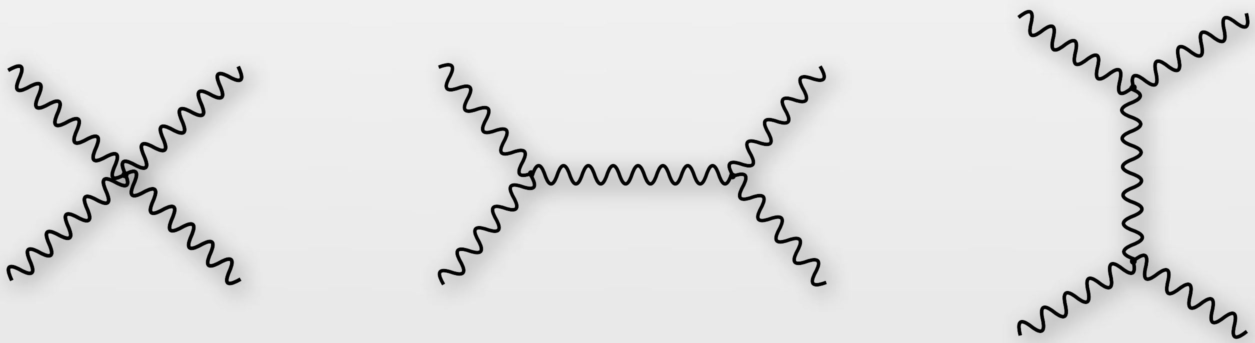
Llewellyn Smith

implies new phenomena at the TeV scale !

- the origin of mass
- the origin of flavour
- the origin of CP violation
- the connection between the electroweak, strong and gravitational forces.

Origin of mass: the Higgs mechanism ?

- in the SM all fundamental fields (EW gauge bosons + fermions) acquire mass through the Higgs mechanism
  - (symmetry-breaking) mass terms arising from scalar-field v.e.v.
  - keeps the theory renormalizable
- Higgs boson treats disease in the $W_L W_L$ scattering :



violates pert. unitarity at $\sqrt{S} \sim$ 1-2 TeV !

- NOTE !

in case Higgs boson (with m_H<700 GeV) is not there, something else (beyond SM) must solve this problem ! Hard to think LHC will not meet the challenge !

What happened since '84 (exp)

SM widely consolidated !!!

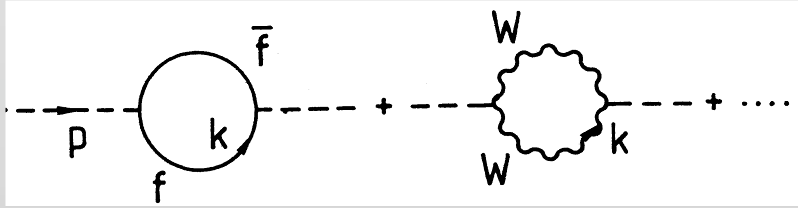
- LEP ('89-'00)
  - test of the SM at loop level
  - non abelian nature of EW couplings
  - EWPT ➡ powerful tool to constrain BSM models
  - direct+indirect mass bounds on SM Higgs :114 GeV< m_H <200 GeV
- TeVatron ('85-'11)
  - finds missing (top) quark with mass according to LEP EWPT
  - 158 GeV< m_H <173 GeV excluded (direct search)
- Neutrino physics : neutrinos are massive ('98); PMNS ≠ CKM
- B factories (2000-2010)
  - CKM matrix dominant source of flavor and CP violation
- Astrophysics: dark matter ? + dark energy ('98) ? + ???

EWSB requires new phenomena at the TeV scale

- Higgs is a peculiar object : first fundamental scalar field (could be just an "effective description" of EWSB)
- problem with scalar fields :

  - $m_f \; \bar{\psi}\psi \xrightarrow{\text{chiral symmetry}} 0 \quad \Rightarrow \quad \delta m \sim m \; \ln \frac{\Lambda_{SM}}{m}$
  - $m_W^2 \; W_\mu W^\mu \xrightarrow{\text{gauge symmetry}} 0 \quad \Rightarrow \quad \delta m^2 \sim m^2 \; \ln \frac{\Lambda_{SM}}{m}$
  - $m_H^2 \; H^2$ *no symmetry in the SM protects* m_H

$$\Rightarrow \quad \delta m^2 \sim \Lambda_{SM}^2$$



extending SM up to large scales requires unnatural cancellations
→ fine-tuning (hierarchy) problem !

Solutions to hierarchy problem discussed in '84

- SuperSymmetry : extends to bosons good convergence properties of fermions
- Technicolor : Higgs field is a composite of new fermion and antifermion as heavy as 1 TeV, bound by superstrong "technicolor" forces
- all particles are composite with a structure resolved at ~ 1 TeV, invalidating the loop calculation at this energy
- strong Higgs self interactions develop at 1 TeV and cut off the loop integral;
  strong WW-interactions develop at $\sqrt{S}$ ~ 1 TeV

CONCLUSION ('84) : with or without Higgs mechanism new phenomena should occur below or around 1 TeV

what happened since '84 (Th)

- "old" solutions to hierarchy problem still well and alive (but more constrained by exp's: EWPT's, FCNC's, light Higgs...)
- from late 90's a series of alternative solutions were proposed :
  - extra space-time dimensions (e.g., bring M_{Planck} down to ~ 1 TeV)
  - "little Higgs" (extra symmetries allow m_H only at two loops and nonperturbative regime starts at Λ~ 10 TeV)
  - "light" composite Higgs (bound state of new strongly interacting dynamics, pseudo-Goldstone of a Sp.Br. Global Sym)
  - . . .
- Dark Matter interpretation as a WIMP often required in model building ➡ DM could be produced and detected at LHC !

WIMP: Weakly Interacting Massive Particles

- assume DM is a thermal relic
  - stable, neutral particle
  - at thermal equilibrium at the starting Universe
  - at a certain (freeze-out) time decouples
- then measured relic density corresponds to annihilation cross sections for EW interacting particles with mass $M_{wimp} \sim (10\text{-}1000)$ GeV
  - measurable production cross section at colliders
  - behaves as a stable heavy neutrino in a collider detector
  - gives rise to missing E/p_T signature
- oldest model with a natural candidate: SuperSymmetry, WIMP mostly given by the lightest neutralino

LHC in an unprecedented enterprise in many respects !

- huge technological, experimental, and sociological challenge...

- also because of the number of different theoretical model to be tested !!!
  outcome of about 30 years of theoretical activity...

Warning : no guarantee for anyone !

BUT we expect something BSM must show up at ~1 TeV

in a sense, Th predictivity diluites with time (and number of New Physics models.....)

- in general prediction of <u>**new particles**</u> :
  heavier replicas of (a few) SM particles
- can affect only Higgs, W, Z sector
- can affect only H, W, Z, top, b sector
- can affect only gravity
- couplings either weak, SM-like, or relatively strong
- if not involving New Exact Global Symmetries (like R-parity), can be produced in resonance
- otherwise produced in pairs (at least lower states in towers) and give rise to E_{miss}

after 30 years, SuSy is still the best candidate to solve all problems connected to (and beyond !) the TeV scale

- weakly coupled theory (coupl.s are known !) : allows accurate and consistent Th predictions even at scales >>TeV
- can in principle be extended up to M_{GUT}, M_{Pl}, and even support the desert hypothesis ➡ consistent with GUT
- stabilizes mass hierarchy;
- predicts light (fundamen.) Higgs boson; radiative EWSB
- delicate impact on EWPT's and FCNC's
- Dark Matter origin as a WIMP

sparticles list

particles list

quarks	$\rightarrow$	squarks	$\tilde{q}_L,\ \tilde{q}_R$	
leptons	$\rightarrow$	sleptons	$\tilde{\ell}_L\ \tilde{\ell}_R$	
$W^\pm$	$\rightarrow$	winos	$\tilde{\chi}^\pm_{1,2}$	charginos
$H^\pm$	$\rightarrow$	charged higgsinos	$\tilde{\chi}^\pm_{1,2}$	charginos
γ	$\rightarrow$	photino	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
Z	$\rightarrow$	zino	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
h,H	$\rightarrow$	higgsinos	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
g	$\rightarrow$	gluino	$\tilde{g}$	

For each fermion f two partners $\tilde{f}_L$ and $\tilde{f}_R$ corresponding to the two helicity states

The SUSY partners of the W and of the $H^\pm$ mix to form 2 charginos

The SUSY partners of the neutral gauge and higgs bosons mix to form 4 neutralinos

so...SuSy is the "perfect" theory (?)

- actually, two weak points for SuSy:
  one on the exp side, the other on the theory side

- on the exp side :
  no susy partner observed in > 30 years of searches;
  present mass bounds on squarks and gluinos (cMSSM)
  ~ 500-900 GeV (LHC) [on EW partners ~ 100 GeV (LEP)]

- on the theory side : (makes implications of previous item less dramatic !)
  remarkable arbitrariness in construction of theoretical models for SuSy breaking
  (on which spectrum of SuSy partners is crucially based) !

a few robust constraints on mass spectrum :

- in order to stabilize SM mass hierarchy, SuSy partner masses should be in the o(TeV) range
- (SuSy breaking) mass terms in SuSy Lagrangian should not spoil the good convergence properties of SuSy !

  ➡ > 100 new parameters (cf. ~ 20 SM mass param's)

  - FCNC's implies squarks and sleptons with same quantum #'s are either almost degenerate in mass or almost diagonal in Yukawa matrices !

    ➡ constrains # of free parameters

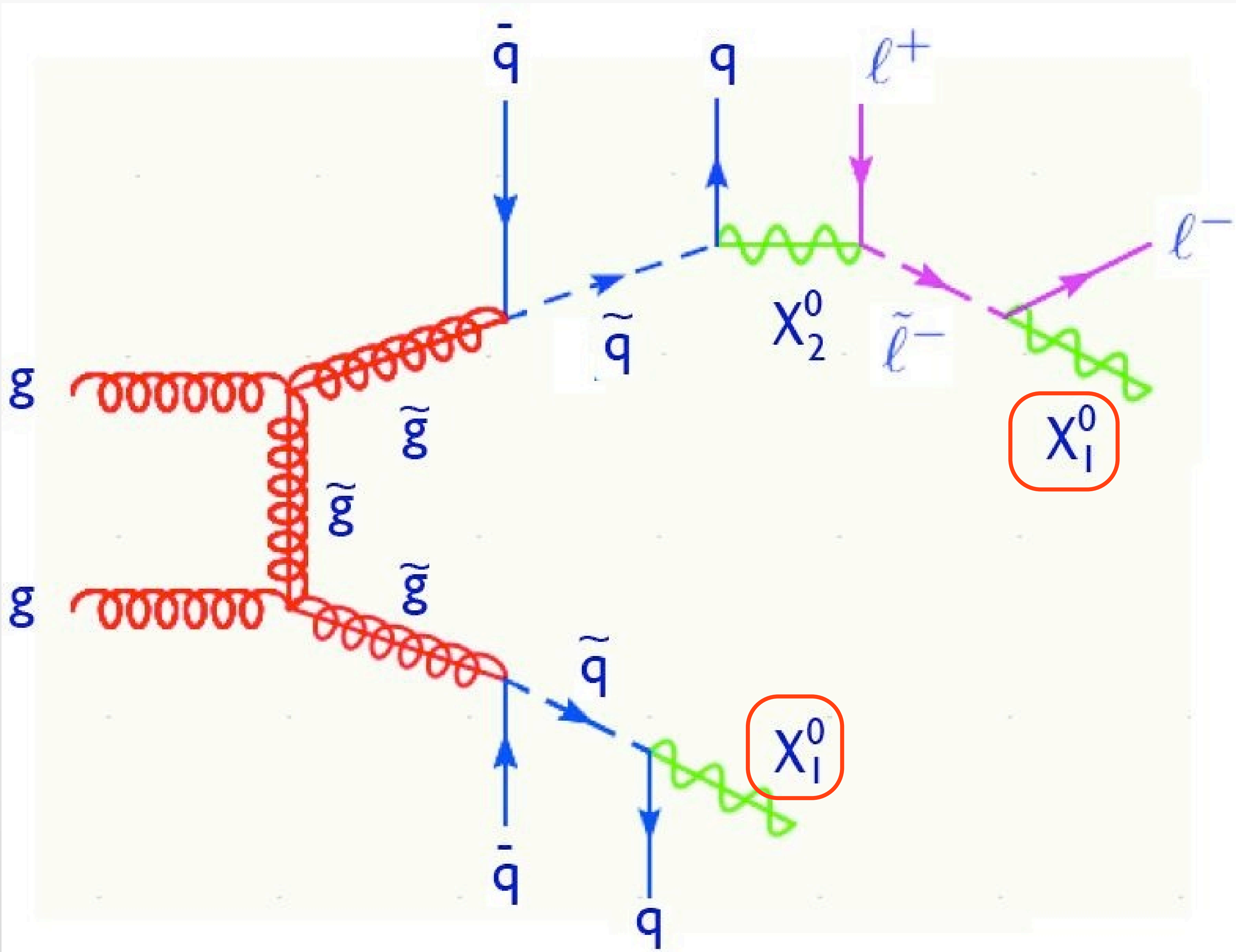
- different SuSy-breaking models proposed (cMSSM most studied) ! (none meets all challenges)

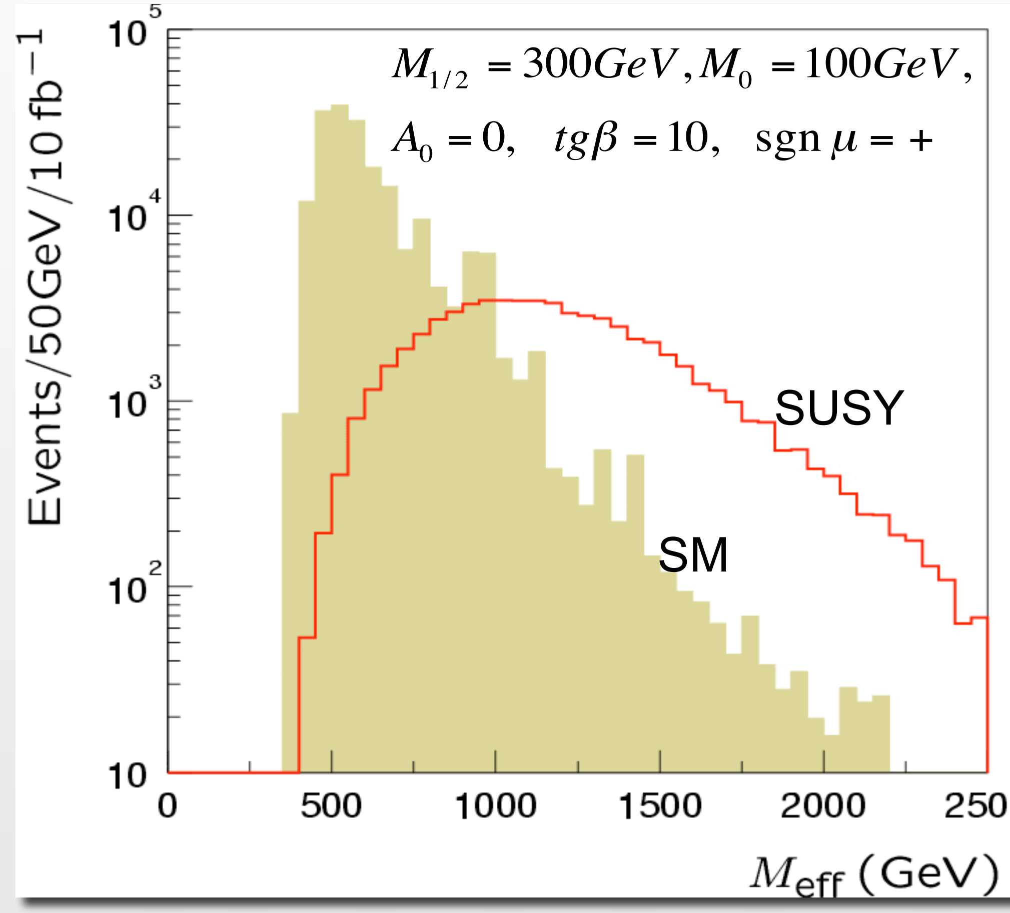
  Note: changing model can crucially affect pheno at LHC !!!

gluino production and decay at LHC

- missing energy + jets (+leptons)

cMSSM





excess in :

$$M_{eff} = E_T^{miss} + \sum_j E_{T,j}$$

where we are today

- in 2010, LHC delivered ~ 45 pb^{-1} in pp collisions at $\sqrt{S}$=7 TeV
- ATLAS and CMS could considerably improve bounds on direct signals from BSM models with respect to TeVatron limits by analyzing ~ 36 pb^{-1} (very sorry not having time to show at least a few of the beautiful results ...)
- "a very important discovery in 2010: experiments have an higher physics reach (for a given luminosity) than predicted by simulations !" Bertolucci (PLHC)
- right now ~1 fb^{-1} of data collected that are being analyzed (outcome expected for summer confs, ATLAS early results on ~0.2 fb^{-1}) 2-3 fb^{-1} expected by the end of 2011
- we will learn an awful lot on the Higgs boson and beyond just in a few months !

what if a BSM signal comes out ?

- not the confirmation of any single theory model !
- just the start-up of
  exploration of the "next layer of the theory"
- considerable degeneracy in the expected phenomenology for quite a number of BSM models
  (eg. missing P_T from many models with a WIMP candidate)
- for any single theory model to be credited, it will have to
  - overcome the "anomaly-fitting phase" (cf.Tevatron anomalies)
  - enter the "prediction phase" !
- it will take time and a lot of work to advance in theory....

3-σ anomalies

- by now there are around quite a few 3-σ anomalies observed in different (precision) observables (A^b_{fb} , g_μ-2, $A(top)_{FB}$, ...).

- could point to initial deviations from the SM

- LHC will be able to test different theor. explanations for their origin quite soon ...

Outlook

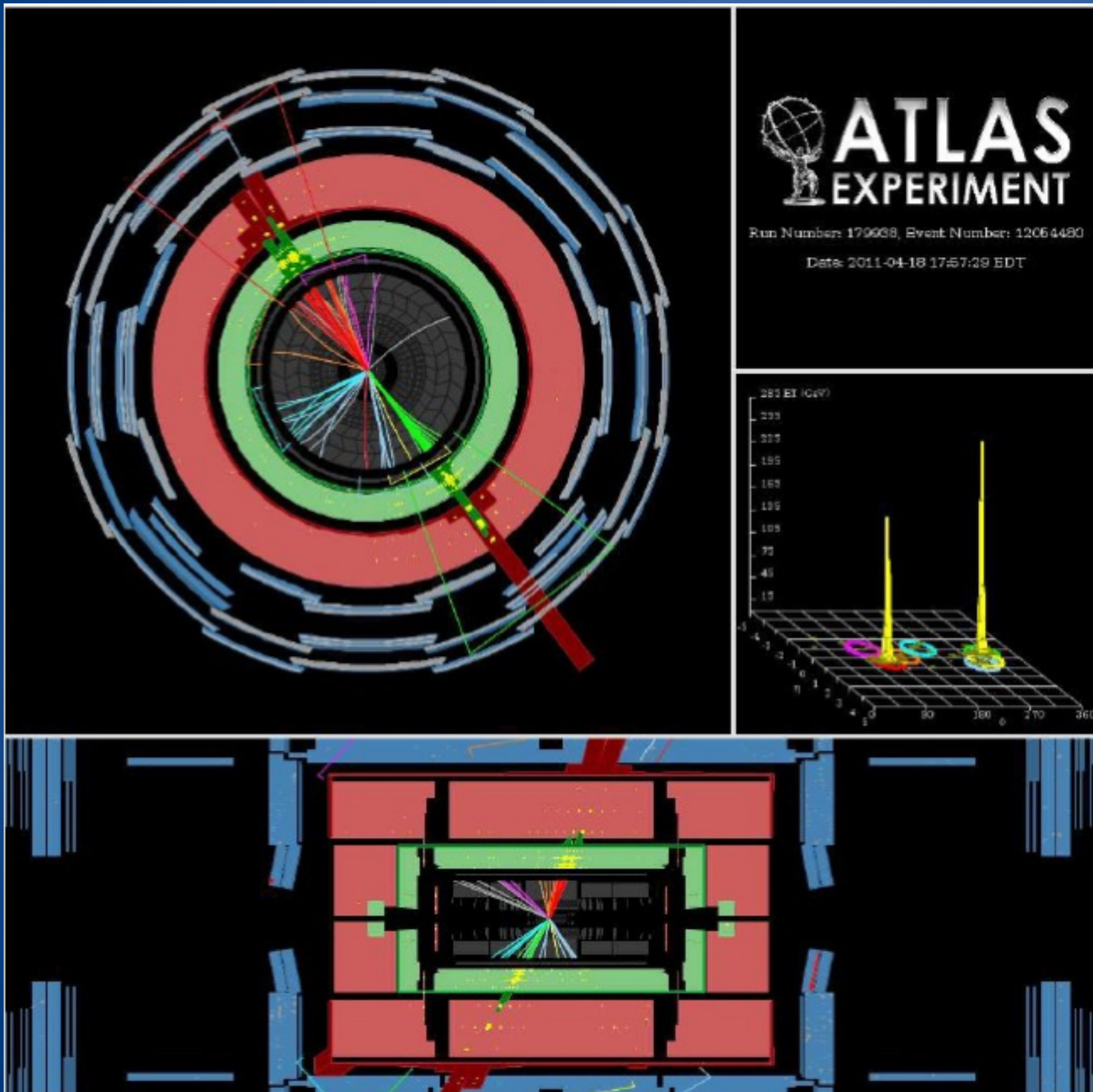
- we have an amazing instrument for directly exploring fundamental interactions in a new energy regime

- present plan : running LHC up to 2030 collecting 3000 fb^{-1} at $\sqrt{S} \sim 14$ TeV (a few 100 fb^{-1}'s by 2020)

- whatever we will find (either Higgs/Higgses or no-Higgs), and however appealing for the media we will make it, the outcome will deeply affect our comprehension of fundamental interactions in the many-TeV regime

- showing just two final plots on real events... (representative of the exciting side and the challenging one)

Highest Dijet Mass: M_{jj}= 4 TeV



- Highest Di-Jet mass in central region
- M_{jj}=4.04 TeV
- P_t^1= 1850 GeV
- P_t^2=1840 GeV
- η^1= 0.32
- η^2=-0.53

The challenges of 2011 data taking