Physics Potential and Detector Implications of an Upgraded LHC

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on behalf of the
ATLAS and CMS collaborations

XV Rencontres de Physique de la Vallee d'Aoste,
La Thuile, March 4-10, 2001

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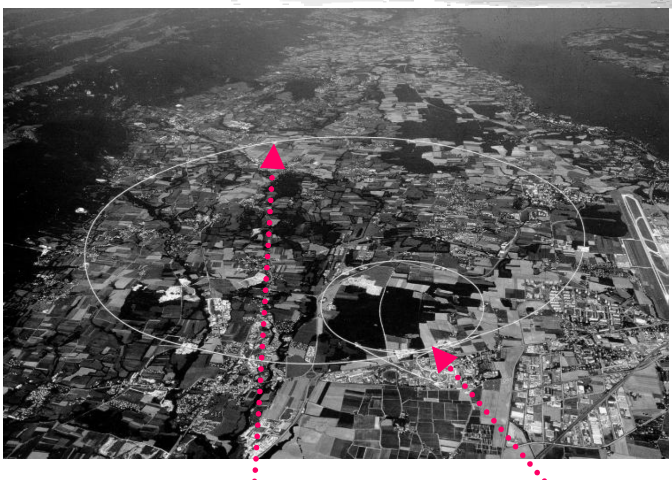
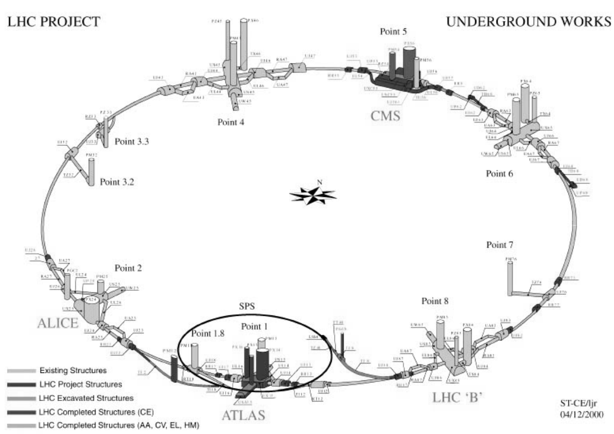
Introduction

- LHC is yet a "virtual" machine. Parameters:
  - ➜ $\sqrt{s}$ = **14 TeV** using 8.3 T dipoles (NbTi @ 1.9 K)
  - ➜ 25 ns bunch spacing, 2835 bunches (10^{11} p/bunch)
    - total current: 0.53 A, synchrotron radiation power: 3.7 kW
  - ➜ L_{design} = $10^{34} cm^{-2} s^{-1}$ ($\rightarrow$ 100 fb^{-1} / year)
    - 23 inelastic events / bunch crossing
- CERN studies options for the future beyond LHC
  - ➜ linear (e^+e^-) collider (CLIC) with $\sqrt{s} \leq 5$ TeV
  - ➜ ν factory and μ collider ($\rightarrow$ talk by A. Blondel)
  - ➜ upgrade of LHC using the existing tunnel
    - increase luminosity and / or center-of-mass energy ?
    - first, very crude assessment of the physics potential of such an upgrade done by CMS and ATLAS

The LHC: making it real



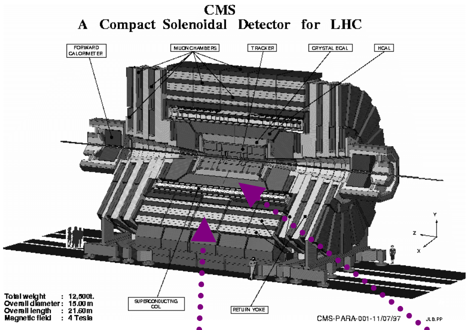


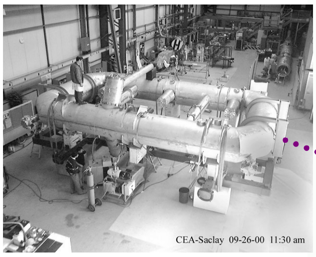
CMS access shaft

ATLAS electronics cavern (USA15)

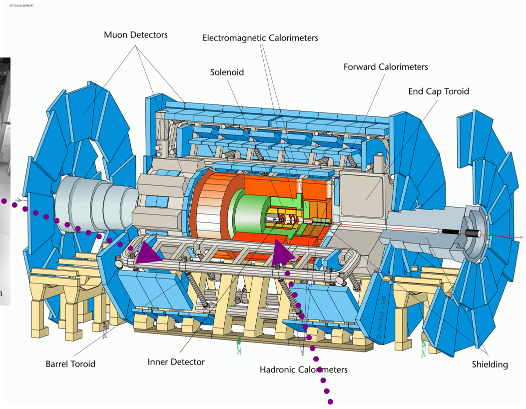
Pre-series LHC dipole

The LHC: making it real (cont'd)

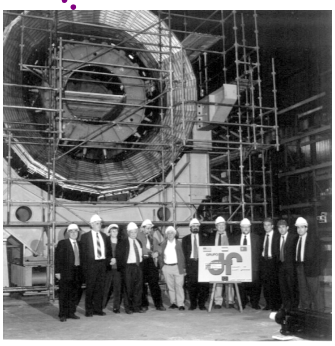




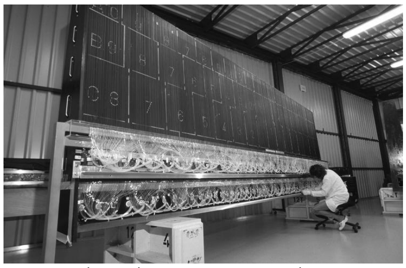
ATLAS Barrel toroid prototype



CMS Barrel Yoke



CMS HCAL half barrel



ATLAS Tile Calorimeter Module

Scenario(s) for upgrade of LHC

- luminosity upgrade (SLHC scenario)
  - increase proton intensity in bunches
  - reduce emittance (?)
  - new focusing quadrupoles (larger aperture, lower β^*)
  - reduce bunch spacing: 12.5 ns

  ➜all together: $L = 5*10^{34} - 10^{35}\ cm^{-2}\ s^{-1}$
  - part of it should be achievable with present machine design
- energy upgrade ?

  ➜present technology: $B_{dipole} \leq 11$ T $\Rightarrow \sqrt{s} \leq 18$ TeV
  - LHC dipole design ($B \leq 9$ T) $\Rightarrow \sqrt{s} \leq 15$ TeV
    - first industrial pre-series dipole reached 9 T without quench
  - synchrotron radiation will become problematic
    - beam screening capabilities limit to field less than 10.5 T?
  - optimisation and R&D need to be done

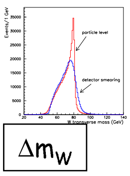
  ➜to see impact on physics potential: study $\sqrt{s} = 28$ TeV

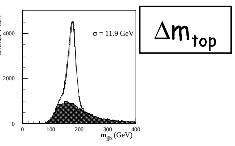
Impact on detector performance

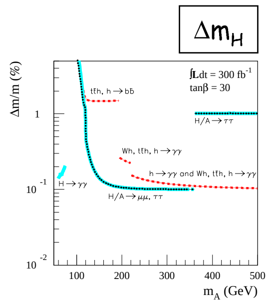
- increase in center-of-mass energy
  - ➜"easy case" (slight increase in inelastic cross-section)
    - ATLAS and CMS would essentially retain their capabilities
- increase in luminosity
  - ➜much more challenging
    - average number of inelastic interactions per bunch crossing increases from 23 to 115
  - ➜significant increase on **detector occupancies**
  - ➜significant increase in **radiation levels**
  - ➜pile-up in calorimeter: 3 times larger
  - ➜consider 2 stages:
    - same detectors (minor upgrades - eletronics, trigger, DAQ)
    - major detector upgrades (tracking)

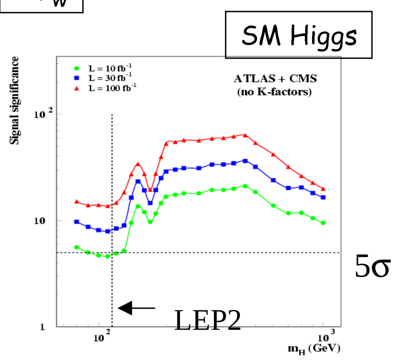
The LHC physics programme

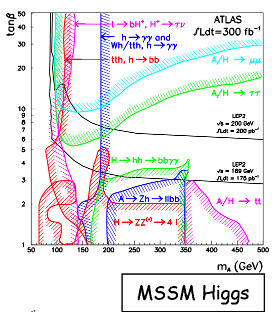
- Precision measurements
  - ➜ m_W to 15 MeV, m_{top} to 1.5 GeV
  - ➜ TGC, $\sin^2\theta_l^{eff}$, ...
- Higgs physics
  - ➜ discovery(SM): full mass range
    - mostly several channels
  - ➜ determine properties
    - mass, width, B.R., spin (?)
  - ➜ A,H and $H^{\pm}$ can not be discovered over full parameter space
- Physics beyond the SM
  - ➜ SUSY: $\tilde{q}$, $\tilde{g}$ up to 2.5 TeV
  - ➜ W'(Z') bosons up to 4.5(6) TeV
  - ➜ compositeness up to 40 TeV

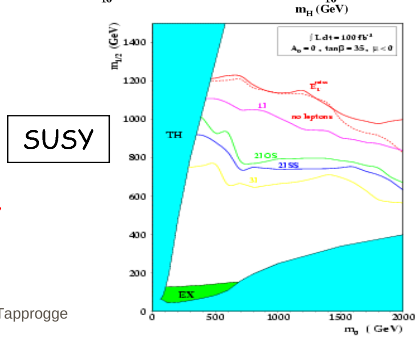


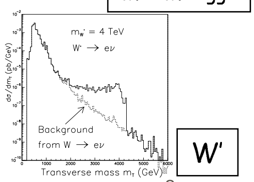








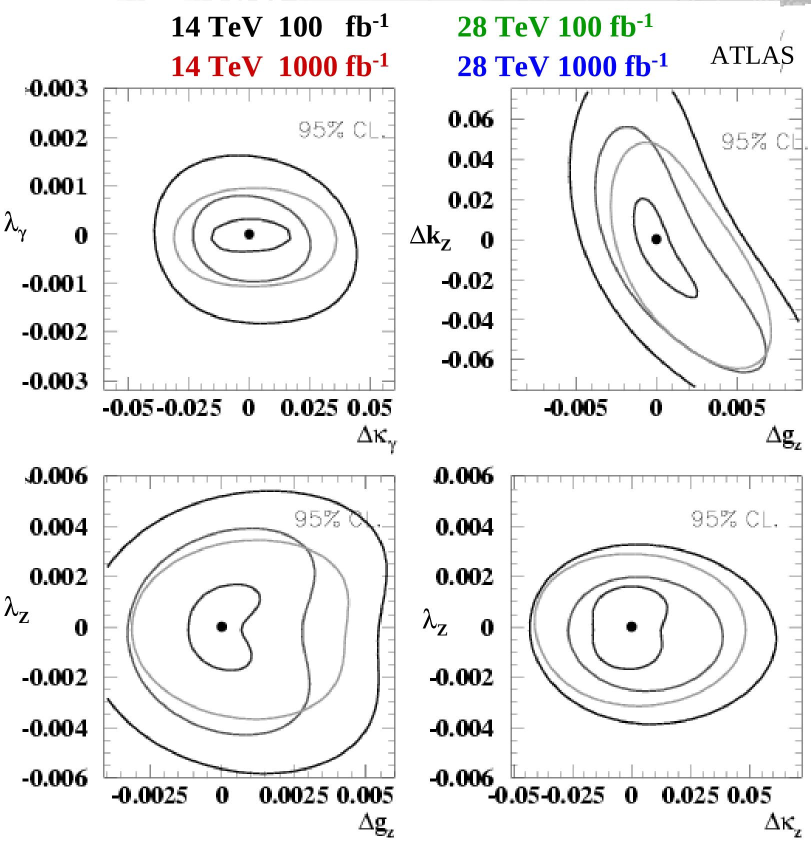


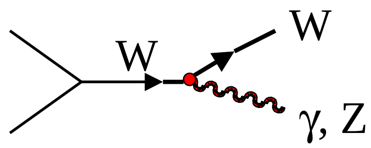


LHC Upgrade: physics impact?

- no significant improvement expected for SM precision measurements (luminosity increase)
  - →loss in detector performance (lepton ID, b-tagging)
    - without major detector upgrades
  - →most measurements are dominated by systematics
- measurements studied for SLHC scenario
  - →triple gauge boson couplings
  - →Higgs properties, SUSY, strong $V_L V_L$ scattering
  - →new gauge bosons, extra dimensions, compositeness, …
- case studies on impact of upgrade
  - →machine luminosity: 10^{34} cm^{-2}s^{-1} vs. 10^{35} cm^{-2}s^{-1}
  - →center-of-mass energy: 14 TeV vs. 28 TeV

Triple Gauge Couplings

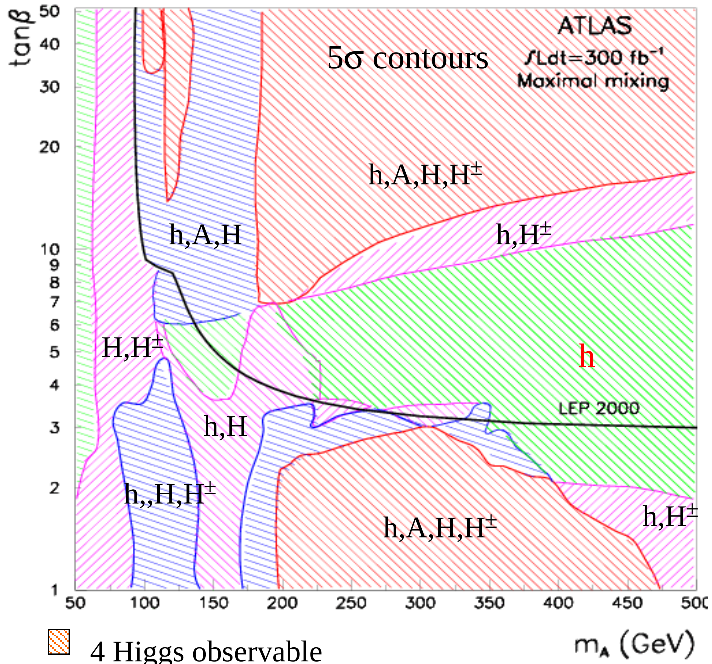




- Wγ(lνγ) or WZ(lνll)
  - → l=e,μ (10^{34} cm^{-2} s^{-1})
  - → l=μ (10^{35} cm^{-2} s^{-1})
- sensitivity using only cross-section, p_T^γ and p_T^Z
  - no angular distributions
- clear increase in sensitivity due to luminosity upgrade

Higgs discovery

MSSM Higgs bosons

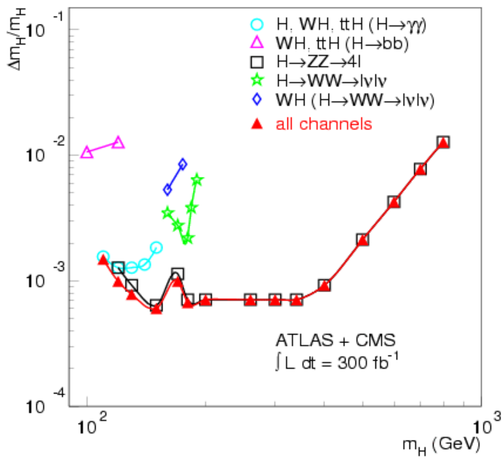


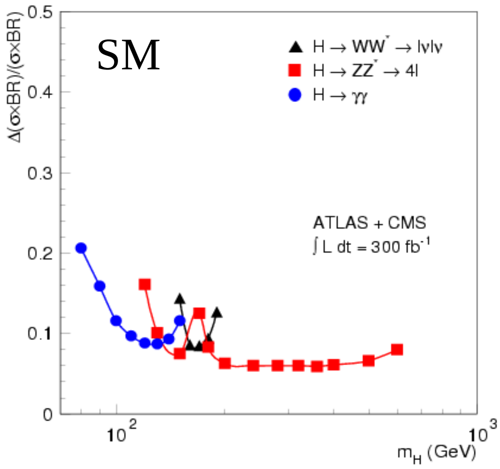
4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

Assuming decays to SM particles only

- SM Higgs @ LHC
  - → discovery over full mass range
  - → several decay modes
- MSSM Higgs @ LHC
  - → full coverage of the m_A - tanβ plane
  - → in most cases more than one Higgs
    - ❍ for 'h only' region more luminosity does not help
    - ❍ A,H,H± seen only if light SUSY particles exist

Higgs properties



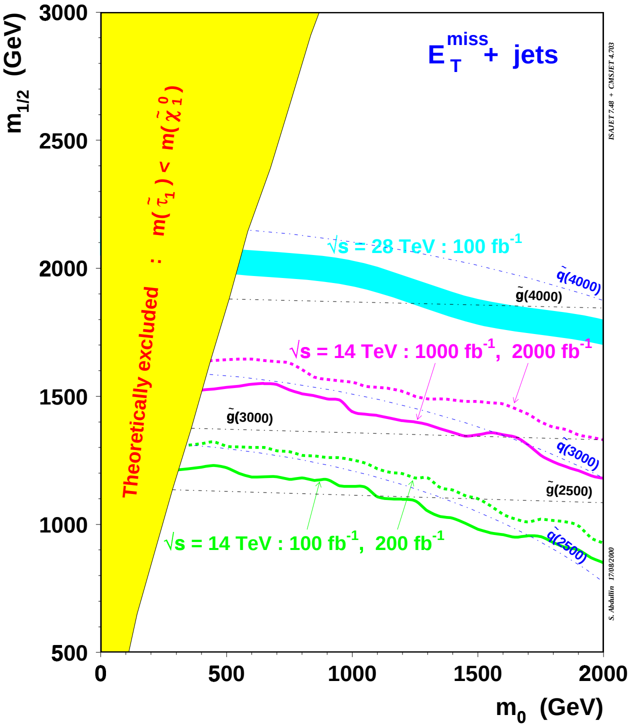


LHC performance

- mass to 0.1%
- width < 10%,
- rates (σ∗B.R.) to ~10%
- coupling ratios (WWH, ZZH, ttH, bbH) to 10 - 20%

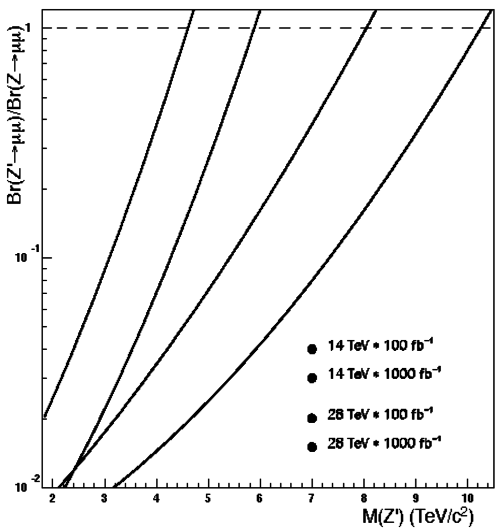
- impact of the SLHC scenario
  - → statistical accuracy for coupling ratios improved to 5 - 10%
    - ❍ however fully functional detector (lepton-ID, b-tag) needed!

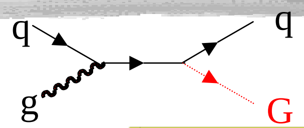
Supersymmetry



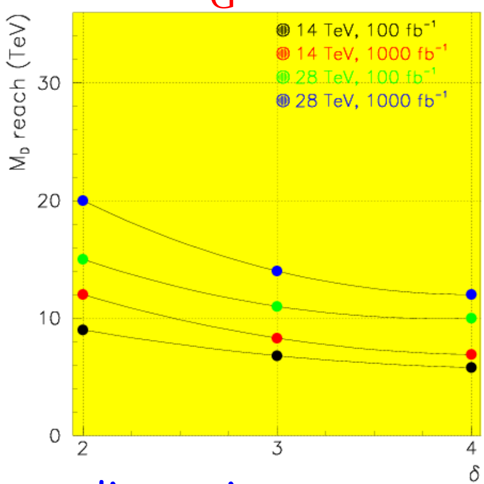
- Extend LHC mass reach for squark/gluino from 2.5 TeV to about **3 TeV**
  - for luminosity upgrade
  - → discovery can be done with calorimetry alone (jets + E^T_{miss})
  - → precision measurements need full detector
    - reconstruct decay cascades
- mass reach to about **4 TeV** for √s = 28 TeV

Beyond the Standard Model





$\sigma \approx M_D^{-(\delta+2)}$



- new gauge bosons
  - → mass reach for $Z' \rightarrow \mu\mu$
    - 5σ limit from CMS
  - → SLHC: increase reach from 4.6 to 5.8 TeV
- extra dimensions
  - → mass reach using jets+E_T^{miss}
    - 5σ limit from ATLAS
    - SLHC: increase from 9 to 12 TeV
  - → σ @ various √s: disentangle M_D, δ

Physics Impact of Upgrade

- SLHC scenario
  - →mass reach increases by about **20% - 30%** ("for free")
  - →however, to fully benefit from increased statistics
    - e.g. for Higgs and SUSY precision measurements
    - ❍ a fully functional detector needed
      - with the planned ATLAS/CMS performance, e.g. for lepton-ID, b-tagging
- larger center-of-mass energy
  - →
  - →feasibility of significant 'jump' in energy unclear
  - →ATLAS and CMS would retain their capabilities
- How to retain present capabilities of ATLAS and CMS in the SLHC scenario (stage 2)?

Tracking at 10^{35} cm^{-2} s^{-1}

- issues (figures of merit)
  - → pattern recognition, momentum resolution, secondary vertexing
- occupancies are increased
  - → use Si based tracker with smaller cell sizes
    - ❍ inner radii: 50∗50 μm^2 pixels
    - ❍ medium radii: μpads / macro pixels (with pixel electronics?)
    - ❍ large radii: short μstrips
- radiation damage
  - → operate Si detector at 130 K (Lazarus effect, cf. RD39)
  - → use diamond detectors (RD42)
  - → regular (frequent?) replacement of detector elements
- readout electronics
  - → reduce cost per channel
  - → develop radiation hard versions

Calorimetry / muons at 10^{35} cm^{-2} s^{-1}

- Calorimeter issues
  - → radiation damage, event pile-up, isolation criteria
- electro-magnetic compartments
  - → liquid Argon (ATLAS): should be ok
  - → crystals (CMS): saturation, leakage current in photo detectors
- hadronic compartments
  - → radiation damage of plastic scintillators (10 Mrad @ η = 3)
  - → ATLAS: scintillators only in barrel: should be ok
  - → CMS: replacement for endcap parts, replacement or use of quartz-quartz fibers for forward part
- muon issues
  - → hits produced by the n/γ gas (10^4 cm^{-2} s^{-1} @ η = 2.4)
- ATLAS
  - → open geometry, designed for $2*10^4$ cm^{-2} s^{-1} with safey factor of 5
  - → if not sufficient: increase shielding (restricts acceptance)
- CMS
  - → closed geometry, designed with safety factor of 3
    - ❍ irradiation studies show drop in efficiency of few % at 10 ∗ design L
  - → if not sufficient, restrict acceptance to e.g. $\eta \leq 2.0$

Conclusions

- SLHC ($\sqrt{s}$ = 14 TeV, L=10^{35}cm^{-2}s^{-1}) will increase mass reach (beyond SM) by 20% - 30%
  - → using only jet, missing E_T and muon signatures ("for free")
  - → for full benefit on precision measurements (statistics increase for heavy objects) significant detector upgrades are needed
- increase in center-of-mass energy by 2 would give larger reach (and less detector challenges)
  - →but it is much more challenging accelerator task!
    - it is probably impossible to obtain such a jump in $\sqrt{s}$ using the LHC tunnel !!
- hadron collider detectors at L > 10^{34} cm^{-2} s^{-1} will be ever more challenging
    - ❍ "black is black" (and not always beautiful ...)
  - →need for new R&D resources (LHC R&D started in 90s)