Physics at Future High Energy Colliders

programme incitatif pour la mobilité internationale des étudiants

Albert De Roeck/CERN
Strasbourg 7-8/07/06

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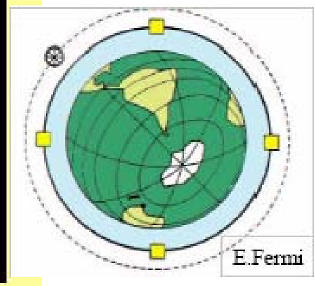
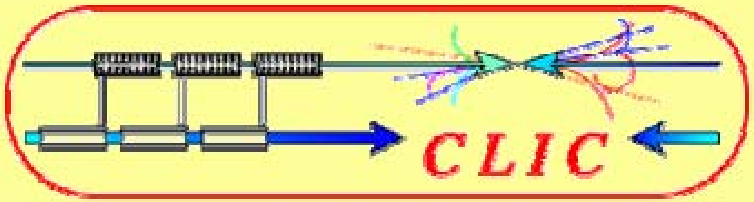
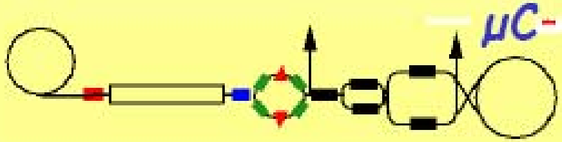






Lecture Plan

- Brief introduction:

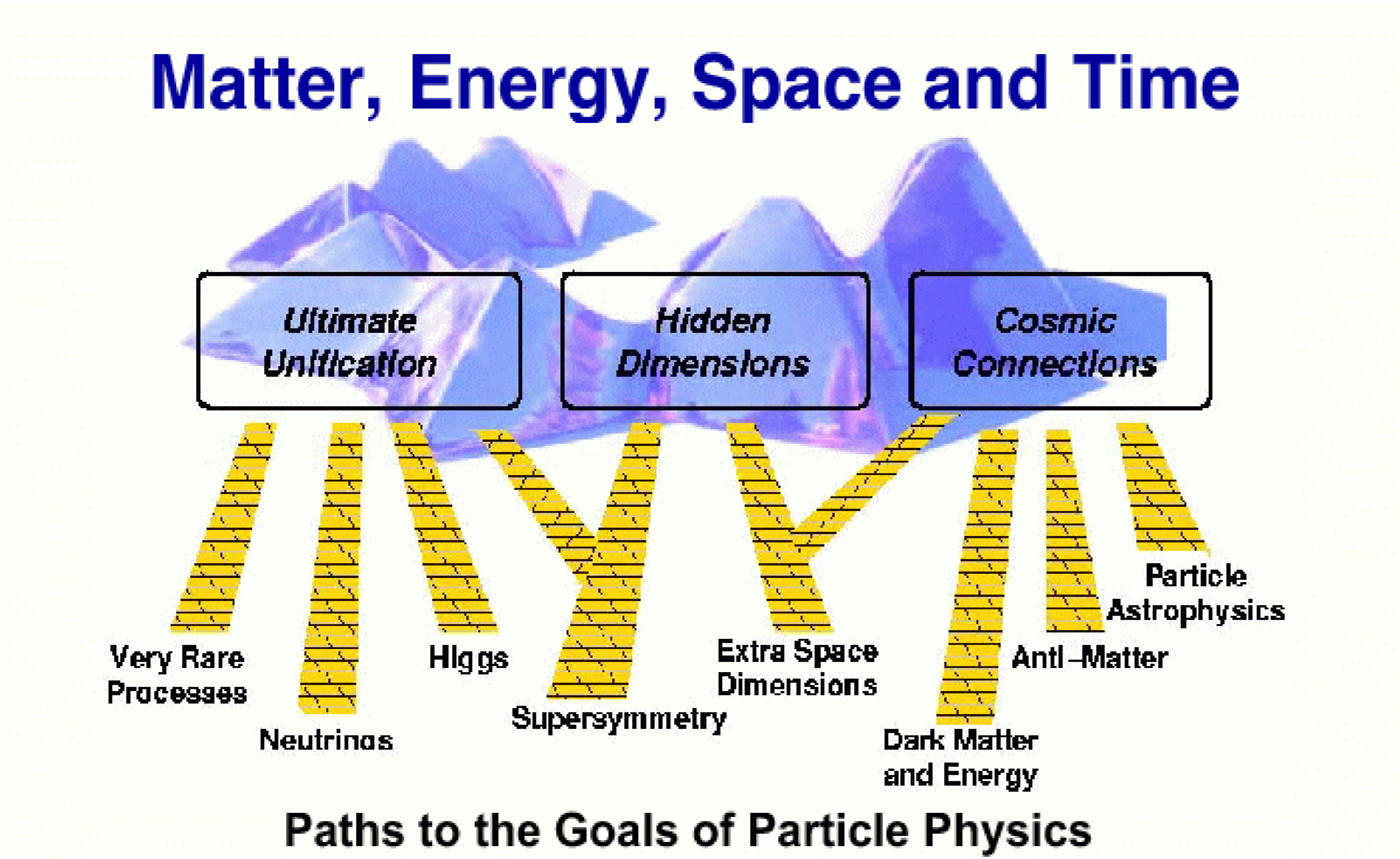
  The Era of the New Machines
- Physics at the Large Hadron Collider LHC
  - Experimental challenges
  - The hunt for the Higgs particle
  - Signals of new physics at the TeV scale
- Options for future colliders
  - The LHC upgrade
  - An e+e- linear collider (LC)
  - A Very Large Hadron Collider (VLHC)
  - A Muon Collider with Neutrino Factory

LECTURE 1

LECTURE 2

Introduction

Particle Connections



Today's fundamental open questions in Particle Physics

- Why is the Z boson massive while the related photon is massless?
  What is the origin of mass? ⇒Electro-weak Symmetry breaking
- Can we obtain experimental evidence to support the hypothesis of Grand Unification of all fundamental forces?
- What is the physics in the higher energy regime that stabelizes the standard model at energies below 1 TeV (radiative corrections)
- Is the dark matter in the universe due to supersymmetric particles?
- Are there more large hidden/extra space-time dimensions?
- Can we account for the matter anti-matter symmetries in our universe?
- What are the masses and mixing parameters of neutrinos
- Are there only 3 families of quarks and leptons
- Do the elementary particles of today have substructure?
- Does a new form of matter --quark-gluon plasma– exist?

Only experiments can answer these questions

Introduction

The High Energy Frontier

Unique:

High Energy = probes smallest distances
= directly produce heavy particles

→ can answer questions otherwise inaccessible
→ extremely rewarding opportunities to answer fundamental questions

High Energy Colliders:

Largest facilities need a global strategy

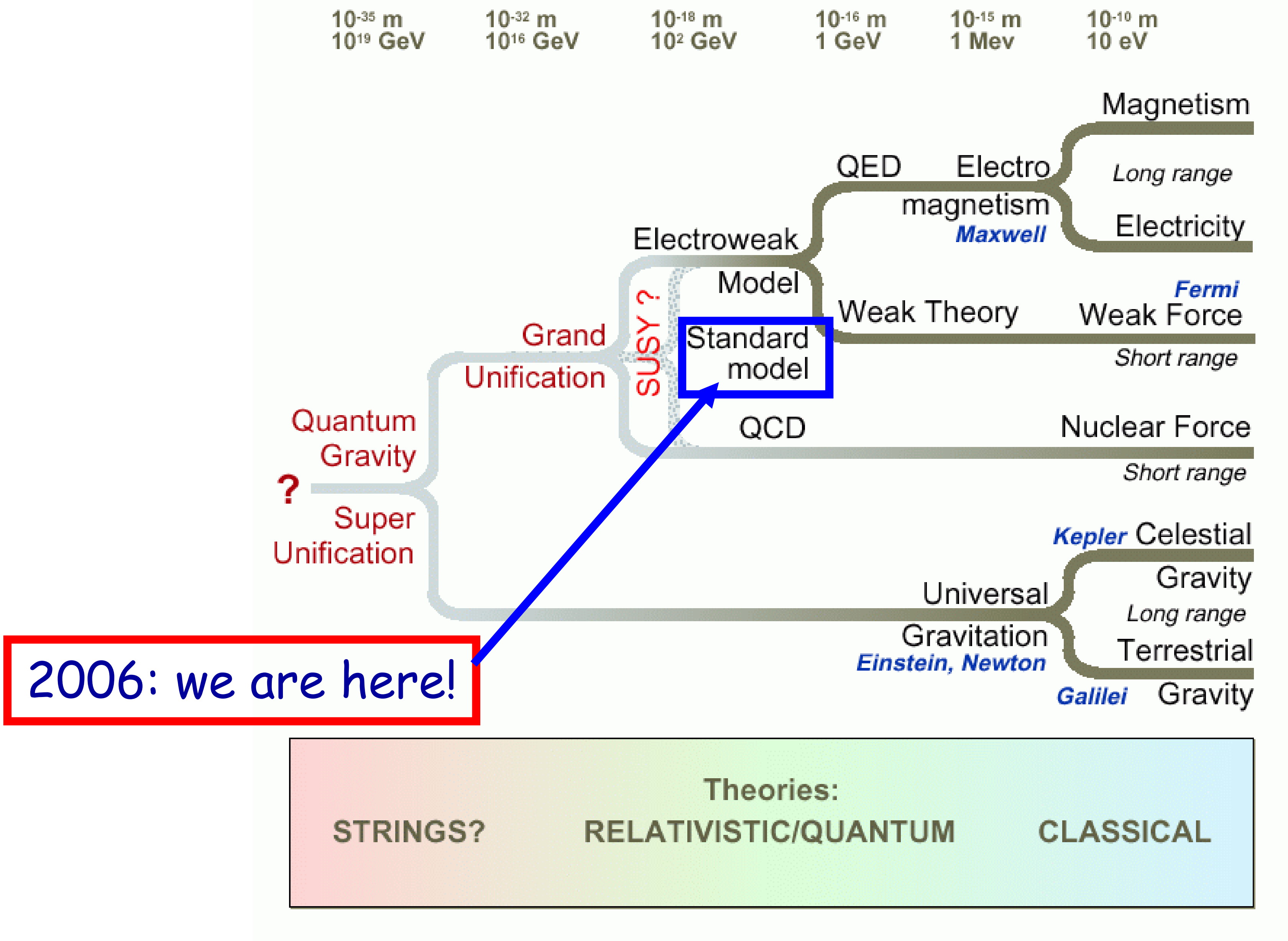
The Orsay Symposium : HEP in Europe

About 400 participants
47 documents submitted

Agenda and talks: http://council-strategygroup.web.cern.ch/council-strategygroup/

Webcast: http://webcast.in2p3.fr/OS2006/

Unification of Forces & scales



The Origin of Particle Masses

The Standard Model of particle physics is formulated for massless particles

but : $m_\gamma = 0$

$m_{W, Z} \approx 100$ GeV

Gauge bosons of the EW theory → ?

⇒Mechanism of Electroweak Symmetry Breaking
⇒Higgs Mechanism (Higgs Particle)? Other?

Note: particle masses determine our size

$$r \approx \frac{1}{m_e}$$

radius of hydrogen atom

electron mass

if m_e were 10 times larger, everything would be 10 times smaller !

Is the Standard Model the Ultimate theory?

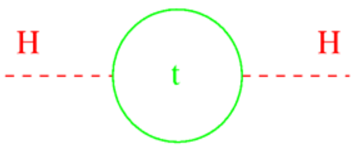
…if we add (~ad hoc) a Higgs field to it…?

SM predictions confirmed by experiments (at LEP, Tevatron, SLAC, etc.) with precision $\approx 10^{-3}$ or better

So, what is wrong with it ?

- About 20 free parameters (masses of fermions and bosons, couplings
- $m_H \approx 115$ GeV? : New Physics for $\Lambda < 10^6$ GeV
- "Naturalness" problem :

radiative corrections



$\delta m_H^2 \sim \Lambda^2$ $\rightarrow$ diverge for large Λ
$\rightarrow$ fine tuning!!

- "Hierarchy" problem: why $M_{EW}/M_{Planck} \sim 10^{-17}$?

+ contribution of EW vacuum to cosmological constant ($\sim v^4$) is ~ 55 orders of magnitudes too large !

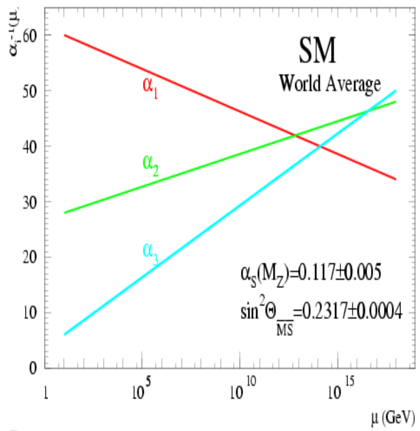
+ flavour/family problem, coupling unification, gravity incorporation, ν masses/oscillations, …

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

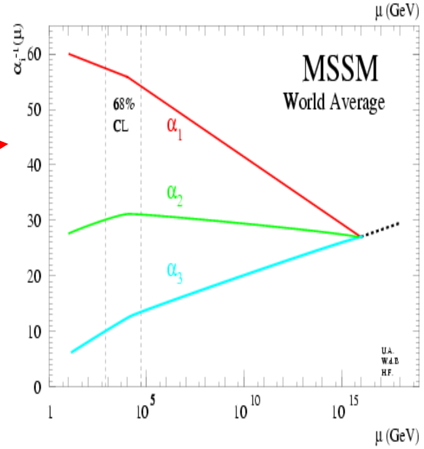
Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



Most popular extensions these days

If a Higgs field exists:
- Supersymmetry
- Extra space dimensions



If there is no Higgs below ~ 700 GeV
- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models…

What can we expect?
Ask an (un)baised theorist:

Murayama LP03

High Energy Colliders

The Terascale

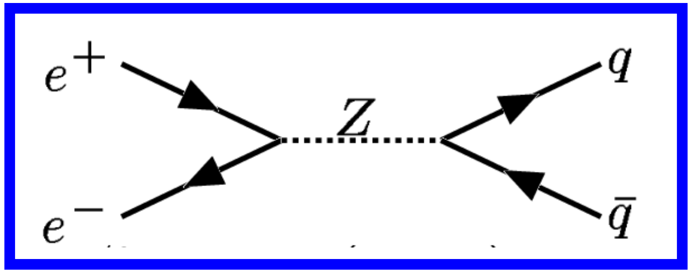
Very good reasons to explore the TeV-scale:

- Evidence for light Higgs
- SM without Higgs violates unitarity at ~1.3 TeV
- Hierarchy between m_{weak} and m_{Planck} to be protected at TeV scale
- Dark matter consistent with sub-TeV-scale WIMP (e.g. SUSY-LSP)
- $2m_{top}$ = 350 GeV

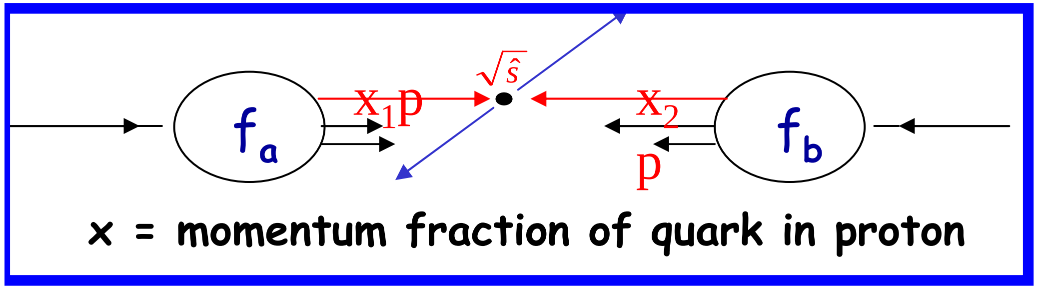
But no clear case yet to enter the 10-TeV scale
(need TeV scale knowledge)

→ Either at least one Higgs exists with mass below 1 TeV, or new phenomena (strong EWSB?) set on in the TeV region
→ New physics prefers the TeV scale (Hierarchy problem, fine tunning) but not fully guaranteed

ee/pp/ep colliders

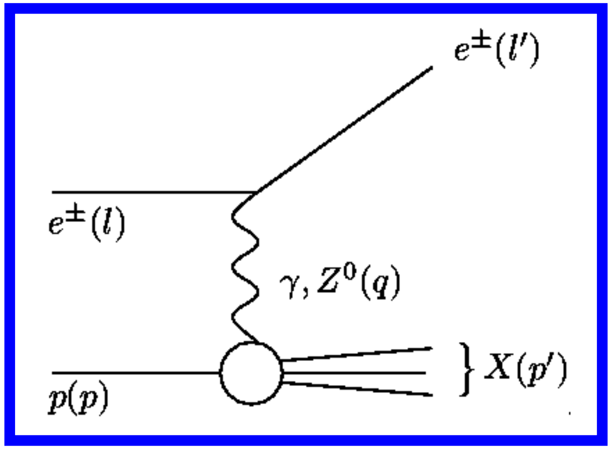


e+e- collisions (SLC/LEP)
*Precisely calculable to 0.1% level
*Clean collisions
*Allow for high precision measurements



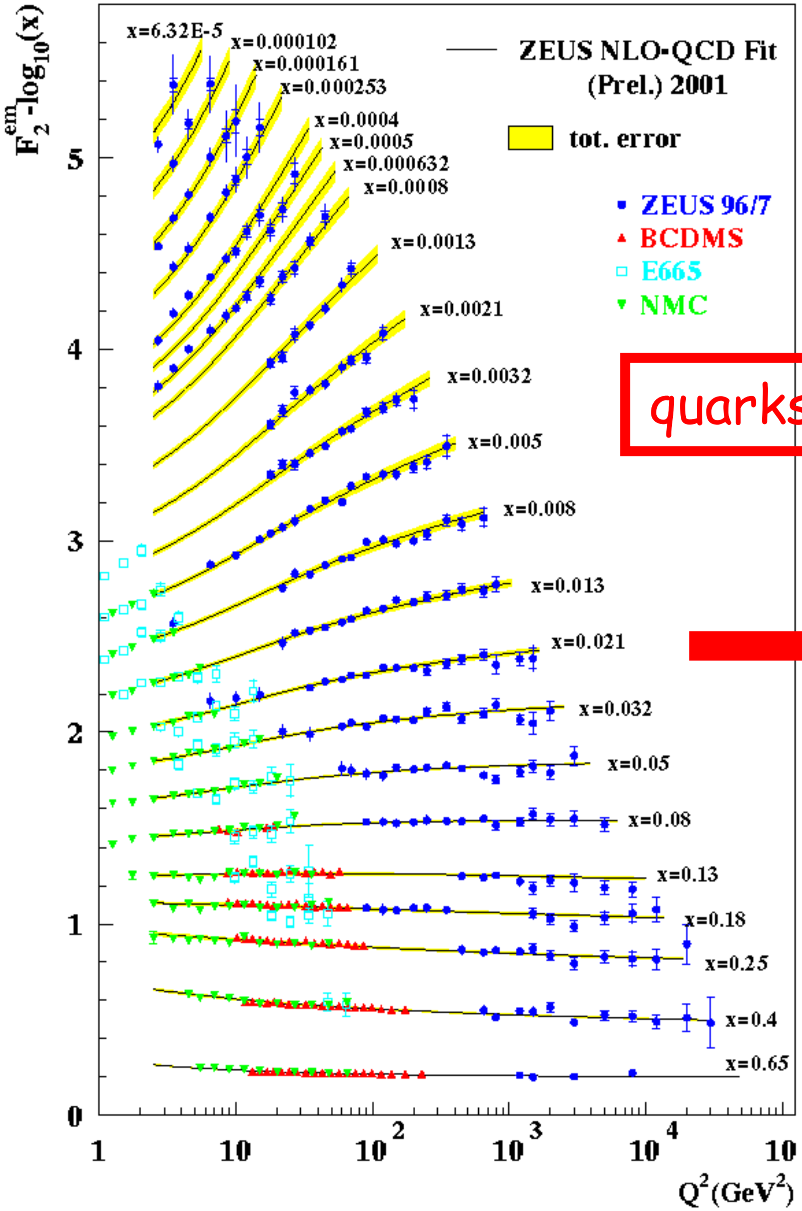
pp collisions (SPPS, Tevatron, LHC)
*Highest energies reachable
*Can reach highest masses for new particles production
*Precision compromised by knowledge of quark structure of the protons

$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$

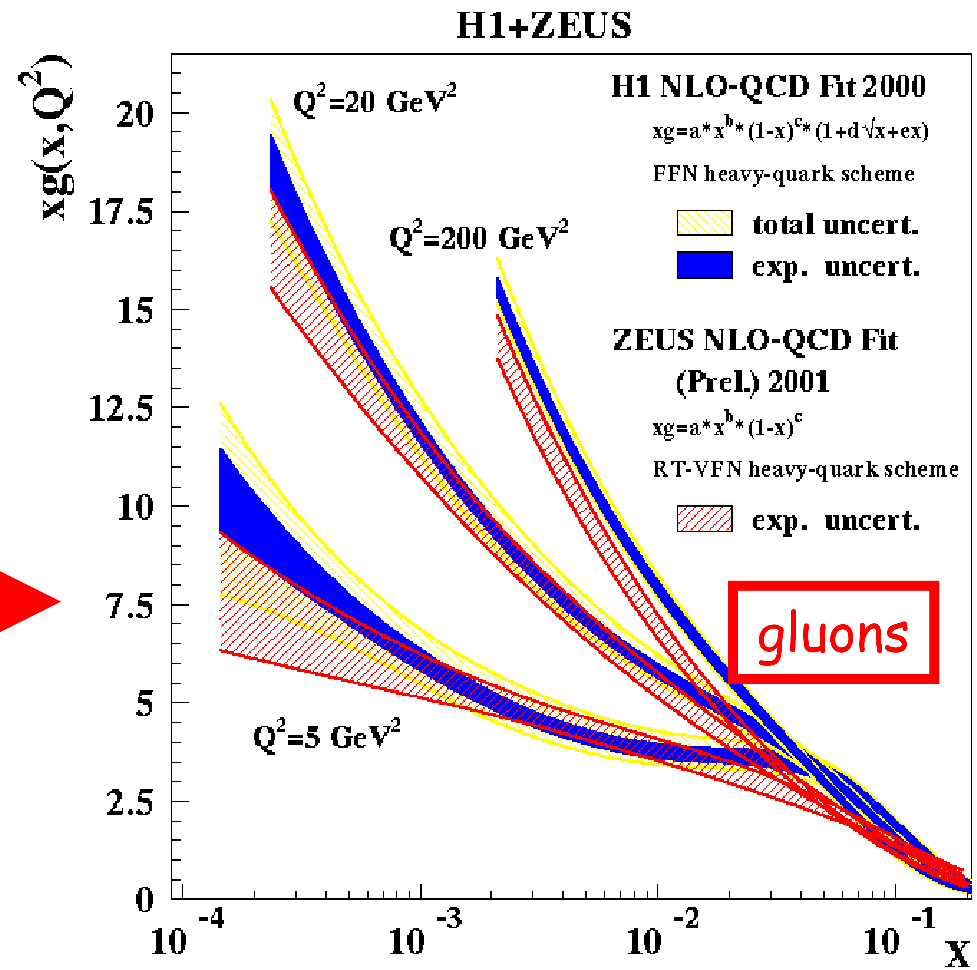


ep collisions (HERA)
*Intermediate to the above machines
*Ideal tool to study the structure of hadrons via deep inelastic scattering (structure functions/parton densities)

Structure of the proton at HERA



quarks

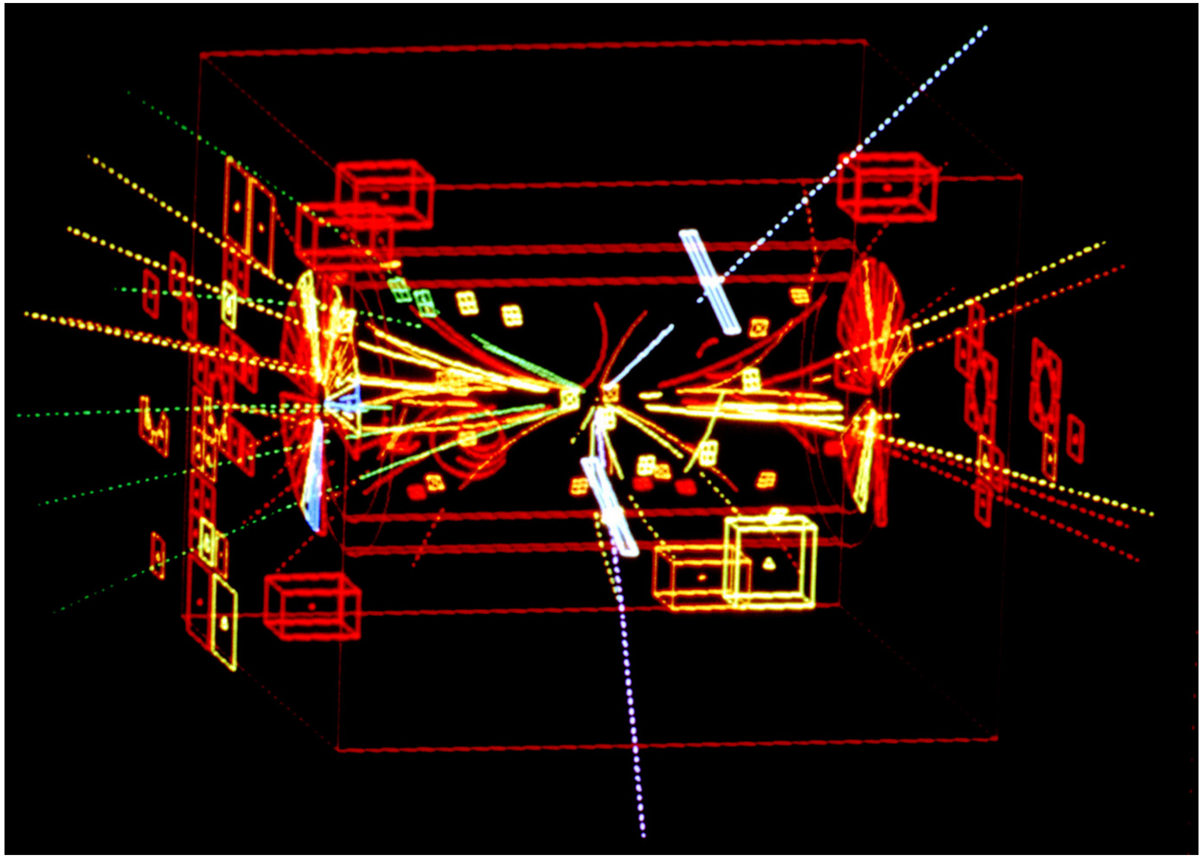


gluons

Proton structure (f(x,Q^2)) known
to a few % in a large area of x and Q^2

Proton –(anti) Proton colliders
Highest Energy: Discovery Machines

Discovery of the Z and W bosons in UA1/UA2 (1983)



Collaboration includes Helsinki Univ.

'Picture' of the first

$p\bar{p} \rightarrow Z + X$
$\rightarrow e^+e^- + X$

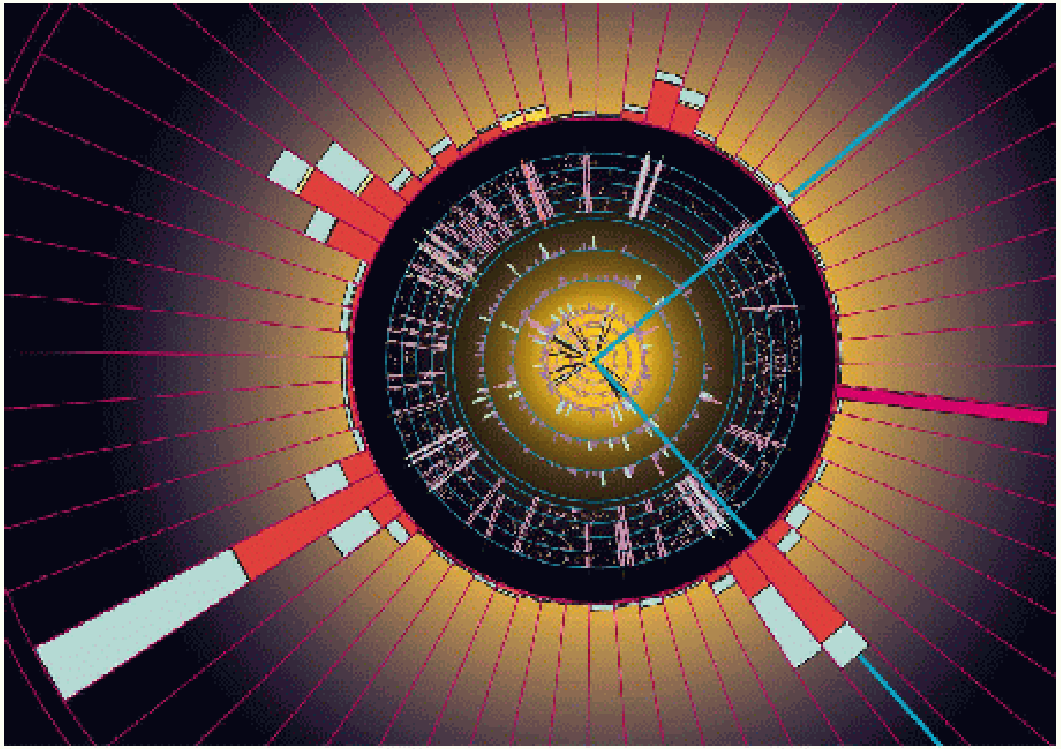
event in the UA1 detector at the $Sp\bar{p}S$, for a centre of mass energy ($\sqrt{s}$) = 630 GeV

(30/4/1983)
Success story of the $Sp\bar{p}S$ machine at CERN rebuilt from a fixed target machine to a collider

Tevatron at Fermilab (Chicago)

Recent Steps

The Last Quark



Top Quark discovered at Fermilab

1994
Top mass
174 +/- 5 GeV

i.e. this quark is as heavy as a gold nucleus

In 2000: also the Tau-neutrino was seen directly
(DONUT exp. at FNAL)

All 3 families in the SM are now complete

The Large Hadron Collider LHC

The LHC Machine and Experiments

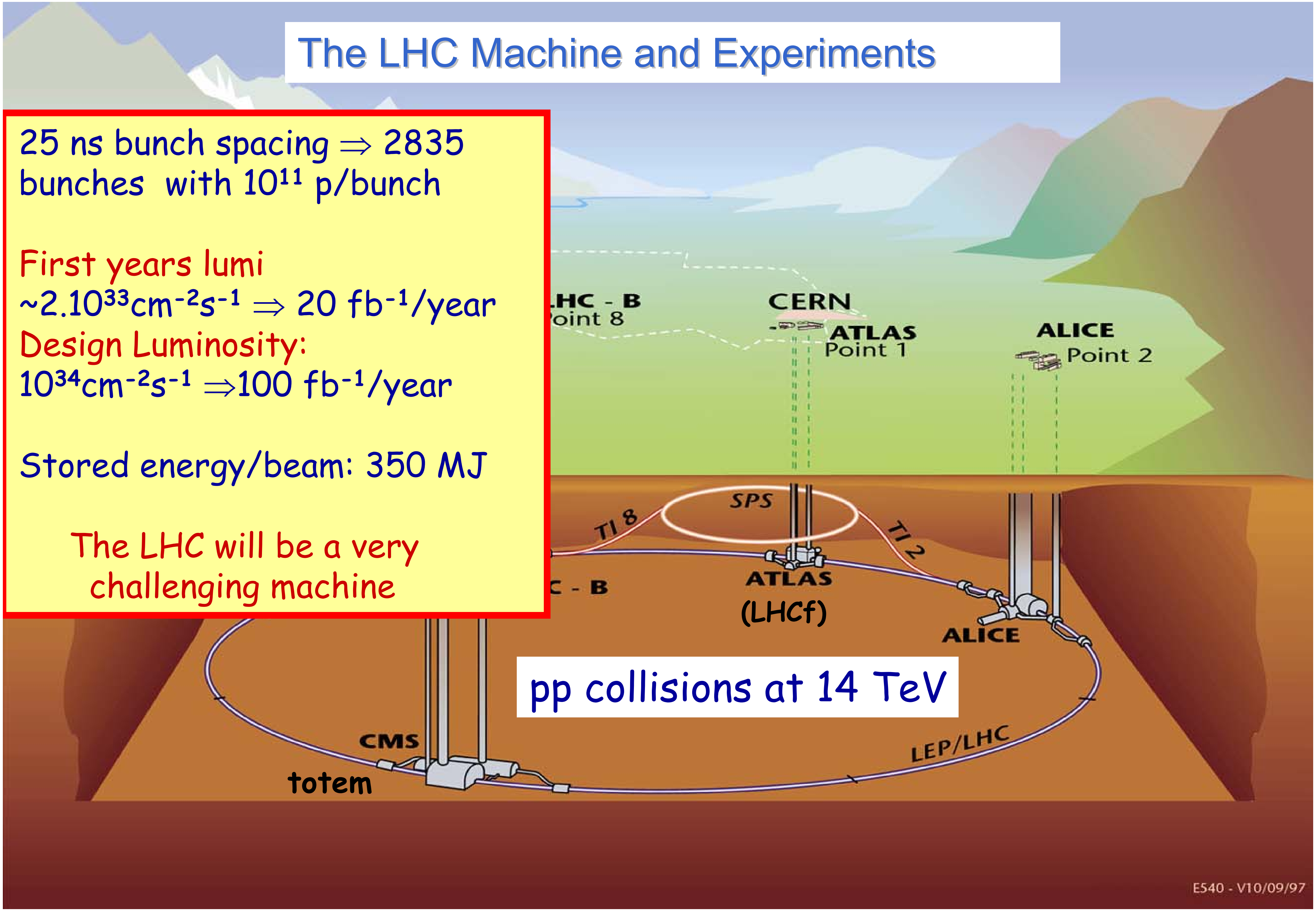
25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch

First years lumi
~$2.10^{33}cm^{-2}s^{-1}$ ⇒ 20 fb^{-1}/year
Design Luminosity:
$10^{34}cm^{-2}s^{-1}$ ⇒100 fb^{-1}/year

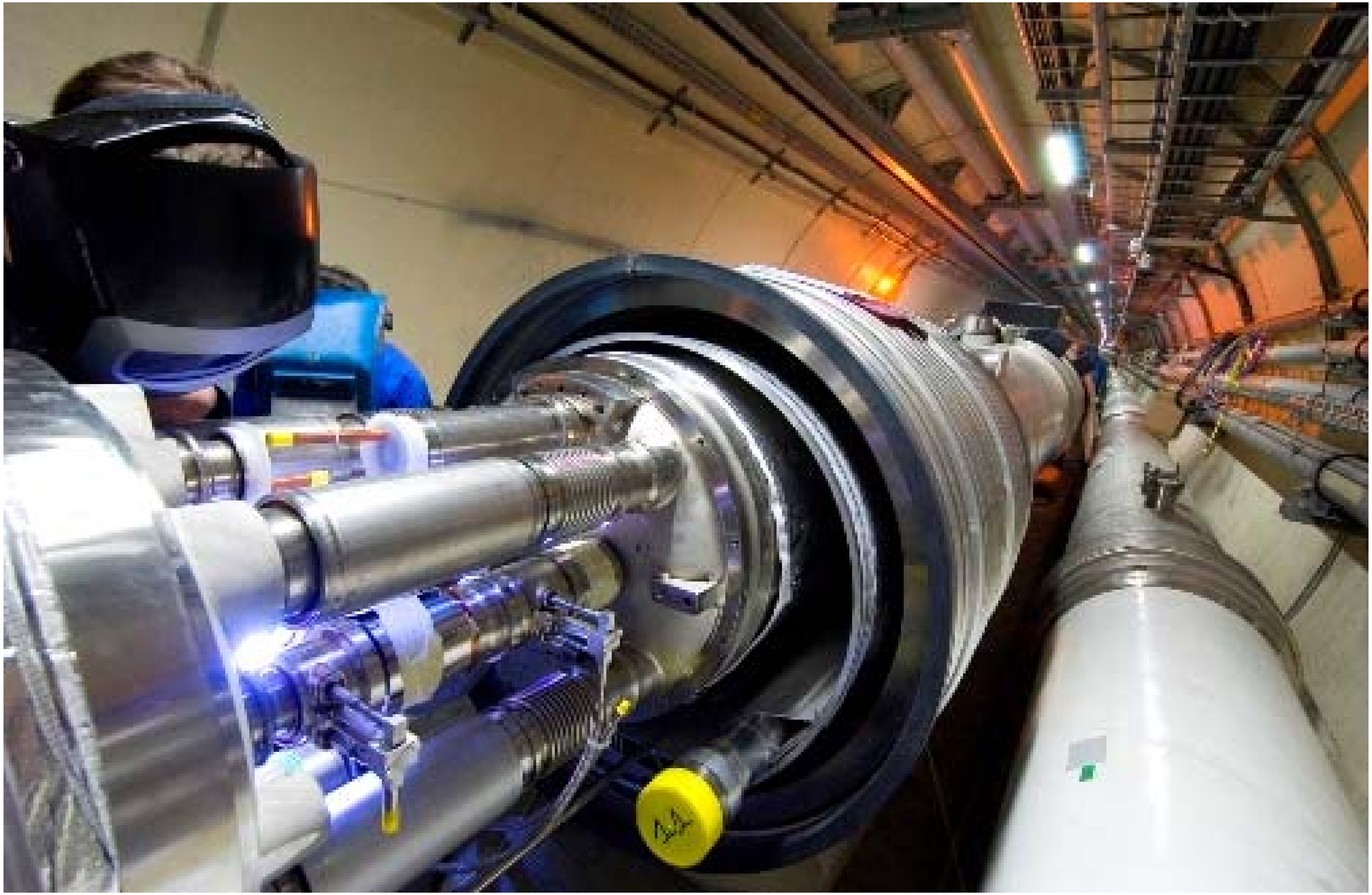
Stored energy/beam: 350 MJ

The LHC will be a very challenging machine

pp collisions at 14 TeV

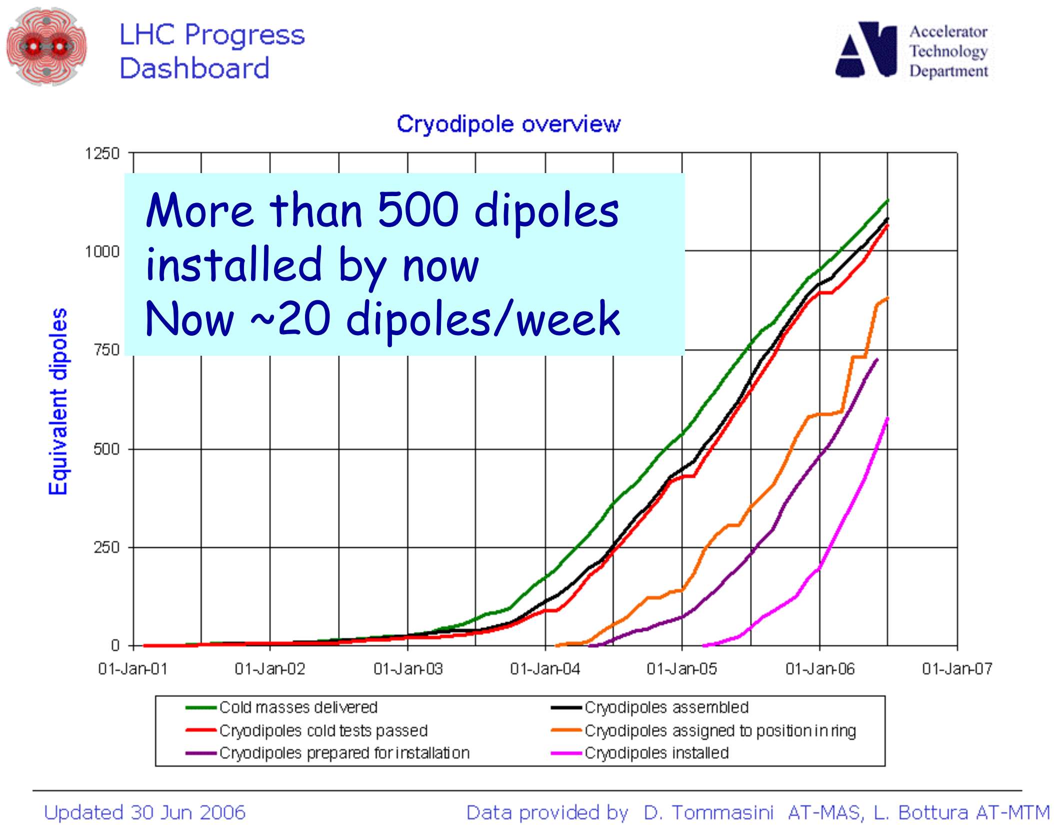


The LHC is Coming!



The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



The LHC Schedule(*)

- LHC will be closed and set up for beam on 1 September 2007
  - LHC commissioning will take time!
- First collisions expected in October/November 2007
  - Followed by a short pilot run
  - Collisions will be at injection energy ie cms of 0.9 TeV
- First physics run in 2008
  - one to a few fb^{-1}? 14TeV!
- Physics run in 2009 +…
  - 10-20 fb^{-1}/year $\Rightarrow$100 fb^{-1}/year

(*) eg. M. Lamont et al, April 2005.
Achtung! Lumi estimates are mine, not from the machine
Includes updates from Jujne 06

The ATLAS and CMS experiments

Don' t know how New Physics will manifest
$\rightarrow$ detectors must be able to detect as many particles and signatures as possible:

e, μ, τ, ν, γ, jets, b-quarks, ….

$\Rightarrow$ " multi-purpose" experiments.

• Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers plus gas detectors).

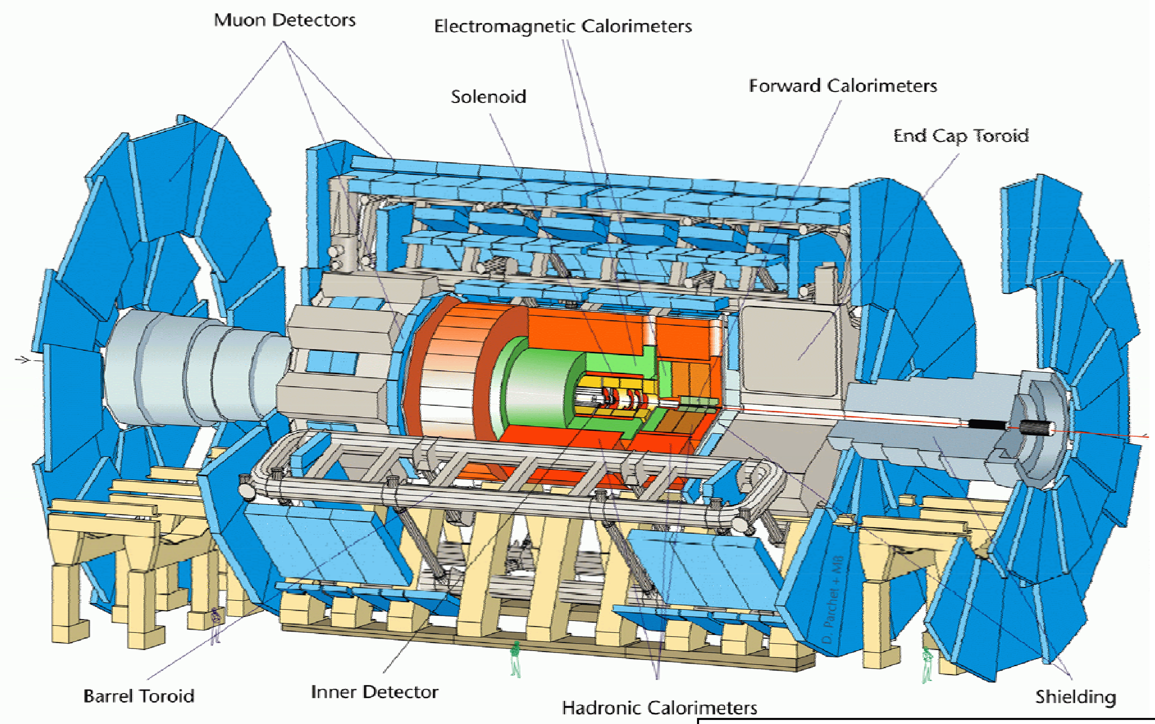
• Energy and positions of electrons and photons measured in electromagnetic calorimeters.

• Energy and position of hadrons and jets measured mainly in hadronic calorimeters.

• Muons identified and momentum measured in external muon spectrometer (+ central tracker).

• Neutrinos "detected and measured" through measurement of missing transverse energy (E_T^{miss}) in calorimeters $\rightarrow$ hermeticity!!.

The ATLAS experiment



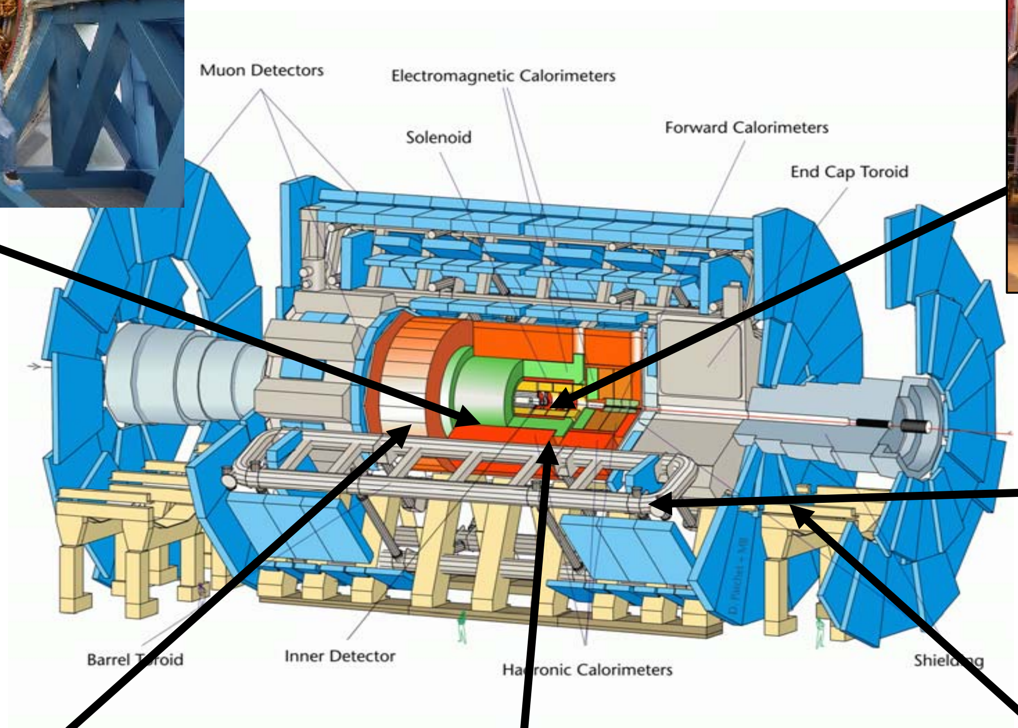
ATLAS

Length : ~40 m
Radius : ~10 m
Weight : ~ 7000 tons

- 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

ATLAS

Solenoid



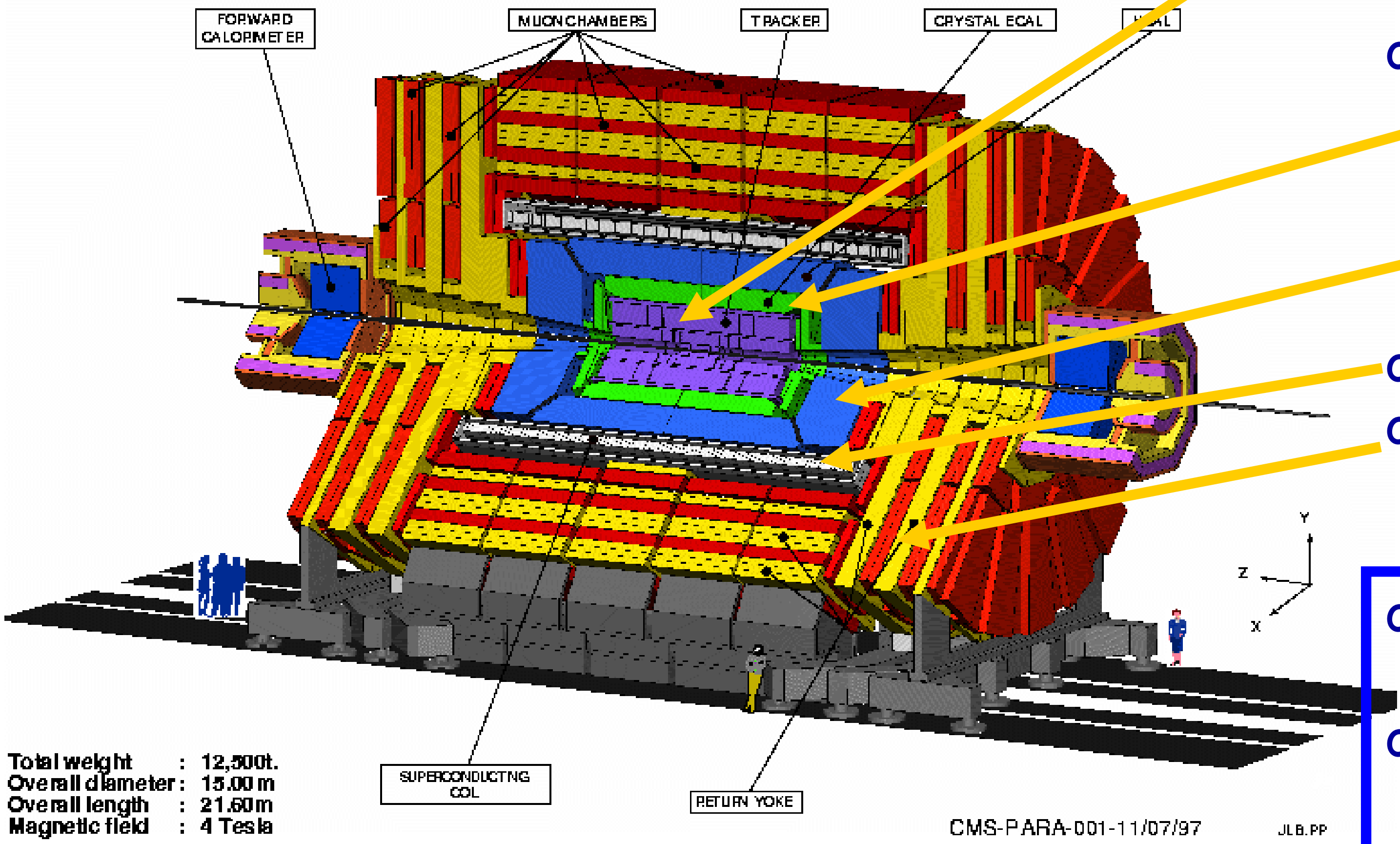
Barrel LAr ECAL

Length : ~40 m
Radius : ~10 m
Weight : ~ 7000 tons

Barrel coil cryostat

TRT end-cap wheel

The CMS experiment

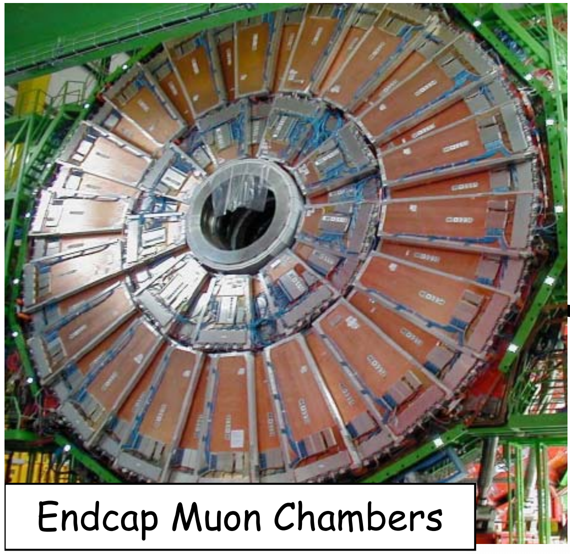


- o Tracking
  - o Silicon pixels
  - o Silicon strips
- o Calorimeters
  - o PbW04 crystals for Electro-magn.
  - o Scintillator/steel for hadronic part
- o 4T solenoid
- o Instrumented iron for muon detection

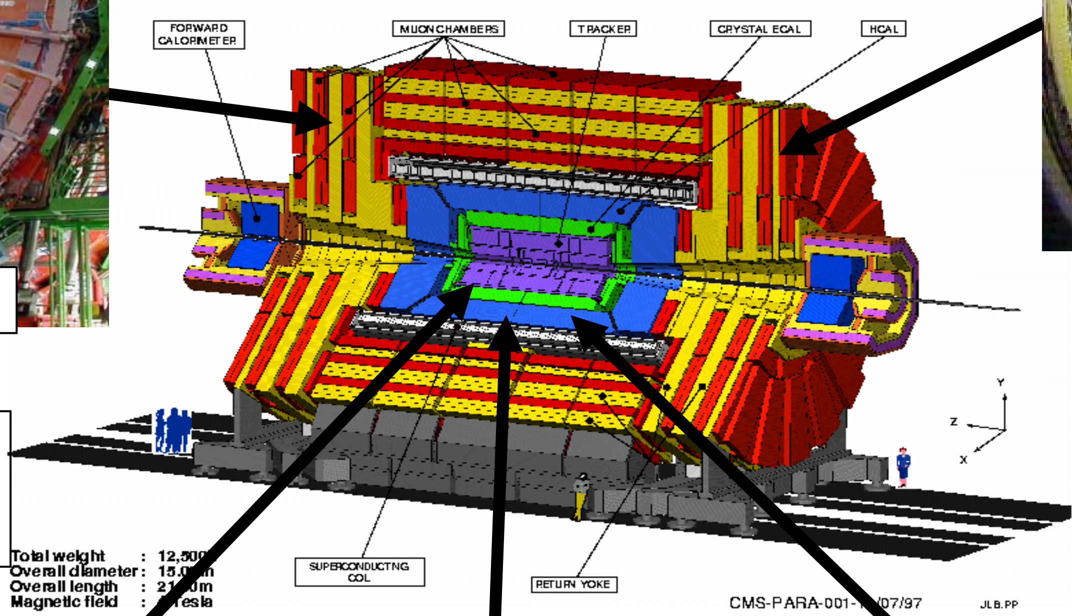
A Huge enterprise !

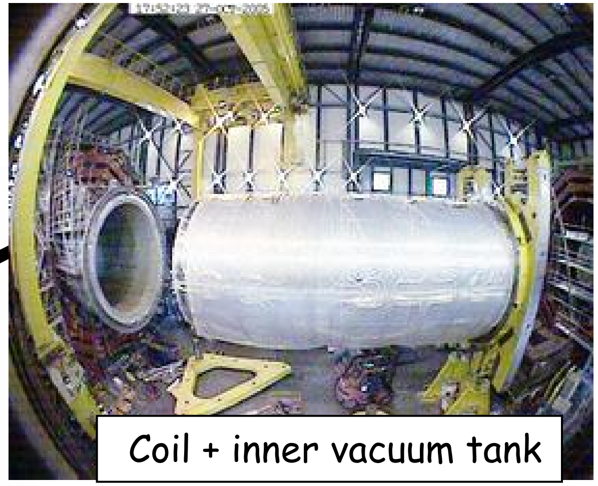
- o In total about 98 000 000 channels
- o Size of 1 event 1 000 000 Bytes
- o Readout to disk 100 events/sec

CMS



Endcap Muon Chambers

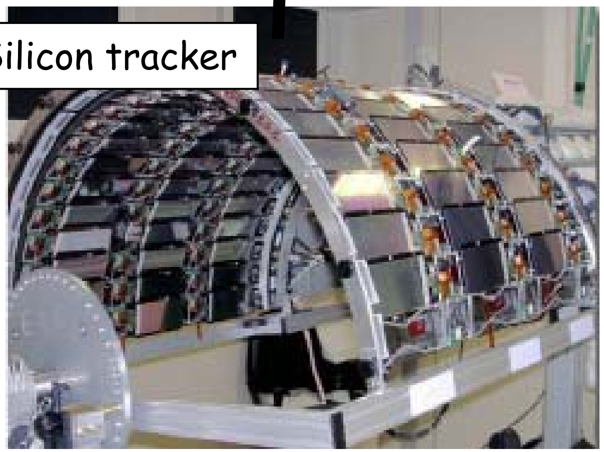




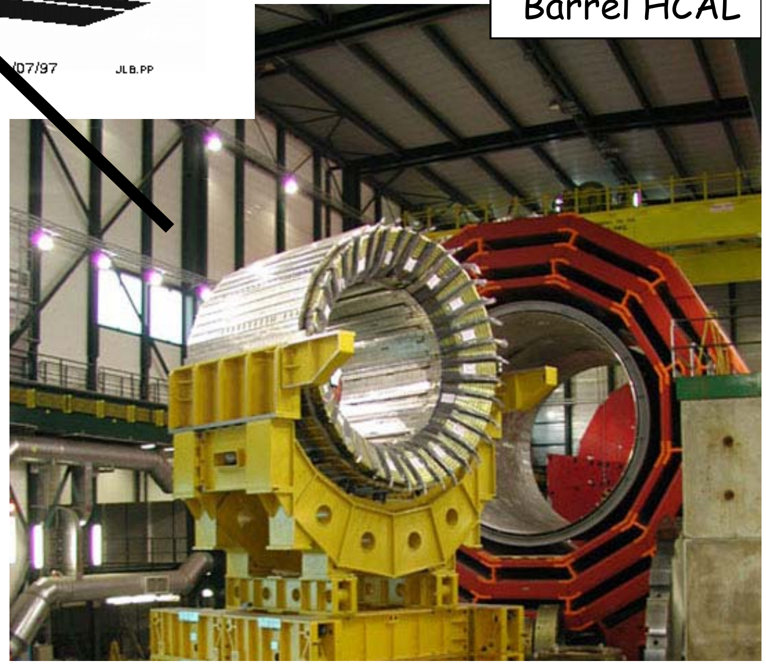
Coil + inner vacuum tank

Length : ~20 m
Radius : ~7 m
Weight : ~ 13000 tons

ECAL crystals



Silicon tracker



Barrel HCAL

A few LHC numbers…

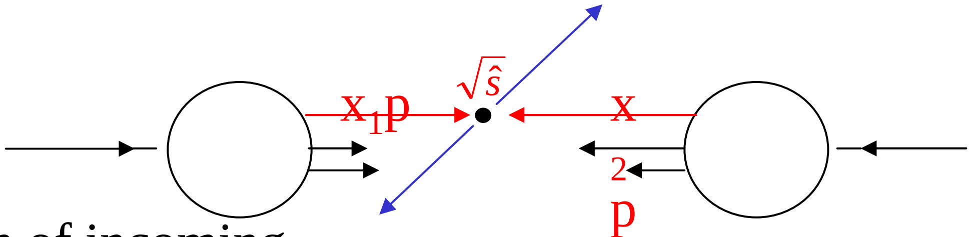
- Rate of pp interactions at 10^{34} : 10^9 events per second
- Energy of pp is about 7 times higher than that of the Tevatron at FNAL
- Weight of the CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)
- Amount of cables used in ATLAS : ~ 3000 km
- Data volume recorded at the front-end in CMS is 1 TB/second which corresponds to 10,000 Encyclopedia Britannica
- Data recorded during the 10-20 years of LHC life will be equivalent to all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy the beam is of 1 small aircraft carrier of 10^4 tons going 20 miles/ hour
- Machine temperature : 1.9 K (largest cryogenic system in the world)
- Total cost of machine + experiments : ~ 5000 MCHF
- Total number of involved physicists : ~ 5000

….

Challenges for Experiments at the LHC

Proton-proton collisions

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering (“ head on”) between constituents of incoming protons occurs.



p ≡ momentum of incoming protons = 7 TeV

Need:
- High Energy
- Many collisions

High luminosity = events/cross section/time

E.g. 1 pb^{-1}/hour means you will get 150 000 pp → W events per hour

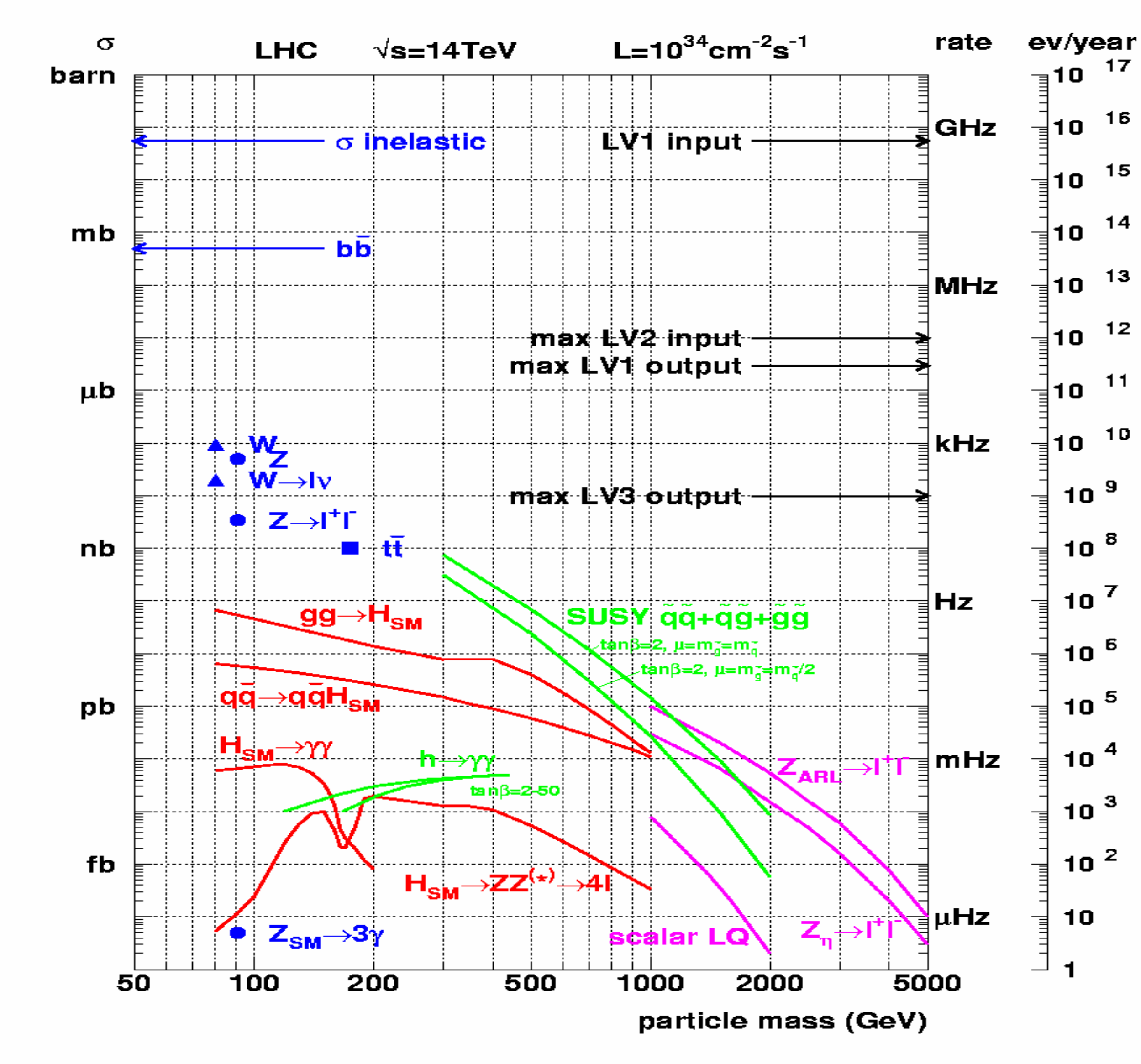
Interactions at small distance → large momentum transfer → massive particles and/or particles at large angle are produced.

These are interesting physics events but they are rare.

Ex. $u + \bar{d} \rightarrow W^+$

$\sigma\,(pp \rightarrow W) \approx 150\text{ nb} \approx 10^{-6}\,\sigma_{tot}\,(pp)$

Cross sections at the LHC



"Well known" processes, don't need to keep all of them …

New Physics!!
This we want to keep!!

Expected Event rates

Process	Events/s	Events/year	Other machines
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tev
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
QCD jets p_T > 200 GeV	10^2	10^9	10^7

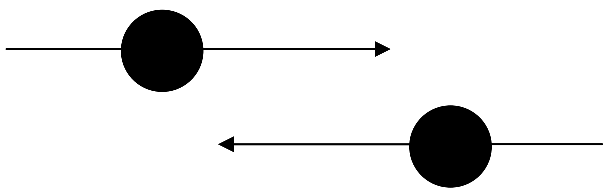
Huge event rates:
($10^{33} cm^{-2} s^{-1}$)

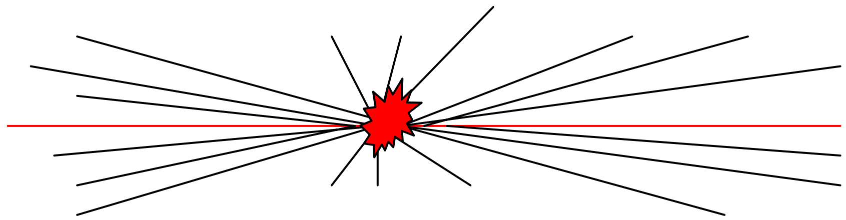
The LHC will be a W-factory, a Z-factory, a top factory, a Higgs factory etc..

Precision EW physics will be limited by systematics

Proton-proton collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)
→particles in final state have large longitudinal momentum but small
→transverse momentum (scattering at large angle is small)





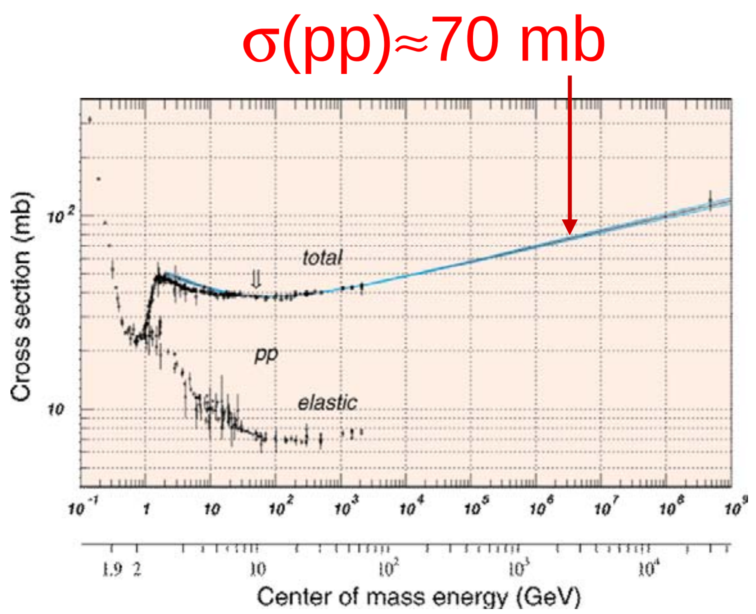
$< p_T > \approx 500$ MeV   of charged particles in final state

Most energy escapes down the beam pipe.

These are called minimum-bias events (" soft " events)..

pp cross section and minimum bias

- # of interactions/crossing:
  - Interactions/s:
    - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}Hz$
      $\sigma(pp)$ = 70 mb (non-diffractive)
    - Interaction Rate, R = 7×10^8 Hz
  - Events/beam crossing:
      Δt = 25 ns = 2.5×10^{-8} s
    - Interactions/crossing=17.5
  - Not all p bunches are full
    - Approximately 4 out of 5 (only) are full
    - Interactions/"active" crossing = 17.5 x 3564/2835 = 23

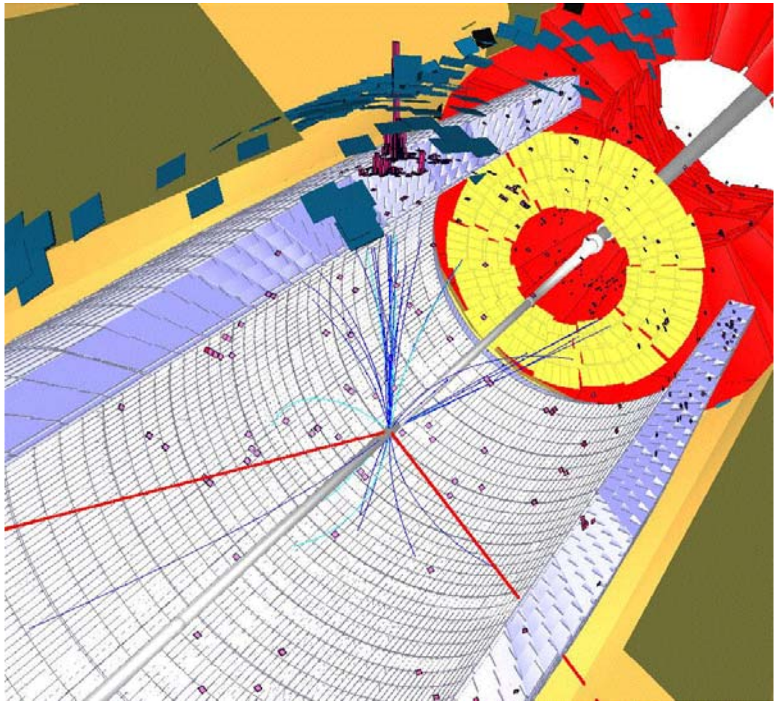


Operating conditions (summary):

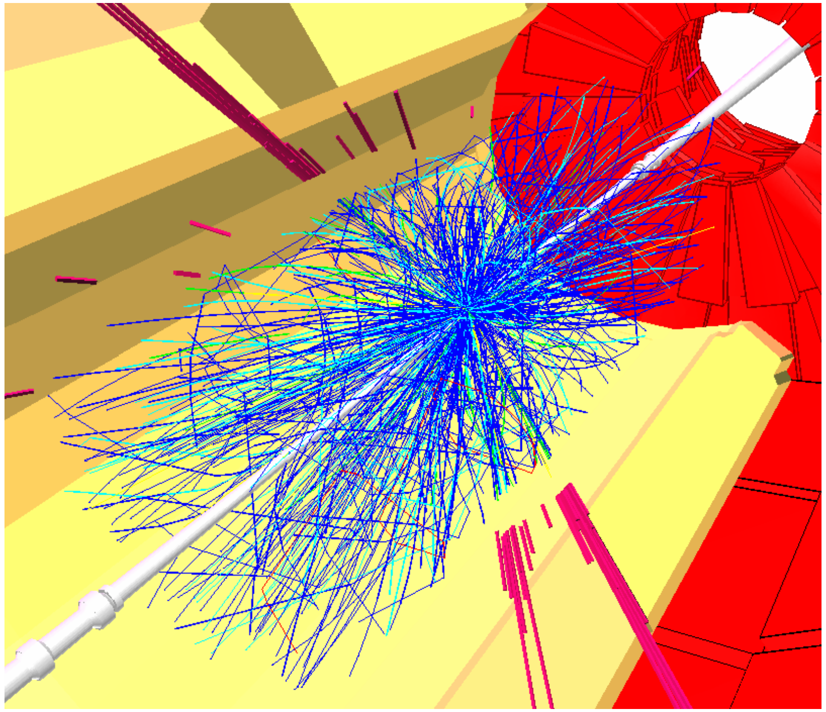
1) A "good" event containing a Higgs decay +
2) ≈ 20 extra "bad" (minimum bias) interactions

Pile-up at the LHC

Pile-up ⇒ additional -mostly soft- interactions per bunch crossing
Startup luminosity $2 \bullet 10^{33} cm^{-2}s^{-1}$ ⇒ 4 events per bunch crossing
High luminosity $10^{34} cm^{-2}s^{-1}$ ⇒ 20 events per bunch crossing
Luminosity upgrade $10^{35} cm^{-2}s^{-1}$ ⇒ 200 events per bunch crossing



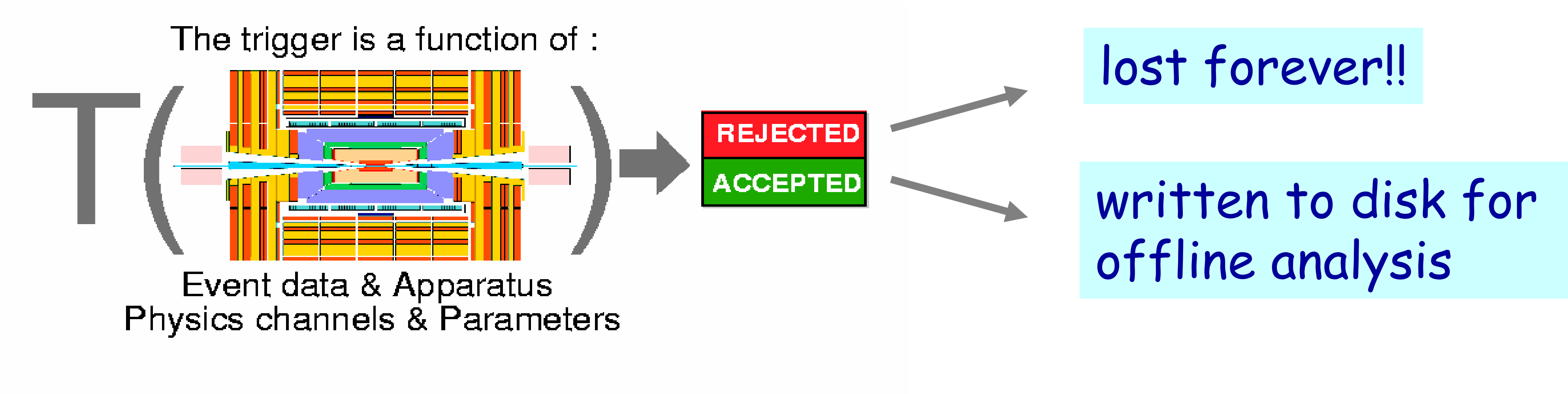
SUSY event (no pileup)



SUSY event ($10^{34} cm^{-2}s^{-1}$)

Event filtering: the trigger system

Collision rate is 40 MHz   Event size ~1 Mbyte
2007 technology (and budget) allows only to write 100 Hz of events to tape → need a factor ~10^7 online filtering!!



The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing Et,...

Example: CMS HLT trigger table

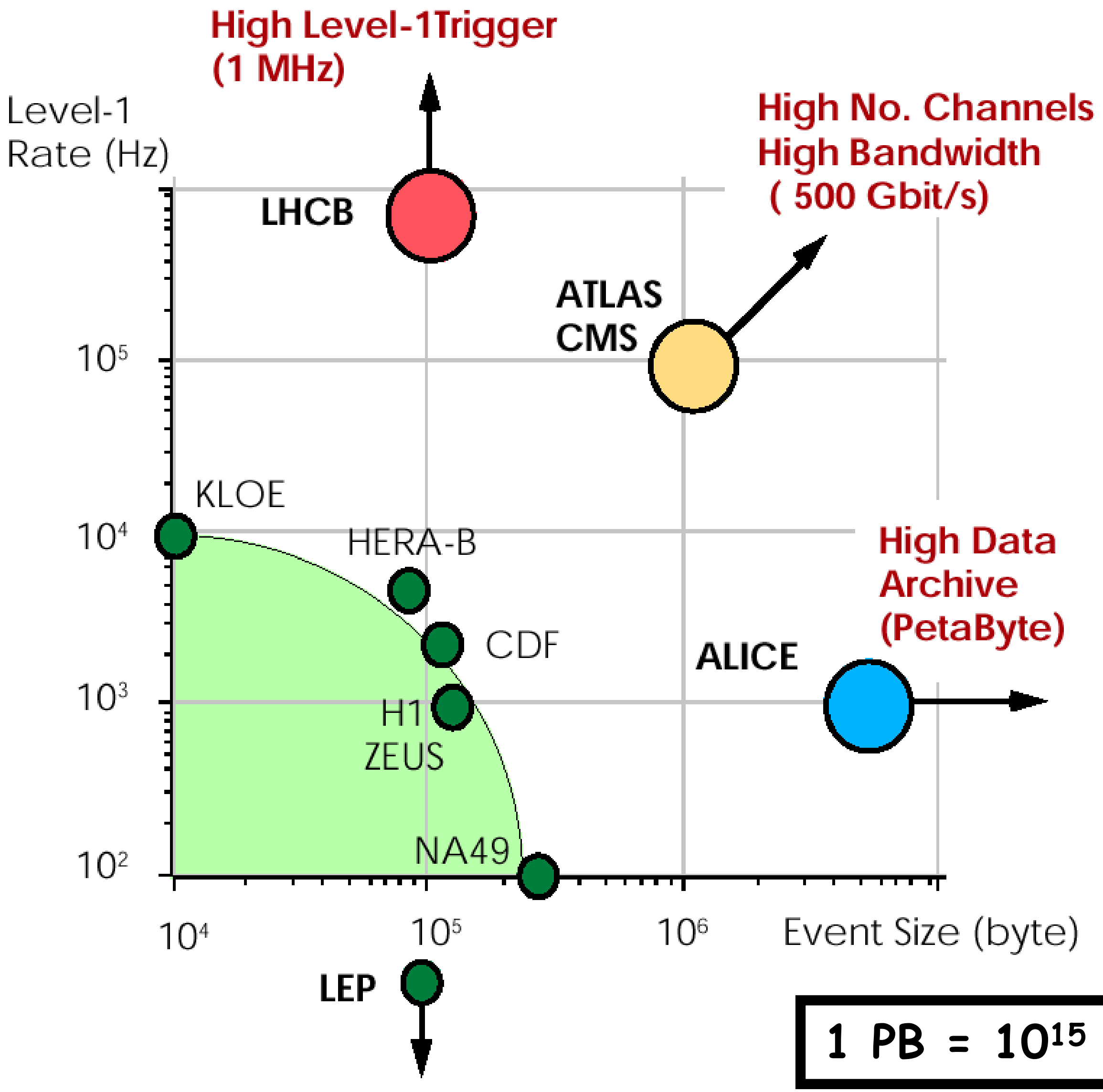
Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
inclusive electron	29	33	33
di-electron	17	1	34
inclusive photon	80	4	38
di-photon	40, 25	5	43
inclusive muon	19	25	68
di-muon	7	4	72
τ-jet * $\not{E}_T$	86 * 65	1	73
di-τ-jets	59	3	76
1-jet * $\not{E}_T$	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
electron * τ-jet	19 * 45	0.4	89.4
muon * τ-jet	15 * 40	0.2	89.6
inclusive b-jet	237	5	94.6
calibration and other events (10%)*		10	105
TOTAL			**105**

CMS DAQ TDR 2002

Similar numbers for ATLAS

More combined triggers as eg. jets + leptons or leptons + MET possible will be included as well

Comparison of LHC with other experiments



Huge computing Effort!

- 1 PB of raw data/year
- 3000 CPU's at CERN
  + >5000 in regional centers
- Data GRID project
  ⇒ LHC experiments are heavily involved

The grid will be important for LHC data analysis

1 PB = 10^{15} B =1 000 000 000 000 000 Bytes

Finding New Physics at the LHC

Per year, the LHC will provide ~10^{16} *pp* collisions (few/ 25 nanoseconds)

An observation of ~ 10 events could be a discovery of new physics.

→ One has to find these 10 events among 10^{16} non-interesting ones!!

Searching for a needle in a hay stack?

- typical needle: 5 mm^3
- typical haystack: 50 m^3

→ needle : haystack = 1 : 10^{10}

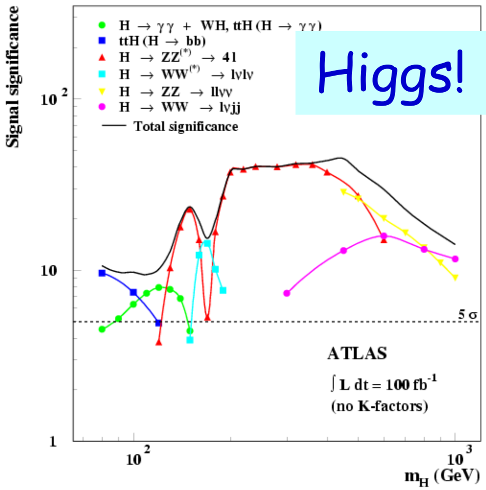
→ Looking for new physics at the LHC is like looking for a needle in 100000 haystacks …

Physics at the LHC

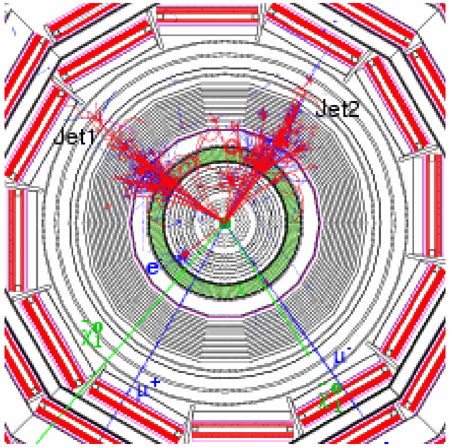
LHC Physics Program

- Discover or exclude the Higgs in the mass region up to 1 TeV. Measure Higgs properties
- Discover Supersymmetric particles (if exist) up to 2-3 TeV
- Discover Extra space dimensions, if these are on the TeV scale, and black holes?
- Search other new phenomena (e.g. strong EWSB, new gauge bosons, Little Higgs model, Split Supersymmetry)
- Study CP violation in the B sector
- Precision measurements of m_{top}, m_W, anomalous couplings…
- Heavy ion collisions and search for quark gluon plasma
- QCD and diffractive (forward) physics in a new regime
- …

Physics at the LHC: pp @ 14 TeV

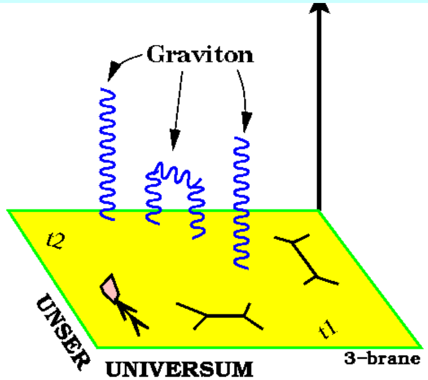


Higgs!

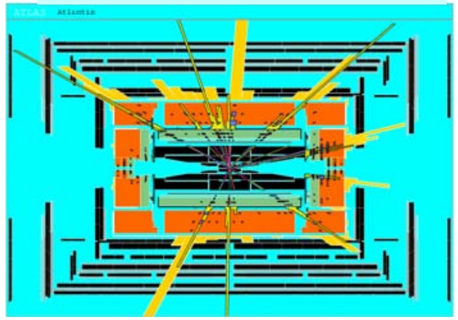


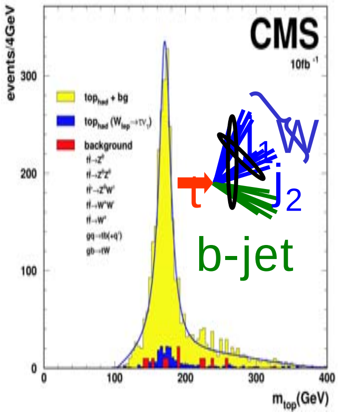
Supersymmetry?

Extra Dimensions?

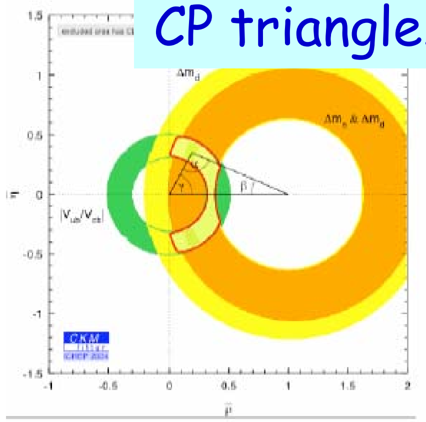


Black Holes???



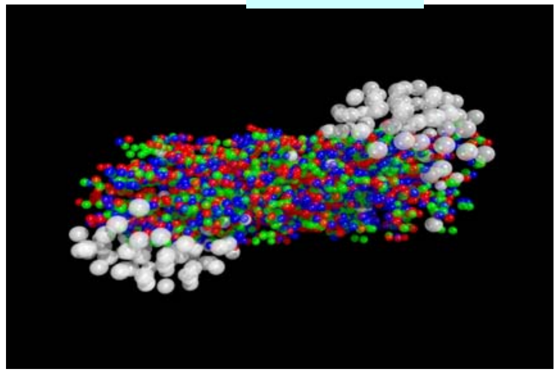


Precision measurements e.g top!



CP triangle!

QGP?

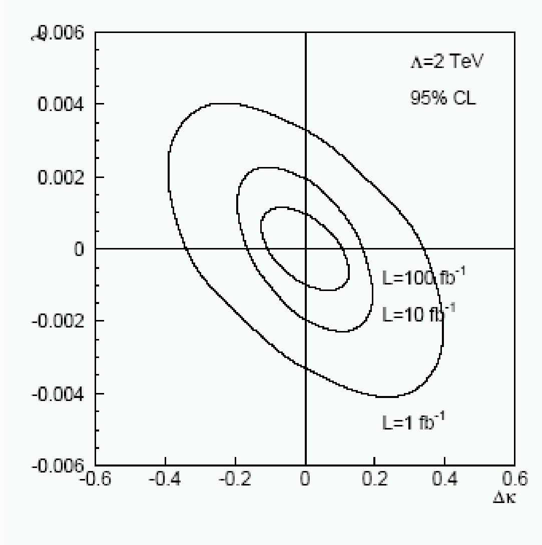


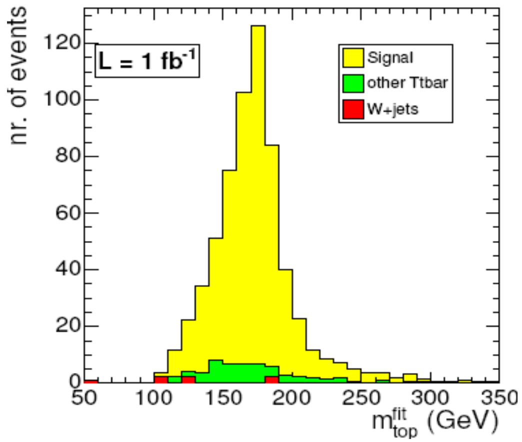
The LHC will be the new collider energy frontier

Standard Model Precision Measurements

Examples

- Measure ΔM_W down to 15 MeV
- Measure Triple Gauge Couplings →
- Precise Drell-Yan cross sections
  $\sin^2\theta_{eff}^{lept}$ to better than 10^{-4}
- Measure Top quarks
  - Δ M(top) down to 1.0-1.5 GeV
  - Top polarization
  - V_{tb} ~ 5-10% (single top production)
  - BR($t \rightarrow bH+$) ~ 3%
  - Rare decays: e.g. $t \rightarrow u\gamma$: ~ 10^{-4}

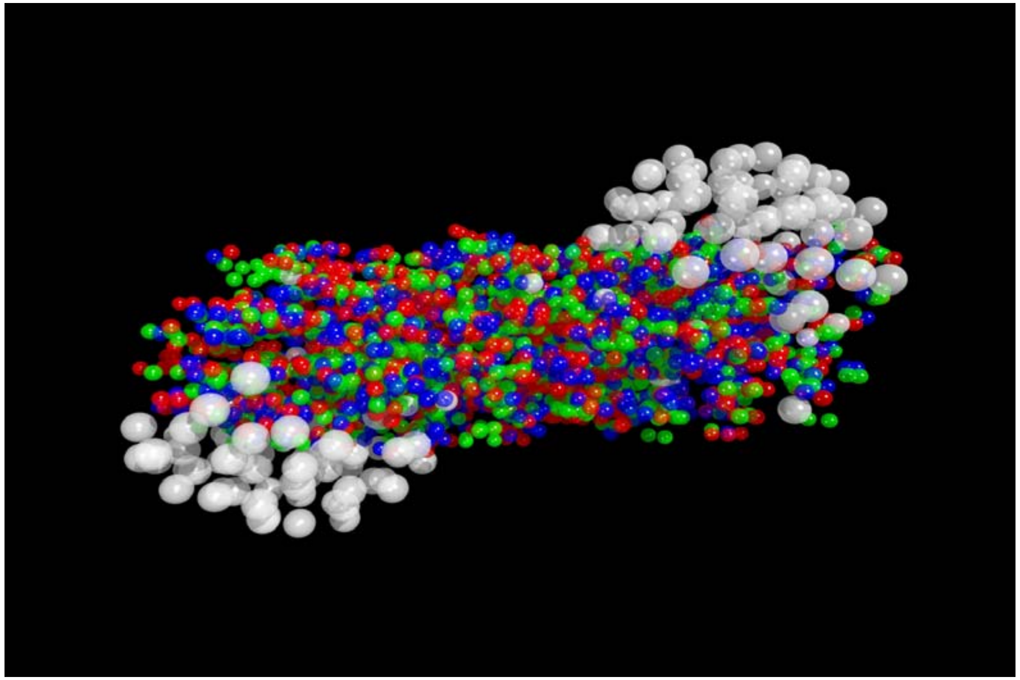




challenges

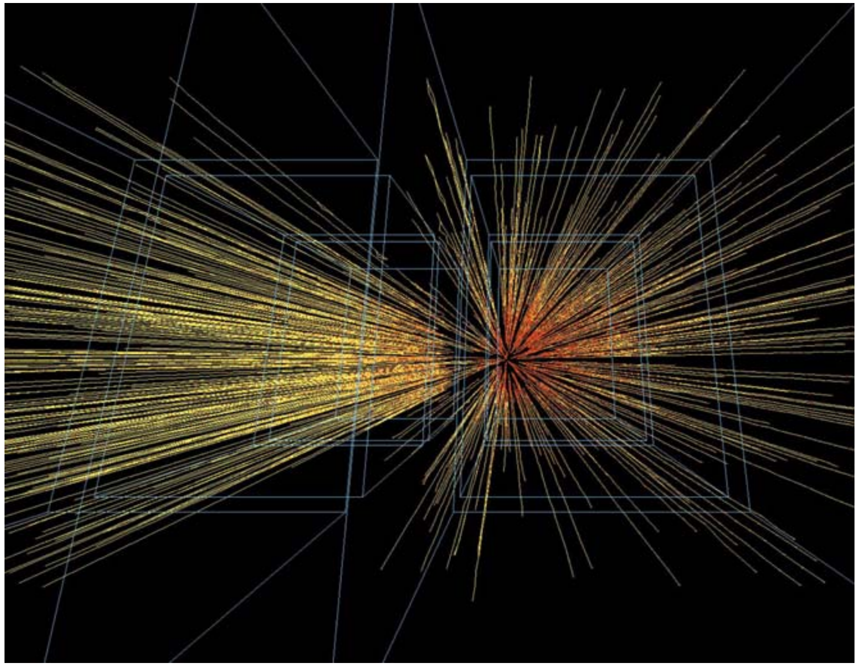
! It will be a though job ! Main challenges:
To keep the systematic errors under control

Heavy Ions in LHC



Search for a new state of matter: quark gluon plasma

At LHC: ALICE & CMS (& ATLAS?)



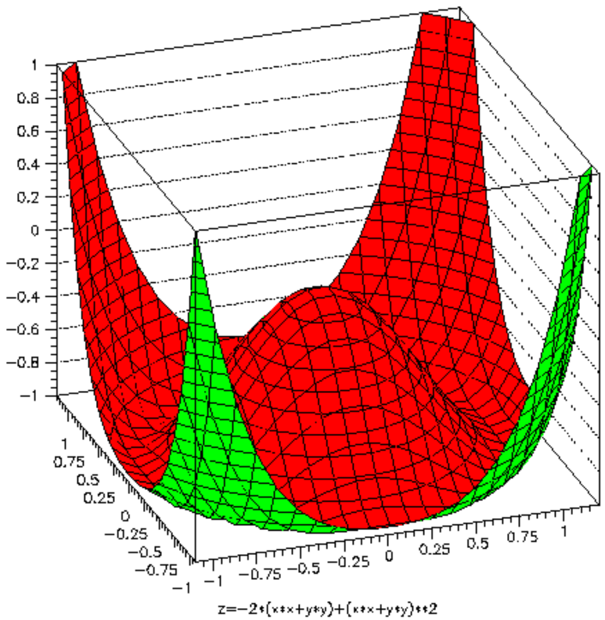
Some evidence from CERN fixed target and RHIC experiments (J/ψ suppression, strangeness production, low mass e^+e^- pairs…)

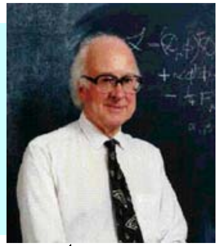
Higgs Physics

⇒ What is the origin of Electro-weak Symmetry Breaking?

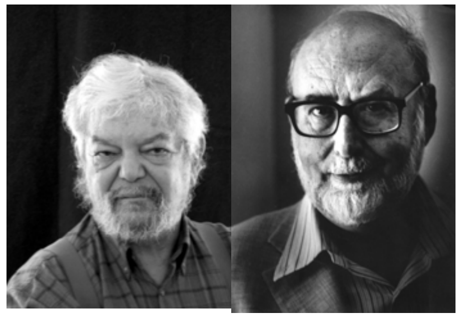
⇒ If Higgs field at least one new scalar particle should exist: The Higgs

One of the main missions of LHC: discover the Higgs for m_H< 1 TeV





The only Higgs sighted so far



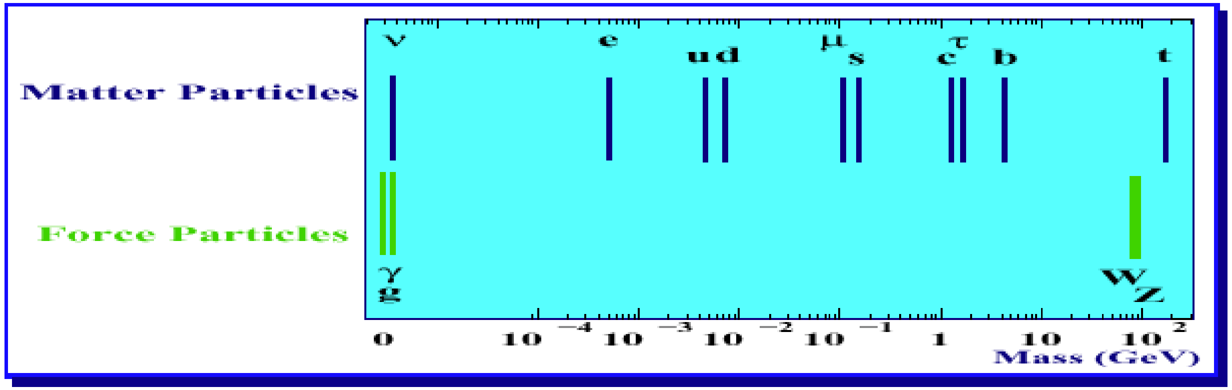
Brout, Englert

The Higgs Mechanism

Proposed solution for this problem in the 60's

➡ The Higgs Mechanism

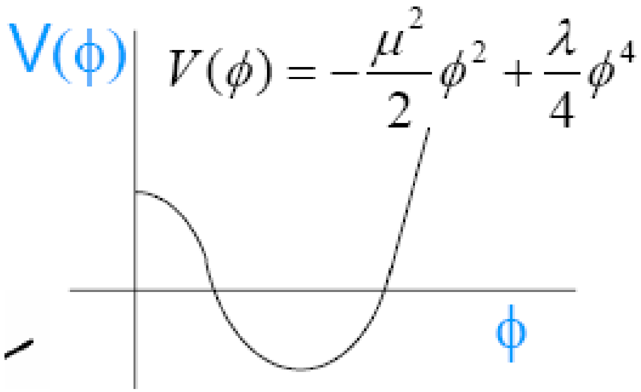
Observed mass pattern m_{top}/m_e= 350000



1964 Higgs, Englert and Brout propose to add a complex scalar field to the Langrangian

$$\phi = \phi_1 + i\phi_2$$

$$\mathcal{L} = (\partial^\mu \phi^\dagger)(\partial_\mu \phi) - \mu^2 \mid \phi \mid^2 - \lambda \mid \phi \mid^4$$



Expect at least one new scalar particle: Higgs

Electro-Weak Symmetry Breaking (EWSB)

- Why are the masses of the fundamental particles not equal to zero

  $\Rightarrow$ Electroweak Symmetry breaking
  - EWSB mechanism requires (at least) one new particle
  - energy scale of EWSB must be ~ TeV to preserve unitarity of V-V (V=W, Z) scattering matrix
- Current wisdom: SB mechanism generates Goldstone bosons $\rightarrow$ longitudinal degrees of freedom for W & Z
  - But underlying nature of dynamics not known $\rightarrow$ traditionally:two possibilities: weakly-coupled and strongly-coupled dynamics

⬇

- Weakly-coupled: self-interacting scalar fields: E.g the Higgs field
  - Self-interaction $\rightarrow$ non-vanishing vacuum expectation value
  - Then: interactions with bosons/fermions $\rightarrow$ gives mass to them
  - Must stabilize mass of the field $\rightarrow$ some additonal mechanism (SUSY?)
    - New ideas: whole new "world": extra space dimensions
- Strongly-coupled: new strong interaction at ~TeV scale
  - Fermion-antifermion pair condensates

Electro-Weak Symmetry Breaking (EWSB)

Footnote:

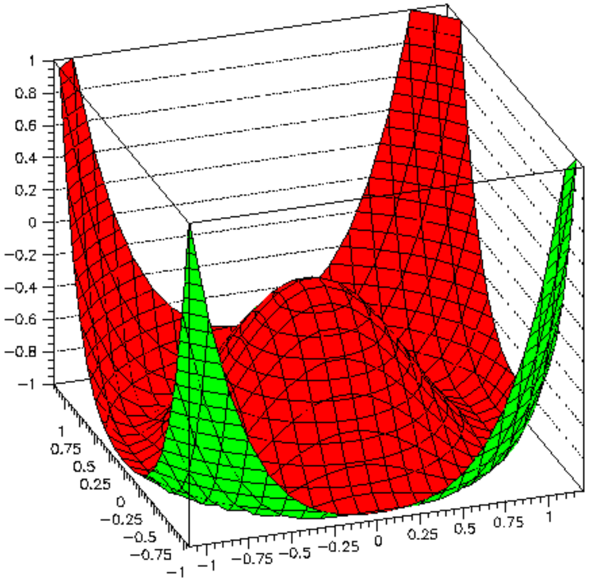
- More recent models (topcolor, little Higgs, EDM…) allow for intermediate Mass Higgs bosons and incorporate both strong and weak interactions. Other models incorporate SUSY but still have new strongly interaction sectors

The Higgs Mechanism

The Higgs Field

$$\mathcal{V}(\phi) = \mu^2 \mid \phi(x) \mid^2 + \lambda \mid \phi(x) \mid^4$$

⇒ Particles acquire mass trough interaction with the Higgs field



At least one scalar Higgs boson should be discovered
We do not know its mass!!!
Except → Theory $M_H < \sim 1$ TeV

The Higgs coupling to particles is proportional to their mass
⇒Needs to be checked

Reconstruct the Higgs potential (depends on the new physics)

Potential energy density of the Higgs field: lowest value is not at zero!

$$g_{HVV} = 2M_V^2/v$$

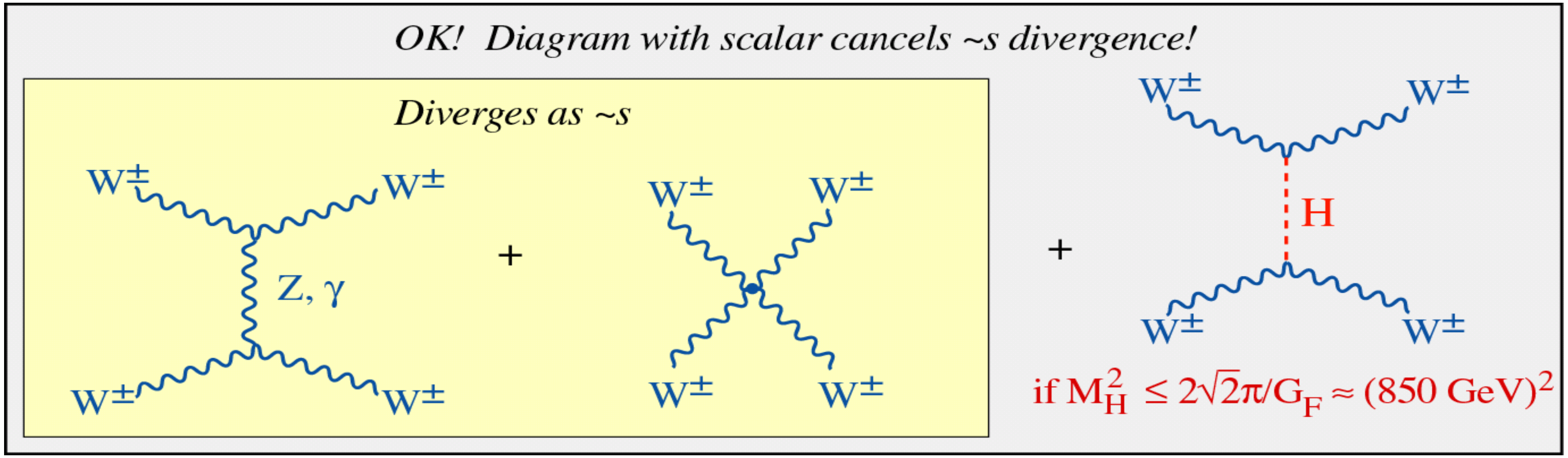
$$g_{Hff} = m_f/v$$

$$(\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

Vacuum expectation value of the Higgs field

The Higgs Mechanism

Scalar field is needed to maintain tree-level unitarity (and renormalisability)



What if there is no Higgs boson?

→ New physics have to appear in WW/ZZ scattering around 1 TeV

Everything you always wanted to know on the Higgs

LPT–Orsay–05–17
March 2005

The Anatomy of Electro–Weak Symmetry Breaking

Tome I: The Higgs boson in the Standard Model

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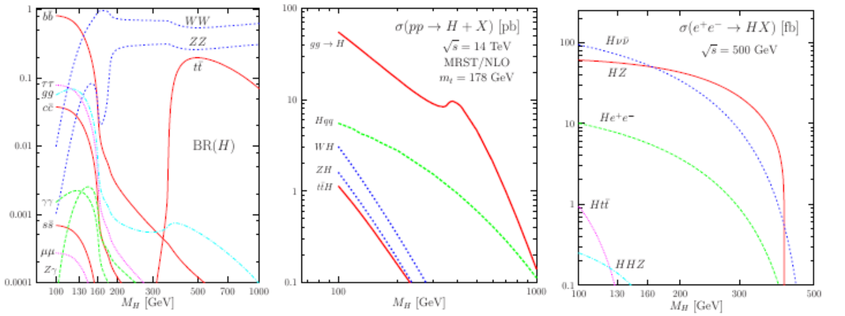
Abstract

This review is devoted to the study of the mechanism of electroweak symmetry breaking and this first part focuses on the Higgs particle of the Standard Model. The fundamental properties of the Higgs boson are reviewed and its decay modes and production mechanisms at hadron colliders and at future lepton colliders are described in detail.



The decay branching ratios of the Standard Model Higgs boson and its production cross sections in the main channels at the LHC and at a 500 GeV e^+e^- collider.

> 700 pages...

LPT–Orsay–05–18
March 2005

The Anatomy of Electro–Weak Symmetry Breaking

Tome II: The Higgs bosons in the Minimal Supersymmetric Model

Abdelhak Djouadi

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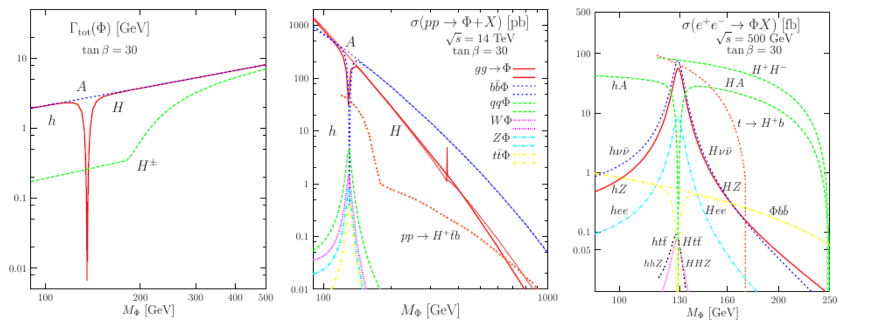
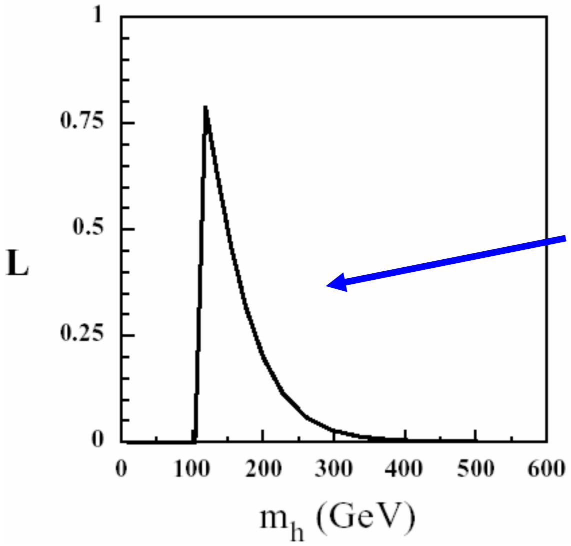
Abstract

The second part of this review is devoted to the Higgs sector of the Minimal Supersymmetric Standard Model. The properties of the neutral and charged Higgs bosons of the extended Higgs sector are summarized and their decay modes and production mechanisms at hadron colliders and at future lepton colliders are discussed.



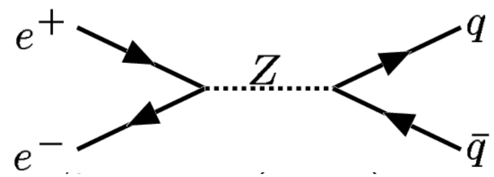
The total decay widths of the neutral and charged MSSM Higgs bosons and their production cross sections at the LHC and at a 500 GeV e^+e^- collider in the main channels.

What do we know about the Higgs?

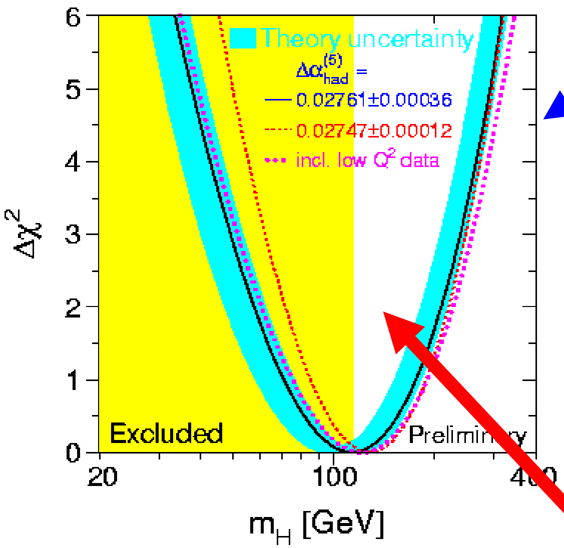


Probability for m_H combining direct and indirect information

LEP e+e- (200 GeV) Collider at CERN



Electro-weak precision measurements



114.4 < M_{higgs} < 186 GeV

⇒ Light Higgs preferred by EW data
⇒ Light Higgs needed for SUSY (<135 GeV)

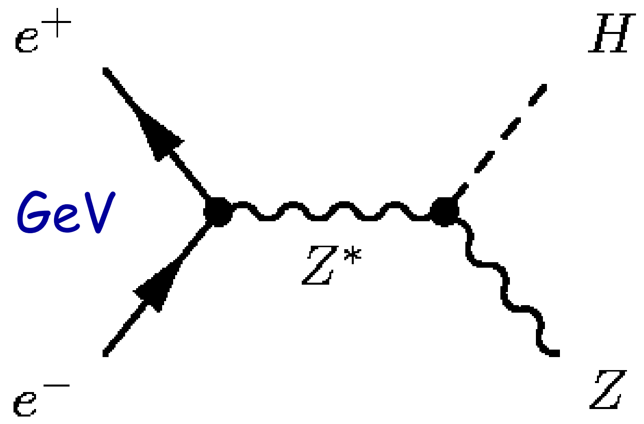
Caution … some recent developments

- Higgs + higher dimensional operators
  (→ Higgs could be heavy)
- Higgsless models in Extra Dimensions scenarios
- EW fit criticism…

⇒ A light Higgs is not guaranteed

Higgs Production at LEP?

√s=209 GeV



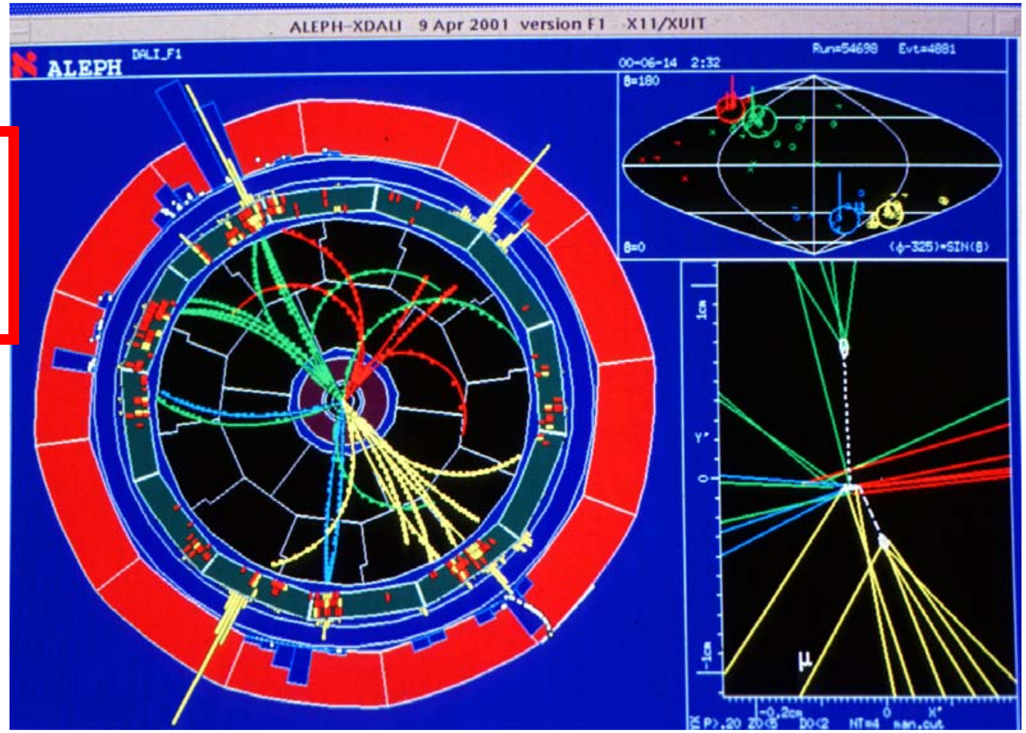
Main Production Mechanism:

Higgs Strahlung

Observe 4-jets, 2-jets+ 2 leptons etc.

Experimental reach M_H ~112-115 GeV

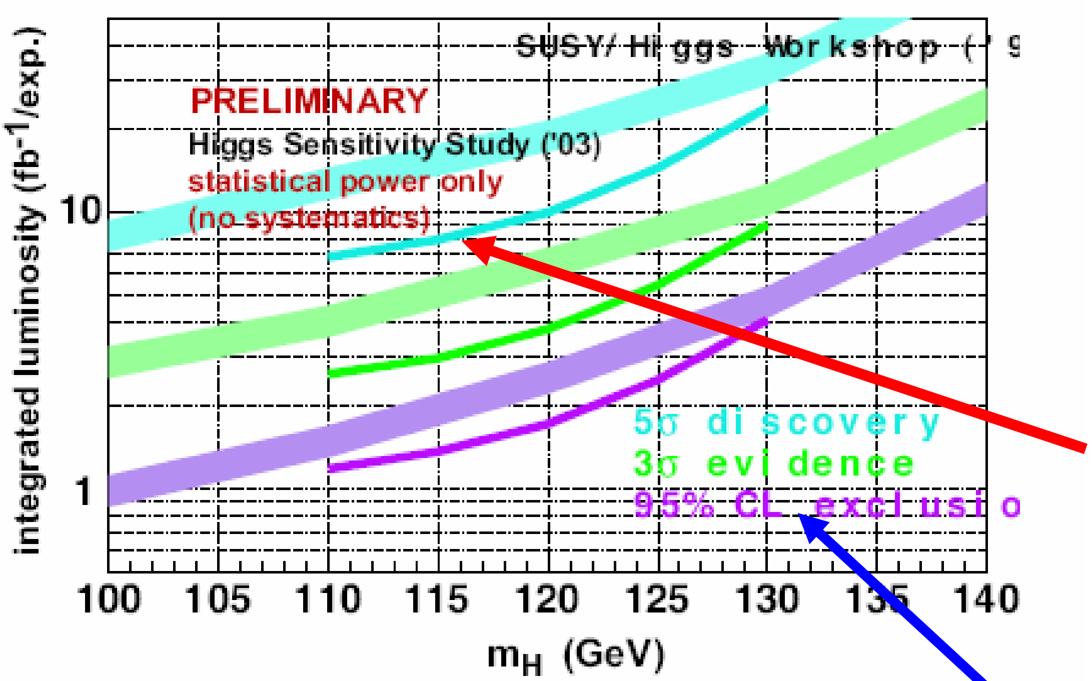
Intriguingly… just before the closure of LEP (Nov 2000) some events with the right characteristics where observed



A first glimpse of the Higgs?
Then M_H ~115 GeV, so very light!

But LEP was stopped in 2000 so we have to wait!!!

Who is next to hunt for the Higgs?



The Tevatron pp collider ($\sqrt{s}$ = 2 TeV) at Fermilab has started a second run, with increased luminosity

For M_{Higgs} = 115-120 GeV about 8-10 fb^{-1} are needed

Could be reached in 2009

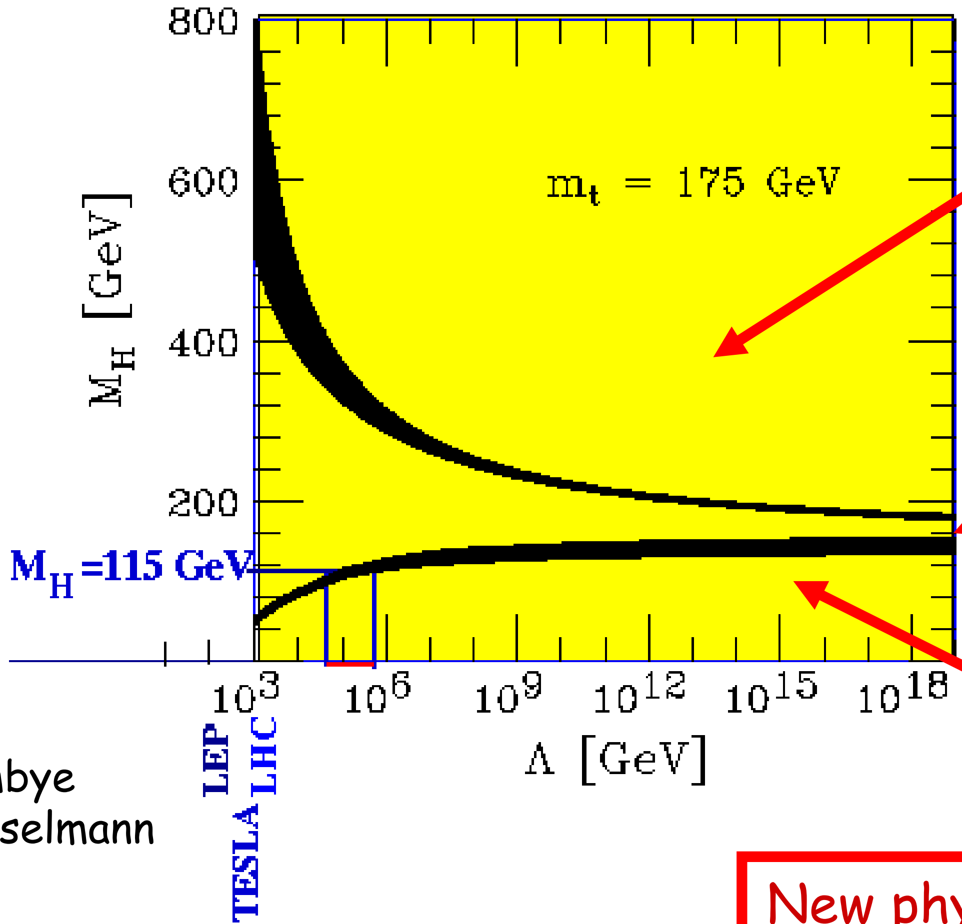
$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= signal events
N_B= background events

Will use similar techniques as the LHC

A light Higgs…important consequences

A light Higgs implies that the Standard Model cannot be stable up to the GUT or Planck scale (10^{19} GeV)



Hambye
Riesselmann

The effective potential blows up, due to heavy top quark mass

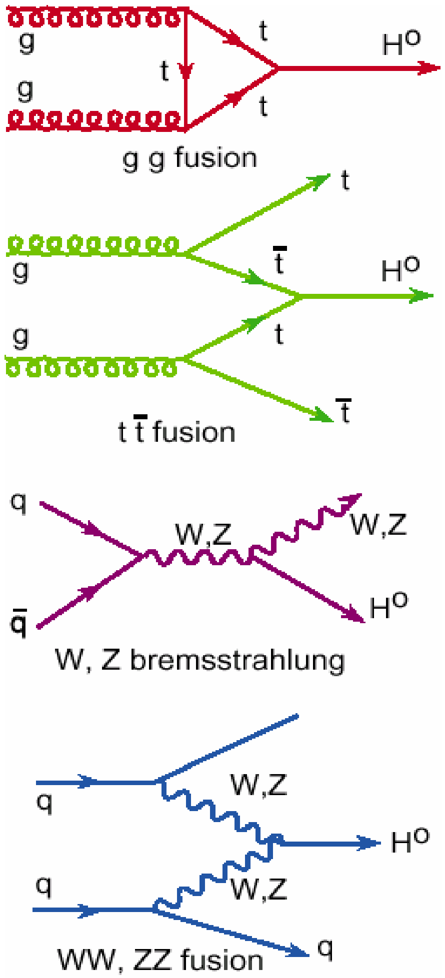
Allowed corridor but needs strong fine-tuning…

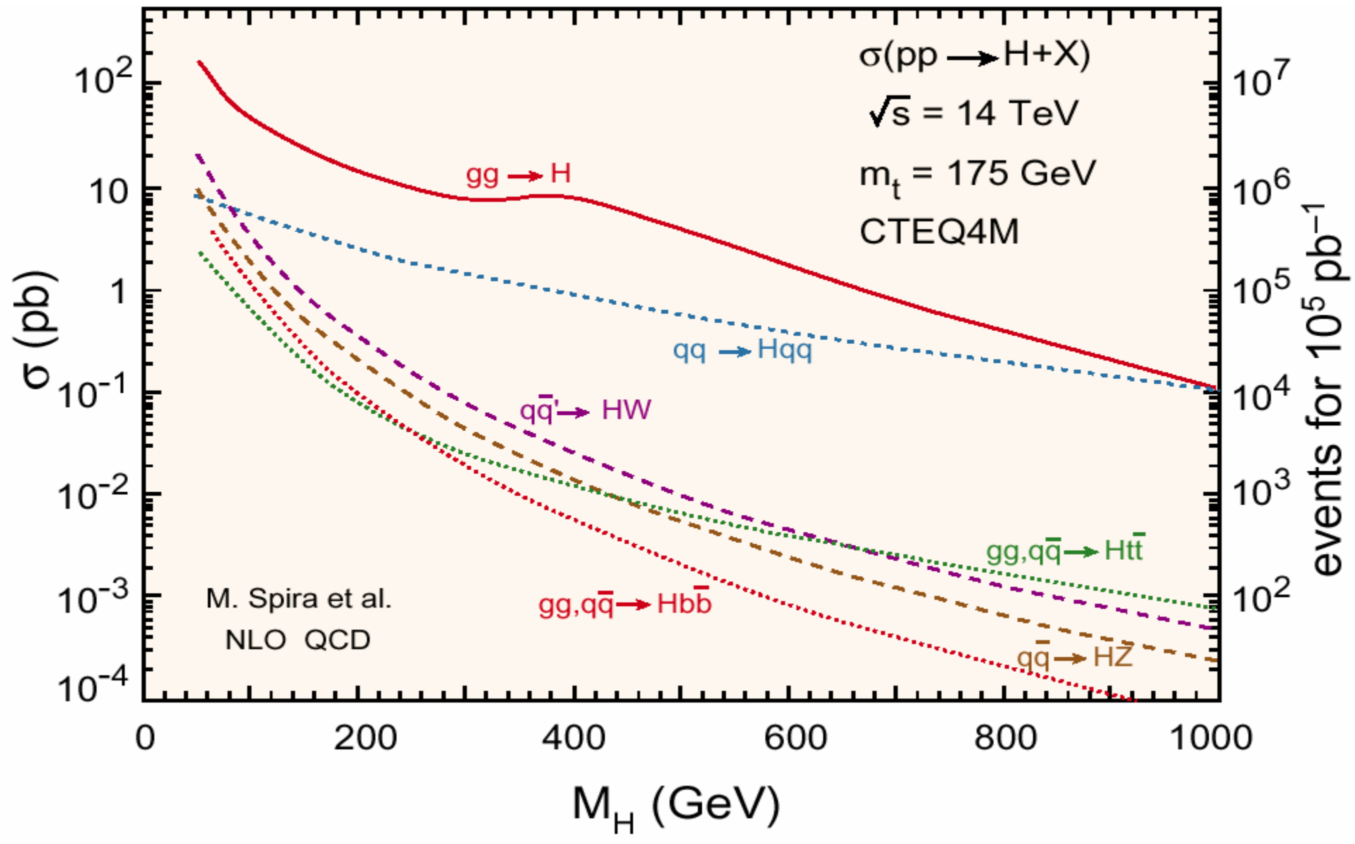
The electroweak vacuum is unstable to corrections from scales Λ >> v= 246 GeV

New physics expected in TeV range

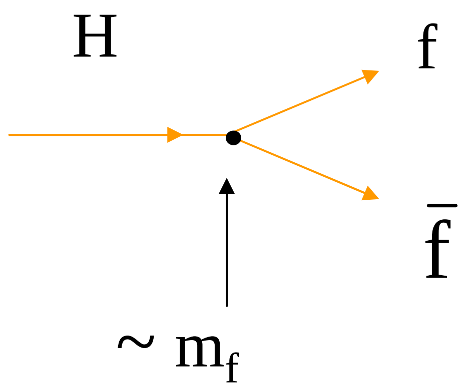
SM Higgs at the LHC

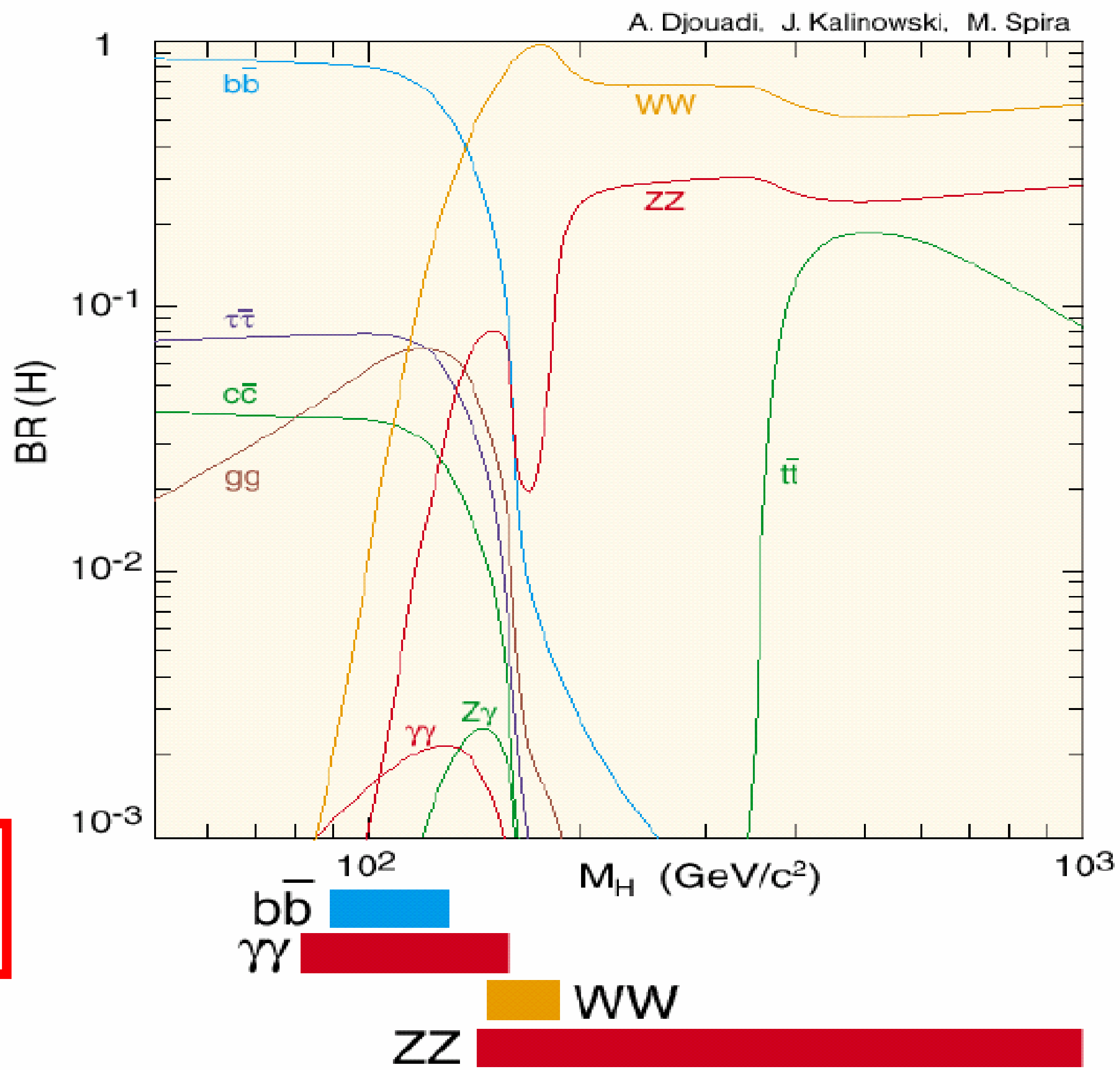
Production mechanisms & cross section





Higgs Decays: branching ratios





Decay in fermions or
Guage bosons

SM Higgs Search Strategy

Fully hadronic final states dominate but cannot be extracted from large QCD background $\rightarrow$ look for final states with leptons and photons.

Main channels:

- Low mass region ($m_H < 150$ GeV):

-- $H \rightarrow b\bar{b}$: BR ~ 100% $\rightarrow$ $\sigma \approx 20$ pb

however: huge QCD background ($N_S/N_B < 10^{-5}$)

$\rightarrow$ can only be used with additional leptons:

$W H \rightarrow \ell\nu\, b\bar{b}$, $t\bar{t}\, H \rightarrow \ell\nu X\, b\bar{b}$ associated production ($\sigma \approx 1$ pb)

-- $H \rightarrow \gamma\gamma$: BR ~ 10^{-3} $\rightarrow$ $\sigma \approx 50$ fb

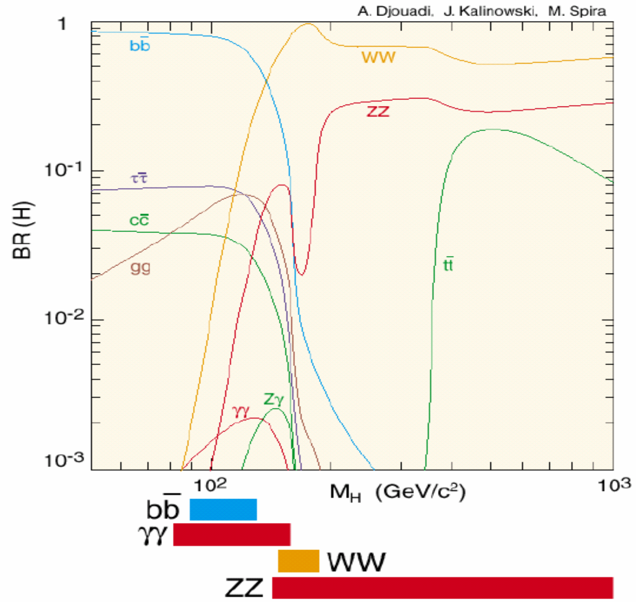
however: clean channel ($N_S/N_B \approx 10^{-2}$)

SM Higgs search channels

Low mass $M_H \lesssim 200$ GeV

M. pieri

Production / DECAY	Inclusive	VBF	WH/ZH	ttH
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$			YES	YES
$H \rightarrow \tau\tau$		YES		
$H \rightarrow WW^*$	YES	YES	YES	
$H \rightarrow ZZ^*$, $Z \rightarrow \ell^+\ell^-$, ℓ=e,μ	YES			
$H \rightarrow Z\gamma$, $Z \rightarrow \ell^+\ell^-$, ℓ=e,μ	very low σ			



Intermediate mass
(200 GeV $\lesssim M_H \lesssim$ 700 GeV)

inclusive $H \rightarrow WW$
inclusive $H \rightarrow ZZ$

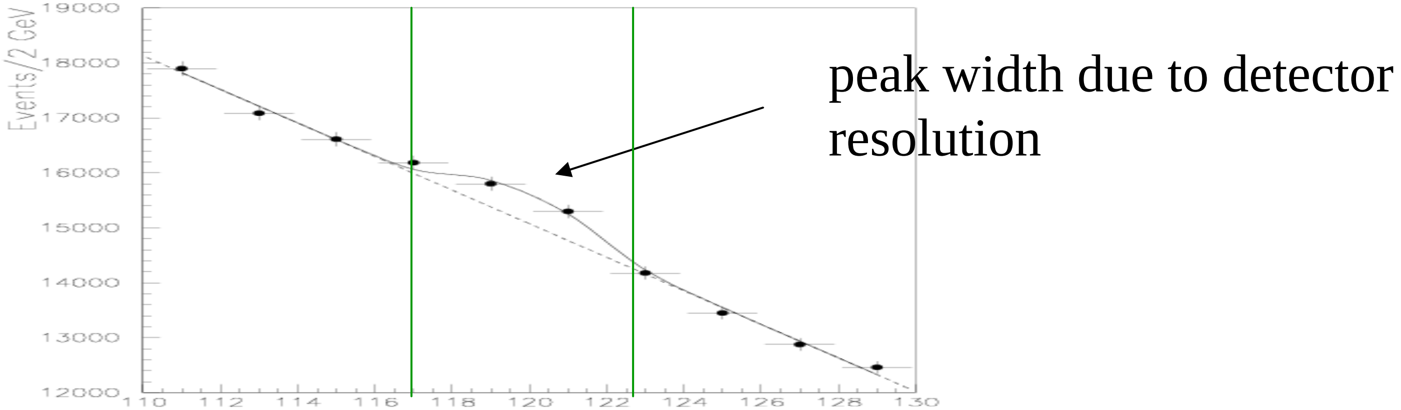
High mass ($M_H \gtrsim$ 700 GeV)

VBF $qqH \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
VBF $qqH \rightarrow WW \rightarrow \ell\nu jj$

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ are the only channels with a very good mass resolution ~1%

How can one claim a discovery ?

Suppose a new narrow particle $X \rightarrow \gamma\gamma$ is produced:



$m_{\gamma\gamma}$

Signal significance :

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= number of signal events
N_B= number of background events

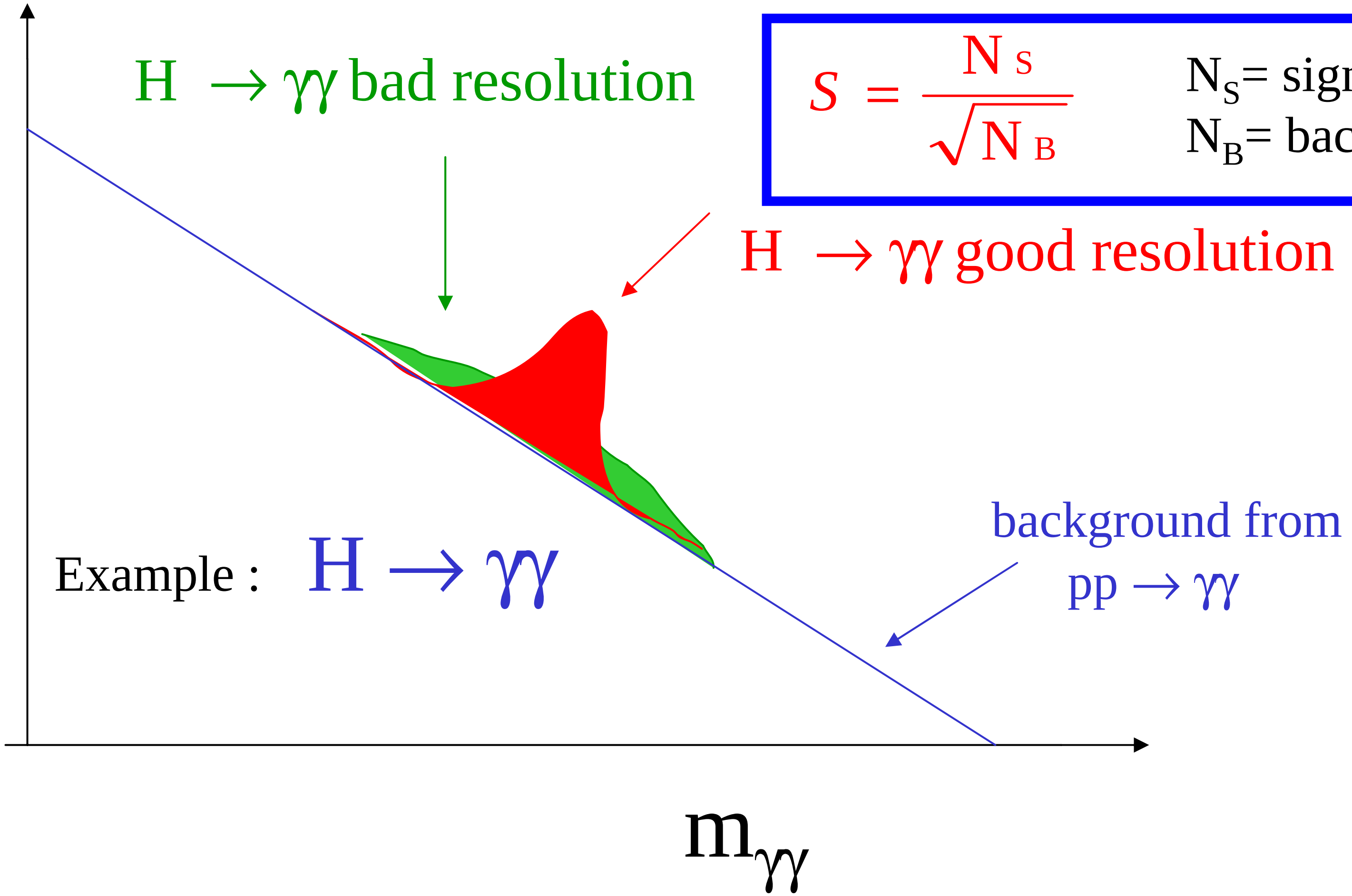
} in peak region

$\sqrt{N_B} \equiv$ error on number of background events

$S > 5$: signal is larger than 5 times error on background.
Probability that background fluctuates up by more than 5σ : $10^{-7} \rightarrow$ discovery

SM Higgs Search Strategy

- Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

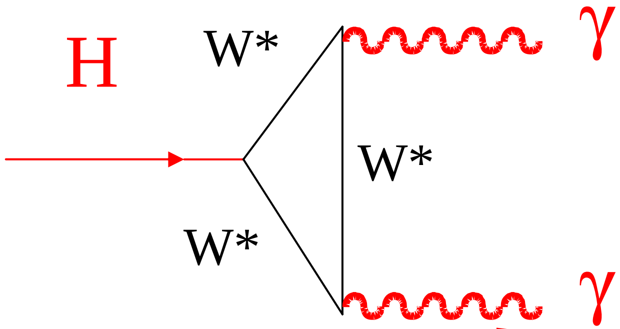


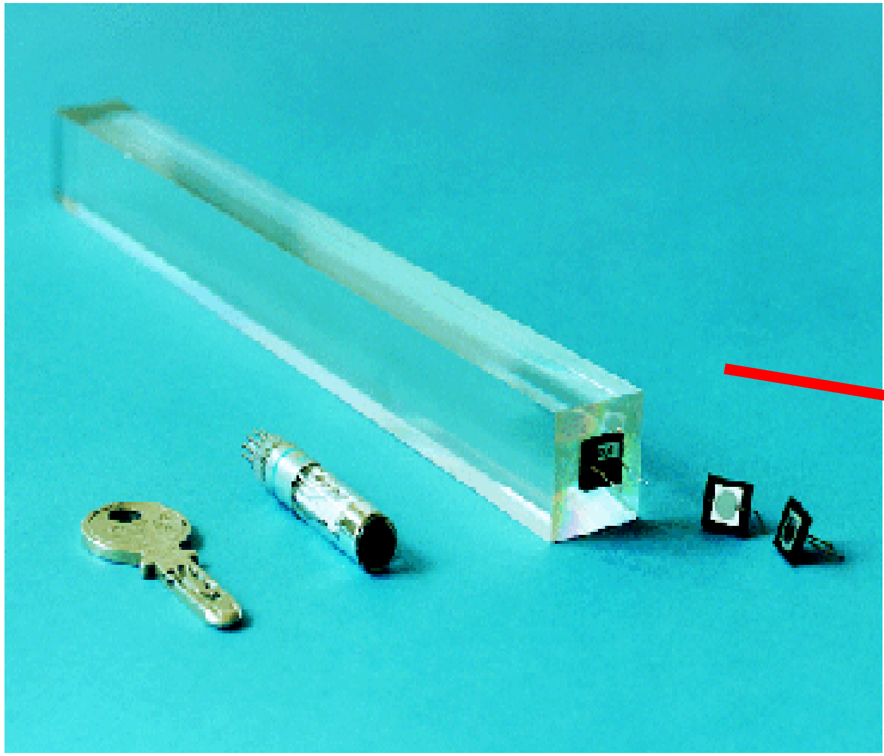
$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= signal events
N_B= background events

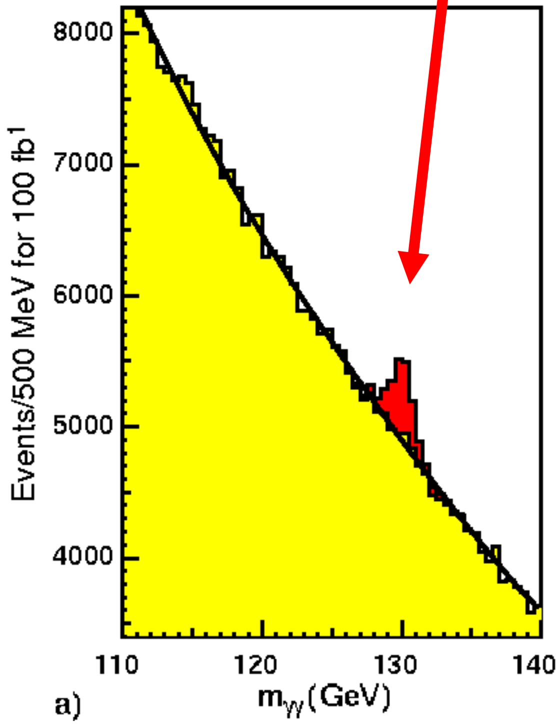
Measurements of a light Higgs

If the Higgs is light (115-120 GeV) then one of the most promising signals is $H \rightarrow \gamma\gamma$ (i.e. 2 photons)





Excellent calorimetery needed ($PbWO_4$)

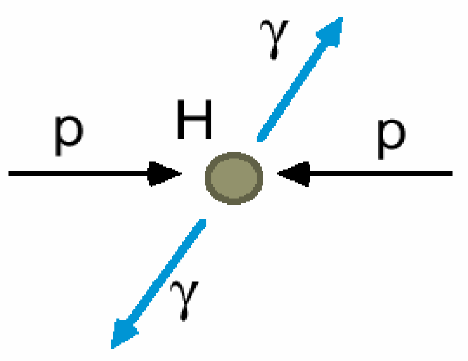


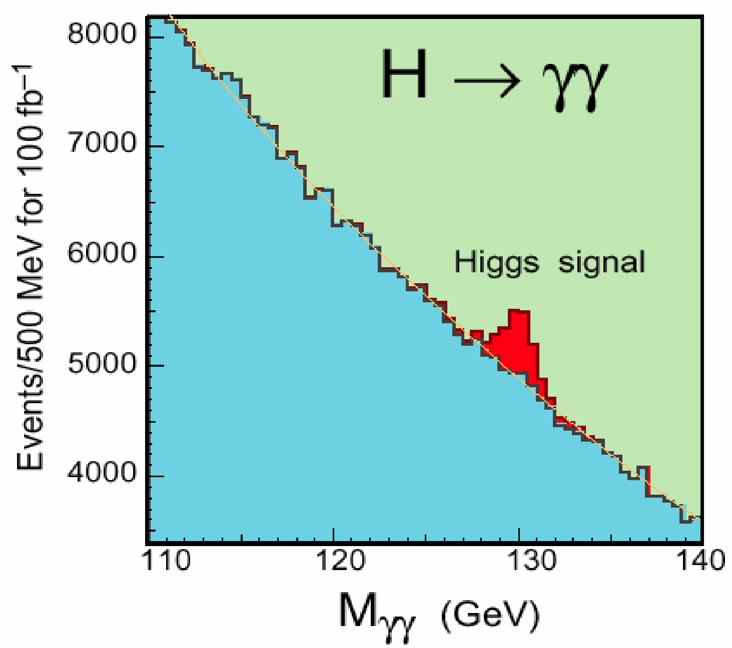
10 fb^{-1}

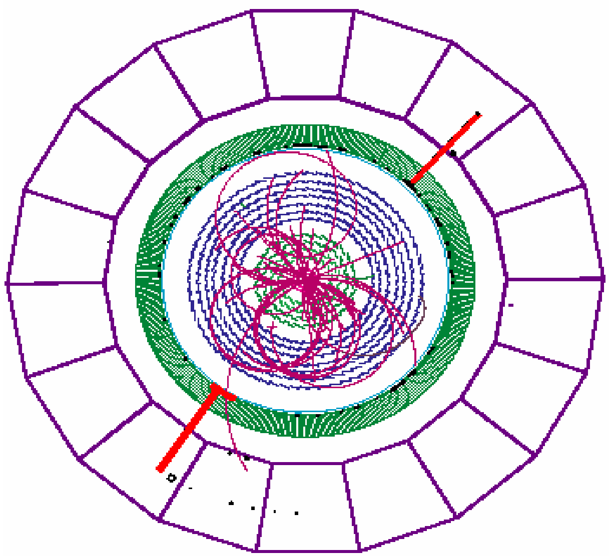
(First year)

Examples: Low mass Higgs (M_H<140 GeV/c^2)

- $H \to \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)
  - But with good resolution, one gets a mass peak
  - Motivation for LAr/$PbWO_4$ calorimeters
  - CMS example: at 100 GeV, $\sigma \approx$1GeV
    - S/B ≈ 1:20

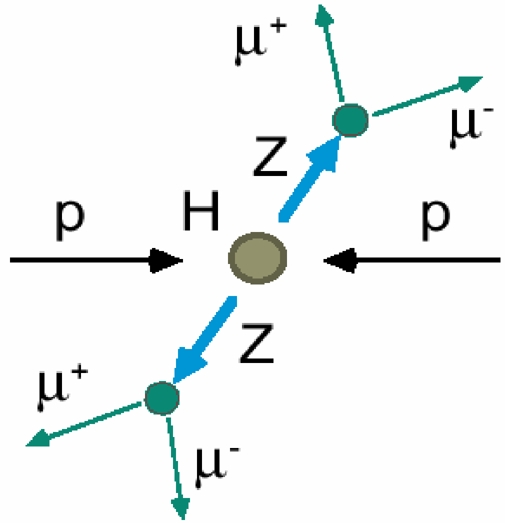


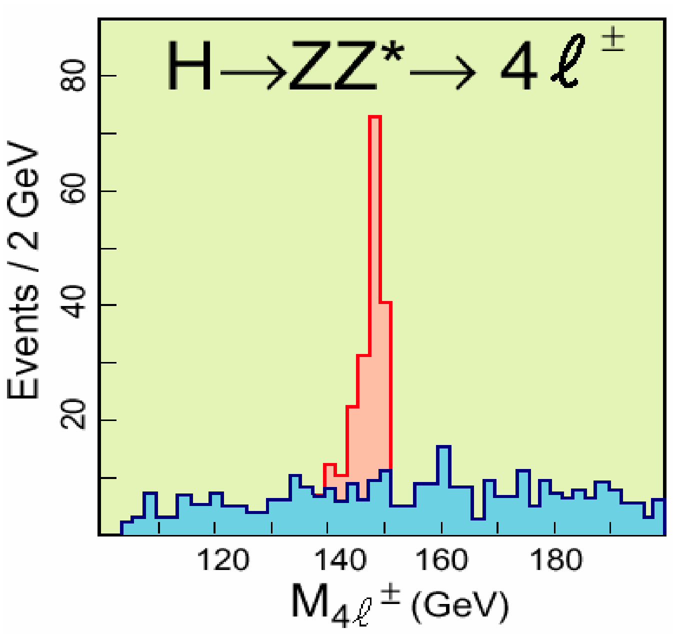


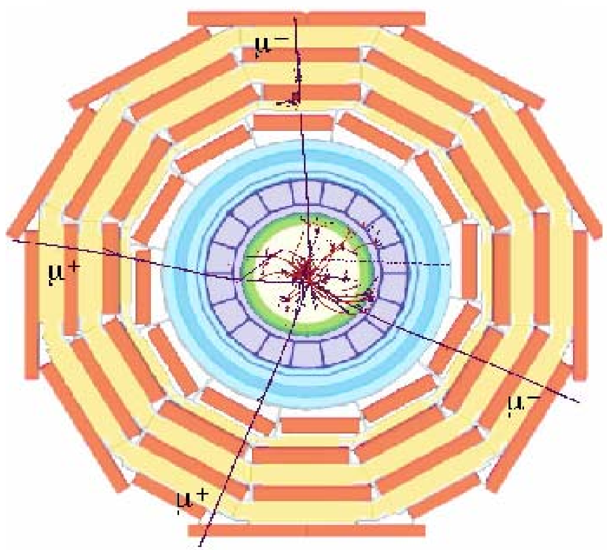


Example: Intermediate mass Higgs: ZZ*

- $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ \ell^+\ell^-$ (ℓ =e,μ)
  - Very clean
    - Resolution: better than 1 GeV (around 100 GeV mass)
  - Valid for the mass range 130<M_H<500 GeV/c^2

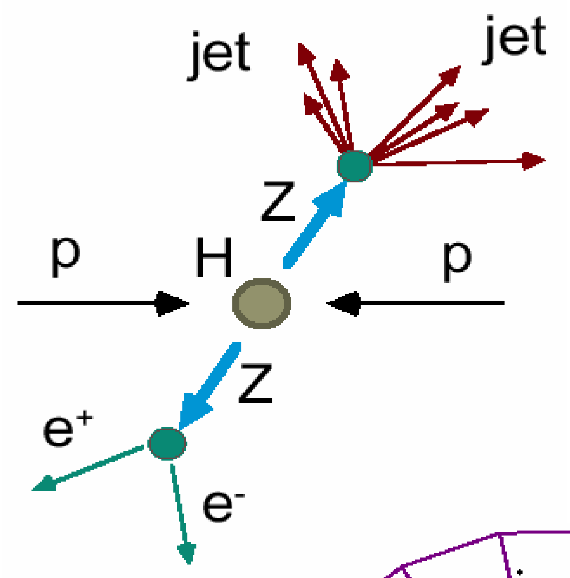


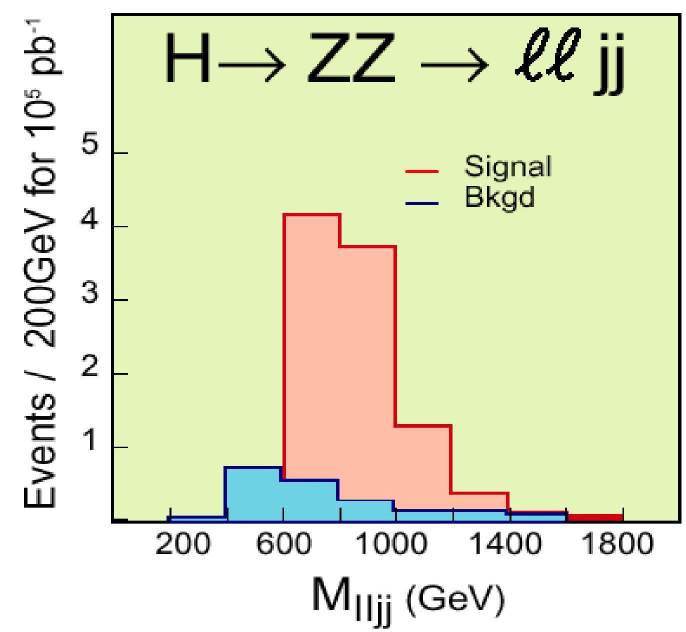


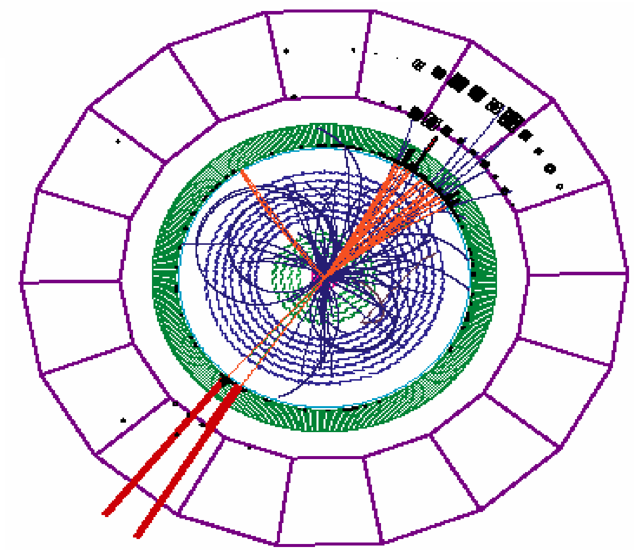


Example: (Very) High mass Higgs

- $H \to ZZ \to \ell^+\ell^-$ jet jet
  - Need higher Branching fraction (also νν for the highest masses ~ 800 GeV/c^2)
  - At the limit of statistics

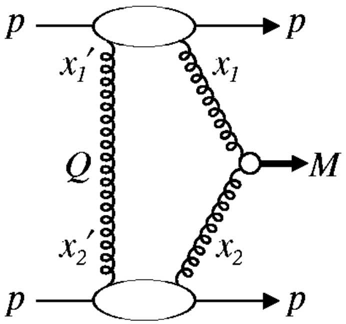


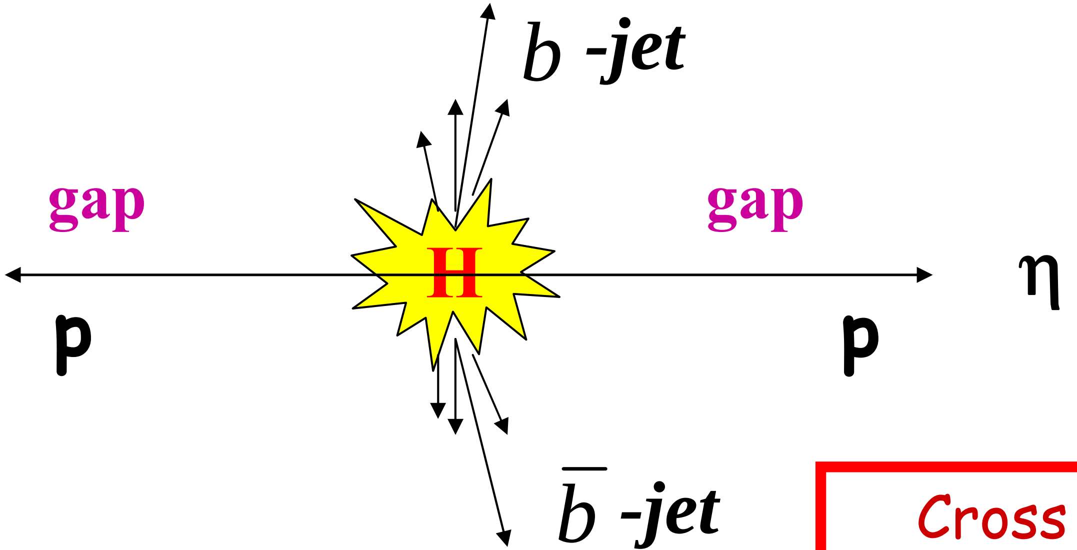




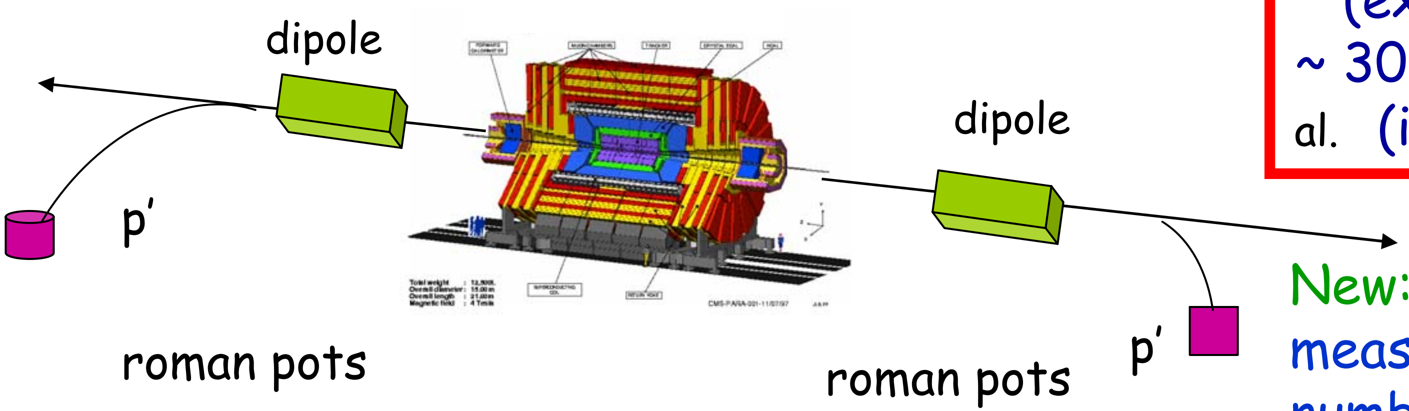
Exclusive Higgs

A recent development: search for exclusive Higgs production pp→ p H p





beam



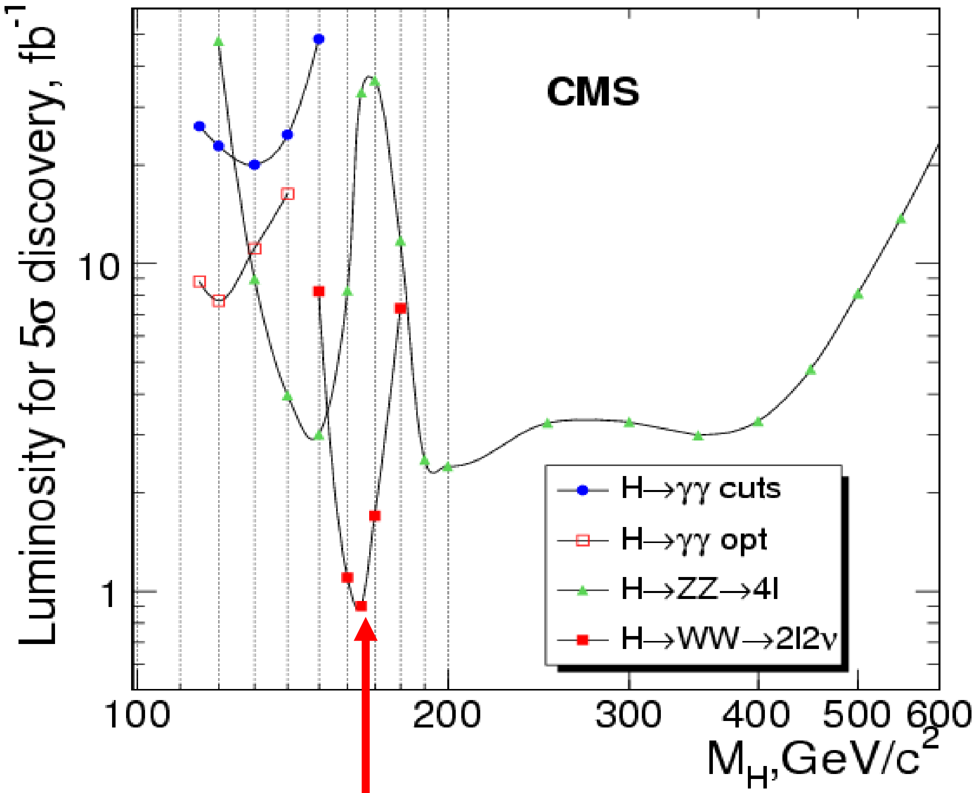
Cross sections

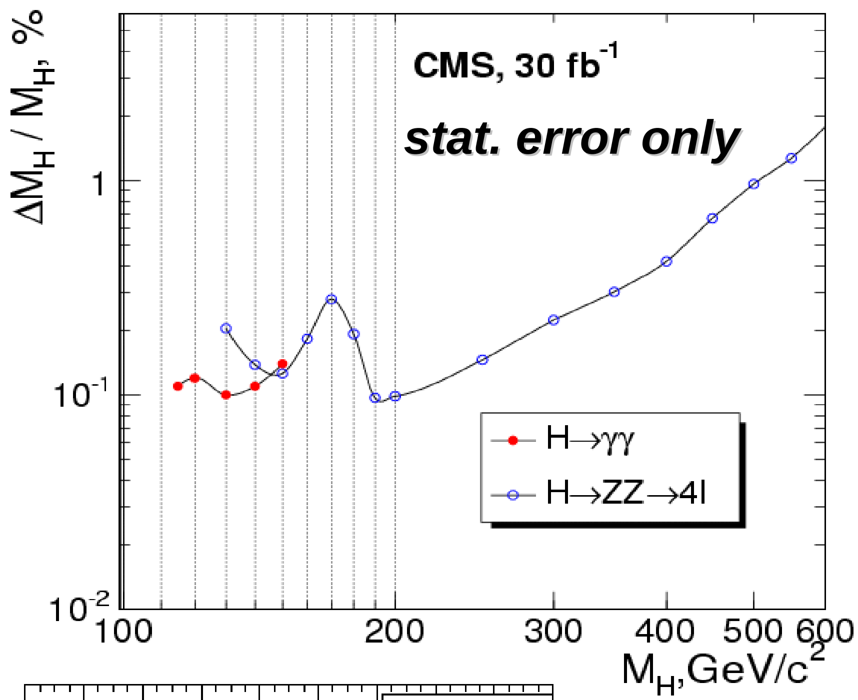
~ 3 fb Khoze et al. (exclusive)

~ 300 fb Boonekamp et al. (inclusive)

New: allows to measure CP quantum numbers of the Higgs

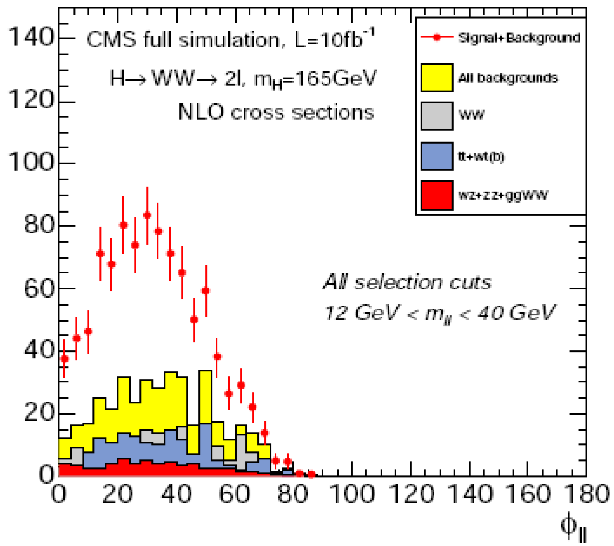
SM Higgs boson discovery and mass measurement





Discovery with ~1 fb^{-1}

Very detailed studies
on SM backgrounds
and related systematics



Ratios of couplings

How to learn something on the
Couplings of the Higss to the
Bosons and fermions?

This is important to establish that
We are really looking at the Higgs

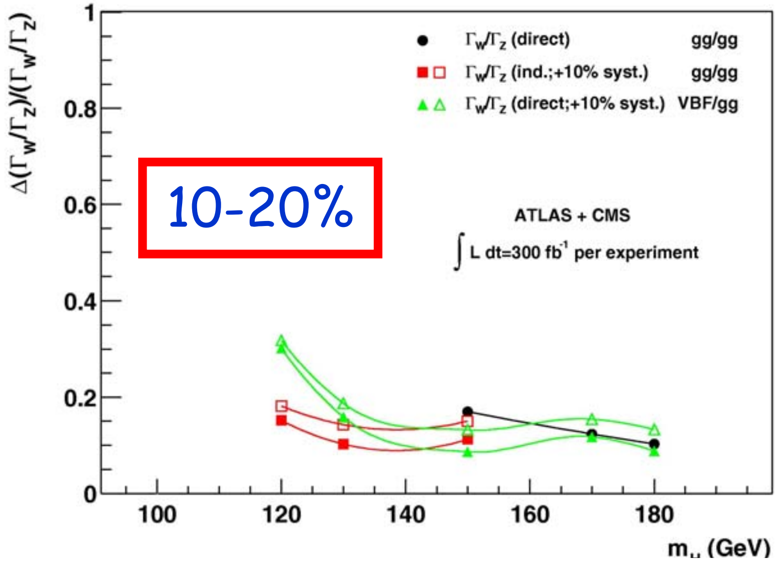
Coupling ~ mass of the particle!

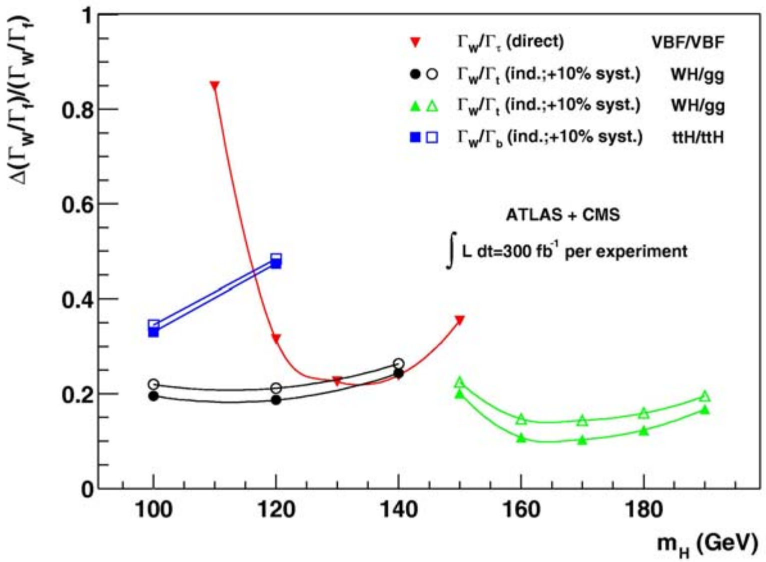
LHC solution: measure ratios

Example

$$-\ \frac{\sigma \times BR(H \to WW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$

$$-\ \frac{\sigma \times BR(H \to \gamma\gamma)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_g \Gamma_Z} \sim \frac{\Gamma_W}{\Gamma_Z}$$

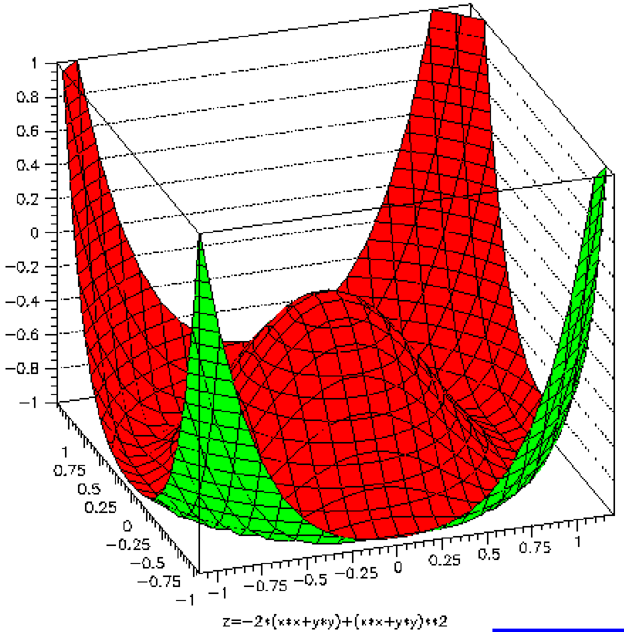


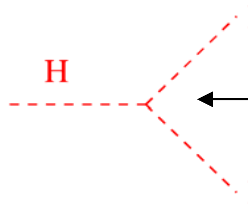


Higgs Self Coupling Measurements

Once the Higgs particle is found, try to reconstruct the Higgs potential

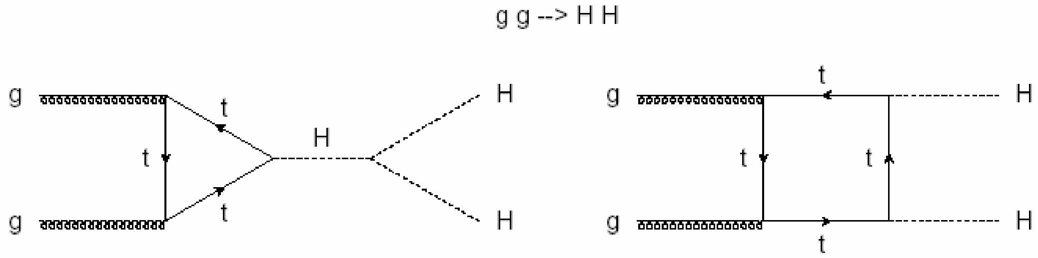
$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

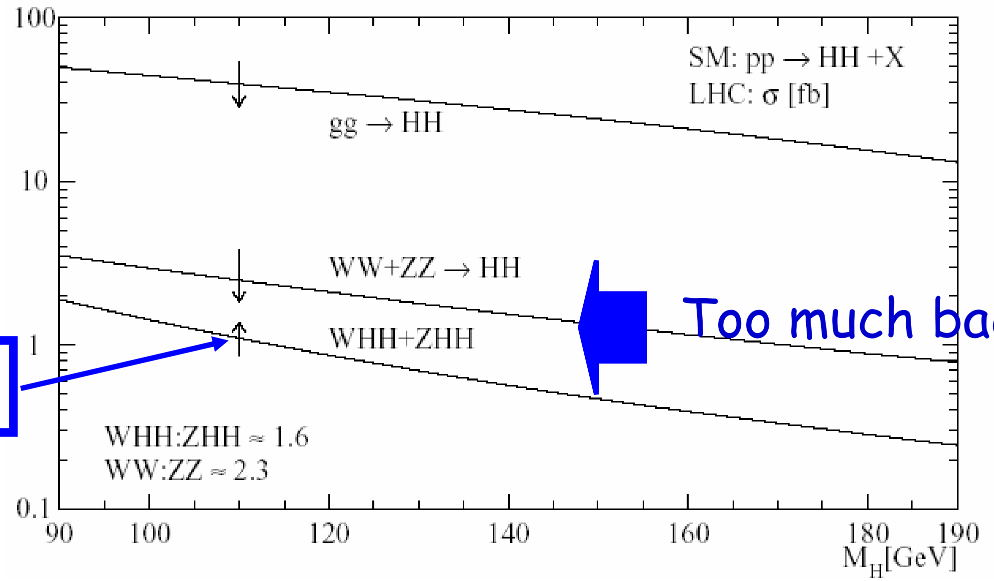




~ λv

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





Djouadi et al.

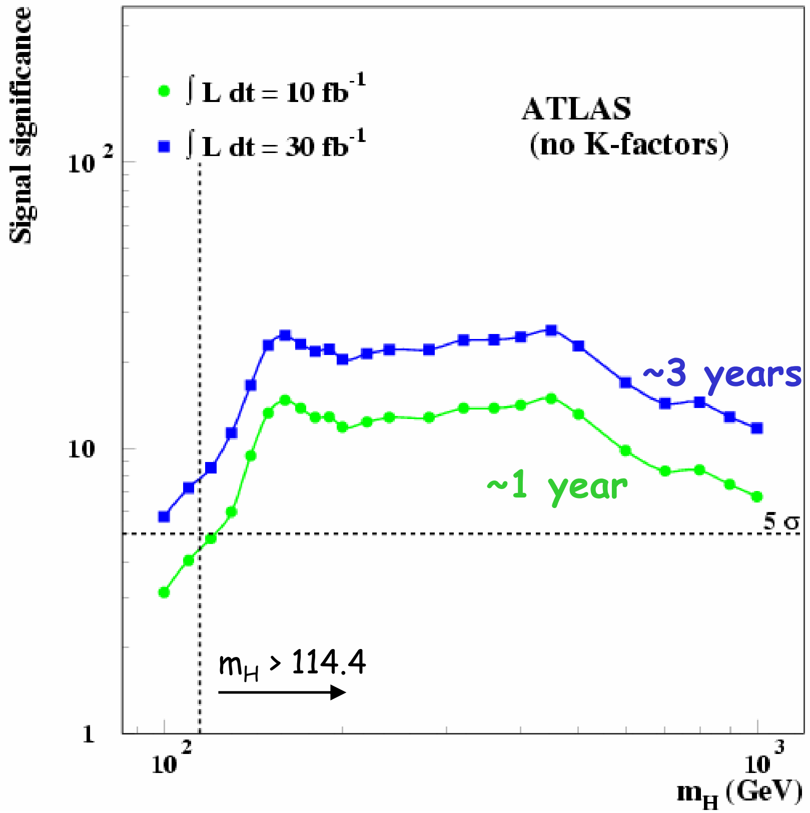
Dawson et al.

$\lambda/2 < \lambda < 3\lambda/2$

Too much backgr.

Difficult/impossible at the LHC

Higgs Reach



5σ ≡ dis

- Higgs can be discovered over full allowed mass range in 1 year of good LHC operation
  → final word about SM Higgs mechanism by 2009 or so
- 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

What can the LHC do?

- LHC will discover the SM Higgs in the full region up to 1 TeV or exclude its existence. If no Higgs, other new phenomena in the WW should be observed around 1 TeV
- The LHC will measure with full luminosity (100 fb^{-1})
  - The Higgs mass with 0.1-1% precision
  - The Higgs width, for m_H> 200 GeV, with ~5-8% precision
  - Cross sections x branching ratios with 5-20% precision
  - Ratios of couplings with 10-30% precision
  - Absolute couplings only with additional assumptions
  - Spin information in the ZZ channel for m_H>200 GeV
  - CP information from exclusive central production: $pp \rightarrow pHp$

..⇒will get a pretty good picture of the Higgs @ LHC
More detailed information at an ILC

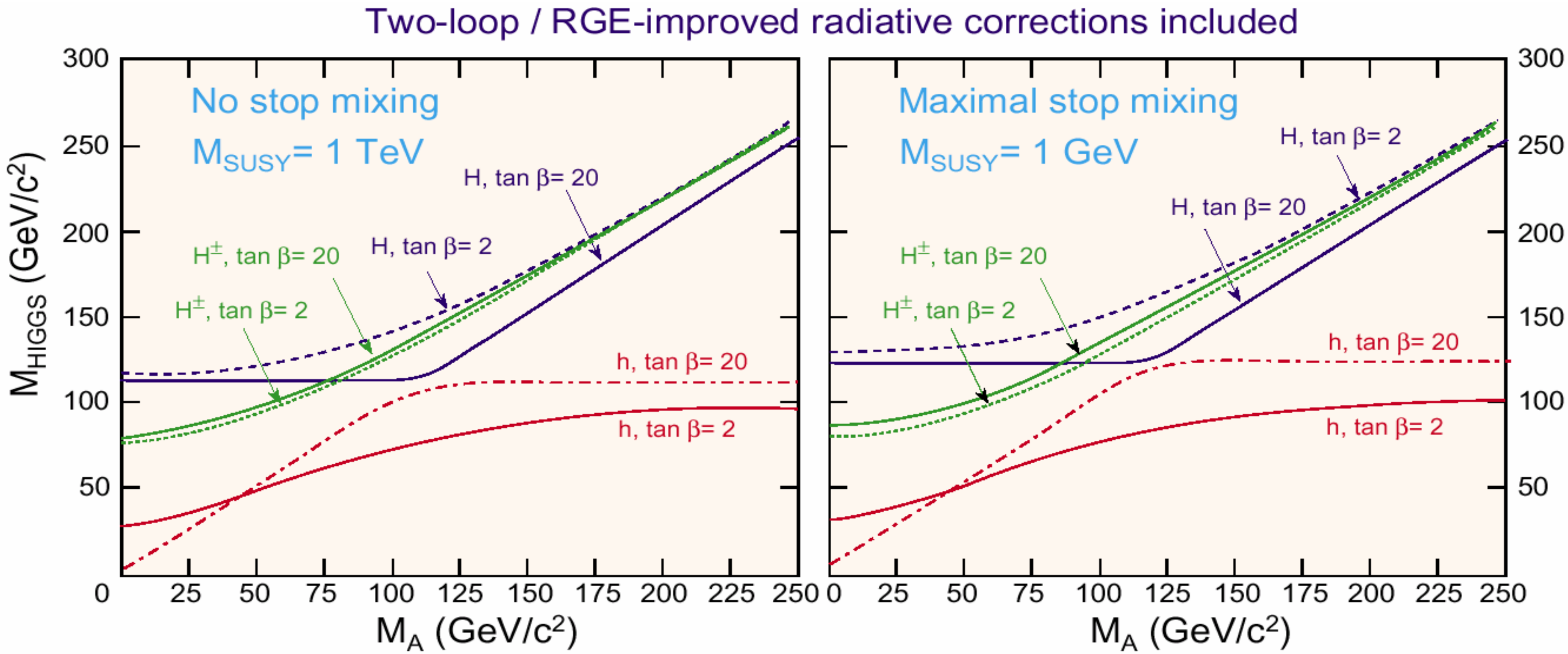
Beyond the Standard Model

Usually more that one Higgs
E.g. Supersymmetry:

5 physical Higgs bosons

2 charged : H^+ and H^-
2 CP even neutral : H and h
1 CP odd neutral : A

Mass spectra for M_{SUSY}=1TeV
The good news: M_h<135 GeV/c²



tanβ = v1/v2 v1 vacuum expectation of first higgs, v2 of the other

Heavy MSSM Higgs search

At high tan β, A/H →ττ and H$^{\pm}$→τν seem to be most promising.

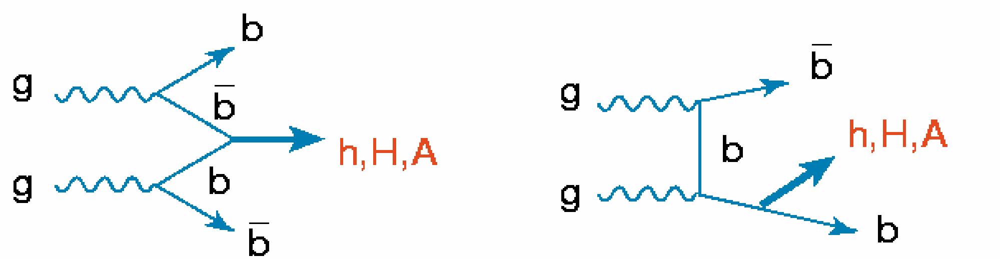
Methods :

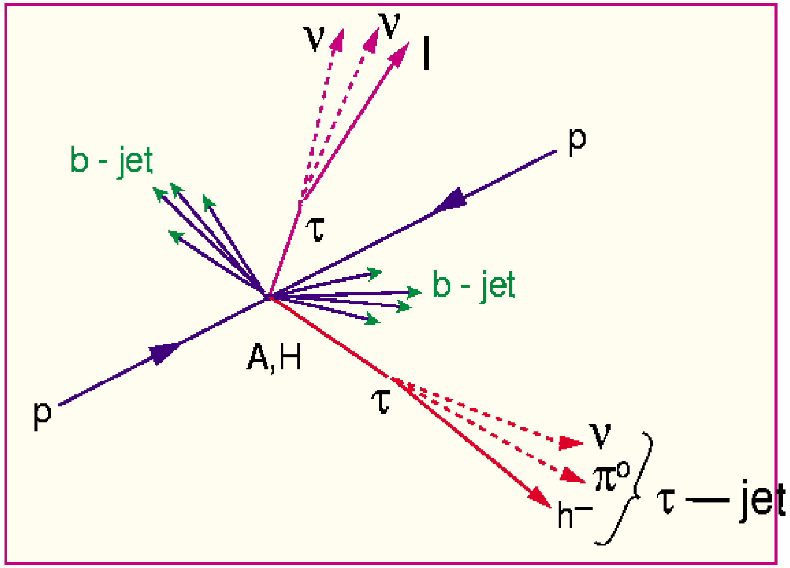
$pp \to A, H \to \tau\tau$, with one $\tau \to \mu\nu_\mu\nu_\tau$ and the other $\tau \to e\,\nu_e\nu_\tau$

$A, H \to \tau\tau$, with one $\tau \to l\nu\nu$ and the other $\tau \to \text{hadron}^- + \pi^0\text{'s} + \nu$

$A, H \to \tau\tau$, with one $\tau \to \text{hadron}^- + \pi^0\text{'s} + \nu$ and the other $\tau \to \text{hadron}^\mp + \pi^0\text{'s} + \nu$

Production:





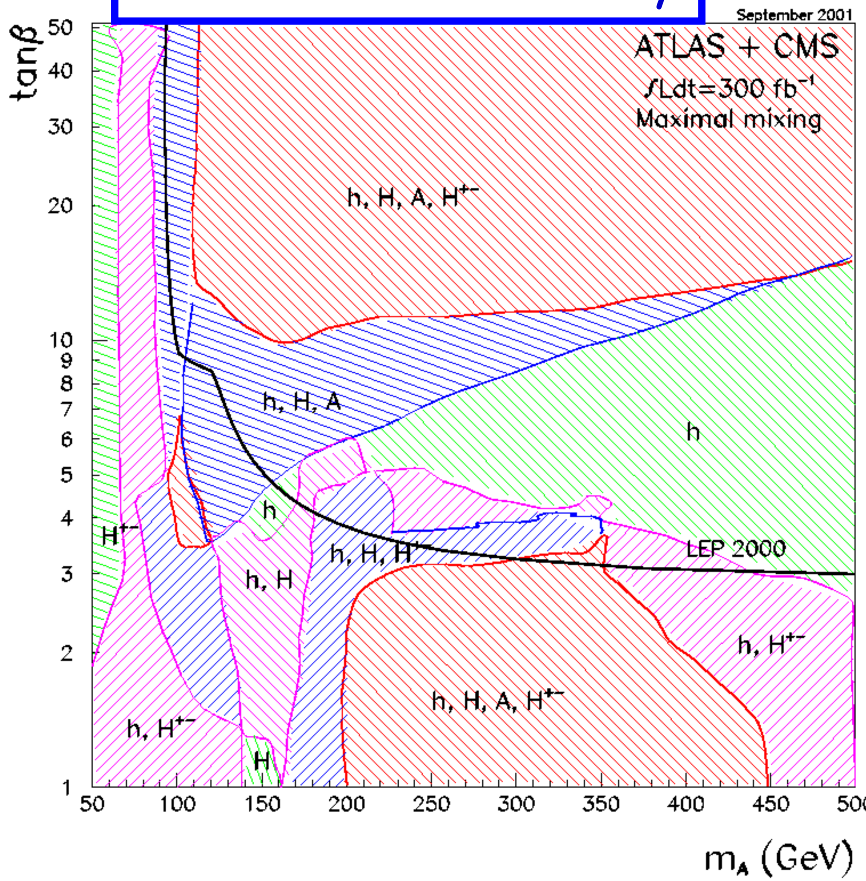
Heavy MSSM Higgs search

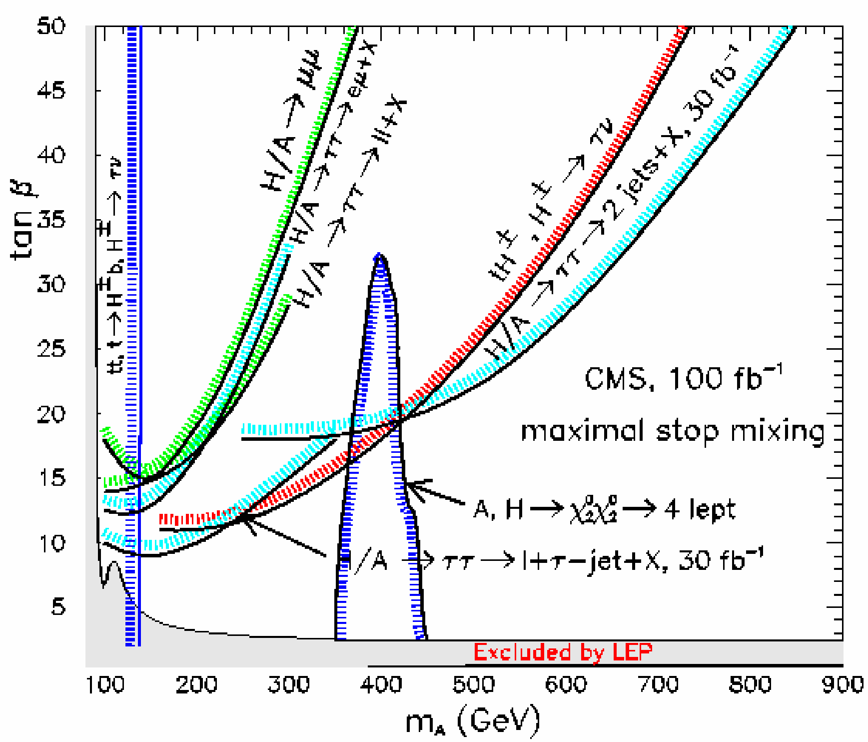
- A/H → ττ
- H± → τν
- A/H → μμ
- H± → tb
- A/H → bb in bb H/A (New studies)

NEW: at low tan β, we may exploit the sparticle decay modes:

$A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + E_T^{miss}$

Plot for 5 σ discovery



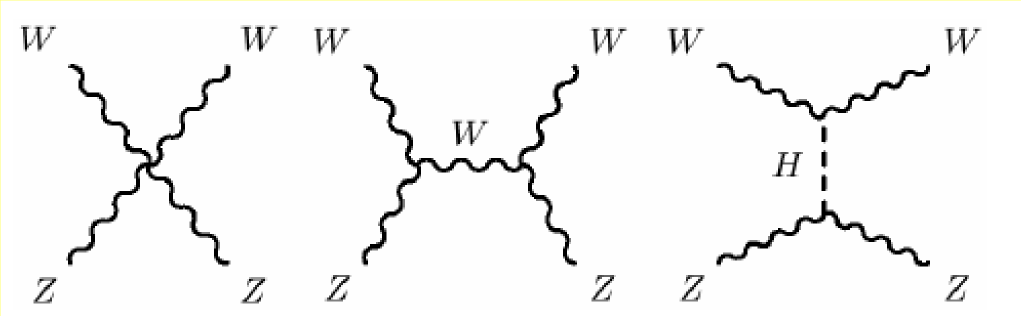


Expected tanβ accuracy 5-25% (300 fb-1)

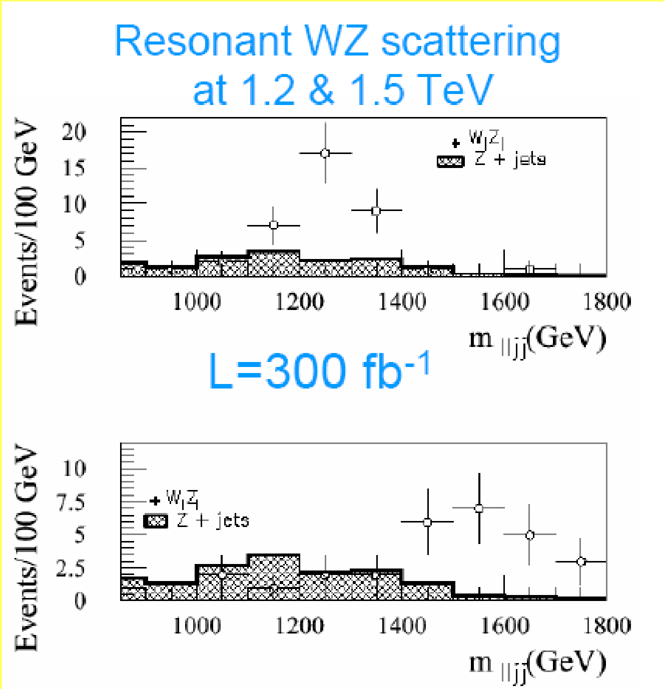
EWSB: What if no Higgs exists

Vector Boson scattering amplitudes violate unitarity for s~ 1TeV

New physics must enter to cure this problem



- Examples
  - Strongly interacting vector bosons
    - Study WW,WZ,ZZ scattering
  - Technicolor
    - New particles (Techni-ρ, techni-π,…)



Mantra: LHC will either discover Higgs or find new dynamics ~ 1 TeV

Summary of the First Lecture

- Hadron machines have a large discovery potential
- The LHC will be our next step towards a large discovery machine
- Experimenting at the LHC will be a challenge!
- Is the particle mass generated by the Higgs mechanisme?
- The LHC will provide answers!
- LHC will start with a low energy pilot tun in 2007 and a first physics run in 2008.

END OF LECTURE 1