The LHC experimental challenges

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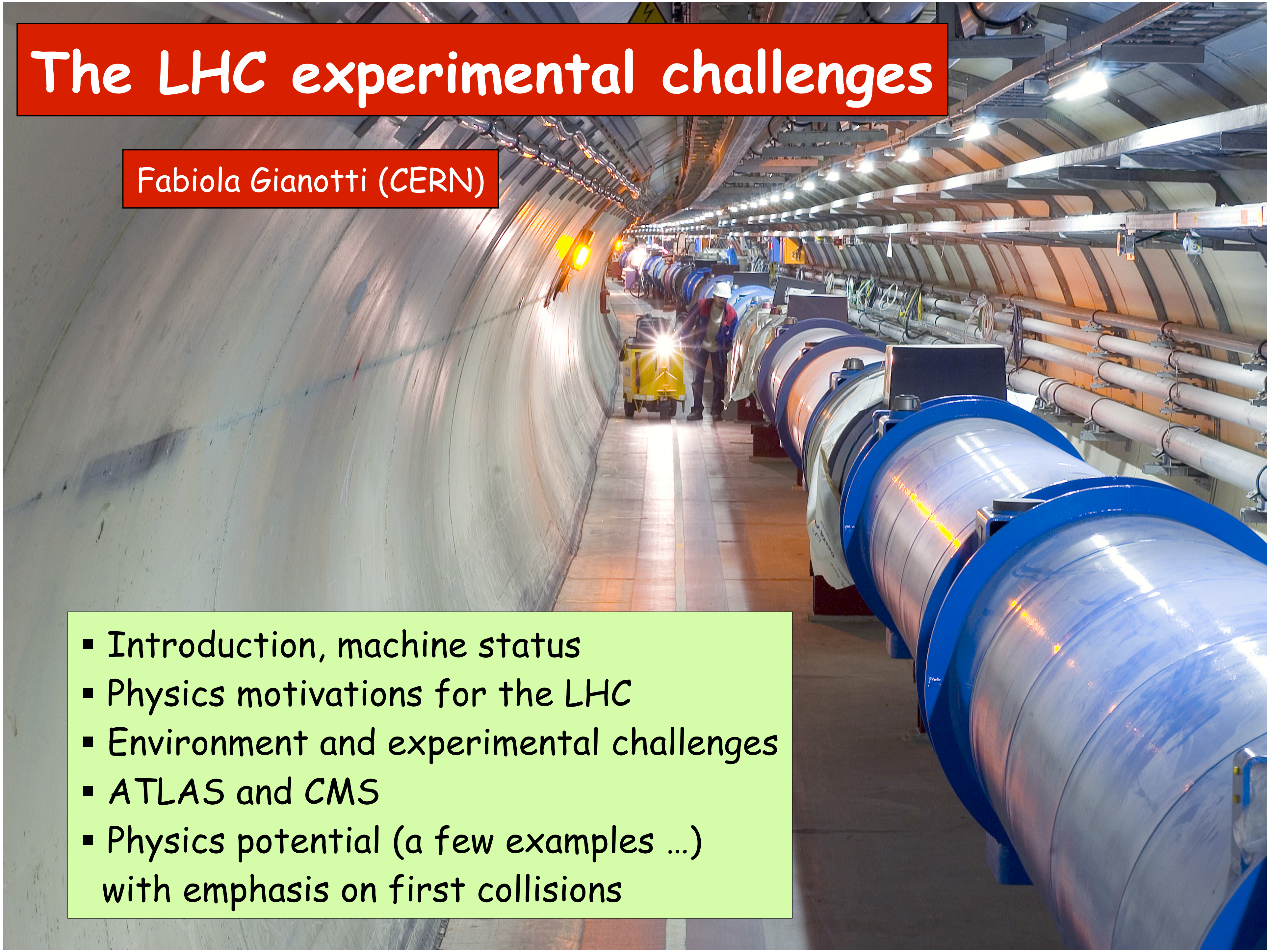
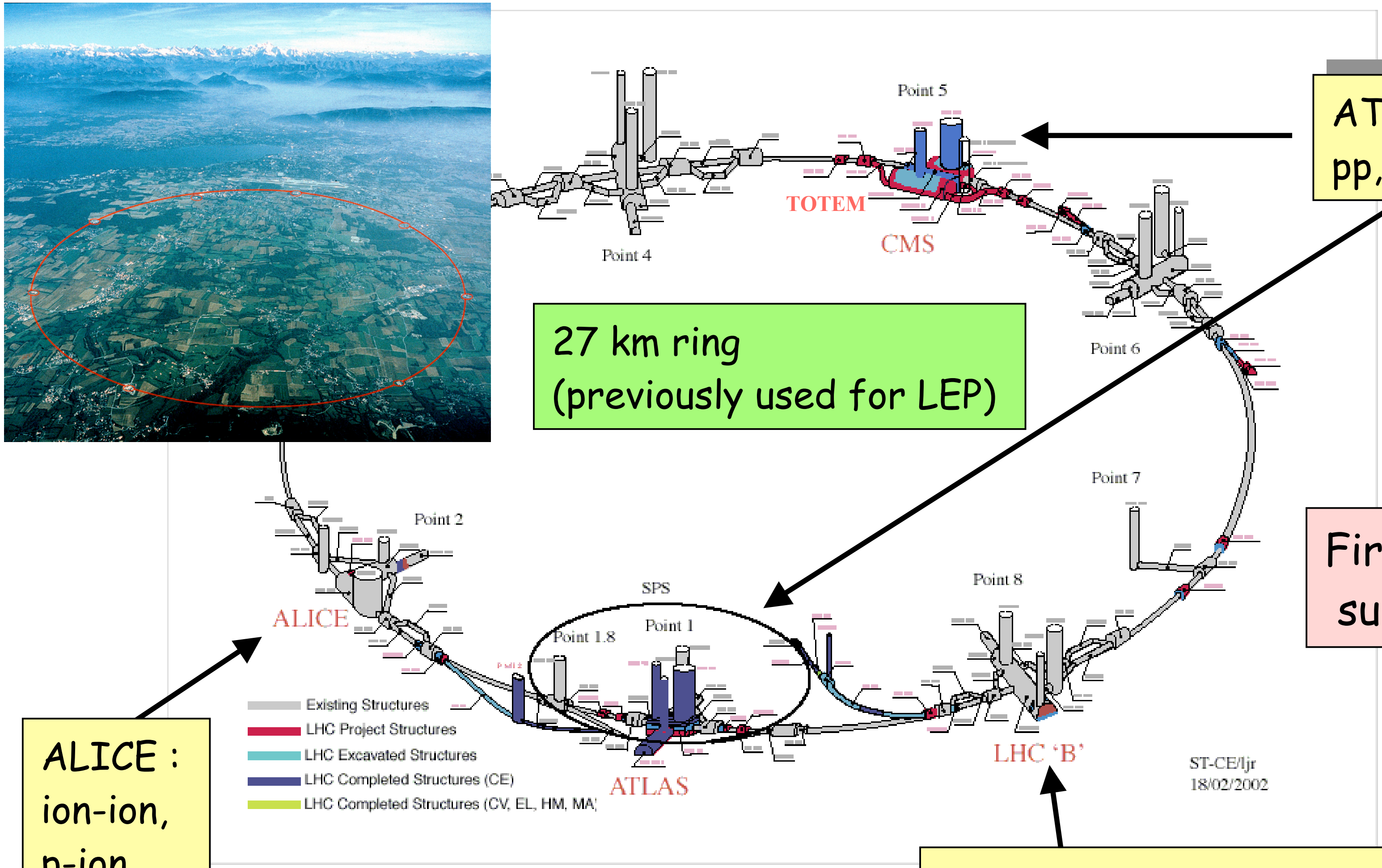


- Introduction, machine status
- Physics motivations for the LHC
- Environment and experimental challenges
- ATLAS and CMS
- Physics potential (a few examples …)
  with emphasis on first collisions

Introduction
Machine main parameters and status

LHC

- pp $\sqrt{s} = 14$ TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2009)
  $L_{initial} \leq$ few x $10^{33}\ cm^{-2}\ s^{-1}$ (until 2009)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s} \sim 1000$ TeV)



27 km ring
(previously used for LEP)

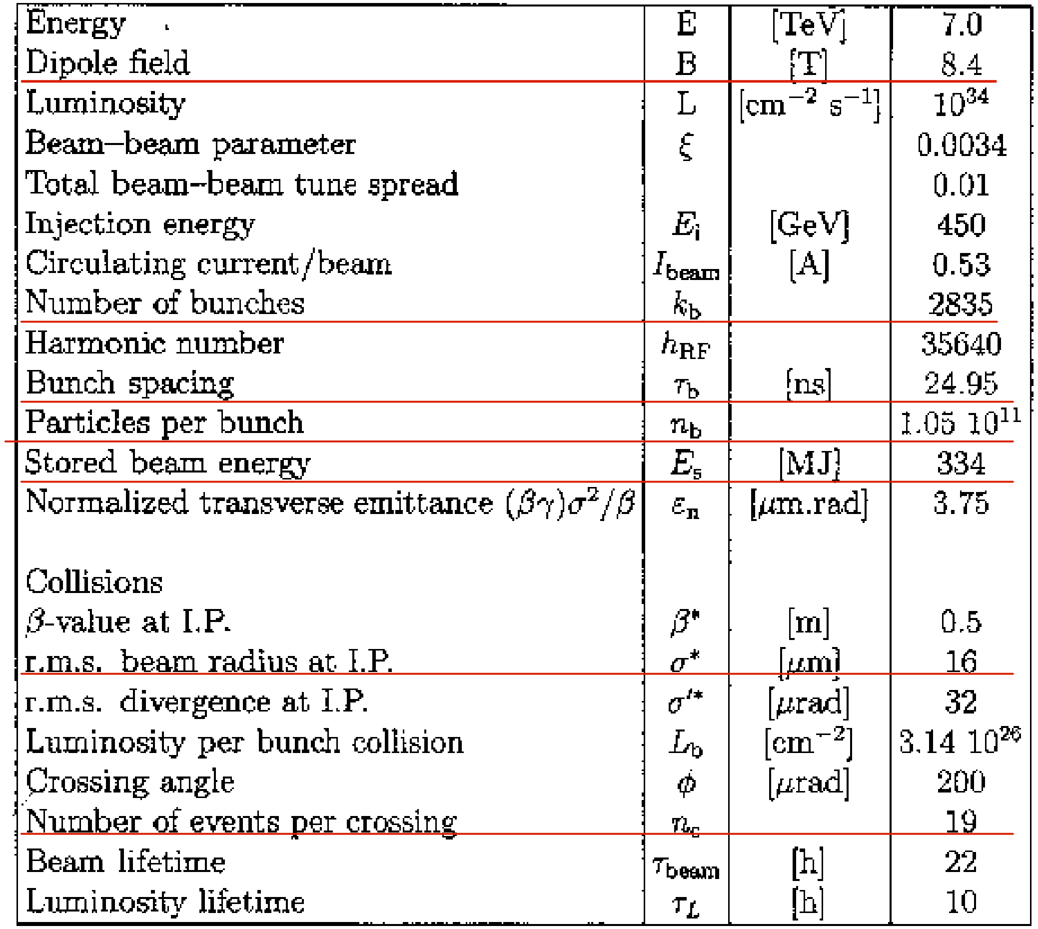
ATLAS and CMS :
pp, general purpose

First collisions:
summer 2007

ALICE :
ion-ion,
p-ion

LHCb :
pp, B-physics, CP-violation

LHC machine



Energy	E	[TeV]	7.0
Dipole field	B	[T]	8.4
Luminosity	L	$[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	10^{34}
Beam–beam parameter	ξ		0.0034
Total beam–beam tune spread			0.01
Injection energy	E_i	[GeV]	450
Circulating current/beam	I_{beam}	[A]	0.53
Number of bunches	k_b		2835
Harmonic number	h_{RF}		35640
Bunch spacing	τ_b	[ns]	24.95
Particles per bunch	n_b		$1.05\ 10^{11}$
Stored beam energy	E_s	[MJ]	334
Normalized transverse emittance $(\beta\gamma)\sigma^2/\beta$	ε_n	[μm.rad]	3.75
Collisions			
β-value at I.P.	β^*	[m]	0.5
r.m.s. beam radius at I.P.	σ^*	[μm]	16
r.m.s. divergence at I.P.	σ'^*	[μrad]	32
Luminosity per bunch collision	L_b	$[\mathrm{cm}^{-2}]$	$3.14\ 10^{26}$
Crossing angle	ϕ	[μrad]	200
Number of events per crossing	n_c		19
Beam lifetime	τ_{beam}	[h]	22
Luminosity lifetime	τ_L	[h]	10

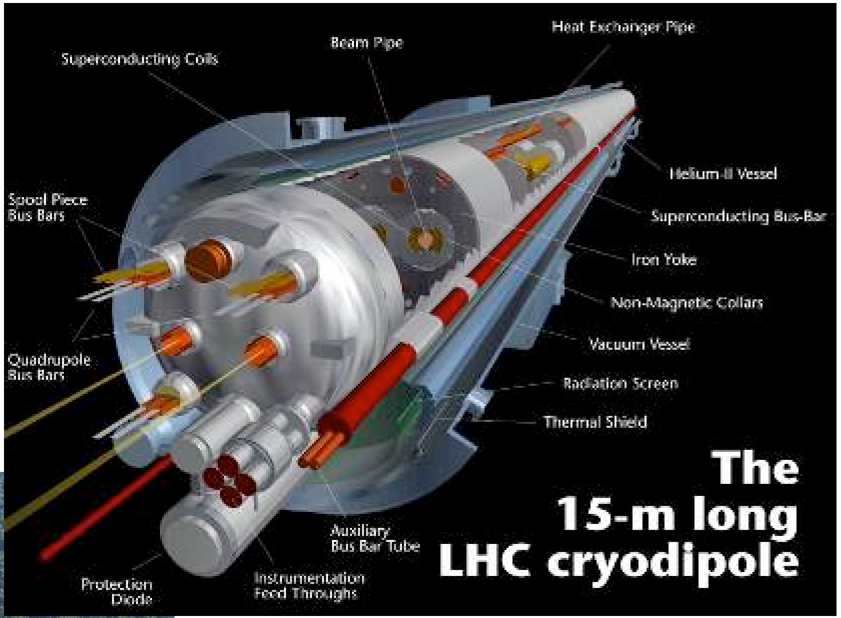
Limiting factor to √s : bending power needed to keep beams in 27 km LEP ring:

$$p(\mathrm{TeV}) = 0.3\ B(\mathrm{T})\ R(\mathrm{km})$$

with typical magnet packing factor of ~ 70%,
need 1232 dipoles with B=8.3 T for 7 TeV beams

About 1100 dipoles out of 1232 delivered at CERN and more than 450 installed in the underground tunnel

Dipole quality (from warm/cold tests) is excellent

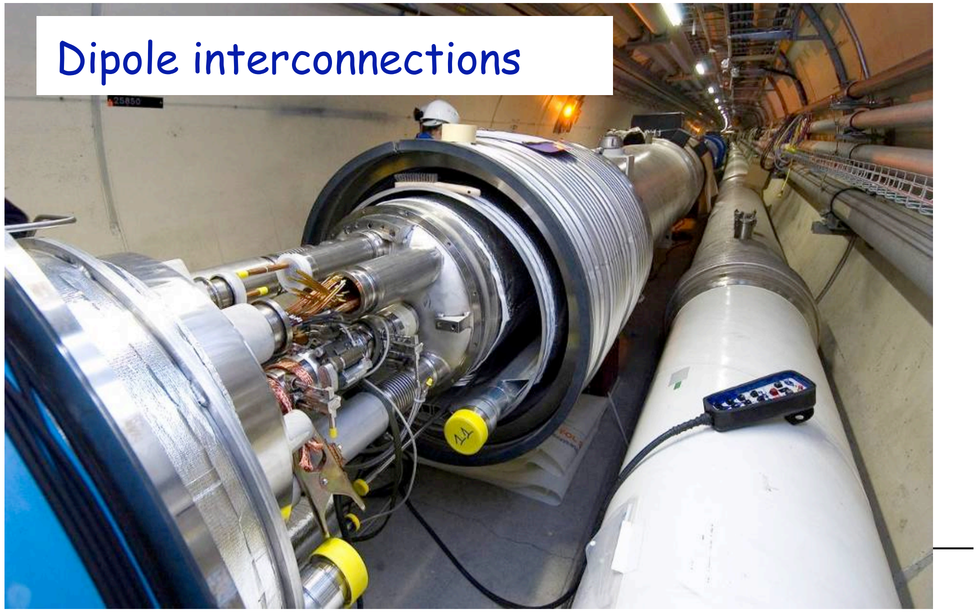


The 15-m long LHC cryodipole

Underground

Dipole installation rate : > 20 /week
Compatible with completion of machine installation end of February 2007

Ramping up of dipole interconnection work is the main issue to watch now



Dipole interconnections

600 m of cryoline successfully cooled down on September 14 2005

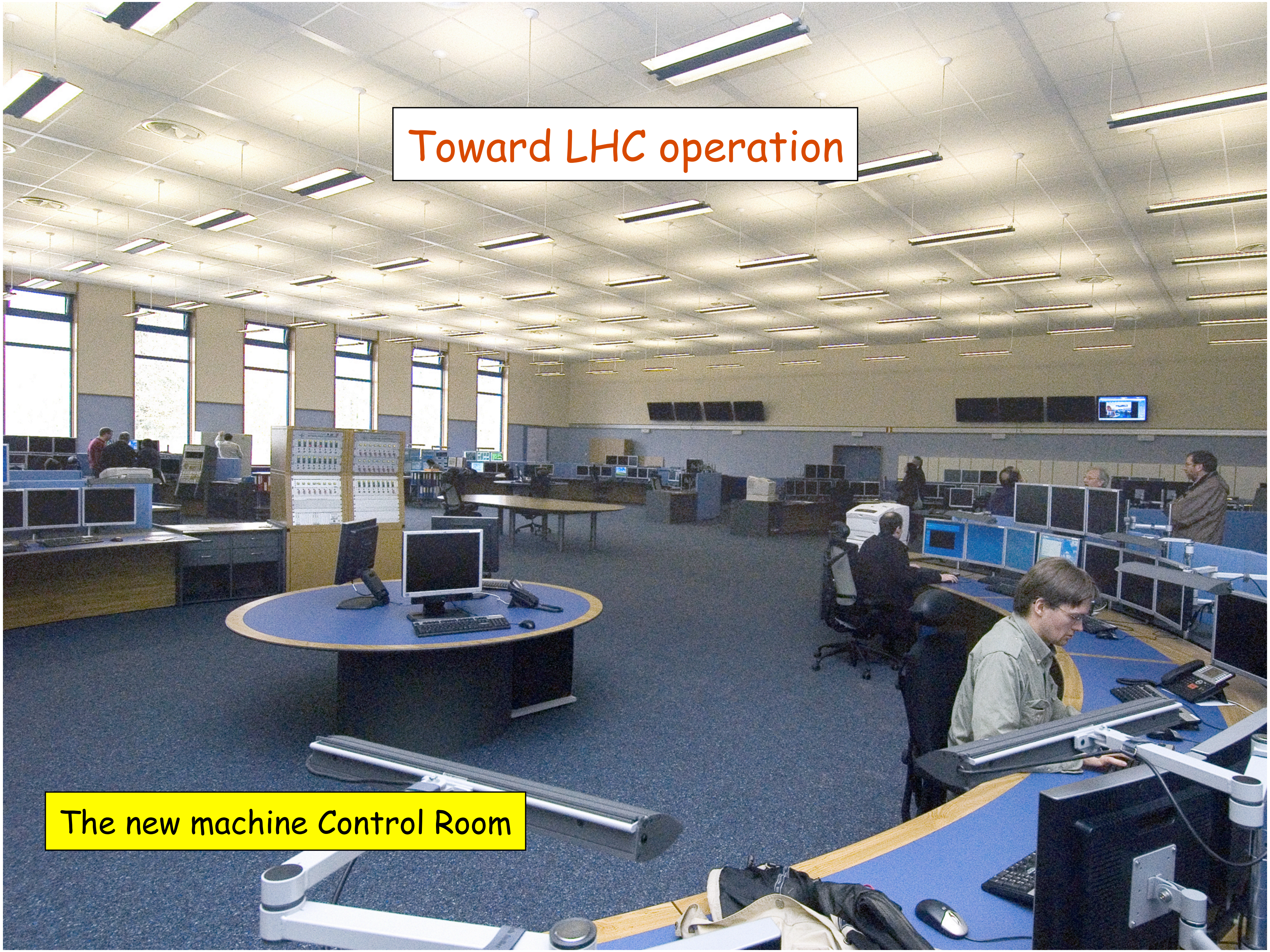
Not only dipoles ….

Dipoles	1232
Quadrupoles	400
Sextupoles	2464
Octupoles/decapoles	1568
Orbit correctors	642
Others	376
Total	~ 6700

Inner triplet quads assembly hall 181

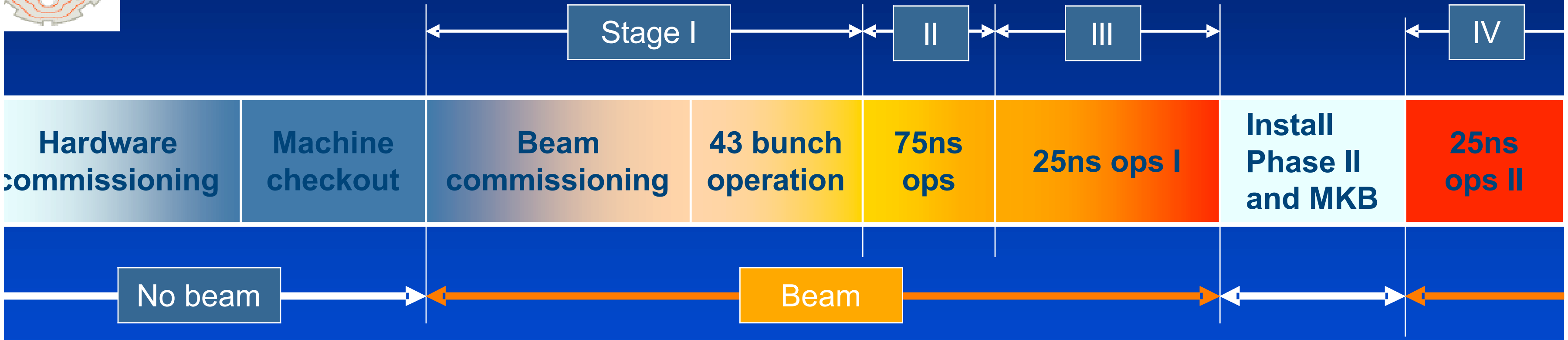
Assembly of Short Straight Session hall SMI2

Toward LHC operation



The new machine Control Room

Staged commissioning plan for protons



Stage I
II
III
IV

Hardware commissioning
Machine checkout
Beam commissioning
43 bunch operation
75ns ops
25ns ops I
Install Phase II and MKB
25ns ops II

No beam
Beam

I. Pilot physics run

- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

2007 ?

up to 100 pb^{-1} ?

II. 75ns operation

- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

early 2008

III. 25ns operation I

- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

2008-2009

~ 5 fb^{-1} end 2008,
~ 20 fb^{-1} end 2009 ?

IV. 25ns operation II

- Push towards nominal performance

≥ 2010

$O(100)$ fb^{-1}

Note: dates and integrated luminosities are MY guess/interpretation

Conclusions on machine status

Enormous progress over the last year, including:

- about 1/3 of the machine is installed and many tests already performed
- problems with cryogenic line solved (this is not on the critical path any more)
- better understanding of machine commissioning and operation, and their time profile

Present schedule foresees:

- completion of machine installation end of February 2007
- experiments closed and machine set up for beam starting July 1st 2007

This schedule will be confirmed/revised end of June, when some critical issues (e.g. dipole interconnection) will be clearer.

A few more numbers .....

LHC √s is 7 times higher than at the Tevatron, luminosity is 100 times higher

Machine temperature : -271 degrees
(largest cryogenic system in the world, cooler than the Universe CMB)

ATLAS size : length = 46 m, height=25 m
Weight of CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)

ATLAS and CMS equipped with 10^8 electronic channels
Amount of cables used in ATLAS : ~ 3000 km

Data collected by CMS in 1 second: equivalent to 10000 Encyclopedia Britannica
Data collected by experiments in 1 year: ~ 30 km of CD ROM

Number of physicists involved : > 4000
Etc. etc. etc.

WHY ???

Physics motivations for the LHC

The Standard Model of the elementary particles and their interactions

Contains 3 families of elementary "matter" particles

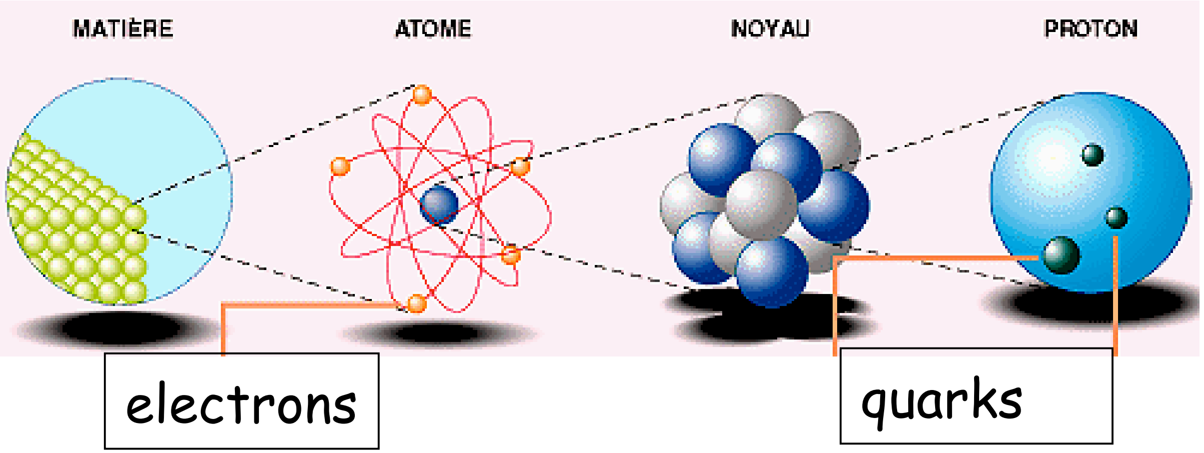
Matter particles : fermions, spin =1/2

ν_1	ν_2	ν_3	q = 0
e	μ	τ	q = -1

🟧🟦🟩

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

+ anti-particles

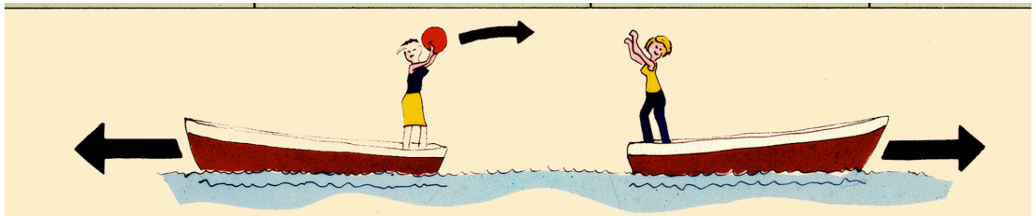


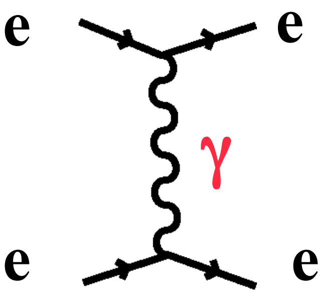
Note :

-- our world is made mainly of 1st family …

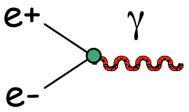
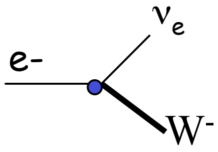
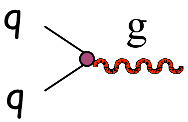
-- m(e-) ~ 0.5 MeV, m(top)~ 175 GeV !

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

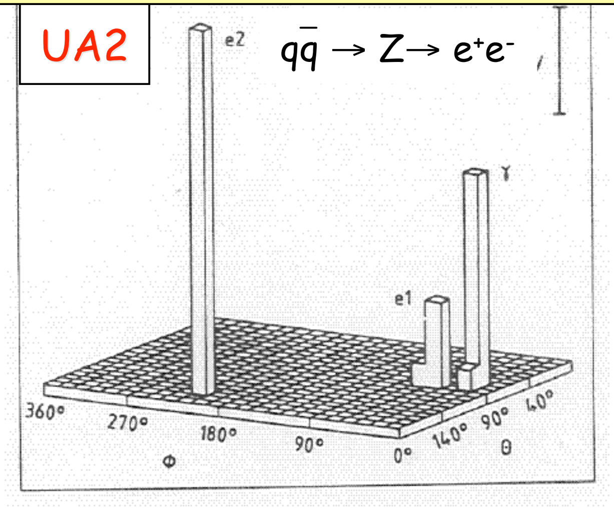
Particle	Force		Coupling (E~100 GeV)	Mass	Intensity
γ	EM (charged particles)		$\alpha_{EM} = \frac{e^2}{4\pi} \approx 0.008$	0	~ 10^{-1}
$W^{\pm}$, Z	weak (q, l, $W^{\pm}$, Z)		$\alpha_W = \frac{g^2}{4\pi} \approx 0.03$	~ 100 GeV	~ 10^{-5}
8 g	strong (q, g)		$\alpha_s = \frac{g_s^{\ 2}}{4\pi} \approx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

relative
to strong

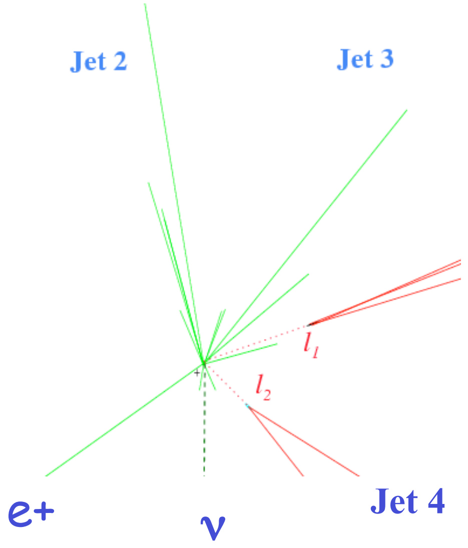
Why do we like the Standard Model ?

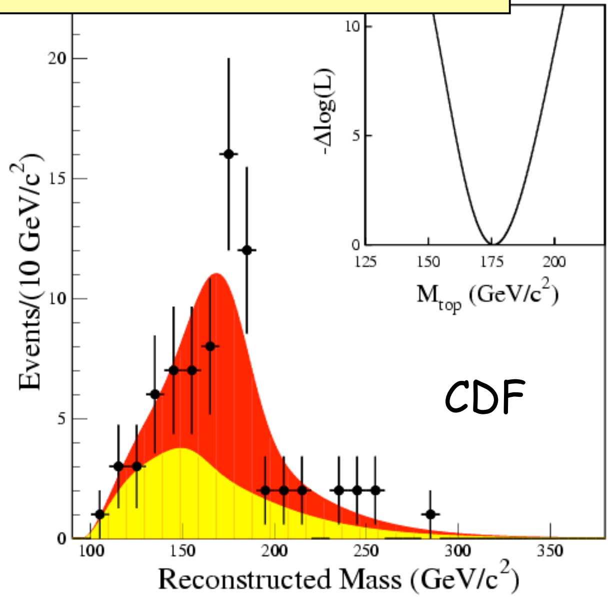
All the SM predictions (but one …), in terms of particles and features of their interactions, have been verified by many experiments at many machines

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



1995 : top quark discovered at Tevatron $p\bar{p}$ Collider ($\sqrt{s}$ ~ 2 TeV) m ~ 175 GeV



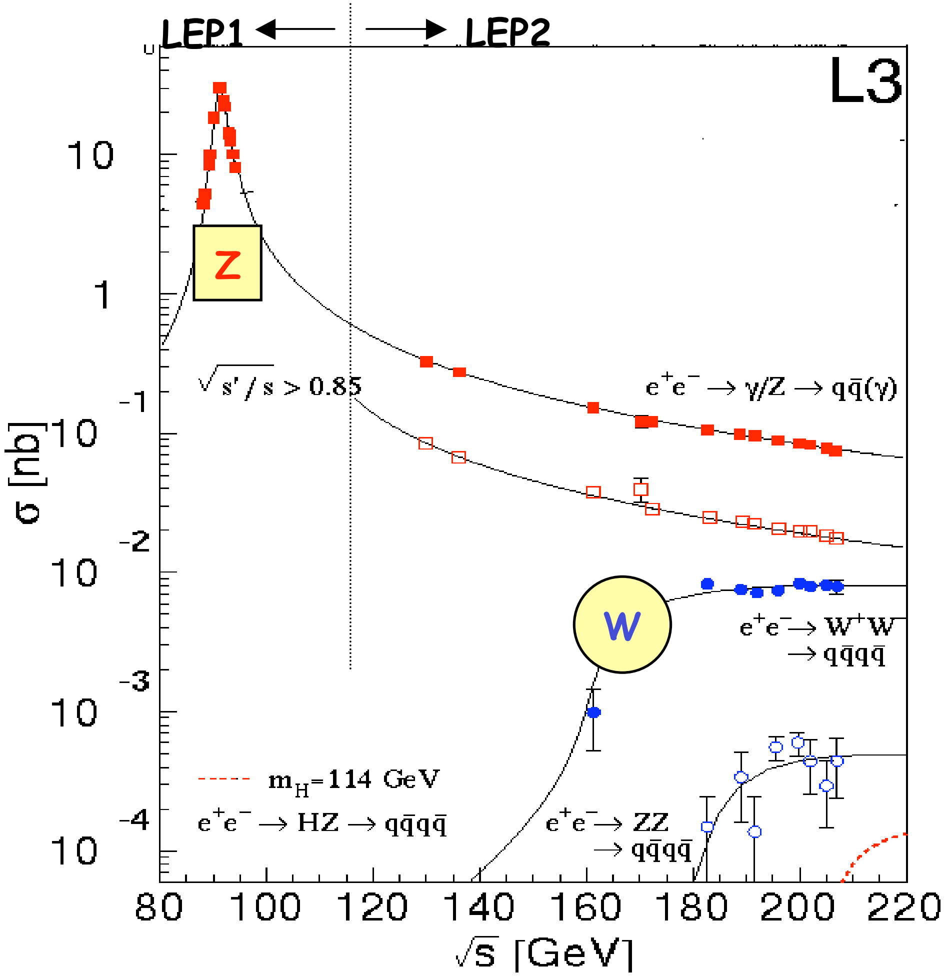


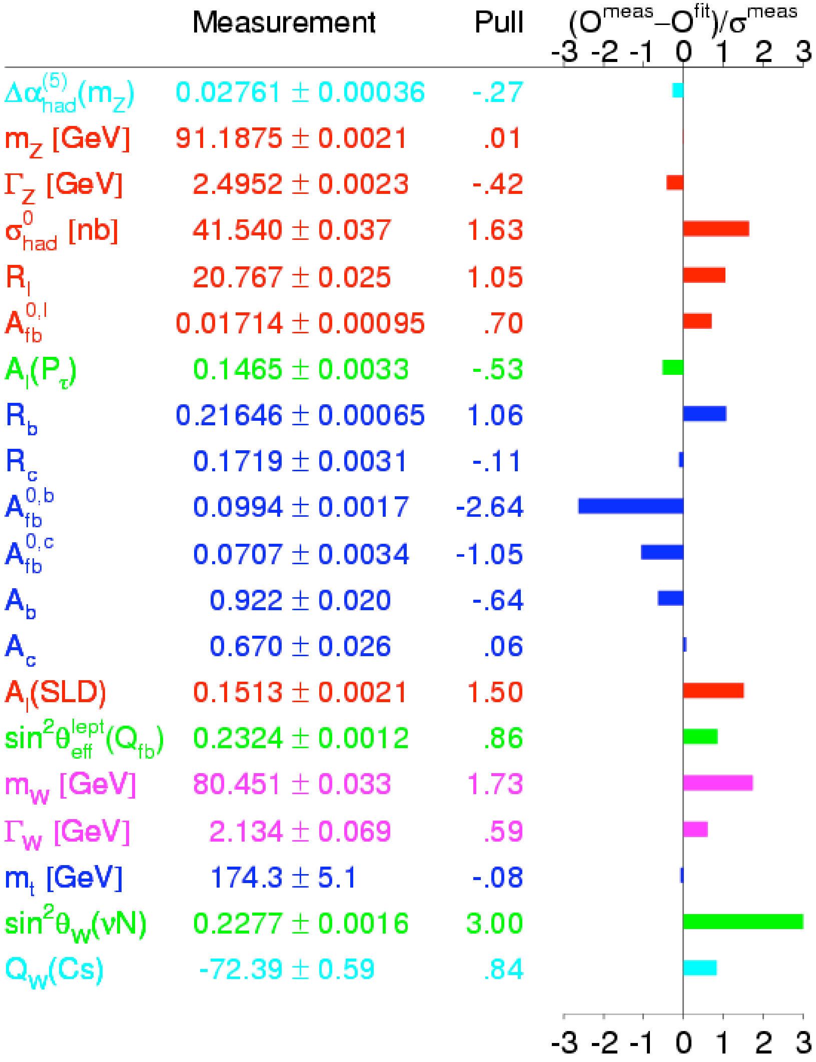
$t\bar{t} \rightarrow bW\,\bar{b}W \rightarrow bl\nu\,\bar{b}jj$ event from CDF data

Measurements at e+e- Colliders : LEP (CERN), SLC (SLAC)

LEP : 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
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ_{had}^0 [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A_{fb}^{0,l}$	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
$A_{fb}^{0,b}$	0.0994 ± 0.0017	-2.64
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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

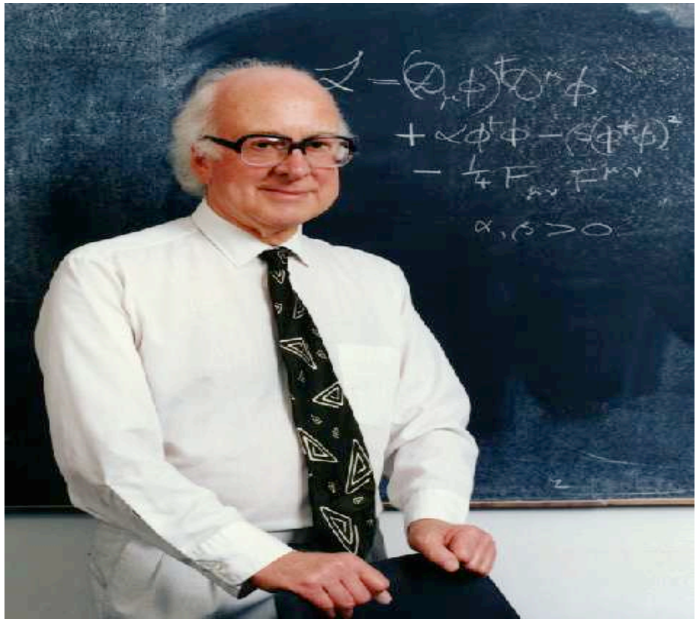
Many spectacular measurements at LEP and SLC : agreement theory-data at the permil level !

Why we don't like the Standard Model ?

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

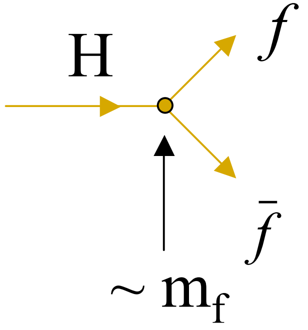
1) What is the origin of the particle masses ?

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



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

SM : Higgs mechanism gives mass to particles



$m_H < 1$ TeV from theory

However:

-- Higgs not found yet: only missing (and essential !) piece of SM

-- present limit : $m_H > 114.4$ GeV (from LEP)

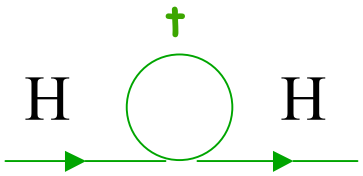
→ need a machine to discover/exclude the Higgs particle over 115-1000 GeV

Only example of observed Higgs as of today …

2) Is the SM the "ultimate theory" ? Most likely not ….

- Higgs mechanism is weakest part of the SM:

  Higgs mass goes as $m_H \sim \Lambda$, where Λ = energy scale up to which SM is valid



$\Delta m_H^2 \sim \Lambda^2$

Higgs mass diverges in SM
→ " bad behaviour " of the theory

- Many other open questions:
  -- Why 3 lepton families ? Why is the first family "special" ?
  -- Are there additional (heavy) leptons and bosons ?
  -- Are quarks and leptons really elementary ?
  -- "Hierarchy" problem : why $M_{EW}/M_{Planck} \sim 10^{-17}$? Is there anything in between ?
  -- What is the origin of the matter / anti-matter asymmetry in the Universe ?
  -- What is the origin of the Universe dark matter and dark energy ?
  -- Unification of coupling constants ?
  -- What is the origin of ν masses ?

All this calls for

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

Difficult task : solve SM problems without contradicting experimental data

Best candidates : Supersymmetry
Extra-dimensions

But also: Technicolour, Little-Higgs, split-SUSY, etc.

← all predict New Physics at
≈ **TeV scale**

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

LHC physics goals

Search for the Standard Model Higgs boson over $\sim 115 < m_H < 1000$ GeV.

Explore the highly-motivated TeV-scale, search for physics beyond the SM (Supersymmetry, Extra-dimensions, q/l compositness, leptoquarks, W'/Z', heavy q/l, etc.)

Precise measurements :

- -- W mass
- -- top mass, couplings and decay properties
- -- Higgs mass, spin, couplings (if Higgs found)
- -- B-physics (mainly LHCb): CP violation, rare decays, B^0 oscillations
- -- QCD jet cross-section and α_s
- -- etc. ....

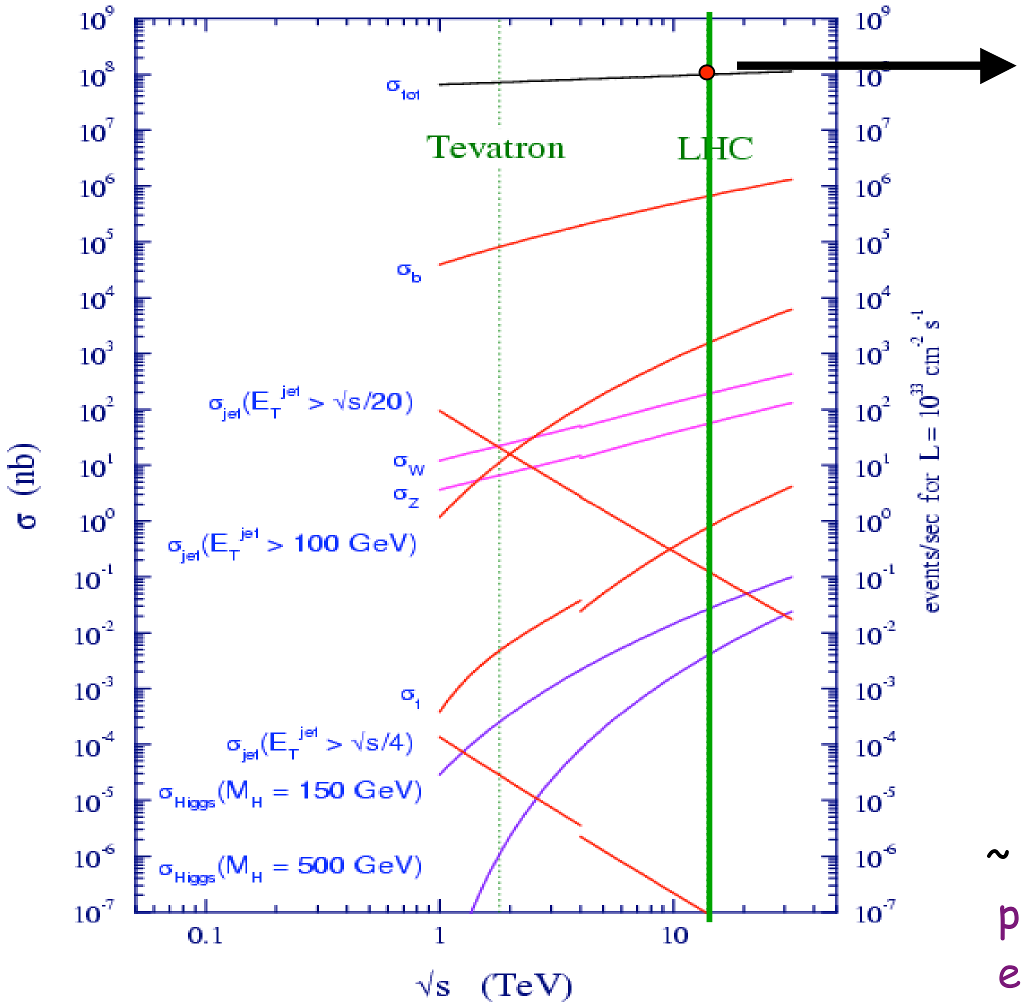
Study phase transition at high energy density from hadronic matter to quark-gluon plasma (mainly ALICE).

Etc. etc. .....

Here : high-p_T physics (ATLAS and CMS)

The environment and the experimental challenges

❶ Event rate and pile-up (consequence of machine high luminosity …)



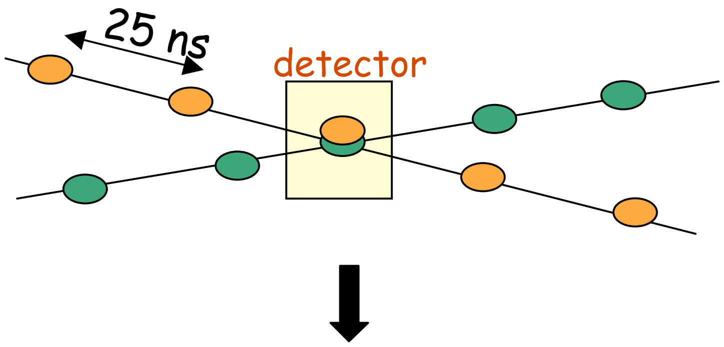
Event rate in ATLAS, CMS :

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

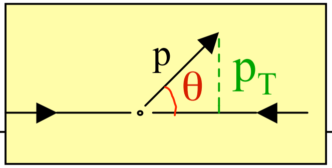
$\approx 10^{9}$ interactions/s

Proton bunch spacing : 25 ns

Protons per bunch : 10^{11}



~ 20 inelastic (low-p_T) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing → pile-up

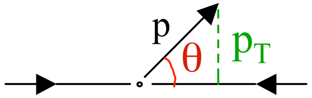


Simulation of CMS tracking detector

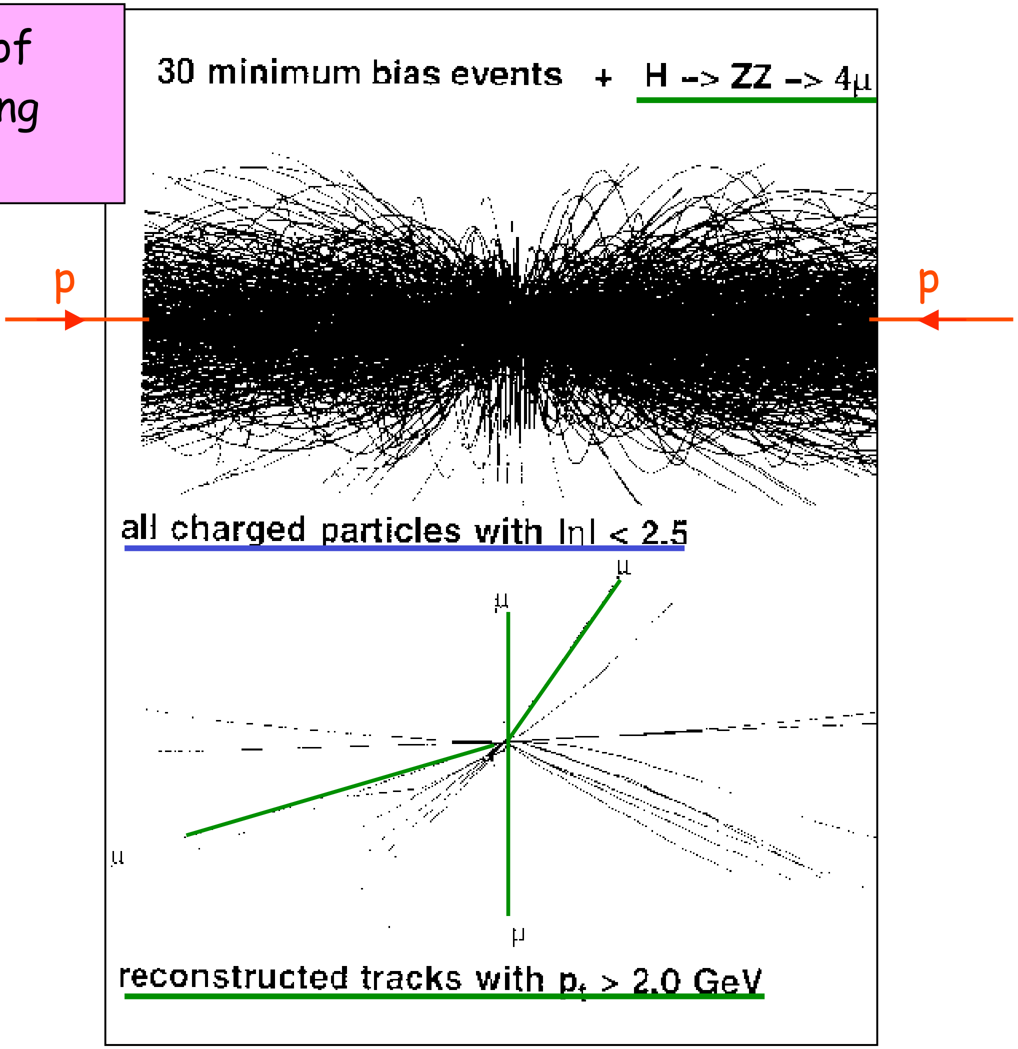
At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$ $(10^0 < \theta < 170^0)$

However : $< p_T > \approx 500$ MeV

→ applying p_T cuts allows extraction of interesting events



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



Impact of pile-up on detector requirements and performance:

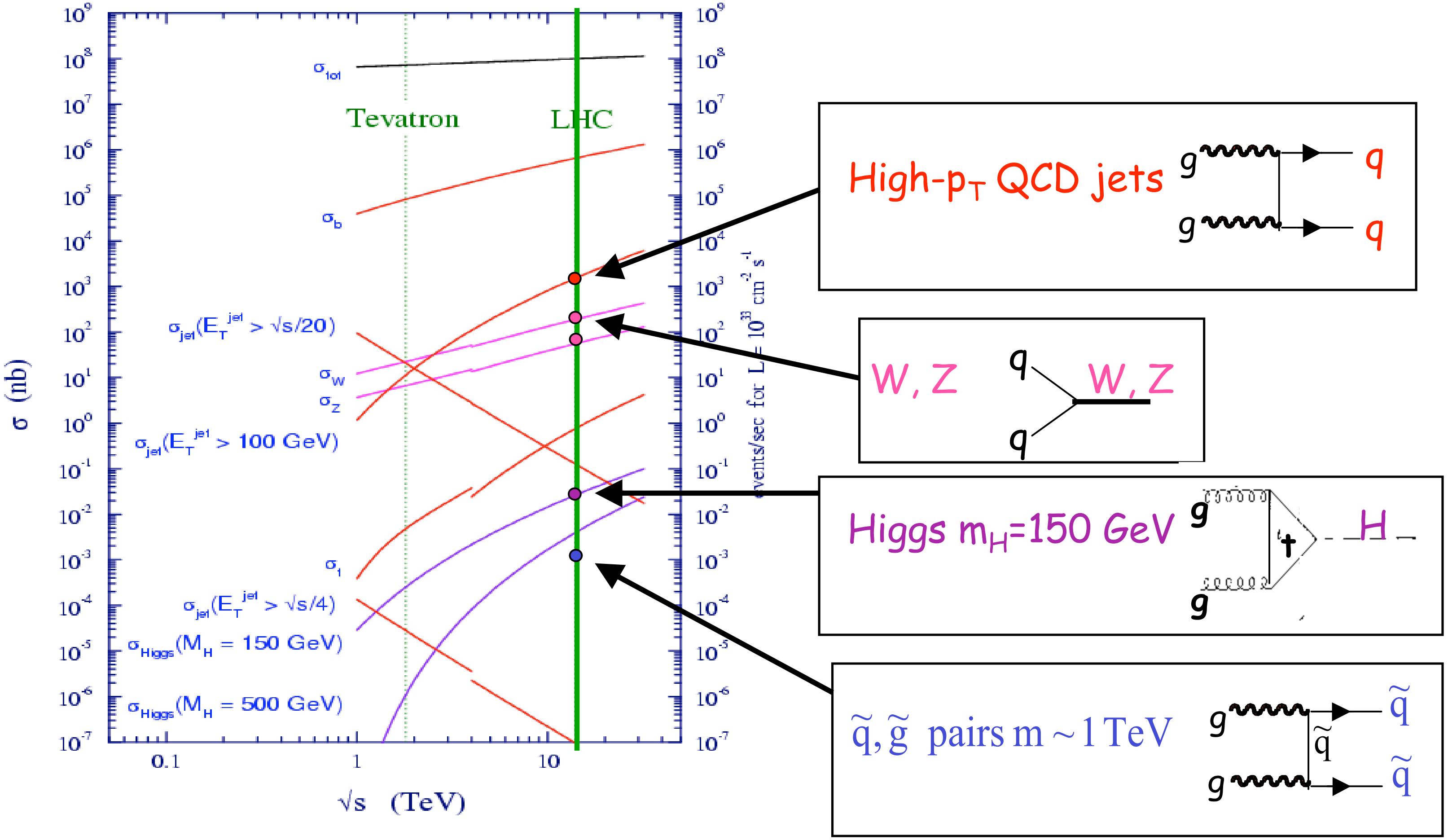
-- fast response : ~ 50 ns

-- 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

❷ Huge (QCD) backgrounds (consequence of high energy …)



High-p_T QCD jets

W, Z

W, Z

Higgs m_H=150 GeV

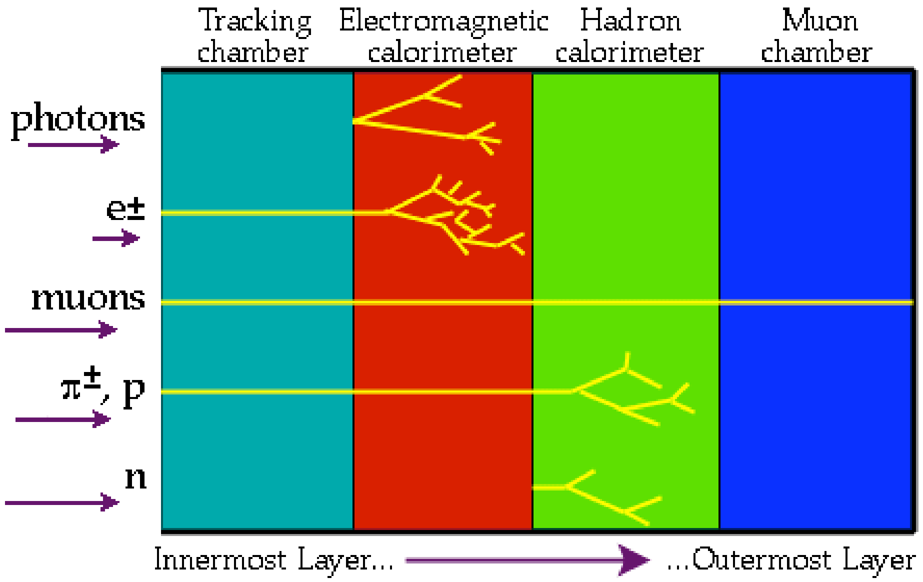
$\tilde{q}, \tilde{g}$ pairs m ~ 1 TeV

- 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, and excellent particle identification (e.g. e/jet separation)
- S (EW) /B (QCD) larger at Tevatron than at LHC

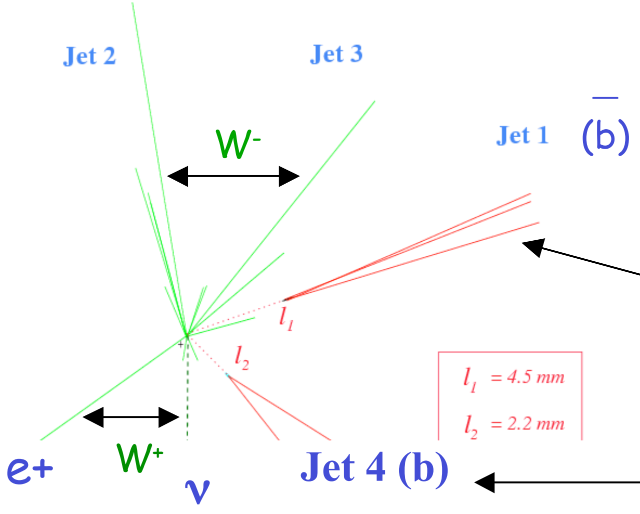
❸ Detector performance requirements

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



$t\bar{t} \to bW\,\bar{b}W \to bl\nu\,\bar{b}jj$ 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

Examples of detector performance requirements

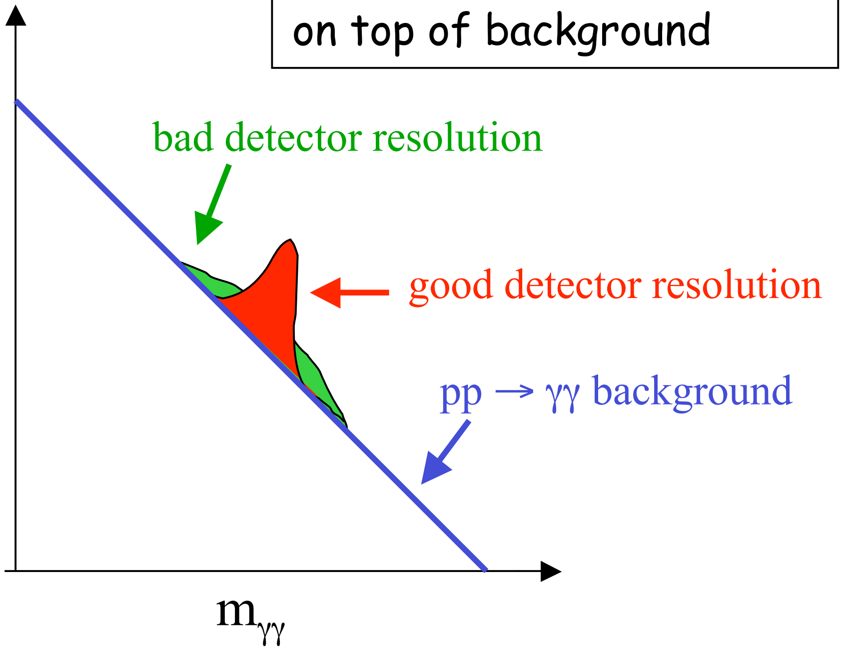
Lepton measurement: $p_T \approx$ GeV → 5 TeV (b → l+X, W′/Z′, …)

Mass resolutions:

$\approx$ 1% decays into leptons or photons
(Higgs, new resonances)

$\approx$ 10% W → jj, H → bb
(top physics, Higgs, …)

Hypothetical X → γγ signal on top of background



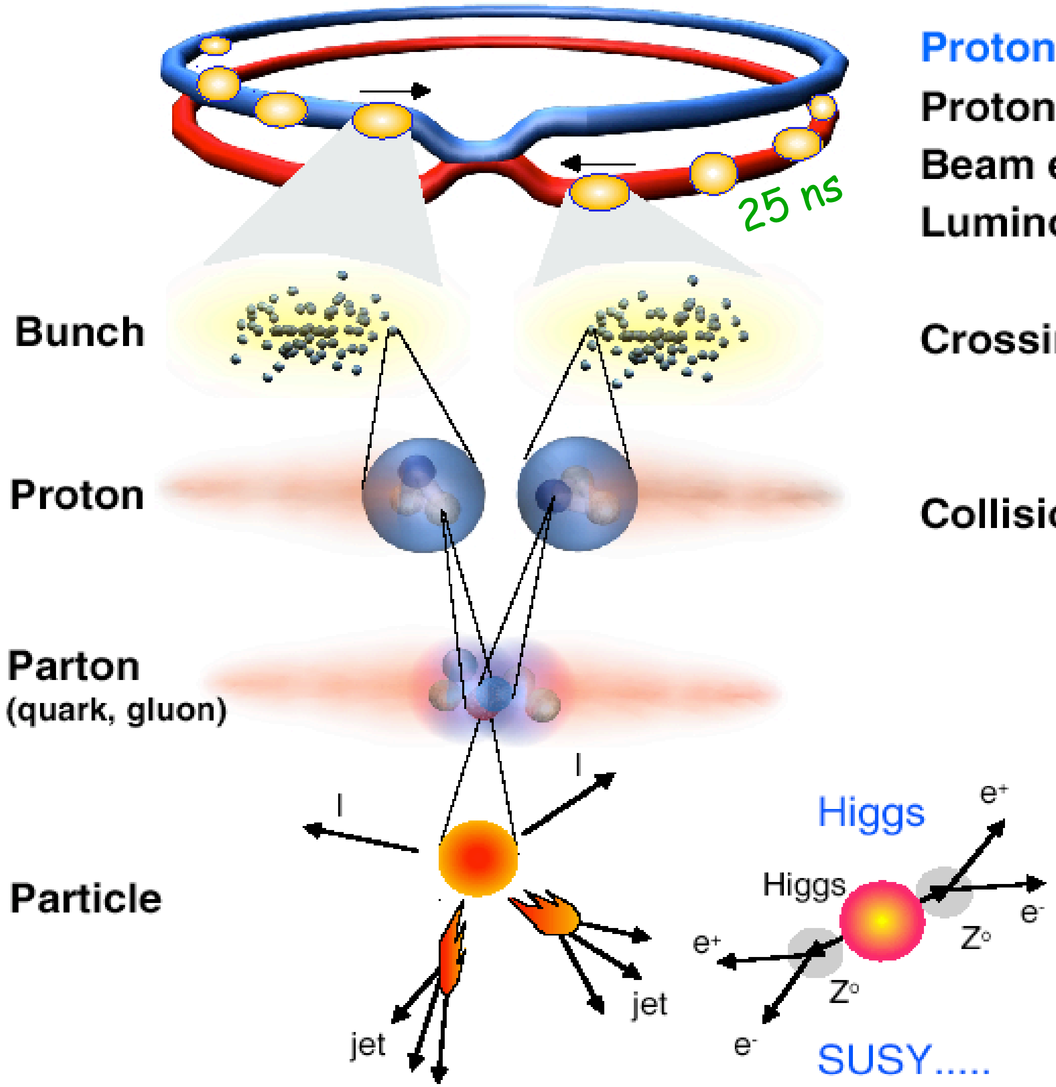
Particle identification:

- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 10^3 (H → γγ)
- e/jet separation : ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

Very selective triggers (online event selection system):

10^9 Hz (interaction rate) → 200 Hz (affordable rate-to-storage)

1 H → 4e event every 10^{13} interactions



Proton-Proton	**2835 bunch/beam**
Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**
Crossing rate	**40 MHz**
Collisions ≈	**10^7 - 10^9 Hz**

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