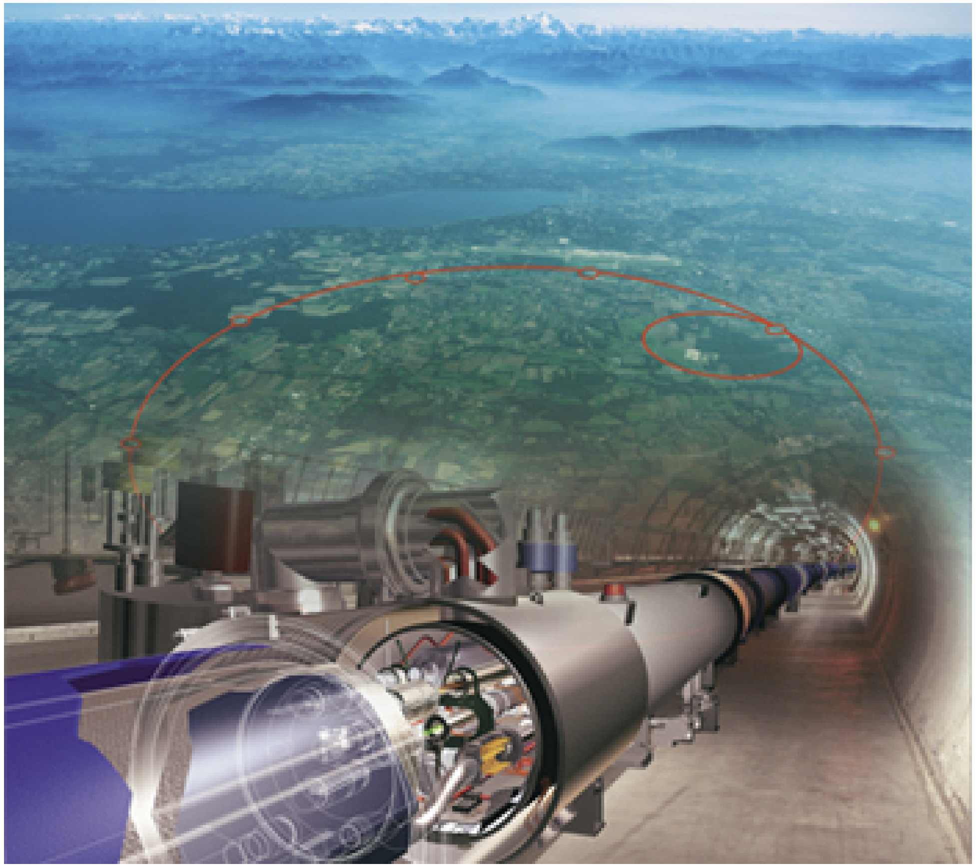
Physics at the Large Hadron Collider

Part I: The Experimental Challenge

Part II: Precision Physics and Searches

Lake Louise Winter Institute
Chateau Lake Louise
Alberta, Canada
20-26 February 2005



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Part I: The Experimental Challenge

Motivations
The LHC and related experiments
Overview of the physics programme
Basics of proton-proton collisions at the LHC
The ATLAS and CMS experiments

Part II: Precision Physics and Searches

Precision measurements
Higgs searches
Physics beyond the Standard Model
- SUSY
- extra-dimensions
- other exciting searches

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The Standard Model Particles

fermions (matter)

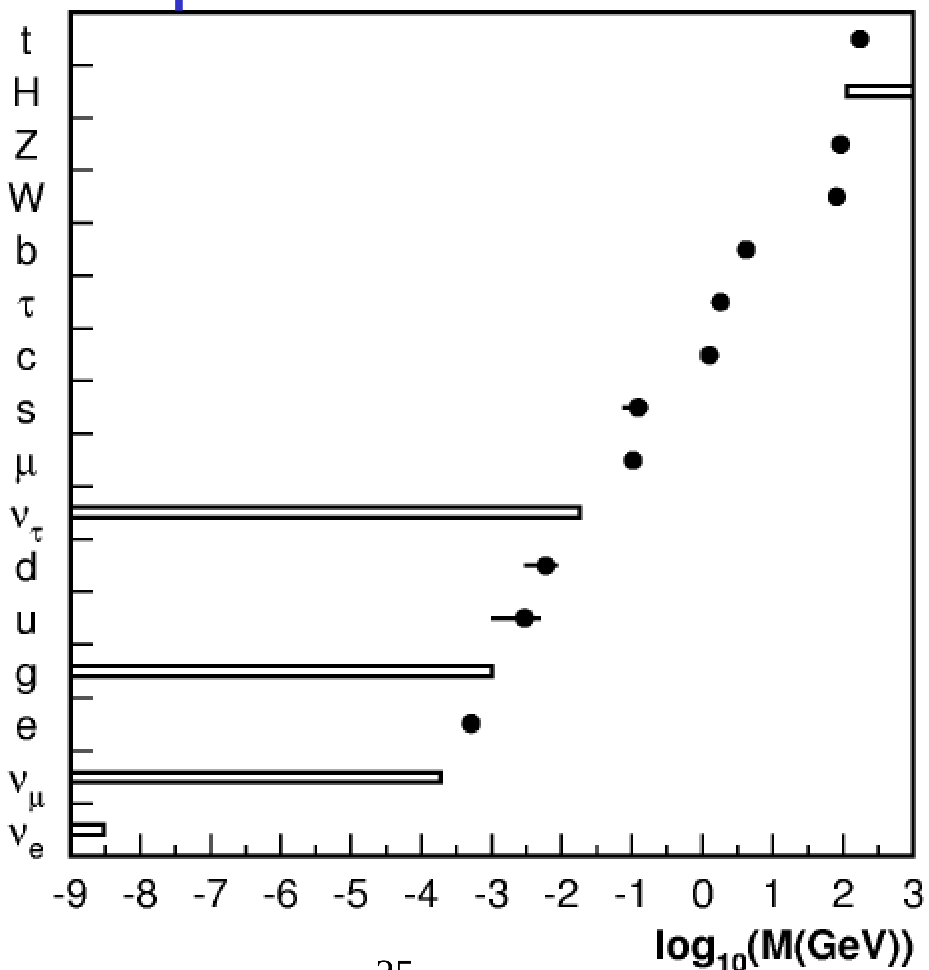
				charge
leptons	ν_e	ν_μ	ν_τ	0
	e	μ	τ	-1
quarks	u	c	t	+2/3
	d	s	b	-1/3

bosons (radiation)

$U(1)_Y$	B	~~EW~~ →	γ	electro-weak
$SU(2)_L$	W_1, W_2, W_3		W^+, W^-, Z^0	electro-weak
$SU(3)_C$	g_{1-8}		g_{1-8}	strong
Higgs doublet	$\varphi_1+i\varphi_2$, $\varphi_3+i\varphi_4$		H^0 →	**wanted!**

Fundamental Mass Values

Experimental values or limits



$\leftarrow \; m_\gamma < 2\times10^{-25}$ GeV

The SM does not say anything about the origin of the VALUES of the masses… They have to be obtained from EXPERIMENT

exception: photons and gluons are predicted to be massless

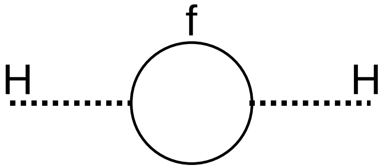
Why such a large range of fundamental masses?

Indirect searches yield very small neutrino masses… why are neutral fermions so light?

Hierarchy Problem

- Spontaneous symmetry hiding involves the inclusion of a fundamental scalar Higgs field
  - scalars are the only fields that can have non-zero vacuum expectation values without breaking Lorentz invariance
- The masses of such scalars suffer quadratically divergent renormalization corrections

$$\delta M_{\mathrm{H}}^2 \sim g^2 \Lambda^2$$



- If the SM is to be valid all the way to the scale Λ, and if we require $M_{\mathrm{H}} = O(M_{\mathrm{W}})$, then we require fine tuning of the Higgs couplings so that

$$\delta M_{\mathrm{H}}^2 \sim g^2 \Lambda^2 \sim O(1)$$

  - if Λ is the Planck scale 1.2×10^{19} GeV, possible if $130 < M_{\mathrm{H}} < 180$ GeV, then this corresponds to fine tuning of 1 part in 10^{38} !
  - “Naturalness Problem”
- Why is $M_{\mathrm{EW}} << M_{\mathrm{Planck}}$?
  - “Hierarchy Problem”

Vacuum Energy

- Higgs potential energy density after electroweak symmetry hiding

$$\mathcal{V}(\varphi)_{\text{min}} = -\frac{1}{8\sqrt{2}}\frac{M_{\text{H}}^2}{G_{\text{F}}} = \rho_{\text{H}}$$

$$= -1.4\times10^{49}\ \text{GeV}\cdot\text{cm}^{-3} \qquad (M_{\text{H}} = 120\ \text{GeV})$$

$$= -2.6\times10^{25}\ \text{g}\cdot\text{cm}^{-3}$$

- Dark energy density

$$\Omega_\Lambda = 0.73 \pm 0.04$$

$$\rho_\Lambda = \Omega_\Lambda \rho_{\text{c}}$$

$$= 3.9\times10^{-6}\ \text{GeV}\cdot\text{cm}^{-3}$$

$$= 6.9\times10^{-30}\ \text{g}\cdot\text{cm}^{-3}$$

55 orders of magnitude!

See Dr. E.W. Kolb's lectures for more cosmic connections!

$$\Lambda = (8\pi G_{\text{N}})\rho_{\text{vac}}$$

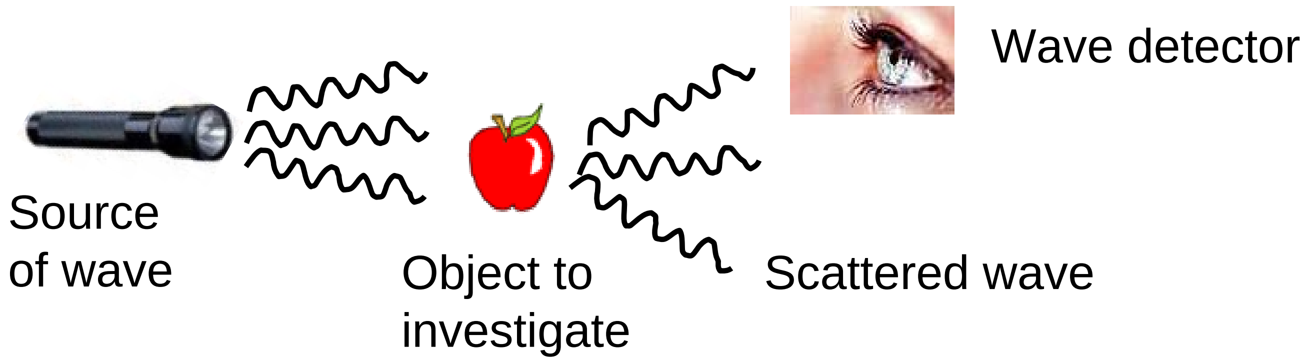
Many Unanswered Questions

- Is the Higgs mechanism really the electroweak symmetry hiding mechanism?
- Where does $SU(3)_C \times SU(2)_L \times U(1)_Y$ come from?
- Why is the weak interaction chiral?
- Why three generations?
- What sets the measured particle mass ratios?
- Is Nature supersymmetric?
- Are there extra dimensions?
- Can all forces be unified?
- What is the size of an electron? of the Z? of the top quark?
- What is the origin of the asymmetry between matter and antimatter?
- What is the origin of QCD confinement? Can quarks and gluons be deconfined in a plasma?
- What is dark matter?
- Why is the cosmological constant so small?

LHC Physics Programme

- Search for the Standard Model Higgs boson
  - mass range ~120 GeV to ~1 TeV
- Search for Supersymmetry and other physics beyond the Standard Model up to masses ~5 TeV
  - supersymmetric particles, quark and lepton compositeness, leptoquarks, extra massive gauge bosons W' and Z', extra dimensions, etc.
- Precision measurements
  - W mass
  - WWγ, WWZ triple gauge couplings
  - top mass, couplings and decay properties
  - Higgs mass, spin, couplings (if Higgs found!!)
  - B-Physics: CP violation, rare decays, B^0 oscillations
  - QCD jet cross section and α_s
  - etc.
- Study of phase transition at high density from hadronic matter to plasma of deconfined quarks and gluons

Scattering Experiment



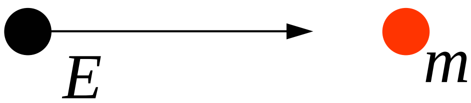
Matter waves: the Einstein — de Broglie

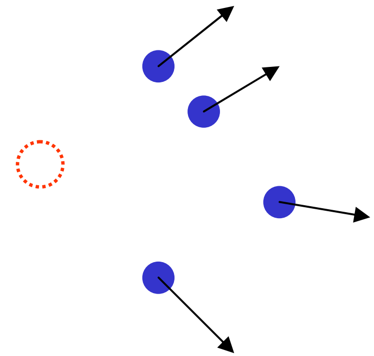
$$\text{particle aspect} \quad \left\{ \begin{array}{ccc} p & = & \dfrac{h}{\lambda} \\ E & = & h\nu \end{array} \right\} \quad \text{wave aspect}$$

The matter wave can resolve features about the size of its wavelength, given sufficient luminosity

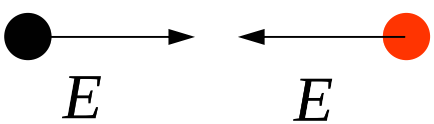
Colliding Particles

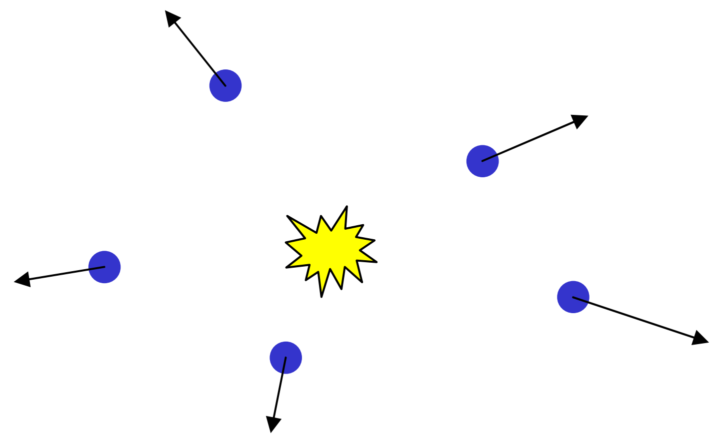
"Fixed target":
available energy $\simeq \sqrt{2mE}$





"Collider":
available energy $\simeq 2E$





Luminosity

Let

L: Machine luminosity (in cm^{-2}s^{-1})

σ: cross section for the relevant scattering process

R: event production rate

Then we have $R = L\sigma$ 1 barn = 10^{-28} m^2

Defining the integrated luminosity

$$\mathscr{L} = \int L \, \mathrm{d}t$$

then the number of events is given by

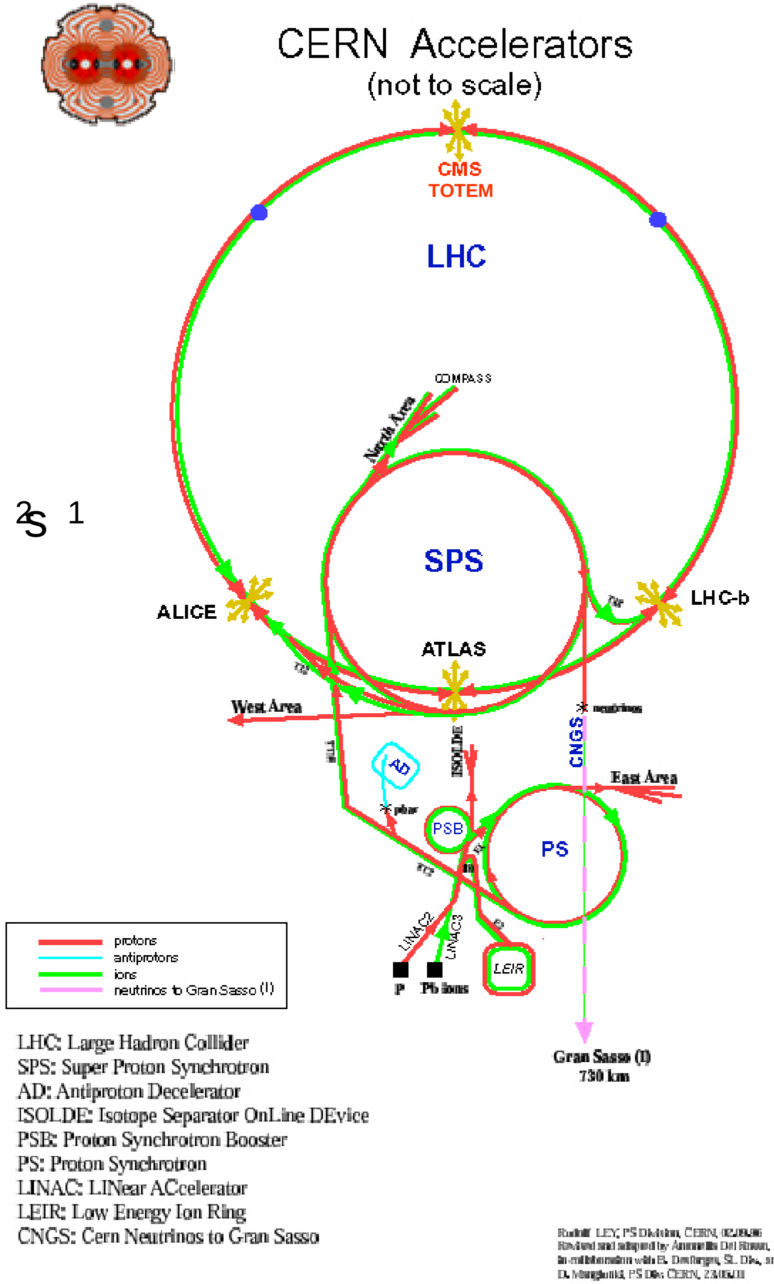
$$N = \mathscr{L}\,\sigma$$

Therefore if you want to make a measurement of a rare process (low cross section) with any significance, you need a large integrated luminosity. If you want to achieve this in a reasonable time, you need a large luminosity!

Aerial View of CERN

Large Hadron Collider

- Proton-Proton collisions
  - 7 TeV on 7 TeV $\sqrt{s} = 14$ TeV
  - probing nature at the energy frontier, down to ≈ 10^{-18} m
  - ATLAS and CMS experiments 10^{34} cm^{-2} s^{-1}
  - LHCb experiment 10^{32} cm^{-2} s^{-1}
  - TOTEM experiment
- Lead-Lead collisions ($^{208}Pb^{82+}$)
  - 2.76 TeV/u on 2.76 TeV/u
  - 1148 TeV center of mass energy
  - Investigate quark-gluon plasma
  - ALICE experiment (also ATLAS and CMS) 10^{27} cm^{-2} s^{-1}



LHC Parameters

	commis	first year	nominal	
Number of particles per bunch	1.15	0.4	1.15	10^{11}
Number of bunches	44	2808	2808	
Bunch harmonic number	44	3564	3564	
Bunch spacing	2021	25	25	ns
DC beam current	0.009	0.20	0.582	A
Stored beam energy	5.65	127	362	MJ
Luminosity (ATLAS and CMS)	0.015	0.12	1.0	10^{34} cm^{-2}s^{-1}
Events per bunch crossing	21.2	2.7	22.2	for 70 mb

Experimental challenges

- **high collision rate**
- **pileup of events**

A380 (max take-off weight of 560 t) moving at 130 km/h

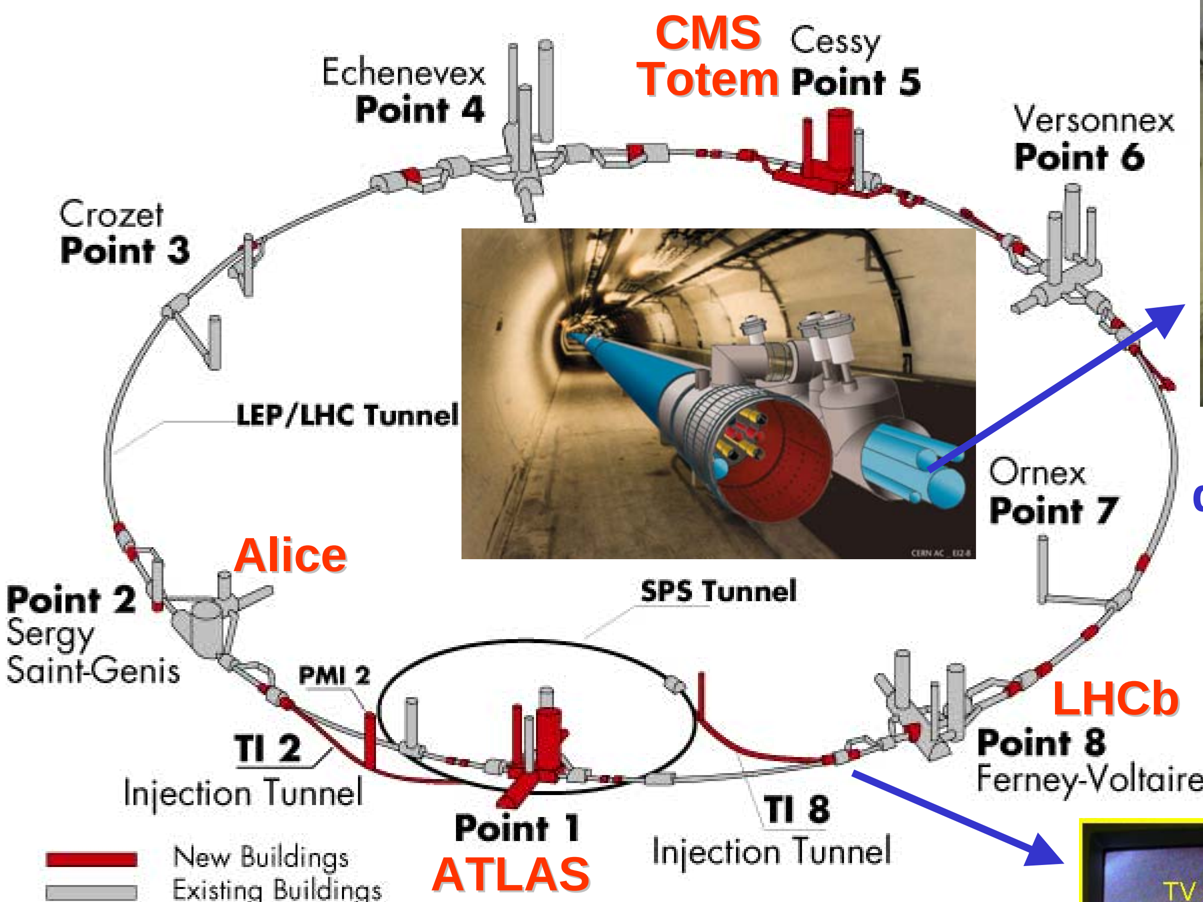
$$(70\ \text{mb})(10^{34}\ \text{cm}^{-2}\text{s}^{-1})\left(\tfrac{3564}{2808}\right)(25\ \text{ns})$$

Total inelastic cross section at 14 TeV

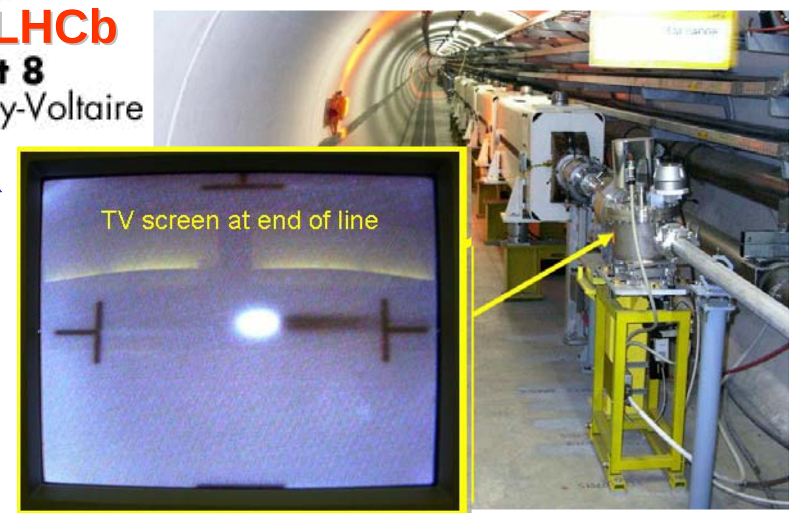
$$\text{Rate} = L\sigma_{\text{inel}}(\text{pp}) = 0.7\times10^{9}\ \text{interaction/s}$$

10^{34} cm^{-2}s^{-1}

LHC Progress

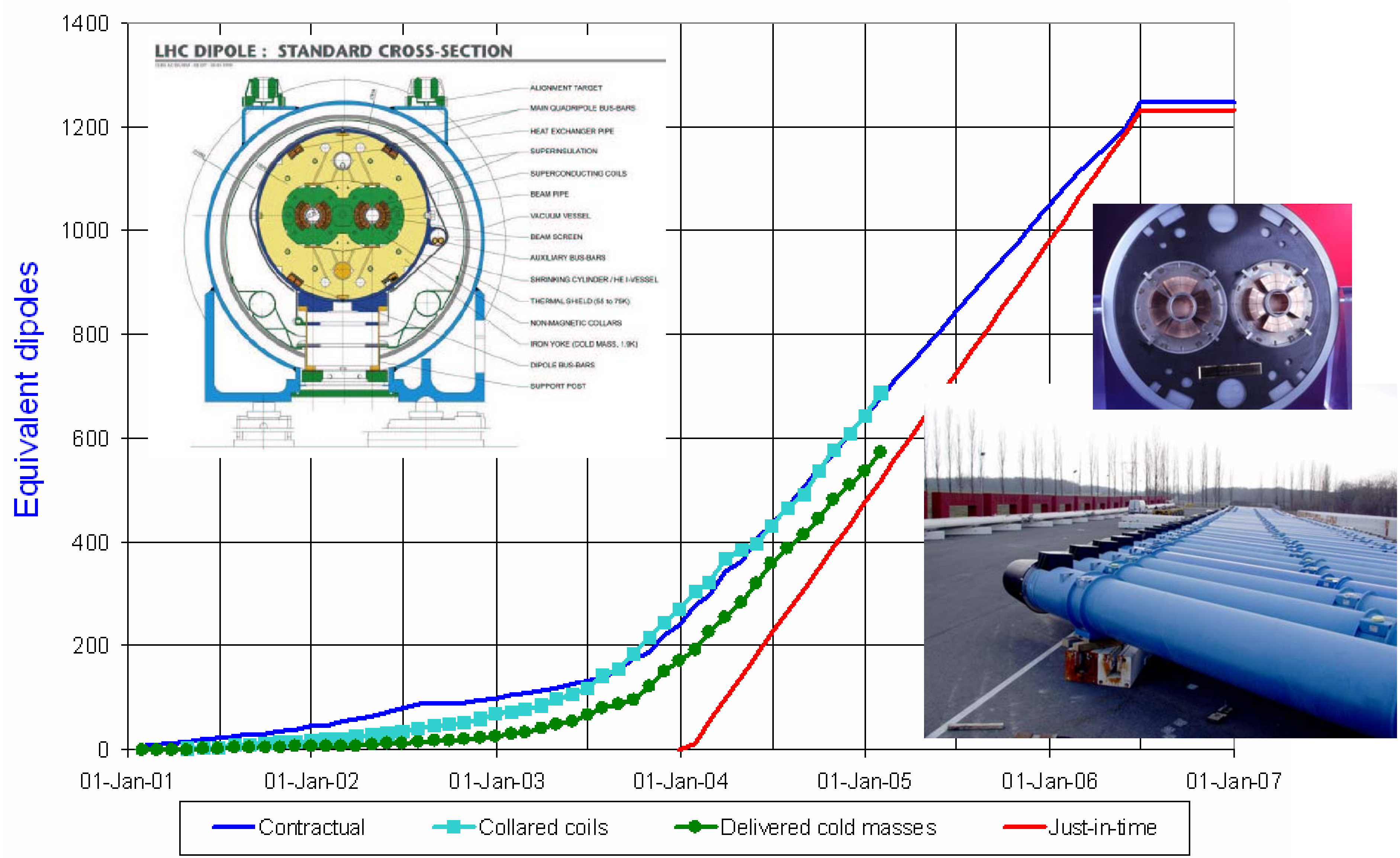


Problems with cryogenic distribution lines identified. Aggressive corrective measures in place



2004/10/23 First beam test of TI 8 transfer line, ≈ 2.5 km, success at first attempt

LHC Dipole Cold Masses



LHC Schedule

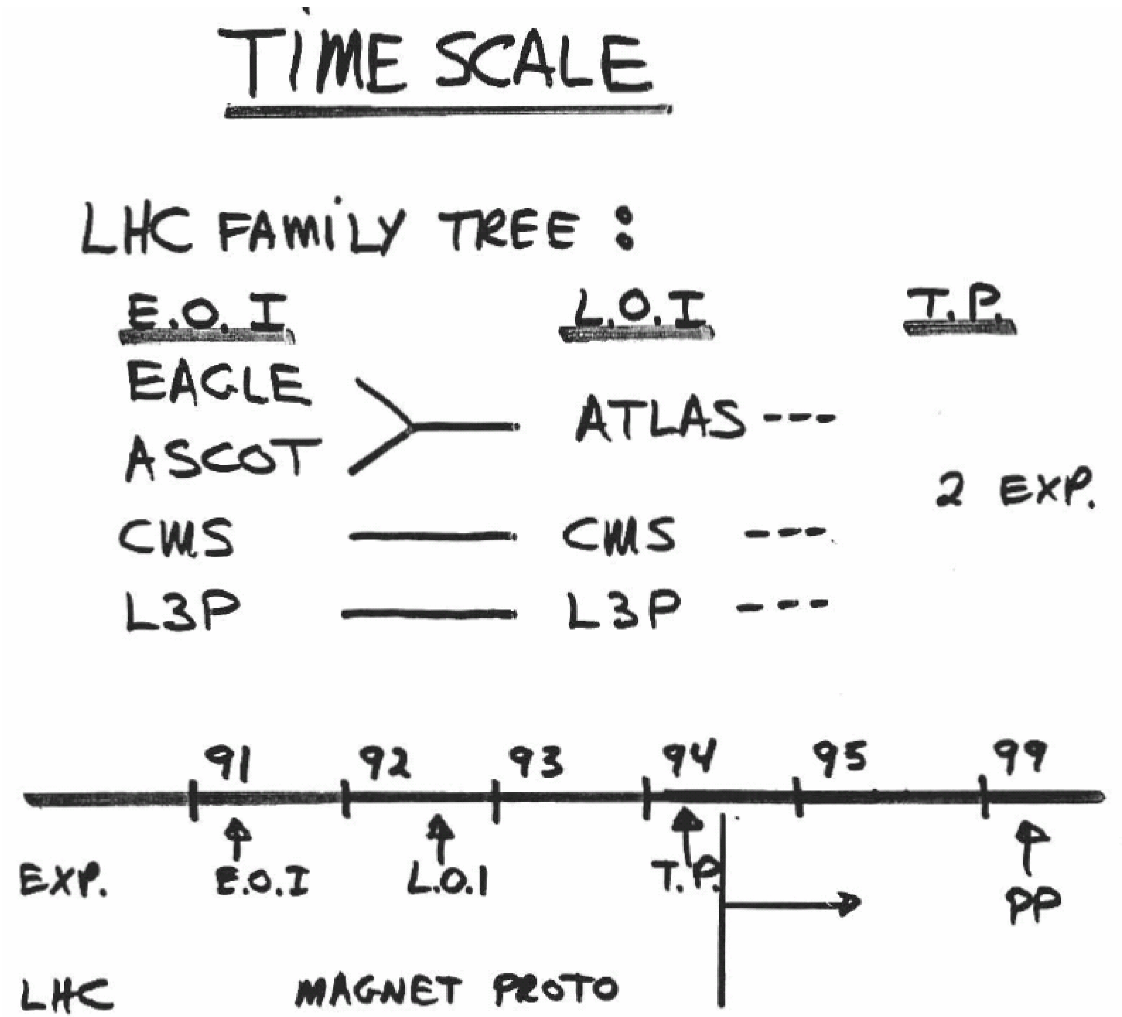
Director General Robert Aymar confirms CERN's very strong commitment to the LHC project

- Complete LHC installation towards end 2006
- first collisions by summer 2007

- Industrial production of machine components is compatible with this objective
- Installation of cryomagnets in tunnel is due to start March 2005

P. Lebrun, CERN Accelerator Technology Department, address to ATLAS Plenary meeting, 18 Feb 2005

LHC Schedule... in Feb 1993!

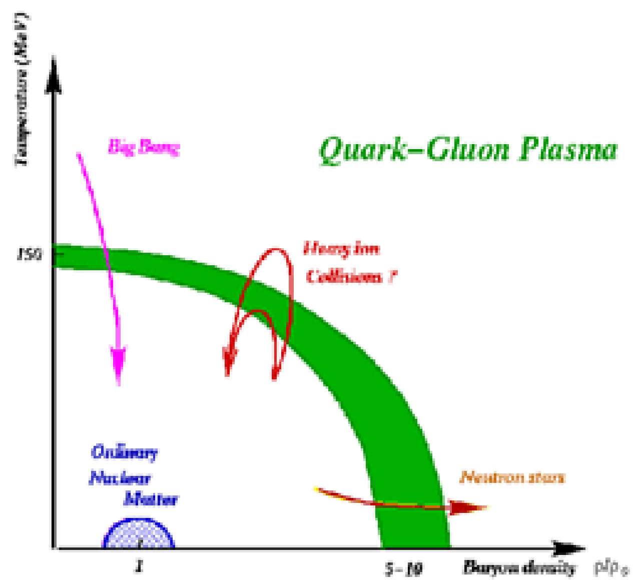


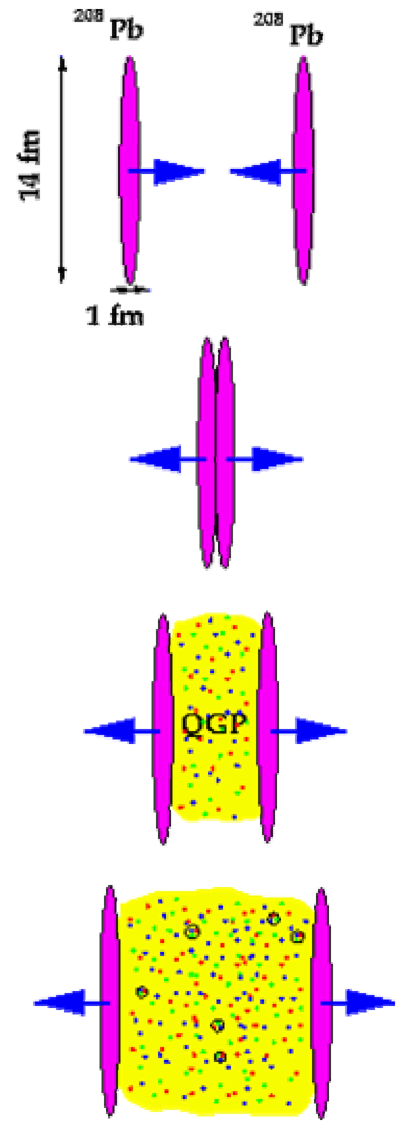
Scan of a slide I showed in Lake Louise in Feb 1993!

ALICE Experiment

See Dr. K. Rajagopal's lectures!

- dedicated heavy ion experiment
- luminosity = 10^{27} cm^{-2}s^{-1}
- study quark gluon plasma: key issues in QCD for the understanding of confinement and chiral-symmetry restoration
- Plasma $\rightarrow$ hadronic matter transition occurred ~10^{-5} s after the Big Bang!



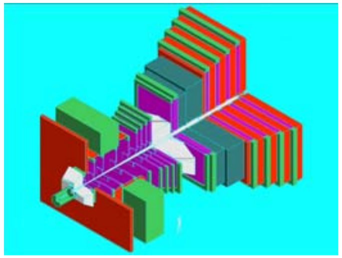


LHCb Experiment

See Dr. R.Fleischer's lectures!
Also J. Storey (LHCb) and
J. Catmore (ATLAS)

- pp experiment dedicated to b physics and CP violation studies

- Where has all the anti-matter gone?

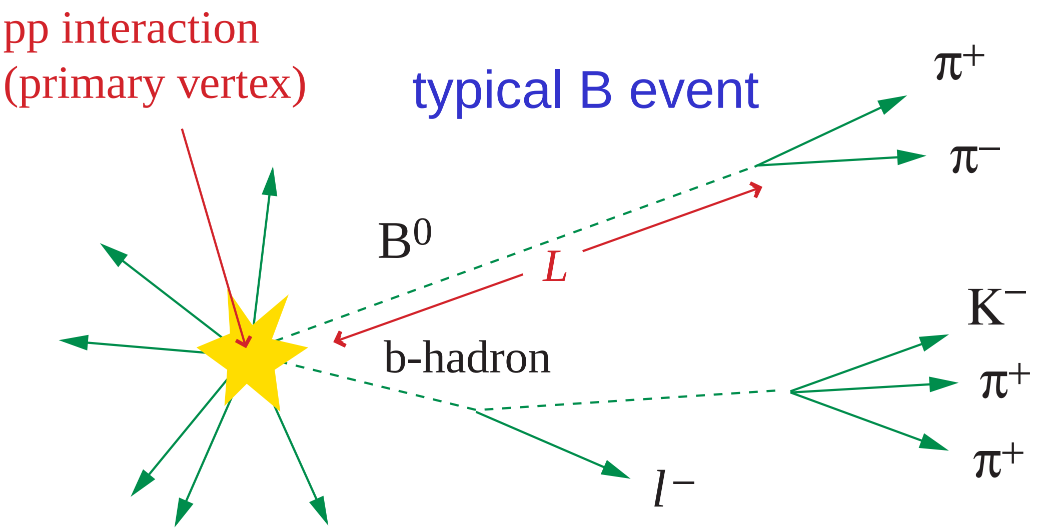


- Choose to run at ~ 2×10^{32} cm^{-2}s^{-1} (defocus beam locally), dominated by single interactions: easier to identify B decays from vertex structure

- B hadrons mostly produced in the forward direction: use a forward spectrometer 10-300 mrad

- Need to measure proper time of B decay ($\rightarrow L$) and momentum of decay products

- Need to tag production state of B: B^0 or $\bar{B}^0$. Use charge of lepton or kaon from decay of other b-hadron



R. Forty, WHEPP8, IIT Bombay, Jan 2004

Useful Kinematics

Consider one beam along the z axis $\sin\theta = \frac{p_T}{p}$ $\cos\theta = \frac{p_z}{p}$ $\beta = \frac{p}{E}$

$$m_T \equiv \sqrt{p_x^2 + p_y^2 + m^2}$$ transverse mass

$$p_T \equiv \sqrt{p_x^2 + p_y^2}$$ transverse momentum

$$y \equiv \tfrac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right) = \tfrac{1}{2}\ln\left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)$$ rapidity

$$\tanh y = \beta\cos\theta$$

$$E = m_T \cosh y$$
$$p_x = p_T \sin\varphi$$
$$p_y = p_T \cos\varphi$$
$$p_z = m_T \sinh y$$

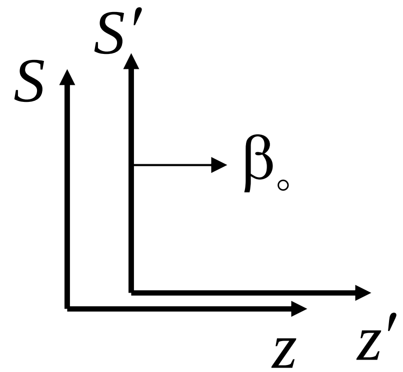
$$\eta = \lim_{m \to 0} y = \tfrac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\ln\tan\frac{\theta}{2}$$ pseudorapidity

$$\sinh\eta = \frac{1}{\tan\theta} \qquad \cosh\eta = \frac{1}{\sin\theta} \qquad \tanh\eta = \cos\theta$$

Useful Kinematics

Consider the Lorentz transformations for longitudinal (*z*) boost:

$$z' = \gamma_\circ (z - \beta_\circ ct) \qquad z = \gamma_\circ (z' + \beta_\circ ct')$$
$$ct' = \gamma_\circ (ct - \beta_\circ z) \qquad ct = \gamma_\circ (ct' + \beta_\circ z')$$

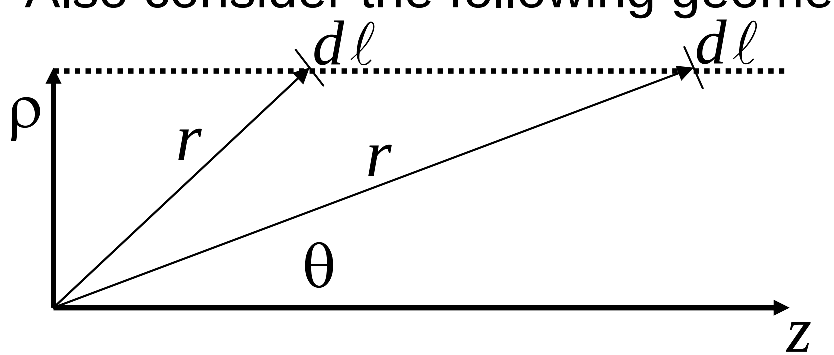


It is straightforward to show that

$$y' = y + \tfrac{1}{2}\ln\left(\frac{1-\beta_\circ}{1+\beta_\circ}\right) \quad \rightarrow \quad \Delta y' = \Delta y$$

$$p'_{\mathrm{T}} = p_{\mathrm{T}}$$
$$m'_{\mathrm{T}} = m_{\mathrm{T}}$$

Also consider the following geometrical results for pseudorapidity



$$d\ell = \rho \, d\eta$$

For a fixed ρ, *dl* is constant for a constant $d\eta$!

Total proton-proton Cross Section

$$\text{total}\begin{cases}\text{elastic} & pp \to pp \\ \text{inelastic...} & \begin{cases}\text{diffractive.........} \begin{cases}\text{single diffractive} & pp \to pX \\ \text{double diffractive} & pp \to ppX\end{cases} \\ \text{non-diffractive} \quad pp \to X\end{cases}\end{cases}$$

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

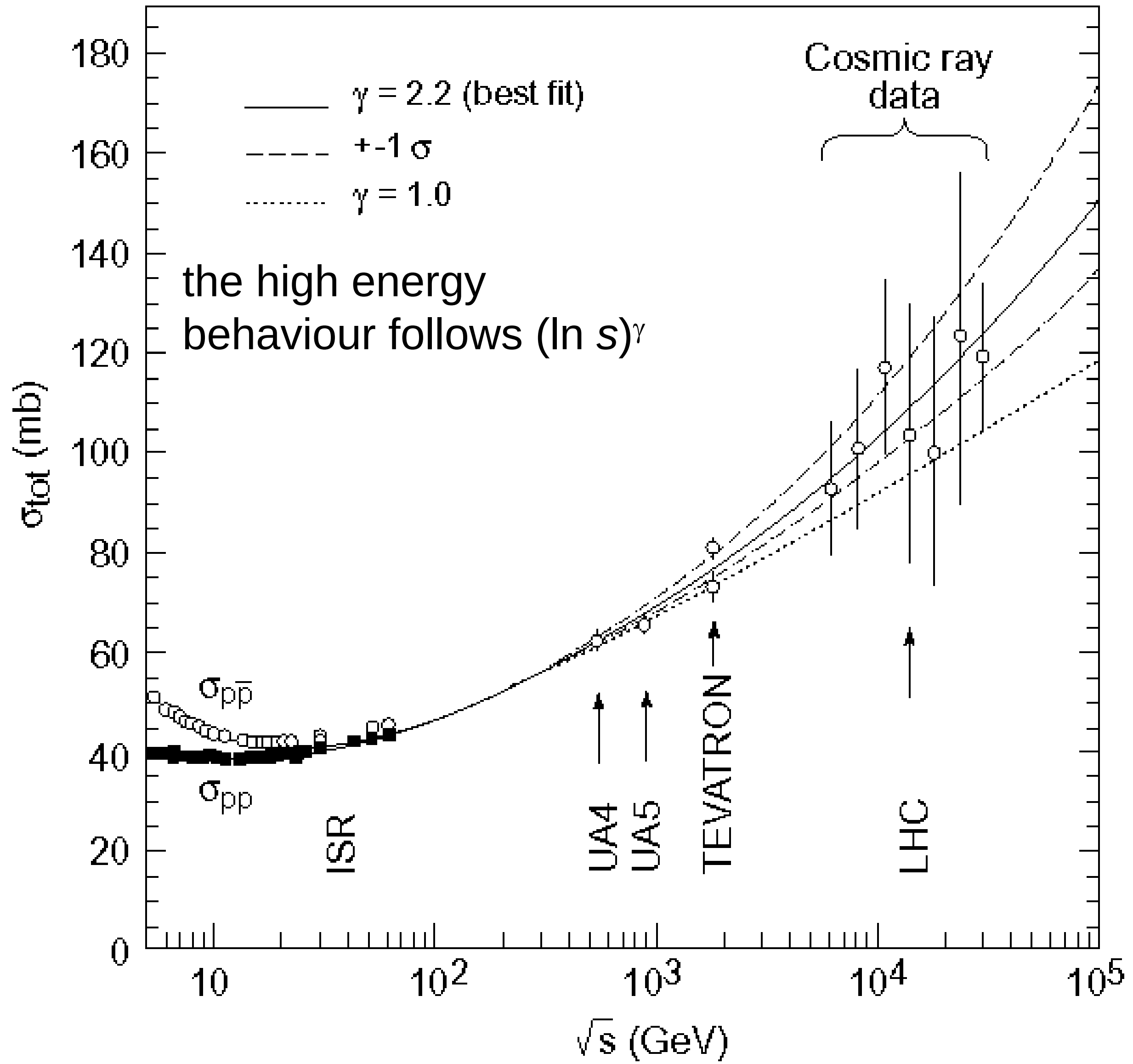
Elastic: both hadrons are not broken up to form new hadrons.

Diffractive: one (or both) hadron gets excited to a more massive state with the same quantum numbers which subsequently decays, as in $p \to N^* \to p\pi$.

A double pomeron exchange event is equivalent to a central diffractive event, a special type of double diffractive event.

Total Cross Section

The total cross section for pp̄ and pp scattering



TOTAL CROSS SECTION AND LUMINOSITY. By G. Matthiae (Rome U., Tor Vergata & INFN, Rome). 2002. 16pp.
Prepared for 3rd International Symposium on LHC Physics and Detectors (LHC 2001), Chia, Sardinia, Italy, 25 27 Oct 2001.
Published in **Eur.Phys.J.direct C4S1:13,2002**

TOTEM Experiment

EPJDirect A1 1-11 (2003)

- Measure the total proton-proton cross section
  - aim at $\Delta\sigma$ = 1 mb (~ 1%)
  - luminosity independent method
  - measure simultaneously the elastic and inelastic cross sections
  - installed in the CMS forward region
  - only needs a few 1-day runs at $10^{28}\text{cm}^{-2}\text{s}^{-1}$

$$\left.\begin{aligned} \mathscr{L}\,\sigma_{\text{tot}} &= N = N_{\text{elas}} + N_{\text{inel}} \\ \mathscr{L}\,\sigma_{\text{tot}}^2 &= \frac{16\pi}{1+\rho^2}\left(\frac{dN}{dt}\right)_{t=0} \end{aligned}\right\}$$

obtain $\mathscr{L}$ and σ_{tot} from measurable quantities

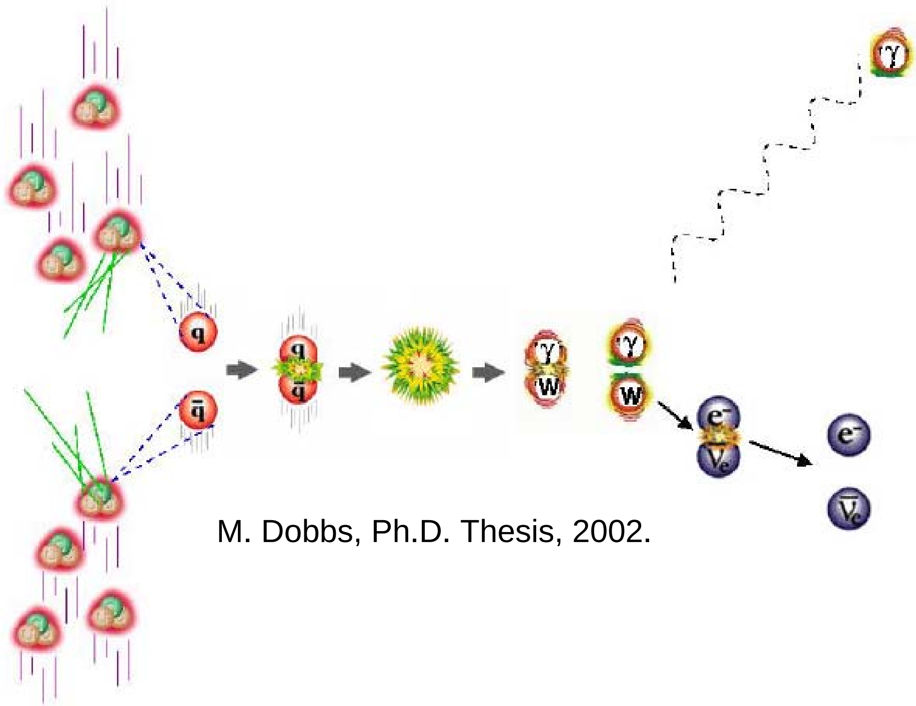
Optical theorem. ρ is small (0.1-0.2) at high high energy, so it's error contributes little to the measurements

Minimum Bias Events

- Inelastic proton-proton collisions are dominated by soft (low p_T) interactions; Sometimes, one gets a hard scatter.
- Inelastic events are selected with a “minimum bias trigger”. These minimum bias events are usually associated with inelastic non-single-diffractive events.
- These events are due to collisions at large distance between the incoming proton which interact as a whole:
  - small momentum transfer
  - final state particles with large p_L but small p_T, small angle scattering
  - most energy escapes down the beam pipe

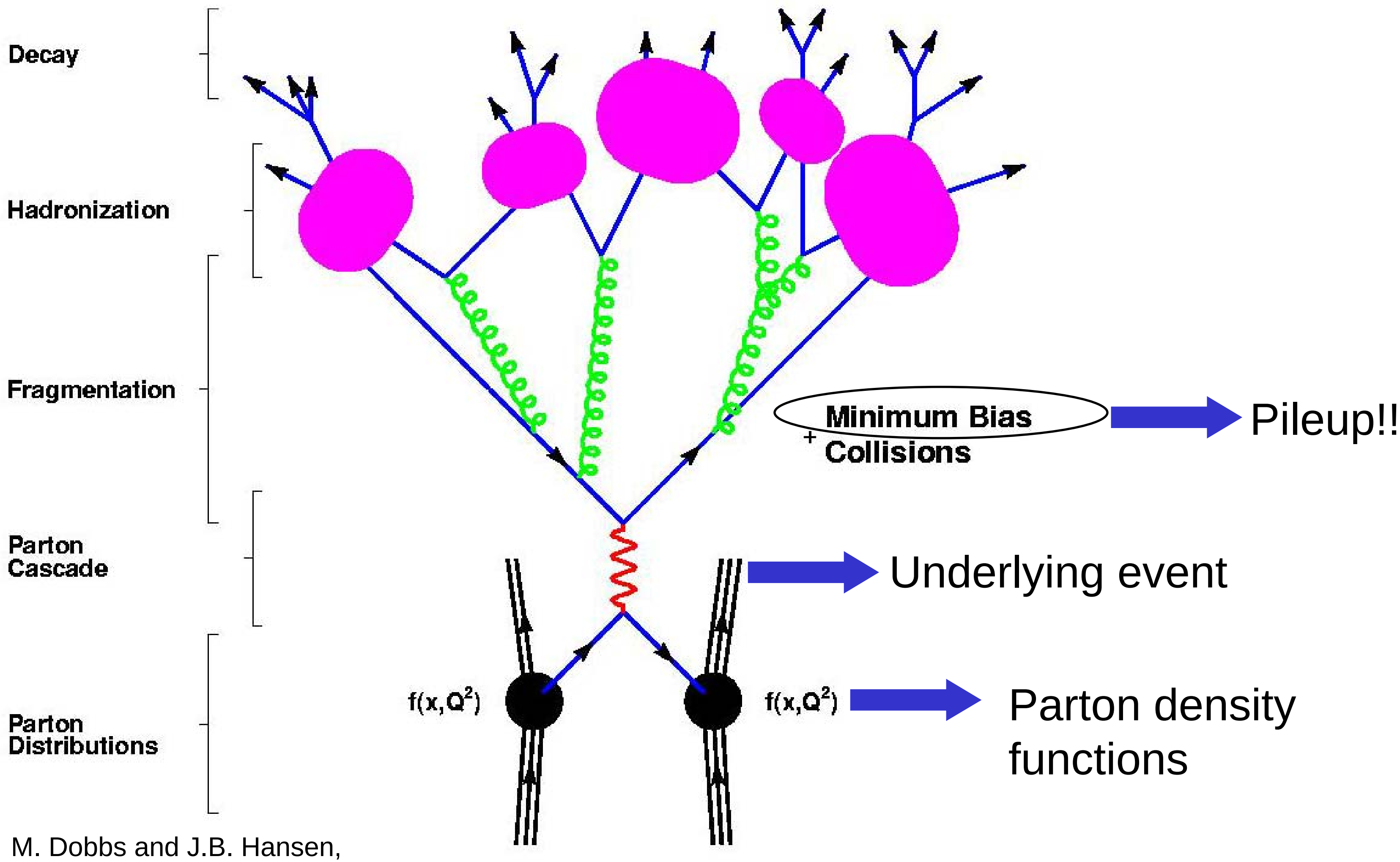
Hard Scatter

- A proton beam can also be seen as a beam of quark and gluons with a wide band of energy
- Occasionally a hard scatter (collision at short distance) takes place
  - large momentum transfer
  - final state particles with large mass and/or large scattering angles
  - interesting, but rare events!!
- Understanding the minimum bias events helps understanding the underlying event



M. Dobbs, Ph.D. Thesis, 2002.

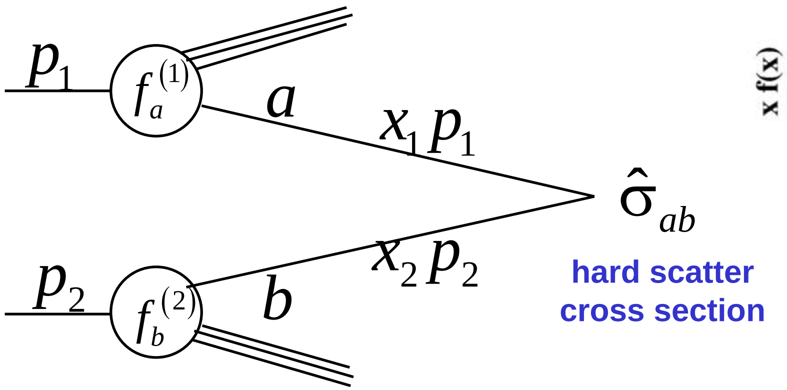
Hadron-Hadron Collisions



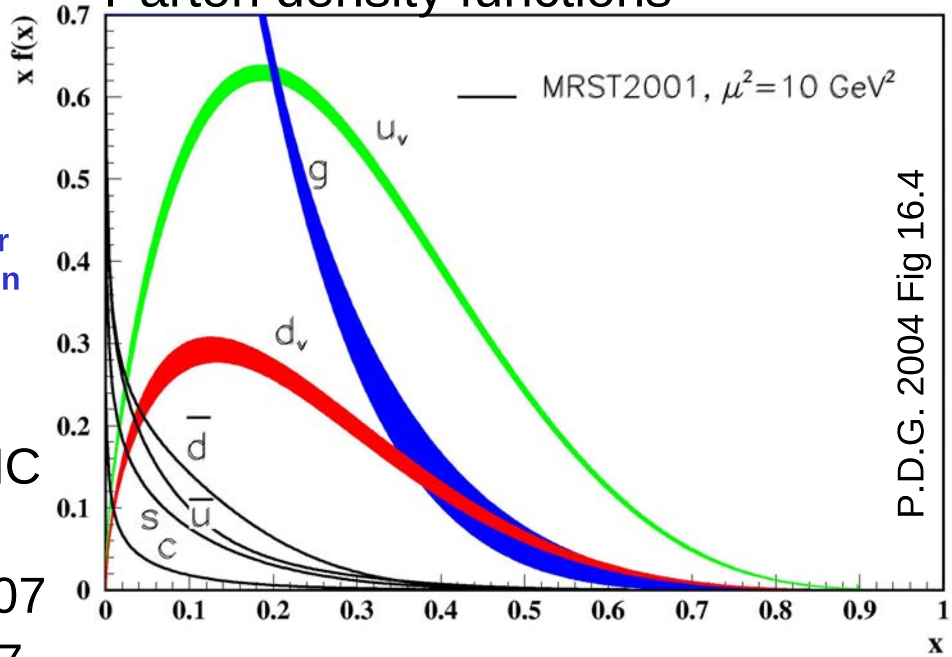
M. Dobbs and J.B. Hansen,
Comp. Phys. Comm. 134 (2001)
41 46.

Hadron-Hadron Collisions

- Unlike in $e^+ + e^-$, the hard scatter particles (hadron constituents a and b) carry only a fraction of the incoming hadrons (1 and 2) momentum:



Parton density functions



P.D.G. 2004 Fig 16.4

If $x_1 \sim x_2 \Rightarrow x \sim \frac{\sqrt{\hat{s}}}{\sqrt{s}}$ So, at LHC

to produce m ~ 100 GeV → x ~ 0.007

to produce m ~ 1 TeV → x ~ 0.07

$$\sigma = \sum_{a,b} \int dx_1 dx_2\, f_a^{(1)}\left(x_1, Q^2\right) f_b^{(2)}\left(x_2, Q^2\right) \hat{\sigma}_{ab}\left(x_1, x_2\right)$$

Event Pileup

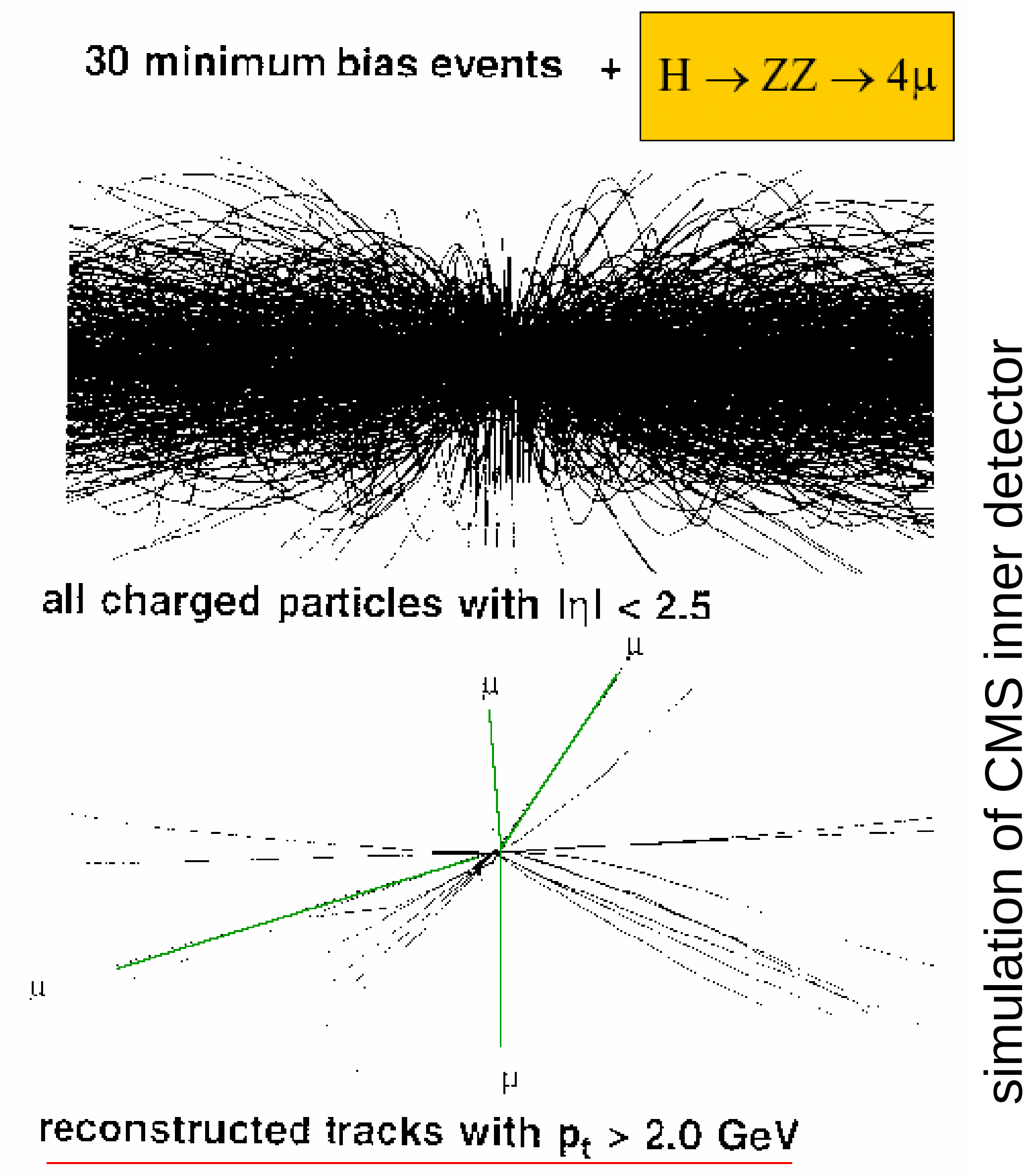
- For each bunch crossing, an average about 22 minimum bias events are produced. These events overlap with the interesting high p_T physics events: pileup

$$\frac{dN_{\rm ch}}{d\eta} \approx 7 \quad \text{for } |\eta| \leq 5 \qquad\qquad \langle p_T \rangle \approx 500 \text{ MeV}$$

→ control detector channel occupancy through segmentation in constant η intervals

- About 800 charged particles produced over $|\eta| < 2.5$ at each bunch crossing, most of low p_T

Event Pileup



- applying a p_T cut allows the extraction of interesting particles

Event Pileup

High rate event pileup is one of the most serious experimental difficulty at the LHC

Large impact on detector design

- Typical detector response time is 20 to 50 ns
  - integrate over 1 to 2 bunch crossings
  - pileup of 25 to 50 minimum bias events
  - this is very challenging for readout electronics
- Detectors must be highly granular to reduce the chance of pileup particles overlapping with interesting signal particle in the same detector element
  - large number of readout channels, so high cost
- Detectors must be radiation resistant
  - high flux of particles from pp collisions produces a high radiation environment ($\propto d^{-2}$ from beam axis), in particular in the forward regions
  - up to 10^{17} n/cm^2 and 10^7 Gy (J/kg) in 10 years of LHC operation
  - affects all detector components and on-detector electronics

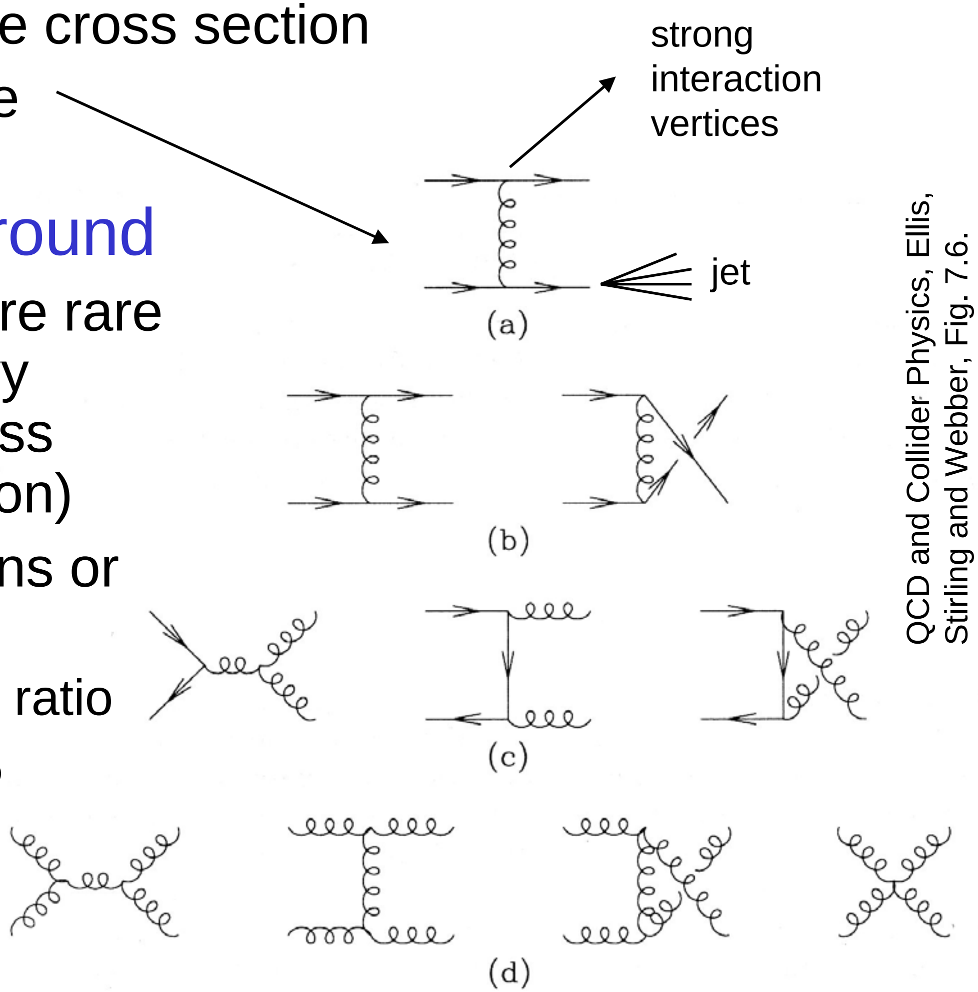
QCD Background

Common to all hadron colliders

- High p_T events are dominated by QCD jet production
- Strong production $\rightarrow$ large cross section
- Many diagrams contribute

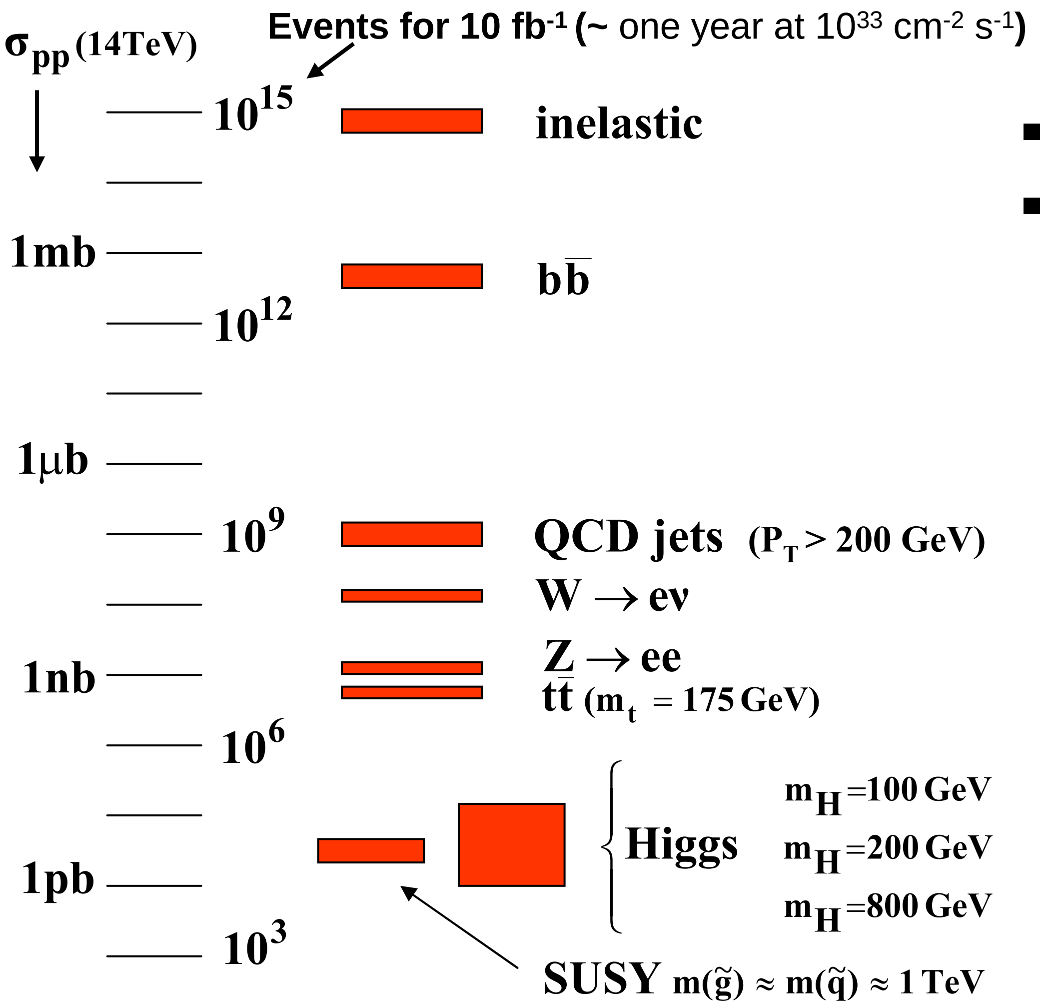
Controlling QCD background

- Most interesting events are rare processes involving heavy particles and/or weak cross sections (e.g. W production)
- Look at decays into leptons or photons
  - pay a price in branching ratio
  - e.g. H(120GeV) $\rightarrow \gamma\gamma$ ~ 2‰
  - e.g. W $\rightarrow l\nu$ ~ 30%



QCD and Collider Physics, Ellis, Stirling and Webber, Fig. 7.6.

LHC PP Cross Section



- One LHC year ~ 10^7 s
- "Discovery signal" down ~ 10 orders of magnitude in rate compared with the total cross section!!

LHC PP Cross Section

10^{33} cm^{-2}s^{-1}

Process	Events per LHC Low Luminosity Year
total inelastic event rate	10^{15}
$pp \to t\bar{t} + X$	6.1×10^{6} → ~1Hz !!
$pp \to b\bar{b} + X$	7.0×10^{12}
$pp \to Z^0/\gamma + X$ with $\sqrt{\hat{s}} > 10$ GeV	1.1×10^{9}
$pp \to W^{\pm} + X$	1.8×10^{9}
$pp \to W^{+}W^{-} + X$	7.7×10^{5}
$pp \to W^{\pm}Z^0 + X$	2.9×10^{5}
$pp \to Z^0Z^0 + X$	1.2×10^{5}
$pp \to Z^0\gamma + X$ with $P_\gamma^T > 10$ GeV	1.4×10^{6}
$pp \to W^{\pm}\gamma + X$ with $P_\gamma^T > 10$ GeV	1.8×10^{6}

Table 1.2: Inclusive event rates are presented for some of the processes of interest at the LHC. The event rates are for one year of low luminosity LHC running, which corresponds to an integrated luminosity of 10 fb^{-1}. The cross sections are calculated at leading order with the general purpose event generator Pythia 6.152 [Sjö01a] using the program's default parameters.

M. Dobbs, Ph.D. Thesis, Victoria, 2002.

ATLAS and CMS Experiments

Detectors must be able to detected as many observables as possible, ready for the unexpected!

e, μ, τ, ν, γ, $\pi^{\pm}$, q and g jets, tag b-jets, ...

ATLAS and CMS are multi-purpose detectors

- Momentum/charge of tracks and secondary vertices are measured in the central tracker. Excellent momentum and position resolution required
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent resolution and particle identification required
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity required
- Muons identification and momentum measurement in external muon spectrometer and central tracker. Excellent resolution for p_T from ~5 GeV to ~1 TeV required
- Neutrinos (or other undetectable particles) globally measured through the missing transverse energy E_T^{miss}. Calorimeter coverage over $|\eta| < 5$ needed.

Missing Transverse Energy

- Neutrinos (and possibly other new particles) traverse the detector without interacting
- At hadron colliders the longitudinal momentum of the hard scatter is not known, but $\vec{p}_{\mathrm{T}i} = 0$
- If a high p_{T} neutrino is produced, then

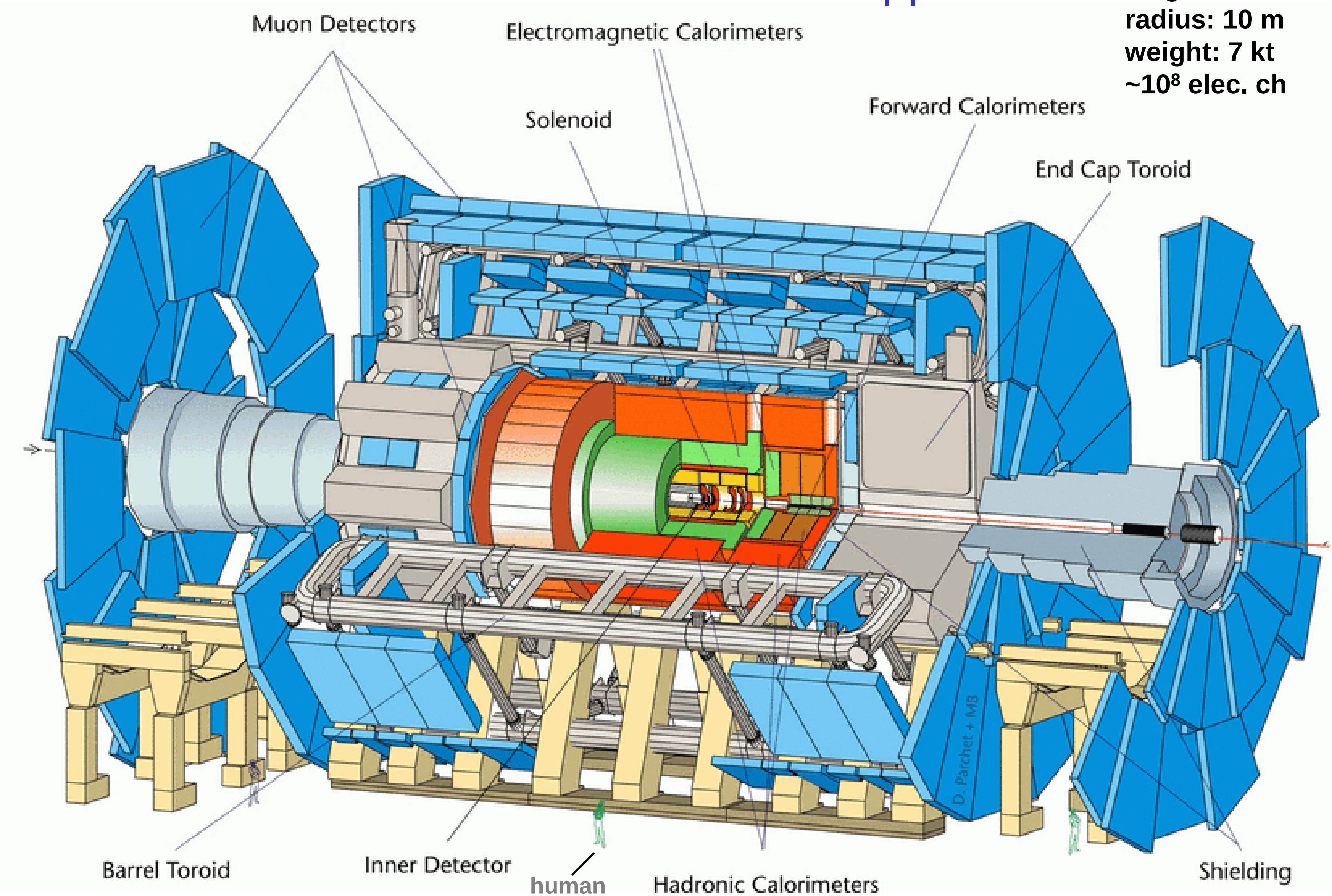
$$\vec{p}_{\mathrm{T}\nu} = -\vec{p}_{\mathrm{T}f}$$

$$\left|\vec{p}_{\mathrm{T}\nu}\right| = \left|\vec{p}_{\mathrm{T}f}\right| = E_{\mathrm{T}}^{\mathrm{miss}}$$

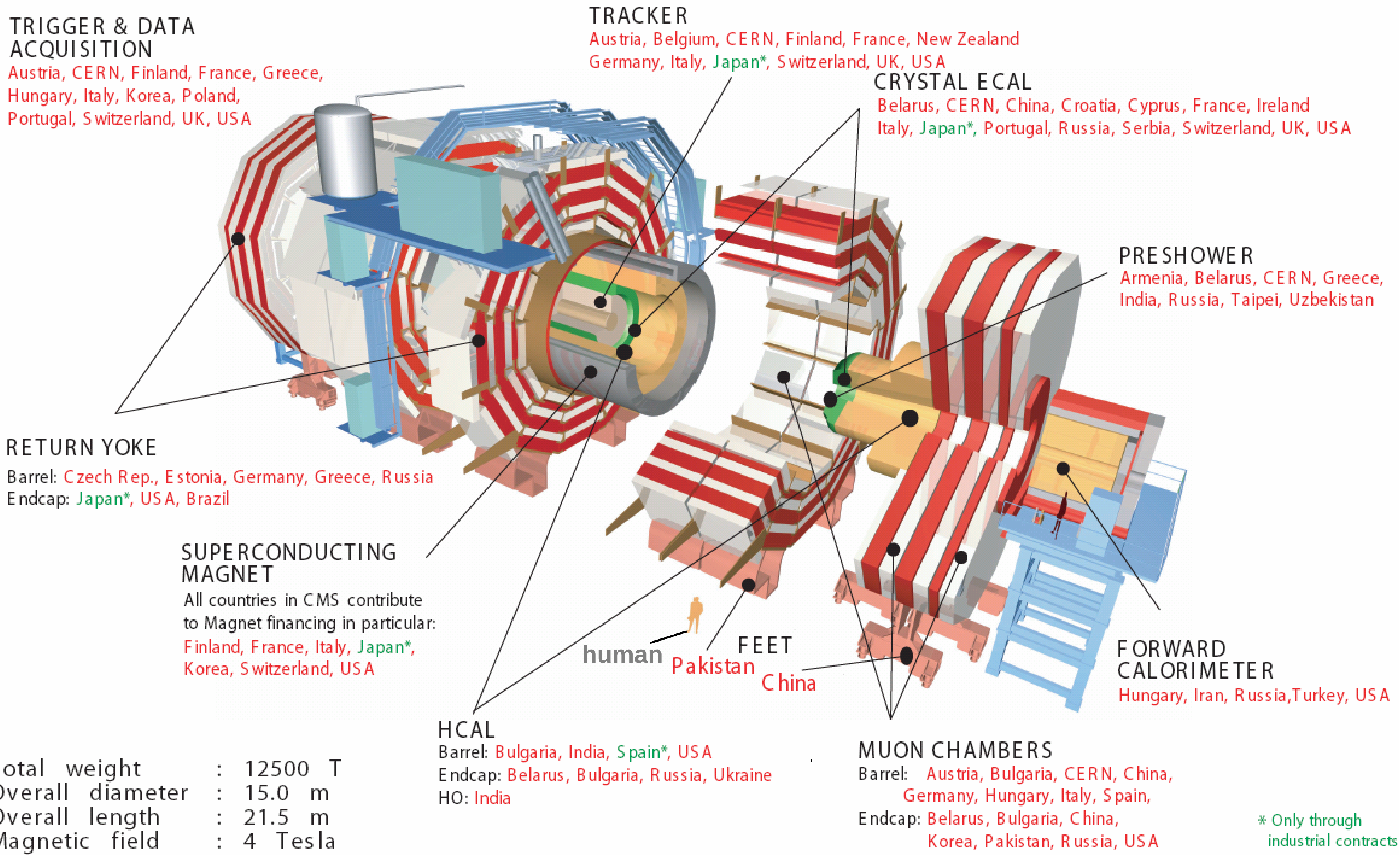
- The missing transverse energy resolution is therefore an important quantity. It is worsen by detector imperfections (incomplete coverage, miscalibration) and pileup

ATLAS Detector A Toroidal Lhc ApparatuS

length: 40 m
radius: 10 m
weight: 7 kt
~10^8 elec. ch

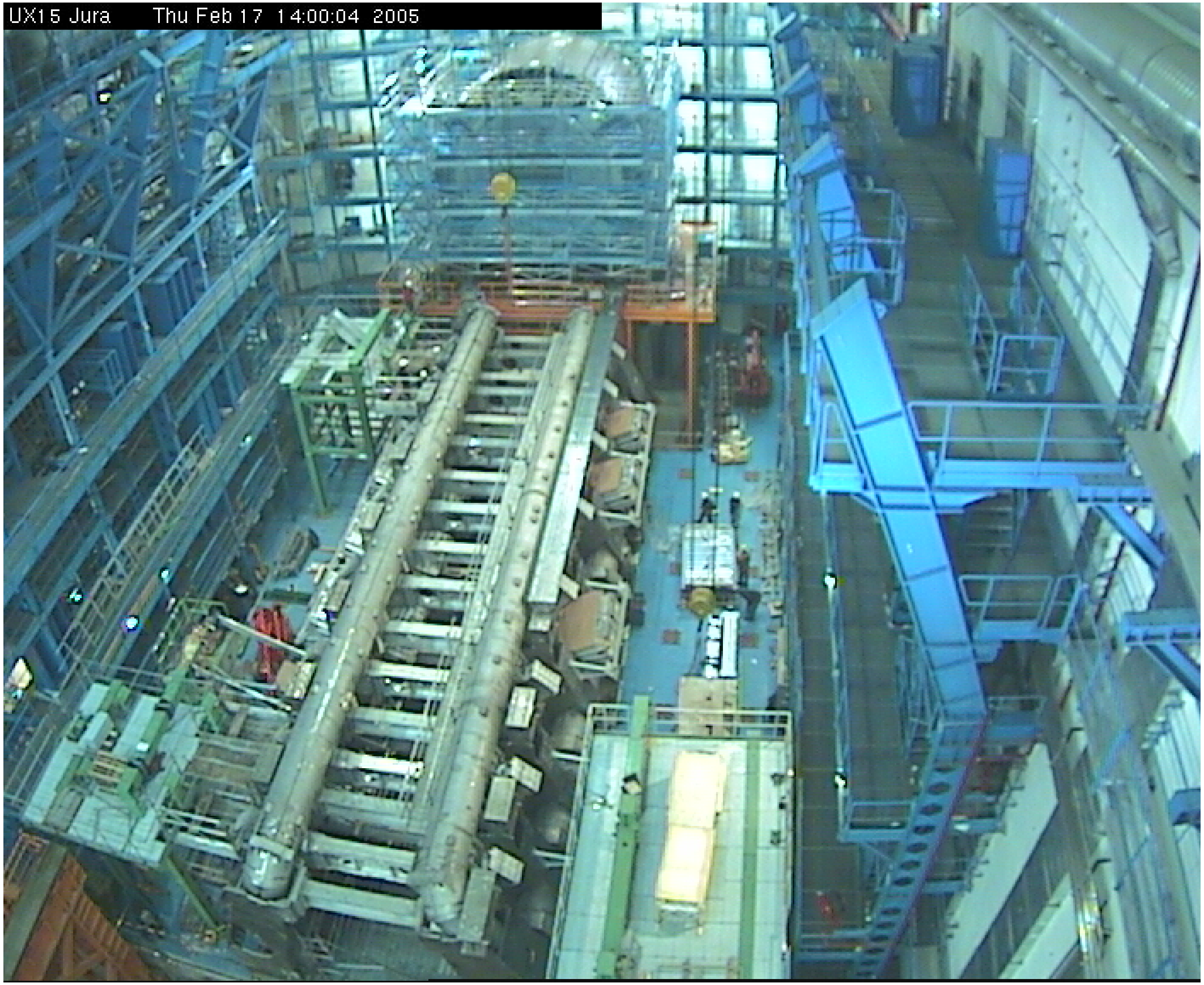


CMS Detector Compact Muon Solenoid



Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla

ATLAS web cam

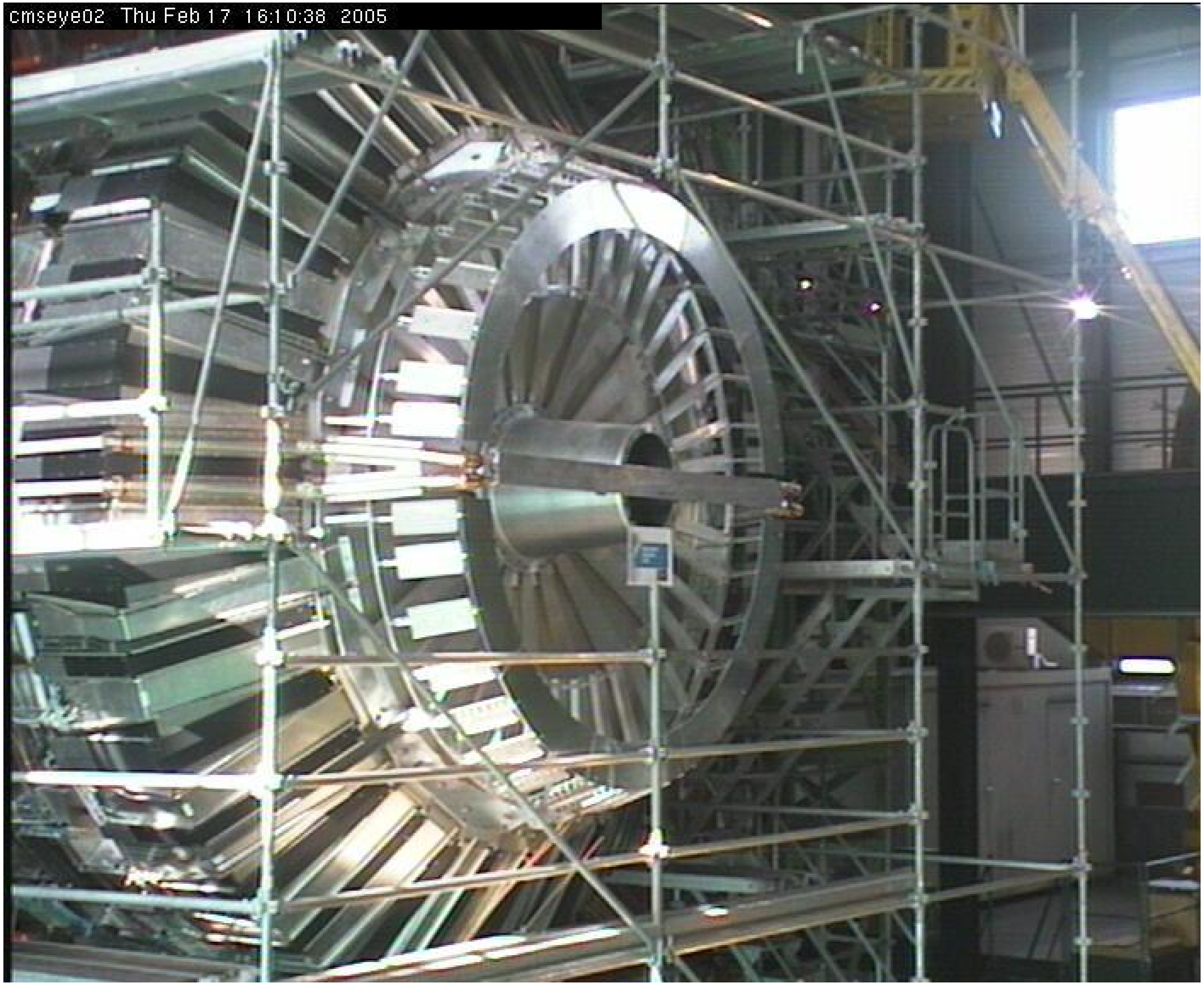


ATLAS Detector Components

ATLAS barrel cryostat, containing the solenoid and the electromagnetic barrel calorimeter, being lowered in the pit

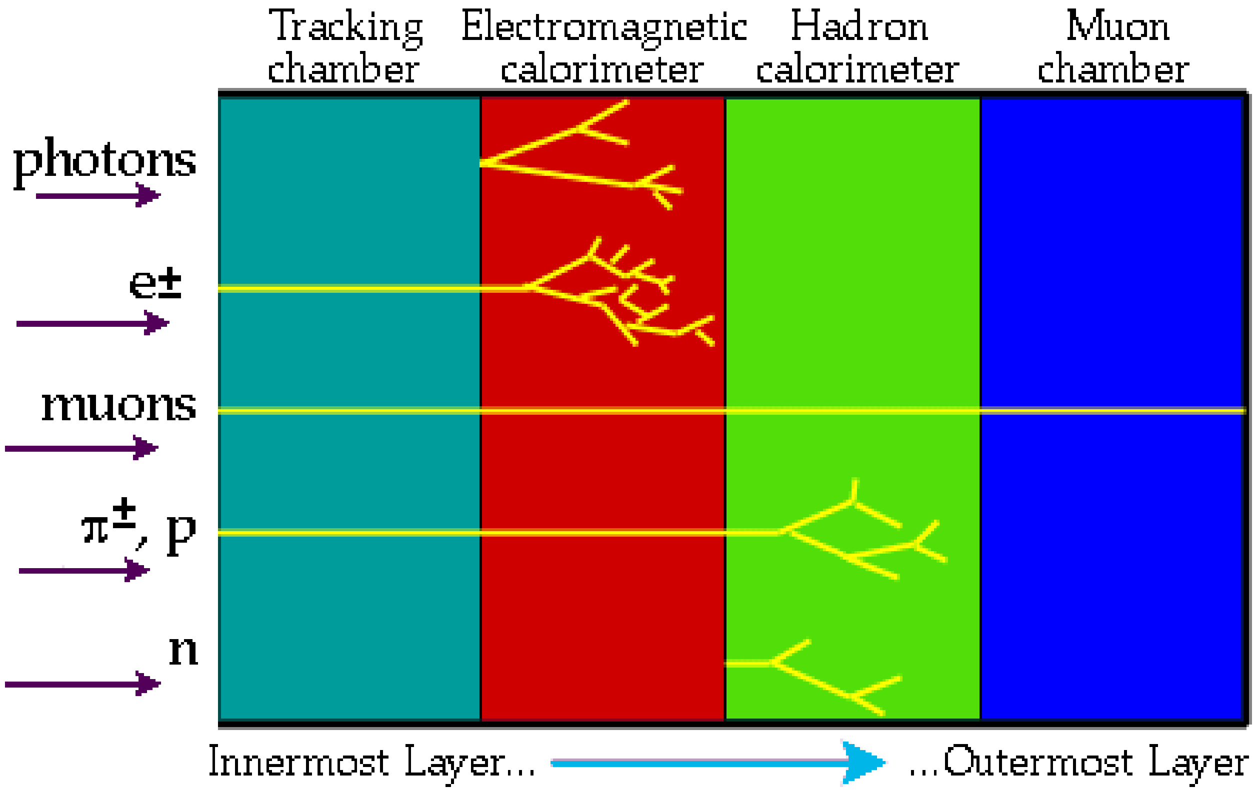
ATLAS Detector Components

CMS web cam



view of one of the HCAL endcaps installed on an endcap yoke disk

Typical Detector Components



Need good e/γ, e/jet, γ/jet separation

ATLAS and CMS

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRD → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 70\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

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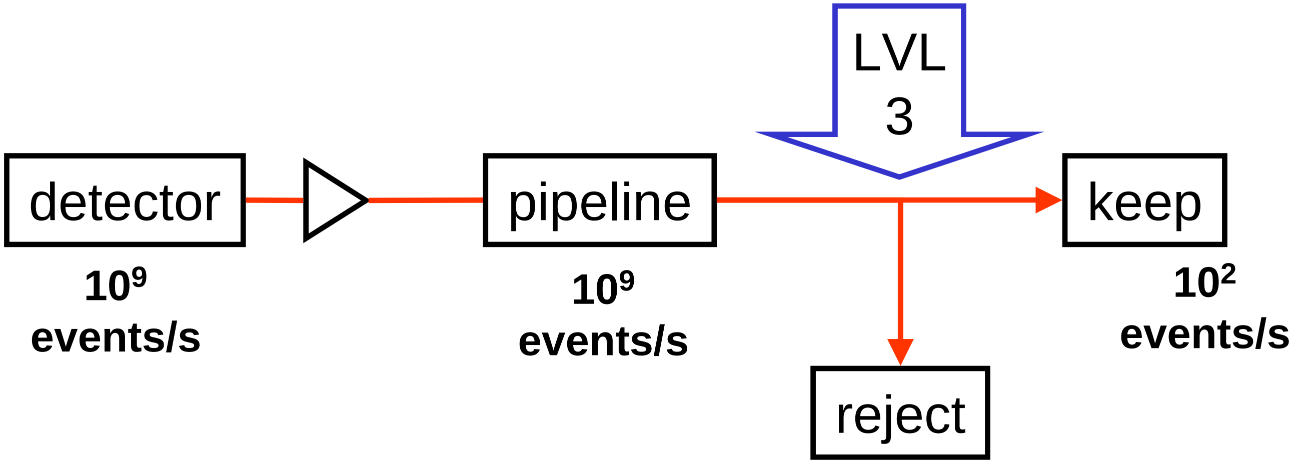
Event Triggering

- Much more difficult that at e^+e^- machines
- interaction rate ~ 10^9 events/s
- acquisition capacity ~ 100 events/s @ ~1MByte/event
- trigger rejection factor or ~ 10^7
- trigger decision time ~ 1 μs >> 25 ns
- need to store large amount of data in pipelines while the trigger performs calculations



Summary of Part I

The Large Hadron Collider will soon open a new window into Nature's innermost secrets

- first 14 TeV pp collisions expected summer 2007
- challenging environment: 25 ns bunch crossing and high luminosity
- also Pb-Pb collisions
- extensive physics programme
  - ATLAS, CMS, LHCb, ALICE
  - TOTEM