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Physics in pp collisions

LHC, machine, detectors, physics

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Content

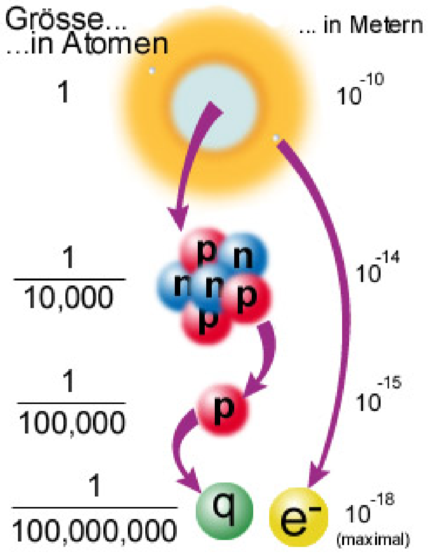
Today:

- Motivation/Introduction: open questions in particle physics
  - The Standard Model
  - New physics?
- Hadron Collider Physics
  - Overview of colliders
  - pp colliders vs e^+e^- colliders
  - LHC
    - Conditions of data taking
    - Main physics goals
- Detectors: ATLAS and CMS
  - Reminder: general design of collider detectors
  - Main features ATLAS
  - Main features CMS
  - Data acquisition and trigger systems

Tomorrow:

- Physics: Existing results and prospects at the LHC:
  - Test of the SM at Hadron Colliders (Top, W/Z, QCD)
  - Higgs
  - SUSY

Aims of particle physics



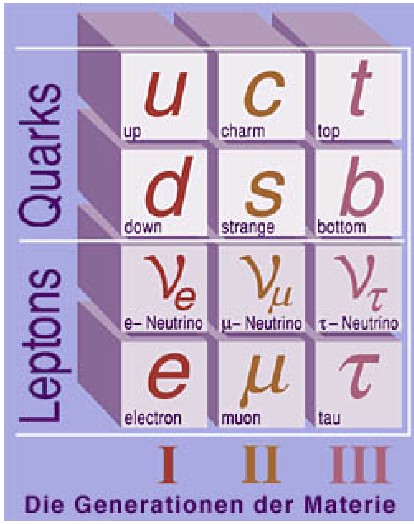
Answers to the most fundamental questions:

- What is the world made of ?
- Origin and fate of the universe
- What are the fundamental particles and their interactions?

small → large early → today/late

Answer of the Standard Model:

- The elementary particles of matter are quarks and leptons
- Interactions described by exchange of gauge bosons (γ,W/Z)



	I	II	III
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e– Neutrino	ν_μ μ– Neutrino	ν_τ τ – Neutrino
	e electron	μ muon	τ tau

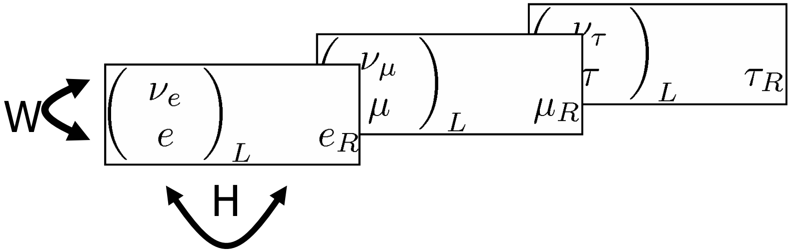
Die Generationen der Materie

One-page summary: the standard model

- The SM is a local gauge symmetry with the gauge group $U(1)_Y \times SU(2)_L \times SU(3)_C$

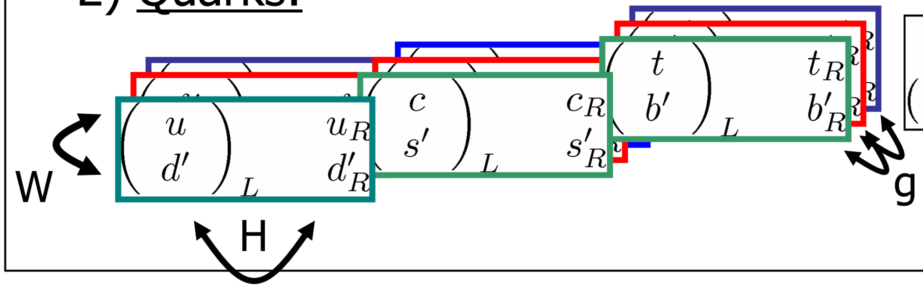
Spin ½: Matter-Particles

1) Leptons



$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \quad e_R \qquad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L \quad \mu_R \qquad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L \quad \tau_R$$

2) Quarks:



$$\begin{pmatrix}u\\ d'\end{pmatrix}_L \quad u_R \quad d'_R \qquad \begin{pmatrix}c\\ s'\end{pmatrix}_L \quad c_R \quad s'_R \qquad \begin{pmatrix}t\\ b'\end{pmatrix}_L \quad t_R \quad b'_R$$

Quantum numbers
(Q,SU(3), SU(2))
($\underline{3}$=Triplett)
($\underline{1}$=Singlett)

$$\begin{matrix}(0,\underline{1},+\frac{1}{2}) & \\ (-1,\underline{1},-\frac{1}{2}) & (-1,\underline{1},\underline{1})\end{matrix}$$

$$\begin{matrix}(\frac{2}{3},\underline{3},+\frac{1}{2}) & (\frac{2}{3},\underline{3},\underline{1}) \\ (-\frac{1}{3},\underline{3},-\frac{1}{2}) & (-\frac{1}{3},\underline{3},\underline{1})\end{matrix}$$

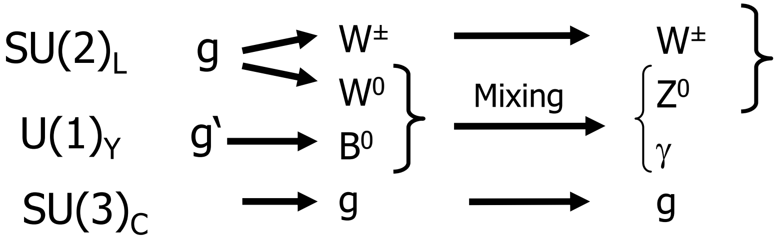
Spin 0 Higgs, resp. for mass

- SU(2) Doublett:

$$\Phi = \begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} \Rightarrow H = \mathrm{Higgs}$$

- Higgs-Pot. V(Φ)
- Spontaneous symmetry breaking:
- V(Φ=0) is not minimum
- Vacuum = minimum of V(Φ) breaks the SU(2)-symmetry

Spin 1 gauge symmetries of Lagragian predict Gauge Bosons and interactions:

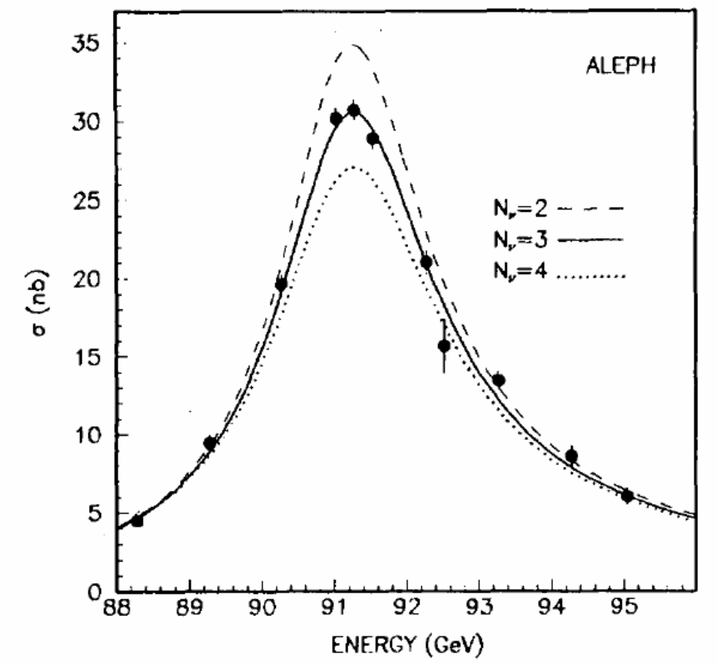


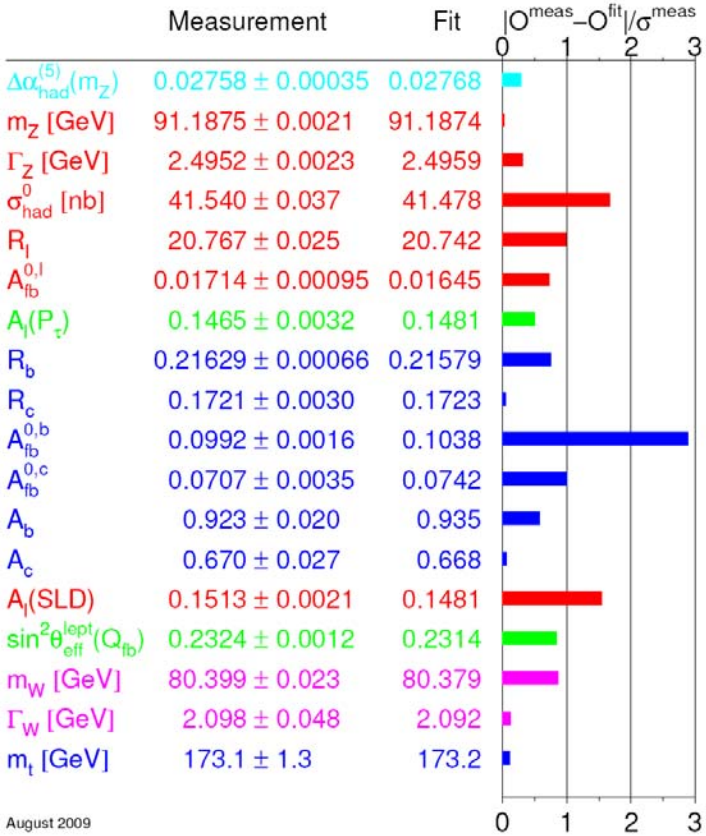
$SU(2)_L$ g → $W^\pm$ → $W^\pm$
$SU(2)_L$ g → W^0
$U(1)_Y$ g\` → B^0
W^0, B^0 → Mixing → Z^0, γ
$SU(3)_C$ → g → g

Weak Interaction:	$\alpha_w=g^2/4\pi=0.03$
Electromagnetic IA:	$\alpha=e^2/4\pi=1/137$
Strong IA:	$\alpha_s=0.12\ \ldots\sim 1$

Status of the Standard Model

- So far the Standard Model describes all measurements of scatering experiments with impressive precision (up to 10^{-5} in some cases)
  - High energy regime and low energy regime
- Most precise measurements: properties of the Z boson at the e^+e^- collider LEP





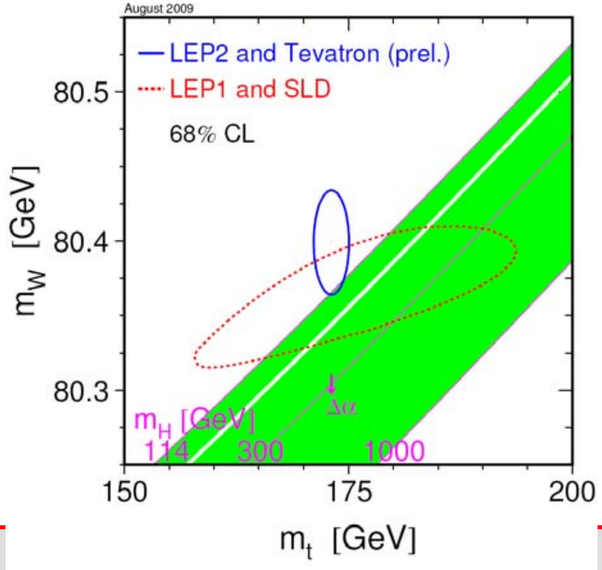
	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.098 ± 0.048	2.092	
m_t [GeV]	173.1 ± 1.3	173.2	

August 2009

- SM describes all these measurements
- Extremely successful !!!

Status of the Standard Model

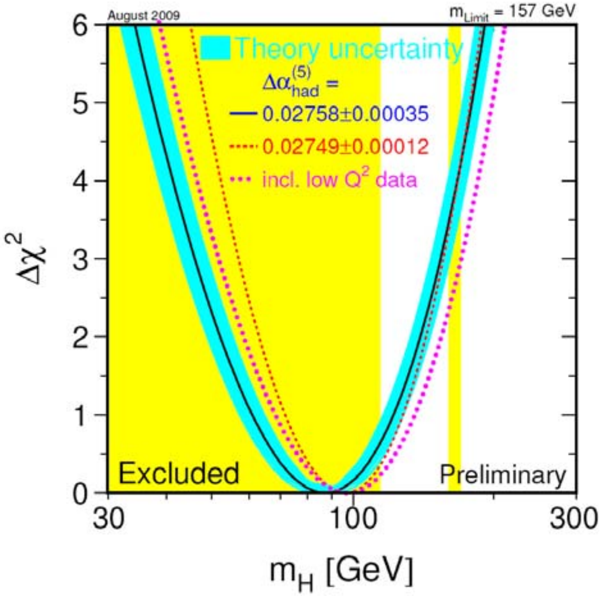
- Measurements are very precise
- Comparison with calculations including higher orders needed.
- Parameters not directly accessible can be determined since they enter the calculations
- Comparison of indirect predictions (from calculations) with direct measurements
  - Prediction of the top mass
  - Prediction of the W mass



Excellent agreement

$$\chi^2 = \sum_i \frac{\left(x_{i,\mathrm{exp}} - x_{i,\mathrm{theo}}(y)\right)^2}{\sigma_i^2}$$

- Same procedure today: Prediction of the SM Higgs Mass

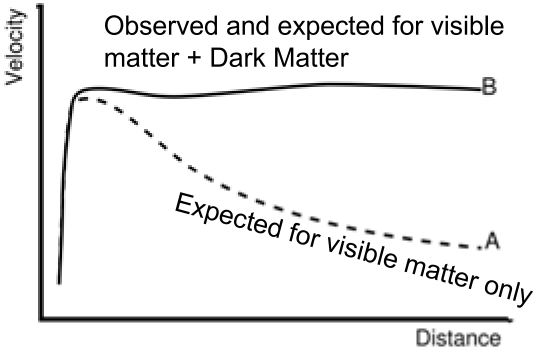


- So far Higgs not yet discovered.
- Full SM confirmation needs: discovery of Higgs and measurement of its mass!

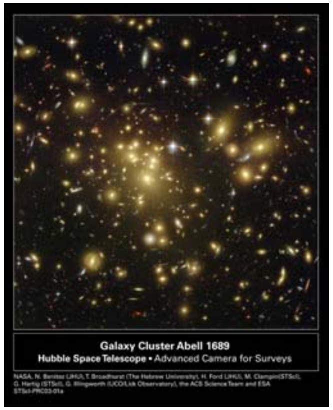
Why New Physics?

Experimental Hints for New Physics:

Velocities of galaxy rotation



Deflection of light of far objects on galaxy clusters (gravitational lenses)

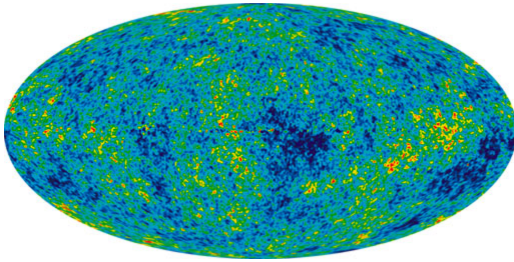


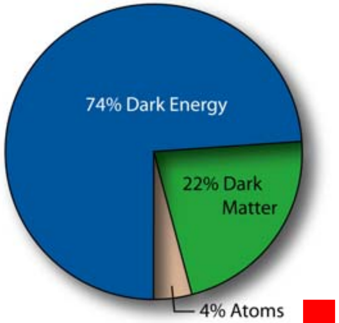
In both cases: visible (SM) matter is not enough for description of observations

Measurement of the fluctuations of the cosmic microwave background

→ Composition of the energy density of the universe

WMAP (2003):





With the SM only a fraction of the matter in the universe can be described

Established: A type of matter exists in the universe which is not described by the SM → ”Dark Matter”

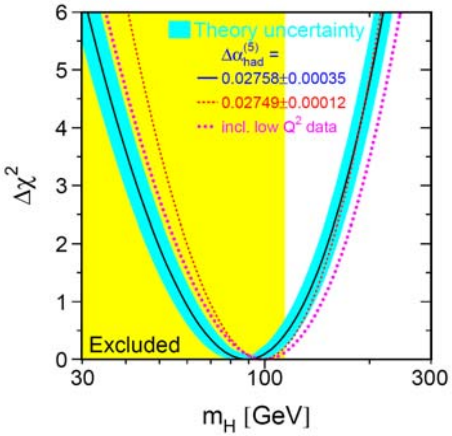
Why New Physics (cont.) ?

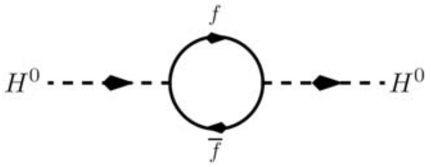
theoret. problem of the SM

- Gravitation is neglected in the SM.
- But: Gravitation gets strong at small scales ($r \sim 1.6 \cdot 10^{-35}$ m), i.e. large energies ($E_P = 1.2 \cdot 10^{19}$ GeV).
- No prediction power of the SM in this regime.

SM has internal problem with mass of the Higgs boson:

- Determination from experimental measurements:
  - indirectly: $m_H \sim 100$ GeV
- theoretical calculation:
  - Fermion loops result in quadratic divergent contribution to mass
  - Λ „cut-off" is the energy up to which the SM is applicable (e.g. E_P).
  - natural Higgs mass is rather $m_H \sim 10^{14}$-10^{17} GeV





$$M_H^2 = M_{H,bare}^2 + \delta M_H^2$$

$$\delta M_H^2 = \frac{|g_f|^2}{16\pi^2}[-2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f)]$$

„Hierarchy- Problem" of the SM

- wanted: theory which is able
  - to describe the experimental data
  - to solve the problems of the SM

  → extensions of the SM

Possible solution: Supersymmetrie (SUSY)

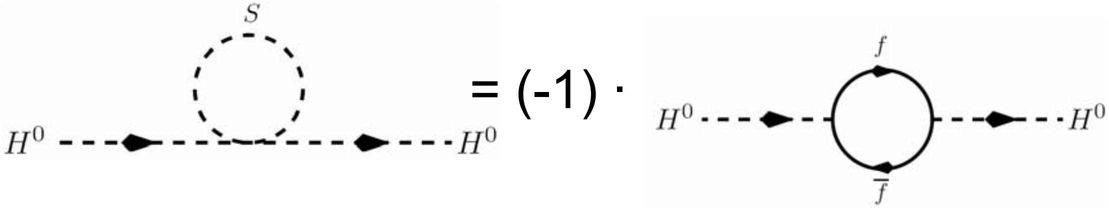
- Introduction of a new „SuperSymmetry“ Fermion ←→ Boson
- Introduction of SUSY Partners for all SM particles

SM Teilchen (R=1)	**SUSY Partner (R=-1)**
Quarks q	Squarks $\tilde{q}$
Leptons l	Sleptons $\tilde{l}$
$W^\pm$, Z^0,γ, Higgs: h, A^0, H^0, $H^\pm$	Neutralinos, $\chi^0_{1,2,3,4}$ Charginos $\chi^\pm_{1,2}$
Gluons g	Gluino $\tilde{g}$

→ New contributions to Higgs Mass

- contributions cancel if ΔM< 1 TeV

→ Solution to hierarchy problem



SUSY can provide explanation for Dark Matter:

If stable, the Lightest Susy Particle leads to the correct relic density in the universe

→ SUSY is first candidate theory for New Physics

… and note: M_{SUSY} < 1 TeV

Summary so far

- The Standard Model was/is extremely successful
  - Most precise verifications at e^+e^- collisions at LEP
  - Prediction of the top mass prior to its discovery
  - Prediction of the Mass of the Higgs → light Higgs, not yet discovered, last particle!
- We know that the SM is not the final theory
  - Gravity is not included → internal problem of hierarchy
  - Dark Matter not described in SM
  - Several theories proposed: most attractive: SUSY
  - Expect deviation from SM below 1 TeV
- most important open questions in particle physics:
  - Search for the SM Higgs
  - Search for new physics (e.g. SUSY)
- Possible reasons why both effects have not been seen yet:
  - Relevant masses maybe be higher than experimentally accessible so far?
  - Processes extremely rare?

➡ These are the reasons to build a collider with high centre-of-mass energy and high luminosity: the Large Hadron Collider

Luminosity

- The rate of produced events for a given physics process is given by

$$\boxed{N \quad = \quad L \quad \sigma}$$

L= Luminosity
σ= cross section

- Dimensions: $s^{-1} \quad = \quad cm^{-2}s^{-1} \quad cm^{2}$

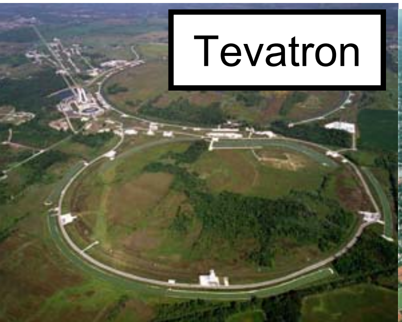
1 b= $10^{-28}m^{2}$

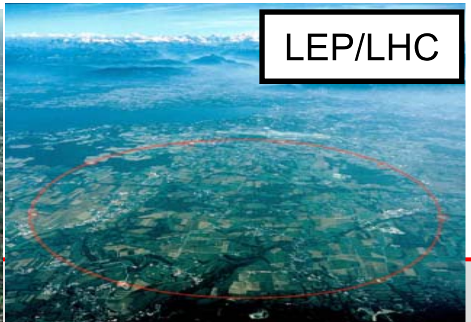
- Luminosity depends on machine parameters:
  - Number of particles per bunch, beam width at IA region, repetition frequency, etc.
- In order to achieve acceptable production rates for interesting physics processes, the luminosity must be high
  - $L = 2 \cdot 10^{32} cm^{-2}s^{-1}$ TeVatron
  - $L= 10^{33}\ cm^{-2}s^{-1}$ planned for the initial phase of the LHC (1-2 years)
  - $L= 10^{34}\ cm^{-2}s^{-1}$ LHC design luminosity, very large!

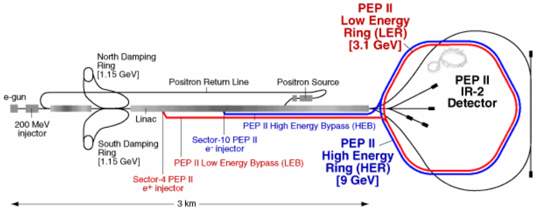
- One experimental year has ~10^{7}s → integrated luminosity at the LHC
  - 1 fb^{-1} per year in the initial phase (after a slow start-up)
  - 100 fb^{-1} per year at design luminosity

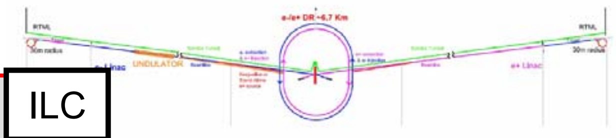
Overview: current colliders

	beams, energies (GeV)	$\sqrt{s}$ (GeV)	Data taking	L ($10^{30}\,s^{-1}cm^{-2}$)	L_{int} (pb^{-1})	site
LEP	e^+e^-: 45(104)x45(104)	90-208	1992-2000	100	LEPI: ~160 (je Exp.)	CERN
HERA	$e^\pm p$: 30 x 920	320	1991-2007	50	~ 600	DESY
TeVatron	$p\bar{p}$: 980 x 980	1 960	92-96, 01-11(?)	200	160, ~ 8 000	FNAL
PEPII	e^+e^-: 9.0x3.1	10.6	1999-2008	12.000	450 000	SLAC
KEKB	e^+e^-: 8.0x3.5	10.6	1999-2009(?)	17 000	700 000	KEK
LHC (!)	pp: 7000 x 7000	14 000	2009 - ?	10 000	?	CERN
ILC	e^+e^-: 500 x 500	1 000	2015(?)-	20 000		??

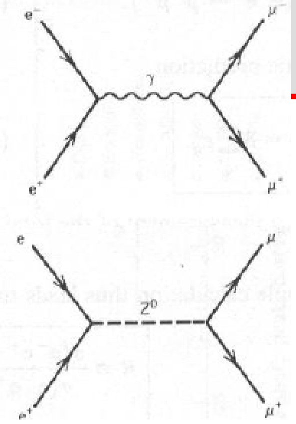


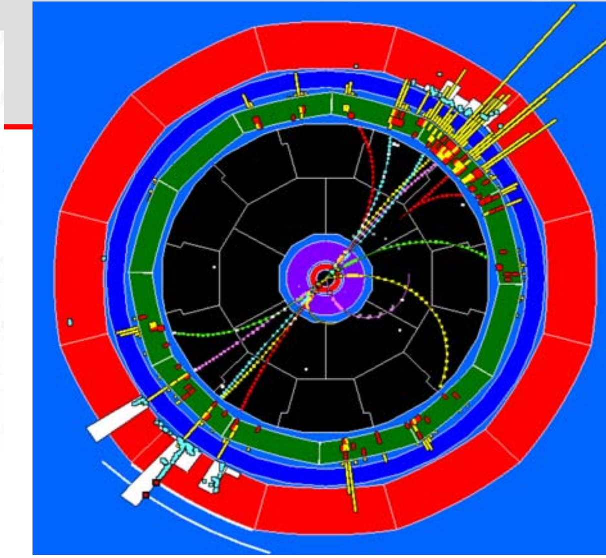






e^+e^- vs. pp colliders





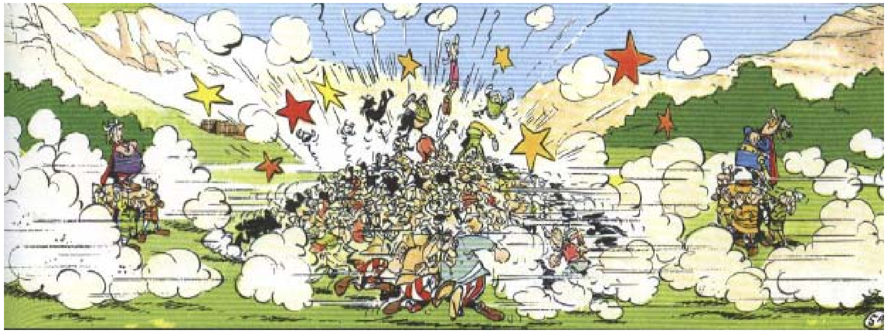
e^+e^- collider:

- ➢ Collisions of fundamental particles → clean events since no further partons involved
- ➢ If both beam have the same energy, centre-of-mass system identical to lab system.
- ➢ Complete annihilation: kinematics fixed, since initial state exactly known.
- ➢ $\Sigma P_x=0$, $\Sigma P_y=0$, $\Sigma P_z=0$, $\Sigma E=2E_{beam}$ known and conserved, can be used in the reconstruction of the events in the final state → missing energy

→ Excellent machines for precision measurements

pp collider:

- ➢ Beam particles are made of partons (gluons and quarks)
- ➢ pp collisions are much more complex



Why pp colliders?

e^+e^- colliders vs. pp colliders

<u>Main drawback of e^+e^- colliders:</u>

- Energy loss due to synchrotron radiation
- Calculable in classical electrodynamics: accelerated charges radiate
- Lost power in ring with radius R and beam energy E:

$$P = \frac{2e^2 c}{3R^2}\left(\frac{E}{mc^2}\right)^4$$

- Energy loss per turn:

$$-\Delta E \approx \frac{2\pi R}{c} P = \frac{4\pi e^2}{3R}\left(\frac{E}{mc^2}\right)^4$$

- Ratio of energy loss between protons and electrons:

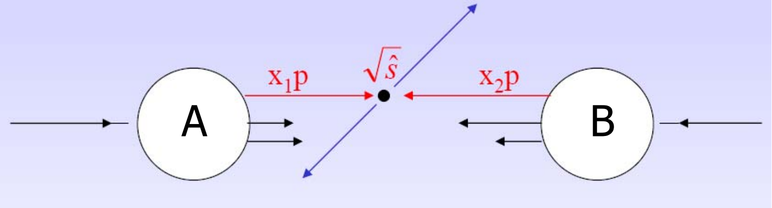
$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

future colliders:

- pp Ring-accelerator (LHC)
- e^+e^- Linear Collider (ILC)
- Muon Collider ??

Kinematics in pp collisions

- Proton beam can be seen as a beam of quarks and gluons with a wide range of energies
- The proton constituents (partons) carry only a fraction 0< x< 1 of the proton momentum



$$p_1 = x_1\, p_A \qquad \sqrt{\hat{s}} = \sqrt{x_1\, x_2\, s} = x\,\sqrt{s}$$

$$p_2 = x_2\, p_B \qquad \text{simplification} \quad (\text{if } x_1 = x_2 = x)$$

- Moving centre-of-mass system ($x_1 \neq x_2$)
- P_z is not known, since x values of individual event unknown.
- Important variable: transverse momentum: P_T
- Reduced centre-of-mass energy

Example:

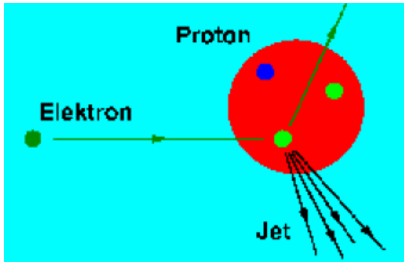
- LHC: √s=14 TeV, TeVatron: √s=1.9 TeV
- To produce a particle with a certain mass m: x√s>m

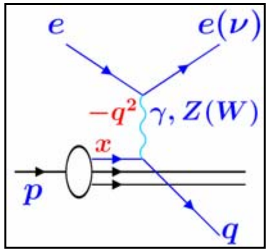
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--

- At the LHC: for SM processes (~100 GeV) partons with small x needed
- because of proton structure (see next slide): LHC =„gluon collider"

Structure of the proton

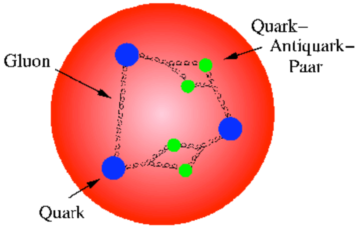
- ➢ From where do we know the x values?
- ➢ The structure of the proton is investigated in Deep Inelastic Scattering

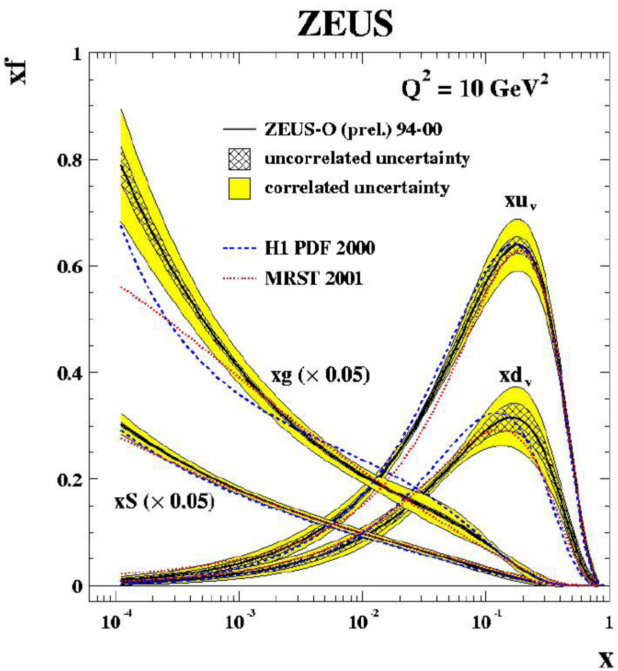




- ➢ Highest energies are reached at the ep collider HERA: Scattering of 30 GeV electrons on 900 GeV Protons: Test of the proton structure down to 10^{-18}m

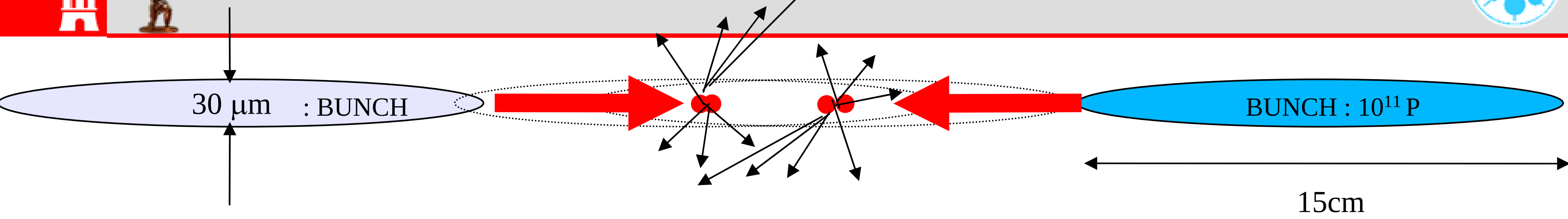
- ➢ Structure of the proton: Parton density functions (PDFs)





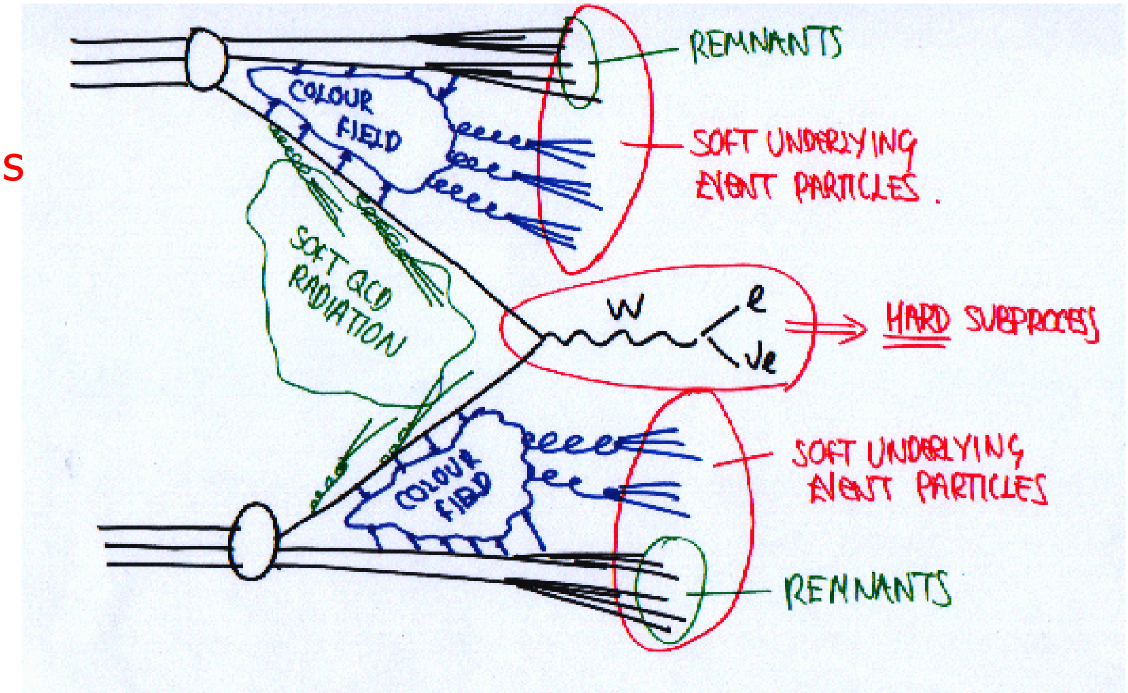
- ➢ u- and d-quarks at high values of x
- ➢ Gluons dominate at low values !!
- ➢ Knowledge of PDFs very important for LHS predictions

Characteristics of hadron collisions



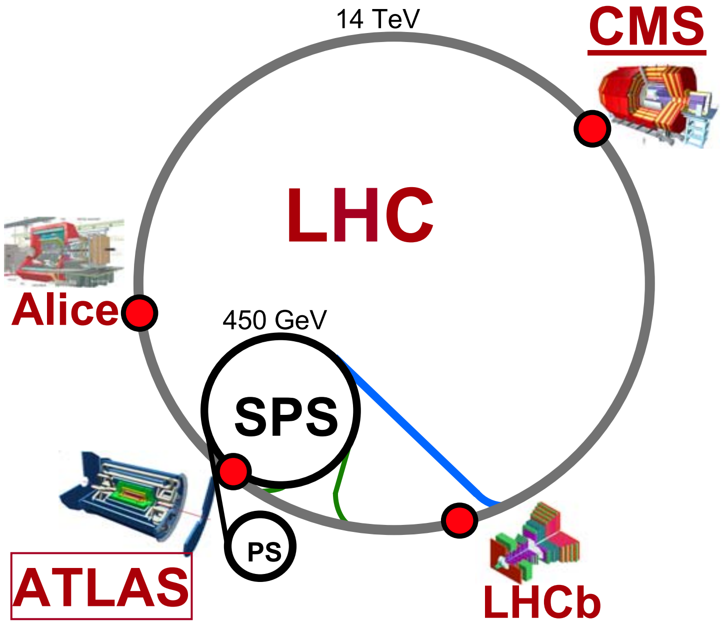
- Partons in the proton are strongly interacting particles
  - → high cross sections
  - → high rates
- Even possible: several interactions in one bunch crossing
- Rate: ~$1/Q^4$
  - Q: transferred 4-momentum
  - Most of the events are "soft"
  - Only a small fraction contains interesting events with high energies

- In addition the interpretation of a typical hard event is difficult due to QCD:



- In general: events from pp collisions are difficult to analyze

Discovery machine: LHC



Machine parameters	LHC
Luminosity [cm^{-2}s^{-1}]	**10^{34}**
√s [TeV]	**14**
BC interval [ns]	**25**
BC rate [MHz]	**40**
Bunches per beam	**2835 (3564)**

- Proton-Proton-Collider
- 4 experiments: Atlas, CMS , (LHCb, Alice)
- √s=14 TeV !!   (x7 Tevatron)
- L: 100 times TeVatron

Discovery machine LHC

superconducting dipole magnets

- challenge: magnetic field of 8.33 Tesla
- in total 1232 magnets, each 15 m long
- operation temperature of 1.9 K

LHC is the largest cryogenic system in the world

Beam energy	7 TeV
Luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam

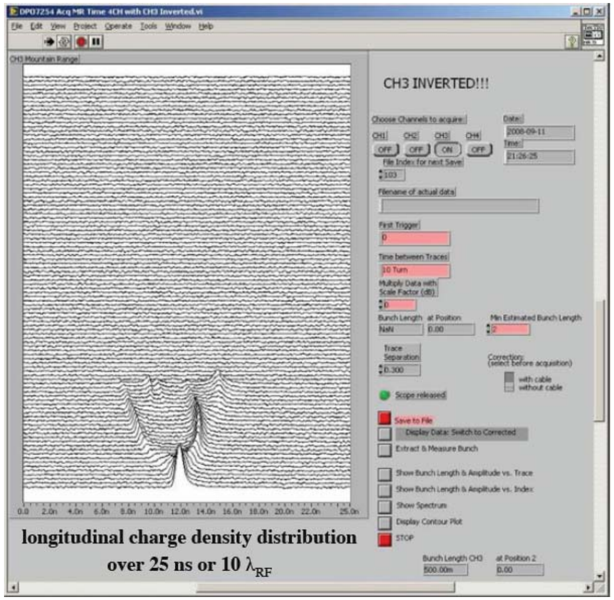
▪ **Energy stored in the magnet system:**	**10 GJoule**	Airbus A380, 560 t
▪ **Energy stored in one (of 8) dipole circuits:**	**1.1 GJ (sector)**	at 700 km/h
▪ **Energy stored in one beam:**	**362 MJ**	20 t plane
▪ **Energy to heat and melt one kg of copper:**	**0.7 MJ**	

September 2008

- In September 2008 the first beams circulated in the machine
- Huge media presence at CERN

- Very nice start-up of the accelerator
- E.g RF-capture of the bunches:

First attempts:

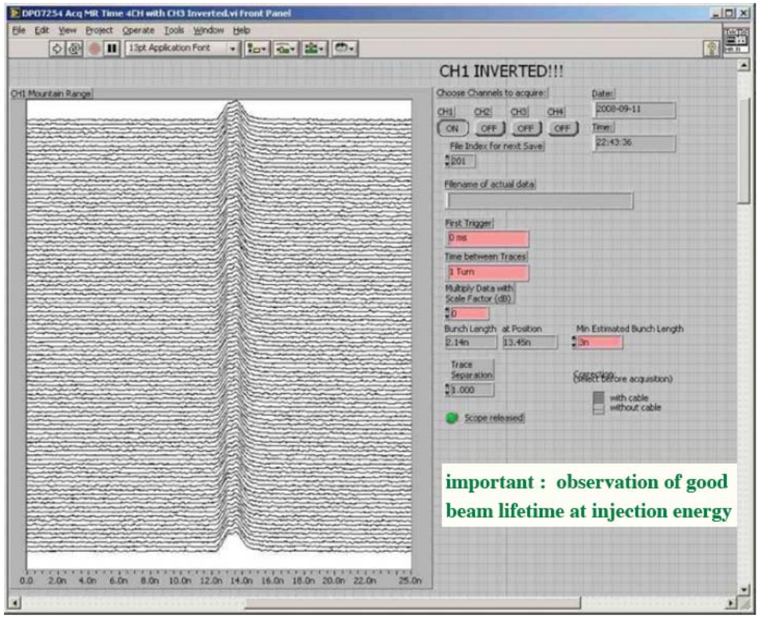


CH3 INVERTED!!!

Choose Channels to acquire:
CH1 OFF CH2 OFF CH3 ON CH4 OFF
Date: 2008-09-11
Time: 21:26:25
File Index for next Save: 103
Filename of actual data:
First Trigger: 0
Time between Traces: 10 Turn
Multiply Data with Scale Factor (dB): 0
Bunch Length: NaN at Position: 0.00
Min Estimated Bunch Length: 2
Trace Separation: 0.300
Correction: (select before acquisition)
with cable
without cable
● Scope released
Save to File
☐ Display Data: Switch to Corrected
☐ Extract & Measure Bunch
☐ Show Bunch Length & Amplitude vs. Trace
☐ Show Bunch Length & Amplitude vs. Index
☐ Show Spectrum
☐ Display Contour Plot
STOP
Bunch Length CH3: 500.00m at Position 2: 0.00

longitudinal charge density distribution over 25 ns or 10 λ_{RF}

Later:

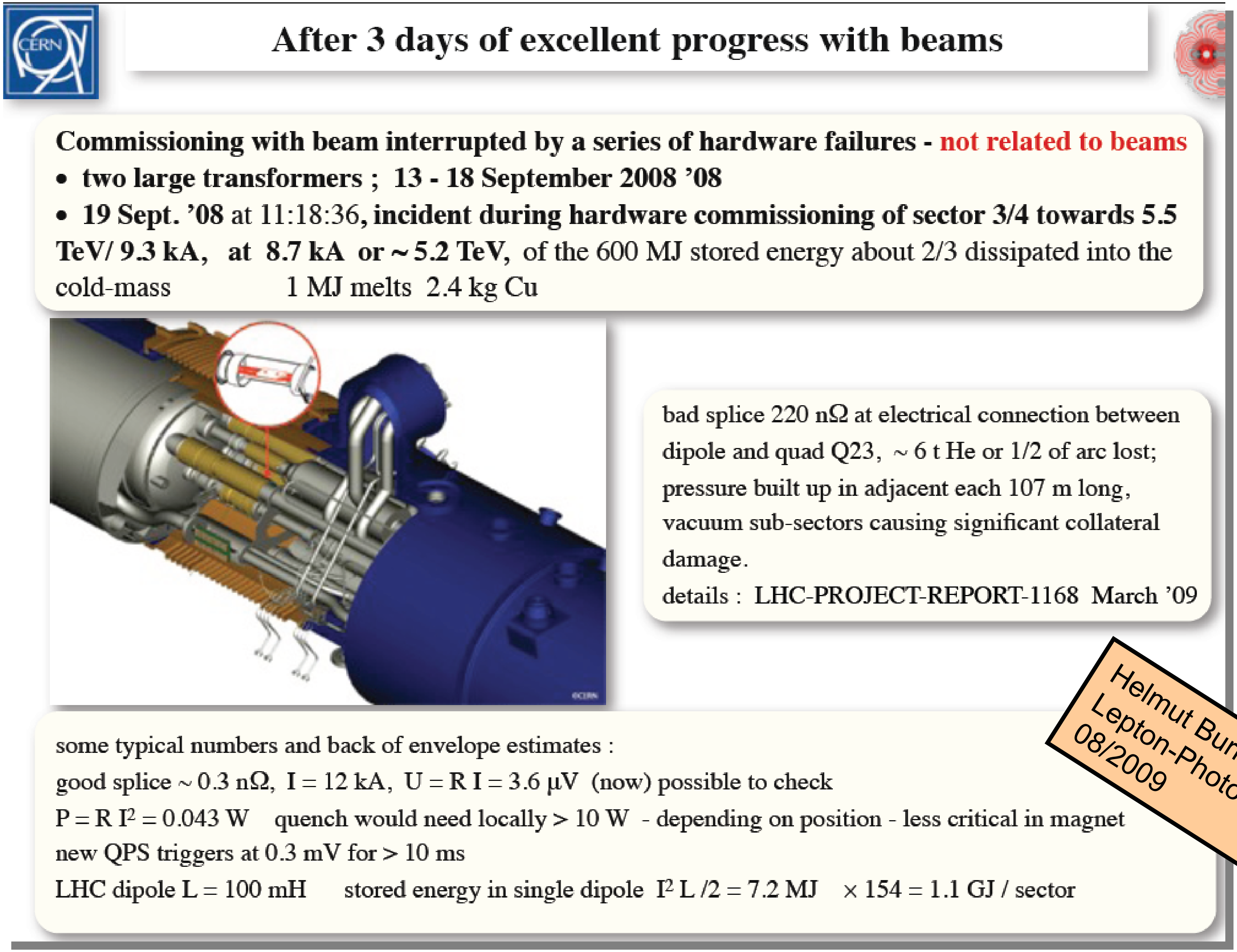


CH1 INVERTED!!!

Choose Channels to acquire:
CH1 ON CH2 OFF CH3 OFF CH4 OFF
Date: 2008-09-11
Time: 22:43:36
File Index for next Save: 201
Filename of actual data:
First Trigger: 0 ms
Time between Traces: 1 Turn
Multiply Data with Scale Factor (dB): 0
Bunch Length: 2.14n at Position: 13.45n
Min Estimated Bunch Length: 3n
Trace Separation: 1.000
Correction: (select before acquisition)
with cable
without cable
● Scope released

important : observation of good beam lifetime at injection energy

September 2008



After 3 days of excellent progress with beams

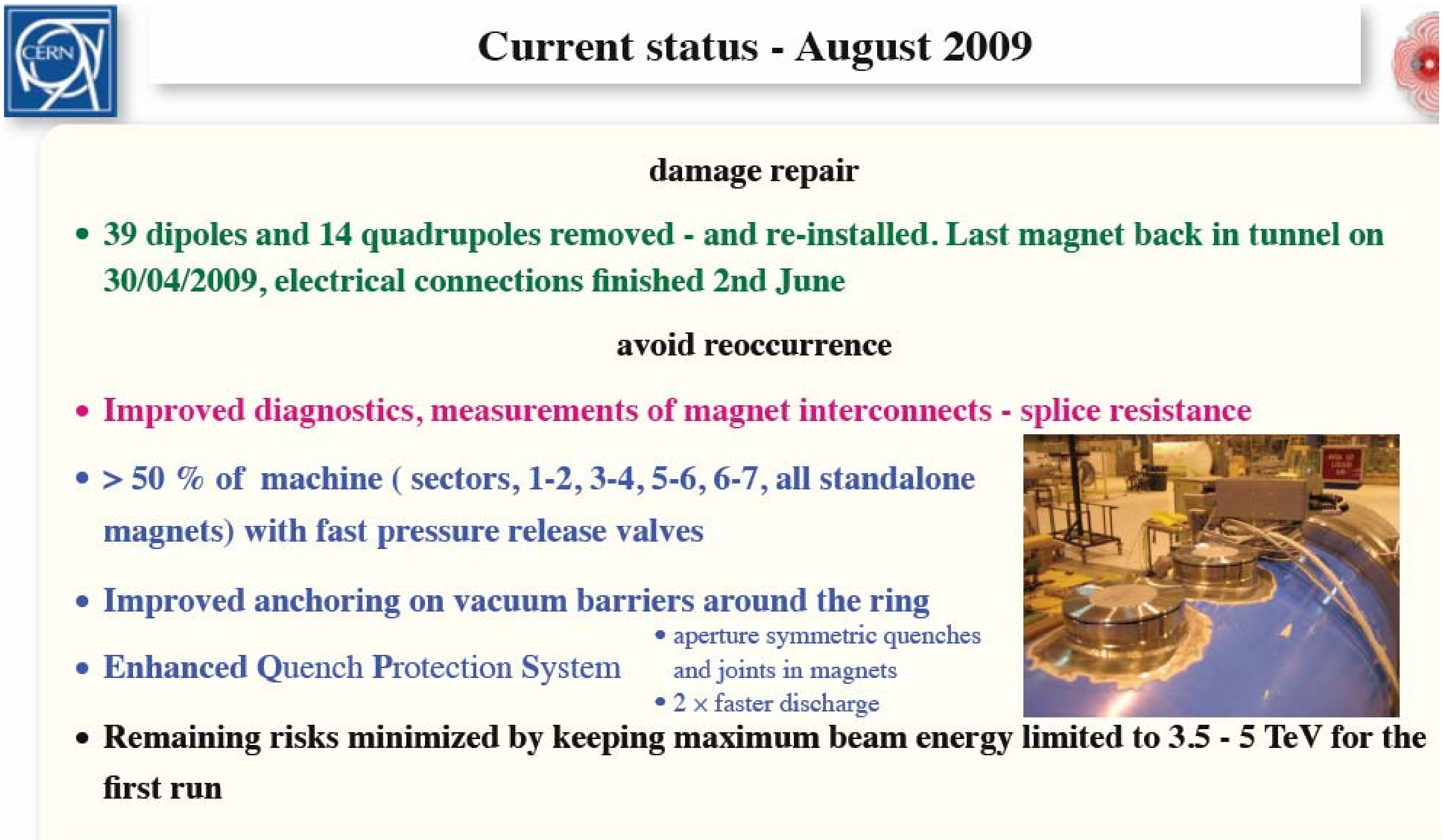
Commissioning with beam interrupted by a series of hardware failures - **not related to beams**
- **two large transformers ; 13 - 18 September 2008 '08**
- **19 Sept. '08** at 11:18:36, **incident during hardware commissioning of sector 3/4 towards 5.5 TeV/ 9.3 kA, at 8.7 kA or ~ 5.2 TeV,** of the 600 MJ stored energy about 2/3 dissipated into the cold-mass 1 MJ melts 2.4 kg Cu

bad splice 220 $n\Omega$ at electrical connection between dipole and quad Q23, ~ 6 t He or 1/2 of arc lost; pressure built up in adjacent each 107 m long, vacuum sub-sectors causing significant collateral damage.
details : LHC-PROJECT-REPORT-1168 March '09

some typical numbers and back of envelope estimates :
good splice ~ 0.3 $n\Omega$, $I = 12$ kA, $U = R\,I = 3.6\ \mu V$ (now) possible to check
$P = R\,I^2 = 0.043$ W quench would need locally > 10 W - depending on position - less critical in magnet
new QPS triggers at 0.3 mV for > 10 ms
LHC dipole $L = 100$ mH stored energy in single dipole $I^2 L/2 = 7.2$ MJ × 154 = 1.1 GJ / sector

Helmut Burkhard (CERN) at
Lepton-Photon conference
08/2009

Current status, strategy for restart



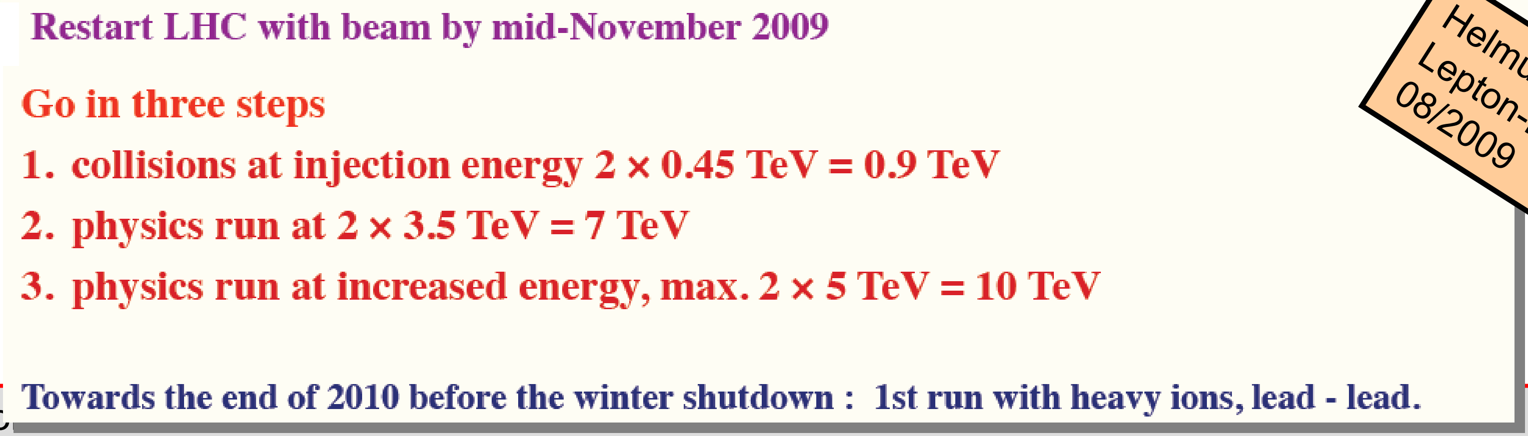
Current status - August 2009

damage repair

- 39 dipoles and 14 quadrupoles removed - and re-installed. Last magnet back in tunnel on 30/04/2009, electrical connections finished 2nd June

avoid reoccurrence

- Improved diagnostics, measurements of magnet interconnects - splice resistance
- > 50 % of machine (sectors, 1-2, 3-4, 5-6, 6-7, all standalone magnets) with fast pressure release valves
- Improved anchoring on vacuum barriers around the ring
- Enhanced Quench Protection System
  - aperture symmetric quenches and joints in magnets
  - 2 × faster discharge
- Remaining risks minimized by keeping maximum beam energy limited to 3.5 - 5 TeV for the first run



Restart LHC with beam by mid-November 2009

Go in three steps

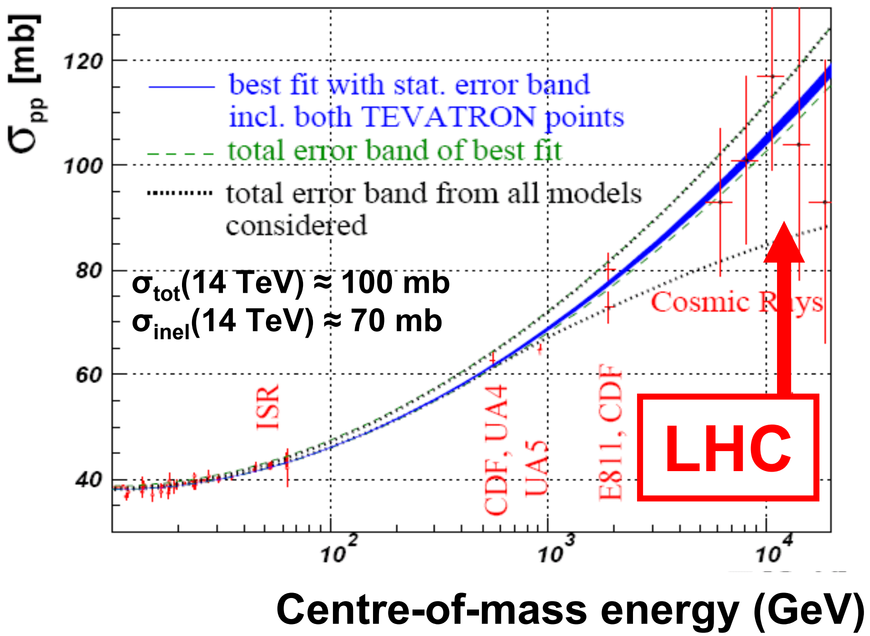
1. collisions at injection energy 2 × 0.45 TeV = 0.9 TeV
2. physics run at 2 × 3.5 TeV = 7 TeV
3. physics run at increased energy, max. 2 × 5 TeV = 10 TeV

Towards the end of 2010 before the winter shutdown : 1st run with heavy ions, lead - lead.

Helmut Burkhard (CERN) at Lepton-Photon conference 08/2009

Discovery machine: LHC

Total pp- cross section:

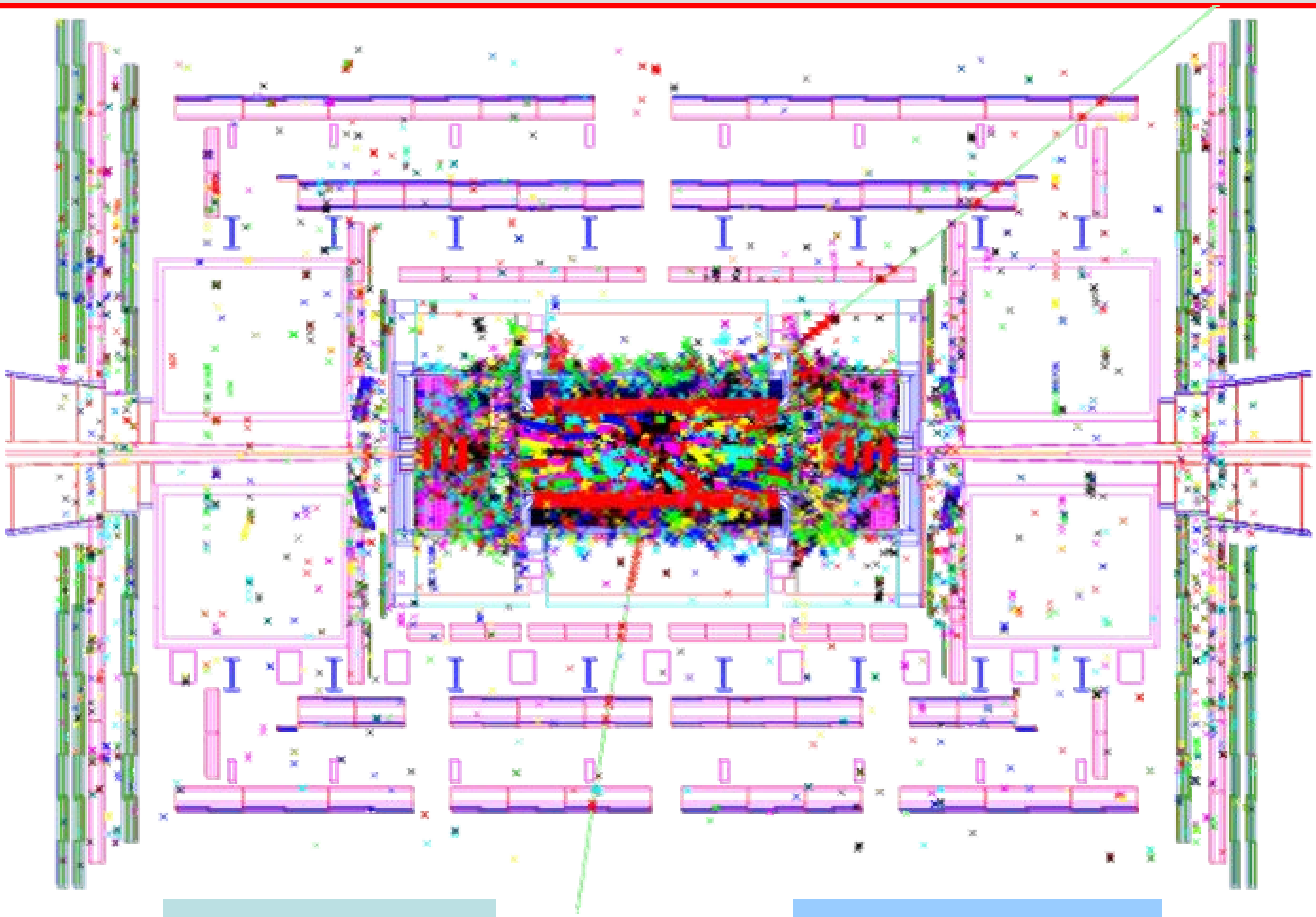


σ_{tot}(14 TeV) ≈ 100 mb
σ_{inel}(14 TeV) ≈ 70 mb

- High centre-of-mass energy
- High cross section
- High design luminosity

- ~23 Interactions / Bunch crossing
- ~1700 Particles / Bunch crossing

Data taking at LHC design luminosity



H → ZZ → 2e+2μ

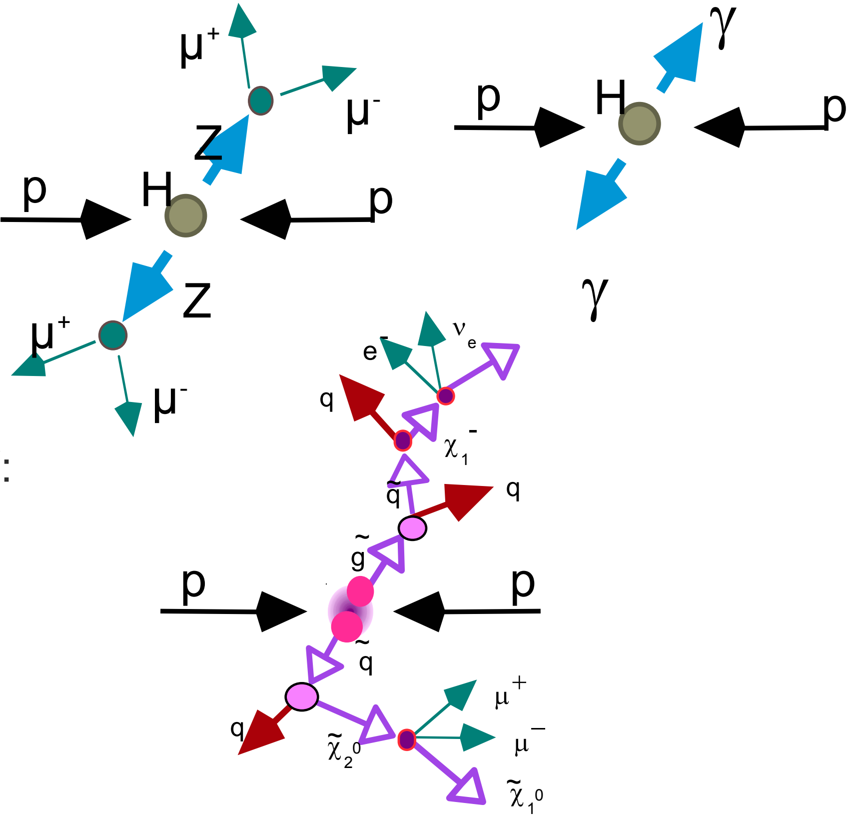
23 soft pp-events

!! with 40 MHz !!

- Detectors and event selection systems at the LHC are designed to cope with these conditions

LHC detector design

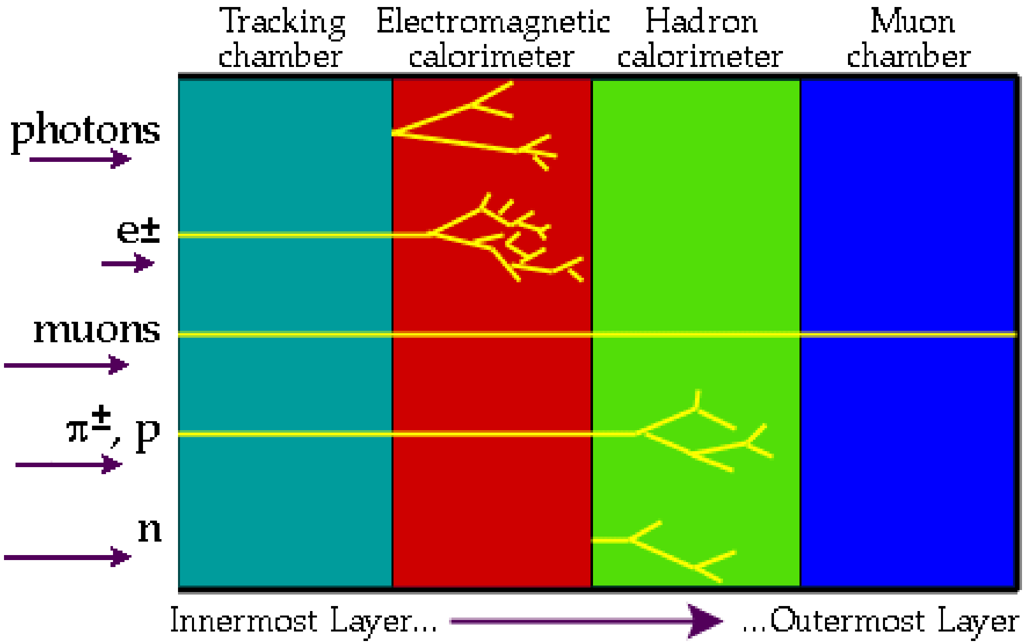
- The physics aims of the experiments have driven their design
- Quickly here: golden channels at the LHC
  - Search for the Higgs Boson:
  - Search for New Physics/ SUSY:



Important experimental signatures:
muons, photons, electrons, jets, missing E_T

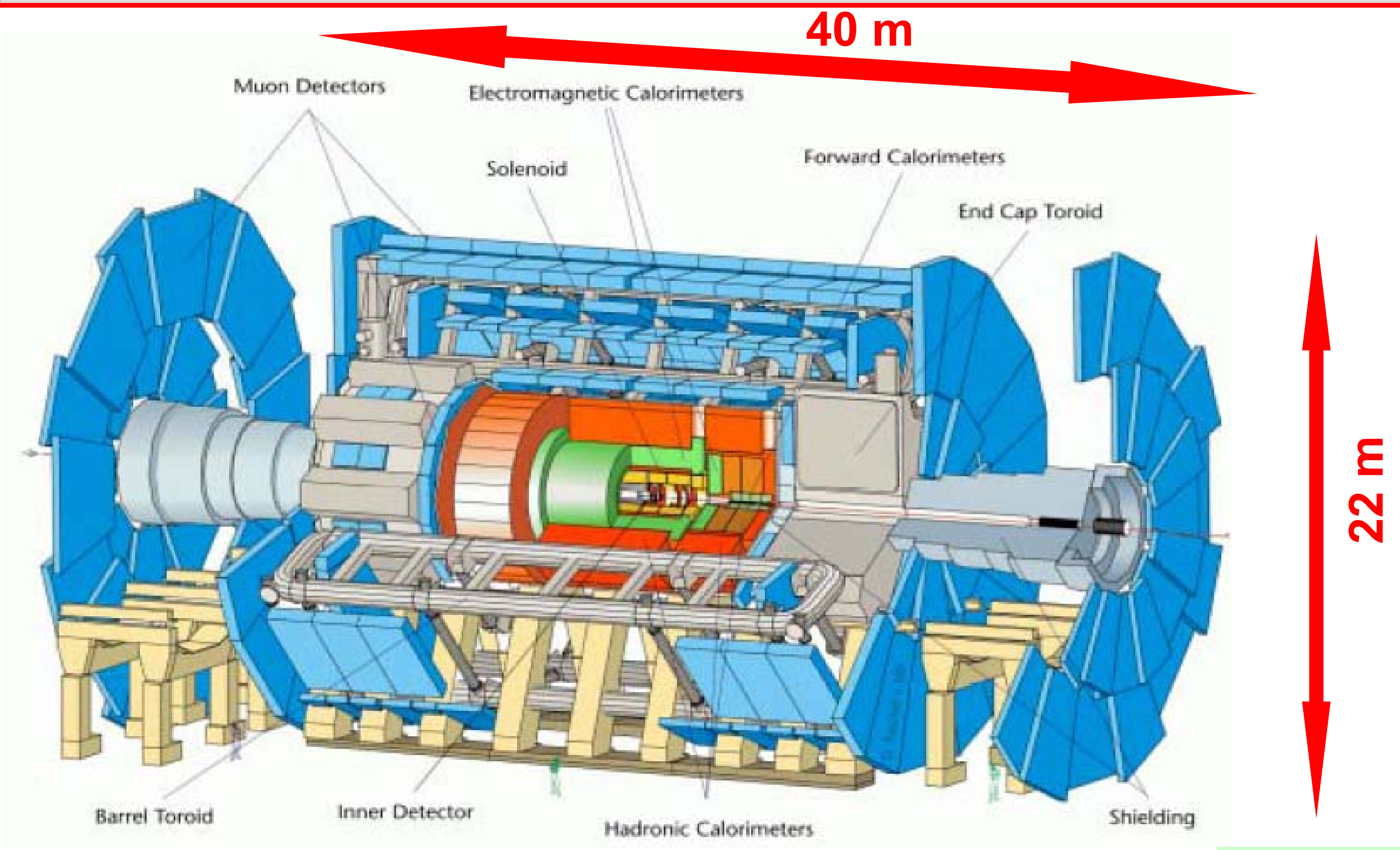
LHC detector design

- Remember the principles of collider detectors:
  - Subdetectors arranged in several layers around the interaction point



High particle density	→	Small particle density
High granularity	→	Small granularity
High precision	→	Low precision
Small thickness	→	Massive material

LHC detectors: ATLAS



characteristic features:

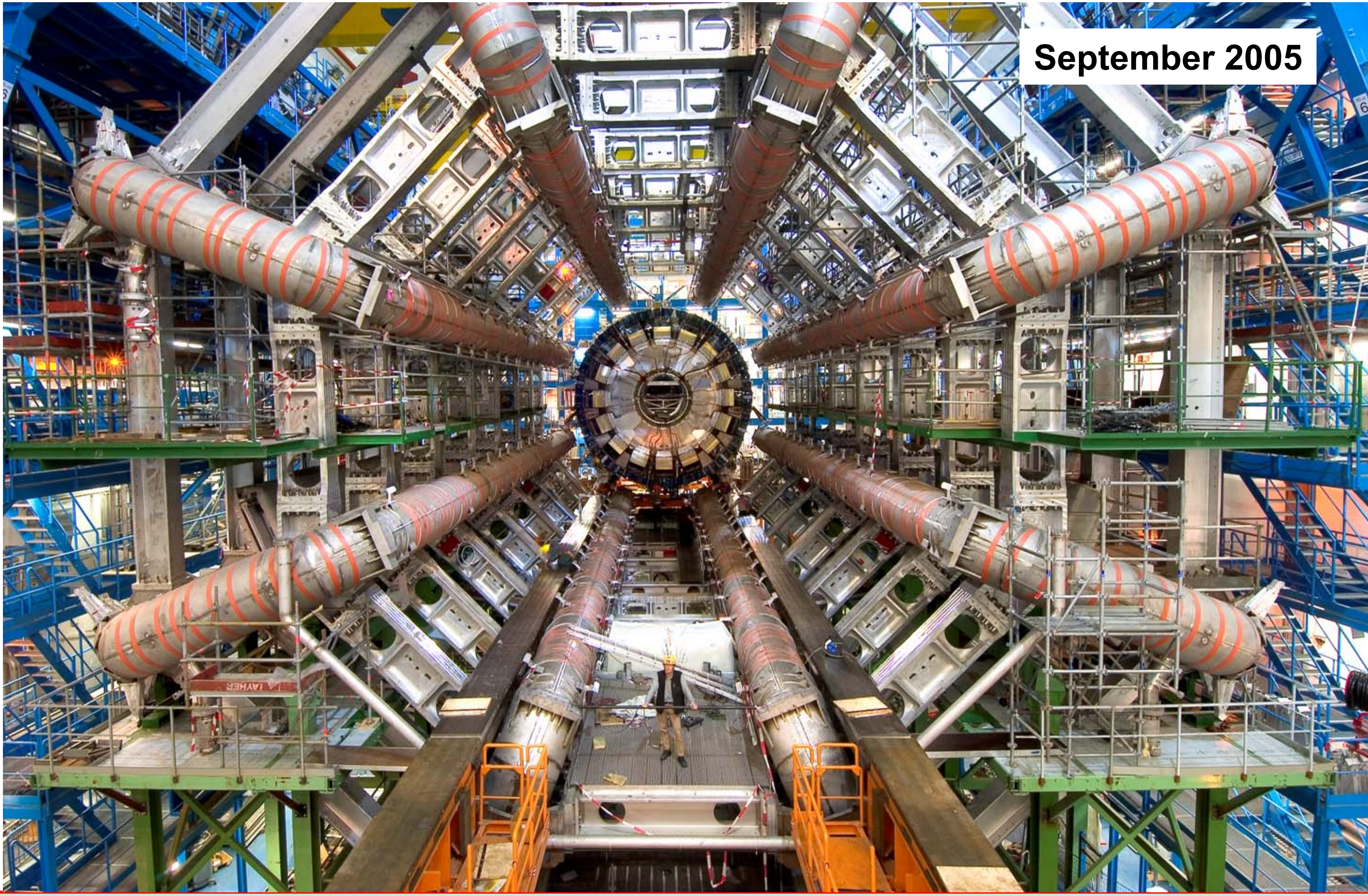
- Muon spectrometer with three toroidal magnets ($H \rightarrow 4\mu$)
- highly segmented LAr em calorimeter ($H \rightarrow 4l$, $H \rightarrow \gamma\gamma$)
- Tile calorimeter for hadronic activity

largest collider detector ever built

ATLAS toroid

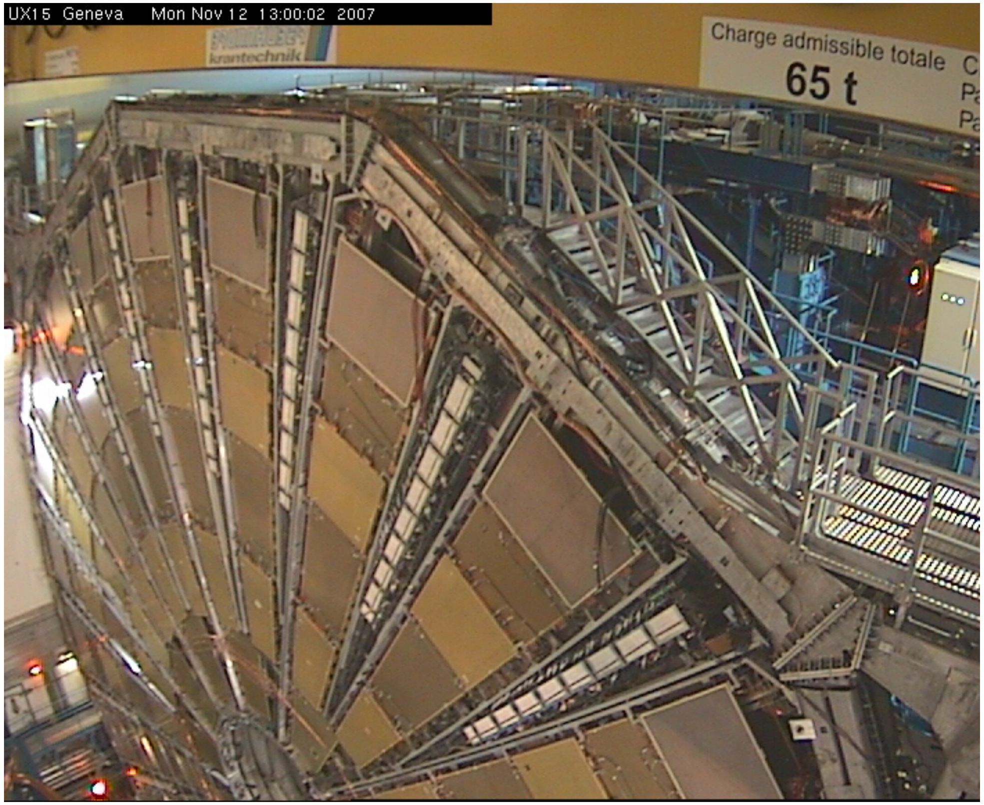
Feb 2003

ATLAS toroid

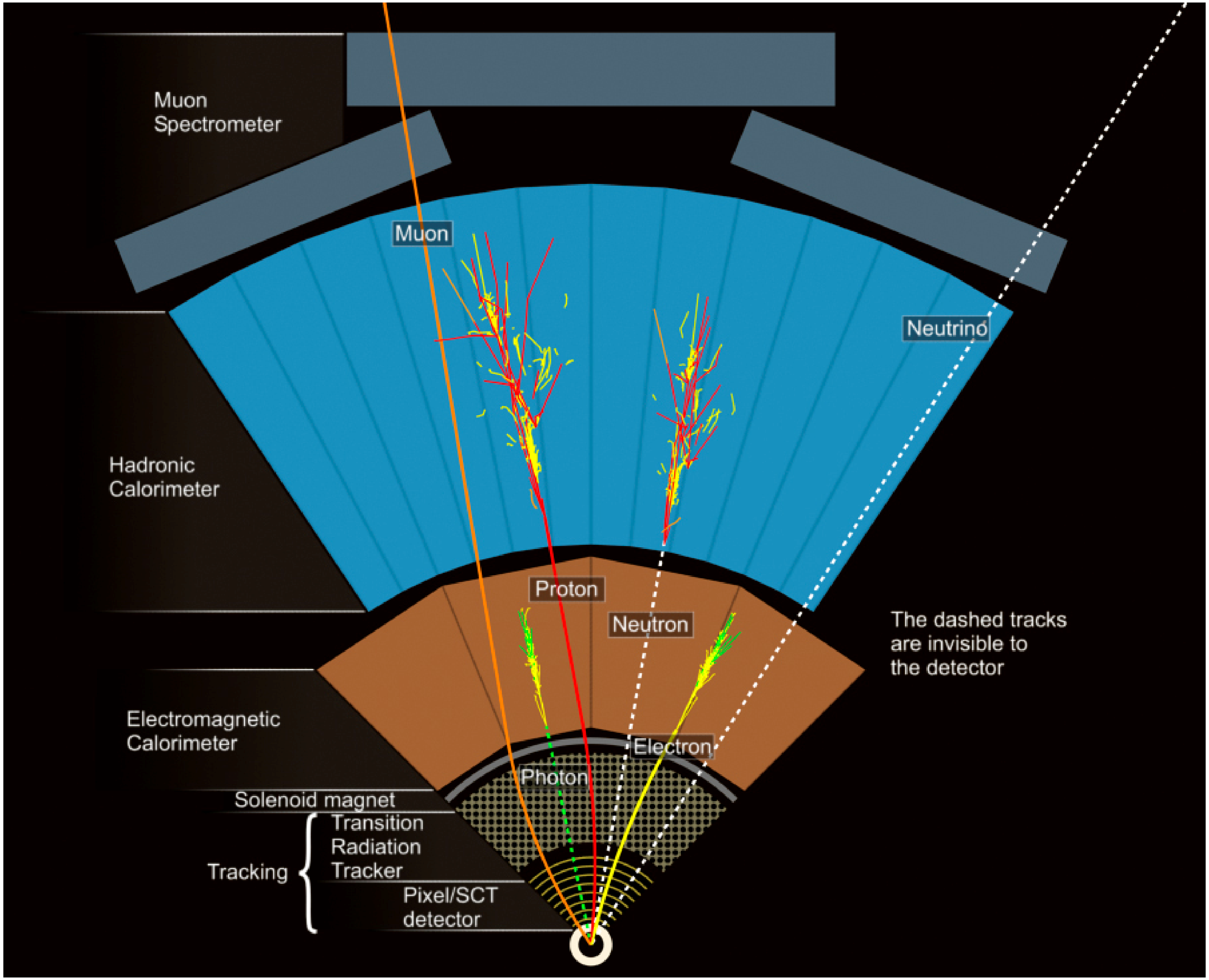


September 2005

ATLAS toroid and muon system

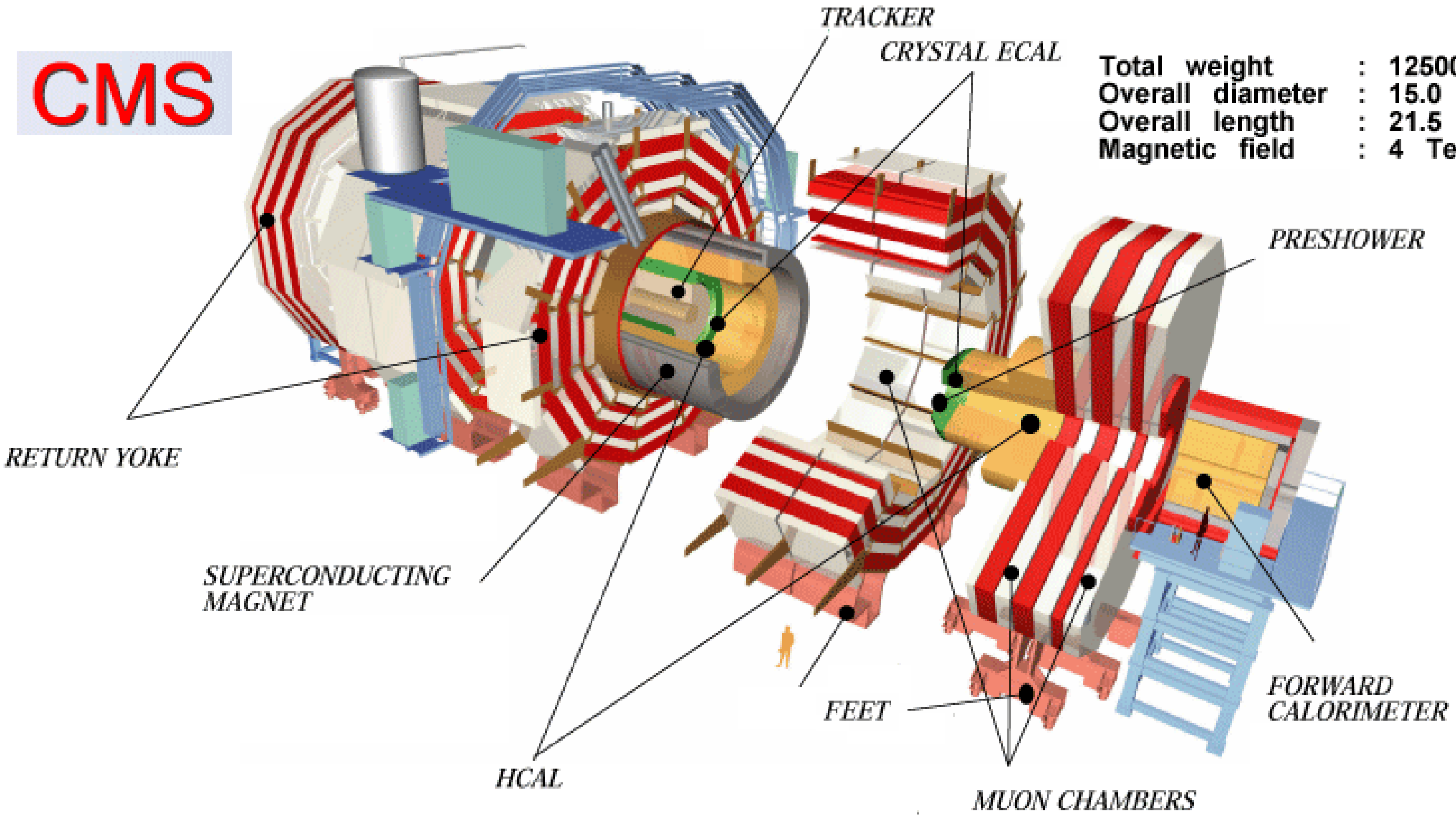


Detectors: ATLAS



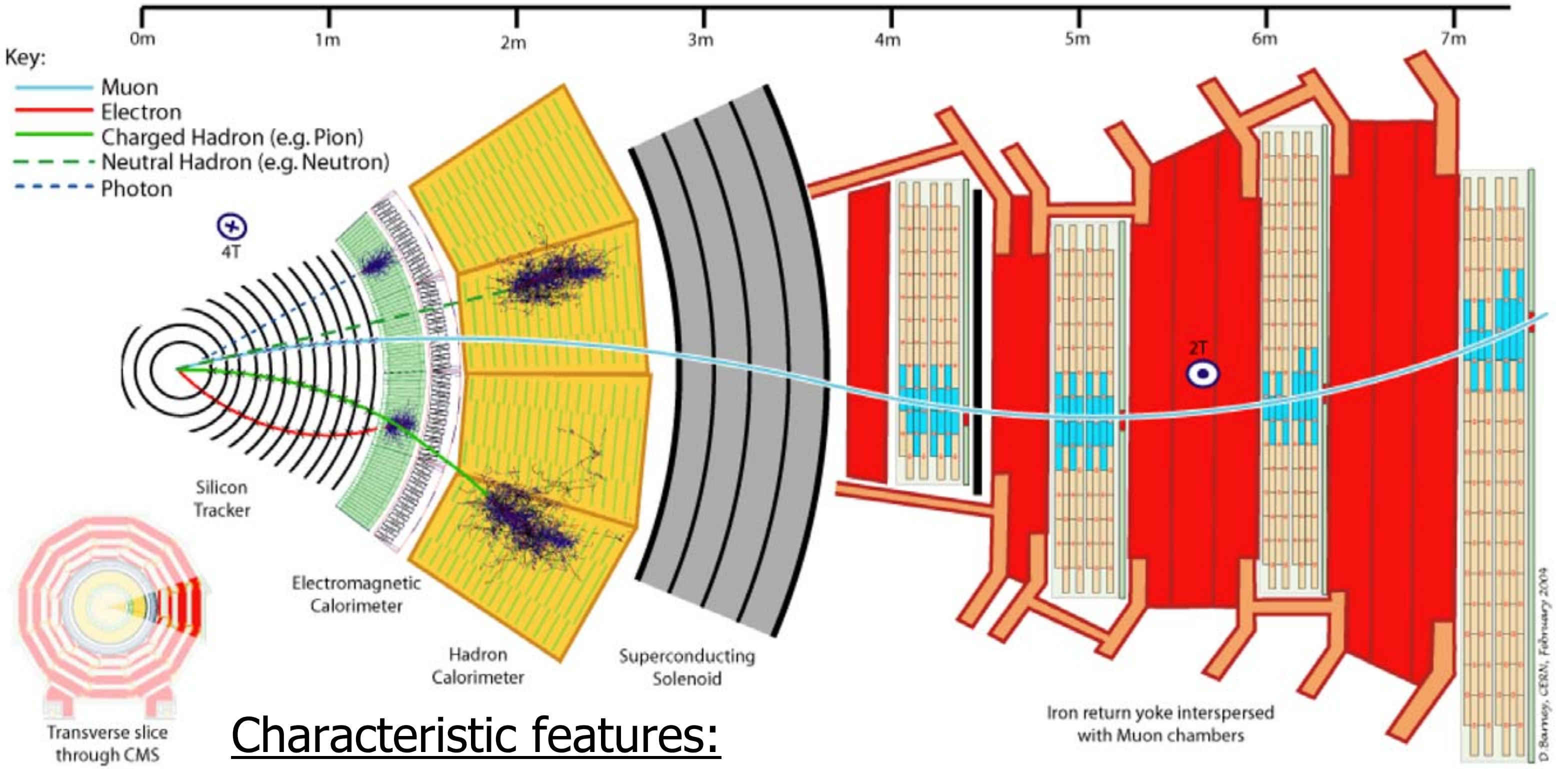
The dashed tracks are invisible to the detector

Detectors: CMS



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

Detectors: CMS

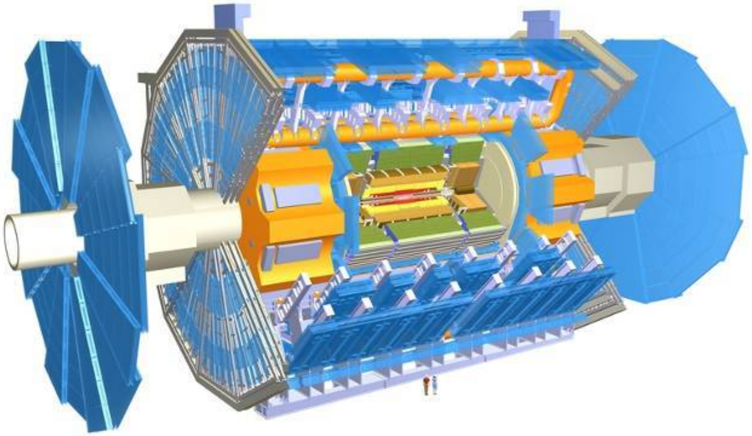


Characteristic features:

- Full inner detector is Si-based.
  - advantage: a single homogeneous system, precise position measurements
  - disadvantage: a lot of material in front of the calorimeters (particles can shower before) , expensive
- No longitudinal segmentation in electromagnetic calorimeter
- Coil for B field <u>after</u> calorimeter („large coil solution“)
  - Advantage: less material in front of calorimeter
  - Disadvantage: expensive, calorimeter restricted in width

data taking at LHC design luminosity

- Up to 23 overlay events: „Pile-up“ → Detectors with high granularity

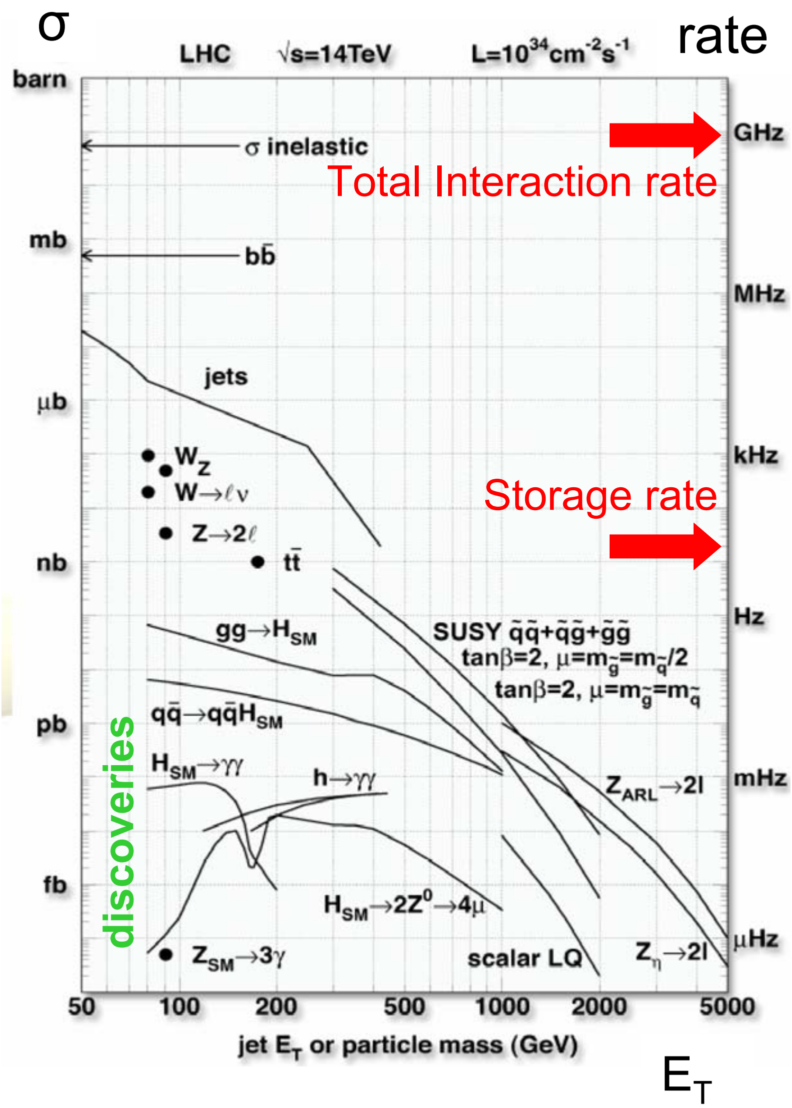


	Subdetector	channels	Fragment size [KB]
Inner Detect.	Pixel	$8.0*10^7$	60
	SCT	$6.2*10^6$	110
	TRT	$3.7*10^5$	307
Calo-rimeter	LAr	$1.8*10^5$	576
	Tile	$1.0*10^4$	48
μ-System	MDT	$3.4*10^5$	154
	CSC	$3.1*10^4$	10
	RPC	$3.5*10^5$	12
	TGC	$3.2*10^5$	6
	L1 Trigger		46

- ATLAS/CMS Event size: ~1.5 MB → high demands for data acquisition systems (“DAQ”)

- Affordable capacities for storage and reprocessing of data: <300 MB/sec
- Ergo: maximum storage rate restricted to <200 Hz
- Trigger and Data-acquisition system are crucial at LHC/Hadron-Colliders

physics goals and event rates at the LHC



- only 1 out of 200 000 Events can be stored.
- „trigger“ selection is crucial for physics goals:
  - Selection of rare discovery physics : Higgs, SUSY, Exotics
  - Known SM physics (W, Z, top): for calibration, efficiency studies, etc.
- Strategy: “inclusive” selection of
  - Leptons: e, μ, τ
  - Jets
  - Photons
  - E_T^{miss}

→ „not to miss the unexpected“, New Physics !!

Inclusive trigger strategy

- A possible trigger menue: ($L=10^{33}cm^{-2}s^{-1}$)

Signatur	Rate [Hz]	Physik-goal
μ20i	40	ttH, H→WW, ZZ, top, W‘, Z‘, Z→ll, LQs
2μ10	10	H→WW, ZZ, Z→ll
e25i,γ60i	40,25	ttH, H→WW, γγ, top, W‘, Z‘, Z→ll, W→νl LQs
2e15i,2γ20i	<1,2	H→WW, ZZ, γγ, Z→ll
j400	10	QCD, New Physics
3j165	10	QCD, New Physics
4j110	10	QCD, New Physics
j70+xE70	20	Supersymmetry
μ10+e15i	1	H→WW, ZZ, tt

- Always: trigger thresholds are a compromise:
  - Coverage of phase space: → low thresholds
  - small trigger rate → high thresholds

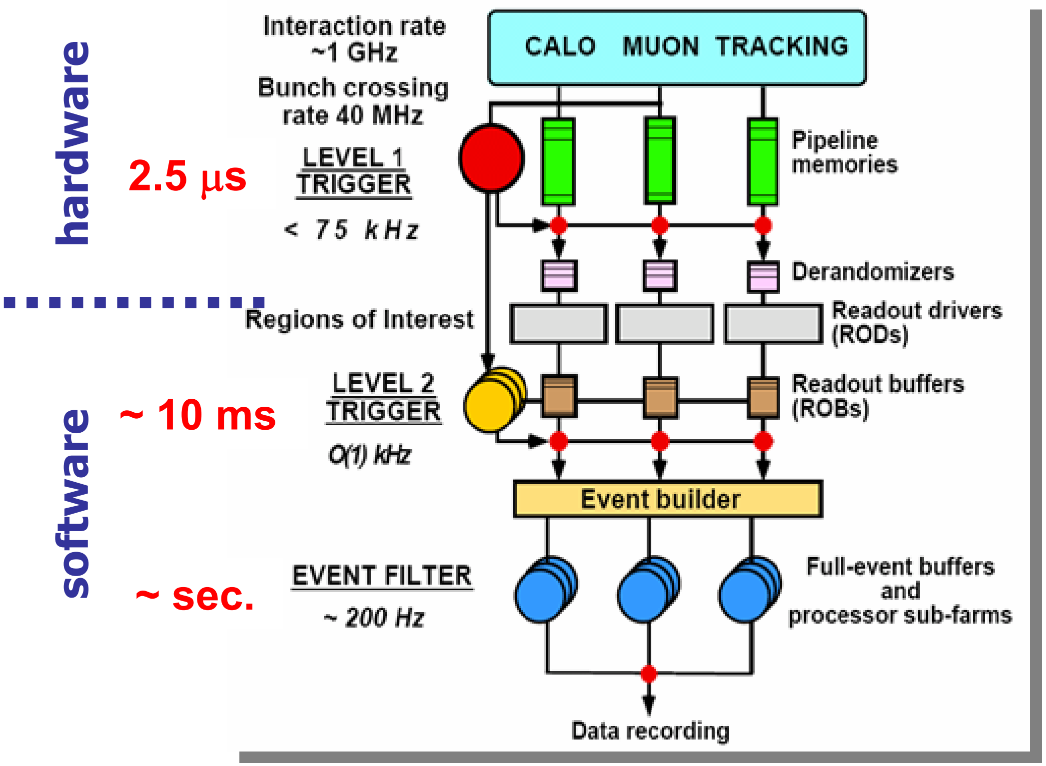
- Requirements on trigger systems:
  - High rejection rates
  - Efficient selection

→ LHC: multi-layer trigger systems:

- Level-1:
  - Fast, coarse calculations
  - Custom-made hardware
- Higher trigger levels:
  - More time available
  - More exact calculations („refinement“)
  - selection in software, large computer farms

ATLAS Trigger: general overveiw

3-Level Trigger System:



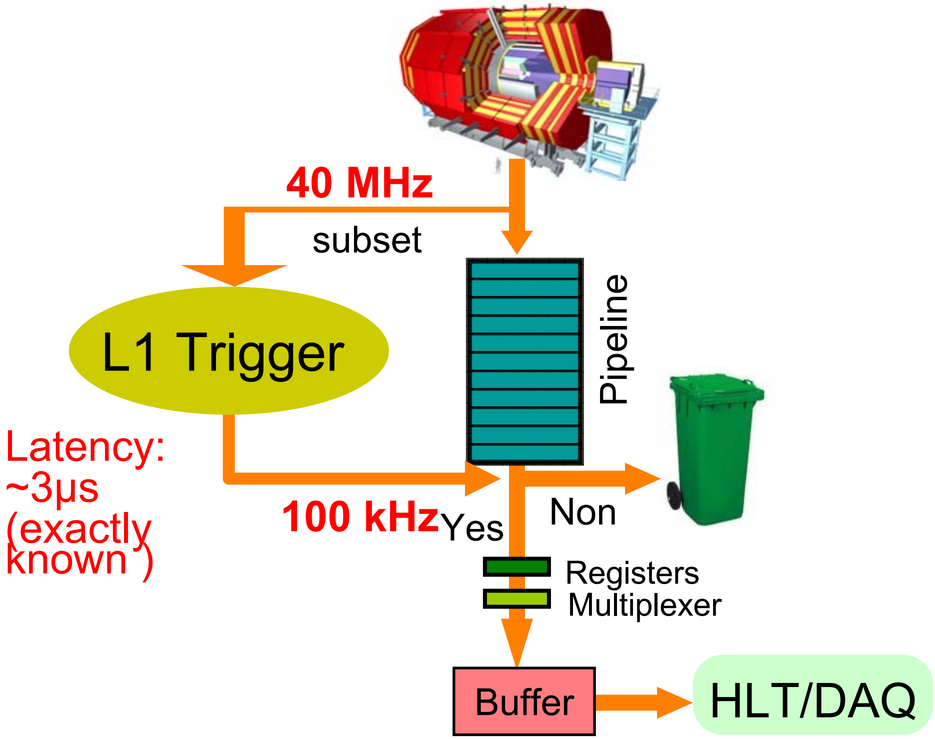
1) **LVL1** decision based on data from calorimeters and muon trigger chambers; synchronous at 40 MHz; bunch crossing identification

2) **LVL2** uses Regions of Interest (identified by LVL1) data (ca. 2%) with full granularity from all detectors, asynchronous

3) **Event Filter** has access to full event and can perform more refined event reconstruction

Typical design of trigger systems at the LHC: Level-1

- Δt_{BC}=25ns « possible latency
- But: dead time must be small
- schematic design of Level-1 (ATLAS and CMS):



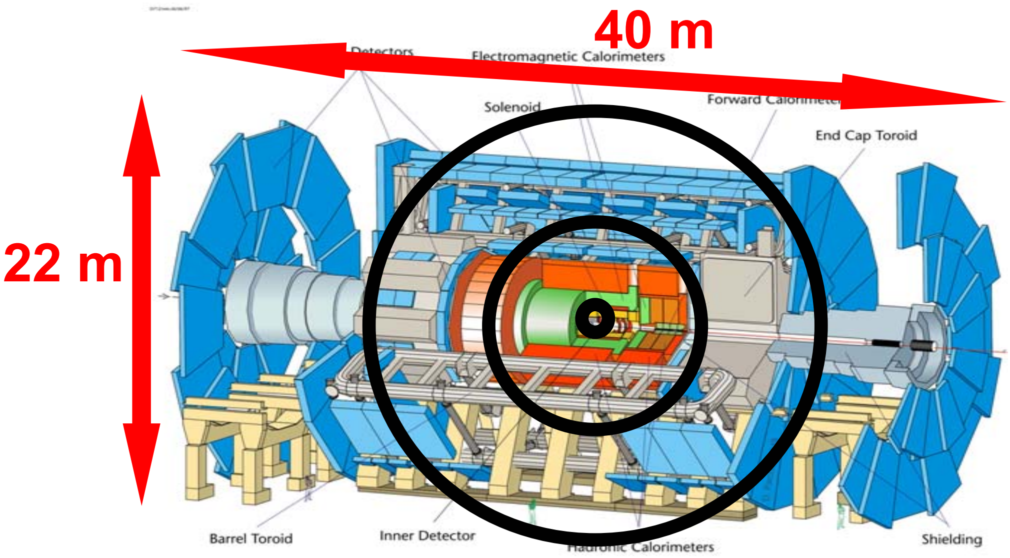
- During the latency all data must be kept in pipelines.
- Important: small latency

◊ Fast decision
◊ Hardware Trigger

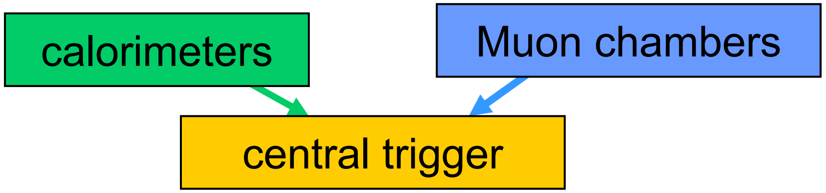
Level-1: synchronization and time resolution

- Trigger decision should be based on signals of a single bunch crossing
- But: LHC intervall is small and LHC Detectors are huge
- Flight distance of particles between 2 BCs: 7.5m

Maschine	**Δt_{BC} [ns]**
LEP	22 000
Tevatron 1	3 500
Tevatron 2	396/132
HERA	96
LHC	25



- needed:
    - synchronization of signals with delays
    - correct identification of corrects BC (needs good time resolution)

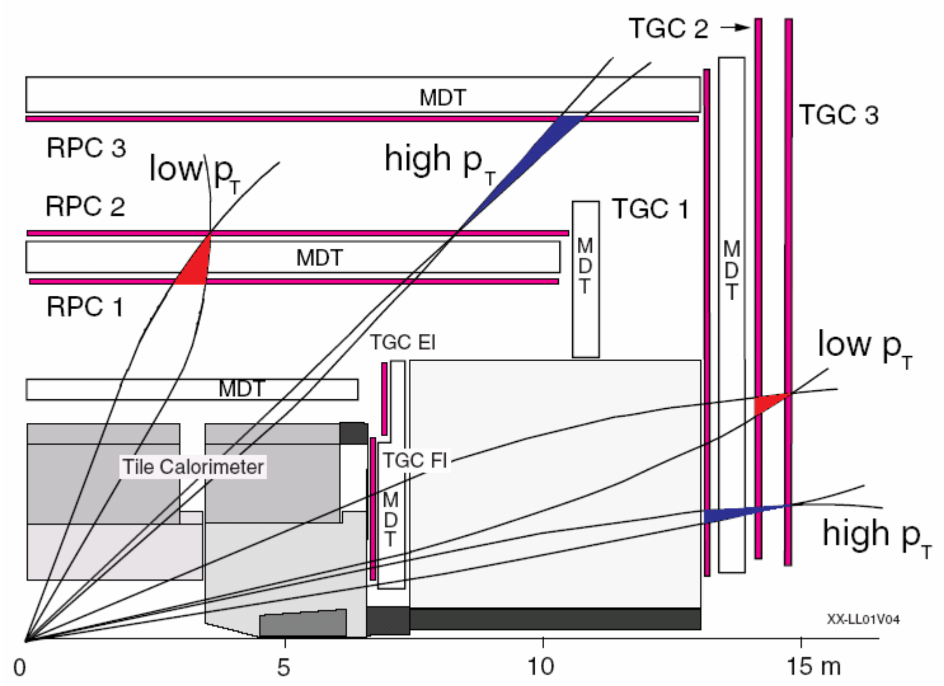


calorimeters

Muon chambers

central trigger

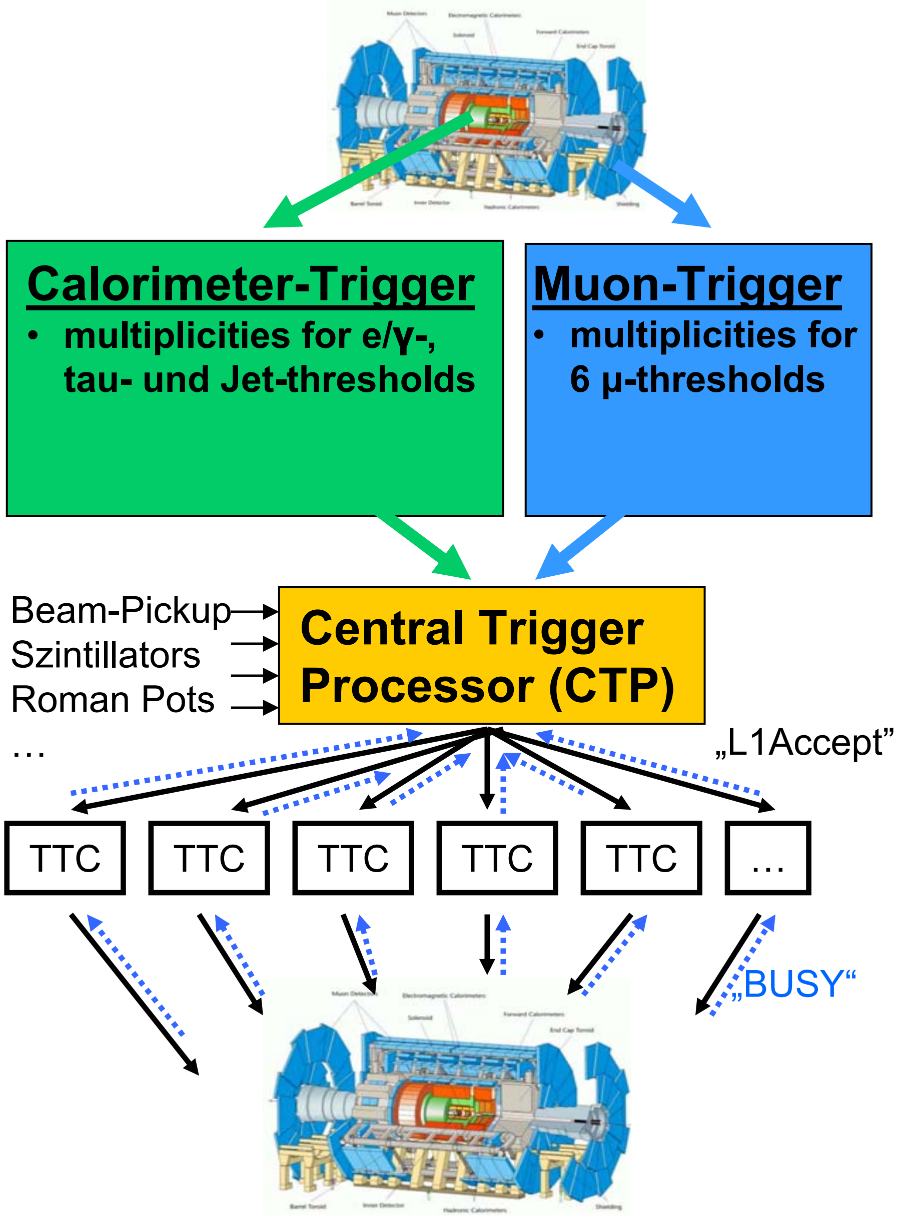
Level-1 Myon-Trigger: Beispiel ATLAS



- Dedicated muon chambers with good time resolution:
- Local track search by electronics installed on the detector

- Search for coincidences in different detector layers
- Programmable width of coincidence windows allows coarse determination of the transverse momentum

Example: ATLAS central Level-1 trigger



Calorimeter-Trigger

- **multiplicities for e/γ-, tau- und Jet-thresholds**

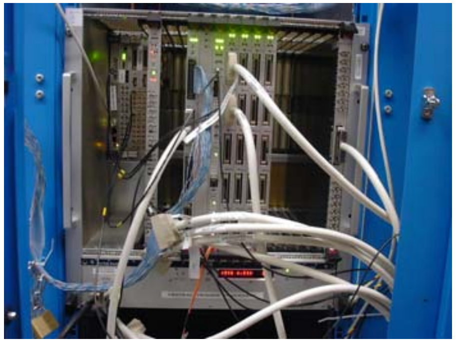
Muon-Trigger

- **multiplicities for 6 μ-thresholds**

Beam-Pickup
Szintillators
Roman Pots
…

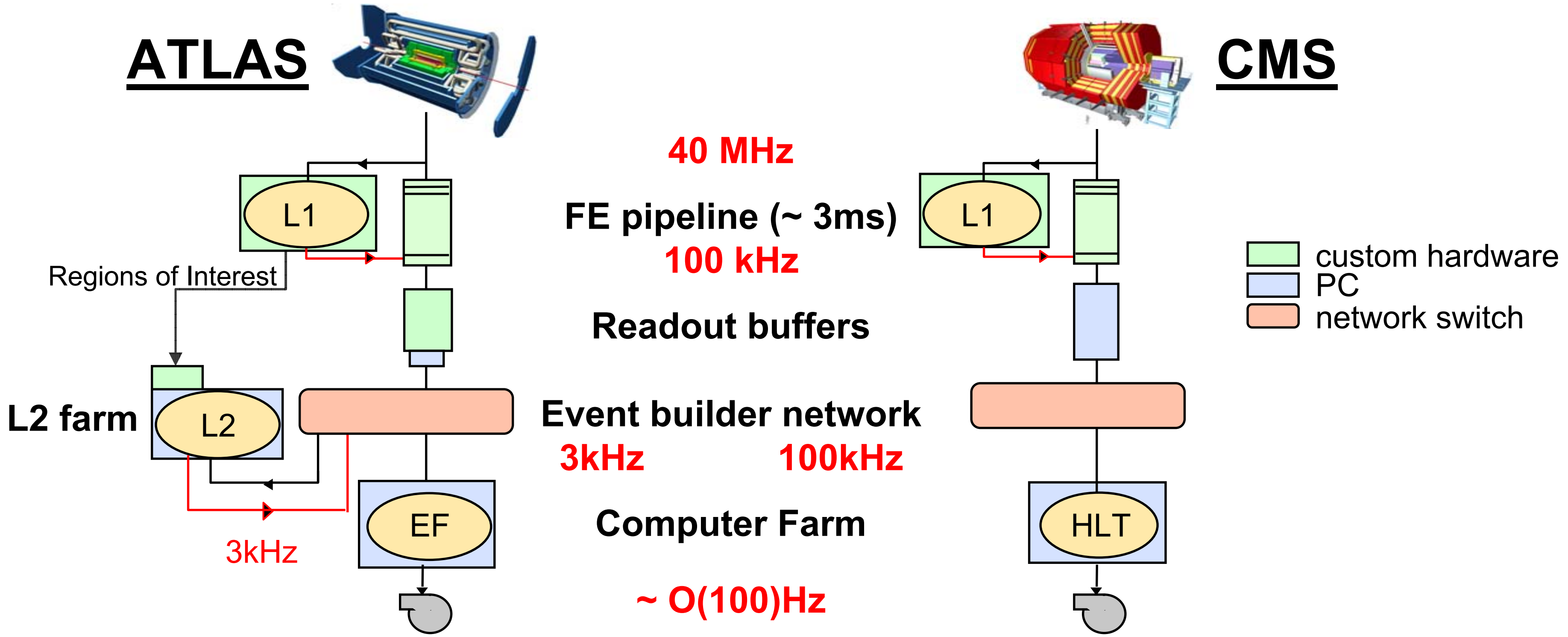
Central Trigger Processor (CTP)

„L1Accept"



- Central Trigger Processor calculated Level-1-decision
- „L1Accept"-Signal (L1A): OR from 256 „Trigger Items"
- Distribution of L1A-Signal via optical fibres (TTC system) to start detector readout

Design of LHC Trigger systems: higher trigger levels



ATLAS

CMS

40 MHz

L1

FE pipeline (~ 3ms)

100 kHz

Regions of Interest

Readout buffers

L2 farm

L2

Event builder network

3kHz **100kHz**

Computer Farm

EF

HLT

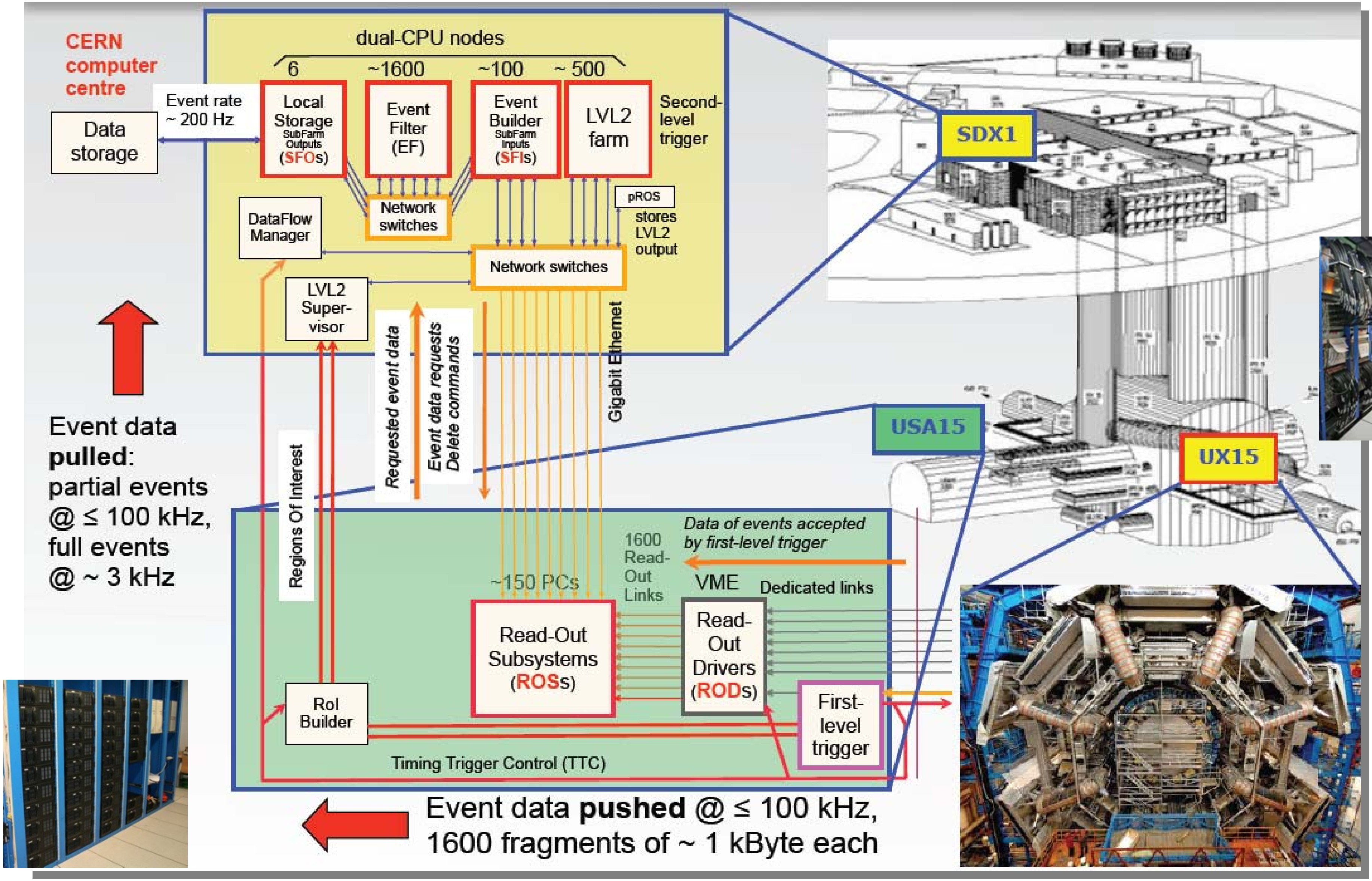
3kHz

~ O(100)Hz

🟩 custom hardware
▭ PC
🟧 network switch

- In common:
  - Readout-Buffer: decoupling of HLT and L1
  - Huge Network Switches for parallel event building (point-to-point).
  - Huge, fully programmable and scalable computer farms
- Differences::
  - CMS: Event building with full Level-1 rate ◊ demanding for network
  - ATLAS: L2-Farm used as a pre-selection step
    - Looks only at interesting regions of the event
    - Event building with „only“ 3kHz

ATLAS Trigger & DAQ Implementation



Event data **pulled**:
partial events
@ ≤ 100 kHz,
full events
@ ~ 3 kHz

Event data **pushed** @ ≤ 100 kHz,
1600 fragments of ~ 1 kByte each

Summary so far

- Main physics goal of the LHC
  - Search for the Higgs
  - Search for deviations from the SM, New physics
- pp colliders: discovery machines
- e^+e^- colliders: precision measurements

- LHC:
  - Highest energy collider
  - Highest luminosity collider

- Data taking at the LHC is an unprecedented challenge for detectors and their DAQ and trigger systems

- Triggering:
  - Multi-level system used
  - First level in custom made hardware
  - Higher levels run in huge computer farms at the surface