DESY Summer Student Program
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Physics in pp collisions

LHC, machine, detectors, physics

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outlook

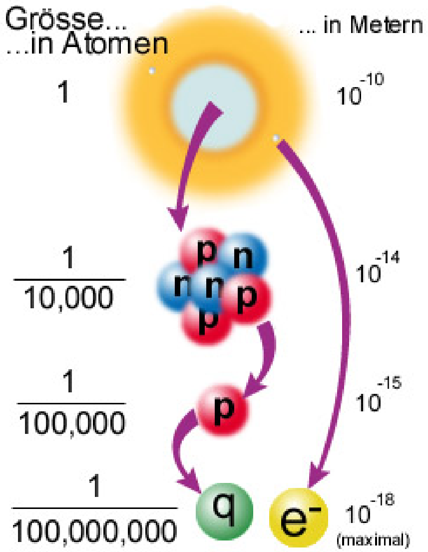
Today:

- 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

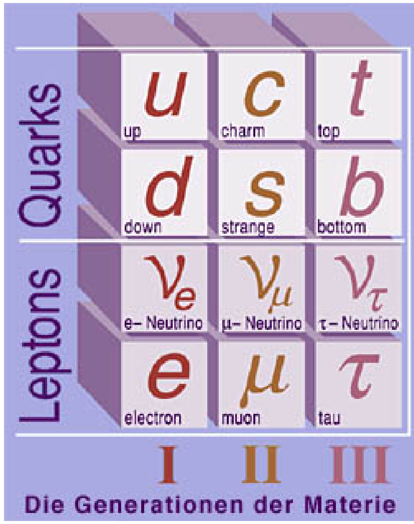


Answers to the most fundamental questions:

- Origin and fate of the universe
- What is the world made of ?

Answer of the Standard Model:

The elementary particles of matter are quarks and leptons



	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

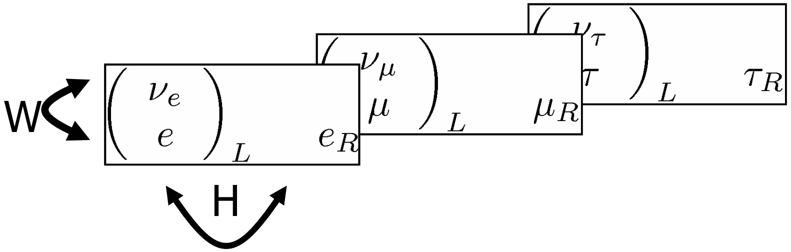
Only first generation of fermions are relevant for daily life → atoms

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

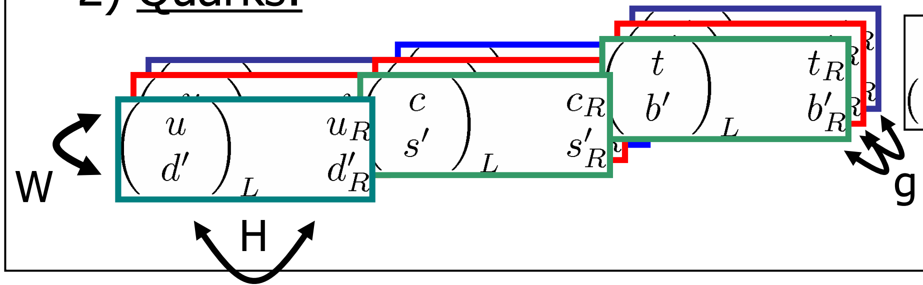


$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \; e_R \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \; \mu_R \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \; \tau_R$$

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

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

2) Quarks:



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

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

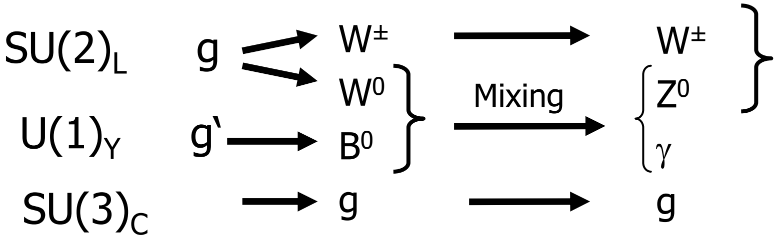
Spin 0 Higgs, resp. for mass

- SU(2) Doublett:

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

- 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:



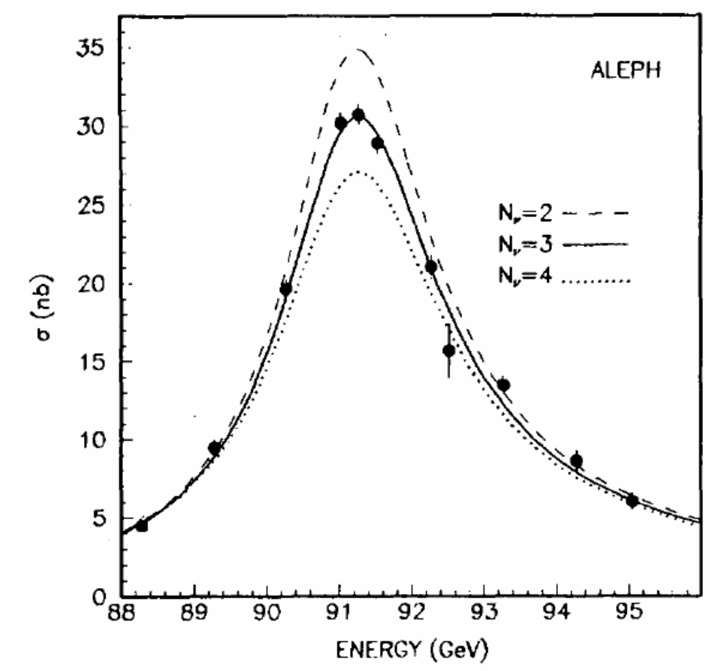
Weak Interaction: $\alpha_w = g^2/4\pi = 0.03$

Electromagnetic IA: $\alpha = e^2/4\pi = 1/137$

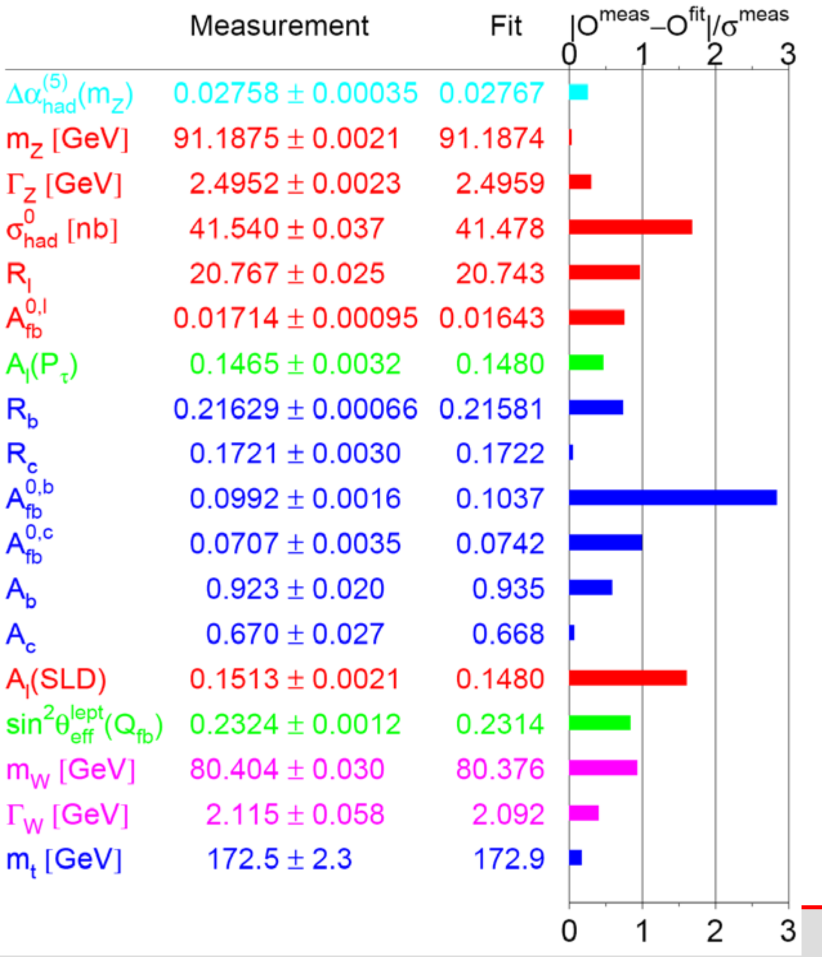
Strong IA: $\alpha_s = 0.12 \ldots \sim 1$

Status of the Standard Model

- So far the Standard Model describes all measurements of particle physics 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



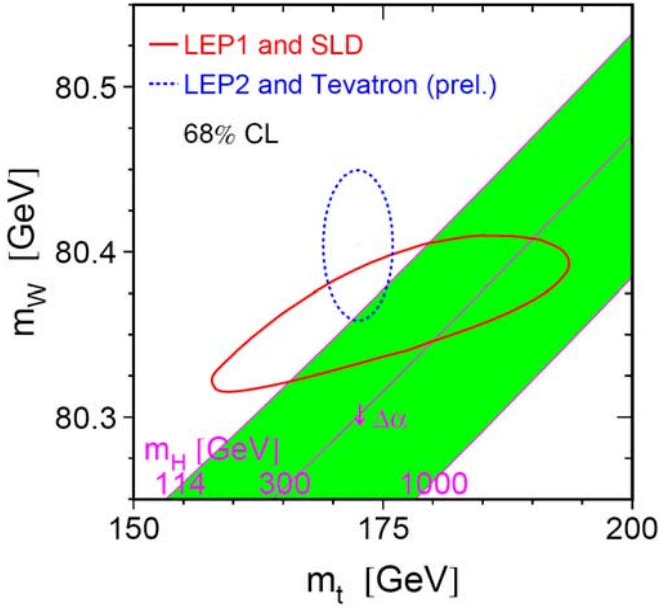
- SM describes all these measurements
- Extremely successful !!!



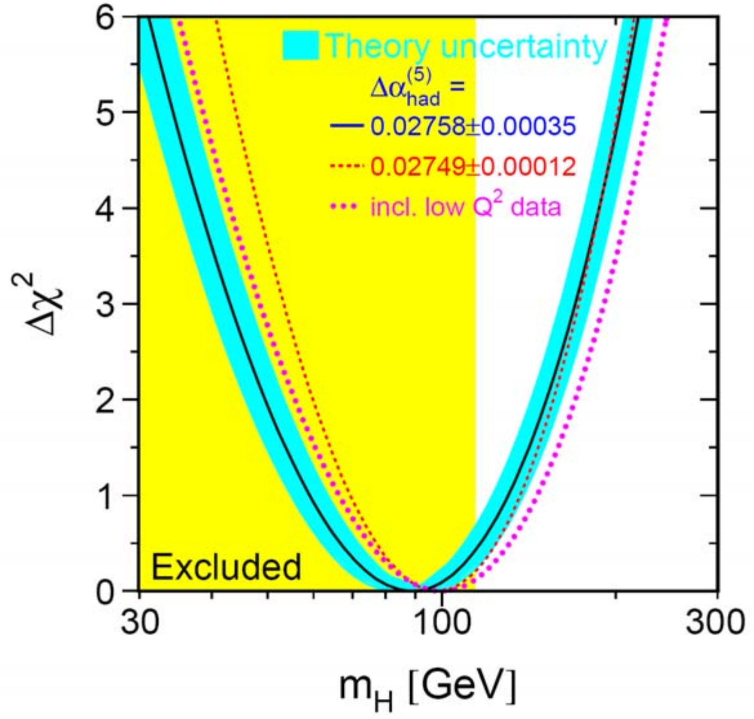
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	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	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.404 ± 0.030	80.376
Γ_W [GeV]	2.115 ± 0.058	2.092
m_t [GeV]	172.5 ± 2.3	172.9

Status of the Standard Model

- Since measurements are very precise: The internal consistency of the SM can be tested by comparing indirect predictions (from higher order calculations) with direct measurements
  - Prediction of the top mass
  - Prediction of the W mass
- Excellent agreement



- Same procedure today: Prediction of the SM Higgs Mass

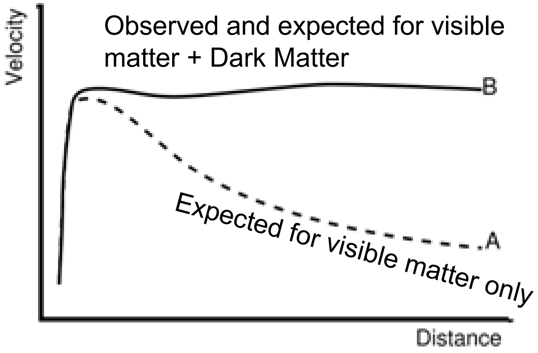


- So far Higgs not yet discovered.
- Discovery of Higgs and Measurement of Higgs mass needed!

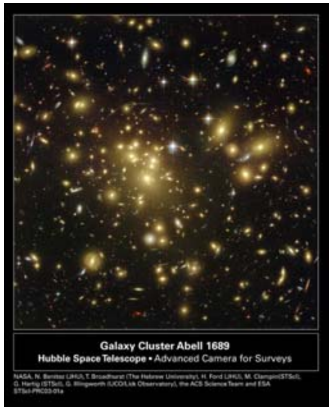
Why New Physics?

Experimental Hints for New Physics:

Velocities of galaxy rotation



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

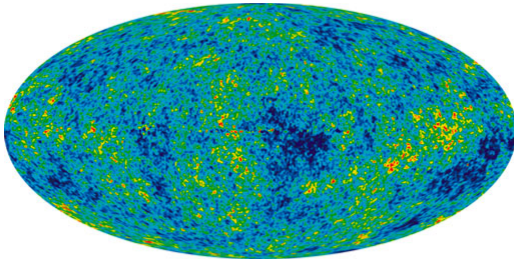


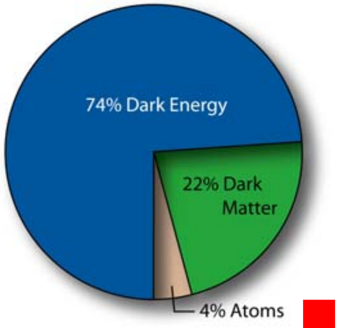
In both cases: visible (SM) matter is not enough for description of observations

Measurement of the fluctuations of the cosmic microwave background

→ Composition of the energy density of the universe

WMAP (2003):





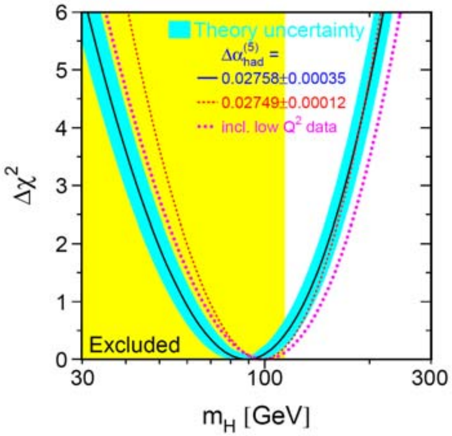
With the SM only a fraction of the matter in the universe can be described

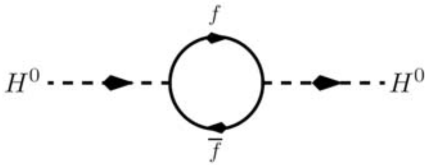
Established: A type of matter exists in the universe which is not described by the SM → "Dark Matter"

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.





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

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

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

„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

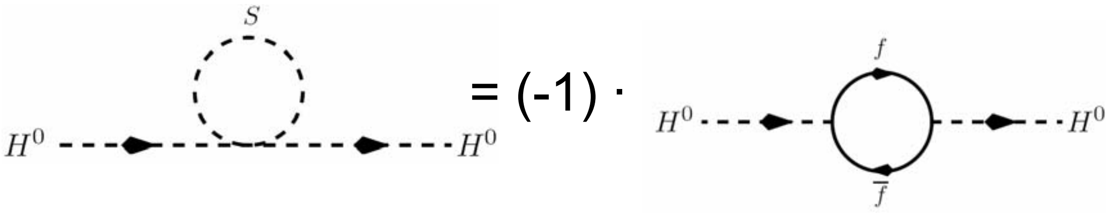
⇨

SM Teilchen (R=1)	**SUSY Partner (R=-1)**
Quarks q	Squarks $\tilde{q}$
Leptons l	Sleptons $\tilde{l}$
W±, 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



<u>SUSY can provide explanation for Dark Matter:</u>

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 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
- Ergo: most important open questions in particle physics:
  - Search for the SM Higgs
  - Search for new physics
- 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

$$N = L \, \sigma$$

L= Luminosity
σ= cross section

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

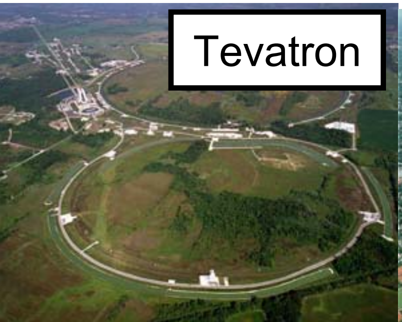
1 b= $10^{-28}m^2$

- 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!

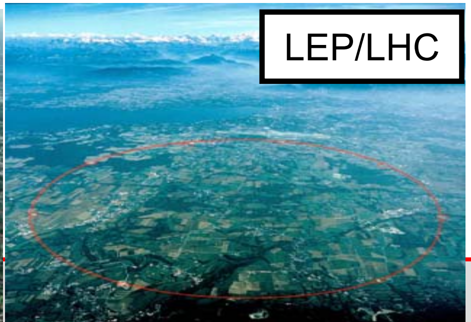
- One experimental year has ~10^7s → integrated luminosity at the LHC
  - 1 fb^{-1} per year, in the initial phase
  - 100 fb^{-1} per year, later

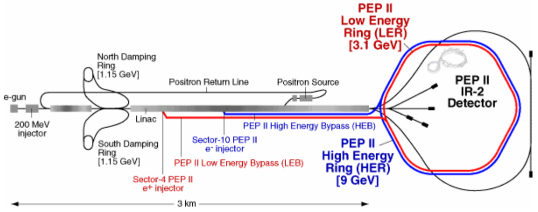
Overview: current colliders

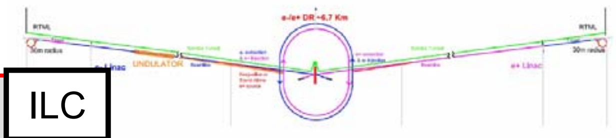
	beams, energies (GeV)	$\sqrt{s}$ (GeV)	Data taking	L (10^{30} s^{-1}cm^{-2})	L_{int} (pb^{-1})	site
LEP	e^+e^-: 45(104)x45(104)	90-208	1992-2000	100	LEPI: ~160 (je Exp.)	CERN
HERA	$e^\pm p$: 30 x 920	320	1991-2007	50	~ 600	DESY
TeVatron	$p\bar{p}$: 980 x 980	1 960	92-96, 01-10(?)	200	160, ~ 8 000	FNAL
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	2008 - ?	10 000		CERN
ILC	e^+e^-: 500 x 500	1 000	2015(?)-	20 000		??


Tevatron

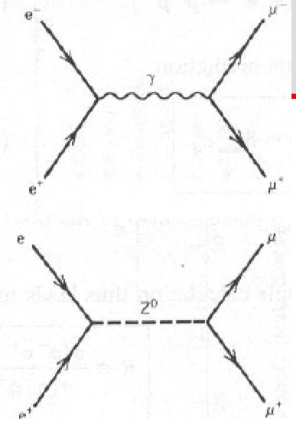

HERA

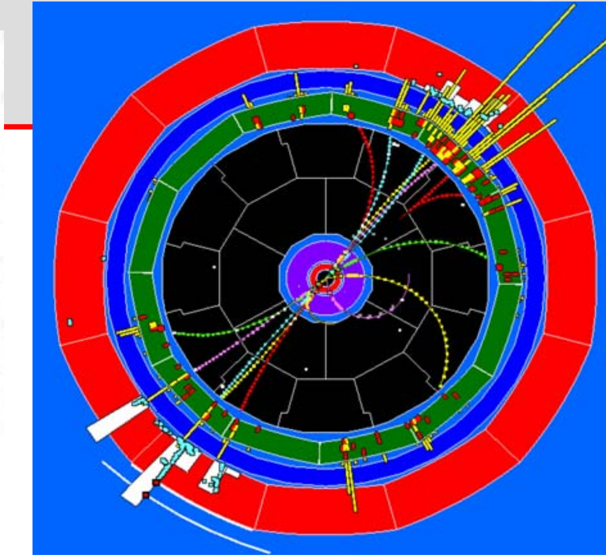

LEP/LHC




ILC

e^+e^- vs. pp colliders





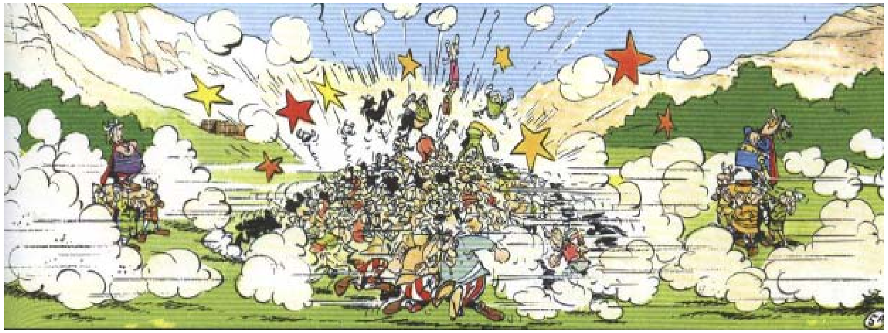
e^+e^- collider:

- 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 reconstruction of the events → missing energy

→ Excellent machines for precision measurements

pp collider:

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



Why pp colliders?

e^+e^- colliders vs. pp colliders

- Main drawback of e^+e^- colliders:
  - 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:

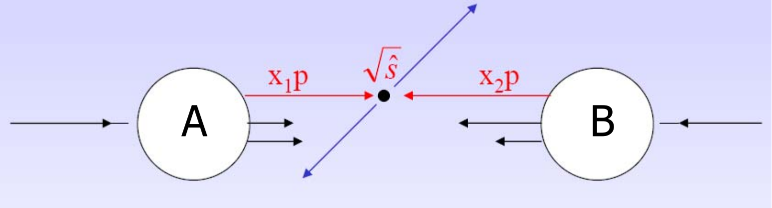
$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

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



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

simplification

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

- 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

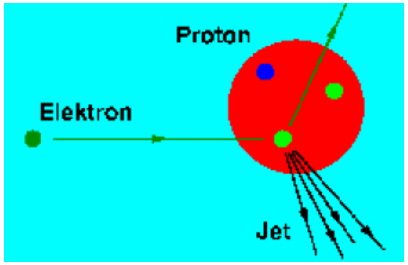
- example:
  - LHC: √s=14 TeV, TeVatron: √s=1.9 TeV
  - To produce a particle with a certain mass:

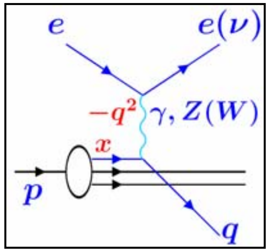
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--

  - 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

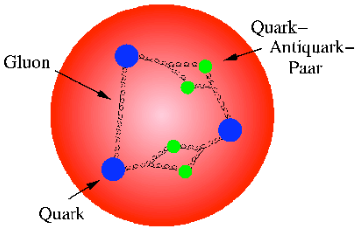
- From where do we know the x values?
- The structure of the proton is investigated in Deep Inelastic Scattering

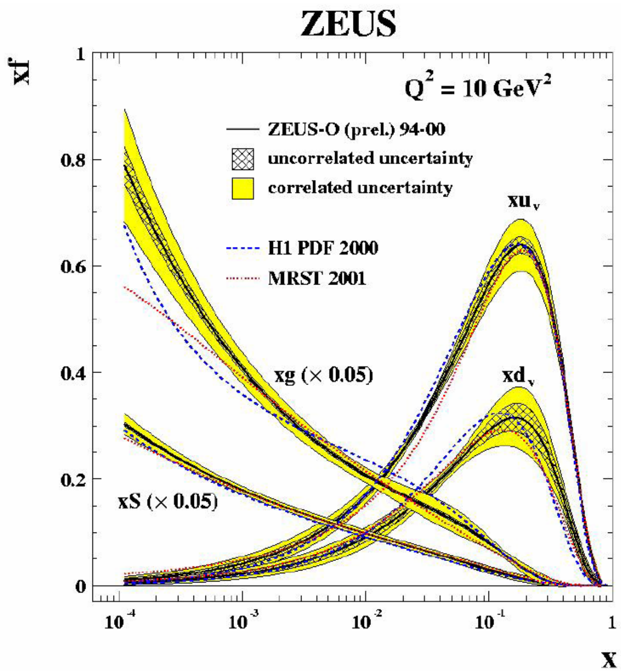




- Highest energies are reached at the ep collider HERA: Scattering of 30 GeV electrons on 900 GeV Protons: Test of the proton structure down to 10^{-18}m

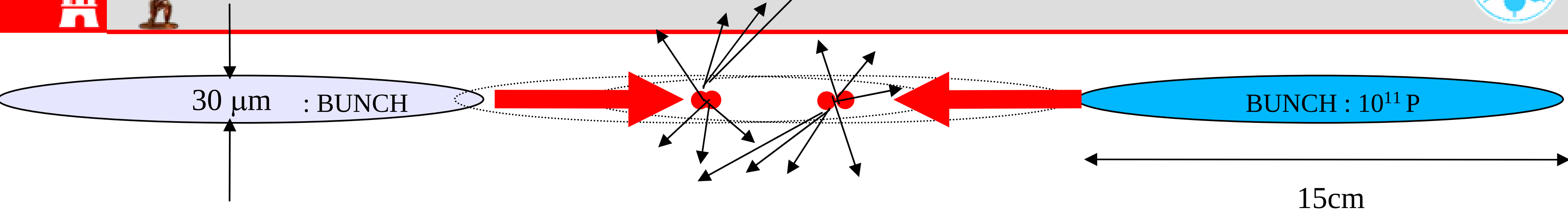
- Structure of the proton: Parton density functions





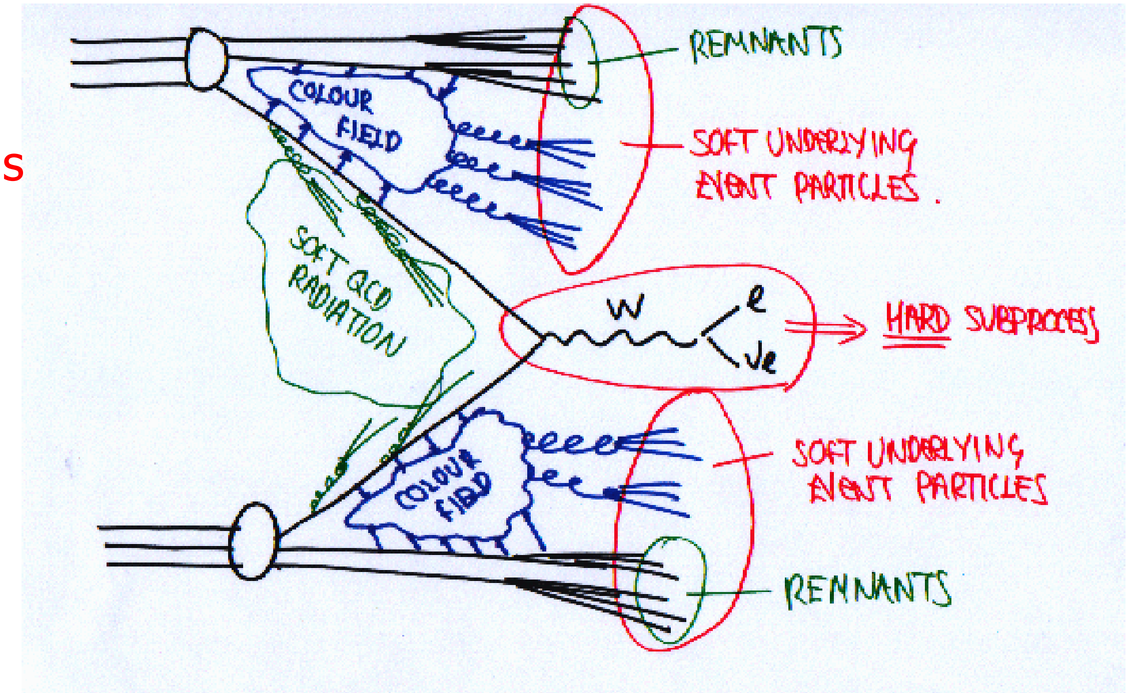
- u- and d-quarks at high values of x
- Gluons dominate at low values !!

Characteristics of hadron collisions



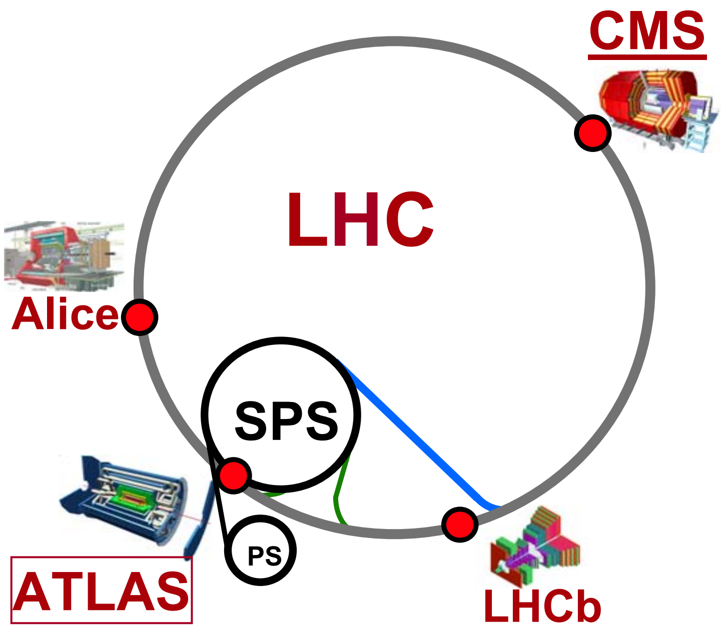
- Partons in the proton are strongly interacting particles
  - → high cross sections
  - → high rates
- Even possible: several interactions in one bunch crossing
- Rate: ~$1/Q^4$
  - Q: transferred 4-momentum
  - Most of the events are soft
  - Only a small fraction contains interesting events with high 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 !!
- L: 100 times TeVatron
- Machine is currently being commissioned
- First injection during week-end successful

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

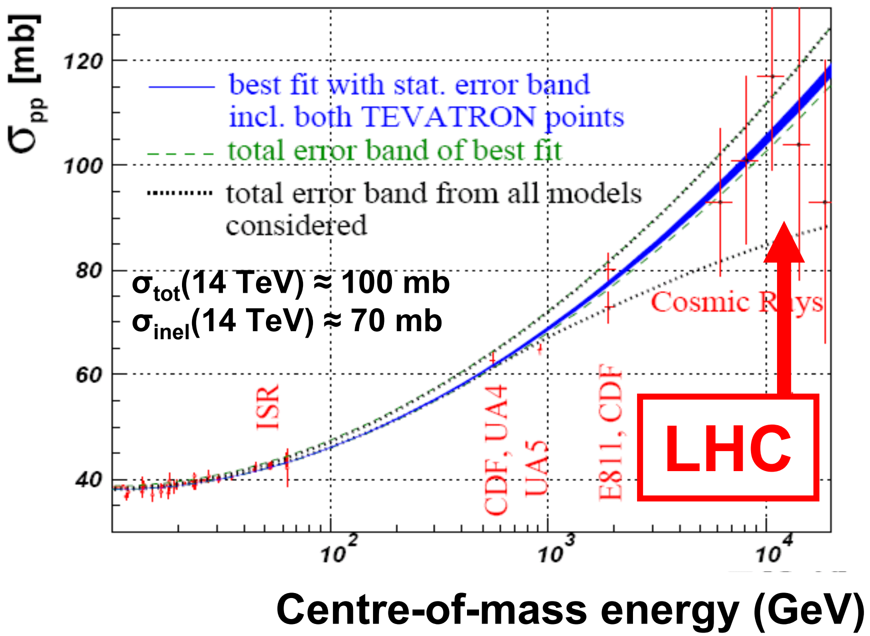
LHC is the largest cryogenic system in the world

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

- Installation complete and machine cooled down
- First beam injection test during last week successful

Discovery machine: LHC

Total pp- cross section:

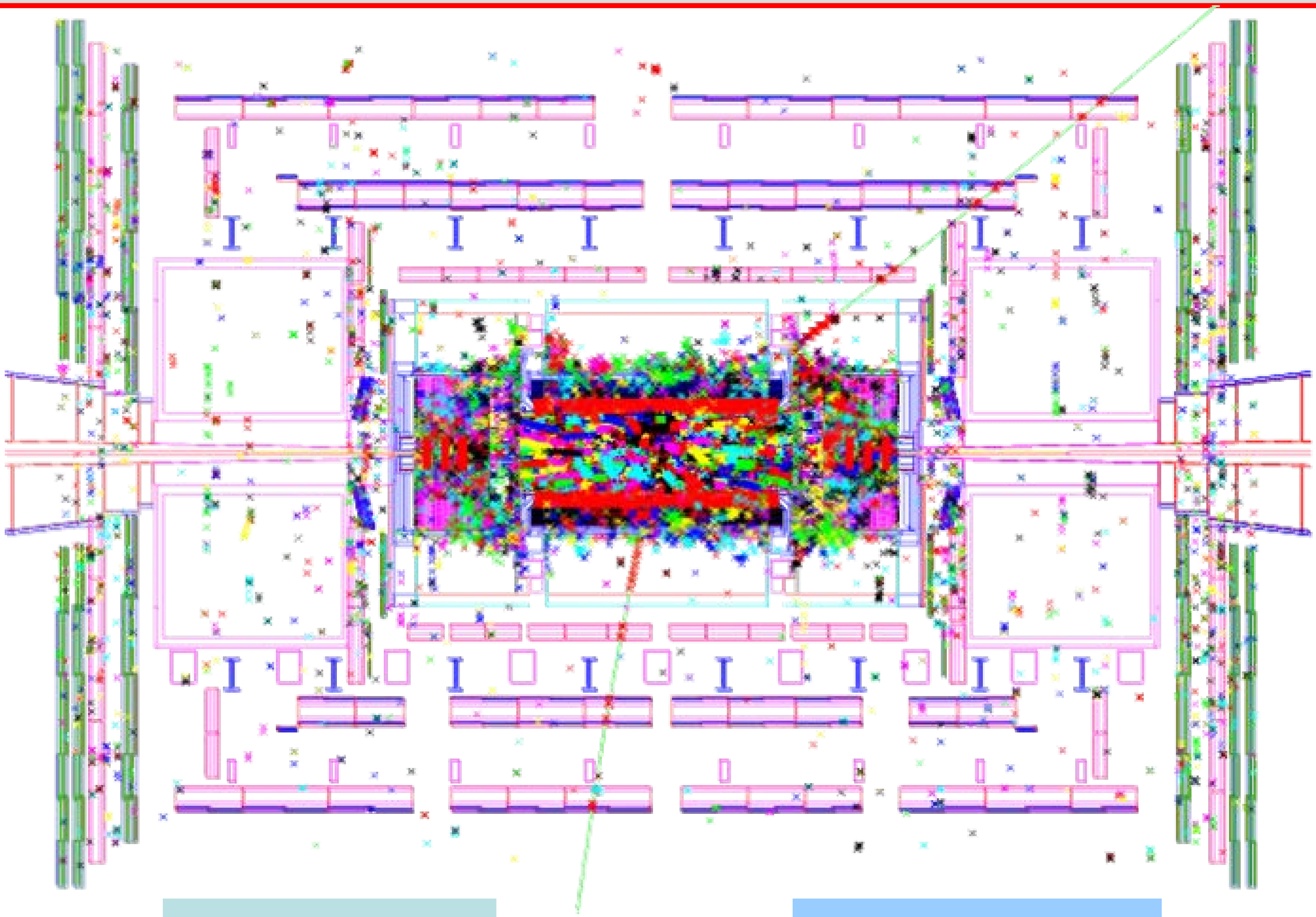


σ_{tot}(14 TeV) ≈ 100 mb
σ_{inel}(14 TeV) ≈ 70 mb

- 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

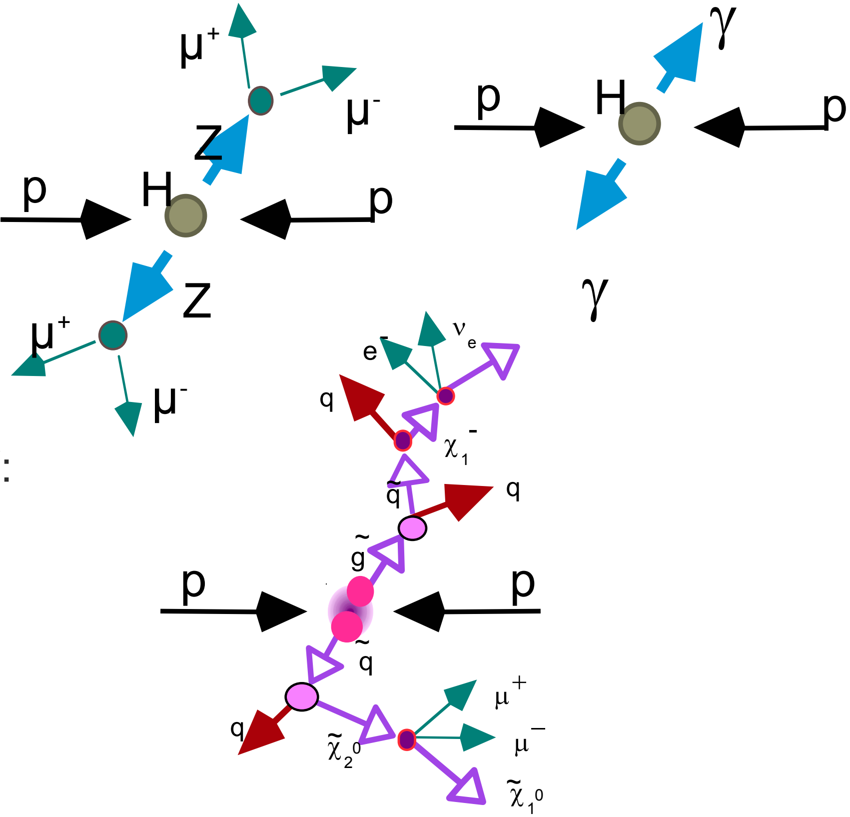
23 soft pp-events

!! with 40 MHz !!

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

LHC detector design

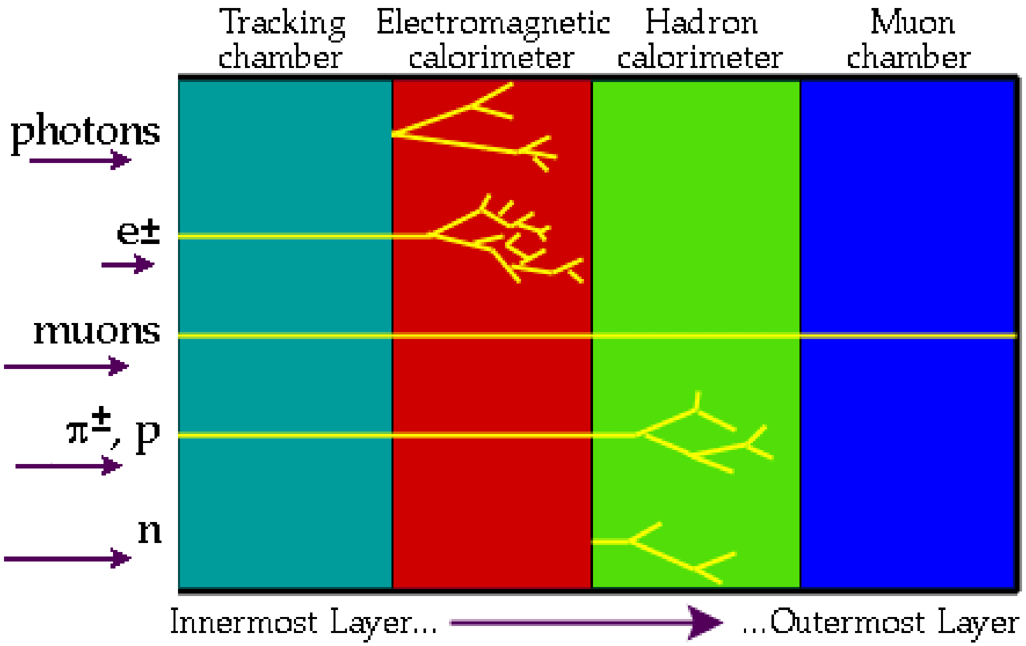
- The physics aims of the experiments have driven their design
- Quickly here: golden channels at the LHC
  - Search for the Higgs Boson:
  - Search for New Physics/ SUSY:



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

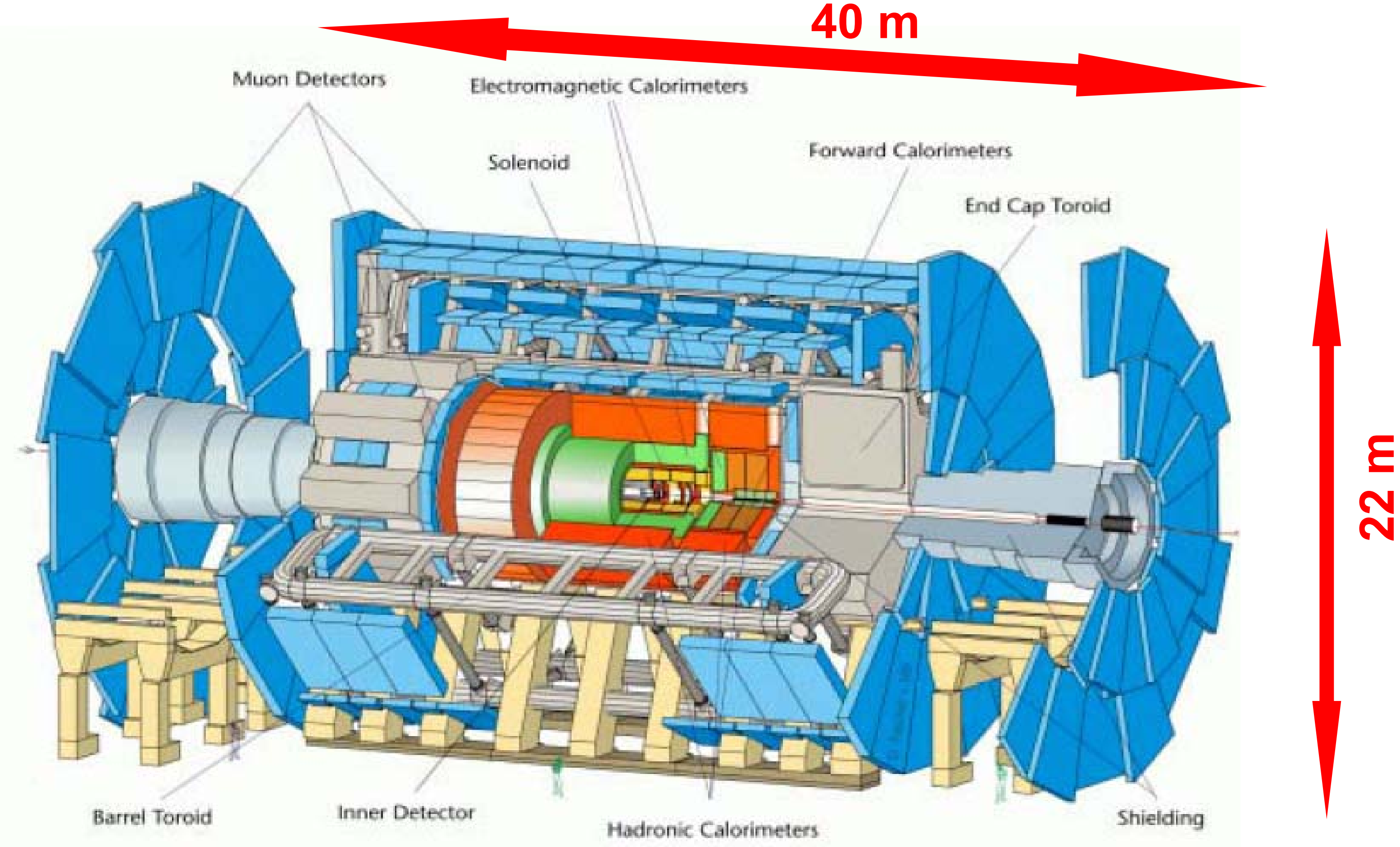
LHC detector design

- 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



<u>characteristic features:</u>

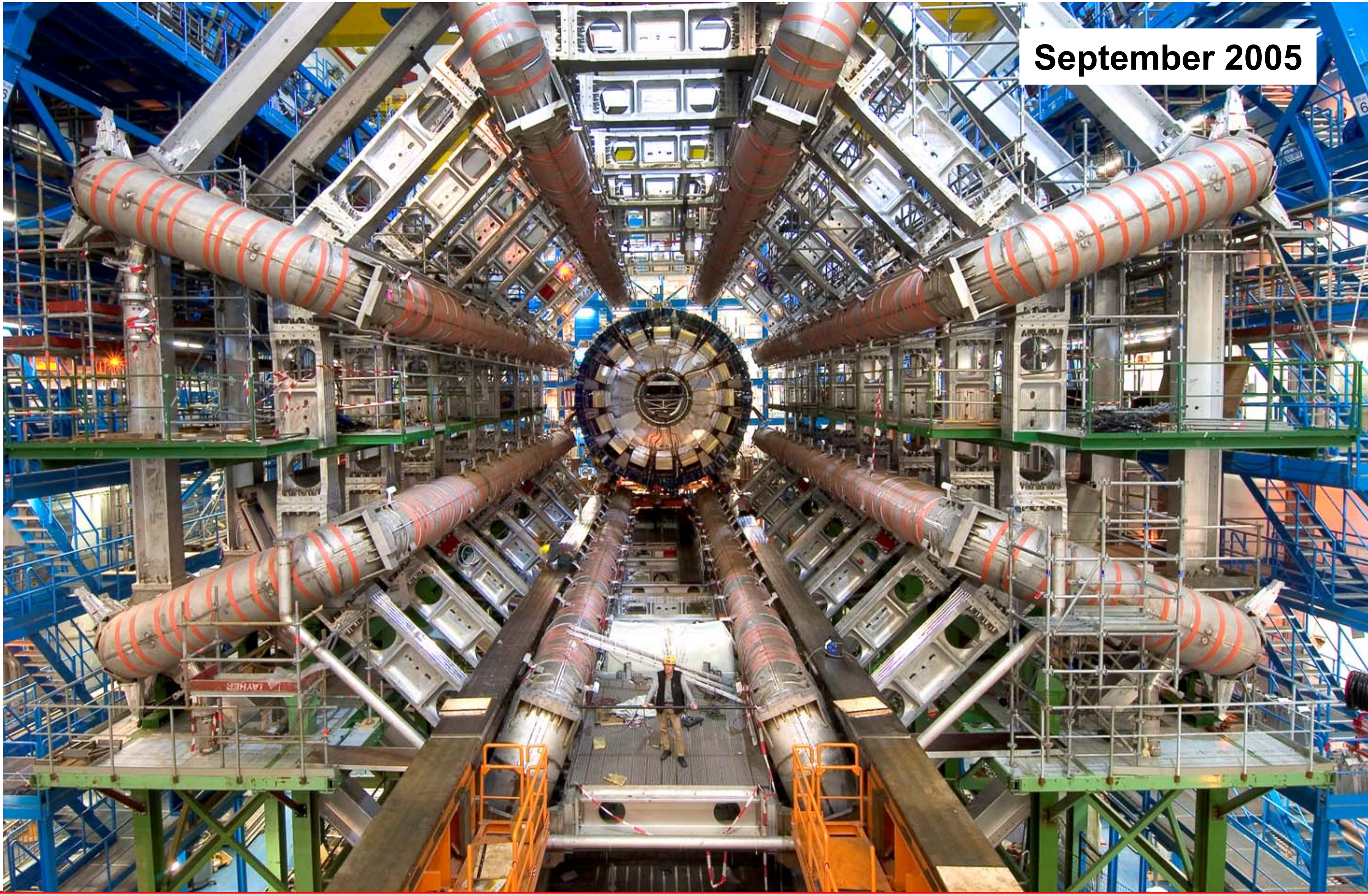
- **Muon spectrometer** with three toroidal magnets ($H \rightarrow 4\mu$)
- highly segmented LAr em calorimeter ($H \rightarrow 4l$, $H \rightarrow \gamma\gamma$)
- Tile calorimeter for hadronic activity

largest collider detector ever built

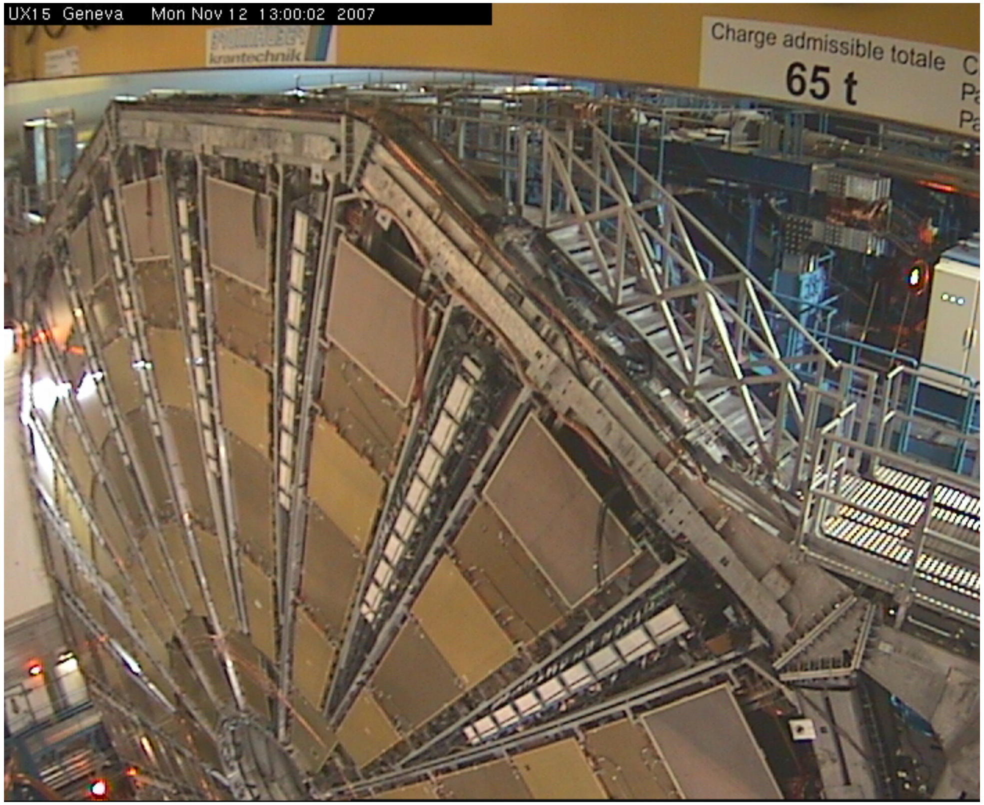
ATLAS toroid

Feb 2003

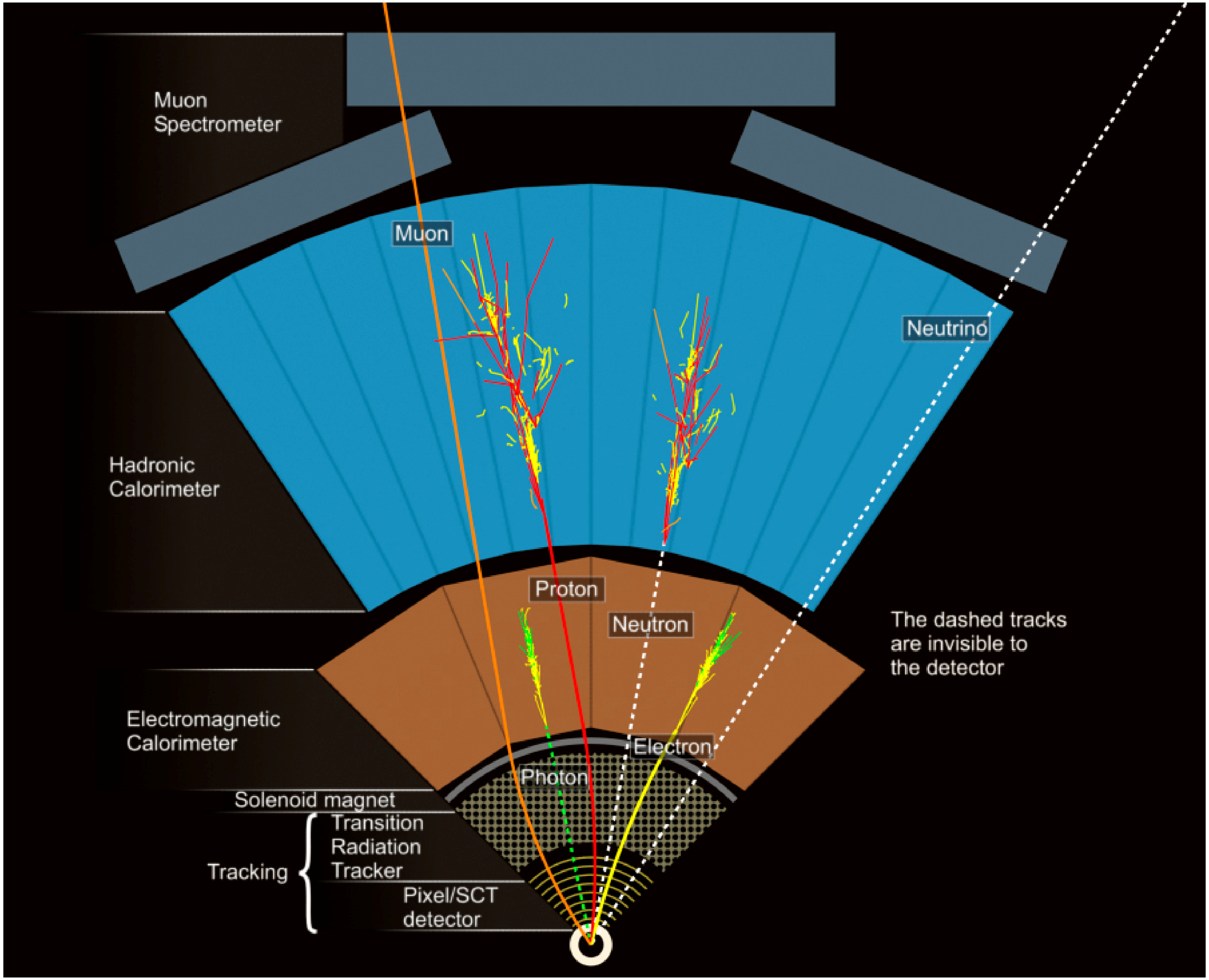
ATLAS toroid


September 2005

ATLAS toroid and muon system

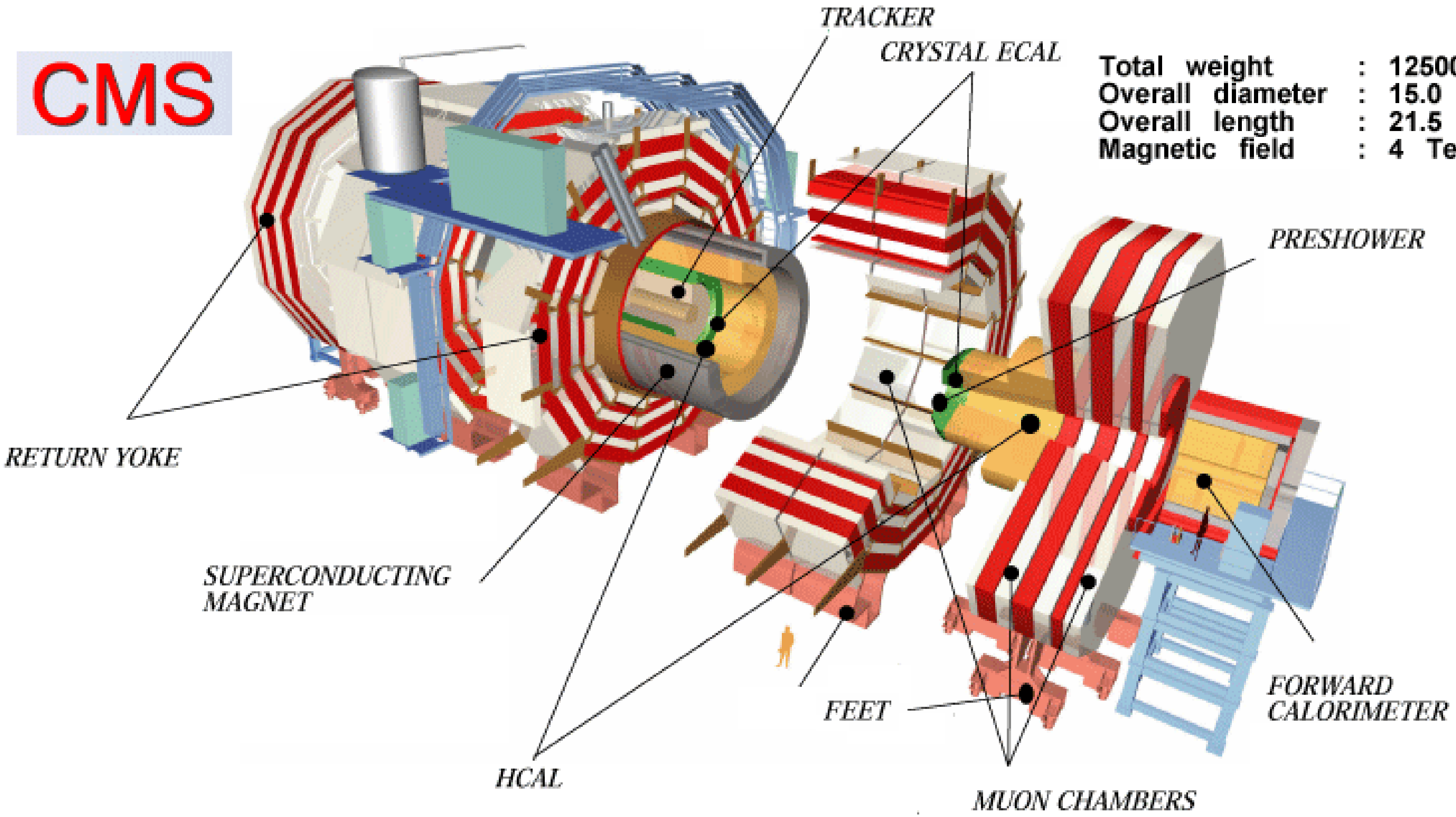


Detectors: ATLAS



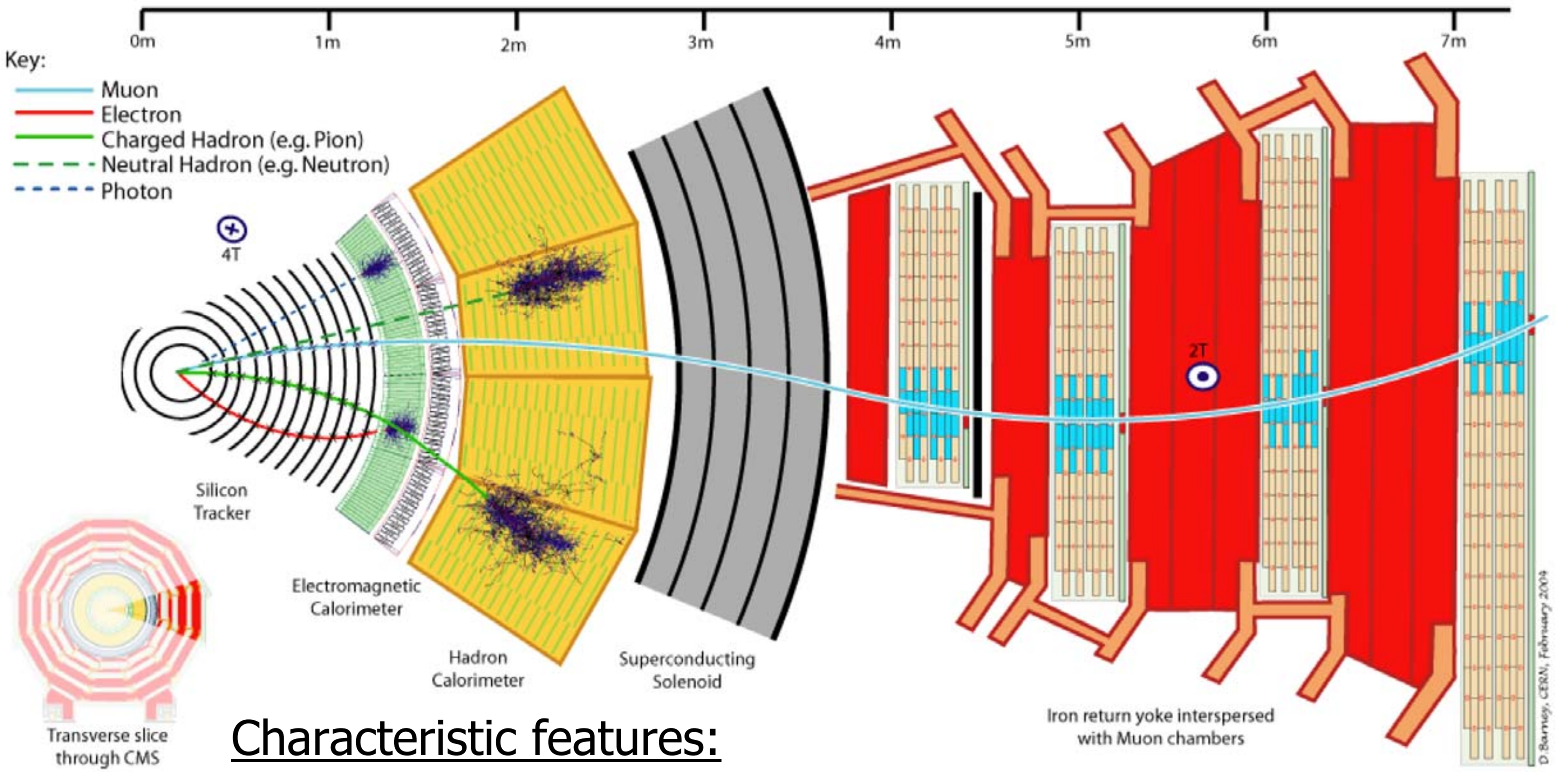
The dashed tracks are invisible to the detector

Detectors: CMS



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

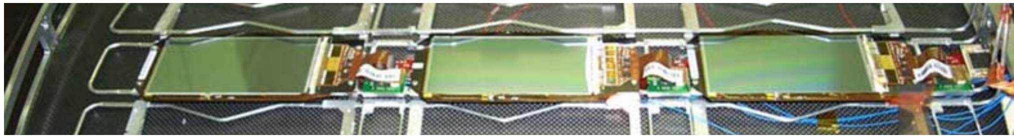
Detectors: CMS



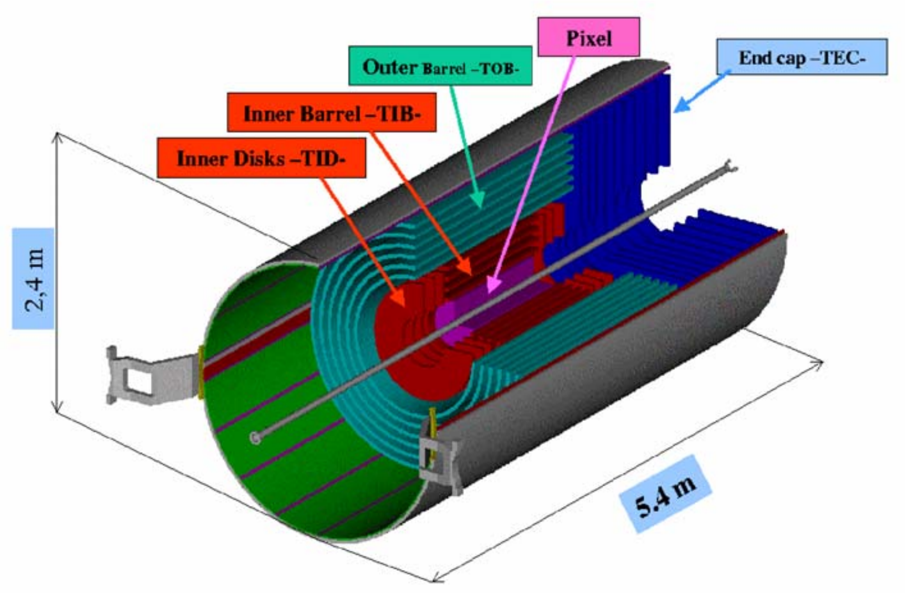
Characteristic features:

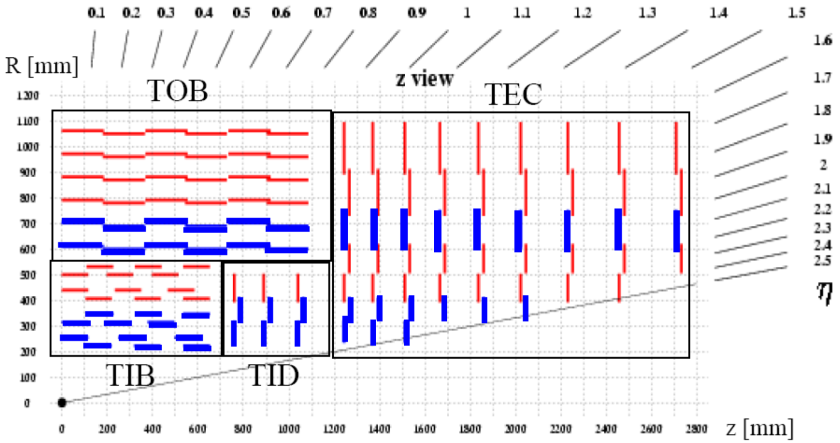
- Full inner detector is Si-based.
  - advantage: a single homogeneous system, precise position measurements
  - disadvantage: a lot of material in front of the calorimeters (particles can shower before) , expensive
- No longitudinal segmentation in electromagnetic calorimeter
- Coil for B field <u>after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

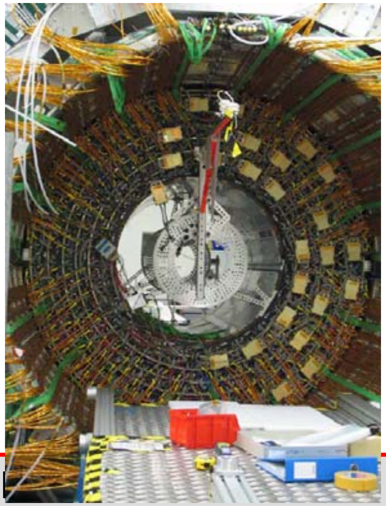
CMS-Si-Tracker

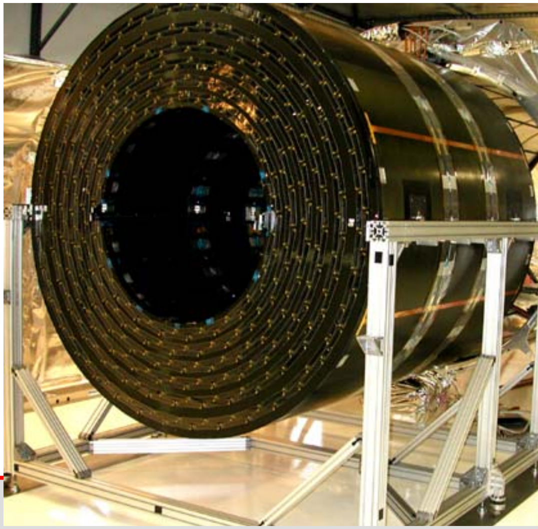


- The full track detector in CMS is Si based
- **Pixel:**
  - 3 Pixel-Layers (r=4.4cm, 7.3cm, 10.2cm, 150 μm x 100 μm),
  - 2 discs in end caps
- **Strip-Detector:**
  - area: 210 m^2
  - total 15232 Module
    - Partly built in HH
  - Strip pitch: 80μm to 205μm
  - Barrel: 10 Layers
  - Length: 5.4m, Radius: 2.4 m
  - Operation at -20°C



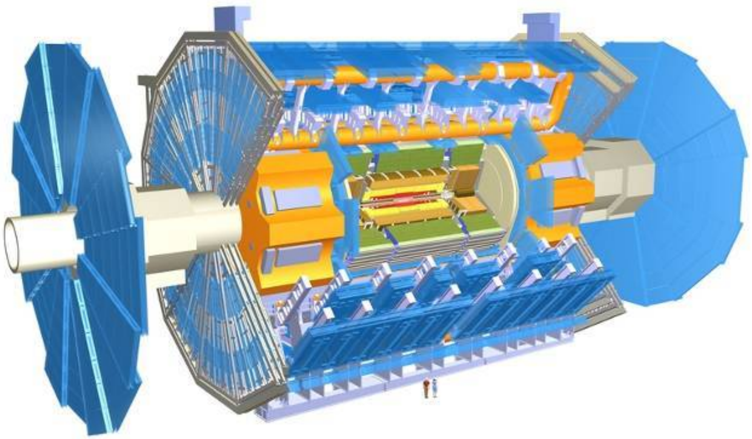






data taking at LHC design luminosity

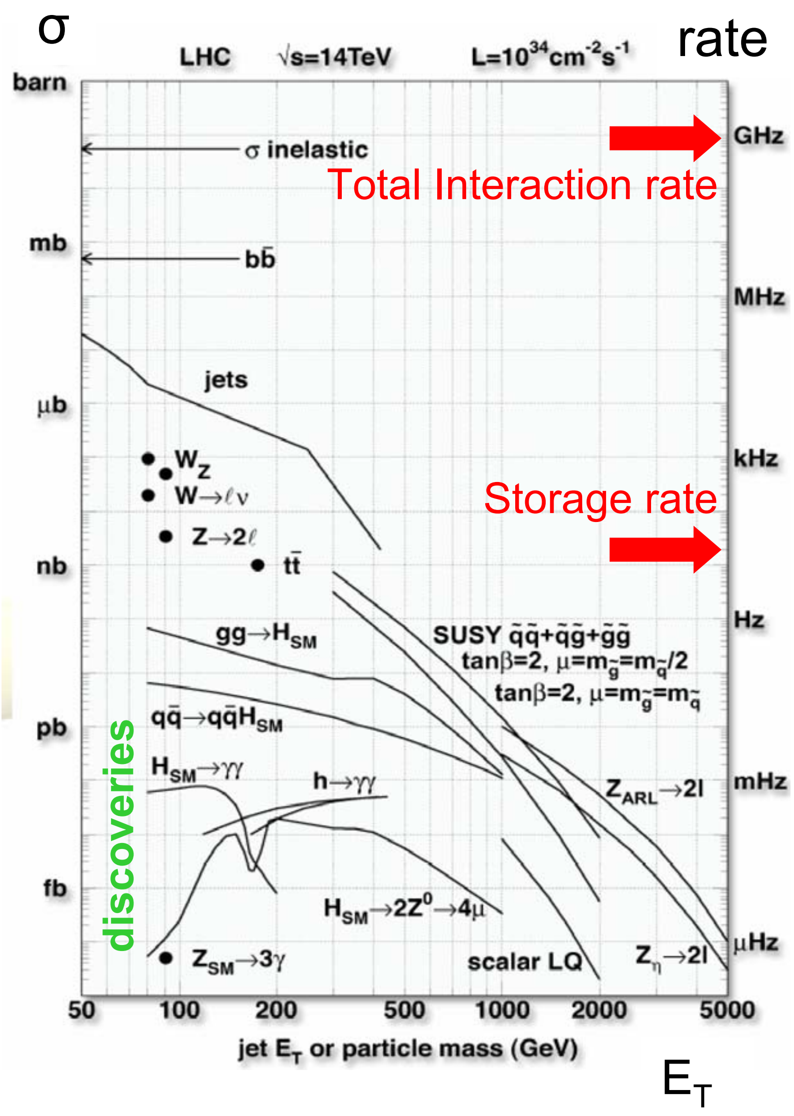
- Up to 23 overlay events: „Pile-up“ → Detectors with high granularity



	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
Calorimeter	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

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

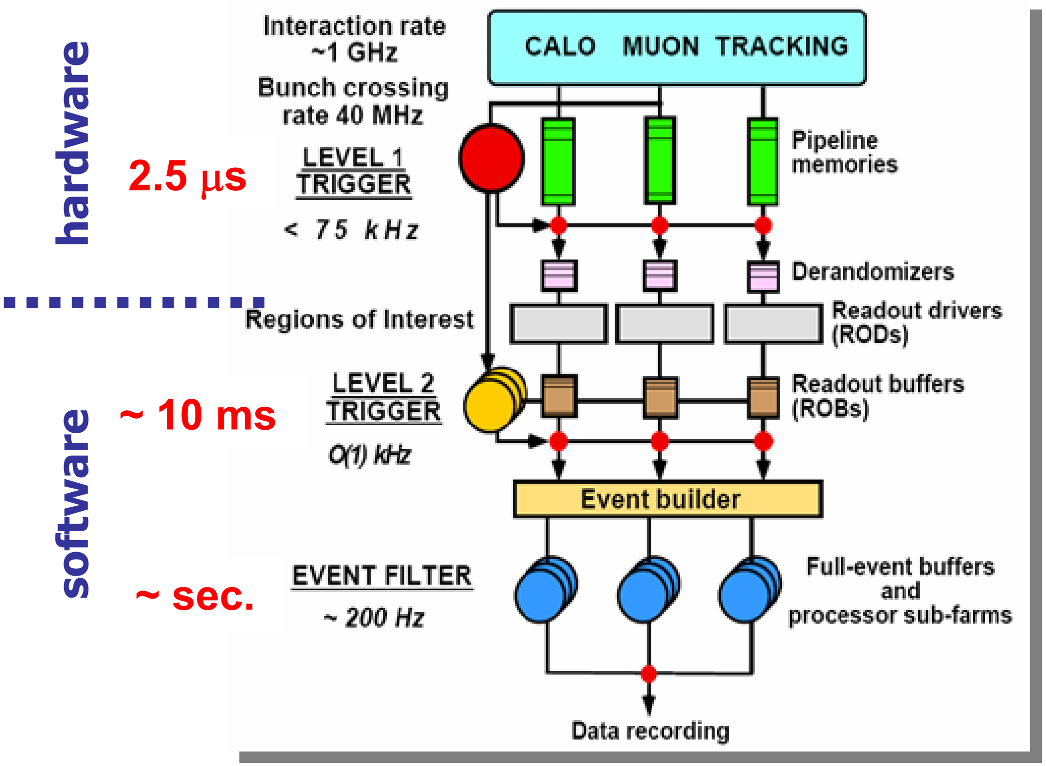
- Requirements on trigger systems:
  - High rejection rates
  - Efficient selection

→ 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:



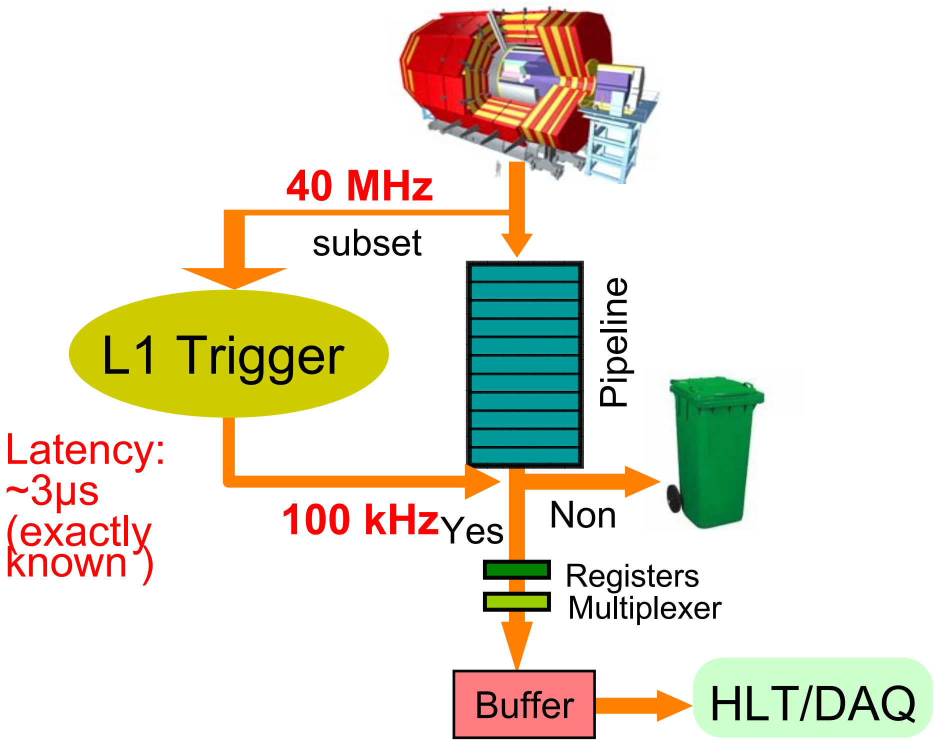
1) **LVL1** decision based on data from calorimeters and muon trigger chambers; synchronous at 40 MHz; bunch crossing identification

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):



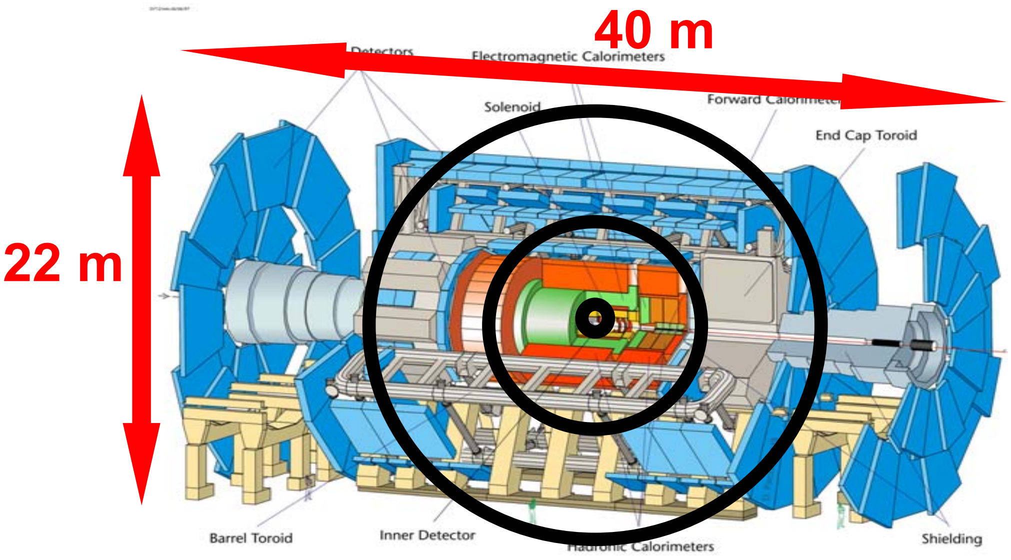
- During the latency all data must be kept in pipelines.
- Important: small latency

→ Fast decision
→ Hardware Trigger

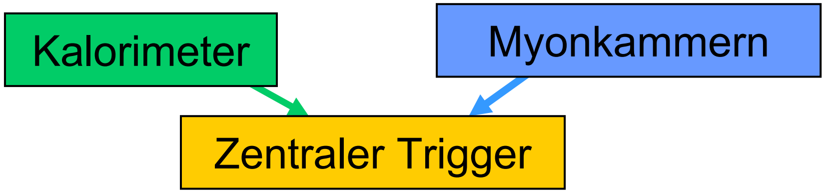
Level-1: synchronization and time resolution

- 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)

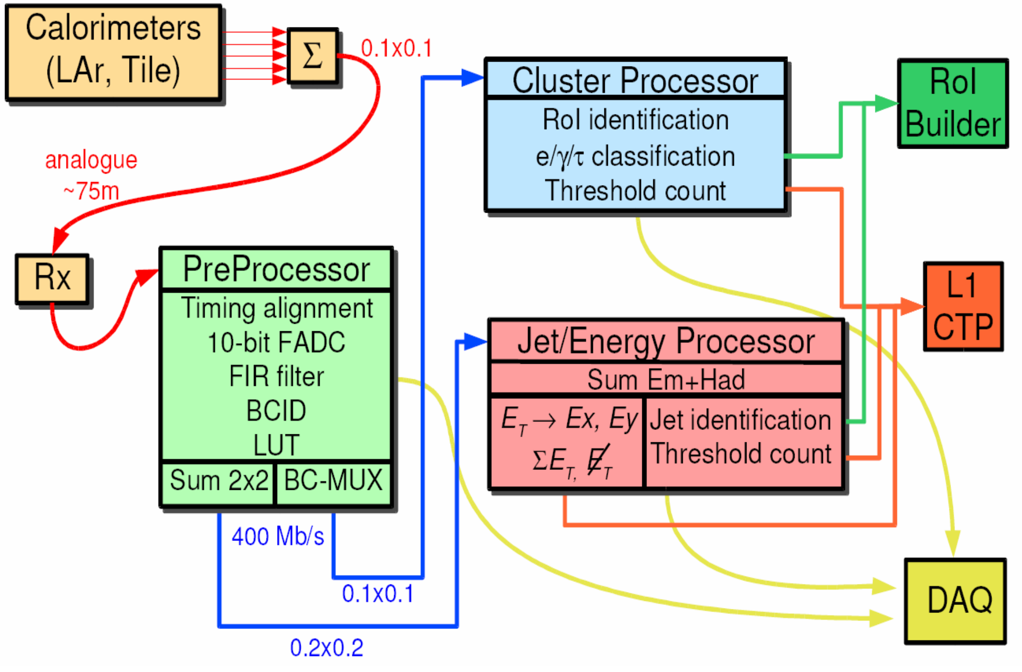

Kalorimeter

Myonkammern

Zentraler Trigger

Example: ATLAS Level-1 calorimeter trigger

- Elektronic components
  - Installed outside of experimental cavern
  - Mainly based on FPGAs


Calorimeters (LAr, Tile)

Σ

0.1x0.1

analogue ~75m

Rx

PreProcessor

Timing alignment
10-bit FADC
FIR filter
BCID
LUT

Sum 2x2 | BC-MUX

400 Mb/s

0.1x0.1

0.2x0.2

Cluster Processor

RoI identification
e/γ/τ classification
Threshold count

Jet/Energy Processor

Sum Em+Had

$E_T \to Ex, Ey$
$\Sigma E_T, \not{E}_T$

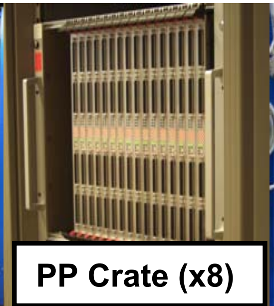
Jet identification
Threshold count

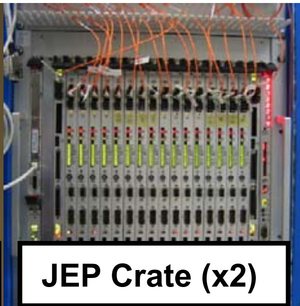
RoI Builder

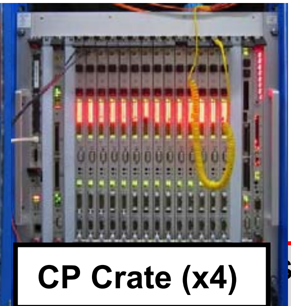
L1 CTP

DAQ

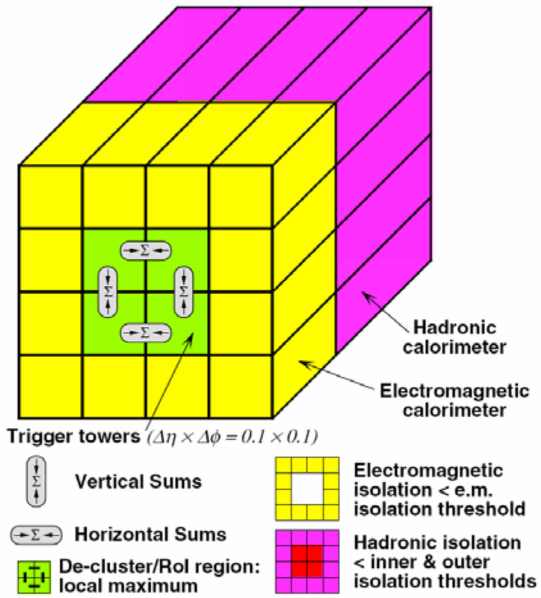

An. cables


PP Crate (x8)

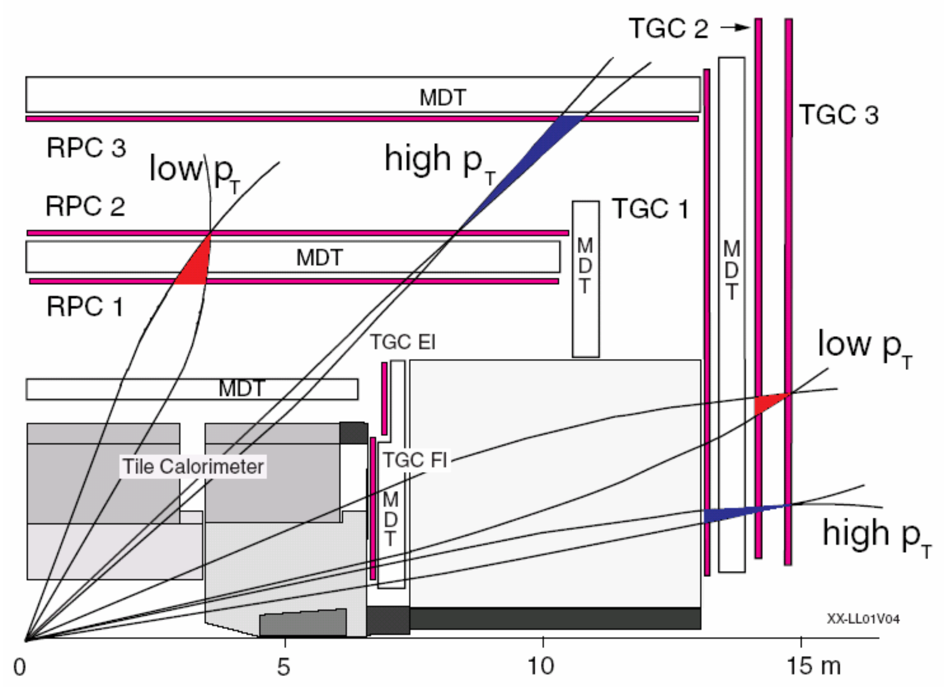

JEP Crate (x2)


CP Crate (x4)

- example algorithms:
  e/photon-Identification
  - aim: good discrimination e/Photon ←→ Jets
  - Identification of 0.2x0.2 region with local E_T maximum
  - cluster- und isolation cuts on various E_T sums.



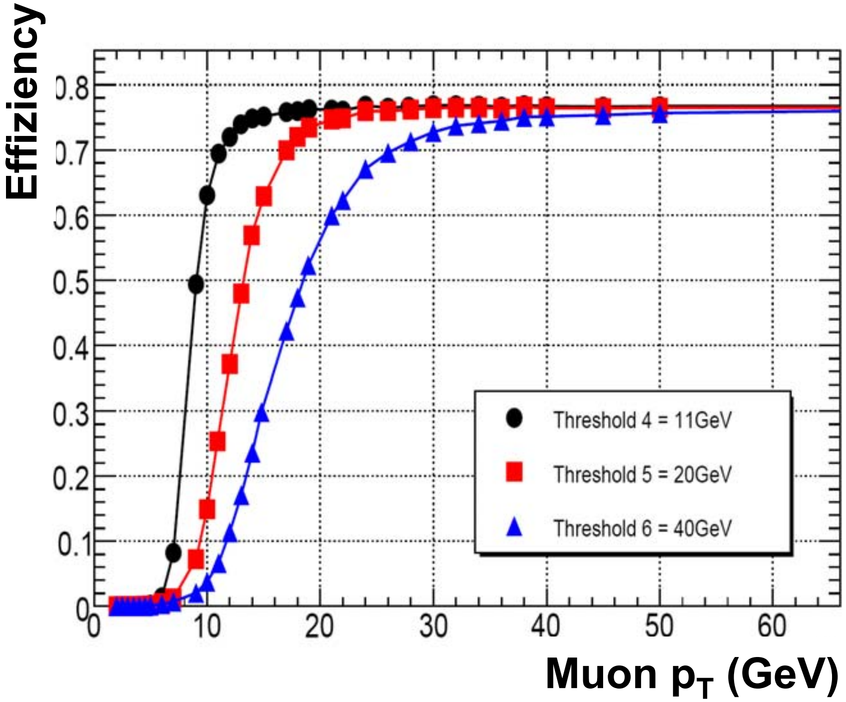
Level-1 Myon-Trigger: Beispiel ATLAS



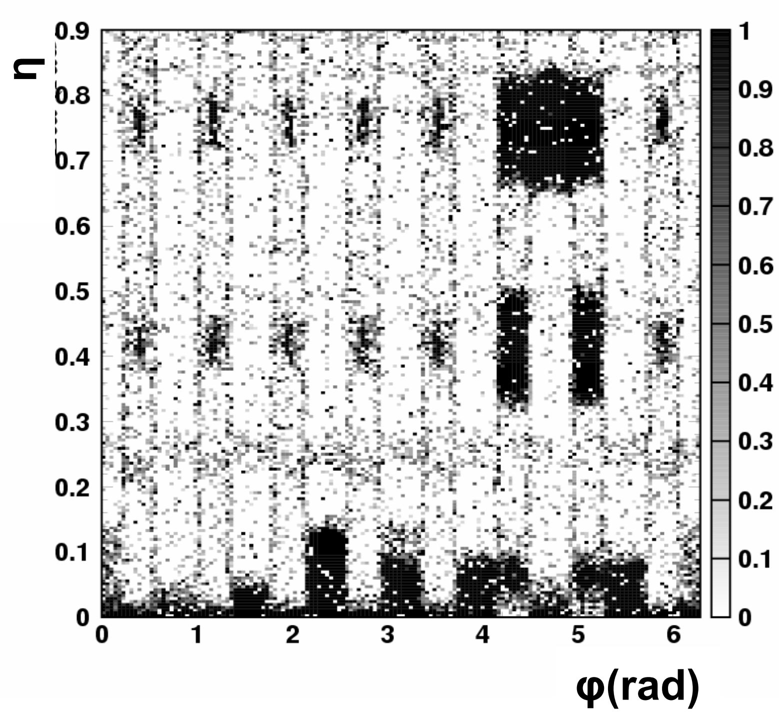
- Dedicated muon chambers with good time resolution:
- Local track search by electronics installed on the detector
- Search for coincidences in different detector layers
- Programmable width of coincidence windows allows coarse determination of the transverse momentum

Example: ATLAS Level-1 Muon-Trigger

„turn-on“–curves of the efficiency

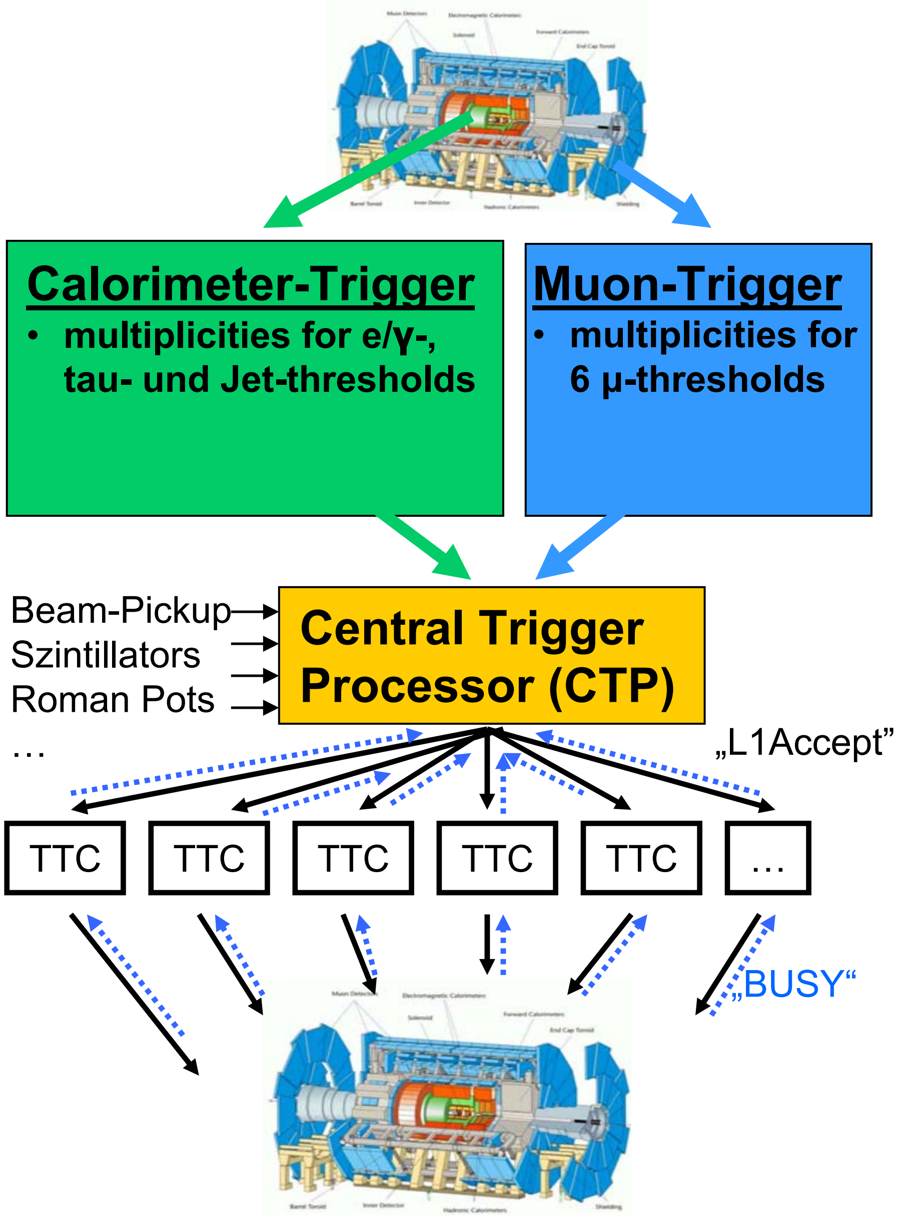


geometrical acceptance:



- efficiency in plateau: ~ 80%
- reason for inefficiency: geometrical acceptance

Example: ATLAS central Level-1 trigger



Calorimeter-Trigger

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

Muon-Trigger

- **multiplicities for 6 μ-thresholds**

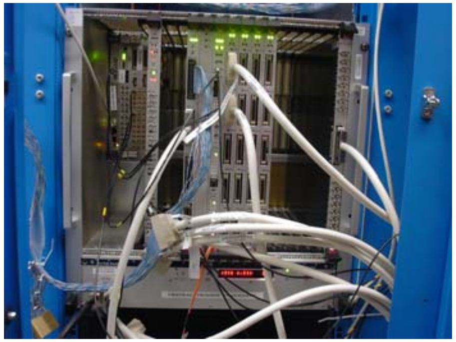
Beam-Pickup
Szintillators
Roman Pots
…

Central Trigger Processor (CTP)

„L1Accept"

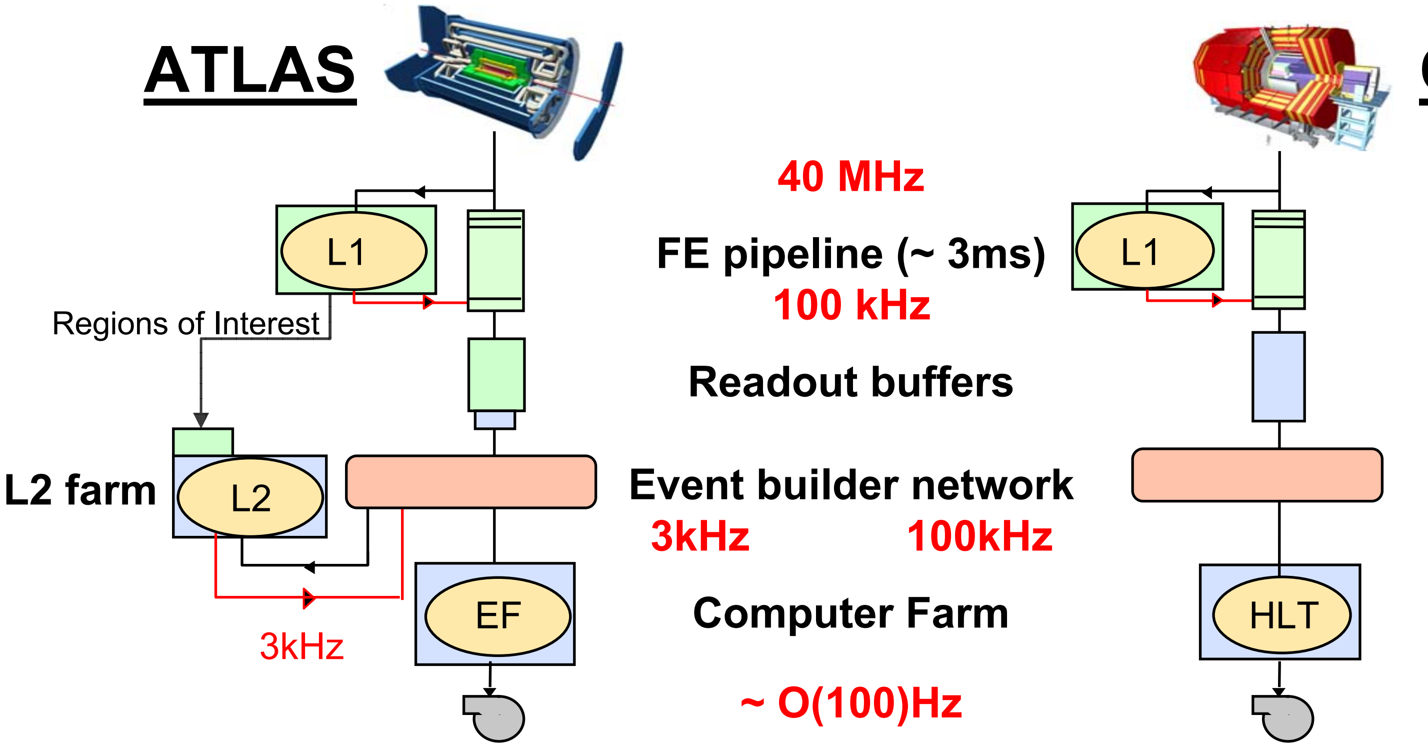
TTC | TTC | TTC | TTC | TTC | …

„BUSY"



- 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



40 MHz

FE pipeline (~ 3ms)

100 kHz

Readout buffers

Event builder network

3kHz 100kHz

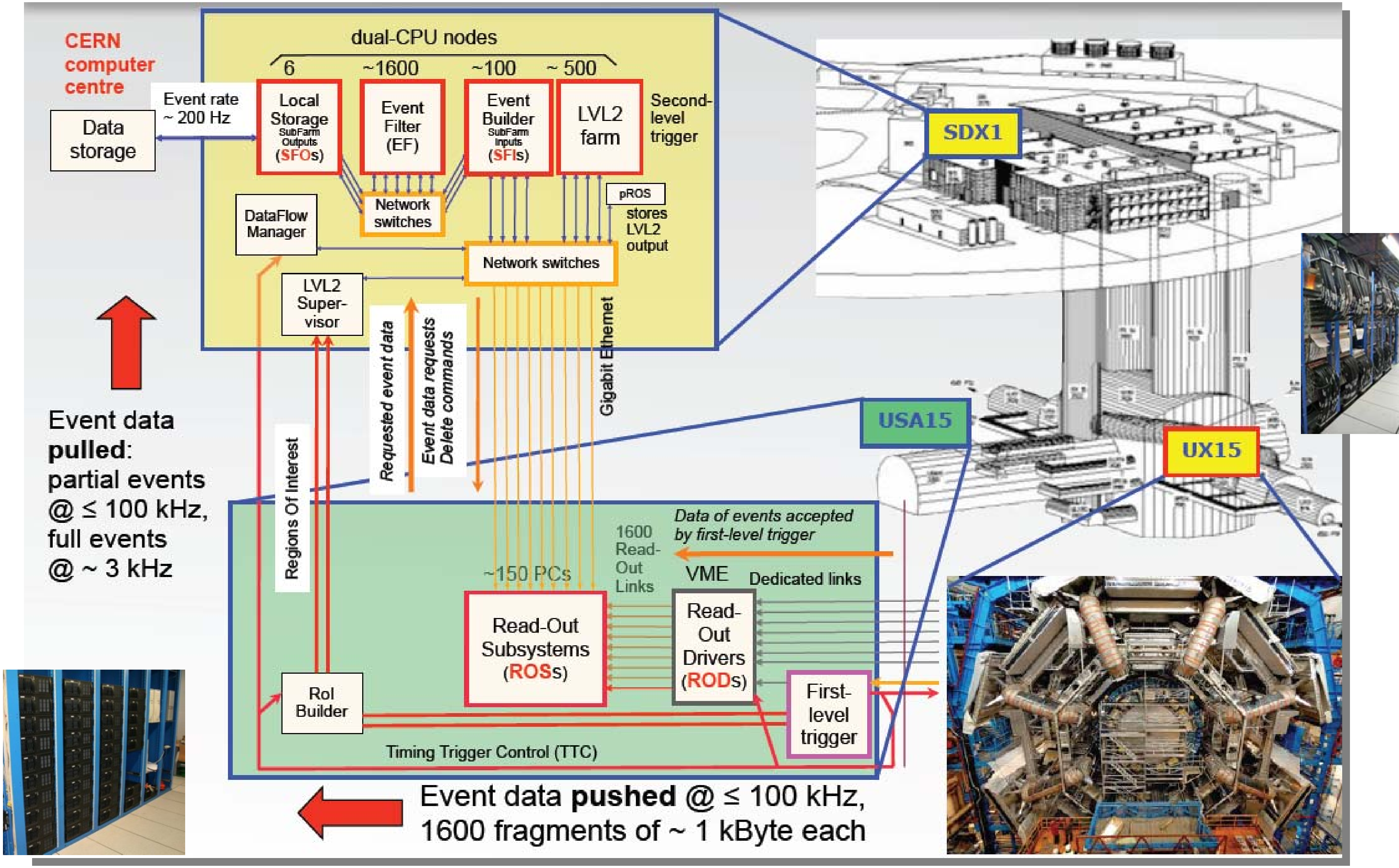
Computer Farm

~ 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



CERN computer centre

Data storage

Event rate ~ 200 Hz

dual-CPU nodes

6 | ~1600 | ~100 | ~ 500

Local Storage SubFarm Outputs (SFOs)

Event Filter (EF)

Event Builder SubFarm Inputs (SFIs)

LVL2 farm

Second-level trigger

Network switches

pROS

stores LVL2 output

DataFlow Manager

Network switches

LVL2 Super-visor

Requested event data

Event data requests
Delete commands

Gigabit Ethernet

Regions Of Interest

Data of events accepted by first-level trigger

1600 Read-Out Links

~150 PCs

VME

Dedicated links

Read-Out Subsystems (ROSs)

Read-Out Drivers (RODs)

First-level trigger

RoI Builder

Timing Trigger Control (TTC)

SDX1

USA15

UX15

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