CMS : an introduction

CMS detector: why is it like it is ?

T.Camporesi

A bit of history

Aachen 1990:

- Concept of a compact detector based on high B field superconducting solenoid

Evian 1992

- Conceptual Design

Letter of Intent, October 1992 [CERN/LHCC 92-3]

Technical Proposal, Dec 1994 [CERN/LHCC 94-38]

Memorandum of Understanding (MoU) 1998

Technical Design Reports (available from the CMS secretariat)

- Detectors 1997-98;
- Lvl-1 Trigger: 2000;
- DAQ/HLT: 2002
- Computing & Physics TDR: 2005-06

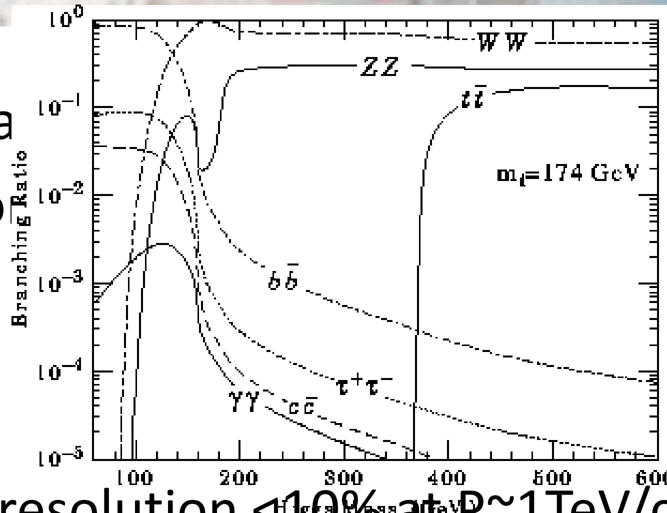
2008: First data taking: LHC Incident. Restart in 2009.

2010-2013 Data taking [Run I]:

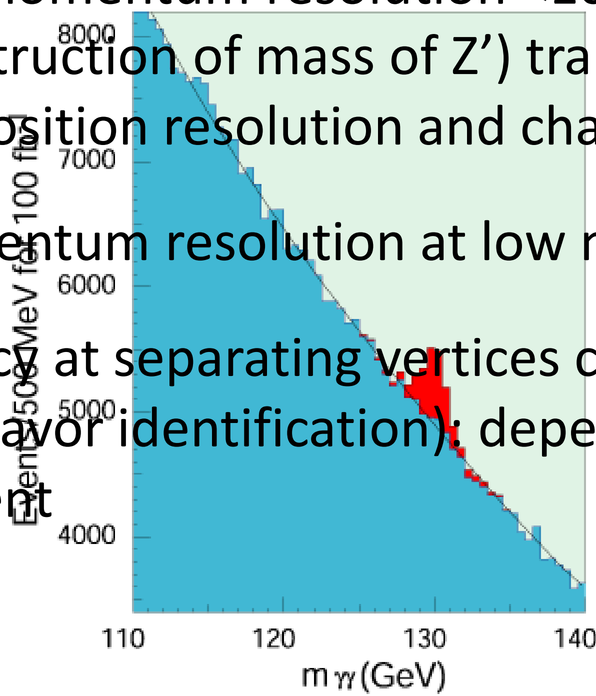
- 7 TeV (5fb–1)
- 8 TeV (20 fb–1)
- Heavy Ion: Pb-Pb and p-PB

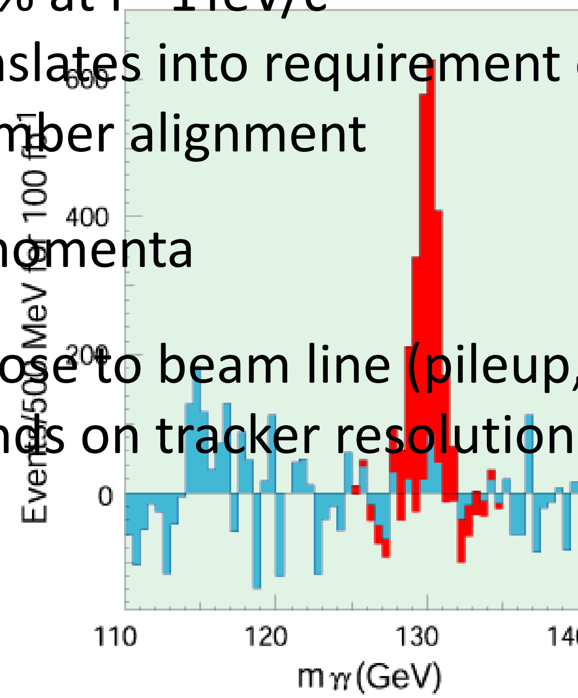
pp physics objectives

- The LHC primary goa … etry breaking:
- Higgs decay in γγ: co … of EM energy resolution <0.5%

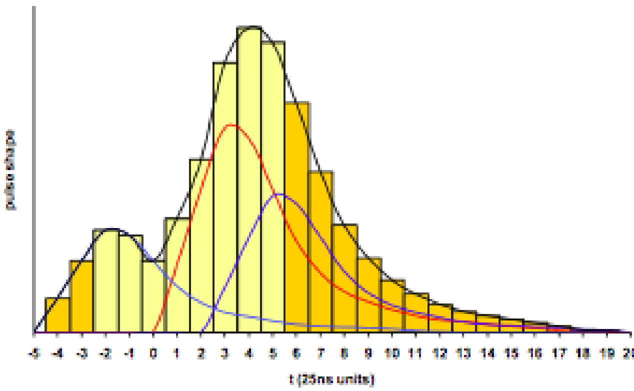


- Muon momentum resolution <10% at P~1TeV/c (reconstruction of mass of Z') translates into requirement on m-hit position resolution and chamber alignment
- % momentum resolution at low momenta
- Efficiency at separating vertices close to beam line (pileup, heavy flavor identification): depends on tracker resolution and alignment

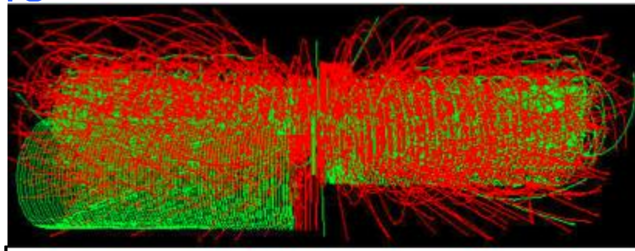




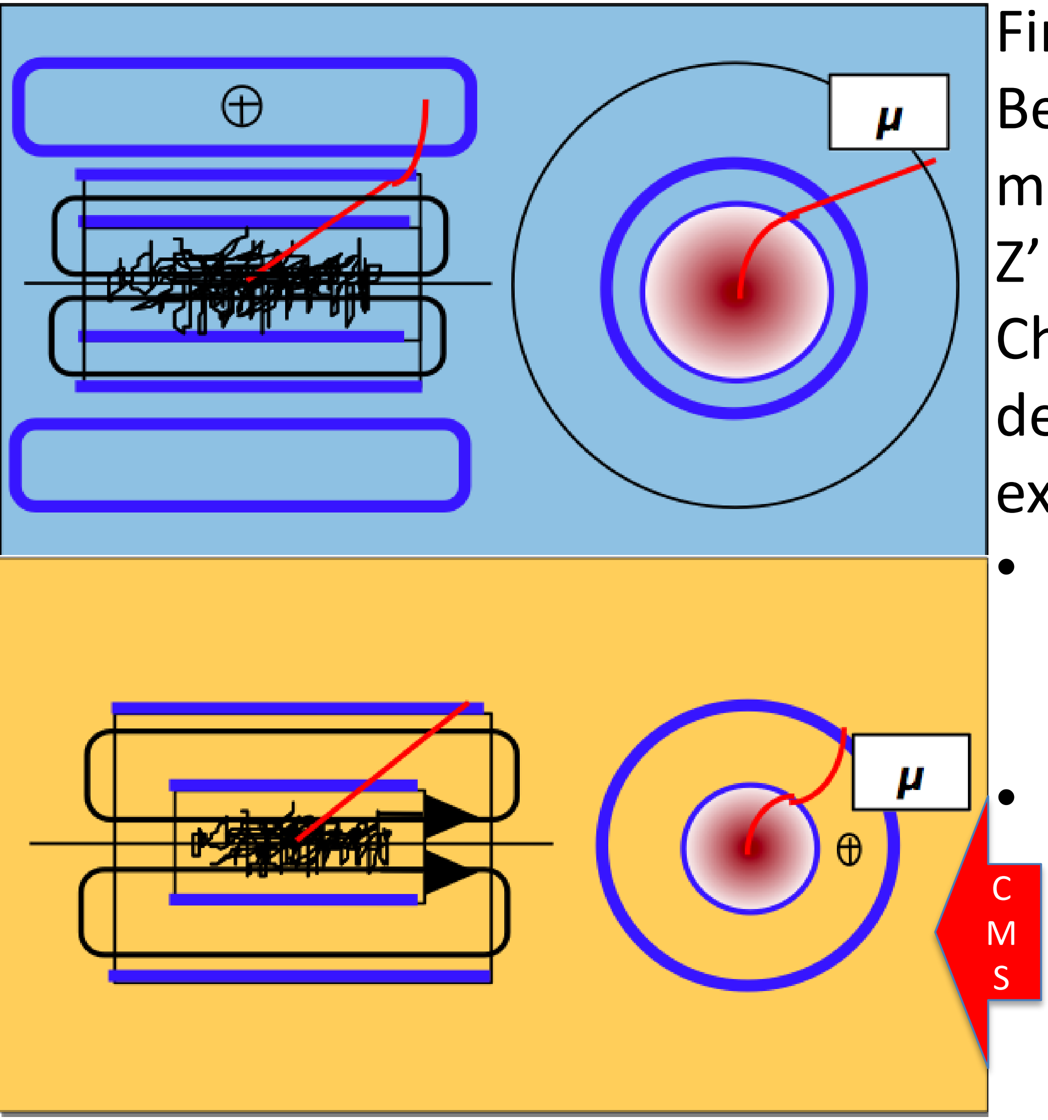
The LHC constraints



- Bunch separation 25 ns: a challenge for the readout electronics
  - Need of fast electronics to avoid piling up signals from one bunch to the next
  - Need of bunch identification (even a trigger level)
- Ultimate luminosity 2 10^{34} cm^2/s : ~ 40 interactions per crossing
  - Need highly granular detector to mitigate 'channel' pileup: many channels
- Radiation damage: the high rate hadron production in LHC requires development of radiation hard detector/electronics
  - Forward calorimeters elements will integrate in excess of 10^{16} neutron over 10 years of LHC operation
  - Forward trackers will integrate in excess of 10^{16} charged particles over the operation of LHC



A pp general purpose detector



First thing first: tracking: Benchmark 10% P resolution for muons of 1 TeV (in order to detect Z')

Choice of magnet configuration determines the geometry of the experiment: CMS

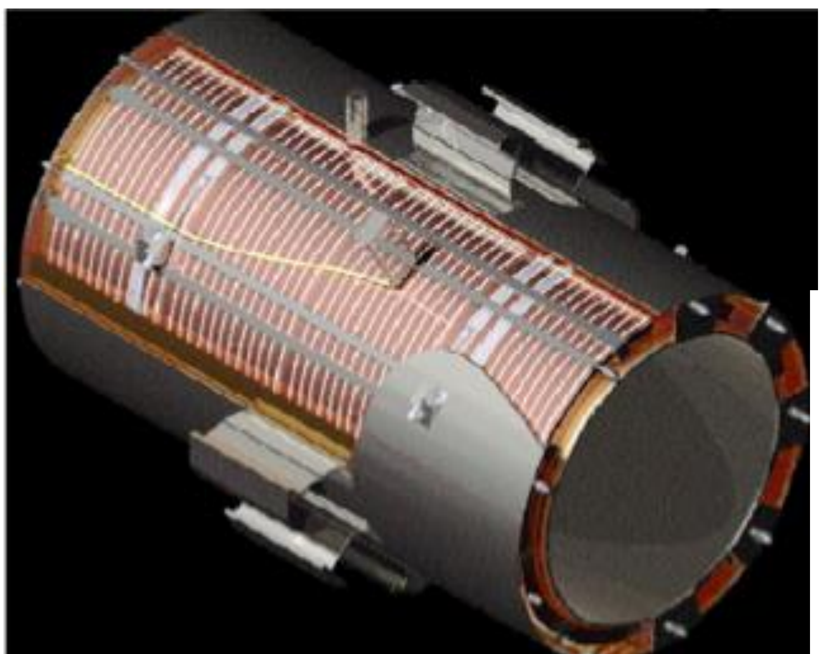
- Measurement of p in tracker and B return flux; Iron-core solenoid.
- Properties:
  - Can use vertex to constrain track
  - Large B and large dL

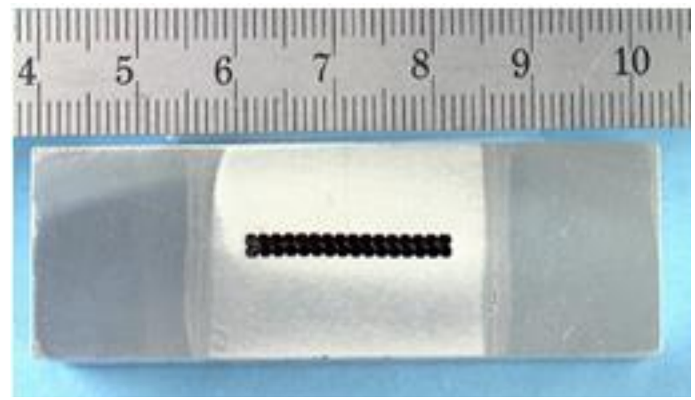
CMS solenoid: an engineering achievement

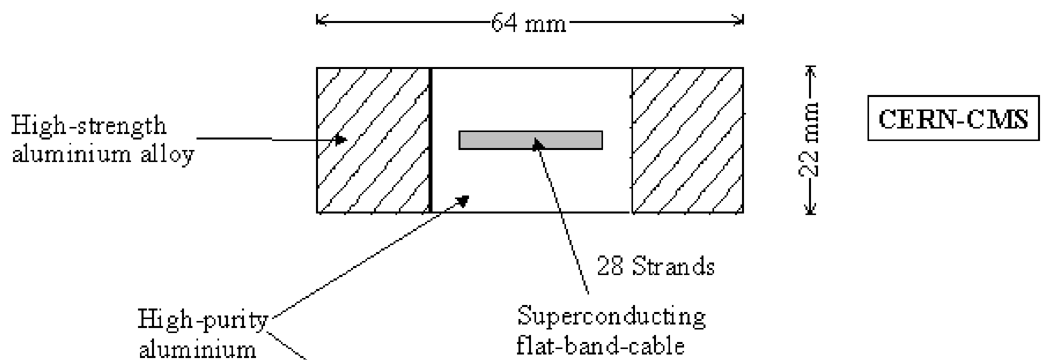
B= 4 tesla (magnetic energy stored : 2.7 GJ !!)

$B=\mu_0 nI$; @2168 turns/m hence 20 KA

Challenge: Superconducting cable structure to withstand the magnetic forces



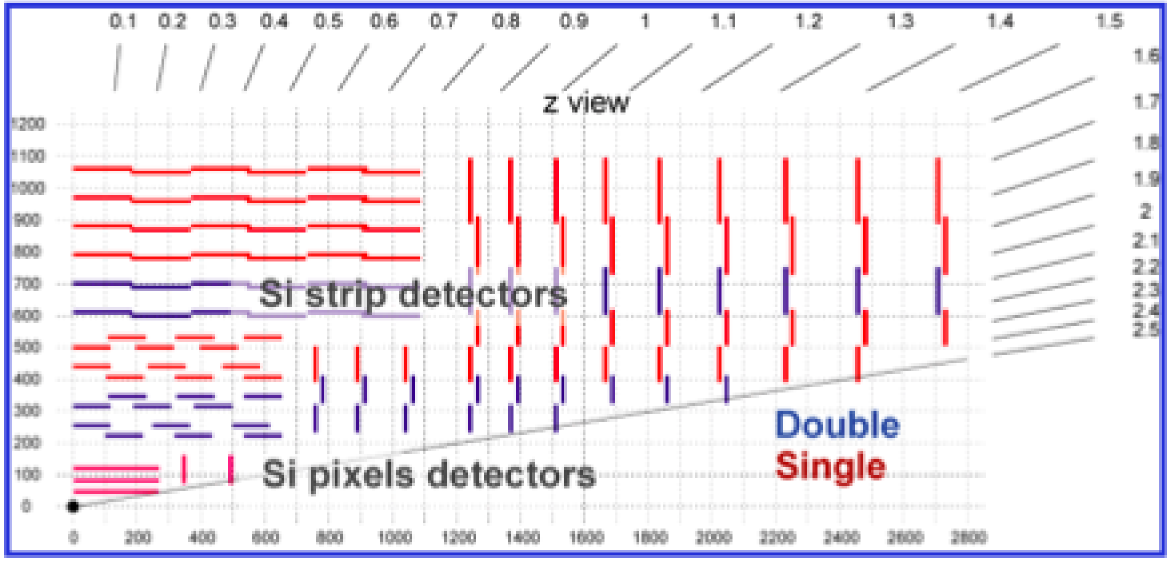




Tracker

- Resolution goals:
  - $\Delta p_T/p_T \sim 0.1 p_T[\text{TeV}]$
  - Good resolution for narrow Signal ($H \to 4\mu$)
  - Match calo resolution / Calo calibration ($W \to e\nu$)
  - ..and good isolation capability (2 particle separation etc.)
- CMS solution: 10 Si Strip (4 double) layers + 3 Si pixel layers/fwd disks (added after initial proposal)

Tracker



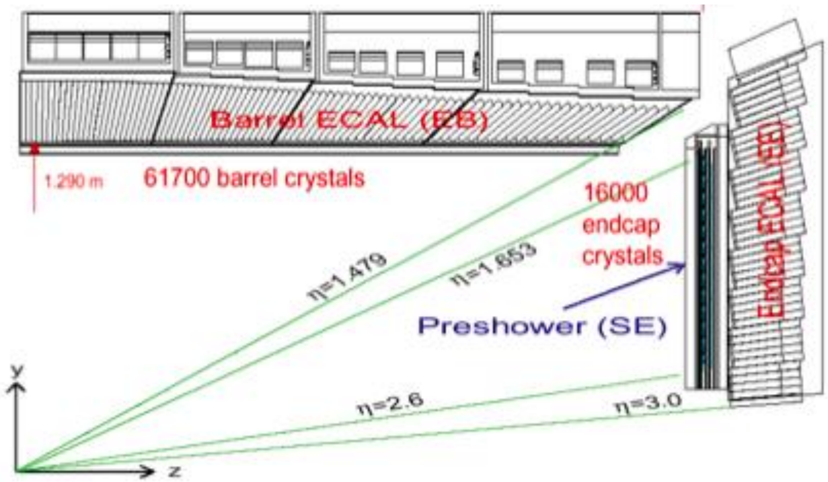
Outer radius: 110 cm
Length = 270 cm
B= 4Tesla
On average 12 hits per track
Hit resol: pitch/√12

$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100\mu m}\right)^{1} \left(\frac{1.1m}{L}\right)^{2} \left(\frac{4T}{B}\right)^{1} \left(\frac{p}{1Tev}\right)$$

Pitch ~100 μm
66 Million pixels, 10 million strips: low occupancy at ultimate Lumi
Run at <-10ºC for rad hardness (>100 time better than at 25ºC)

ECAL

- Benchmark: H→γγ. S/N determined by calo resolution (Higgs width very narrow and QCD background 2 order of magnitude larger)
- CMS choice : Crystal calorimeter



Properties of some crystals

Crystal	X_0 (cm)	R_M (cm)	Light Yield Gammas/MeV	Peak (nm)	Decay (ns)
BaF_2	2.06	3.4	2000	210	0.6
			6500	310	620
CeF_3	1.68	2.6	2000	300	5
				340	20
$PbWO_4$	0.89	2.2	250 !	440	5-15

76000 Crystals
Need of new Photodetector (B-Field)

Avalanche Photo Detector (APDs)

HCAL

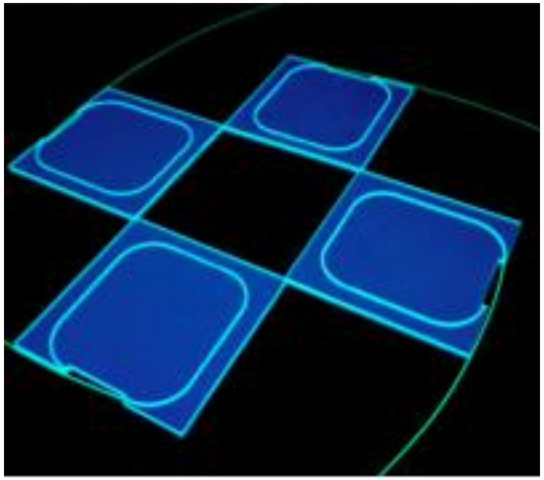
- HCAL requirement:
  - Jet energy resolution:
    limited by jet algorithm, fragmentation, magnetic field and pileup at high luminosity . At high momentum need fine lateral segmentation as jets are collimated.
  - Missing transverse energy resolution (SUSY searches)
    Forward coverage to $|\eta|<5$
    Hermeticity – minimize cracks and dead areas
    Absence of tails in energy distribution: more important that a low value in the stochastic term
- Good forward coverage required to tag processes from vector-boson fusion

HCAL

$$\frac{\sigma_E}{E}(\%) \sim \frac{100-150\%}{\sqrt{E}}$$

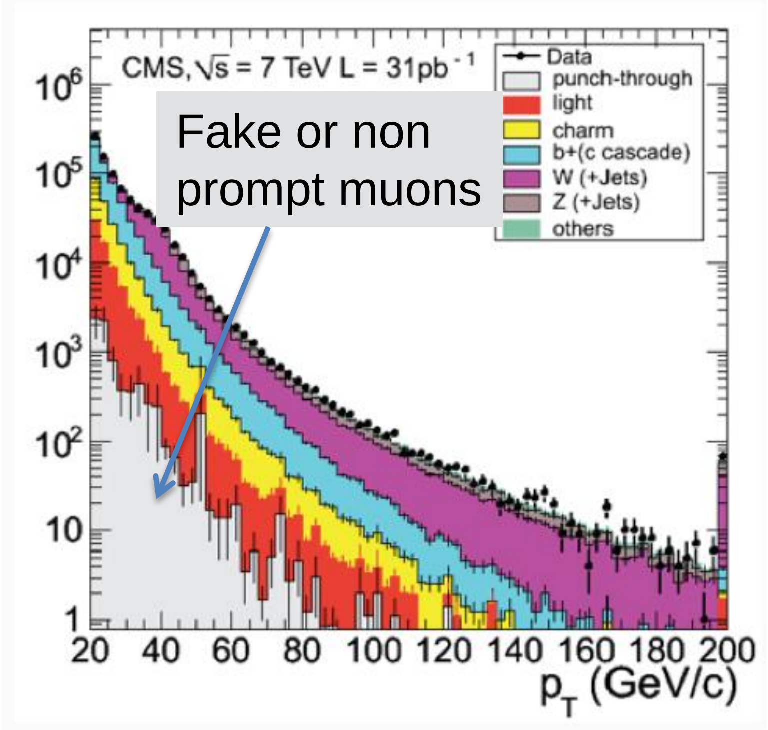
Tower size: Δη x Δφ=0.087 x 0.087

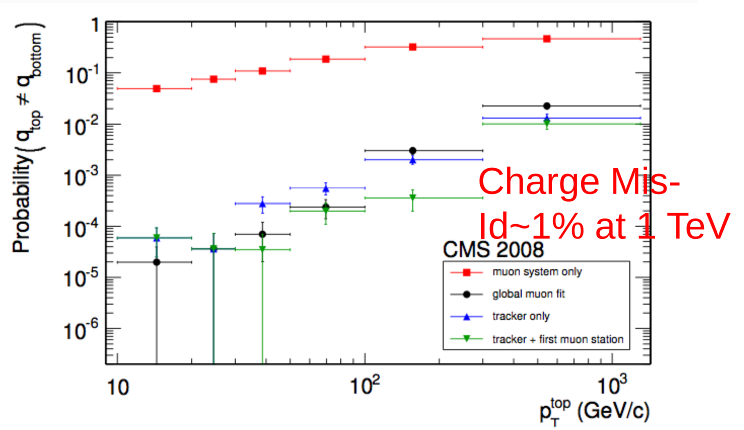
This is the basic trigger unit



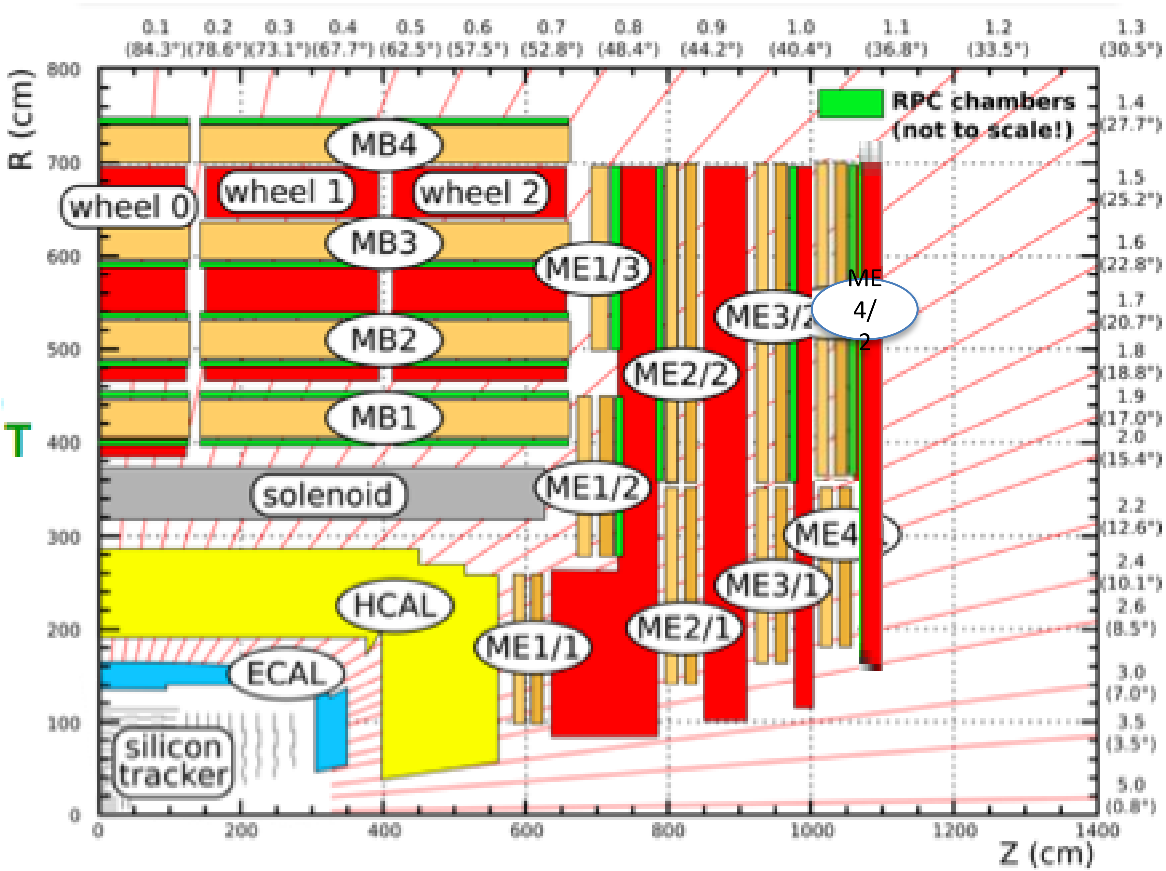
Muons

- Performance requirements
  - L1 trigger: very high rate from Real muons (semileptonic decays of b,c). Need to keep p_T cut as low as possible (~5 GeV)
  - P_T Resolution: need very high $B d\ell$ for high momentum muons and good chamber hit resolution (~100 μm). At low momentum Si tracking is better
  - Charge mis-id ~1% at 1 TeV





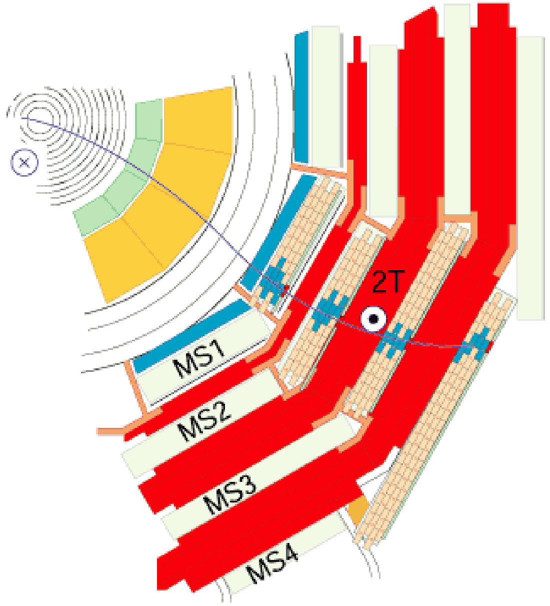
Muons



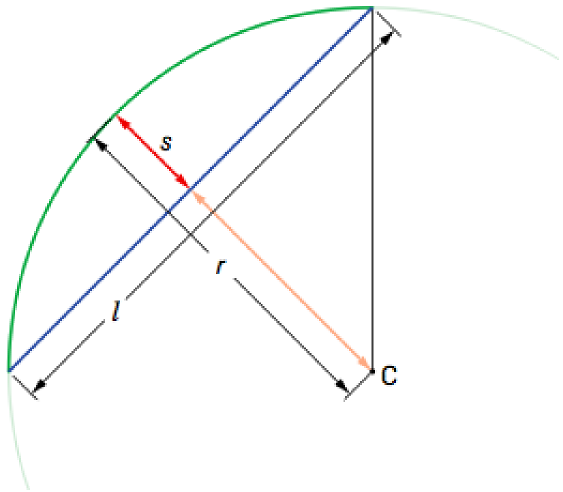
12 ktons of iron absorber and B-field flux return

Bending in iron + muon tracking: trigger info; and link with main tracker

Sophisticated alignment system



Particle radius in B field



$$r = \frac{\ell^2}{8s} + \frac{s}{2}$$

When s small (ie. Relatively high Pt)

$$r \gg \frac{\ell^2}{8s}$$

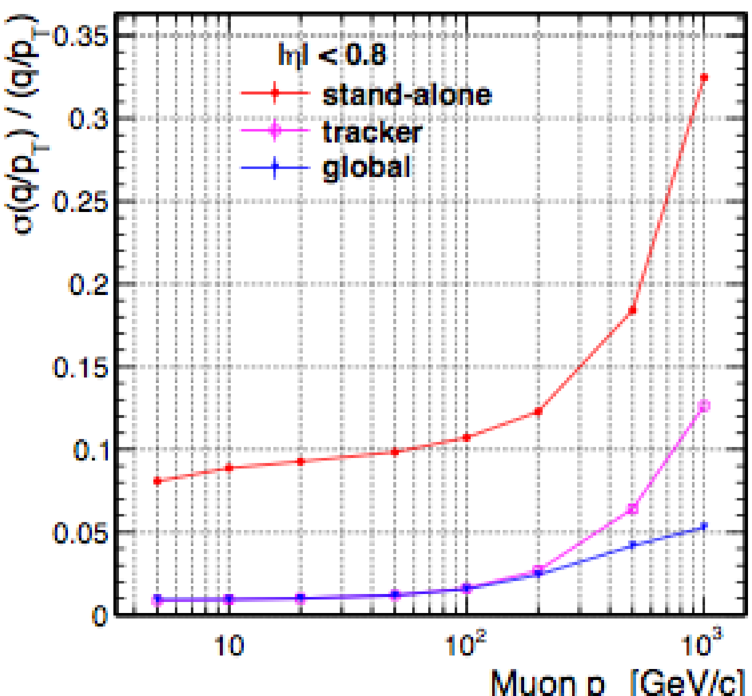
Note about CMS μ measurement

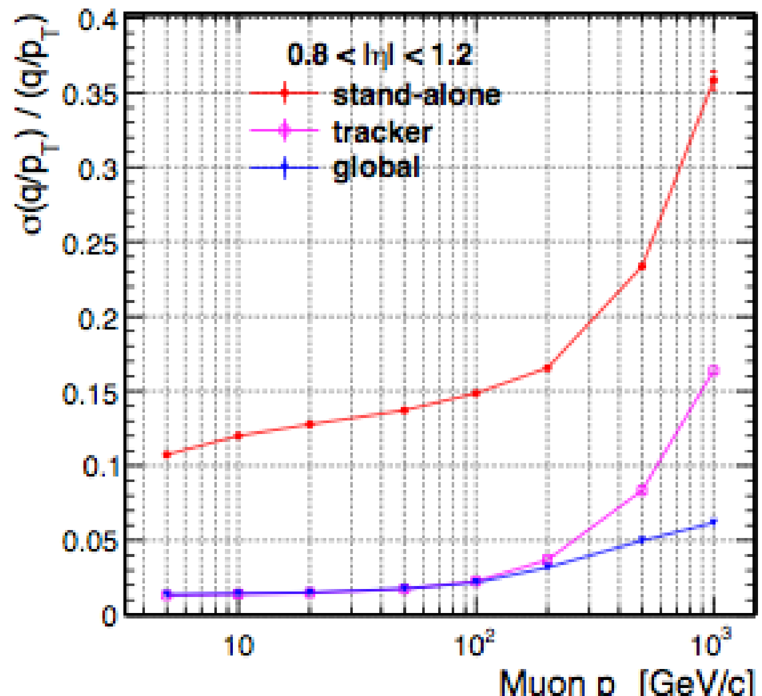
$$P_t \; \mu \; 0.3 \times B \times r$$

$$r \; » \; \frac{\ell^2}{8s} \qquad \frac{\Delta P_t}{P_t} \propto \frac{\Delta s}{\ell^2} + \ldots$$

Where ℓ is the 'cord' length of the track in the B field and S the sagitta

In CMS the tracker ends at 1.1 m radius while the first layer of the DT is just outside the coil (i.e. a track integrates constant B up to the inner edge of the solenoid i.e. ~3 m)

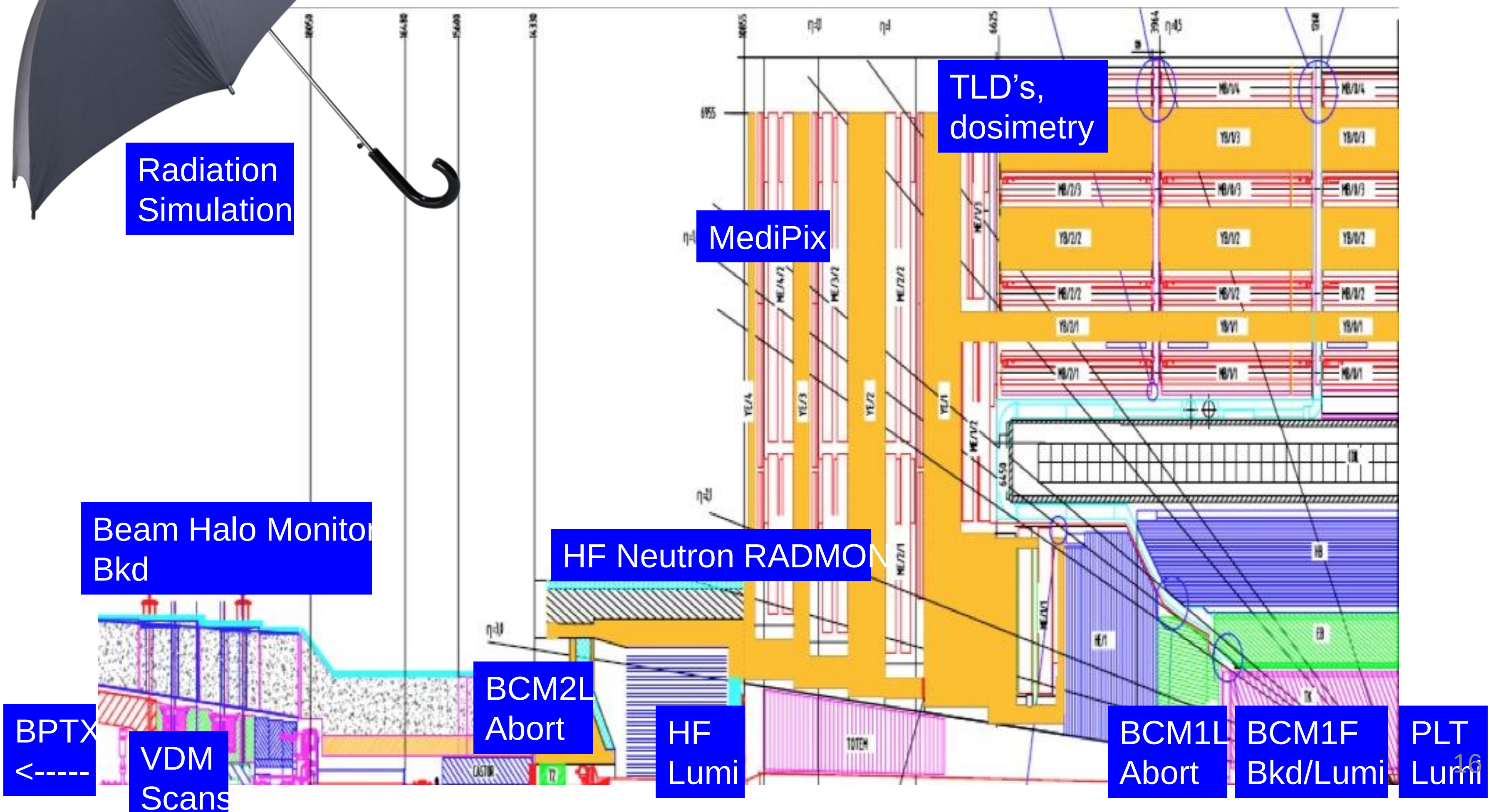




A new Project : BRIL

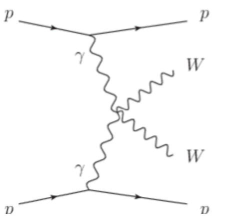
- ➔ LHC
- ➔ CMS TC
- ➔ CMS RC
- ➔ CMS POG

Covering anything related to interfacing CMS to the LHC



A new project :CTPPS

- We have signed a MOU with TOTEM to create the Totem CMS PPS project (agreed on PM: Joao Varela & TC: Joachim Baechler)
- Roman pots (new or re-engineered) moved 147m to 220 region; housing pixel tracking + fast timing detectors



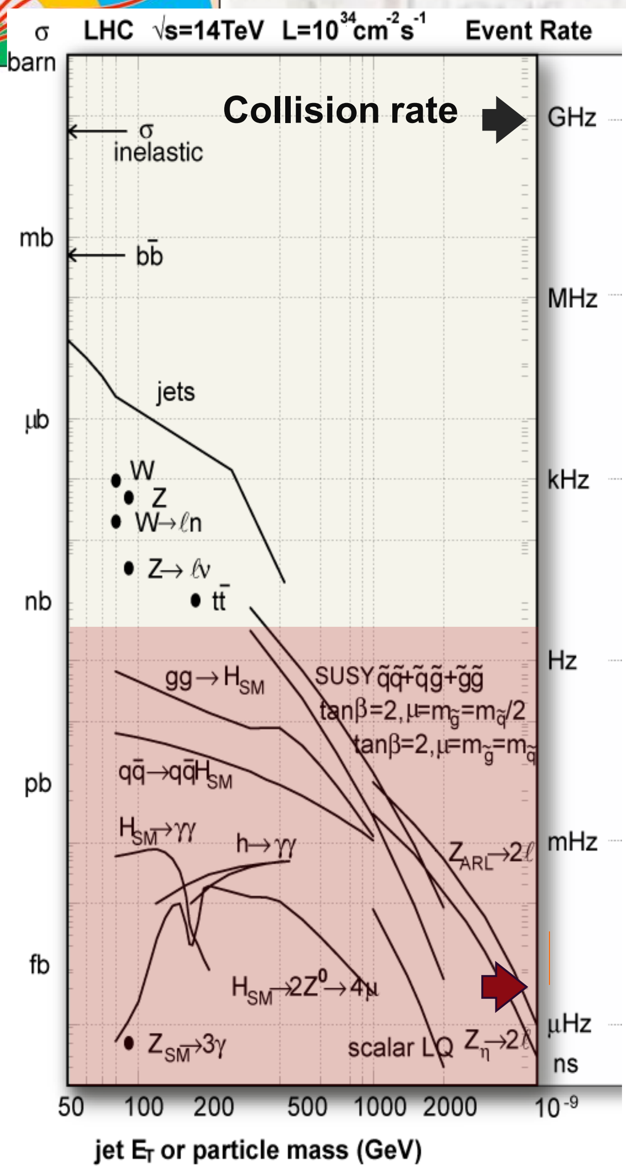
- Measure $\gamma\gamma \rightarrow W^+W^-$
- **Quartic gauge boson coupling WW$\gamma\gamma$**
  sensitivity to anomalous couplings larger than at LEP, or Tevatron
- Also search for SM forbidden ZZ$\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings

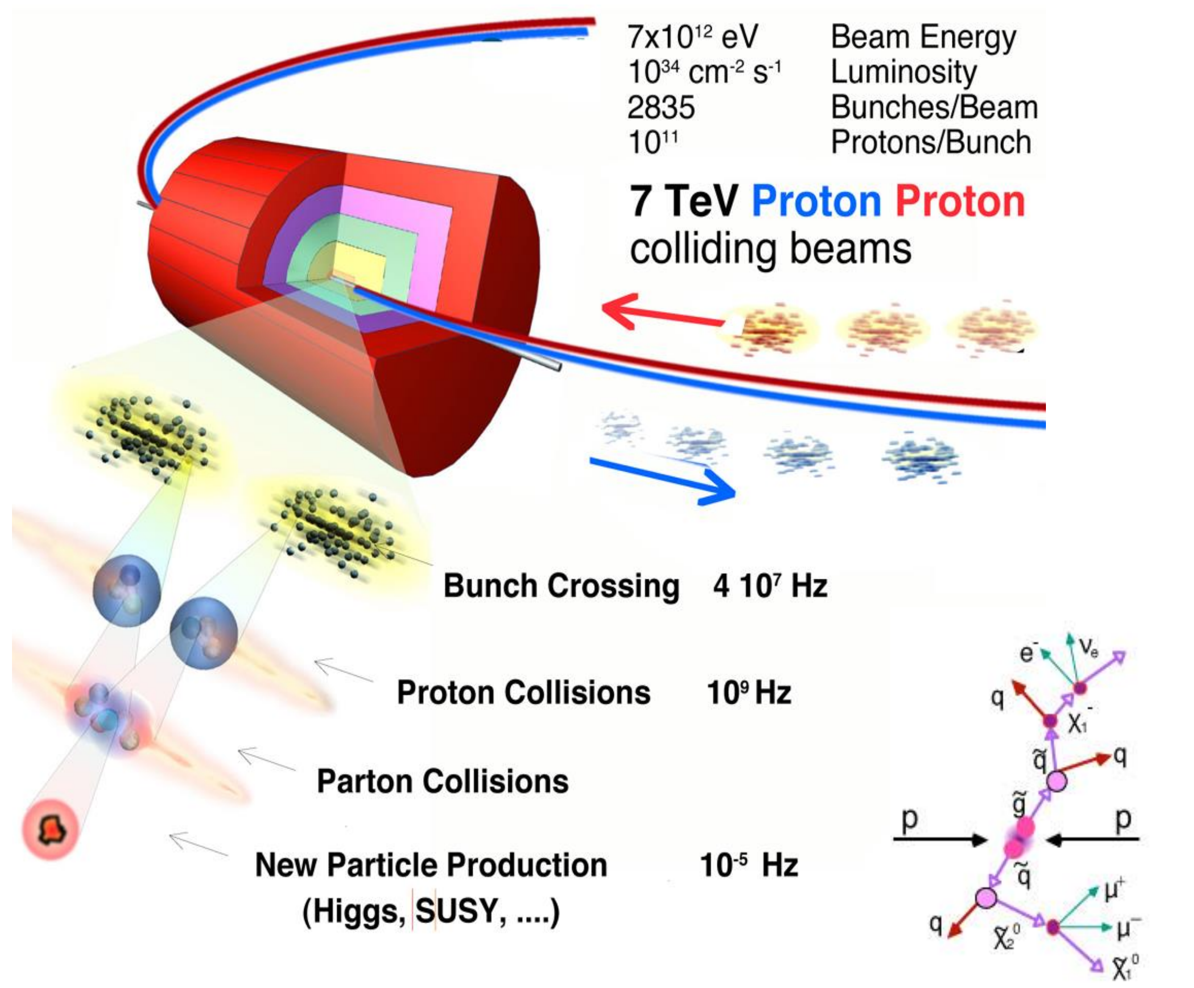
LHC used as a “tagged” photon-photon collider at √s(©©) larger than the ones explored at LEP

- Exclusive dijets, M(jj) up to ~ 750-1000 GeV.
- **Pure gluon-jets**, small component of b-bbar dijets
  - q-qbar dijets forbidden for massless quarks at t = 0.
- Test of pQCD mechanisms of exclusive production.

Gluon-jet factory, with very little quark-jet contamination

P P collisions at LHC

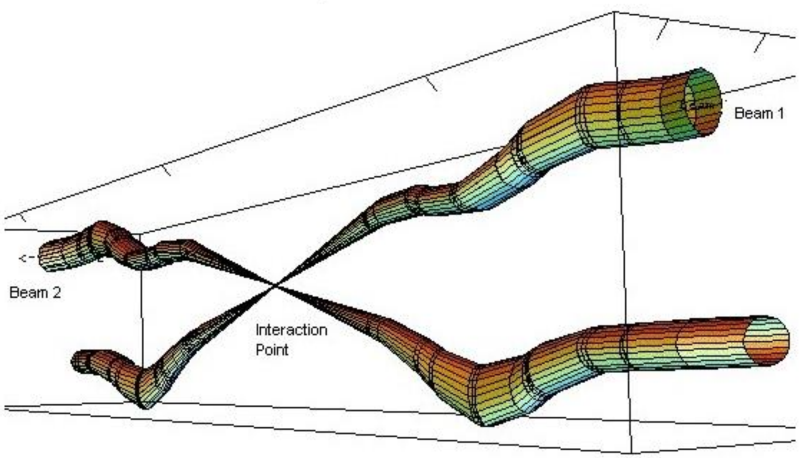




Collision Rates: **$\sim 10^9$ Hz,**
Event Selection: **$\sim 1/10^{13}$**

LHC and lumi : a digression

A few definitions of quantities you will hear mentioned often



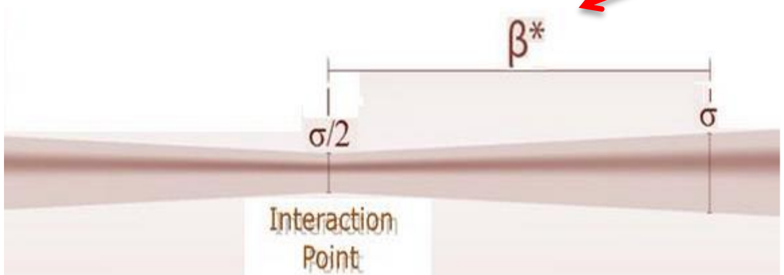
Transverse Emittance (ε) can be defined as the smallest opening you can squeeze the beam through, and can also be considered as a measurement of the parallelism of a beam.

The amplitude function, β , is determined by the accelerator magnet configuration (basically, the quadrupole magnet arrangement) and powering. When expressed in terms of σ (cross-sectional size of the bunch) and the transverse emittance, the amplitude function β becomes $\beta = \pi \cdot \sigma^2 / \varepsilon$

β^* is referred as the distance from the focus point that the beam width is twice as wide as the focus point

$$L = f \cdot N_1 N_2 / (4 \pi \sigma_x \sigma_y)$$

$$L = f \cdot N_1 N_2 / (4 \cdot \varepsilon \cdot \beta^*)$$



At design time ultimate
lumi = $2\ 10^{34}$ cm^2/s defined by :
f= $40\ 10^6$ Hz
N< $1.3\ 10^{11}$ p/bunch
ε_n = 3,75 μm
β^* =0.55 m

Achieved so far
lumi = 710^{33} cm^2/s
f= $20\ 10^6$ Hz
N< $1.7\ 10^{11}$ p/bunch
ε_n = 1,75 μm
β^* =0.60 m

Lumi: how to measure

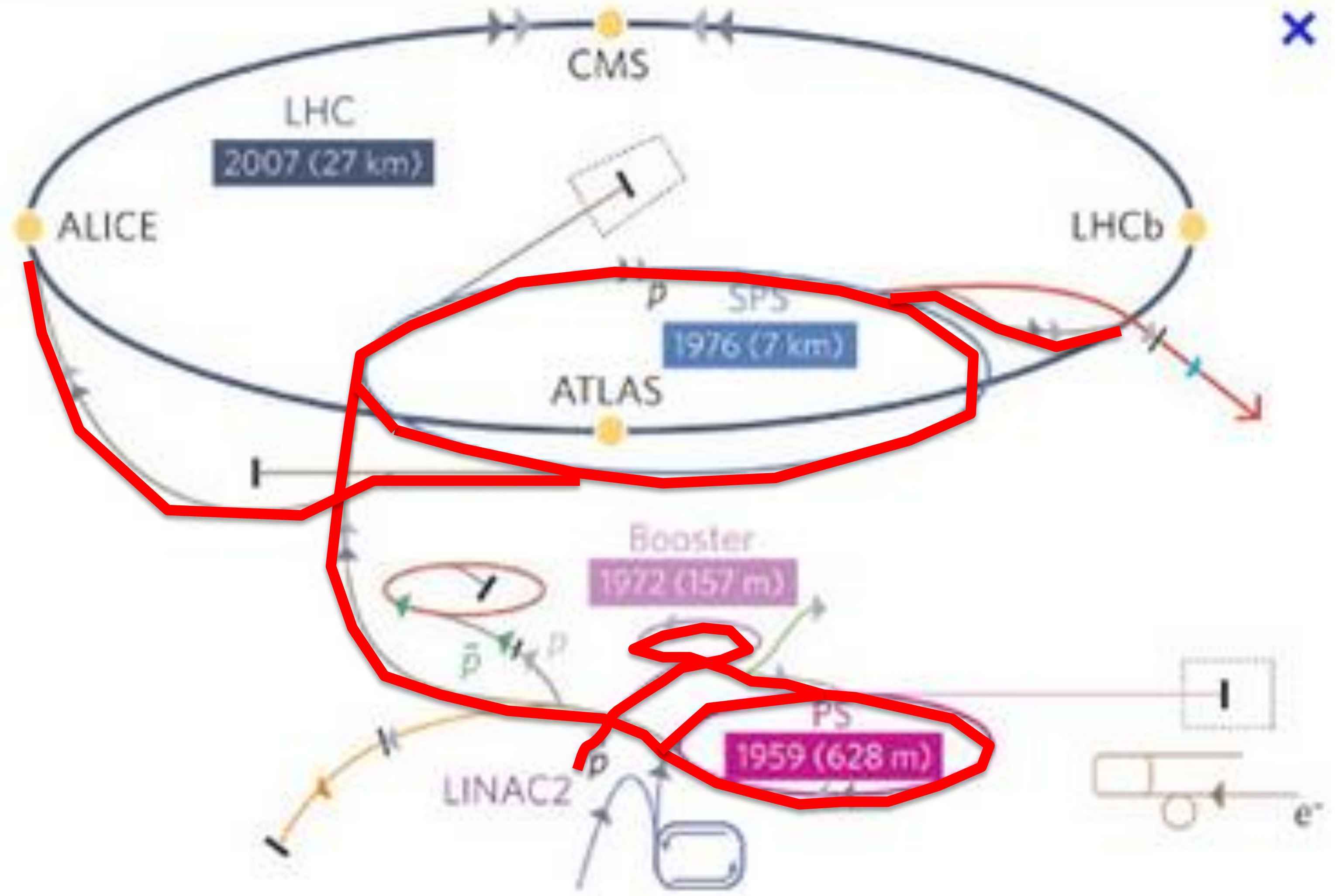
$$dR/dt = L\,\sigma$$

Where dR/dt is the rate of production of a pocess which has cross sectio σ
The luminosity L quantifies the performance of the collider in this respect (units $cm^{-2}s^{-1}$)
In practice if σ_x and σ_y are respectively the transverse areas of the beam interaction region we use the equivalent formula to measure the Luminosity. The areas of the beam are obtained by scanning the two beams and measuring the rate of collisions while the numbero of protons in the bunches is measured by dedicated devices of the accelerator

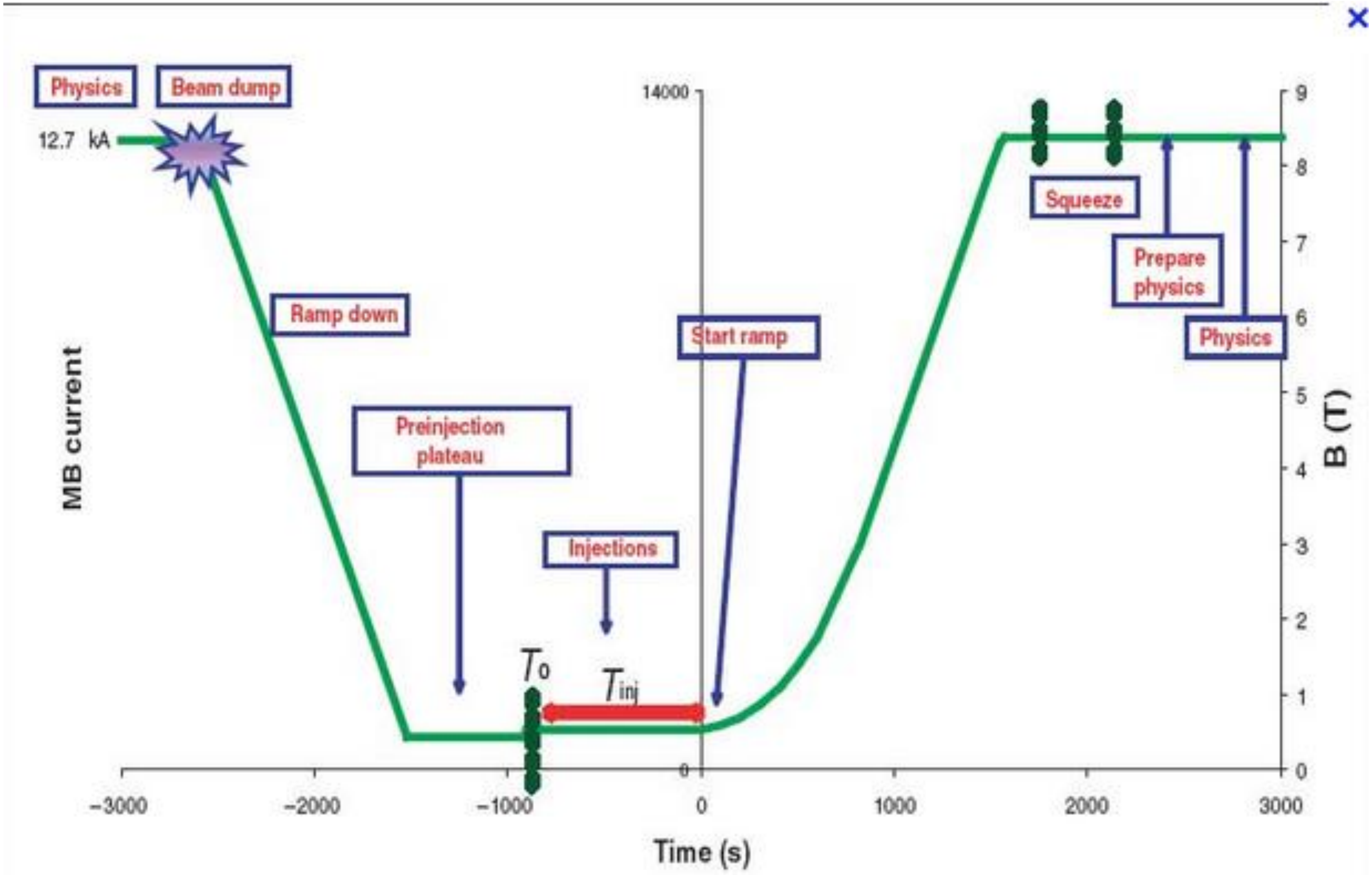
$$L = f \cdot N_1 N_2 /(4\pi\sigma_x\,\sigma_y)$$

Beams at CERN

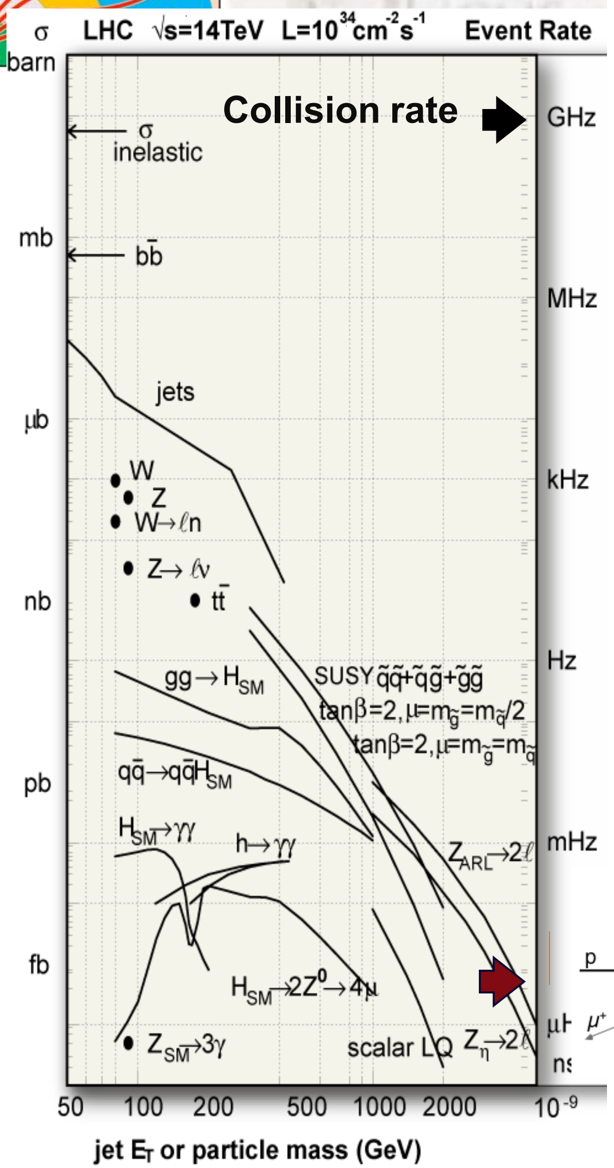
Most fo the CERN accelerator complex is involved in LHC operation: the efficiency for having beam (35% in 2012) is actually VERY good

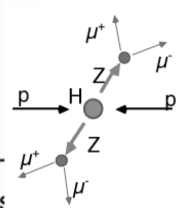


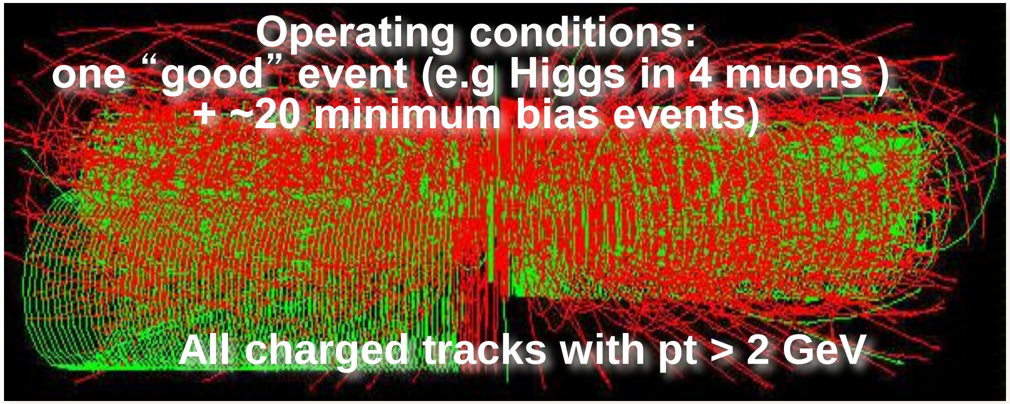
LHC operation

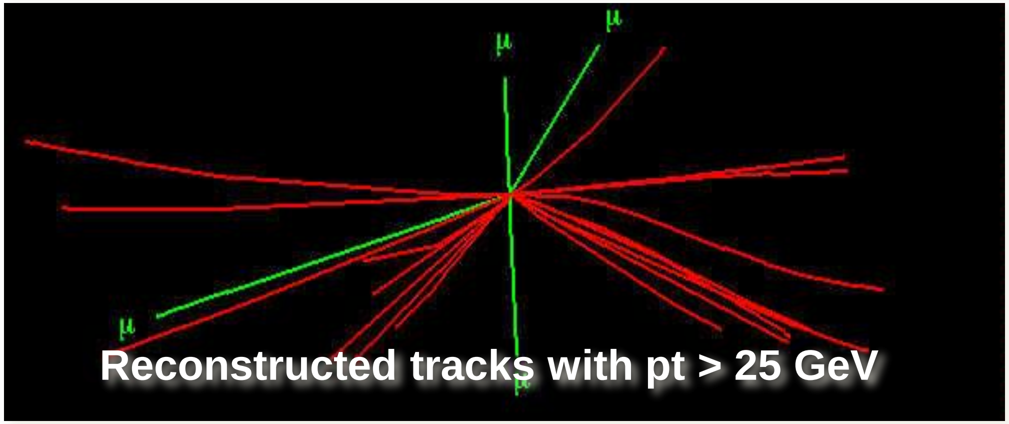


Data detection and data filtering









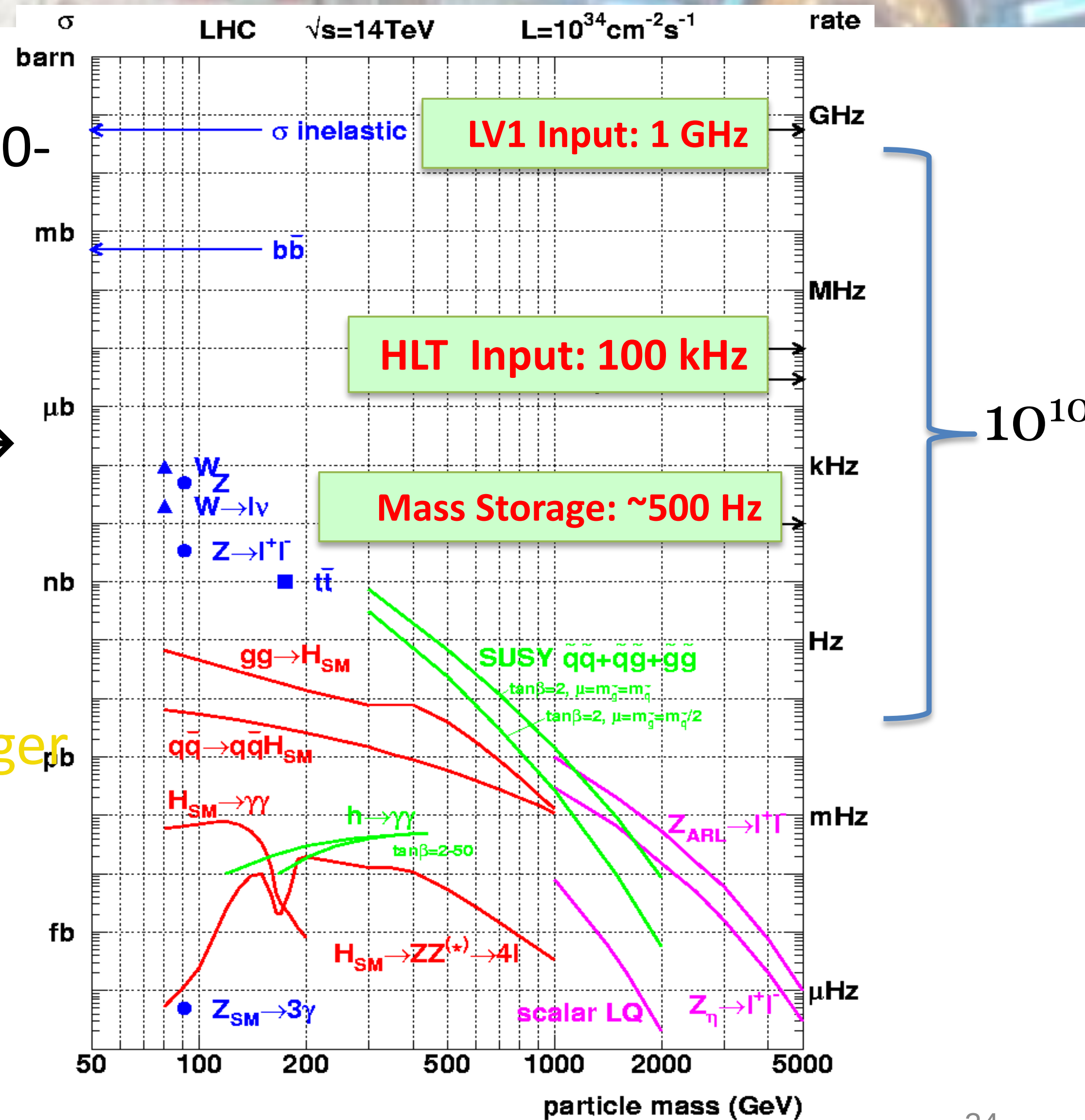
Detector granularity	**~ 10^8 cells**
Event size:	**~ 1 Mbyte**
Processing Power:	**~ Multi-TFlop**

Towards physics: CMS triggers

At LHC the collision rate is 20-40 MHz
The Event size <1 Mbyte

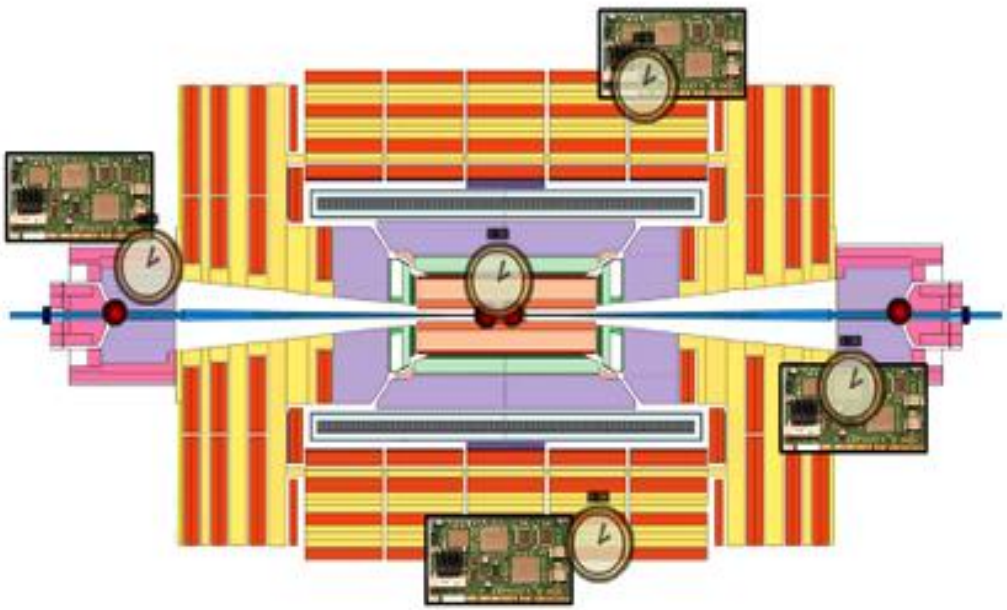
Band width limit ~ 200 GB→
Mass storage rate
~300-500 Hz

First step in 'analysis' is trigger



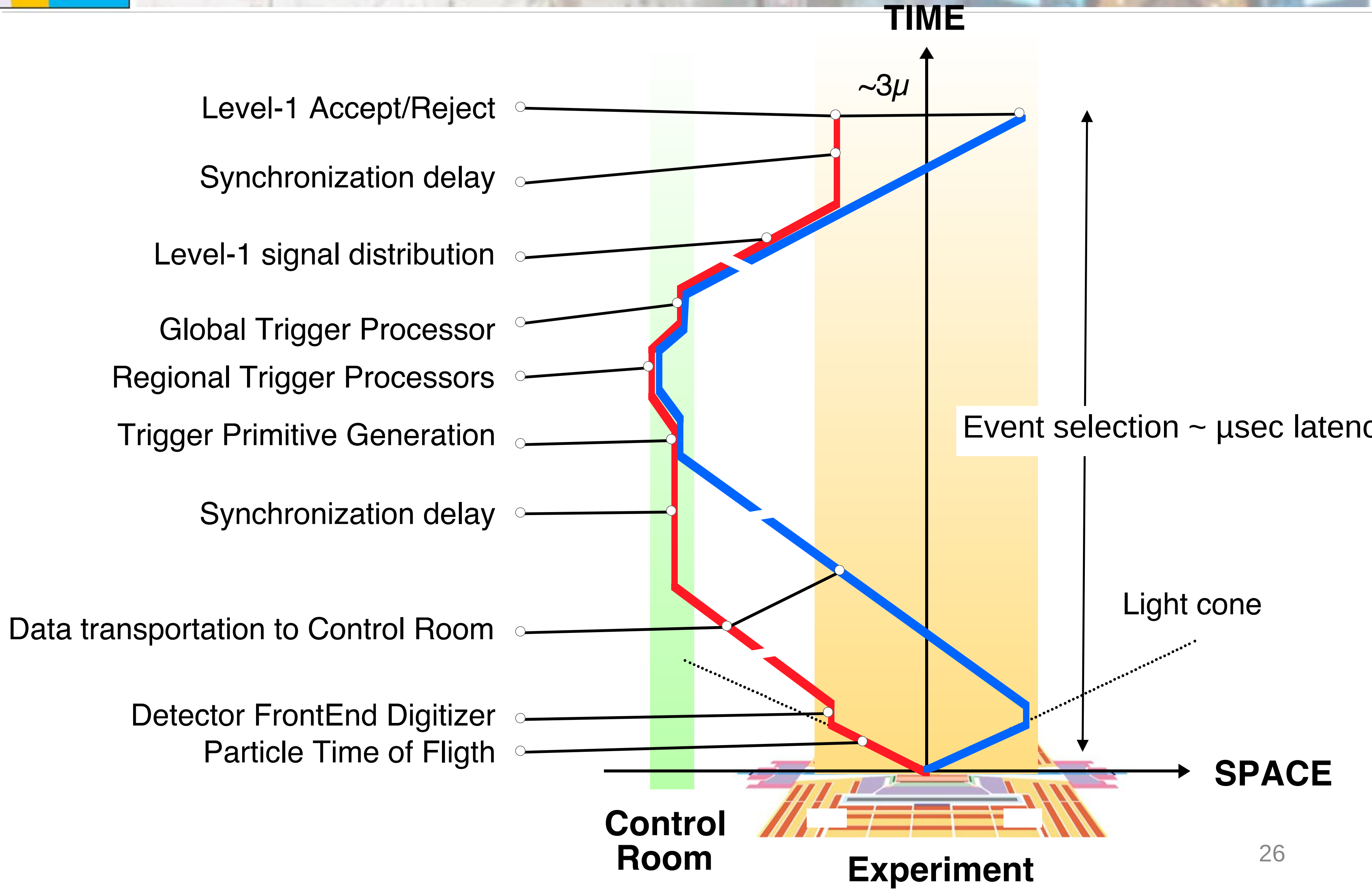
Space & time constraints

- LHC has ~3600 bunches (2835 filled) Distributed over 27 Km
-Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = **25ns (bx)**
- Apparatus dimensions 30 m -> 5 bx

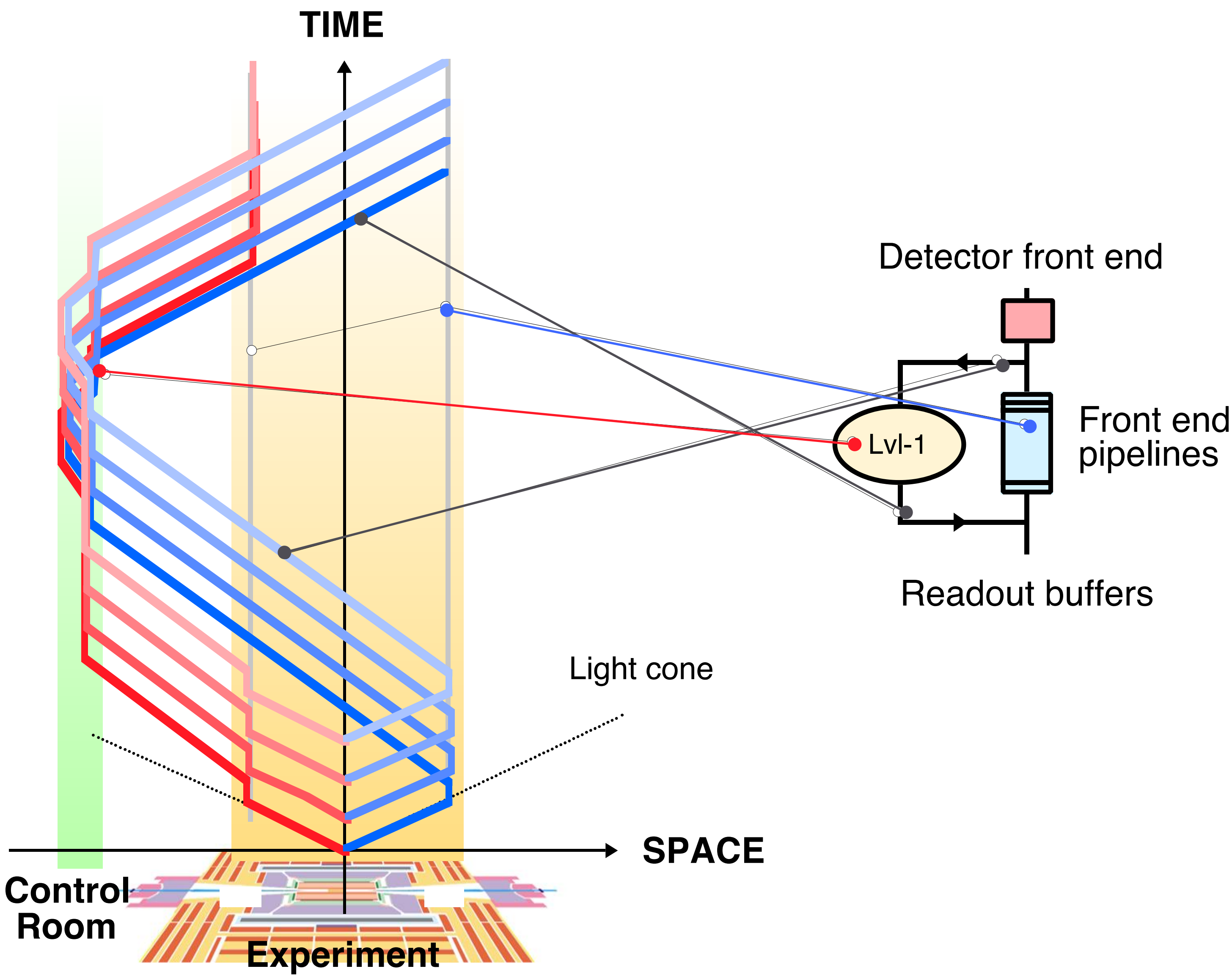


~30 m, c = 3 ns/m

Event signals kinematic



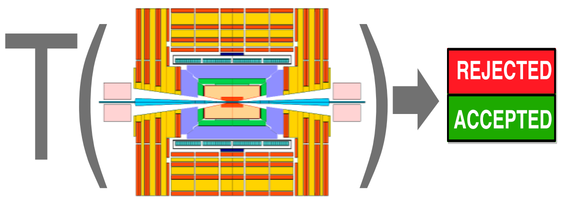
Events signal handling



Trigger levels

L1 trigger

The trigger is a function of :



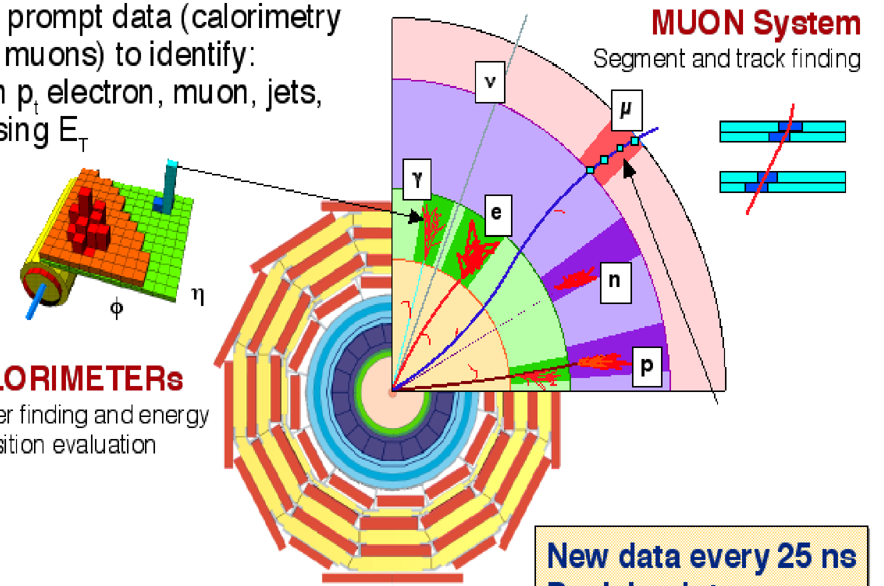
Event data & Apparatus
Physics channels & Parameters

Since the detector data are not all promptly available and the function is highly complex, T(...) is evaluated by successive approximations called :

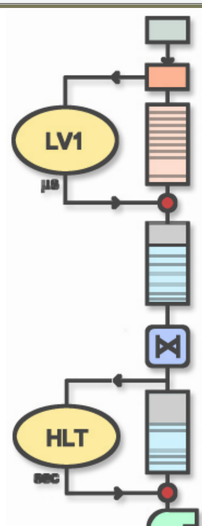
TRIGGER LEVELS

(possibly with zero dead time)

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



New data every 25 ns
Decision latency ~ μs



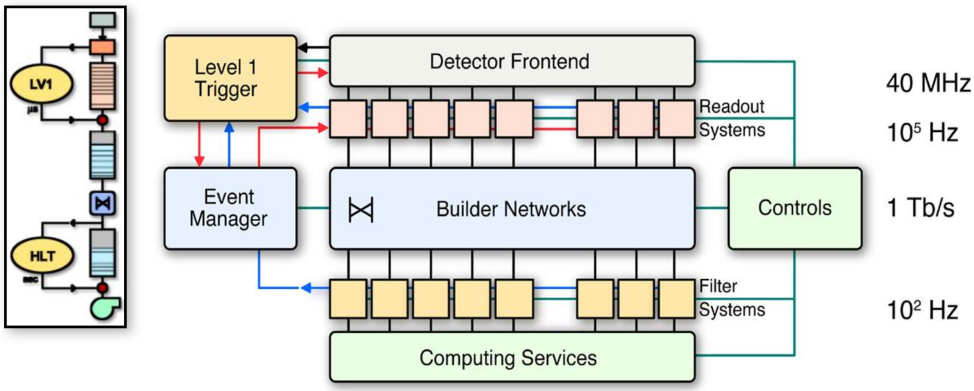
On-line requirements

Collision rate	40 MHz
Event size	1 Mbyte
Level-1 Trigger input	40 MHz
Level-2 Trigger input	100 kHz
......	
Mass storage rate	~100 Hz
Online rejection	99.999%
System dead time	~ %

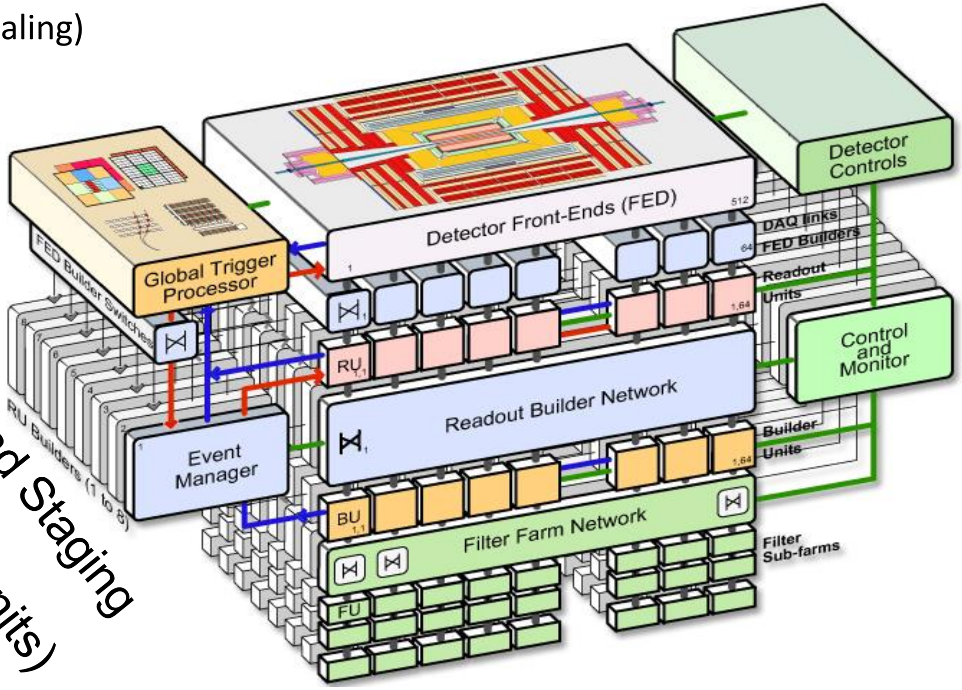
DAQ

DAQ design issues

Data network bandwidth (EVB)	~ Tb/s
Computing power (HLT)	~ 10 Tflop
Computing cores	~ 10000
Local storage	~ 300 TB

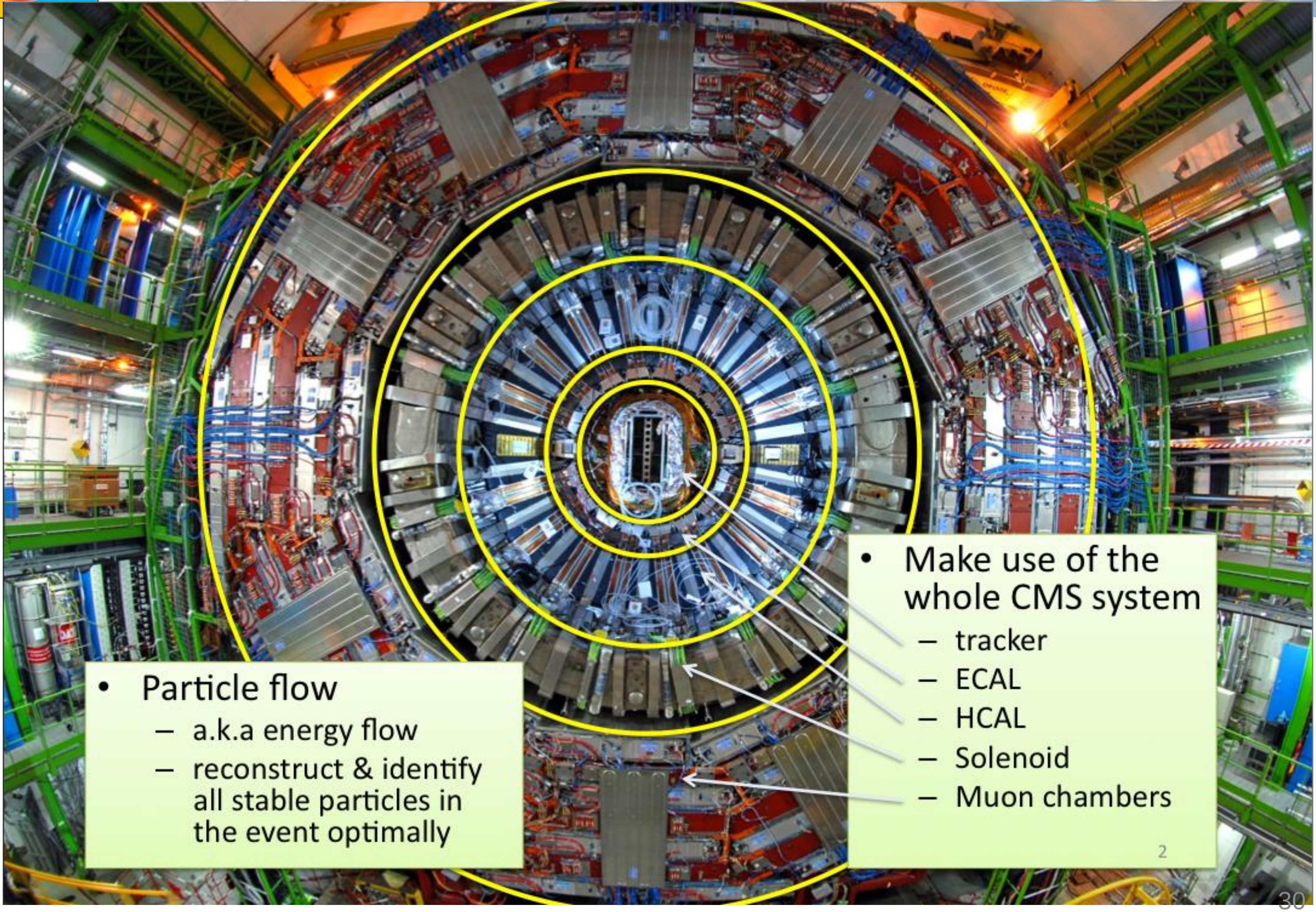


Minimize custom design
Exploit data communication and computing technologies
DAQ staging by modular design (scaling)

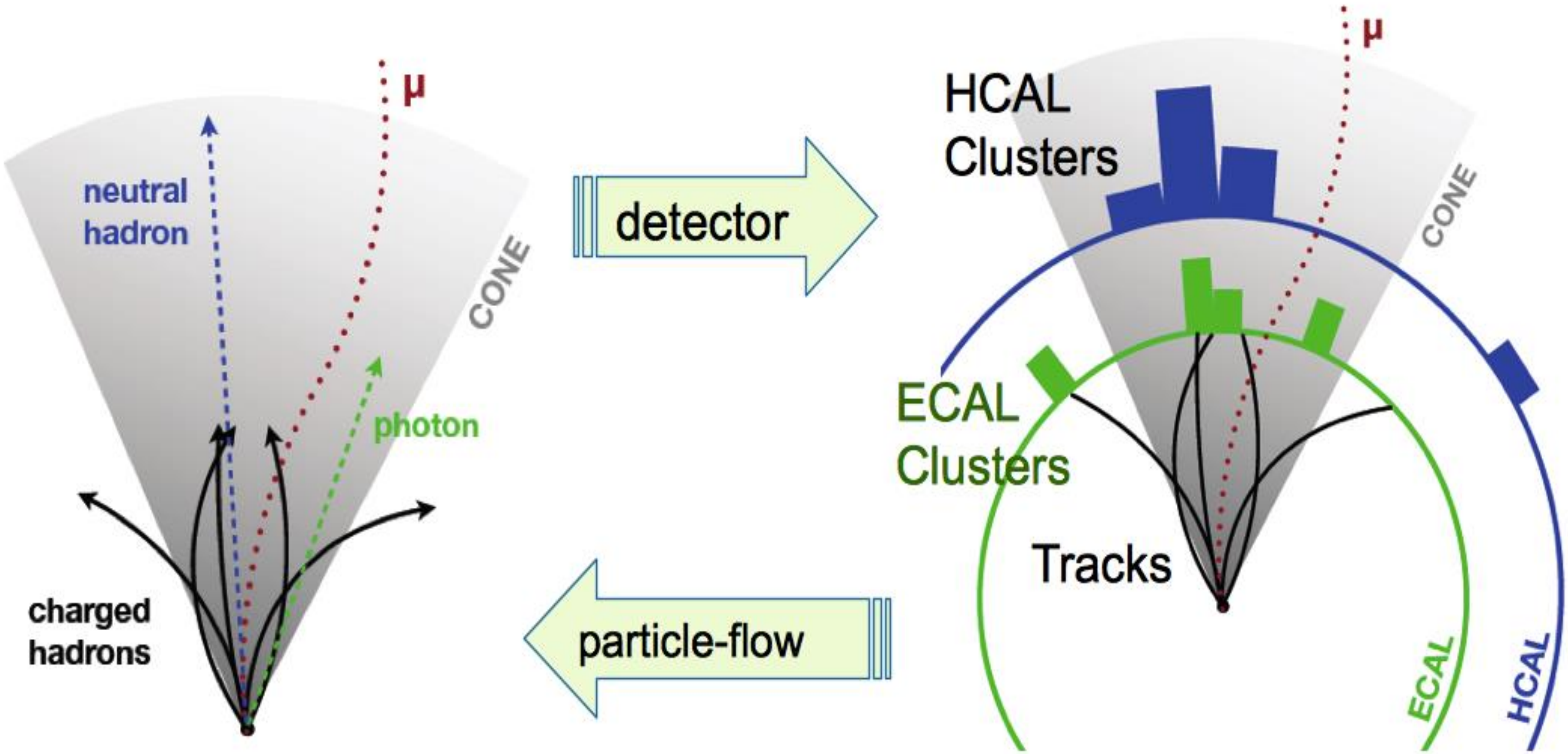


8 x (12.5 kHz DAQ units)
Scaling and Staging

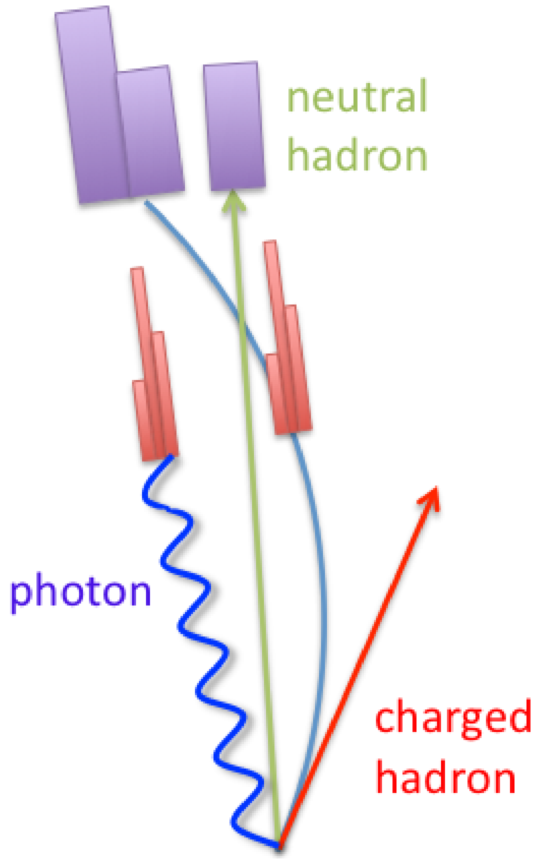
Event reconstruction



Particle flow



Why particle flow?



- Calorimeter jet:
  - $E = E_{HCAL} + E_{ECAL}$
  - σ(E) ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- Particle flow jet:
  - 65% charged hadrons
    - σ(pT)/pT ~ 1%
    - direction measured at vertex
  - 25% photons
    - σ(E)/E ~ 1% / √E
    - good direction resolution
  - 10% neutral hadrons
    - σ(E)/E ~ 120 % / √E
  - **Need to resolve the energy deposits from the neutral particles…**

Better performance expected, at least on jet and MET reconstruction

CMS

187 Institutes from 42 Countries

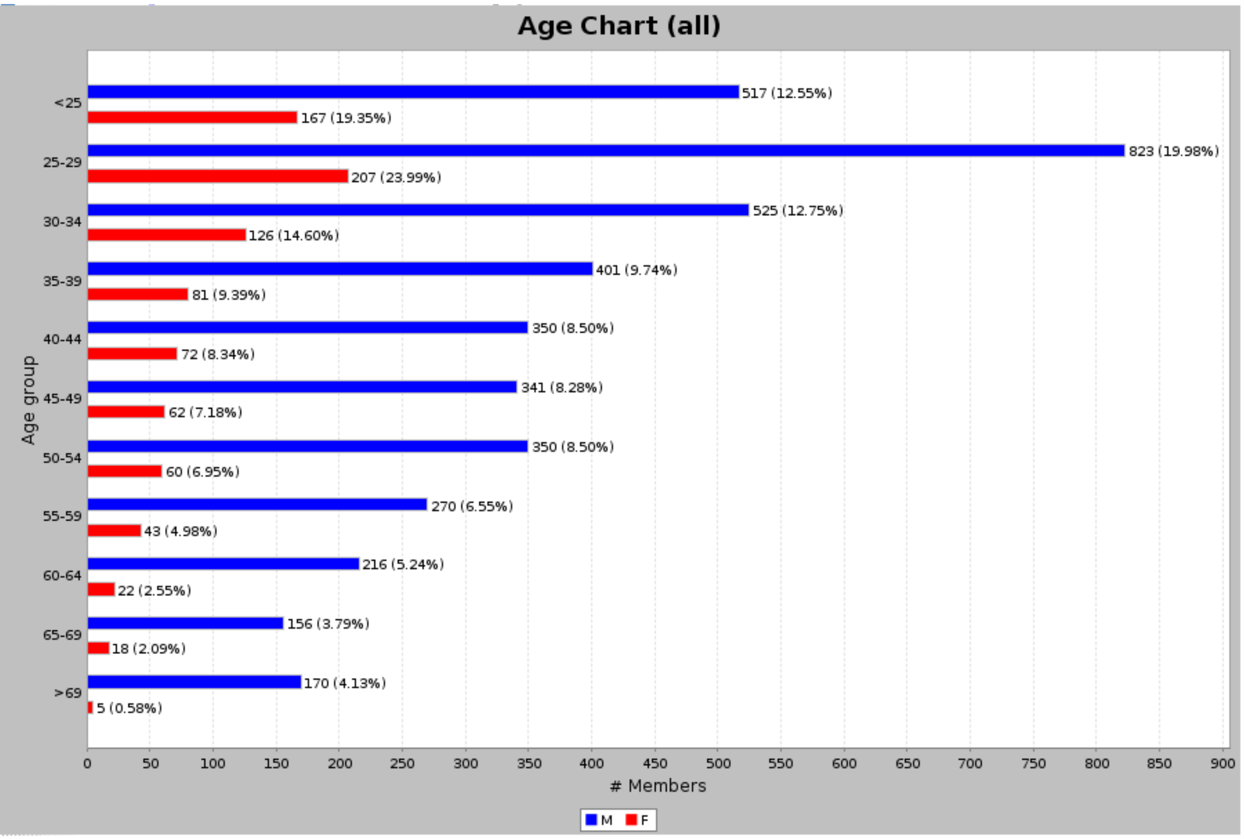
>4000 members (~2200 signing CMS papers)

papers are signed by PhDs contributing M&O A (support for the operation), students, emeritus and ex-members for a limited period after they leave CMS

~17% of CMS researchers are females

The Collaboration Board is the CMS ‘parliament’: each institutes with at least 3 PhDs elects the Spokesperson and the CB Chair.

CMS : age distribution



Top 10 funding agencies :
United States (1191, 30%)
Italy (416, 10%)
Germany (320, 8%)
CERN (281, 7%)
Russian Federation (191, 4.8%)
France (162, 4.1%)
United Kingdom (146, 3.7%)
Belgium (135, 3.4%)
India (106, 2.7%)
Switzerland (85, 2.1%)

CMS

Thank you !