Design Principles and Performance of CMS

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Academic Training
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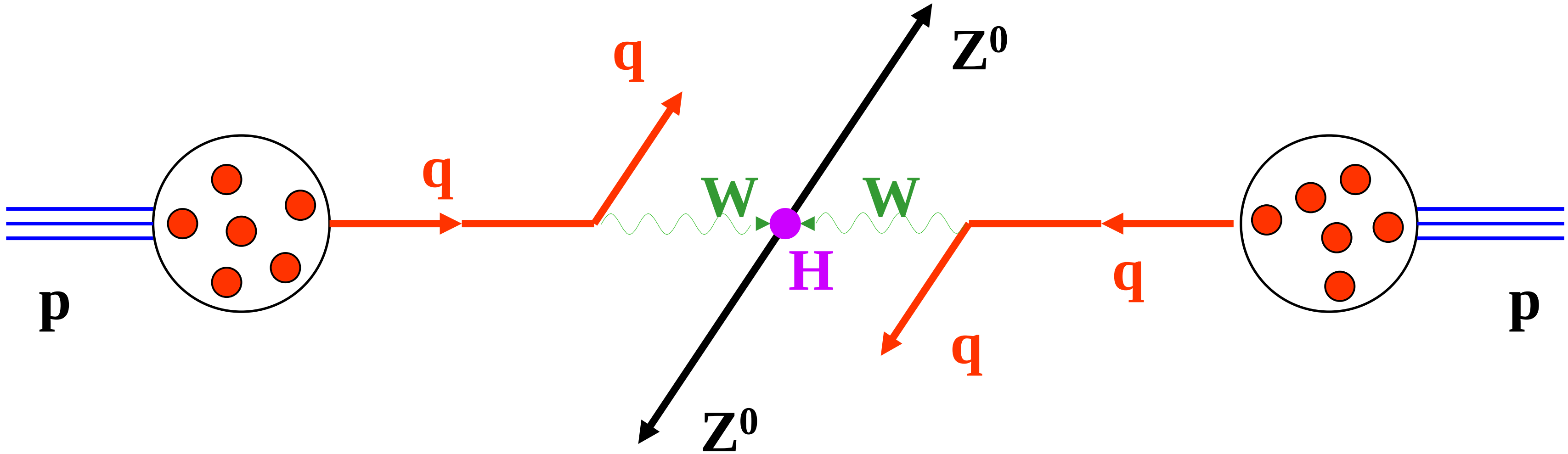
Outline

- **The LHC and its (high-P_T) pp experiments**
  - **The machine, ATLAS & CMS**
- **Designing a detector for the LHC**
  - **Muons, the magnet**
- **ATLAS/CMS choices**
  - **The CMS design**

The TeV scale

- **LEP, SLC and the Tevatron: established that we really understand the physics at energies up to 100 GeV**
  - **And any new particles have masses above 200-300 GeV and in some cases TeV**
- **The Higgs itself can have a mass up to ~700-800 GeV;**
  - **if it's not there, something must be added by ~1.2 TeV, or WW scattering exceeds unitarity**
- **Even if the Higgs exists, all is not 100% well with the Standard Model alone: next question is why is the (Higgs) mass so low?**
  - **The same mechanism that gives all masses would drive the Higgs to the Planck scale. If SUSY is the answer, it must show up at O(TeV)**
  - **Recent: extra dimensions. Again, something must happen in the O(1-10) TeV scale if the above issues are to be addressed**
- **Conclusion: we need to study the TeV region**

Higgs Production in pp Collisions



M_H ~ 1000 GeV

$E_W \geq$ 500 GeV

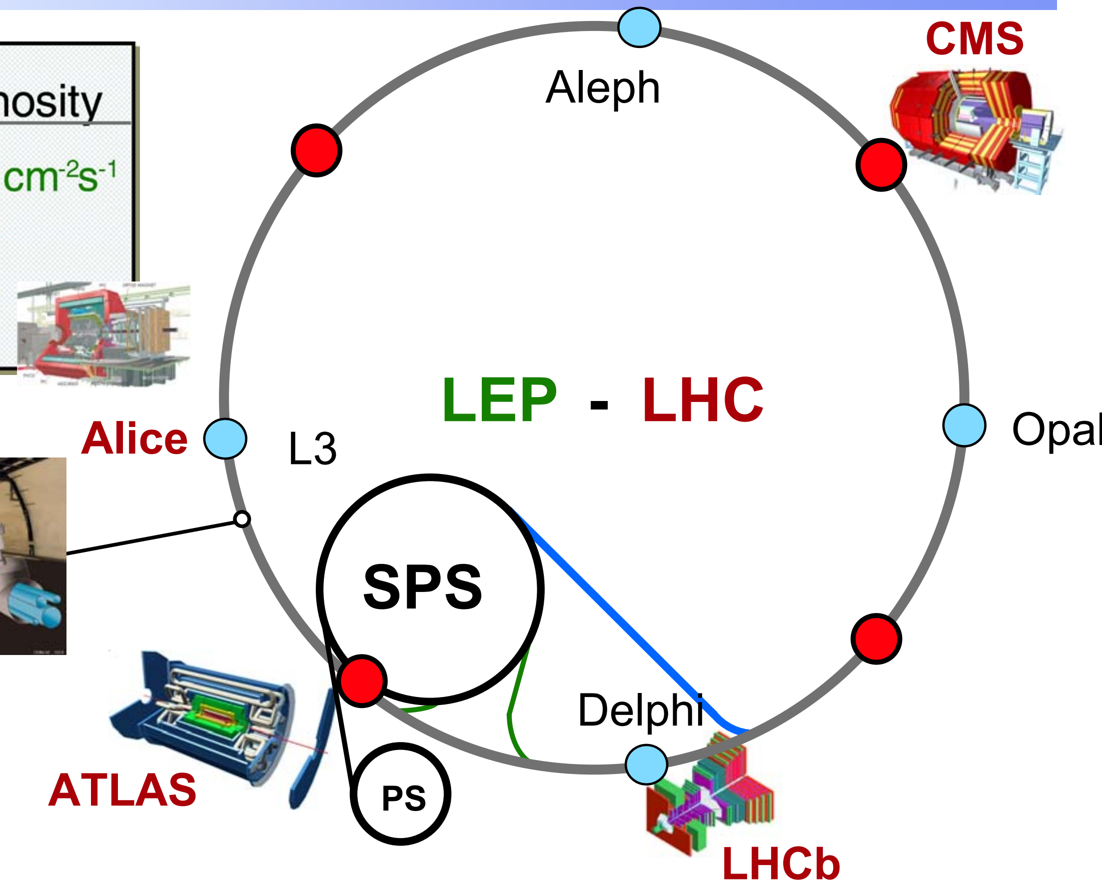
$E_q \geq$ 1000 GeV (1 TeV)

$E_p \geq$ 6000 GeV (6 TeV)

→ Proton Proton Collider with $E_p \geq$ 7 TeV

Experiments at the LHC

	Beams	Energy	Luminosity
LEP	e^+e^-	200 GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14 TeV	10^{34}
	$P_b P_b$	1312 TeV	10^{27}



Two super-conducting magnet rings in the LEP tunnel

9T magnets

Experiments at LHC

ATLAS A Toroidal LHC ApparatuS. (Study of Proton-Proton collisions)

CMS Compact Muon Solenoid. (Study of Proton-Proton collisions)

ALICE A Large Ion Collider Experiment. (Study of Ion-Ion collisions)

LHCb (Study of CP violation in B-meson decays at the LHC collider)

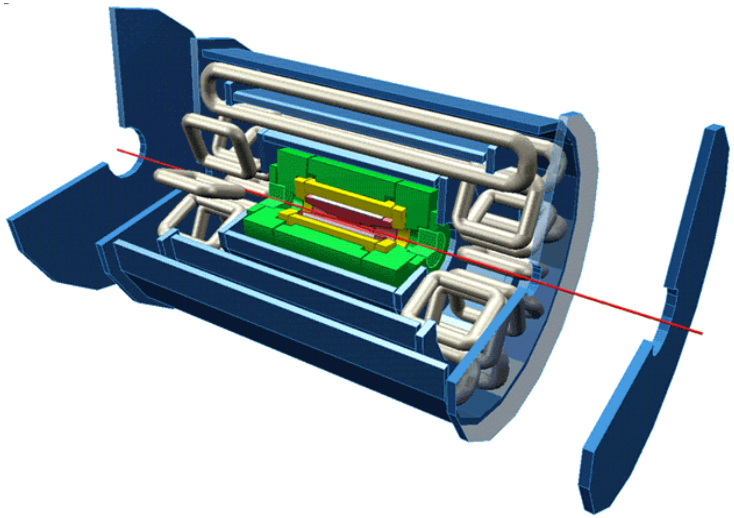
Timeline (CMS)

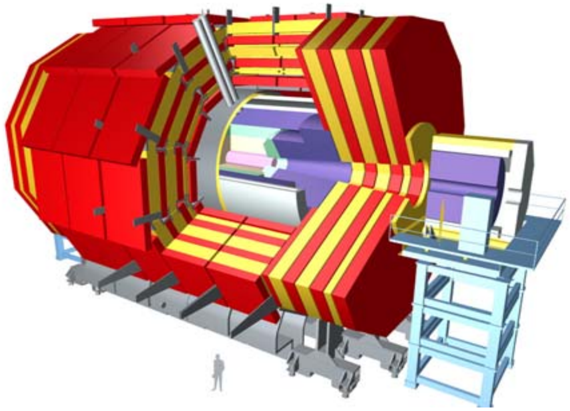
- LHC Workshop, Aachen 1990
  - Concept of a compact detector based on a 4T superconducting solenoid
- Expression of Interest, Evian 1992
  - Conceptual Design
- Letter of Intent, October 1992
  - CERN/LHCC 92-3
- Technical Proposal, Dec 1994
  - CERN/LHCC 94-38
- Interim Memorandum of Understanding (IMoU) 1995
- Memorandum of Understanding (MoU) 1998
- Detector Technical Design Reports: 1997-98; Lvl-1 Trigger: 2000; DAQ/HLT: 2002.
- Computing & Physics TDR: ongoing; 2005-06.

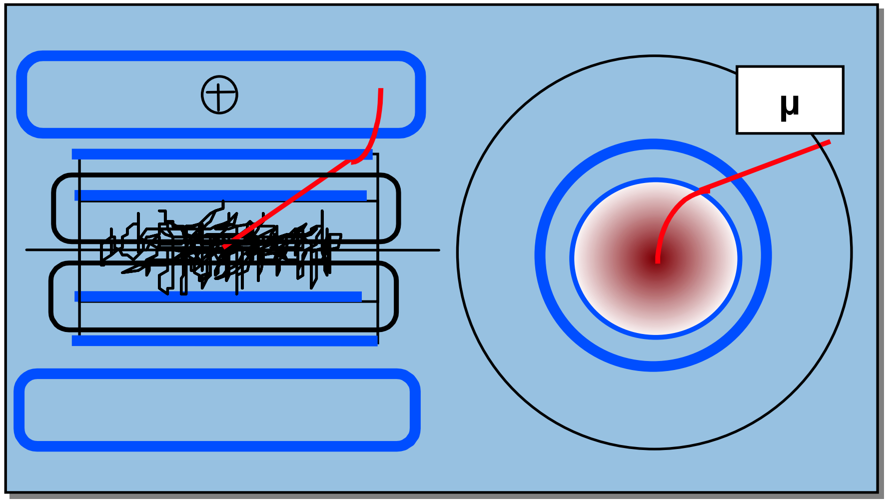
LHC: pp general-purpose experiments

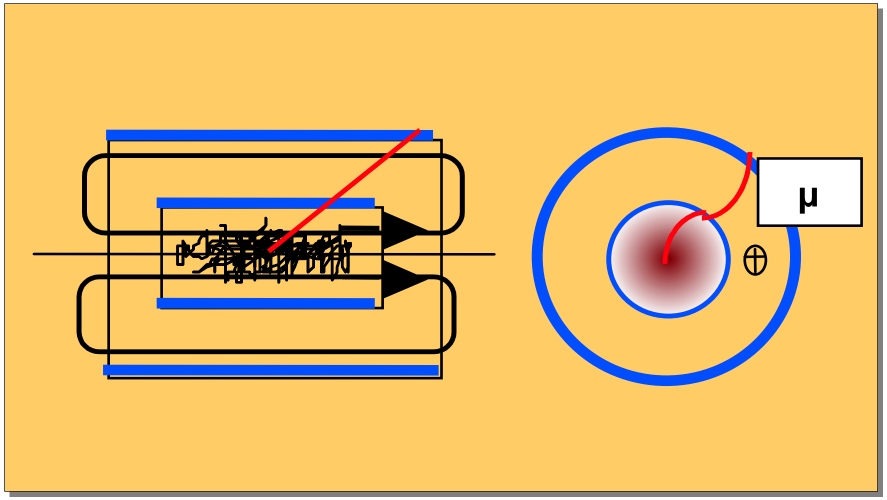
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid





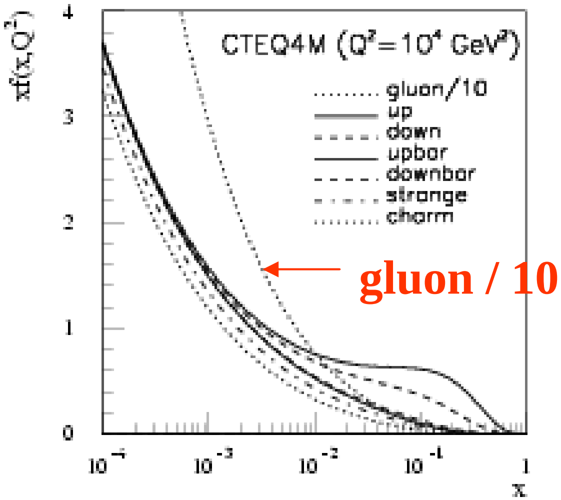




Further conditions

- **LHC: make up for the lower production cross section**
  - **Normally, $\sigma \sim 1/s$, so a factor x in c.m. energy needs a factor x^2 in luminosity (for the same number of events; $N=\sigma L$)**
    - **Not true at a hadron-hadron collider:**

$$\sigma = \frac{1}{s}\sum_{a,b}\int_{x_a x_b = m^2/s}^{1} \hat{\sigma}_{ab}\, dx_a\, dx_b\, F_a(x_a,Q^2)\, F_b(x_b,Q^2)$$

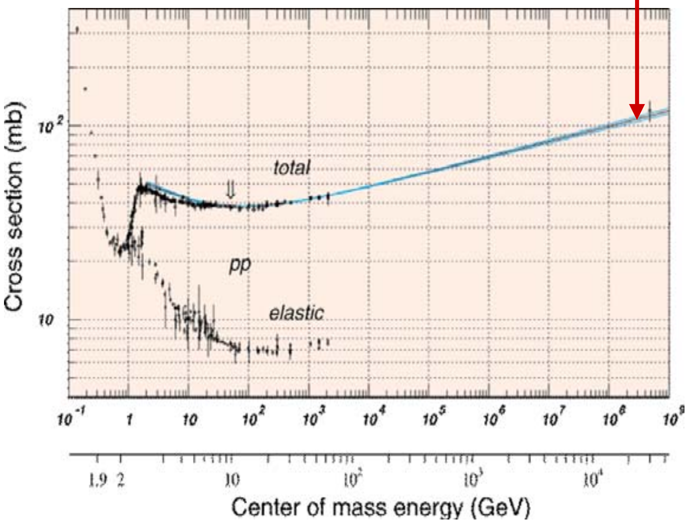


    - **Very rapid increase of structure functions at low x**
      - → **Very significant increase in σ as s increases**
  - **Rough rule of thumb: a factor 2 in s is equivalent to a factor ~10 in luminosity**
  - **LHC must run at a higher luminosity (than the SSC would)**
    - **Full "design" luminosity: 10^{34} cm^{-2}s^{-1}**
    - **"Low", luminosity: 10^{33}cm^{-2}s^{-1}**
    - **Recent: startup luminosity is 2×10^{33}cm^{-2}s^{-1}**

pp cross section and min. bias

- **# of interactions/crossing:**
  - **Interactions/s:**
    - **Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}$Hz**
    - **σ(pp) = 80 mb**
    - **Interaction Rate, R = 8×10^8 Hz**
  - **Events/beam crossing:**
    - **Δt = 25 ns = 2.5×10^{-8} s**
    - **Interactions/crossing=20**
  - **Not all p bunches are full**
    - **2835 out of 3564 only**
    - **Interactions/"active" crossing = 20 x 3564/2835 = 25**

$\sigma_{inel}(pp) \approx 80$ mb



Operating conditions (summary):
(1) A "good" event containing a Higgs decay +
(2) ~ 25 extra "bad" (minimum bias) interactions

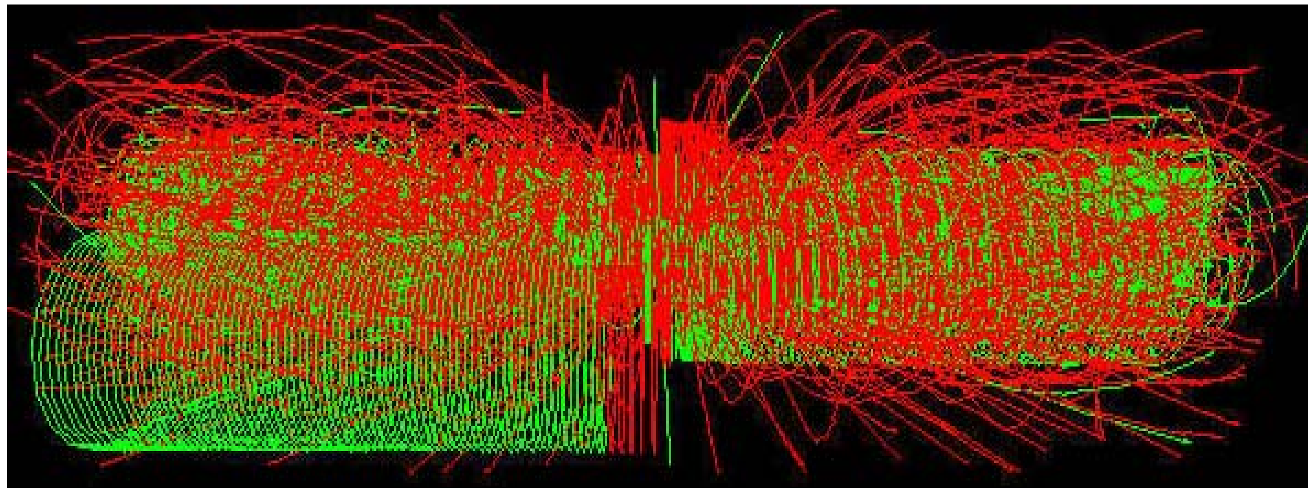
pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

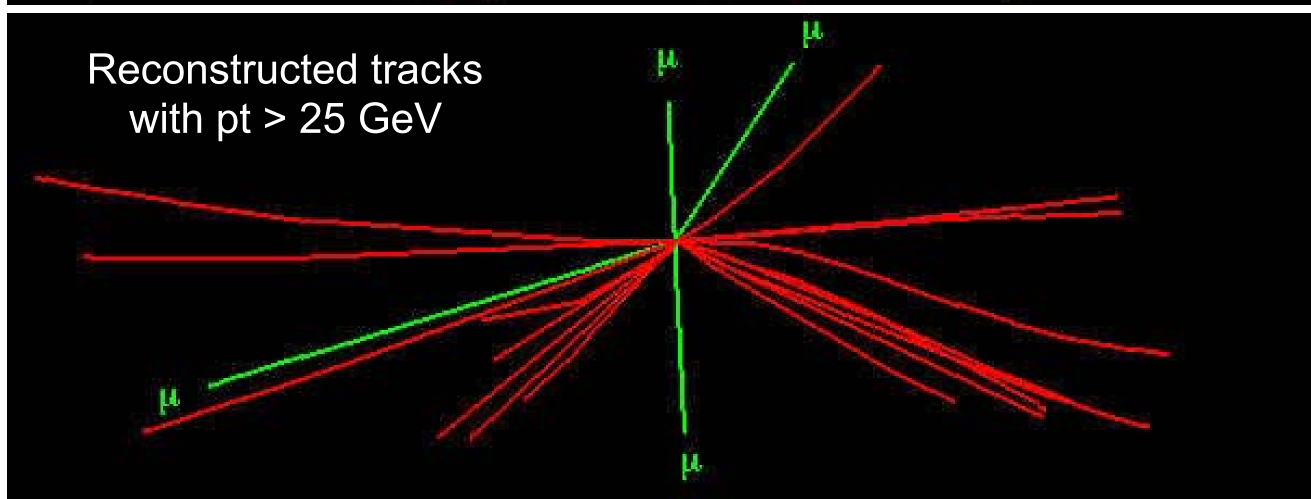
- **25 min bias events overlap**
- **H→ZZ**

Z →μμ

H→ 4 muons: the cleanest ("golden") signature

And this (not the H though…) repeats every 25 ns…





Impact on detector design

- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns

    → integrate over 1-2 bunch crossings → pile-up of 25-50 min-bias

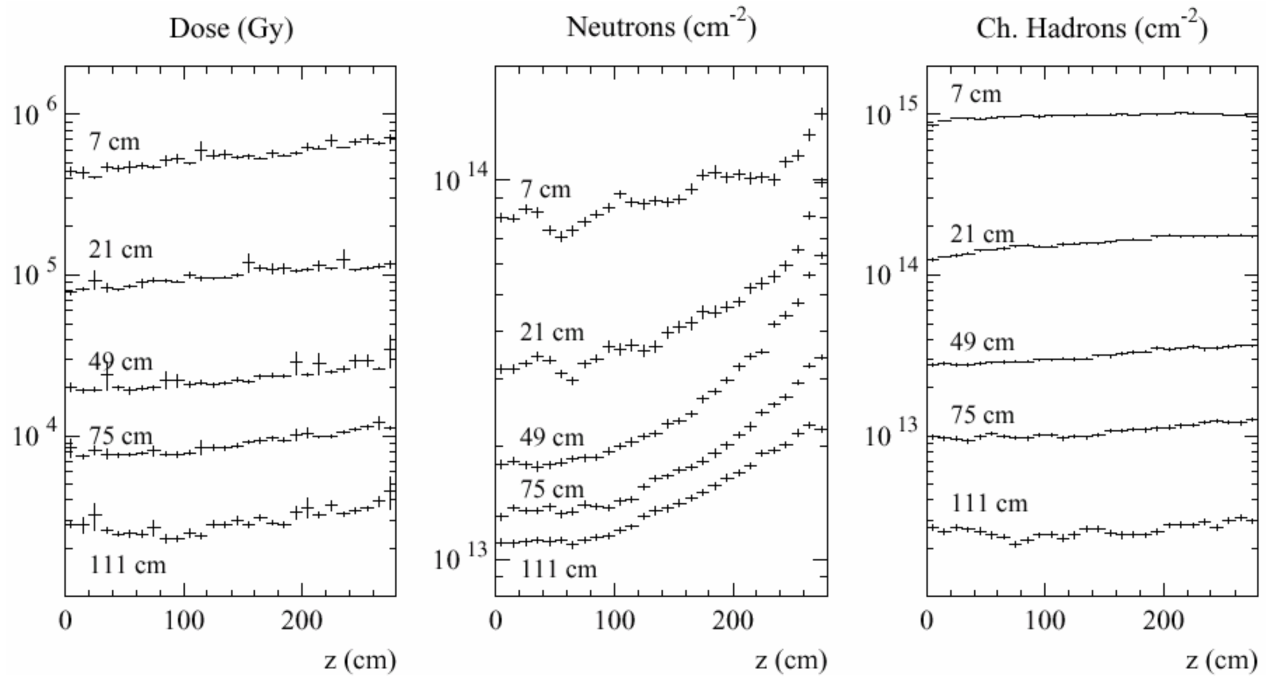
    → very challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \to \gamma\gamma$ decays)

    → large number of electronic channels

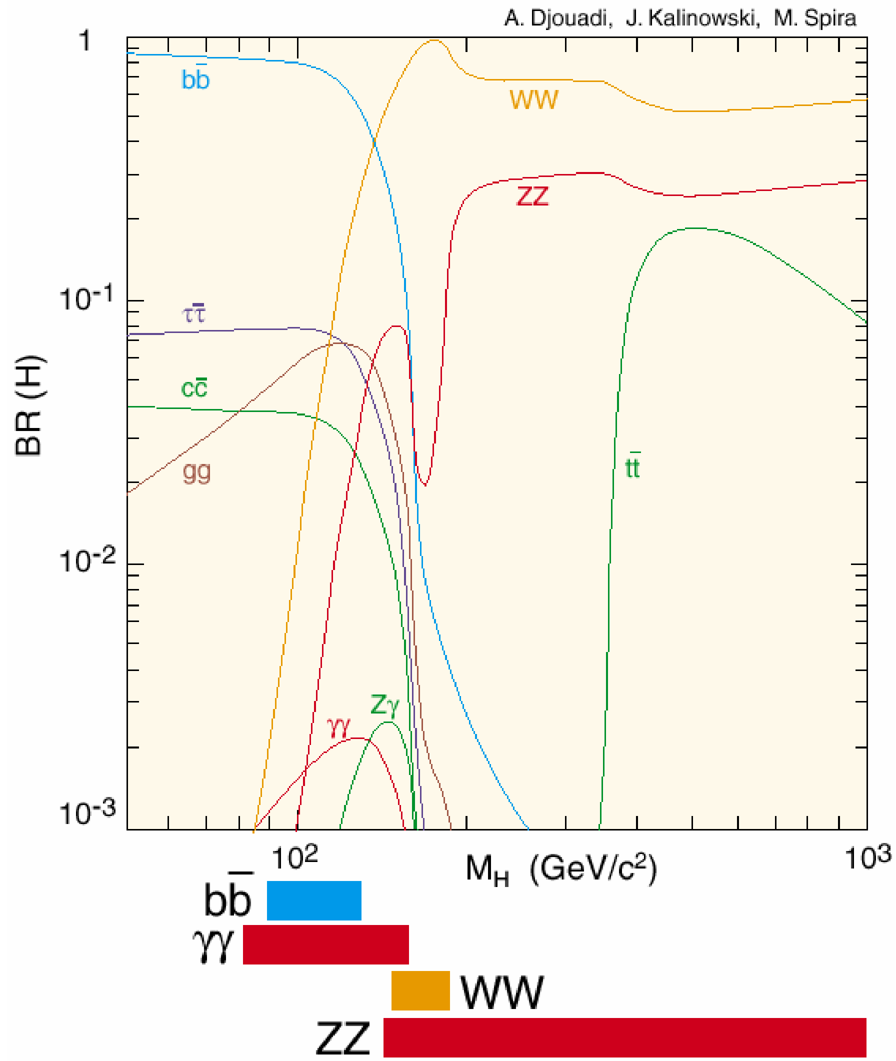
    → high cost
- **LHC detectors must be radiation resistant:**
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

Radiation damage

- **Characteristics/Implications:**
  - decreases like distance^2 from the beam → detectors nearest the beam pipe are affected the most
  - need also radiation-hard electronics (military-type technology; 0.25 μm methods)
  - need quality control for every piece of material
  - detector + electronics must survive 10 years of operation



- **Decays & discovery channels**
  - Higgs couples to m_f^2
    - Heaviest available fermion (b quark) always dominates
    - Until WW, ZZ thresholds open
  - Low mass: b quarks→ jets; resolution ~ 15%
    - Only chance is EM energy (use γγ decay mode)
  - Once $M_H > 2M_Z$, use this
    - W decays to jets or lepton+neutrino (E_T^{miss})

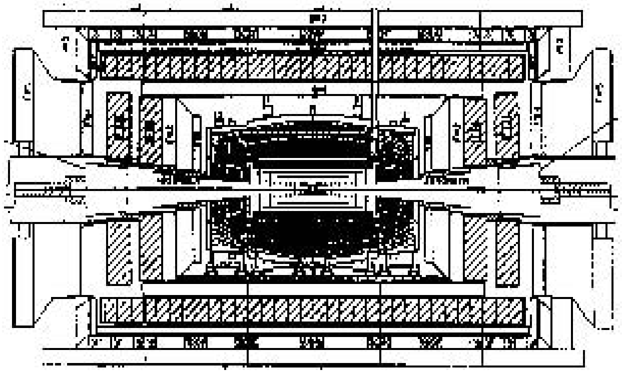


ATLAS & CMS detectors

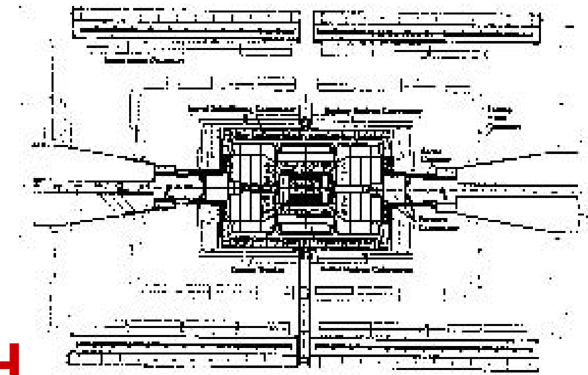
- Basic principle: need "general-purpose" experiments covering as much of the solid angle as possible ("4π") since we don't know how New Physics will manifest itself
  - $\rightarrow$ detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….
- Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers plus gas detectors).
- Energy and positions of electrons and photons measured in electromagnetic calorimeters.
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters.
- Muons identified and momentum measured in external muon spectrometer (+central tracker).
- Neutrinos "detected and measured" through measurement of missing transverse energy (E_T^{miss}) in calorimeters.

Designs of Various Detectors

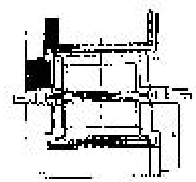
SDC



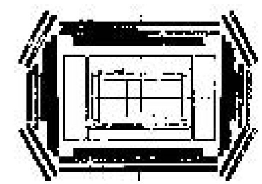
GEM



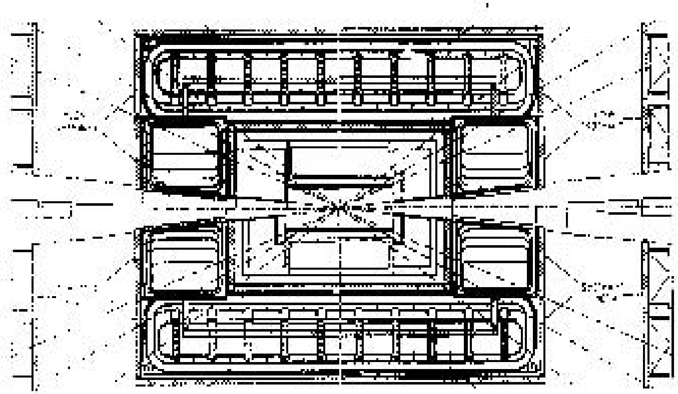
ALEPH



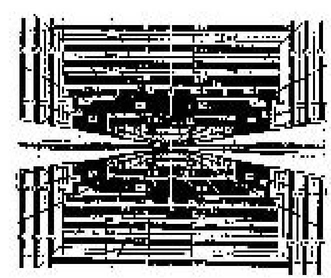
UA1



ATLAS



CMS



Detector design at hadron colliders

- **At high luminosity hadron colliders: need to measure muon momenta online – with sufficient accuracy for triggering**

Solenoid	BR^2	Tm^2	Tm	Δr(Fe) (m)
1.GEM	$0.8*9^2$	65	7	-
2.CMS	$4*3^2$	36	12	~1.5
3.ALEPH'	$3*2.5^2$	19	7.5	<1
4.ATLAS	$2*1.2^2$	3	2.4	-

1: low-field inner tracking

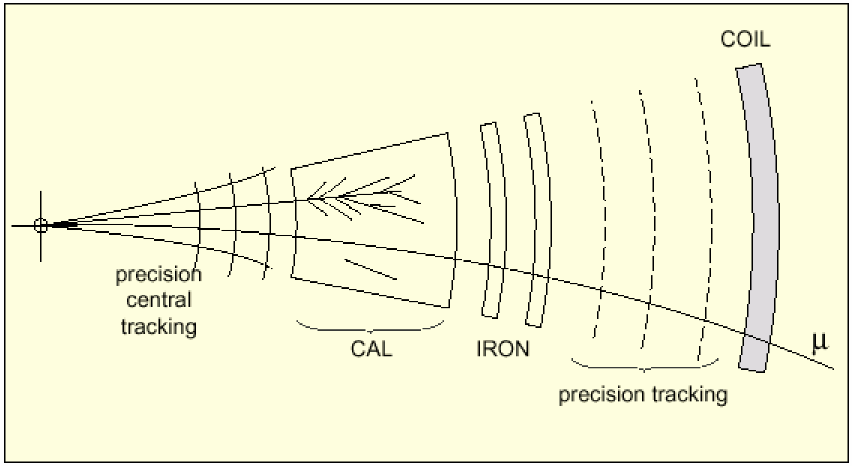
2: bending power at high eta

3: Coil at hadron shower max, saturated iron for muons too thin

4: need toroid magnets, coil-ECAL interface

Designing an LHC experiment

- **THE issue: measure momenta of charged particles (e.g. muons); so which measurement "architecture"?**

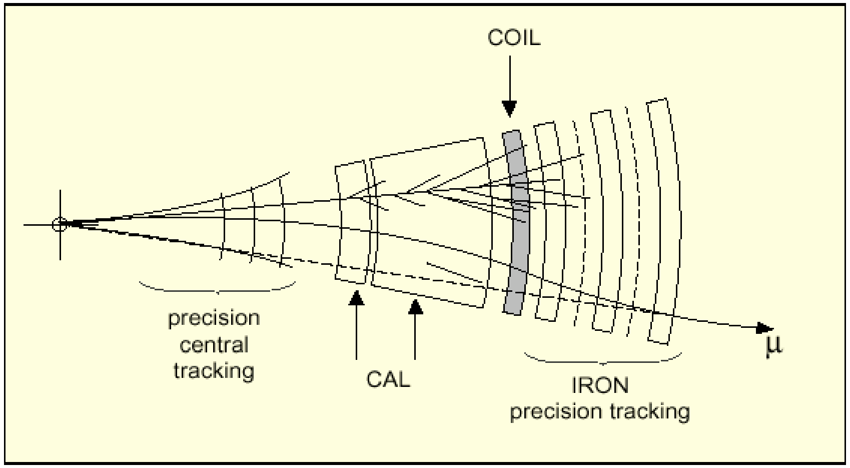


ATLAS

Standalone p measurement; safe for high multiplicities;

Air-core torroid

Property: σ flat with η



CMS

Measurement of p in tracker and B return flux;

Iron-core solenoid

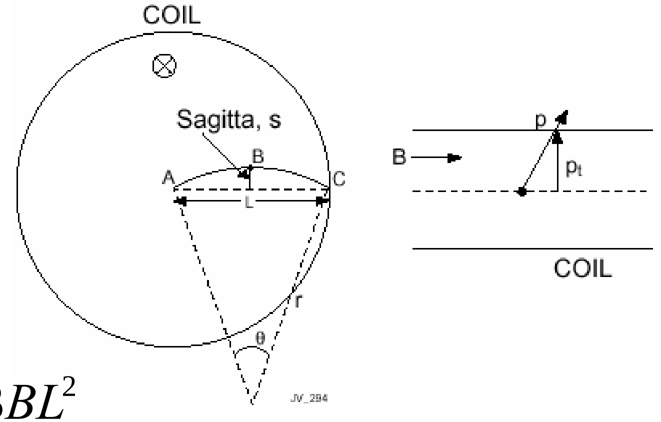
Property: muon tracks point back to vertex

Momentum measurement

- **Need high BL^2 or small σ_s:**
  - **Quick reminder: P_T=0.3 B r**
    - **In practice, measure s, not r**

$$\sin(\theta/2) = \frac{L}{2r} \Rightarrow \theta \approx \frac{L}{r} = \frac{0.3BL}{r}$$

$$s = r - r\cos(\theta/2) \approx r\left[1 - \frac{1}{2}\frac{\theta^2}{4}\right] = \frac{r\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$



- **Thus, resolution on p given by** $\frac{\sigma(P_T)}{P_T} = \frac{\sigma_s}{s}$
- **Toy detector with 3 points measured, each with σ_p:** $\sigma_s = \sqrt{\frac{3}{2}}\sigma_p$

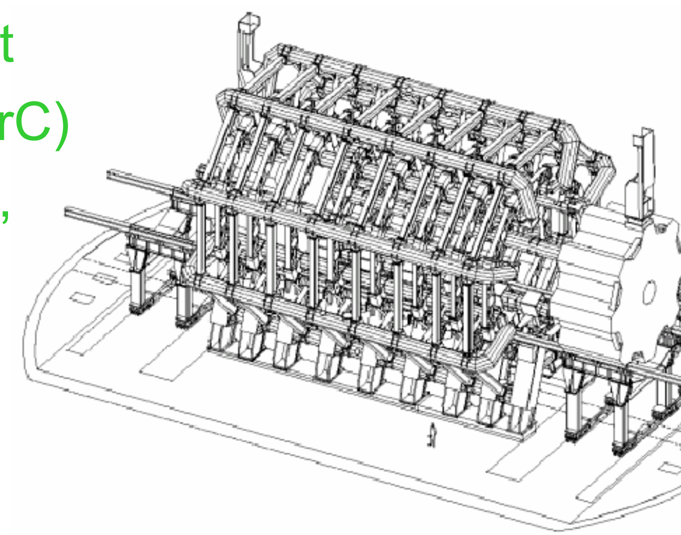
$$\frac{\sigma(P_T)}{P_T} \approx 4\sqrt{3}\ \sigma_x\ \frac{p_T}{0.3BL^2}$$

- **In more realistic detector with N points (equally spaced):**

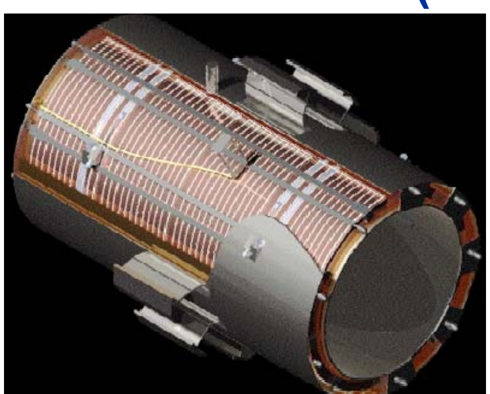
$$\frac{\sigma(P_T)}{P_T} \approx \sqrt{\frac{720}{N+4}}\sigma_x\ \frac{p_T}{0.3BL^2}$$

Choice of magnet (I)

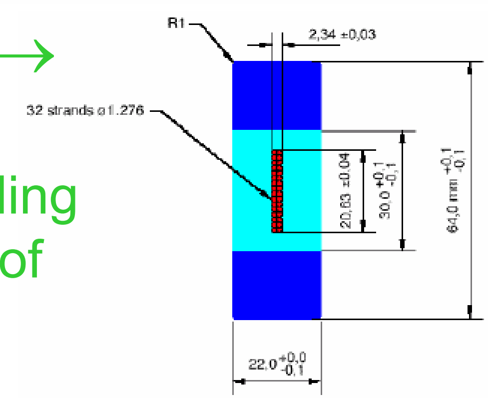
- **Basic goal: measure 1 TeV muons with 10% resolution**
  - **ATLAS: <B>~0.6T over 4.5 m $\rightarrow$ s=0.5mm $\rightarrow$ need σ_s=50μm**
    - Ampere's thm: $2\pi RB=\mu_0 nI \rightarrow nI=2\times10^7$ At
    - With 8 coils, 2x2x30 turns: I=20kA (superC)
    - Challenges: mechanics, 1.5GJ if quench, spatial & alignment precision over large surface area



  - **CMS: B=4T (E=2.7 GJ!)**

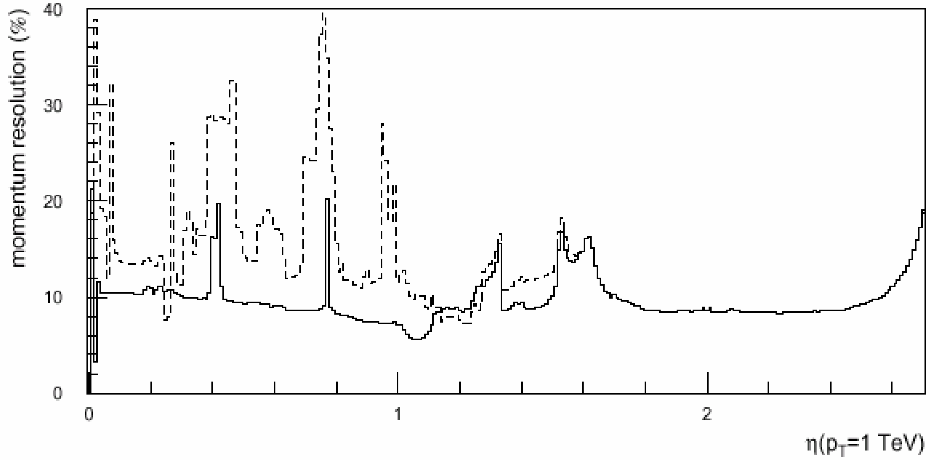


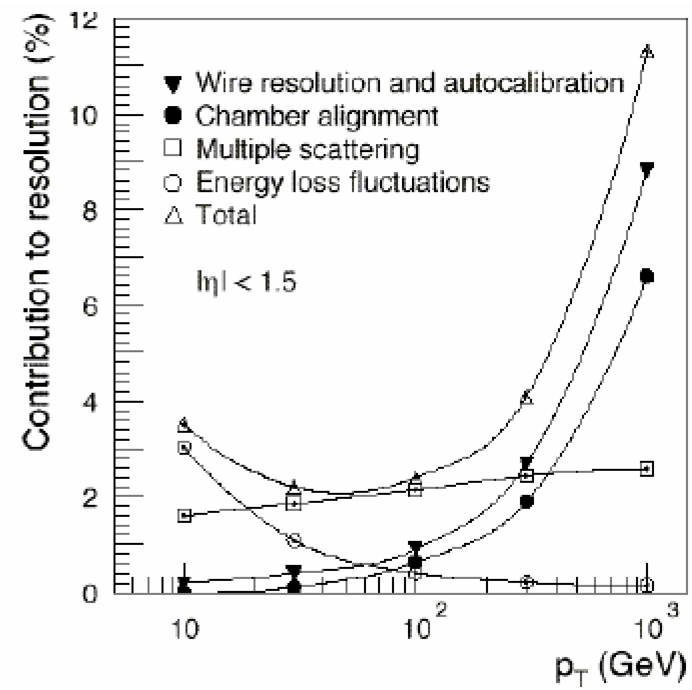
- $B=\mu_0 nI$; @2168 turns/m$\rightarrow$ I=20kA (SuperC)
- Challenges: 4-layer winding to carry enough I, design of reinforced superC cable



Choice of magnet (II)

- **Torroid: gives flat σ vs η:**

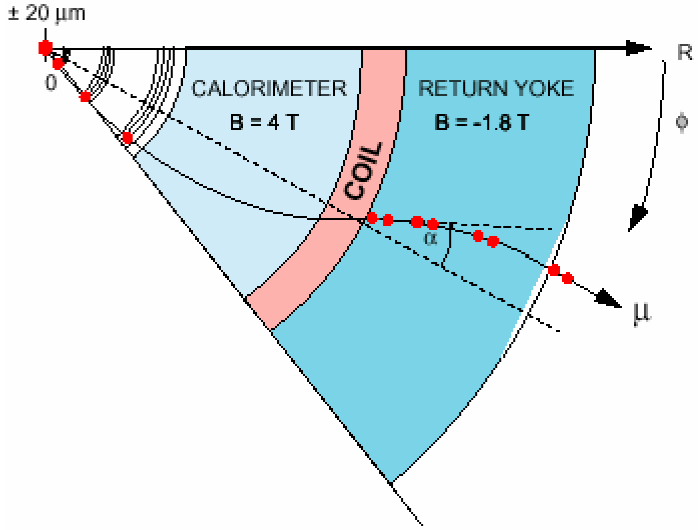




- ◆ **But: (a) does not benefit from beam spot (20 μm @ LHC)**
  (b) need additional solenoid for internal track measurement
  - **ATLAS: B=2T solenoid**
- ◆ **Calorimetry: a new question: inside or outside solenoid?**
  - **ATLAS: outside; CMS: inside**

Choice of magnet (III)

- **Solenoid:**

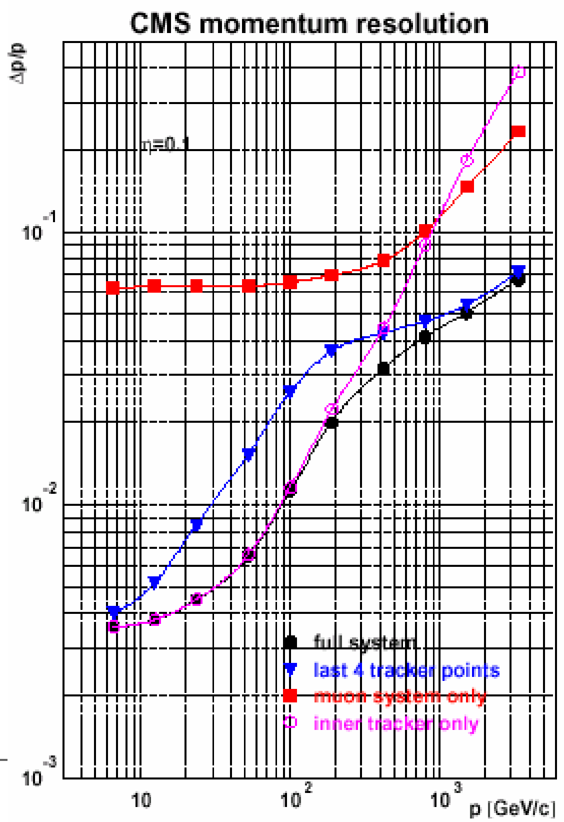


Bending in transverse plane

Use 20µm beam spot

BUT: 4T brings problems

(e.g. cannot use PM tubes)



- **Iron-core → multiple scattering**
  - **Tracking in magnetized iron:**

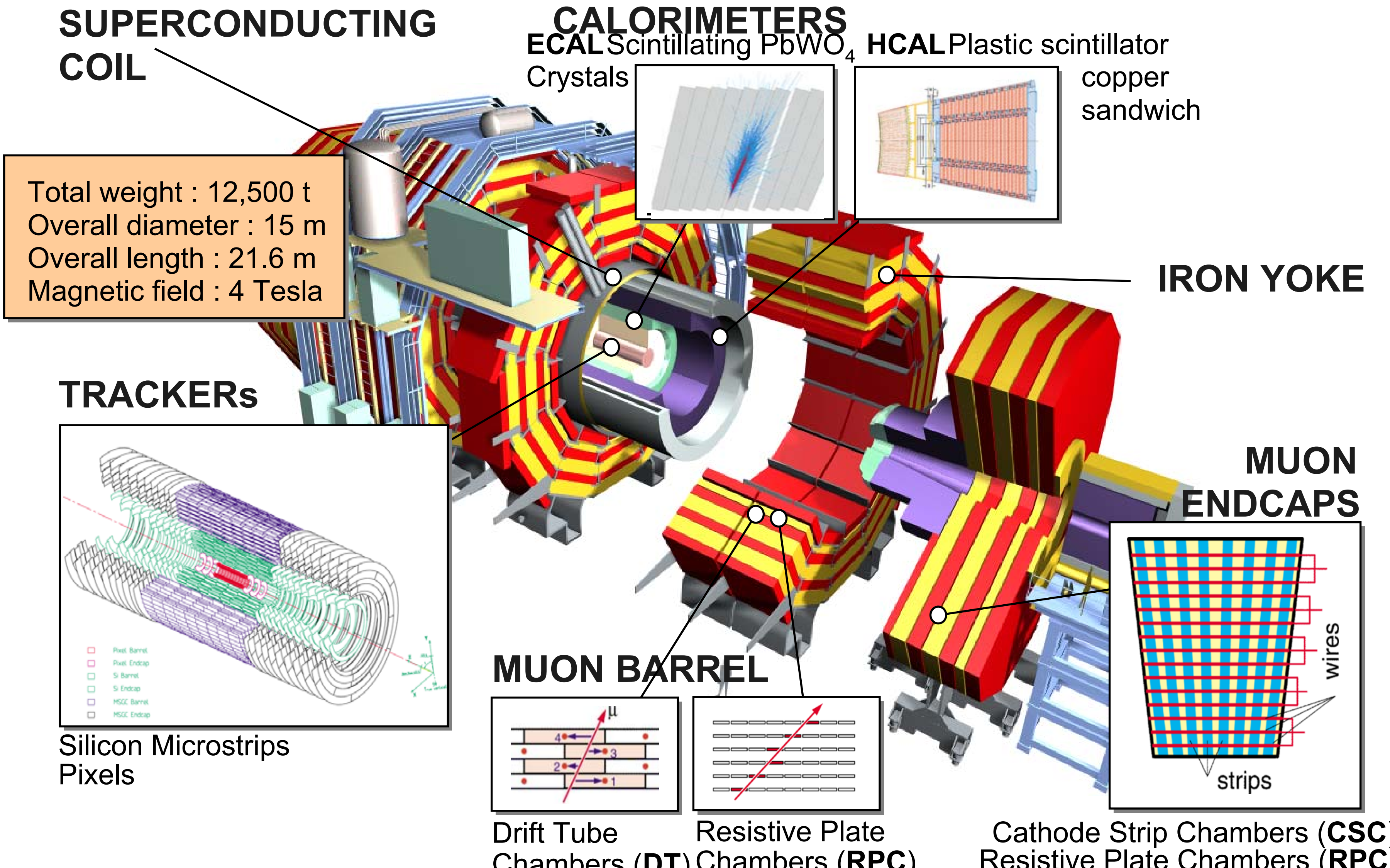
$$\frac{\Delta p}{p} = \frac{40\%}{B\sqrt{L}}$$

  - **BUT measurement much better when combined with the tracker**

Muon system

- Muon identification should be easy at $L=10^{34}cm^{-2}s^{-1}$
  - Muons can also be identified inside jets
    - b-tagging, also control efficiency of isolation cuts
- Factors that affect performance
  - Level-1 trigger
    - Rate from genuine muons ($b,c \rightarrow \mu$) is very high. Must make a P_T cut with very high efficiency, and a flexible threshold (P_T in the range 5-75 GeV)
  - Pattern recognition
    - Hits can be spoiled by correlated backgrounds: δ's, EM showers, punchthrough. Uncorrelated bkgs: neutrons and associated photons
  - Momentum resolution
    - High momenta: need large int(B.dl); good chamber resolution (<100μm) and alignment. Low momenta: inner tracking better
- Both detectors: multiple stations with multiple hits

The Compact Muon Solenoid (CMS)



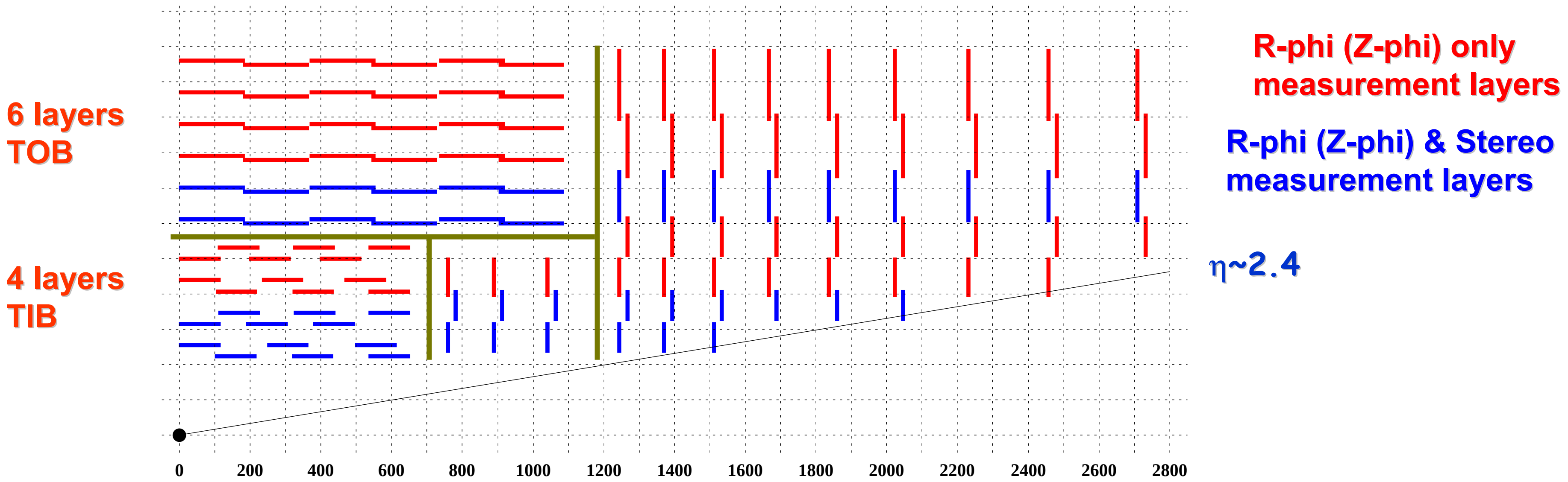
Tracking

- **Momentum resolution goal: $\Delta p_T/p_T = 0.1 p_T$ [TeV] $|\eta|<2$**
  - Narrow signals: $H \rightarrow 4\mu$
  - Match Z natural width
  - Measure lepton charge up to p~2TeV
  - Match calorimeter resolution (electrons)
  - Calorimeter calibration (ECAL)
- **Pattern recognition:**
  - Large-p_T leptons: muons (isolated/in jets); electrons (isolated)
  - Also large-p_T tracks around lepton
  - Identify all tracks with p_T>2GeV
- **CMS solution: few, very accurate points**
  - ATLAS solution: continuous tracking
- **Both, post LoI: add pixels for vertex tagging**

Tracking (I)

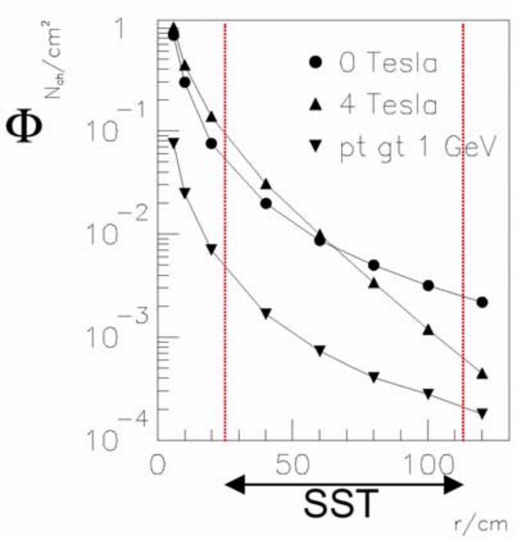
- **Few, very precise and clean measurements layers.**
  - **2-3 Silicon Pixel & 10-14 Silicon Strip Measurement Layers**

Radius ~ 110cm, Length ~ 270cm



Tracking (II) Requirements

- **Efficiency: need low, ~few % occupancy; Resolution**



Twelve hits; 4T field
spatial resolution: (pitch/ √12)
Radius: 110 cm
→momentum resolution:

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

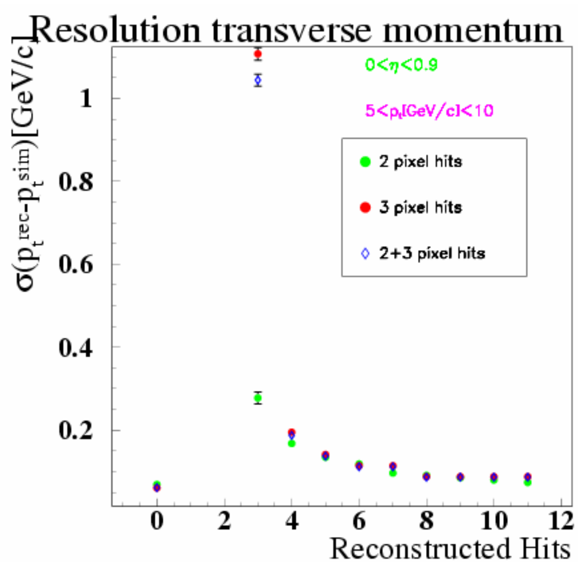
→Need pitch ~100μm.

small radii: need cell size < 1cm²
+ fast (~25ns) shaping time
condition is relaxed at large radii

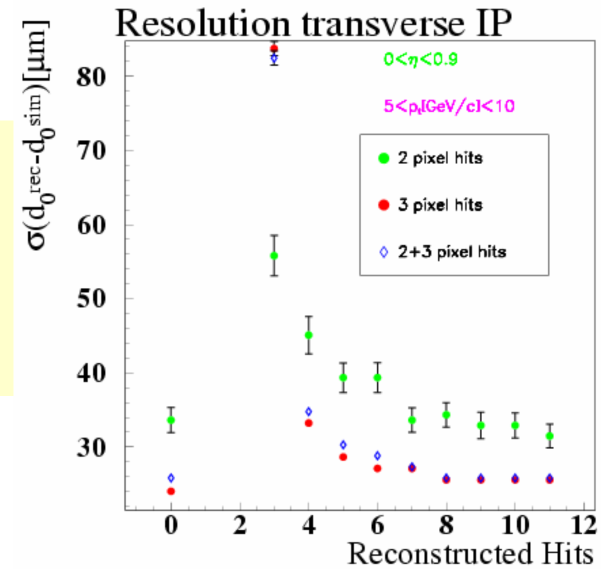
- **Strip size**
  - Strip length: 10cm (inner layers) to 20cm (outer layers).
  - Pitch: 80μm (inner layers) to 200μm (outer layers)

Tracker (III)

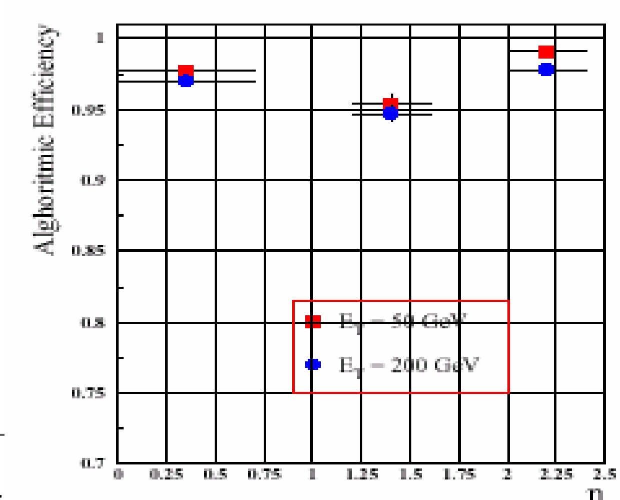
- **Performance**

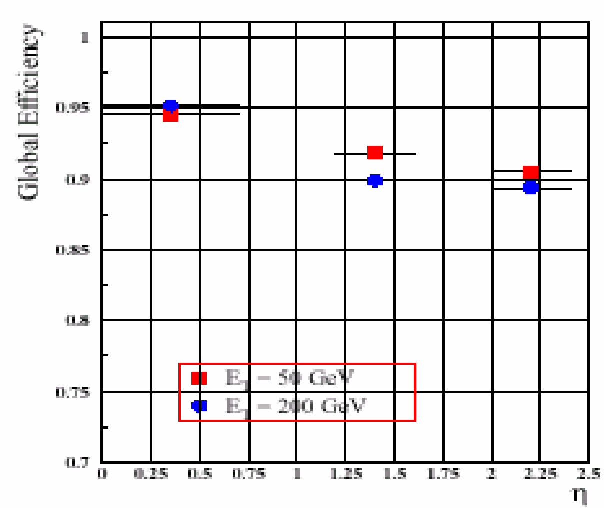


Most of the performance already with ~4-5 hits (useful for HLT)



Pions vs particles in jets: mostly material effects

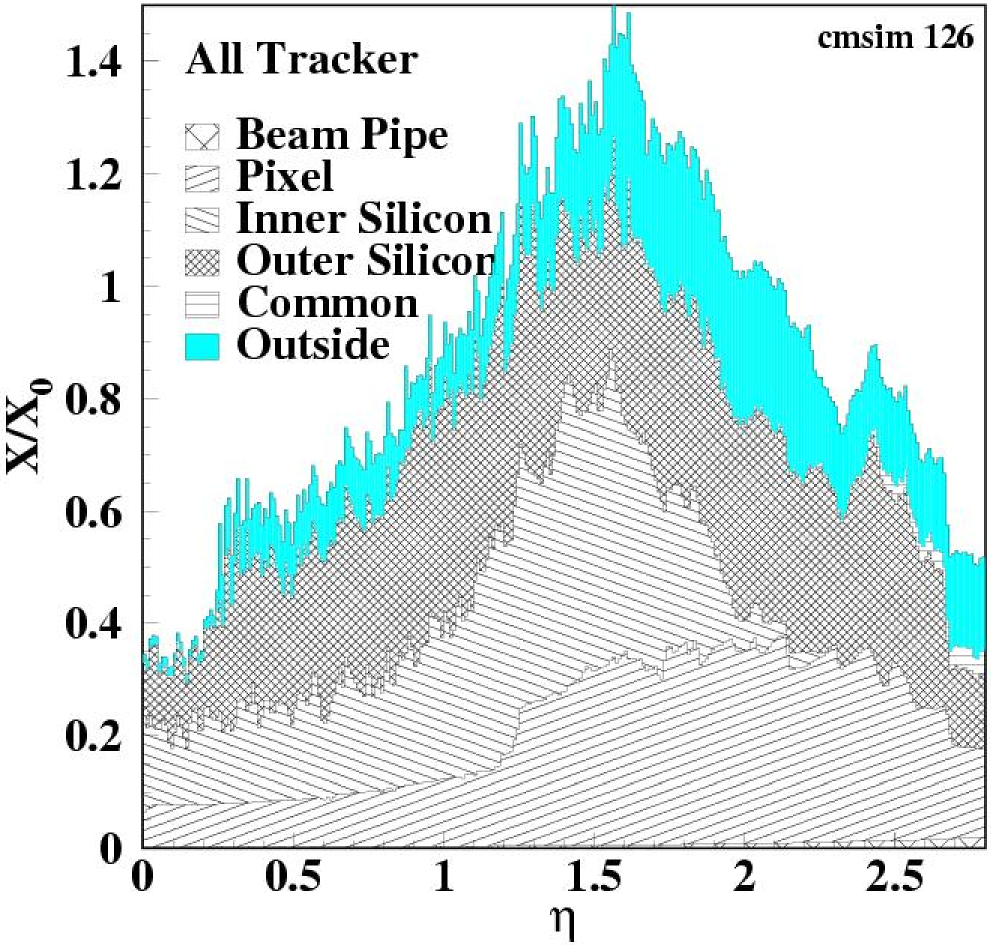




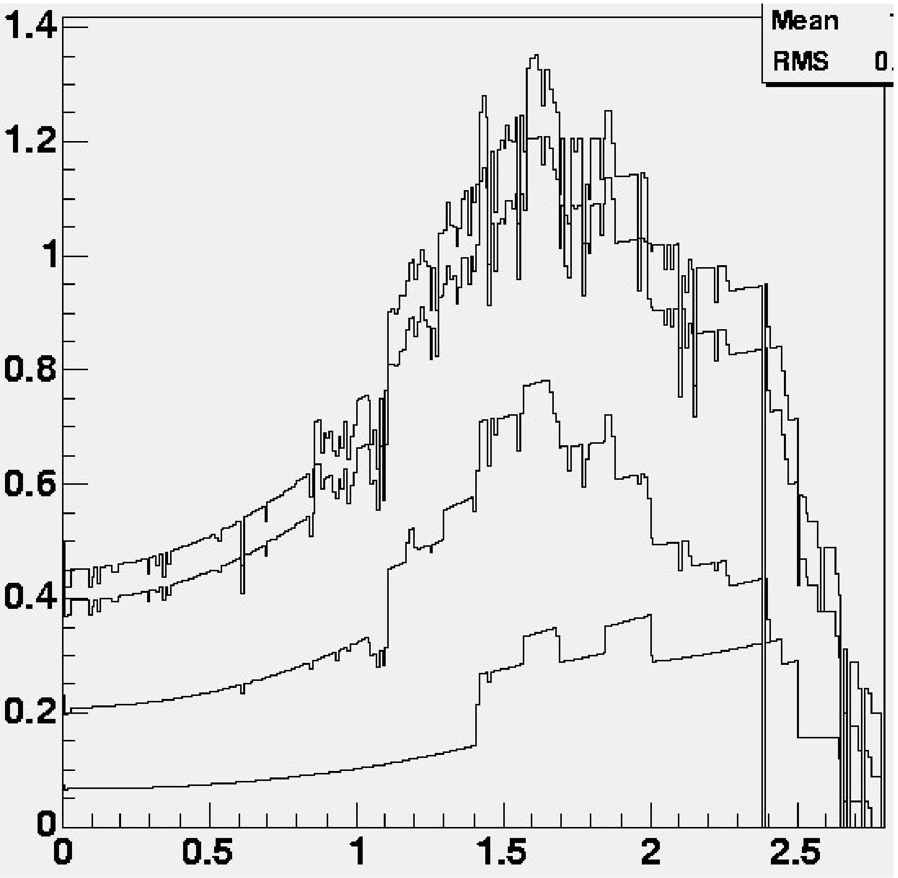
Tracker material

- **Material effects**

(CMSIM)

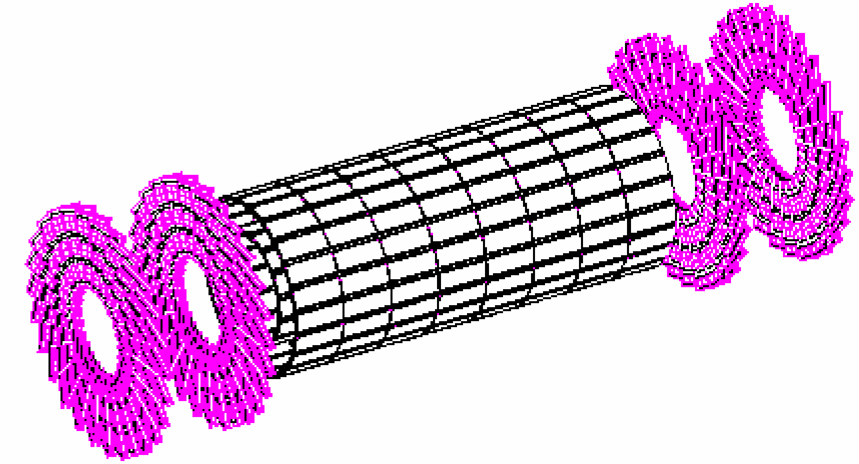


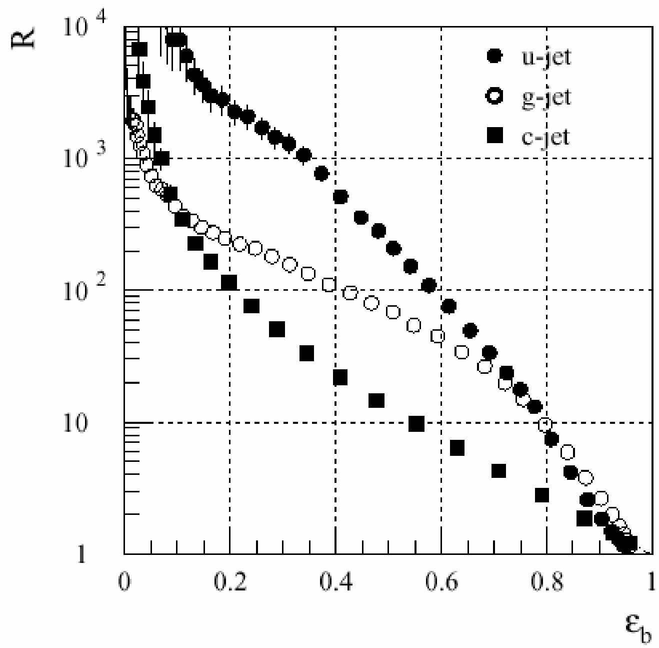
(FAMOS)



b identification

- **Pixel detectors**
  - **Both ATLAS and CMS**
    - **Very close to beam pipe (first point at 4cm) Different scenario for High luminosity**
  - **Small pixel size (150μm). Occupancy: 10^{-4}. Resolution: ~20μm.**

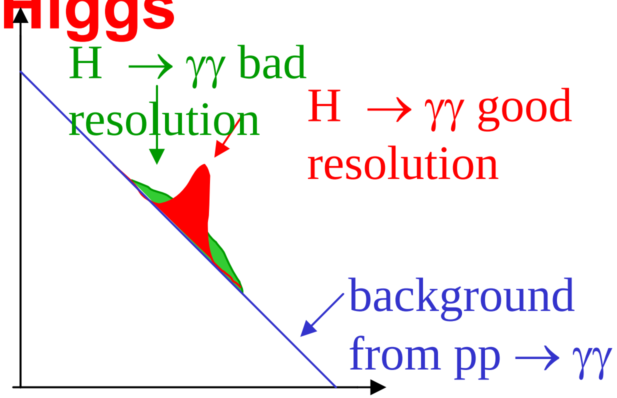




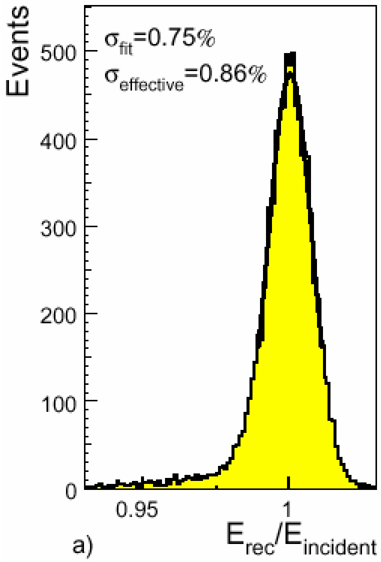
Rejection of c jets limited by τ_c
Rejection of g jets limited by g-splitting:
@ kinematics of M_H=400 GeV,
BR(g→cc)=6%
BR(g→bb)=4%

Other challenges; calorimetry

- **Need excellent energy resolution of EM calorimeters for e/γ; Example: $H \rightarrow \gamma\gamma$ for low mass Higgs**
  - **Higgs width is very narrow, so S/N directly $\propto$ to signal resolution**
  - **Moreover, initial background: x100 larger**
    - **π^0 rejection: strips (ATLAS), crystal size (isolation) (CMS); preshower in the endcap**



Tracker vs ECAL resolution match: at ~50 GeV (spot on for Higgs)



Calorimetry (I)

- **Electromagnetic calorimeter**
  - **Liquid argon by ATLAS. Not enough space in CMS for cryogenics. Need something more compact. Crystal ECAL**

Properties of some crystals

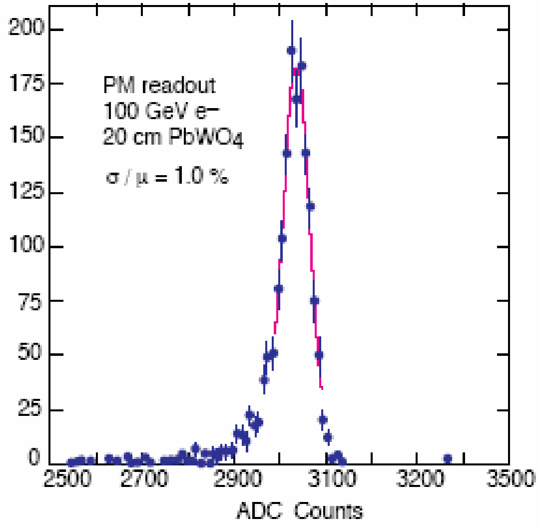
Crystal	X_0 (cm)	R_M (cm)	Light Yield Gammas/MeV	Peak (nm)	Decay (ns)
BaF_2	2.06	3.4	2000 6500	210 310	0.6 620
CeF_3	1.68	2.6	2000	300 340	5 20

  - **CeF_3 best choice. Good light yield; short X_0; short τ; good radiation resistance**
  - **Post LoI: PbWO4**

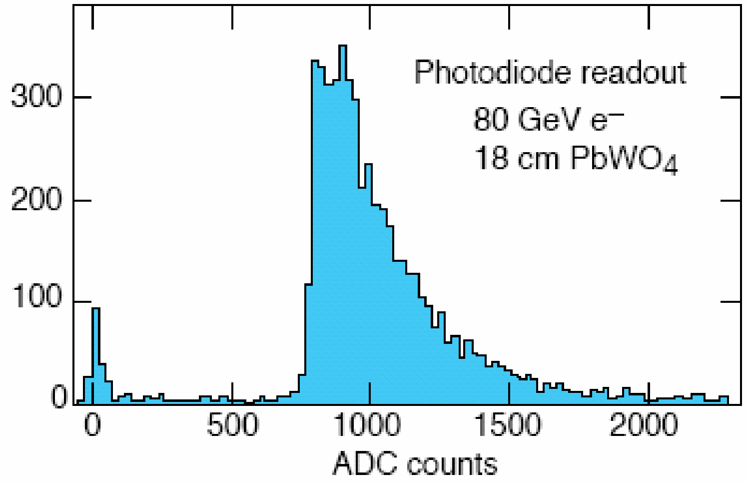
$PbWO_4$	0.89	2.2	250	440	5-15

- **$PbWO_4$: scintillation light and development of photodetector**

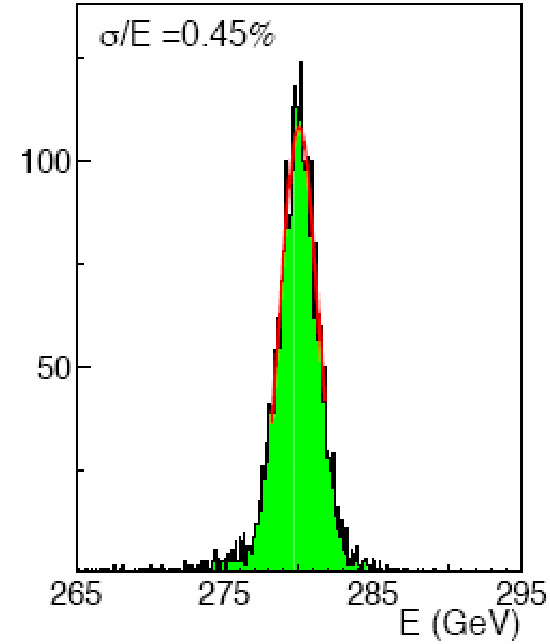
Photomultiplier Readout



Si Photodiode Readout



Avalanche Photodiode Readout

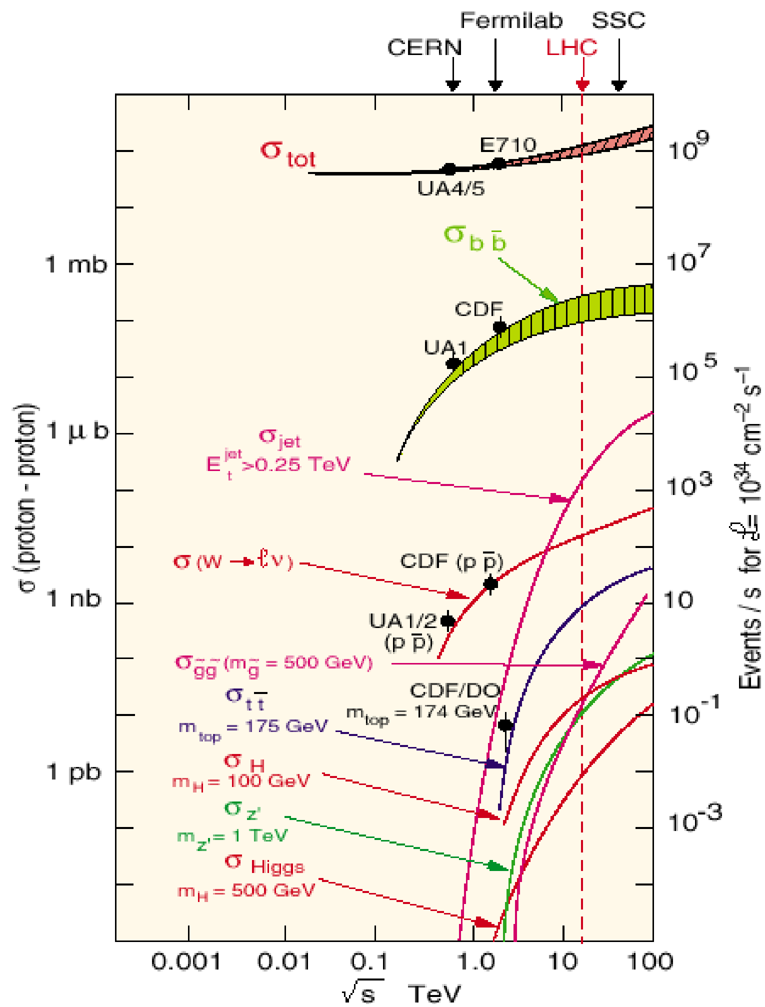


Calorimetry (III)

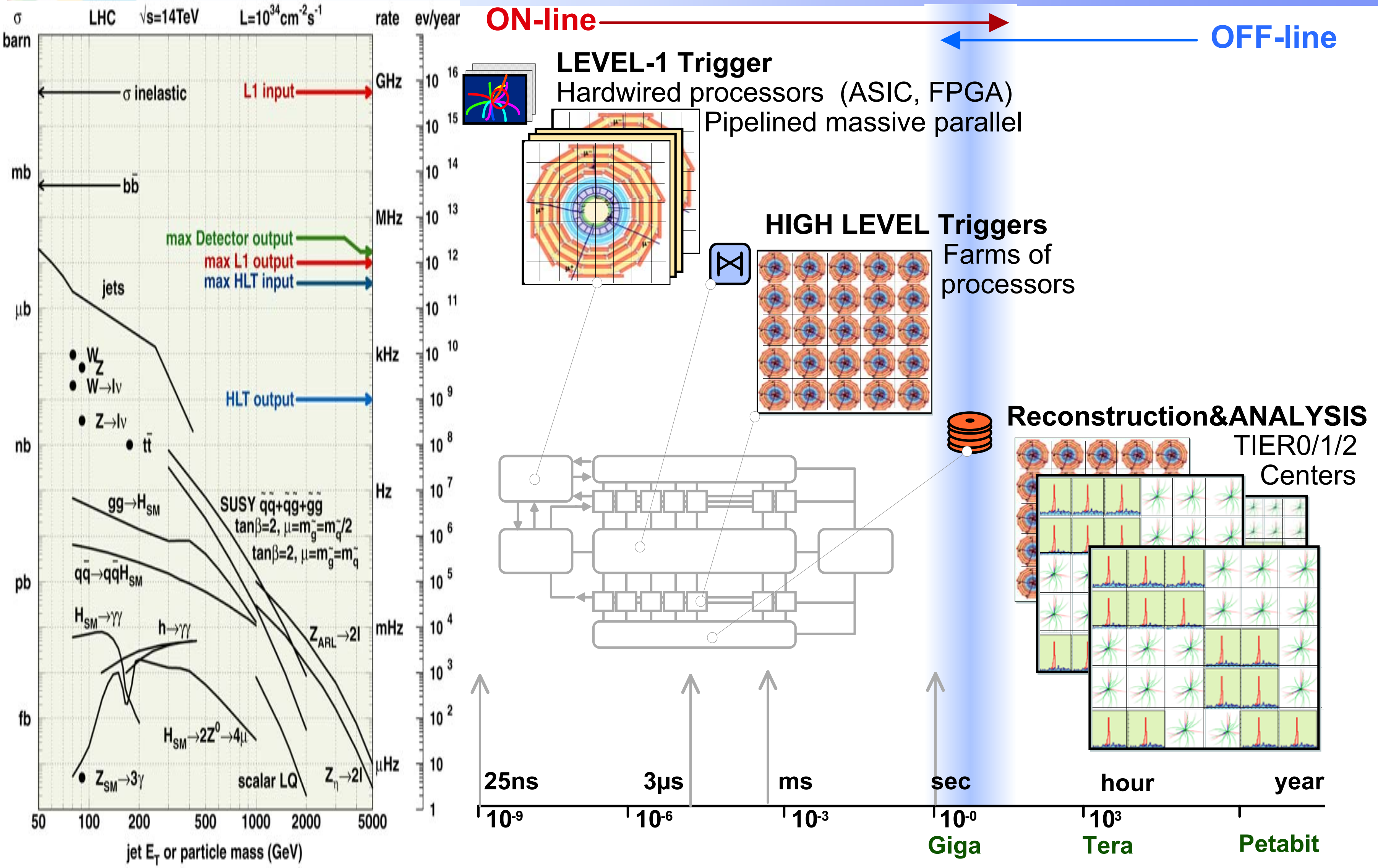
- **Hadron calorimeter requirements**
  - Jet energy resolution: limited by jet algorithm, fragmentation, magnetic field and pileup at high luminosity
    - A good figure of merit: width of the jet-jet mass distribution
      - → Low-p_T jets: W, Z → Jet-Jet, e.g. in top decays
      - → High-p_T jets: Z' → Jet Jet (M(Z')~1 TeV)
    - At very high-p_T: need fine lateral granularity (for very collimated jets)
  - Missing transverse energy resolution
    - Gluino and squark production/decay
      - → 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

Selectivity: the physics

- **Cross sections for various physics processes vary over many orders of magnitude**
  - **Inelastic: 10^9 Hz**
  - **W→ ℓ ν: 10^2 Hz**
  - **t t production: 10 Hz**
  - **Higgs (100 GeV/c²): 0.1 Hz**
  - **Higgs (600 GeV/c²): 10^{-2} Hz**
- **Selection needed: $1{:}10^{10-11}$**
  - **Before branching fractions...**

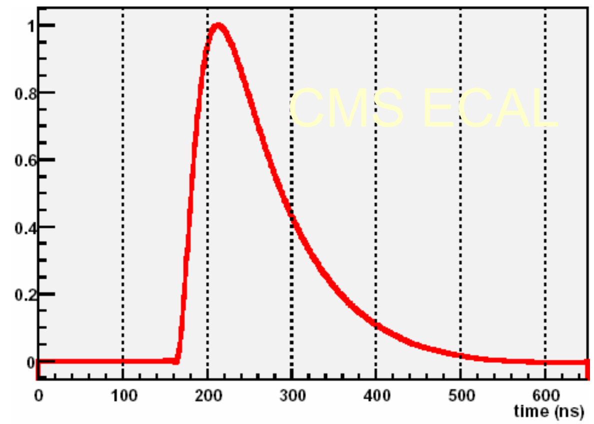


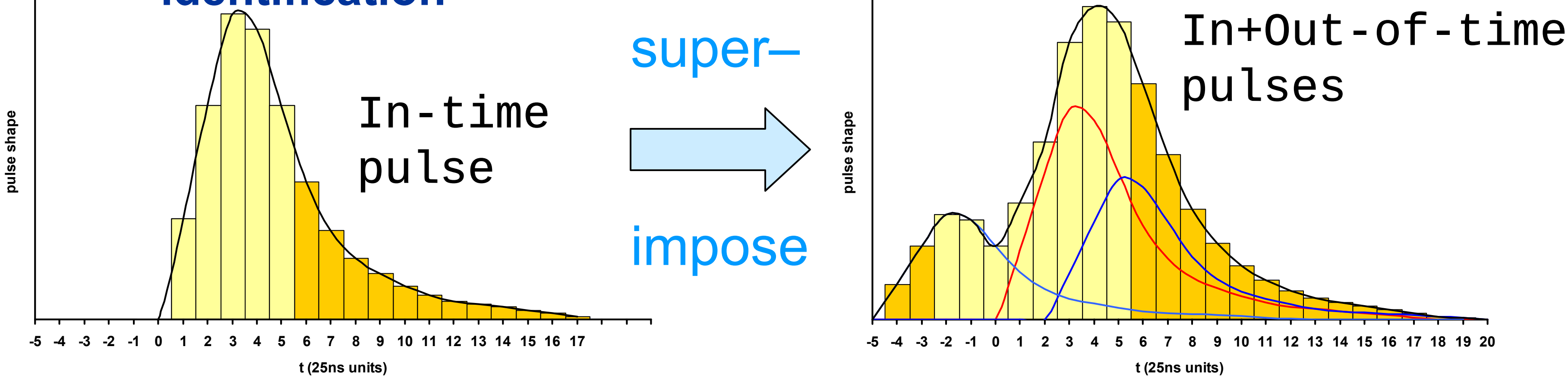
Physics selection at the LHC



Pile-up & Electronics; BCID

- **“In-time” pile-up: particles from the same crossing but from a different pp interaction**
  - **Long detector response/pulse shapes:**
    - **“Out-of-time” pile-up: left-over signals from interactions in previous crossings**
    - **Need “bunch-crossing identification”**





Synchronization

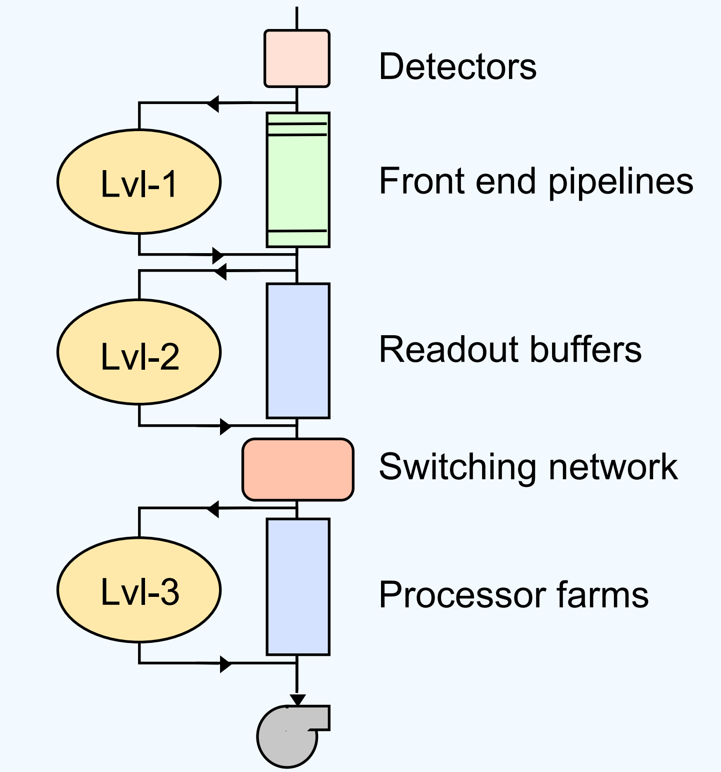
- Time-of-flight (25 ns = 7.5 m < detector size)
  - Plus intra-channel synchronization
  - Plus inter-detector synchronization
- http://cmsdoc.cern.ch/cms/TRIDAS/html/WELL2.html

Trigger/DAQ requirements/challenges

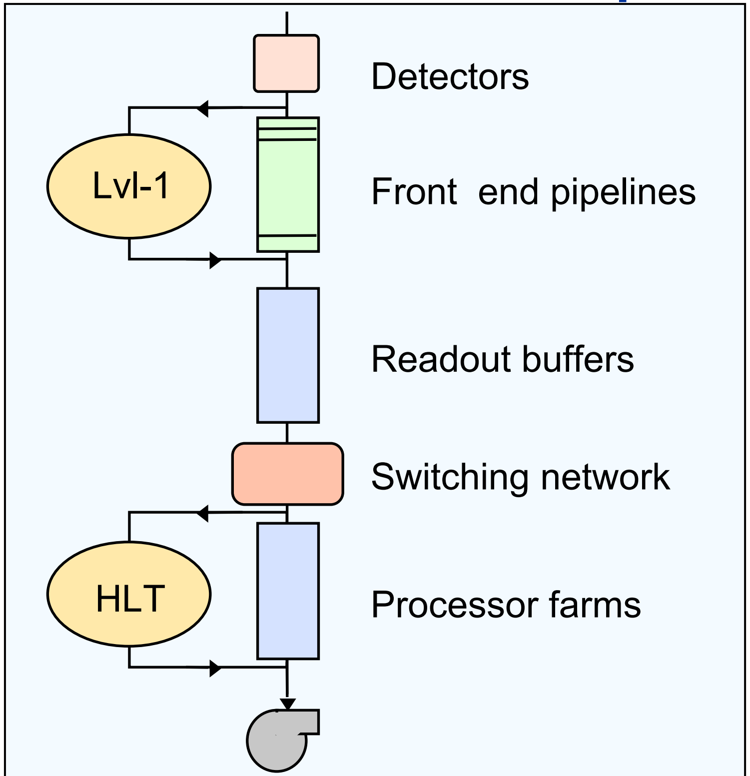
- **N (channels) ~ O(10^7); ≈20 interactions every 25 ns**
  - need huge number of connections
  - need information super-highway
- **Calorimeter information should correspond to tracker info**
  - need to synchronize detector elements to (better than) 25 ns
- **In some cases: detector signal/time of Flight > 25 ns**
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing...
- **Can store data at ~ (1-2)x10^2 Hz**
  - need to reject most interactions
- **It's On-Line (cannot go back and recover events)**
  - need to monitor selection

Online Selection Flow in pp

- **Level-1 trigger: reduce 40 MHz to 10^5 Hz**
  - **This step is always there**
  - **Upstream: still need to get to 10^2 Hz; in 1 or 2 extra steps**



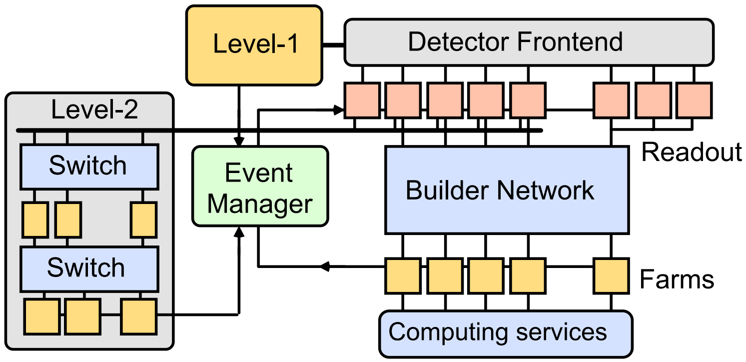
"Traditional": 3 physical levels

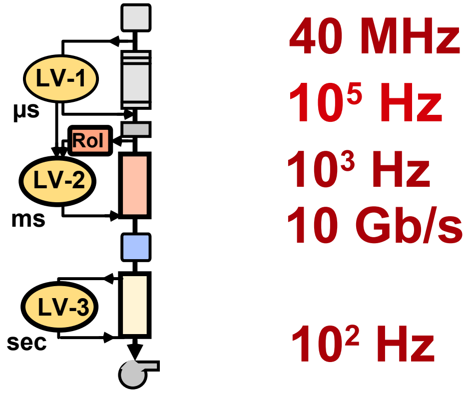


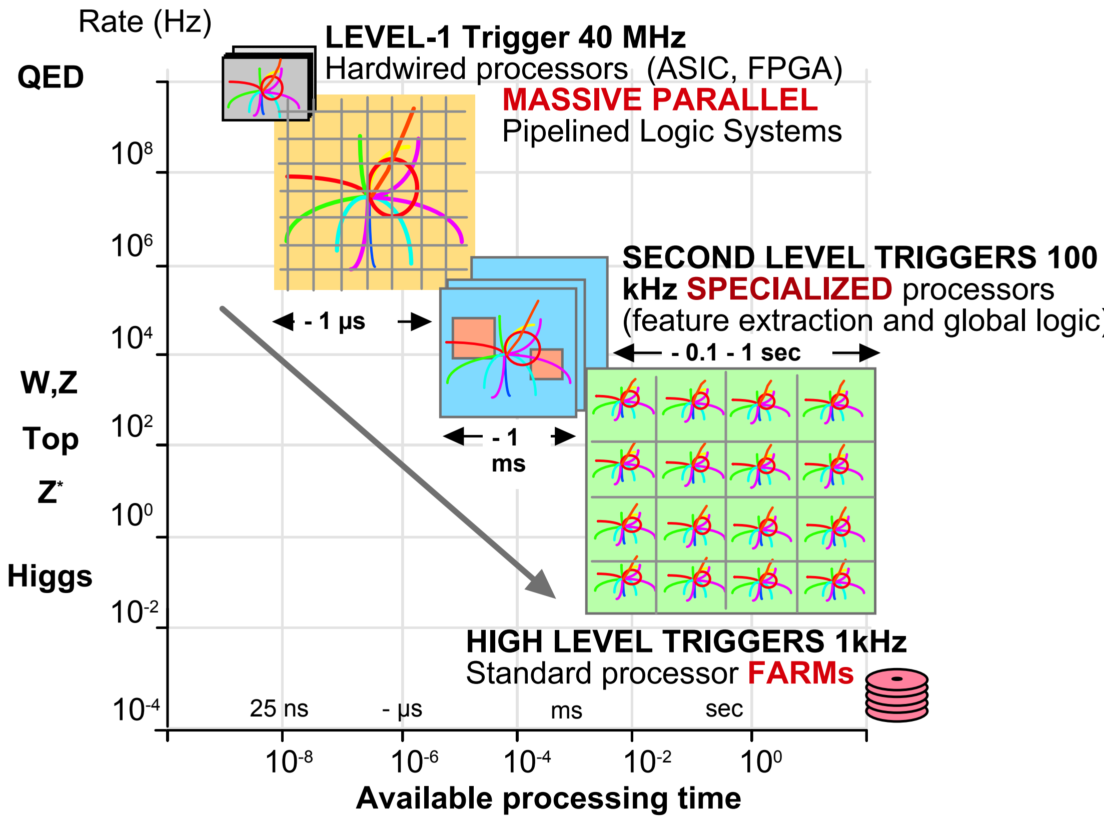
CMS: 2 physical levels

Three physical entities

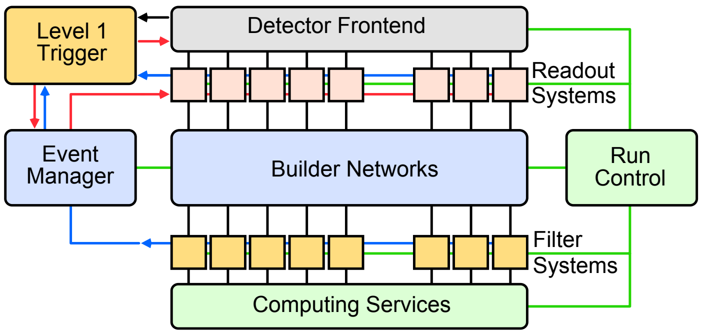
- **Additional processing in LV-2: reduce network bandwidth requirements**

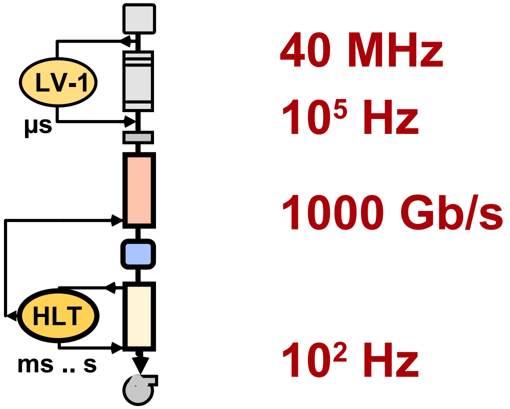


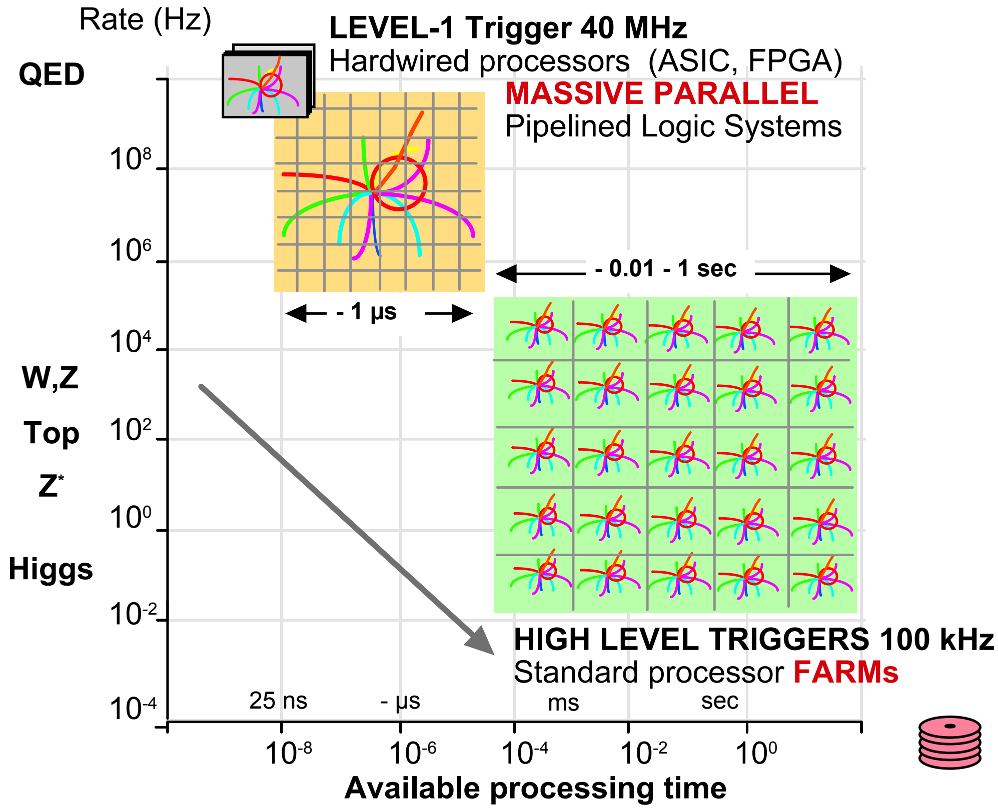




Two physical entities



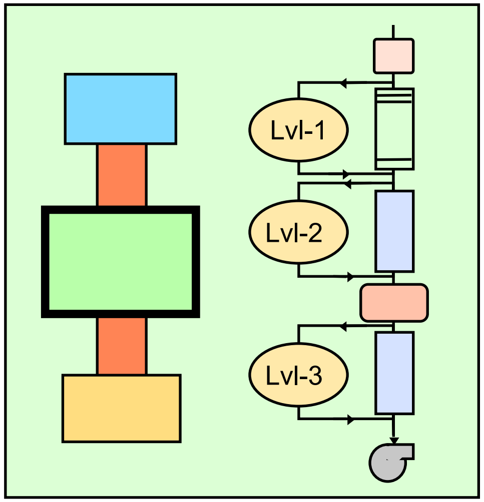




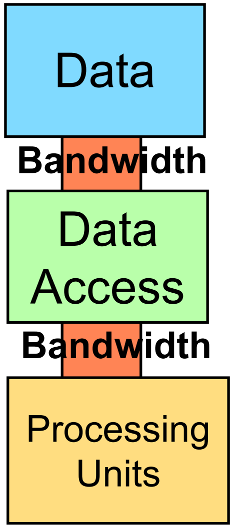
- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

Comparison of 2 vs 3 physical levels

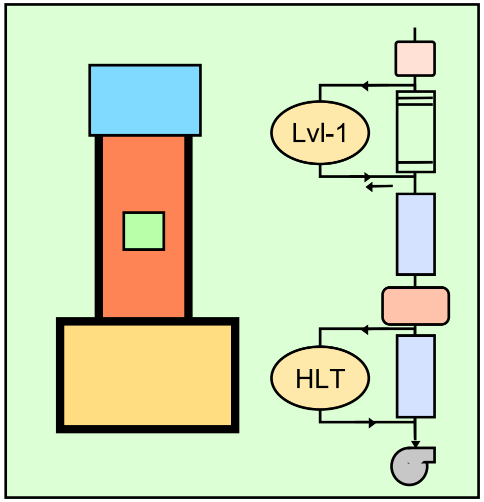
- **Three Physical Levels**
  - Investment in:
    - Control Logic
    - Specialized processors



Model



- **Two Physical Levels**
  - Investment in:
    - Bandwidth
    - Commercial Processors



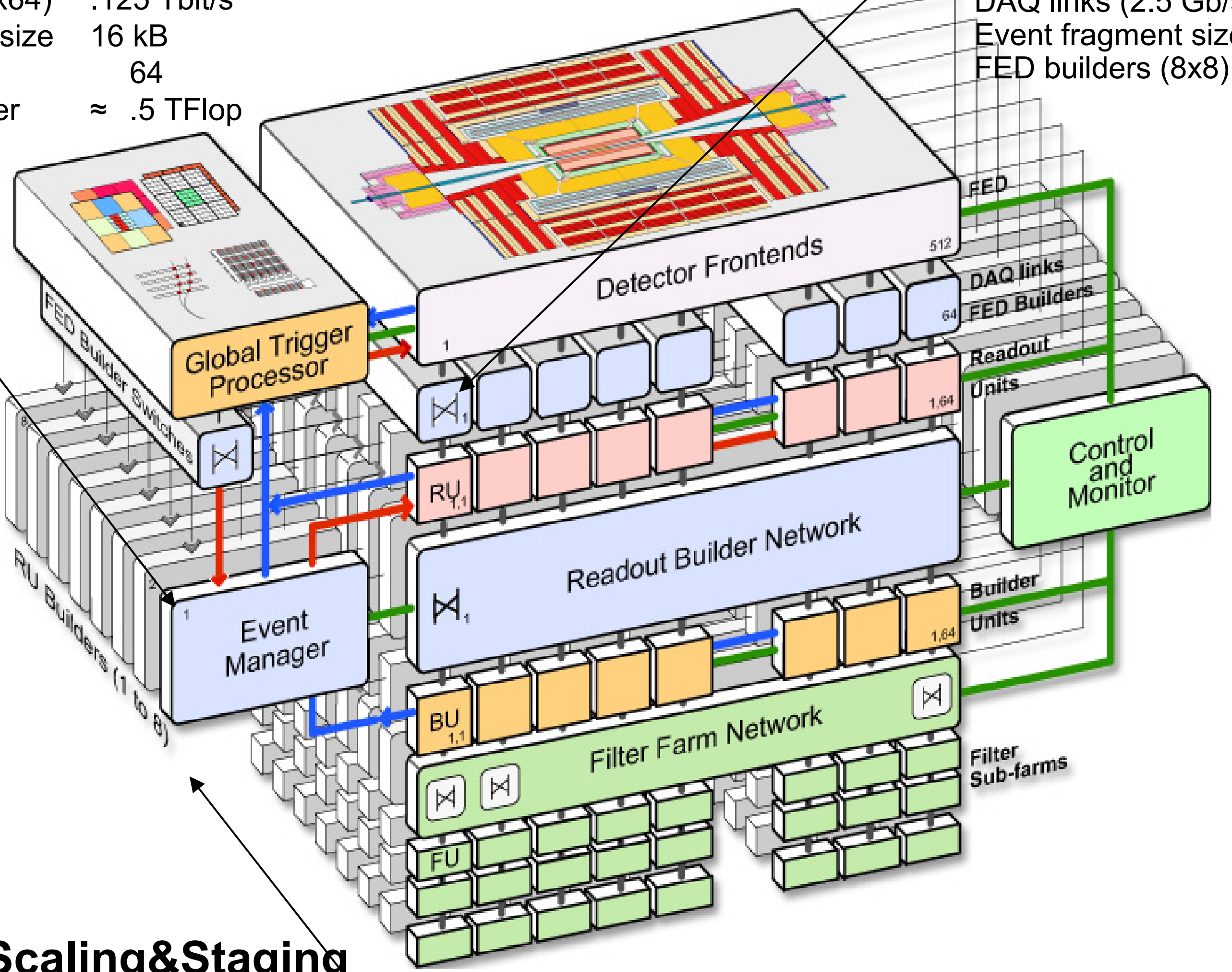
3D-EVB: DAQ staging and scaling

DAQ unit (1/8th full system):

Lv-1 max. trigger rate	12.5 kHz
RU Builder (64x64)	.125 Tbit/s
Event fragment size	16 kB
RU/BU systems	64
Event filter power	≈ .5 TFlop

Data to surface:

Average event size		1 Mbyte
No. FED s-link64 ports	>	512
DAQ links (2.5 Gb/s)		512+512
Event fragment size		2 kB
FED builders (8x8)	≈	64+64



DAQ Scaling&Staging

8-fold (DAQ) way

Data to surface:

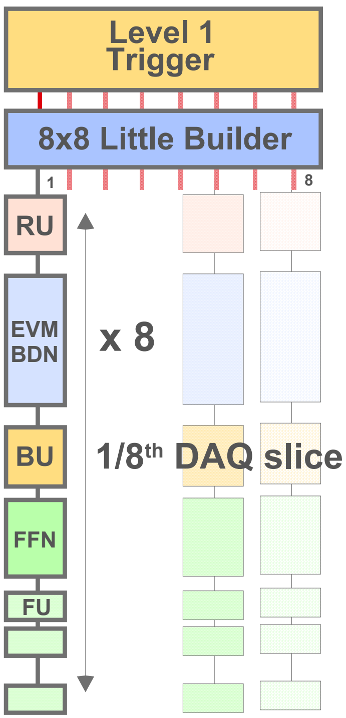
Average event size	1 Mbyte
No. FED s-link64 ports	> 512
DAQ links (2.5 Gb/s)	512+512
Event fragment size	2 kB
Little builders (8x8)	- 64+64

The DAQ system consists of two parts:

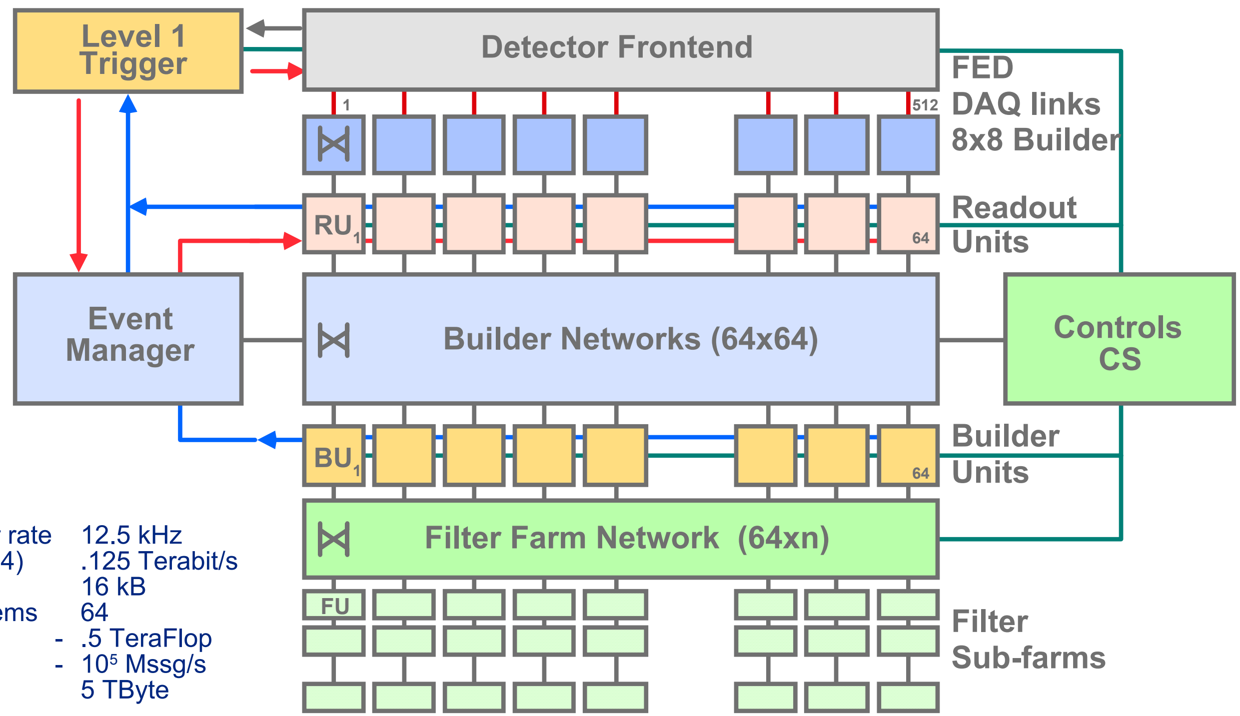
- The front end electronics readout and the data link to surface

-The DAQ core implemented as 8 DAQ slices each processing a fraction of the trigger rate

'Side' View



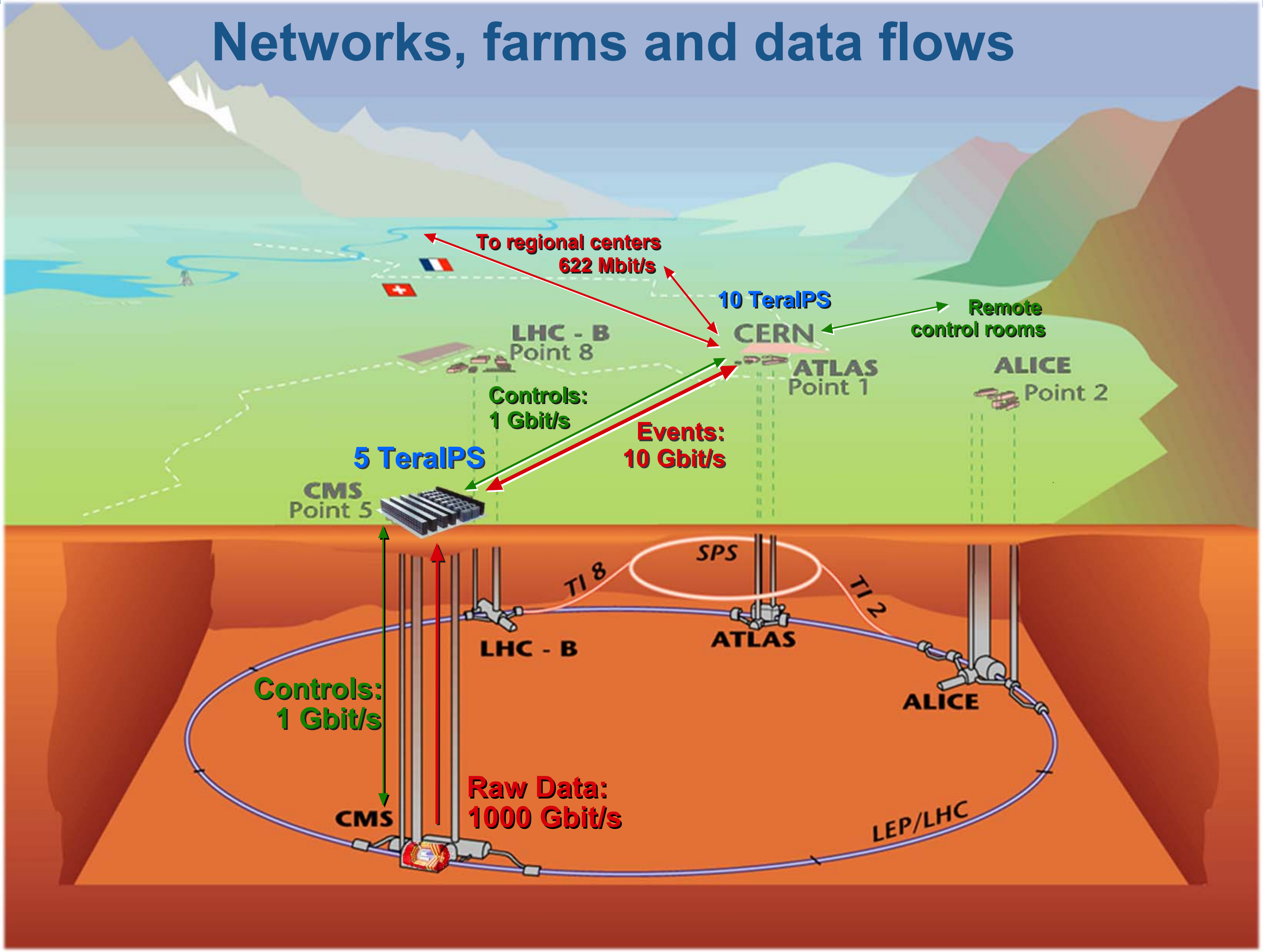
'Front' view



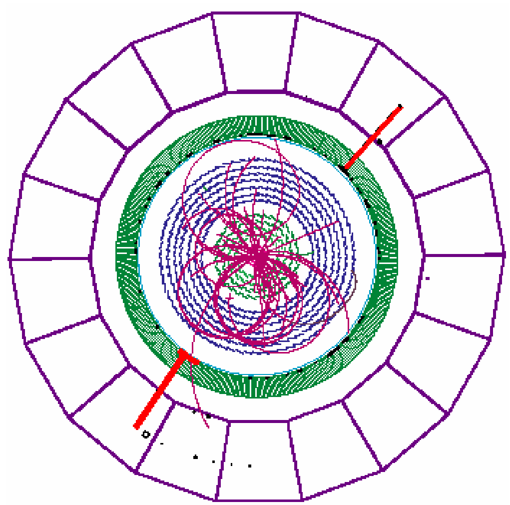
1/8th DAQ slice:

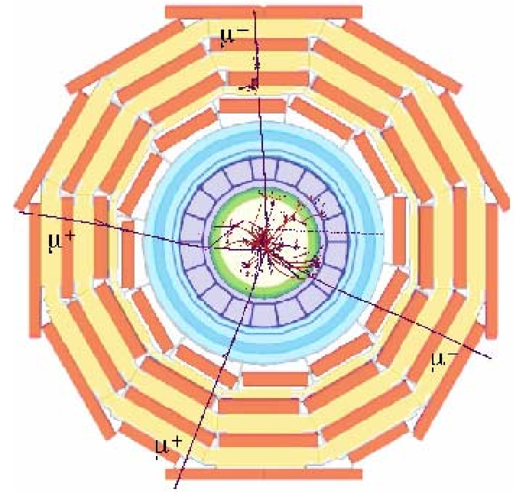
Lv-1 maximum trigger rate	12.5 kHz
Builder network (64x64)	.125 Terabit/s
Event fragment size	16 kB
Readout/Builder systems	64
Event filter power	- .5 TeraFlop
Event flow control	- 10^5 Mssg/s
Local mass storage	5 TByte

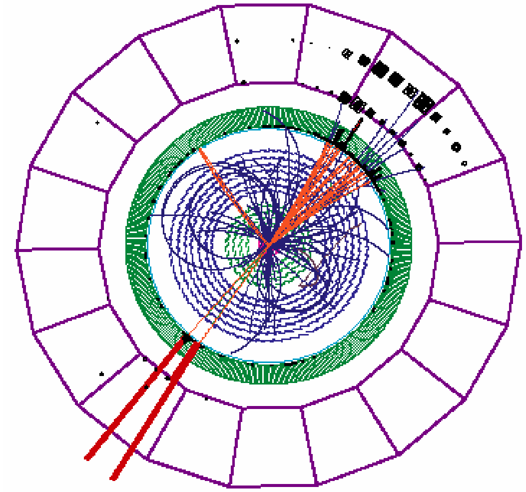
After the Trigger and the DAQ/HLT

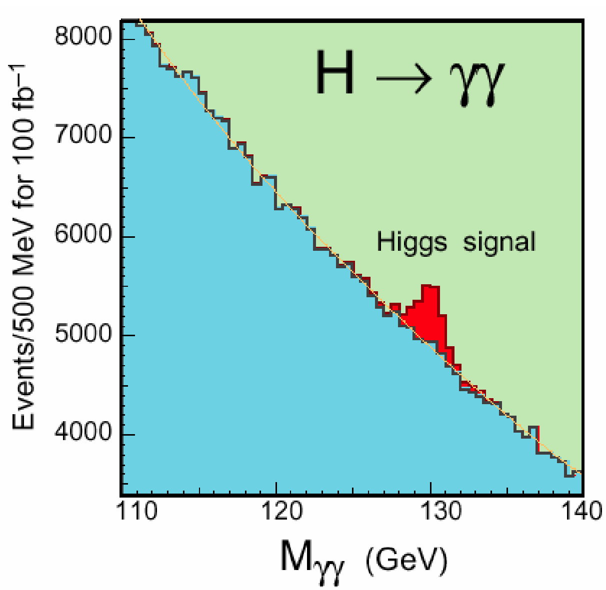


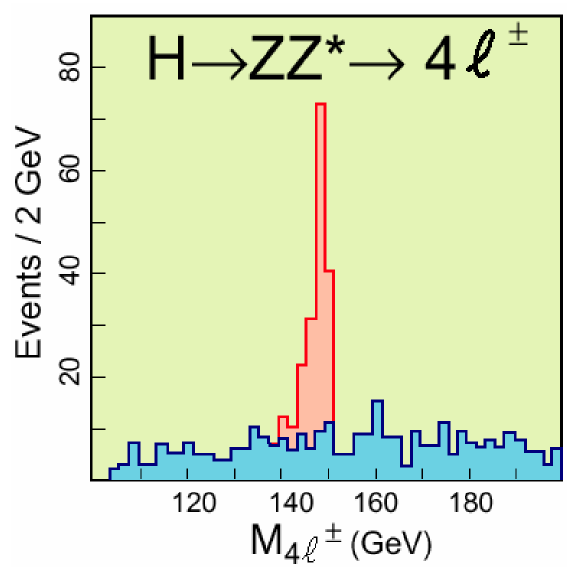
The Higgs in the detector

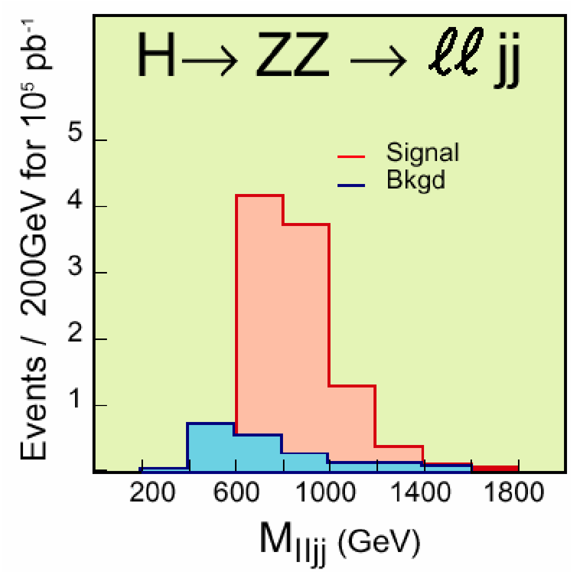






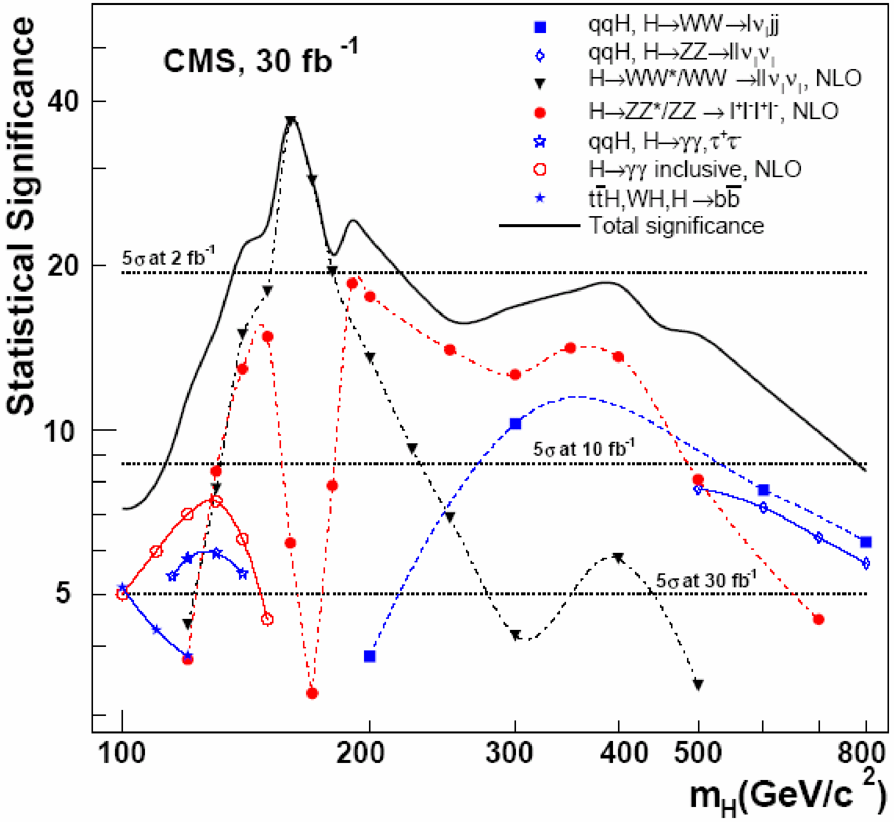






Higgs reach

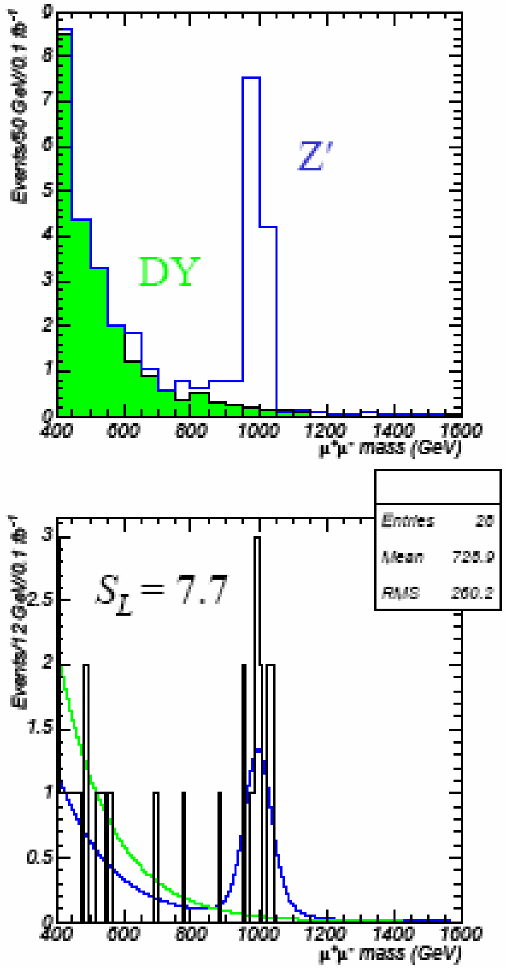
- **CMS can probe the entire set of "allowed" Higgs mass values;**
  - **in most cases a few months at $2x10^{33}$ $cm^{-2}s^{-1}$ are adequate for a 5σ observation**

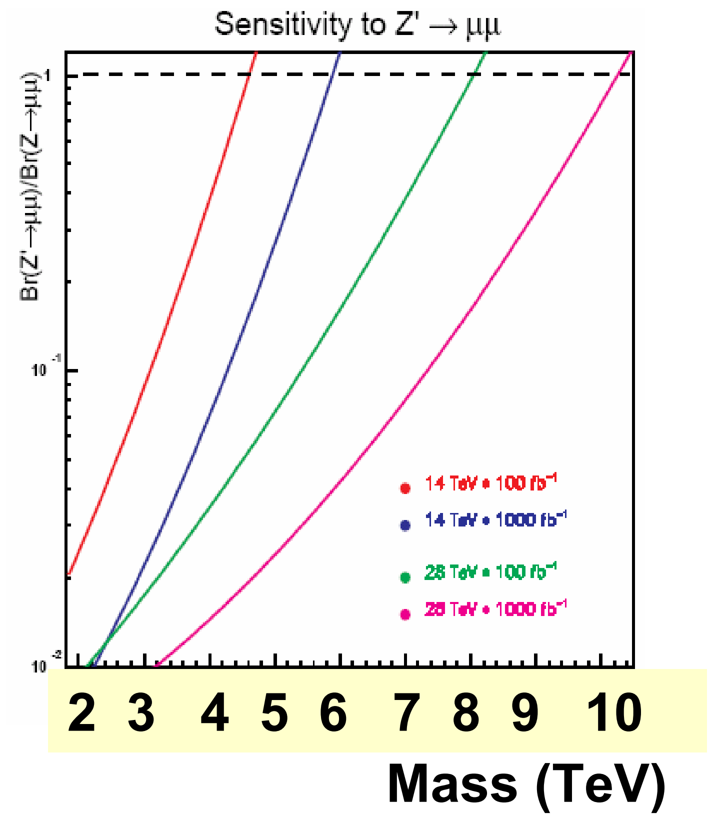


New (un)expected Physics

- **From SUSY to extra-dimensions:huge physics potential**

$Z' \to \mu\mu$ with $0.1\ fb^{-1}$; $M(Z')=1TeV$





Summary

- **A set of unprecedented challenges**
  - From the rate of events, to the selectivity, to the hostility of the environment and the need for very high resolutions and acceptances, a very difficult job
- **Different "architectures" – the magnet being a key choice**
  - To a large extent, the rest of the design follows. Precision: ECAL in front of magnet. Small (not deep HCAL); crystals (short X_0). Muons: multi-station, return-yoke bending. Trigger/DAQ: use two physical trigger entities (Level-1/HLT)
- **Simulation says that CMS will probe the Physics that the LHC will deliver very effectively**
- **Current issues: calibration, alignment, what-if scenarii**
  - Installation and commissioning of the detector.
  - And then: control and monitor…