Introduction to CMS

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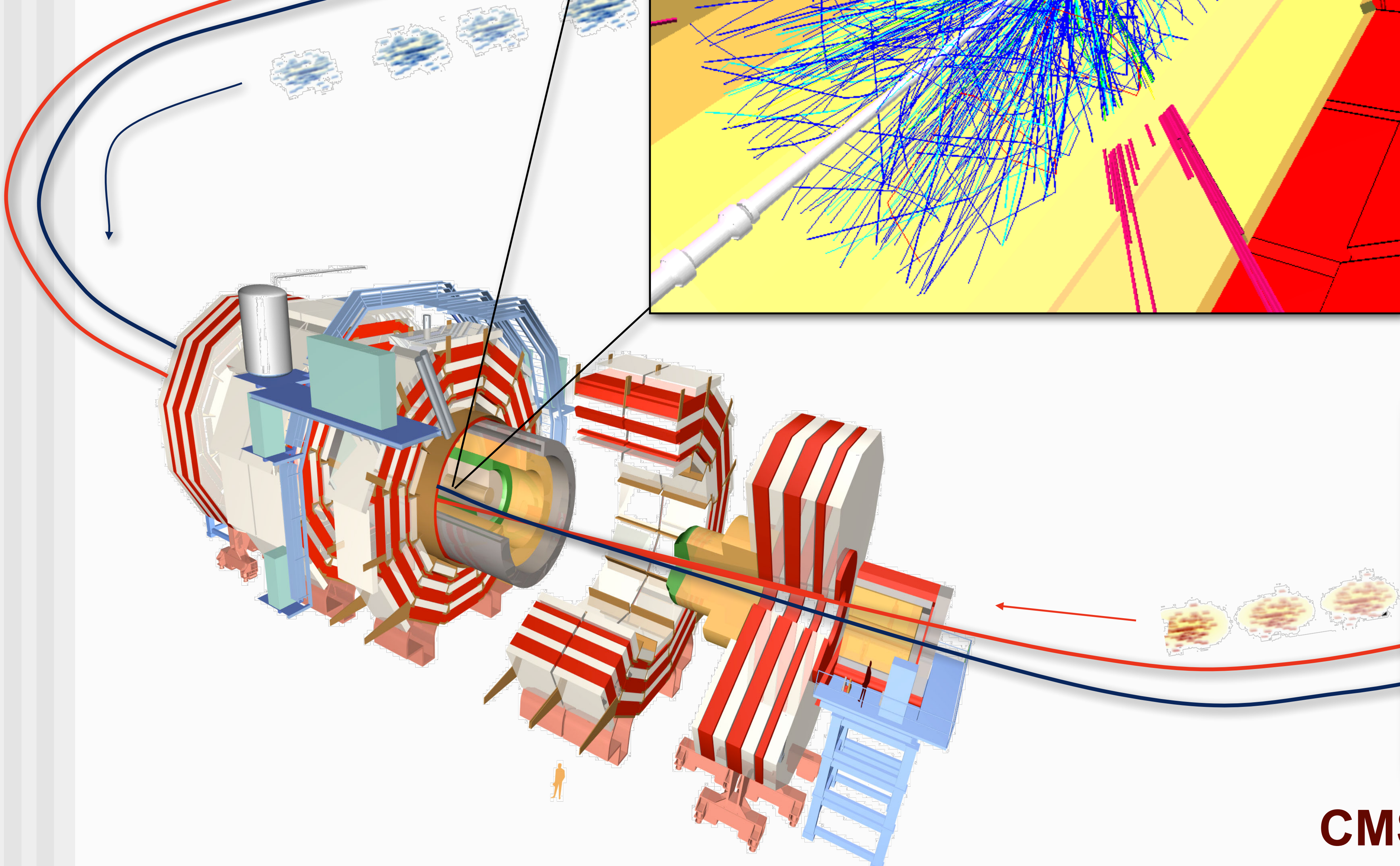
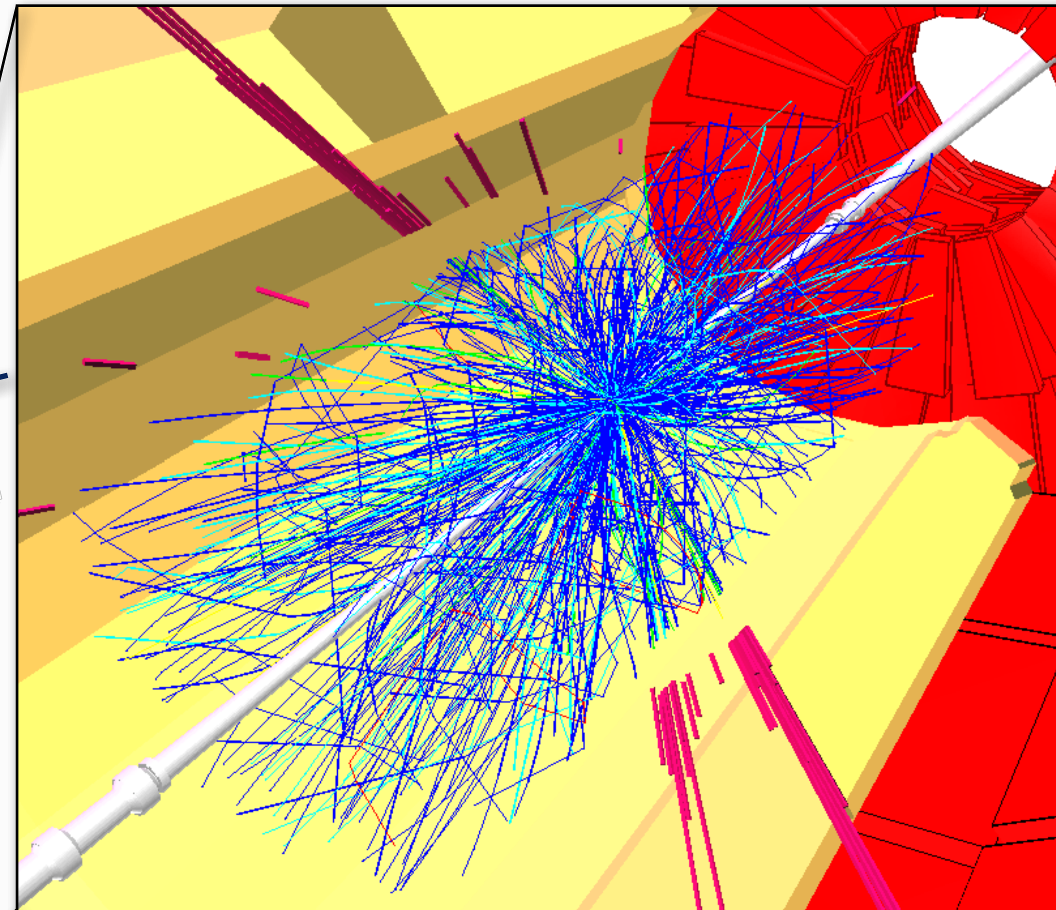
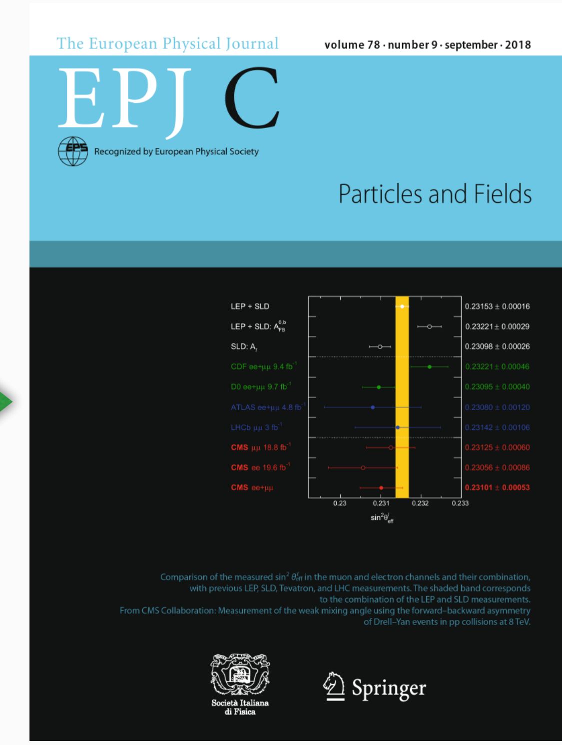
Uni Padova & INFN

Thanks to G. Dissertori
for most of the slides





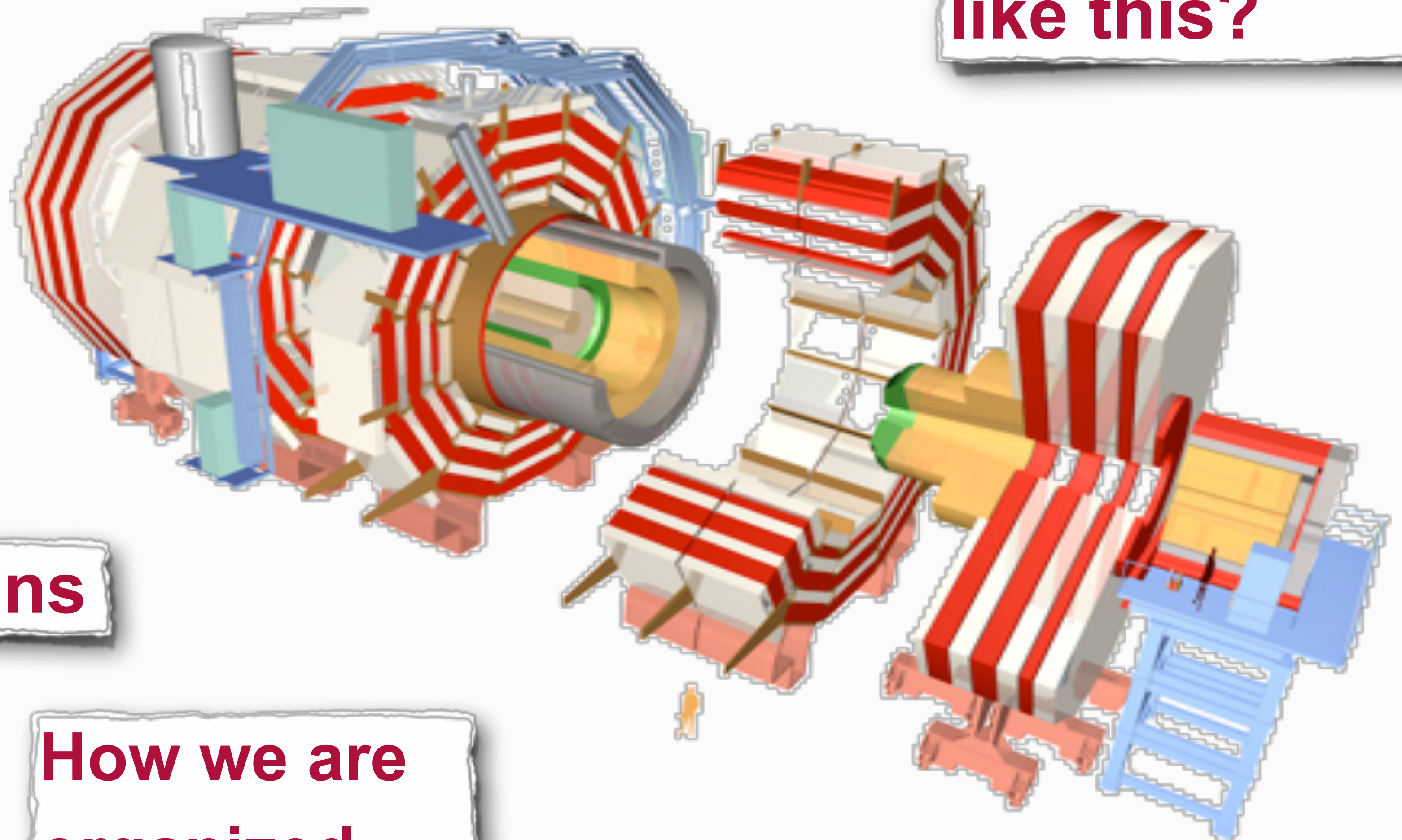


CMS Induction Day
January 30th 2019

Outline:

Some History

Why does it look like this?



Future plans

How we are organized

CMS at P5…

Note: much more details in the other talks to come…

Some History

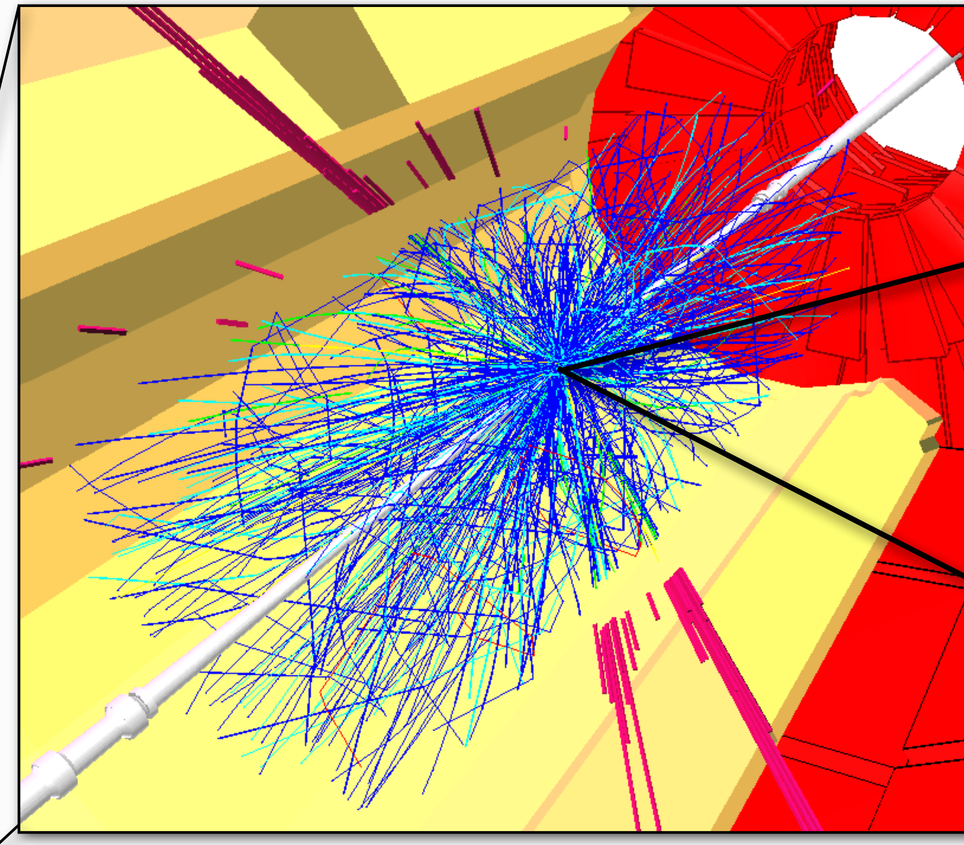
A truly gobal project

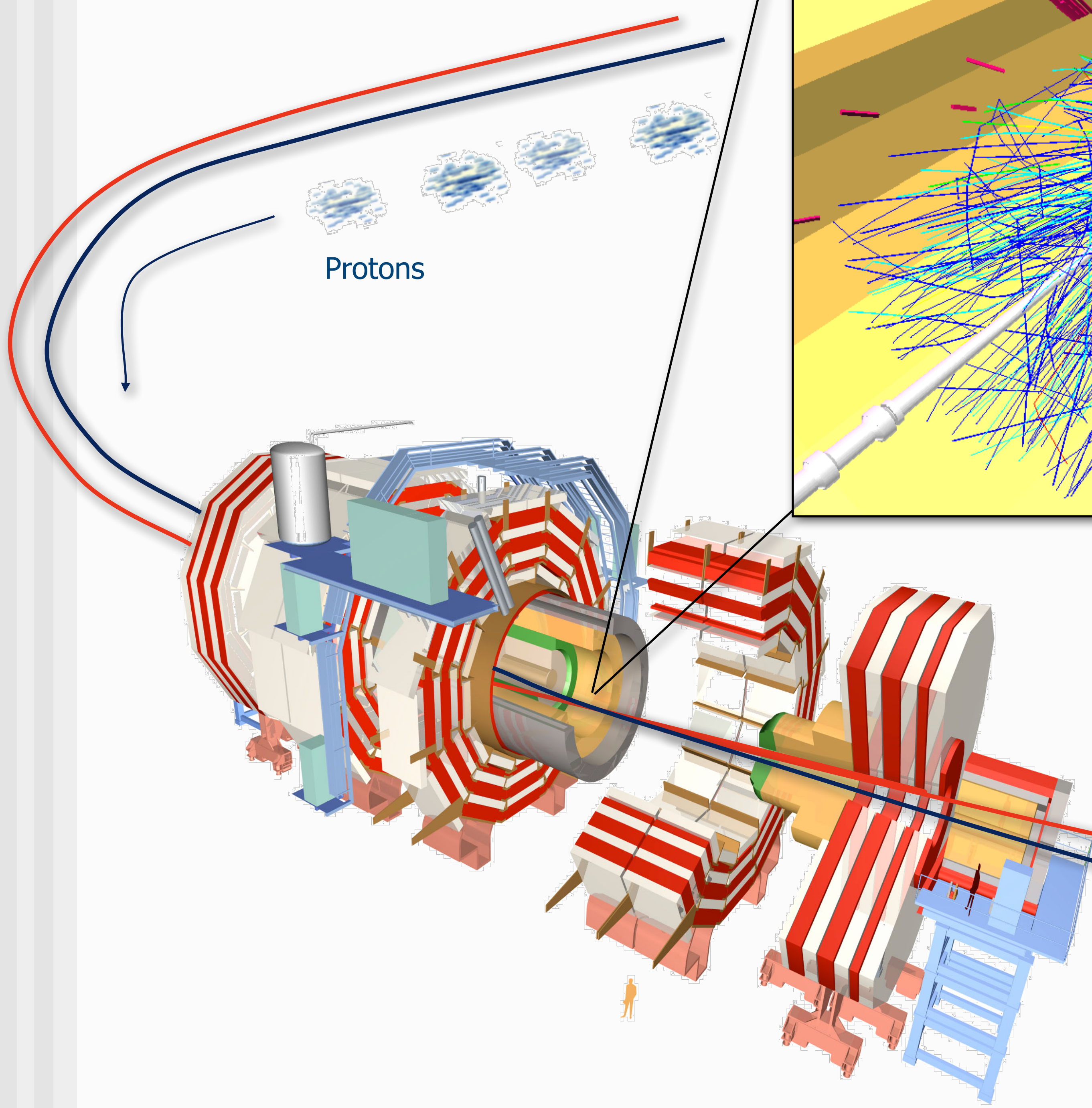
CMS Collaboration
~4000 members
~40 countries
~200 Institutes

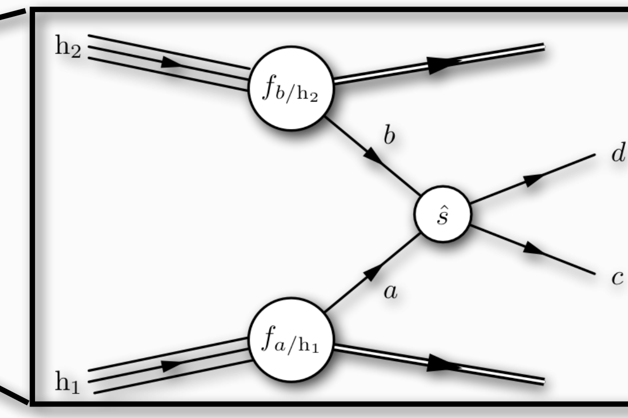
Why does it look like as it looks like?

Collisions at the LHC

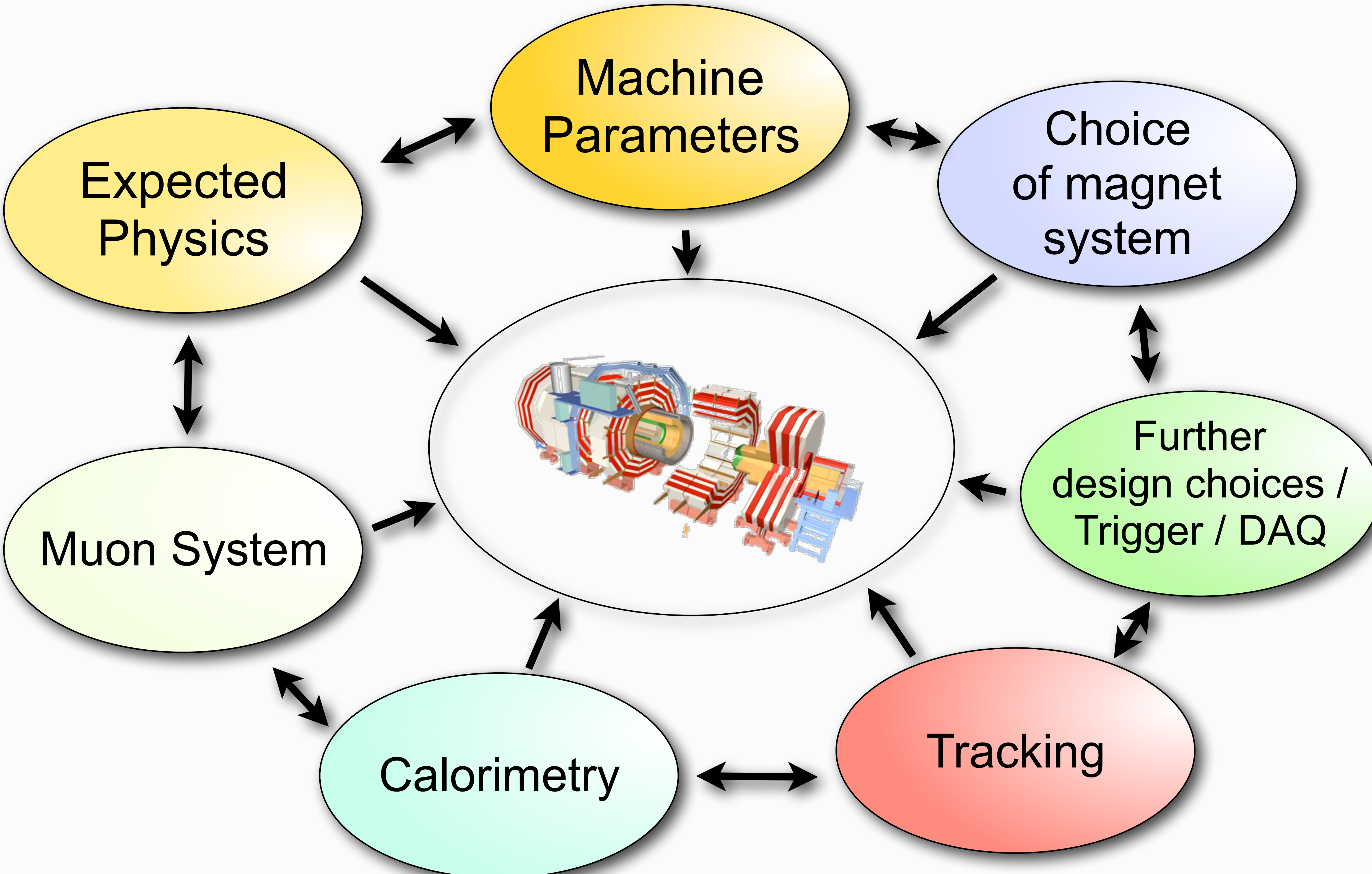
Centre-of-Mass Energy = 0.9 - 2.36 - 7 - 8 - 13/14 TeV
Bunch separation : 50 - 25 ns
Beam crossings : 20-40 Million / sec
p p - Collisions : ~1 Billion / sec
Events to tape : ~1000 / sec, each 1-2 MB







How to design your detector



pp-Interactions at the LHC

σ_{tot} =

≈100mb

diffractive

≈10mb

+

diffractive

≈10mb

+

PPS

double diffractive

≈"small"

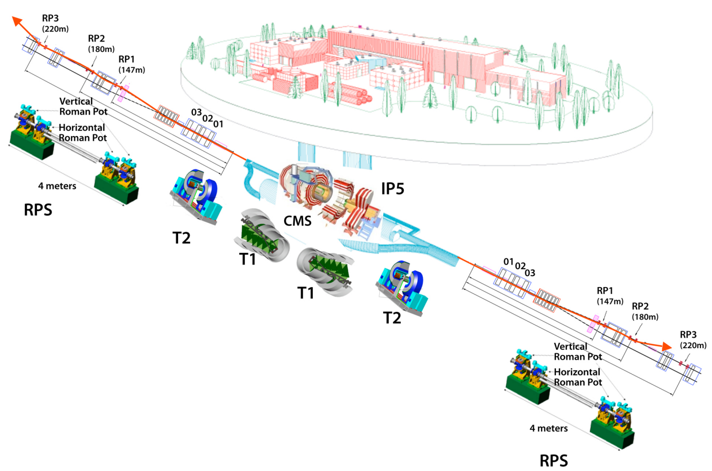
+

elastic

≈10mb

+

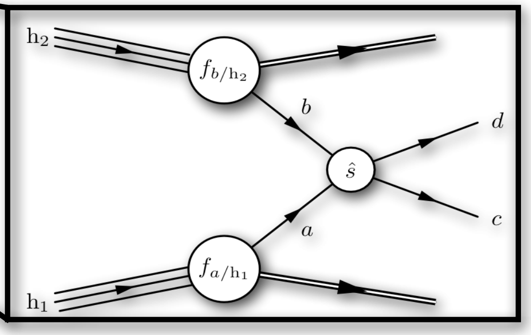
C. Schwick



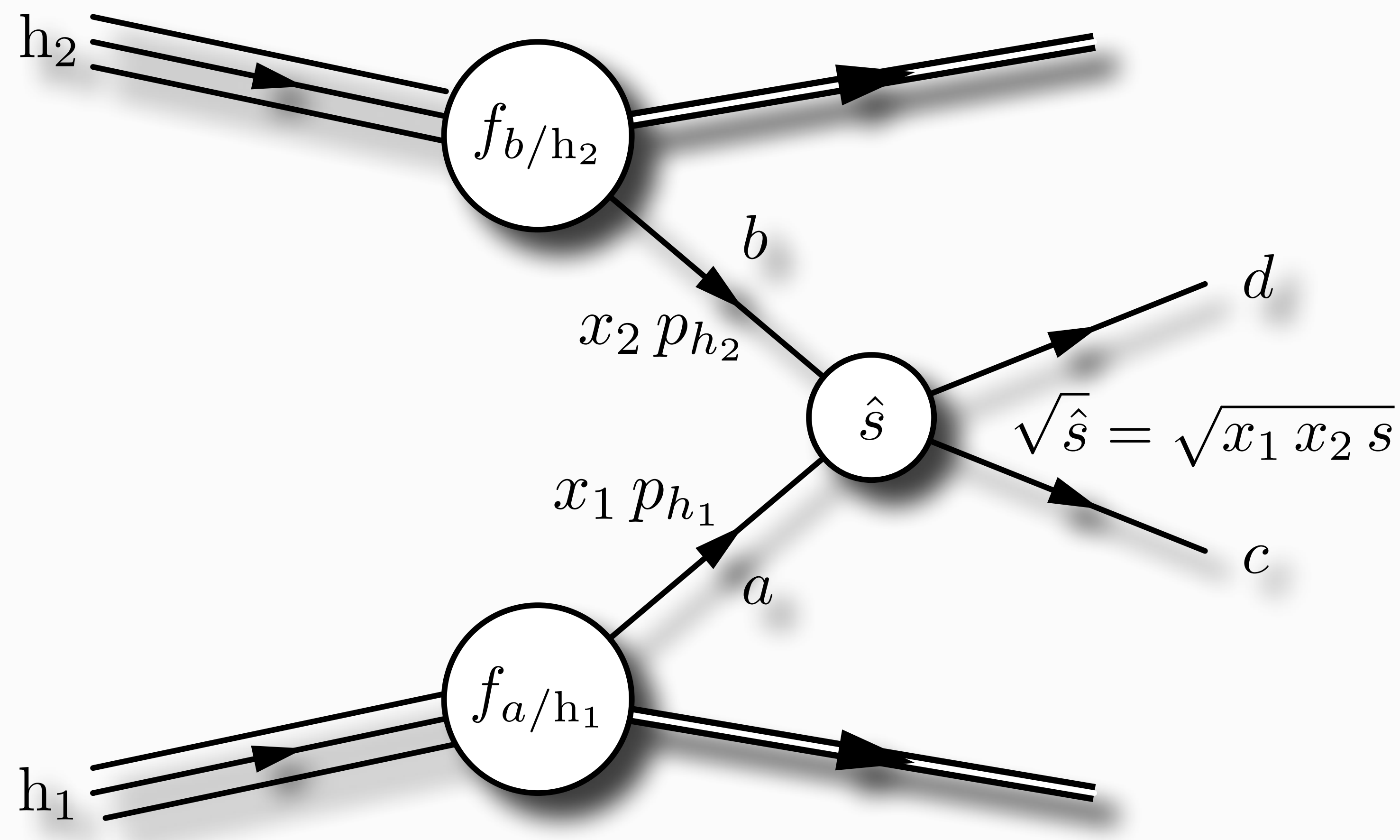
non-diffractive

inelastic

≈70mb



Most of the focus: hard scattering



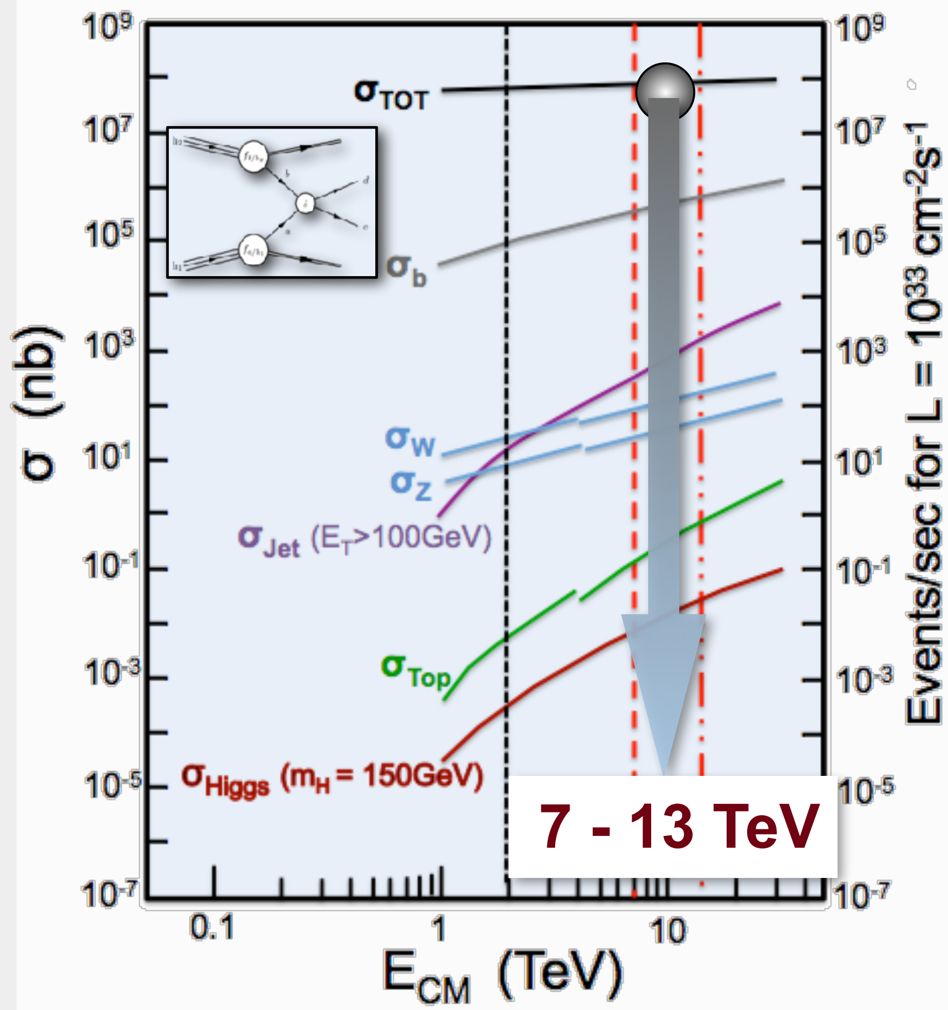
$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

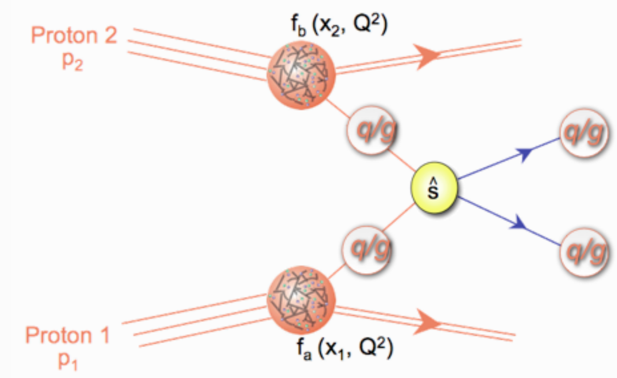
Hard Scattering = processes with large momentum transfer (Q^2)

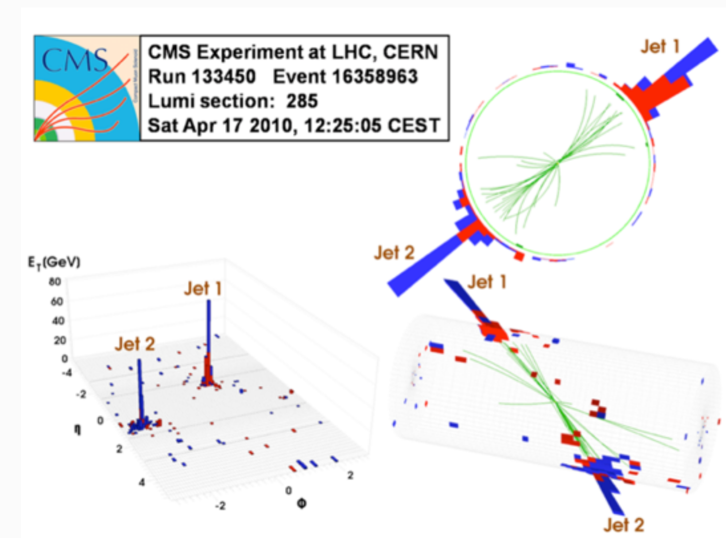
Represents only a tiny fraction of the total inelastic pp cross section (~ 70-80 mb)

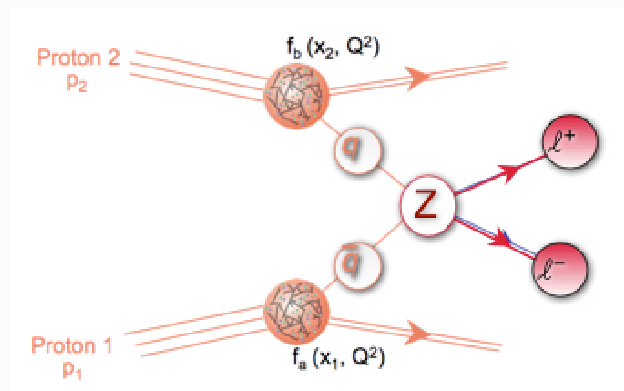
eg. **σ(pp → W+X)** ~ 150 nb ~ **2 · 10^{-6} σ_{tot}(pp)**

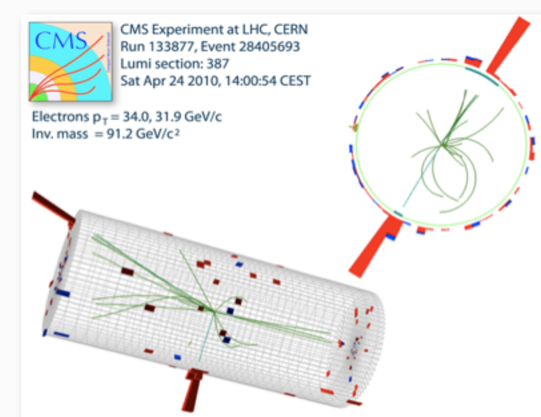
“scanning” the SM

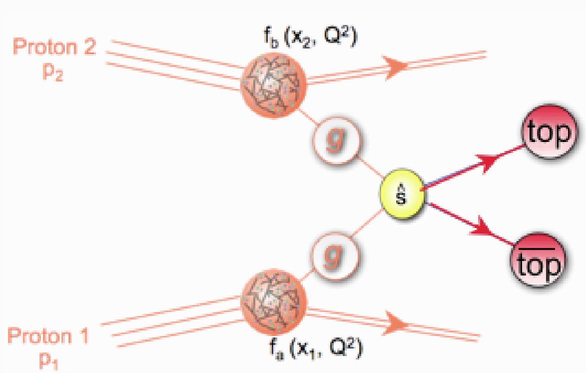


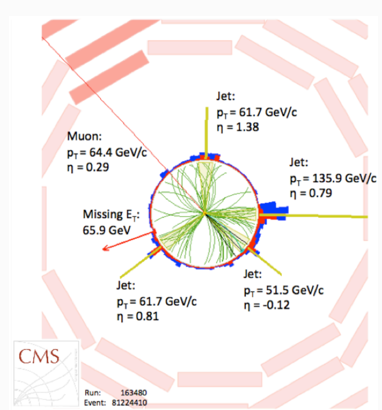


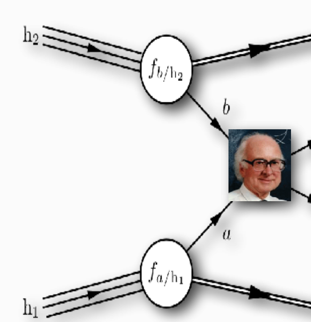


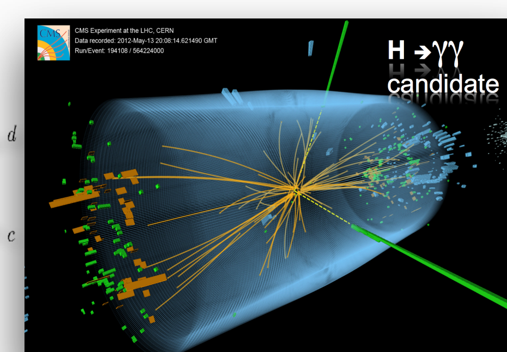




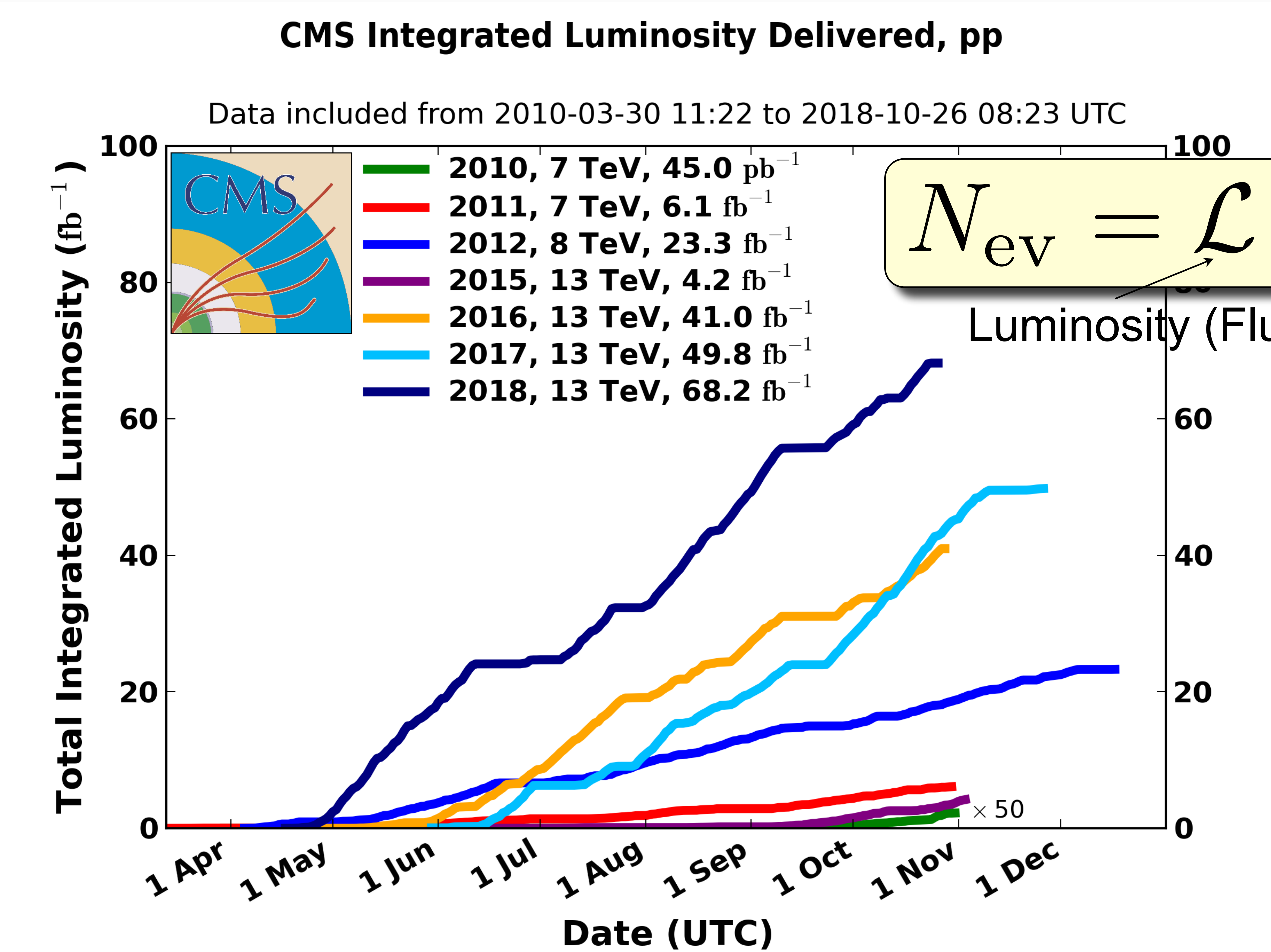








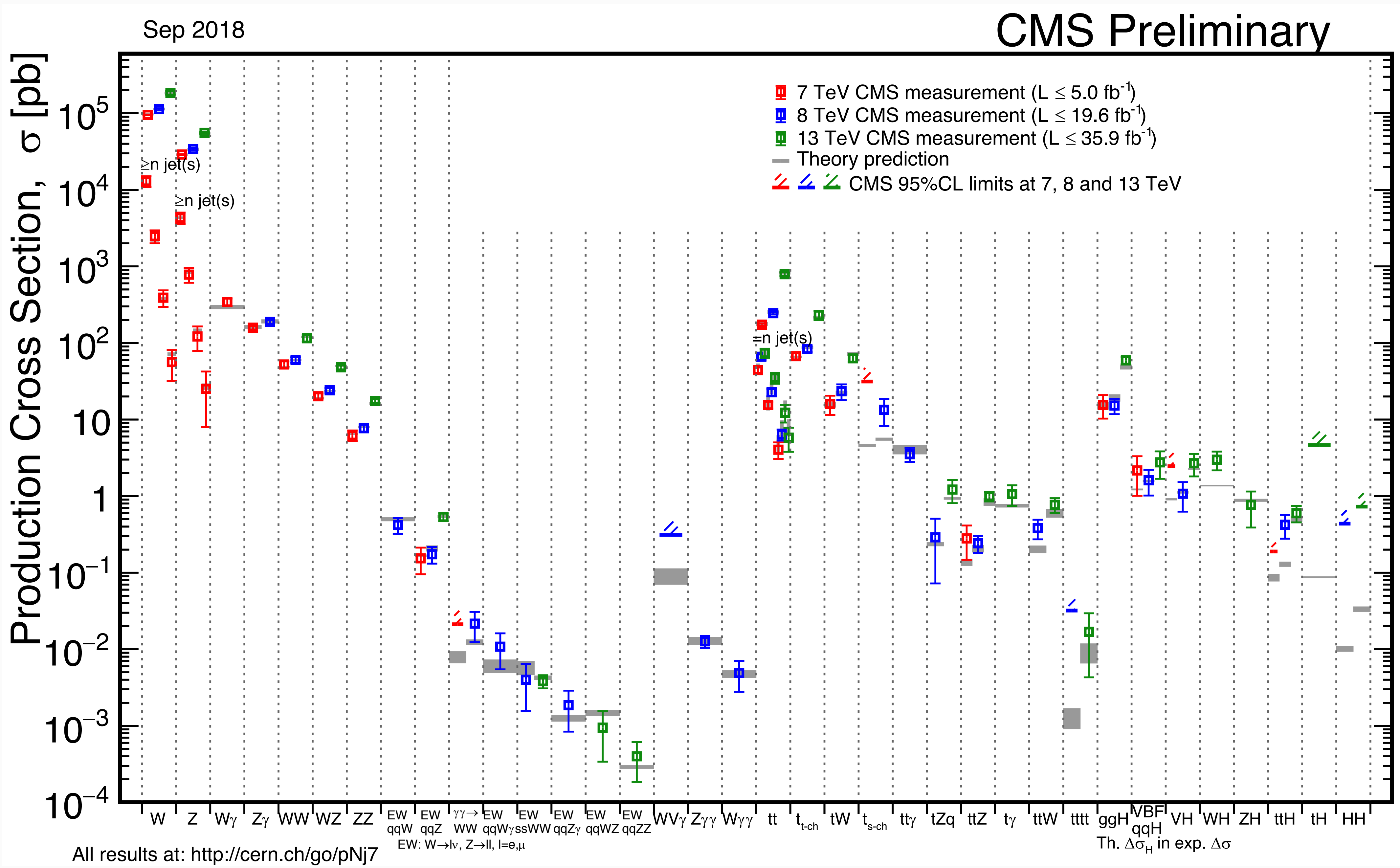
Delivery of (lots of) data



$$N_{\mathrm{ev}} = \mathcal{L} \times \sigma$$

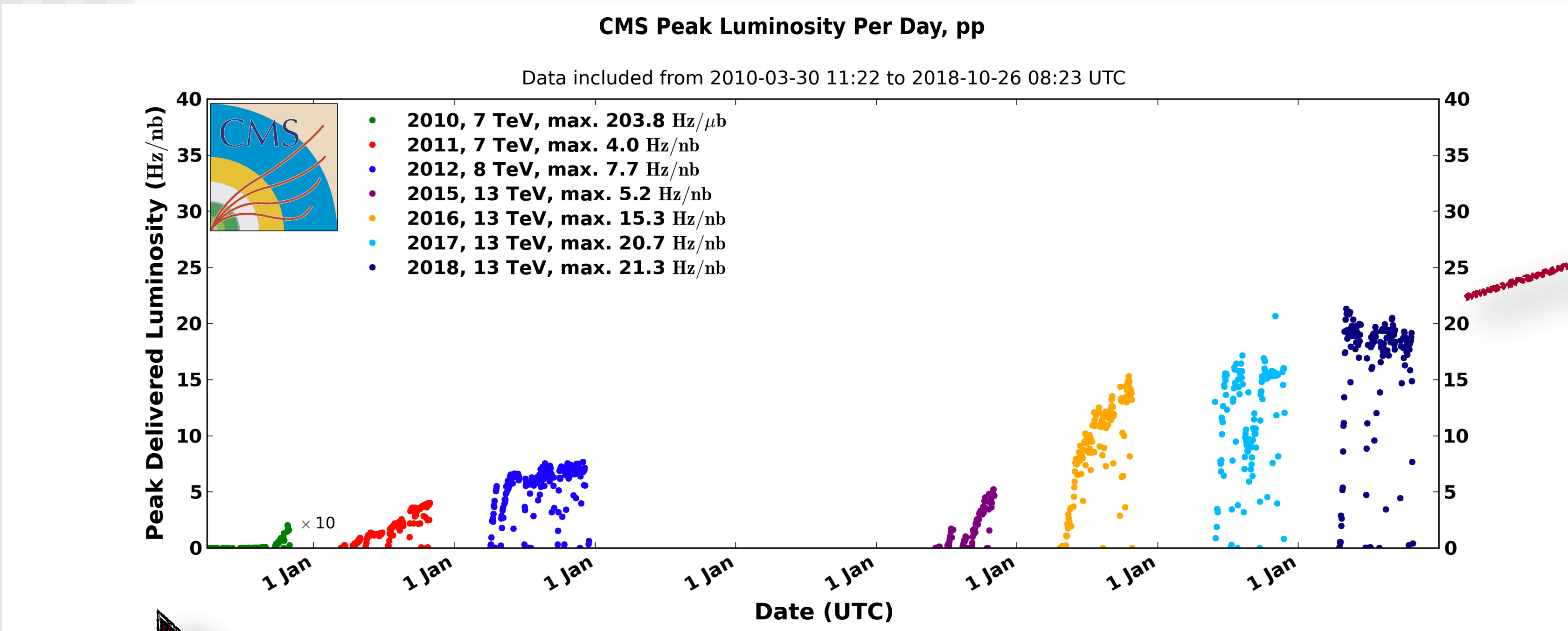
Luminosity (Flux) [cm^{-2}]

Stairway to ….



> 850 publications so far, 141 in 2018 !

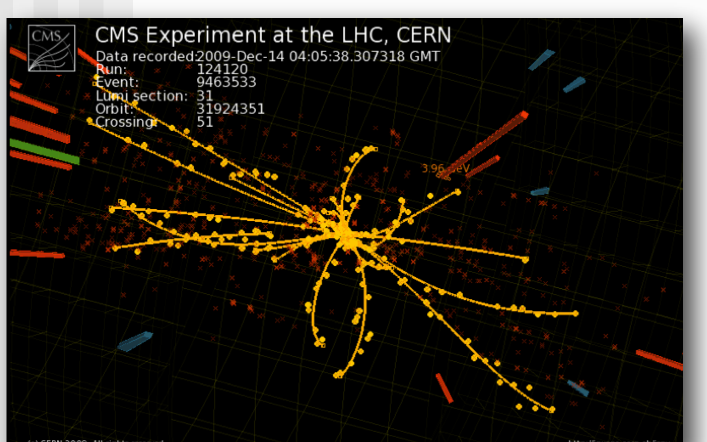
Conditions at the LHC



Luminosities of
$L \sim 2 \times 10^{34}\ Hz/cm^2$
reached already

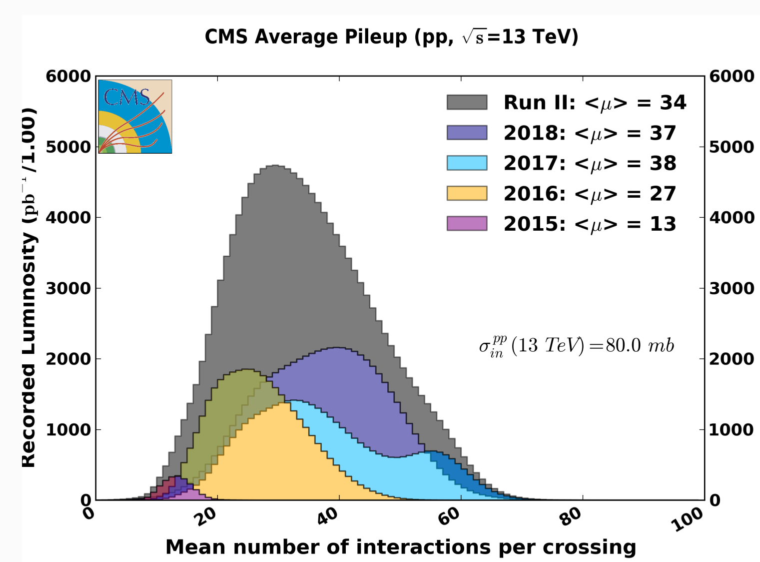
Number of simultaneous proton-proton collisions per bunch crossing:

L x total cross section x bunch separation time
$\sim 2 \times 10^{34}\ cm^{-2}s^{-1}\ \times\ 100\ mb \times 25\ ns$

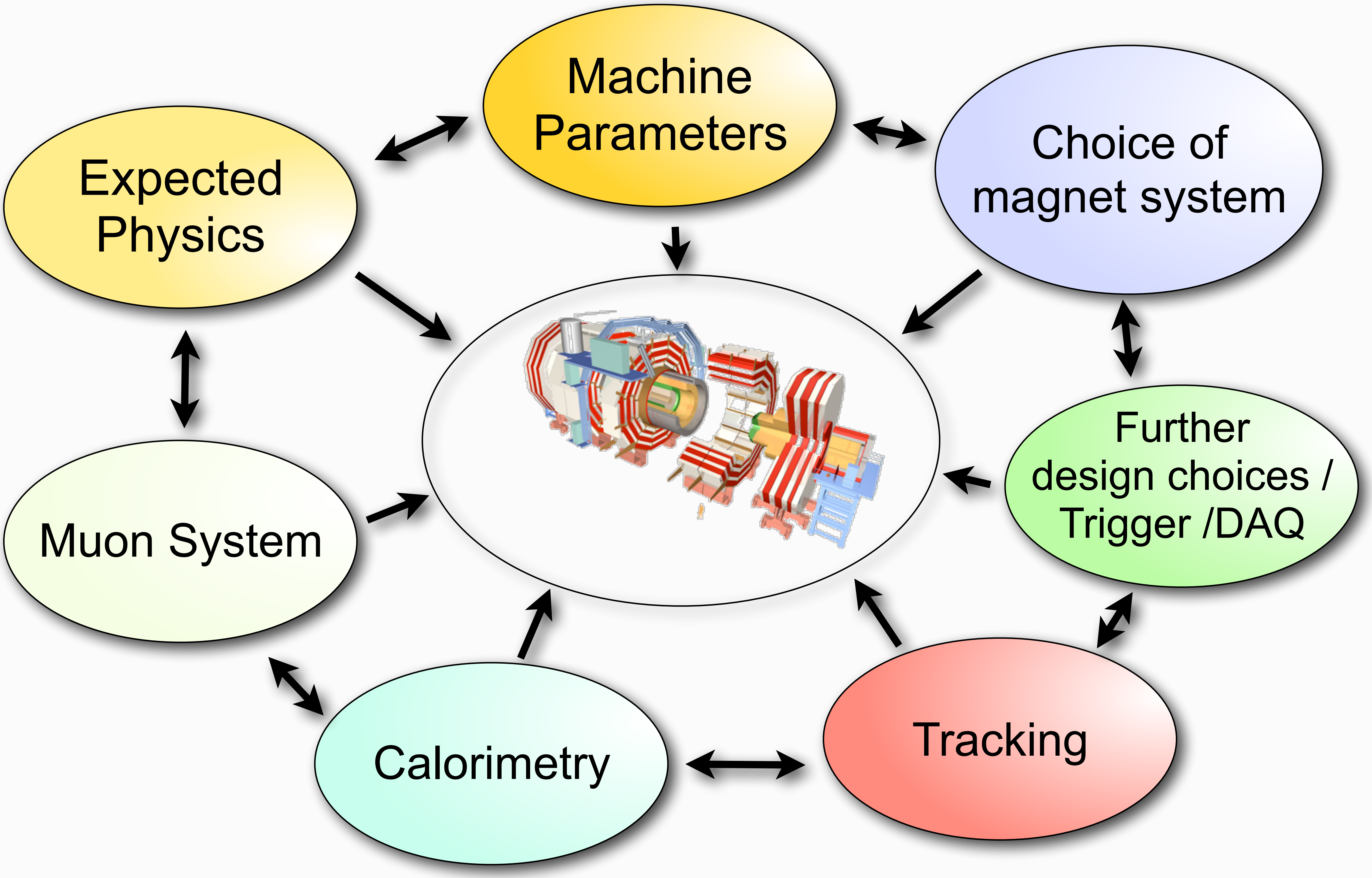


~ 50 !

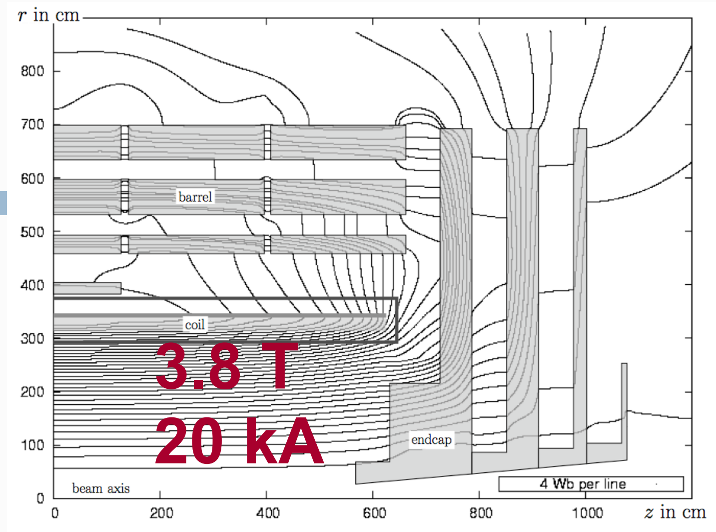
Each of these:
~ 6 charged particles per unit rapidity,
over range of +- 5 units in rapidity:
O(1000) particles per collision !!



How to design your detector

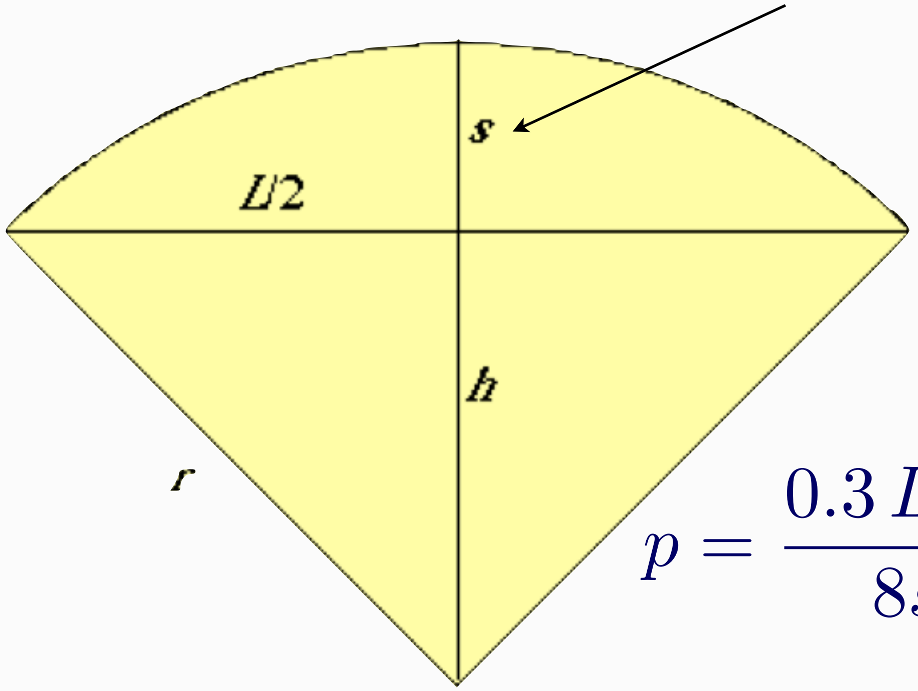


Magnet Systems

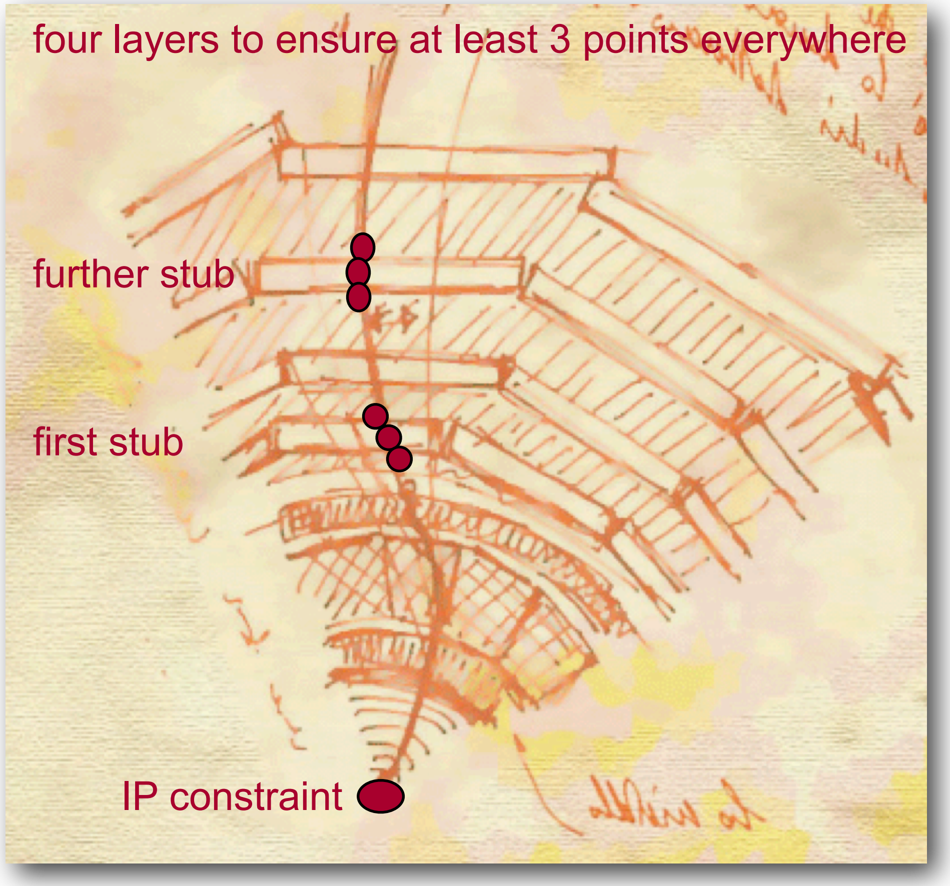


- Among the most important design choices
  - fixes many other parameters/sizes
- Example of CMS, early days:
  - assumed that a tracking system might not be possible (too harsh backgrounds), rad-hard Si-Detectors not yet sufficiently developed
  - so, put all effort on muons, in a robust manner; put absorber to get rid of the rest (a strong magnetic field also helps here) and try to get best possible muon measurement.

Momentum measurement via sagitta:



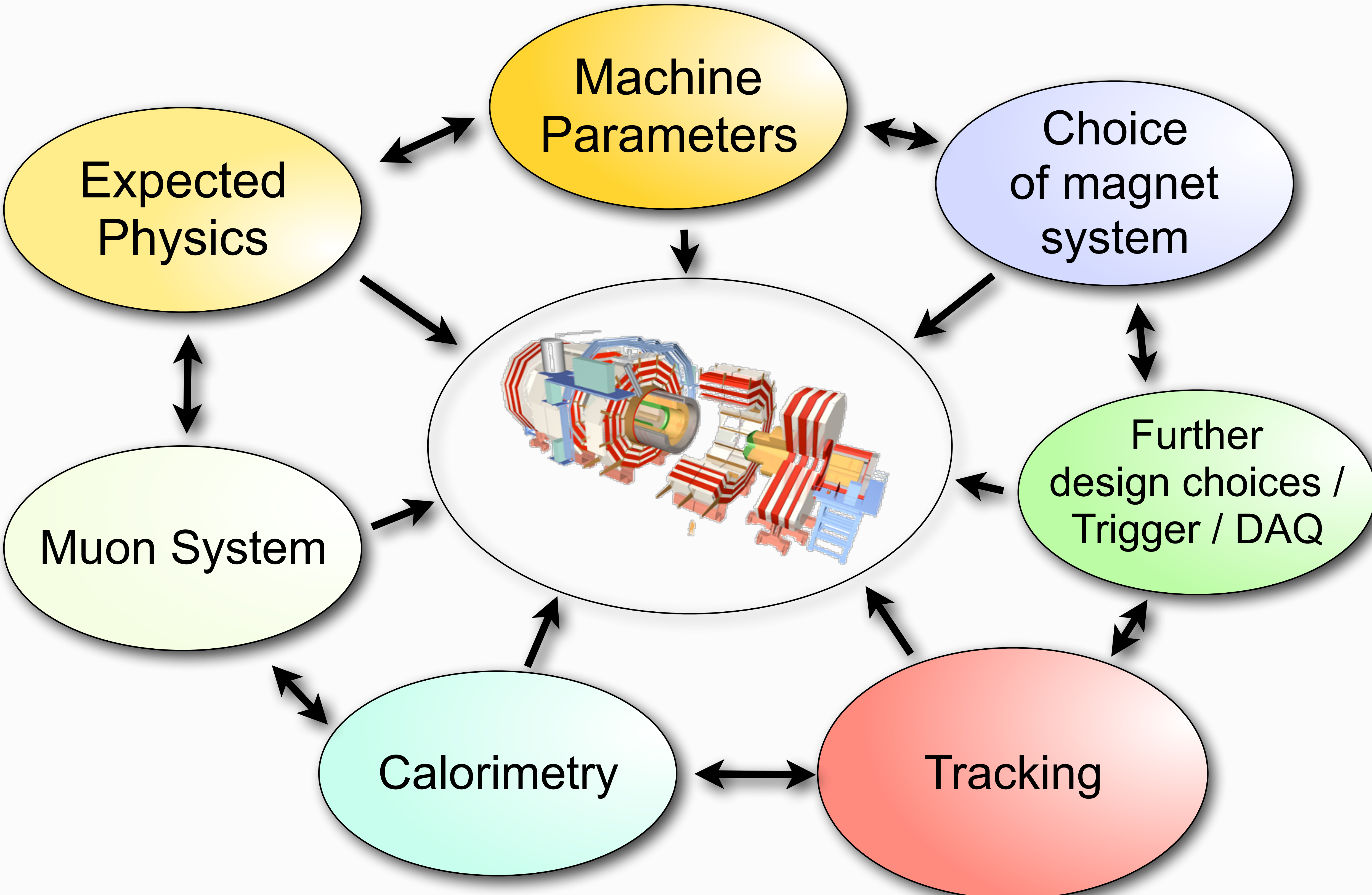
$$p = \frac{0.3\,L^2 B}{8s}$$



$$\frac{\delta p}{p} = \frac{8}{0.3}\frac{1}{L^2 B}\,p\,\delta s = \frac{\delta s}{s}$$

maximize... but note that L drives cost of detector very much.

How to design your detector



Basic tracking requirements

- Robust and redundant pattern recognition
  - efficient / precise reco of all charged particles with p_T > 0.1-1 GeV, up to rapidity ~ 2.5
- Reconstruction of secondary vertices, impact parameters
  - heavy flavours, b-jets, B decays
- Reconstruction of hadronic tau decays (one-prong, three-prong, thin jets)
- **"Conflict of interest" :**
  - many layers (many hits) for robust track reco -->
    many channels; lots of supports (cables, cooling, ...)
  - but not too much material, bad for ECAL resolution and multiple scattering
- Remember: momentum resolution

$$\frac{\delta p}{p} = \frac{\delta s}{s} = \frac{8}{q}\frac{1}{L^2 B}\, p\, \delta s$$

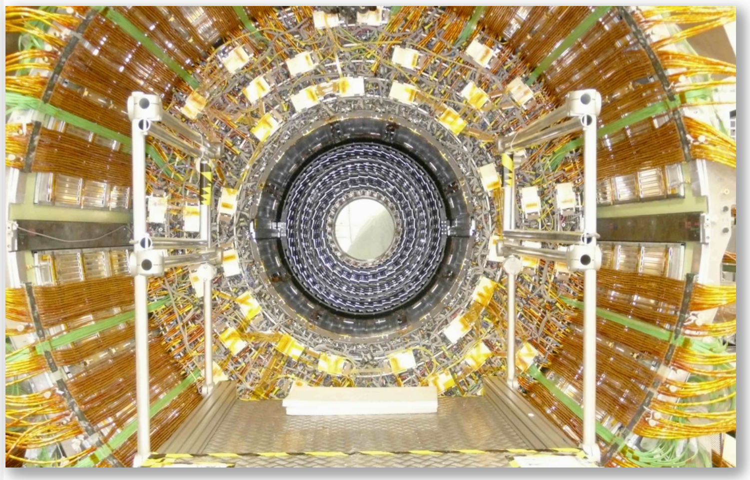
$$\text{for } L = 1\,\text{m}\ ,\ B = 4\,\text{T}\ ,\ p = 100\,\text{GeV}$$

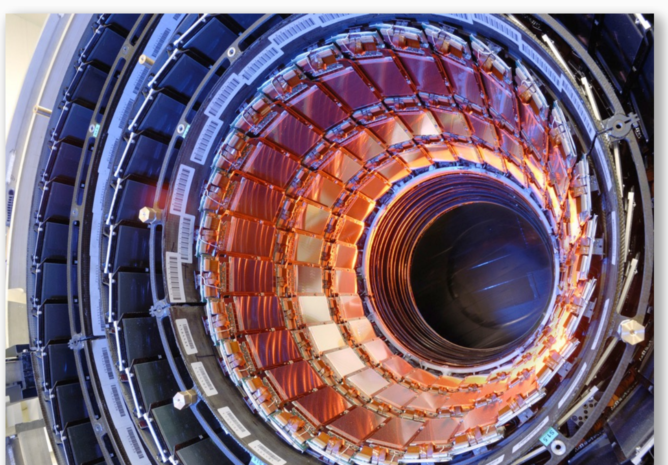
$$\frac{\delta p}{p} = 1\,\% \ \text{ for } \ \delta s \approx 15\,\mu\text{m}$$

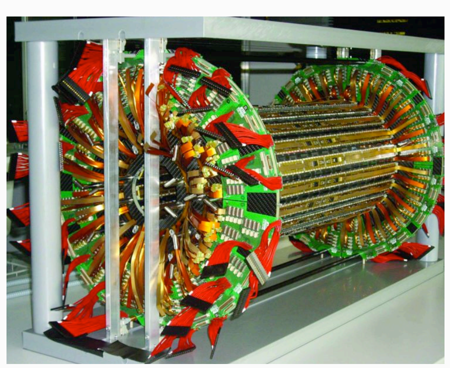
➡ need hit reconstruction at this level of prec. !

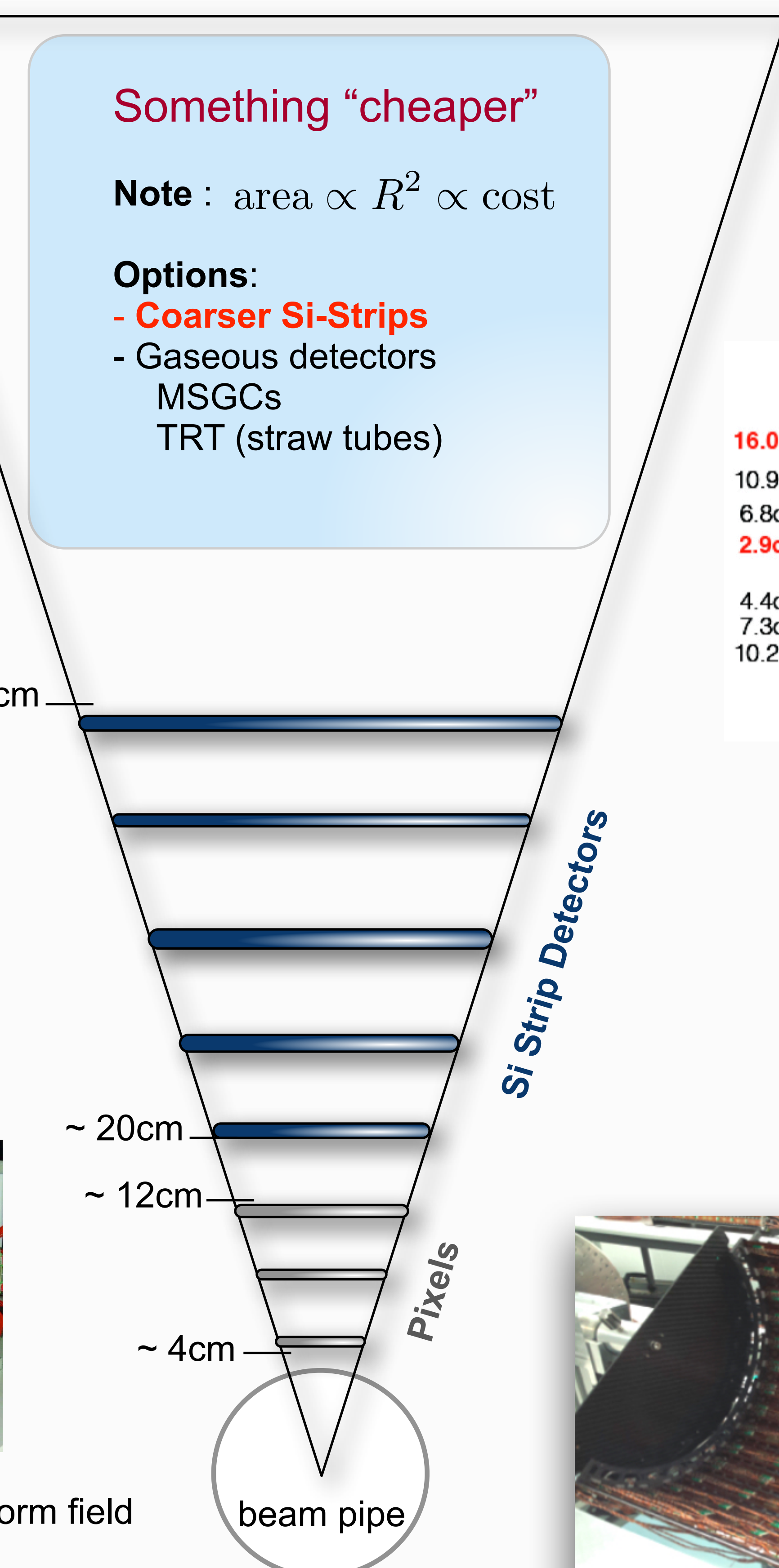
➡ e.g. Si-Tracker : optimize carefully pitch vs. strip length vs. # channels (material) vs. occupancy

Basic layout









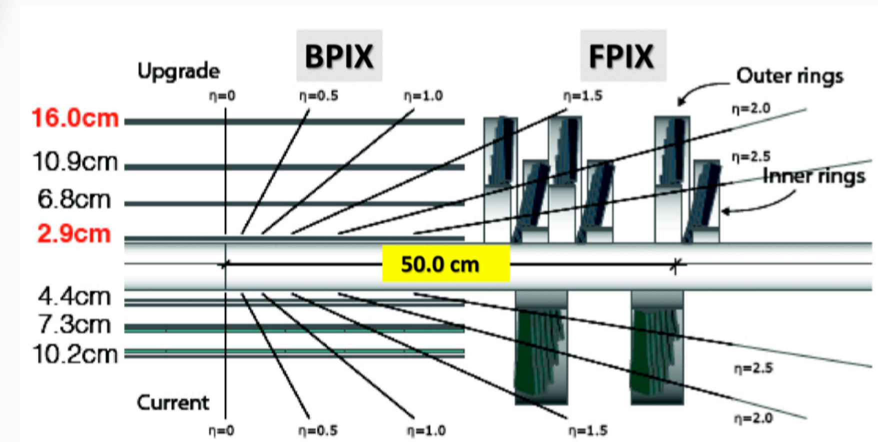
Something "cheaper"

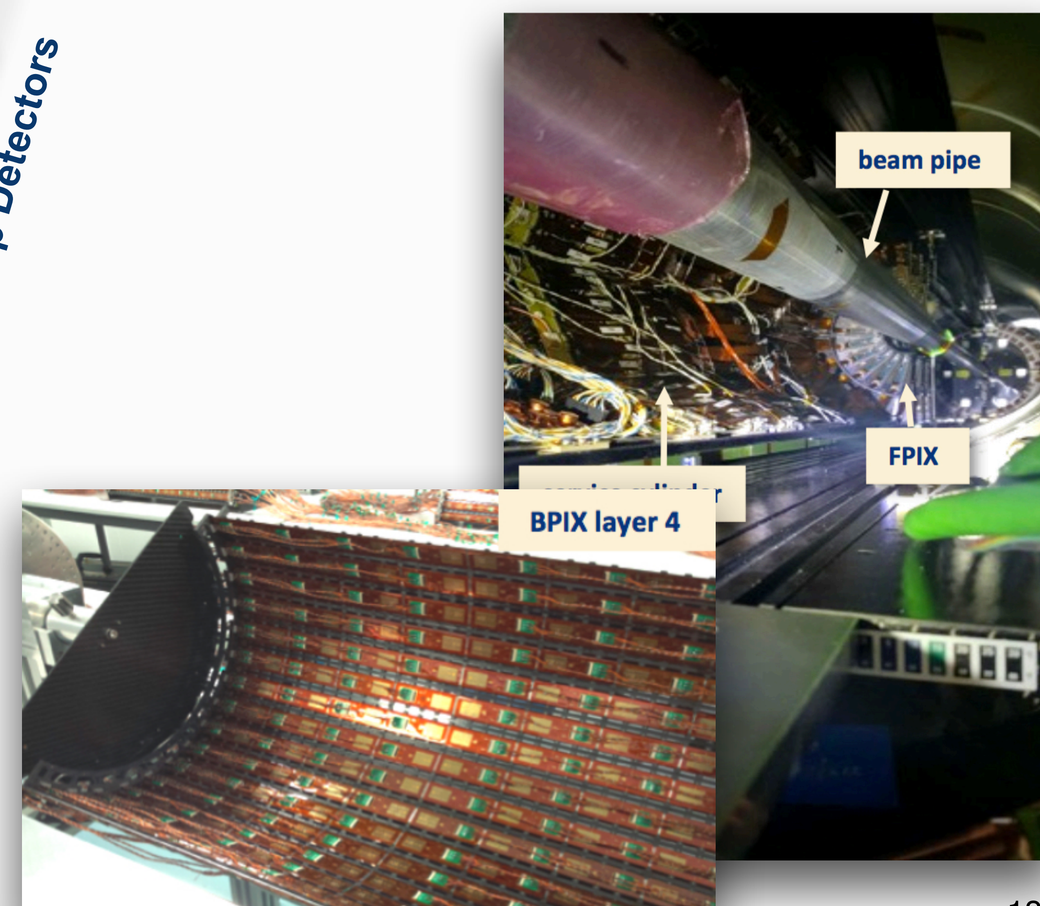
Note : area $\propto R^2 \propto$ cost

Options:
- Coarser Si-Strips
- Gaseous detectors
  MSGCs
  TRT (straw tubes)

during EYETS 2017:

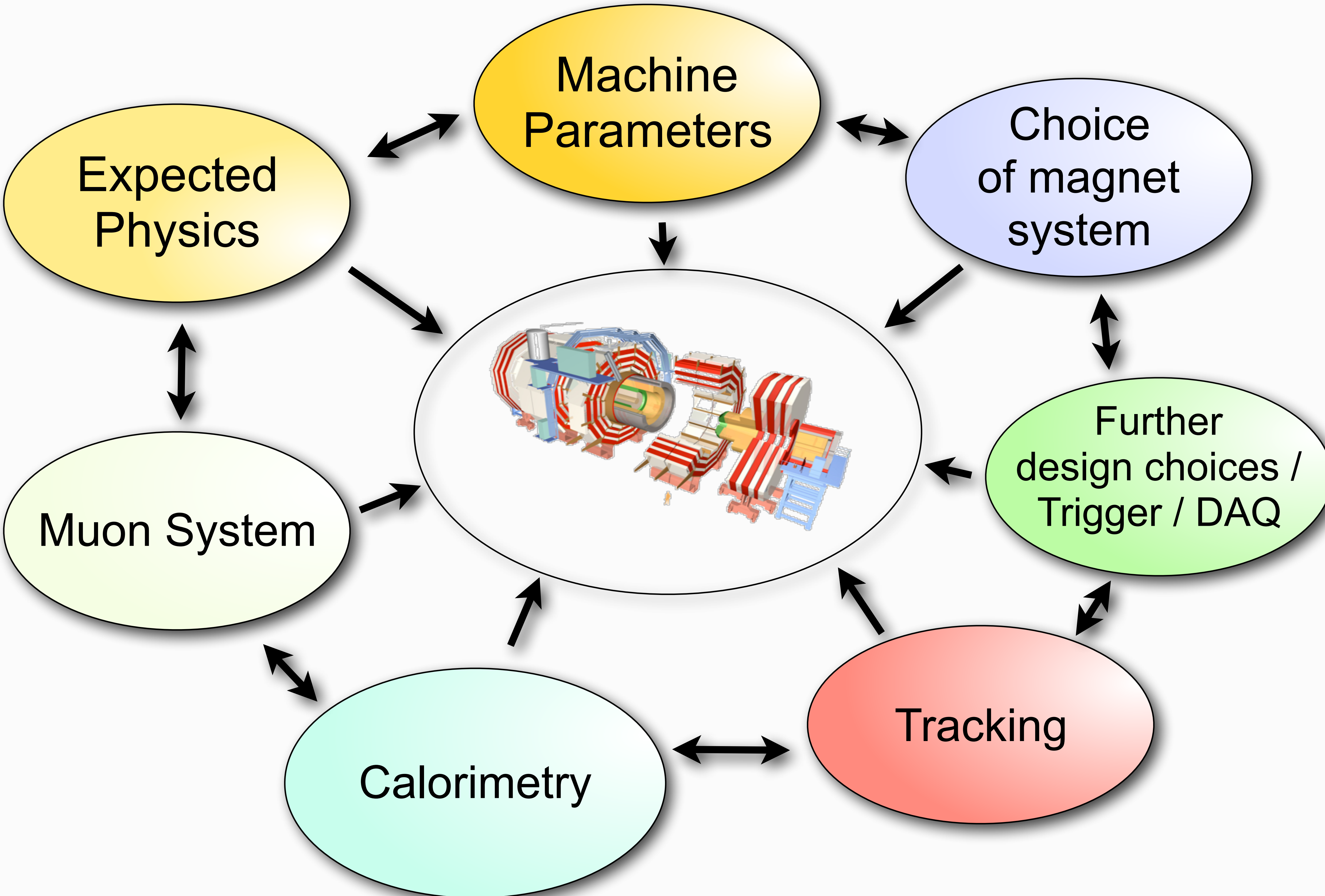
Pixel Phase1 upgrade





Note : Tracker well within solenoid (3.8 T) : uniform field

How to design your detector

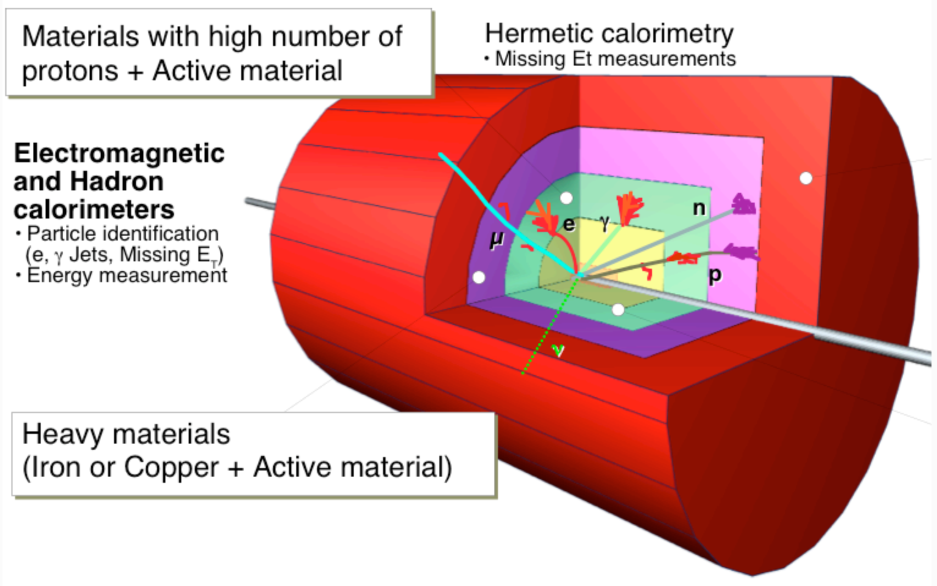


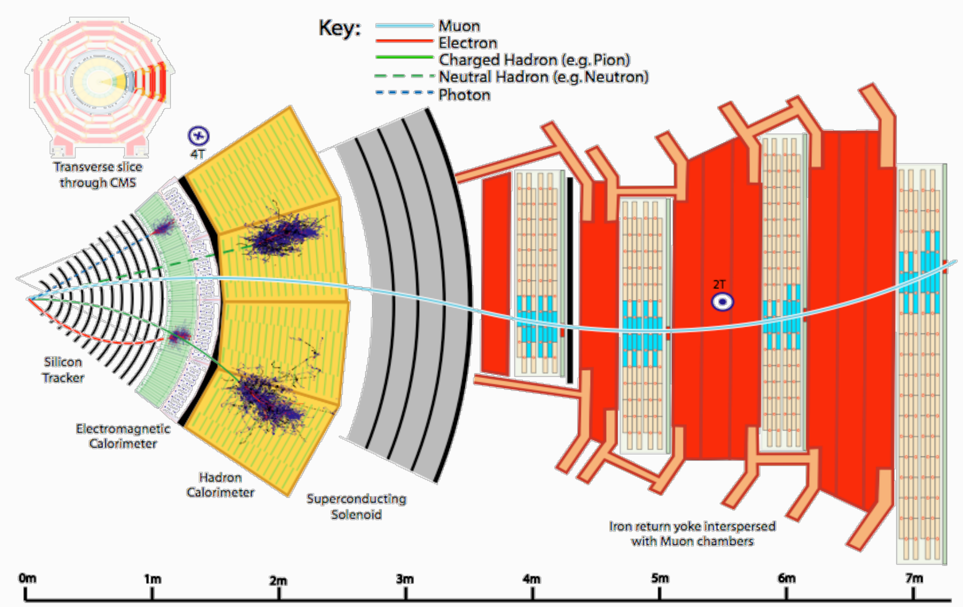
Calorimetry: Main principles

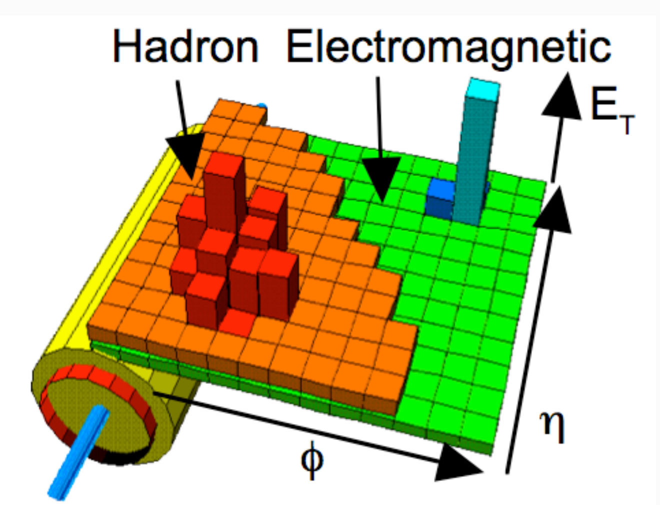
- Excellent energy measurement of electrons, photons, jets
  - good coverage up to η ~ 5, also for E_{Tmiss}

$$\text{Calorimeter} \quad \frac{\delta E}{E} \propto \frac{1}{\sqrt{E}} \qquad \text{Spectrometer} \quad \frac{\delta p}{p} \propto p$$

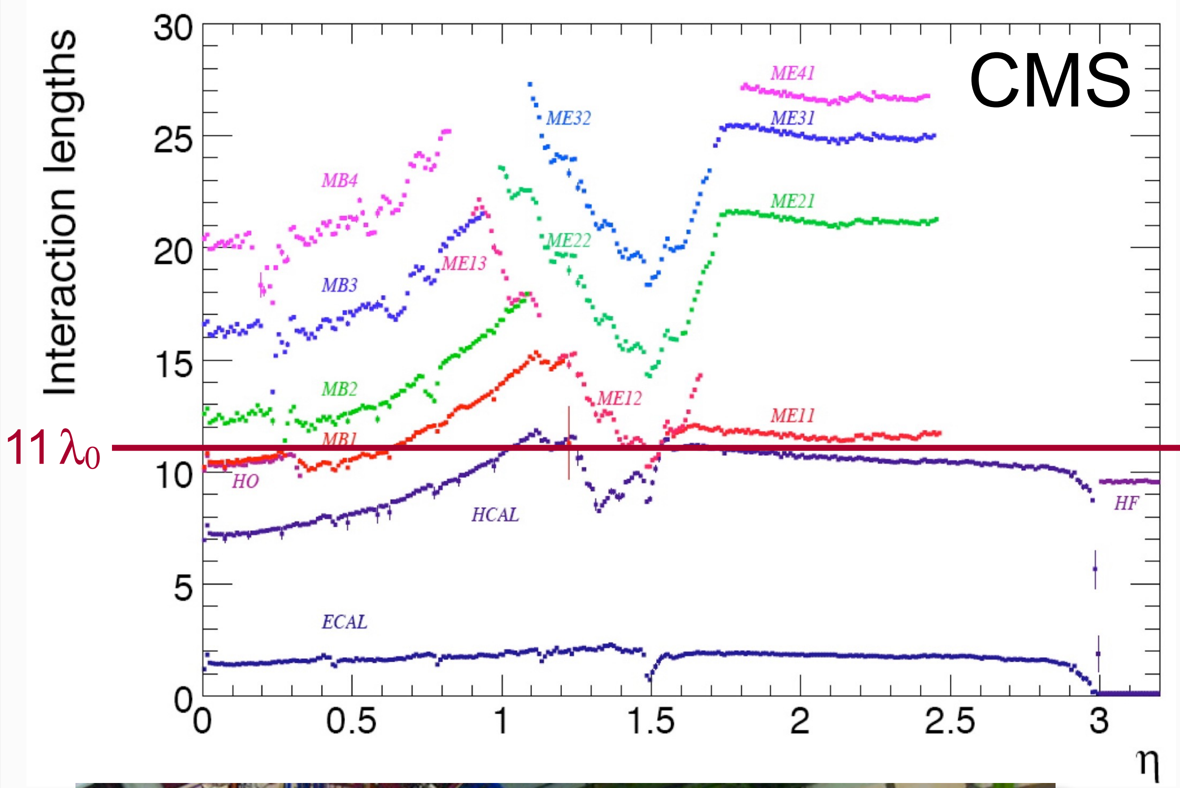
- Trigger on high-p_T objects
- Fine segmentation (lateral, longitudinal) for shower analysis
- Have to absorb ~ TeV objects (e,gamma,jets)
  - shower max position $x_{max} \propto x_0 \ln E$
  - to cover elmg. shower of ~ 1 TeV : ~ 25 X_0
  - to contain hadronic jets of ~ 1 TeV : 11 λ_0
  - ECAL: take $(X_0)_{PbWO4}$ = 0.89 cm + electronics
- CMS : R_{coil} - $R_{tracker}$ - ECAL (+electronics) ~ 1 m !!
  - only space for 6 λ_0 , 7 λ_0 including ECAL
  - added tail catcher (HO) after coil

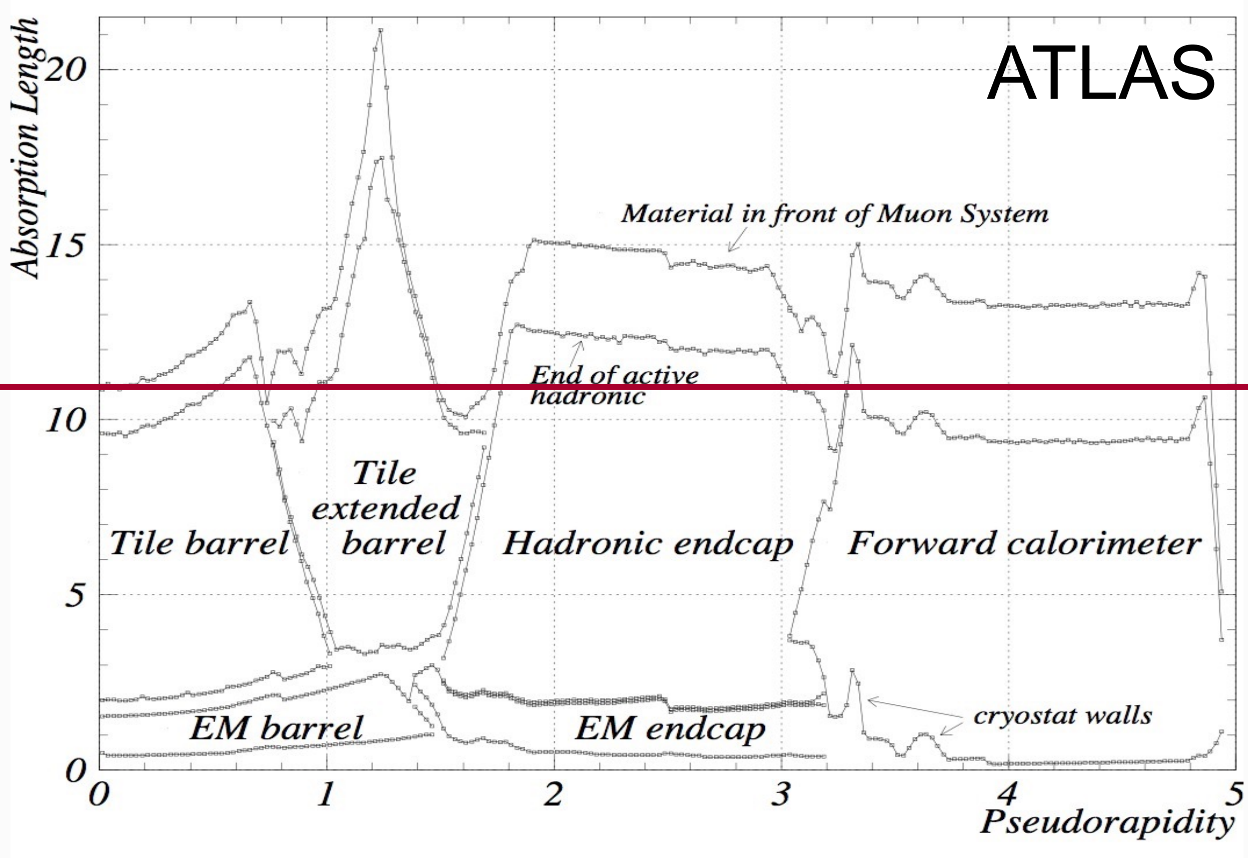


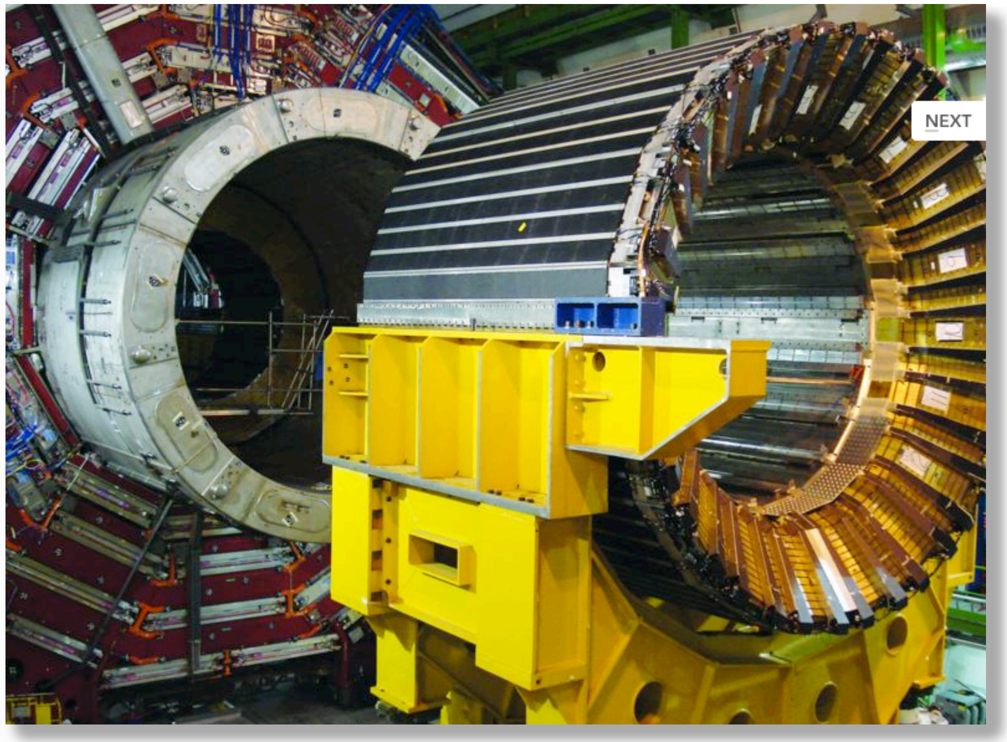


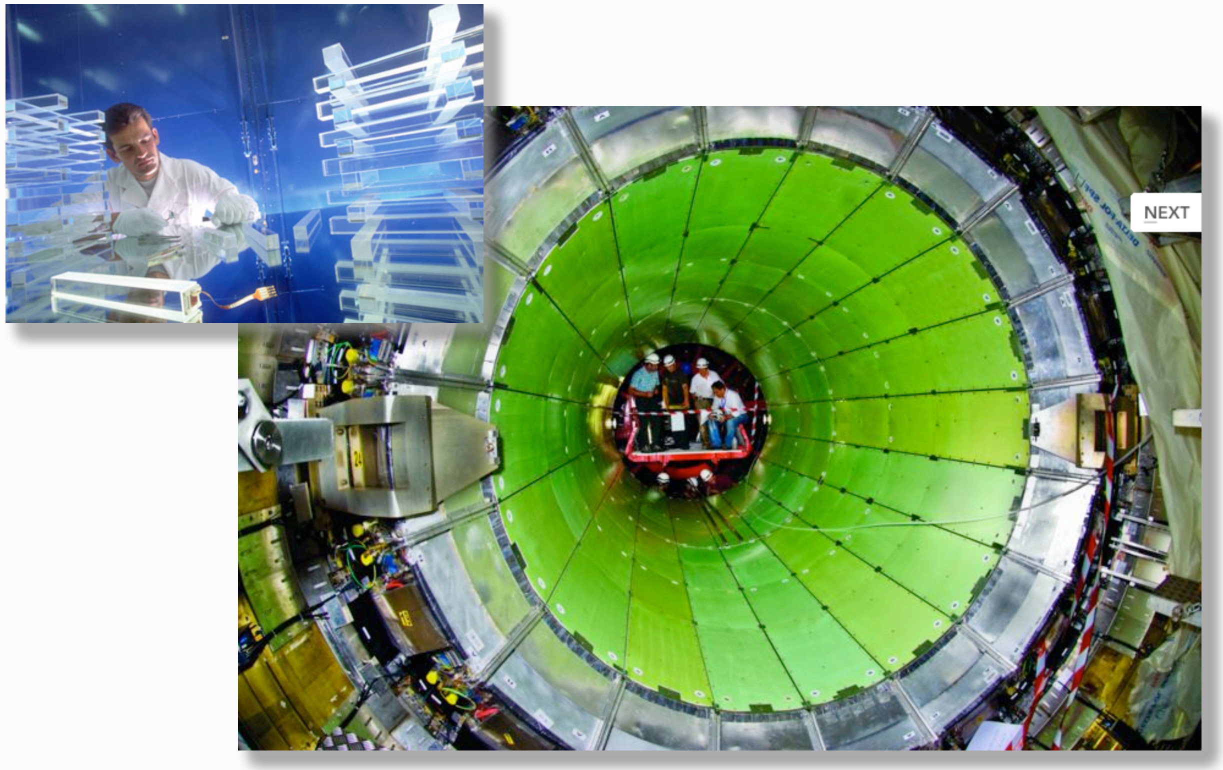


Coverage



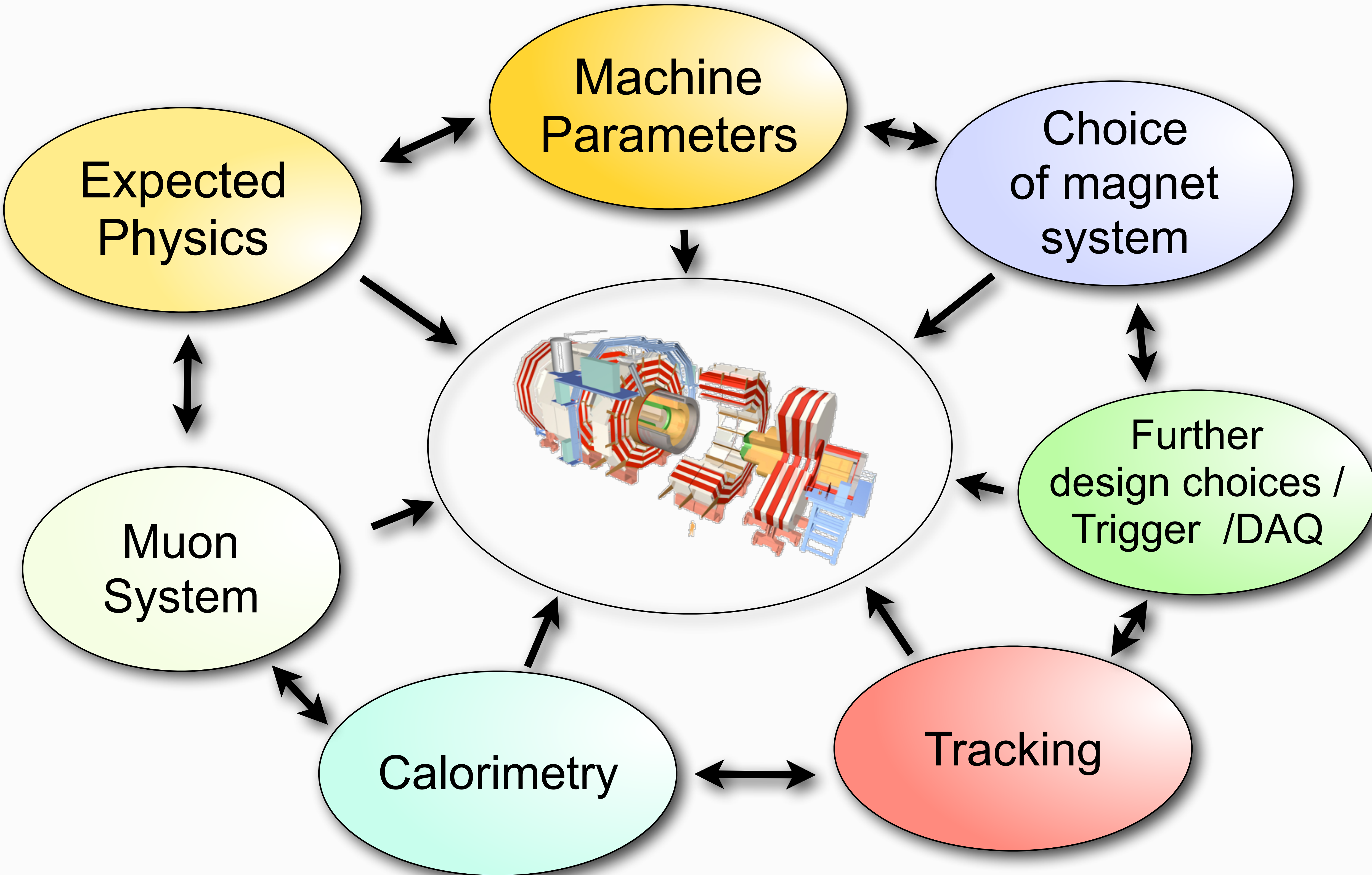






Upgrade of HB readout ongoing right now, HE already done

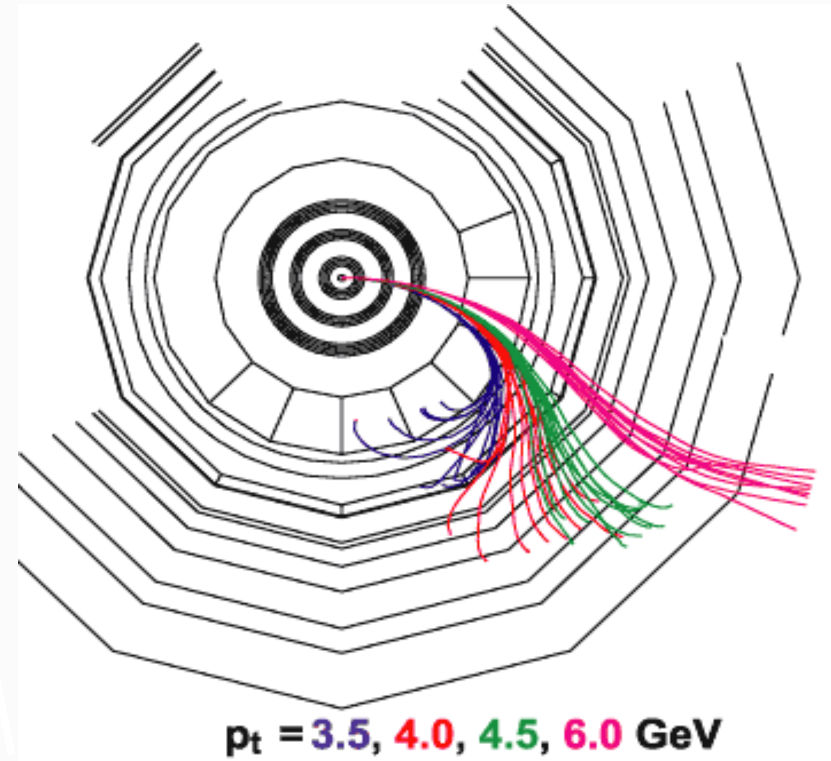
How to design your detector

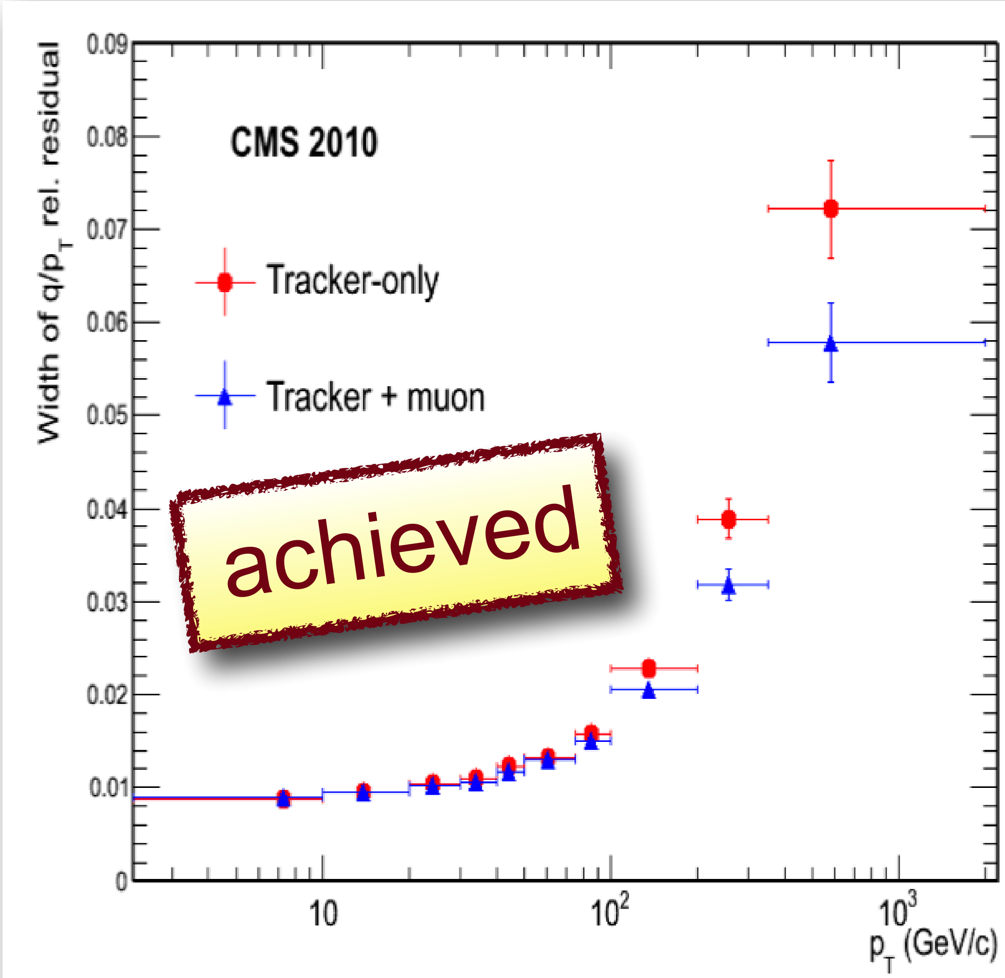


Muons : Requirements were

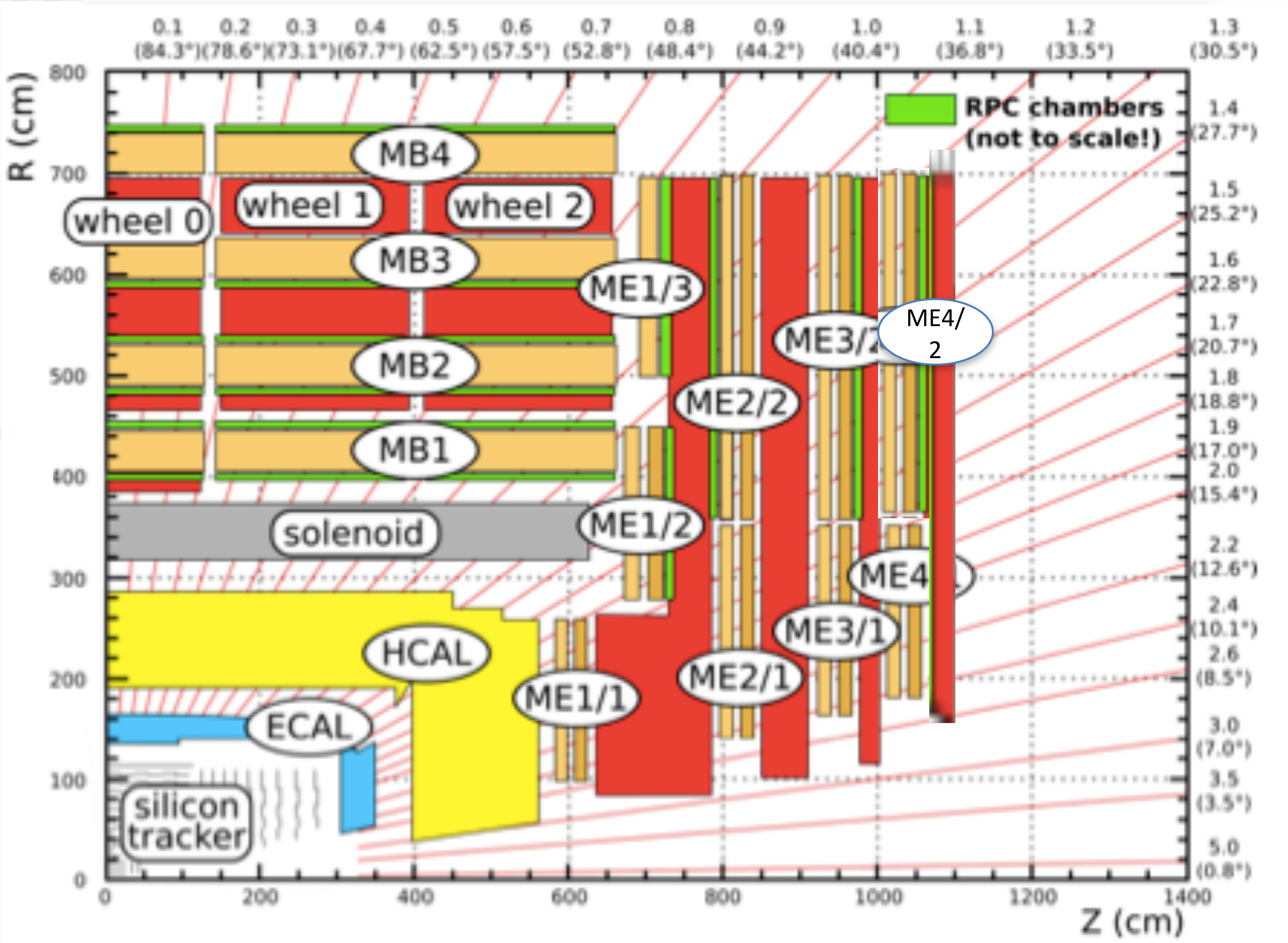
- Reconstruct mass of narrow 2-muon state (eg. Z mass) at 1% precision
- Reconstruct 1 TeV muons with 10% precision
- Over wide rapidity range
- Identification in dense environment
- Measure and trigger on muons in standalone mode, for momenta above ~ 5 GeV
  - CMS can use IP as further constraint
- Combine different technologies for chambers
  - **redundancy**, **robustness**, radiation hardness, different speed
- Issues
  - Alignment
  - Punch-through
  - Multiple scattering $\frac{\delta p_{\mathrm{MS}}}{p} \approx \frac{52 \cdot 10^{-3}}{\beta\, B \sqrt{L\, x_0}}$

$$\text{for } \beta \approx 1\ ,\ B = 2\,\mathrm{T}\ ,\ L \approx 2\,\mathrm{m}\ ,\ x_0 = 0.14\,\mathrm{m} \quad \Rightarrow \quad \frac{\delta p_{\mathrm{MS}}}{p} \approx 5\,\%$$



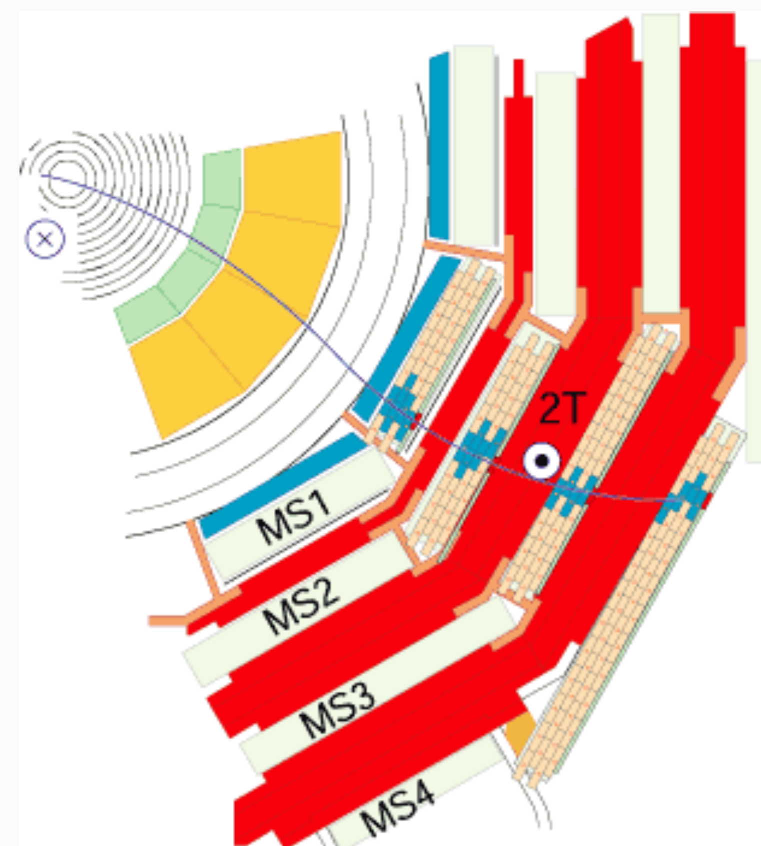


Muons

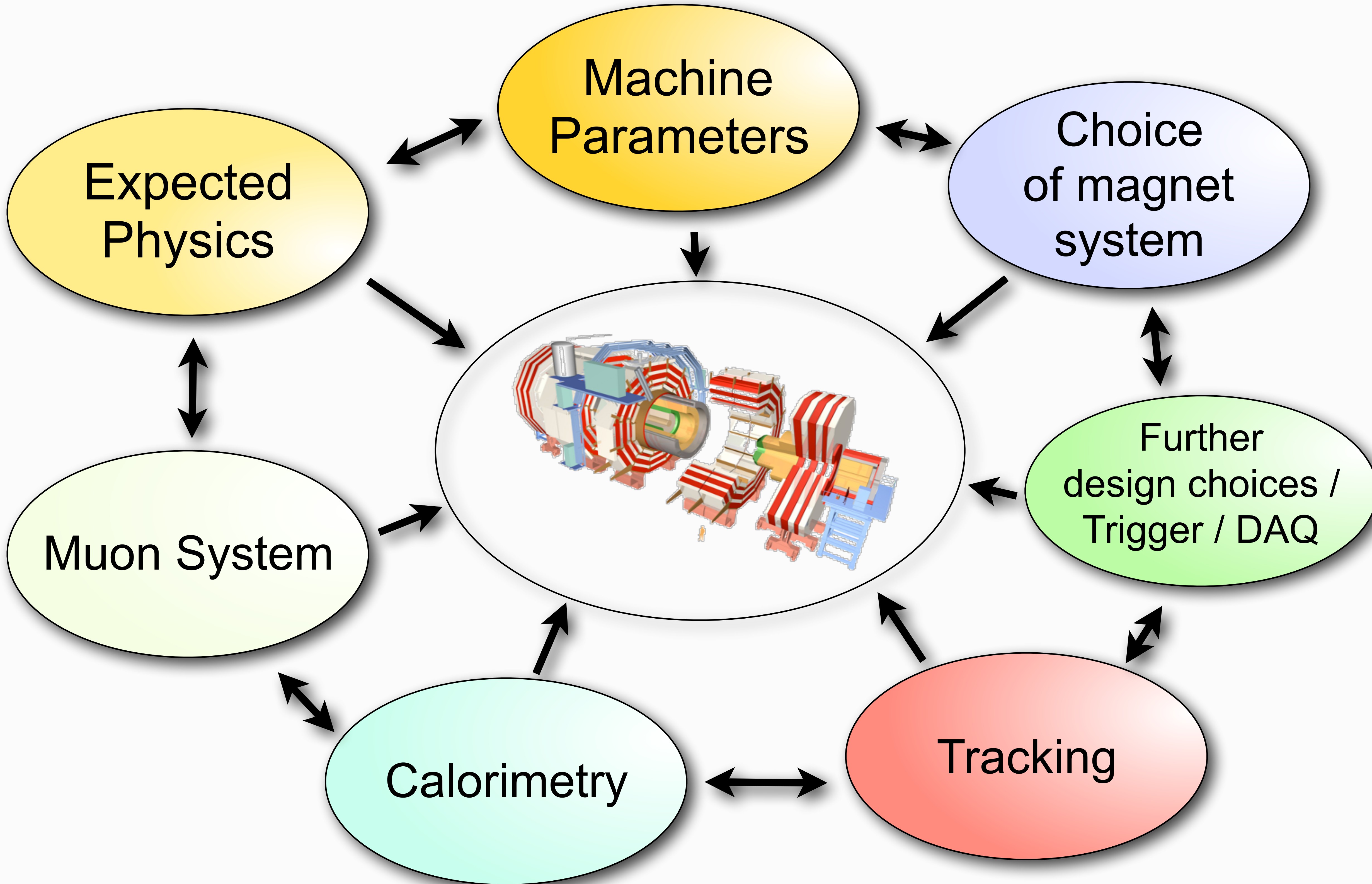


12 ktons of iron absorber and B-field flux return

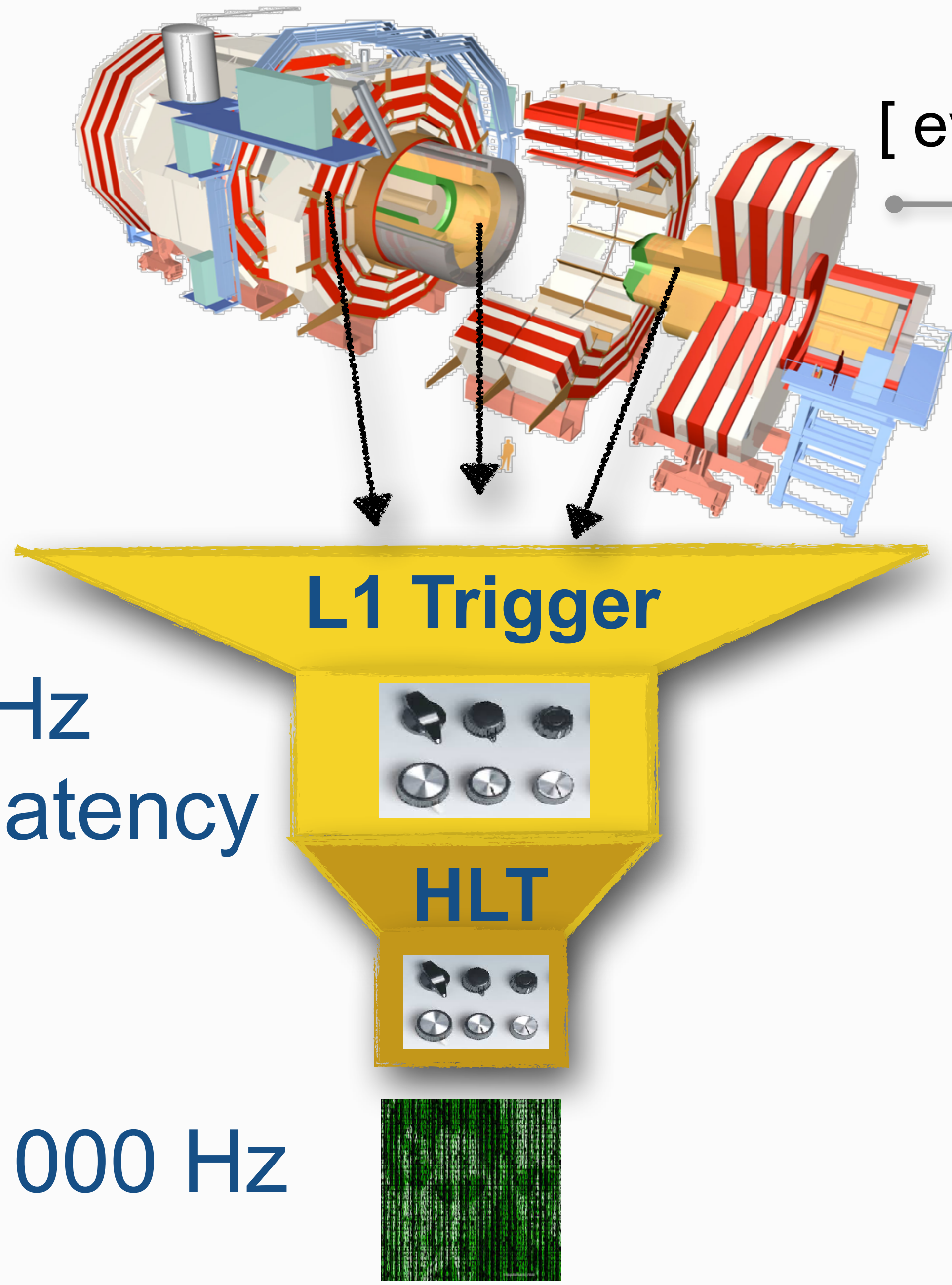
Bending in iron + muon tracking: trigger info; and link with main tracker



How to design your detector



The Trigger / DAQ Challenge

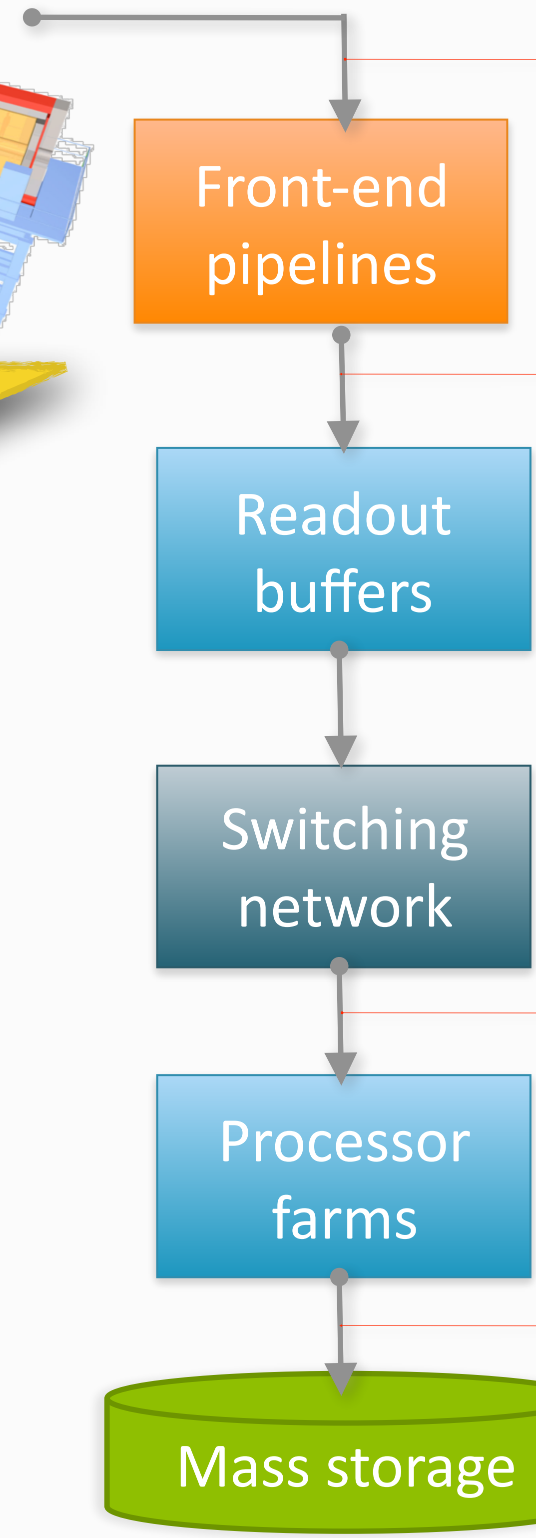


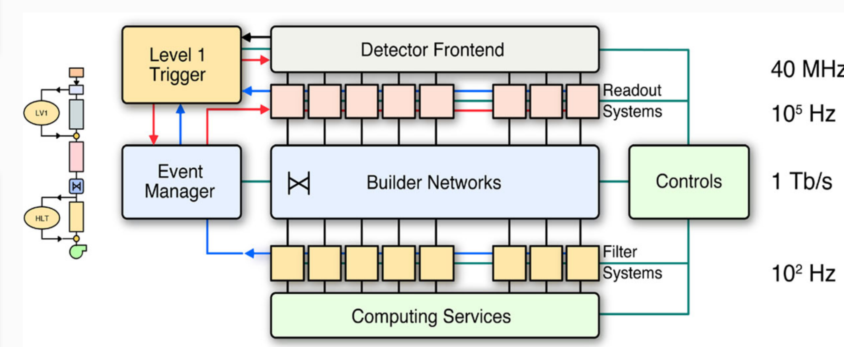
~100 kHz
3.6 µs latency

~1000 Hz

Finite Bandwidth !

Detector signals
[every 25 ns = 40 MHz]

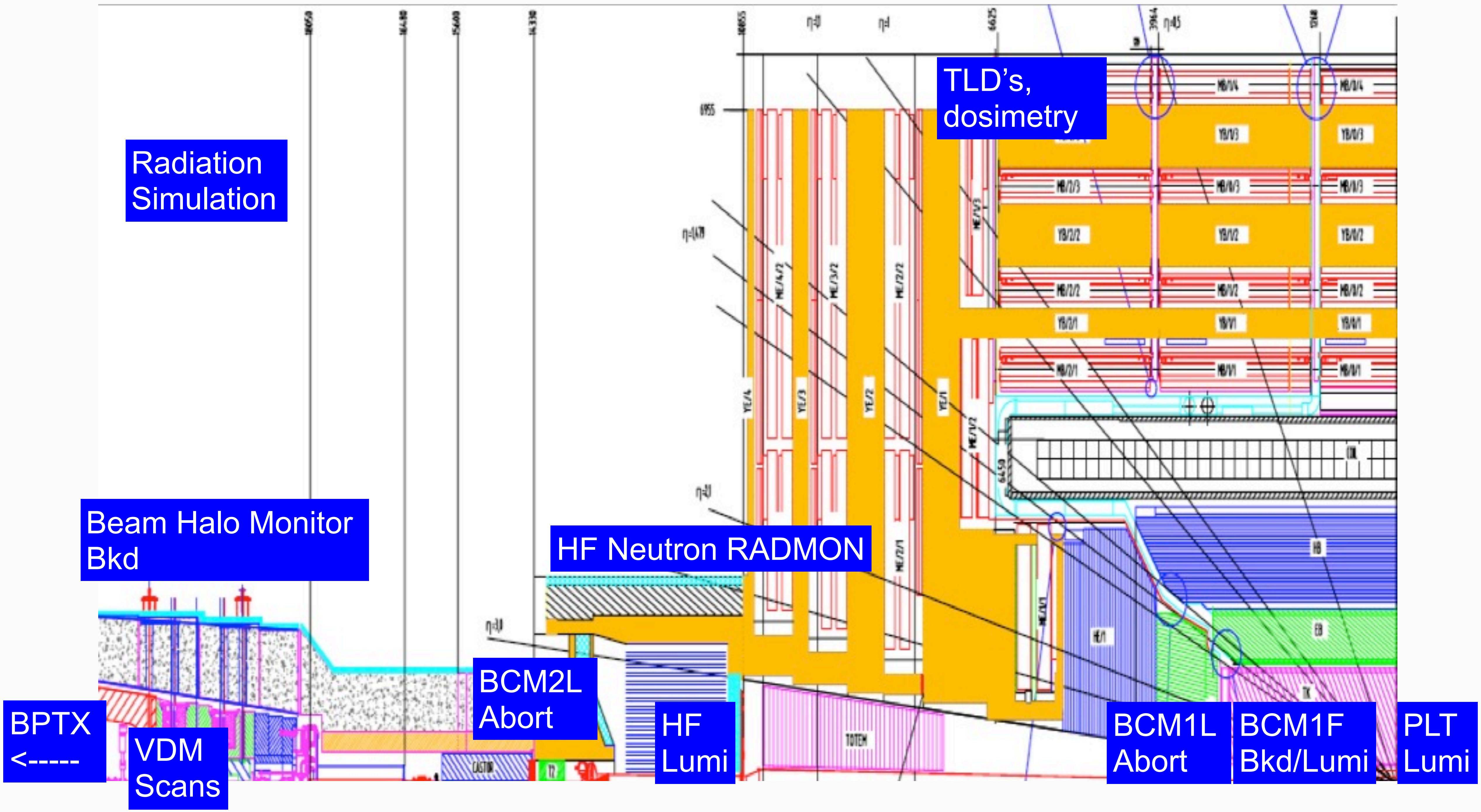




~ 2000 CPUs farm,
full event available,
“offline quality” reconstruction
same software as offline
maximal flexibility

BRIL : caring about the Beam

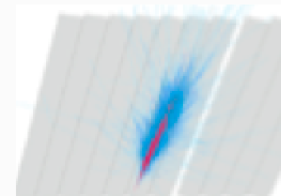
Covering anything related to interfacing CMS to the LHC



Finally:
The Detector

Compact Muon Solenoid

Superconducting Coil, 3.8 Tesla

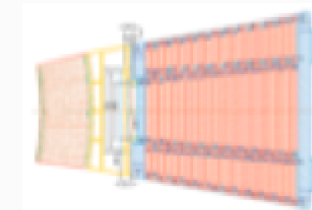


CALORIMETERS

ECAL

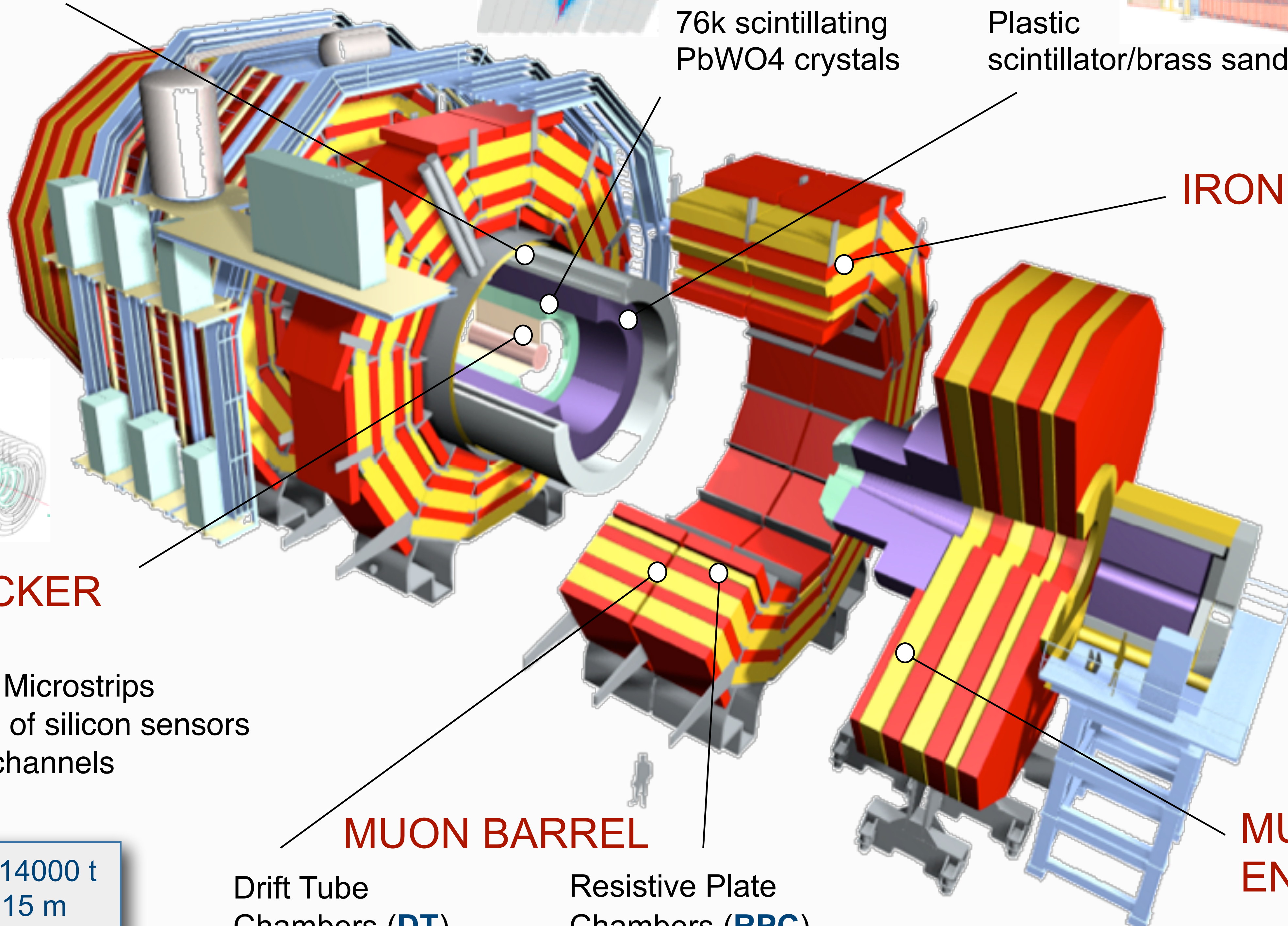
76k scintillating PbWO4 crystals

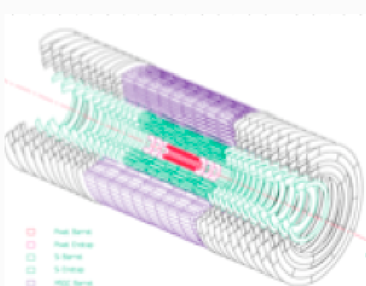
HCAL



Plastic scintillator/brass sandwich

IRON YOKE





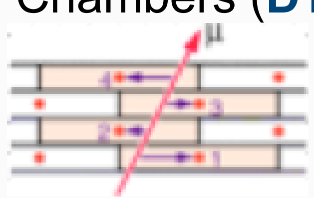
TRACKER

Pixels
Silicon Microstrips
210 m² of silicon sensors
9.6 M channels

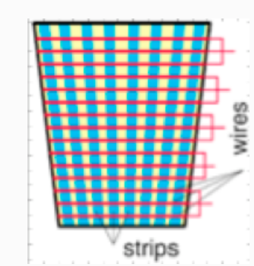
Total weight	14000 t
Overall diameter	15 m
Overall length	21 m

MUON BARREL

Drift Tube Chambers (**DT**)



Resistive Plate Chambers (**RPC**)

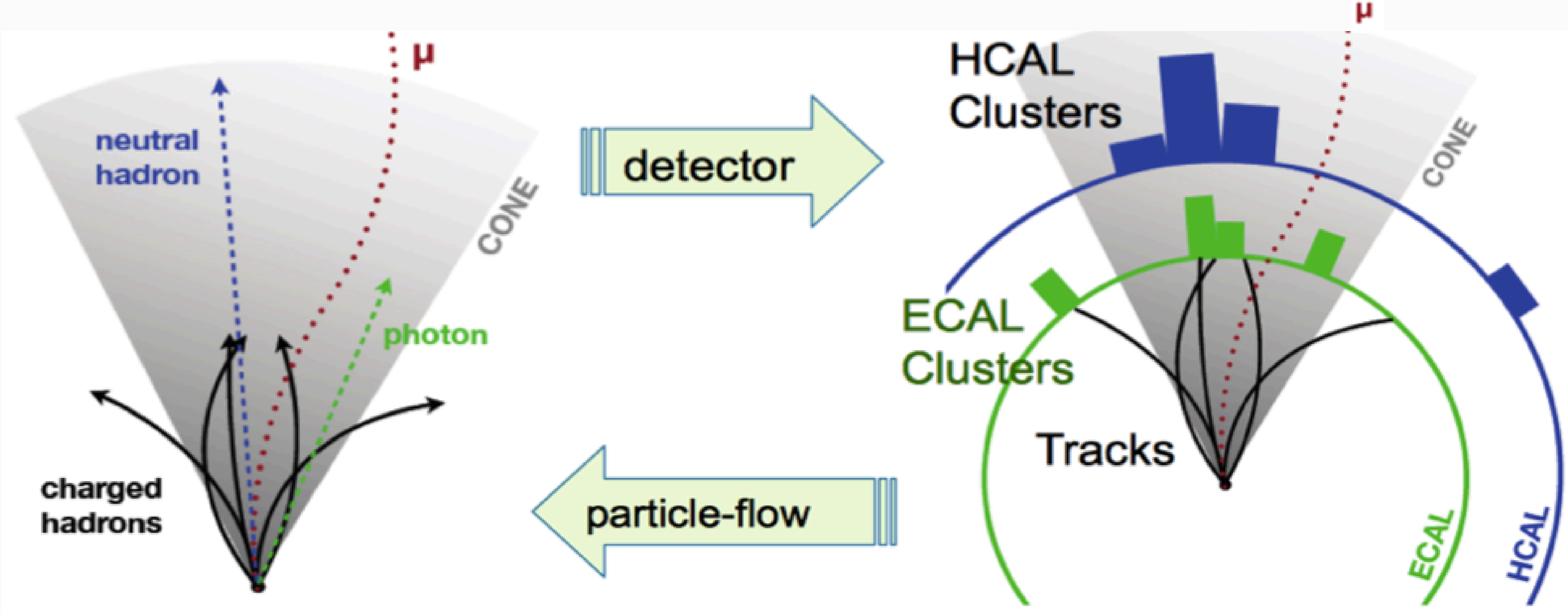


MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Particle Flow

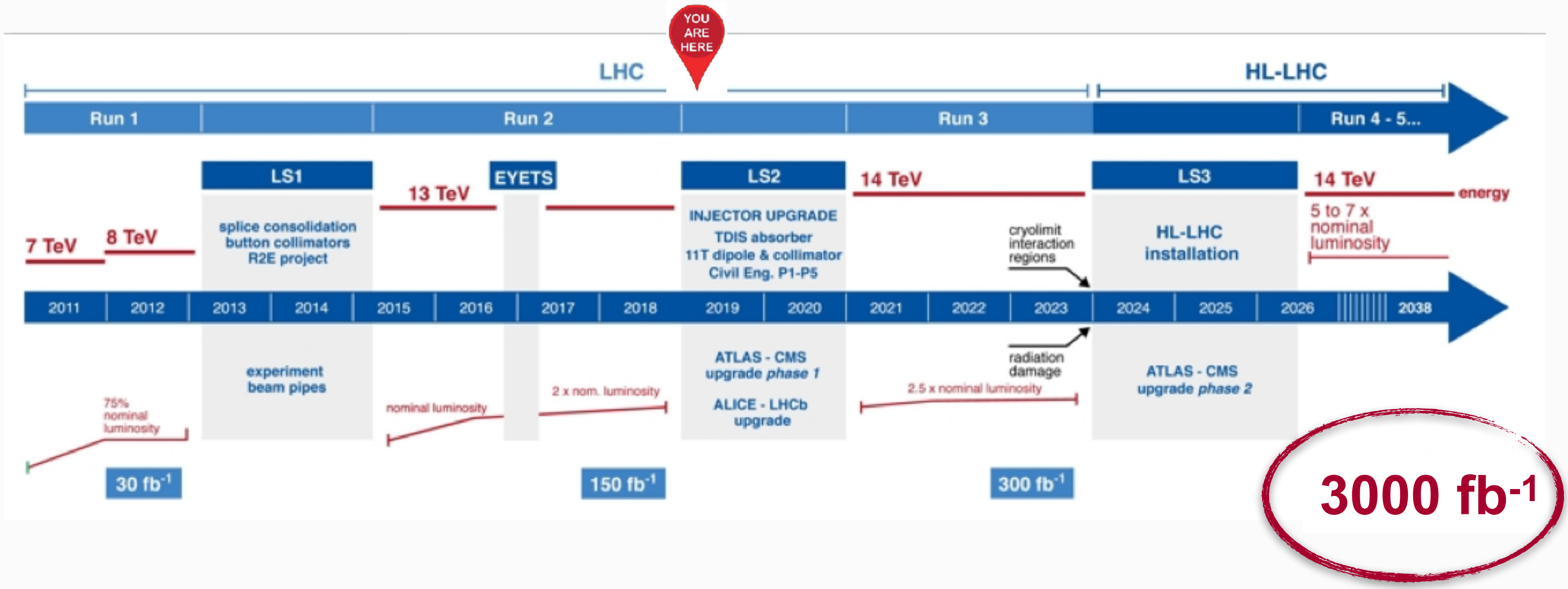
Use of global event description



- Charged particles well separated in large tracker volume & 3.8T B field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution
- **In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)**
- Therefore: **Use a global event description** :
  - Optimal combination of information from all subdetectors
  - Returns a list of reconstructed particles (e,mu,photons,charged and neutral hadrons)
  - Used as building blocks for jets, taus, missing transverse energy, isolation and PU particle ID

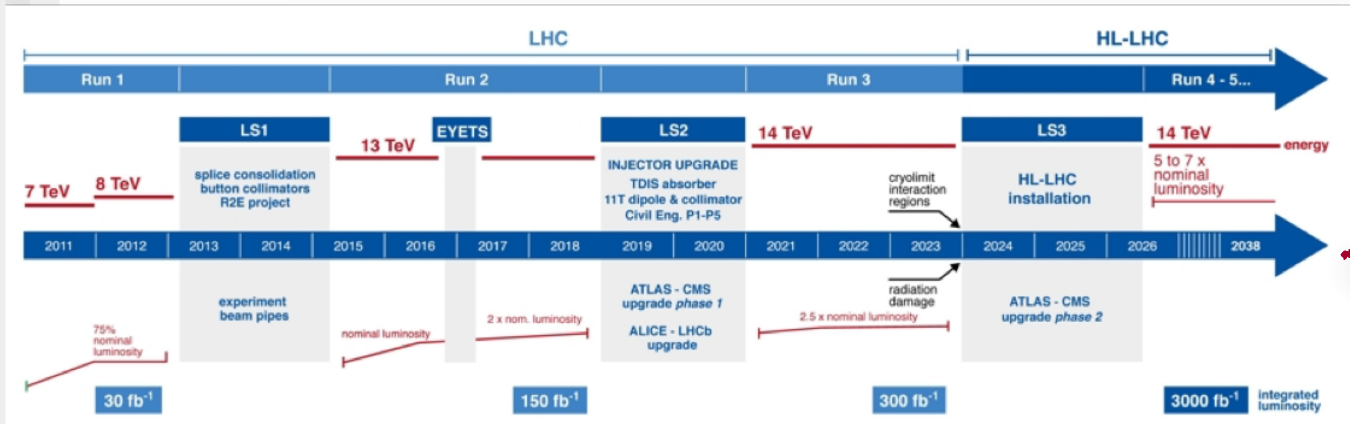
Future Plans

The Plan



so far, recorded only <5% of total expected data set !

Pile-up (1)



Luminosities of

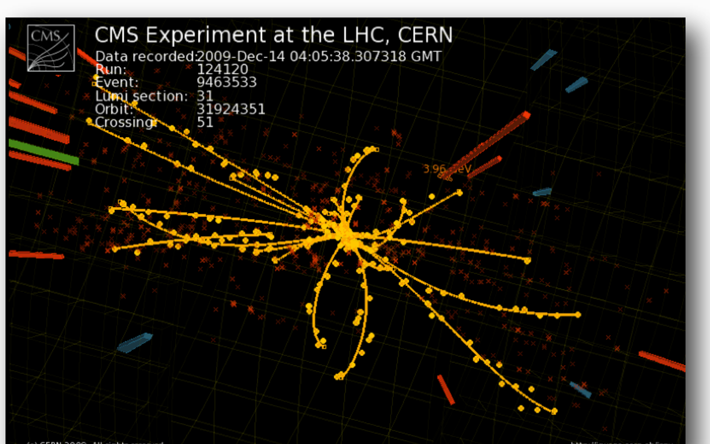
$L \sim 5 - 7.5 \times 10^{34}\ cm^{-2}s^{-1}$

Number of simultaneous proton-proton collisions per bunch crossing:

L x total cross section x bunch separation time

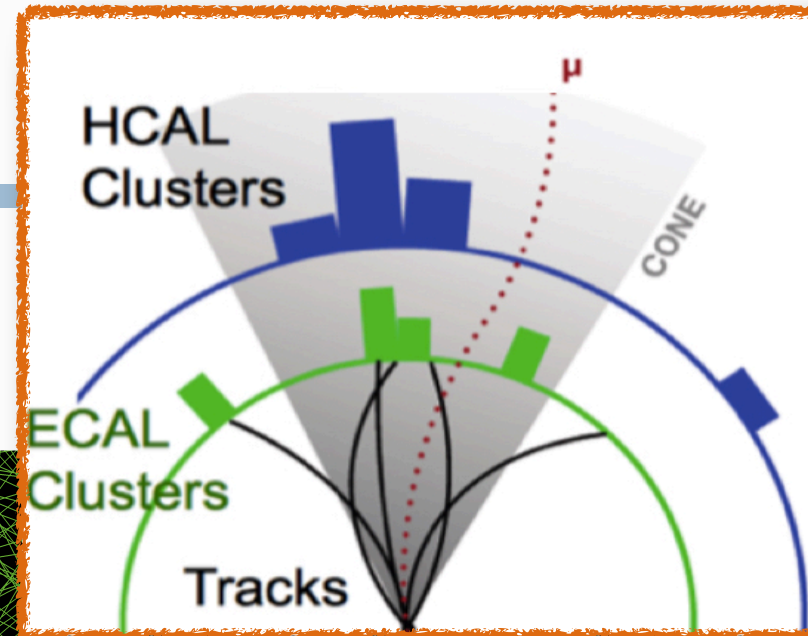
$\sim (5 - 7.5)\ 10^{34}\ cm^{-2}s^{-1}\ \times\ 100\ mb \times 25\ ns\ \sim$

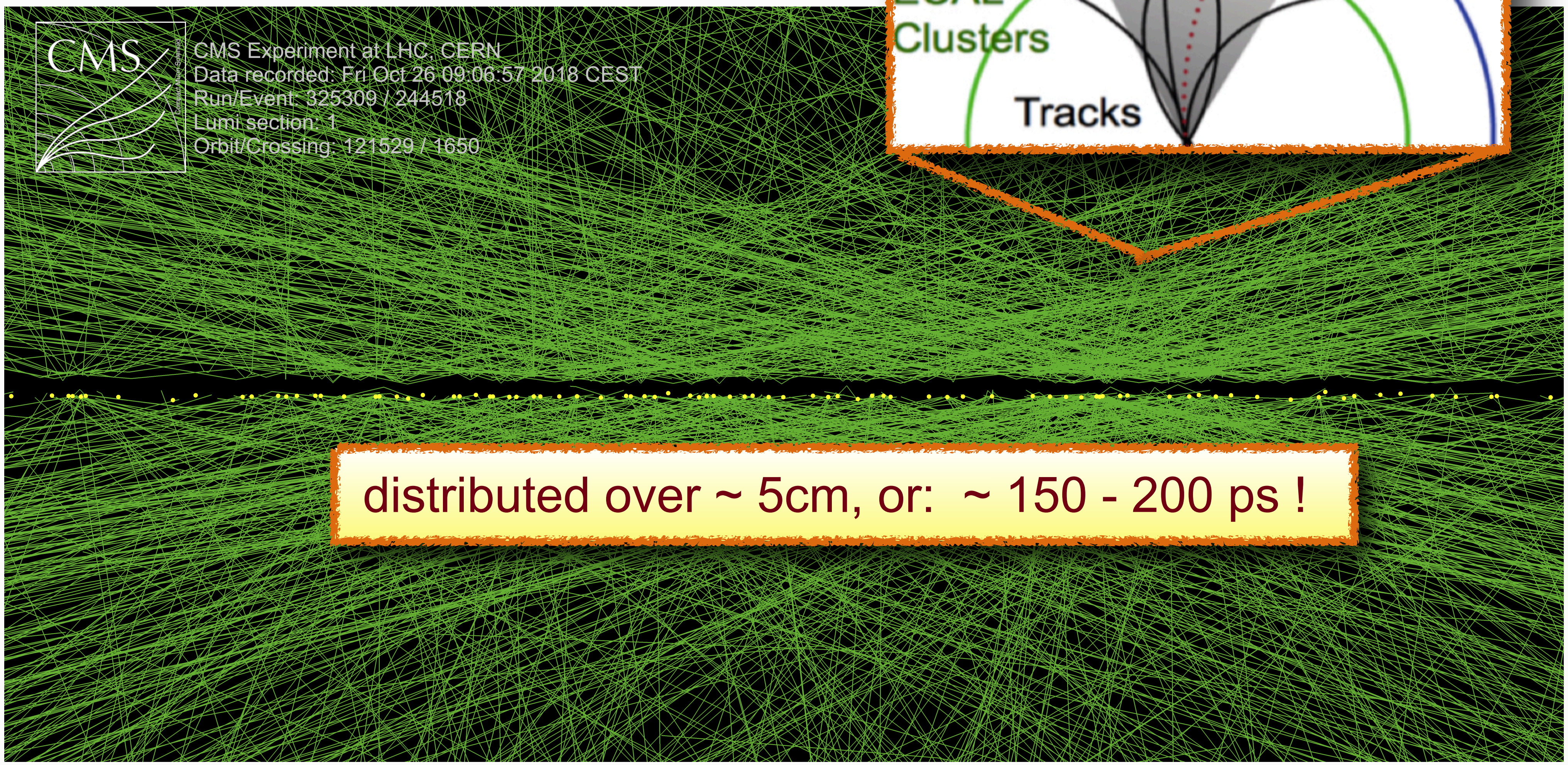
125 - 190 !



Each of these:
~ 6 charged particles per unit rapidity,
over range of +- 5 units in rapidity:
O(10000) particles per collision !!

Pile-up (2)



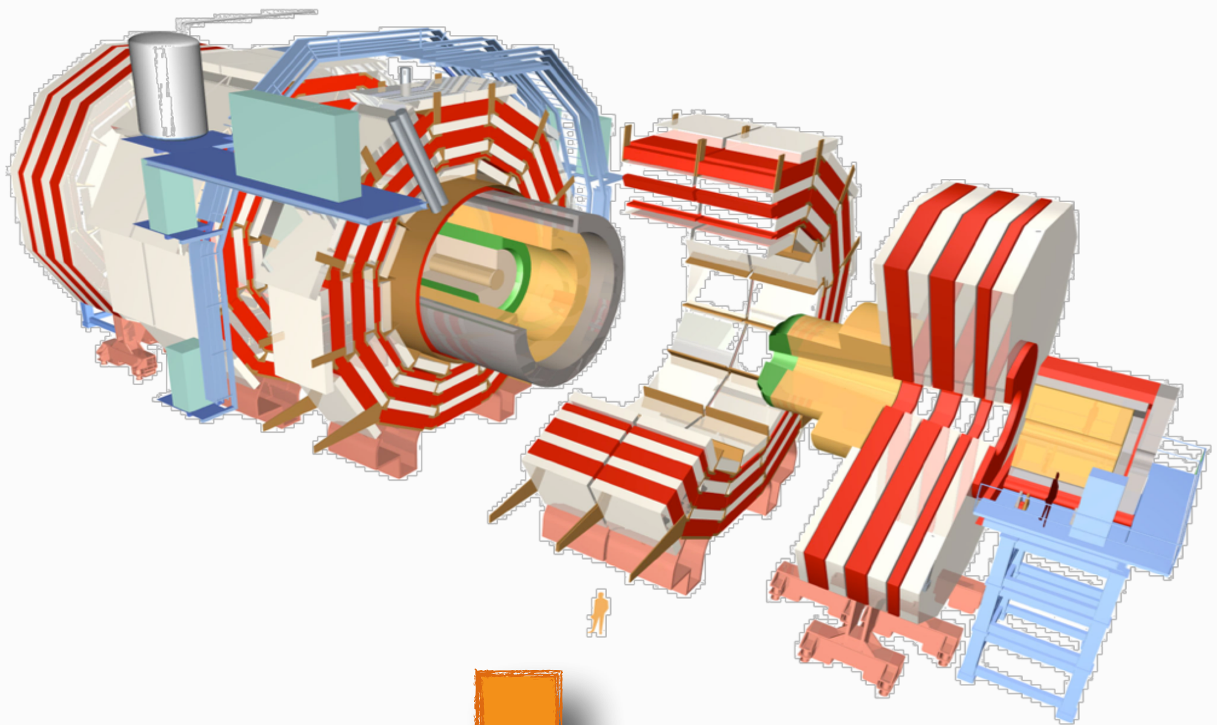


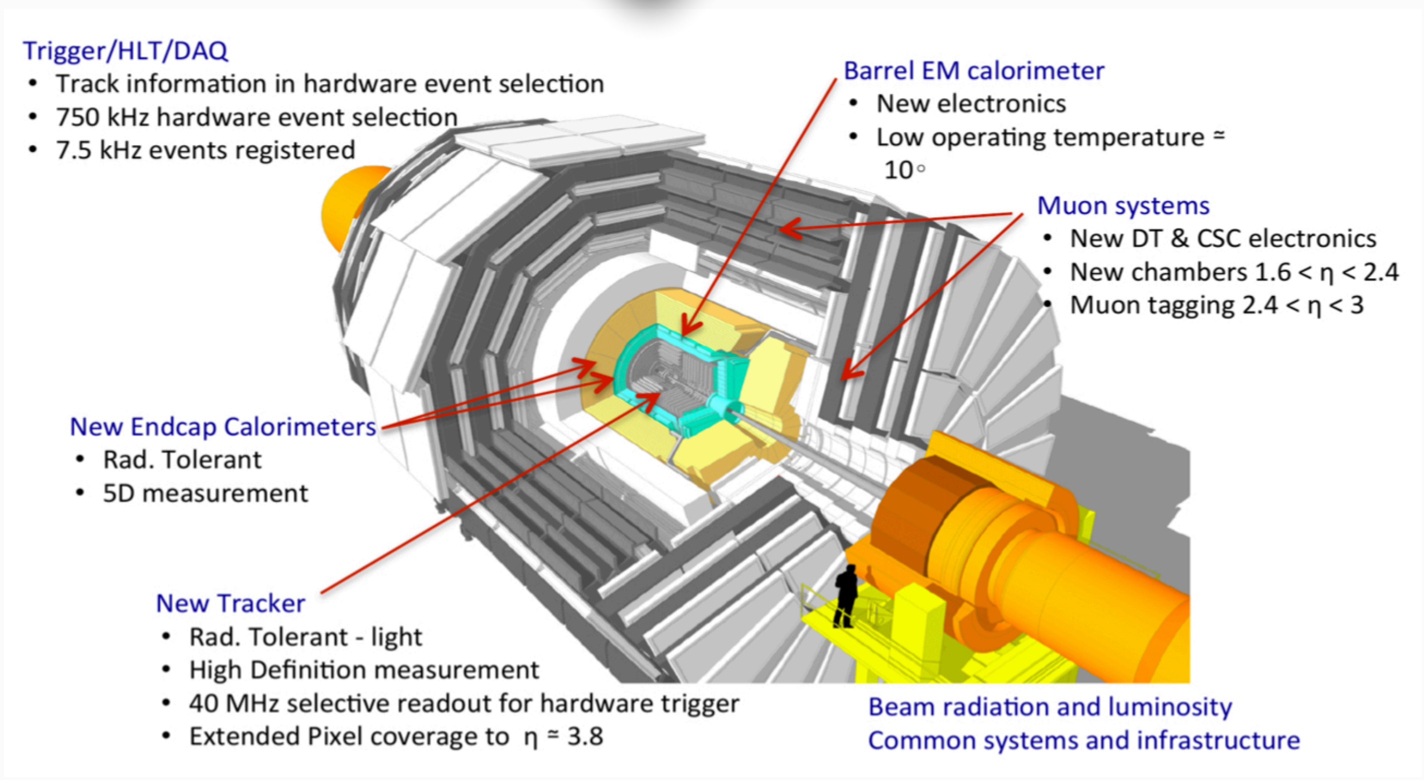
distributed over ~ 5cm, or: ~ 150 - 200 ps !

precision timing information will help
(adds an extra "dimension")

So : Detector requirements

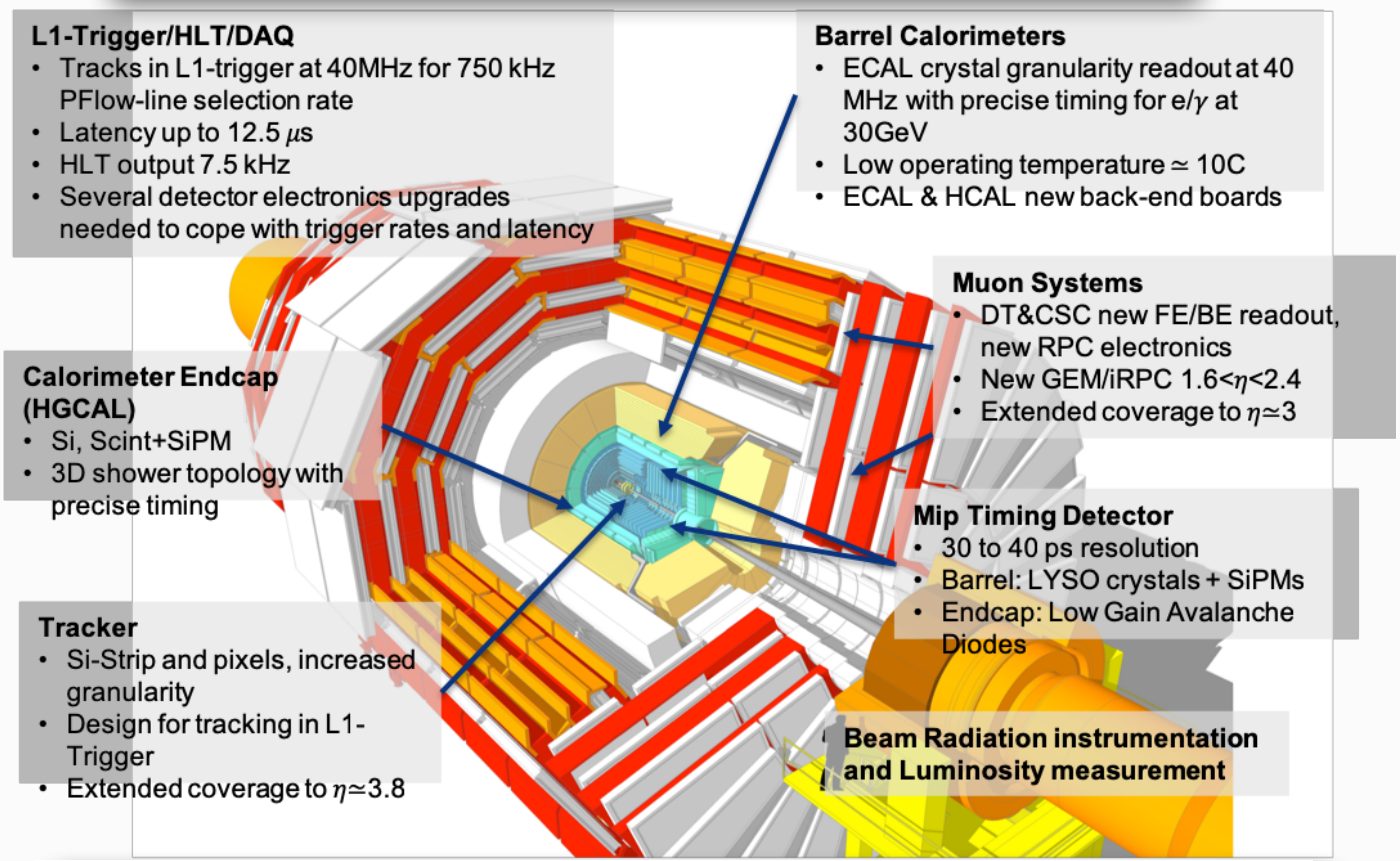
- High granularity, fast readout, radiation hardness
  - minimize pile-up particles in same detector element
  - precise and efficient tracking and vertex reconstruction
  - add timing information
  - fast response time for electronics, enough latency (for adding tracking information) and large throughput rate for triggers





In a nutshell….

Upgrade of very large scope: complexity and size similar to original construction! International project!



"*CMS likes to do bold projects….*" (J. Butler)

How we are organized

Our "nation"

"The Parliament"

Collaboration Board

One rep. per institute

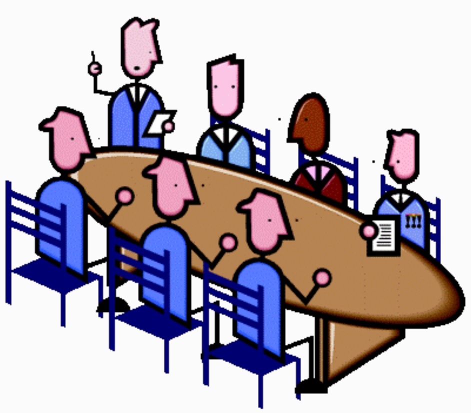
"The Government"

Management Board

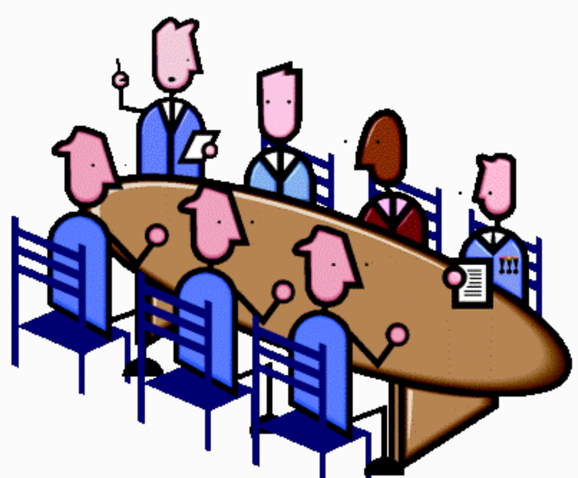
Coordinators, System Managers, Reg. Reps, …

chaired by Spokesperson

Conf. Committee



Pub. Committee



etc

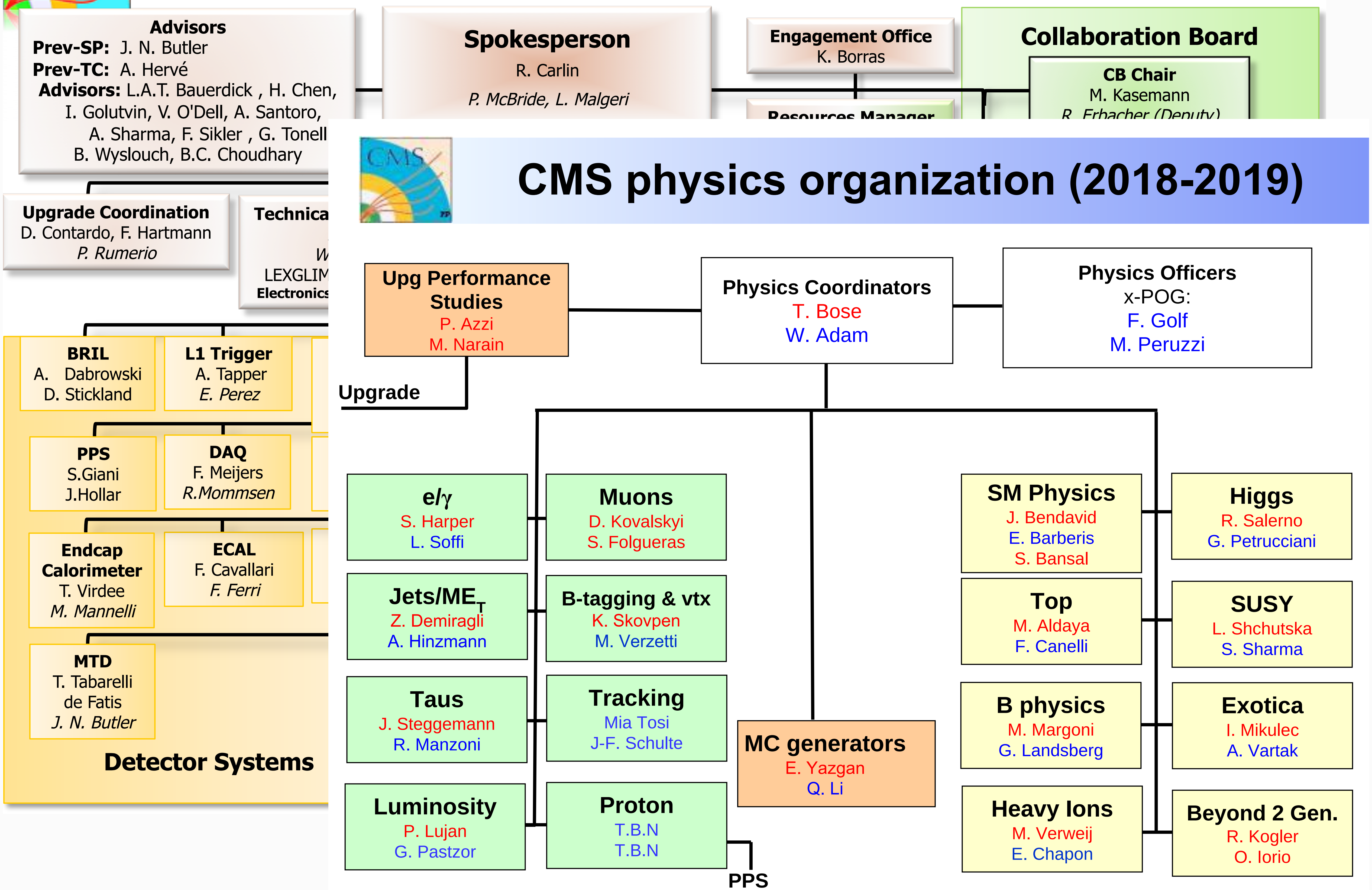
Extended Executive Board (XEB)

How do we function ?

The CMS Collaboration is led by the Spokesperson who is the Chairperson of the Management Board and the Executive Board and is responsible for the scientific and technical direction of the experiment, following the policies agreed by the Collaboration Board. The Spokesperson is the principal representative of CMS in interactions with CERN and its committees, with the wider physics community and with the general public. The Spokesperson is elected by the Collaboration Board.

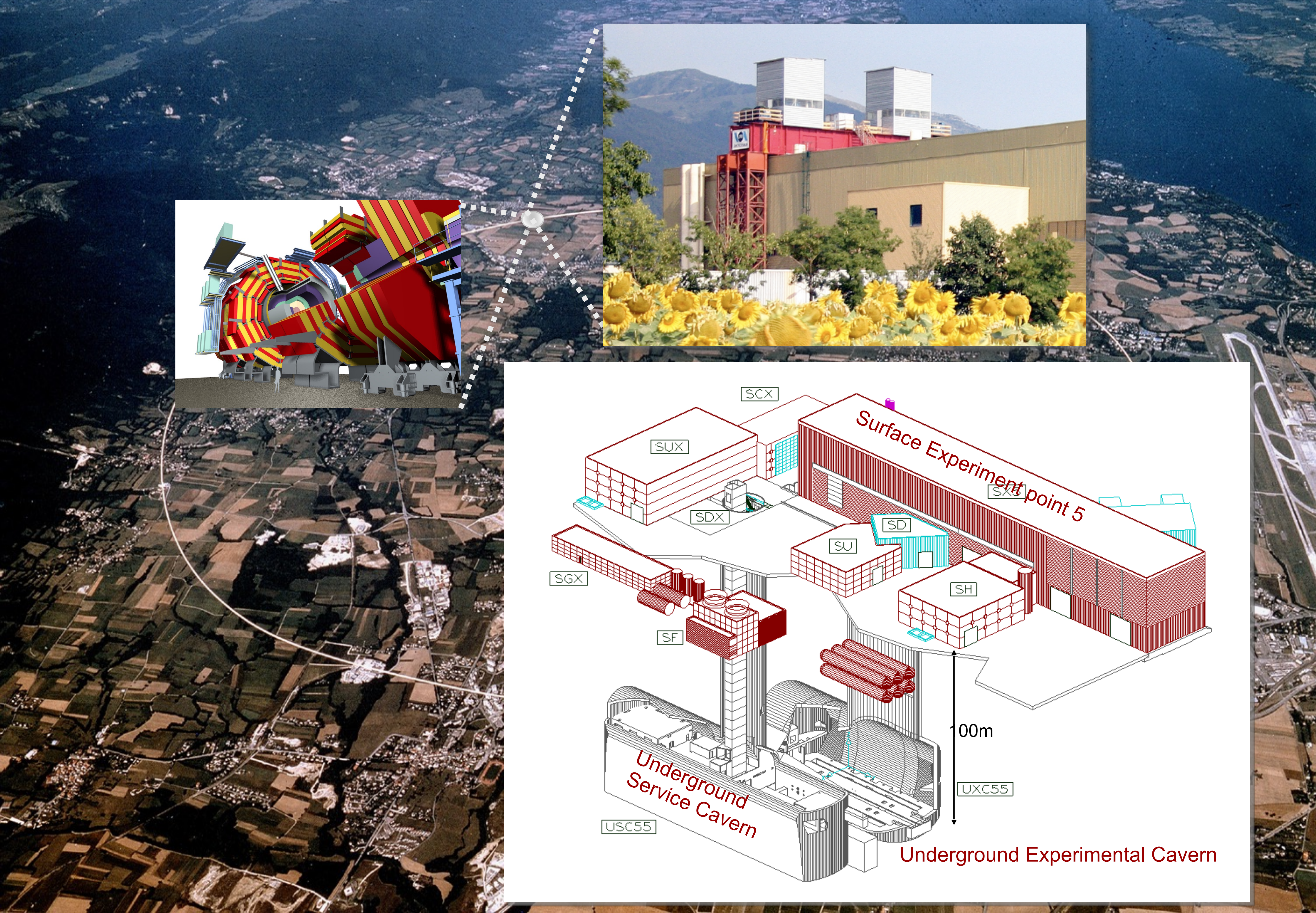
- CMS activities are divided into areas with co-coordinators for each area
- CMS subsystems have each a Subsystem manager (aka System Manager, SM)
- The Coordinators and SM meet each **Tuesday at 13:00** in the Executive Board chaired by the SP; the EB is responsible day to day tactical and technical operation of CMS.
- The Management Board , chaired by the SP, has the same composition as the EB plus representatives of the major regions/countries of CMS, the former SP and Tech. Coord., the resource manager, various chairs of CB committees and a set of SP advisors chosen by the SP. The MB is responsible for directing the CMS experiment and for drawing up policy. The MB meets typically 8-10 times per year.
- The CMS Collaboration Board (collecting representatives of each institute participating in CMS) is the governing body of the experiment and makes/endorses all major decisions within the Collaboration. The CB meets during the CMS. Physics and Upgrade weeks. In particular the CB elects the SP and the Chair of the CB which is invited in every CMS committees.

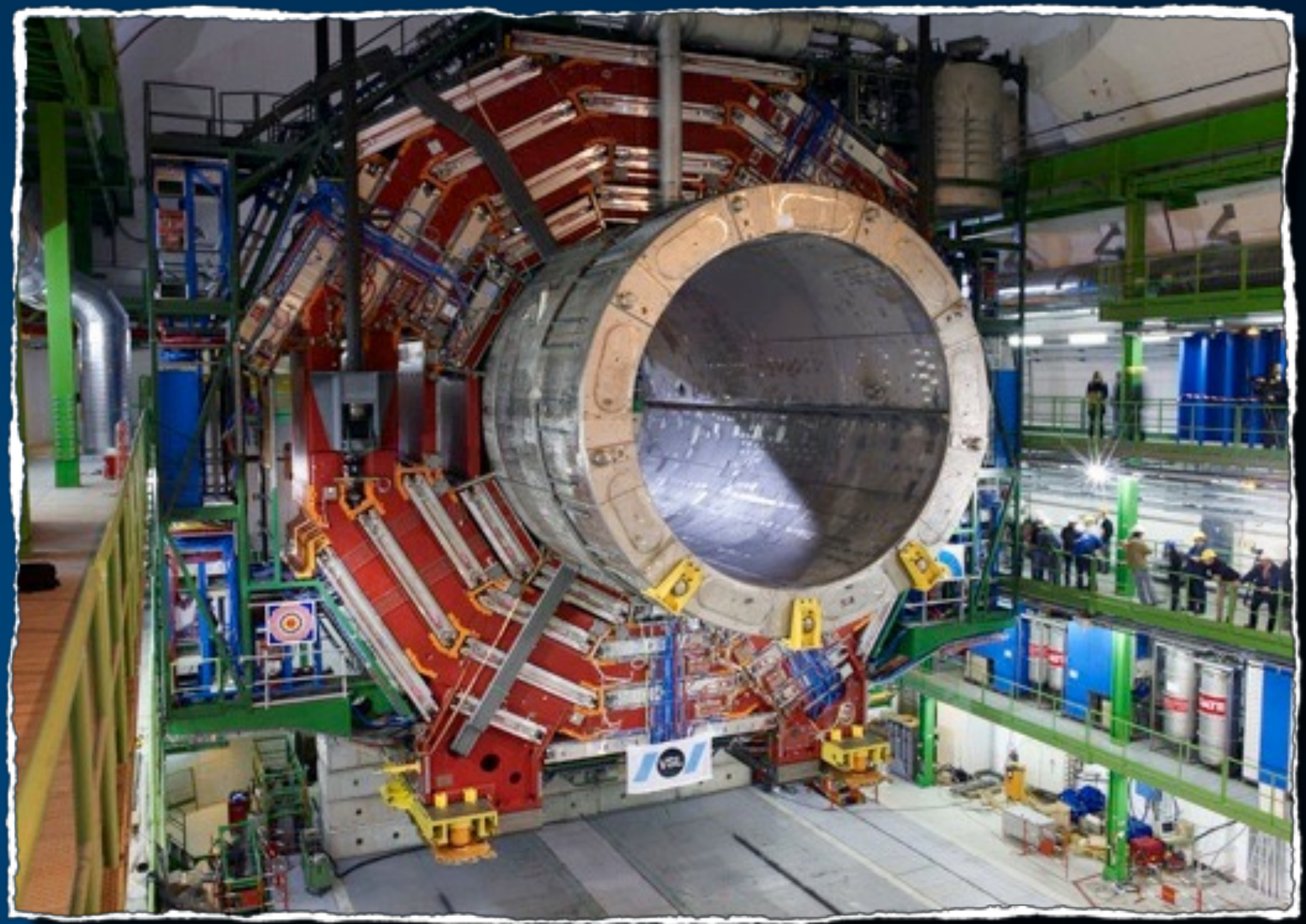
CMS Management Board-September 2018



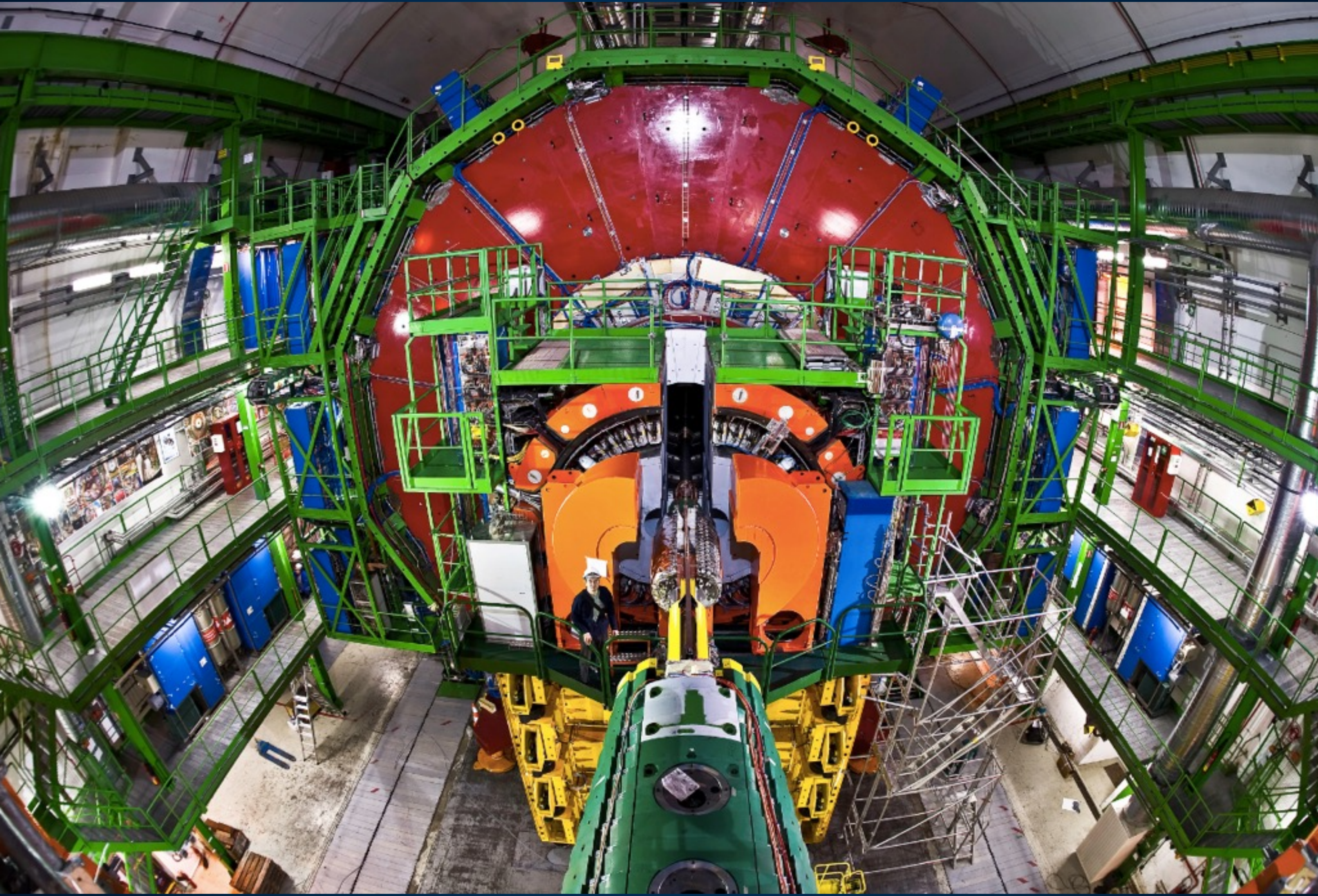
CMS at P5

CMS at P5


SCX
SUX
SDX
SGX
SF
SU
SD
SH
Surface Experiment point 5
100m
UXC55
Underground Service Cavern
USC55
Underground Experimental Cavern



~ 2000 t
~ 5 Jumbo Jets



Last but not least

The really important ones

- Our friendly secretariat!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/DrupalContactCMS

Anca Patru

Ekaterina Osipova

Tania Pardo

Zsuzsanna Garai

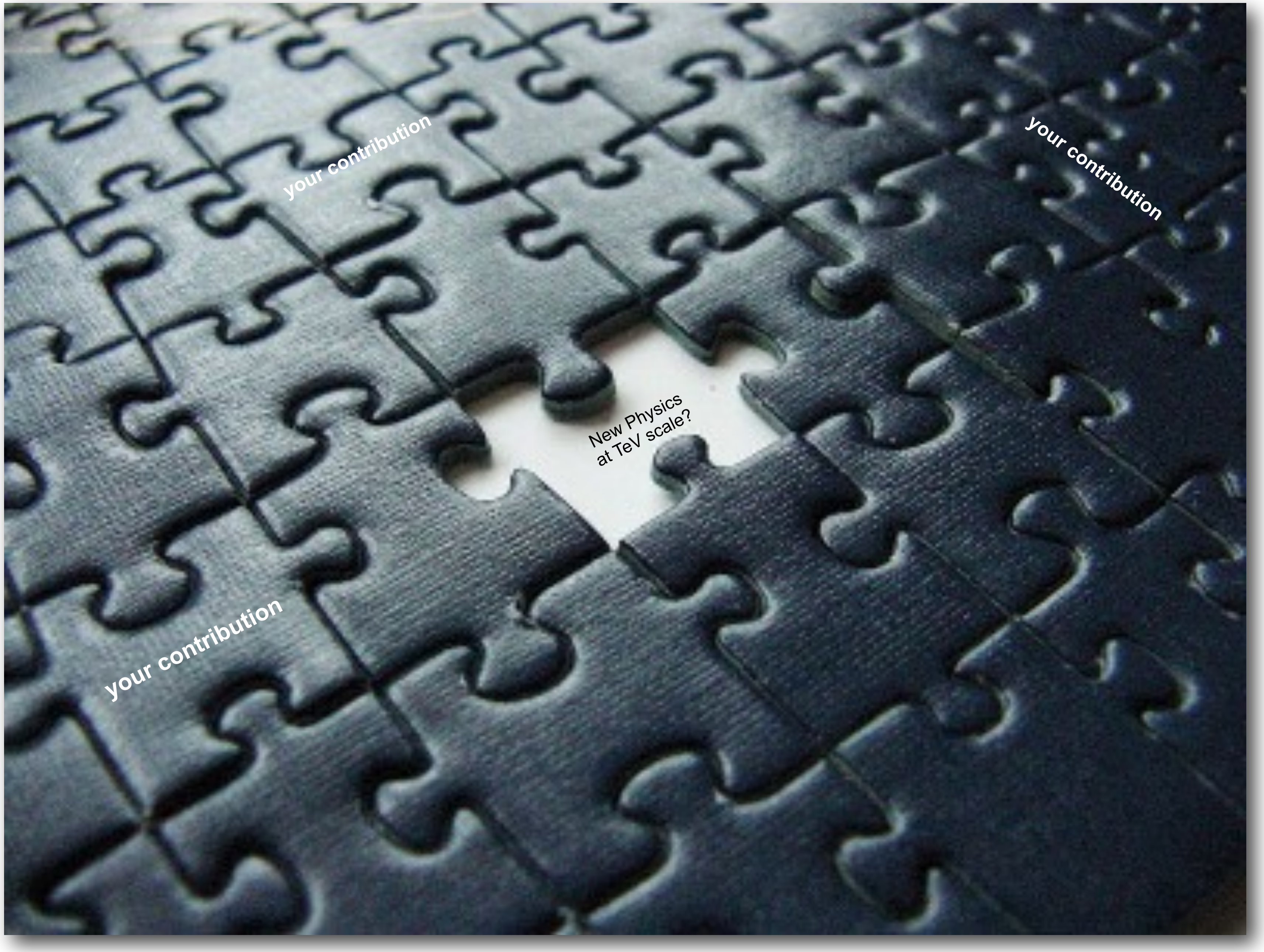
Welcome to CMS!!!

I wish you a wonderful experience for the rest of your Induction into CMS,
and of course during your future activities in our collaboration!

It is a moment of unique opportunities in the life of a High Energy Physicist!

Excellent performance of the CMS Detector is due to the ingenuity, expertise and hard work of all collaborators

Welcome to CMS!!!



Doing something ordinary is a waste of time.

Madonna