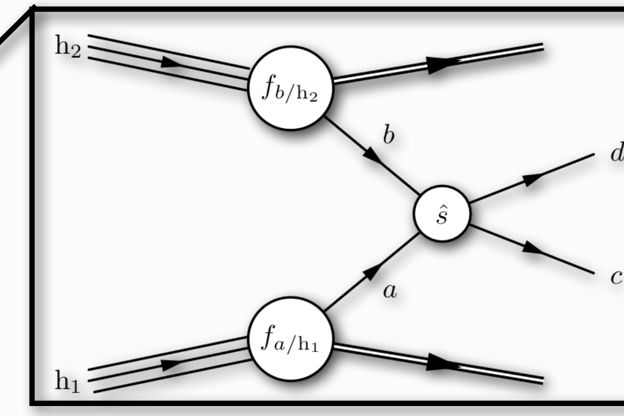
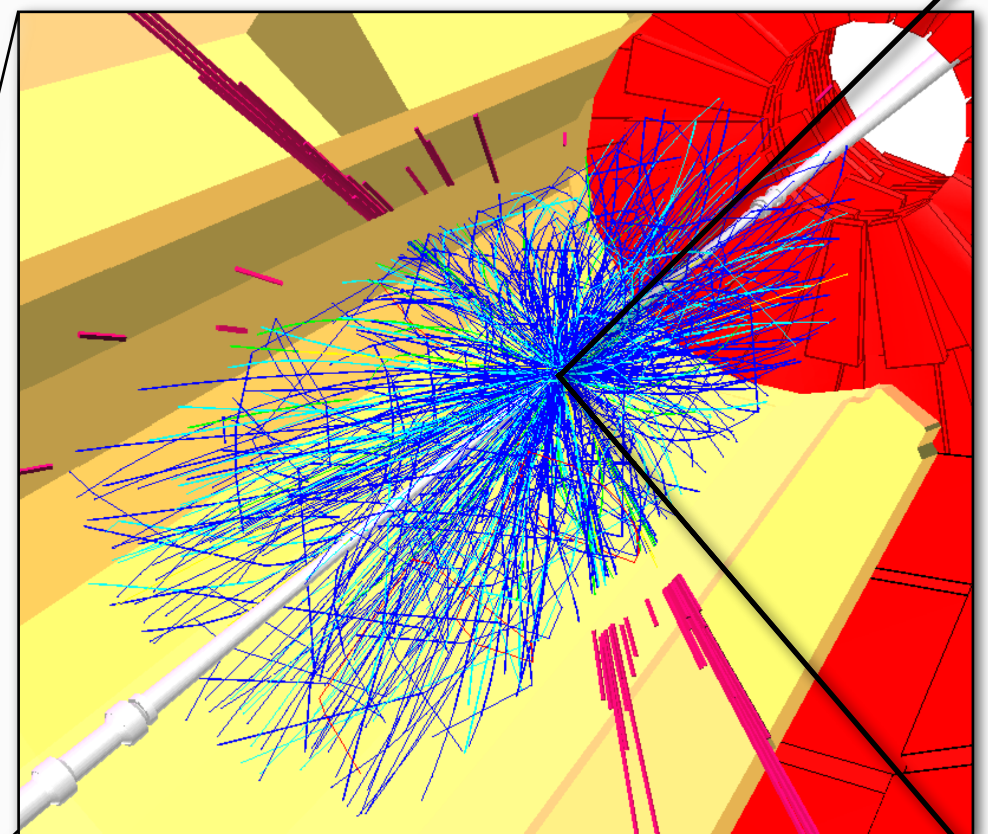
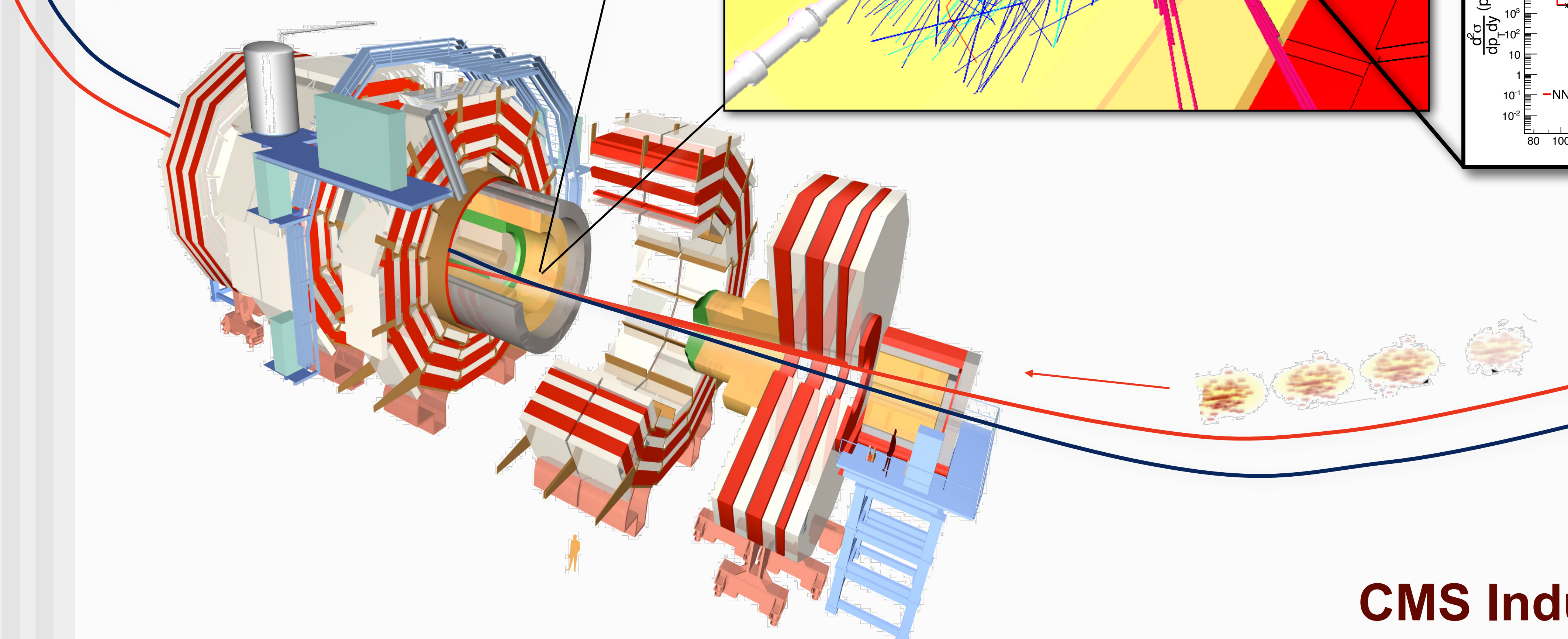
Introduction to CMS

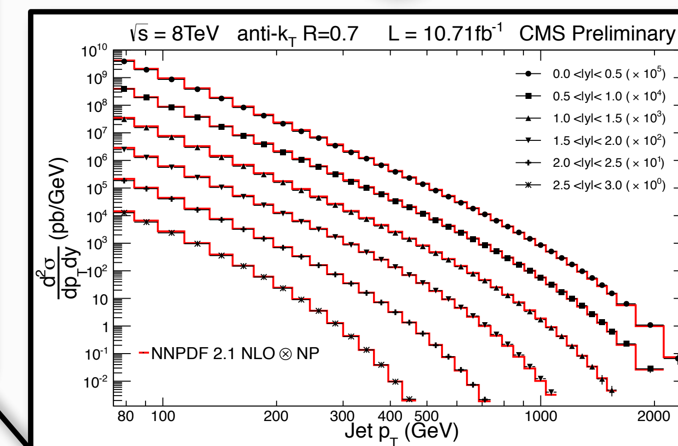
Günther Dissertori

ETH Zürich









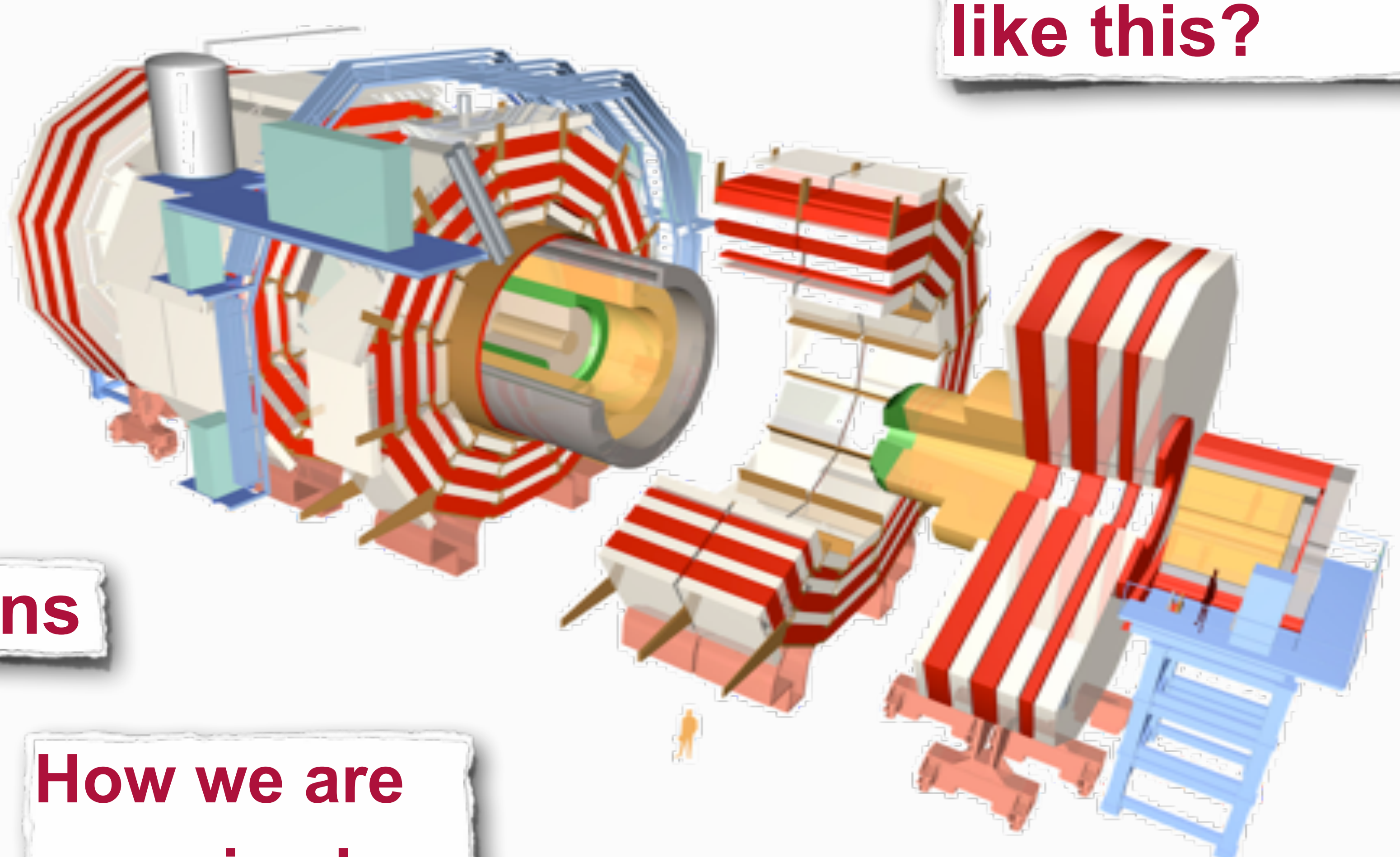
CMS Induction Day

31st of January 2018

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

A truly gobal project

CMS Collaboration
~4000 members
~40 countries
~200 Institutes

A truly gobal project

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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

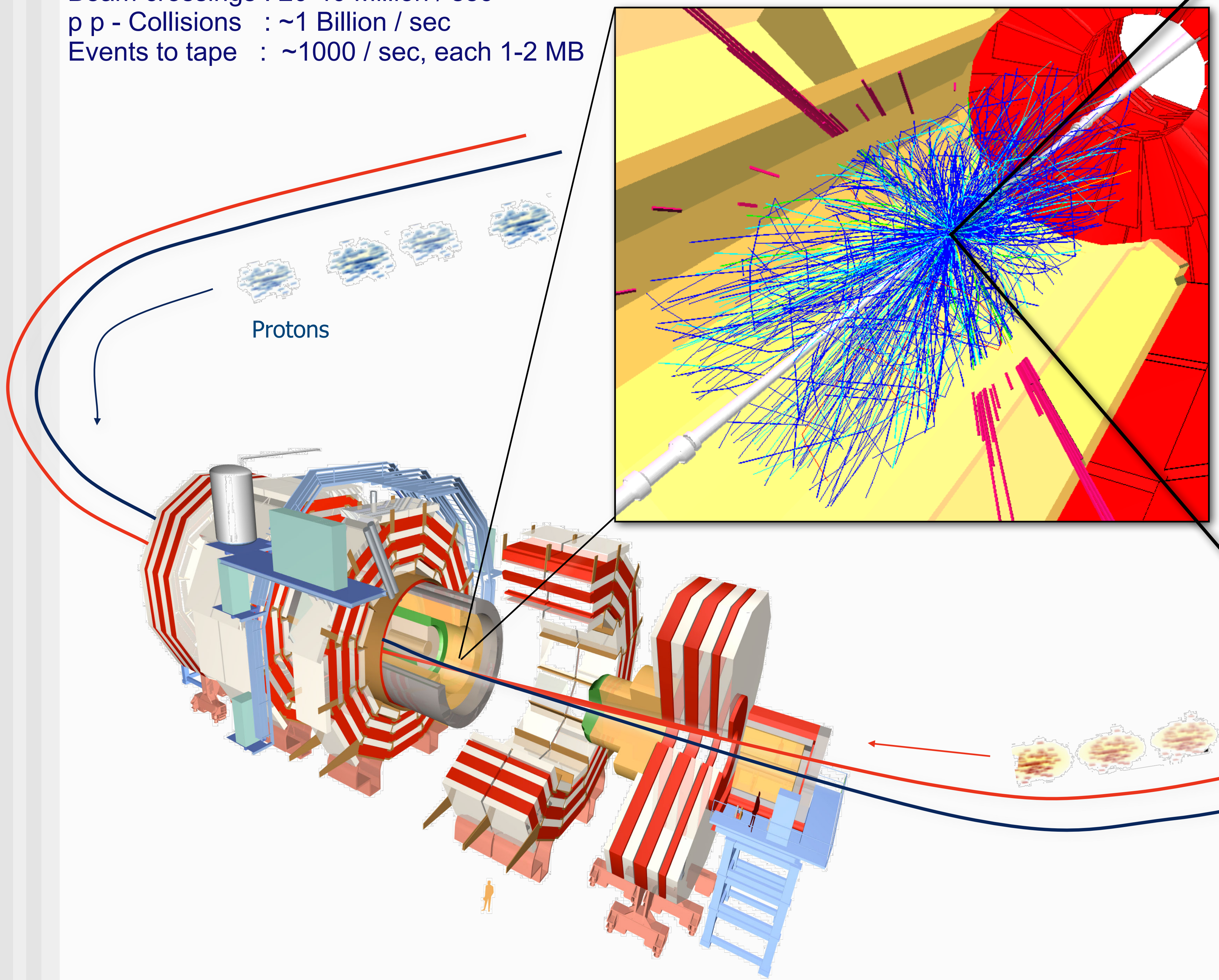
Technical Design Reports (available from the CMS secretariat)

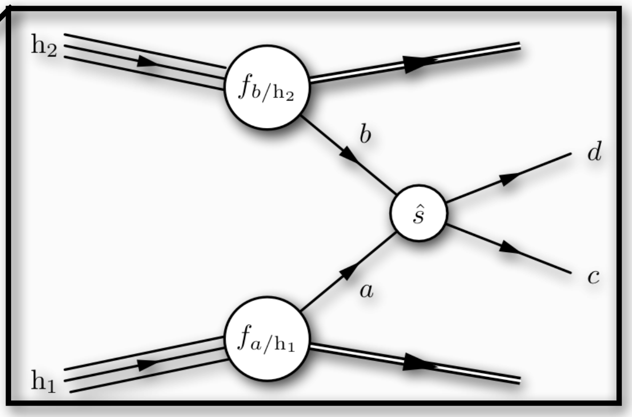
- 2008: First data taking: LHC Incident. Restart in 2009.
- **Since Nov 2009**: **data taking**, p-p, Pb-Pb, p-Pb, Xe-Xe

Why does it look like as it looks like?

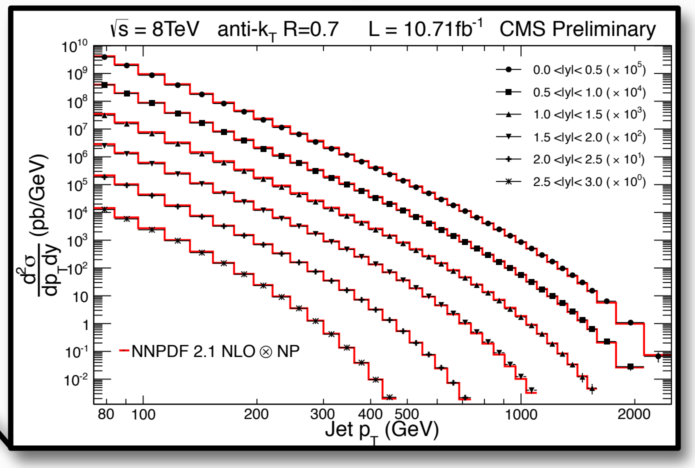
Collisions at the LHC

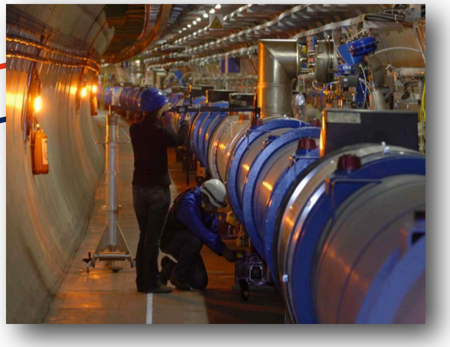
Centre-of-Mass Energy = 0.9 - 2.36 - 7 - 8 - 13/14 TeV
Bunch separation : 50 - 25 ns
Beam crossings : 20-40 Million / sec
p p - Collisions : ~1 Billion / sec
Events to tape : ~1000 / sec, each 1-2 MB



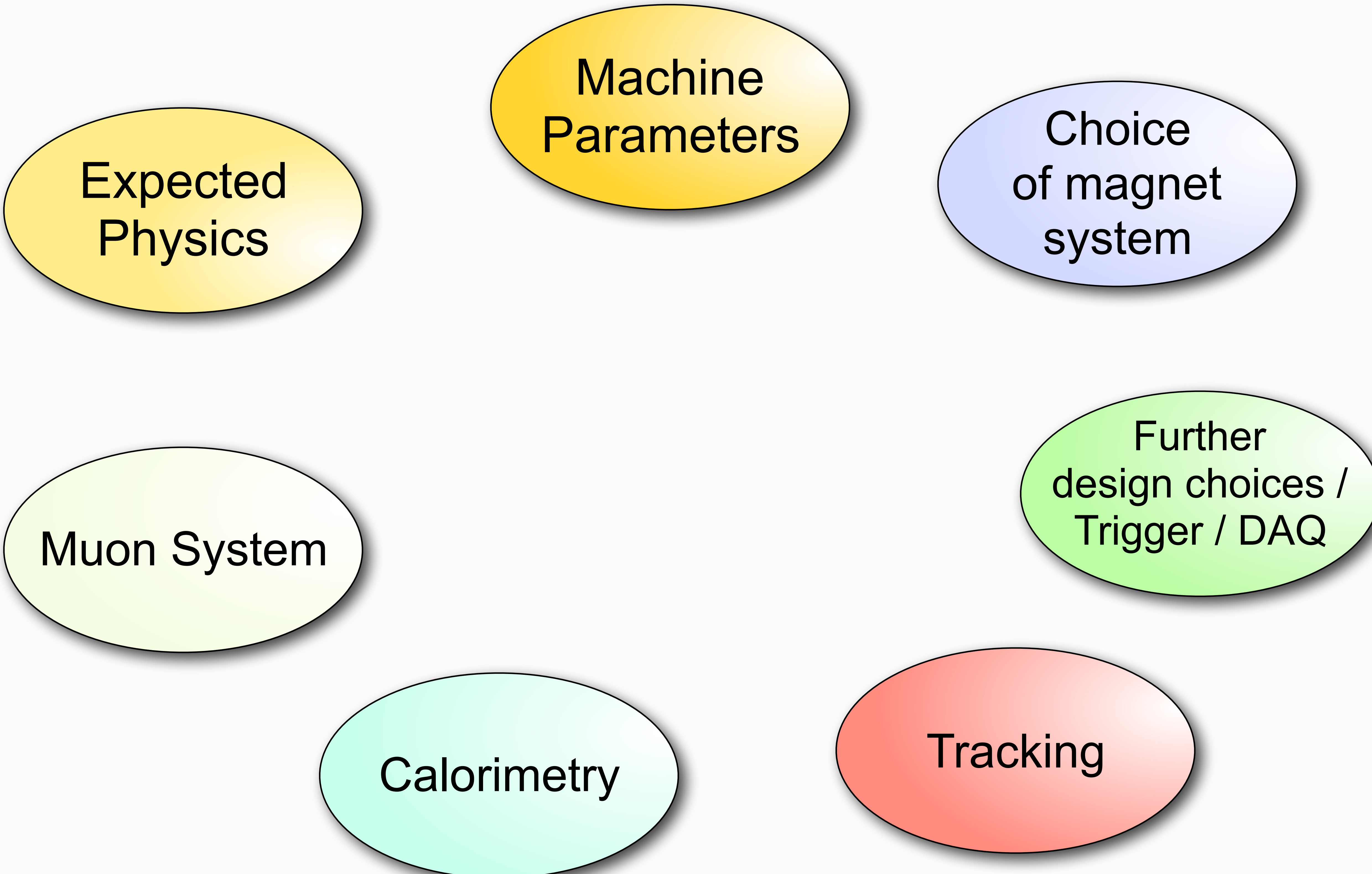


compare





How to design your detector



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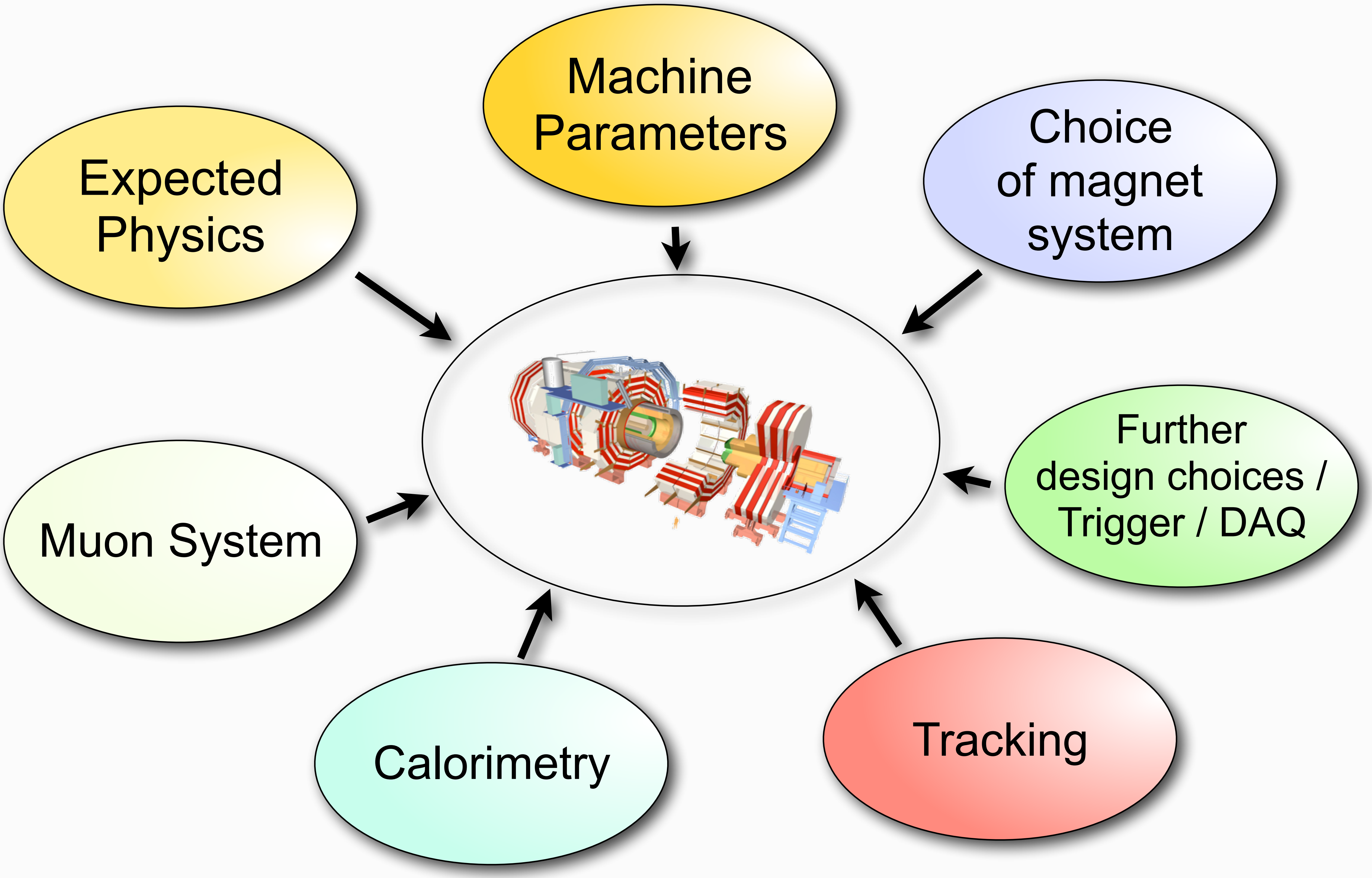

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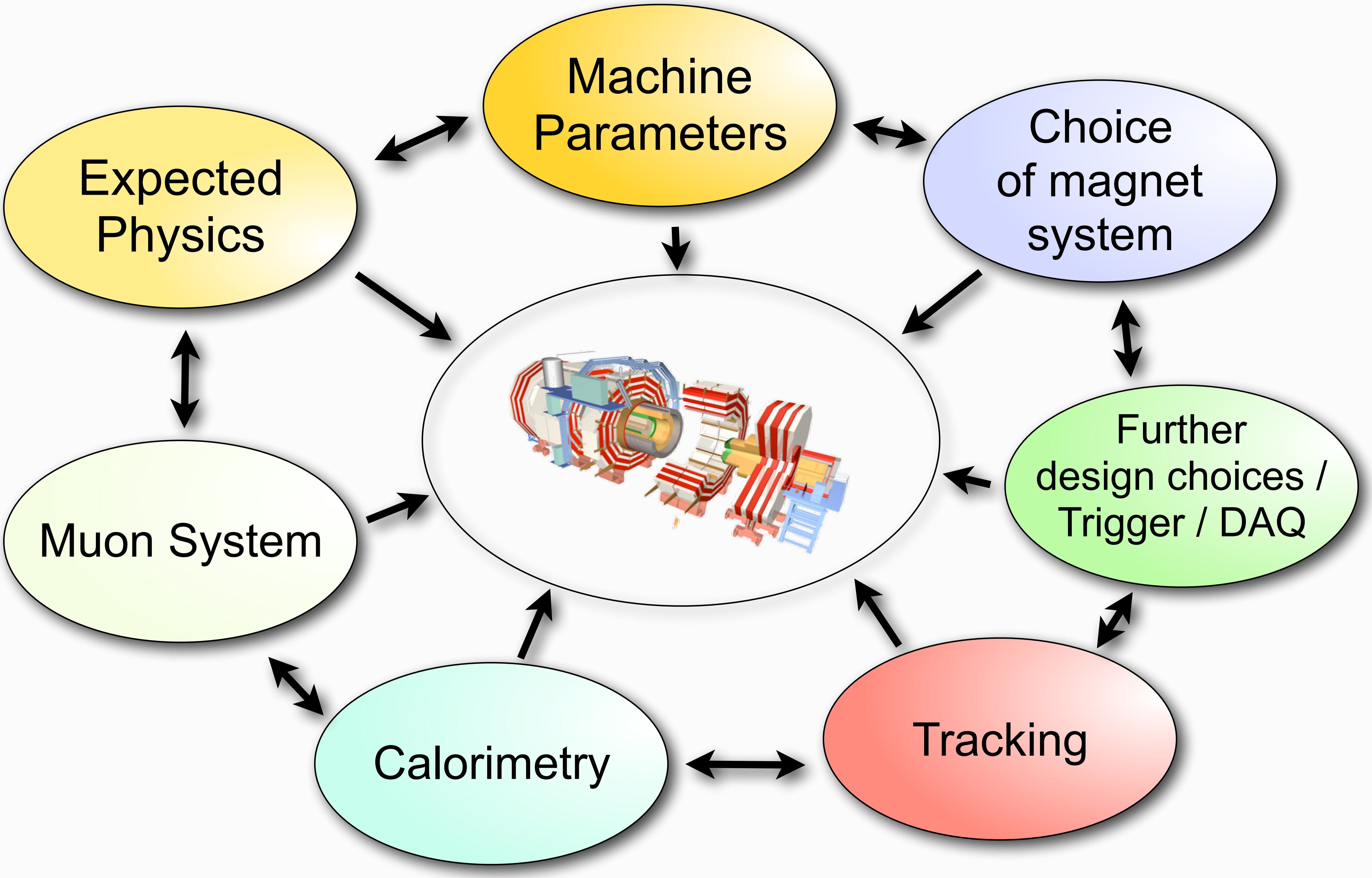

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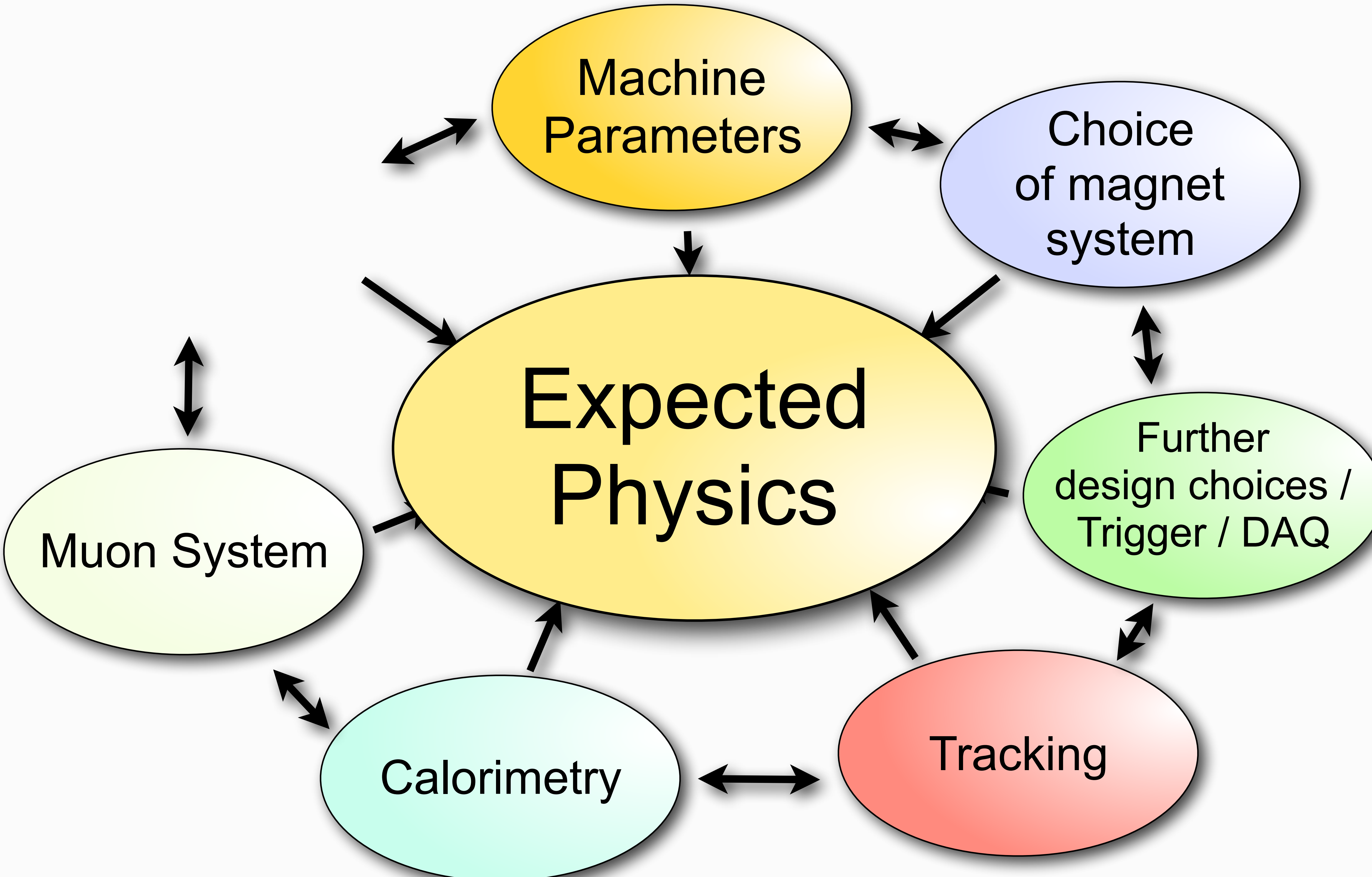
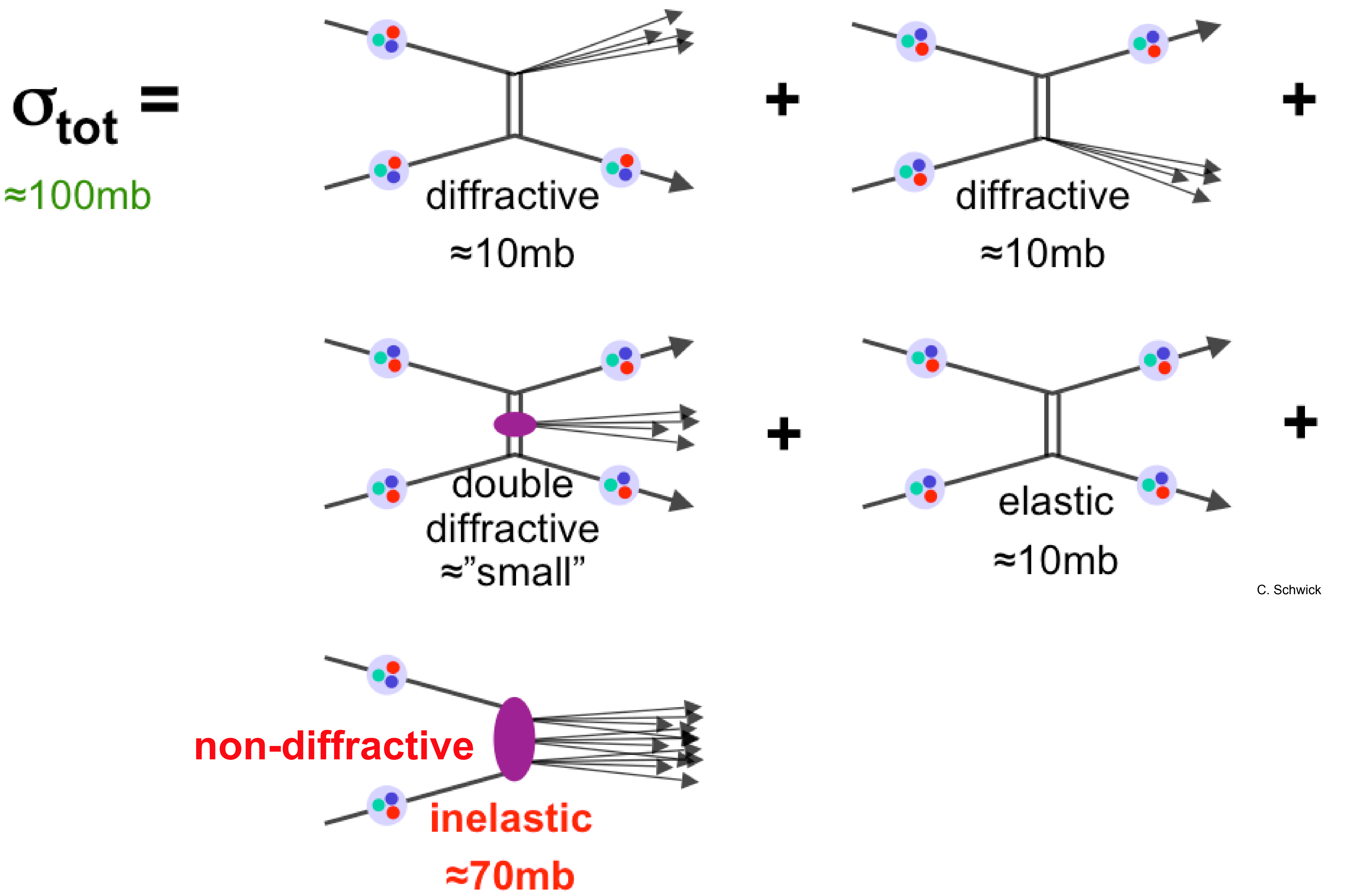


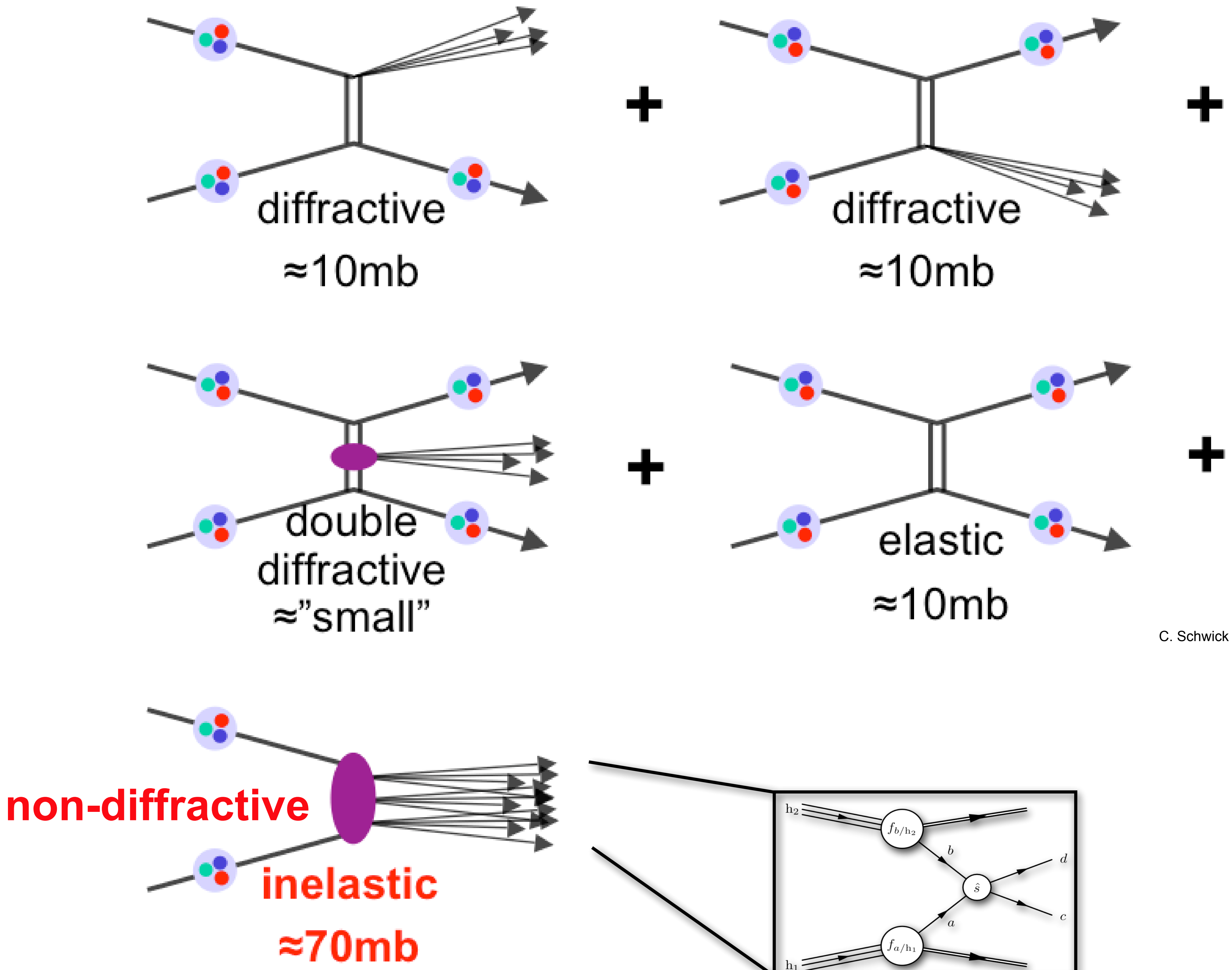
pp-Interactions at the LHC



pp-Interactions at the LHC

σ_{tot} =

≈100mb



C. Schwick

pp-Interactions at the LHC

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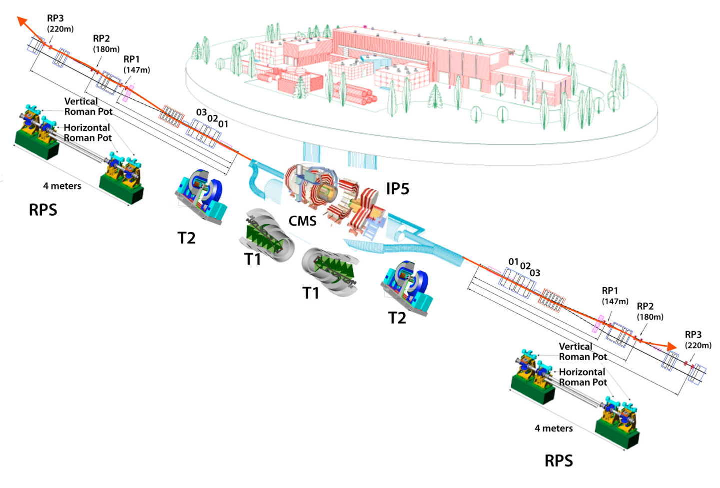
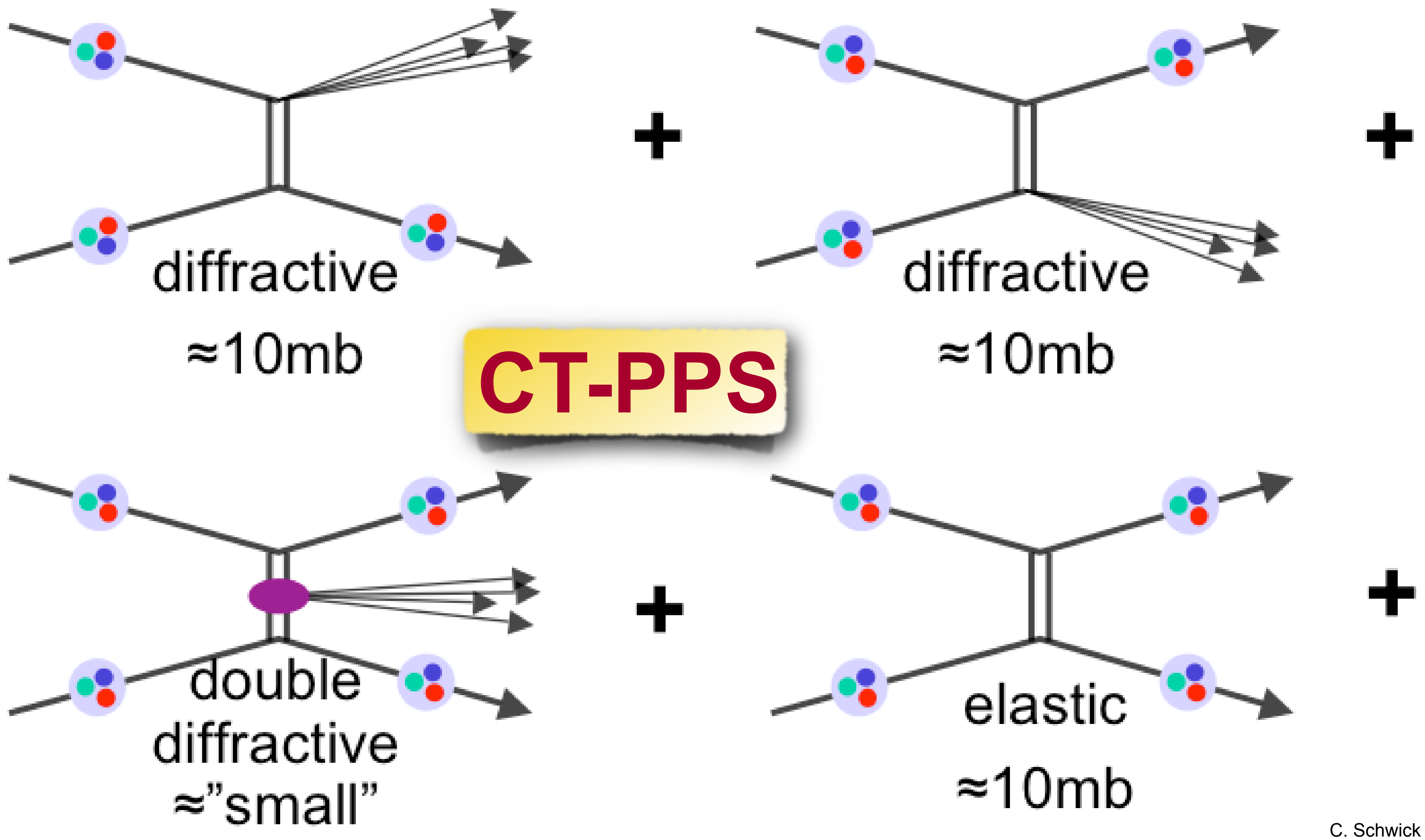
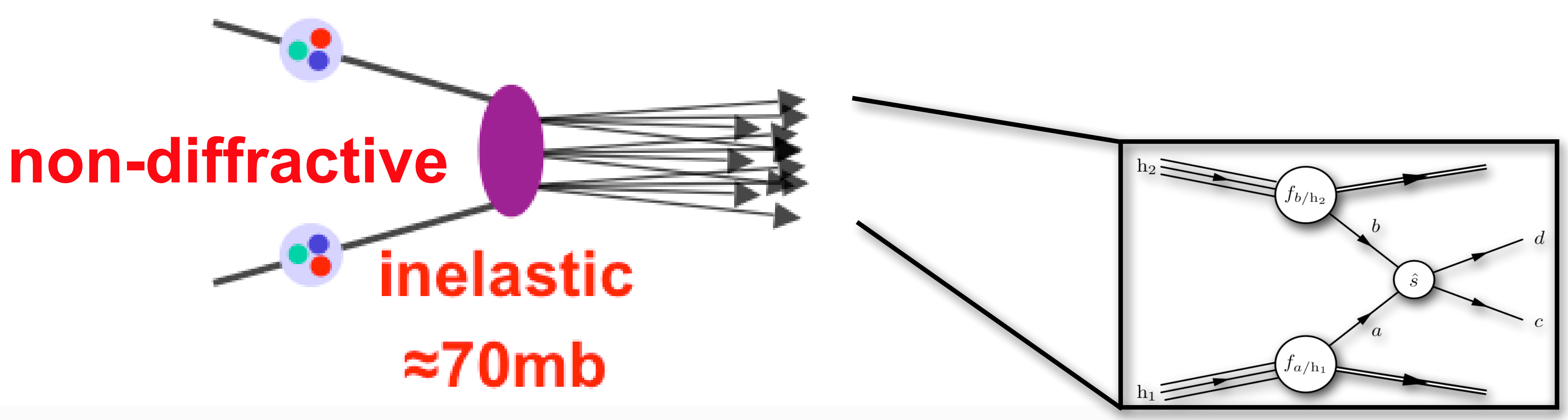
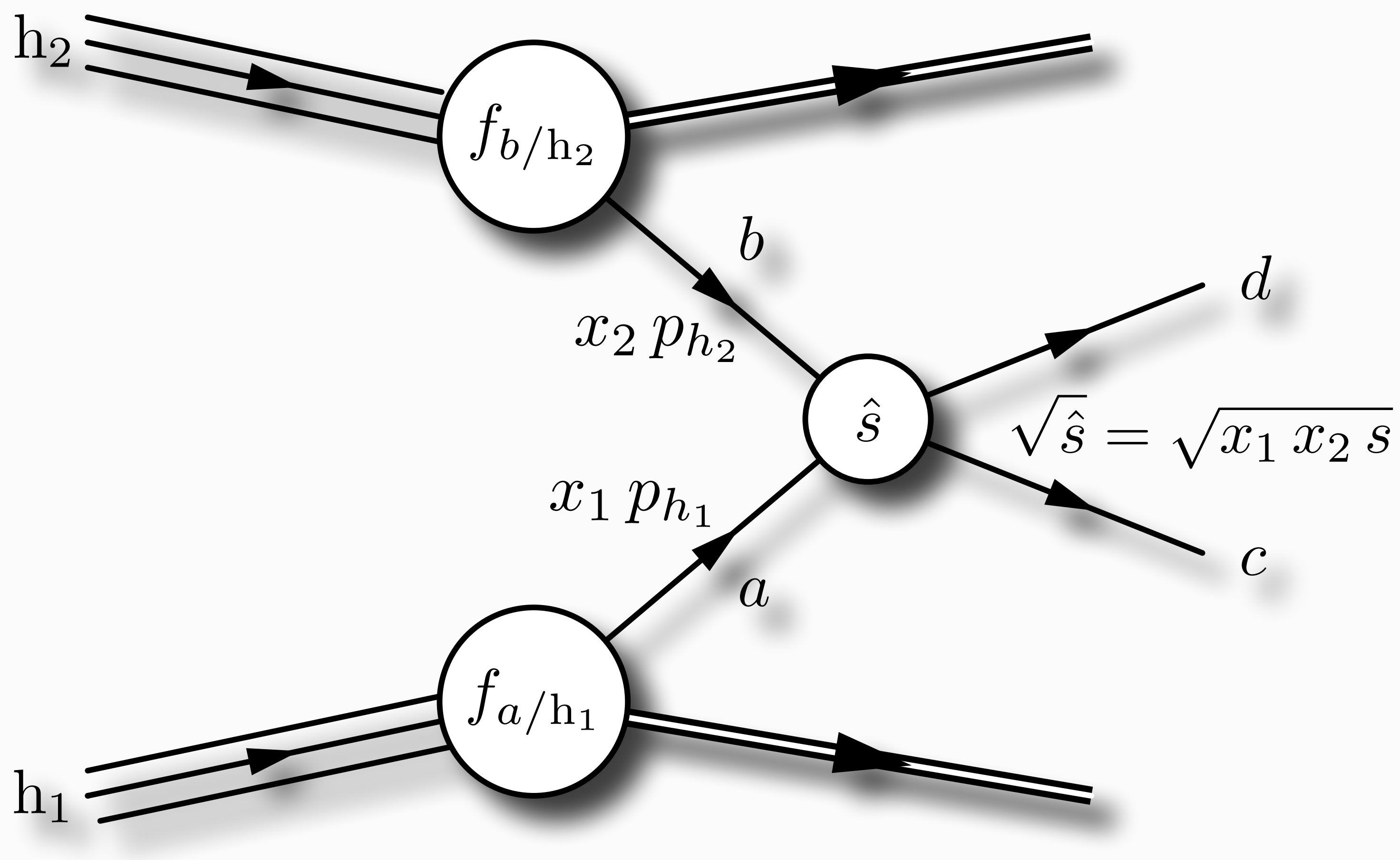






Most of the focus: hard scattering



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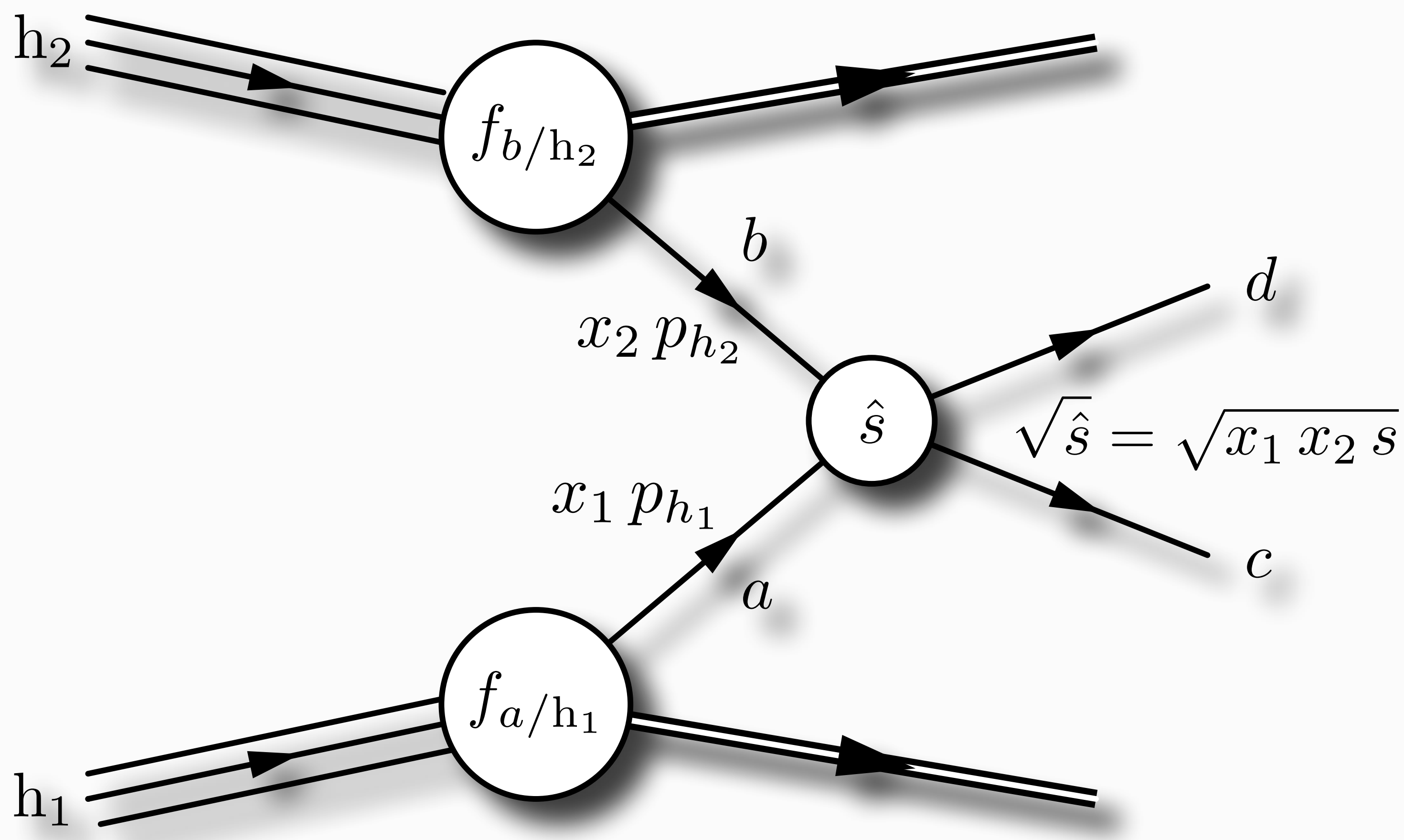

$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

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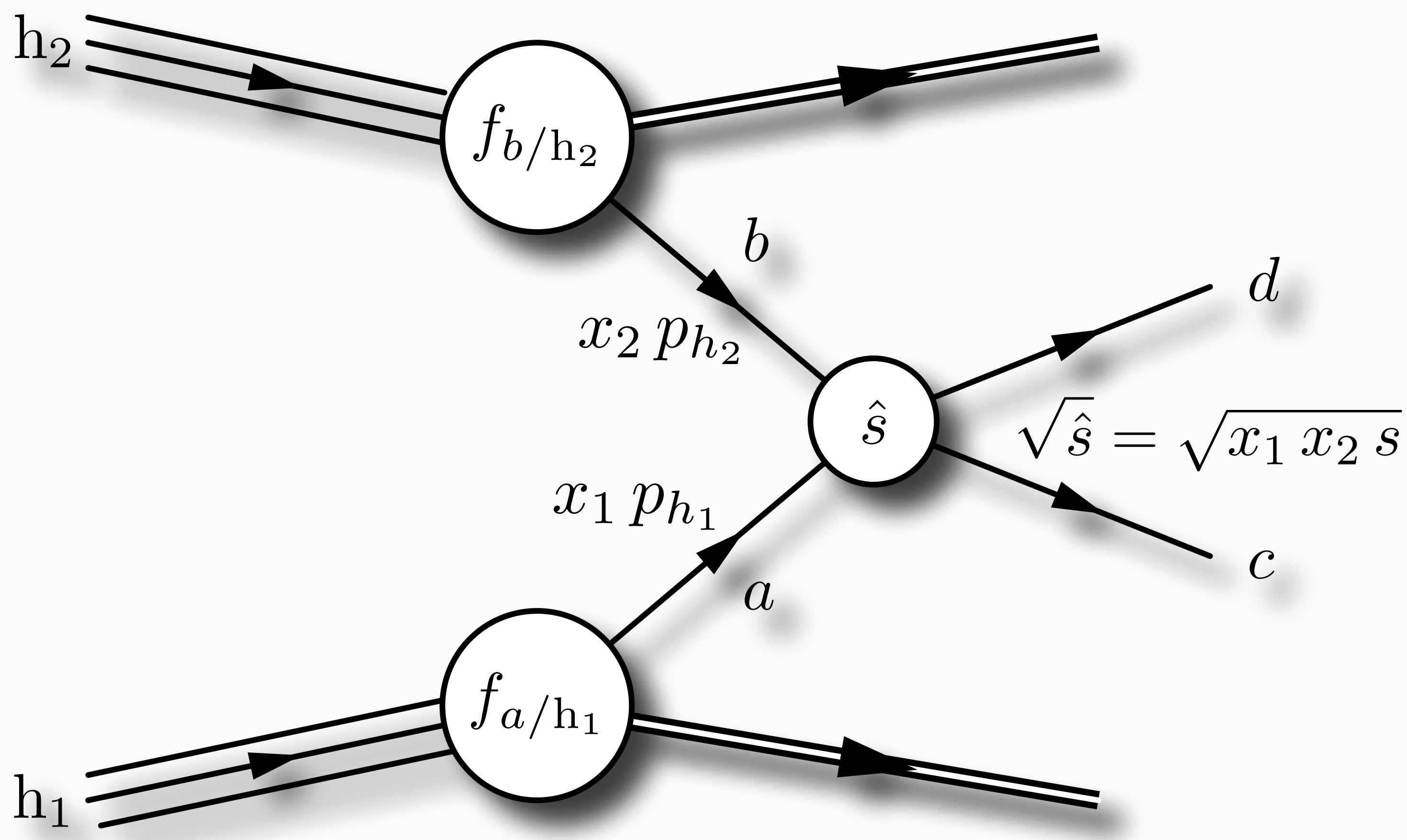

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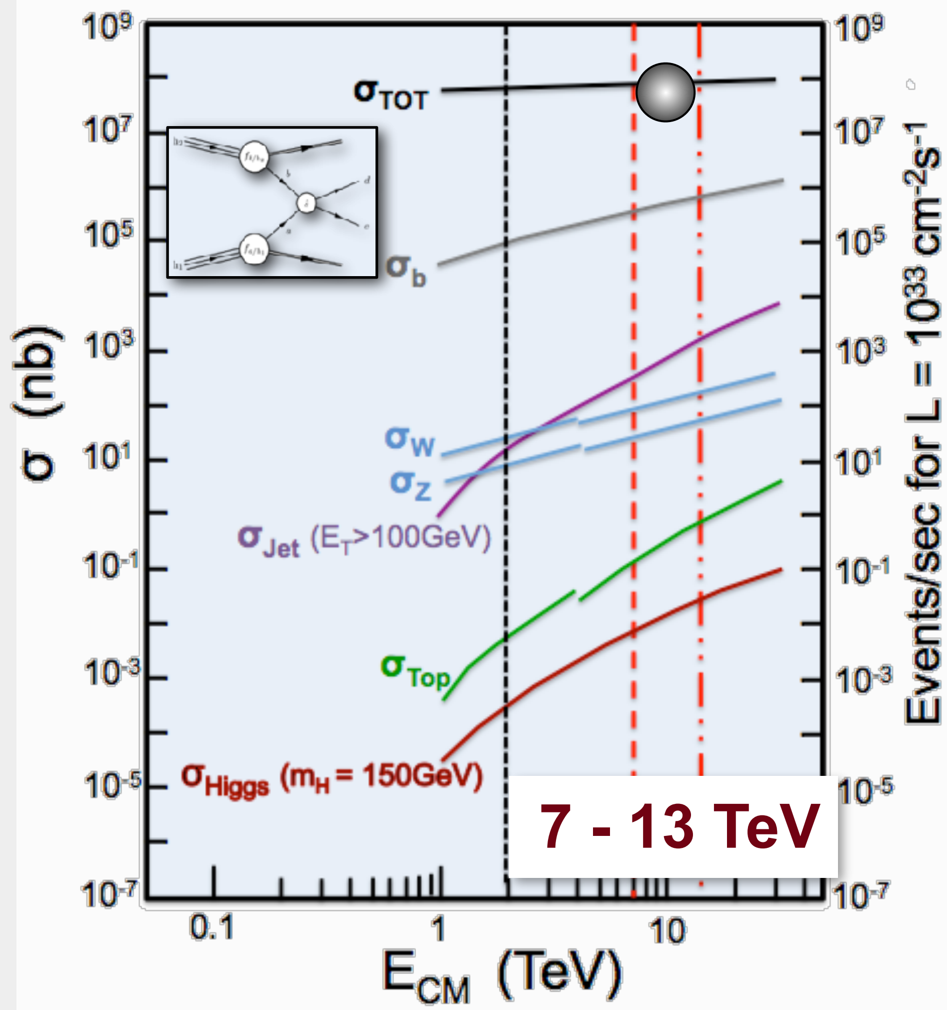
Hard Scattering = processes with large momentum transfer (Q^2)

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



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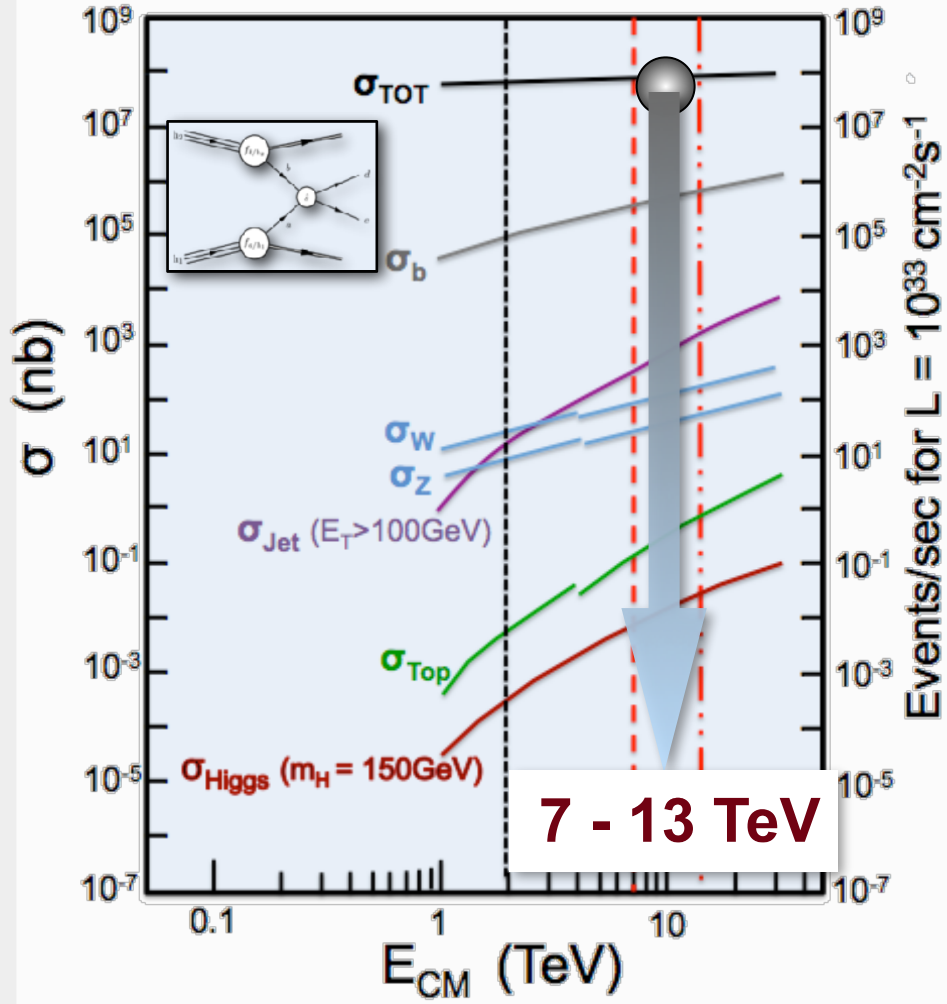

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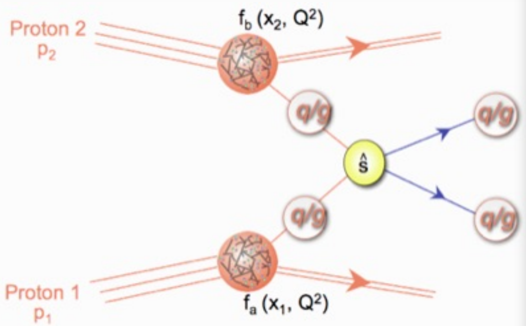

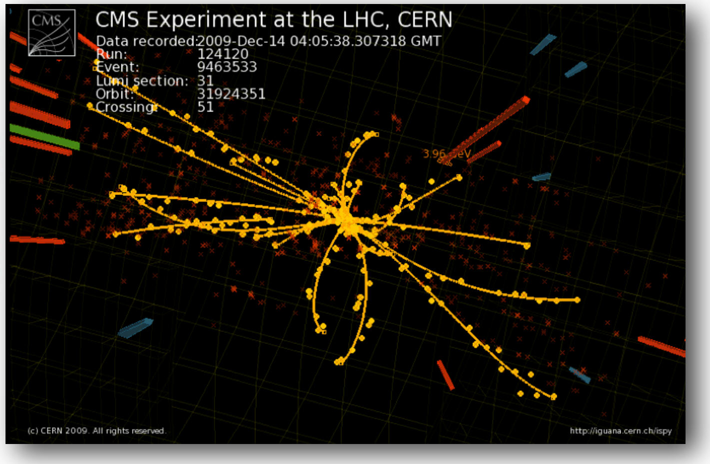

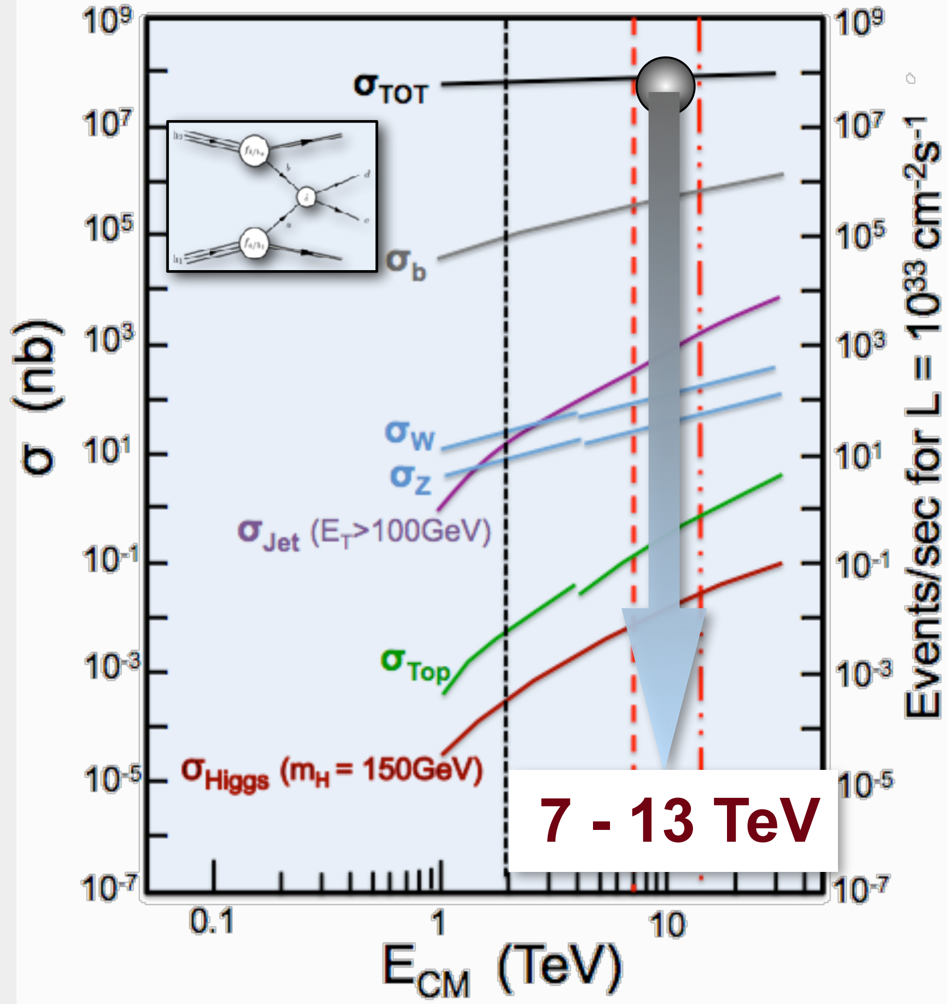

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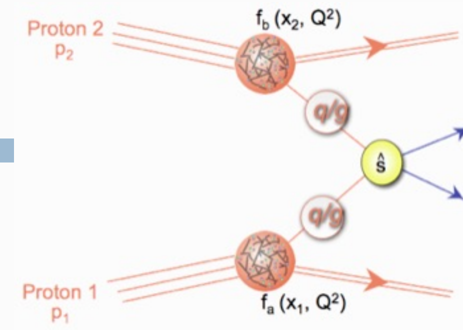

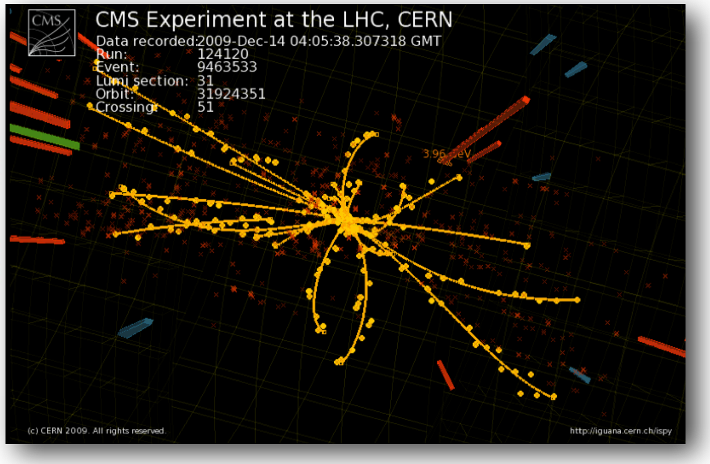

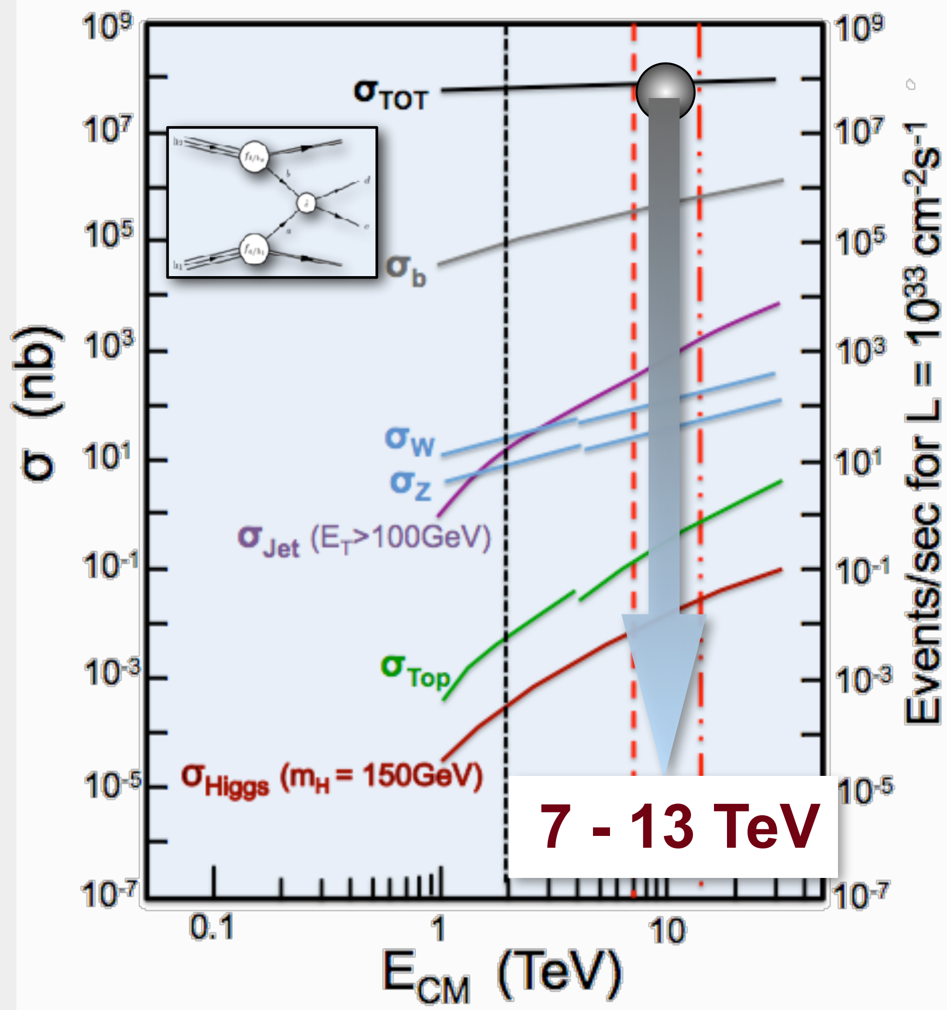

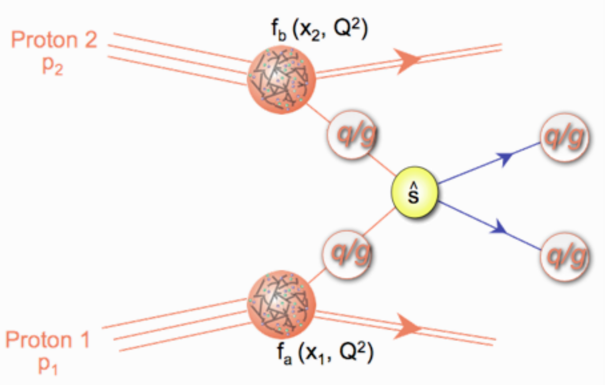

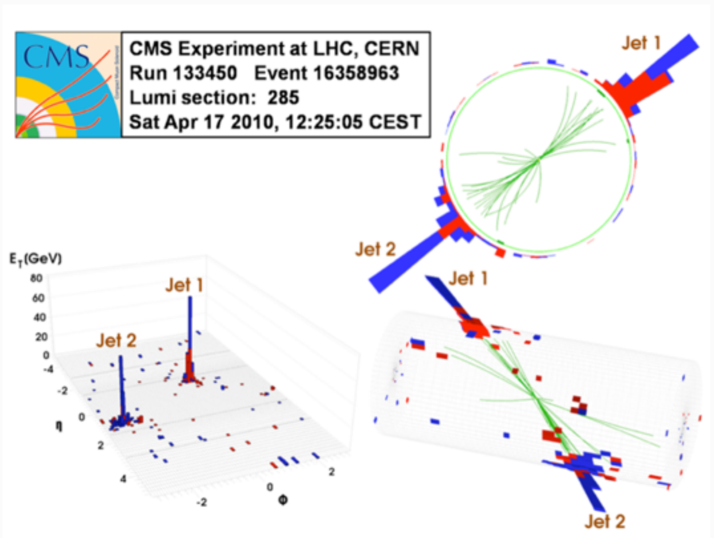

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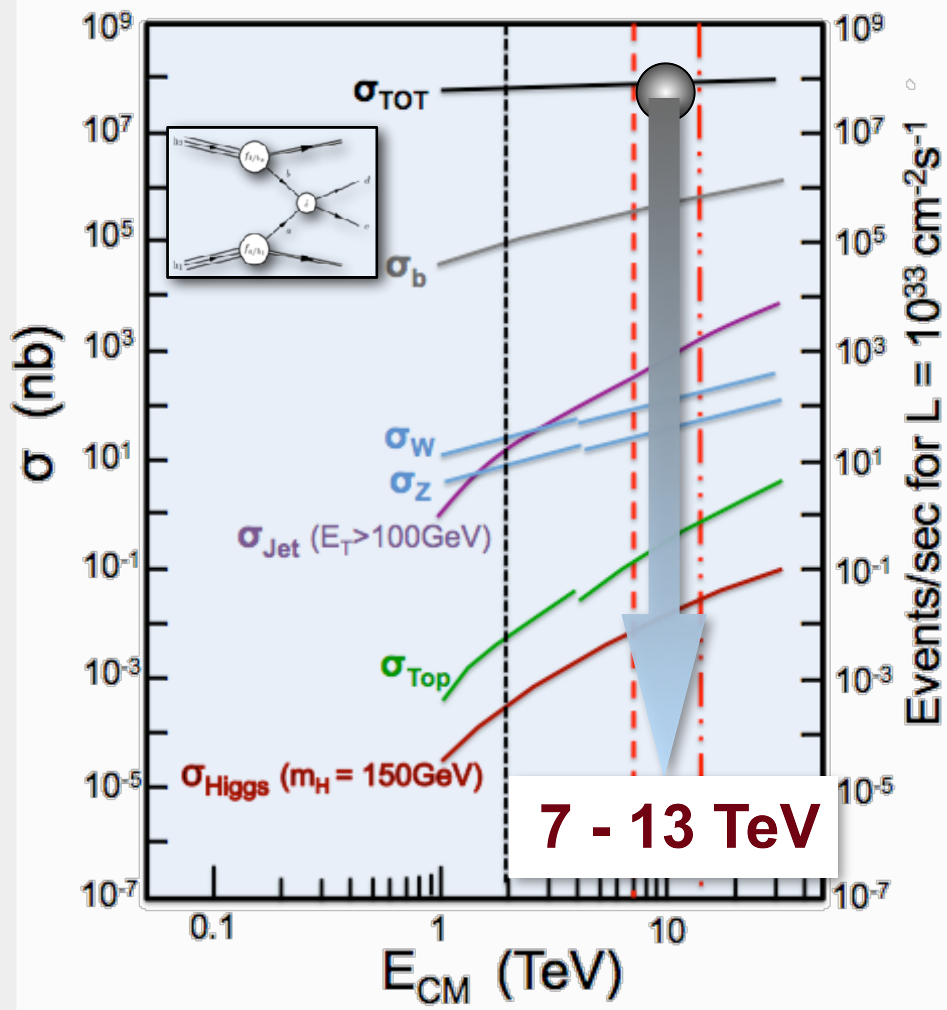

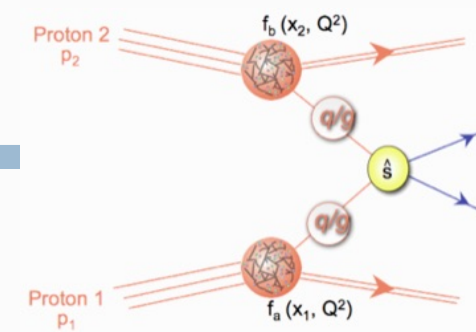

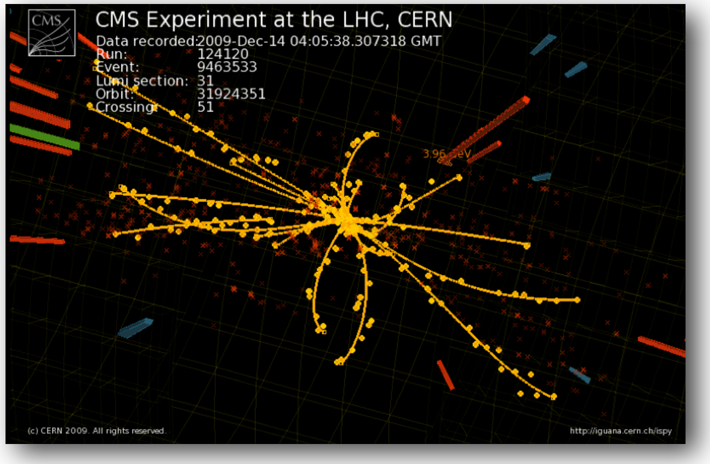

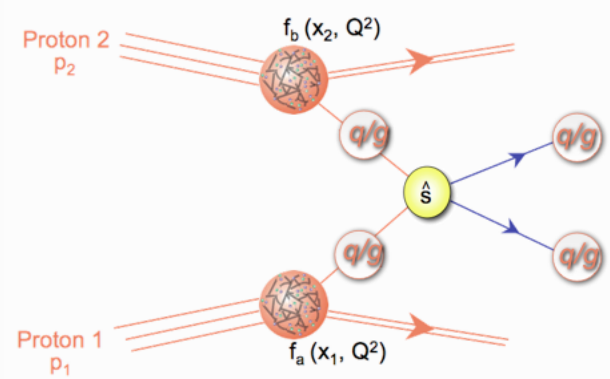

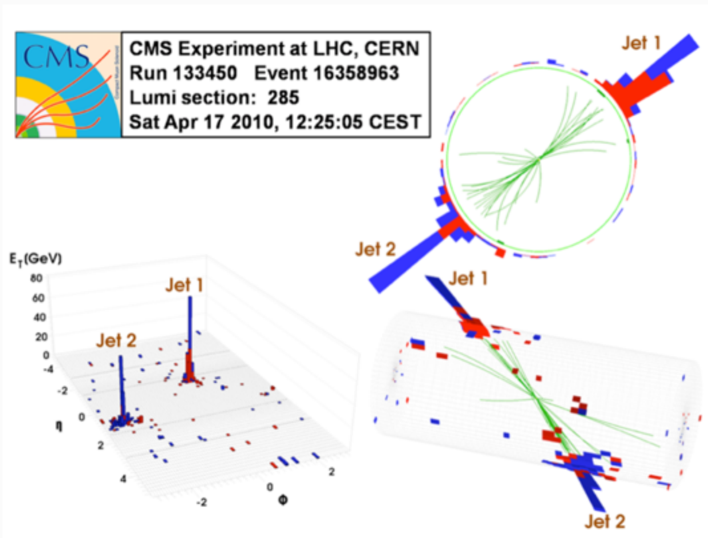

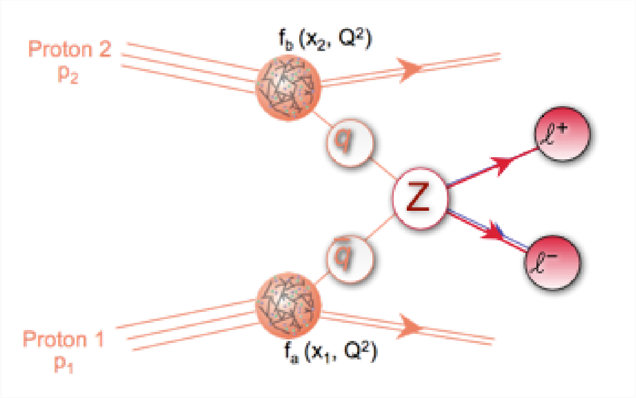

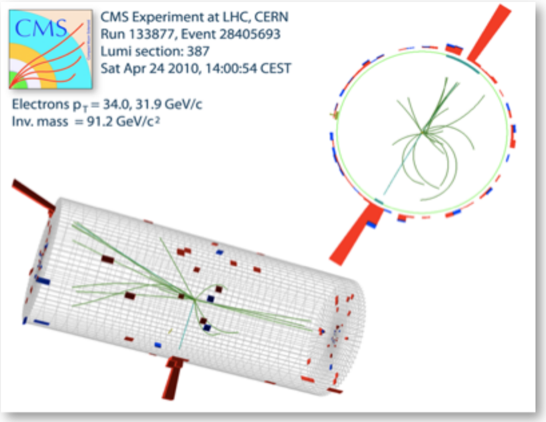

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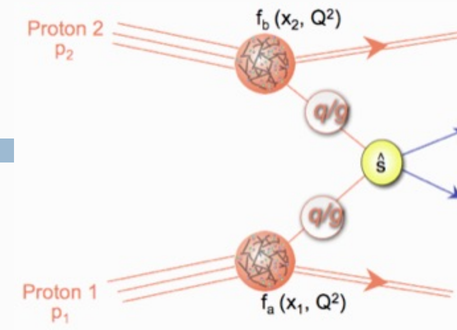

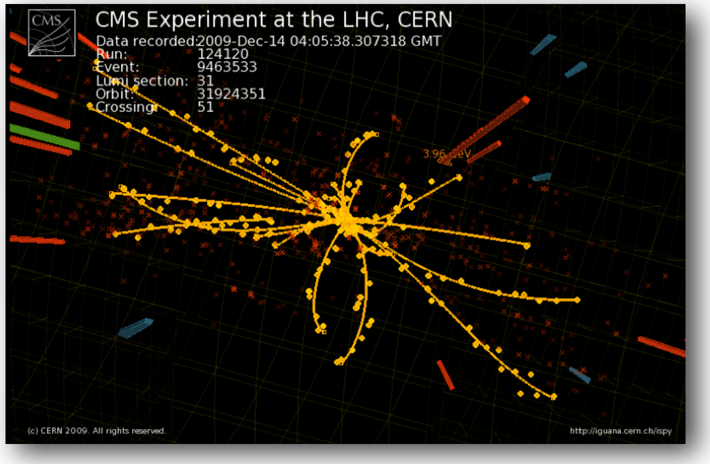

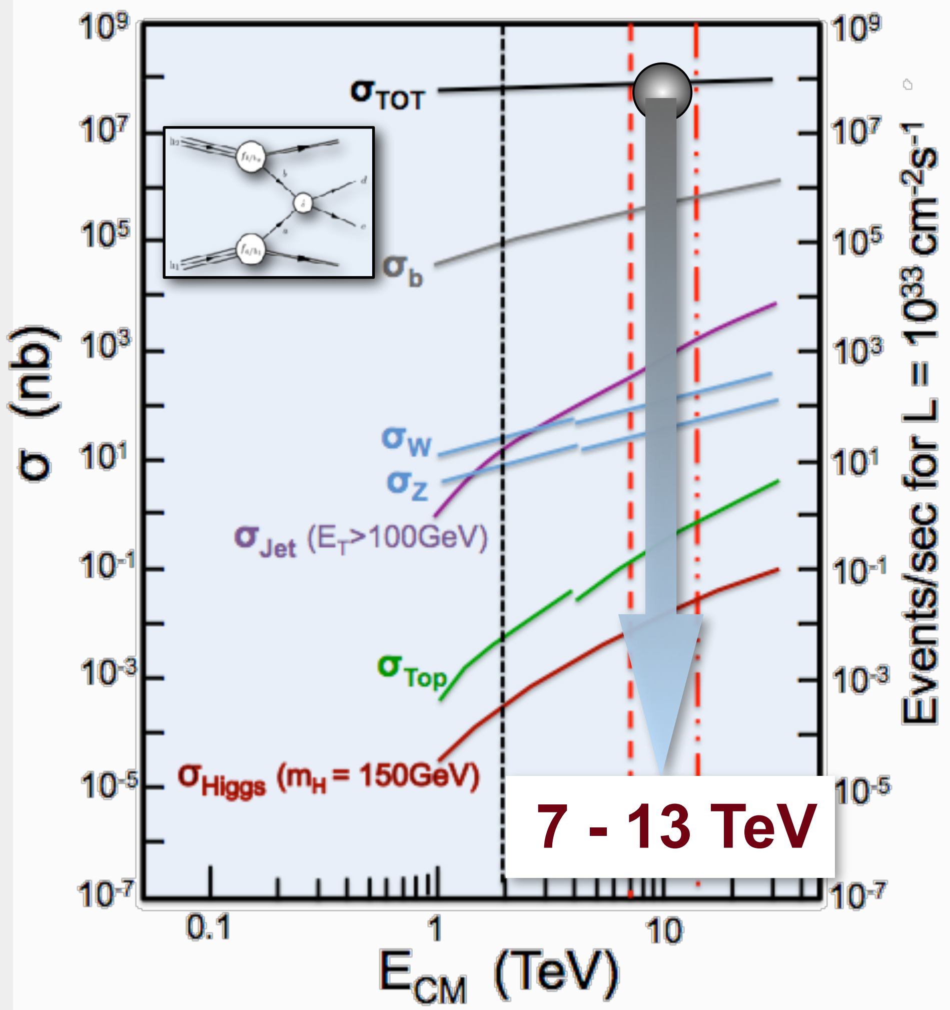

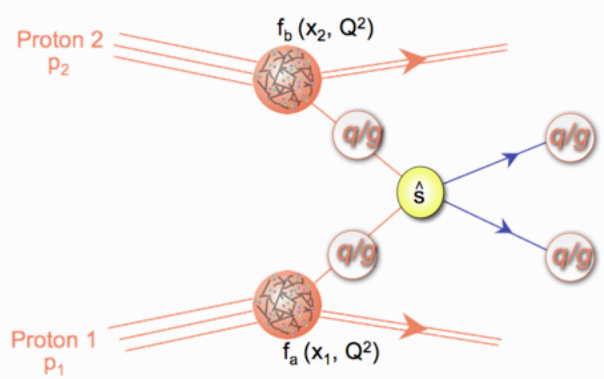

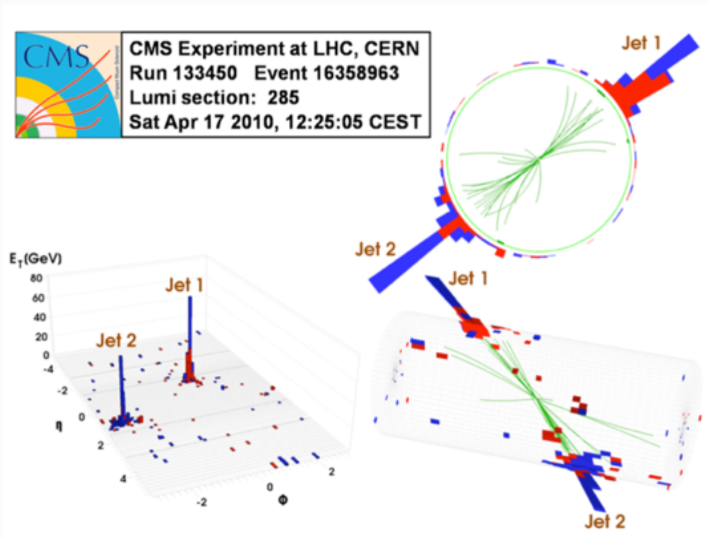

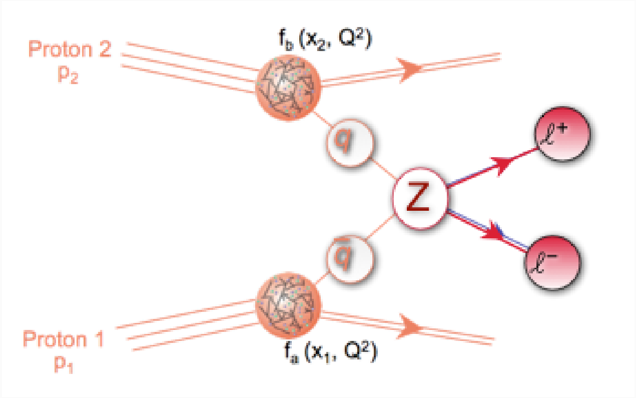

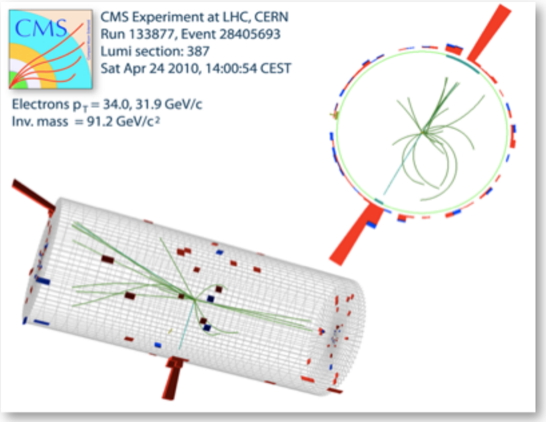

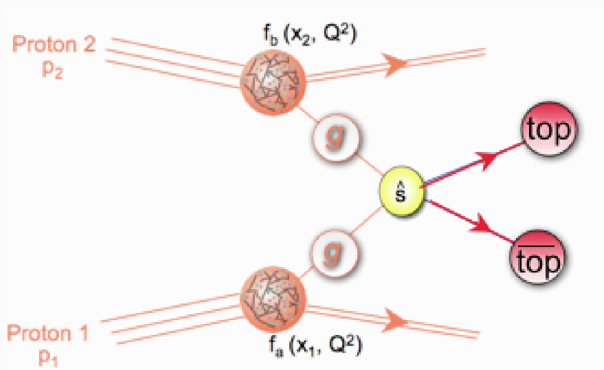

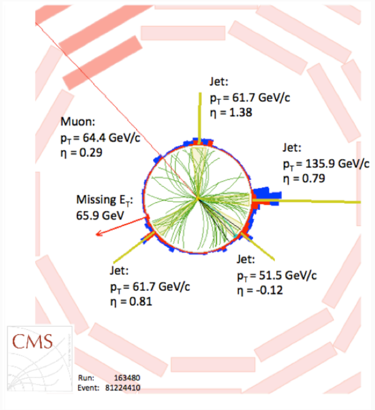

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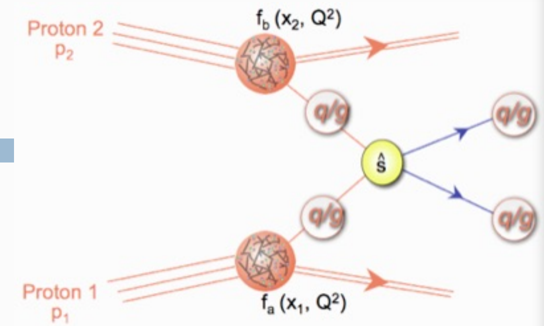
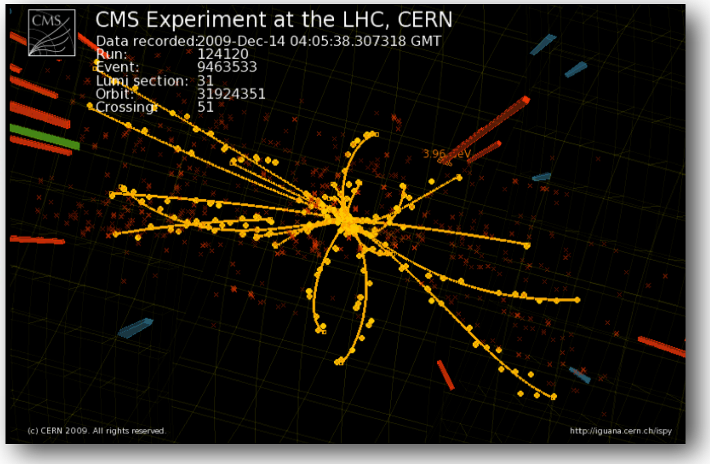
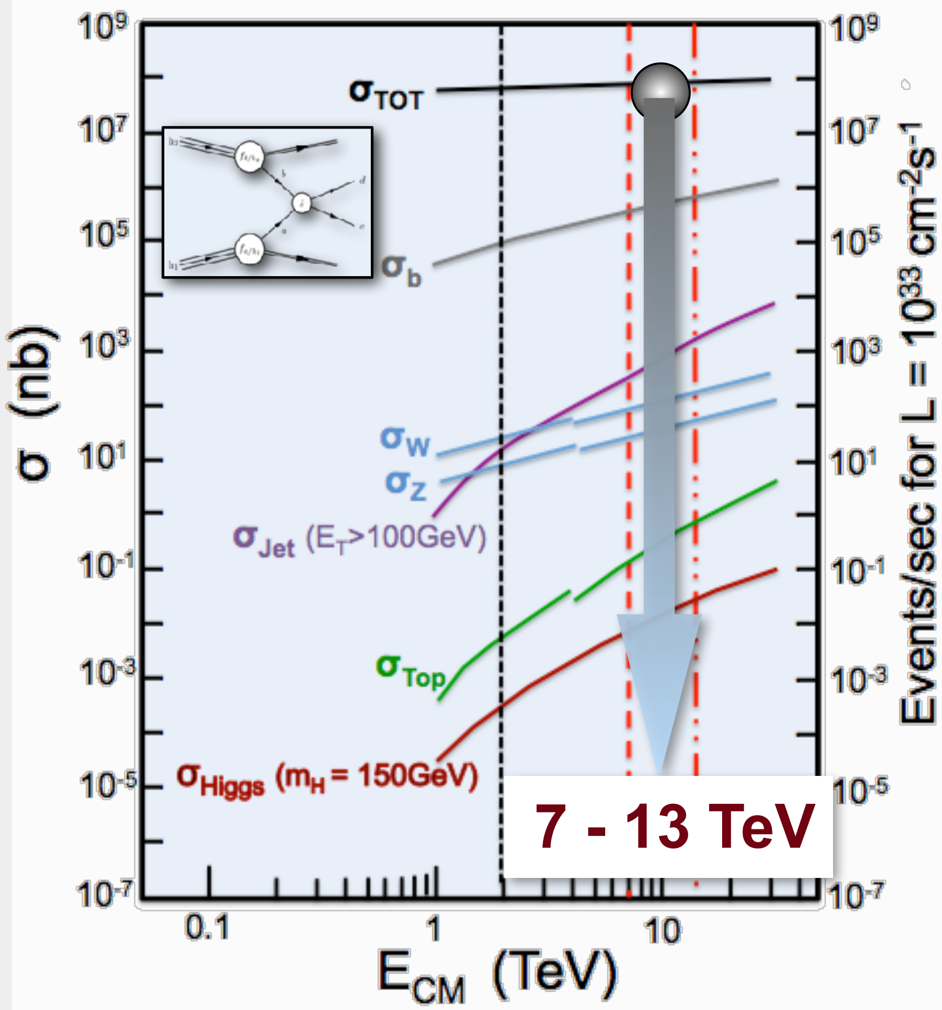
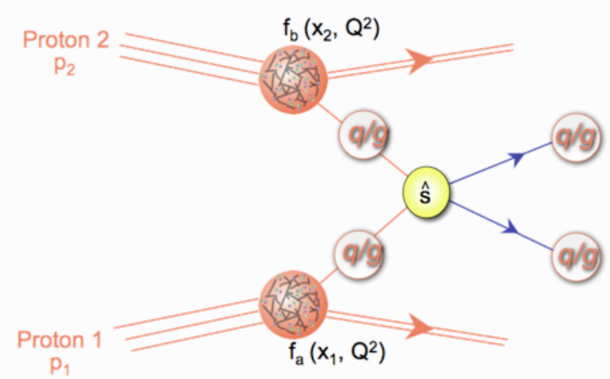
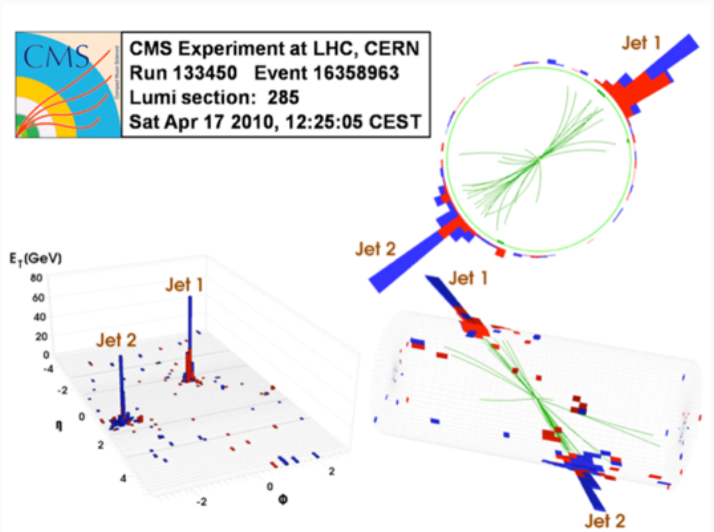
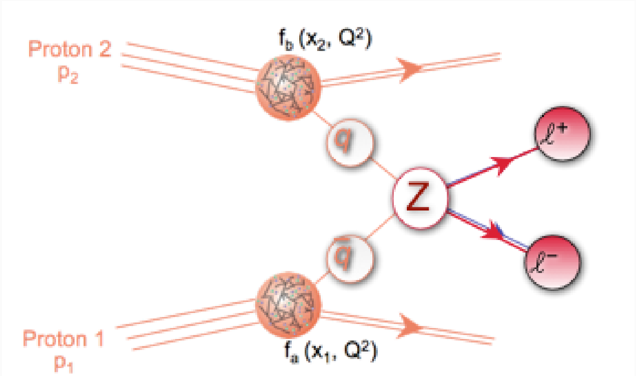


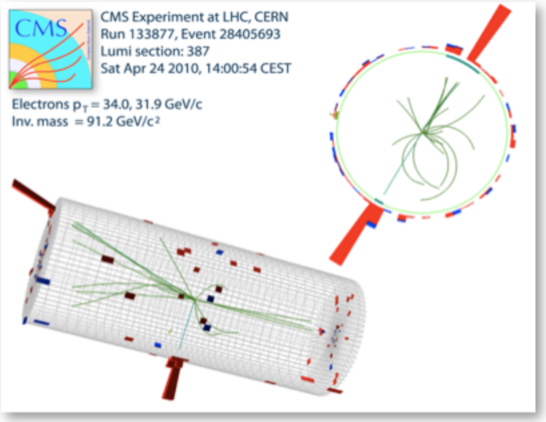


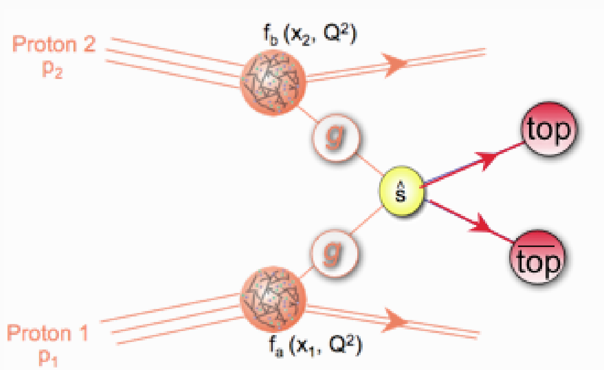


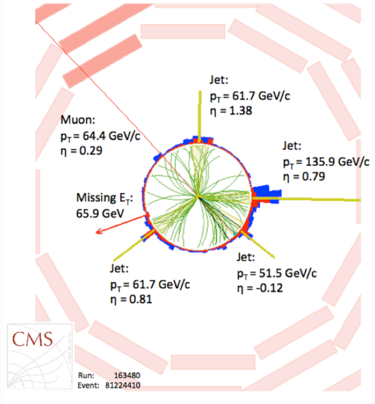


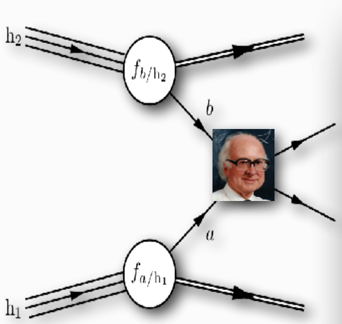


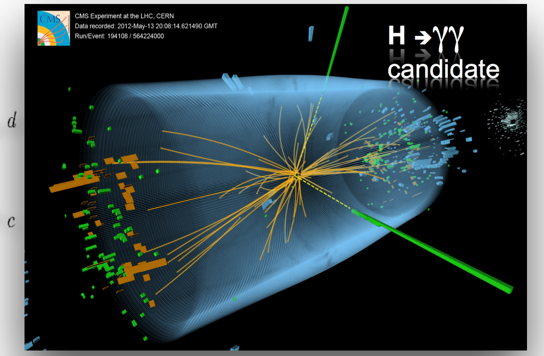




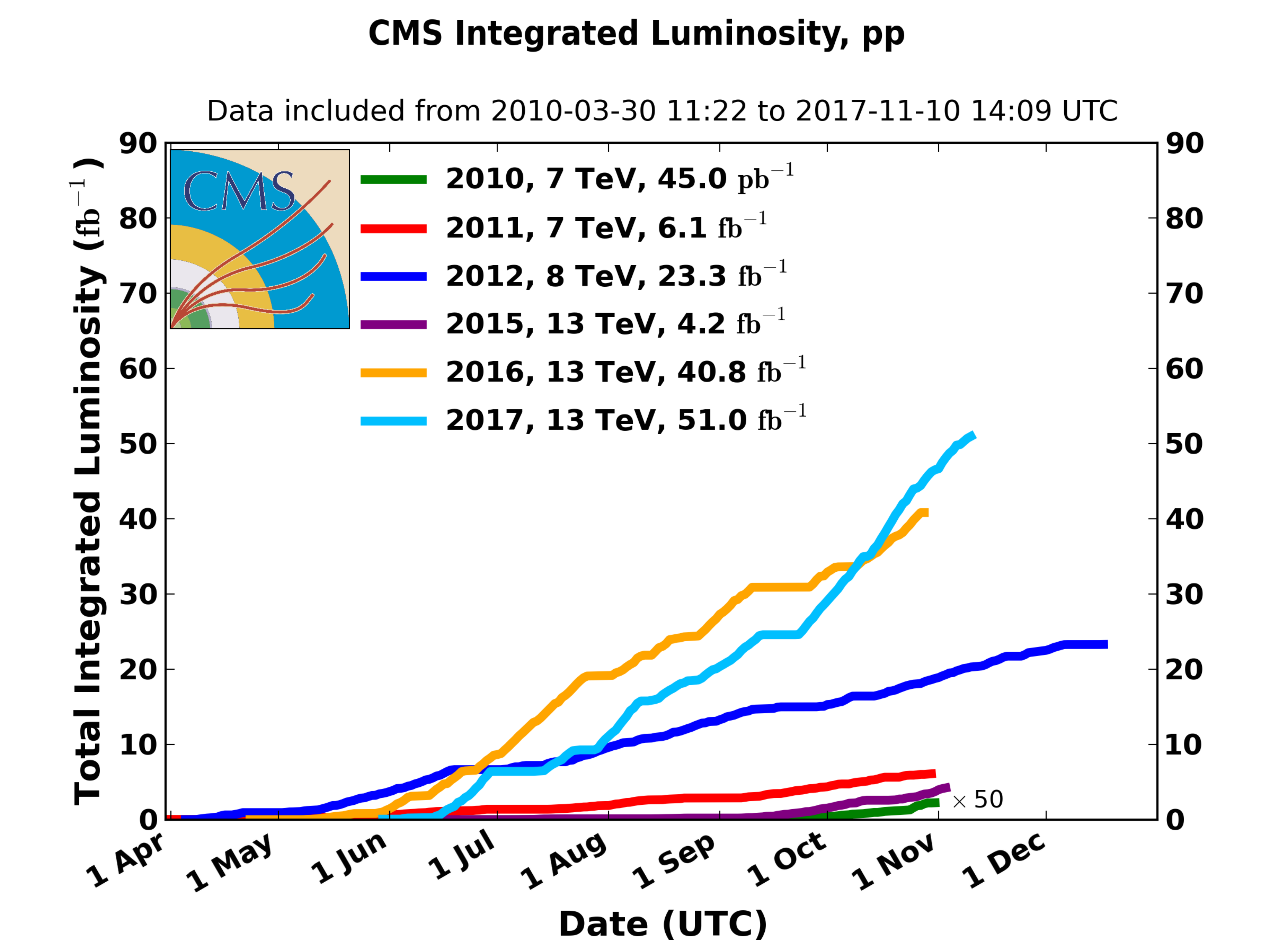








Delivery of (lots of) data



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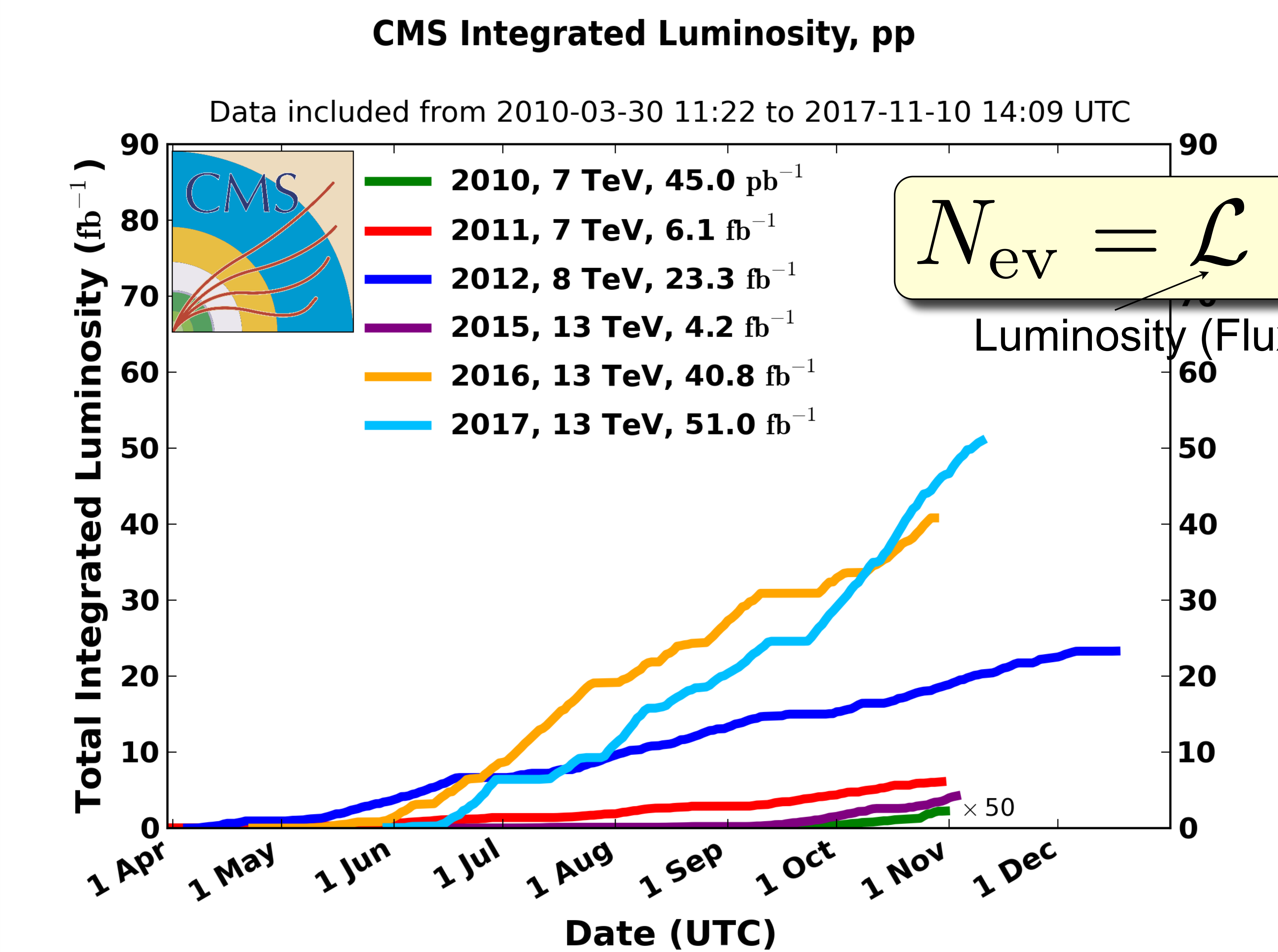
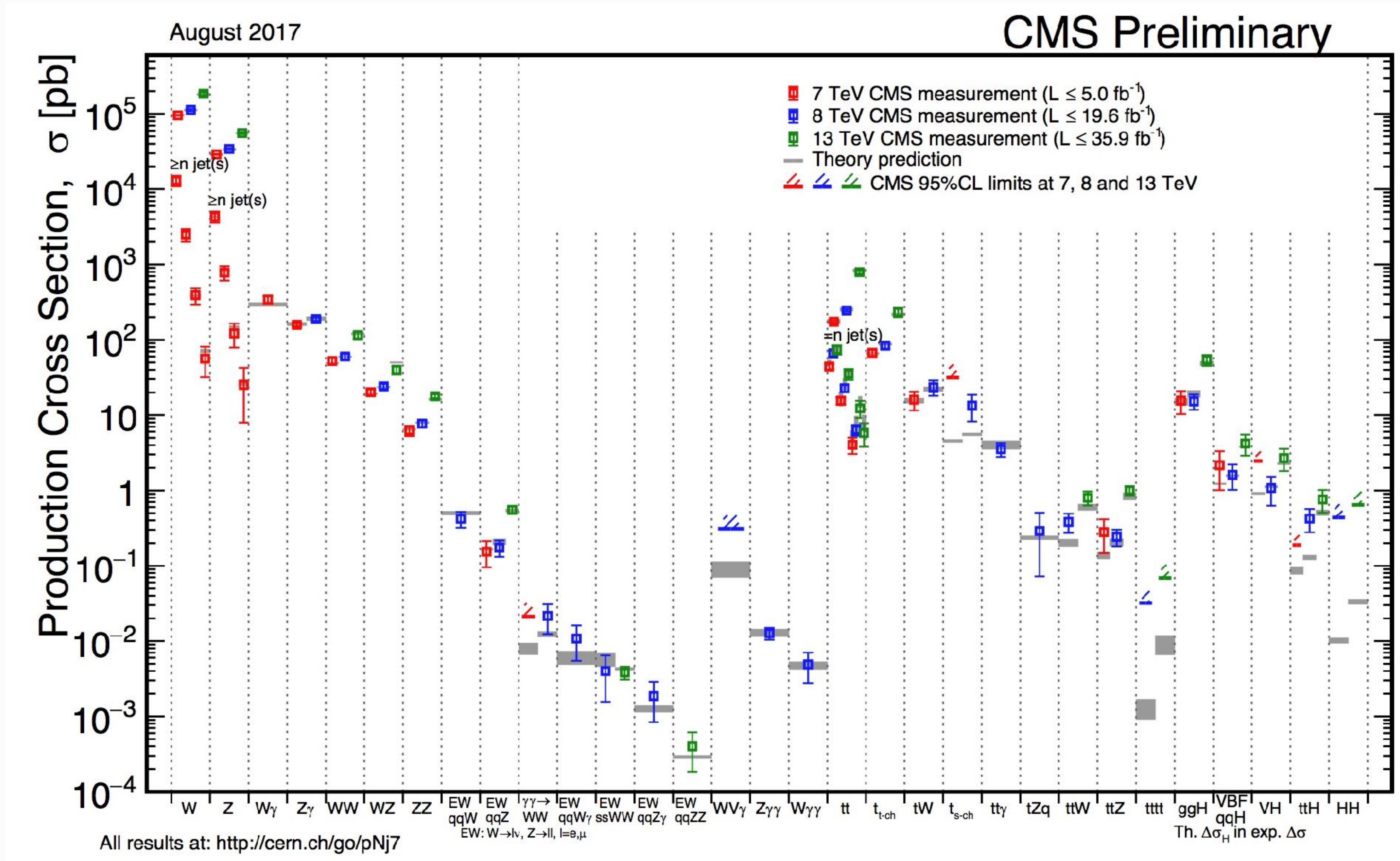


$$N_{\mathrm{ev}} = \mathcal{L} \times \sigma$$

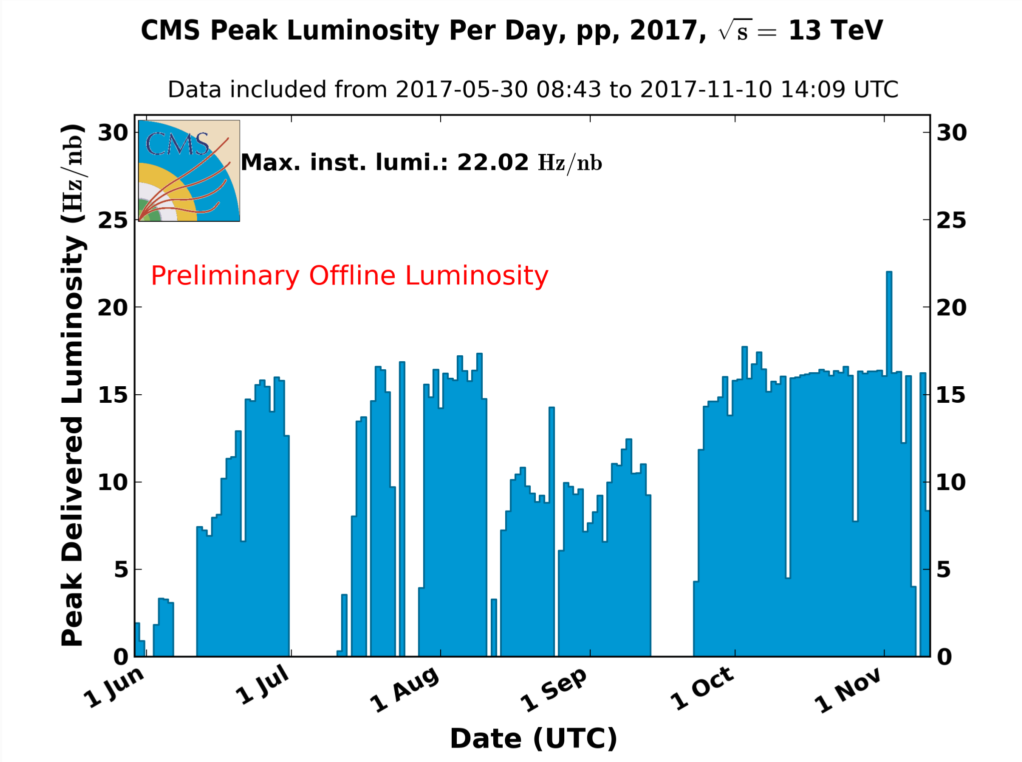
Luminosity (Flux) [cm^{-2}]

Stairway to ….



> 700 publications so far, 132 in 2017 !

Conditions at the LHC

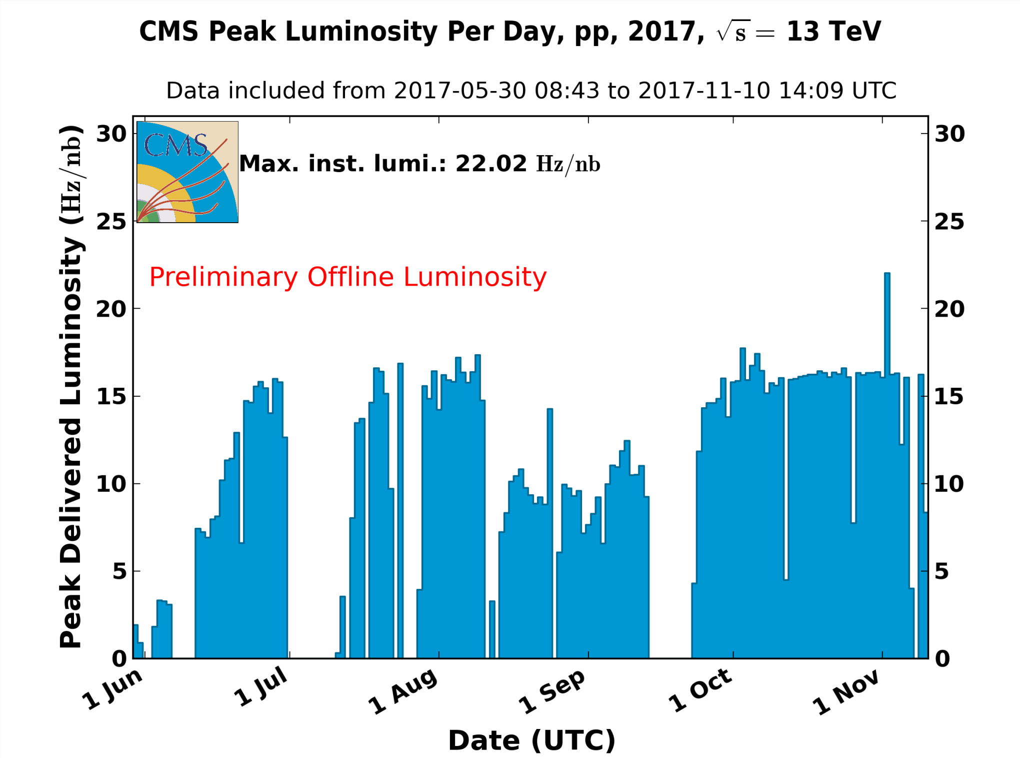


Luminosities of

$L \sim (1.5\text{-}2) \times 10^{34}\ cm^{-2}s^{-1}$

reached already

Conditions at the LHC

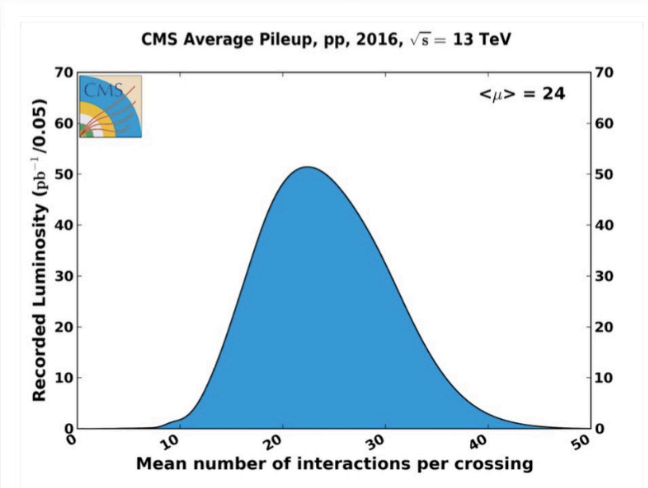


Luminosities of
$L \sim (1.5\text{-}2) \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
reached already

Number of simultaneous proton-proton collisions per bunch crossing:

L x total cross section x bunch separation time
$\sim (1.5\text{-}2) \times 10^{34}\ \mathrm{cm^{-2}s^{-1}} \times 100\ \mathrm{mb} \times 25\ \mathrm{ns} \sim$

38 - 50 !



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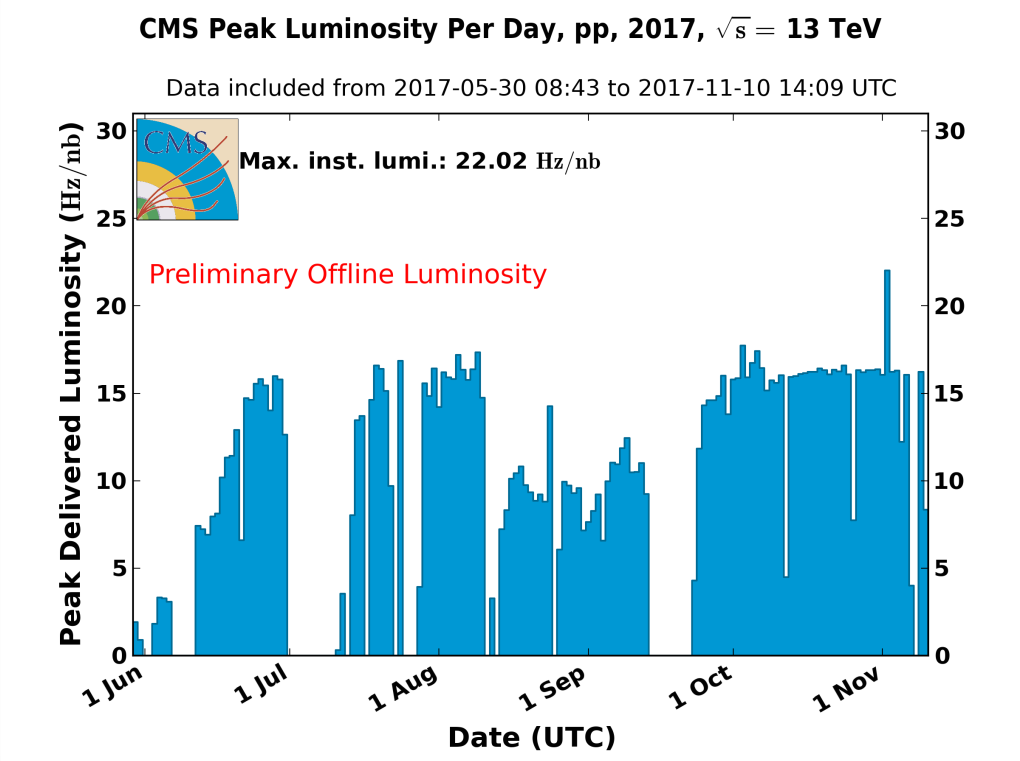

Luminosities of
L ~ (1.5-2) x 10^{34} cm^{-2}s^{-1}
reached already

Number of simultaneous proton-proton collisions per bunch crossing:

L x total cross section x bunch separation time
~ (1.5-2) x 10^{34} cm^{-2}s^{-1} x 100 mb x 25 ns ~

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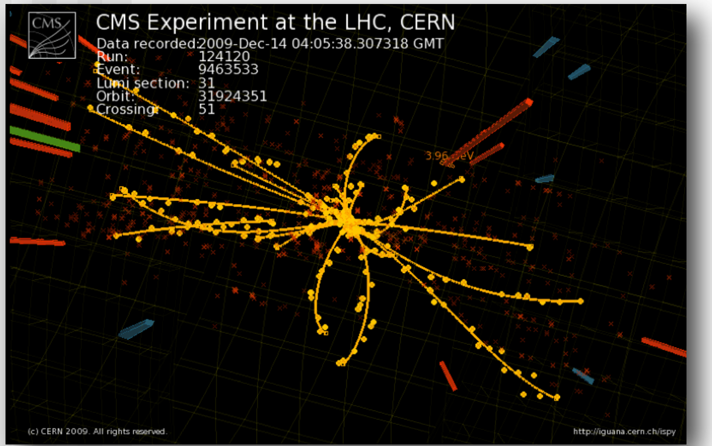
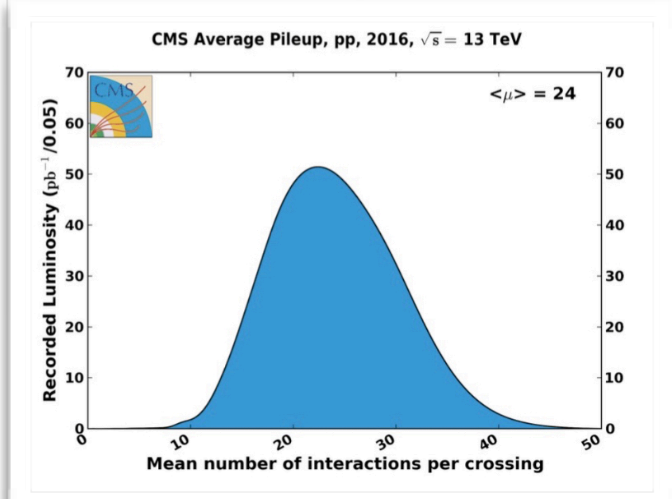


Each of these:
~ 6 charged particles per unit rapidity,
over range of +- 5 units in rapidity:
O(1000) particles per collision !!



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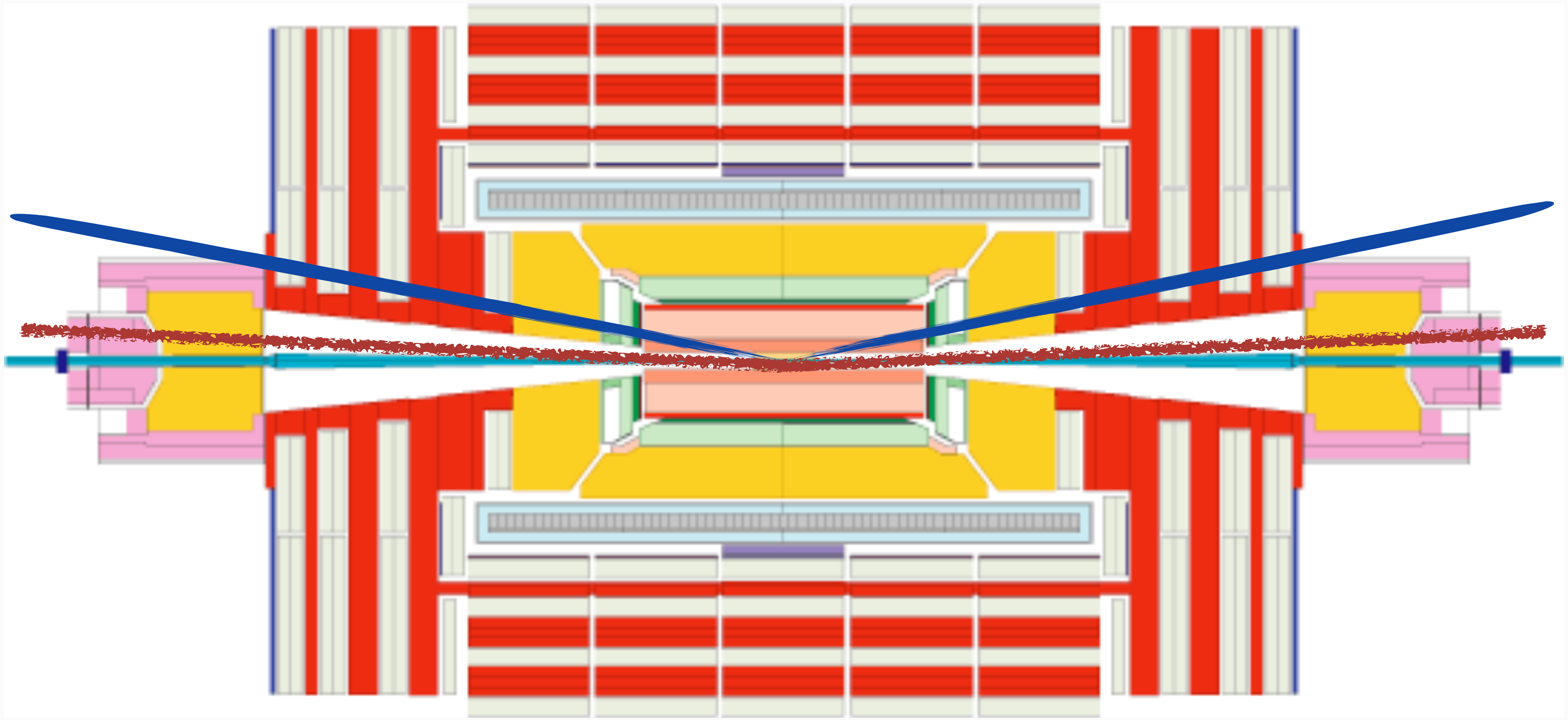
Typical detector acceptance



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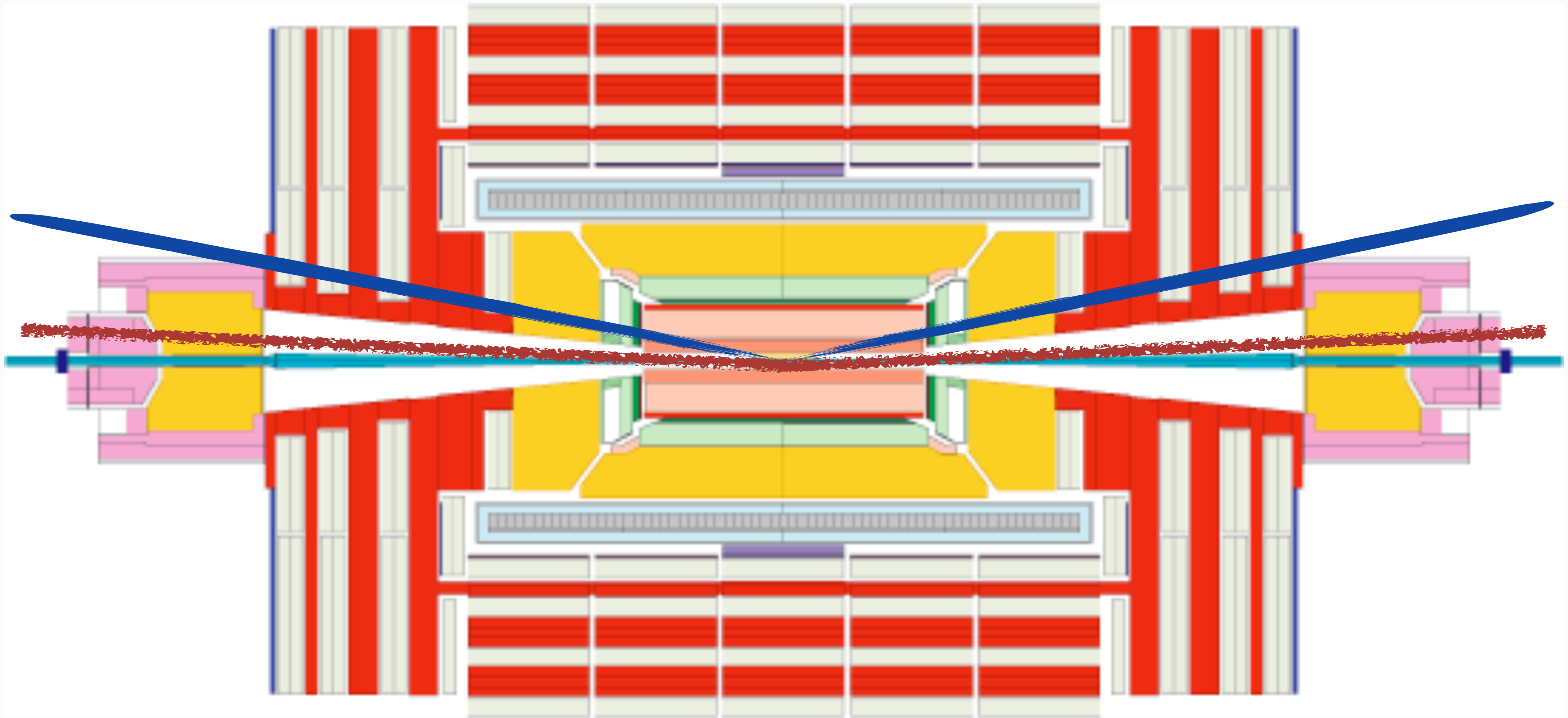

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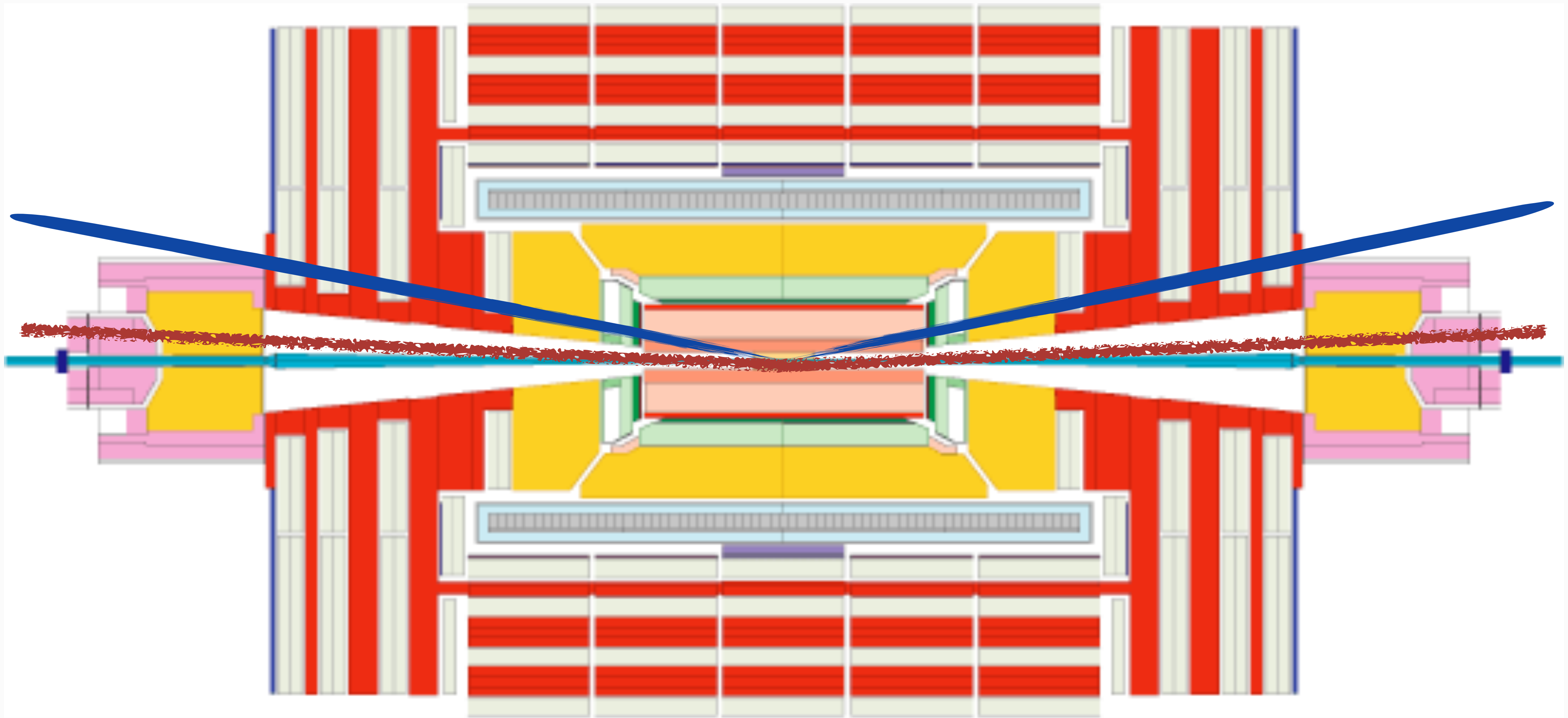

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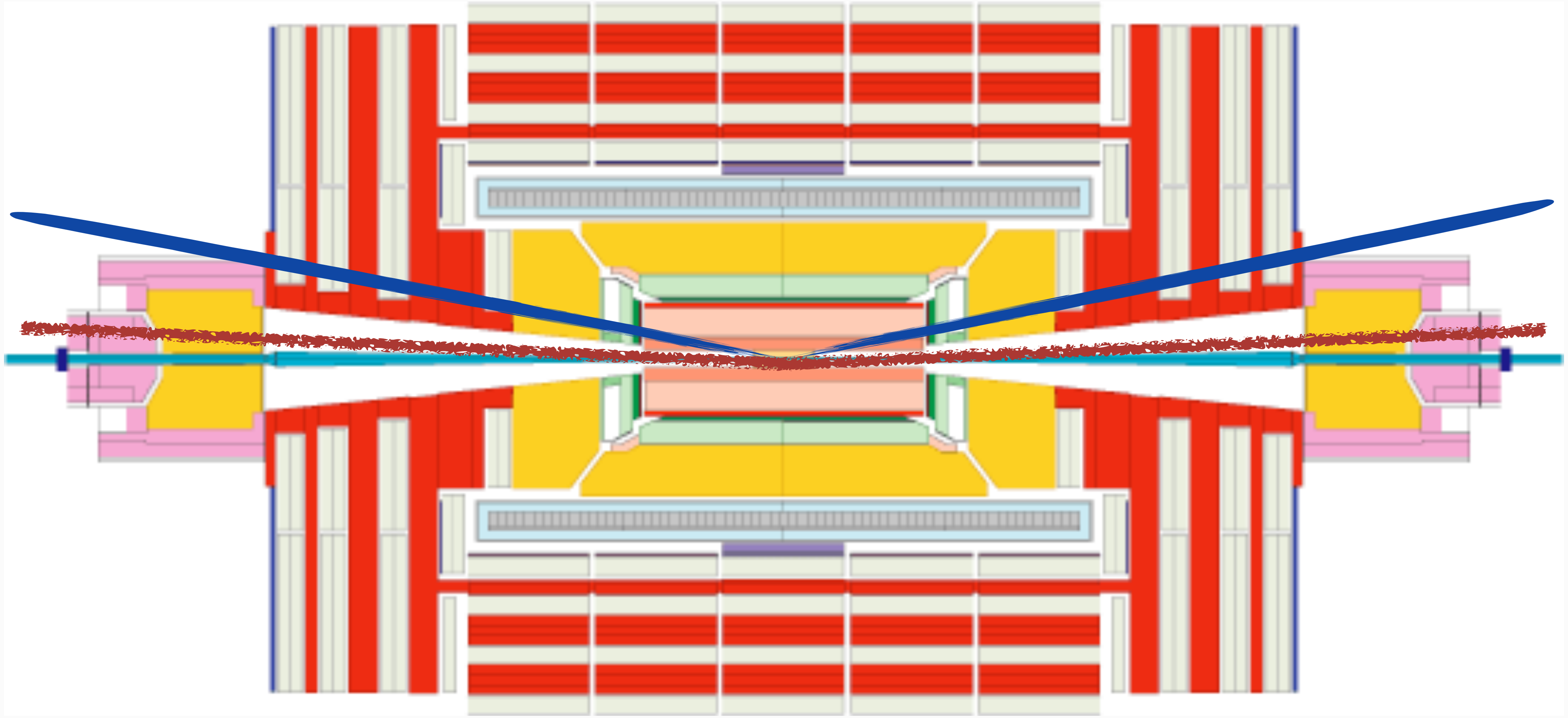

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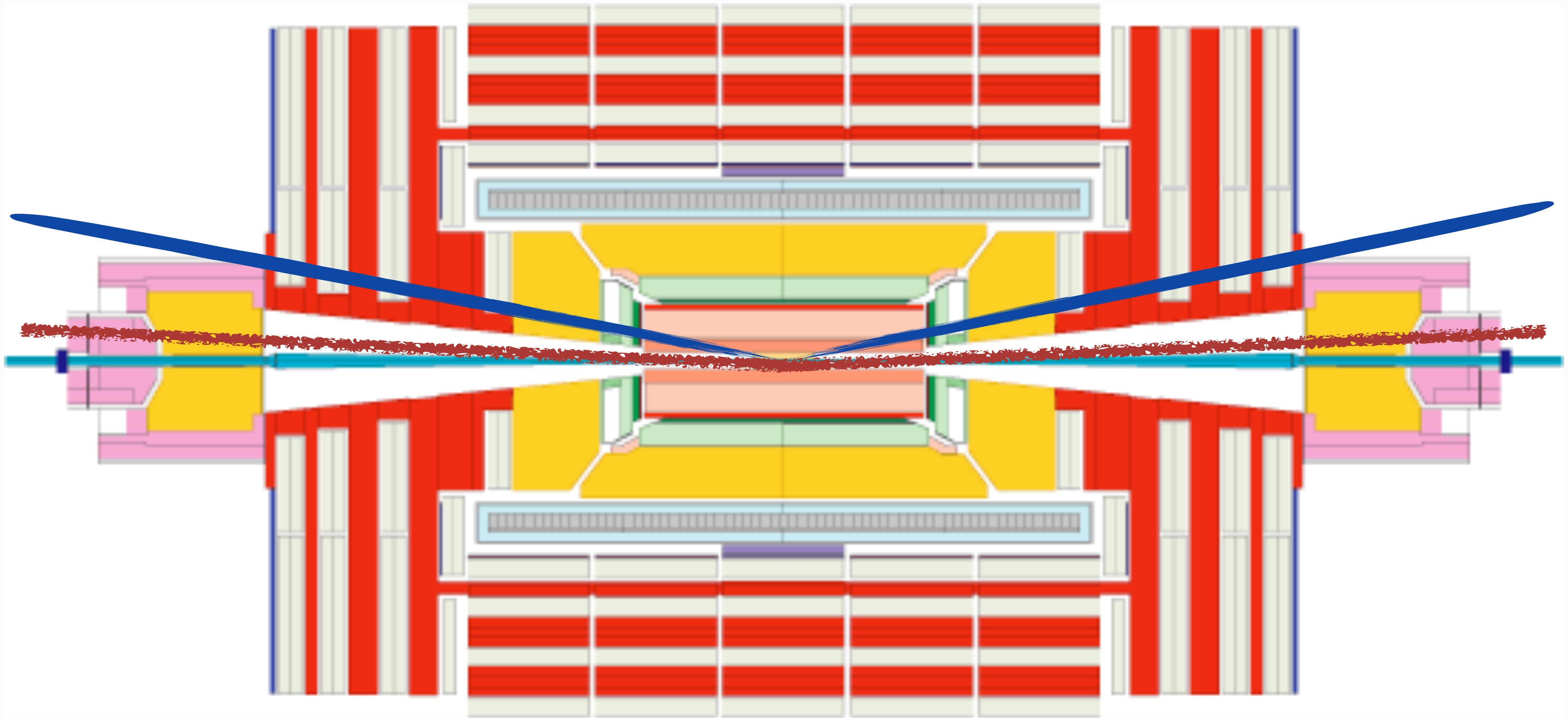

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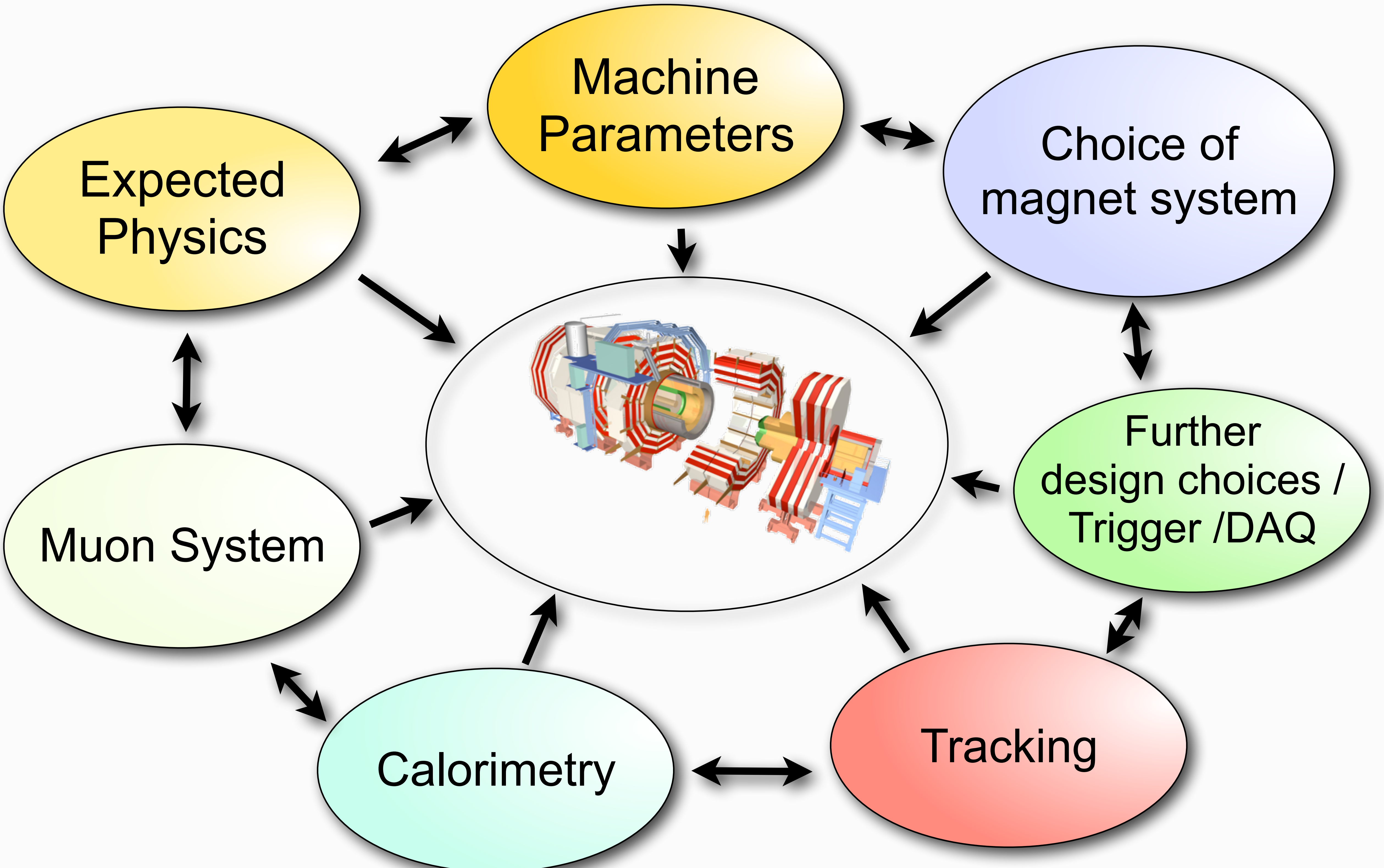
How to design your detector



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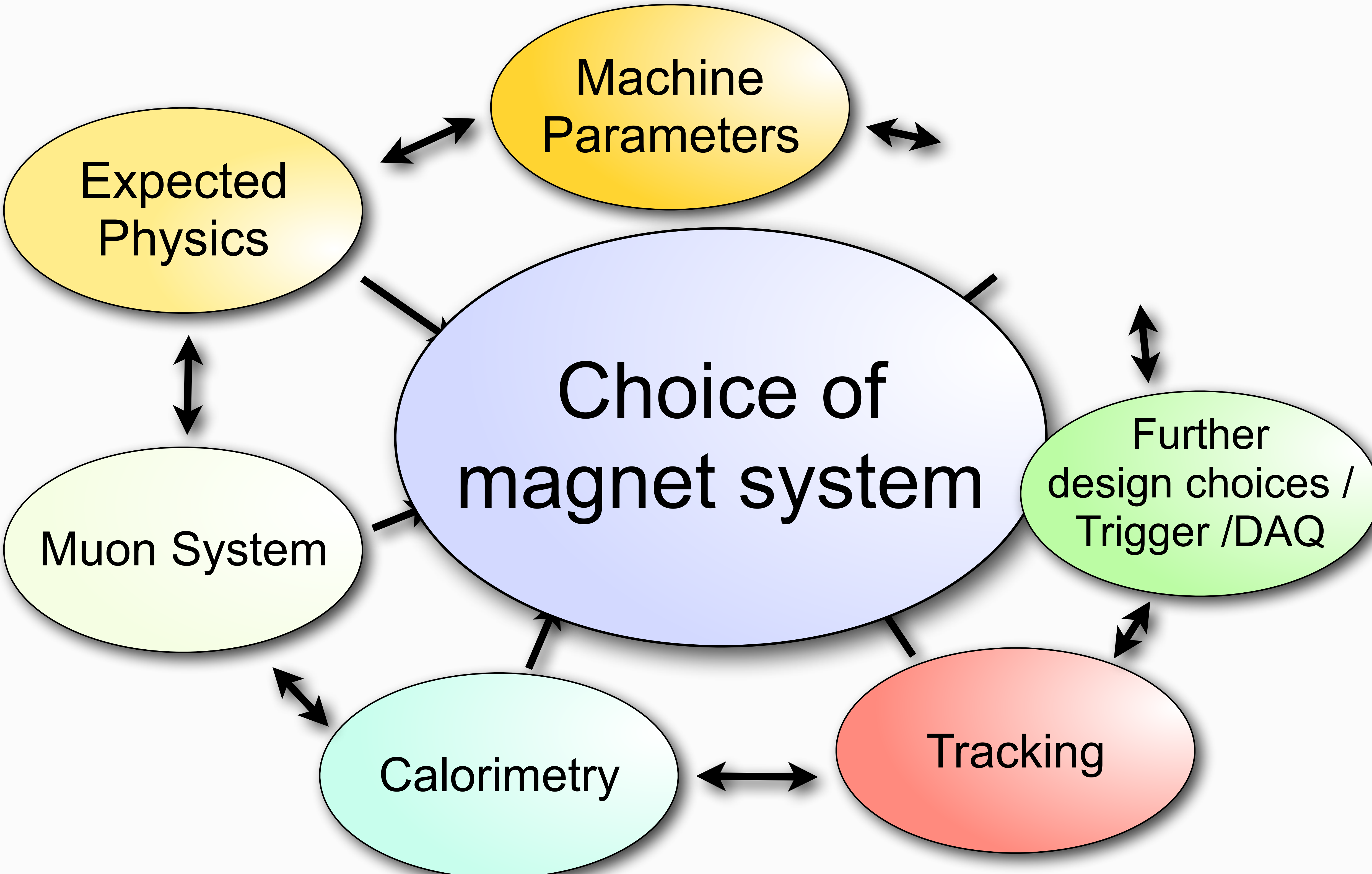

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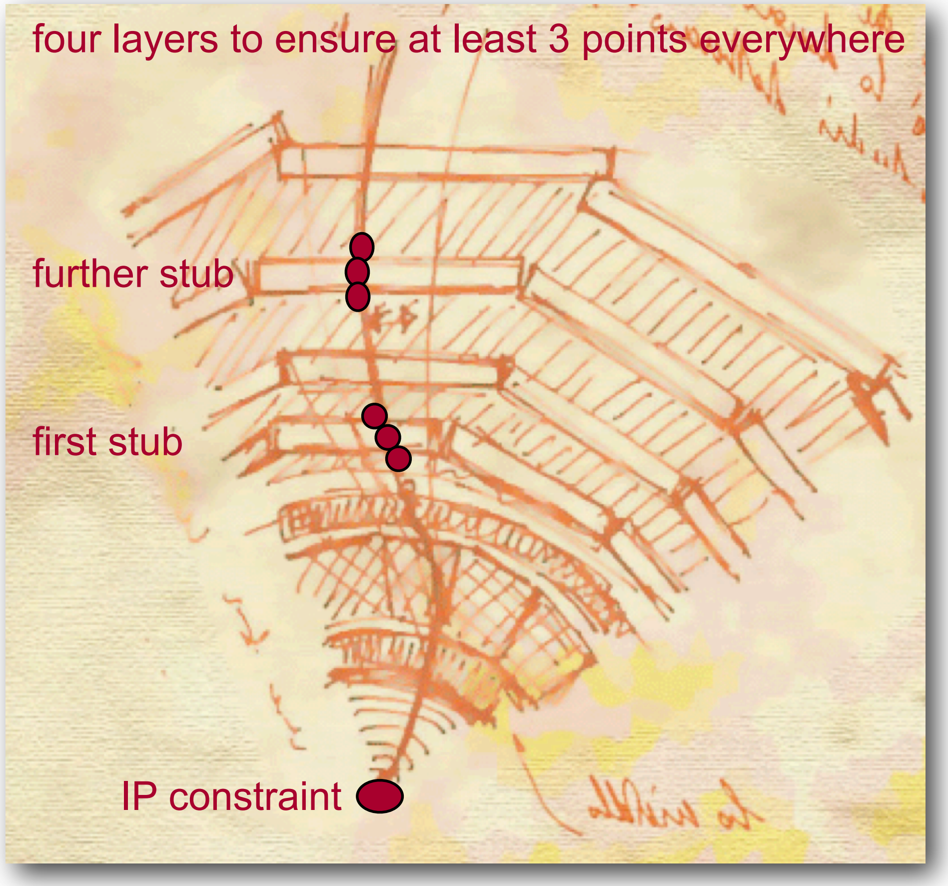

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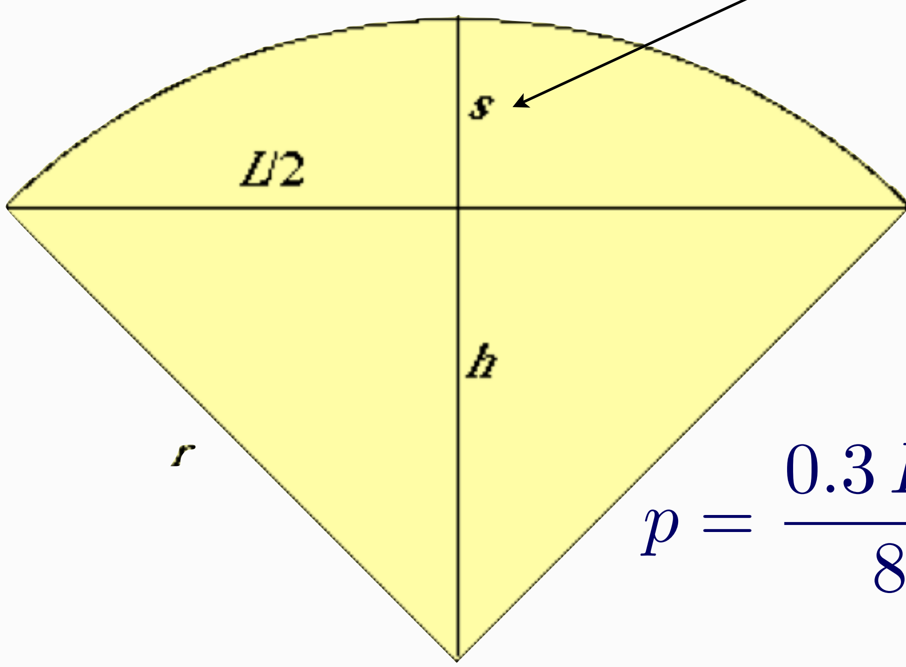
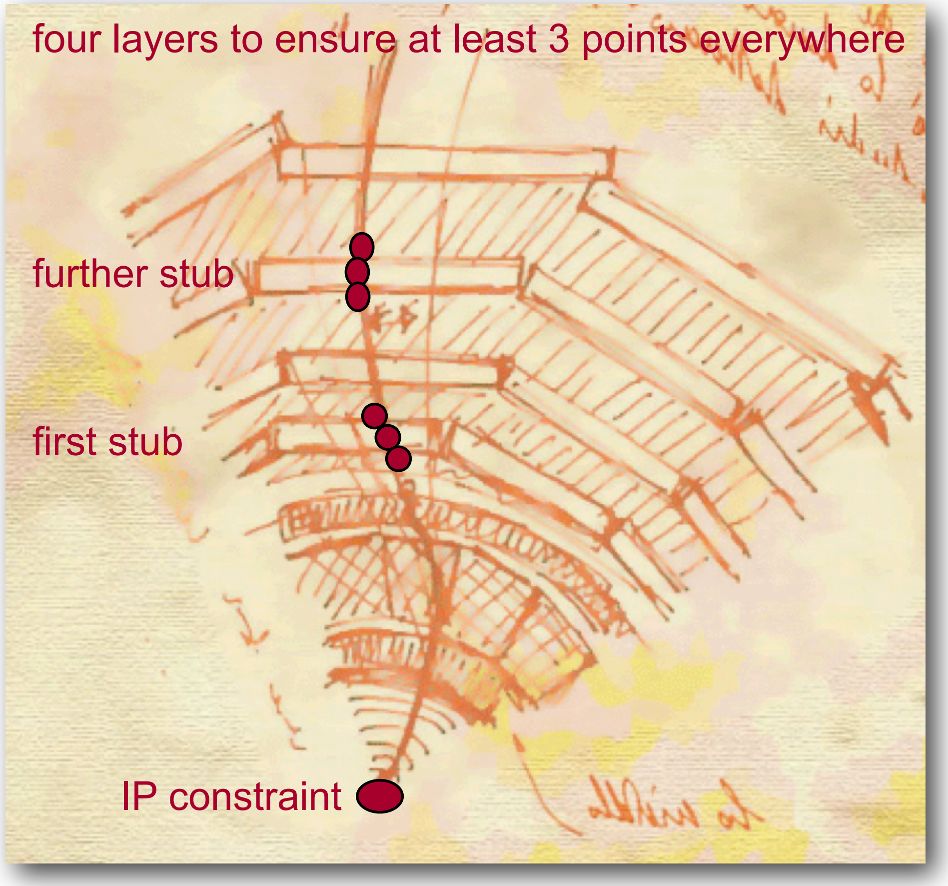


$$p = \frac{0.3\, L^2 B}{8s}$$



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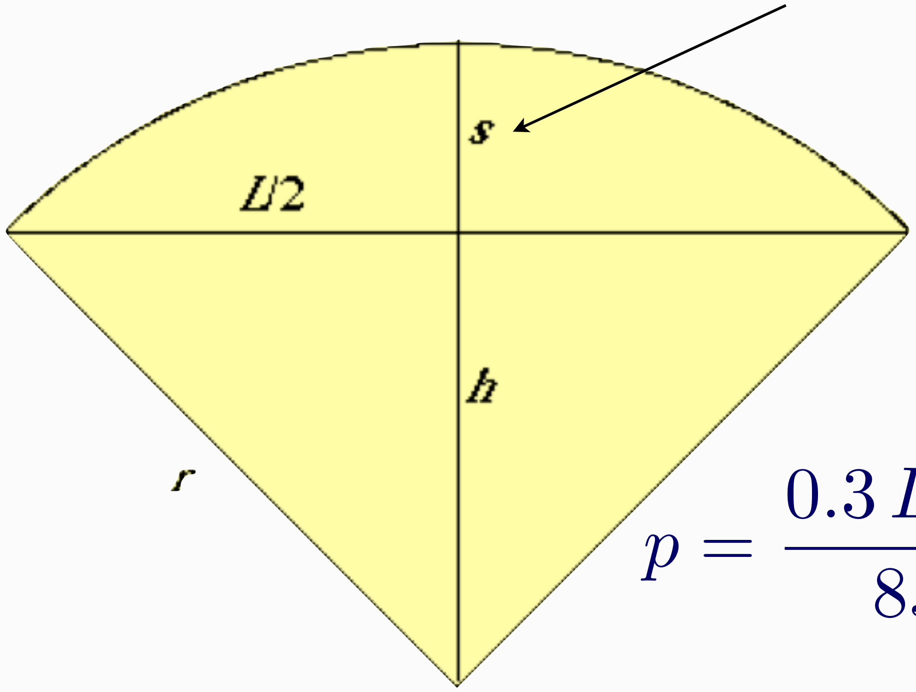

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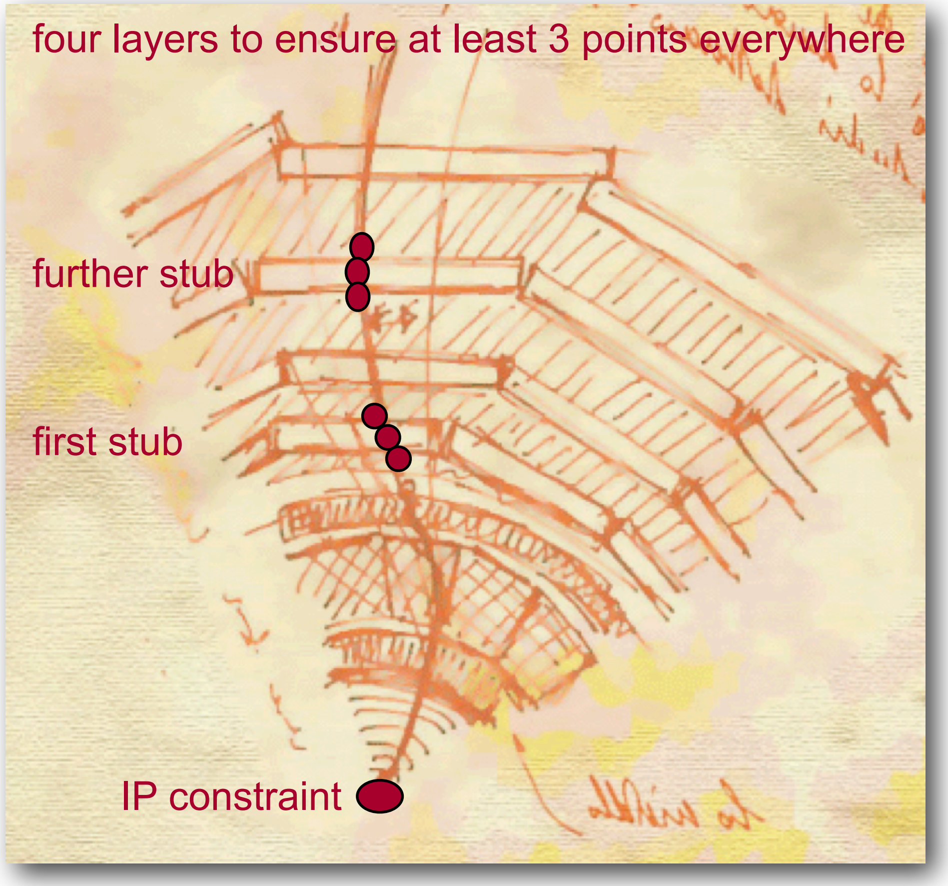

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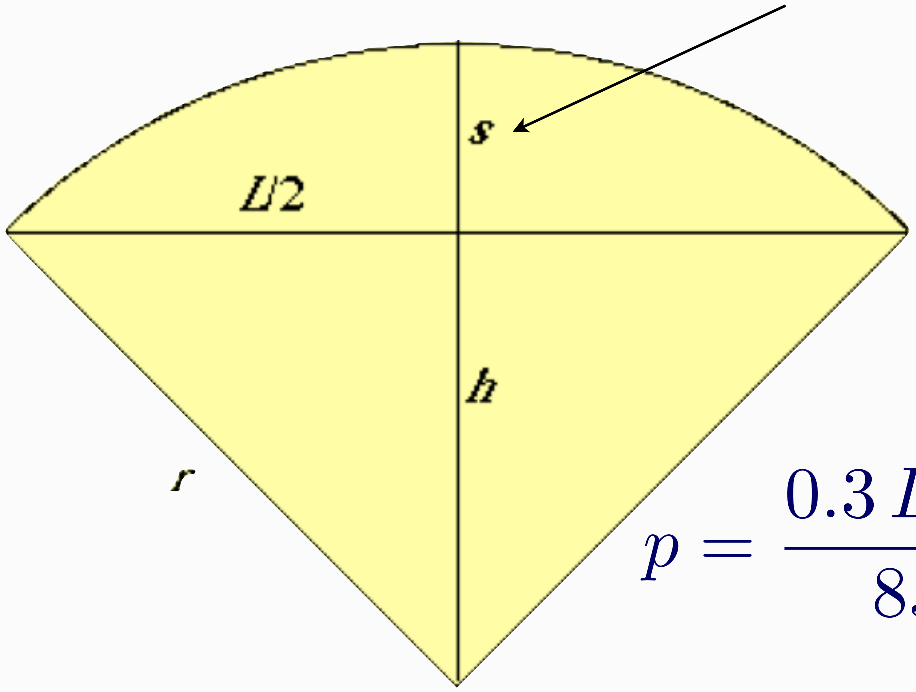

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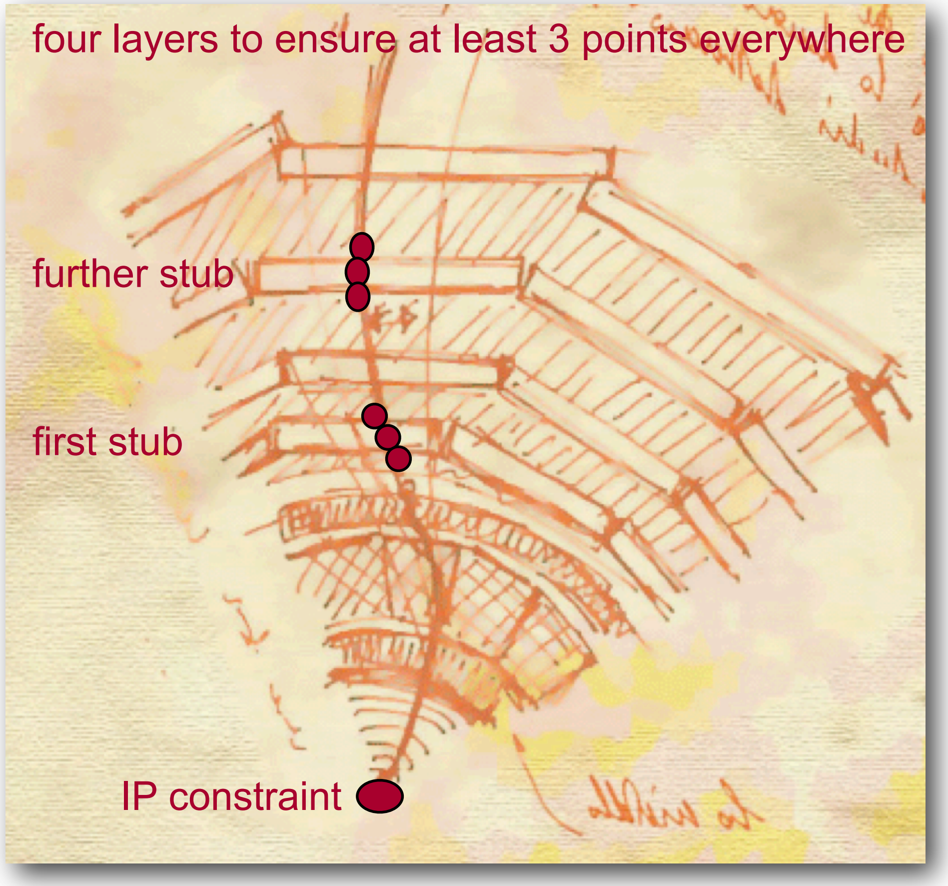
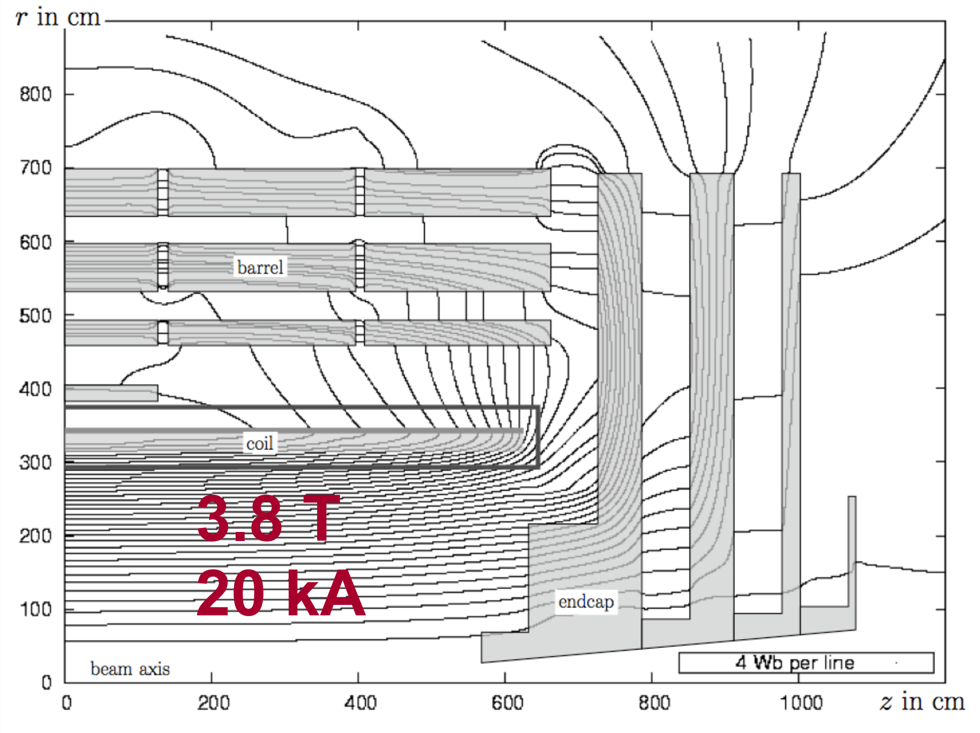
maximize... but note that L drives cost of detector very much.



Various topologies...



- But : Pending power prop.to. $\int Bdl$ of path **perpendicular** to B field.
- Solenoid not optimal in forward direction
- For large solenoid radius: have to make it long in order to cover large rapidity
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  eg. with R_{sol}=3m, $R_{Tracker}$=1.2-1.3m,

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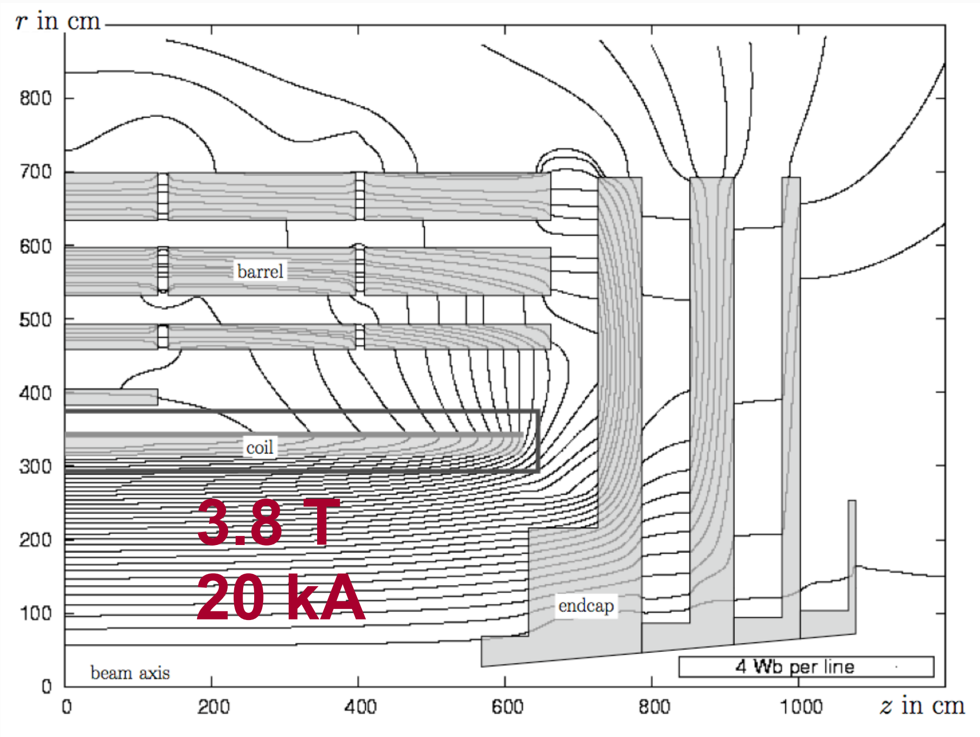

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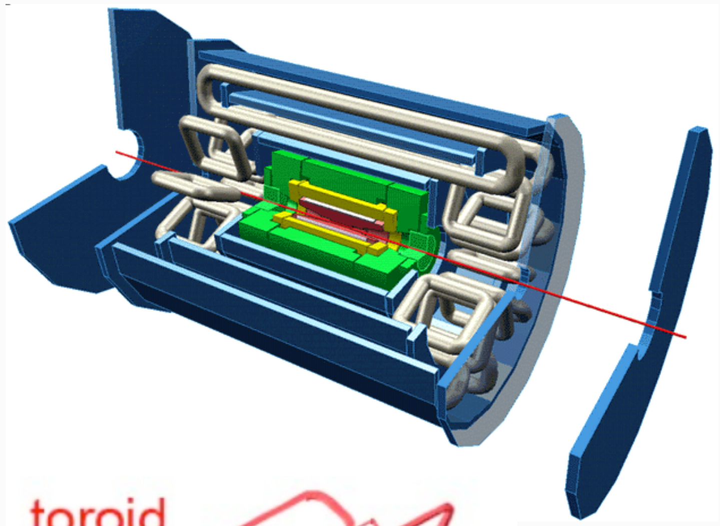
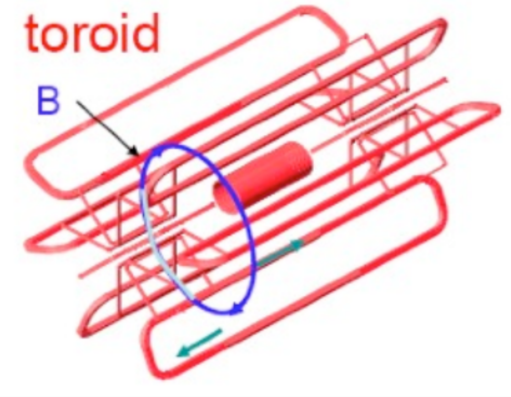
- Alternative: Toroid system. Large BL^2. Good pending power also in forward direction
- Keeps detectors inside toroids free of B field
- But : for large system: becomes expensive, needs very precise knowledge of (complicated) B-field, difficult alignment
- For tracking near IP: additional solenoid





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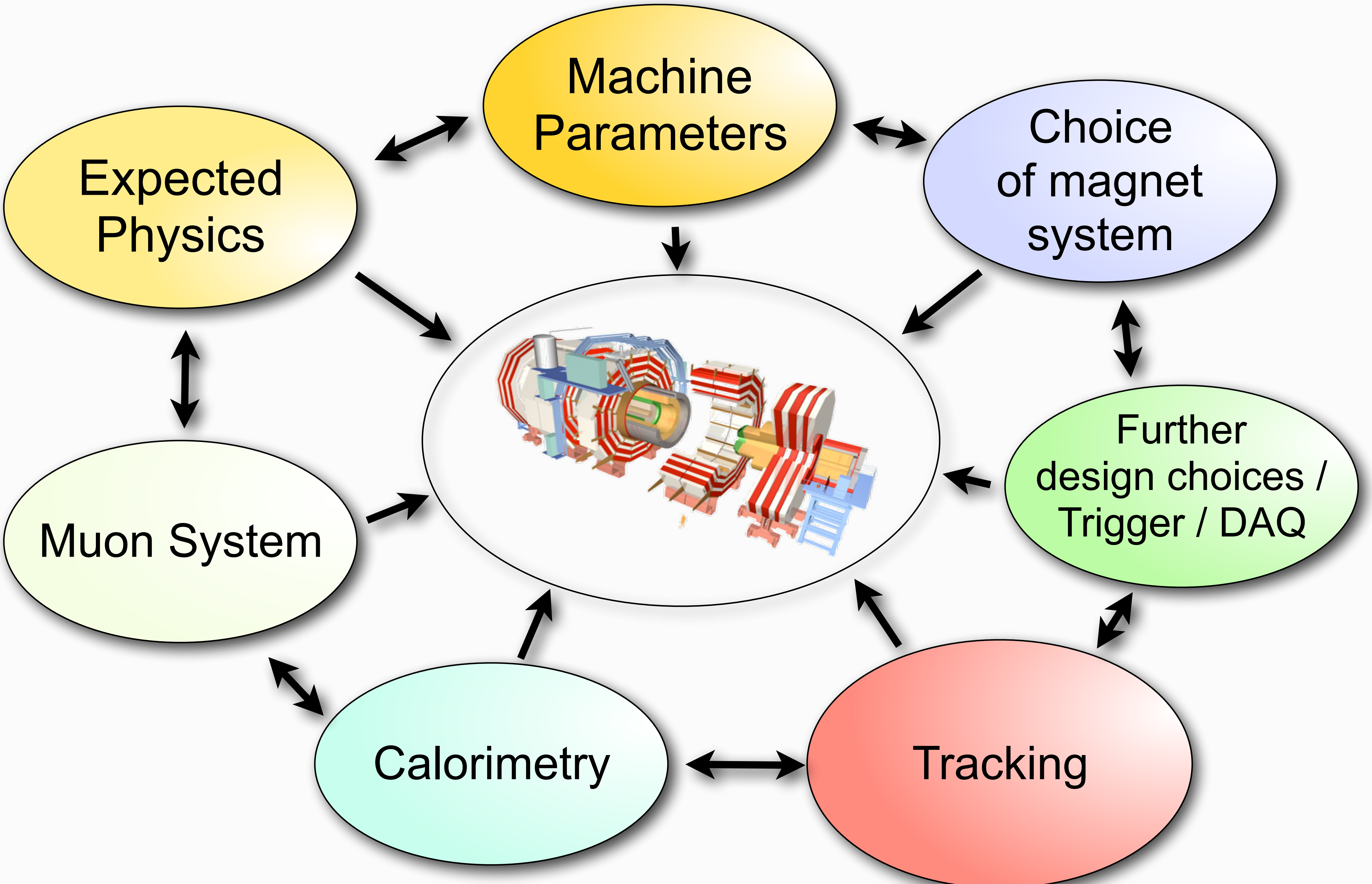

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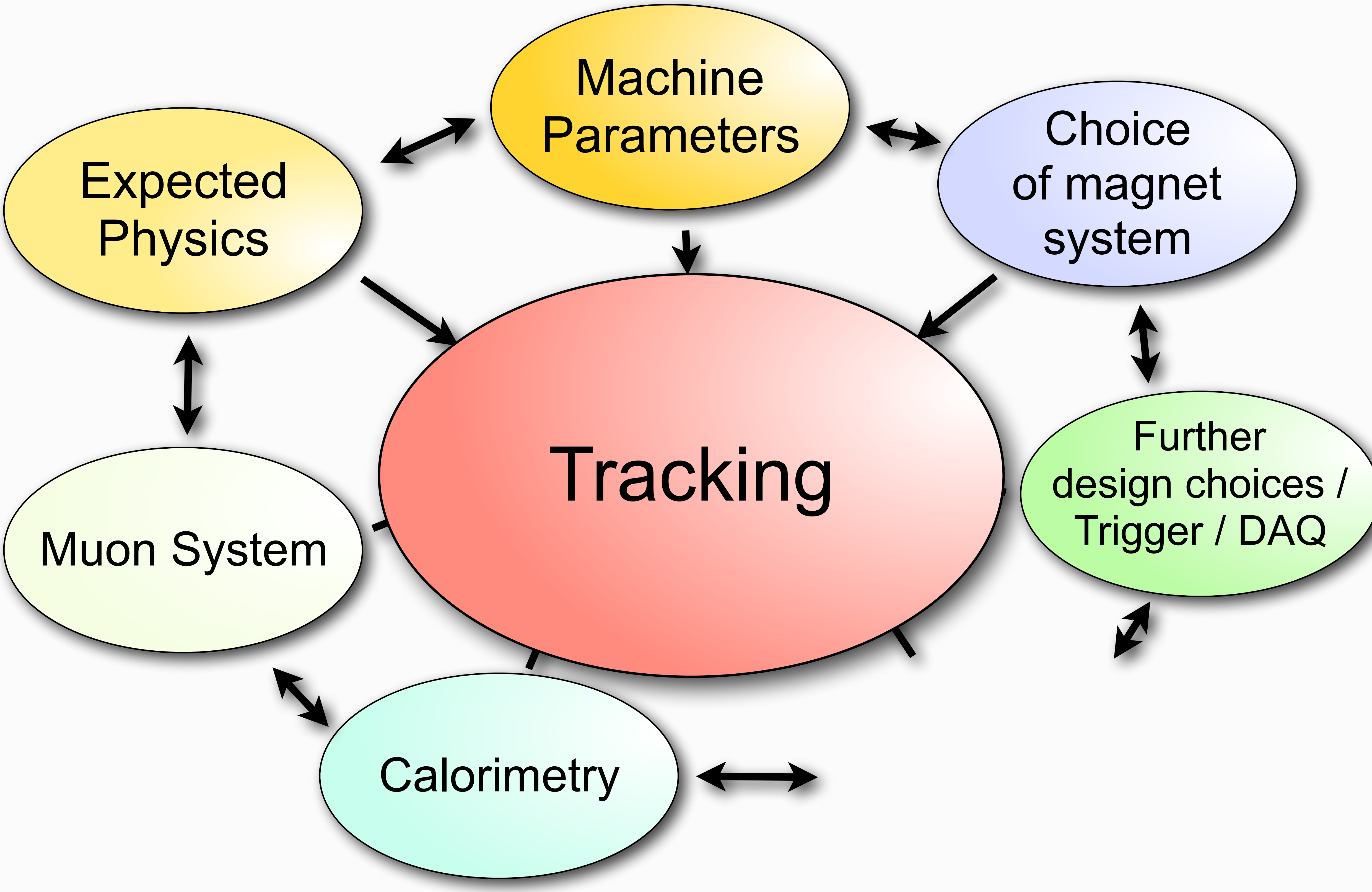

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$$\frac{\delta p}{p} = 1\,\% \ \text{ for } \quad \delta s \approx 15\,\mu\mathrm{m}$$

➡ need hit reconstruction at this level of prec. !

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

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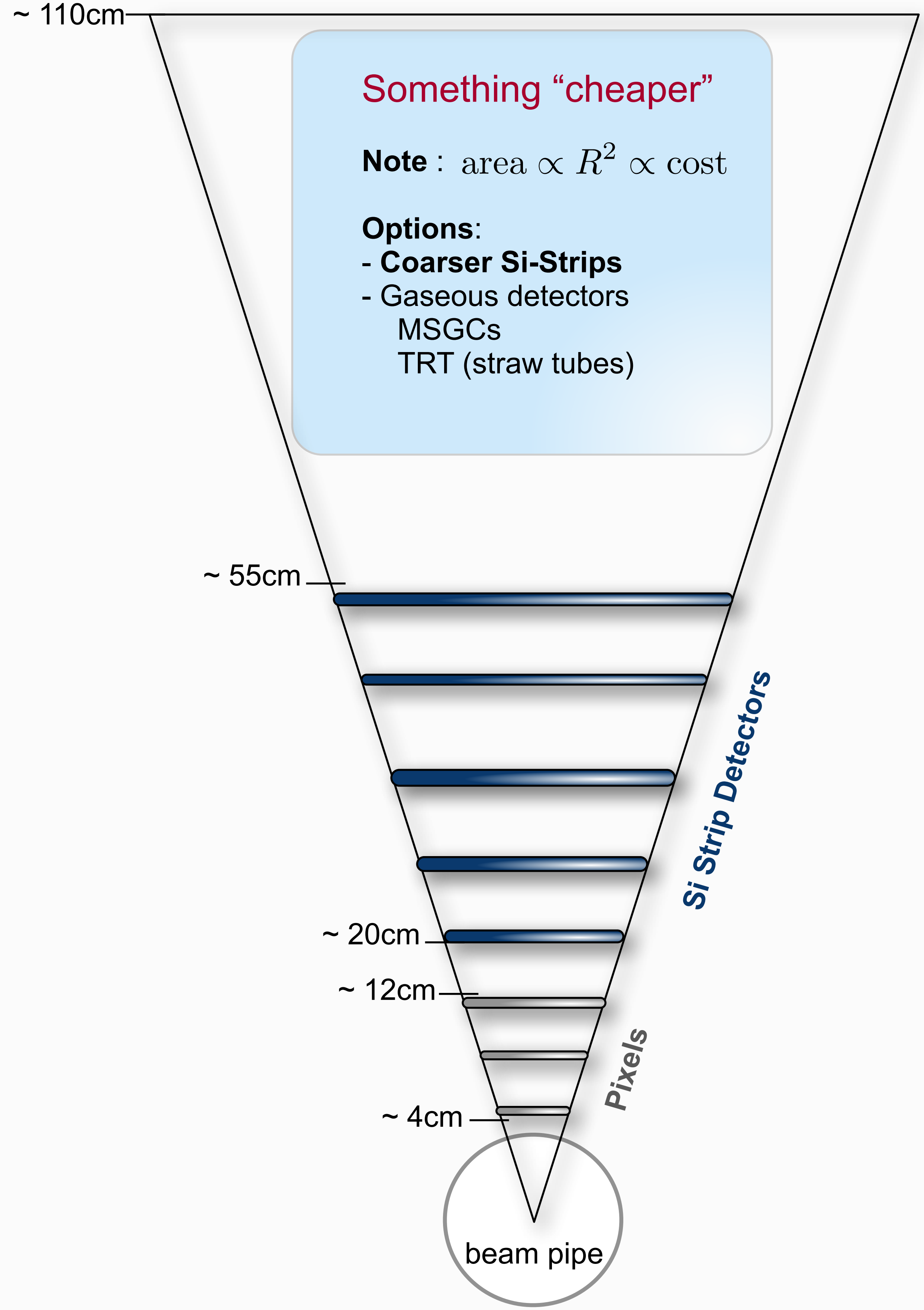

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Note : $\text{area} \propto R^2 \propto \text{cost}$

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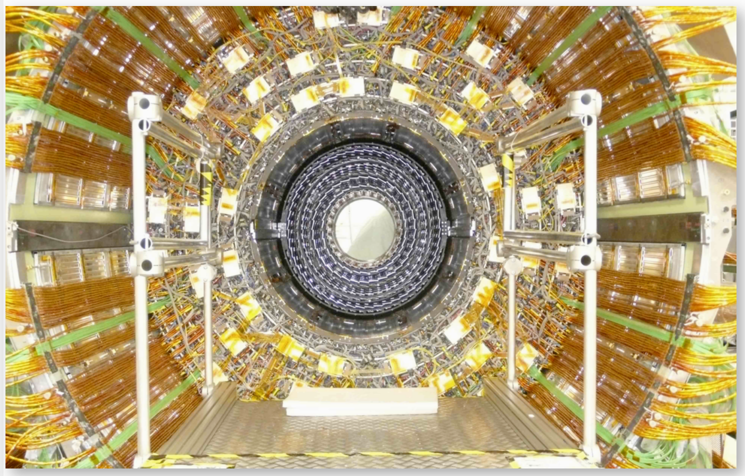

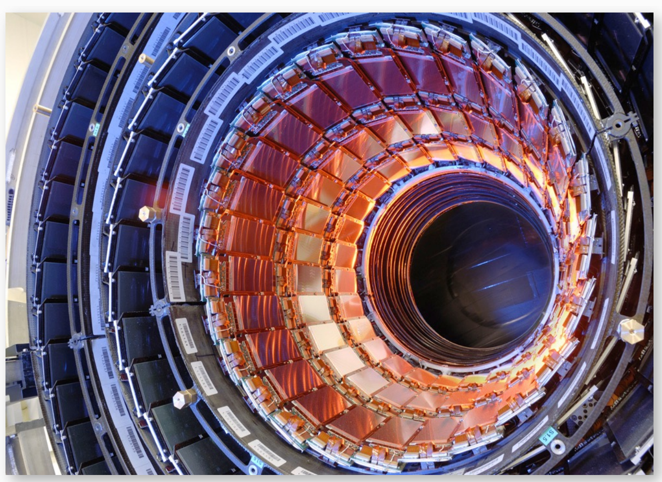

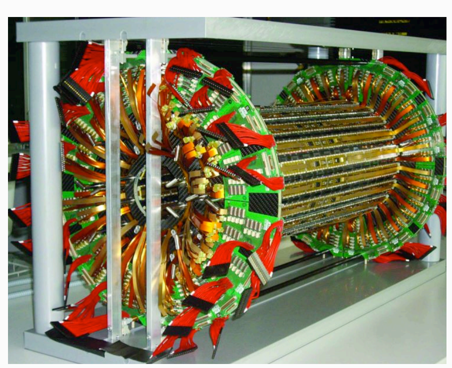

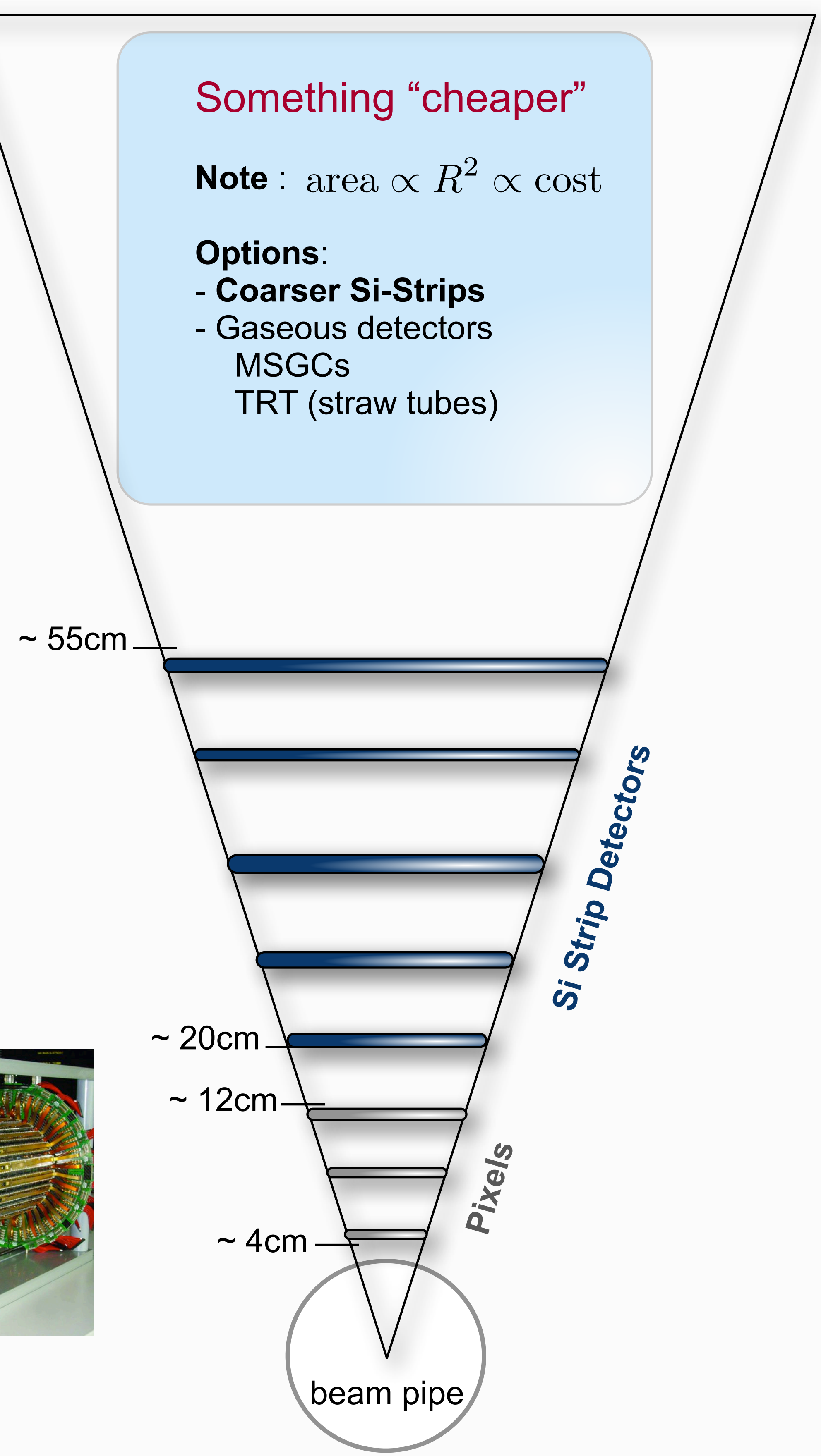

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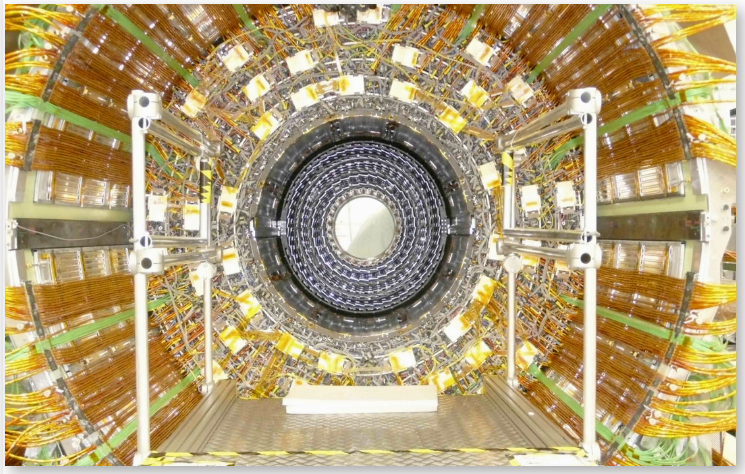

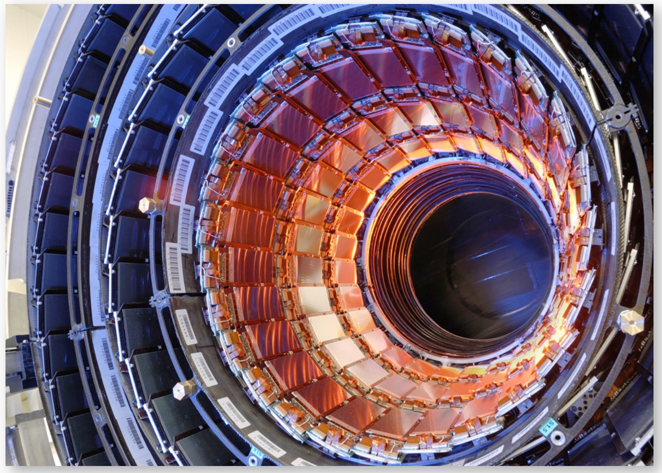

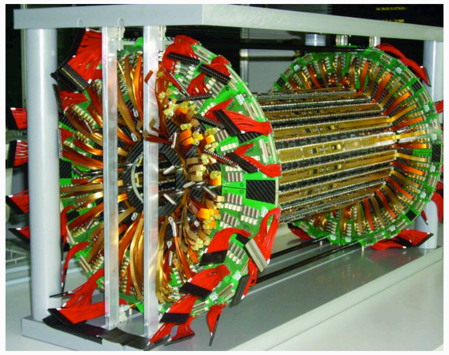

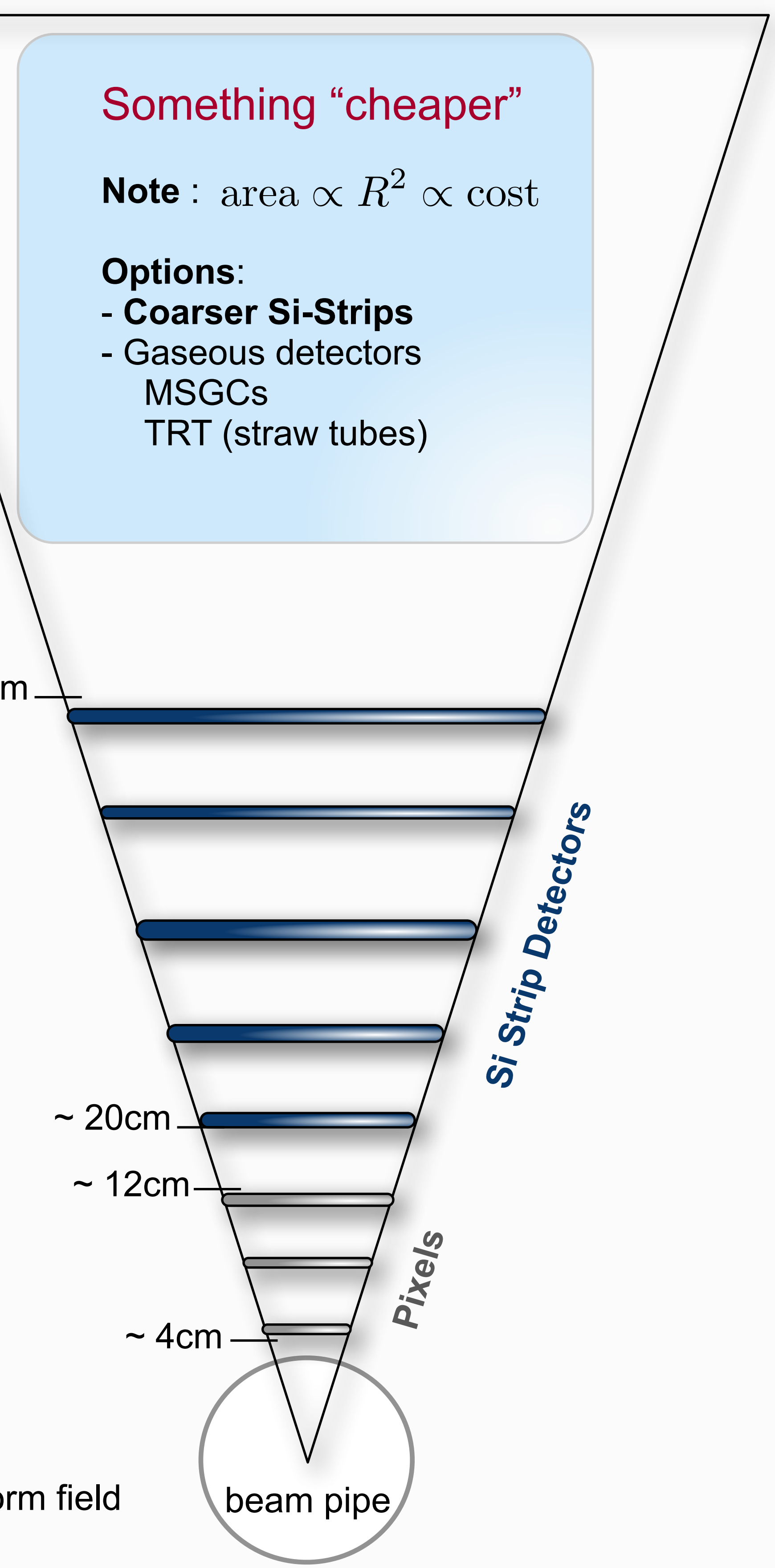

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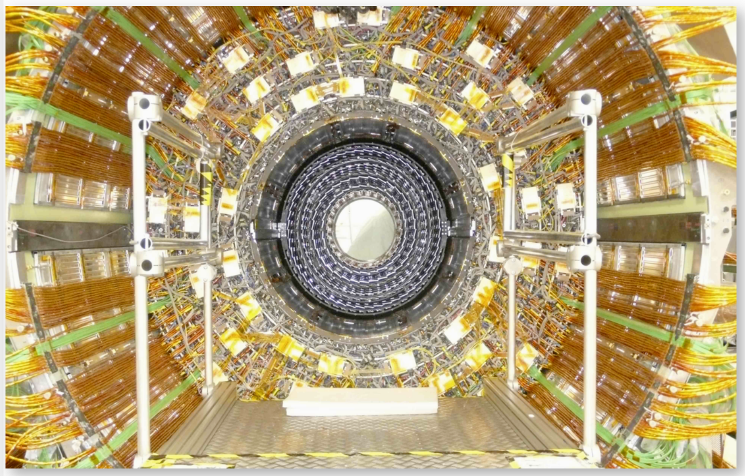

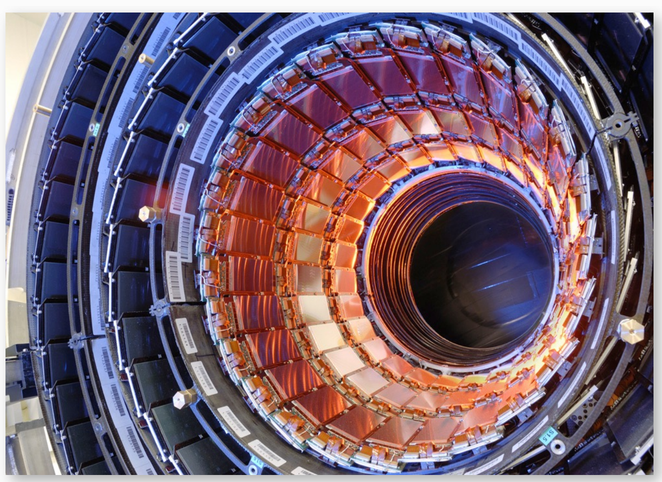

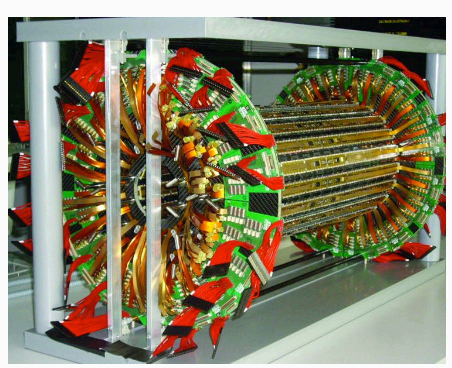

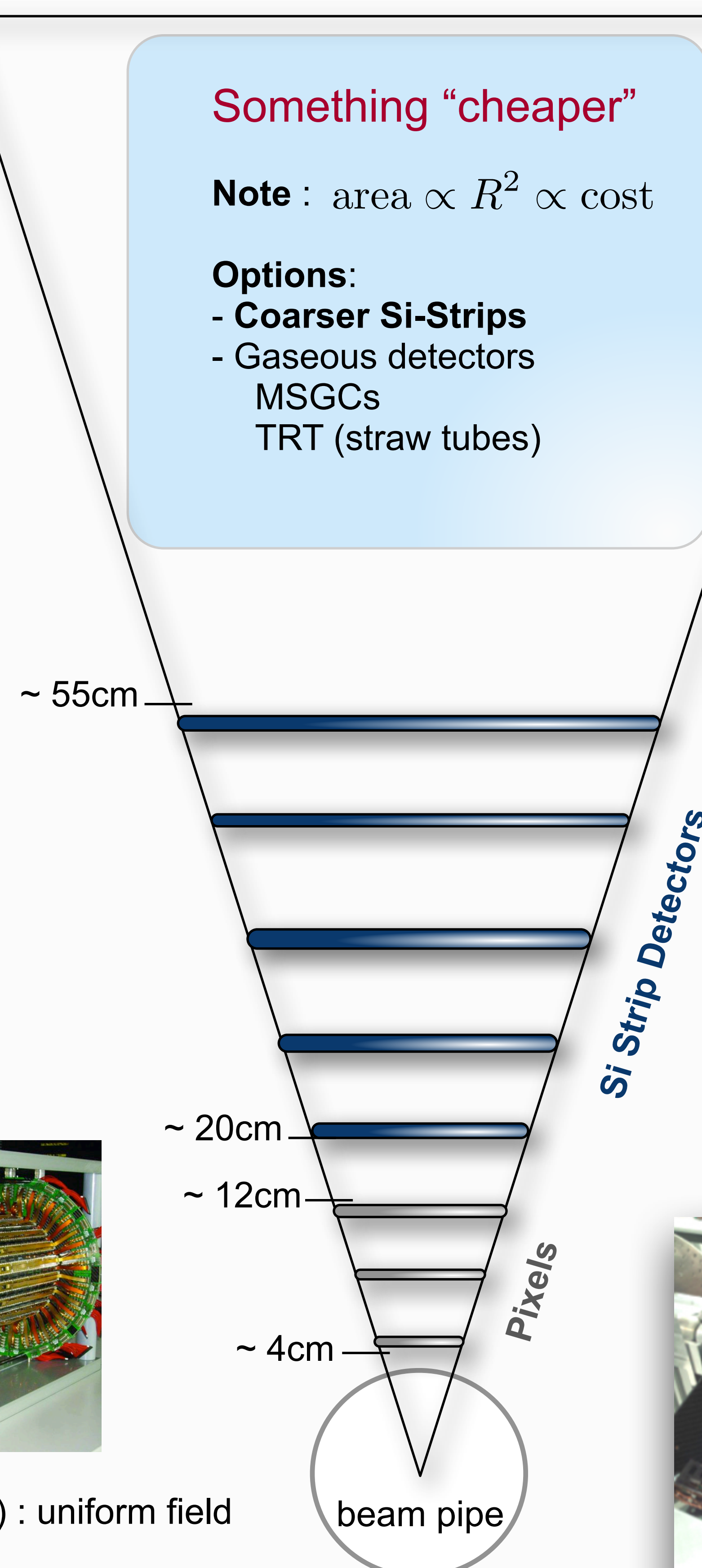

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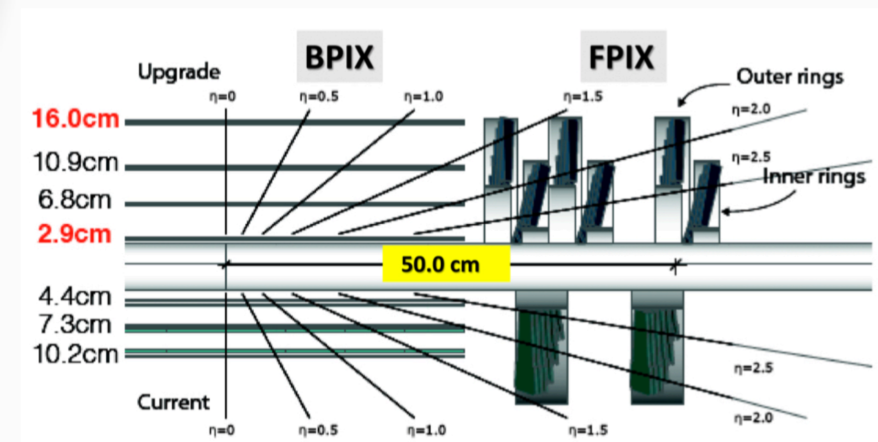
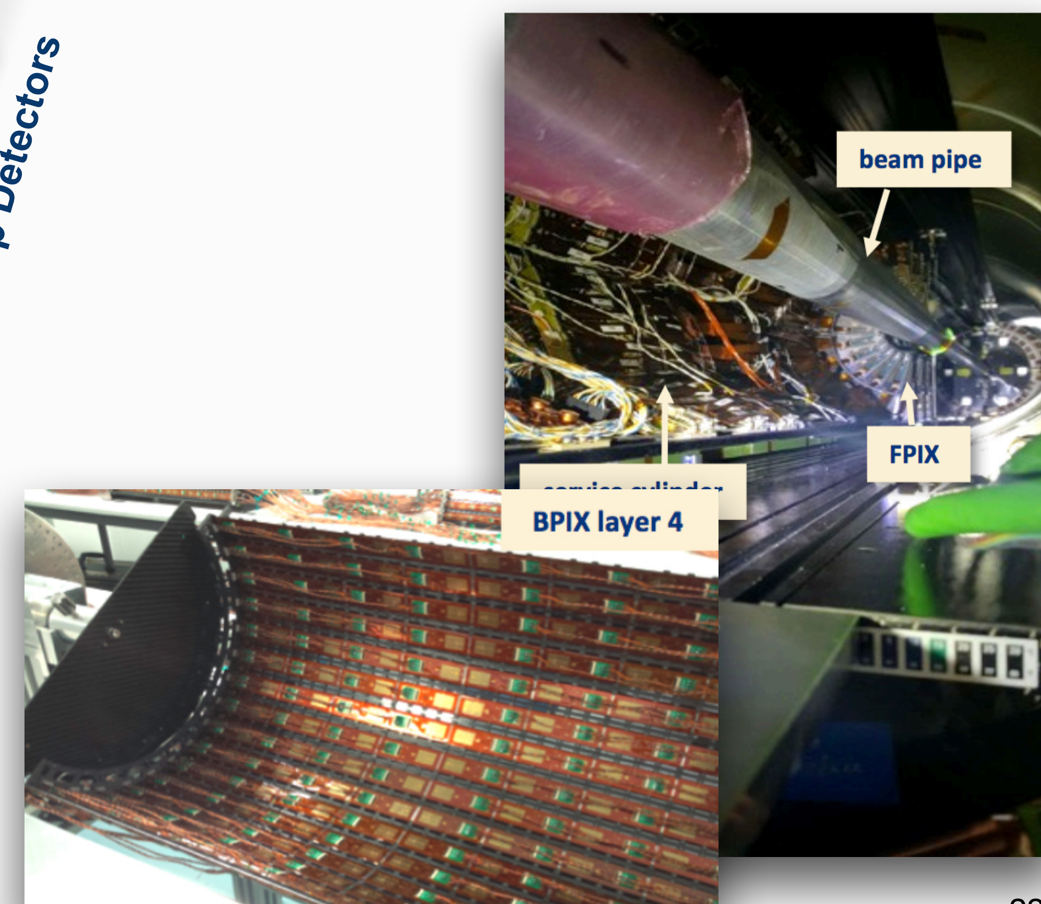
during EYETS 2017:

Pixel Phase1 upgrade





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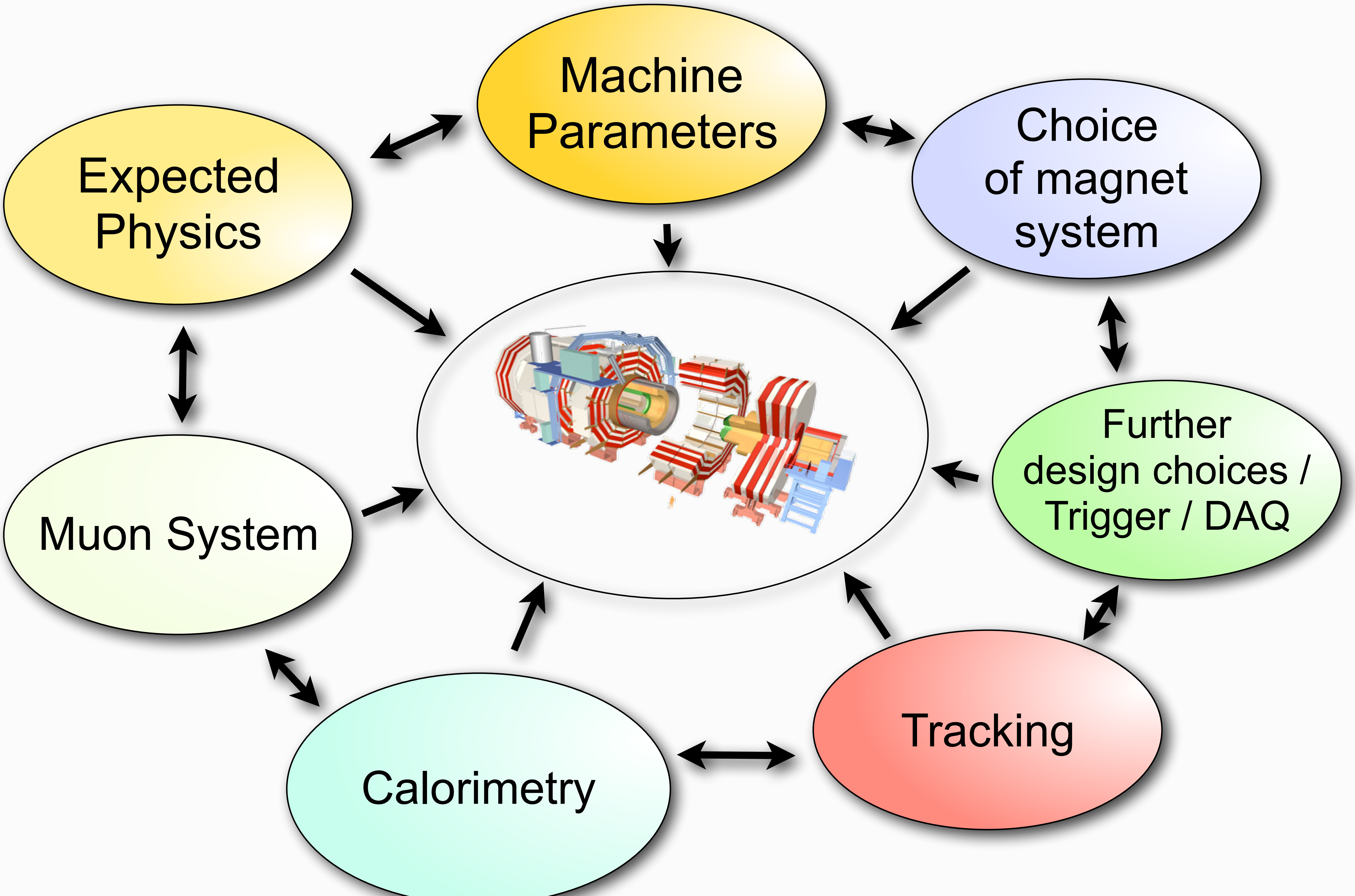

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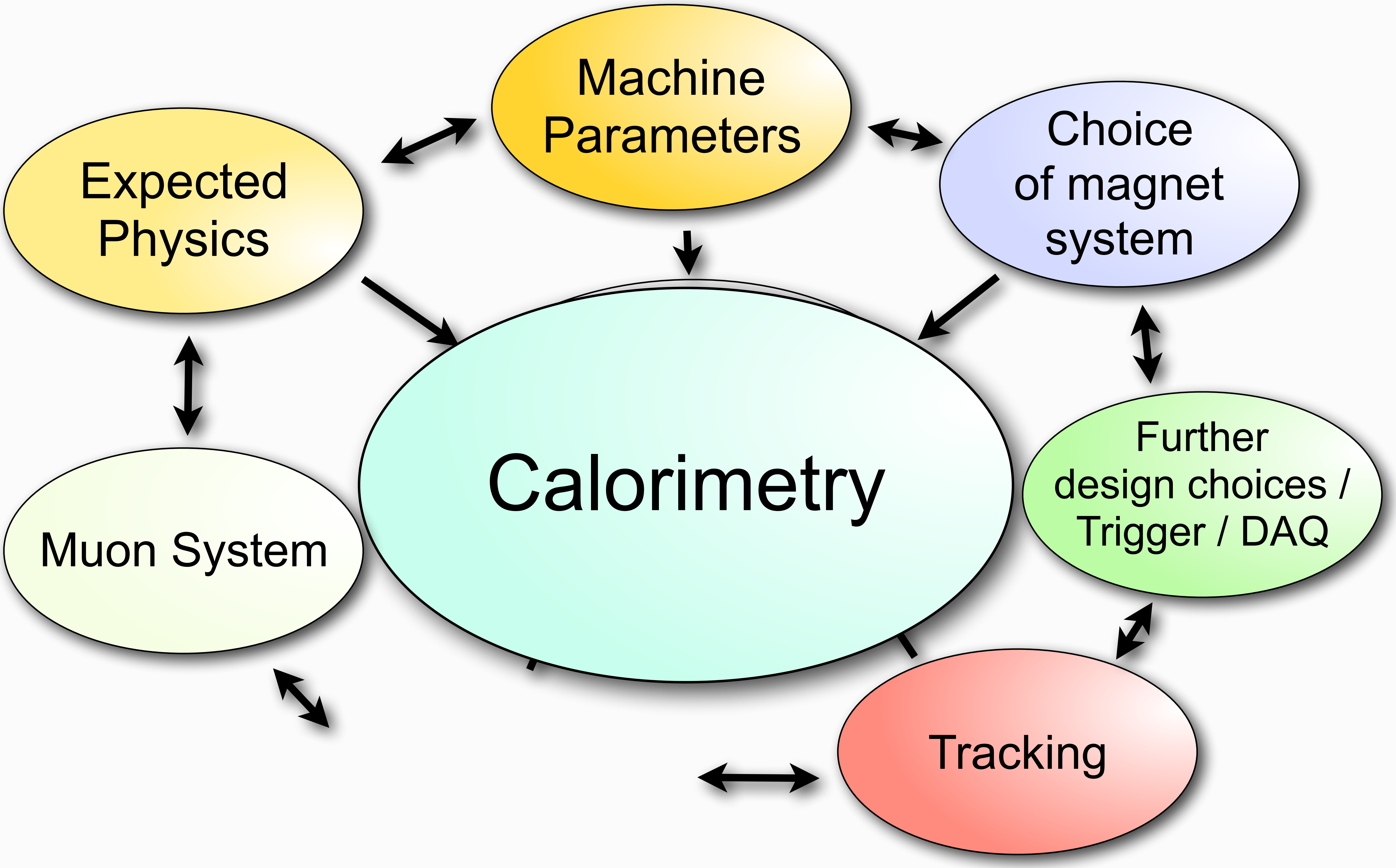
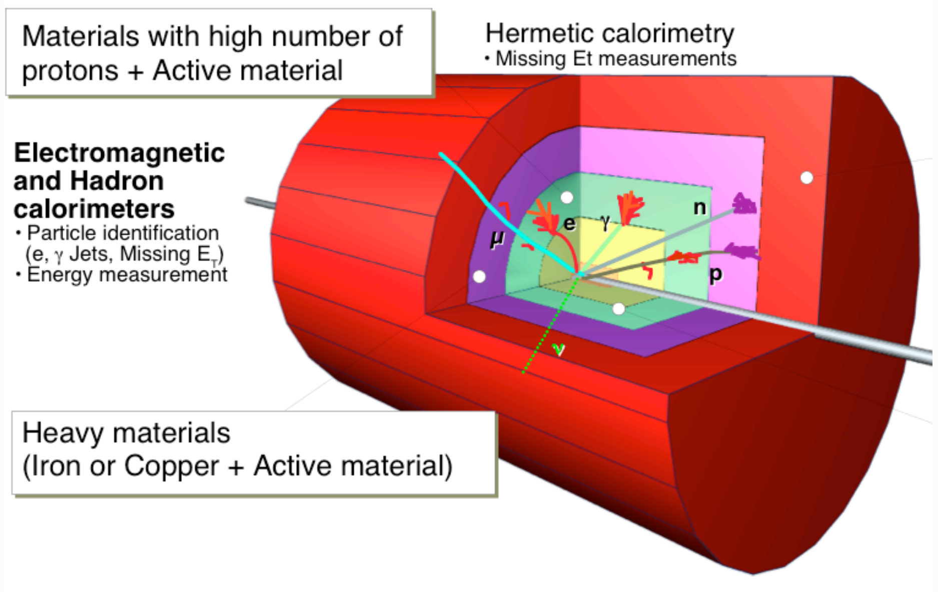


Calorimetry: Main principles

- Excellent energy measurement of electrons, photons, jets
  - good coverage up to $\eta \sim 5$, also for E_{Tmiss}



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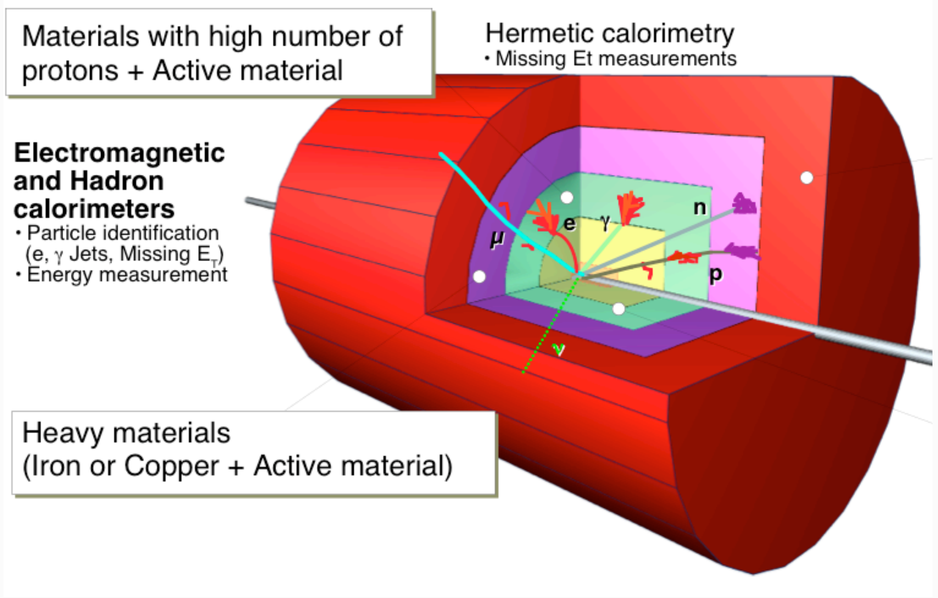

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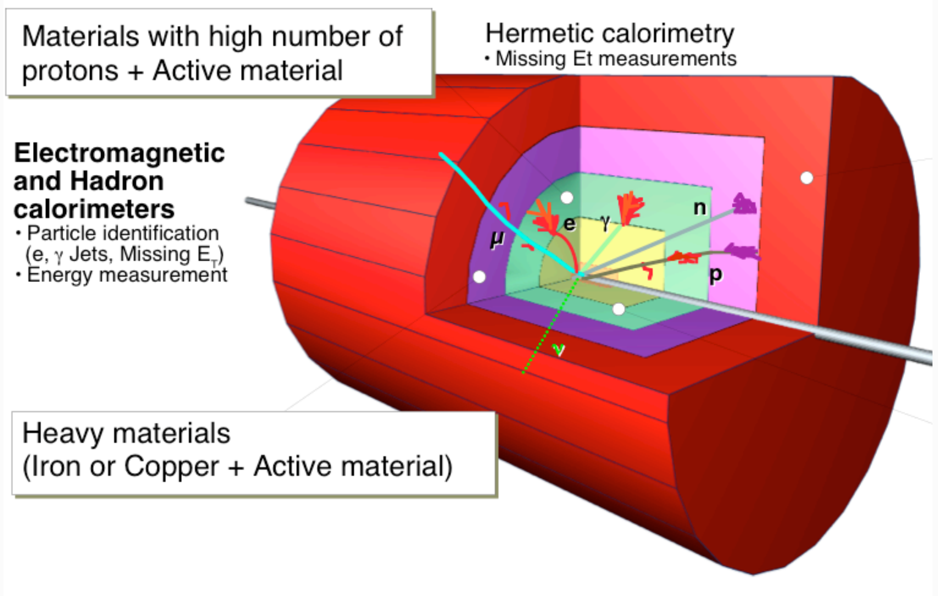

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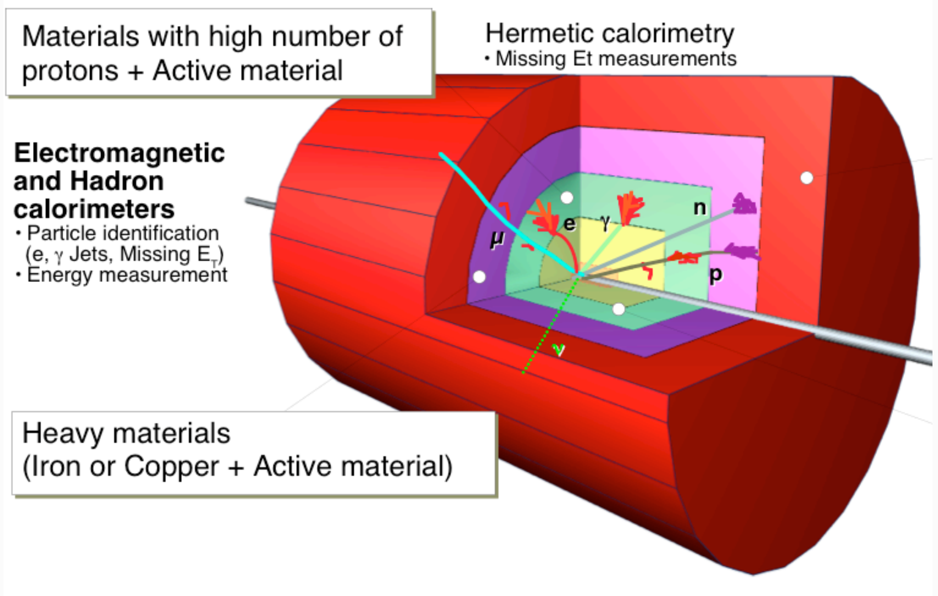

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  - to contain hadronic jets of ~ 1 TeV : 11 λ_0
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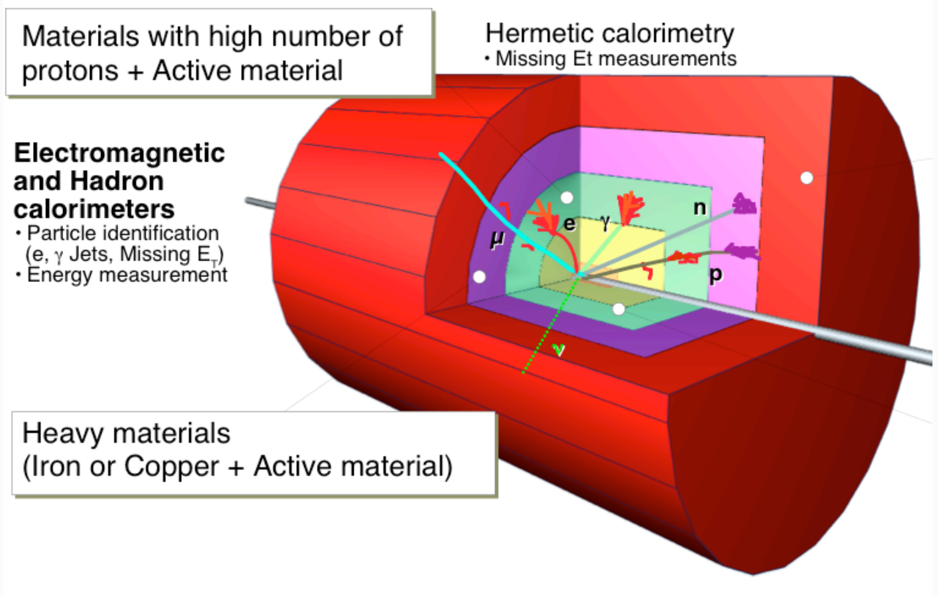
  - take $(\lambda_0)_{Fe}$ = 16.8 cm : would need ~ 180 cm



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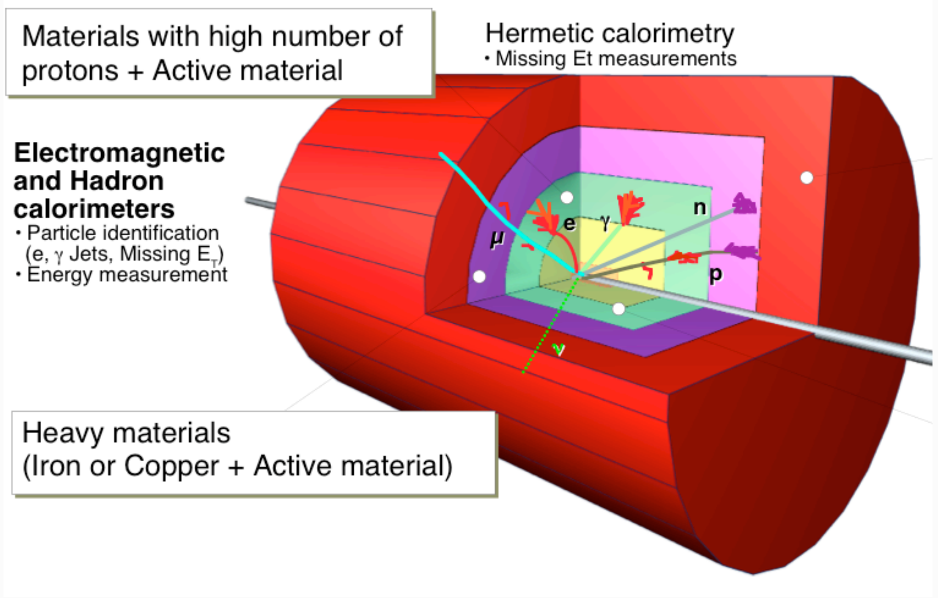

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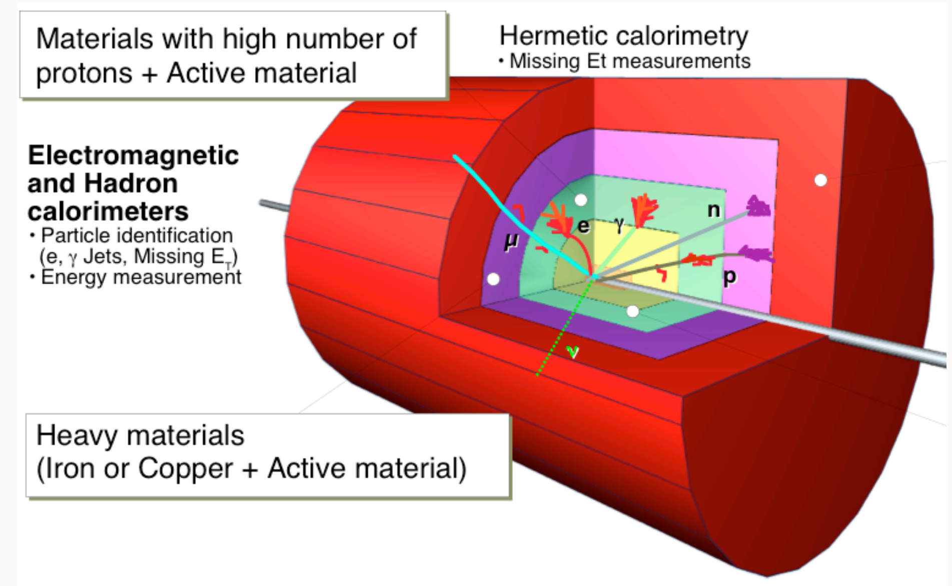

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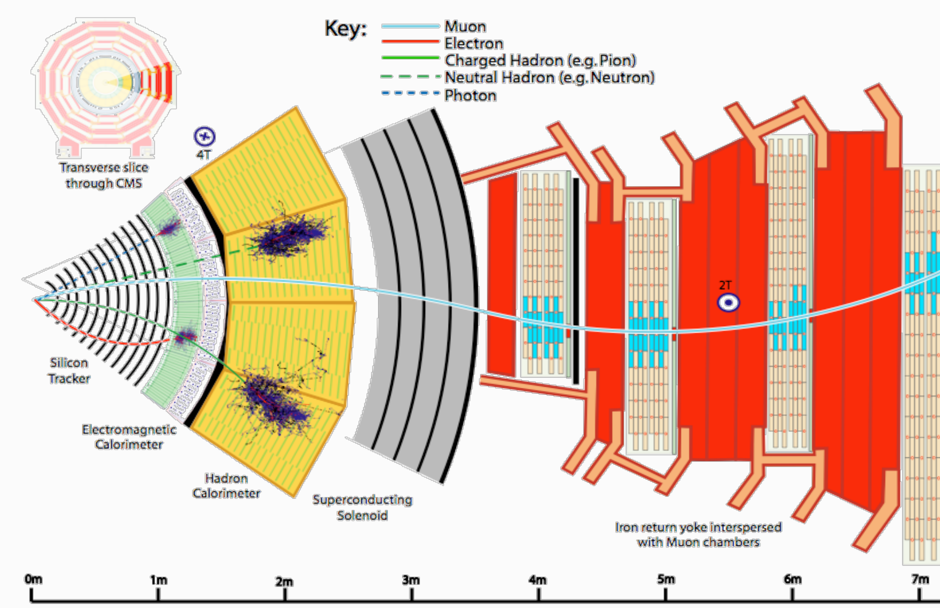

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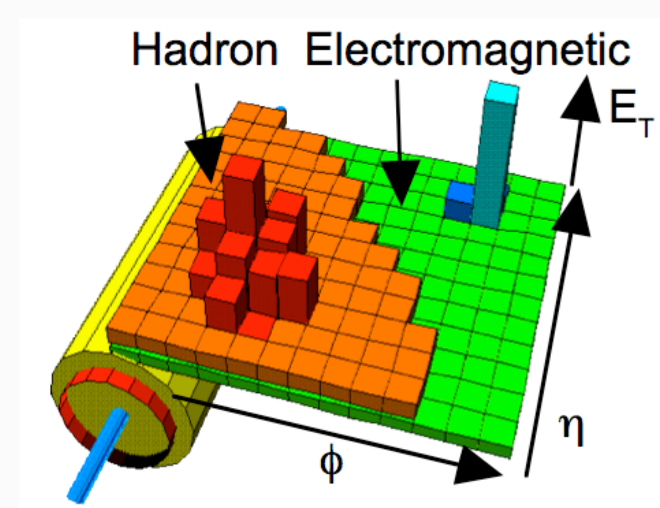
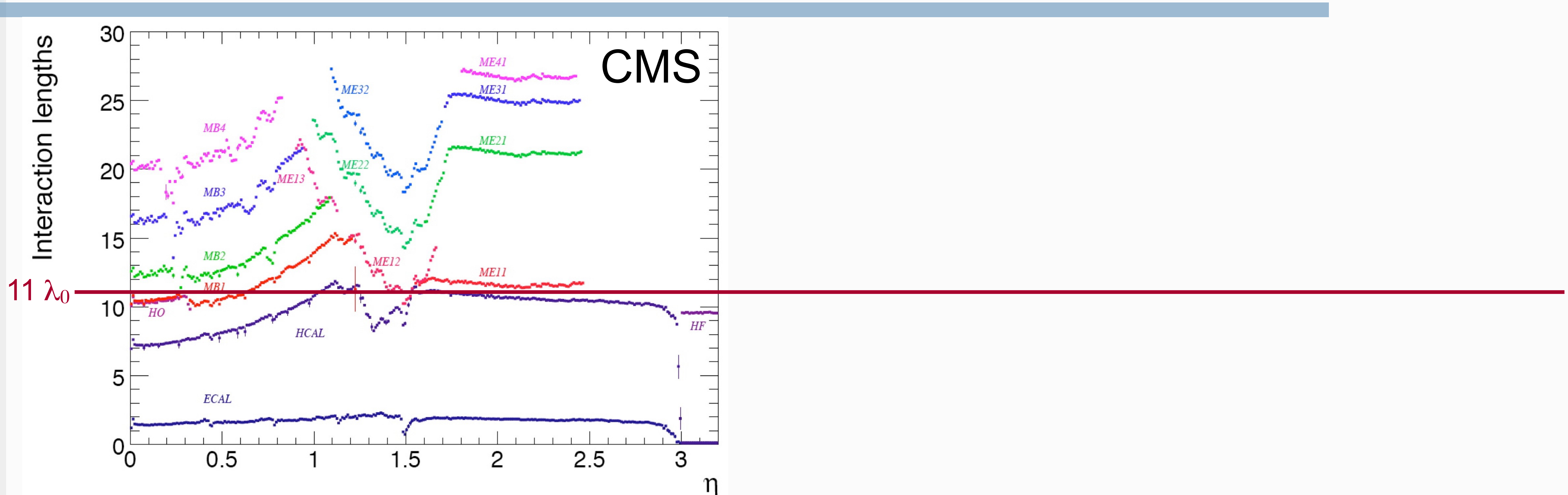
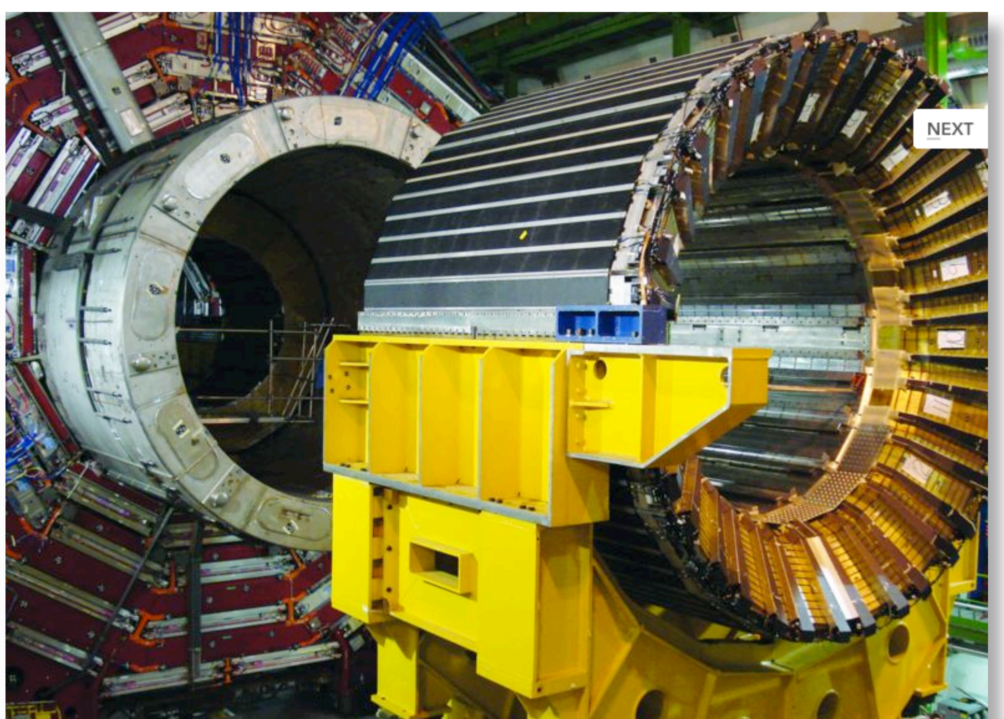
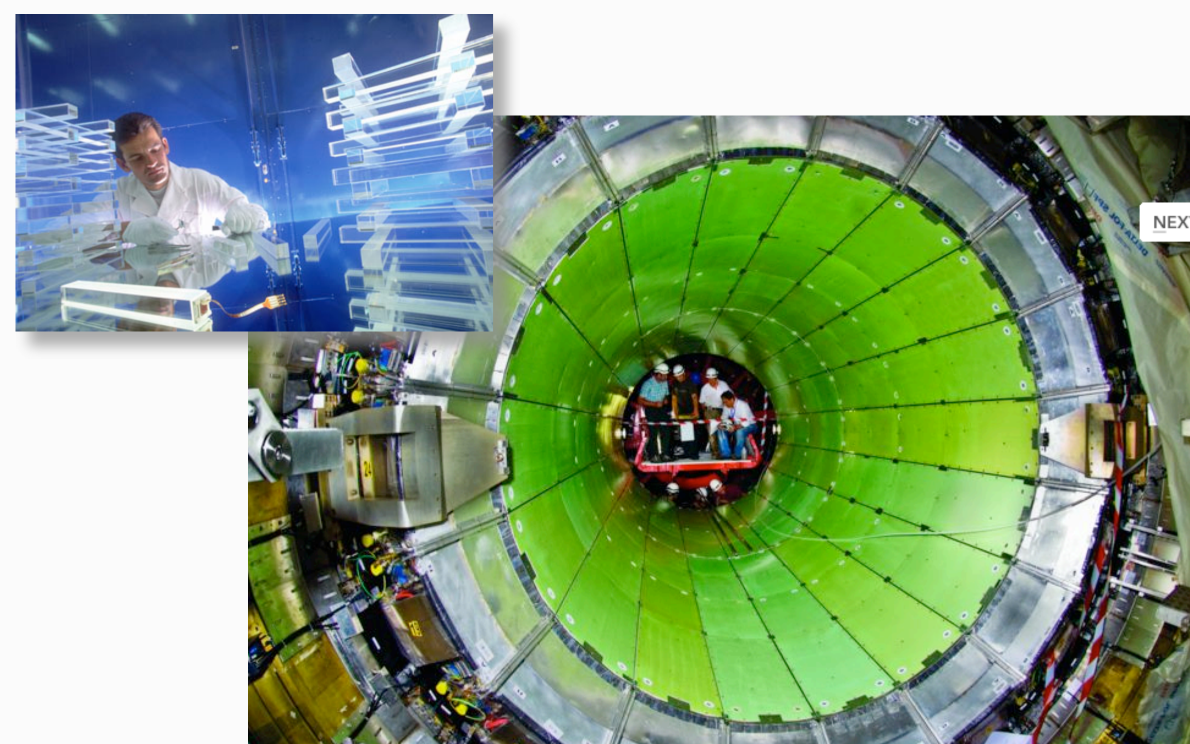
- Further considerations
  - Homogenous vs. sampling calorimeter
  - Very forward calo : at large distance (less radiation) or closer (better uniformity of rap coverage)
  - Projective Tower sizes
    - relevant parameters: Moliere Radius, Occupancy
    - eg. $\Delta\eta \times (\Delta\Phi/2\pi) = 0.1 \times 0.1 \quad \text{over} \quad 2 \cdot y_{\max} = 10 \;\Rightarrow \mathcal{O}(10000)$ towers



Coverage







Upgrade of HE
readout ongoing right now…

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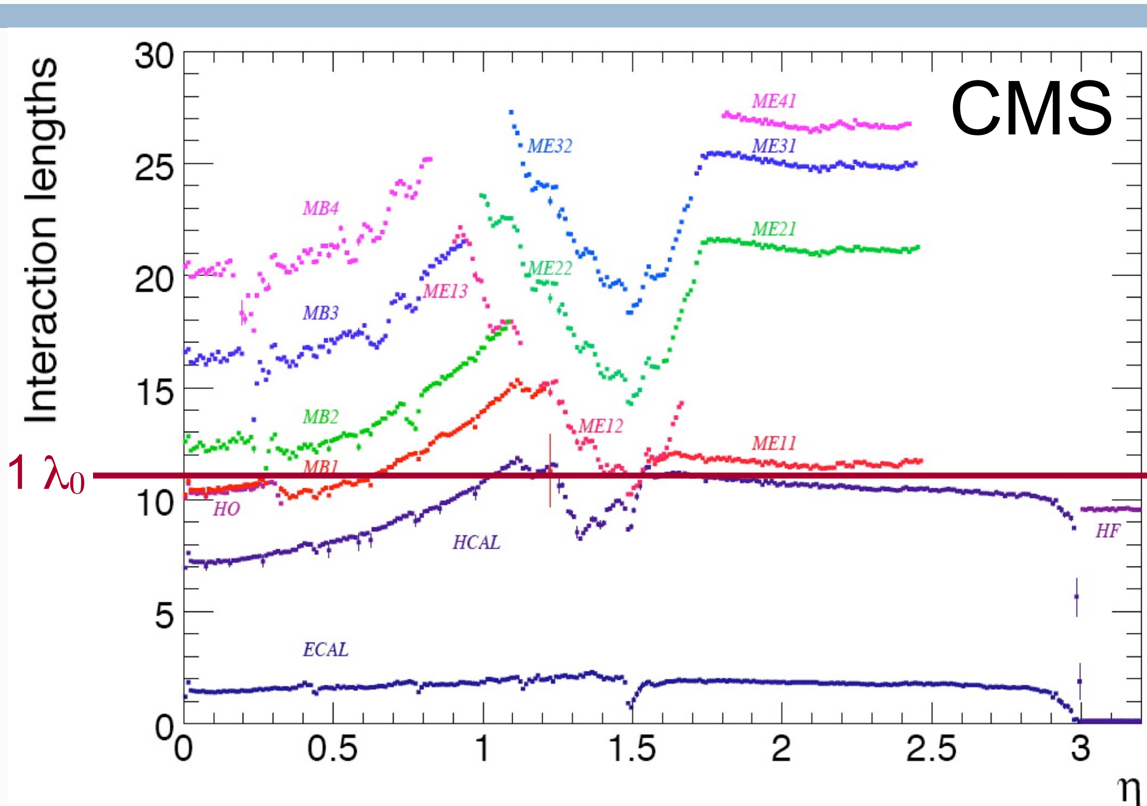
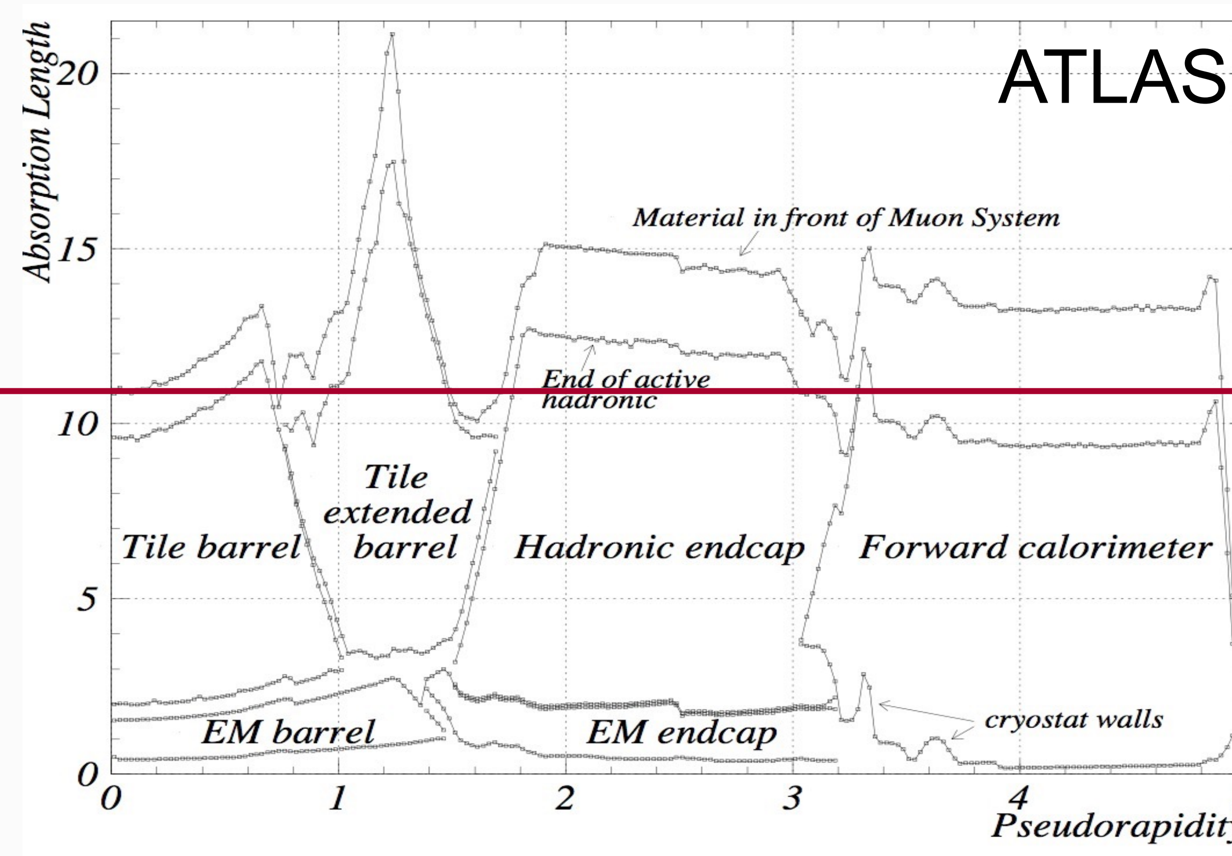
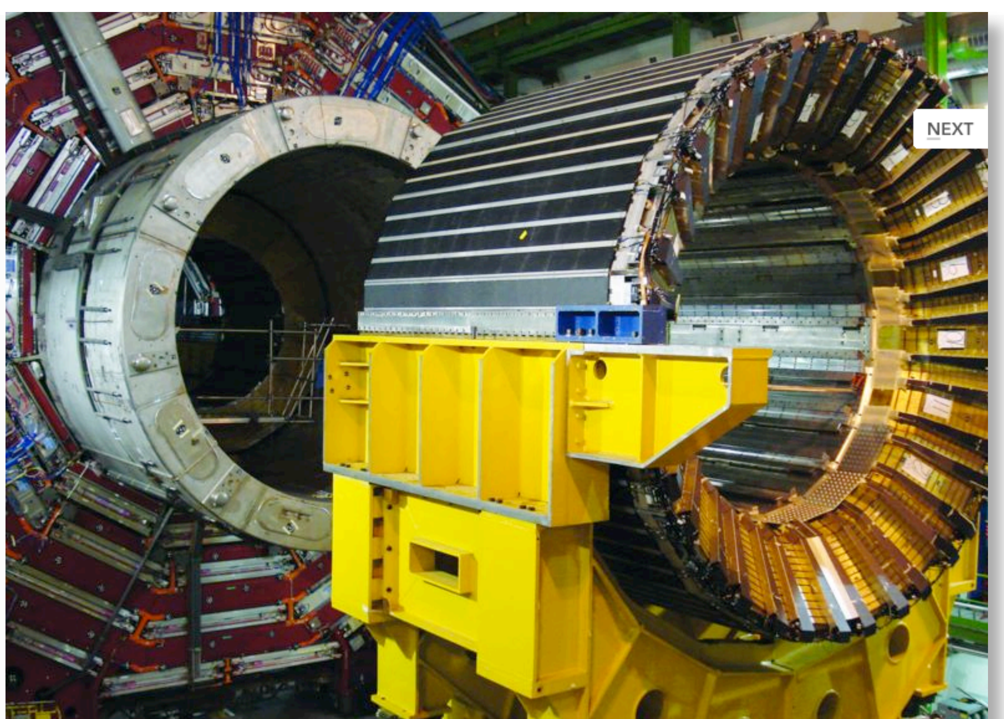
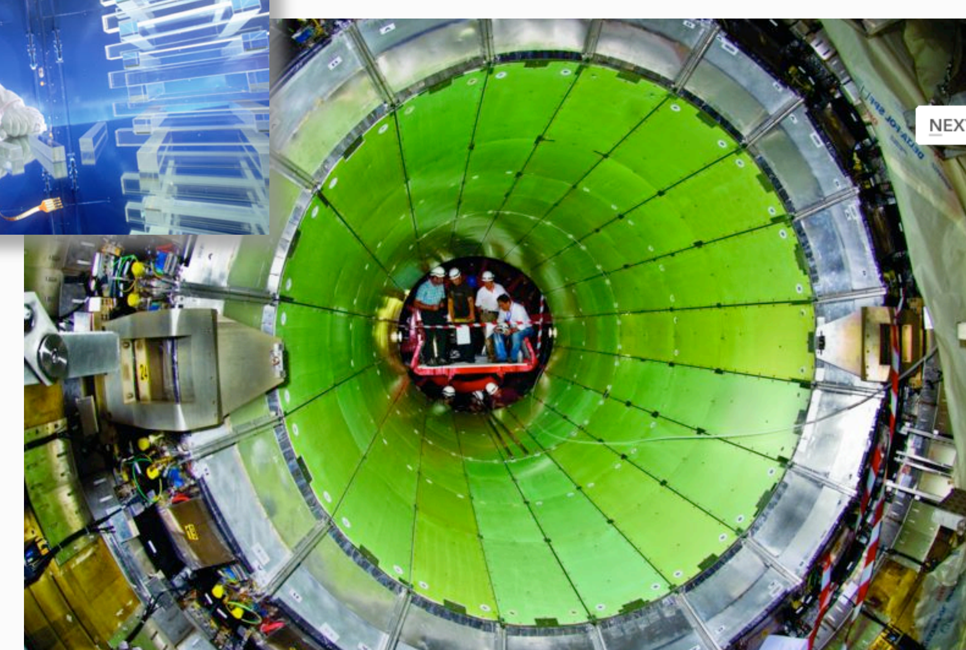


11 λ_0







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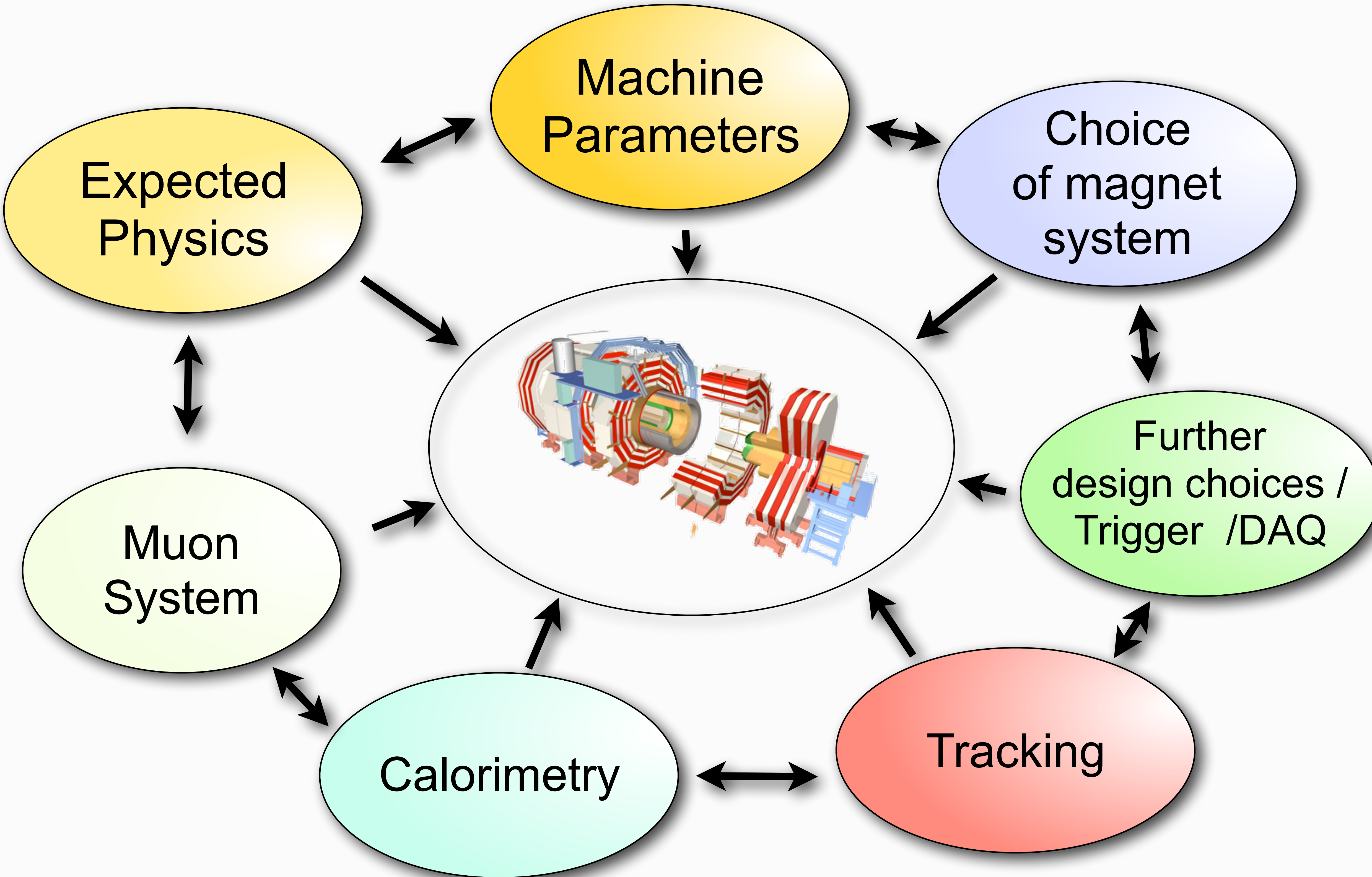
How to design your detector



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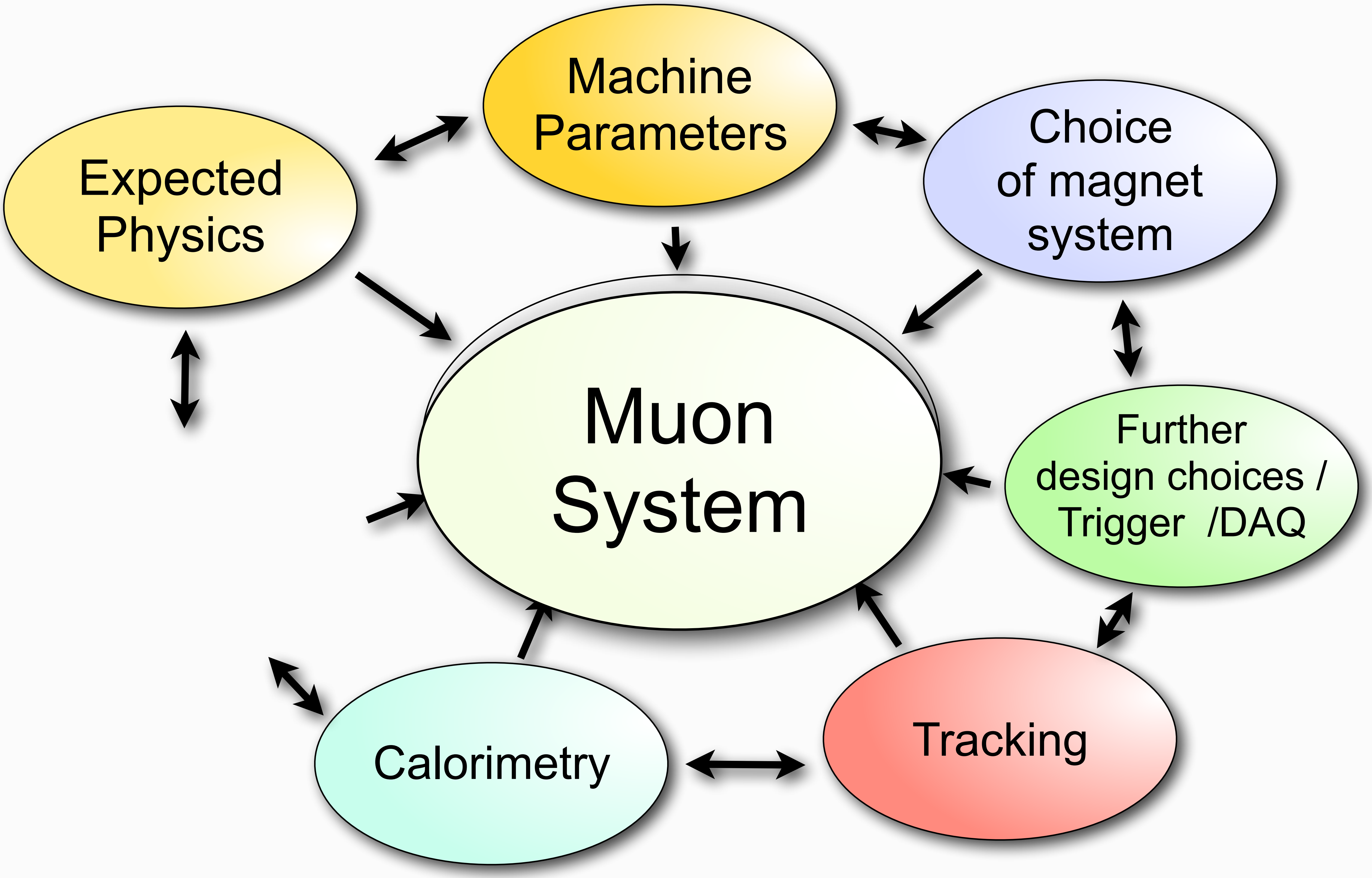

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- Reconstruct mass of narrow 2-muon state (eg. Z mass) at 1% precision
- Reconstruct 1 TeV muons with 10% precision
- Over wide rapidity range
- Identification in dense environment
- Measure and trigger on muons in standalone mode, for momenta above ~ 5 GeV
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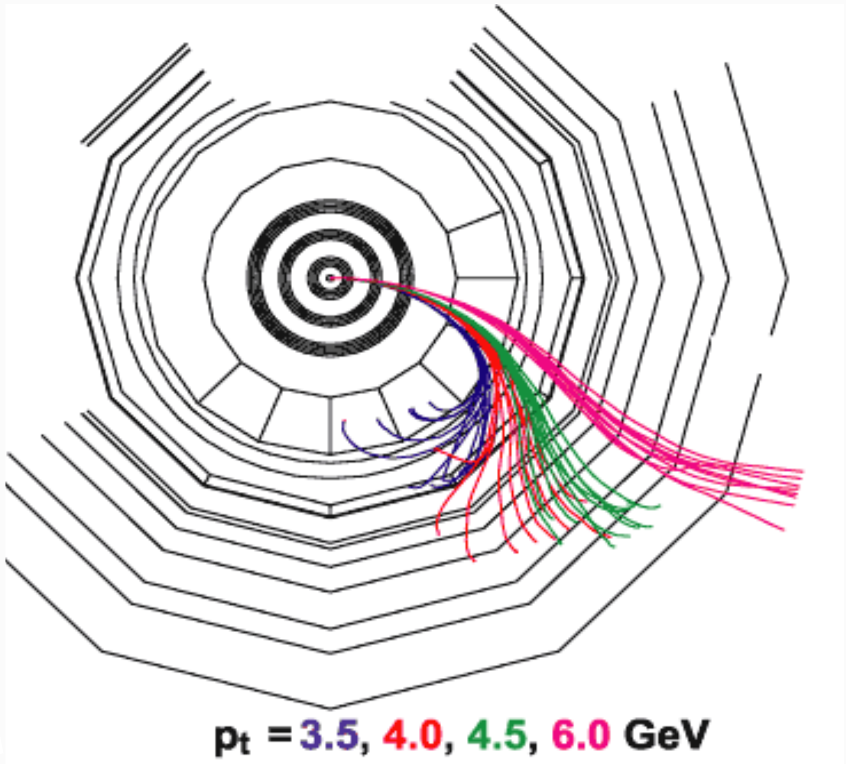

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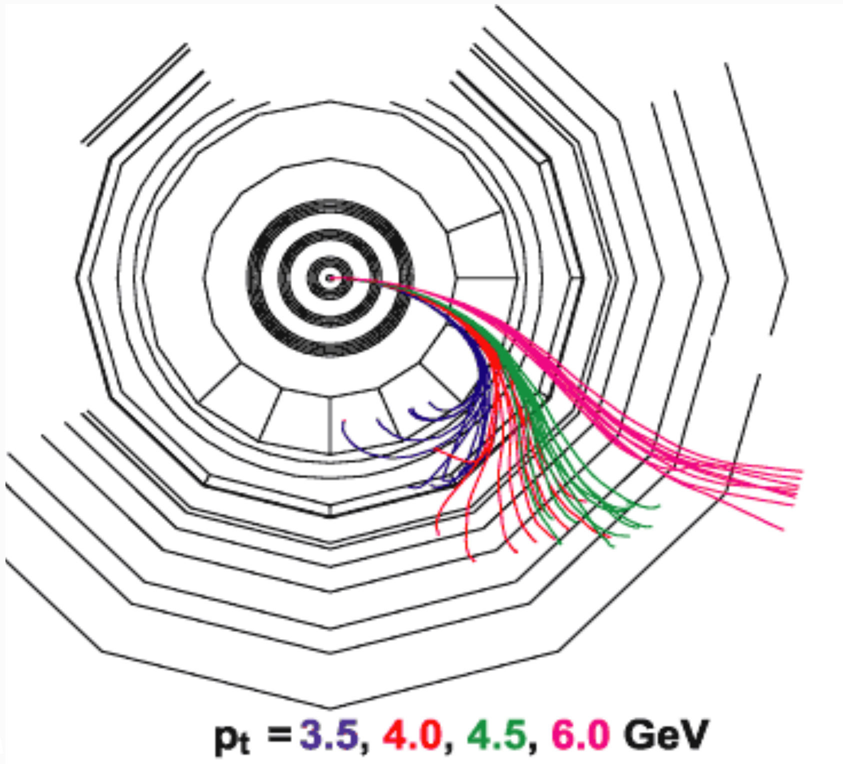

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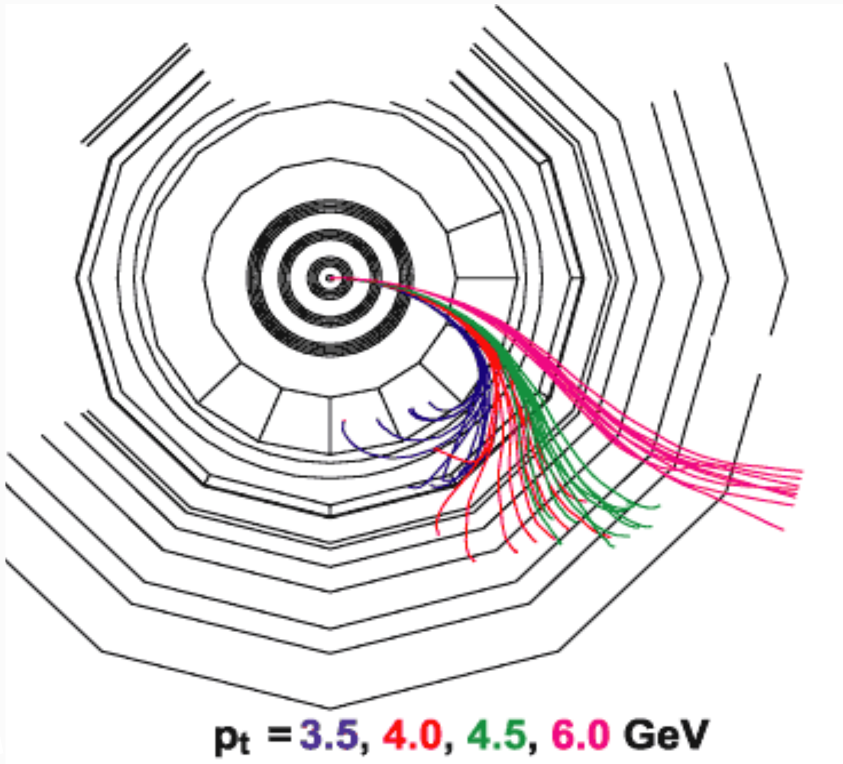

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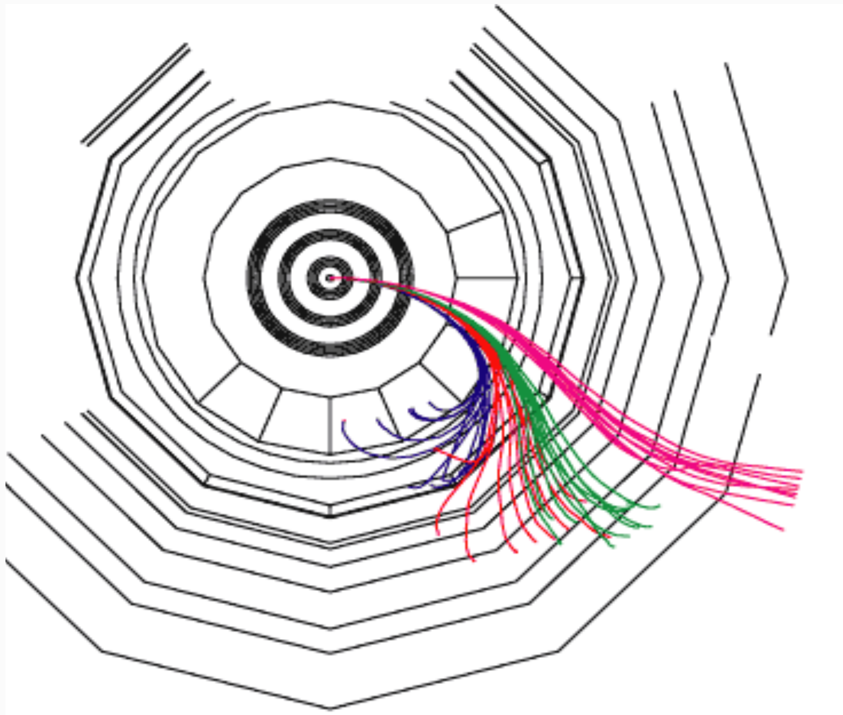

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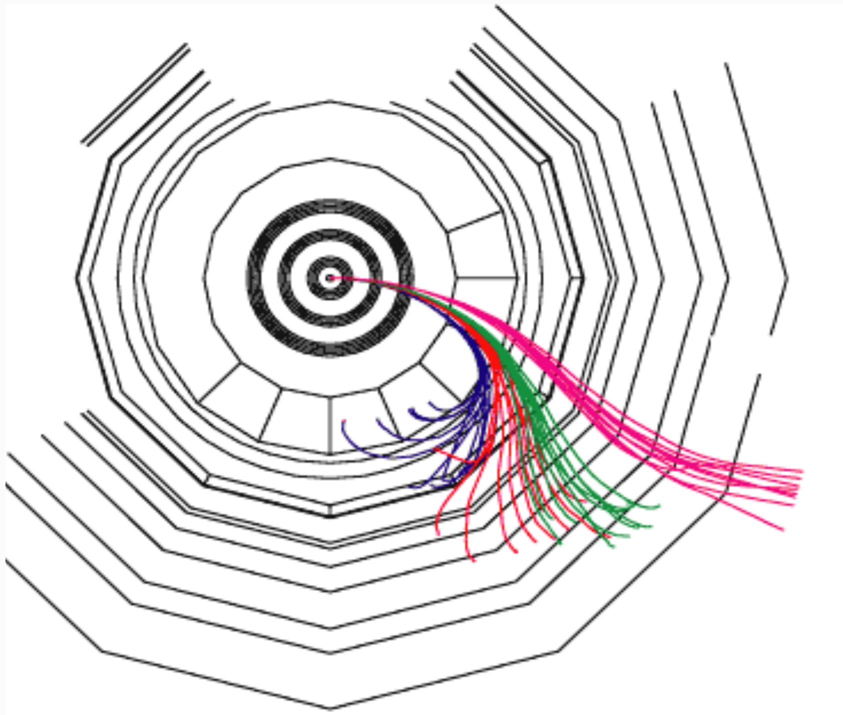

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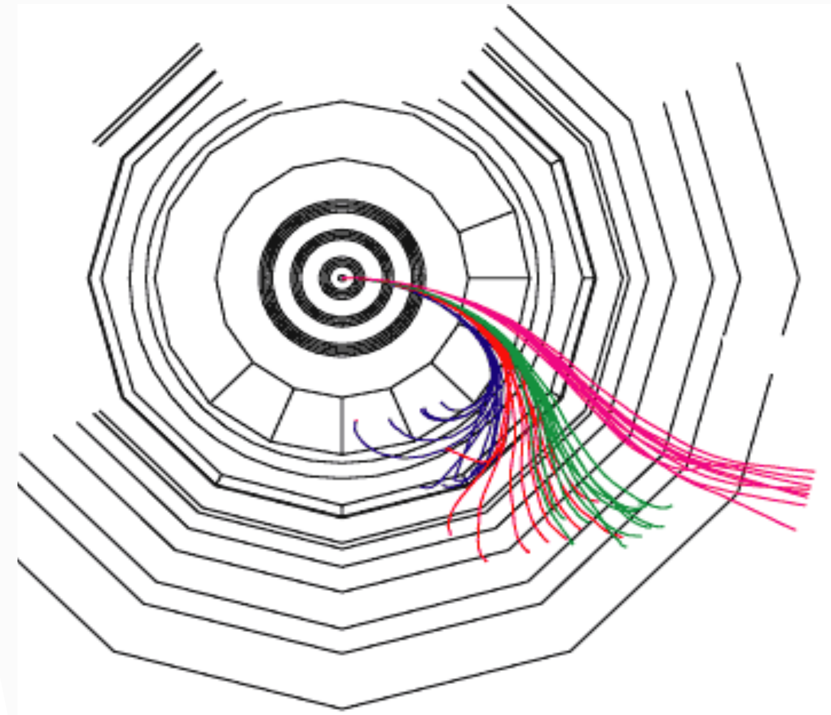
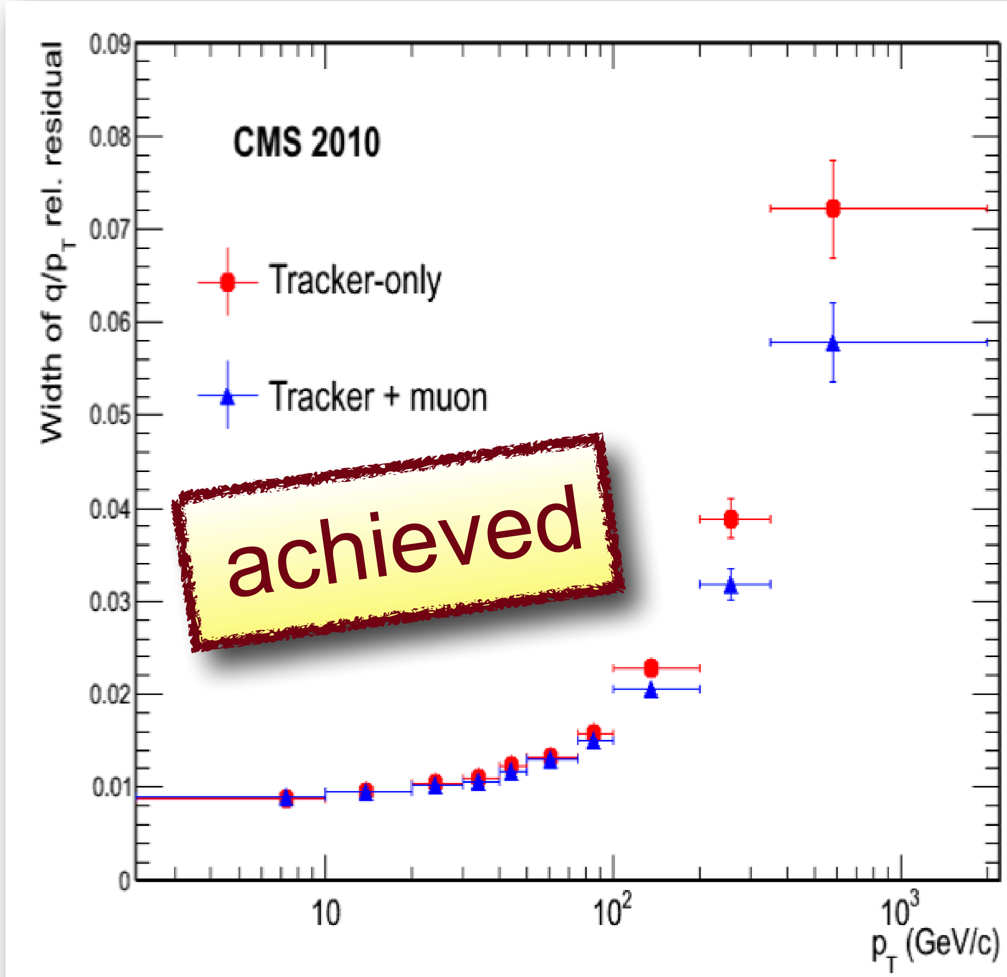


p_t = 3.5, 4.0, 4.5, 6.0 GeV



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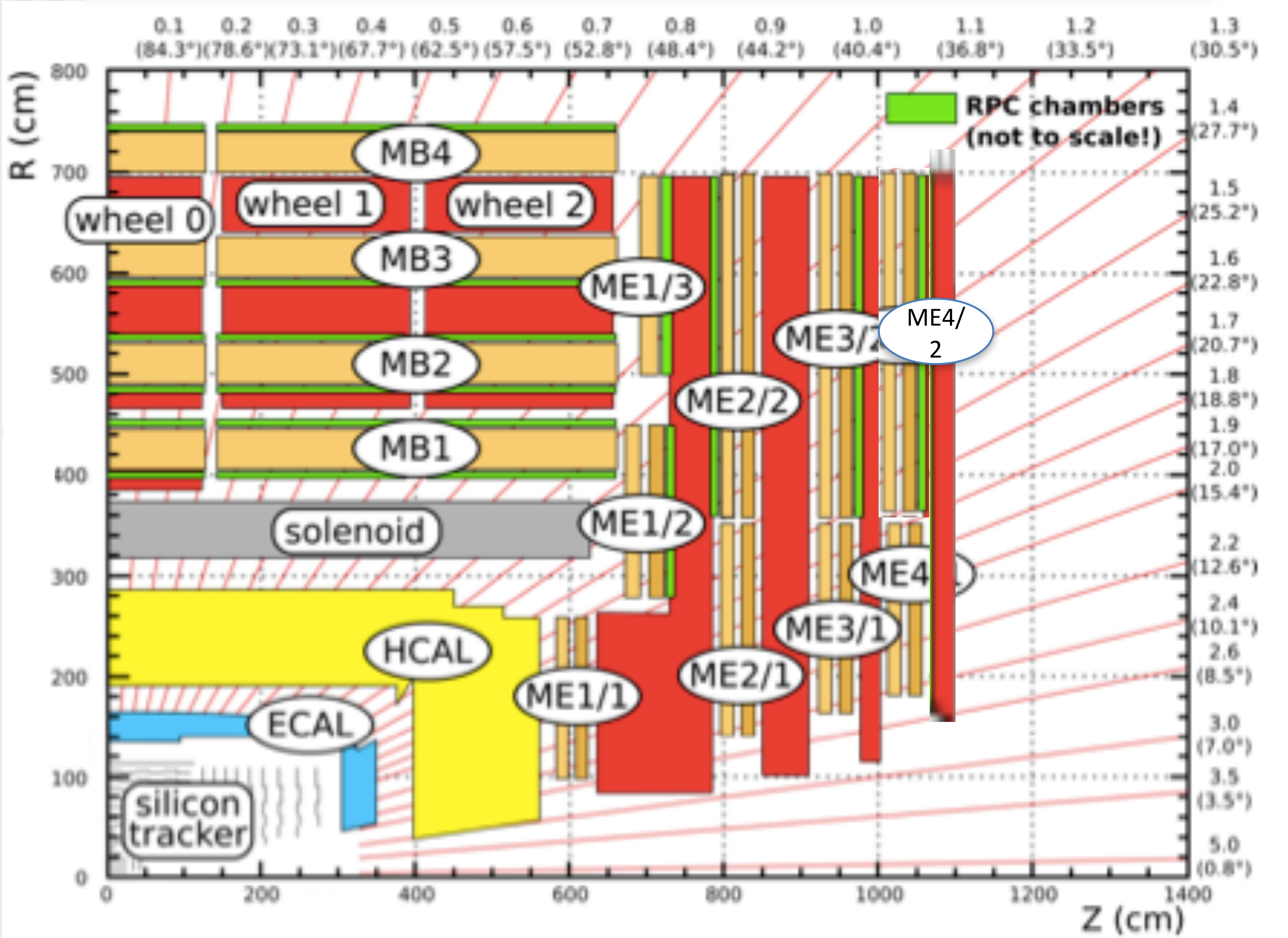
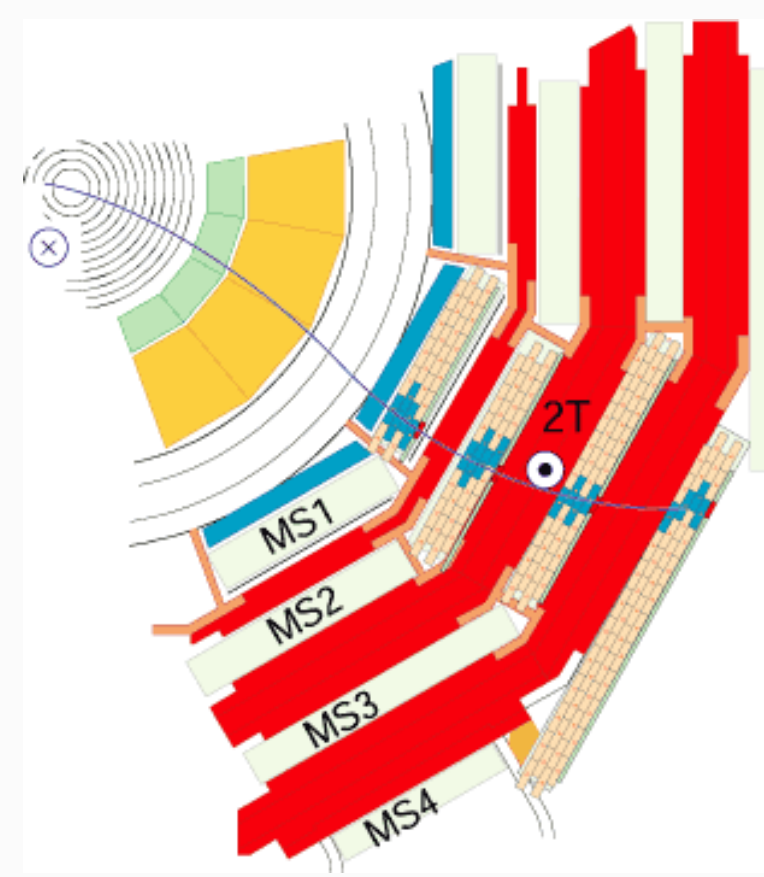


12 ktons of iron absorber and B-field flux return

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

Sophisticated alignment system



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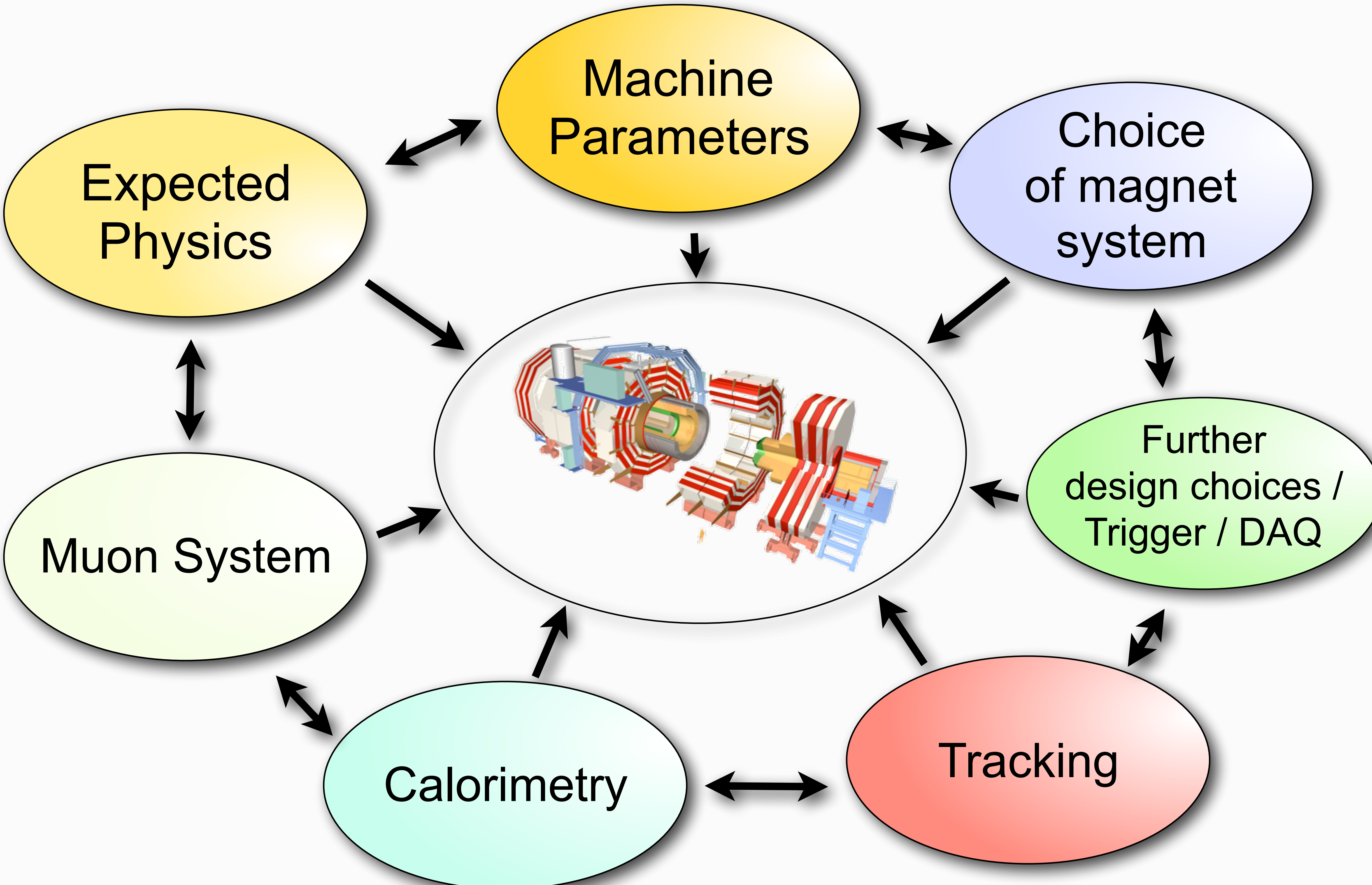

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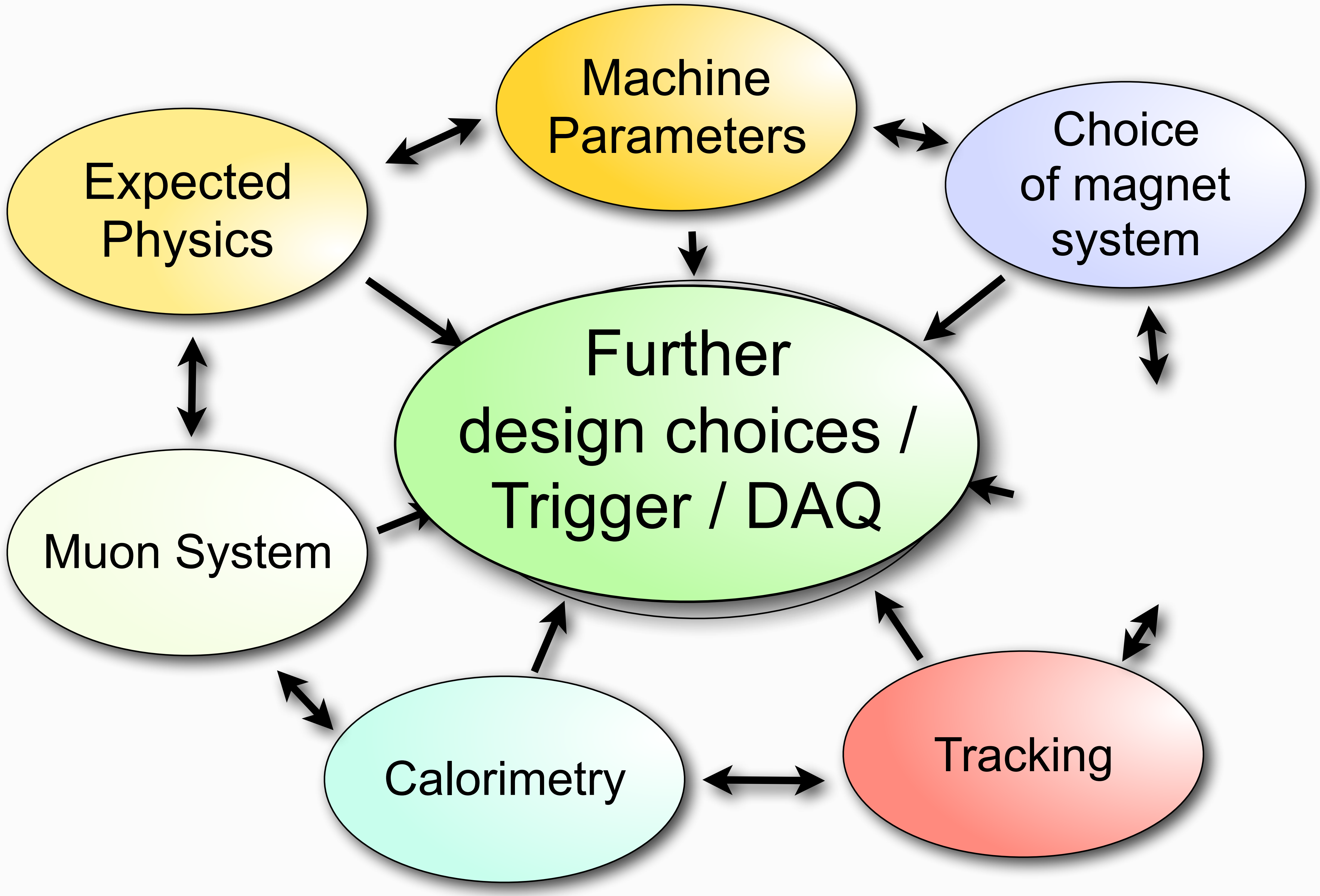
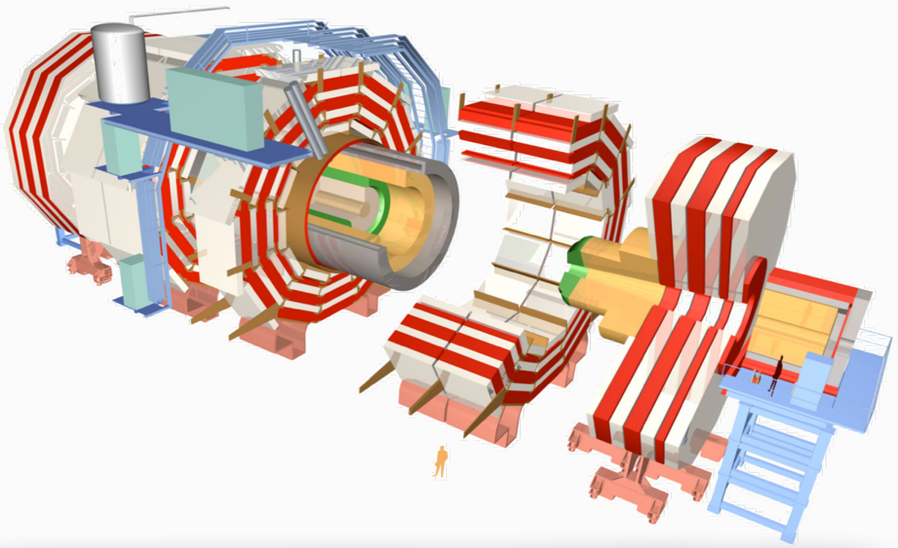
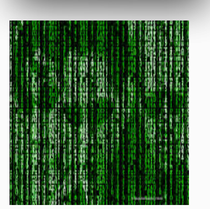


The Trigger / DAQ Challenge





Finite Bandwidth !

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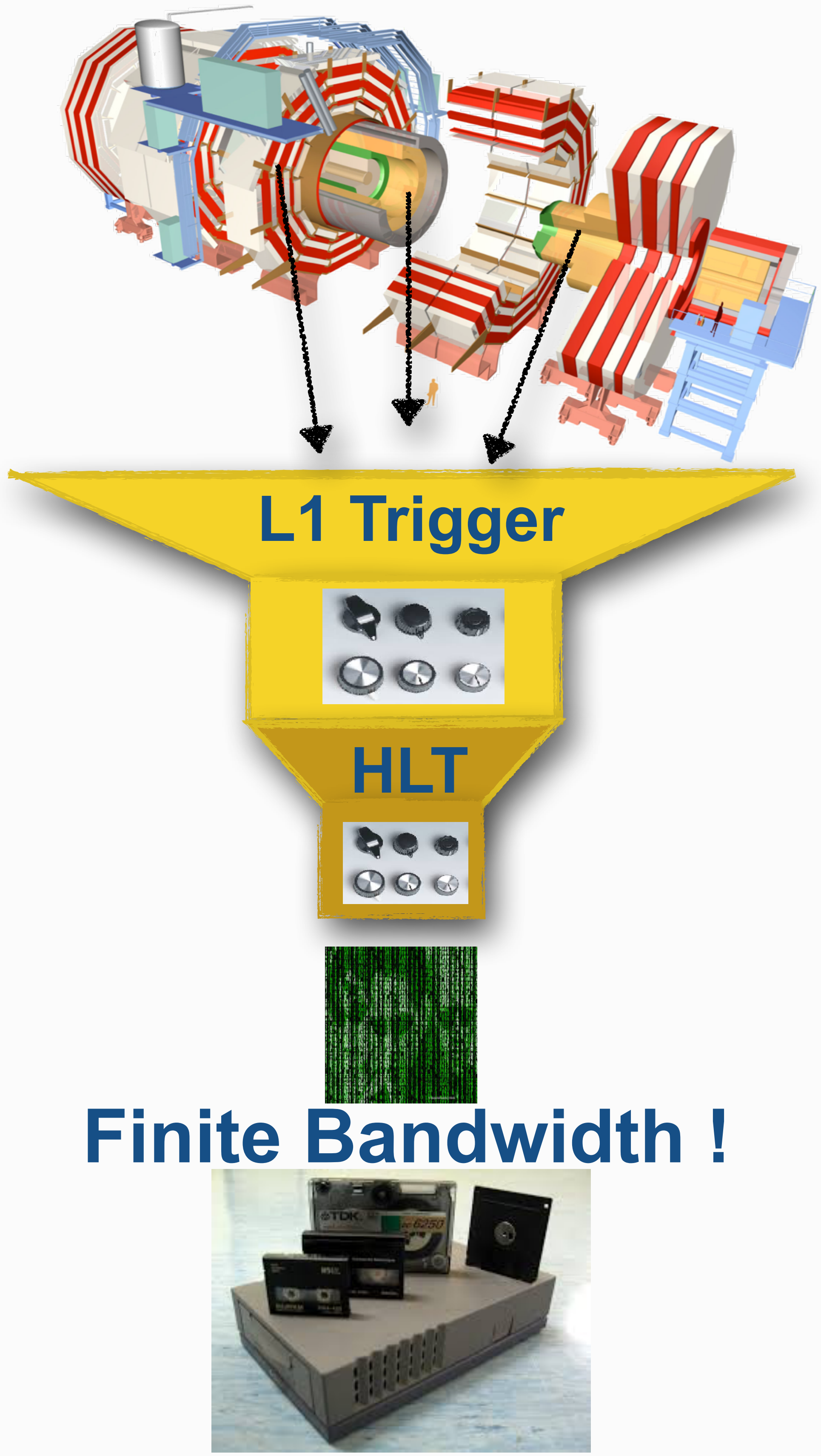

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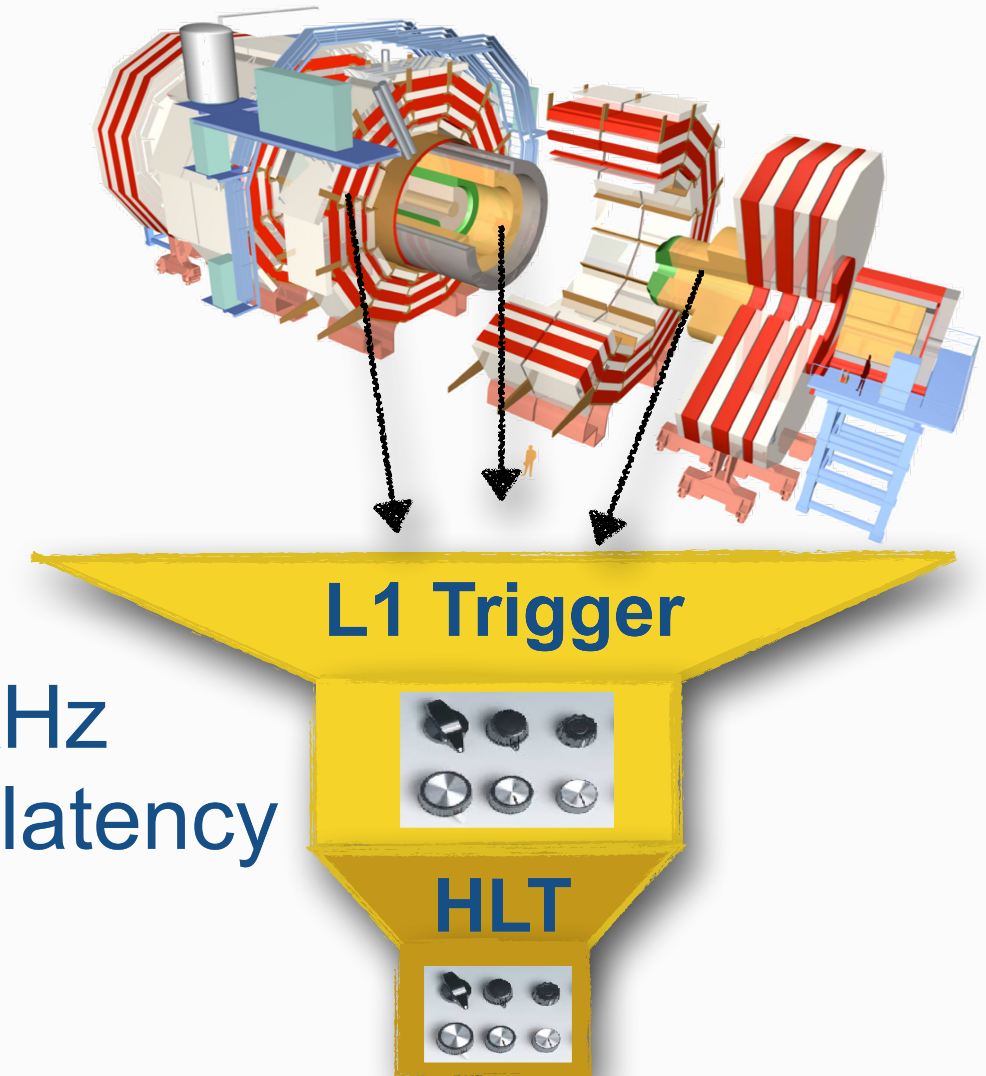
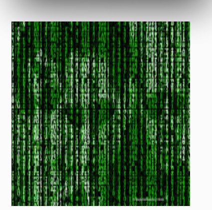


~100 kHz
3.6 μs latency

~1000 Hz



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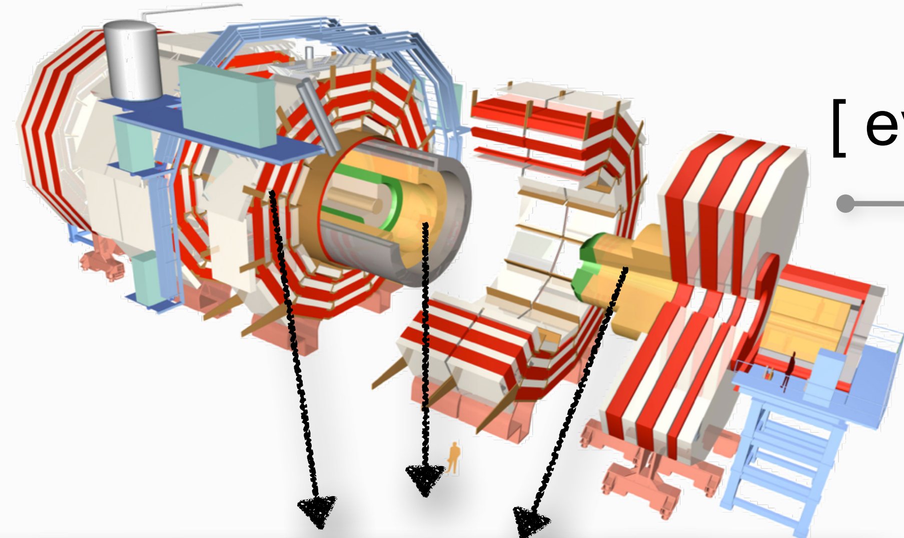

Detector signals
[every 25 ns = 40 MHz]

Front-end pipelines

Level-1

Readout buffers

Switching network

Processor farms

HLT

Mass storage

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3.6 μs latency

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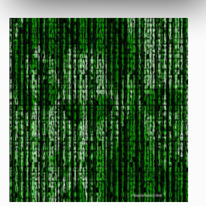

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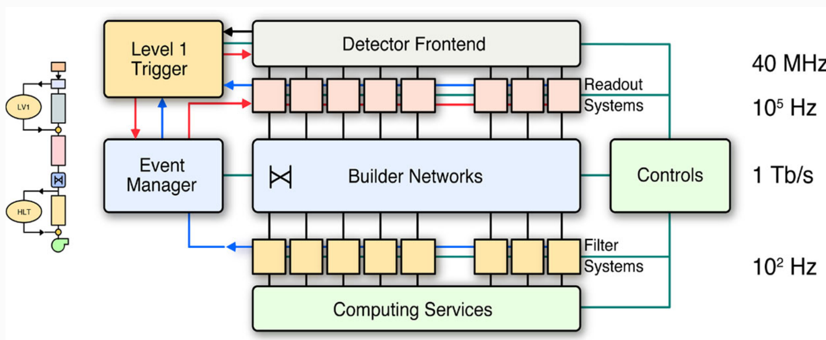


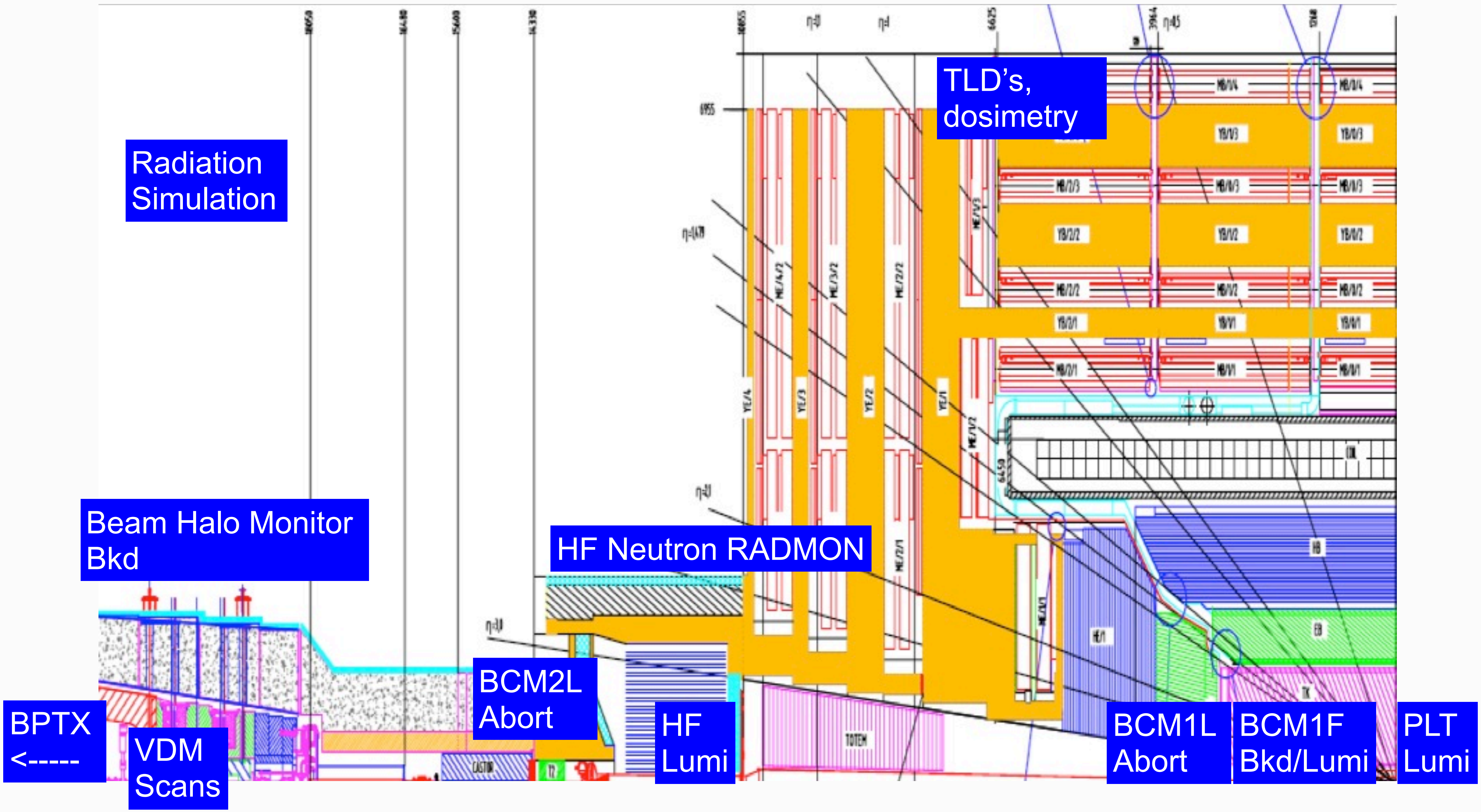
~ 2000 CPUs farm,
full event available,
"offline quality" reconstruction
same software as offline
maximal flexibility

BRIL : caring about the Beam

Beam **R**adiation **I**nstrumentation and **L**uminosity

CMS induction , T. Camporesi

Covering anything related to interfacing CMS to the LHC



Design choices: Some examples...

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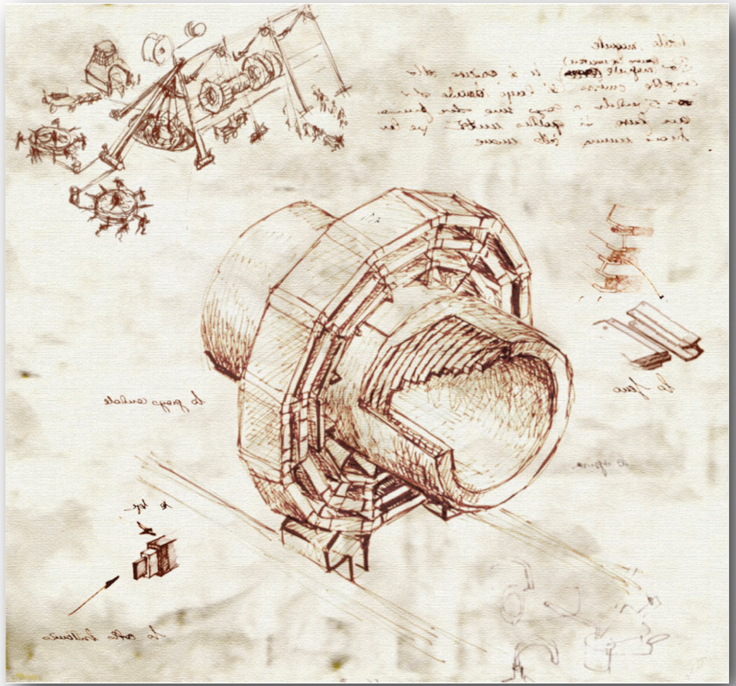
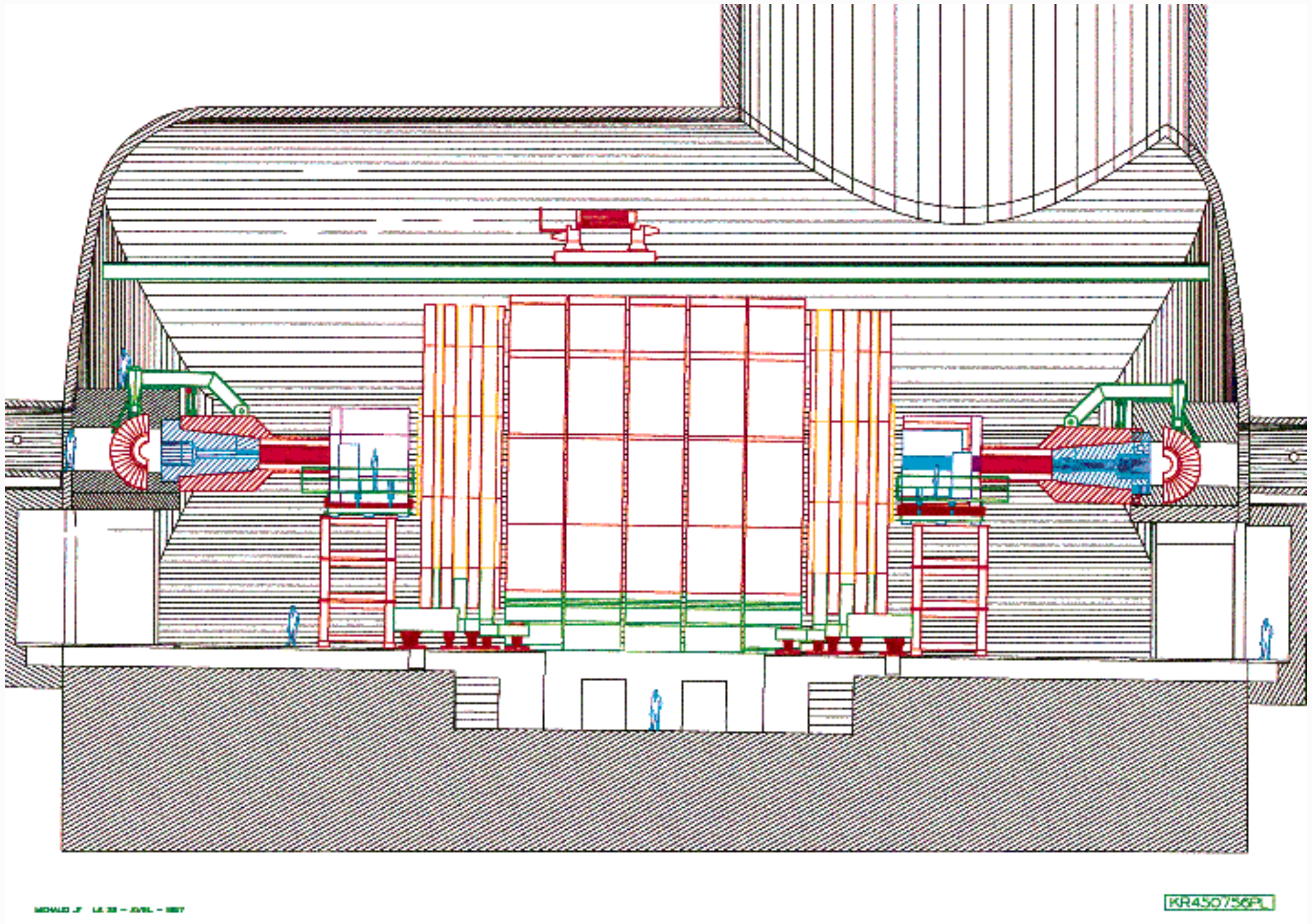
  - eg. CMS Barrel 13m long:
    not possible to build such long muon-chambers
  - Idea of wheels. All cabling independent. Flexibility.





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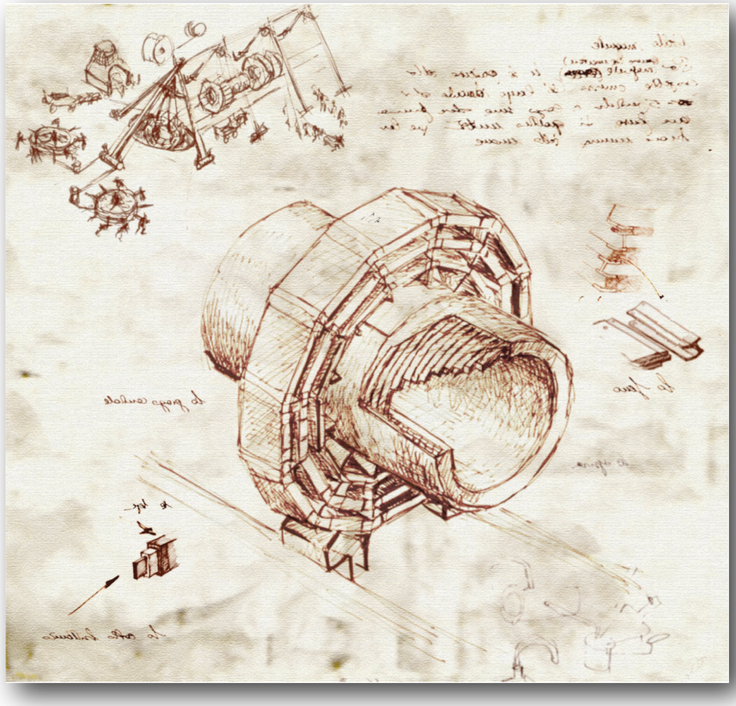

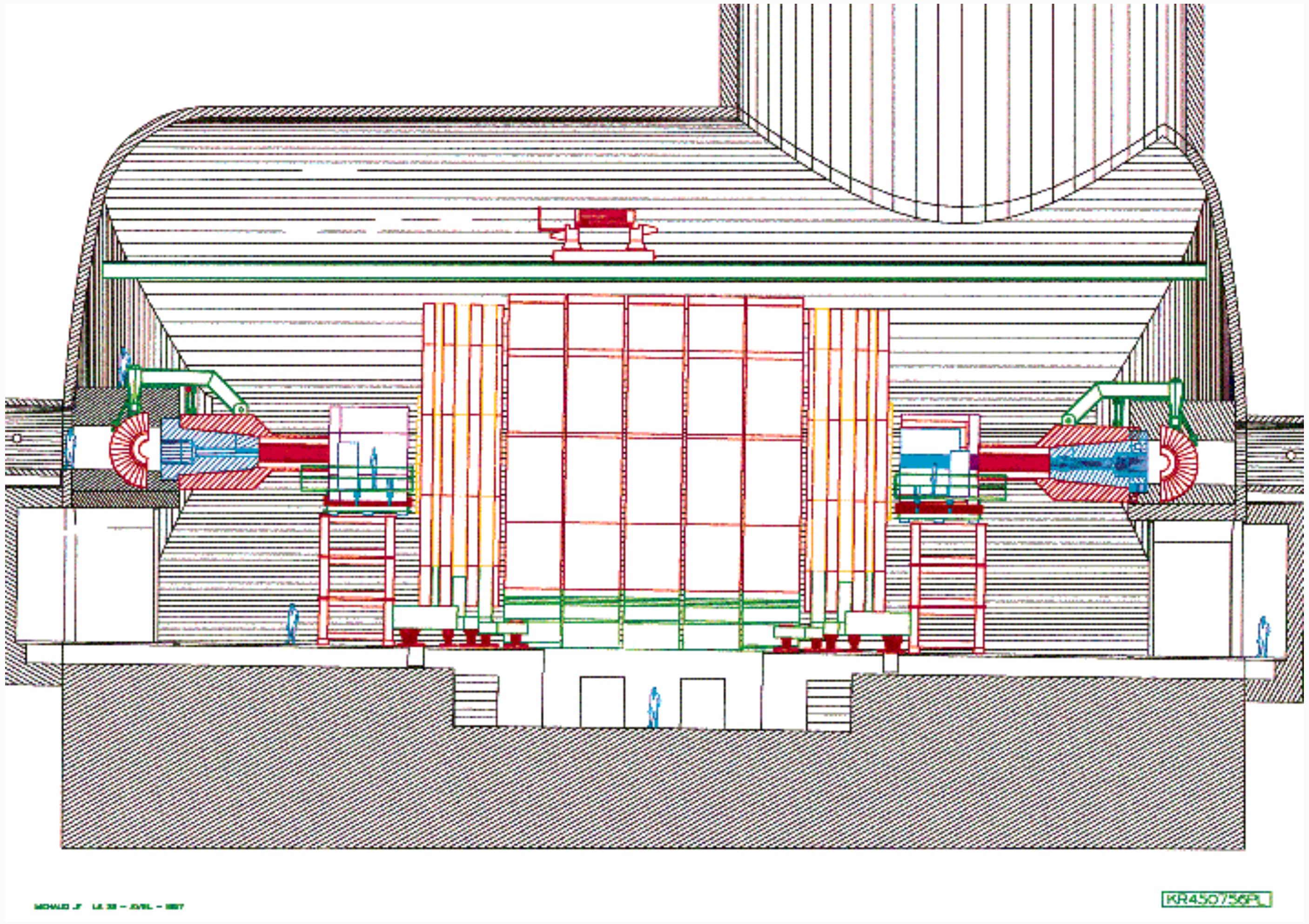

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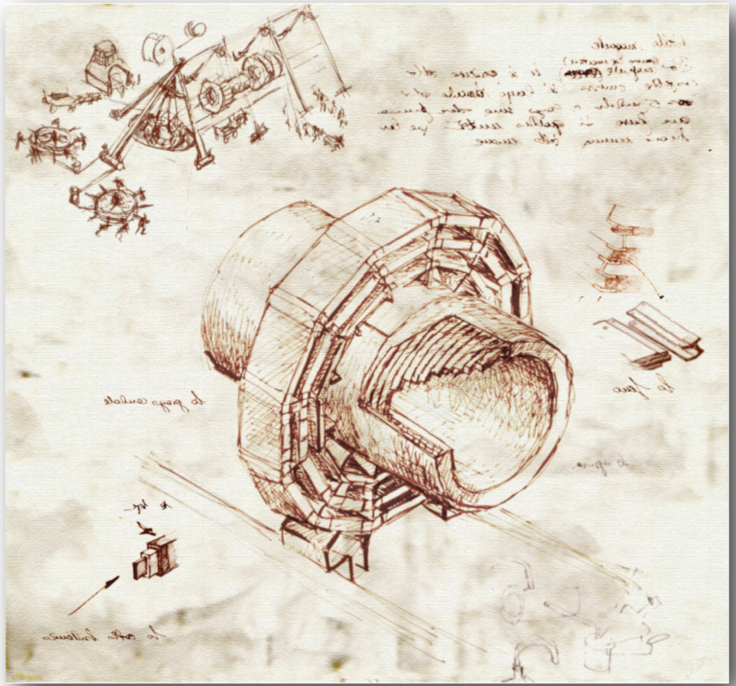

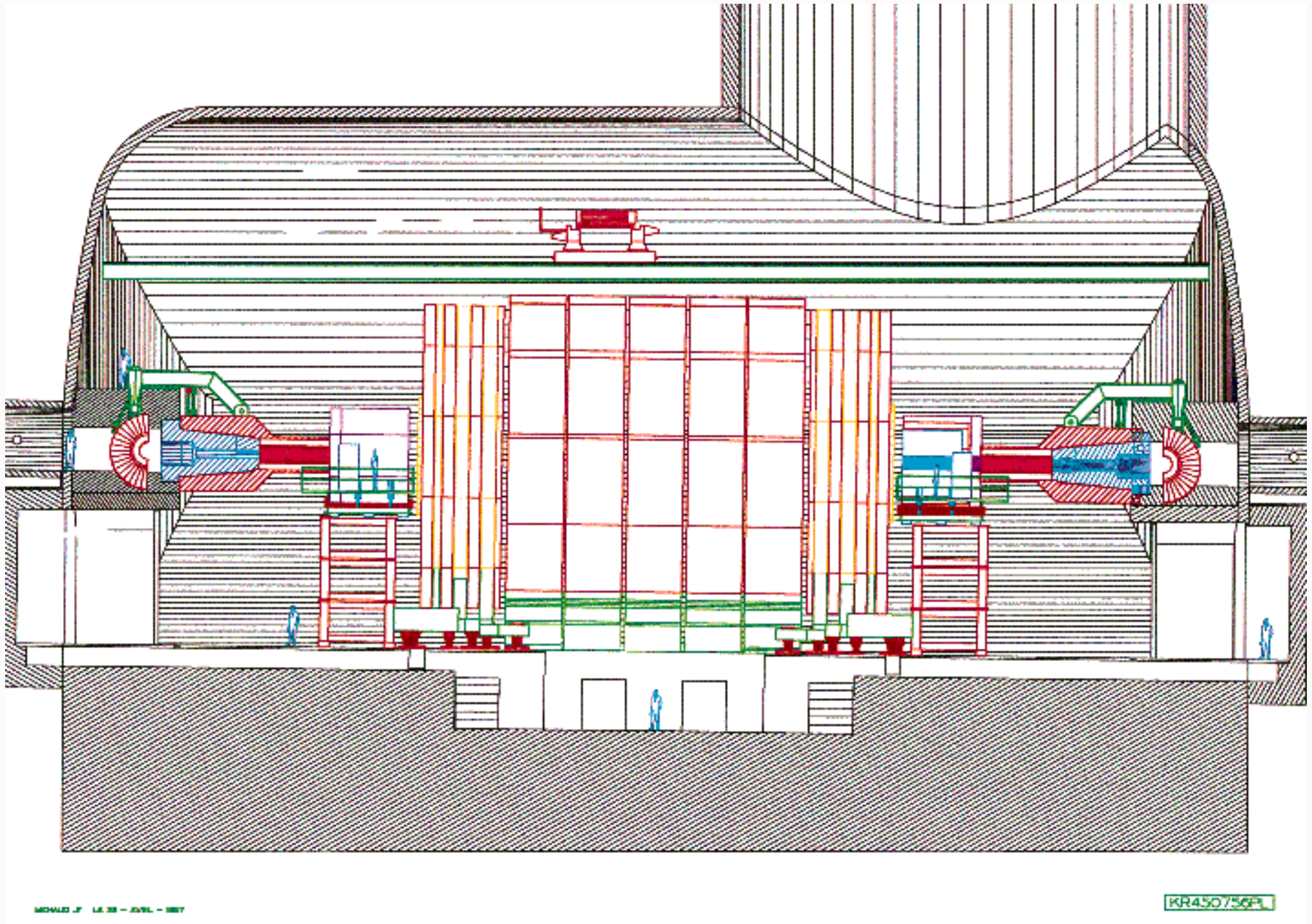

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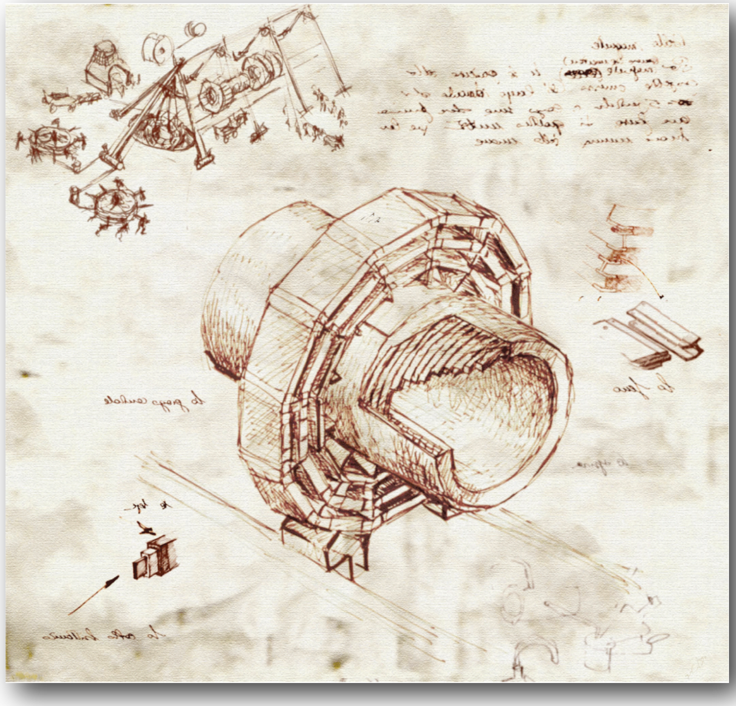

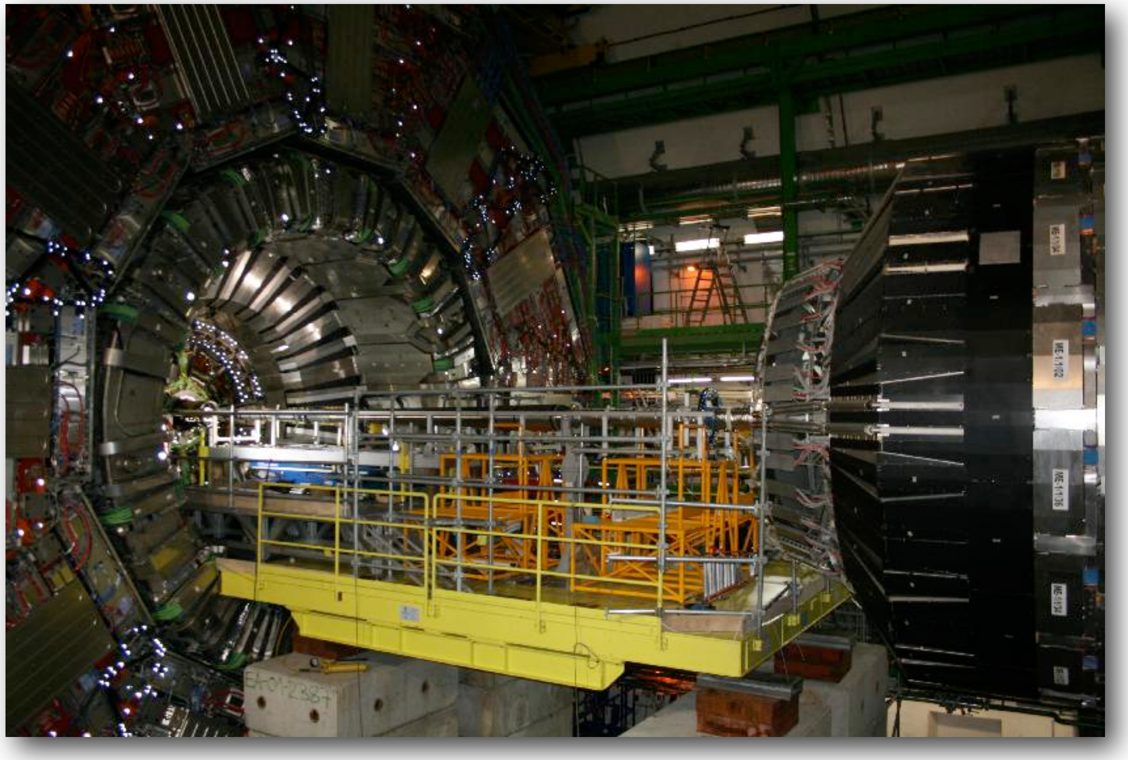

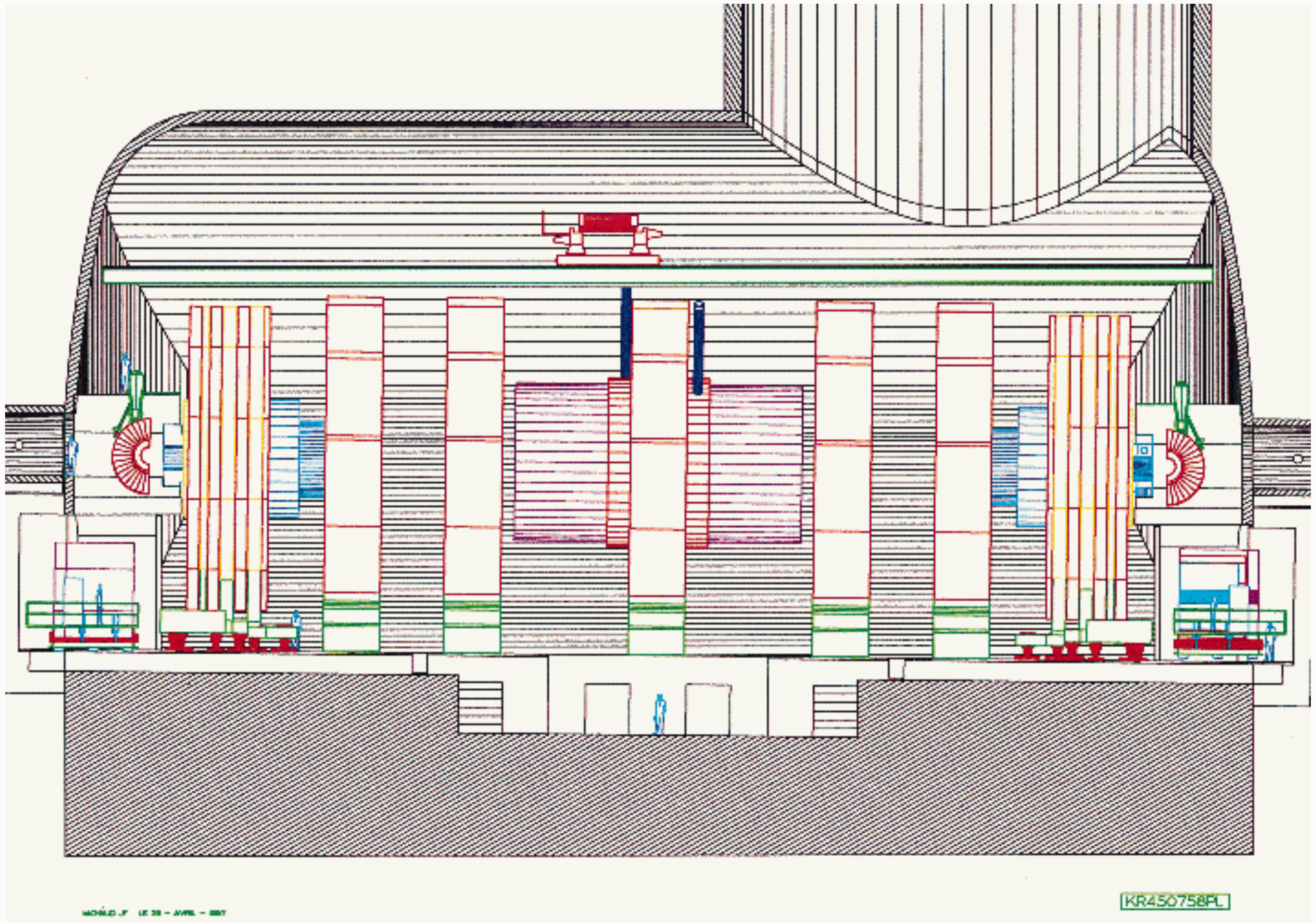

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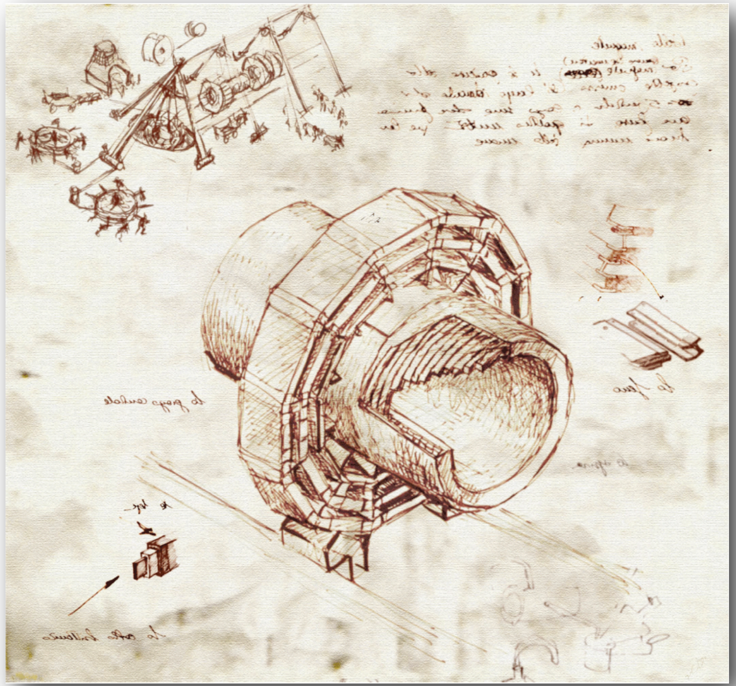
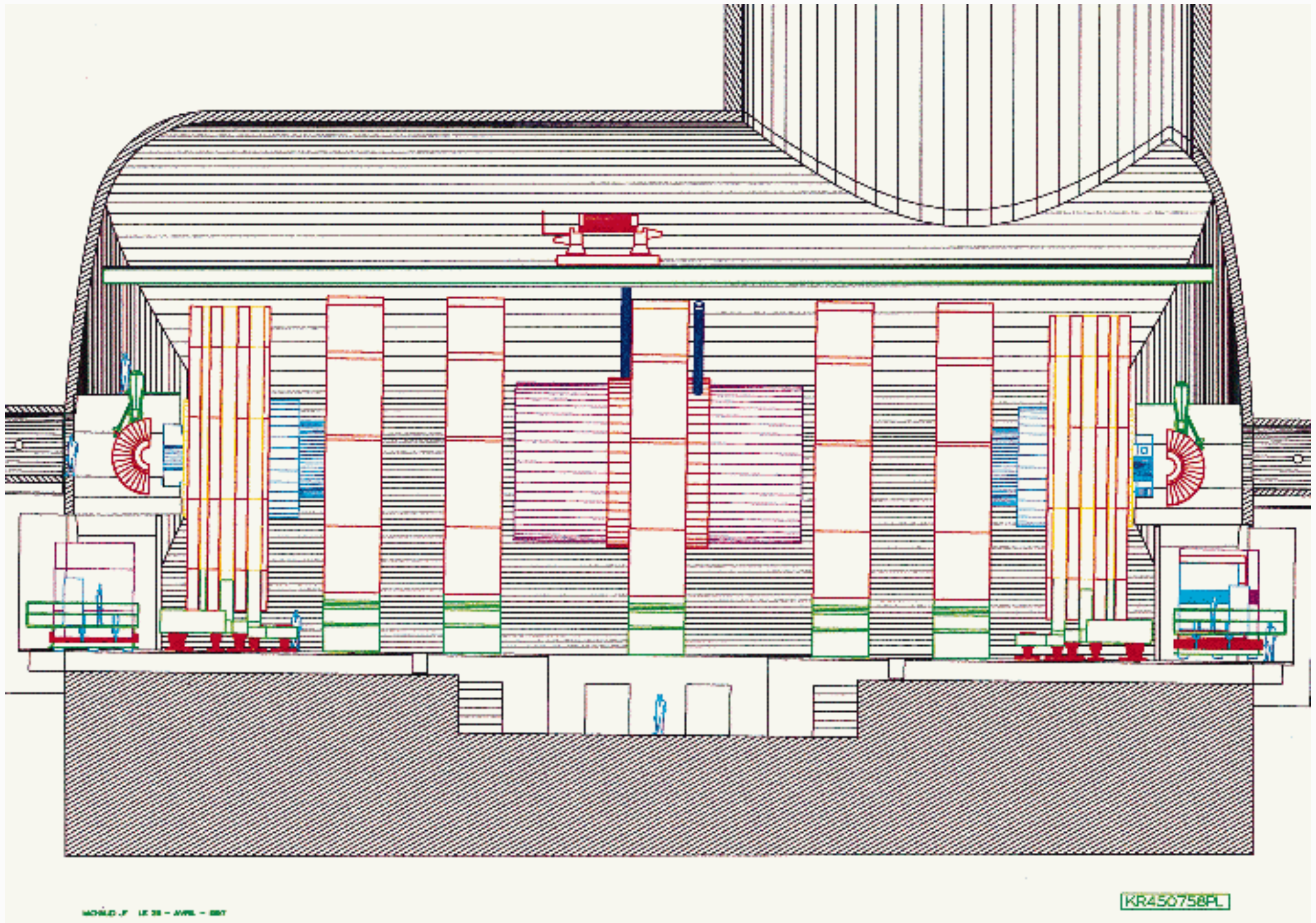
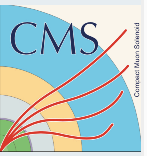




Finally:
The Detector

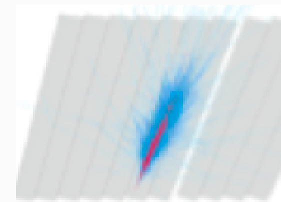
Compact Muon Solenoid

Superconducting Coil, 3.8 Tesla

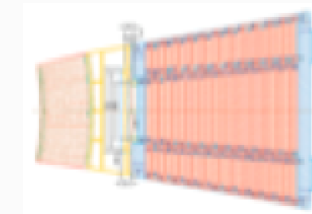


CALORIMETERS

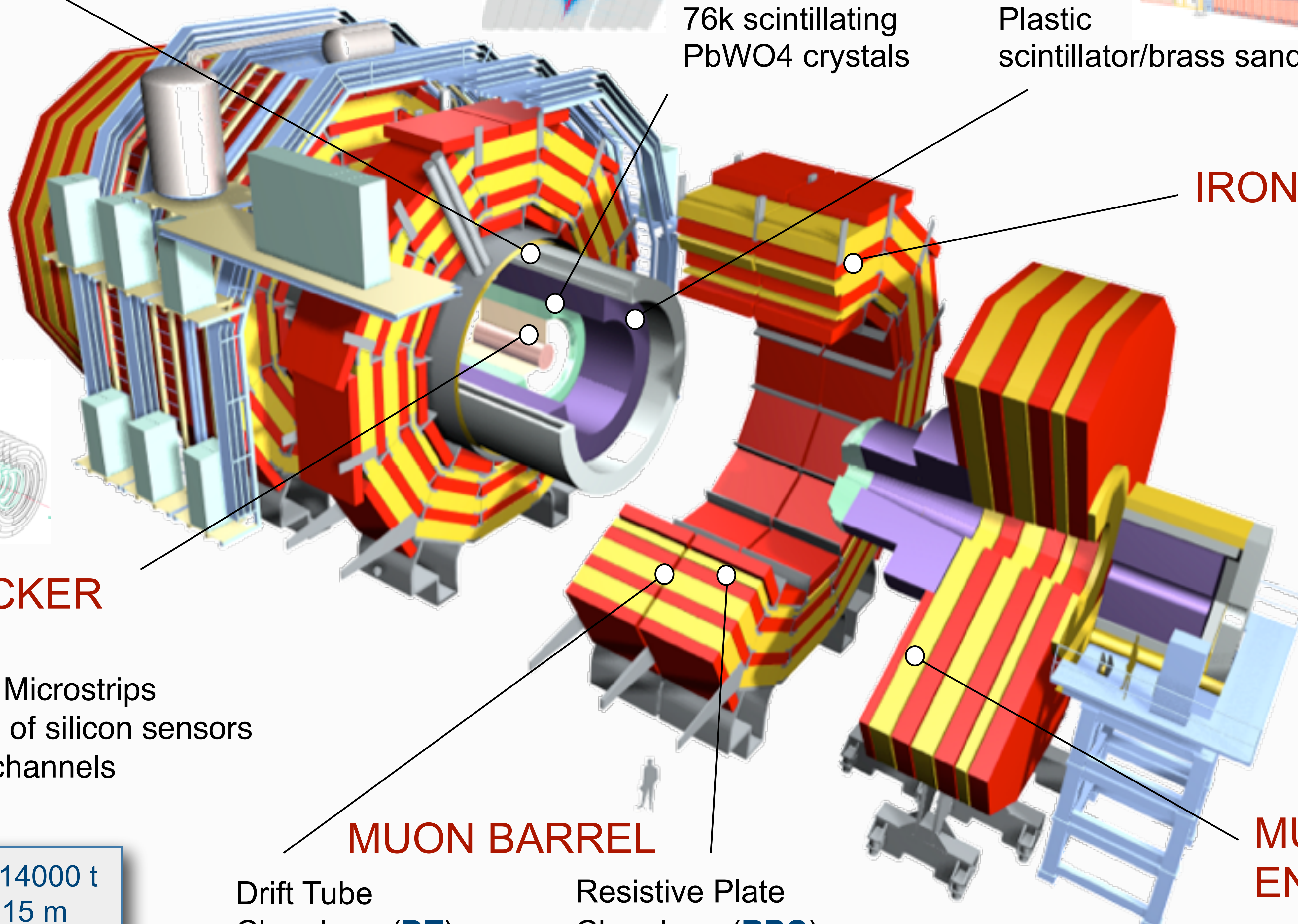
ECAL
76k scintillating PbWO4 crystals



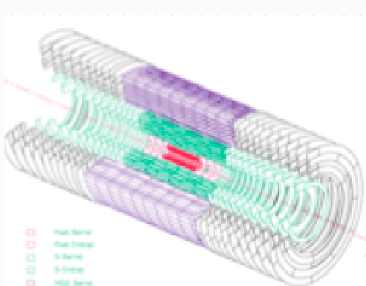
HCAL
Plastic scintillator/brass sandwich



IRON YOKE



TRACKER

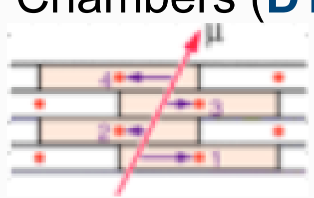


Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6 M channels

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

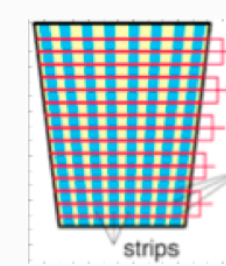
MUON BARREL

Drift Tube Chambers (**DT**)



Resistive Plate Chambers (**RPC**)

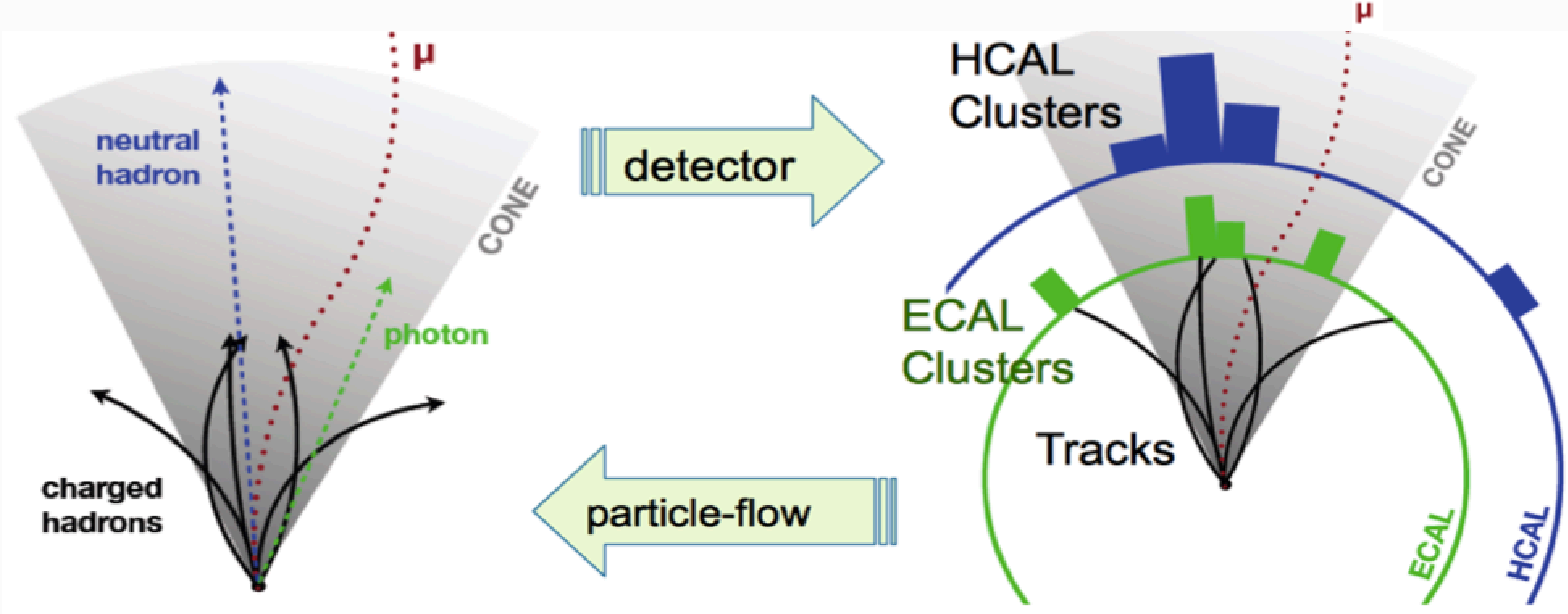
MUON ENDCAPS



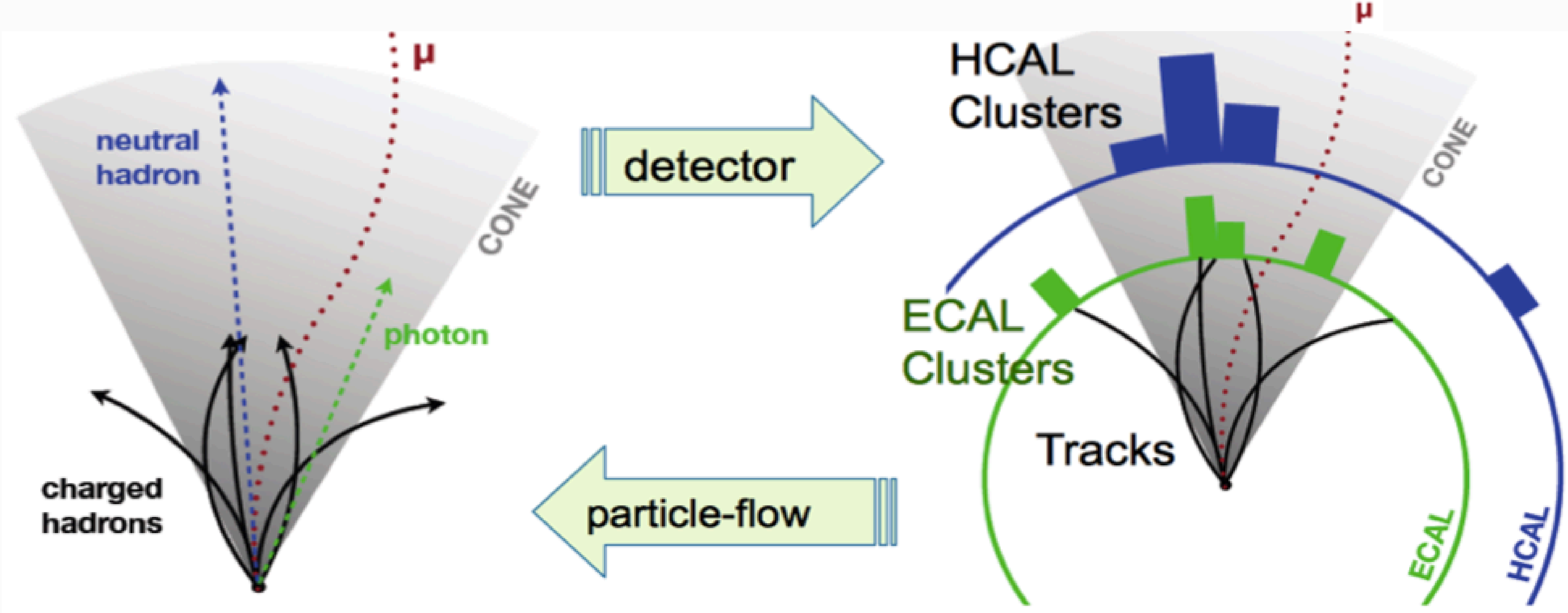
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Particle Flow

Use of global event description



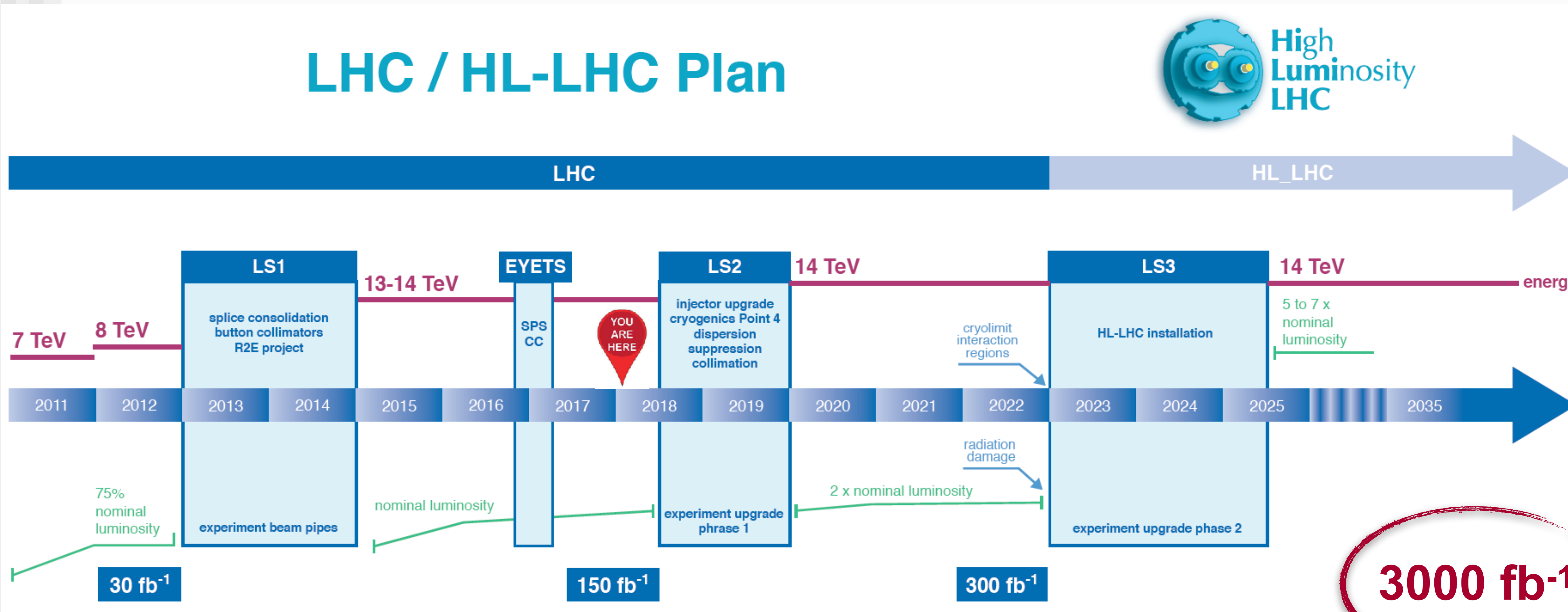
Use of global event description



- 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

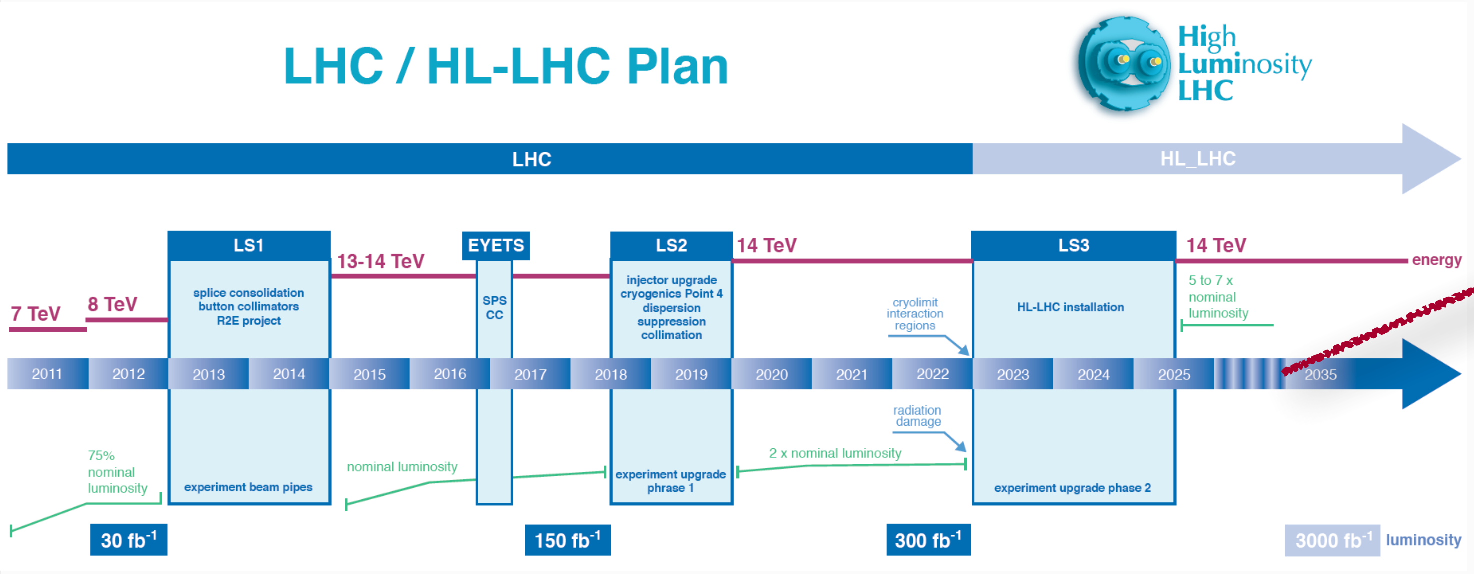
The Plan



3000 fb^{-1}

so far, recorded only <3% of total expected data set !

Pile-up (1)



Luminosities of

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

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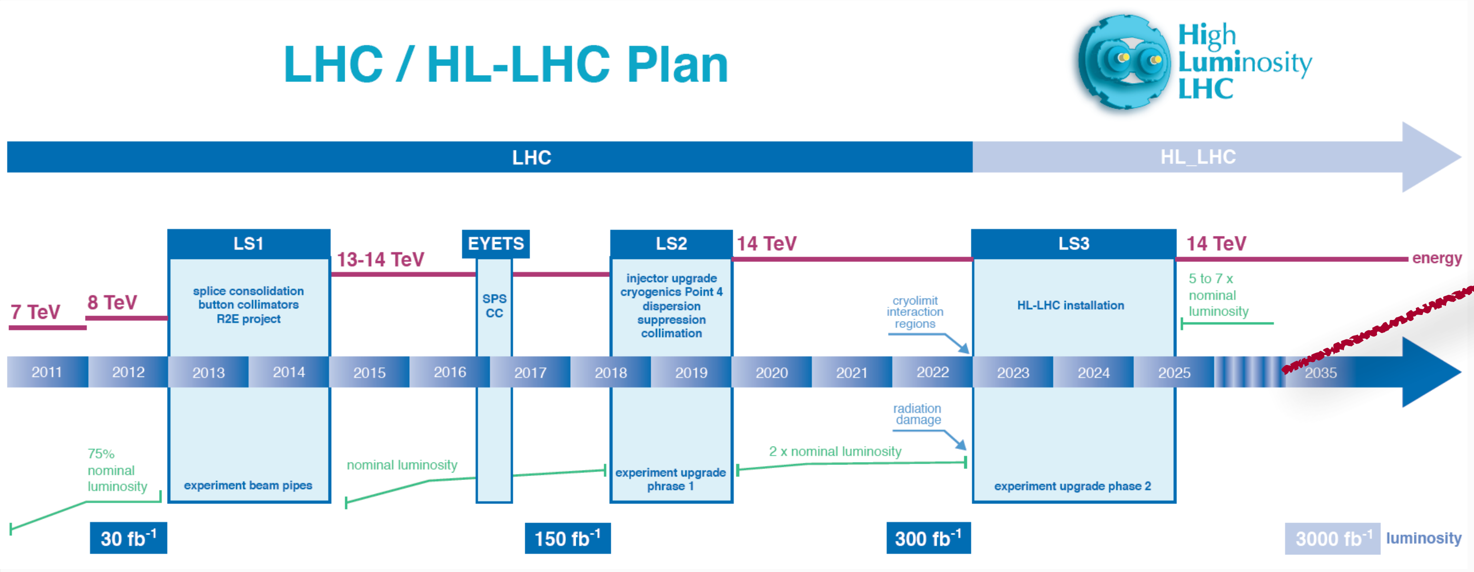

Luminosities of
$L \sim 5 - 7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

Number of simultaneous proton-proton collisions per bunch crossing:

L x total cross section x bunch separation time

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

125 - 190 !

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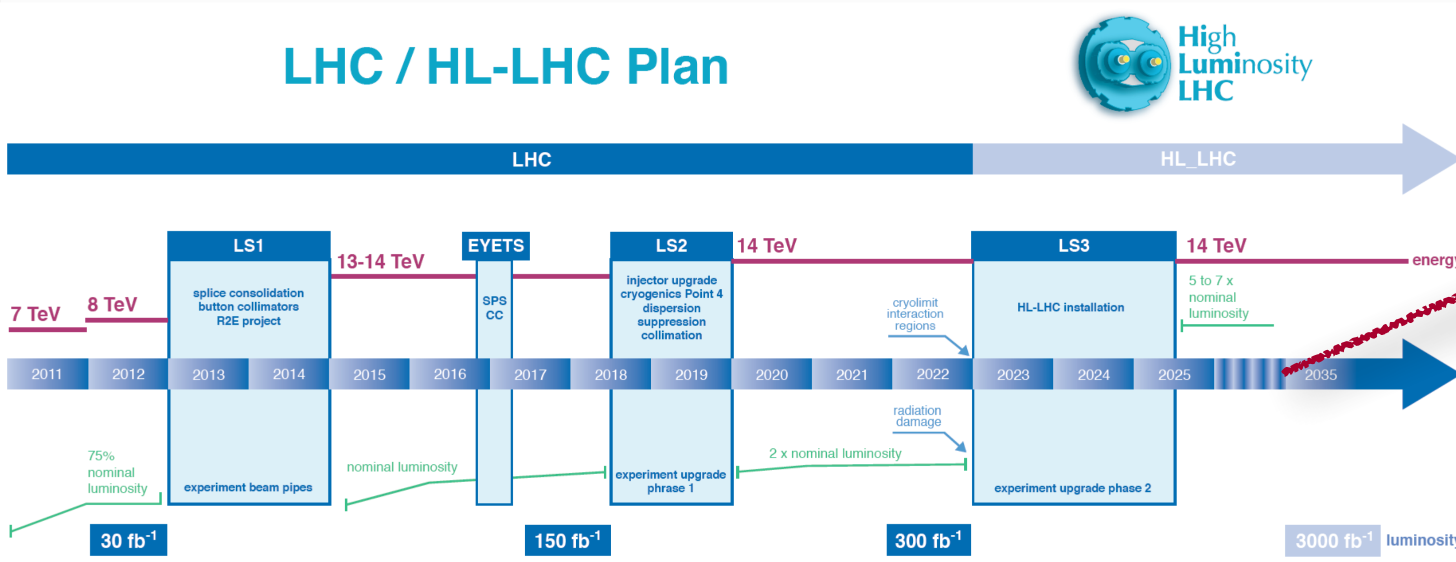

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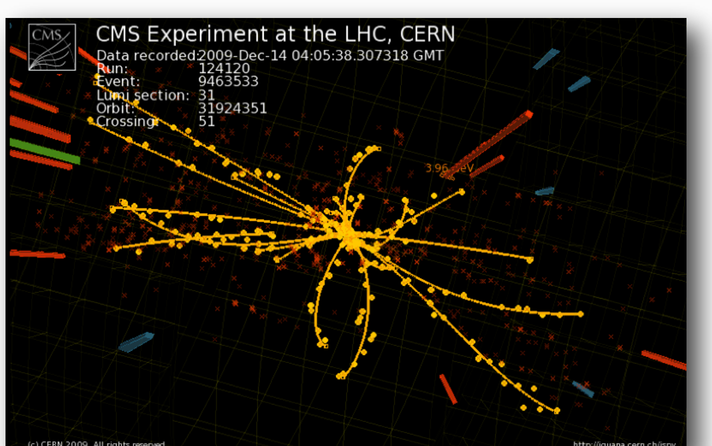
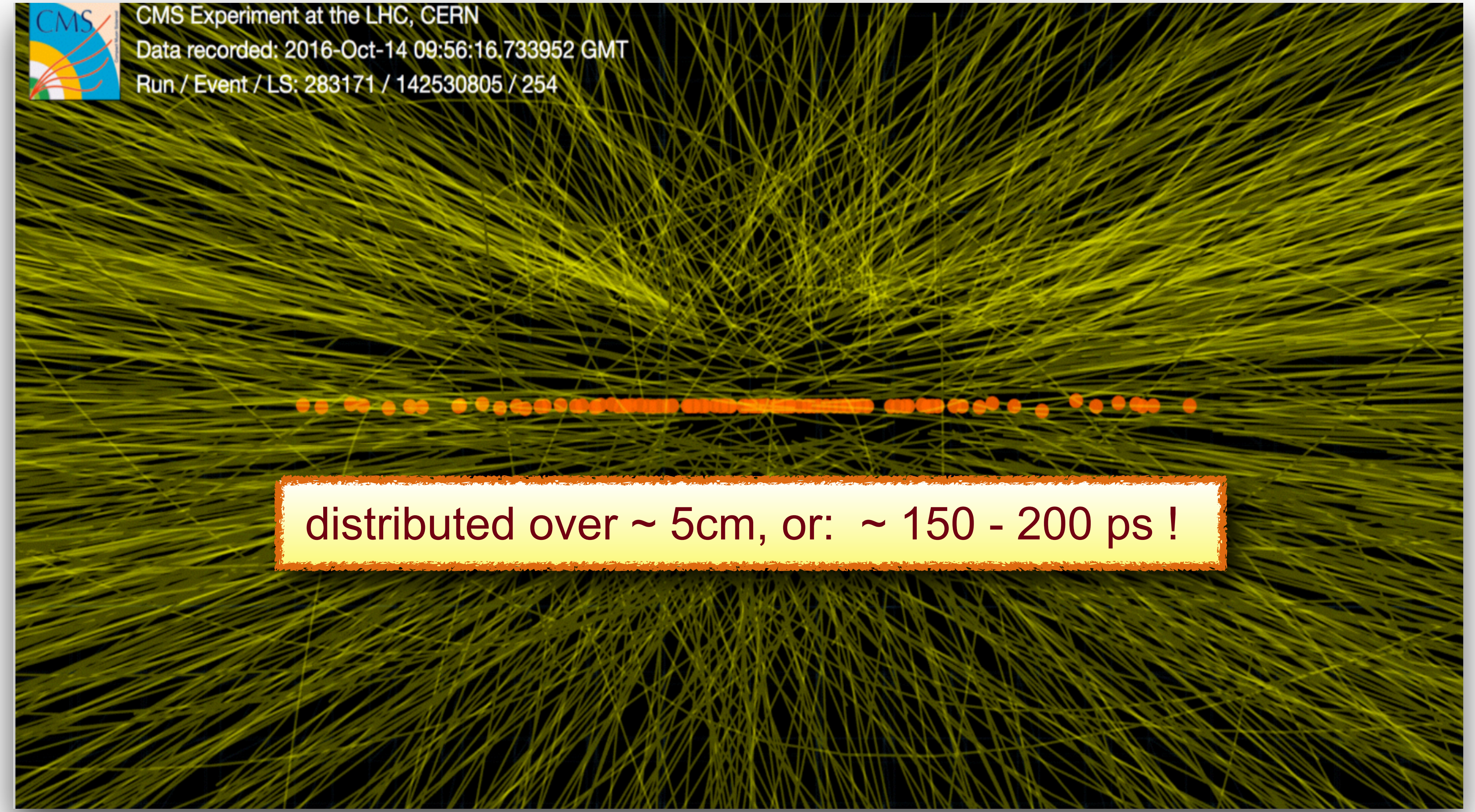


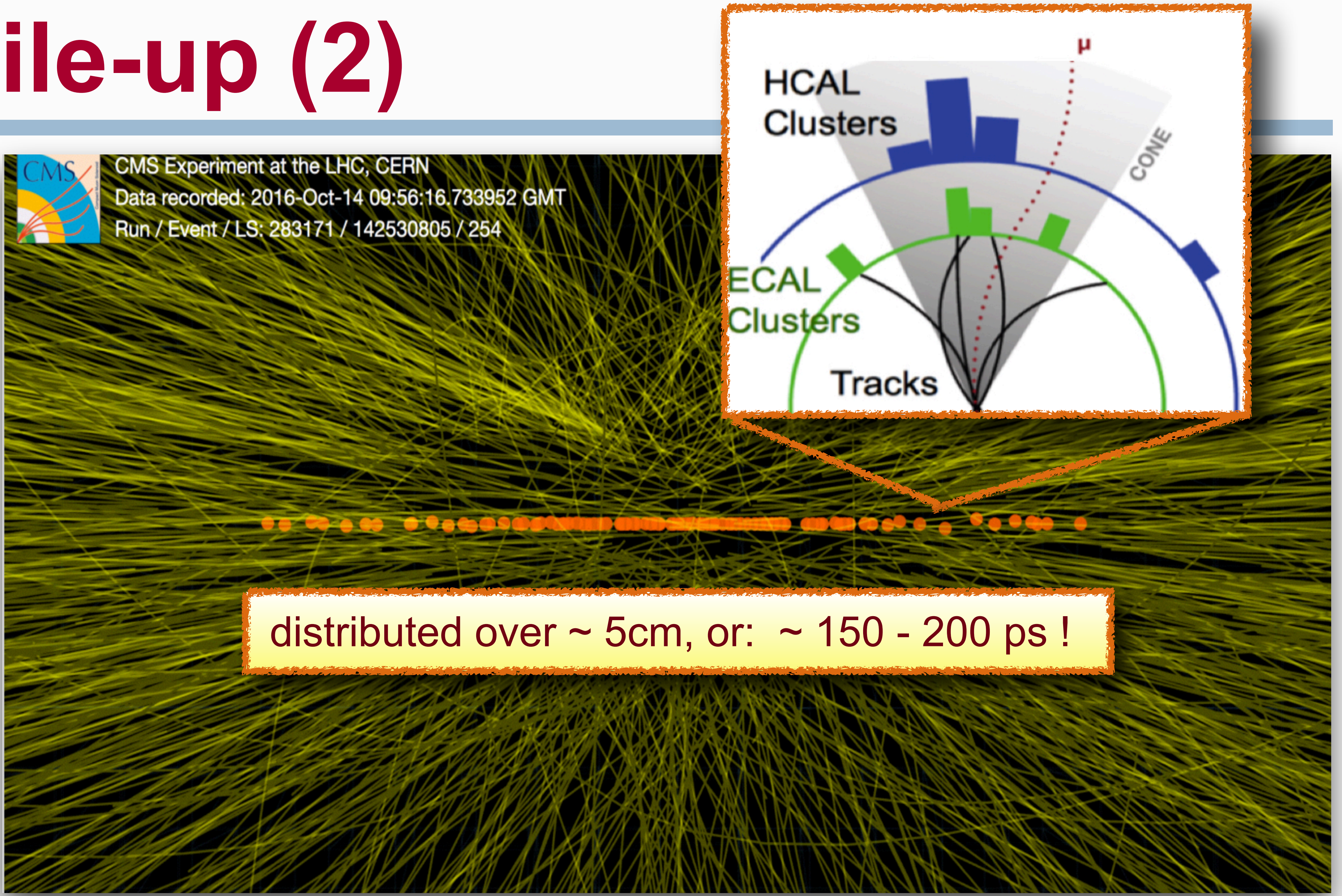
Each of these:
~ 6 charged particles per unit rapidity,
over range of +- 5 units in rapidity:
O(10000) particles per collision !!

Pile-up (2)



precision timing information will help
(adds an extra “dimension”)

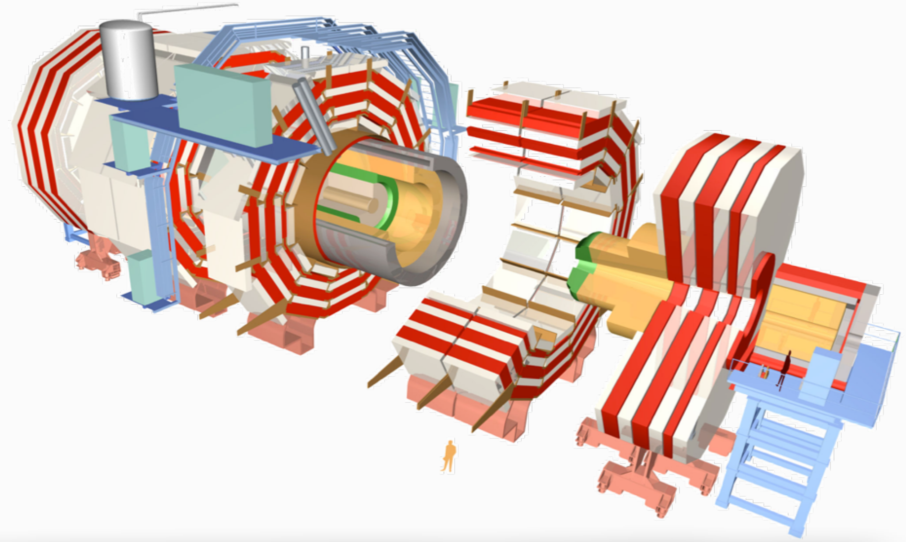
Pile-up (2)



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

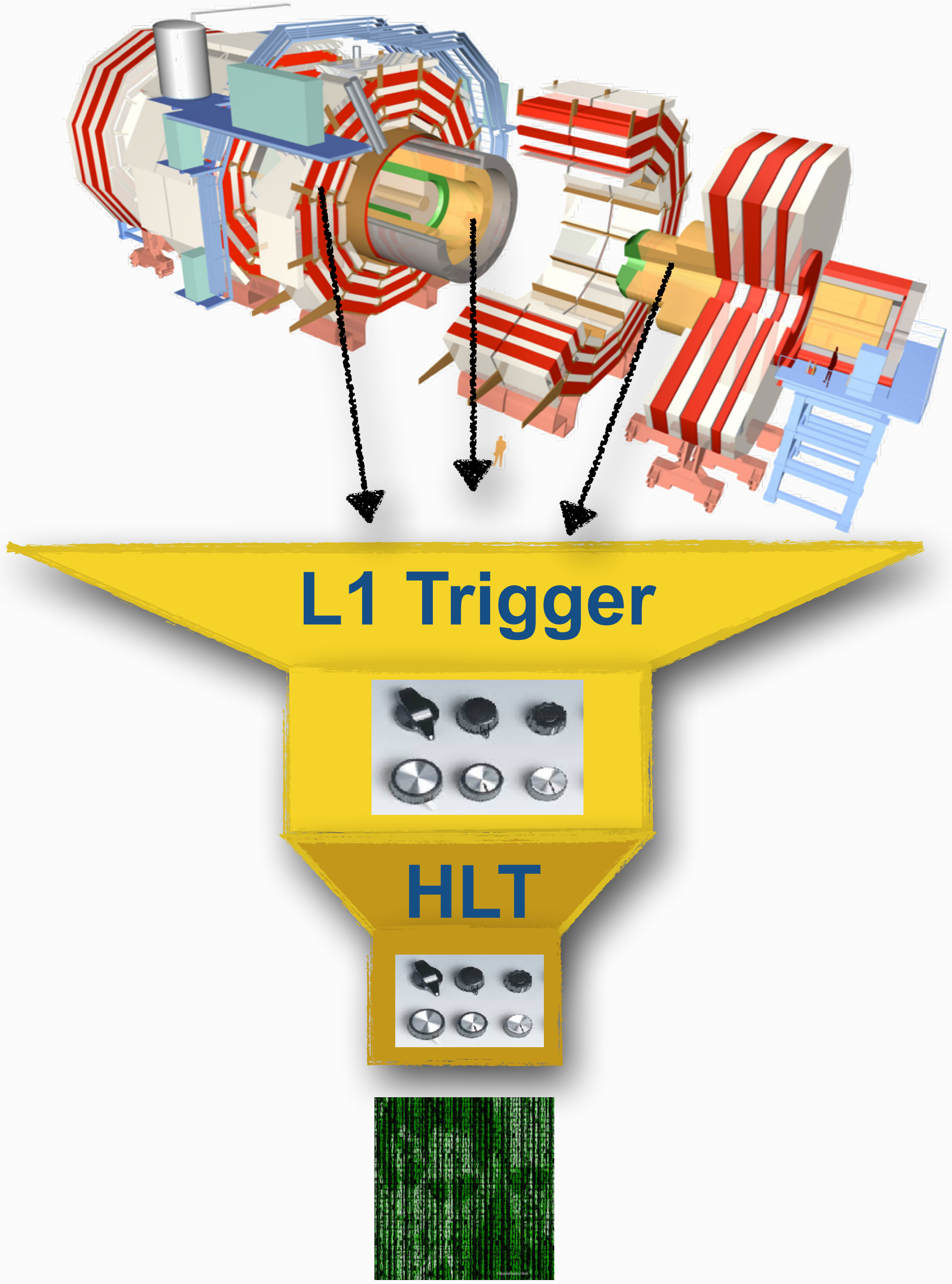
precision timing information will help
(adds an extra “dimension”)

The Trigger Challenge



Finite Bandwidth !

The Trigger Challenge

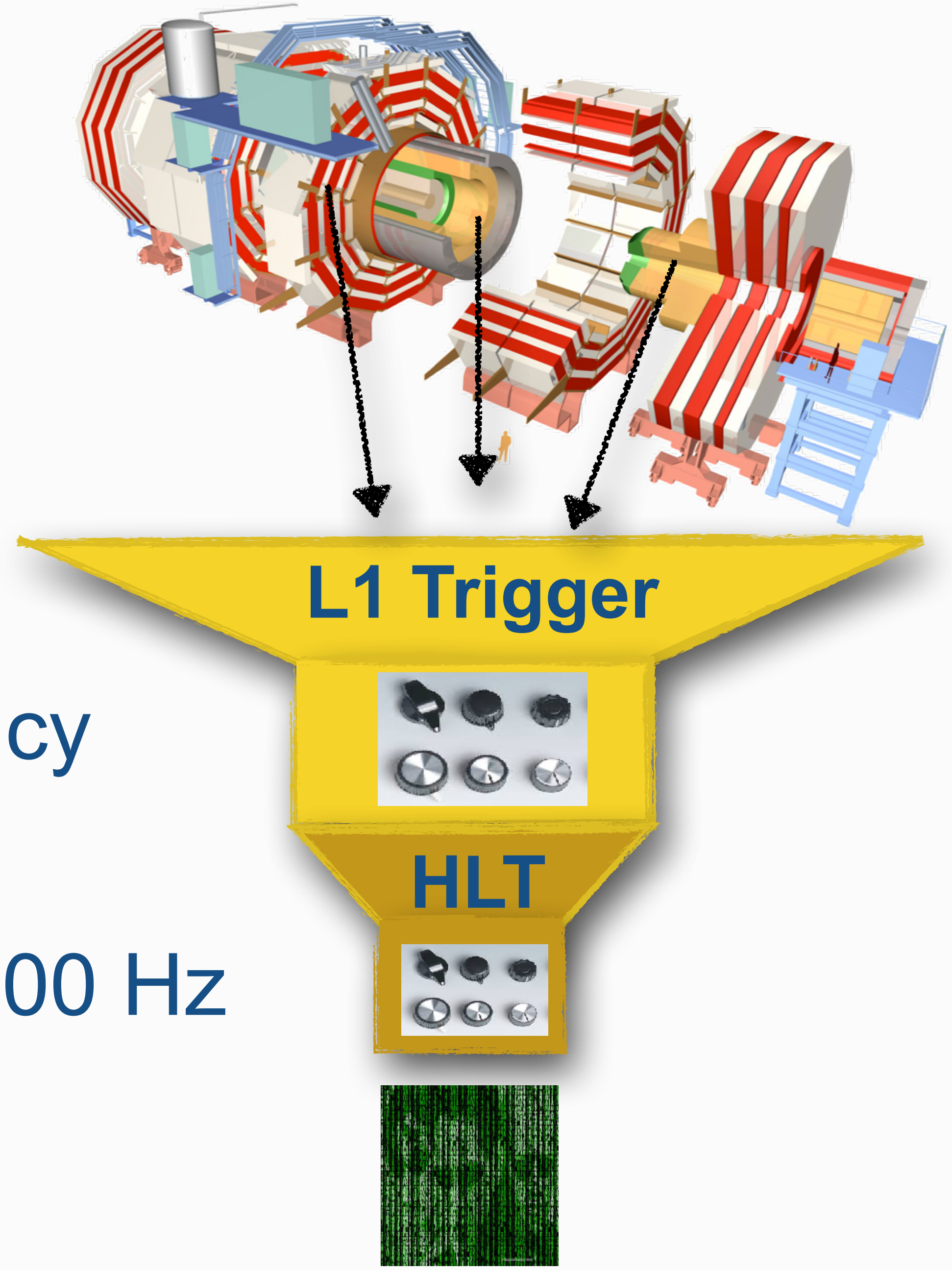


Finite Bandwidth !

The Trigger Challenge

LHC:

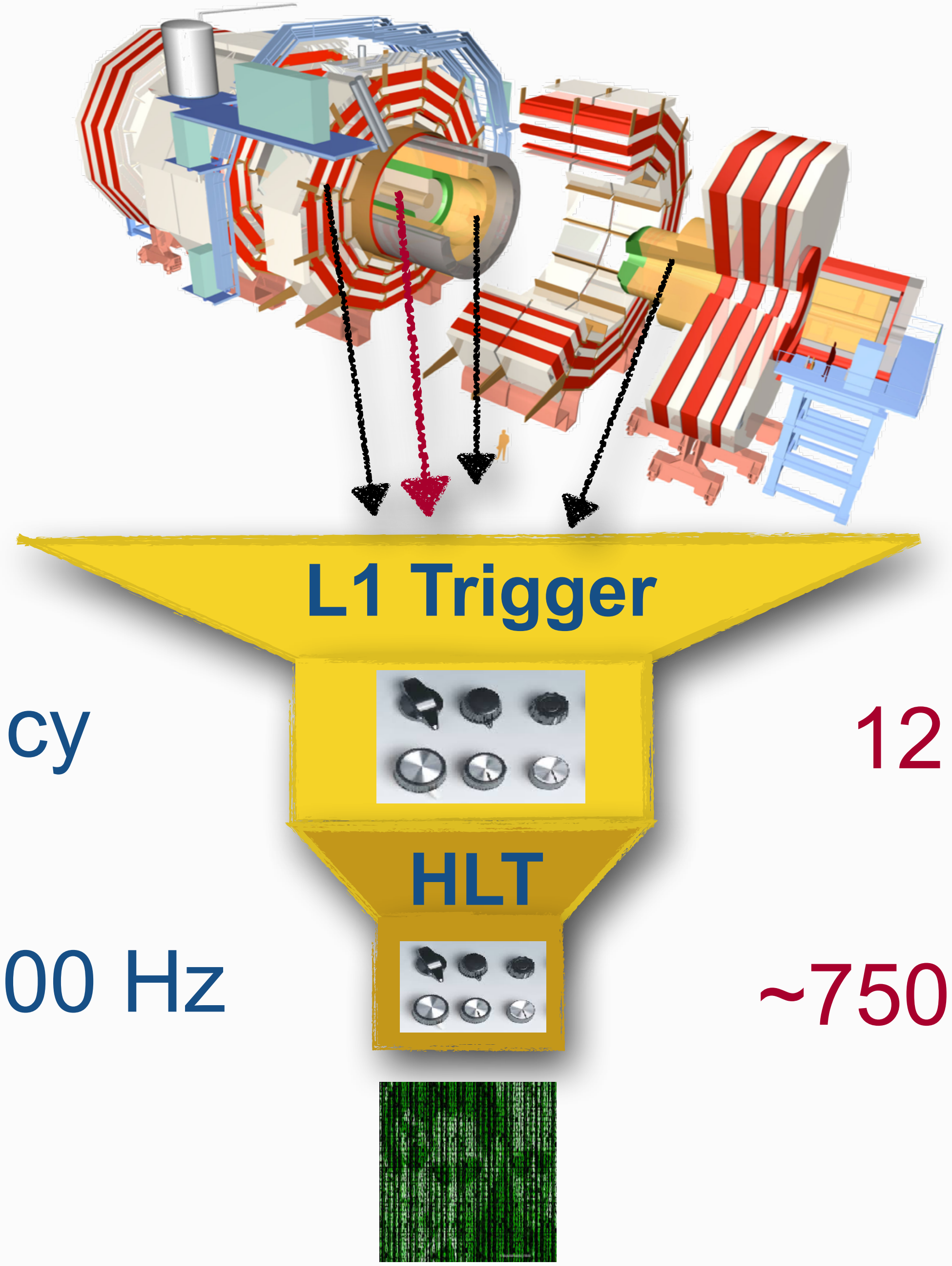
~100 kHz
3.6 μs latency



~1000 Hz

Finite Bandwidth !

The Trigger Challenge



LHC:

~100 kHz
3.6 μs latency

~1000 Hz

HL-LHC:

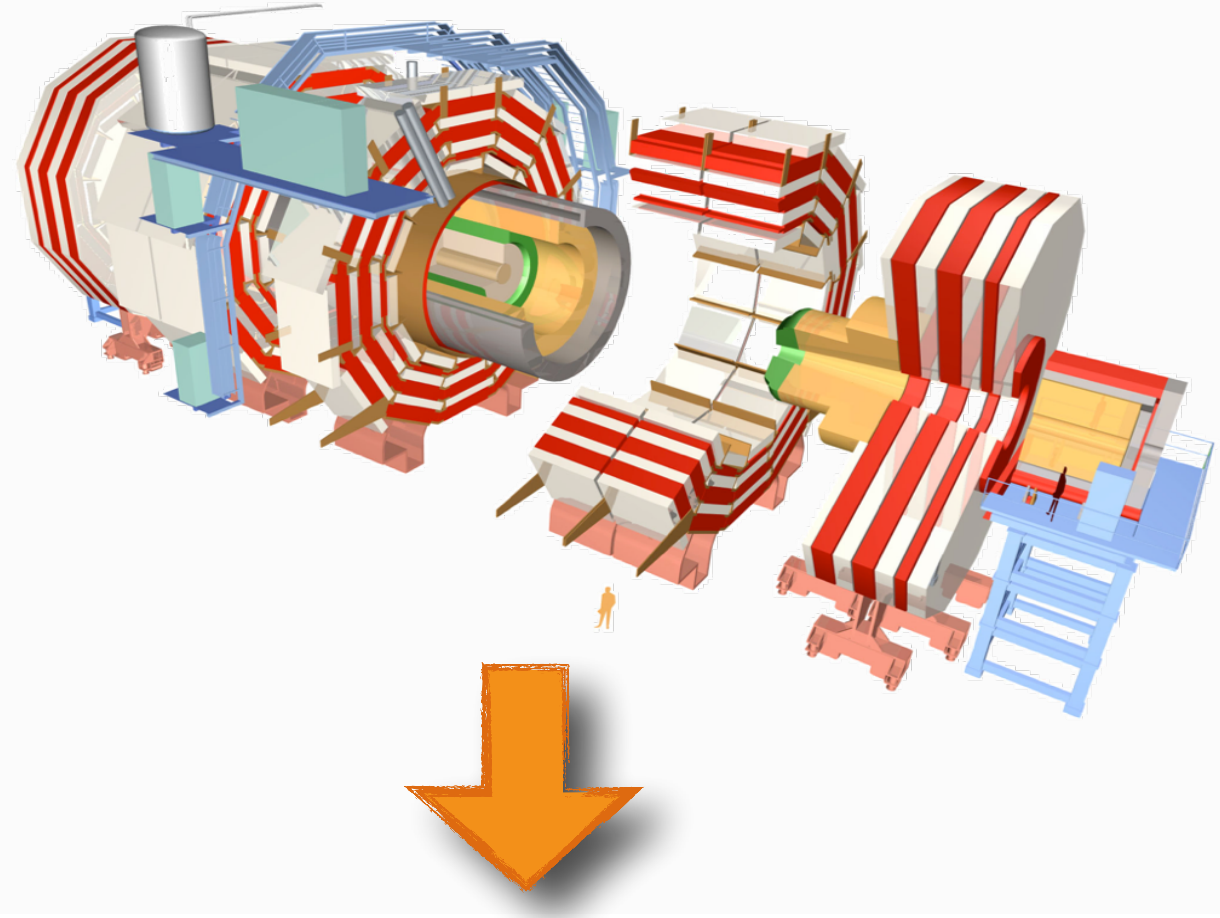
~750 kHz
12.5 μs latency

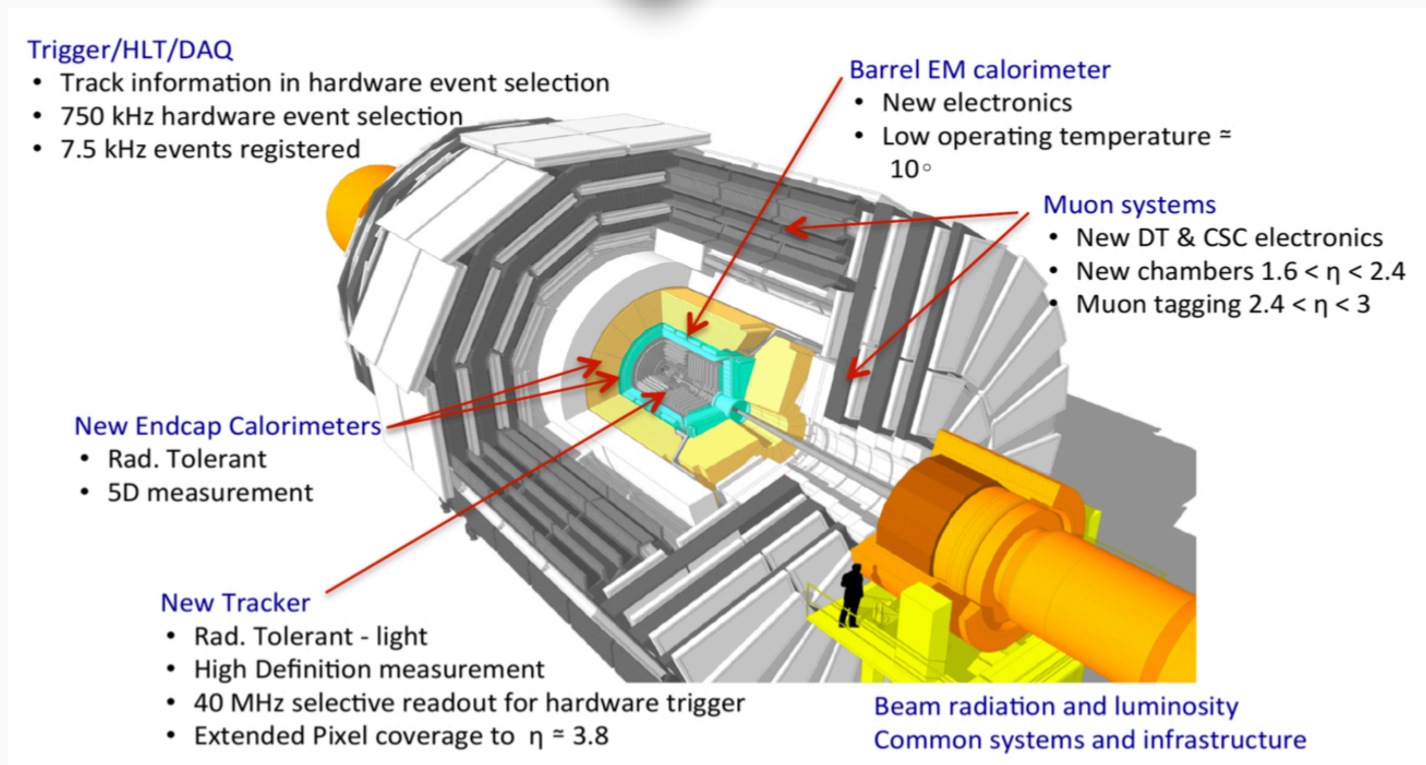
~7500 Hz

Finite Bandwidth !

So : Detector requirements

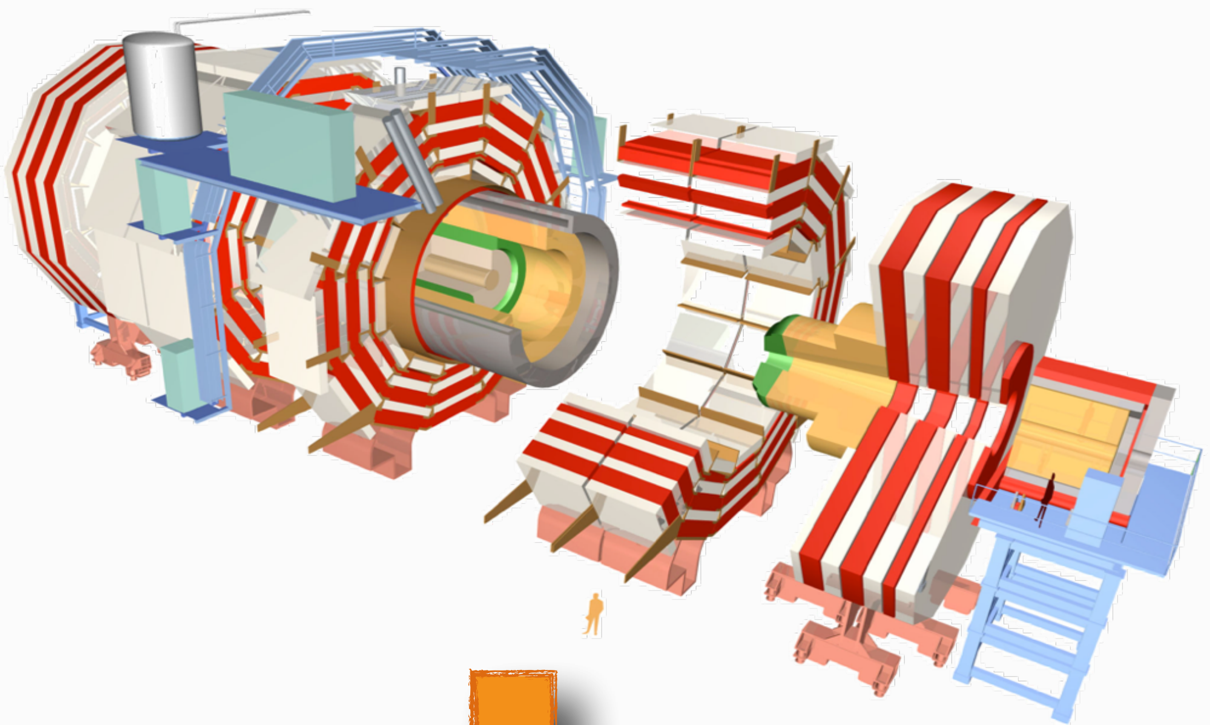
- High granularity,
  fast readout,
  radiation hardness

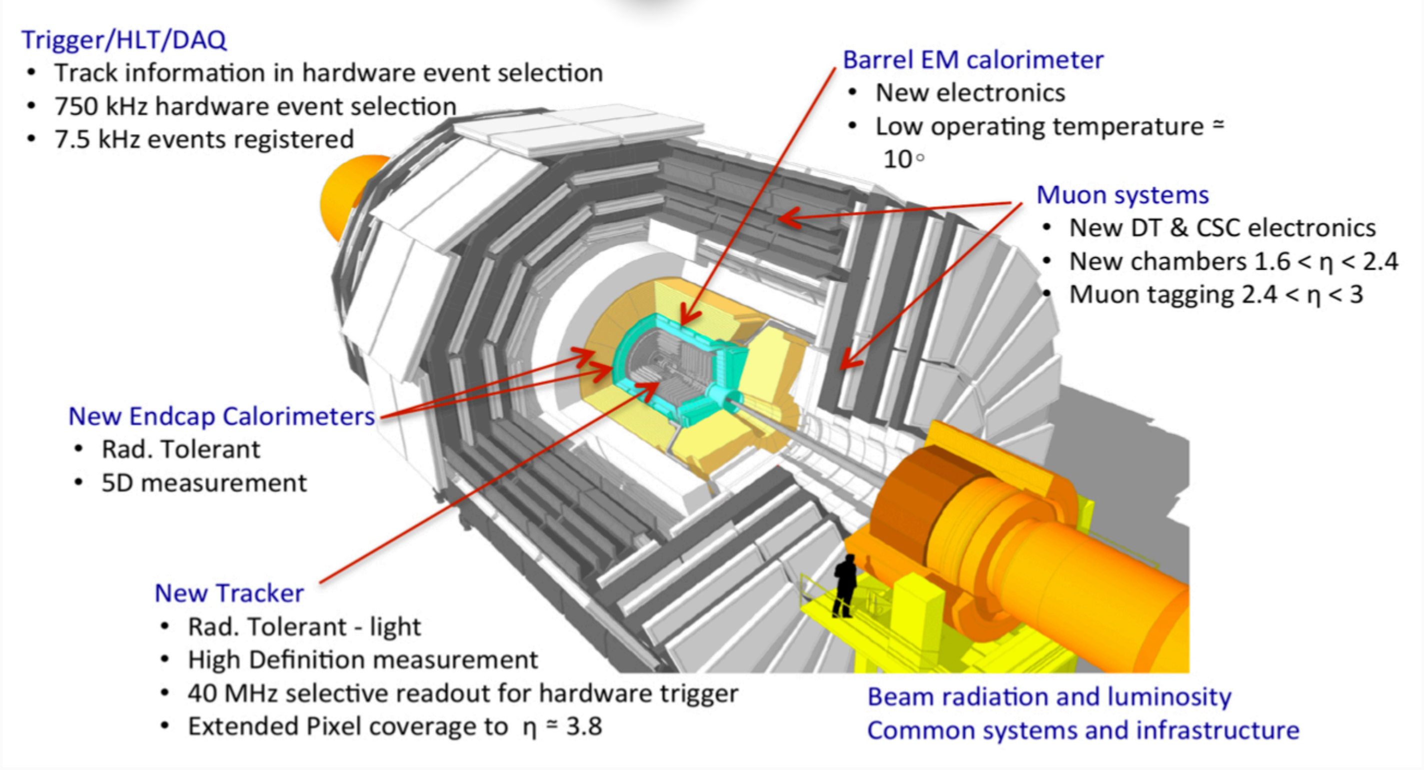




So : Detector requirements

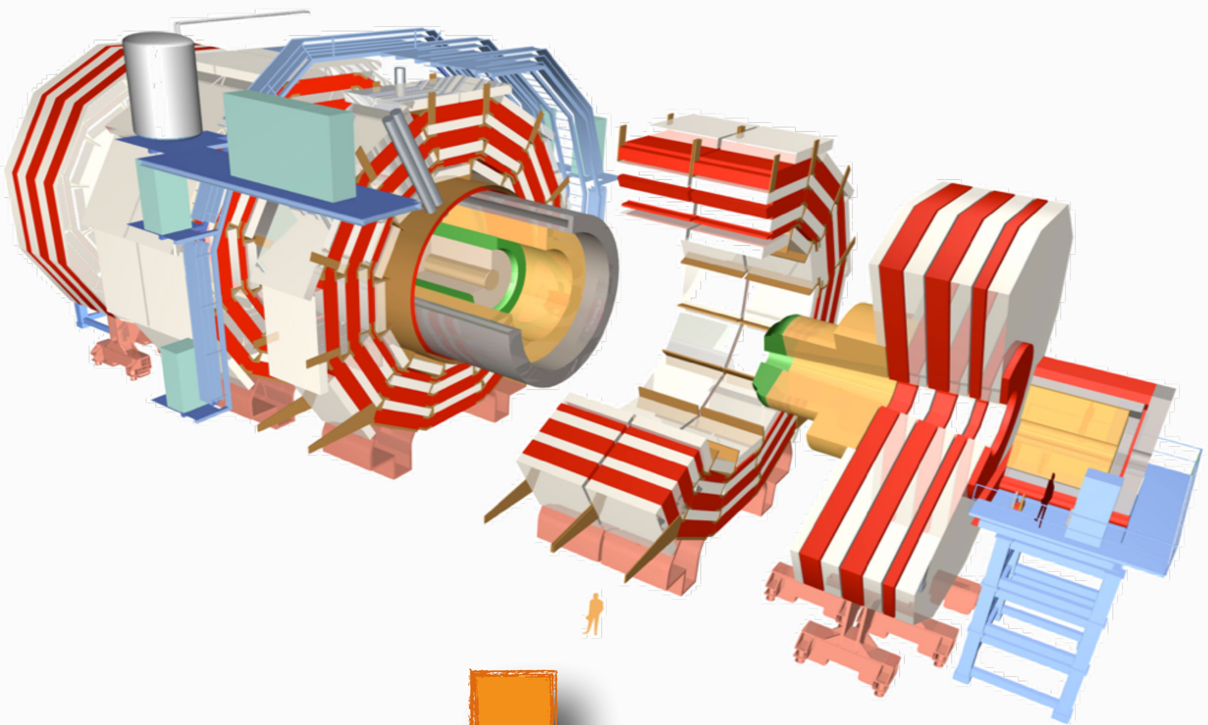
- High granularity, fast readout, radiation hardness
  - minimize pile-up particles in same detector element

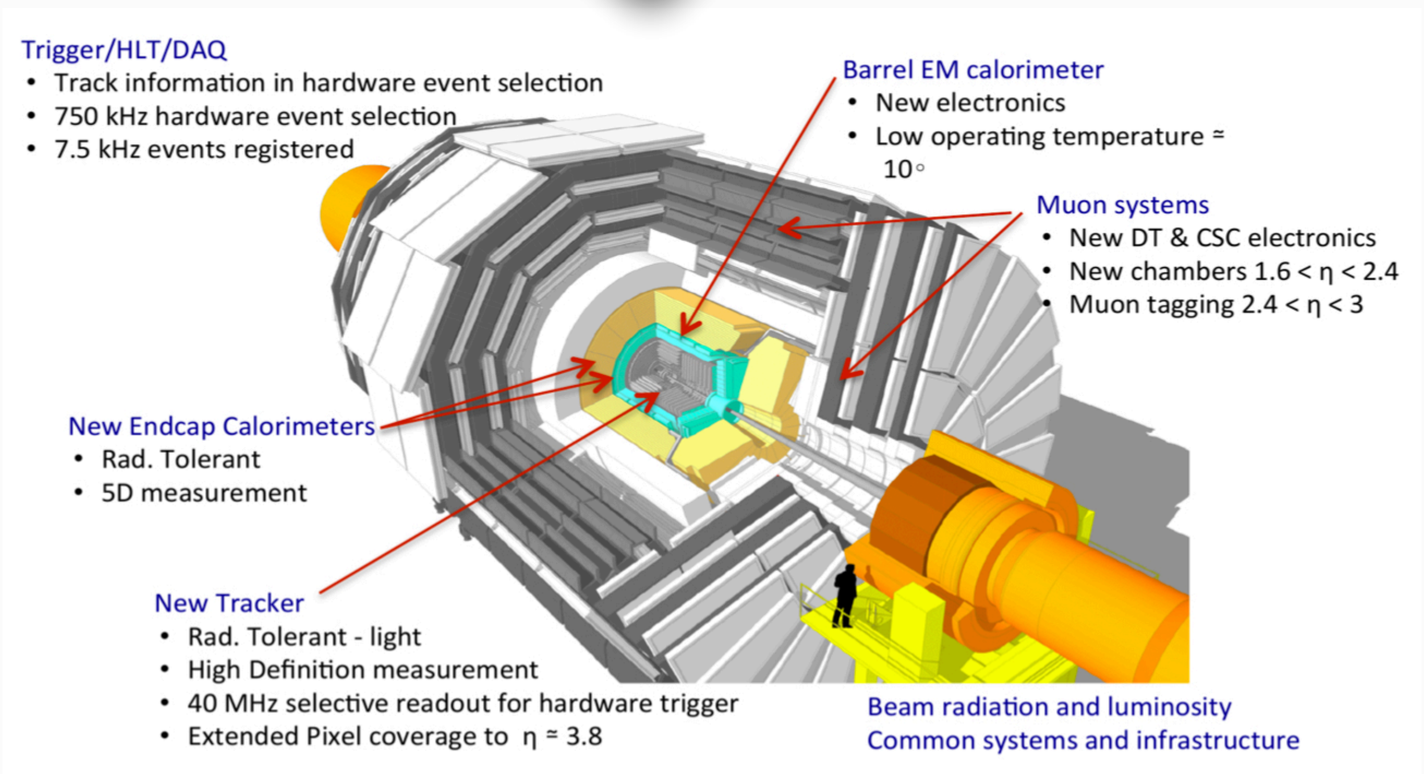




So : Detector requirements

- High granularity, fast readout, radiation hardness
  - minimize pile-up particles in same detector element
  - precise and efficient tracking and vertex reconstruction





So : Detector requirements

- High granularity, fast readout, radiation hardness
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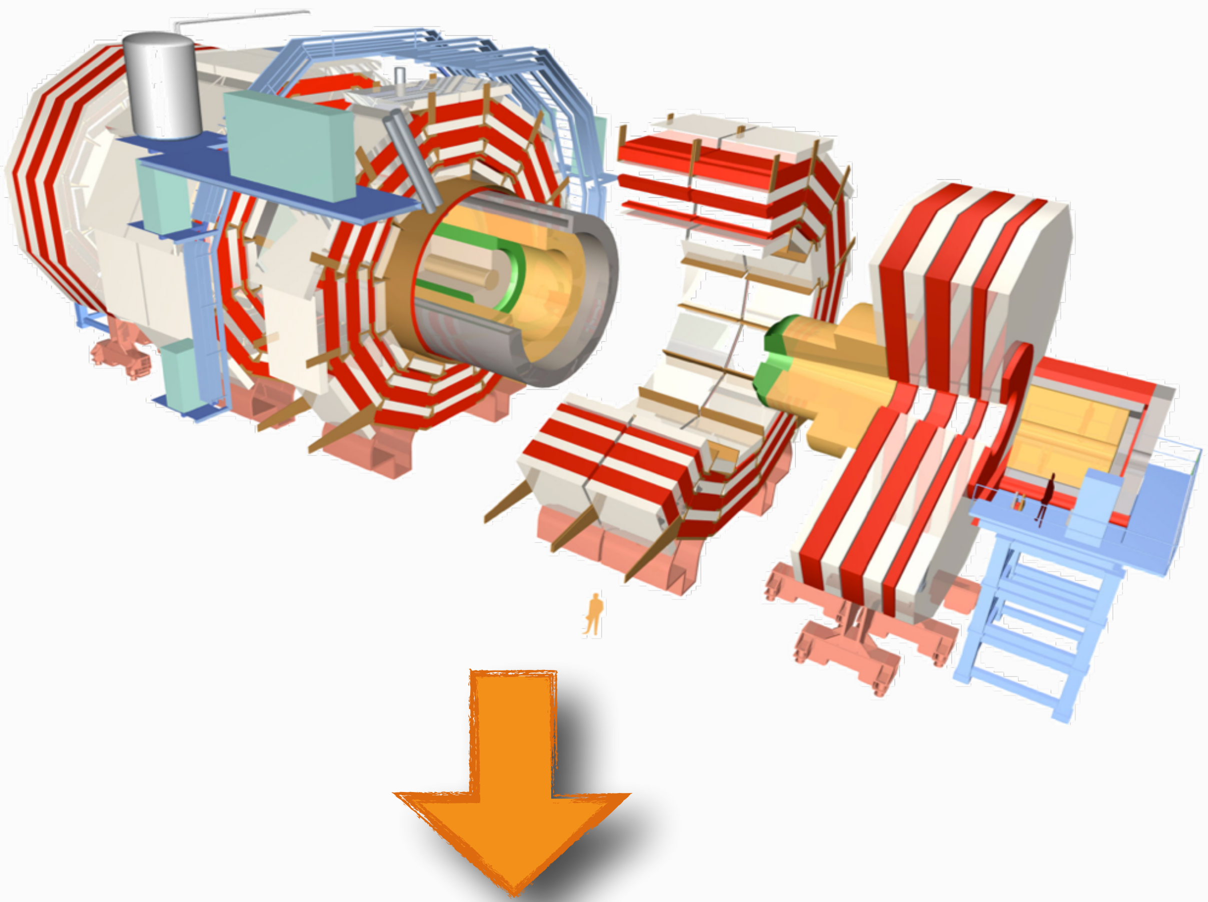
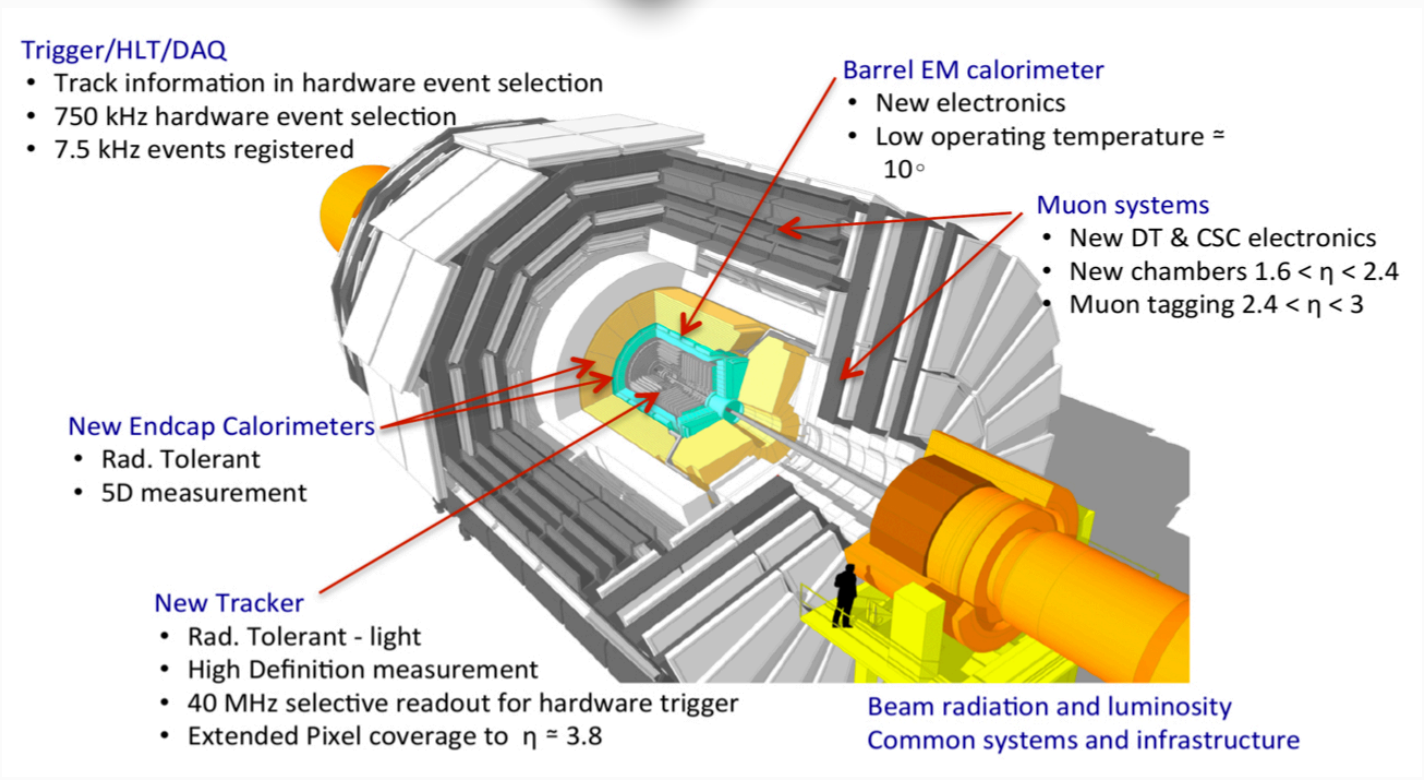
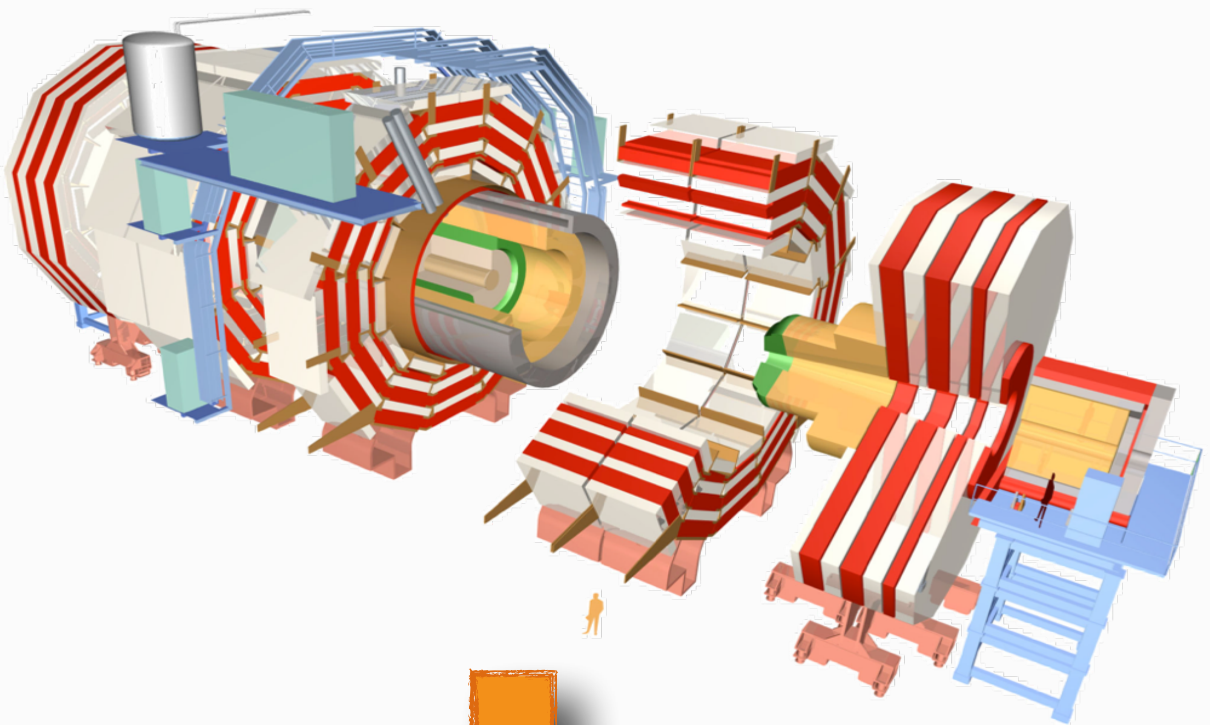
  - precise and efficient tracking and vertex reconstruction
  - add timing information

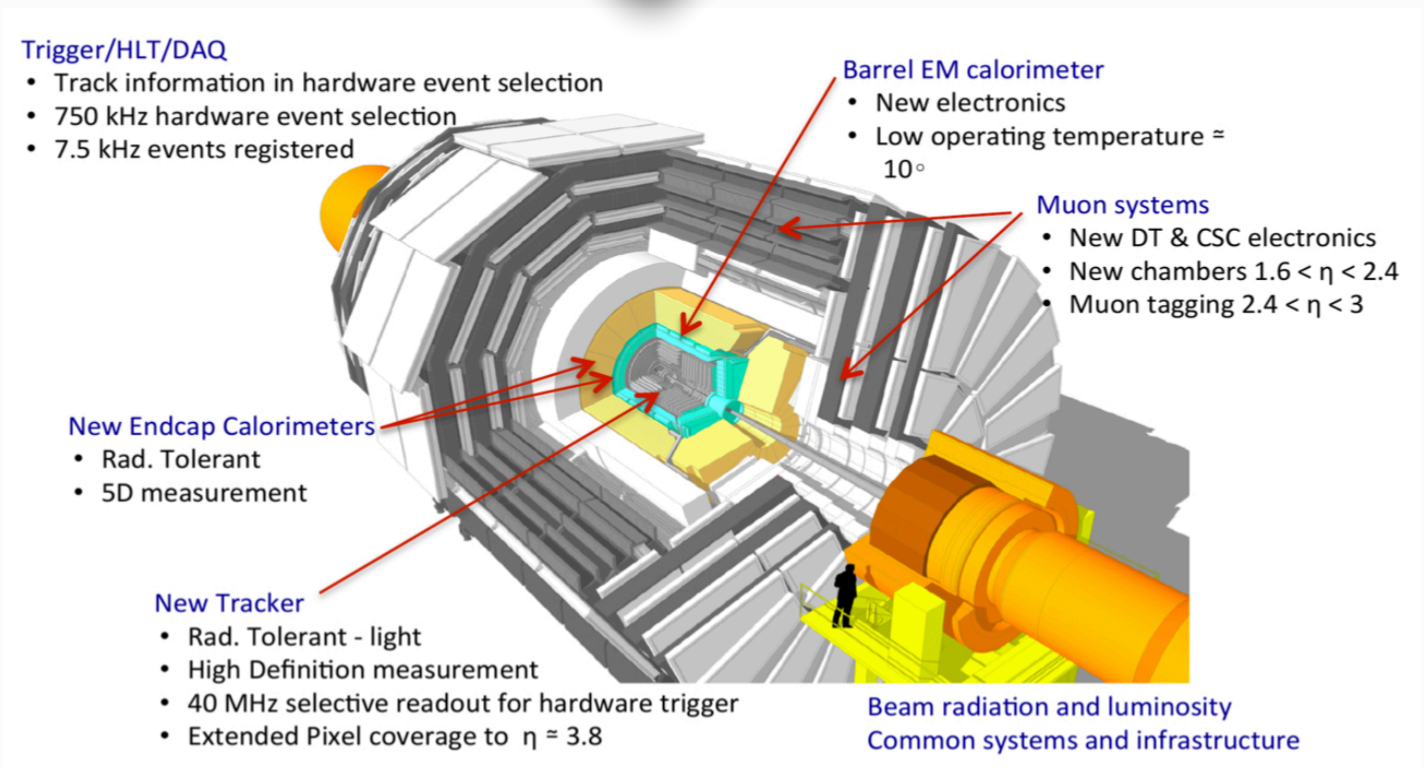




So : Detector requirements

- 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



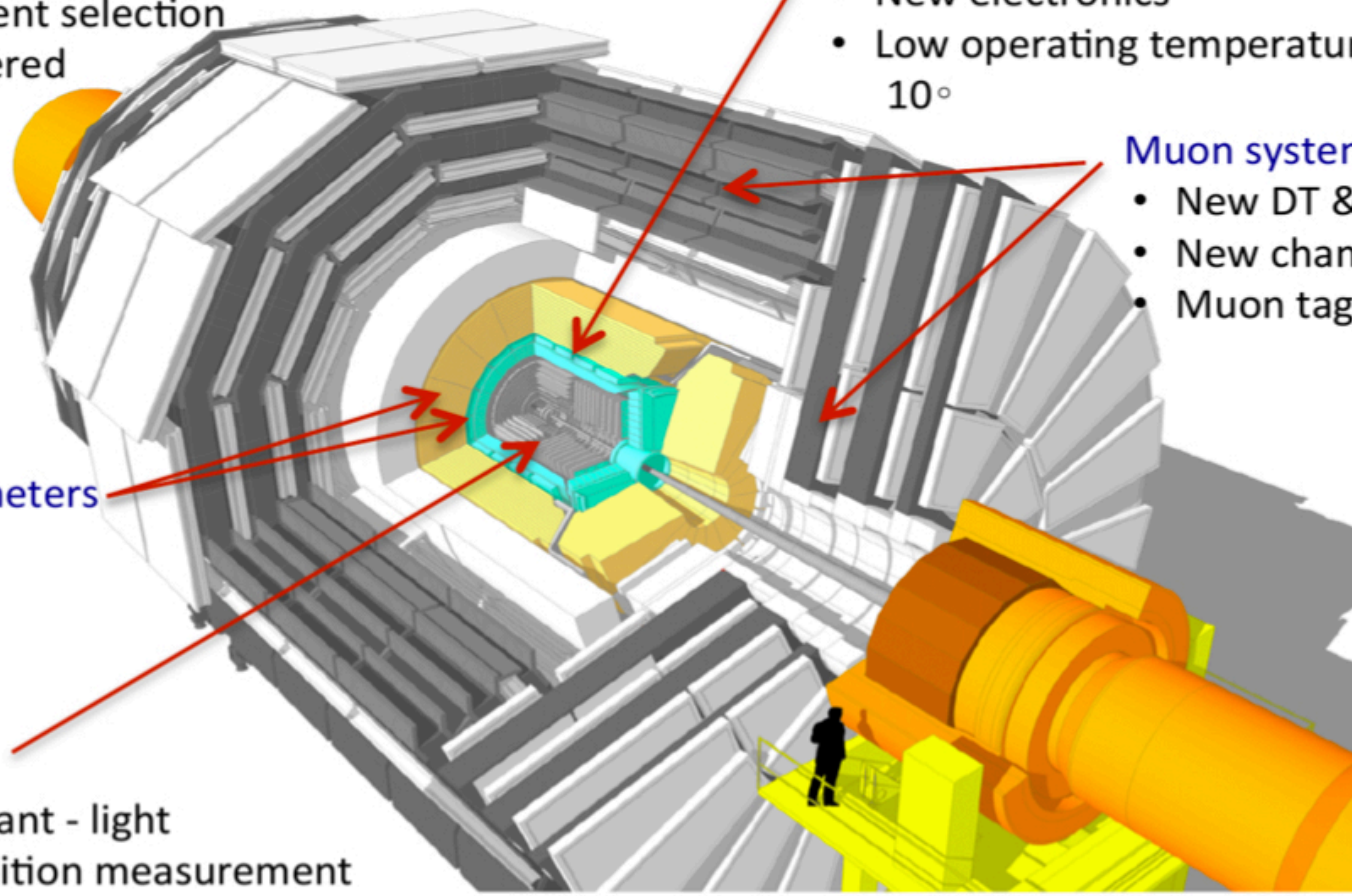


In a nutshell….

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ 10°

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \approx 3.8$

Beam radiation and luminosity
Common systems and infrastructure

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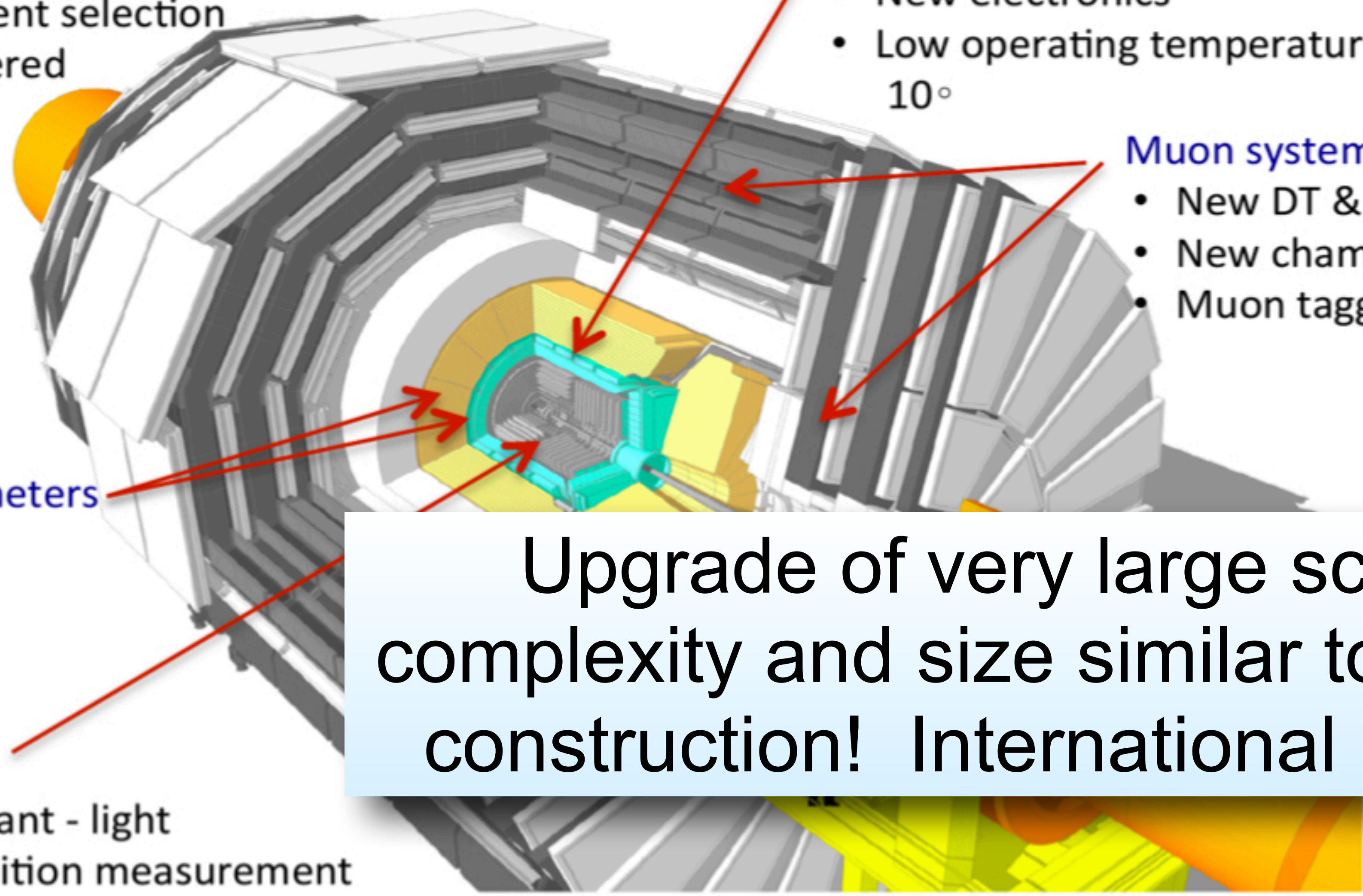

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Upgrade of very large scope: complexity and size similar to original construction! International project!

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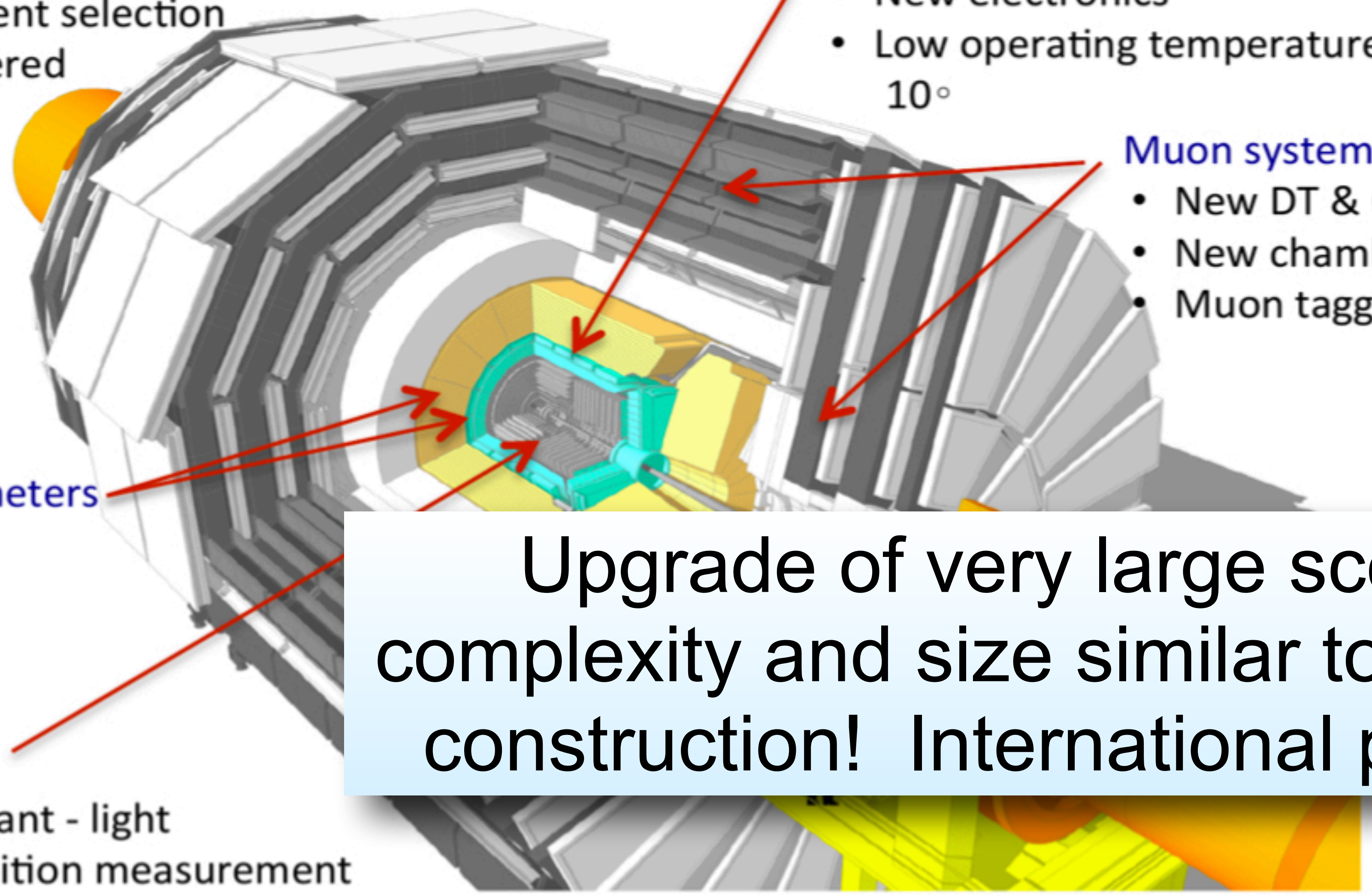

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Common systems and infrastructure

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

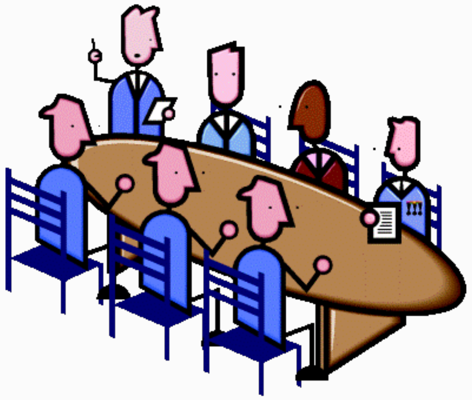
“The Government”

Management Board

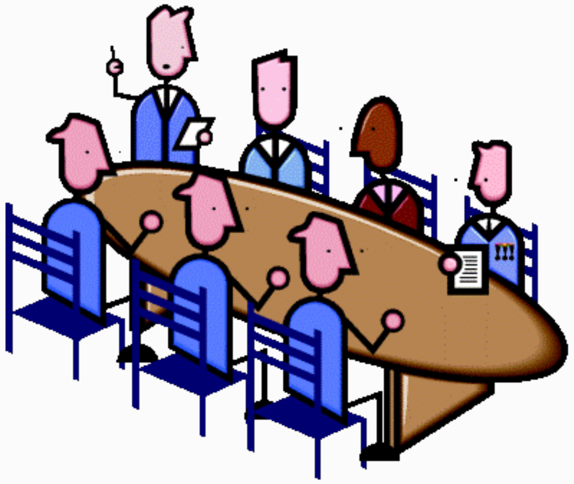
Coordinators, System Managers, Reg. Reps, …

chaired by Spokesperson

Conf. Committee



Pub. Committee



etc

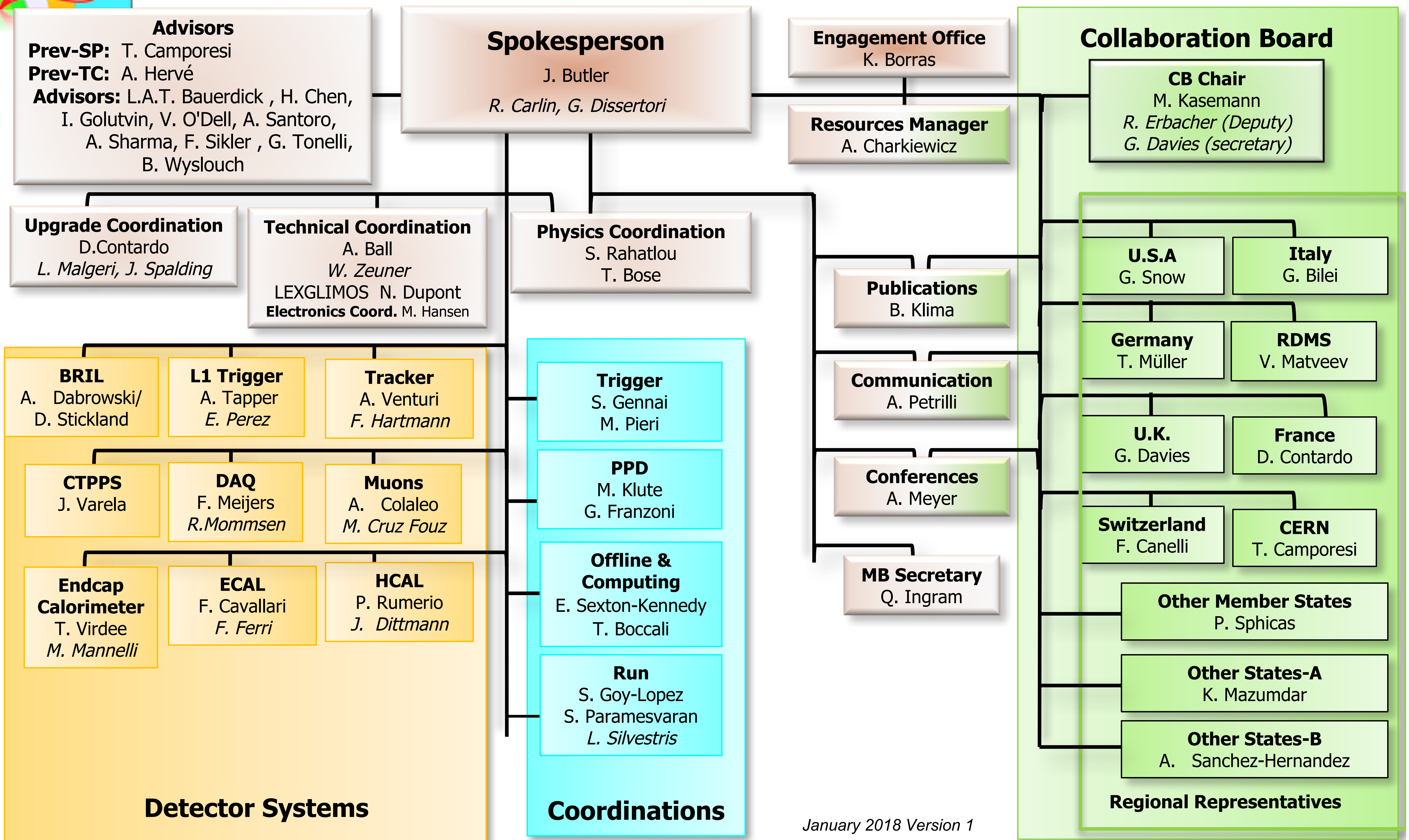
Extended Executive Board (XEB)

How do we function ?

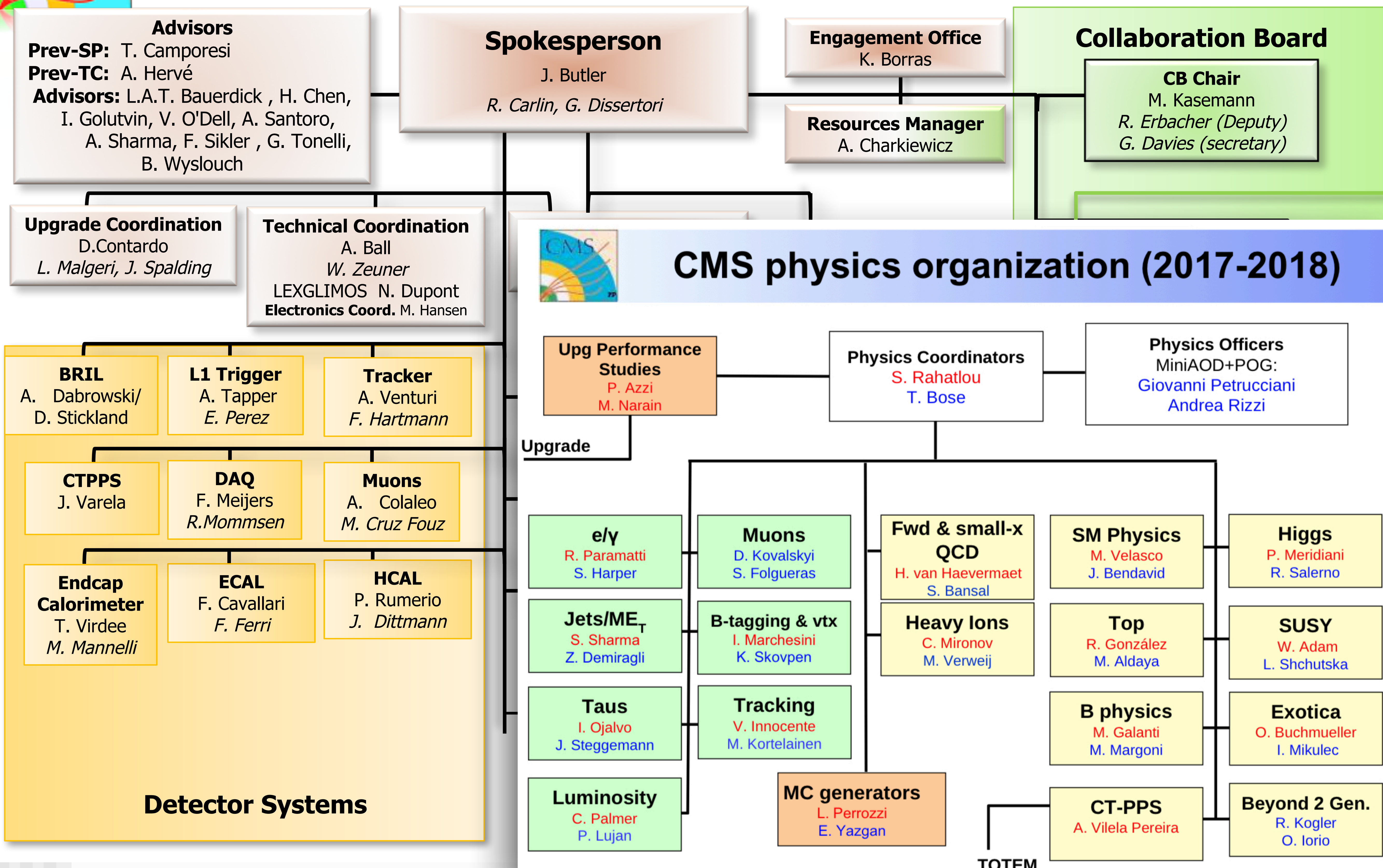
The CMS Collaboration is led by the Spokesperson who is the Chairperson of the Management Board and the Executive Board and is responsible for the scientific and technical direction of the experiment, following the policies agreed by the Collaboration Board. The Spokesperson is the principal representative 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-Jan. 29, 2018



CMS Management Board-Jan. 29, 2018

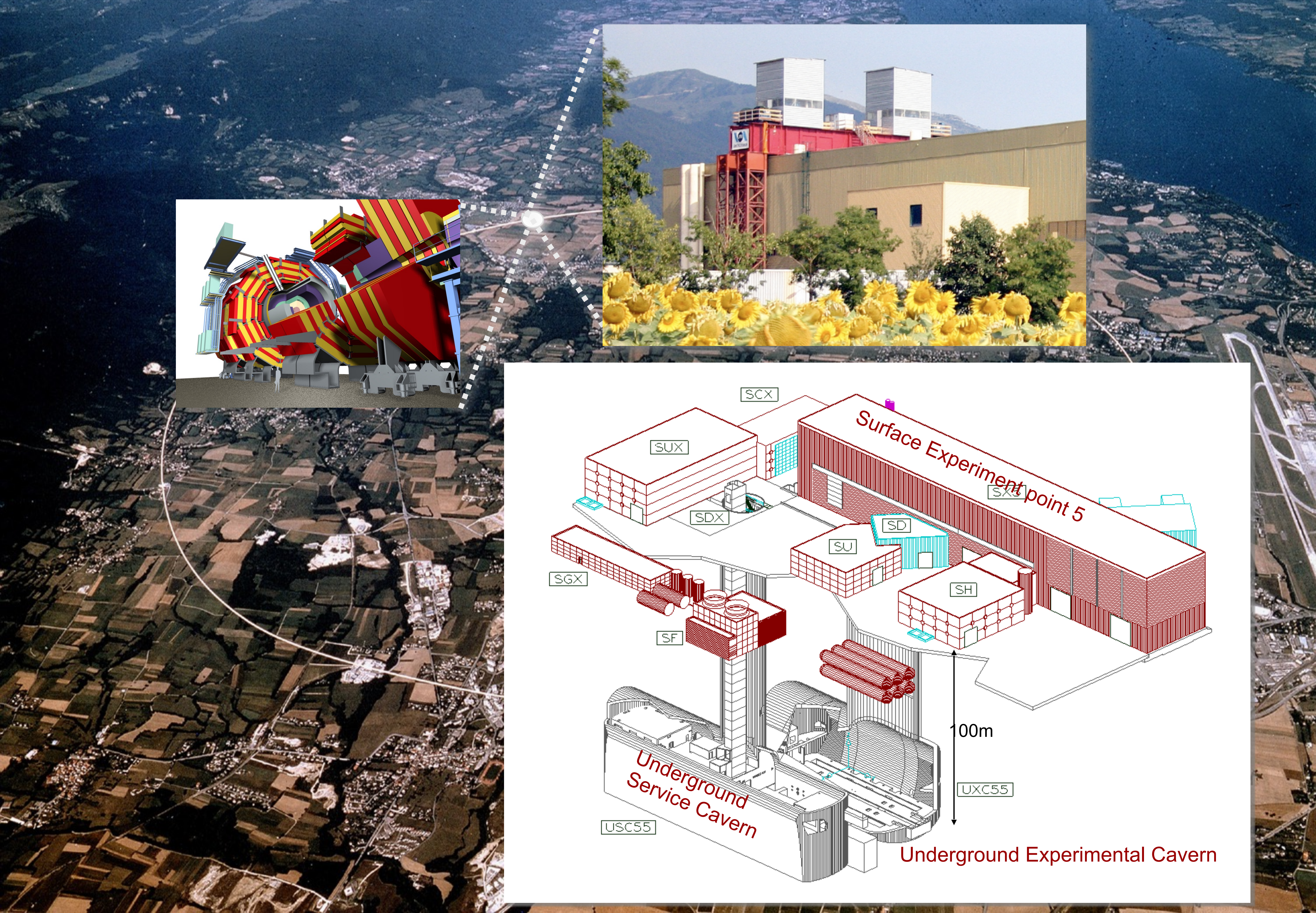


CMS at P5

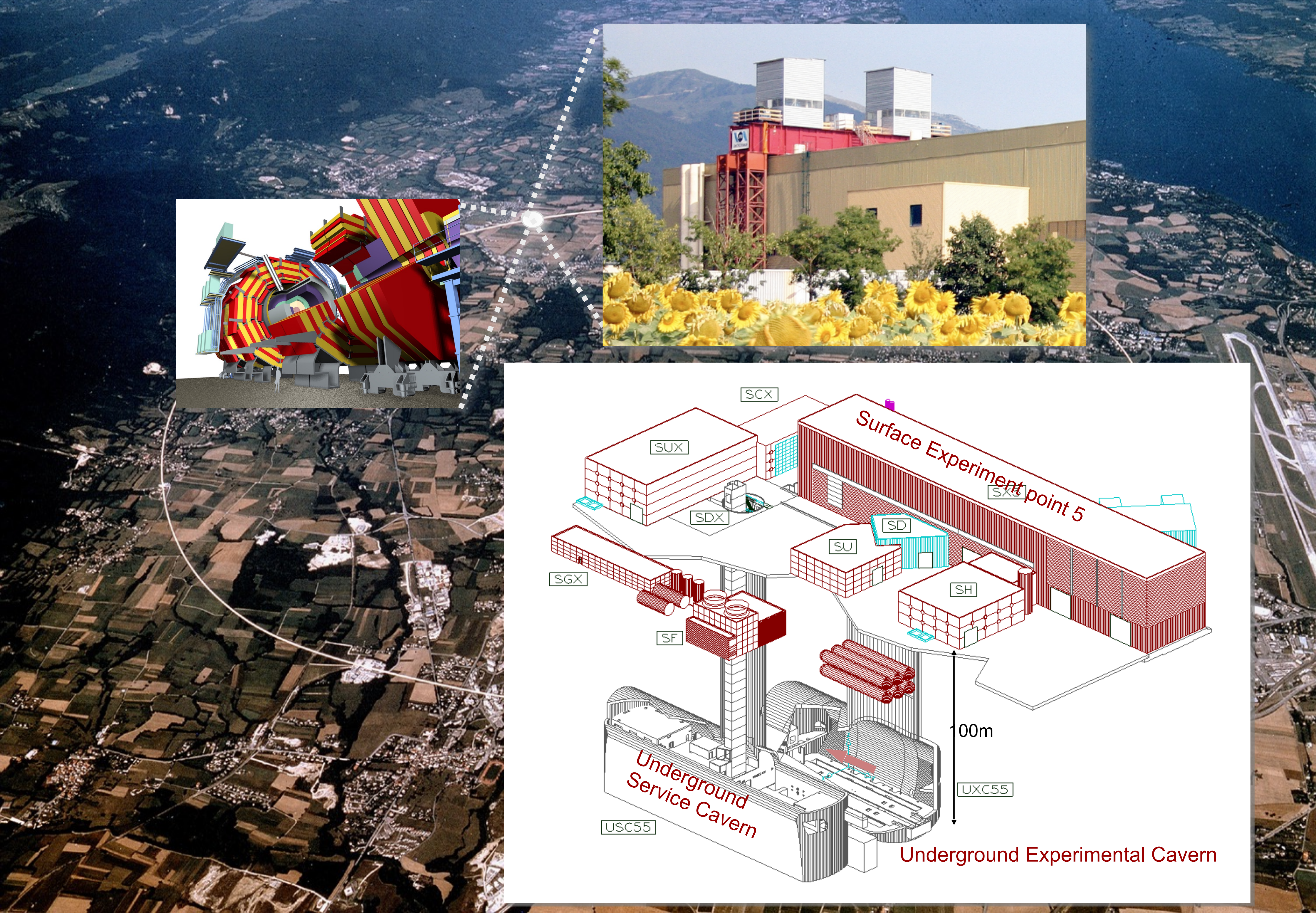
CMS at P5

CMS at P5

CMS at P5


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

CMS at P5



SCX
SUX
Surface Experiment point 5
SX5
SDX
SD
SU
SGX
SH
SF
100m
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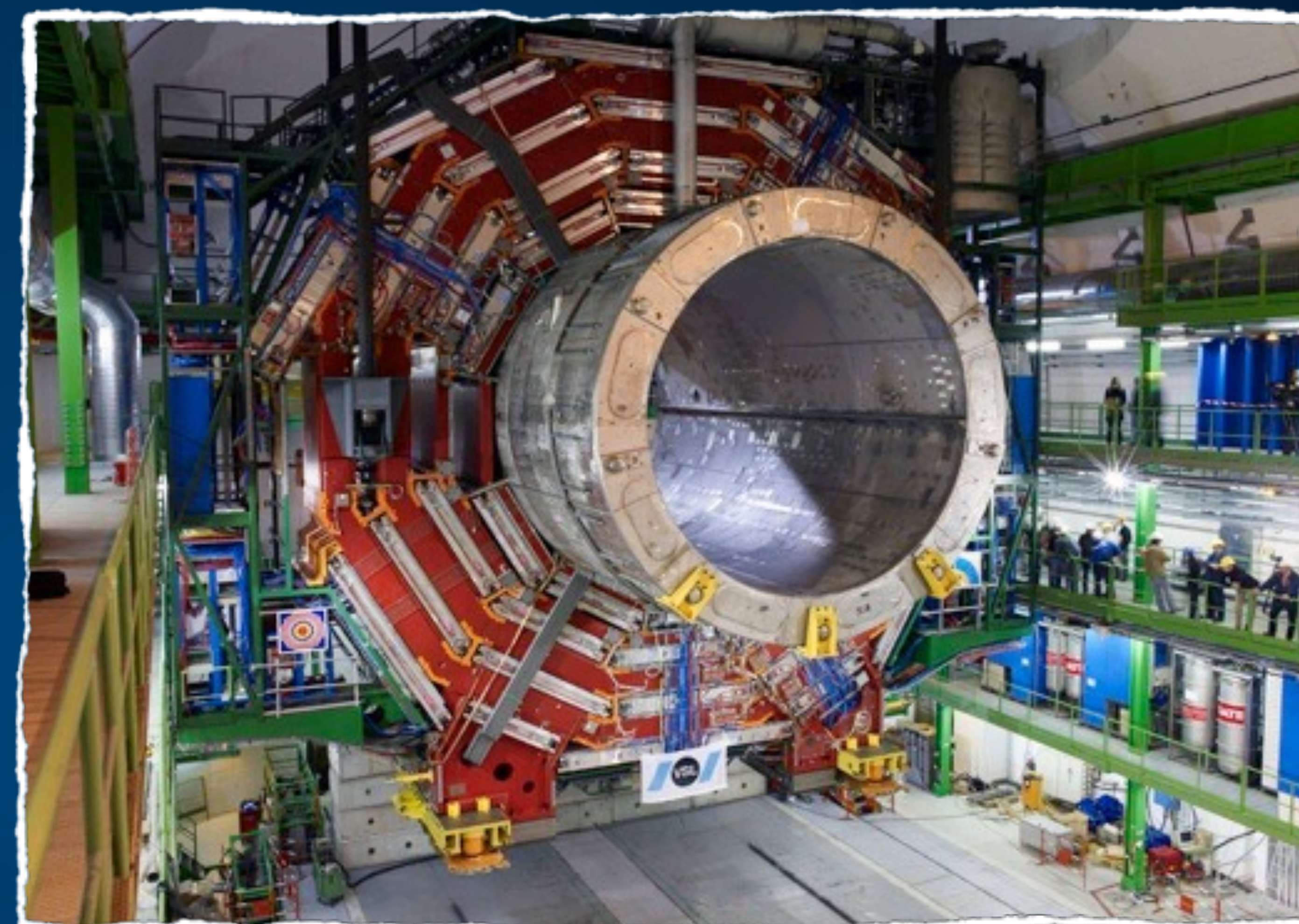
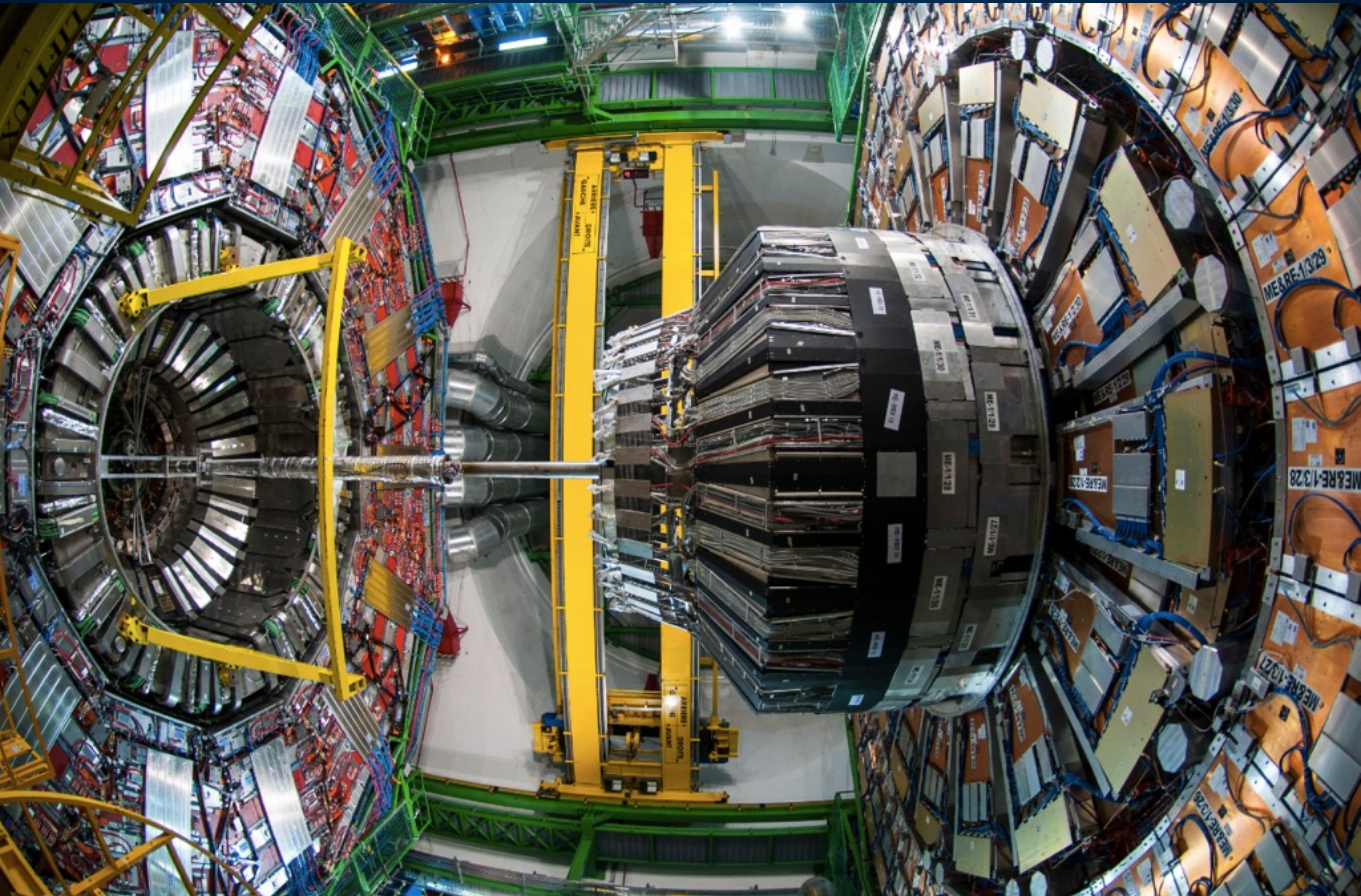
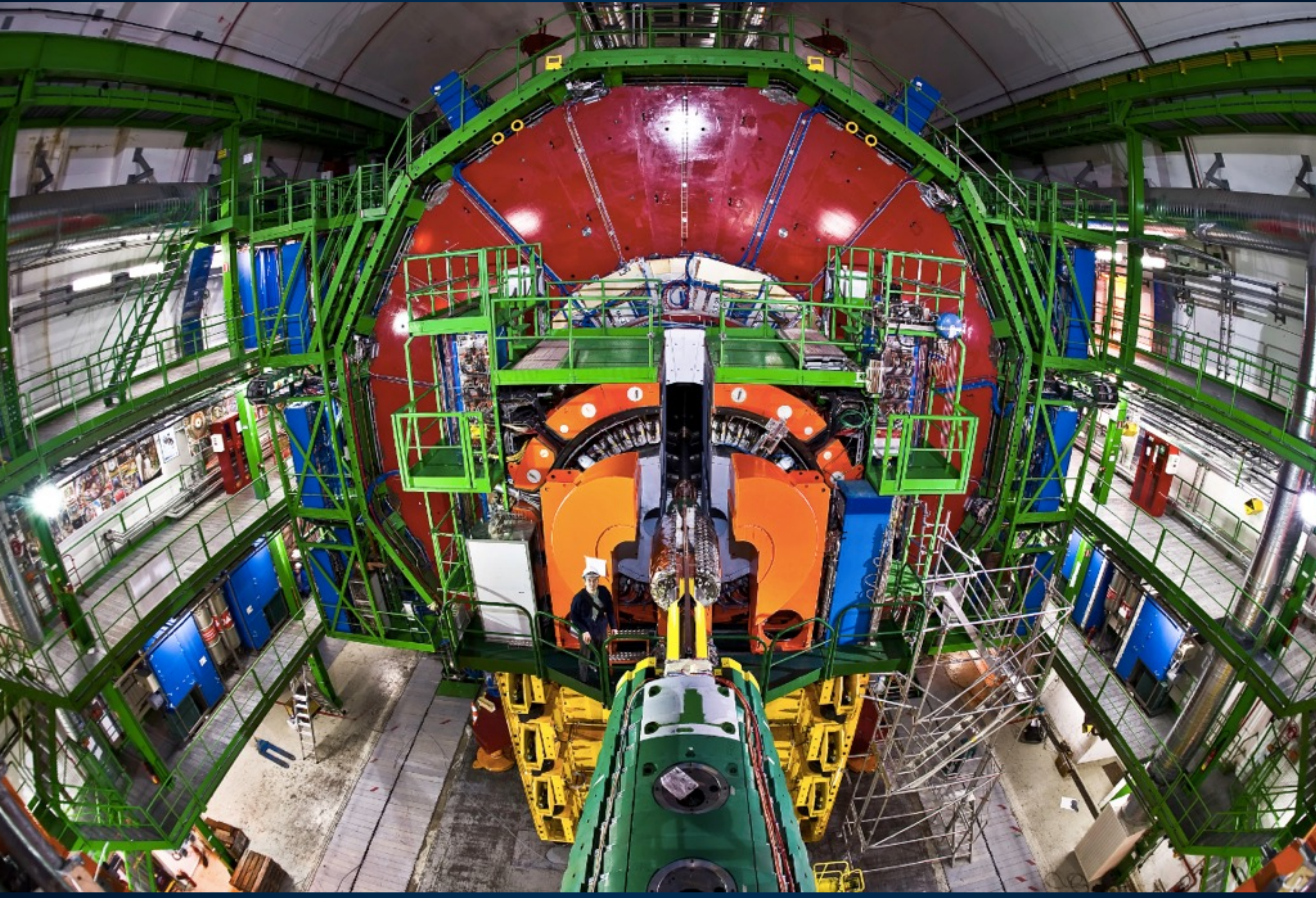
Underground Service Cavern
USC55
Underground Experimental Cavern



~ 2000 t
~ 5 Jumbo Jets


ME&RE-1/3/29
ME&RE-1/3/28



Last but not least

The really important ones

- Our friendly secretariat!

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

Anca Patru

Ekaterina Osipova

Javier Picon Lorca

Tania Pardo

Zsuzsanna Garai

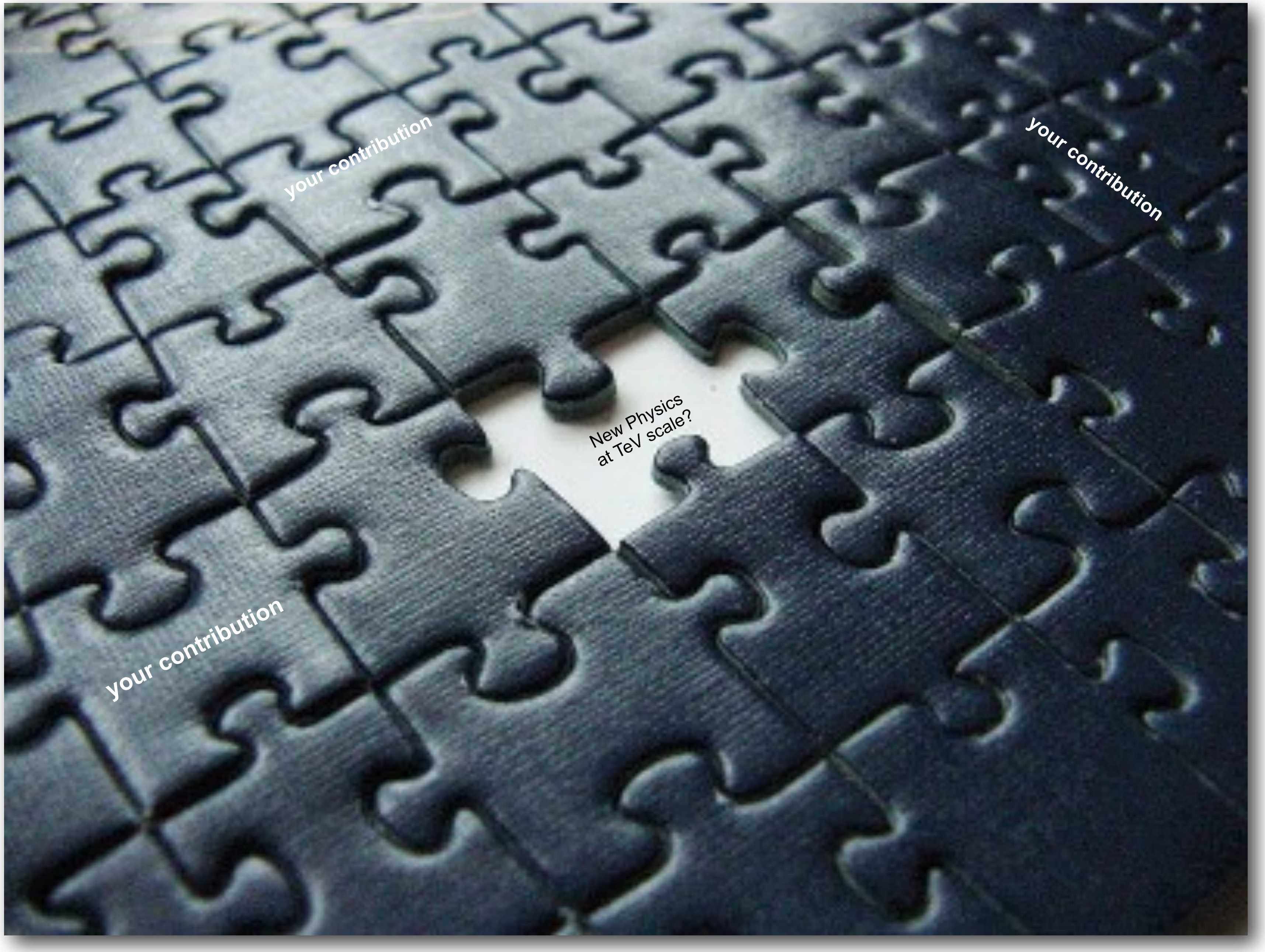
Welcome to CMS!!!

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