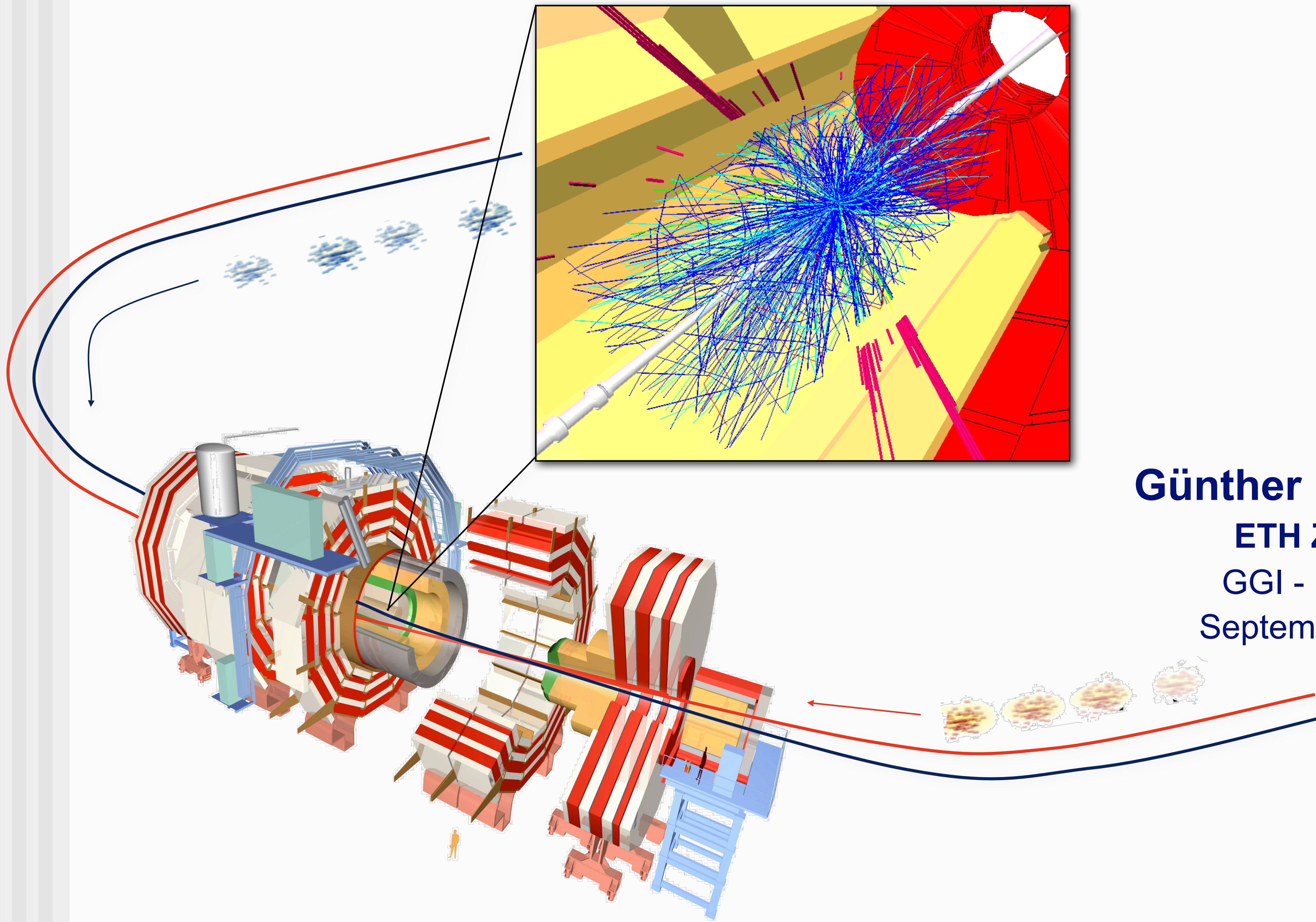
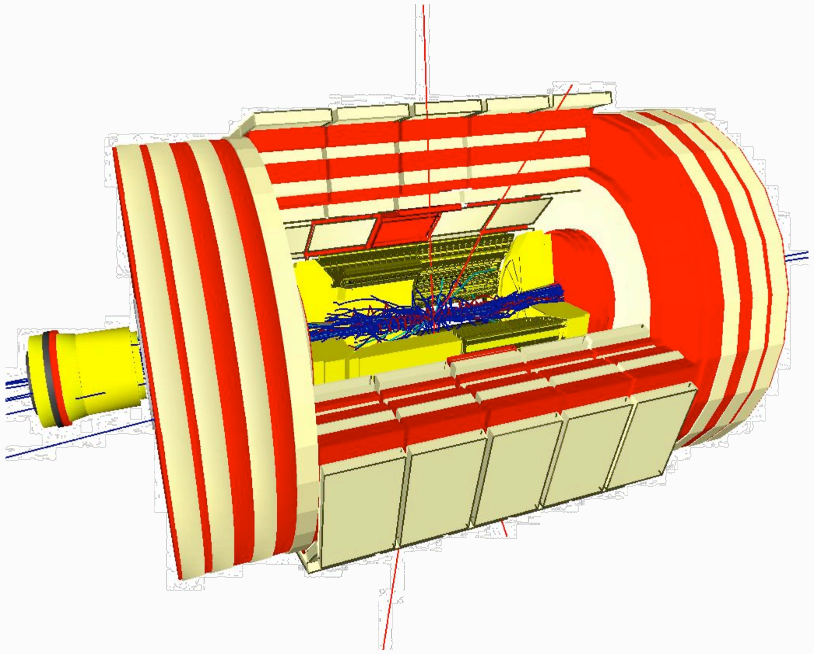
LHC Detectors : Part 1



Günther Dissertori
ETH Zürich
GGI - Firenze
September 2007

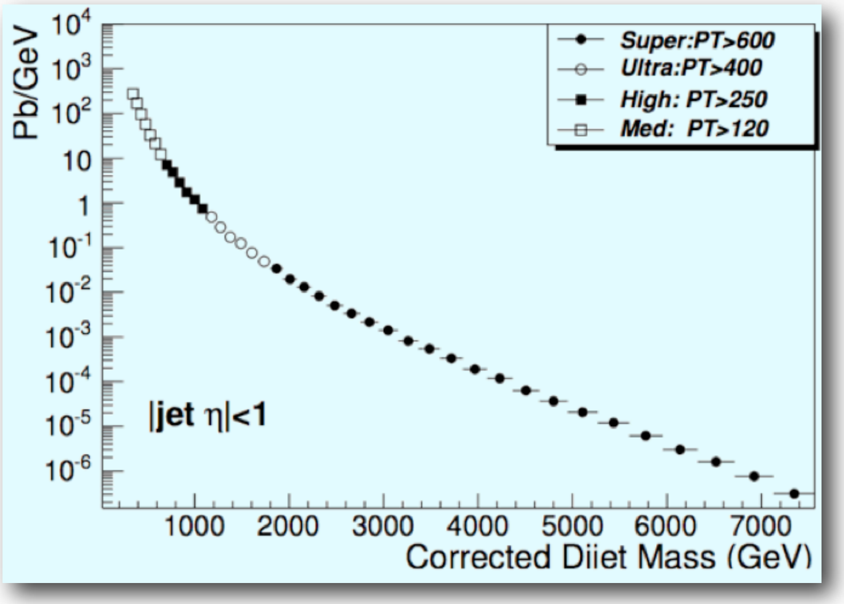
Outline

- What is measured, how and why?
  - Basic processes, rates
  - Resulting difficulties and requirements
  - Basic detector layout



- ATLAS and CMS
  - Overview
  - Construction status
  - Comparison

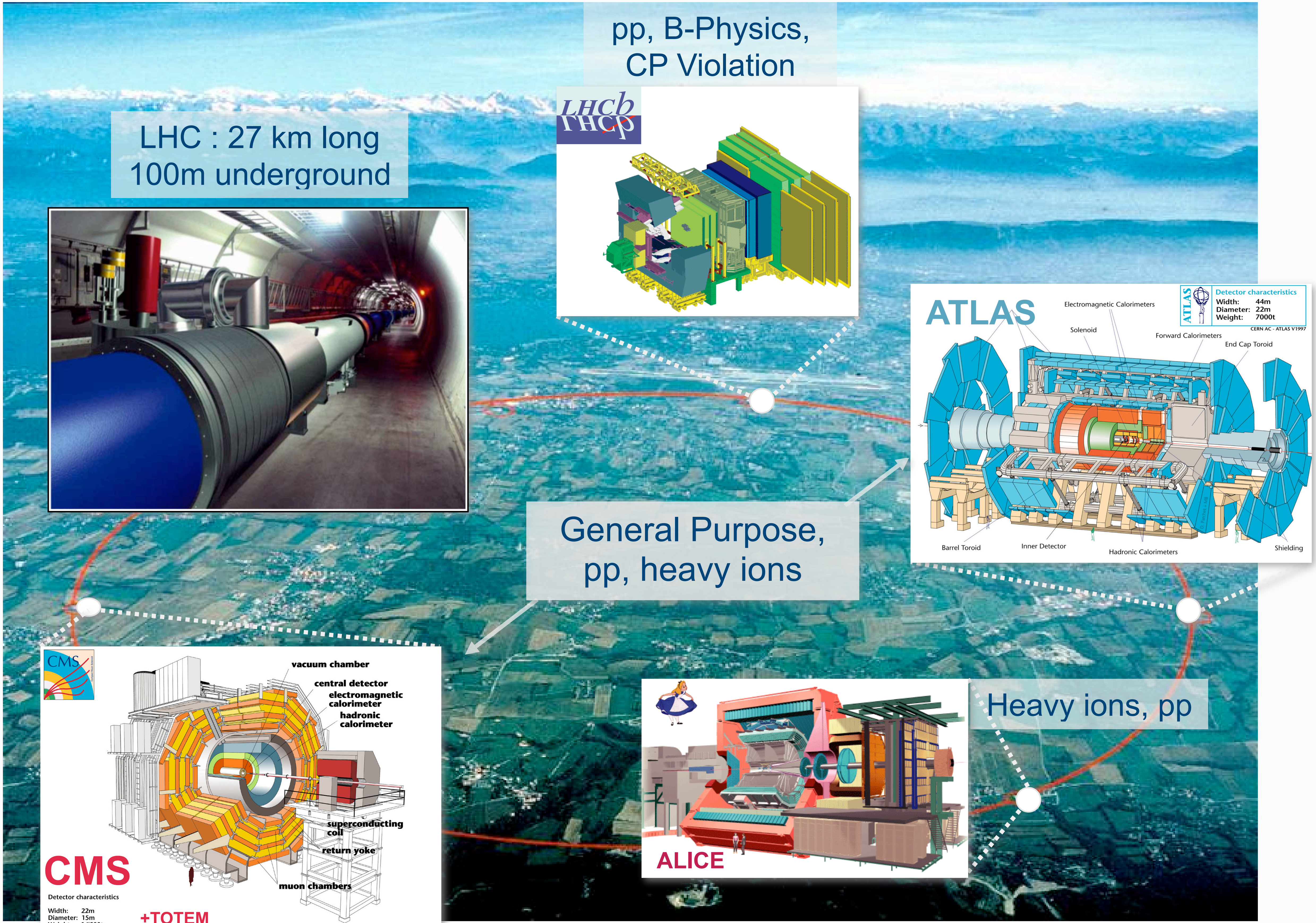
- Experimental issues
  - Some examples of experimental issues to be addressed
  - such as Jet Energy Calibration
  - and background estimations



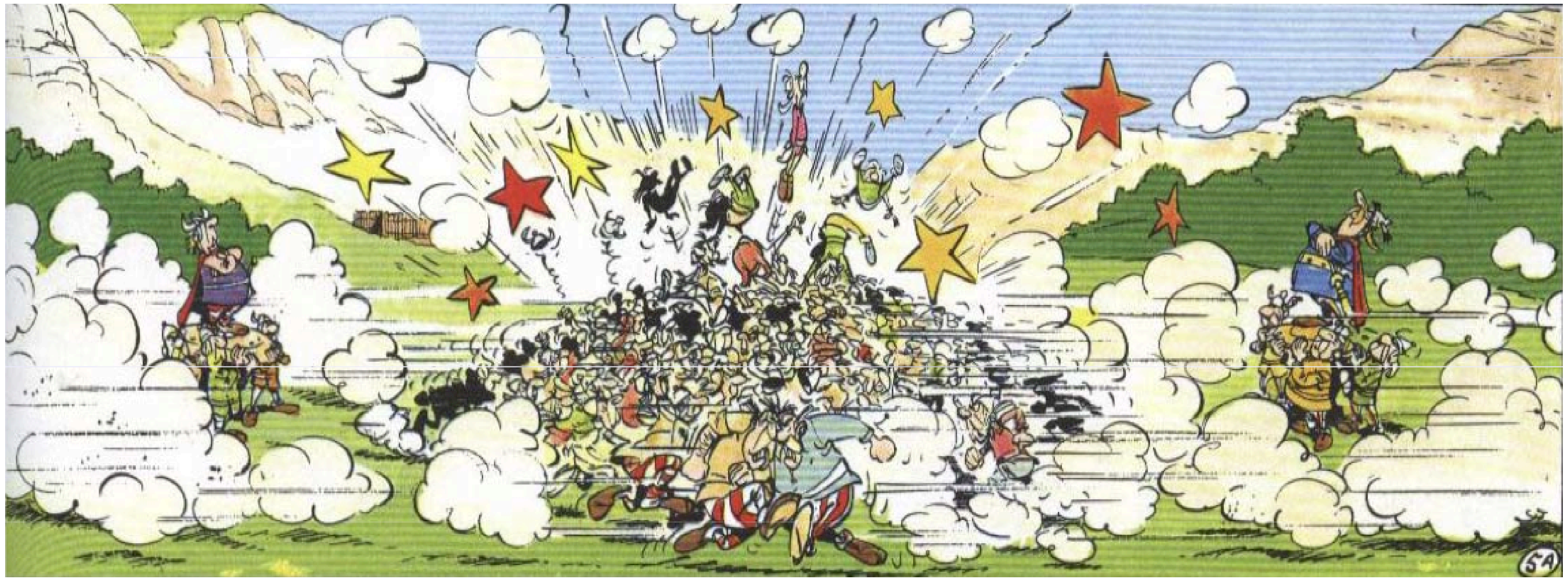
Disclaimer 1 : I concentrate on multi-purpose detector ATLAS and CMS

Disclaimer 2 : Some slides or slide content taken from seminars/lectures of other LHC colleagues, eg. K. Jakobs, O. Buchmüller, L. Dixon, M. Dittmar, D. Froidevaux, F. Gianotti

Our future play ground



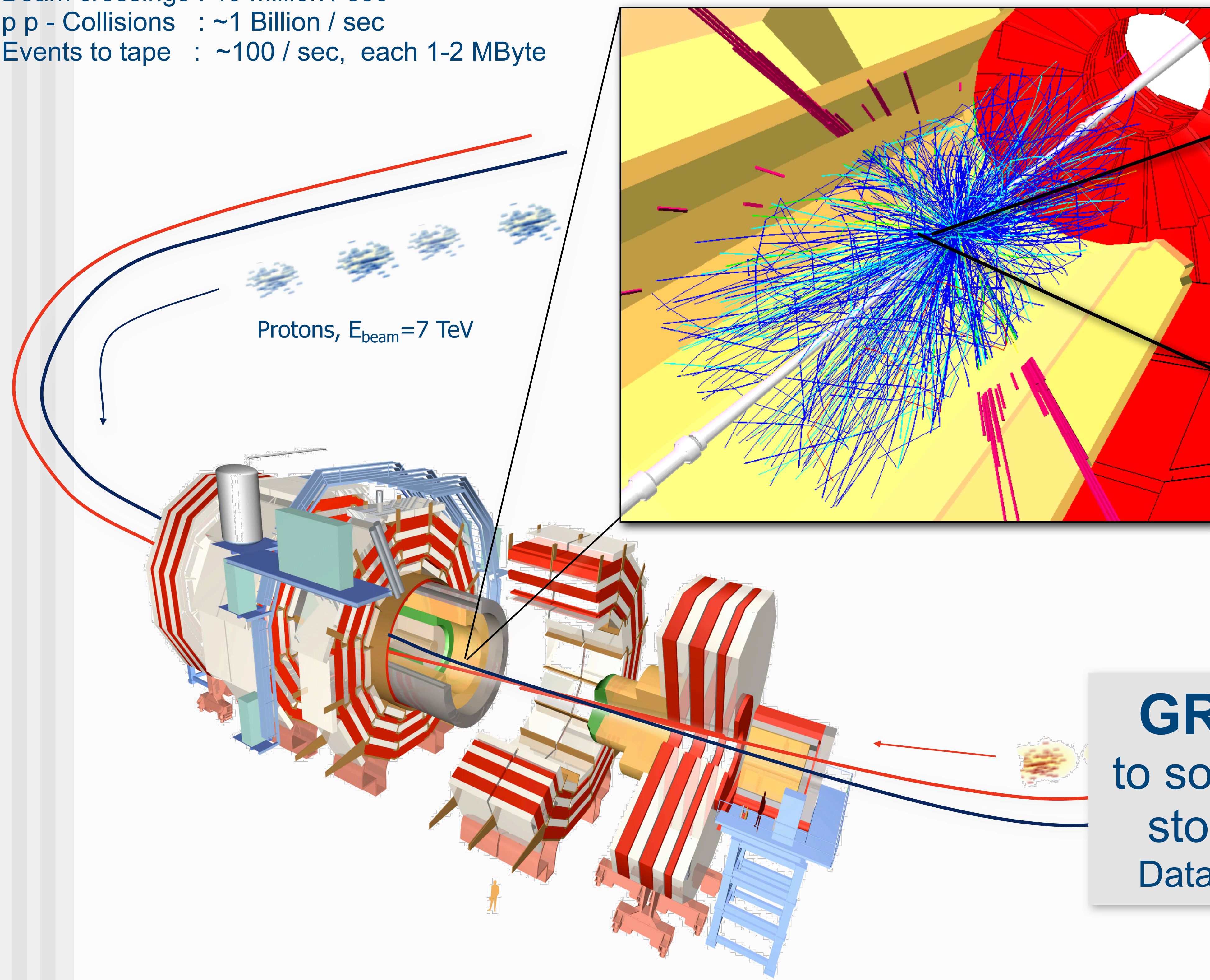
The experiments: What is measured, why and how?

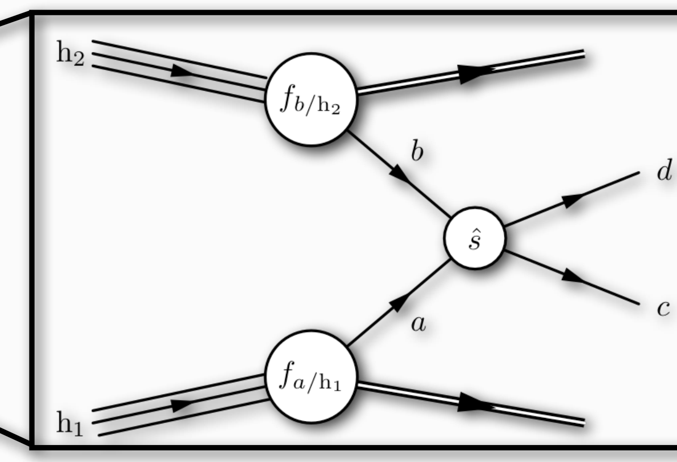


proton - proton collisions are complex....

Collisions at the LHC

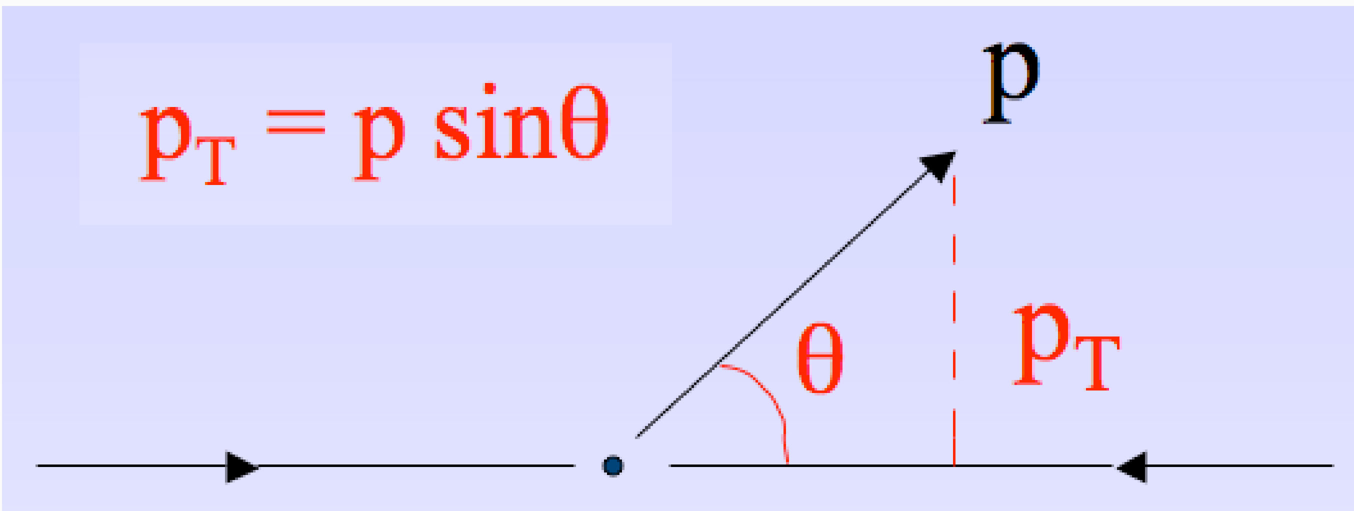
Centre-of-Mass Energy = 14 TeV
Bunch separation : 7.5 m (25 ns)
Beam crossings : 40 Million / sec
p p - Collisions : ~1 Billion / sec
Events to tape : ~100 / sec, each 1-2 MByte





GRID computing
to solve problem of data storage and analysis
Data pro year: **~ Petabytes**

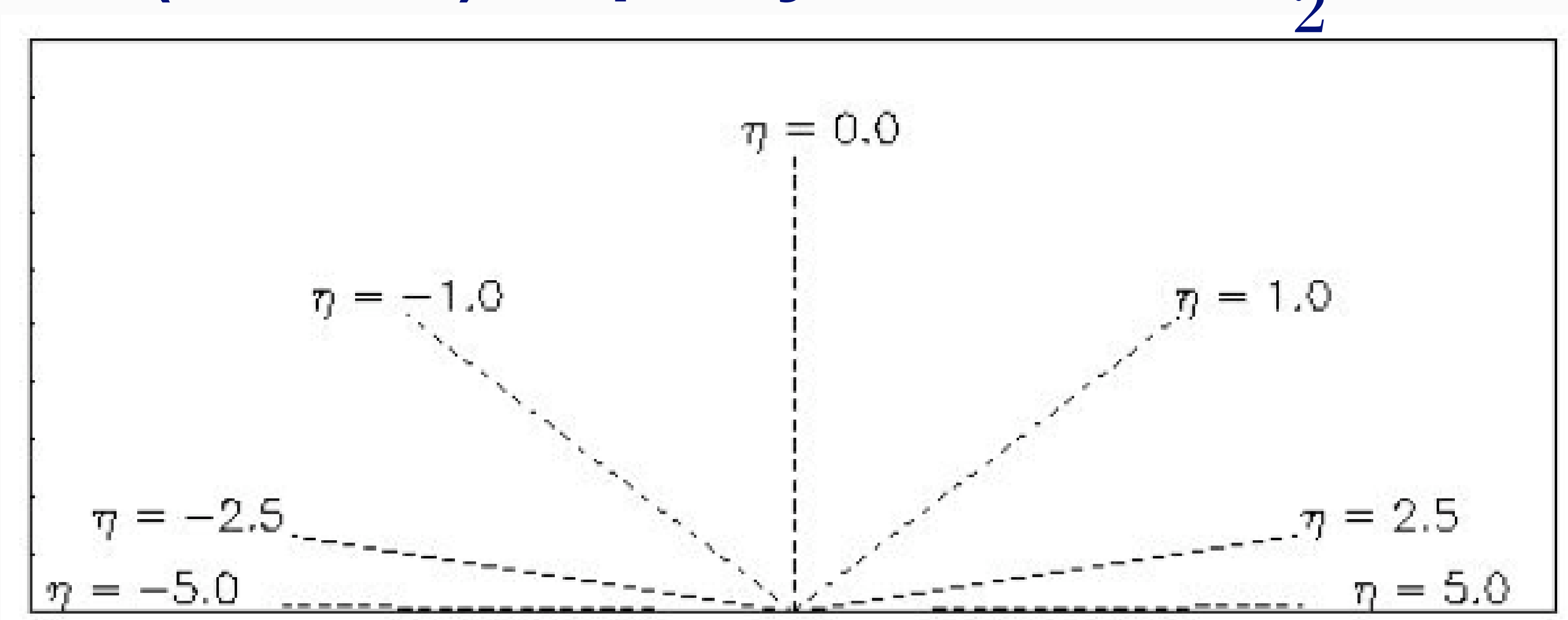
Variables used in pp collisions



Transverse momentum

(in the plane perpendicular to the beam)

(Pseudo)-Rapidity $\eta = -\ln \tan \frac{\theta}{2}$



$\theta = 90^o \rightarrow \eta = 0$

$\theta = 10^o \rightarrow \eta \cong 2.4$

$\theta = 170^o \rightarrow \eta \cong -2.4$

$\theta = 1^o \rightarrow \eta \cong 5.0$

pp-Interactions at the LHC

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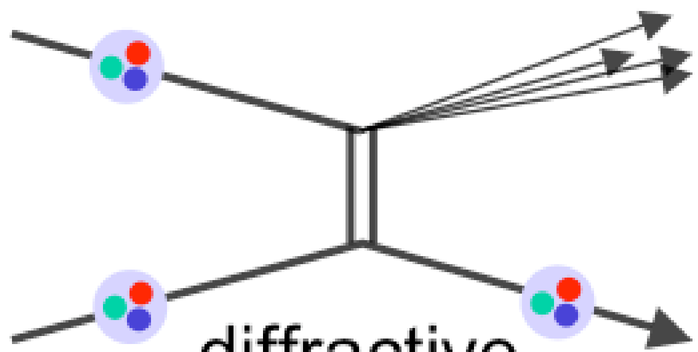
σ_{tot} =

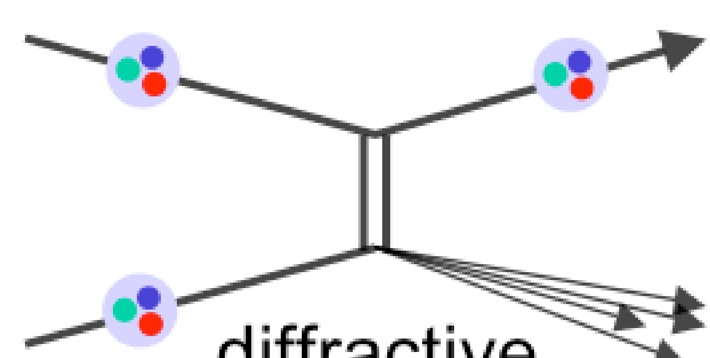
≈100mb



diffractive

≈10mb

+



diffractive

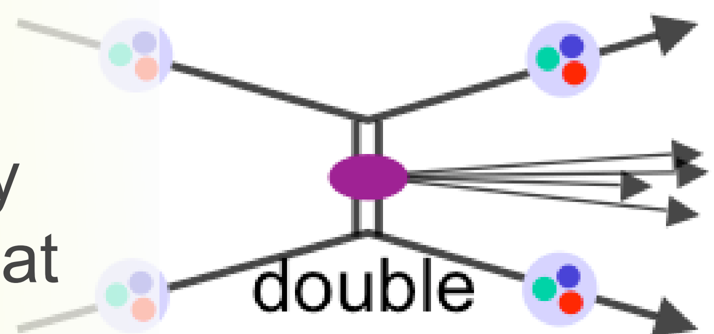
≈10mb

+

For diffractive and elastic scattering:

Put dedicated very forward detectors at small angles,

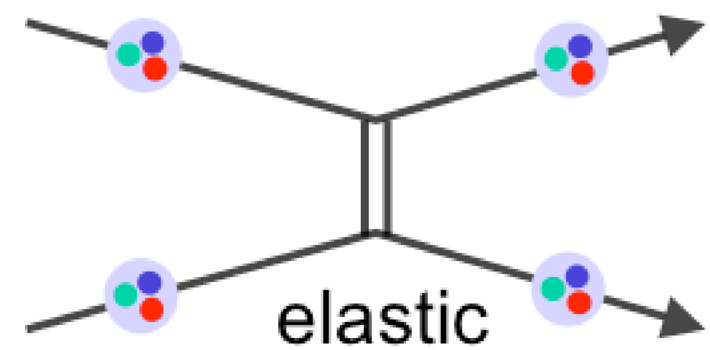
ie. very close to beam pipe



double diffractive

≈"small"

+

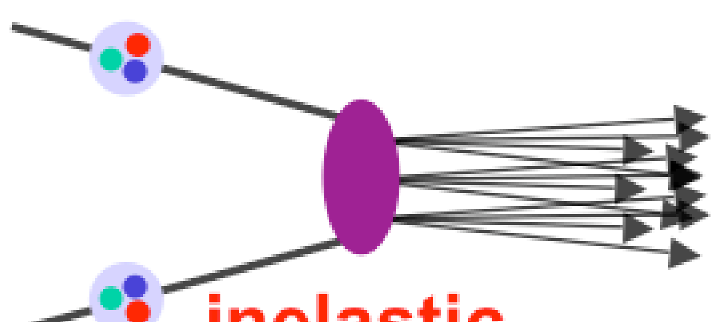


elastic

≈10mb

+

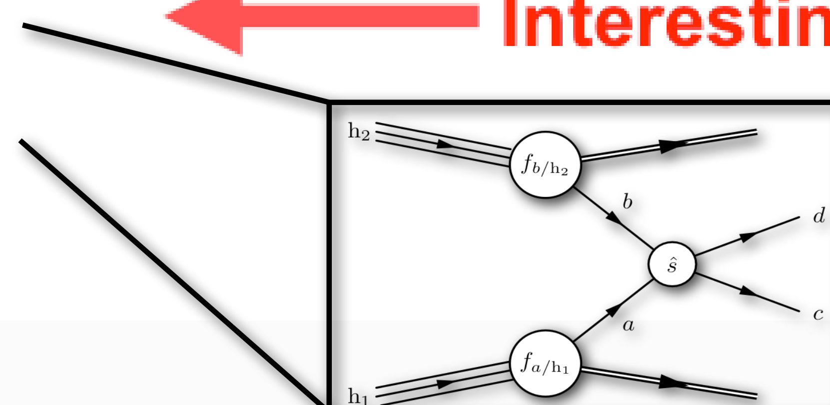
C. Schwick



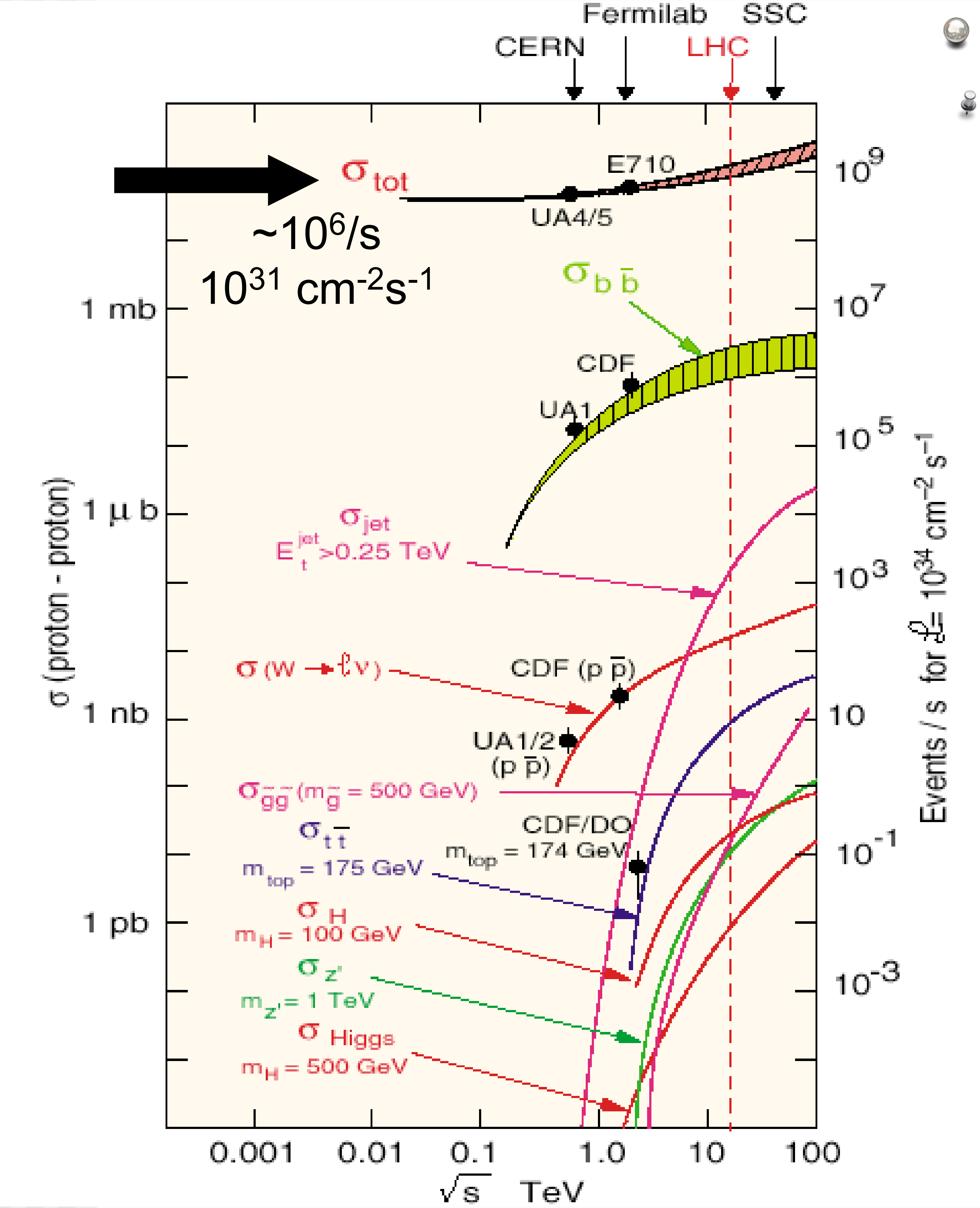
inelastic

≈70mb

Interesting Physics

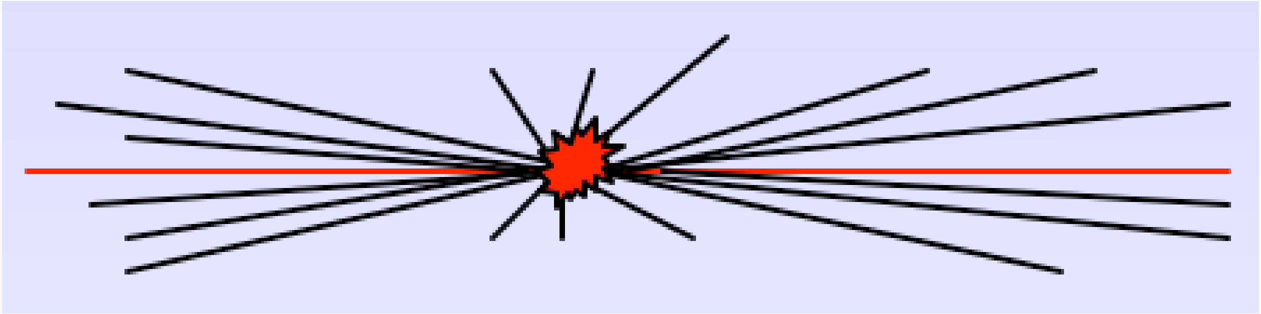


Physics Phases : 1



Inelastic low-p_T pp collisions

- Most interactions are due to interactions at large distance between incoming protons
  - small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum

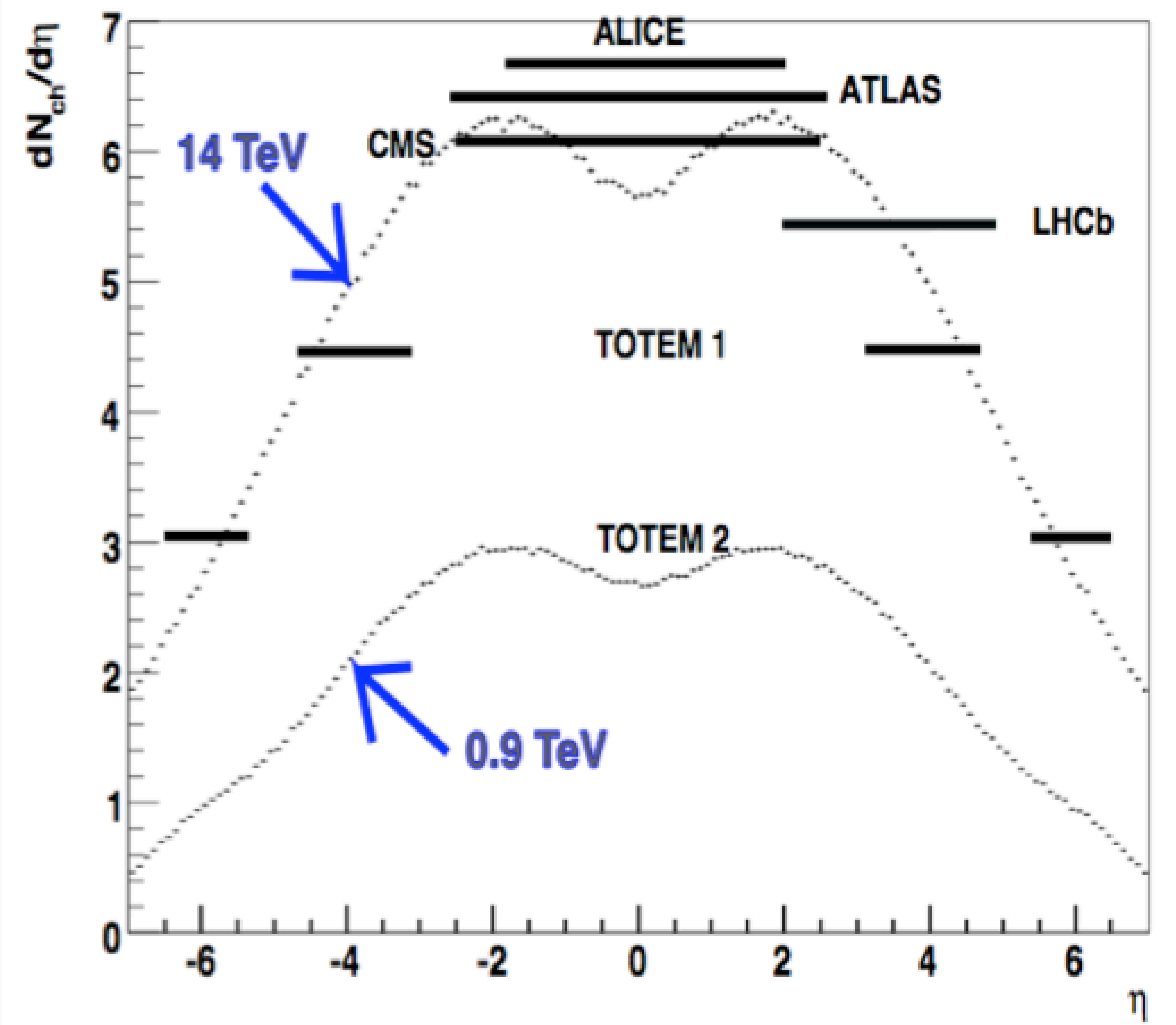


$$\langle p_T \rangle \approx 500\,\mathrm{MeV}$$

$$\frac{dN}{d\eta} \approx 7$$

- ~7 charged particles per unit of pseudorapidity in the central detector region
- uniformly distributed in φ

Minimum Bias events



$$\langle p_T \rangle \approx 500\,\mathrm{MeV}$$

$$\frac{dN}{d\eta} \approx 7$$

Low-p_T inelastic pp-collisions: "Minimum Bias events"

Parameters (multiplicity etc) poorly known (~50% or worse)

Important for tuning MC simulations

ETH Institute for Particle Physics

1 September 2008

Probably the first paper:
not Higgs, not SUSY
but rather "boring bread-and-butter" stuff

Charged particle multiplicity in pp collisions at $\sqrt{s} = 14$ TeV

CMS collaboration

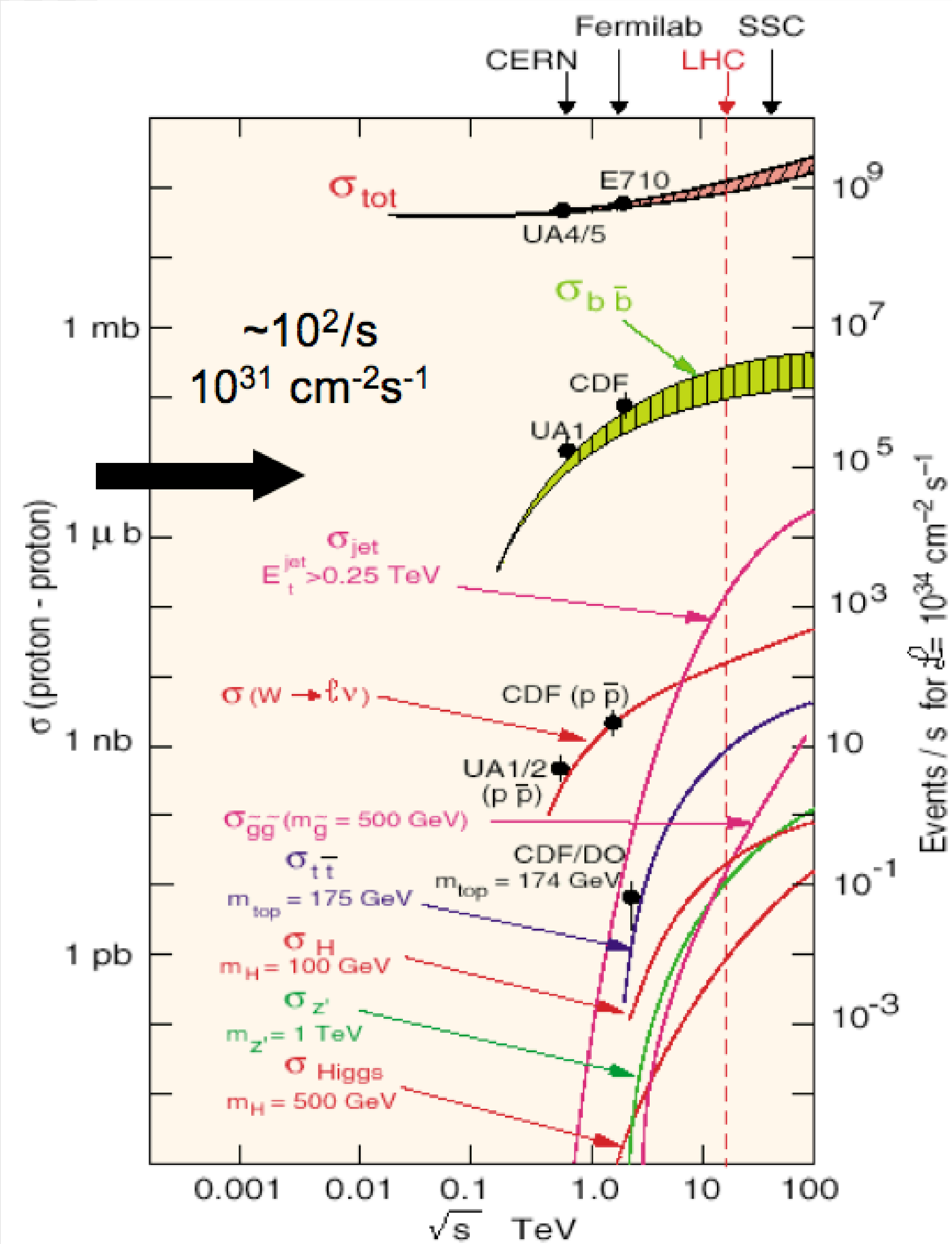
Abstract

We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced in the central region $|\eta| < 1$, at the LHC in pp collisions with $\sqrt{s} = 14$ TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that all models fail dramatically to describe the data.

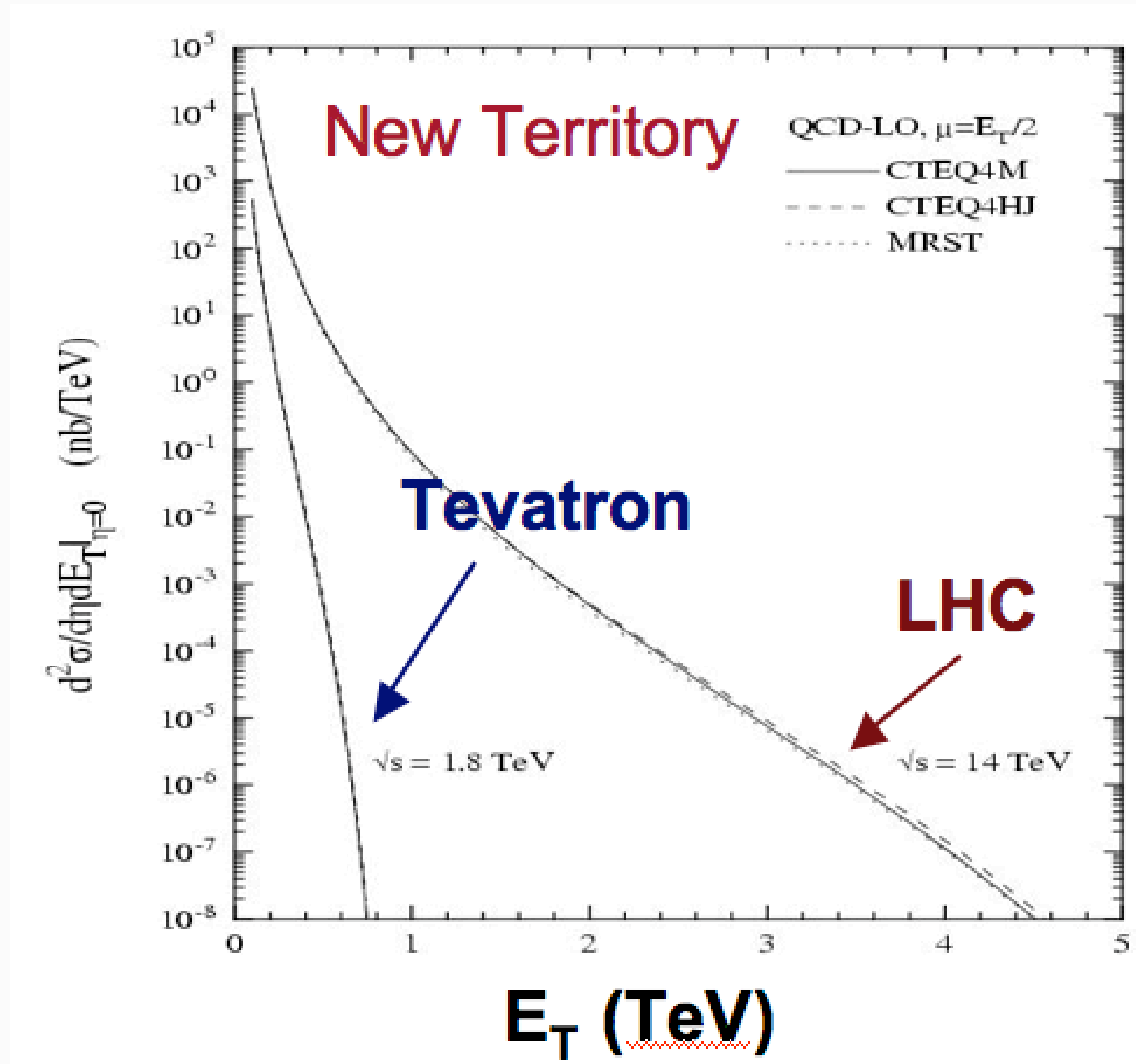
Submitted to *European Journal of Physics*

25/07/2007 HEP 2007 O. Buchmüller

Physics Phases : 2



- Measure Jet cross sections
  - E_T^{Jet} > 500 GeV after a few weeks at startup
  - Going fast beyond the TEVATRON reach
    - early sensitivity to compositeness



- requires good understanding of jets (algorithms, production, jet energy scale), PDFs, pile-up, underlying event, ...

Physics Phases : 3

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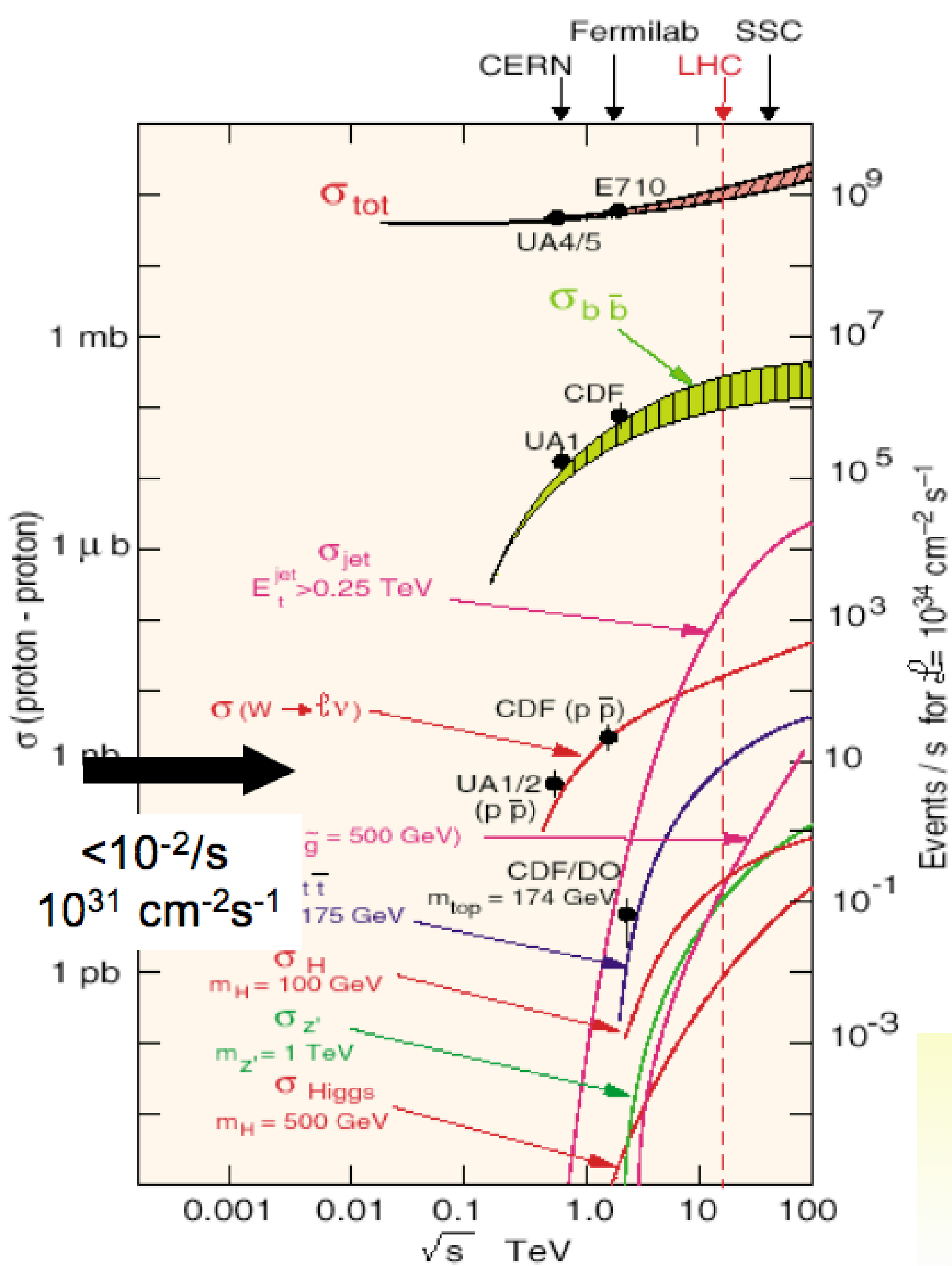


- Re-Discover the SM
  - test (re-establish the SM) and then go beyond
  - most SM cross sections are significantly higher than at the TEVATRON
    - eg. 100x larger top-pair production cross section
    - the LHC is a top, b, W, Z, ..., Higgs, ... factory

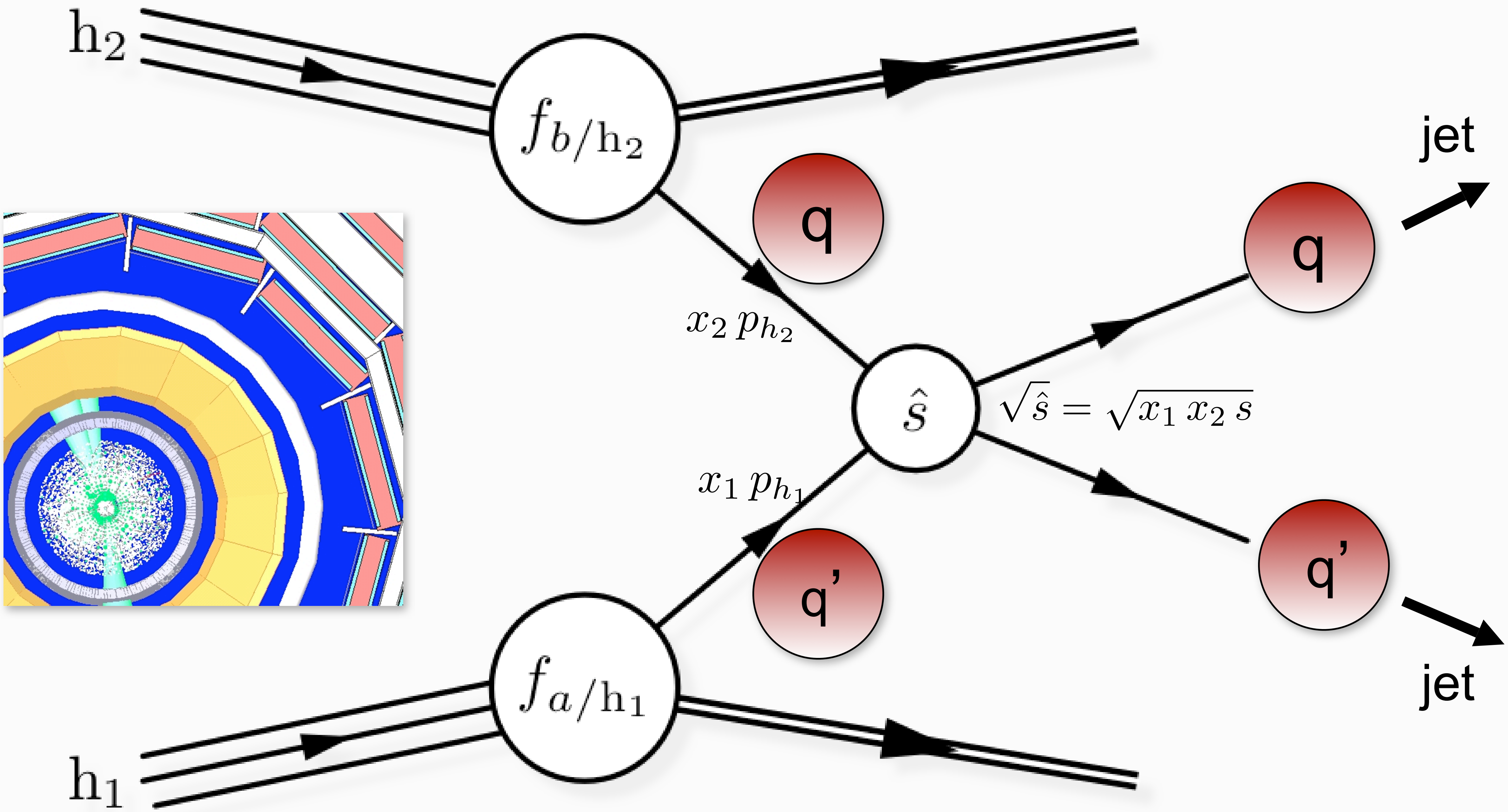
Rates for $L = 10^{31}\ cm^{-2}\ s^{-1}$: (LHC)

• Inelastic proton-proton reactions:	10^6 / s
• bb pairs	$5\ 10^3$ / s
• tt pairs	0.01 / s
• W → e ν	0.15 / s
• Z → e e	0.015 / s
• **Higgs (150 GeV)**	**0.0002 / s**
• **Gluino, Squarks (1 TeV)**	**0.00003 / s**

Important to note:
Concentrate on final states with high-p_T and isolated **leptons and photons** (+ jets)

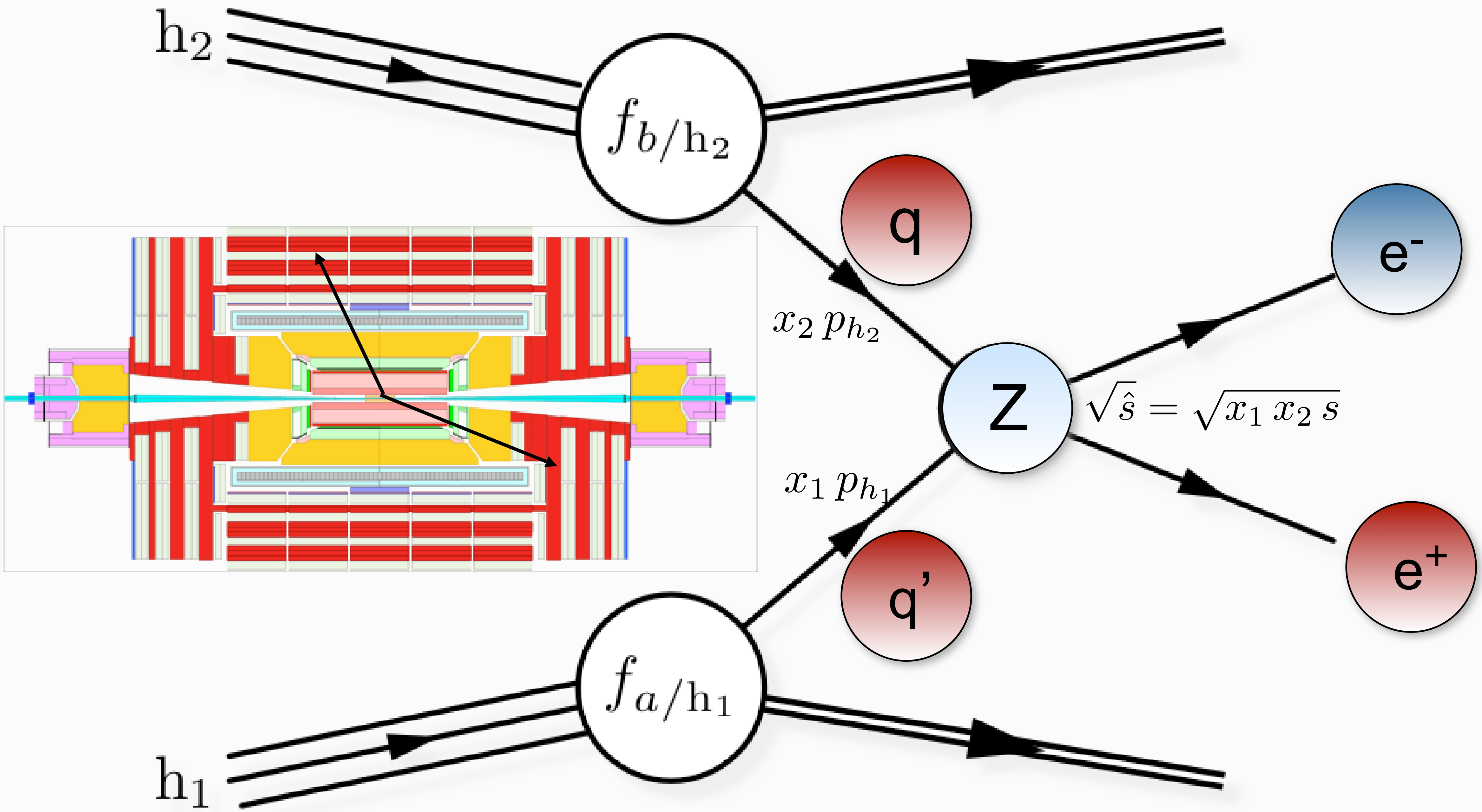
Otherwise overwhelmed by QCD jet background!!

Basic processes



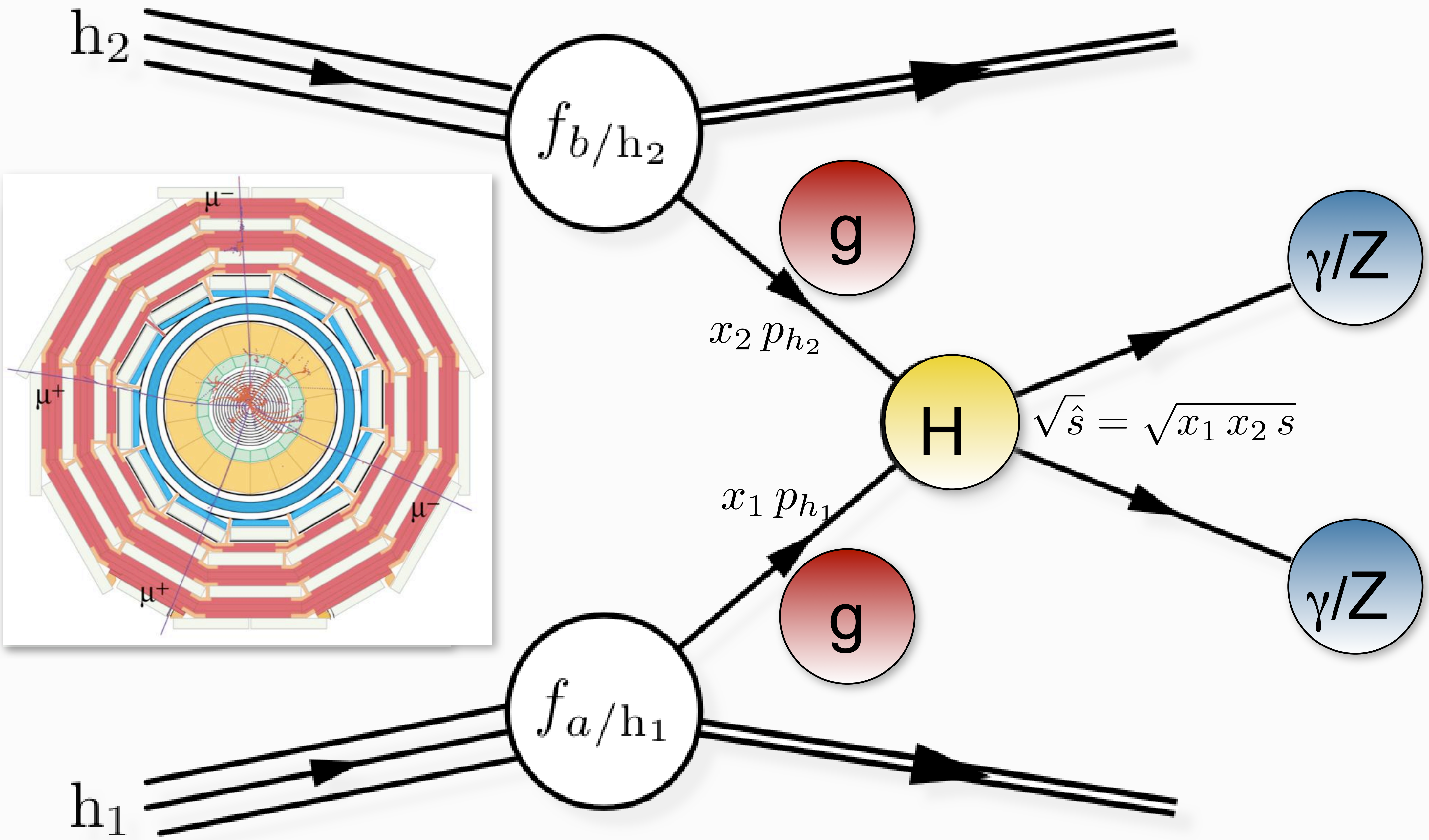
$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

Basic processes



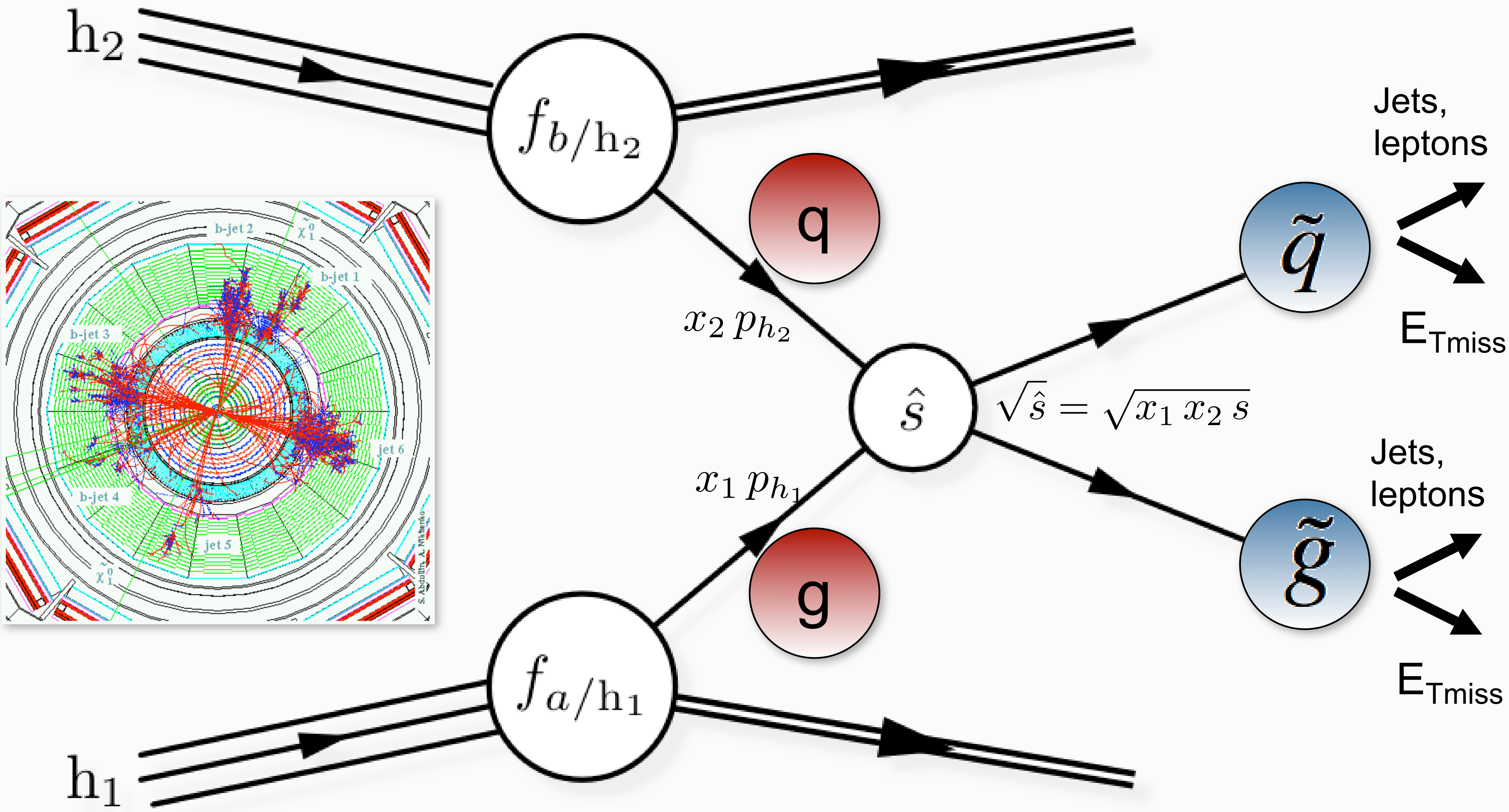
$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

Basic processes



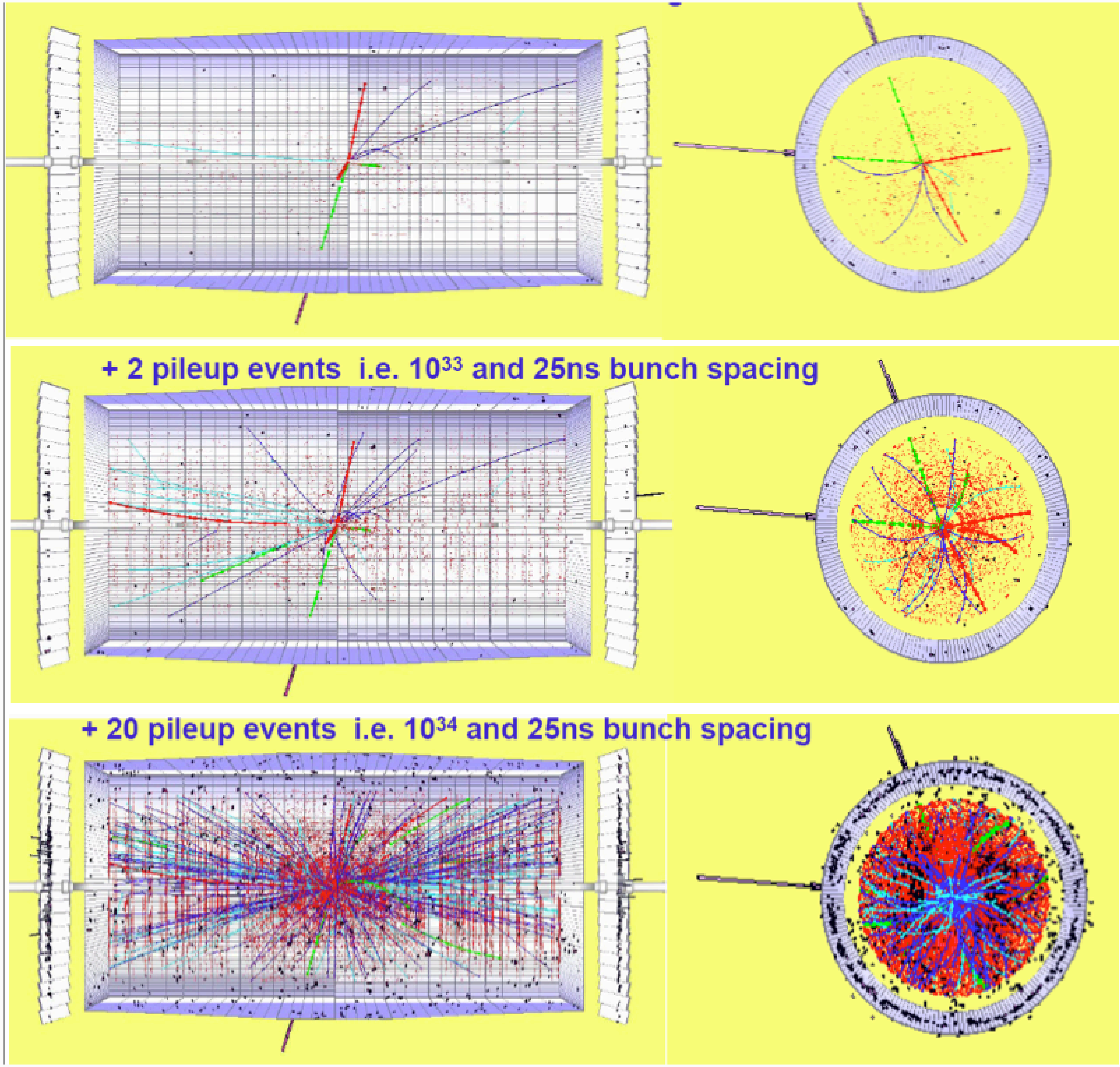
$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

Basic processes



$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

Challenge : Pile-up events



S. Tapprogge, Nov06

- at high lumi: up to 20 additional min bias events
- ~1600 charged particles in the detector
- Example of golden Higgs channel $H \to ZZ \to 2e2\mu$
- Large magnetic field and high granularity helps
- Need to understand detector first before able to exploit full lumi…

The LHC environment : Pretty tough

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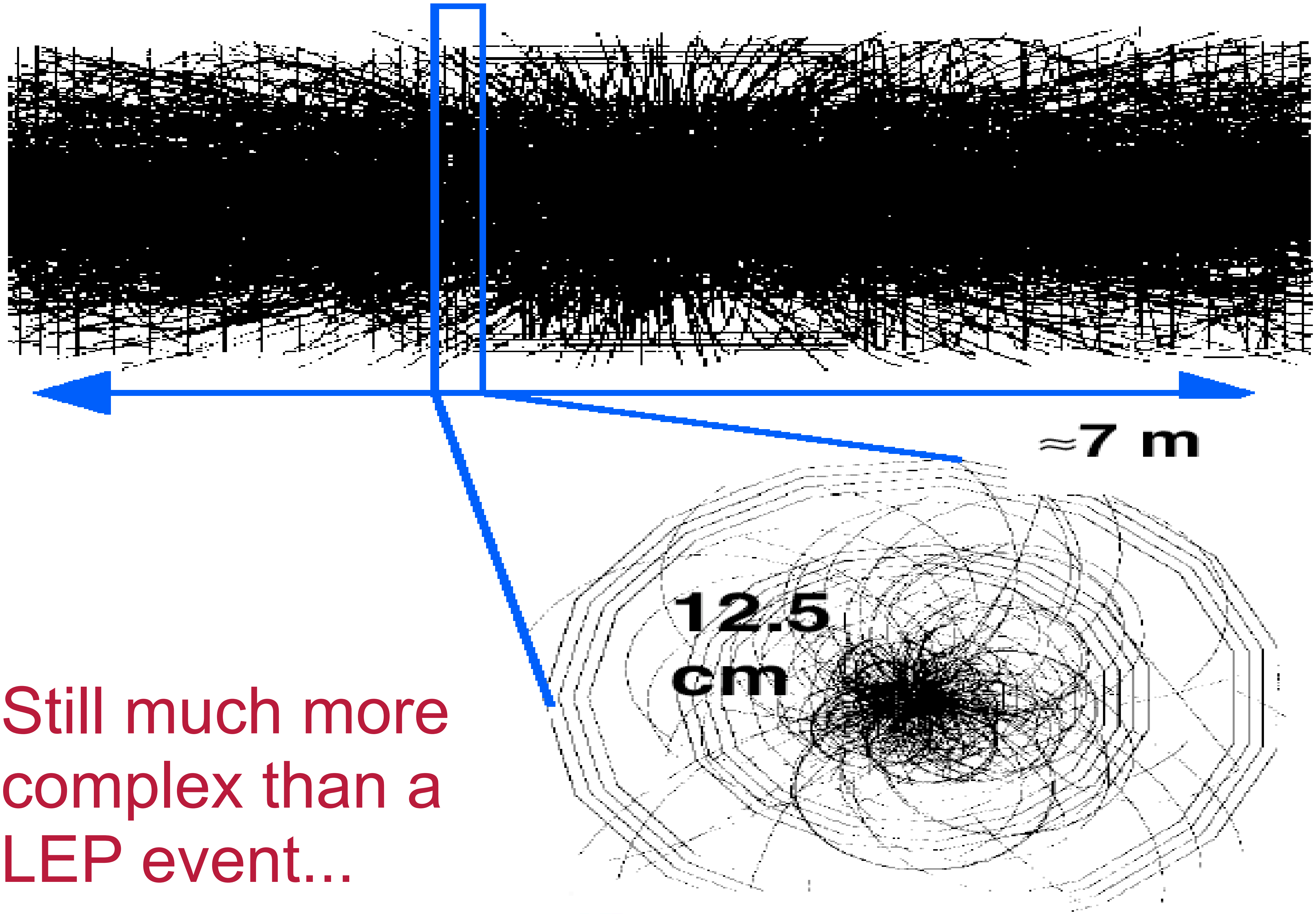
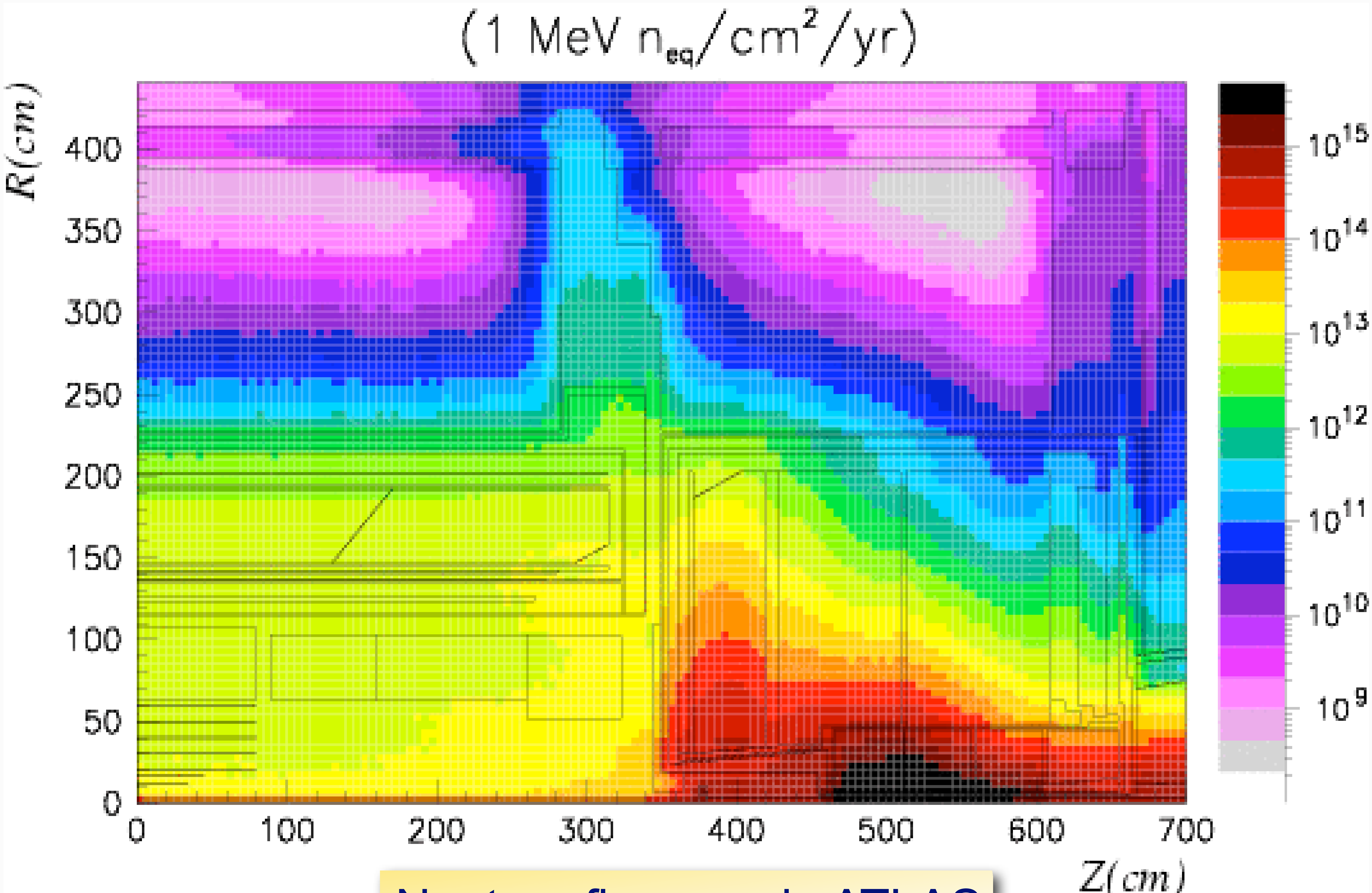


Still much more complex than a LEP event...

D. Froidevaux, CSS 07

The LHC environment...



Neutron fluences in ATLAS

Damage caused by ionising radiation

- caused by energy deposited by particles in the detector material
  - ~ 2 MeV g^{-1} cm^{-2} for a min. ionizing particle
- also caused by photons created in elmg. showers
- damage is proportional to the deposited energy or dose measured in Gy (Gray)
  - 1 Gy = 1 Joule / kg = 100 rads
  - 1 Gy = 3 10^9 particles per cm^2 of material with unit density

at LHC design luminosity :
Ionising dose is ~ 2 10^6 Gy / r_T^2 / year
r_T [cm] : transverse distance to beam

Damage caused by neutrons

- neutrons are created in hadronic showers in the calorimeters and even more so in the forward shielding of the detectors and in the beam collimators
  - energies : 0.1 - 20 MeV

- they bounce back and forth (like gas molecules) on the various nuclei and fill up the whole detector
  - mean free path ~ 5 cm in this energy range

- very large fluences
  - up to 3 10^{13} cm^{-2} per year in the inner tracking systems

Damage caused by neutrons

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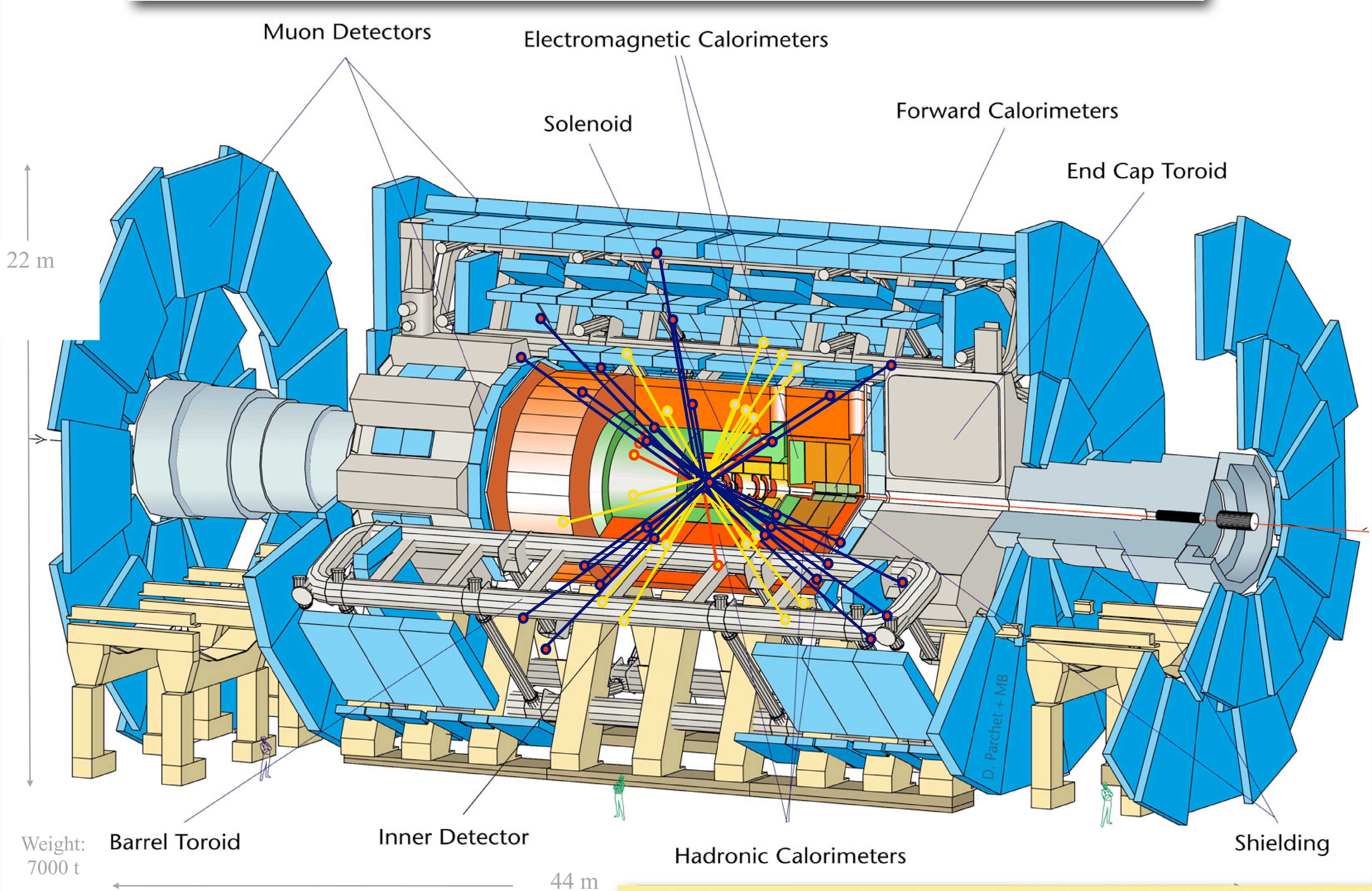
- neutrons wreak havoc in semiconductors, independently of the deposited energy
  - they modify directly the cristalline structure
- So : need radiation-hard electronics as well as radiation-hard active detector material (silicon sensors, crystals etc)
  - military applications only in the early R&D days
  - off-the-shelf electronics usually dies out for doses above 100 Gy and fluences above 10^{13} neutrons/cm^2
  - rad-hard electronics (especially deep-submicron technology) can survive up to 10^5-10^6 Gy and 10^{15} neutrons/cms^2
- Most organic materials survive easily to 10^5-10^6 Gy

Material validation and quality control during production are needed at the same level as for space applications!

The Timing Challenge

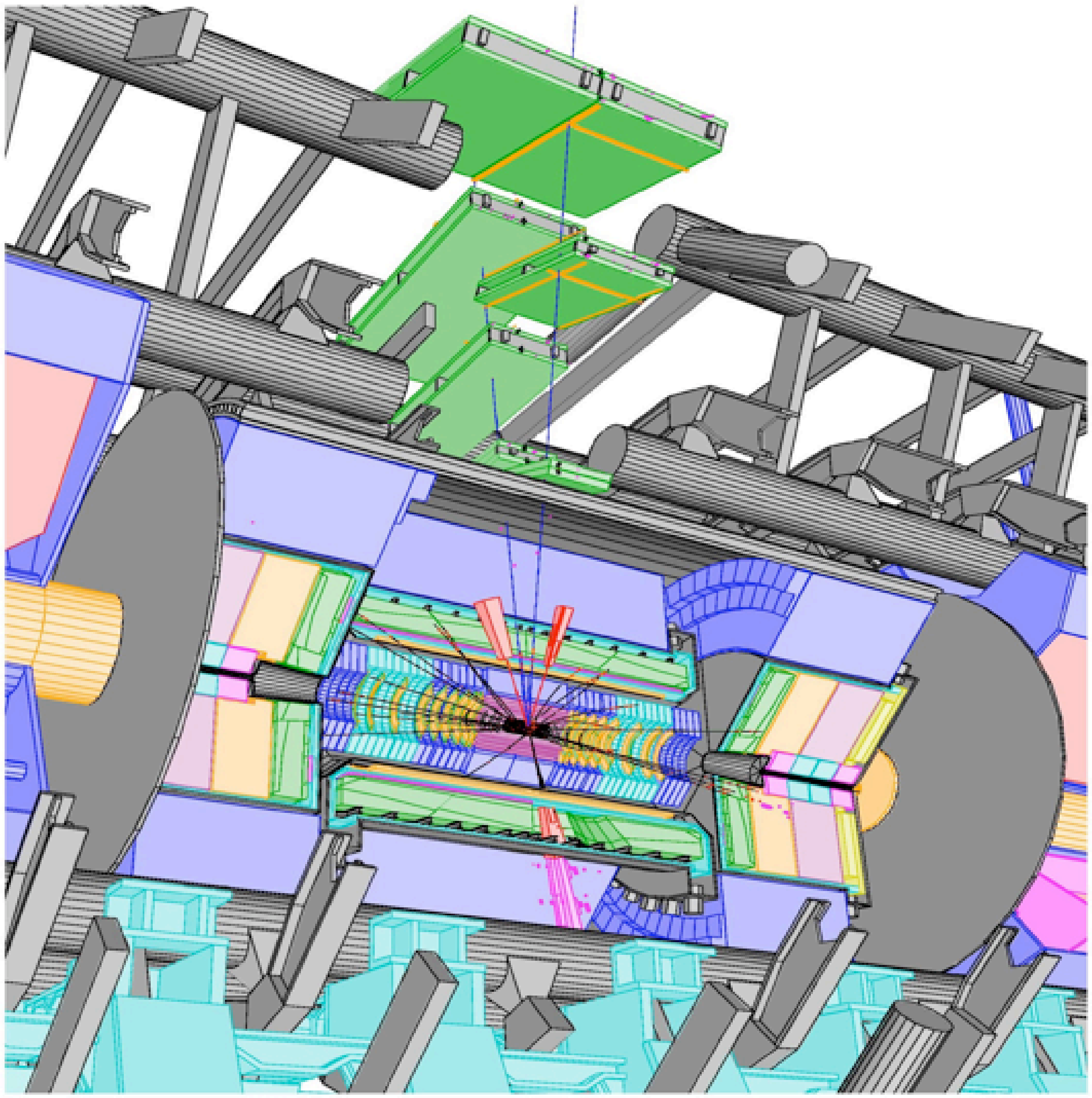
Interactions every 25ns : In 25 ns particles travel 7.5m



Cable length ~100m : In 25 ns signals travel 5 m

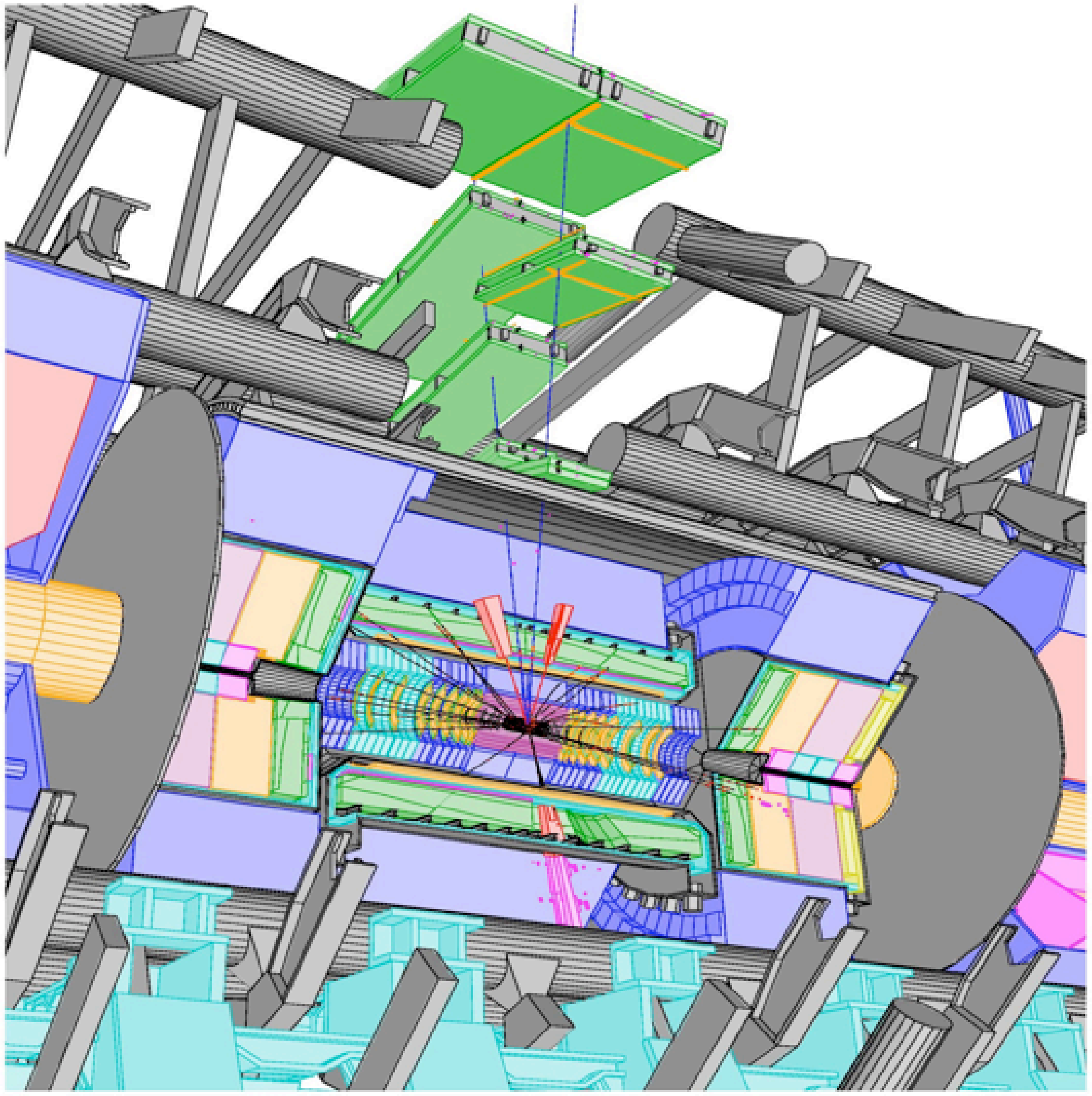
Detector requirements

- High granularity (NEW!), fast readout (NEW!), radiation hardness (NEW!)
  - minimize pile-up particles in same detector element
  - many channels
    eg. 100 million pixels,
    200’000 cells in electromagnetic calorimeter
  - cost !
  - 20-50 ns response time for electronics !
  - in forward calorimeters : up to 10^{17} n/cm^2 over 10 years of LHC operations



Detector requirements

- Detectors must identify extremely rare events, mostly in real time
  - lepton identification above huge QCD background
  - e/jet ratio ~ 10^{-5}, ~100x worse than at Tevatron
  - signal cross section as low as 10^{-14} of total cross section : NEW!
  - Online rejection to be achieved : ~ 10^{7} NEW! (see lectures by Ch. Schwick)
  - Store huge data volumes to disk/tape : ~10^{9} events of ~1 Mbyte / year NEW!



Detector requirements

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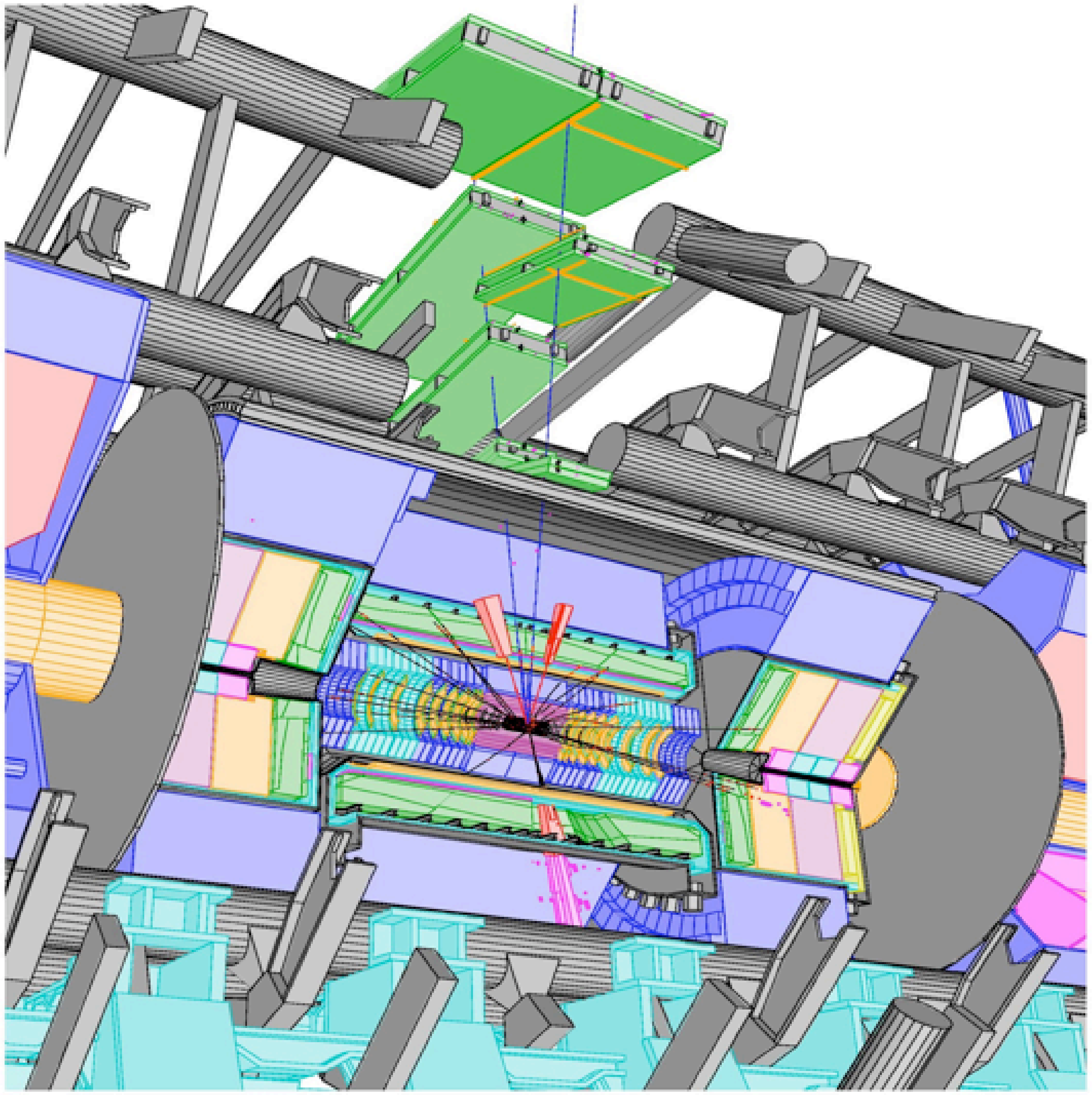
- Good measurement of leptons (e, μ) and photons with large transverse momentum p_T
  - elmg. calorimetry, muon systems
- Good jet reconstruction
  - good resolution, absolute energy measurement, low fake-rate
- Good measurement of missing transverse energy ($E_{T\,miss}$)

  and
- energy measurements in the forward regions
  - thus, hermetic detector and
  - calorimeter coverage down to rapidity ~ 5



- Efficient b-tagging and tau identification (silicon strip and pixel detectors)
  - top physics, Higgs couplings to b and tau enhanced in certain models (eg. MSSM)

Examples of detector performance requirements

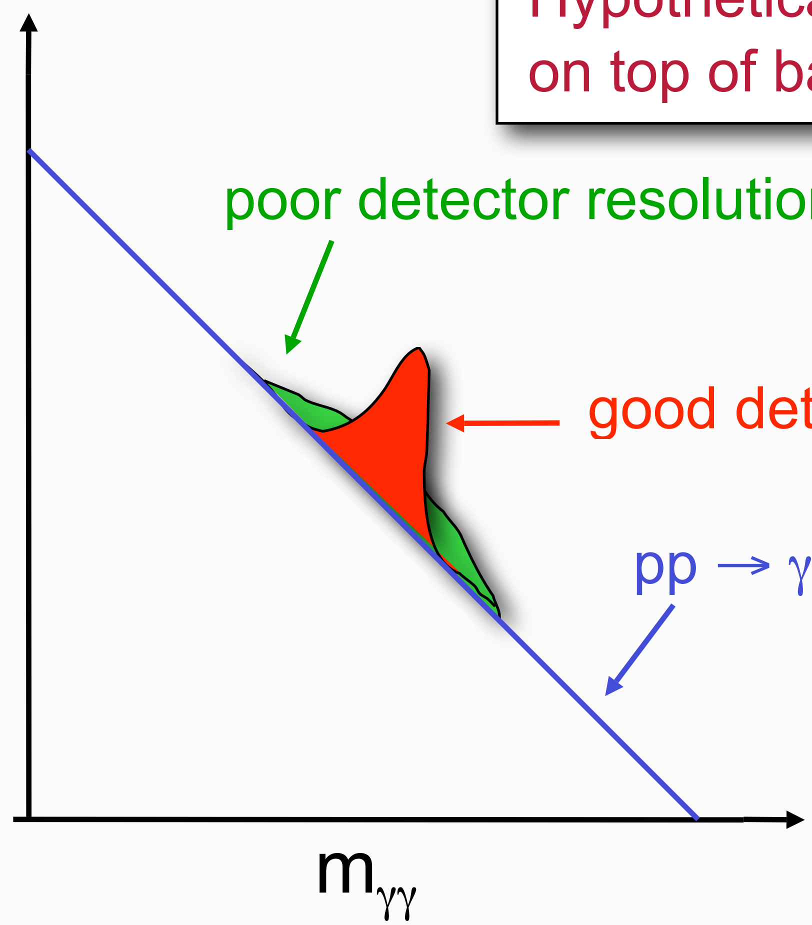
Lepton measurement: $p_T \approx$ GeV → 5 TeV (b → l+X, W/Z, W'/Z', …)

Mass resolutions:

≈ 1% decays into leptons or photons
(Higgs, new resonances)

≈ 10% W → jj, H → bb
(top physics, Higgs, …)

Hypothetical X → γγ signal on top of background



Particle identification:

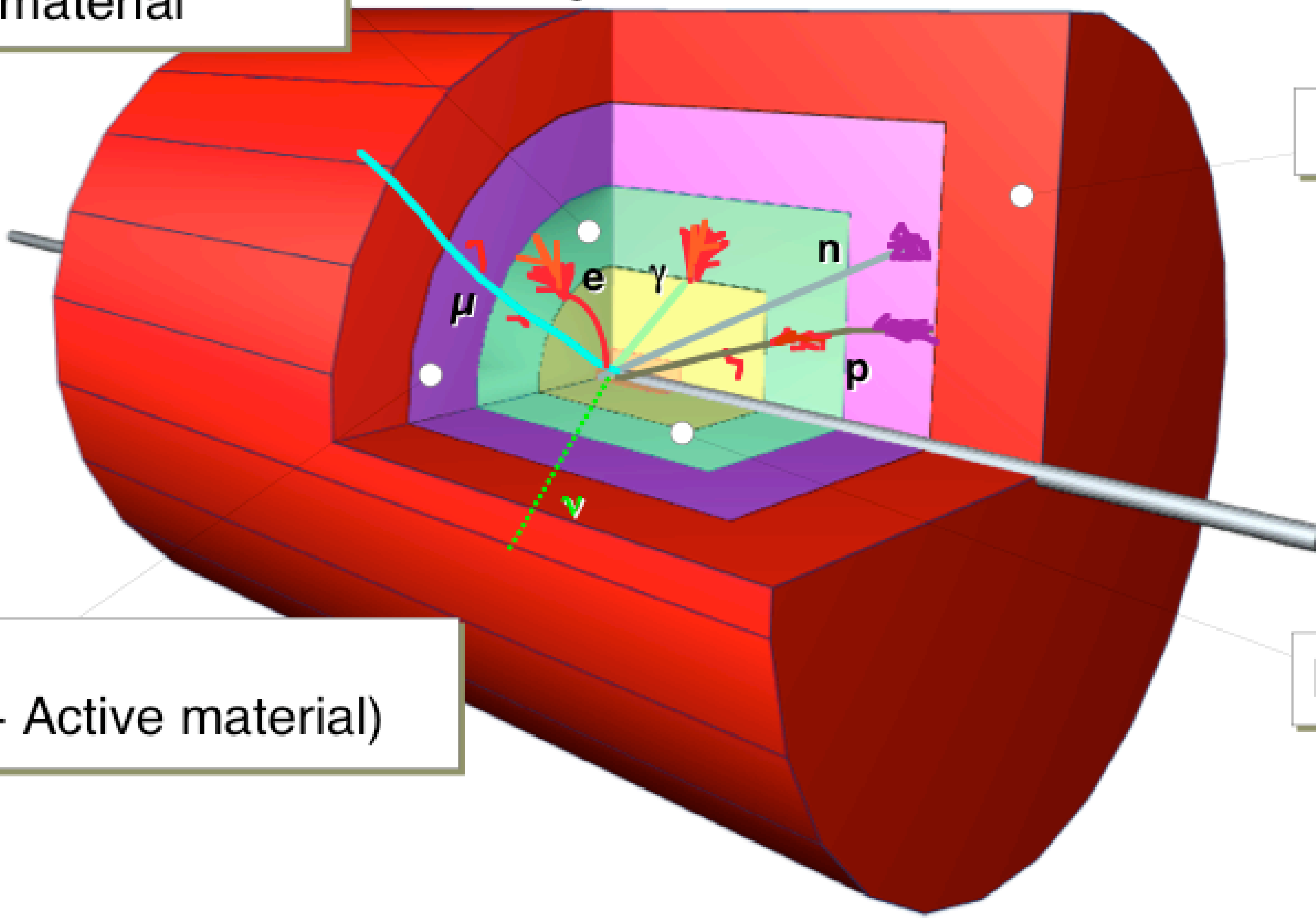
- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 10^3 (H → γγ)
- e/jet separation : ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

LHC Detector : Main principle

Materials with high number of protons + Active material

Hermetic calorimetry
- Missing Et measurements

Electromagnetic and Hadron calorimeters
- Particle identification (e, γ Jets, Missing E_T)
- Energy measurement



Heavy materials

Muon detector
- μ identification

Heavy materials (Iron or Copper + Active material)

Light materials

Central detector
- Tracking, p_T, MIP
- Em. shower position
- Topology
- Vertex

Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

C. Schwick (CERN/CMS)

General Detector Layout: CMS example

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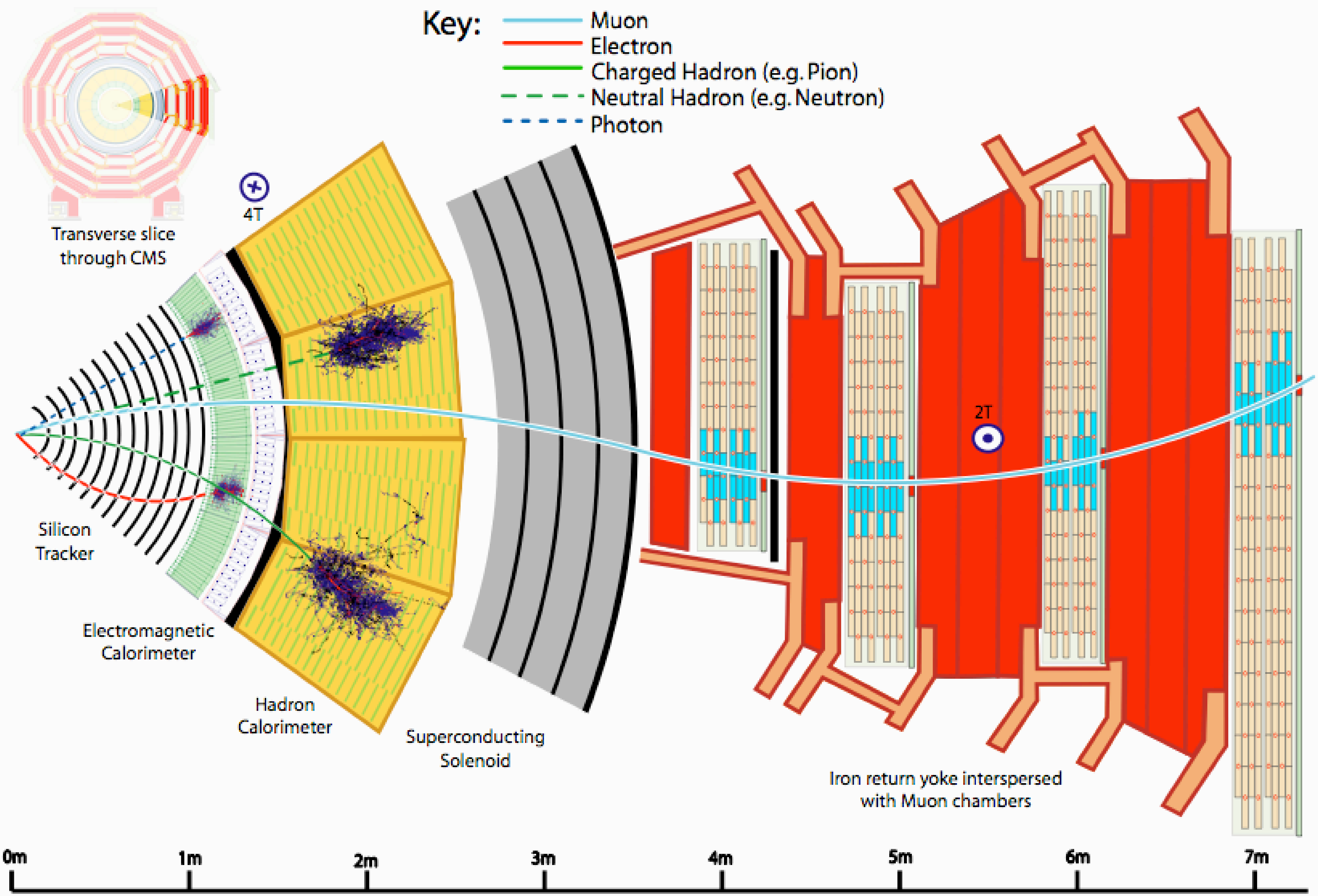
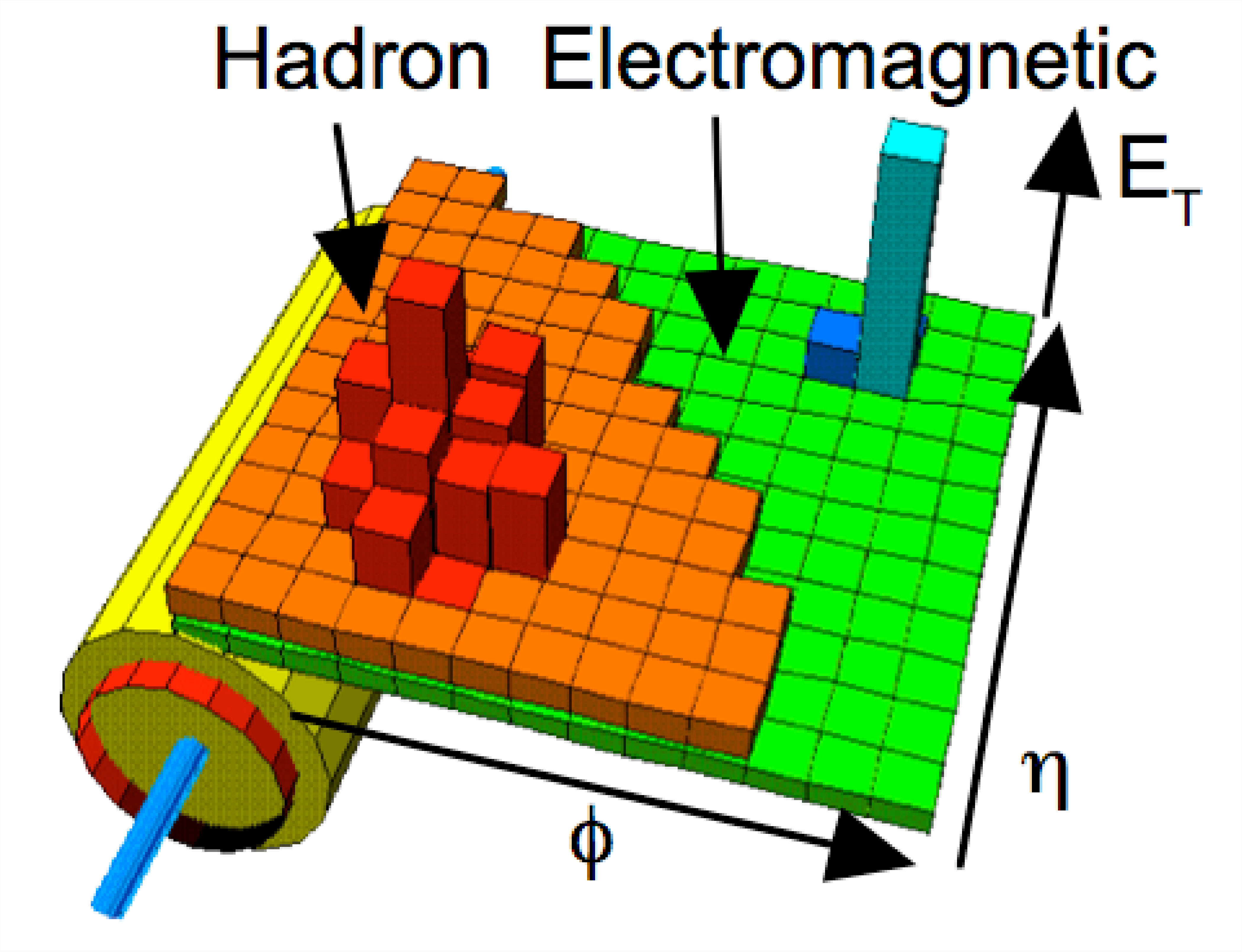


Calorimeters : Subdivision into cells



Finally, need massive (distributed) computing resources (CPU, storage)

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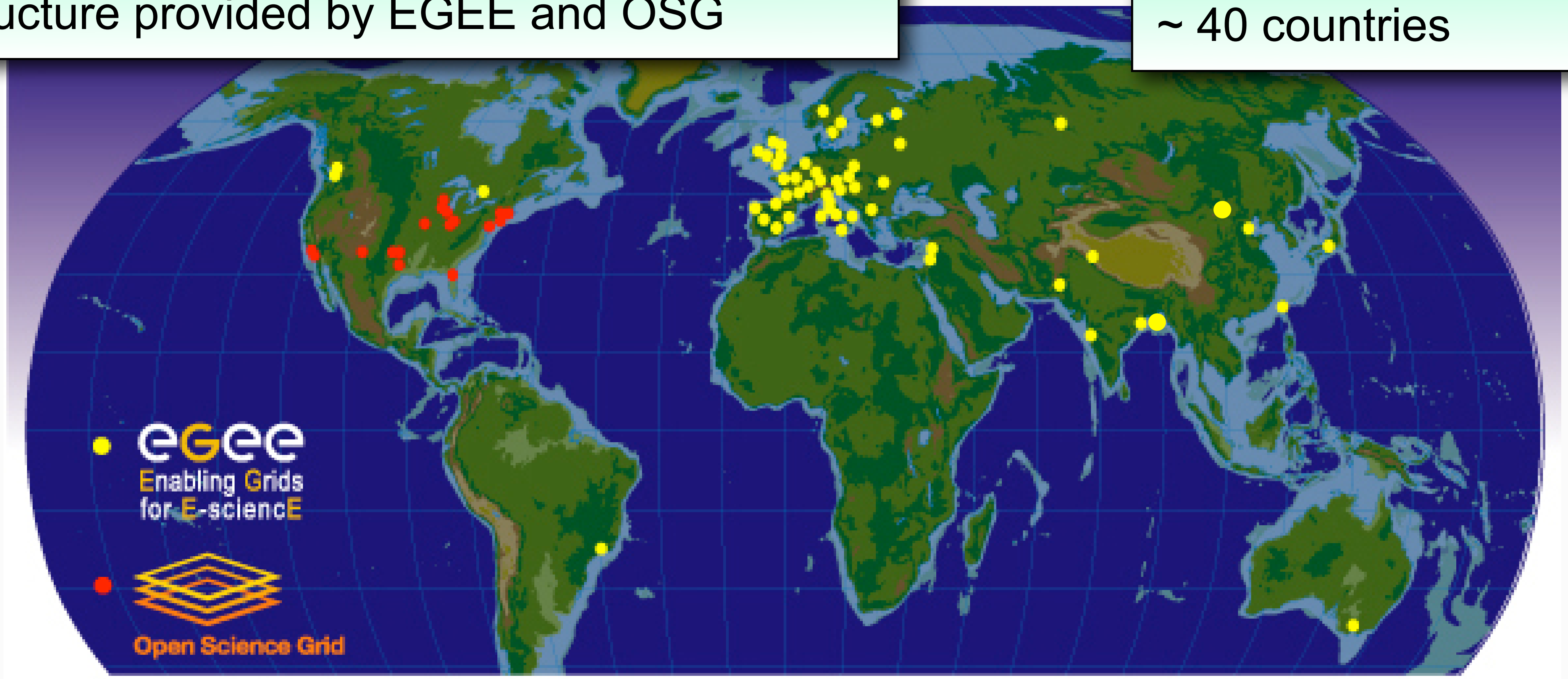
- The LHC experiments will produce 10-15 PB of data per year:
  - corresponds to ~ 20 million CD (a 20 km stack …)
- Data analysis requires computing power equivalent to ~10^5 today's fastest PC processors
- The experiment Collaborations are spread all over the world
  - Computing resources must be distributed.
- The Grid provides seamless access to computing power and data storage capacity distributed over the globe.

A map of the worldwide LHC Computing Grid infrastructure provided by EGEE and OSG

~120 computing centers
~ 40 countries



Summary of Part 1

"Doing something ordinary is a waste of time" (Madonna)

Summary Part 1

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- We have many strong indications that new physics should to show up at the TeV scale
- The LHC is designed to explore this new energy regime
  - a machine of unprecedented complexity
  - the start-up will go in several steps
- The Detectors requirements
  - the LHC environment (physics, rates, backgrounds, radiation, ...) put unprecedented constraints on the detector
  - many years of R&D were needed to meet the challenges