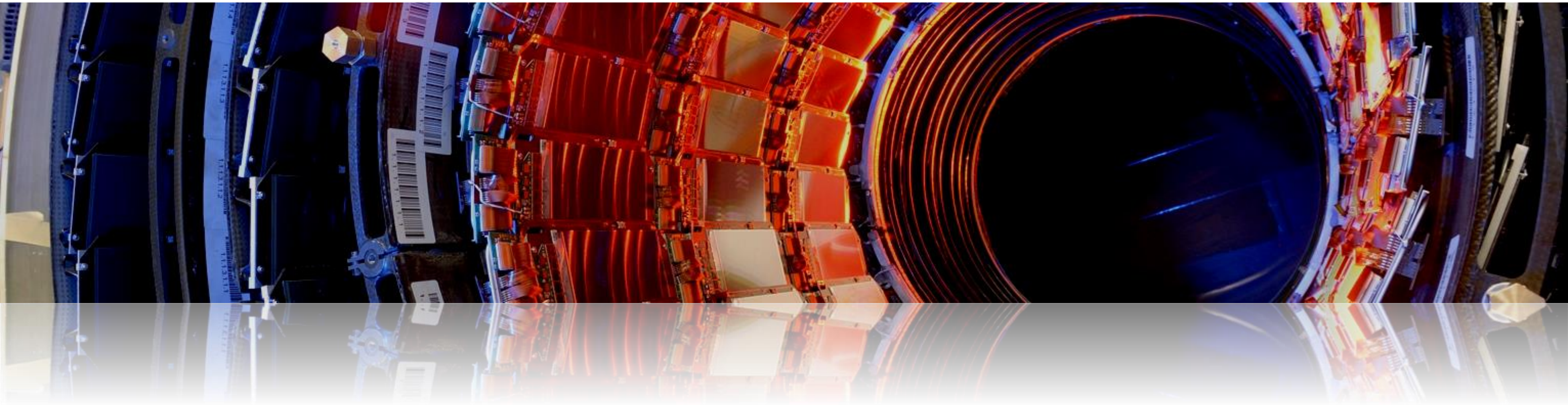
The Experiments

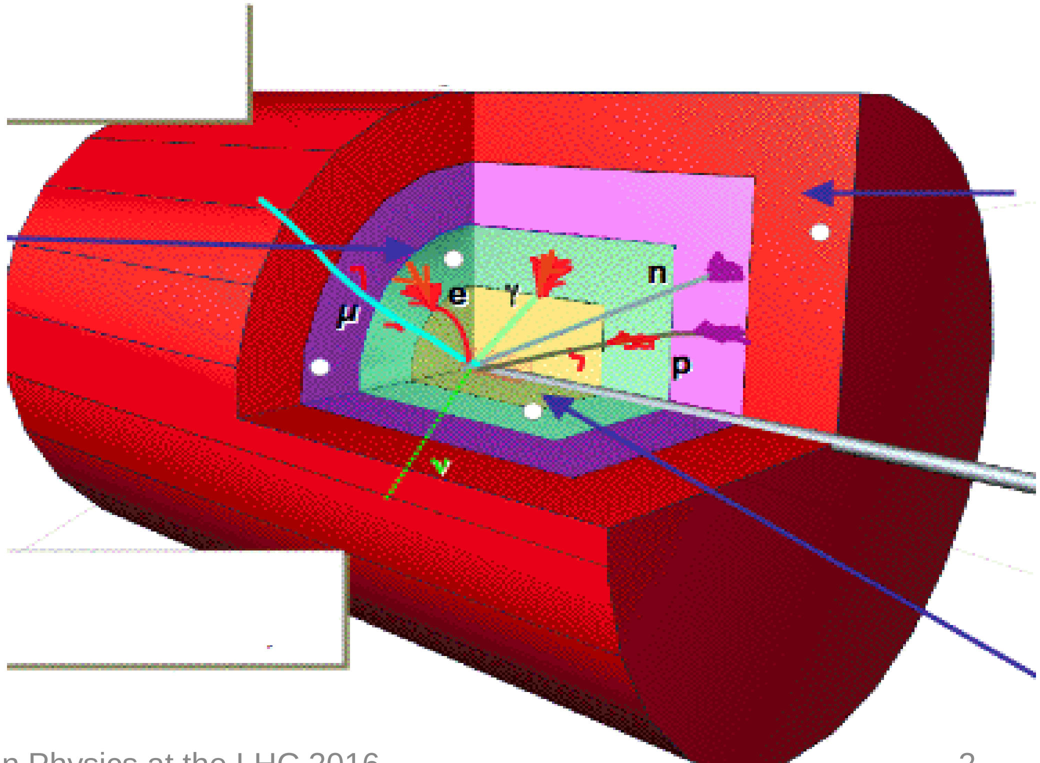


General purpose LHC experiments

Advanced detectors comprising many layers, each designed to perform a specific task.

Together these layers allow to identify and precisely measure the energies of all stable particles produced in collisions.

Photons,
Electrons,
Muons,
Quarks
    (as jets of particles)
Neutrinos
    (as missing energy)



Detector design

Design guided by physics

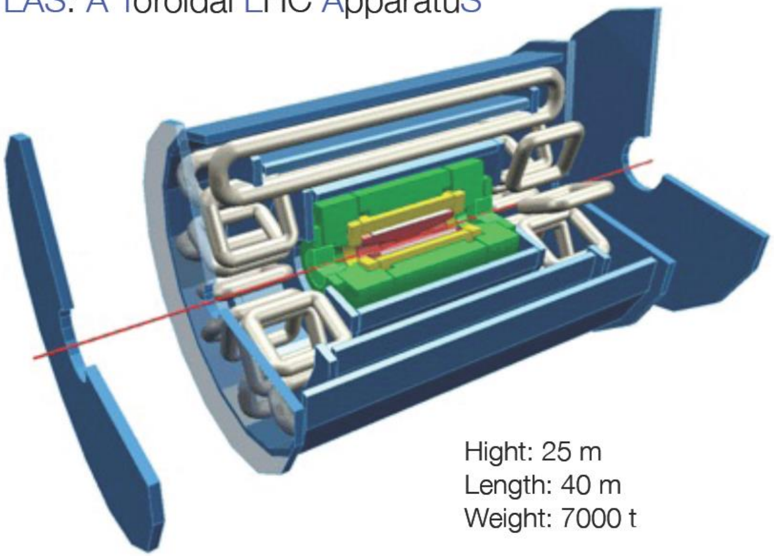
Search and measure the Higgs boson

Search and measure Supersymmetry

Search for any other new physics at high p_T

Two concepts

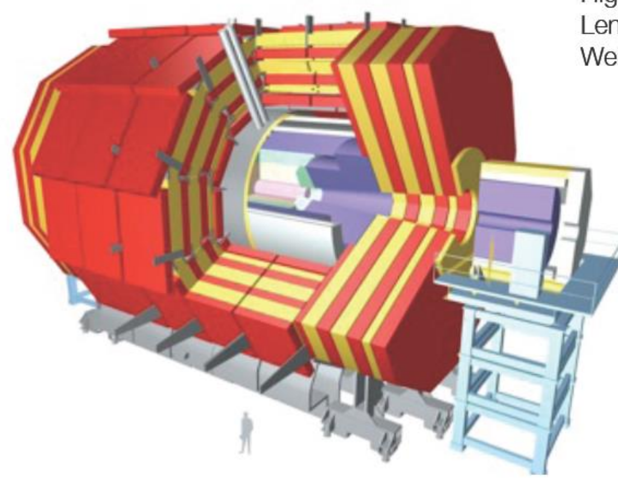
ATLAS: A Toroidal LHC ApparatuS

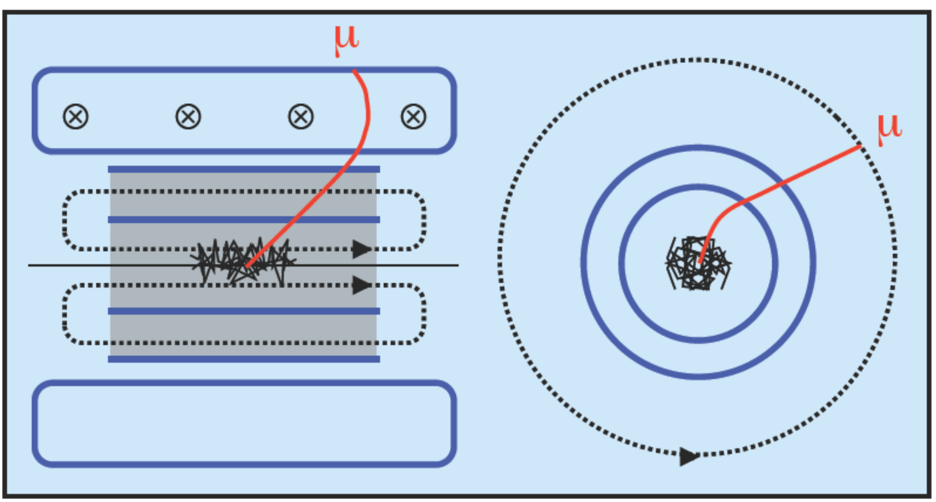


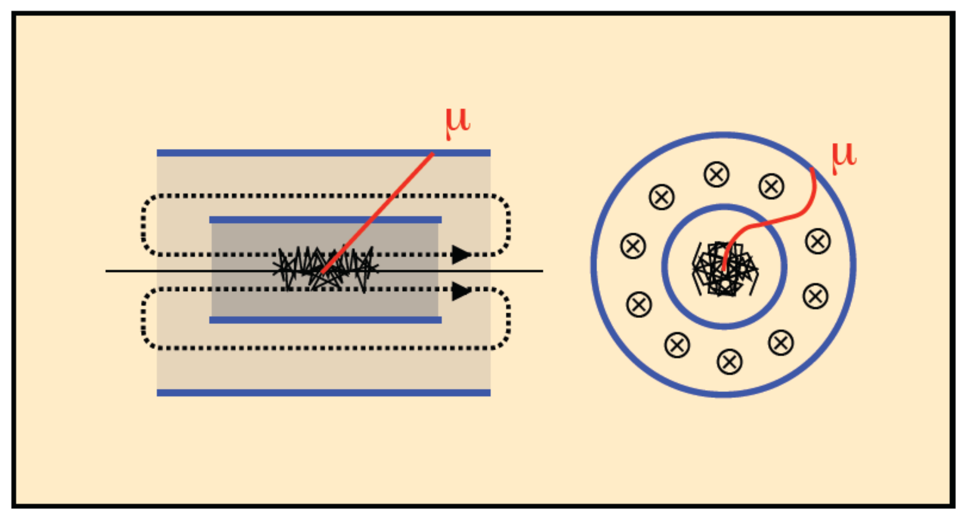
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

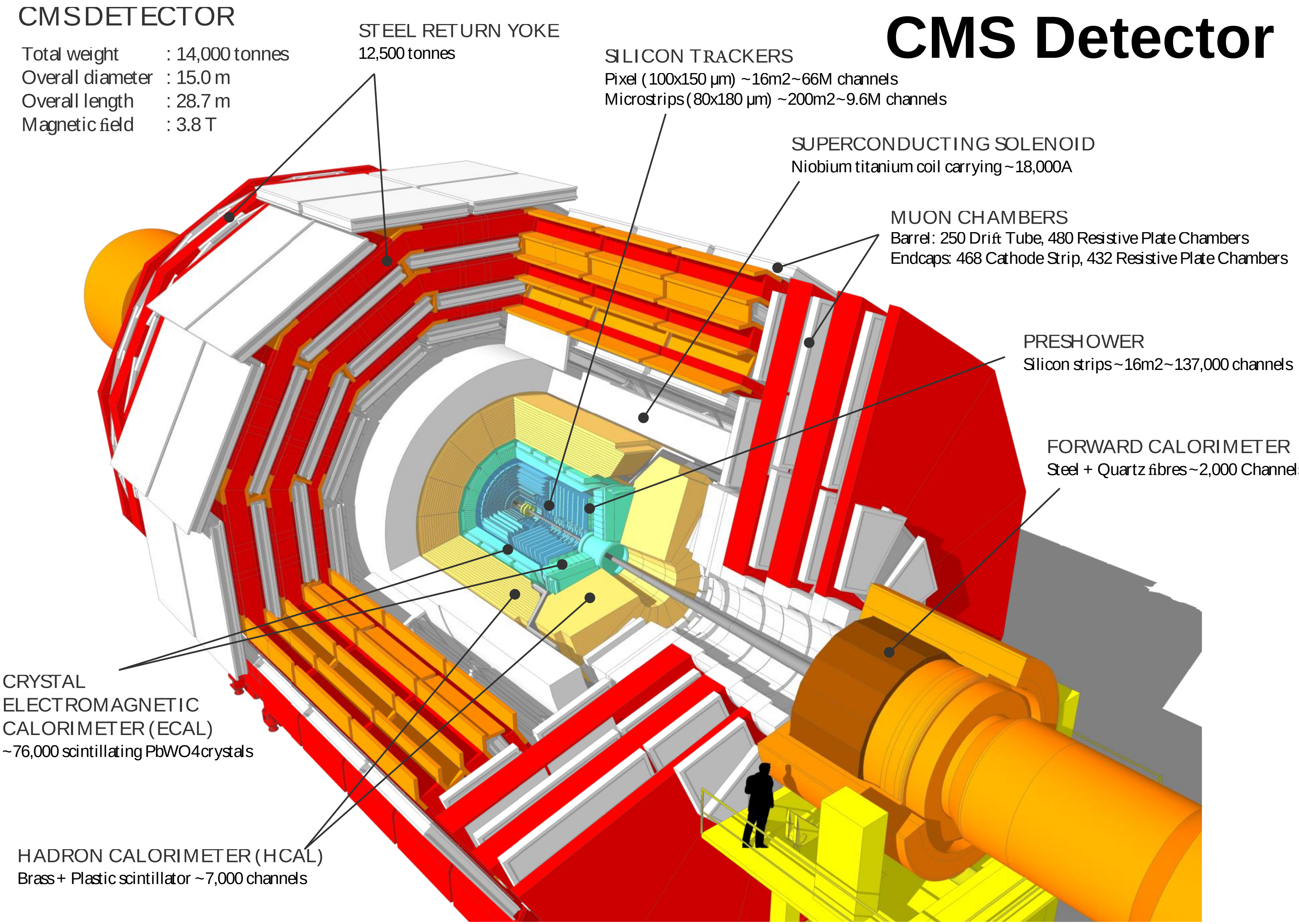
Hight: 15 m
Length: 22 m
Weight: 12500 t



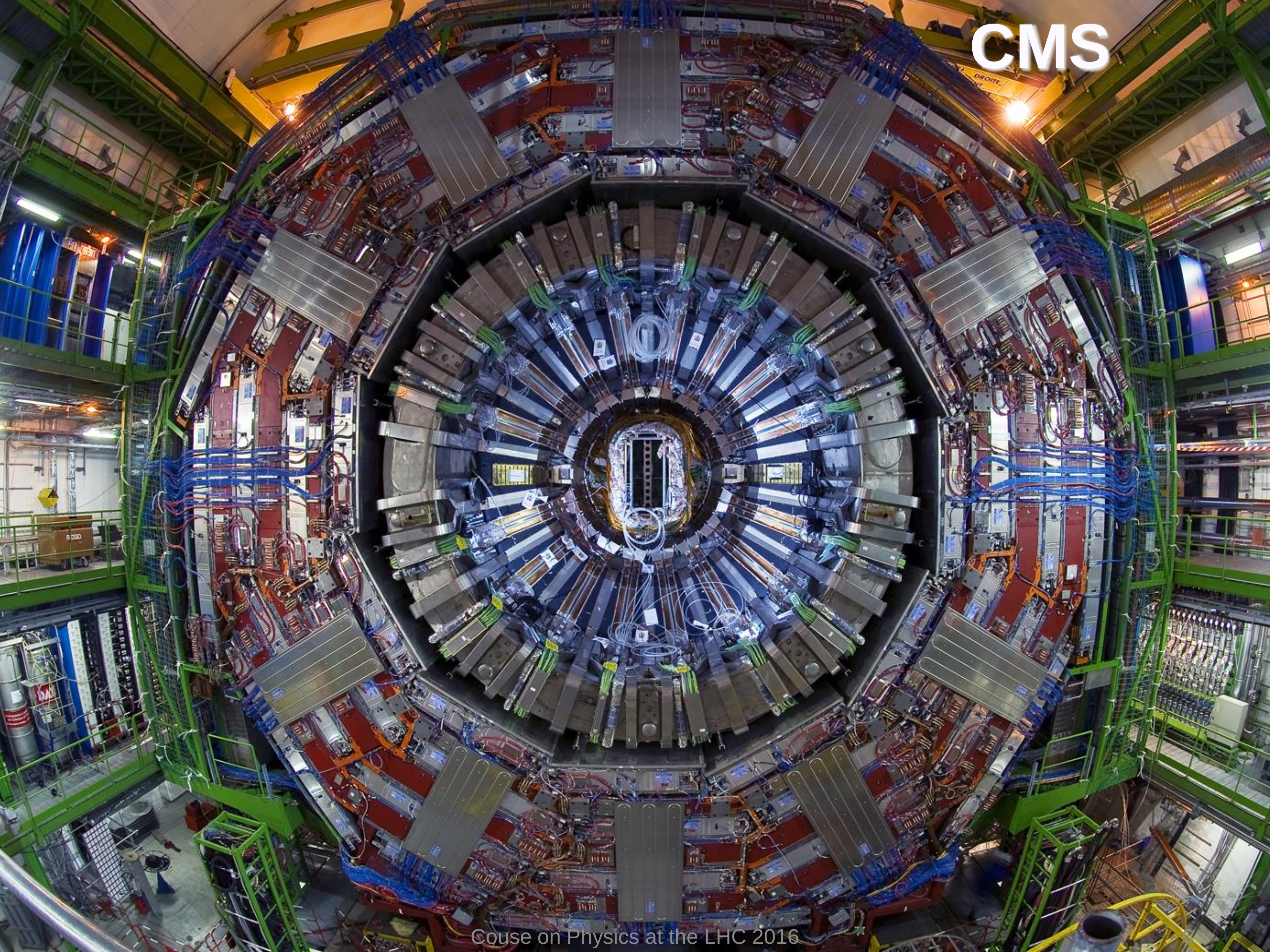




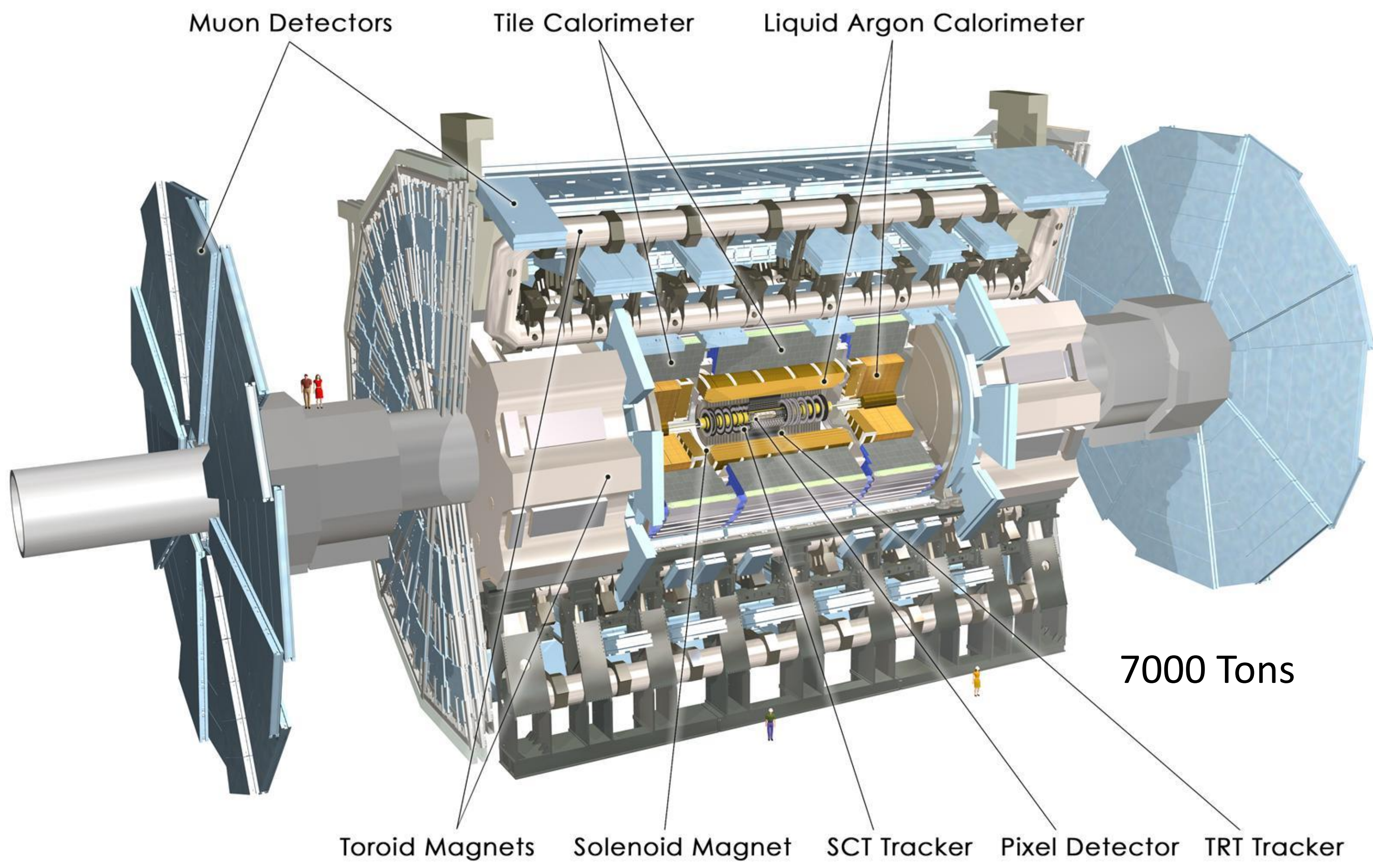
CMS Detector



CMS



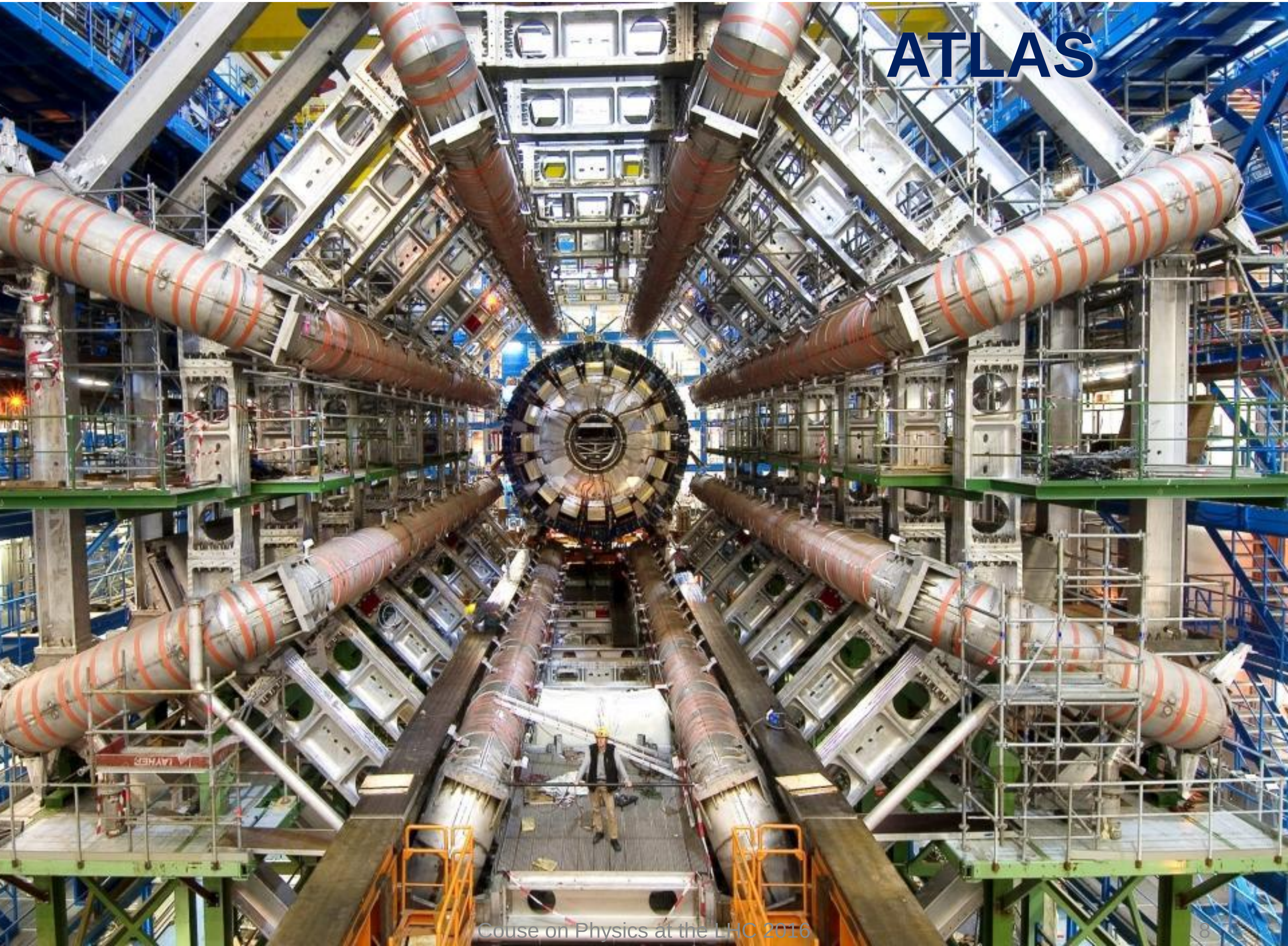
ATLAS detectors



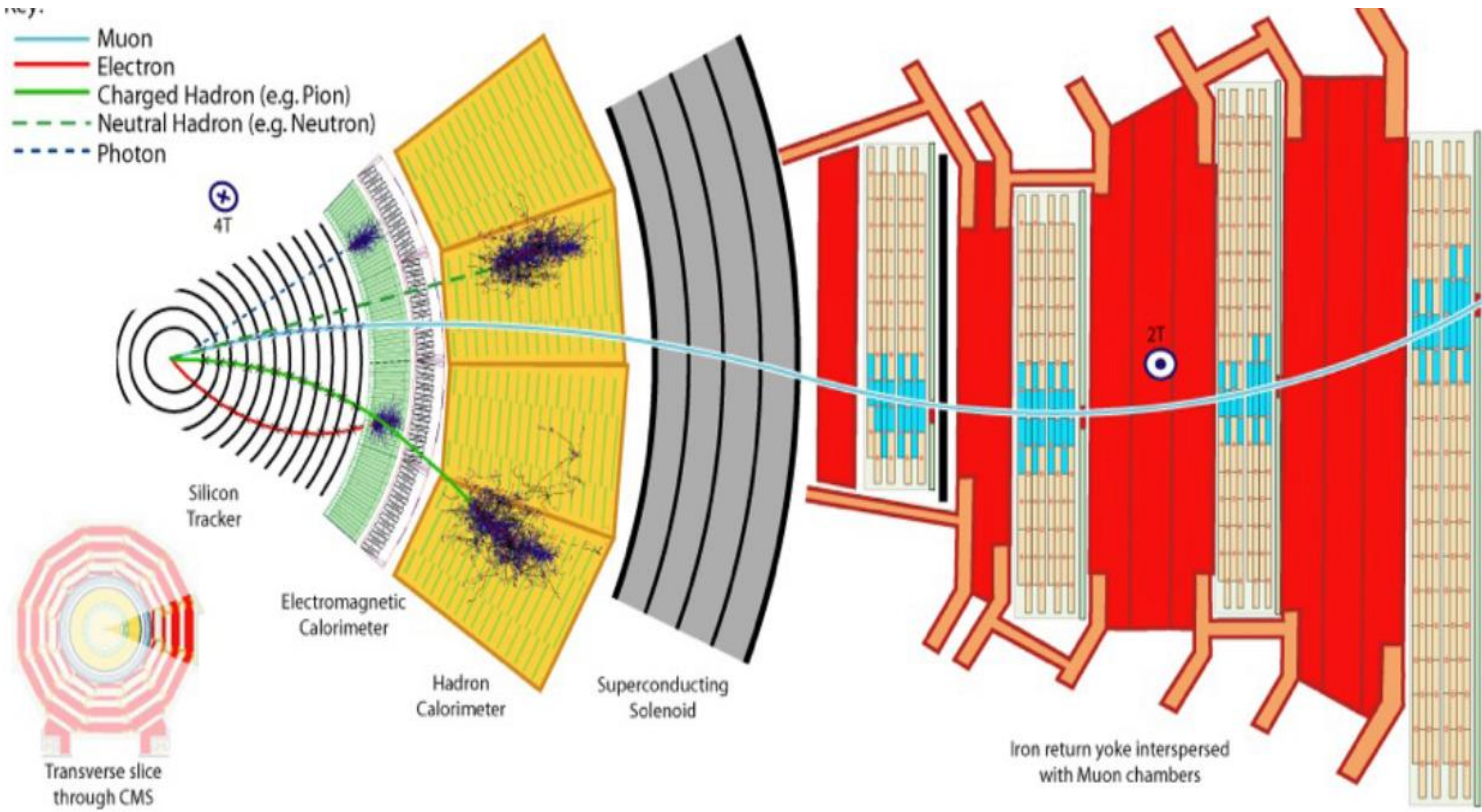
24 m

7000 Tons

ATLAS



Detection of hadrons, e±, γ and μ±



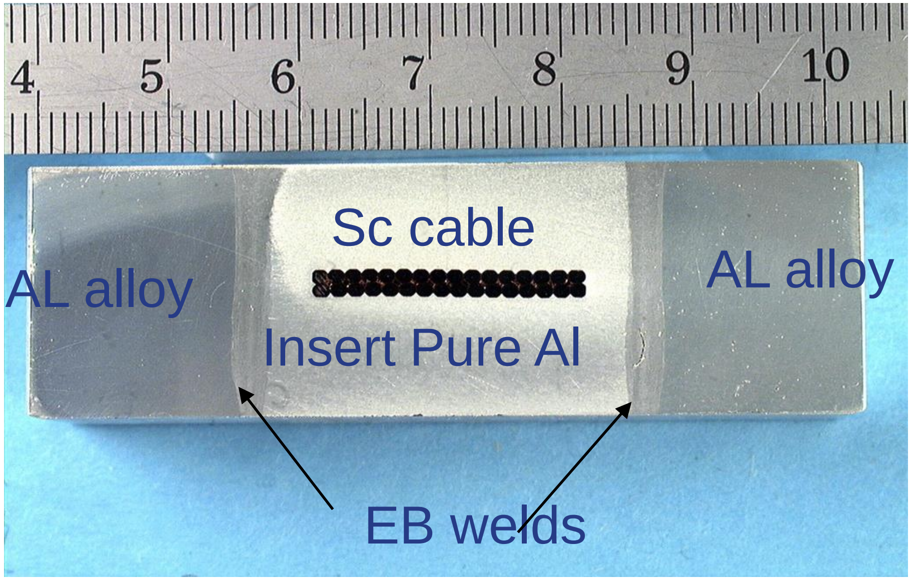
1993-2008: detector R&D and construction

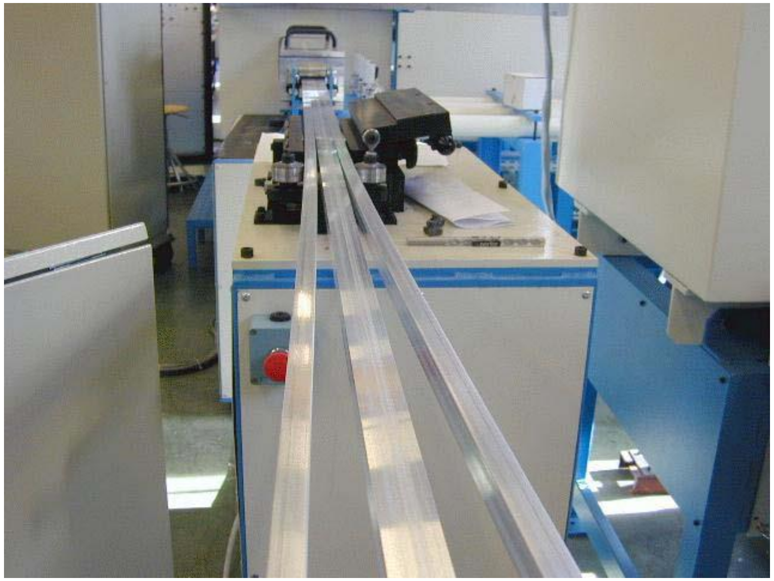
15 years !

Superconducting cable

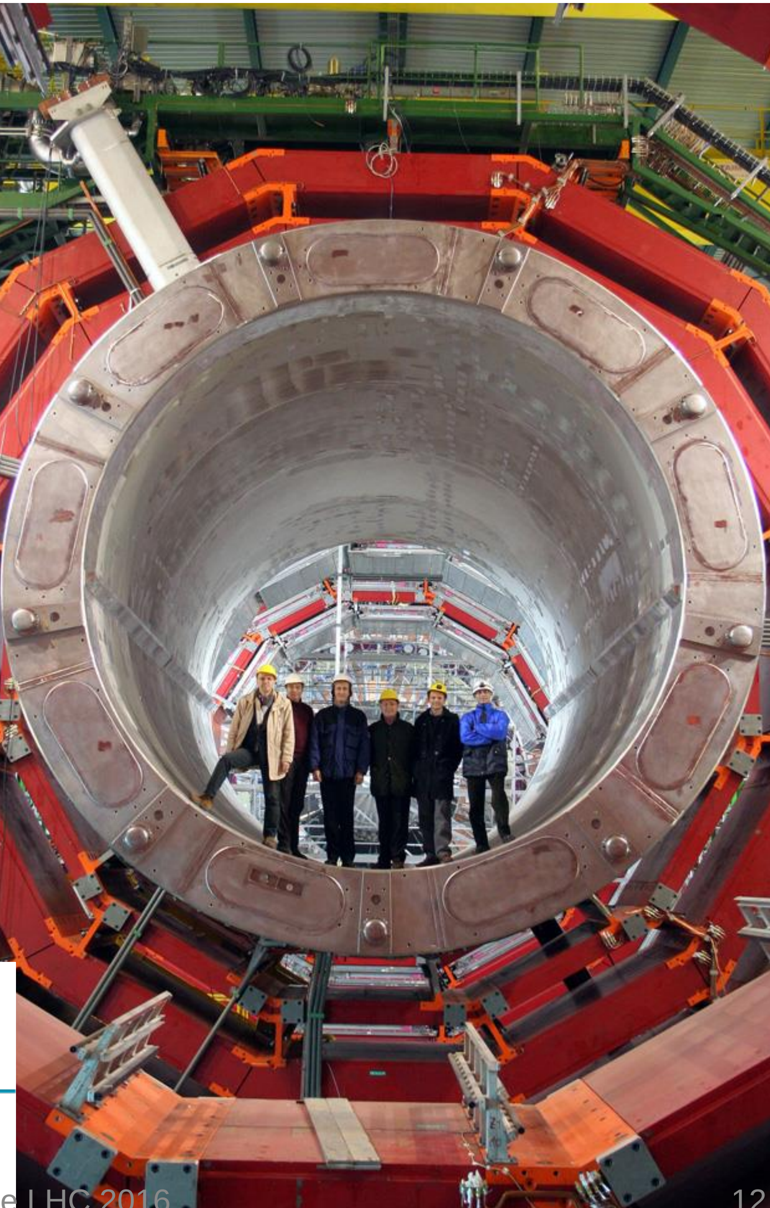
Al stabilized NbTi conductor.

Mechanically reinforced conductor to contain magnetic forces.

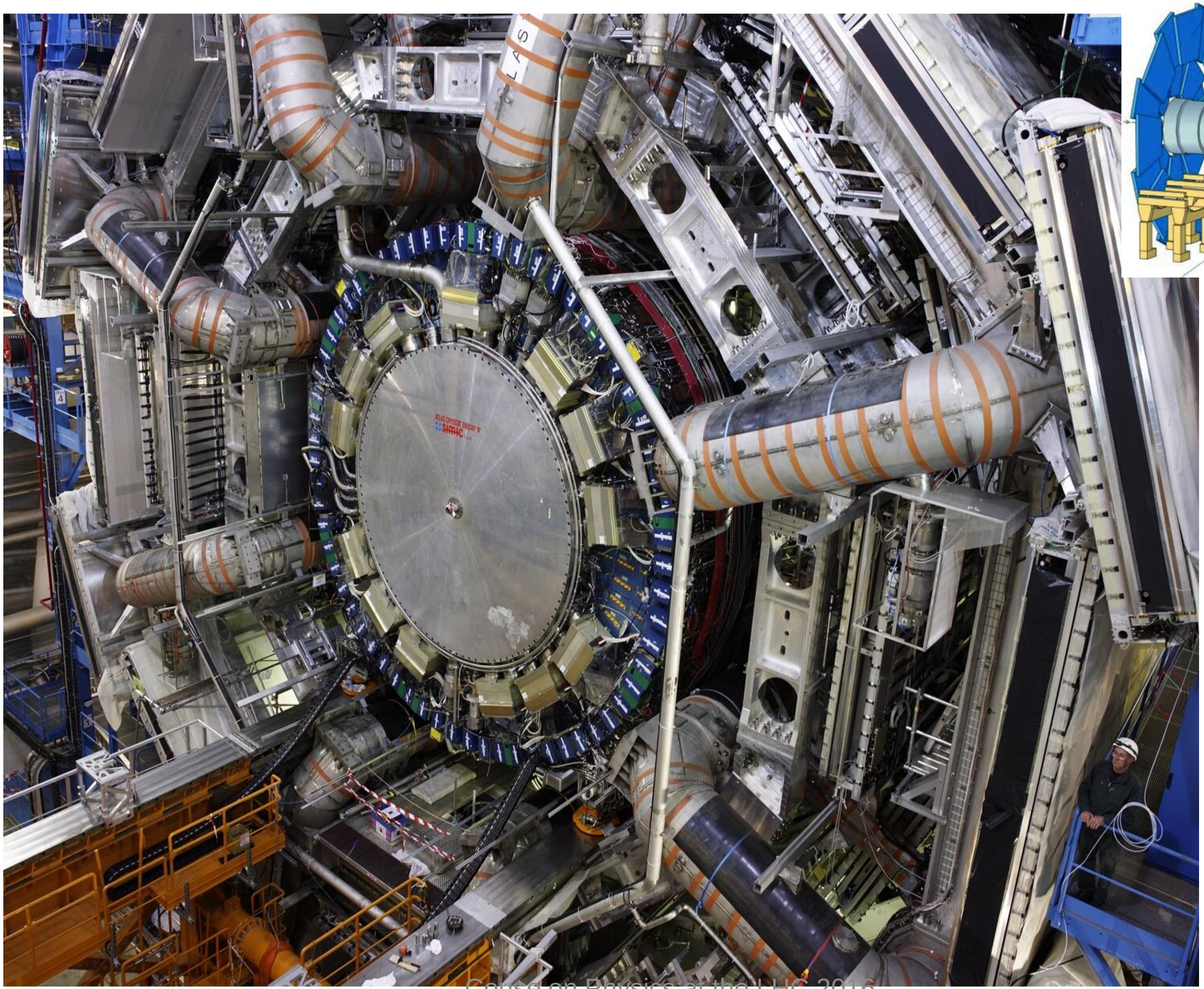


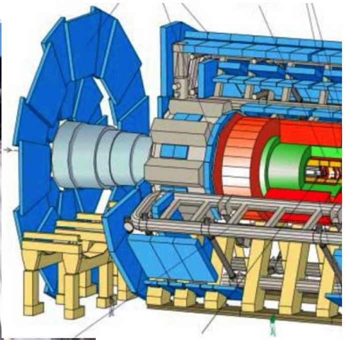


Superconductor solenoid at 3.8 Tesla

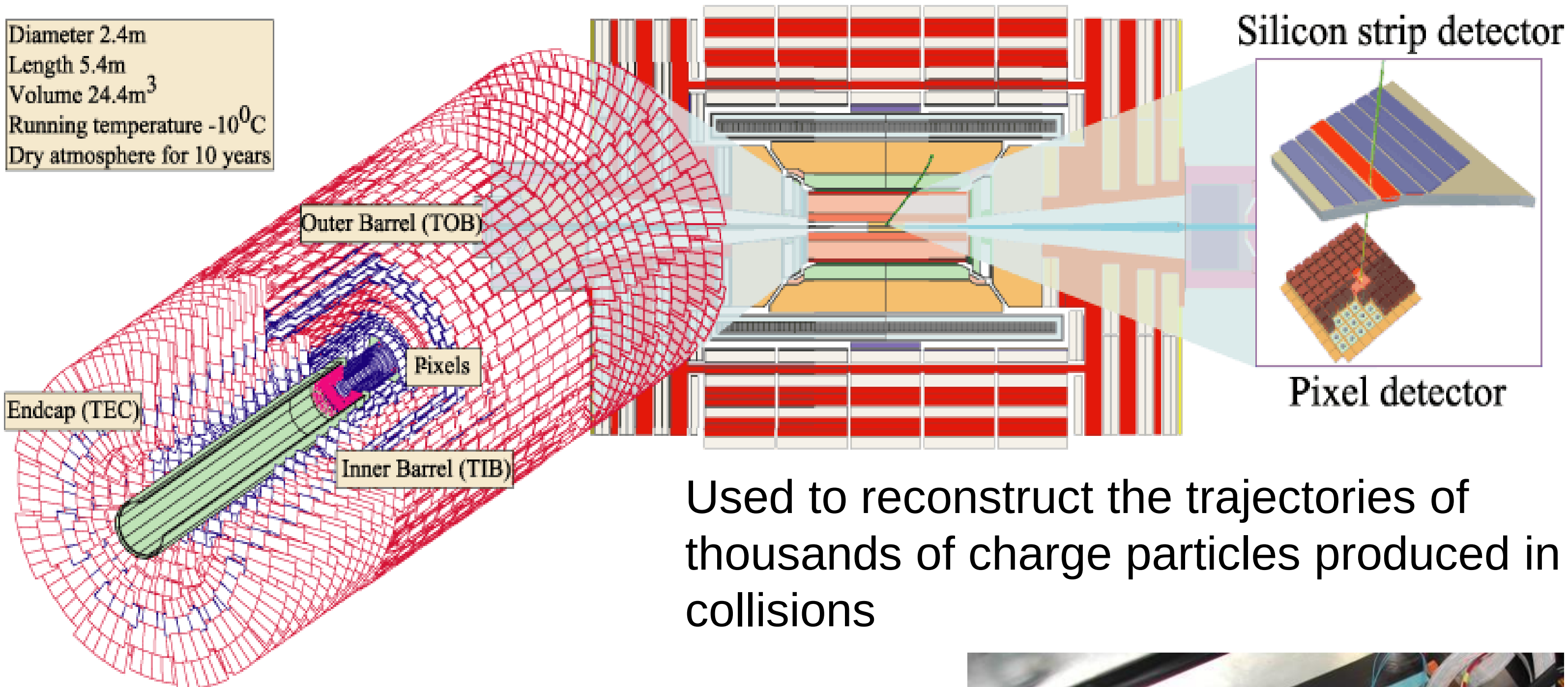


ATLAS Toroidal System

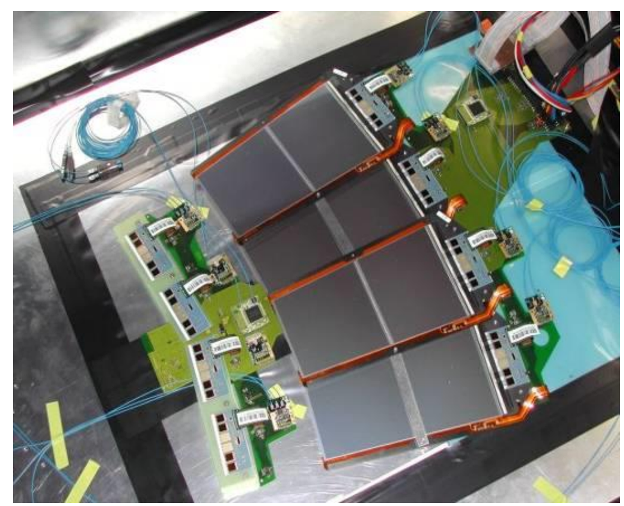




Silicon Tracker

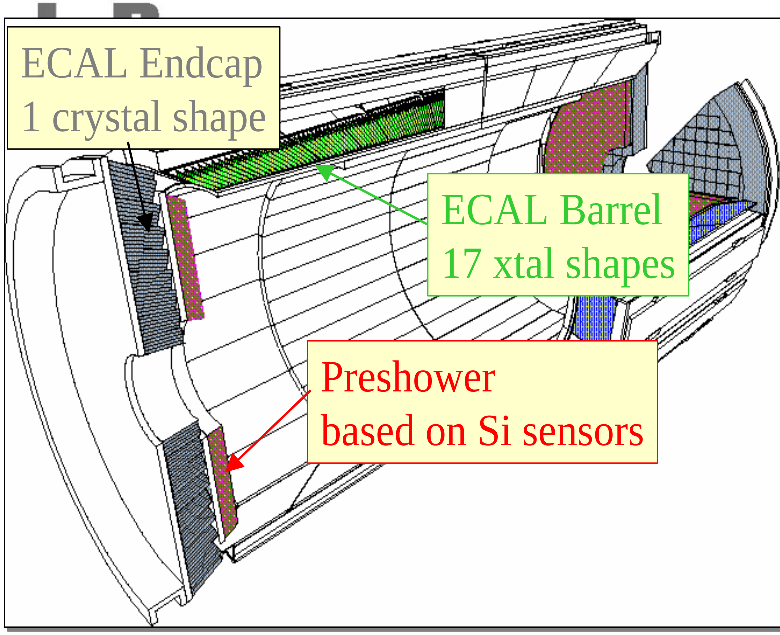


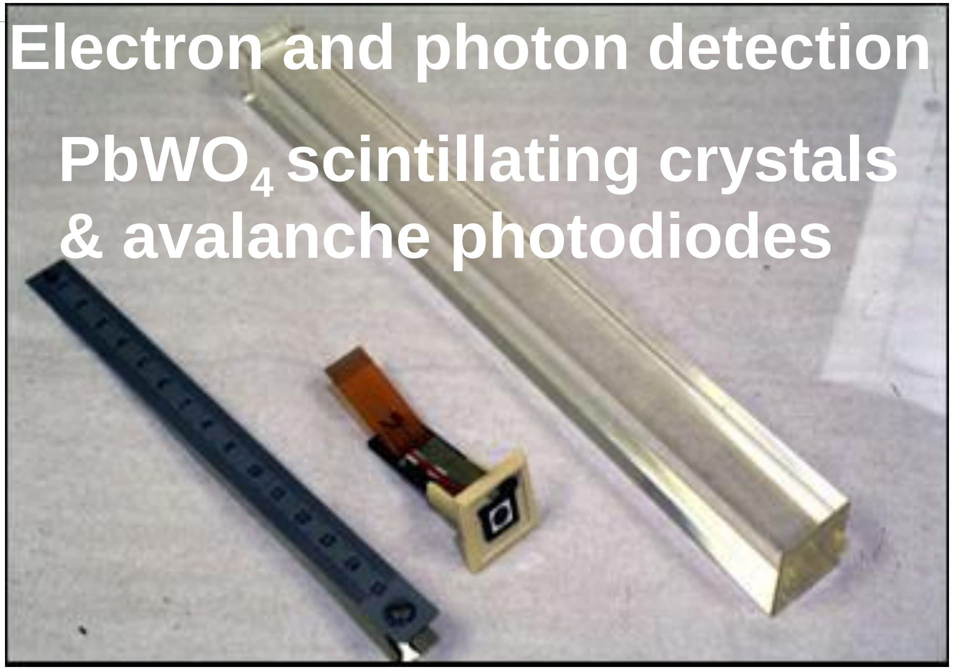
Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

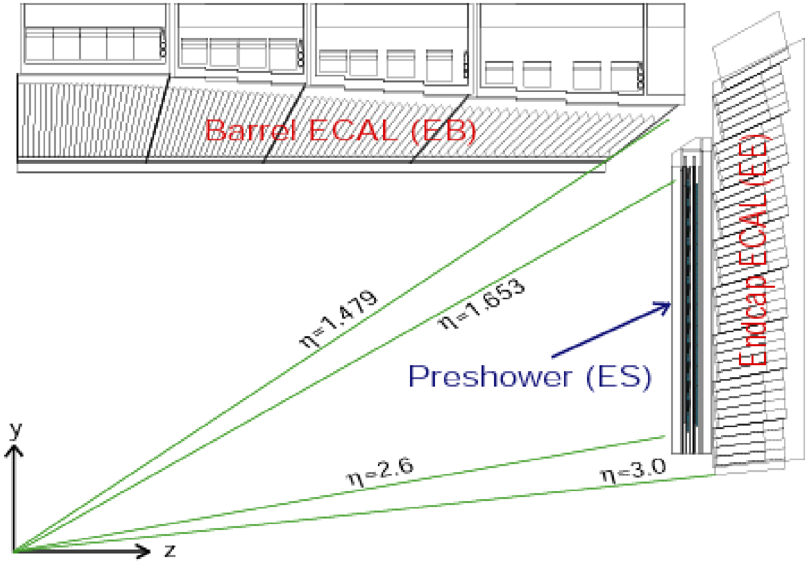


$214m^2$ silicon sensors
11.4 million silicon strips
65.9 million silicon pixels

ECAL Electromagnetic Calorimeter



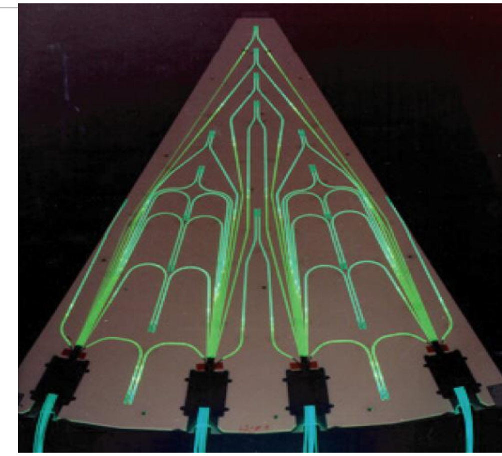




Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

Parameter	Barrel	Endcaps
# of crystals	**61200**	**14648**
Volume	**8.14m^3**	**2.7m^3**
Xtal mass (t)	**67.4**	**22.0**

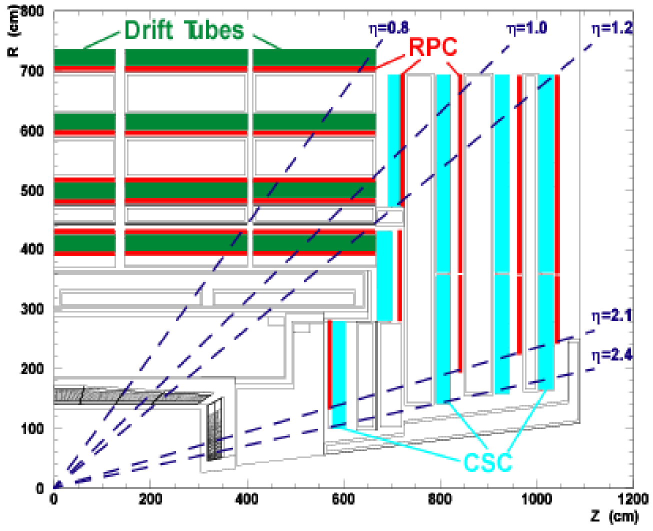
HCAL Hadronic Calorimeter



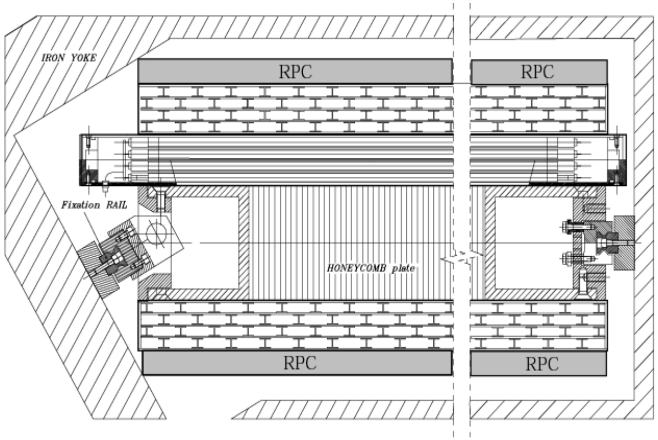
Detection of hadrons:
- protons, neutrons, peons, etc.

- CMS HCAL has three components:
  - Barrel HCAL (HB)
  - Endcap HCAL (HE)
  - Forward HCAL (HF)
- Plastic scintillator and brass
- Quartz fibers and steel

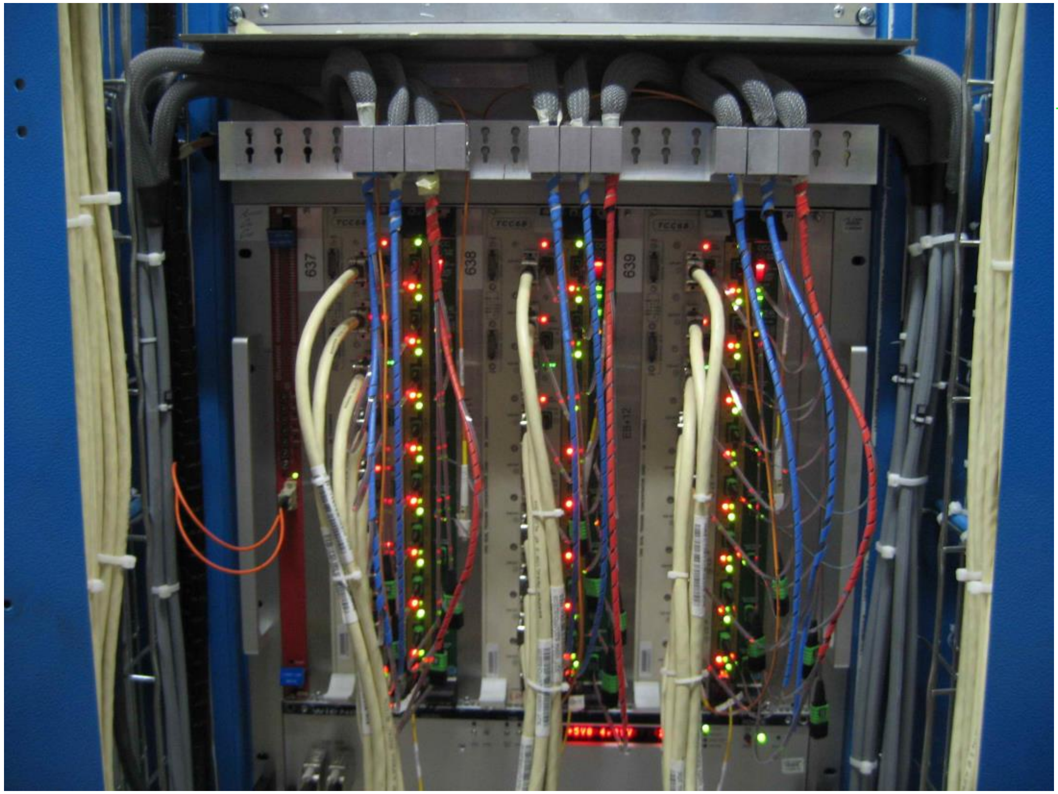
Muon detectors



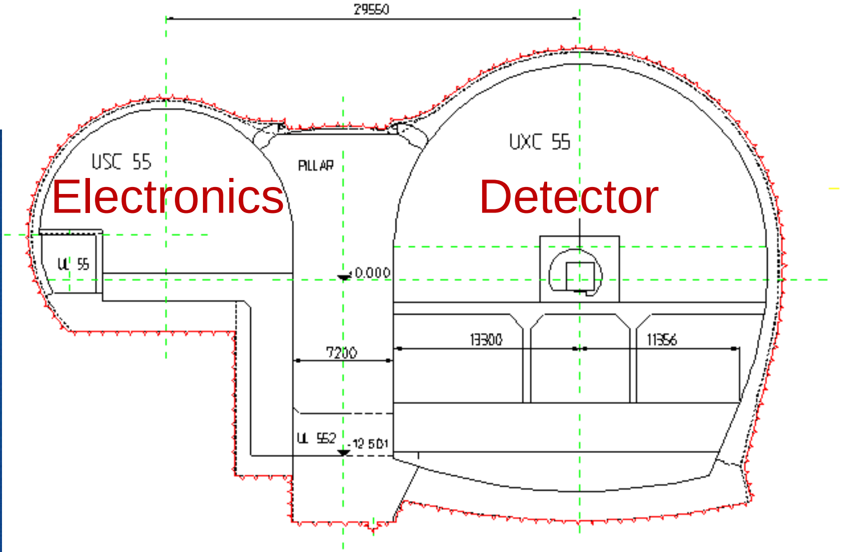
Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

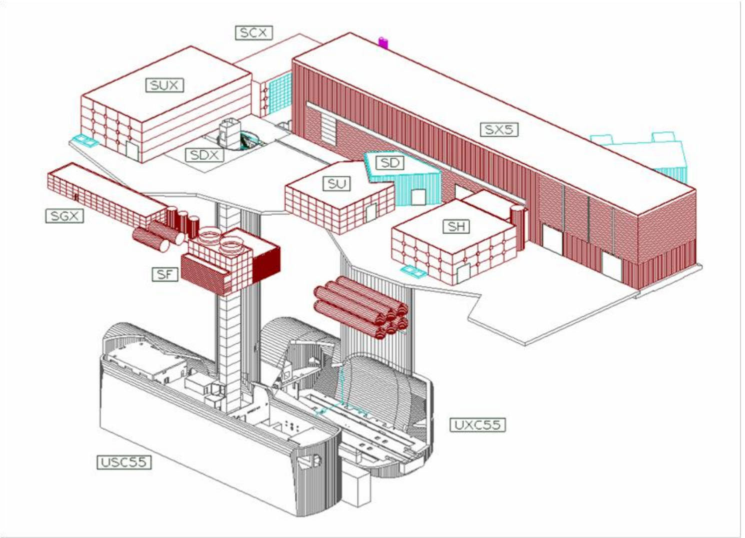


Trigger and readout electronics



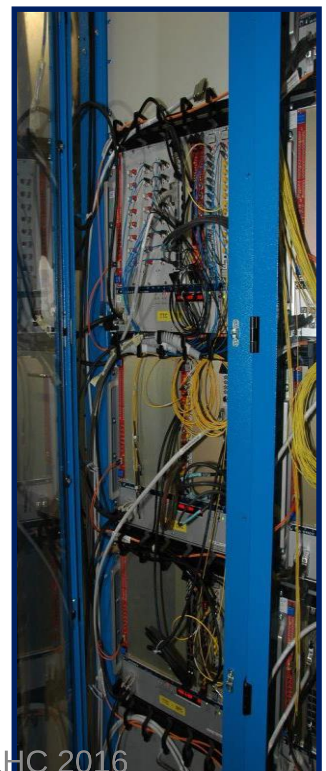
Underground caverns

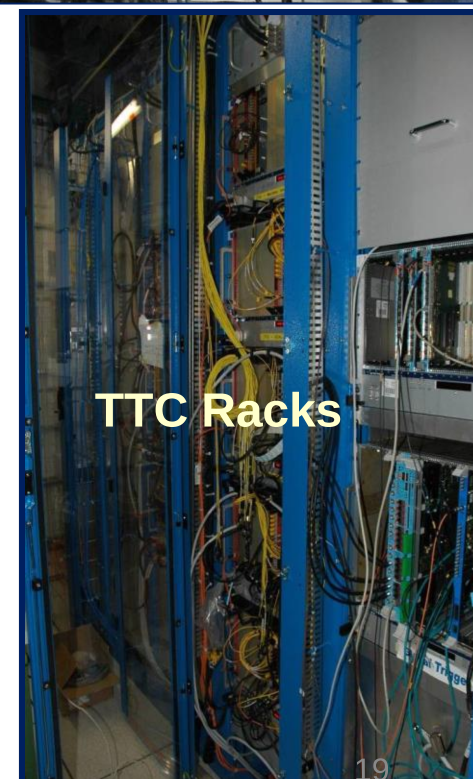




Electronics systems

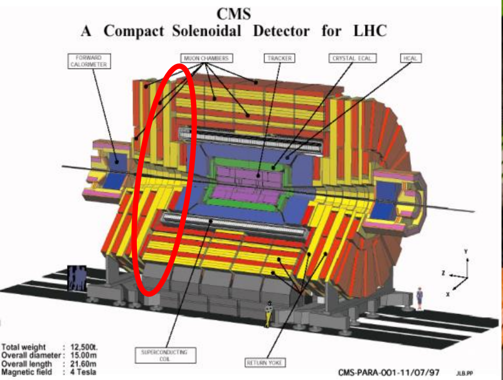
Electronics systems in the Service Cavern.
About 150 racks occupy two floors.
Most electronics was designed and built specifically for the experiment

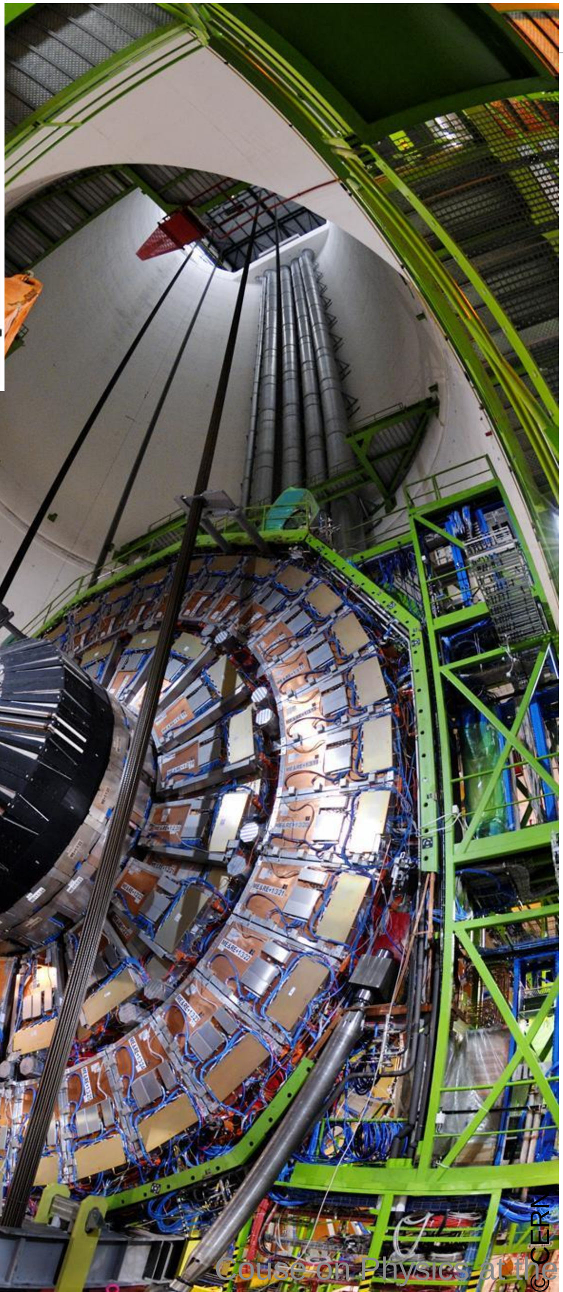


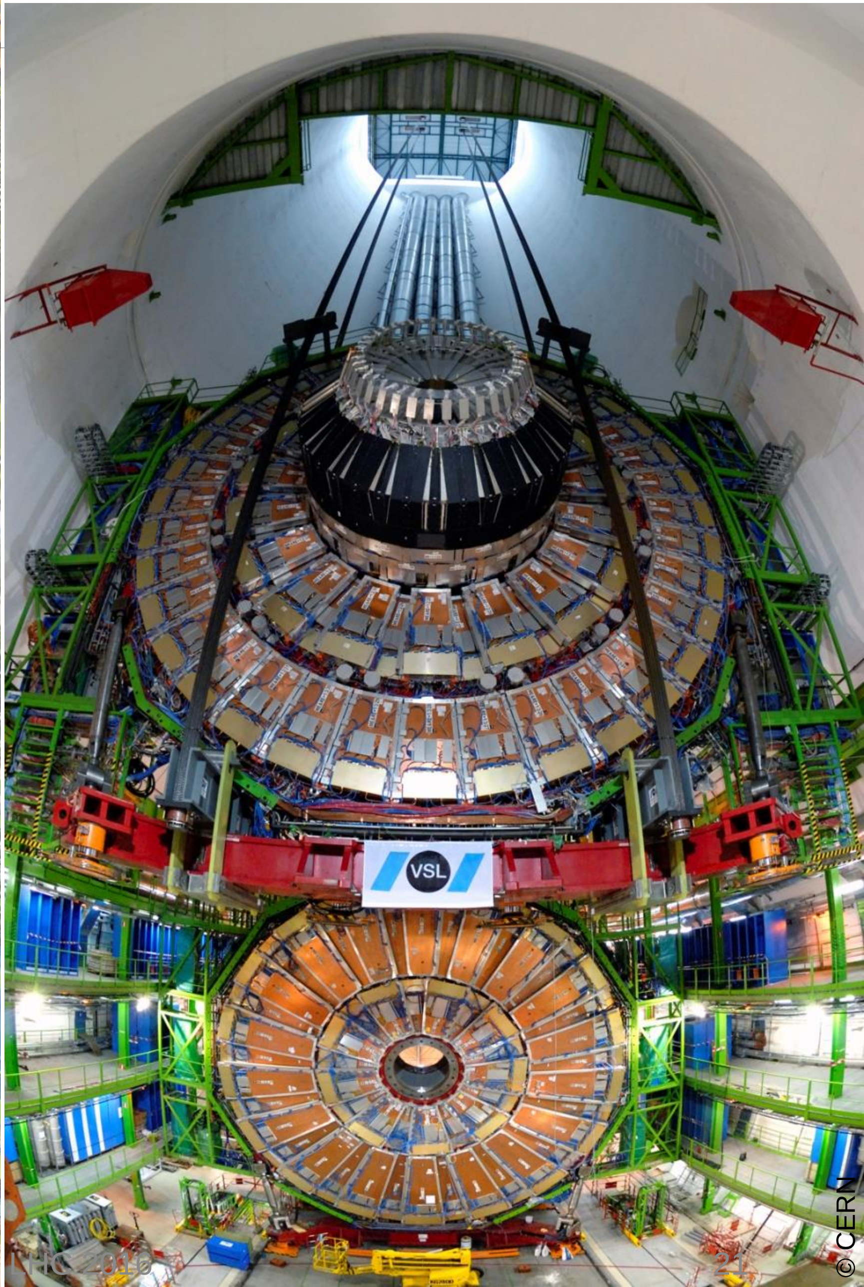


2004: CMS detector cavern

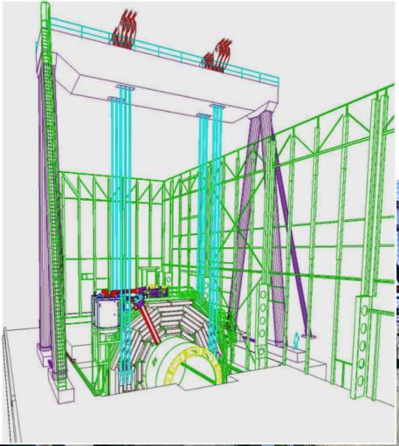
2007: Lowering one of six huge disks

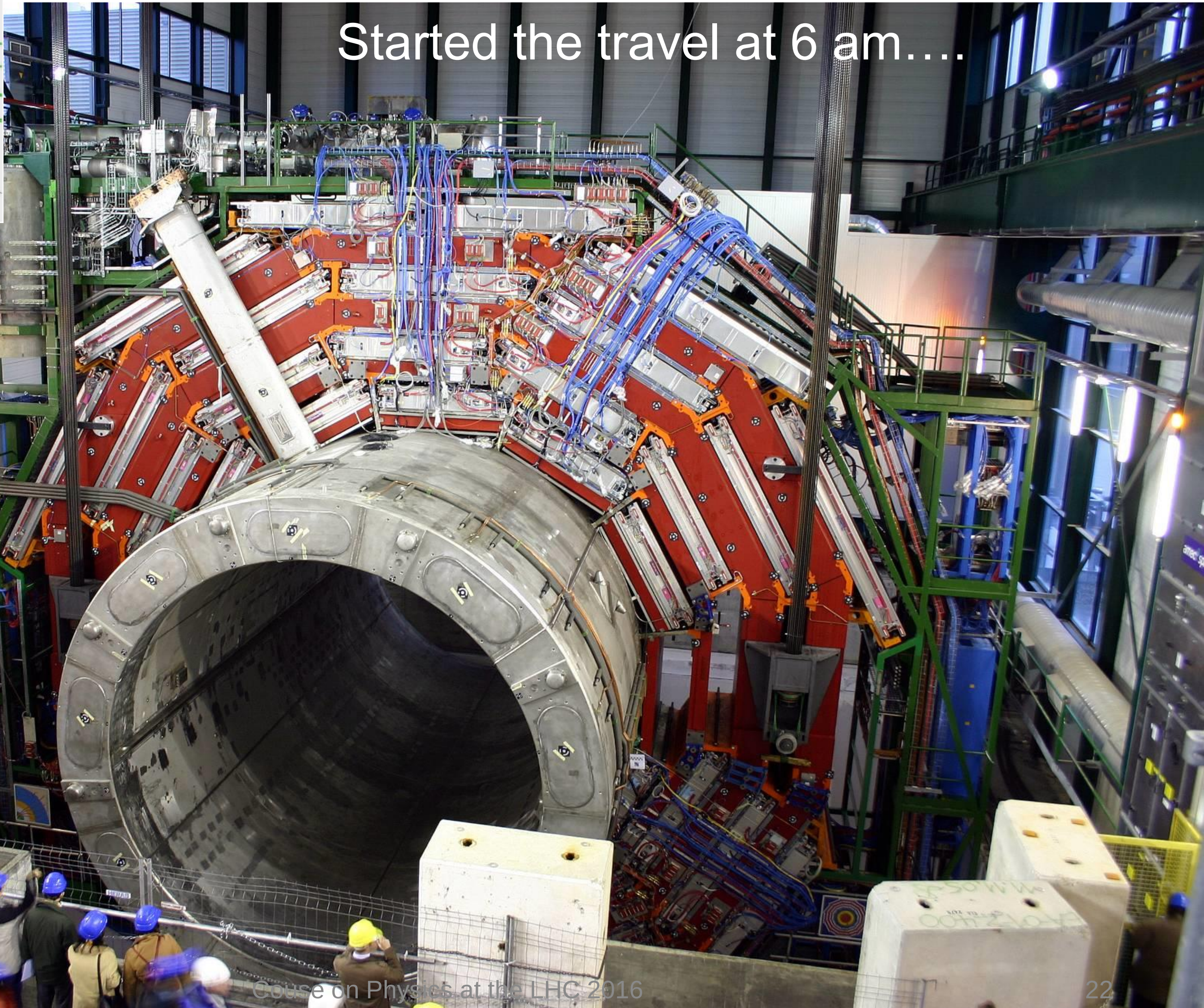






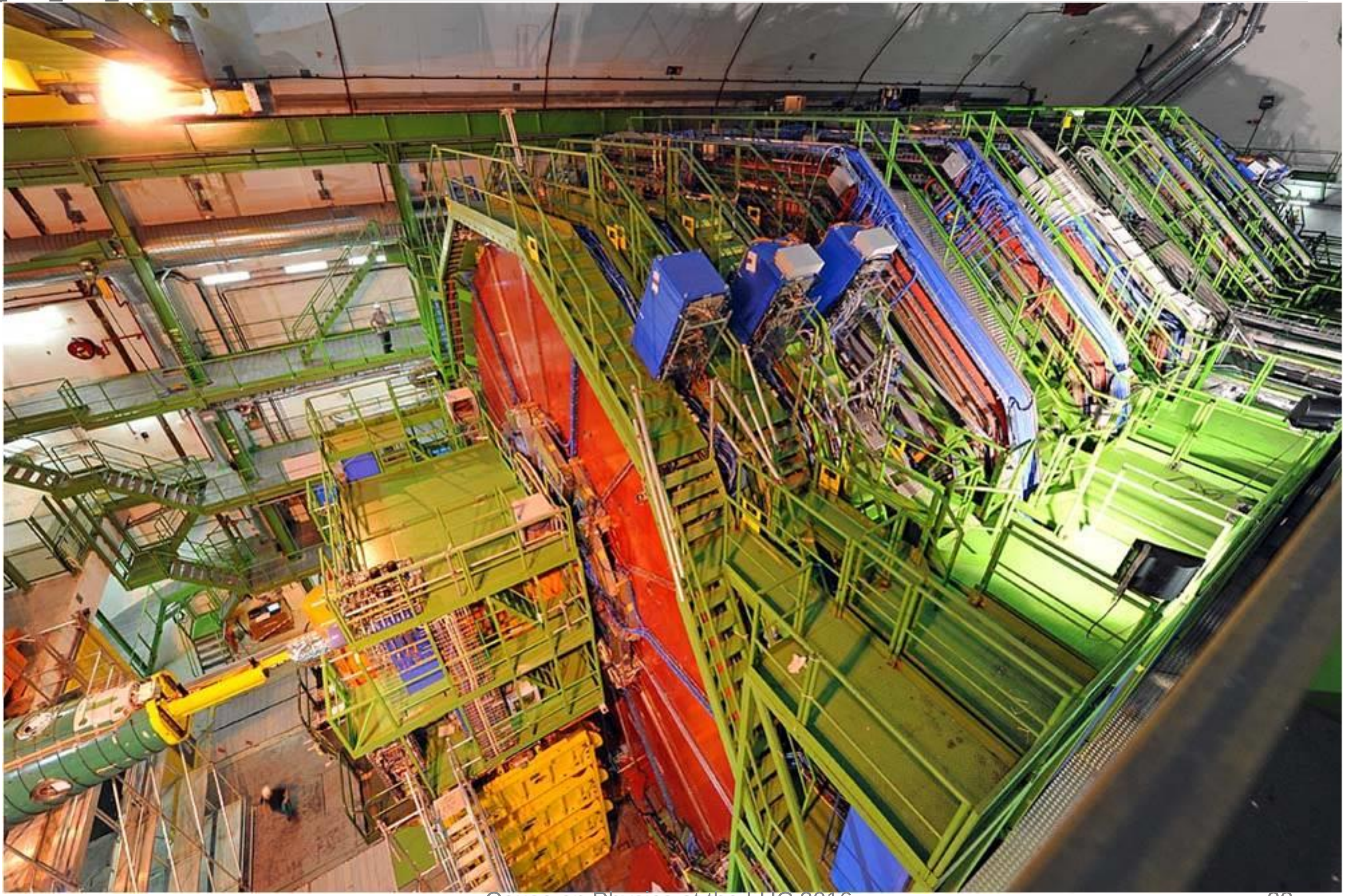
Feb 2007:lowering central “wheel”





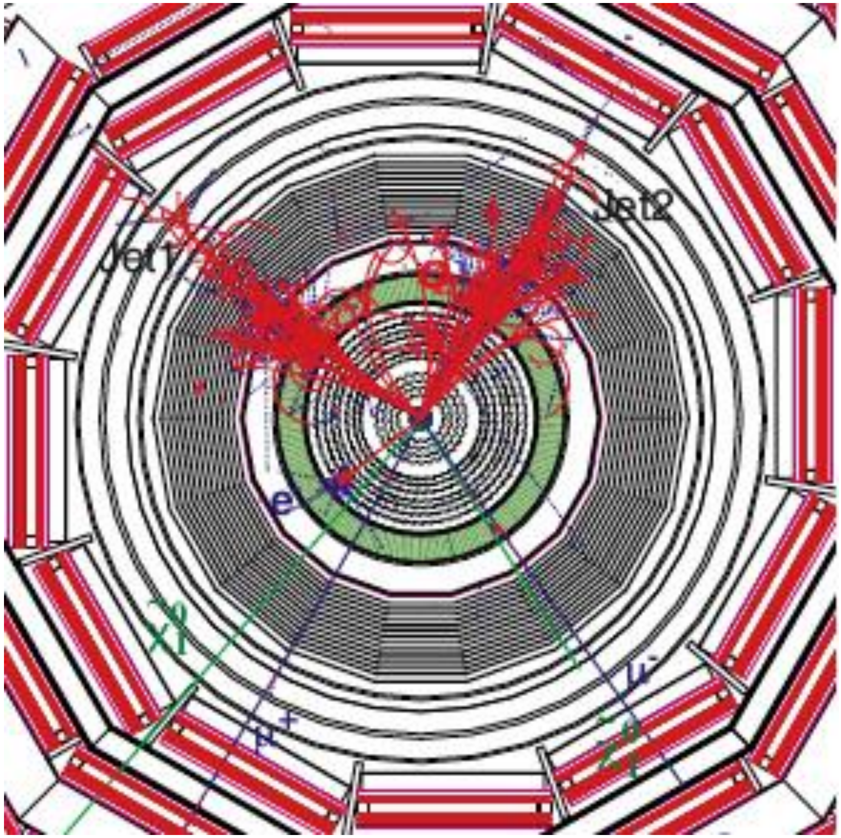
Started the travel at 6 am….

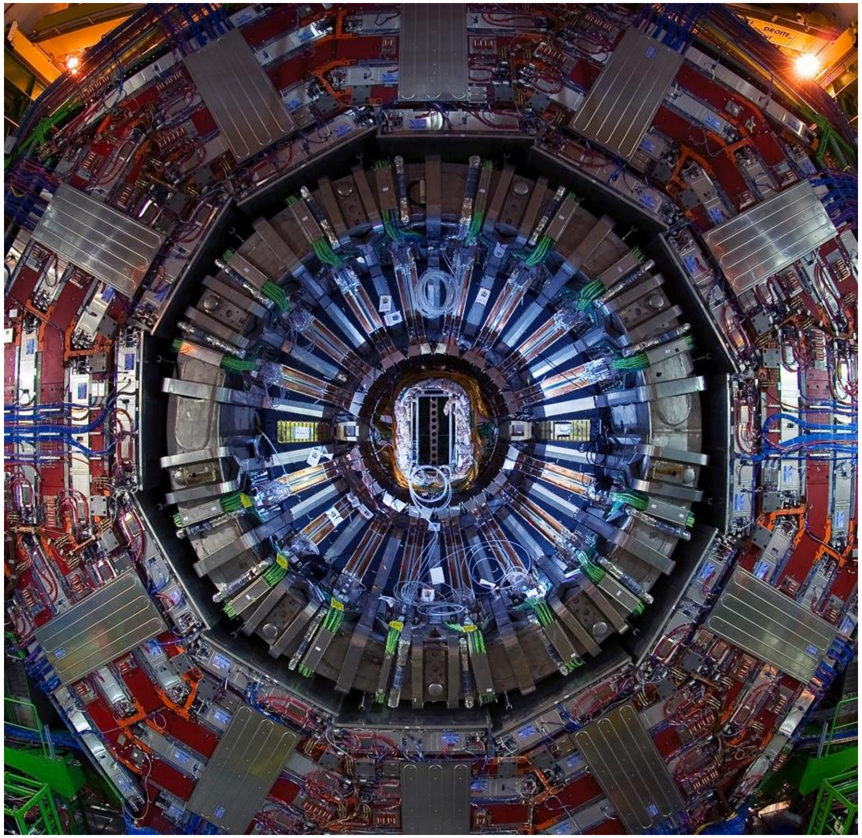
Sep 2008: CMS detector ready for beams



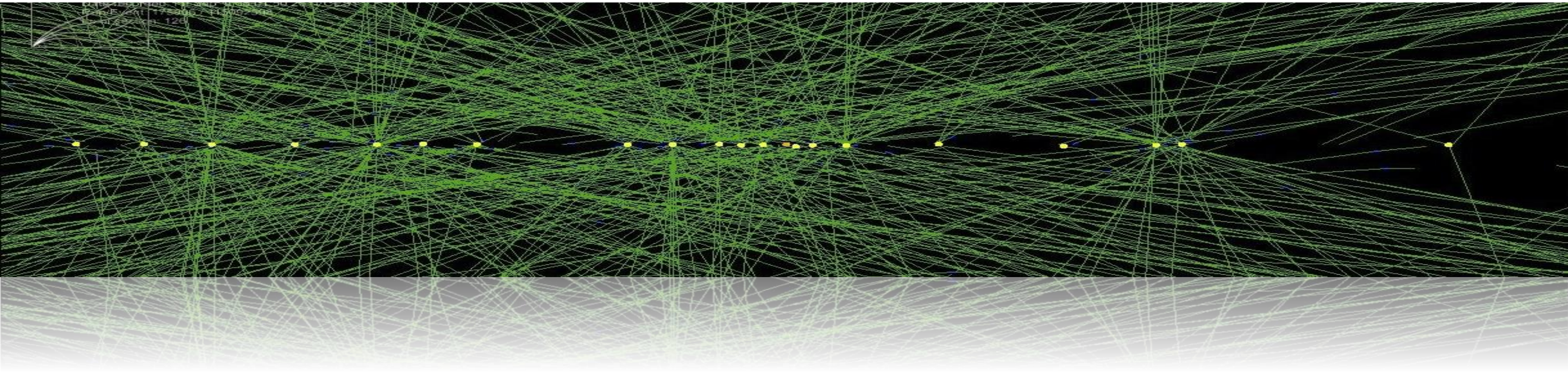
How did we prepare for discoveries?

Simulation of proton-proton collision making two dark matter particles





Experimental challenges



High collision rate

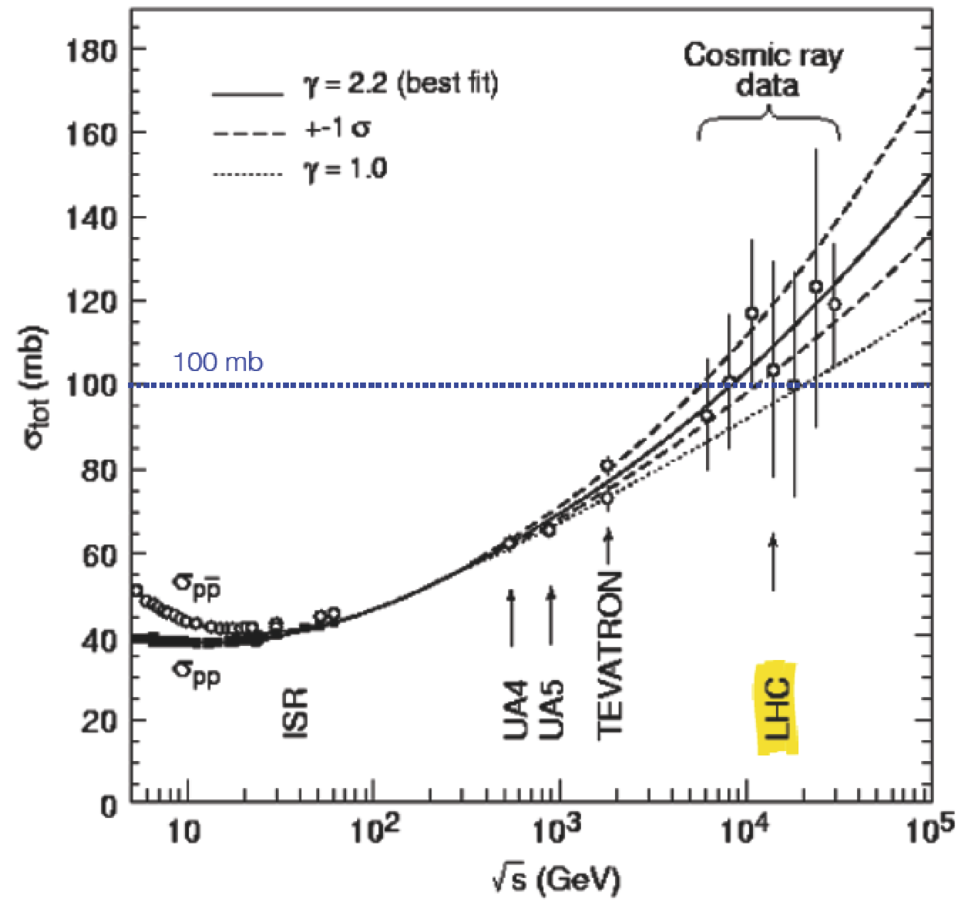
Luminosity:

$L = 10^{34}\ cm^{-2}s^{-1}$
$= 10^{7}\ Hz/mb$

Cross section:

$\sigma \approx 100\ mb$

➡ $N = L\sigma \approx 1\ GHz$



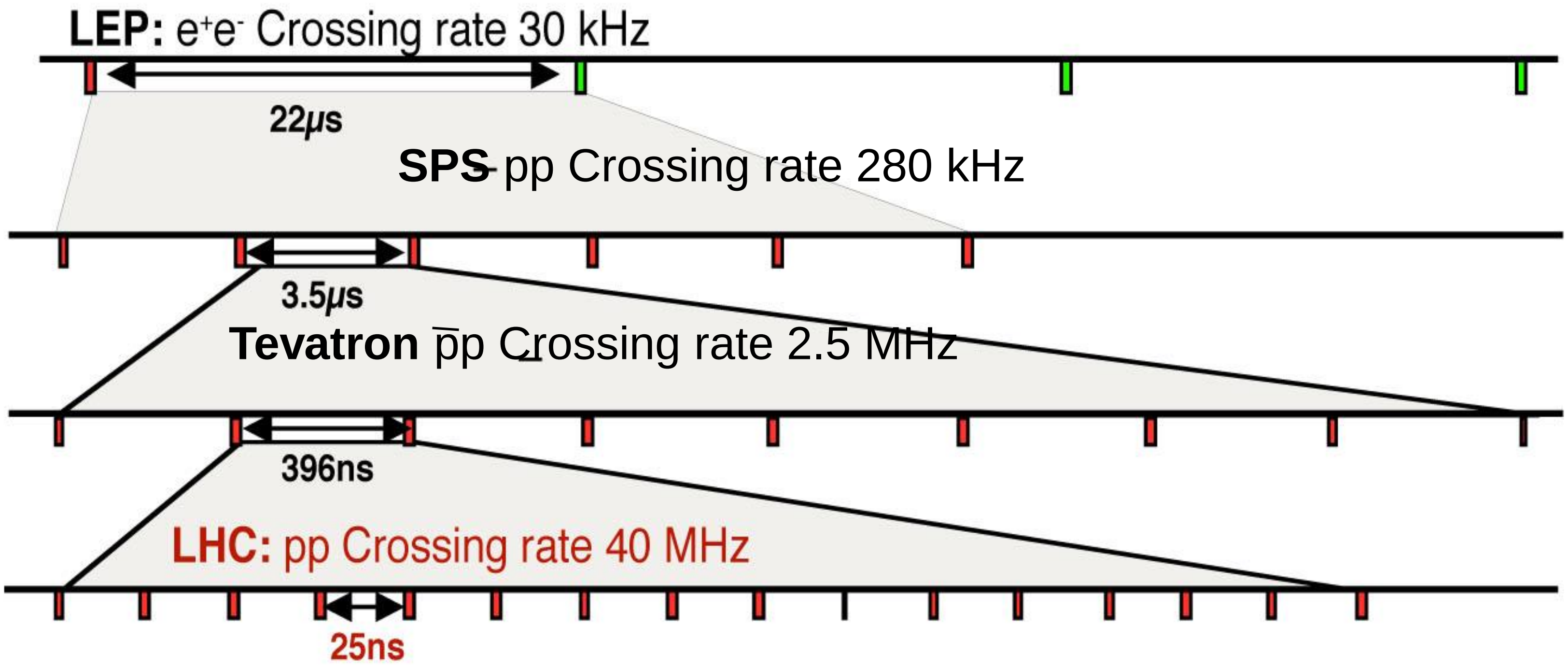
However:

Bunch crossing rate: 40 MHz
∴ Interactions/crossing ~ 25

This is a real challenge !

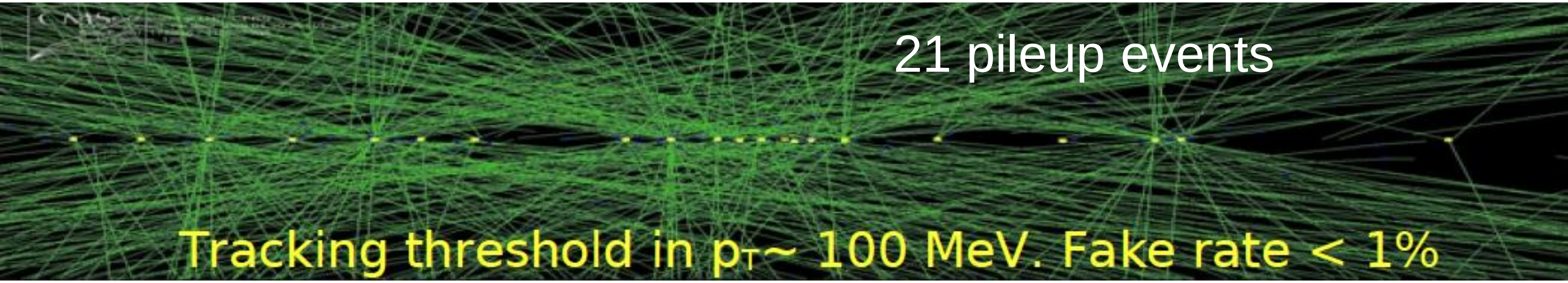
Bunch crossing frequency

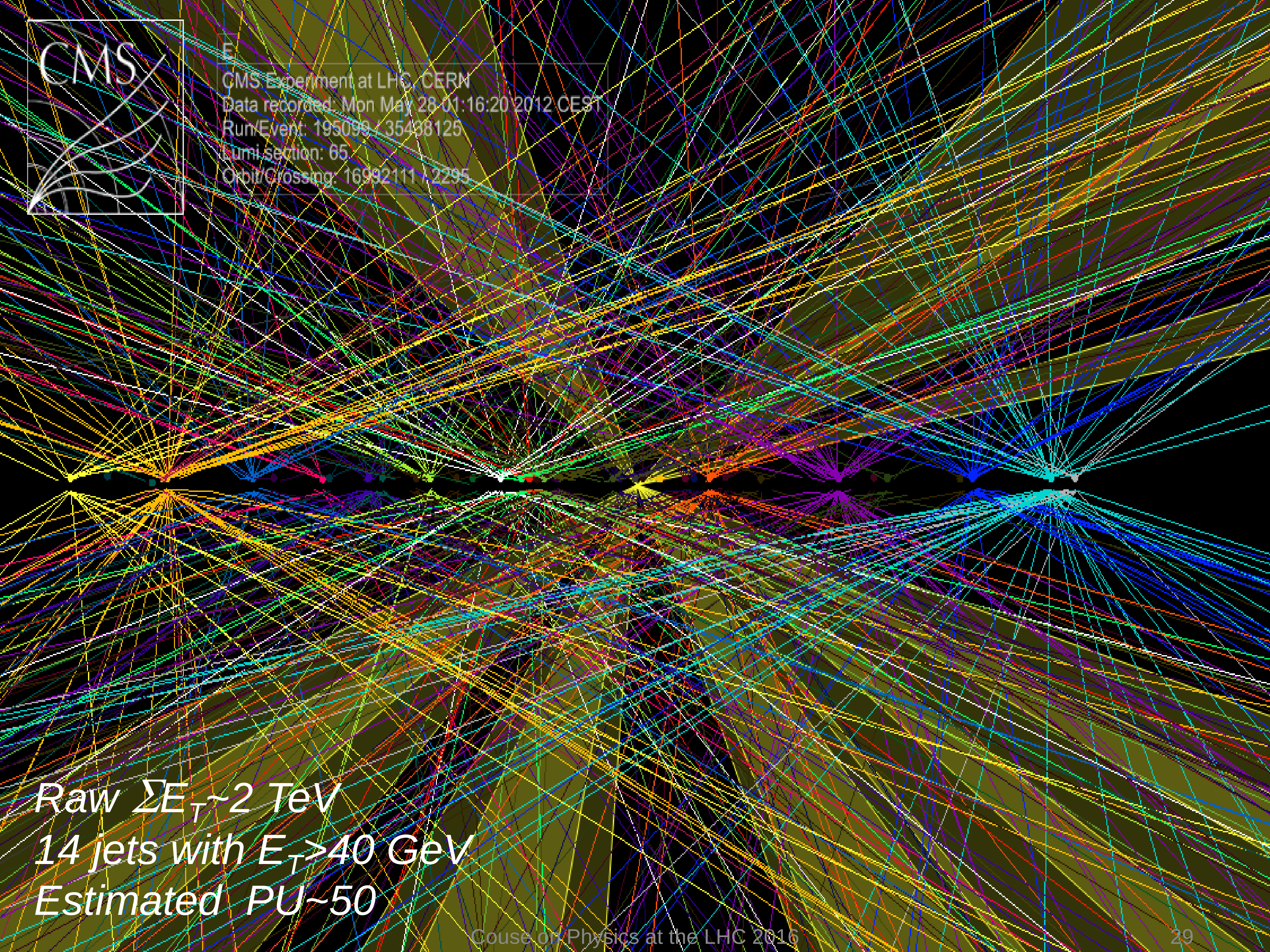
- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25



Event pileup

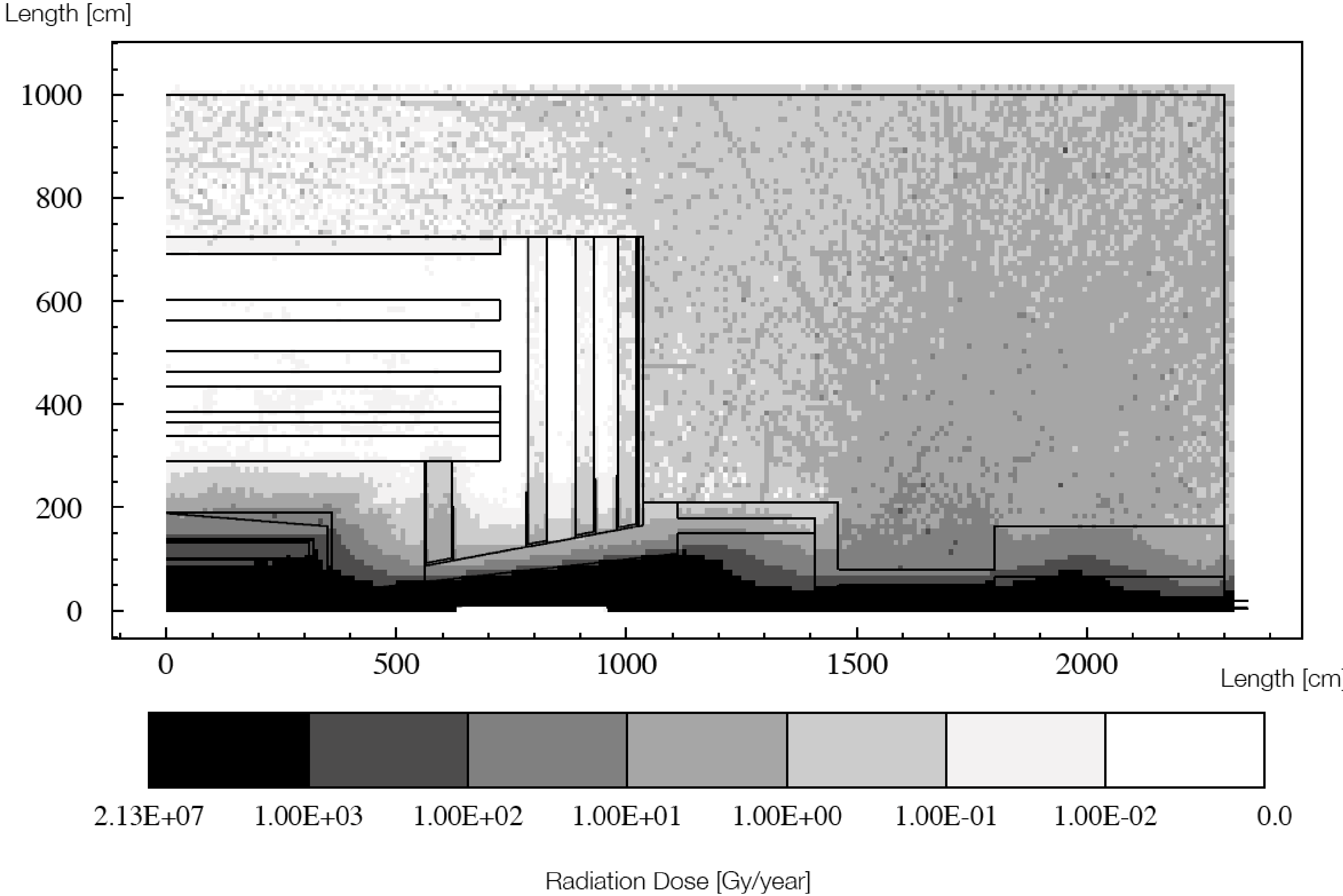
- Proton bunches have a cigar shape, about 5 cm long and 20 microns diameter
- Each bunch has 1.5 10^{11} protons
- At each crossing of bunches, about 25 collision occur
- The particles produced (30x25 = 750 charged particles) are “seen” by the detector as a single image (event)



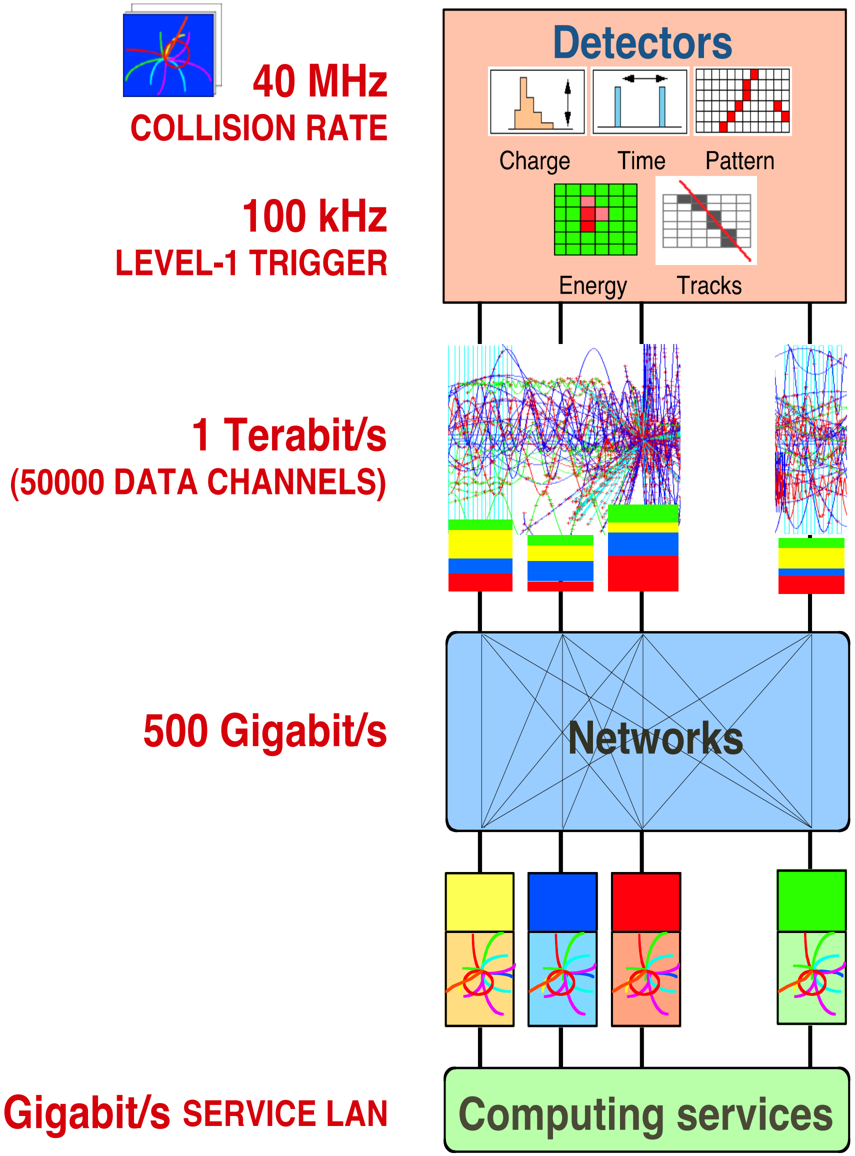


Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50

High radiation levels



Acquiring and recording data of interest



Analogy with a 100 M pixel 3-D digital camera:

40 Million photos/sec

Each photo (~ MB)

- taken in ~ 500 different parts

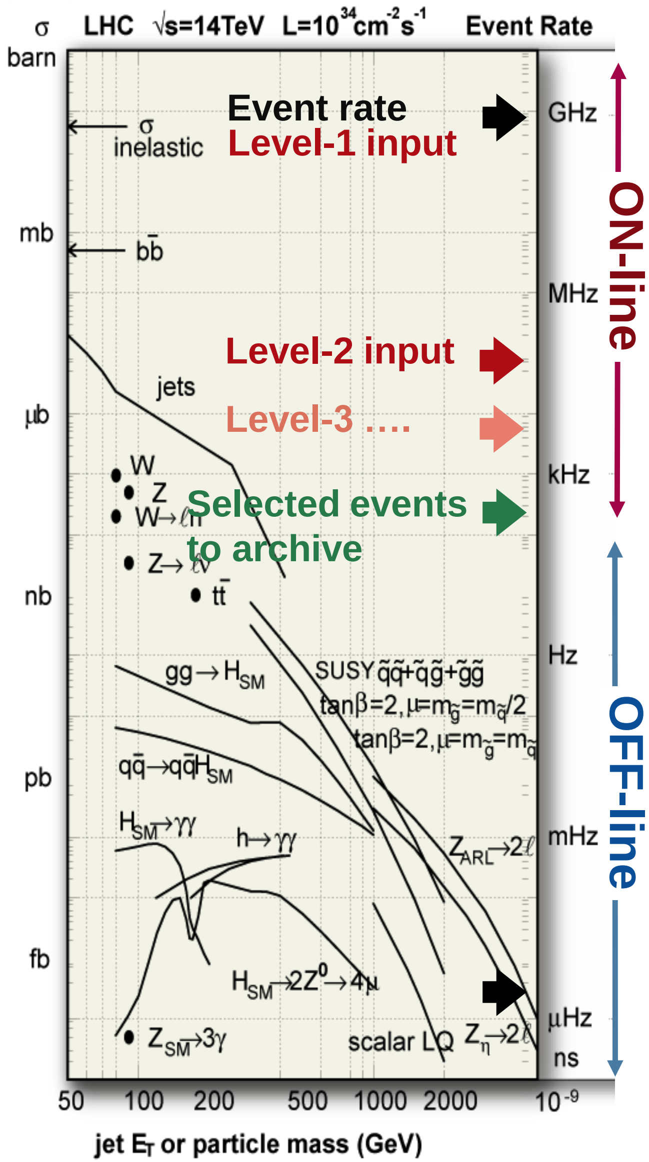
- put together using a telecommunications 'switch'

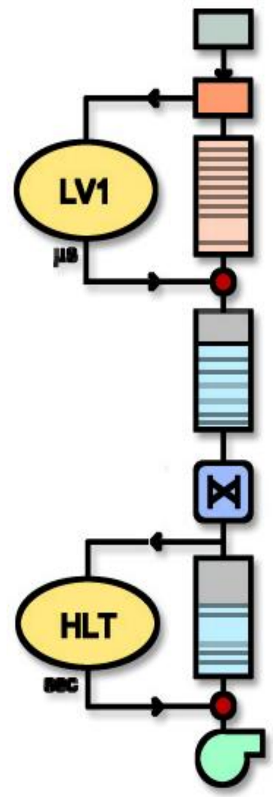
- analysed in a CPU (in a farm of ~ 50000 cores)

Only a few hundred photos/sec stored on disk.

~ 15 PB/year

Two-level trigger



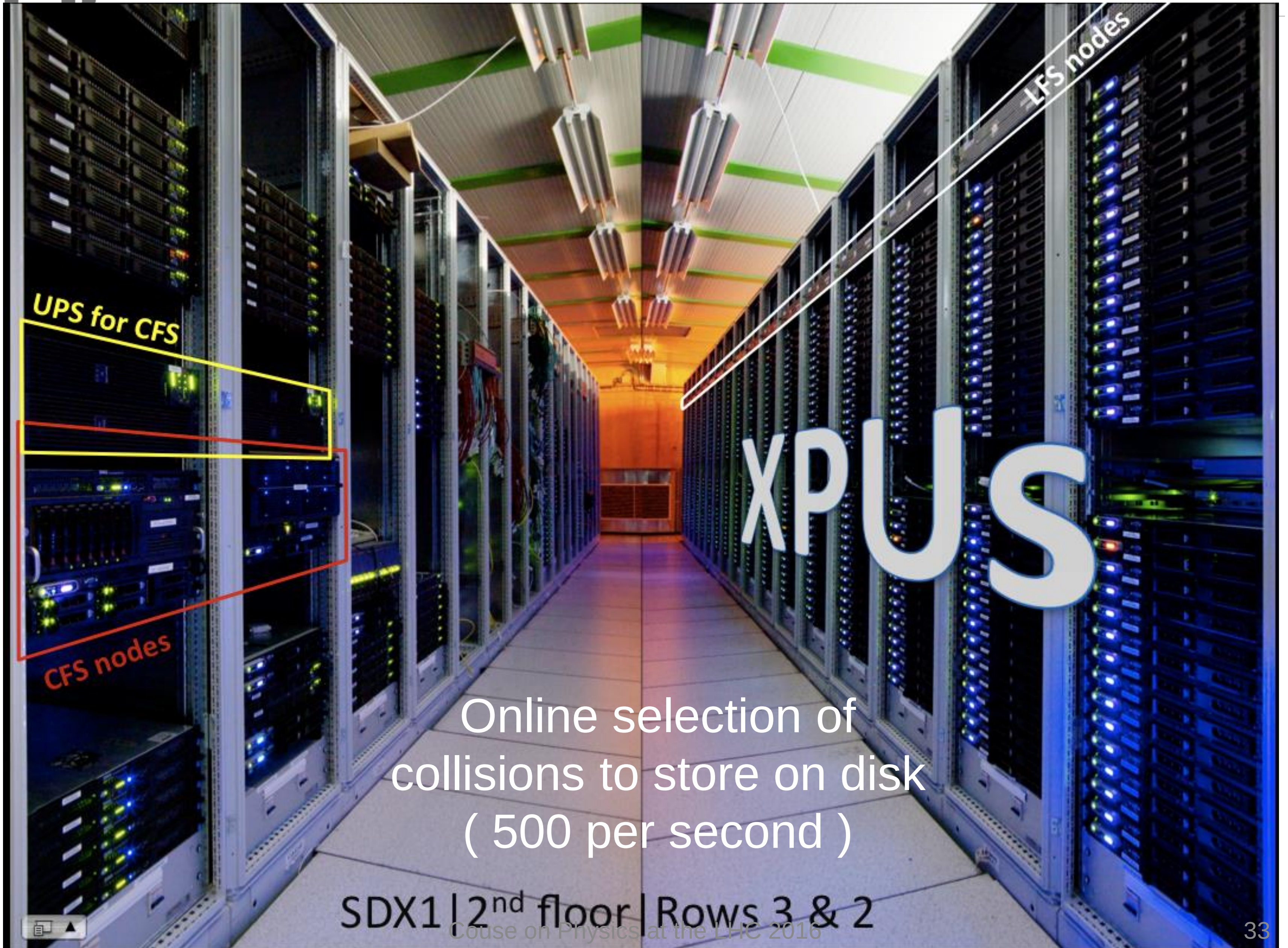


Trigger system decide if the event is interesting to be recorded

Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

Trigger computer farm



Triggers and event selection

- Select processes that produce particles with high transverse energy
- Examples at $5.x10^{33}$ $cm^{-2}s^{-1}$
  - Single lepton and photon triggers (P_T ~ 30 GeV)
  - Multiple lepton and photon triggers (P_T ~ 15 GeV)
  - Missing transverse energy (P_T ~ 50-100 GeV)
  - Multiple jet triggers (P_T ~ 50-100 GeV)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table

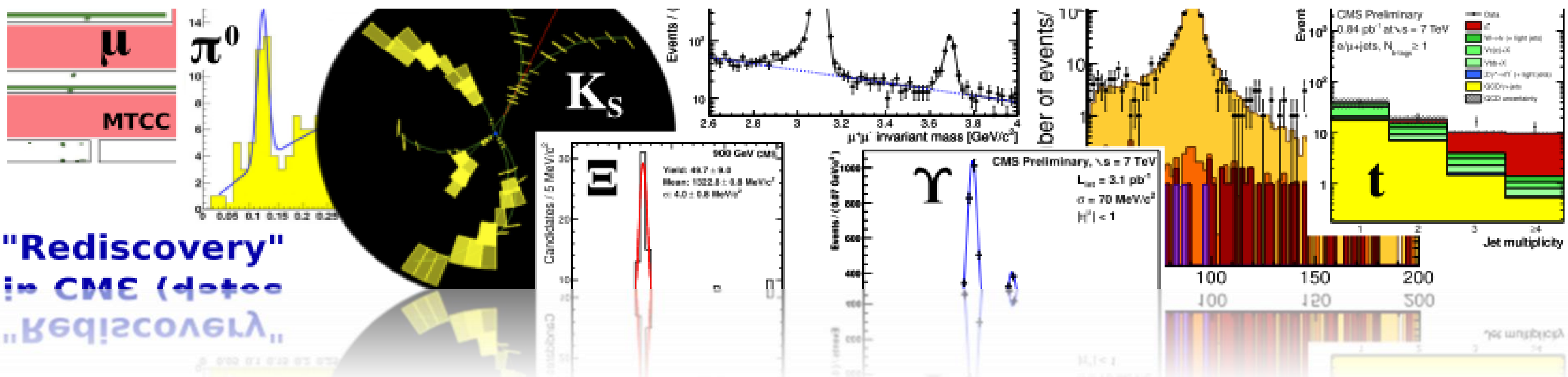
The LHC Computing Grid

The Grid unites computing resources of particle physics institutions around the world

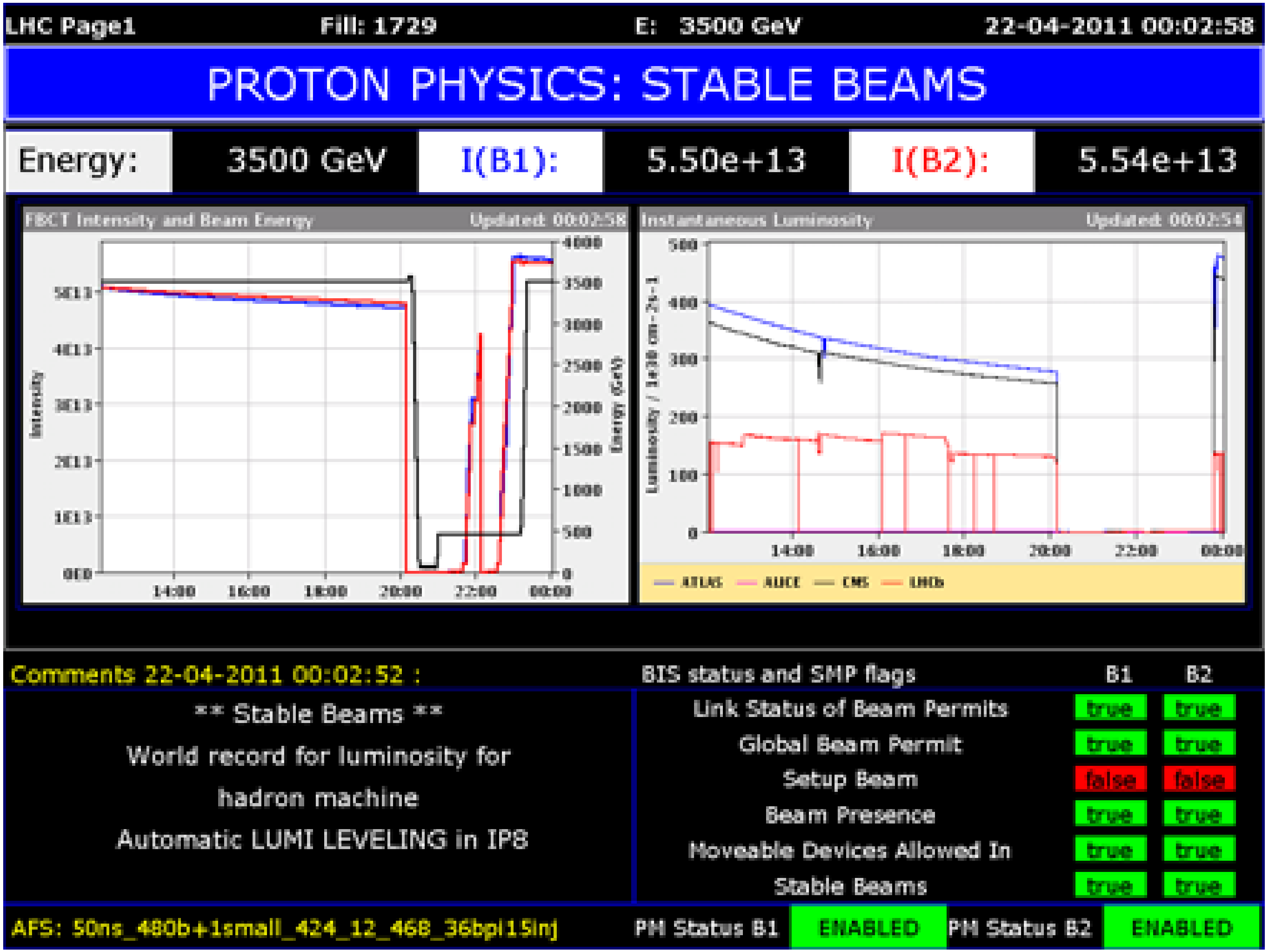
The **World Wide Web** (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations

The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe

Detector commissioning



LHC Page 1: stable beams



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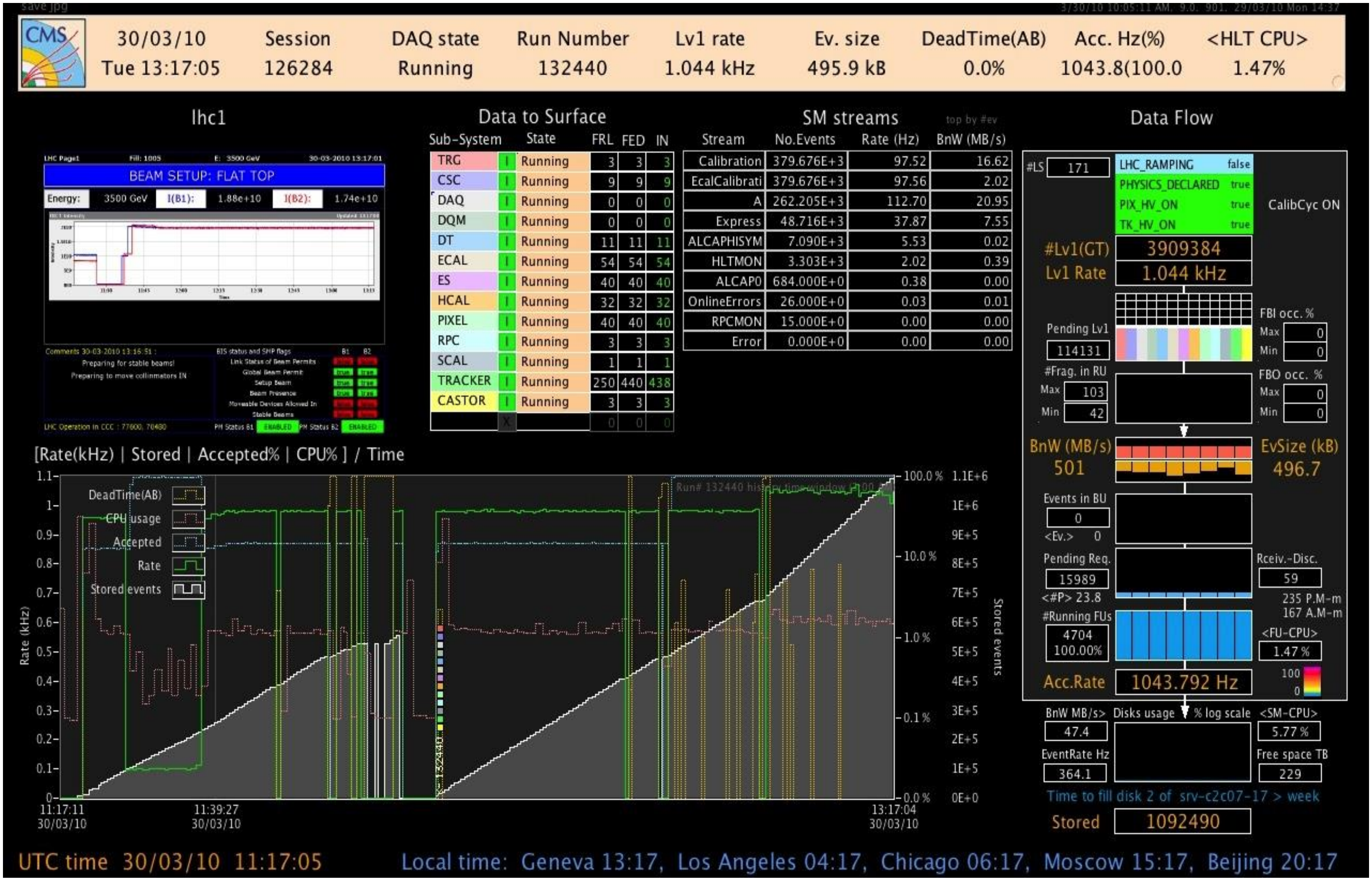


Experiment control rooms

Cessy: Master Control Room

Fermilab: Remote Operations Center

Meyrin: CMS Data Quality Monitoring Center

Any Internet access

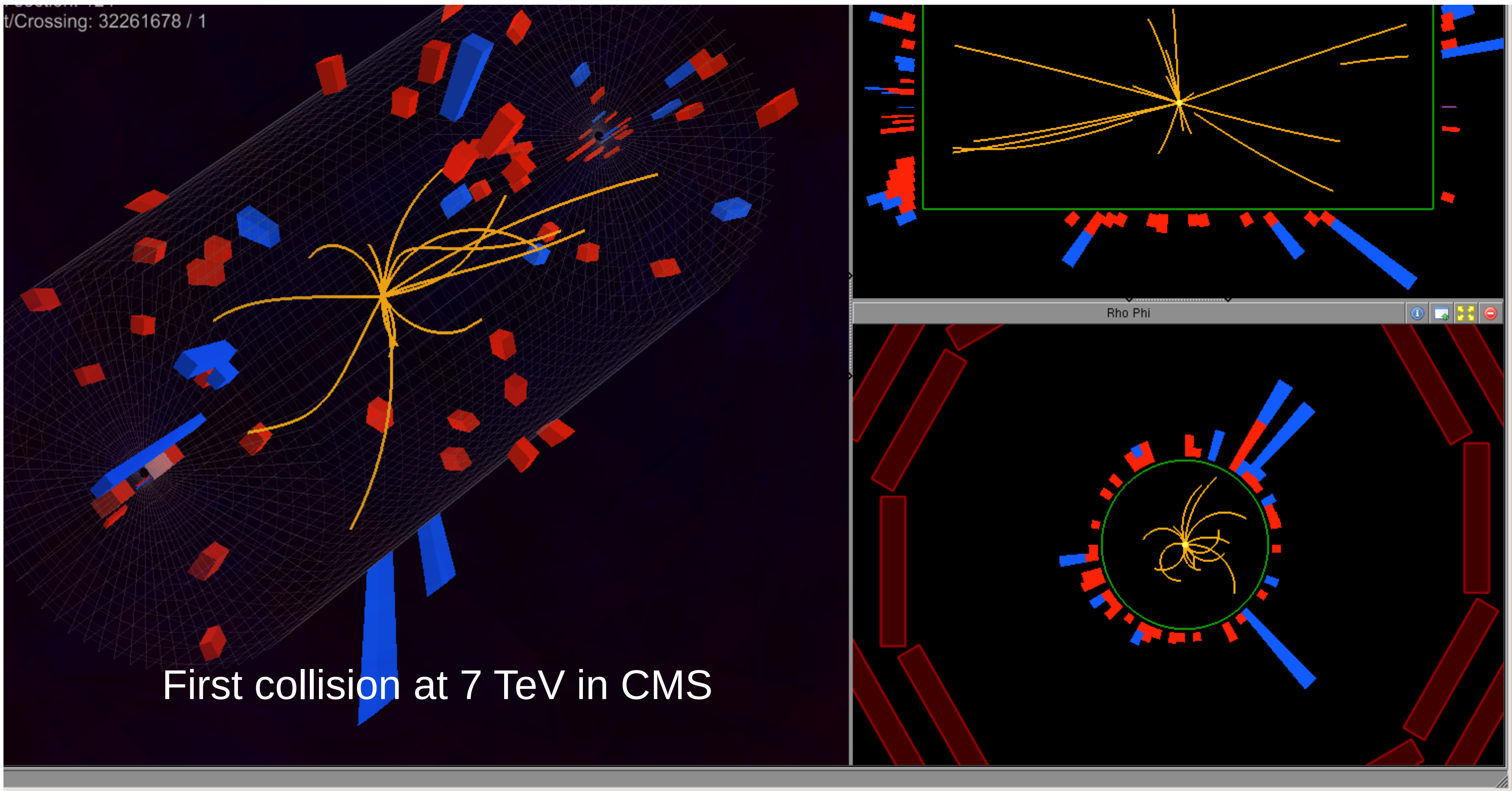
CMS Experiment

2009: First p-p collisions at LHC

November 23, 2009
First collisions at 900 GeV

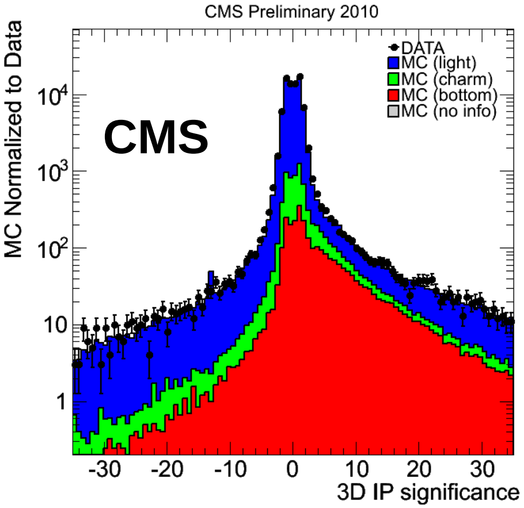
December 14, 2009
First collisions at 2.36 TeV

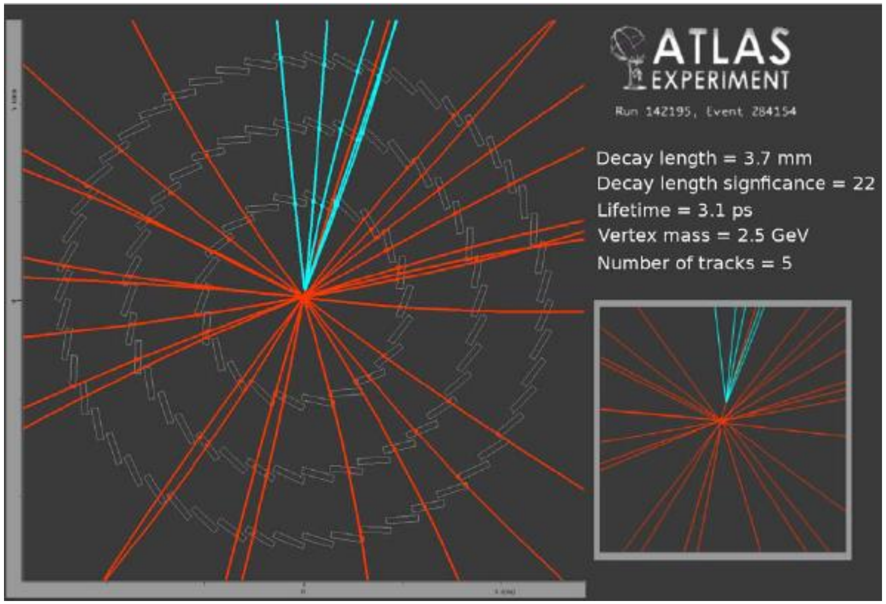
March 30, 2010
First collisions at 7 TeV

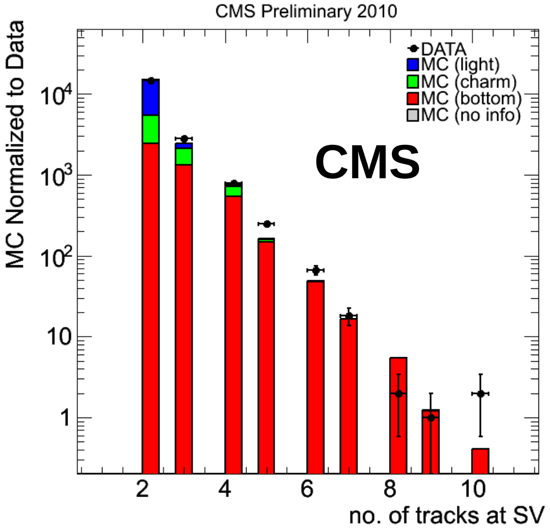


Tracking: secondary vertices

Basic variables relevant for B-tagging are well described by the simulation



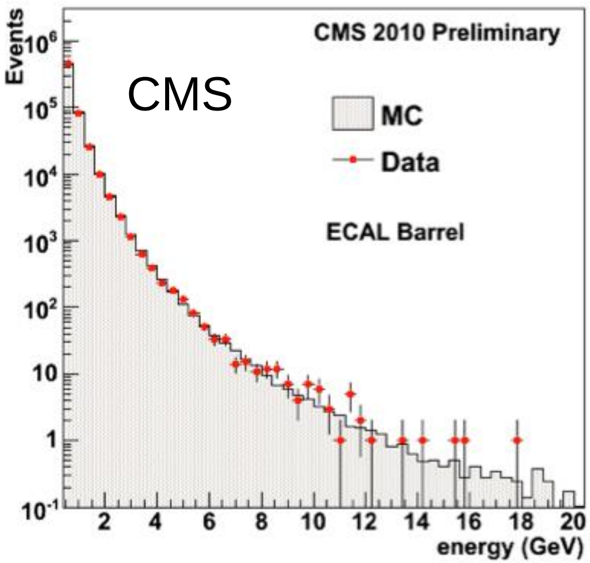


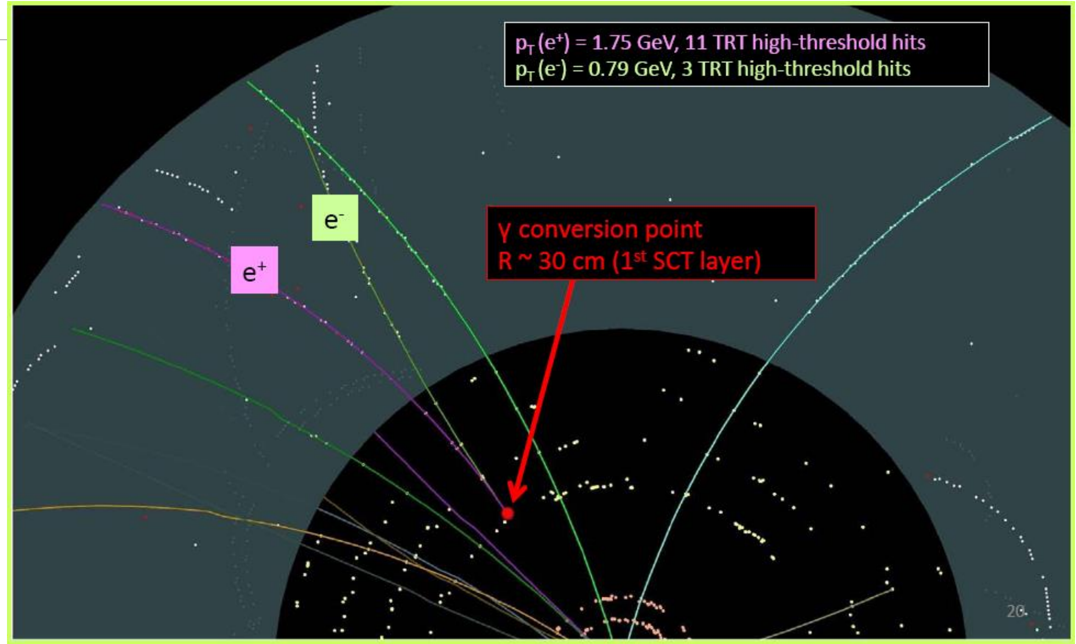


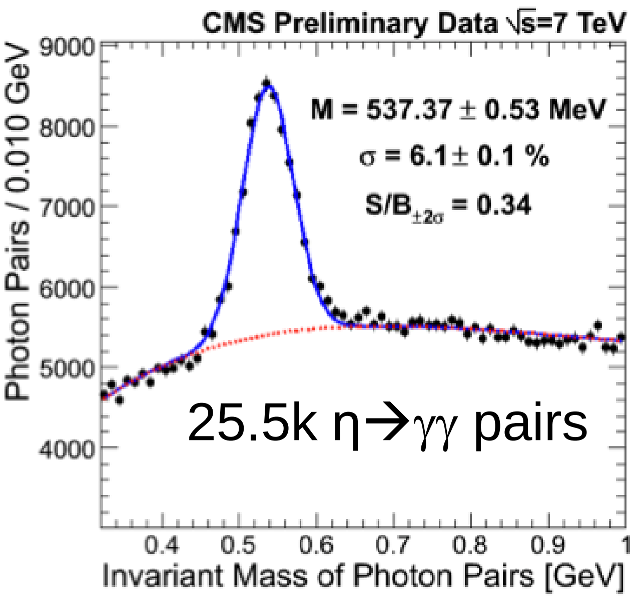
Secondary vertices compatible with heavy flavor production

Photons and electrons

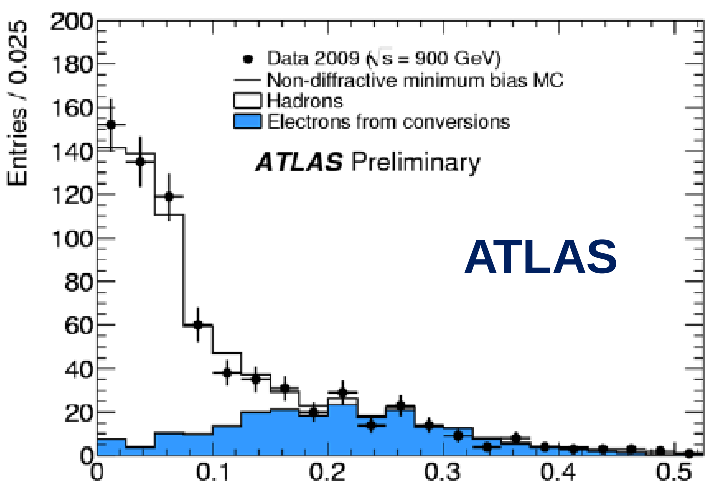
EM cluster energy



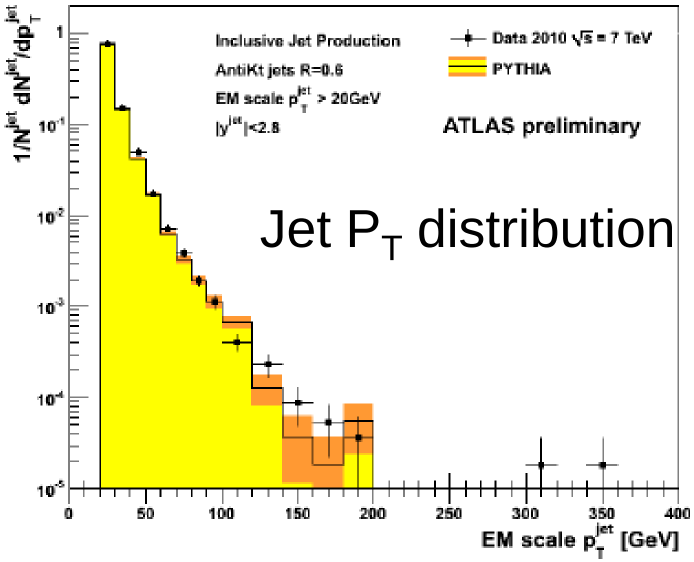




TRT high-threshold hit fraction

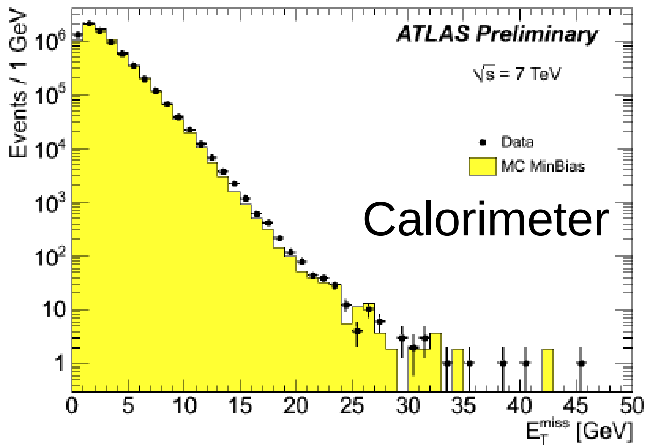


Jets and missing energy

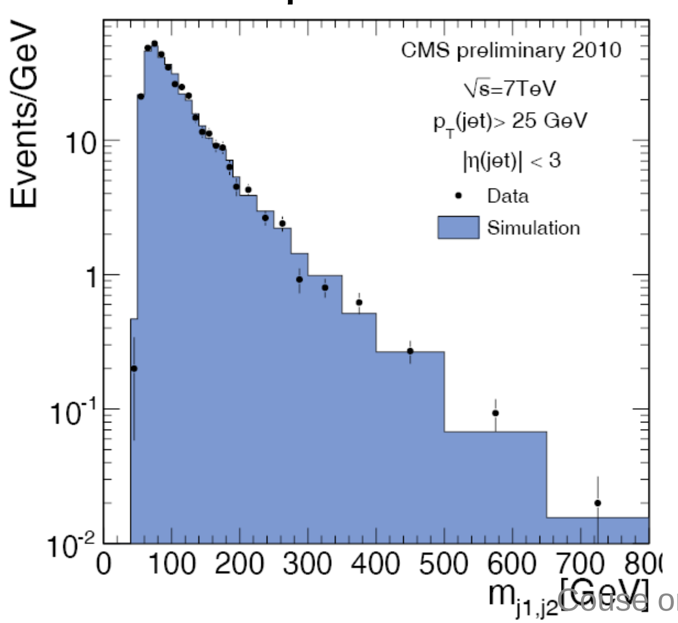


Missing Transverse Energy

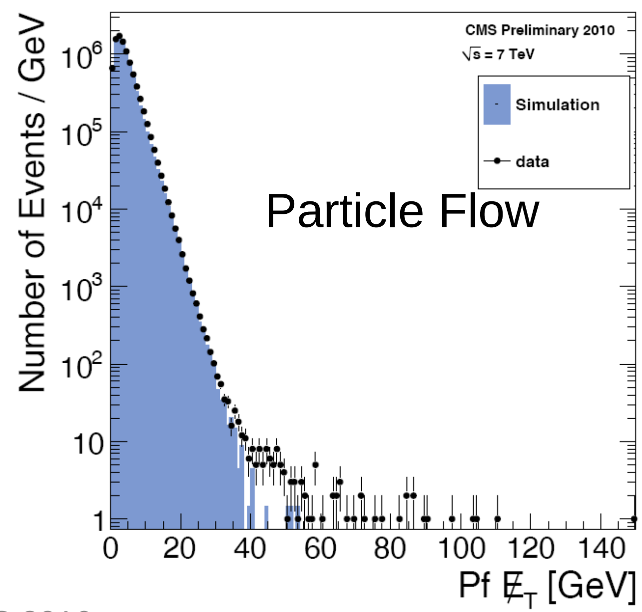
ATLAS



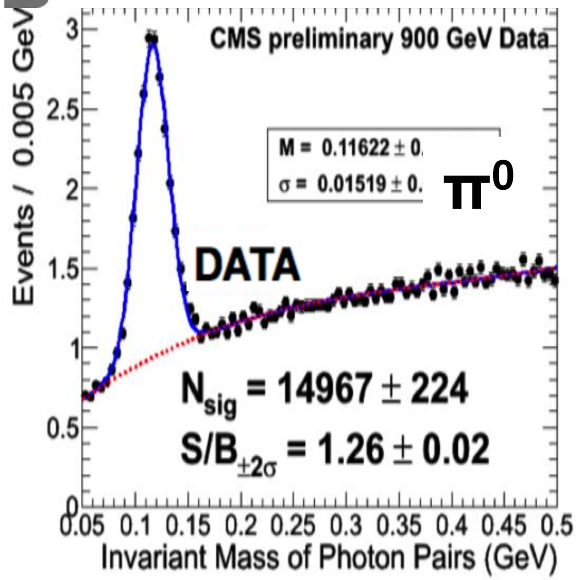
Di-jet mass

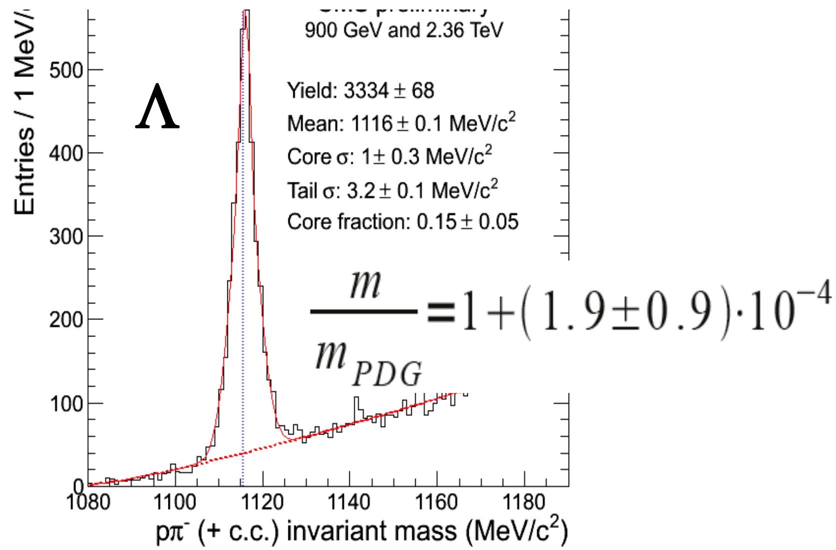


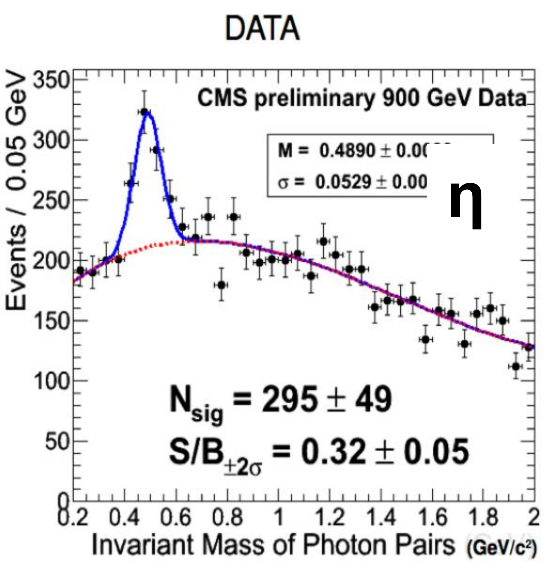
CMS

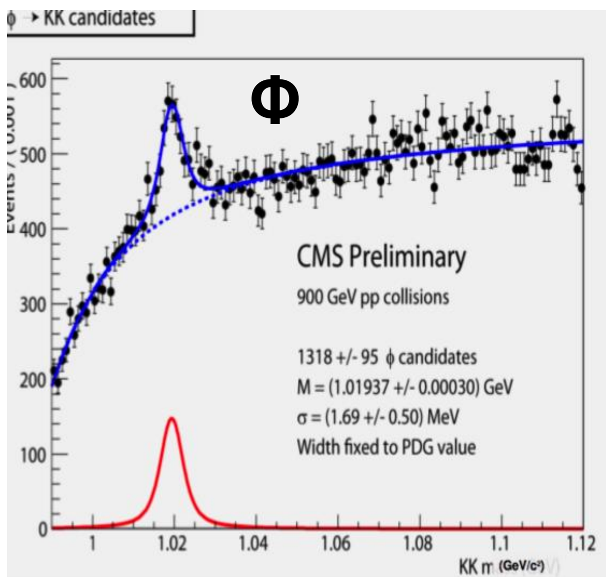


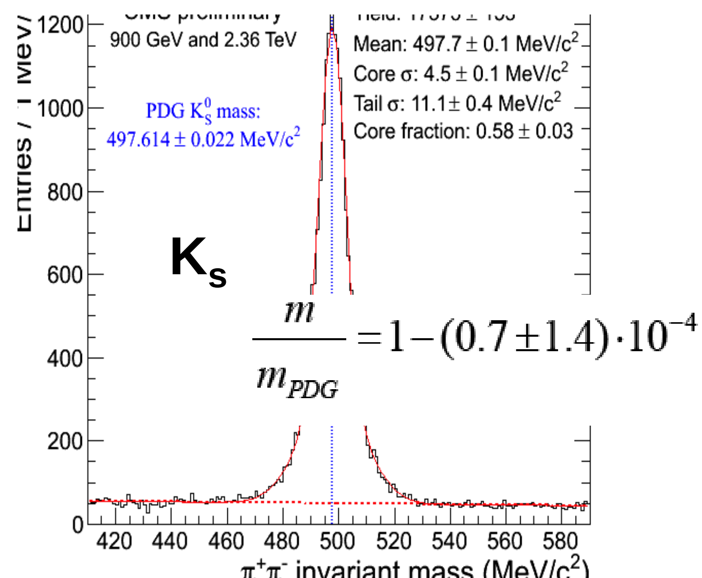
Rediscovery of resonances



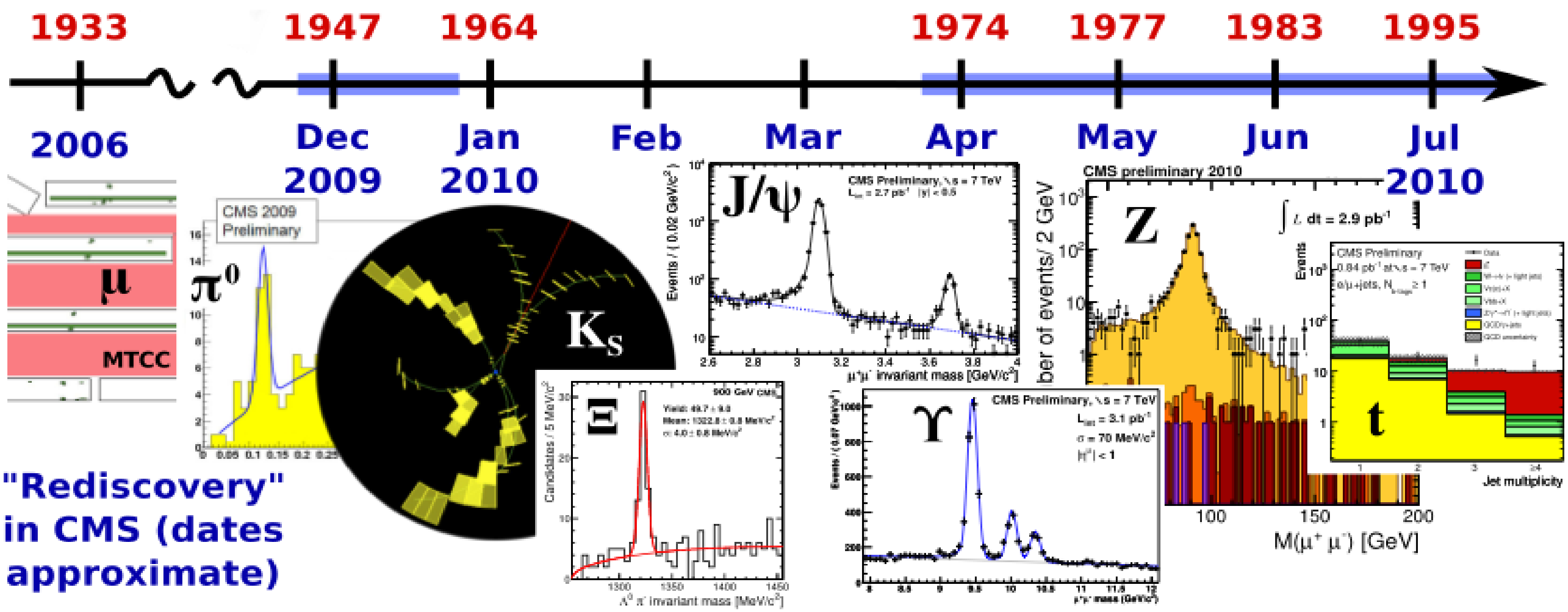




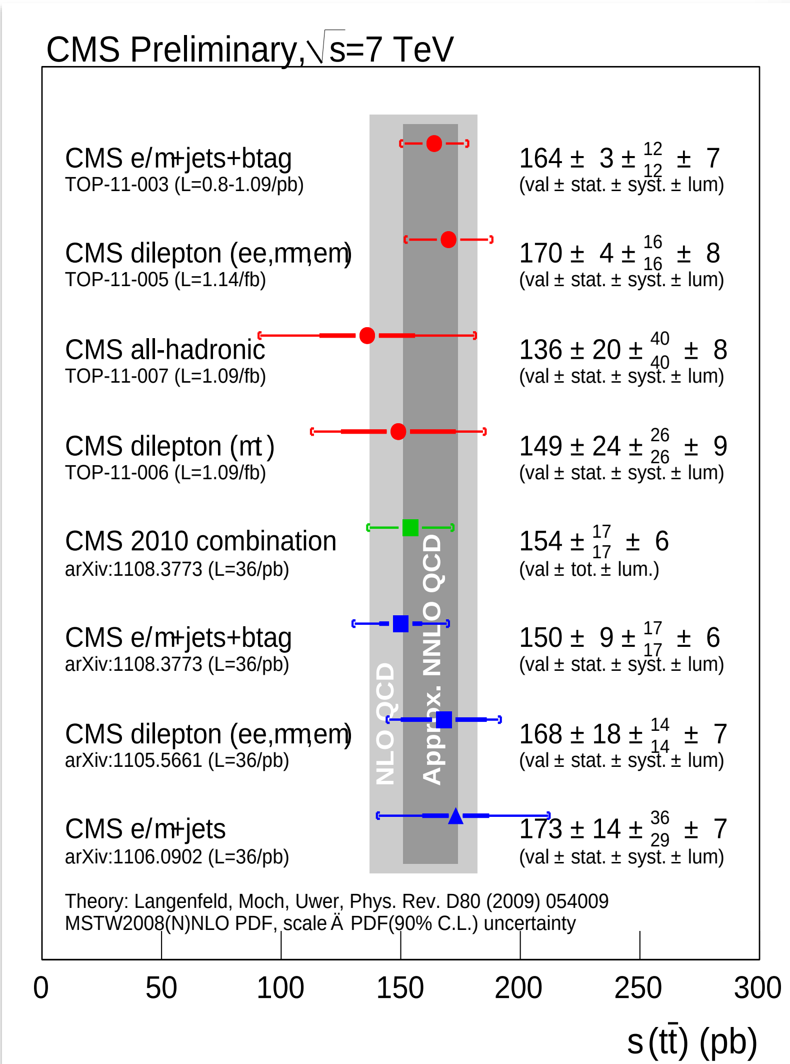


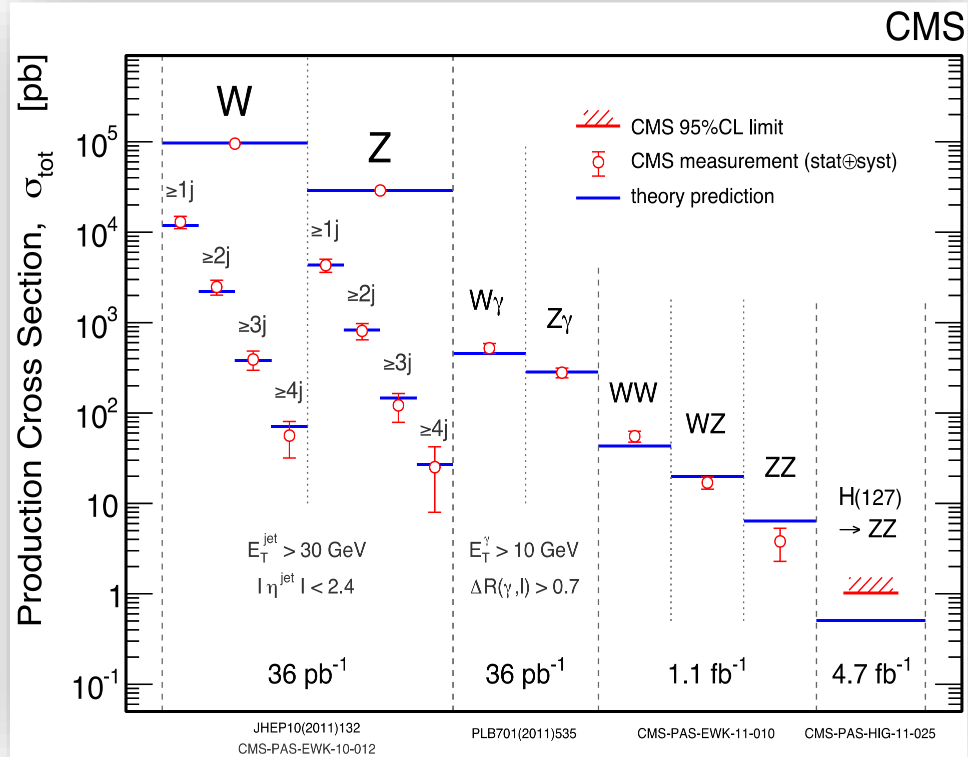


Rediscovery of the Standard Model at LHC



Standard Model at 7 TeV (2010-2011)





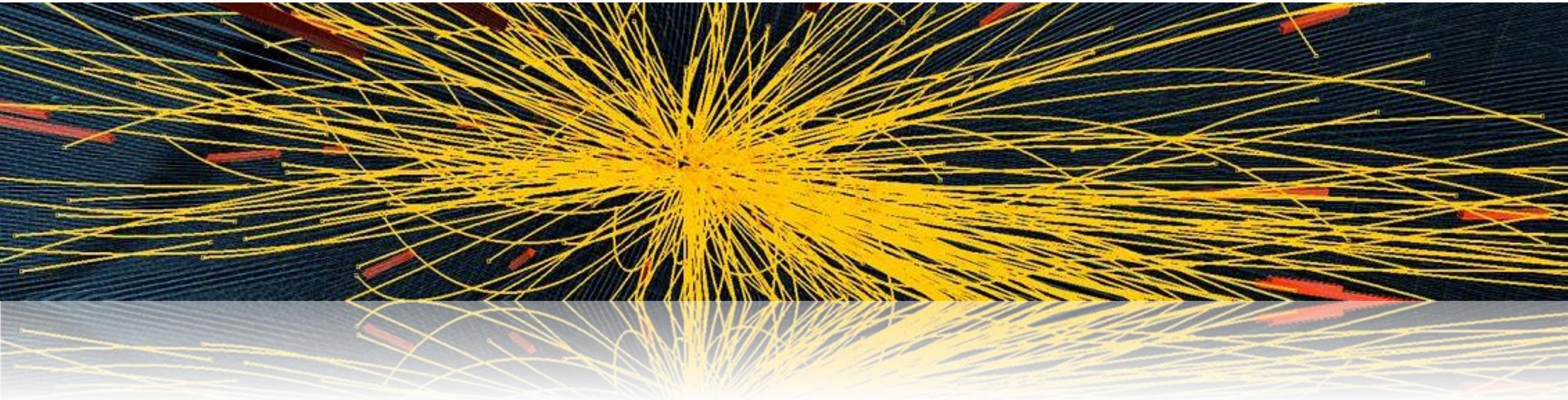
- **Fabulous agreement**
- **Lots of data**

… on to the Higgs…

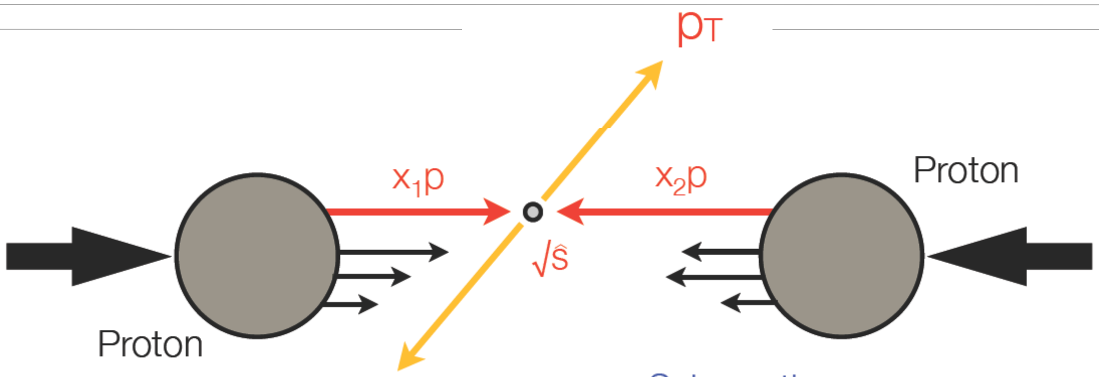
The Standard Model at LHC

1. Hadron interactions
2. QCD and parton densities
3. Monte Carlo generators
4. Luminosity and cross-section measurements
5. Minimum bias events
6. Jet physics
7. W and Z physics

Hadron Interactions



Kinematical variables

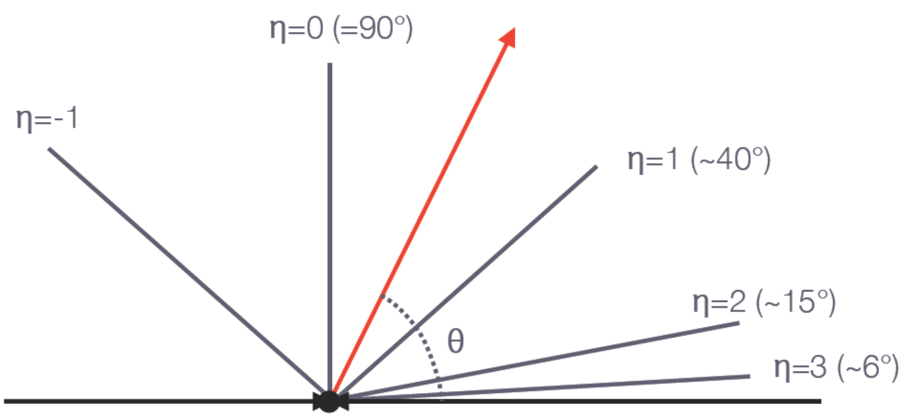


Schematic
proton-proton scattering

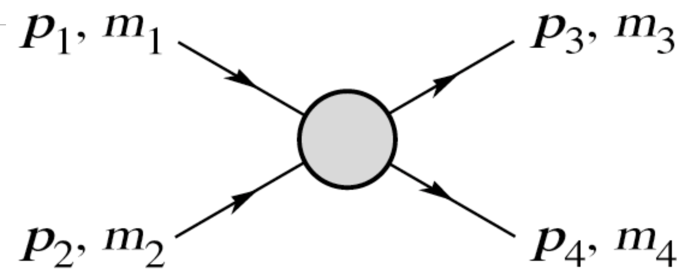
Relevant kinematic variables:

- Transverse momentum: p_T
- Rapidity: $y = ½ \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: η = -ln tan ½θ
- Azimuthal angle: φ

Pseudorapidity



Invariant mass



Invariant Mass:

$$M^2 = (p_1 + p_2)^2$$
$$= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$
$$= m_1^2 + m_2^2 + 2E_1E_2(1 - \vec{\beta}_1\vec{\beta}_2)$$

Center of mass energy

Center-of-mass Energy:

$$E_{\mathrm{cm}} = \left[(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2\right]^{\frac{1}{2}}$$

Particle 2 at rest:

$$\sqrt{s} = \quad E_{\mathrm{cm}} = \left[m_1^2 + m_2^2 + 2E_1 m_2\right]^{\frac{1}{2}}$$

Particle Collider:

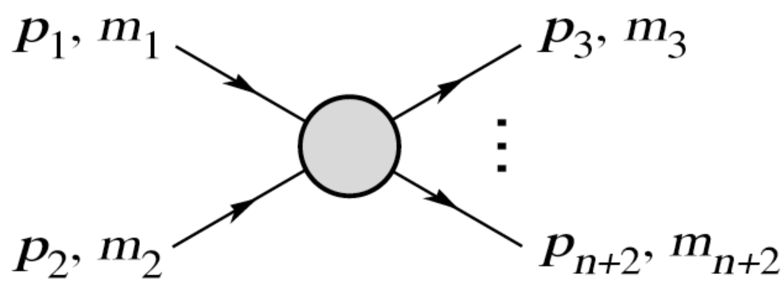
$[E_1 = E_2;\ \vec{p}_1 = -\vec{p}_2;\ m_1 = m_2 \approx 0]$

$$E_{\mathrm{cm}} = 2E$$

Cross section:

Matrix element

Phase space



Differential
Cross Section:

Matrix element

$$d\sigma = \frac{(2\pi)^4 |\mathscr{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2;\ p_3, \ldots, p_{n+2})$$

n-body
phase space

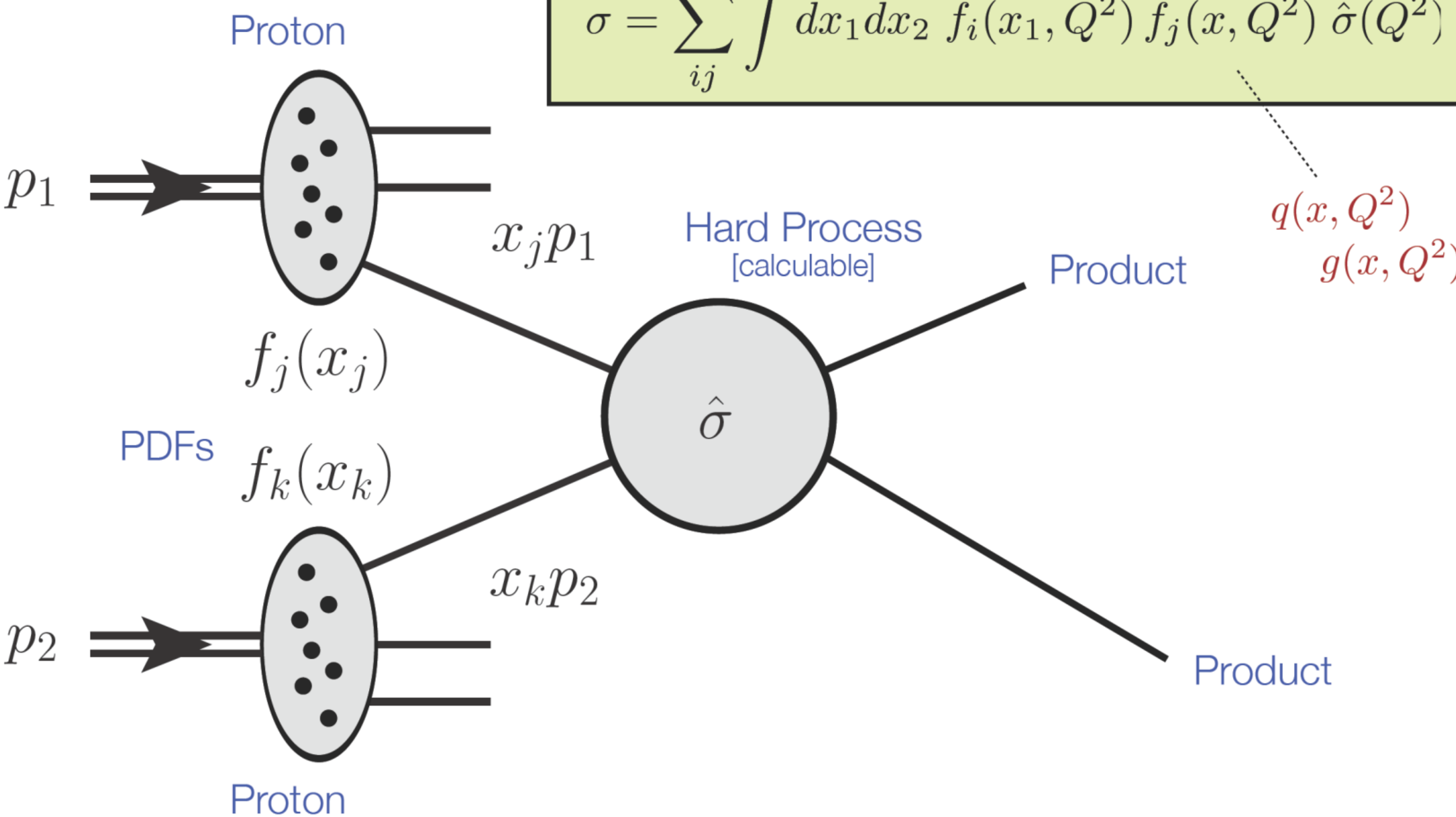
$$d\Phi_n = \ldots$$

$$\ldots = \delta^4 \left(P - \sum_{i=1}^{n} p_i\right) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

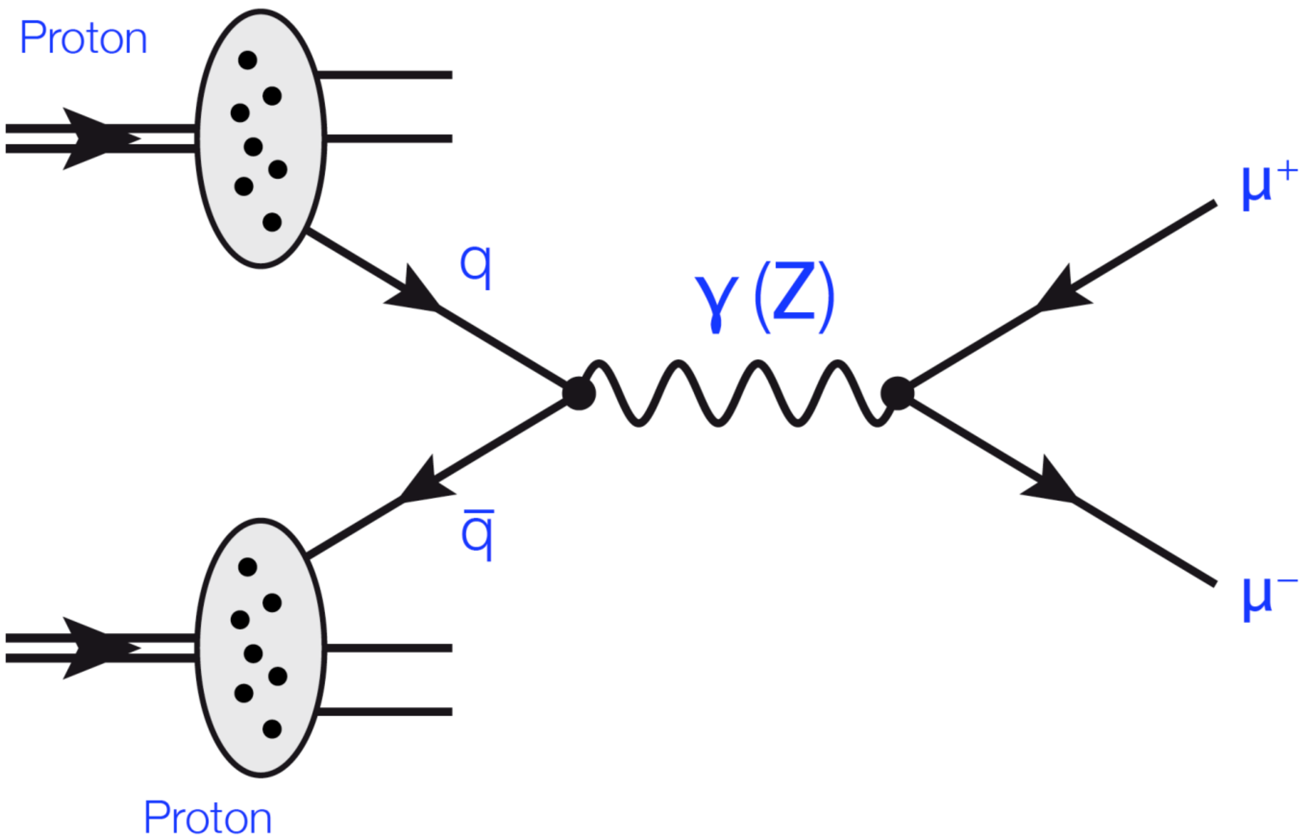
with $P = p_1 + p_2$

Proton-Proton Scattering @ LHC

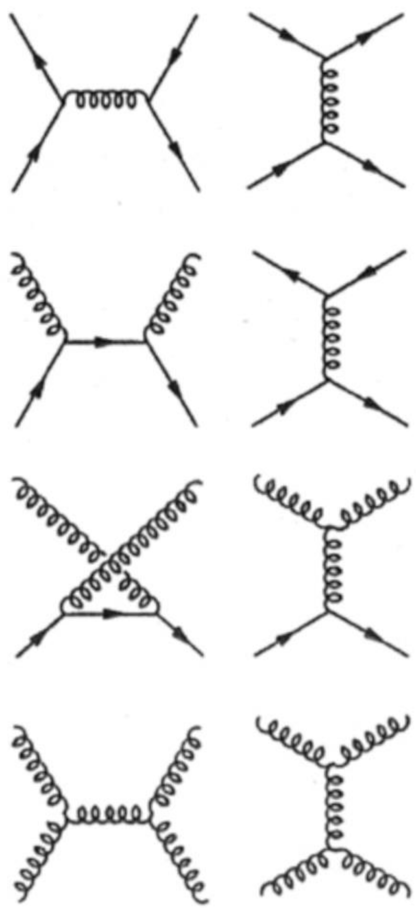
$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\; f_j(x, Q^2)\; \hat{\sigma}(Q^2)$$



Example: Drell-Yan Process



QCD Matrix Elements

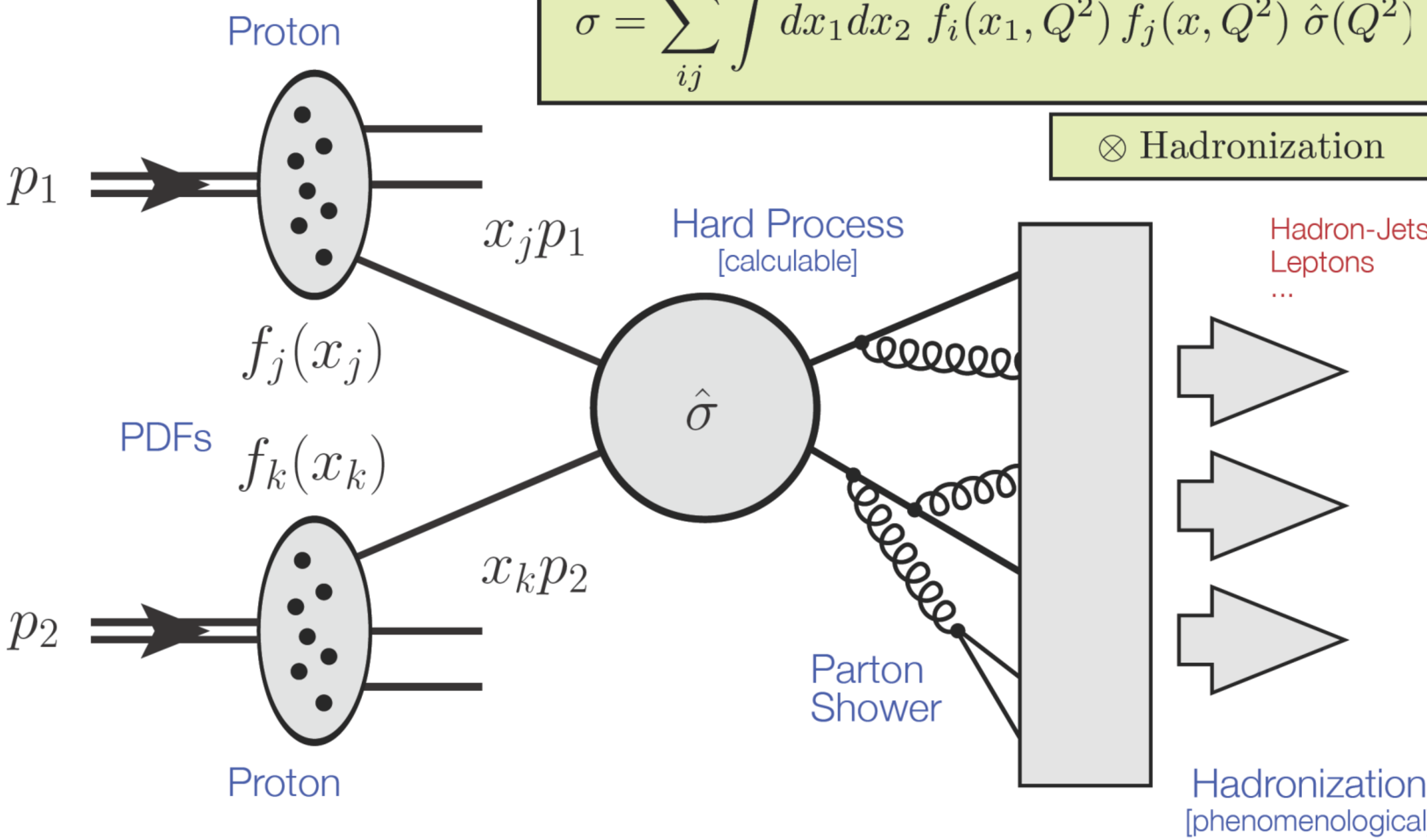


Subprocess	$\|\mathcal{M}\|^2/g_s^4$	$\|\mathcal{M}(90°)\|^2/g_s^4$
$qq' \to qq'$, $q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.2
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{8}{3}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	1.0
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{3}{8}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	0.1
$qg \to qg$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}+3\right)$	30.4

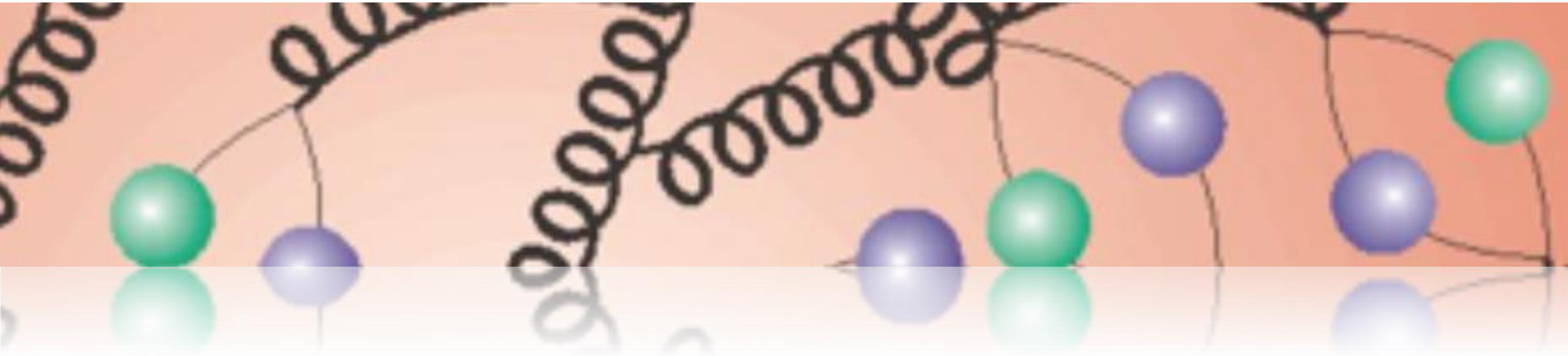
Proton-Proton Scattering @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\, f_j(x, Q^2)\, \hat{\sigma}(Q^2)$$

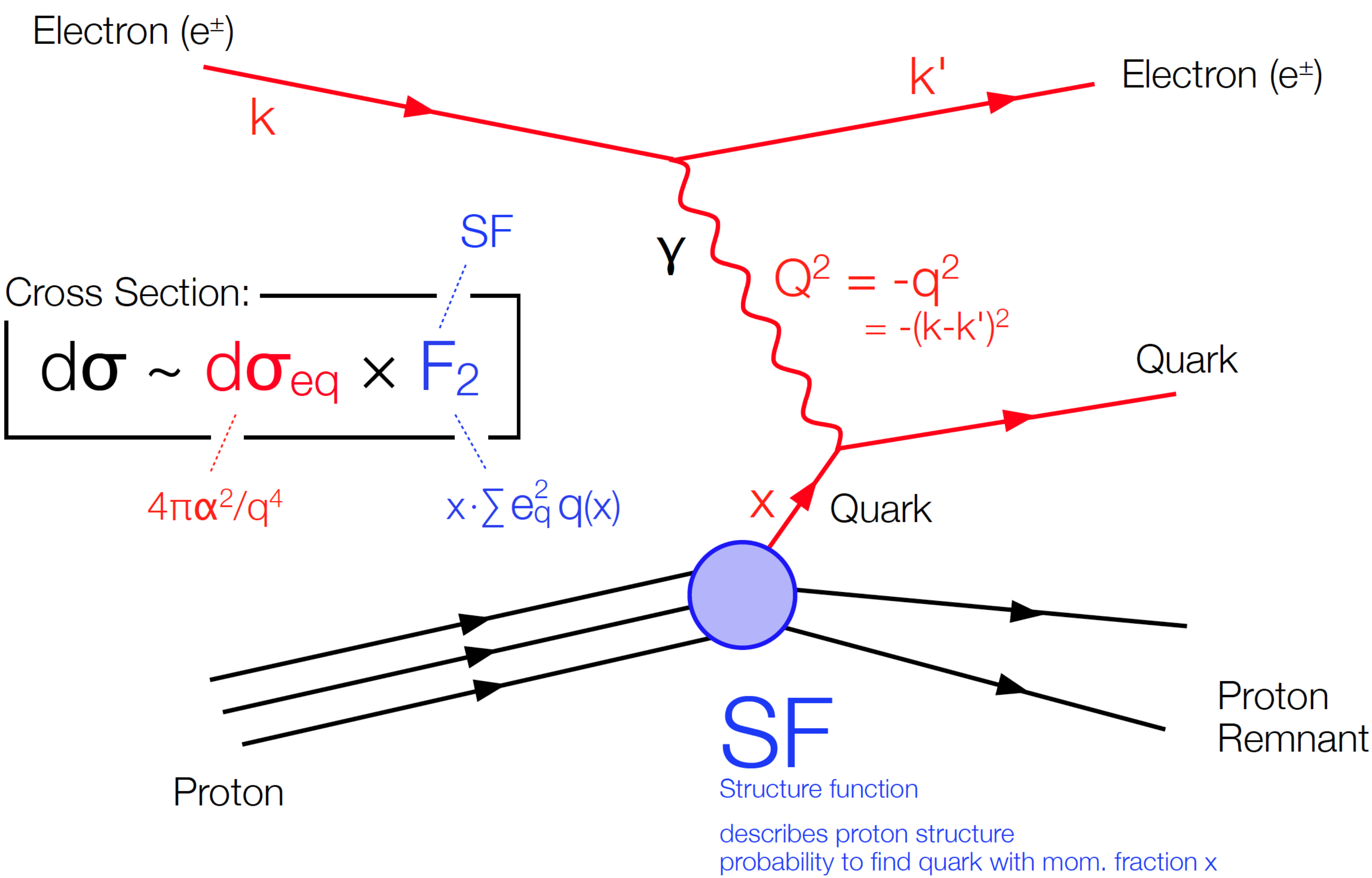
$\otimes$ Hadronization



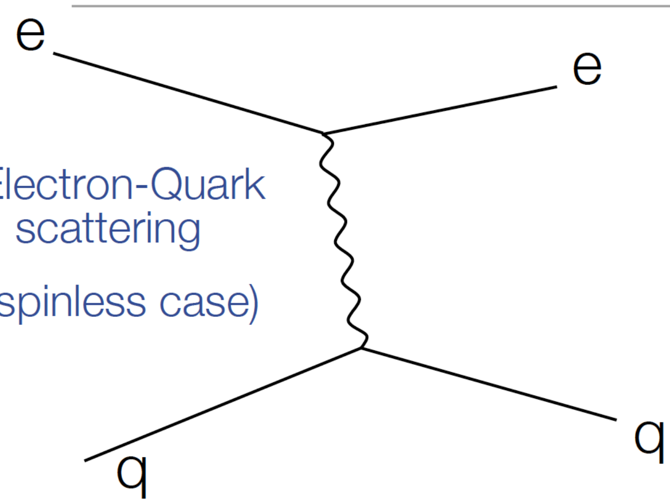
QCD & parton densities



Lepton-proton scattering



Structure Function F_2



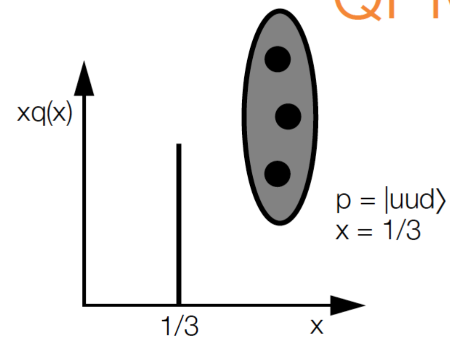
Electron-Quark scattering

(spinless case)

$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

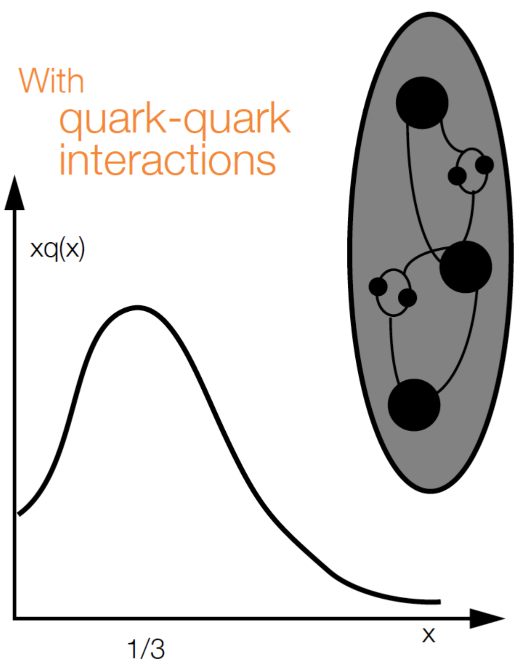
Rutherford scattering on pointlike target

Naive QPM



$$\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4}[2e_u^2 + e_d^2] = \frac{4\pi\alpha^2}{q^4}$$

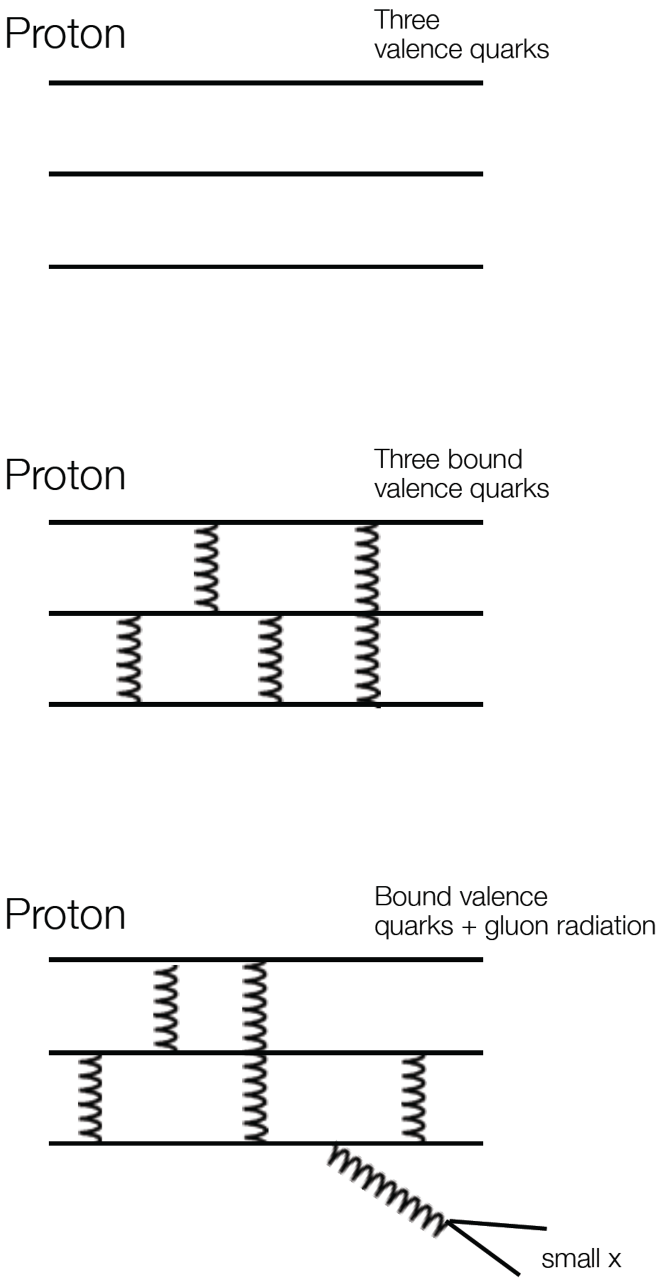
With quark-quark interactions

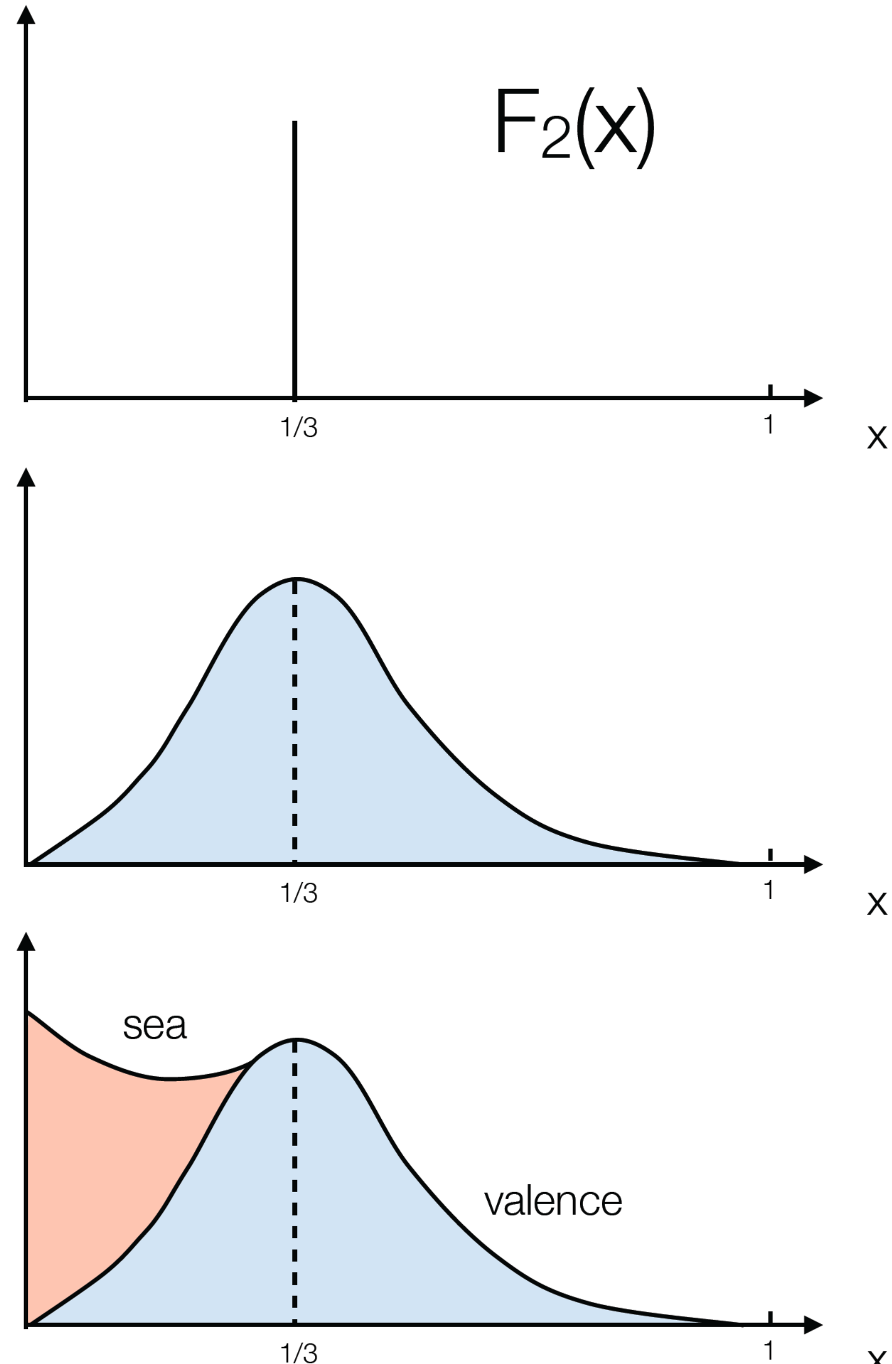


$$\frac{d\sigma(ep)}{dx\,dq^2} = \frac{4\pi\alpha^2}{q^4}[e_u^2 u(x) + e_d^2 d(x) + \dots]$$

$$= \frac{4\pi\alpha^2}{q^4}\frac{F_2(x)}{x}$$

QPM: Structure Functions F_2 independent of Q^2

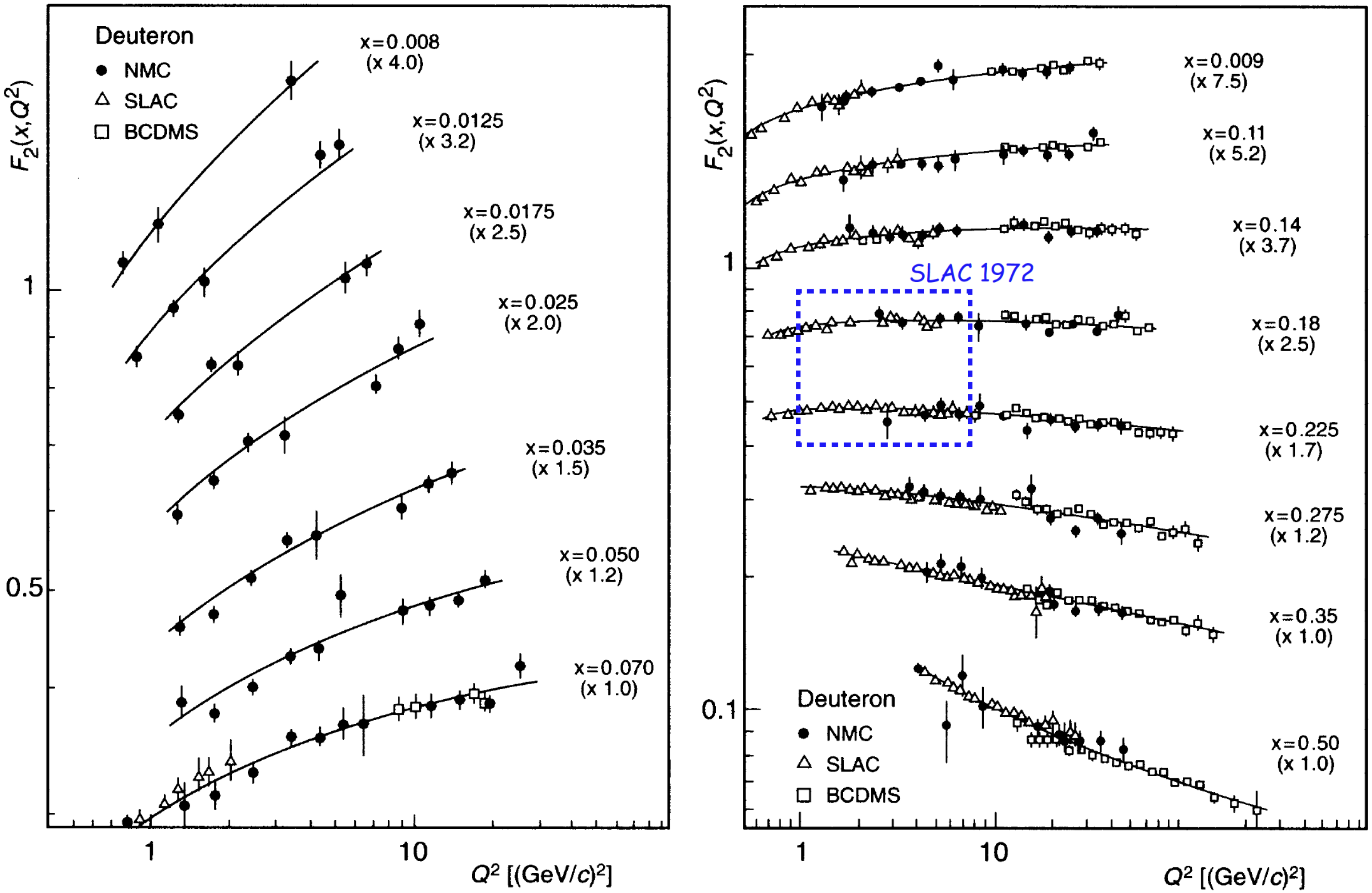




[see e.g. Halzen/Martin]

Scaling violation

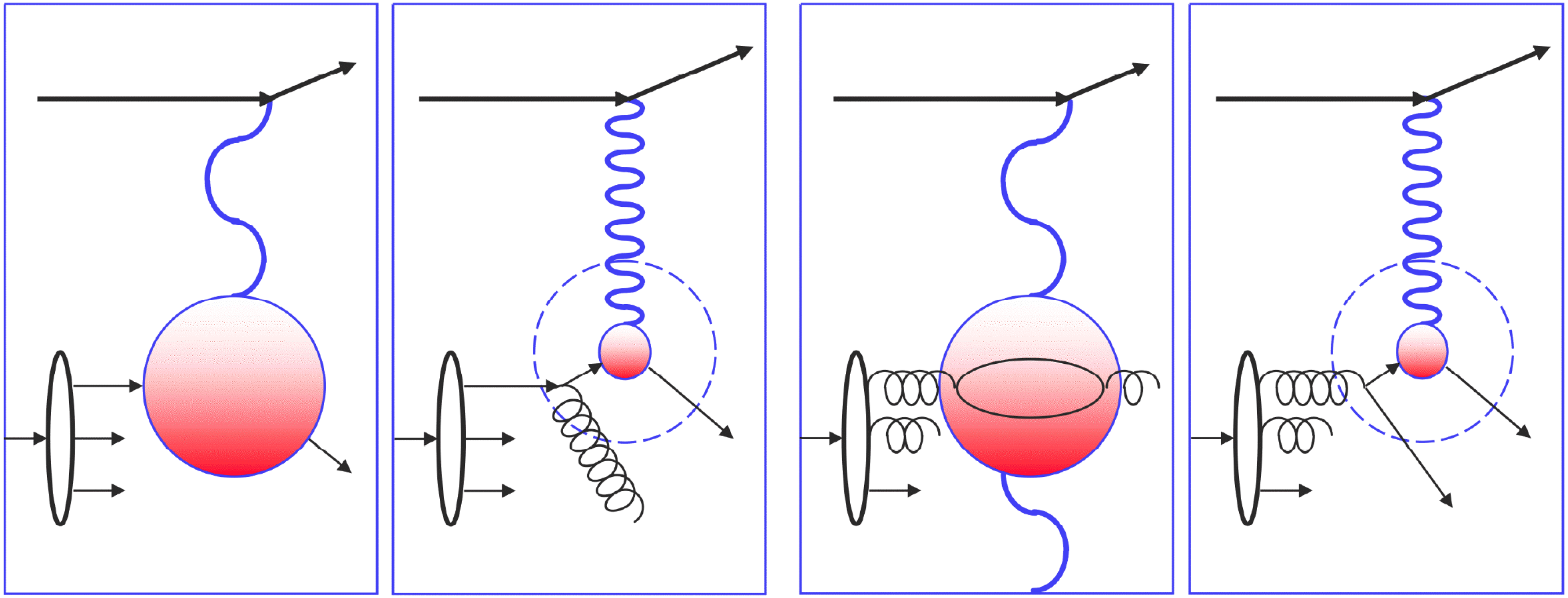
$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$



Scaling violation

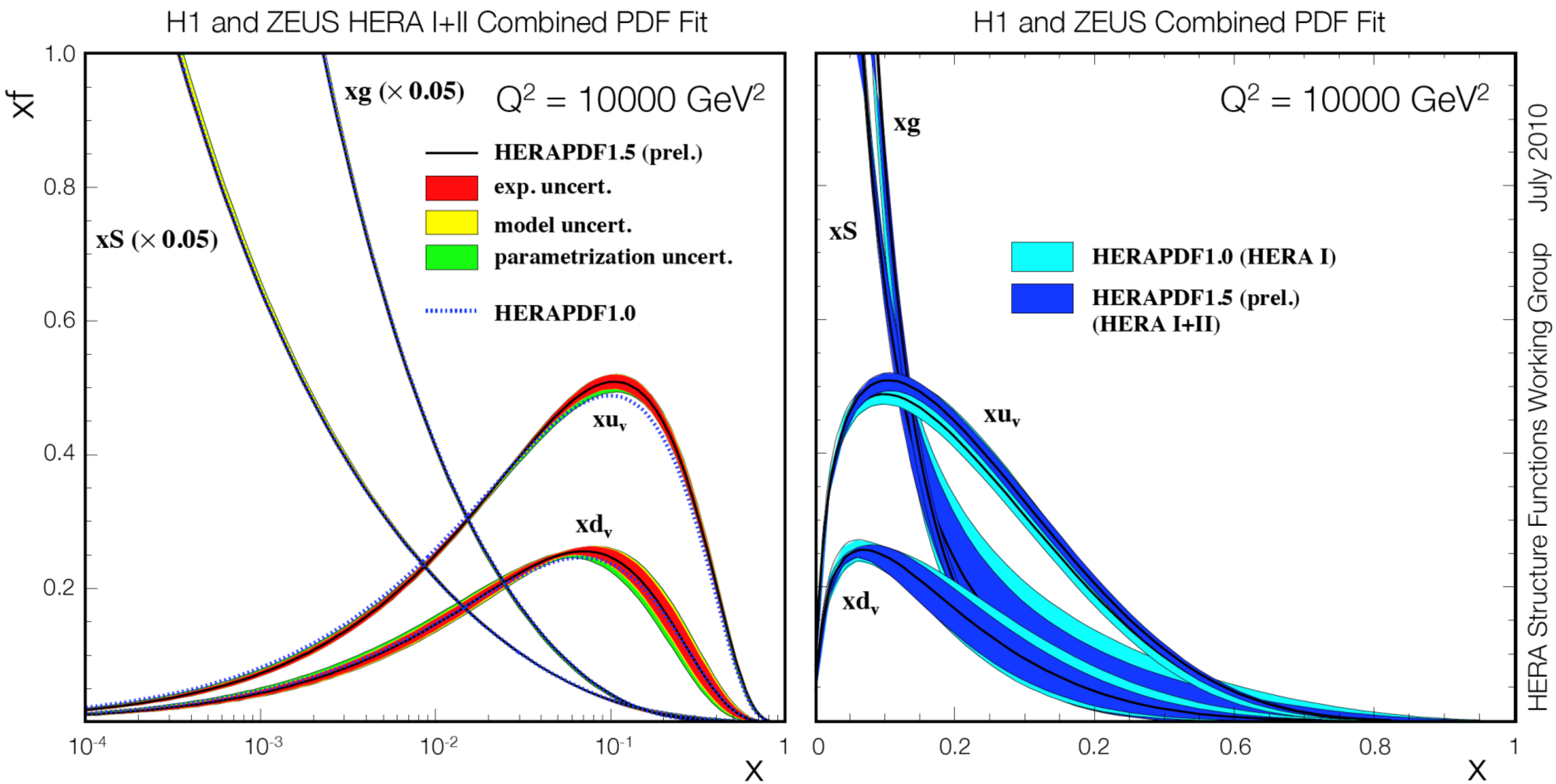
Proton quark dominated:
$Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

Proton gluon dominated:
$Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x

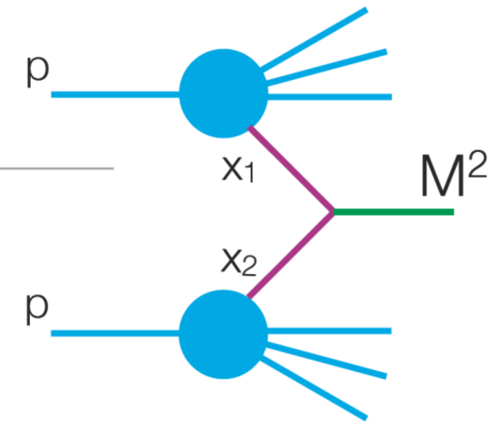


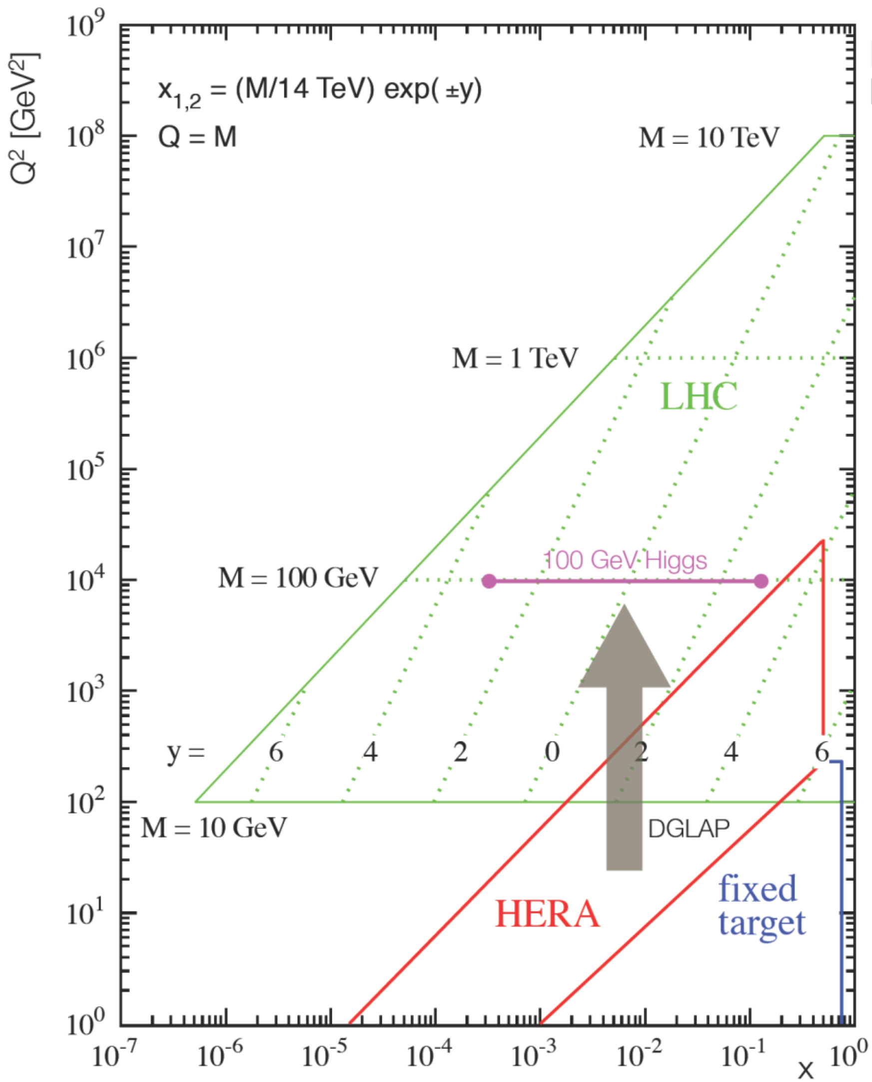
Q^2-evolution described by DGLAP Equations

Proton parton densities



Particle production @ LHC





LHC parton kinematics

$pp \rightarrow X_M$ + remnants

X_M: particle with mass M
e.g. Higgs

$$M^2 = x_1 x_2 \cdot s$$

i.e. to produce a particle with mass M at LHC energies ($\sqrt{s}$ = 14 TeV)

$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$
[$x_1 = x_2$: mid-rapidity]

LHC needs:

Knowledge of parton densities
Extrapolation over orders of magnitudes

End of Lecture 2