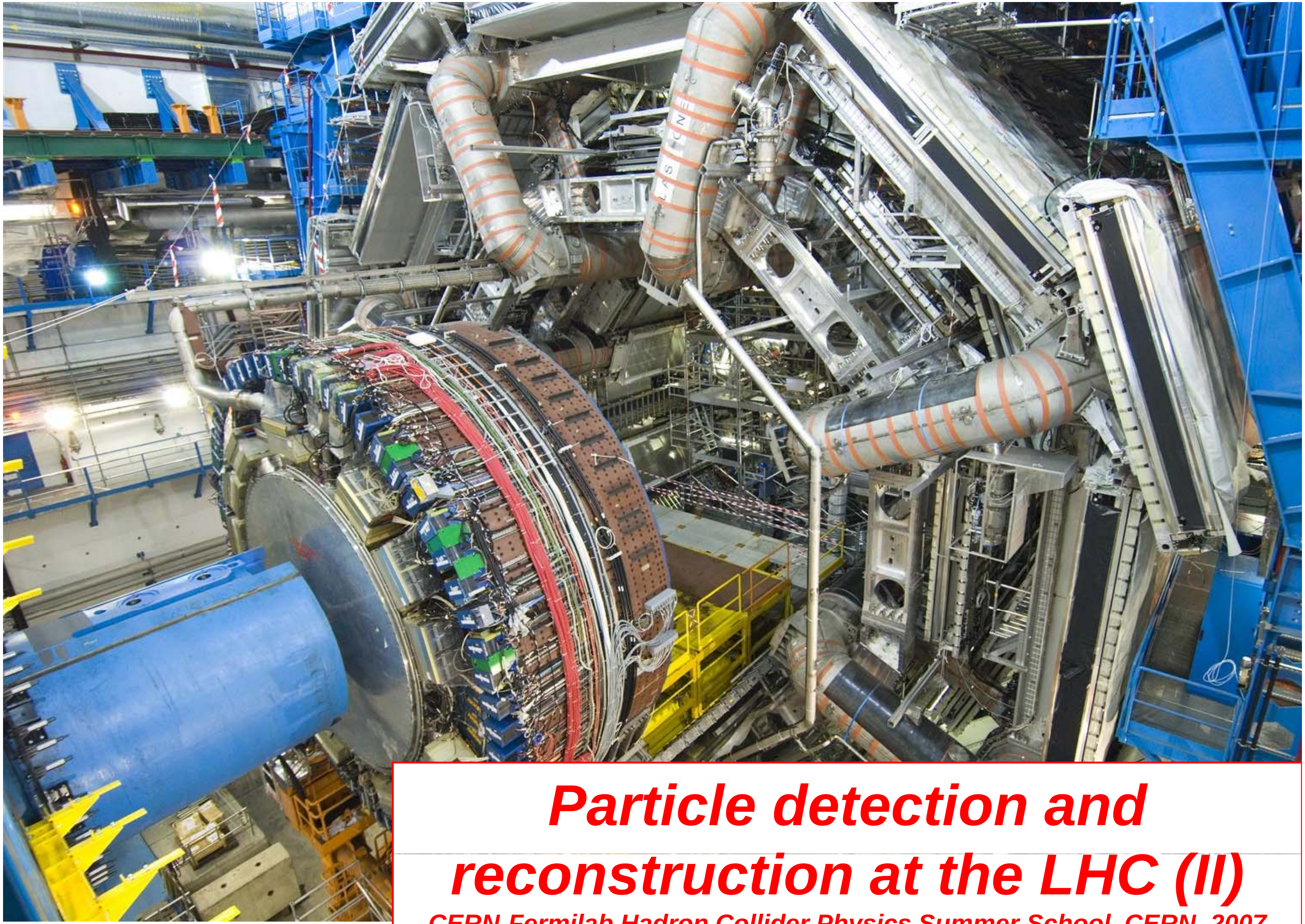


Particle detection and reconstruction at the LHC (II)

CERN-Fermilab Hadron Collider Physics Summer School, CERN, 2007
11th to 14th of August 2007 (D. Froidevaux, CERN)

Particle detection and reconstruction at the LHC (and Tevatron)

Lecture 1

- Historical introduction: from UA1/UA2 to ATLAS/CMS

Lecture 2

- Experimental environment, main design choices and intrinsic performance

Lecture 3

- Electrons, photons, muons, τ-leptons and particle-ID

Lecture 4

- Hadronic jets and neutrinos

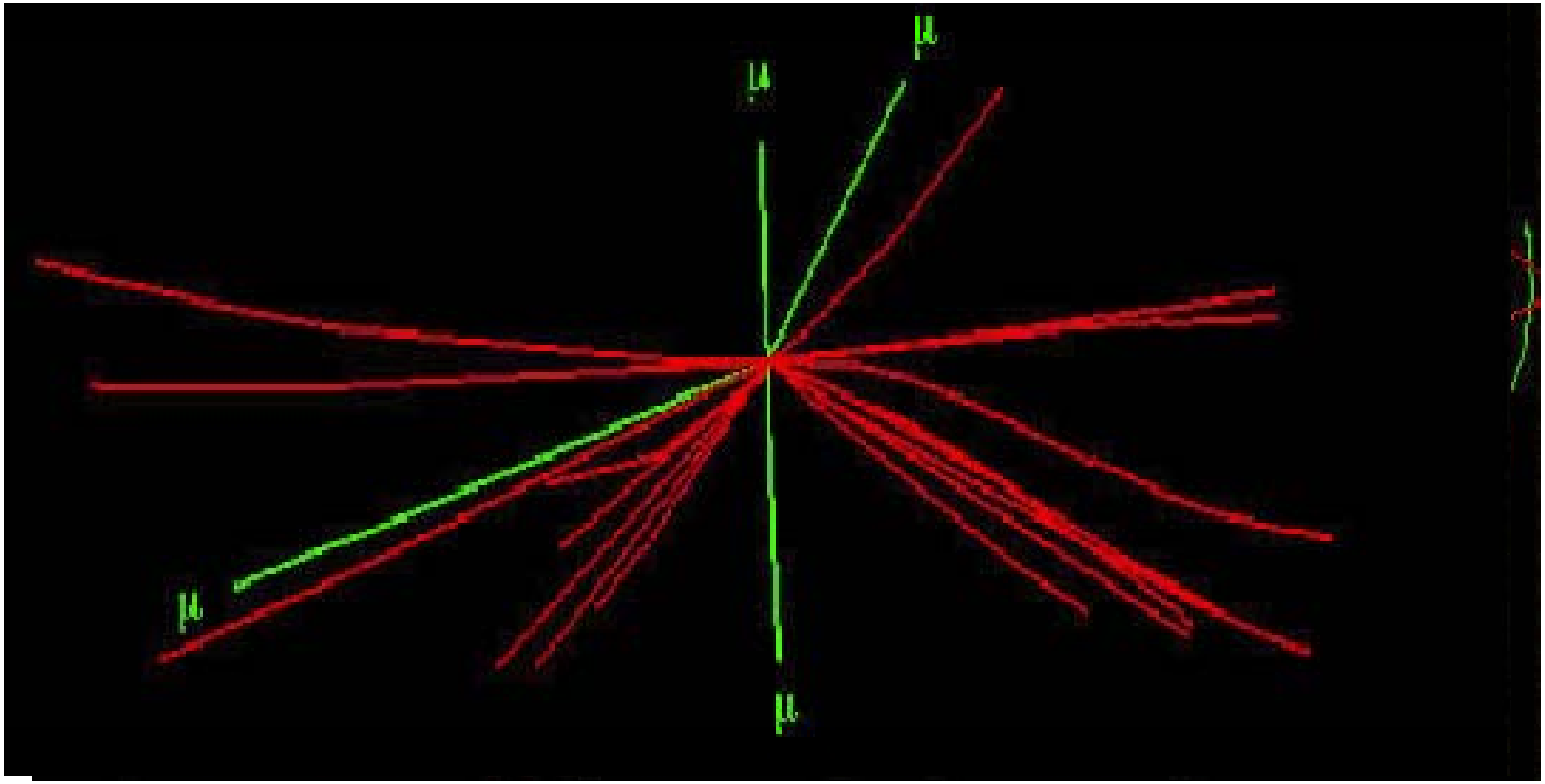
Not covered here

- Trigger, data acquisition and offline (see lectures by A. Yagil)
- Calibration, alignment and commissioning (see lectures by D. Acosta)

Physics at the LHC: the challenge

How to extract this…

… from this …



Higgs ⟶ 4μ

+30 min. bias events

Without knowing really where to look for!

Physics at the LHC: the challenge

Small x-sections

need highest luminosity

L= 10^{34-35} $cm^{-2}s^{-1}$

Orders

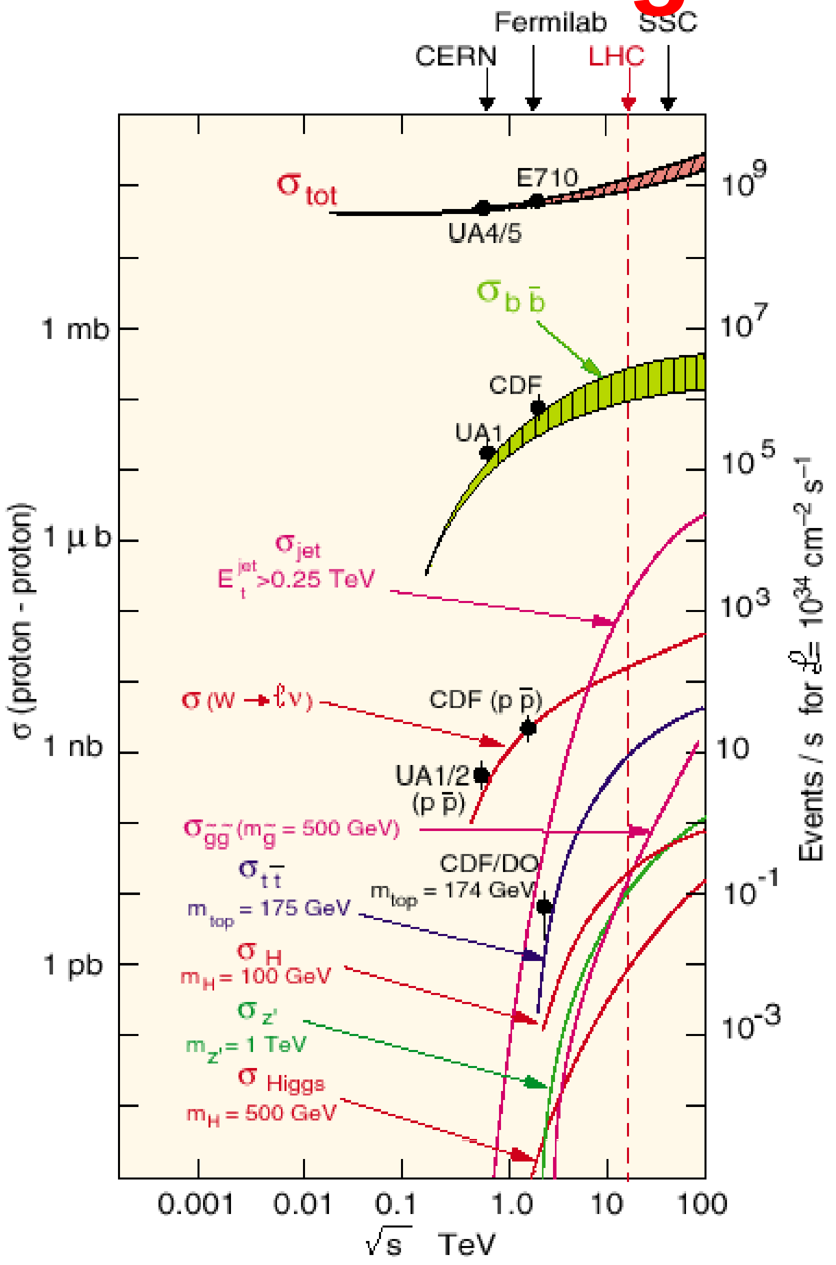
for various physics channels:

- Inelastic : 10^{10} Hz
- W -> lν : 10^{3} Hz
- tt production : 10^{2} Hz
- Higgs (m=100 GeV) : 1 Hz
- Higgs (m=600 GeV) : 10^{-1} Hz

(and include branching ratios: ~ 10^{-2})

Selection power for Higgs discovery ≈ 10^{14-15}

i.e. 100 000 times better than achieved at Tevatron so far for high-p_T leptons!



Physics at the LHC: the challenge

LHC is a factory for top, W/Z, Higgs, SUSY, black hole

Expected event rates for representative (known and new) physics processes at low luminosity (L=10^{33} cm^{-2} s^{-1}) in ATLAS/CMS

Process	Events/s	Events for 10 fb^{-1} (one year)	Total statistics collecte elsewhere by 2008 (?)
W → eν	30	10^8	10^4 LEP / 10^7
Tevatron Z → ee	3	10^7	10^6 LEP
Top	2	10^7	10^4 Tevatron
Beauty	10^6	10^{12} – 10^{13}	10^9
Belle/BaBar H (m=130 GeV)	0.04	10^5	
Gluino (m= 1 TeV)	0.002	10^4	
Black holes m > 3 TeV	0.0002	10^3	

Physics at the LHC: the environment

What do we mean by particle reconstruction and identification at LHC?

Elementary constituents interact as such in "hard processes", namely:

Quarks and leptons as matter particles, and

Leptons	e (0.0005)	μ (0.105)	τ (1.777)
	ν_e	ν_μ	ν_τ
Quarks	u (< 0.005)	c (~ 1.25)	t (~ 175)
	d (< 0.005)	s (~ 0.1)	b (~ 4.2)

Gluons and EW bosons as gauge particles

Gluon(0) Colour octet	Photon (0)	W^+,W^- (80.42)	Z (91.188)

All masses in GeV

Electrons, neutrinos and photons are the only rigorously stable particles in the zoo

At collider energies, muons can be considered as stable too

Some of the other particles are considered as long-lived (τ, c, b) meaning that their decay vertex may be measured by vertexing detector (requires excellent accuracy)

Physics at the LHC: the environment

Which type of particles does one actually see in the final state?

LHC physics processes are dominated by strong interactions (QCD) :

- **hard processes:** quarks and gluons materialise as hadronic jets, which consist mostly of charged and neutral hadrons (pions, kaons, and to a lesser extent protons and neutrons, which at these energies can be all considered as stable). Jets will be discussed in lecture 4.
- **soft processes:** non-perturbative QCD processes with soft gluons materialising as almost uniform soup of charged and neutral pions, kaons, etc.

- Heavy quarks with “long” lifetime are produced abundantly also
- High-p_T (above ~ 10 GeV) leptons are produced mostly in c,b decays.
- High-p_T isolated leptons may be found in fraction of J/ψ and Υ

Physics at the LHC: the environment

What drives the luminosity at the LHC?

$L(\alpha=0) = 1.07\ 10^{-4}\ 1/\Delta t\ N^2 E / \beta_e\ \varepsilon$, where:

- α is the crossing angle between the beams
- Δt is the time between bunch crossings, $\Delta t = 25$ ns
- N is the number of protons per bunch, $N = 10^{11}$
- E is the energy per beam, E = 7 TeV
- β_e is the β-function at the interaction point, $\beta_e = 0.5$ m

Physics at the LHC: the environment

Extract number of inelastic collisions per bunch crossing

$$\langle n\rangle = \sigma_{inel} \times L \times \Delta t \; / \; \varepsilon_{bunch}$$

LHC: $\langle n\rangle = 70\ \text{mb} \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1} \times 25\ \text{ns} \; / \; 0.8 = 23$

Big change compared to recent and current machines:

LEP: $\Delta t = 22\ \mu s$ and $\langle n\rangle \ll 1$

SppS: $\Delta t = 3.3\ \mu s$ and $\langle n\rangle \approx 3$

HERA: $\Delta t = 96\ \text{ns}$ and $\langle n\rangle \ll 1$

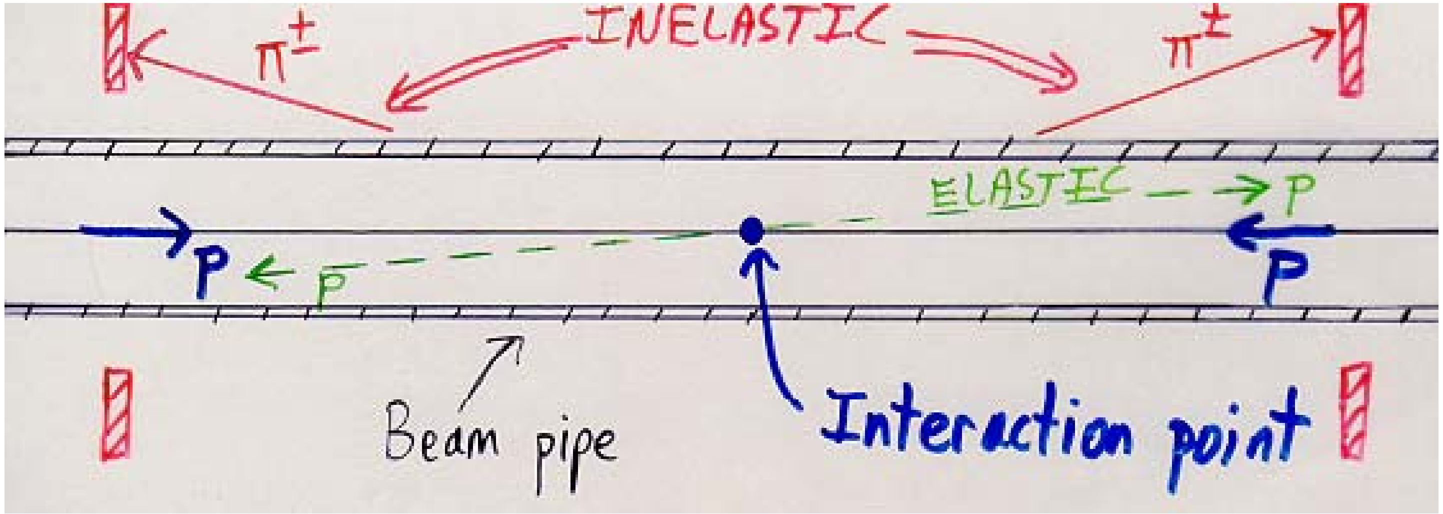
Physics at the LHC: the environment

Experimental environment ≡ Machine performance x Physics

Event rates in detectors:

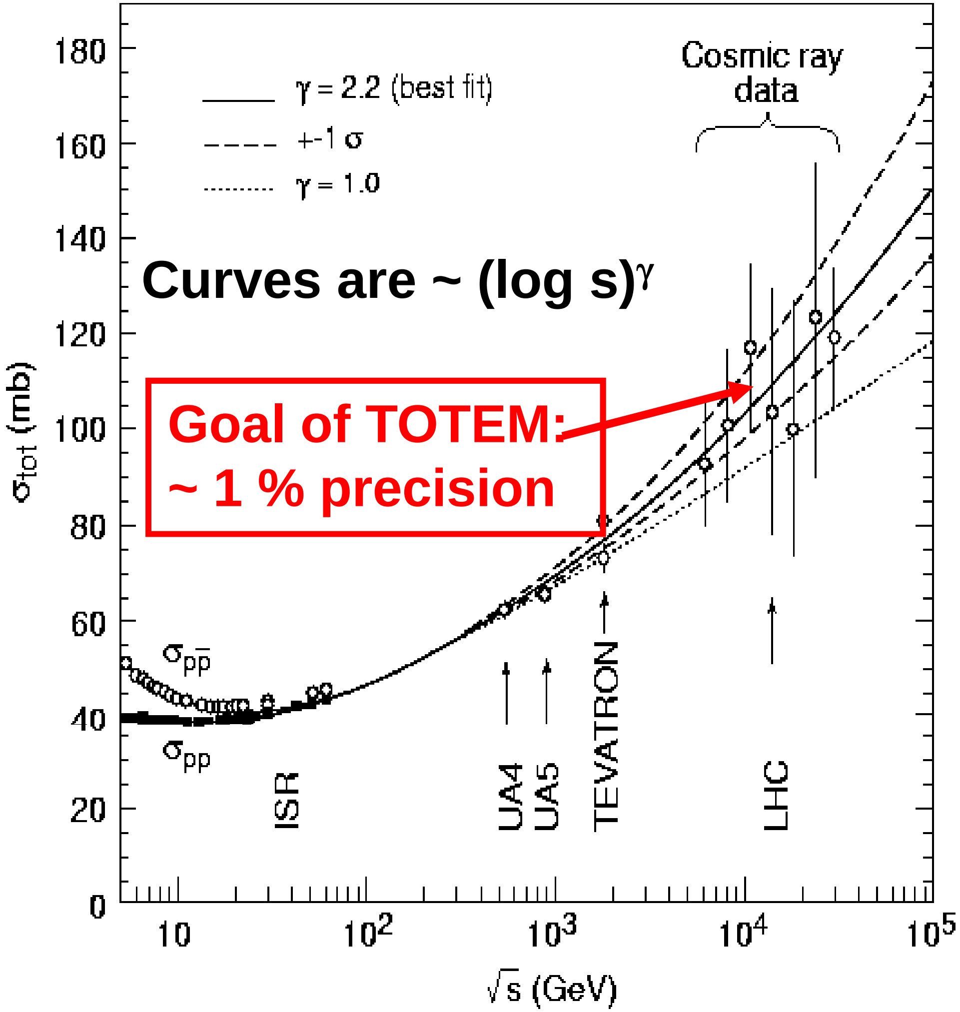
- number of charged tracks expected in inner tracking detectors
- energy expected to be deposited in calorimeters
- radiation doses expected (ionising and neutrons)
- event pile-up issues (pile-up in time and in space)

Need to know the cross-section for uninteresting pp inelastic events: simple trigger on these ≡ “minimum bias” trigger



Physics at the LHC: the environment

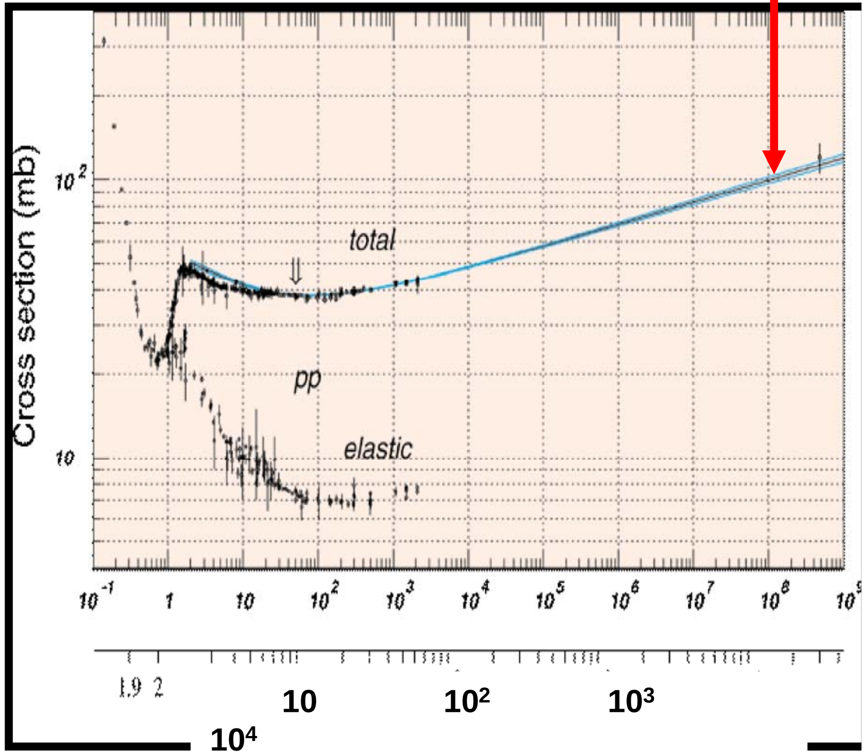
Measurement of σ_{tot} (pp) and $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ -



Curves are ~ (log s)$^\gamma$

Goal of TOTEM:
~ 1 % precision

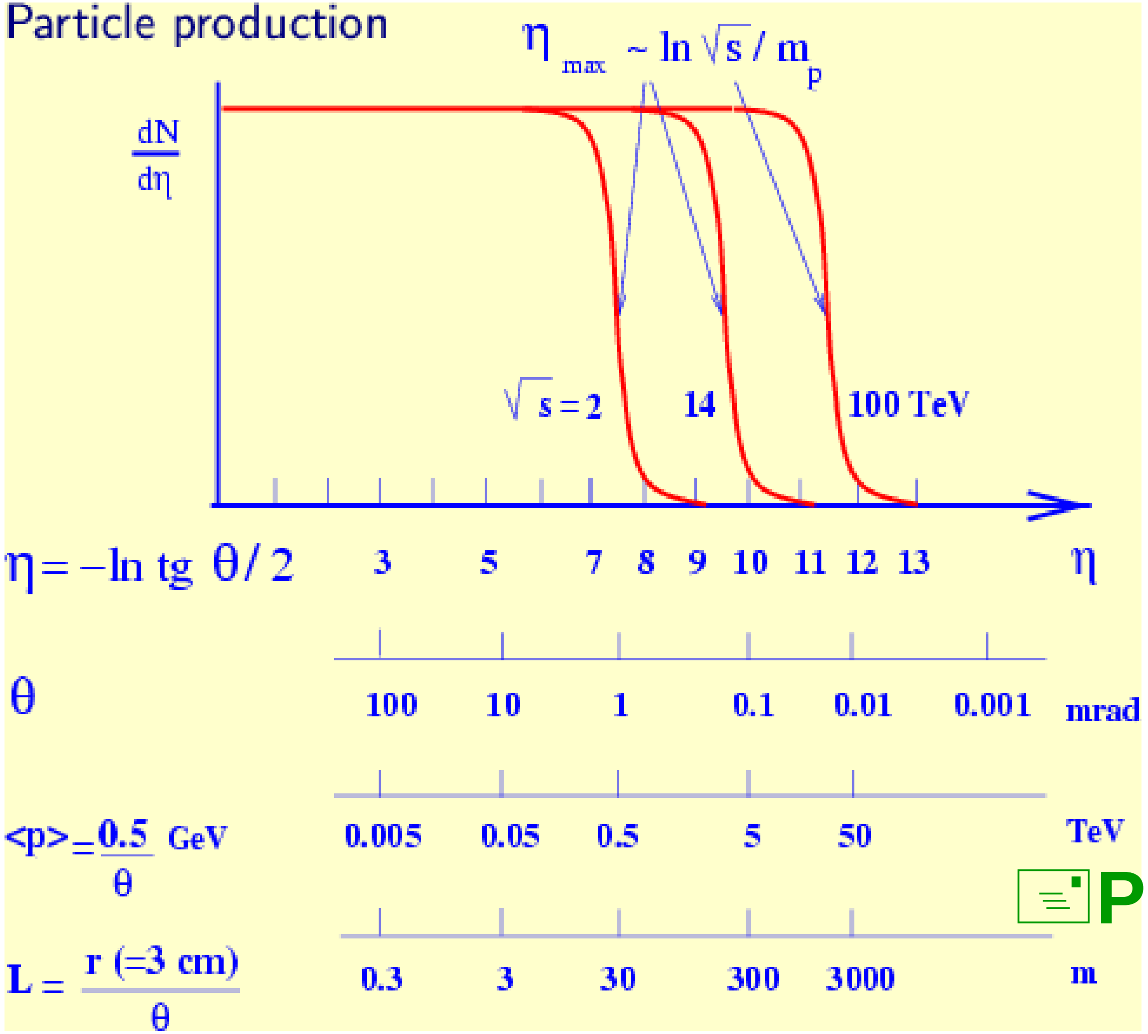
σ_{tot}(pp)≈100 mb

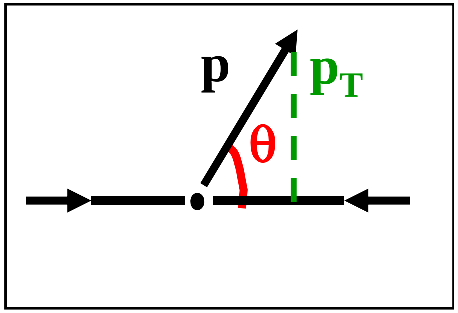


10 10^2 10^3
10^4
Centre-of-mass energy (GeV)

At the LHC, $\sigma_{inel} \approx$ 70 mb

Physics at the LHC: the environment

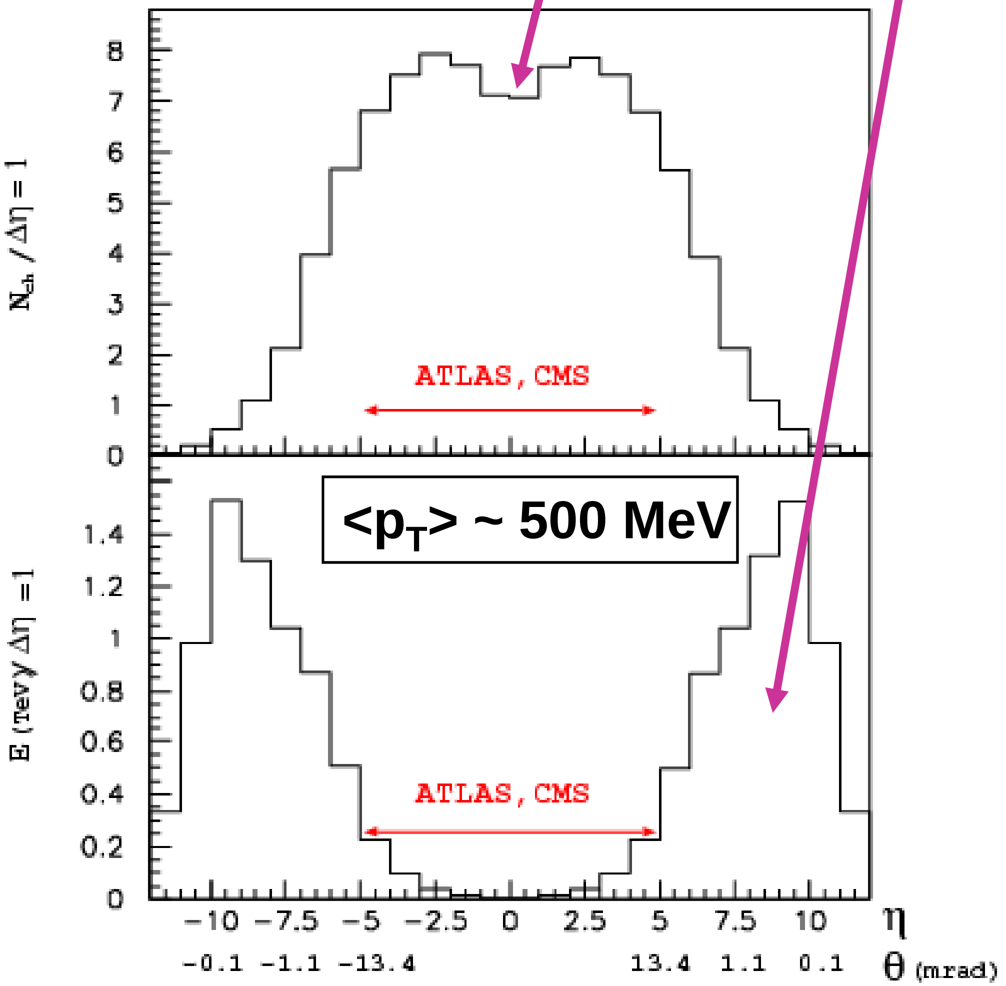




- $d\sigma/dp_T dy$ is Lorentz-invariant
- $\eta = y$ for $m \approx 0$
- Physics is ~ constant versus η at fixed p_T

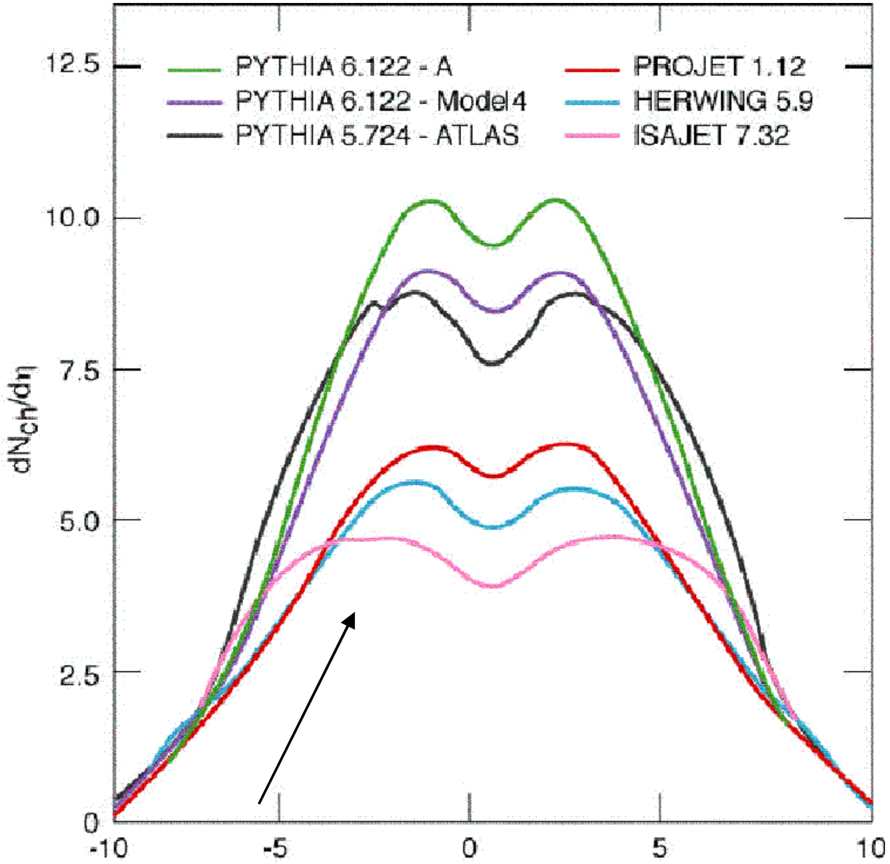
Physics at the LHC: the environment

Charged particle multiplicity and energy
in pp inelastic events at √s = 14 TeV



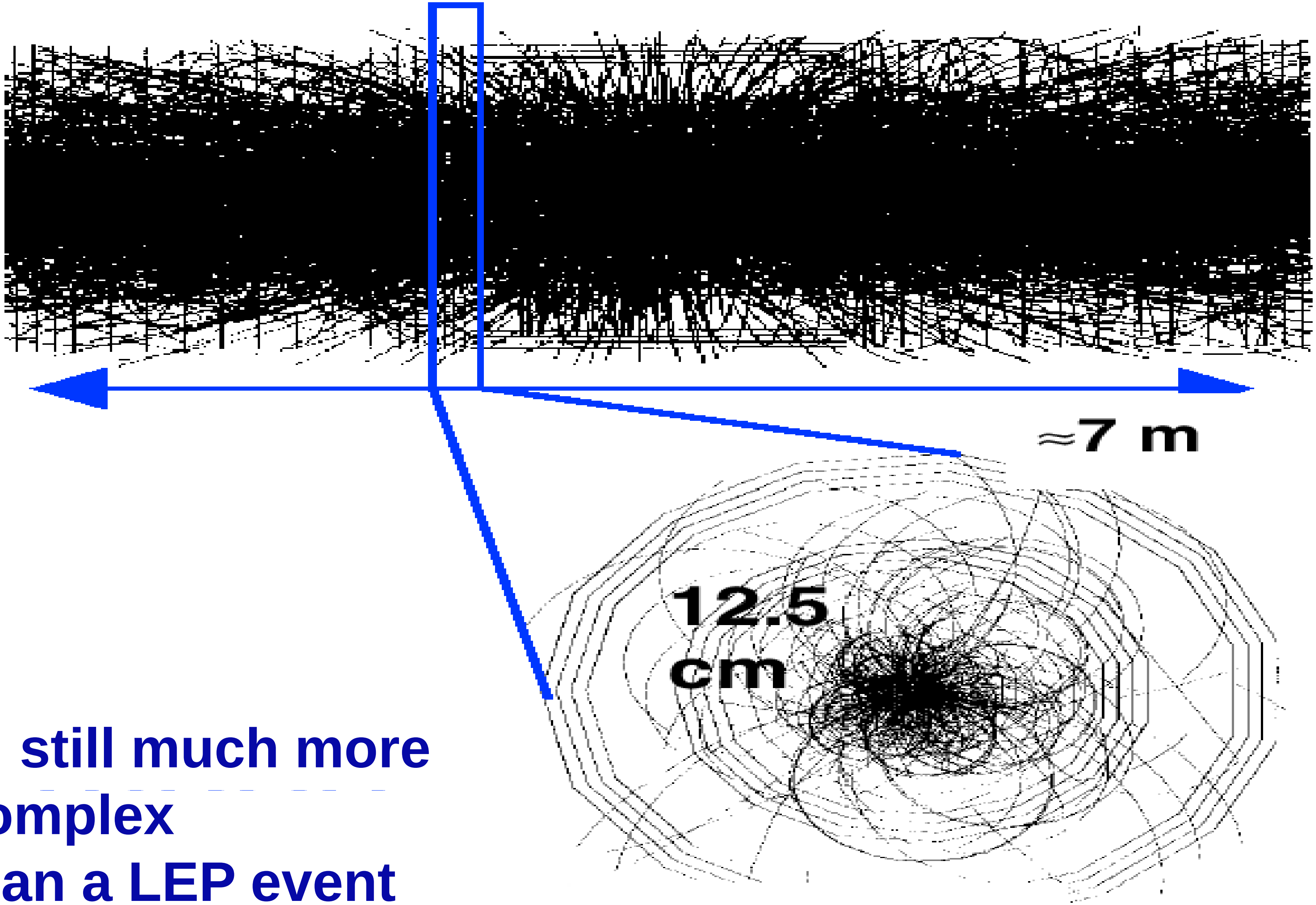
$\langle p_T \rangle \sim 500$ MeV

Charged particle multiplicities
from different models



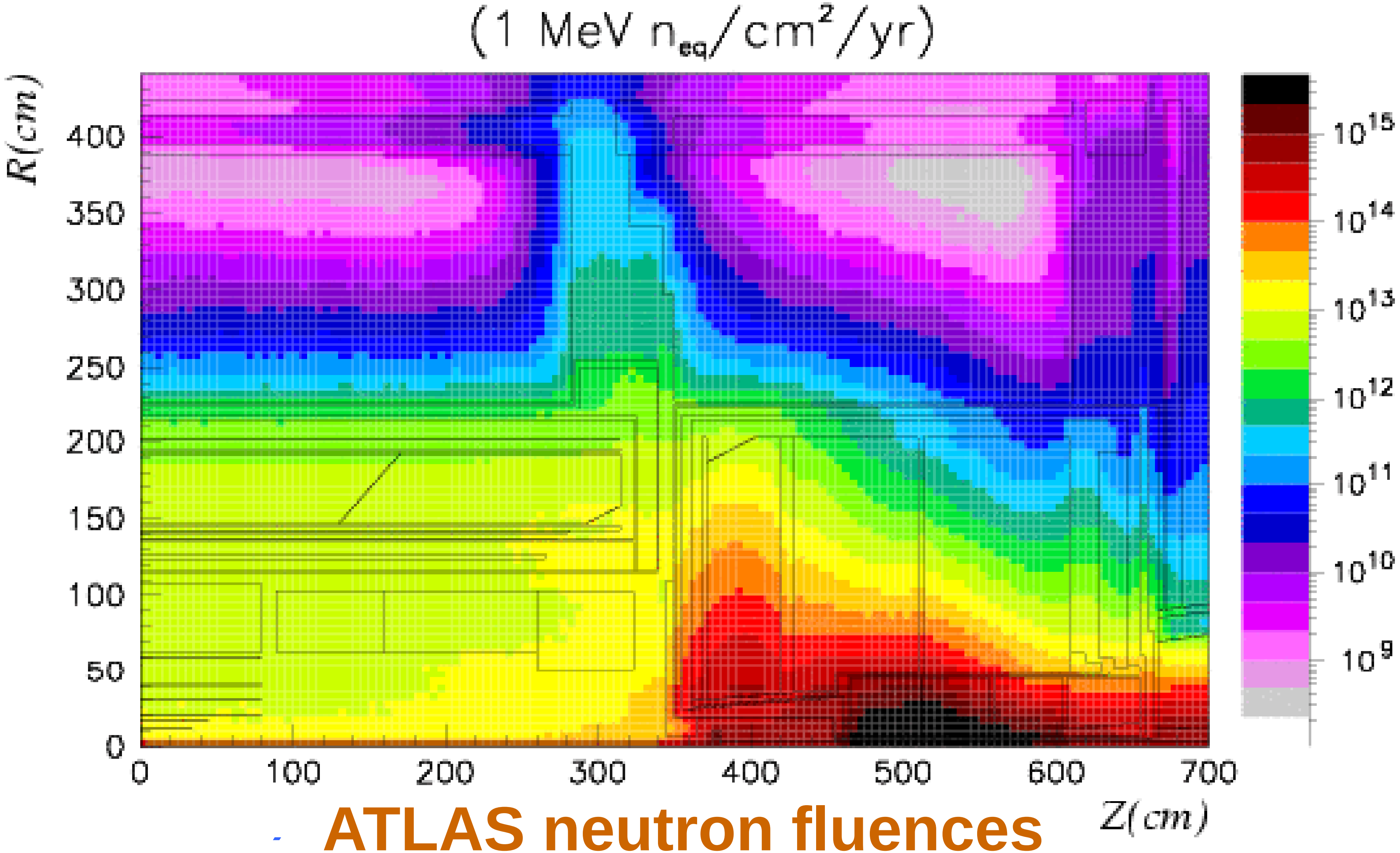
Present models extrapolated from Tevatron give sizeable differences at the LHC

Physics at the LHC: the environment



… still much more complex than a LEP event

Physics at the LHC: the environment



ATLAS neutron fluences

Physics at the LHC: the environment

1. Damage caused by ionising radiation

- caused by the energy deposited by particles in the detector material: $\approx$ 2 MeV g^{-1} cm^{-2} for a min. ion. particl
- also caused by photons created in electromagnetic showers
- the 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, the ionising dose is:

$$\approx \; 2\ 10^6 \text{ Gy} / r_T^2 / \text{year},$$

where r_T (cm) is the transverse distance to the beam

Physics at the LHC: the environment

2. Damage caused by neutrons

- the 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 themselves
- these neutrons (with energies in the 0.1 to 20 MeV range) bounce back and forth (like gas molecules) on the various nuclei and fill up the whole detector

- expected neutron fluence is about 3 10^{13} per cm^2 per year in the innermost part of the detectors (inner tracking systems)
- these fluences are moderated by the presence of Hydrogen:
  - $\sigma(n,H)$ ~ 2 barns with elastic collisions
  - mean free path of neutrons is ~ 5 cm in this energy

Physics at the LHC: the environment

- the neutrons wreak havoc in semiconductors, independently of the deposited energy, because they modify directly the cristalline structure
  → need radiation-hard electronics (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) can survive up to 10^5-10^6 Gy and 10^{15} neutrons/cm^2
- most organic materials survive easily to 10^5-10^6 Gy (beware!)

Material validation and quality control during production

Physics at the LHC: the environment

Pile-up effects at high luminosity

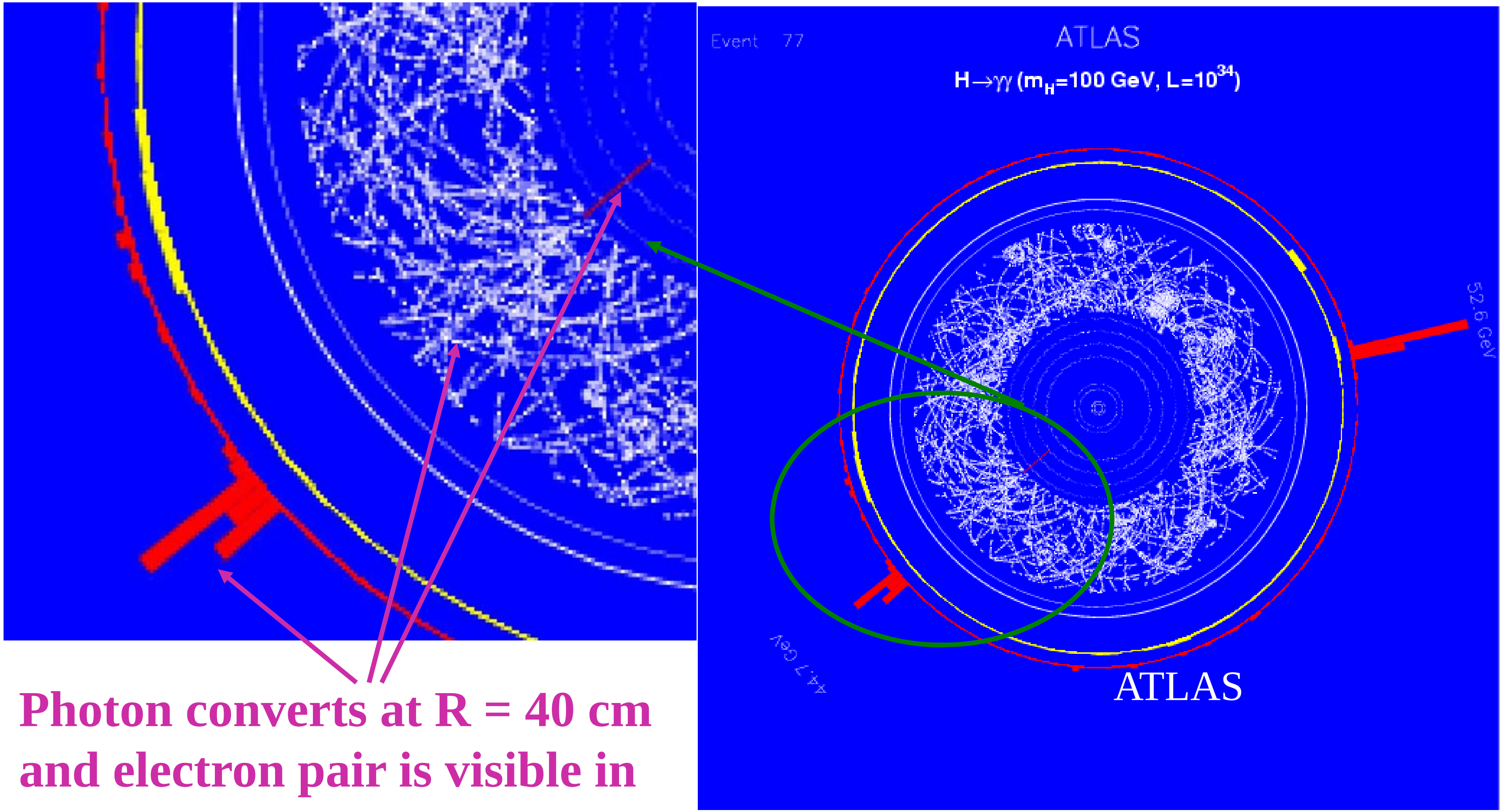
Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus

Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

- a precise (and if possible fast) detector response minimises pile-up in time
  - → very challenging for the electronics in particular
  - → typical response times achieved are 20-50 ns (!)
- a highly granular detector minimises pile-up in space

Physics at the LHC: the environment

Pile-up effects at high luminosity



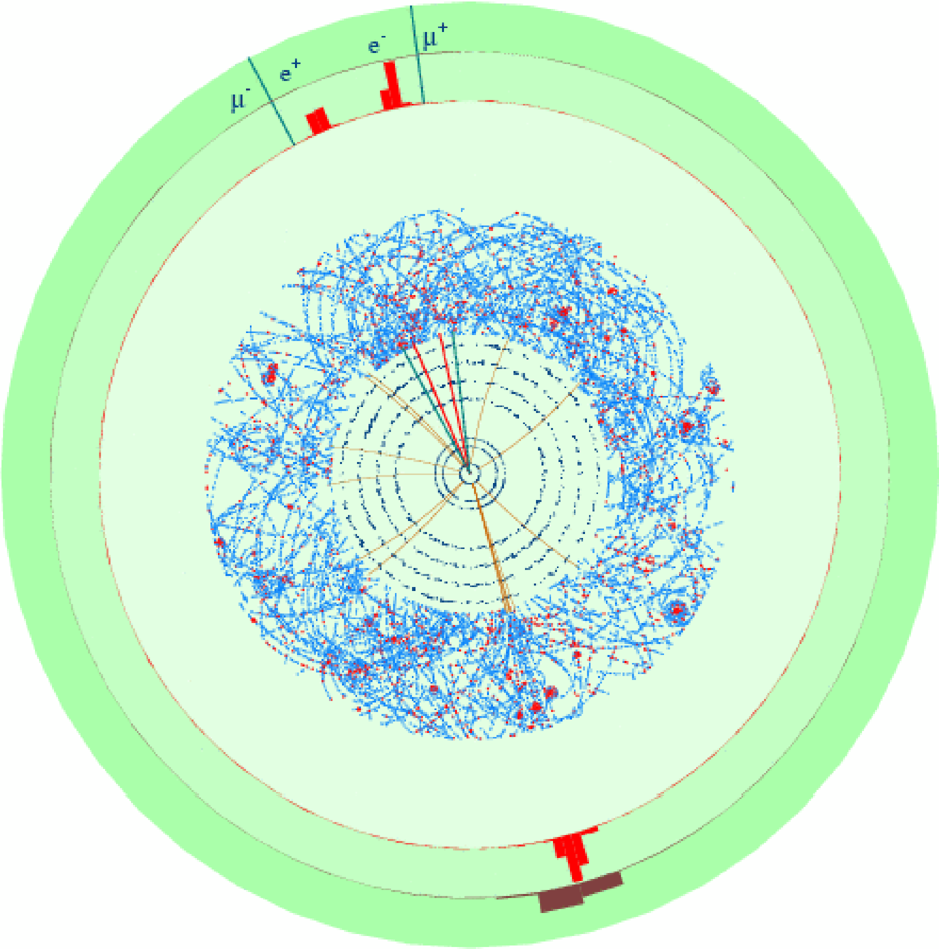
Photon converts at R = 40 cm and electron pair is visible in ATLAS TRT and EM calo

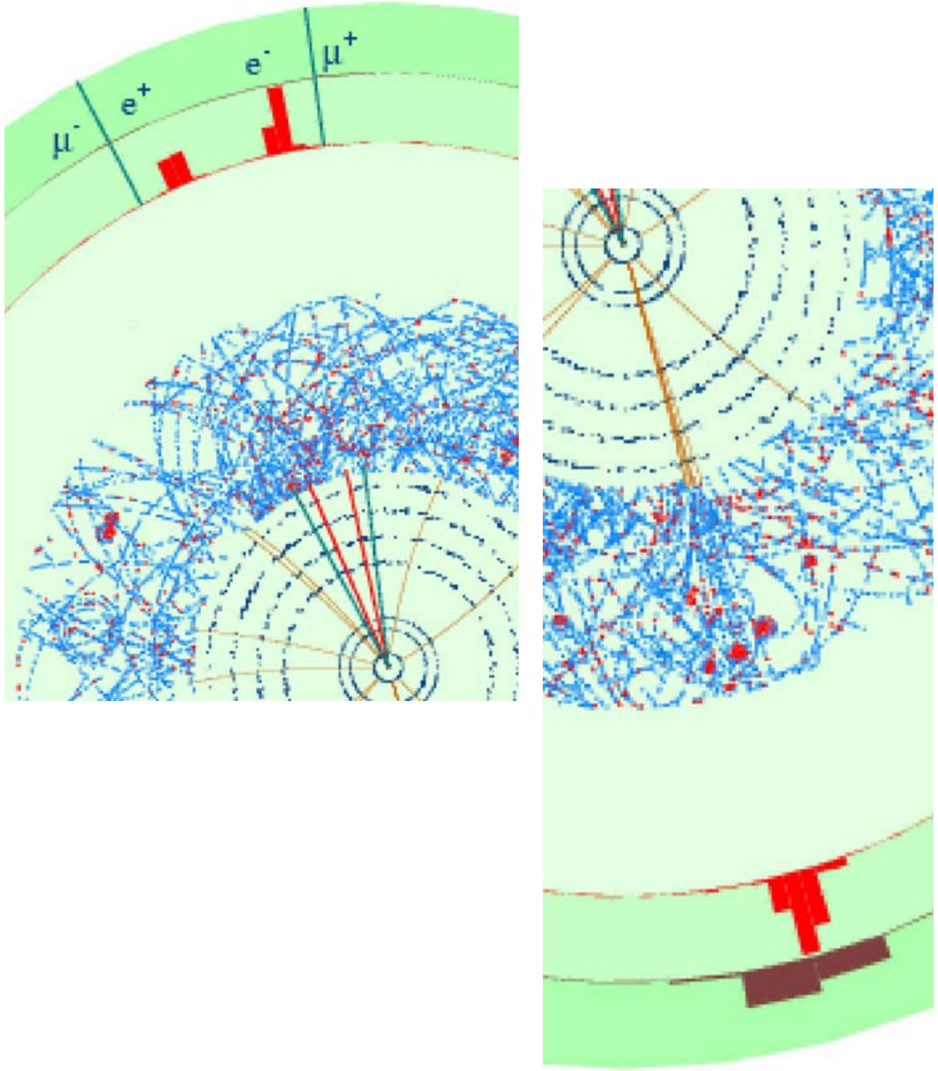
Physics at the LHC: the environment

Pile-up effects at high luminosity

ATLAS barrel

$H \rightarrow ZZ^* \rightarrow ee\mu\mu$ (m_H = 130 GeV)





Physics at the LHC: the environment

Pile-up effects at high luminosity

First consequence of pile-up → reconstruction of vertex position along beam for a given bunch crossing of interest

At the LHC, σ_{bunch} = 8 cm → spread of interaction vertex is 5.6

✓ Need to find about 25 vertices along beam for each trigger

✓ Hard-scattering process usually has higher-momentum tracks and multiplicity, but no clean separation vertex-by-vertex

✓Simulation results for H → γγ at high luminosity:

- Find on average 5 out of 25 vertices produced
- Find H → γγ vertex in 72% of the cases with r.m.s. =

Physics at the LHC: the environment

Pile-up effects at high luminosity

Second consequence of pile-up → at very high luminosity, risk of producing a given final state from the superposition of two independent events

How likely is this to happen for the final state of a process with cross-section σ_{12}, which could be produced by the overlap of two processes 1 and 2 with cross-sections σ_1 and σ_2?

The relationship between σ_{12} and $\sigma_{12}^{\text{pile-up}} = \sigma_{12}^{p}$ depends on the luminosity L and on the spacing Δt between bunches ($<n> = L\,\Delta t$)

Pile-up probability: $P_e = n\,\sigma_{12}^{p} / \sigma_{inel}$ and $P_e = n(n-1)P_1P_2/2$, where $P_1 = \sigma_i / \sigma_{inel} << 1$,

Higgs at the LHC: the environment

Pile-up effects at high luminosity

In practice, if $L = l \,.\, 10^{34}$ cm^{-2} s^{-1} and $\Delta t = m \,.\, 25$ ns, one obtains

$$\sigma_{12}^{p} < \sigma_{12} \text{ if } \quad \sigma_1 \sigma_2 \,/\, \sigma_{12} \; < \; 0.8\ 10^{10} \,/\, l \,.\, m \quad \text{pb}$$

First example: **search for ZZ final states at the LHC**

σ_{12} **= 10 pb for ZZ continuum**

or σ_{12} **= 1 pb for H → ZZ,** m_H **= 800 GeV and**

$$\sigma_1 = \sigma_2 = \sigma_Z = 40 \text{ nb} = 40{,}000 \text{ pb}$$

One then obtains $\sigma_1 \sigma_2 \,/\, \sigma_{12} = 1.6\ 10^{8}$**, from which one deduces that**

$$\sigma_{ZZ}^{e} = \sigma_{ZZ} \text{ for } L \approx 5\ 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$$

Higgs at the LHC: the environment

Pile-up effects at high luminosity

Second example: search for events with two muons, $p_T^\mu > 10$ GeV

$\sigma_{12} = \sigma_{\mu\mu}(p_T^\mu > 10\text{ GeV}) \approx 10$ nb ($Z \rightarrow \mu\mu$ or $pp \rightarrow bb \rightarrow \mu\mu + X$)

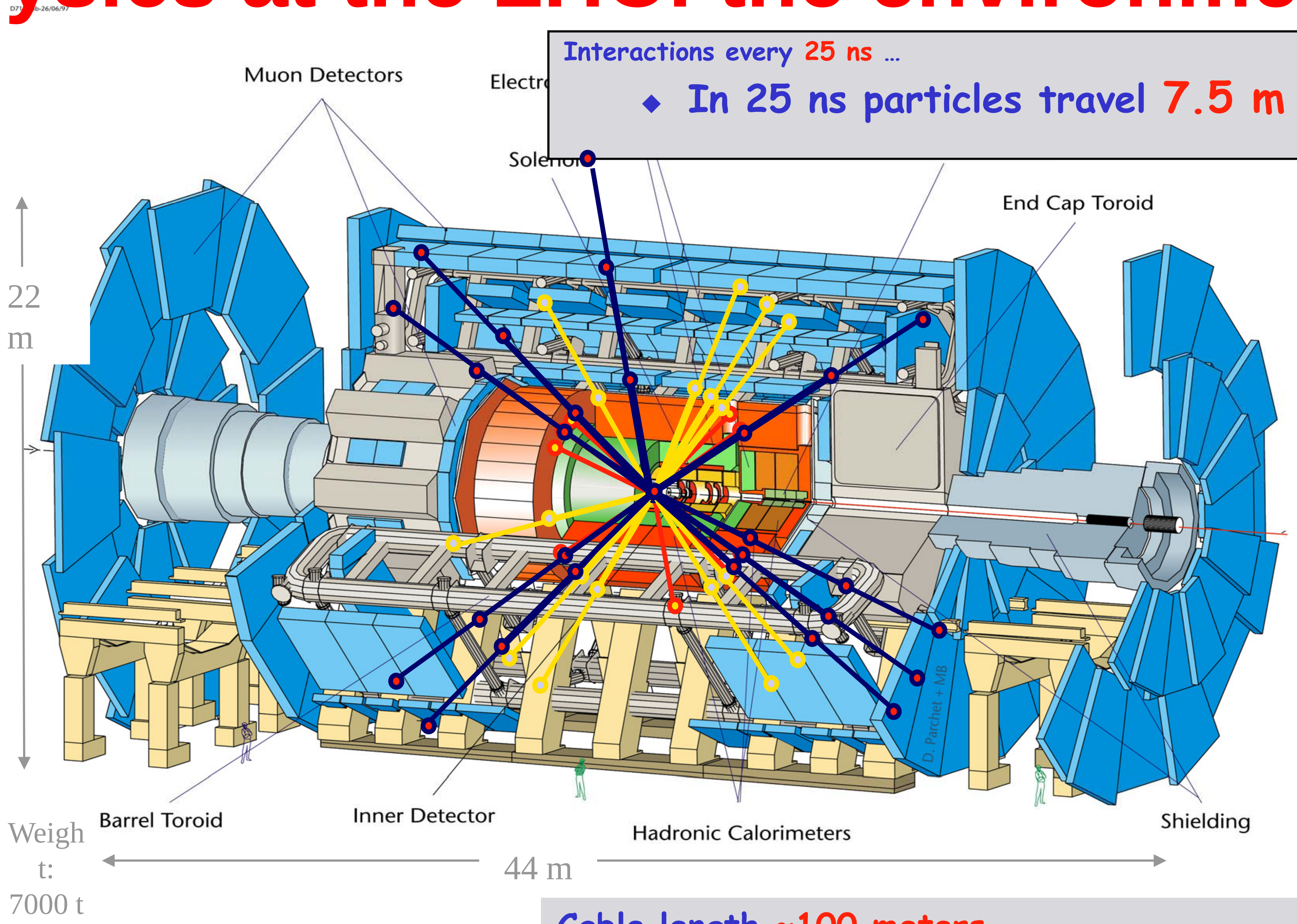
$\sigma_1 = \sigma_2 = \sigma_\mu(p_T^\mu > 10\text{ GeV}) \approx 1000$ nb (semileptonic decays of b's)

One obtains $\sigma_1 \sigma_2 / \sigma_{12} \approx 10^8$, with same result.

Conclusions: in general, pile-up of rare events to mimic even rarer events is negligible.

Physics at the LHC: the environment

Time-of-flight



Interactions every 25 ns …

- In 25 ns particles travel 7.5 m

Cable length ~100 meters …

- In 25 ns signals travel 5 m

D. Froidevaux, CERN

Physics at the LHC: the challenge

Unprecedented scope and timescales for simulations

Many examples from ATLAS/CMS (and also ALICE/LHCb):

- ≈ 30 million volumes simulated in GEANT

- Tbytes (hundreds of millions) of simulated events over 10 years

- Full reconstruction of all benchmark Higgs-boson decays

- Unprecedented amount of material in Inner Detectors leads to significant losses of e.g. charged-pion tracks (up to 20% at 1 GeV) and to significant degradation of EM calo intrinsic performance (mostly for electrons but for photons too)

Main specific design choices of ATLAS/CMS

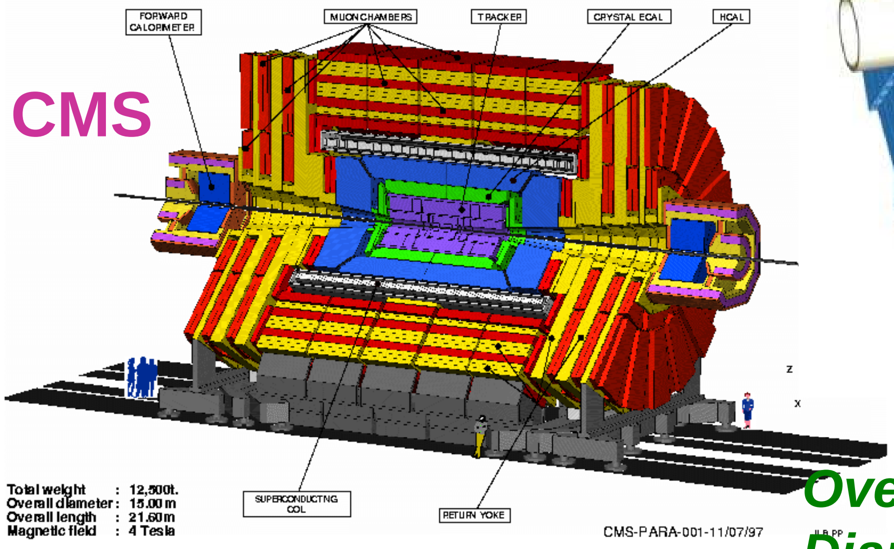
- Size of ATLAS/CMS directly related to energies of particles produced: need to absorb energy of 1 TeV electrons (30 X_0 or 18 cm of Pb), of 1 TeV pions (11 λ or 2 m Fe) and to measure momenta of 1 TeV muons outside calorimeters (BL^2 is key factor to optimise)

- Choice of magnet system has shaped the experiments in a major way
  - Magnet required to measure momenta and directions of charged particles near vertex (solenoid provides bend in plane transverse to beams)
  - Magnet also required to measure muon momenta (muons are the only charged particles not absorbed in calorimeter absorbers)
  - ATLAS choice: separate magnet systems (“small” 2 T solenoid for tracker and huge toroids with large BL^2 for muon spectrometer)
  - Pros: large acceptance in polar angle for muons and excellent muon momentum resolution without using inner tracker
  - Cons: very expensive and large-scale toroid magnet system
  - CMS choice: one large 4 T solenoid with instrumented return yoke
  - Pros: excellent momentum resolution using inner tracker and more compact experiment
  - Cons: limited performance for stand-alone muon measurements (and trigger) and limited space for calorimeter inside coil

How huge are ATLAS and CMS?

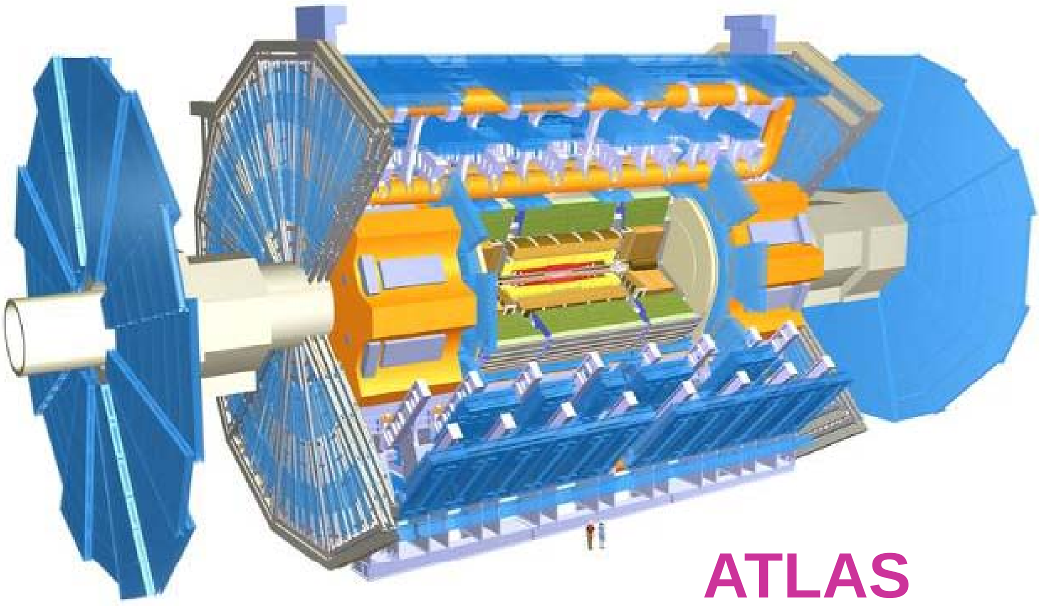
ATLAS superimposed to the 5 floors of building 40

CMS



Total weight : 12,500t.
Overall diameter : 15.00 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

CMS-PARA-001-11/07/97



ATLAS

	ATLAS	CMS
Overall weight (tons)	*7000*	*12500*
Diameter	*22 m*	*15 m*
Length	*46 m*	*22 m*
Solenoid field	*2 T*	*4 T*

Main specific design choices of ATLAS/CMS

- At the LHC, which is essentially a gluon-gluon collider, the unambiguous identification and precise measurement of leptons is the key to many areas of physics:
  - electrons are relatively easy to measure precisely in EM calorimeters but very hard to identify (imagine jet → leading π^- with $\pi^- \to$ leading π^0 very early in shower)
  - muons in contrast are relatively easy to identify behind calorimeters but very hard to measure accurately at high energies

→ This has also shaped to a large extent the global design and technology choices of the two experiments

- EM calorimetry of ATLAS and CMS is based on very different technologies
  - ATLAS uses LAr sampling calorimeter with good energy resolution and excellent lateral and longitudinal segmentation (e/γ identification)
  - CMS use $PbWO_4$ scintillating crystals with excellent energy resolution and lateral segmentation but no longitudinal segmentation
  - Broadly speaking, signals from $H \to \gamma\gamma$ or $H \to ZZ^* \to 4e$ should appear as narrow peaks (intrinsically much narrower in CMS) above essentially pure background from same final state (intrinsically background from fakes smaller in ATLAS)

ATLAS/CMS: from design to reality

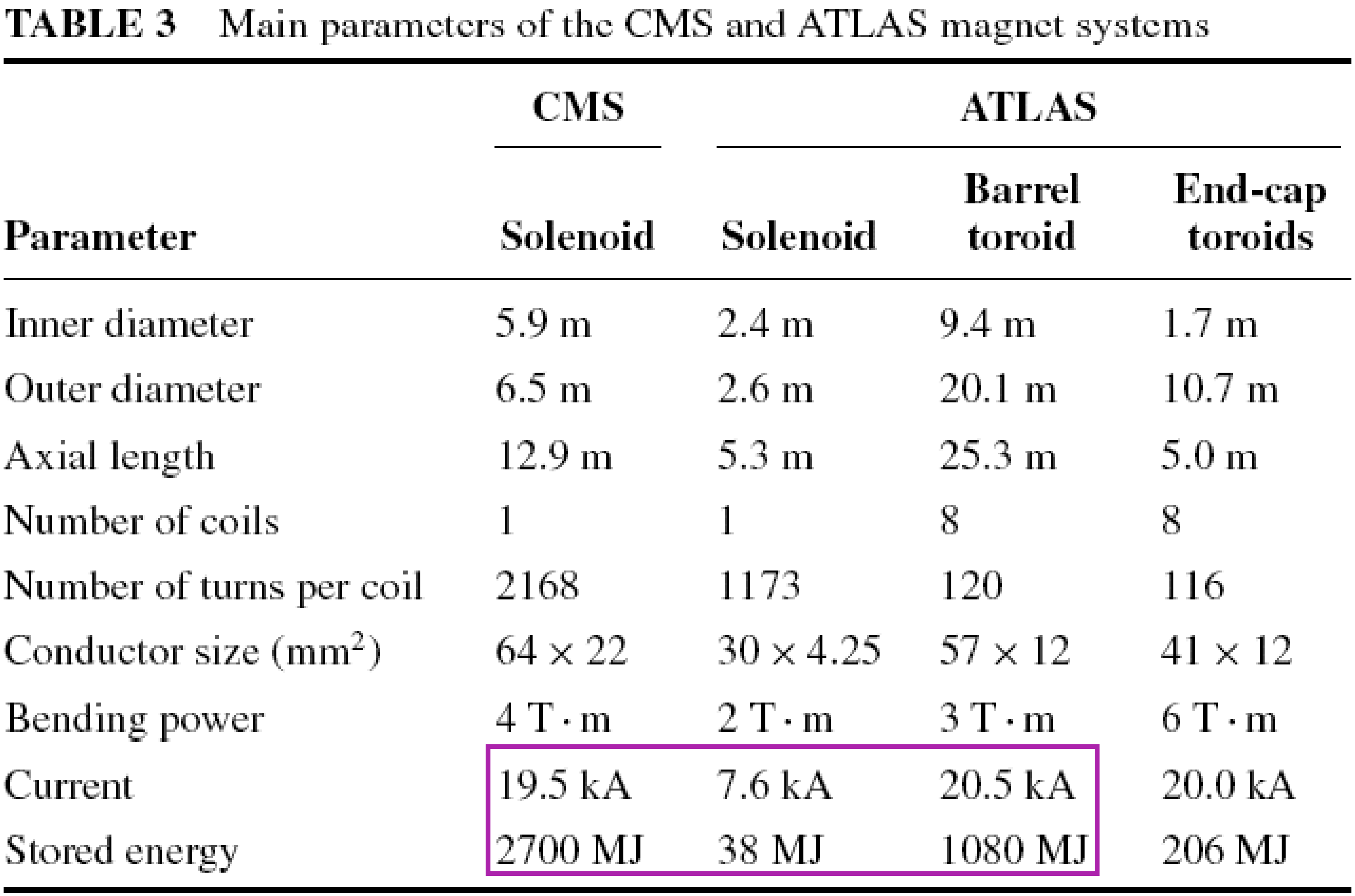


TABLE 3 Main parameters of the CMS and ATLAS magnet systems

	CMS	ATLAS		
Parameter	**Solenoid**	**Solenoid**	**Barrel toroid**	**End-cap toroids**
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64 × 22	30 × 4.25	57 × 12	41 × 12
Bending power	4 T · m	2 T · m	3 T · m	6 T · m
Current	19.5 kA	7.6 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

Three magnets have reached their design currents: a major technical milestone!