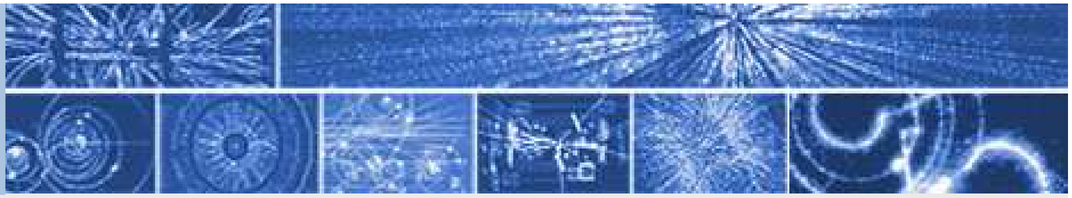


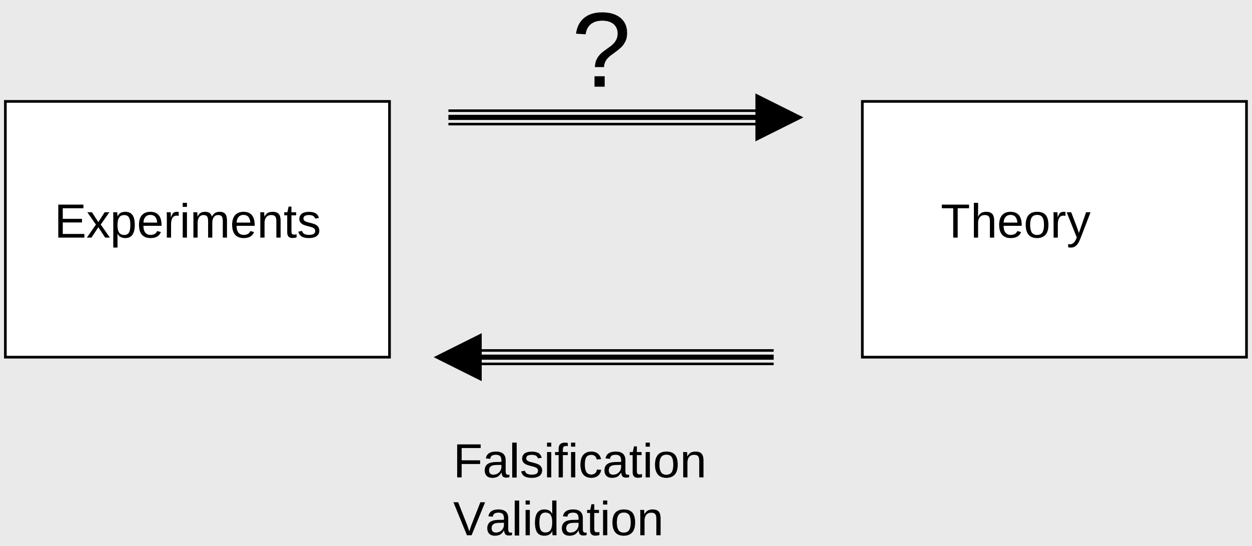
Experimental Methods in Particle Physics

How to get a meaningful result out of a particle physics detector

Emmanuel Tsesmelis
CERN / University of Oxford
APPEAL
3 July 2010

Design of a Particle Physics Experiment

- How physicists go from the basic ideas of measuring some quantities to analyzing physics events from experiments.



?

Experiments

Theory

Falsification
Validation

Theory and Experiments

- Expt: Particles have masses: …..why ?
- Theo: Mass is given by the interaction with the Higgs field.
- Expt: Find the Higgs Boson

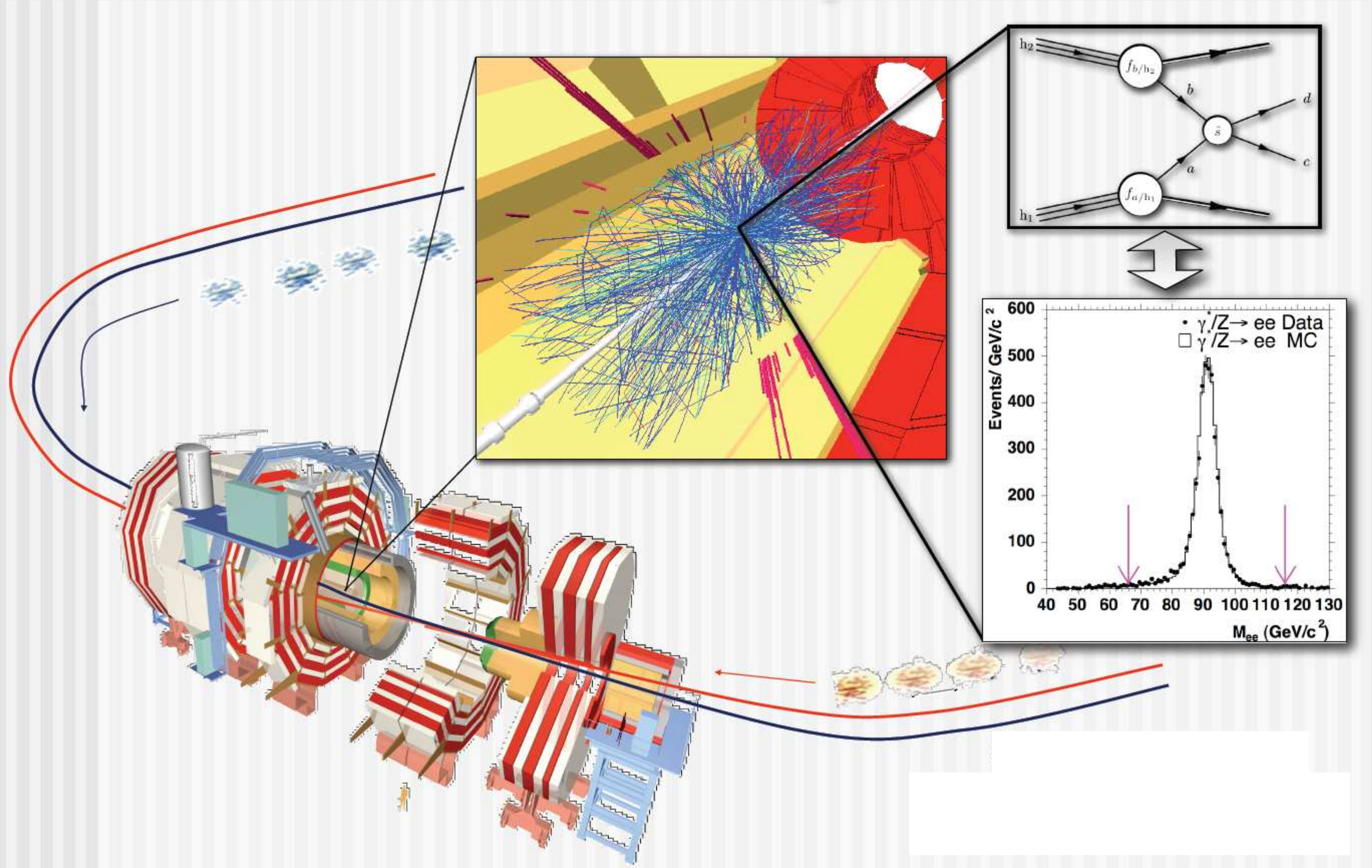
- Expt: There are 3 Forces: ……why ?
- Theo: Supersymmetry unifies the forces
- Expt: Find the signals of Supersymmetry

Two Classes of Experiments

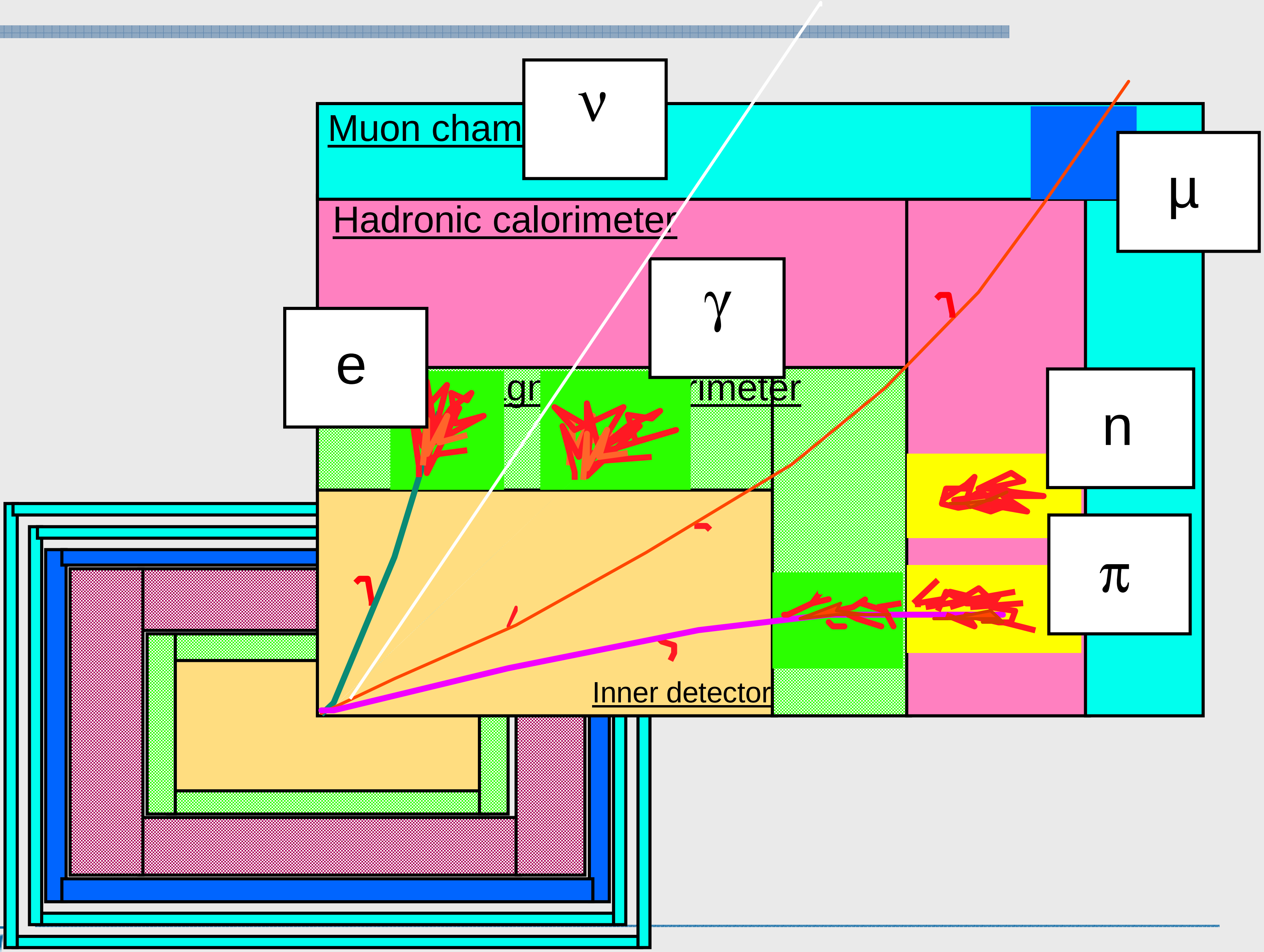
1. Experiments designed to measure typically "one quantity", exploring the "very rare" or "very precise". *They need high intensity beams and/or very high precision.*

2. Experiments that explore the high energy frontier. *They are typically multi-purpose experiments and they also need high intensity beams.*

From Raw Data to Physics Results

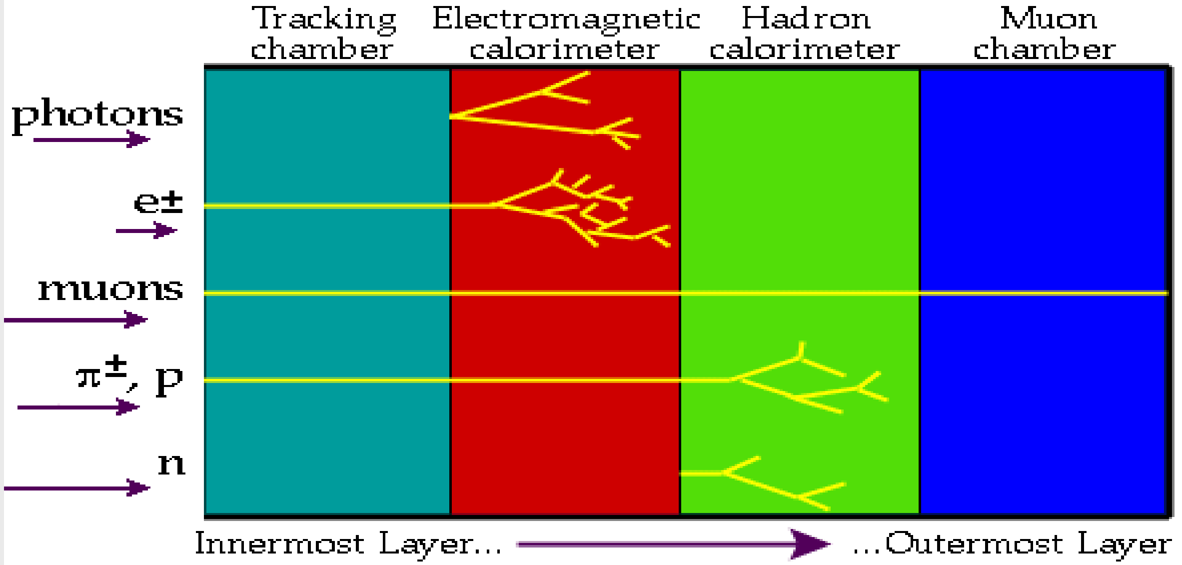


General Principle



General Principle

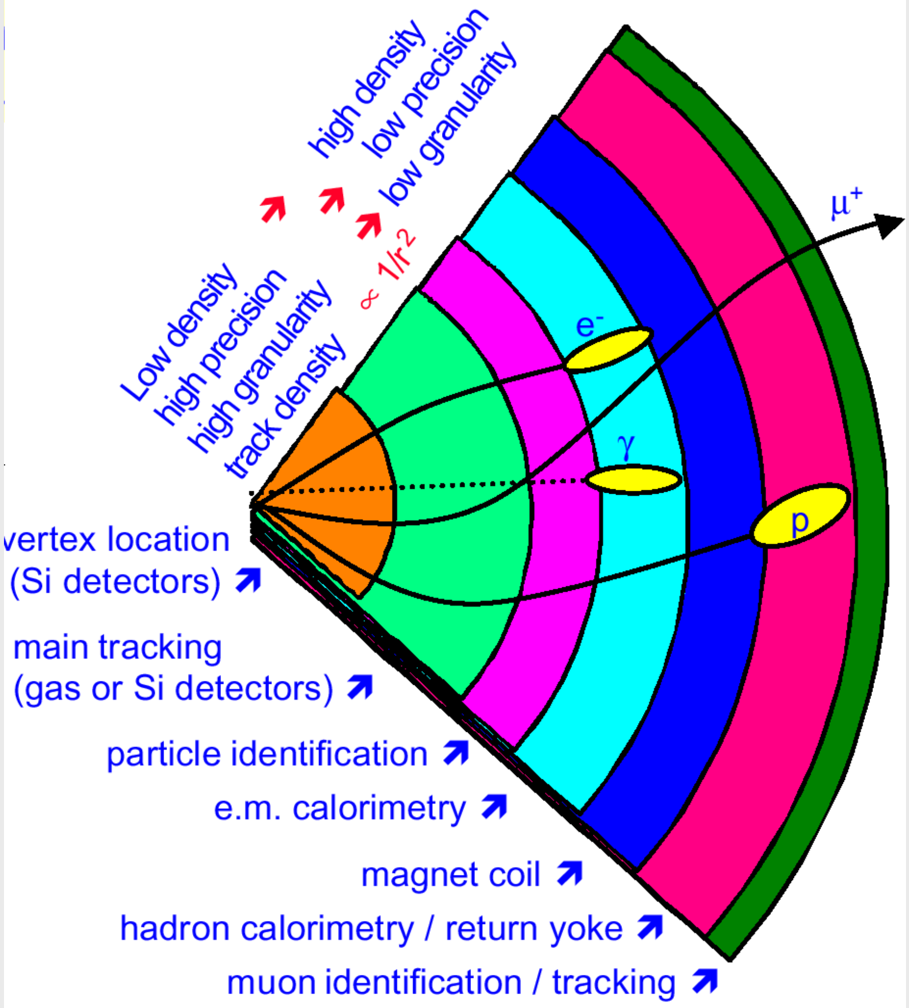
Visible particles are measured by the various sub-detectors and identified from their characteristic pattern.



The parameters of the quarks are reconstructed from the hadronic jets.

The flavor of the quark is determined by reconstructing the hadronic decays of heavy mesons or detecting their detached decay vertex.

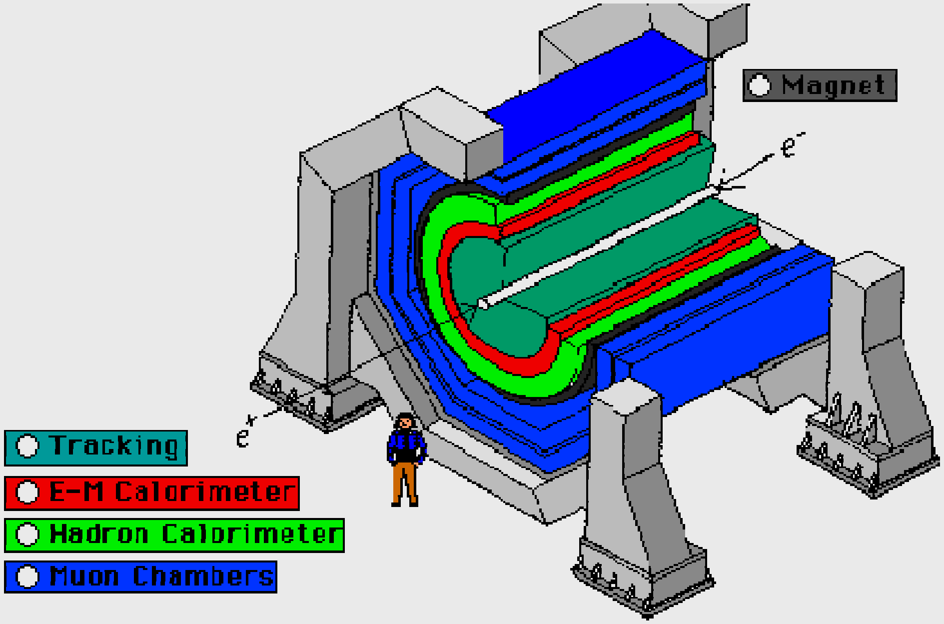
Arrangement of Detectors



Various detectors and combination of information can provide particle identification.

p versus EM energy for electrons; EM/HAD provides additional information, so do the muon detectors, EM response without tracks indicate a photon; secondary vertices identify b,c,τ; isolation cuts help to identify leptons.

General Principle



Collider detectors are similar since they must perform in sequence the same basic measurements.

The dimensions of the detector are driven by the required resolution.

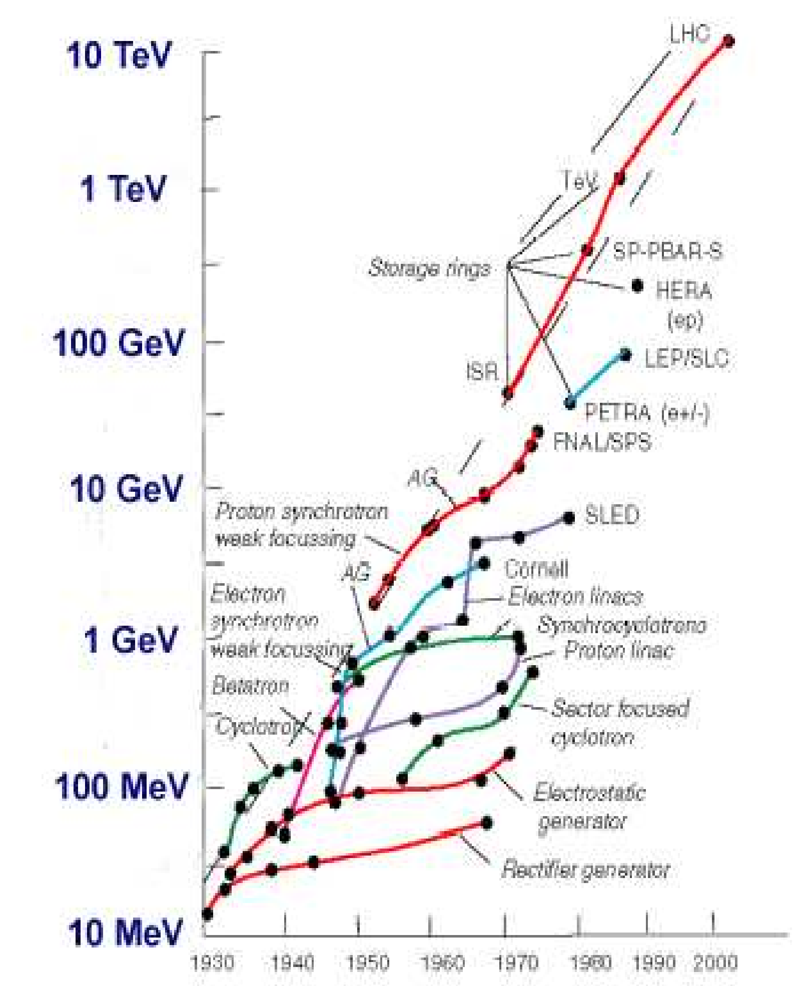
The calorimeter thickness changes only with the logarithm of the energy: for this reason the dimension of the detectors change only slightly with the energy.

Quest for Energy

$$\lambda = \frac{hc}{2\pi}\frac{1}{E}$$

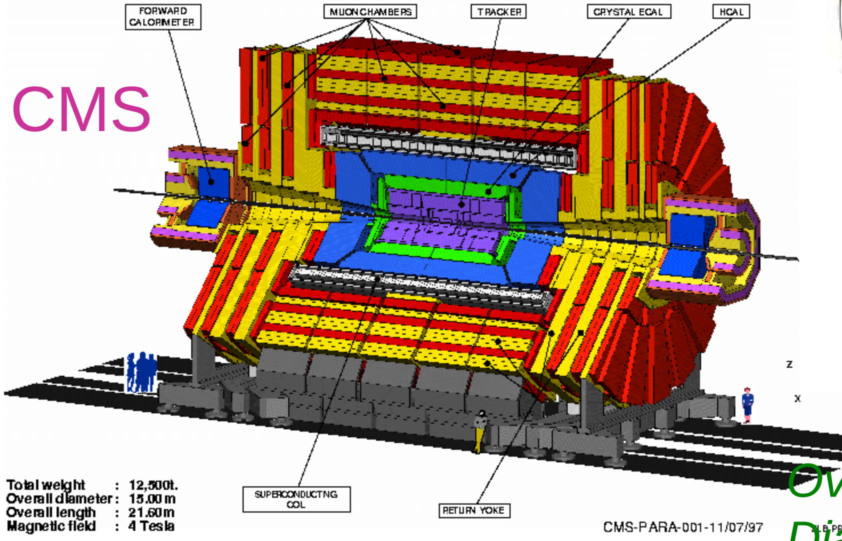
$$\lambda(fm) \approx \frac{0.2}{E(GeV)}$$

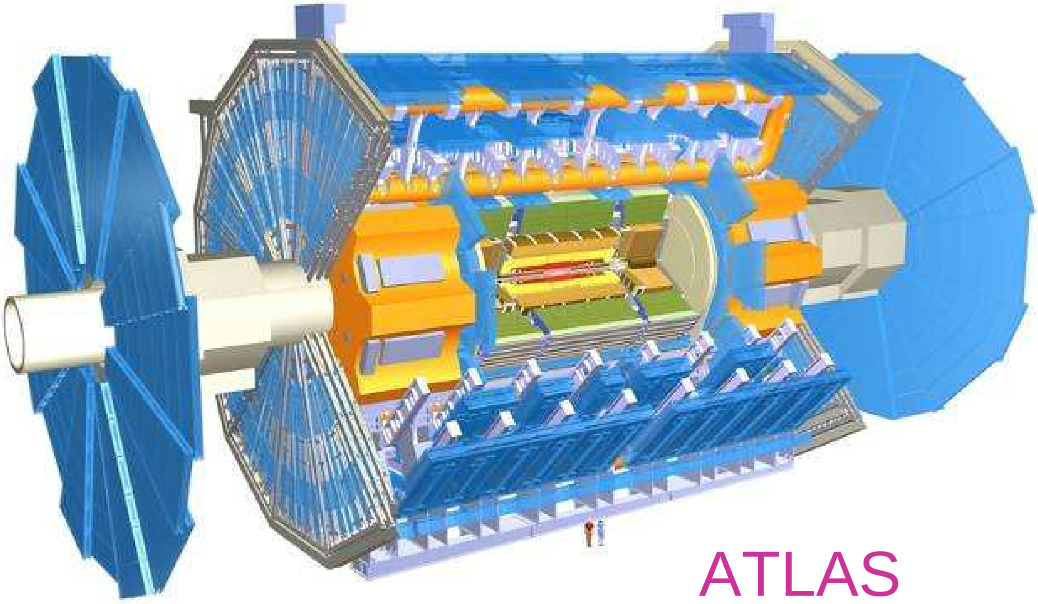
Increasing energy allows experiments to probe Nature at smaller distances with the possibility of crossing the threshold of observing new phenomena



ATLAS and CMS

CMS

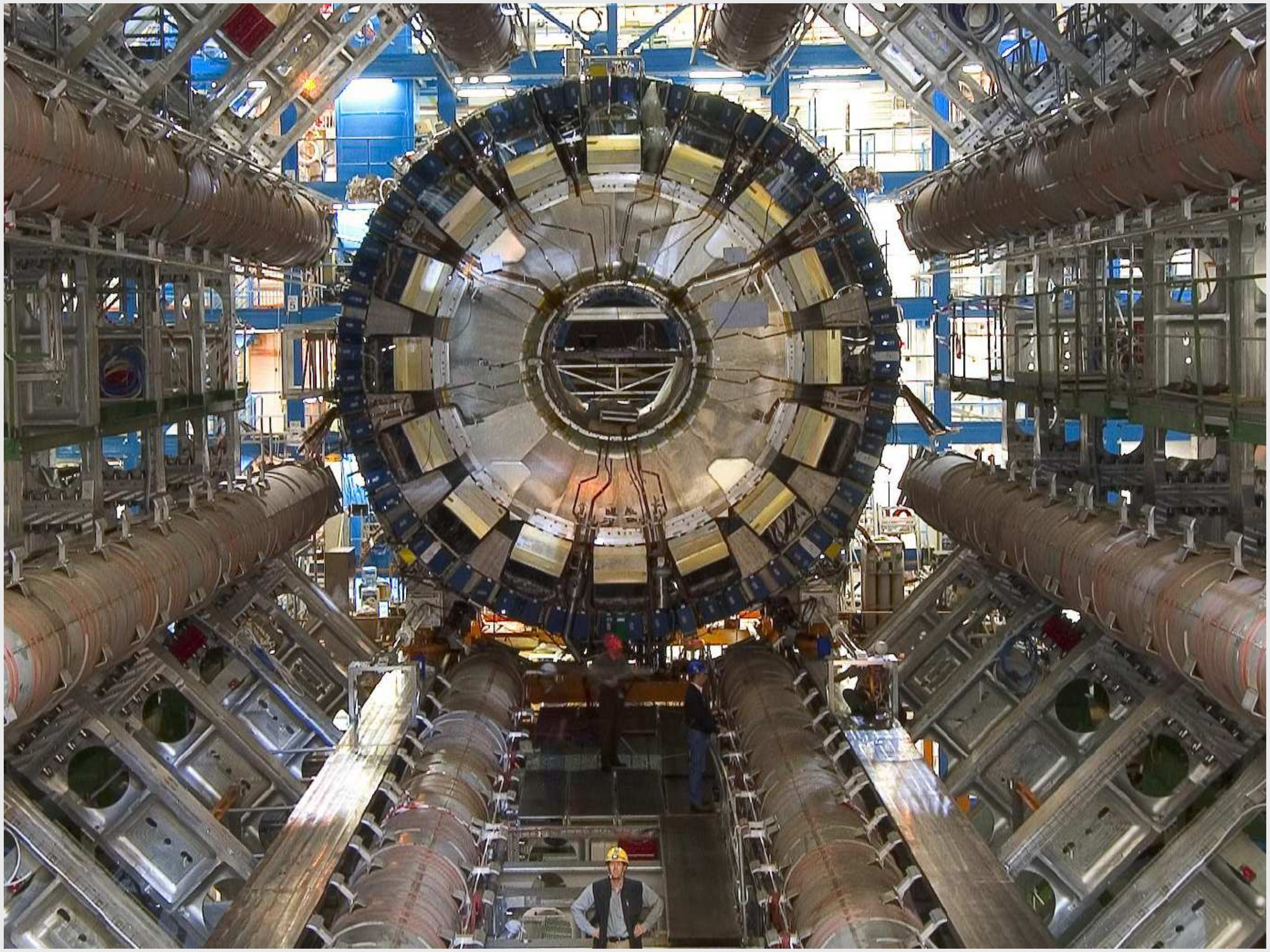




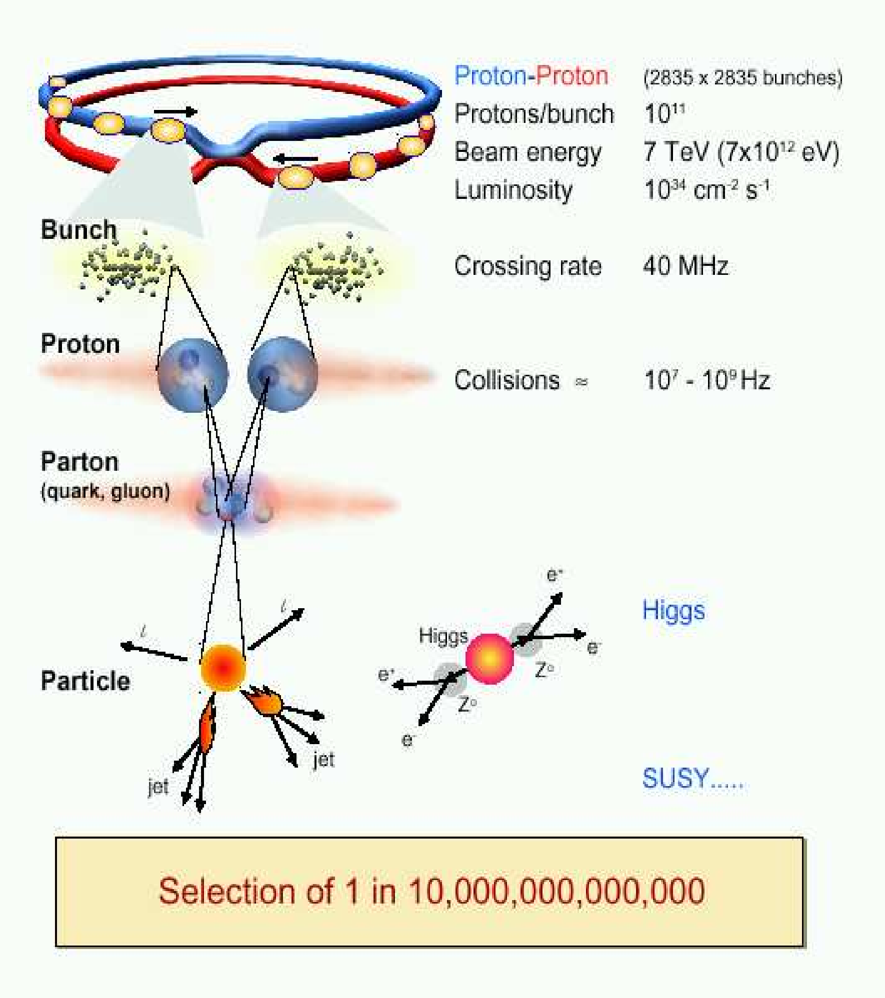
ATLAS

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

ATLAS



Collisions at the LHC



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz
	Higgs
	SUSY.....

Selection of 1 in 10,000,000,000,000

Higgs at the LHC: The Challenge

Small cross-sections

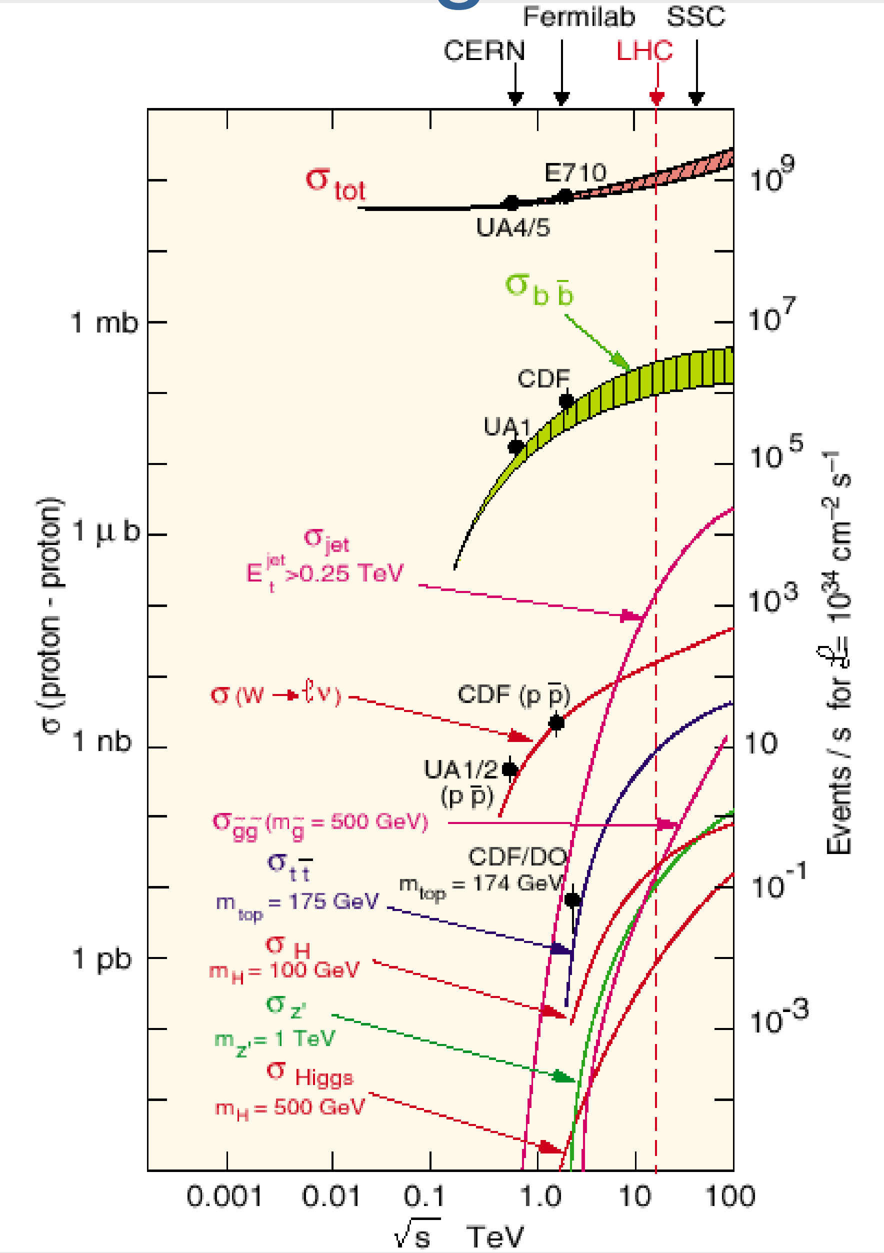
need highest luminosity

⇨ L= 10^{34-35} $cm^{-2}s^{-1}$

Event rates for various physics channels:

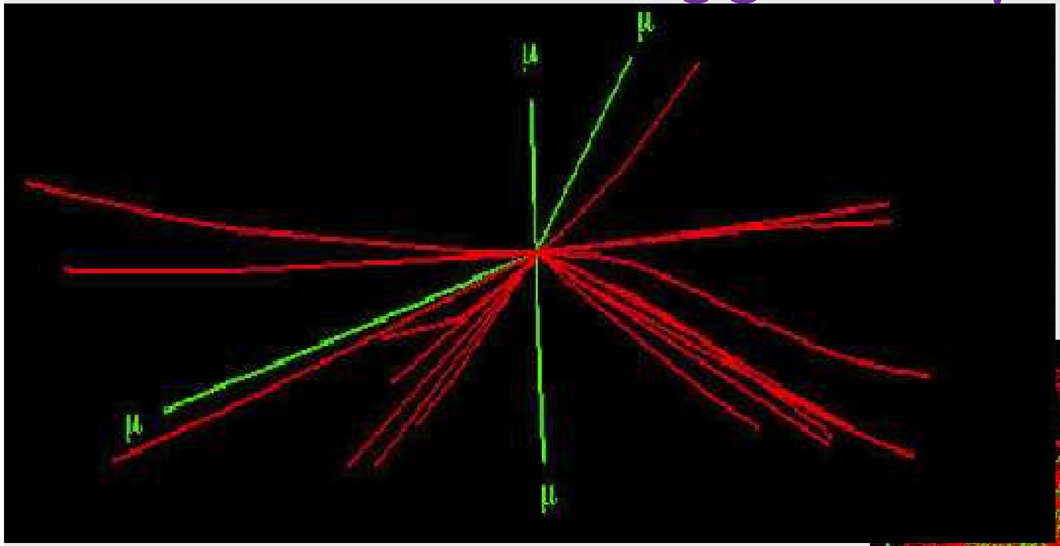
• Inelastic :	10^9 Hz
• W → lν :	10^2 Hz
• tt production :	10^1 Hz
• Higgs (m=100 GeV) :	10^{-1} Hz
• Higgs (m=600 GeV) :	10^{-2} Hz
(including branching ratios:	~ 10^{-3})

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

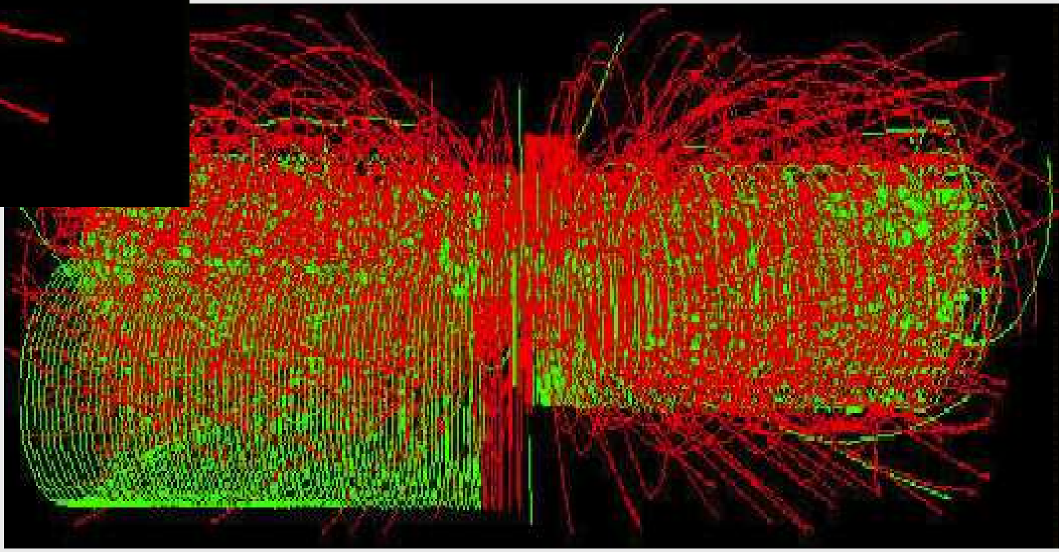


Higgs at the LHC: The Challenge

How to extract Higgs → 4μ

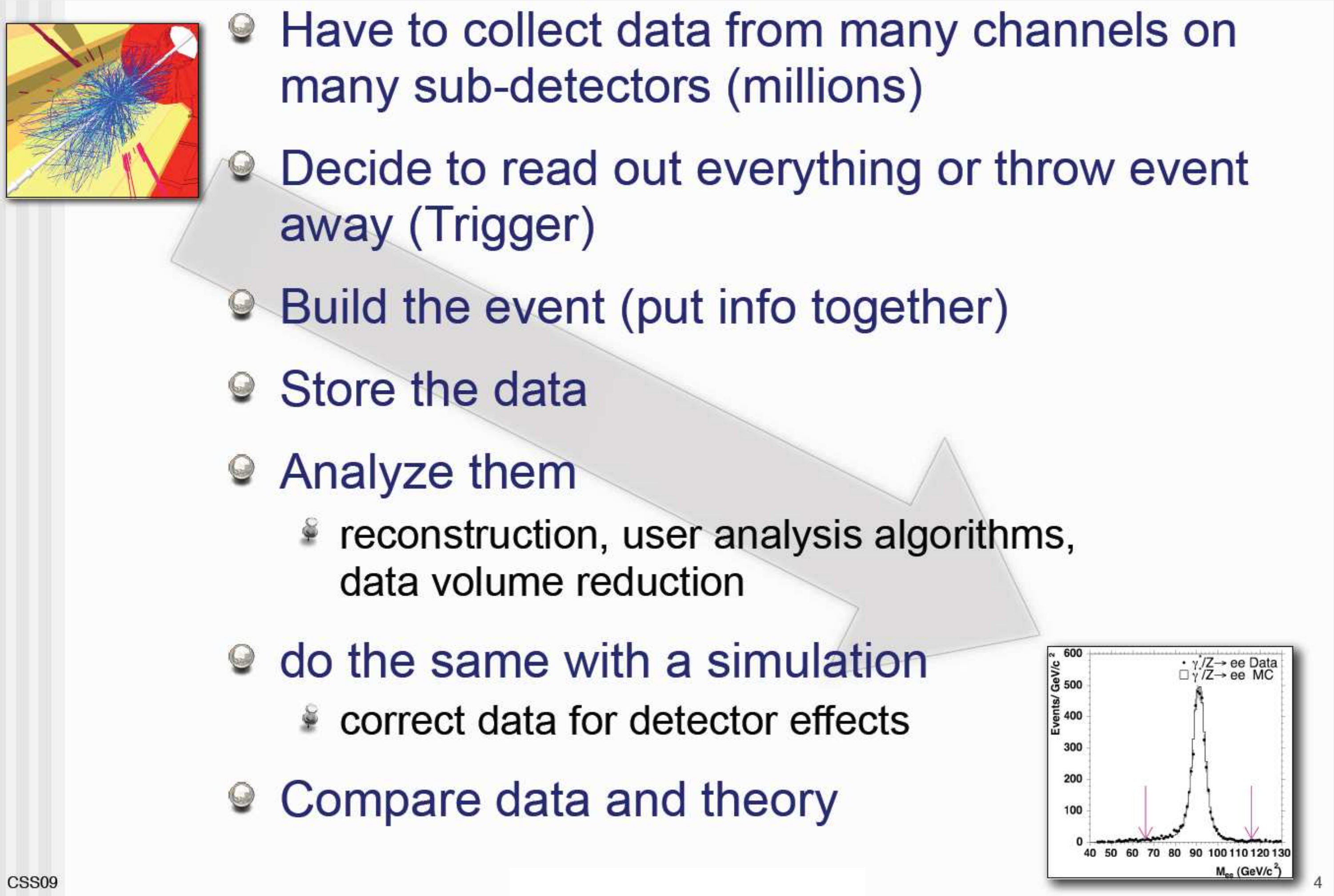


Within 20 overlapping events



Without knowing really where to look for!

Data Analysis Chain

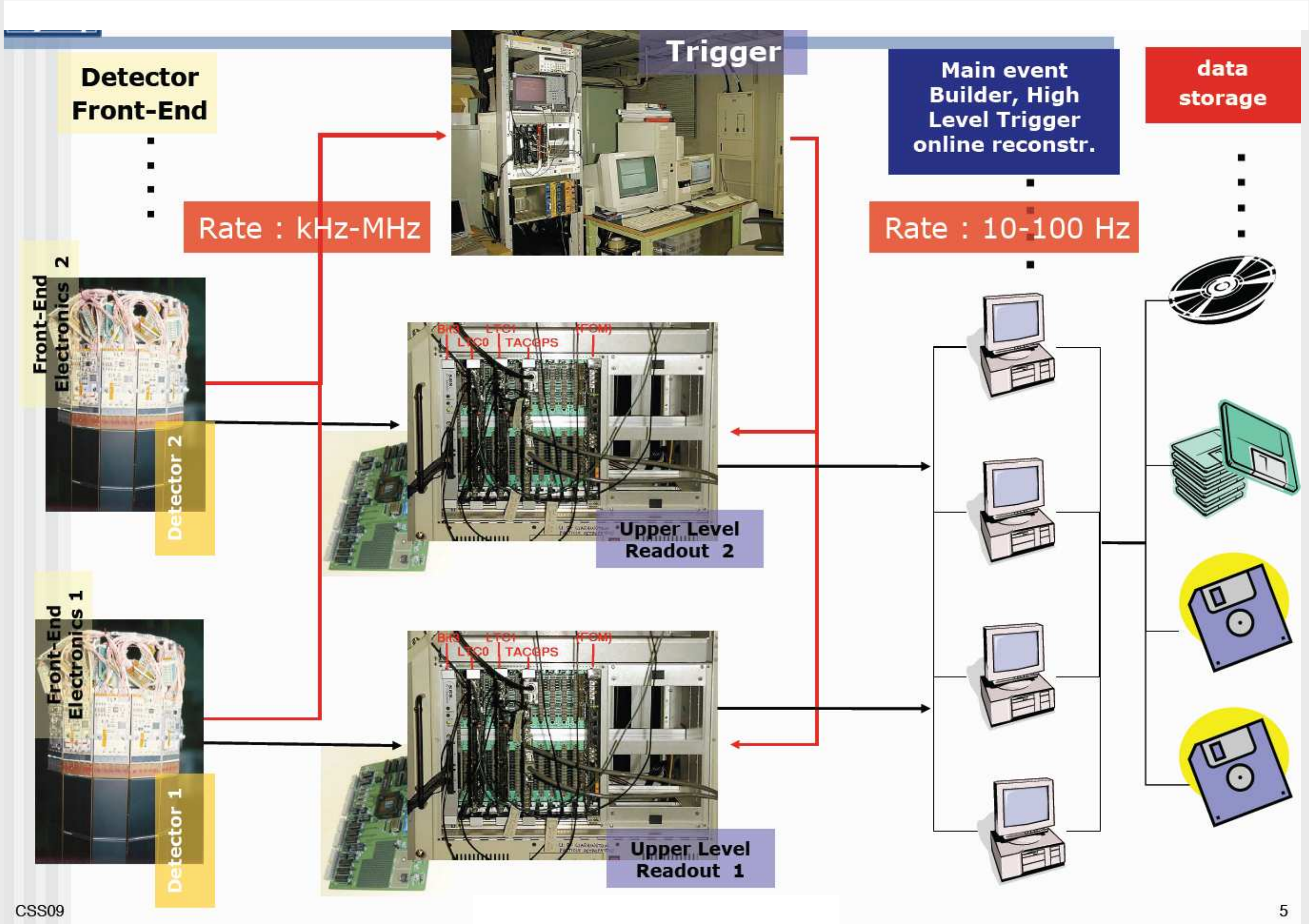


- Have to collect data from many channels on many sub-detectors (millions)
- Decide to read out everything or throw event away (Trigger)
- Build the event (put info together)
- Store the data
- Analyze them
  - reconstruction, user analysis algorithms, data volume reduction
- do the same with a simulation
  - correct data for detector effects
- Compare data and theory

CSS09

4

Data Chain



Detector Front-End

Trigger

Main event Builder, High Level Trigger online reconstr.

data storage

Rate : kHz-MHz

Rate : 10-100 Hz

Front-End Electronics 2

Detector 2

Upper Level Readout 2

Front-End Electronics 1

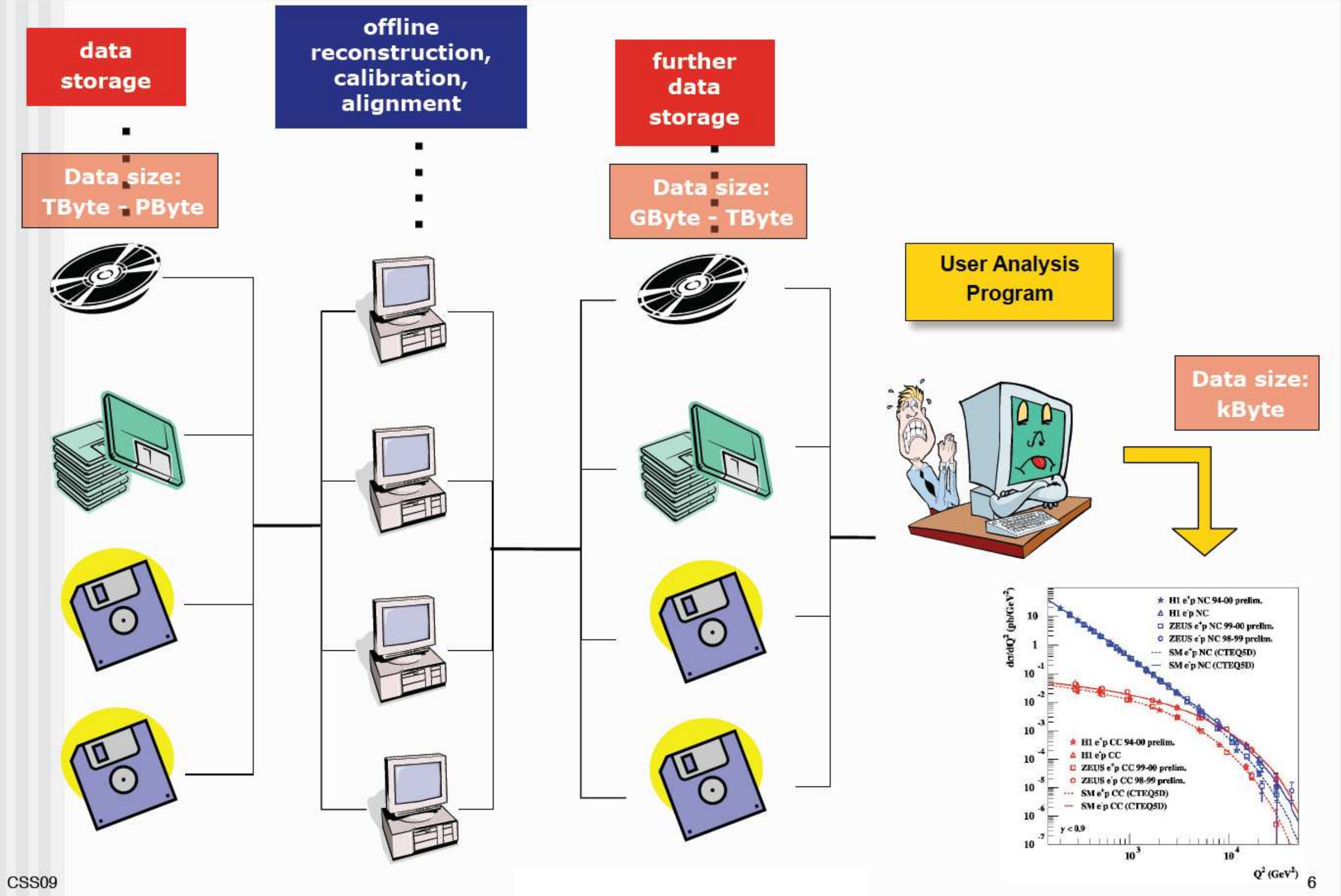
Detector 1

Upper Level Readout 1

CSS09

5

Offline Analysis Chain



data storage

Data size: TByte - PByte

offline reconstruction, calibration, alignment

further data storage

Data size: GByte - TByte

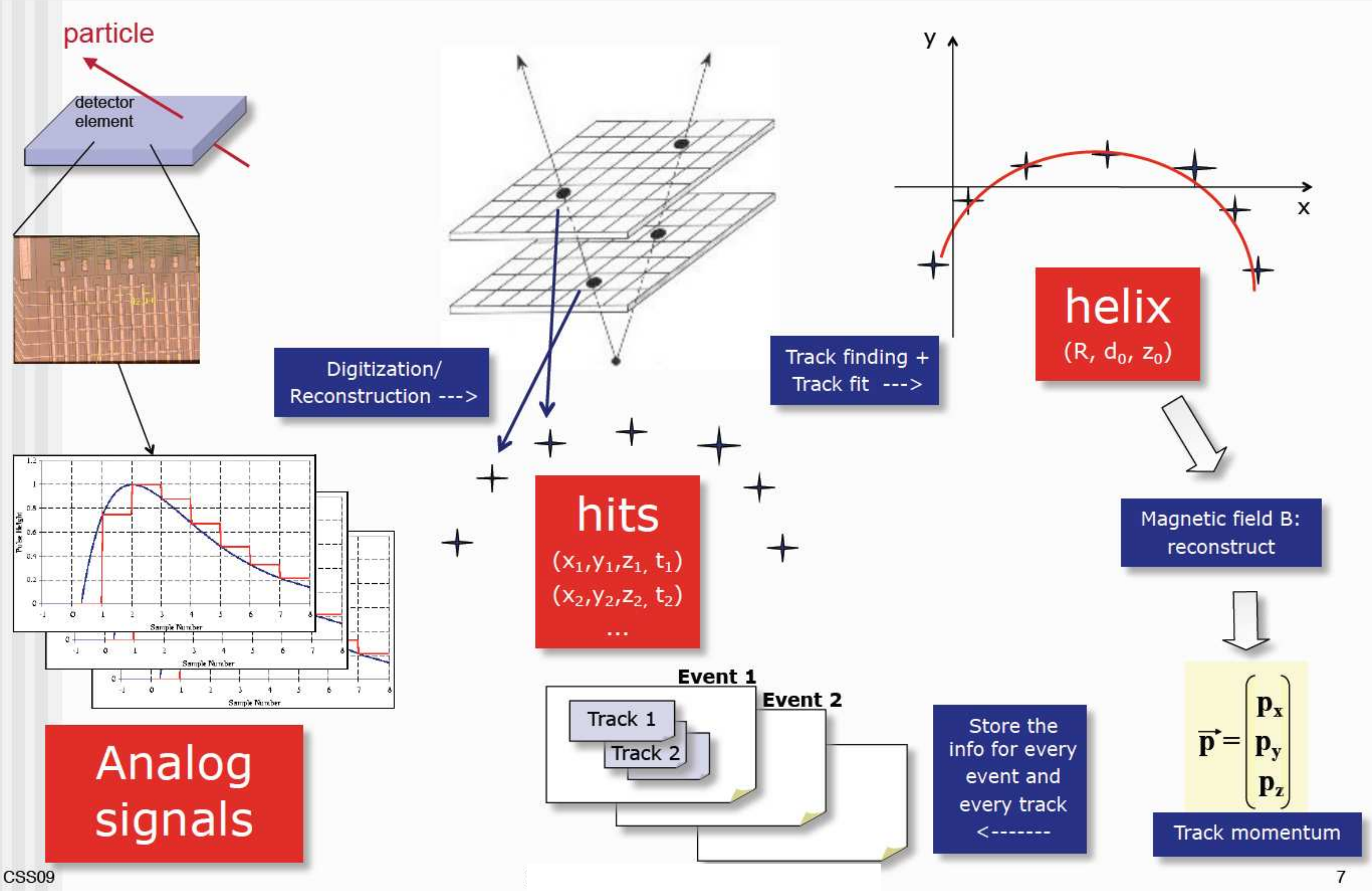
User Analysis Program

Data size: kByte

CSS09

6

Data Reduction



Analog signals

Digitization/ Reconstruction --->

hits

(x_1, y_1, z_1, t_1)
(x_2, y_2, z_2, t_2)
...

Track finding + Track fit --->

helix

(R, d_0, z_0)

Magnetic field B: reconstruct

$$\vec{p} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$$

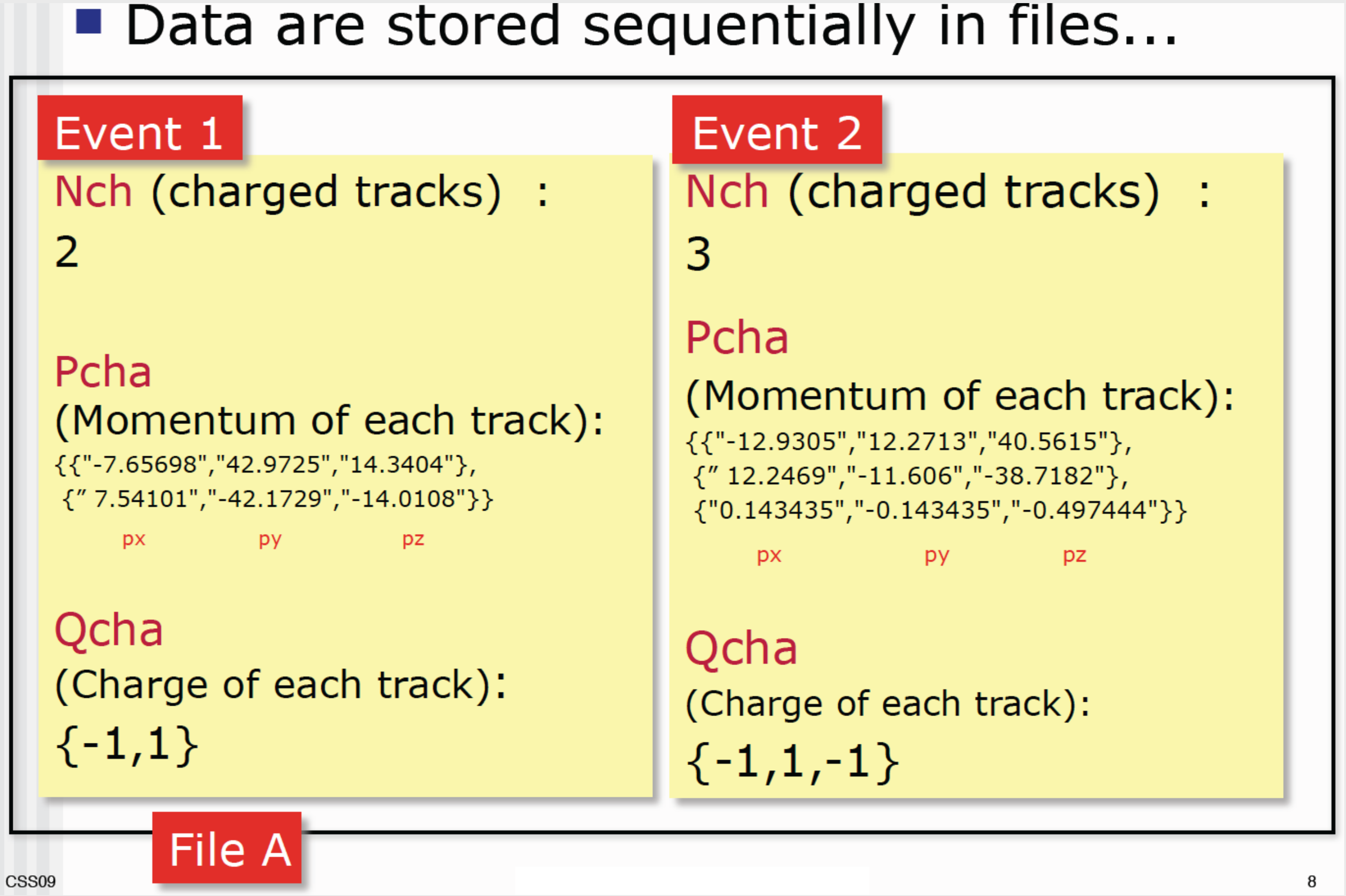
Track momentum

Store the info for every event and every track <-------

CSS09

7

High-level Storage



- Data are stored sequentially in files…

Event 1

Nch (charged tracks) :
2

Pcha
(Momentum of each track):
{{"-7.65698","42.9725","14.3404"},
{" 7.54101","-42.1729","-14.0108"}}
px py pz

Qcha
(Charge of each track):
{-1,1}

Event 2

Nch (charged tracks) :
3

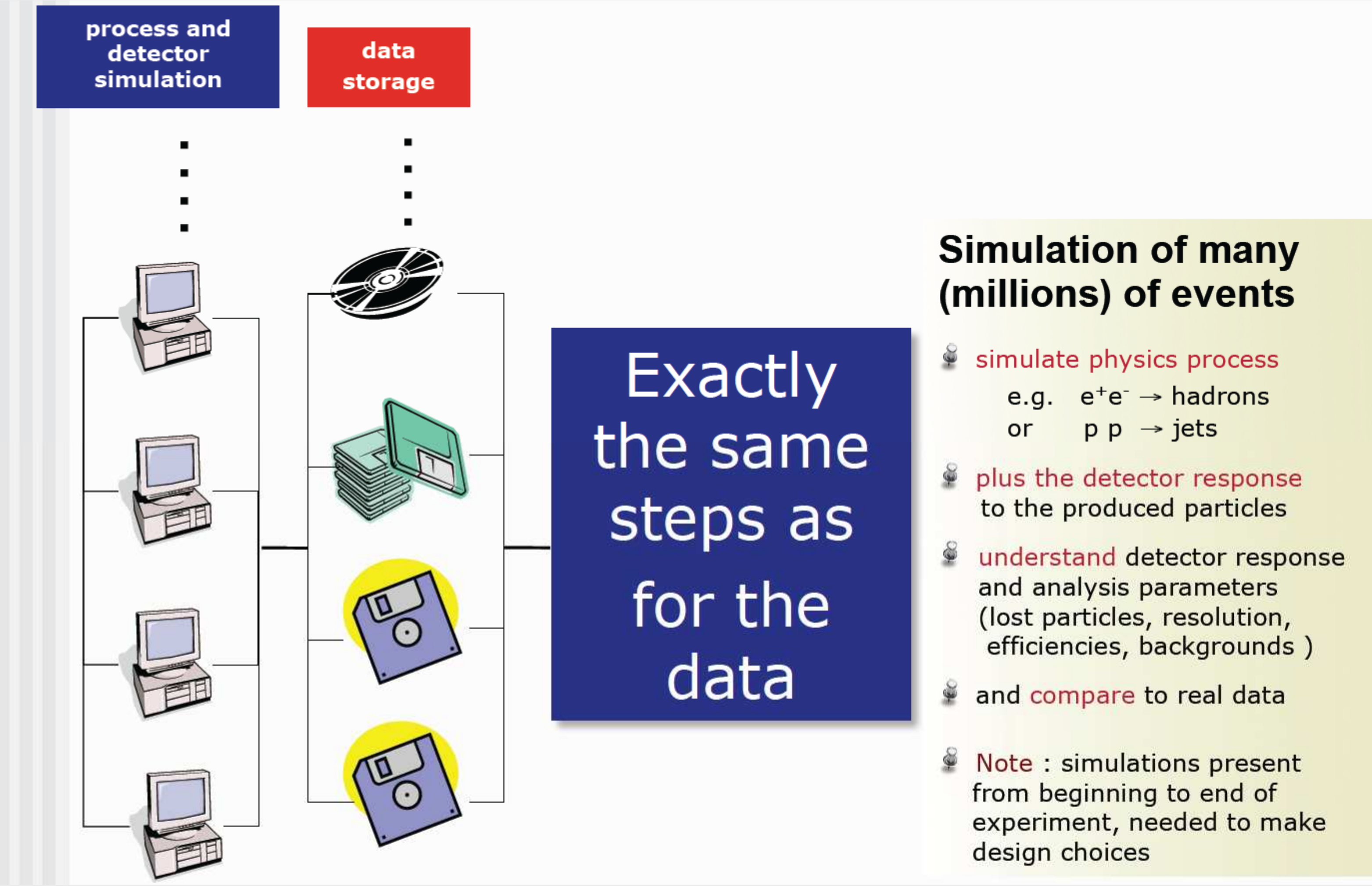
Pcha
(Momentum of each track):
{{"-12.9305","12.2713","40.5615"},
{" 12.2469","-11.606","-38.7182"},
{"0.143435","-0.143435","-0.497444"}}
px py pz

Qcha
(Charge of each track):
{-1,1,-1}

File A

CSS09 8

Simulation

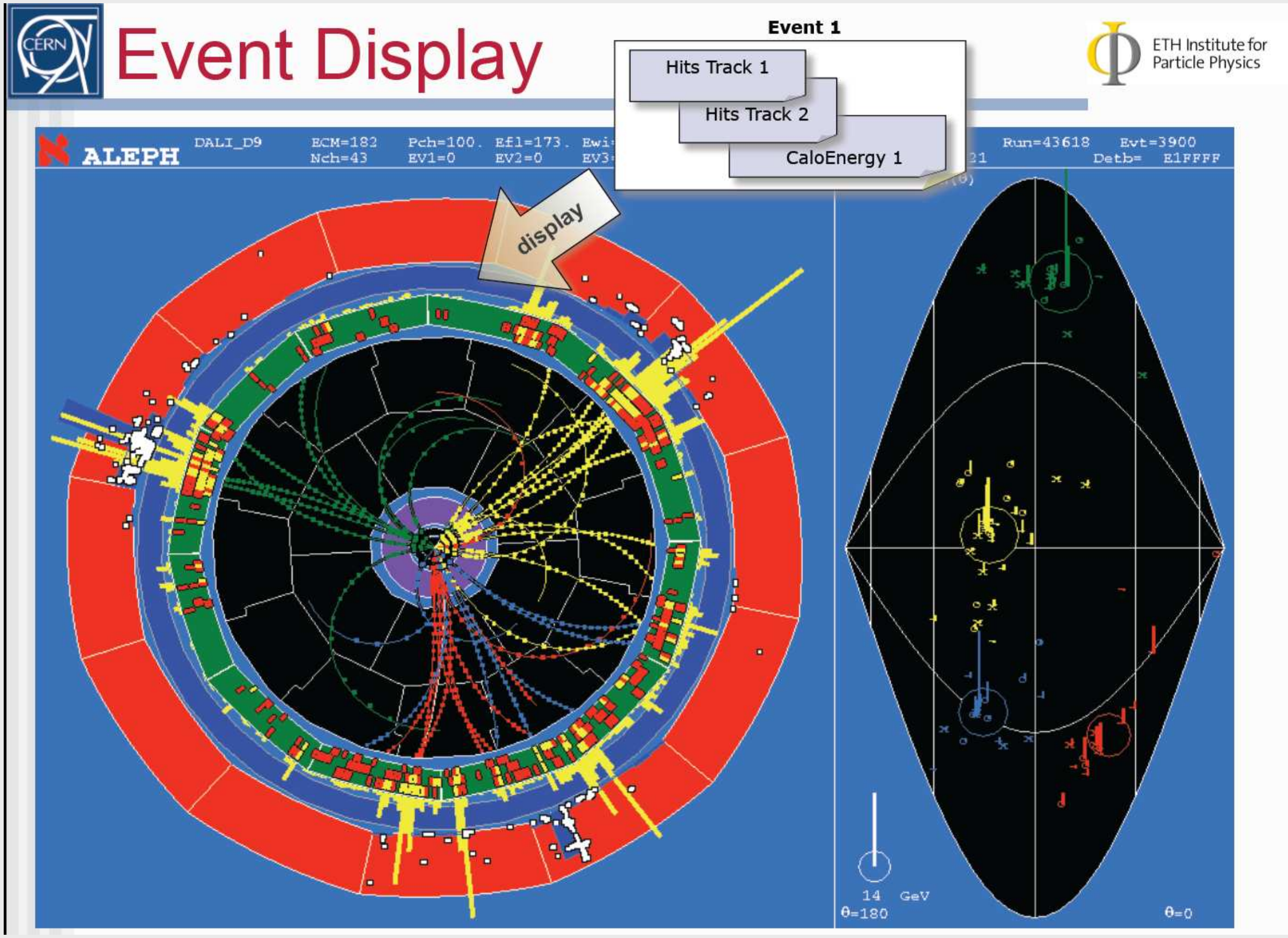


Exactly the same steps as for the data

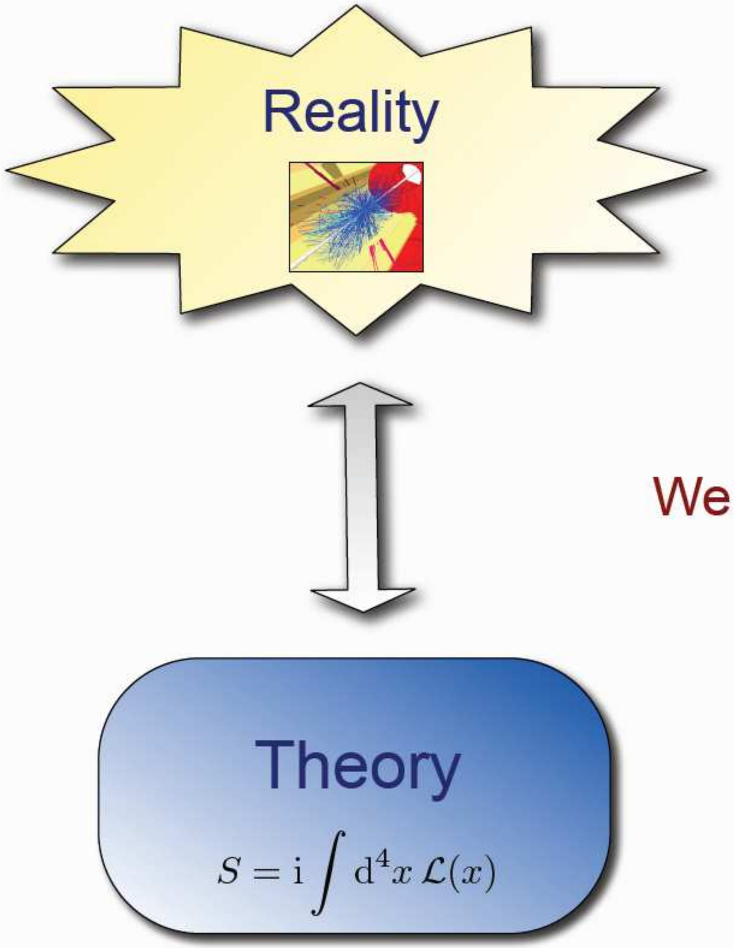
Simulation of many (millions) of events

- simulate physics process
  e.g. $e^+e^- \rightarrow$ hadrons
  or $p\ p \rightarrow$ jets
- plus the detector response to the produced particles
- understand detector response and analysis parameters (lost particles, resolution, efficiencies, backgrounds)
- and compare to real data
- Note : simulations present from beginning to end of experiment, needed to make design choices

Event Display



Our Task



$$S = \mathrm{i}\int \mathrm{d}^4x\,\mathcal{L}(x)$$

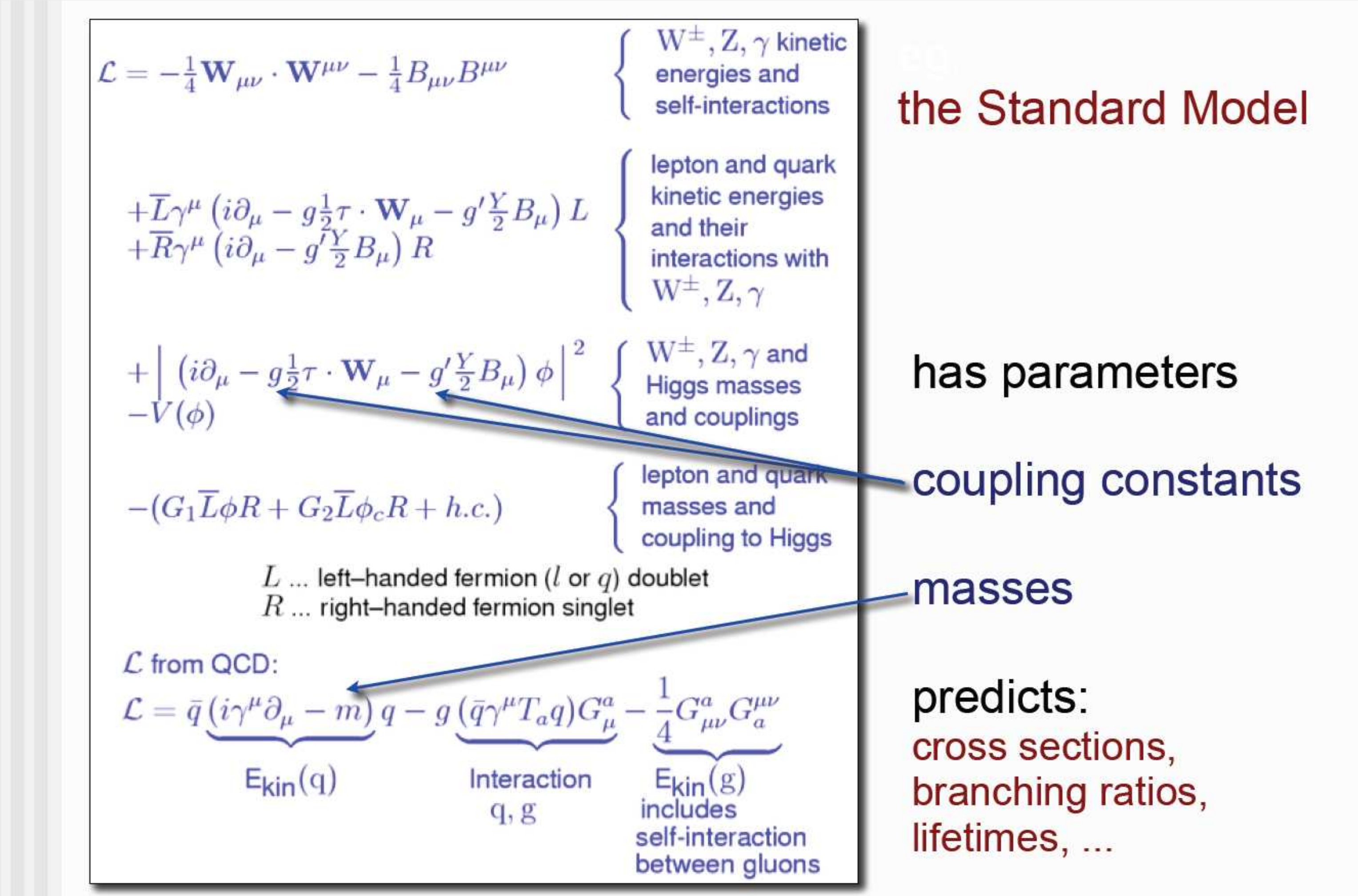
We use experiments to inquire about what “reality” (nature) does

We intend to fill this gap

The goal is to understand in the most general; that’s usually also the simplest.

- A. Eddington

Theory



$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$\mathrm{W}^{\pm}, \mathrm{Z}, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

lepton and quark kinetic energies and their interactions with $\mathrm{W}^{\pm}, \mathrm{Z}, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2} - V(\phi)$$

$\mathrm{W}^{\pm}, \mathrm{Z}, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

lepton and quark masses and coupling to Higgs

L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

$$\mathcal{L} = \bar{q}\underbrace{(i\gamma^{\mu}\partial_{\mu} - m)}_{\mathrm{E_{kin}(q)}}q - g\underbrace{(\bar{q}\gamma^{\mu}T_a q)G^{a}_{\mu}}_{\text{Interaction q, g}} - \underbrace{\frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\mathrm{E_{kin}(g)}}$$

$\mathrm{E_{kin}(g)}$ includes self-interaction between gluons

the Standard Model

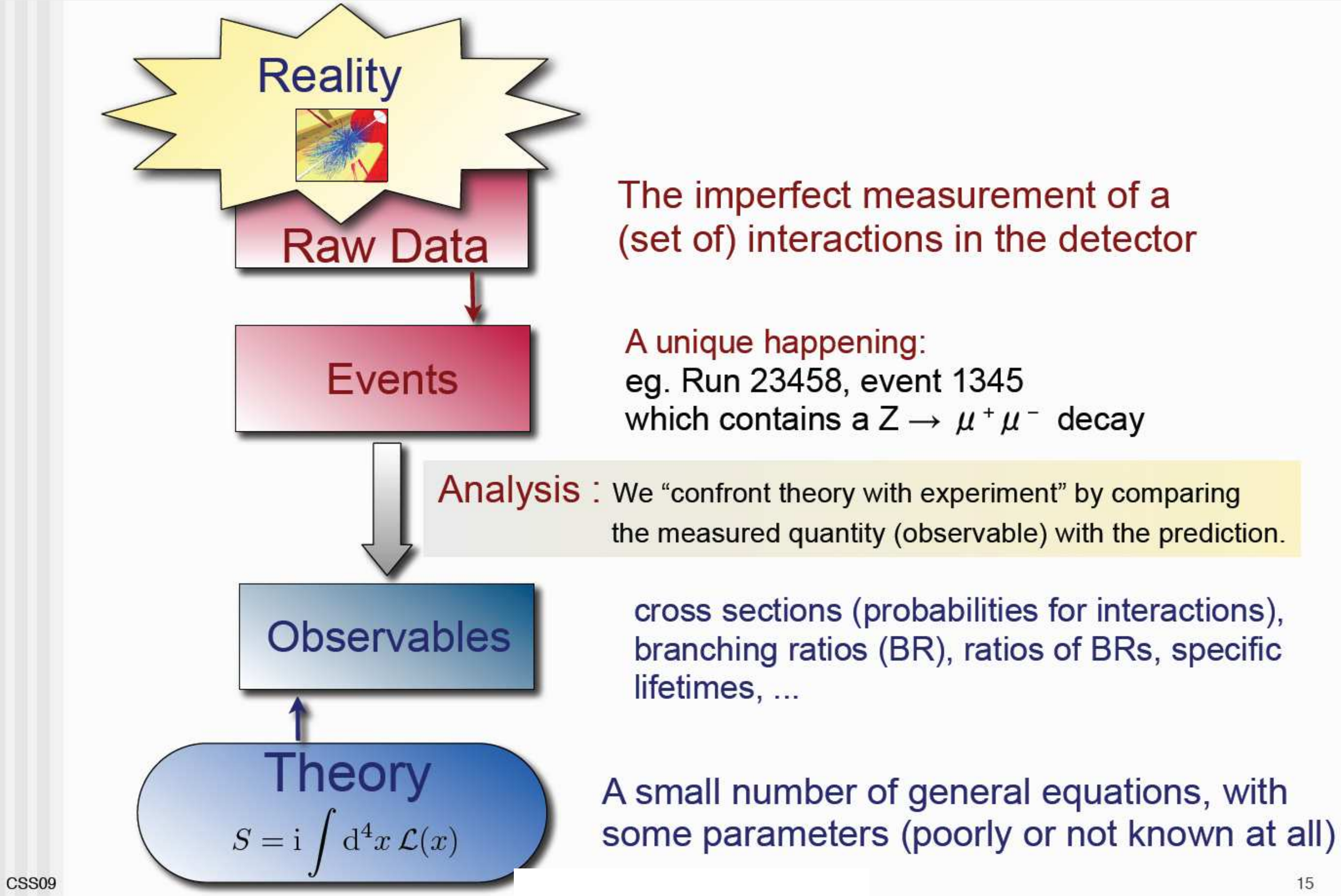
has parameters

coupling constants

masses

predicts:
cross sections,
branching ratios,
lifetimes, ...

Making the Connection



$S = \mathrm{i}\int \mathrm{d}^4x\,\mathcal{L}(x)$

The imperfect measurement of a (set of) interactions in the detector

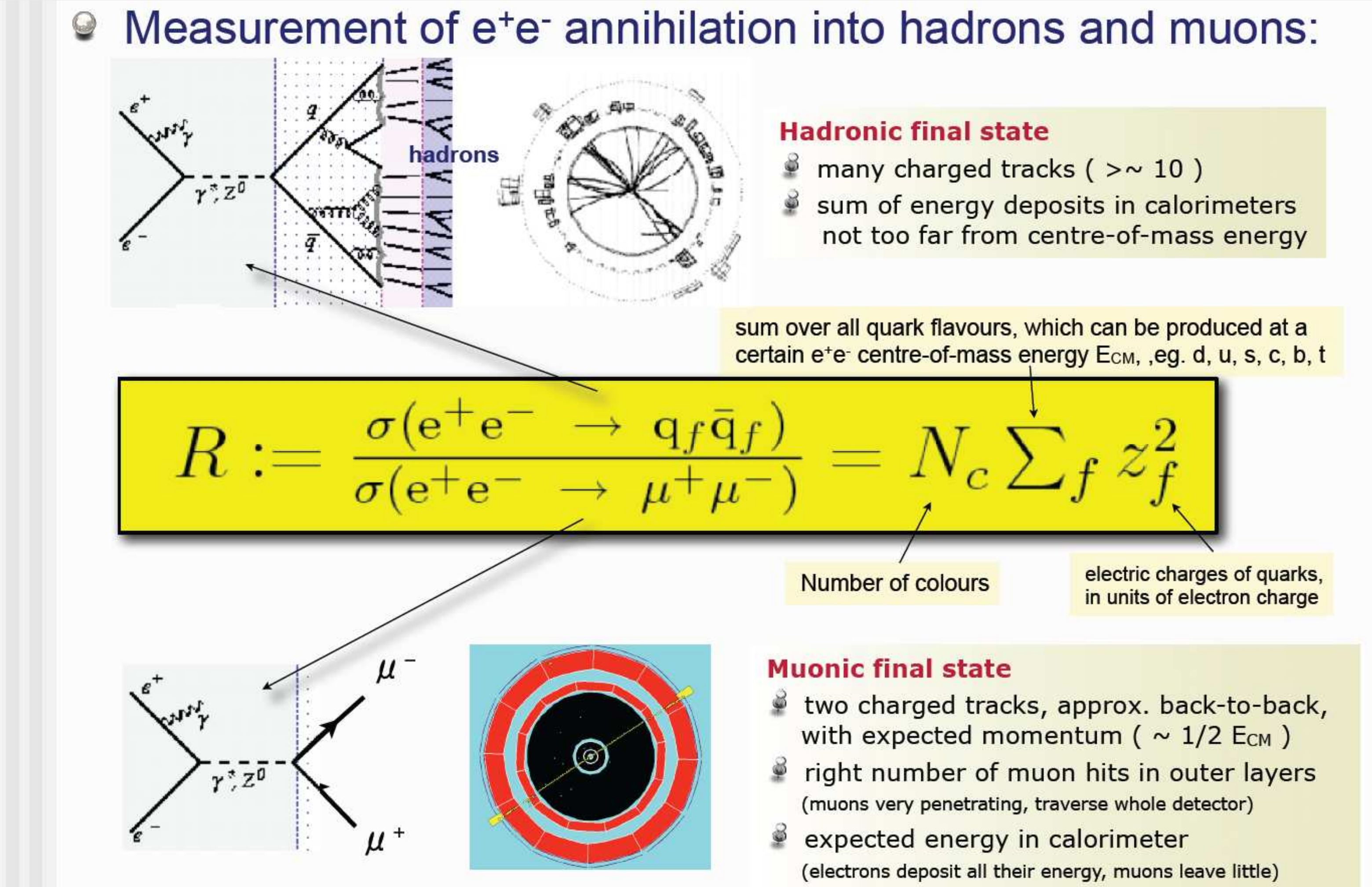
A unique happening:
eg. Run 23458, event 1345
which contains a Z → $\mu^+\mu^-$ decay

Analysis : We “confront theory with experiment” by comparing the measured quantity (observable) with the prediction.

cross sections (probabilities for interactions), branching ratios (BR), ratios of BRs, specific lifetimes, ...

A small number of general equations, with some parameters (poorly or not known at all)

A Simple Counting Experiment



- Measurement of e^+e^- annihilation into hadrons and muons:

Hadronic final state

- many charged tracks (>~ 10)
- sum of energy deposits in calorimeters not too far from centre-of-mass energy

sum over all quark flavours, which can be produced at a certain e^+e^- centre-of-mass energy E_{CM}, ,eg. d, u, s, c, b, t

$$R := \frac{\sigma(e^+e^- \to q_f\bar{q}_f)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_f z_f^2$$

Number of colours

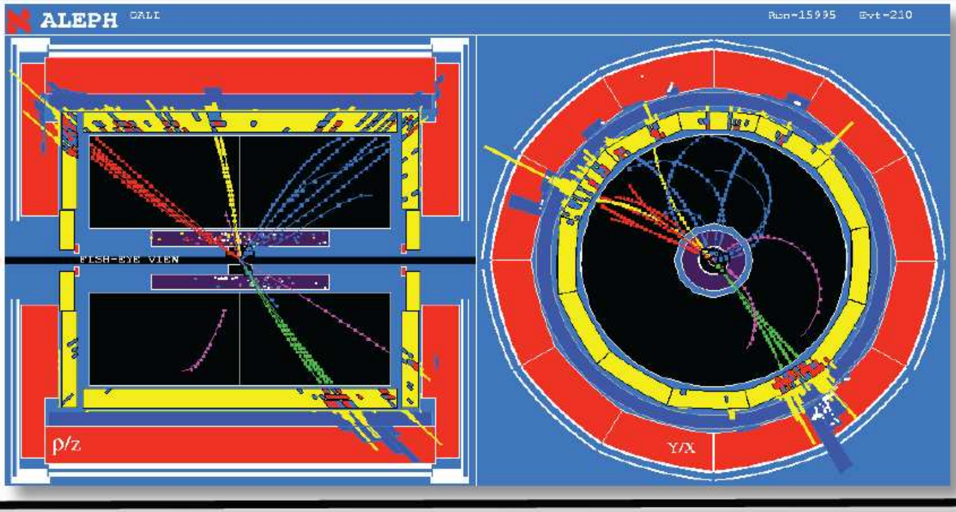
electric charges of quarks, in units of electron charge

Muonic final state

- two charged tracks, approx. back-to-back, with expected momentum (~ 1/2 E_{CM})
- right number of muon hits in outer layers (muons very penetrating, traverse whole detector)
- expected energy in calorimeter (electrons deposit all their energy, muons leave little)

A Simple Counting Experiment

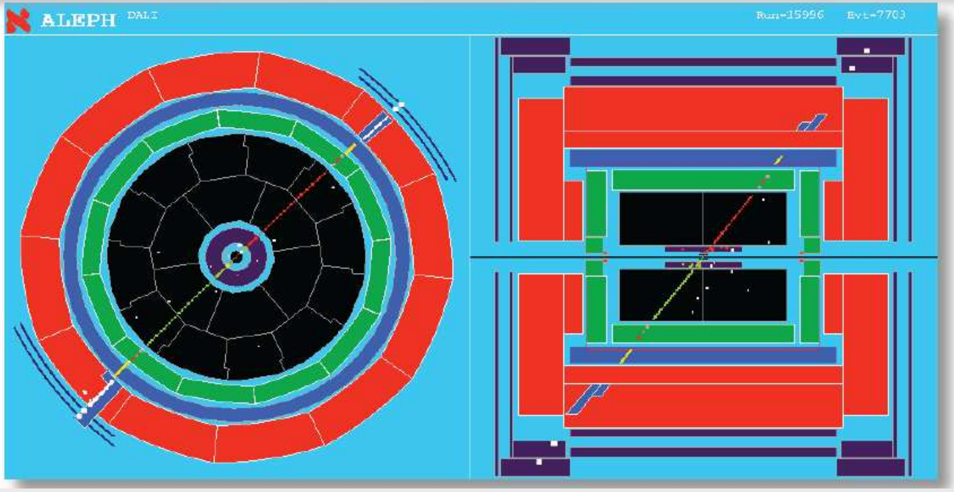
of



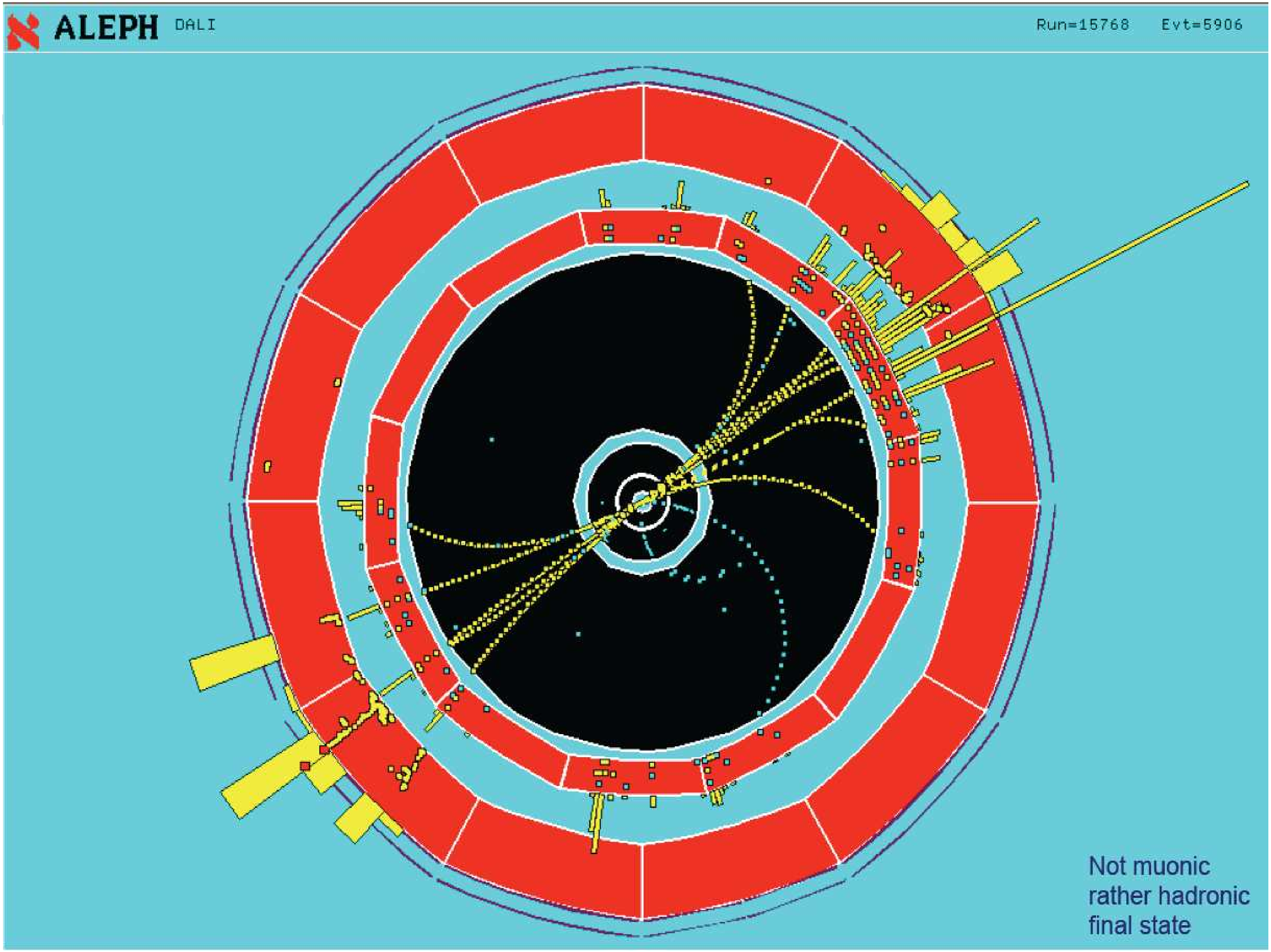
Hadron final states

R =

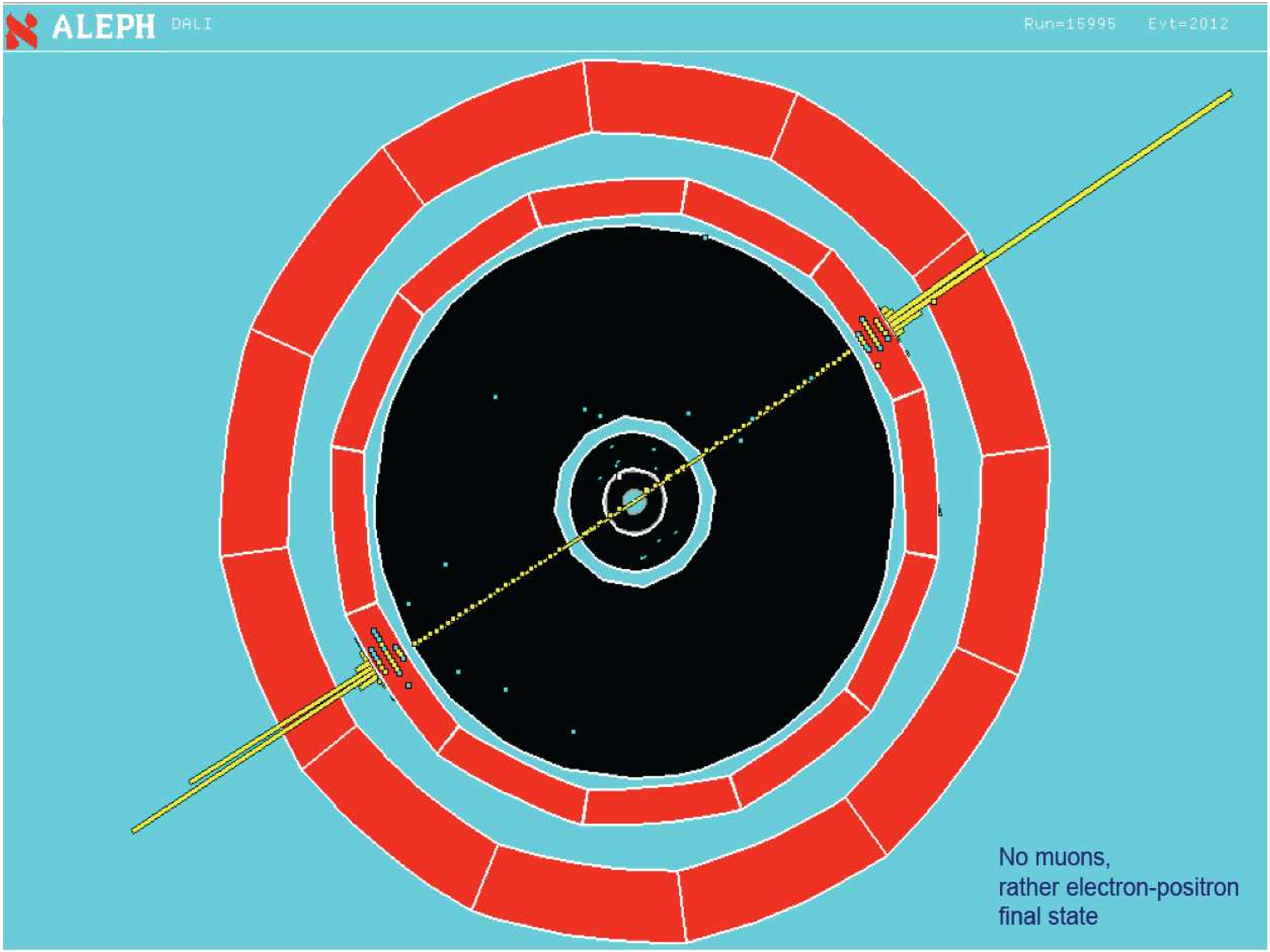
of



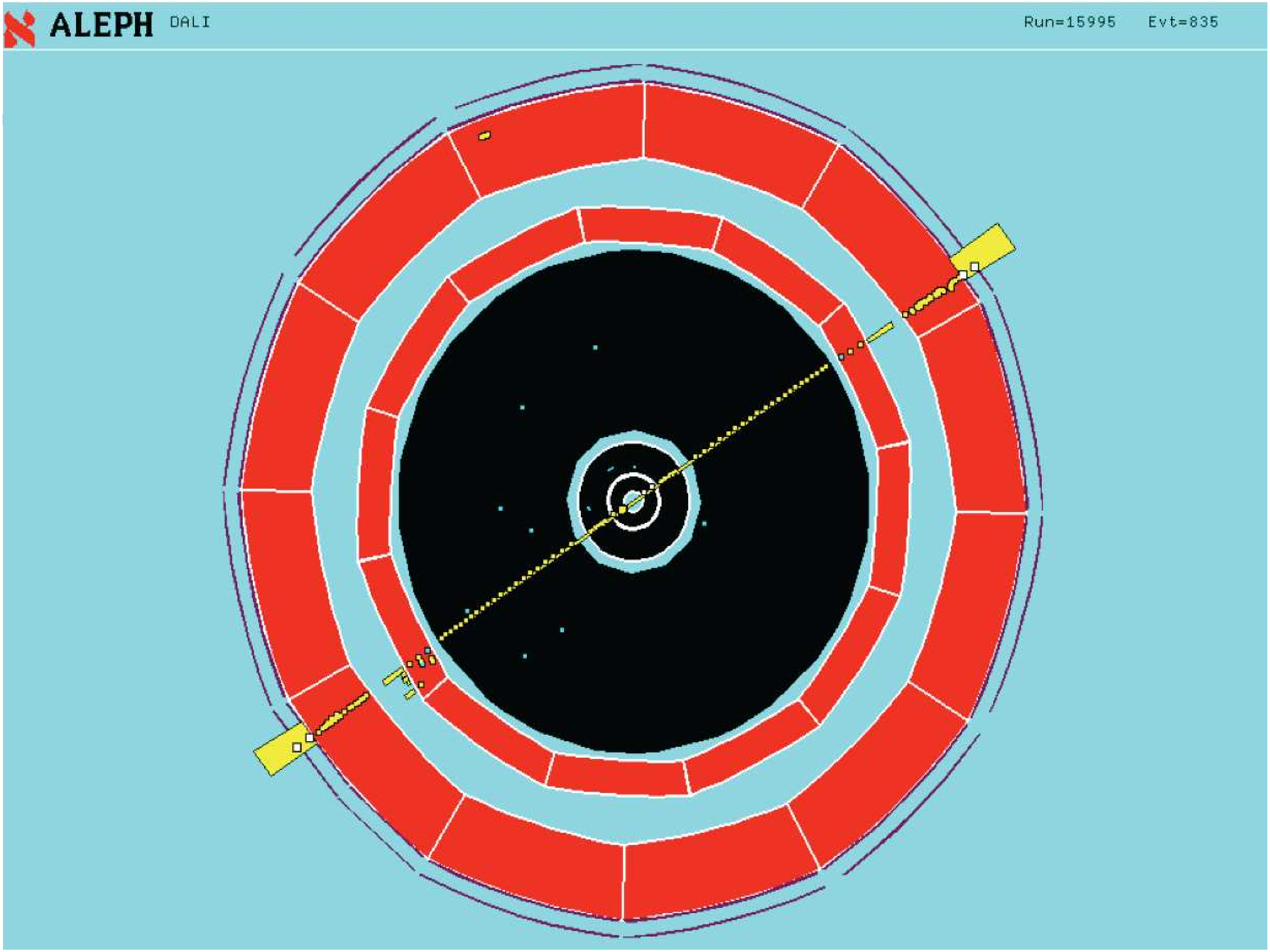
Muon final states

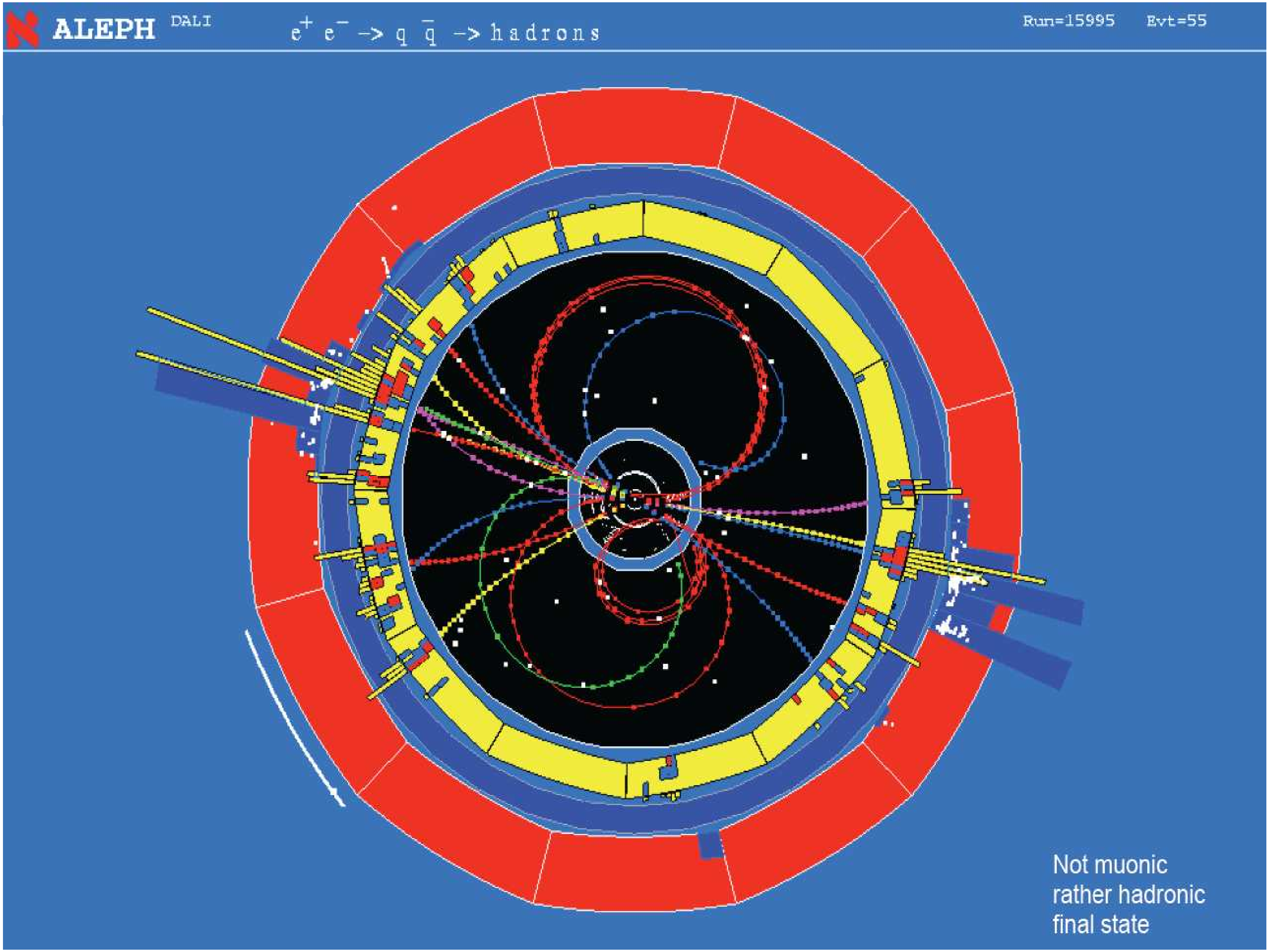


Not muonic
rather hadronic
final state



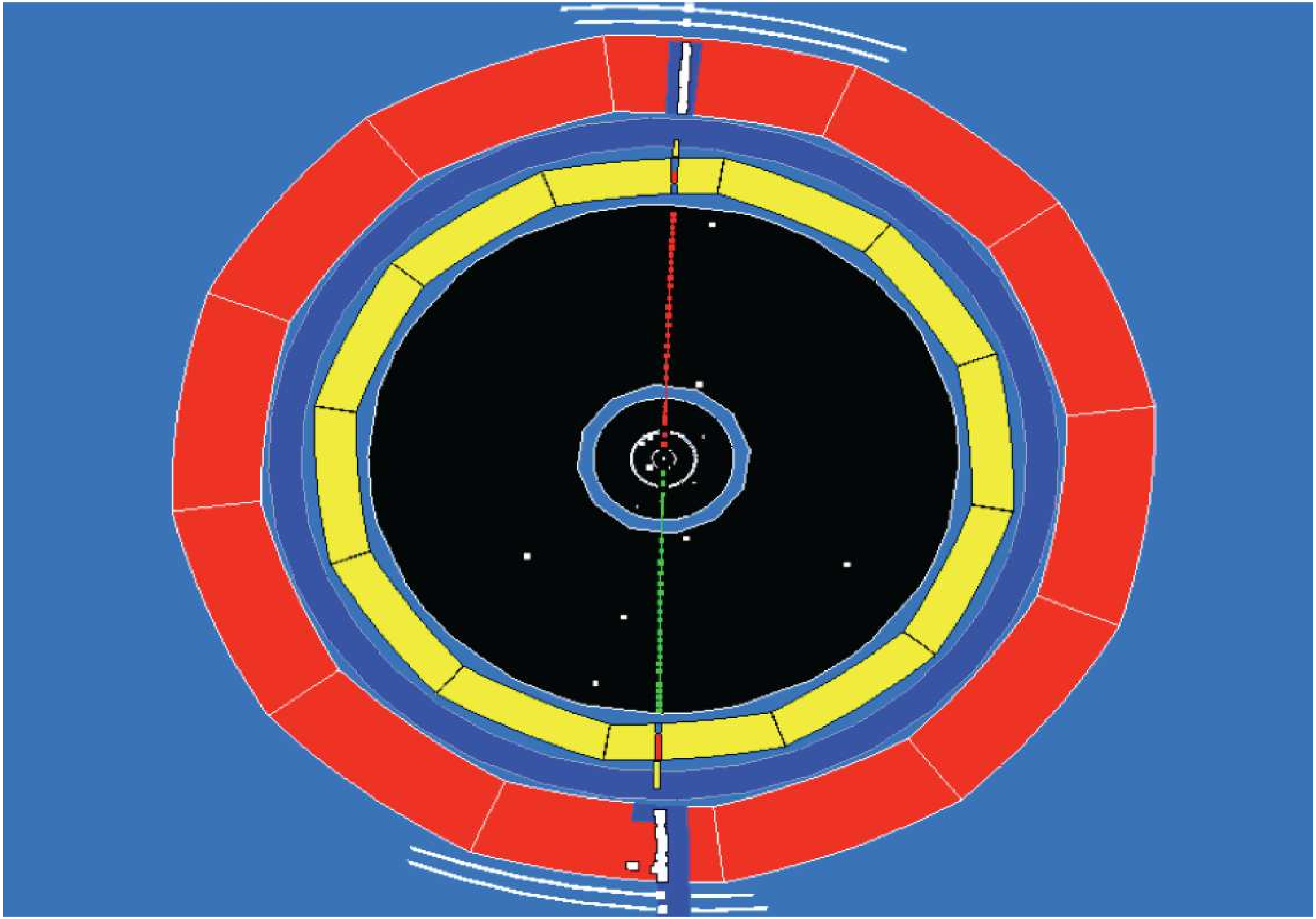
No muons,
rather electron-positron
final state


ALEPH
DALI
Run=15995
Evt=835



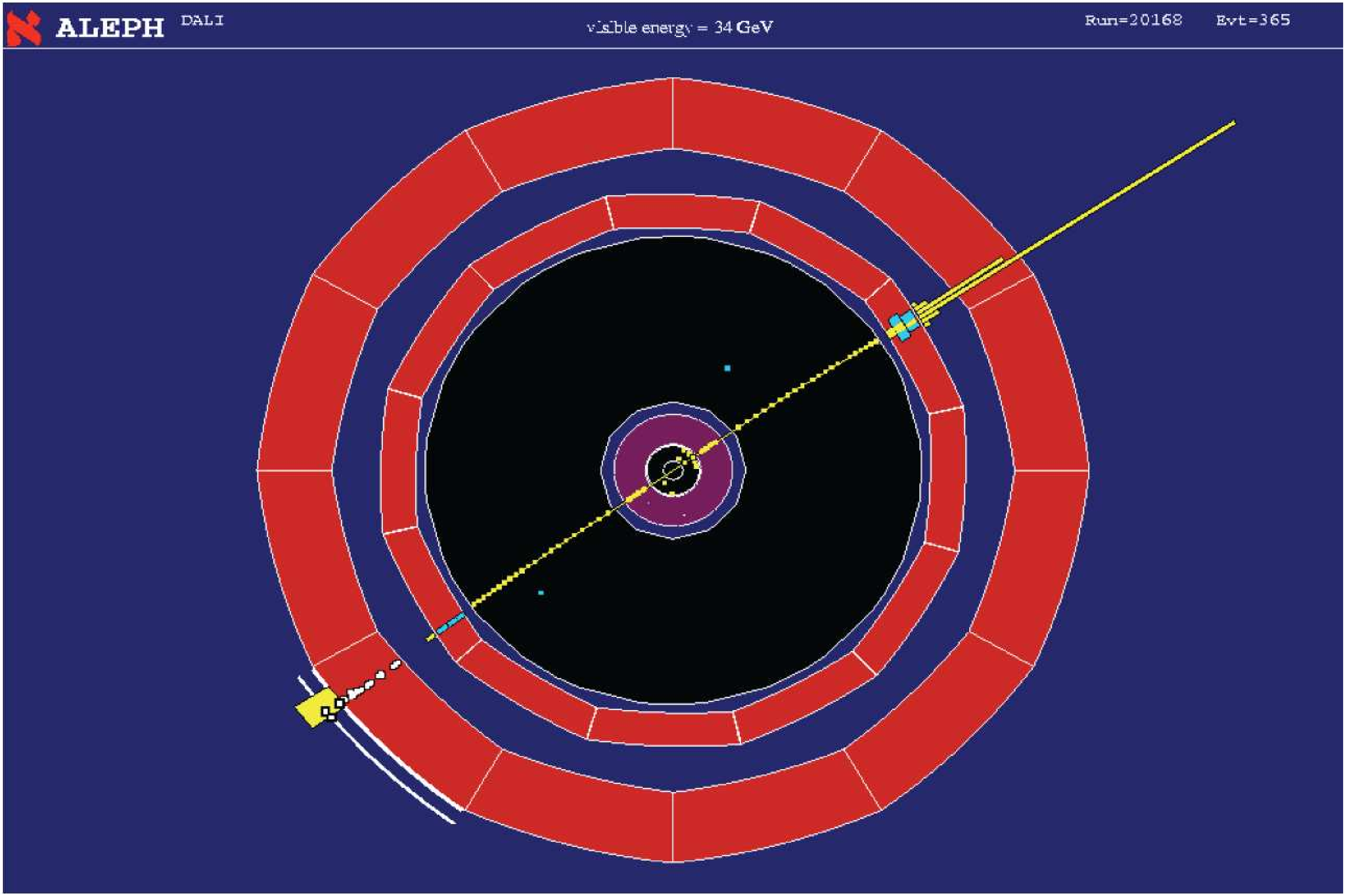
Not muonic
rather hadronic
final state

$Z \rightarrow \mu^+\mu^-$

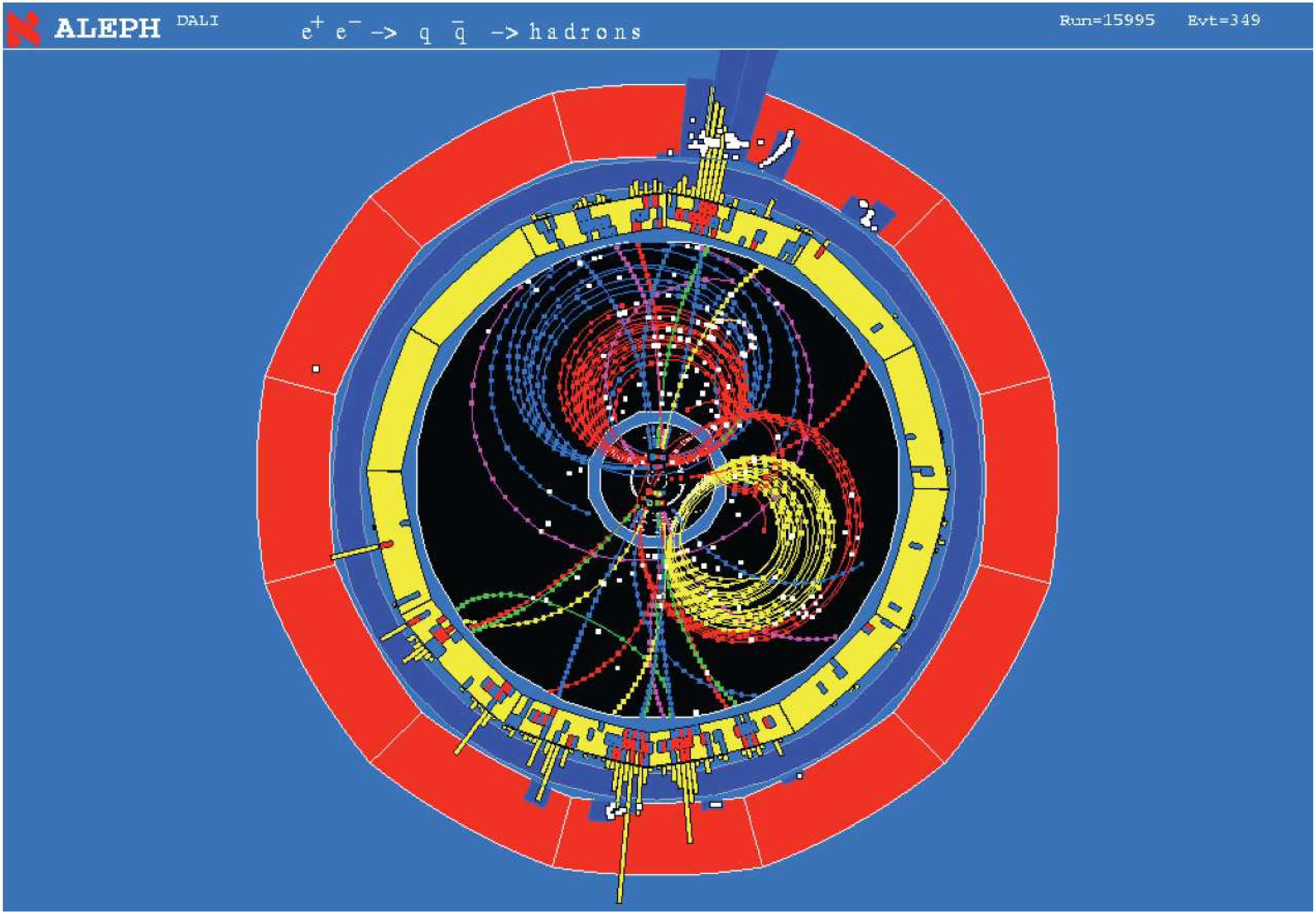


not $Z \to \mu^+\mu^-$

rather Z decay to $\tau^+\tau^-$,
one tau decayed to electron + 2 neutrinos
the other tau decayed to muon + 2 neutrinos



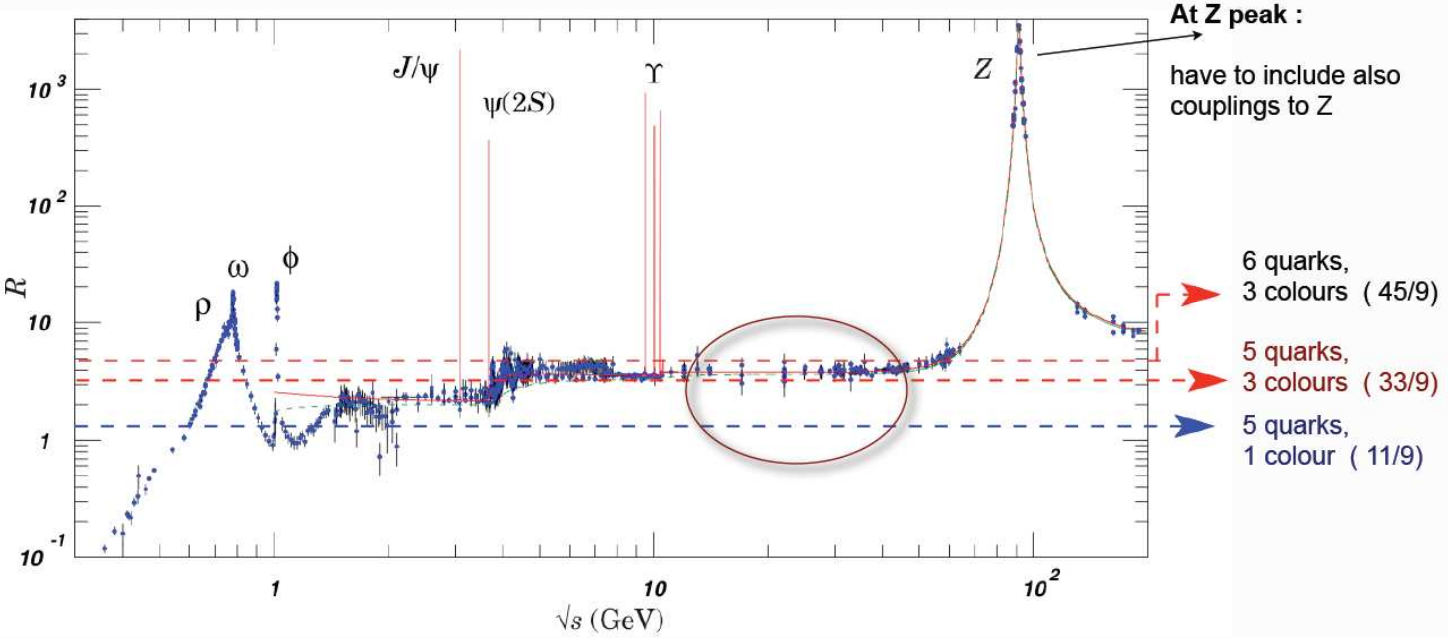
Not muonic, rather hadronic final state



Result

For E_{CM} below the Z peak and above the Υ resonance we expect:

$$R = N_c \sum_f z_f^2 = N_c \cdot [\underset{u}{(\tfrac{2}{3})^2} + \underset{d}{(-\tfrac{1}{3})^2} + \underset{s}{(-\tfrac{1}{3})^2} + \underset{c}{(\tfrac{2}{3})^2} + \underset{b}{(-\tfrac{1}{3})^2}] = N_c \cdot \frac{11}{9}$$



At Z peak :

have to include also couplings to Z

6 quarks,
3 colours (45/9)

5 quarks,
3 colours (33/9)

5 quarks,
1 colour (11/9)

- Confirmation of : Number of colours = 3 !

Note : small remaining difference : because of QCD correction (gluon radiation) = 1 + α_s/π

Uncertainties

- Just having a “counting result” is not all, there’s lot more to do!
- Statistical error
  - We saw 2 muon events, could easily have been 1 or 3
  - Those fluctuations go like the square-root of the number of events

$$BR\left(Z^0 \to \mu^+\mu^-\right) = \frac{N_{\mu\mu}}{N_{total}} \pm \frac{\sqrt{N_{\mu\mu}}}{N_{total}}$$

  - To reduce this uncertainty, you need to record lots (millions) of events in the detector, and process them
- Systematic error
  - What if you only see 50% of the $\mu^+\mu^-$ events?
    - because of event selection (cut), detector imperfections, poor understanding, etc.

“efficiency”

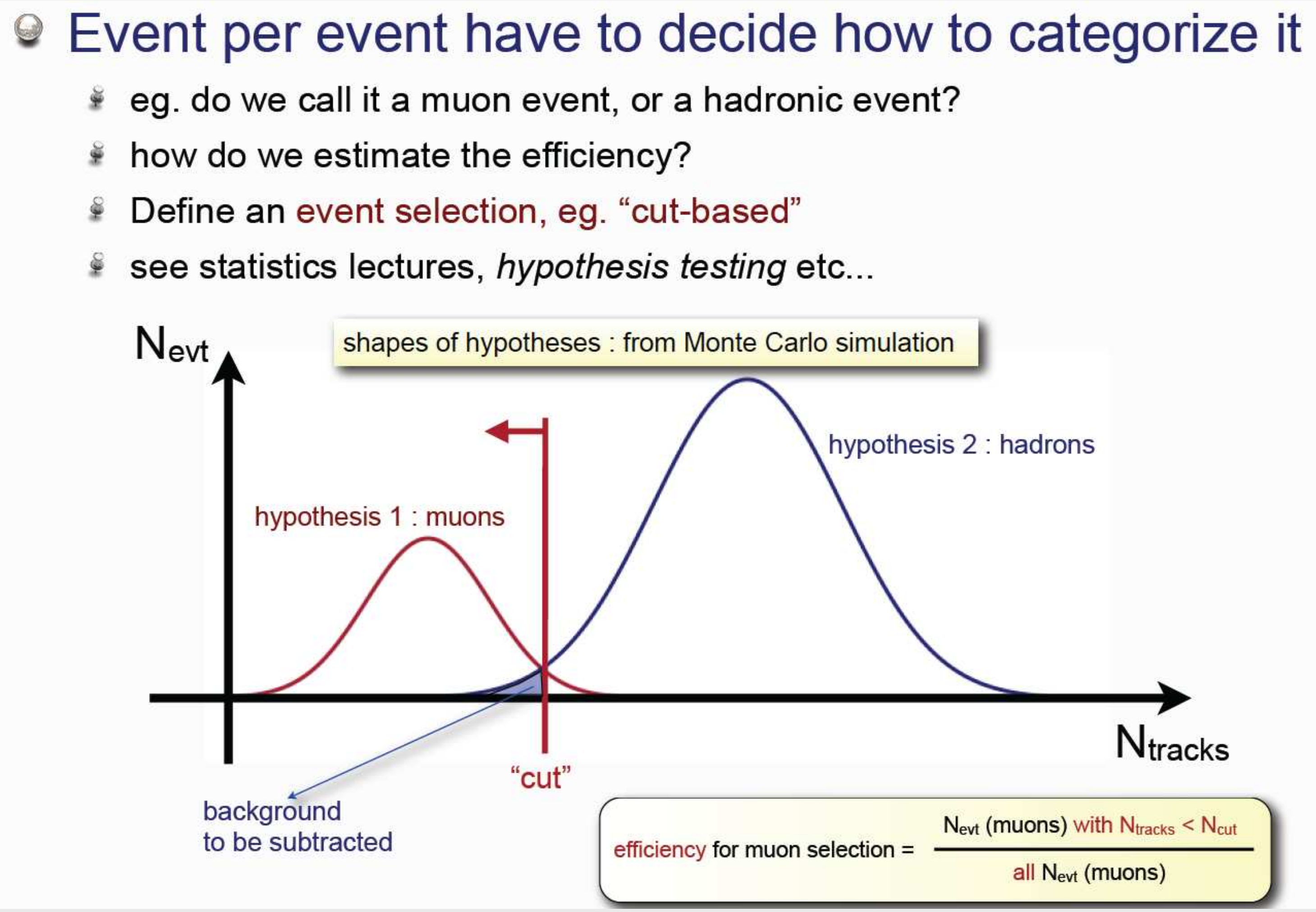
$$N_{\mu\mu\,\mathrm{seen}} = \underset{\uparrow}{\varepsilon} N_{\mu\mu}$$

$$BR\left(Z^0 \to \mu^+\mu^-\right) = \frac{N_{\mathrm{seen}}/\varepsilon}{N_{total}}$$

$$\varepsilon = 0.50 \pm 0.05$$

- from statistical error of detector simulation
- imperfect modeling of geometry in simulation
- model of muon interactions in simulation, etc

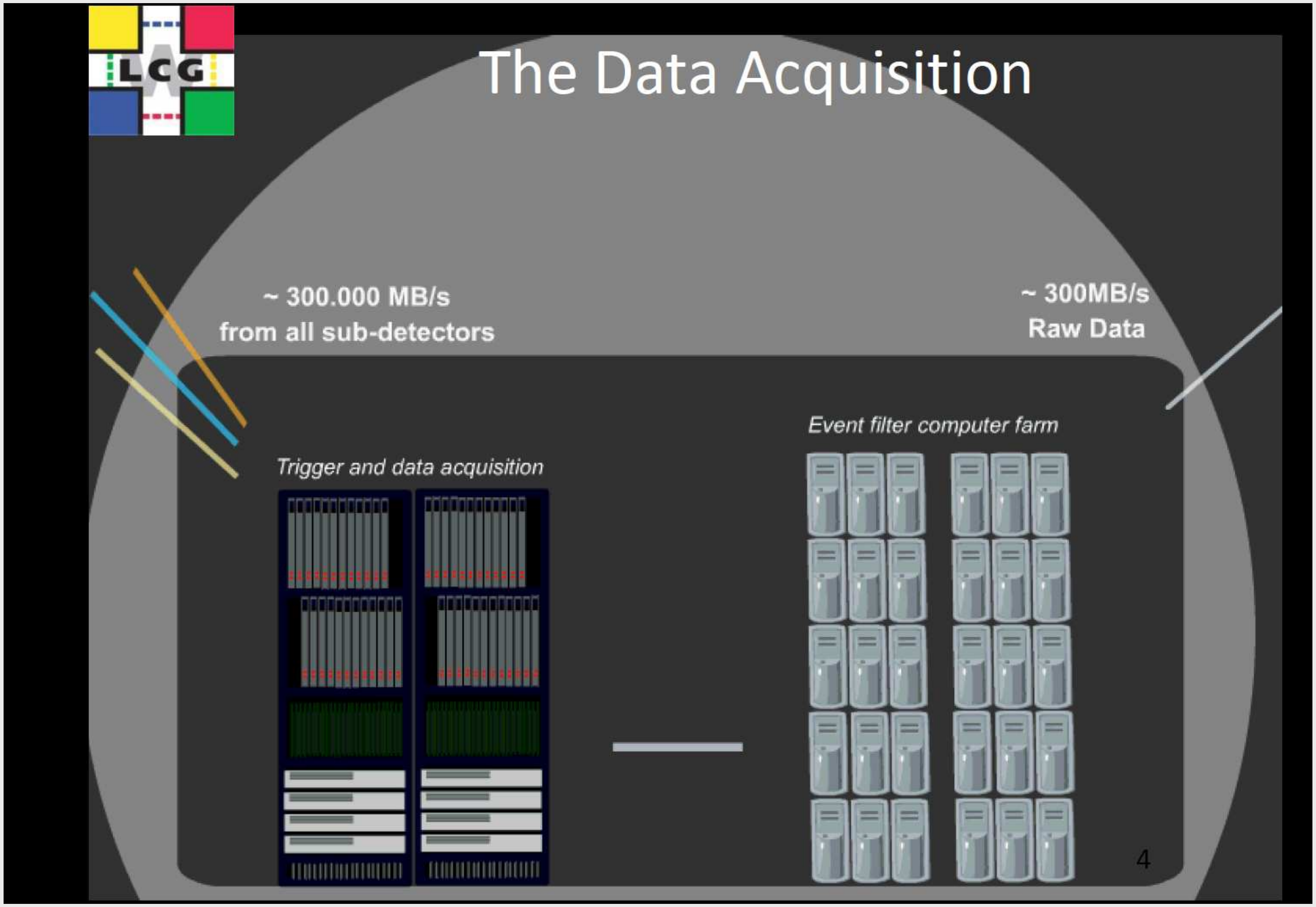
Event Selection



- Event per event have to decide how to categorize it
  - eg. do we call it a muon event, or a hadronic event?
  - how do we estimate the efficiency?
  - Define an event selection, eg. “cut-based”
  - see statistics lectures, *hypothesis testing* etc...

$$\text{efficiency for muon selection} = \frac{N_{evt}\text{ (muons) with } N_{tracks} < N_{cut}}{\text{all } N_{evt}\text{ (muons)}}$$

The Data Acquisition



The Data Acquisition

~ 300.000 MB/s
from all sub-detectors

~ 300MB/s
Raw Data

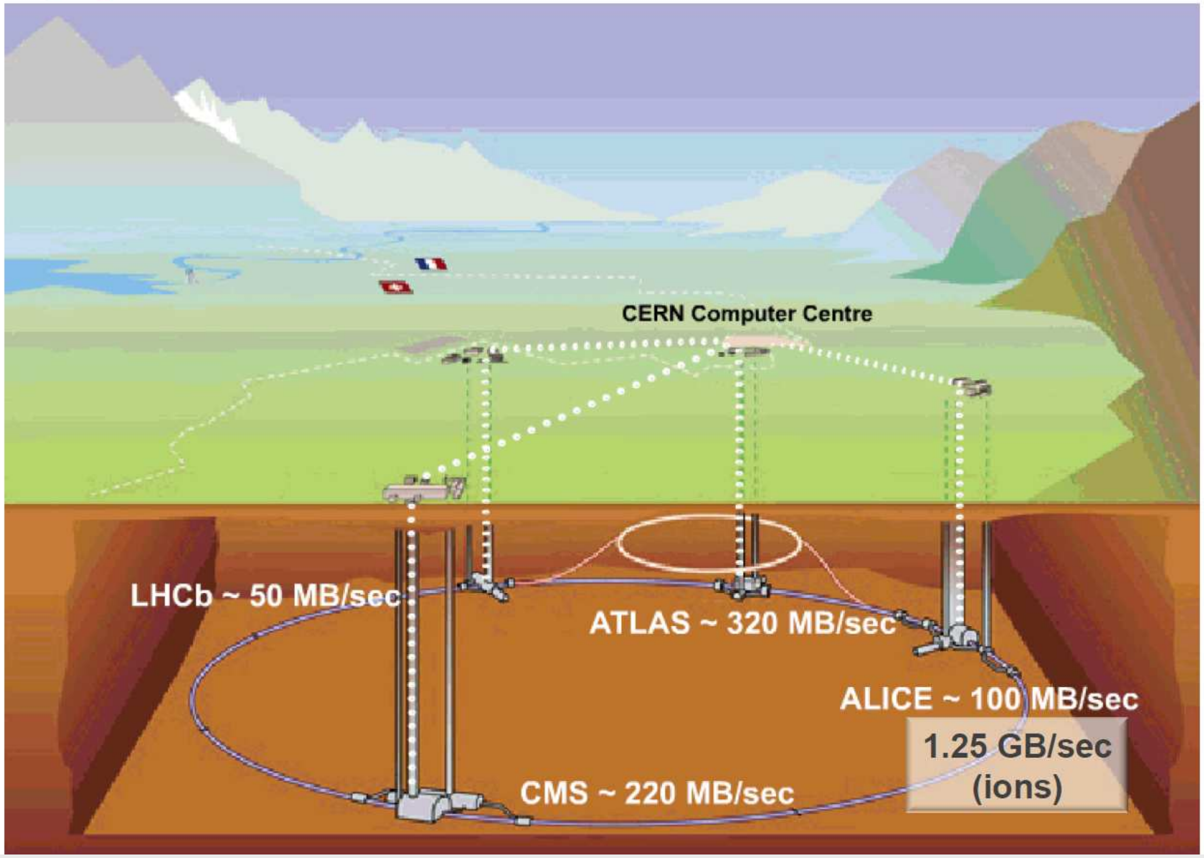
Event filter computer farm

Trigger and data acquisition

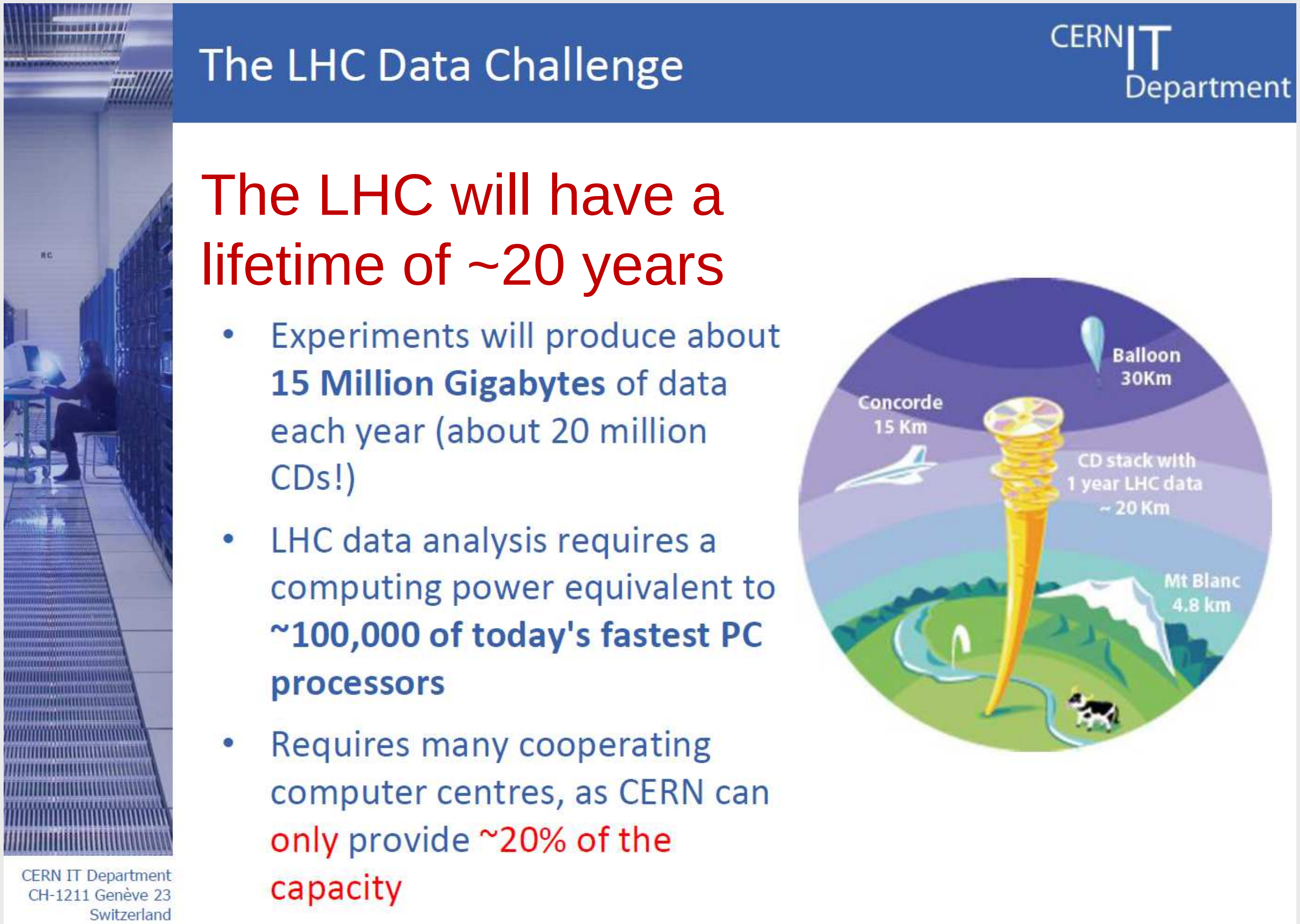
Grid Computing

Tier 0 at CERN: Acquisition, First pass processing

Storage & Distribution



Grid Computing



The LHC Data Challenge

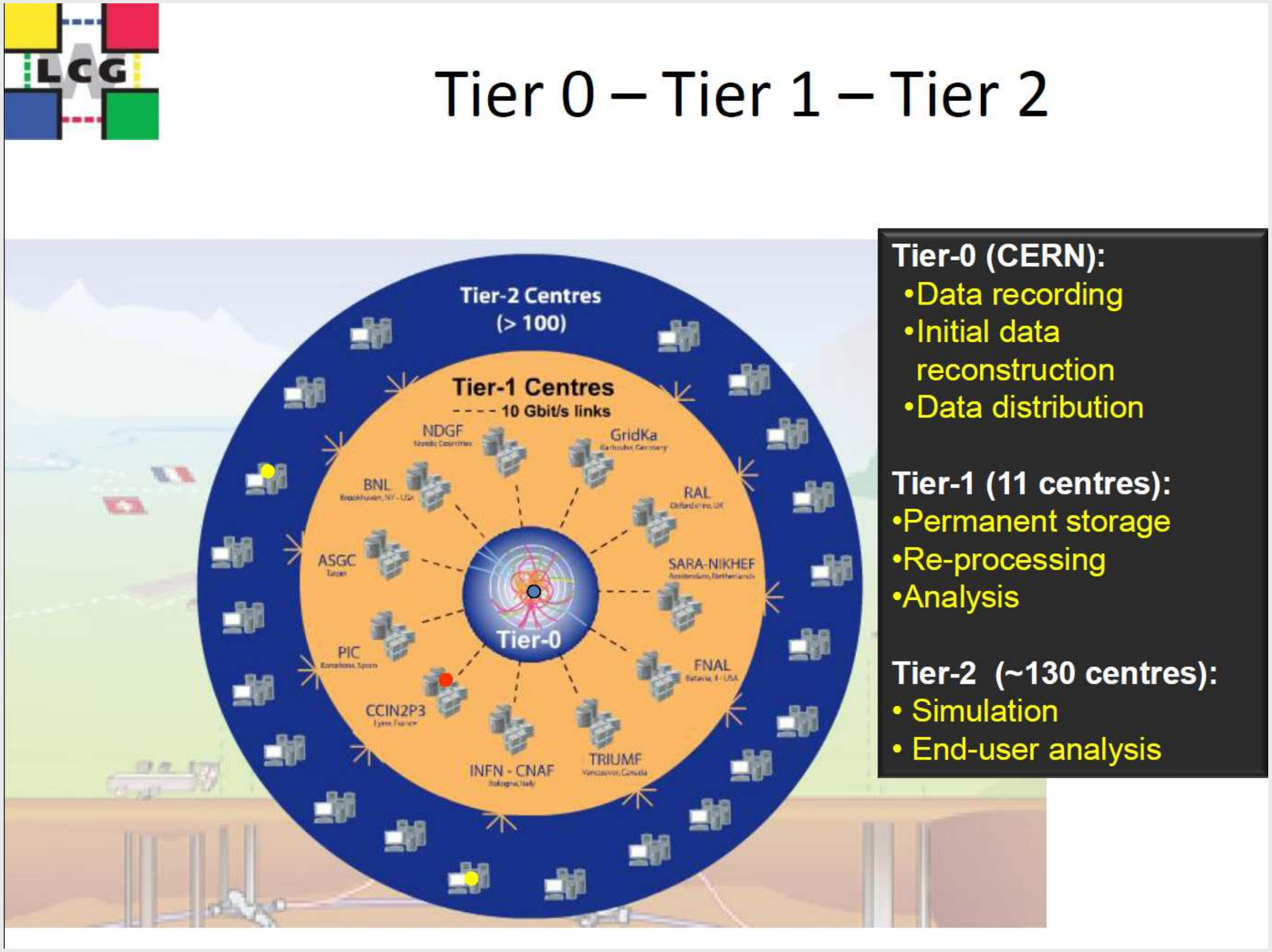
CERN IT Department

The LHC will have a lifetime of ~20 years

- Experiments will produce about **15 Million Gigabytes** of data each year (about 20 million CDs!)
- LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**
- Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity

CERN IT Department
CH-1211 Genève 23
Switzerland

Grid Computing



Tier 0 – Tier 1 – Tier 2

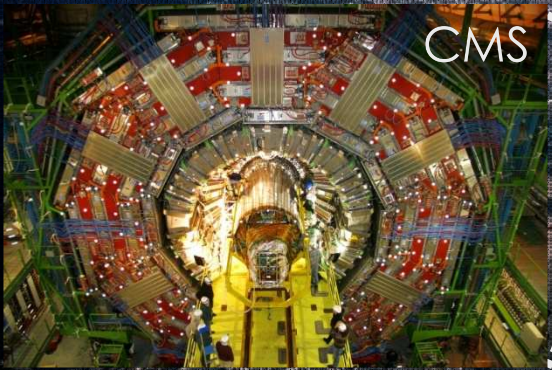
Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis

Tier-2 (~130 centres):
- Simulation
- End-user analysis

Enter a New Era in Fundamental Science

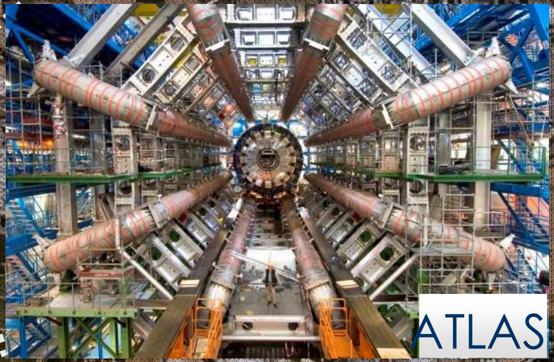
Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.



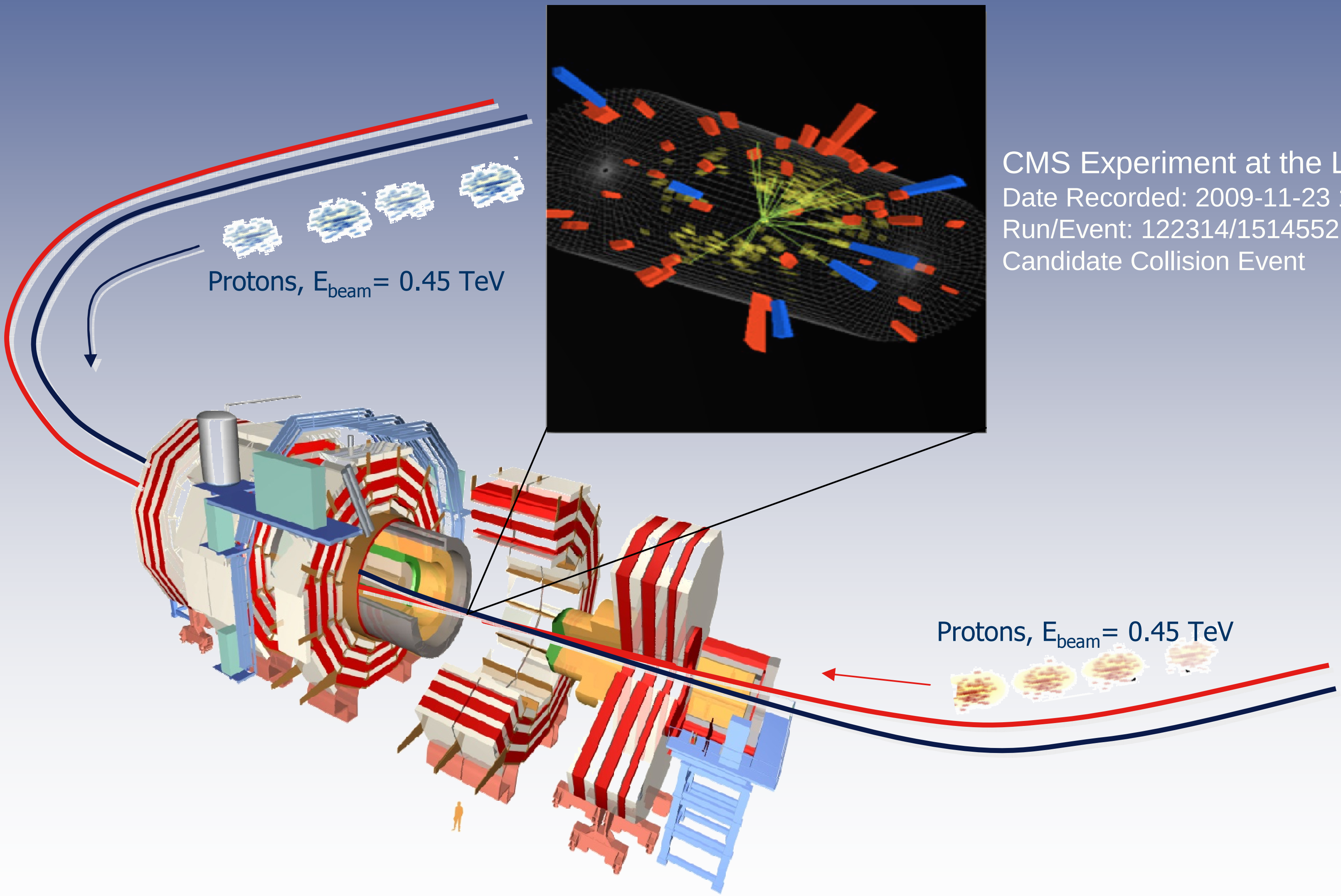
Exploration of a new energy frontier

plus
three smaller experiments

TOTEM
LHCf
MoEDAL



First Collisions at LHC on 23 November 2009 at E_{CM} = 900 GeV

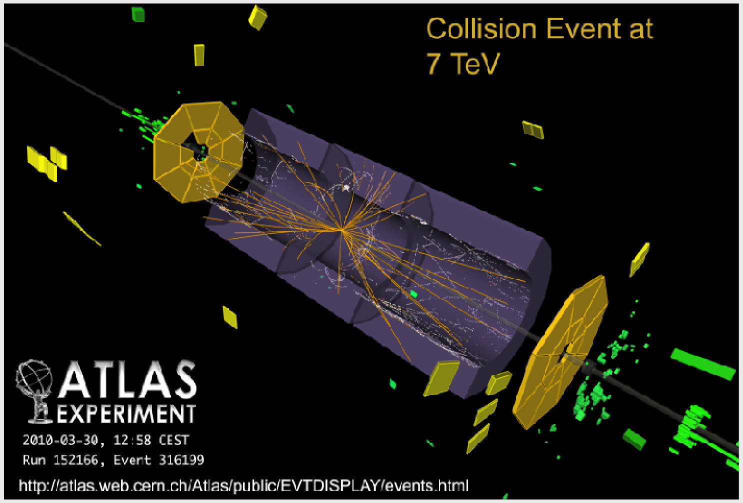


Protons, E_{beam}= 0.45 TeV

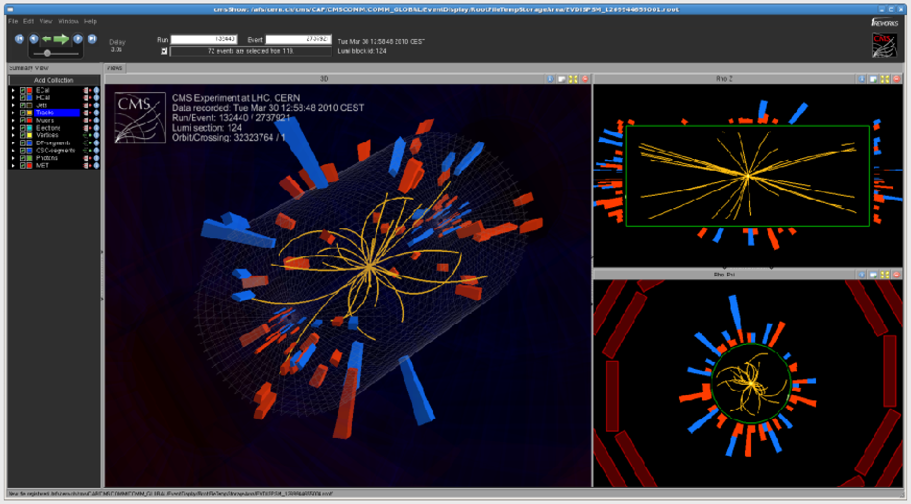
CMS Experiment at the LHC
Date Recorded: 2009-11-23 19:21 CET
Run/Event: 122314/1514552
Candidate Collision Event

Protons, E_{beam}= 0.45 TeV

LHC Started 7-TeV Collisions on 30 March 2010

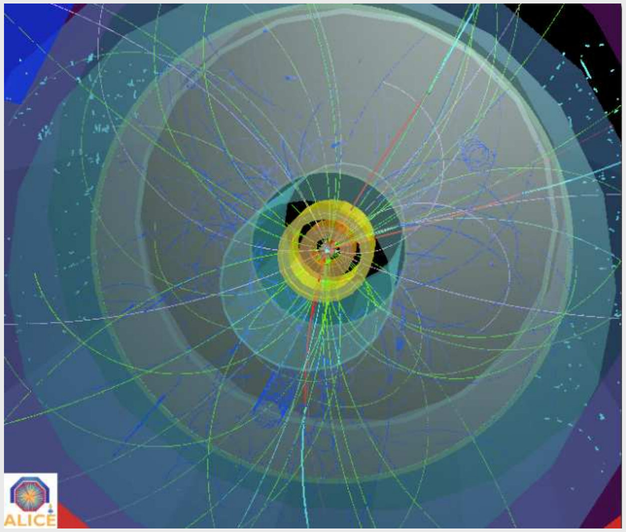

Collision Event at 7 TeV

2010-03-30, 12:58 CEST
Run 152166, Event 316199
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

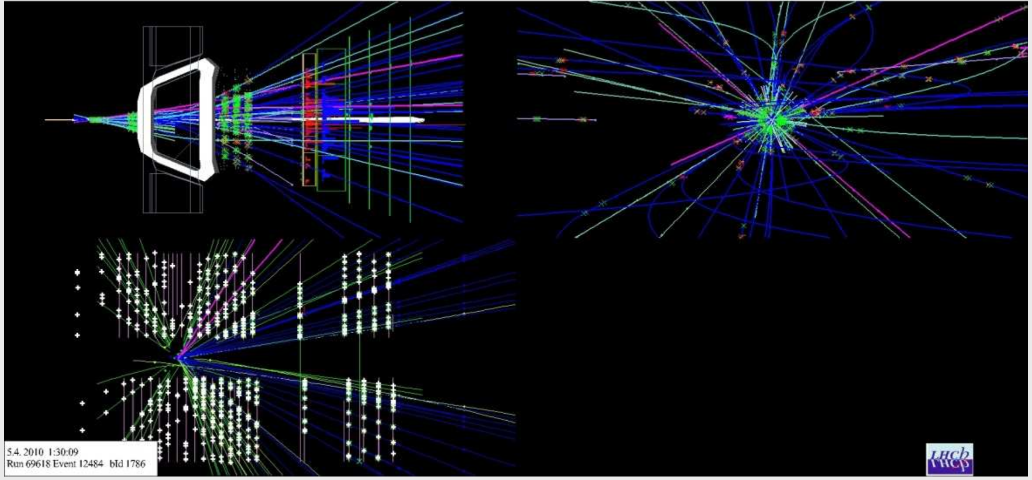


Run 132440 Event 2737921
72 events are selected from 119.
Tue Mar 30 12:58:48 2010 CEST
Lumi block id: 124

CMS Experiment at LHC, CERN
Data recorded: Tue Mar 30 12:53:48 2010 CEST
Run/Event: 132440 / 2737921
Lumi section: 124
Orbit/Crossing: 32323764 / 1



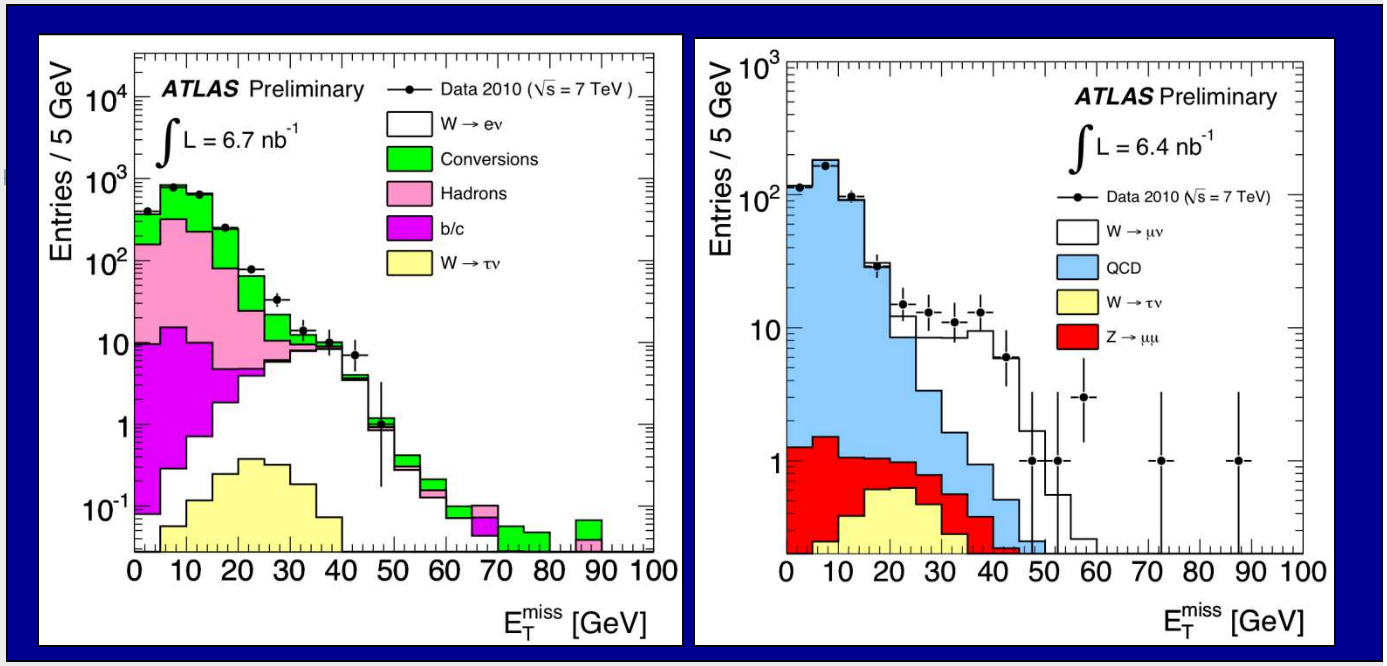
LHCb Event Display


5.4. 2010 1:30:09
Run 69618 Event 12484 bId 1786

After pre-selection:

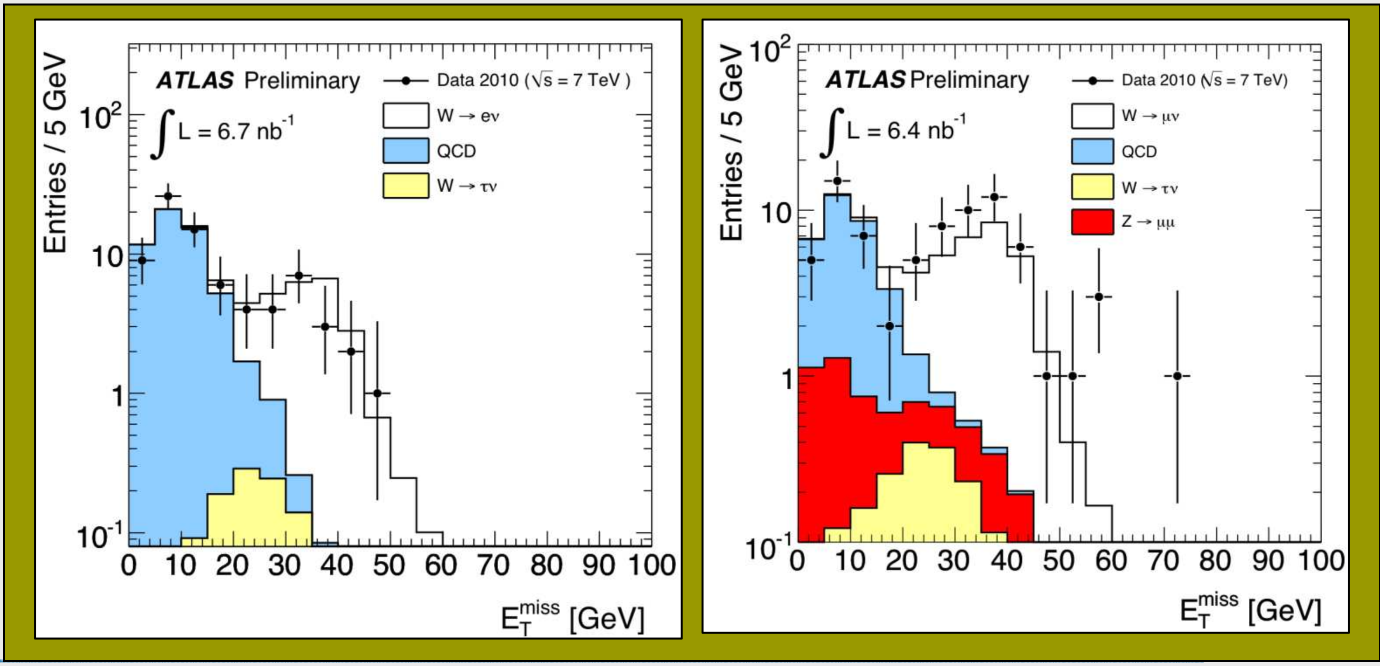
- -- W → eν:
  - loose $e^{\pm}$, $E_T > 20$ GeV
- -- W → μν:
  - $p_T(\mu) > 15$ GeV
  - $|\Delta p_T(\text{ID-MS})| < 15$ GeV
  - $|Z_\mu - Z_{vtx}| < 1$ cm

MC: normalised to data (total number of events)



Observed events: 57

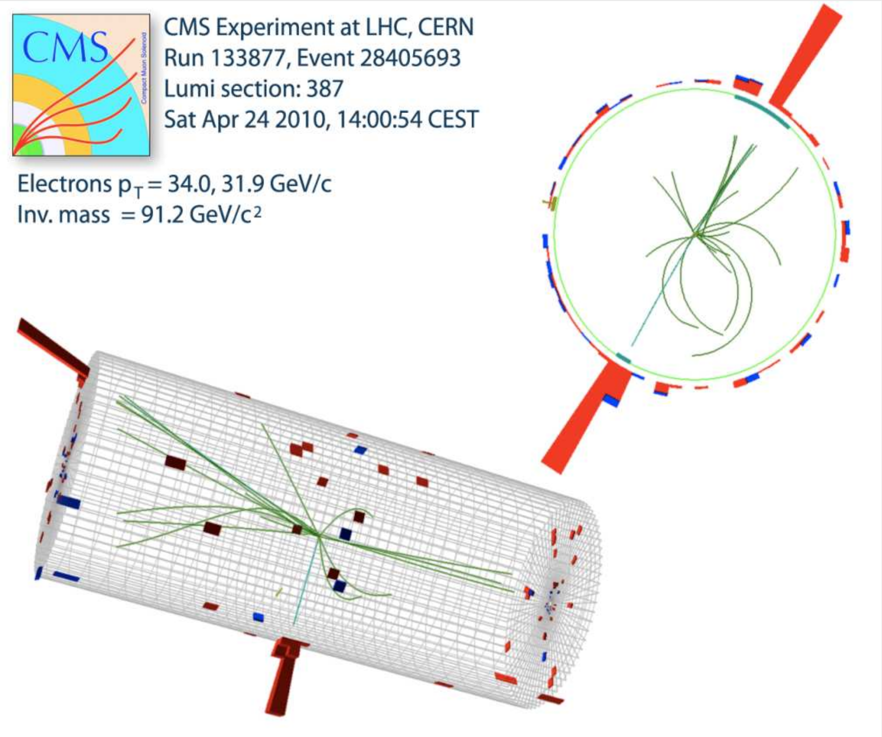
After all cuts but E_T^{miss} and m_T

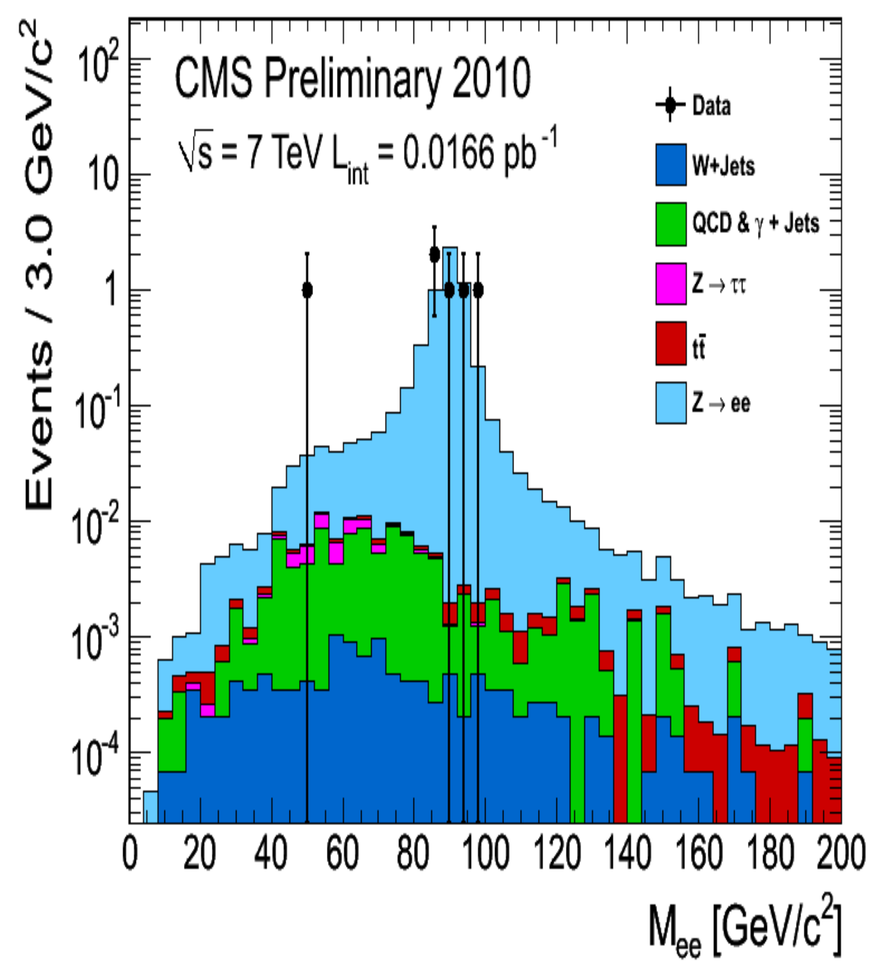


$Z \rightarrow e^+e^-$ Observation

Event selection: *both electrons with a SuperCluster with Et > 20 GeV*

Monte Carlo : *cross section normalized to 17 nb^{-1} integrated luminosity*

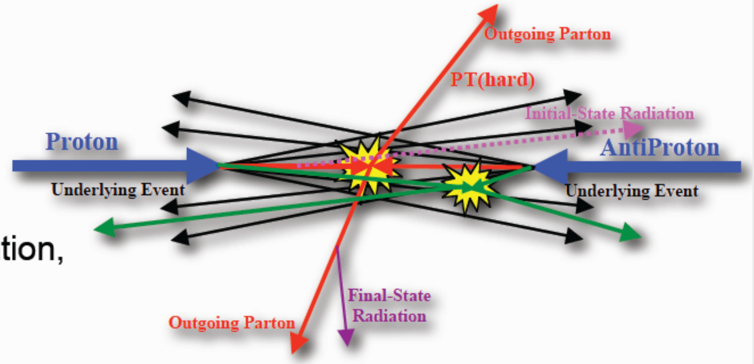




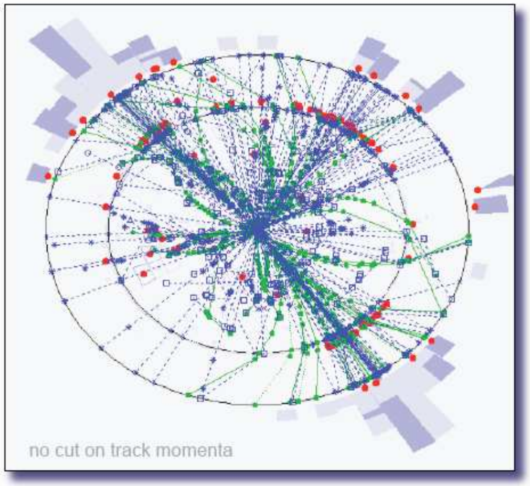
5 $Z \rightarrow e^+e^-$ candidates

Further Difficulties

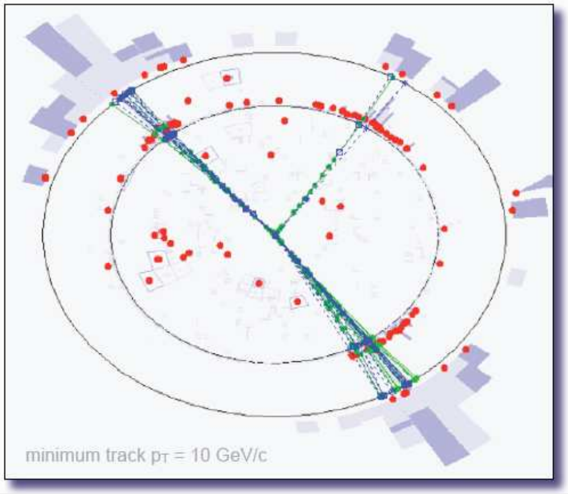
- Pile Up : many additional soft proton-proton interactions
  - up to 20 at highest LHC luminosity
- Underlying event
  - beam-beam remnants, initial state radiation, multiple parton interactions
  - gives additional energy in the event



- All this additional energy has nothing to do with jet energies
  - **have to subtract it**

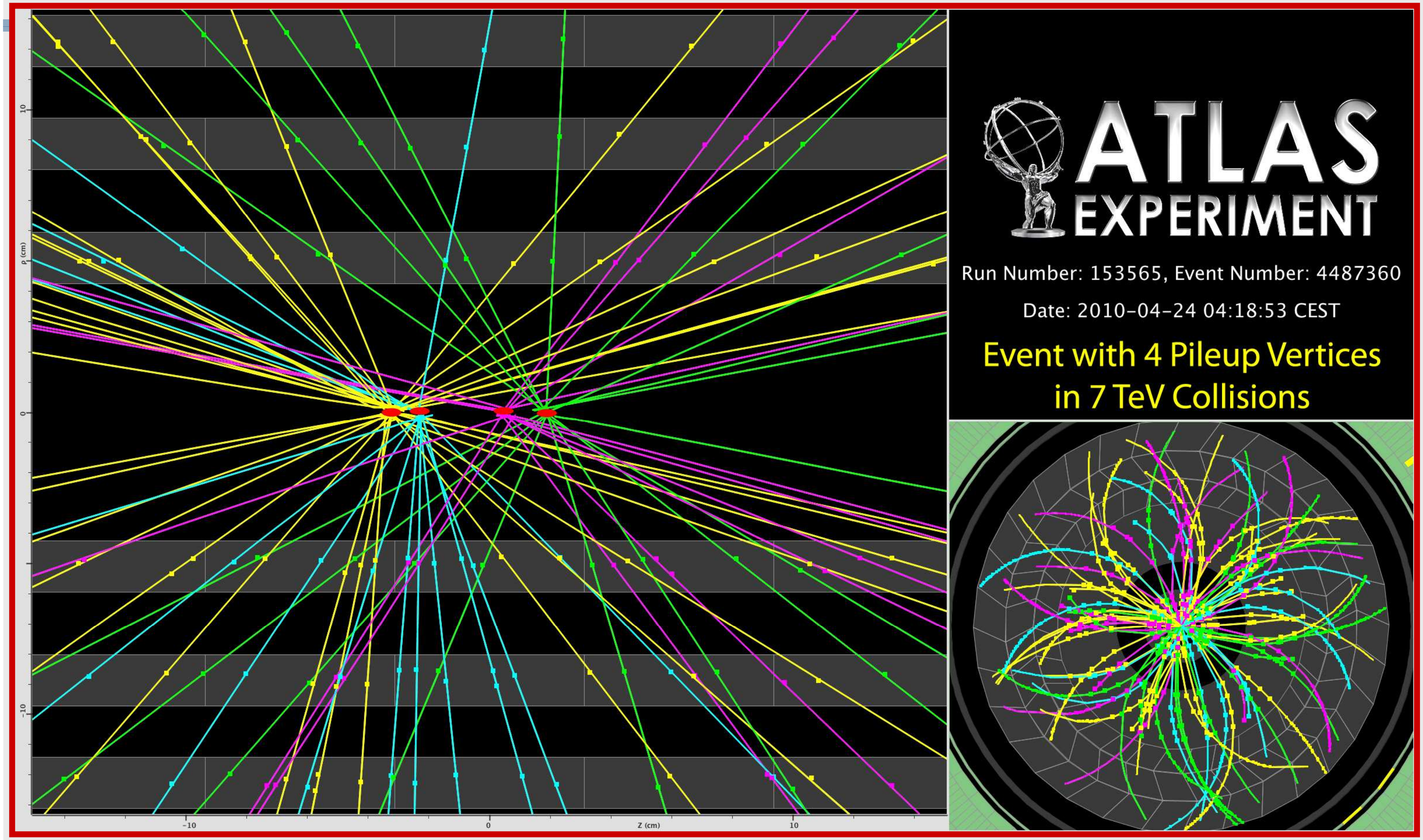


no cut on track momenta



minimum track p_T = 10 GeV/c

Preparing for the future : pile-up reconstruction
4 pp interactions in the same bunch-crossing



~ 10-45 tracks with p_T >150 MeV per vertex
Vertex z-positions : −3.2, −2.3, 0.5, 1.9 cm (vertex resolution better than ~200 μm)

Conclusions

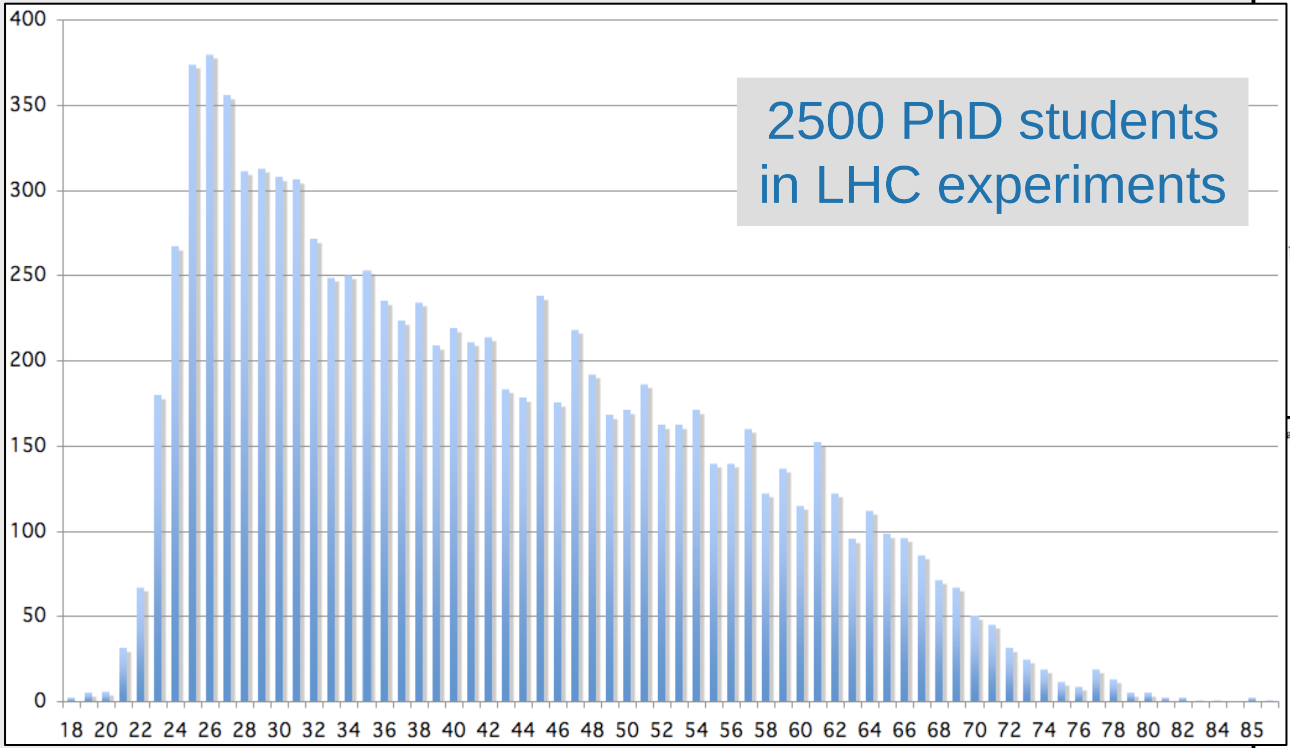
- Experimental methods in Particle Physics is an inter-disciplinary study between
  - Experimental physics
  - Theoretical physics
  - Detector physics (and technology)
  - High-performance computing
  - Accelerator physics
  - Statistical analysis
  - ….

An excellent training ground for young scientists

Age Distribution of Scientists

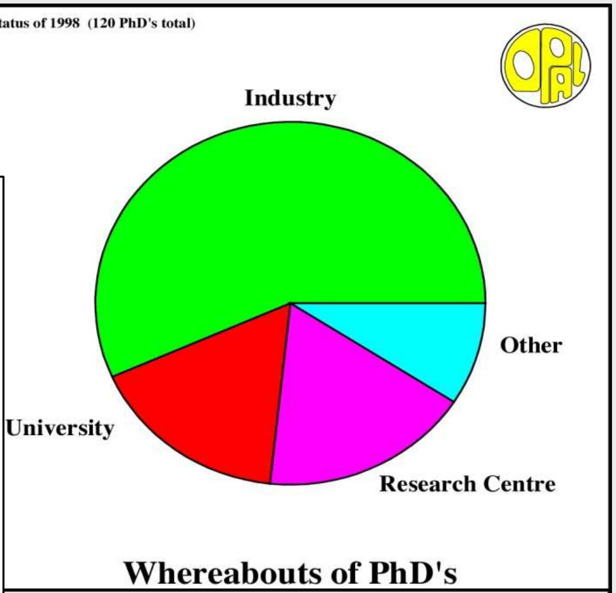
- and where they go afterwards

Survey in March 2009

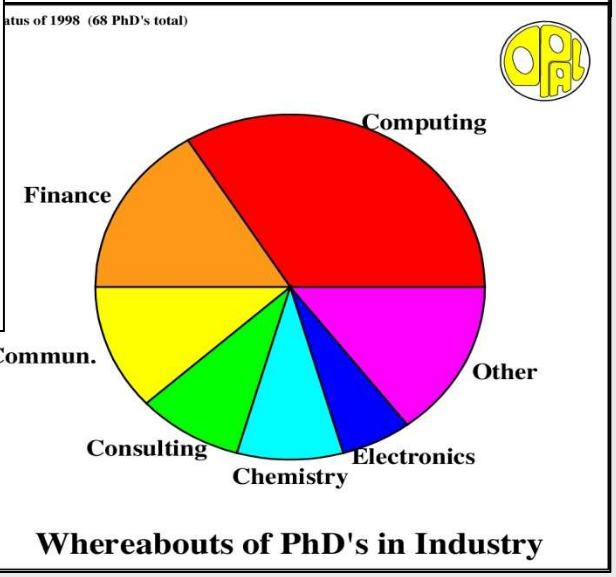


2500 PhD students
in LHC experiments

They do not all stay: where do they go?



Whereabouts of PhD's



Whereabouts of PhD's in Industry