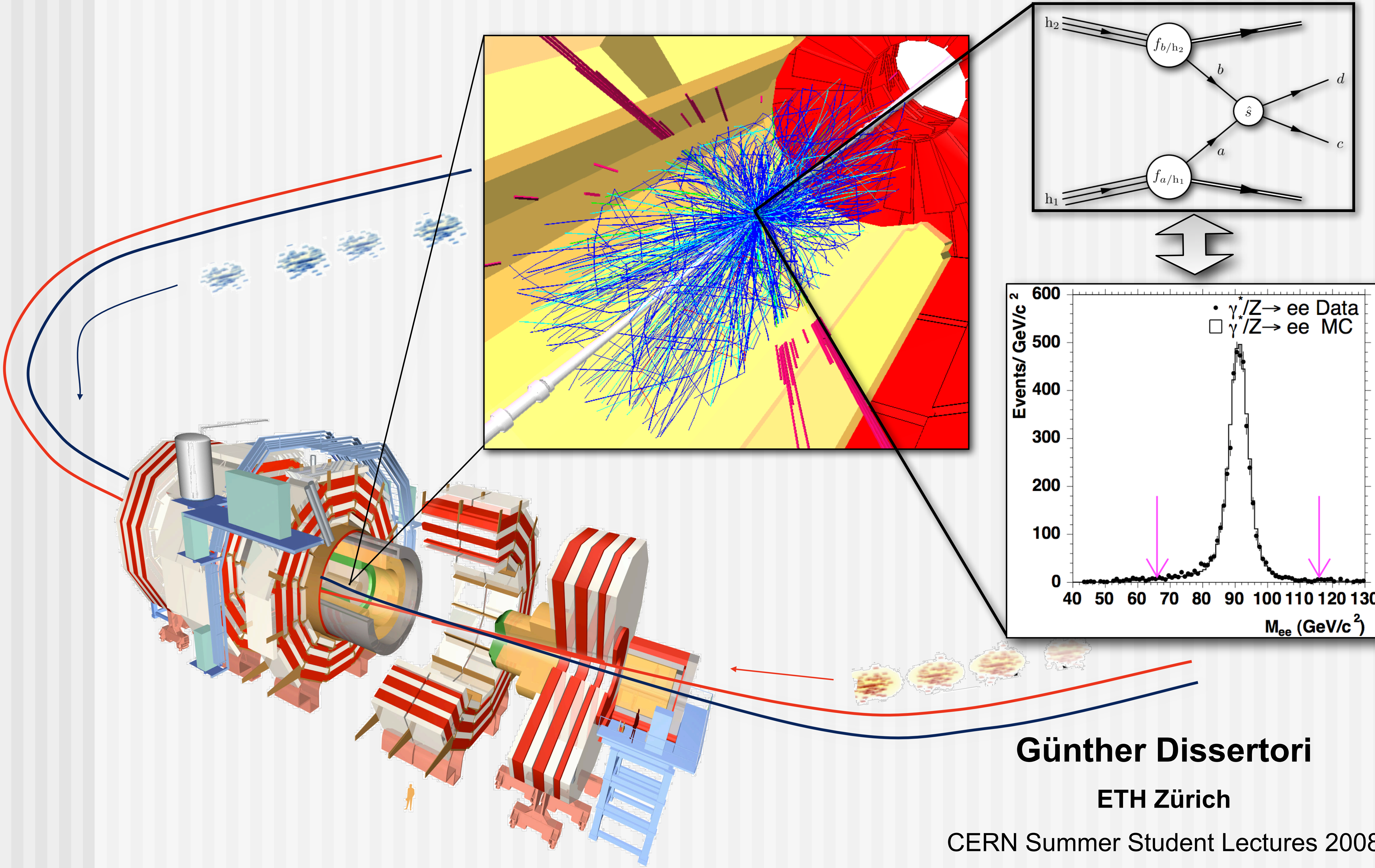
From Raw Data to Physics Results



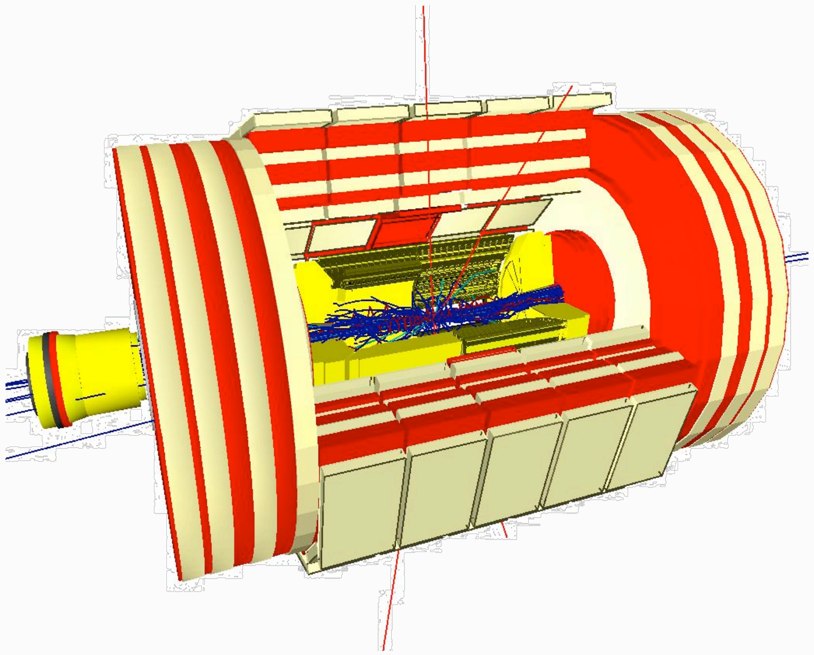
Günther Dissertori

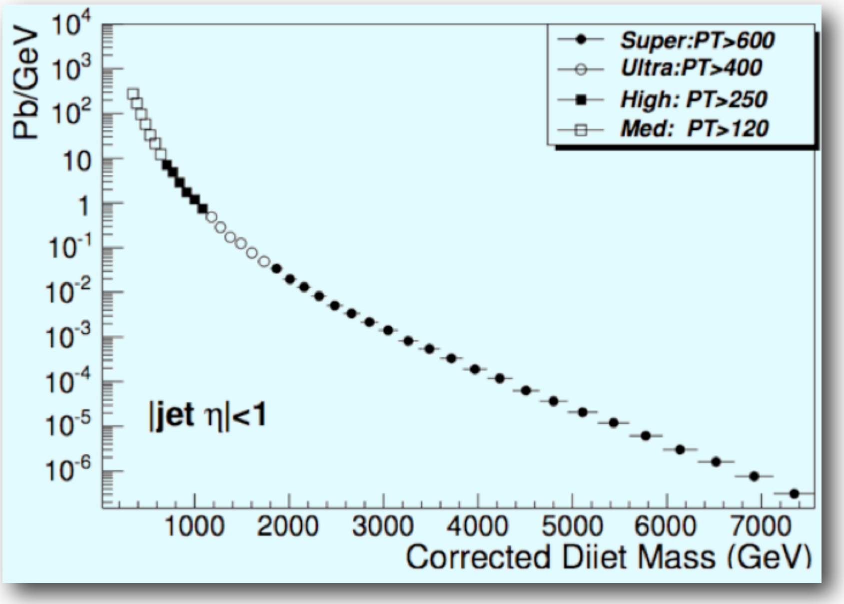
ETH Zürich

CERN Summer Student Lectures 2008

Outline

- “Executive Summary”
  - The whole story in a nutshell
- Some more details
  - Introduction
  - A simple example : Z decays
  - A more complicated example : Jets
- How is it done in practice?
  - Track and Calorimeter energy reconstruction
  - High-level algorithms : Jets
  - The computing part
- Summary



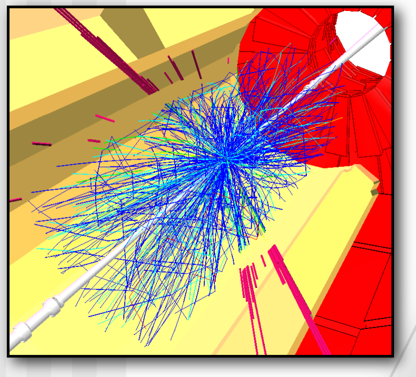


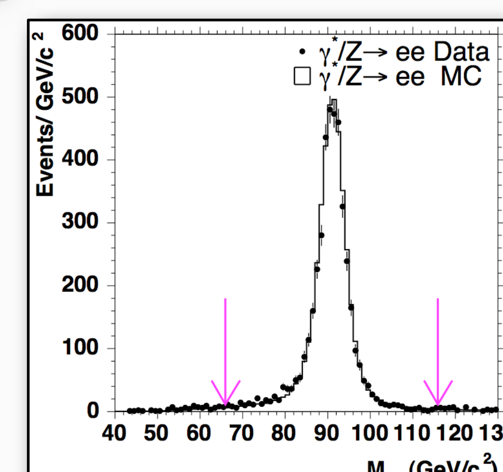
- Disclaimer : Several slides based on past CSS lectures by B. Jacobsen
- thanks also to J. Weng, T. Punz, A. Valassi

The whole lecture in a nutshell

“But you should not leave immediately after this....”

Data Analysis Chain





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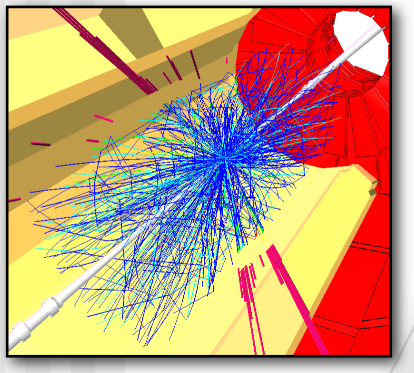
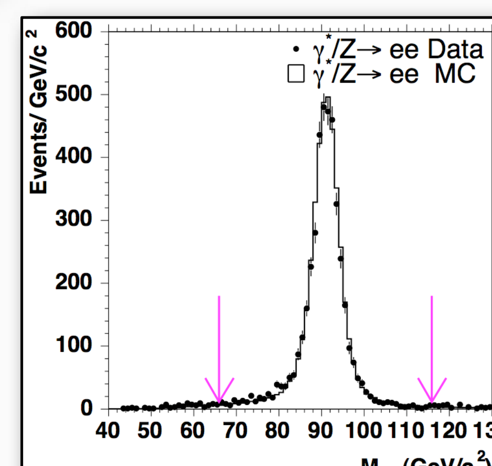


- Have to collect data from many channels on many sub-detectors (millions)



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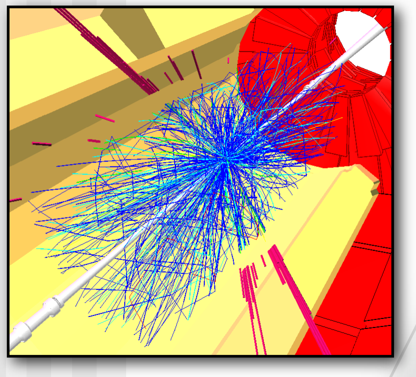

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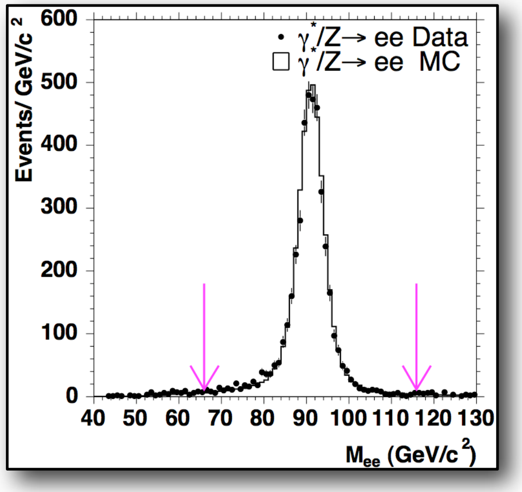

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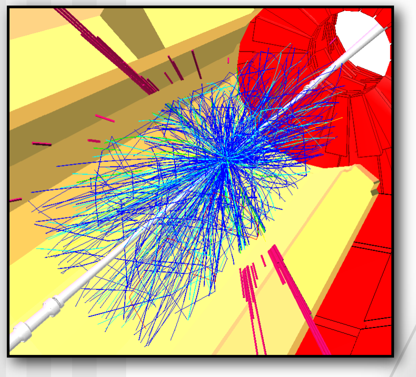

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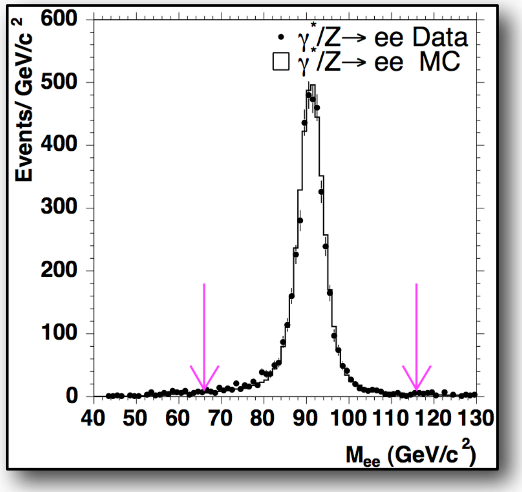

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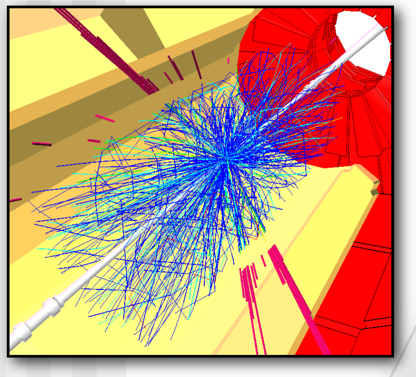

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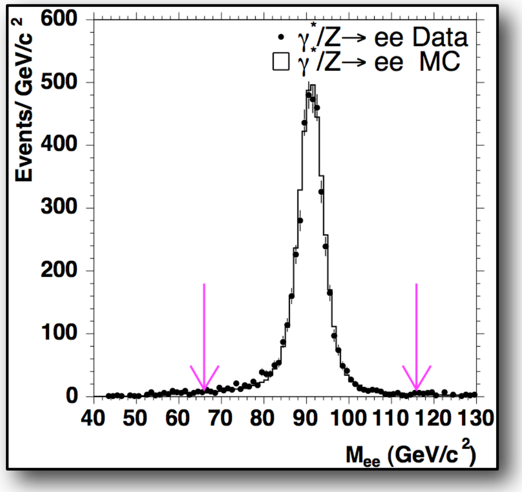
- Decide to read out everything or throw event away (Trigger)
- Build the event (put info together)
- Store the data



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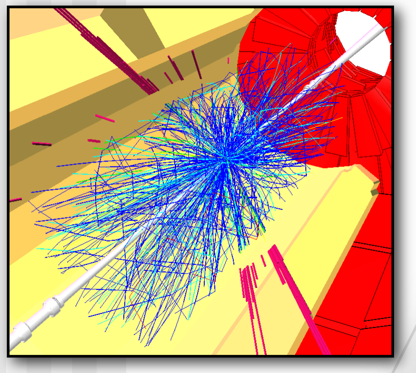

- Have to collect data from many channels on many sub-detectors (millions)
- Decide to read out everything or throw event away (Trigger)
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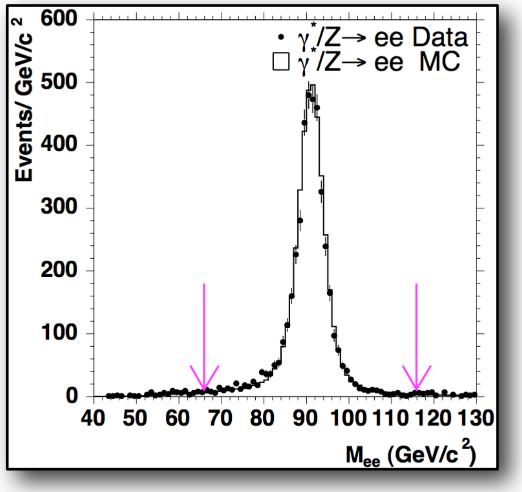
- Analyze them
  - reconstruction, user analysis algorithms, data volume reduction



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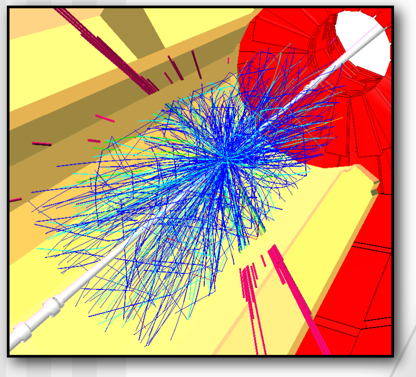

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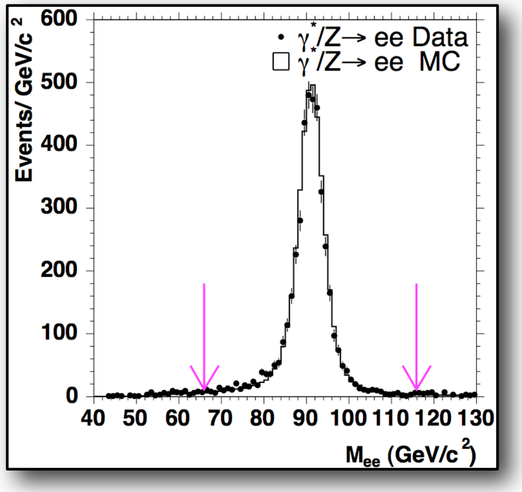
- do the same with a simulation
  - correct data for detector effects



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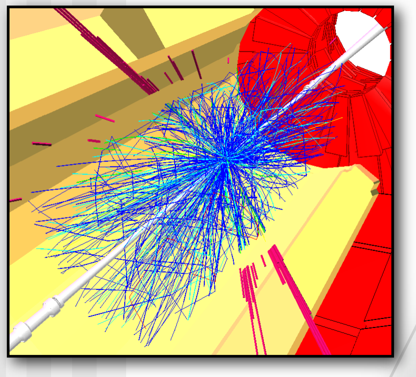

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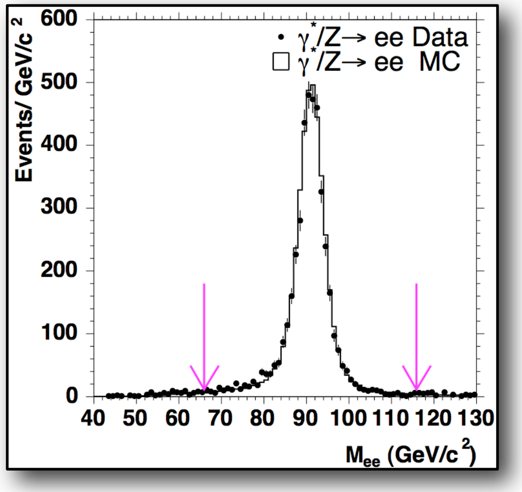
- do the same with a simulation
  - correct data for detector effects
- Compare data and theory



DAQ chain (see lectures by N. Neufeld)

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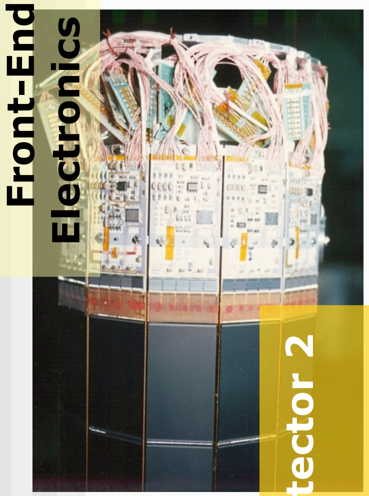
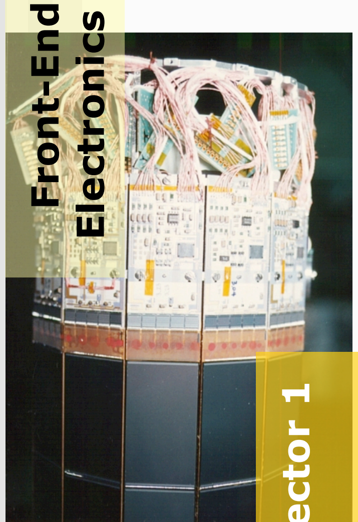
Detector Front-End

⋮





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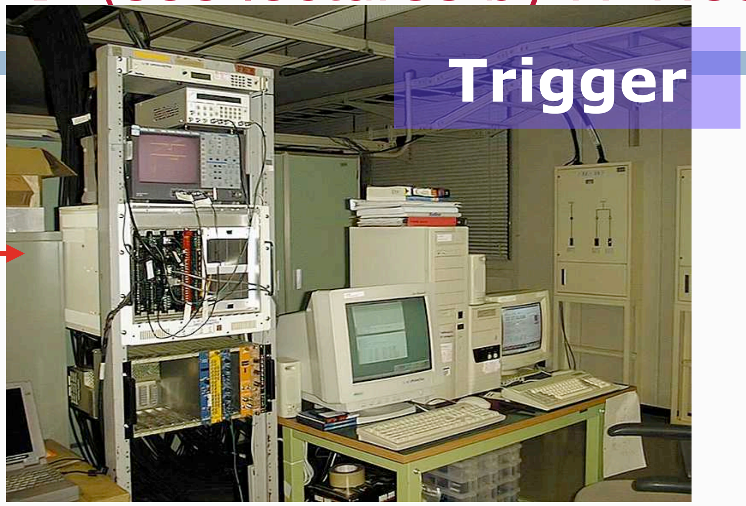

Detector Front-End

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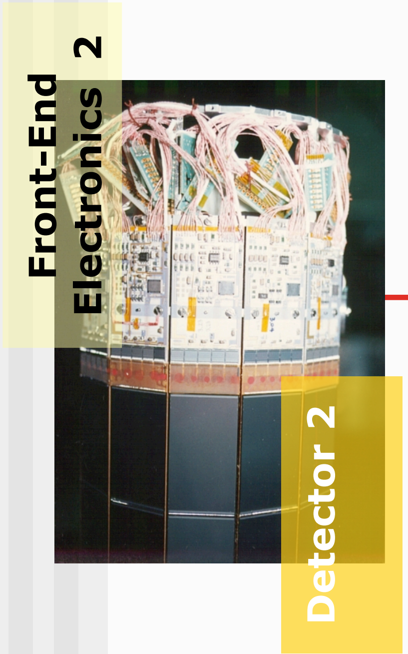

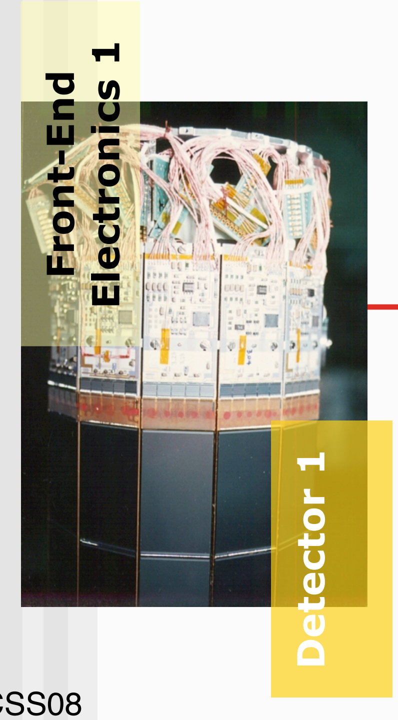

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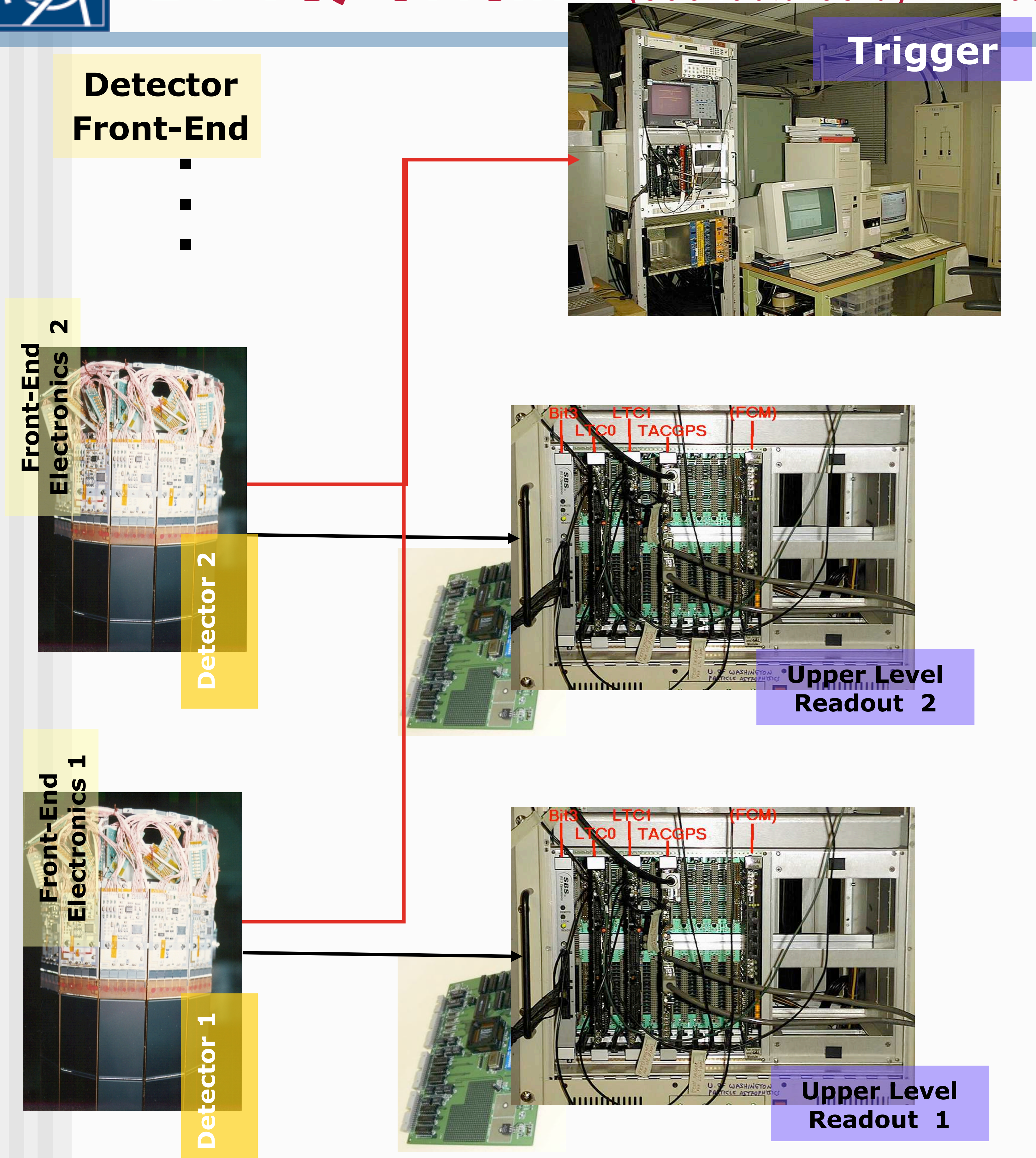

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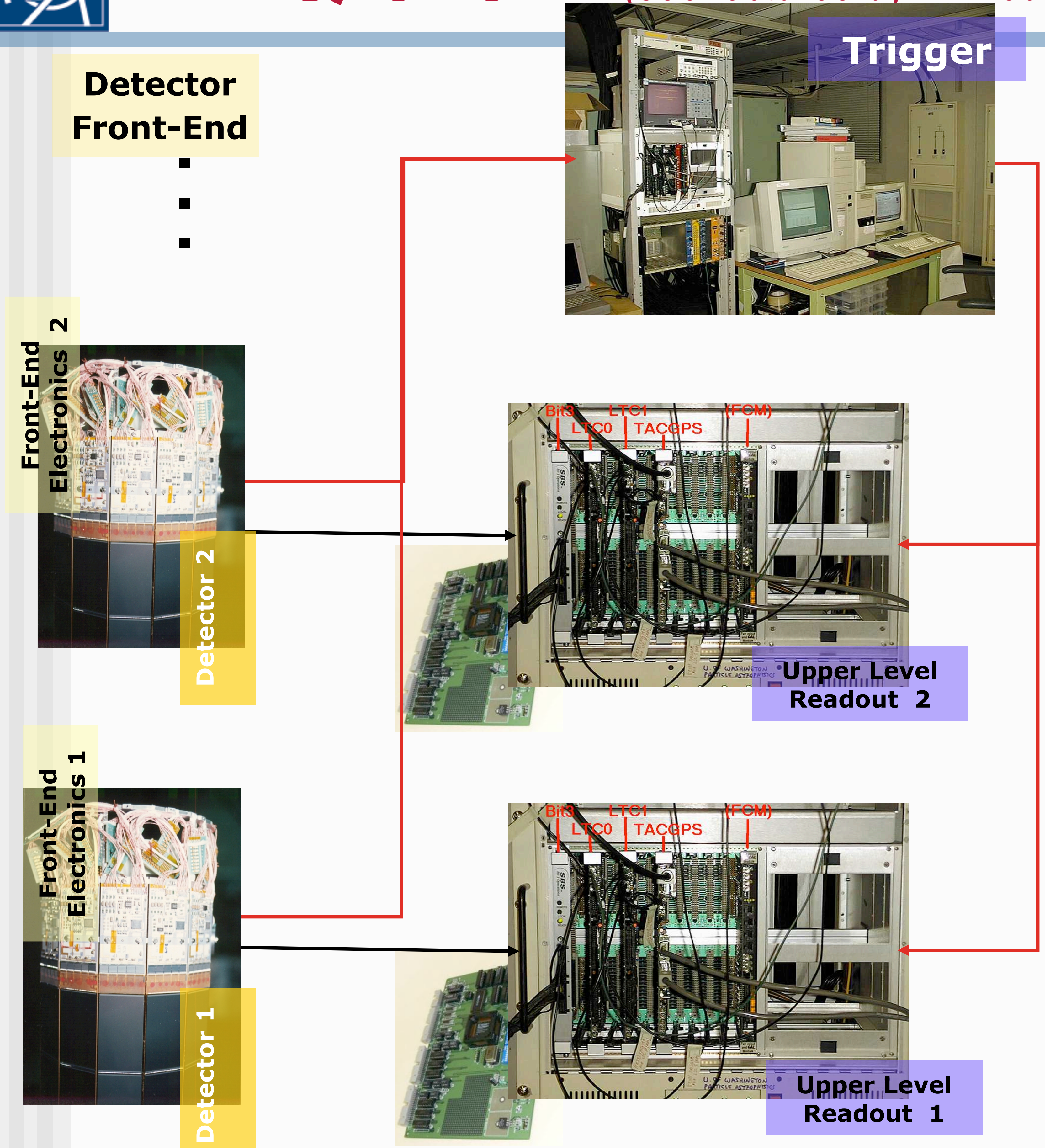

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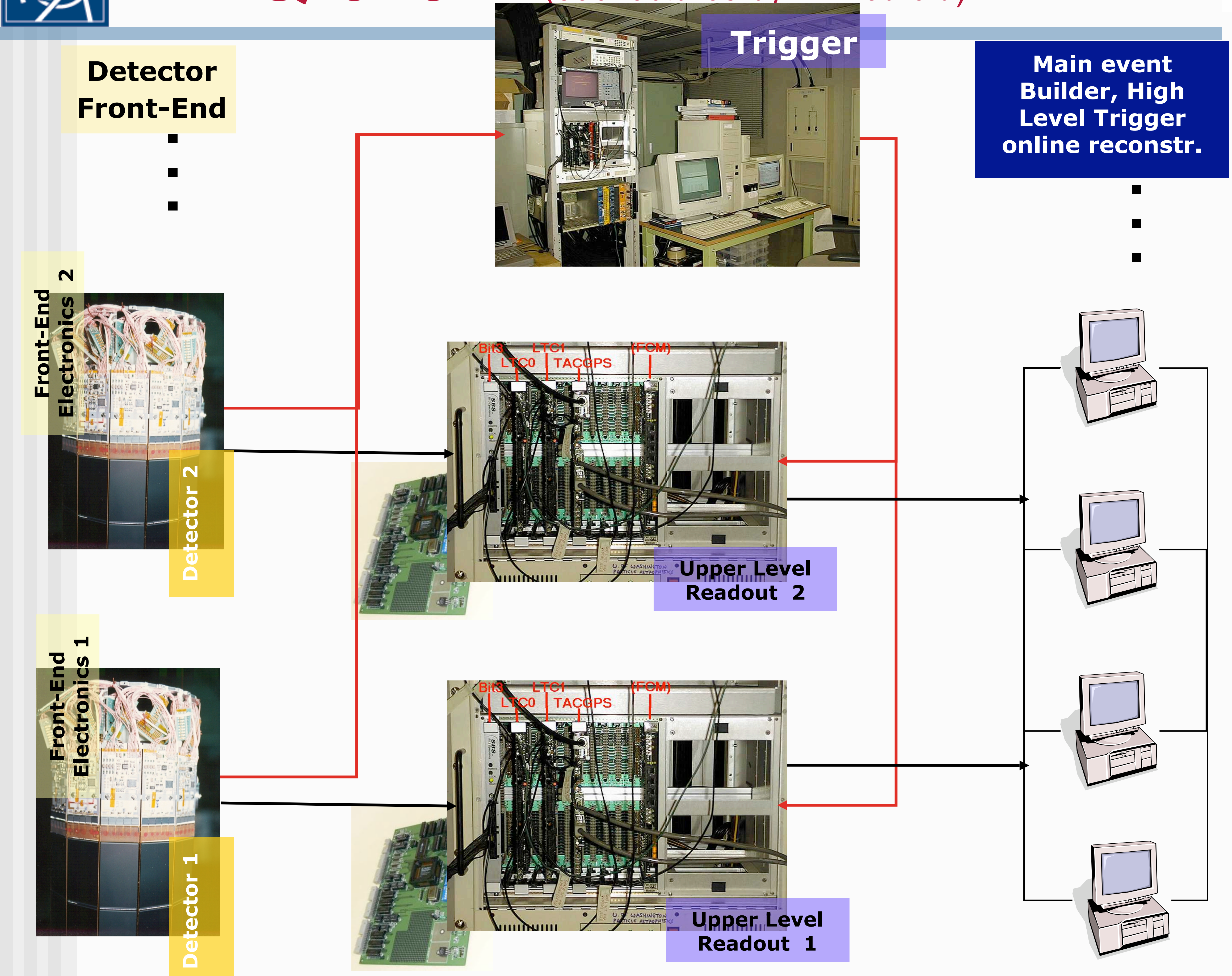

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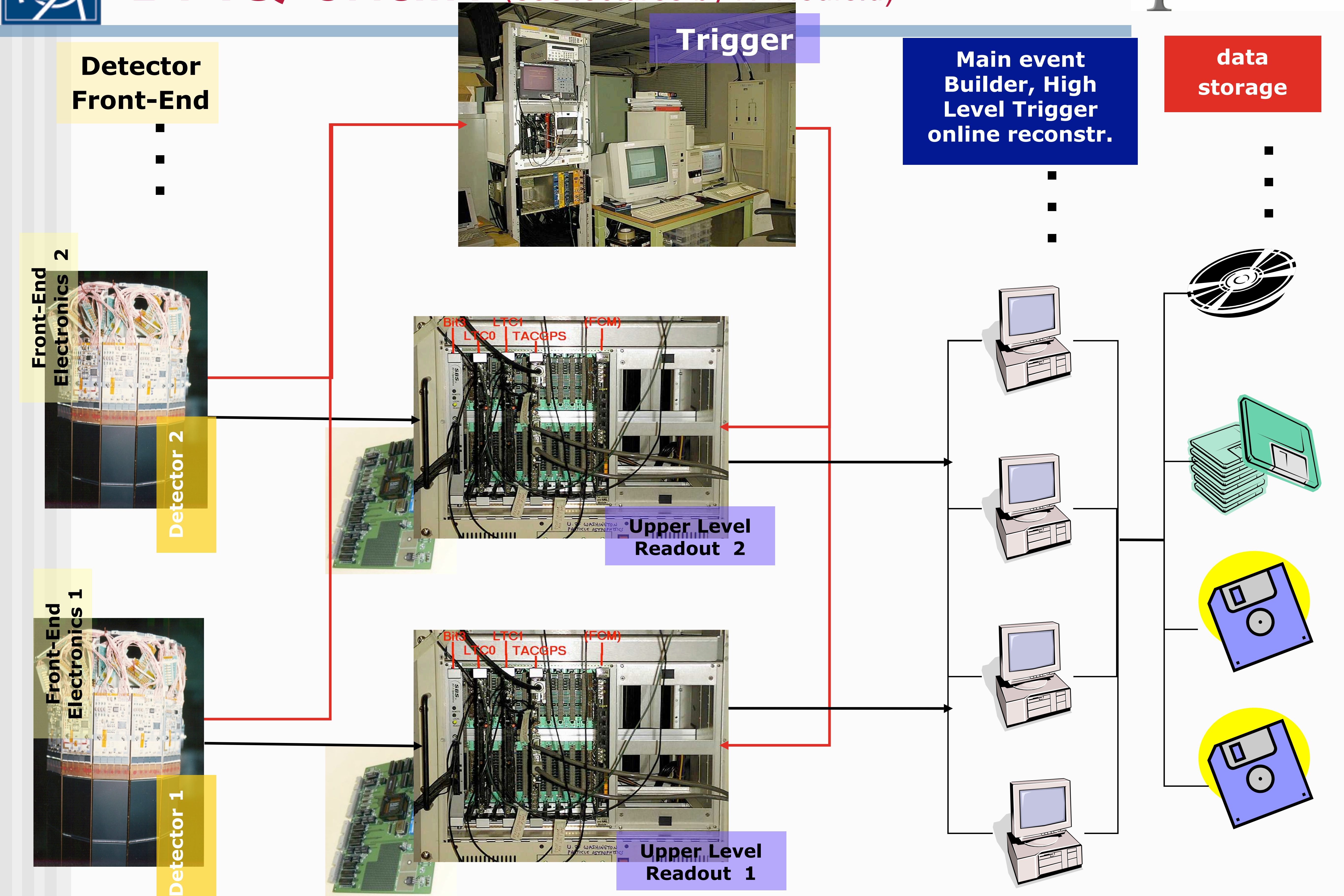

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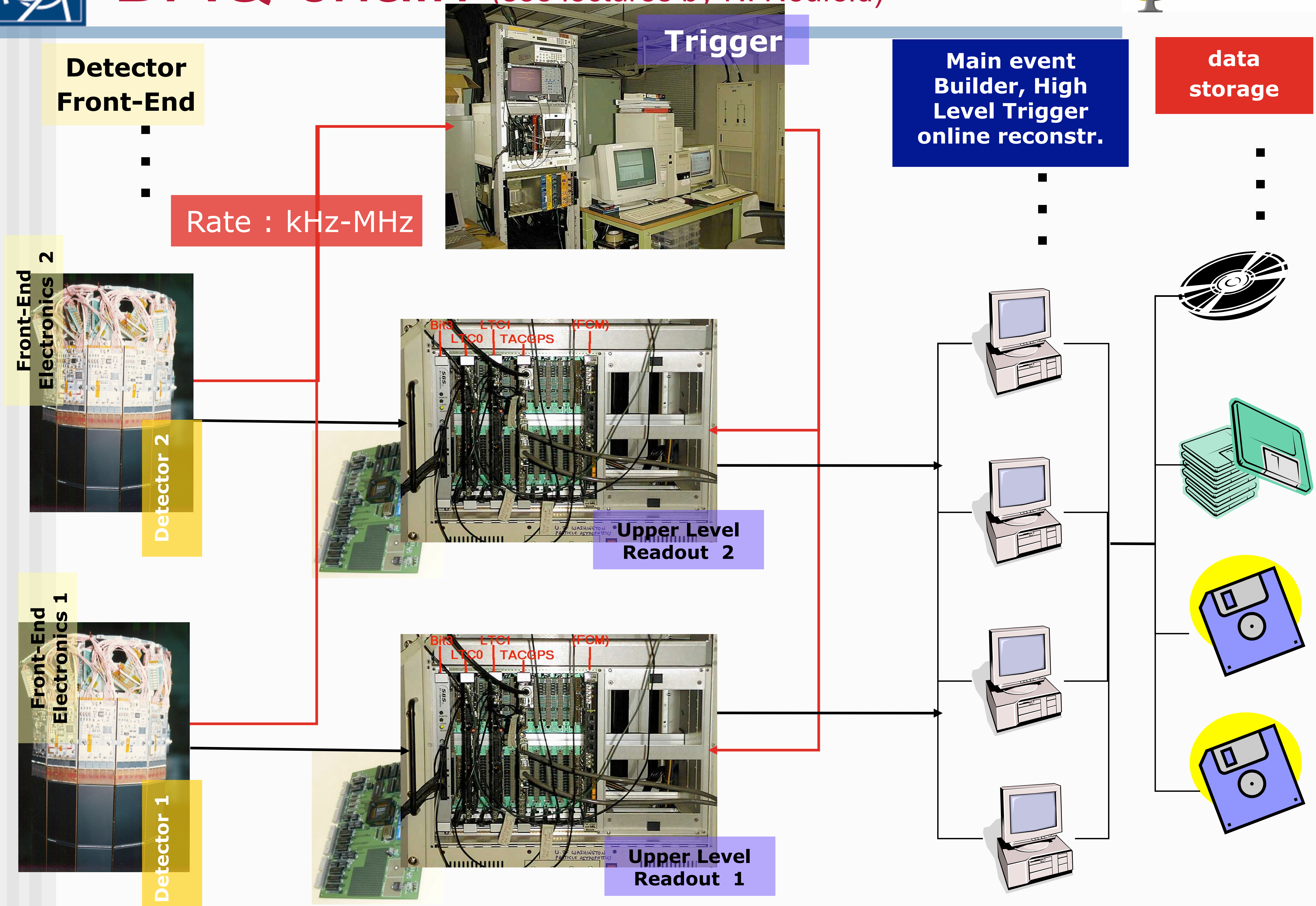

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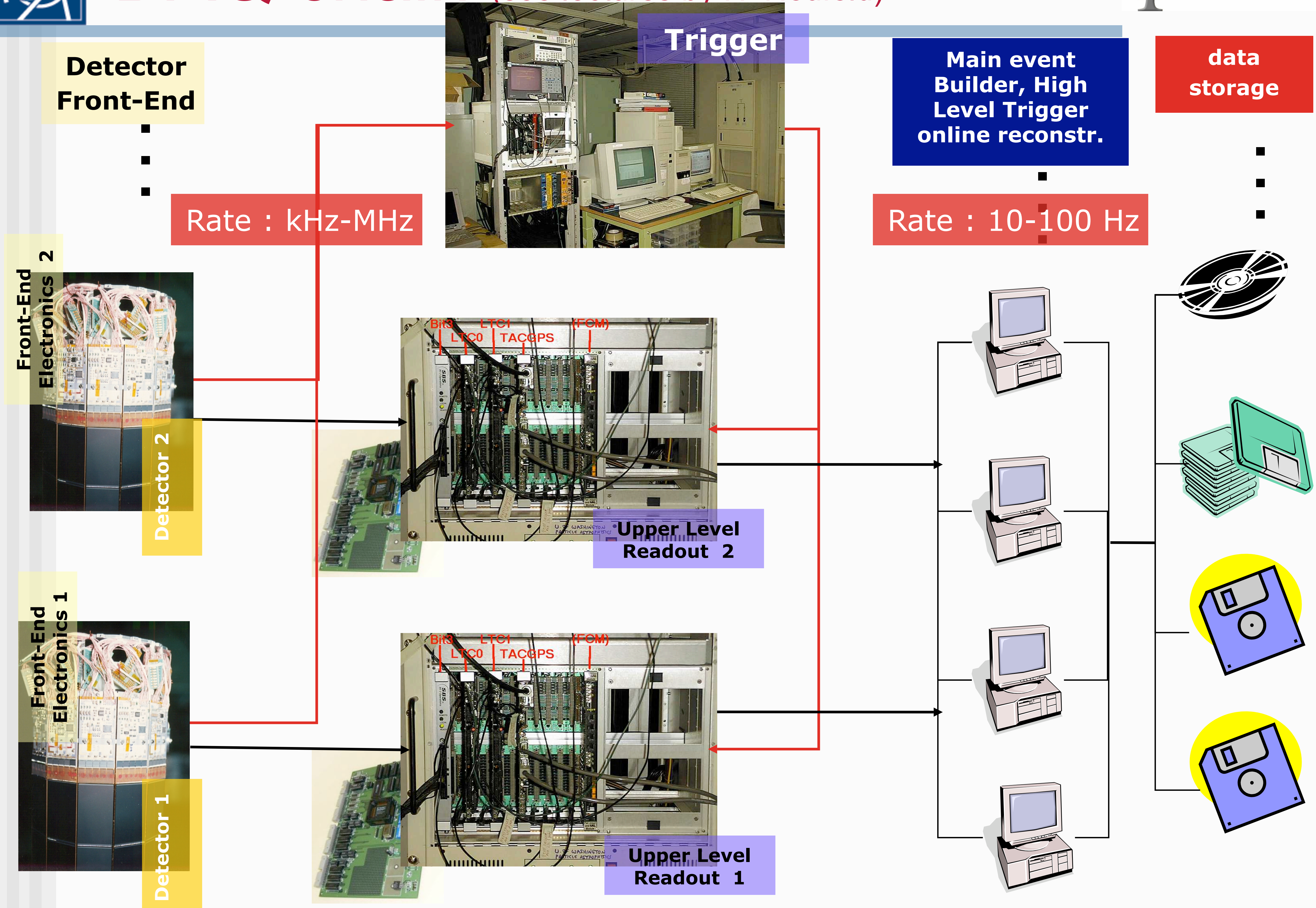
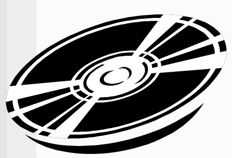


Offline Analysis Chain

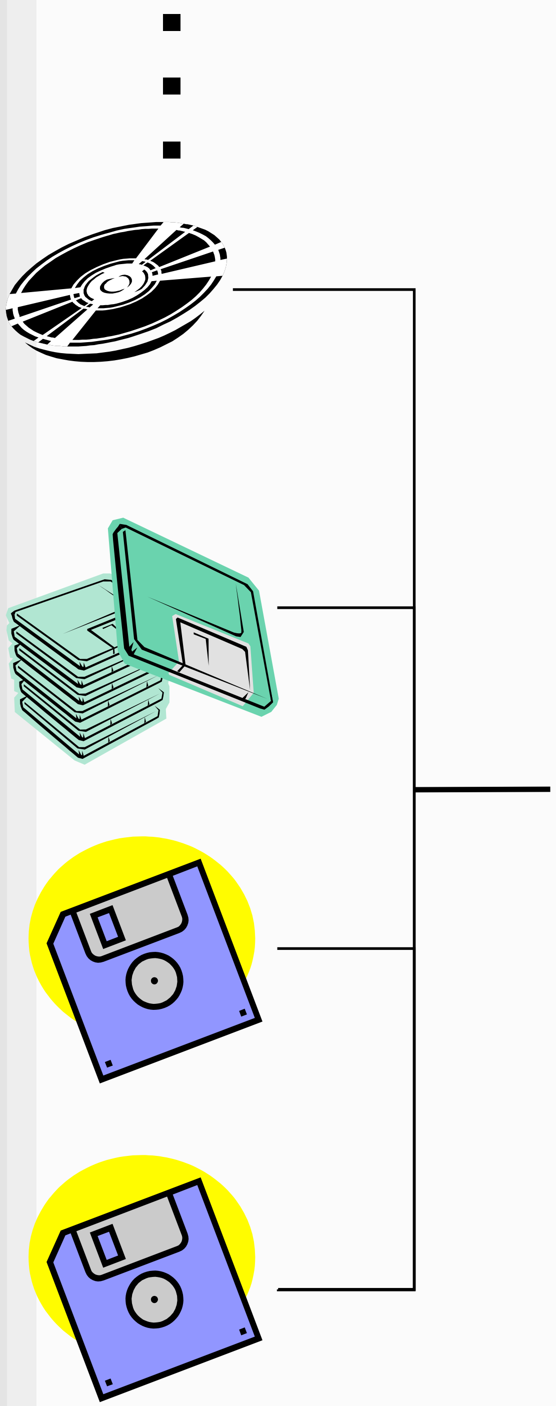
Offline Analysis Chain

data storage



Offline Analysis Chain

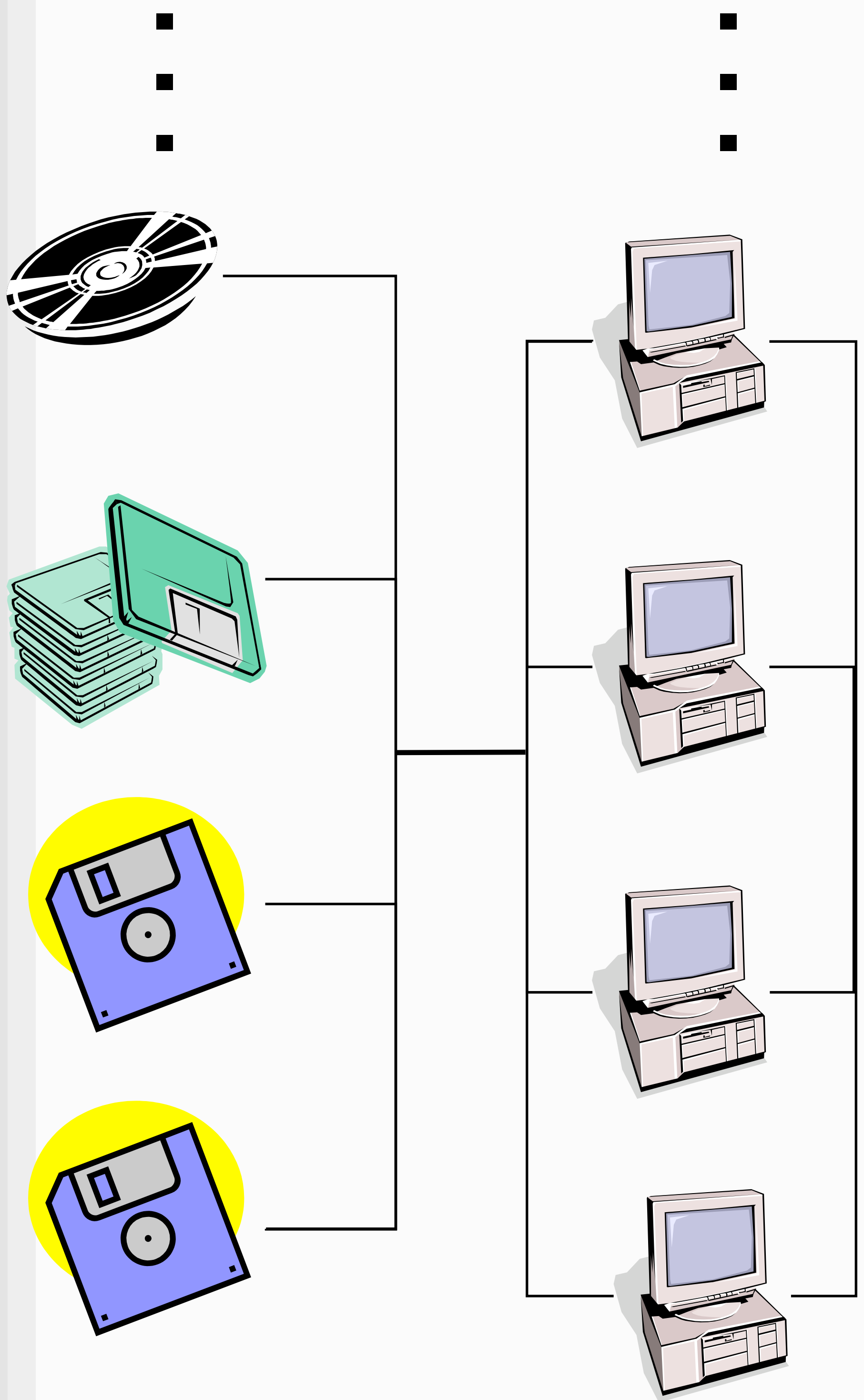
data storage



Offline Analysis Chain

data storage

offline reconstruction, calibration, alignment



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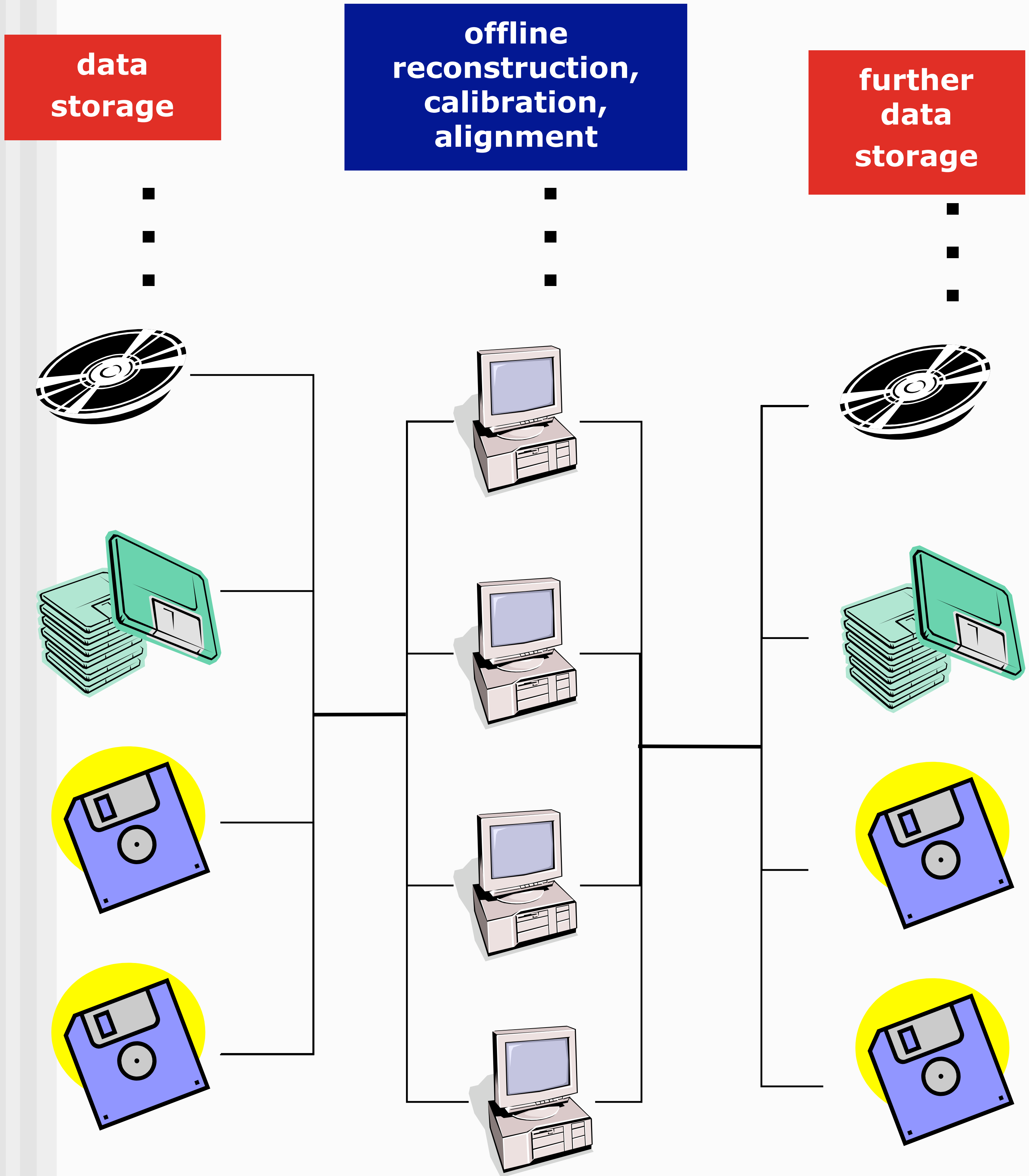

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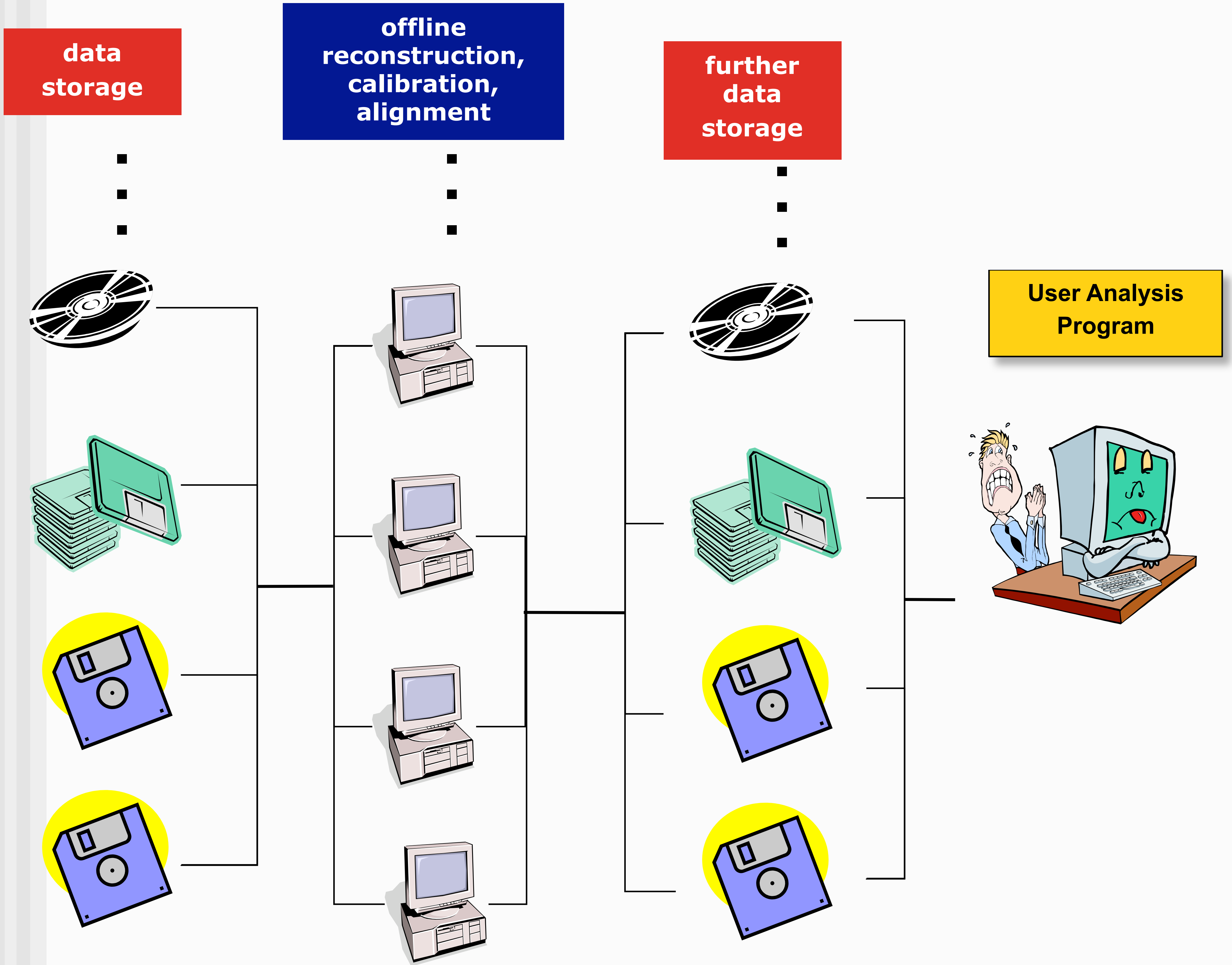

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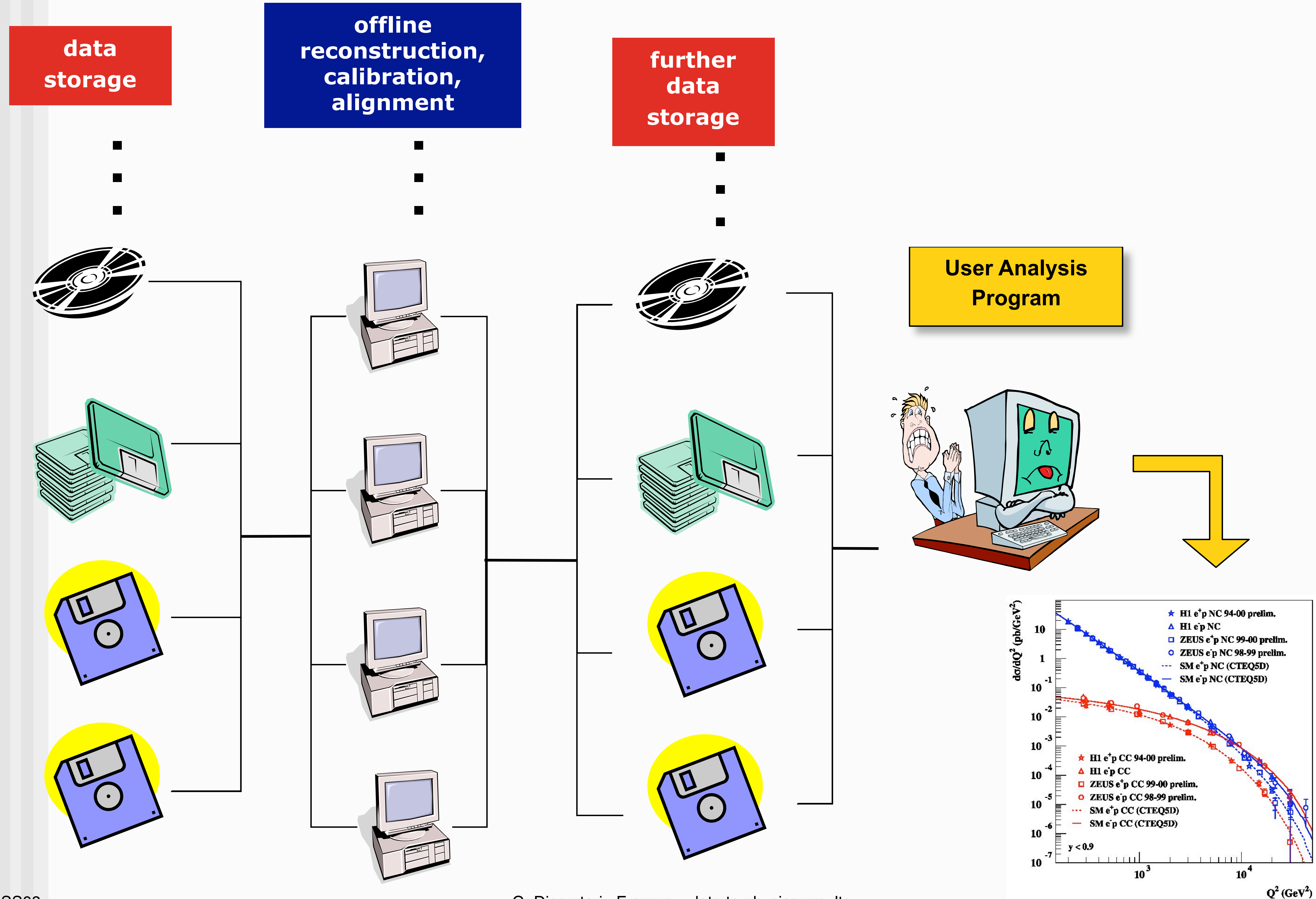

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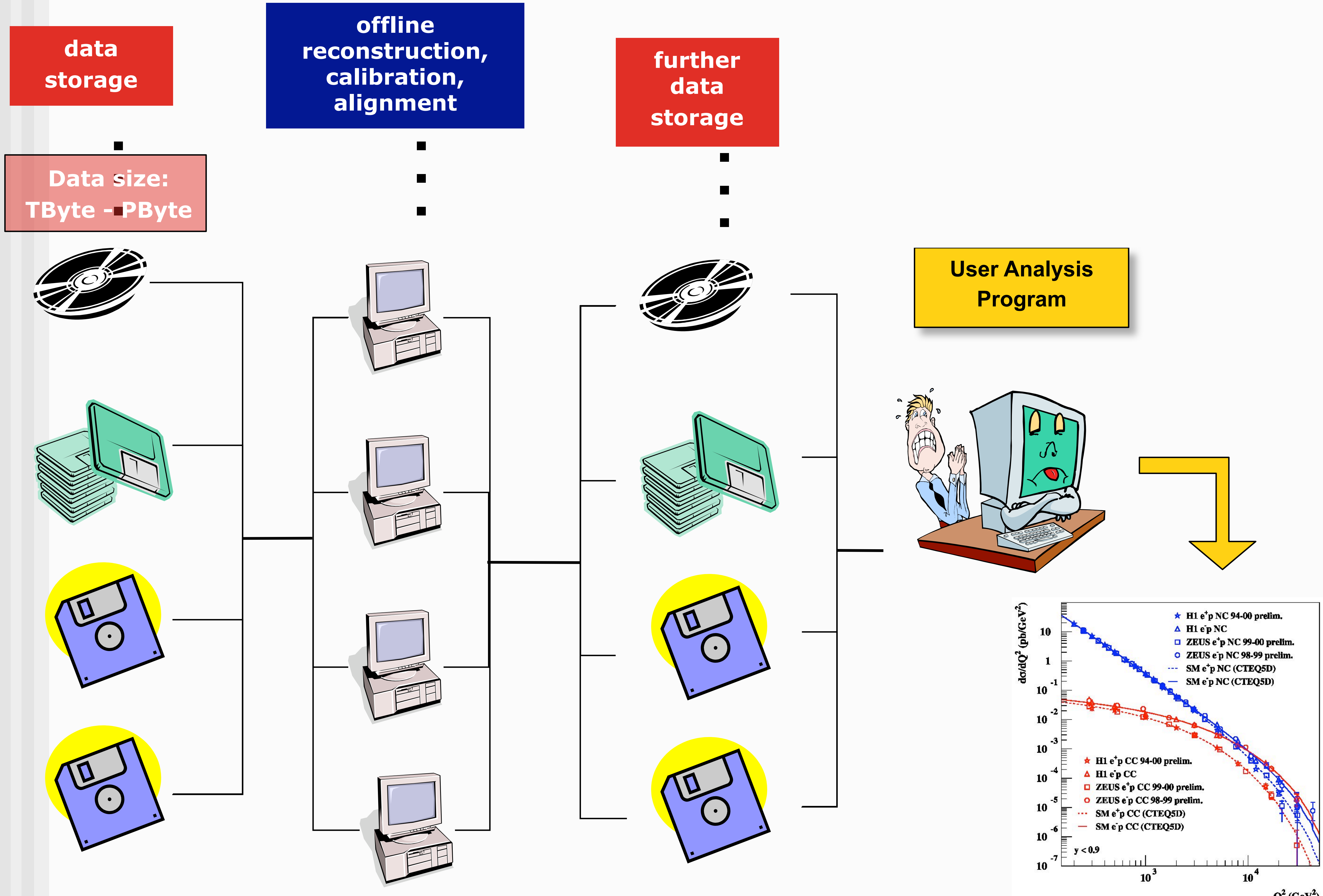

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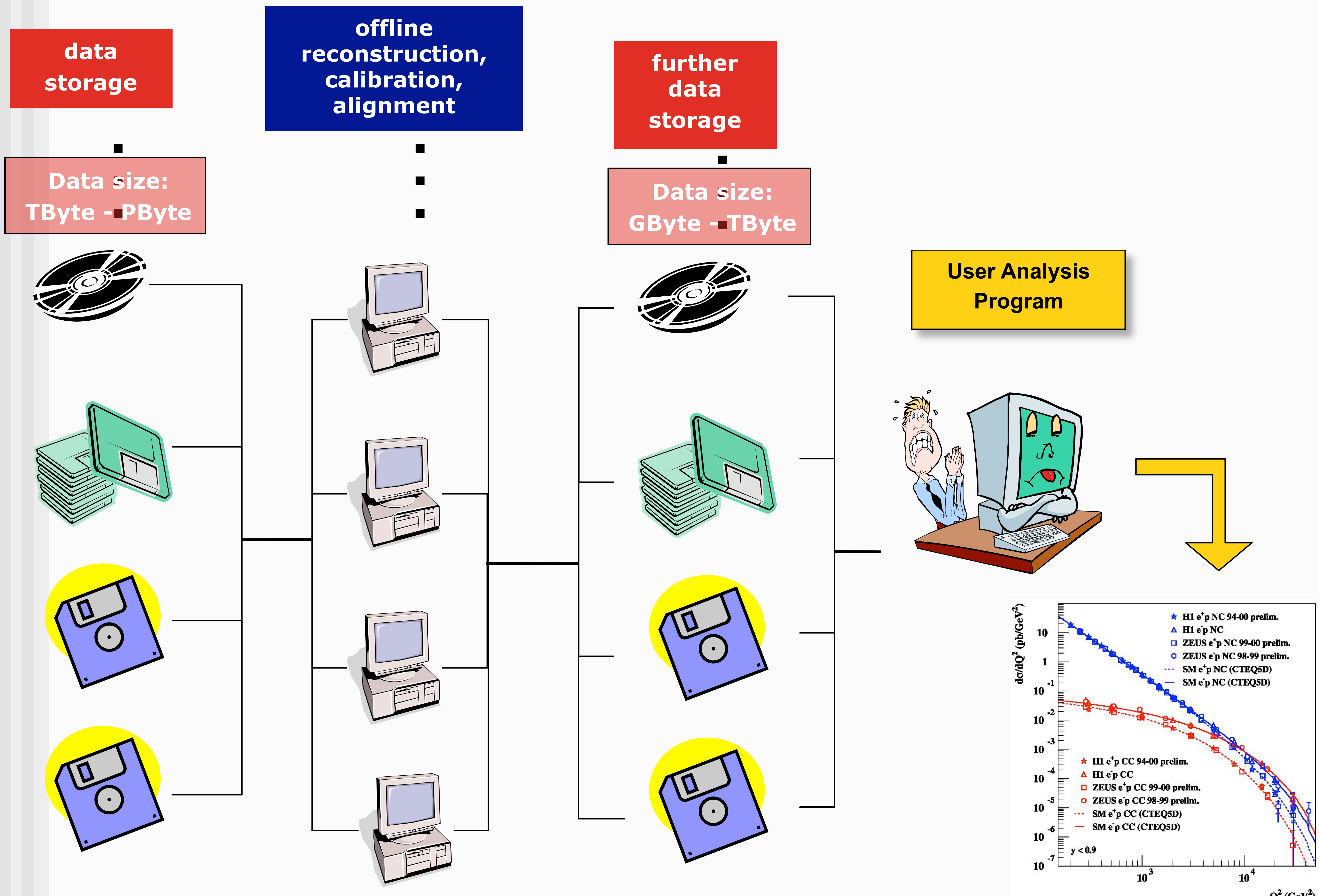


Offline Analysis Chain

ETH Institute for Particle Physics

data storage

Data size: TByte - PByte

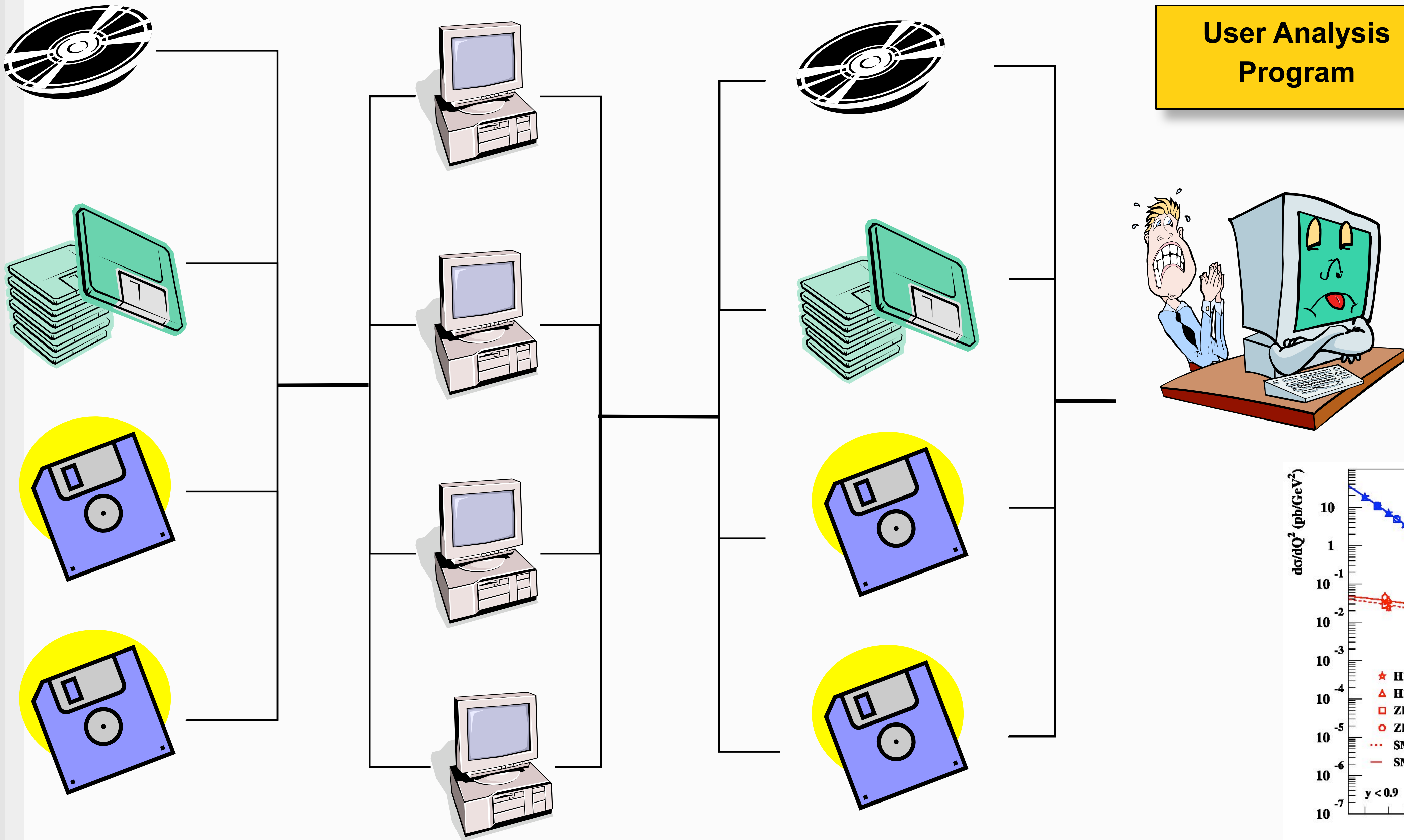
offline reconstruction, calibration, alignment

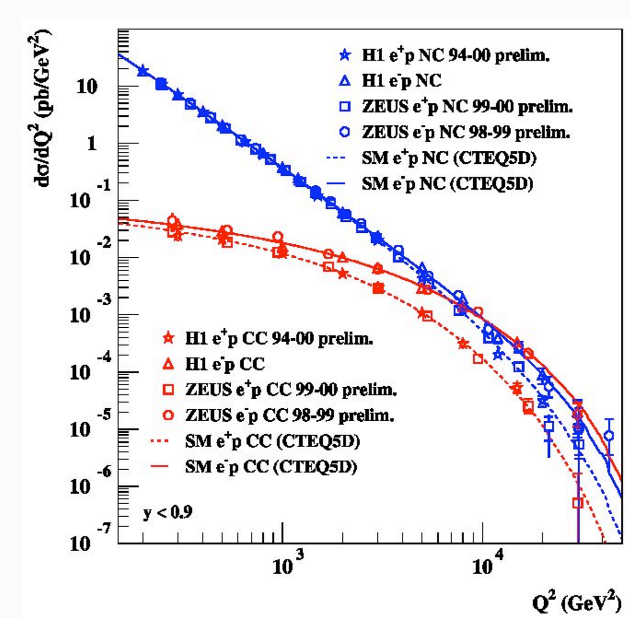
further data storage

Data size: GByte - TByte

User Analysis Program

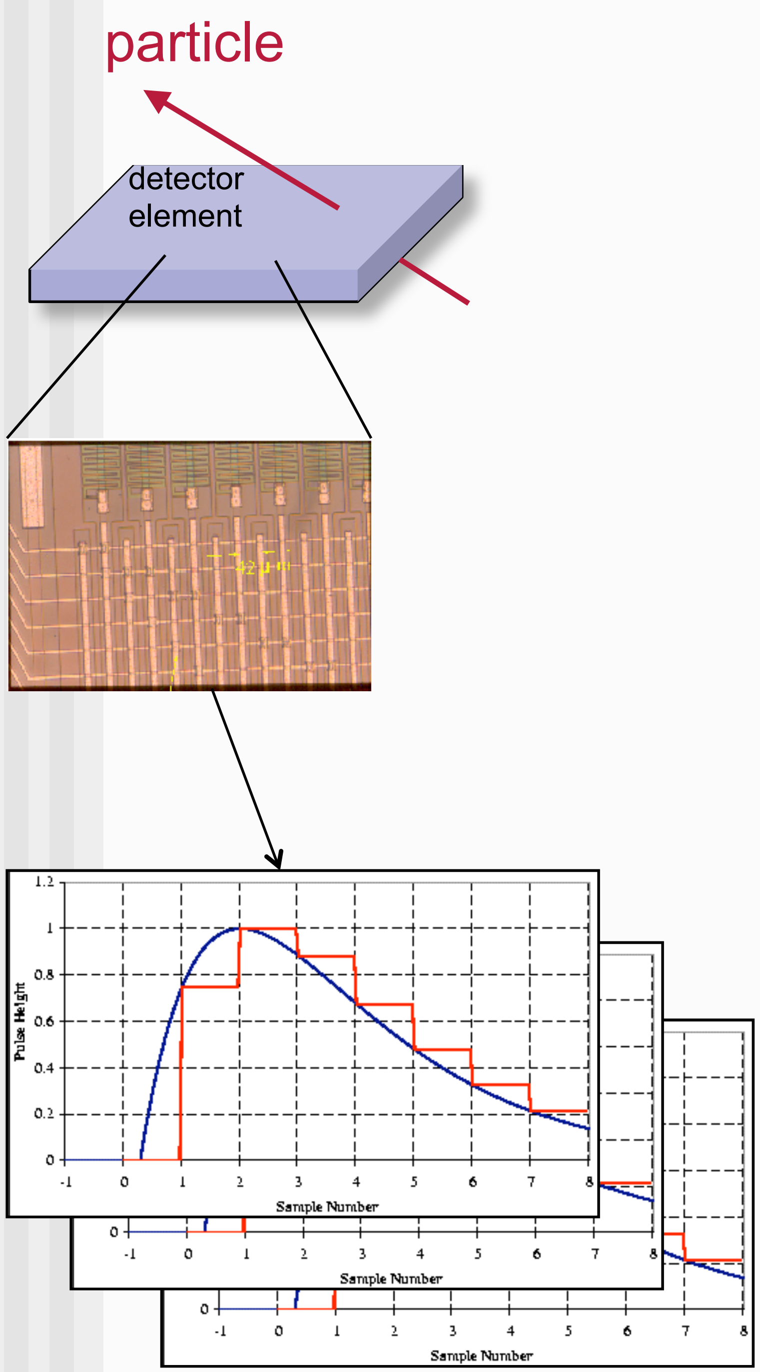
Data size: kByte





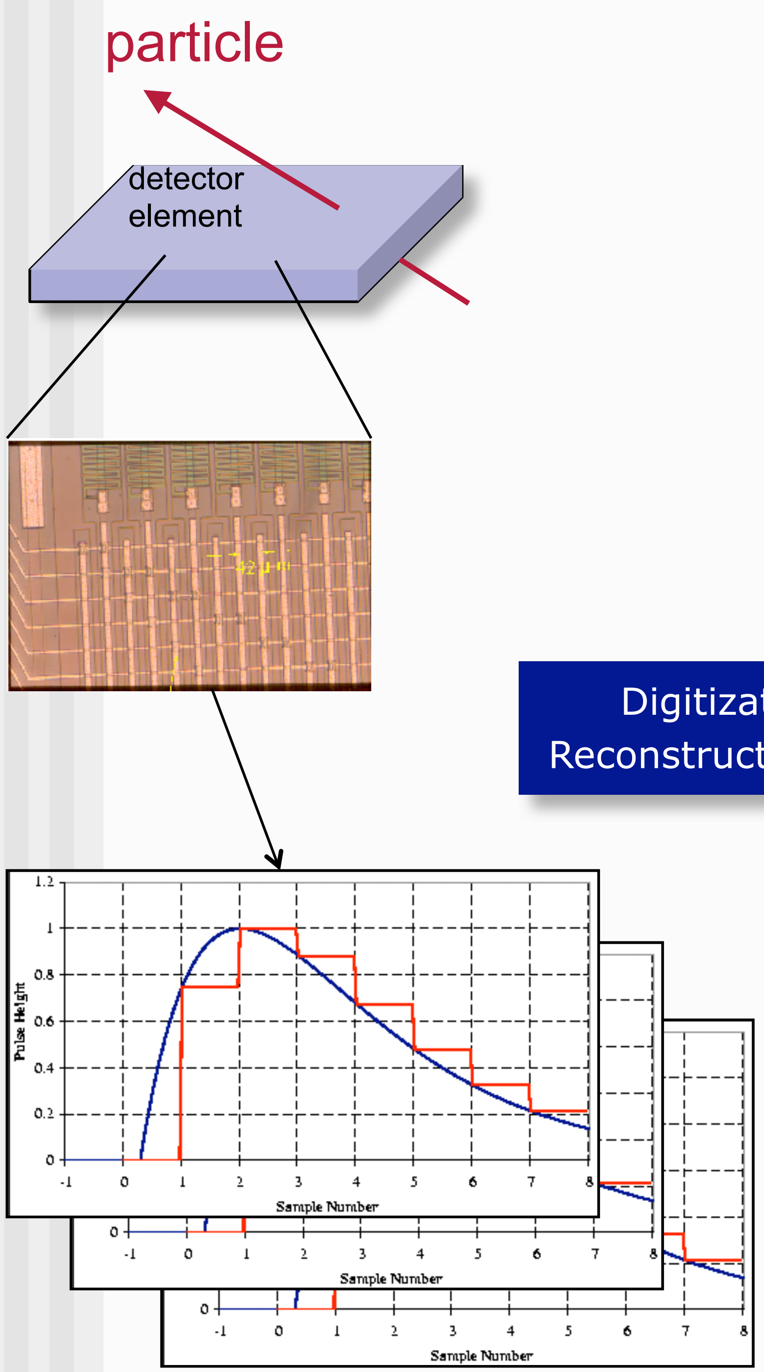
Data reduction/abstraction

Data reduction/abstraction



Analog signals

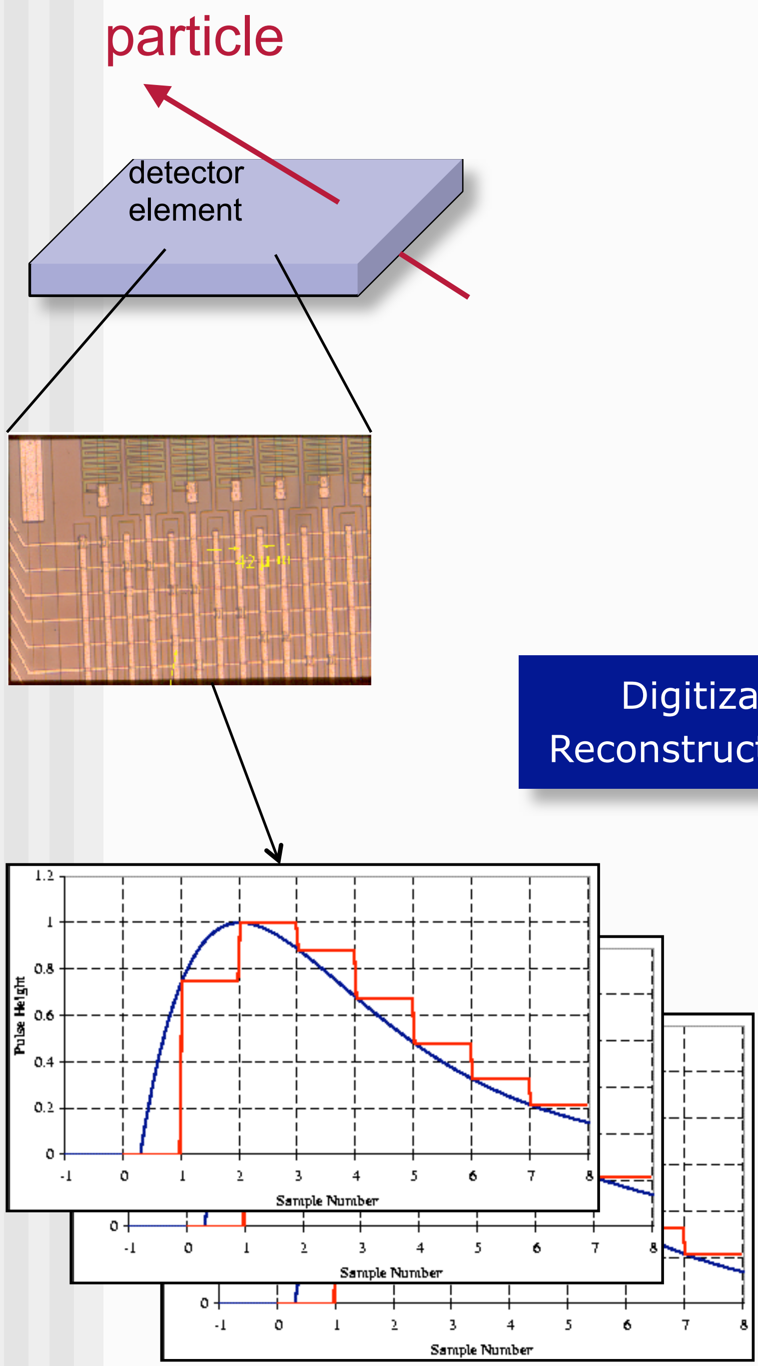
Data reduction/abstraction



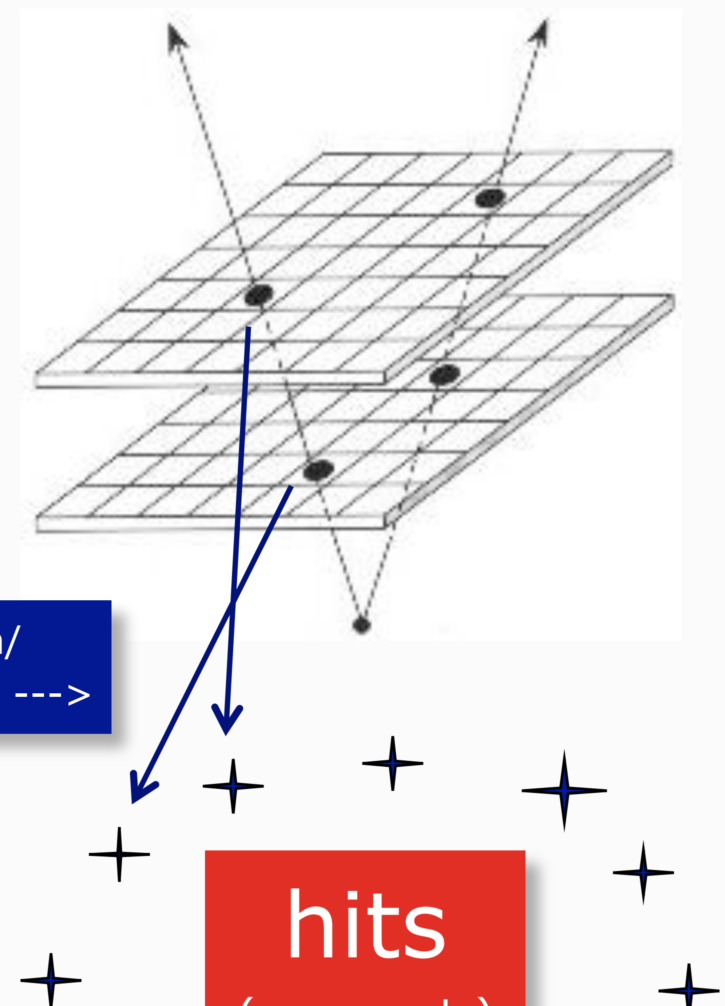
Digitization/
Reconstruction --->

Analog
signals

Data reduction/abstraction



Digitization/
Reconstruction --->



hits

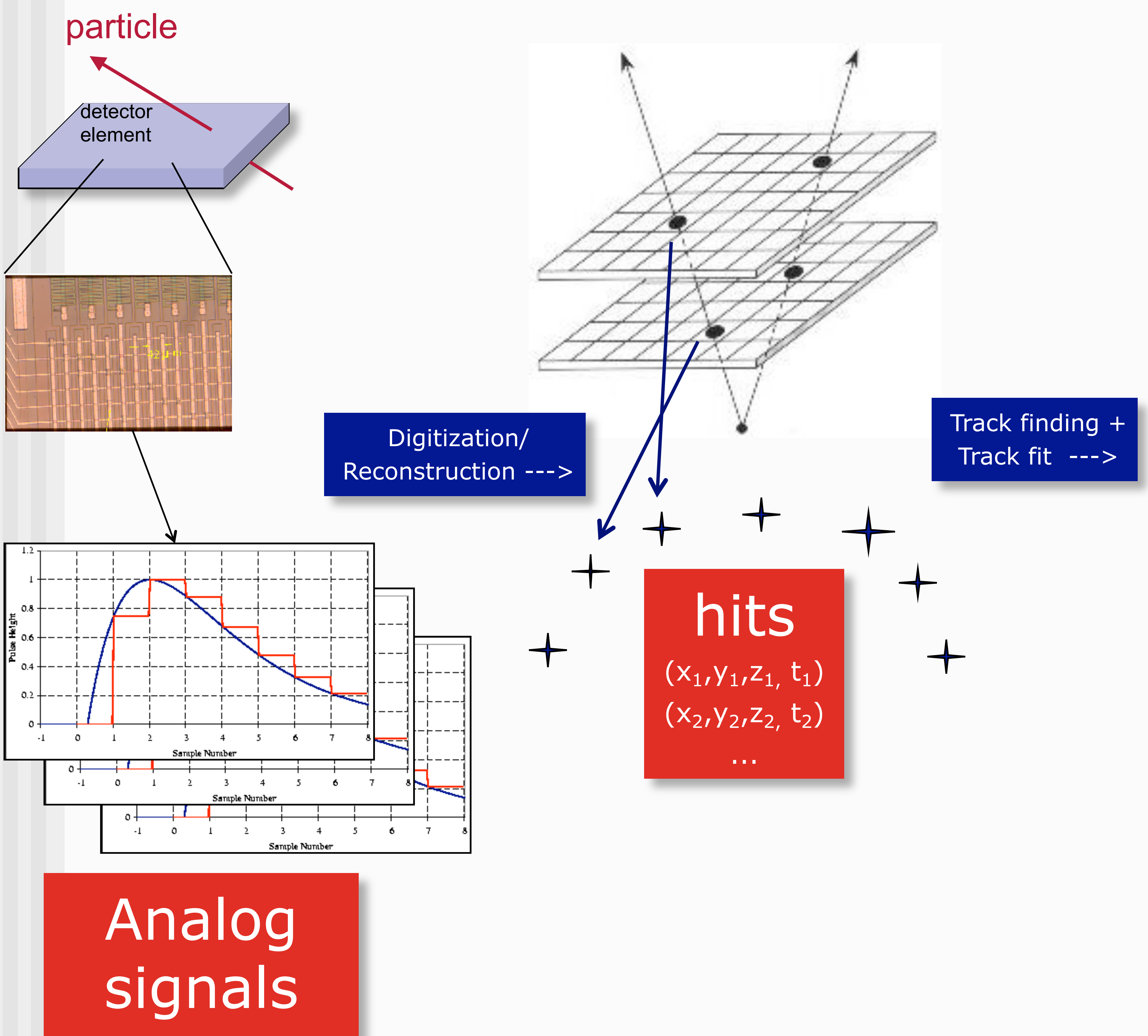
$(x_1,y_1,z_1,\ t_1)$

$(x_2,y_2,z_2,\ t_2)$

...

Analog signals

Data reduction/abstraction



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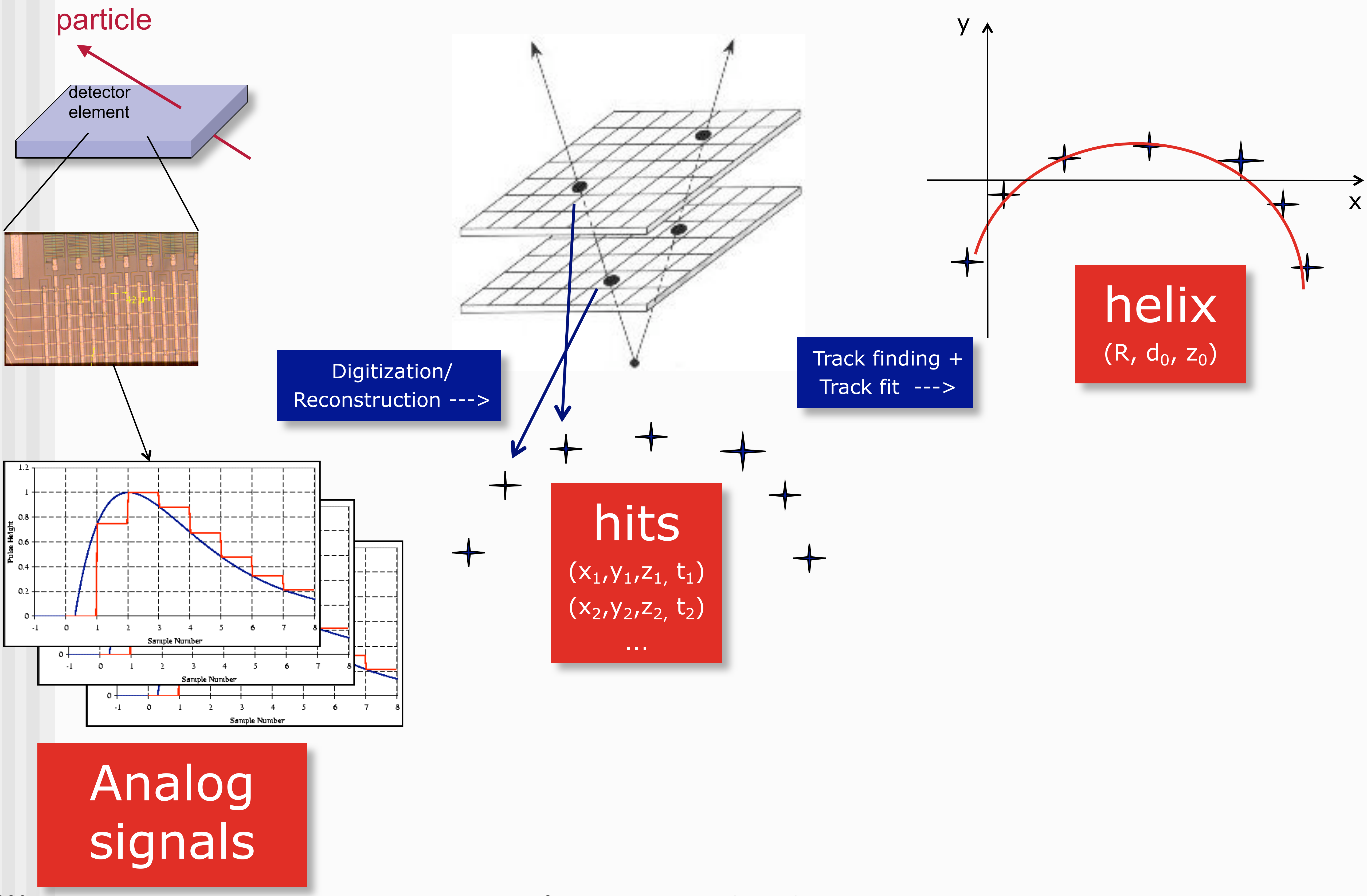

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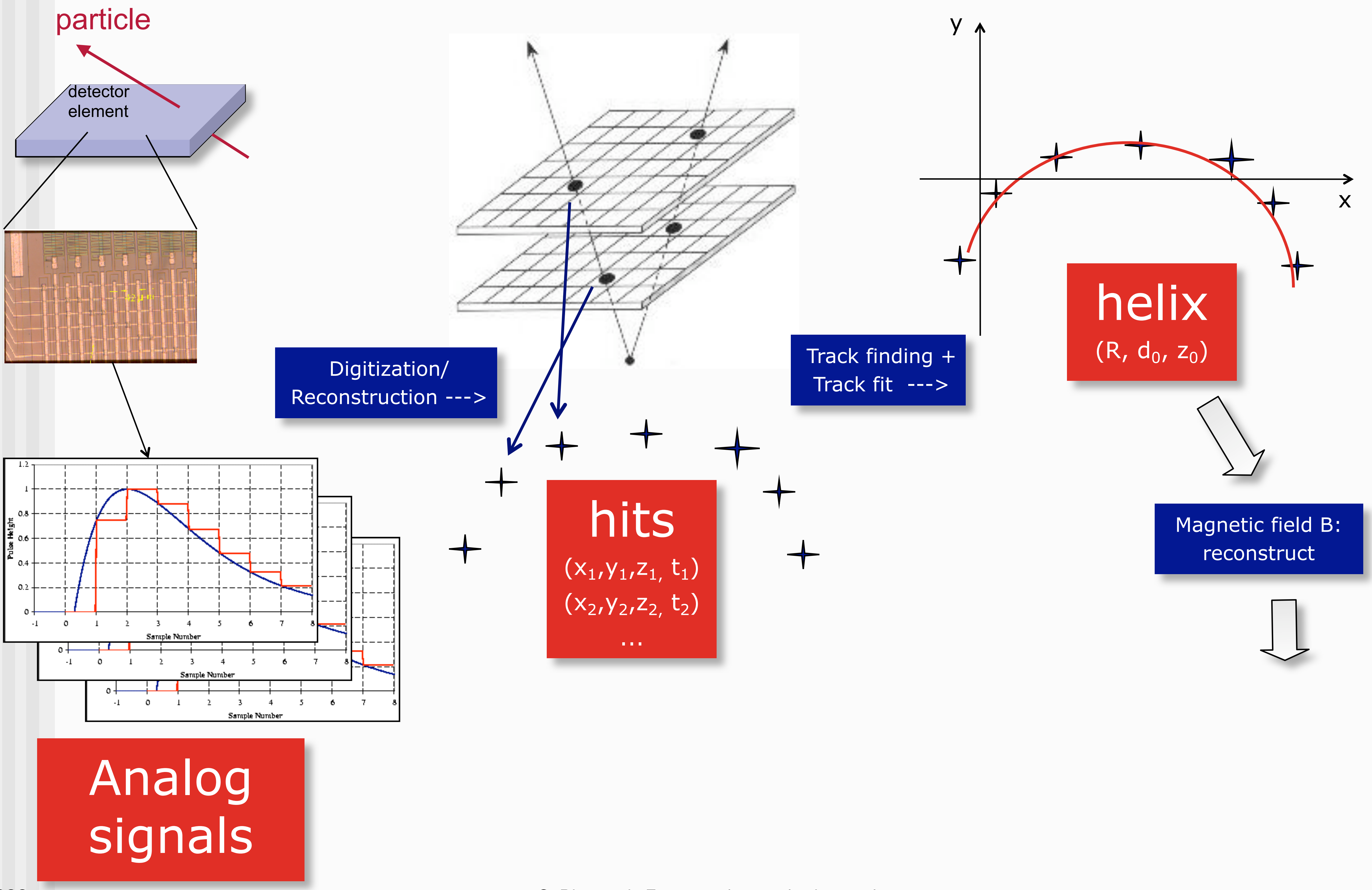

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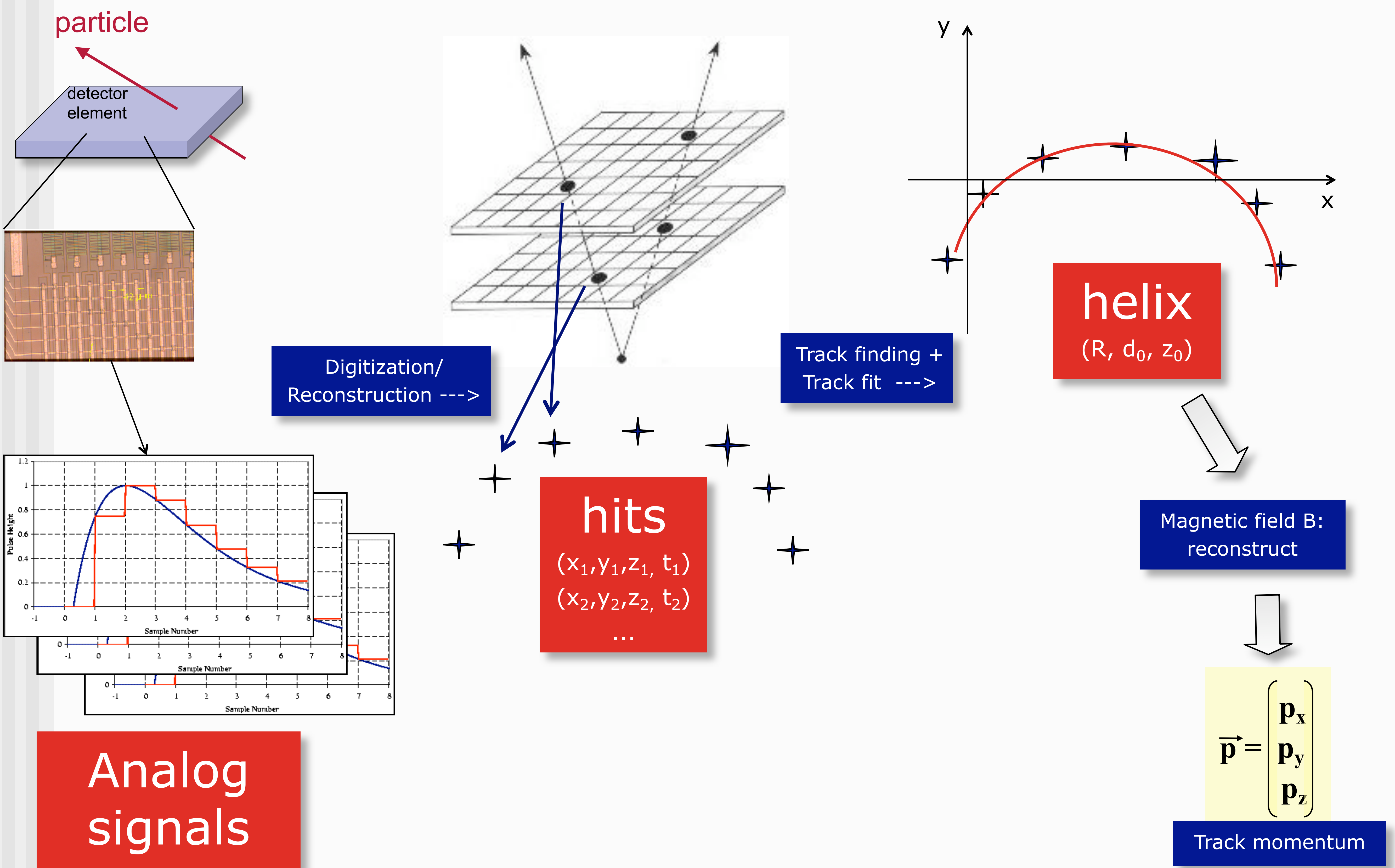

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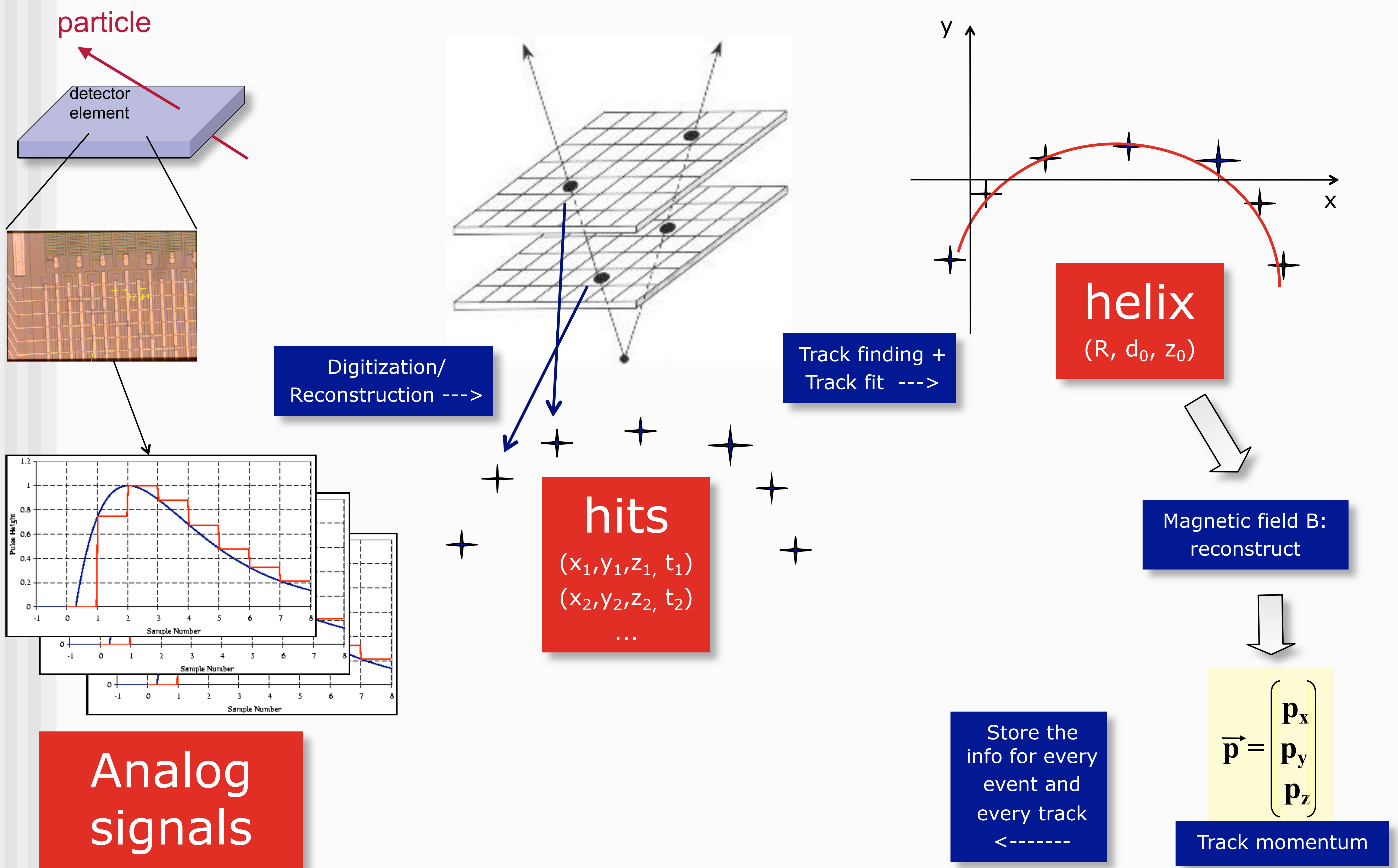

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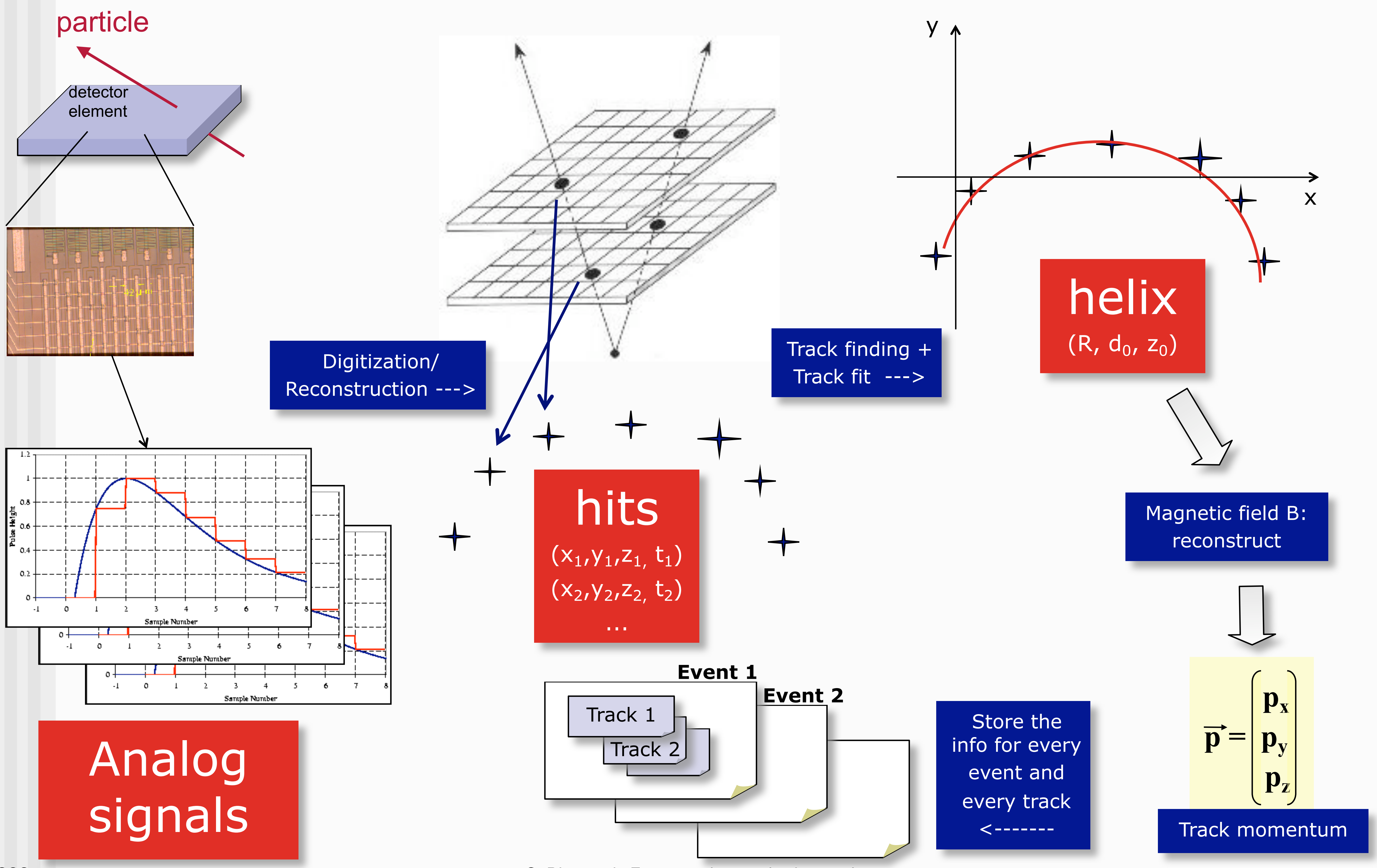


High Level Data Storage

- Data are stored sequentially in files...

File A

High Level Data 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}

File A

High Level Data 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):

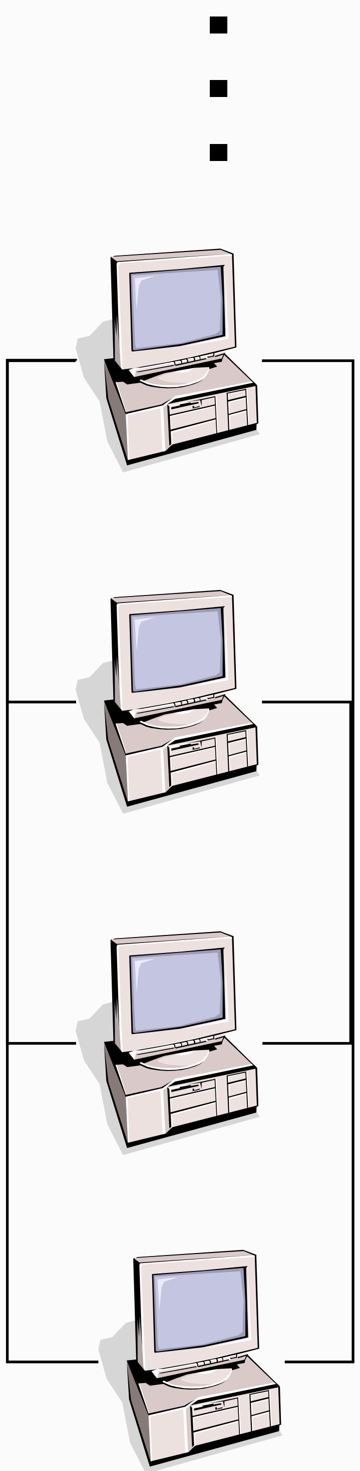
{-1,1,-1}

File A

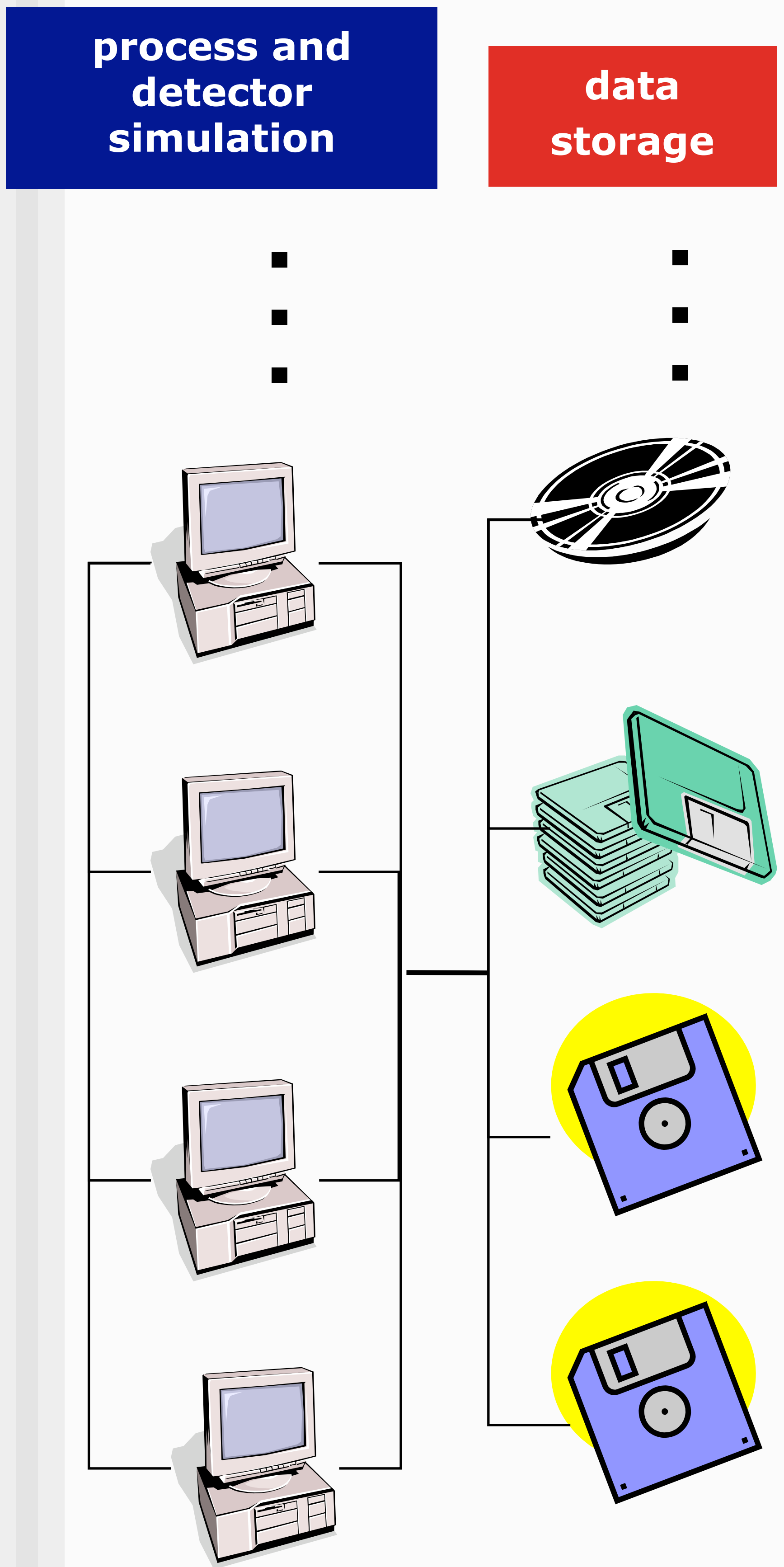
Simulation

Simulation

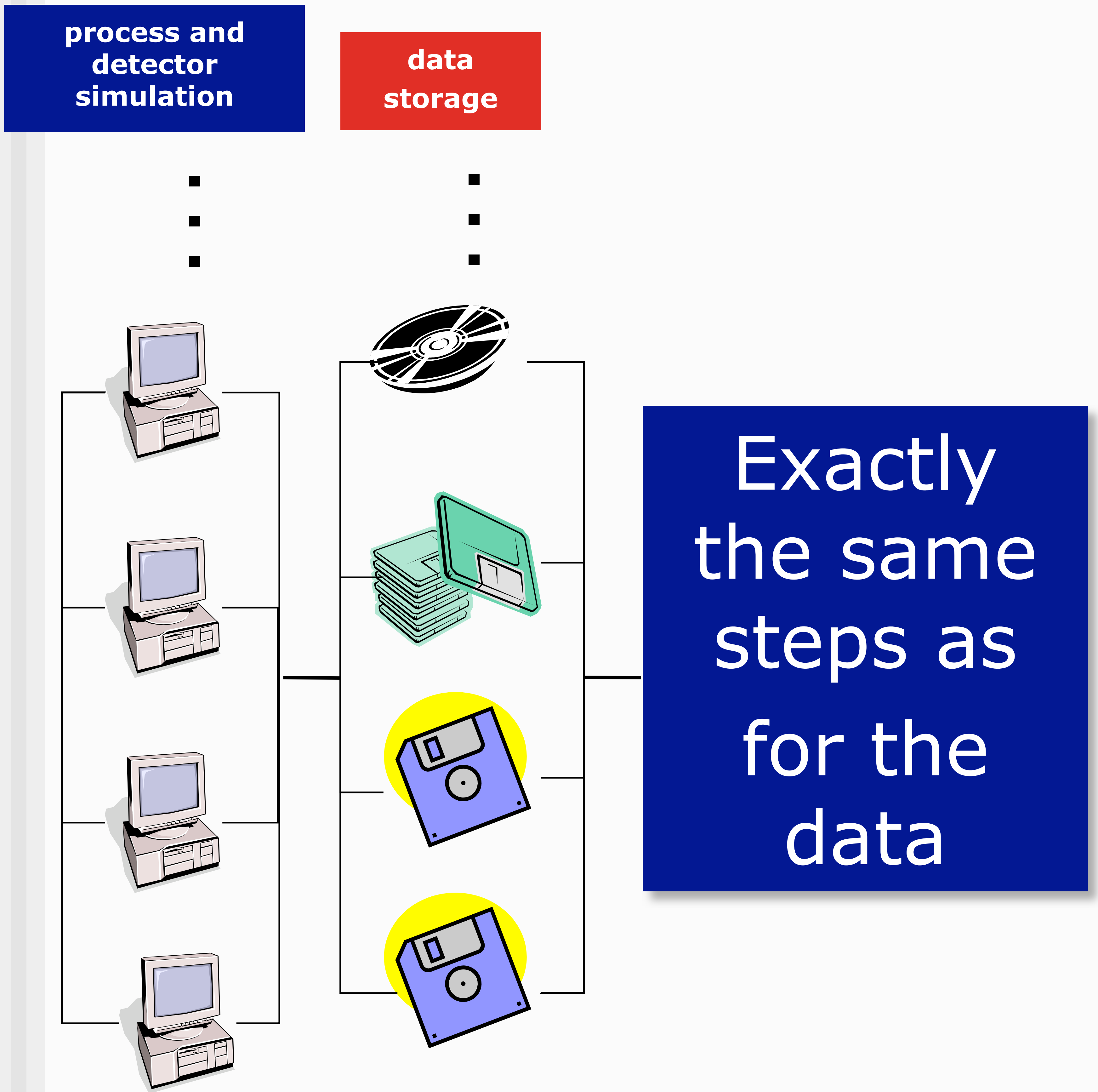
process and detector simulation



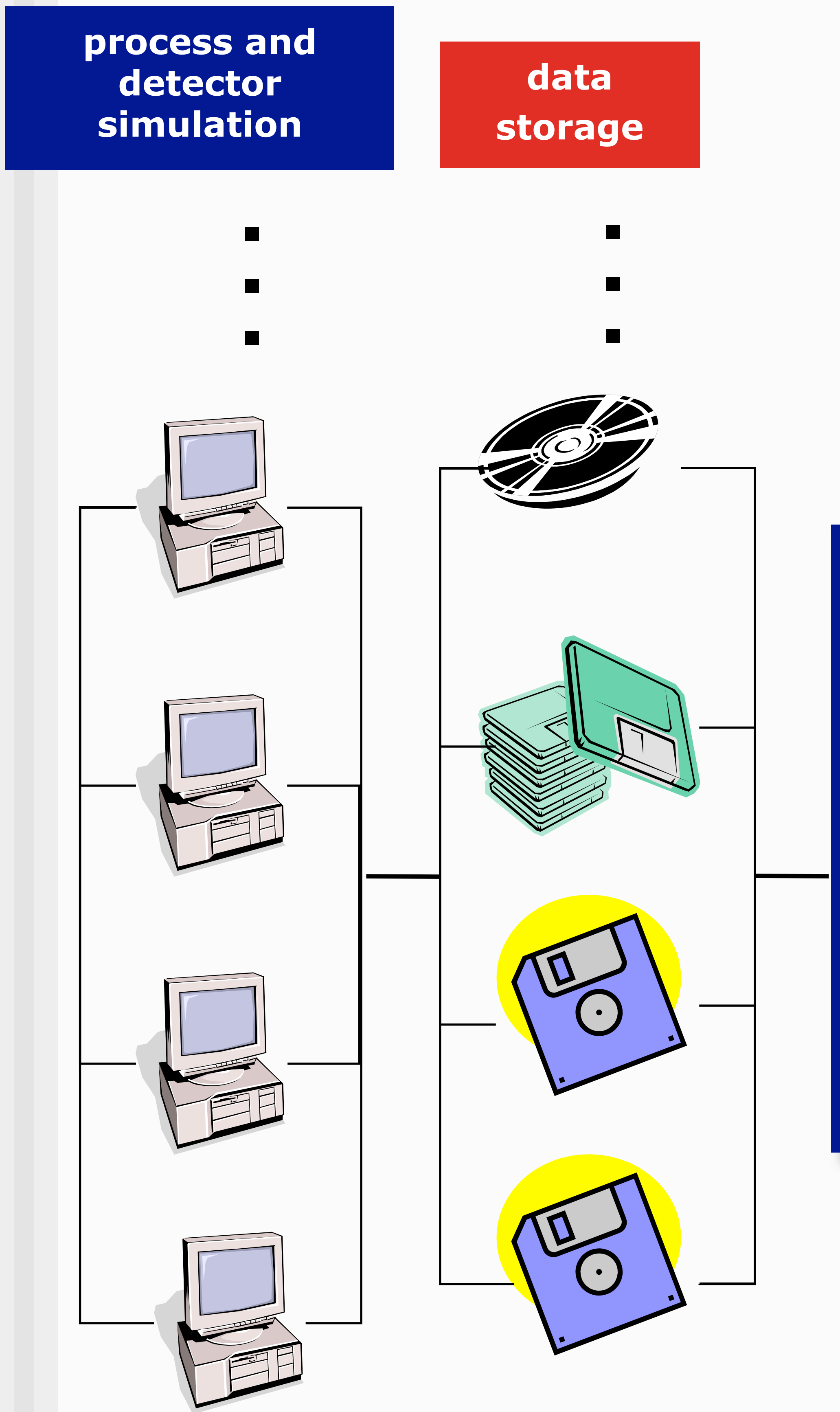
Simulation



Simulation


process and detector simulation
data storage
Exactly the same steps as for the data

Simulation

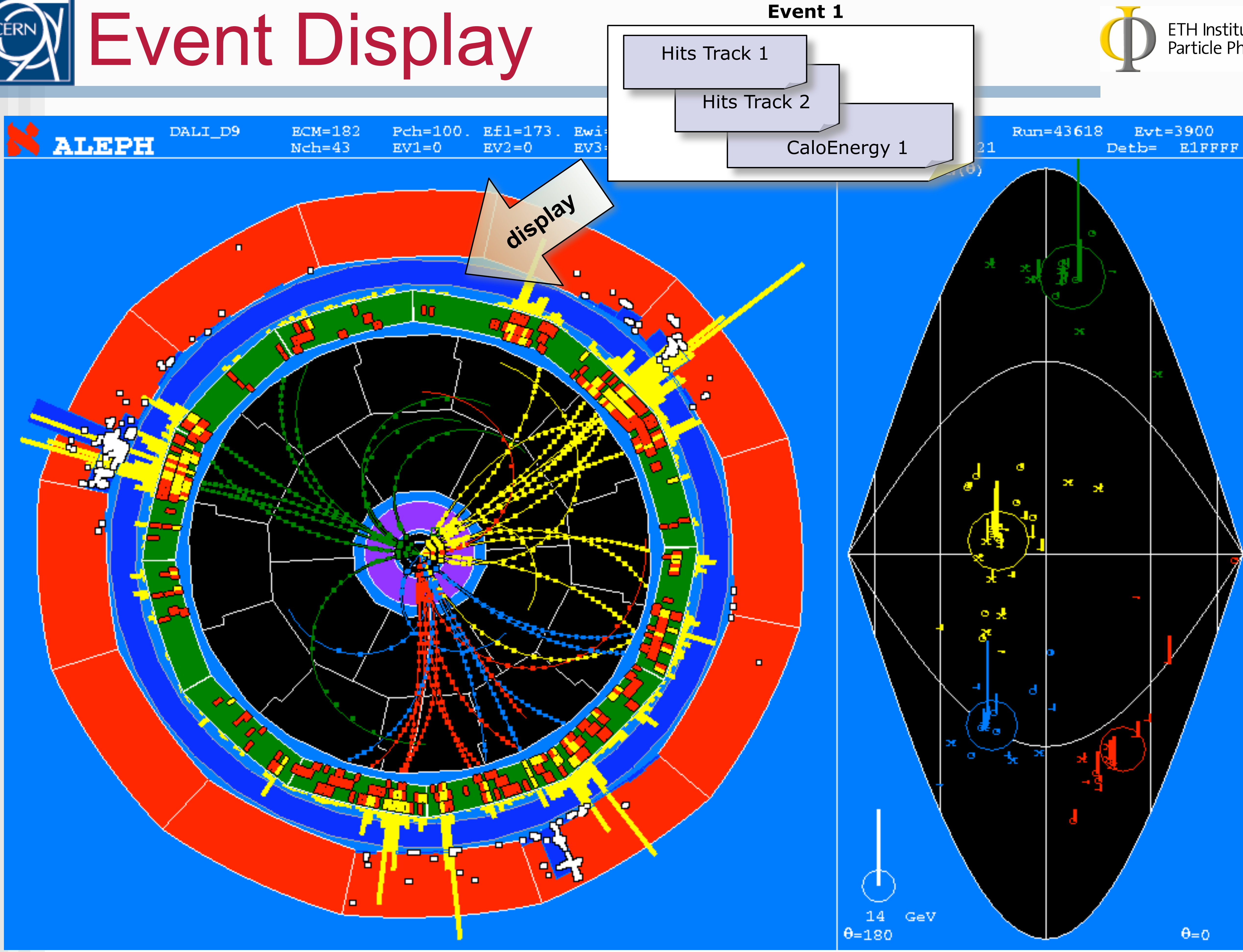


Exactly the same steps as for the data

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

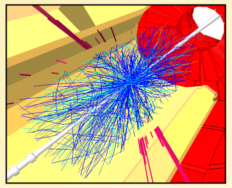
Event Display



And now let's go a little bit more into the details ...

Our Task

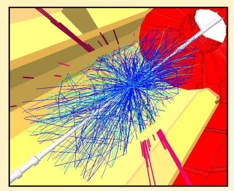
Reality



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

Our Task

Reality



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

Theory

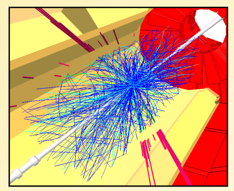
$$S = \mathrm{i} \int \mathrm{d}^4 x \, \mathcal{L}(x)$$

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

- A. Eddington

Our Task

Reality



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

We intend to fill this gap

Theory

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

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

- A. Eddington

Theory...

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

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

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

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

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

$\left\{\right.$ $W^{\pm}, Z, \gamma$ and Higgs masses and couplings

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

$\left\{\right.$ 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:

$$\mathcal{L} = \underbrace{\bar{q}\,(i\gamma^{\mu}\partial_{\mu} - m)\,q}_{\text{E}_{\text{kin}}(\text{q})} - \underbrace{g\,(\bar{q}\gamma^{\mu}T_a q)G^a_{\mu}}_{\text{Interaction q, g}} - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\text{E}_{\text{kin}}(\text{g}) \text{ includes self-interaction between gluons}}$$

eg.
the Standard Model

Theory...

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

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

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

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

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

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

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

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

eg.
the Standard Model

has parameters

coupling constants

masses

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

Experiment...

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```
0x01e84c10:   0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:   0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:   0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:   0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
0x01e84c60:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c70:   0x01e8 0x8824 0x01e8 0x84d8 0x7265 0x6765 0x7870 0x0000
0x01e84c80:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c90:   0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
0x01e84ca0:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cb0:   0x01e8 0x8818 0x01e8 0x8558 0x7265 0x6e61 0x6d65 0x0000
0x01e84cc0:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cd0:   0x01e8 0x8798 0x01e8 0x8598 0x7265 0x7475 0x726e 0x0000
0x01e84ce0:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cf0:   0x01e8 0x87ec 0x01e8 0x85d8 0x7363 0x616e 0x0000 0x0000
0x01e84d00:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d10:   0x01e8 0x87e8 0x01e8 0x8618 0x7365 0x7400 0x0000 0x0000
0x01e84d20:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d30:   0x01e8 0x87a8 0x01e8 0x8658 0x7370 0x6c69 0x7400 0x0000
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0x01e84d50:   0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
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0x01e84d70:   0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
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```

eg.

1/30th of an event in the BaBar detector

- get about 100 evts/sec

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ETH Institute for Particle Physics

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```

eg.

1/30th of an event in the BaBar detector

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"Address" :

- which detector element took the reading

"Value(s)" :

- what the electronics wrote out

Making the connection

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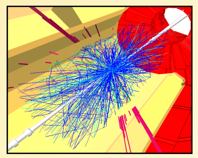
Reality



Raw Data

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

Theory

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

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

Making the connection

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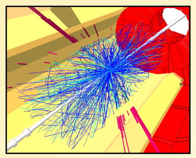

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Events

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eg. Run 23458, event 1345
which contains a Z $\rightarrow \mu^+\mu^-$ decay

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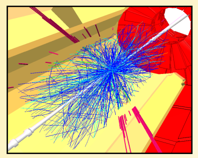

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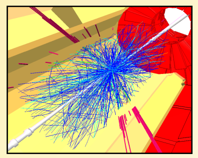

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The imperfect measurement of a (set of) interactions in the detector

Events

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

Observables

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

Theory

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

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A “simple” example

A simple example

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

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

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

Number of colours

electric charges of quarks, in units of electron charge

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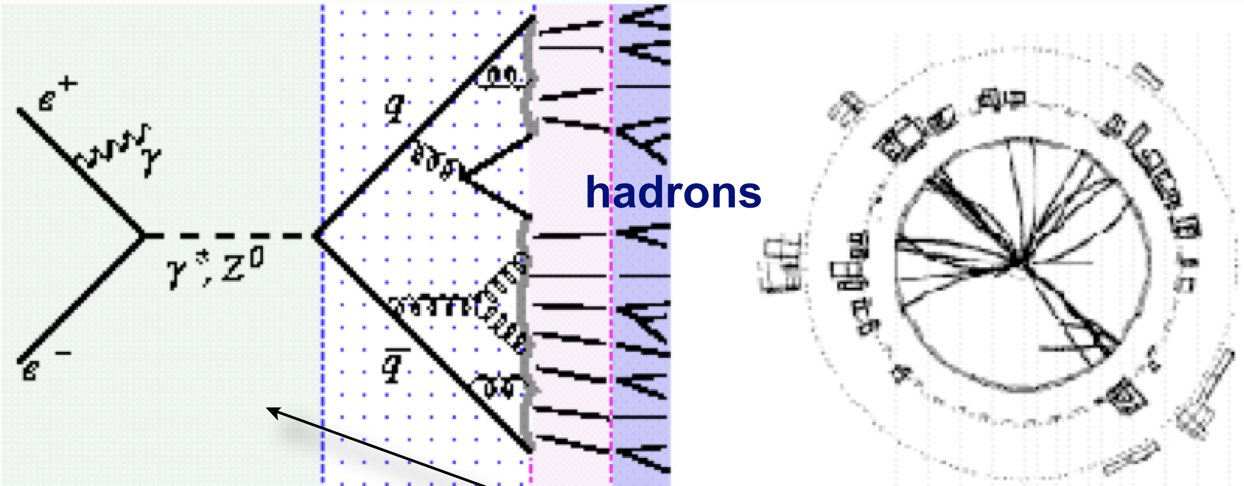

Hadronic final state

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

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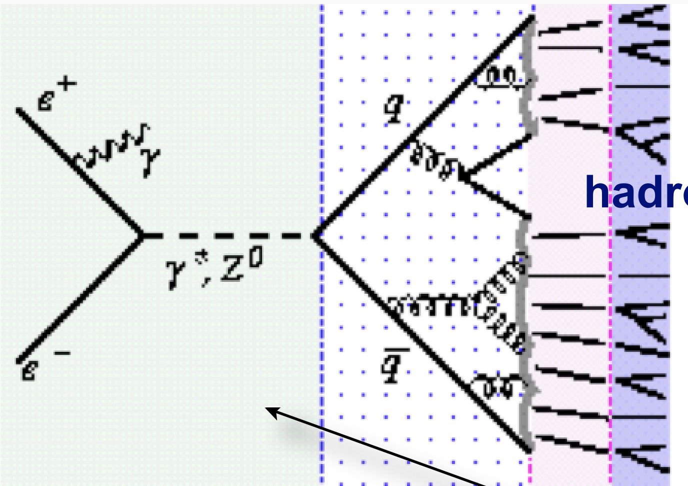

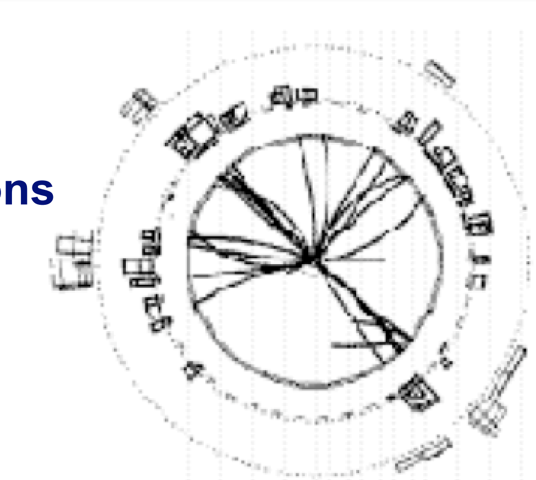

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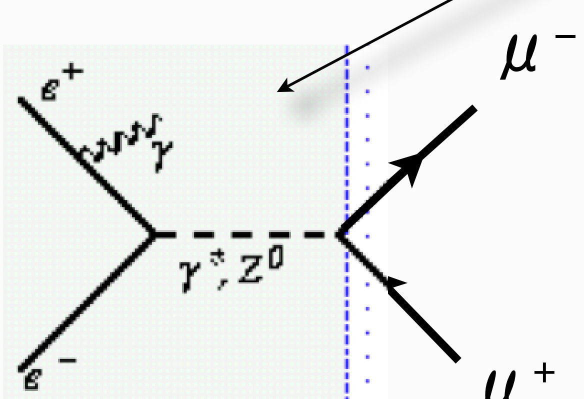

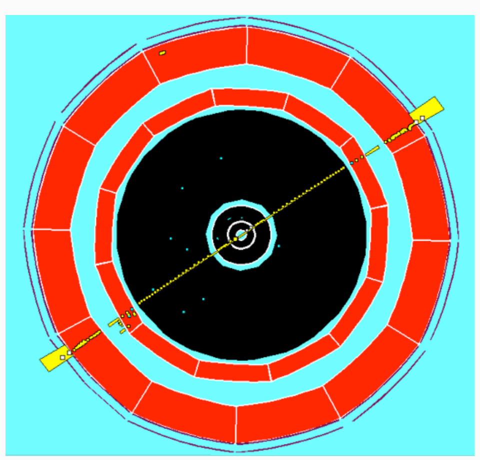

Muonic final state

- 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

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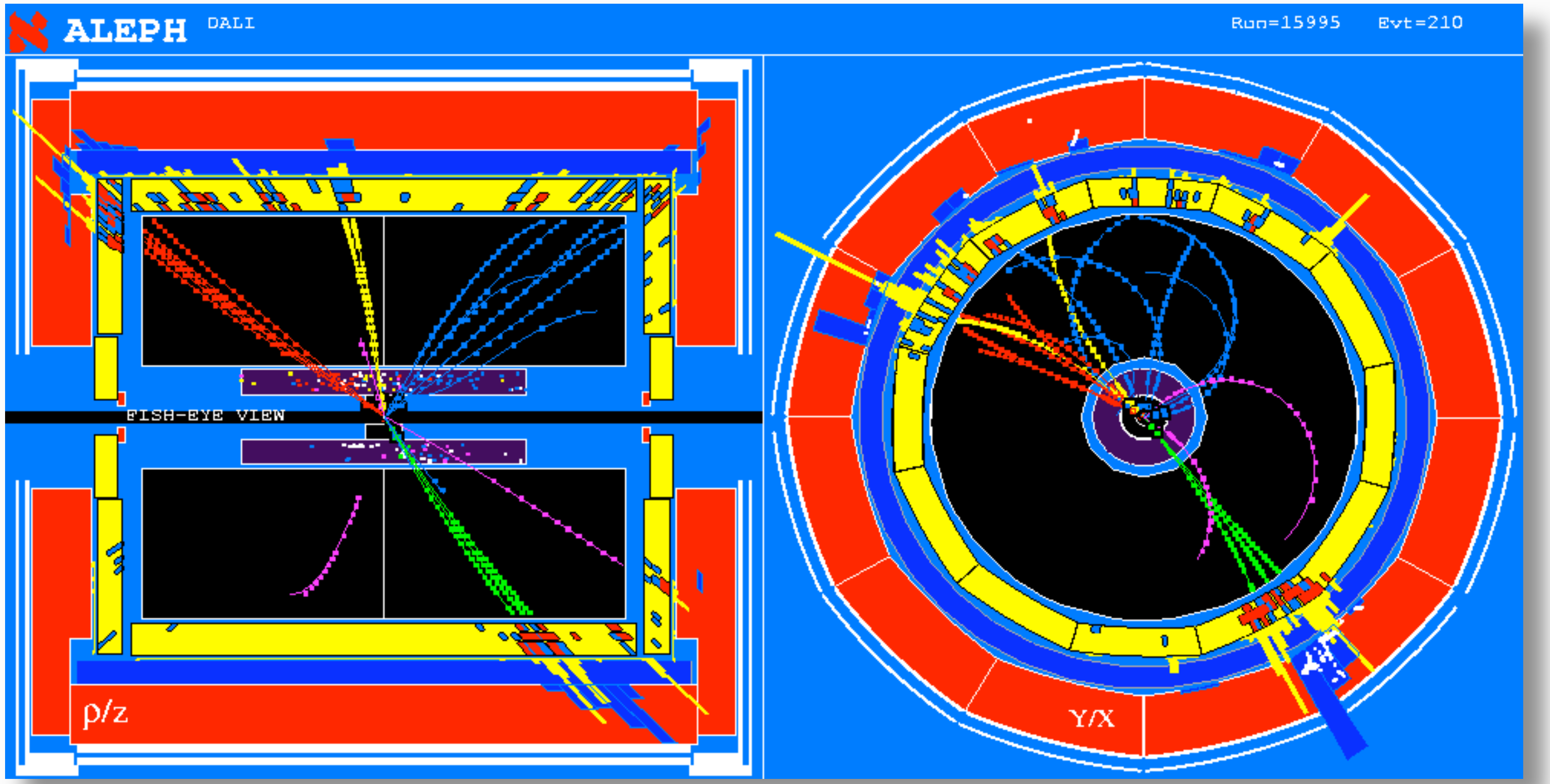
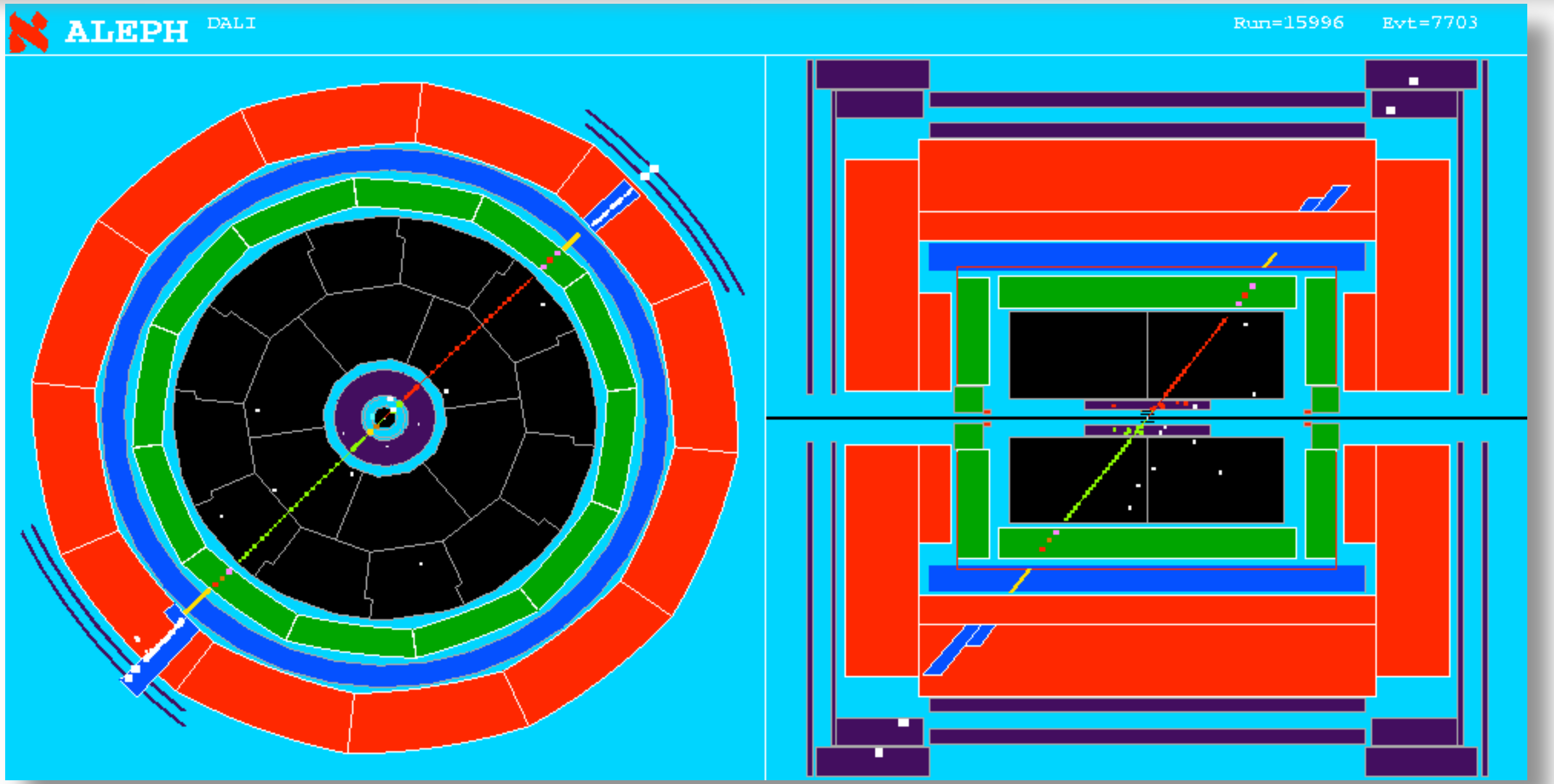
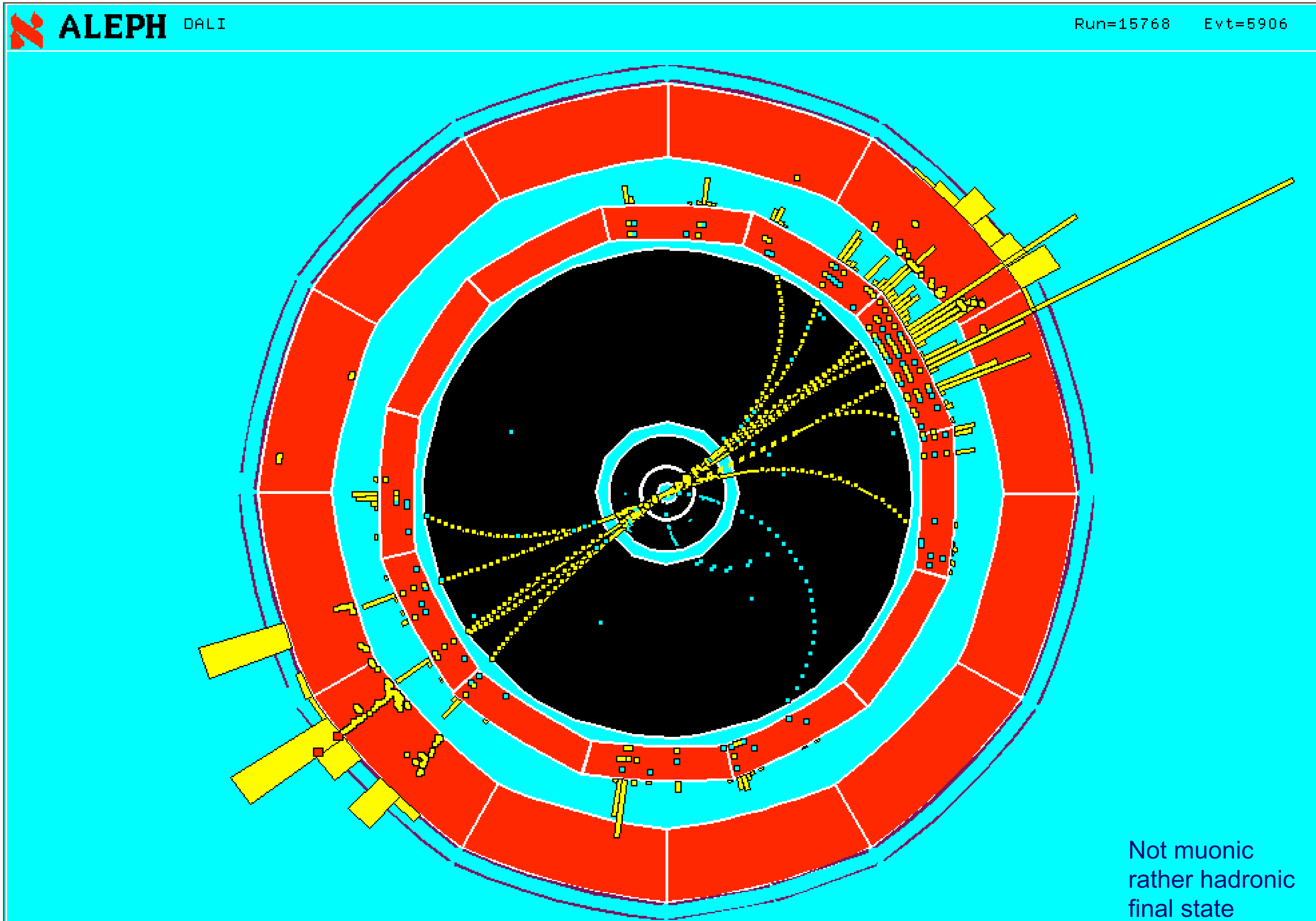
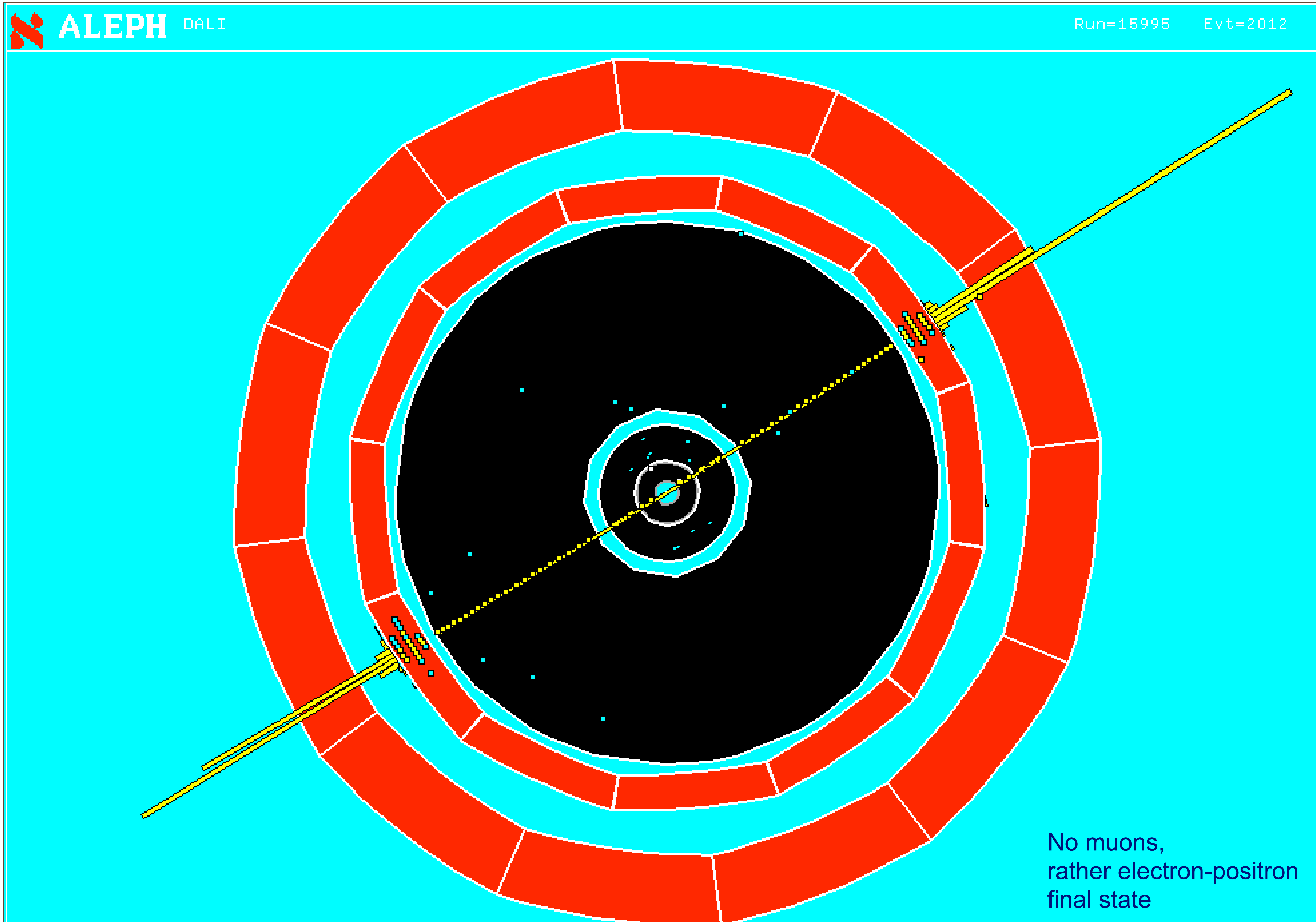
$$R = \frac{\#\text{ of} \quad \text{Hadron final states}}{\#\text{ of} \quad \text{Muon final states}}$$





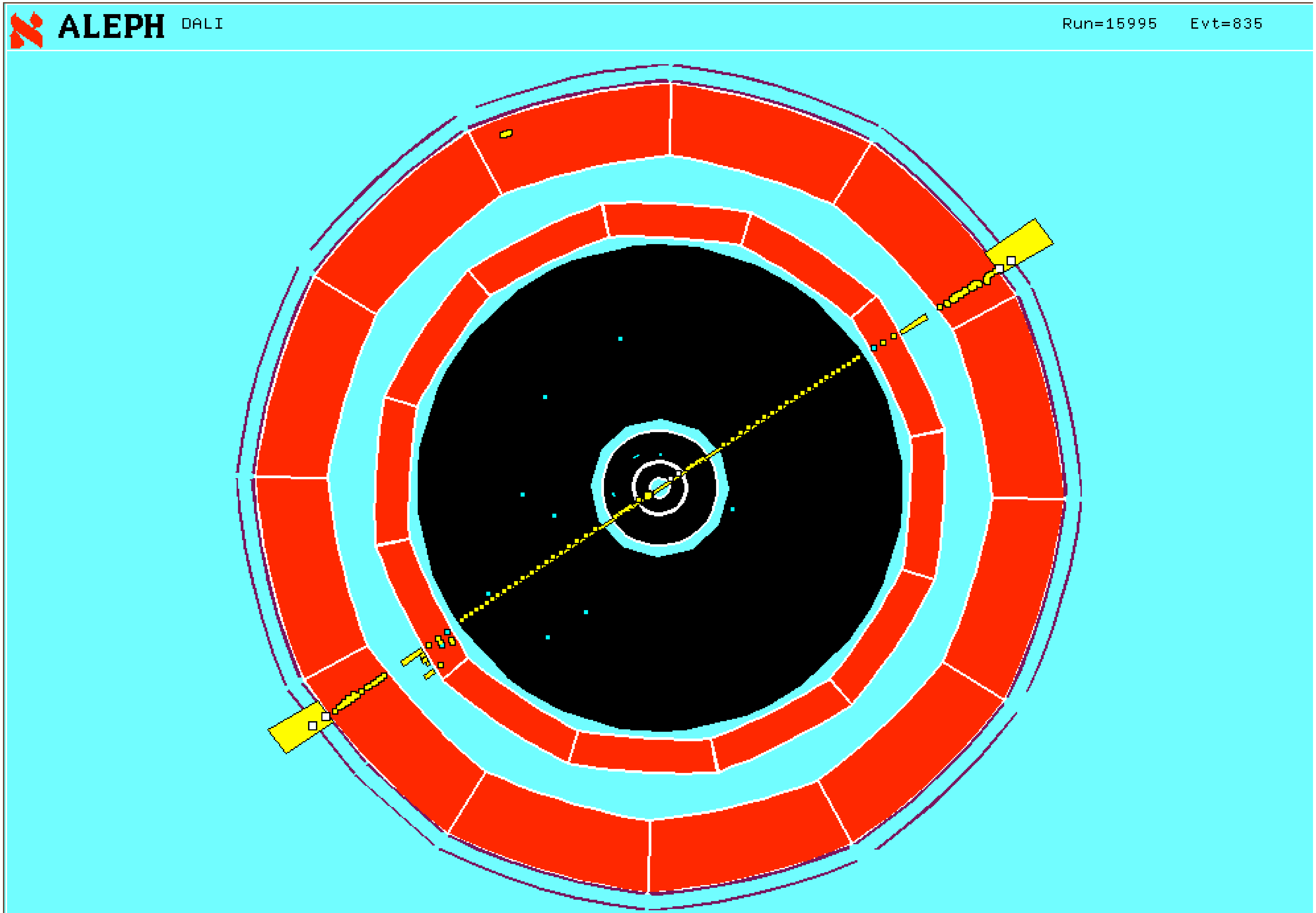


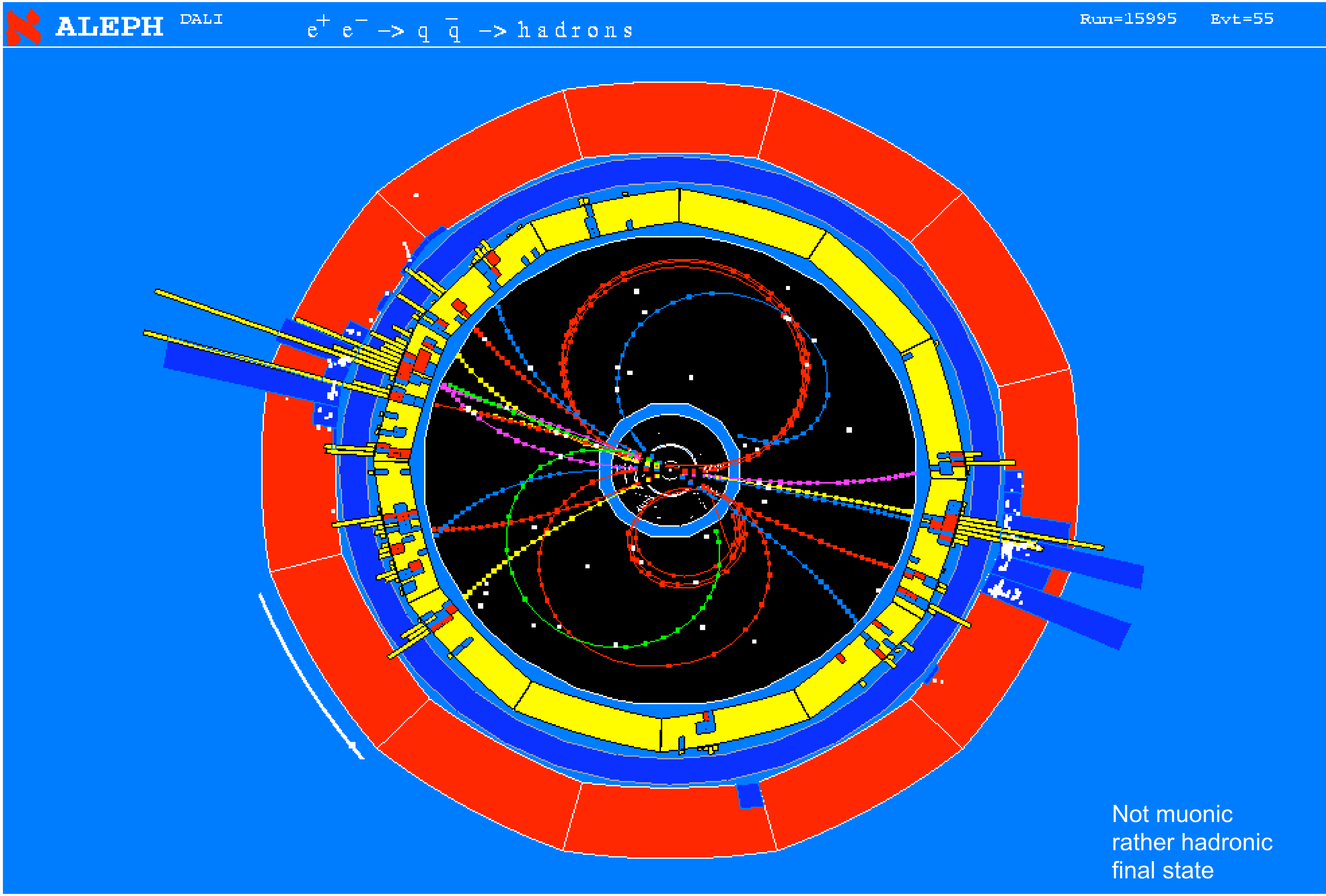
Not muonic
rather hadronic
final state



No muons,
rather electron-positron
final state

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




ALEPH
DALI
$e^+ e^- \to q \bar{q} \to$ hadrons
Run=15995
Evt=55
Not muonic
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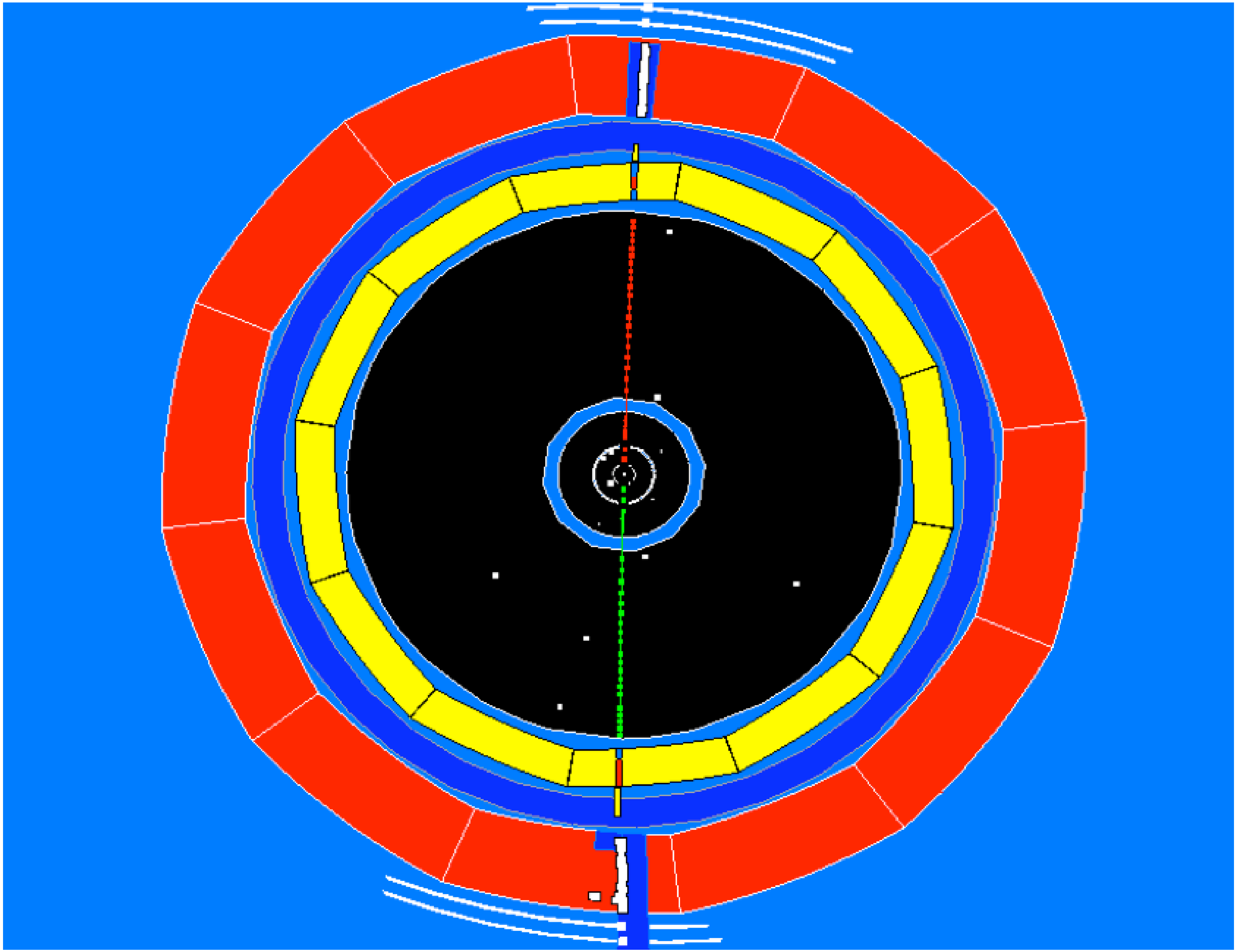
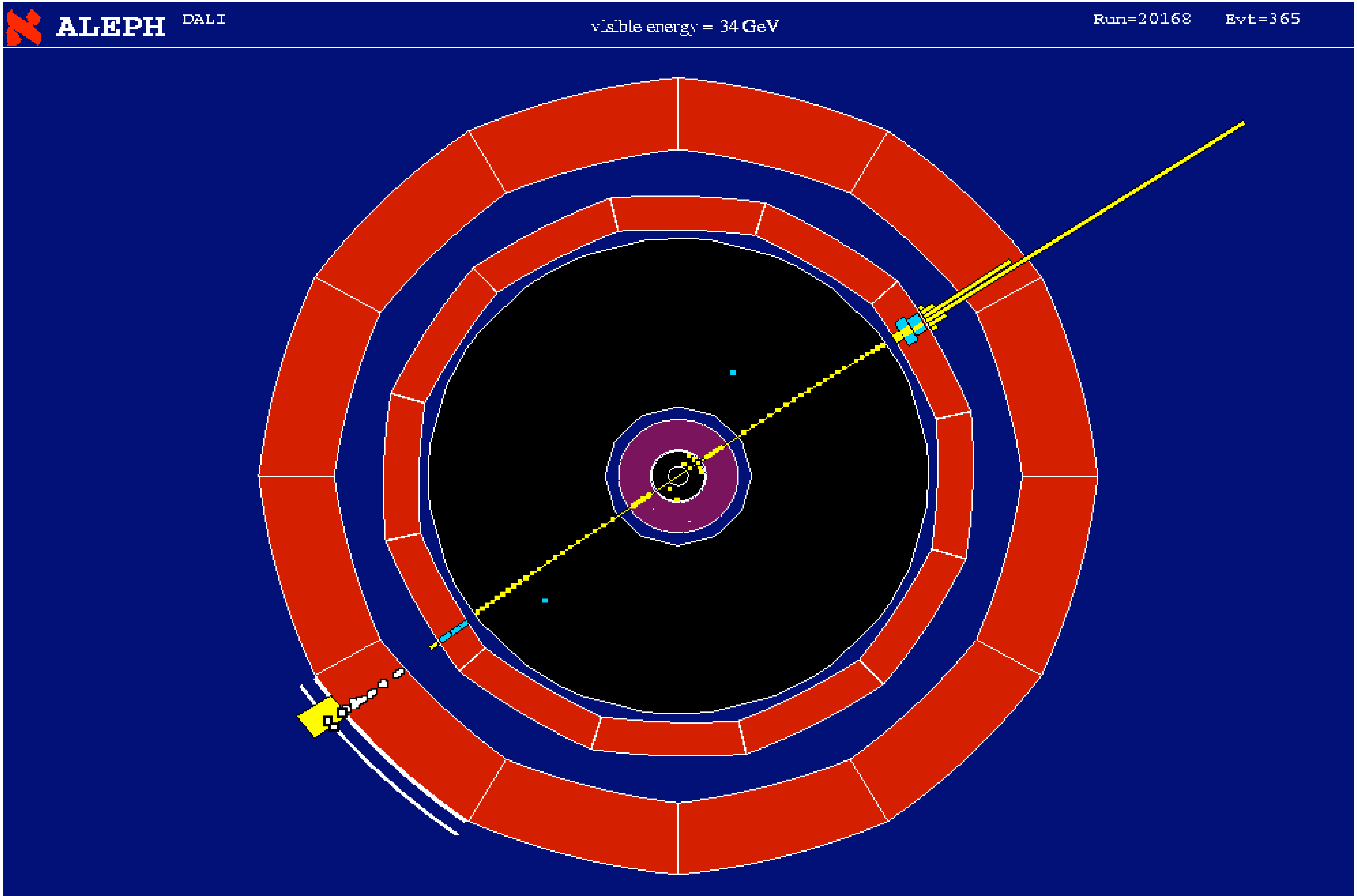
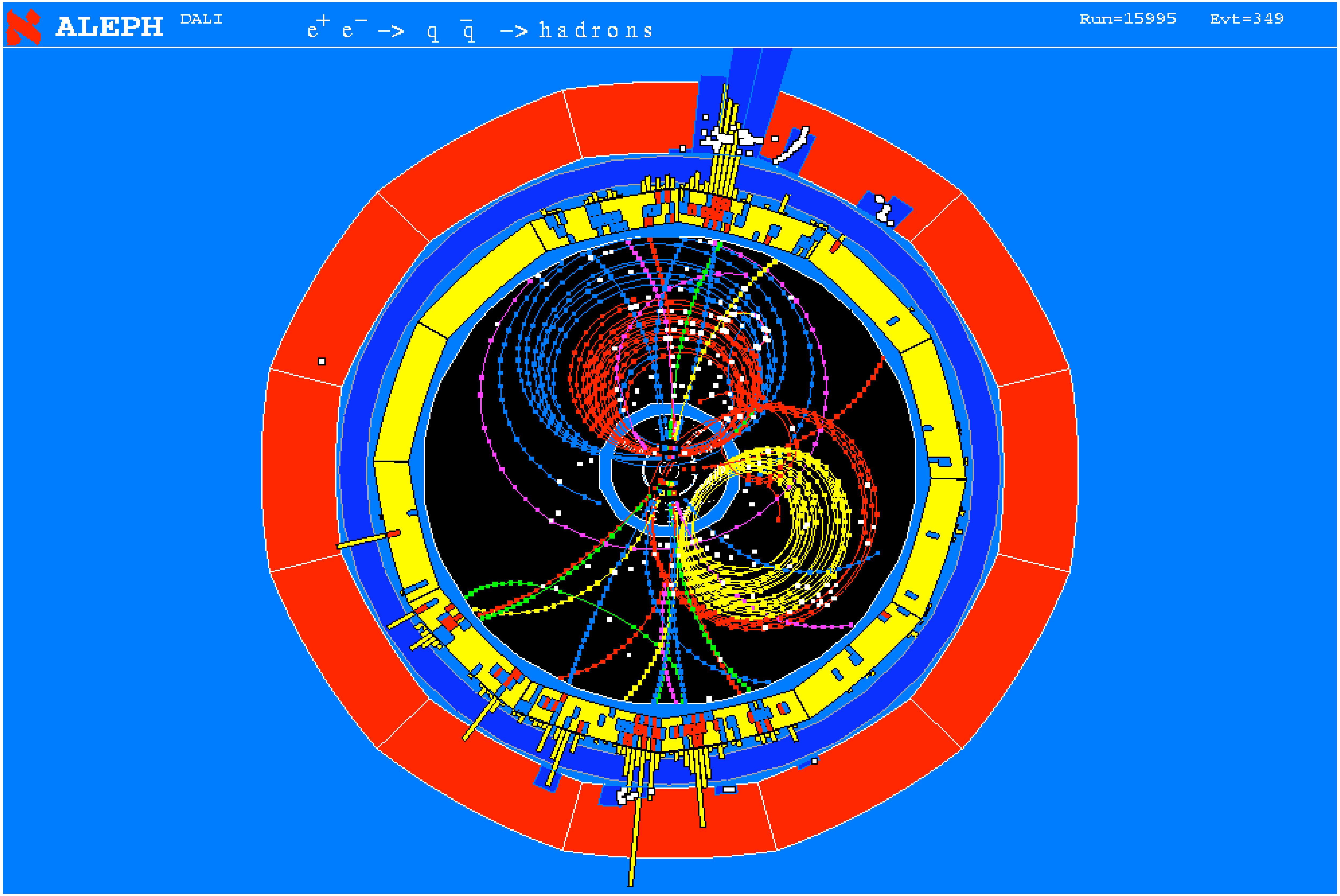


not $Z \rightarrow \mu^+\mu^-$

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



And so on....

Result

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

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

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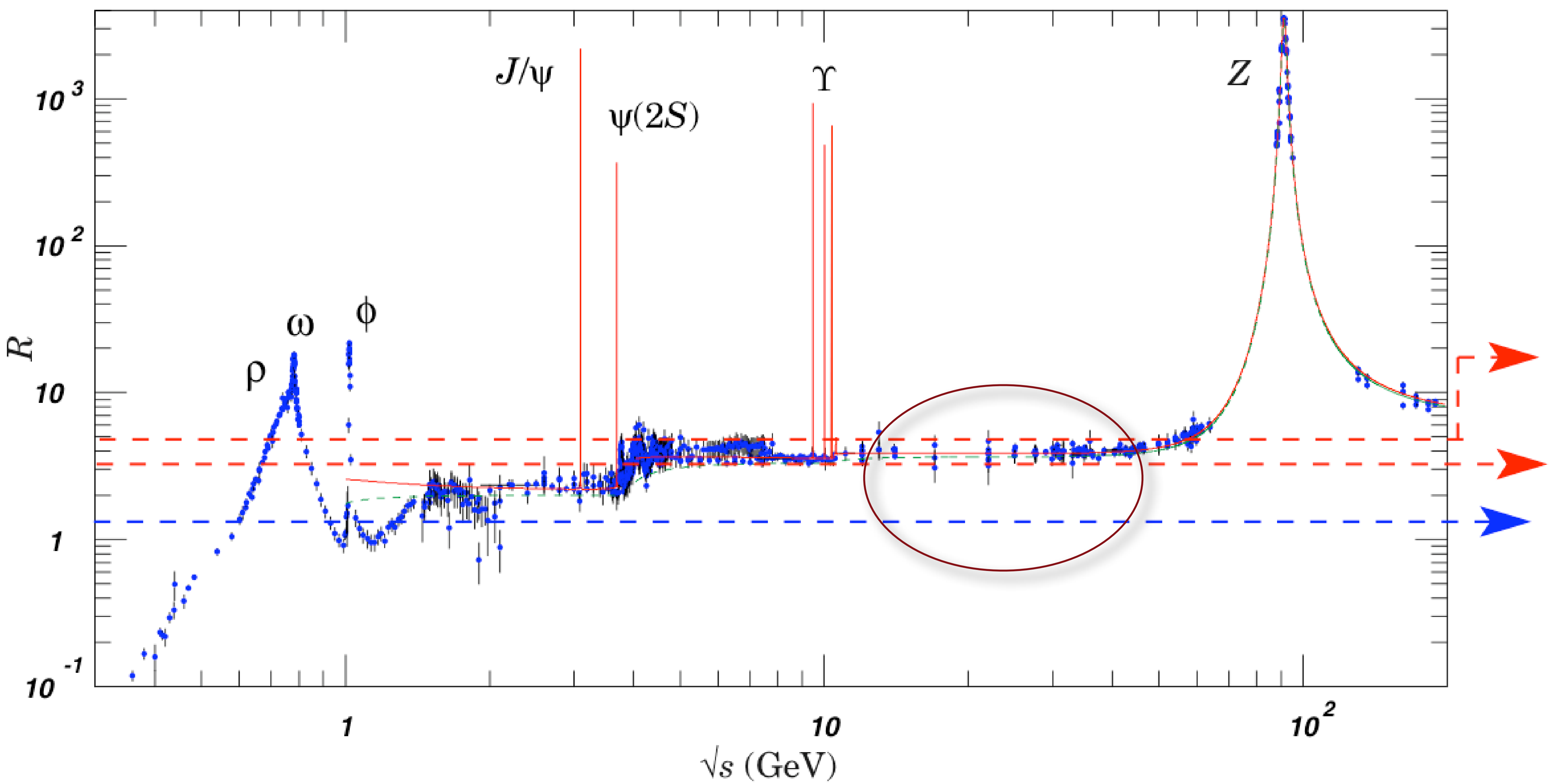

6 quarks,
3 colours (45/9)

5 quarks,
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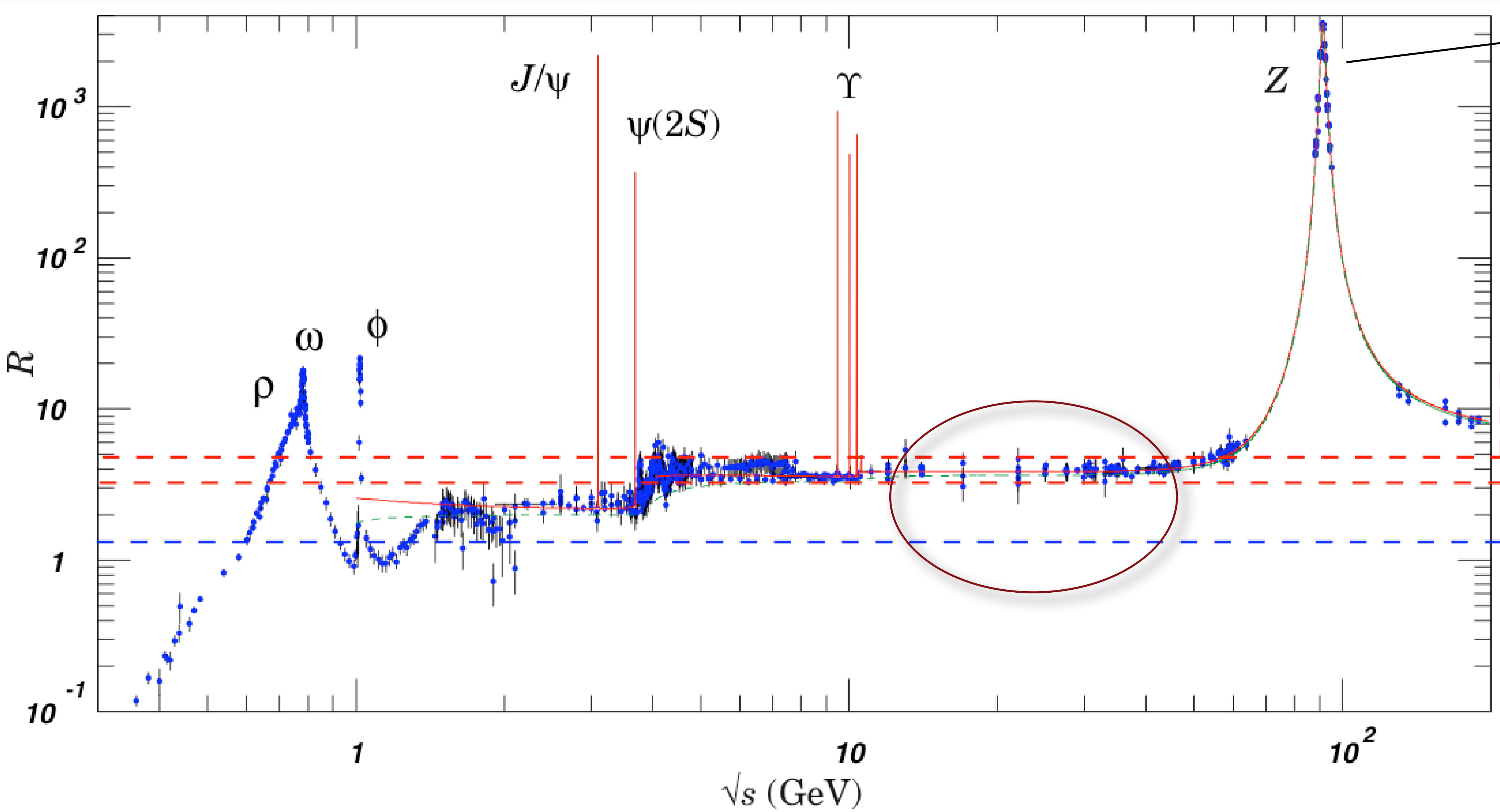

At Z peak :

have to include also couplings to Z

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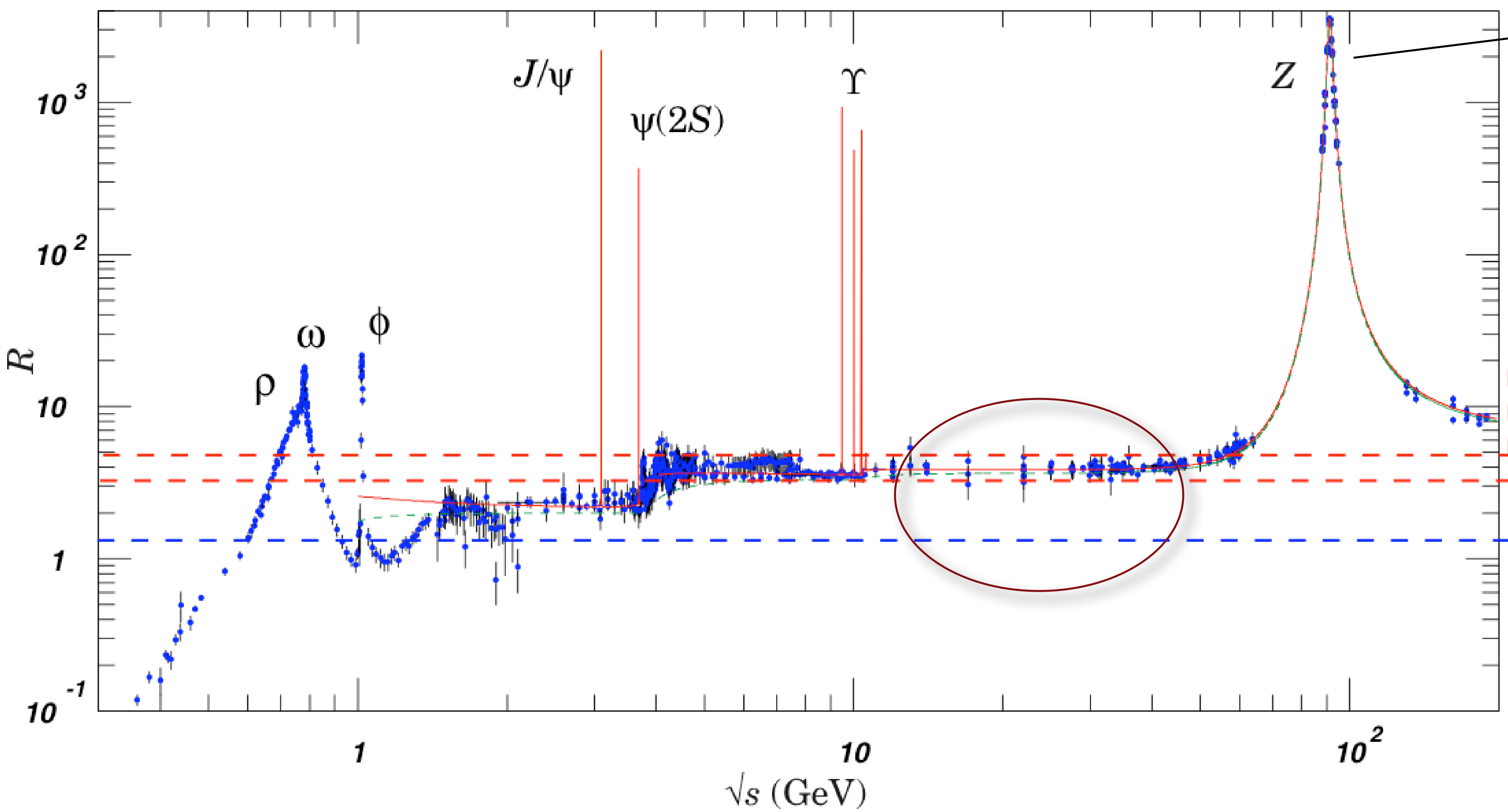

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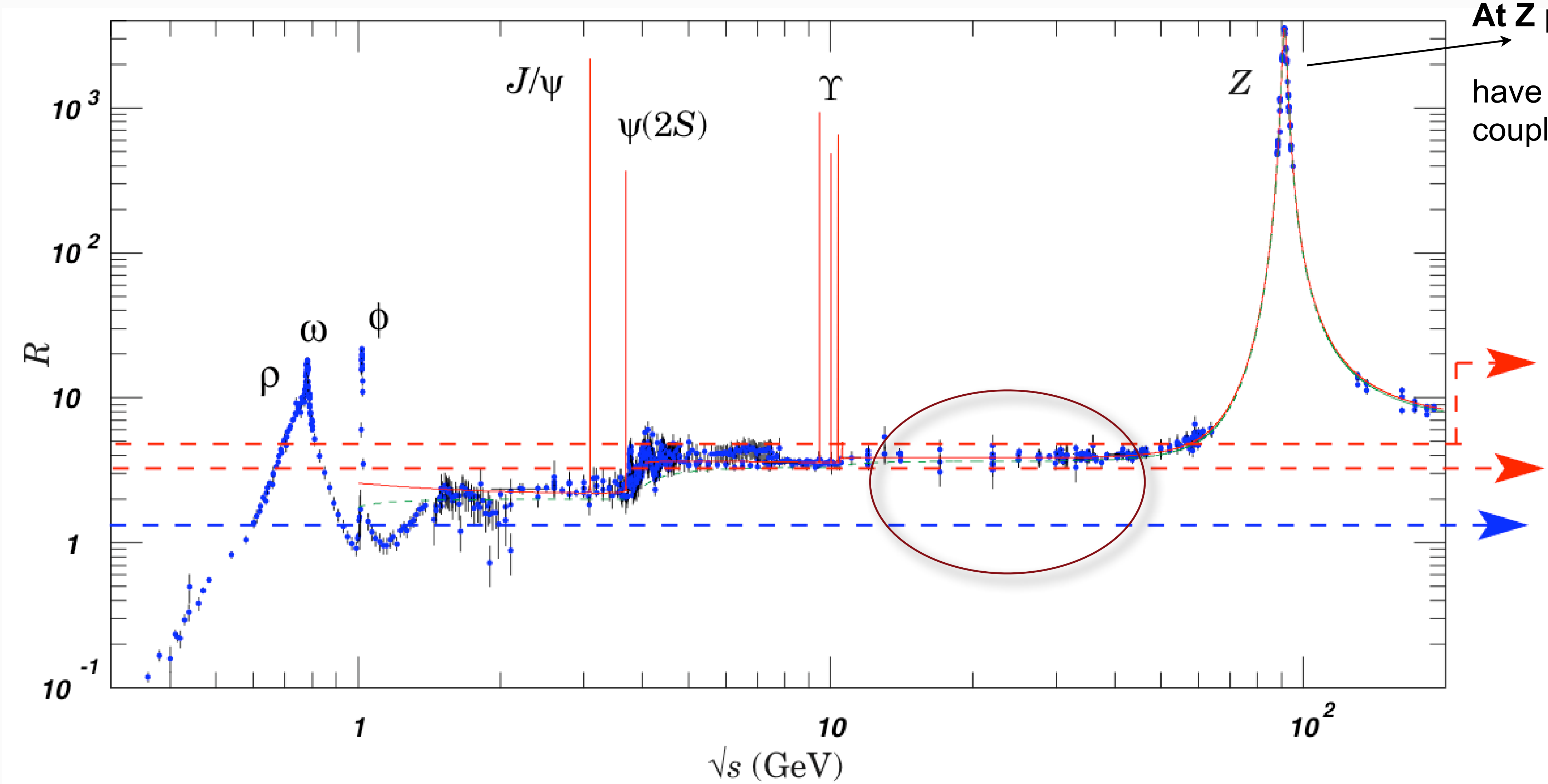

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Note : small remaining difference : because of QCD correction (gluon radiation) = 1 + α_s / π

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- 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

see also lecture by G. Cowan

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"efficiency"

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$$\varepsilon = 0.50 \pm 0.05$$

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

Event selection and all that jazz

- 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...

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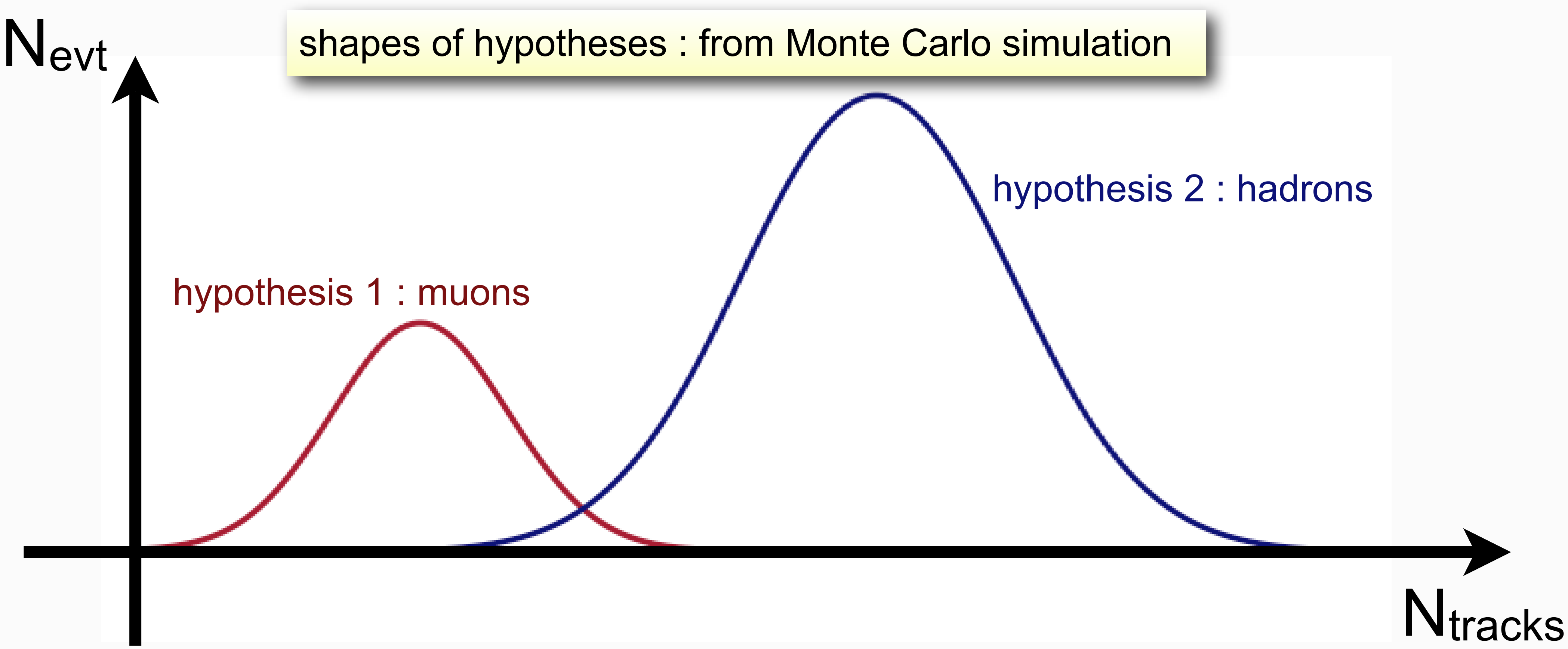

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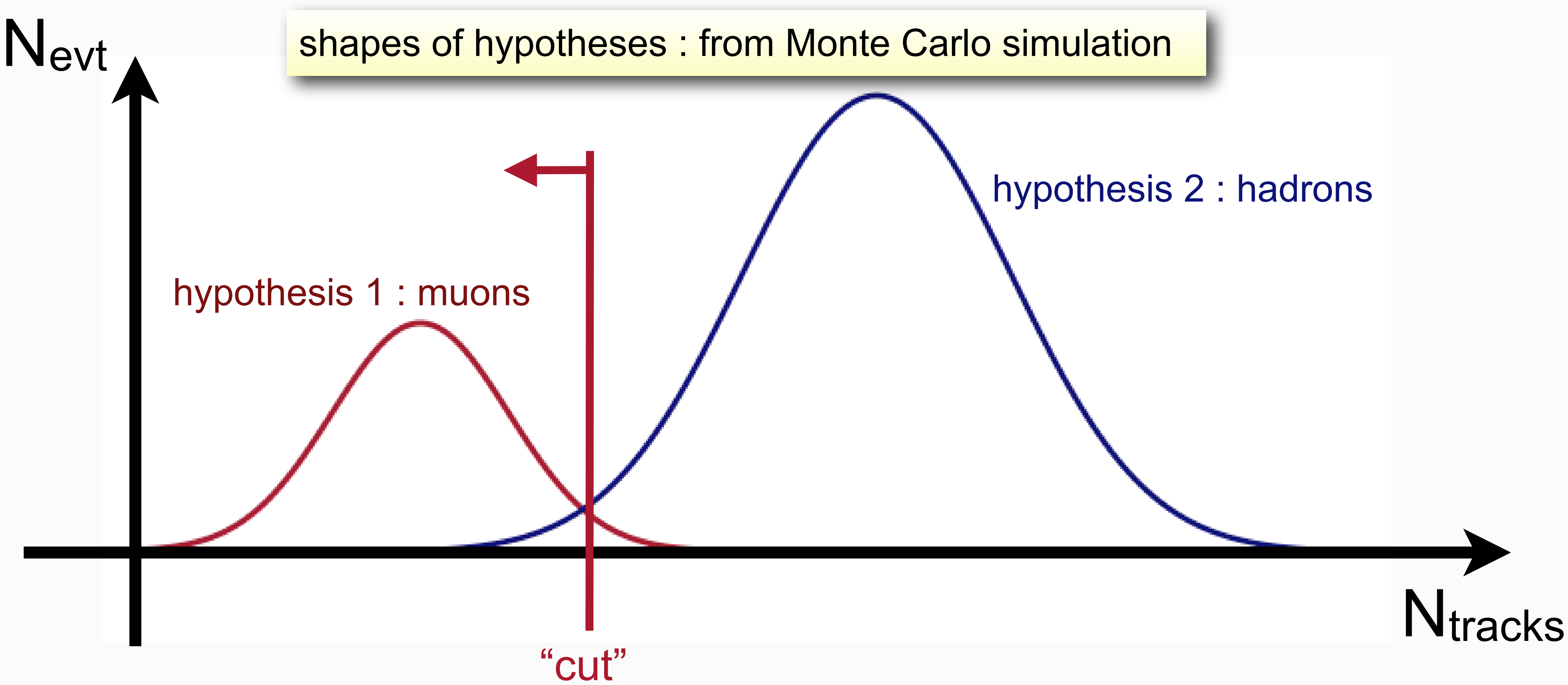

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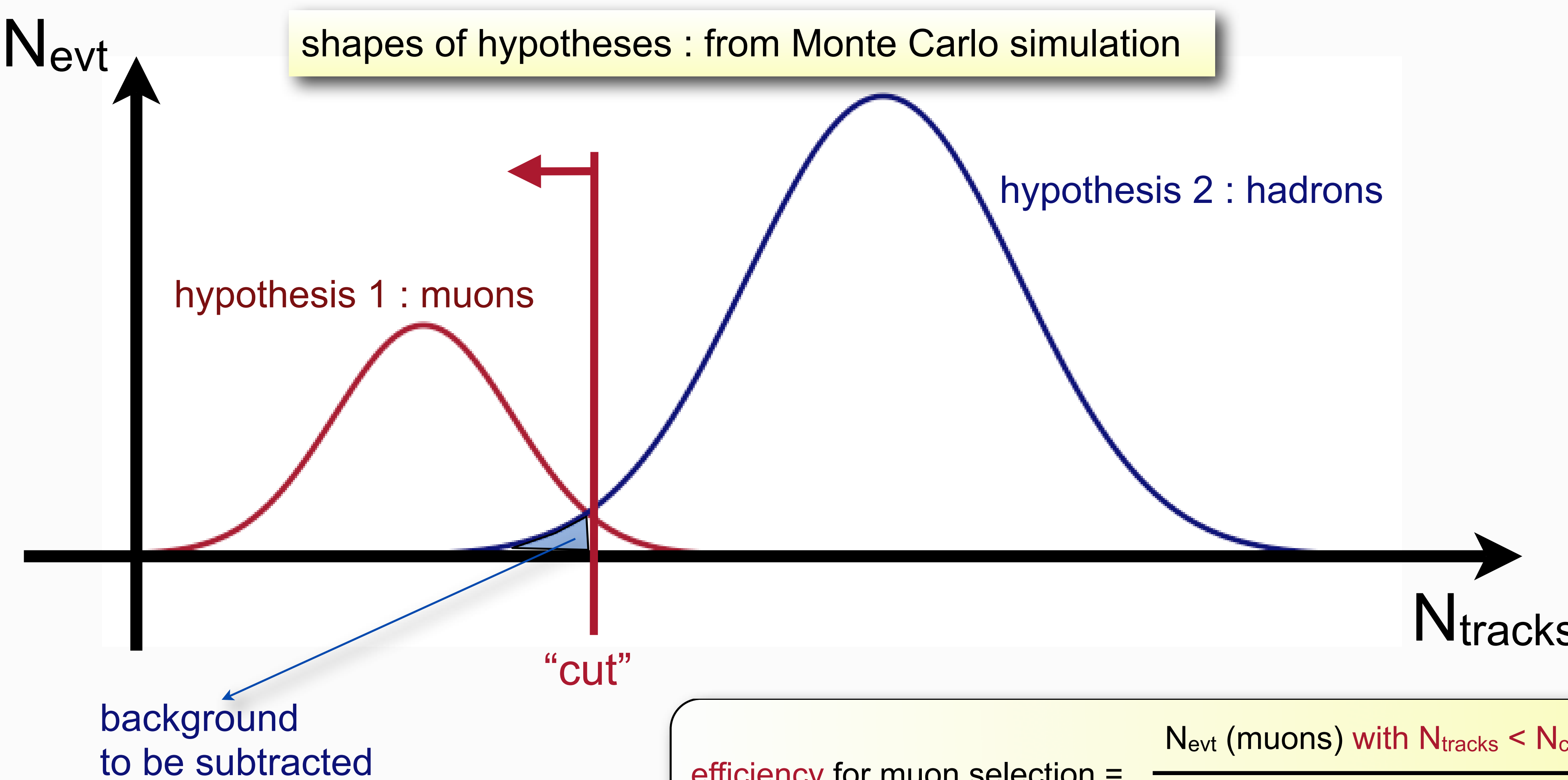

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see also lecture by G. Cowan

A “more complicated” example

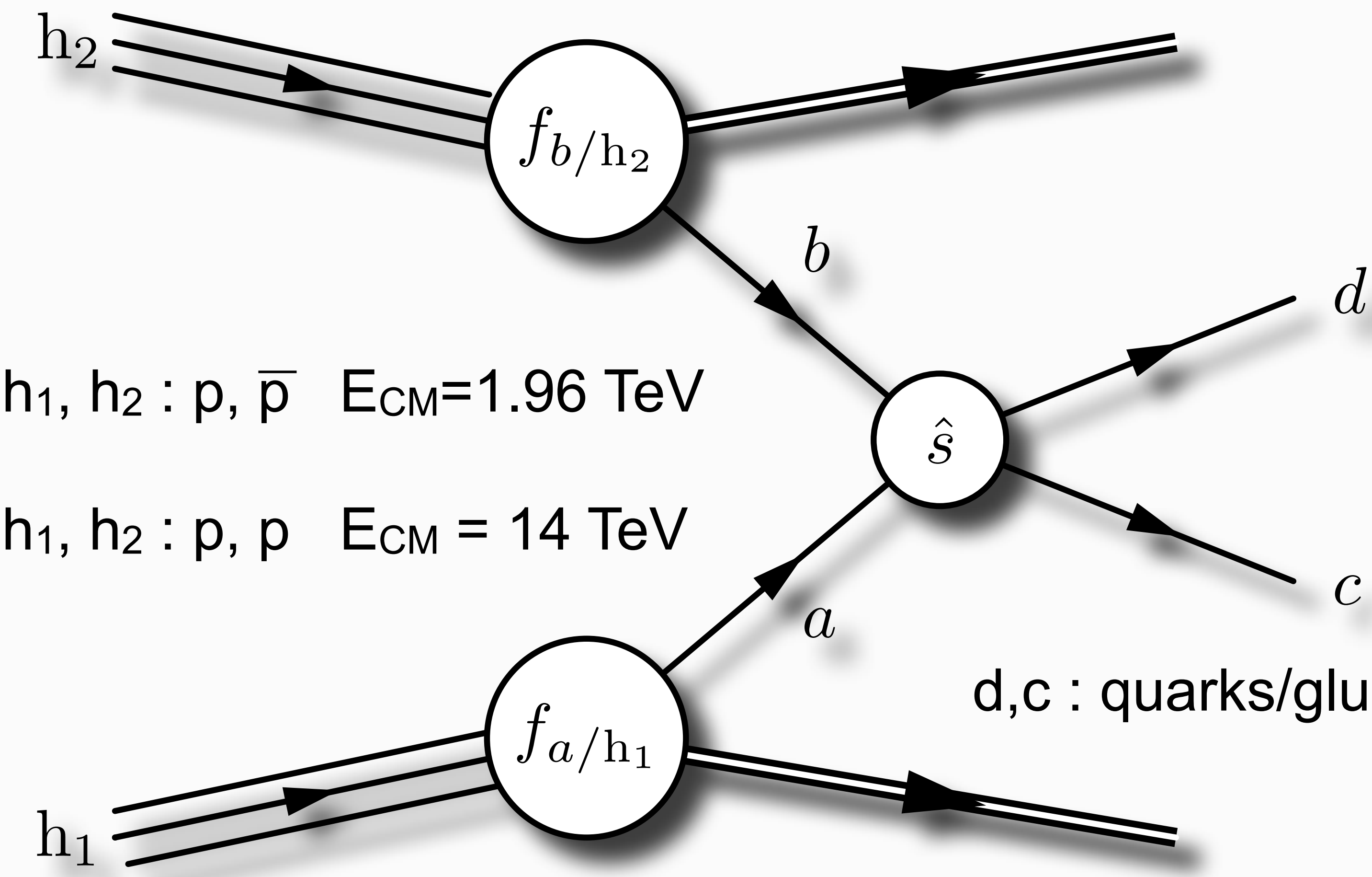
“The greater the obstacle, the more glory in overcoming it.” (Moliere)

JET production at hadron colliders

ETH Institute for Particle Physics

see also lecture by B. Heinemann

- at the Tevatron, or in the future at the LHC



h_1, h_2 : p, $\bar{p}$ E_{CM}=1.96 TeV

h_1, h_2 : p, p E_{CM} = 14 TeV

d,c : quarks/gluons

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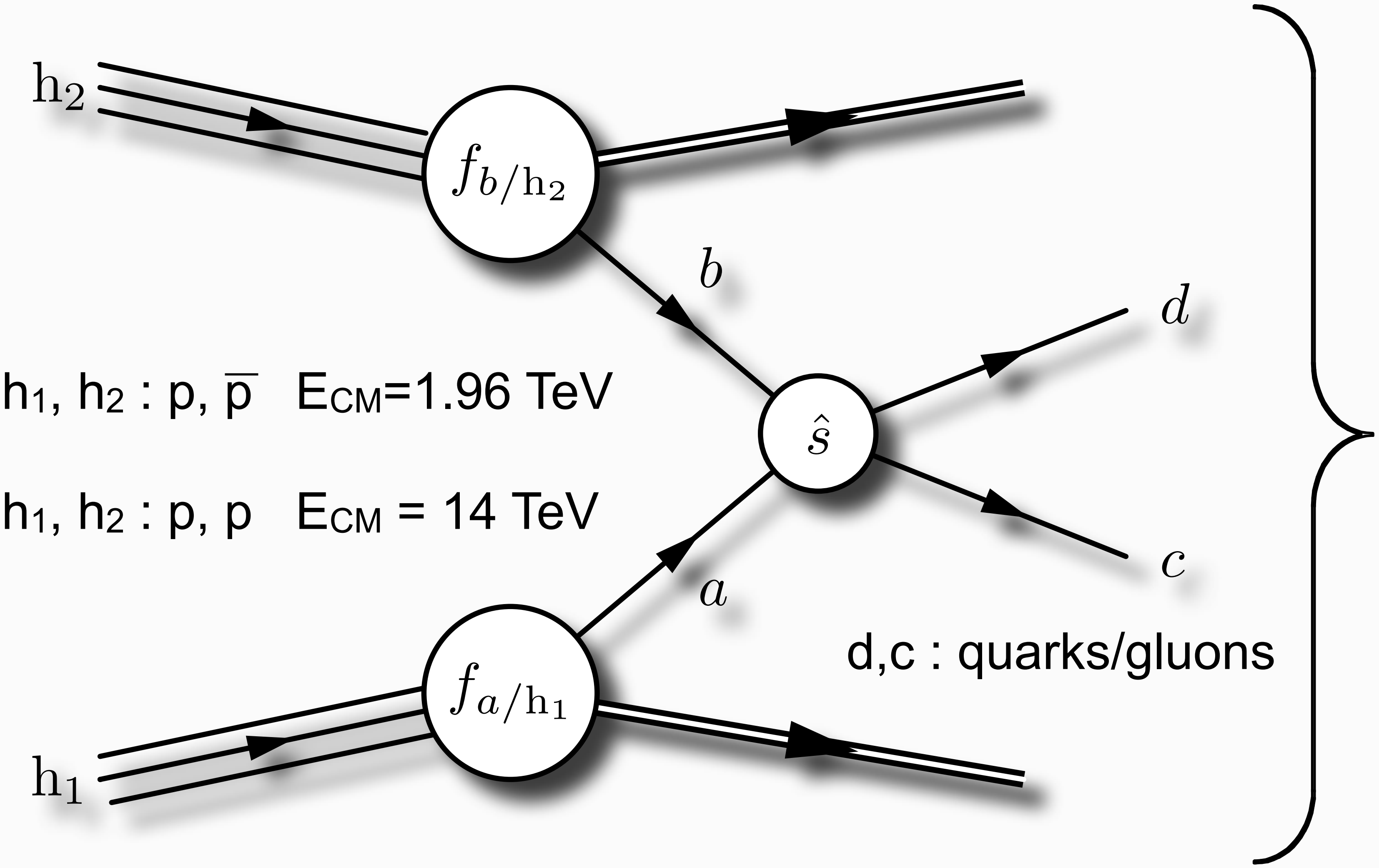

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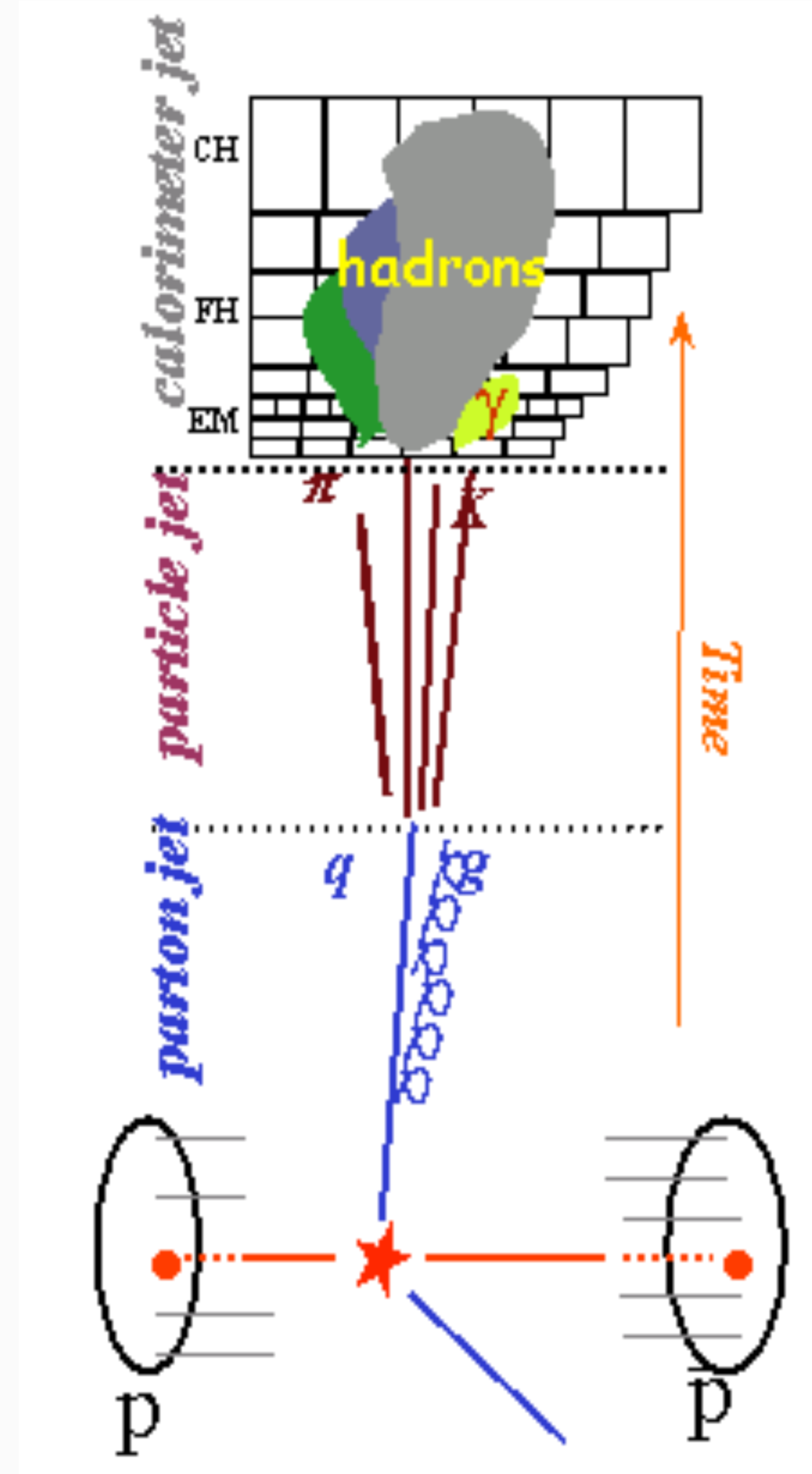

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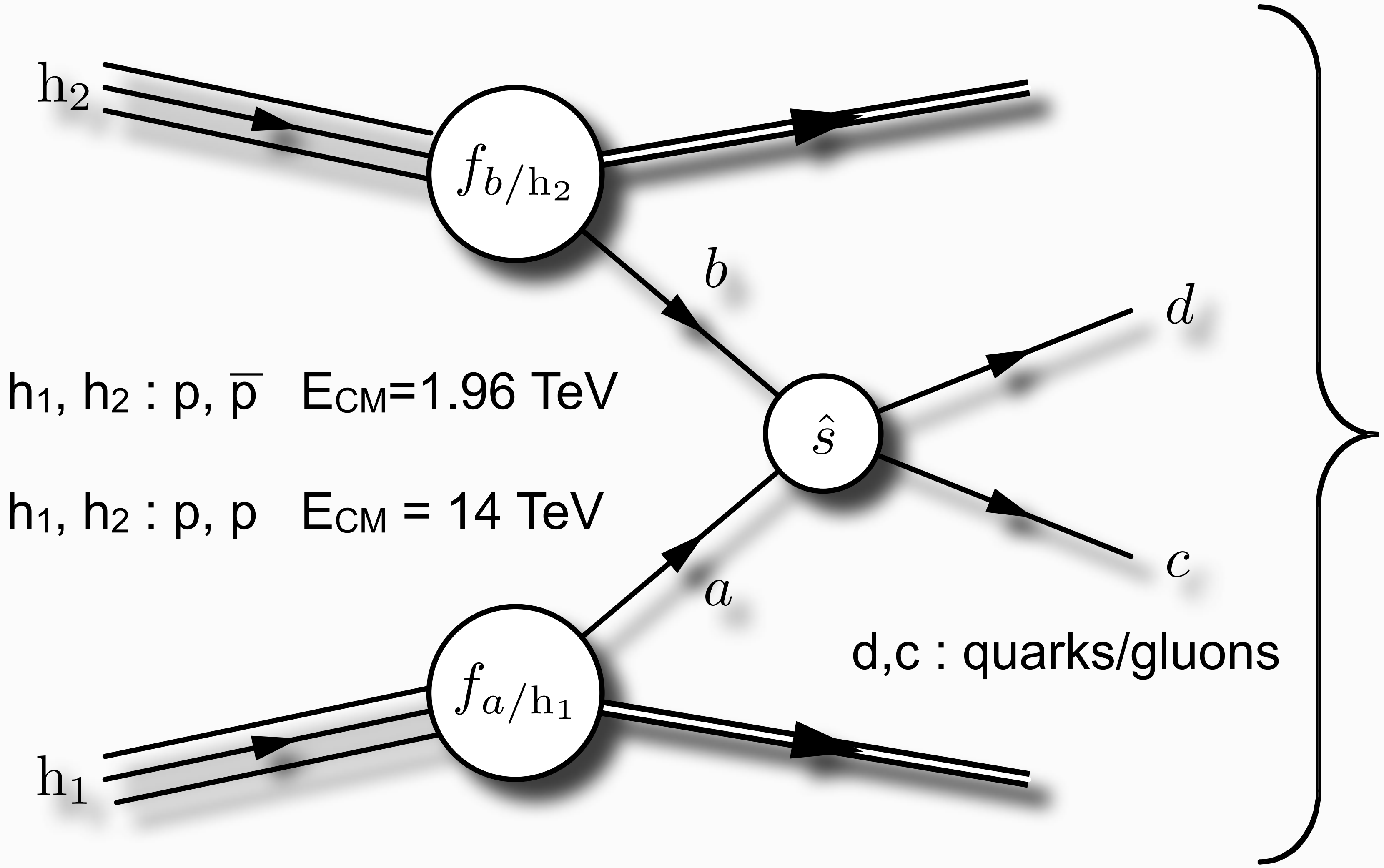

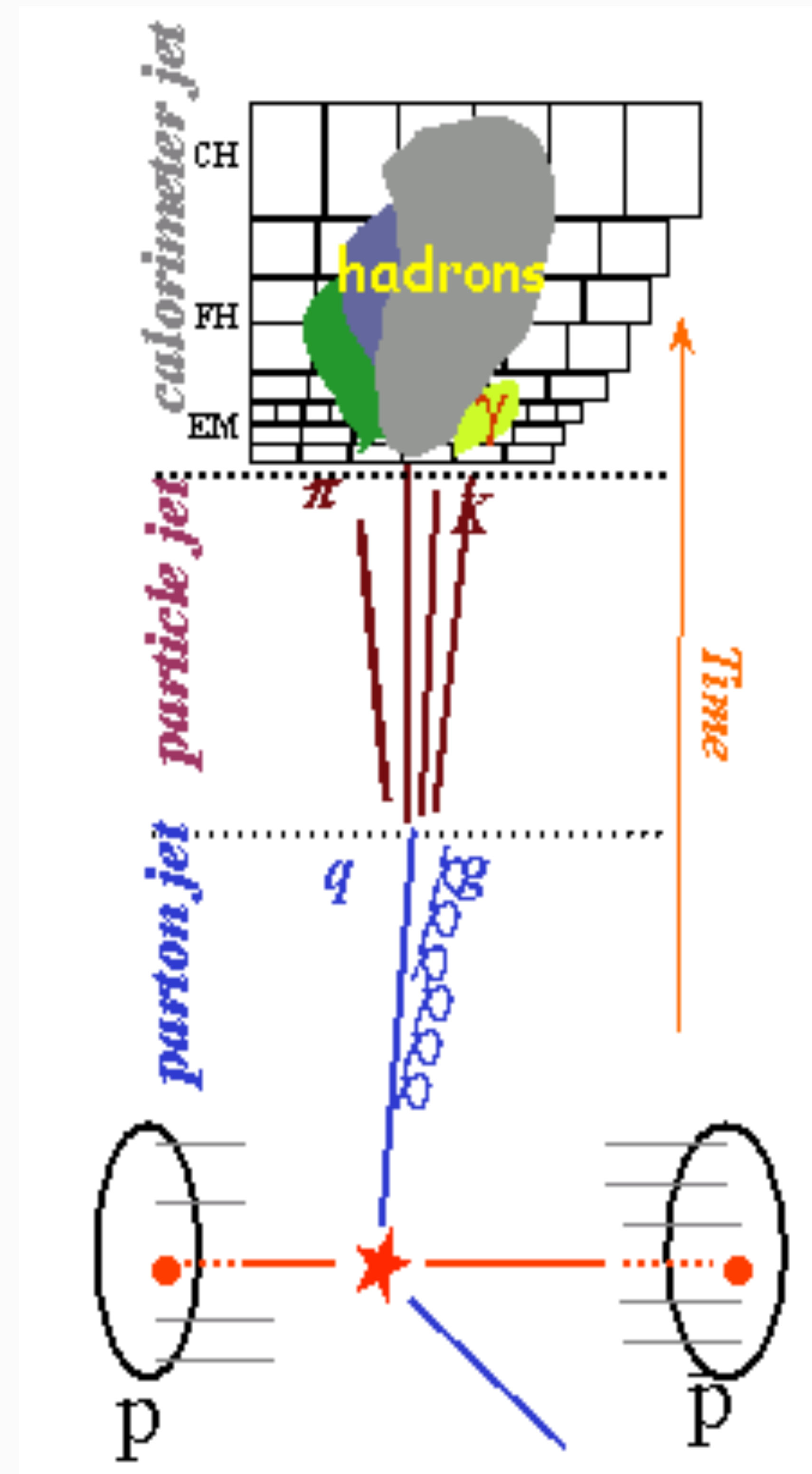

Goal

- measure probability that quarks/gluons are produced with a certain energy, at a certain angle
- Problem : do not observe quarks and gluons directly, only hadrons, which appear collimated into **jets**
- Reconstruct tracks and/or energy clusters in the calorimeter

What do we have to measure?

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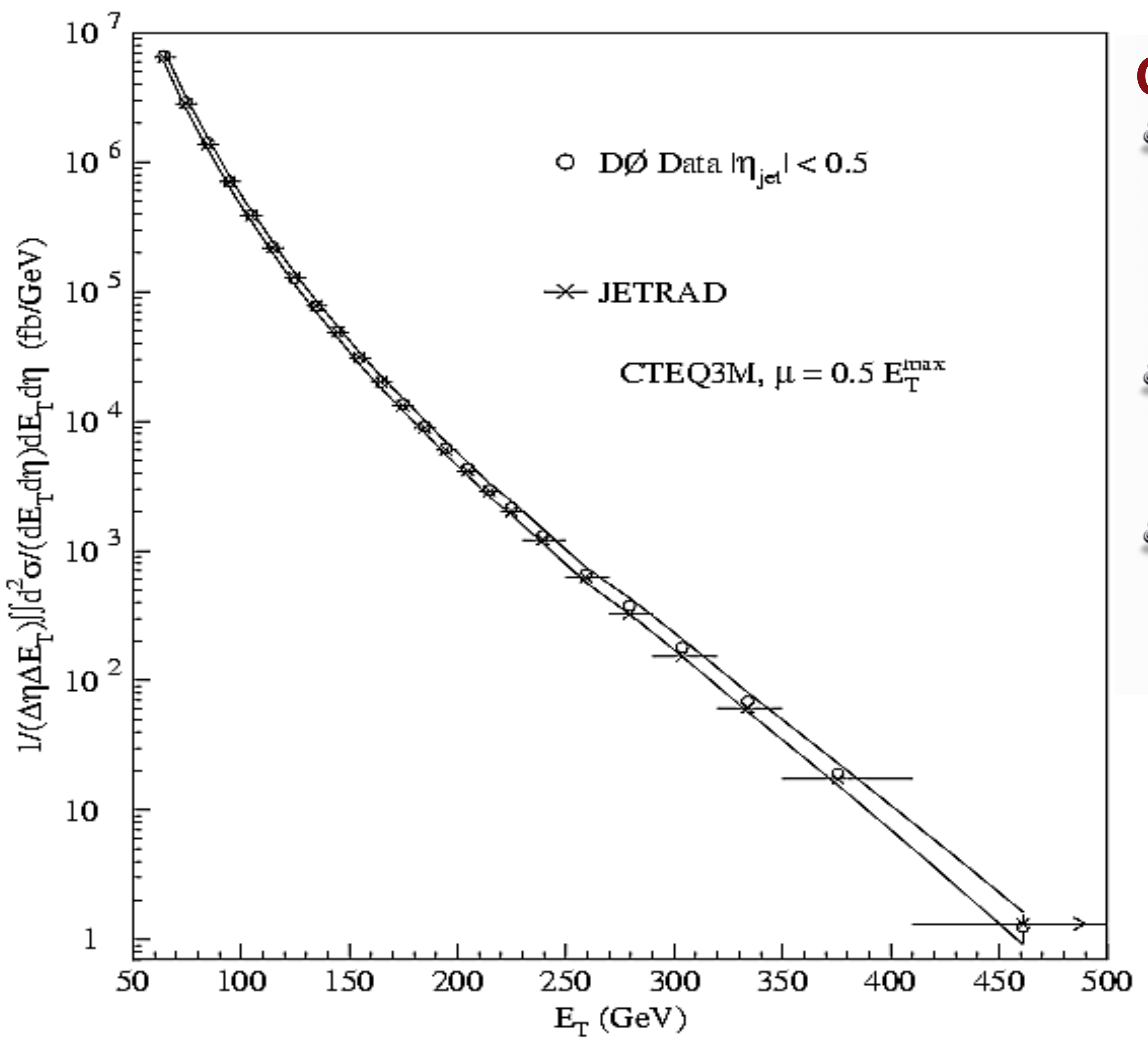

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- measure cross section (probability) that jets are produced with a certain transverse energy E_T, within a certain rapidity range
- Test of perturbative QCD, over many orders of magnitude!
- Look at very high energy tail, new physics could show up there in form of excess (eg. sub-structure of quarks?)

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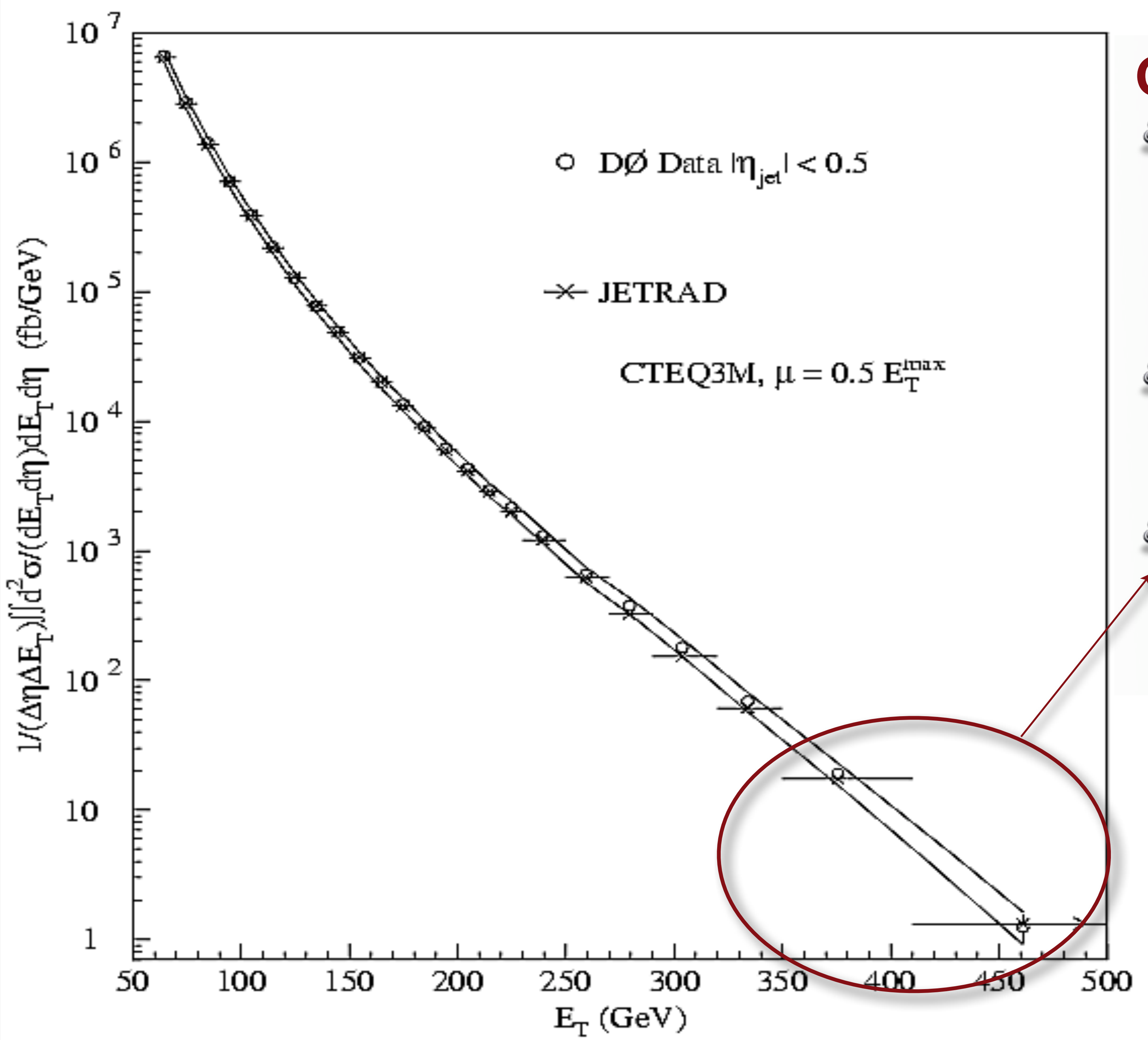

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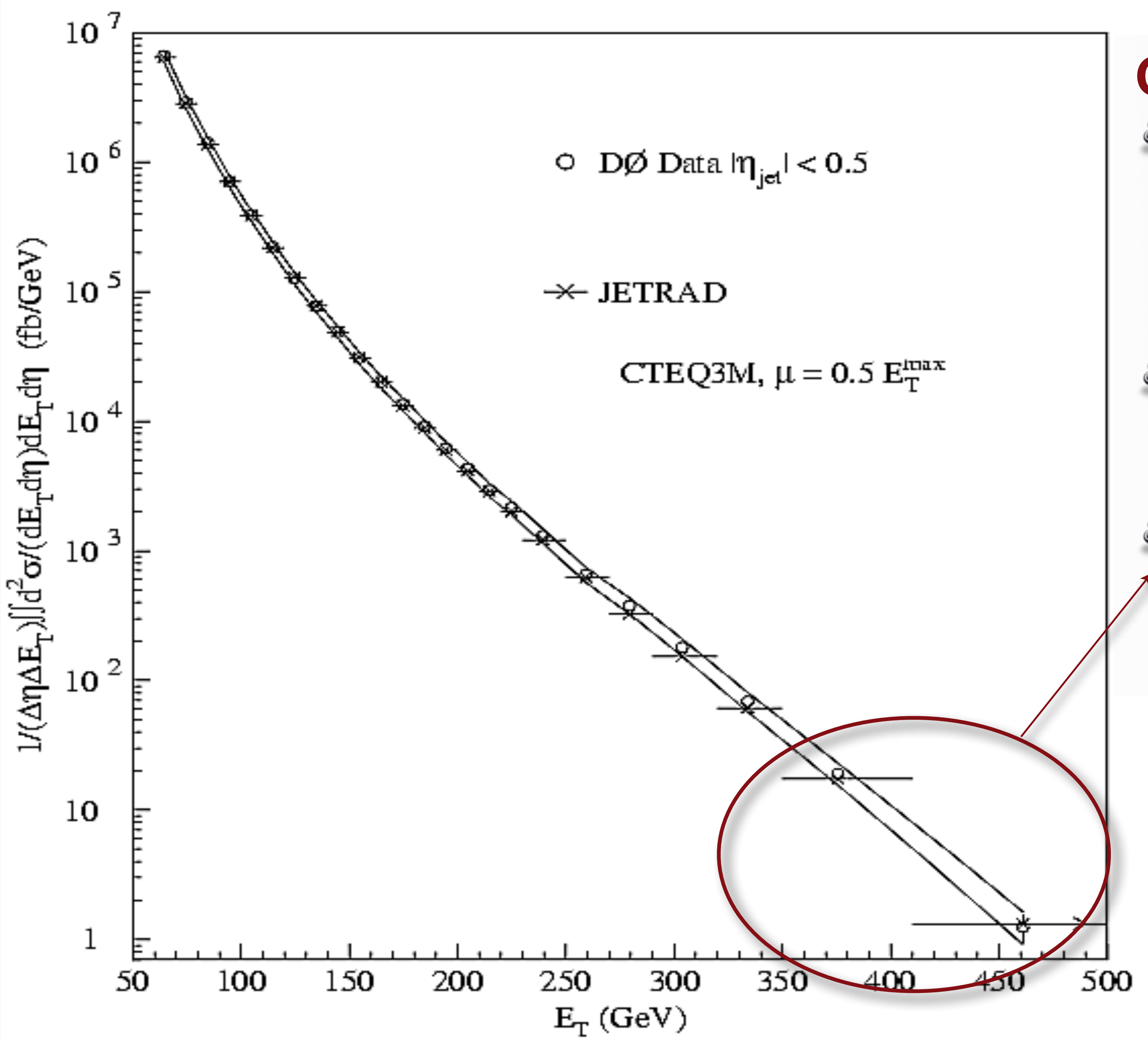

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$$\left\langle \frac{d^2\sigma}{dE_T d\eta} \right\rangle = \frac{N}{\Delta E_T \Delta\eta\, \epsilon\, \mathcal{L}}$$

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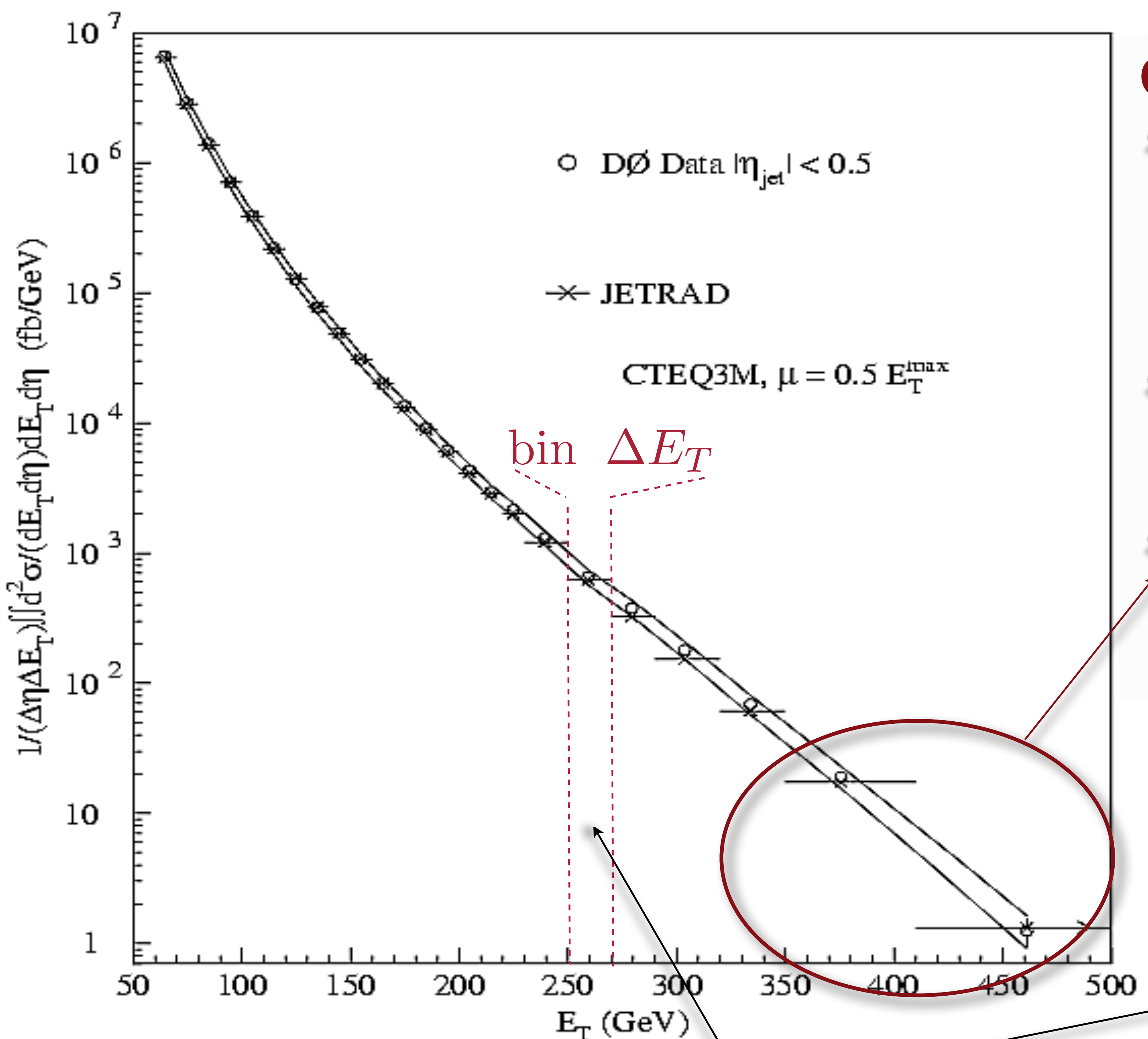

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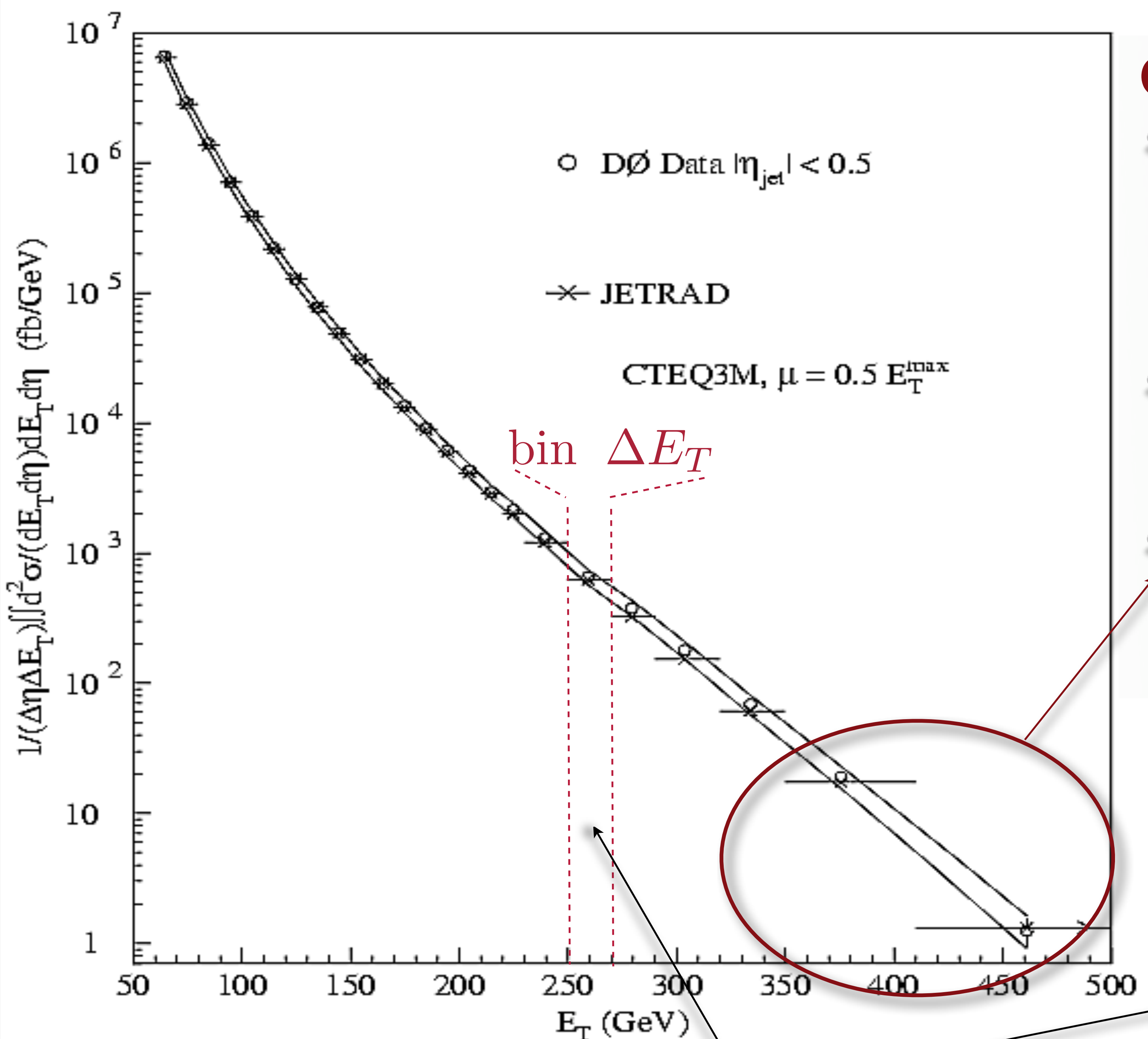

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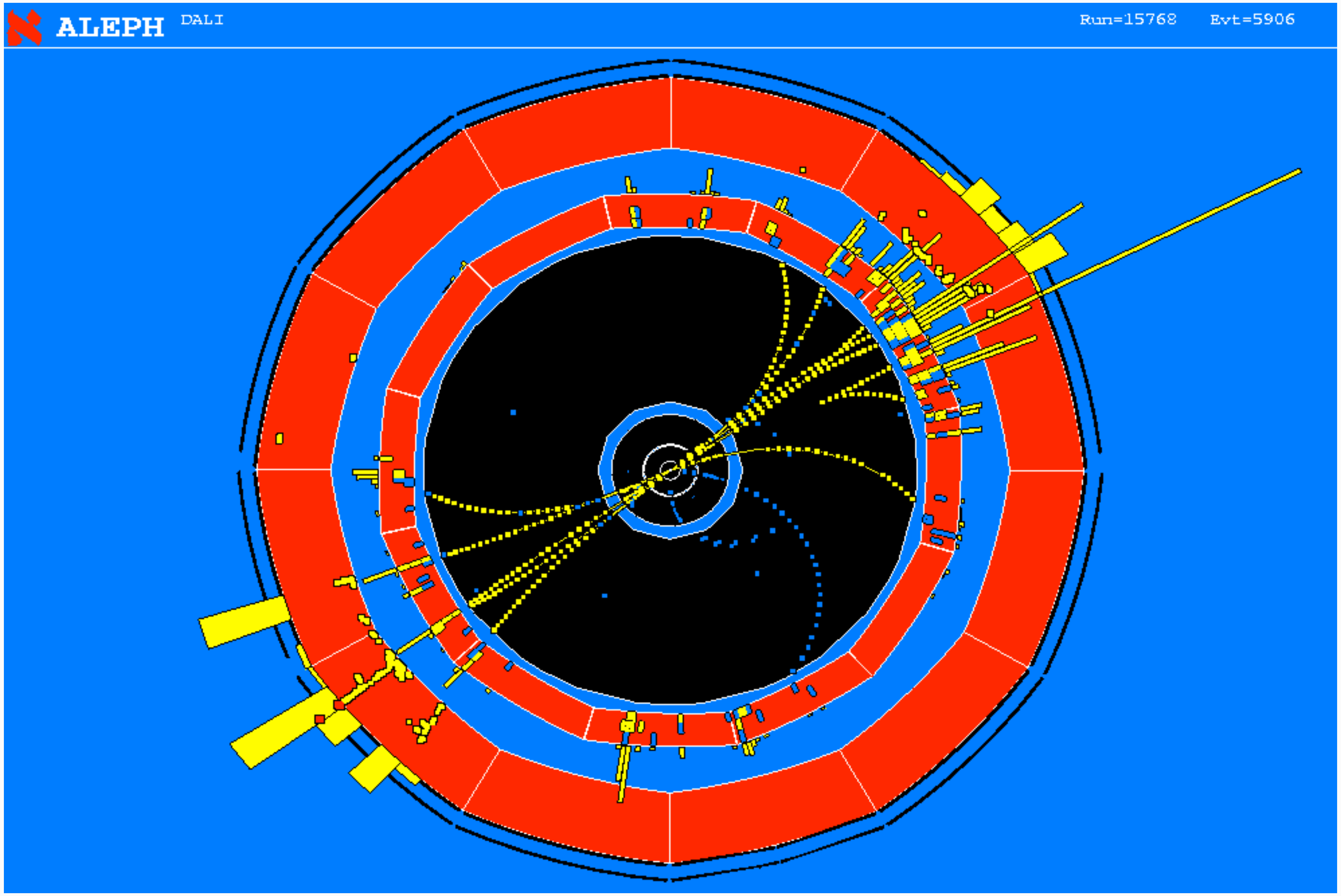
efficiency to reconstruct jets

integrated accelerator luminosity

What is a jet?



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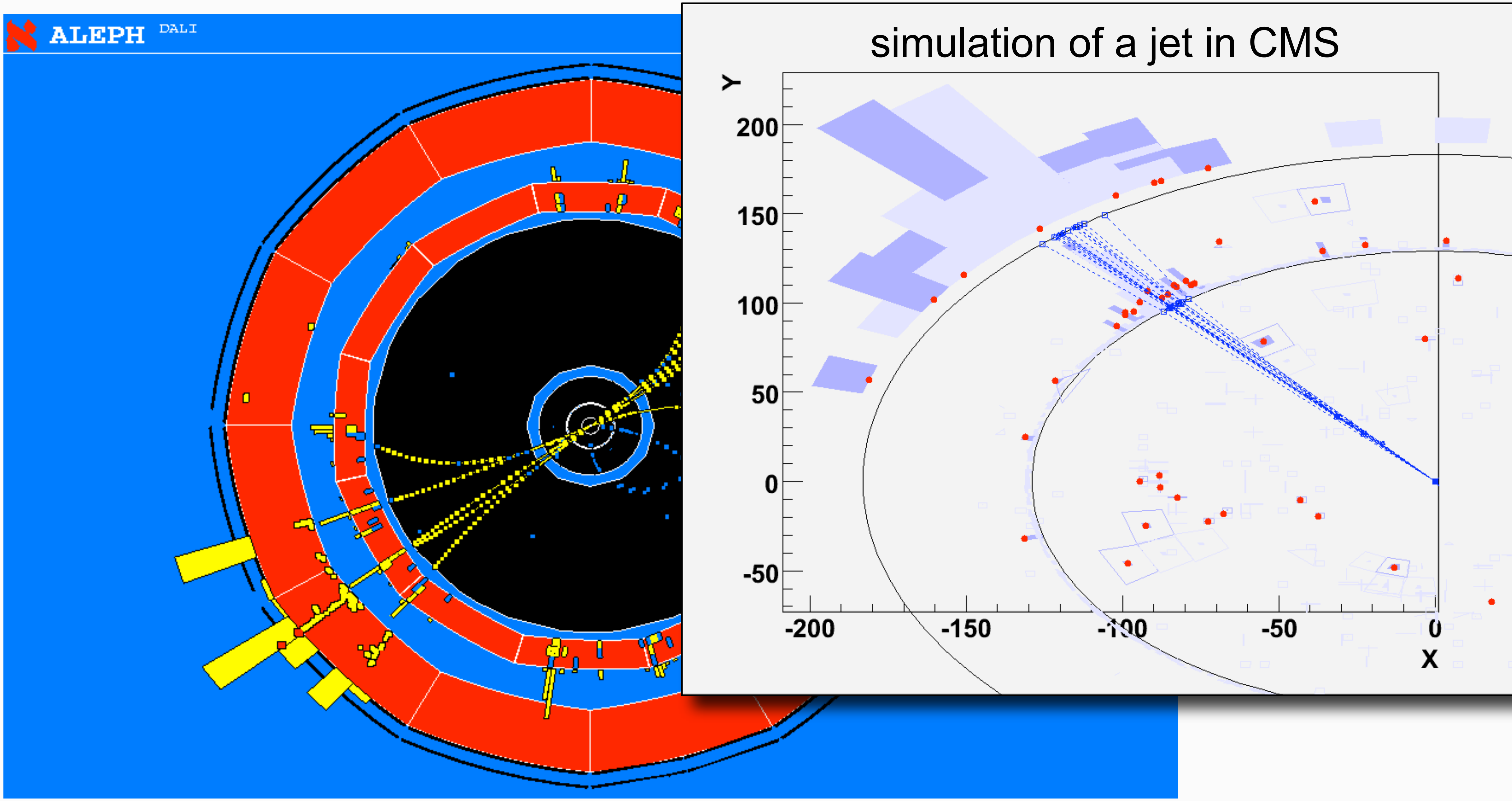

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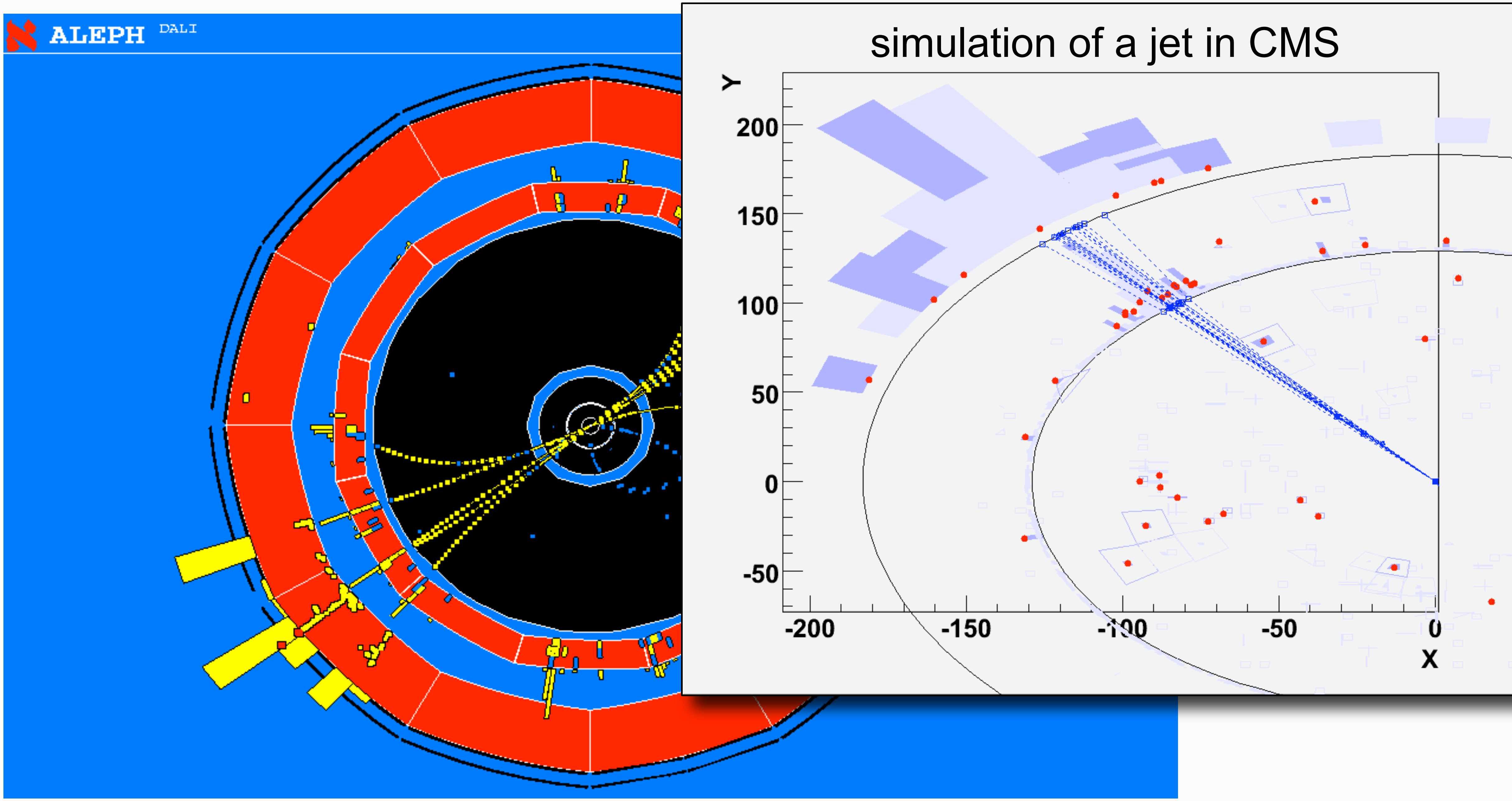
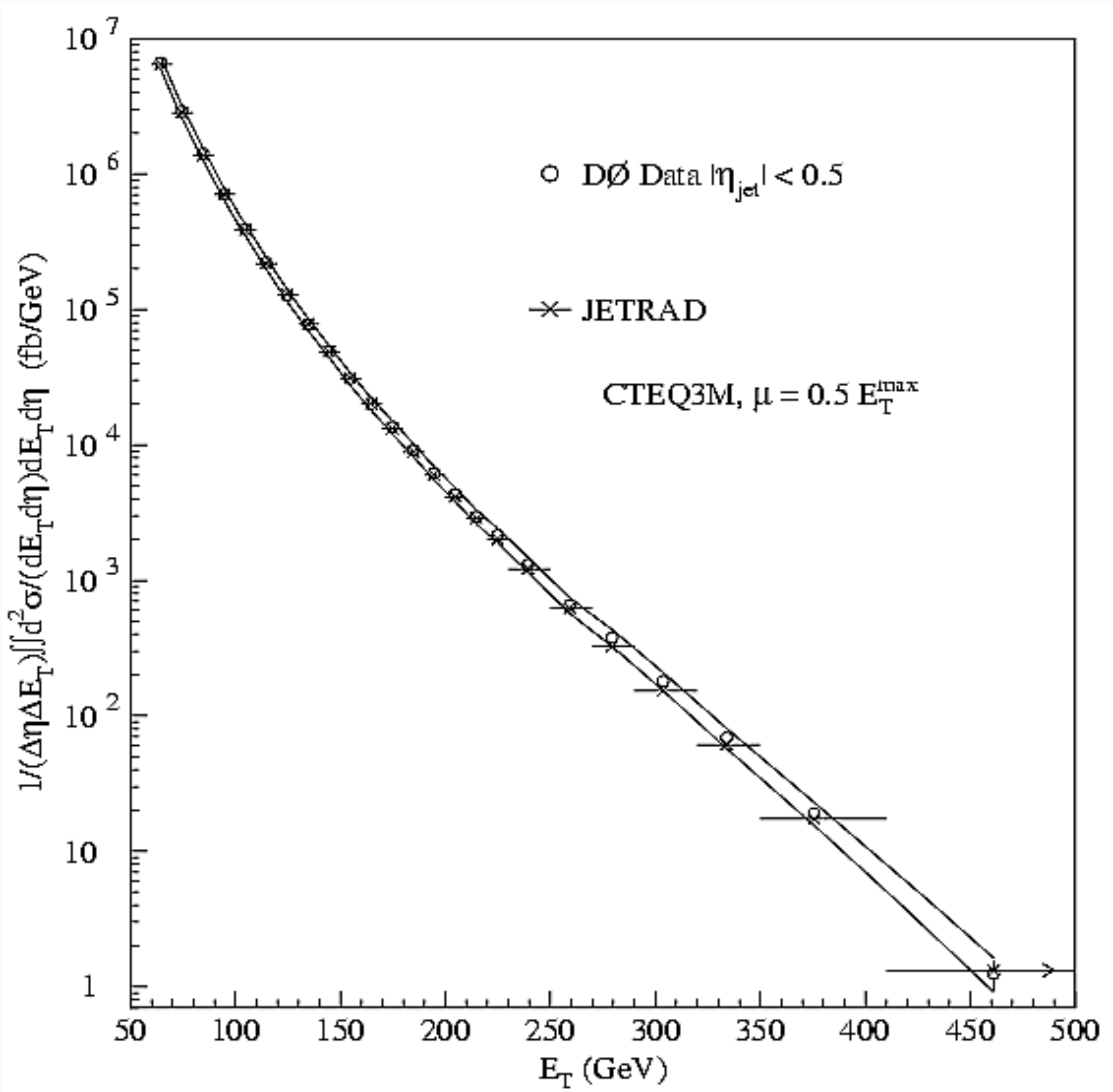


"cluster/spray of particles (tracks, calorimeter deposits) or flow of energy in a restricted angular region"

- clear : need some algorithmic definition. See later..

Problem 1 : Energy scale

- Question : how well do we know the energy calibration?
- Critical because of very steeply falling spectrum!



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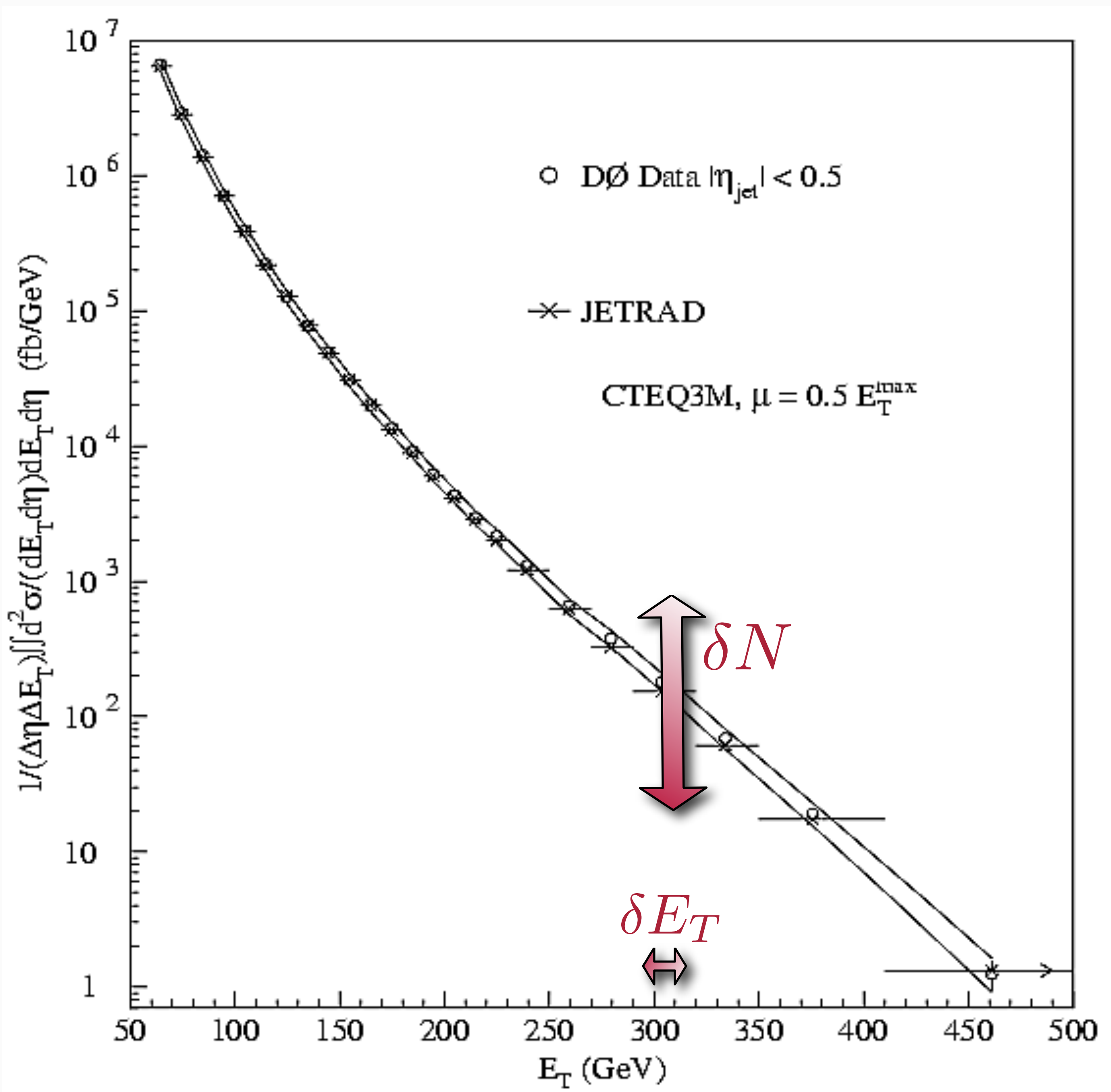

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relative uncertainties

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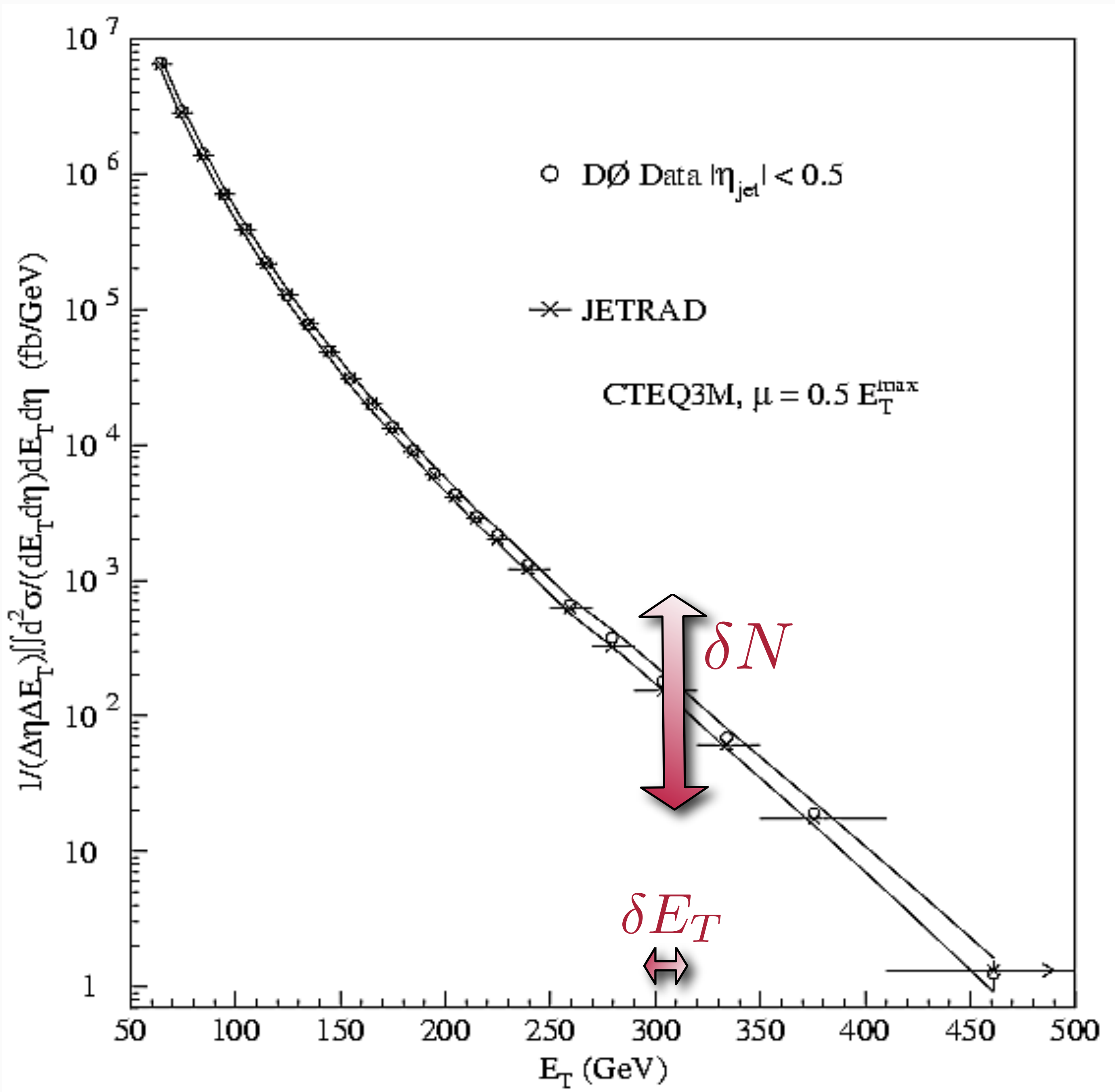

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so beware:

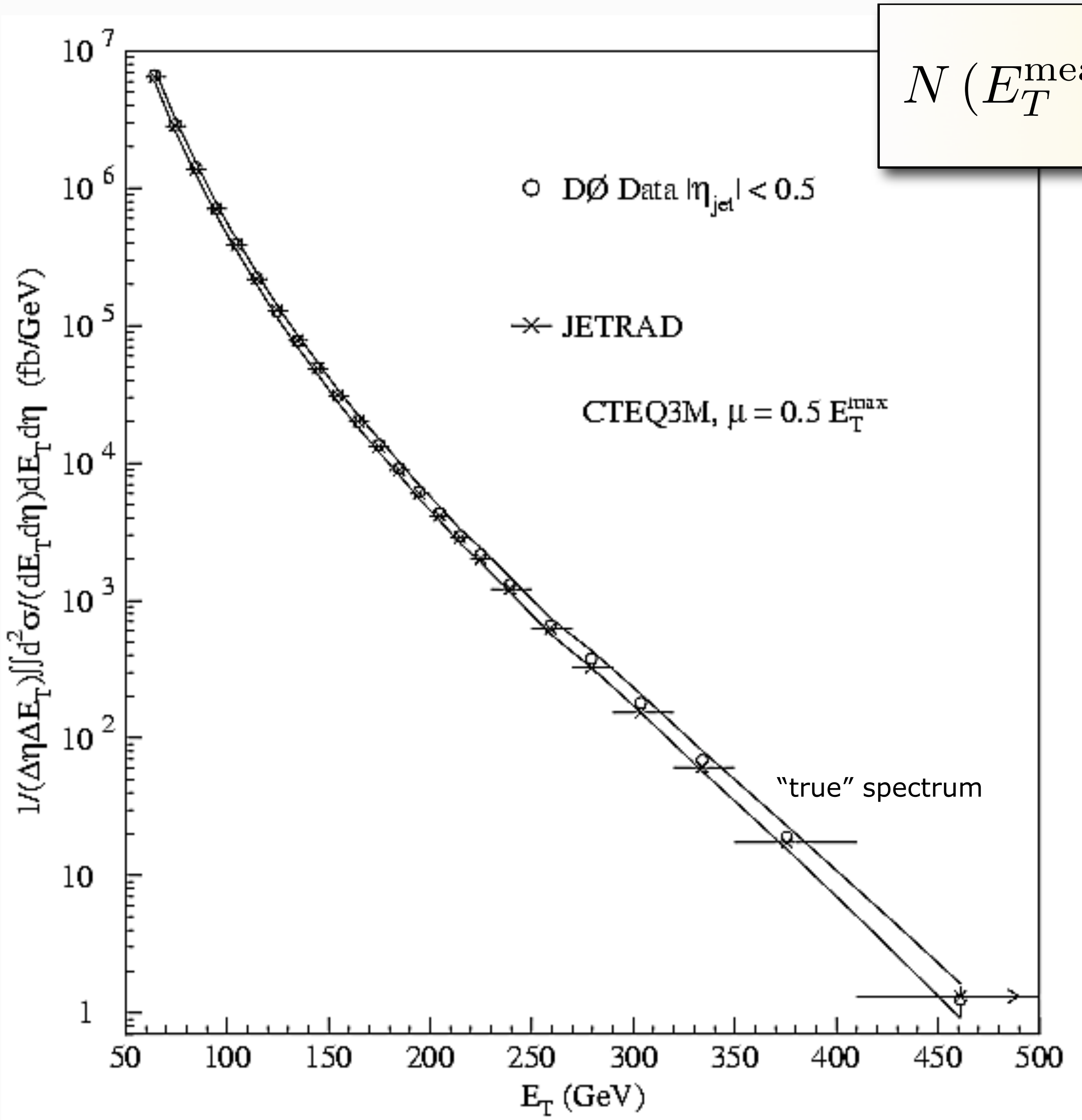
eg. an uncertainty of **5%** on absolute energy scale (calibration)

➔ an uncertainty of **30%** (!) on the measured cross section

Problem 2 : Energy resolution

- The energy resolution can distorts the spectrum
- Again : Critical because of very steeply falling spectrum!

$$N\left(E_T^{\mathrm{meas}}\right) = \int_0^{\infty} N\left(E_T^{\mathrm{true}}\right) \cdot \mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \mathrm{d}E_T^{\mathrm{true}}$$



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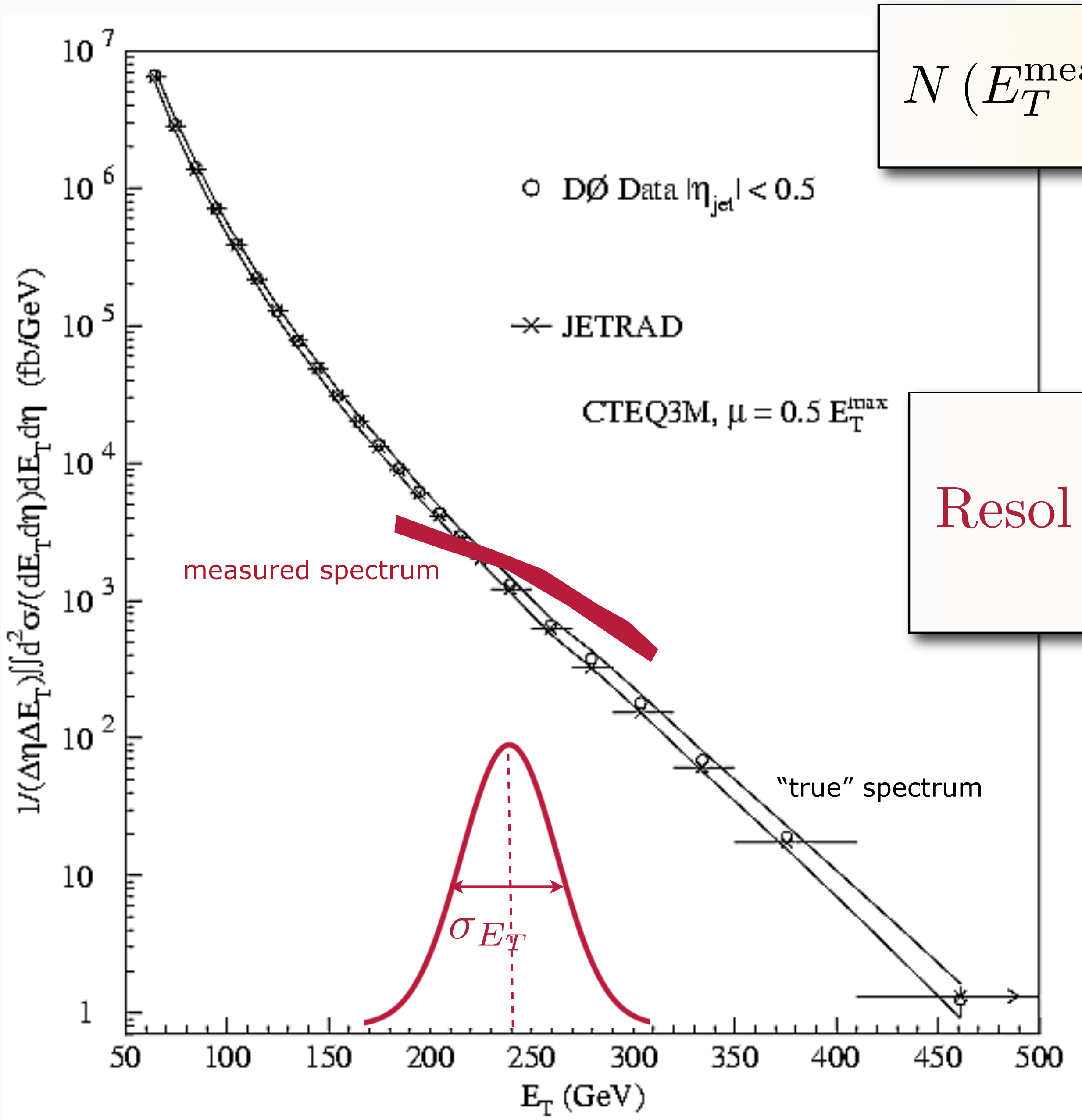

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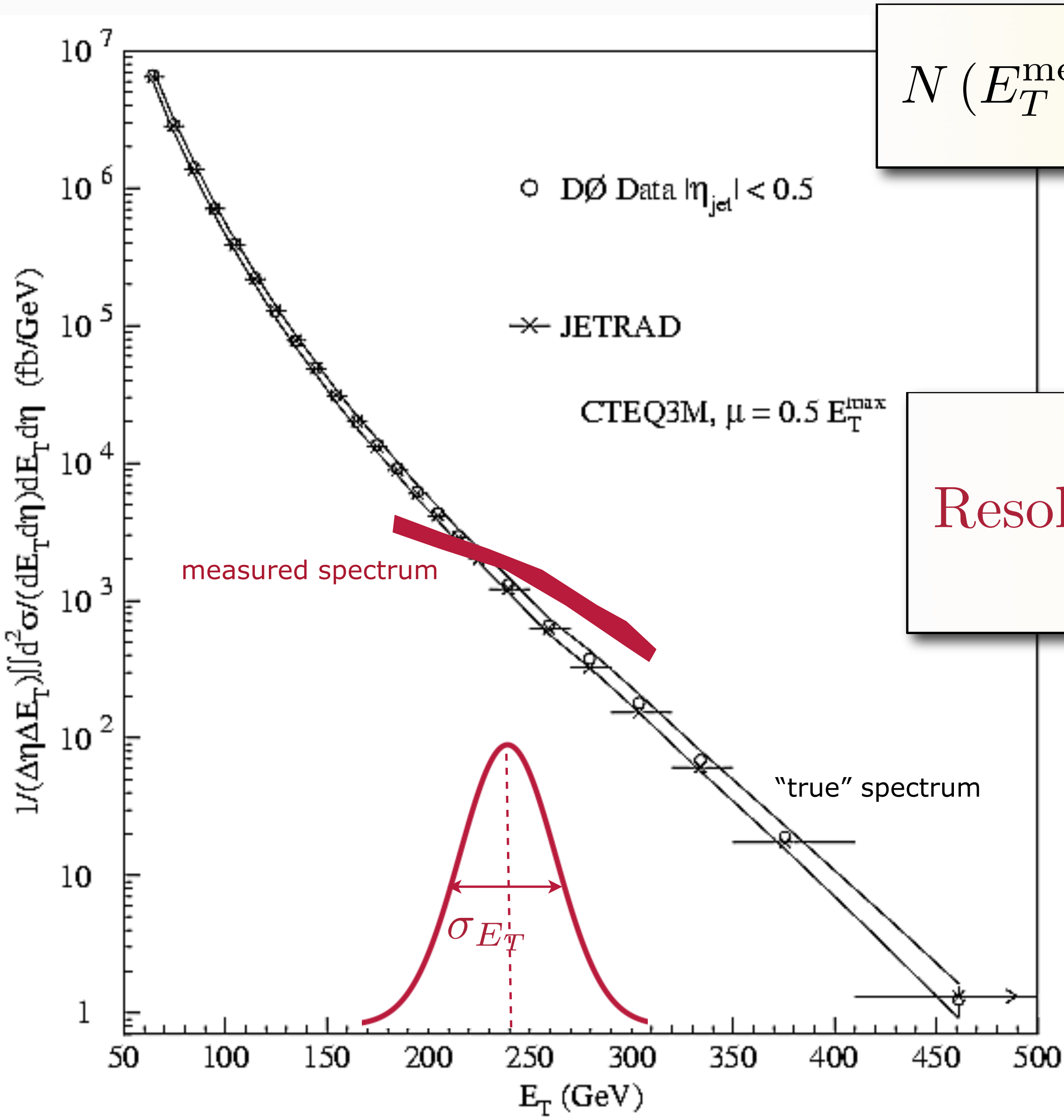

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so beware:

A bad energy resolution can distort the true spectrum

➔ have to determine the energy resolution

➔ have to "unfold" the measured spectrum

➔ problem is minimized if bin width ~ σ_{E_T}

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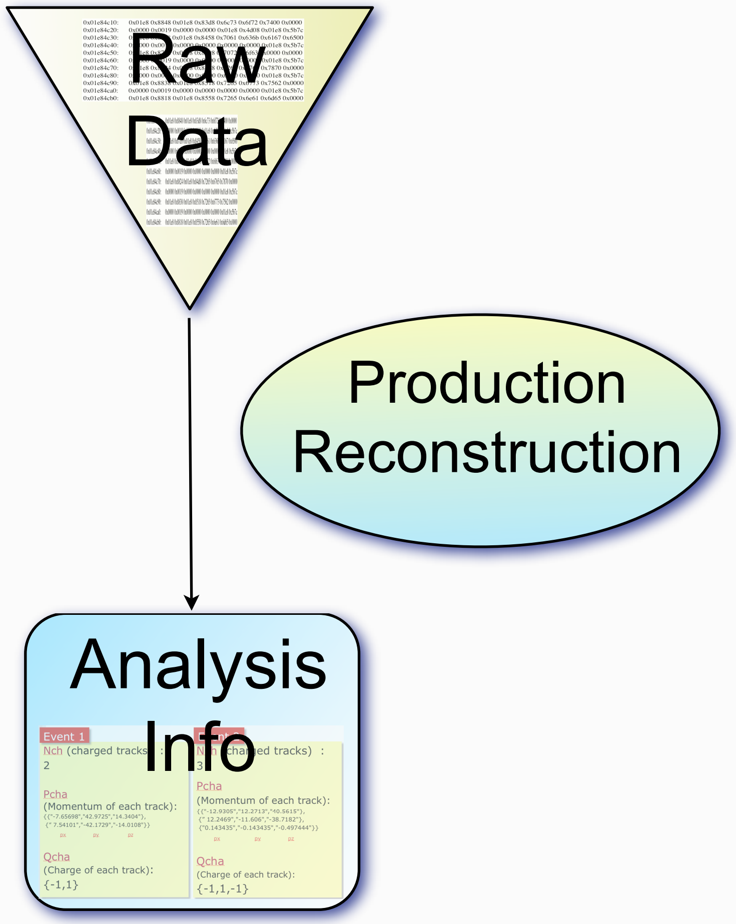
  - determine parameters, eg. by fitting the prediction to the data

How is all this done in practice?

"The only place you'll find SUCCESS before WORK is in the dictionary" (May B. Smith)

The process in practice

- The reconstruction step is usually done in common
  - "Tracks", "particle ID", "calorimeter towers" etc are general concepts, not analysis-specific. Common algorithms make it easier to understand how well they work
  - "very coordinated" data access



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  - Many different measurements being done at once
  - Small groups working on topics they are interested in
  - Many different time scales for these efforts
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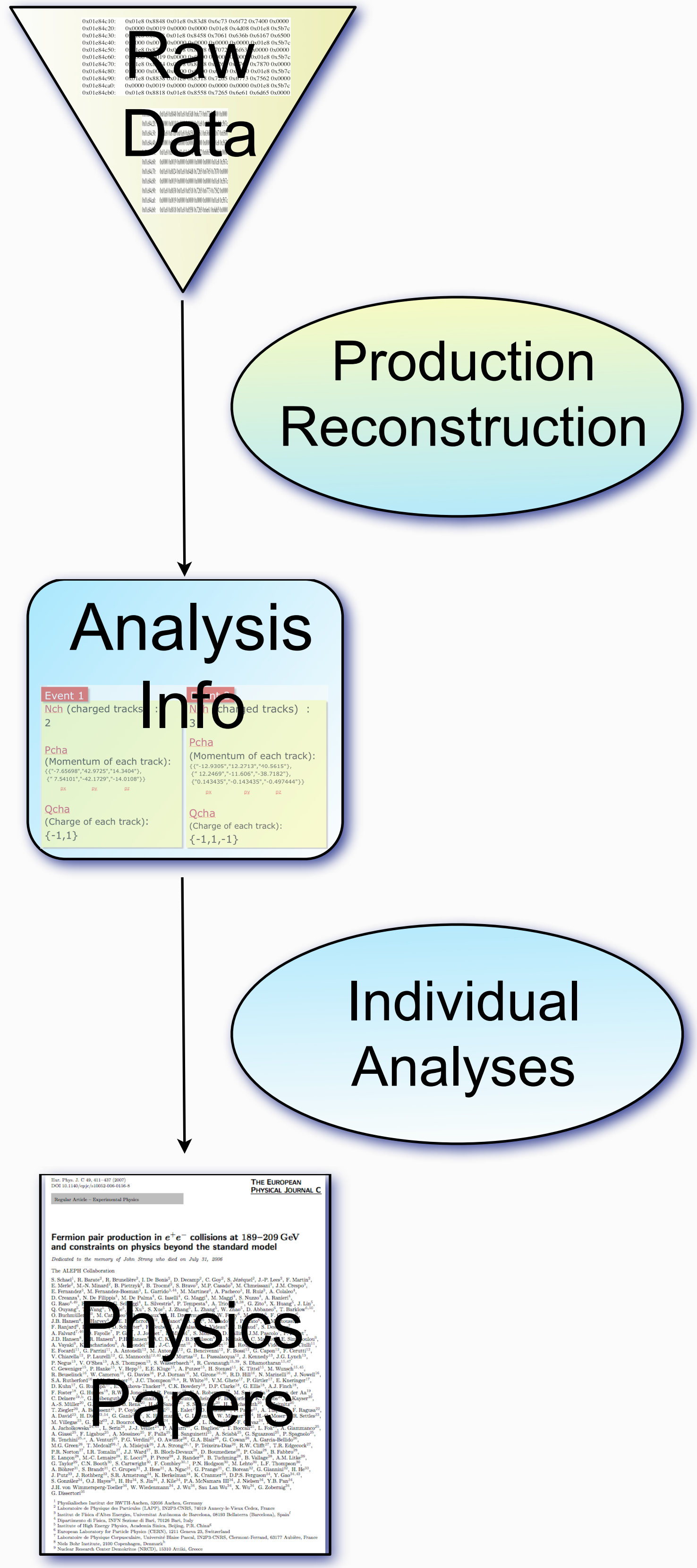

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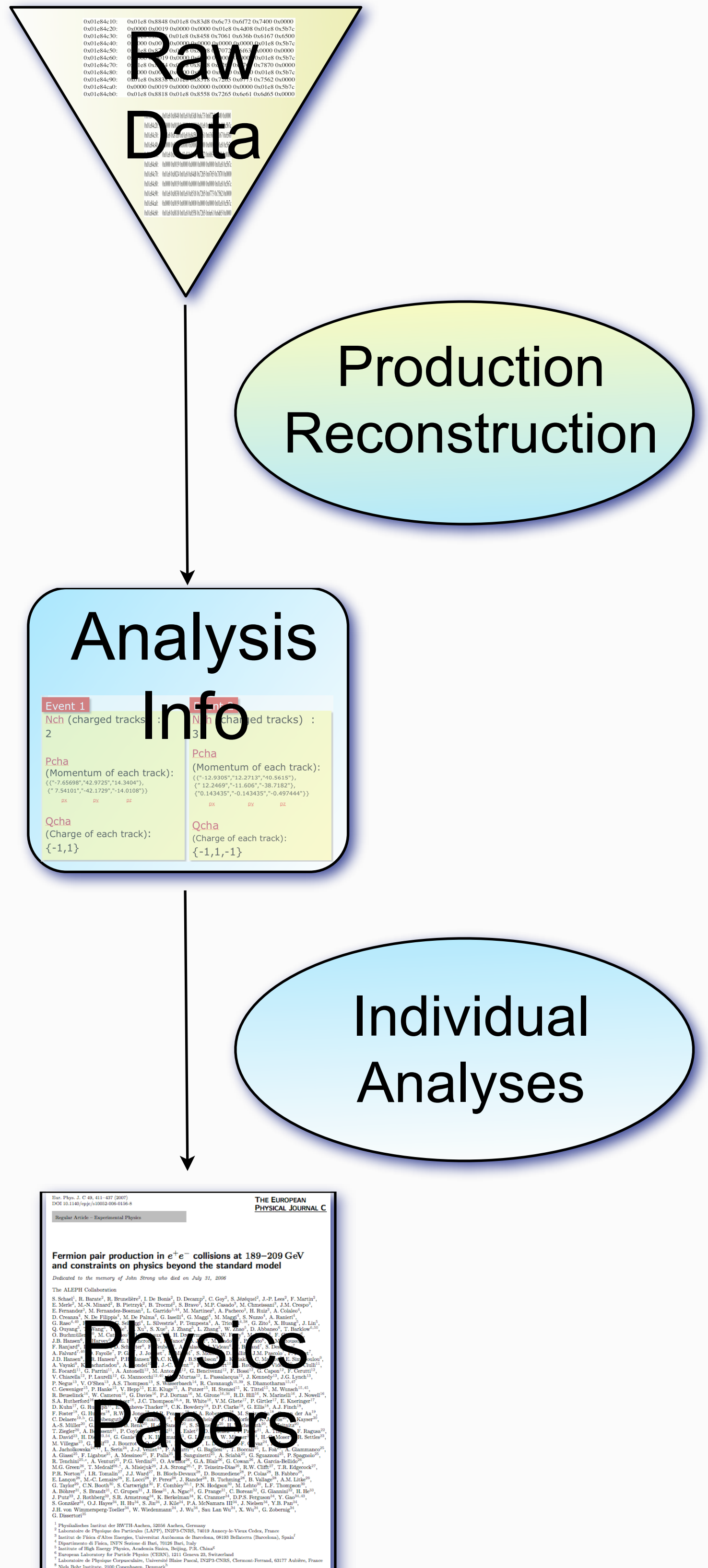
- Collaborations build offline computing systems to handle all this



Track finding

Why does tracking need to be done well?

- Determine how many charged particles were created in an event
- Measure their momentum
  - direction, magnitude
  - combine these to look for decays of particles with known masses
  - only final stable particles are visible

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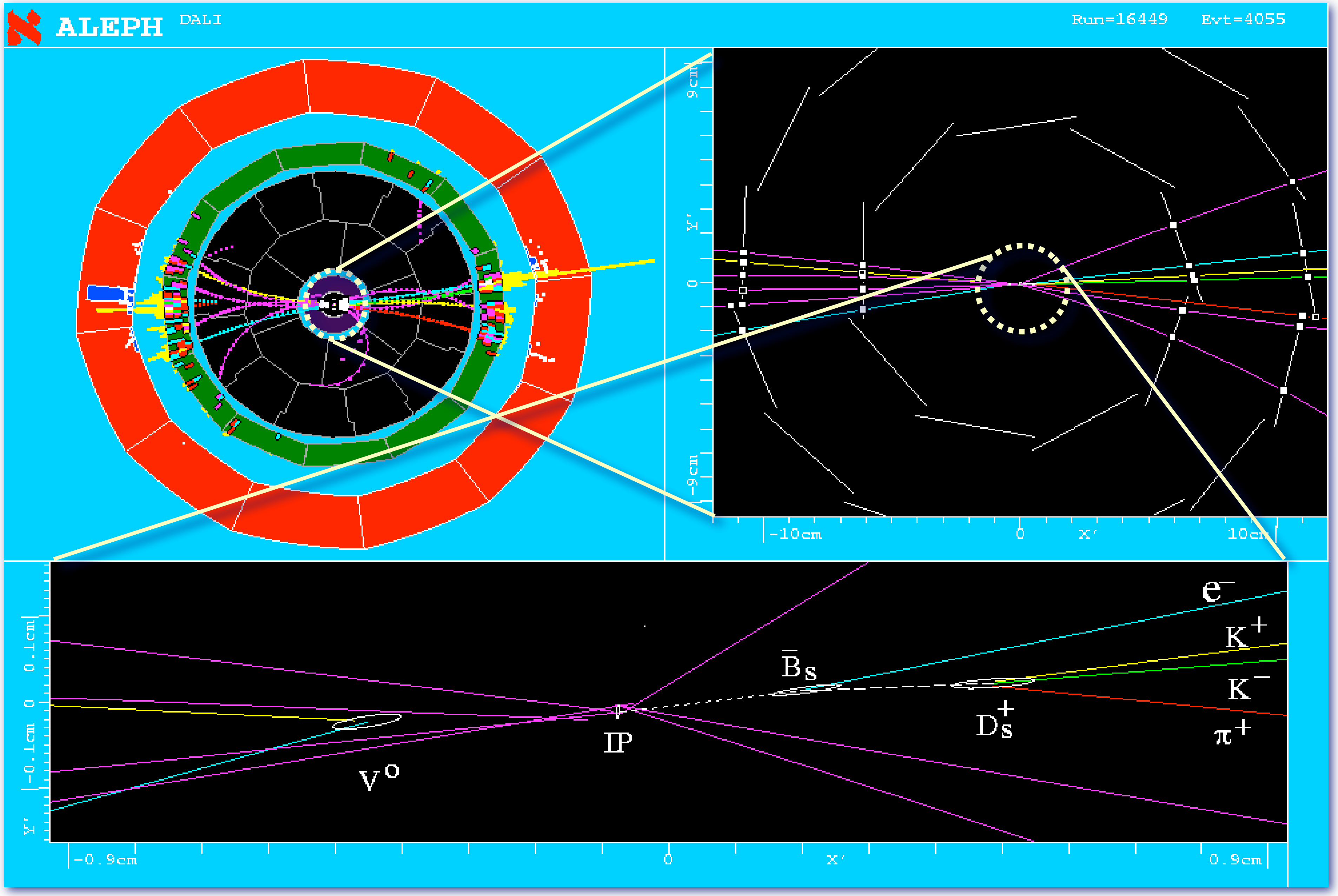
- Measure spatial trajectories
  - combine to look for separated vertices, indicating particles with long lifetimes



Track Fitting

- 1D straight line fit as simple case
- Two perfect measurements
  - away from interaction point
  - no measurement uncertainty
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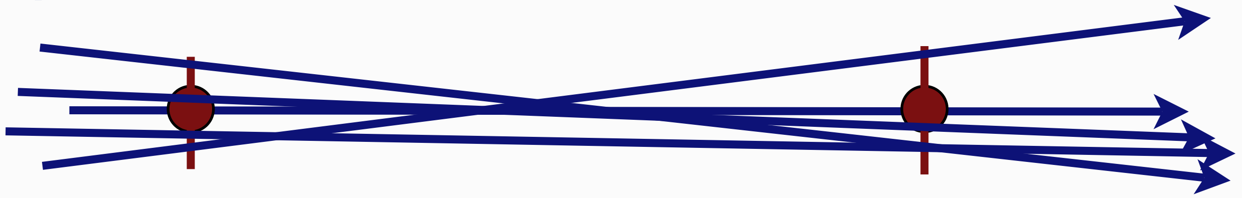

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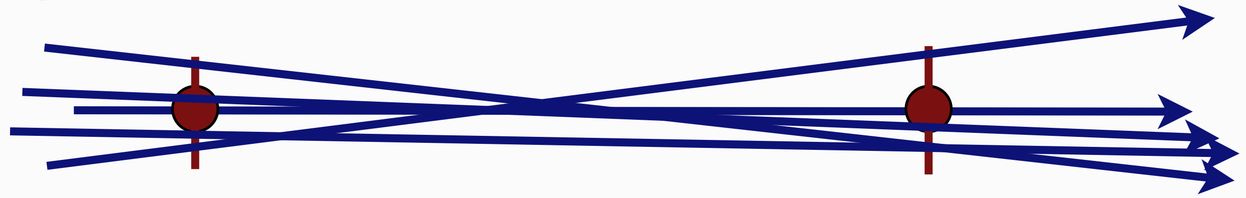
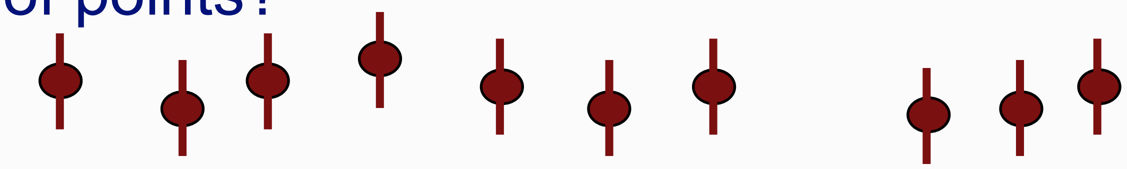


- Smaller errors and more points help to constrain the possibilities.
  But how to find the best point from a large set of points?



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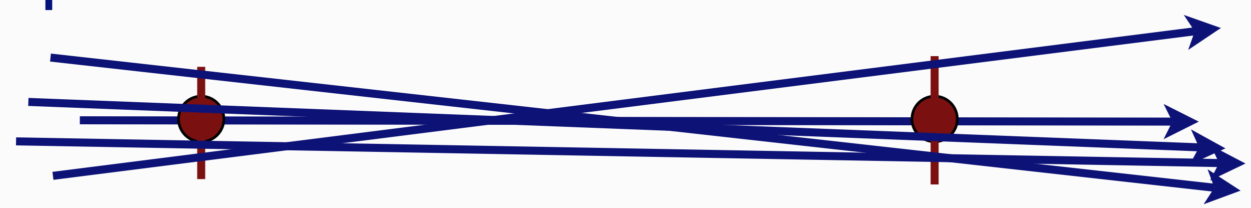

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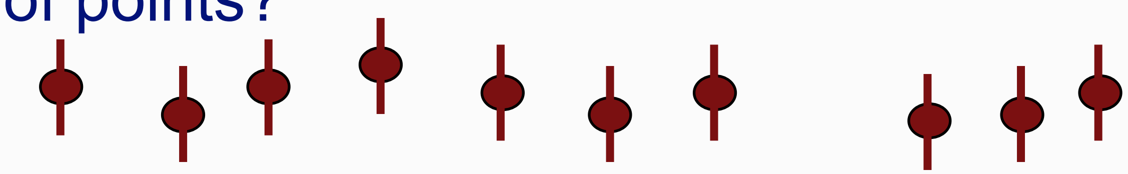

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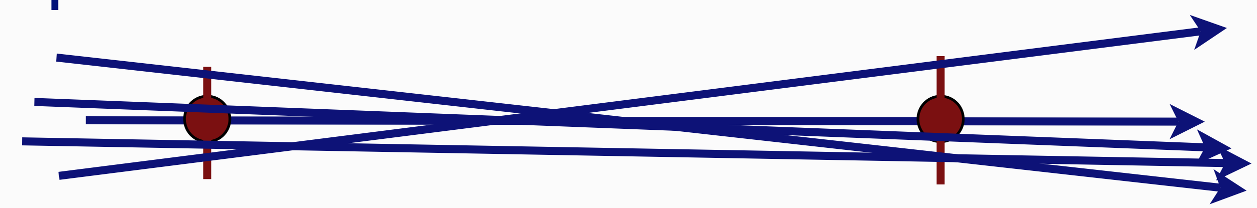
Track Fitting

- 1D straight line fit as simple case
- Two perfect measurements
  - away from interaction point
  - no measurement uncertainty
  - just draw a straight line through them and extrapolate

- Imperfect measurements give less precise results
  - the farther you extrapolate, the less you know



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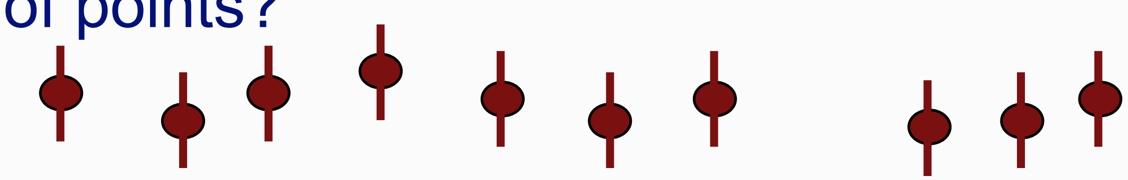

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predicted track position at i^{th} hit

position of i^{th} hit

$$\boxed{\chi^2 = \sum_{i=1}^{n_{\text{hits}}} \frac{\left(y_i - y(x_i)\right)^2}{\sigma_i^2}}$$

uncertainty of i^{th} measurement

see also lecture by G. Cowan

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ETH Institute for Particle Physics

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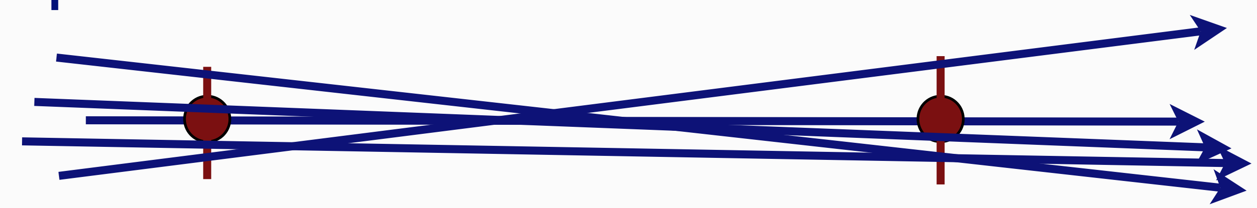

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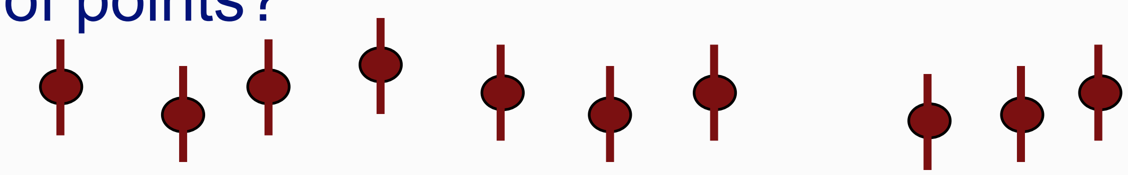

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  - Obtain also uncertainties on track parameters

$\delta\theta \qquad \delta d$

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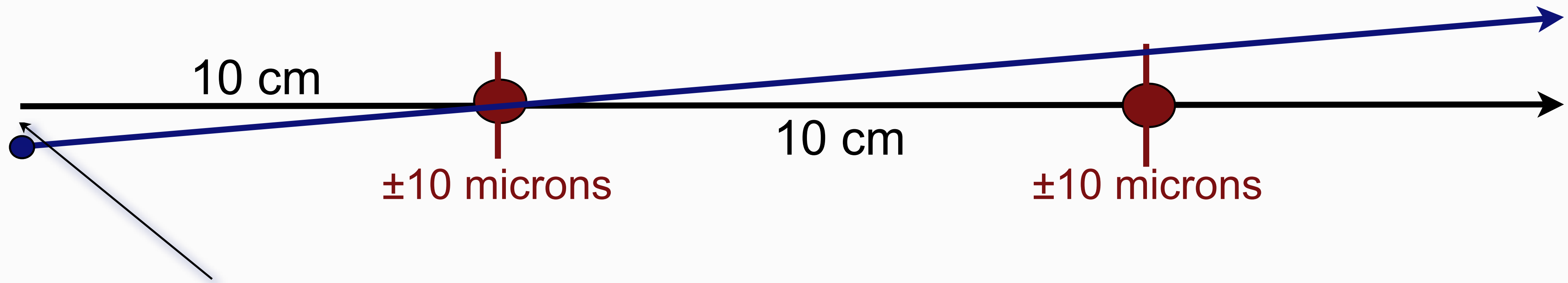
"Typical" size of errors



- Error δd on position is about ±10 microns
- Error $\delta\Theta$ on angle is about ±0.1 milliradians (±0.002 degrees)
- Satisfyingly small errors
  - allows separation of tracks that come from different particle decays (which can be separated at the order of mm)

- However
  - we "see" particles by interaction with a detector (=material)

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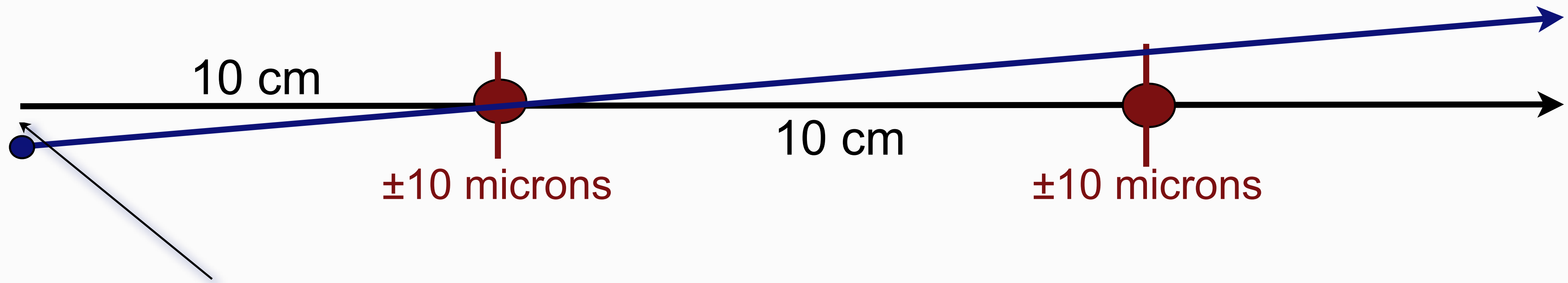

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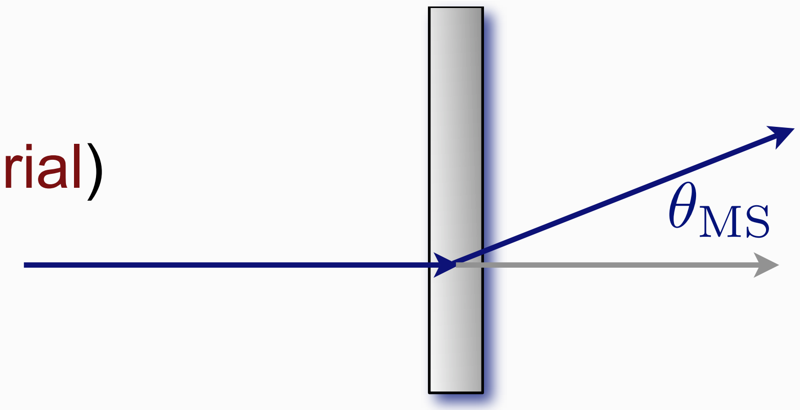

“Typical” size of errors

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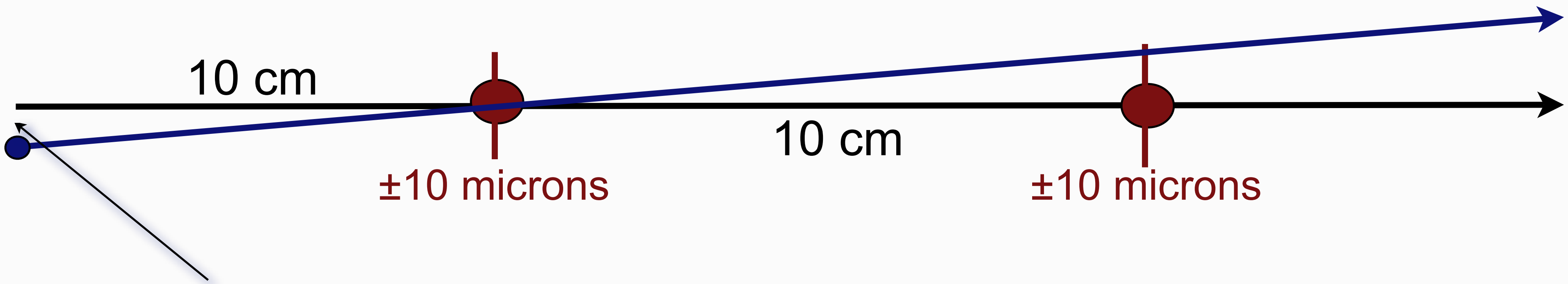

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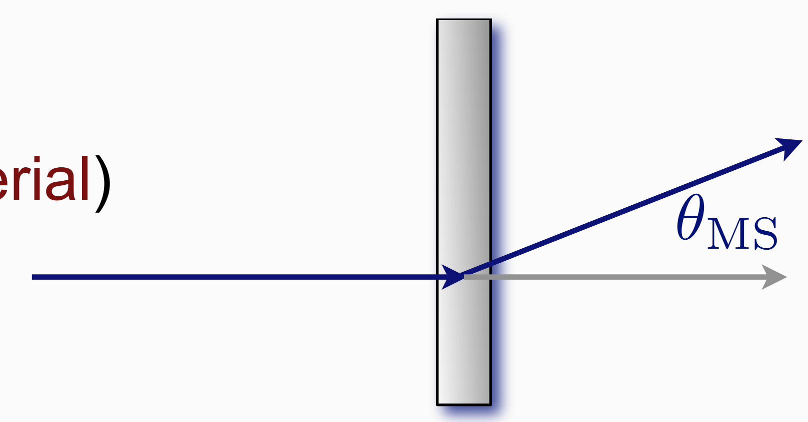
- However
  - we “see” particles by interaction with a detector (=material)
  - interaction leads to : energy loss, change in direction
  - This is **Multiple Scattering**
    - Charged particles passing through matter “scatter” by a random angle



$$\sqrt{\langle \theta^2_{\mathrm{MS}} \rangle} = \frac{15\,\mathrm{MeV}/c}{\beta p} \sqrt{\frac{\mathrm{thickness}}{X_{\mathrm{rad}}}}$$

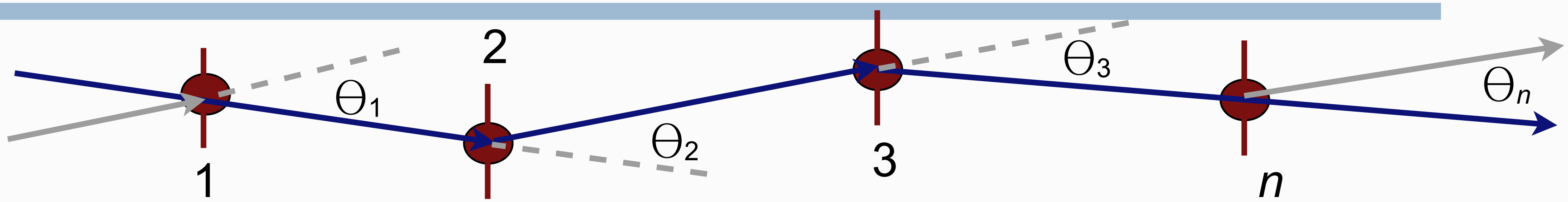
examples:

300 micron Si : RMS = 0.9 mrad / βp

1 mm Be : RMS = 0.8 mrad / βp

➔ leads to additional position errors

Kalman filter



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  - *n* additional parameters $y(x) = d + \theta\, x + \Theta(x - x_1)\theta_1(x - x_1) + \Theta(x - x_2)\theta_1(x - x_2) + \cdots$
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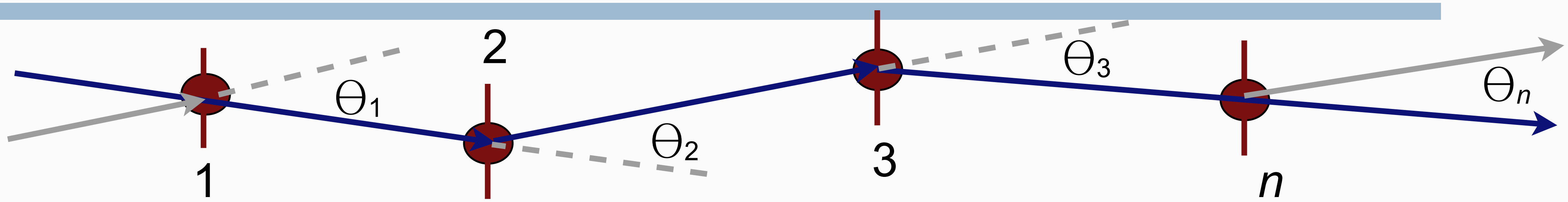

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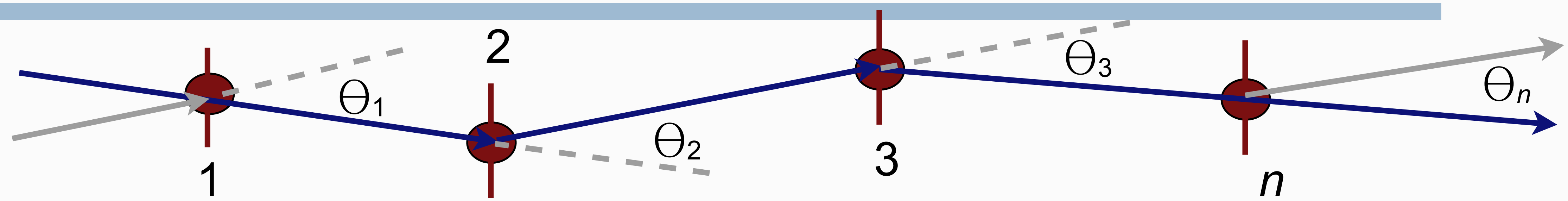

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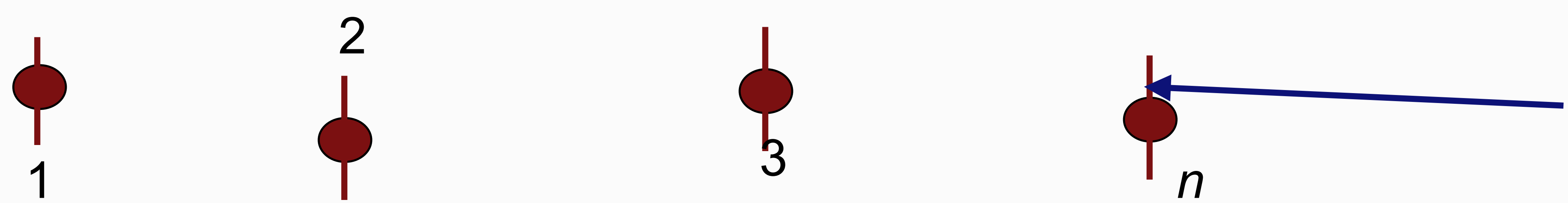

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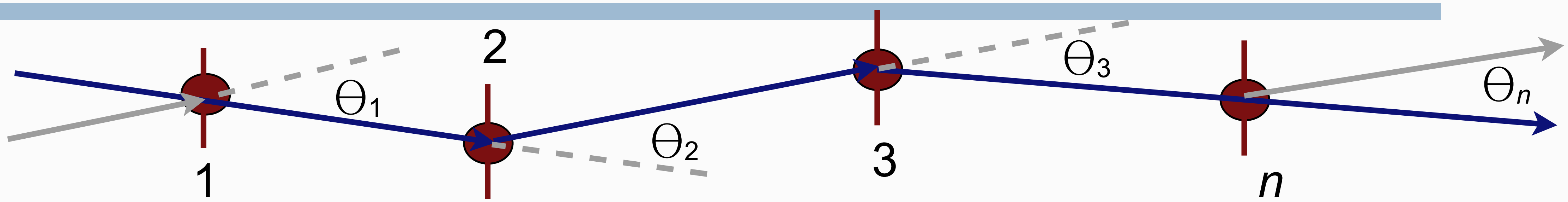

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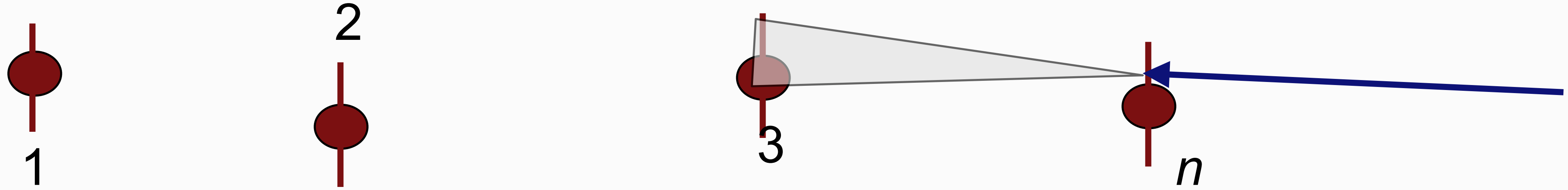

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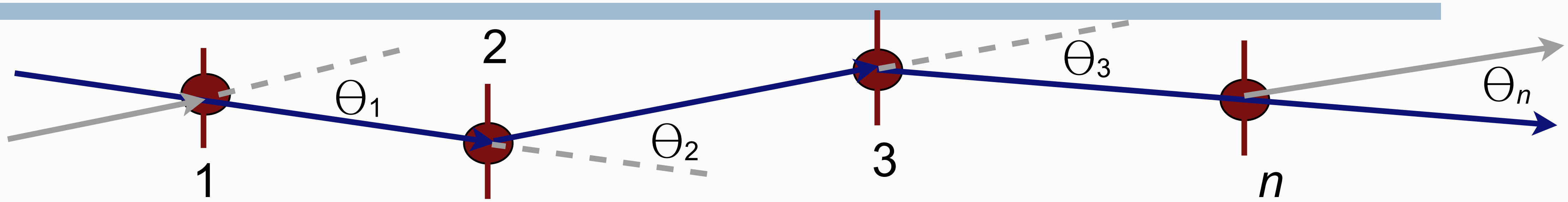

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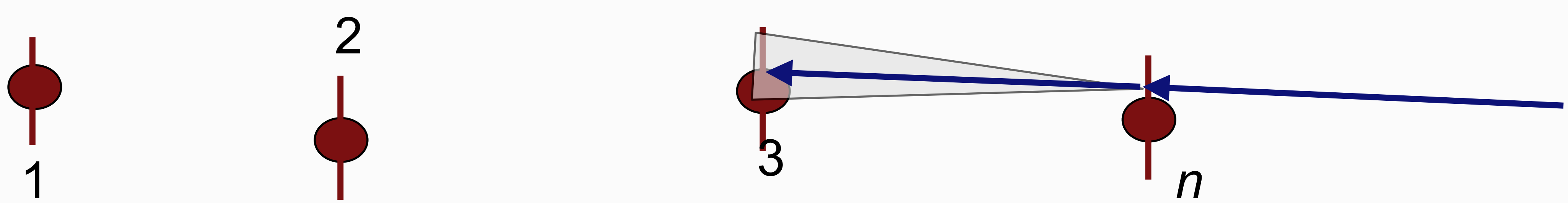

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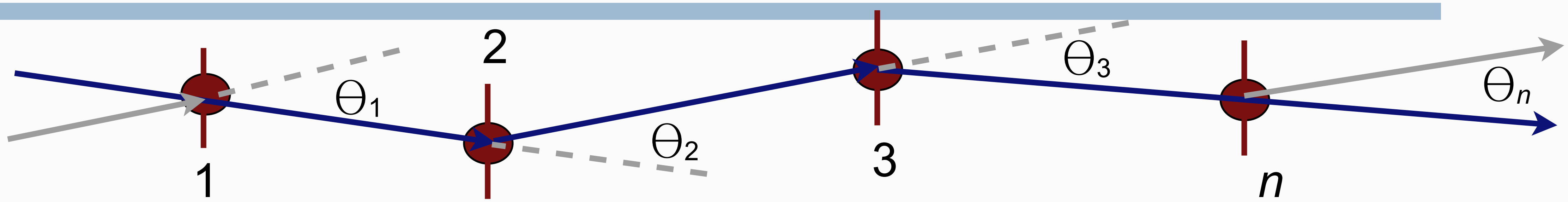

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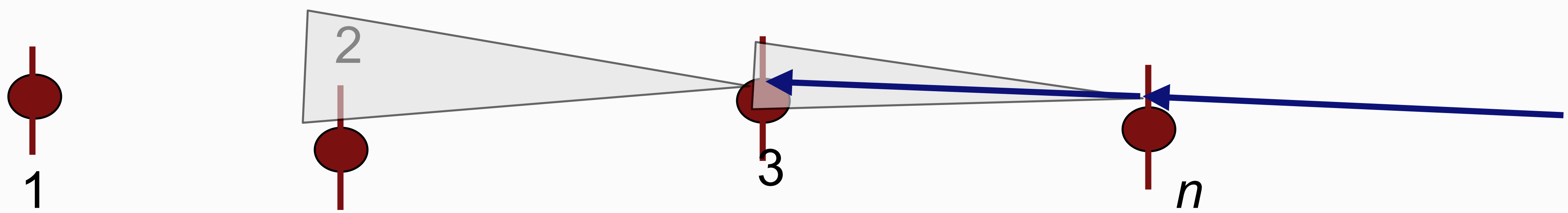

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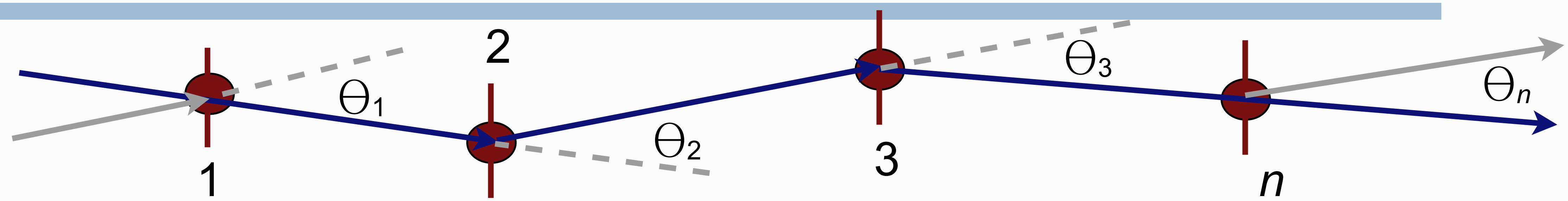

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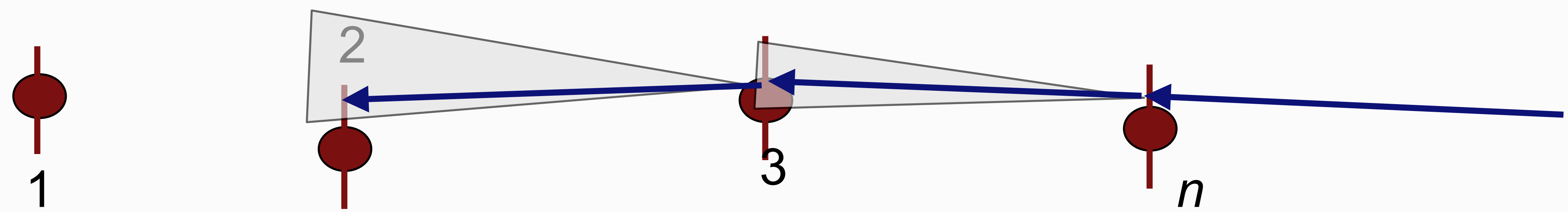

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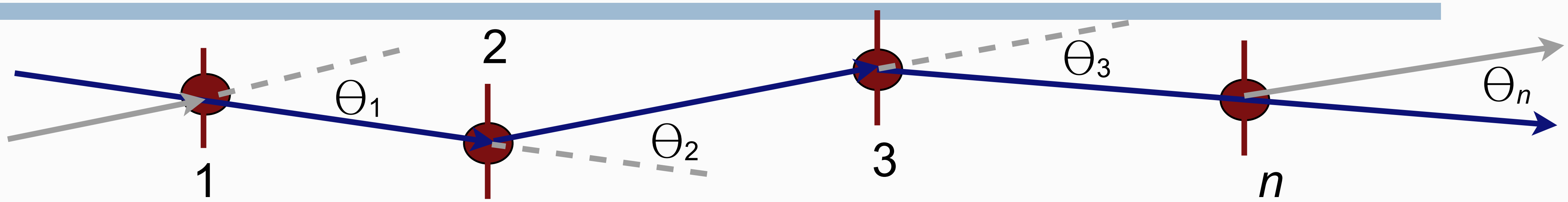

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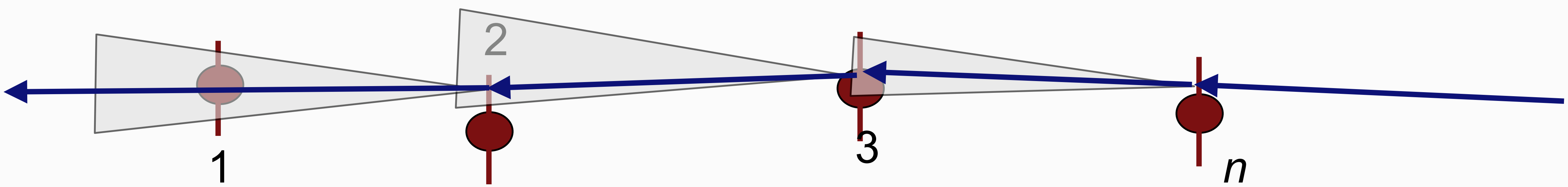

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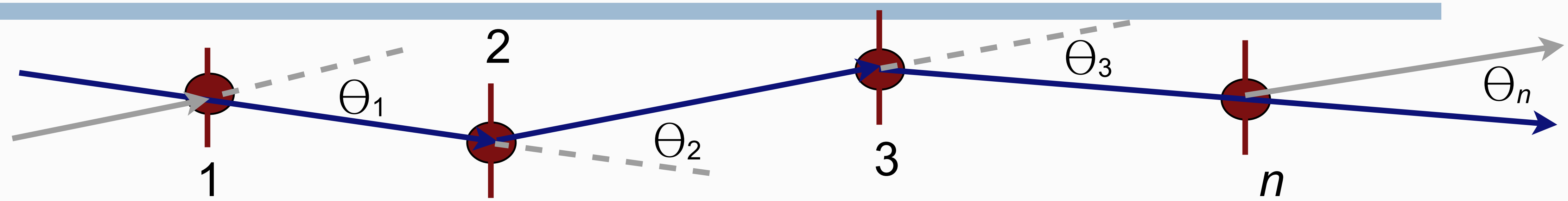

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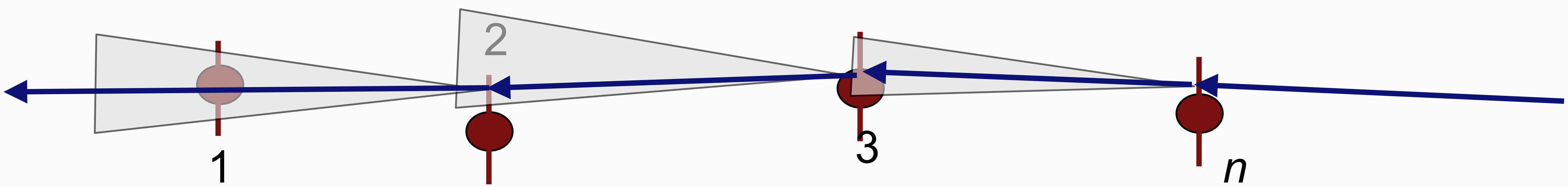
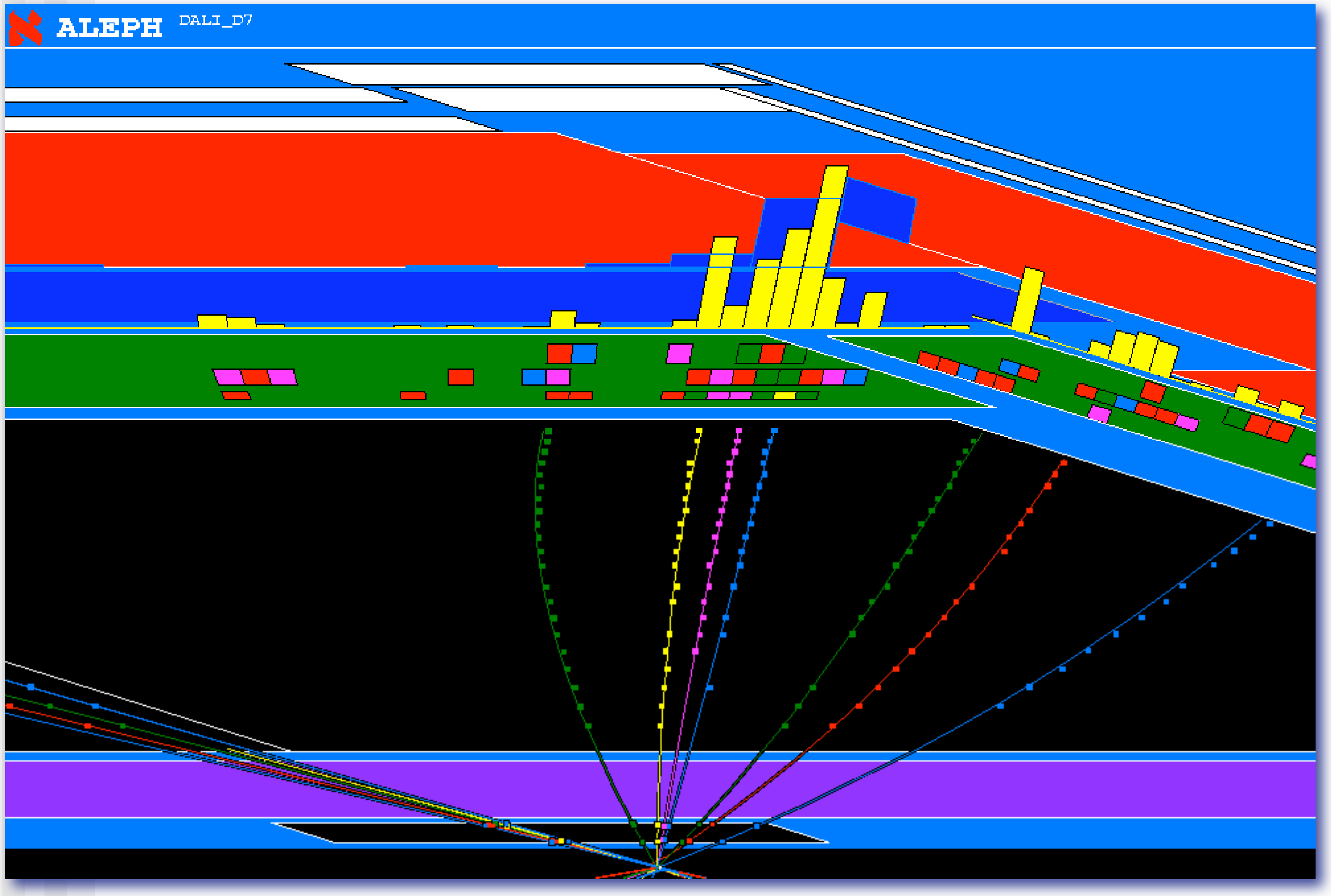


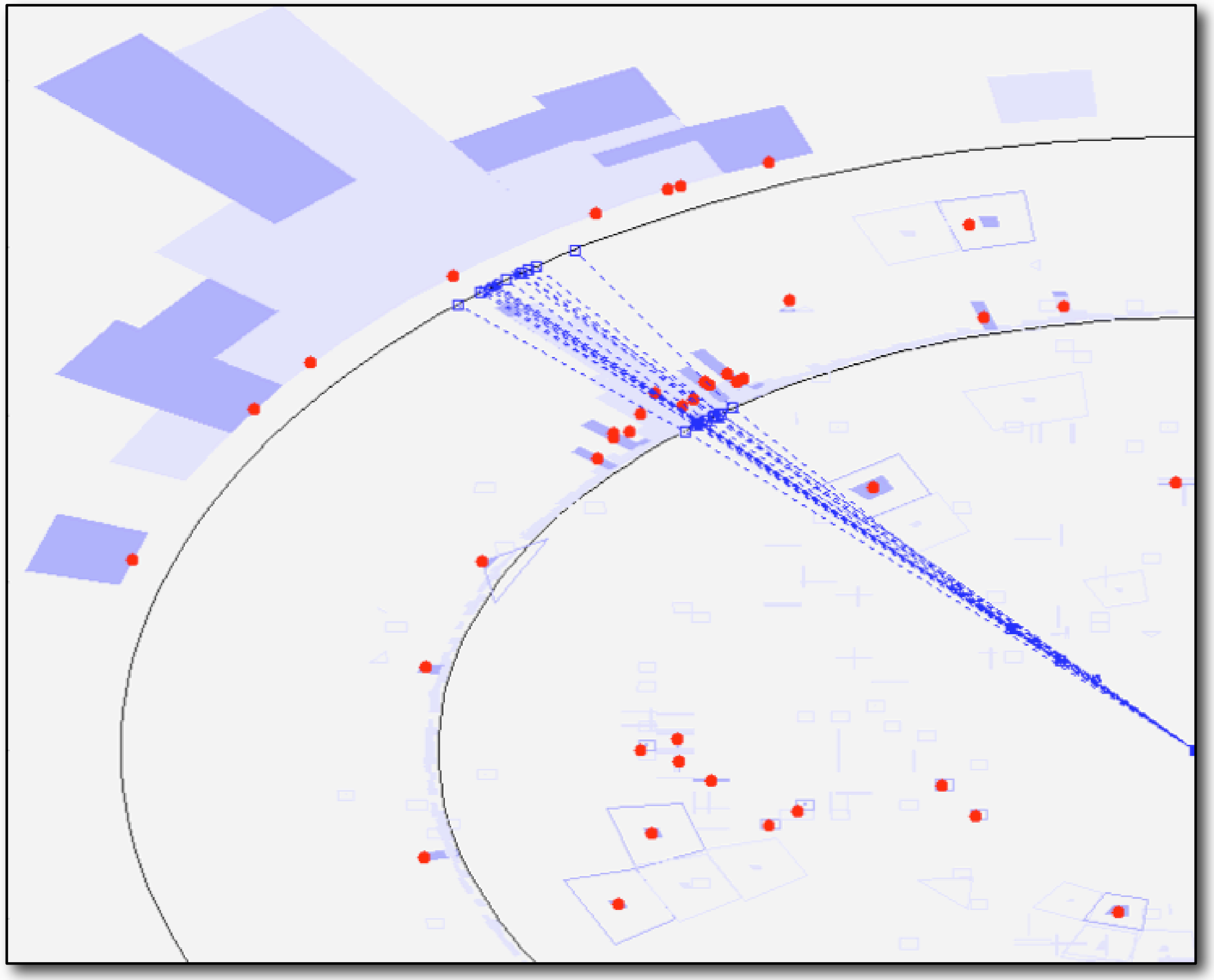
  - leads to O(*n*) computations!
  - in each step, make extrapolation to next layer, using information from current track parameters, expected scattering error, and measurement at next layer
  - Needs a starting estimate (seed) and may need some iterations, smoothing
  - This method is based on theory of the **Kalman Filter**

Calorimeter energy reconstruction

Goals

- Reconstruct energy deposited by charged and neutral particles
- Determine position of deposit, direction of incident particles
- Be insensitive to noise and “un-wanted” (un-correlated) energy





- and obtain the best possible resolution!

Clusters of energy

- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the “center-of-gravity” of the deposits in the various cells

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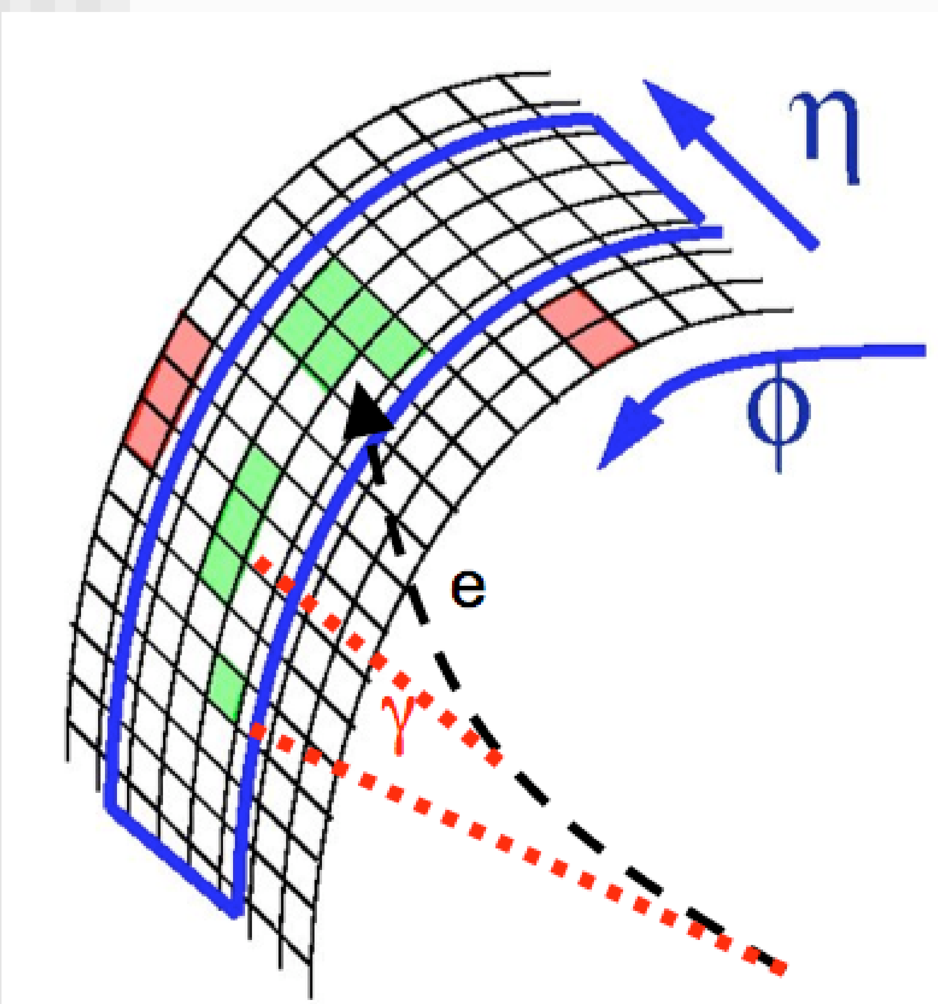
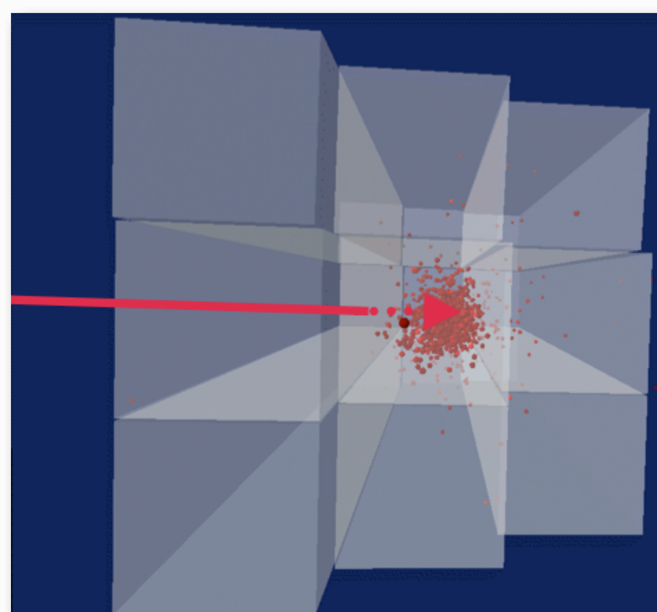
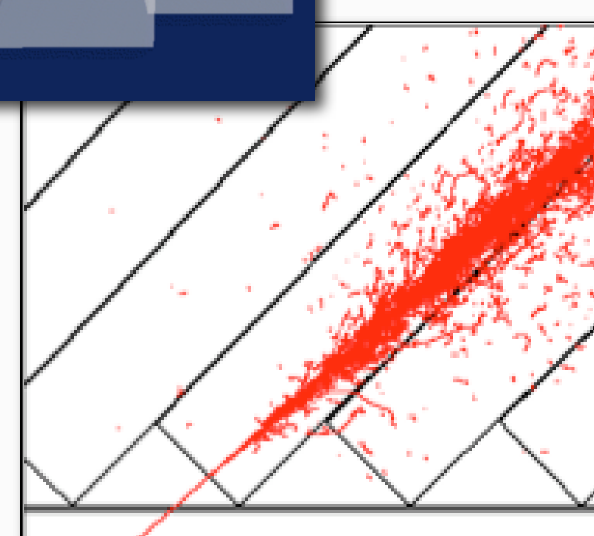
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %




front view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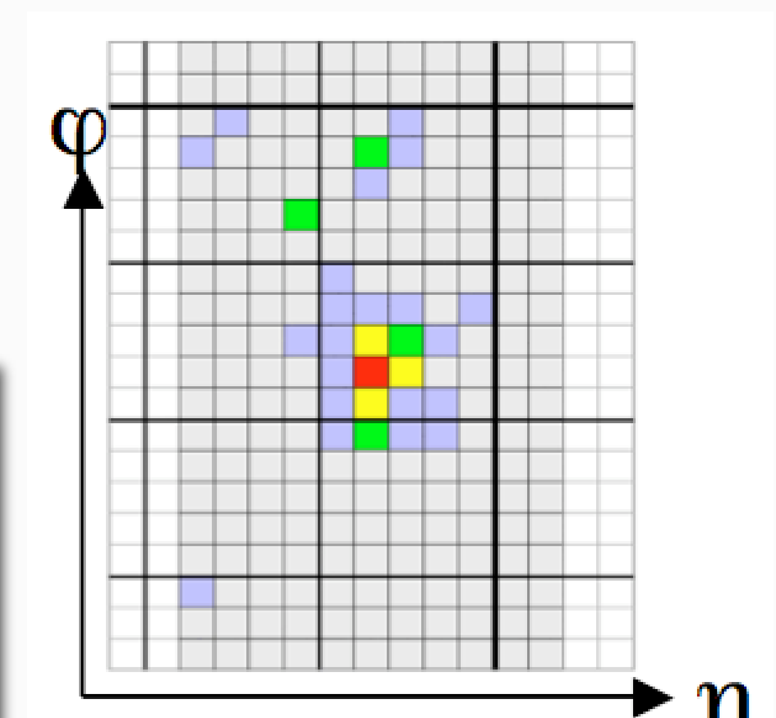

view in (φ,η) cells

Clusters of energy

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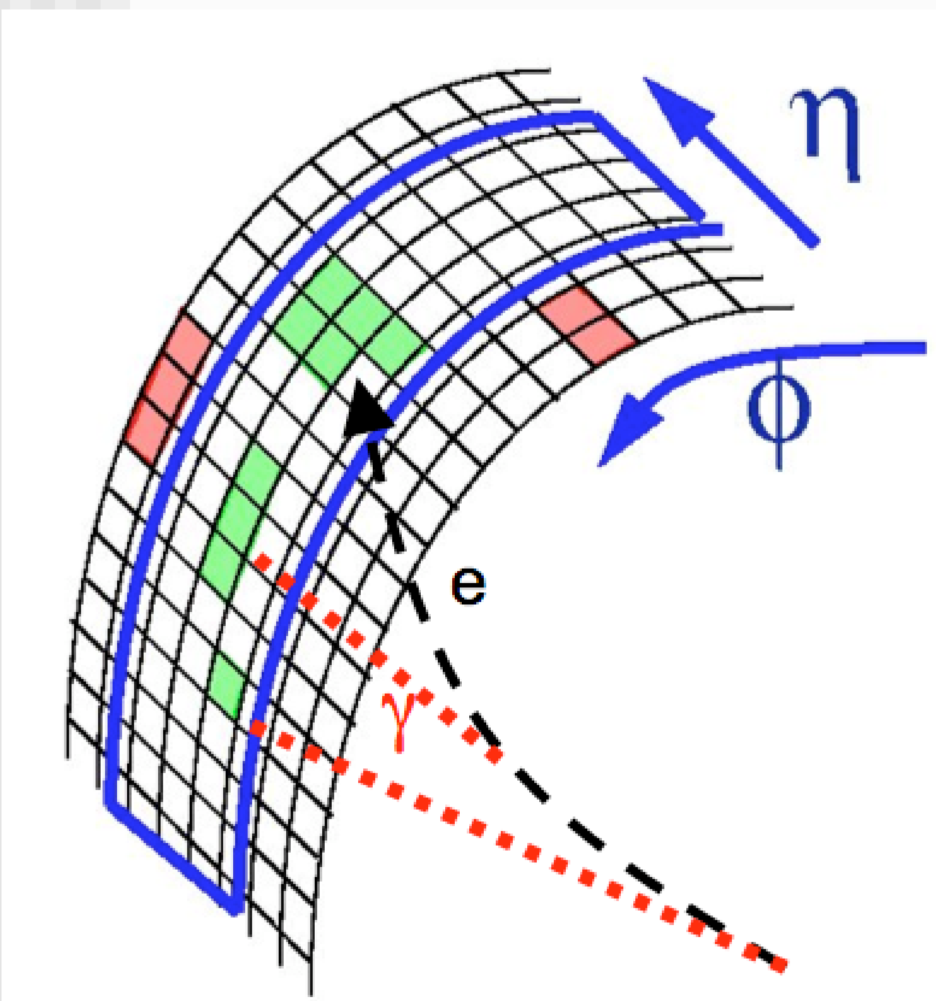
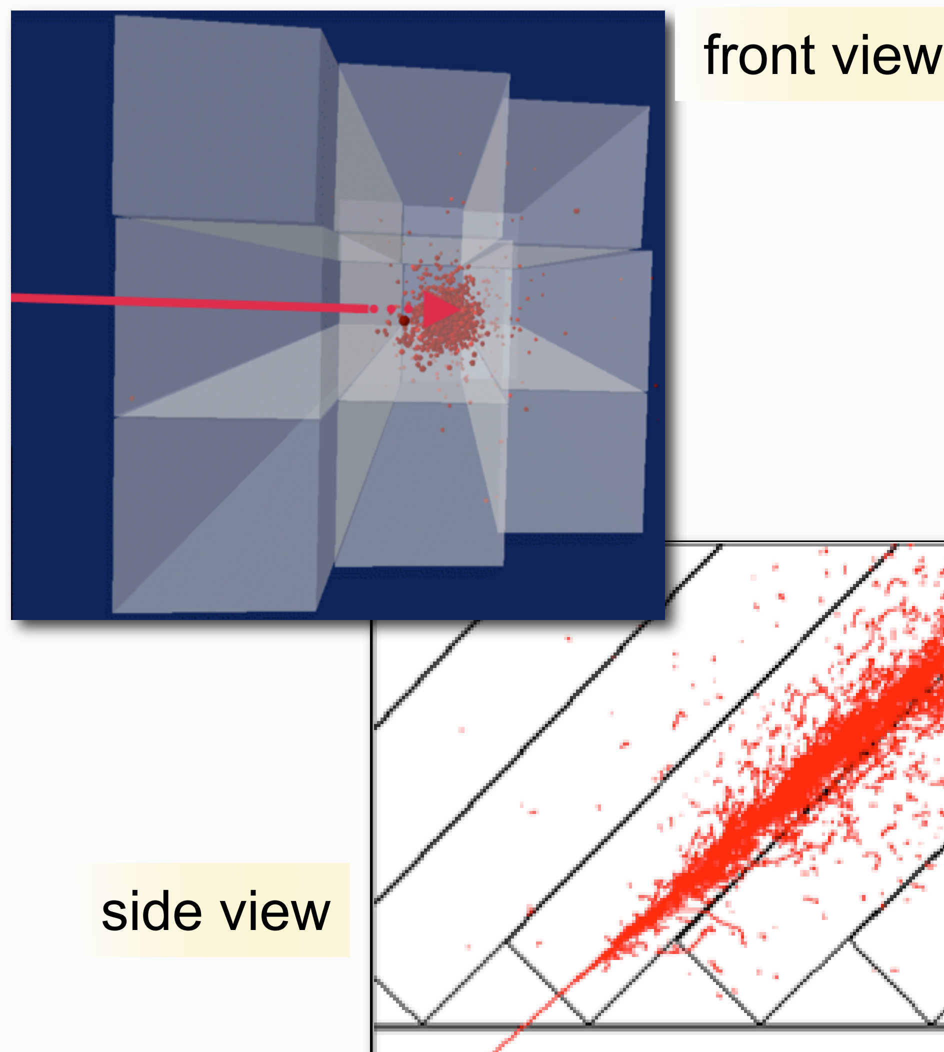
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %
- So task is : identify these clusters and reconstruct the energy they contain

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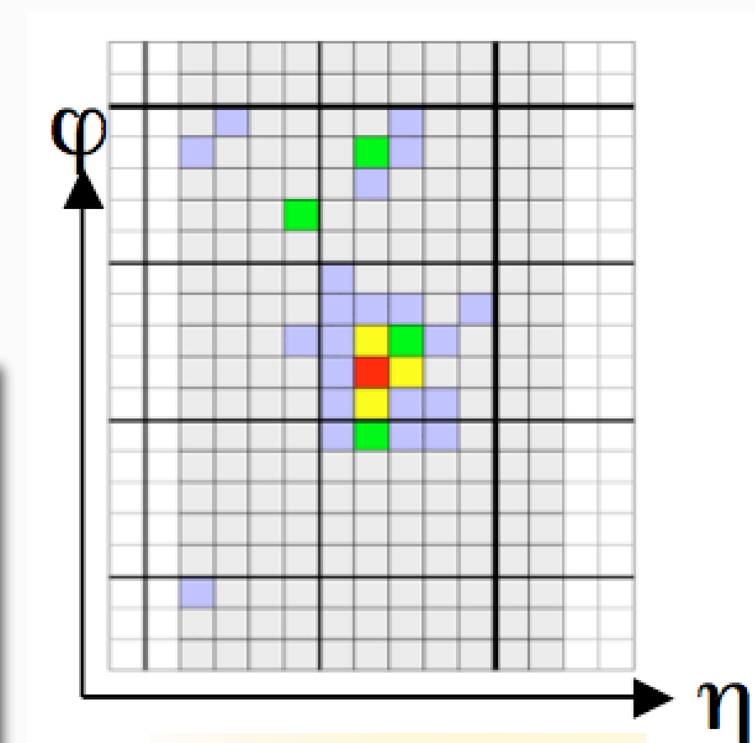

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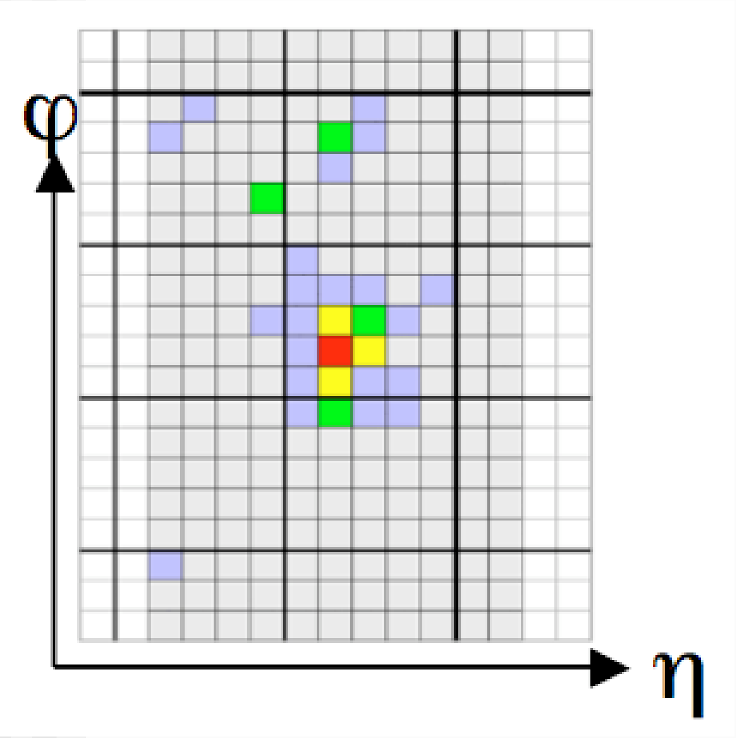
Cluster Finding

- Clusters of energy in a calorimeter are due to the original particles
  - Clustering algorithm groups individual channel energies
  - Don’t want to miss any; don’t want to pick up fakes



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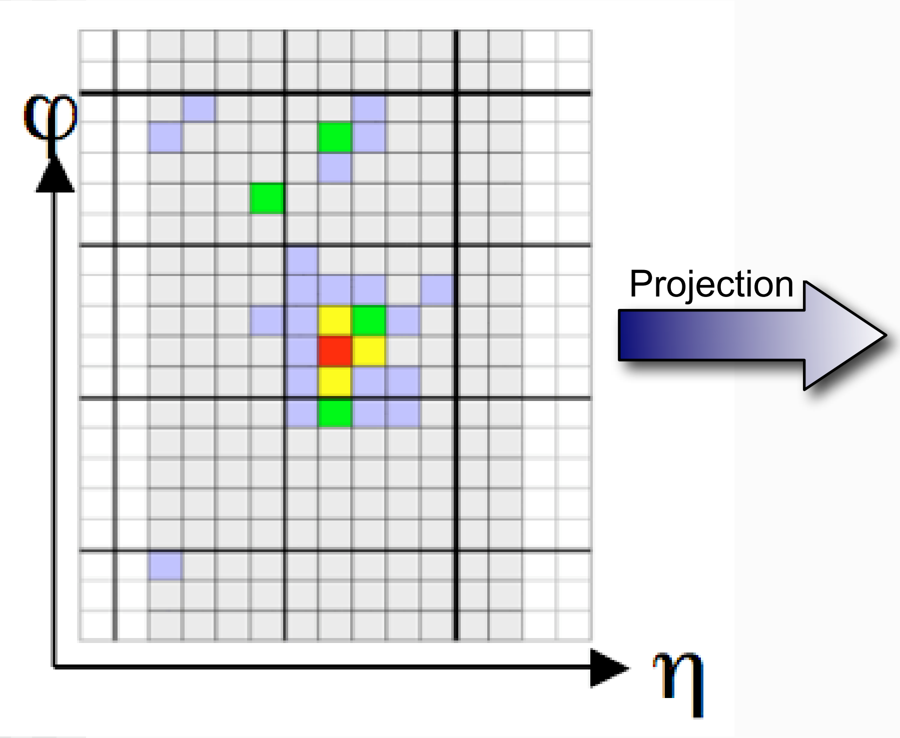

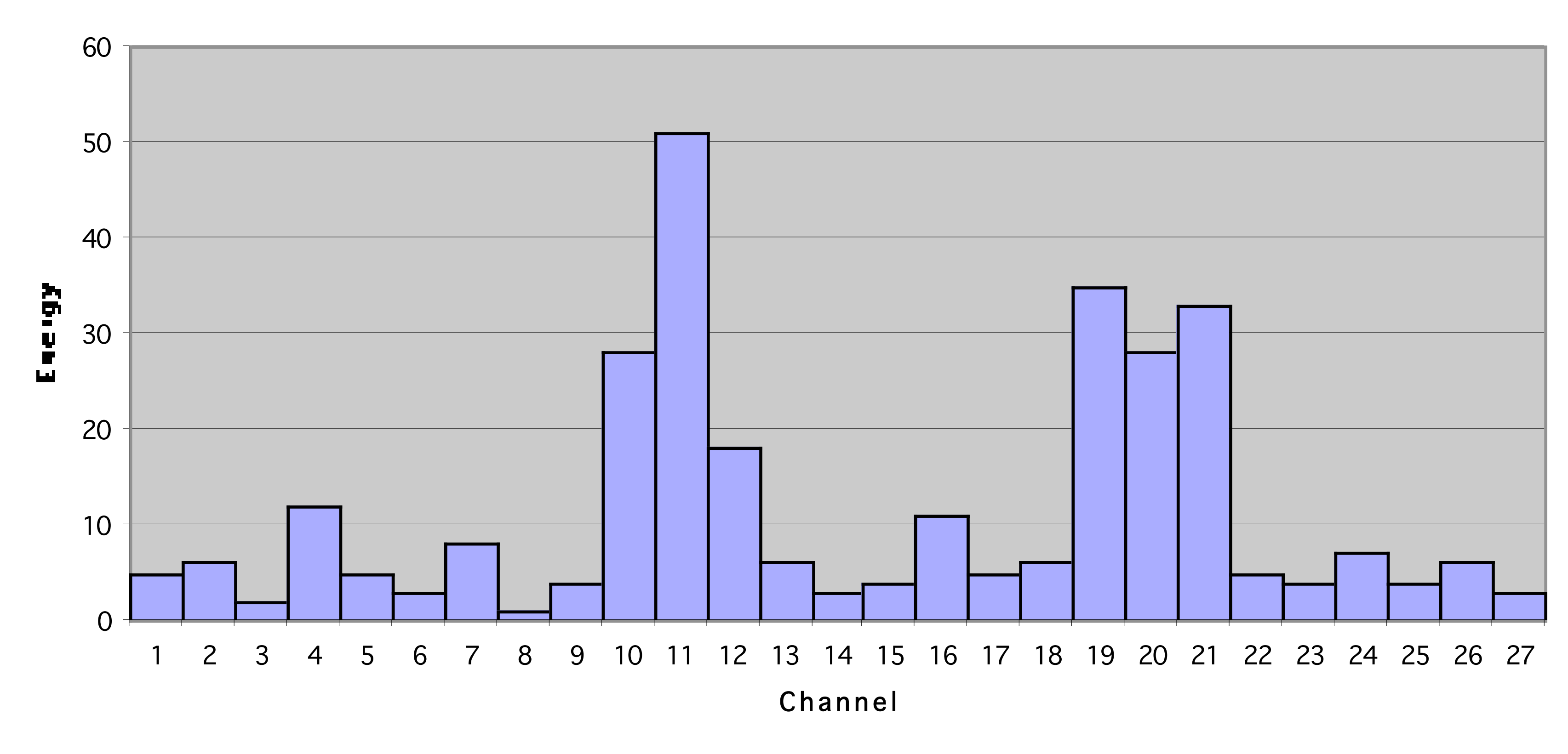

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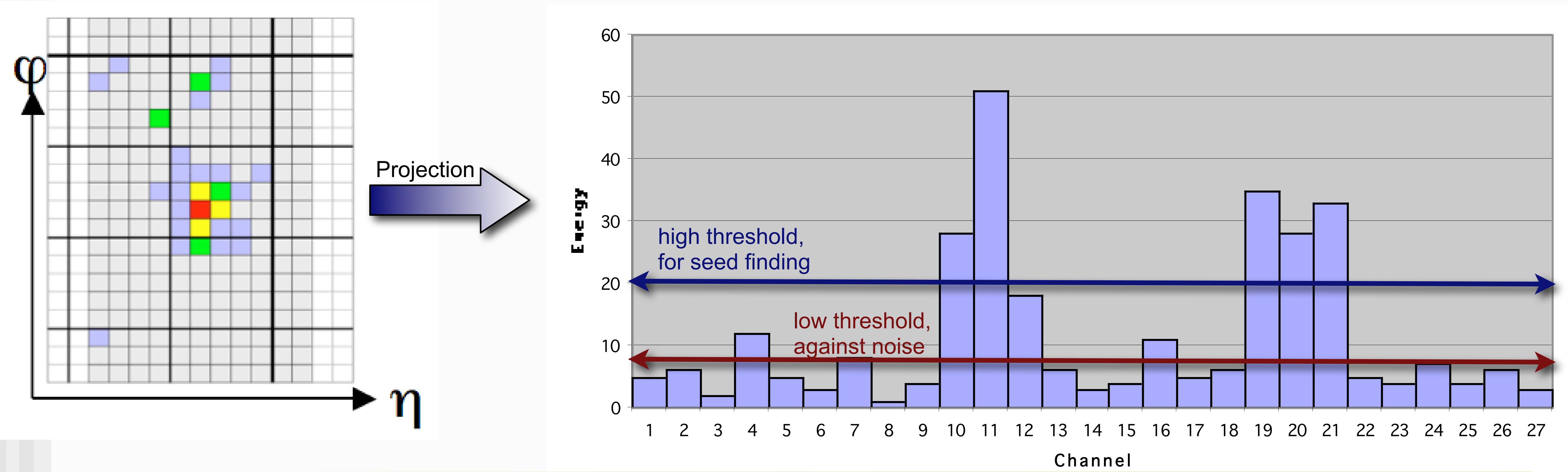


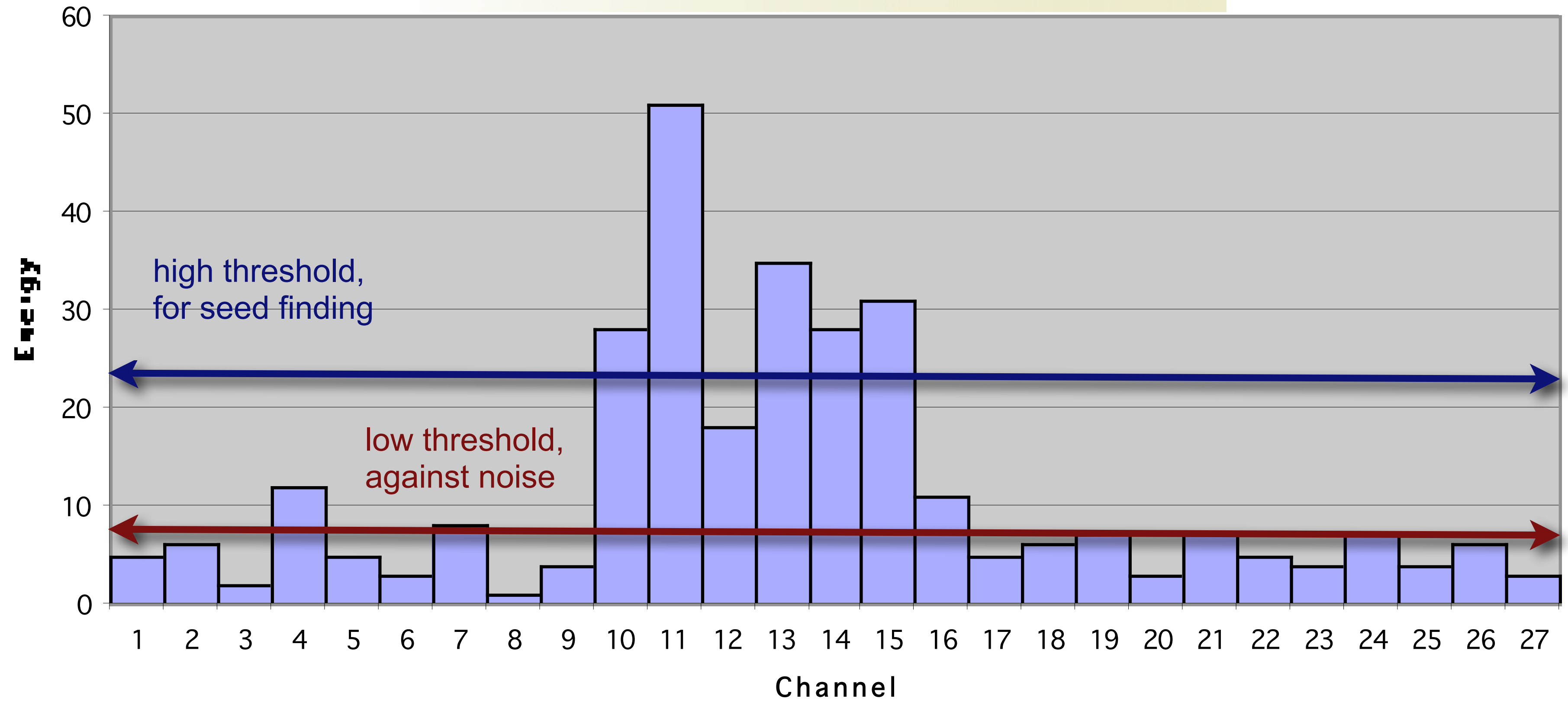
Simple example of an algorithm

- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are **added to the cluster if**
  1. The crystal's energy is above the noise level (lower threshold)
  2. The crystal has not been assigned to another cluster already
  3. The previous crystal added (in the same direction) has higher energy

Difficulties

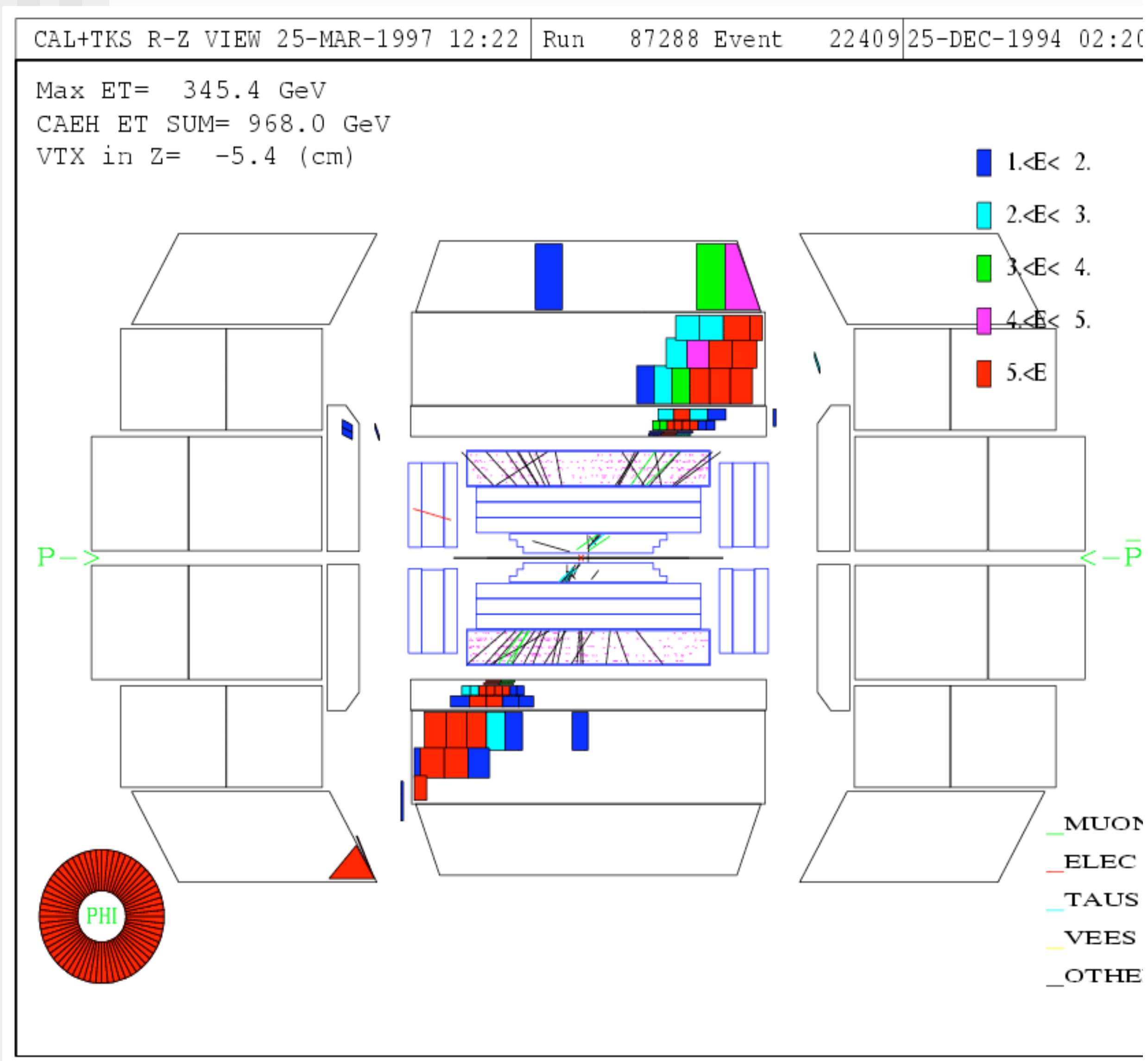
- Careful tuning of thresholds needed
  - needs usually learning phase
  - adapt to noise conditions
  - too low : pick up too much unwanted energy
  - too high : loose too much of “real” energy. Corrections/Calibrations will be larger
- Sometimes several clustering stages, in order separate or combine nearby clusters

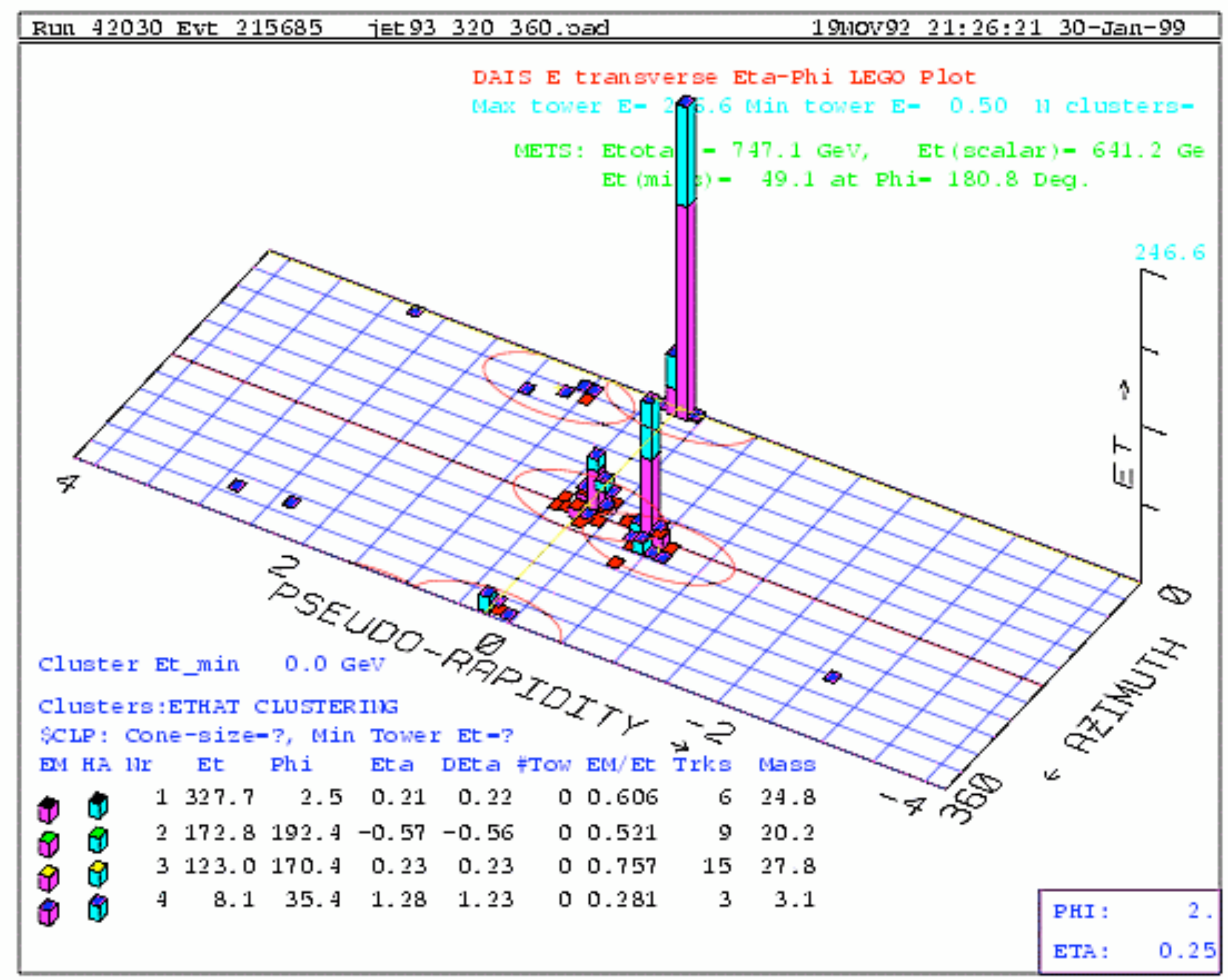
example : one lump or two?



Jet Algorithms

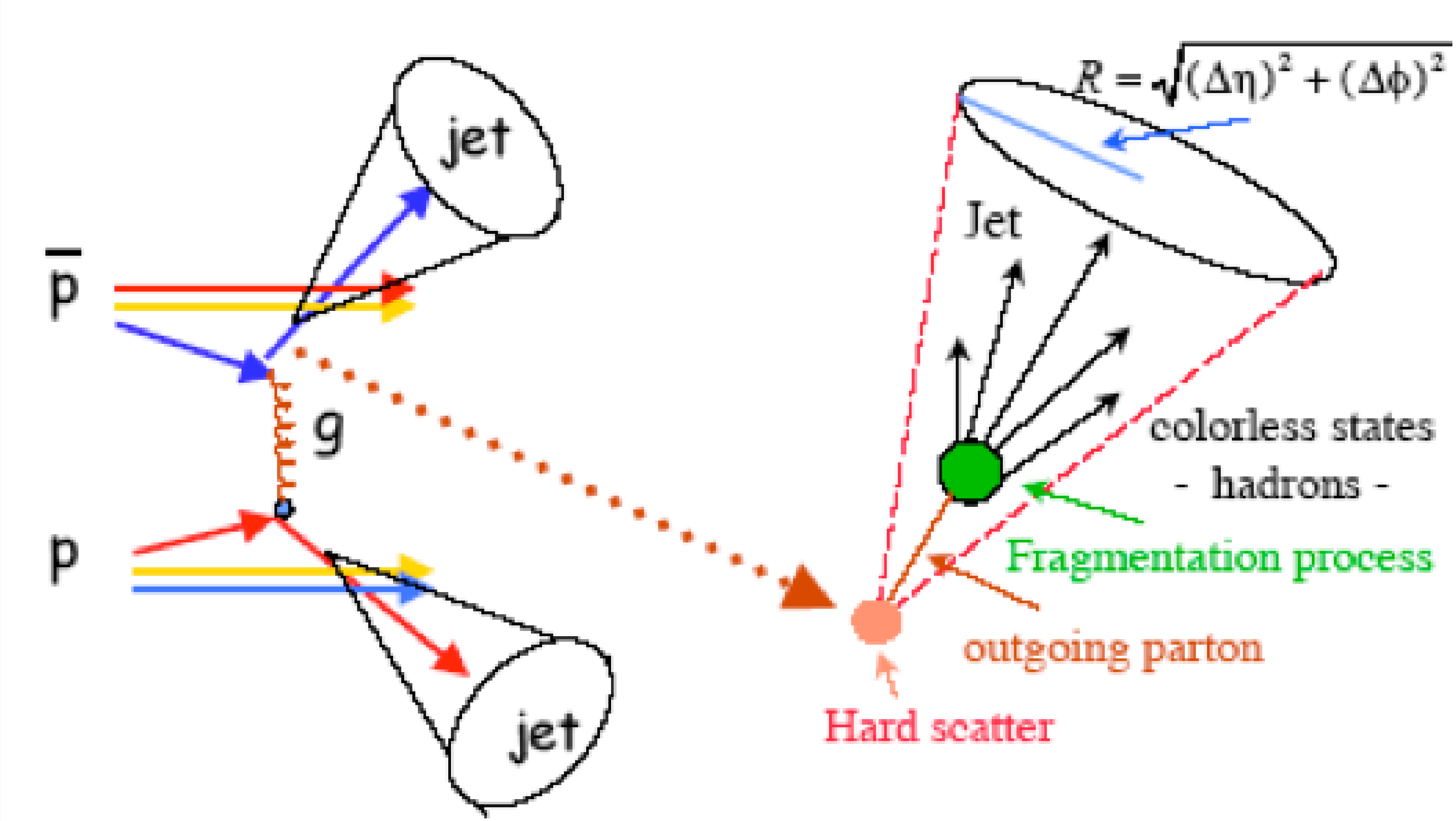
Jets in DØ CDF





- Introducing a cone prescription seems “natural”...
- But how to make it more quantitative?
  - don’t want people “guessing” at whether there are 2,3, ... jets

Cones...

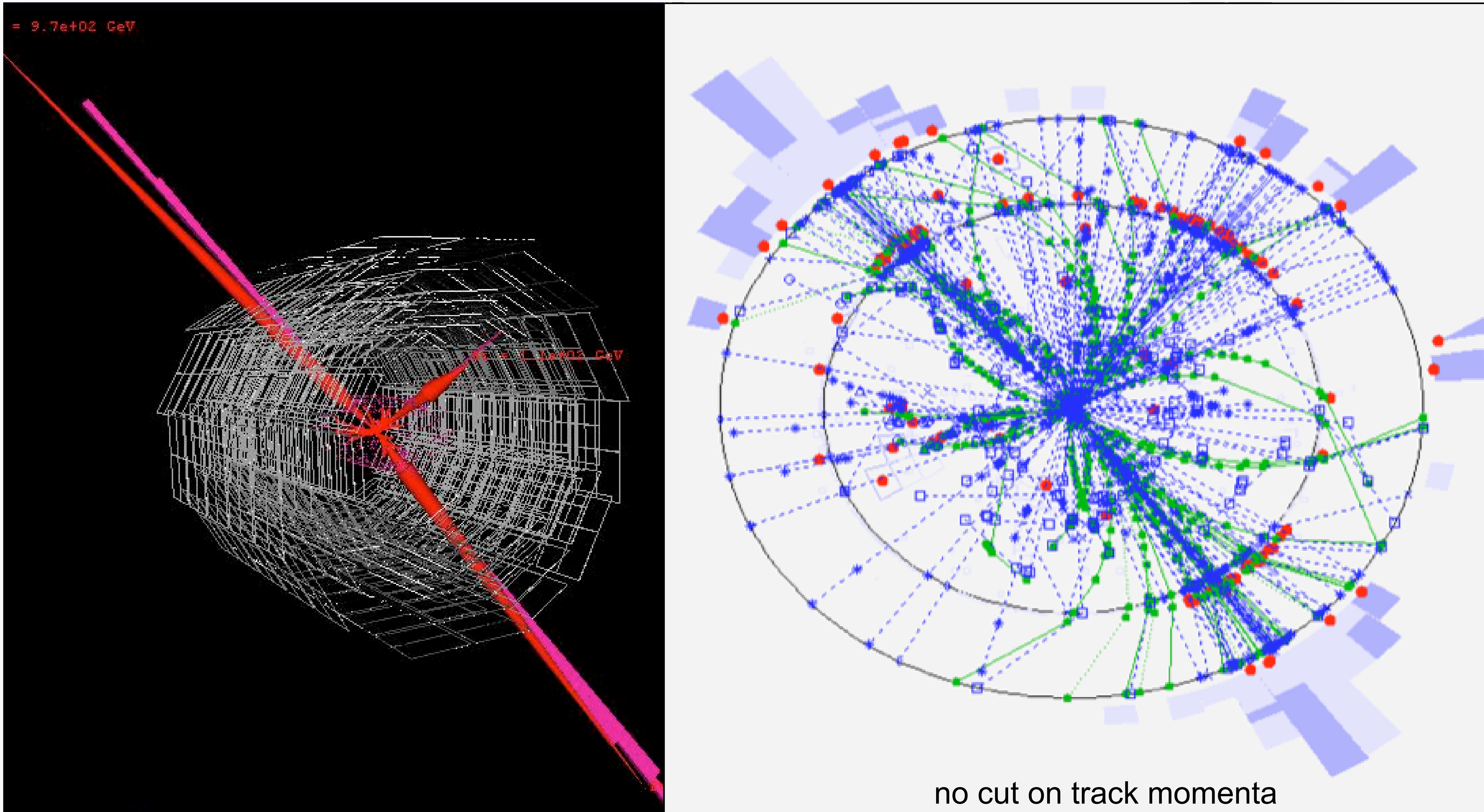


The natural (?) definition of a jet in a hadron collider environment

from J. Huston, CTEQ summer school 2004

Jets in Hadron Collider Detectors

(simulated) Jets in CMS



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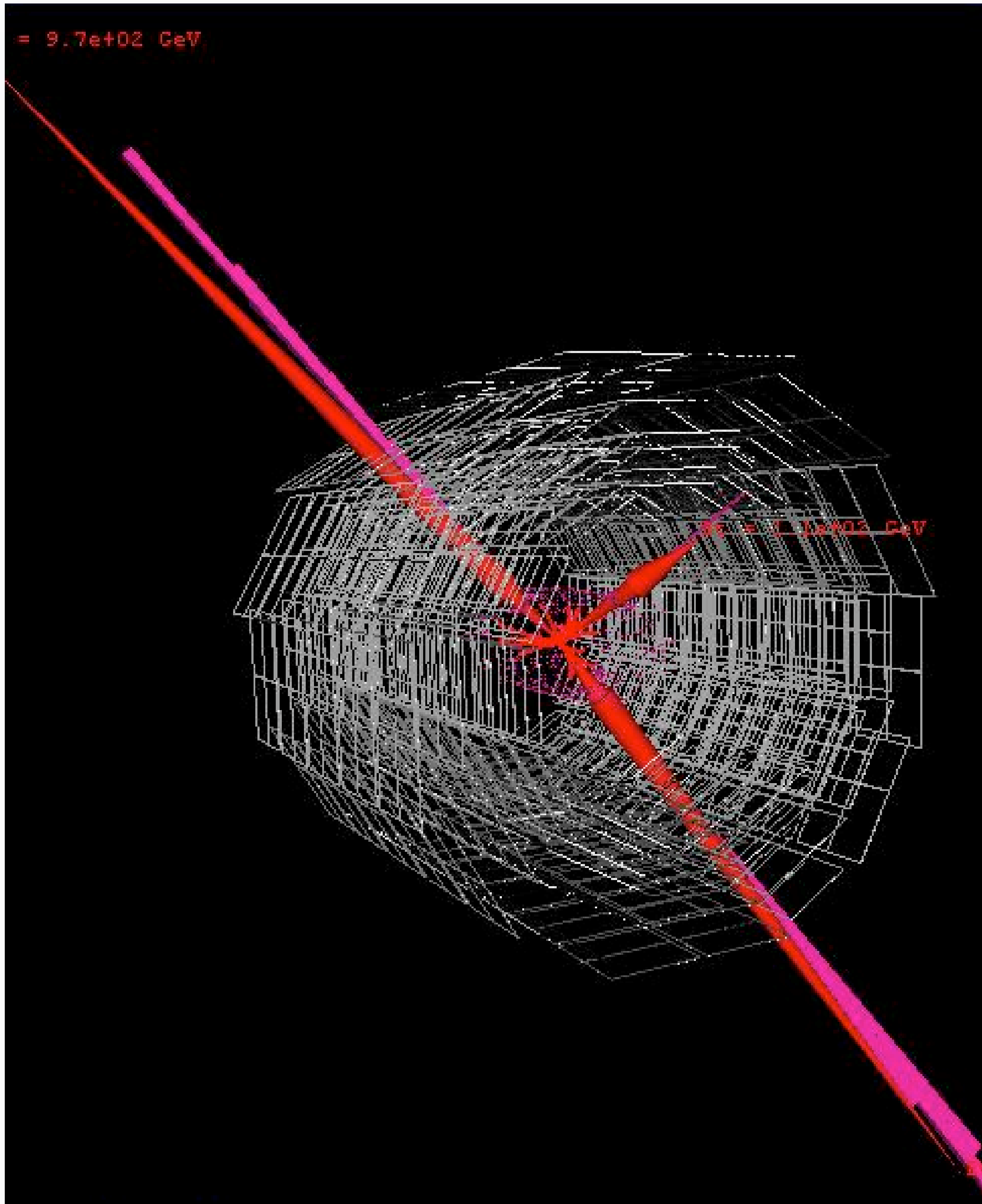
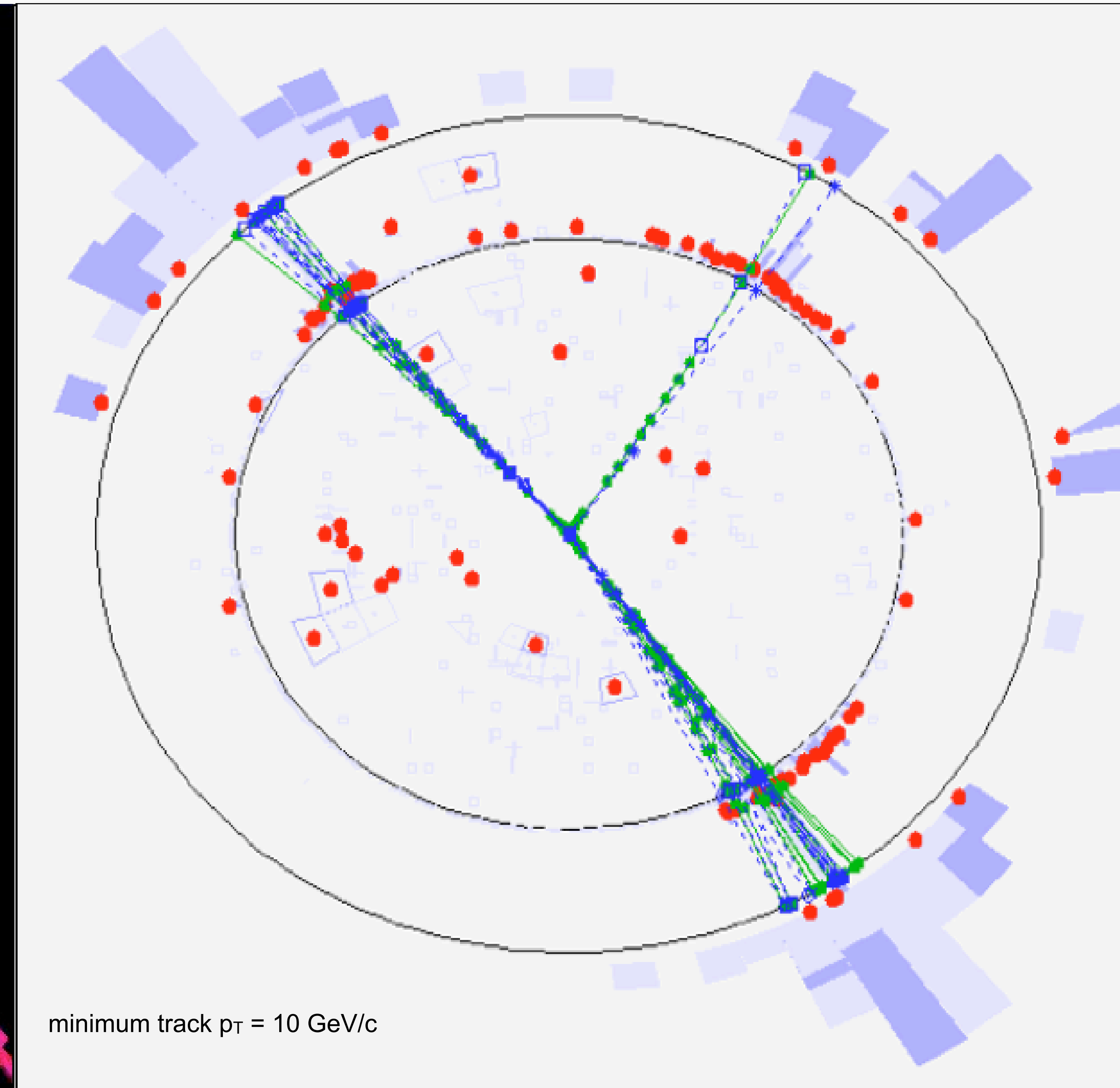
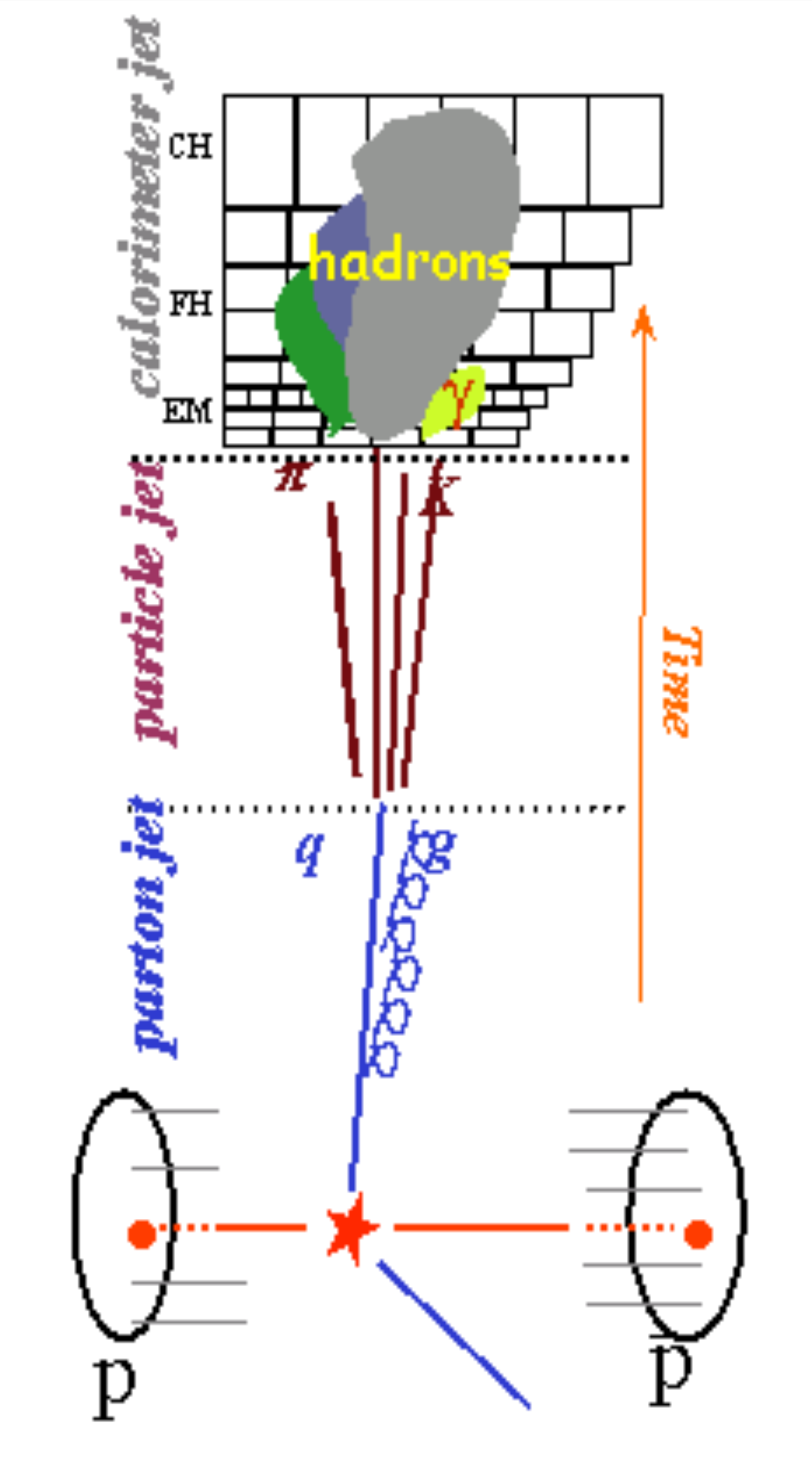




Requirements

- Applicable at all levels
  - partons, stable particles
    - for theoretical calculations
  - measured objects (calorimeter objects, tracks, etc)
  - and always find the same jet



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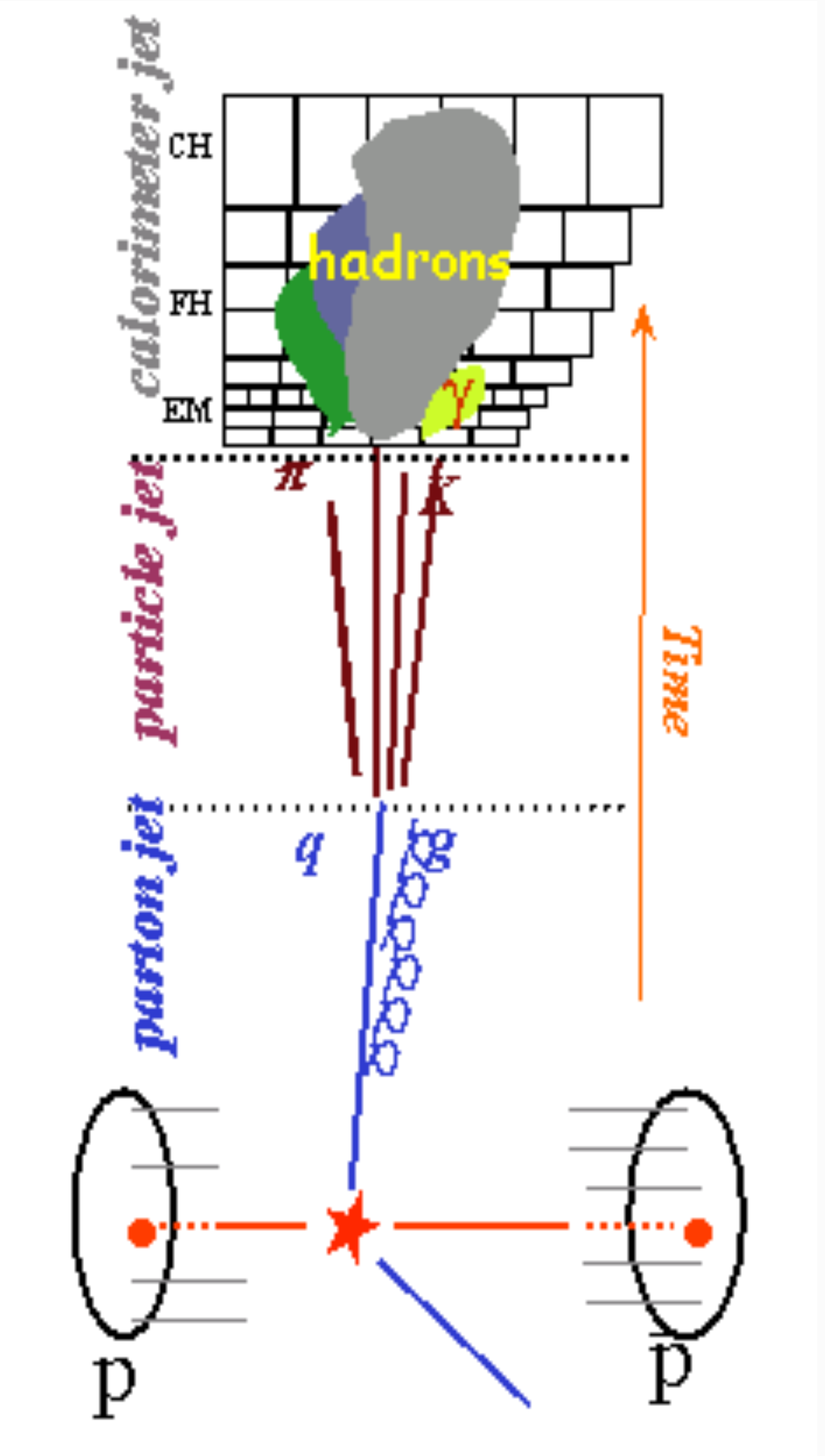

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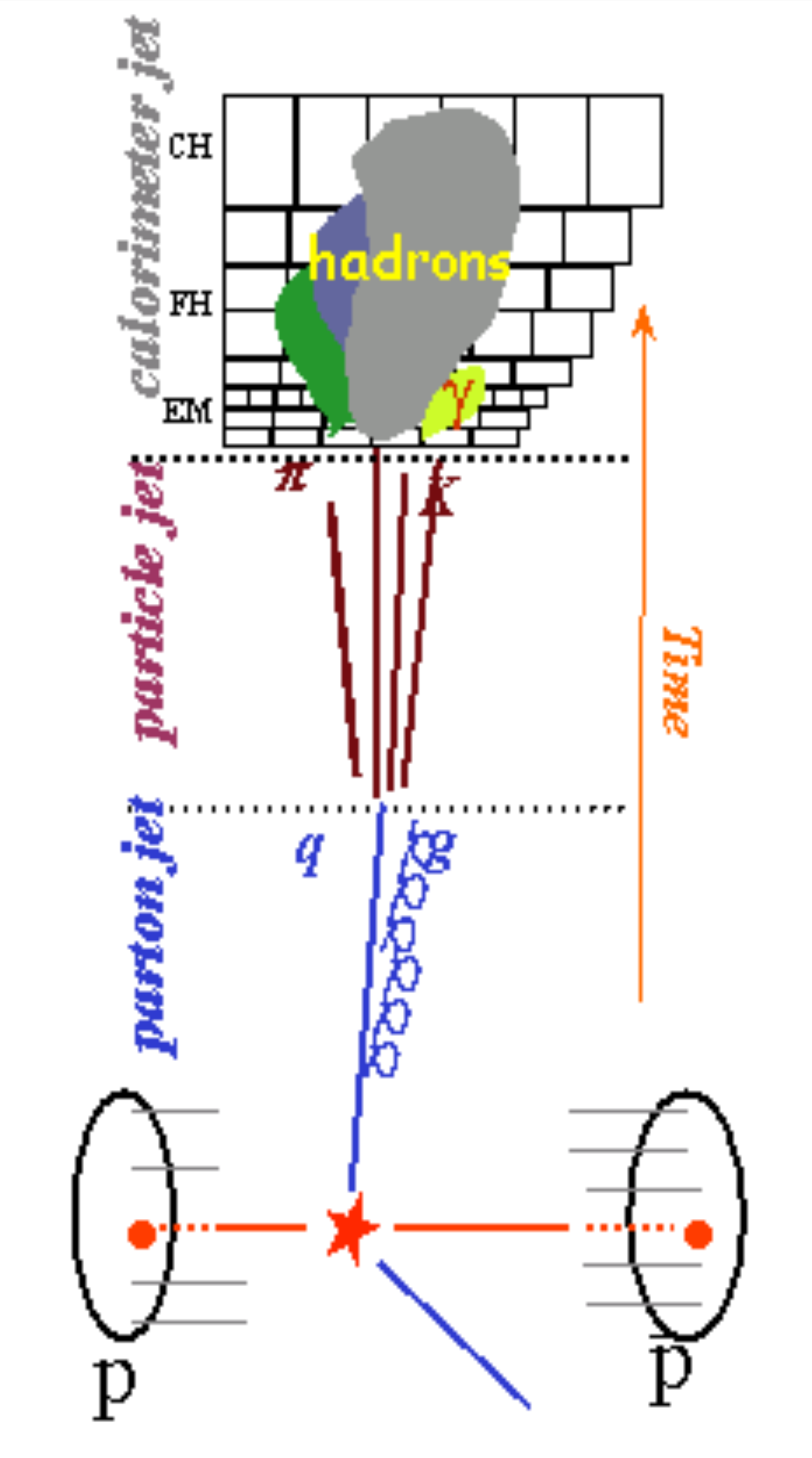

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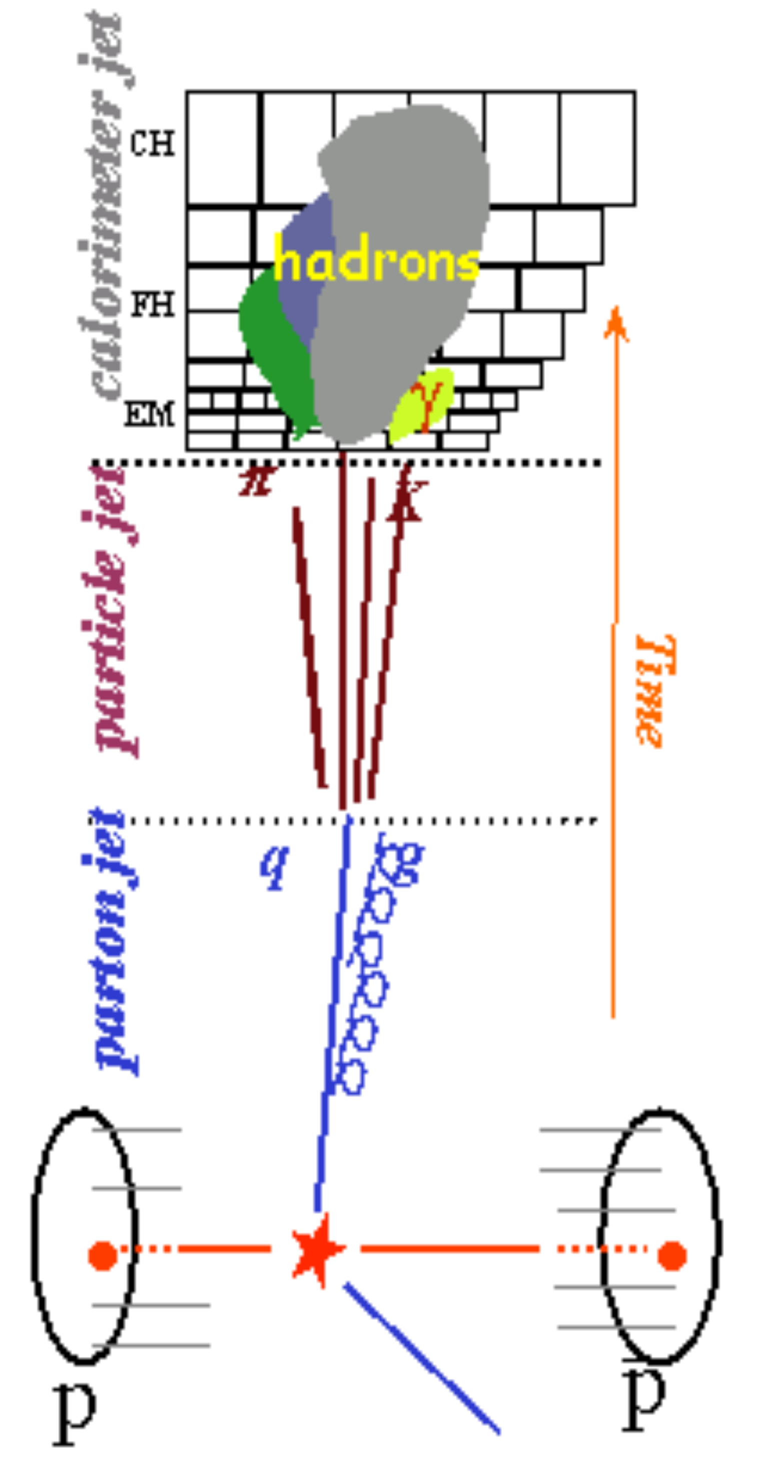
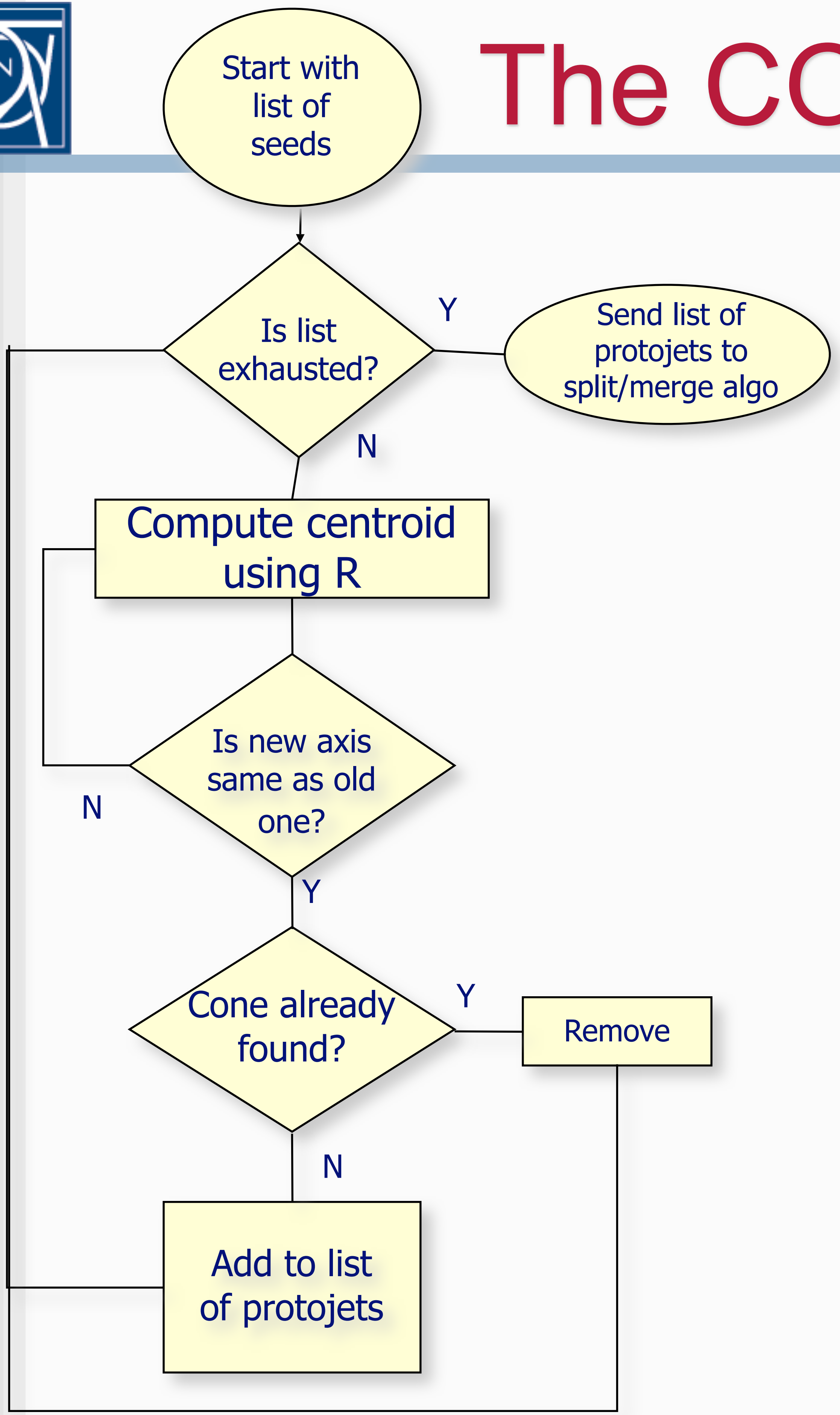
$$P_{parton} \Longleftrightarrow P_{jet}$$

Energy
Momentum
angle



The CONE algorithm



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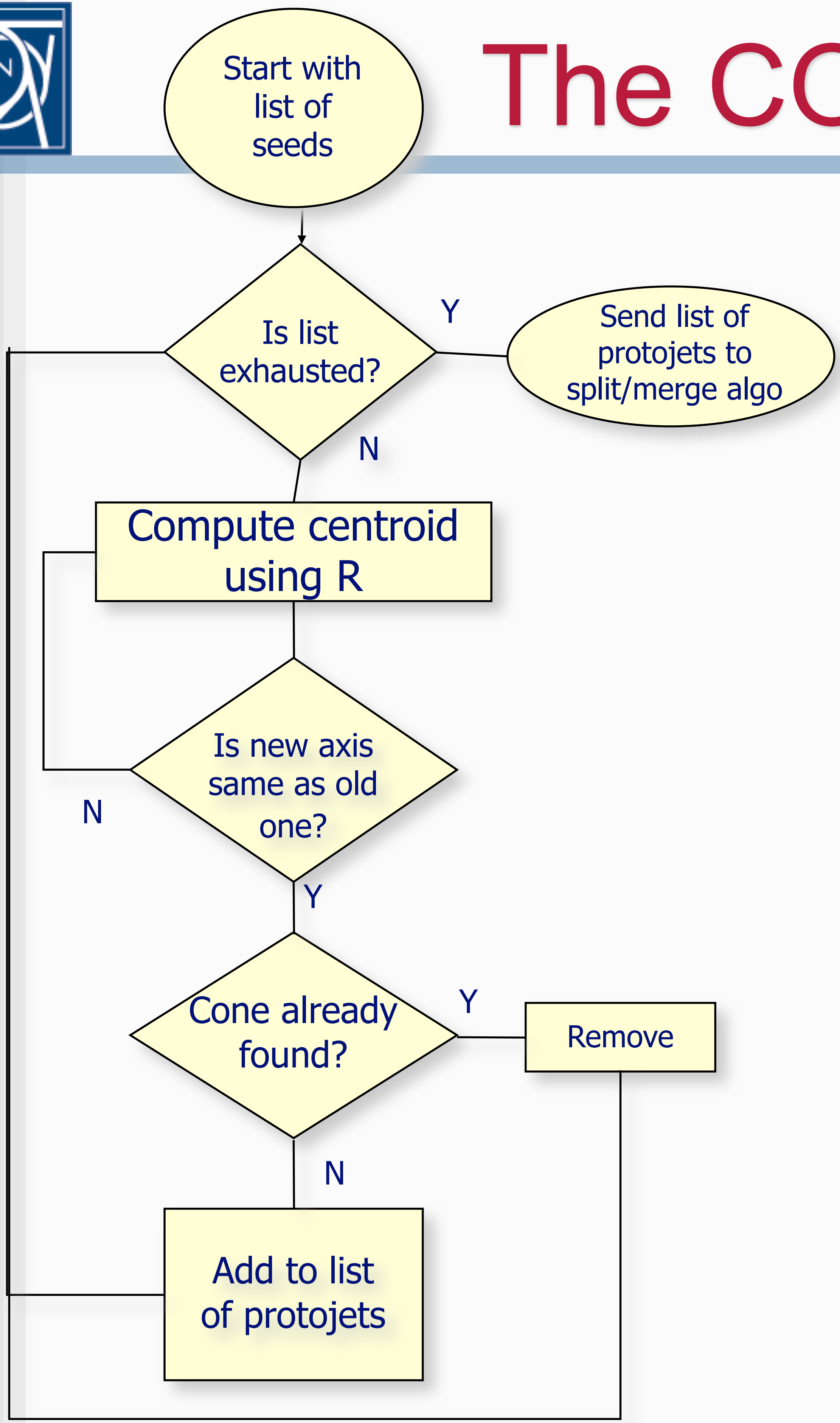

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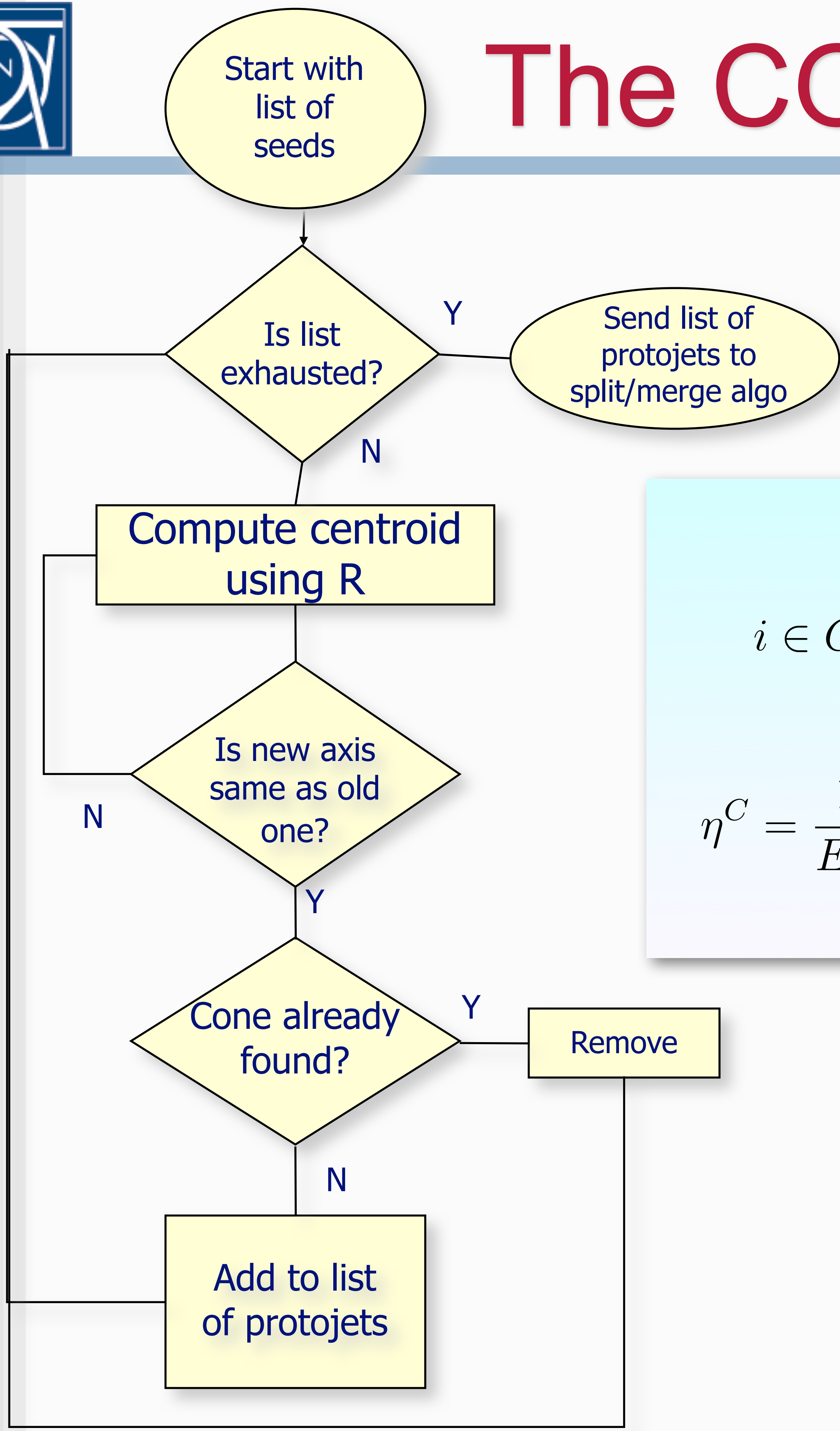

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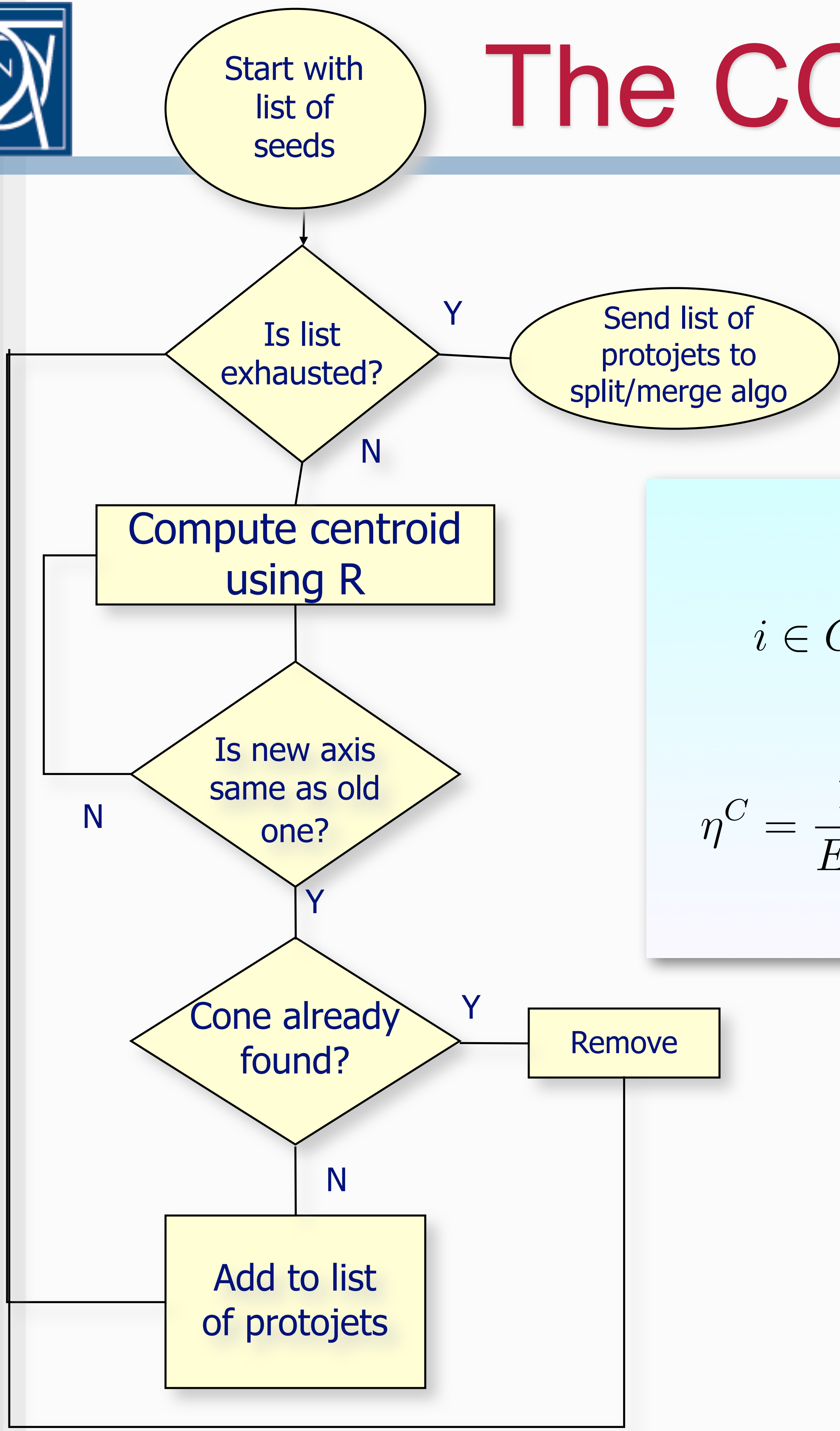

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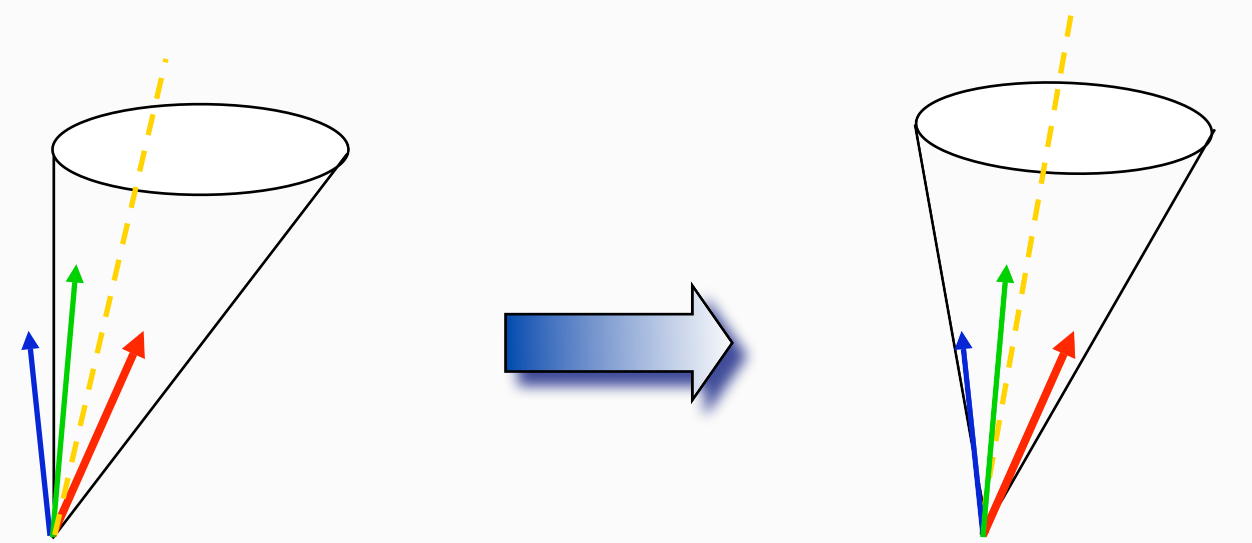

Further difficulties

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- Pile Up : many additional soft proton-proton interactions
  - up to 20 at highest LHC luminosity

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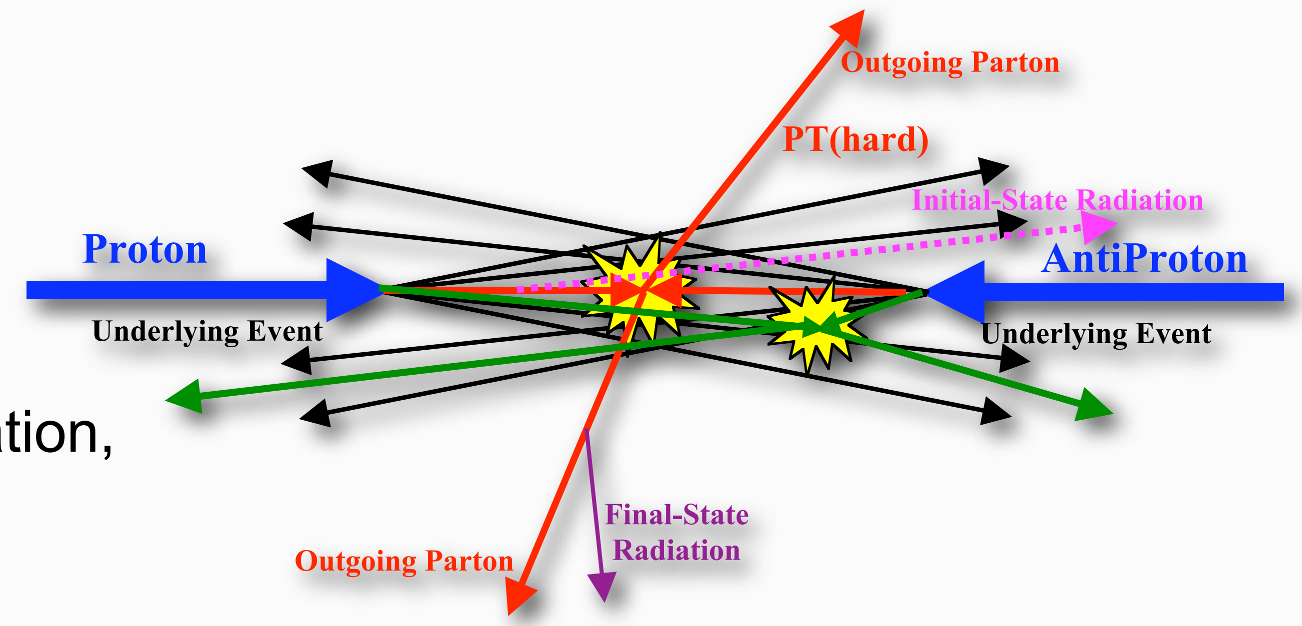

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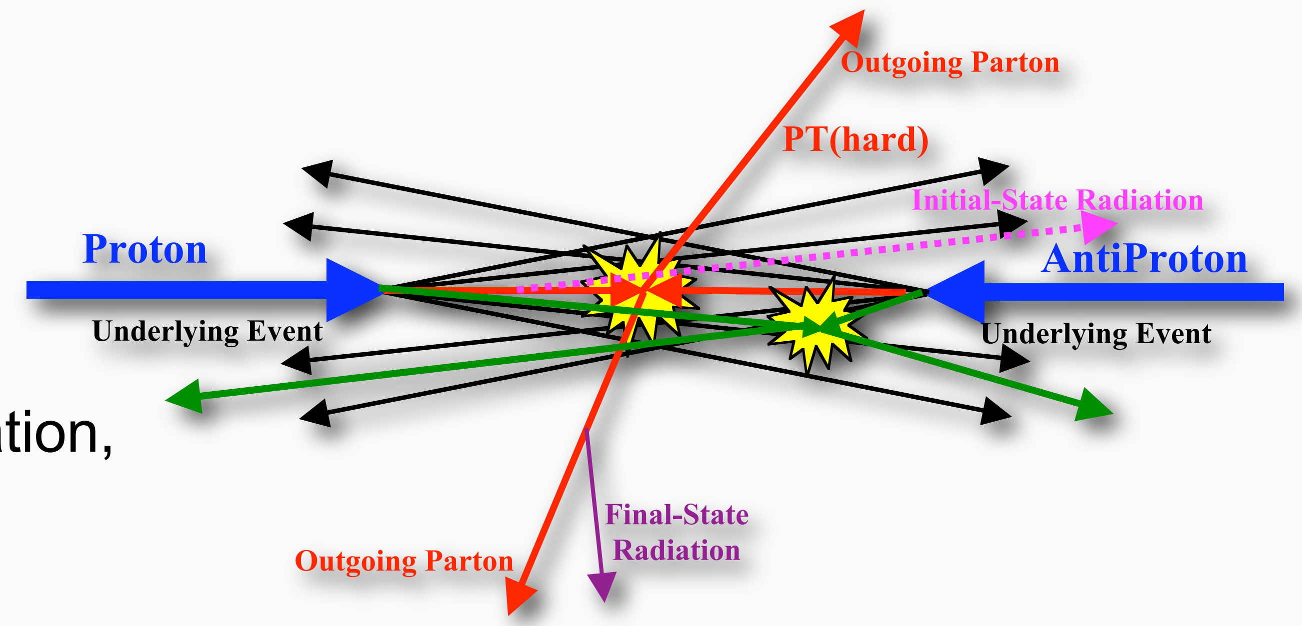

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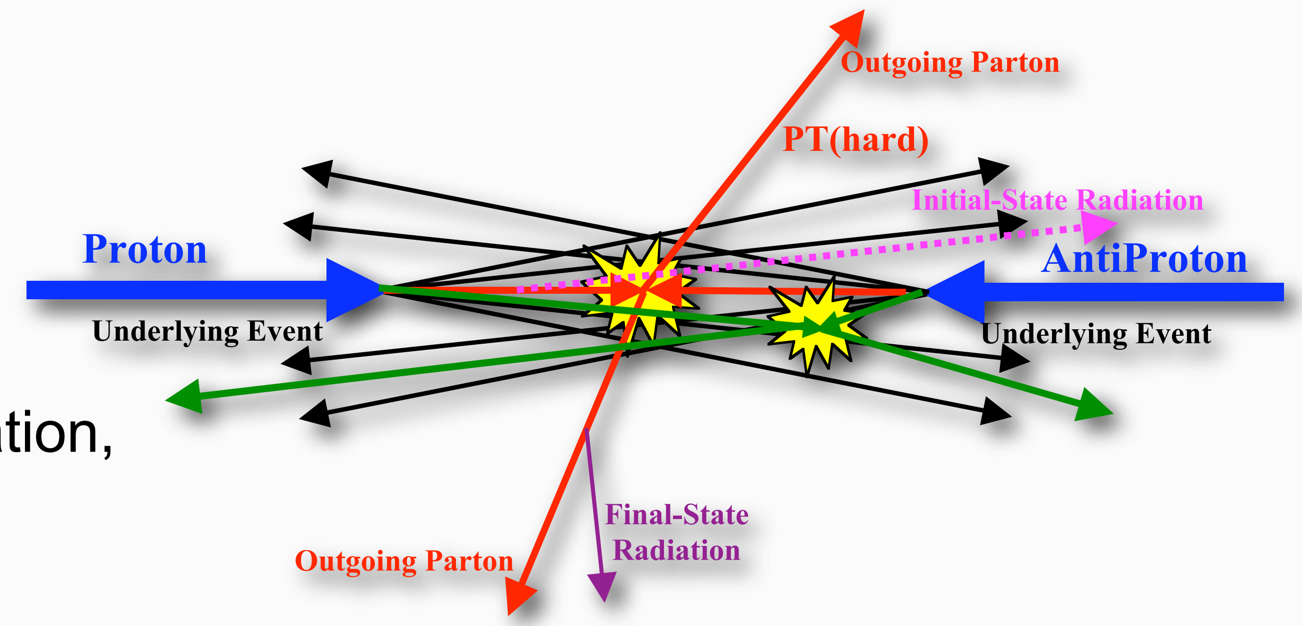

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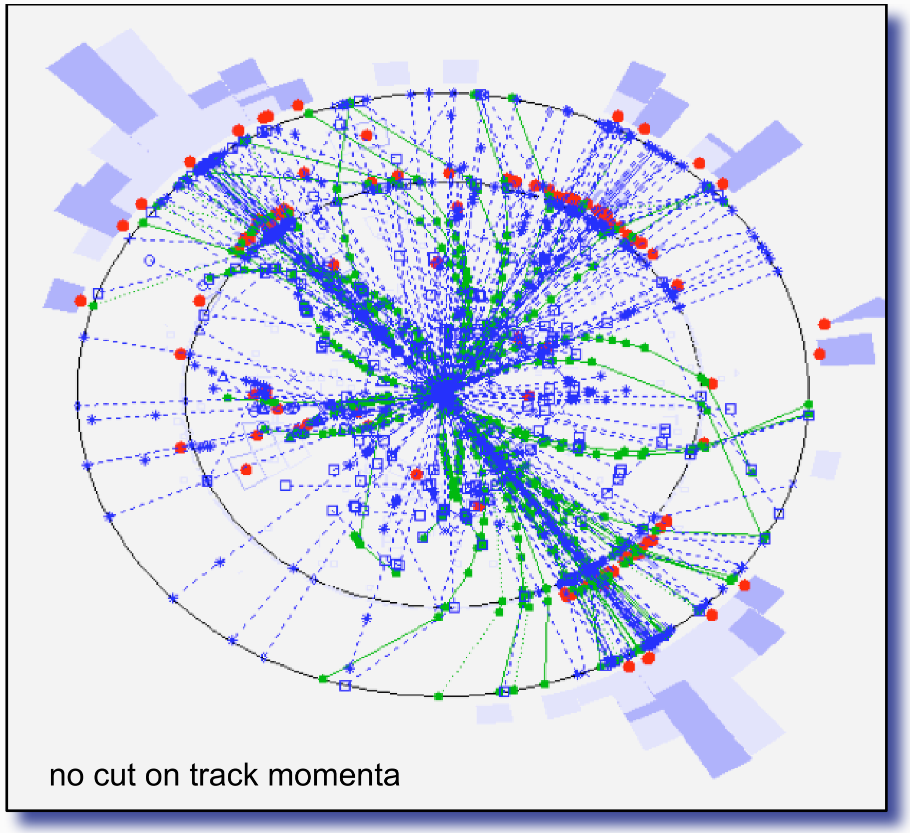

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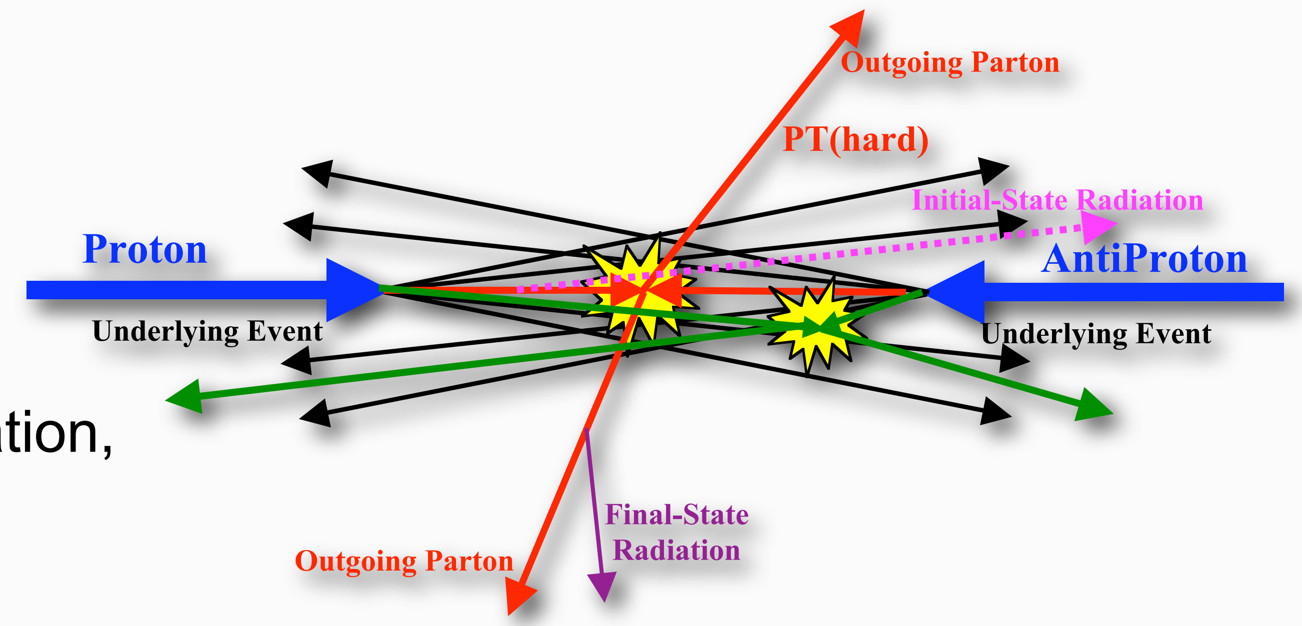

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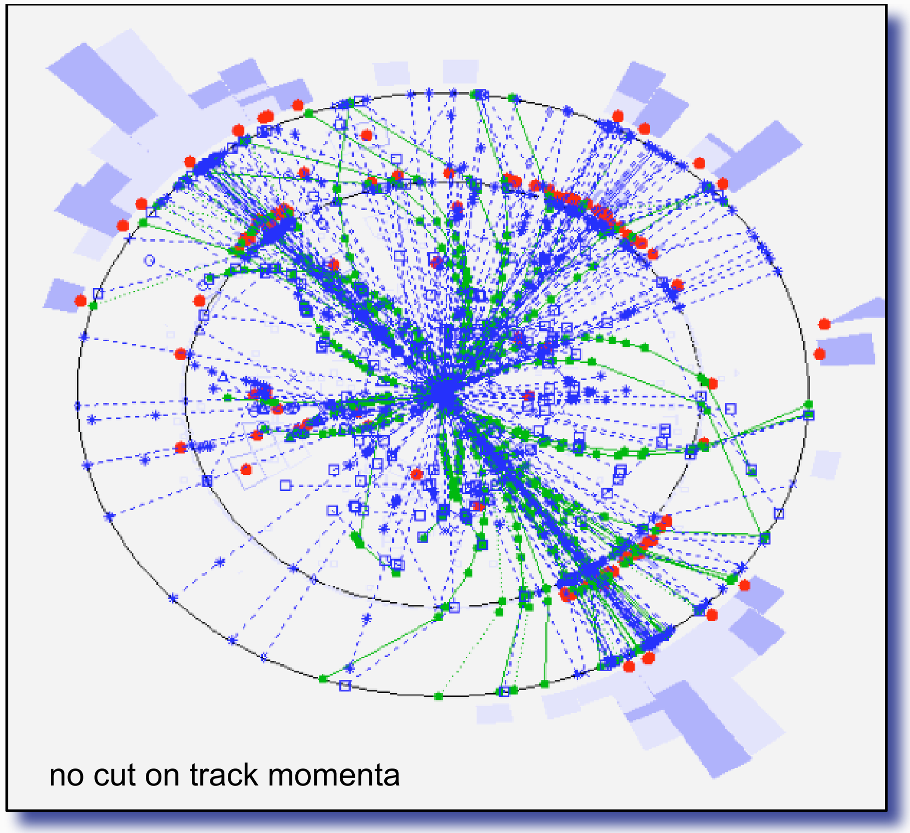

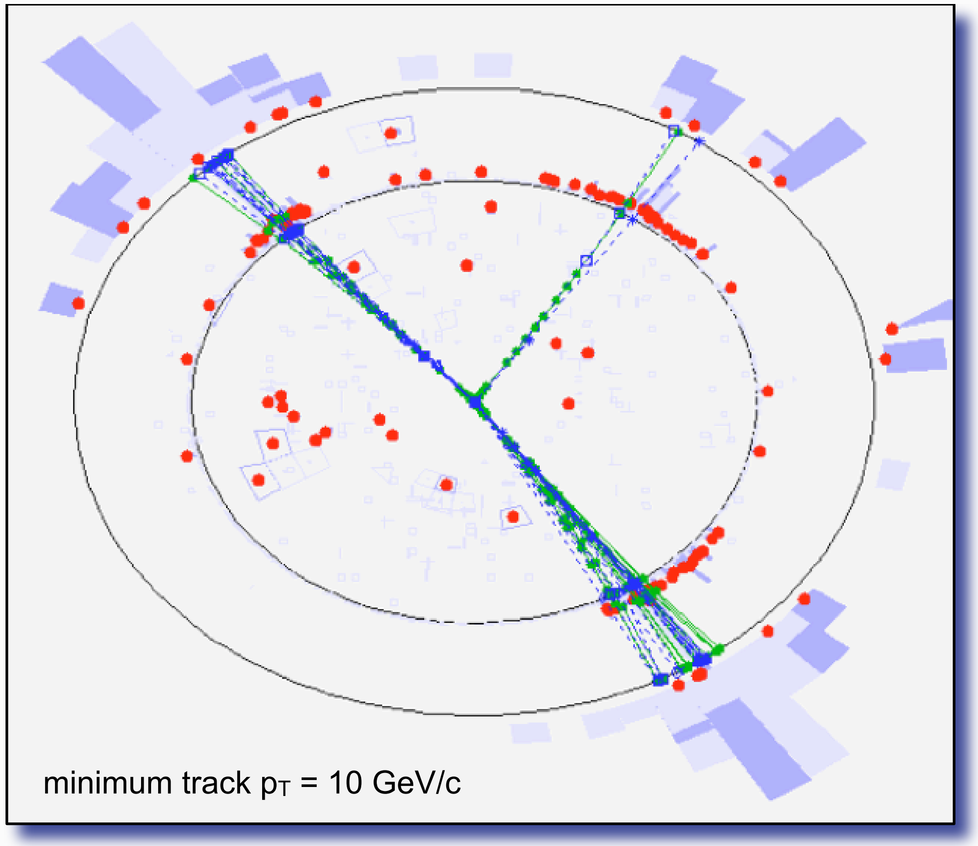

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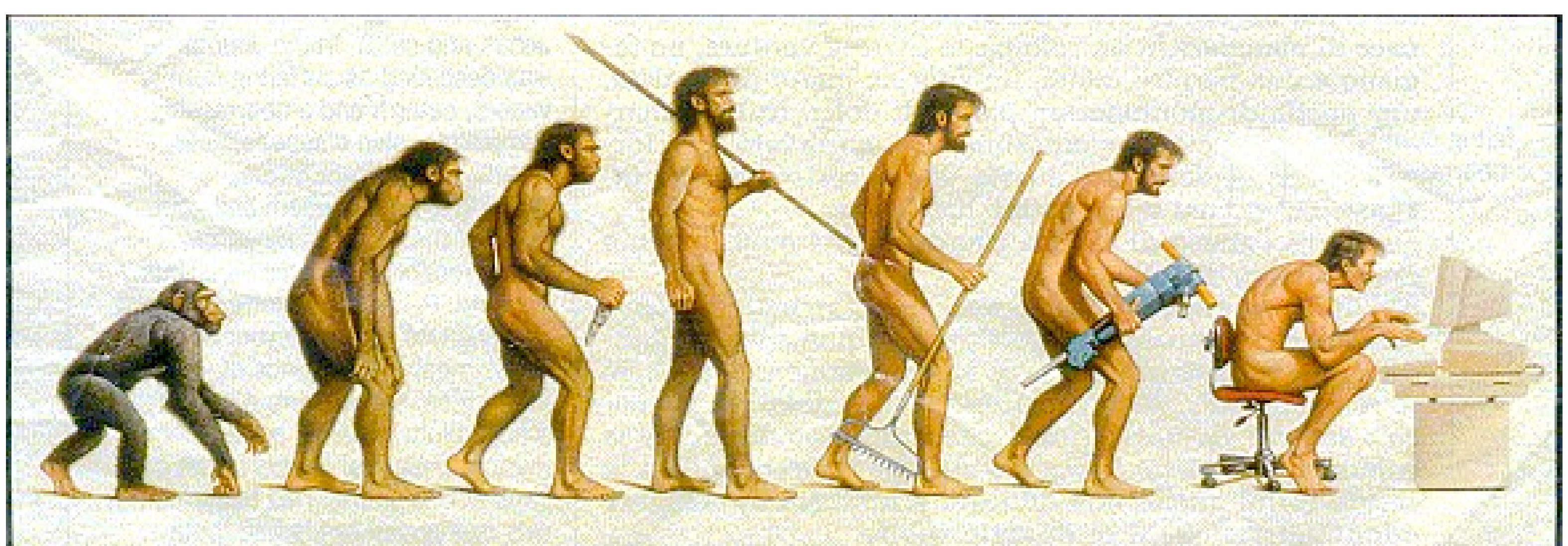
The computing behind all this



Somewhere, something went terribly wrong

Some numbers

- Examples from CMS, estimates
  - Rate of events streaming out from High-Level Trigger farm ~150 Hz
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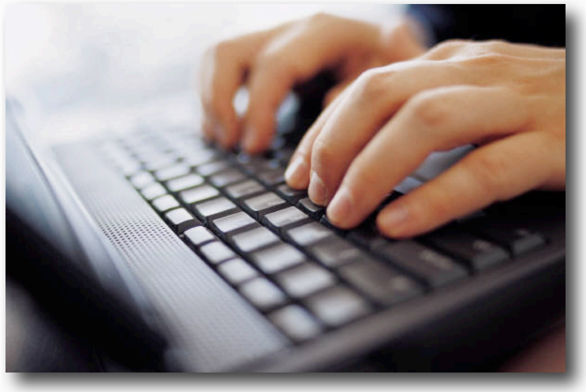

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  - Reco time per event on std. CPU: < 5 sec (on lxplus)
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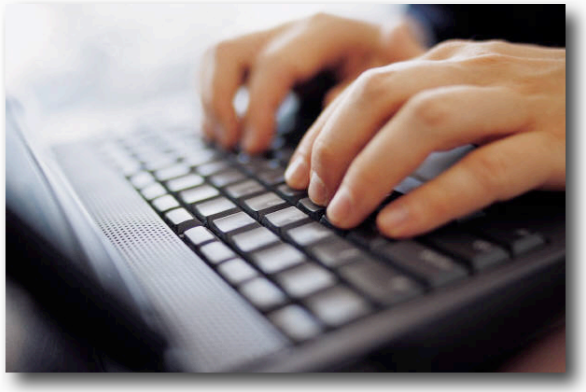

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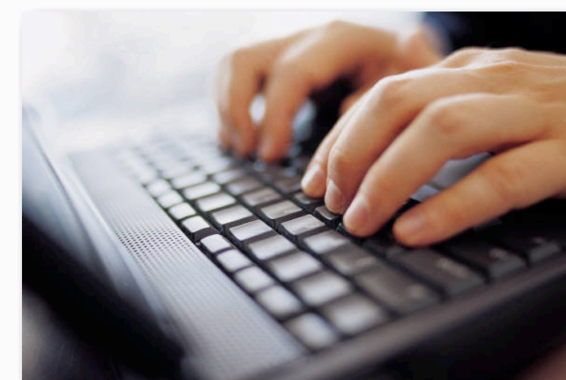

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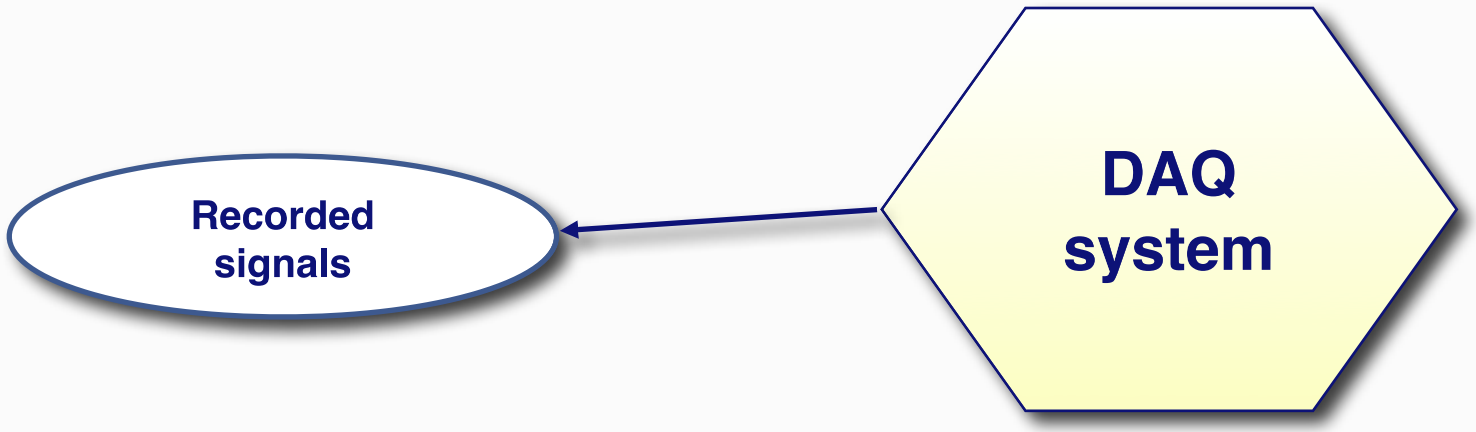
- Now : ~2 million lines of code (reconstruction and simulation)

RECO flow



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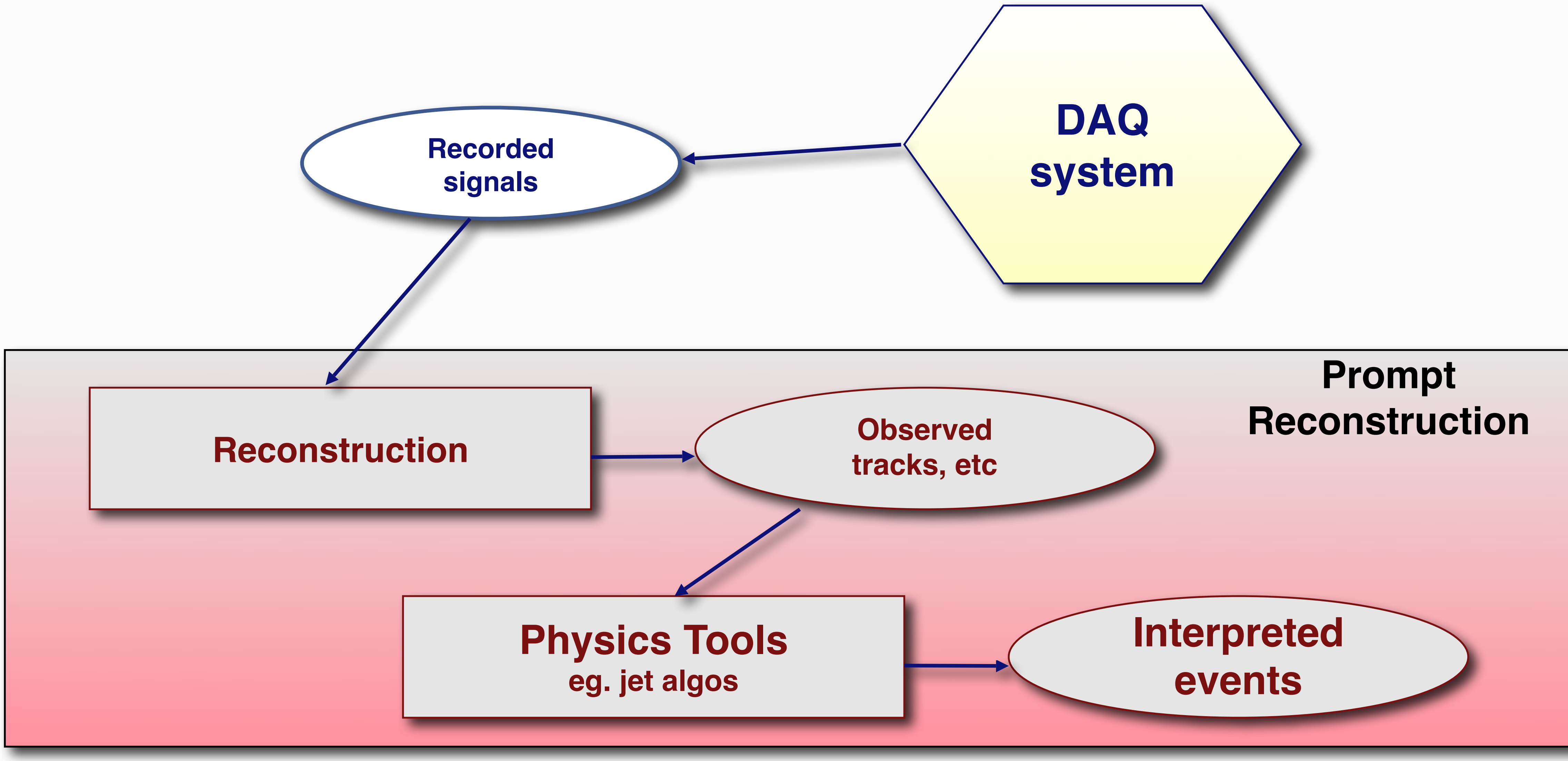

DAQ system
Recorded signals
Prompt Reconstruction
Reconstruction
Observed tracks, etc
Physics Tools
eg. jet algos
Interpreted events

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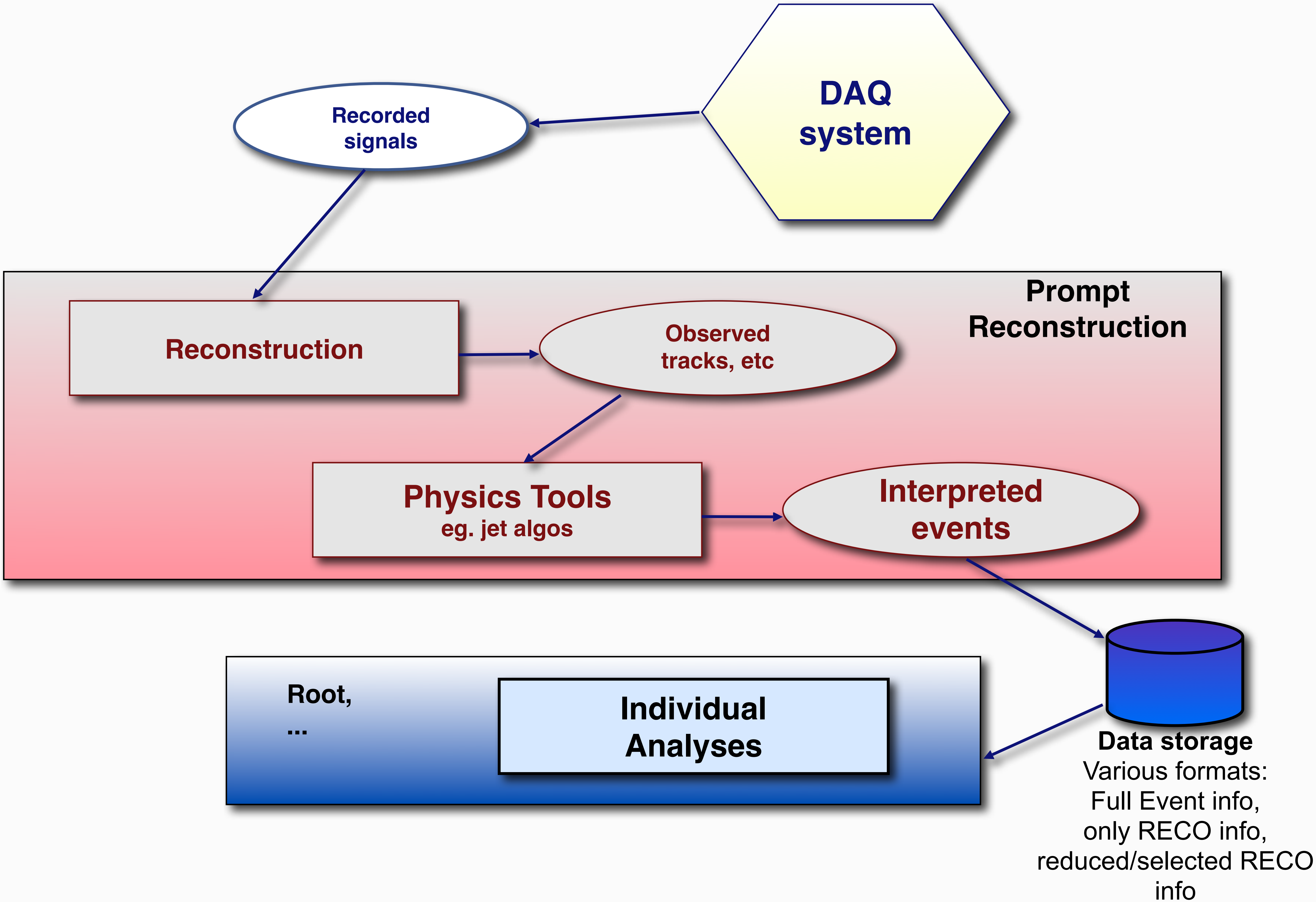

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Root,
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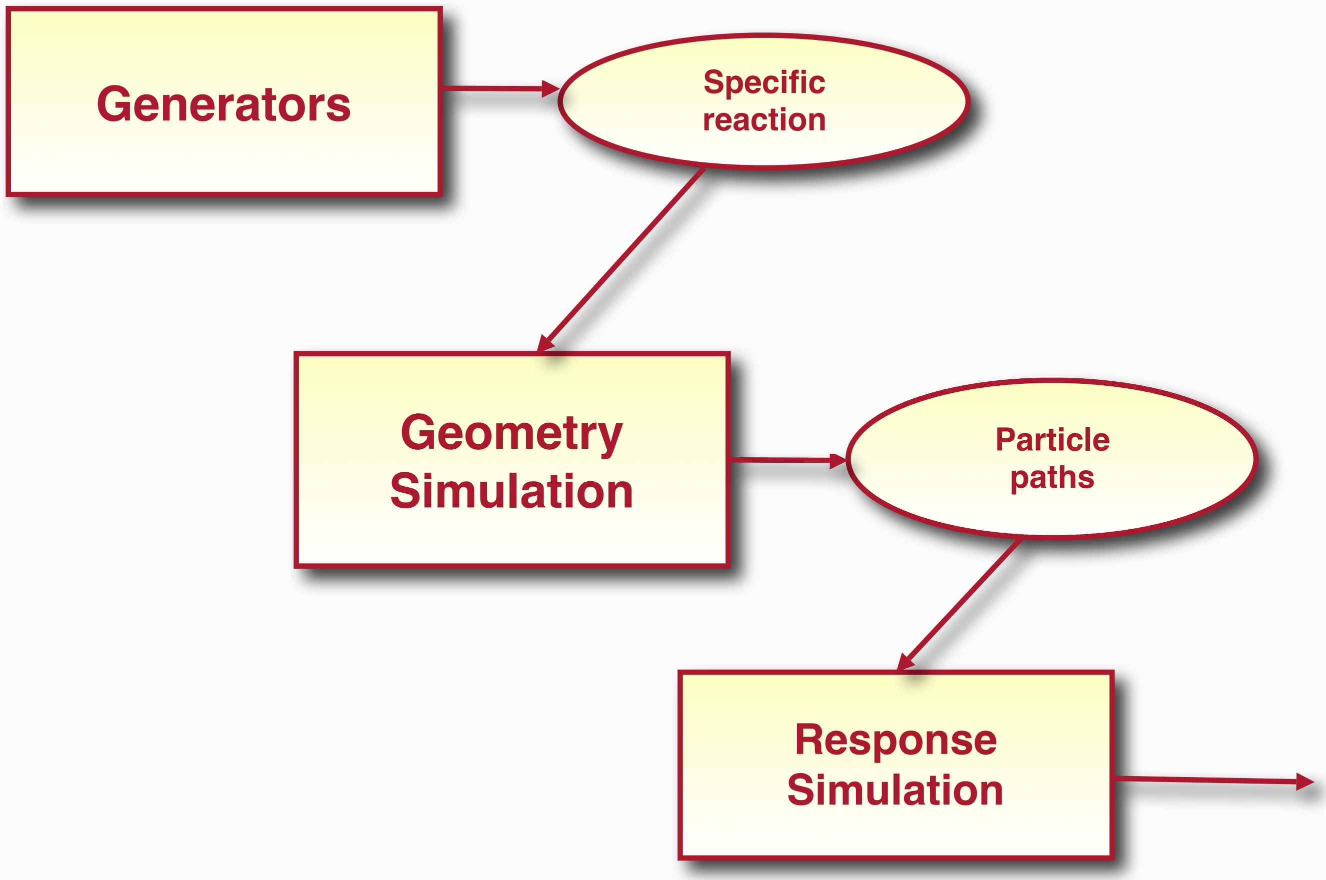
Individual Analyses
Data storage
Various formats:
Full Event info,
only RECO info,
reduced/selected RECO info

Flow of simulated data



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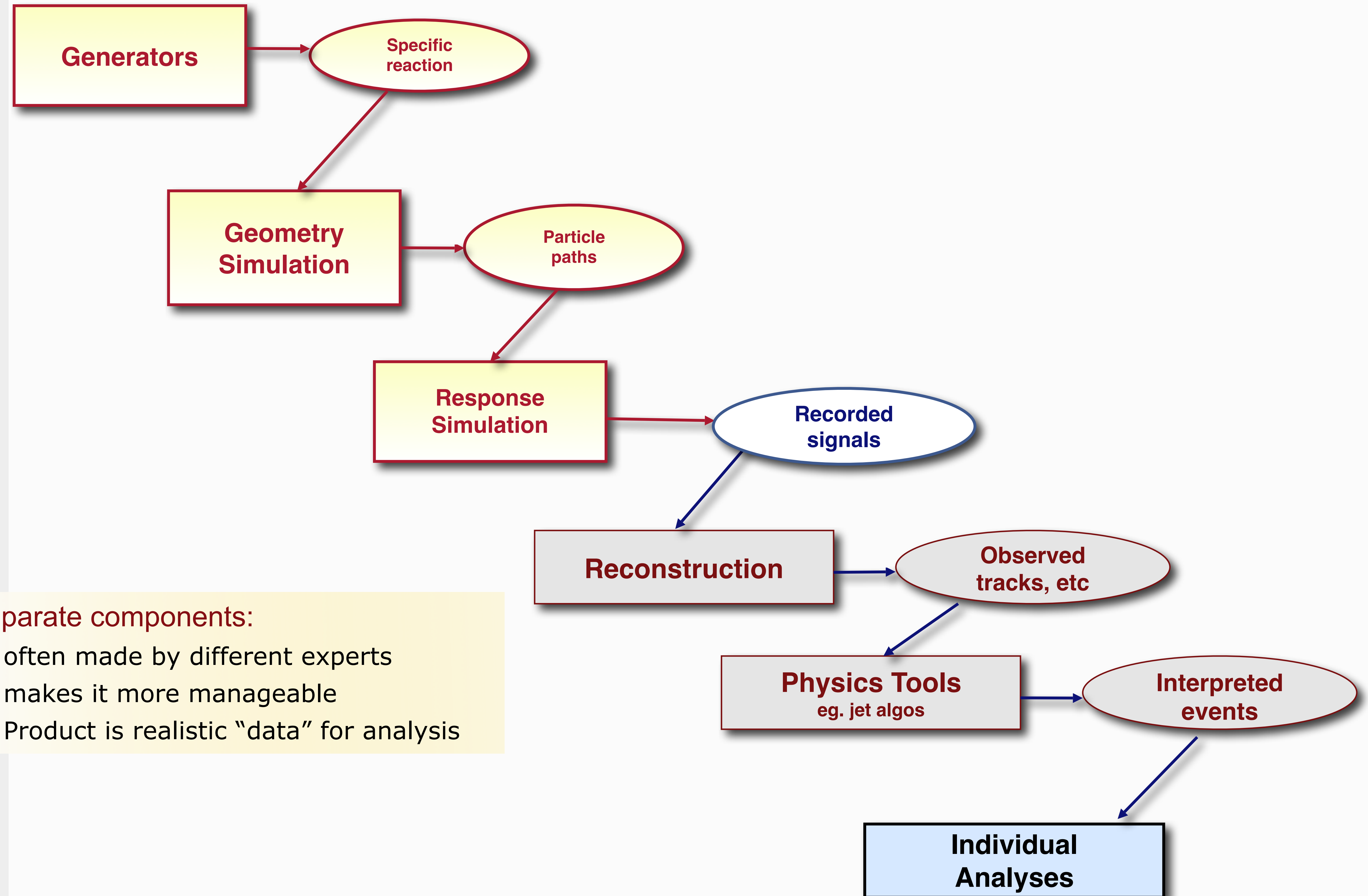

Separate components:

- often made by different experts
- makes it more manageable
- Product is realistic "data" for analysis

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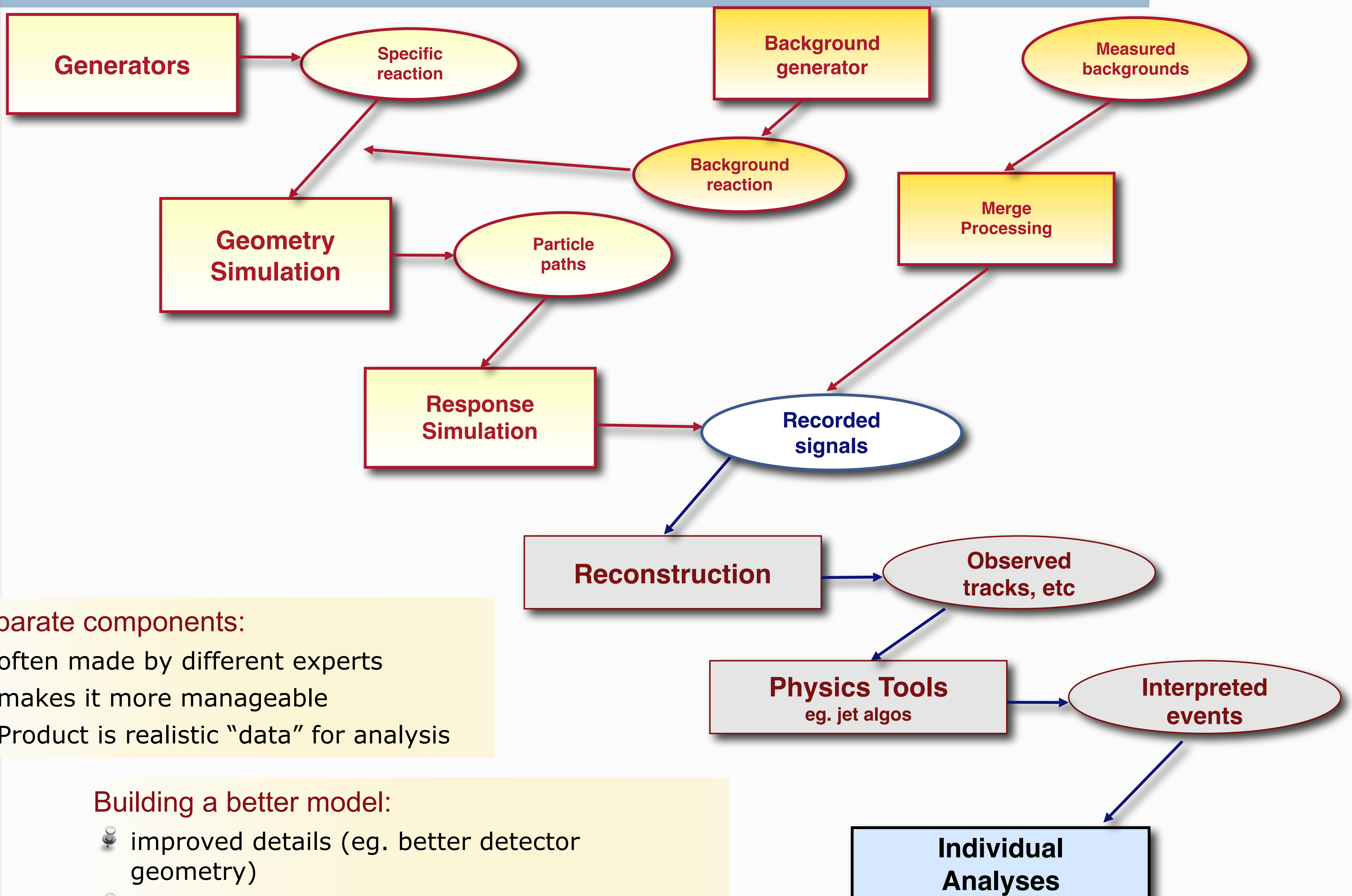

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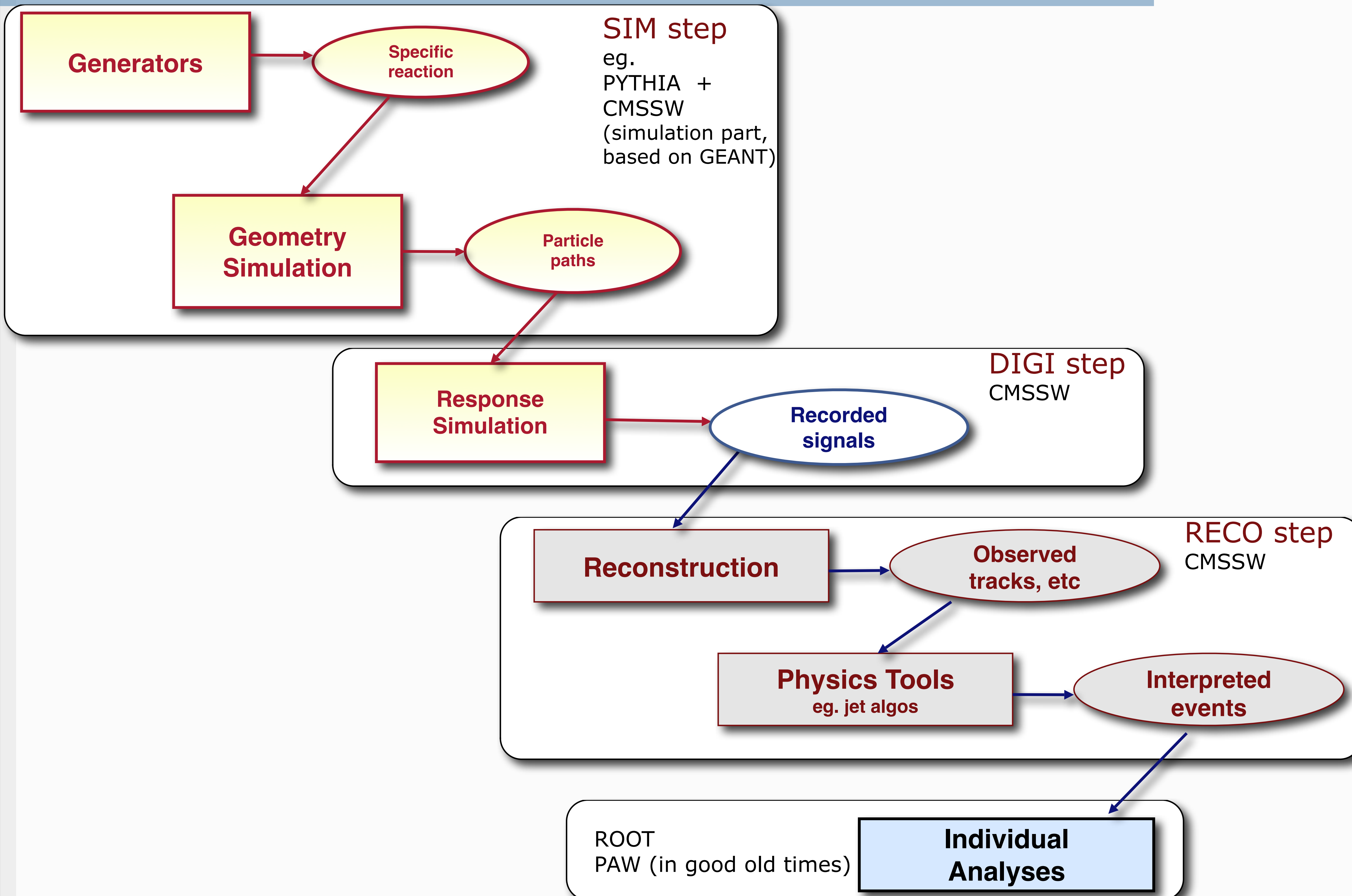
Building a better model:
- improved details (eg. better detector geometry)
- real backgrounds

Partitioning production systems



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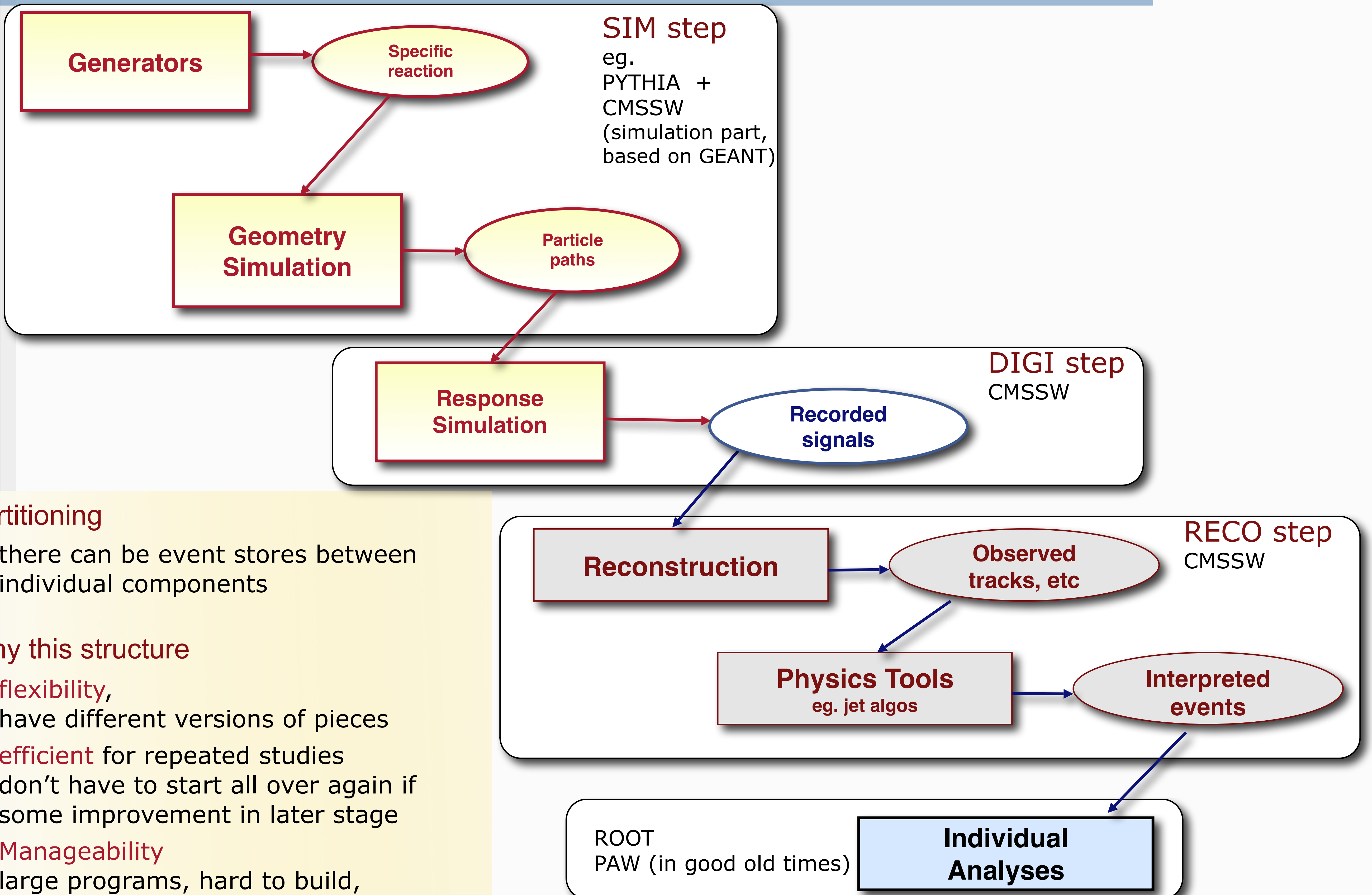

Partitioning

- there can be event stores between individual components

Why this structure

- flexibility,
  have different versions of pieces
- efficient for repeated studies
  don't have to start all over again if some improvement in later stage
- Manageability
  large programs, hard to build, understand, debug, maintain, ...

Partitioning production systems

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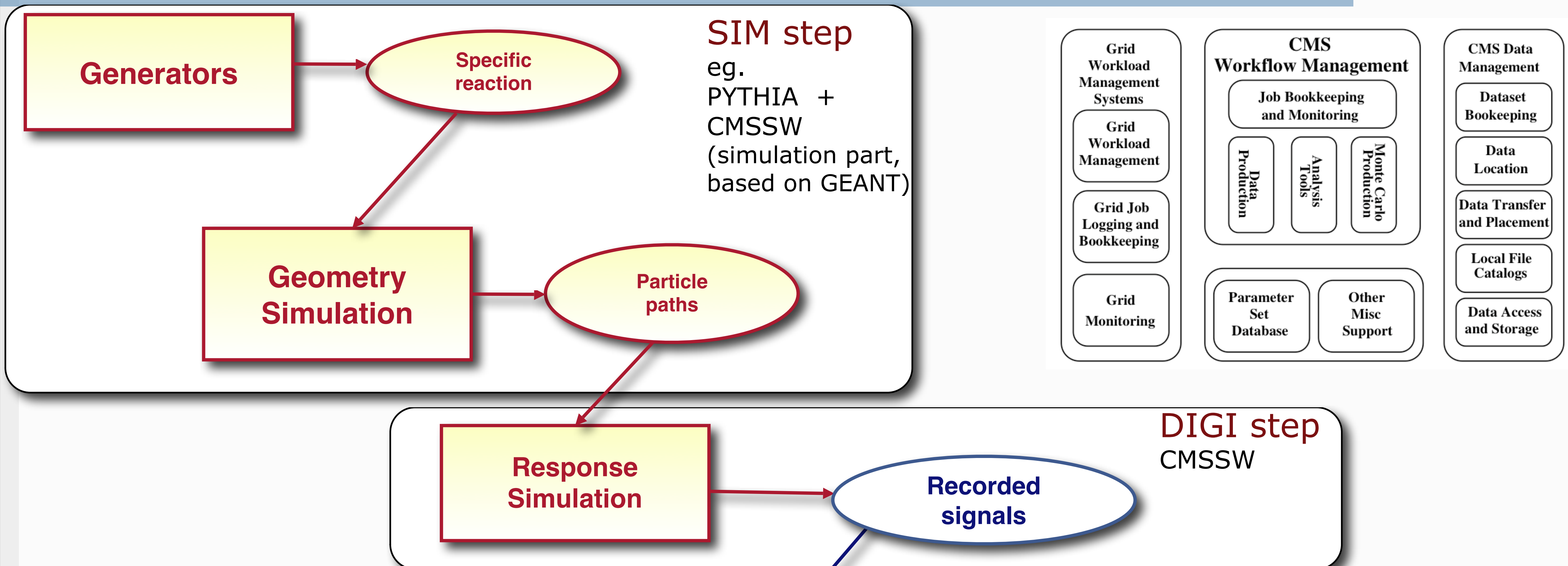

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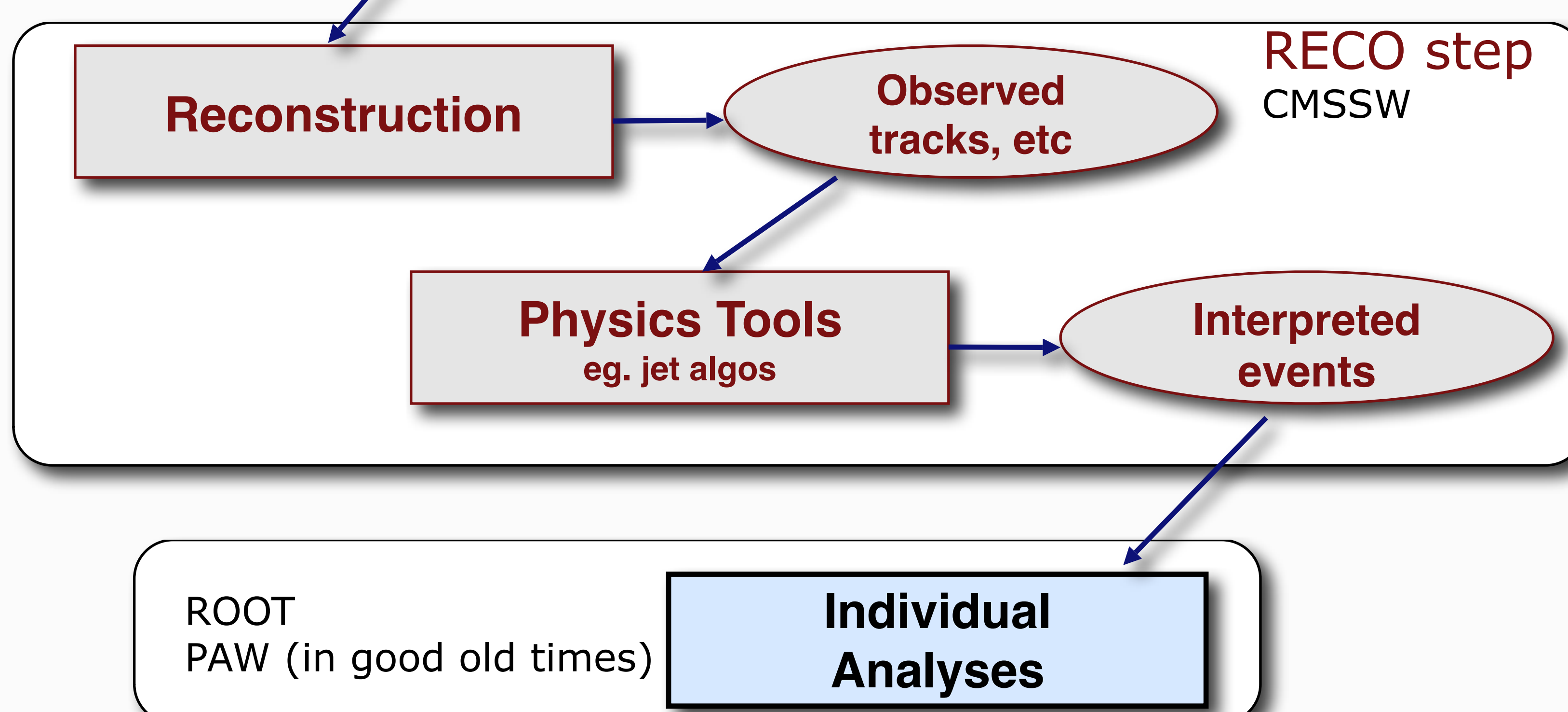

GRID distribution : example

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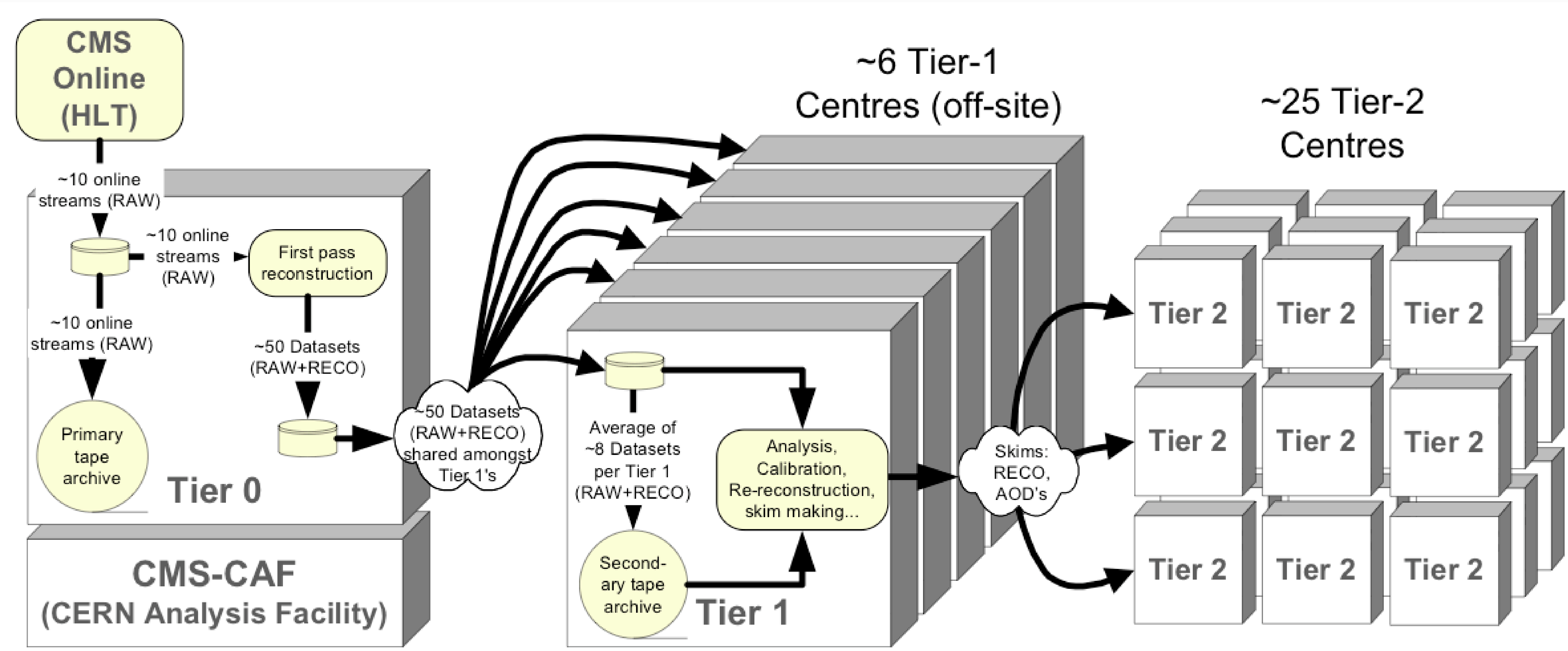
CMS Computing Model: Data Flow



Summary

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

What wasn't covered

- Details on track fitting, Kalman filters
- Secondary Vertex finding
- Alignment
- Particle Identification
- Calibration techniques, "in-situ" methods
- Particle/Energy flow
- Trigger menus, their studies
- more details on parameter fitting,
  eg. lifetime and mass measurements
- how to estimate systematic errors
- Databases, persistent data storage
- Programming languages in use (F77, C, C++, JAVA, ...)
- .....

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