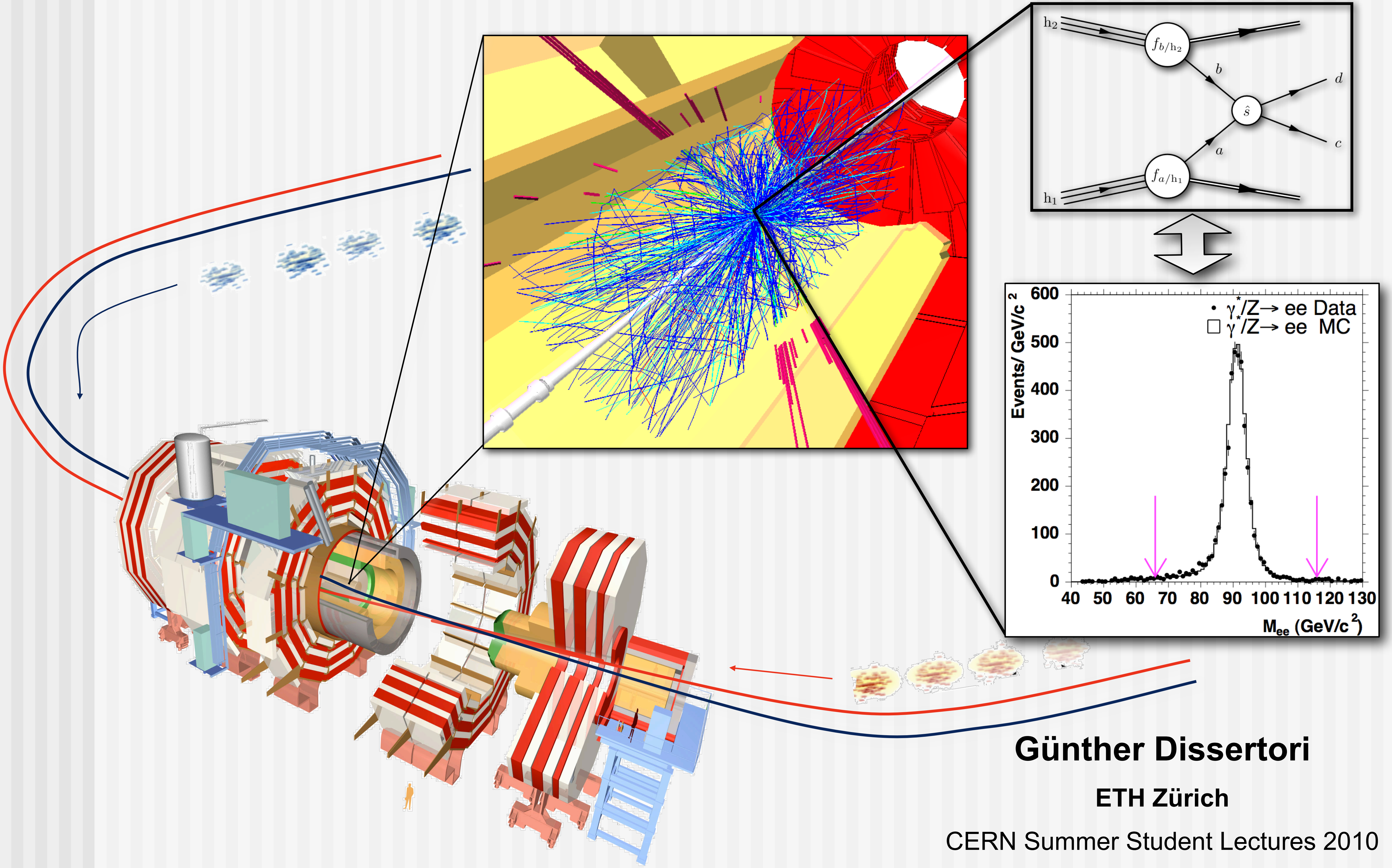
From Raw Data to Physics Results



Günther Dissertori

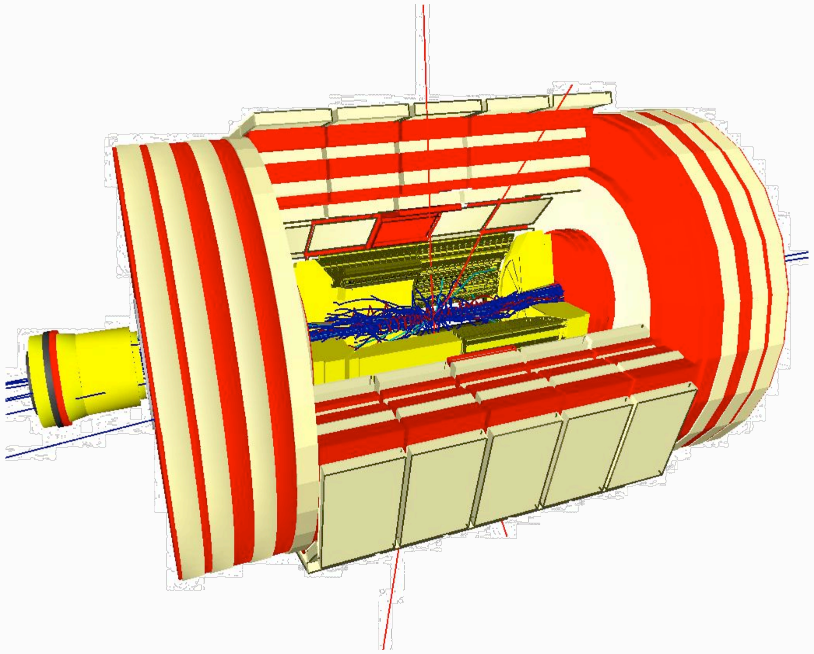
ETH Zürich

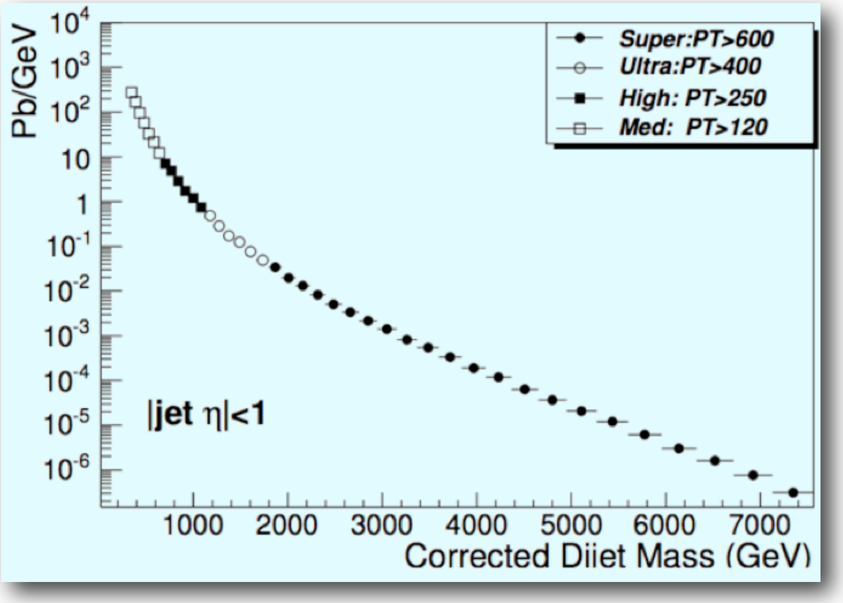
CERN Summer Student Lectures 2010

Outline

ETH Institute for Particle Physics

- “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



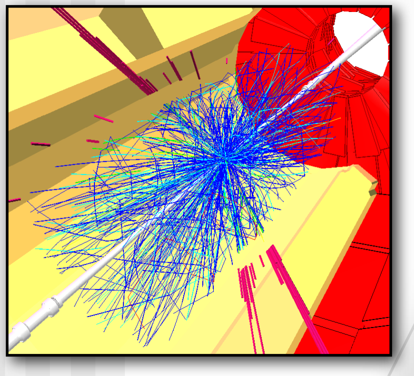


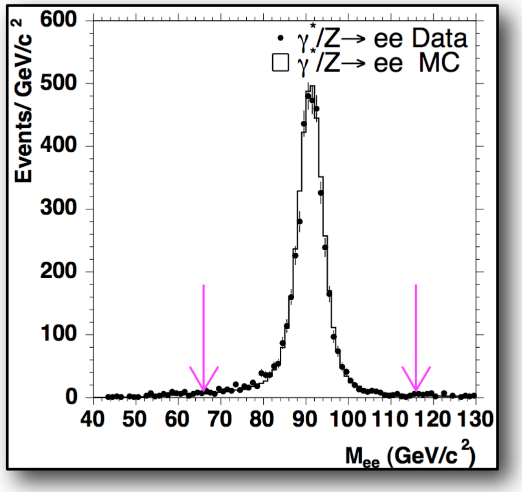
- Disclaimer : Several slides based on past CSS lectures by B. Jacobsen
- thanks also to J. Weng, T. Punz, A. Valassi

The whole lecture in a nutshell

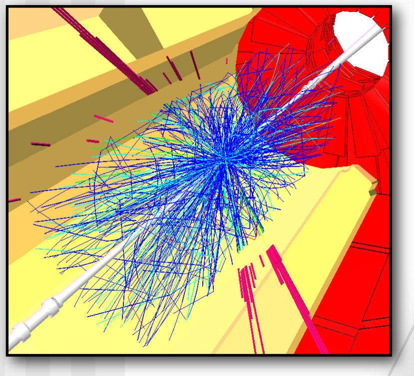
"But you should not leave immediately after this...."

Data Analysis Chain

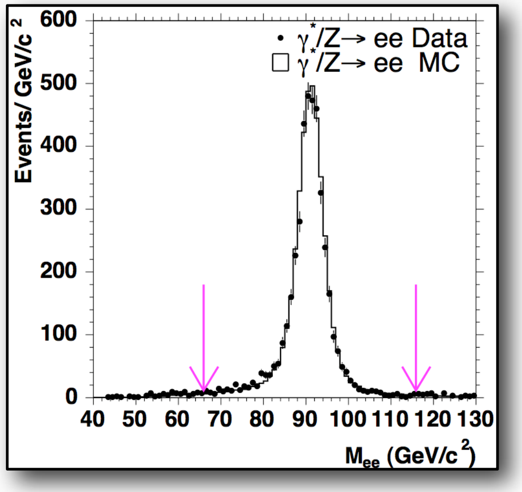




Data Analysis Chain



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



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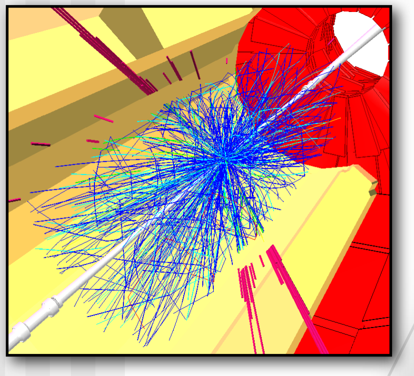
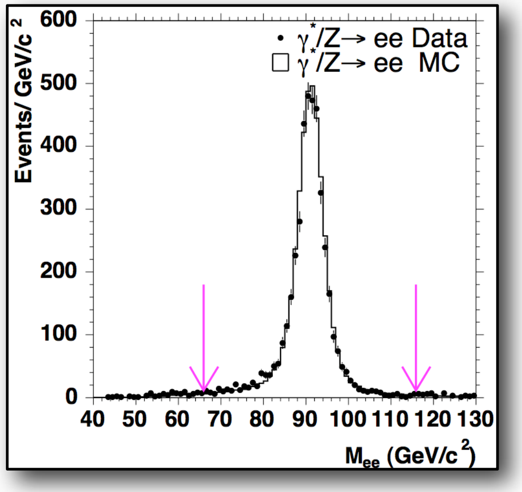
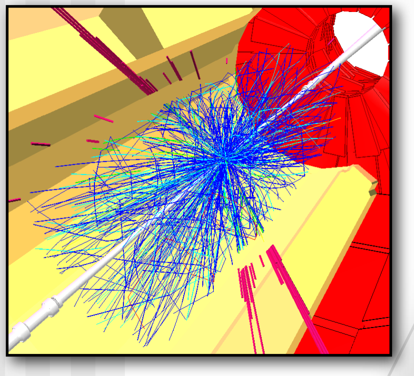


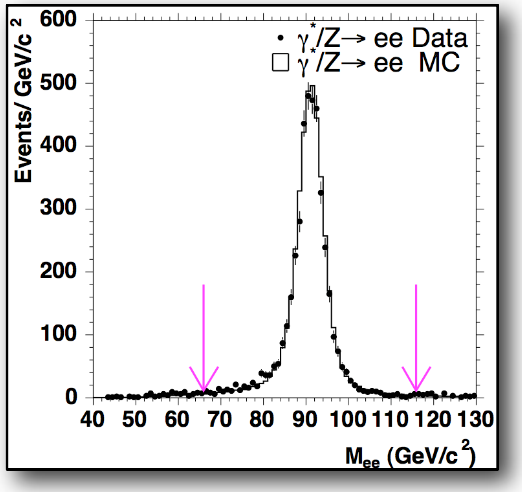
- Have to collect data from many channels on many sub-detectors (millions)
- Decide to read out everything or throw event away (Trigger)



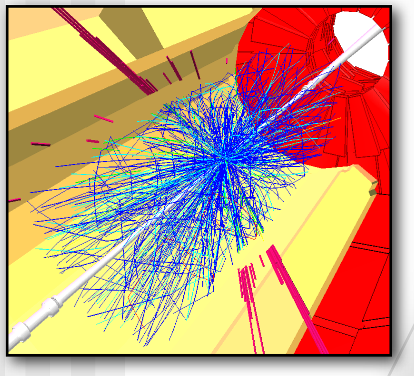
Data Analysis Chain



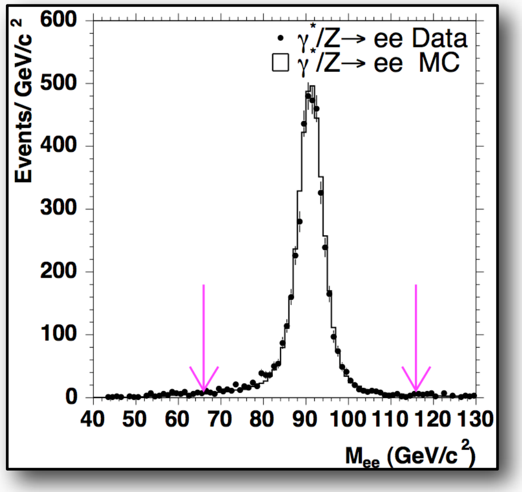
- Have to collect data from many channels on many sub-detectors (millions)
- Decide to read out everything or throw event away (Trigger)
- Build the event (put info together)



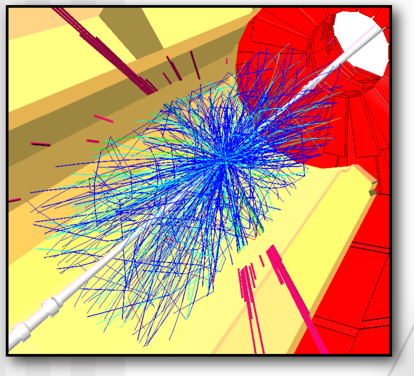
Data Analysis Chain



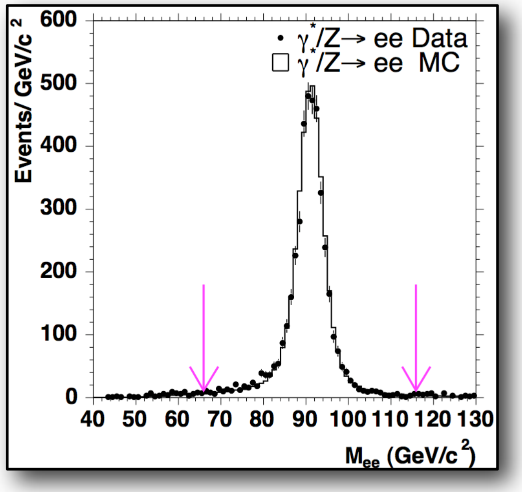
- Have to collect data from many channels on many sub-detectors (millions)
- Decide to read out everything or throw event away (Trigger)
- Build the event (put info together)
- Store the data



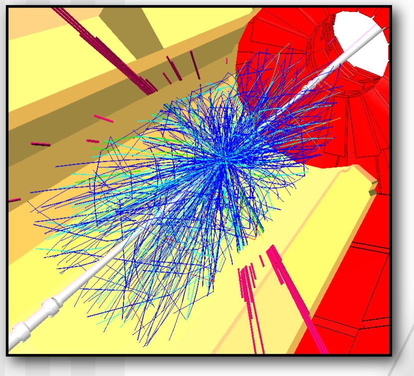
Data Analysis Chain



- 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



Data Analysis Chain



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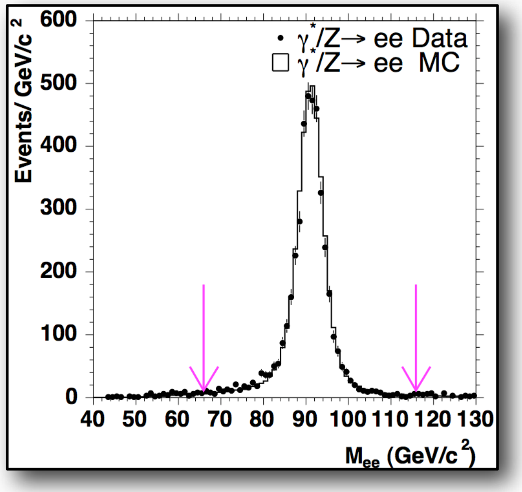
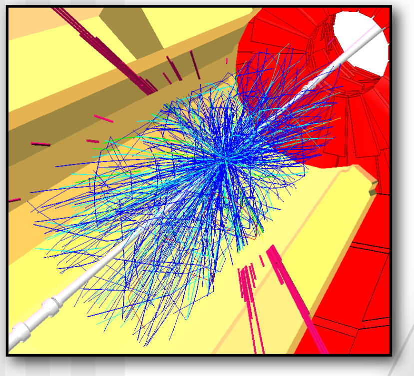
  - reconstruction, user analysis algorithms, data volume reduction
- do the same with a simulation
  - correct data for detector effects



Data Analysis Chain



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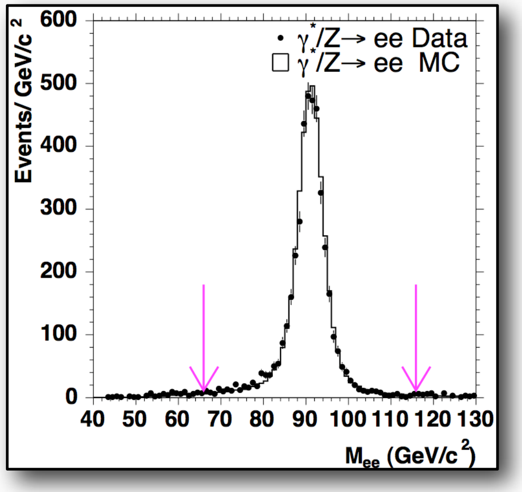
- Build the event (put info together)
- Store the data
- Analyze them
  - reconstruction, user analysis algorithms, data volume reduction
- do the same with a simulation
  - correct data for detector effects
- Compare data and theory



DAQ chain (see lectures by N. Neufeld)

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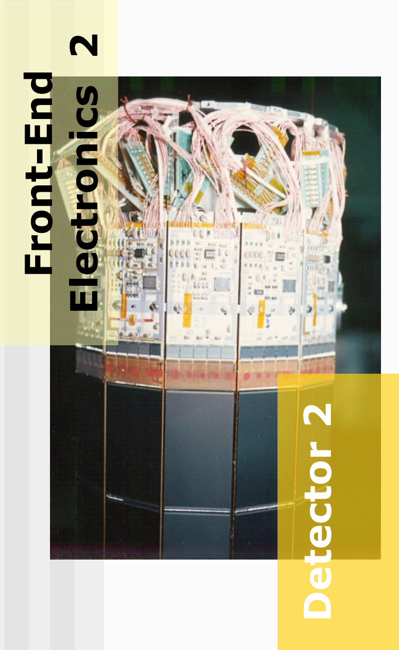
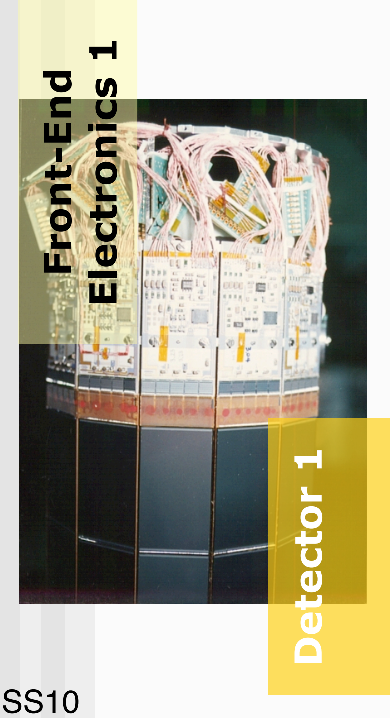
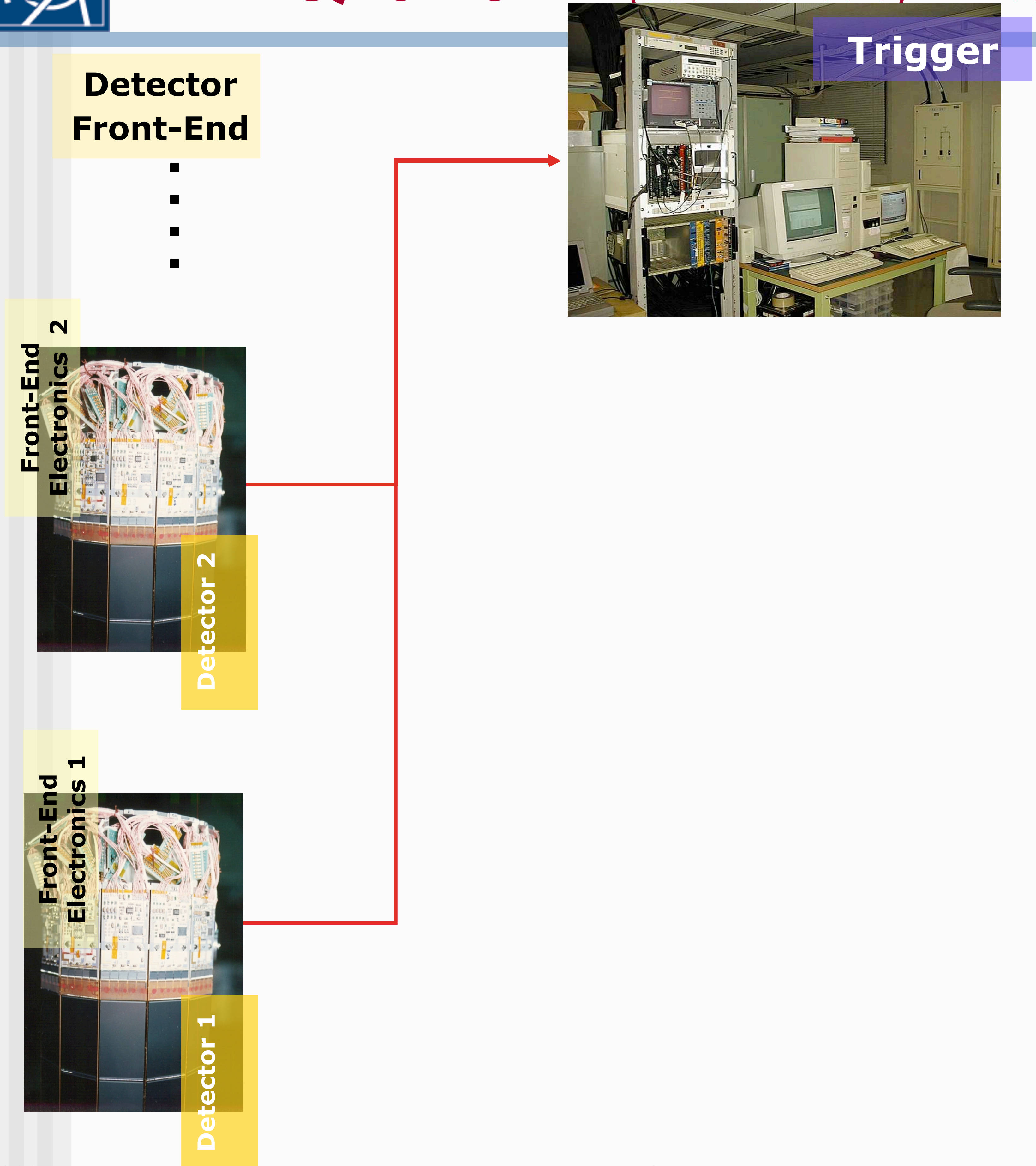
Detector Front-End

⋮





DAQ chain (see lectures by N. Neufeld)



Detector Front-End

⋮

Front-End Electronics 2

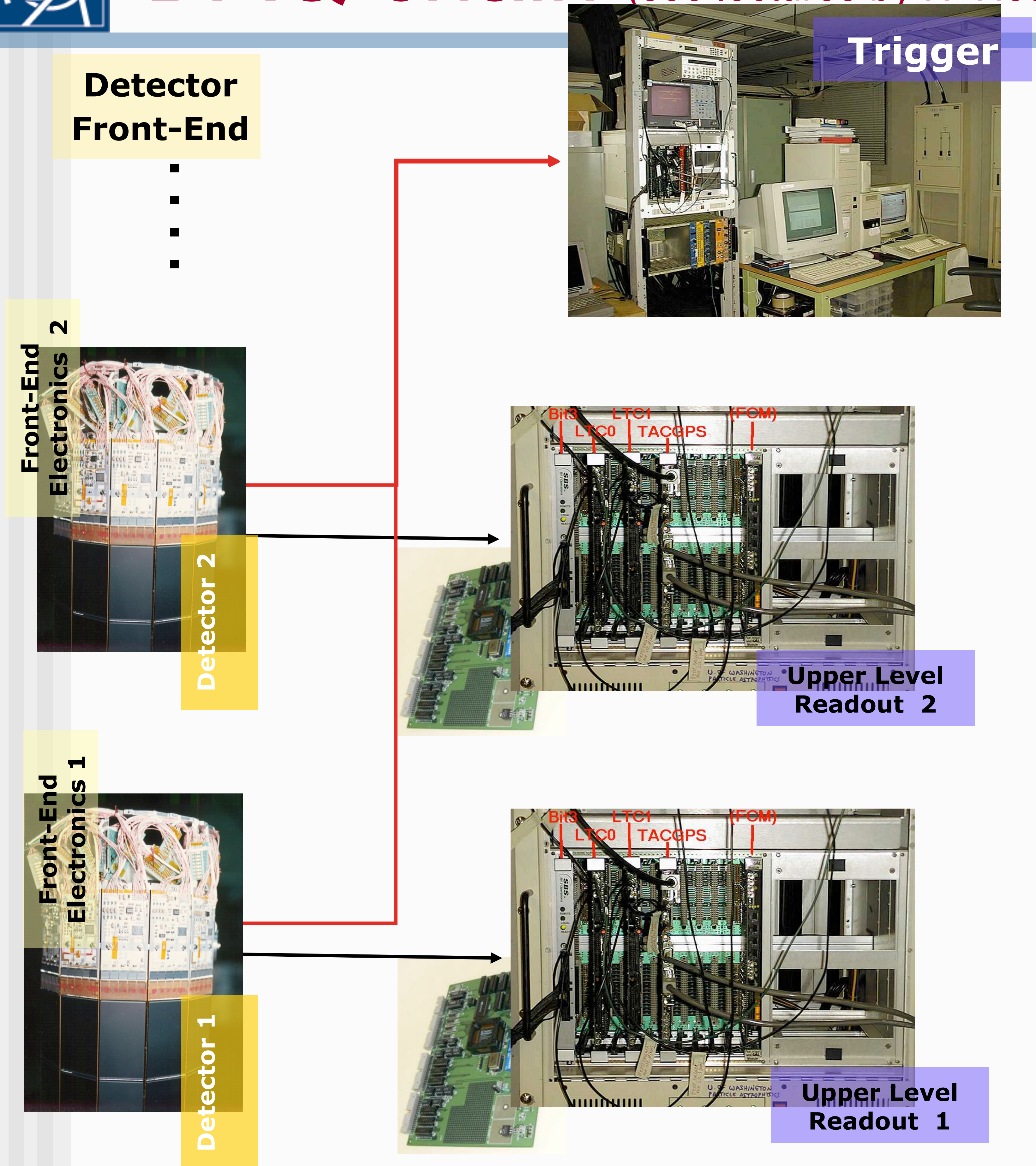
Detector 2

Front-End Electronics 1

Detector 1

Trigger

DAQ chain (see lectures by N. Neufeld)



Trigger

Detector Front-End

⋮

Front-End Electronics 2

Detector 2

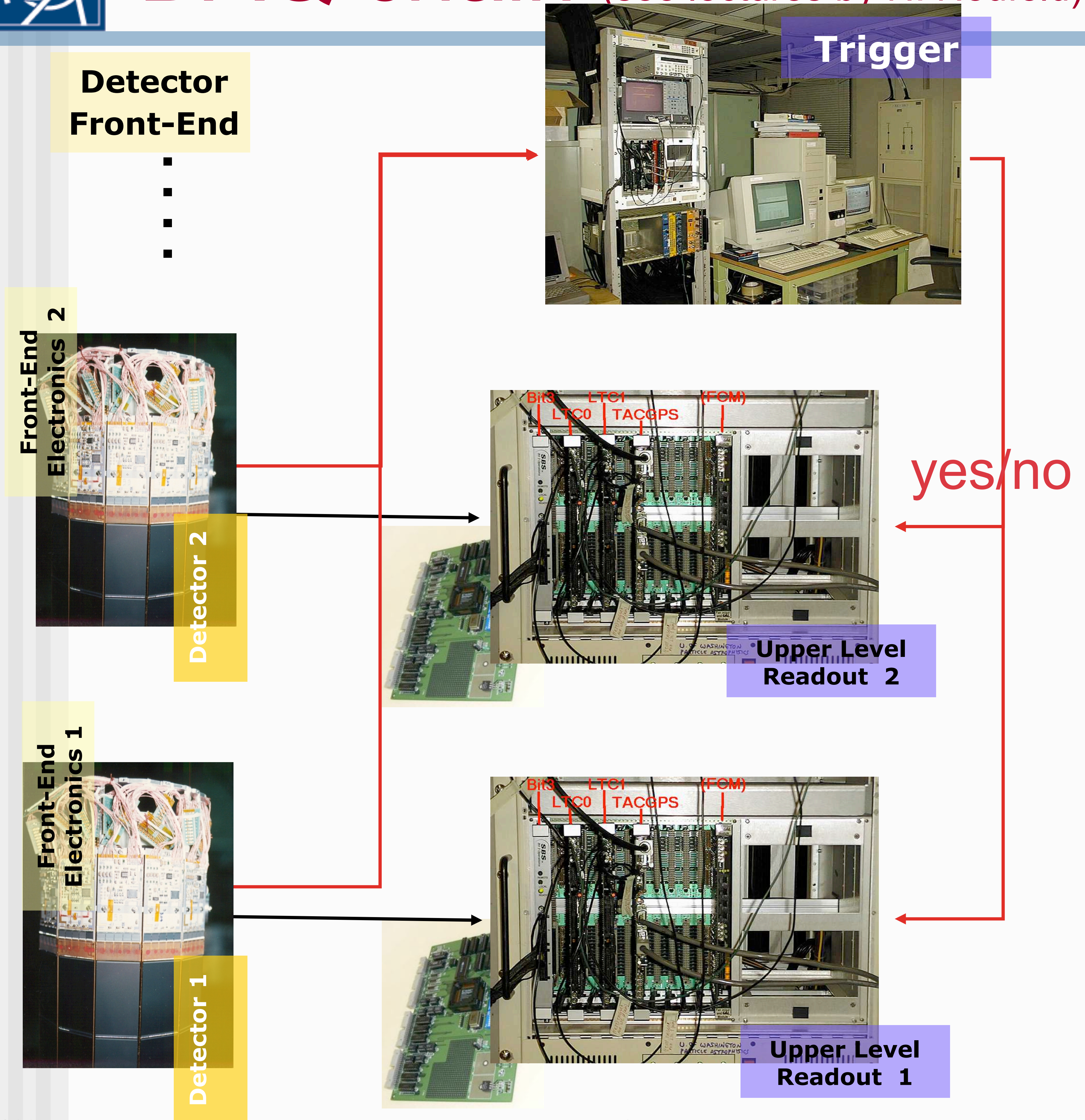
Upper Level Readout 2

Front-End Electronics 1

Detector 1

Upper Level Readout 1

DAQ chain (see lectures by N. Neufeld)



Trigger

Detector Front-End

Front-End Electronics 2

Detector 2

Front-End Electronics 1

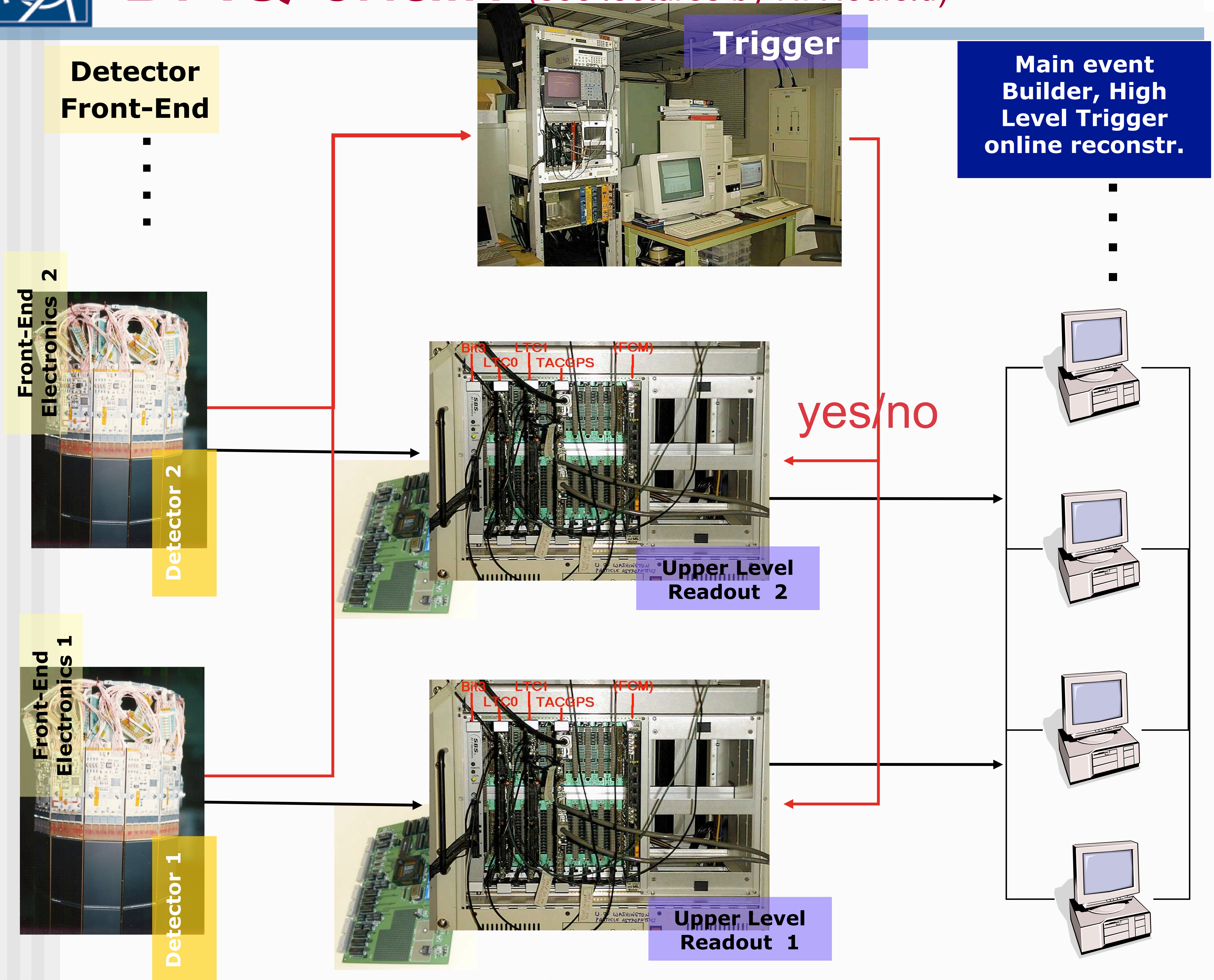
Detector 1

yes/no

Upper Level Readout 2

Upper Level Readout 1

DAQ chain (see lectures by N. Neufeld)



Trigger

Main event Builder, High Level Trigger online reconstr.

Detector Front-End

Front-End Electronics 2

Detector 2

Upper Level Readout 2

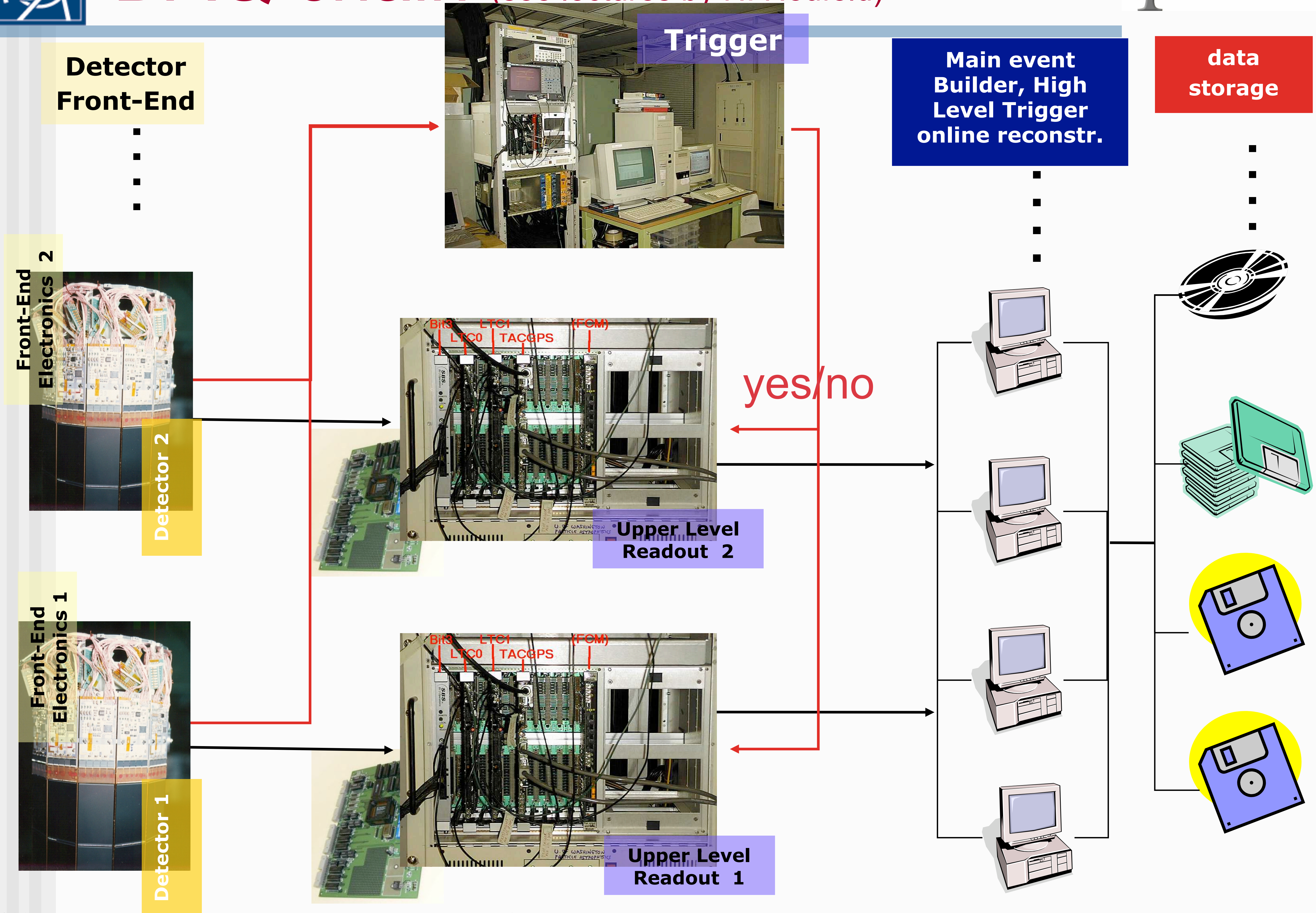
yes/no

Front-End Electronics 1

Detector 1

Upper Level Readout 1

DAQ chain (see lectures by N. Neufeld)



Detector Front-End

Trigger

Main event Builder, High Level Trigger online reconstr.

data storage

Front-End Electronics 2

Detector 2

yes/no

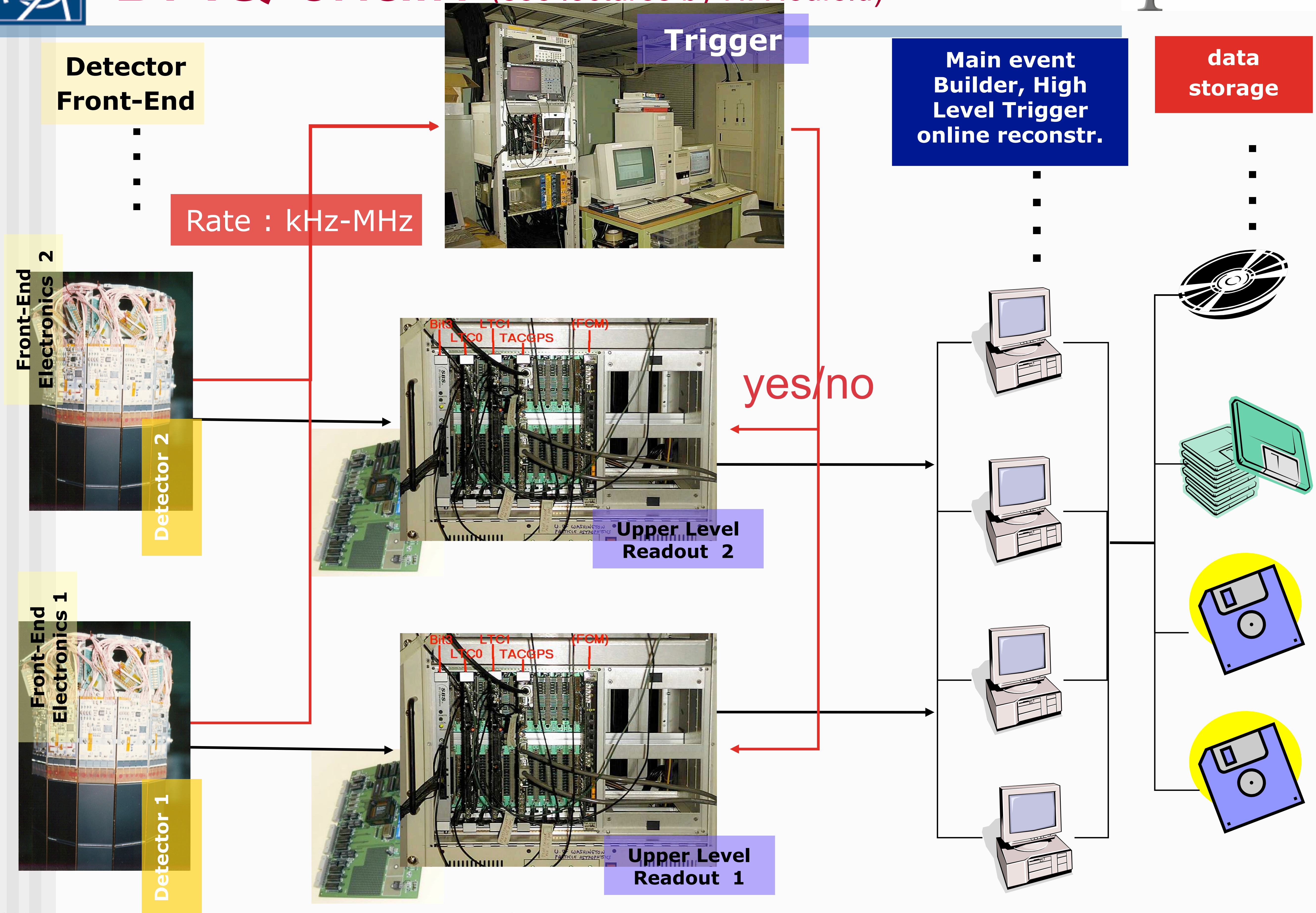
Upper Level Readout 2

Front-End Electronics 1

Detector 1

Upper Level Readout 1

DAQ chain (see lectures by N. Neufeld)



Detector Front-End

Rate : kHz-MHz

Trigger

Main event Builder, High Level Trigger online reconstr.

data storage

Front-End Electronics 2

Detector 2

yes/no

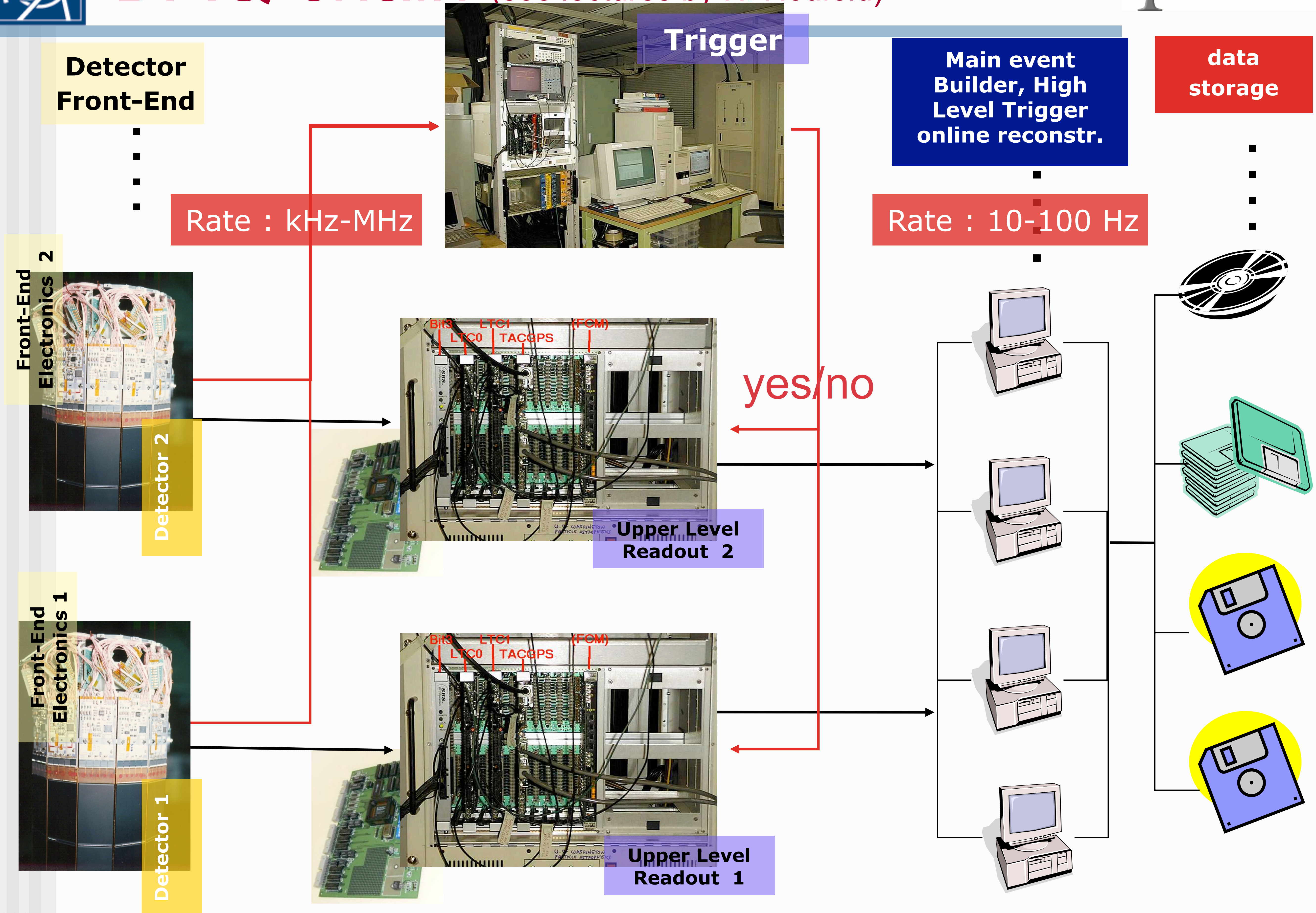
Upper Level Readout 2

Front-End Electronics 1

Detector 1

Upper Level Readout 1

DAQ chain (see lectures by N. Neufeld)



Detector Front-End

Trigger

Main event Builder, High Level Trigger online reconstr.

data storage

Rate : kHz-MHz

Rate : 10-100 Hz

yes/no

Front-End Electronics 2

Detector 2

Upper Level Readout 2

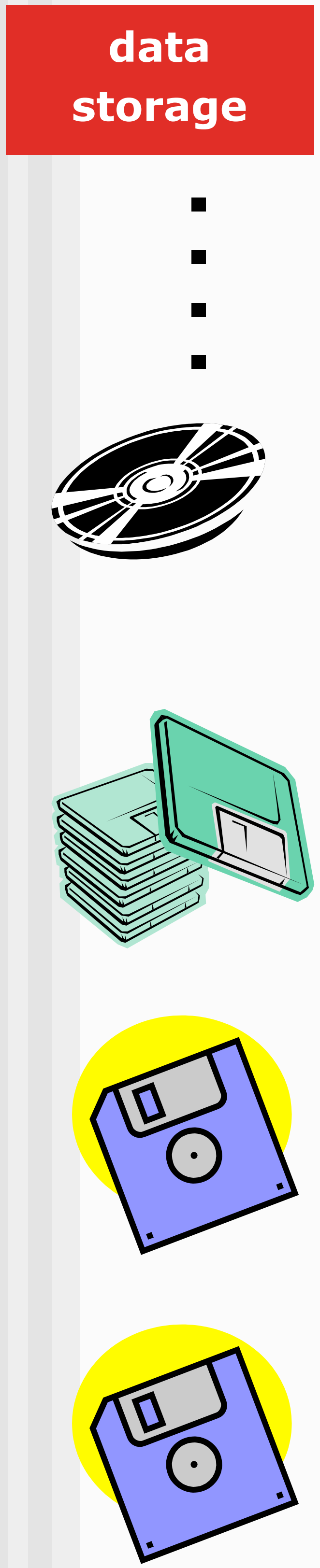
Front-End Electronics 1

Detector 1

Upper Level Readout 1

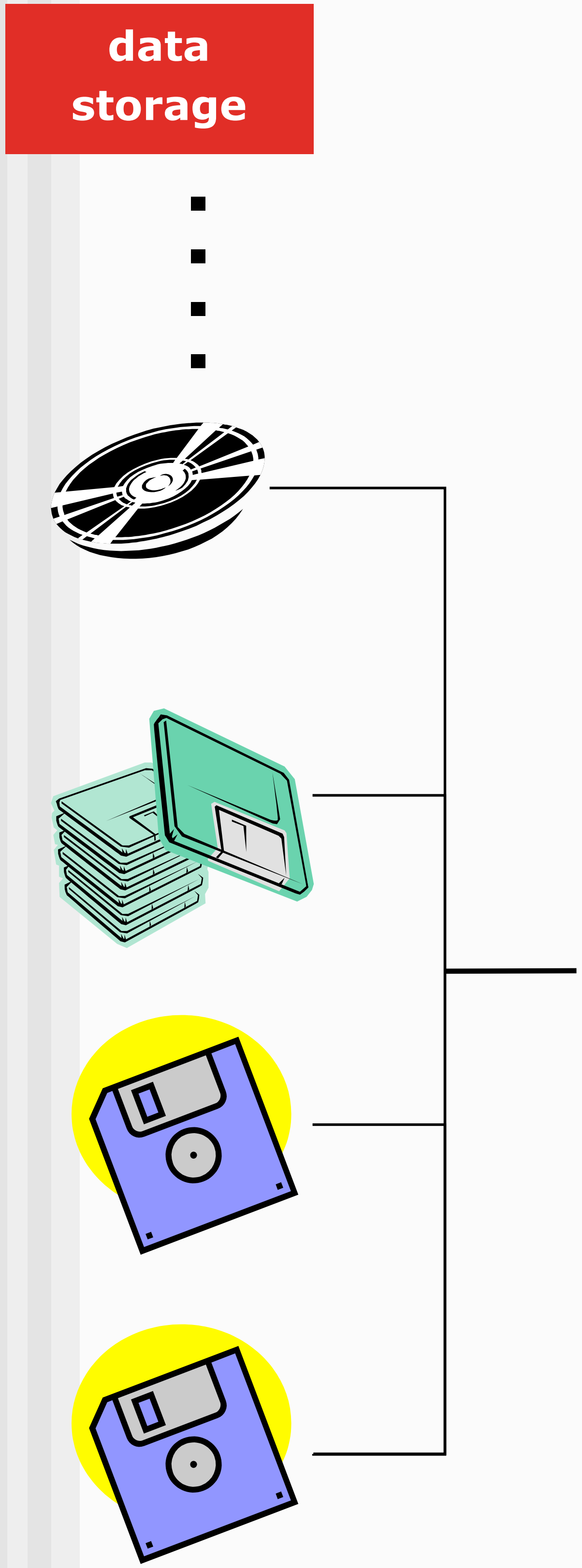
Offline Analysis Chain

Offline Analysis Chain



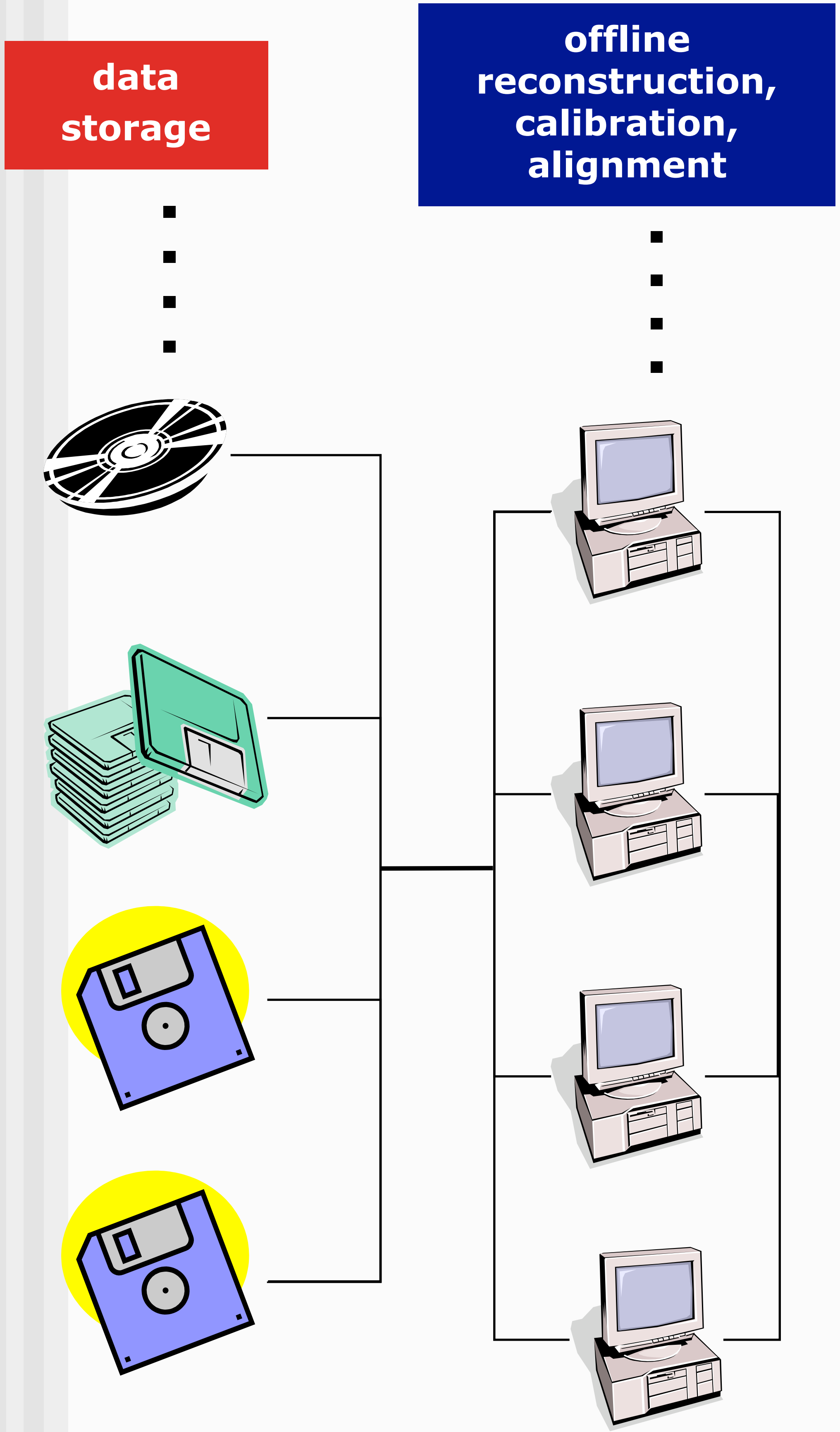
data storage

Offline Analysis Chain



data storage

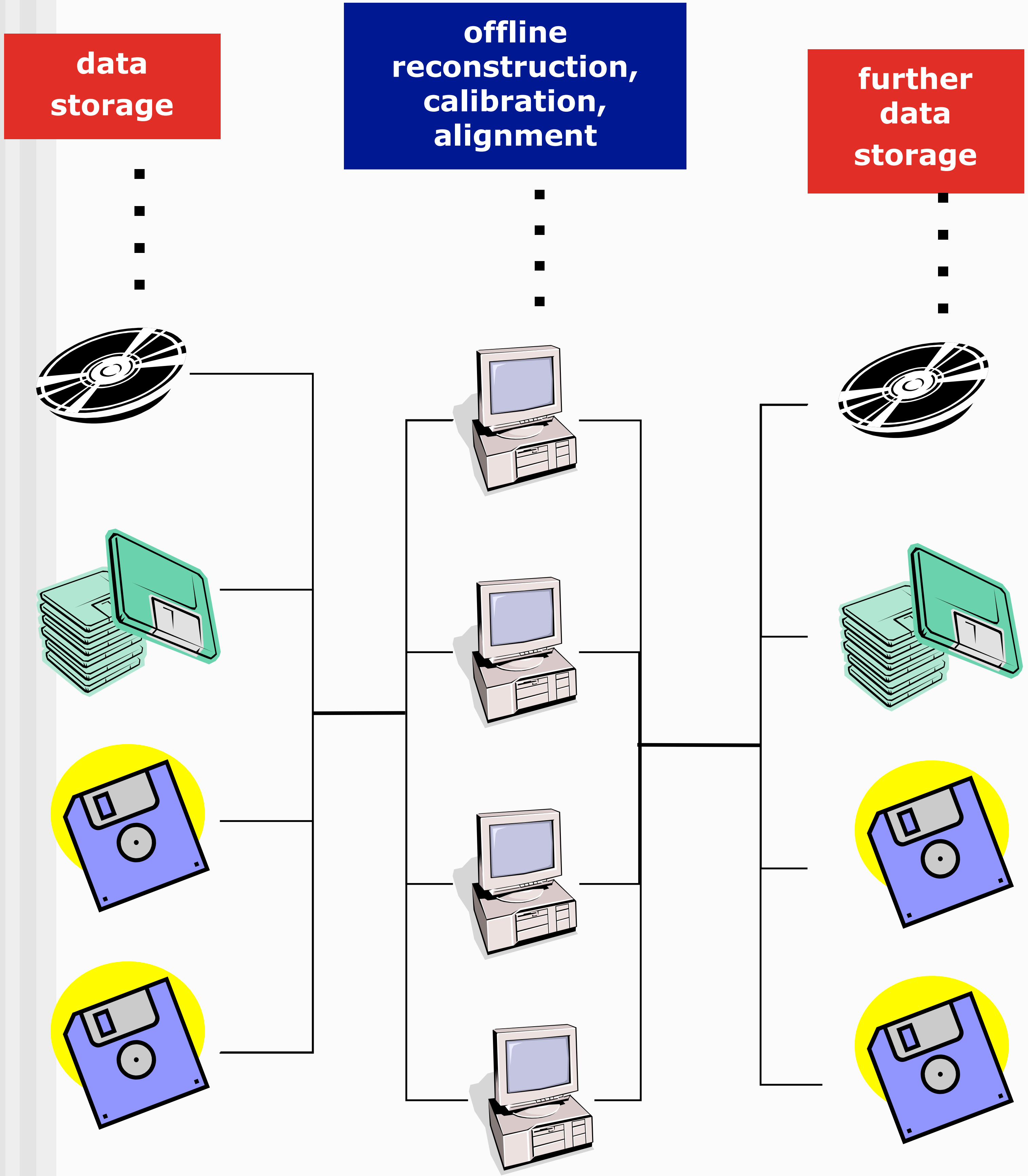
Offline Analysis Chain



data storage

offline reconstruction, calibration, alignment

Offline Analysis Chain

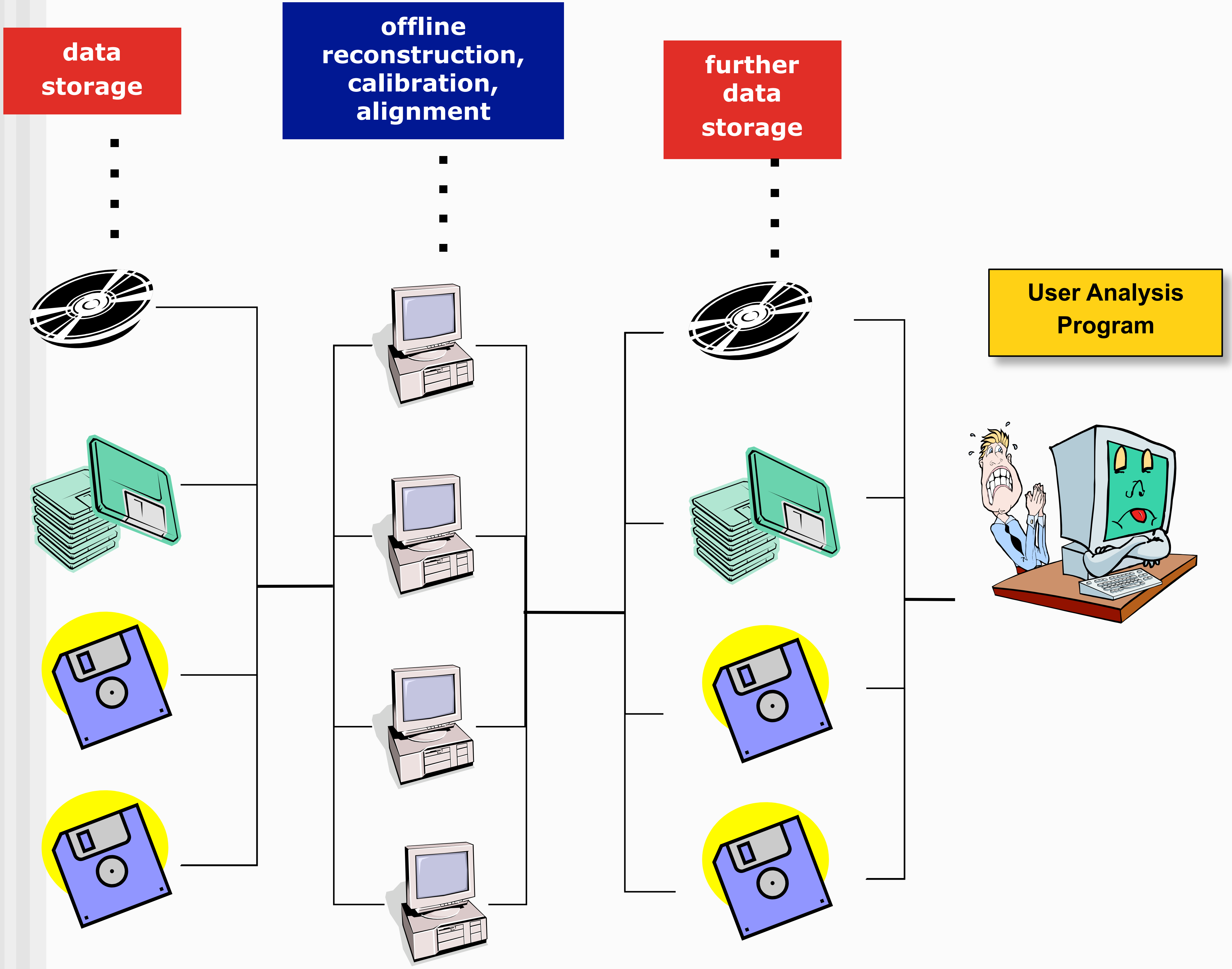


data storage

offline reconstruction, calibration, alignment

further data storage

Offline Analysis Chain



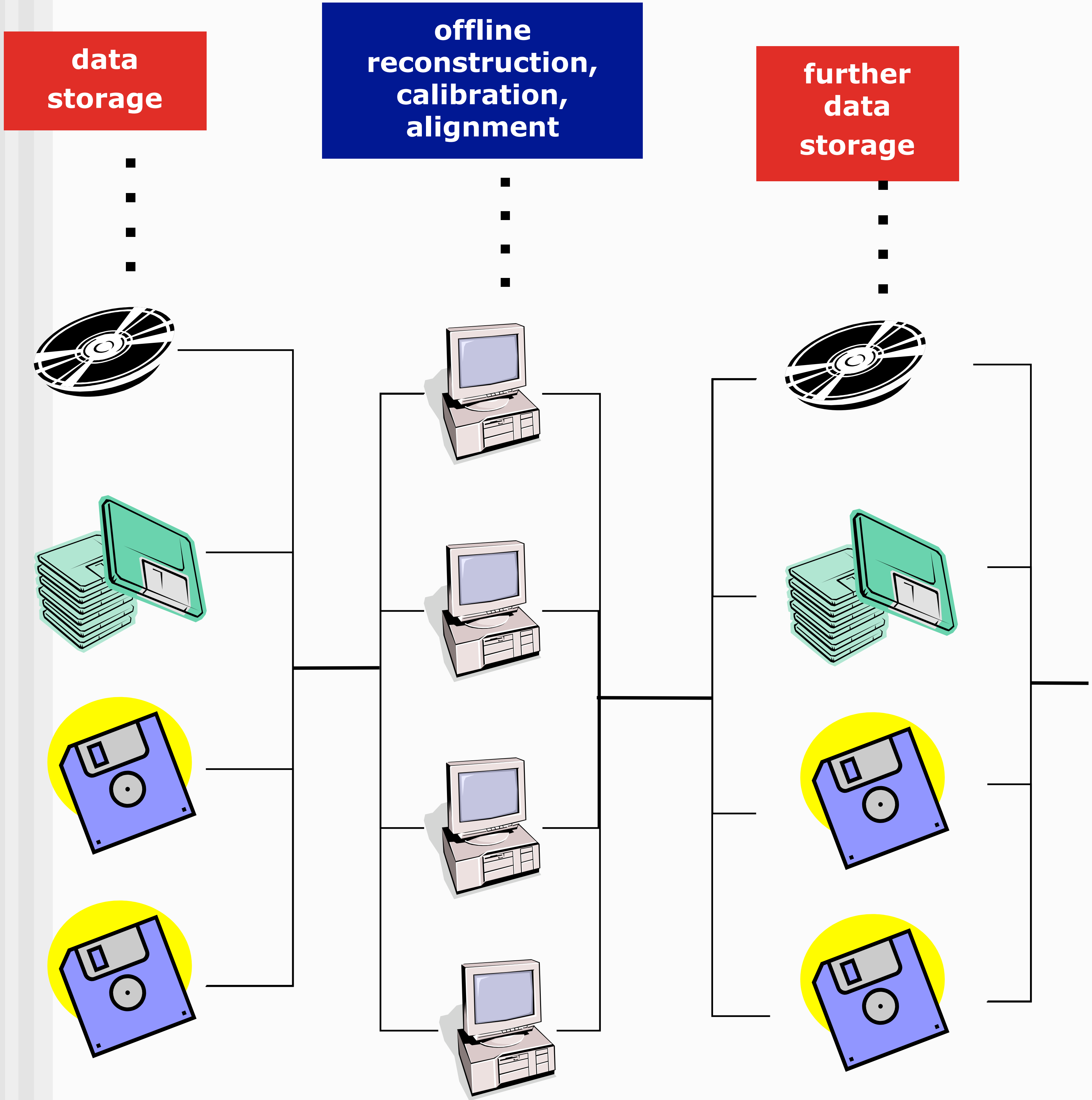
data storage

offline reconstruction, calibration, alignment

further data storage

User Analysis Program

Offline Analysis Chain

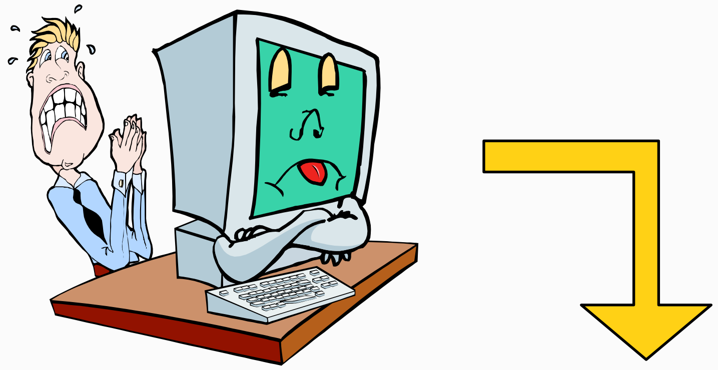


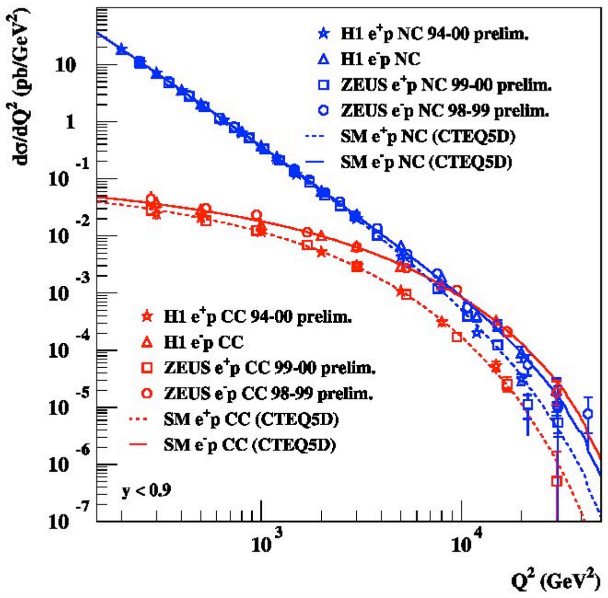
data storage

offline reconstruction, calibration, alignment

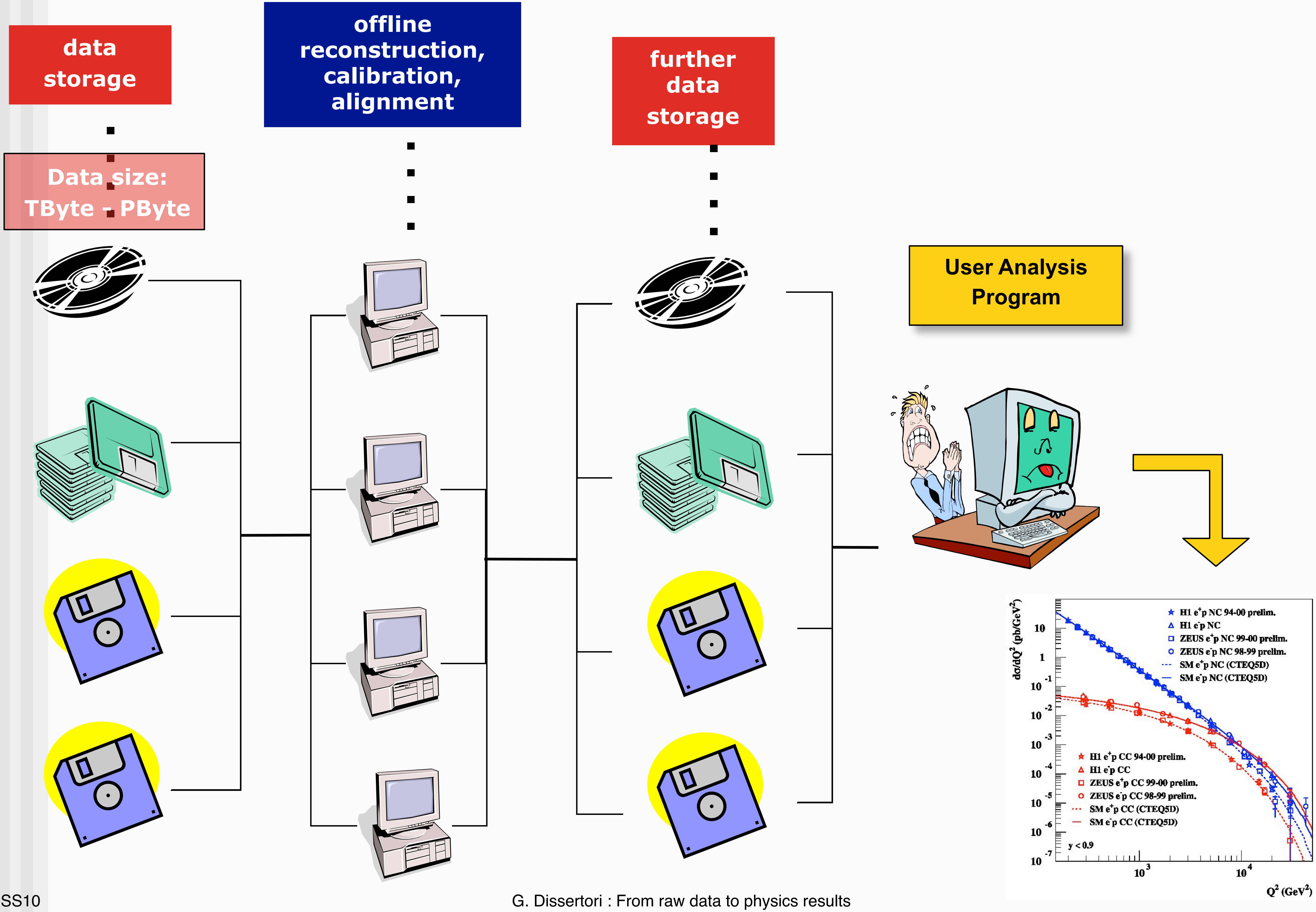
further data storage

User Analysis Program





Offline Analysis Chain



data storage

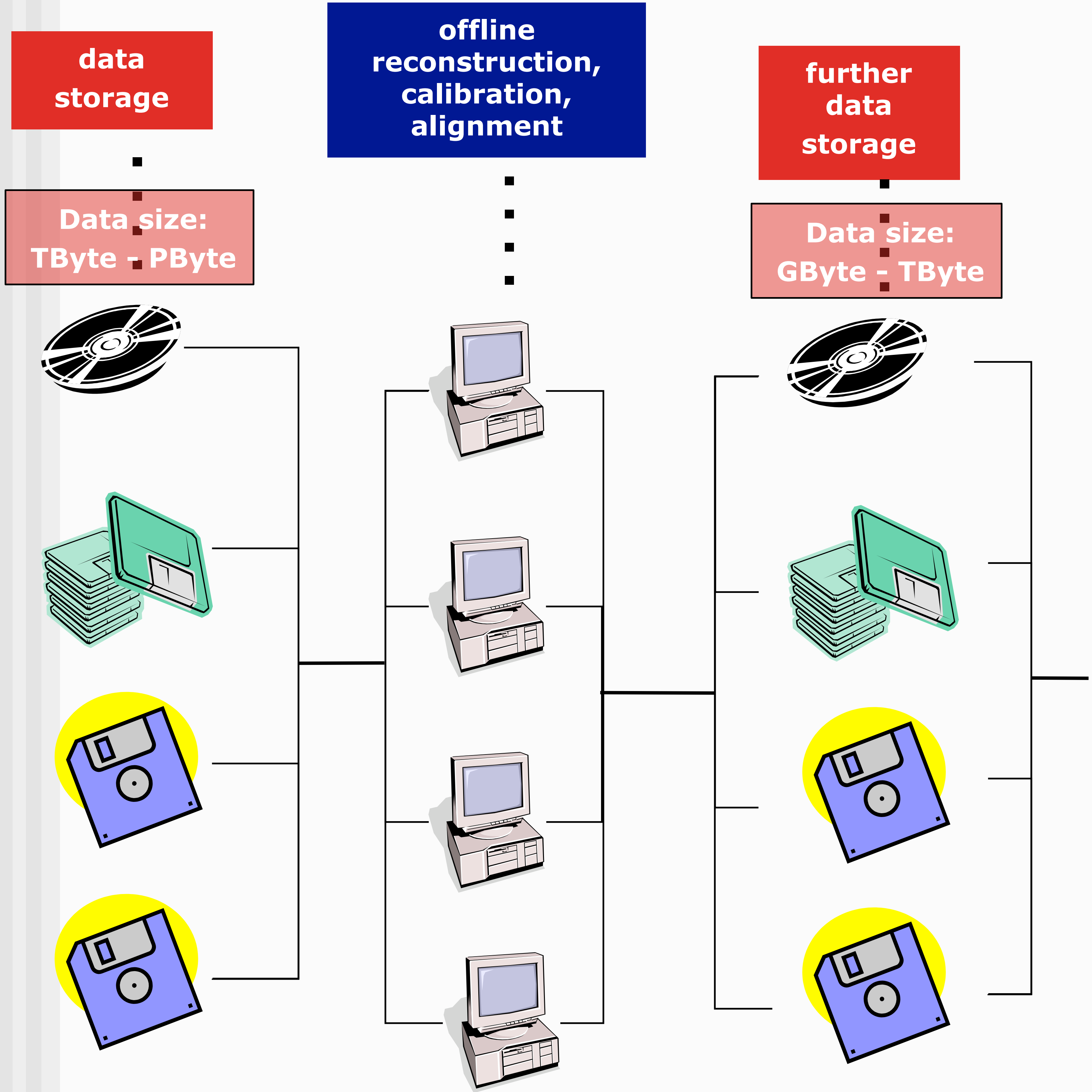
Data size: TByte - PByte

offline reconstruction, calibration, alignment

further data storage

User Analysis Program

Offline Analysis Chain



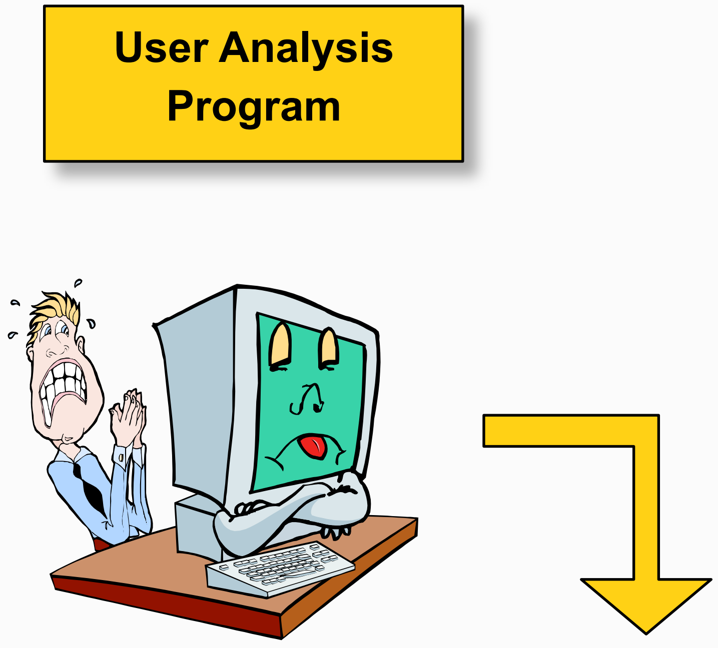
data storage

Data size: TByte - PByte

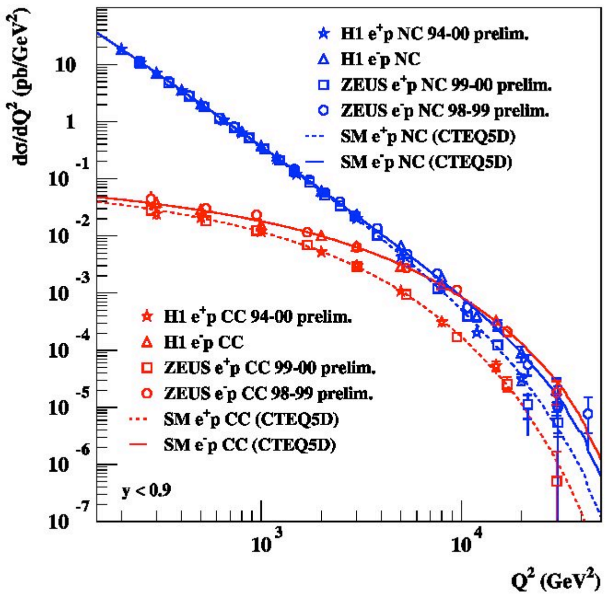
offline reconstruction, calibration, alignment

further data storage

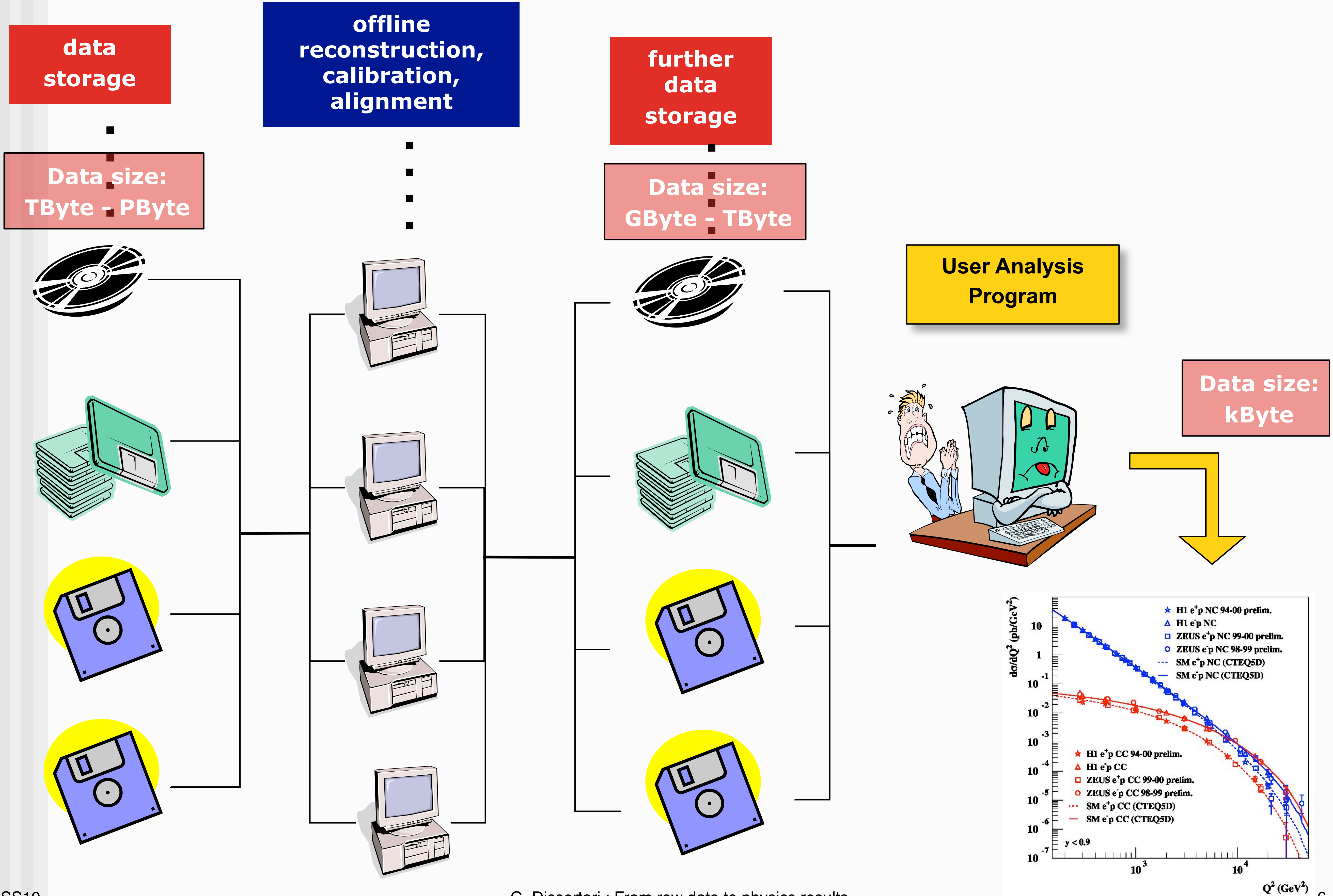
Data size: GByte - TByte



User Analysis Program



Offline Analysis Chain



data storage

Data size: TByte - PByte

offline reconstruction, calibration, alignment

further data storage

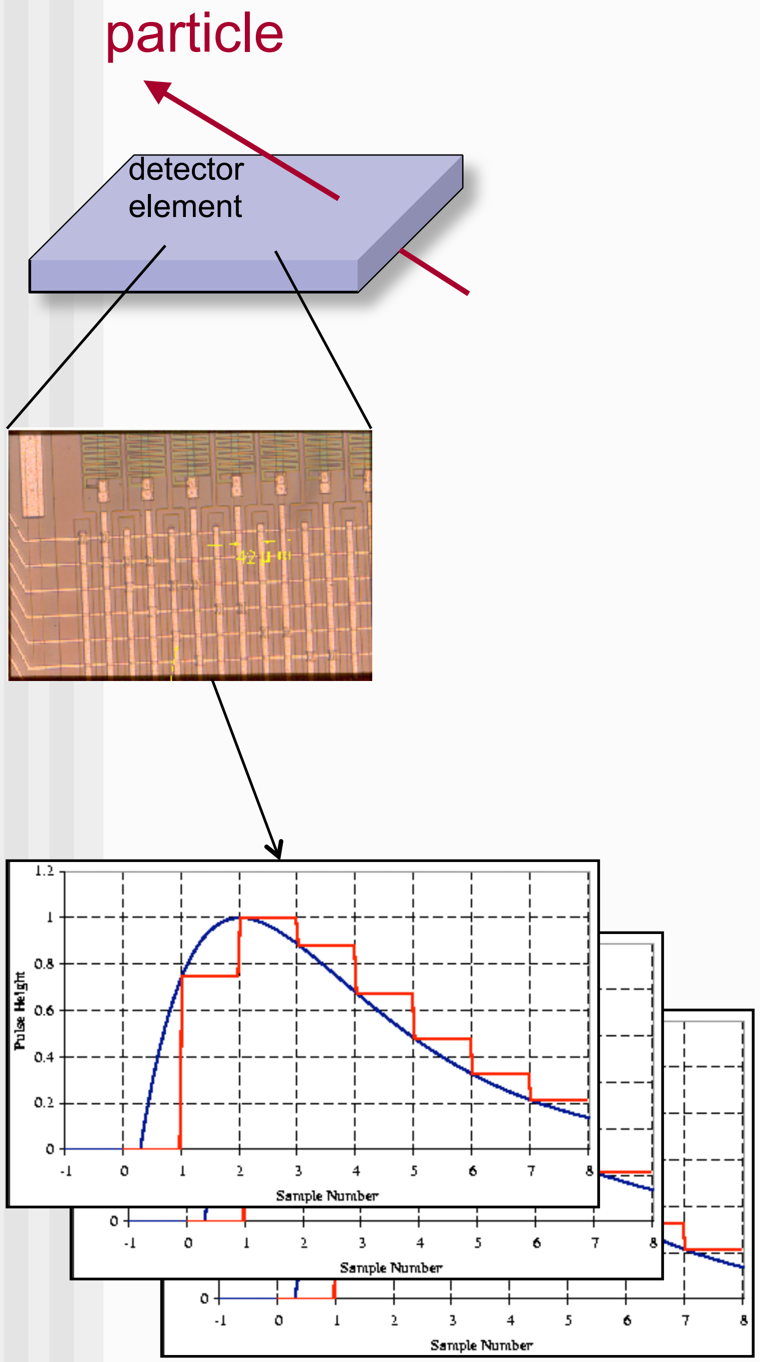
Data size: GByte - TByte

User Analysis Program

Data size: kByte

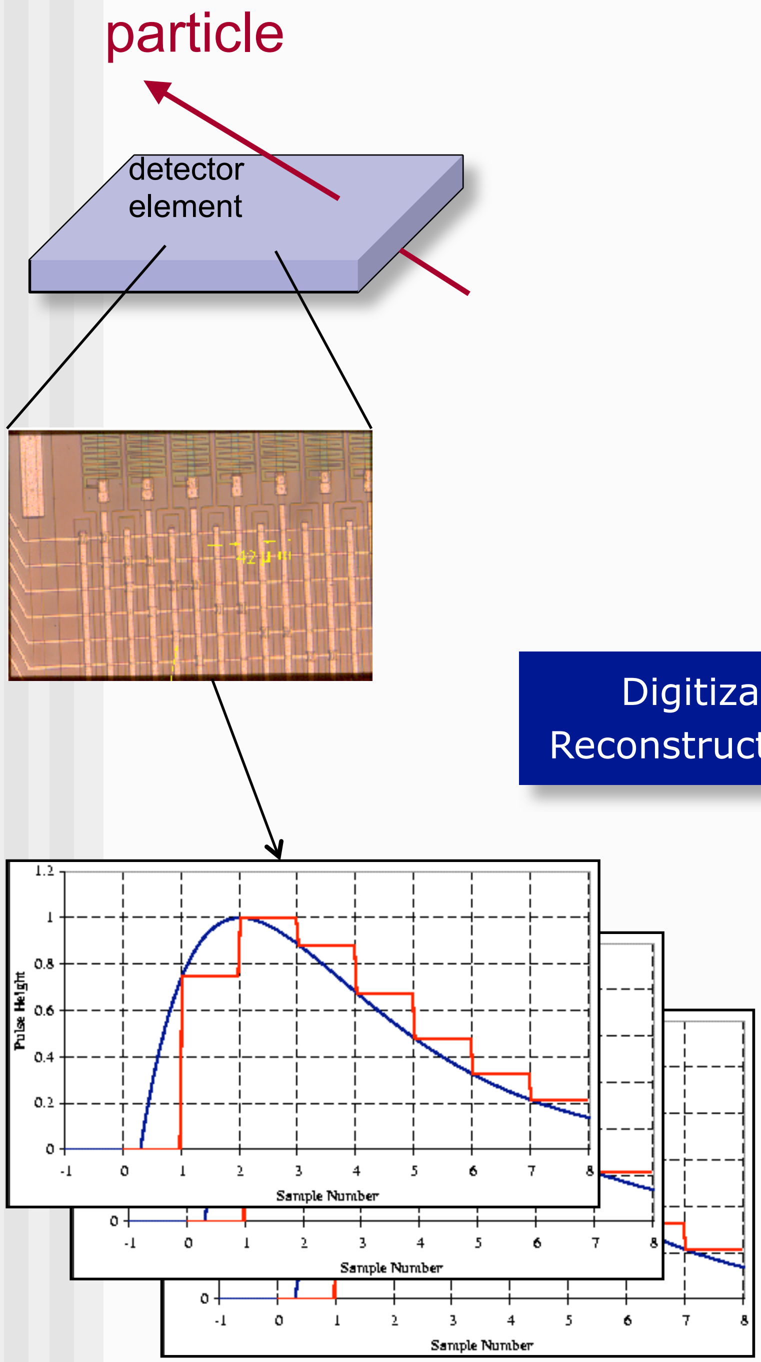
Data reduction/abstraction

Data reduction/abstraction



Analog signals

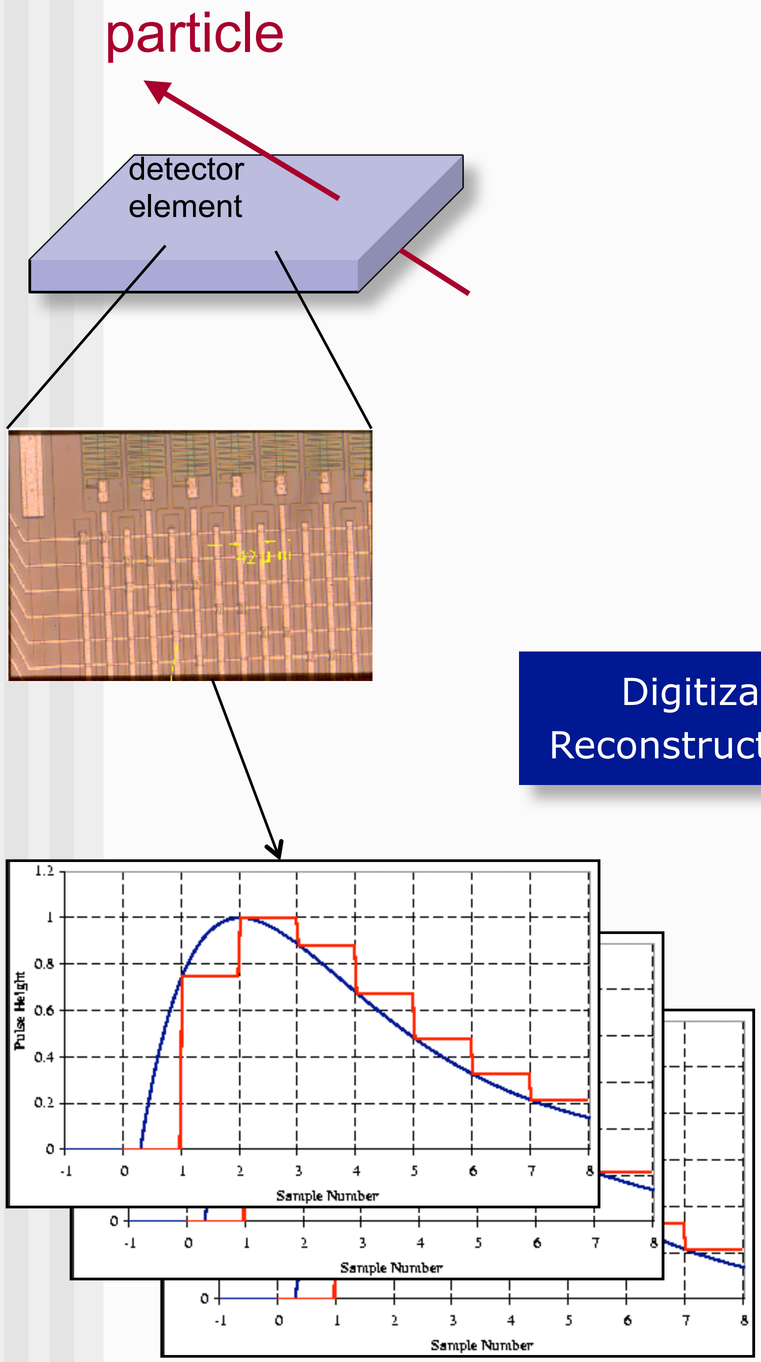
Data reduction/abstraction

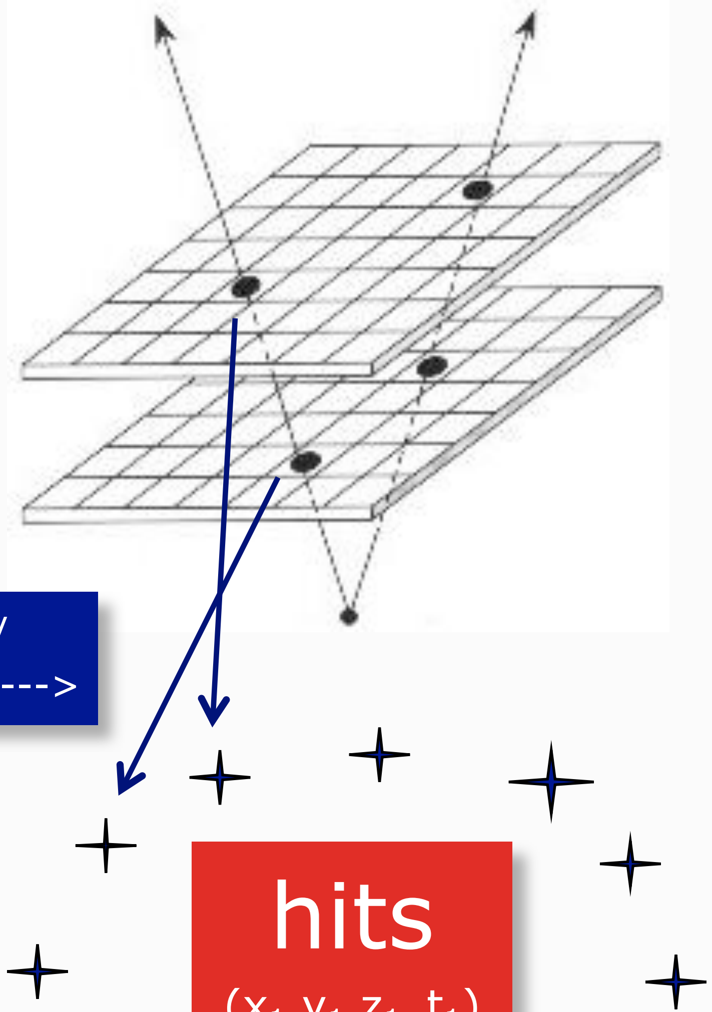


Digitization/
Reconstruction --->

Analog signals

Data reduction/abstraction





Digitization/
Reconstruction --->

hits

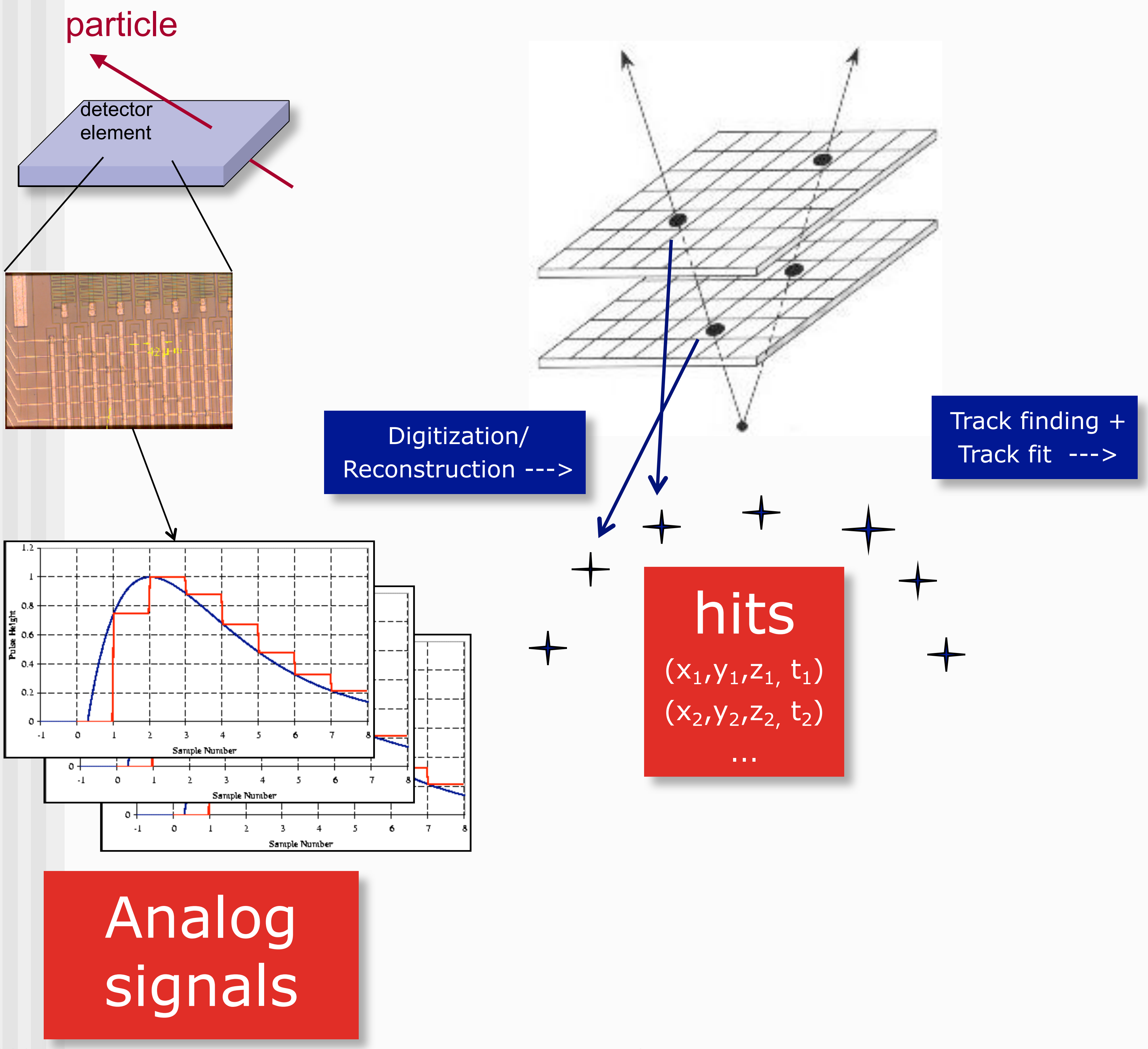
(x_1,y_1,z_1, t_1)

(x_2,y_2,z_2, t_2)

…

Analog signals

Data reduction/abstraction



Digitization/
Reconstruction --->

Track finding +
Track fit --->

hits

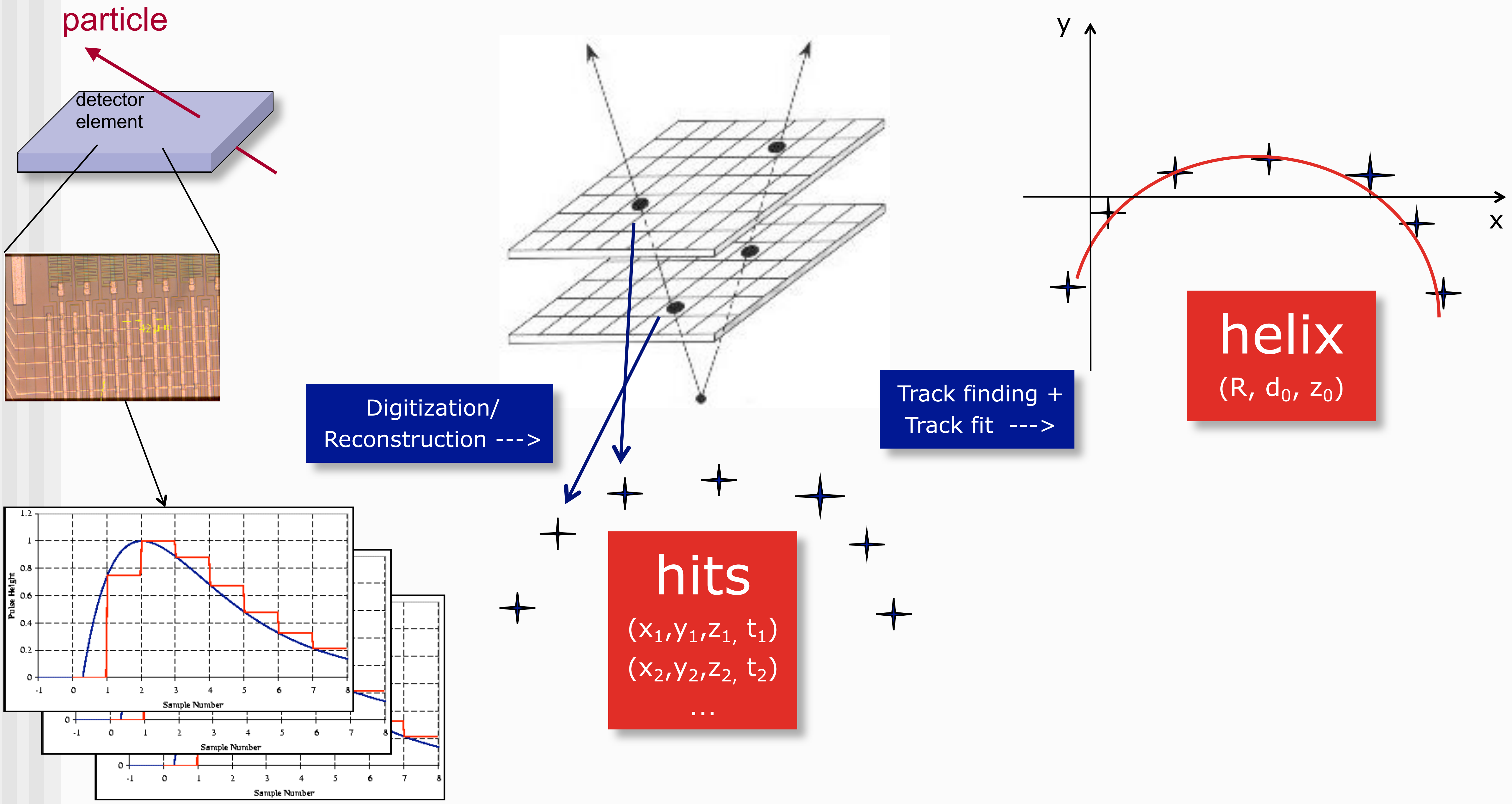
(x_1,y_1,z_1, t_1)

(x_2,y_2,z_2, t_2)

…

Analog signals

Data reduction/abstraction



particle

detector element

Digitization/ Reconstruction --->

Track finding + Track fit --->

hits

(x_1, y_1, z_1, t_1)

(x_2, y_2, z_2, t_2)

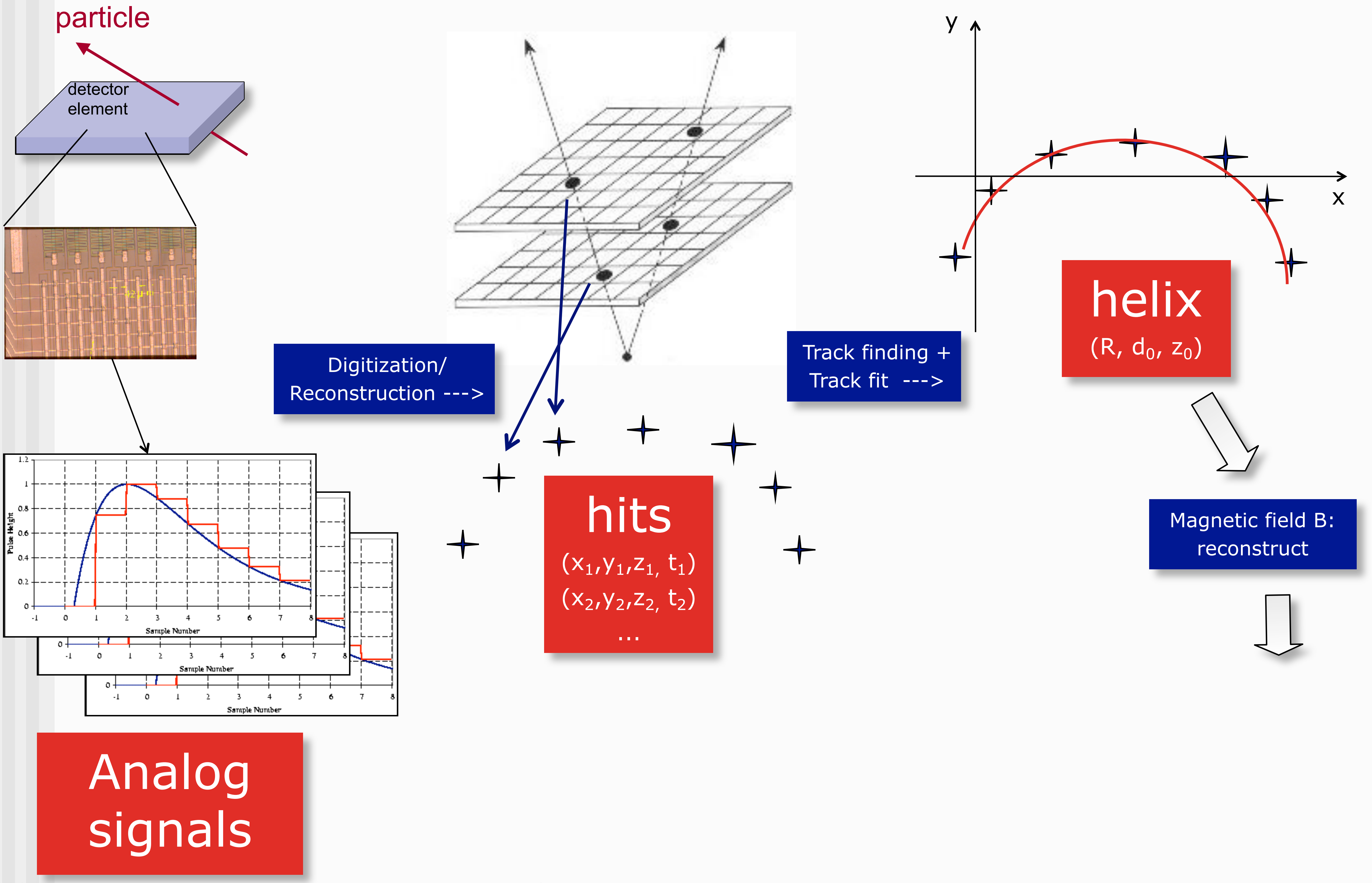
…

helix

(R, d_0, z_0)

Analog signals

Data reduction/abstraction



Digitization/
Reconstruction --->

Track finding +
Track fit --->

Analog signals

hits

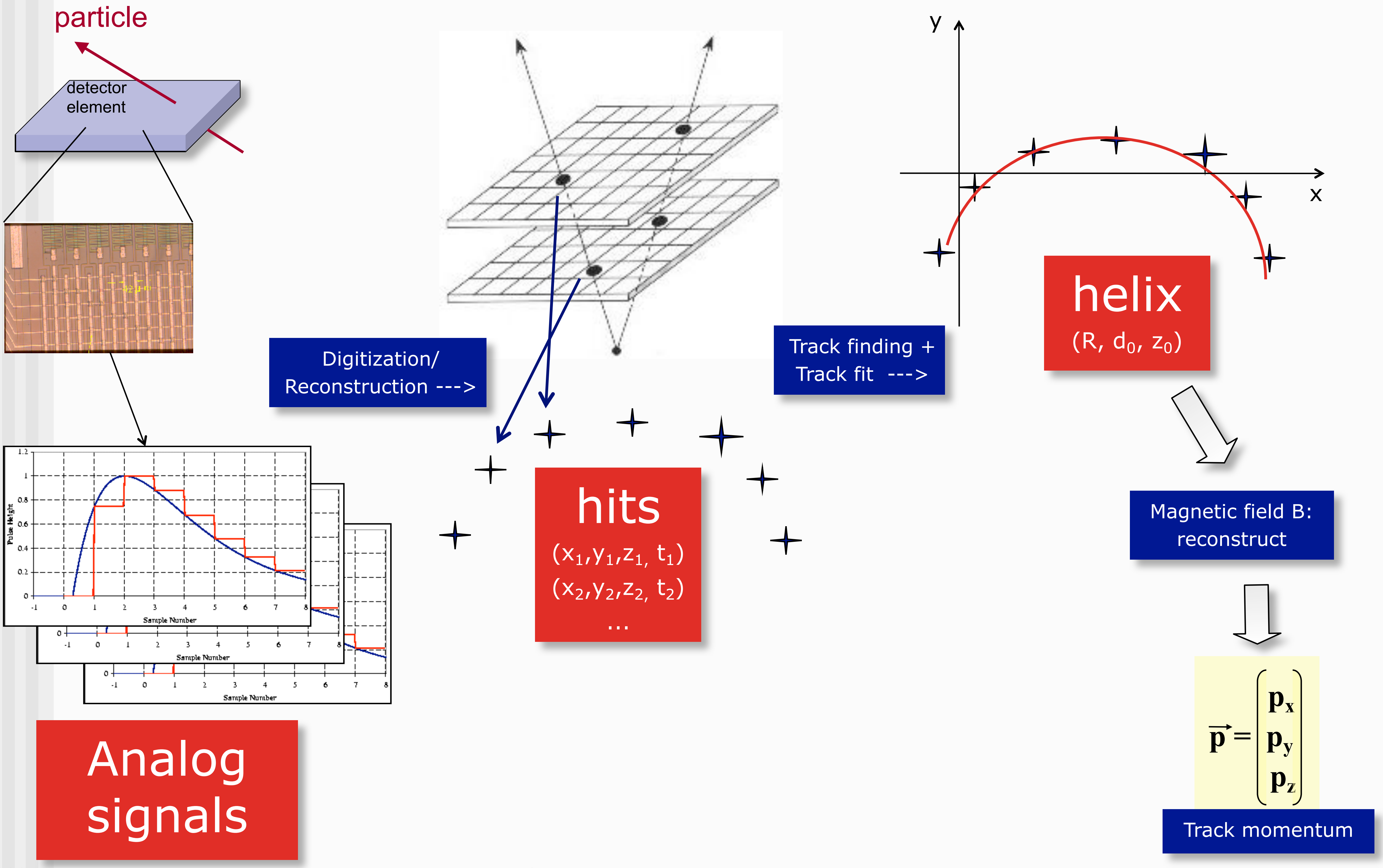
$(x_1,y_1,z_1,\ t_1)$
$(x_2,y_2,z_2,\ t_2)$
…

helix

$(R,\ d_0,\ z_0)$

Magnetic field B:
reconstruct

Data reduction/abstraction



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

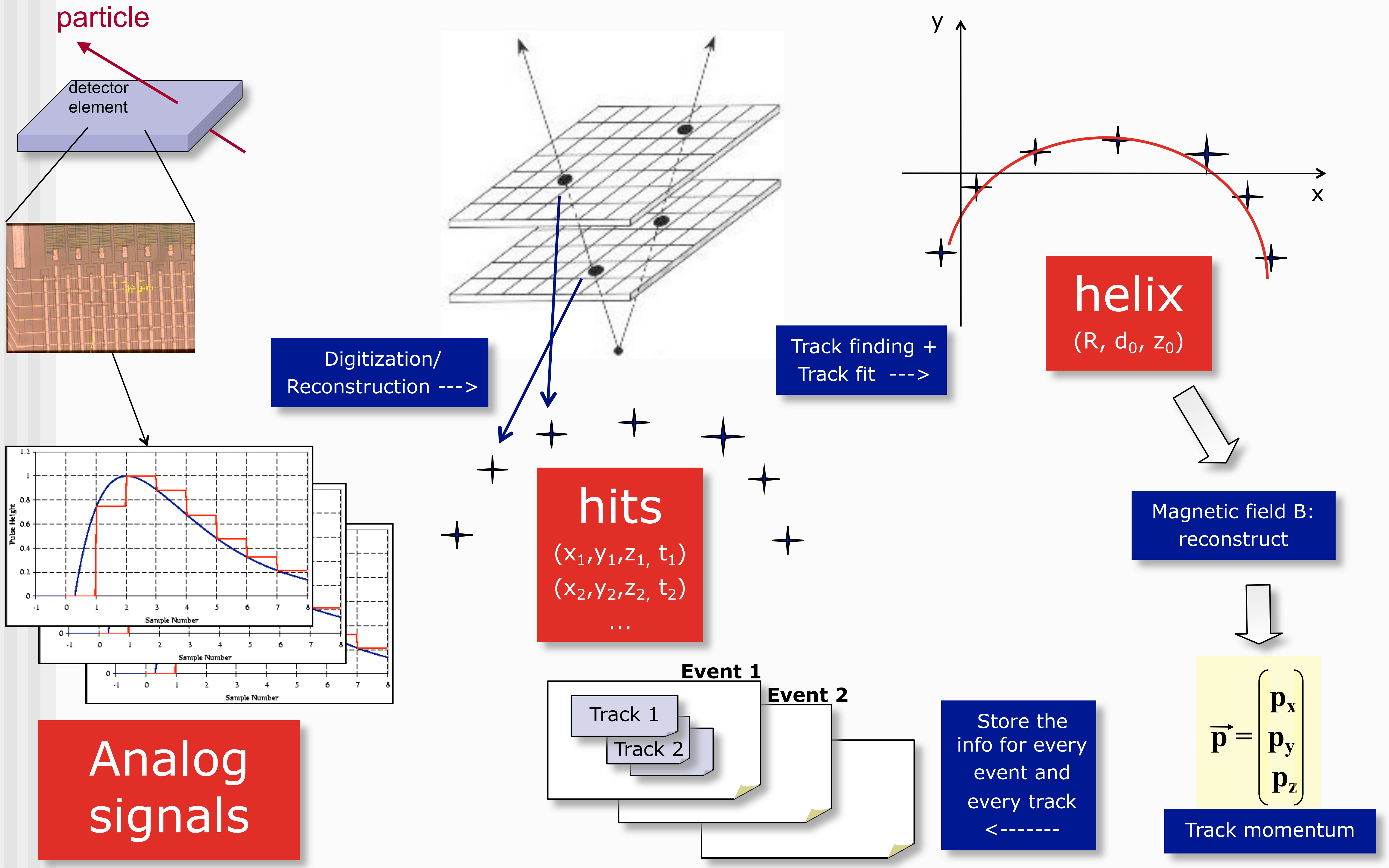
(R, d_0, z_0)

Magnetic field B: reconstruct

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

Track momentum

Data reduction/abstraction



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 <-------

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

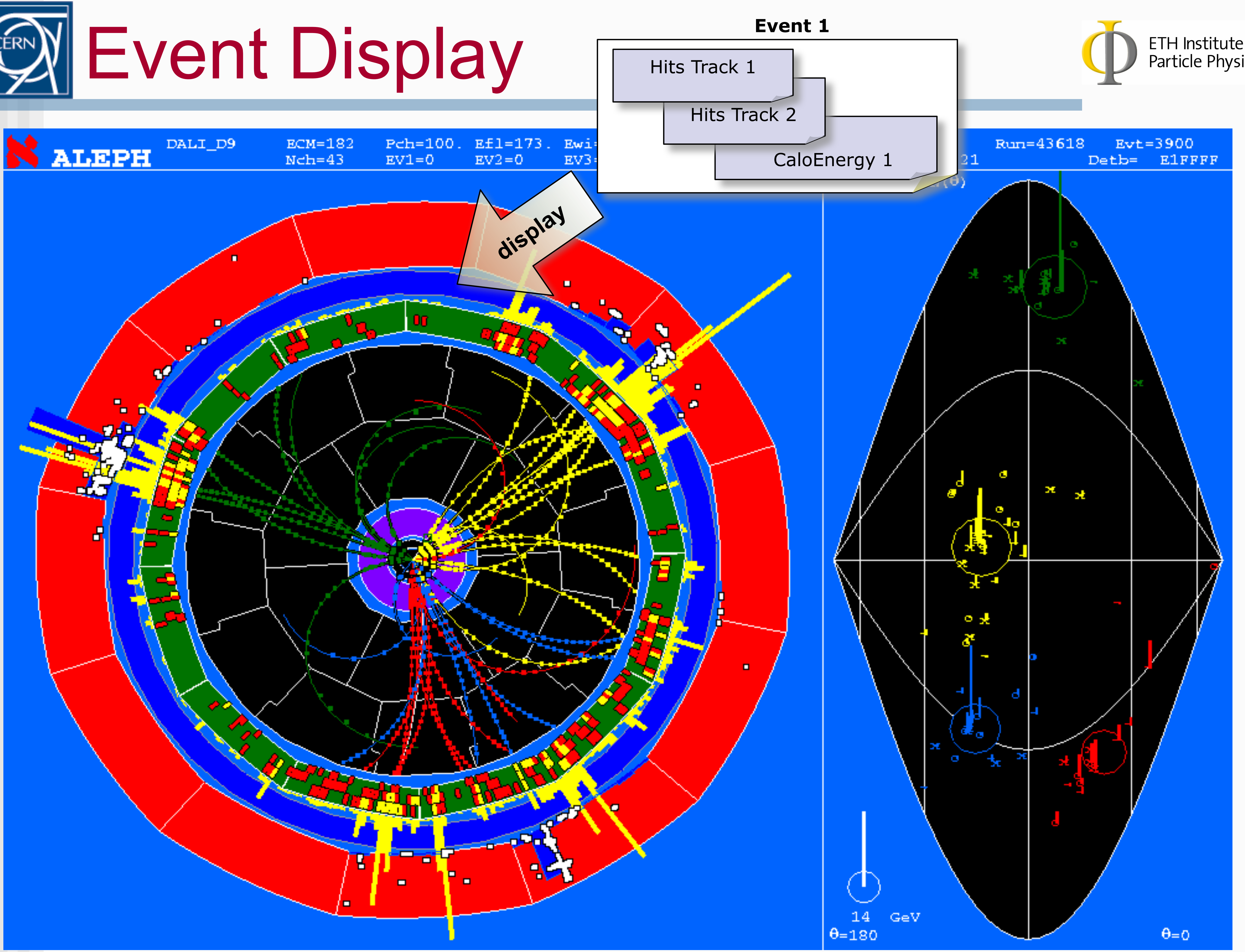
Qcha

(Charge of each track):

{-1,1,-1}

File A

Event Display



Event 1

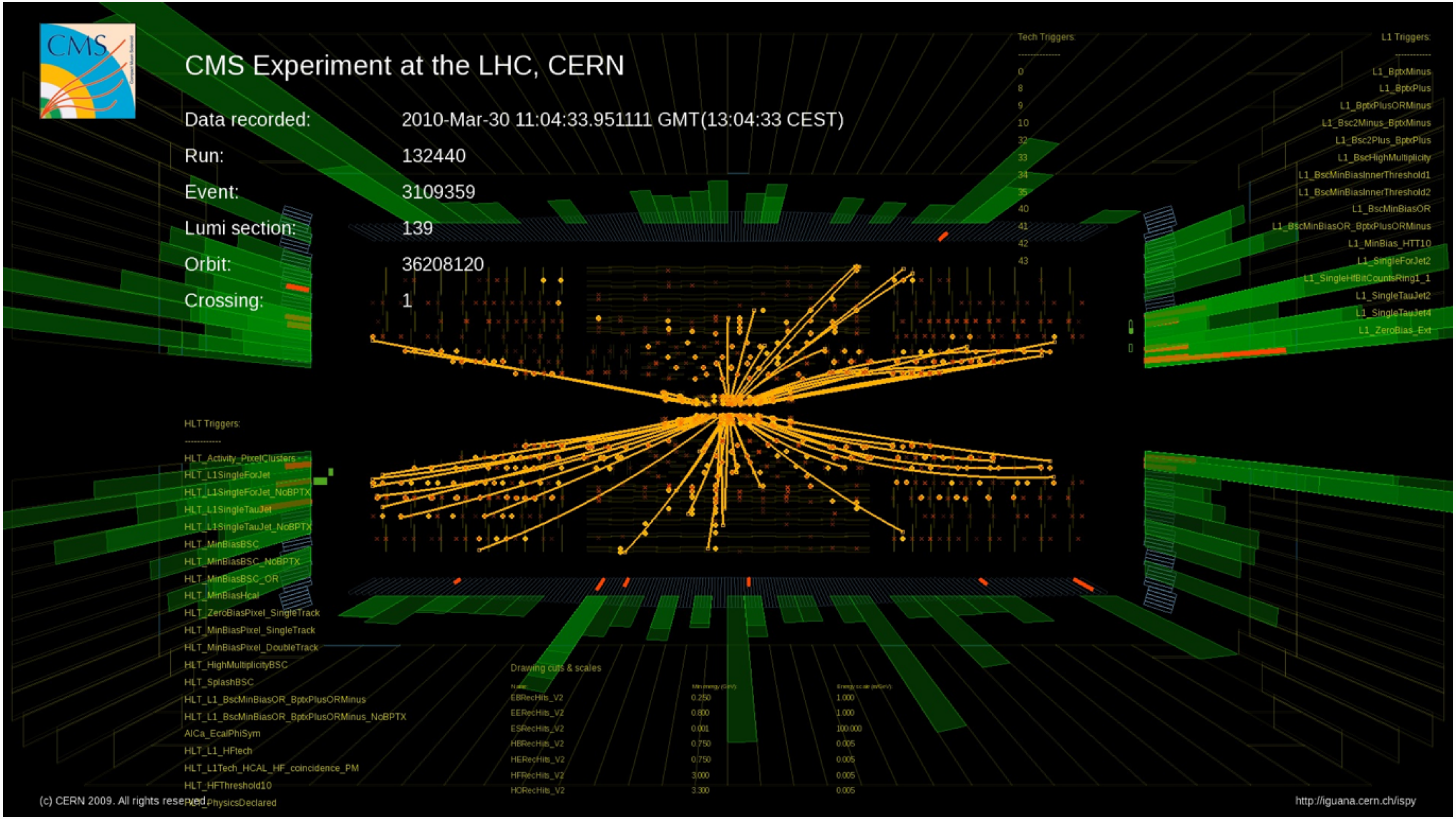
Hits Track 1

Hits Track 2

CaloEnergy 1

display

Event Display



CMS Experiment at the LHC, CERN

Data recorded:	2010-Mar-30 11:04:33.951111 GMT(13:04:33 CEST)
Run:	132440
Event:	3109359
Lumi section:	139
Orbit:	36208120
Crossing:	1

Tech Triggers:

0
8
9
10
32
33
34
35
40
41
42
43

L1 Triggers:

L1_BptxMinus
L1_BptxPlus
L1_BptxPlusORMinus
L1_Bsc2Minus_BptxMinus
L1_Bsc2Plus_BptxPlus
L1_BscHighMultiplicity
L1_BscMinBiasInnerThreshold1
L1_BscMinBiasInnerThreshold2
L1_BscMinBiasOR
L1_BscMinBiasOR_BptxPlusORMinus
L1_MinBias_HTT10
L1_SingleForJet2
L1_SingleHfBitCountsRing1_1
L1_SingleTauJet2
L1_SingleTauJet4
L1_ZeroBias_Ext

HLT Triggers:

HLT_Activity_PixelClusters
HLT_L1SingleForJet
HLT_L1SingleForJet_NoBPTX
HLT_L1SingleTauJet
HLT_L1SingleTauJet_NoBPTX
HLT_MinBiasBSC
HLT_MinBiasBSC_NoBPTX
HLT_MinBiasBSC_OR
HLT_MinBiasHcal
HLT_ZeroBiasPixel_SingleTrack
HLT_MinBiasPixel_SingleTrack
HLT_MinBiasPixel_DoubleTrack
HLT_HighMultiplicityBSC
HLT_SplashBSC
HLT_L1_BscMinBiasOR_BptxPlusORMinus
HLT_L1_BscMinBiasOR_BptxPlusORMinus_NoBPTX
AlCa_EcalPhiSym
HLT_L1_HFtech
HLT_L1Tech_HCAL_HF_coincidence_PM
HLT_HFThreshold10
HLT_PhysicsDeclared

Drawing cuts & scales

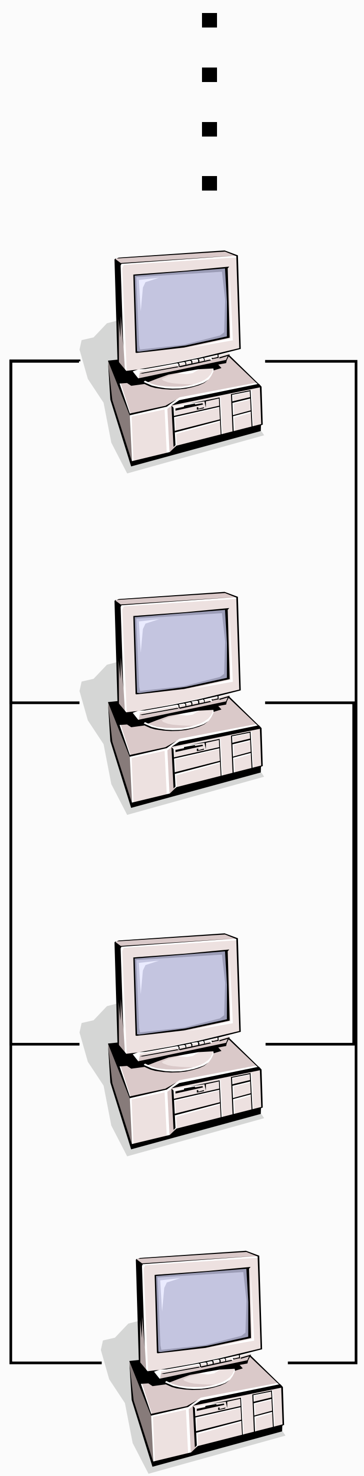
Name:	Min energy (GeV):	Energy scale (m/GeV):
EBRecHits_V2	0.250	1.000
EERecHits_V2	0.800	1.000
ESRecHits_V2	0.001	100.000
HBRecHits_V2	0.750	0.005
HERecHits_V2	0.750	0.005
HFRecHits_V2	3.000	0.005
HORecHits_V2	3.300	0.005

http://iguana.cern.ch/ispy

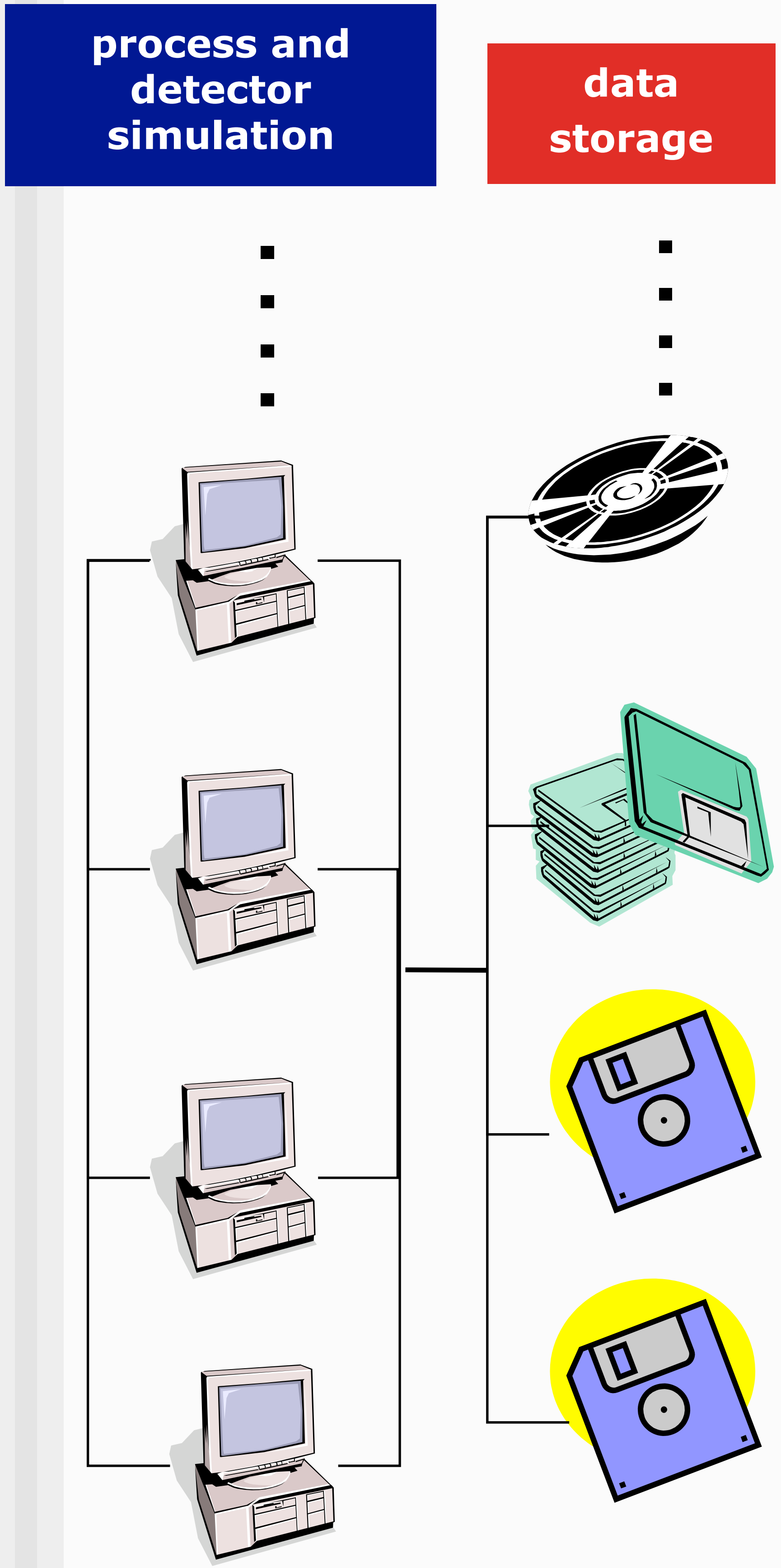
Simulation

Simulation

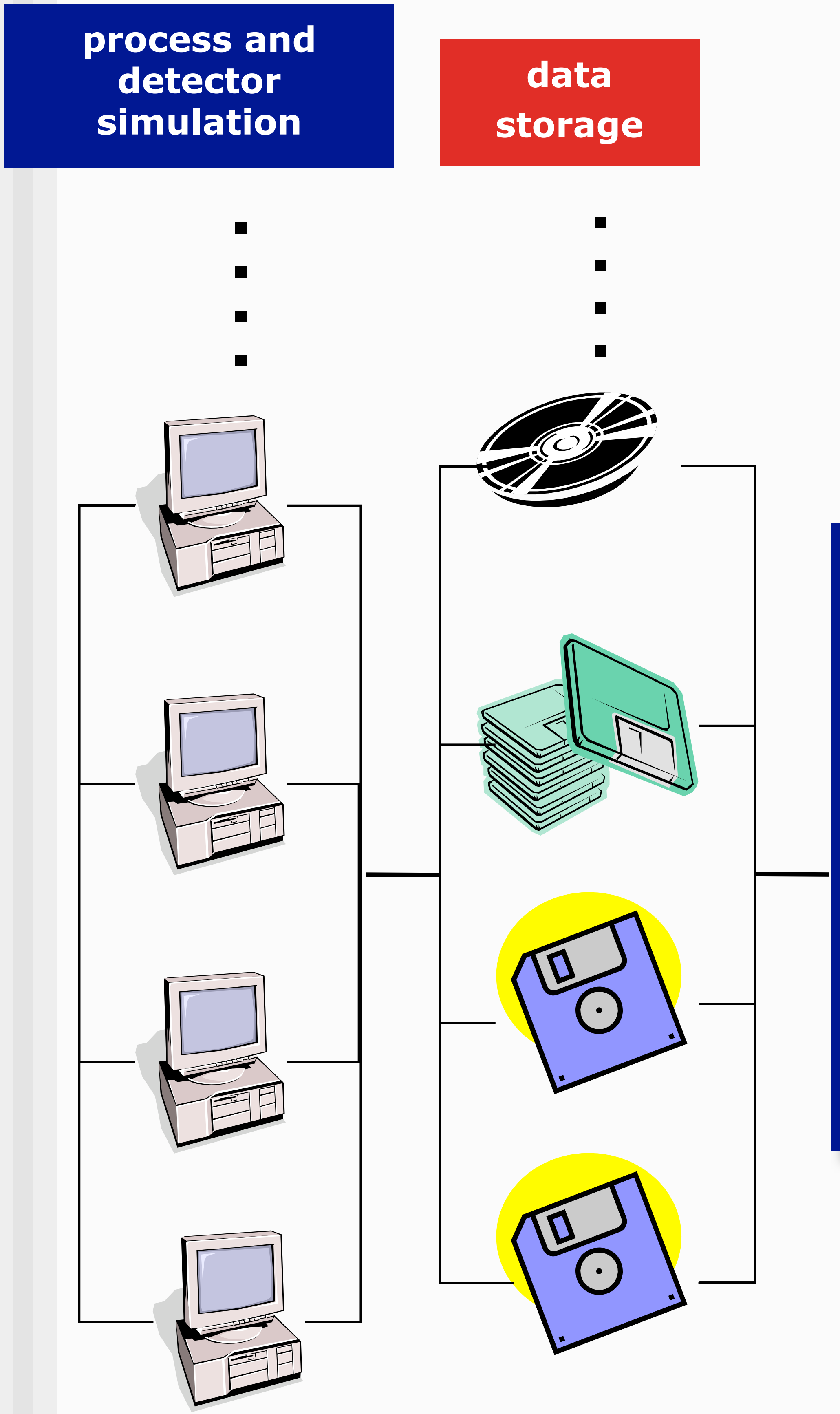
process and detector simulation



Simulation

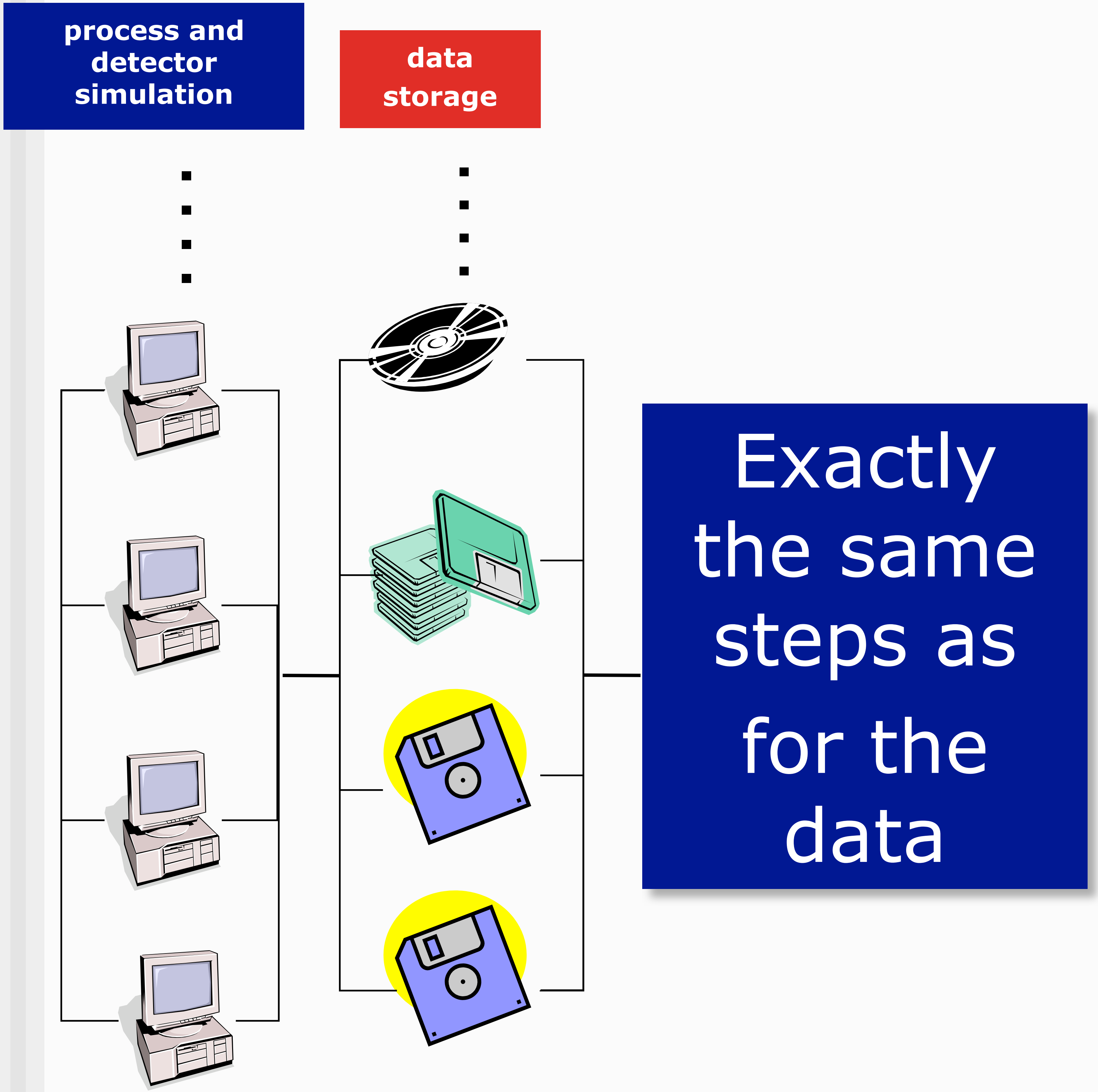


Simulation



Exactly the same steps as for the data

Simulation



Exactly the same steps as for the data

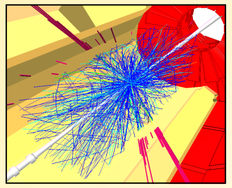
Simulation of many (millions) of events

- 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

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

Our Task

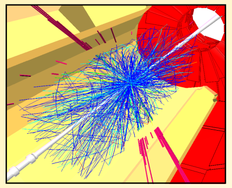
Reality



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

Our Task

Reality



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

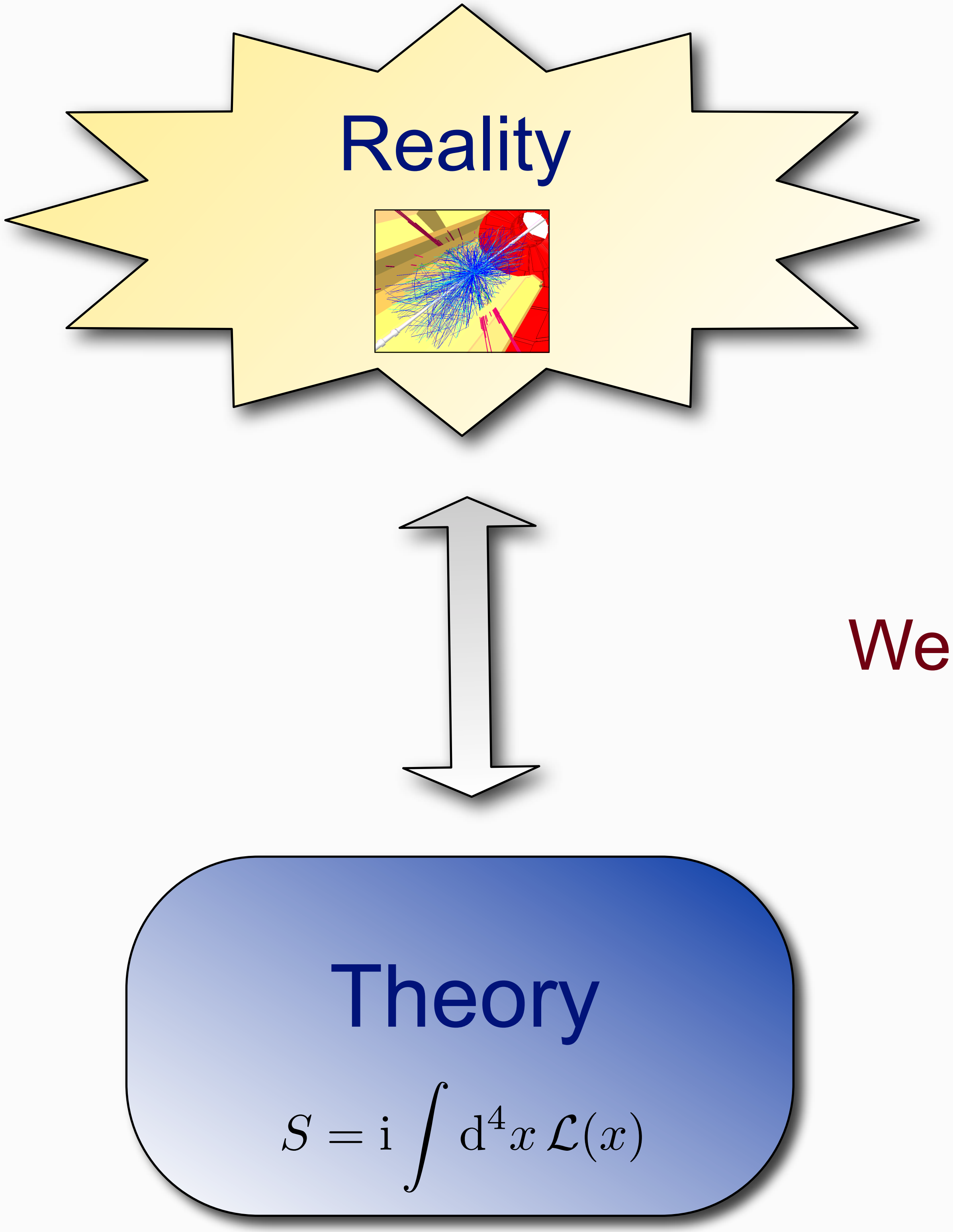
Theory

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

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

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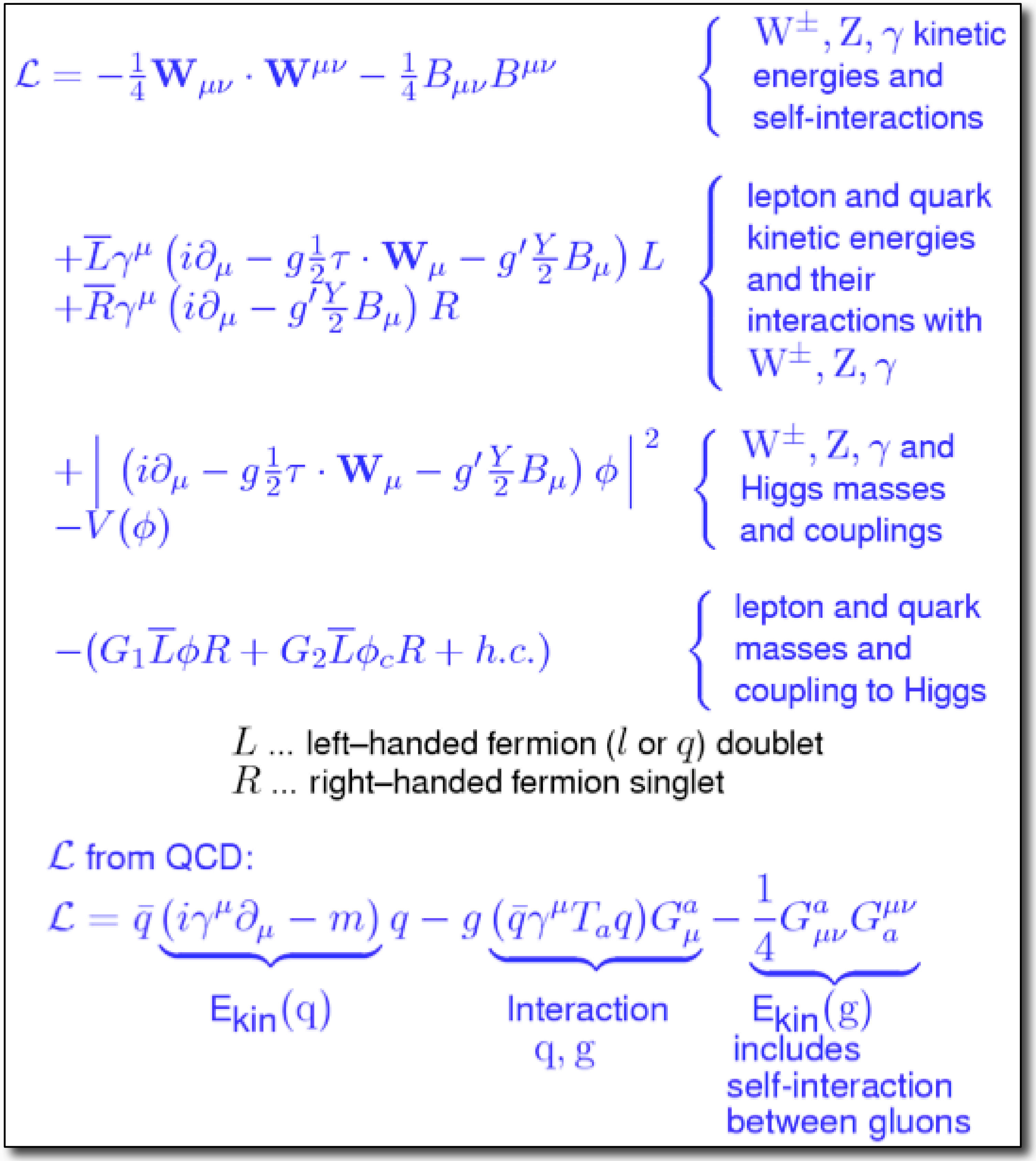
Theory...



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

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

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

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

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

lepton and quark masses and coupling to Higgs

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

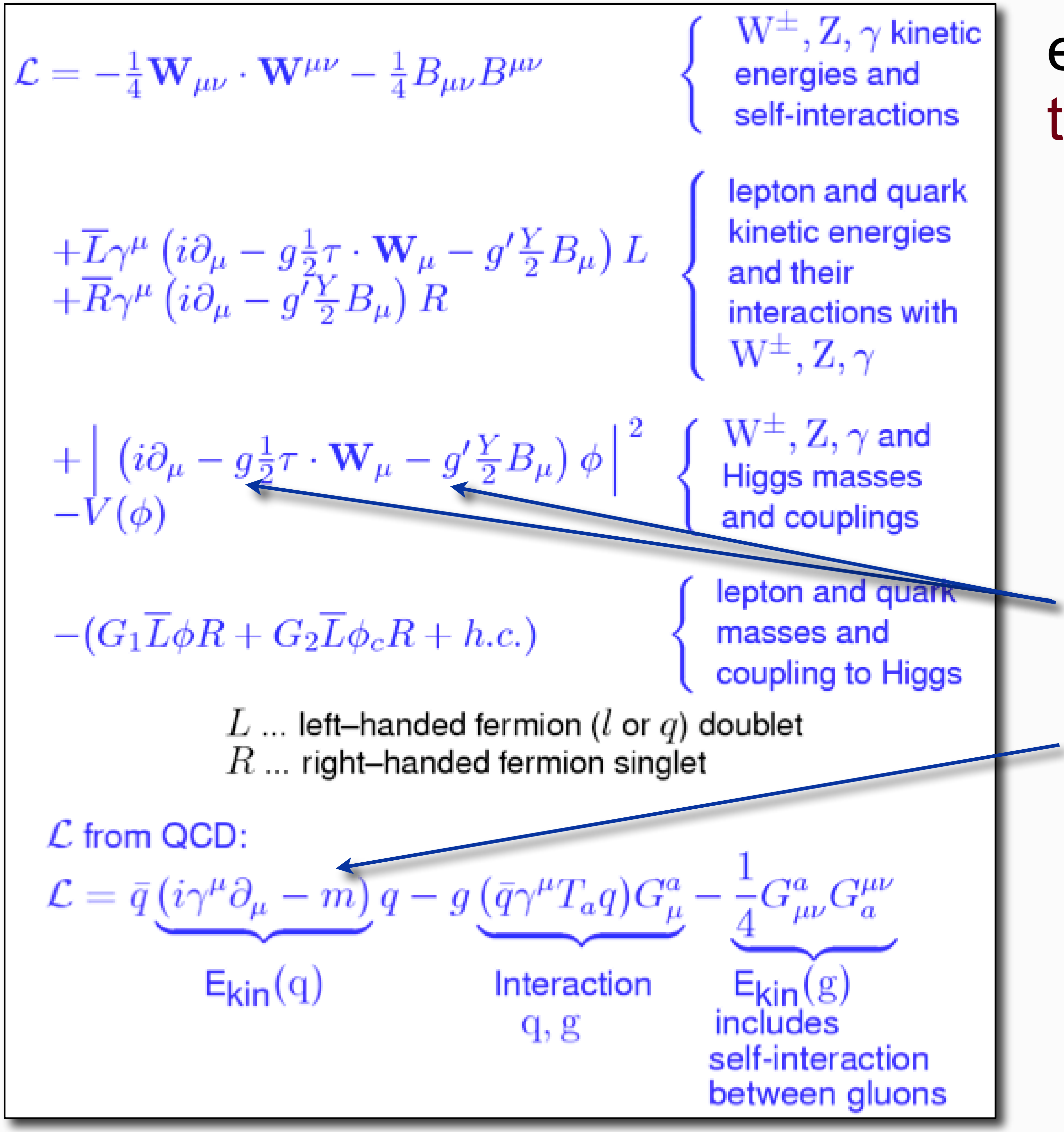
$\mathcal{L}$ from QCD:

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

eg.

the Standard Model

Theory...



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$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu}\right)R$$

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

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

$W^{\pm}, Z, \gamma$ 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

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

eg.
the Standard Model

has parameters

coupling constants

masses

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

Experiment...

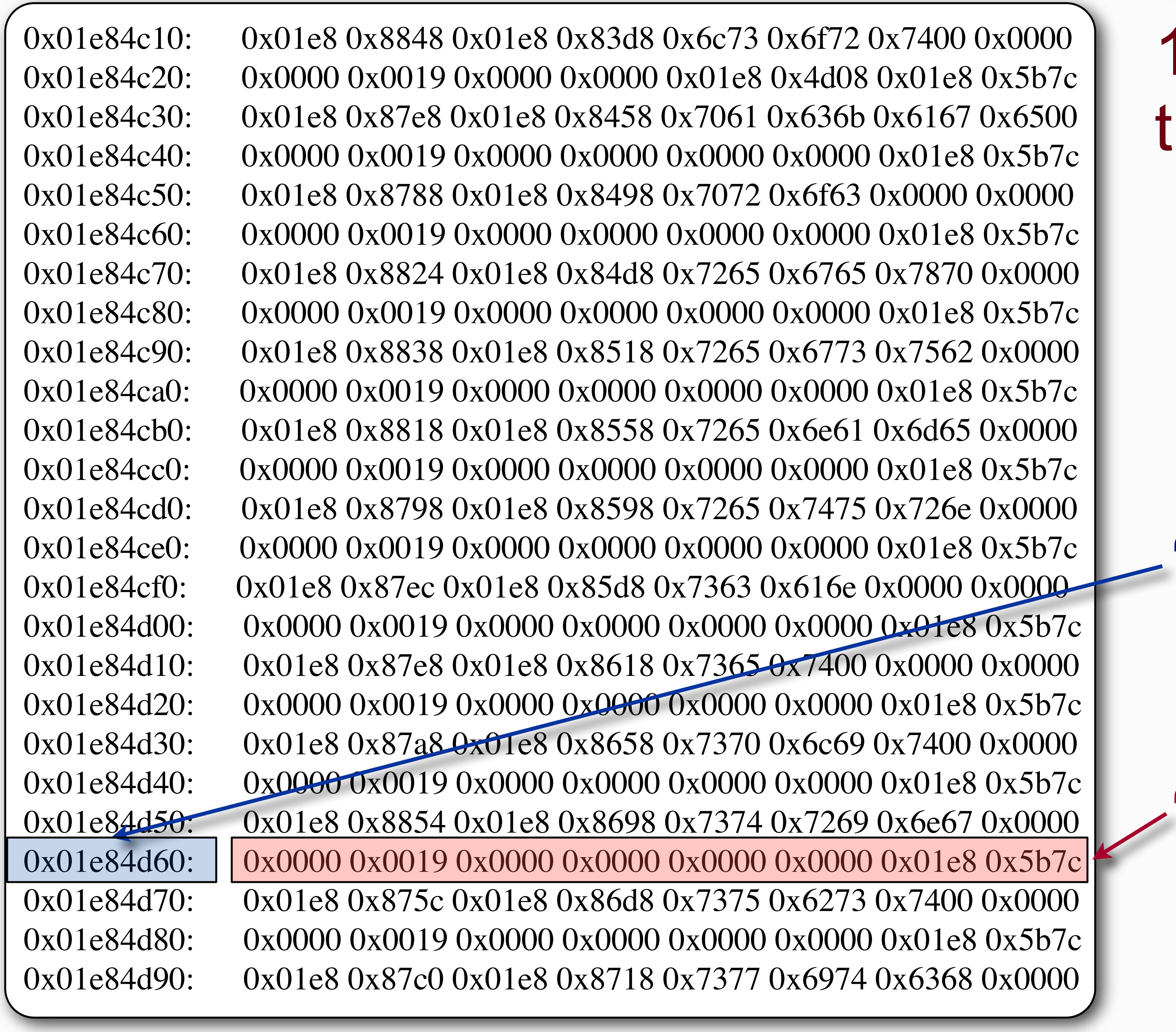
```
0x01e84c10:    0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:    0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:    0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:    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
0x01e84d40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:    0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:    0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:    0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```

eg.

1/30th of an event in the BaBar detector

- get about 100 evts/sec

Experiment...



```
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
0x01e84d40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:    0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:    0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
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0x01e84d90:    0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```

eg.

1/30th of an event in the BaBar detector

- get about 100 evts/sec

"Address" :

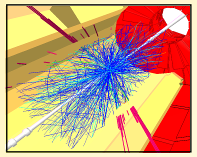
- which detector element took the reading

"Value(s)" :

- what the electronics wrote out

Making the connection

Reality



Raw Data

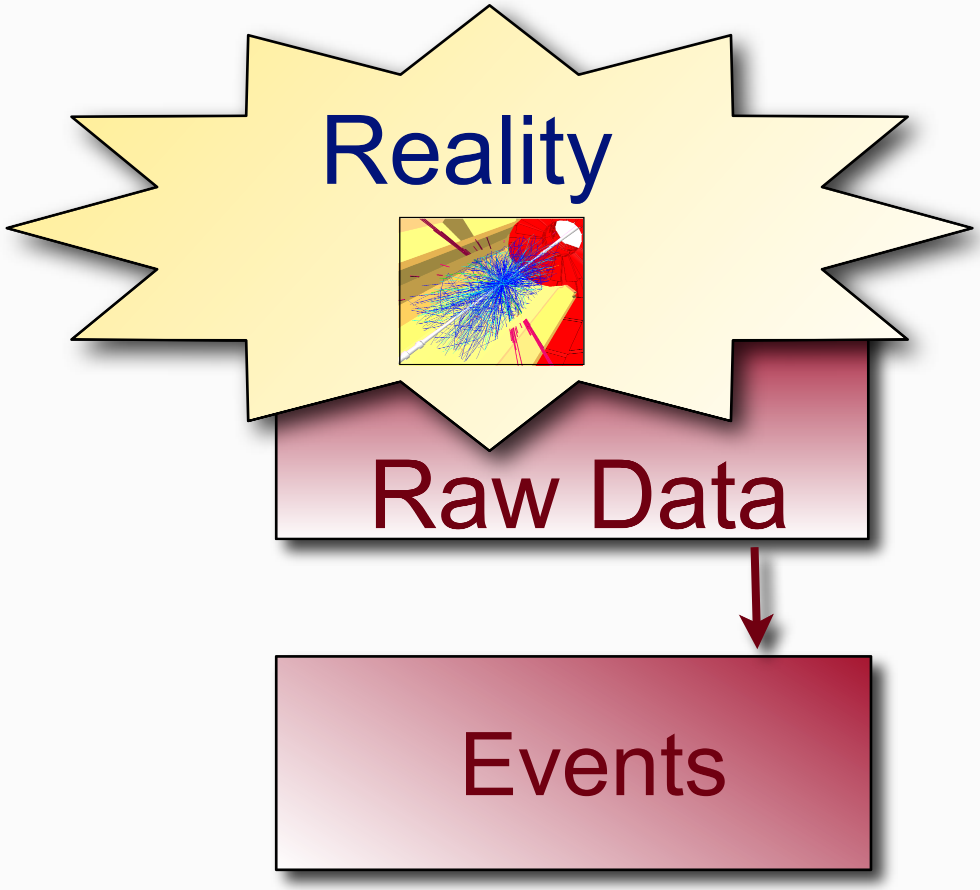
The imperfect measurement of a (set of) interactions in the detector

Theory

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

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

Making the connection



Reality

Raw Data

Events

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

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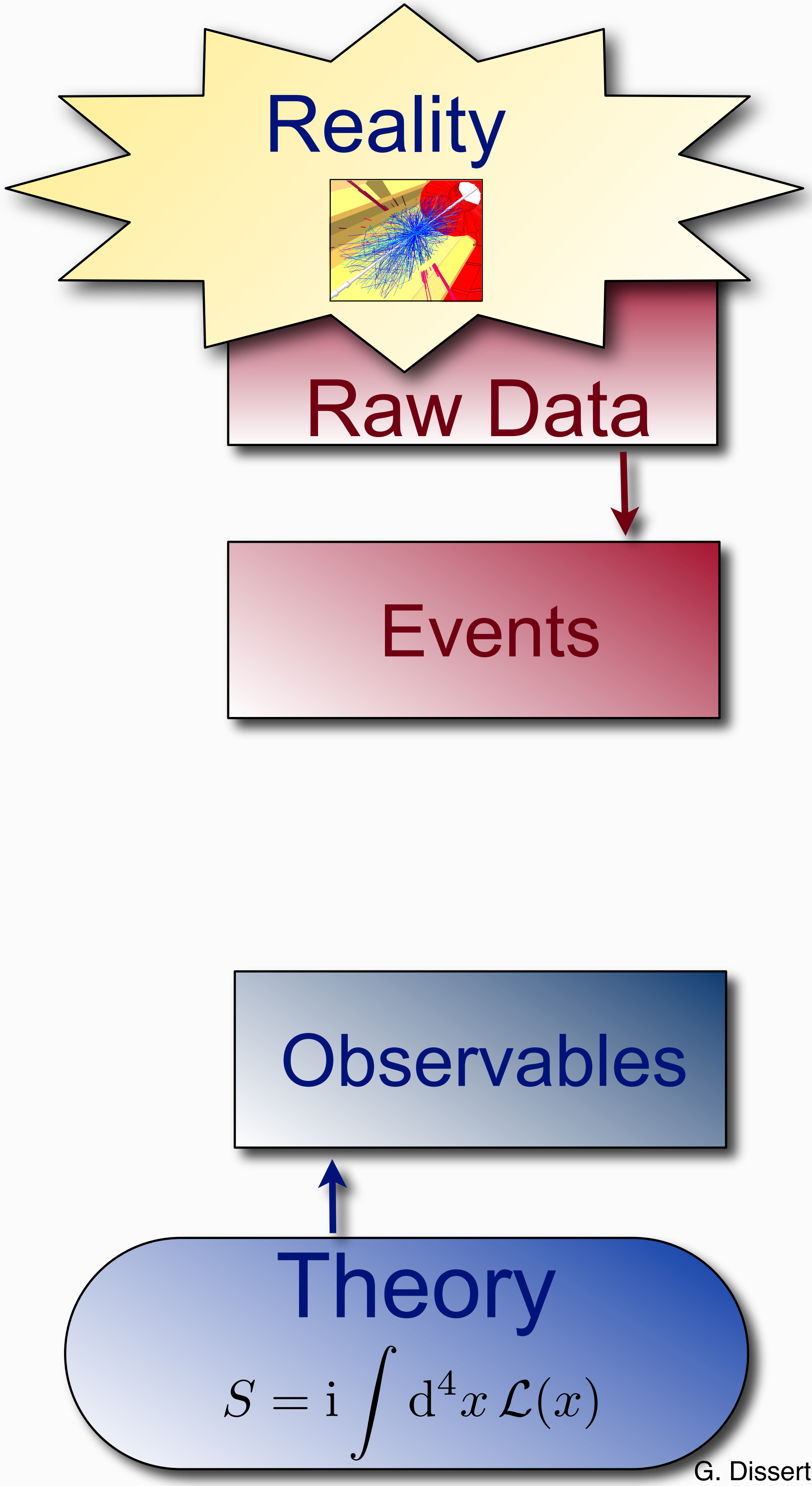

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A unique happening:
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Observables

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

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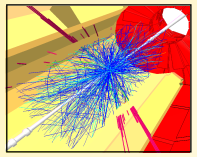
Making the connection

Reality



Raw Data

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

Events

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.

Observables

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

Theory

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

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

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

A simple example

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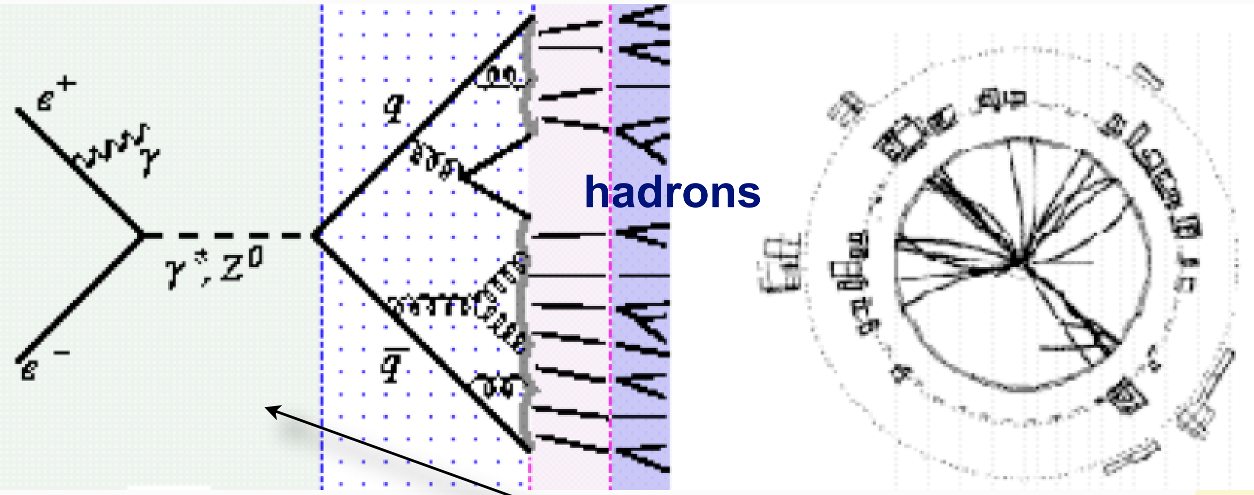

Hadronic final state

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

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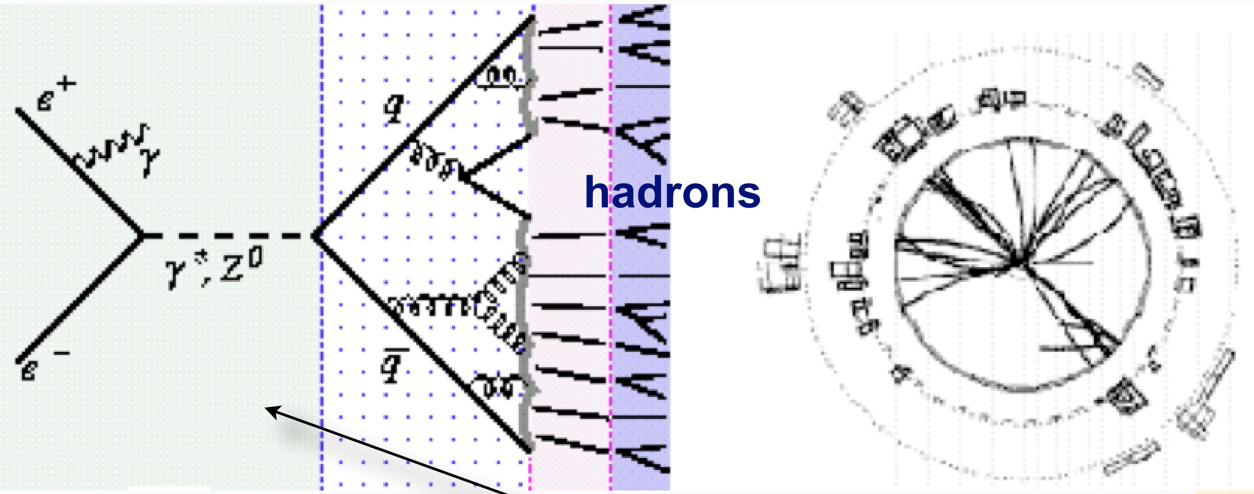

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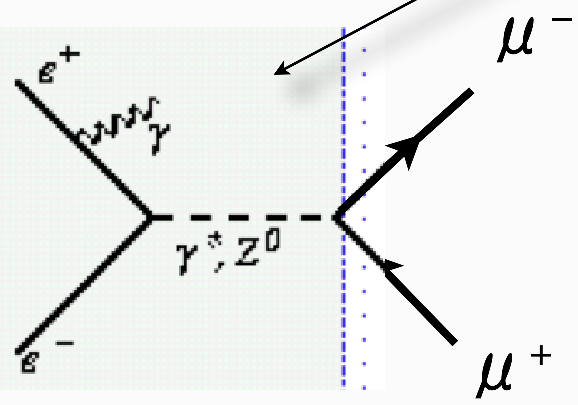
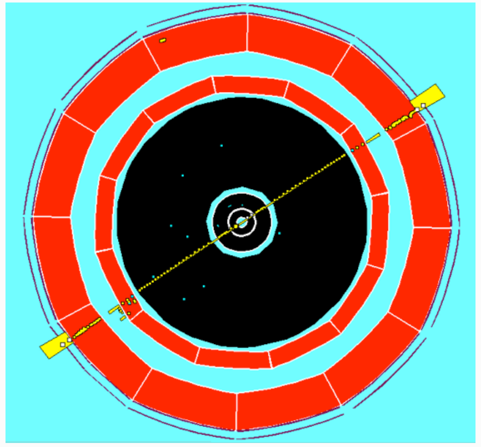


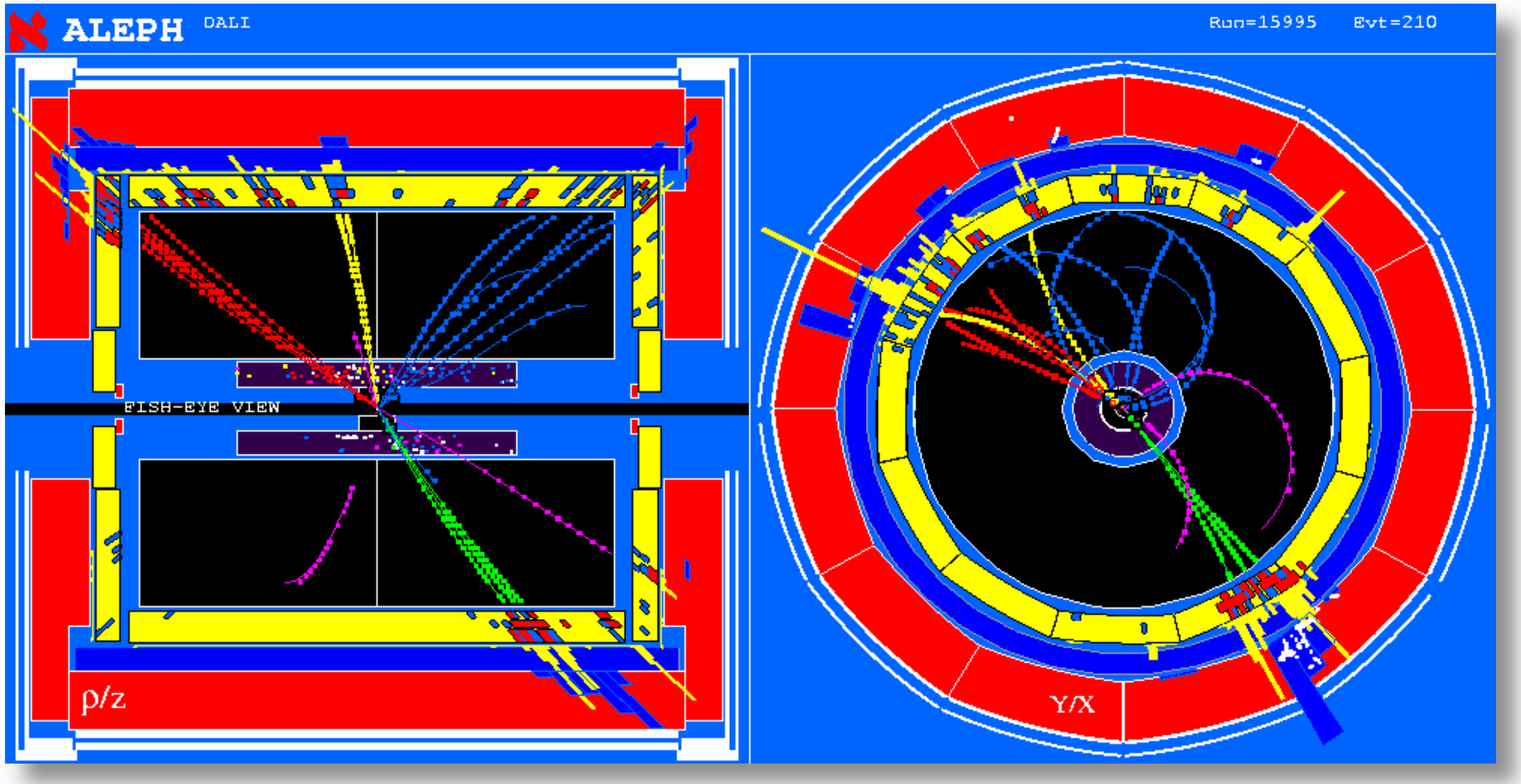


Muonic final state

- 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

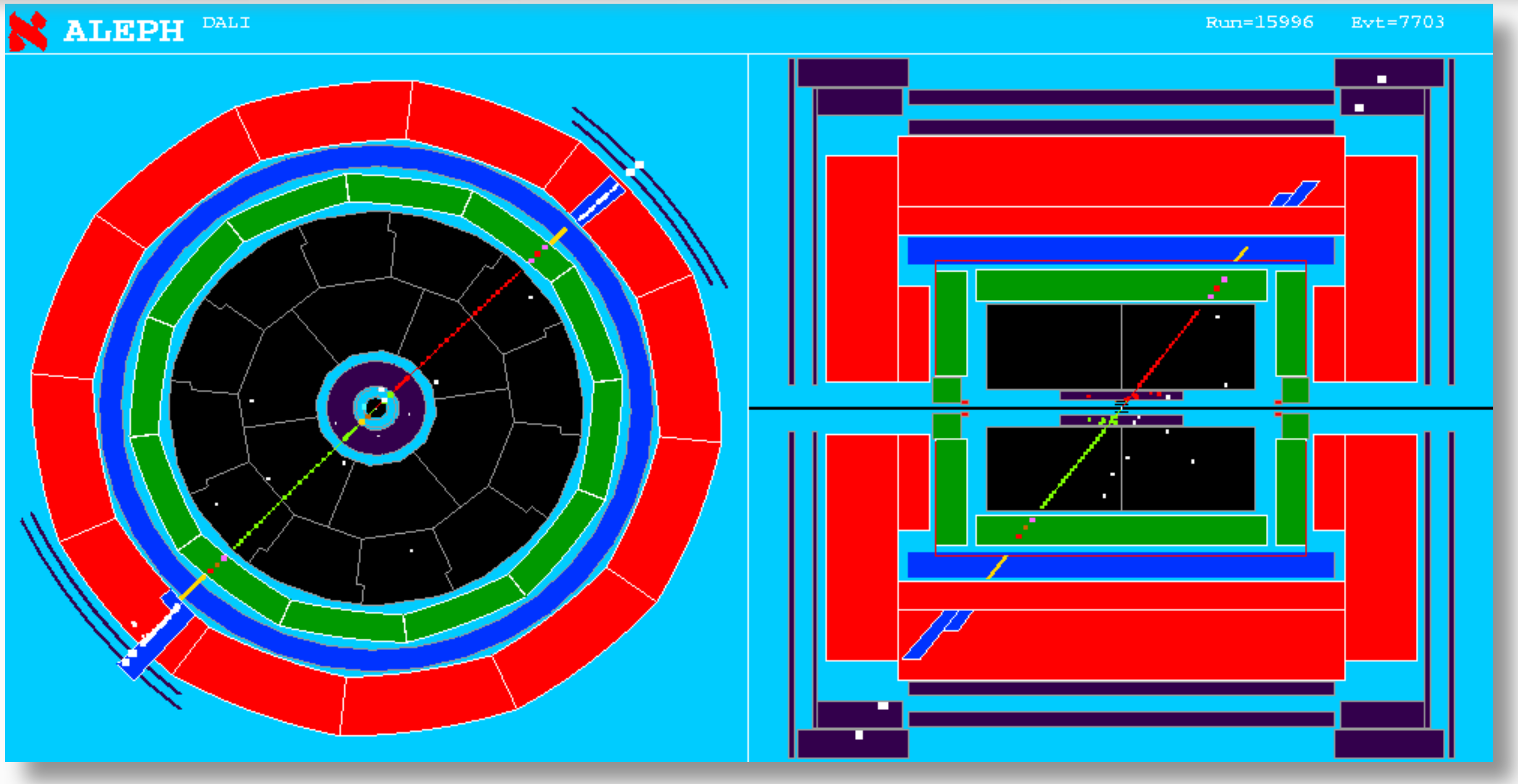
of



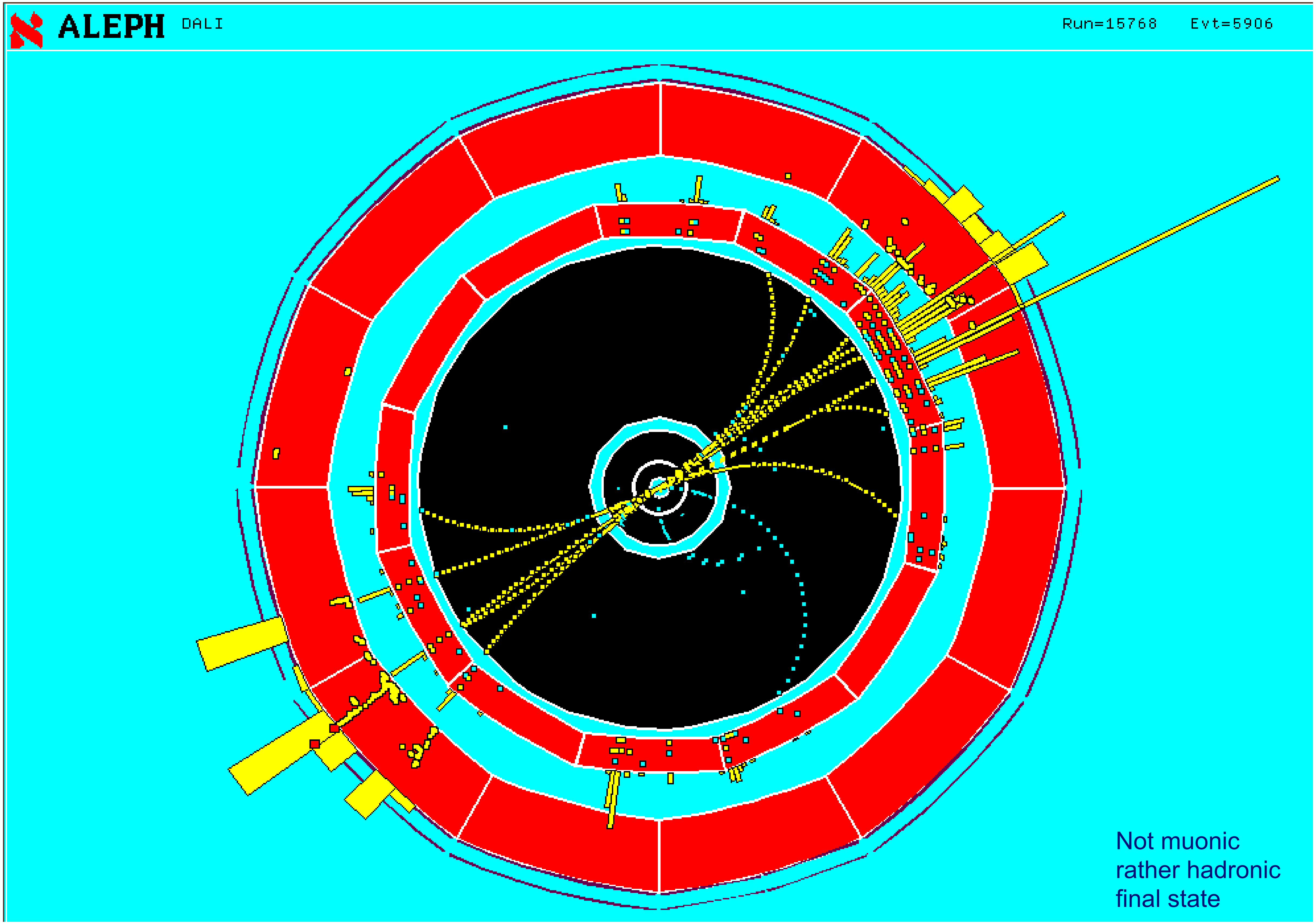
Hadron final states

R =

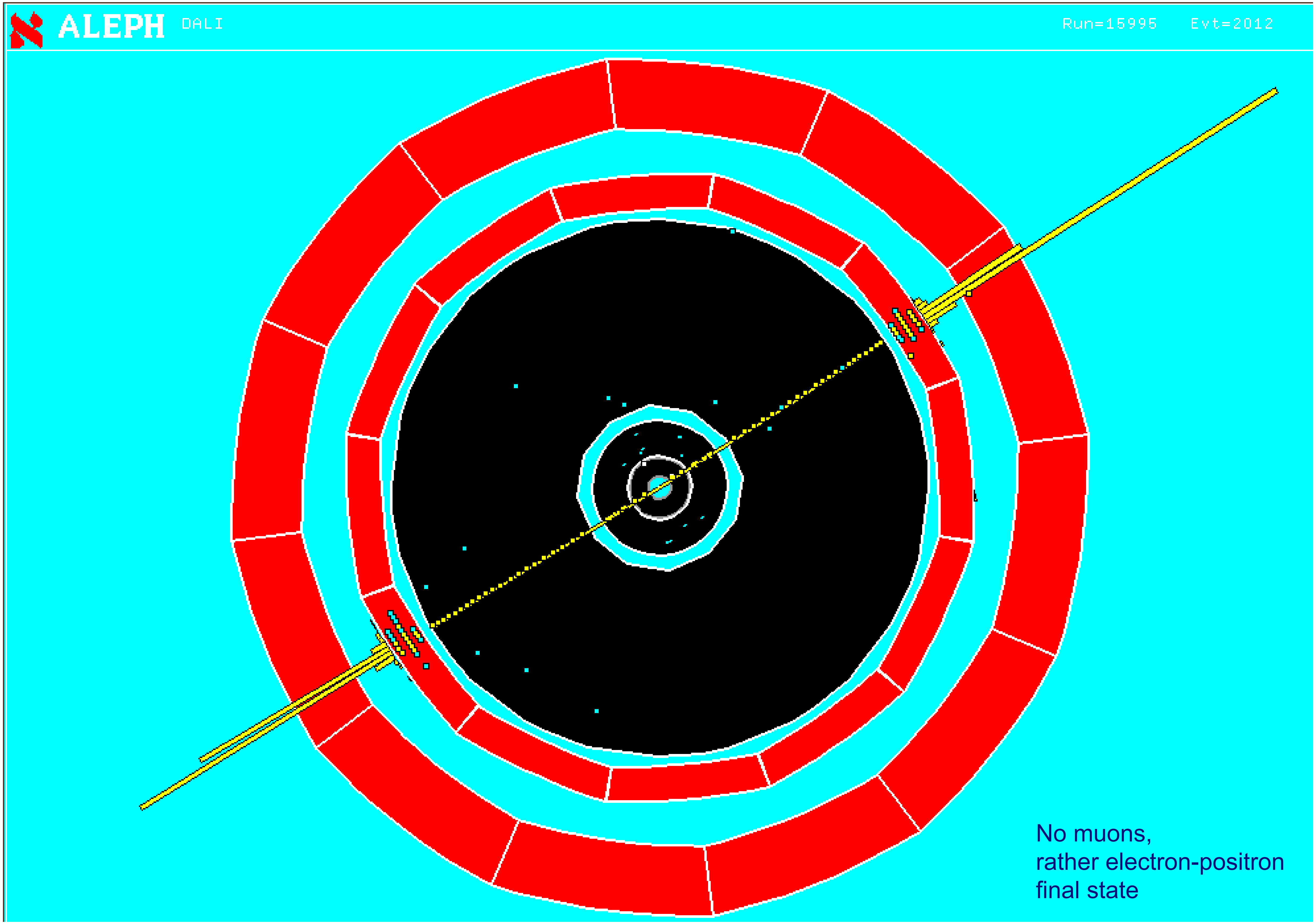
of



Muon final states

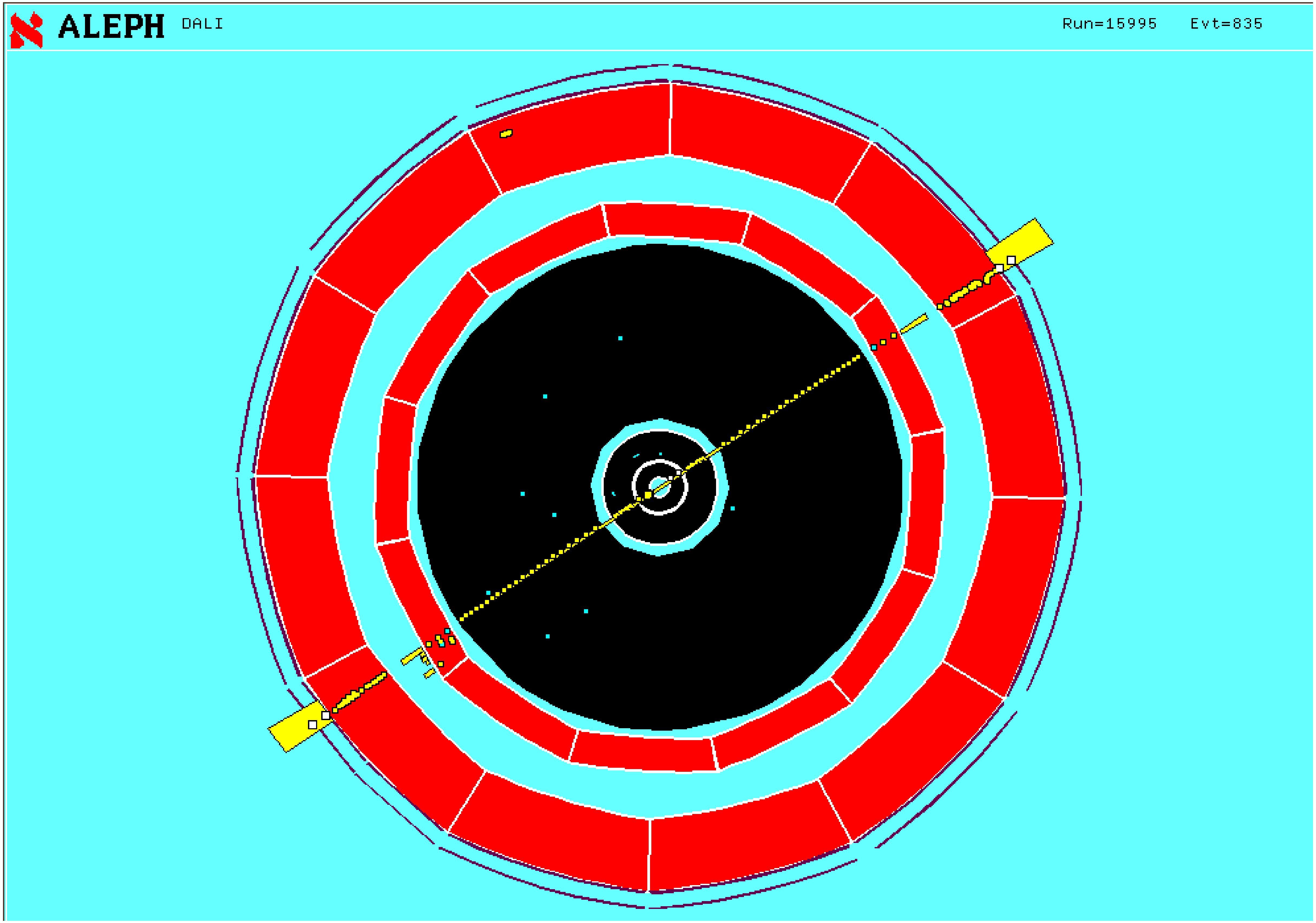


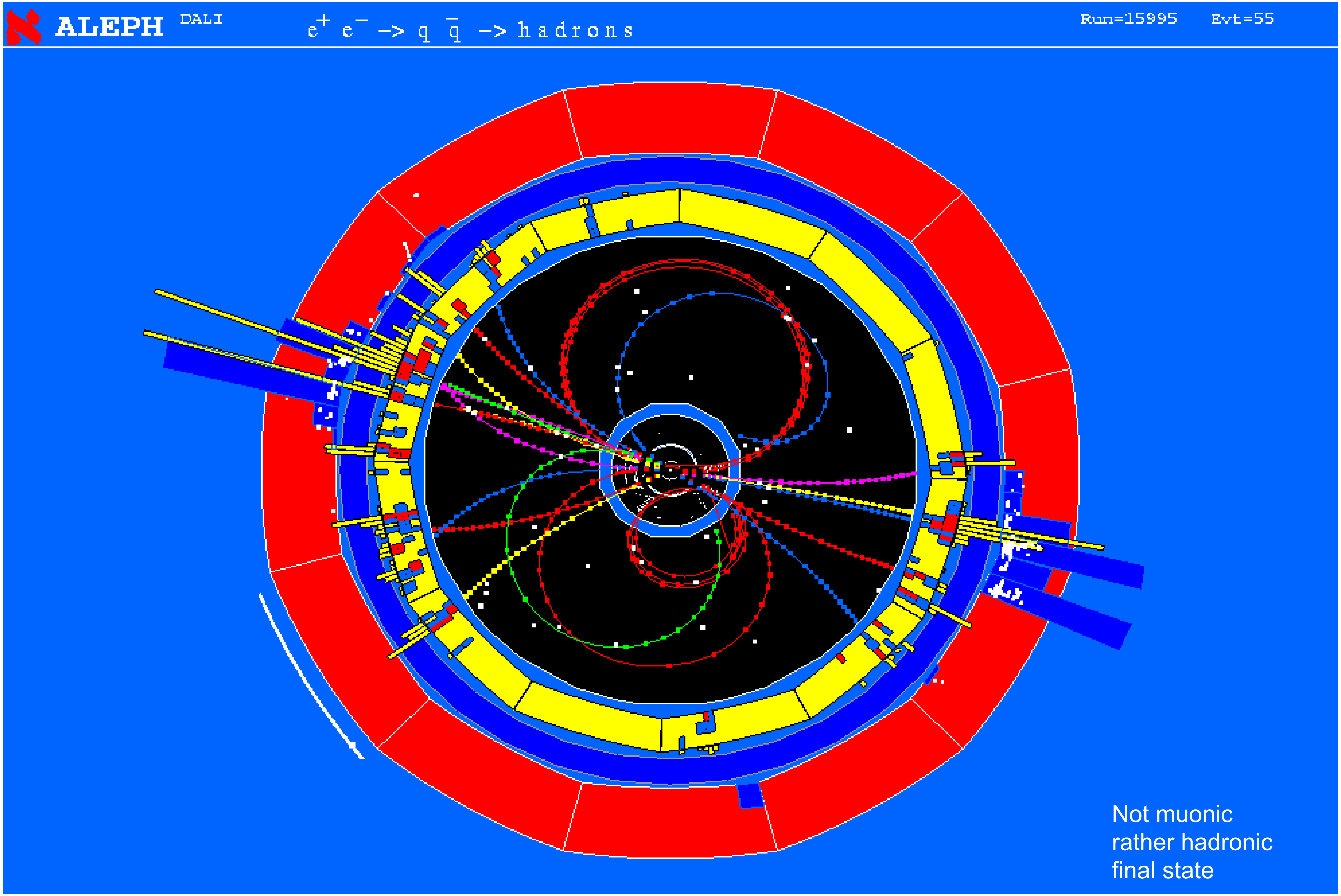
Not muonic
rather hadronic
final state



No muons,
rather electron-positron
final state

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





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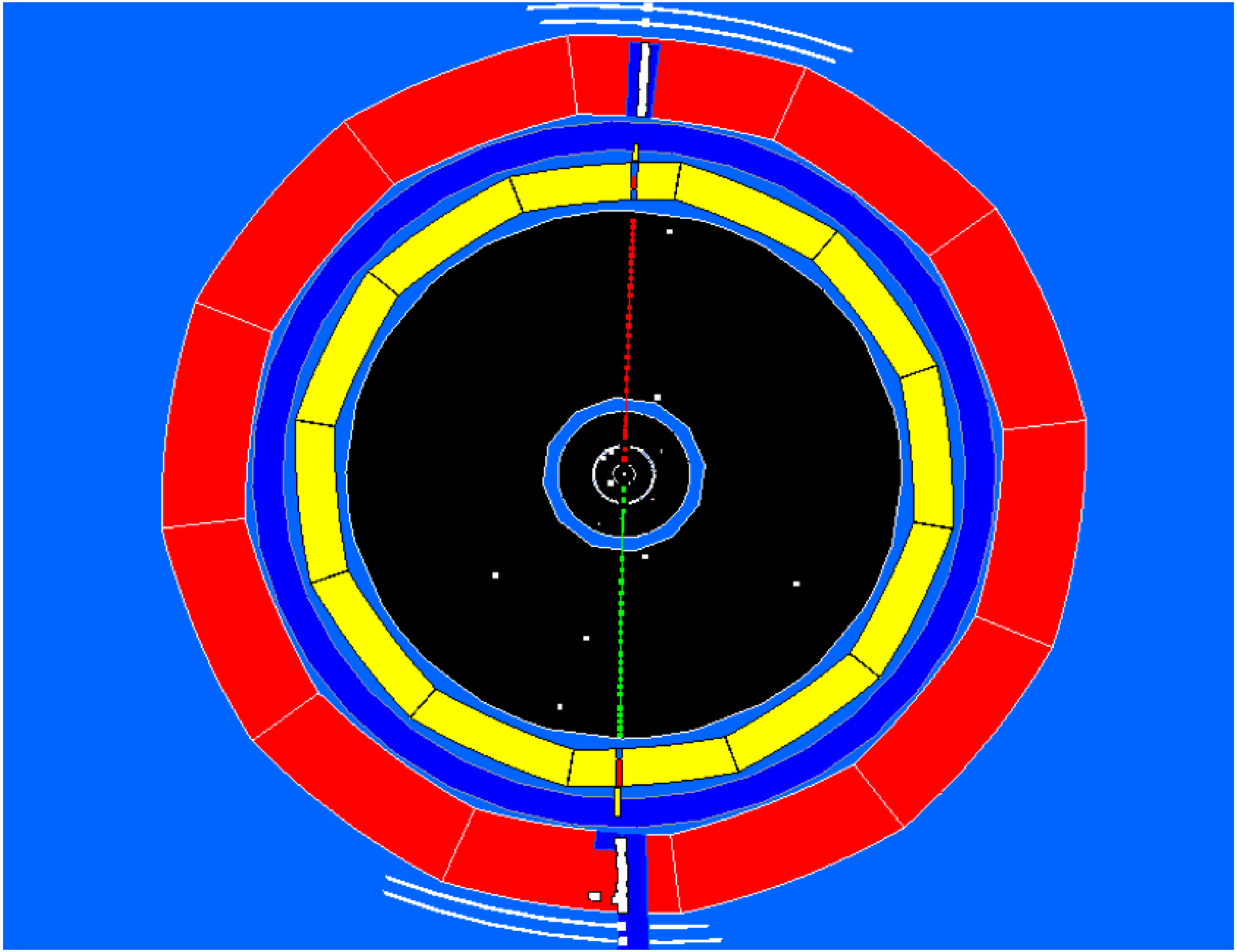
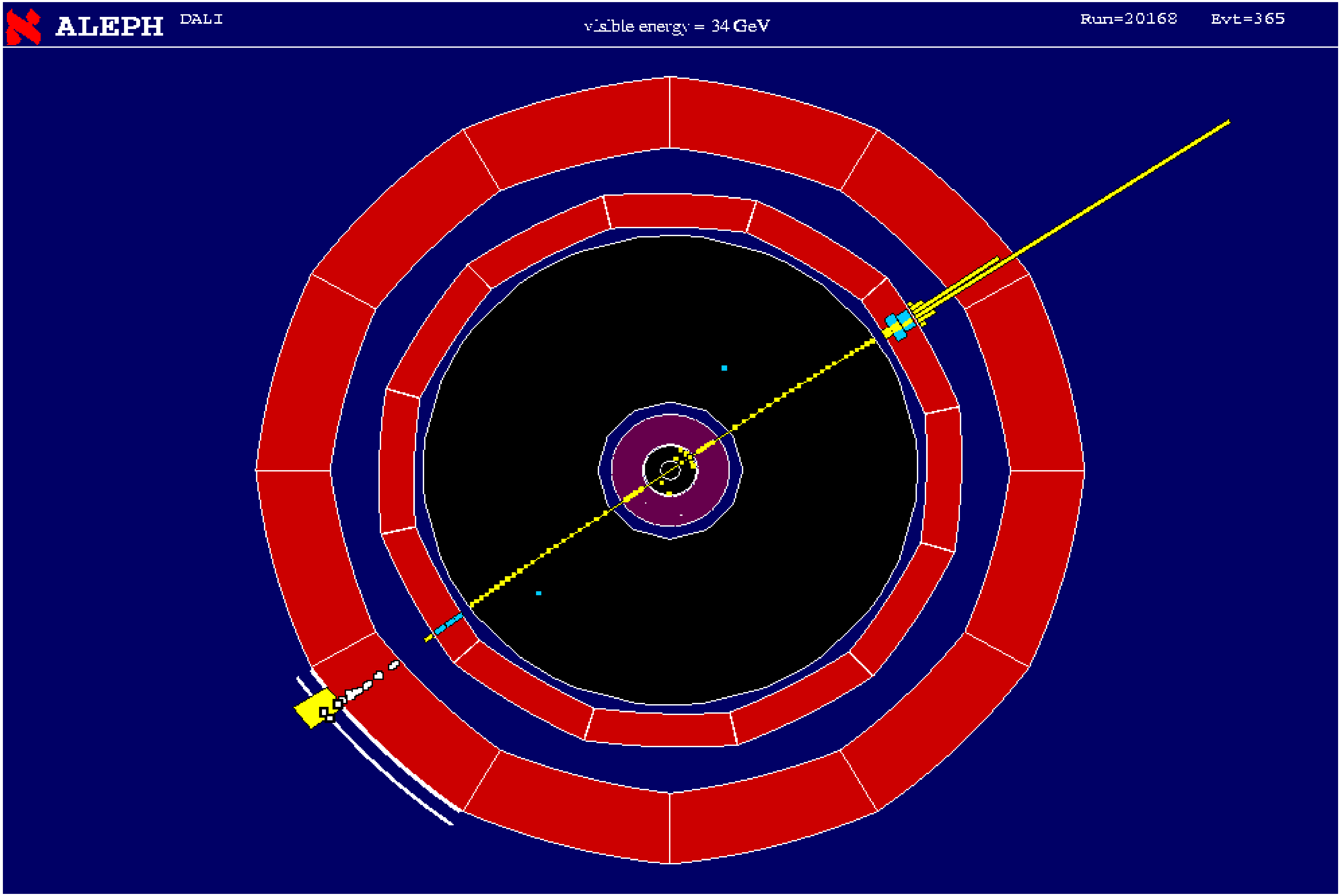
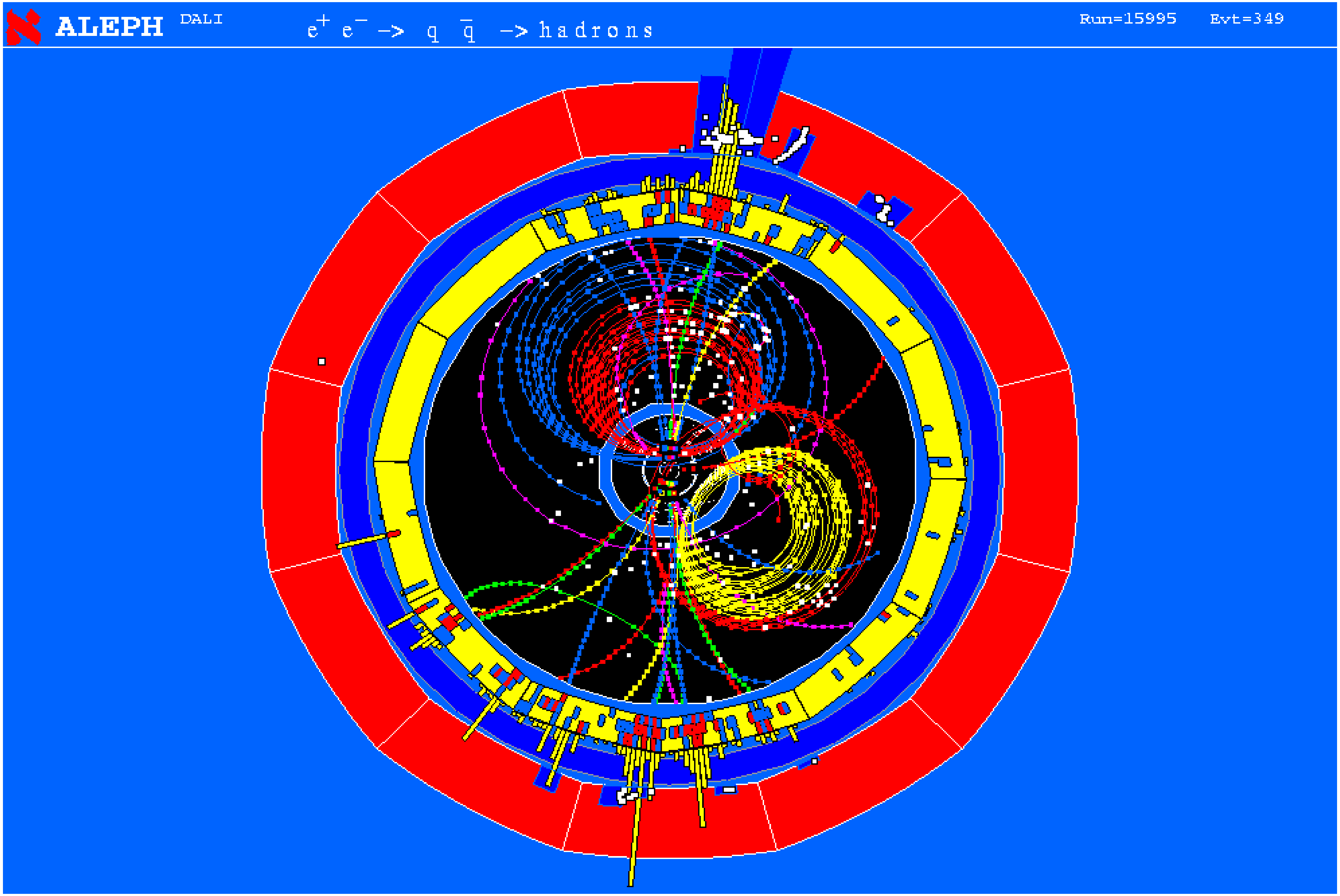


not $Z \rightarrow \mu^+\mu^-$

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:

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

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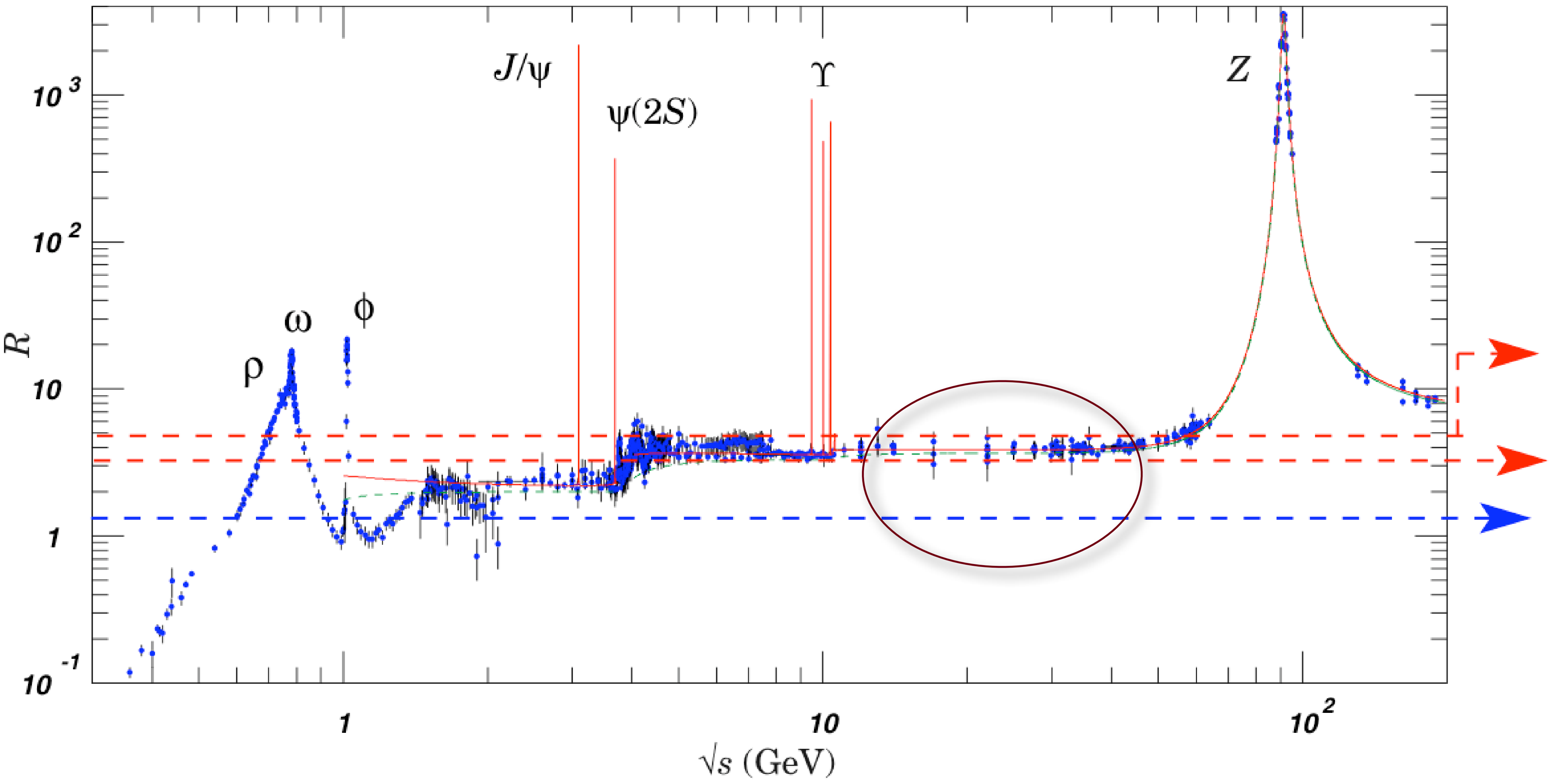

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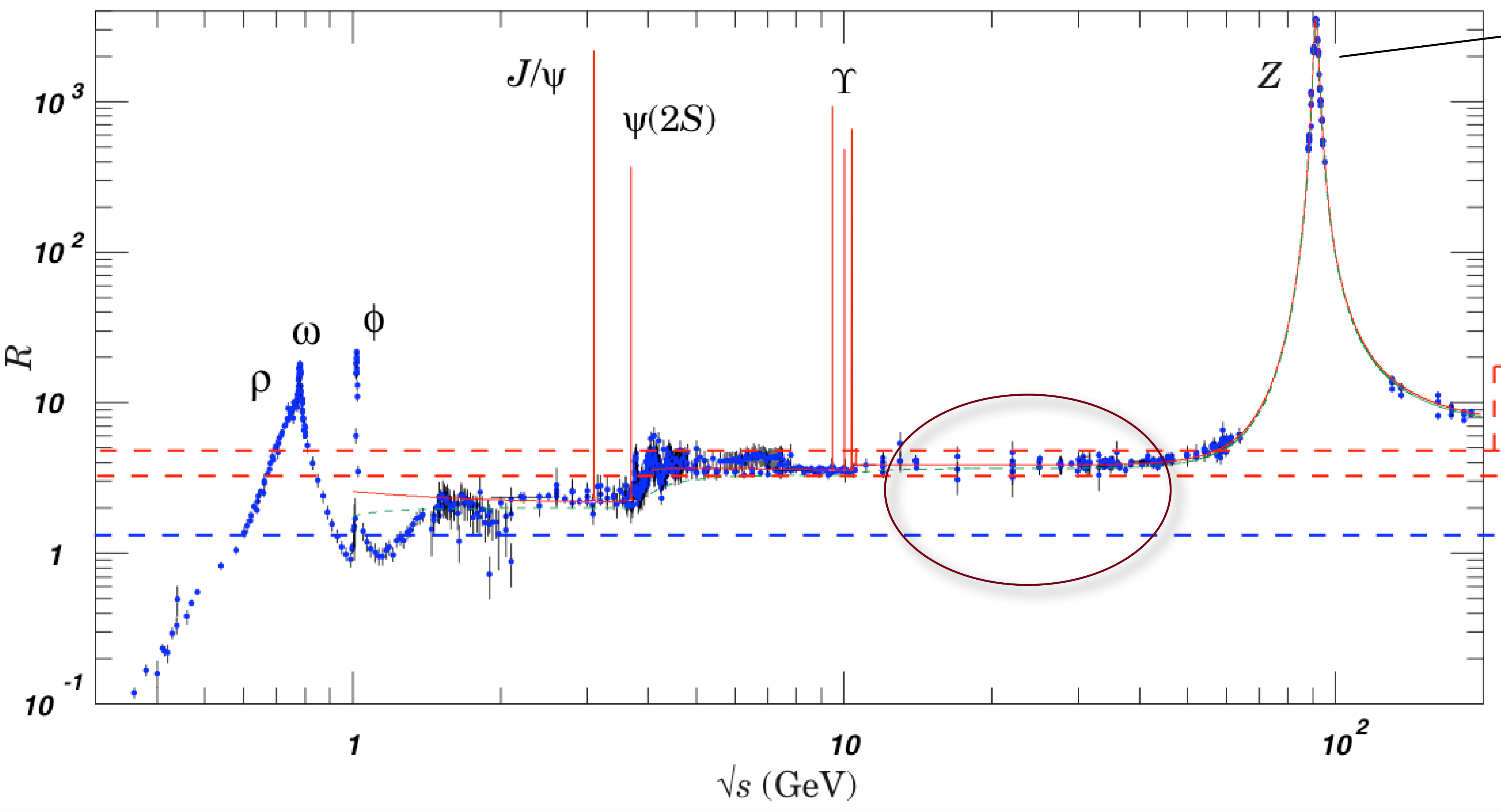

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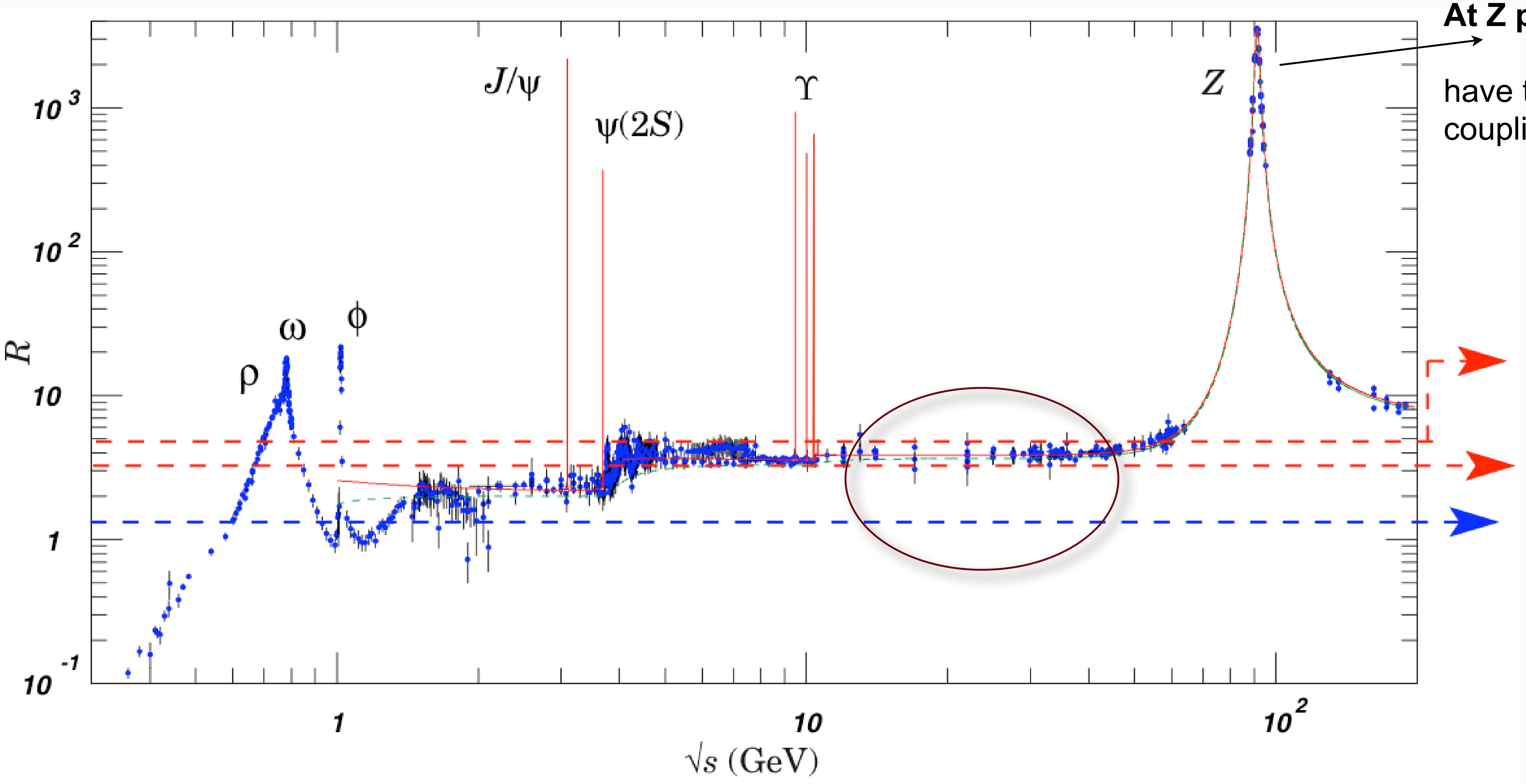

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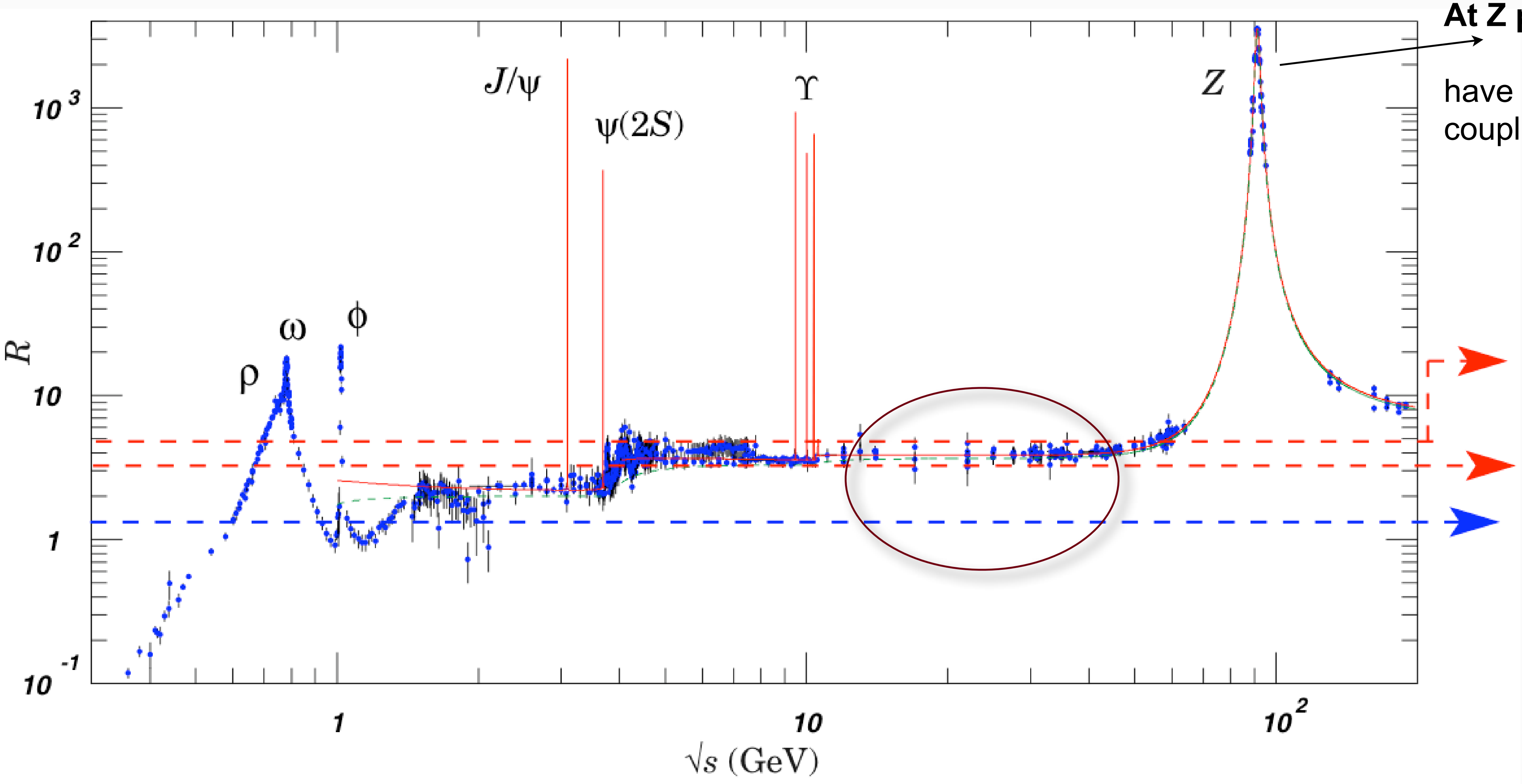

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Note : small remaining difference : because of QCD correction (gluon radiation) = 1 + α_s / π

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$$\varepsilon = 0.50 \pm 0.05$$

- 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?
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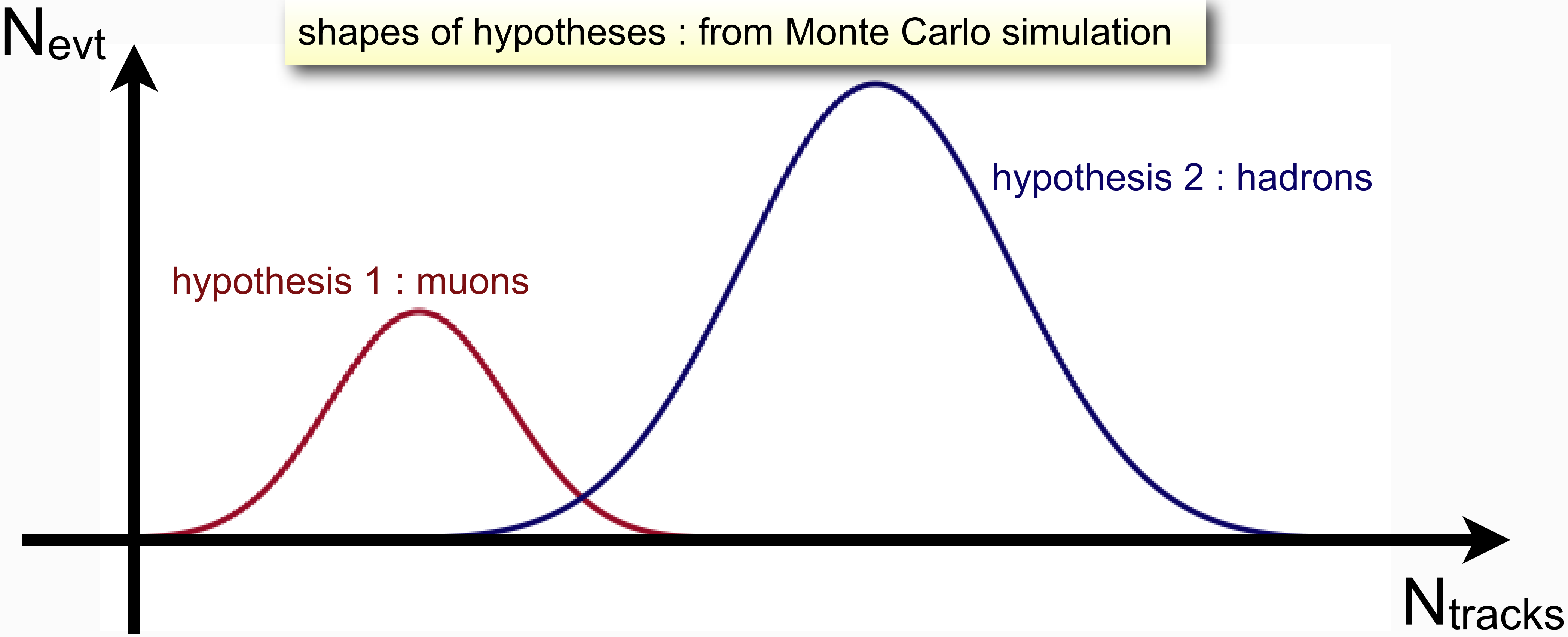

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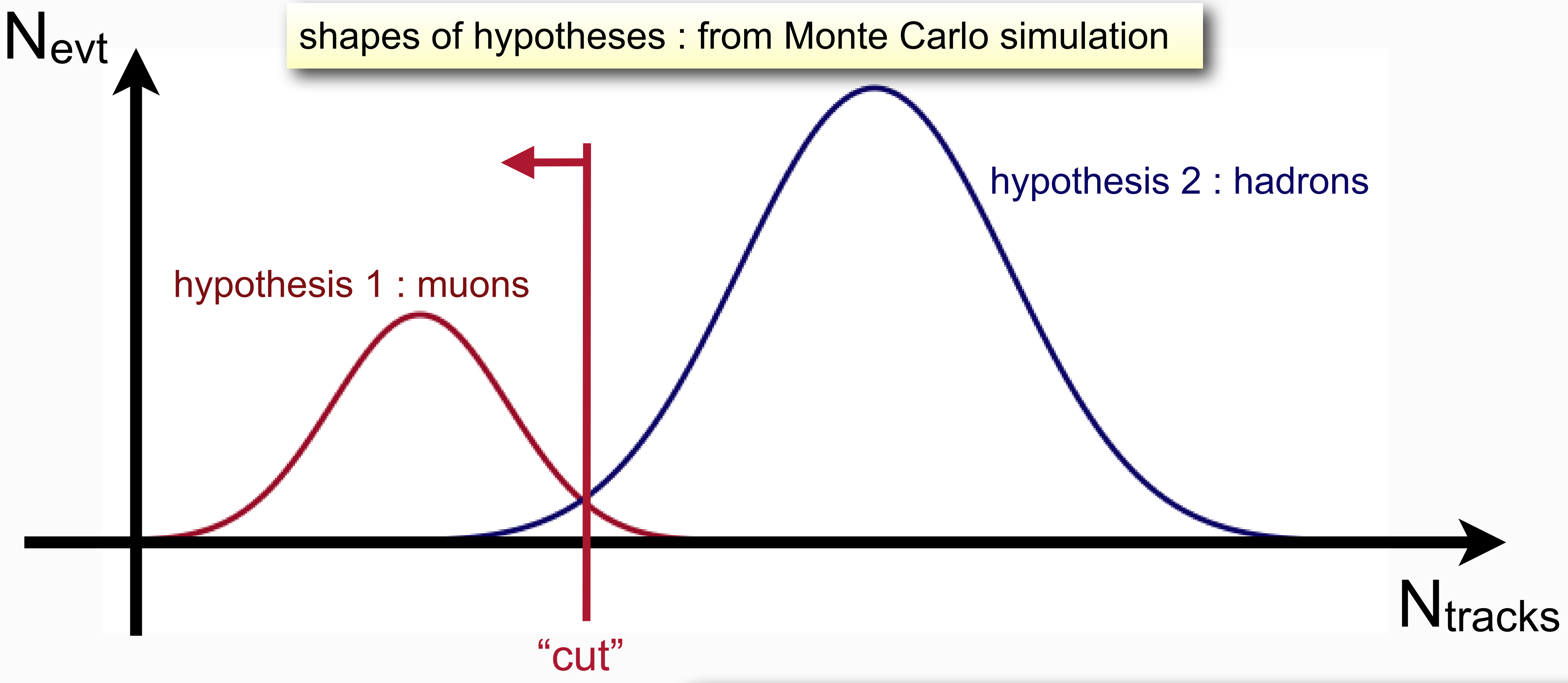

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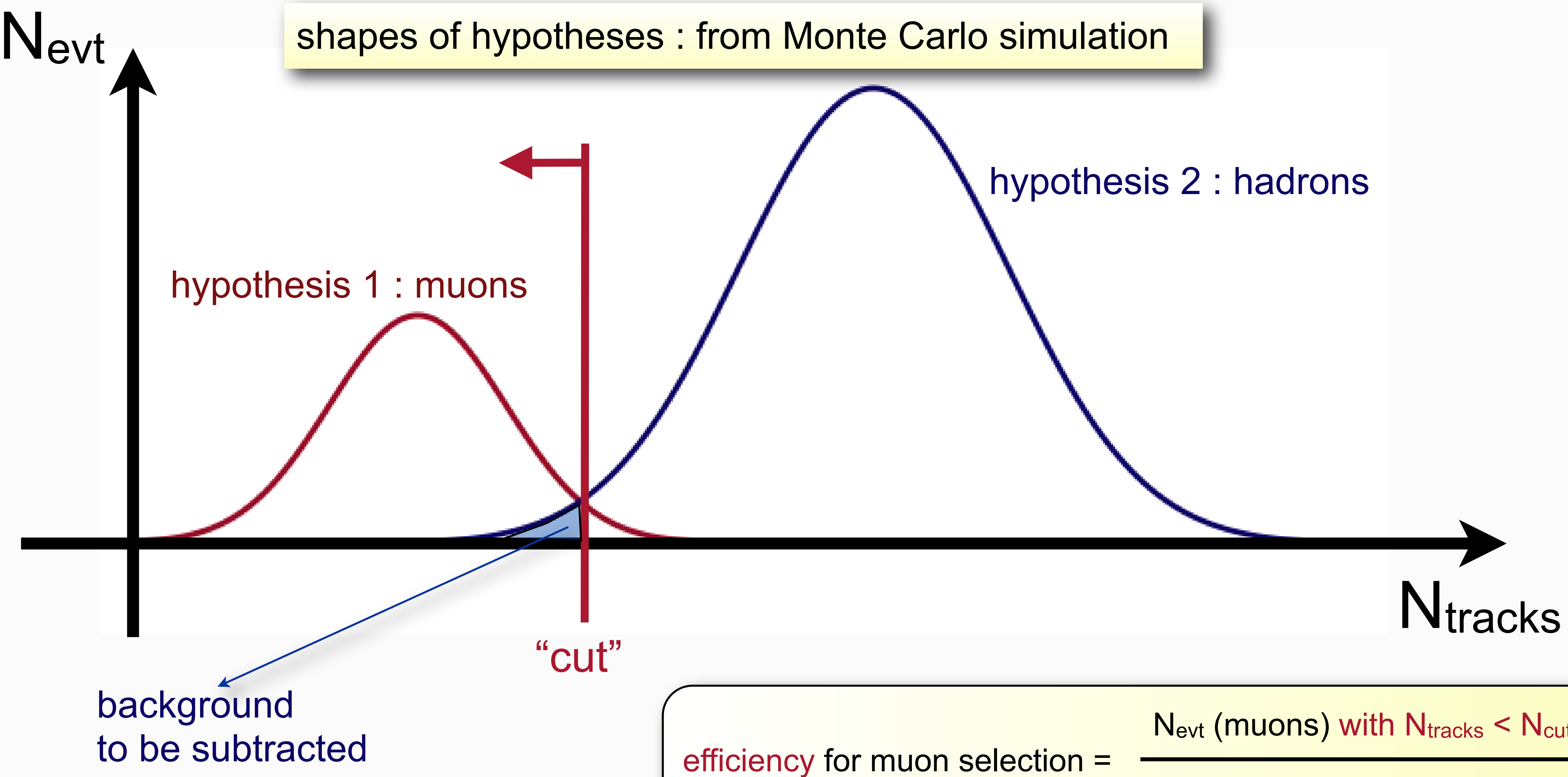

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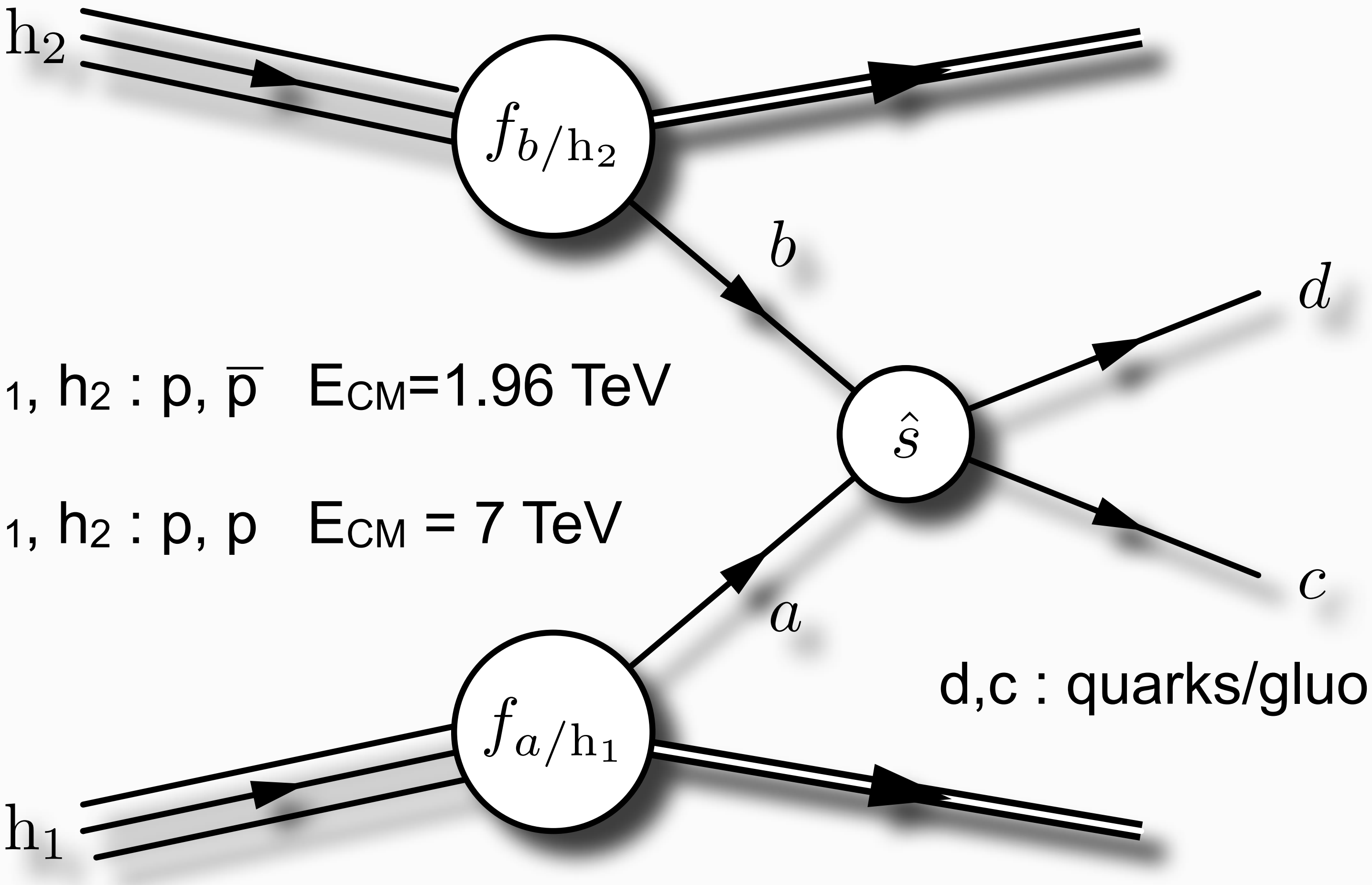
A “more complicated” example

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

JET production at hadron colliders

see also lectures by B. Heinemann and by S. Ellis

- at the Tevatron, or now at the LHC



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

h_1, h_2 : p, p E_{CM} = 7 TeV

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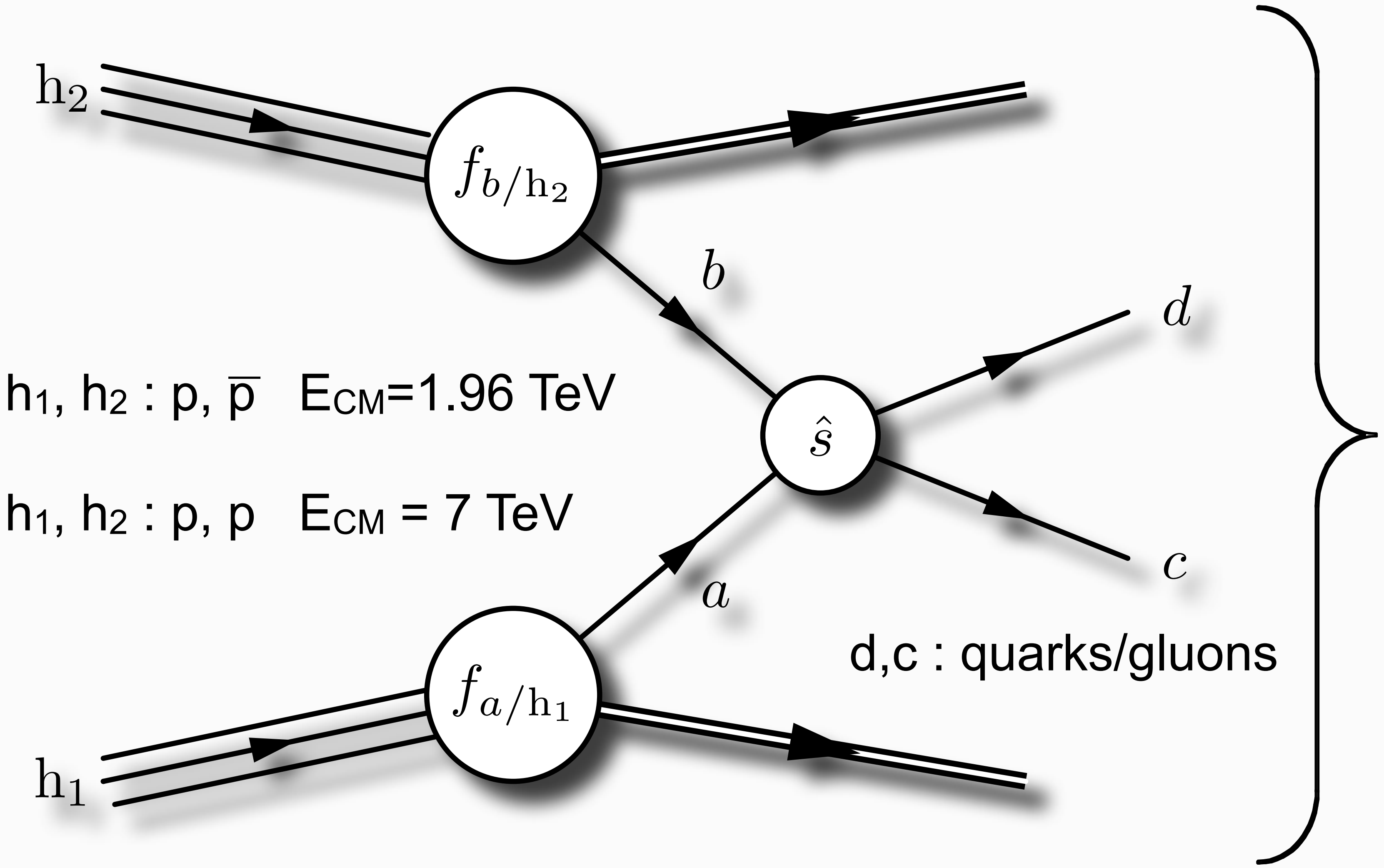

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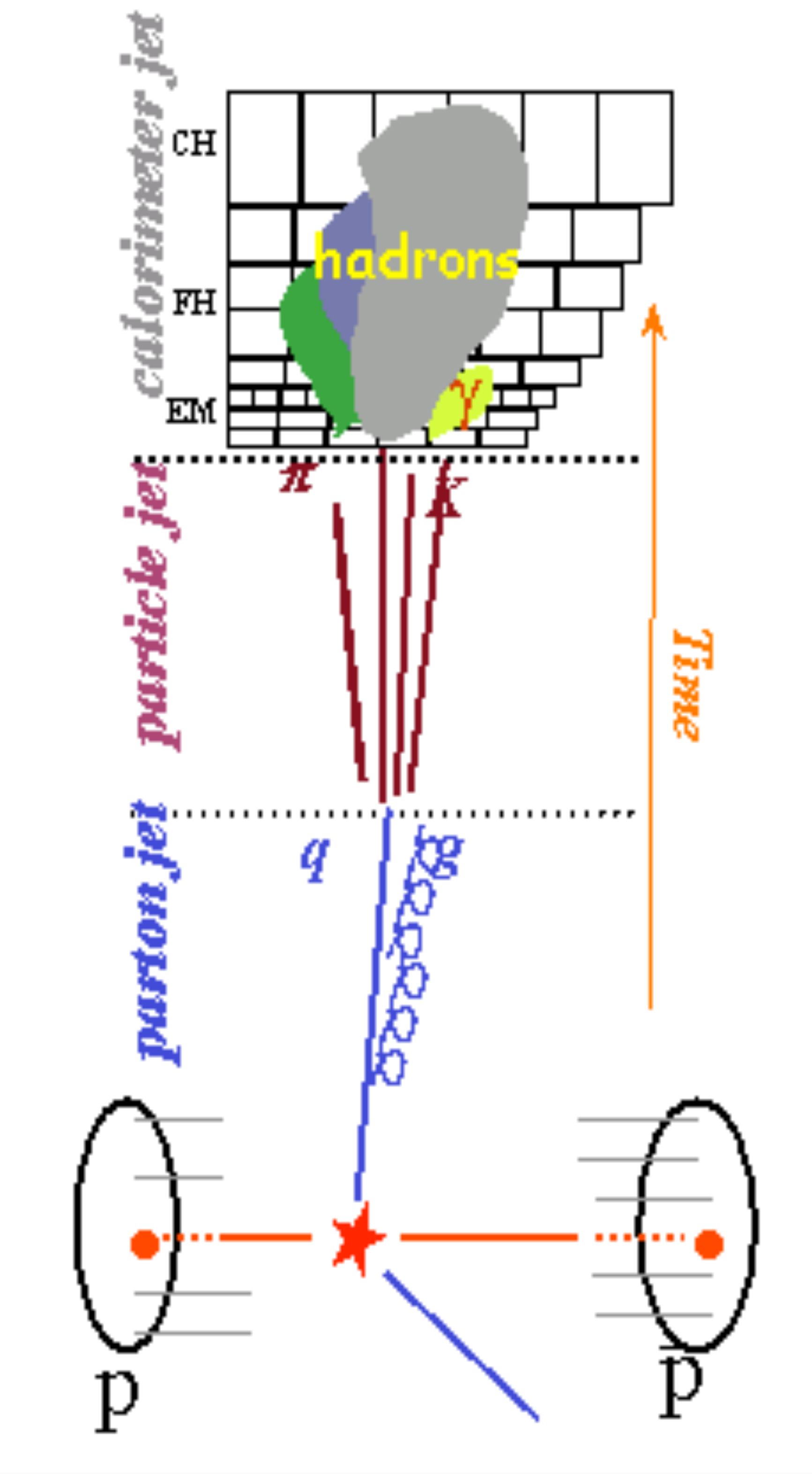

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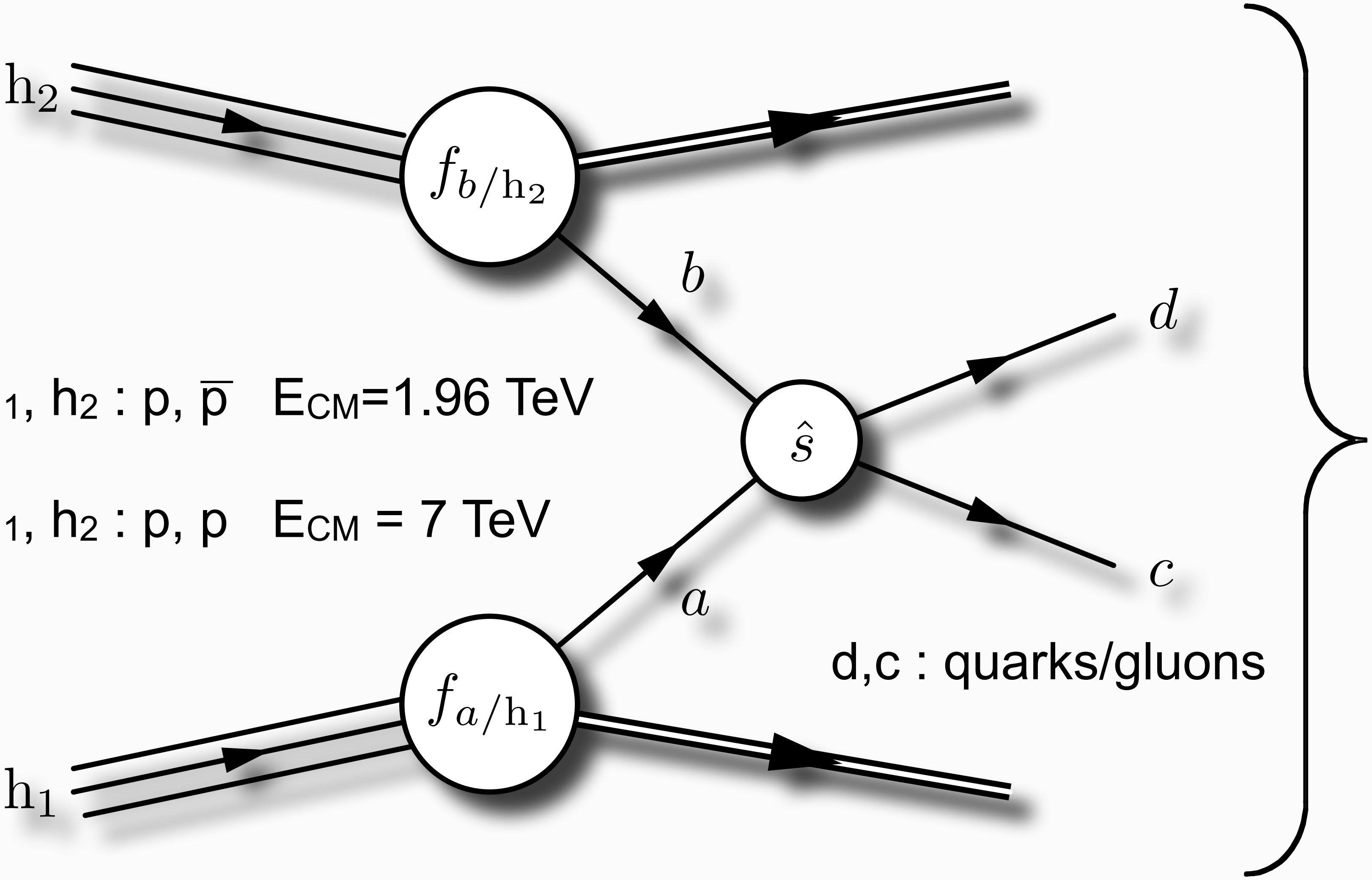

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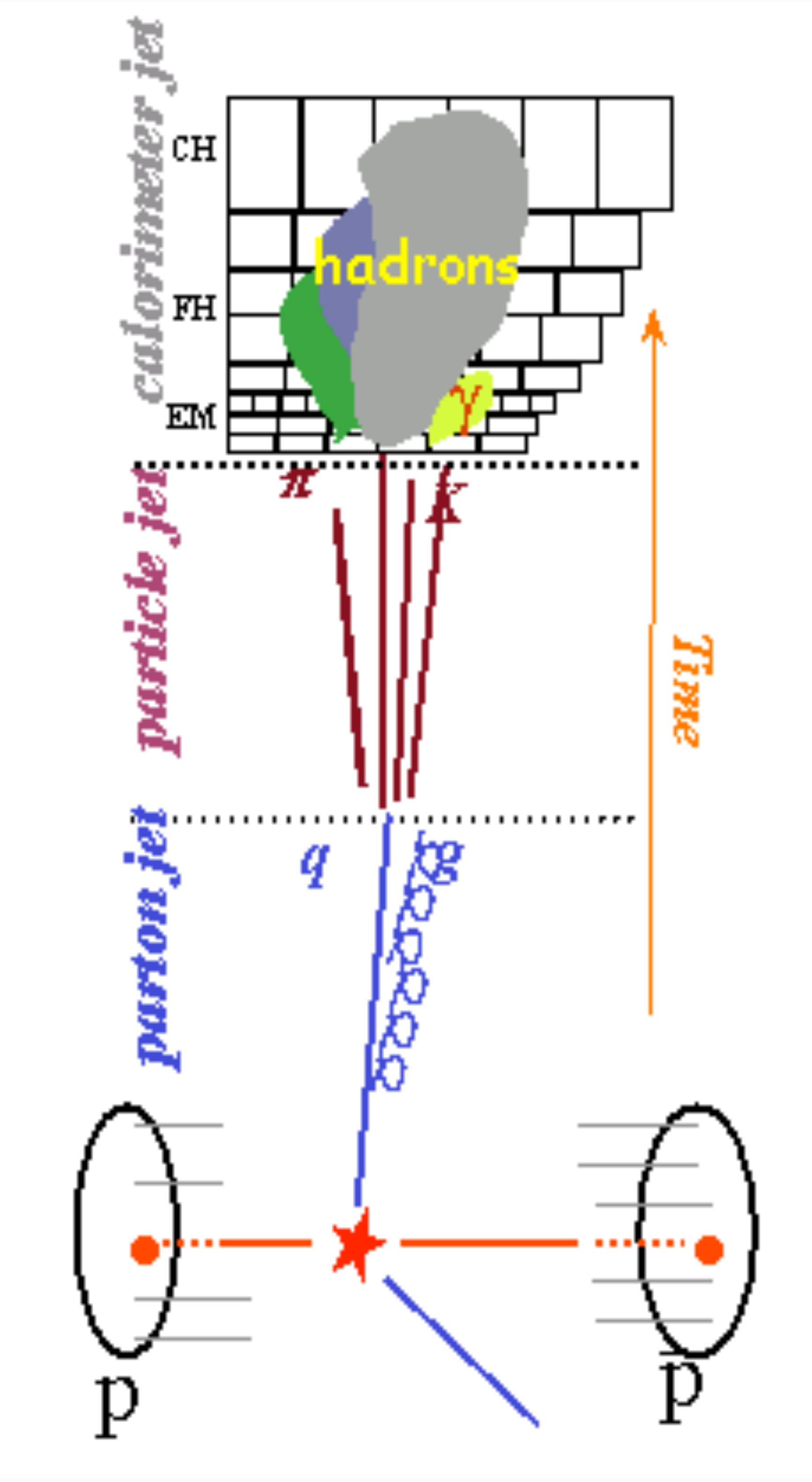
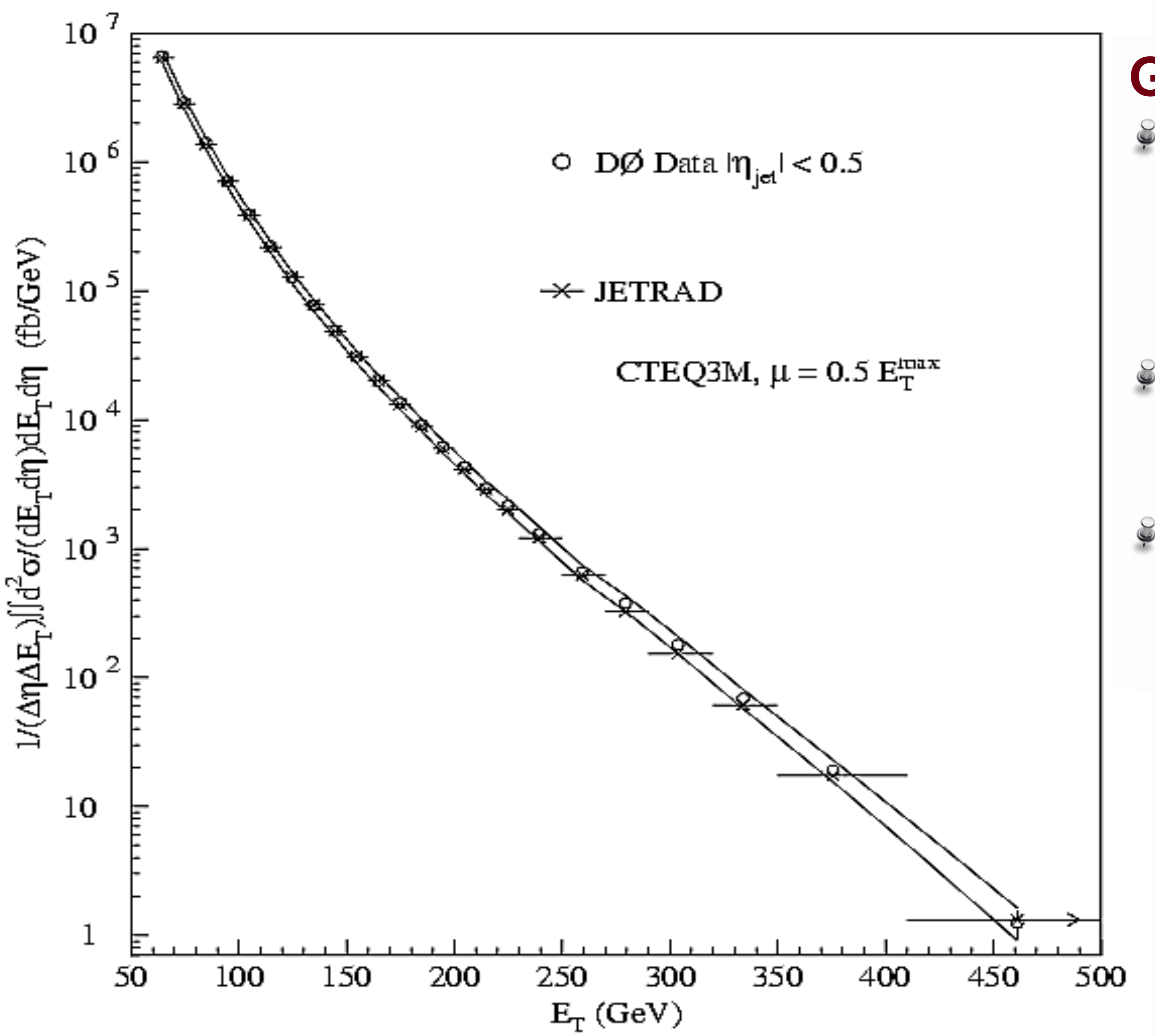


Goal

- 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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- measure cross section (probability) that jets are produced with a certain transverse energy E_T, within a certain rapidity range
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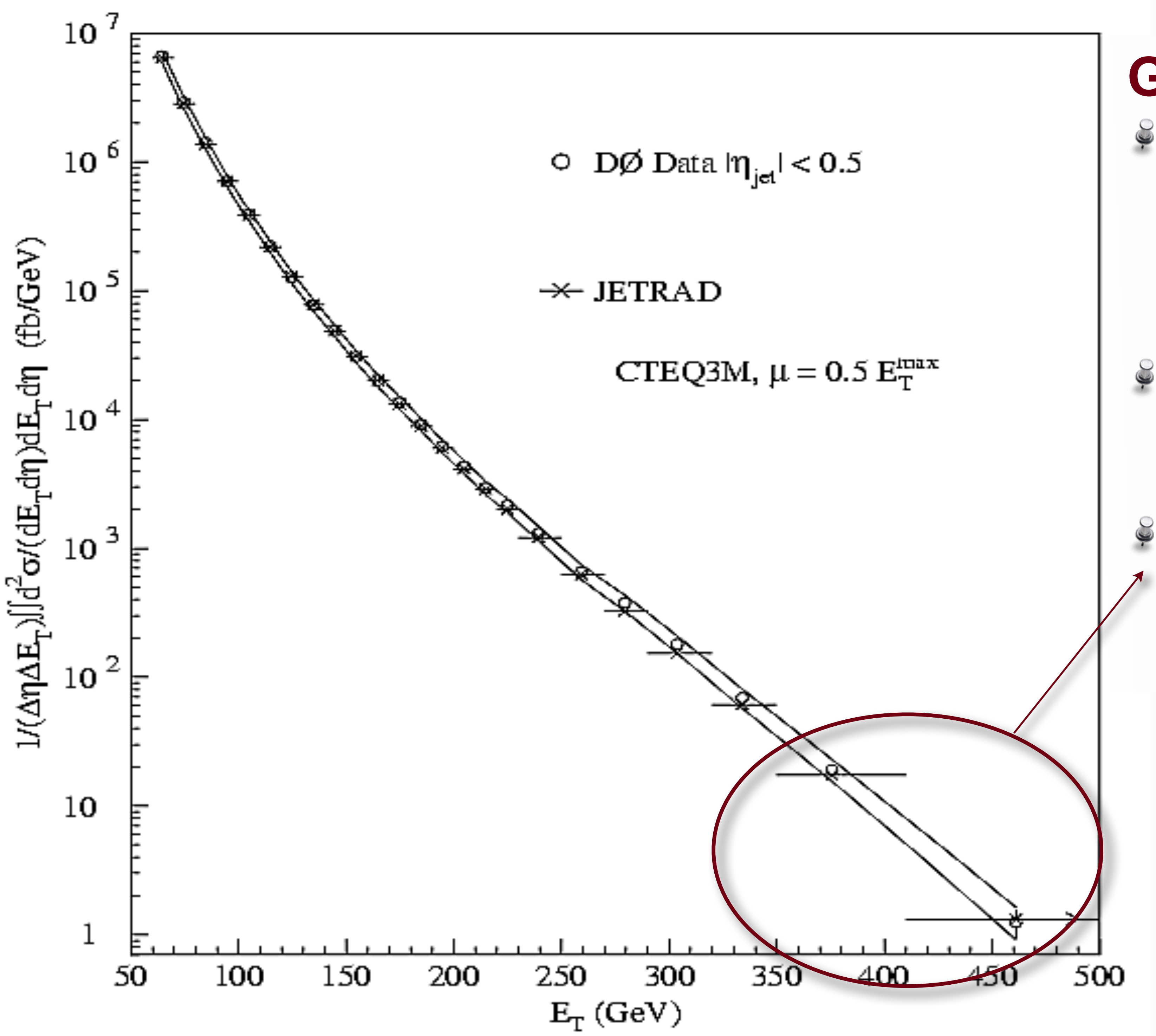

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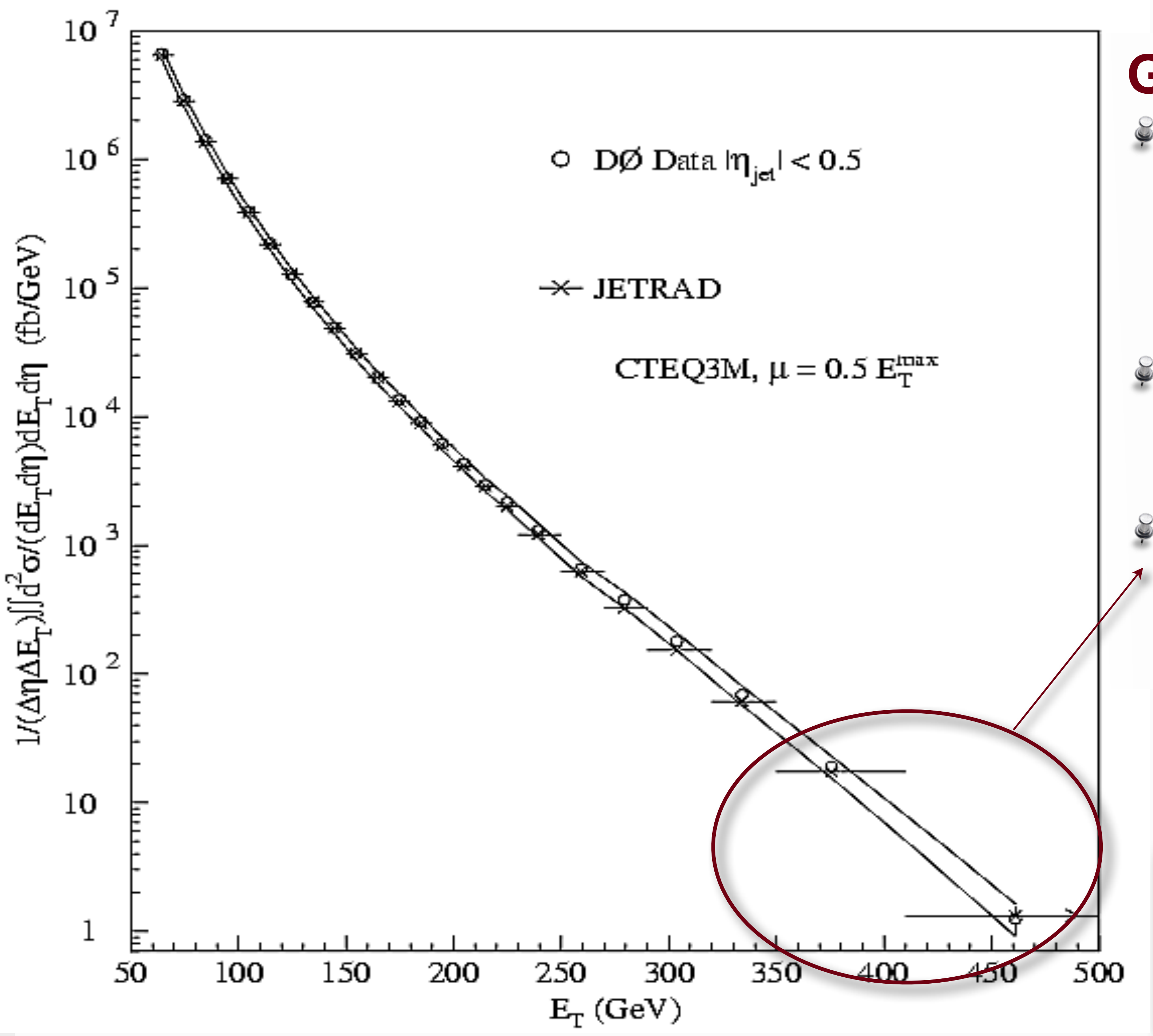

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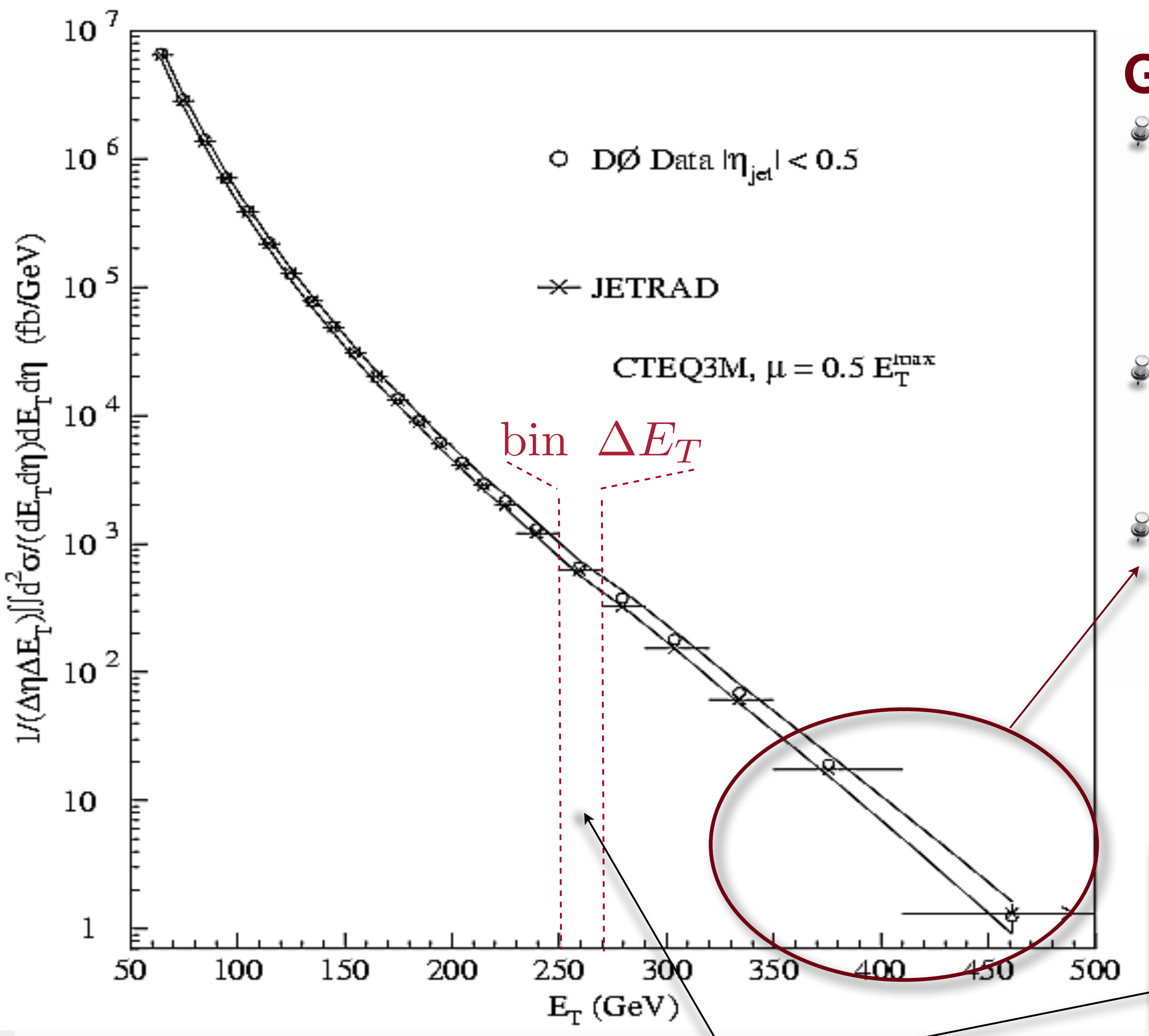

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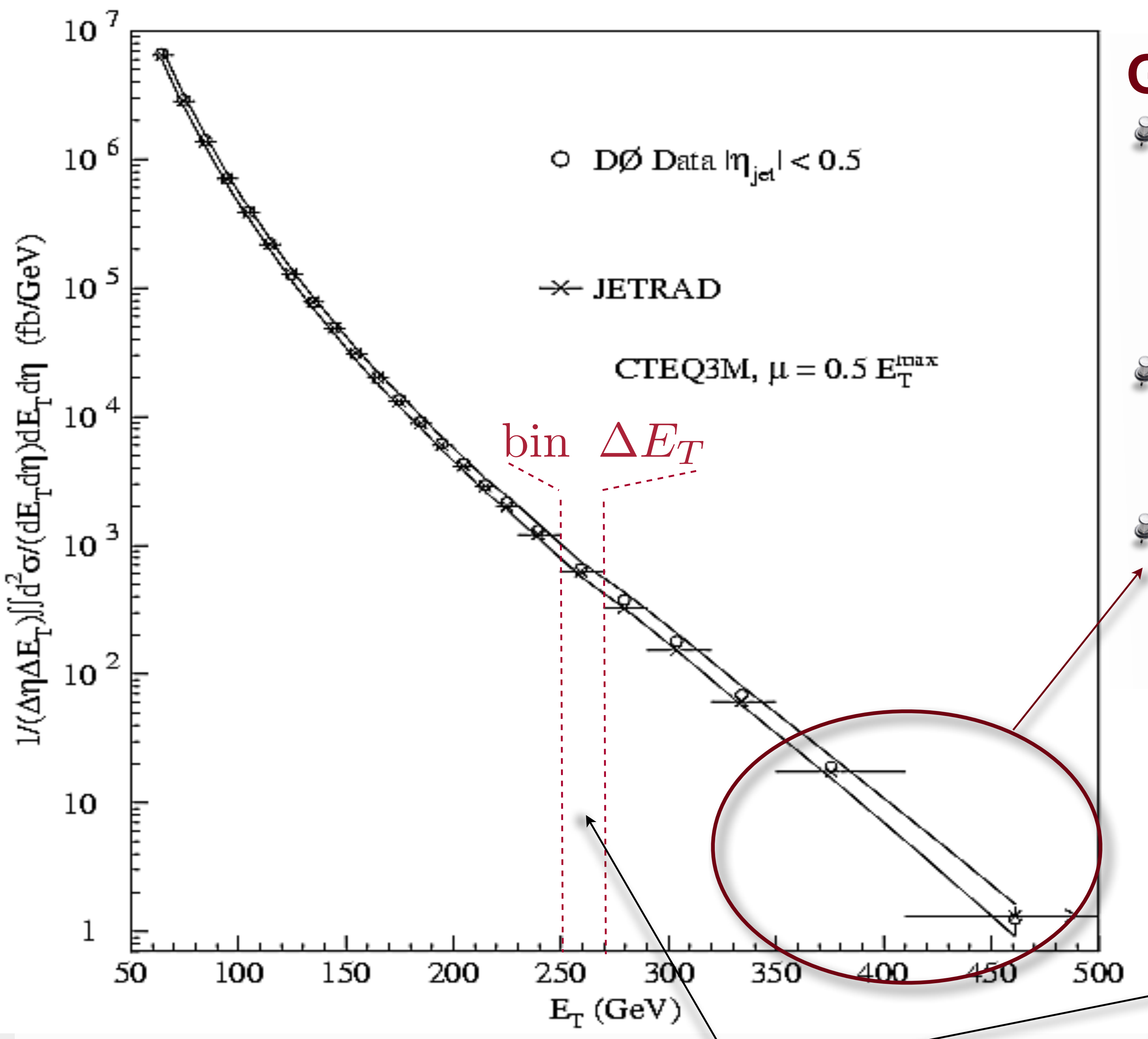
ETH Institute for Particle Physics



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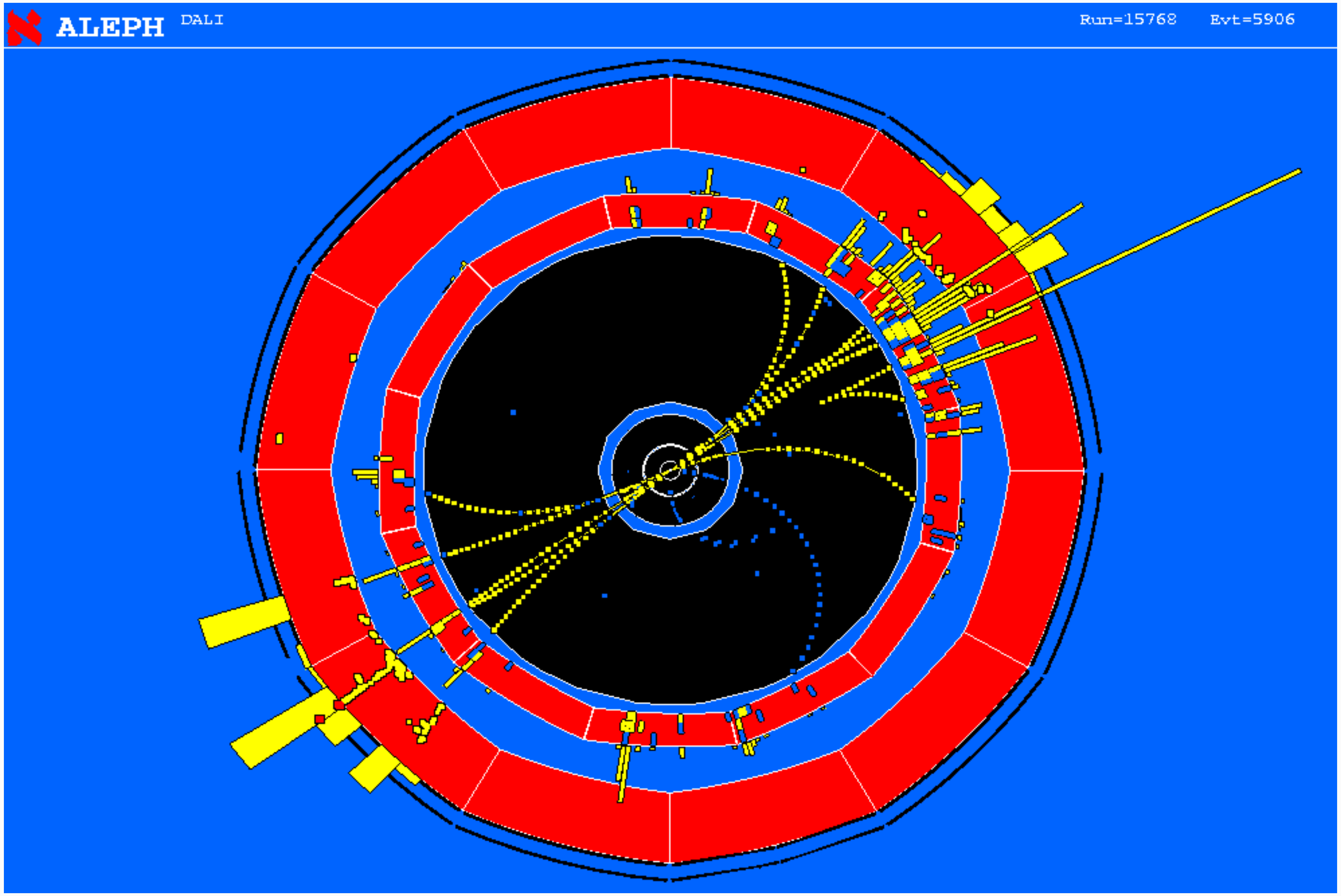
efficiency to reconstruct jets

integrated accelerator luminosity

What is a jet? (see lecture by S. Ellis)



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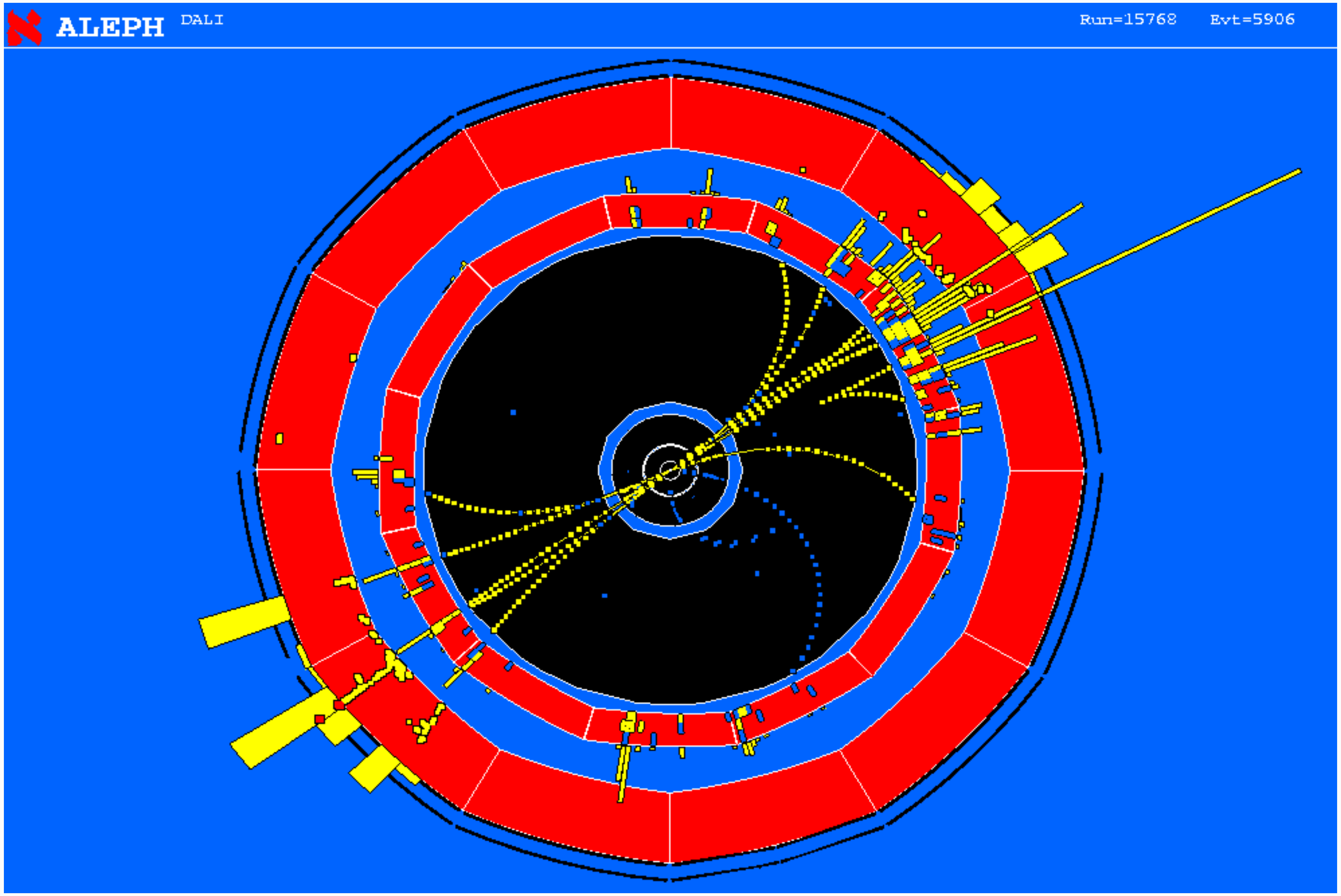

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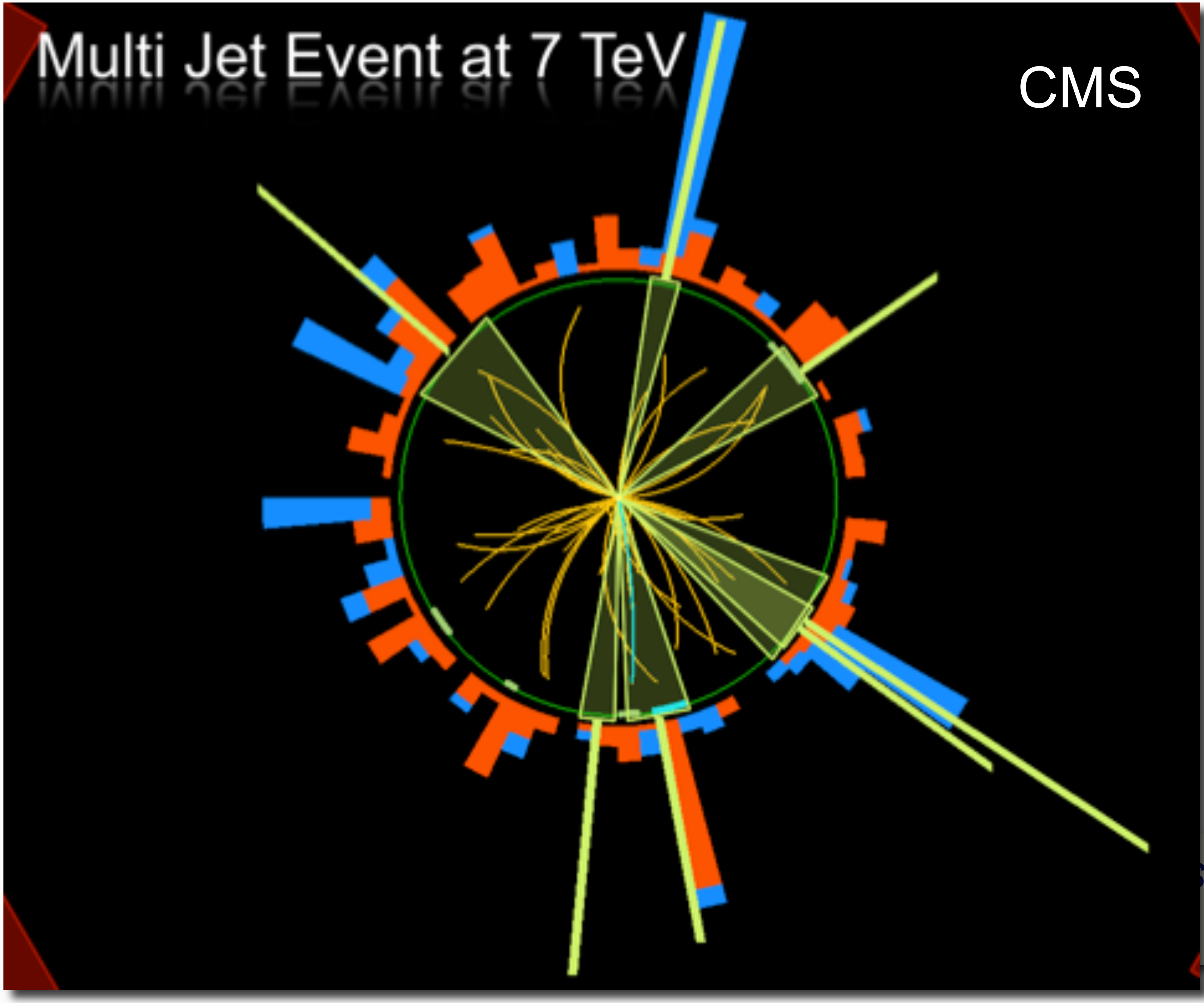

its) or flow

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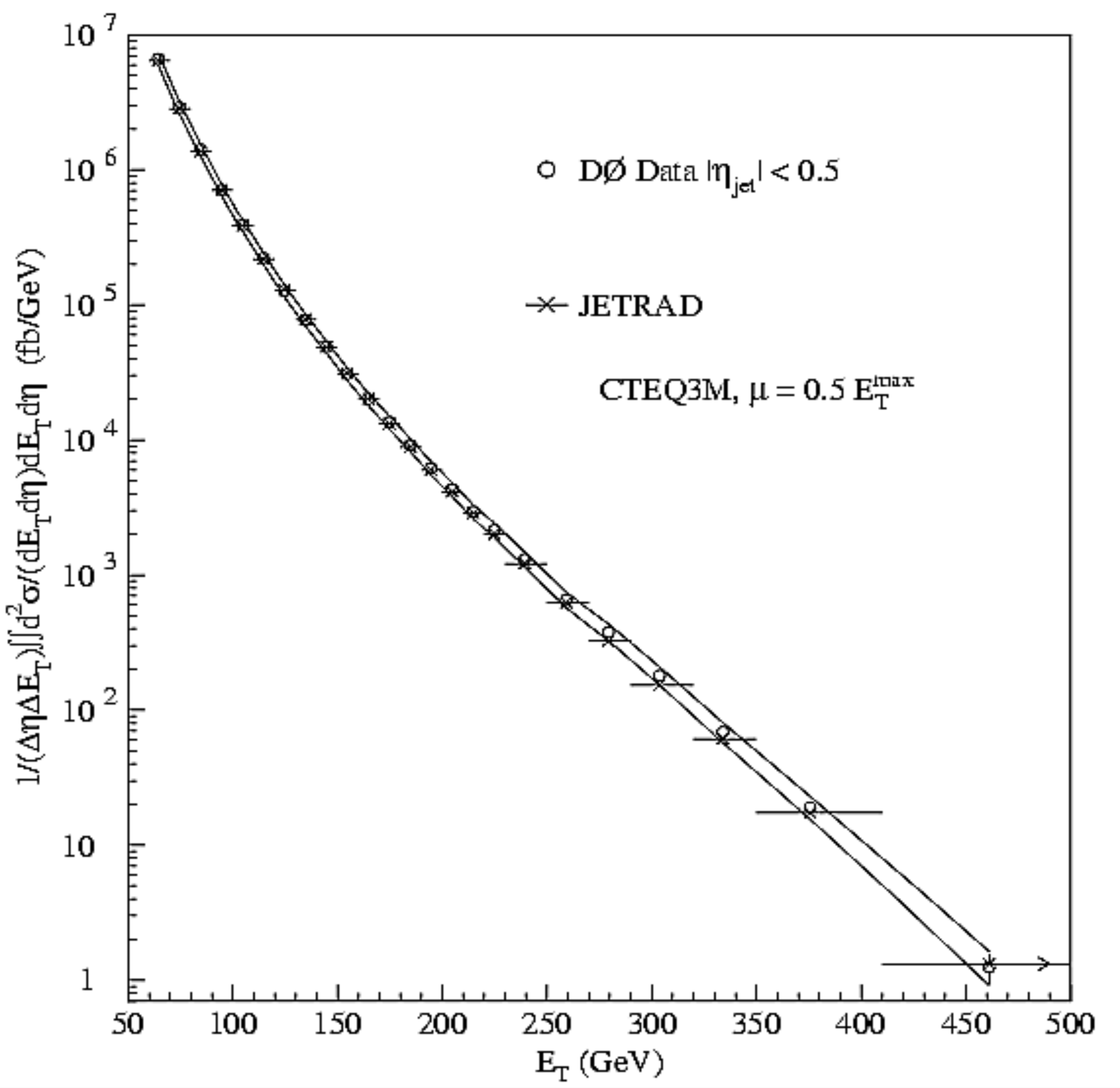
Problem 1 : Energy scale

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



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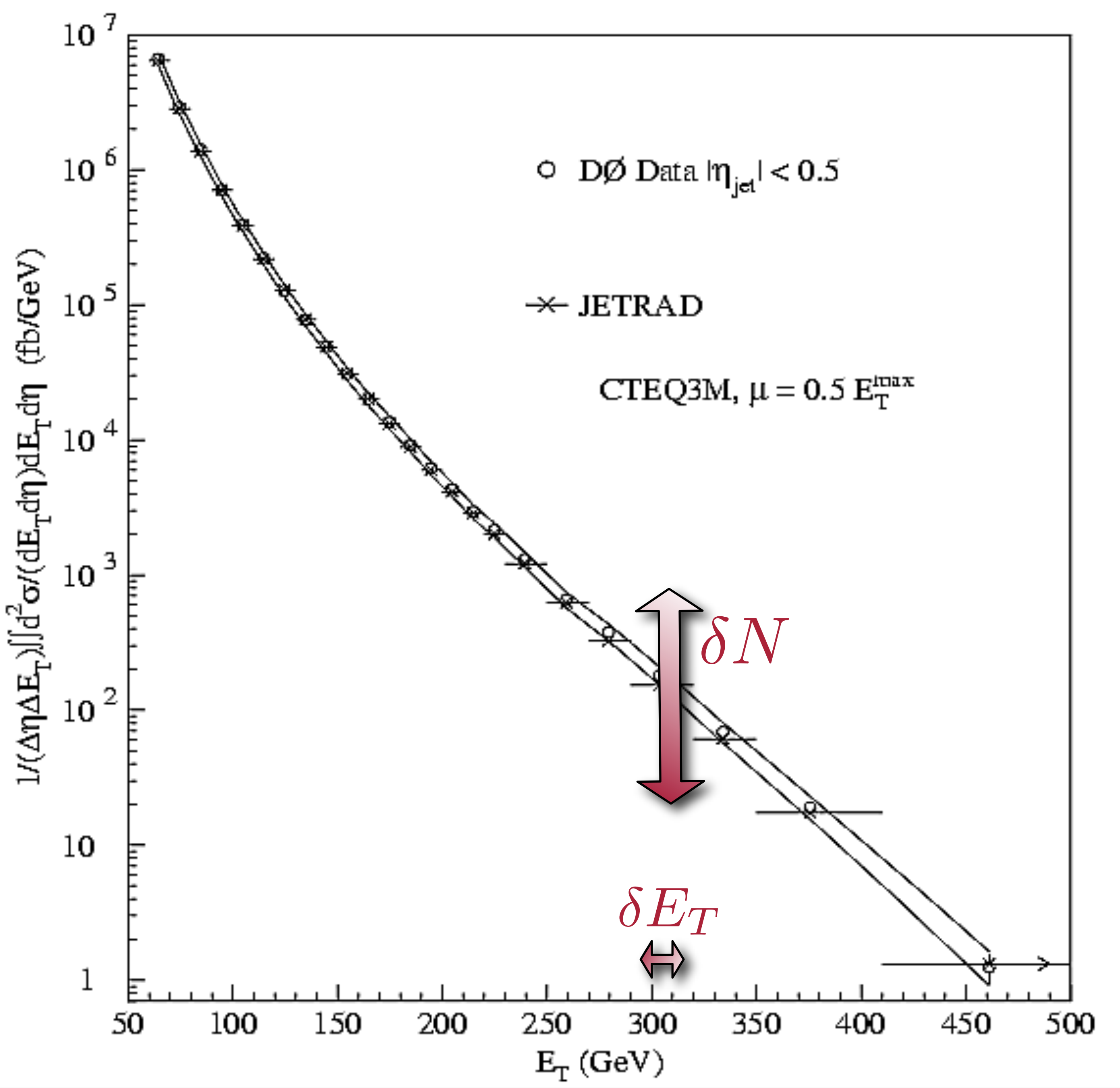

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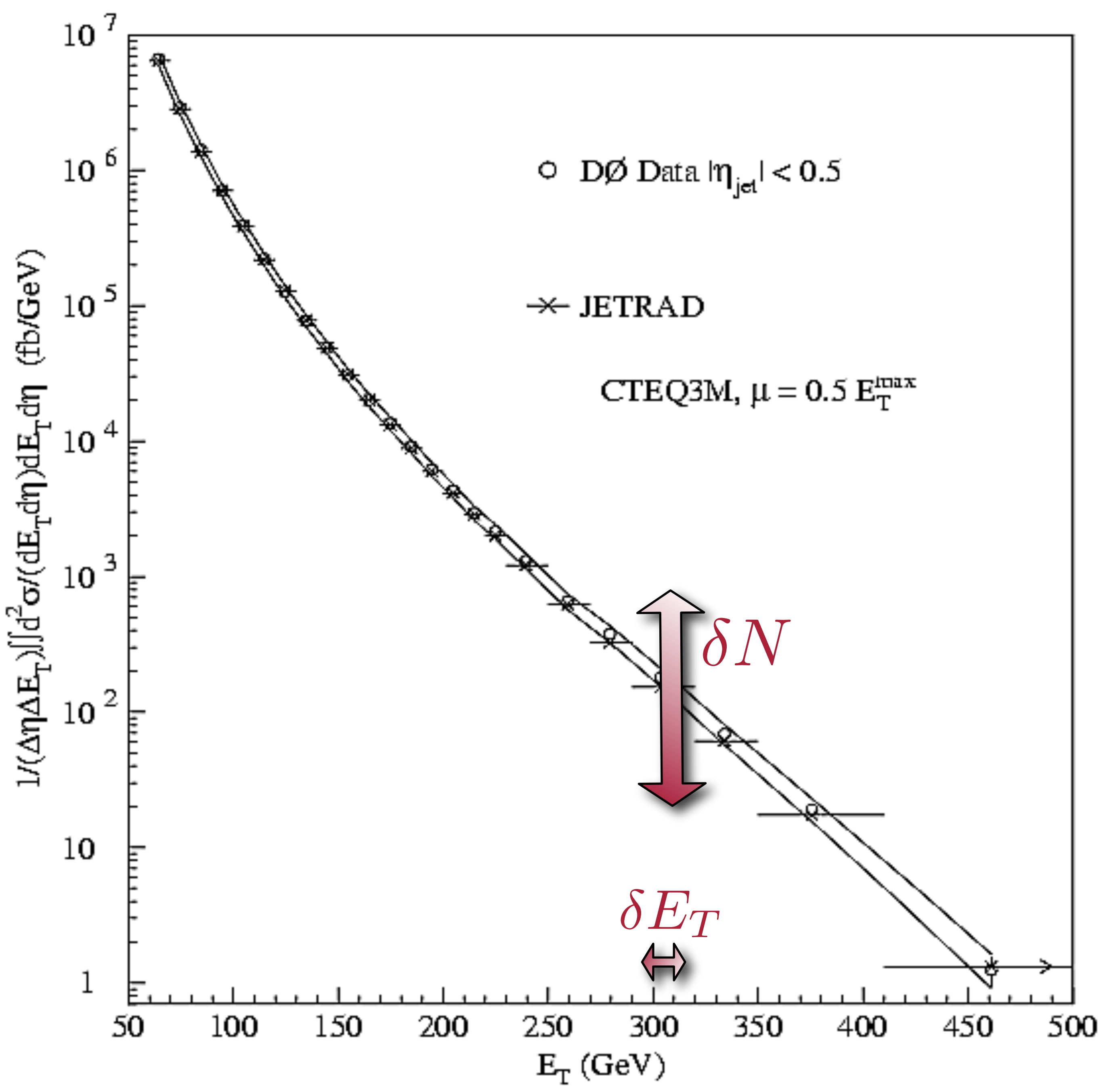

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so beware:

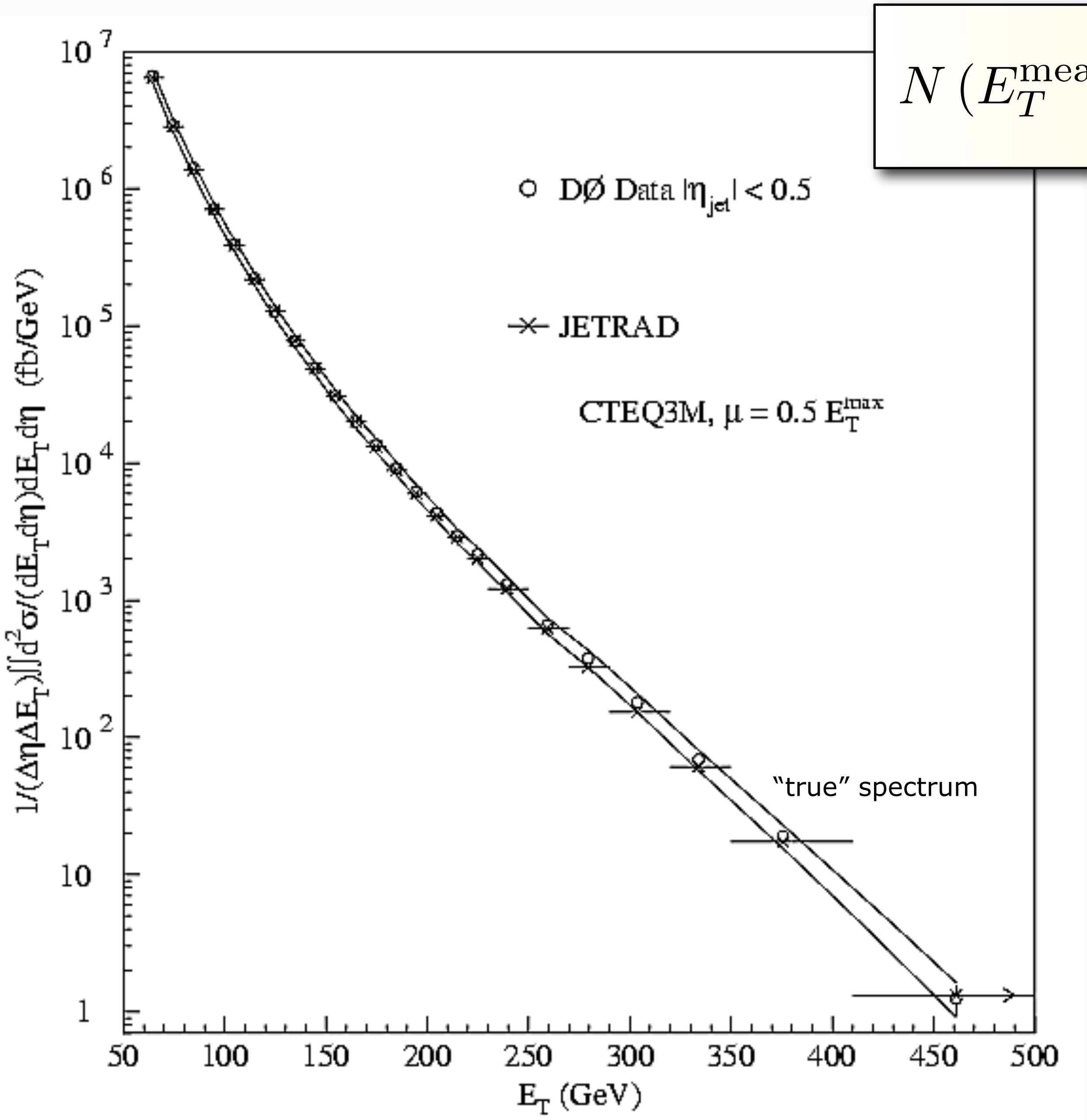
eg. an uncertainty of **5%** on absolute energy scale (calibration)

➔ 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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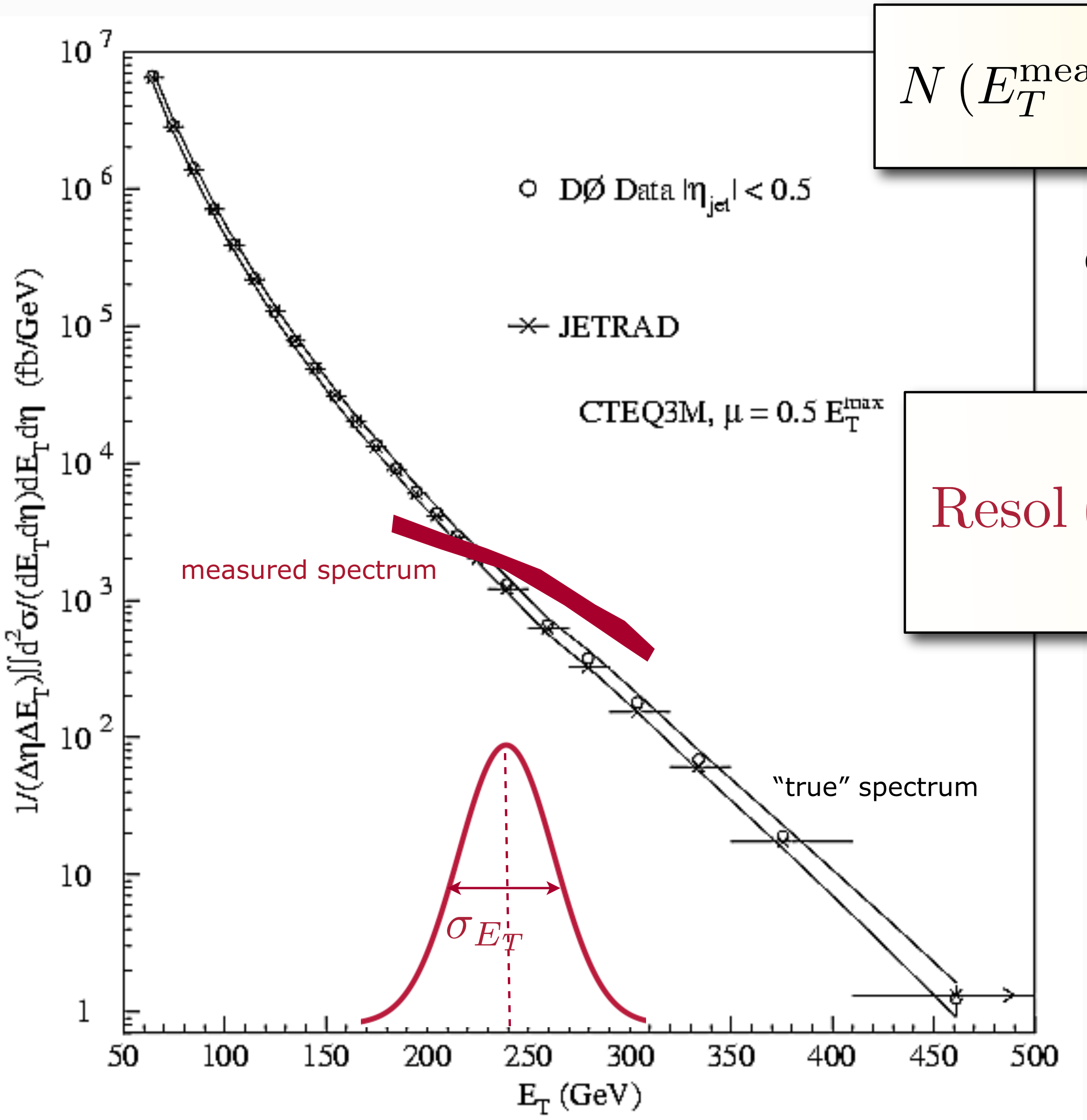

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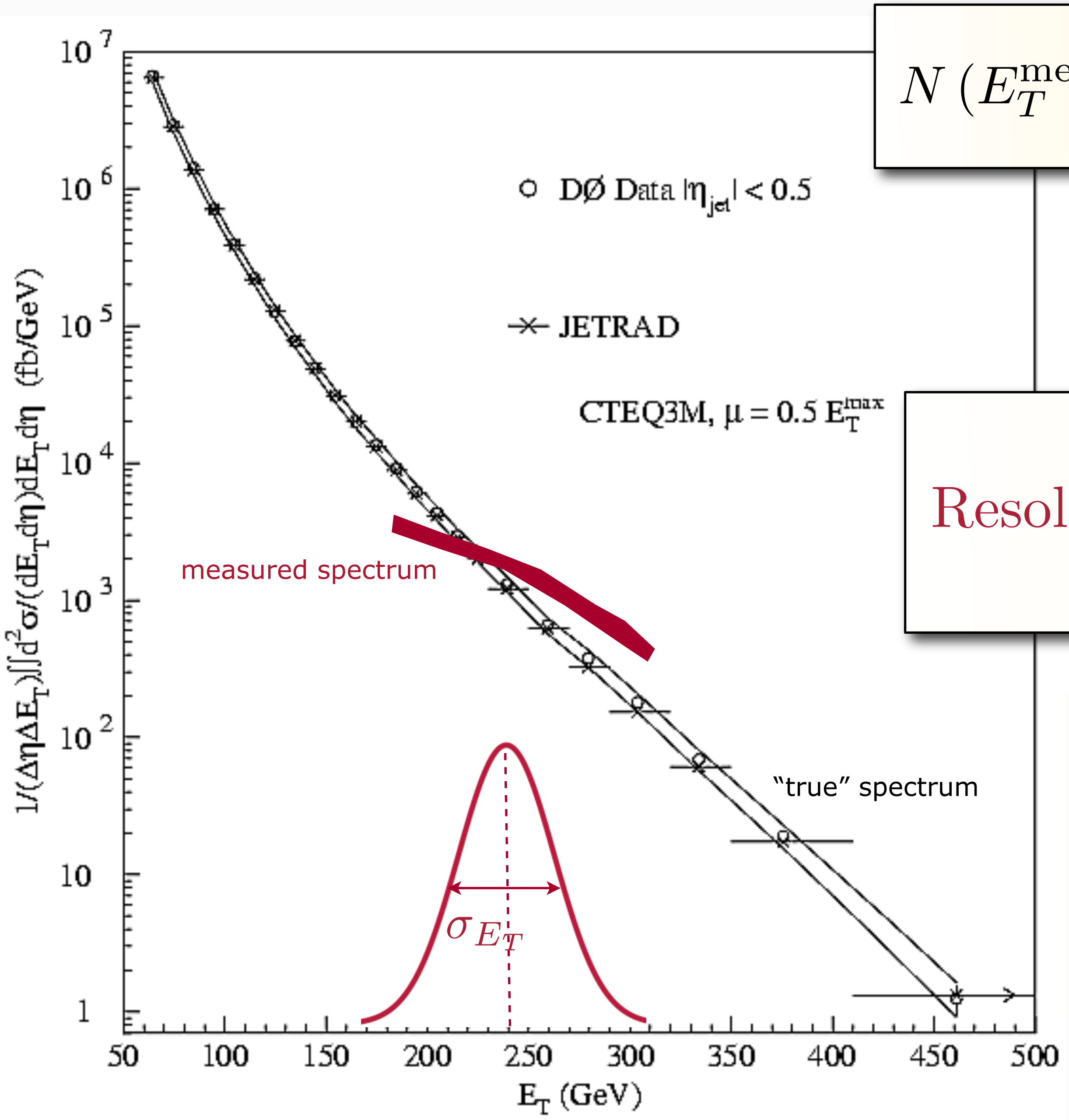

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A bad energy resolution can distort the true spectrum

➔ 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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  - if distributions are measured : take care of absolute calibrations and effects because of detector resolution/smearing
    - correct for these effects

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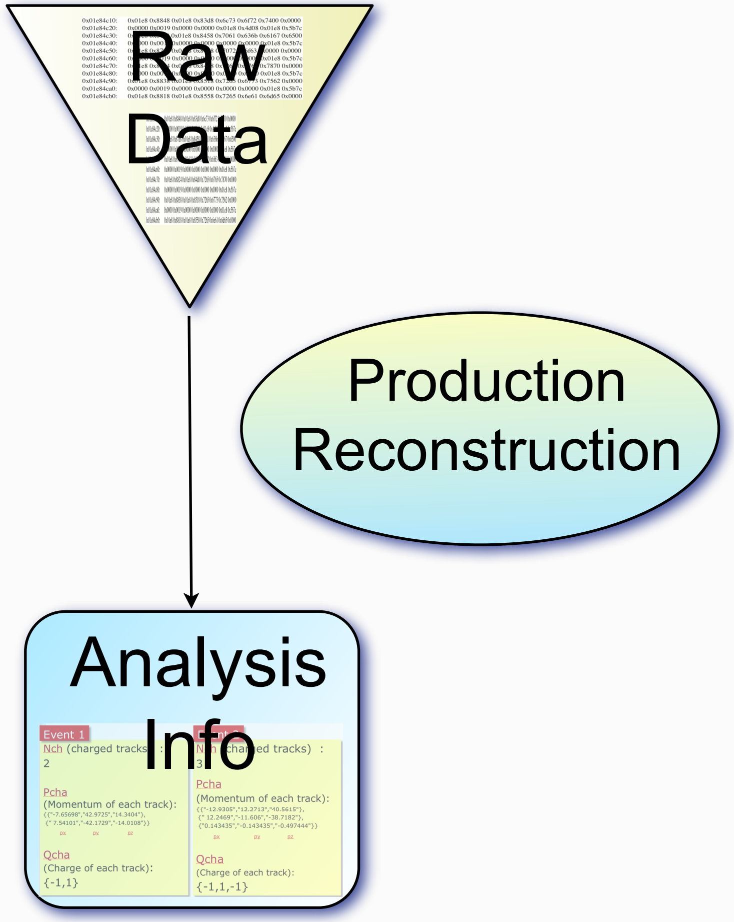
  - determine parameters, eg. by fitting the prediction to the data

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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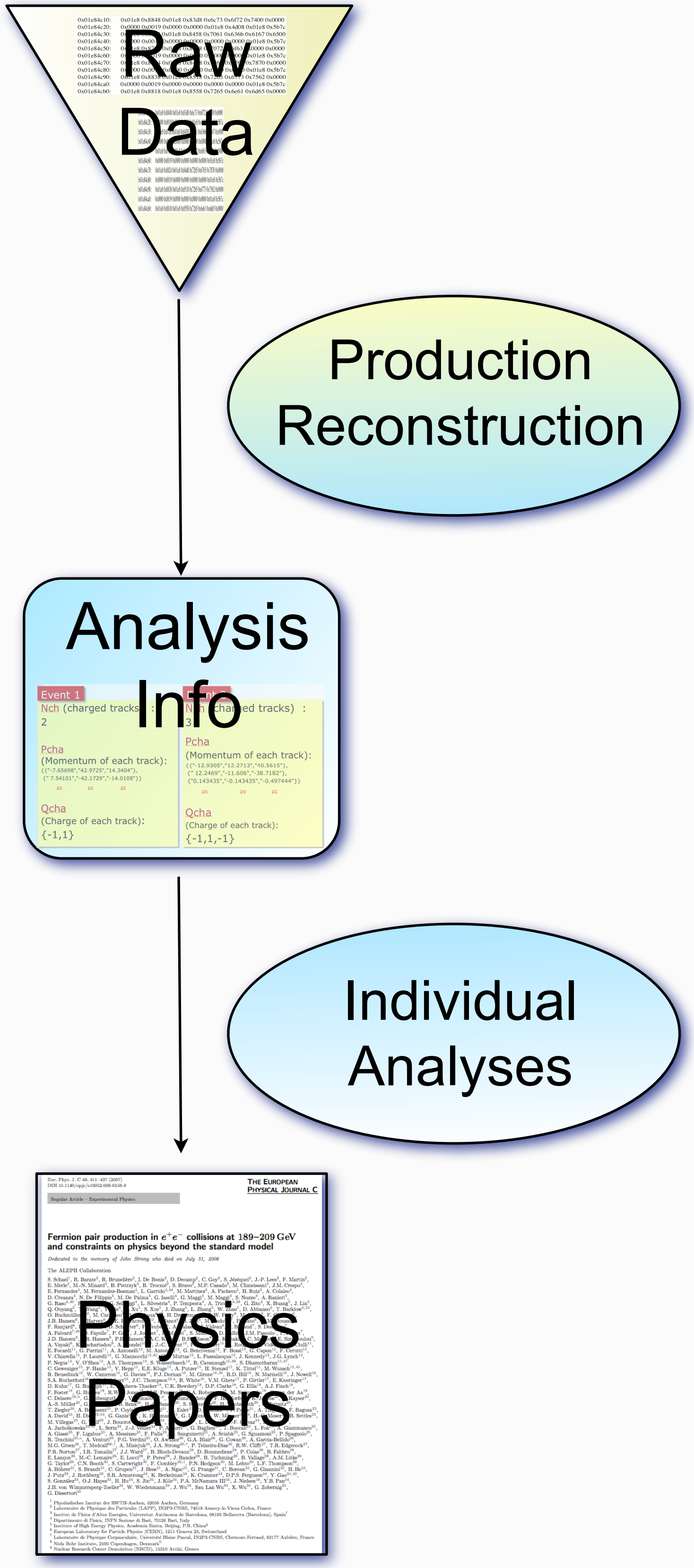

Raw Data

Production Reconstruction

Analysis Info

Individual Analyses

Physics Papers

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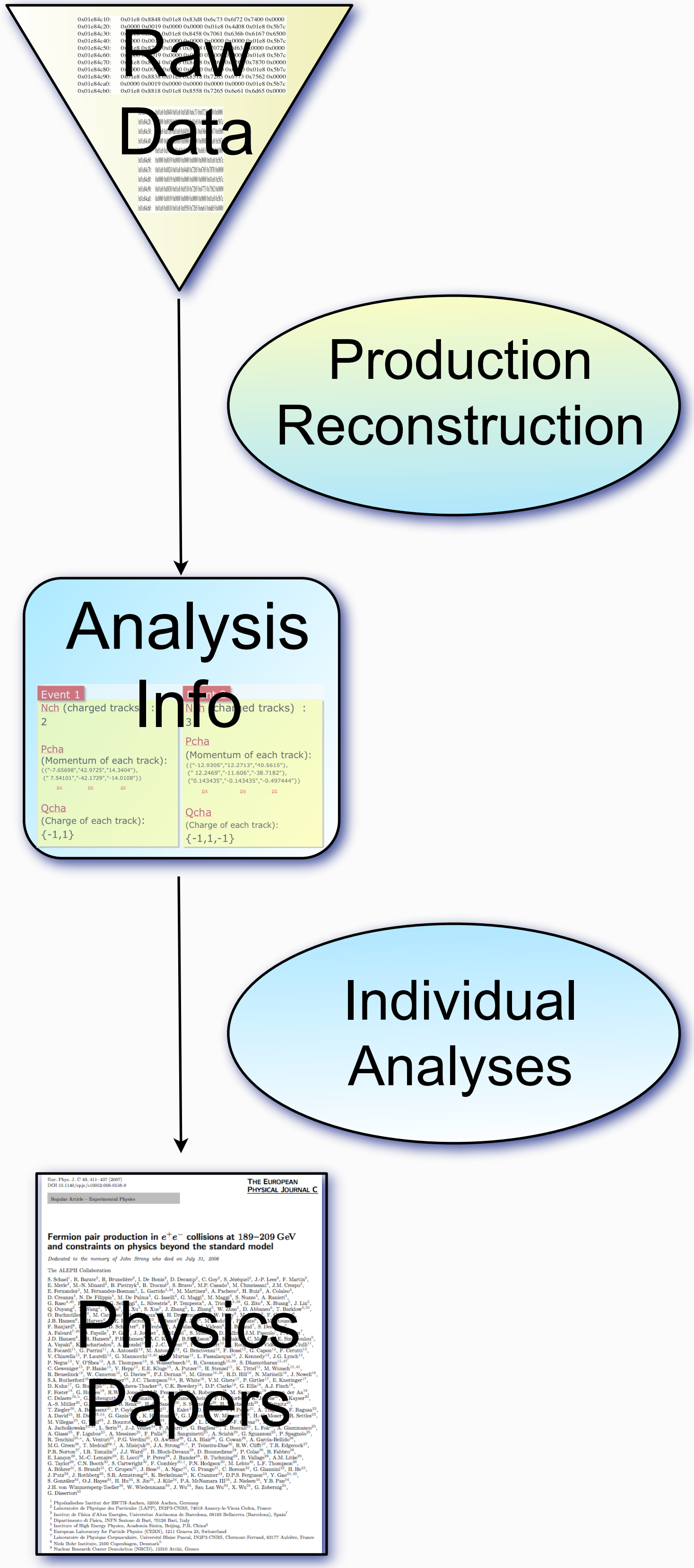
- Collaborations build offline computing systems to handle all this



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Track finding

Why does tracking need to be done well?

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  - direction, magnitude
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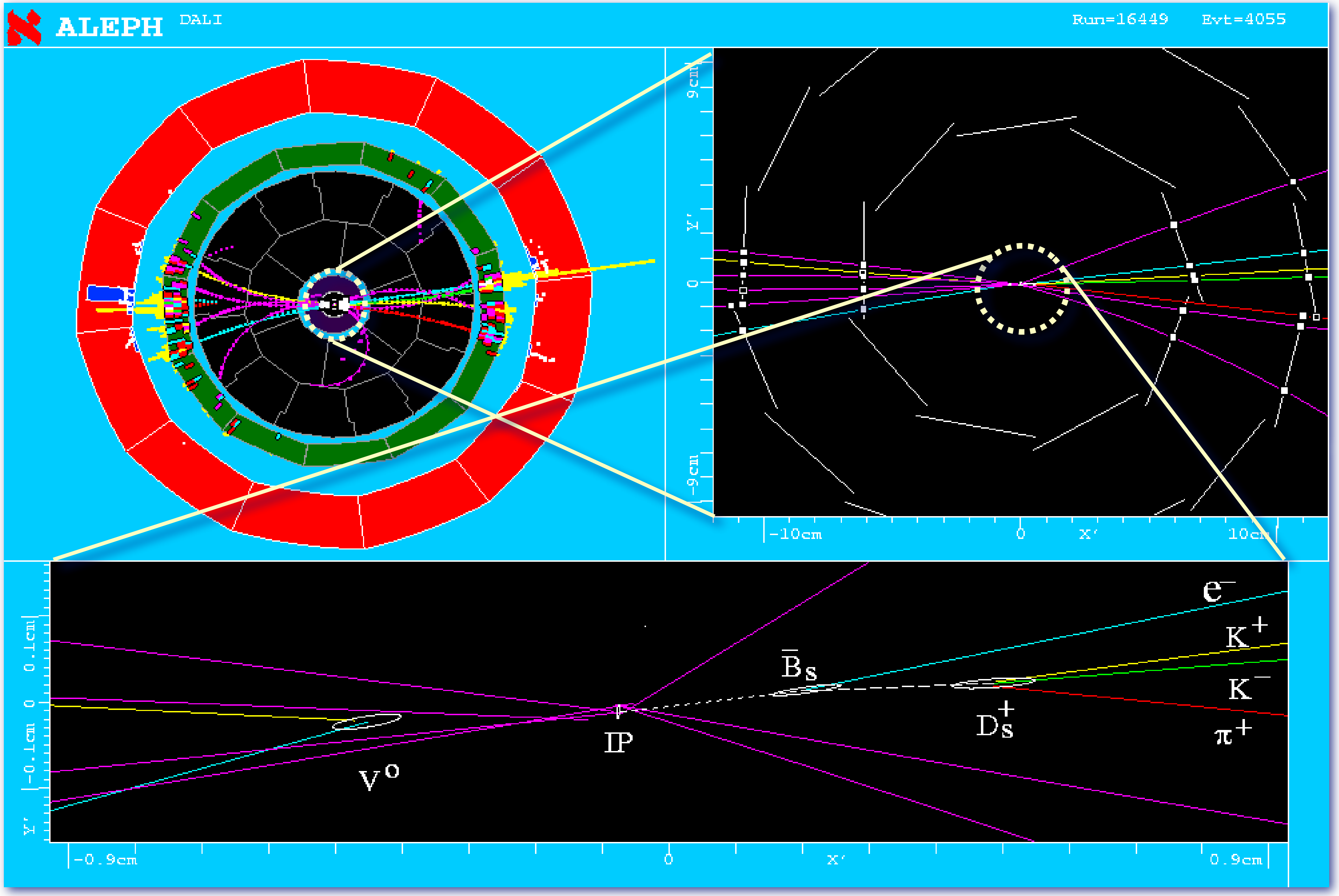

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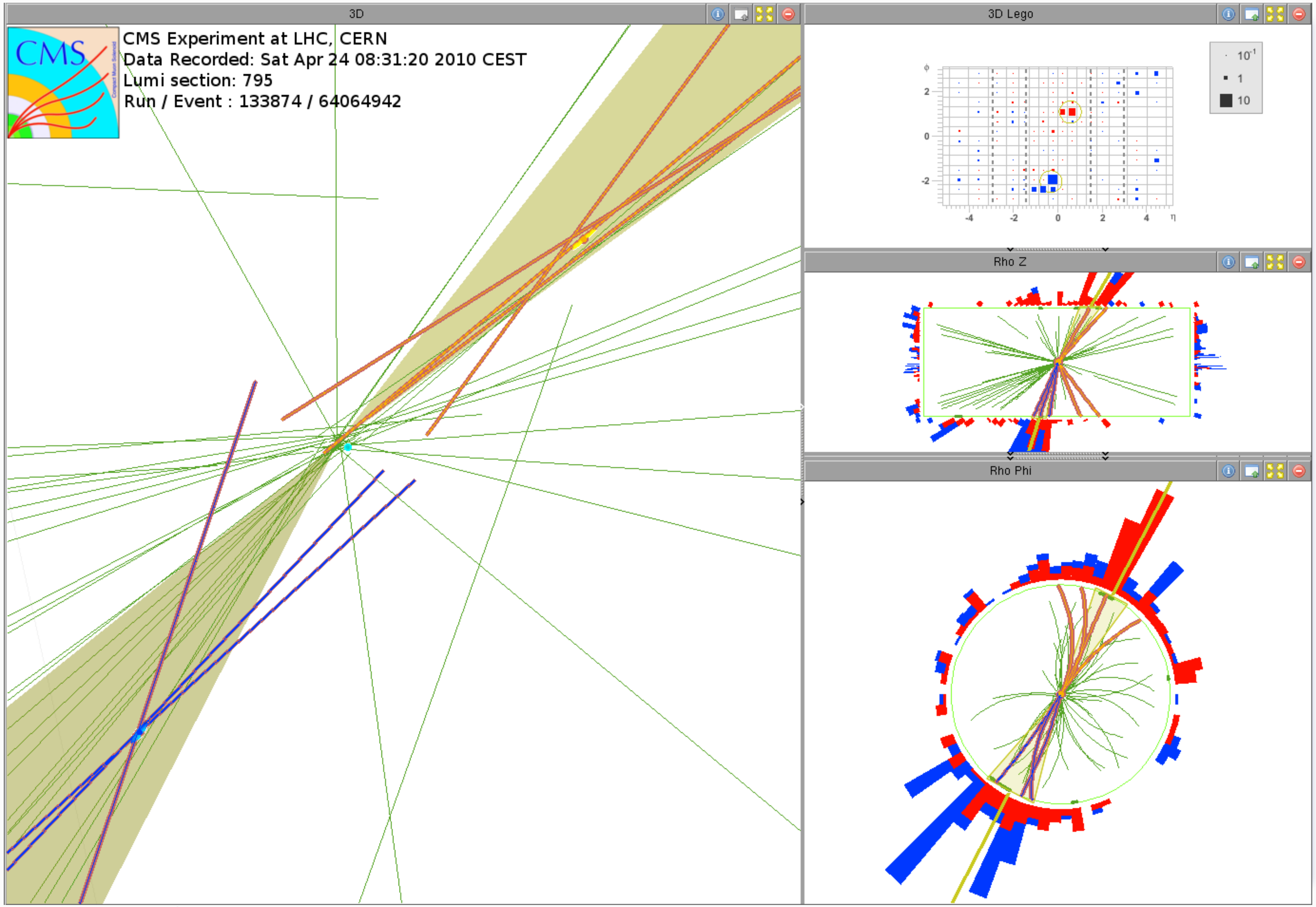

CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
Run / Event : 133874 / 64064942

Track Fitting

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- Two perfect measurements
  - away from interaction point
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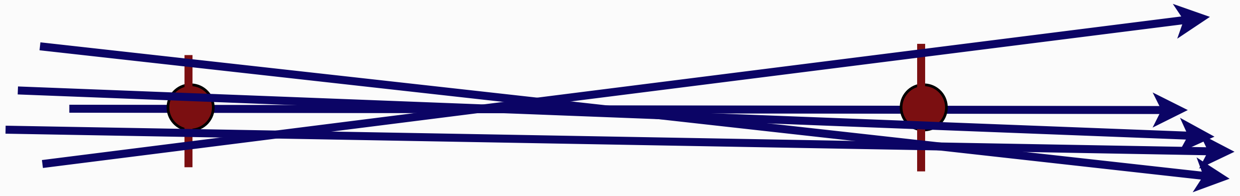

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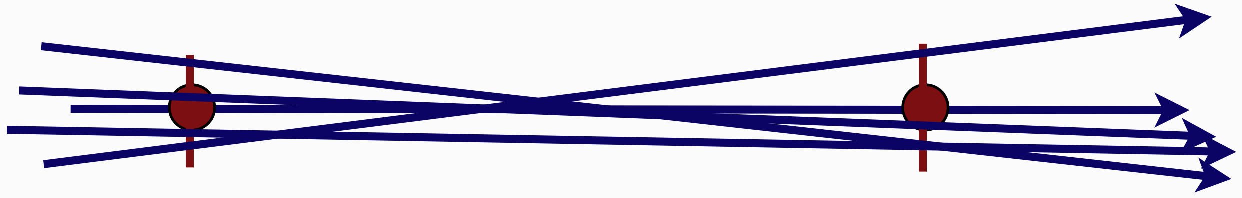

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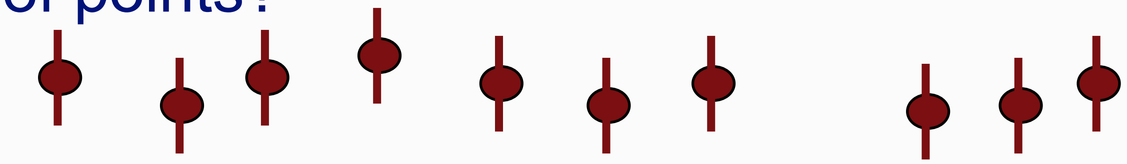

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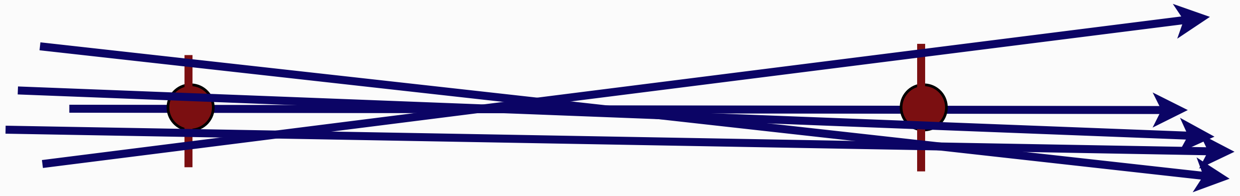

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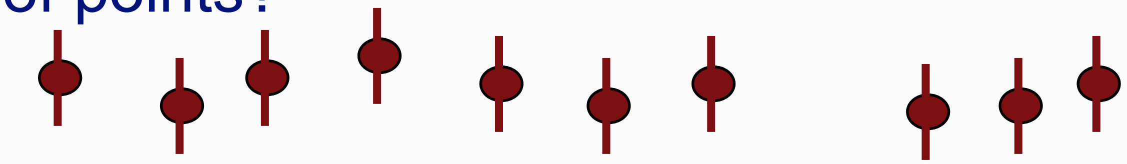

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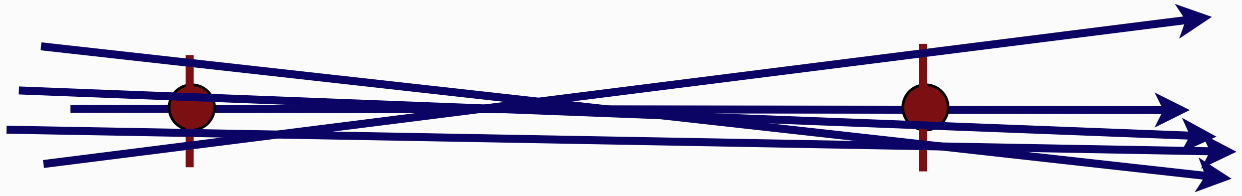

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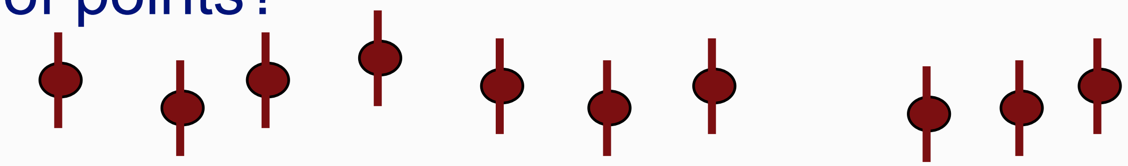

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predicted track position at i^{th} hit

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see also lecture by G. Cowan

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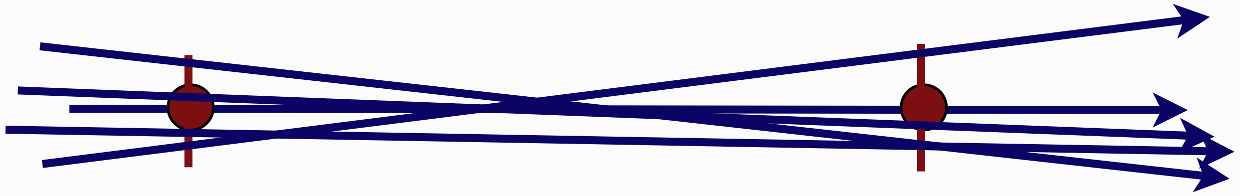

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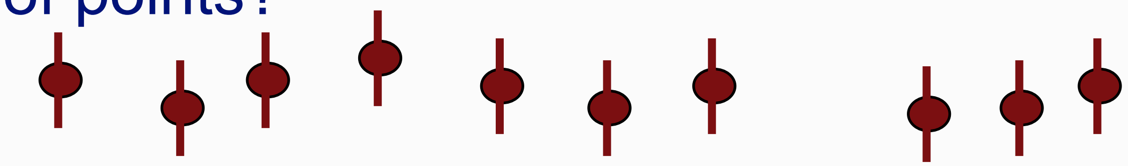

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$$\delta\theta \qquad \delta d$$

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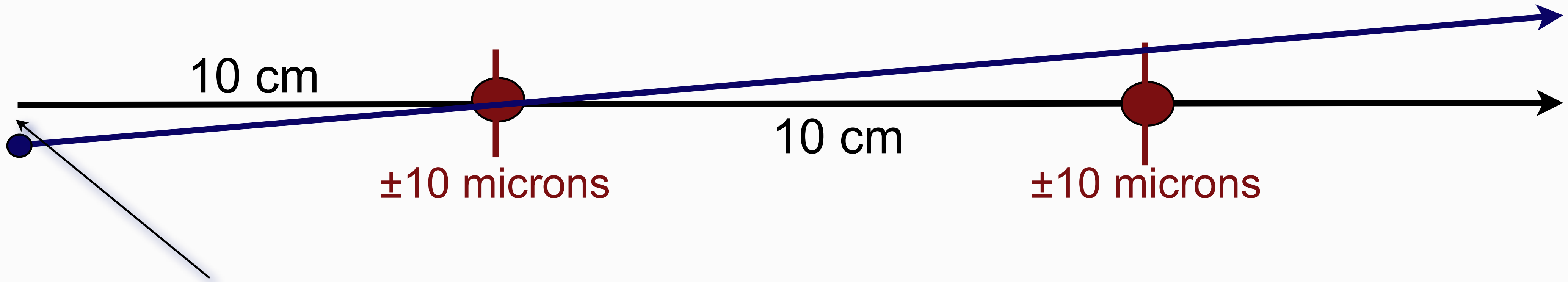
“Typical” size of errors



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- Error δΘ on angle is about ±0.1 milliradians (±0.002 degrees)
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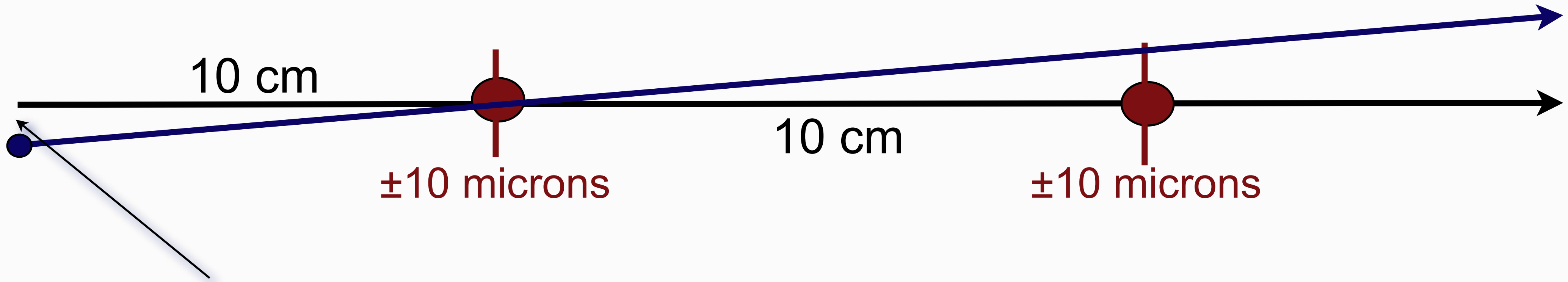

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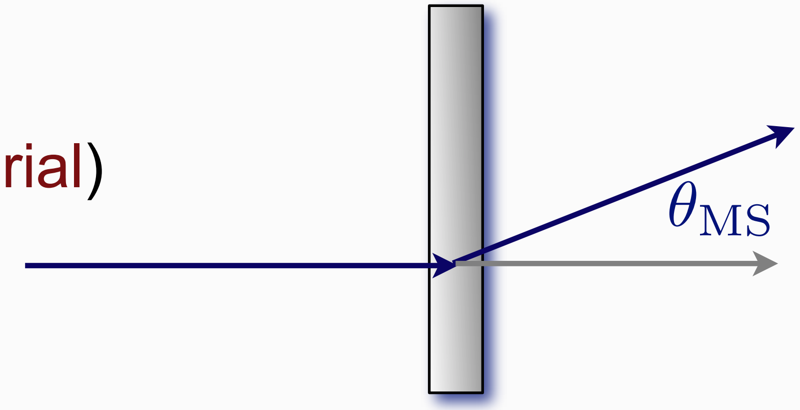

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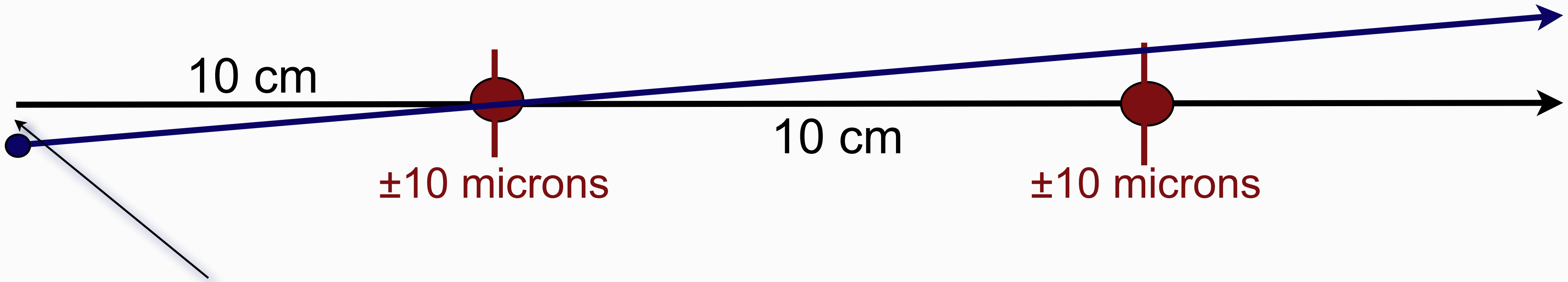

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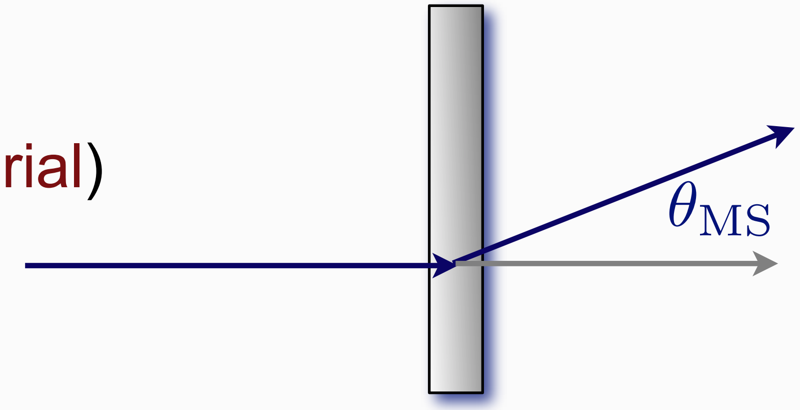

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  - we “see” particles by interaction with a detector (=material)
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  - This is **Multiple Scattering**
    - Charged particles passing through matter “scatter” by a random angle

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

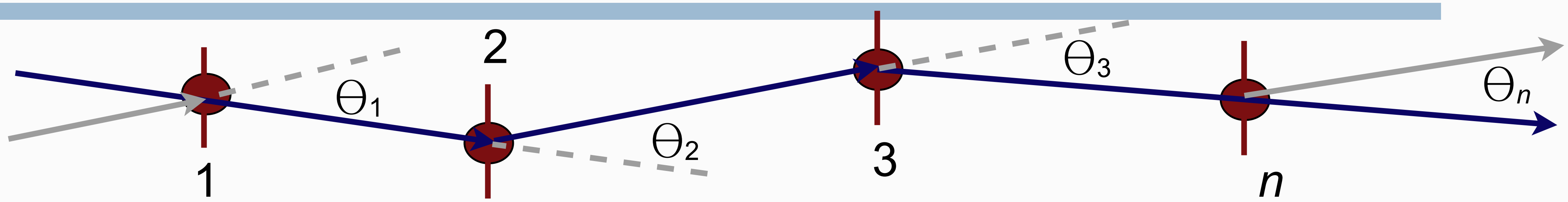
examples:

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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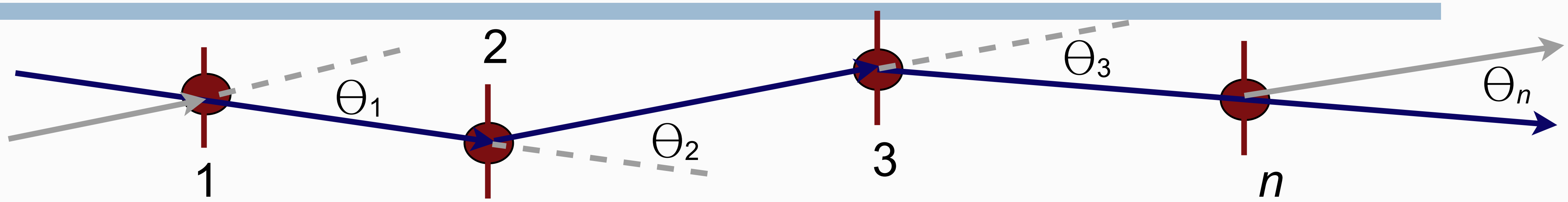

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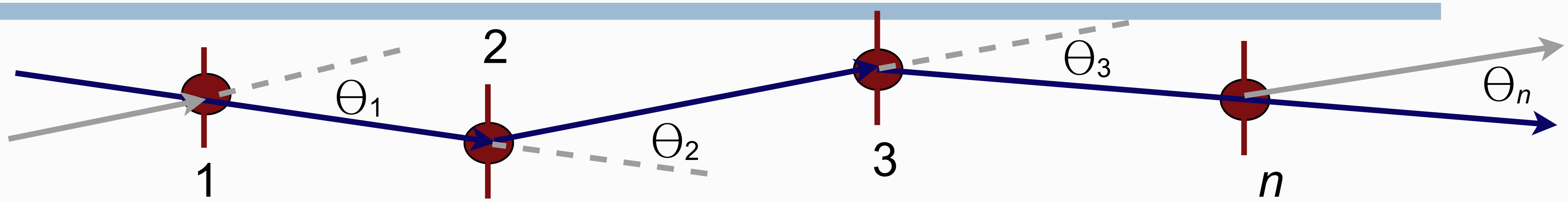

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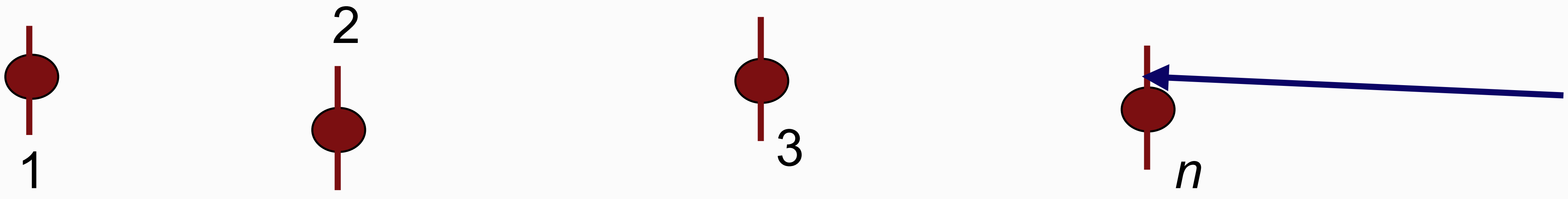

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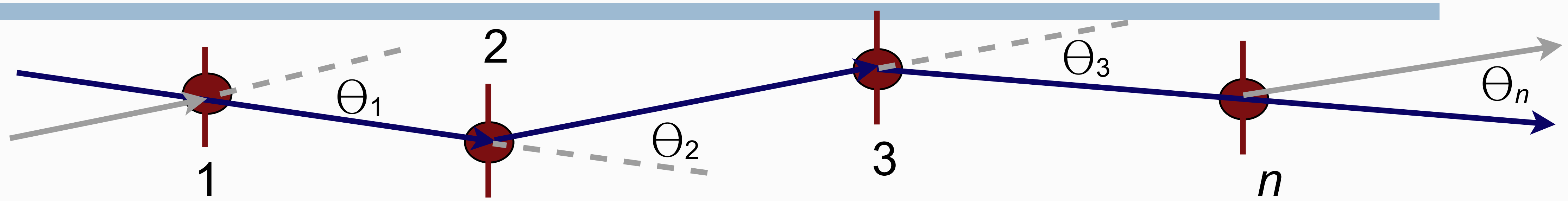

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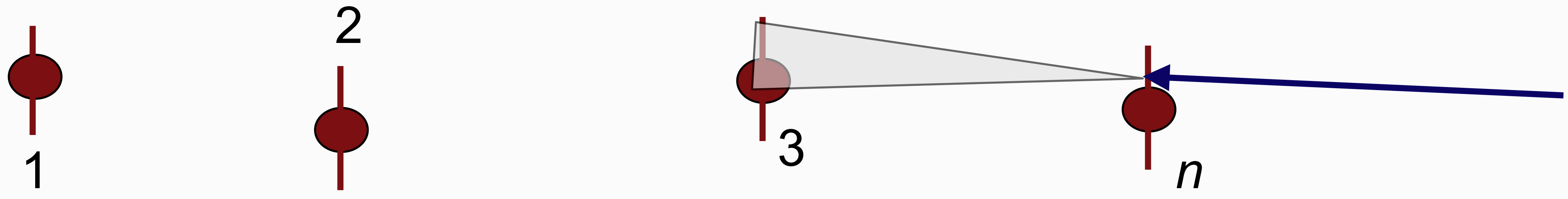

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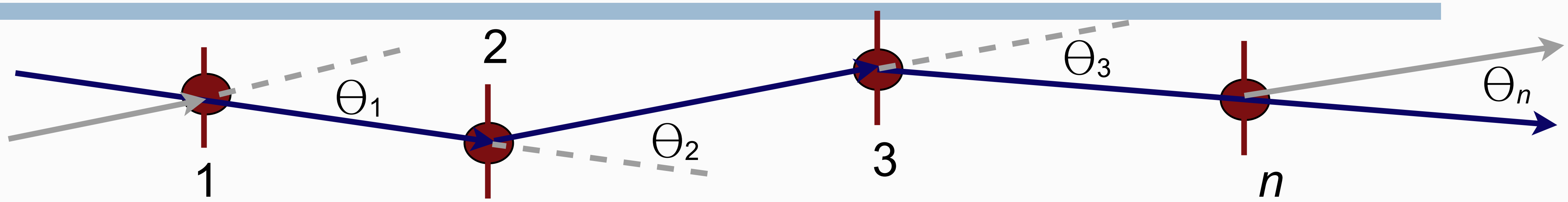

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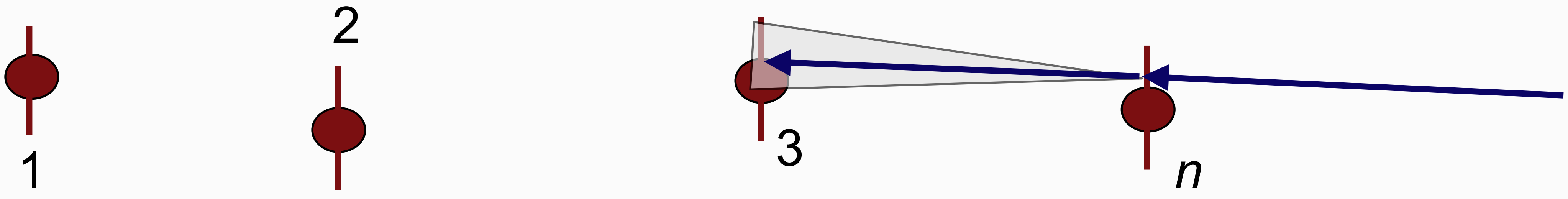

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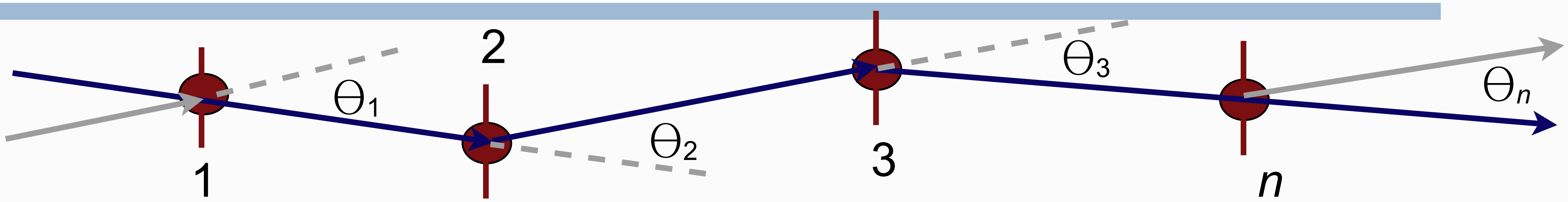

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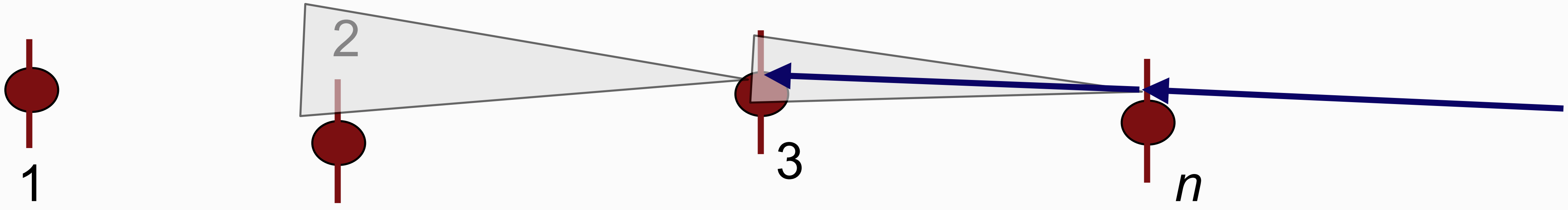

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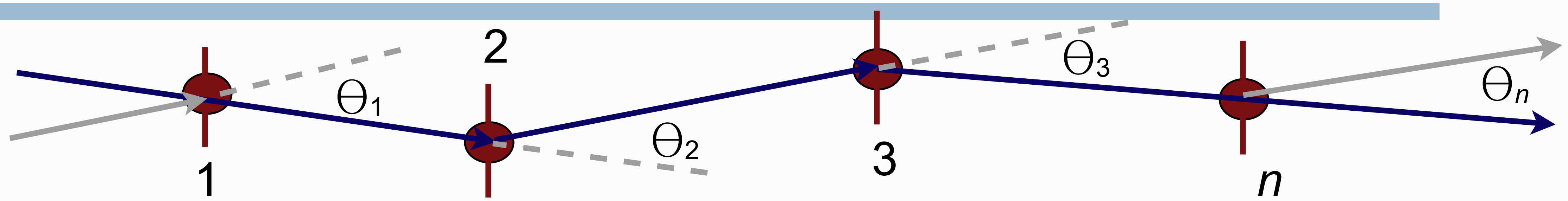

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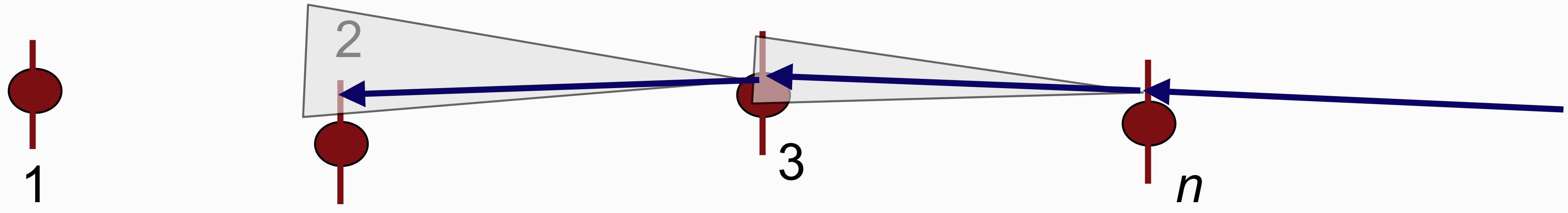

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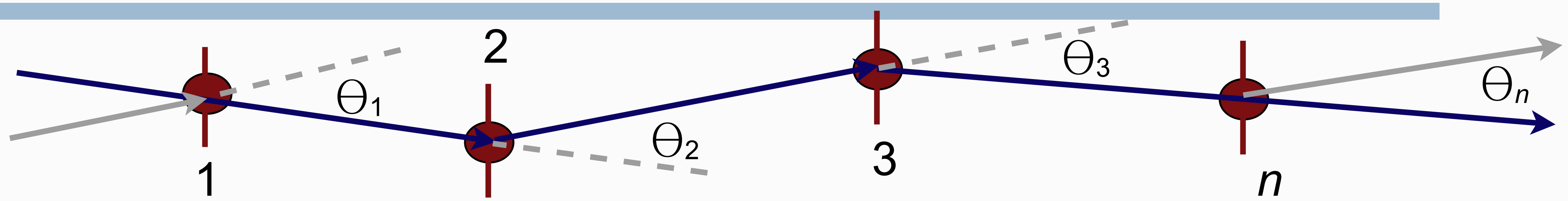

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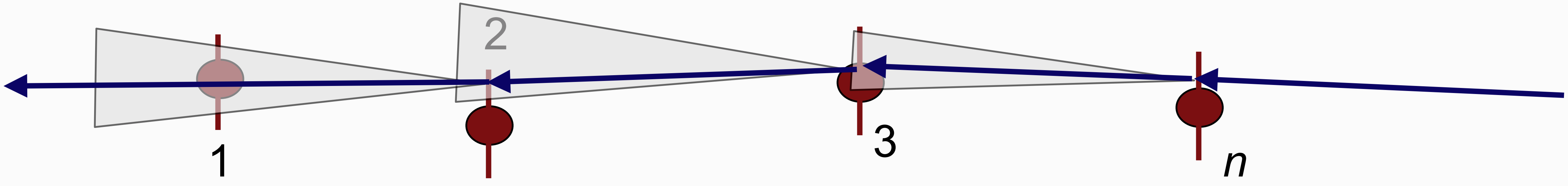

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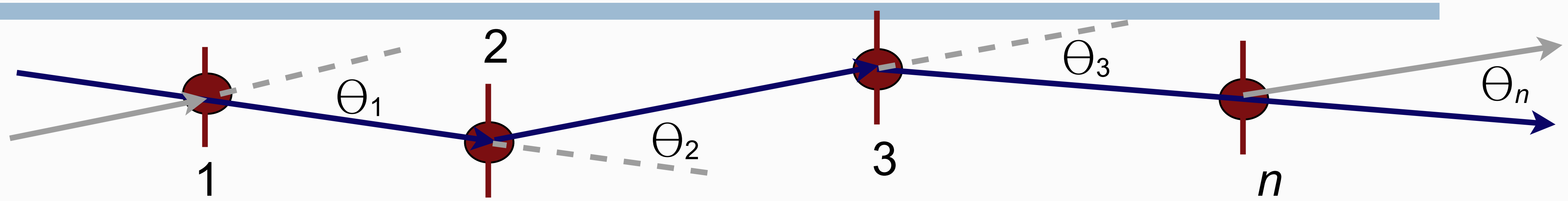

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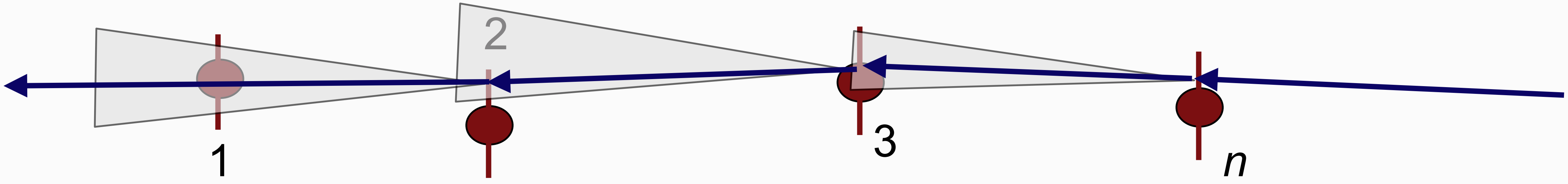
  - anyway, not interested in all these angles, only in parameters at the origin

$$\chi^2 = \chi^2_{\mathrm{old}} + \sum_i \frac{\theta_i^2}{\sigma^2_{\mathrm{MS}}}$$

- Instead, approximate, work inward *N* times

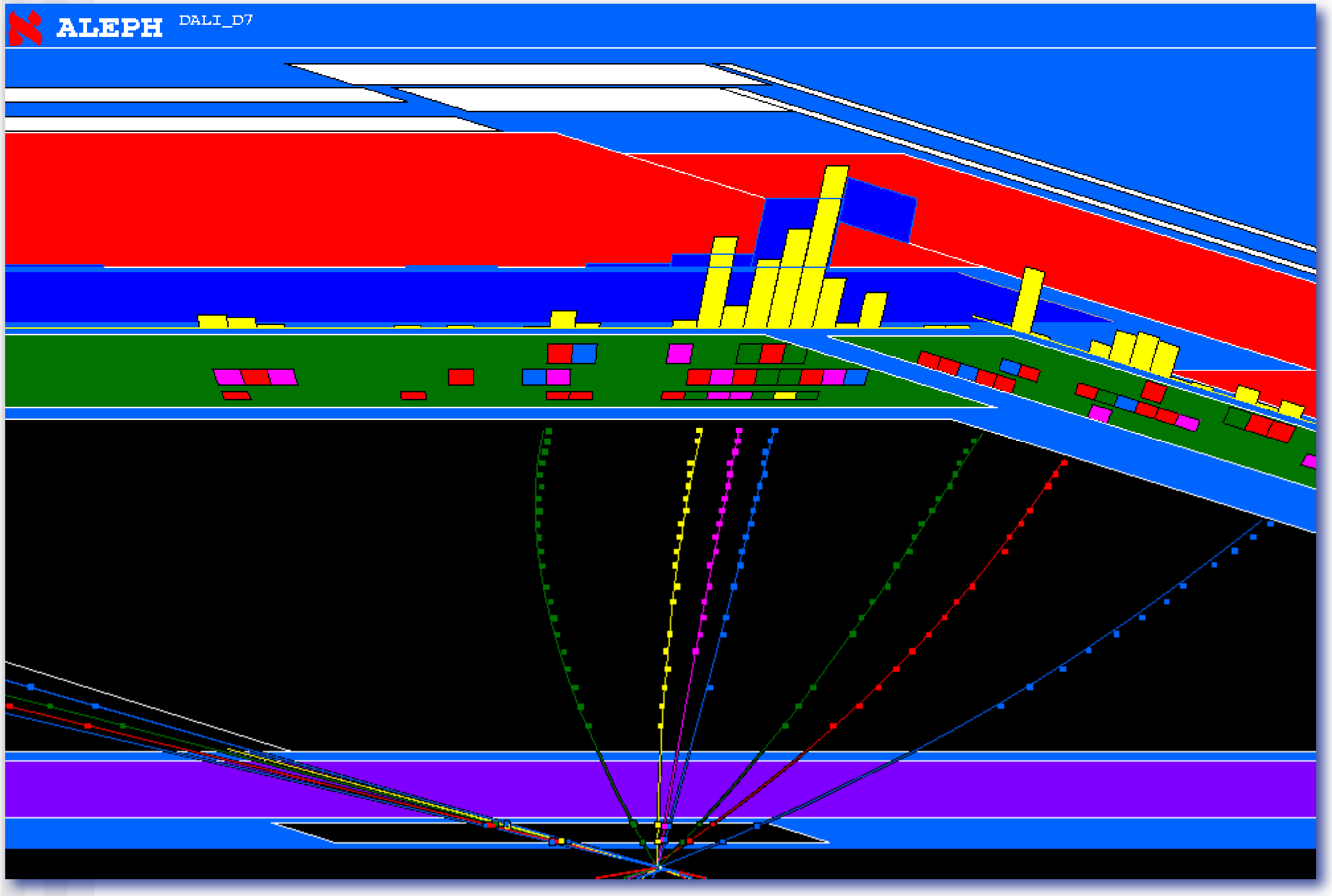


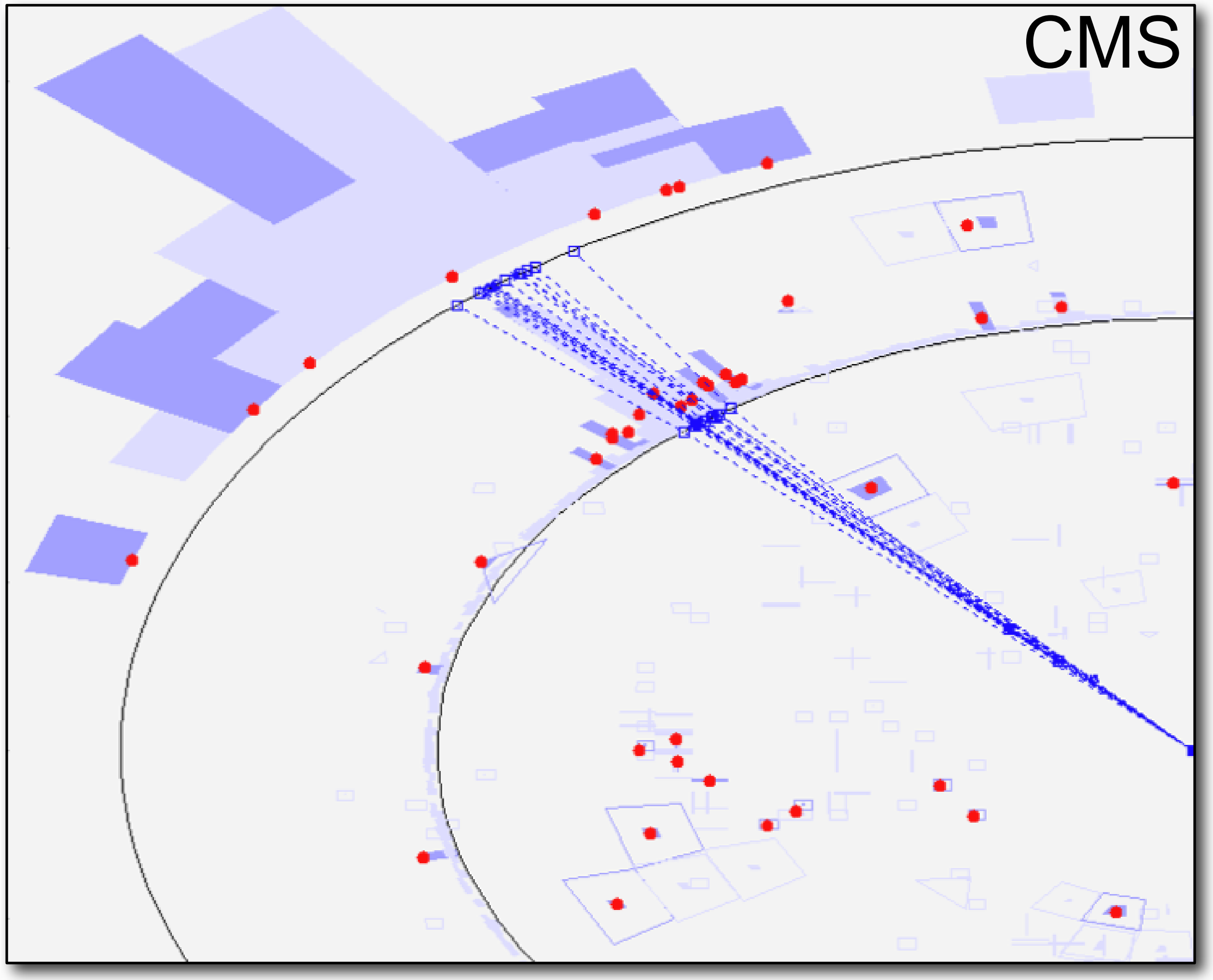
  - leads to O(*n*) computations!
  - in each step, make extrapolation to next layer, using information from current track parameters, expected scattering error, and measurement at next layer
  - Needs a starting estimate (seed) and may need some iterations, smoothing
  - This method is based on theory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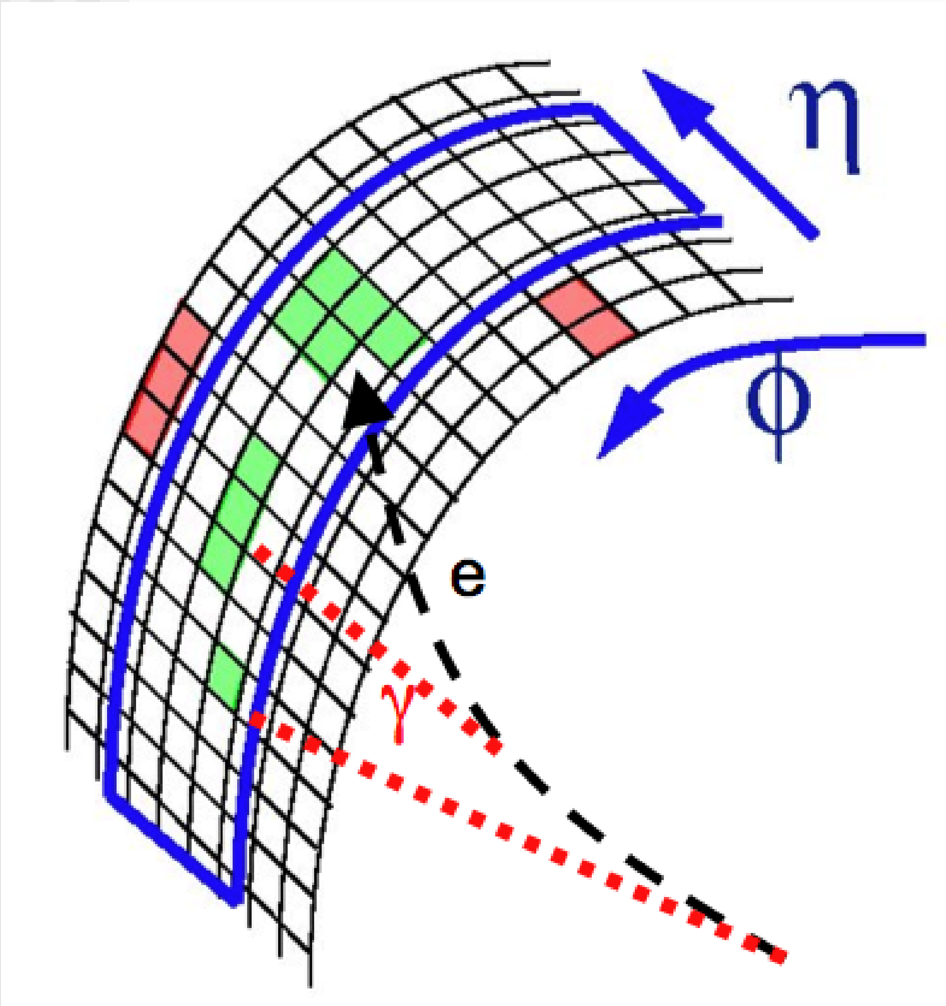
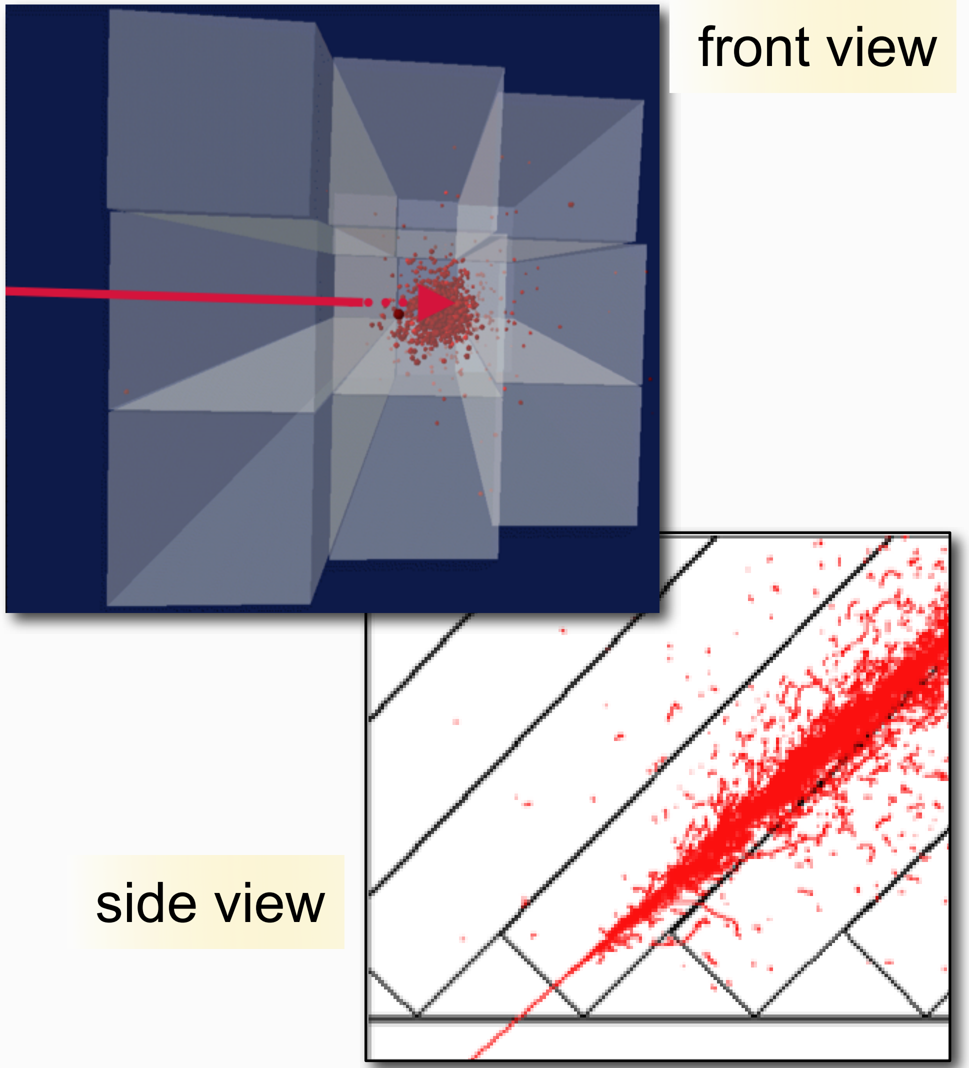
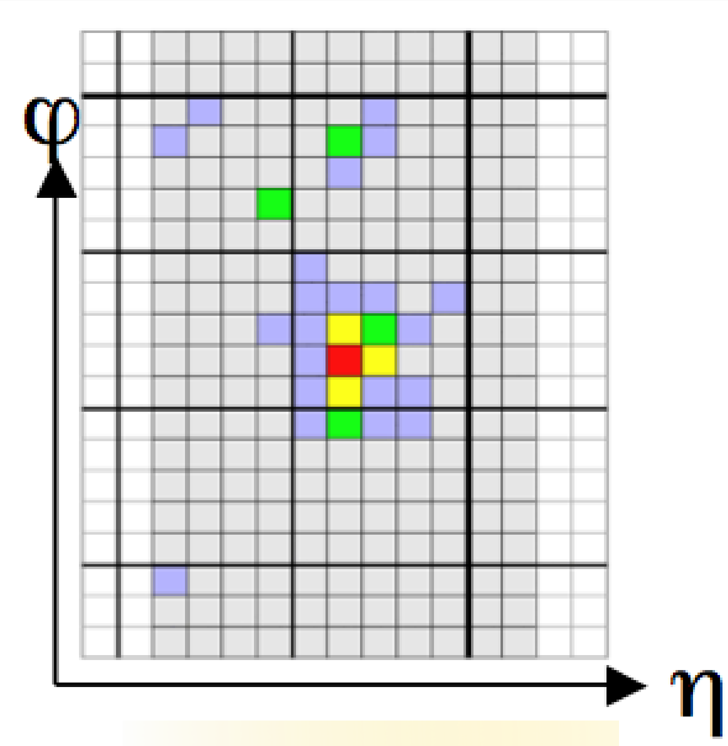



front view

side view



view in (φ,η) cells

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- Example CMS Crystal Calorimeter:
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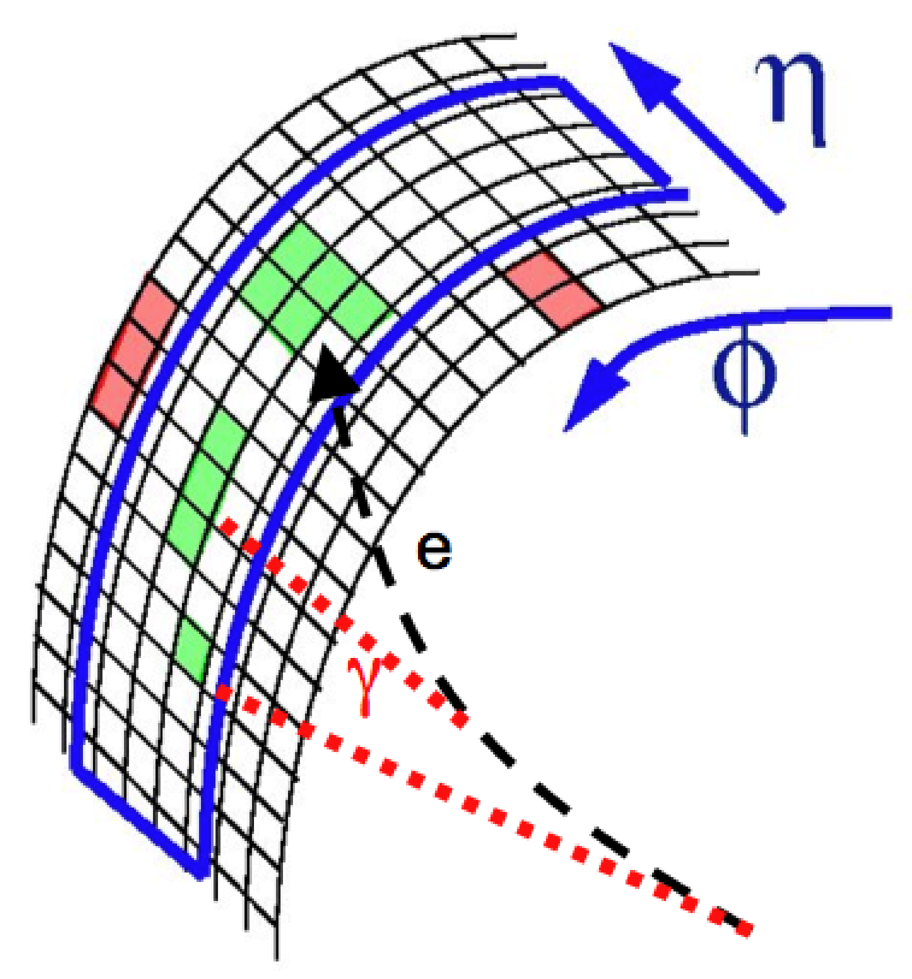
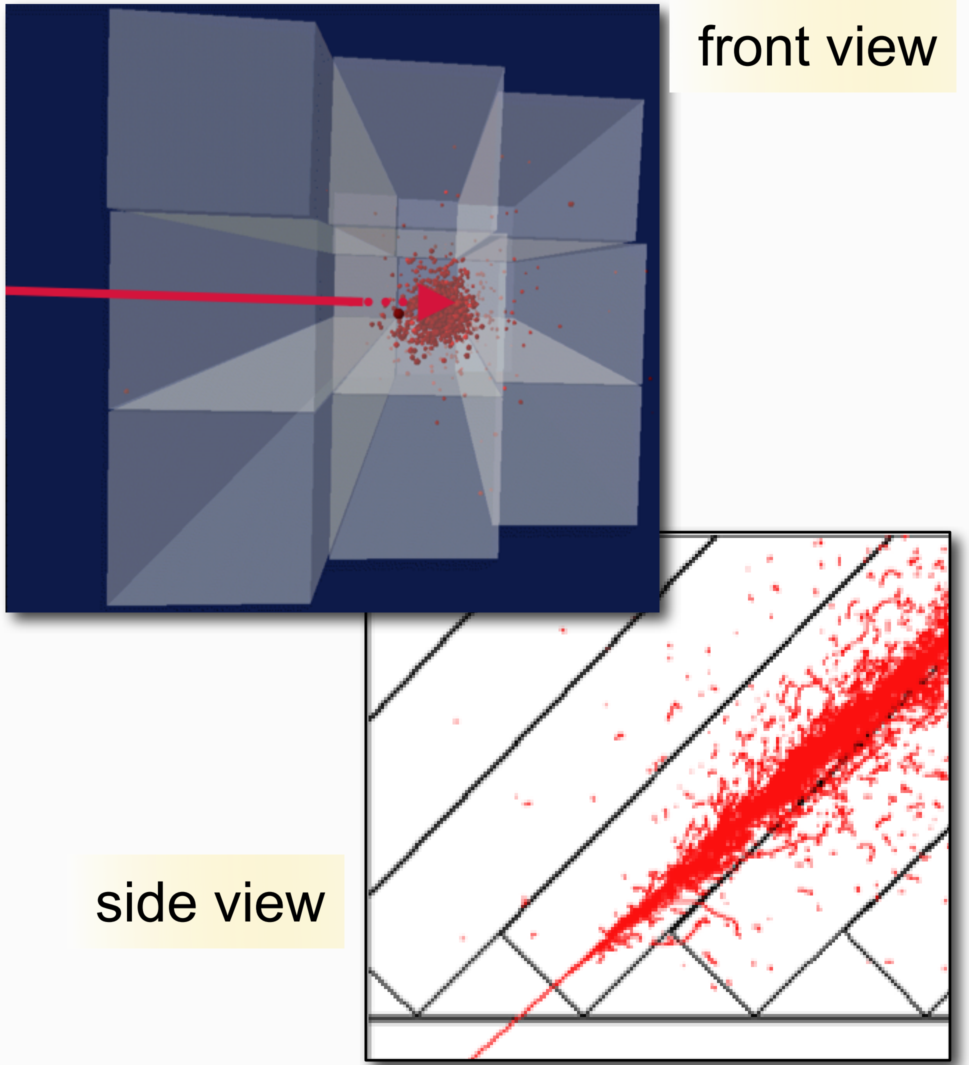
- So task is : identify these clusters and reconstruct the energy they contain

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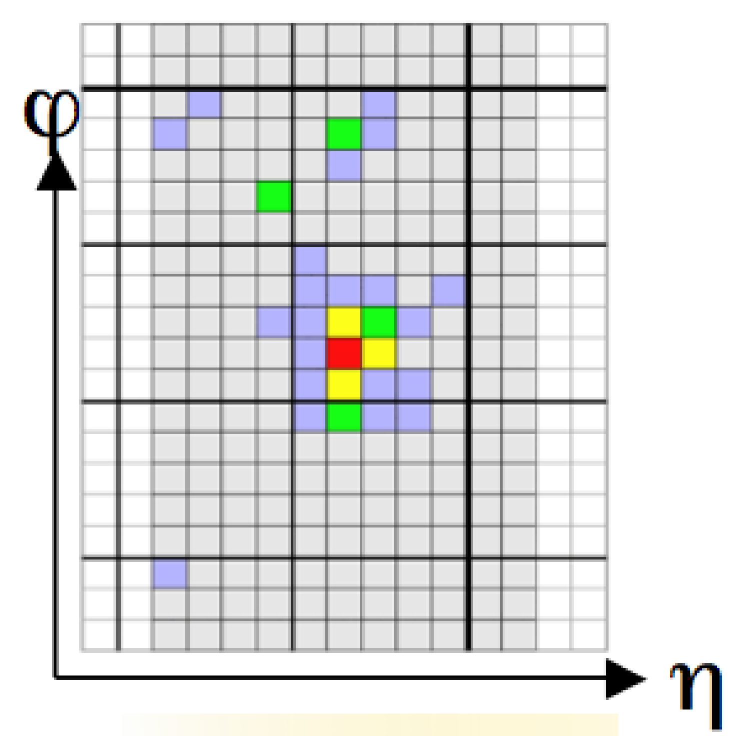

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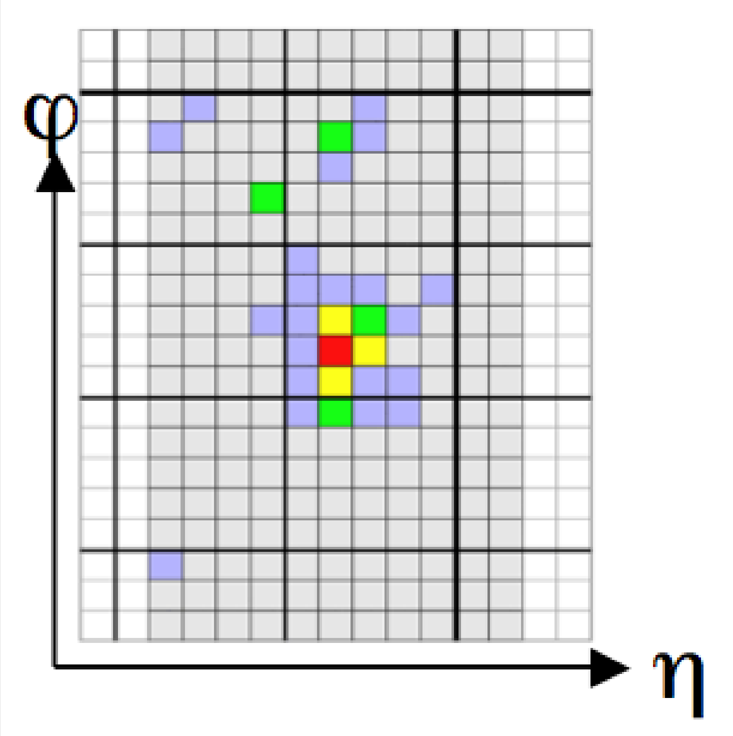
Cluster Finding

- 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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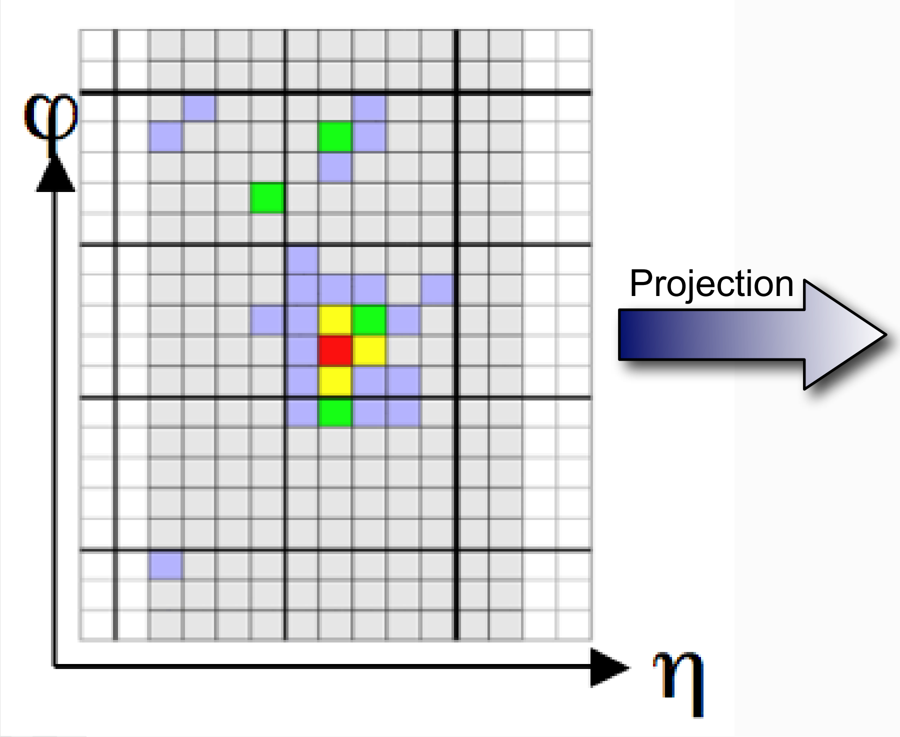

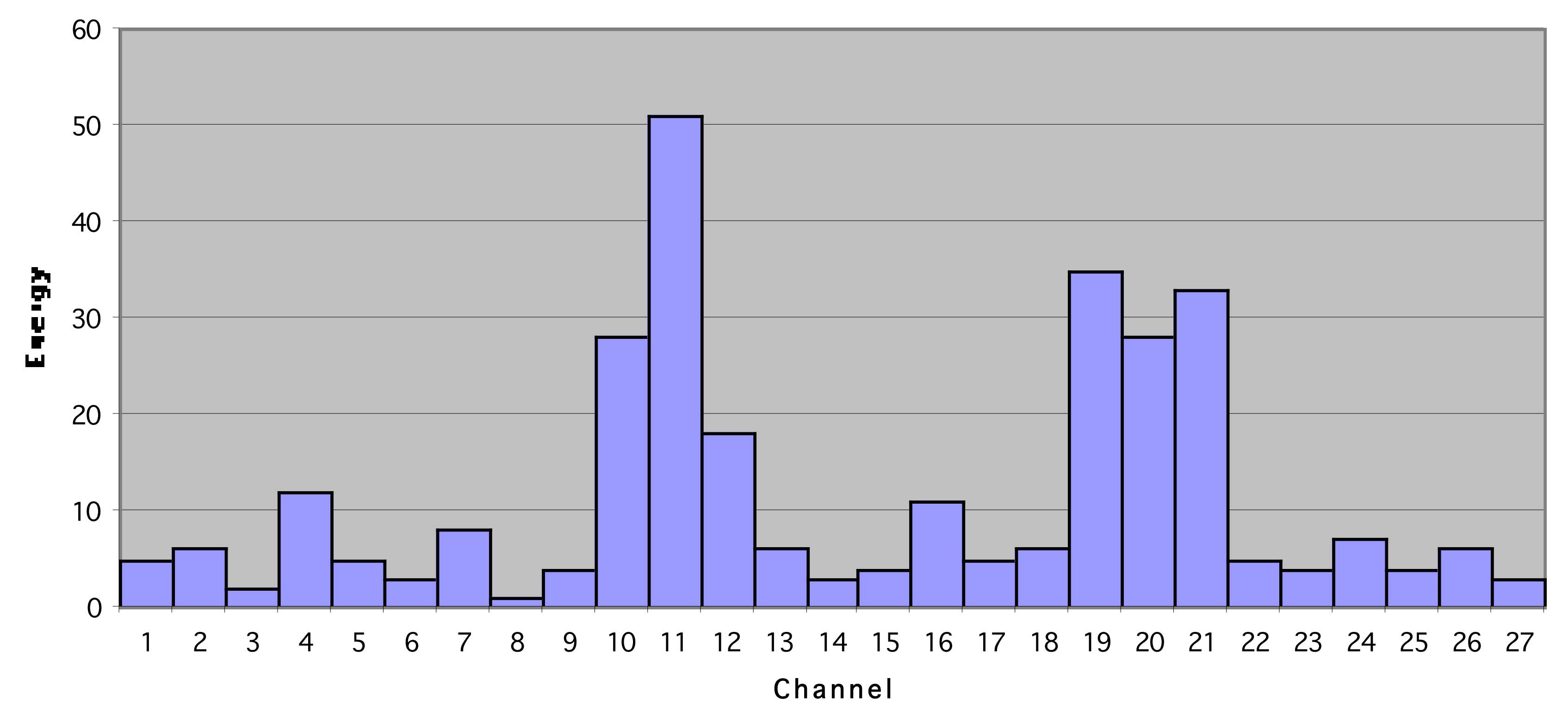

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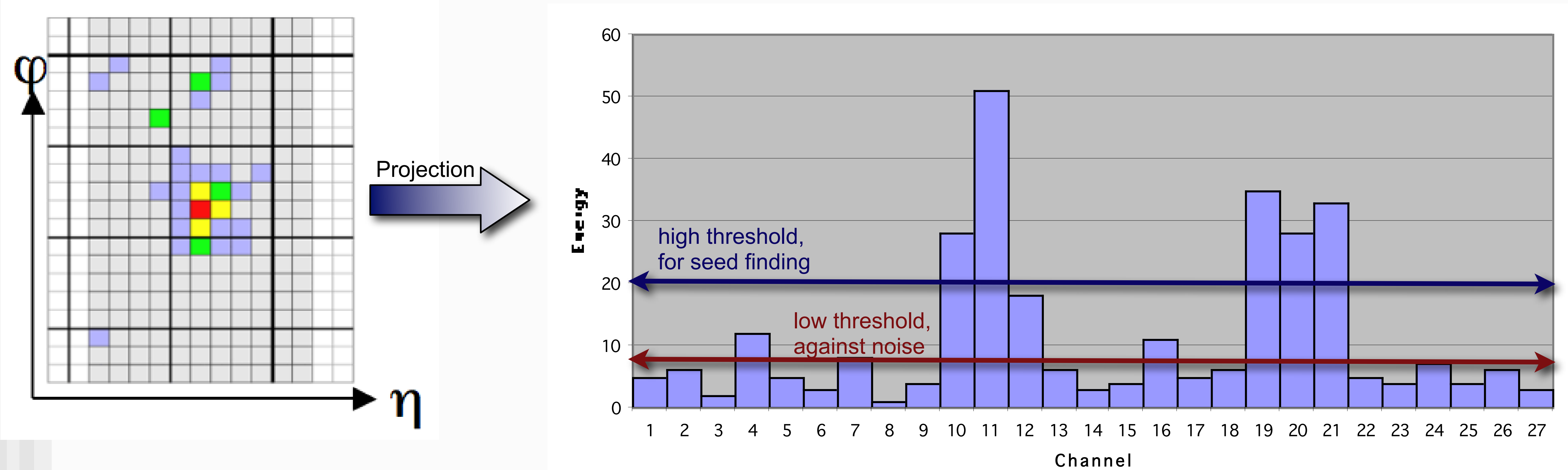


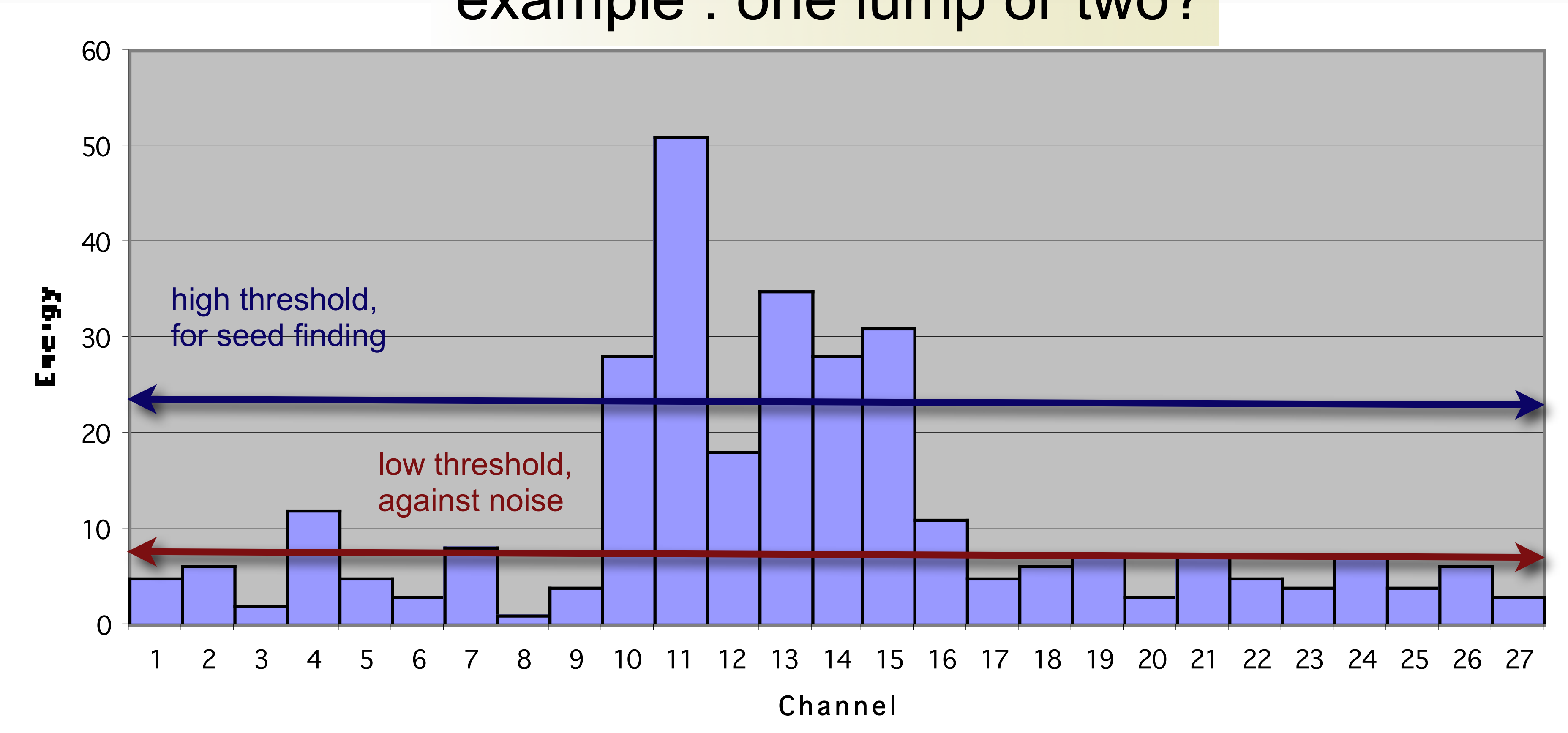
Simple example of an algorithm

- 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

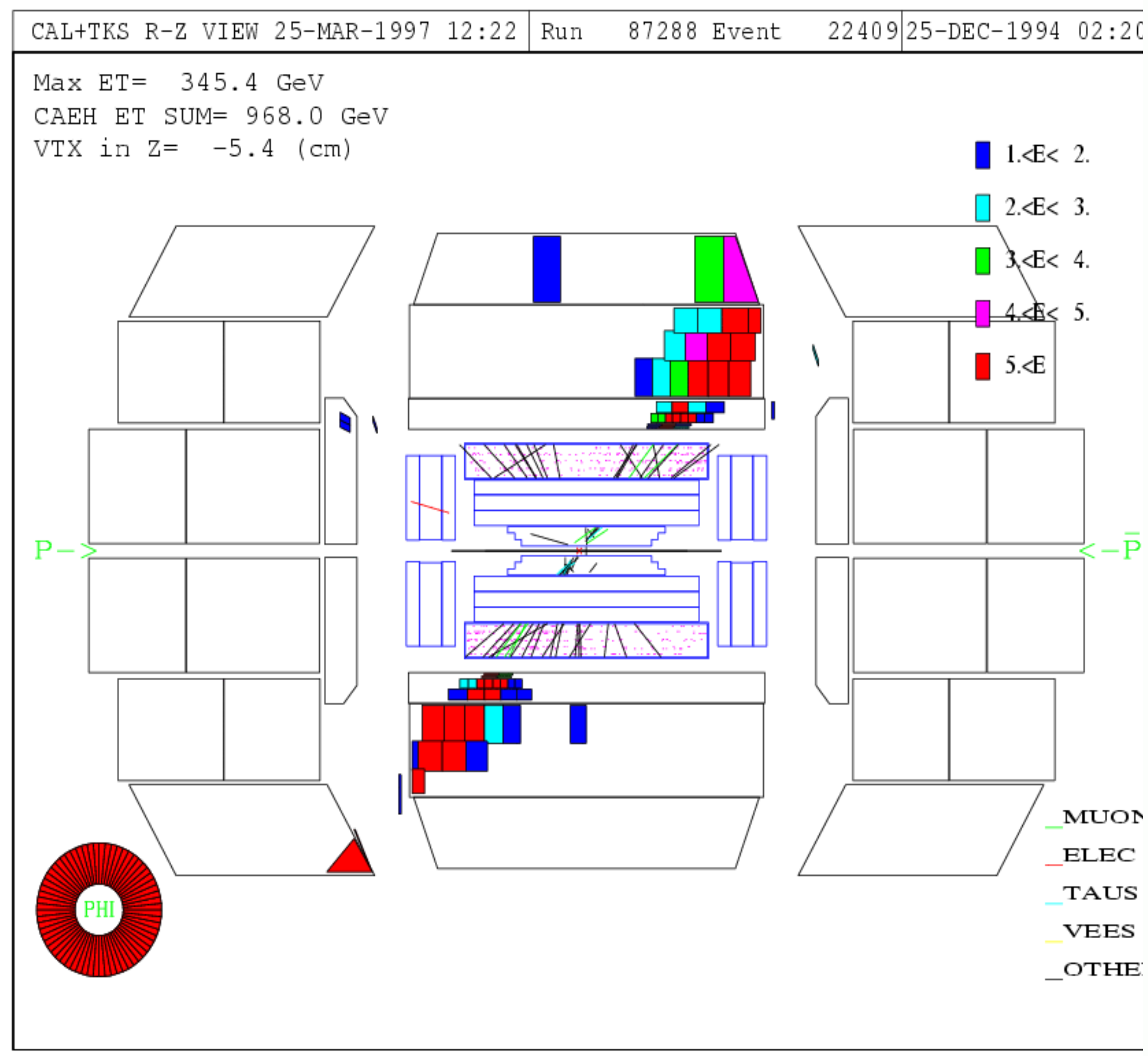
example : one lump or two?



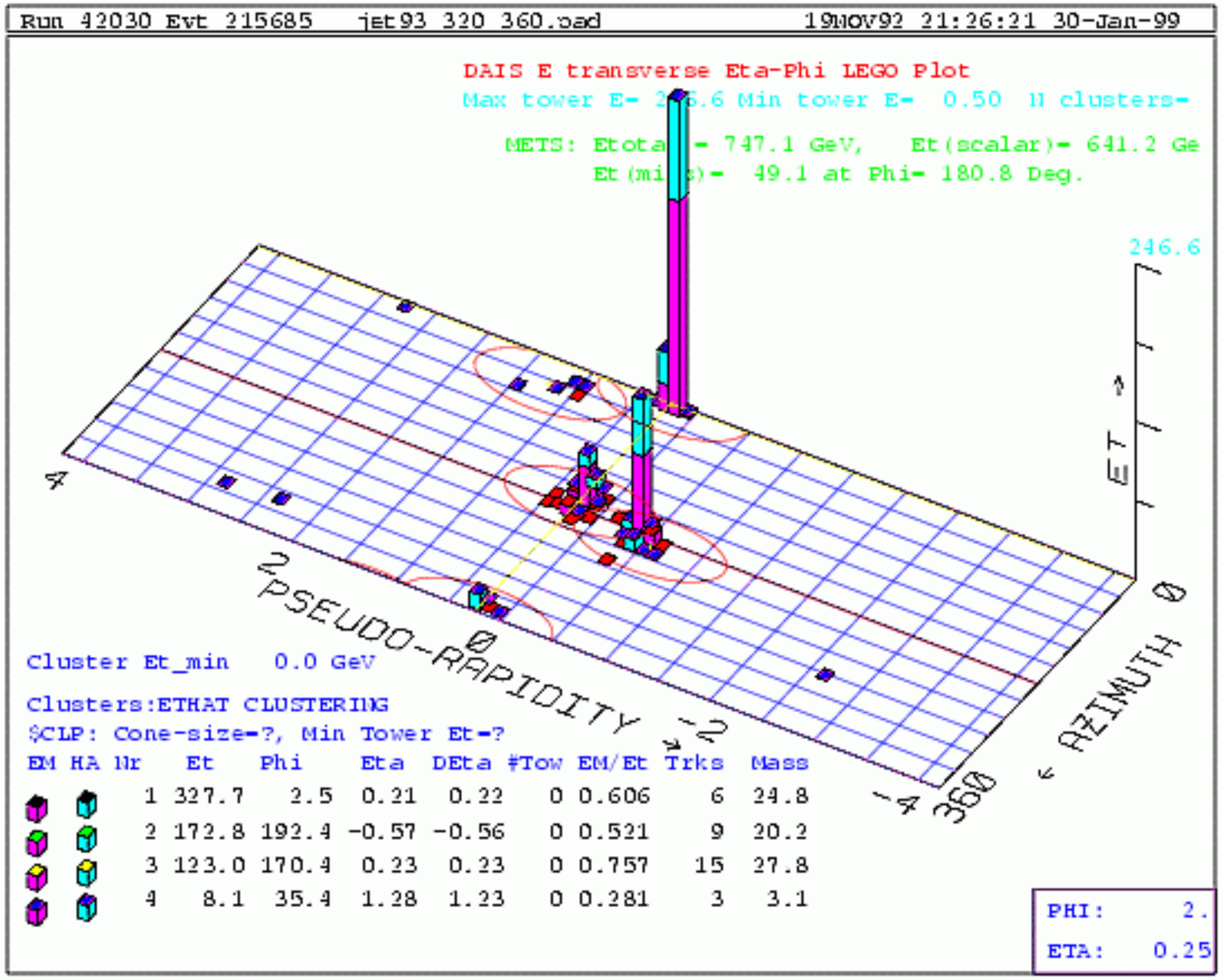
Jet Algorithms

Jets in Hadron Collider Detectors

Jets in DØ CDF



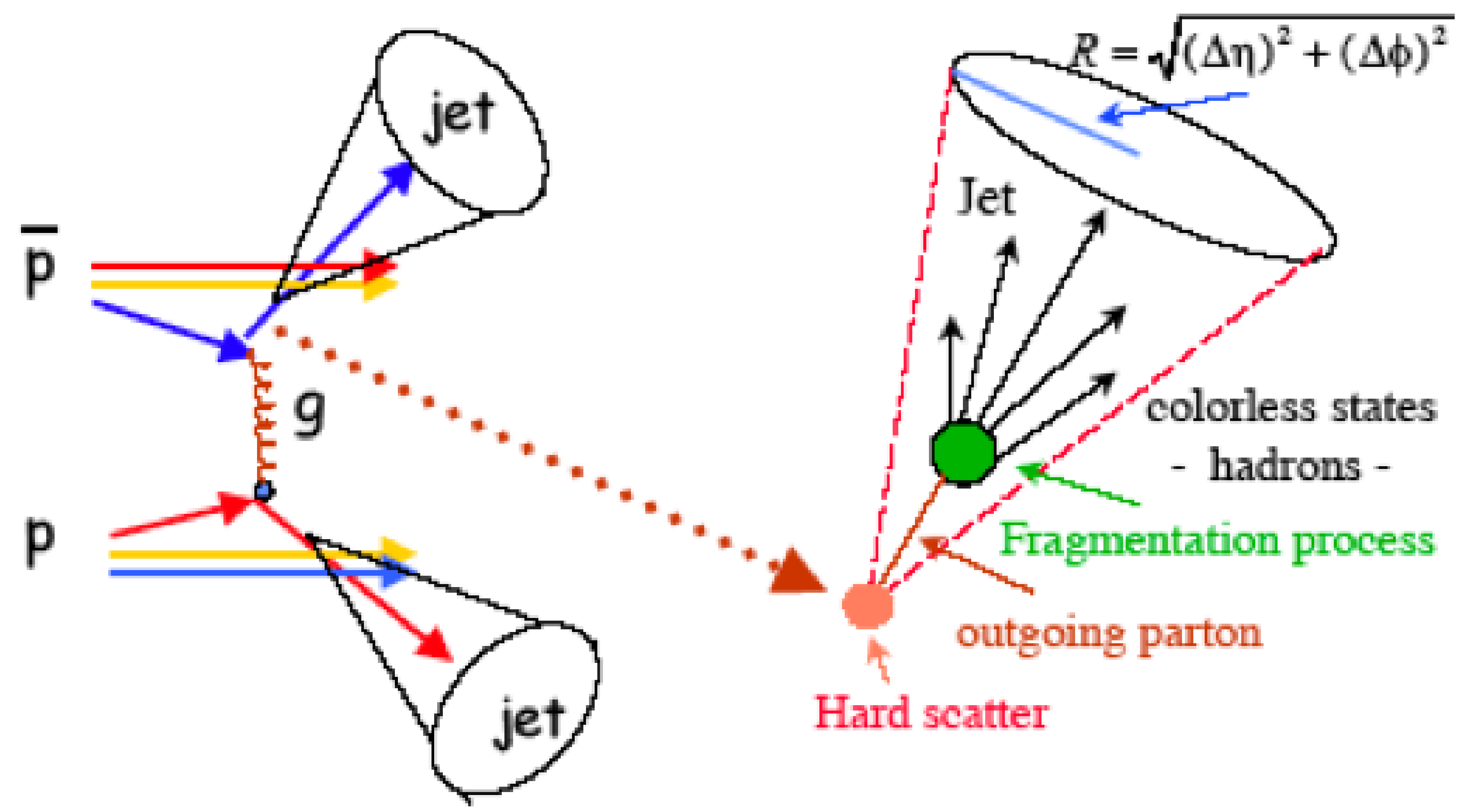
```
CAL+TKS R-Z VIEW 25-MAR-1997 12:22 | Run    87288 Event    22409 | 25-DEC-1994 02:2
Max ET=   345.4 GeV
CAEH ET SUM= 968.0 GeV
VTX in Z=  -5.4 (cm)
```



```
Run 42030 Evt 215685   jet93 320 360.pad            19NOV92 21:26:21 30-Jan-99
DAIS E transverse Eta-Phi LEGO Plot
Max tower E= 2 6.6 Min tower E=  0.50  11 clusters=
METS: Etota  = 747.1 GeV,   Et(scalar)= 641.2 Ge
         Et(mi  s)=  49.1 at Phi= 180.8 Deg.

Cluster Et_min   0.0 GeV

Clusters:ETHAT CLUSTERING
$CLP: Cone-size=?, Min Tower Et=?
EM HA Nr    Et    Phi    Eta   DEta #Tow EM/Et Trks  Mass
        1 327.7    2.5   0.21   0.22   0 0.606    6  24.8
        2 172.8  192.4  -0.57  -0.56   0 0.521    9  20.2
        3 123.0  170.4   0.23   0.23   0 0.757   15  27.8
        4   8.1   35.4   1.28   1.23   0 0.281    3   3.1

PHI:     2.
ETA:   0.25
```

- 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...

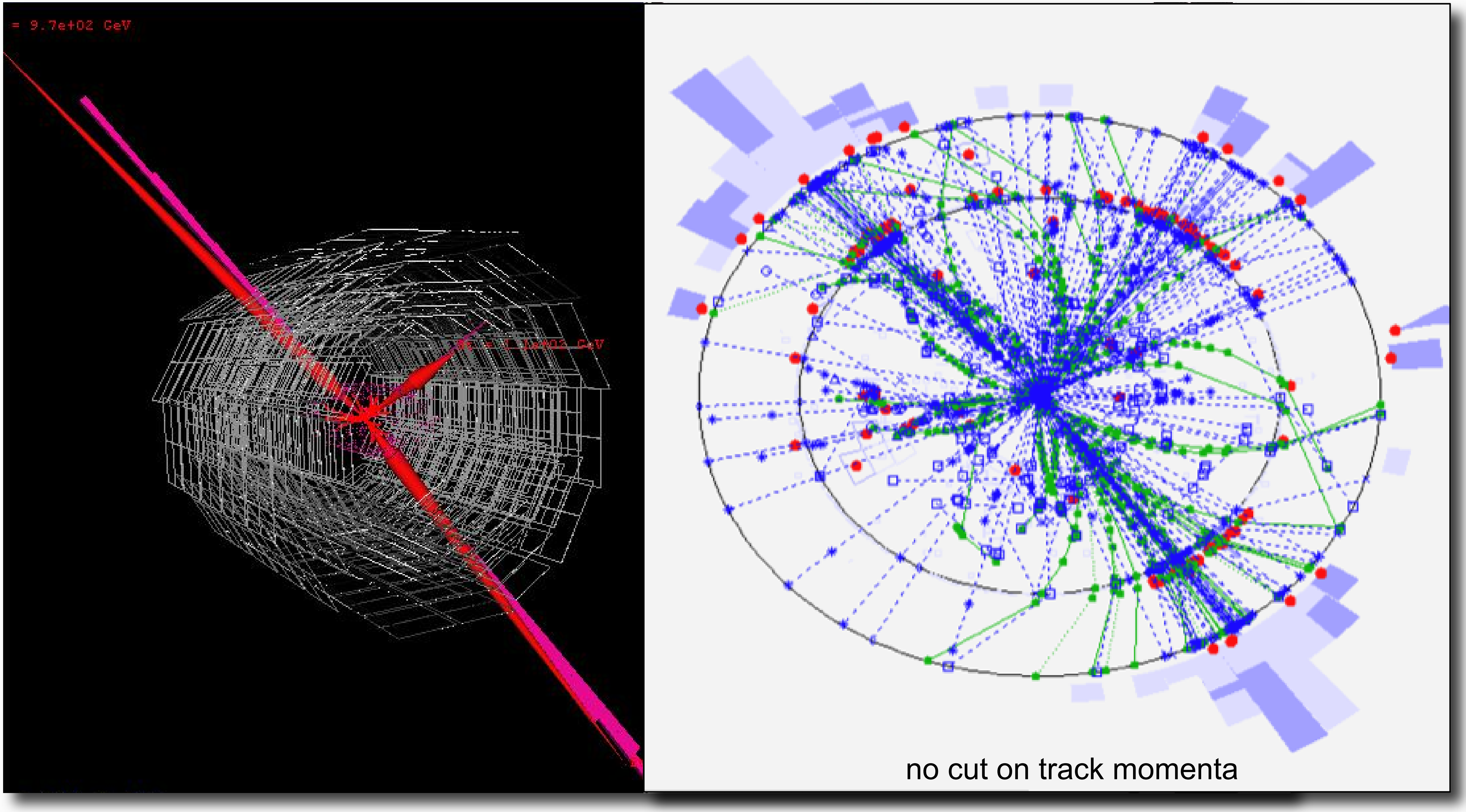


The natural (?) definition of a jet in a hadron collider environment

from J. Huston, CTEQ summer school 2004

Jets in Hadron Collider Detectors

Jets in CMS



no cut on track momenta

Jets in Hadron Collider Detectors

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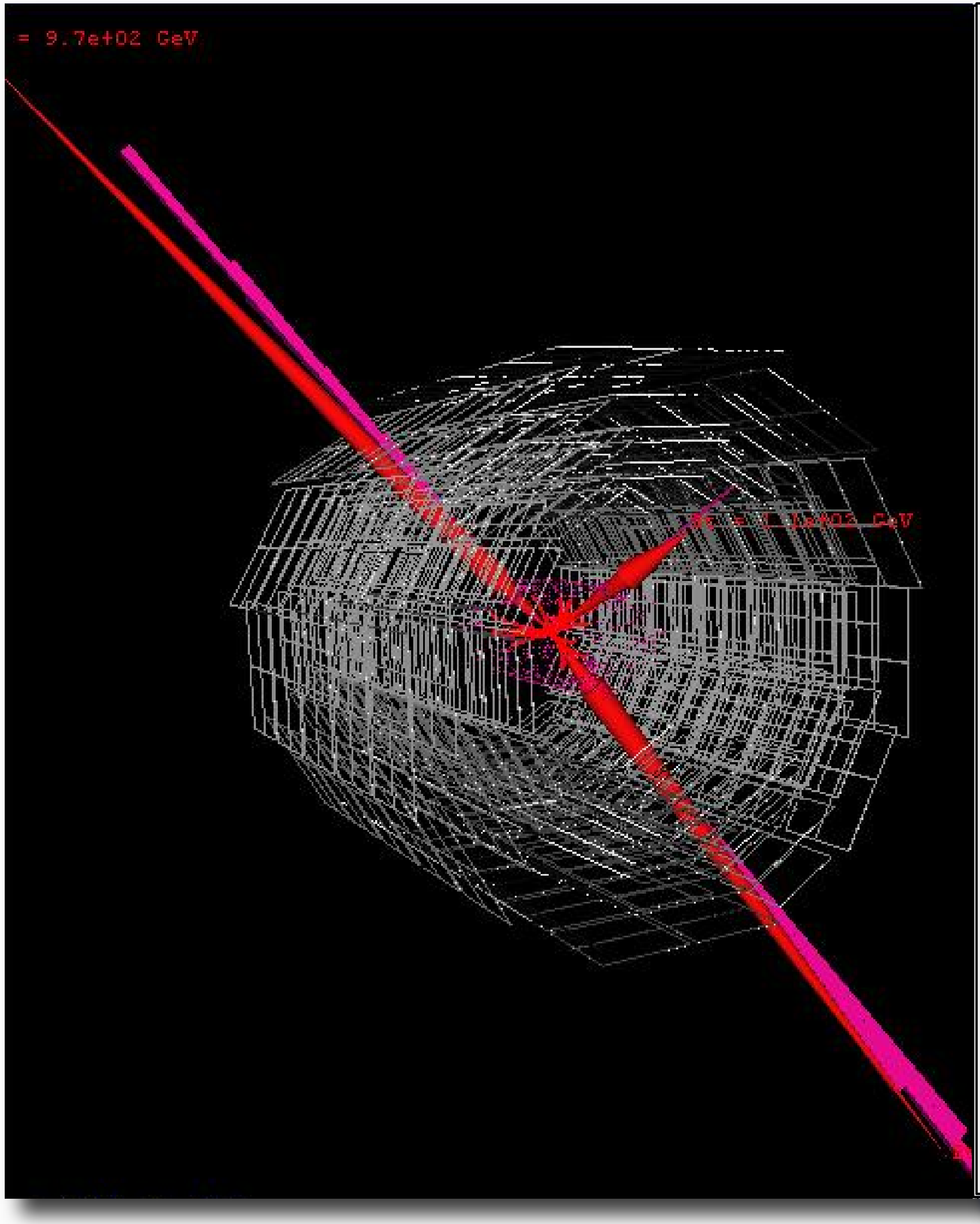

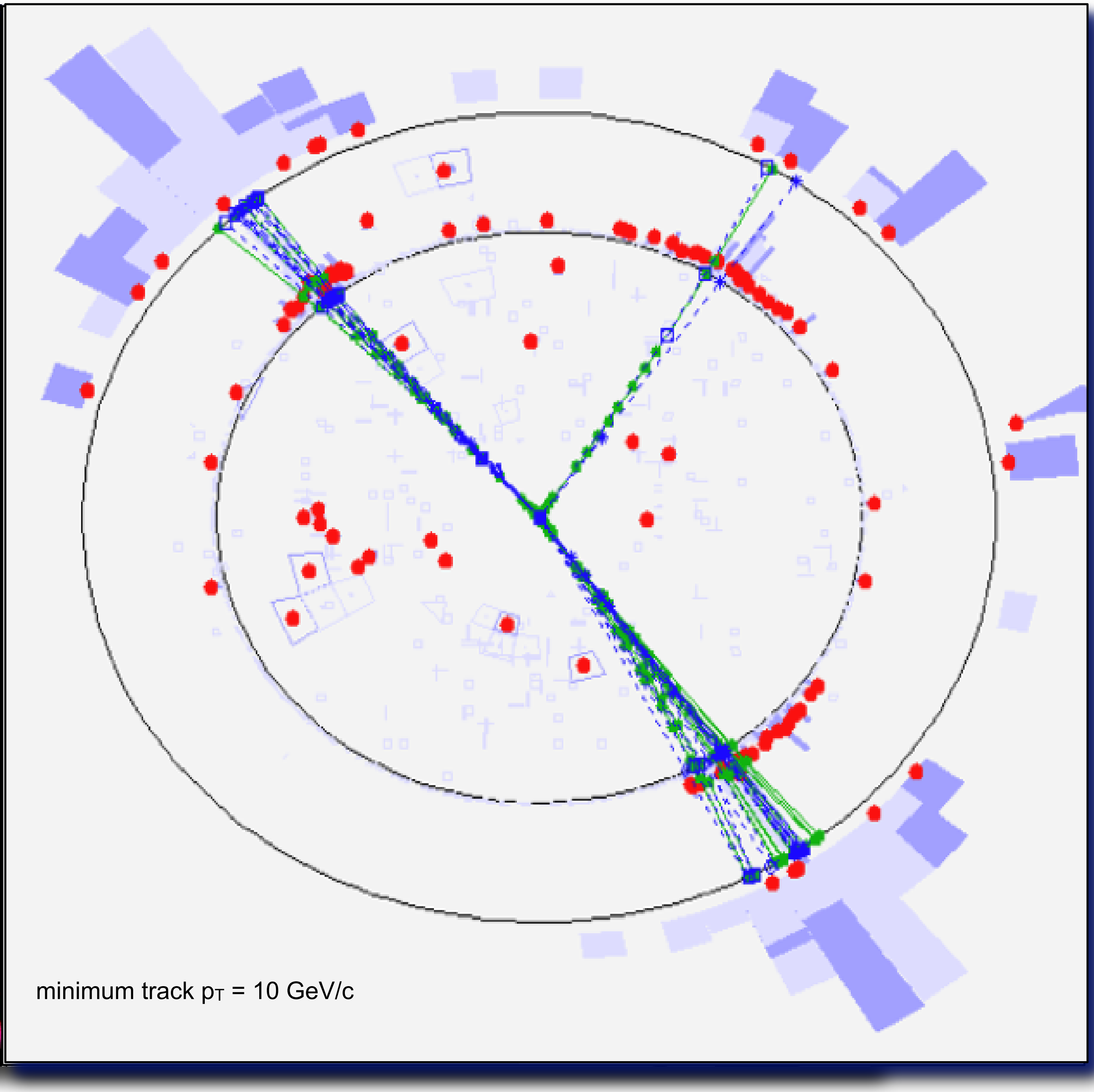
minimum track p_T = 10 GeV/c

Jets in Hadron Collider Detectors

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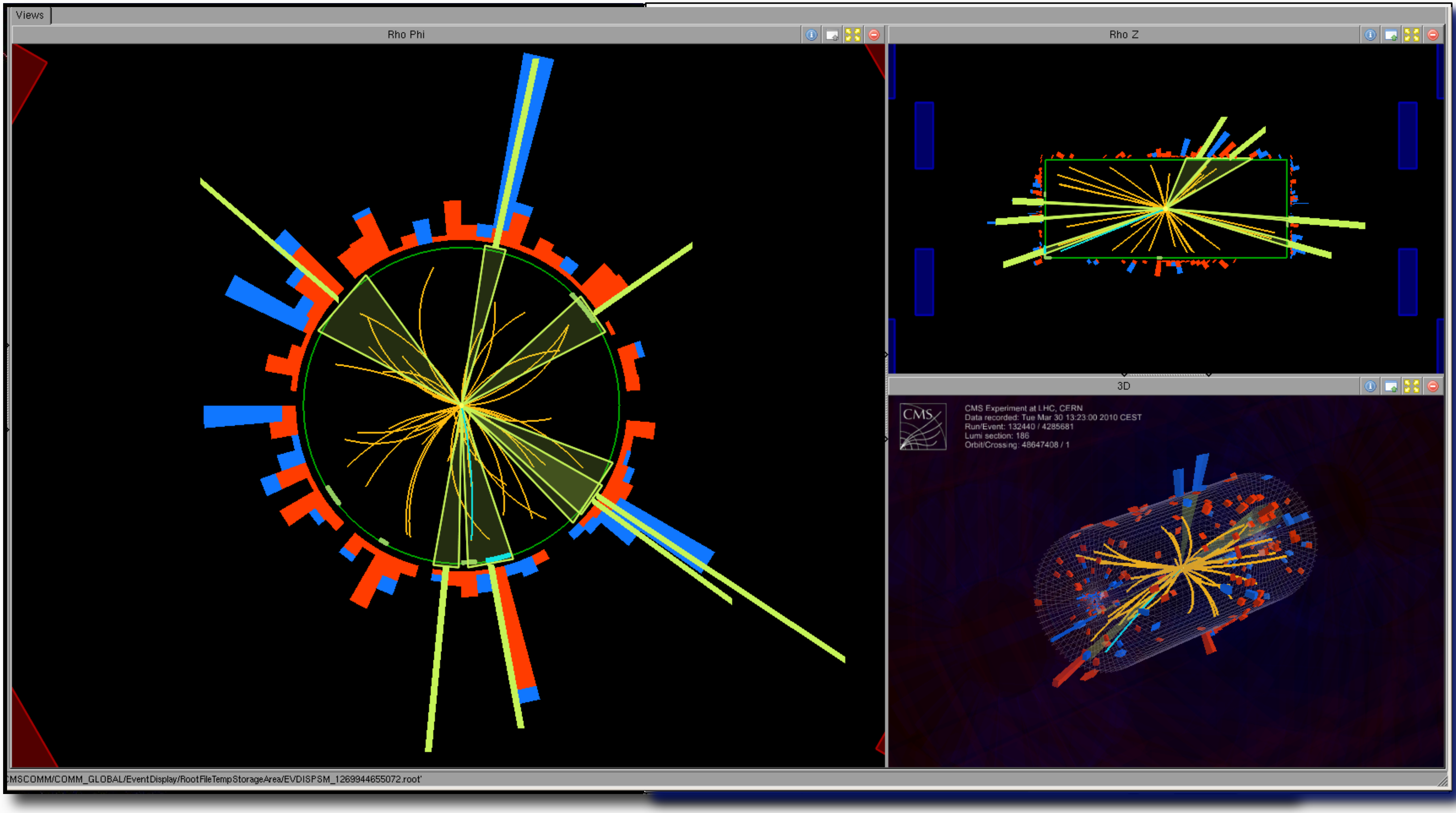
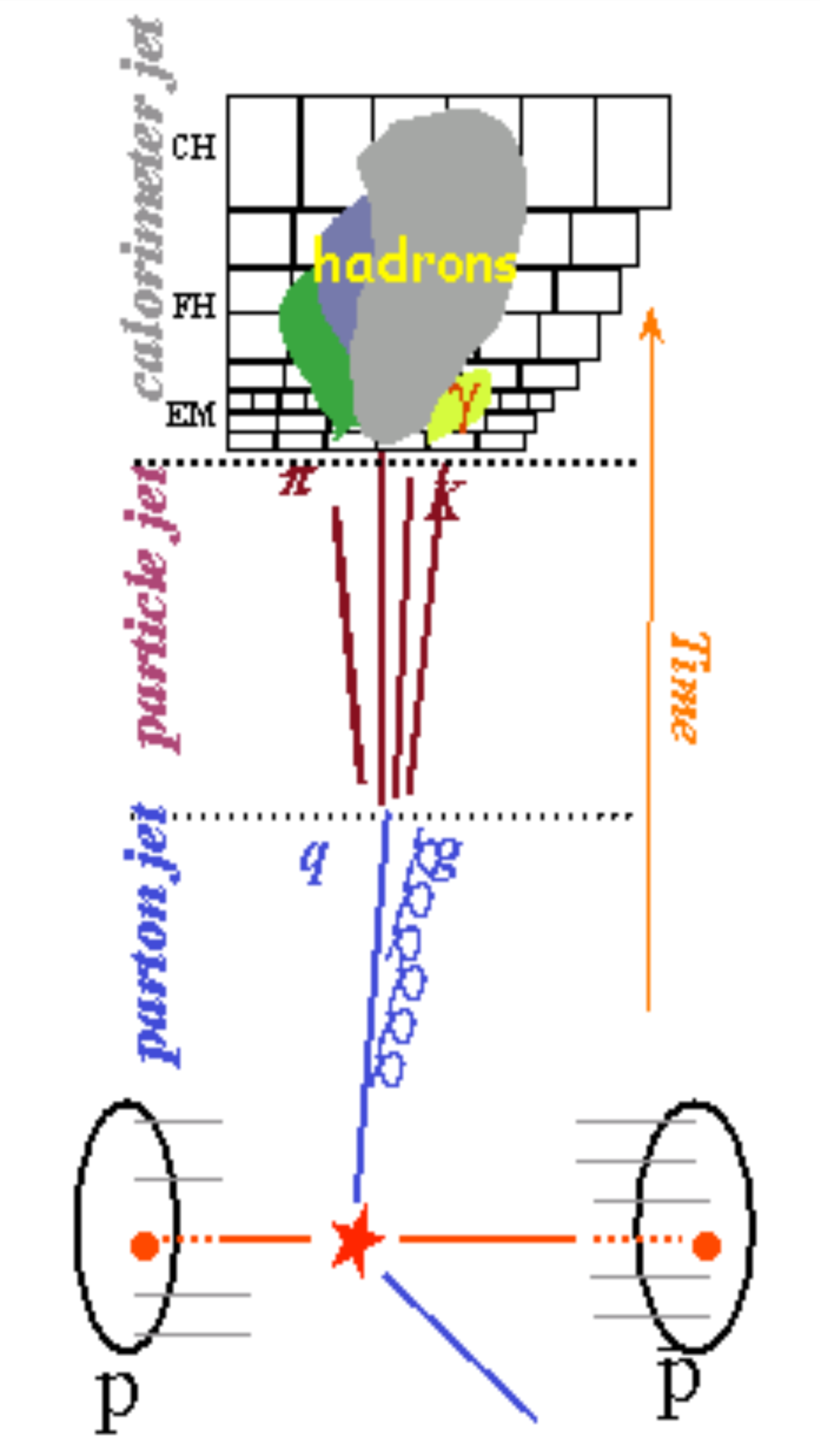


CMS Experiment at LHC, CERN
Data recorded: Tue Mar 30 13:23:00 2010 CEST
Run/Event: 132440 / 4285681
Lumi section: 186
Orbit/Crossing: 48647408 / 1

`CMSCOMM/COMM_GLOBAL/EventDisplay/RootFileTempStorageArea/EVDISPSM_1269944655072.root'`

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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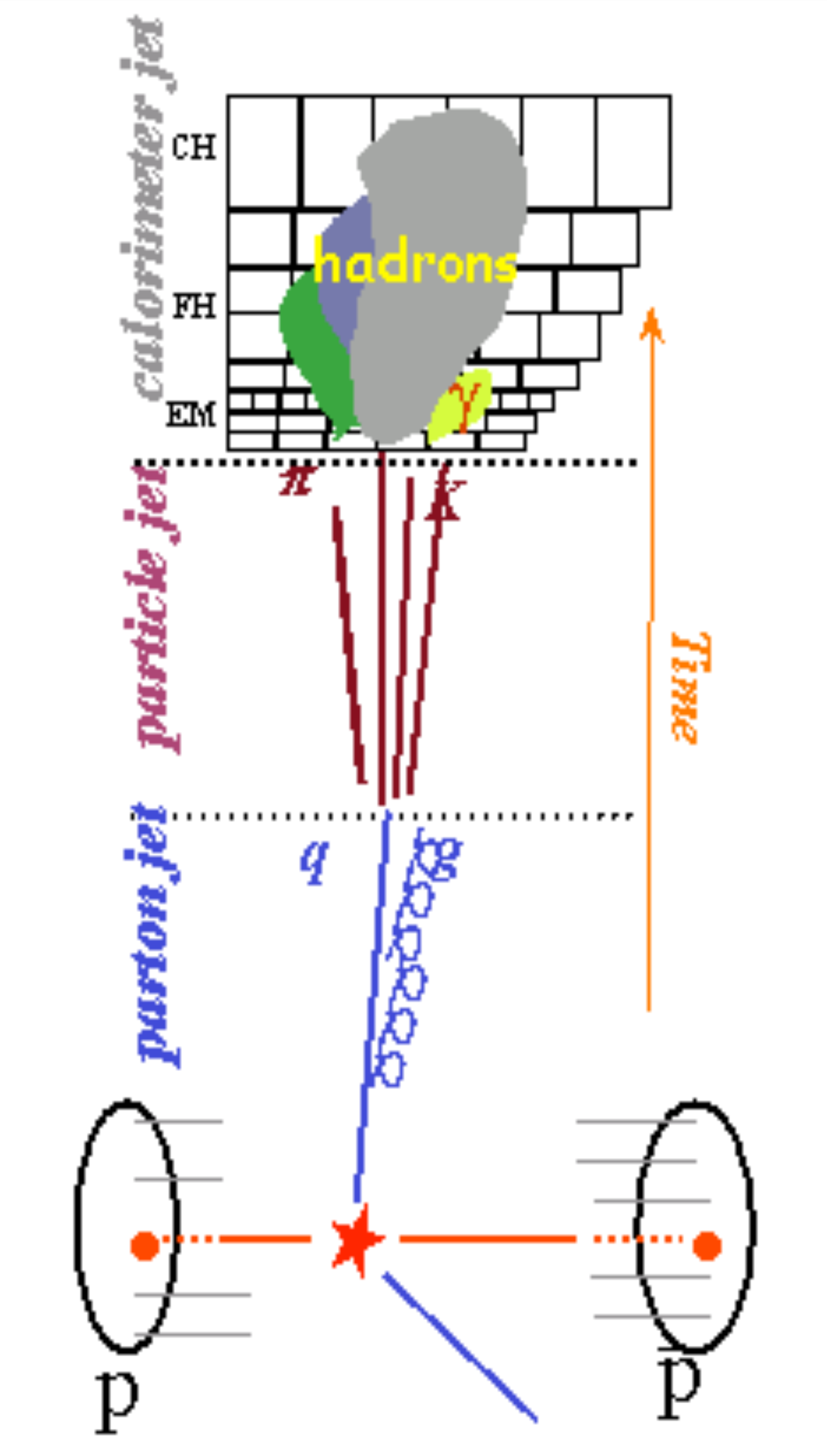
  - example : granularity of the calorimeter, energy response,...



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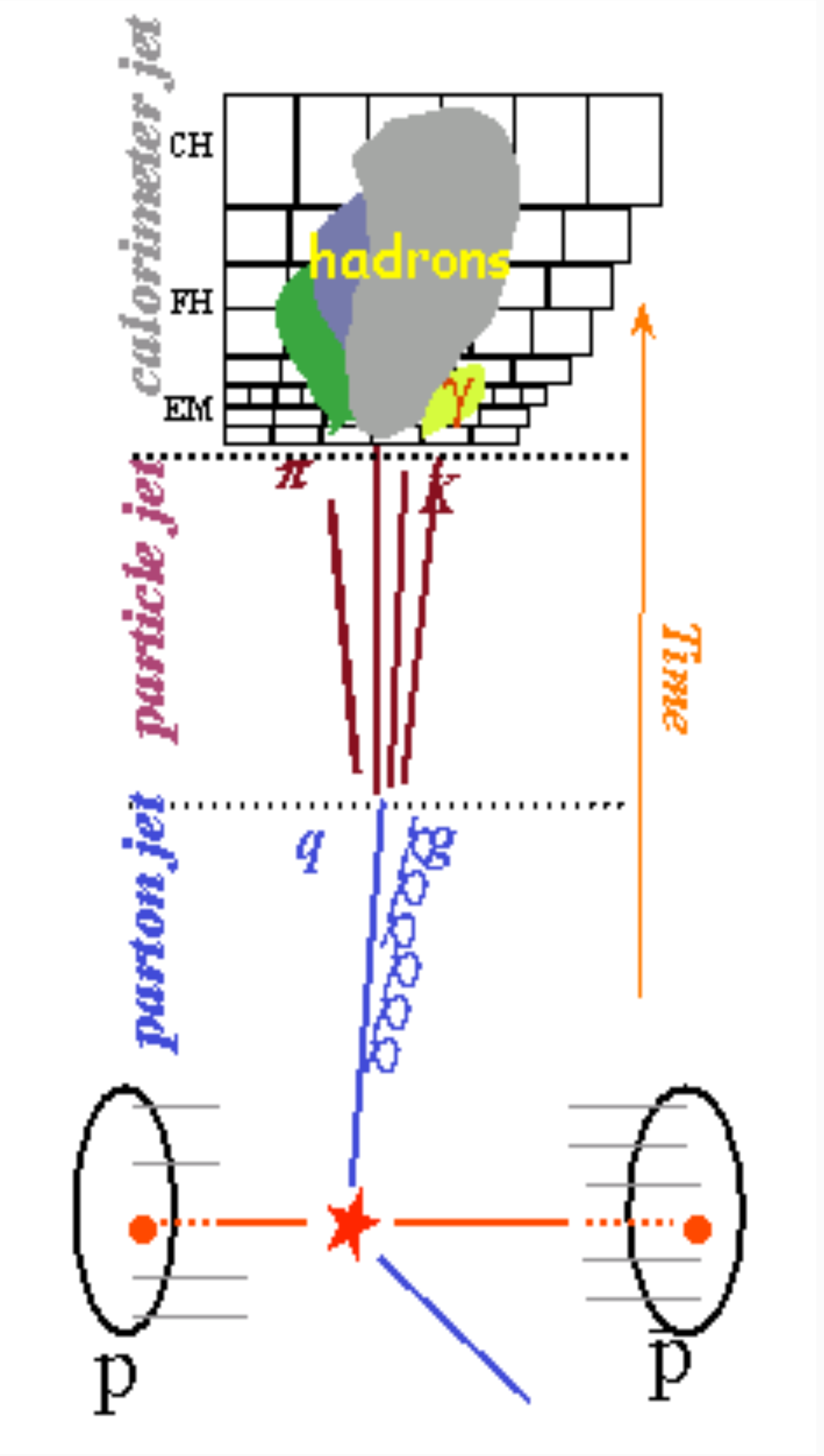

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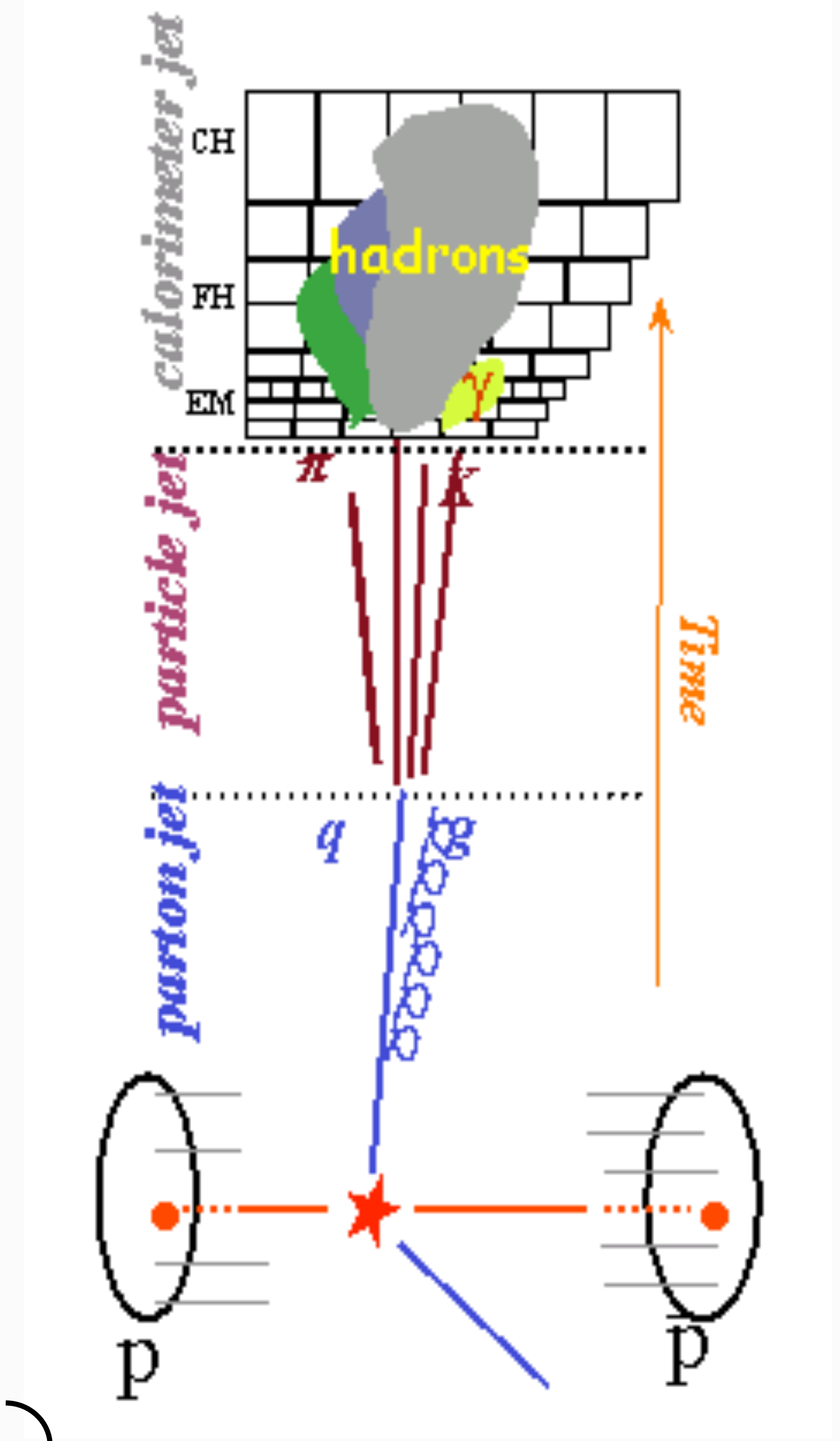
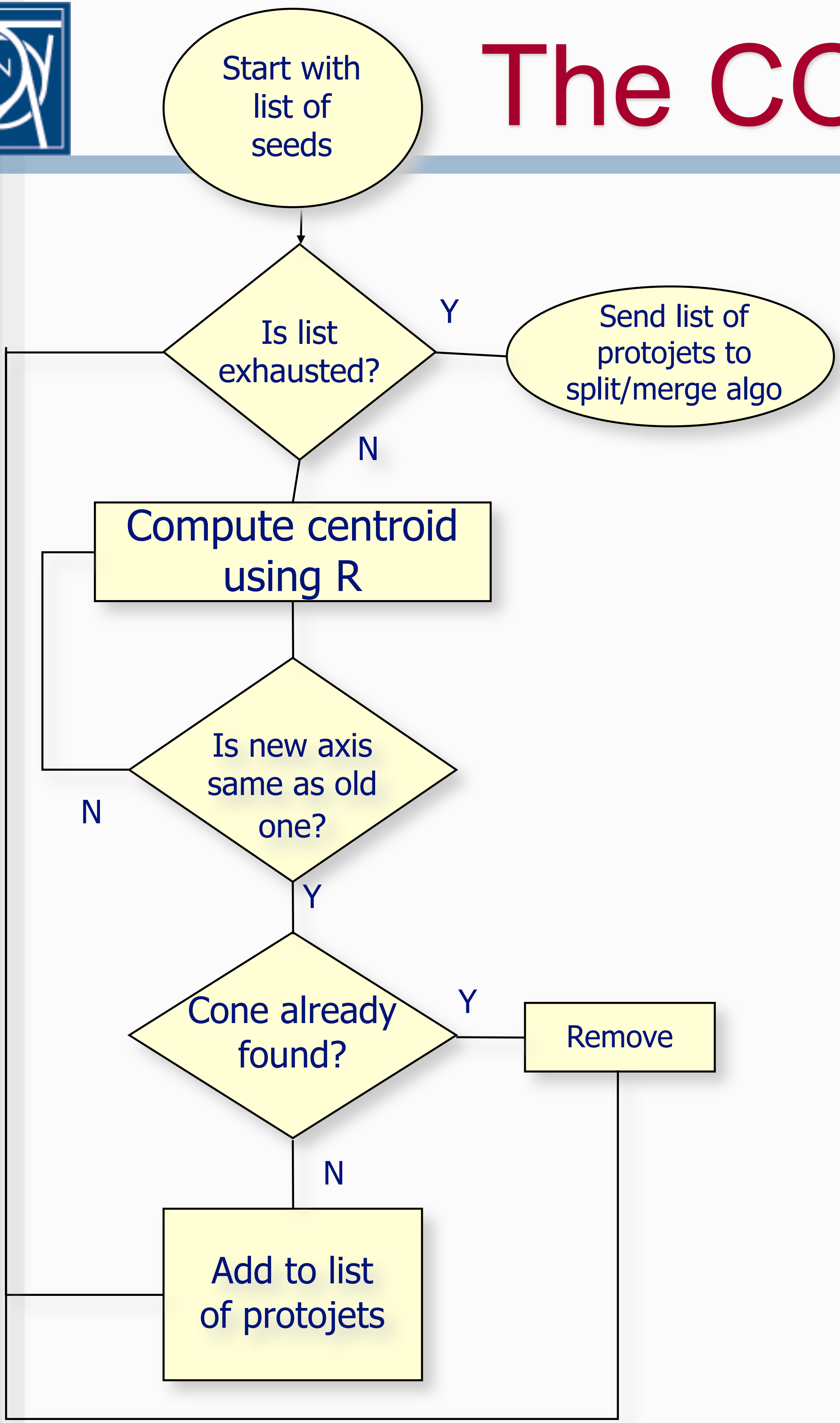
- Close correspondence between

$$P_{parton} \leftrightarrow P_{jet}$$

Energy
Momentum
angle



The CONE algorithm



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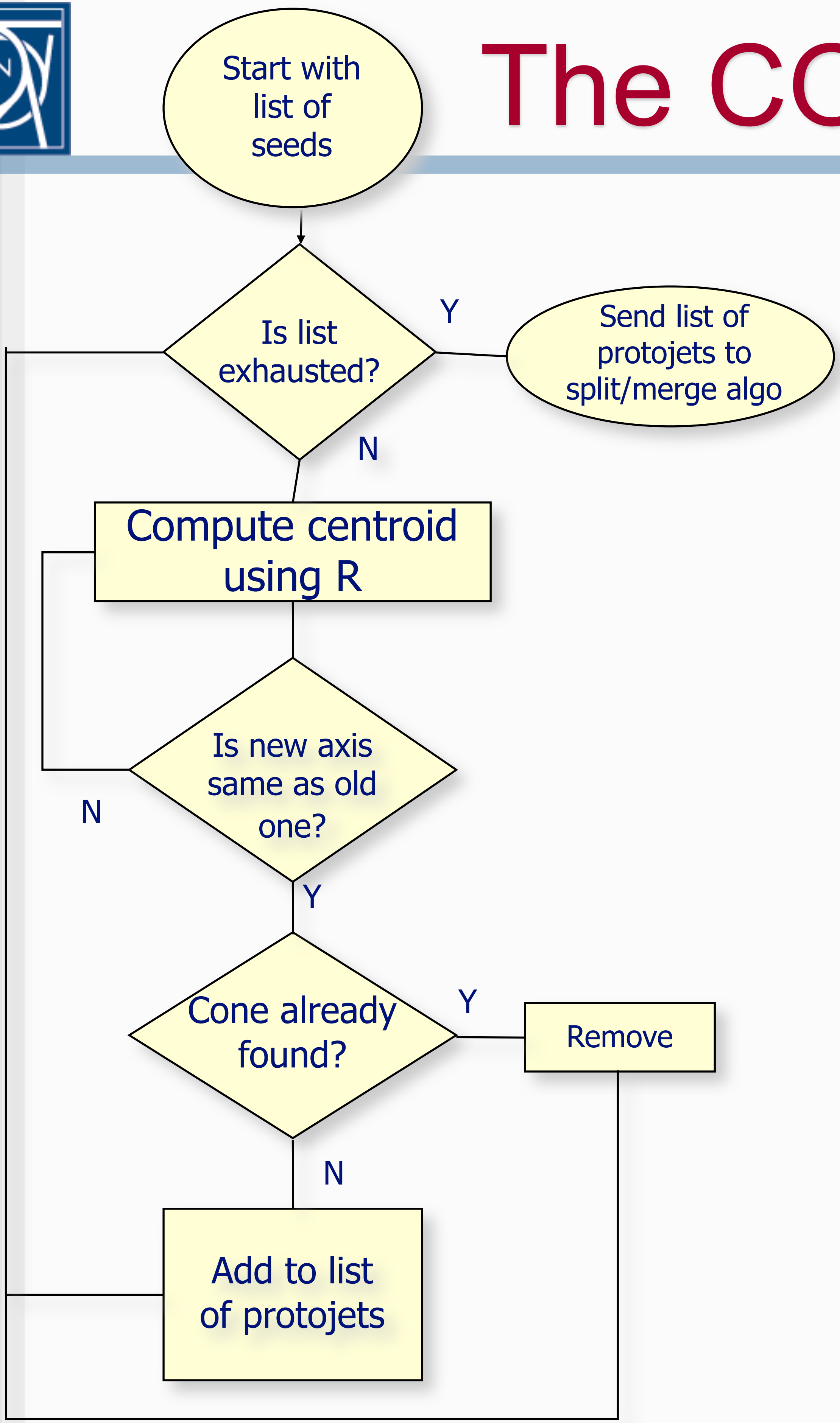

Seeds: for example, energy deposits with transverse energy ($E_T = E \sin\theta$) > 2 GeV in a tower of the calorimeter

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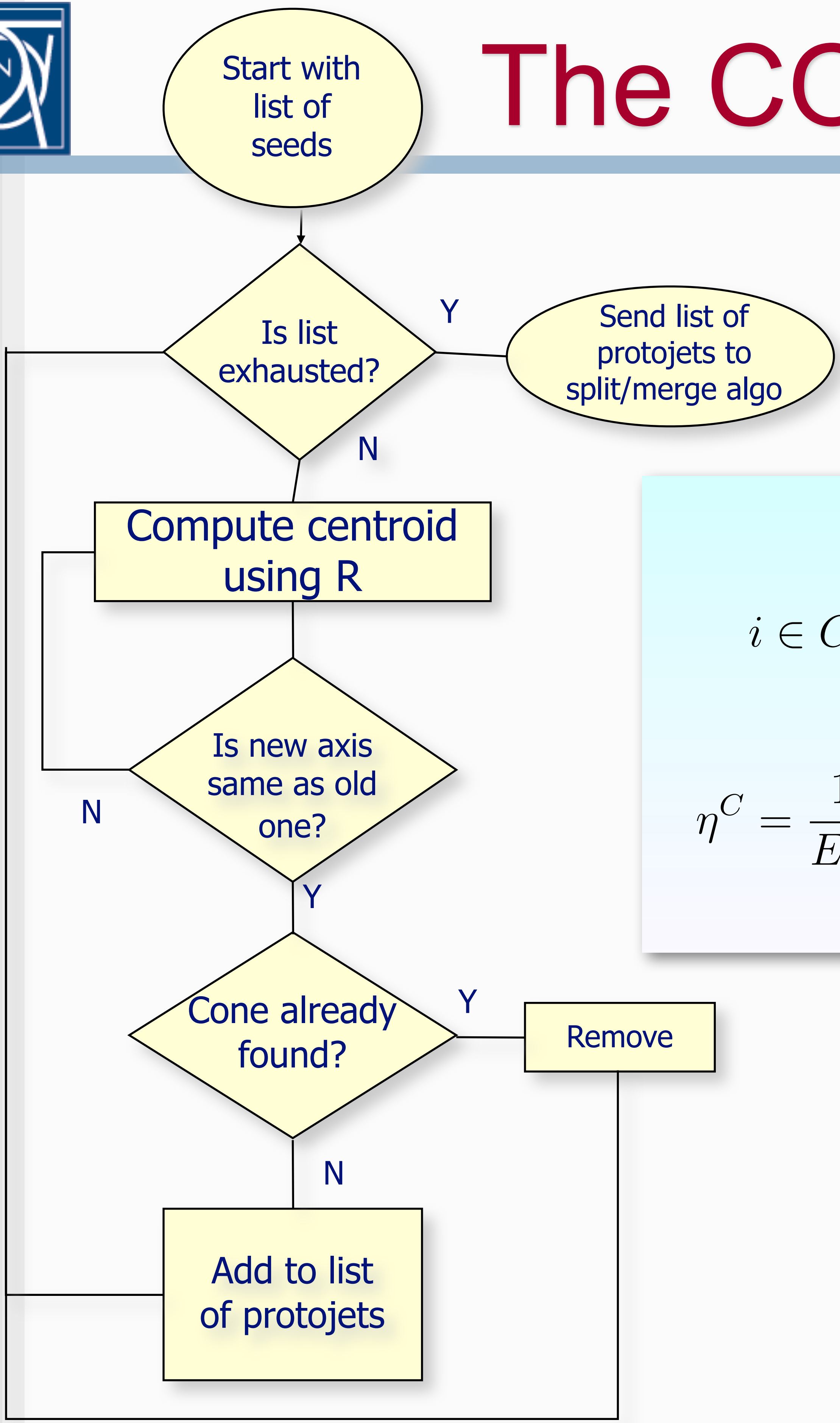

Start with list of seeds

Is list exhausted?

Send list of protojets to split/merge algo

Compute centroid using R

Is new axis same as old one?

Cone already found?

Remove

Add to list of protojets

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Centroid (one possible def) :

$$i \in C \quad : \quad \sqrt{(\eta^i - \eta^C)^2 + (\Phi^i - \Phi^C)^2} \leq R \quad \text{cone radius}$$

$$\eta^C = \frac{1}{E_T^C} \sum_{i \in C} E_T^i \eta^i \quad ; \quad \Phi^C = \frac{1}{E_T^C} \sum_{i \in C} E_T^i \Phi^i \quad ; \quad E_T^C = \sum_{i \in C} E_T^i$$

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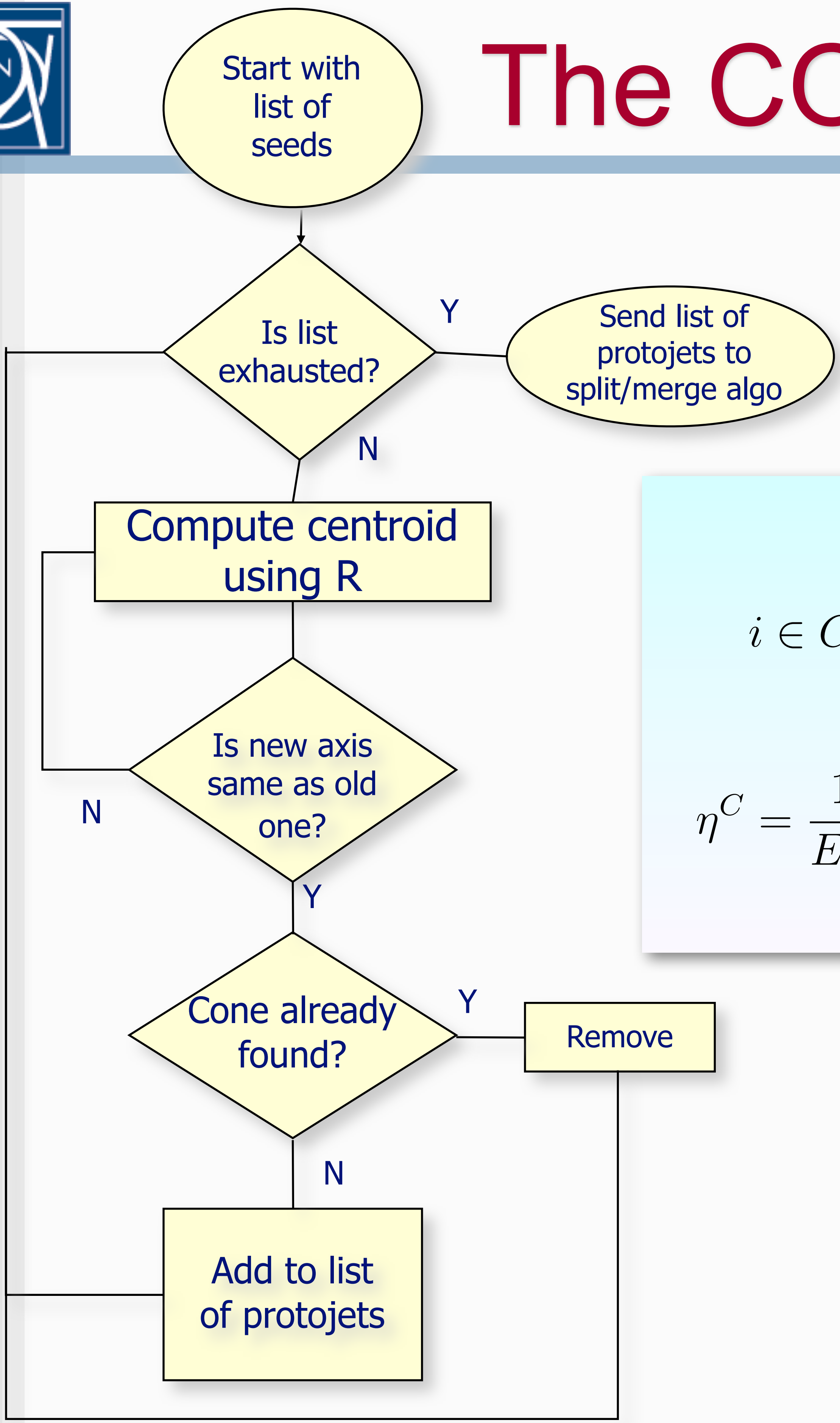

Start with list of seeds

Is list exhausted?

Y

Send list of protojets to split/merge algo

N

Compute centroid using R

Is new axis same as old one?

N

Y

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Y

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N

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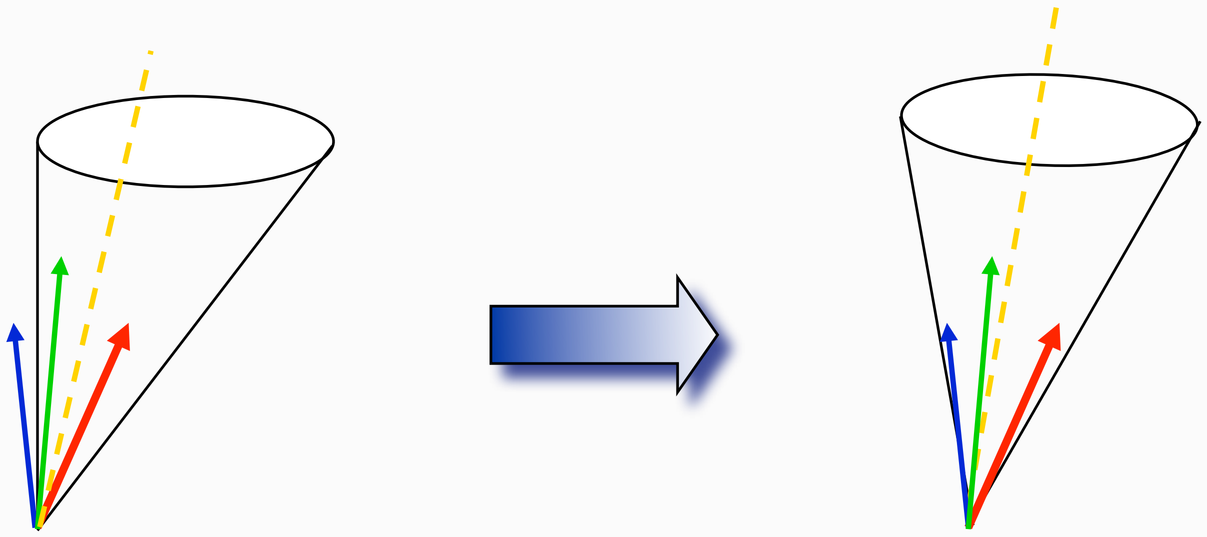

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  - up to 20 at highest LHC luminosity

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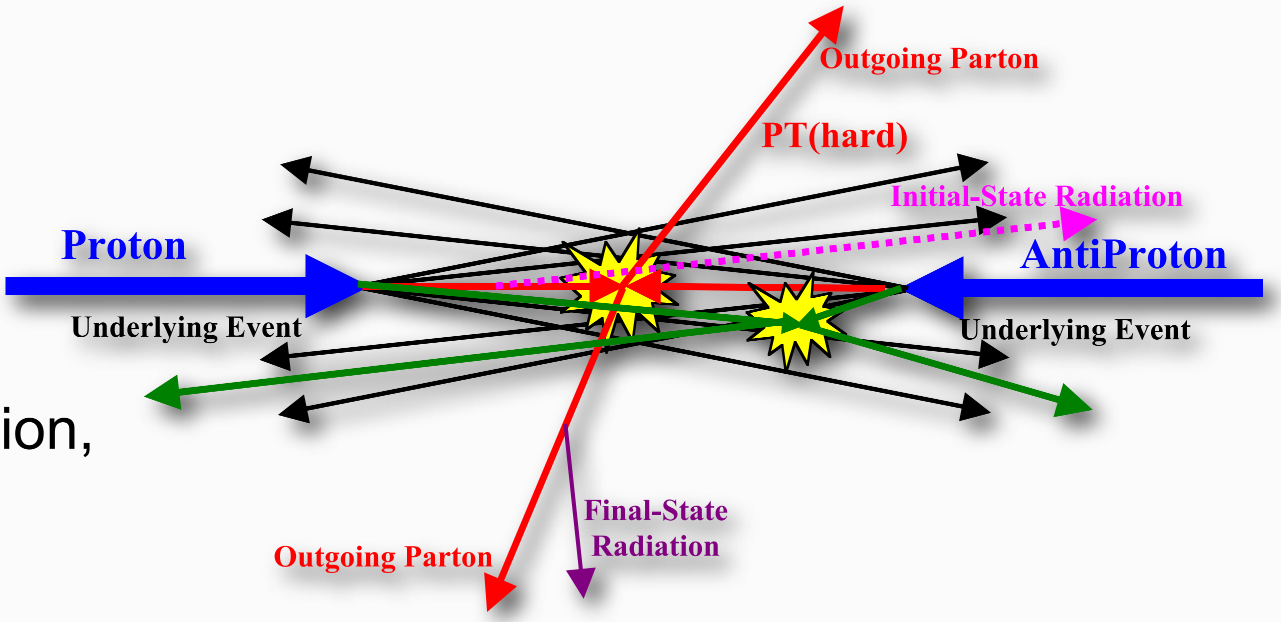

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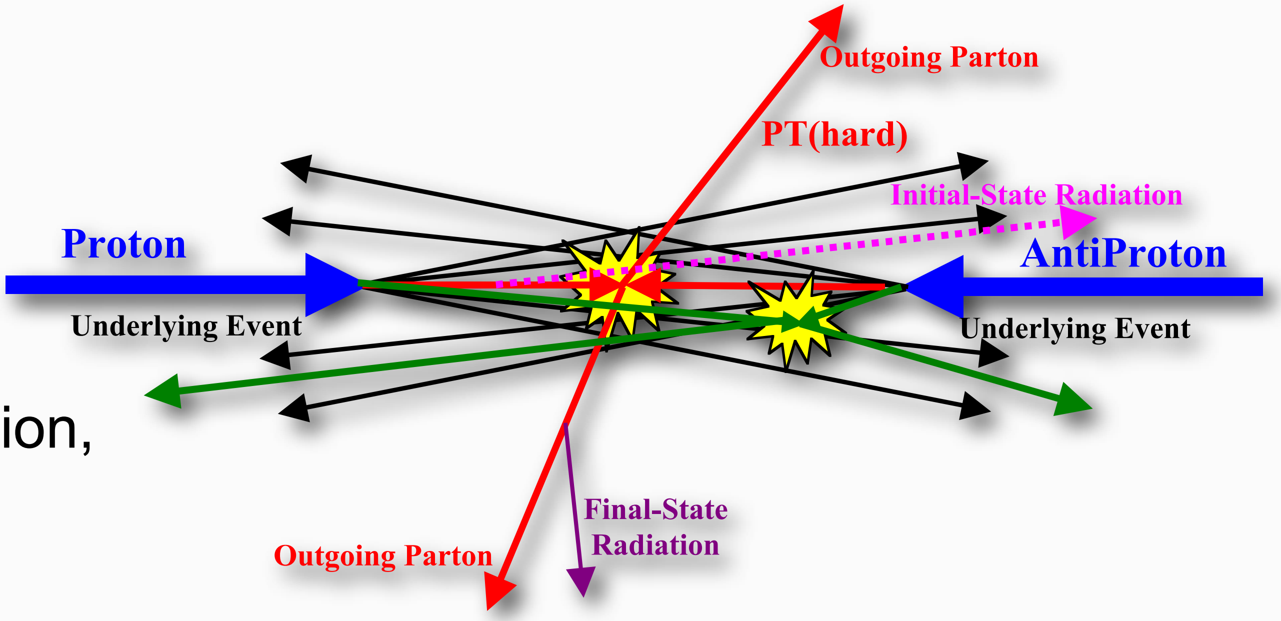

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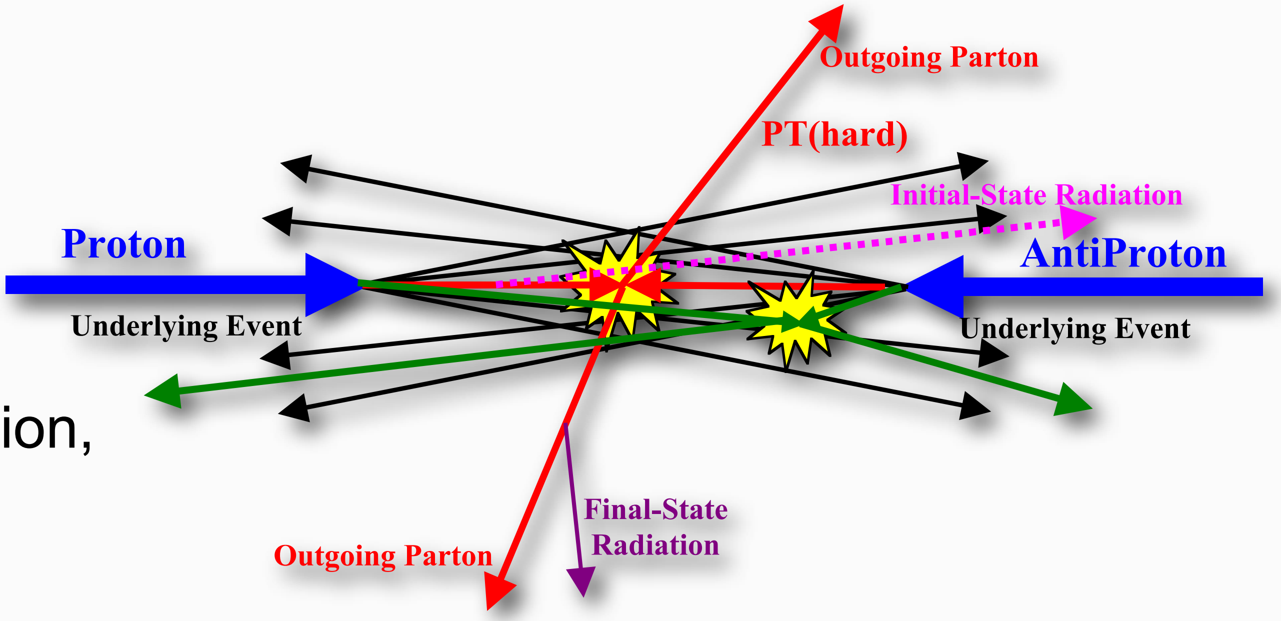

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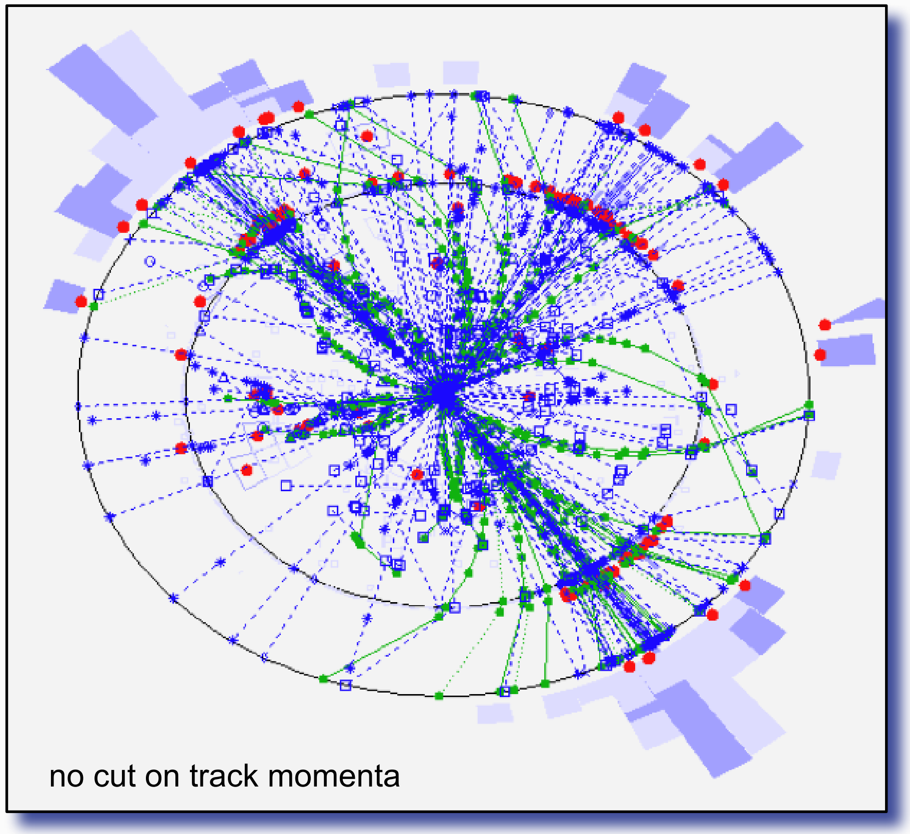
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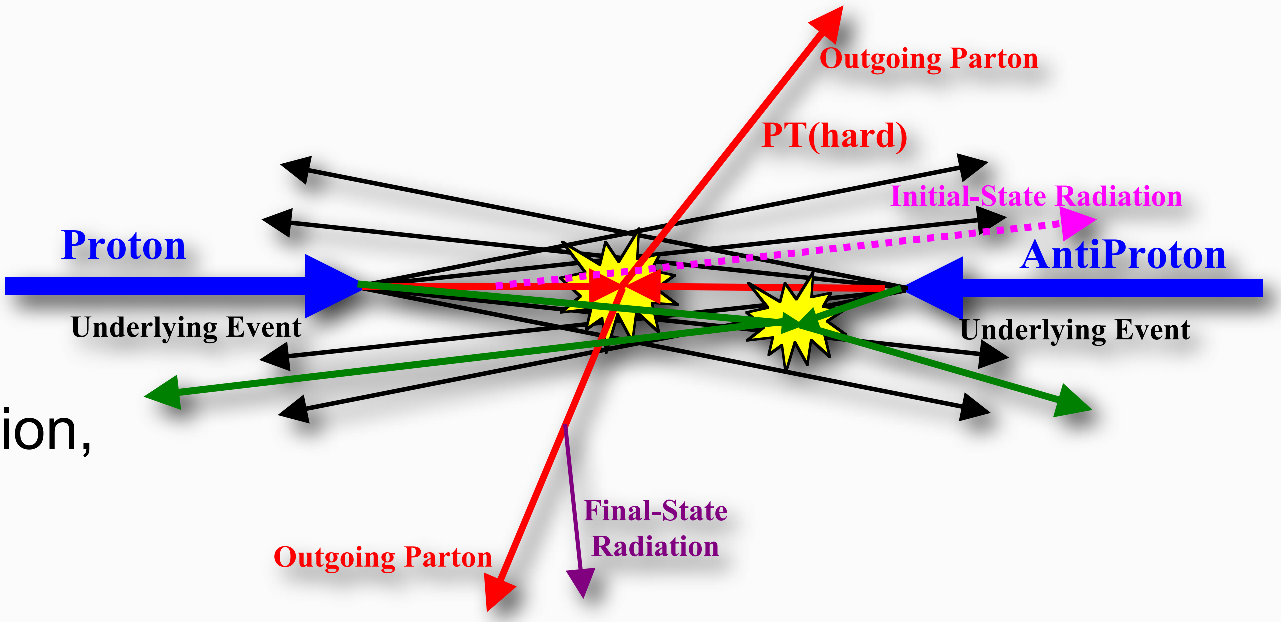

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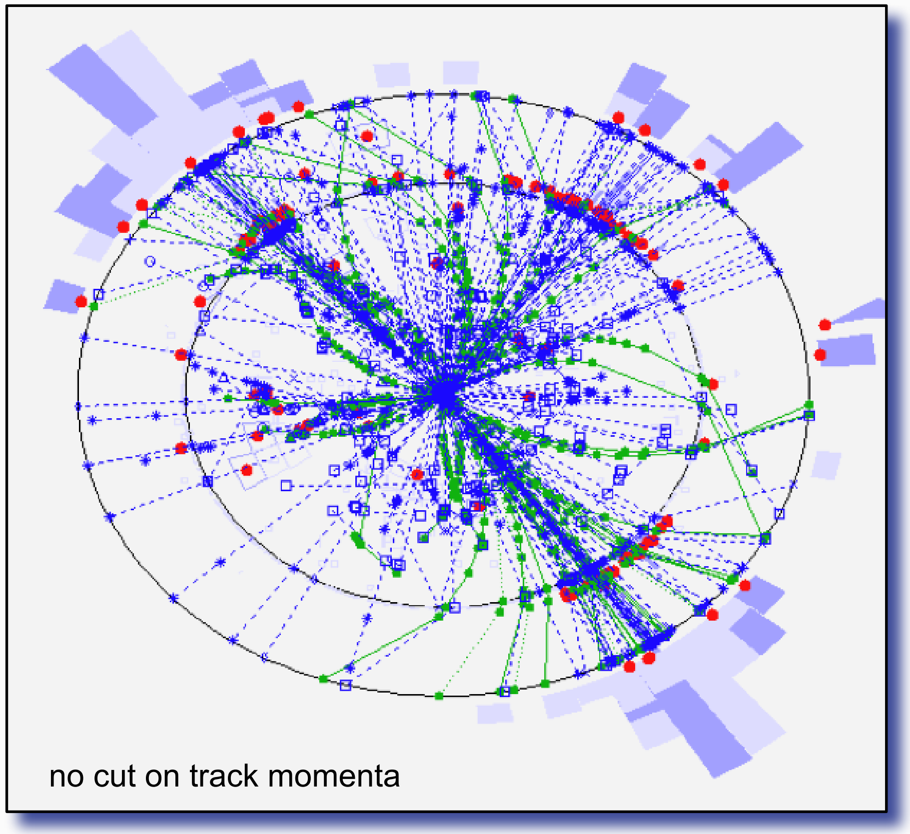

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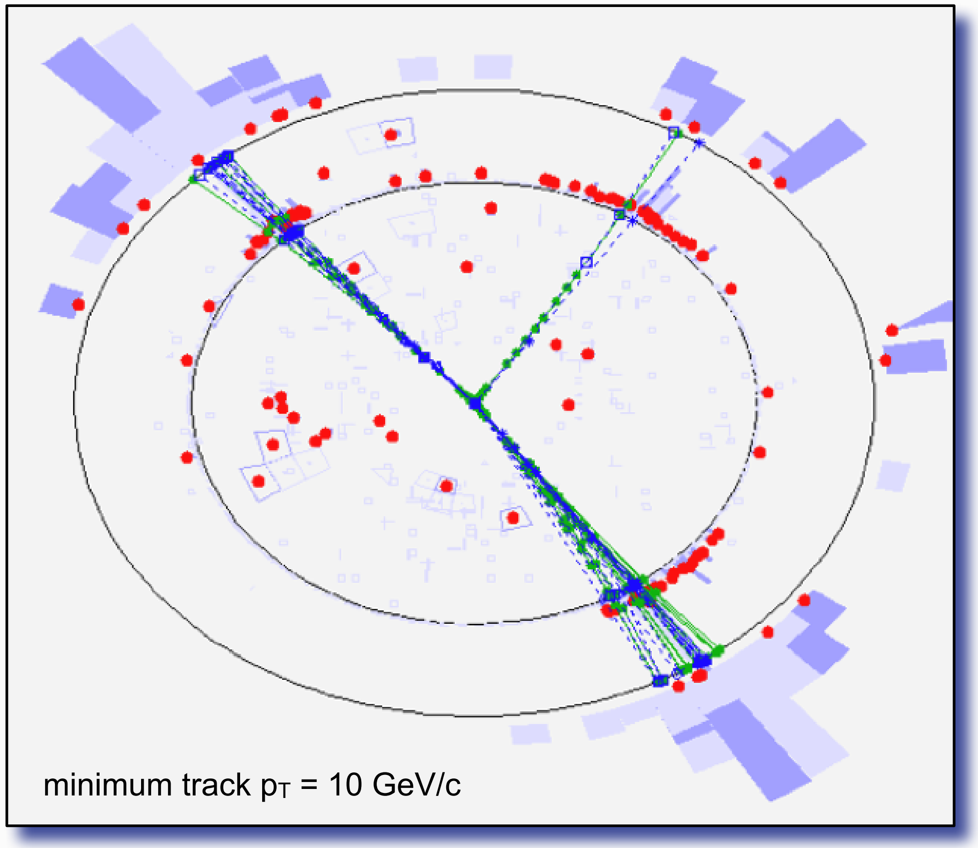
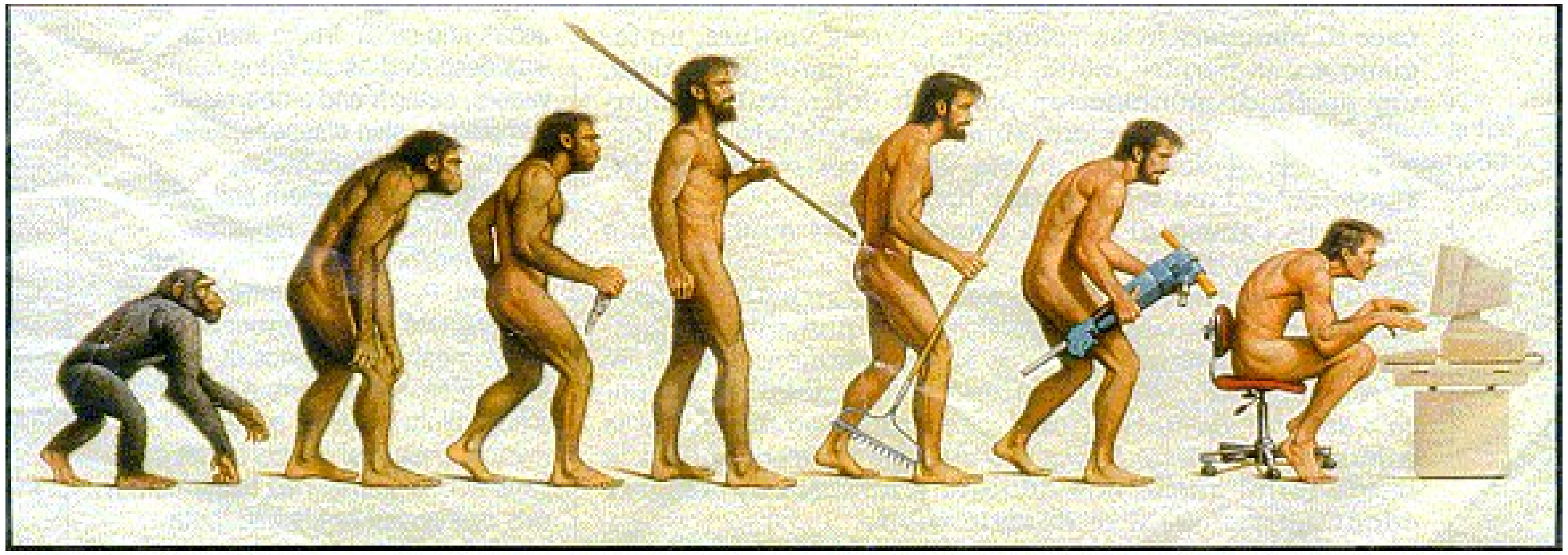


minimum track p_T = 10 GeV/c

The computing behind all this



Somewhere, something went terribly wrong

Some numbers

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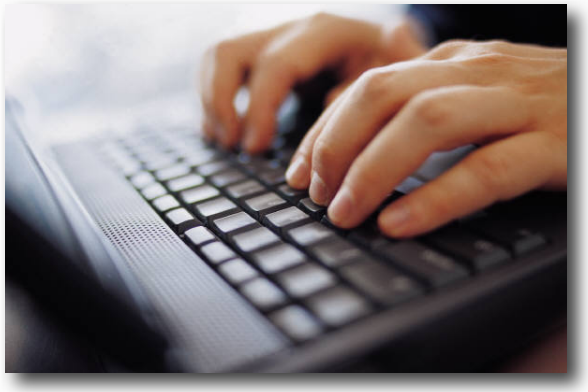

- “prompt” processing
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  - Reco time per event on std. CPU: < 5 sec (on lxplus)
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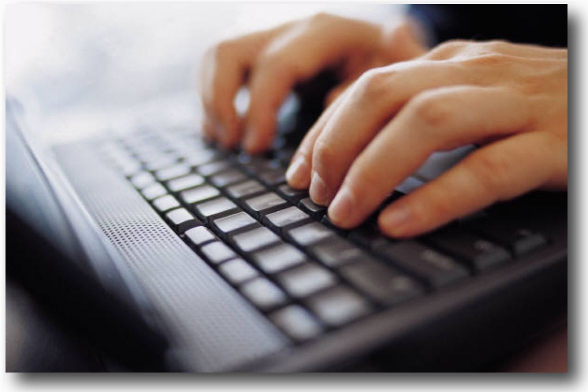

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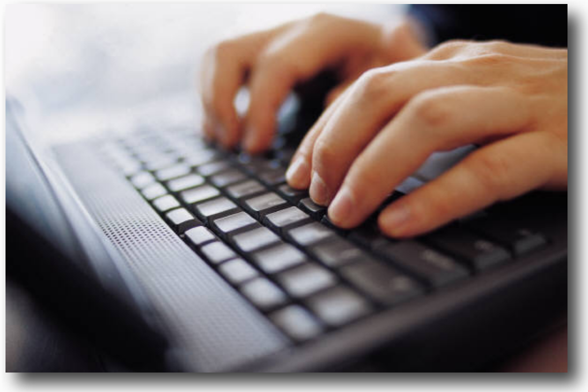

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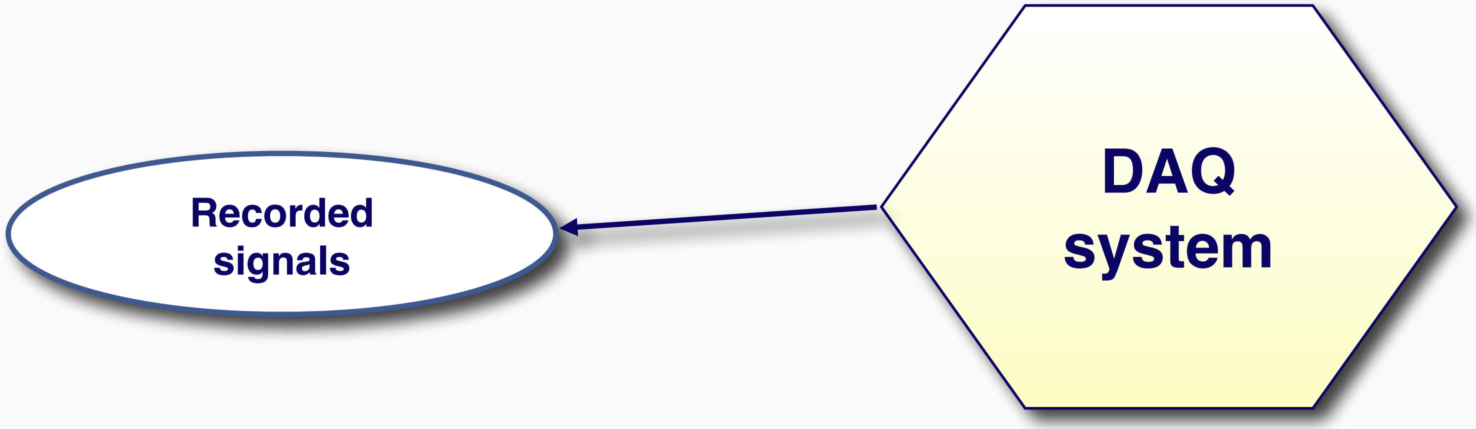
- ~2 million lines of code (reconstruction and simulation)

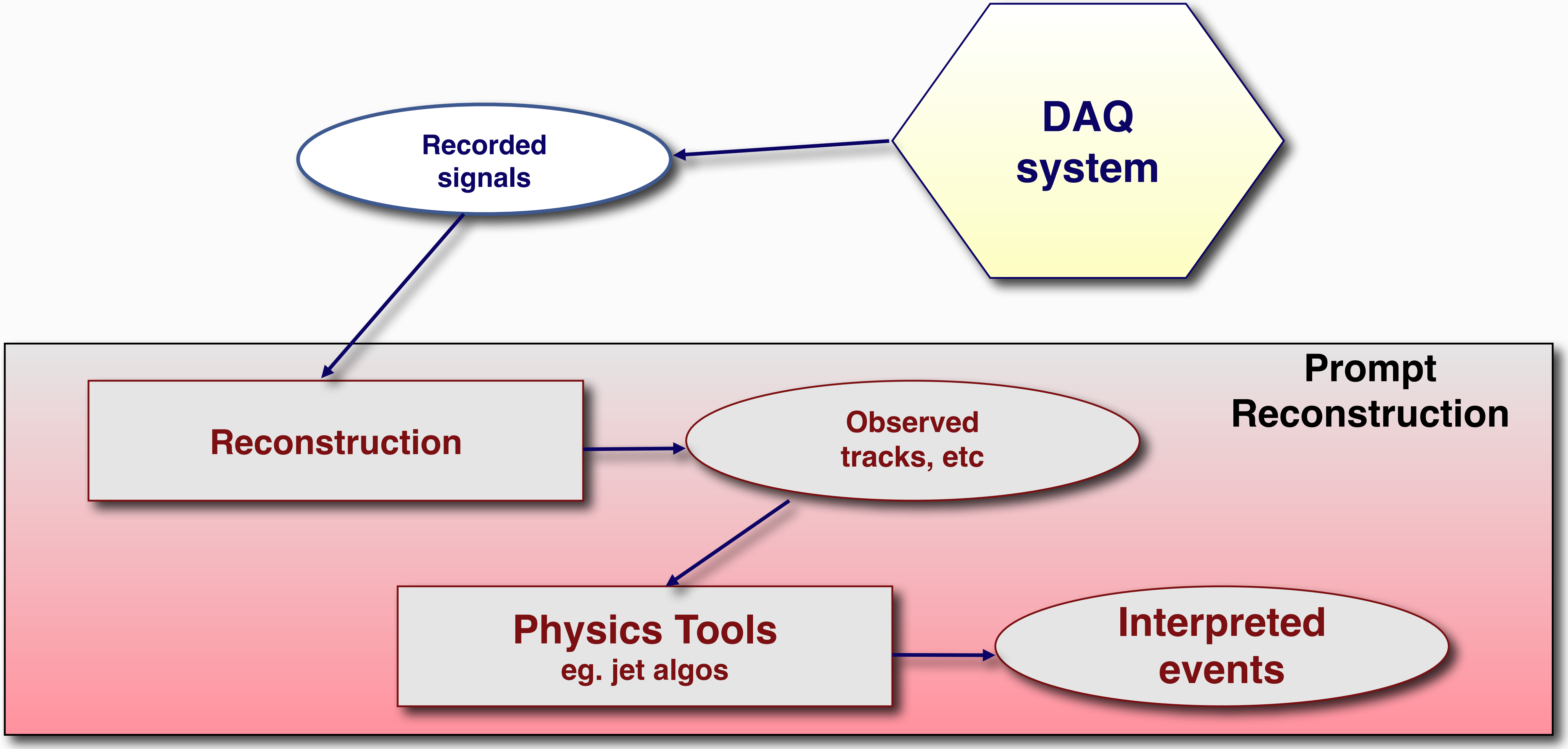
RECO flow



Recorded signals

DAQ system

RECO flow



DAQ system

Recorded signals

Prompt Reconstruction

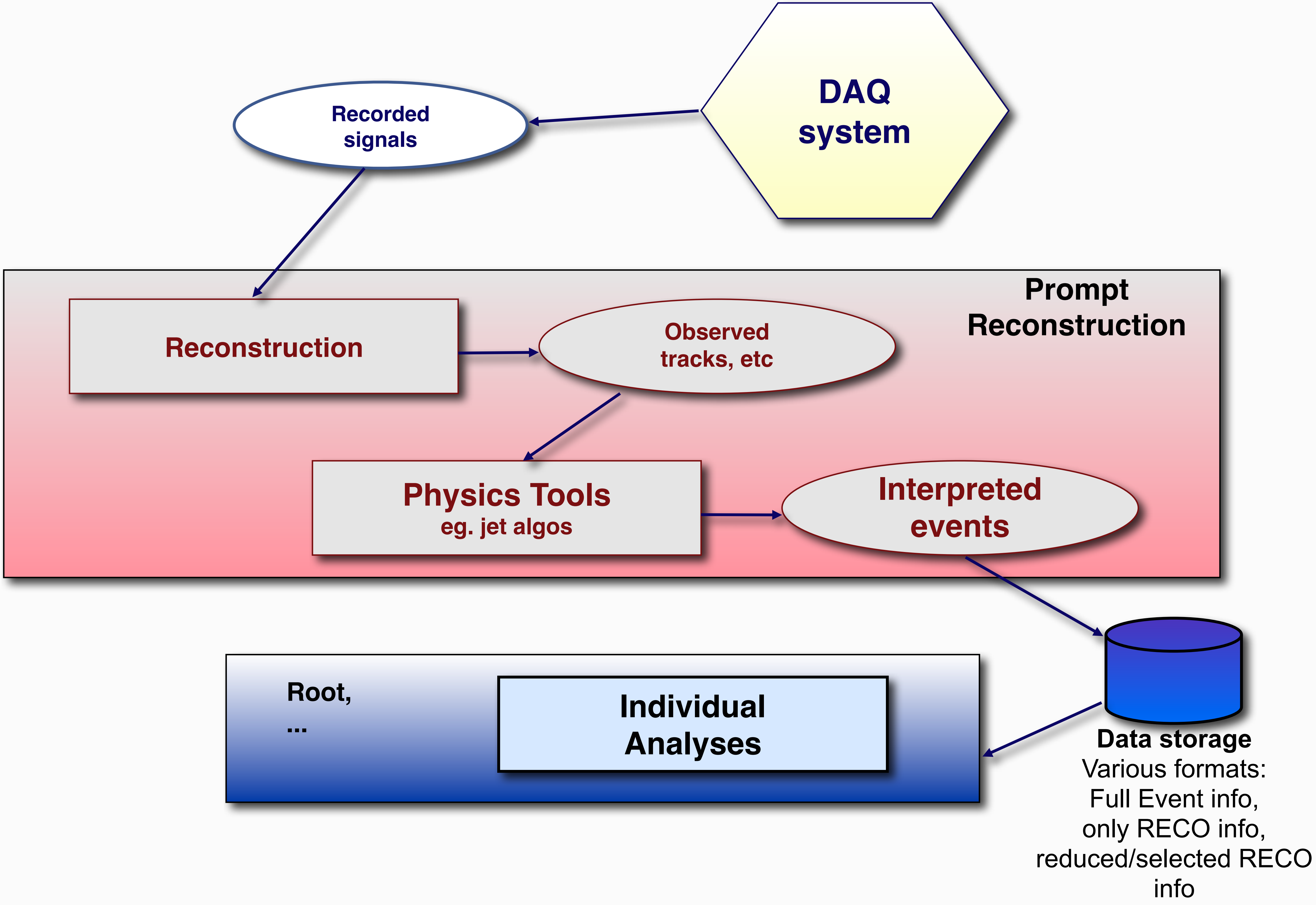
Reconstruction

Observed tracks, etc

Physics Tools
eg. jet algos

Interpreted events

RECO flow



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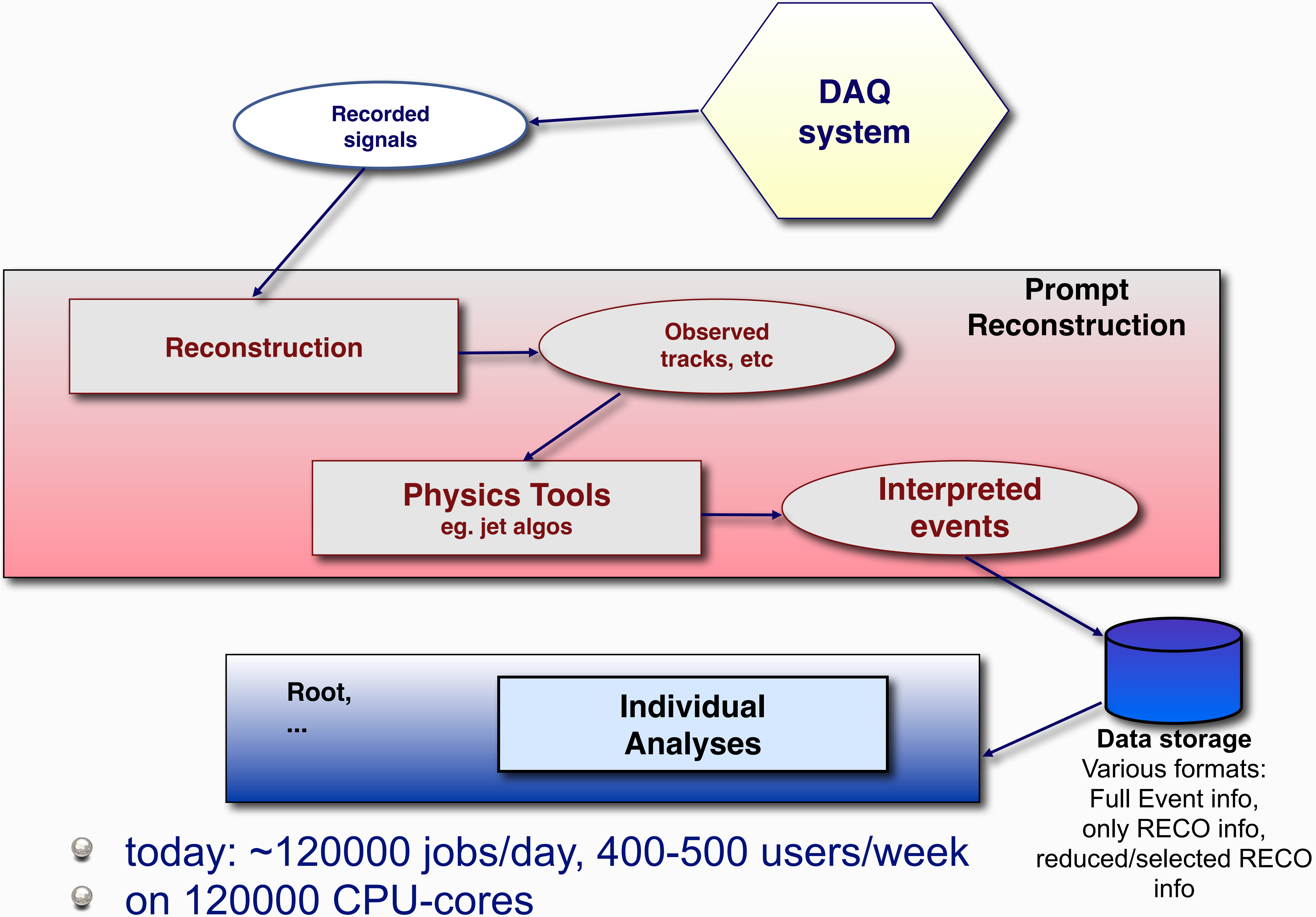
Data storage
Various formats:
Full Event info,
only RECO info,
reduced/selected RECO info

Root,
...

Individual Analyses

RECO flow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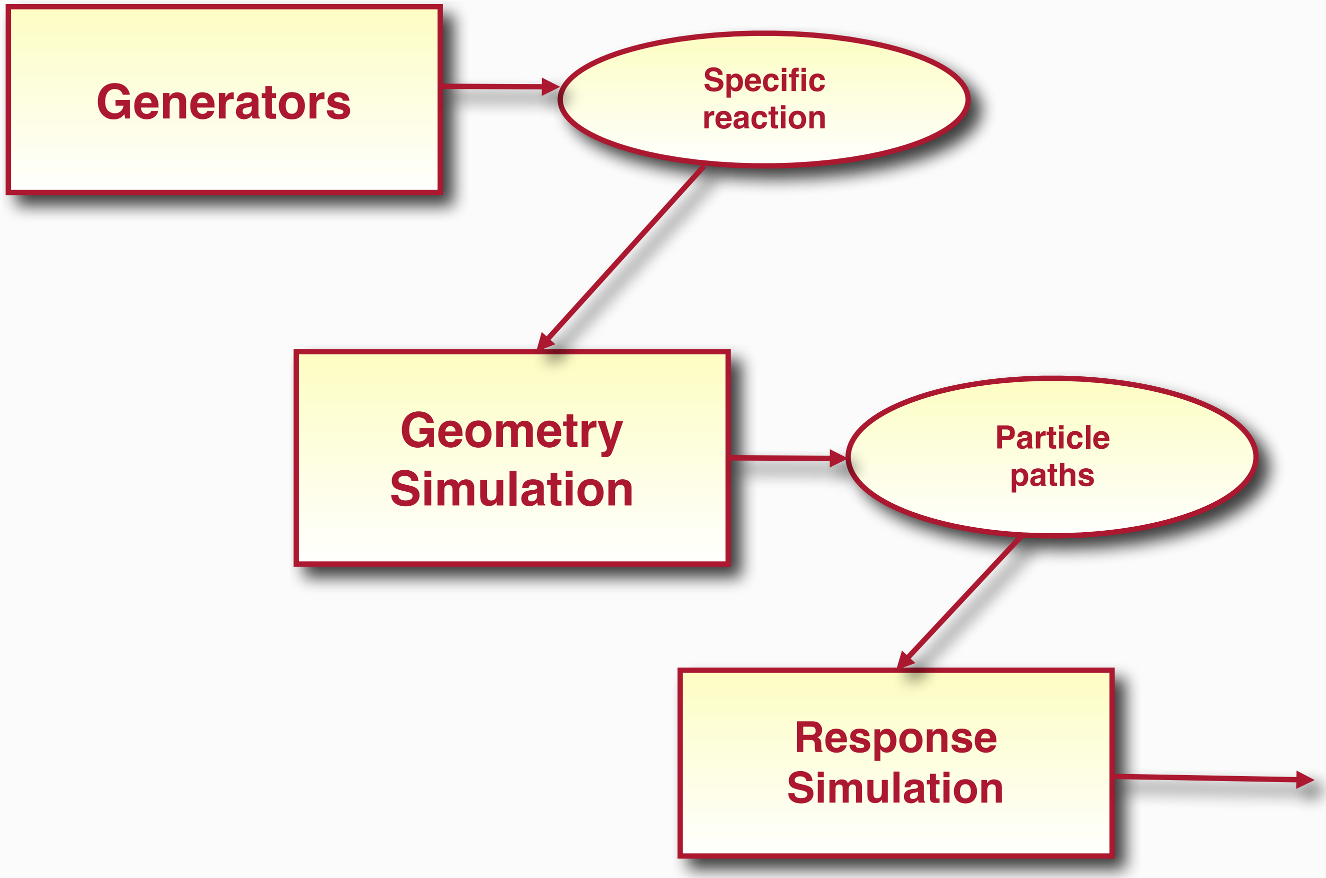
Individual Analyses

- today: ~120000 jobs/day, 400-500 users/week
- on 120000 CPU-cores

Flow of simulated data



Generators

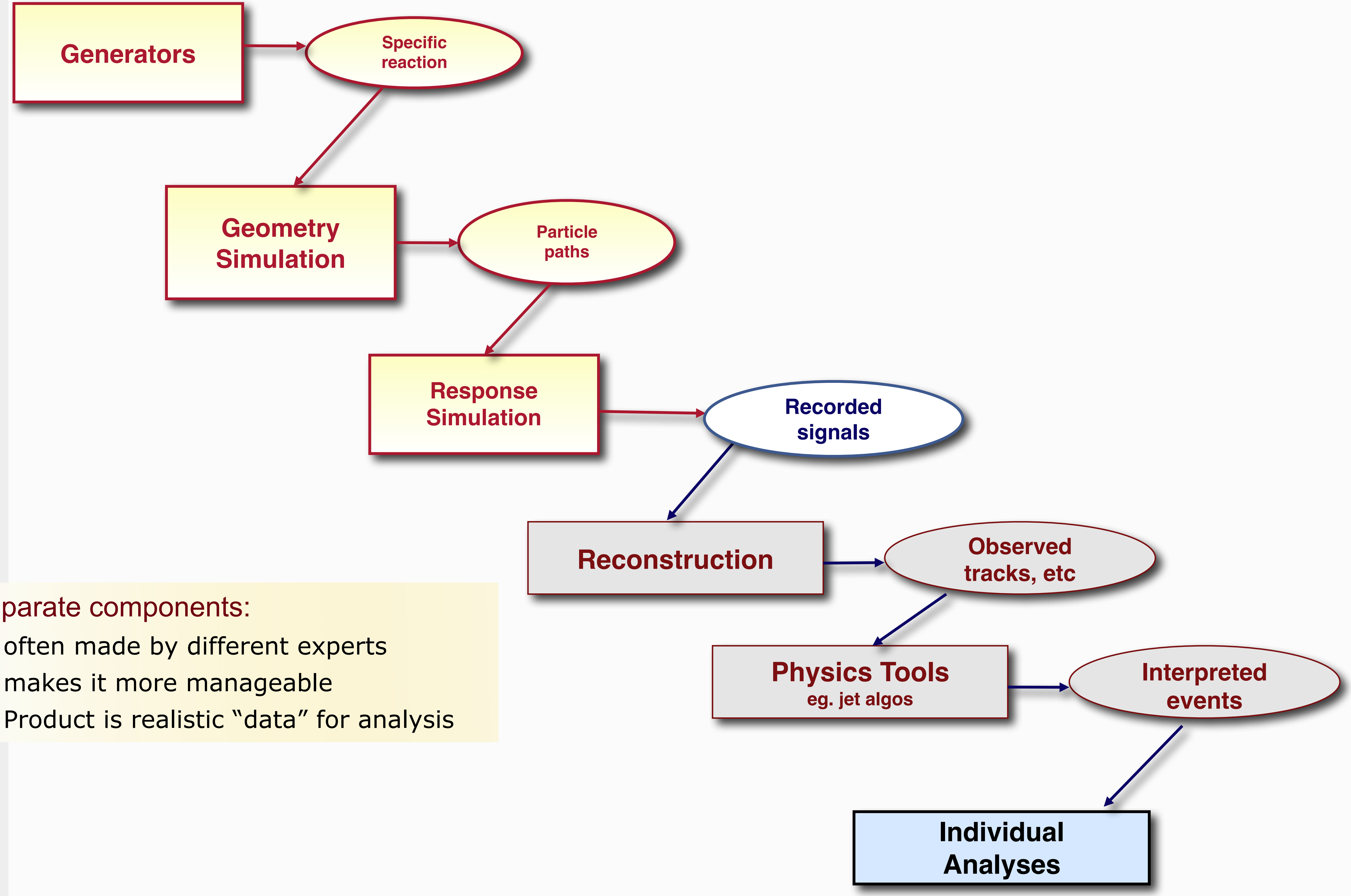
Specific reaction

Geometry Simulation

Particle paths

Response Simulation

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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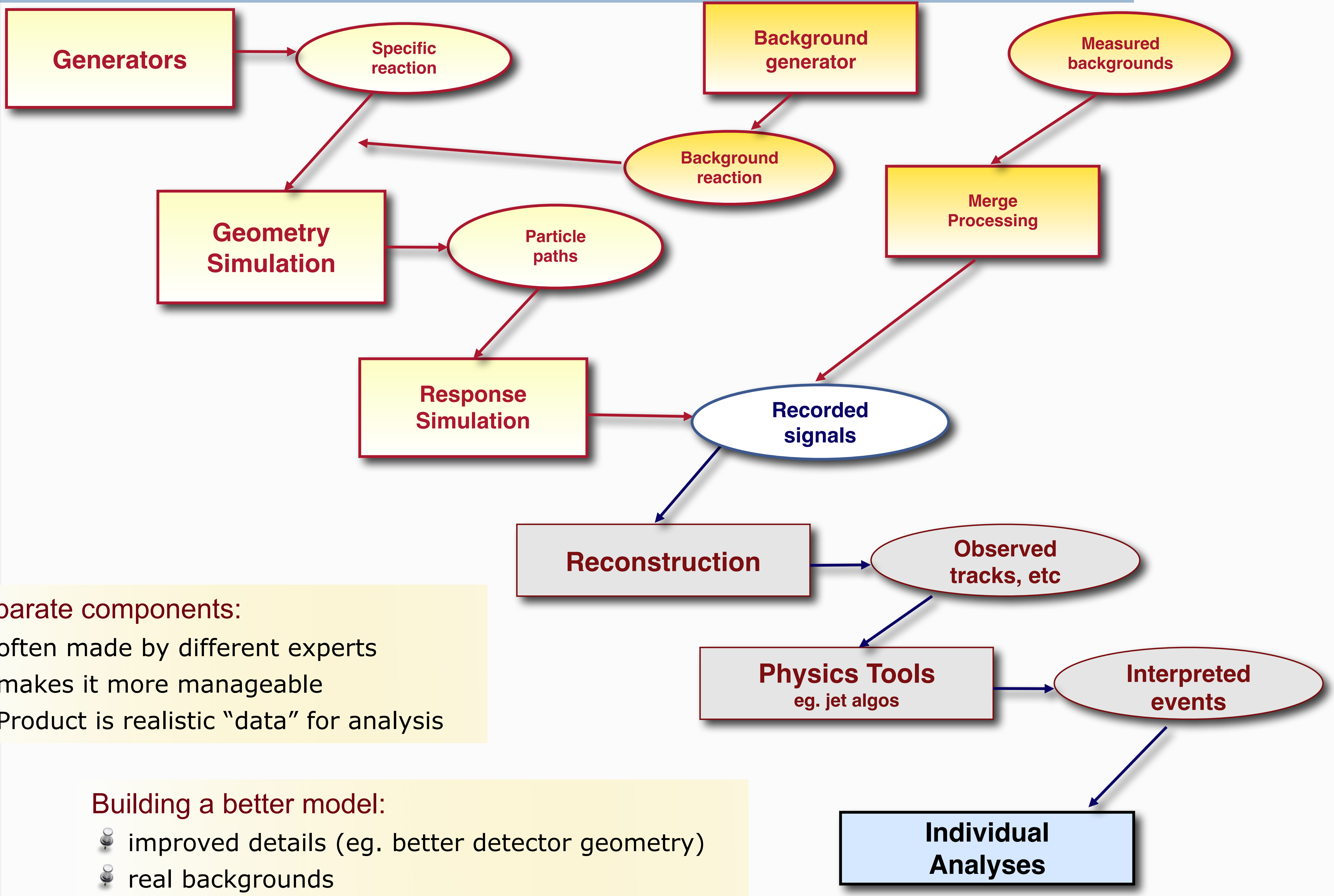

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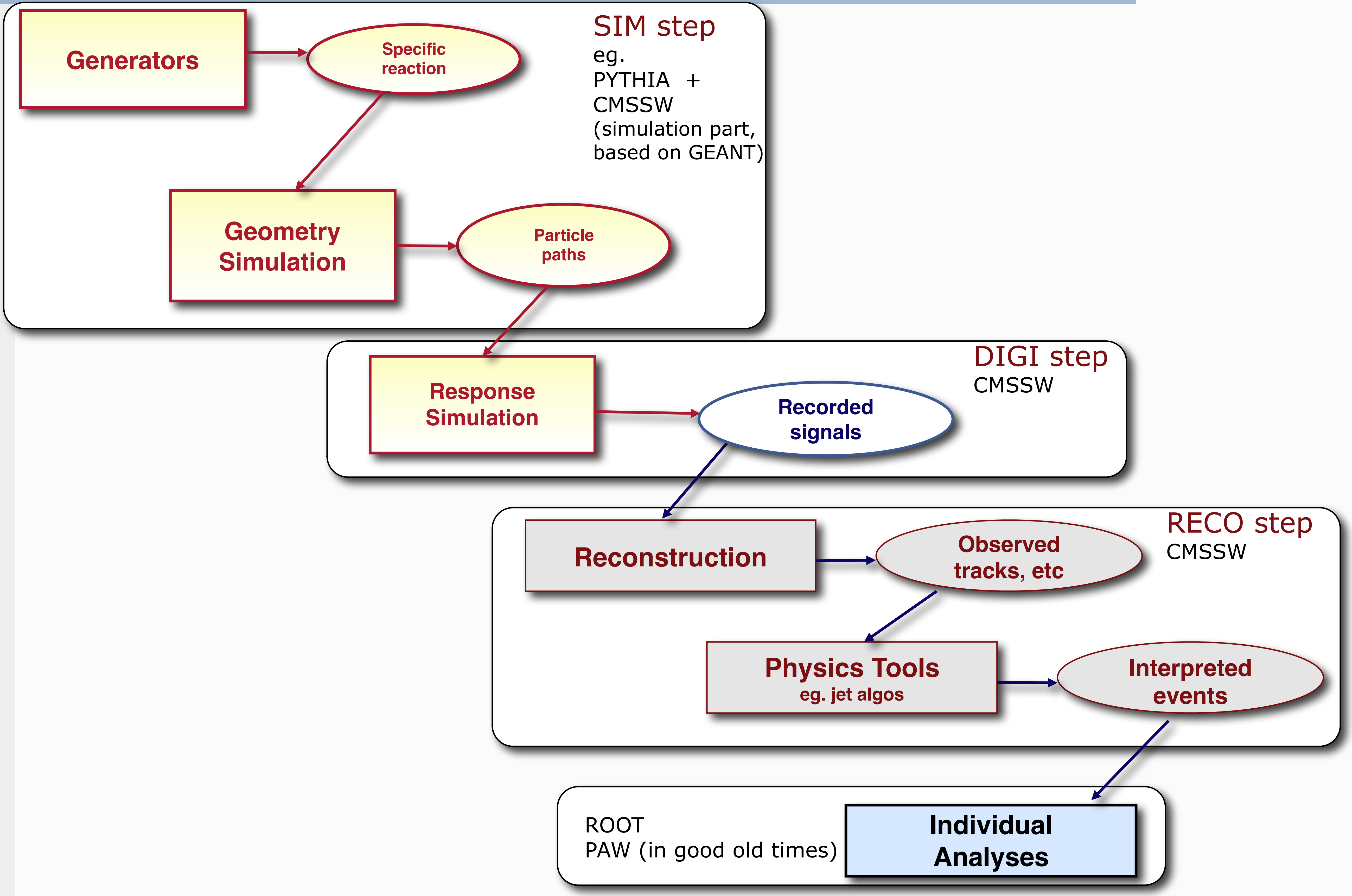
Building a better model:

- improved details (eg. better detector geometry)
- real backgrounds

Partitioning production systems



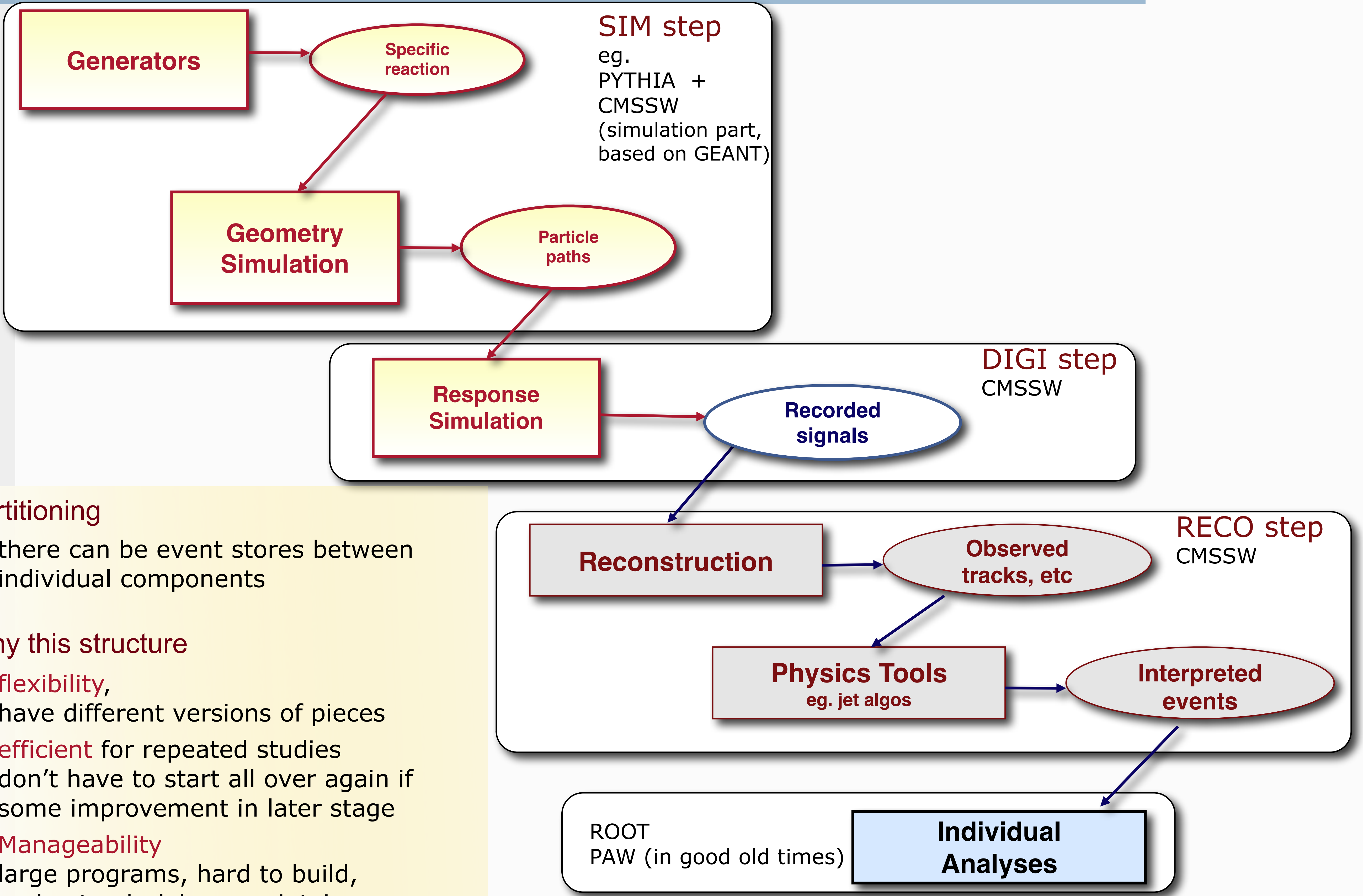
SIM step
eg.
PYTHIA +
CMSSW
(simulation part,
based on GEANT)

DIGI step
CMSSW

RECO step
CMSSW

ROOT
PAW (in good old times)

Partitioning production systems



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Individual Analyses

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

ETH Institute for Particle Physics

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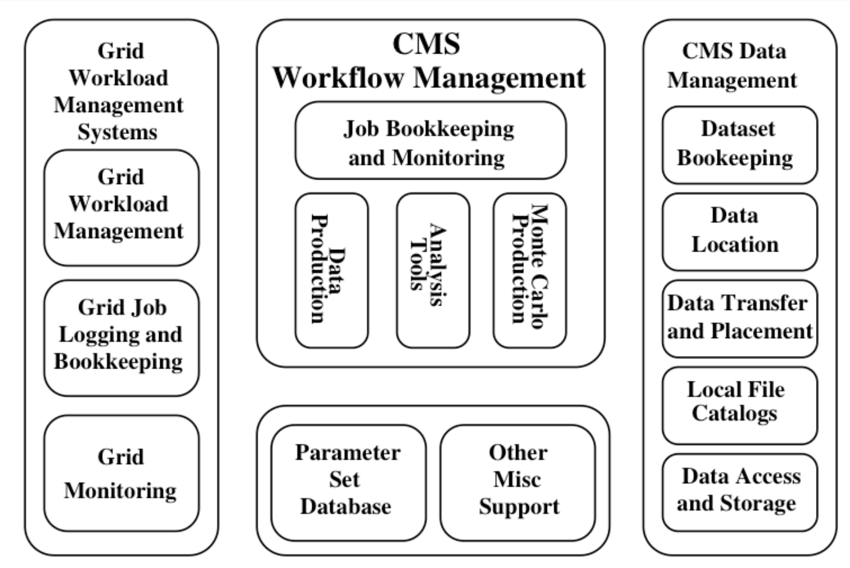

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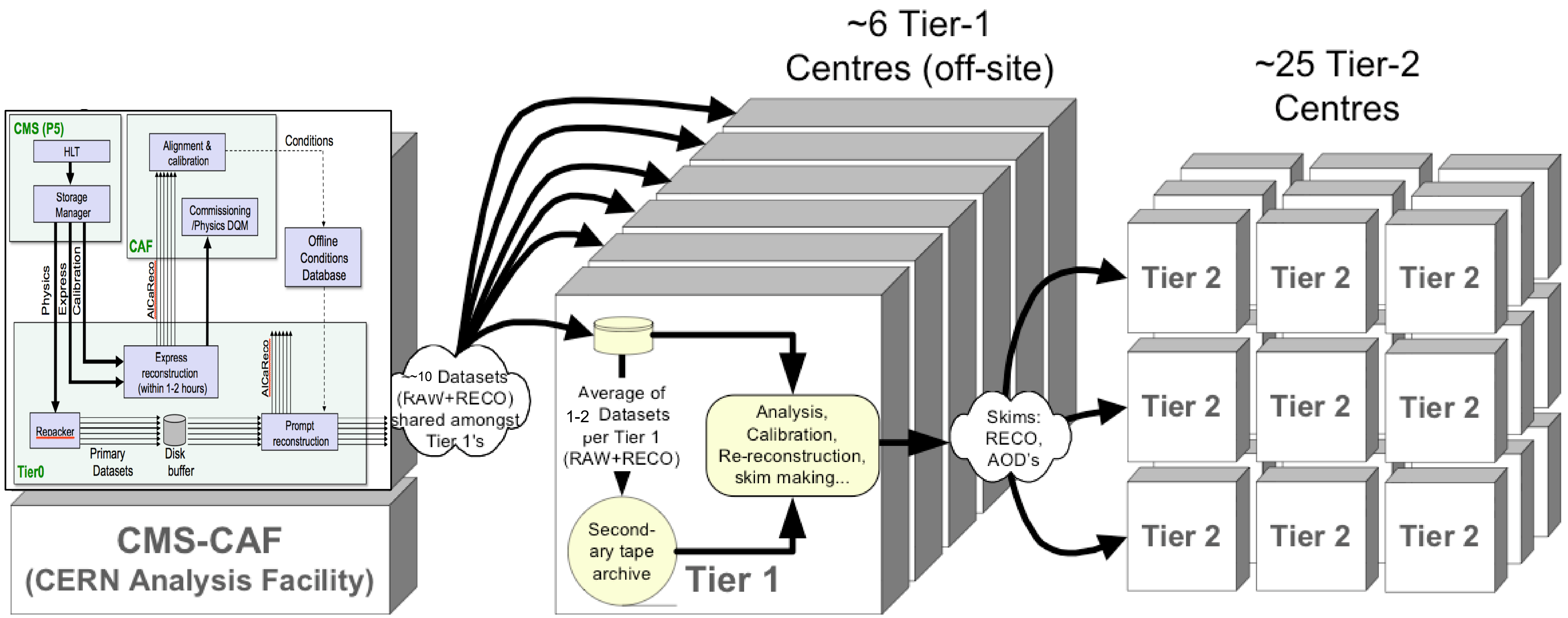
GRID distribution : example

CMS Computing Model: Data Flow



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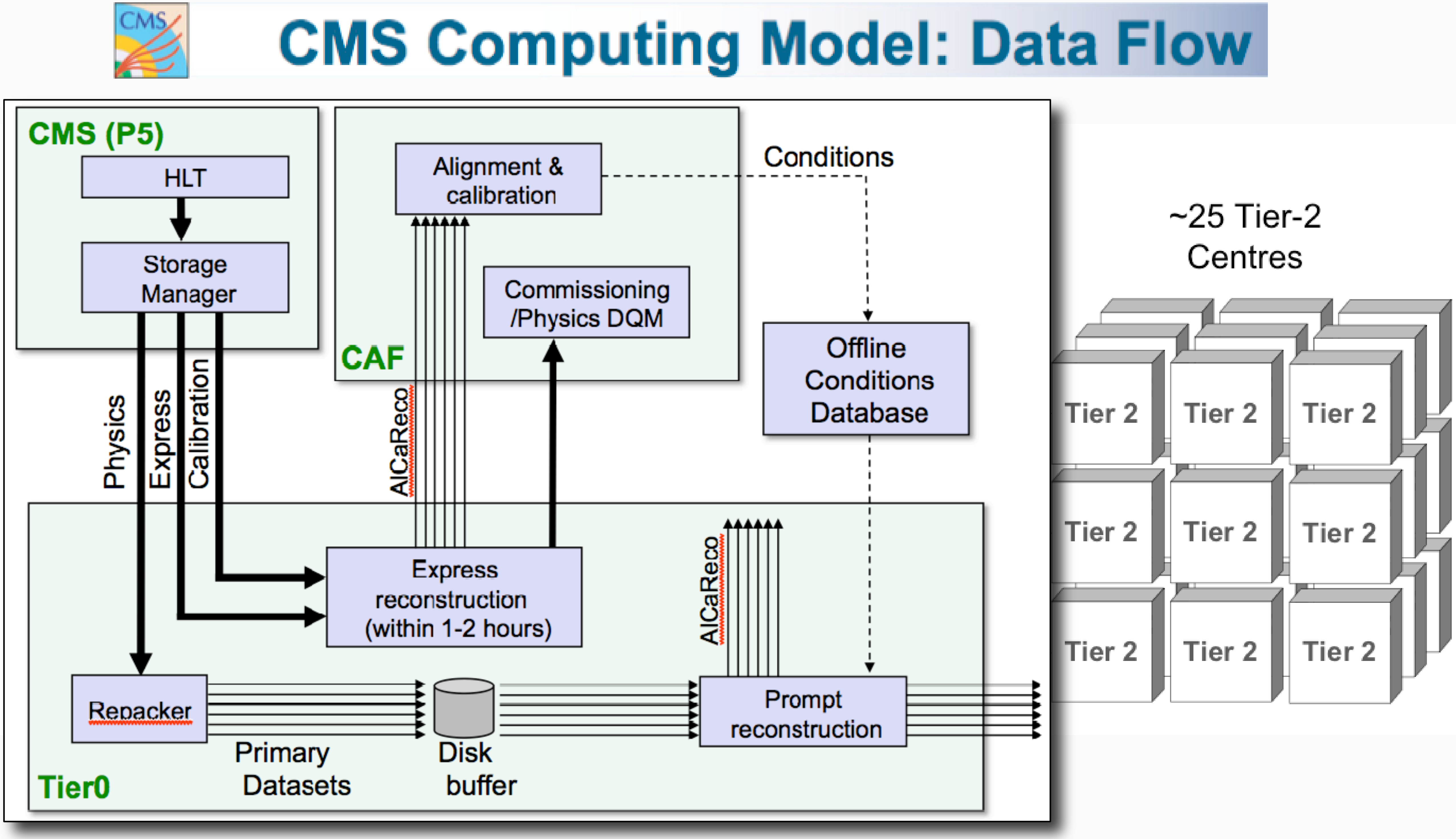

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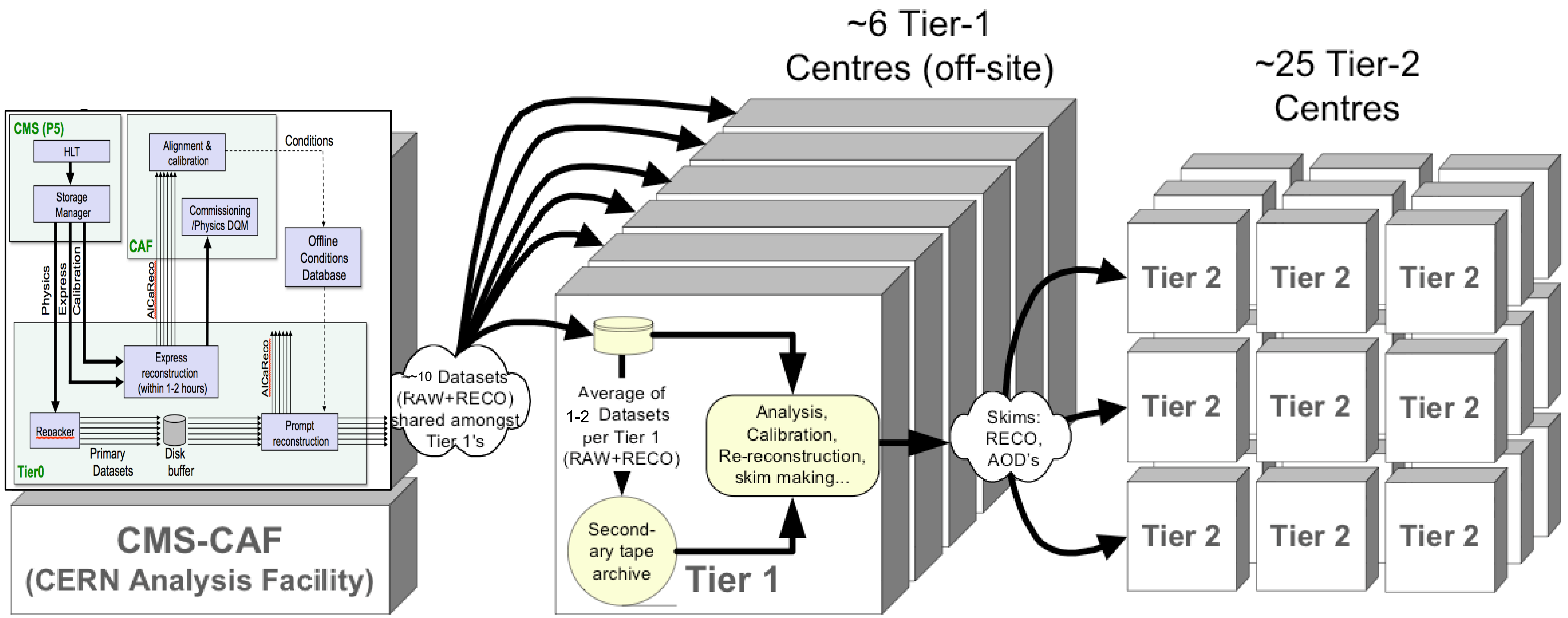

Summary

"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, ...)
- .....

Conclusions

- Reconstruction and Analysis
  is how we get from raw data to physics papers

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