LHC for SUSY Theorists

1. Overview of the LHC Experiments

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PiTP Summer School
July 2007

The natural mass scale for supersymmetric particles is the scale of electroweak symmetry breaking, the mass scale of a few hundred GeV. It was interesting bet that the most recent generation of particle accelerators - SLC, LEP, and the Tevatron - would have enough energy to reach the SUSY scale. But it was not required that this be so.

For LHC, the prospects are very different. We expect that proton beams at the LHC energy will produce SUSY particles in significant numbers.

We should now be planning for the discovery at the LHC of SUSY or another comparable model of electroweak symmetry breaking.

A discovery era in fundamental physics is very different from the era of study and confirmation of a 'Standard Model'.

The major issues for the SLC, LEP, and Tevatron experiments have been

Can the experimental data be accounted for by known electroweak and strong interaction sources ?

What precision can be achieved in the Standard Model parameters when we use QCD and the electroweak theory to model the data ?

Which observations of agreement between the Standard Model and the data give the best limits on new physics ?   Which observations might be most sensitive to the first appearance of new physics ?

When our standard theory fails to account for the data, new types of question arise:

In what channels are anomalies observed ? Do we understand the standard prediction, in each case, well enough to claim an anomaly. Could the anomaly be an experimental artifact or misinterpretation ?

Can we assemble a pattern of anomalies into evidence for a specific new physics model ?

What additional anomalies must we observe to confirm this model ? What observations claimed by the experiments must be incorrect ?

These questions require new and unfamiliar skills. We all need to develop these skills.

In these lectures, I will discuss some topics that I expect will be relevant to these questions:

1. How will the experiments at the LHC be done ? What are the difficulties ? To what extent do these create opportunities for misinterpretation ?

2. Can we understand the Standard Model at a sufficient level to claim that data is inconsistent with its predictions ? SUSY predicts complex events. How do we compute the Standard Model backgrounds to these complex event topologies ?

3. How can we use LHC observations to constrain the spectrum of SUSY particles in a way that is as model-independent as possible ?

1. How will the experiments at the LHC be done ? What are the difficulties ? To what extent do these create opportunities for misinterpretation ?

What considerations drive the design of the LHC experiments ?

We are interested in observing cross sections at the level of

1 - 10 pb

for SUSY pair production and Higgs boson production. These must often be multiplied by branching ratios

$$BR(Z^0 \to \mu^+\mu^-) = 0.034 \qquad BR(h^0 \to \gamma\gamma) \sim 2 \times 10^{-3}$$

So we need luminosities of the order of

$$10 \ \mathrm{fb}^{-1}/\mathrm{yr} \quad \mathrm{or} \quad 1 \ \mathrm{nb}^{-1}/\mathrm{sec}$$

The LHC design luminosity is 10 times higher. However, the initial LHC running should be at about this level.

The proton bunches collide and interact every 25 nsec.

So,

for a cross section of 1 nb,
we have 1 event / second

for a cross section of 0.1 barn,
we have 2.5 events / bunch crossing

for example,

$$\sigma(pp \to t\bar{t} + X) \sim 0.8 \text{ nb}$$

so we will see almost 1 $\bar{t}t$ pair per second, and (hopefully) many SUSY events per hour.

However, there are relevant processes with rates of events/crossing:

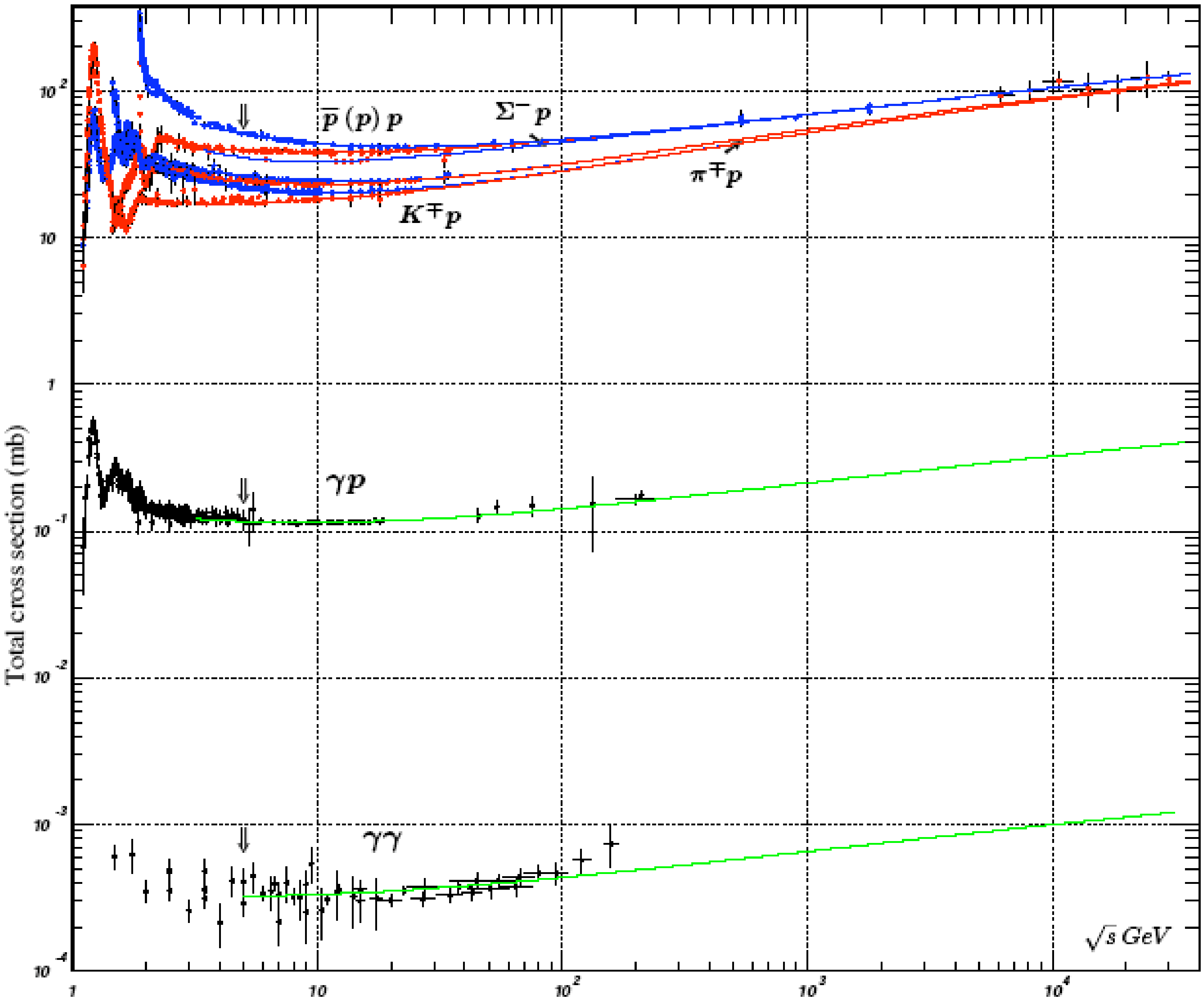
the proton-proton total cross section is expected to be
100 mb, or 2.5 events/crossing

the parton-parton hard scattering cross section reaches
these rates for $p_T \sim 10 \ \mathrm{GeV}$

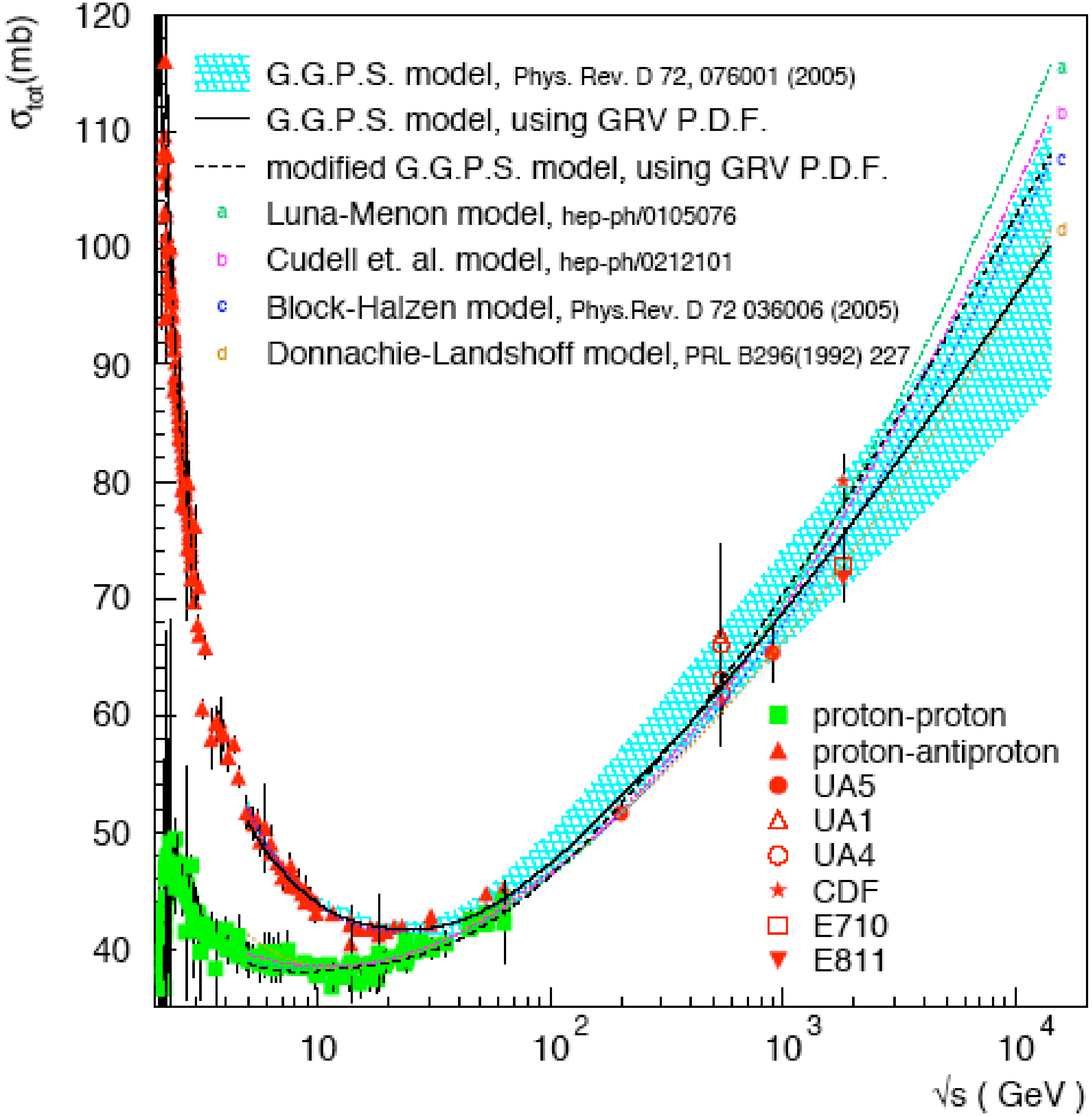
So

We need to be able to observe processes at $10^{-10} - 10^{-14}$
of the rates for these dominant reactions.

Every observed new physics event will be accompanied by additional 'minimum bias' events and by additional jets.



PDG compilation



Godbole et al, hep-ph/0604214

If events occur at every bunch crossing, we must ask what fraction of these events will be recorded into permanent storage.

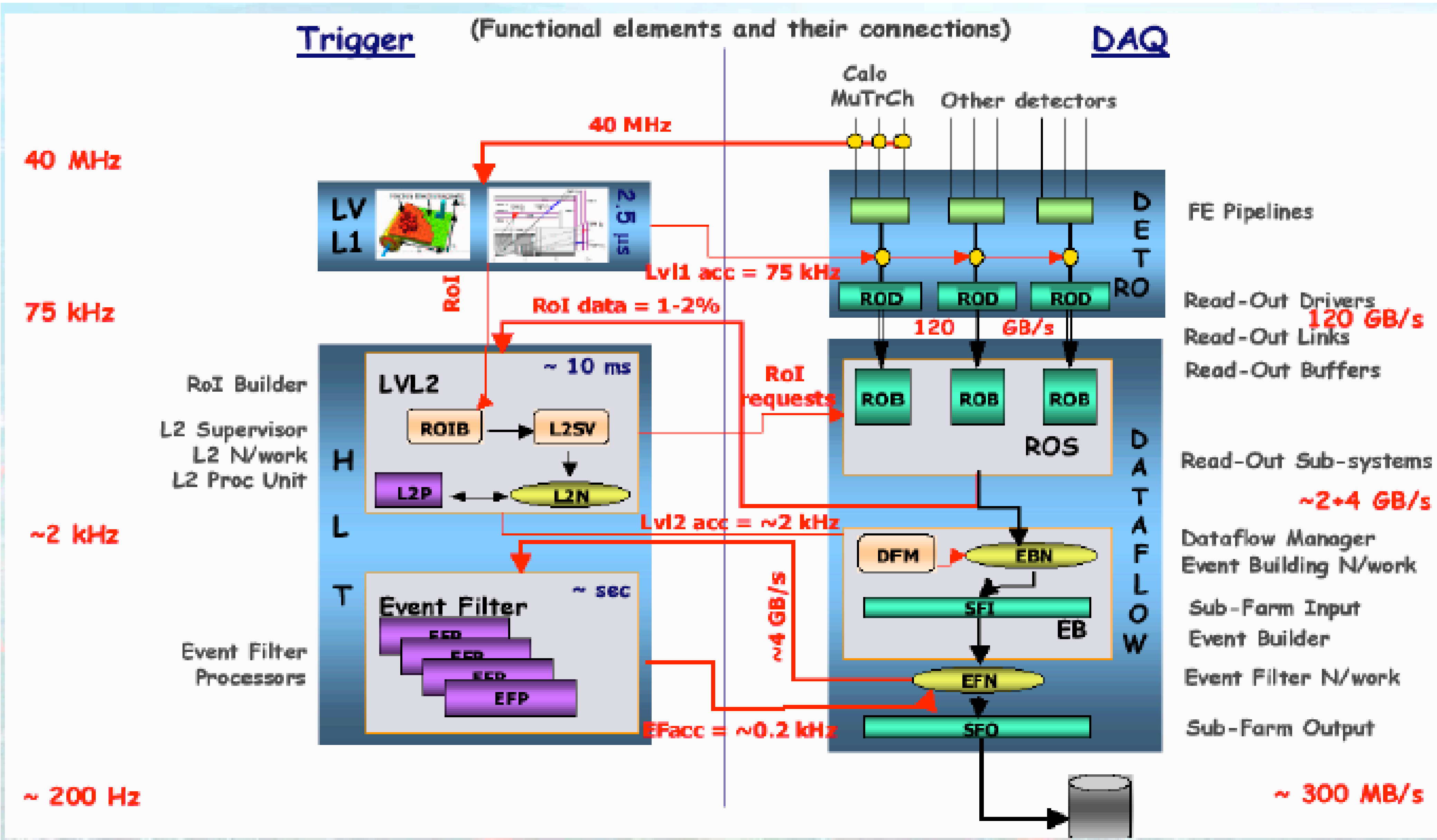
The current plan is to record about 200 events/sec , compared to the bunch crossing rate of $40 \times 10^6/\mathrm{sec}$.

At about 100 Mb/event, this gives a database of 20 Pb / yr. The reduced data sets used for scanning and crude analysis are of size 200 Tb / yr.

The reduction from 40 MHz to 100 Hz must be done automatically, without direct human intervention. This is done by the trigger, a network of computers and data pipelines. In ATLAS, the trigger has 3 levels. Conceptually,

	allowed rate	decision time
Level 1	1 MHz	100 microsec
Level 2	10 kHz	10 msec
Level 3	100 Hz	1 sec

more precisely:



N. Ellis, ATLAS

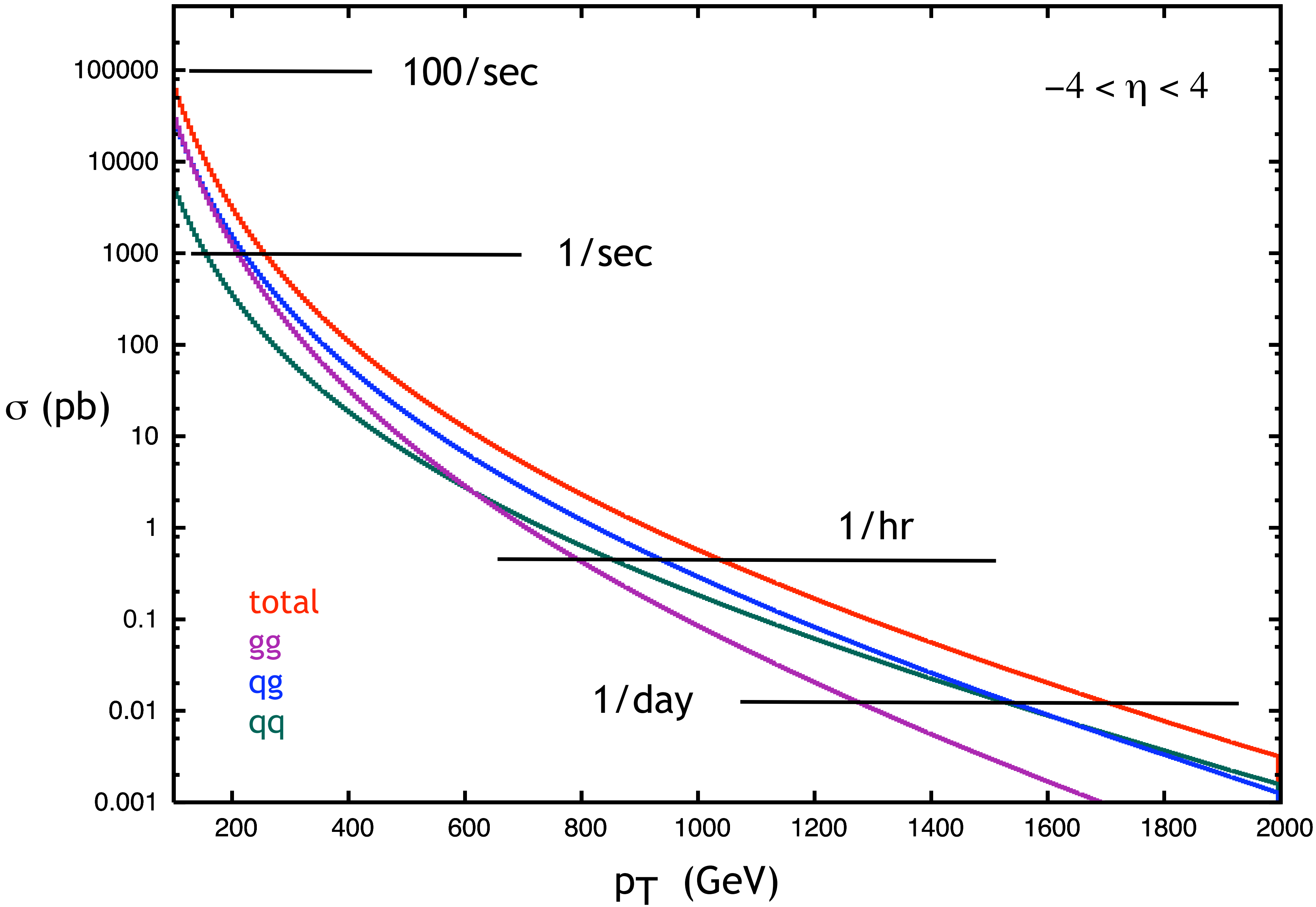
With this background, we can look at the rates of jet production and similar processes.

To understand the jet rates, we should look at the integral p_T spectrum for jet production

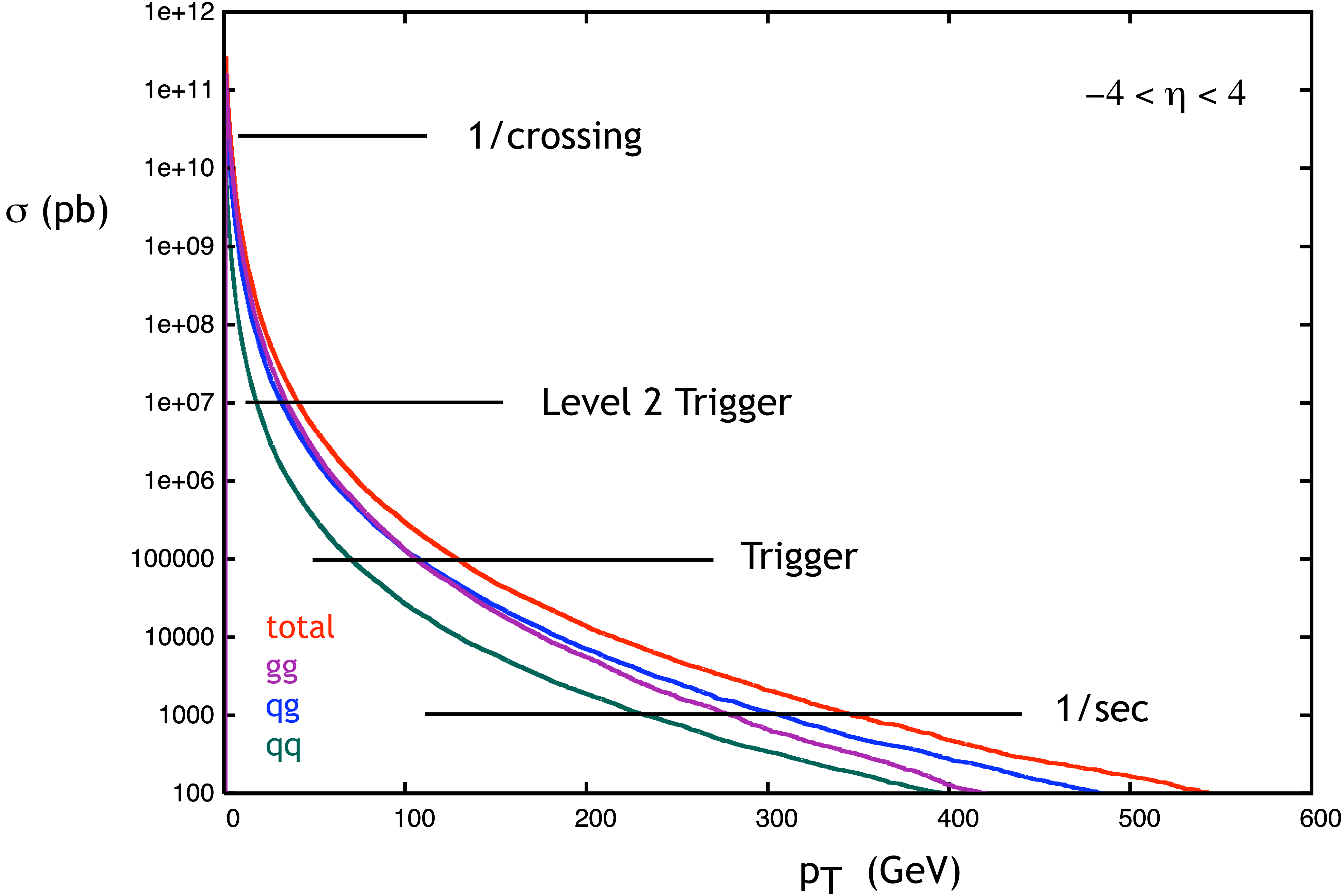
$$\int_{P_T}^{\infty} dp_T \; \frac{d\sigma}{dp_T}$$

as computed from the parton distributions and QCD.

It is acceptable that this quantity becomes larger than the pp total cross section. This only indicates that there are multiple parton scattering events per pp collision.



100000
10000
1000
100
10
1
0.1
0.01
0.001
σ (pb)
100/sec
1/sec
1/hr
1/day
−4 < η < 4
total
gg
qg
qq
200
400
600
800
1000
1200
1400
1600
1800
2000
pT (GeV)



1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
100000
10000
1000
100
σ (pb)
0
100
200
300
400
500
600
pT (GeV)
−4 < η < 4
1/crossing
Level 2 Trigger
Trigger
1/sec
total
gg
qg
qq

To deal with the event rate, we must first demand the presence of jets with sufficiently large values of p_T . We then need to look for other indicators that the reaction is not simple parton-parton scattering:

high deposited energy

central angular distribution

multiple jets

missing p_T

isolated or high p_T leptons

b quarks

tau leptons

Two of these items deserve special comment.

In pp collisions, much of the particle production occurs at extremely forward angles. A variable more convenient than angle is rapidity y defined by

$$E = \mathcal{P}_T \cosh y \quad p^z = \mathcal{P}_T \sinh y \quad \mathcal{P}_T = \sqrt{p_T^2 + m^2}$$

We then refer to particles or jets by their position in the

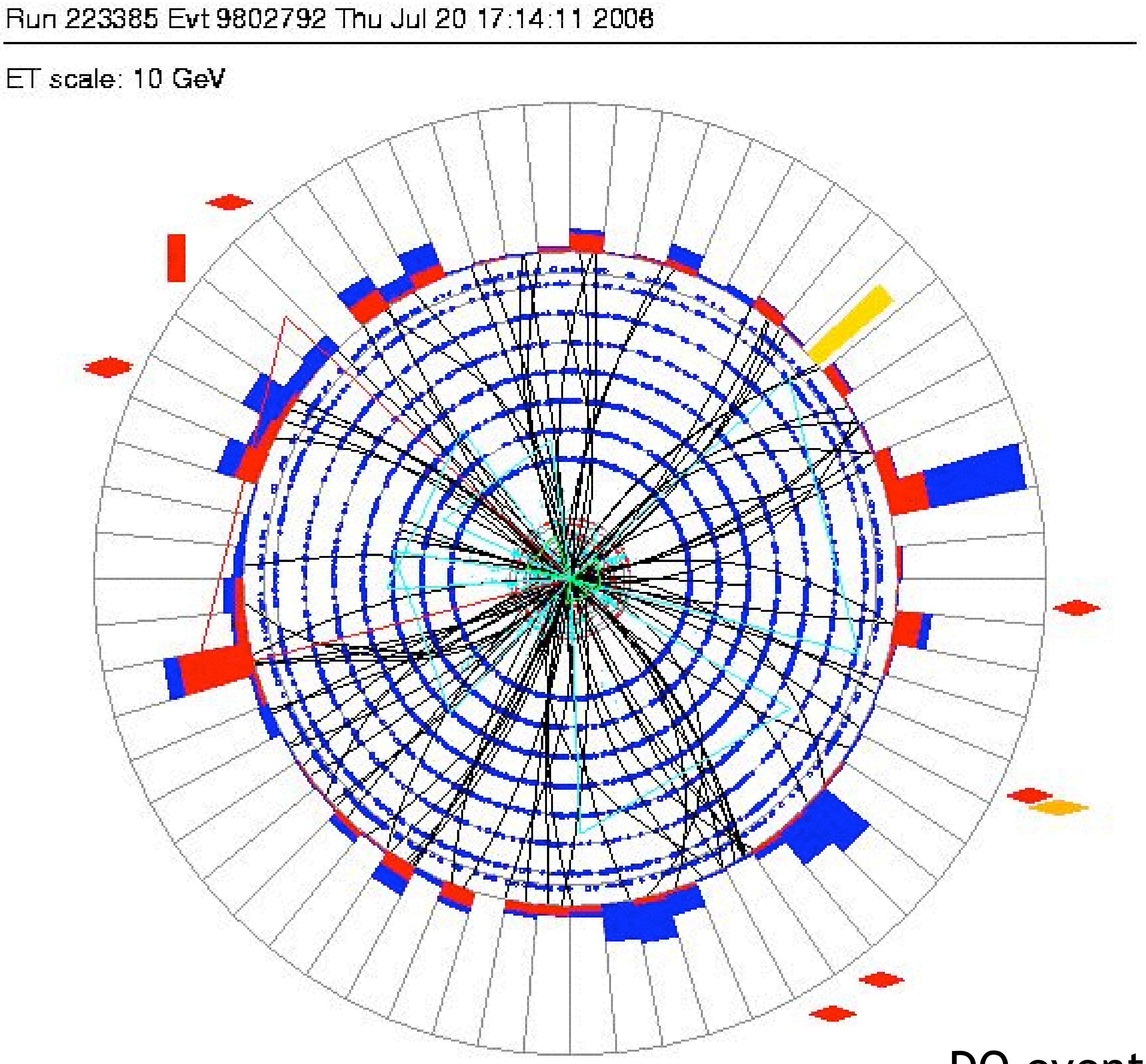
$$(y, \phi, p_T)$$

space. The very useful 3-d plot of p_T over the (y, ϕ) plane is called the Lego Plot.

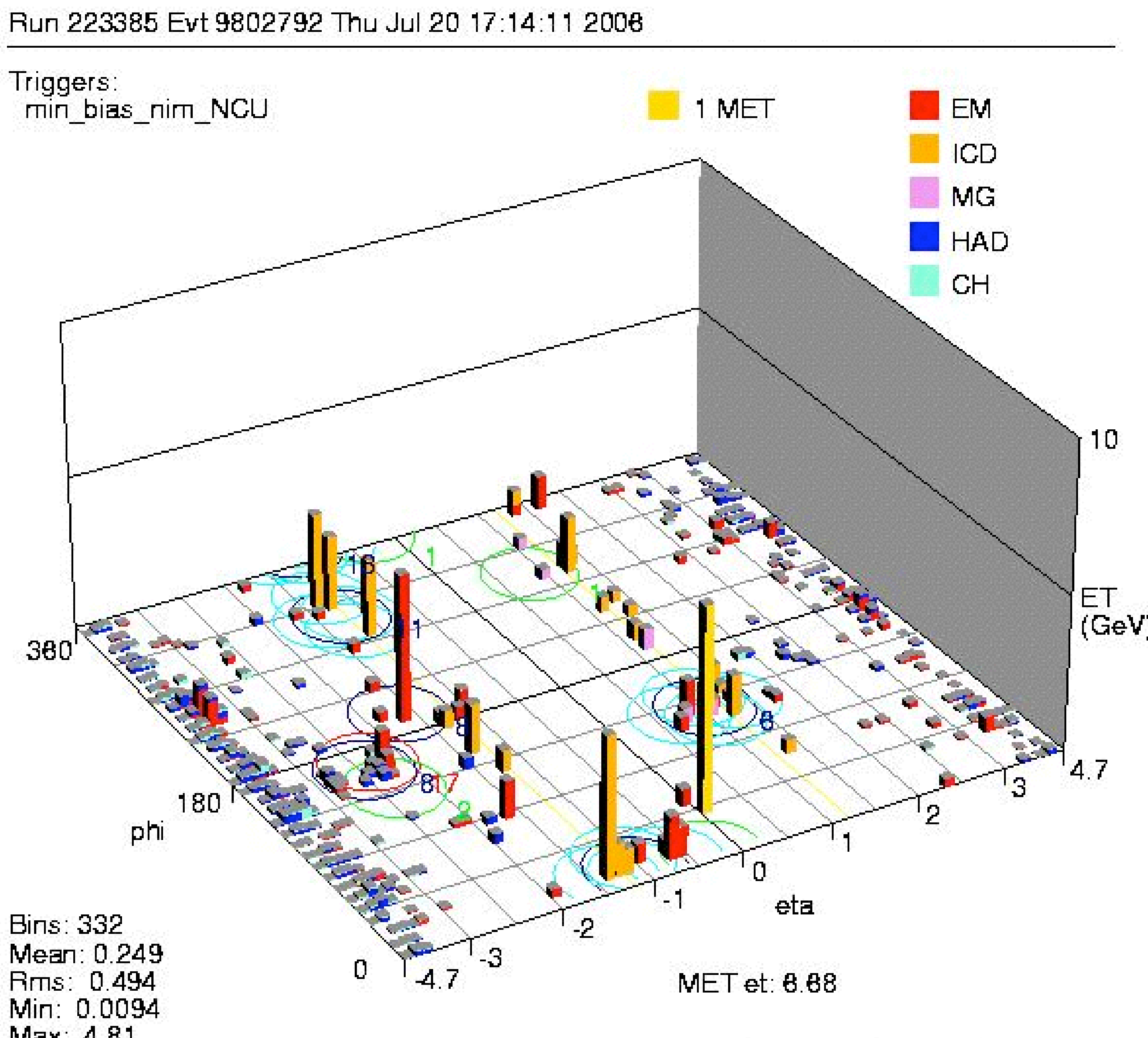
Often we ignore m and replace polar angle by pseudorapidity η

$$\cos\theta = \tanh\eta \quad \text{or} \quad \eta = \frac{1}{2}\log\frac{1+\cos\theta}{1-\cos\theta}$$

Boosts are translations in rapidity. Generic particle production and low-p_T jets result from parton reactions randomly distributed over boosts and are thus approximately uniform in rapidity. HIgh-p_T collisions occur near y = 0.

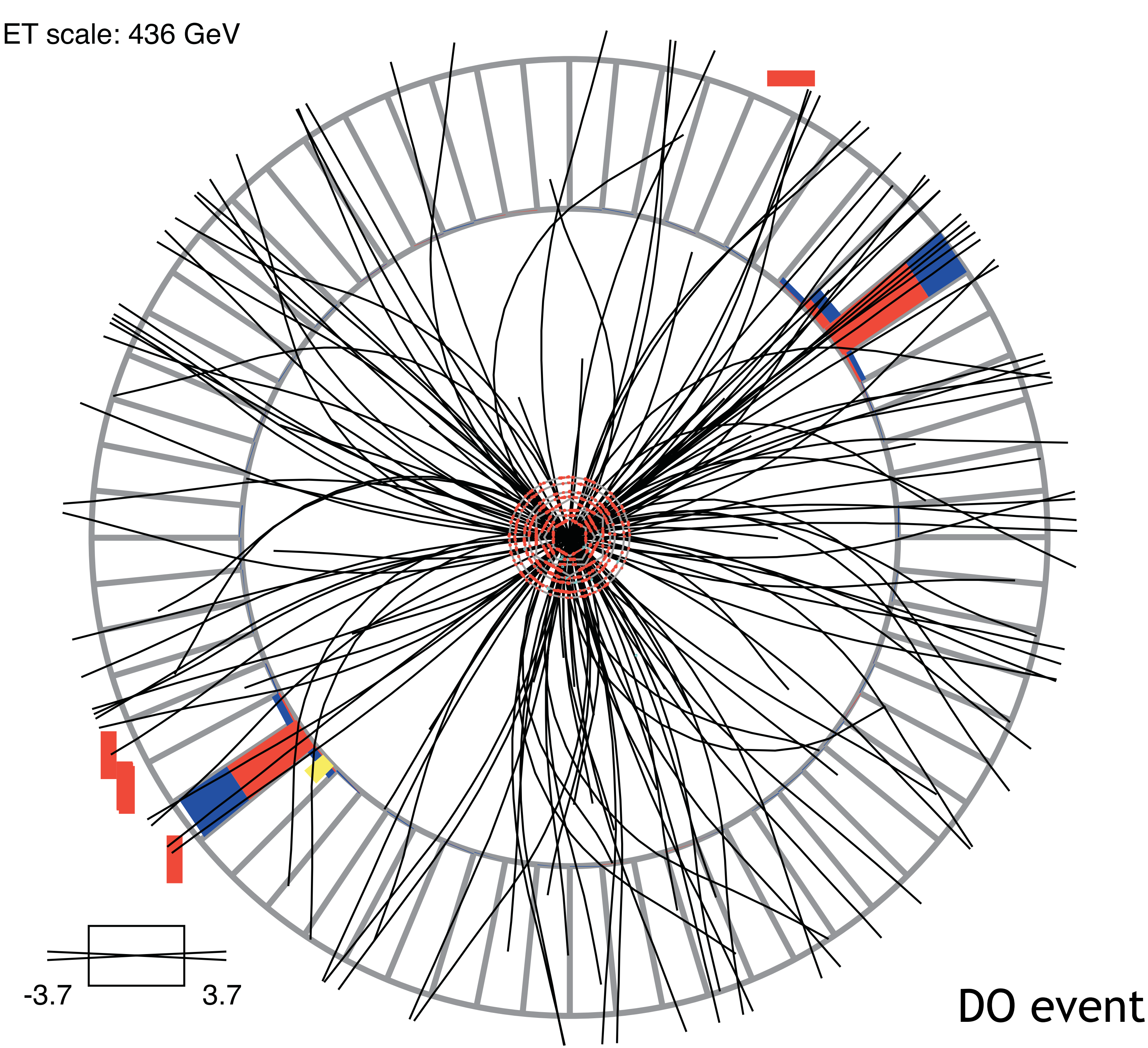


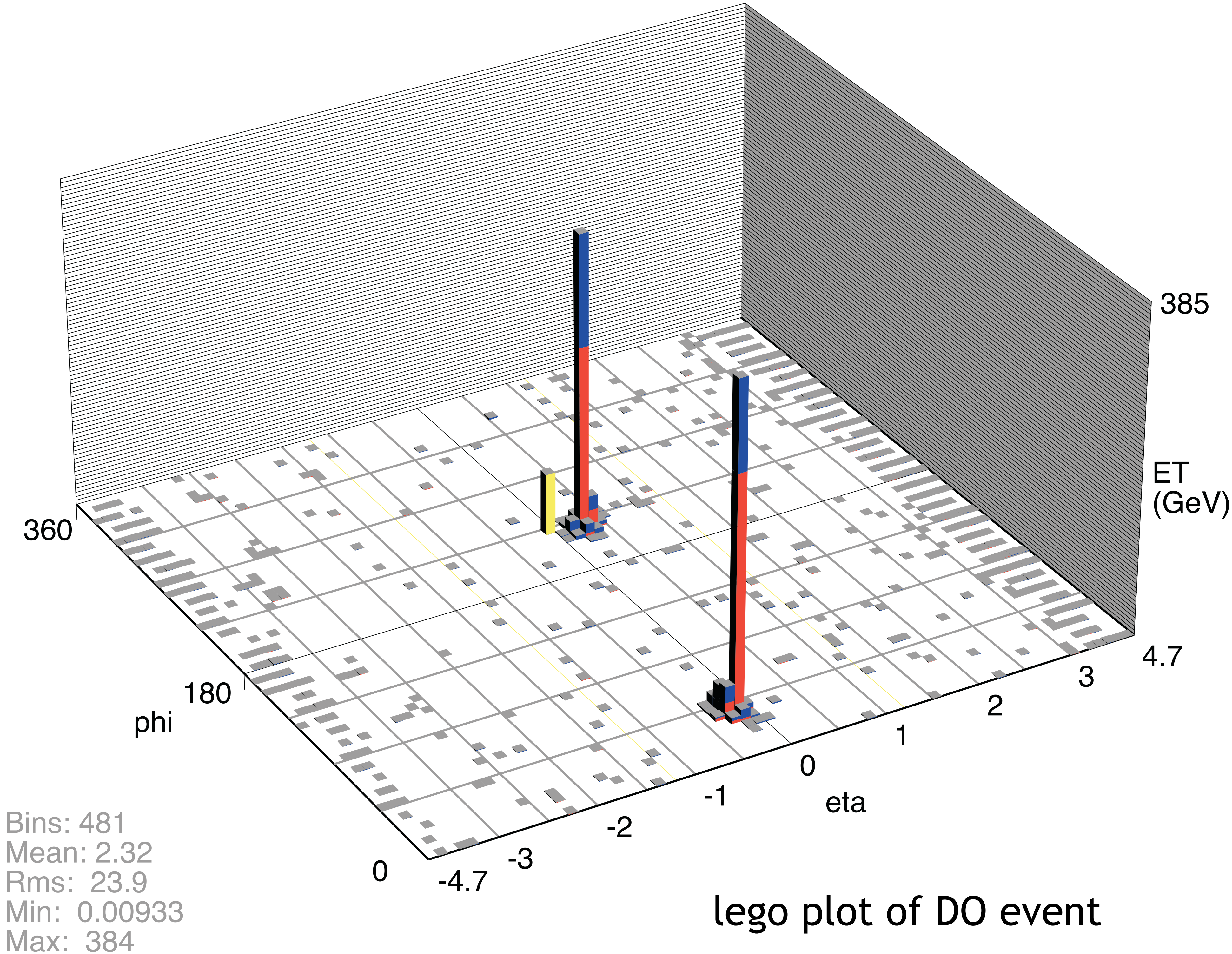
DO event



lego plot of DO event

Run 178796 Event 67972991 Fri Feb 27 08:34:15 2004





lego plot of DO event

It is difficult to produce leptons without accompanying jets in typical QCD reactions, so isolated leptons are important indicators for new physics.

Electrons are detected in the inner detector by the same technologies that are used for jets, but muons are highly penetrating and can be studied outside the region where the hadrons are absorbed. This makes the study of muons a 'safe' objective for the LHC experiments, even at high luminosity.

Thus, the LHC detectors are designed to be precision muon spectrometers. This is the most important consideration for the large-scale design of ATLAS and CMS.

The LHC cross sections for vector boson production and decay to leptons (e or mu, accepted in $|\eta| < 2.5$) are

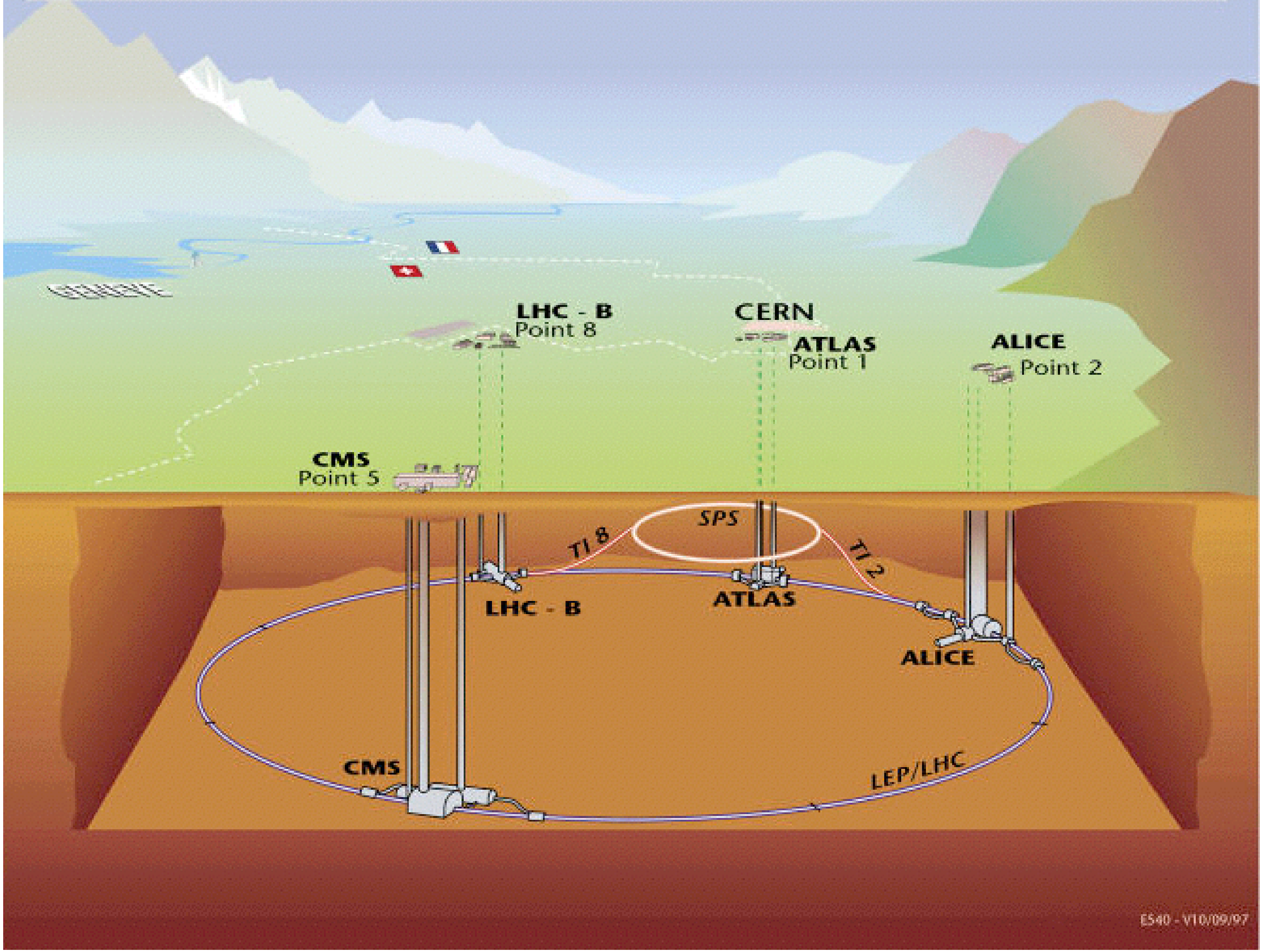
W+	10	nb
W-	8	nb
Z	1.5	nb

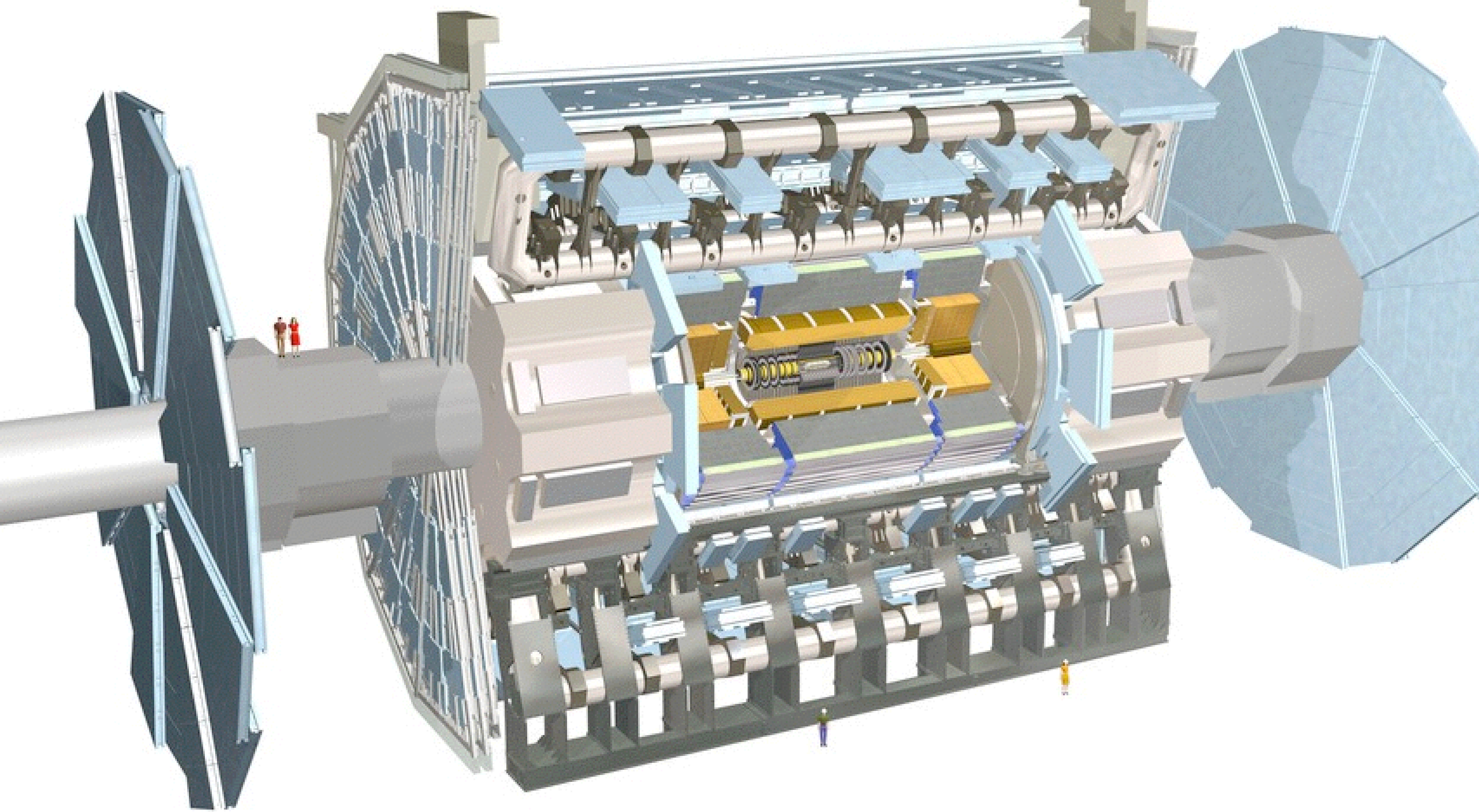
So we can in principle write this whole sample to permanent storage. The rates for hadronic W and Z decays are also quite acceptable (~ 50 nb). However, it is not clear how to trigger on general hadronic or tau decays of W, Z without some additional signature.

the Geneva region

with the CERN Large Hadron Collider

Overall view of the LHC experiments.

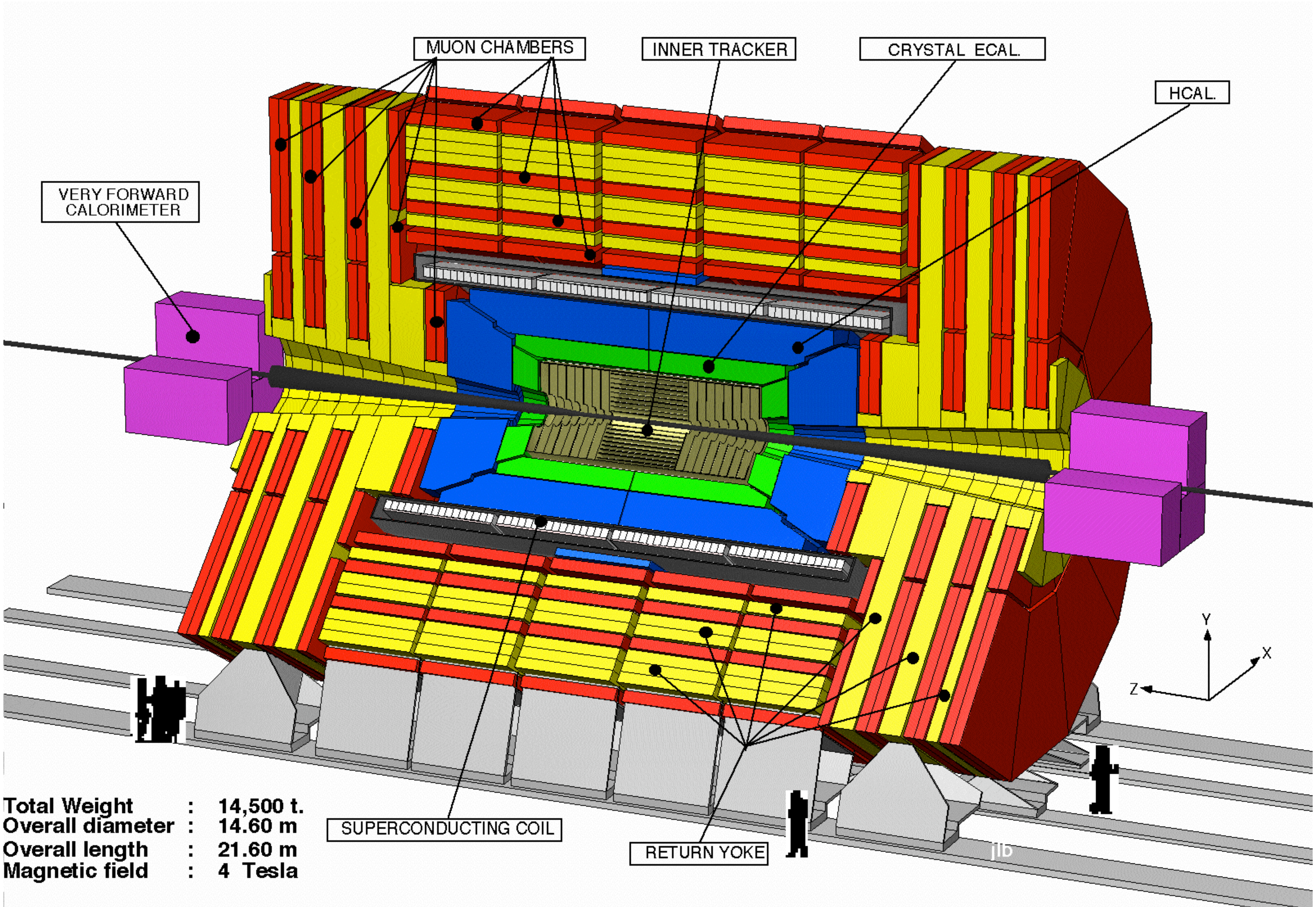




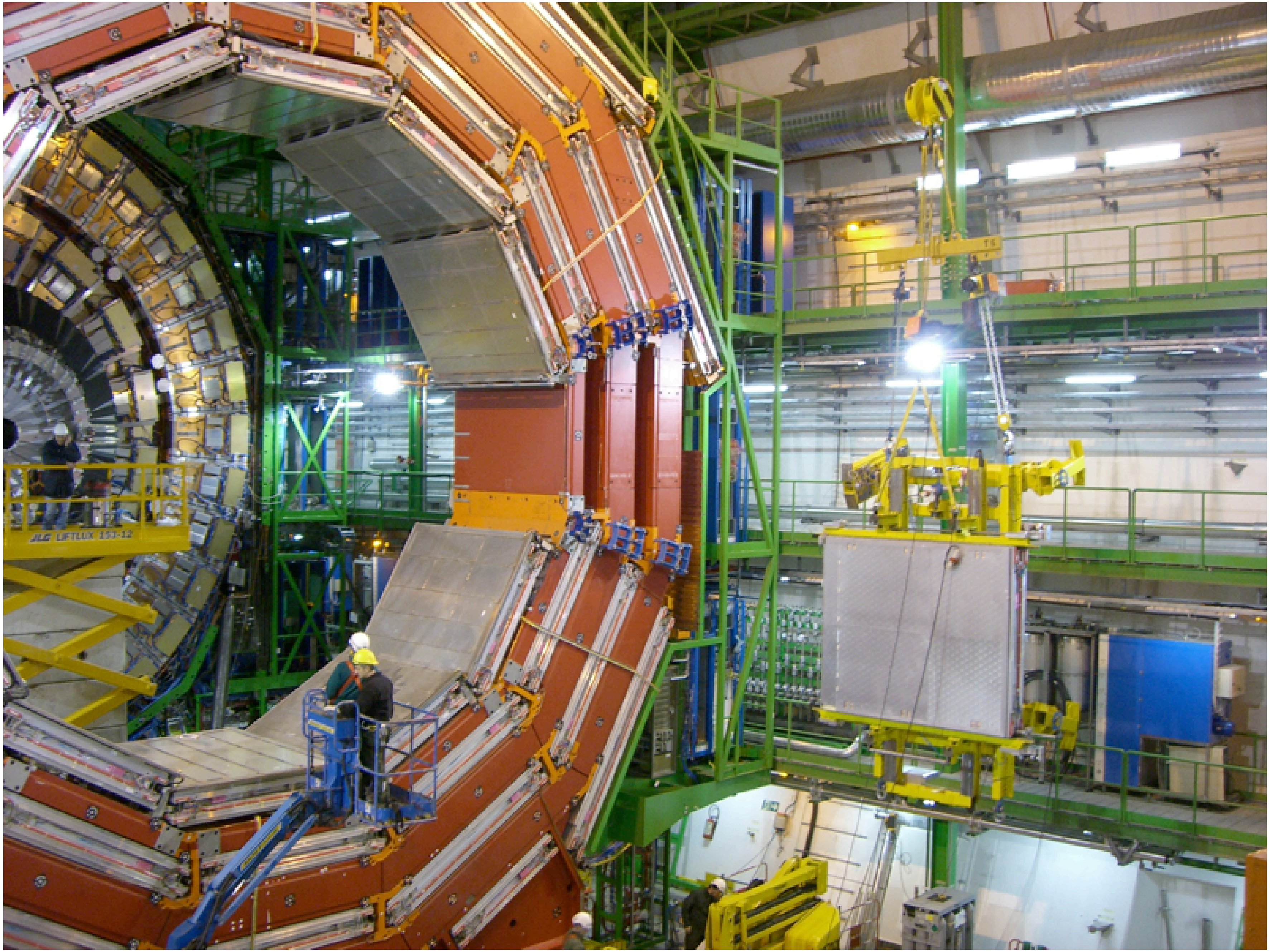
the ATLAS experiment

arrival of a superconducting muon toroid at CERN

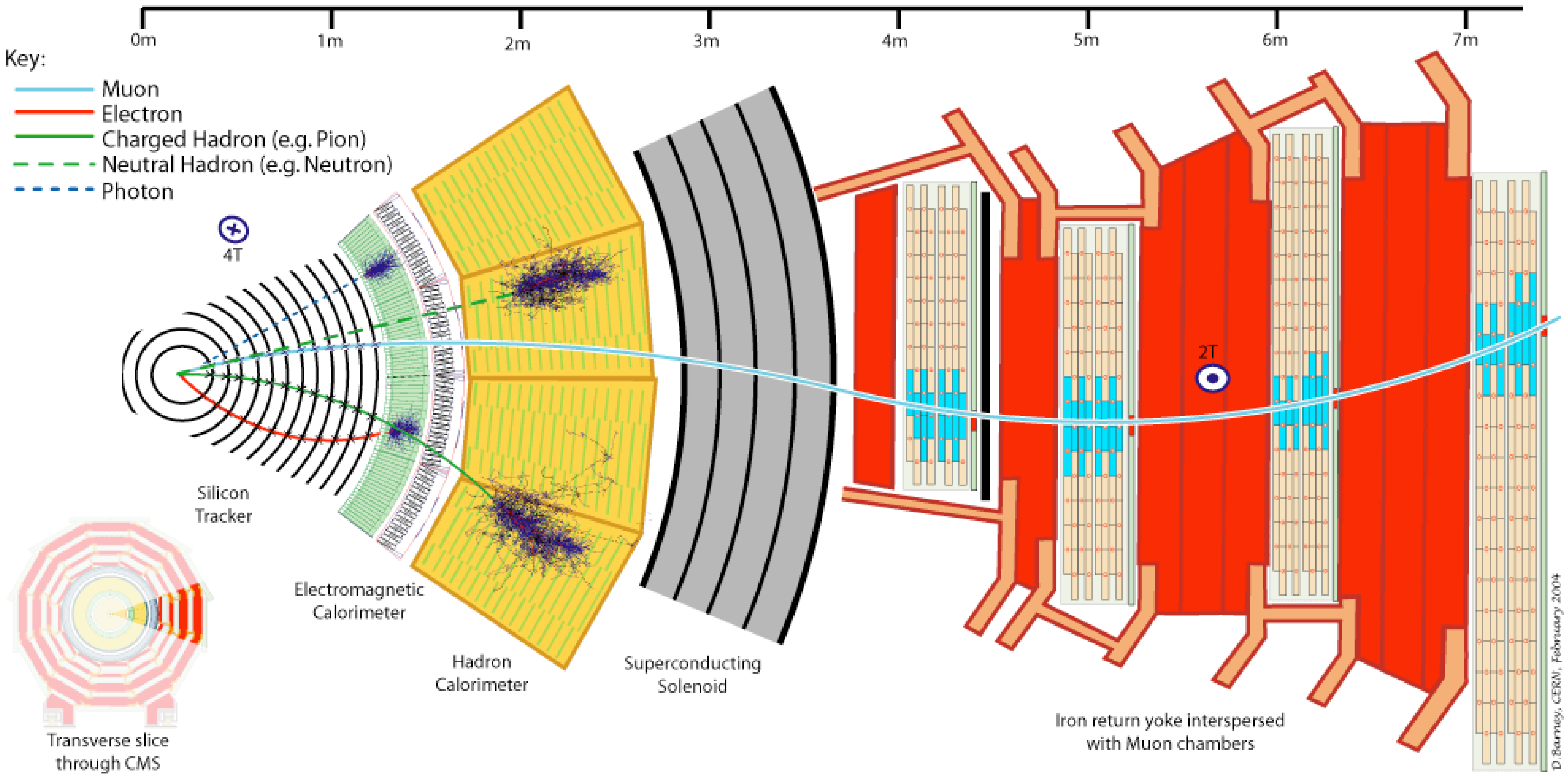
A Compact Solenoidal Detector for LHC

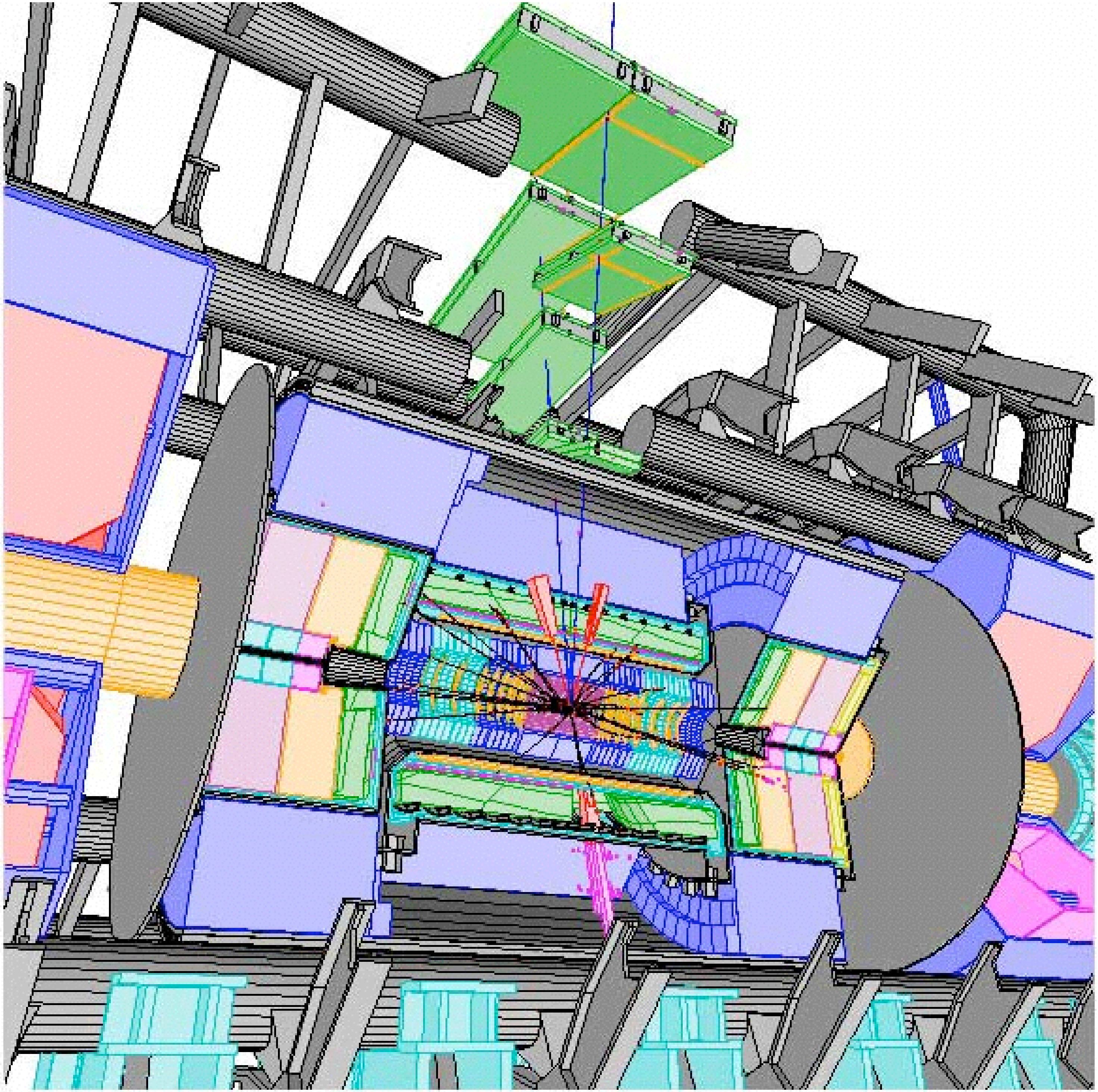


Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

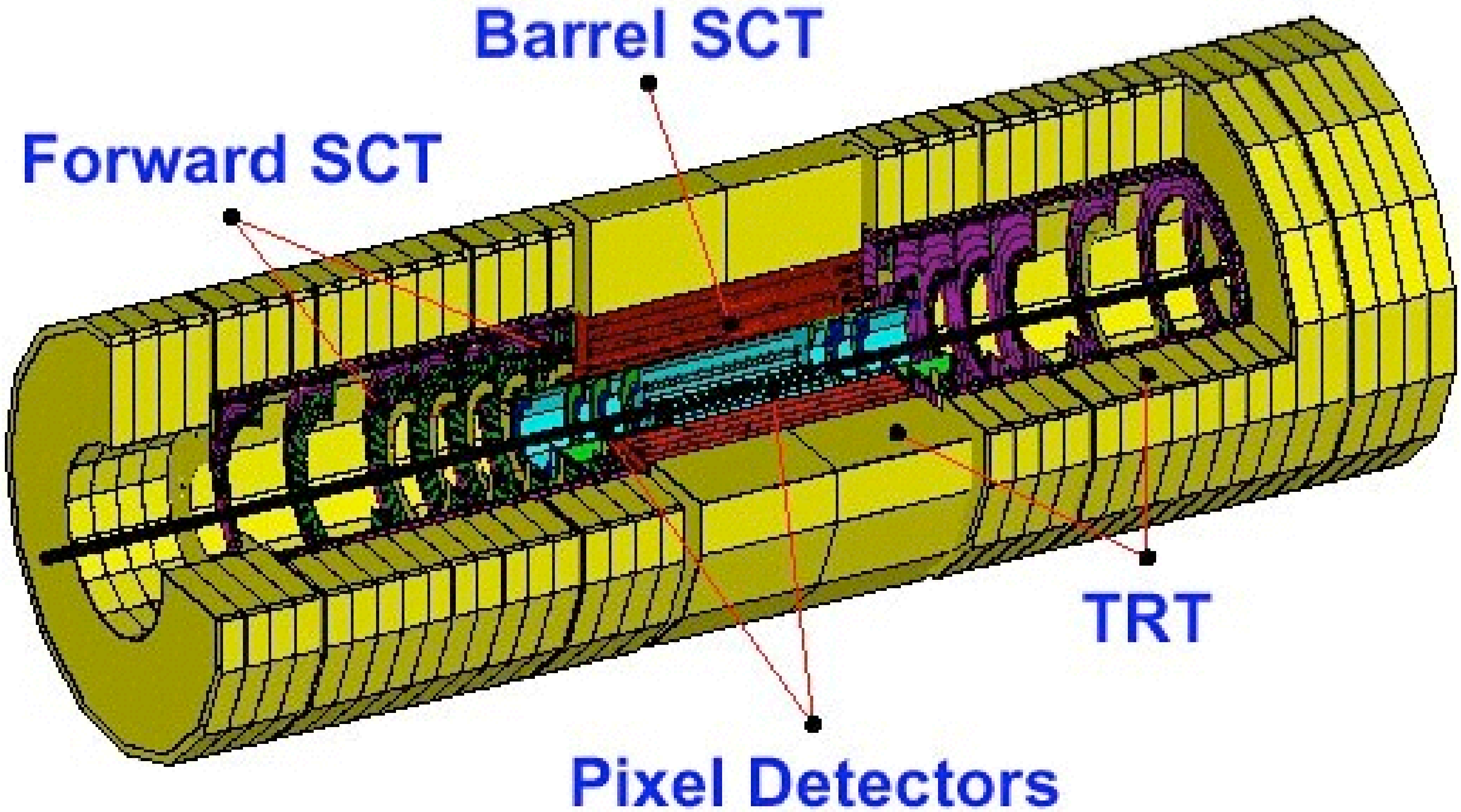


JLG LIFTLUX 153-12


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

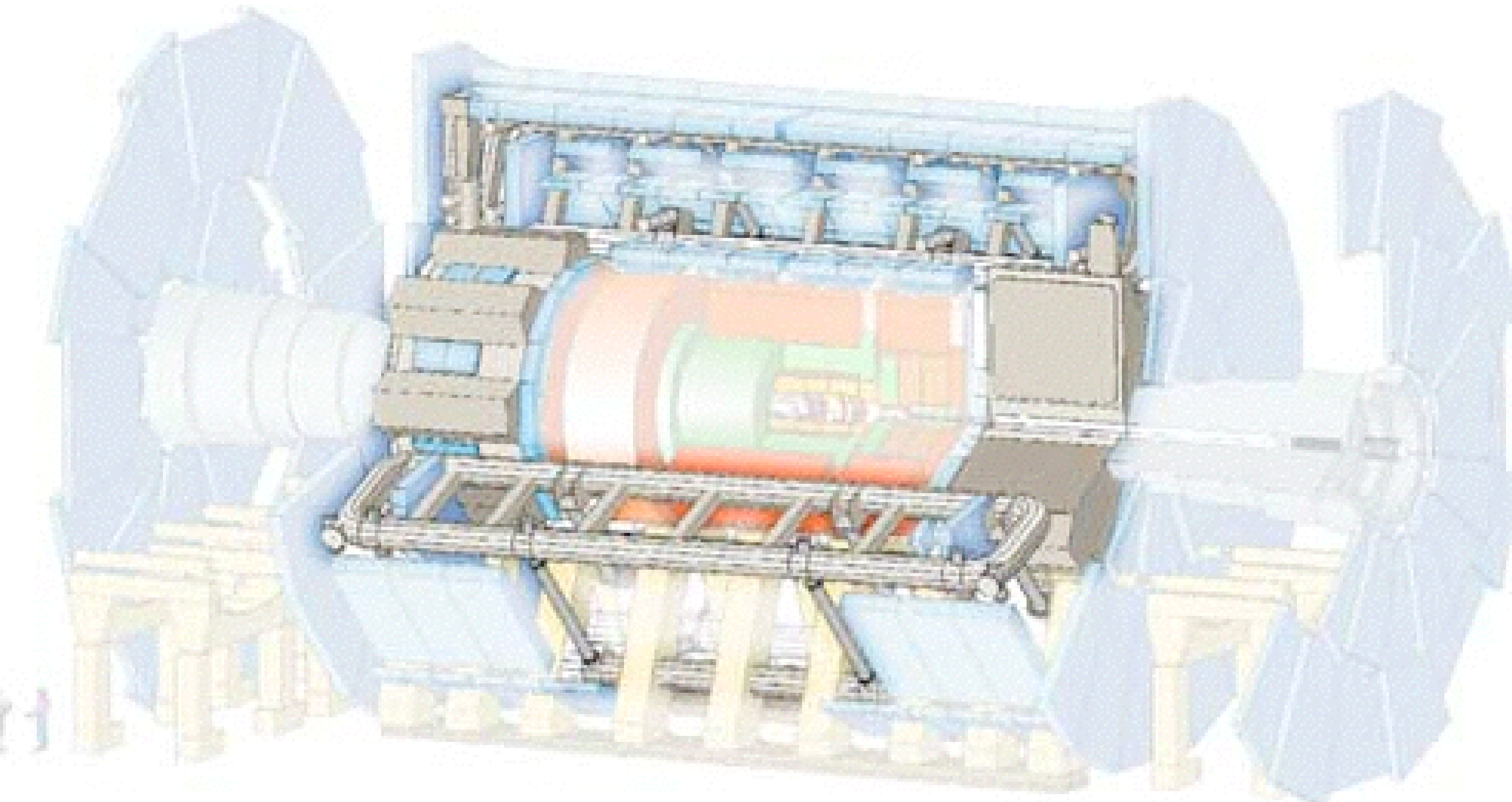


simulated high-energy event in ATLAS



ATLAS tracking detector

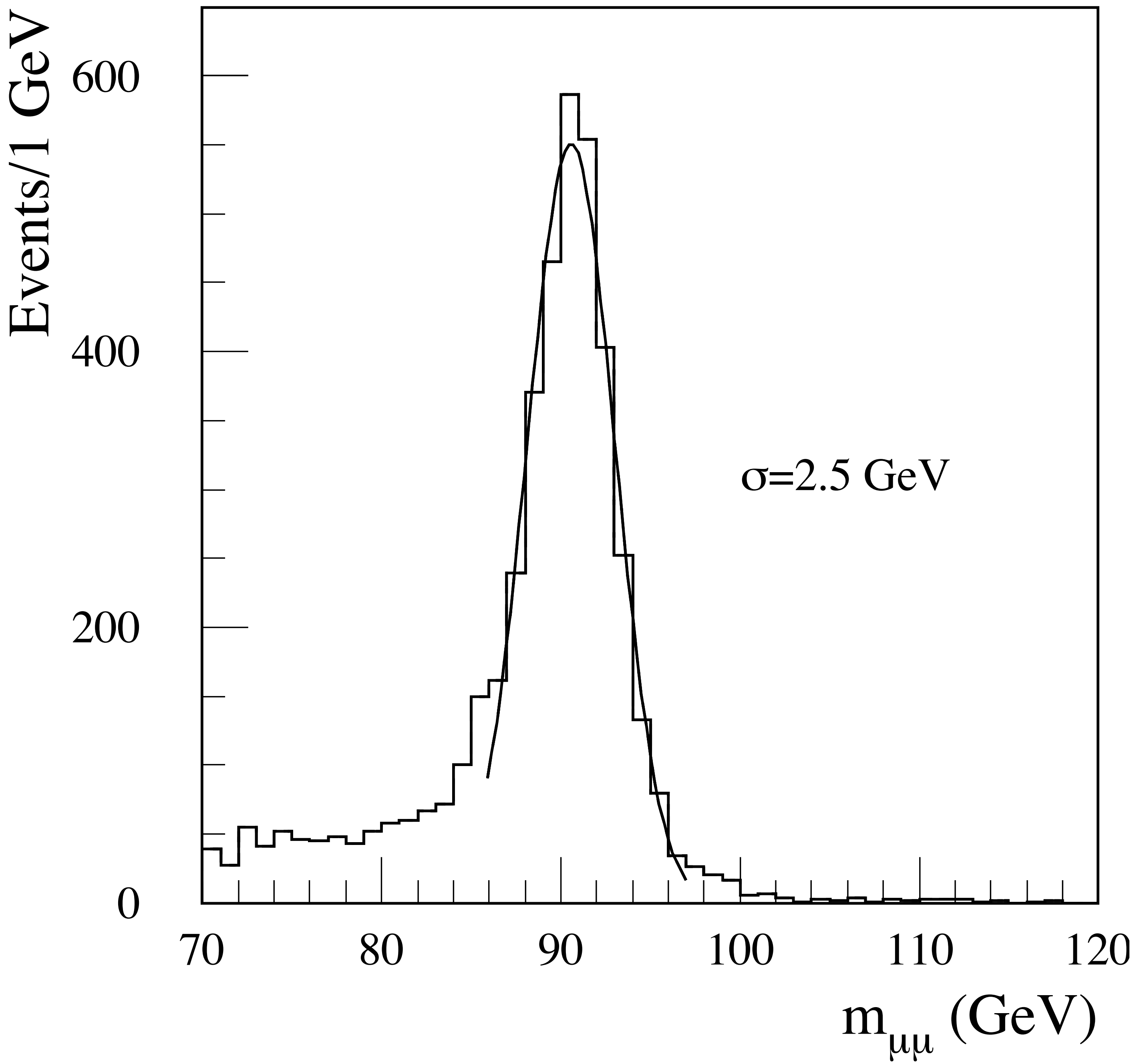
$$\sigma(\frac{1}{p_T}) = \frac{\sigma(p_T)}{p_T^2} = 3.6 \times 10^{-4} \oplus \frac{1.3 \times 10^{-2}}{\sqrt{p_T^2 \sin\theta}} \ (\mathrm{GeV}^{-1})$$



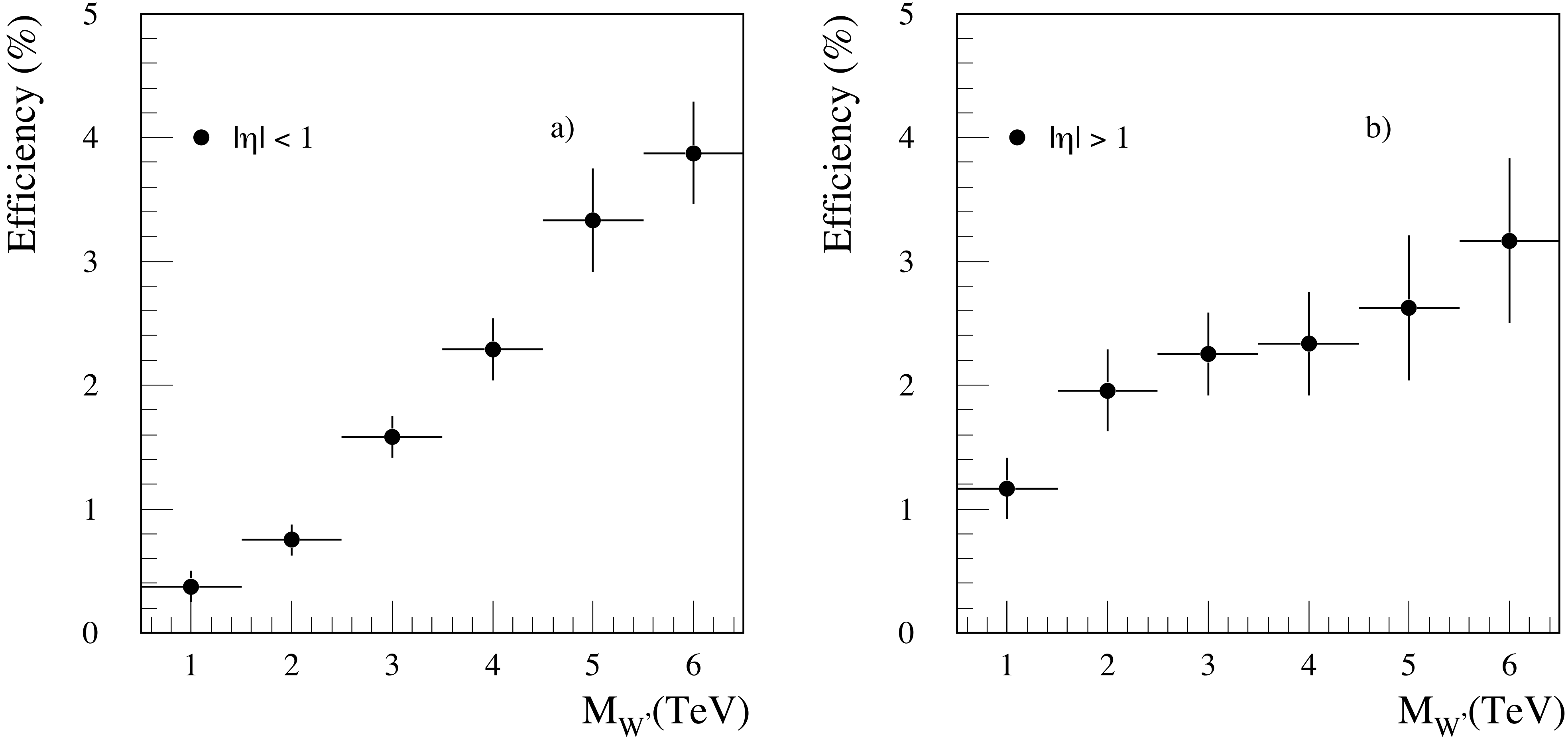
ATLAS toroidal-field muon spectrometer

for the complete muon system

$$\frac{\sigma(p_T)}{p_T} = \begin{cases} 2\% & 100 \text{ GeV } \mu \\ 10\% & 1 \text{ TeV } \mu \end{cases}$$

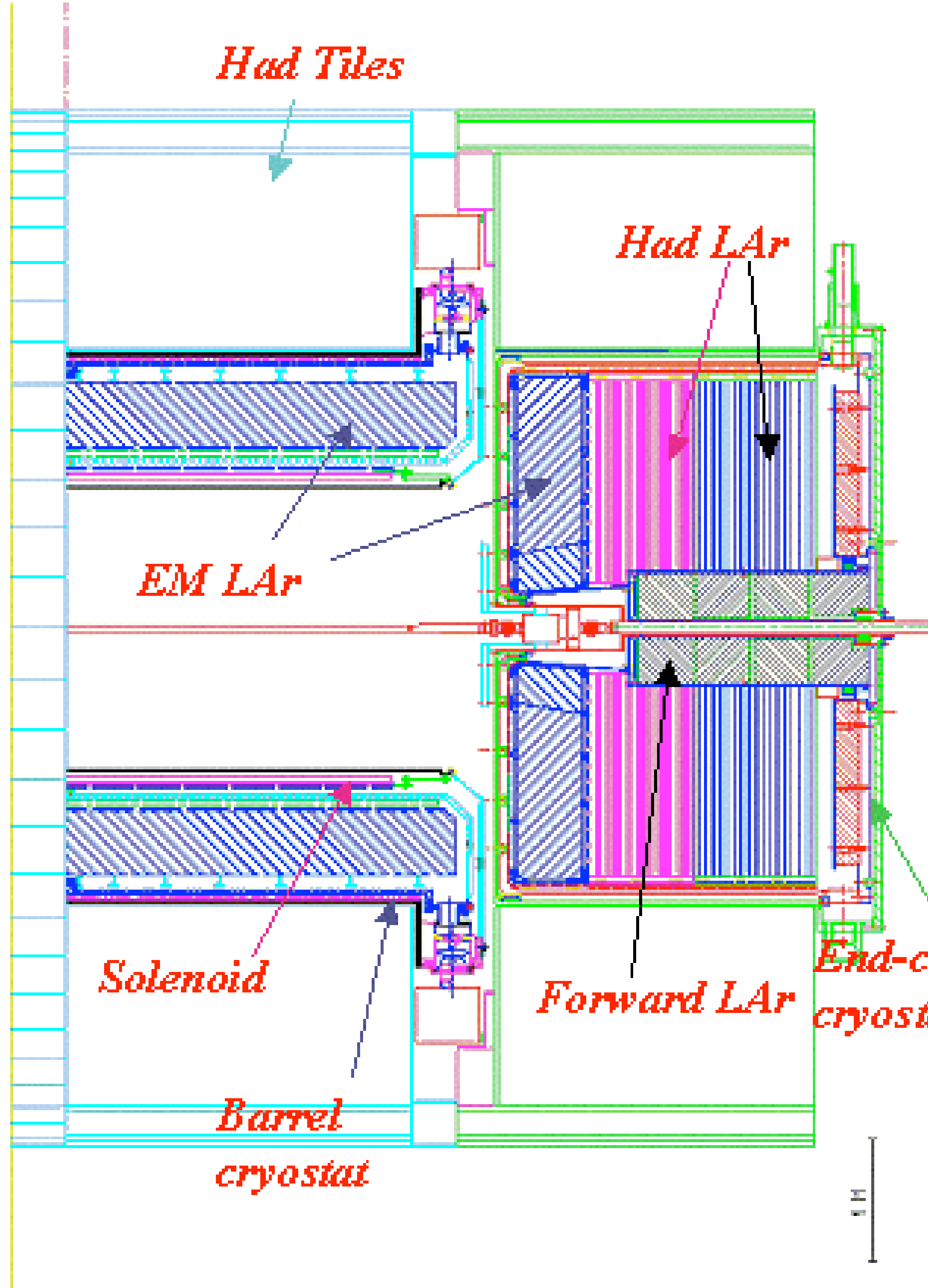


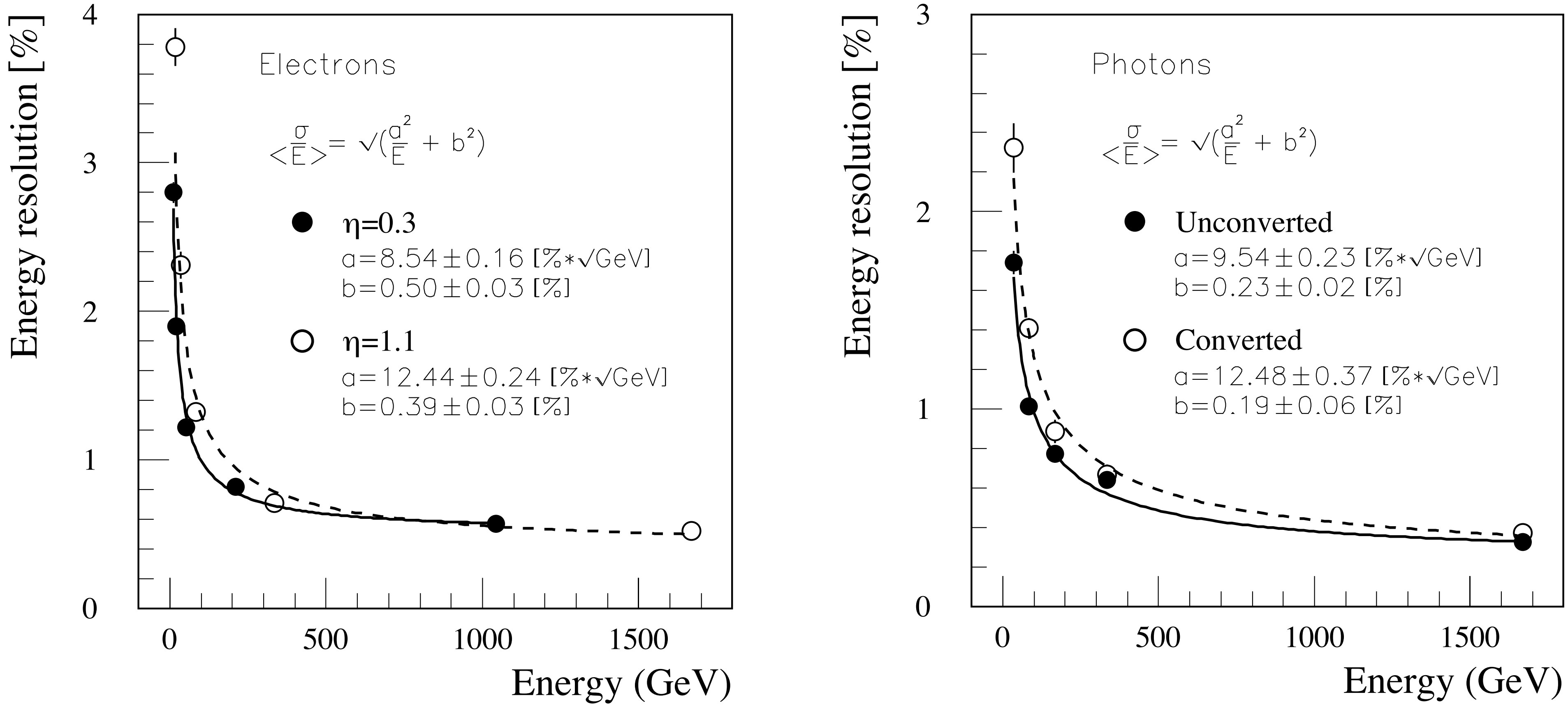
ATLAS - Z mass resolution in $Z \rightarrow \mu^+\mu^-$



ATLAS - muon charge misidentification probability

ATLAS
liquid-argon
calorimeter

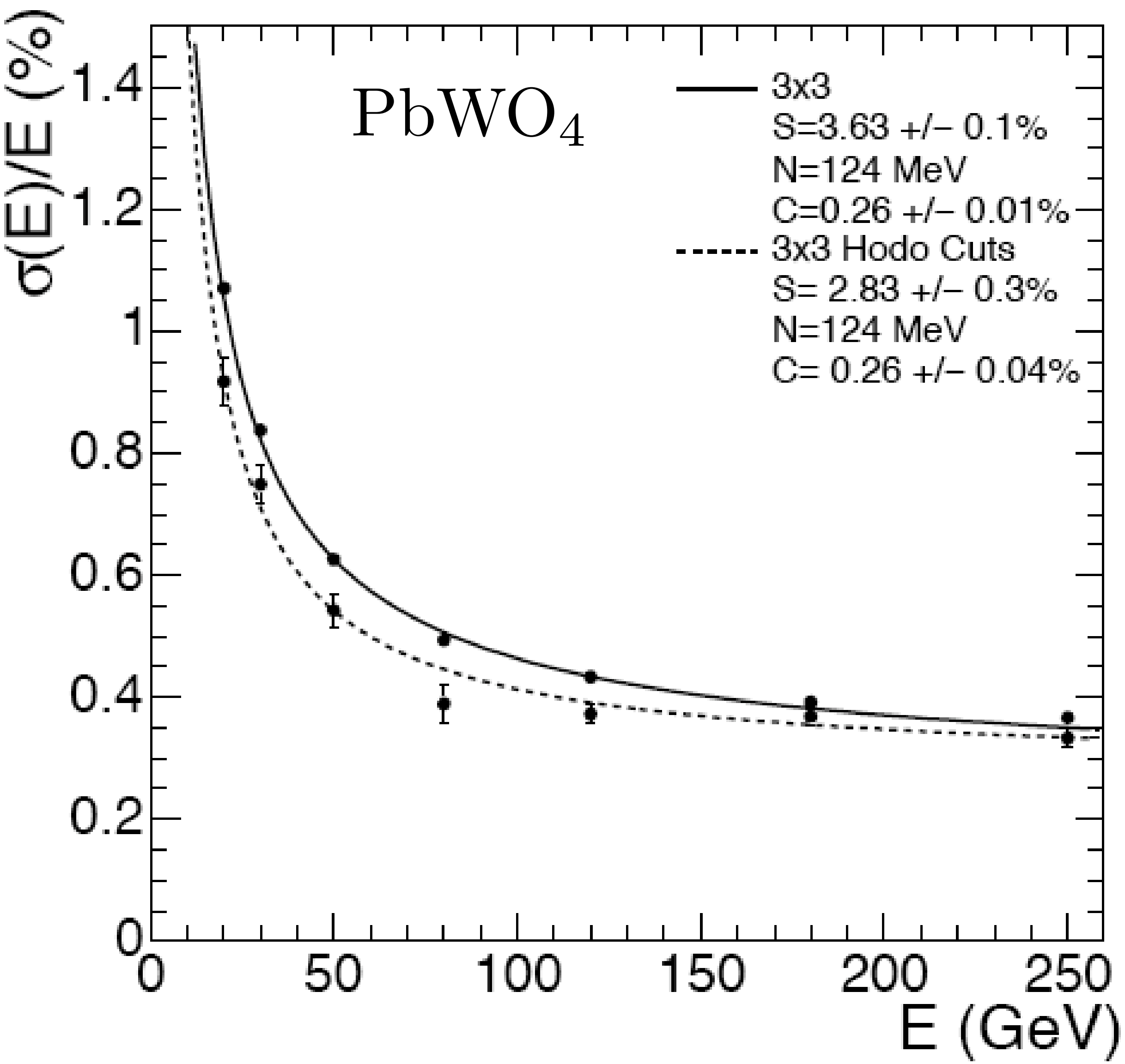




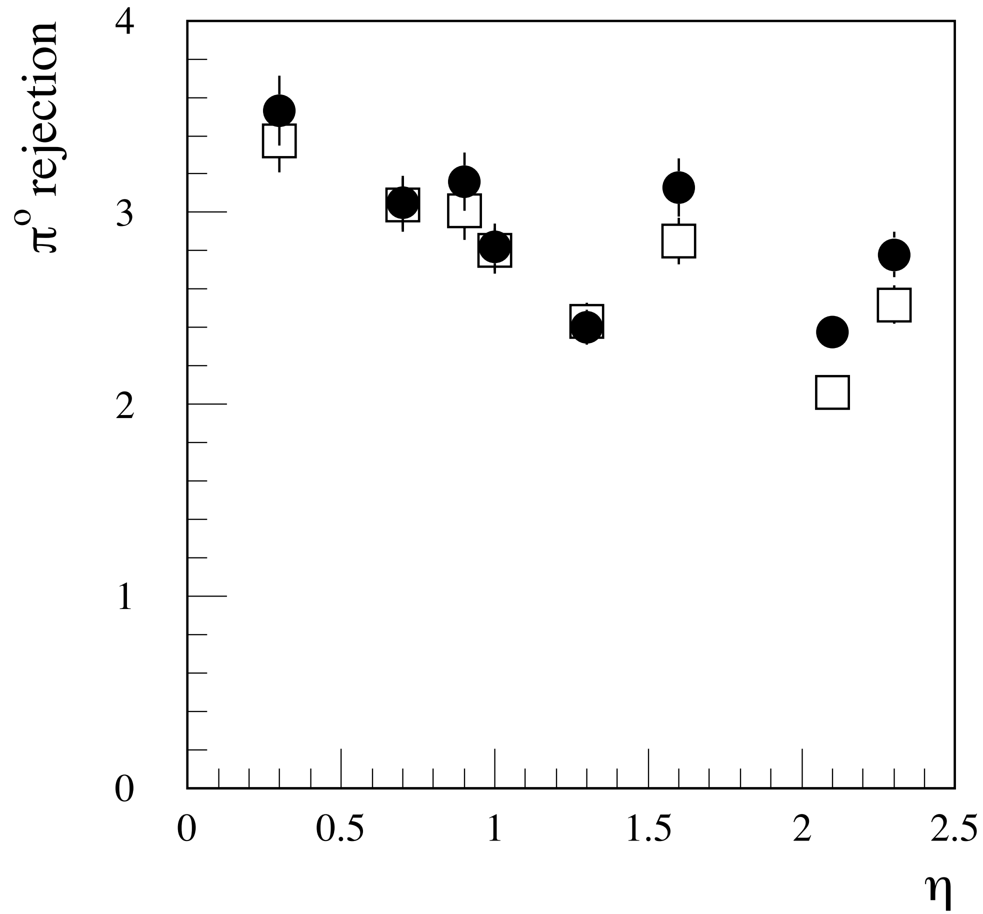
ATLAS liquid Ar calorimeter energy resolution for electrons and photons.

electrons at η = 0.3: $$\frac{\sigma}{E} = \left((\frac{8.5\%}{\sqrt{E}})^2 + (0.5\%)^2 \right)^{1/2}$$

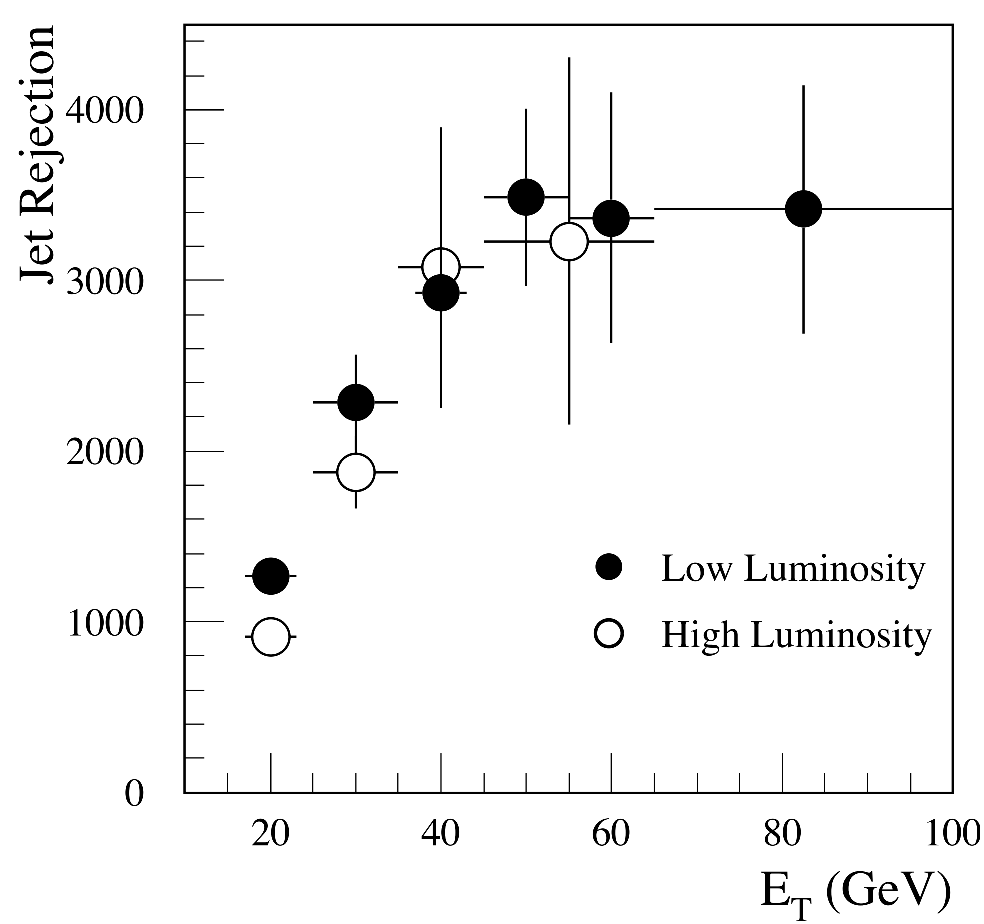
energy resolution of the CMS crystal calorimeter



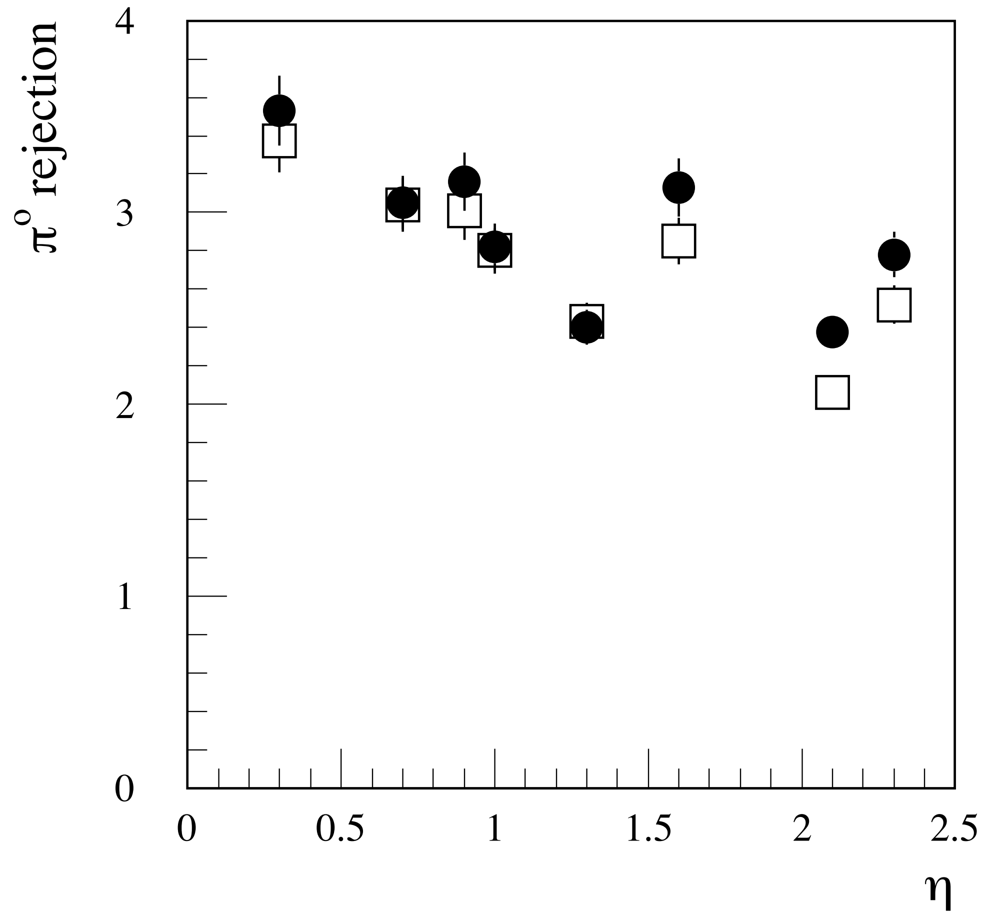
$$\frac{\sigma}{E} = \frac{3.6\%}{\sqrt{E}} \oplus \frac{12\%}{E} \oplus 0.26\%$$



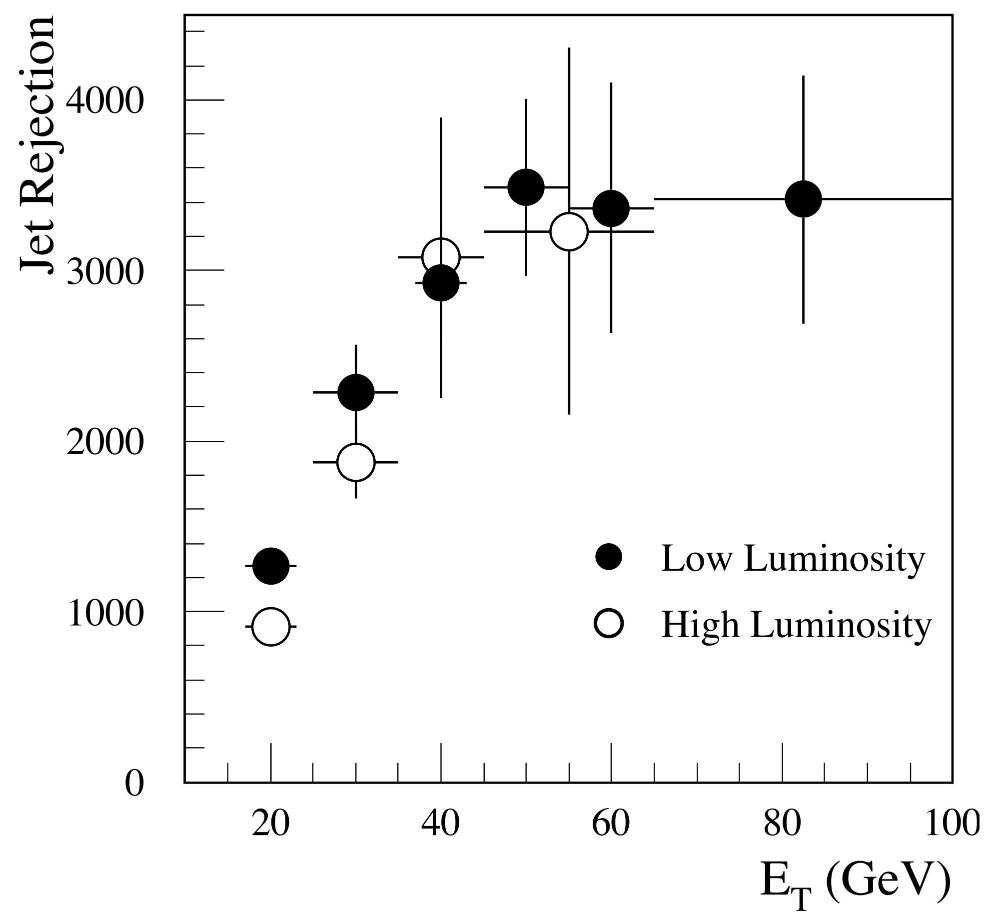
ATLAS - π^0 rejection in photon detection (50 GeV pions)



ATLAS - rejection factor for jets in photon selection

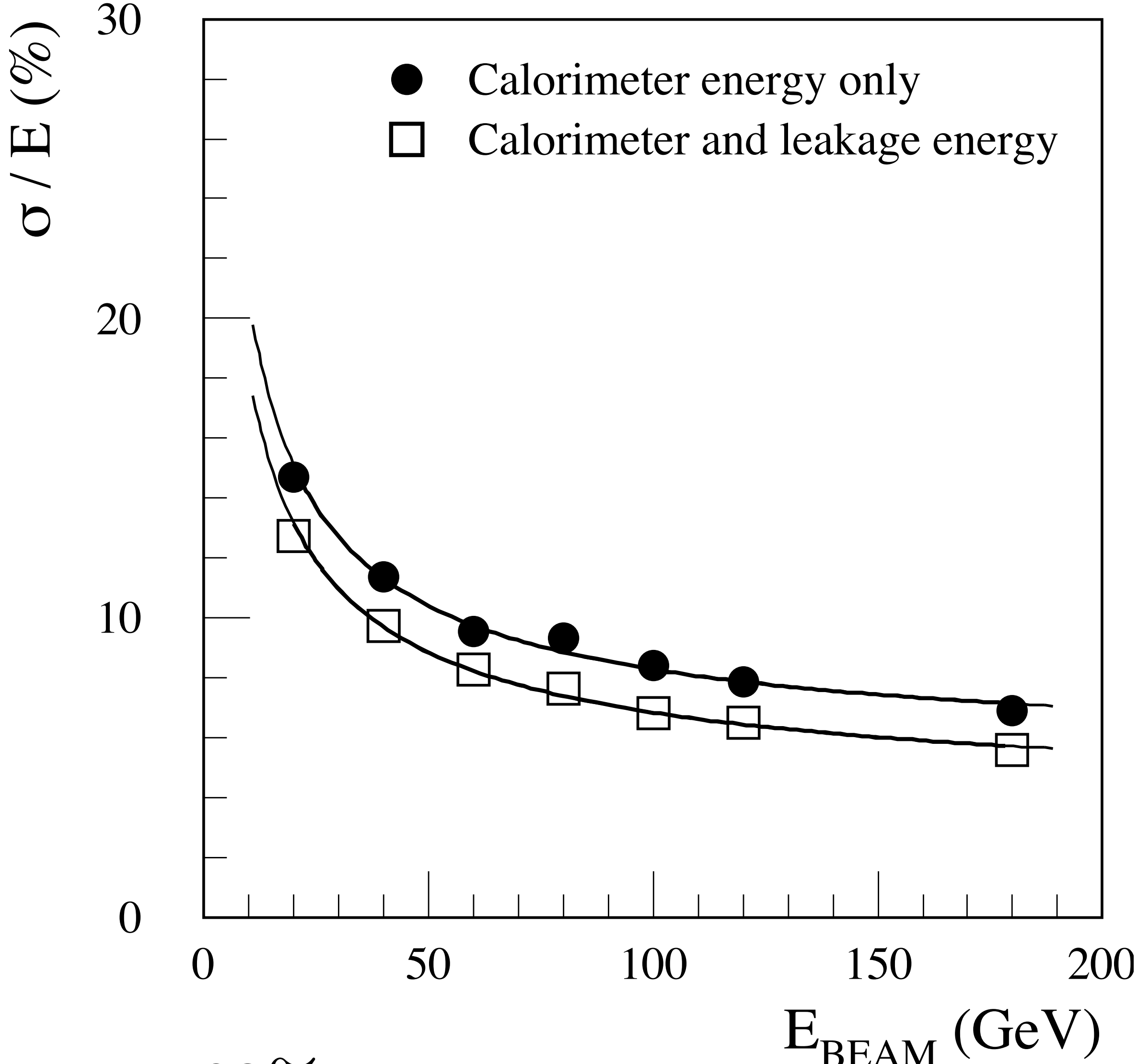


ATLAS - π^0 rejection in photon detection (50 GeV pions)



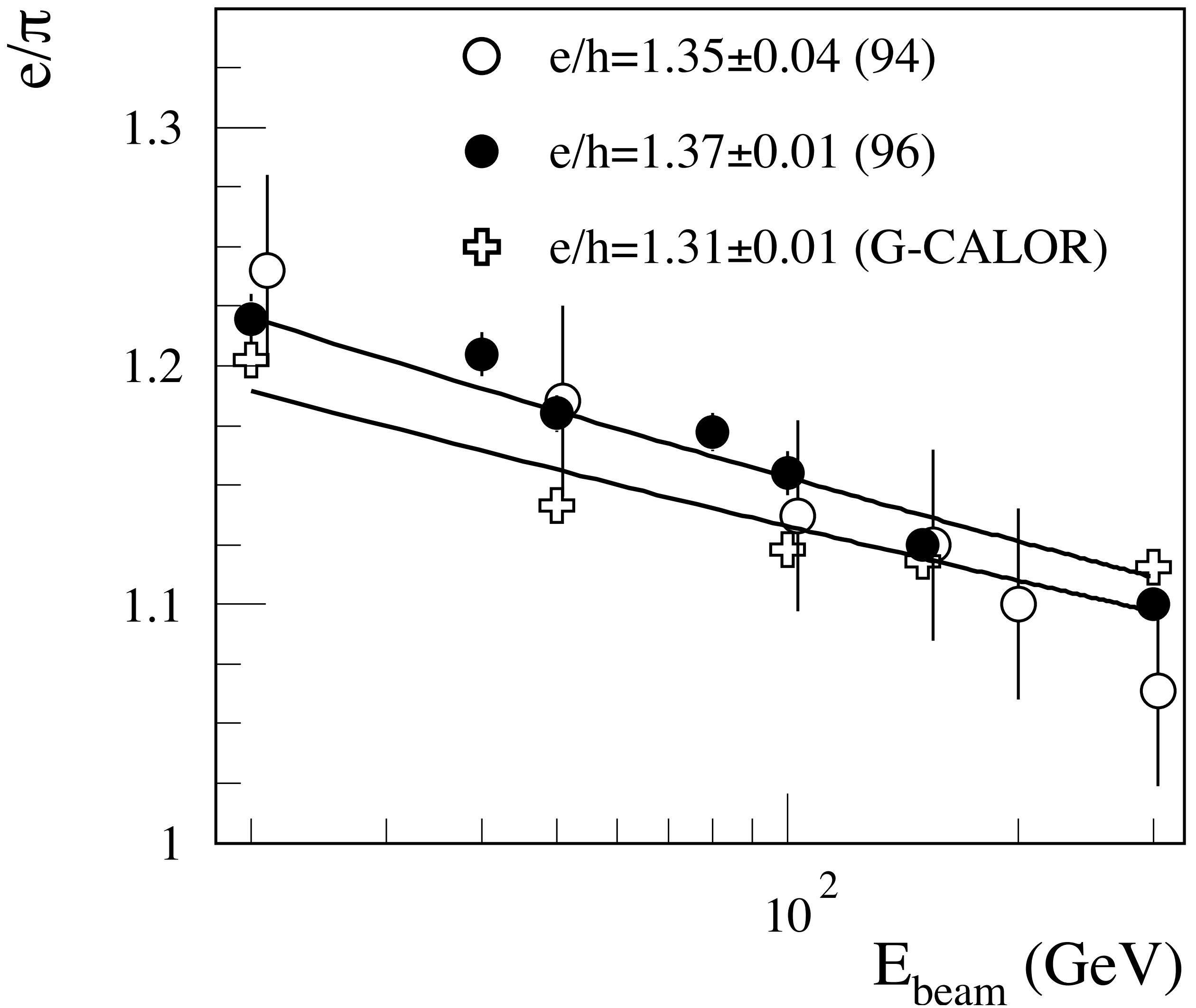
ATLAS - rejection factor for jets in photon selection

ATLAS calorimeter resolution for pions



single pions: $$\frac{\sigma}{E} = \frac{63\%}{\sqrt{E}} \oplus 5.4\%$$

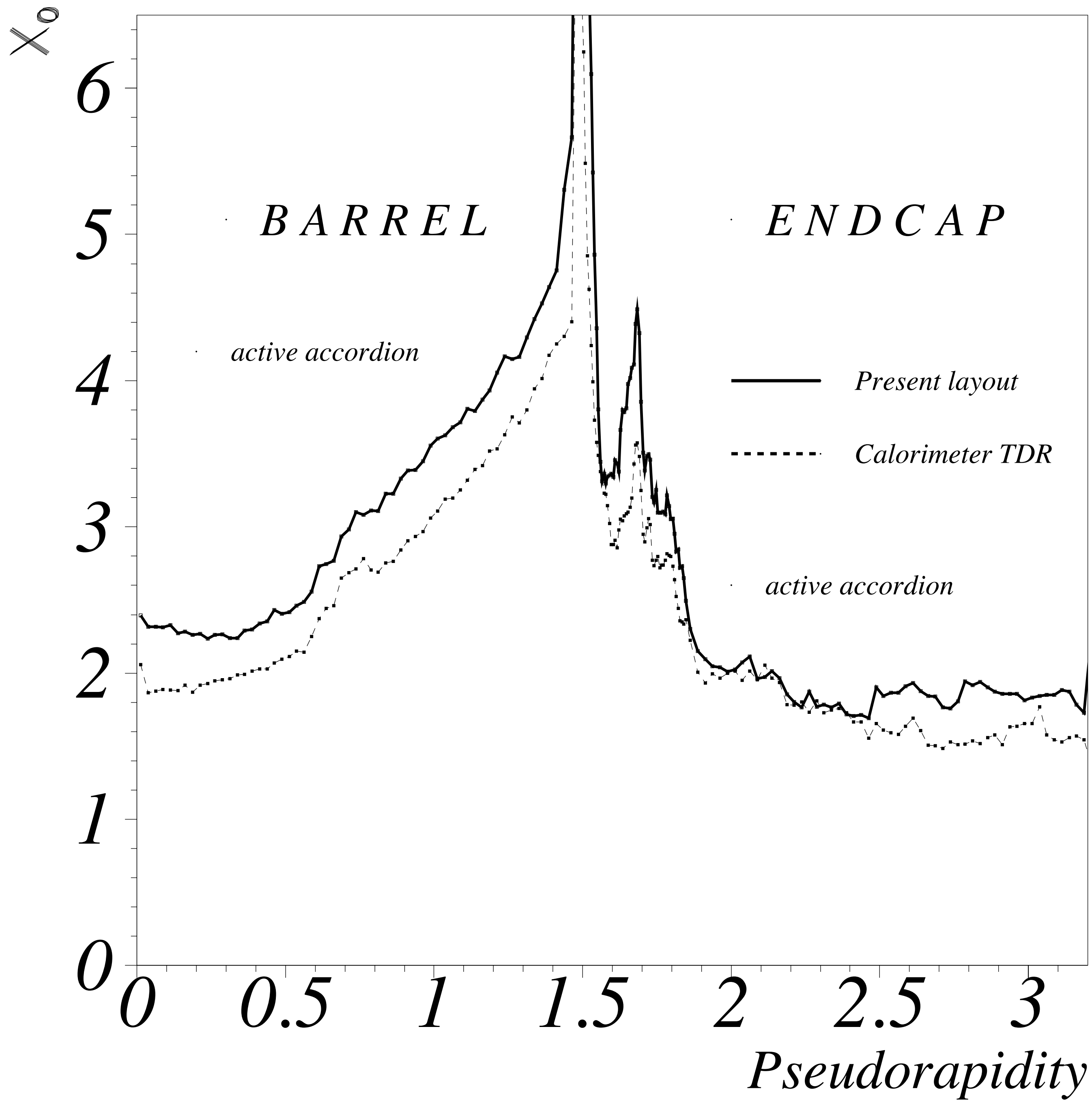
jets: $$\frac{\sigma}{E} = \frac{81\%}{\sqrt{E}} \oplus 1.7\% \oplus \frac{3.9}{E}$$

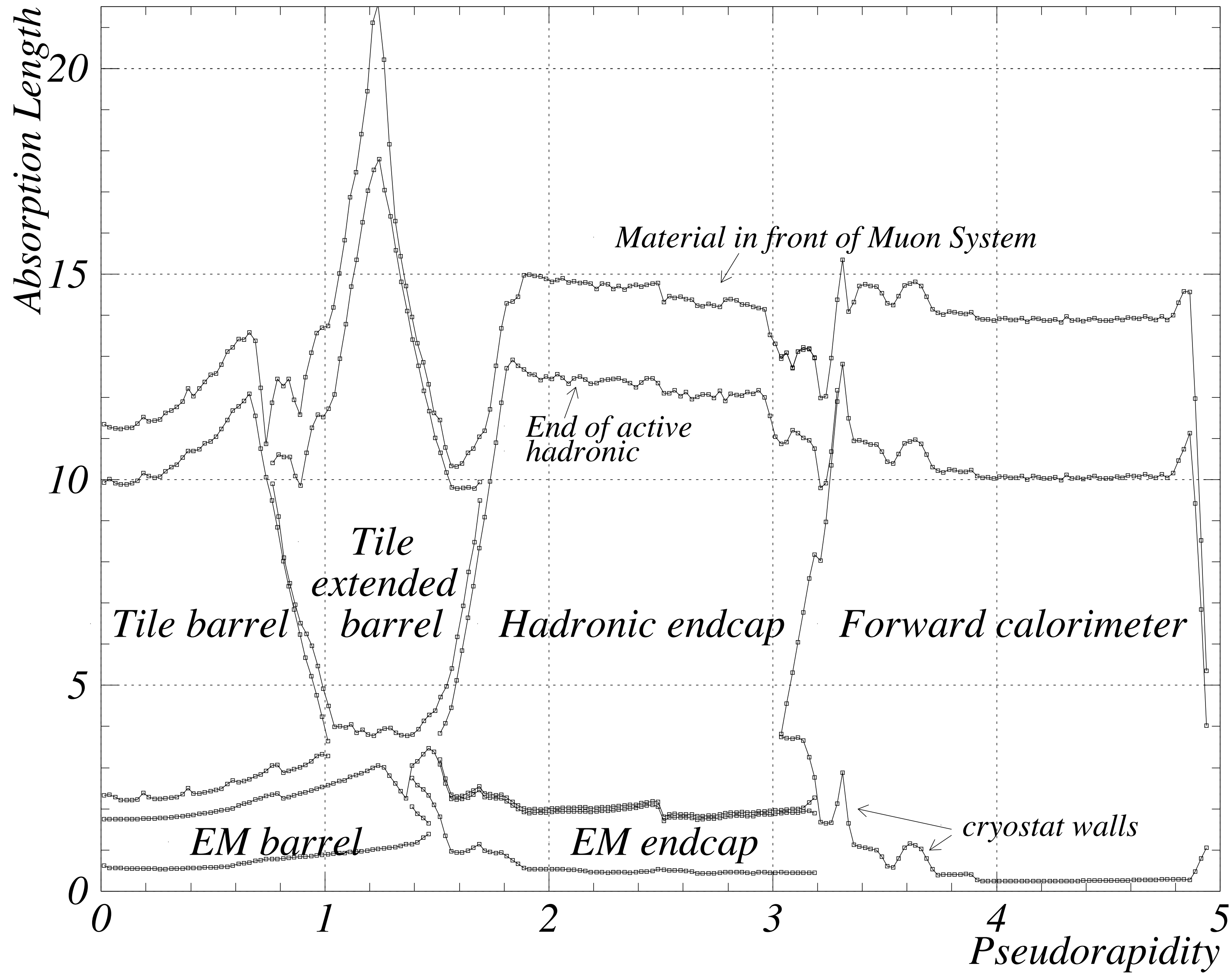


ATLAS calorimeter electron/pion response

ATLAS: material in front of the ECAL as a function of pseudorapidity

(less than 0.25 is due to the inner detector)





thickness of the ATLAS calorimetry as a function of η

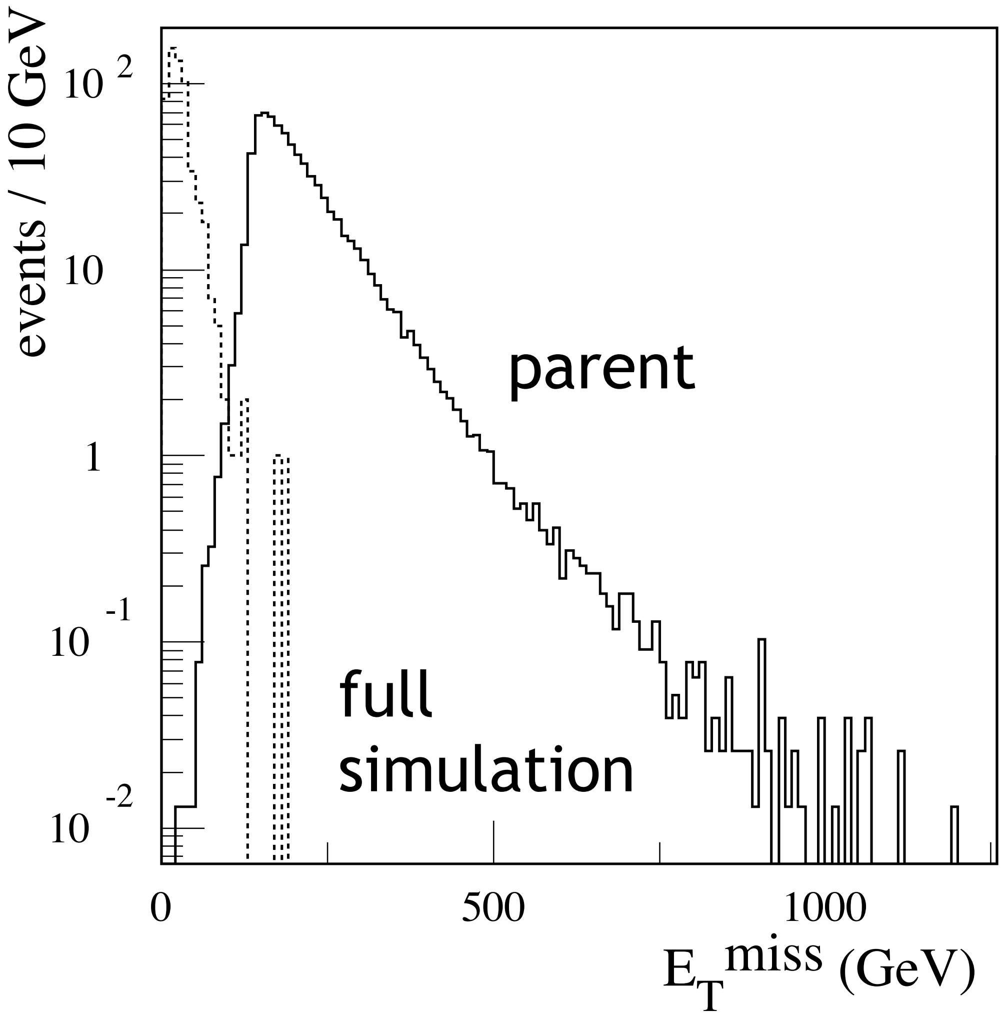
The geography of the detector becomes an issue in thinking about missing ET. If a part of the detector does not function, you will see missing ET.

More generally, mismeasurement, especially of jets, will produce unbalanced ET.

To control for this, it is necessary to

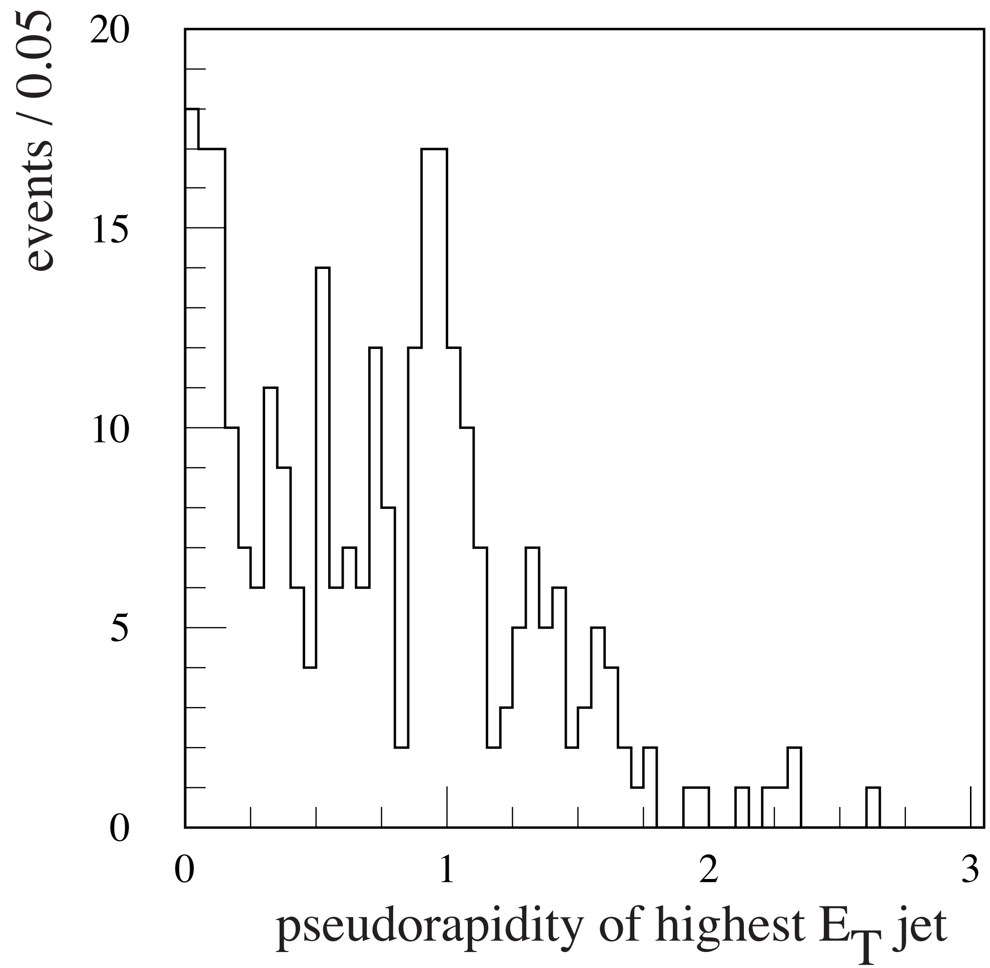
calibrate the response of the detector elements using 2-jet events and $pp \to \gamma + \mathrm{jet}$

look at the geometry of signal event and reject them if they are likely to have been mismeasured.



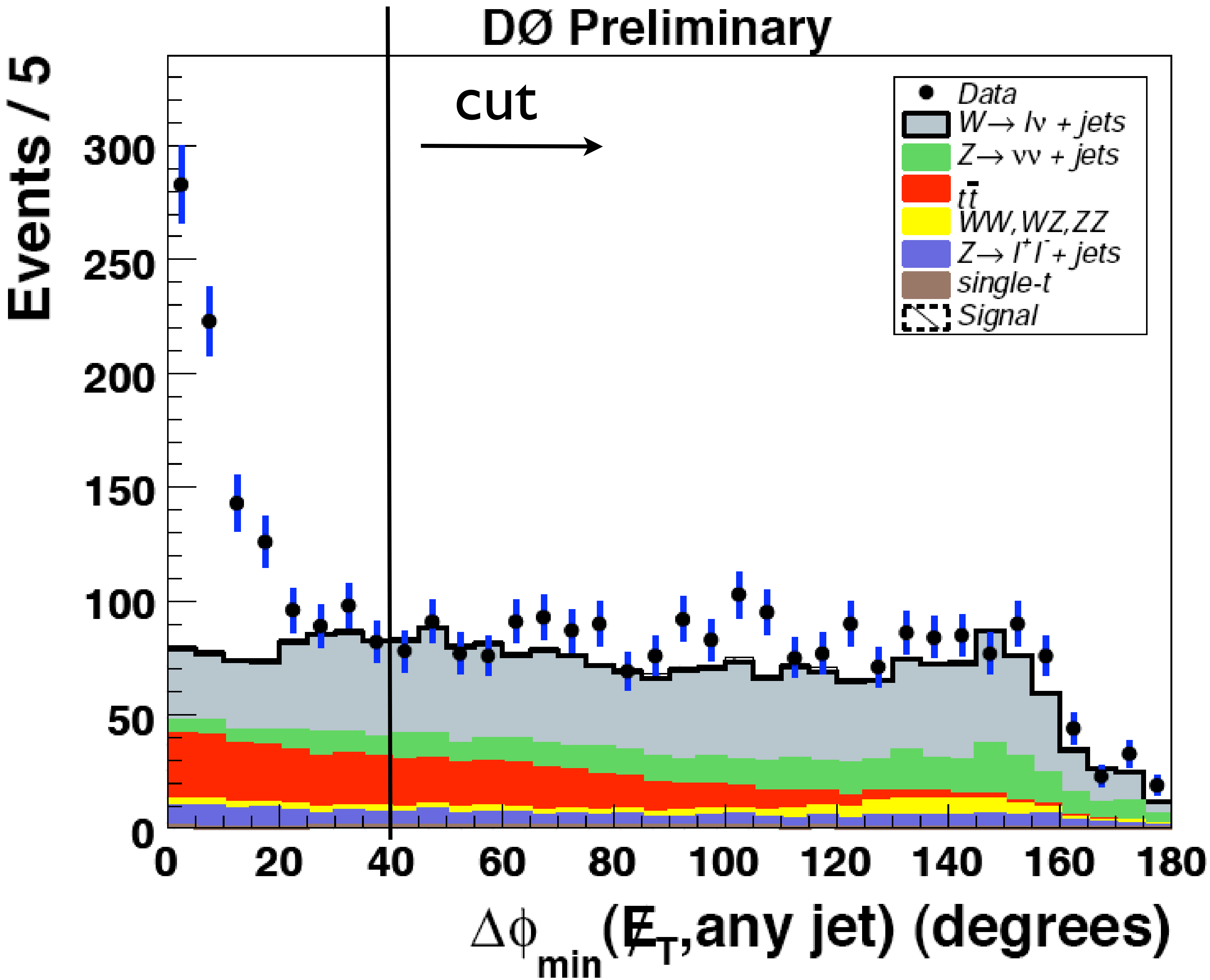
ATLAS simulation of missing ET in

$Z(\rightarrow \mu^+\mu^-) + jet$



η of the jet w. the highest ET in events w. ET > 50

DO missing ET search - dijet sample



Finally, since we expect that new physics associated with electroweak symmetry breaking can have preferred coupling to the third generation, it is important to understand the tagging of b quarks and τ leptons.

The principal b tags are

soft lepton tagging:

leptons with pT > 1 GeV with respect to a jet are likely to come from b semileptonic decays

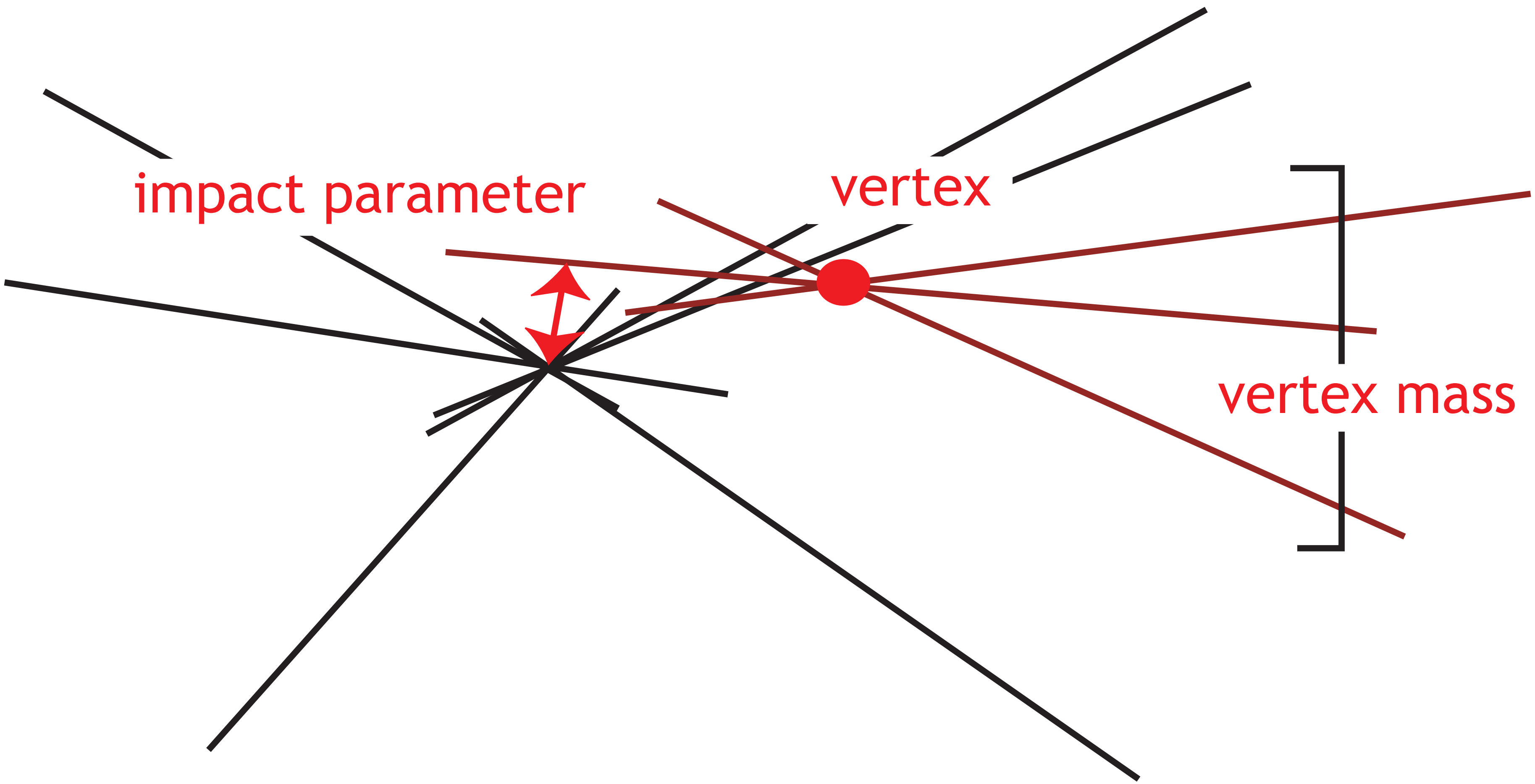
lifetime tagging:

$$c\tau(B^+) = 0.49 \text{ mm} , \quad c\tau(B^0) = 0.46 \text{ mm}$$

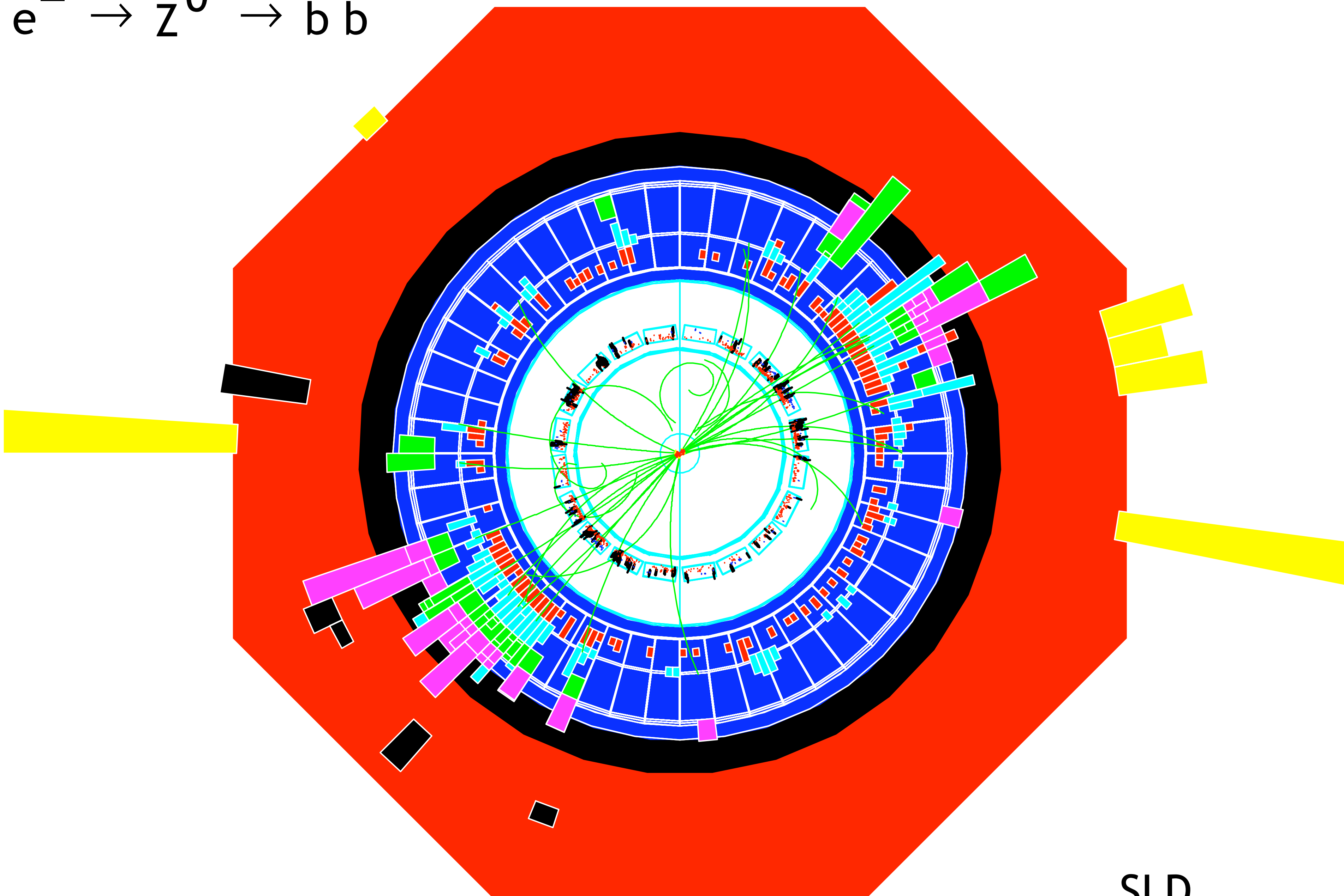
so a precision silicon tracker close to the interaction point should see clusters of tracks displaced from the vertex

Be careful, especially of charm :

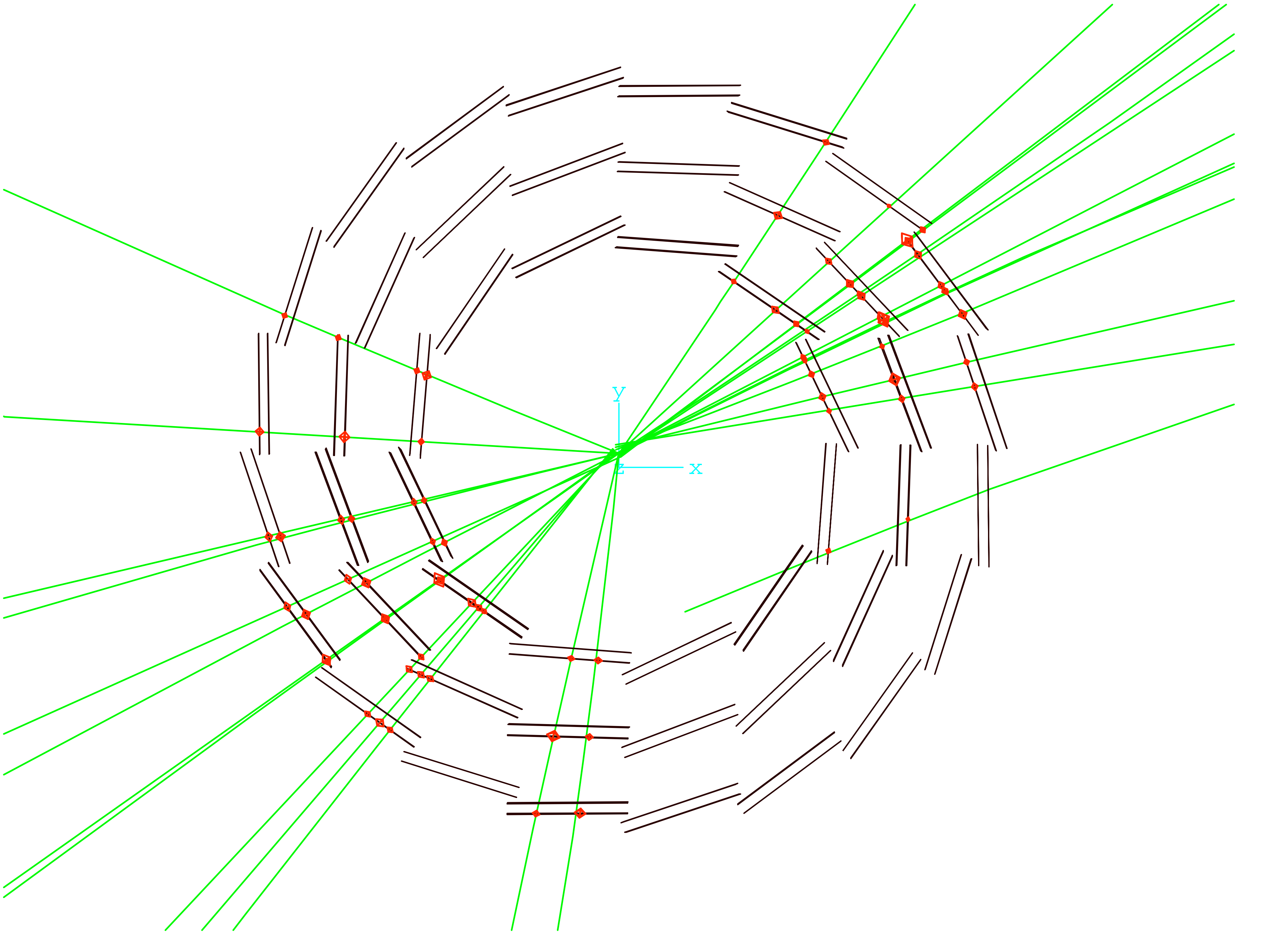
$$c\tau(D^+) = 0.31 \text{ mm} , \quad c\tau(D^0) = 0.12 \text{ mm}$$

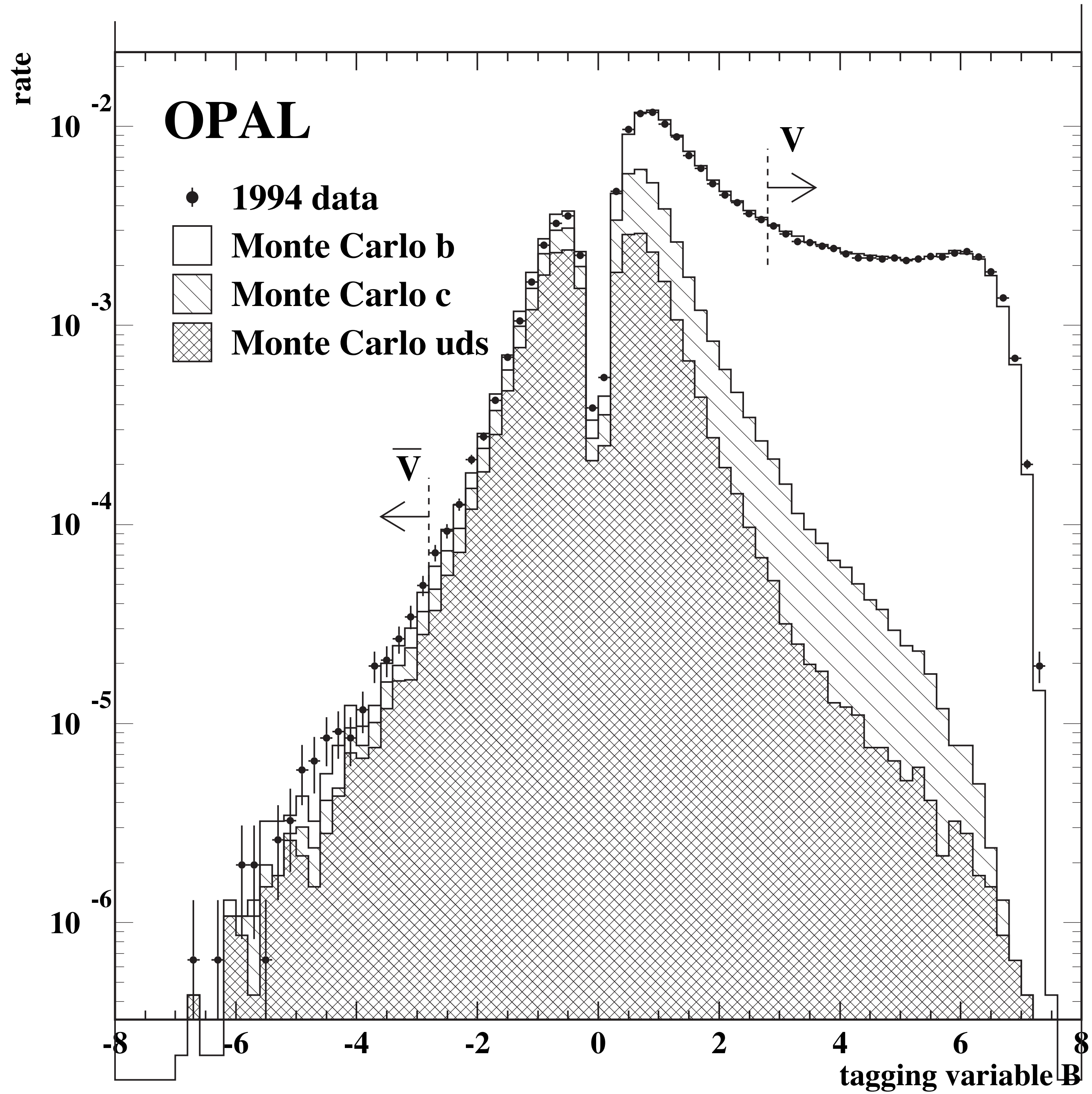

impact parameter
vertex
vertex mass

$e^{+}e^{-} \rightarrow Z^{0} \rightarrow b\,\bar{b}$

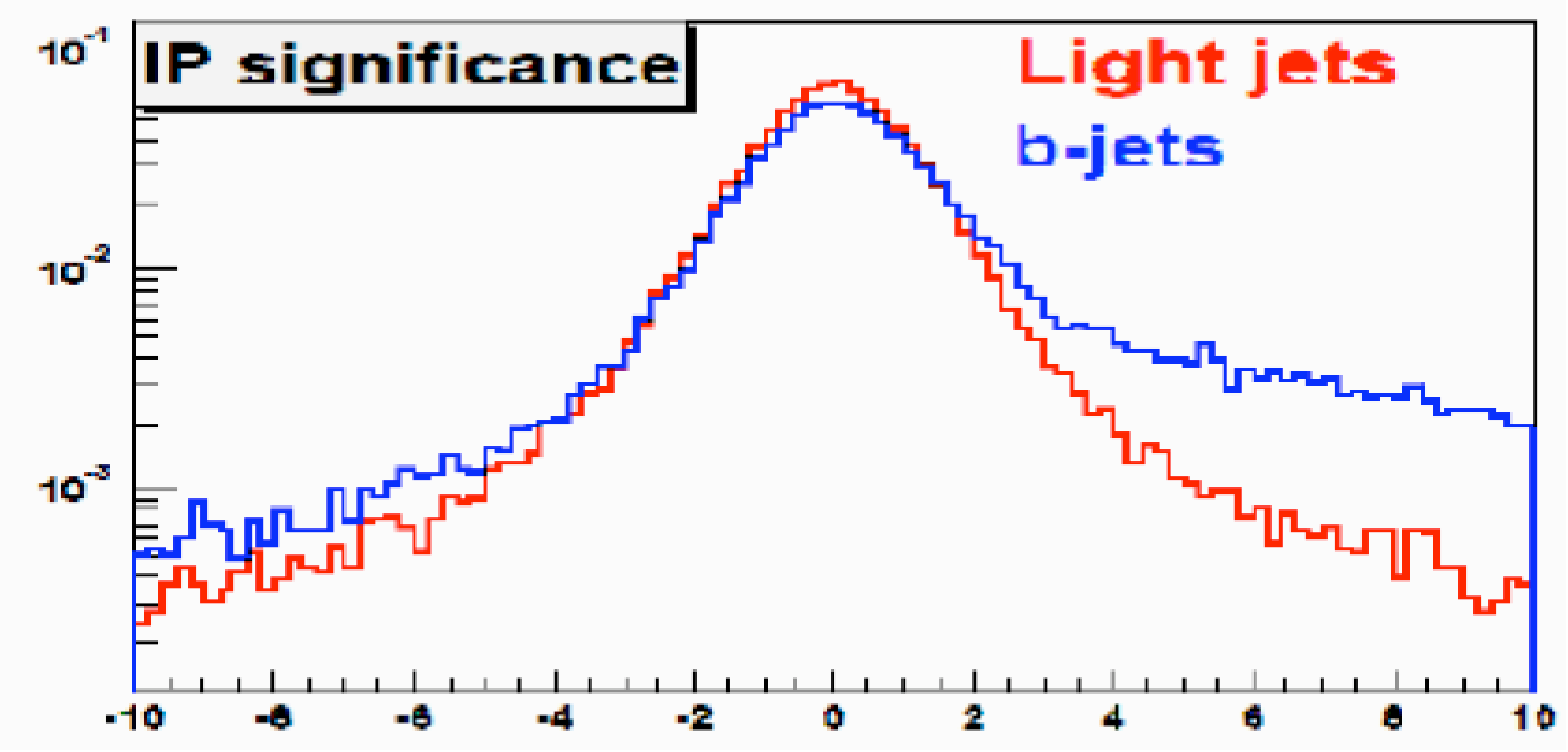


SLD

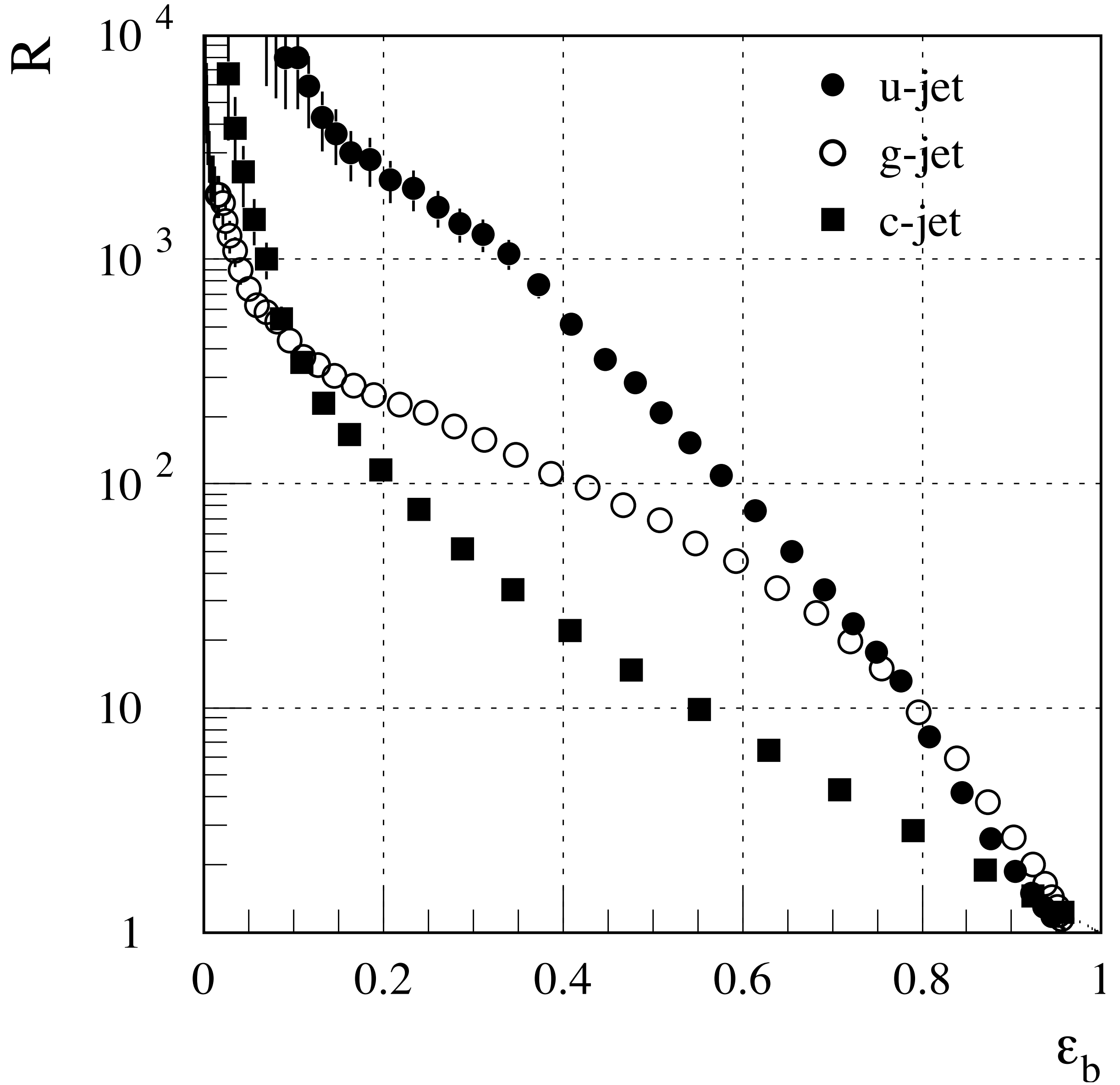

y
x
z



OPAL
rate
1994 data
Monte Carlo b
Monte Carlo c
Monte Carlo uds
V
$\overline{V}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
-8
-6
-4
-2
0
2
4
6
8
tagging variable B



impact parameter significance distribution
at DO



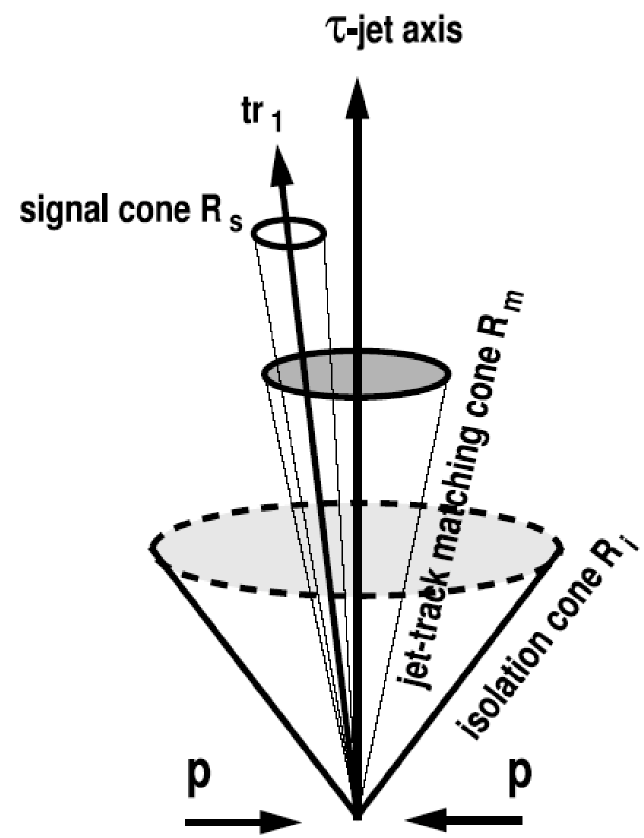
ATLAS TDR - background rejection
as a function of b jet finding efficiency

To tag taus, look for “tau jets”

low multiplicity:

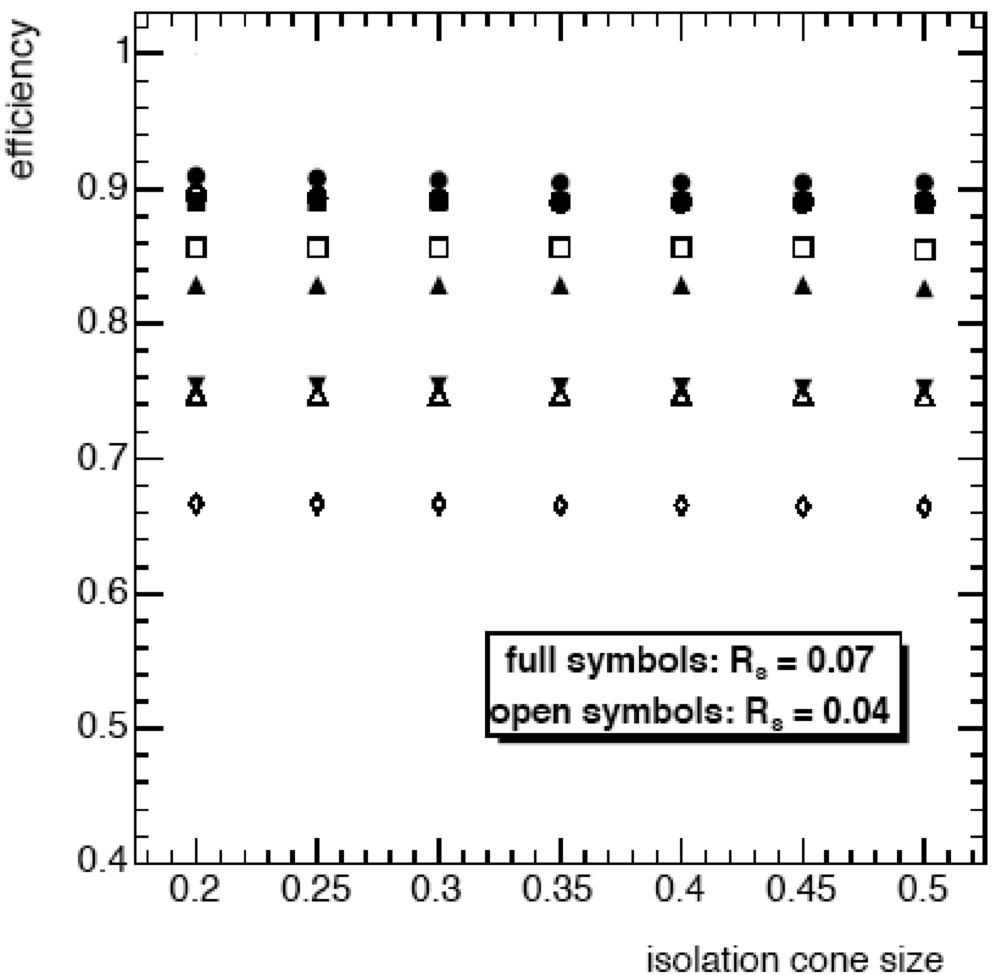
1-prong hadronic decays 50 %
3-prong hadronic decays 15 %

isolated in a narrow cone R < 0.2

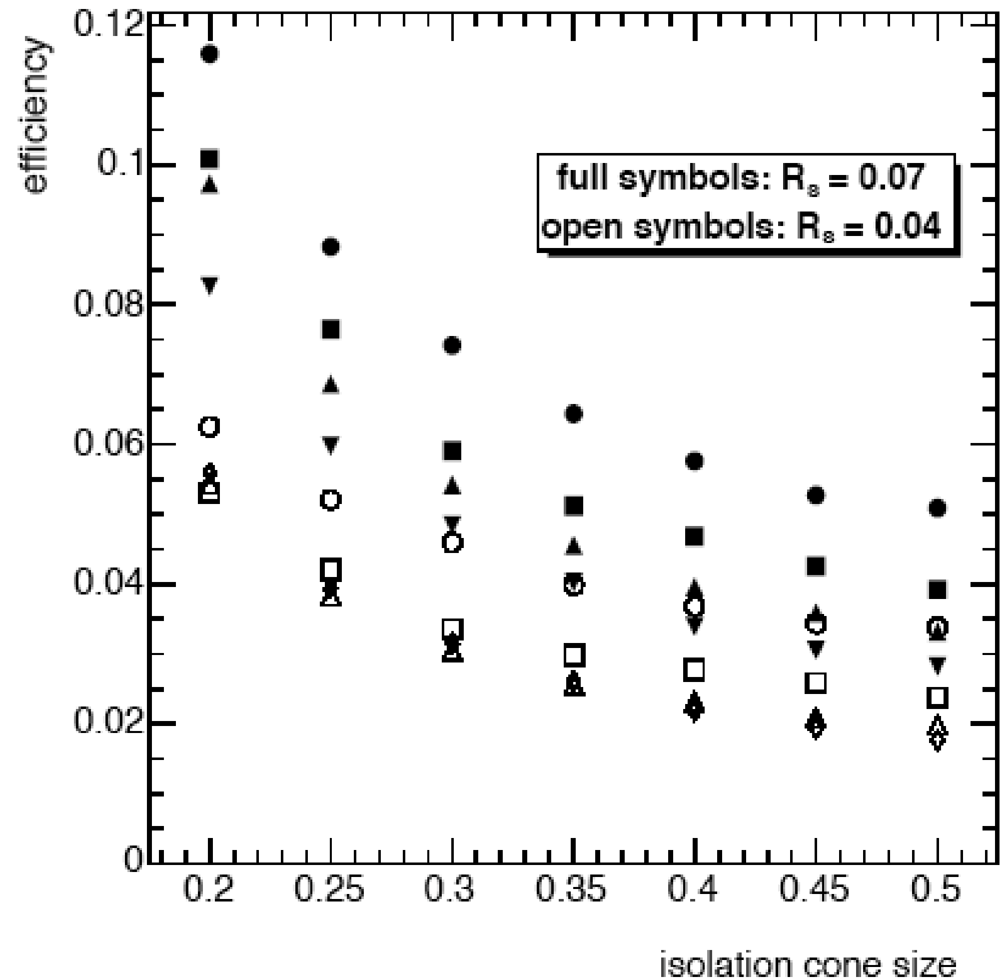


selection efficiency as a function of cone sizes

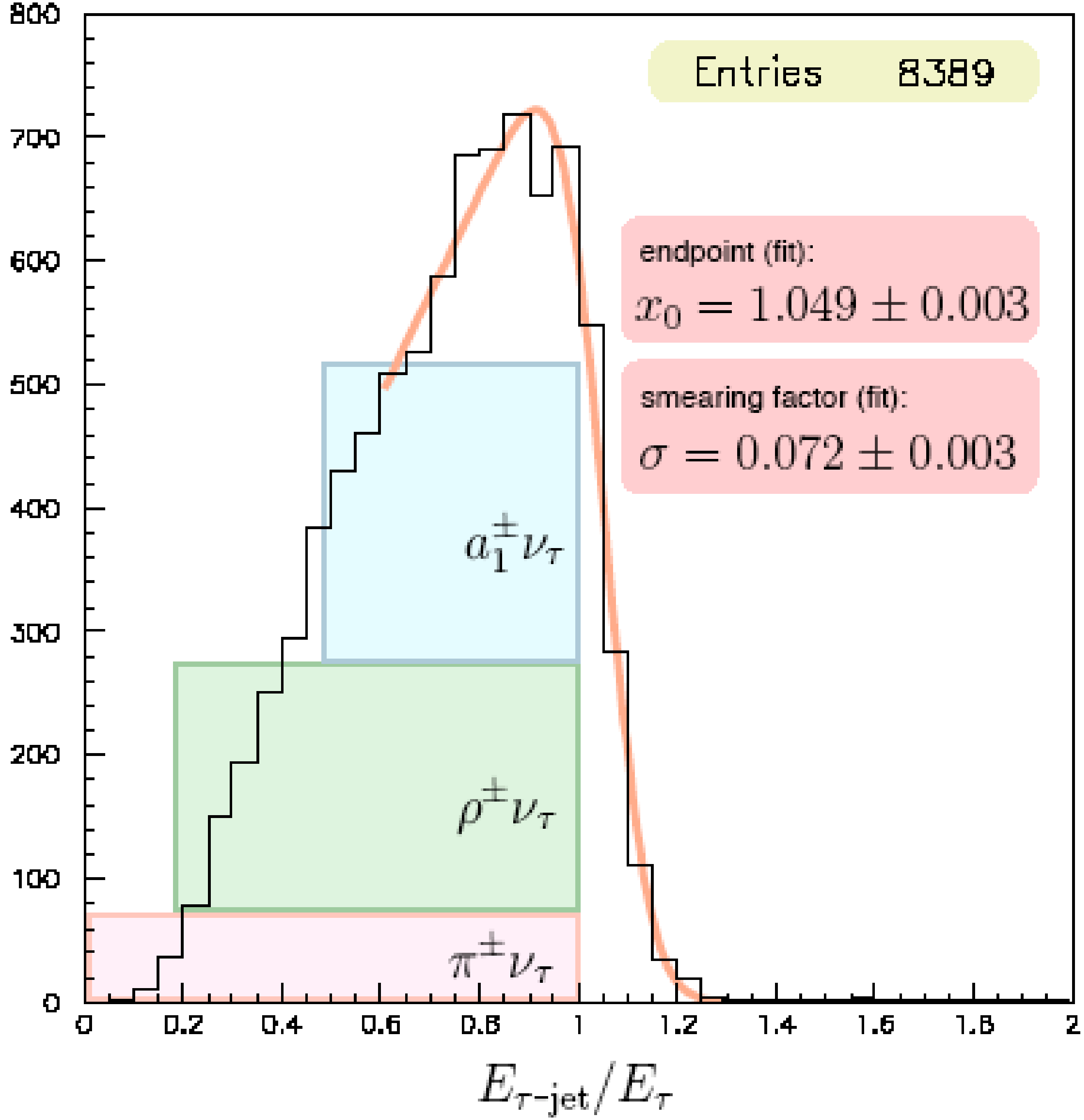
tau jets



QCD jets



CMS



Kitano-Ibe

HERWIG +
TAOULA +
AcerDET

We have now discussed the basic tools for LHC physics. The next step is to discuss the structure of events that resemble new particle production.