Particle Identification at the LHC

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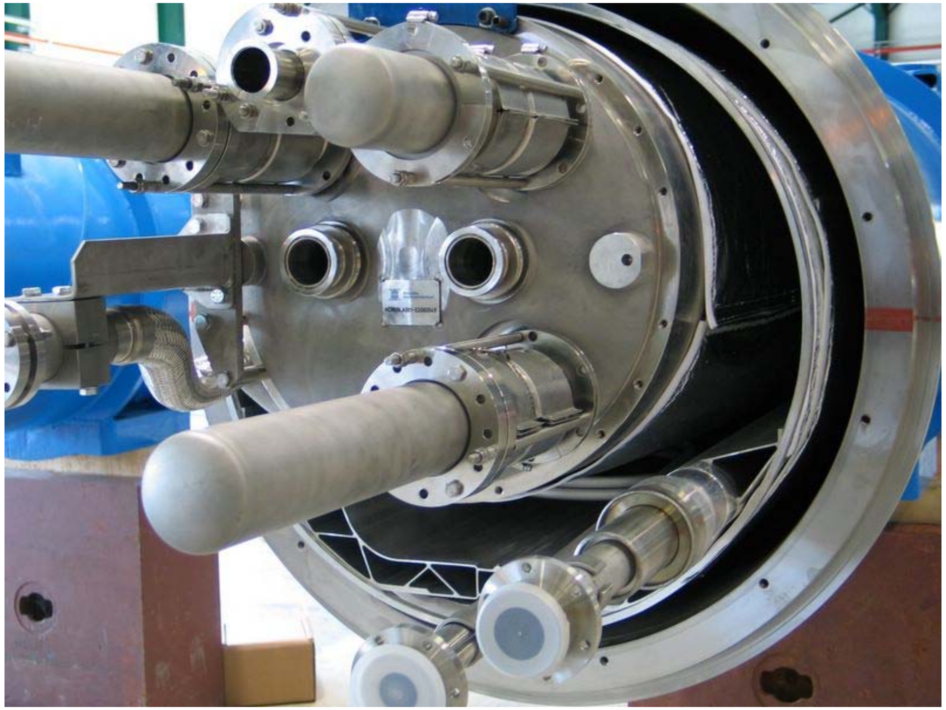
- Introduction
- Pion/kaon/proton id in Alice and LHCb
- Jet fragmentation,showering in calorimeters
- ATLAS and CMS "concepts"
- Muons, electrons and taus
- Photons,Ws and Zs
- B-tagging,top physics
- Particle-id for Higgs search
- Conclusions

Introduction

- LHC parameters
- Cross-sections at $\sqrt{s}$=14 TeV
- “Particles” in soft and hard collisions

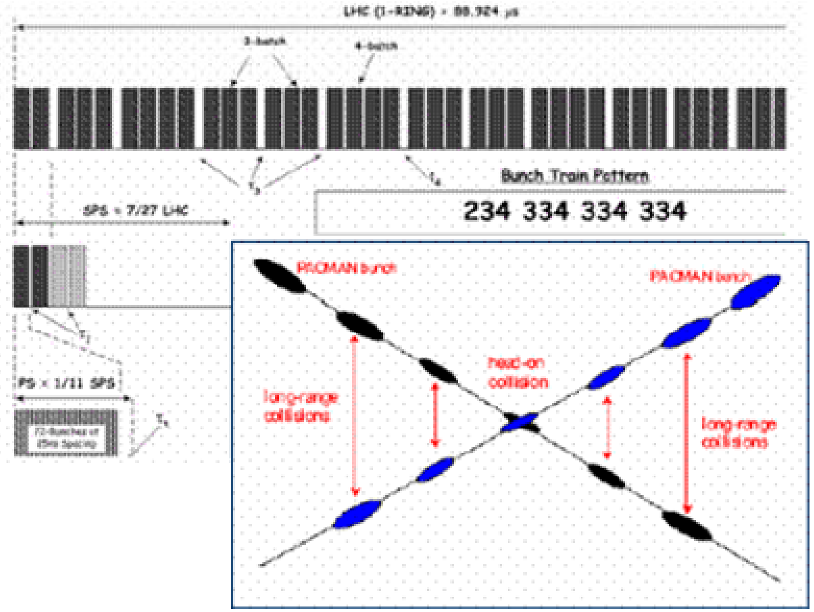


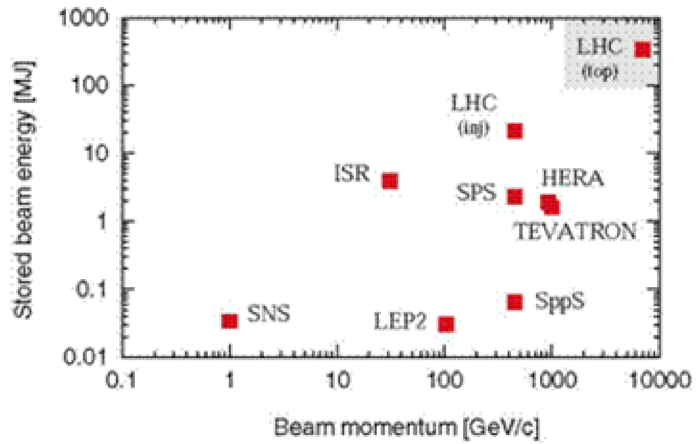
1232 main dipoles
B=8.33 T nominal,9T for cold test
L=14.3 m

Some LHC parameters (1)

Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	1.15 10^{11}
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10

Related parameters	
Luminosity in IP 1 & 5 (cm^{-2} s^{-1})	10^{34}
Luminosity in IP 2 & 8 (cm^{-2} s^{-1})	~5 10^{32}
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362





Some LHC parameters (2)

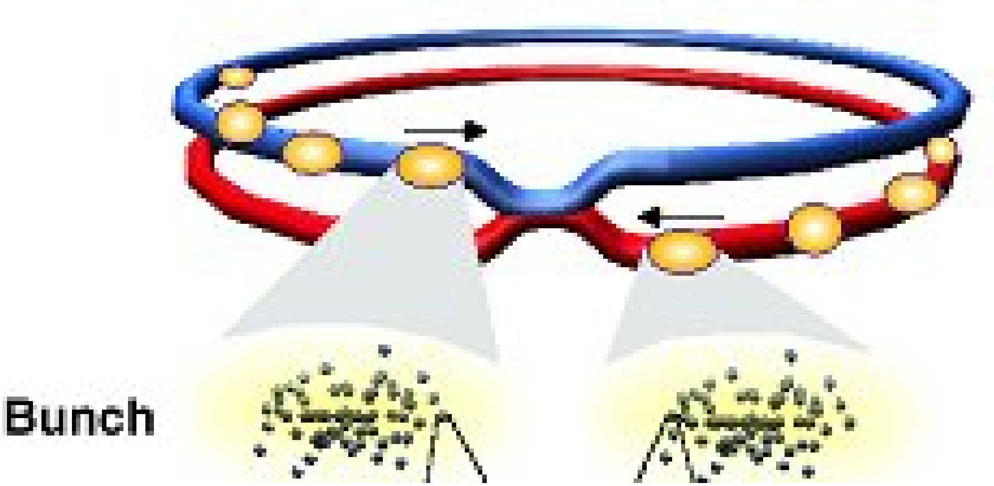


Figure "misleading":
-two beams are side by side
-proton change tubes at
IP1=Atlas
IP2=LHCb
IP5=CMS
IP8=Alice

- Alice in pp : $L < 5 \times 10^{30}$ to cope with detector features (TPC)
  β^* increased to 200m, and/or transversally displaced beams
- LHCb : $L < 2\ 10^{32}$ to have <~1 int/crossing
  β^* and/or transversally displaced beams
- Lead –ion mode : $\sqrt{s}$=5.5 TeV/nucleon, 592 bunches(collisions every 100ns), 10^8 ions/bunch, β =50cm, $L=10^{27}$
- Light ions and p-ions collisions also possible, and foreseen,later

2007 possible start-up conditions

Stage I physics run

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

$$Eventrate/Cross = \frac{L \sigma_{TOT}}{k_b f}$$

From L.Evans

- Start as simple as possible
- Change 1 parameter (k_b N $\beta^*_{1,5}$) at a time
- All values for
  - nominal emittance
  - 7TeV
  - 10m β^* in point 2 (luminosity looks fine)

Protons/beam ? 10^{13}
(LEP beam currents)

Stored energy/beam ? 10MJ
(SPS fixed target beam)

Parameters			Beam levels		Rates in 1 and 5		Rates in 2	
k_b	N	β^* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
1	10^{10}	18	1 10^{10}	10^{-2}	10^{27}	<< 1	1.8 10^{27}	<< 1
43	10^{10}	18	4.3 10^{11}	0.5	4.2 10^{28}	<< 1	7.7 10^{28}	<< 1
43	4 10^{10}	18	1.7 10^{12}	2	6.8 10^{29}	<< 1	1.2 10^{30}	0.15
43	4 10^{10}	2	1.7 10^{12}	2	6.1 10^{30}	0.76	1.2 10^{30}	0.15
156	4 10^{10}	2	6.2 10^{12}	7	2.2 10^{31}	0.76	4.4 10^{30}	0.15
156	9 10^{10}	2	1.4 10^{13}	16	1.1 10^{32}	3.9	2.2 10^{31}	

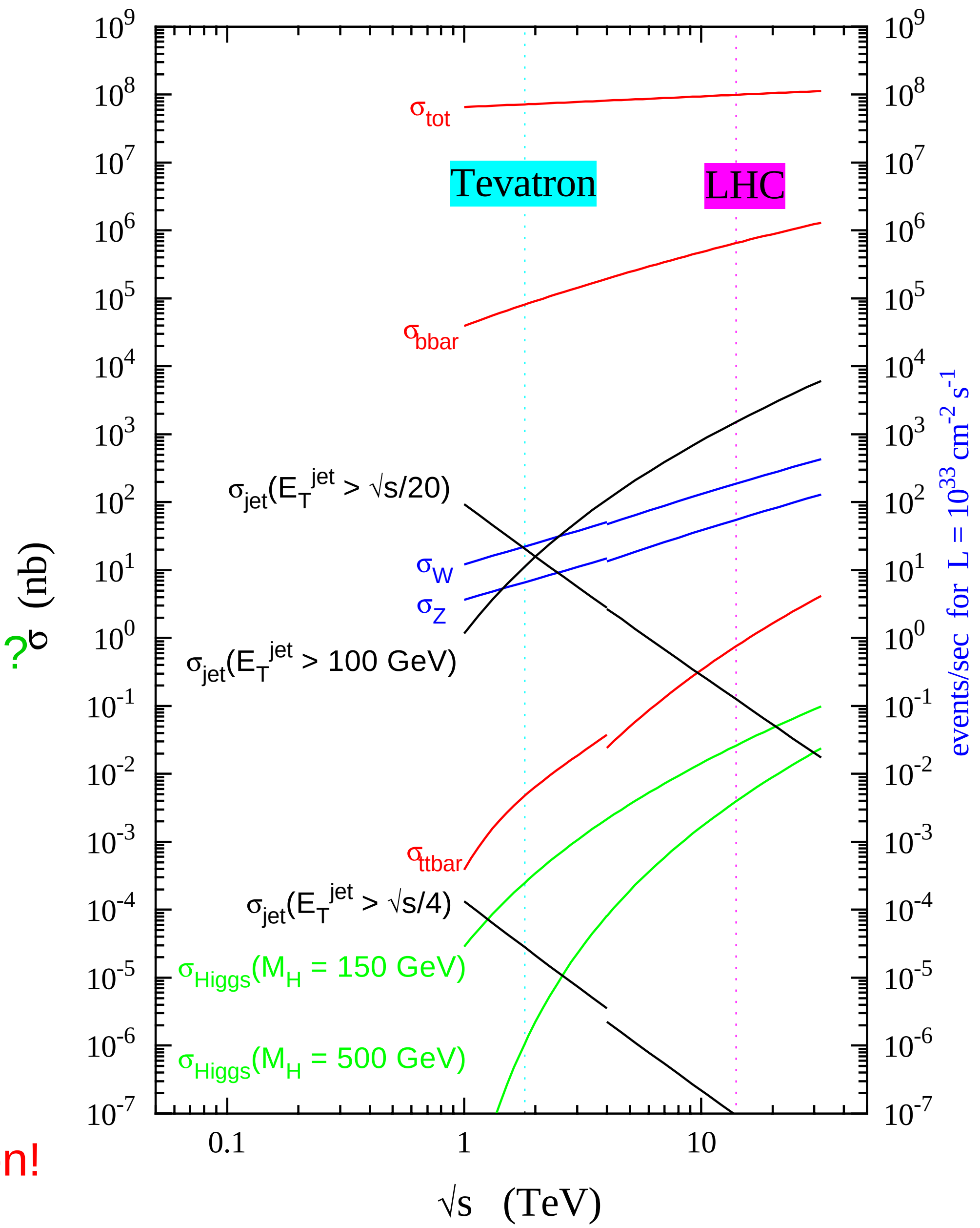
10 days at 10^{32} give 100 pb^{-1}

Proton-proton at $\sqrt{s}$=14 TeV

Cross-sections

- Inelastic , non-diffractive pp cross-section ~70mb
- Bb-bar pairs production is 1% of total
- **High p_T** phenomena (hard processes)? scale given by M_W /2 ,with some margin for triggering,.. **~30 GeV/c**
- Jet-cross section above a fixed E_T increases fast with energy

→QCD Background to e,μ from W/Z decays-or new physics-becomes worse at LHC as compared to Tevatron!



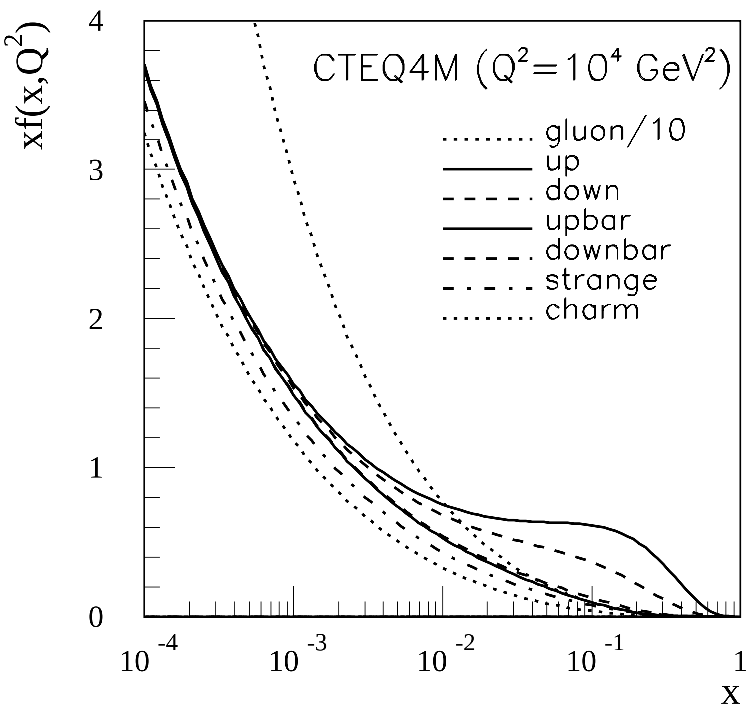
Parton-parton collisions

Hard collisions take place between partons in the protons: quarks and gluons

- The effective center of mass energy is $\sqrt{s} = 2x_1 x_2 \sqrt{S}$
  where x_i is the fraction of momentum carried by parton "i" and $\sqrt{S}$=14TeV

- The center of mass of the sub-process is boosted with $\beta = (x_1 - x_2)/(x_1 + x_2)$
- 2 components only (transverse plane) of the (E,p) conservation useful

- The parton-parton luminosity is calculated from the parton distributions:
  $f(x,Q^2)$ being the probability to find a parton with momentum x in the proton



- Gluon-gluon collisions dominate QCD processes as long as x_1x_2 is not too large(40% of momentum carried by gluons). With $\tau = x_1x_2$

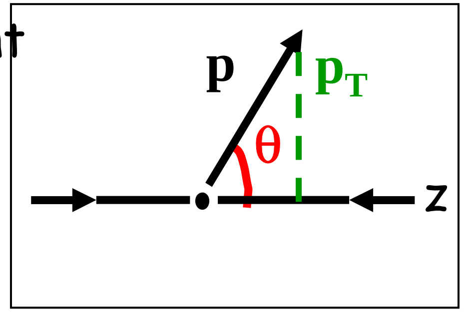
$$\tau dL/d\tau = \int_\tau^1 G(x,Q^2)\, G(\tau/x,Q^2)\, dx/x$$

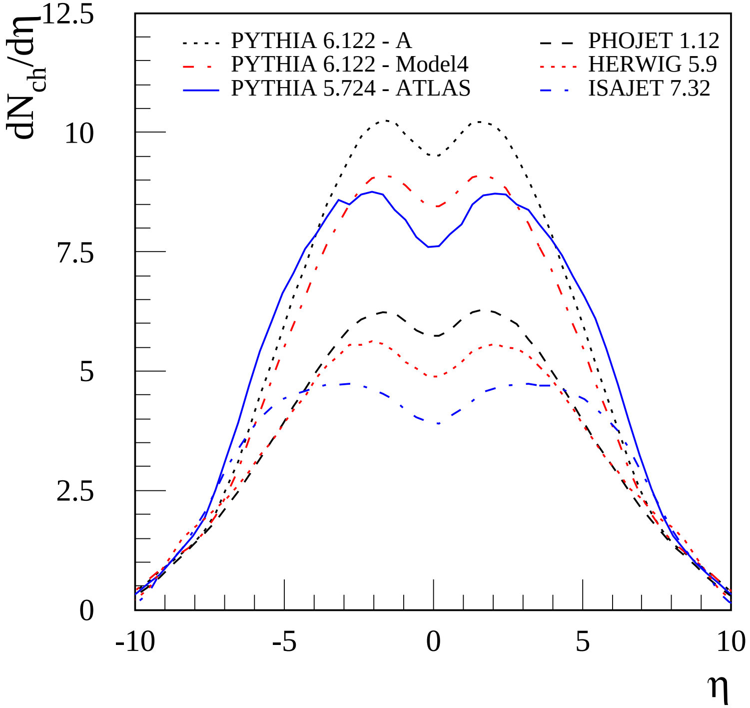
Minimum bias events

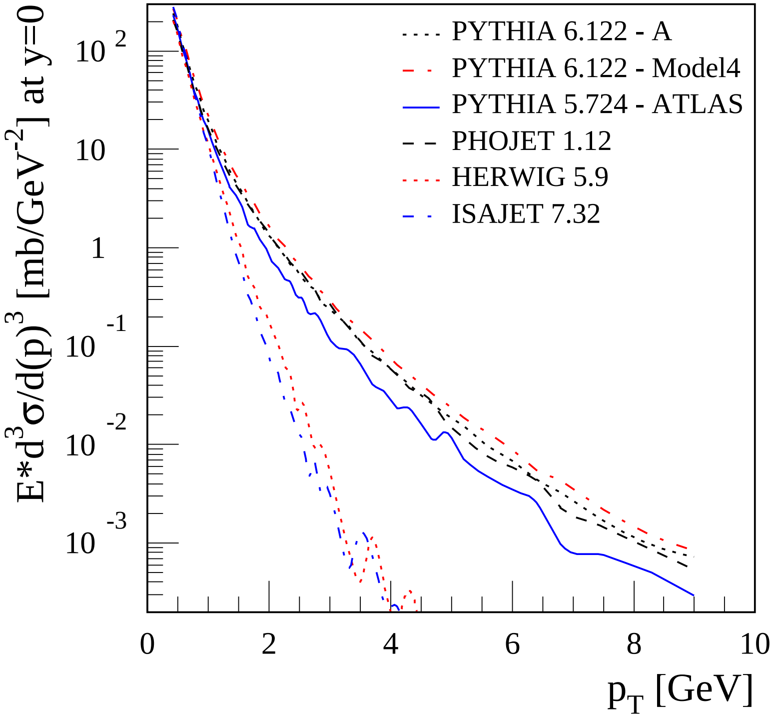
- Most collisions are peripheral, without hard scattering.
- Soft particles (mostly pions)are produced with a constant density in pseudo-rapidity $\eta = -\log(tg(\theta/2))$

  $\eta \sim y$ (rapidity) $y=\log[(E+Pz)/(E-Pz)]$

  at LHC ymax~10
- There is still rather large uncertainty on the level of the "rapidity plateau" expected at LHC.
- The average p_T of min bias charged particles (pions) is ~0.7GeV/c



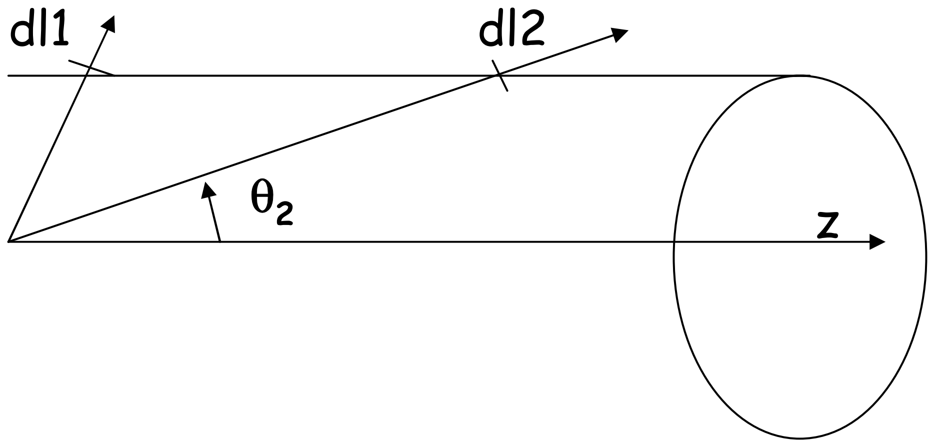




Constant $d\eta$ detector elements

Elements of fixed transverse size, aligned along a cylinder, correspond to a constant $d\eta$

$\rightarrow$the flux of particles they intercept is independent of z
(but the energy intercepted increases as $1/\sin(\theta)$)



dl1=dl2 $\rightarrow$ $d\eta 1=d\eta 2$

"Particles" in hard collisions

Elementary constituents interact as such in "hard processes"
namely : quark and leptons as matter particles, and

leptons	**e**(0.0005)	μ(0.105)	τ (1.777)
	ν_e	ν_μ	ν_τ
quarks	Up<0.005	C~1.25	T (173±3)
	Down	S~0.1	B ~4.2

$\rightarrow$non zero..

gluons and EW bosons as gauge particles

Gluon(0) Color octet	Photon (0)	W+,W- (80.420)	Z (91.188)

- γ,W and Z have SM couplings to quark and leptons:

Γ(W)= 2.12 GeV eν :10.6 % hadrons:68.5% (ud,cs)
Γ(Z)=2.496 GeV ee :3.37% $\nu\nu$:6.6% each hadrons:70% (uu,dd,ss,cc,bb)

- Heavy quarks decay by V-A (W coupling)+CKM. No FCNC

- Missing : the Higg(s) boson(s) M>114 GeV (LEP) and "probably" <~250

- Predicted/Speculated : SUSY particles, KK excitations,…

“Particles” in soft collisions

•Particles with strong interactions = Gluons and quarks materialize as jets (non perturbative aspect of QCD).

•Below some p_T (few GeV) the structure in jets is no longer visible and soft gluons “conspire” to hadrons (π, K,..) of the “minimum” bias evts”.

In this regime of soft collisions the “particles” are pions,,kaons,.....with in general intermediate hadronic resonances (ρ ω η φ ,...)

•Heavy quarks decay by W exchange (no FCNC) and CKM mixing,and appear finally as well as “groups” of pions,kaons,..with also electrons/,muons from the intermediate Ws.

The long life time of b,c (and s) lead to visible path length which allows to sign them.The higher mass states(B) generate distinctive pT (~M/2~2.5GeV) in their decay.

•Narrow resonances of heavy quarks (ψ, Y,..) are interesting signatures, including in heavy ion collisions.

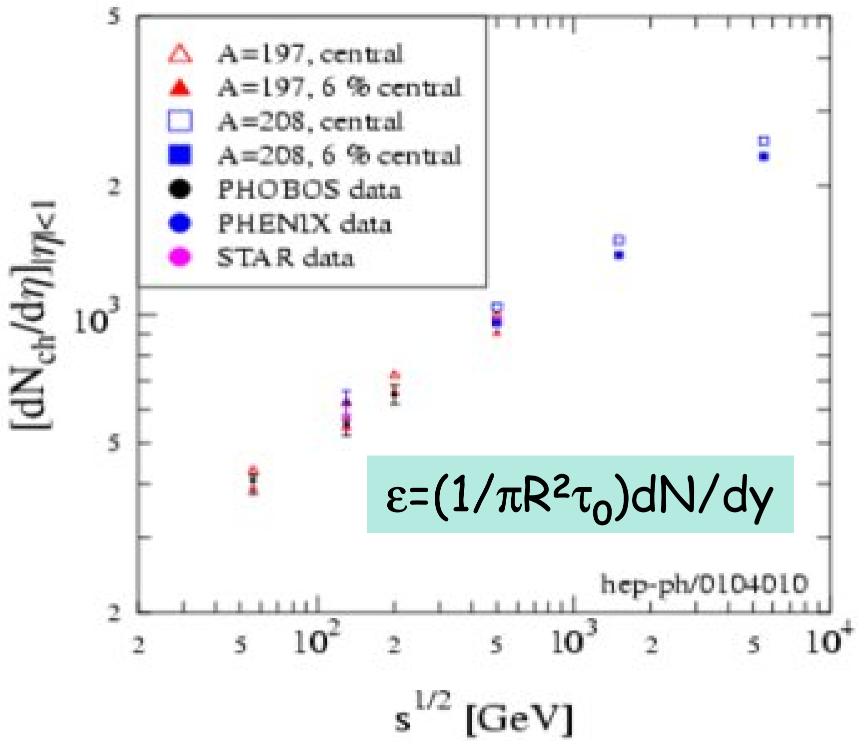
Soft particles in lead-lead collisions

At small impact parameter and high energy,the head on collisions of nuclei generate a large number of soft gluons,which in turn materialise into hadrons.

Expected density of gluons per pseudo-rapidity interval is ~3000 at LHC

There is interest in understanding:

- In which conditions (energy density ε)this evolves through an intermediate quark-gluon plasma (new state of matter, possibly already observed)
- How hard probes (ψ,Y) behave when traversing such a medium
- How this medium "cools-down" to ordinary hadrons.



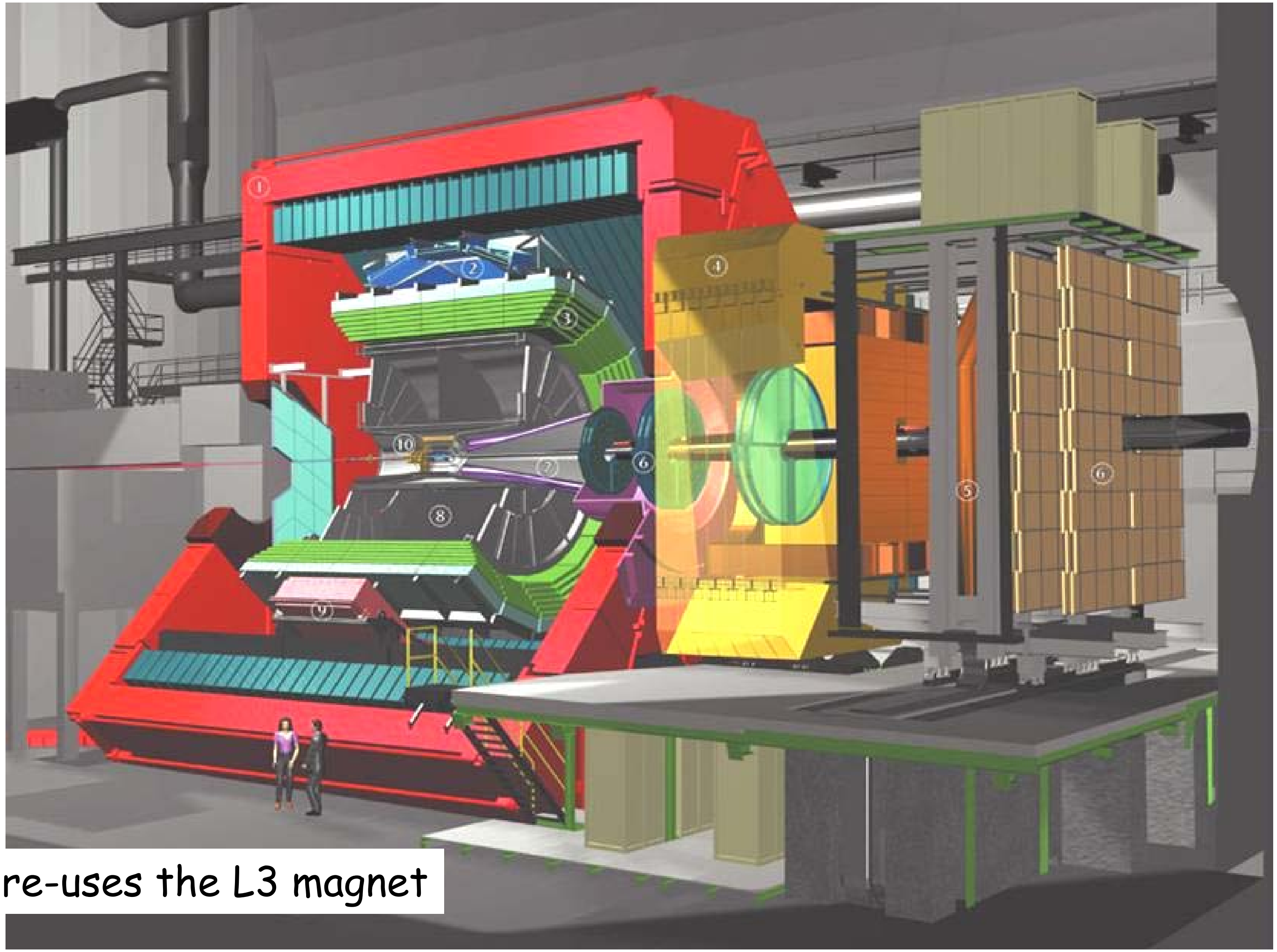
$\varepsilon=(1/\pi R^2\tau_0)dN/dy$

This last part is best studied with soft particles . Important observables are:

- **Nature of produced hadrons (fraction of strange part,..)**
- **Transverse momentum spectrum**
- **Intermediate states (resonances like $\phi\rightarrow KK$),….**

$\rightarrow$ALICE is aiming at 3σ π/K/p ID in the 0.1 GeV to "few GeV" range

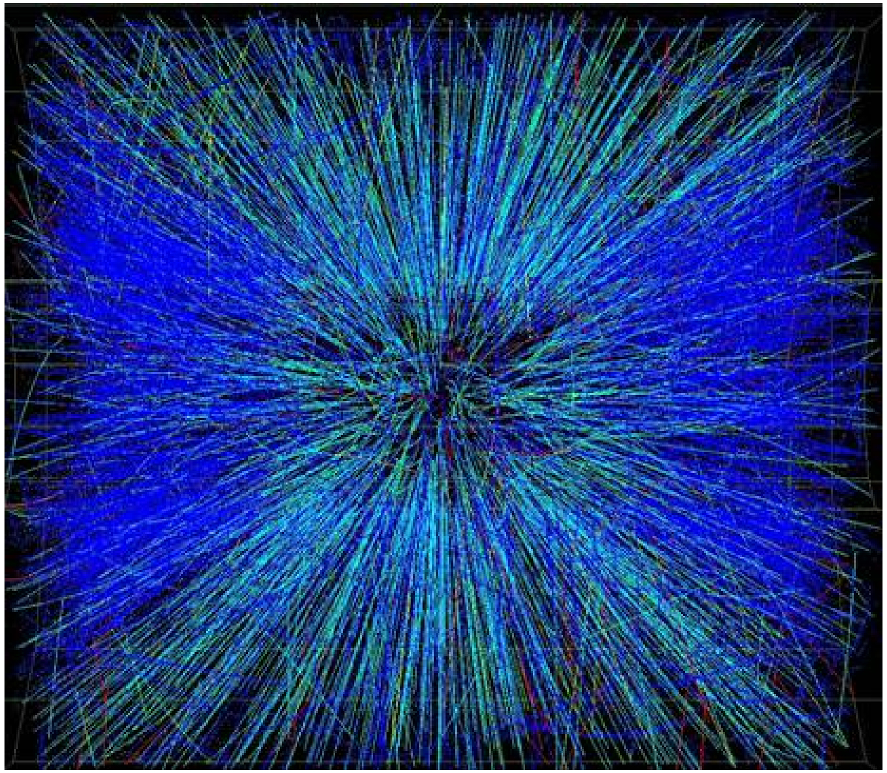
ALICE Detector

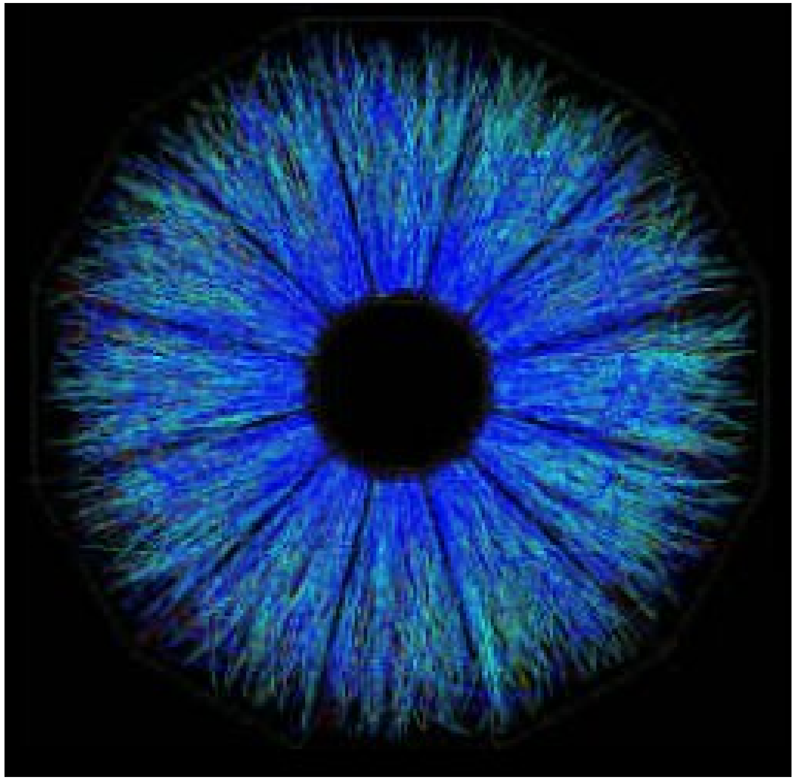


Alice re-uses the L3 magnet

Pb-Pb total Xsection= 8barns $\rightarrow$ at L=10^{27} $cm^{-2}s^{-1}$ the rate is only 8 kHz
Multiplicity is the problem….

An event in STAR at RHIC





The centrality of the collision (impact parameter between the two line of flights) is measured from several observables, in particular :

-the energy in ZDC which allows to count the number of "non-interacting nucleons"

-the multiplicity of charged particles at the vertex.

Central events have the highest probability to contain high energy density areas

The Alice TOF(1)

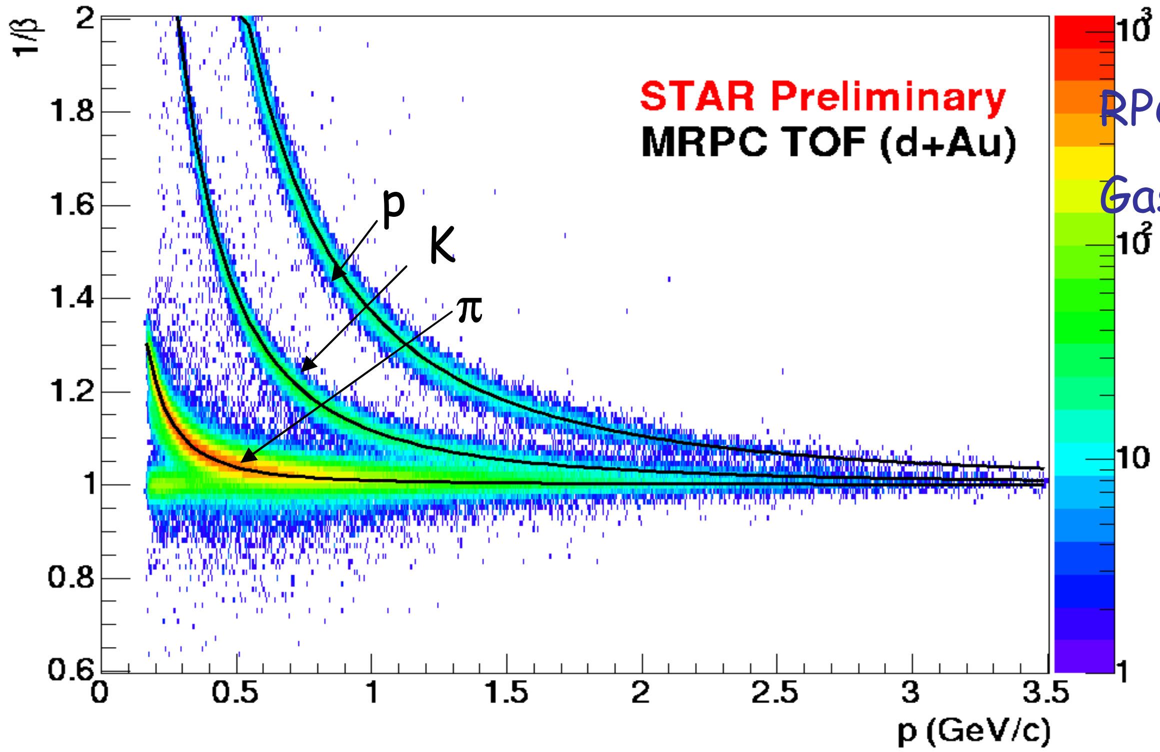
For non relativistic particles TOF is a powerful tool

$t = l/\beta c$ $\beta = p/\sqrt{(p^2+m^2)}$ p measured by TPC+ITS

Useful range increases with **accuracy of time measurement** and **lever arm**

-T_0 bunch collision rms ~200ps (~6 cm bunch length)

-only one collision/bc in Pb-Pb →average of fast tracks better



RPC: "micro-spark chamber"

Gas: $C_2H_2F_4$ / isobutane / SF_6

The Alice TPC (1)

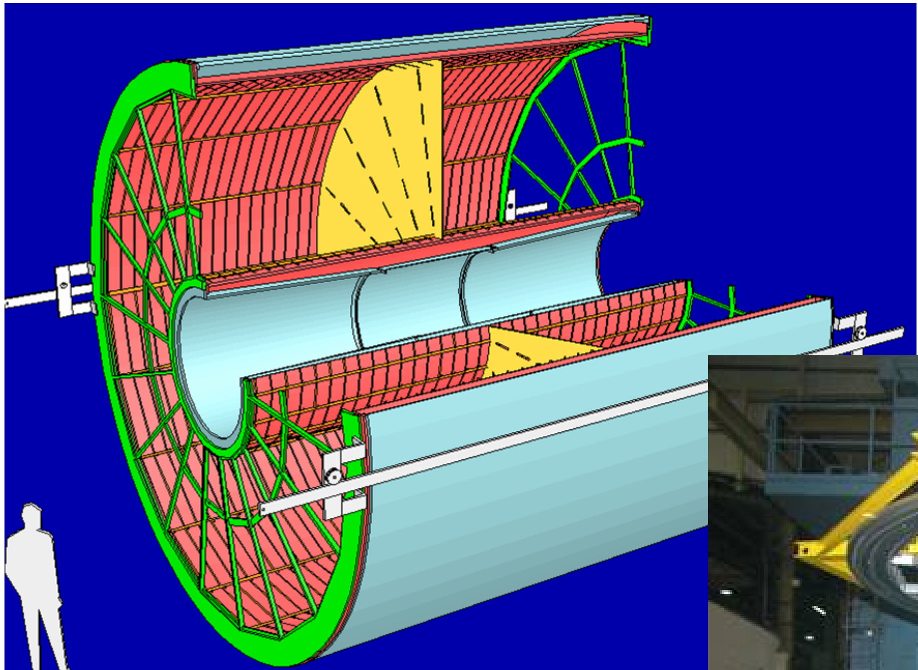
- At sufficiently low rate (<time drift over detector length)a TPC is the choice detector for high multiplicity final states
- Demonstrated by PEP4, Aleph-Delphi, NA49, STAR
- Measurement of dE/dx gives "some" particle id at low momentum

$$-dE/dx = k\ 1/\beta^2 \left(0.5 \, Log(2 m_e c^2 \beta^2 \gamma^2 Tmax/I^2) - \beta^2 - \delta/2 \right)$$

- Specific constraint on gas for HI: low momenta (~150 MeV/c)

  $\rightarrow$low diffusion, low scattering, high ion mobility $\rightarrow$ **Neon** + 10% CO_2
- Overall size: 88 m3 ,5 m diameter,5m overall length
- 100kV on central plane to create E_{drift}=400V/cm
- Transverse diffusion suppressed by B=0.5T; σ=220 μm $\sqrt{L(cm)}$
- Pad size : 4 mm2 at inner radius, in total 560 000 channels with 10 bit dynamics

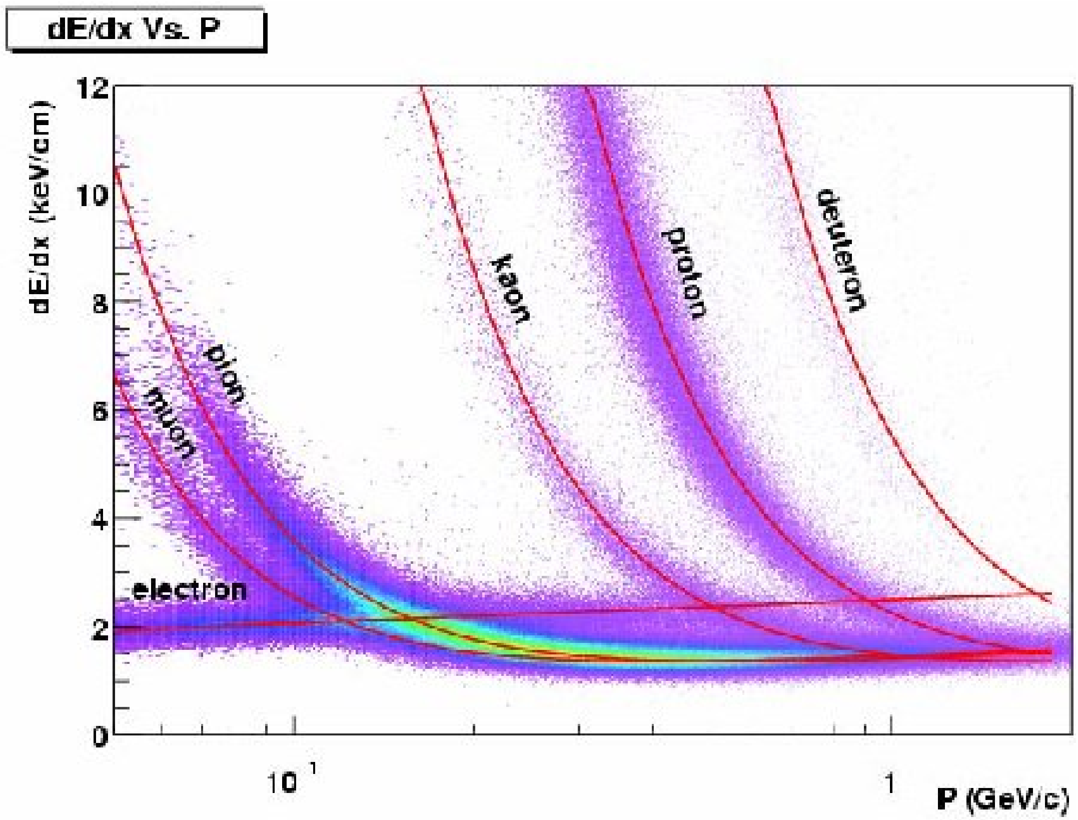
The Alice TPC (2)



The Alice TPC (3)

- dE/dx resolution goes like $N^{-0.43} \times (Pl)^{-0.32}$

  (N nb of samples , P pressure, l length of sample)
- Best dE/dx precision (~2%) was achieved by PEP4 (8 bars)
- Alice expects 5.5% for isolated tracks and 7% with dN/dy ~ 8000
- STAR (at RHIC)obtains the performance below:

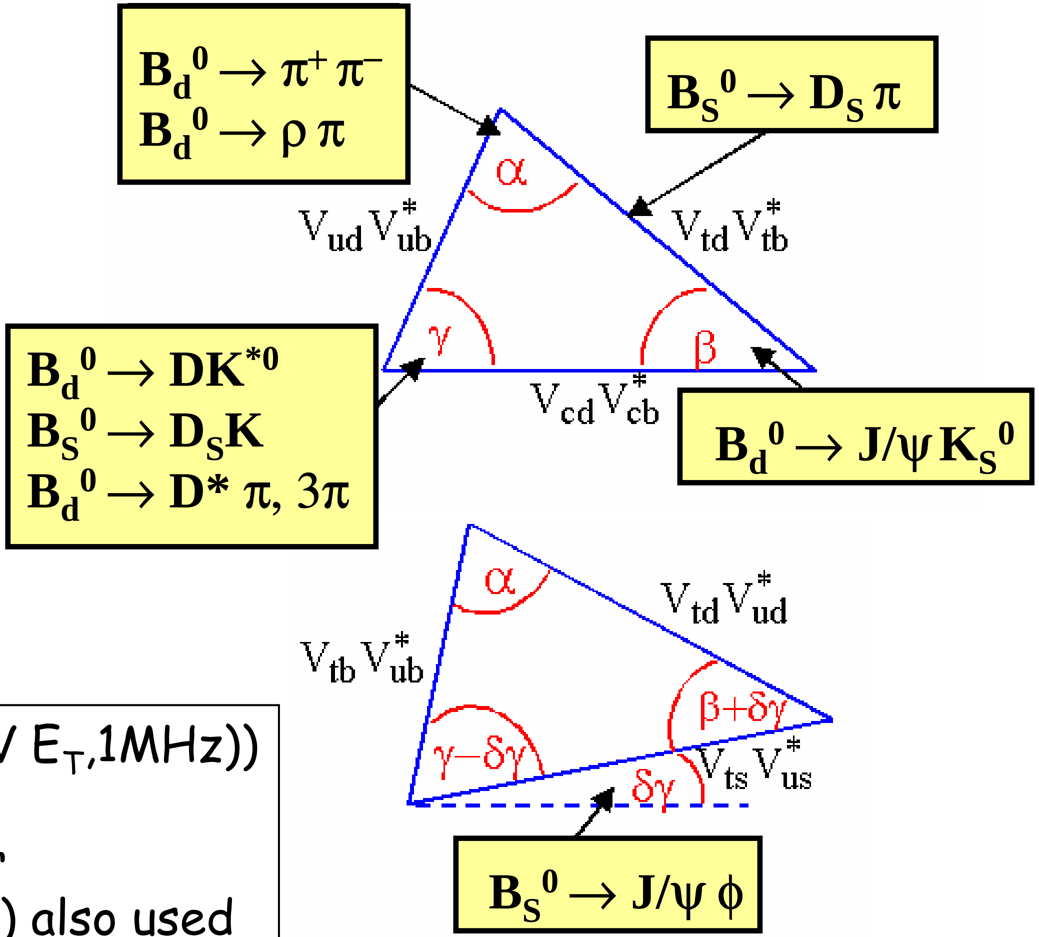


Muon and pions
Resolved below
100 MeV/c

CP violation with LHCb

Among the main goals:
measure α and γ

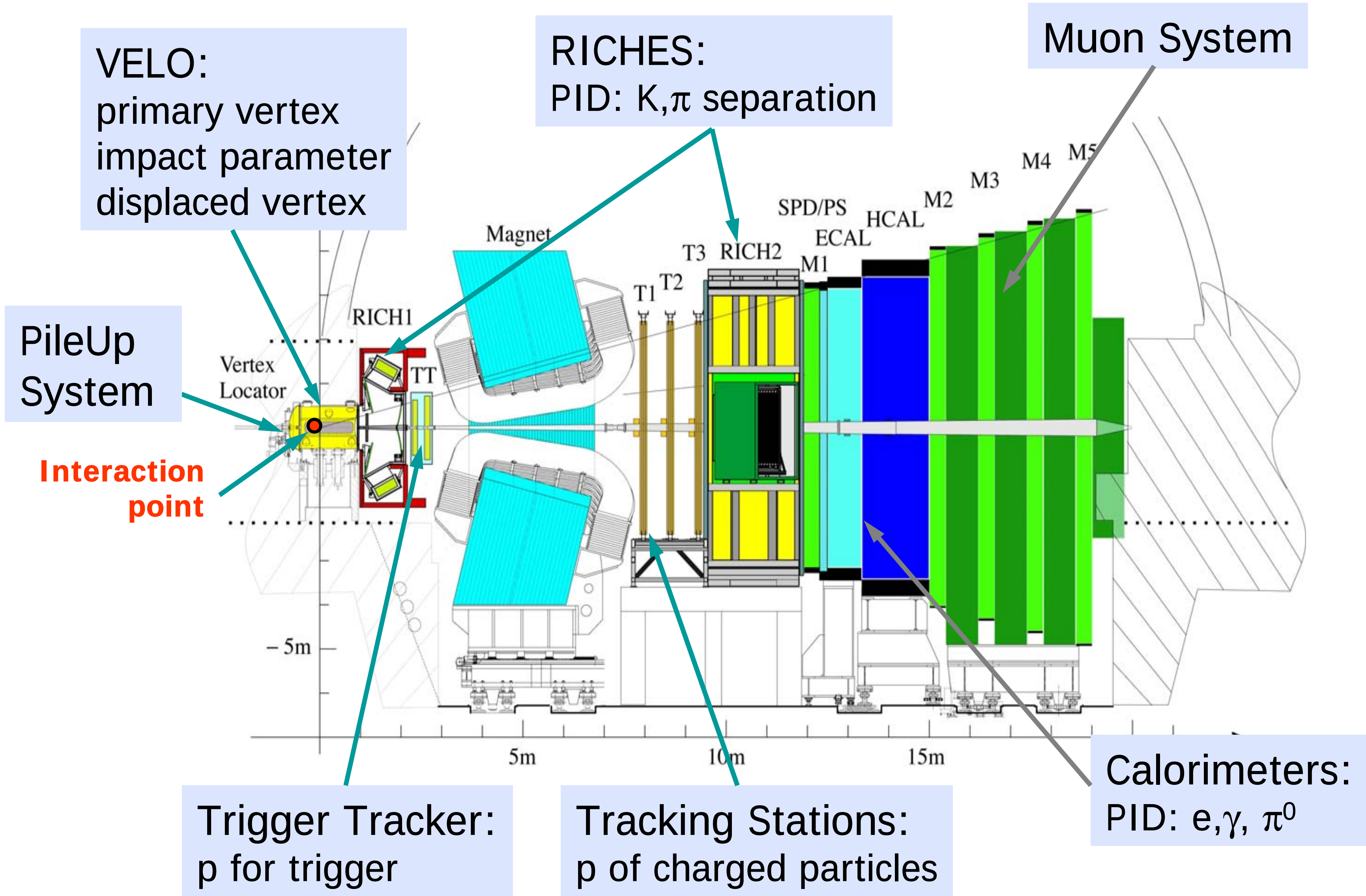
2 CKM Unitary triangle relations most useful:



- Need precise measurements of exclusive modes, with K/π id
- Need trigger on hadronic modes

Hadronic calorimeter trigger(~2GeV E_T,1MHz))
Track trigger
Displaced vertex trigger
Leptonic decay of companion B(tag) also used

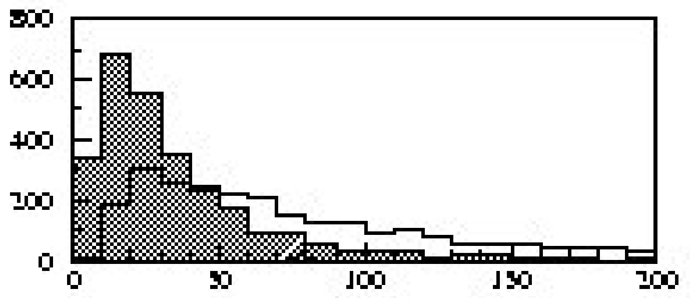
LHCb: single arm spectrometer



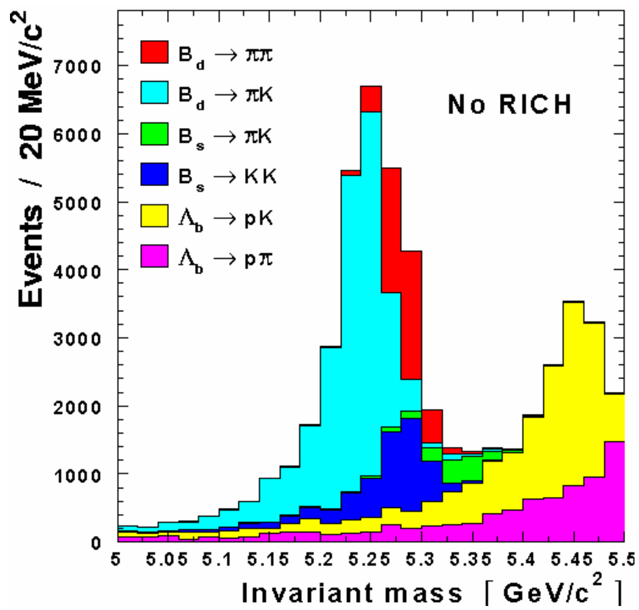
LHCb hadron ID

Requirements:
- Speed: 25 ns or faster
- Angular coverage: 10 to 330 mrad
- Momentum range: 2 GeV/c to 150 GeV/c
- Particle density: ~20/m²/interaction at 10 m from vertex
- Quality of separation : pion rejection>20

Technology choice:Rich with HPD readout
- Aerogel and C_4F_{10} for Rich1 (near= 1m)
- CF_4 for Rich2 (far =10 m)



Momentum of fastest pion from $B \rightarrow \pi\pi$(unshaded)and $B \rightarrow D\pi\pi\pi$(shaded)



LHCb Rich

Rich1:

larger solid angle,lower part of P spectrum

- *Aerogel*
  - -n=1.03→ θ (β=1)=242 mr
  - -thickness=5 cm
  - -nb detected photons=~7/ring (β=1) (hygroscopic…)
- C_4F_{10} p=1013 mb at -1.9C
  - -n=1.0014 /260 nm θ (β=1)=53 mr
  - -thickness=85cm
  - -nb photons=~30/ring

Rich2:

- CF_4 -n=1.0005 /260 nm θ (β=1)=32 mr
  - -thickness=180cm
  - -nb photons=~30/ring

C4F10	3 GeV/c	30 GeV/c
β (pion) θ (cerenkov)	0.9989 0.160 rad	0.999989 0.0526 rad
β (kaon) θ (cerenkov)	0.9864 0.020 rad	0.99986 0.0502rad

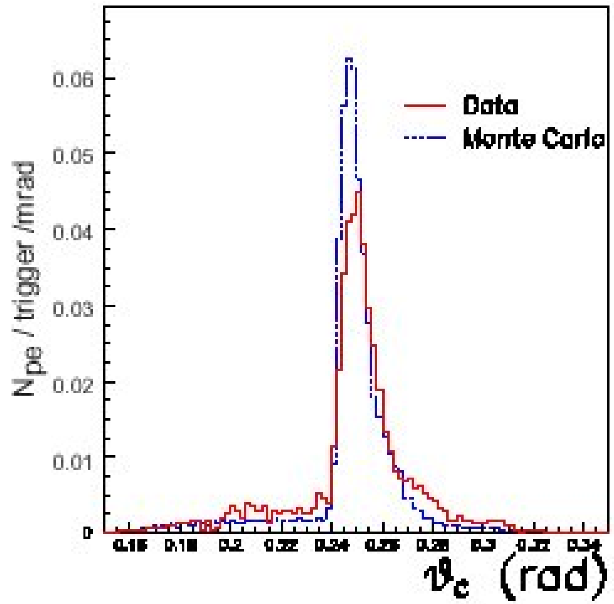


Figure 4.7: Distribution of the reconstructed Cherenkov angle for 4 cm-thick aerogel.

LHCb Rich : mirrors and photodetector

- Thick radiator→spherical mirror
  (convert direction to point in focal plane)

- Photodetector out of particle path

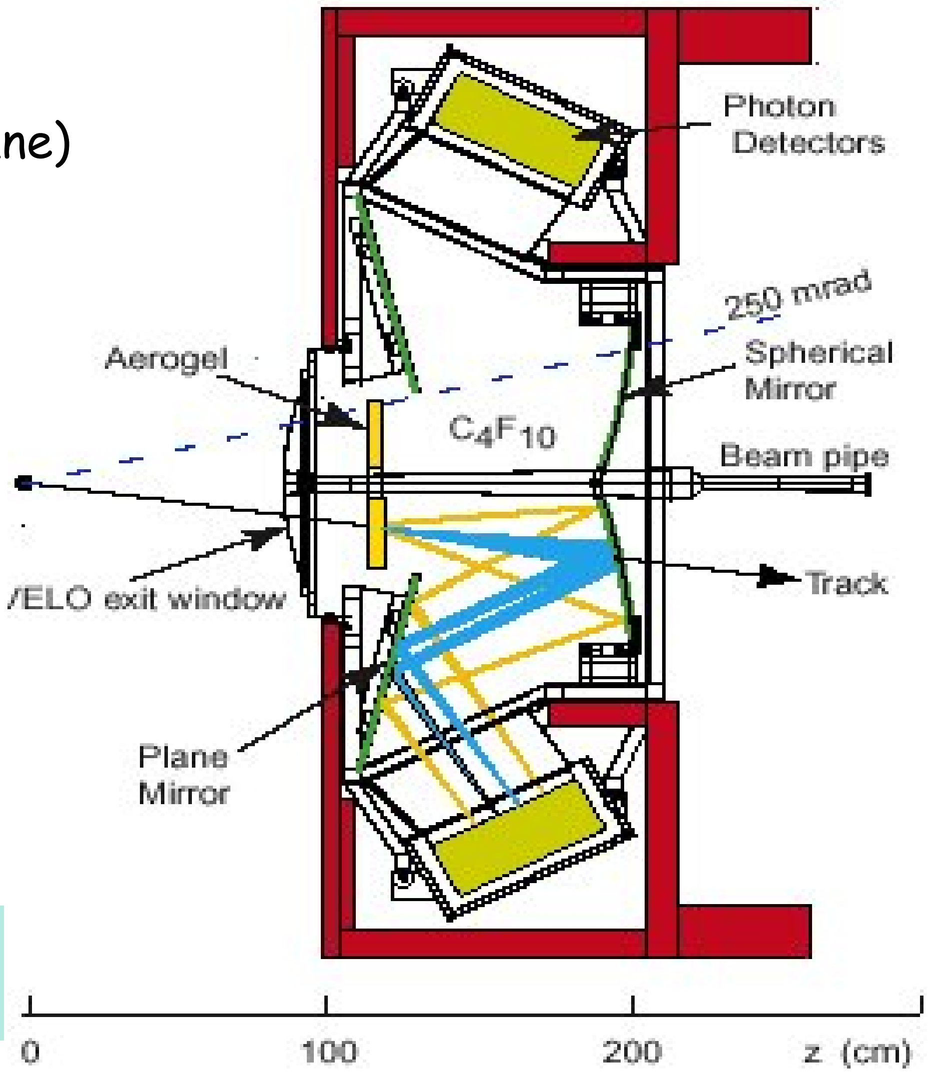
- Granularity of photon detector good enough not to compromise accuracy of ring measurement

- UV sensitive

  →"pad HPD"

(alternative:Multi anode PM)

Thin mirrors needed (beryllium or Carbon fiber)



LHCb pad HPD

- Photocathode at –20kV
- Vacuum tube,window transp to UV
- Demagnified image/5 on pixel sensor
- 256x32 pixels of 62x500 microns
- Electronics bump-bonded
- 40 MHz readout
- Long and difficult R&D at CERN (bonds melt under tube bake out) Works fine now-tested in beam with aerogel in 2003.
- ~500 pieces needed

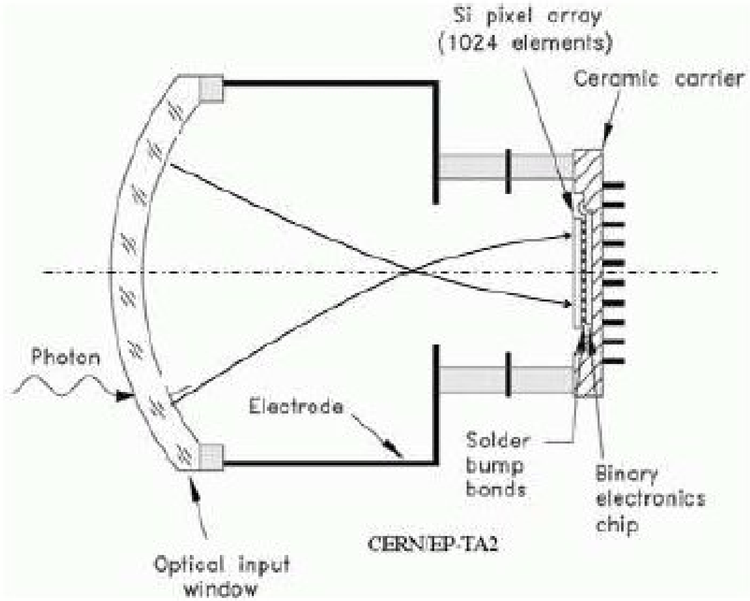
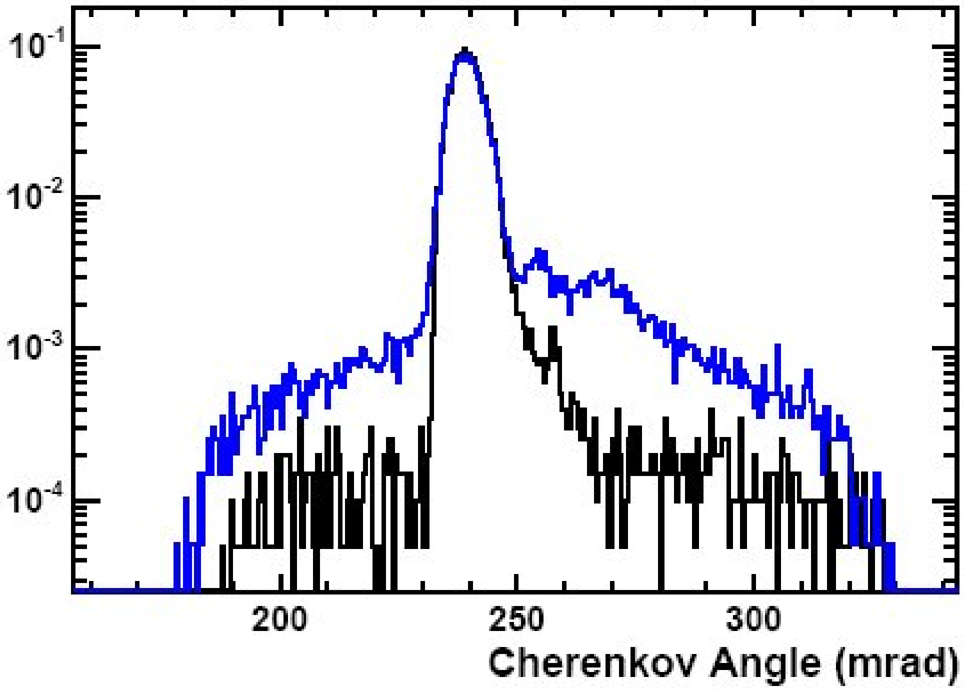


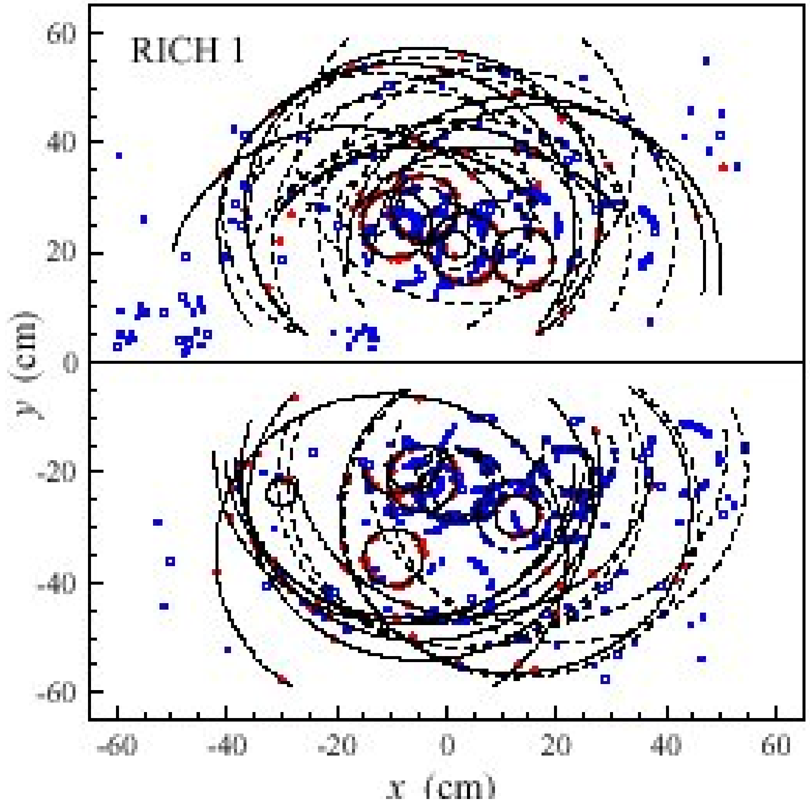
Figure 3: Schematic principle of the HPD.

LHCb Rich1

Full evt simulation

HPD data in test beam(aerogel)





Simulated accuracy of Cerenkov angle =1.9/1.3/0.7 mr/$\sqrt{N_{pe}}$ in aerogel,..
Need of course efficient tracking and accurate enough momentum measurement for the identification approach to be effective.

LHCb : example of trigger steps

•LVL0: Had-cal E_T threshold 2.4 GeV acc=40% rej=50

(+electron & muon) $\rightarrow$ enter at 1 MHz in a pipeline 256 **bc** deep

•LVL1:

-with the calo seed,walk backward with Kalman filter,and find-or not- a track with similar p_T pointing to the cluster acc=0.3,rej=10

-AND verify existence of a detached vertex (2D-straight tracks inVELO) 0.15< d_0<3mm acc=0.5(includes flight dist) rej=25

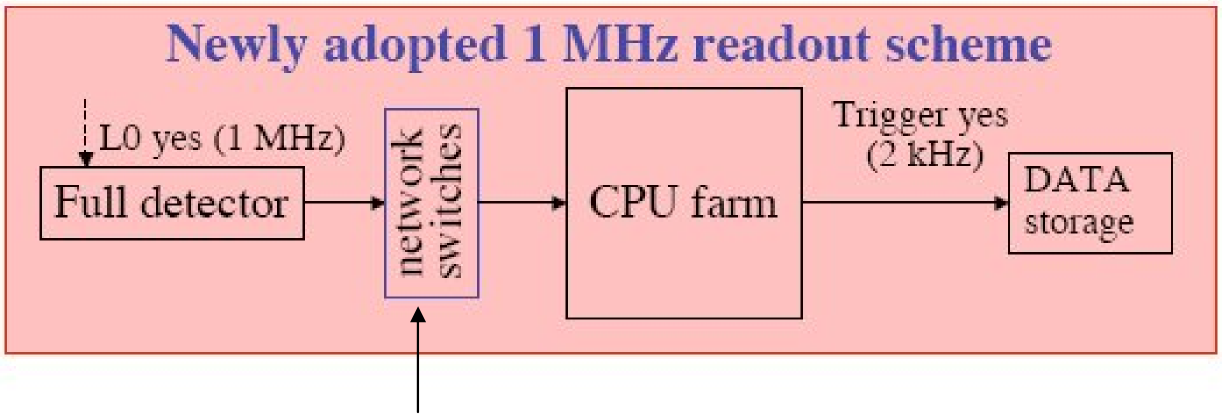
.LVL2(input 40 kHz): reconstruct 3D tracks,use mom,ask for ge.3 detached

.HLT(input 5 kHz) compute invariant masses, apply PID, select phys channels

New approach: (L1,L2,HLT) mixed in a single PC farm

Low PT $\longrightarrow$ start with high rate

LHCb-HLT-DAQ



Rates = 10xAtlas or CMS
Event size = 1/30 Atlas or CMS

With GbEthernet technology

Event size: 52 kBytes / event with safety factor (nominal size 35kBytes)

Data rate: 56 GBytes / second using Multi Event Package

Input link: 727 links, Load $_{max}$<85%

Output link: 530 links, Load $_{average}$~62%

→an example of solutions, Force 10

1260 GbEthernet ports (needed 1257)

150GBytes/sec switching capacity

LHCb performances in perspective (1 year)

Measurement	Channel	LHCb	ATLAS	CMS
β [sin(2β)]	$B^0 \to J/\psi\ K_s^0$	0.3^o to 0.5^o	0.5^o	0.7^o
α [sin(2α)]	$B^0 \to \pi^+\ \pi^-$ (assuming no penguin)	2^o to 10^o	down to 5^o	down to 5^o
α [sin(2α) and cos(2α)]	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$	5^o to 15^o	--	--
$2\beta + \gamma$	$B^0 \to D^{*+}\ \pi^-$	down to 7^o	--	--
γ - $2\delta\gamma$	$B_s^0 \to D_s^-\ K^+$	3^o to 16^o	--	--
γ	$B_d^0 \to D^0\ K^*$	4^o to 18^o	--	--
$\delta\gamma$	$B_s^0 \to J/\psi\ \Phi$	0.6^o	$0.9\ ^o$	
X_s	$B_s^0 \to D_s^-\ \pi^+$	< 90	< 36	< 48
Rare decays	$B_s^0 \to \mu^+\mu^-$ (SM. BR. ~3.5×10^{-9})	4.4σ SM signal	4.7σ SM signal	10σ SM signal
	$B_d^0 \to K^*\ \gamma$	26k evts.	--	--

Particle ID in high P_T reactions(1)

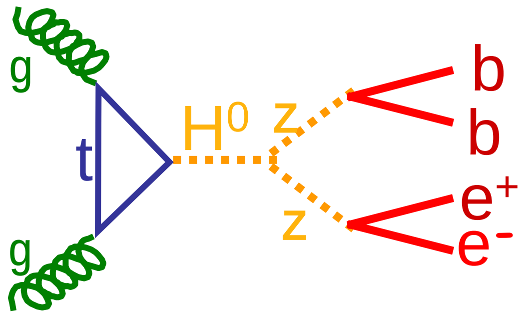
- o Parton reactions,QCD effects
- o Parton fragmentation -jets
- o Showering/absorption in calorimeters
- o ATLAS and CMS design principles

Parton reactions, QCD effects

Exemple of "pedagogical" reaction:
Final state looks simple :

2 b-quark-partons
2 electrons

Each quark-parton will materialize as a jet.



However QCD coupling α_s is large enough that, with sizeable probability:
-further gluon lines are attached to initial gluons (or quarks) = ISR
-gluon lines are attached to final quarks (FSR)

Depending on the random occurrence of ISR/FSR,and on the $P_T$threshold to define a jet, the "bare" graph above will lead to a final state with 2,3,4… Jets (plus the electrons..)

Parton reactions and background

- The "candidate" reaction $gg \rightarrow H \rightarrow ZZ \rightarrow bbee$ is expected to have a σ.BR of ~10 fb if M(H)~150 GeV

- Events with 4 jets or more, of p_T 50GeV ore more are produced with a cross-section of ~30nb from which the candidate reaction should be distinguished. A rejection >>10^6 is needed

    The task is not simple!......

    Fortunately an electron appears extremely different from a jet.....

But

- Among the background are tt events, Zbb events,..containing also b-jets and electrons with a σ BR of ~ 1pb for the former....
- And another problem is pile-up

  In average 7 x 23 x5 ~ 800 charged, and as many neutrals soft particles are produced in any bunch-crossing (at 10^{34}),complicating significantly the electron-jet identification at high luminosity

THREE STEPS for particle ID: Understand the lepton signatures Understand the jet background= fragmentation Understand the experimental effects (resolution, pile-up,..)

Parton fragmentation -jets(1)

Two main quantities of interest:
-transverse momentum of fragment/jet axis.
-fraction x of longitudinal parton momentum taken by fragment.

Best info from e+e- ,in particular LEP/Z^0

$$F^h(x,s) = \frac{1}{\sigma_{\rm tot}}\frac{d\sigma}{dx}(e^+e^- \to V \to hX)$$

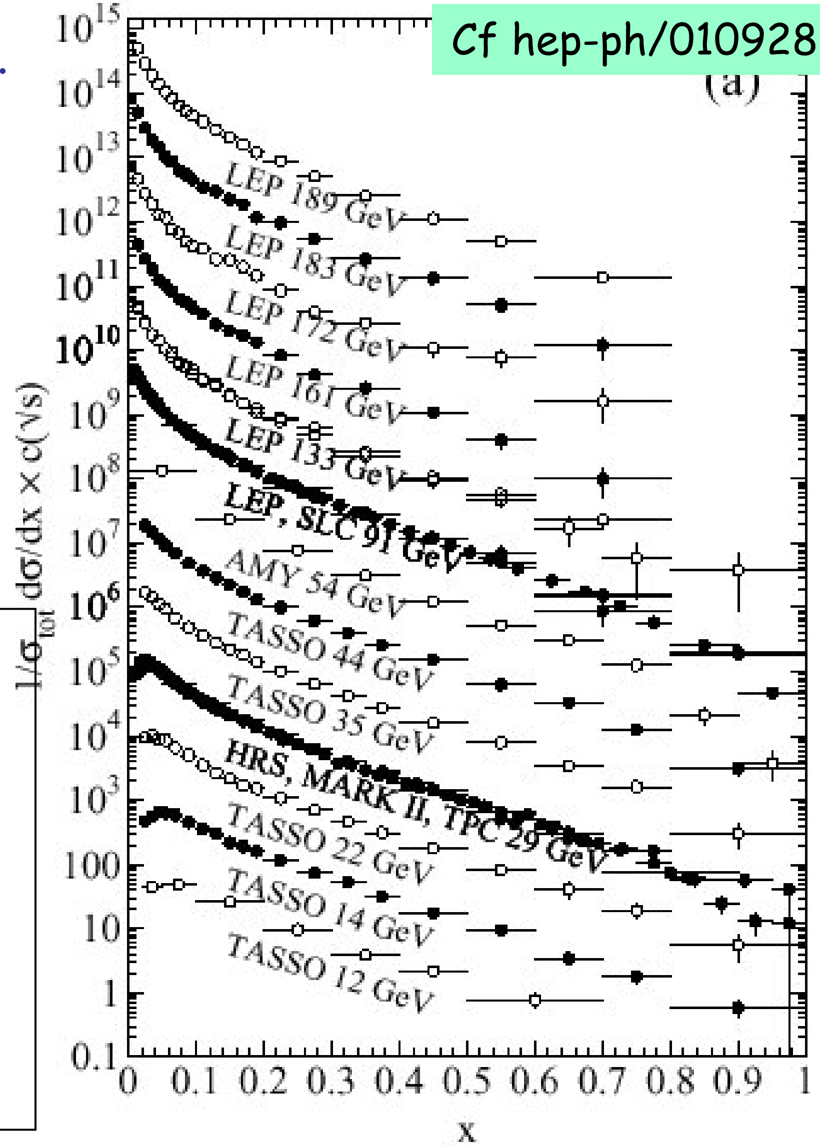
$$F^h(x,s) = \sum_i \int_x^1 \frac{dz}{z} C_i(s;z,\alpha_s) D_i^h(x/z,s) .$$

$D^h_i(x/z,s)$ = parton fragmentation function
In lowest order $C_g=0$, $C_i=g_i(s)\,\delta(1-z)$

Evolution of D(x,t) - increase at low x- is reproduced by DGLAP equations.

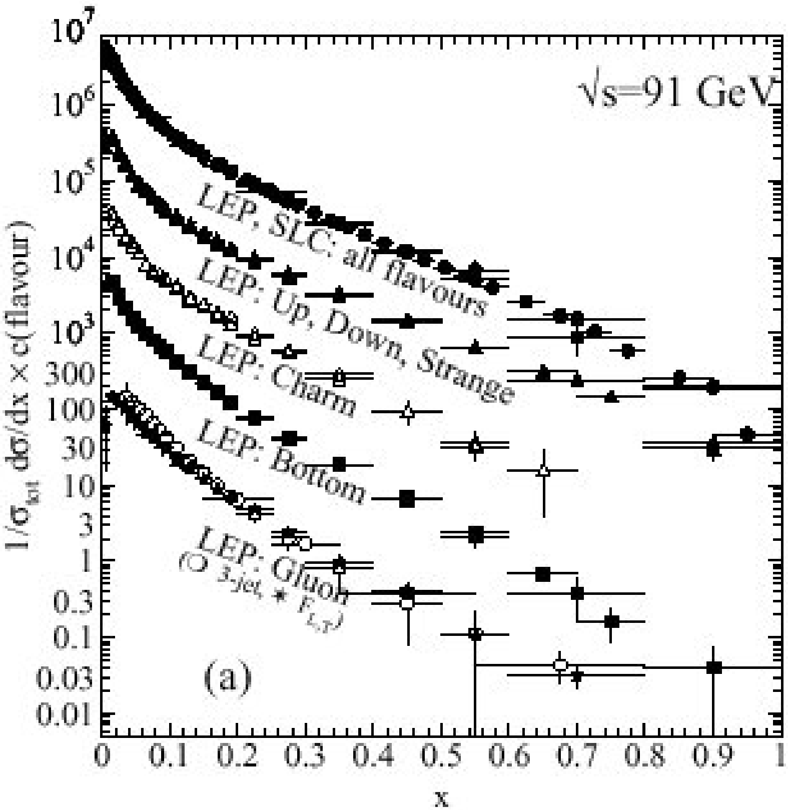
This effect governs multiplicity increase (at the Z0 pole <Nch>=20)

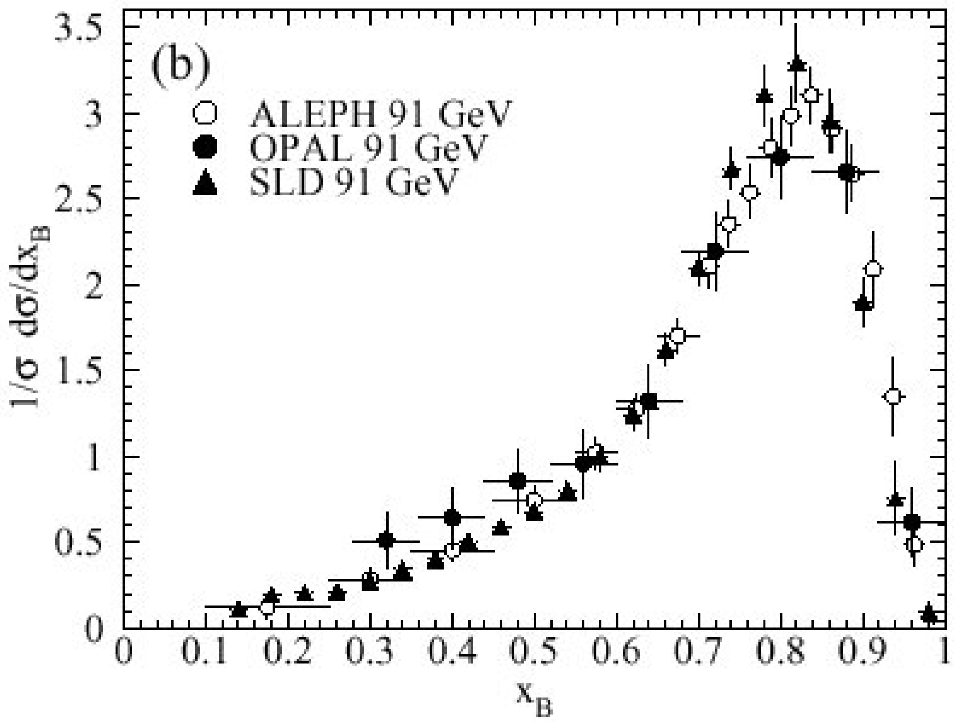
Cf hep-ph/0109282



Parton fragmentation (2)

Flavor tagging allowed to separate charm jets, bottom jets,and also Gluons jets as “third jet” in bbg 3 jet events.
Gluon fragmentation also from $\sin^2(\theta)F_L(x)$ term in $d\sigma/dx d\cos(\theta)$:
$1/\sigma\ d^2\sigma/dx d\cos(\theta)=3/8(1+\cos^2(\theta))F_T+3/4\sin^2(\theta)F_L(x)+3/4\cos(\theta)F_A$
$\rightarrow$b jets and gluon jets give softer particles than light quarks
$\rightarrow$however fragmentation of b parton in b hadron is very hard





Parton fragmentation (3)

Monte-Carlo modelisation : string model

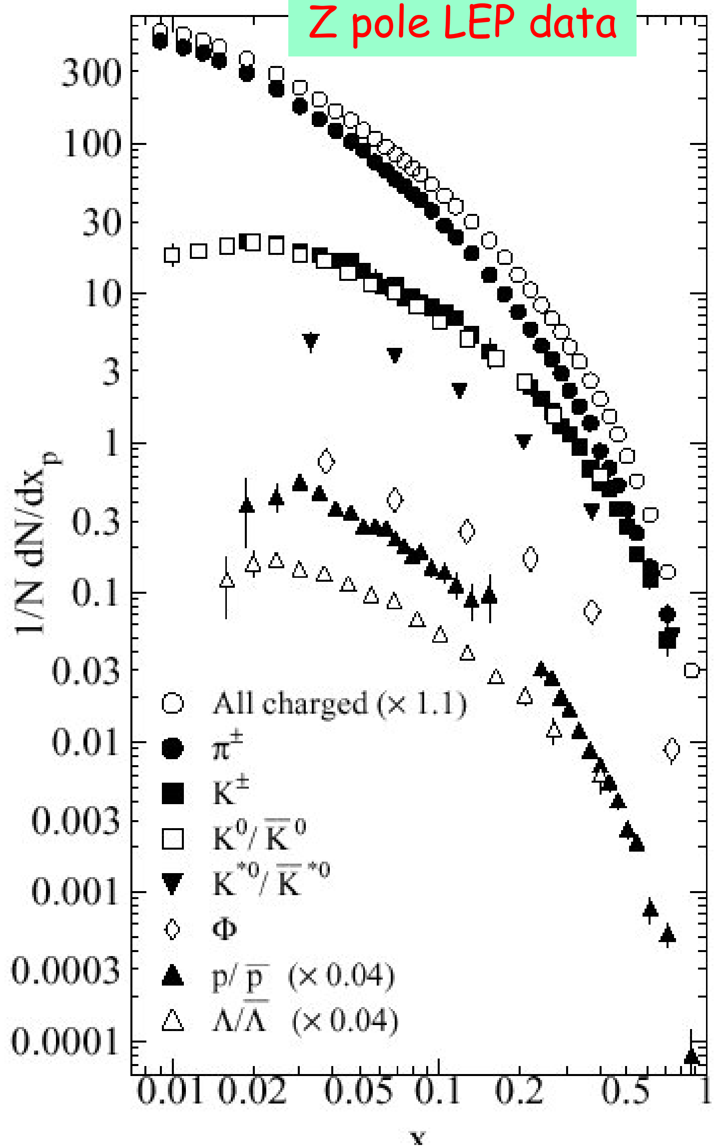
A string representing the QCD colour field
is "stretched' between partons:

If energy stored is sufficient:
A qqbar pair is emitted from vacuum

P(pair creation)α exp-($-\pi m^2_{qT}/\kappa$) where
κ=string tension ~ 1GeV/fm
$m^2_{qT} = m^2_q + p^2_q$
$f(z)=1/z(1-z)^{\alpha}$ exp-(bm^2_{qT}/z)
heavy hadrons-even kaons-
heavily suppressed

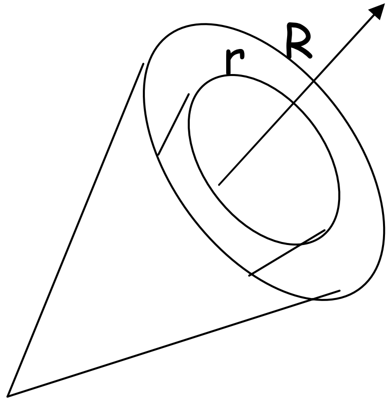
When x$\rightarrow$1 the jet has only one hard particle,….plus pile-up

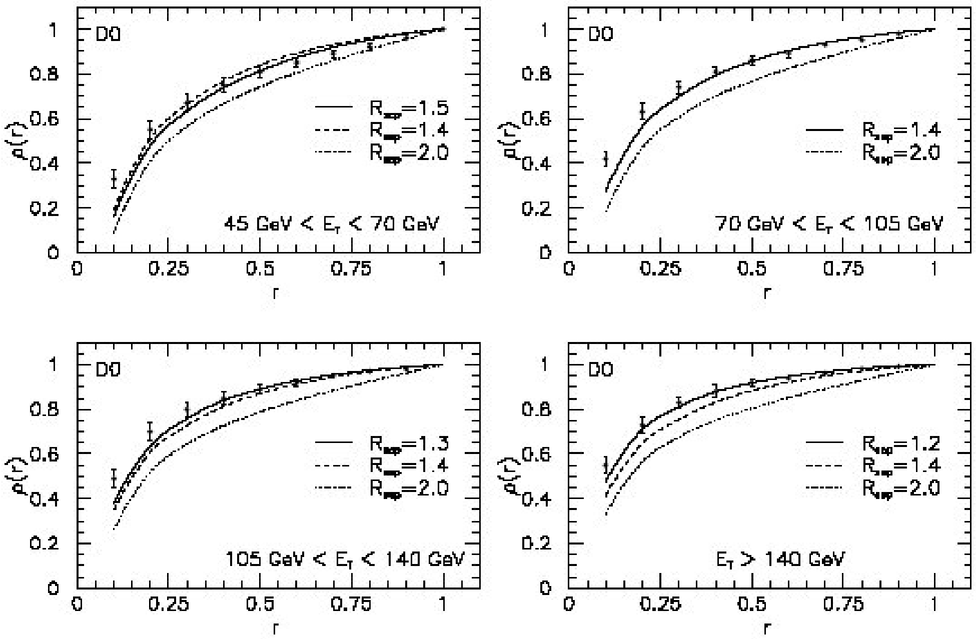
Z pole LEP data



Parton fragmentation (4)

- The transverse momentum structure of a jet is analyzed measuring the fraction ρ of energy contained in a cone of radius r as compared to a radius R taken as reference.
- Data from HERA and Tevatron are well reproduced by NLO calculations.
- Jets defined in this way (cone) vary only slowly in shape with E_T





D0 data
NLO calculations
Separation between jets as parameter

Showering in calorimeters

Particles from the jets go through the “light” tracking systems with a minimum of interactions. Then showering in calorimeters starts

Two rather well separated processes take place:

Electromagnetic showers: photons(prompt or from π^0,..)electrons

Hadronic showers: charged pions, kaons, nucleons,,,from jets

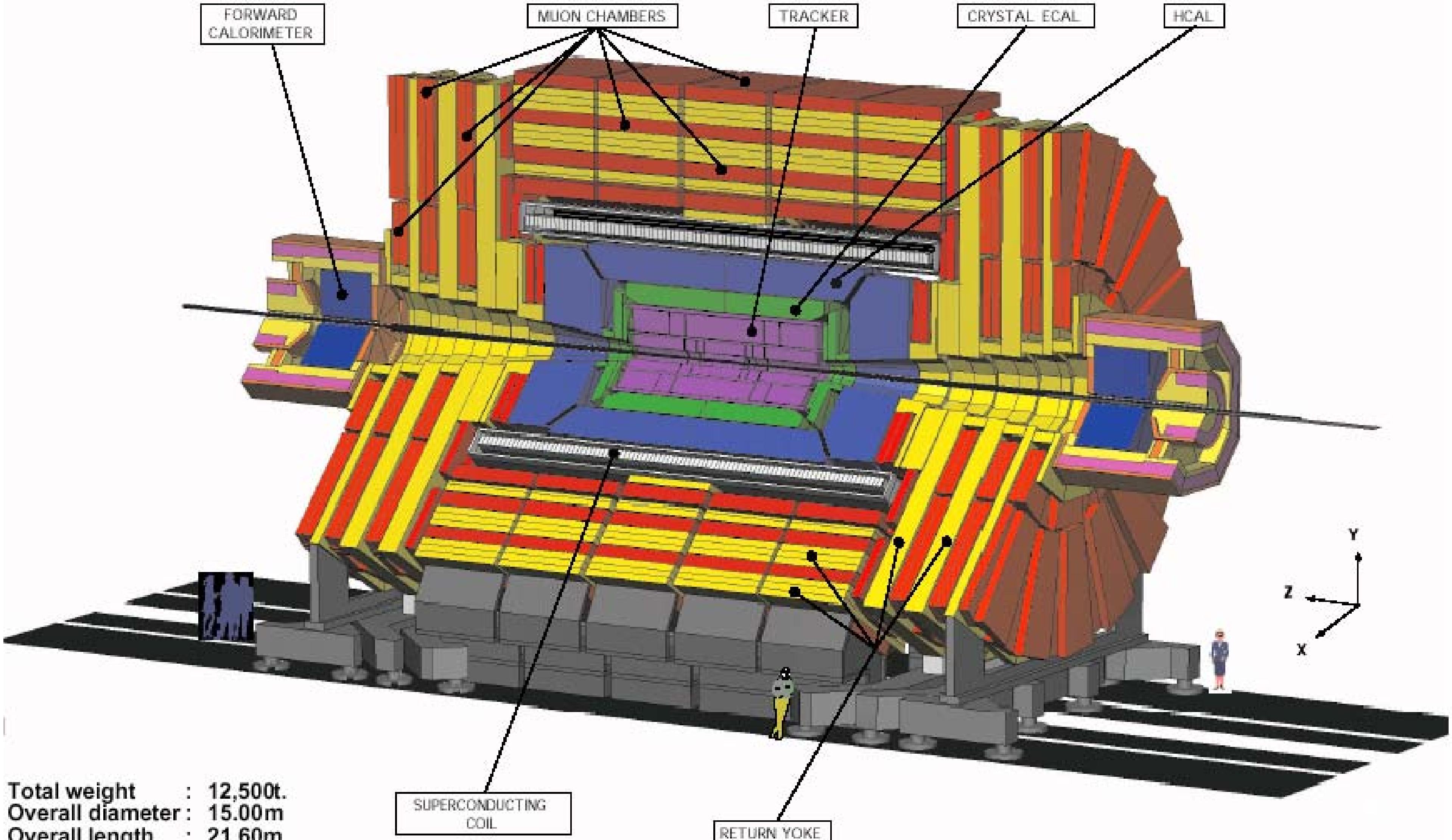
While the hadronic shower develops, secondary π^0 π^+ π^- are produced with equal probability (isospin invariance), and thus a hadronic-initiated shower develops an EM component.

The reverse is not true: an EM initiated shower remains EM (to ~10^{-3})

Muons ,like electrons have “only” EM interactions, but at a much reduced rate due to the $(e^2/m)^2$ factor in radiative cross-sections: Except at the highest energies they “happily” cross through several meters of iron.

$\rightarrow$This gives a robust way of identifying them.

CMS
A Compact Solenoidal Detector for LHC

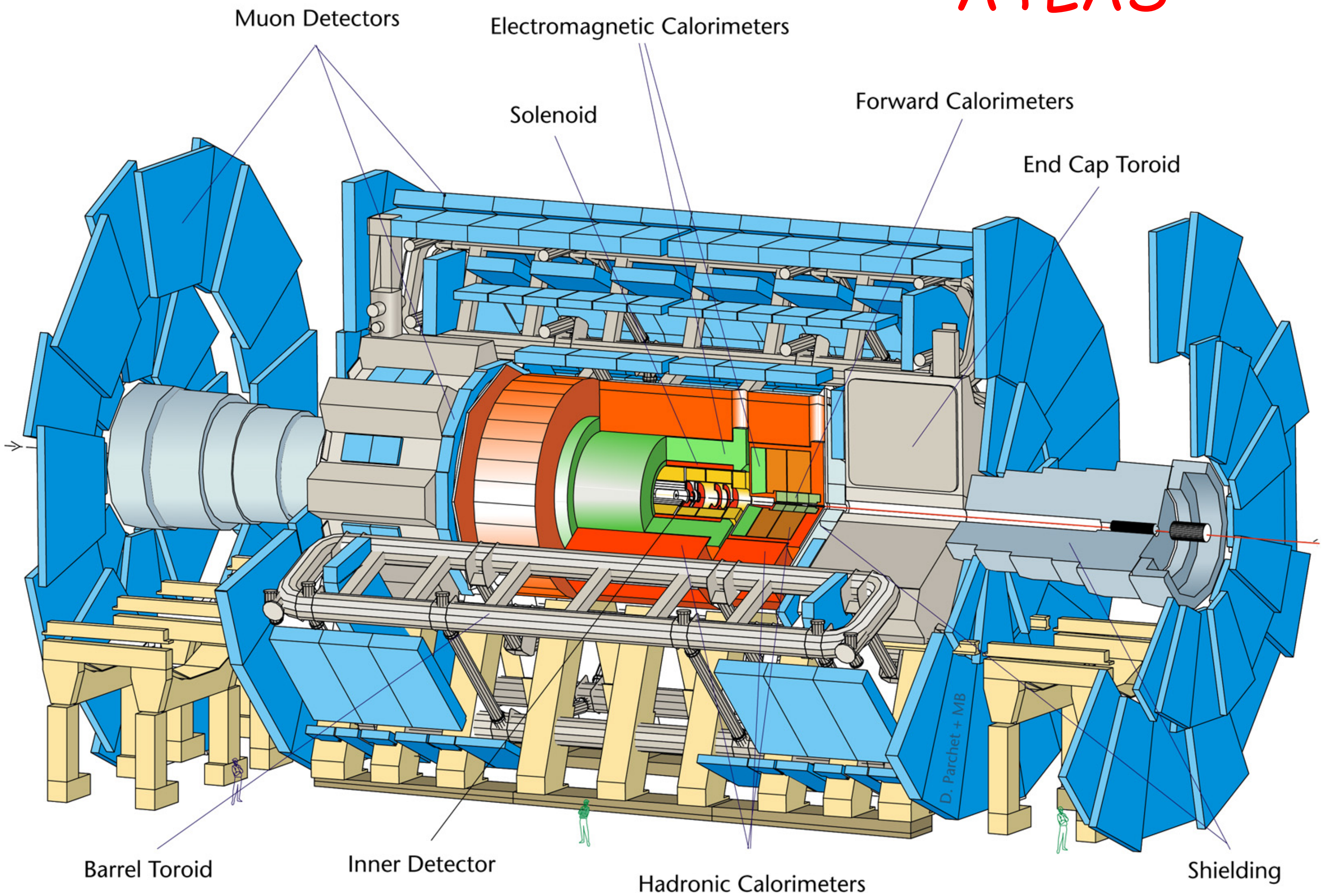


Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

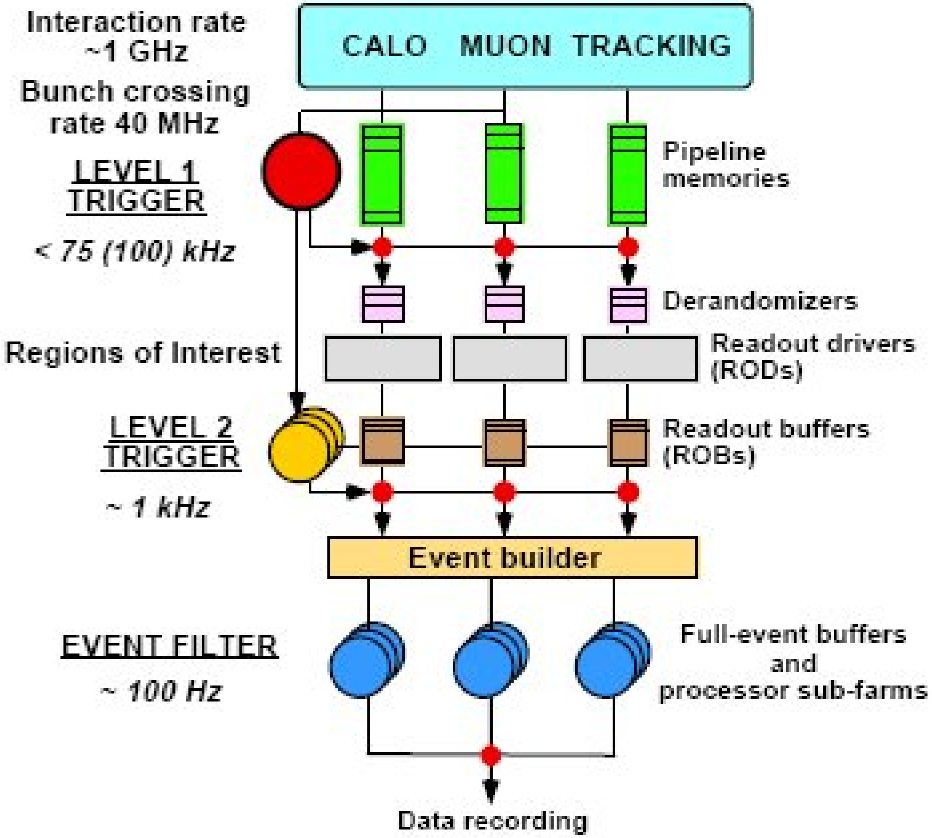
CMS-PARA-001-11/07/97 JLB.PP

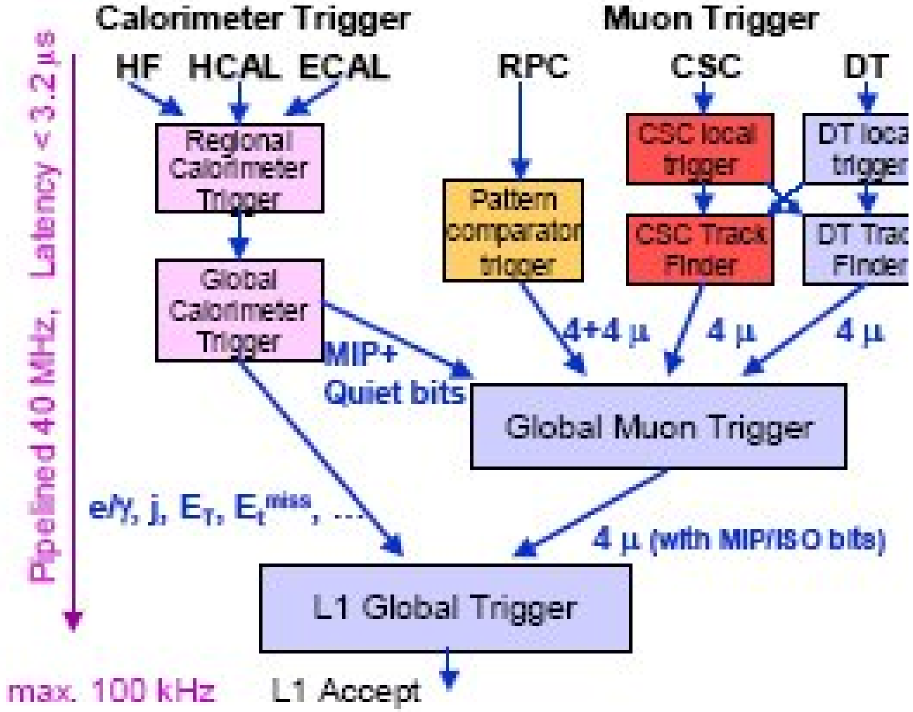
D712/mb-26/06/97

ATLAS



Pipelined-multilevel-triggers





40 MHz LVL1 100 kHz (LVL2+LVL3) 100Hz

synchronous 3 µs asynchronous

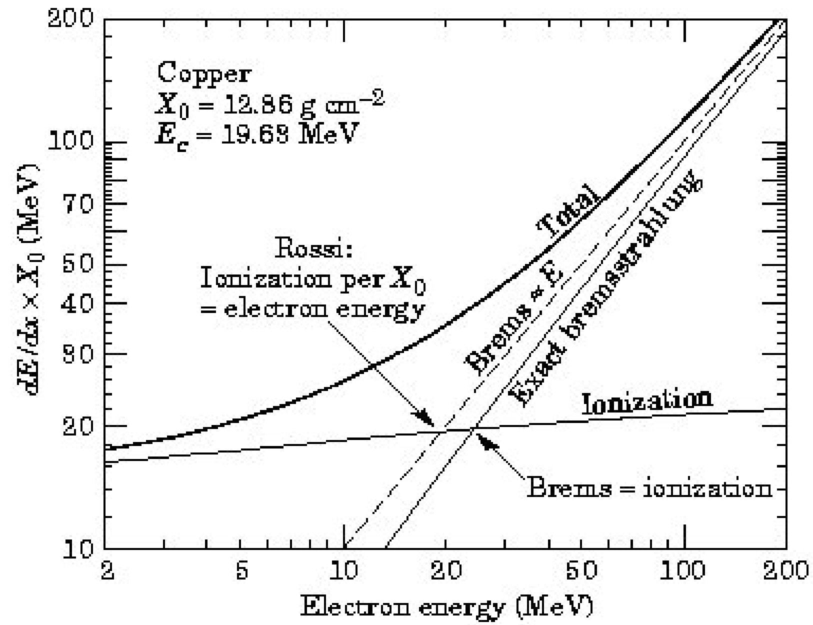
EM showers(1)

High energy photons and electrons interactions with matter are governed by the radiation length :X_0(g/cm²) =716 A/Z(Z+1)log(287/ √Z) (lead X_0 = 6 mm)

- Electron bremsstrahlung $\langle E_{electron} \rangle$ after l : $E=E_0 \exp(-l/X_0)$
- Pair creation: mean free path of photon=9/7 X_0

At any energy electrons are subject, like any other charged particle to energy loss by ionisation (and Cerenkov if v/c>1/n)

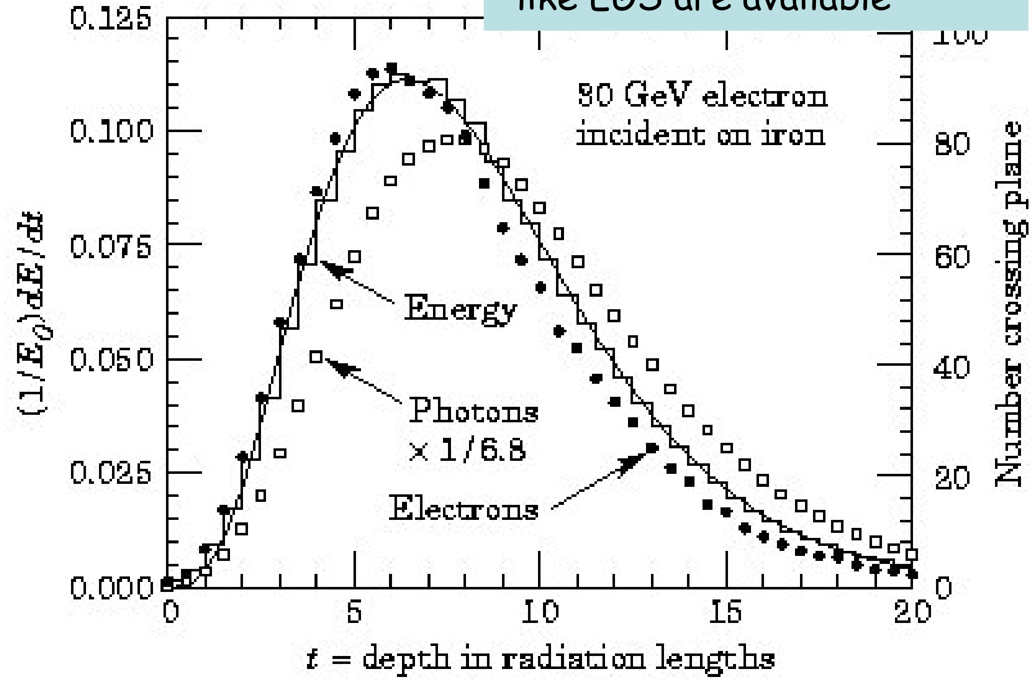
- The energy where the two losses are equal is the critical energy Ec.
- The process of bremsstrahlung remains dominant until E~Ec
- Small values of Ec and X_0 give better sampling calorimeters. For lead Ec=7MeV

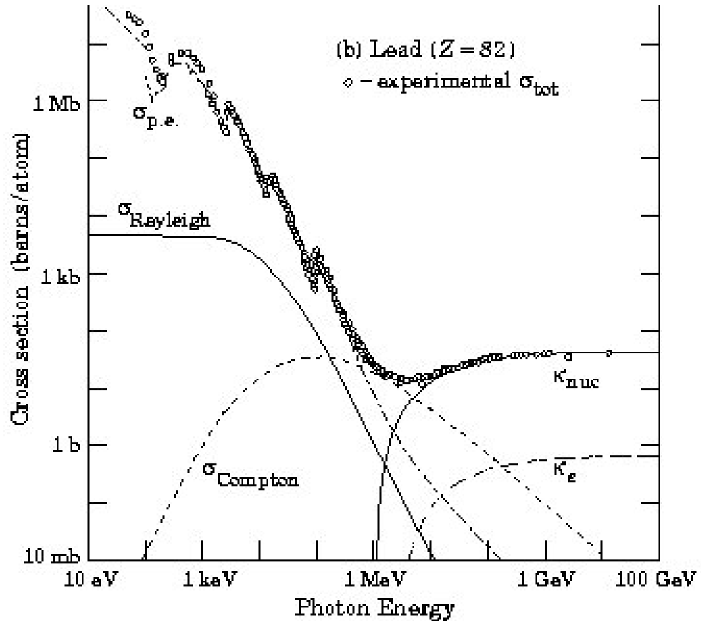


EM showers(2)

- The longitudinal profile of showers expressed in X_0 is almost material independent, and depends only logarithmically of E
  ~30 X_0 (18 cm lead equivalent)is enough to absorb a TeV EM shower
- The transverse profile is driven by multiple scattering (Es=21 MeV) of electrons. It is almost energy independent, and characterized by
  $R_M = X_0 Es/Ec$ the Moliere radius , proportional to the material density
- At high enough energy EM shower fluctuations in shape&size are limited

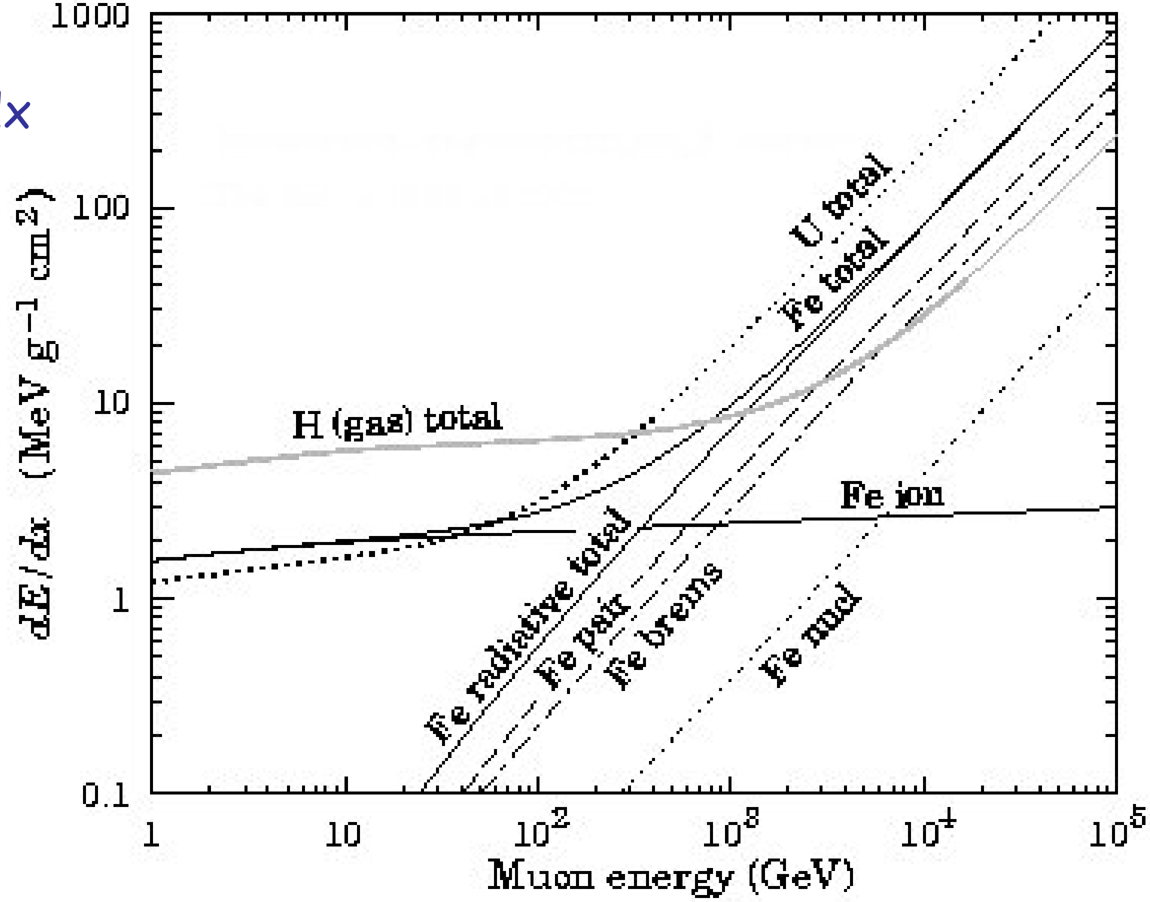
High quality simulation codes like EGS are available





High energy muons in material

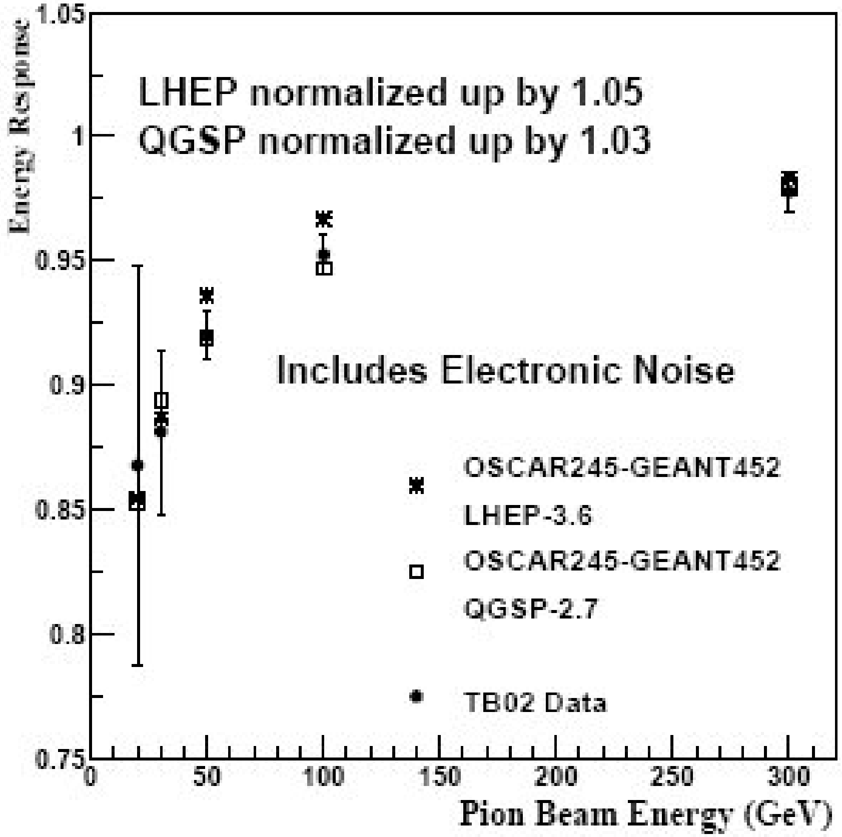
- At high E radiative dE/dx (prop to E) becomes larger than ionisation dE/dx.
- In iron the cross-over (critical energy) is around 200 GeV

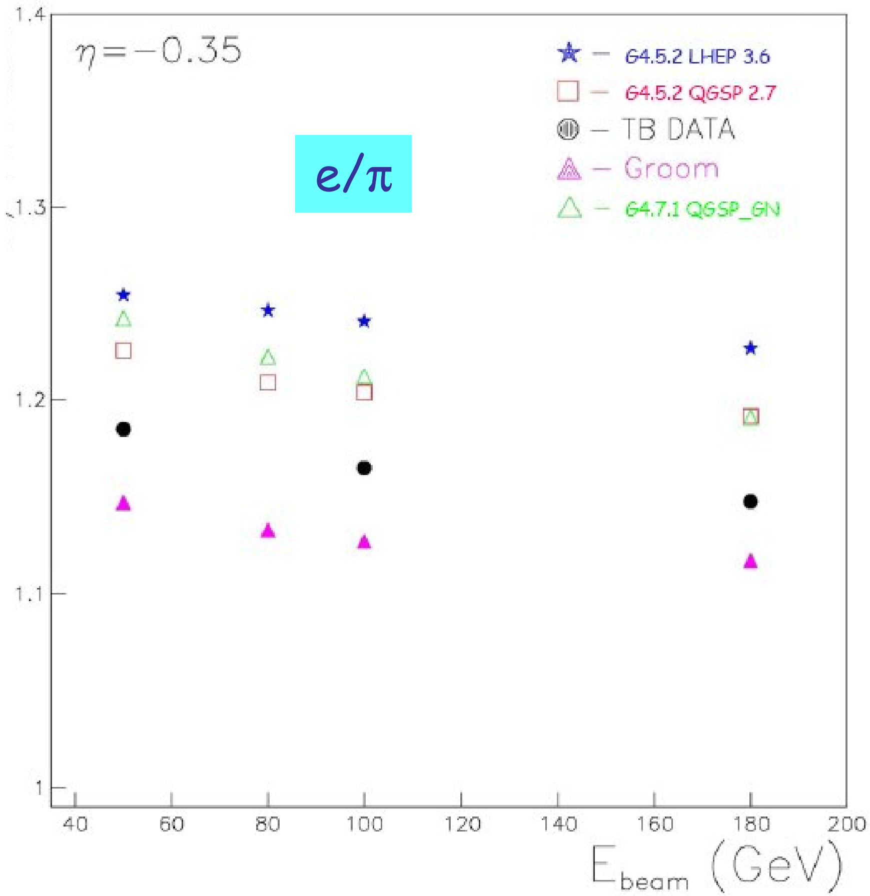


Hadronic showers(1)

- Theory of hadron-nucleus collisions not able to reproduce data ,with multiparticle final states in a reliable way. Rely on models interpolating tabulated cross-sections,
- Analog of X_0 is the interaction length λ,mean free path before the next inelastic collision of a hadron. λ goes with $A^{1/3}$.
- In general $\lambda > X_0$. For iron(lead) λ =17cm(18cm),X_0 = 17,6 mm(6mm)
- Hadronic interactions are more "inelastic" than EM ones,and ~12 λ are enough to absorb a TeV pion
- The choice of material is dictated by density, cost, ease of machining, (non) magnetic properties (copper/iron),..
- In general a hadronic calorimeter is "non-compensating" ($e/\pi > 1$). This is an important limitation which –to some extend- can be alleviated using (depleted) uranium as an absorber.
- Transverse behavior in showers is dominated by p_T of hadronic process
- Monte-Carlo simulations not yet at the level of EM ones. Geant4/LHEP,Geant4/QGSP, FLUKA,...

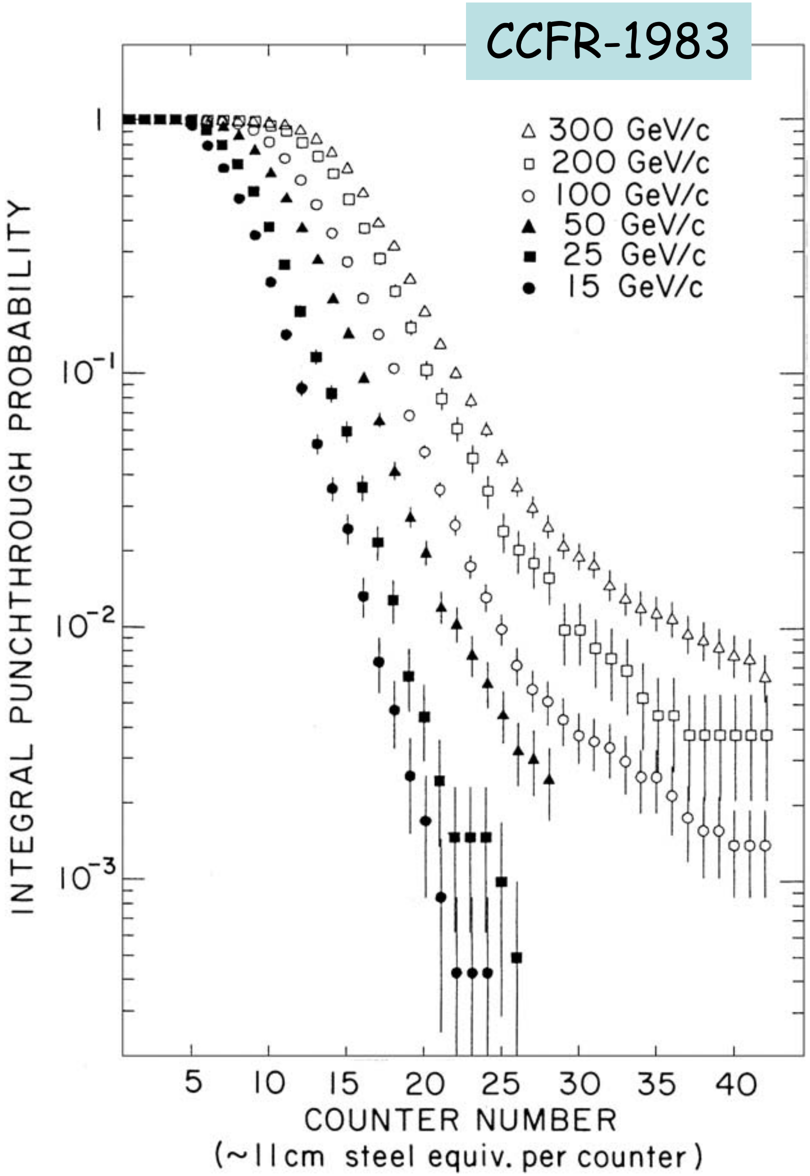
Hadronic showers(2)



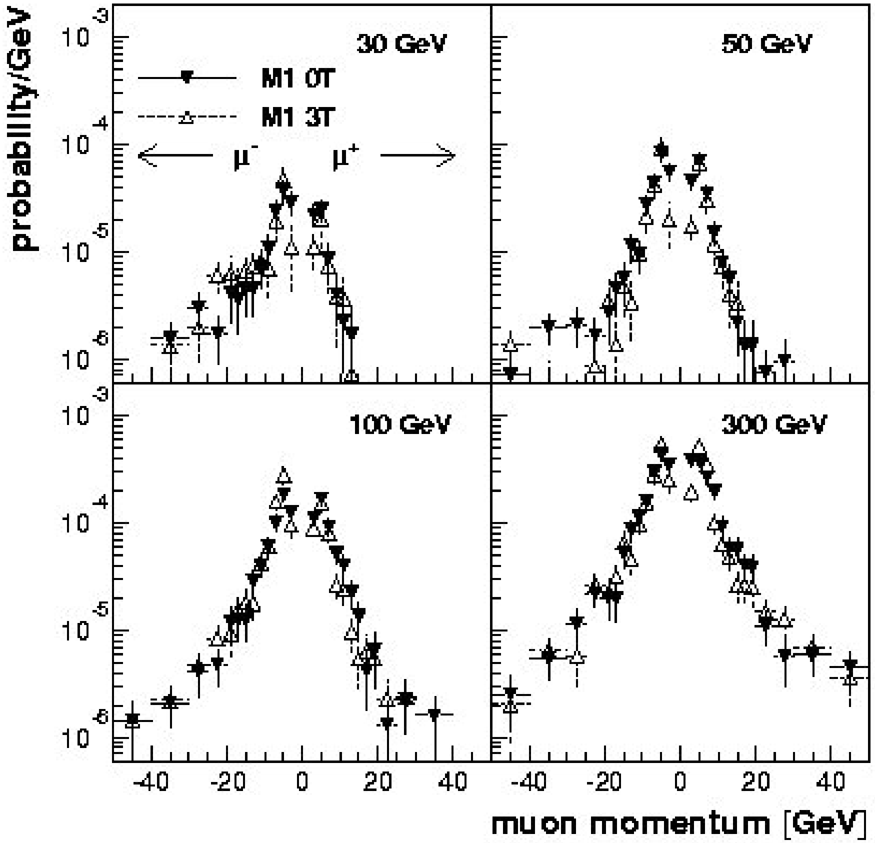


CMS(left) and Atlas Scintillator Had calorimeter response compared to Geant4

Hadronic showers(3) -tails



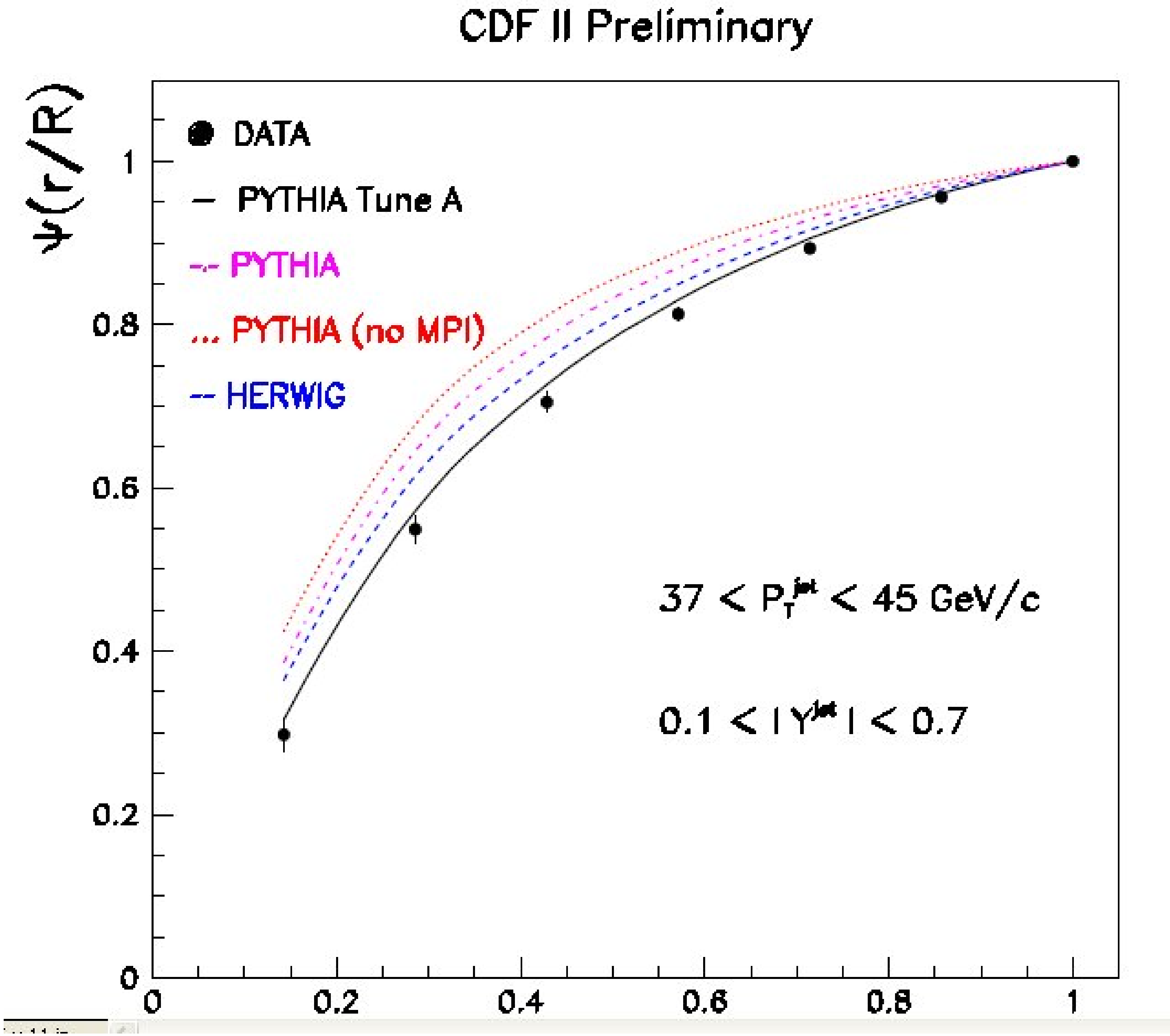
"punch-through"
probability of π^+ after 10λ
as measured by RD-5



To-morrow:

Muons
Electrons
Photons

Back-up transparencies



CDF II Preliminary
ψ(r/R)
DATA
PYTHIA Tune A
PYTHIA
PYTHIA (no MPI)
HERWIG
37 < P_T^jet < 45 GeV/c
0.1 < |Y^jet| < 0.7
0
0.2
0.4
0.6
0.8
1

Some LHC parameters (1)

- RF frequency 400.790 MHz
- Synchro signal TTC to experiments at f/10 in phase with bunch crossings
- Bunch collisions every 25 ns (train of 2808bunches of ~10^{11} p + some holes)

- Nominal high luminosity intersections(ATLAS & CMS): β^*=50cm

  $L=10^{34} \rightarrow$ in average 23 collisions per bc (Poisson)

  (meaning the average collision rate is close to 1 GHz)
- First year nominal luminosity: 2 10^{33} ie in average 4 collisions per bc

  (In 2007 luminosity will be significantly less ,with less bunches in the machine,ie for example 75 ns between crossings, which is good for timing)

  Main worry is safety (beams for 10^{34} carry 360 MJ)

- Transverse size of beam spot ~ 15 microns x and y
- Longitudinal size of collision area σ= 6 cm at injection increasing to ~9cm at end of fill (~10hours)

Quark-gluon plasma conditions