Particle Identification at the LHC

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- o Proton-proton and heavy-ion collisions
- o Soft and hard processes
- o Underlying physics objectives
- o Identification methods in context
- o Detector specific features
- o Trigger aspects

Outline

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

Introduction

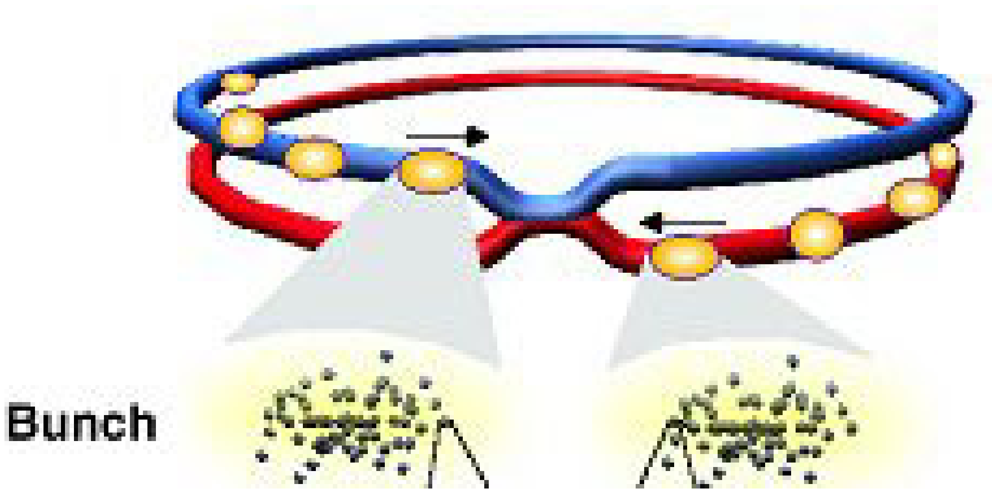
- LHC parameters
- Cross-sections at $\sqrt{s}$=14 TeV
- "Particles" in soft and hard collisions

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 2835bunches 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
- Transverse size of beam spot ~ 15 microns x and y
- Longitudinal size of collision area σ= 4 cm at injection increasing to ~6cm at end of fill (~10hours)



Collision angle: 0.2 mrad
4 intersection regions.

Some LHC parameters (2)

- 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 displaced vertices
- 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

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

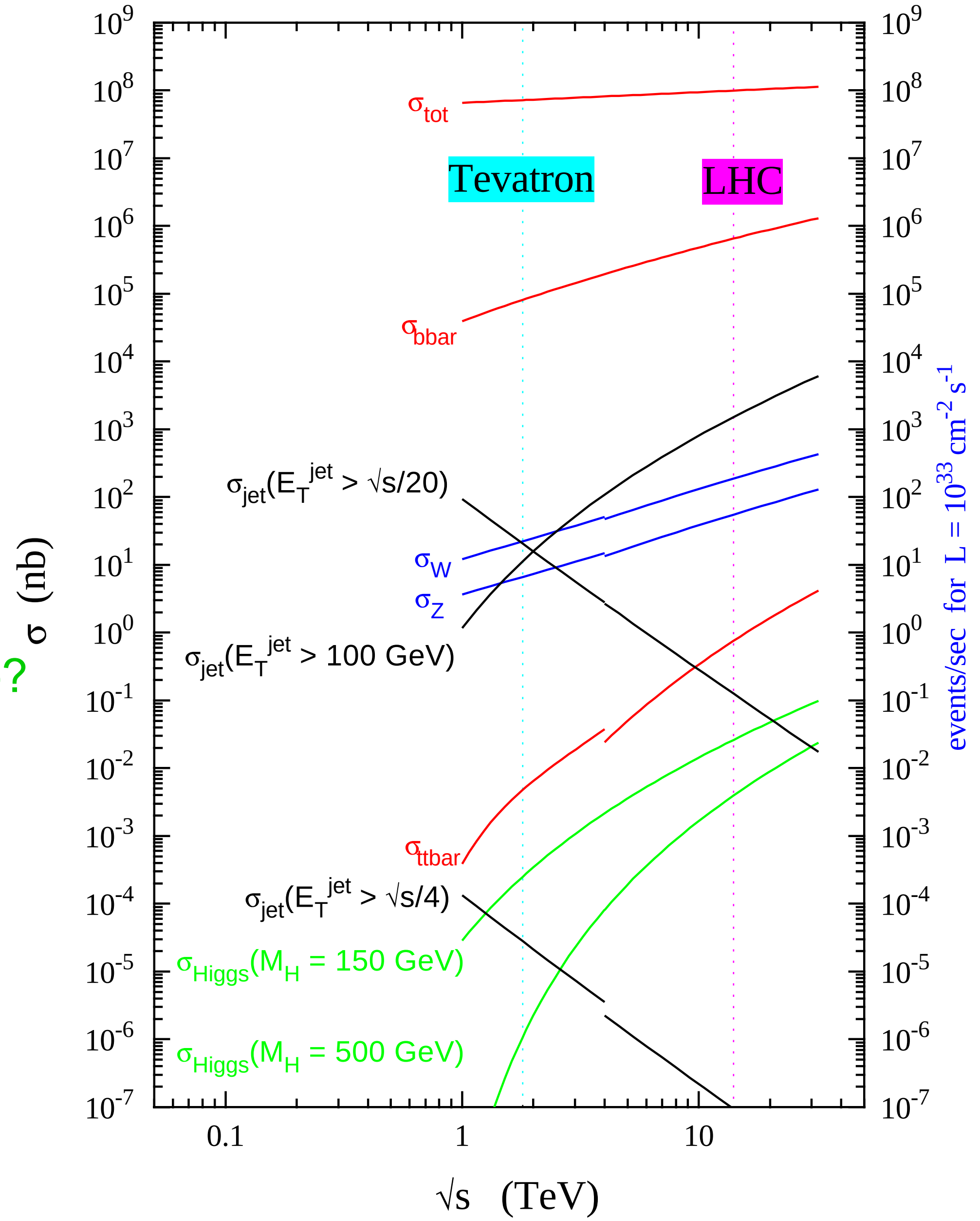
Cross-sections

- 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 trigger,.. **~30 GeV/c**

- Jet-cross section above a fixed E_T increases fast with energy $\rightarrow$QCD Background to e,μ from W/Z decays becomes worse at LHC as compared to Tevatron!

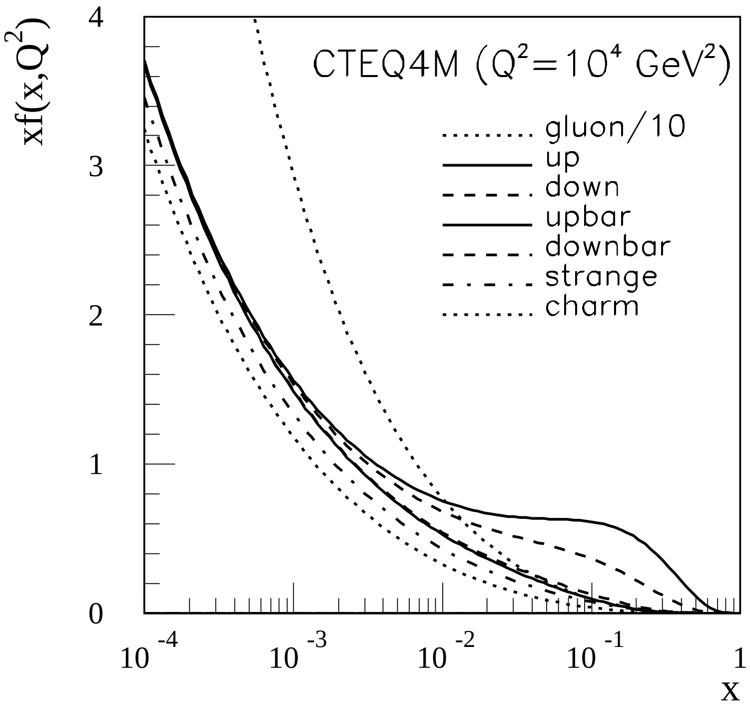


Parton-parton collisions

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 $\tau = x_1x_2$

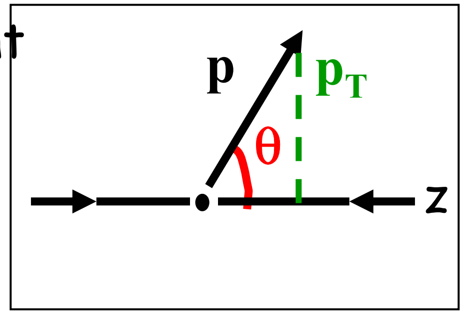
$$\tau dL/d\tau = \int_\tau^1 G(x,Q^2)\, G(\tau/x,Q^2)dx/x$$

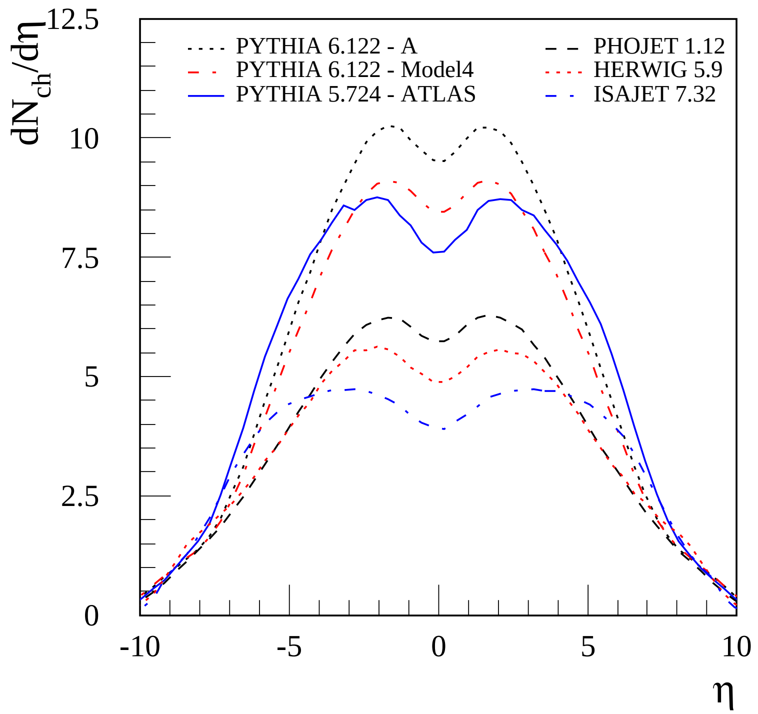
Minimum bias events

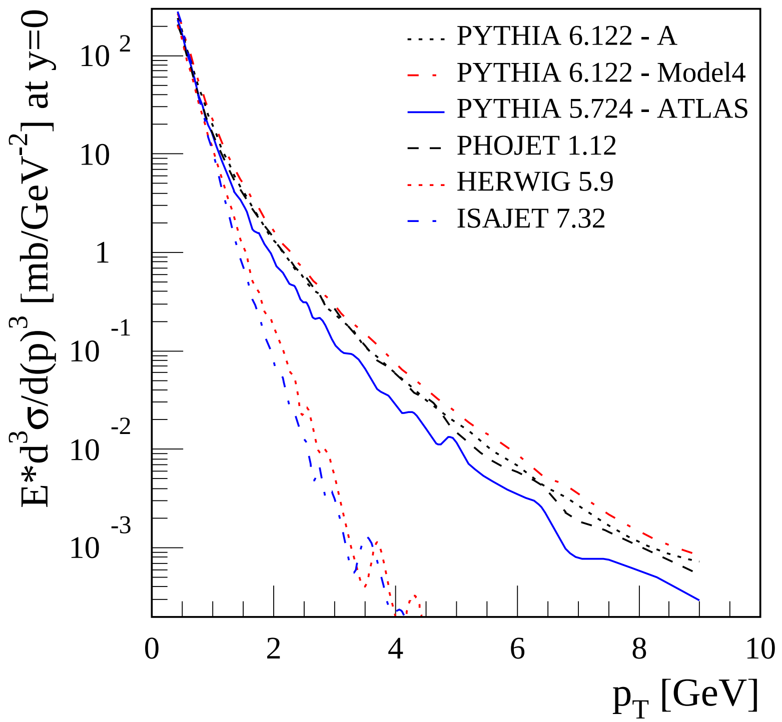
- Most collisions are peripheral, without hard scattering.
- Soft particles (mostly pions)are produced with a constant density in pseudo-rapidity $\eta = -\log(tg(\theta/2))$

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

  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





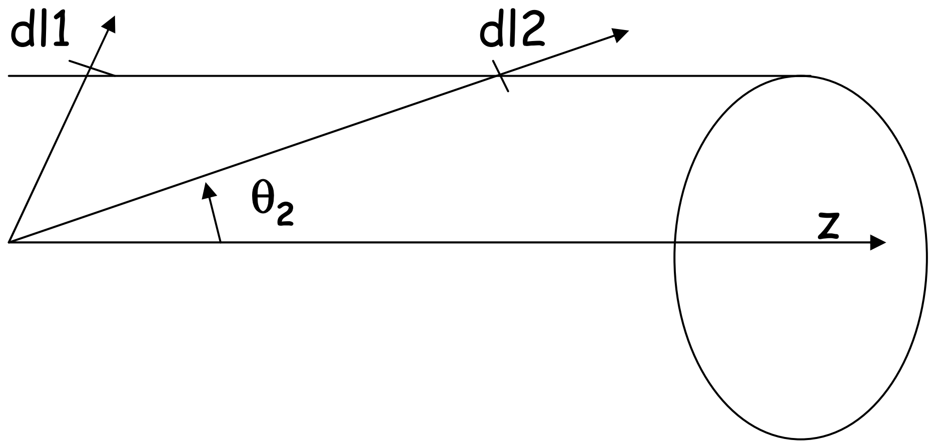


Constant dη detector elements

Elements of fixed transverse size, aligned along a cylinder, correspond to a constant dη

→the flux of particles they intercept is independent of z

(but the energy intercepted increases as $1/\sin(\theta)$)



dl1=dl2 → dη1=dη2

“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 (178+-5)
	Down	S~0.1	B ~4.2

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 $e\nu$: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.

Pion/kaon/proton ID in Alice and LHCb

- Soft particles in Pb-Pb collisions
- The Alice TOF
- The Alice TPC
- The Alice HMPID
- B decay to $\pi\pi$,πK,KK
- LHCb Cerenkov system and HPD readout

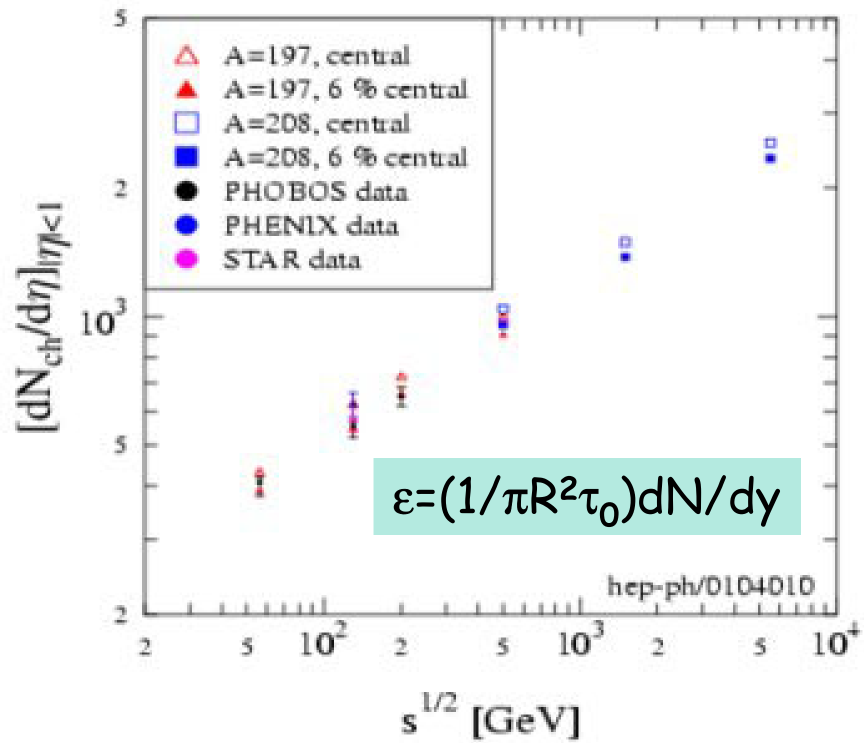
Soft particles in lead-lead collisions

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 great 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.

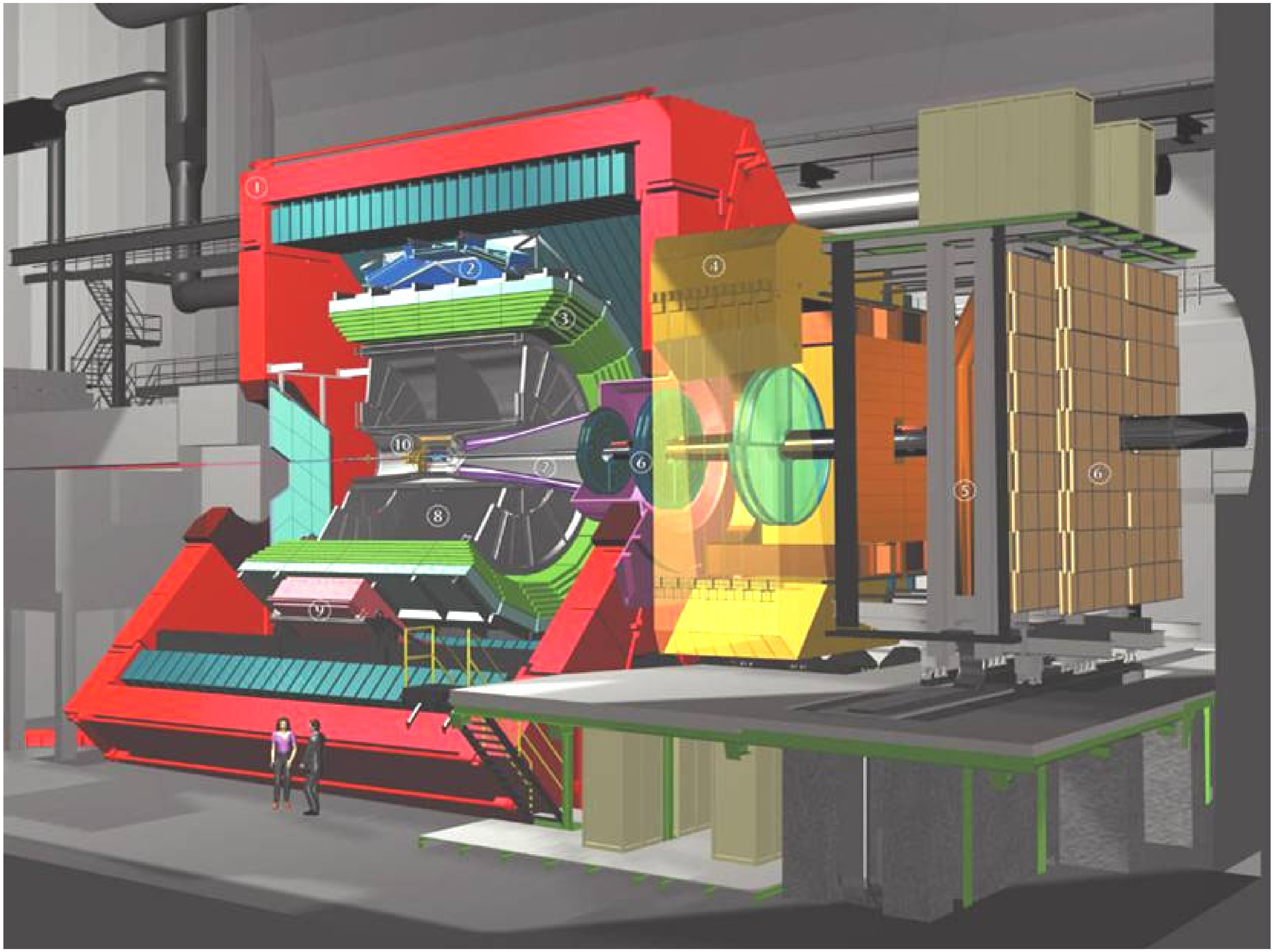


This last part is best studied with soft particles . Important observables are:

- **Nature of produced hadrons (fraction of strange part,)**
- **Transverse momentum spectrum**
- **Intermediate states (resonances like ϕ→KK),….**

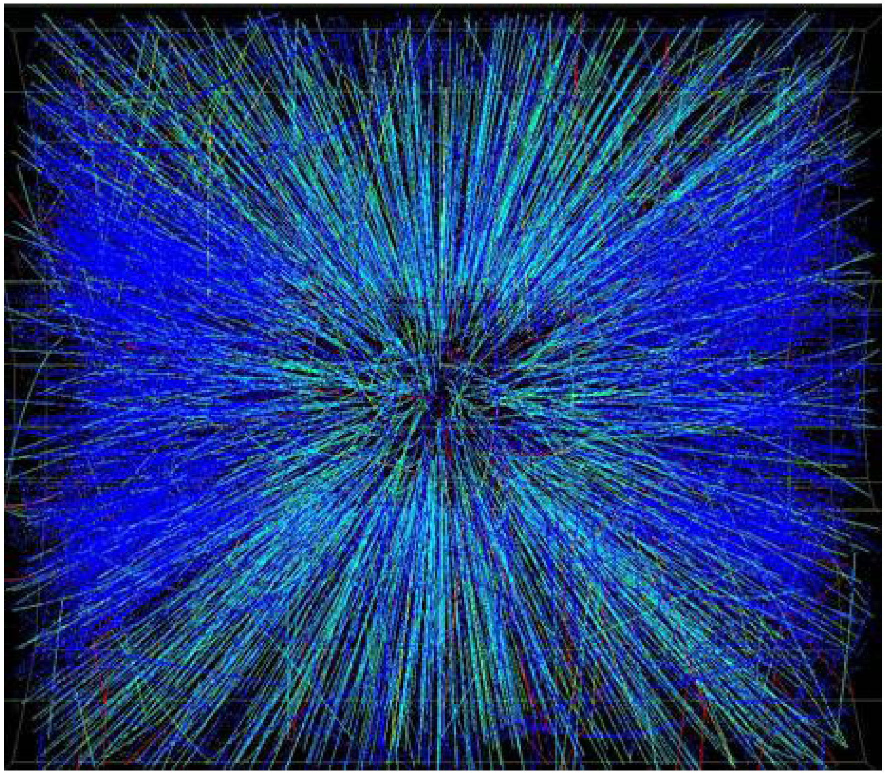
→ALICE aim at 3σ π/K/p ID in the 0.1 GeV to "few GeV" range

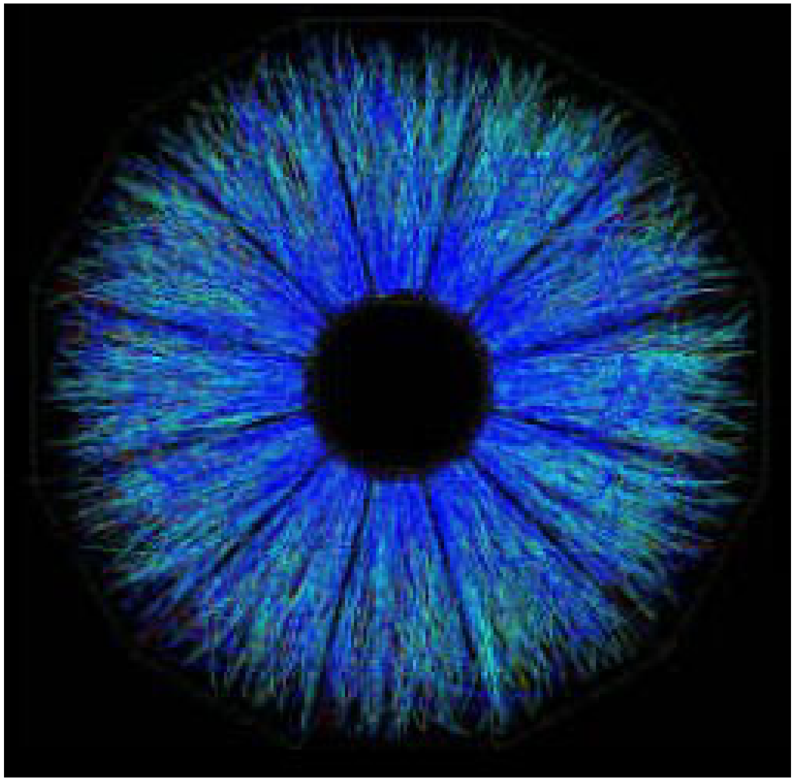
ALICE Detector



Pb-Pb total Xsection= 8barns → 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

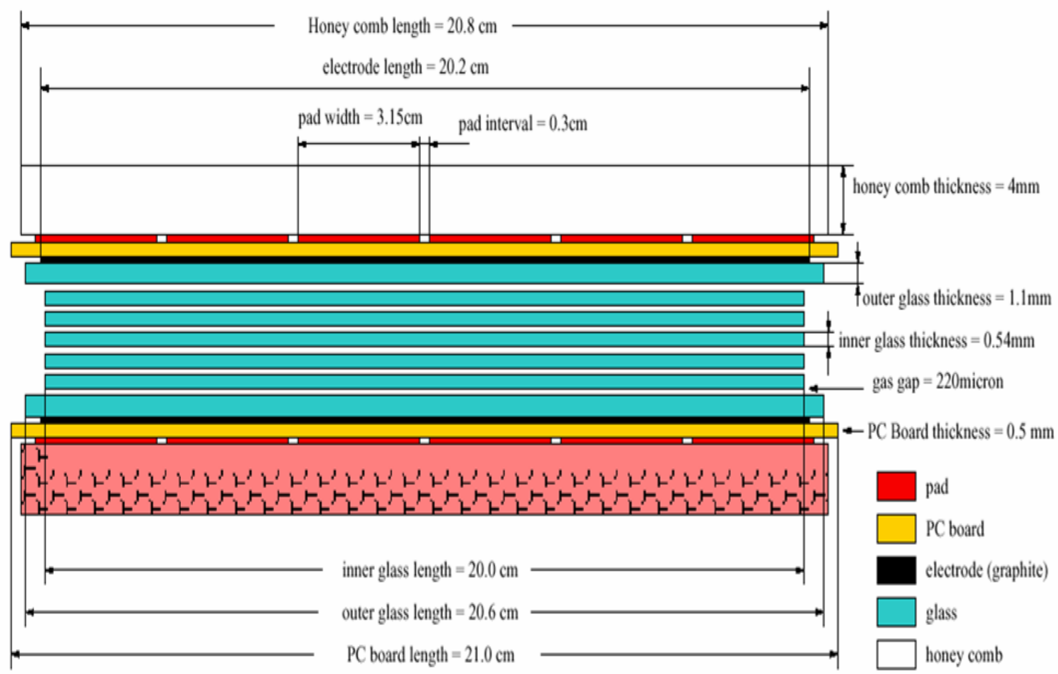
-only one collision/bc in Pb-Pb →average of fast tracks better

Selected technology : MRPC

cheap →large area : 170 m^2 (R_{TOF} = 3.7 m)

Accuracy: ~ 60 ps

prototype tested successfully in STAR



The Alice TOF(2)

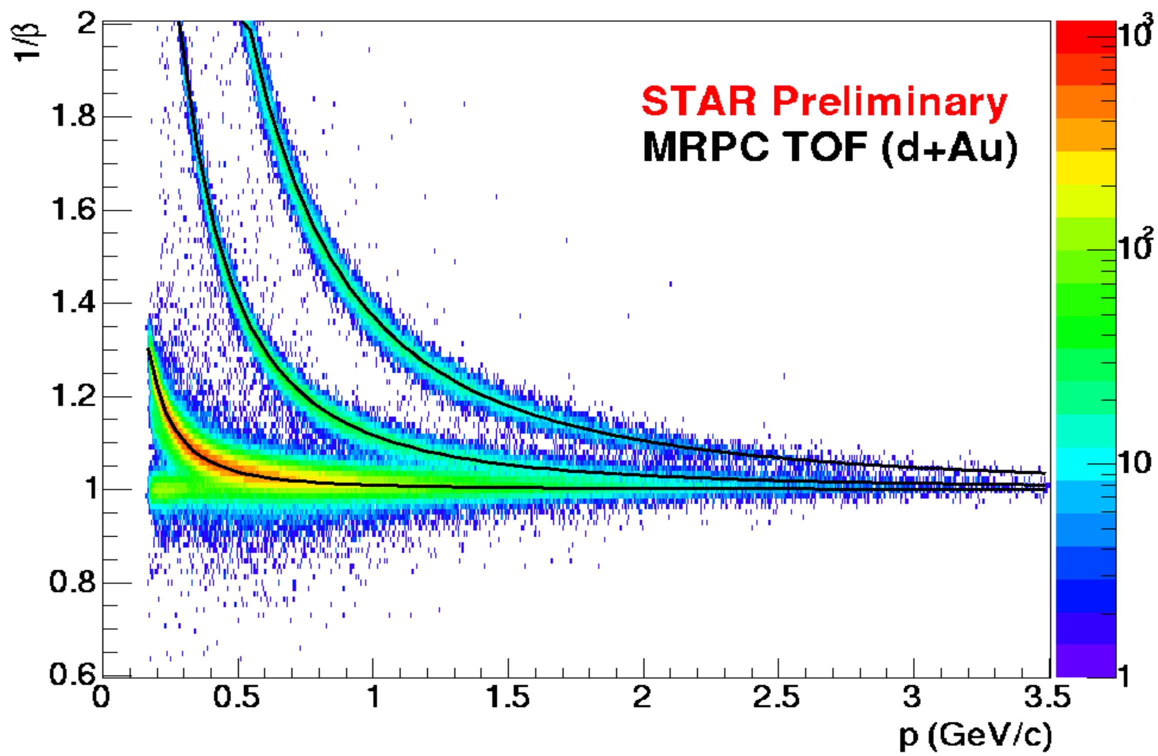
RPC: "micro-spark" chamber: no wires ; Gas: $C_2H_2F_4$ / isobutane / SF_6

Resistive electrodes prevent spark to grow→reasonable rate possible(kHz/cm^2)

Fast: few ns. Become faster with smaller gap (250 microns)

Efficiency requires few mm gases →multigap

Signal picked-up by pads(fast signal traverses resistive layers);~ 10^5 channels



Visible: e, π, K, p

The Alice TPC (1)

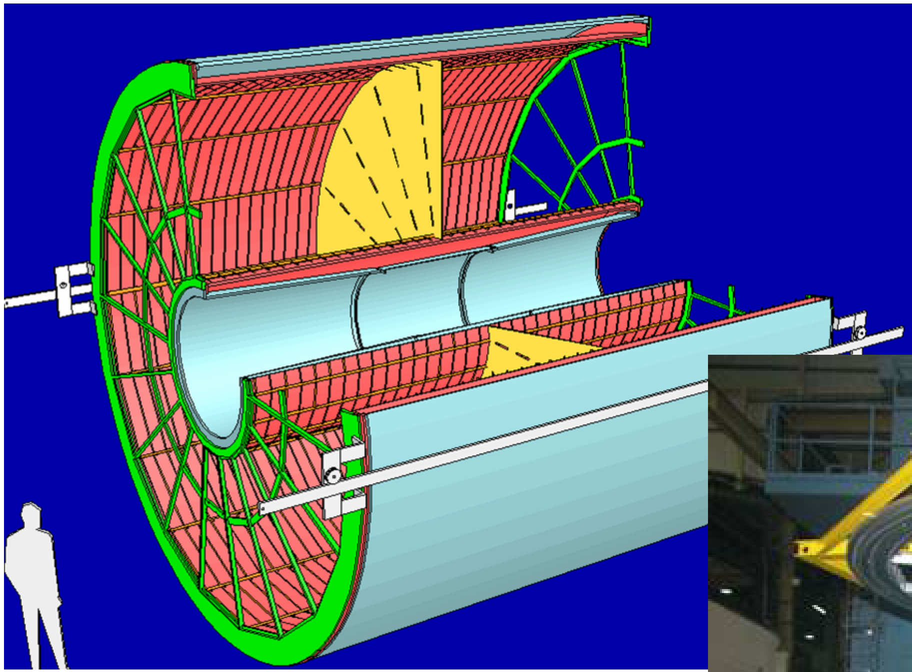
- At sufficiently low rate (<time drift over detector length)a TPC is the choice detector for high multiplicity final states
- Demonstrated by PEP4, Aleph-Delphi, NA49, STAR
- Measurement of dE/dx gives "some" particle id at low momentum

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

- 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; $\sigma = 220\ \mu m \sqrt{L(cm)}$
- Pad size : 4 mm2 at inner radius, in total 560 000 channels with 10 bit dynamics

The Alice TPC (2)

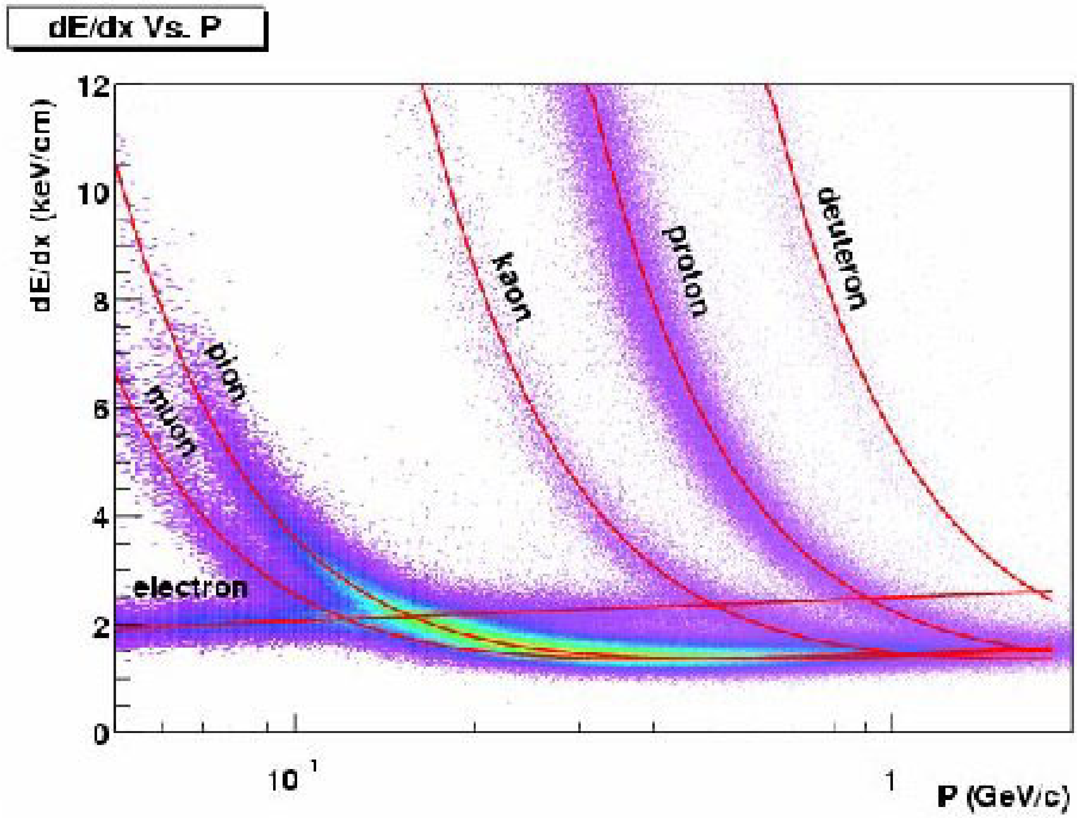


The Alice TPC (3)

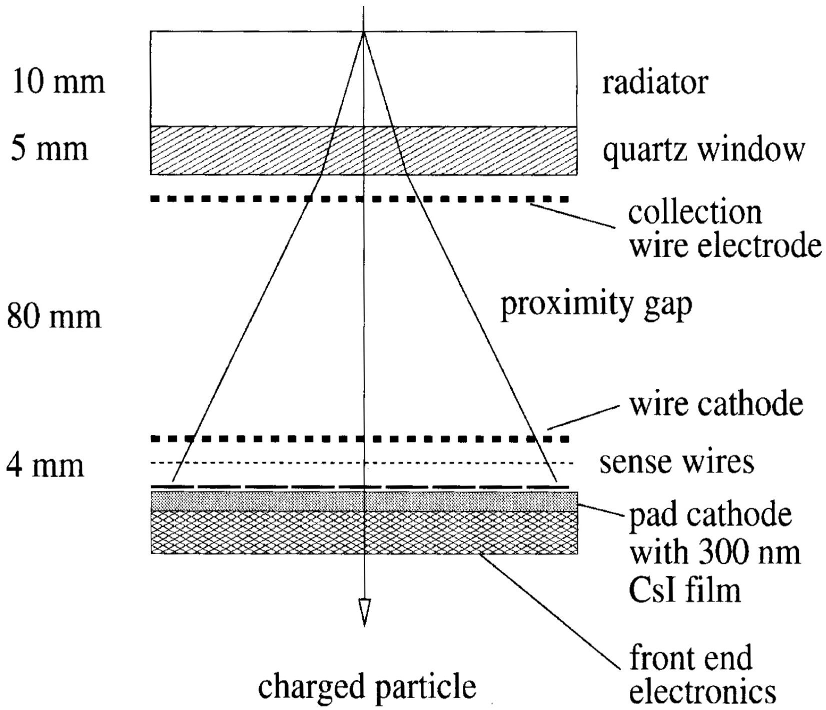
- dE/dx resolution goes like $N^{-0.43} \times (Pl)^{-0.32}$

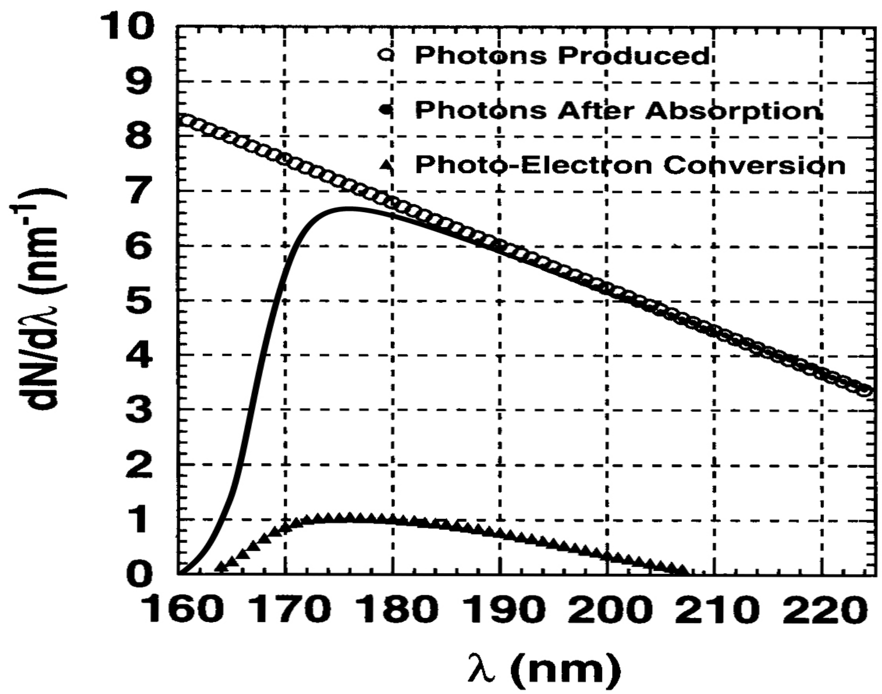
  (N nb of samples , P pressure, l length of sample)
- Best dE/dx precision (~2%) was achieved by PEP4 (8 bars)
- Alice expects 5.5% for isolated tracks and 7% with dN/dy ~ 8000
- STAR obtains the performance below:

Muon and pions
Resolved below
100 MeV/c



The Alice HMPID : CsI Rich





$\cos(\theta_c)=1/\beta n$

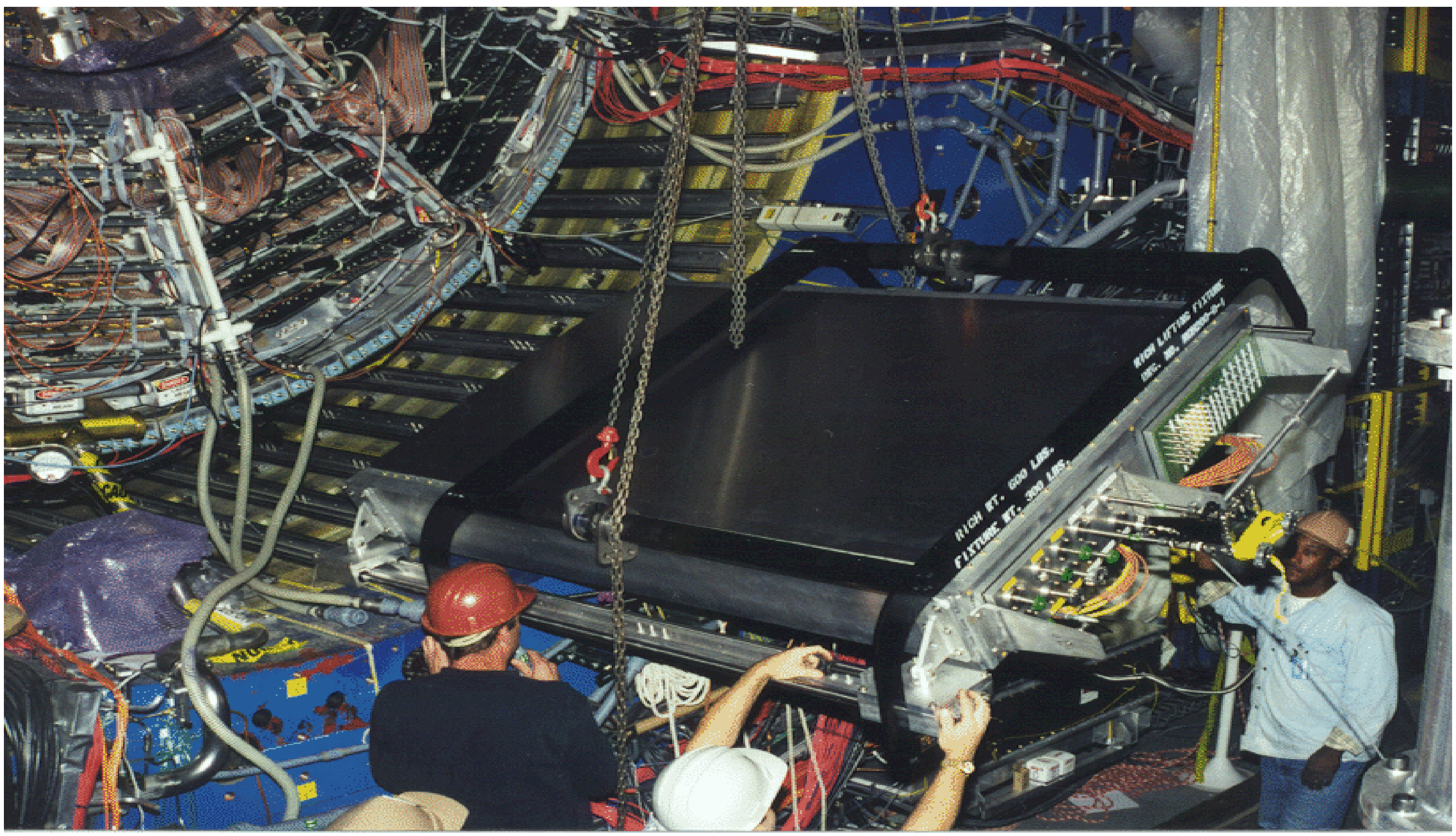
$$N = 2\pi L Z^2 \alpha \int_{\beta n > 1} \left[1 - \frac{1}{(n(\lambda)\beta)^2}\right] \frac{d\lambda}{\lambda^2}$$

Photon conversion threshold of CsI(170nm) matches spectrum after quartz transmission

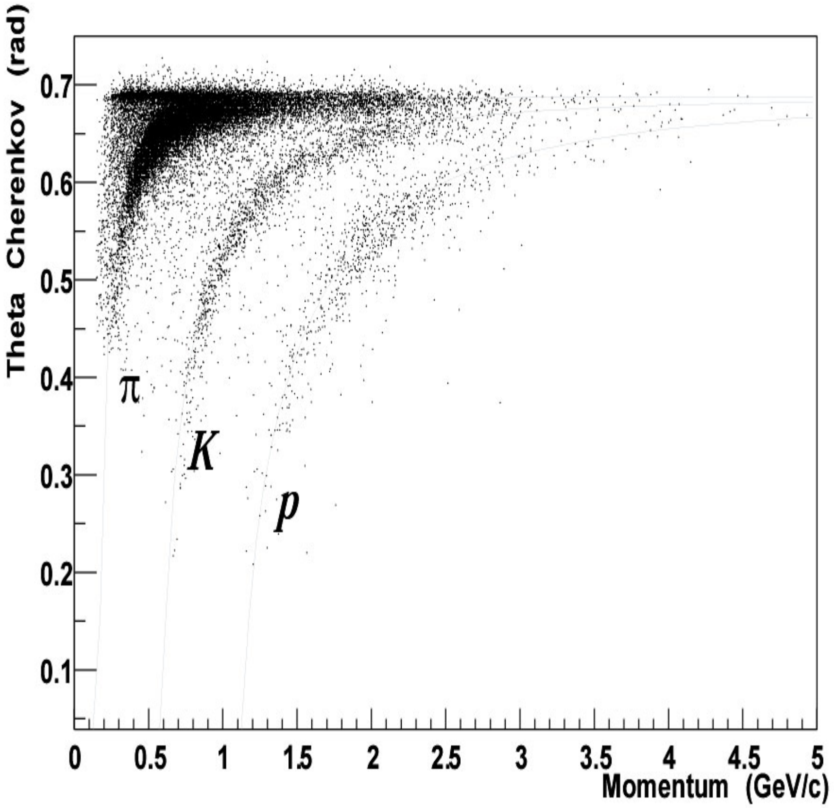
CsI layer (300nm thick) is fragile (no water no air)

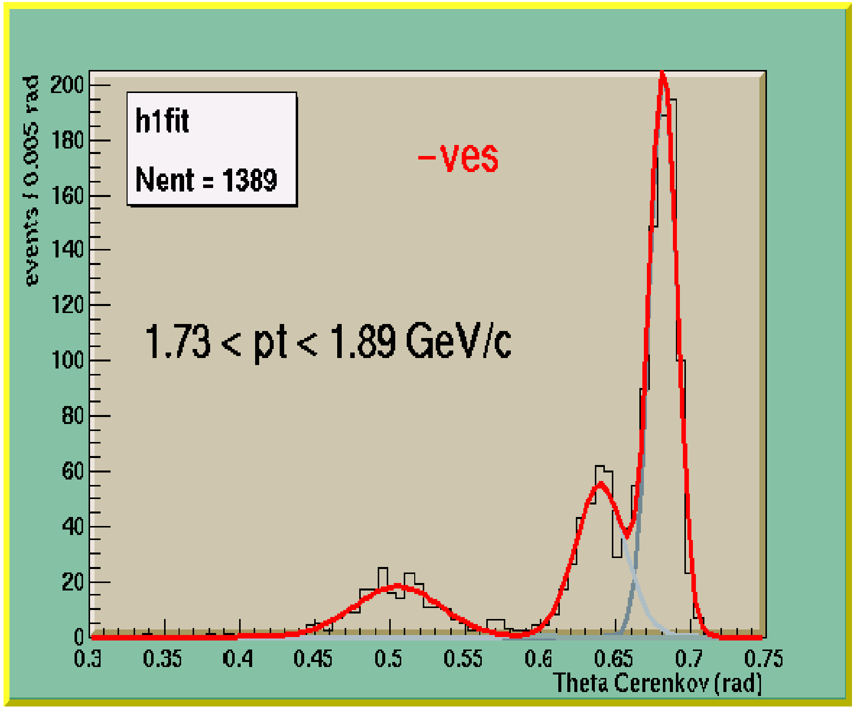
The Alice HMPID (2)

CsI coating on one cathode of a MWPC as photoconverter
Developped in RD26, used in Compass, Hades, and STAR (Alice prototype)



The Alice HMPID(3)





In total there should be in ALICE 12 m^2 of detector following a 15 mm thick liquid radiator of C_6F_{14}

Overall Alice PID plan

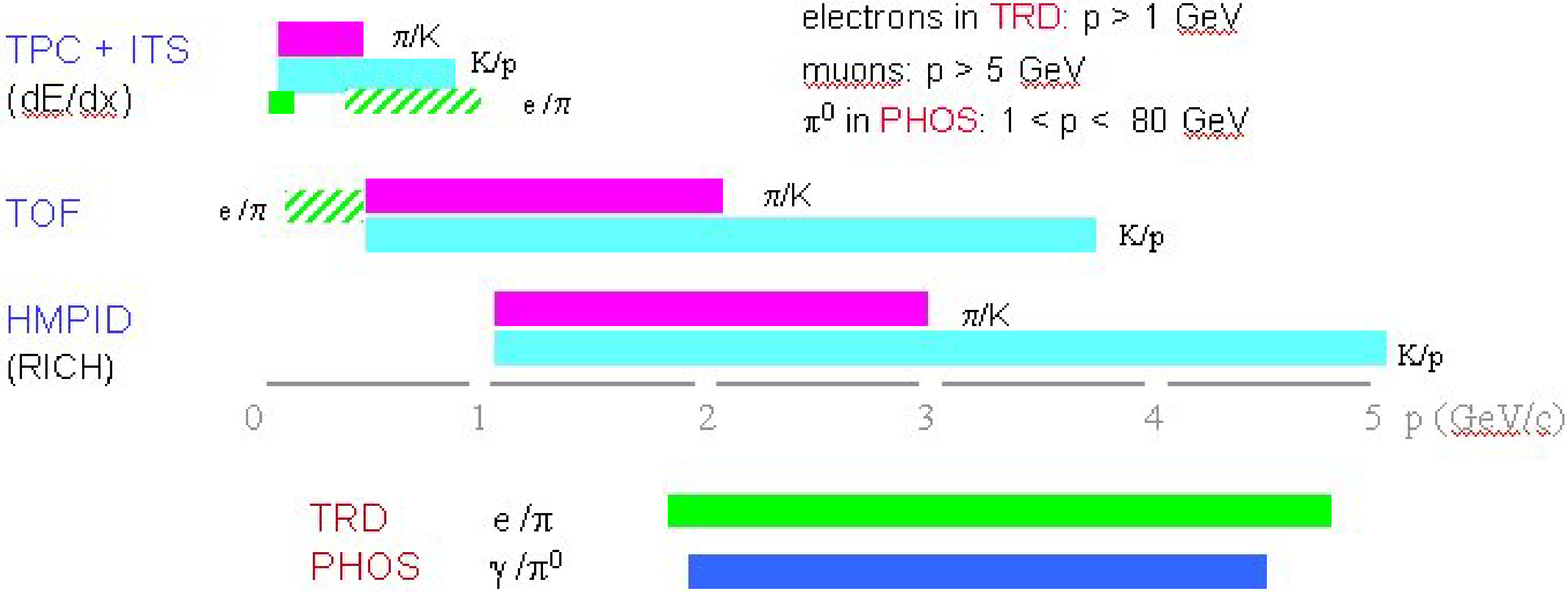
- **stable hadrons (π, K, p): 100 MeV < p < 5 GeV**
  - ⇨ dE/dx in silicon (ITS) and gas (TPC) + Time-of-Flight (TOF) + Cerenkov (RICH)
  - ⇨ dE/dx relativistic rise under study => extend PID to several 10 GeV ??
- **decay topology (K^0, K^+, K^-, Λ)**
  - ⇨ still under study, but expect K and Λ decays up to at least 10 GeV
- **leptons (e, μ), photons, π^0**

Alice uses ~ all known techniques!

electrons in TRD: p > 1 GeV

muons: p > 5 GeV

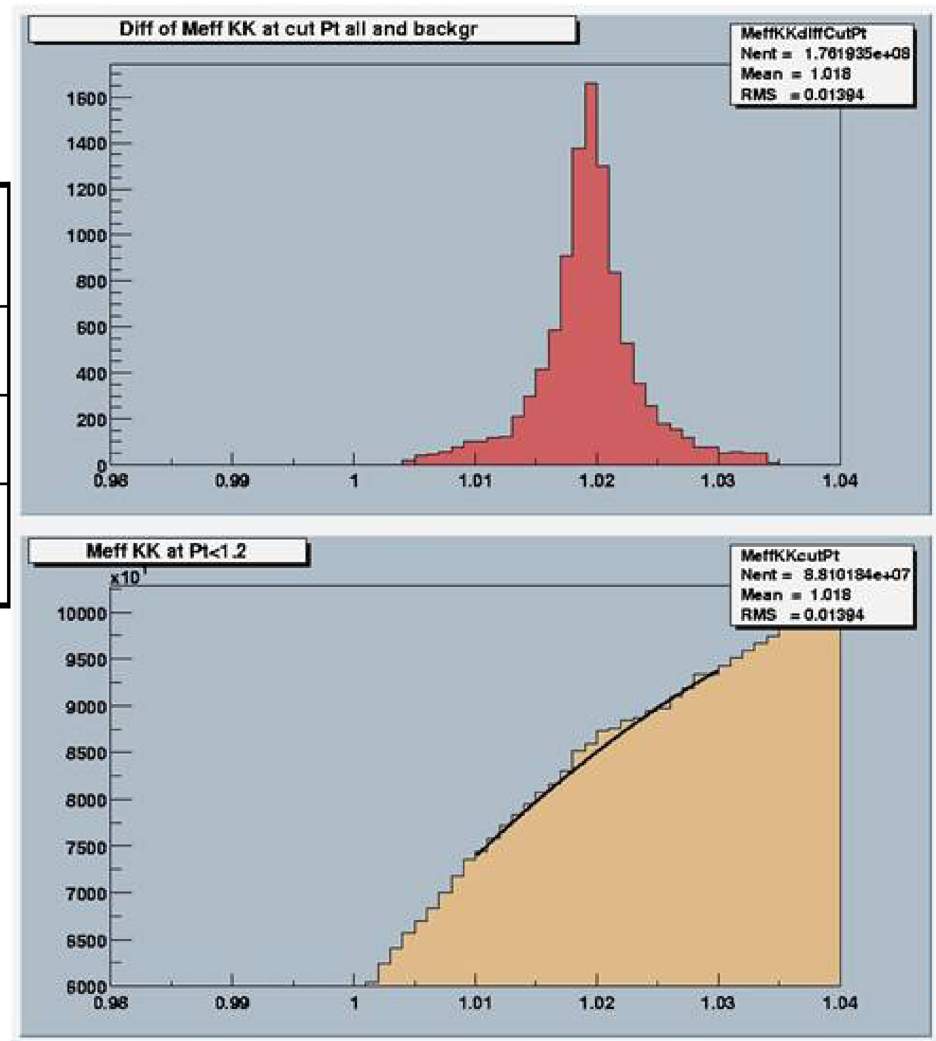
π^0 in PHOS: 1 < p < 80 GeV



ALICE Combined PID : illustration

14 central HIJING events, 0.5 T field, processed in simulation
130000 tracks in TPC,…

	Effic(%)	Contami-nation(%)	# of ESD tracks
Pions	98	1	17337
Kaons	93	20	1566
Protons	97	6	1324



Φ→KK signal over BG

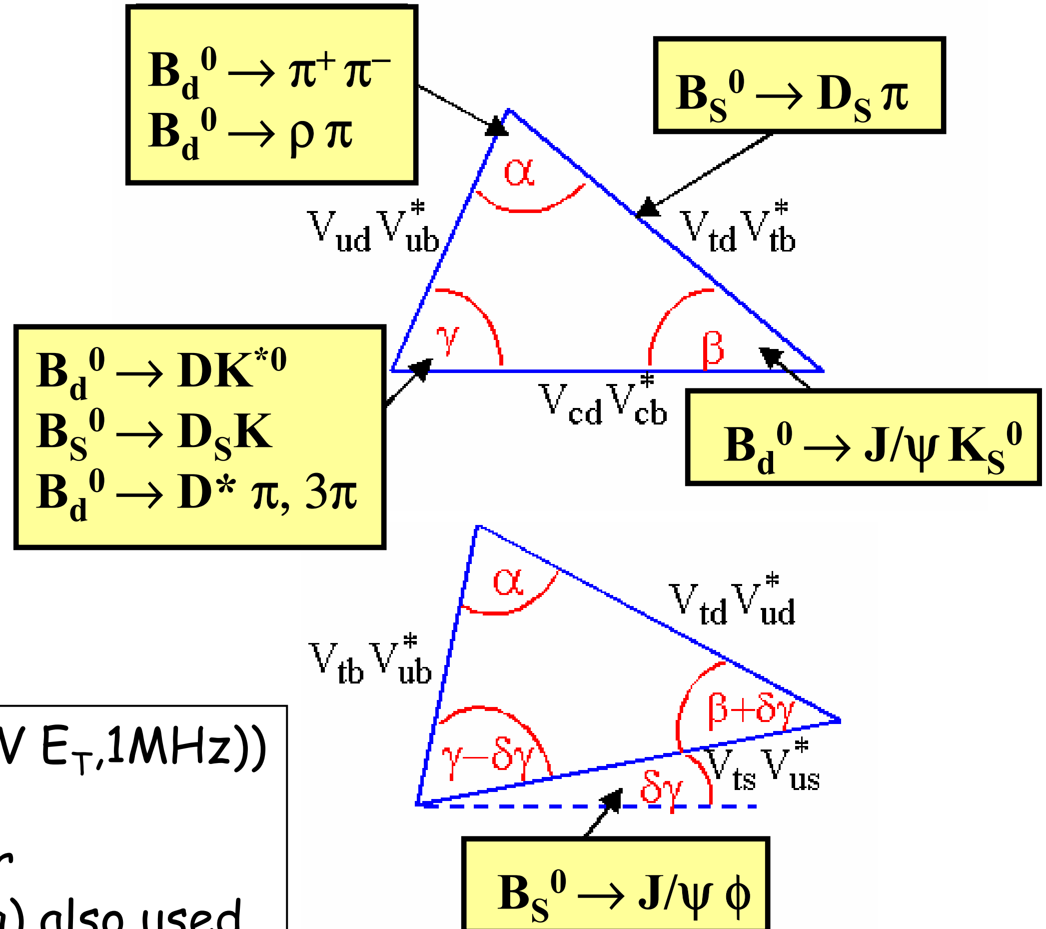
CP violation with LHCb

2 CKM Unitary triangle relations most useful:

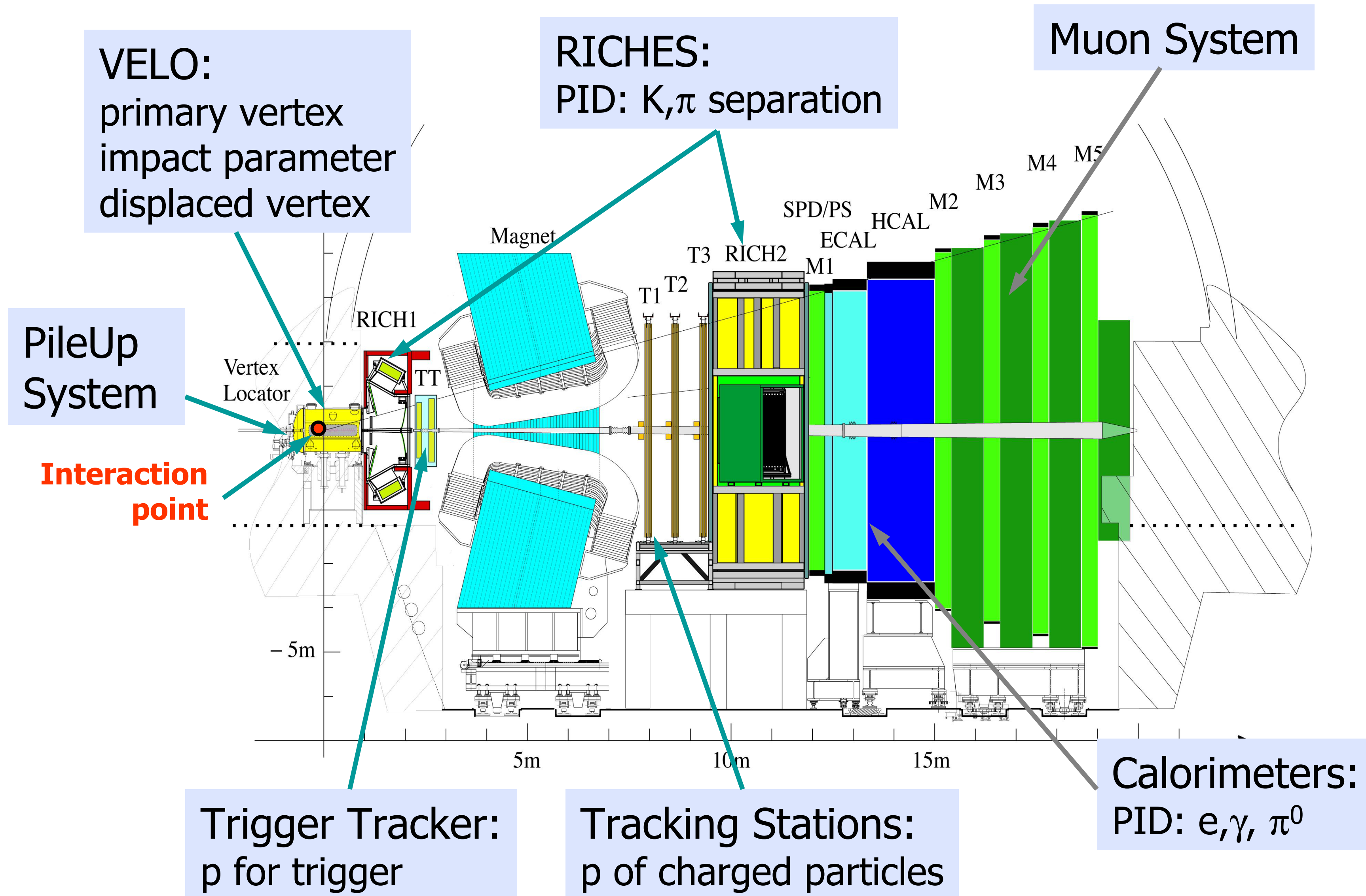
Among the main goals: measure α and γ

- 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-layout


VELO:
primary vertex
impact parameter
displaced vertex
RICHES:
PID: K,π separation
Muon System
PileUp System
Interaction point
Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
– 5m
5m
10m
15m
Trigger Tracker:
p for trigger
Tracking Stations:
p of charged particles
Calorimeters:
PID: e,γ, π0

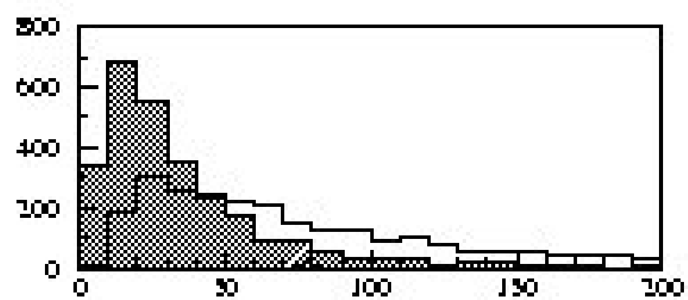
LHCb hadron ID

Requirements:

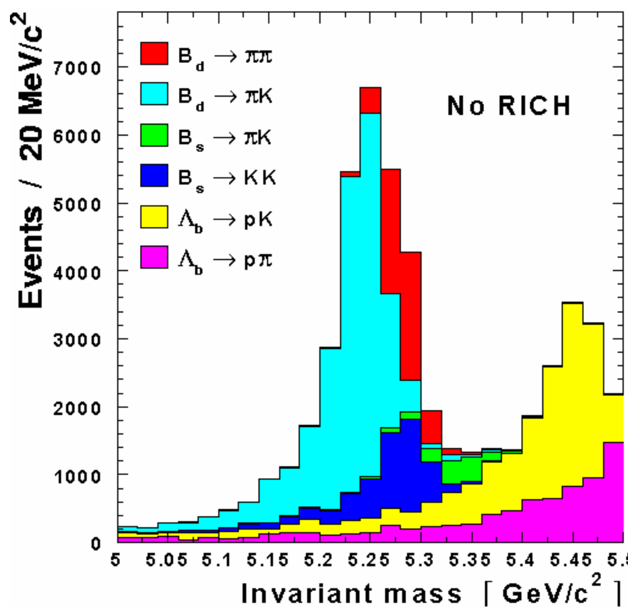
- Speed: 25 ns or faster
- Angular coverage: 10 to 330 mrad
- Momentum range: 2 GeV/c to 150 GeV/c
- Particle density: ~20/m^2/interaction at 10 m from vertex
- Quality of separation : pion rejection>20

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

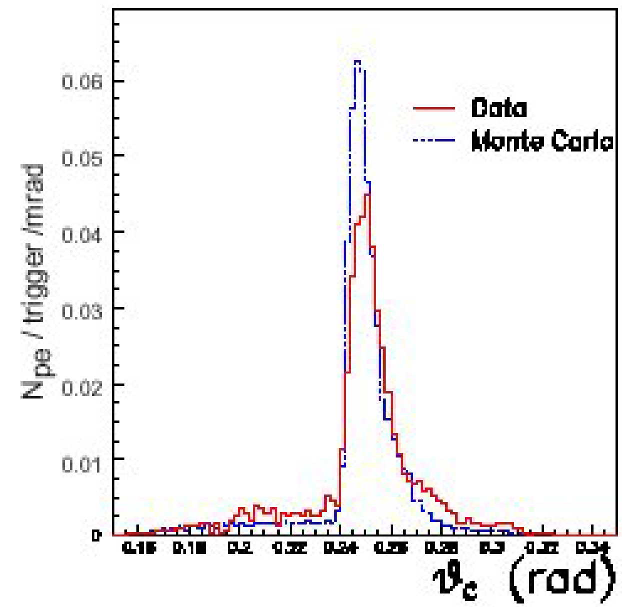


Figure 4.7: Distribution of the reconstructed Cherenkov angle for 4 cm-thick aerogel.

LHCb Rich : mirrors and photodetector

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

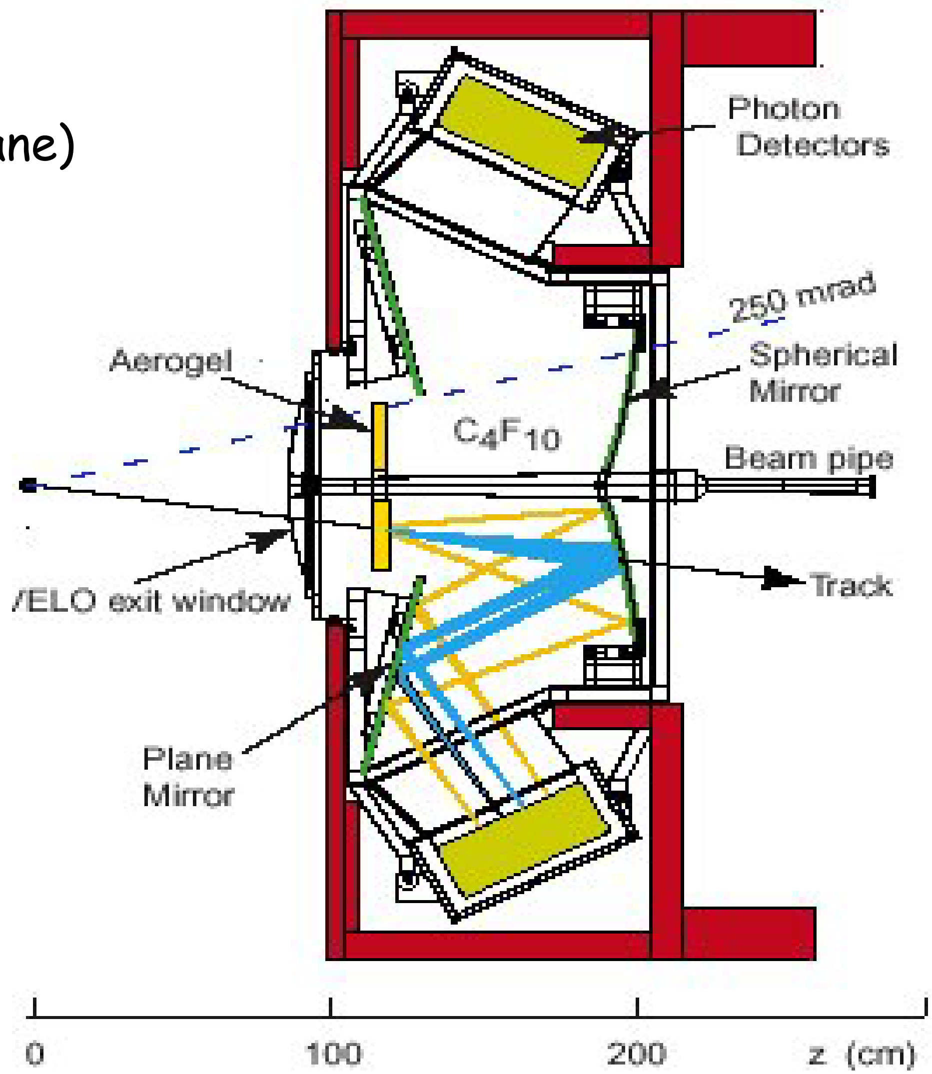
- Photodetector out of particle path

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

- UV sensitive

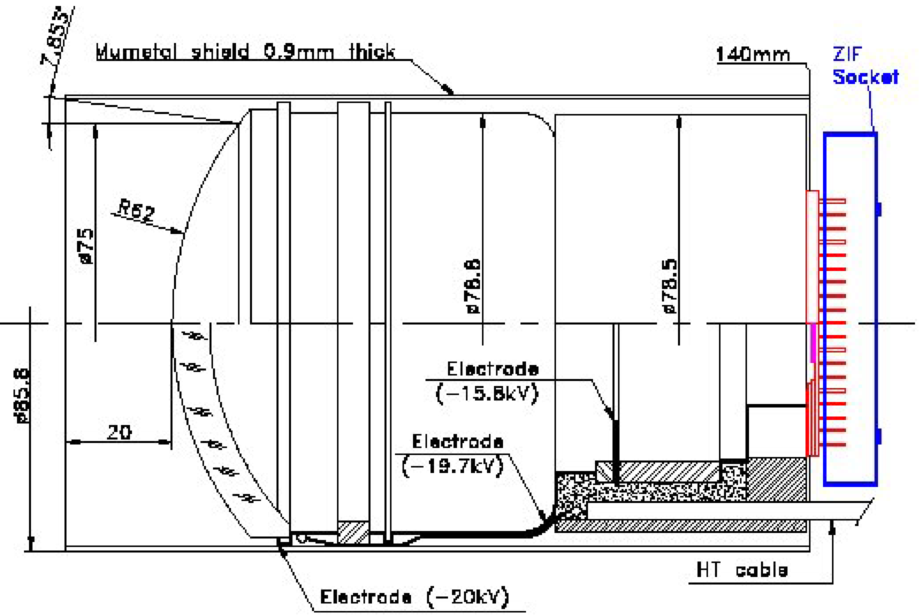
  →"pad HPD"

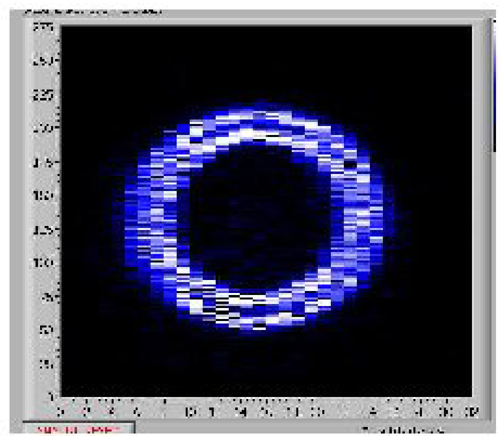
(alternative:Multi anode PM)



LHCb pad HPD

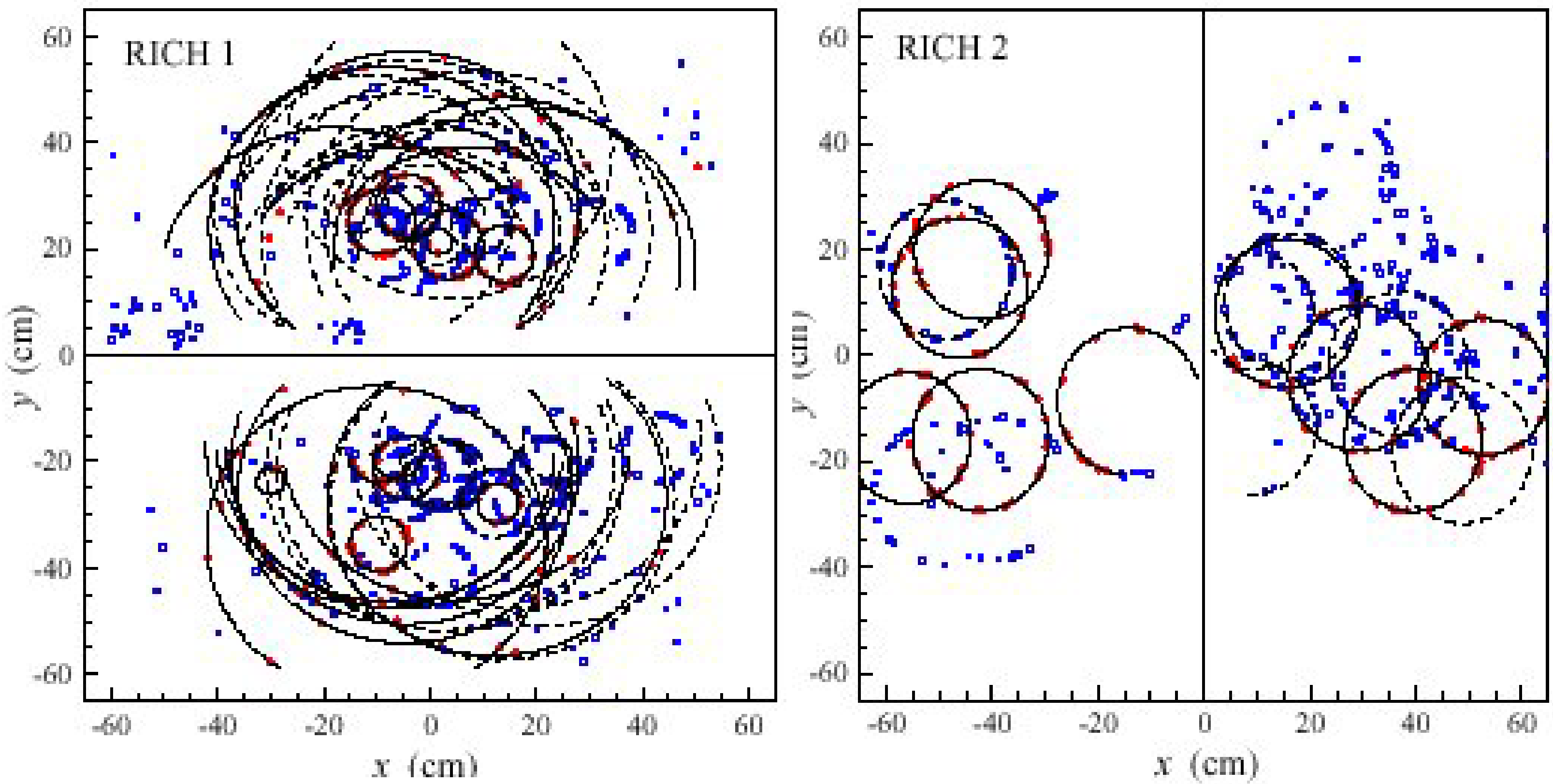
- Photocathode at -20kV
- Vacuum tube,window transp to UV
- Demagnified image/5 on pixel sensor
- 256x32 pixels of 62x500 microns
- Electronics bump-bonded
- 40 MHz readout
- Long and difficult R&D at CERN (bonds melt under tube bake out)
- 500 tubes needed
- Narrow single electron peak





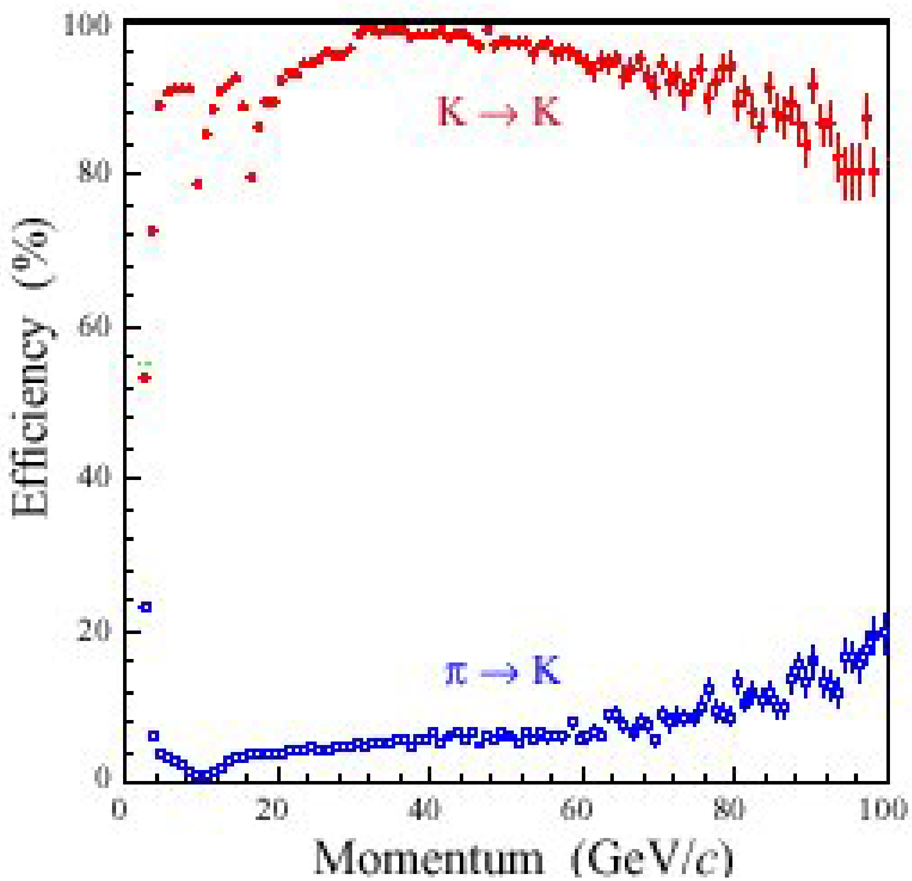
K and π rings
as observed
in T9
(10 GeV/c)

LHCb Rich event simulation (1)



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 Rich event simulation (2)



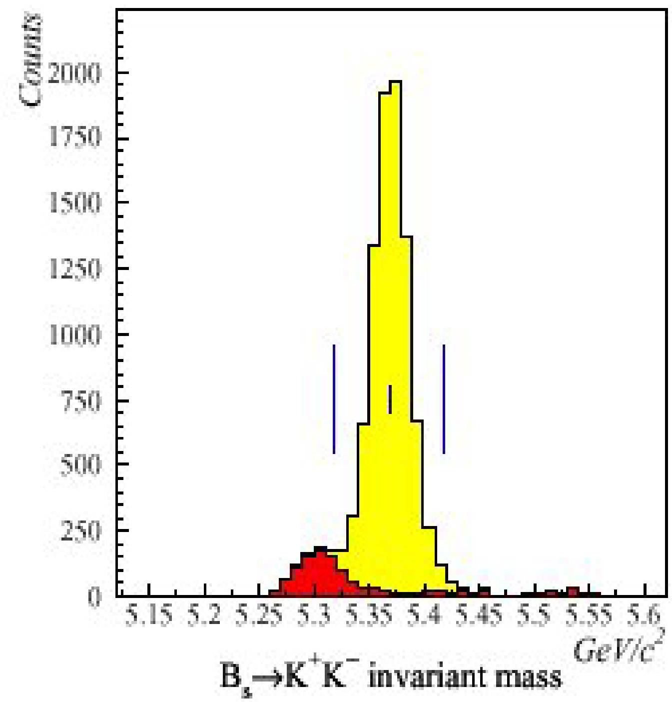


Figure 9.9: Invariant mass distribution of triggered and offline-selected $B_s^0 \to K^+K^-$ candidates. The light-shaded (yellow) histogram is the signal and the dark (red) one represents the background from $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B_s^0 \to \pi^+K^-$, $\Lambda_b \to pK^-$ and $\Lambda_b \to p\pi^-$ decays. The vertical lines indicate the mass cut applied in the selection.

LHCb : example of trigger steps

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

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

•LVL1:

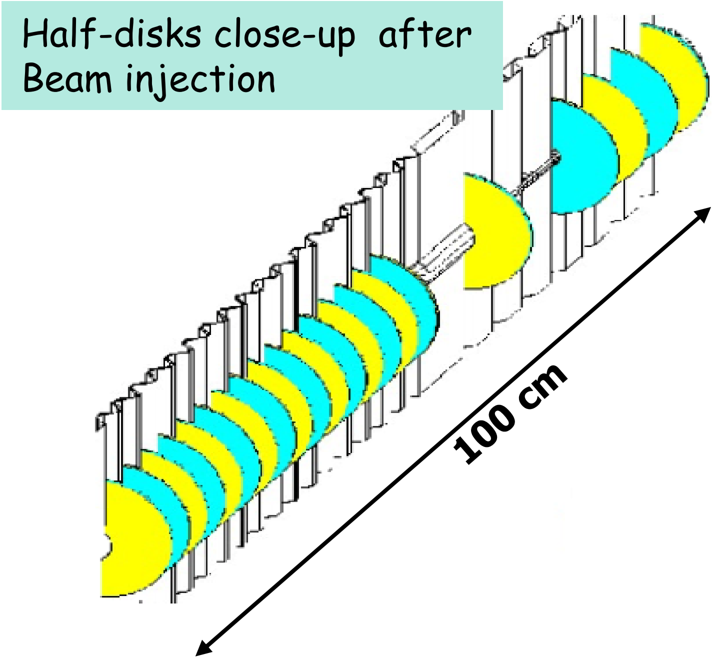
-with the calo seed,walk backward with Kalman filter,and find-or not- a track with similar p_T pointing to the cluster acc=0.3,rej=10

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

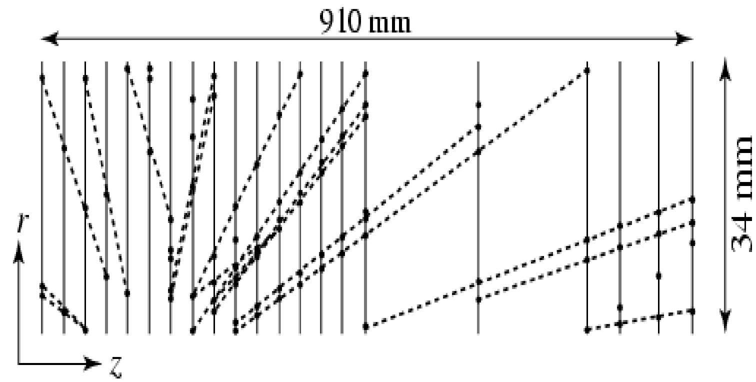
.LVL2(input 40 kHz): reconstruct 3D tracks,use mom,ask for ge.3 detached

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

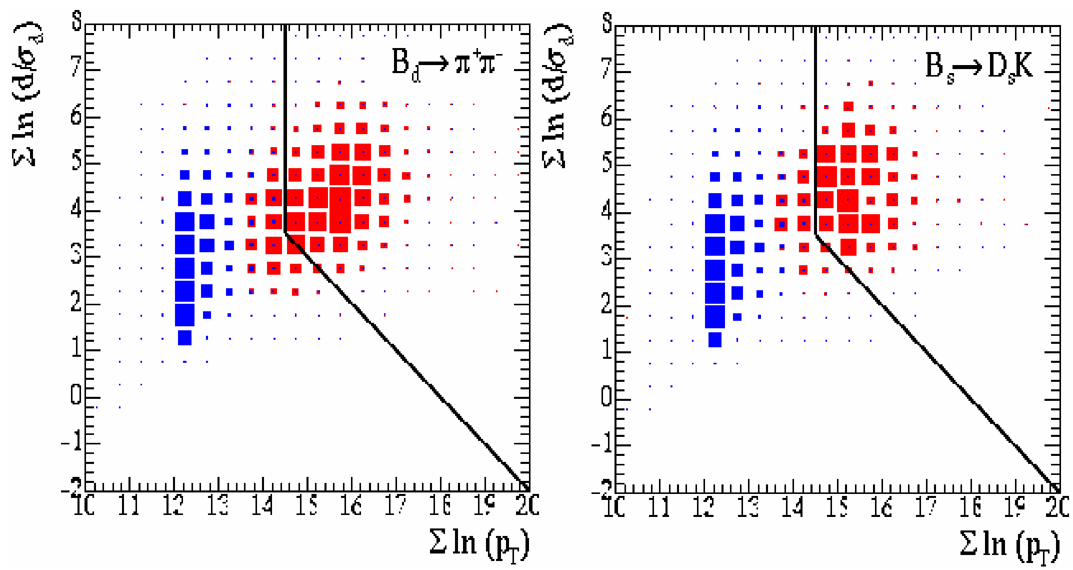
LHCb:Vertex Locator in trigger



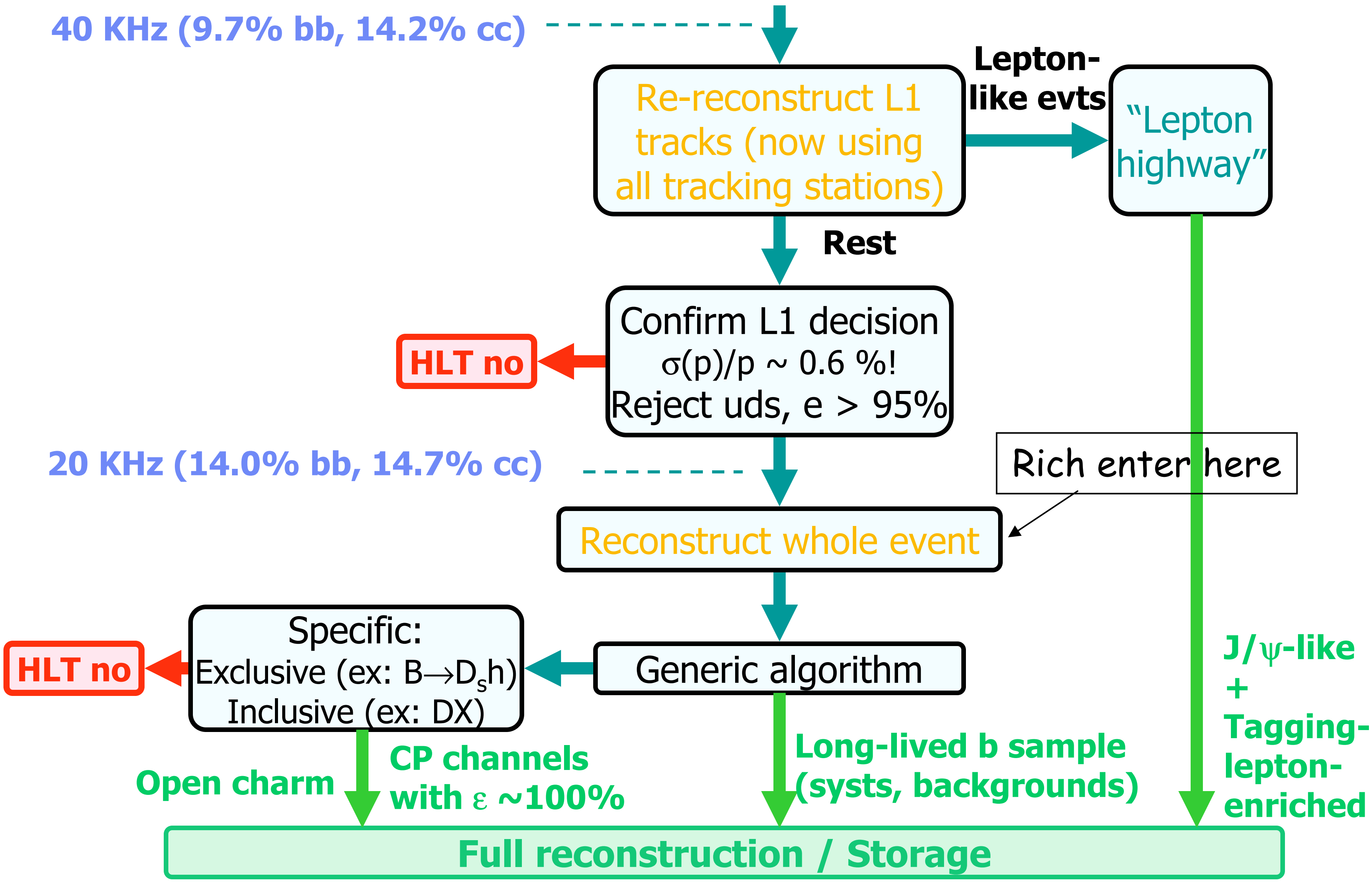
The LHCb VELO
21 stations (~ 100 cm)
Alternated R-Φ sensors
40 μm to 100 μm pitch



Fast track finding in rz view



LHCb-HLT flow diagram(prel)



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.	--	--