Muon and neutral hadron detection in high energy physics

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- Detector for muon system

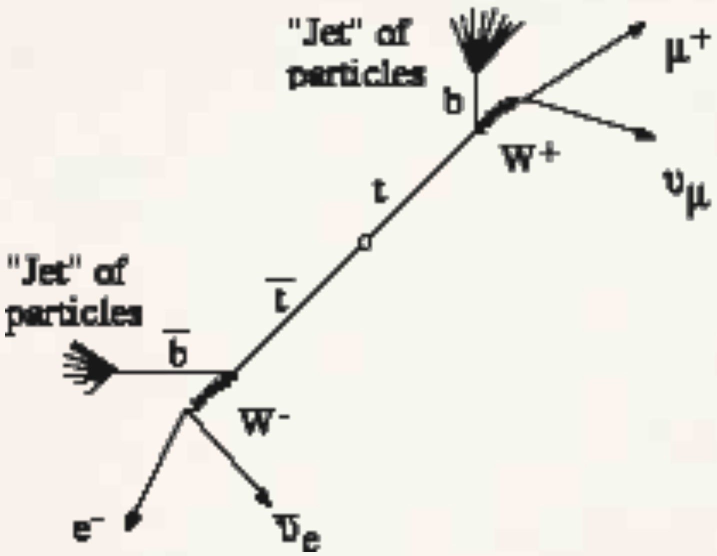
Introduction

- Charged particle identification is a strong tool for high energy physics
- Detection of charged particle might be introduced many places and text books
- Particle identification will be introduced
  - muon : charged lepton
  - K_L : neutral hadron
- Neutron measurement as background

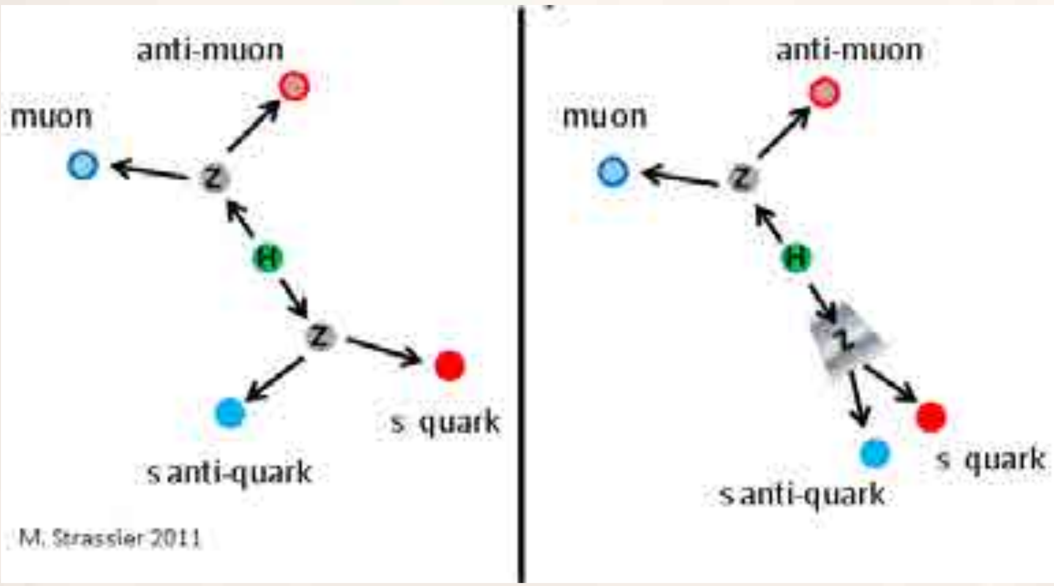
Muon

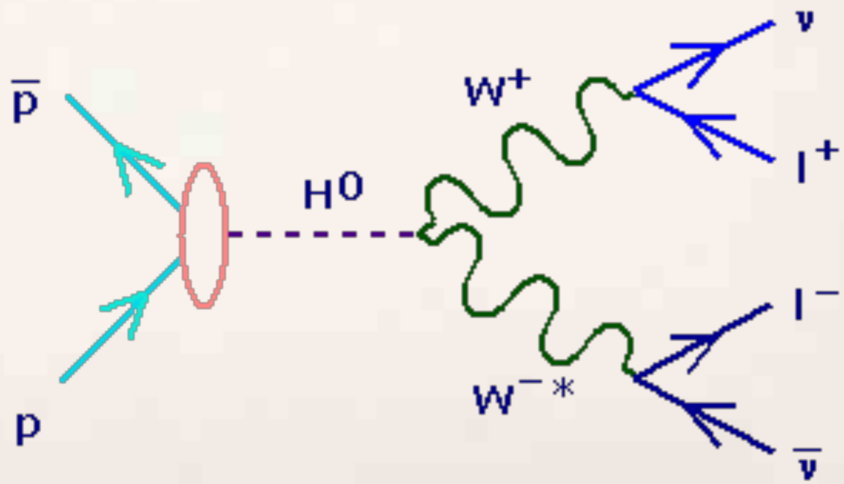
- Important particle for physics analysis
- In B-factory
  - $B \to J/\psi K_S, J/\psi \to \mu^+\mu^-$
  - $B \to D^{(*)}\mu\nu$
  - $BB \to \mu\mu XY$
  - $B \to \mu\nu$
  - $B \to K^{(*)}\mu\mu$
  - $\tau \to \mu\gamma$
  - Tag B^0 or anti-B^0 for ICPV analysis in B-factory

- Tag heavy quarks ($t \rightarrow b\mu\nu, b \rightarrow c\mu\nu,\ c \rightarrow s\mu\nu$)



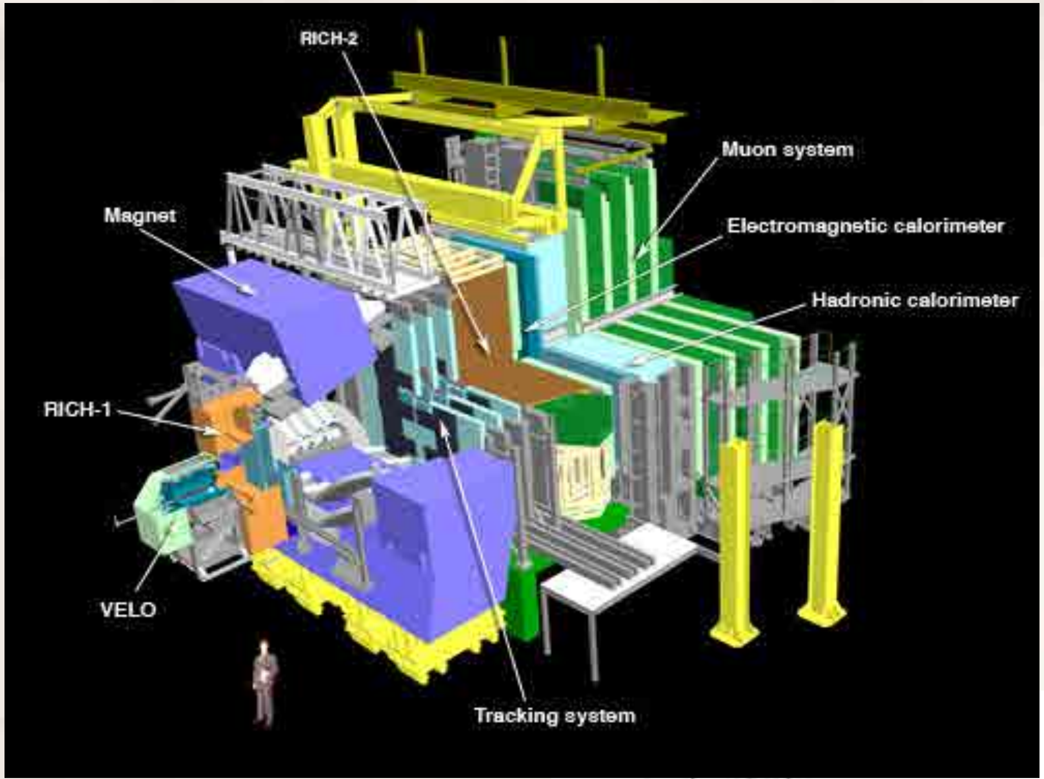
- W decay from Higgs decay ($H^0 \rightarrow$ WW* $\rightarrow \mu\nu$+jet)



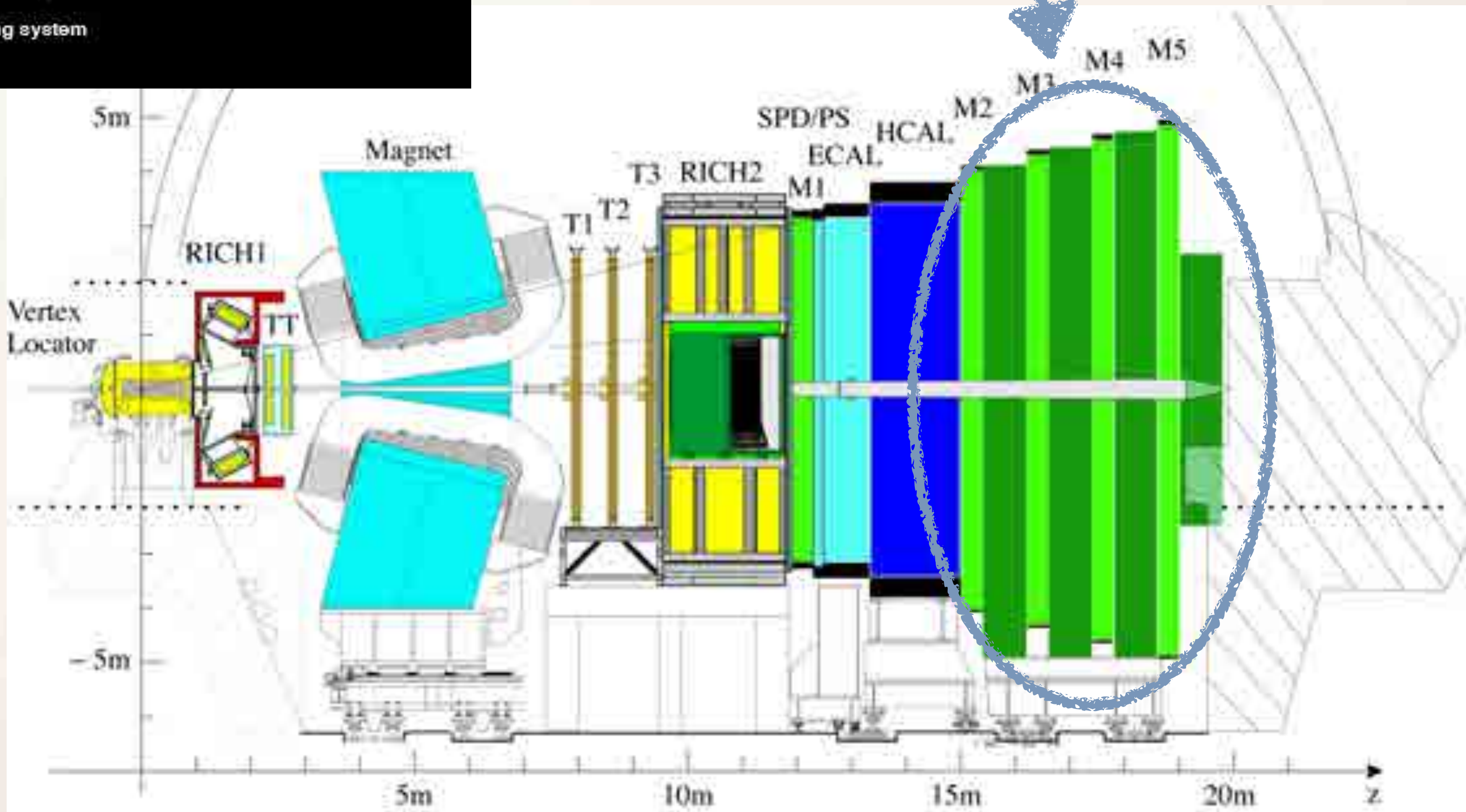


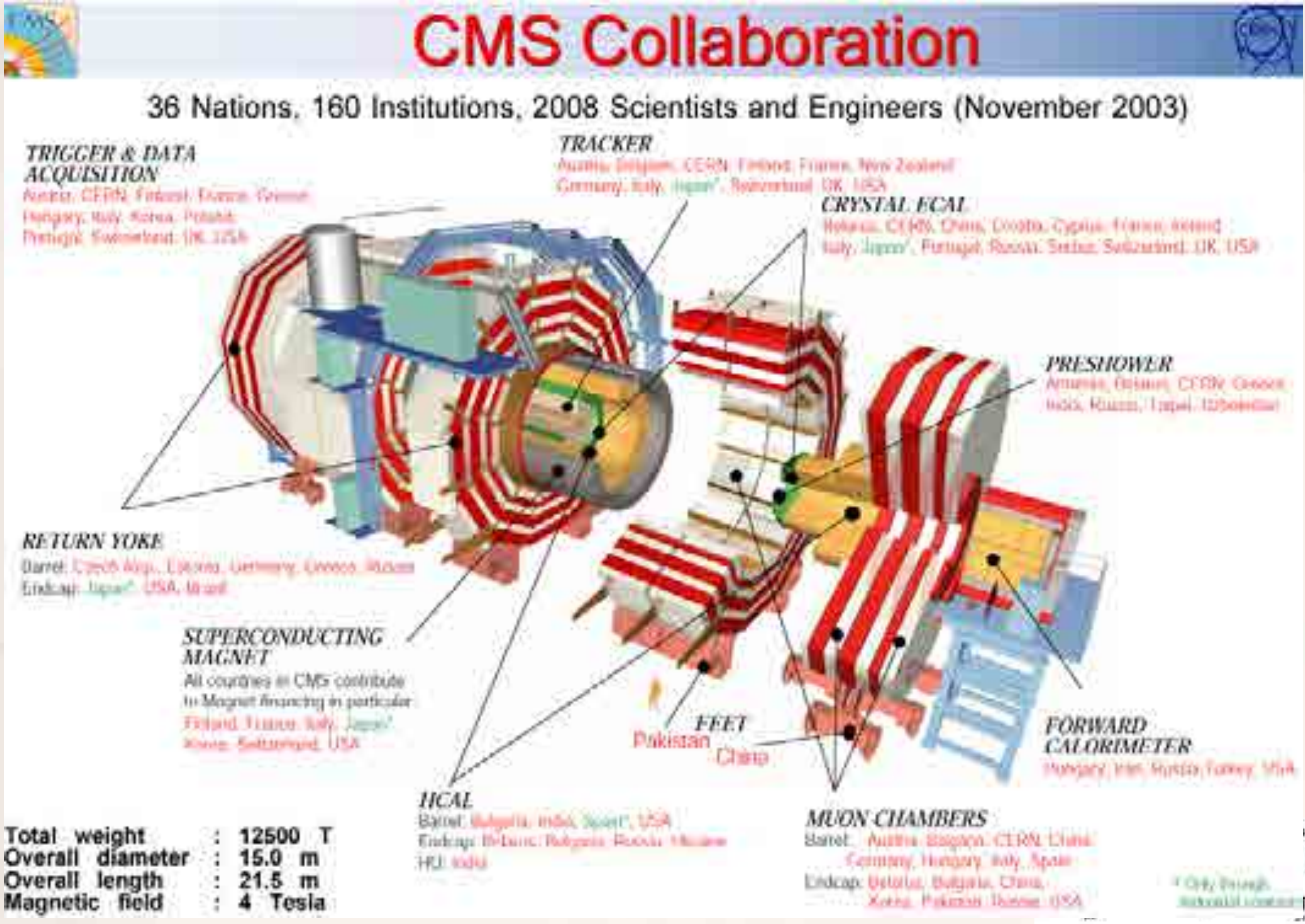
Muon system in Experiments

LHCb detector



Muon system

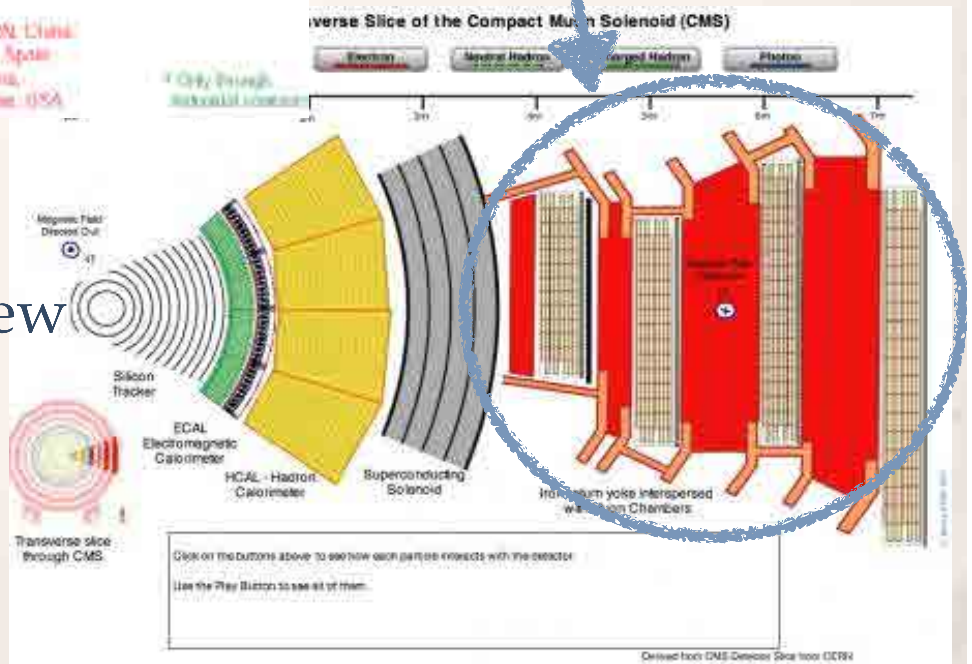


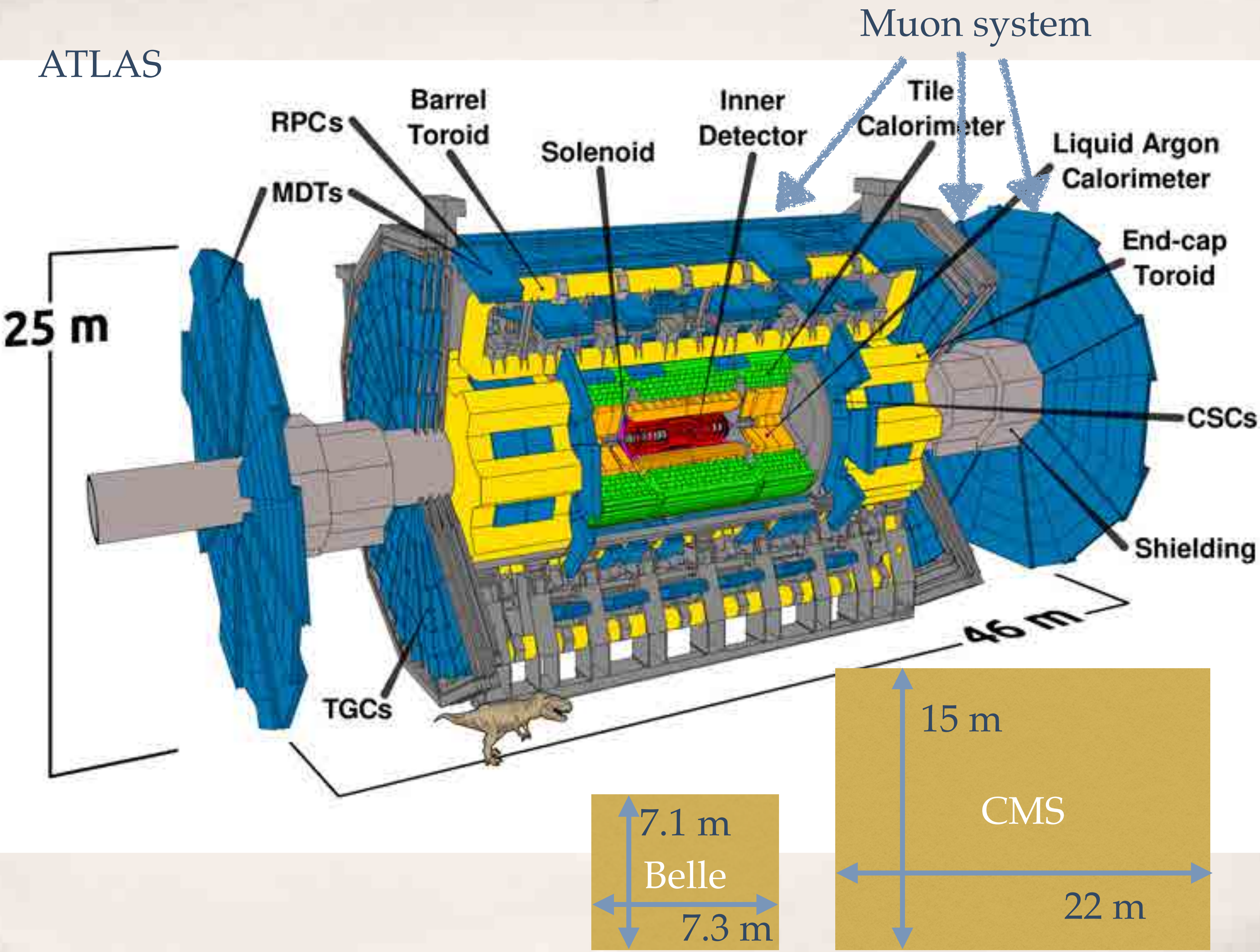


CMS

Muon system

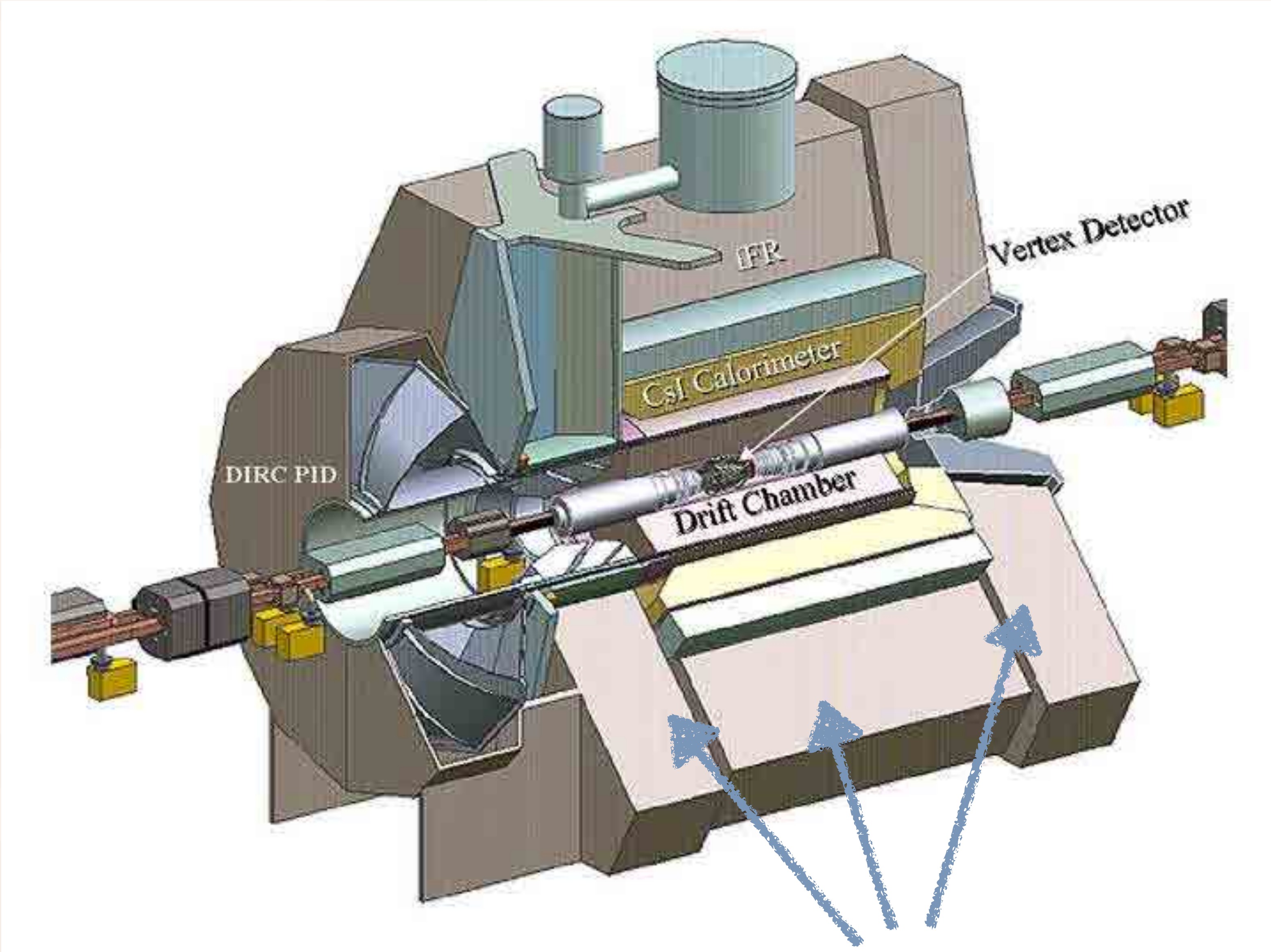
Cross sectional View





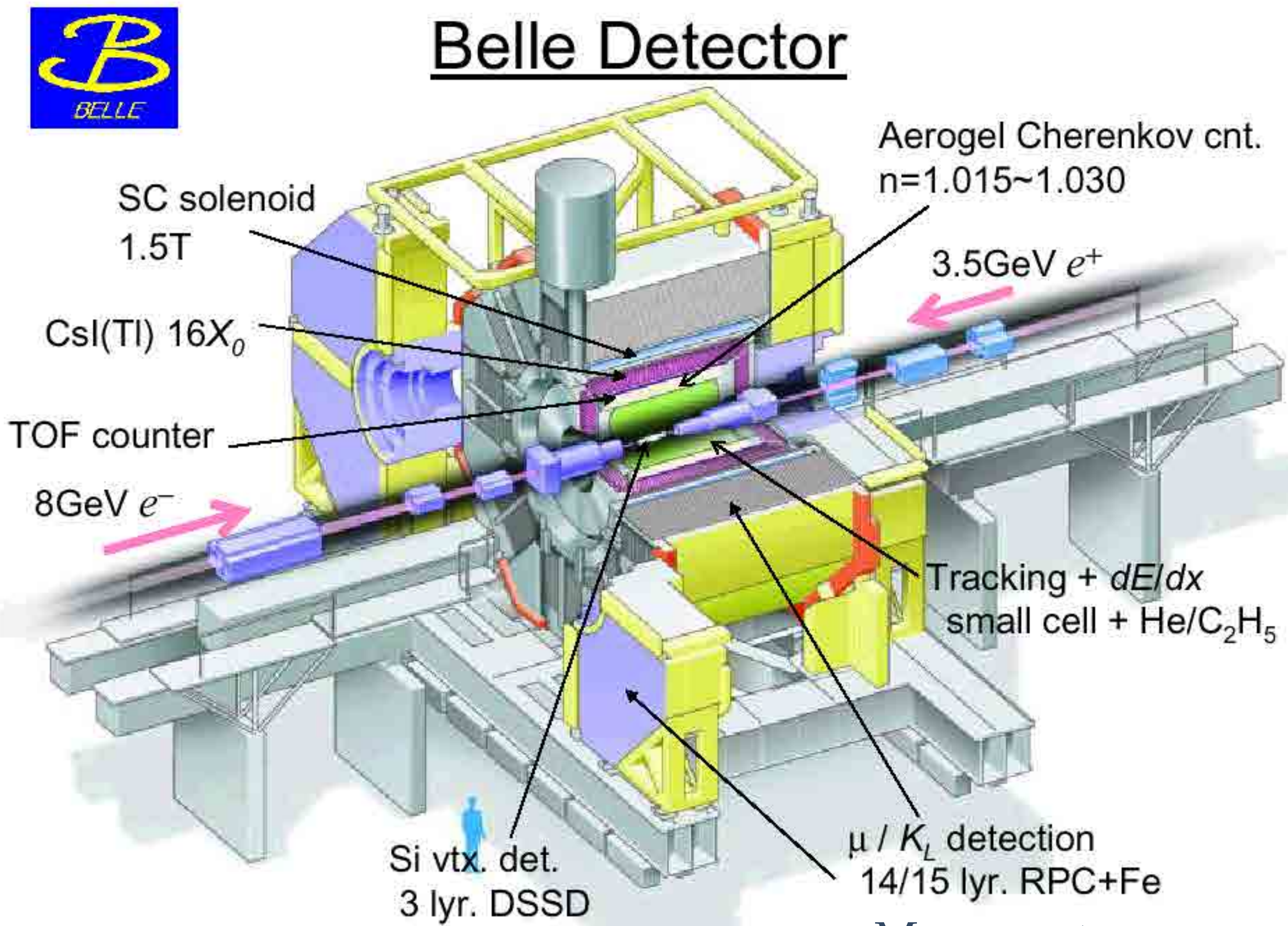
ATLAS
Muon system
RPCs
Barrel Toroid
Solenoid
Inner Detector
Tile Calorimeter
Liquid Argon Calorimeter
MDTs
End-cap Toroid
25 m
CSCs
Shielding
TGCs
46 m
15 m
CMS
22 m
7.1 m
Belle
7.3 m

BaBar



Muon system

Belle Detector



Muon system

ILD

Muon system

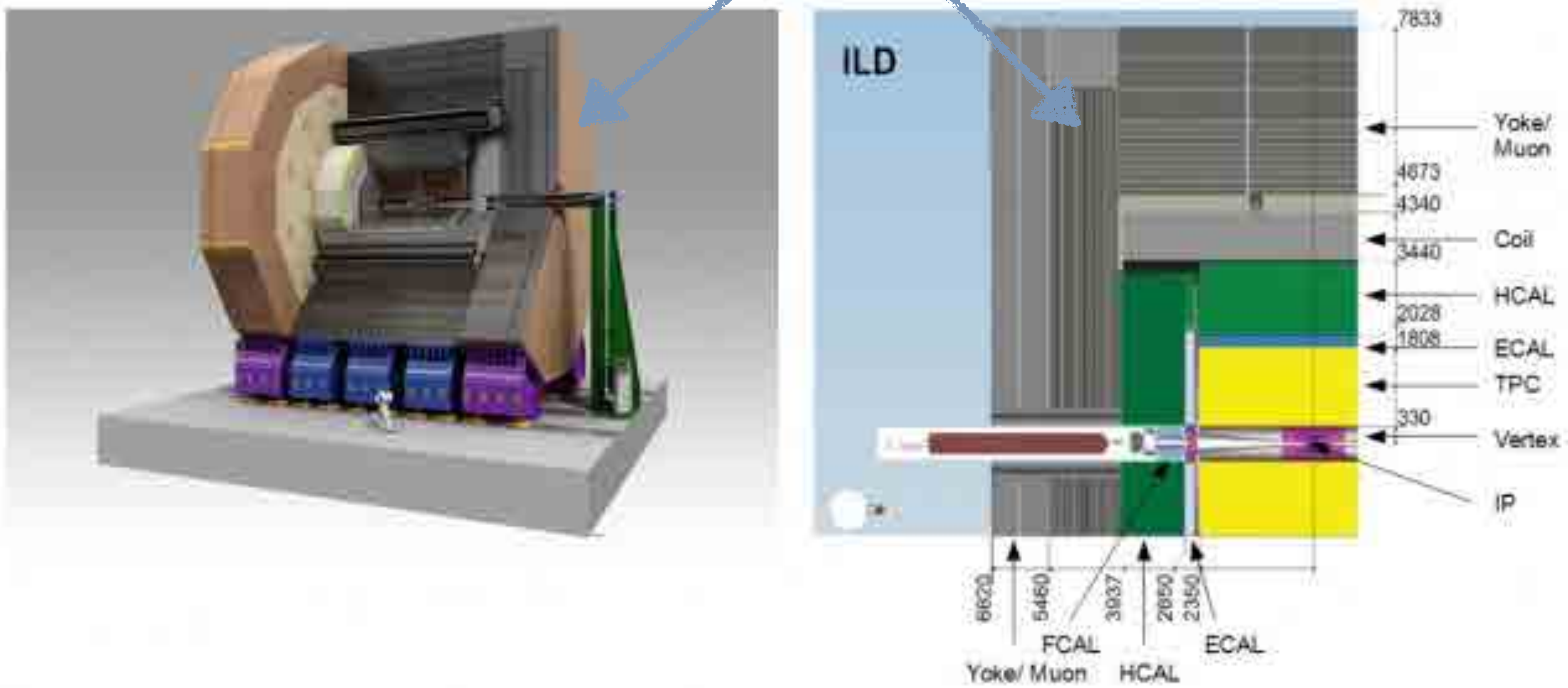


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

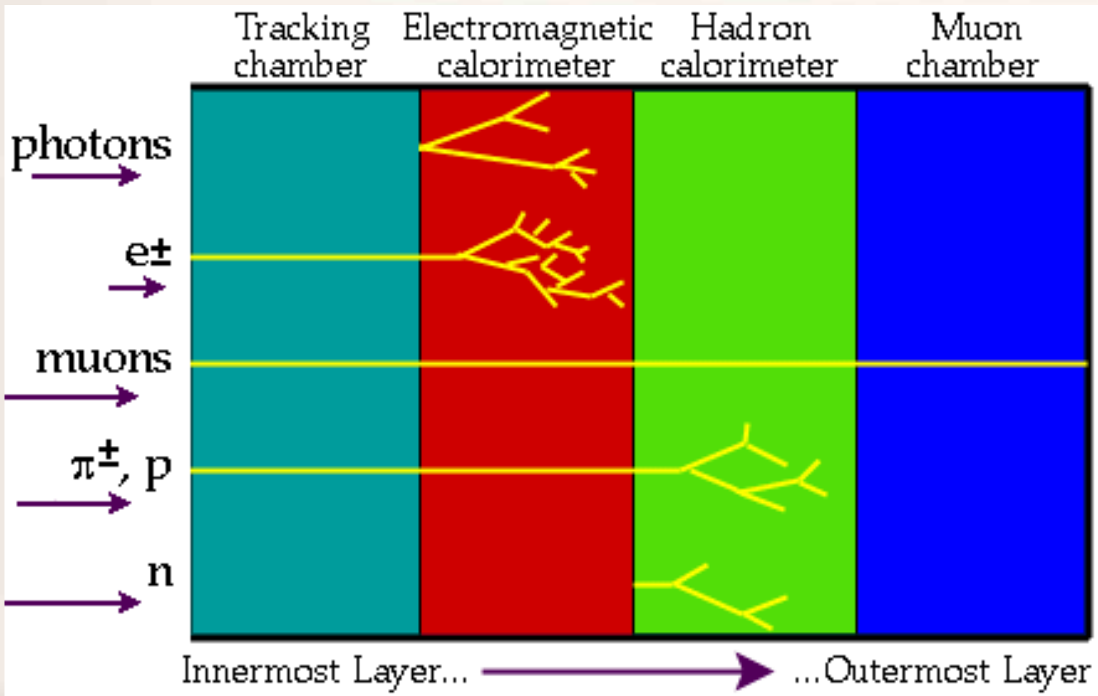
Life time of particle

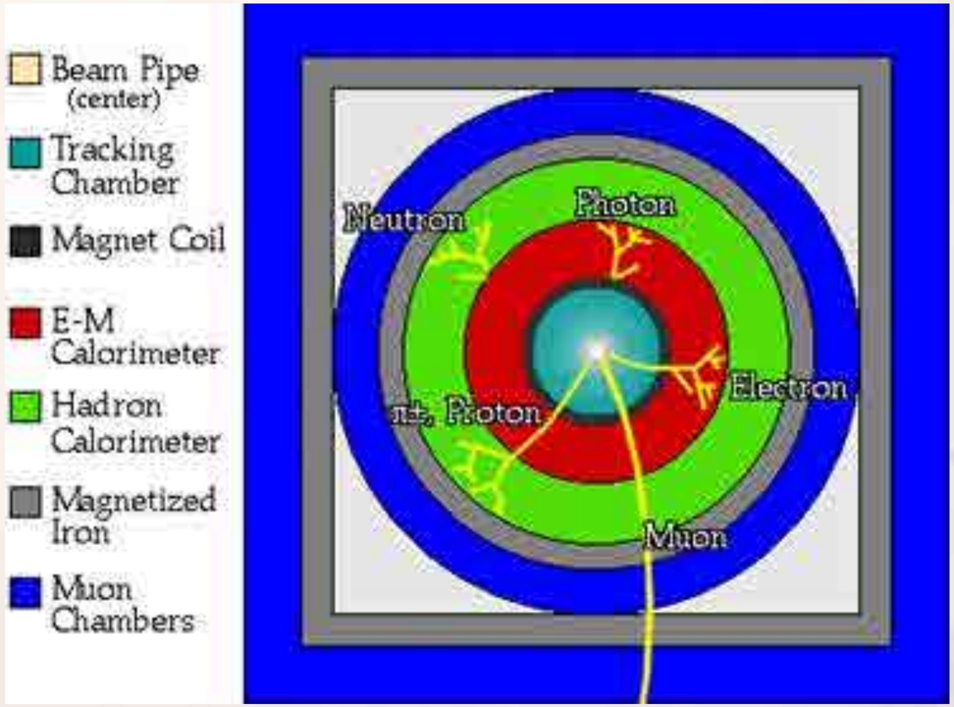
		life time (	$c\tau$	detect
charged	electron	-	-	directly
	muon	2.20×10	659	directly
	π	2.60×10	7.80	directly
	K	1.24×10	3.712	directly
	proton	-	-	directly
	D	1.04×10	312×10	decay product
	tau	291×10	87.1×10	decay product
neutral	γ	-	-	directly
	π	8.52×10	25.5×10	$\gamma\gamma$
	K	0.895×10	2.68×10	π
	K	5.12×10	15.34	hadronic interaction
	Λ	2.63×10	7.89×10	$p\pi$
	Ξ	2.90×10	8.71×10	decay product

- detectable particle
  - charged : electron, muon, pion, Kaon or proton
  - neutral : γ, K_L
- others : reconstruct by decay products
  - $Ks \rightarrow \pi^+\pi^-$, $D^0 \rightarrow K^-\pi^+$, $\pi^0 \rightarrow \gamma\gamma$

Conceptual Configuration

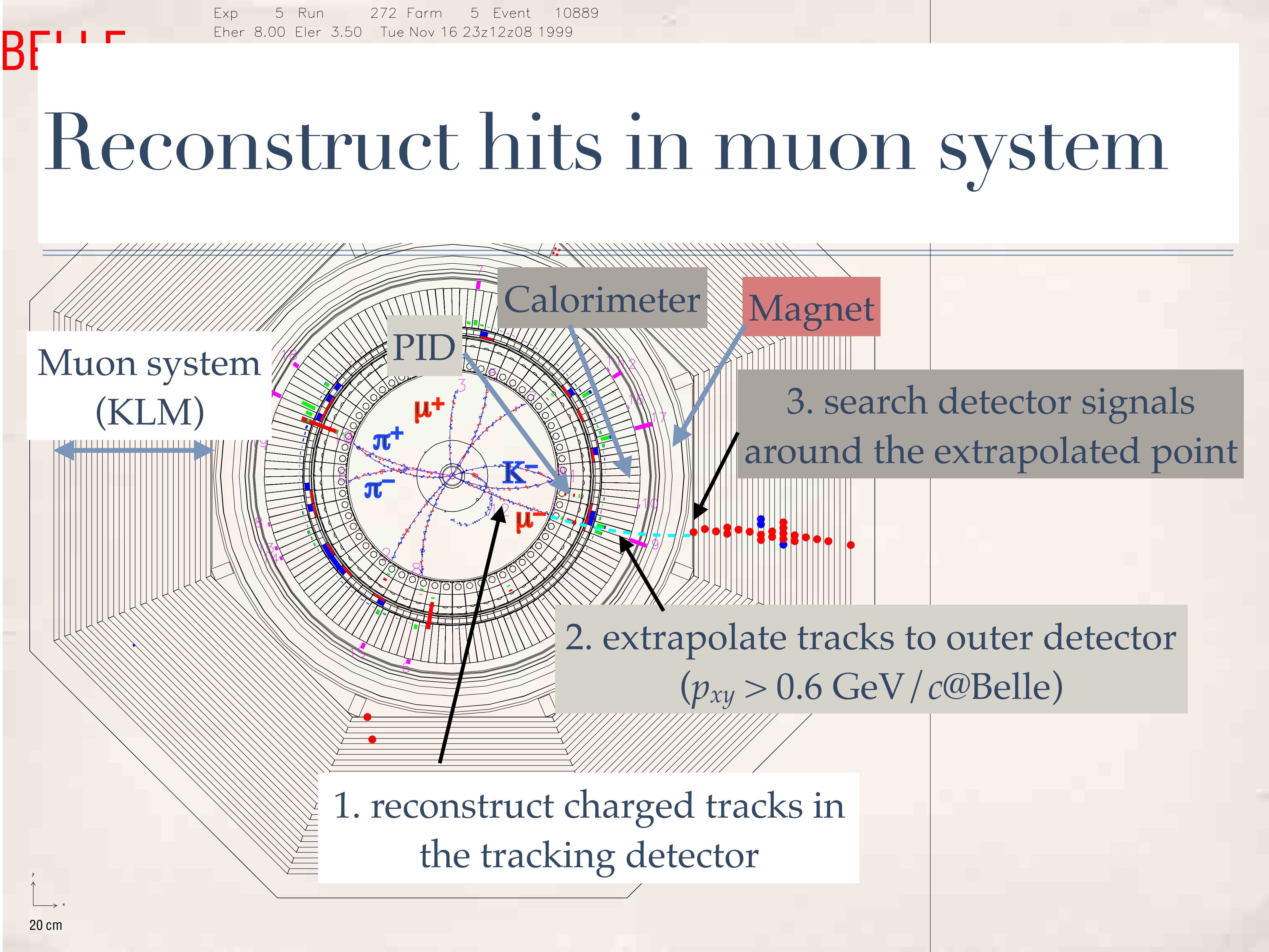
- Muon system is located outermost(collider) or lower stream(fixed target) of detectors.
- Necessary to cover large area
- Even though rough segmentation, number of channel is large

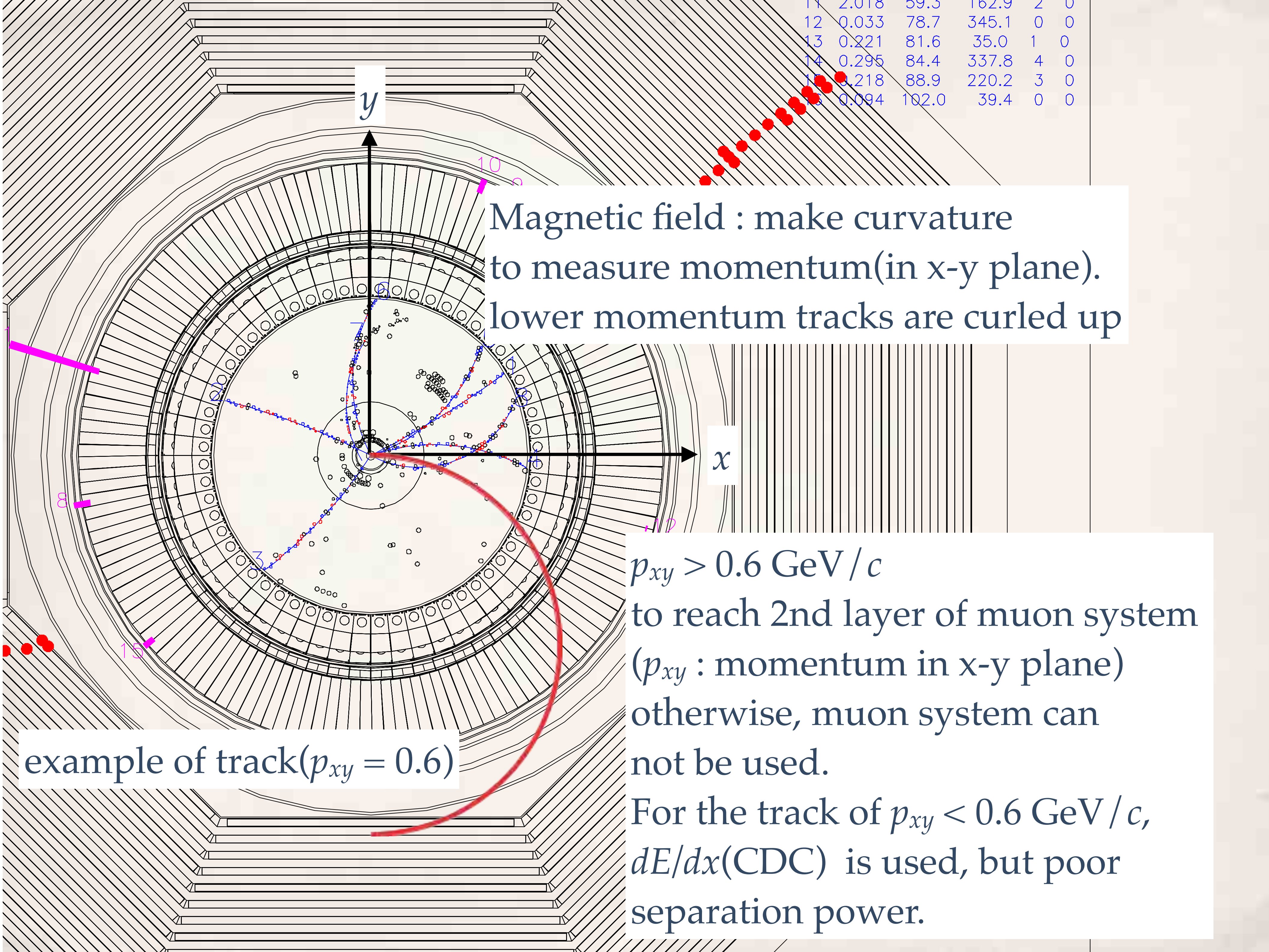




Muon detection (Belle)

Reconstruct hits in muon system





Magnetic field : make curvature
to measure momentum(in x-y plane).
lower momentum tracks are curled up

$p_{xy} > 0.6$ GeV / c
to reach 2nd layer of muon system
(p_{xy} : momentum in x-y plane)
otherwise, muon system can
not be used.
For the track of $p_{xy} < 0.6$ GeV / c,
dE/dx(CDC) is used, but poor
separation power.

example of track($p_{xy} = 0.6$)

- After tracking detector, heavy material is exist i.e. Calorimeter, Solenoid Magnet and muon system structure
  - large scattering angle is expected : directions between before and after heavy material is different
  - In many cases, muon system is built in flux return iron
    - direction of magnetic field is opposite that of inside of solenoid magnet.
    - inside of solenoid magnet : almost uniform both magnitude and direction
    - outside of solenoid : not uniform
  - simple extrapolation can not work in muon system

- Kalman filter like extrapolation

   1. extrapolate track parameter to the innermost layer of KLM and search hit point within search area

   2. update track parameter arrowing to make “kink” at the Calorimeter (kink point can be updated)

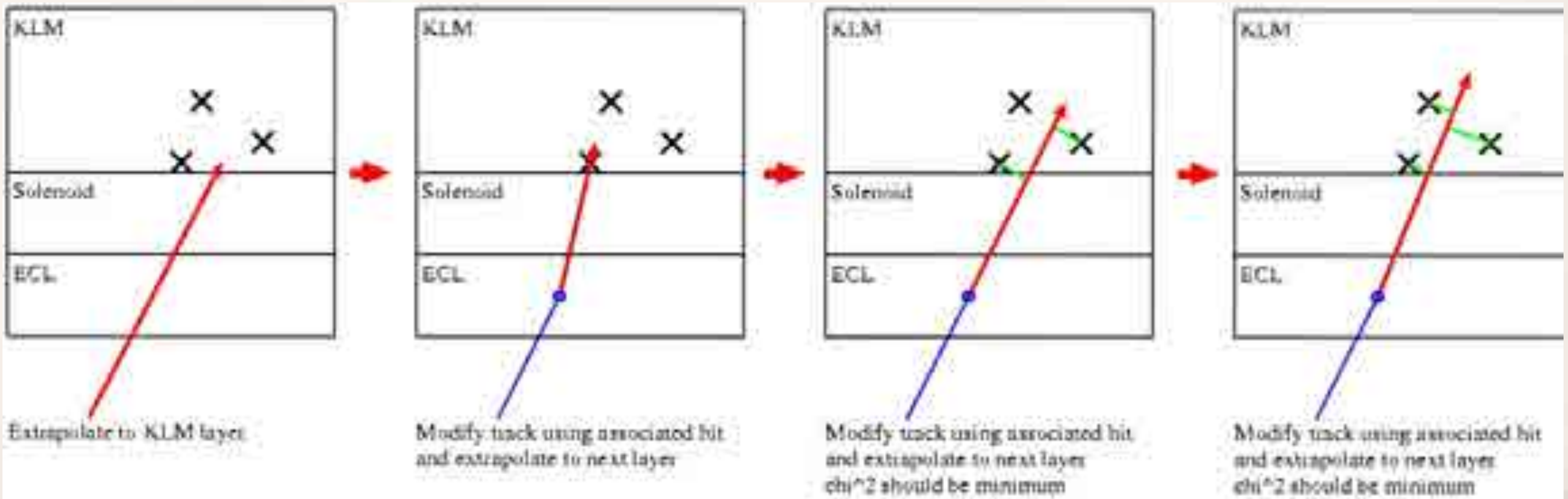
   3. extrapolate track parameter to the next layer and search hit point

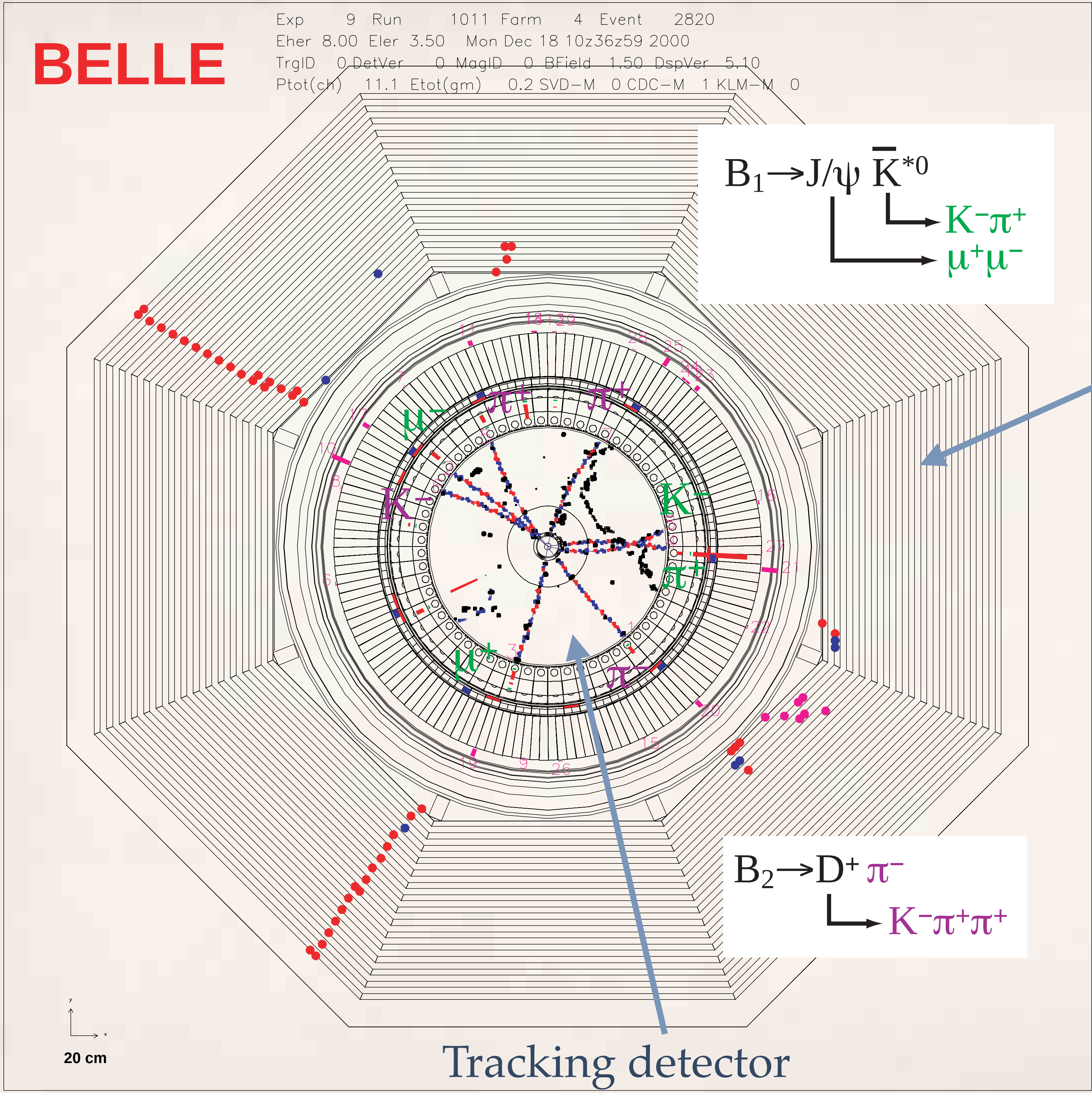
      - search area is depend on material in front of the next layer

      - if there is no hit point in the next layer, extrapolate one more layer

   4. repeat step 2 & 3 until outer most layer

   5. a set of hit points are formed





Reconstructed hits in detectors

Muon system (KLM)

Tracking detector

Muon identification

- Final state particle : electron, muon, pion, kaon, proton
- muon? or others(pion, kaon, proton, electron)?
- PID methods : dE/dx, ToF, Cherenkov, TRD etc.
- rough ratio $e : \mu : \pi : K : p \sim O(1) : O(1) : O(10) : O(1) : O(0.1)$
  - all charged tracks are assumed to be pion, among them select as electron ,muon, kaon or proton
  - pion is the most significant background
- e : electromagnetic shower, dE/dx
- K : Cherenkov, dE/dx, ToF

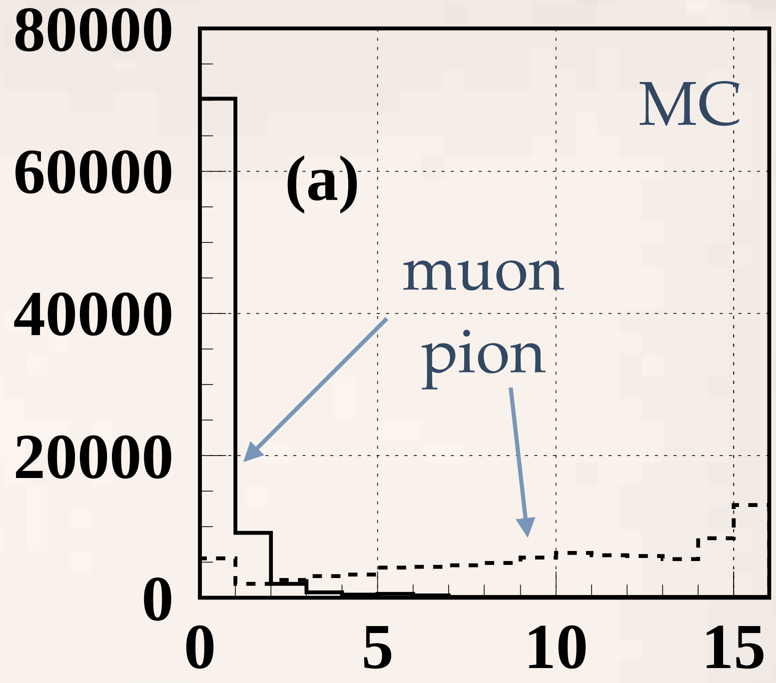
- muon 105.6 MeV $/ c^2$, pion 139.6 MeV $/ c^2$
  - similar mass : PID methods in previous page are not powerful for μ / π separation
    - Cherenkov : only narrow momentum region
    - dE/dx : very low momentum region
    - ToF : almost no hope
- difference : lepton or hadron → interaction with heavy material
  - Range
  - scattering
- To measure range and scattering, heavy material and sampling detector are the best combination

Range

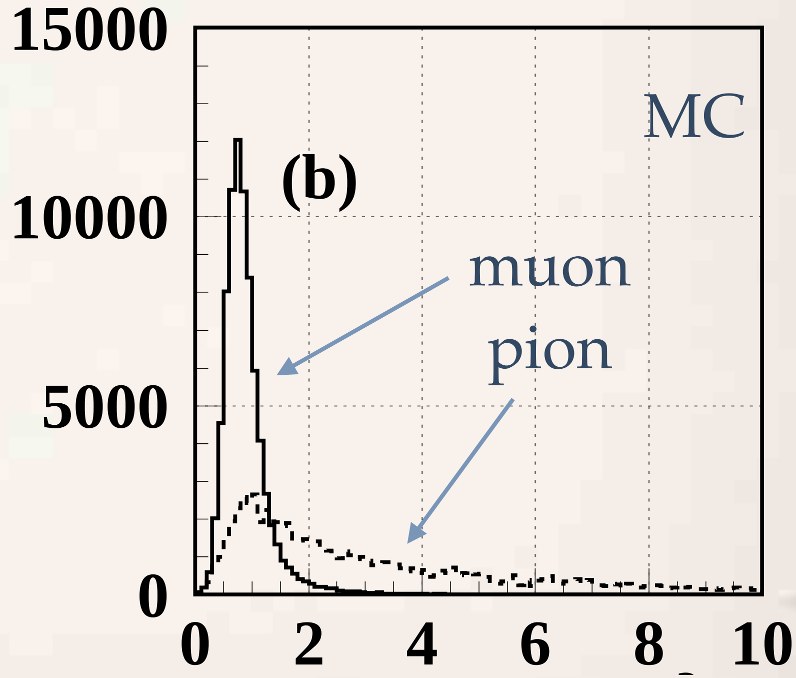
- passing through length in (heavy) material of the charged particle
- If the charged particle losses its energy only by electromagnetic interaction (i.e. lepton), range is defined by integrating dE/dx equation
  - electron : make electromagnetic shower
  - muon : pass through material without making shower (<1 TeV)
- hadron : hadronic interaction, 1 interaction length ~ 17 cm
  - pion : pass length < that of muon

material	ρ cm	radiation length		interaction length		Range (cm)			
		X	x	λ	x	0.5 GeV/	0.7 GeV/c	1.0 GeV/	1.5 GeV/
Fe	7.874	13.8	1.8	132	16.8	31.0	46.9	69.7	106.0

- Difference of the range is defined as
- ΔR = expected as muon - measured

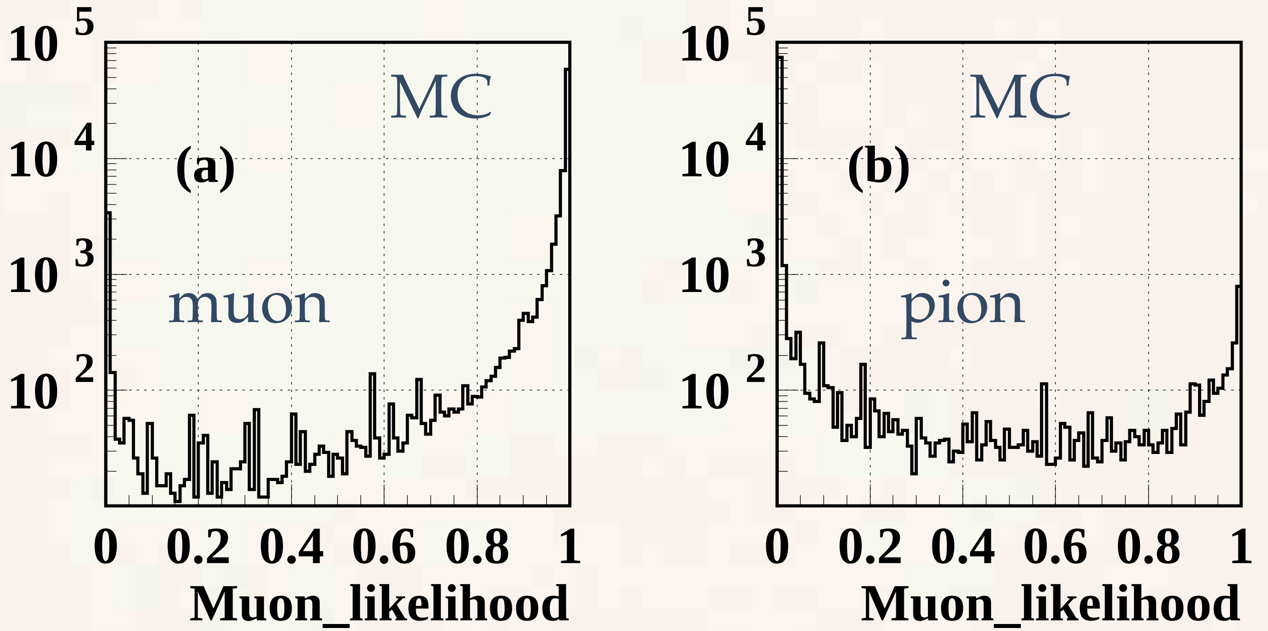


- $\chi^2/N = \Sigma(\text{hit point - expected point})^2/\sigma^2/N$
- to be valid, $N > 1$.
- to evaluate lateral scattering



- tracks penetrates muon system → only χ^2/N is used

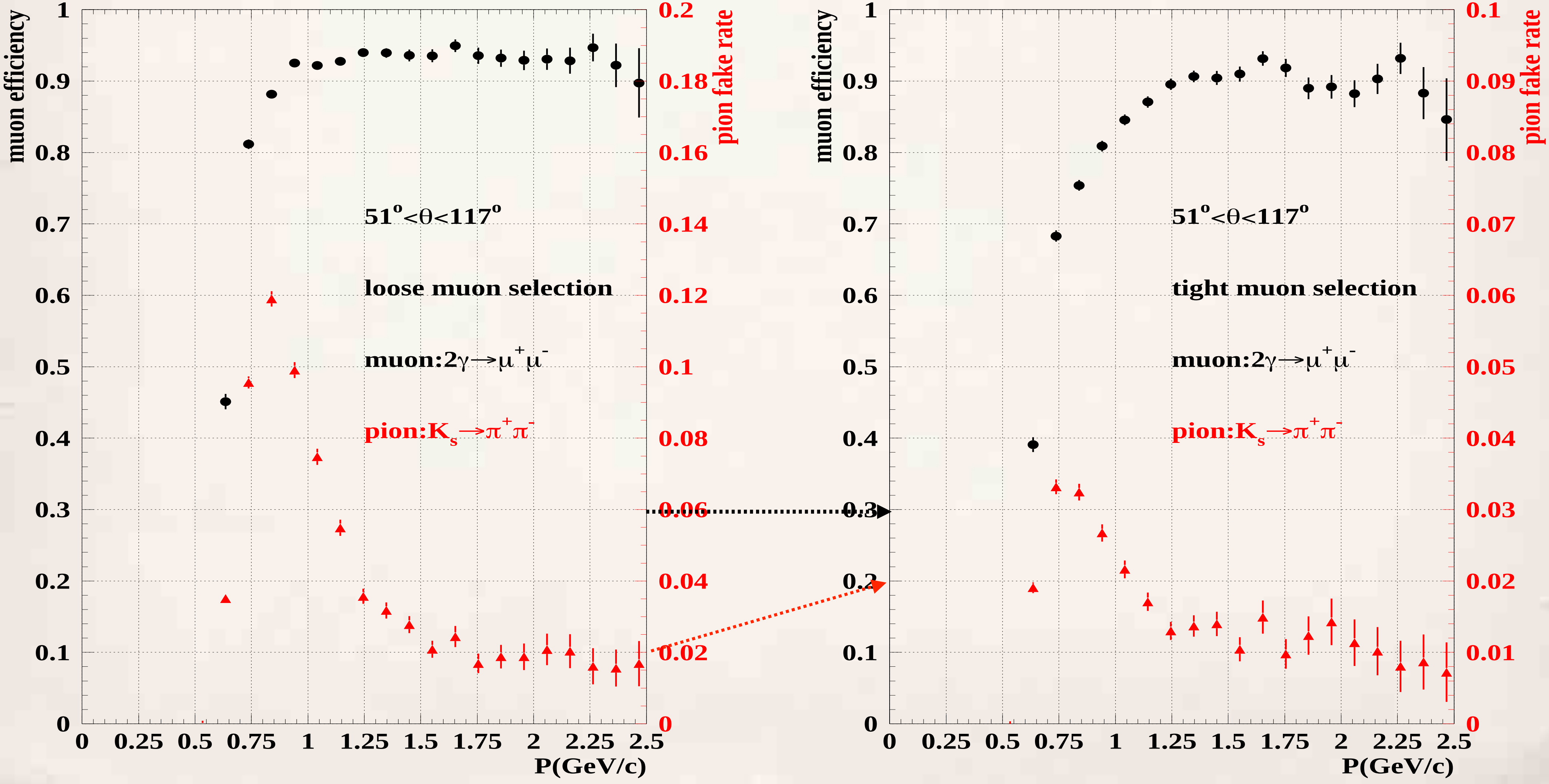
- Probability Density Functions of ΔR and $\chi^2/N \rightarrow$ muon likelihood is calculated



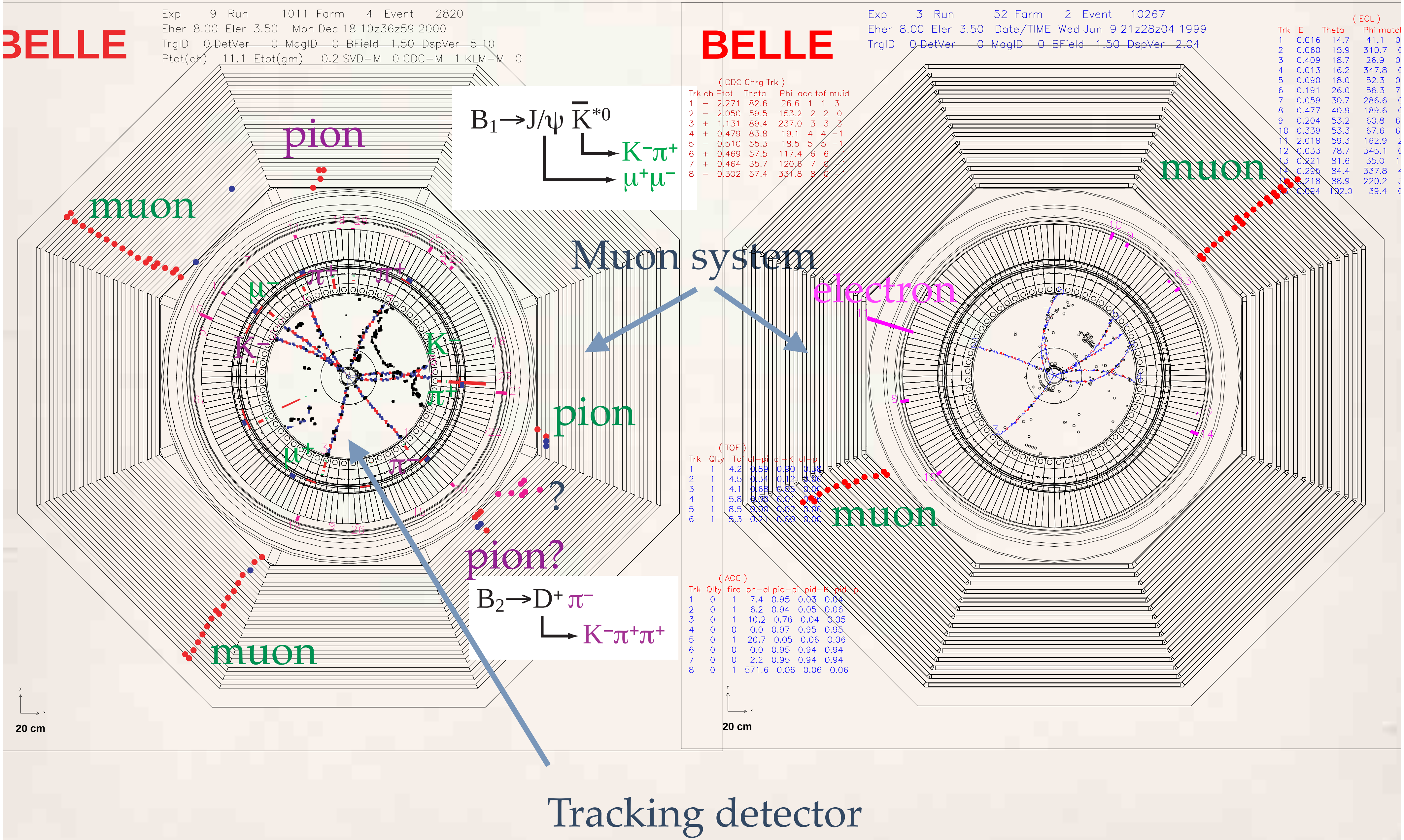
- some amount of pion(kaon) can has high muon likelihood → not completely remove pion(kaon). muon efficiency and pion(kaon) mis-identification are trade-off relation.

- i.e. muon is selected by applying Muon_likelihood > 0.9. Pions or kaons has possibility to be selected as muon candidate.

- example of efficiency and mis-identification
- loose cut : high efficiency & high fake rate(mis-identification)
- tight cut : slightly lower efficiency & low fake rate



Tracks identified as muon



Trigger system

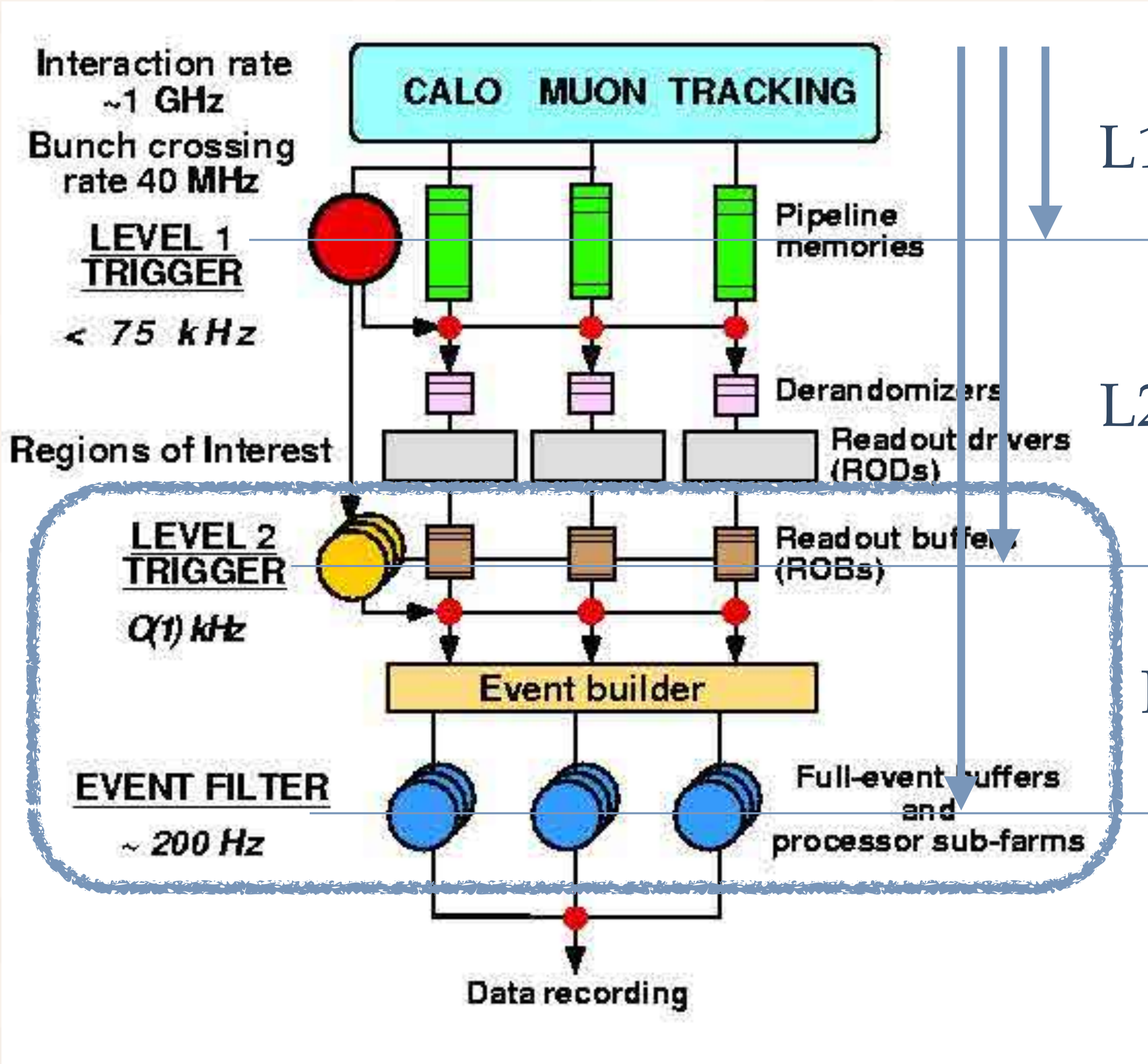
Why trigger is necessary?

- If data transfer time is zero and we have infinite data storage, trigger system is not necessary.
  - signal can be selected at offline from saved data which includes background. And we need huge CPU power.
- In actually, data transfer takes time and data storage is limited.
  - background rejection at online level
  - Level-1 : hardware
  - HLT : software
- Trigger decision should be done within $O(1)$ μs : limited by memory size of DAQ system

Muon Trigger

- muon system is located outermost place of the detector
- to reach muon system, high transverse momentum (p_t) is necessary
- high-p_t muon : feature of heavy quark decay
- muon as decay product of new particle or signal of Higgs decay
- events including muons should be recorded as much as possible

ATLAS

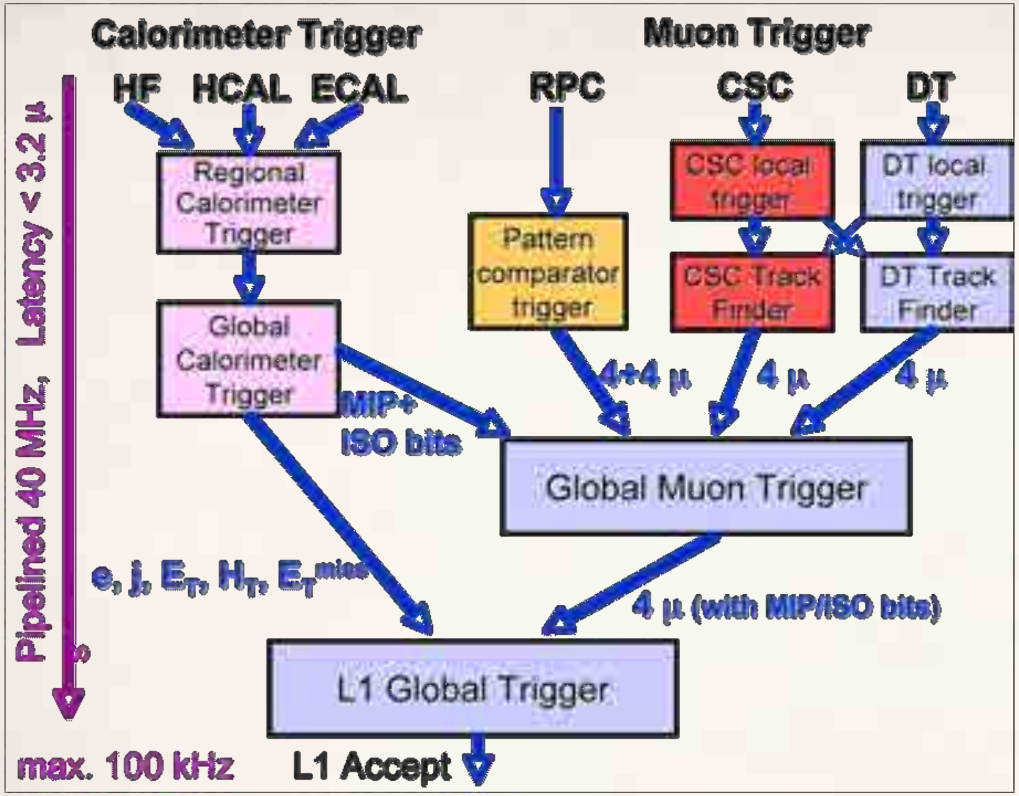


L1 ~ 2.5 μs

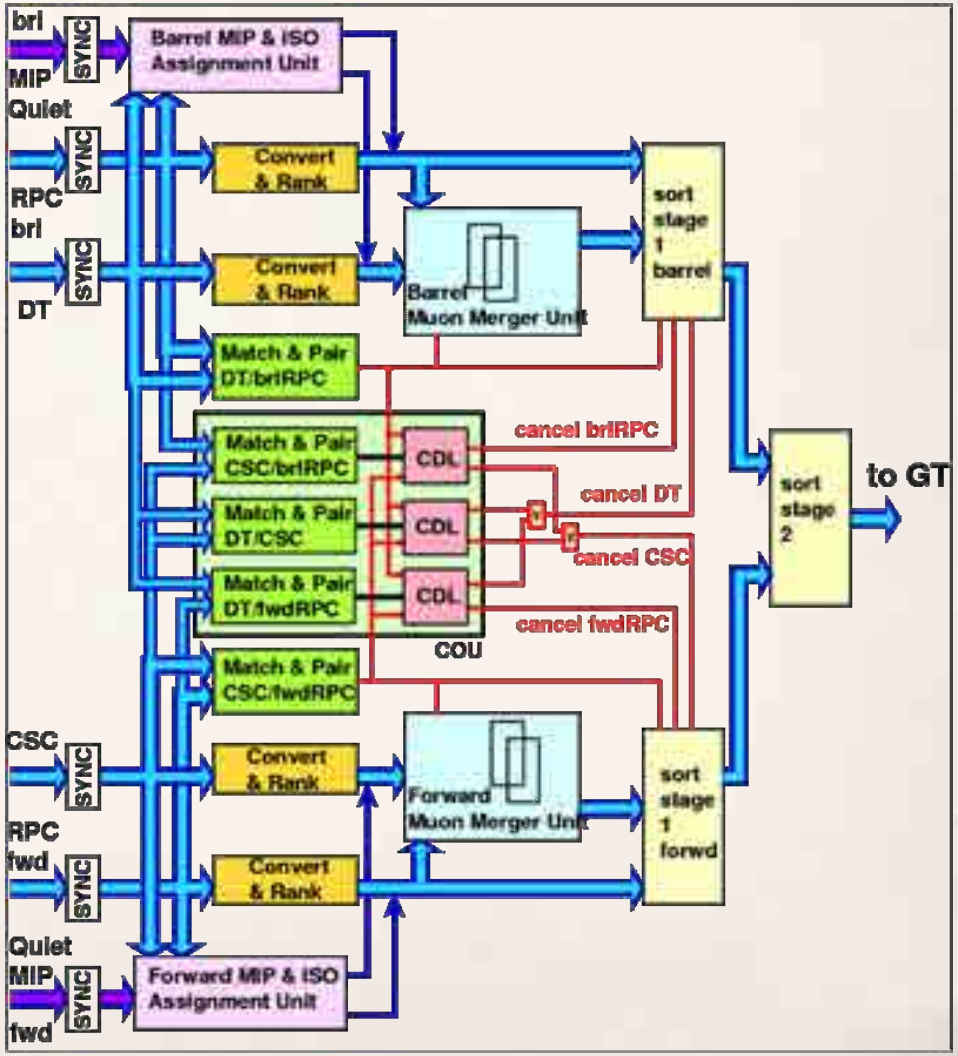
L2 ~ 40 ms

EF ~ 4 s

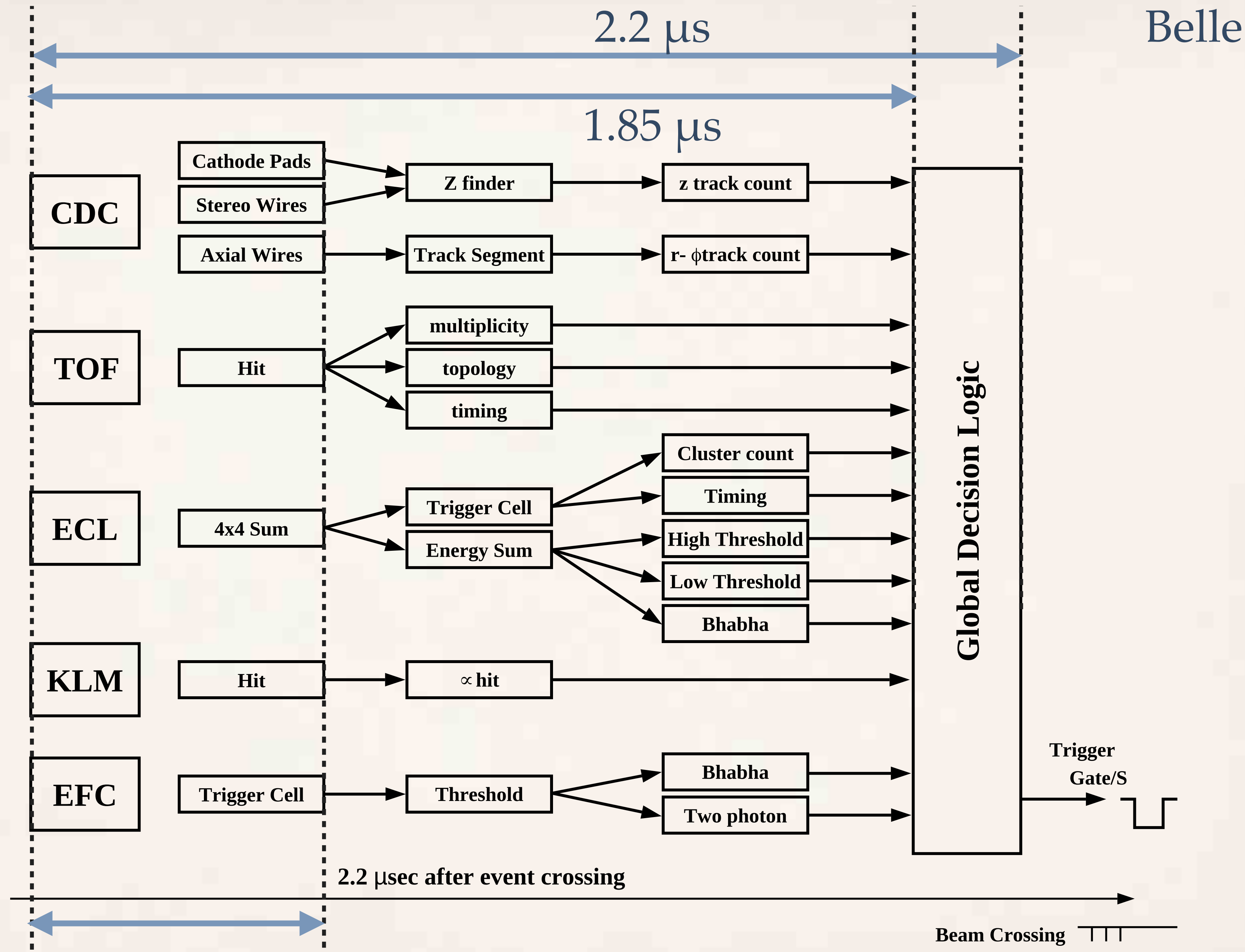
Latency : time costed by decision logic and delay time in cable



Calorimeter Trigger
Muon Trigger
HF
HCAL
ECAL
RPC
CSC
DT
Regional Calorimeter Trigger
CSC local trigger
DT local trigger
Pattern comparator trigger
CSC Track Finder
DT Track Finder
Global Calorimeter Trigger
4+4 μ
4 μ
4 μ
MIP+ ISO bits
Global Muon Trigger
Pipelined 40 MHz, Latency < 3.2 μs
e, j, E_T, H_T, E_T^miss
4 μ (with MIP/ISO bits)
L1 Global Trigger
max. 100 kHz
L1 Accept



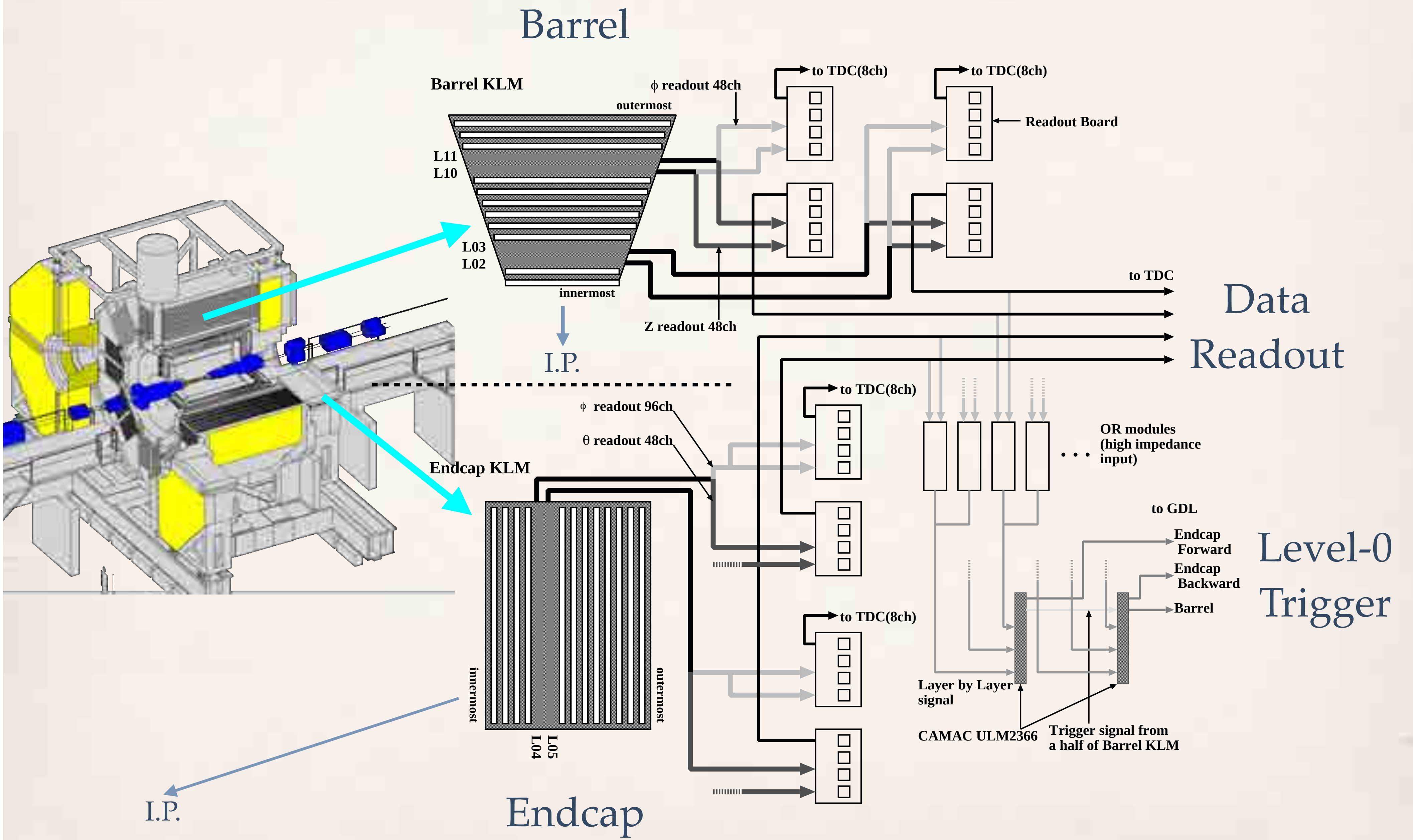
brl
MIP
Quiet
SYNC
Barrel MIP & ISO Assignment Unit
RPC brl
DT
Convert & Rank
Convert & Rank
Barrel Muon Merger Unit
sort stage 1 barrel
Match & Pair DT/brlRPC
Match & Pair CSC/brlRPC
Match & Pair DT/CSC
Match & Pair DT/fwdRPC
CDL
CDL
CDL
COU
cancel brlRPC
cancel DT
cancel CSC
cancel fwdRPC
sort stage 2
to GT
Match & Pair CSC/fwdRPC
CSC
RPC fwd
Convert & Rank
Convert & Rank
Forward Muon Merger Unit
sort stage 1 forwd
Quiet
MIP
fwd
Forward MIP & ISO Assignment Unit



(Drift, propagation)
Amplify, Shaping, Digitize and Cable Delay

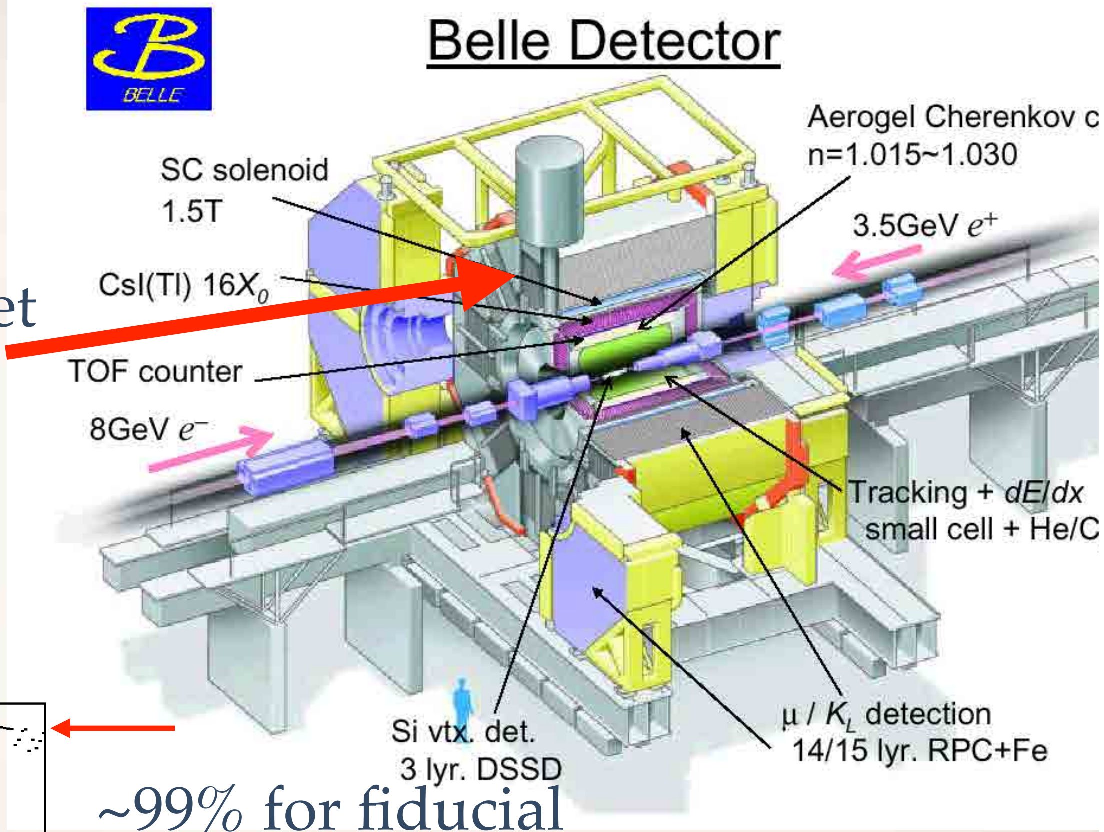
Belle Muon Trigger

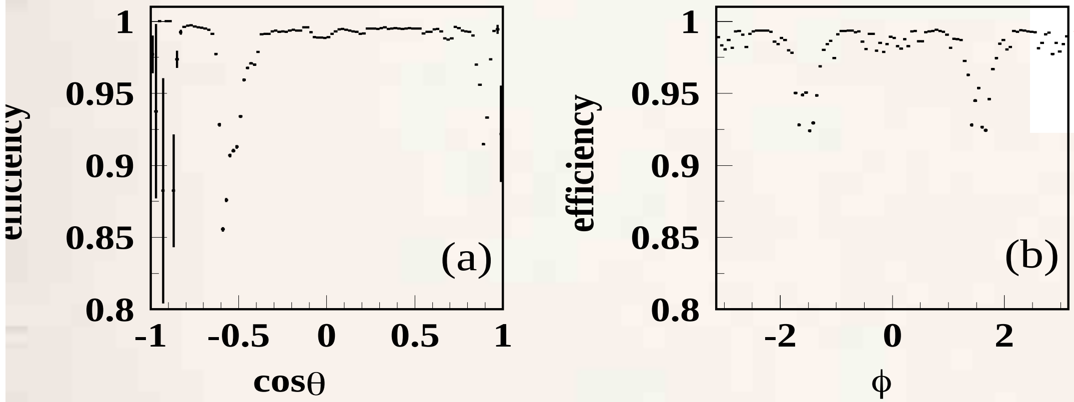
- One of Sources of Level-1 trigger
- To select interesting events : ex. $J/\psi \to \mu\mu$
  - ~2% level inefficiency
  - Redundancy is guaranteed by Track trigger for muon inclusive events
  - purity is not so important
  - efficiency
  - Background might be rejected by Track trigger
    - note : to reconstruct muon, tracking information should be exist


Barrel
Barrel KLM
ϕ readout 48ch
outermost
L11
L10
L03
L02
innermost
Z readout 48ch
I.P.
to TDC(8ch)
to TDC(8ch)
Readout Board
to TDC
Data
Readout
Endcap KLM
ϕ readout 96ch
θ readout 48ch
innermost
outermost
L04
L05
to TDC(8ch)
to TDC(8ch)
OR modules
(high impedance
input)
to GDL
Endcap
Forward
Endcap
Backward
Barrel
Level-0
Trigger
Layer by Layer
signal
CAMAC ULM2366
Trigger signal from
a half of Barrel KLM
I.P.
Endcap

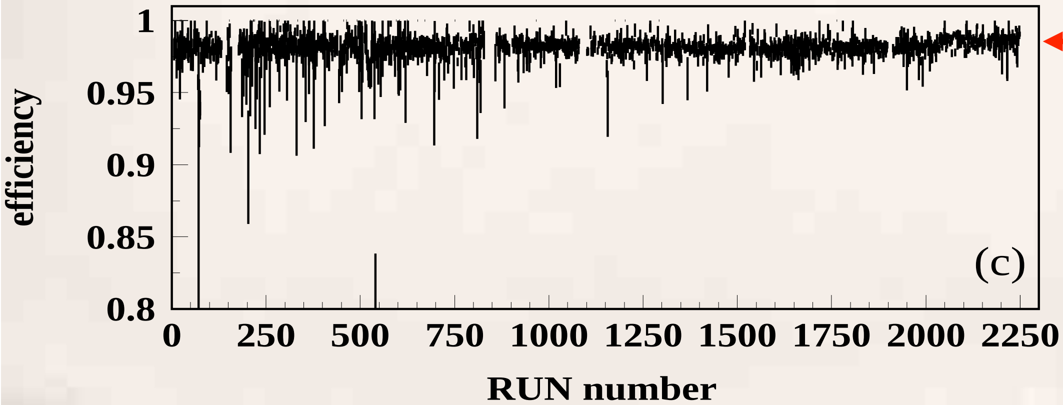
inefficiency caused by
the chimney for solenoid magnet

by product of data sample
for this analys





~99% for fiducial
of KLM



~98% including
inefficient region

K_L detection (Belle)

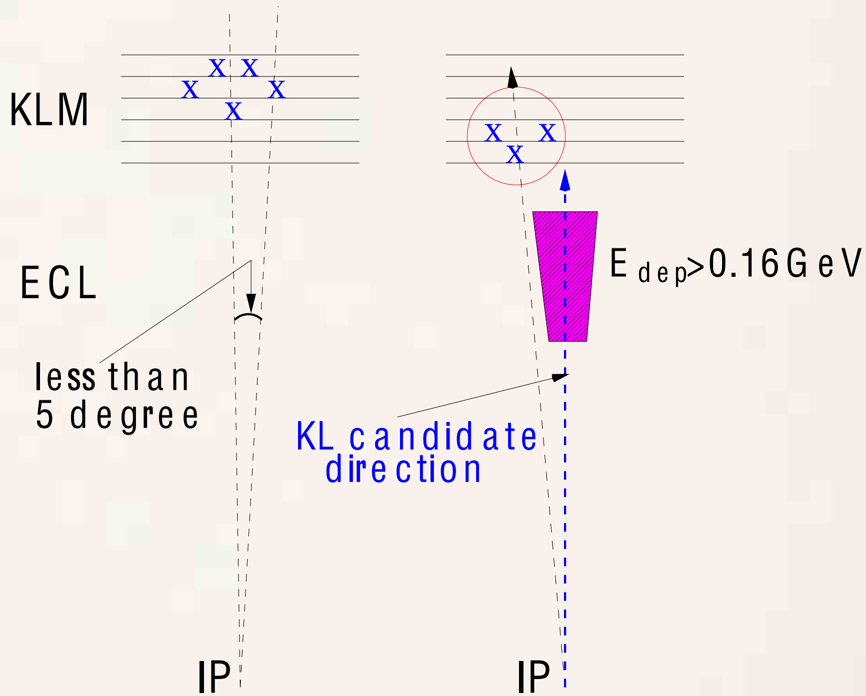
- K_L : neutral hadron, life time ~50 ns, $c\tau$ ~15 m
- K_L escapes detector if we wait K_L decay
  - hadronic interactions between K_L and materials (Calorimeter or iron yoke)

- muon system is also used as K_L detector
- In front of muon system, calorimeter exists
  - CsI(Tl) : $\rho = 4.51$ g/cm^3, $X_0 = 1.86$ cm, $\lambda_I = 39.3$ cm
- 30 cm CsI(Tl) $\rightarrow 16.1 X_0$, $0.76 \lambda_I$
- How to detect K_L
  - signals in calorimeter or muon system
  - define K_L direction
  - not associated with charged track

- K_L + Fe → hadronic shower (charged particle)

- signals in KLM are combined if those are located within 5° opening angle from interaction point(I.P.). I.P. is regarded as origin of K_L

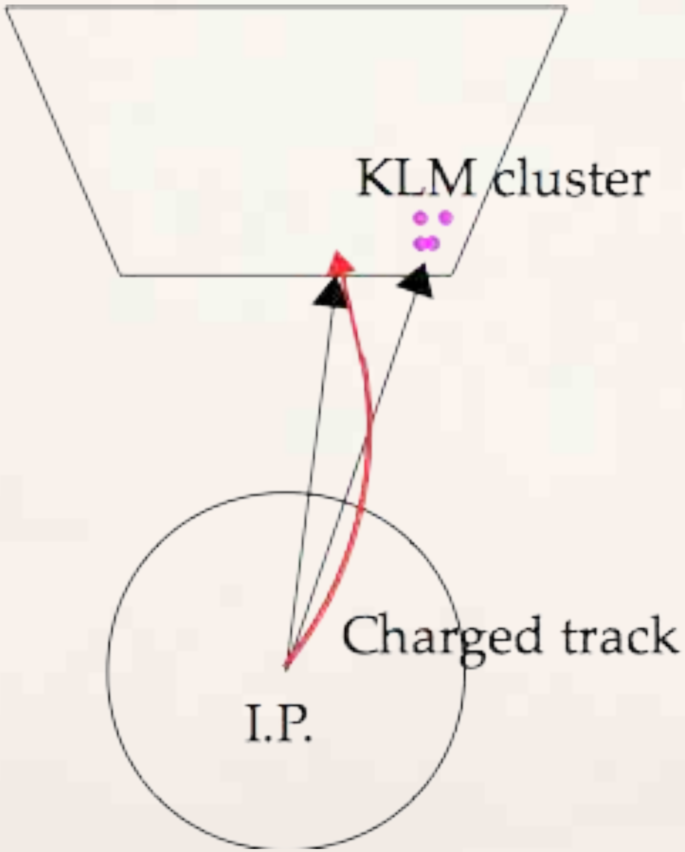
- this process is repeated until there is no signal within 5° opening angle → KLM cluster

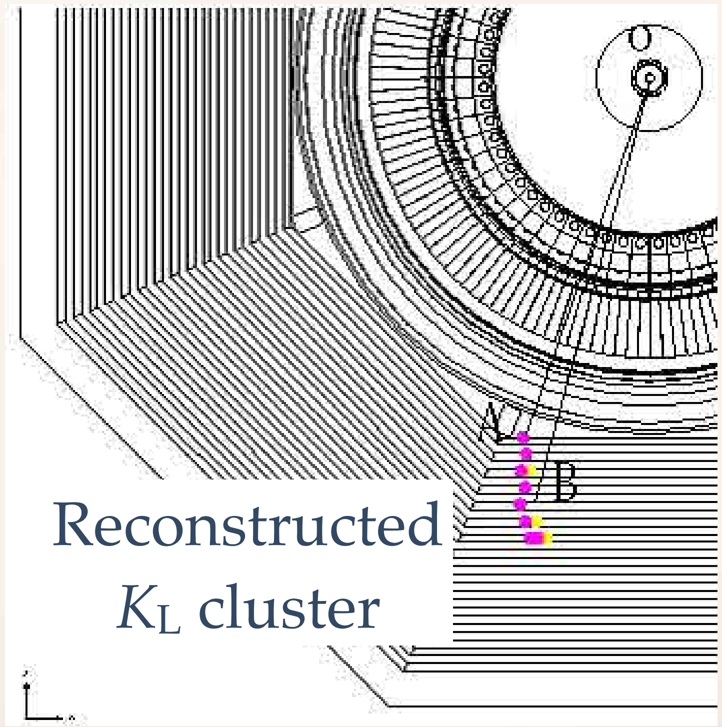


- If the opening angle between KLM cluster and calorimeter cluster of $E > 0.16$ GeV, this cluster is accosted with the KLM cluster

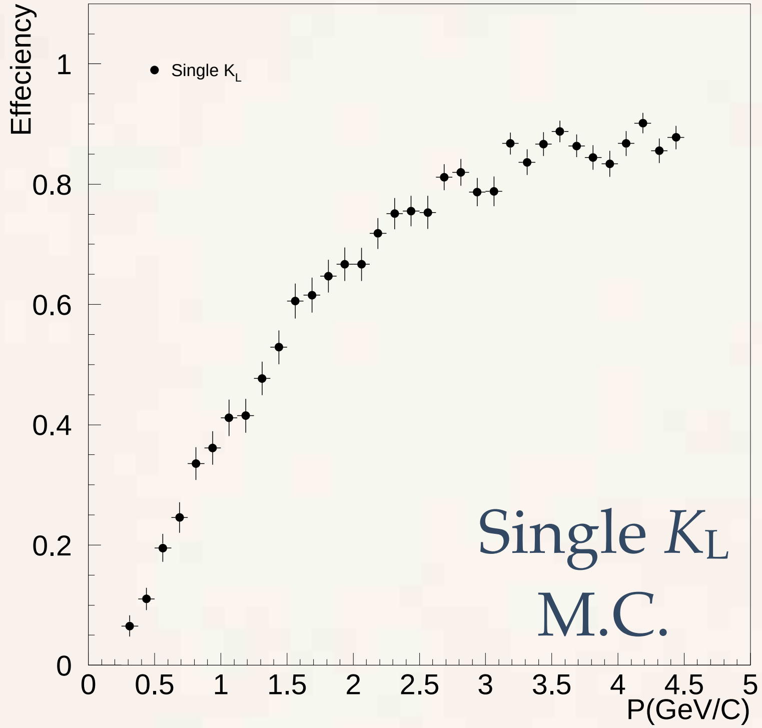
- When the KLM cluster only, 2 or more KLM layer have signals to eliminate background
    - direction of the KLM cluster is direction of the K_{L} candidates
    - If the calorimeter cluster is associated, direction of the calorimeter cluster is direction of the K_{L} candidates

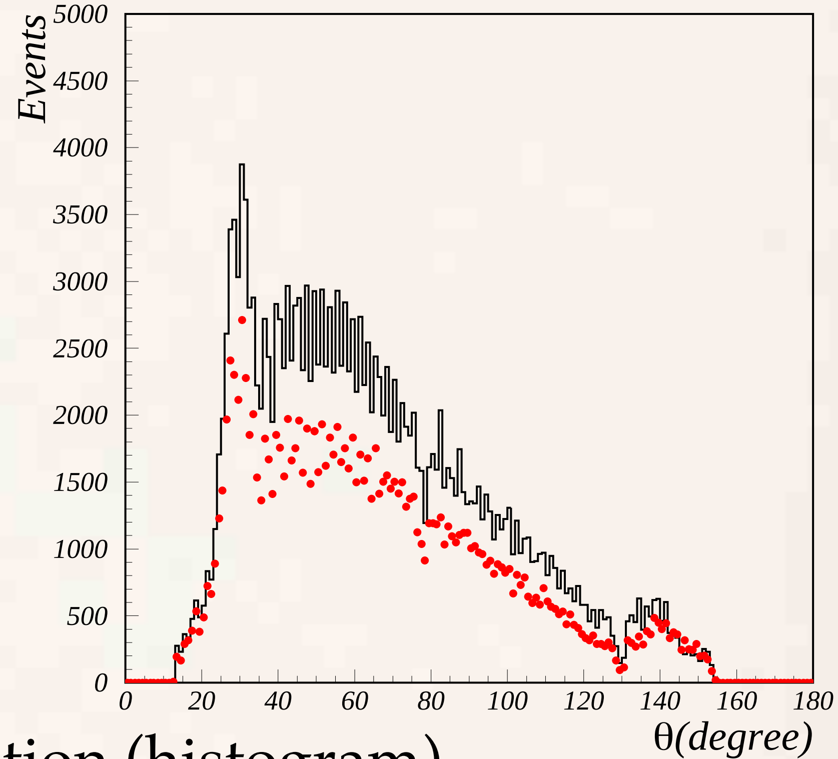
- charged track is extrapolated to the KLM and make straight line between extrapolated point and IP.
- If the opening angle between KLM cluster and this line is greater than 15°, this cluster is neutral cluster.



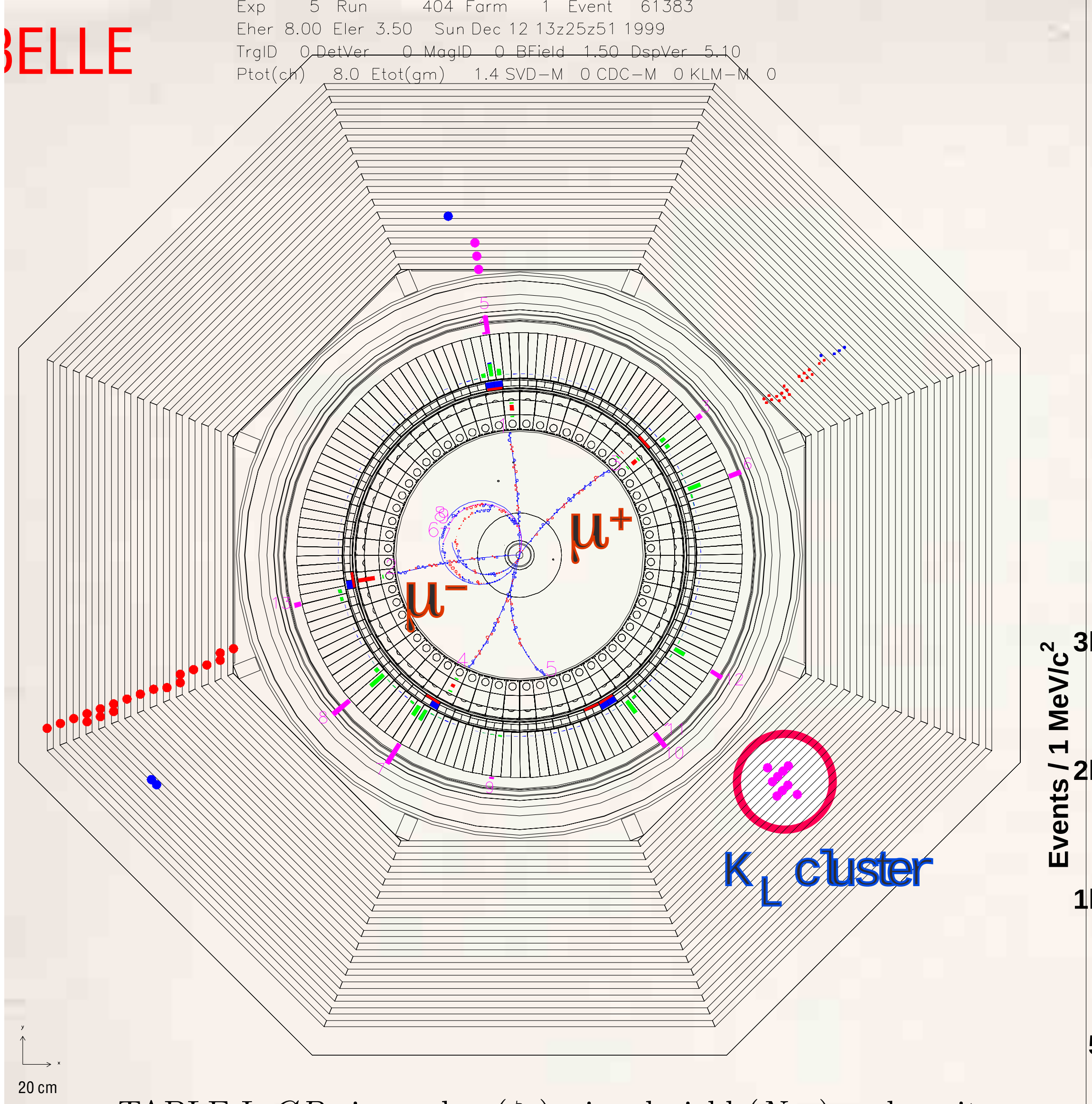


- K_L detection efficiency in KLM





- comparison with MonteCarlo simulation (histogram)
  - red : data, lower than M.C.
- K_L : mainly used for $\sin 2\phi_1$ measurements
  - veto for $B \to D^{(*)}\tau\nu$



PRL108(2012)171802

$B^0 \to (cc)K_S$ $\qquad$ $B^0 \to J/\psi K_L$

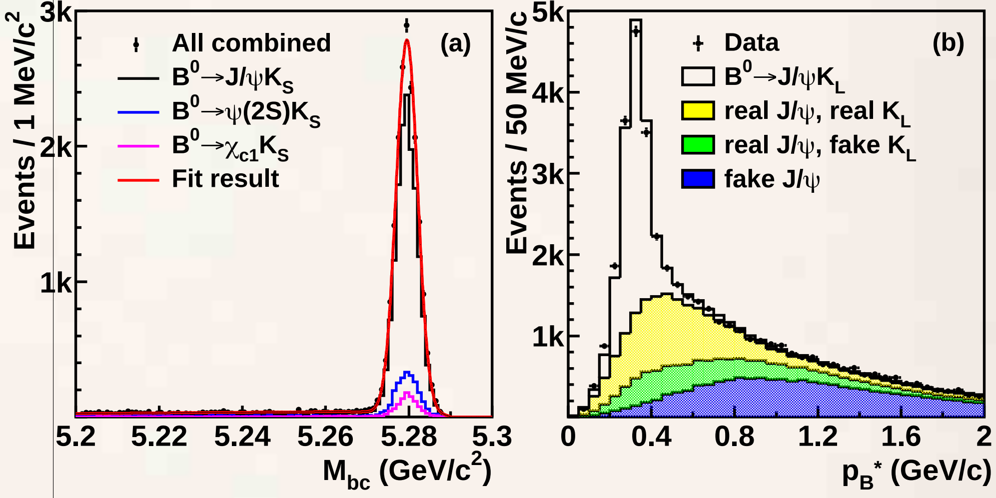


FIG. 1: (color online). (a) $M_{\rm bc}$ distribution within the ΔE signal region for $B^0 \to J/\psi K_S^0$ (black), $\psi(2S)K_S^0$ (blue), and $\chi_{c1}K_S^0$ (magenta); the superimposed curve (red) shows the combined fit result for all these modes. (b) p_B^* distribution of $B^0 \to J/\psi K_L^0$ candidates with the results of the fit separately indicated as signal (open histogram), background with a real J/ψ and real K_L^0's (yellow), with a real J/ψ and a fake K_L^0 candidate (green), and with a fake J/ψ (blue).

TABLE I: CP eigenvalue (ξ_f), signal yield ($N_{\rm sig}$) and purity for each $B^0 \to f_{CP}$ mode.

Decay mode	ξ_f	$N_{\rm sig}$	Purity (%)
$J/\psi K_S^0$	-1	12649 ± 114	97
$\psi(2S)(\ell^+\ell^-)K_S^0$	-1	904 ± 31	92
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$	-1	1067 ± 33	90
$\chi_{c1}K_S^0$	-1	940 ± 33	86
$J/\psi K_L^0$	$+1$	10040 ± 154	63

Neutron (Belle)

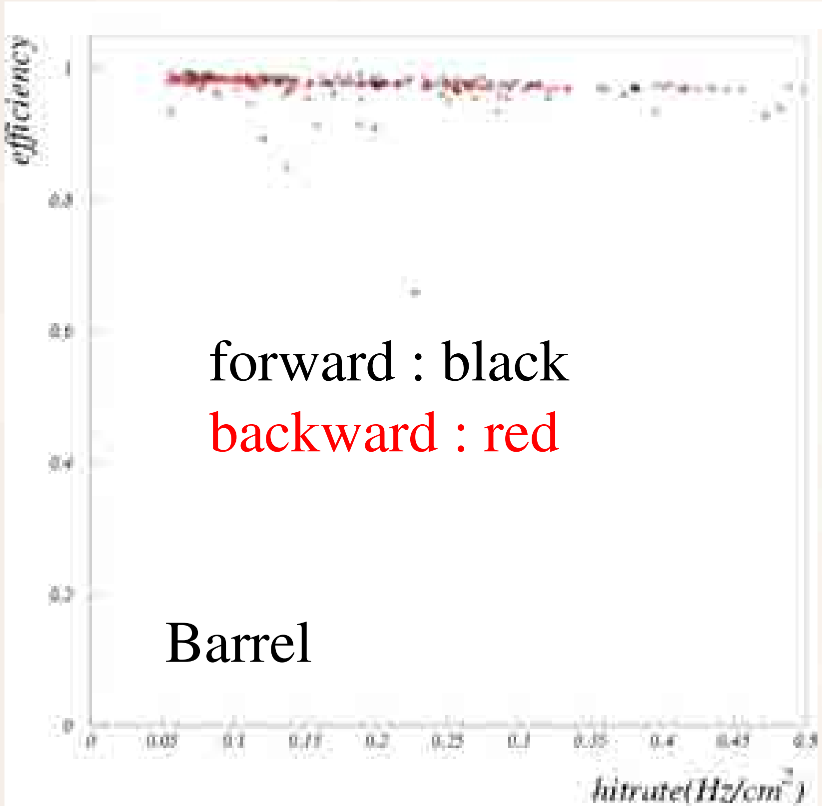
- Neutron in Decay processes is not used for physics analysis
- In Belle exp., neutron background study was carried out to understand background source and also for future project

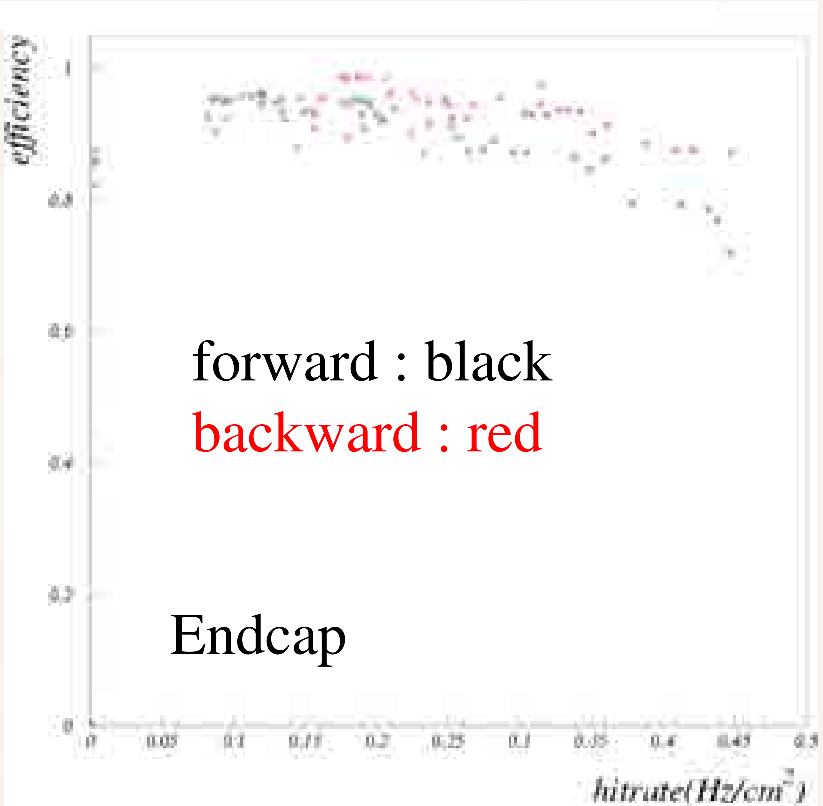
Motivation

- Beginning of Belle, background was unexpectedly high level
- At first, γ ray was thought as background
- lead shield was set
- possibility of neutron was also checked
- Because efficiency of detector for the KLM is strongly depend on hit rate

cosmic ray
~0.01 Hz / cm^2

Efficiency of the KLM detector vs hit rate

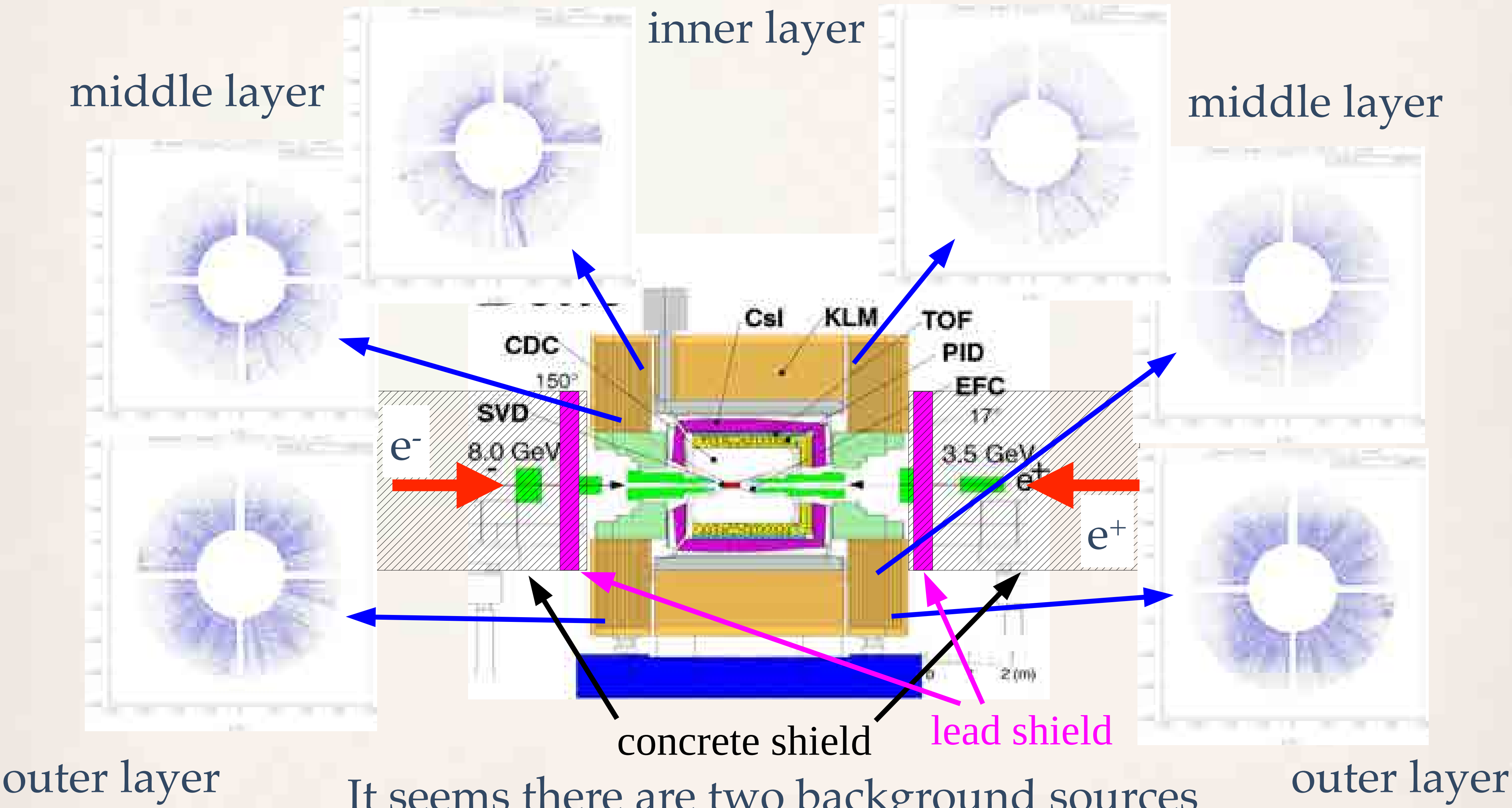




Barrel was made by U.S. glass
Endcap was made by Japan glass

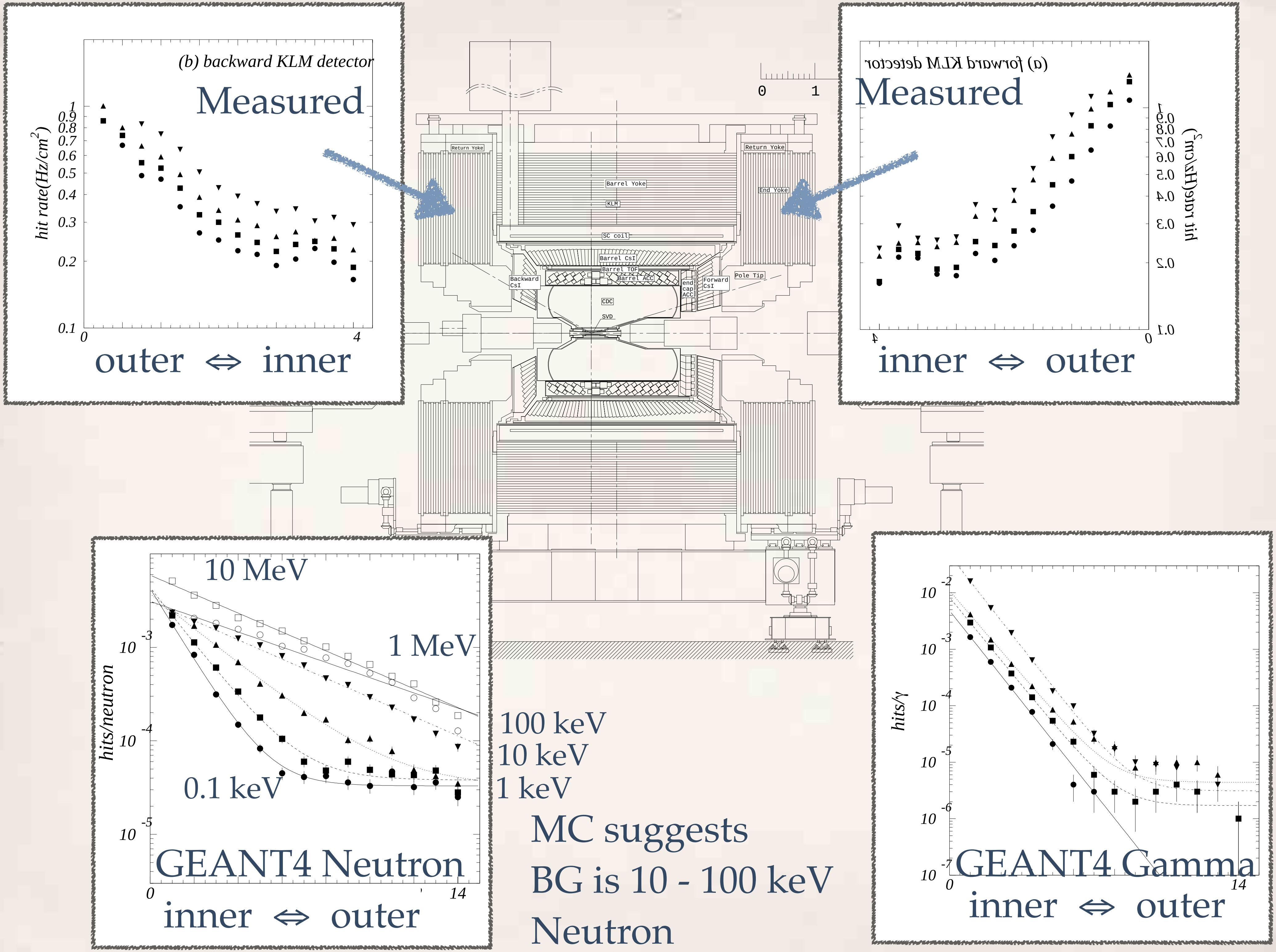
Identify or understand sources of the background
is very important

Result of background measurement

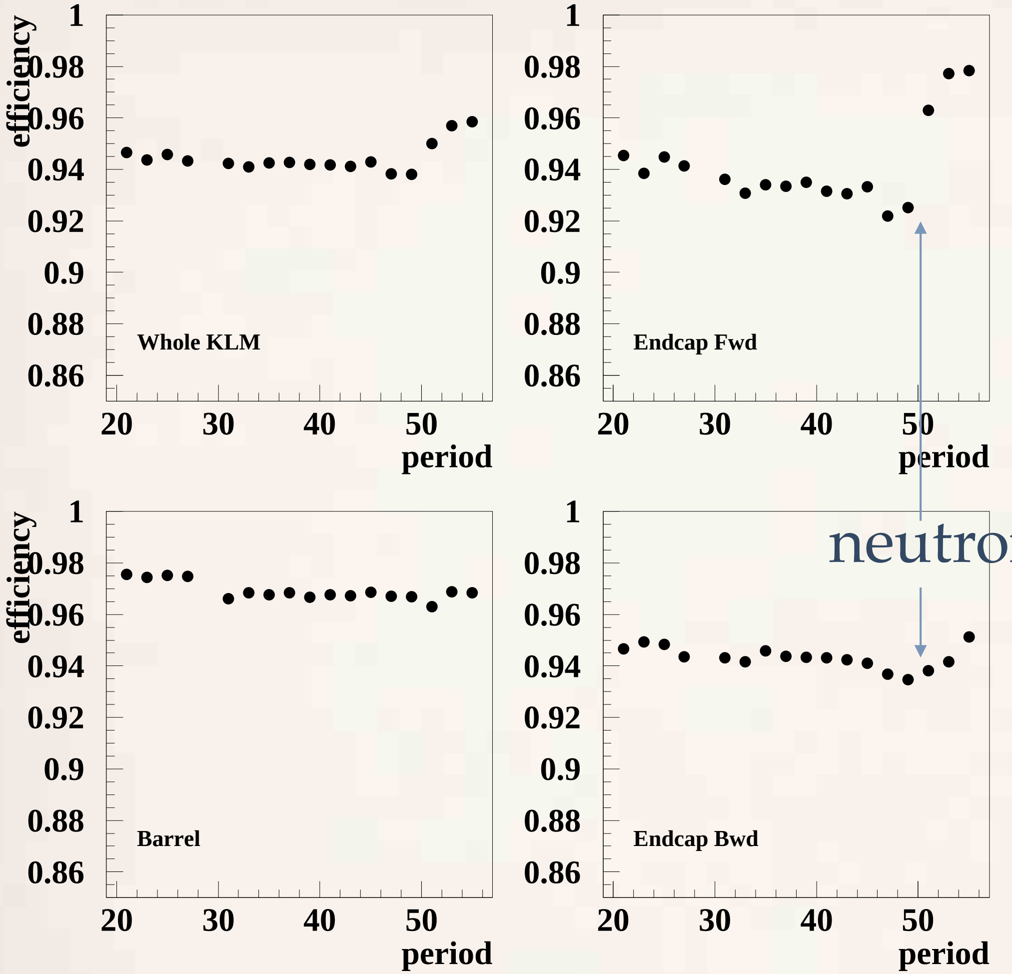


It seems there are two background sources

- upstream of beam
- around beam pipe near the detector


(b) backward KLM detector
Measured
hit rate(Hz/cm^2)
outer ⇔ inner
(a) forward KLM detector
Measured
hit rate(Hz/cm^2)
inner ⇔ outer
Return Yoke
Barrel Yoke
End Yoke
KLM
SC coil
Barrel CsI
Barrel TOF
Barrel ACC
Backward CsI
Forward CsI
end cap ACC
Pole Tip
CDC
SVD
10 MeV
1 MeV
100 keV
10 keV
1 keV
0.1 keV
hits/neutron
GEANT4 Neutron
inner ⇔ outer
hits/γ
GEANT4 Gamma
inner ⇔ outer
MC suggests
BG is 10 - 100 keV
Neutron

muon identification efficiency vs time



neutron background shield was installed

rate was increased by time

It is confirmed that
main background is neutron

- Background source
  - beam-gas : $\propto$ beam current(I) $\times$ vacuum(V)
  - Touschek : density of beam bunch, $\propto I^2$
  - radiative Bhabha : $\propto$ luminosity(L)
- also depend on location of accelerator components
- mechanism of neutron background
  - 10~30 MeV photon from bremsstrahlung of electron
  - giant photonuclear resonance reaction (γ, n)
  - more higher energy photon, photonpion production is increase

- Estimated hit rate and efficiency
  - only extrapolation with some assumption
  - with modification for barrel KLM

Replaced by Scintillator

Barrel	item	extrapolation	modification
L00	rate(Hz/cm	7.5	7.5
	efficiency	0.38	1.0
L01	rate(Hz/cm	4.0	2.7
	efficiency	0.67	1.0
L02	rate(Hz/cm	2.0	0.9
	efficiency	0.83	0.93

- In Belle II, part of Belle KLM will be used for barrel part

Detector for muon system

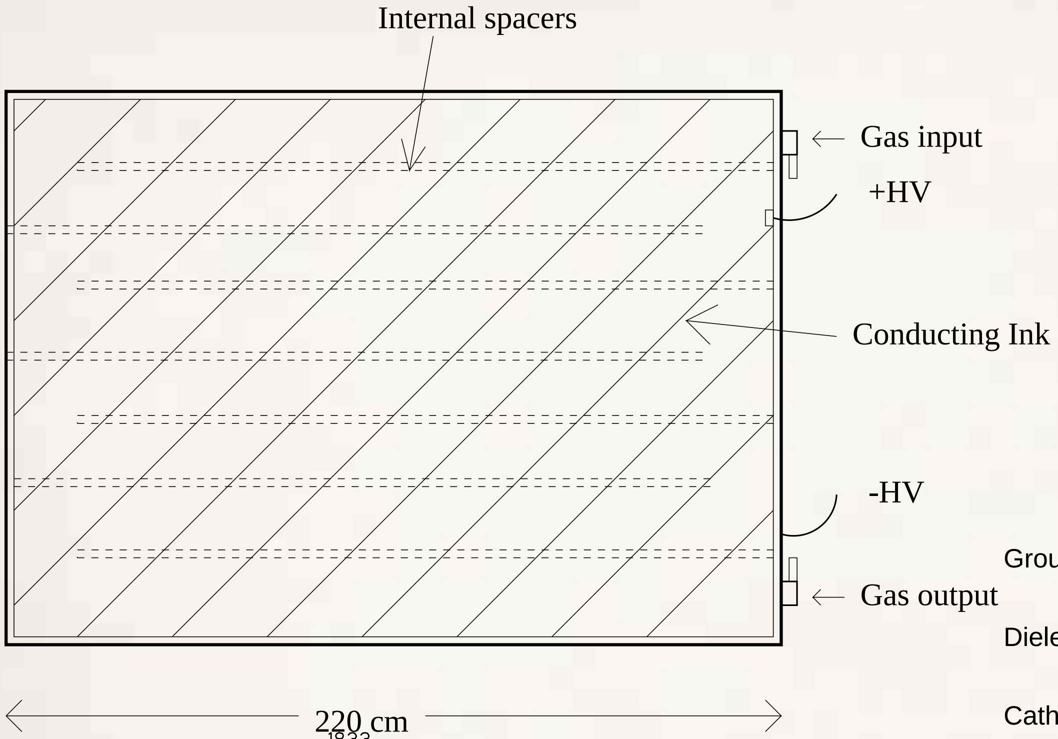
- Located at the outermost of the detector system
  - Sampling
- Covers large area and many layers
  - Detector cost should be lower
  - semi-conductor or cristal can not be used
  - semi-conductor is too fine to use as muon detector

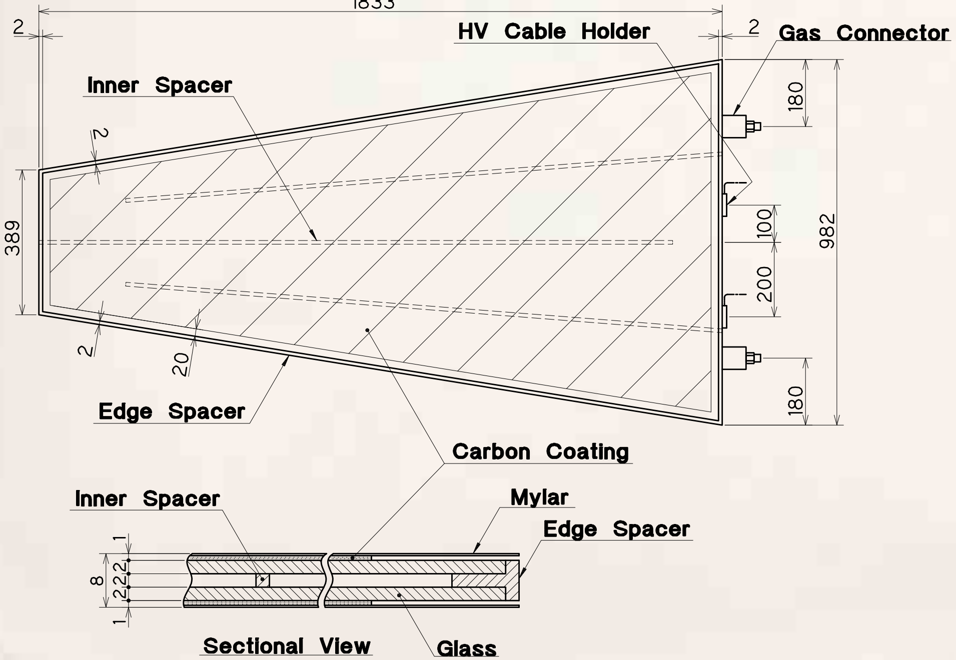
- To cover large area and many layers with reasonable number of channel electronics
  - streamer tube
  - RPC(streamer mode or avalanche mode)
  - Thin Gap Chamber
  - etc.
- Gaseous detector is the candidate
- cheap, easy to make for large area

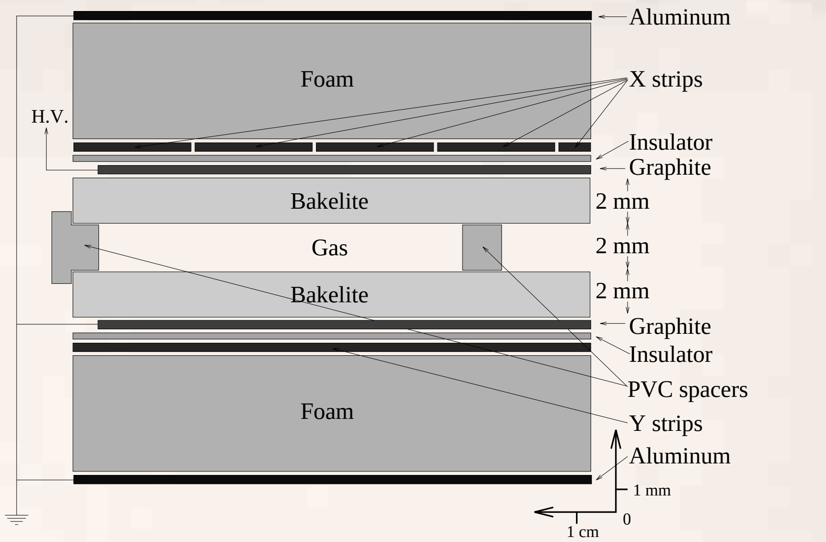
Resistive Plate Chamber (RPC)

- One of gaseous detector
- Developed by R. Santonico et al.(NIM 187(1981). 377)
- streamer mode(earlier) → avalanche mode(later)
- gap between Resistive Plates are filled by gas
- Resistive Plate
  - Bakelite → Glass
- Thinner gap makes excellent timing resolution (~20 ps) : ToF application

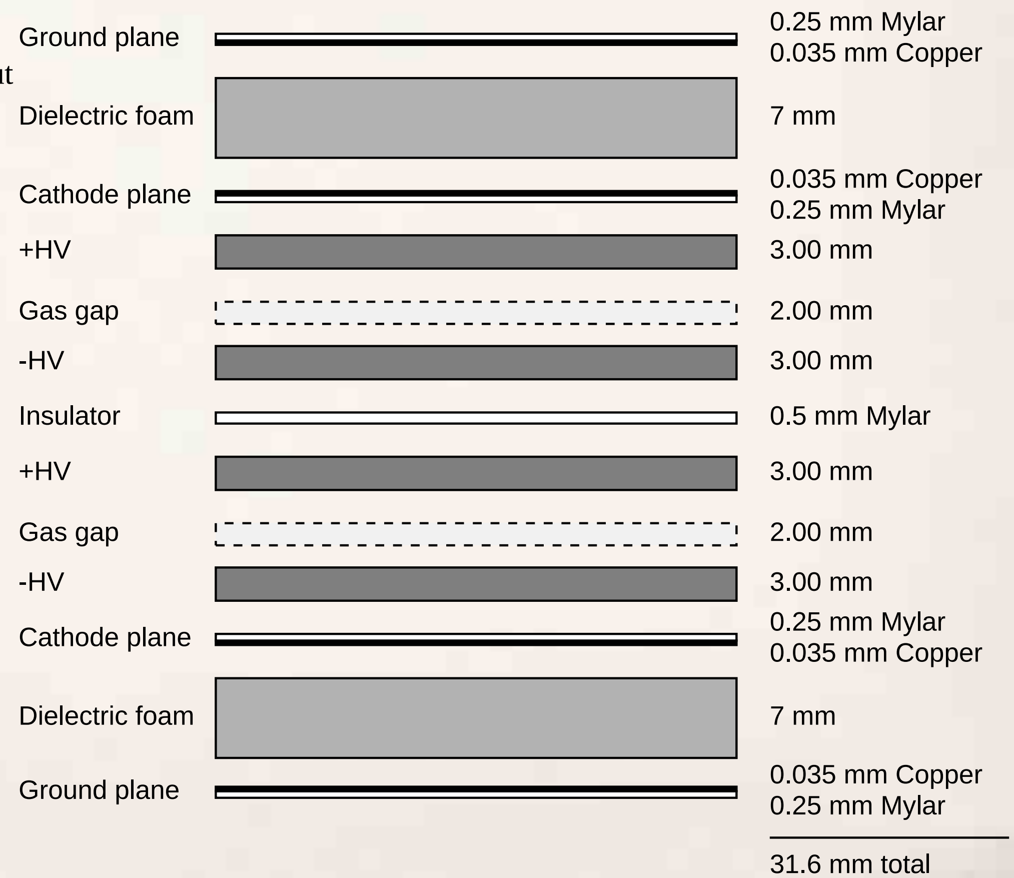
Belle RPC

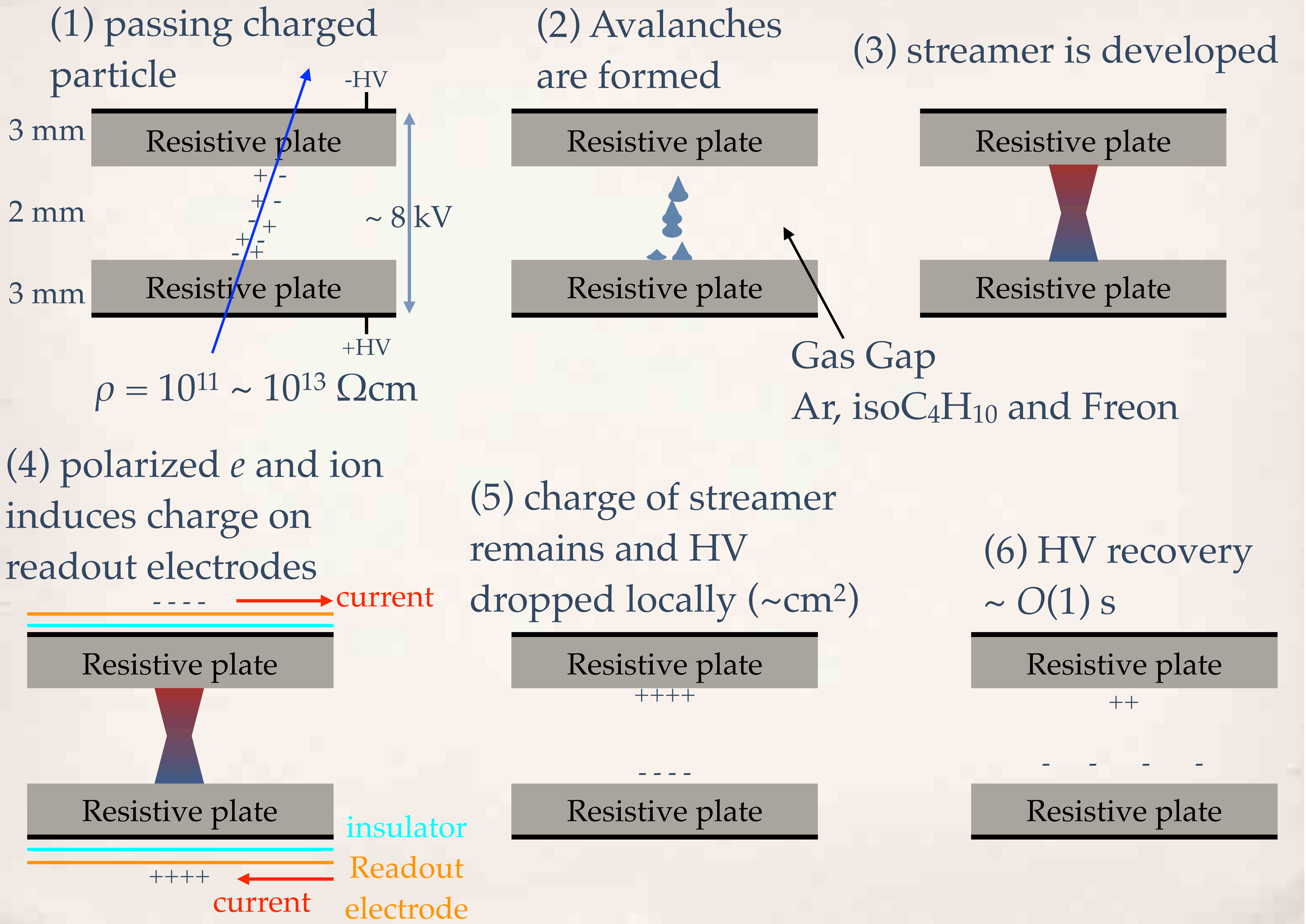






BaBar RPC




(1) passing charged particle
-HV
3 mm
Resistive plate
2 mm
+ -
+ -
- +
+ -
- +
~ 8 kV
3 mm
Resistive plate
+HV
$\rho = 10^{11} \sim 10^{13}$ Ωcm
(2) Avalanches are formed
Resistive plate
Resistive plate
Gas Gap
Ar, isoC_4H_{10} and Freon
(3) streamer is developed
Resistive plate
Resistive plate
(4) polarized e and ion induces charge on readout electrodes
- - - -
current
Resistive plate
Resistive plate
insulator
Readout electrode
++++
current
(5) charge of streamer remains and HV dropped locally (~cm^2)
Resistive plate
++++
- - - -
Resistive plate
(6) HV recovery ~ $O(1)$ s
Resistive plate
++
- - - -
Resistive plate

- RPC (streamer mode)
- Merit
  - rather good timing resolution $\sigma_t \sim 2$ ns
  - better position resolution $\sigma_x \sim$ cm
  - cost effective
  - easy to make for the large area
- Demerit
  - long dead time
  - can not measure energy loss of the particle

Summary

- Muon detection and identification is explained
  - Muon is important player for analysis and tagging
- Also muon triggering is explained
  - for efficiently data acquisition, muon trigger is helpful
- because of outermost location, muon system is affected by background from accelerator
  - keeping high efficiency is import ant issue