Particle Identification

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US Belle II Summer School
Iowa State University
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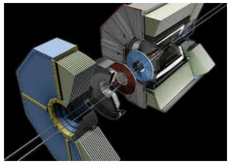
- Cerenkov radiation
  - Belle II iTOP
  - LHCb RICH detectors
- dE/dx and muons

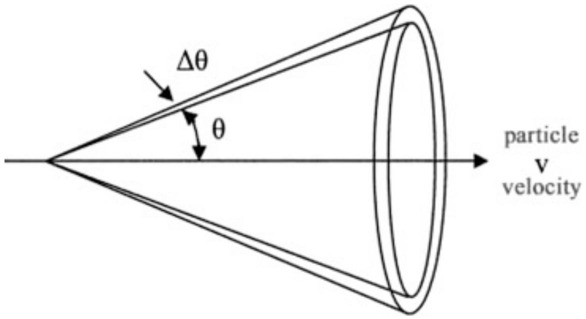


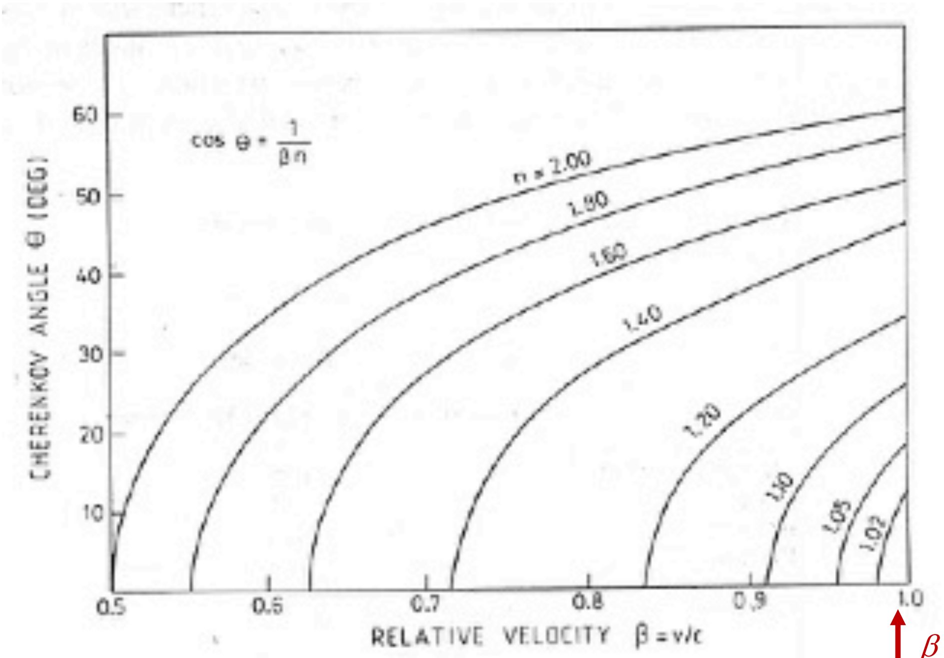
Cerenkov Radiation

The Cerenkov effect:

- When a charged particle traverses a medium with a velocity exceeding that of light in that medium, photons are radiated. The condition is $v > c/n$, or $\beta > 1/n$. the greater the index of refraction n, the lower the threshold velocity β.
- the photons are emitted at an angle:

$$\boxed{\cos\theta_c = \frac{1}{n\beta}}$$

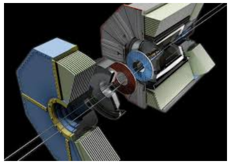




[from Kleinknecht, *Detectors for Particle Radiation*]

$\beta = 0.995$

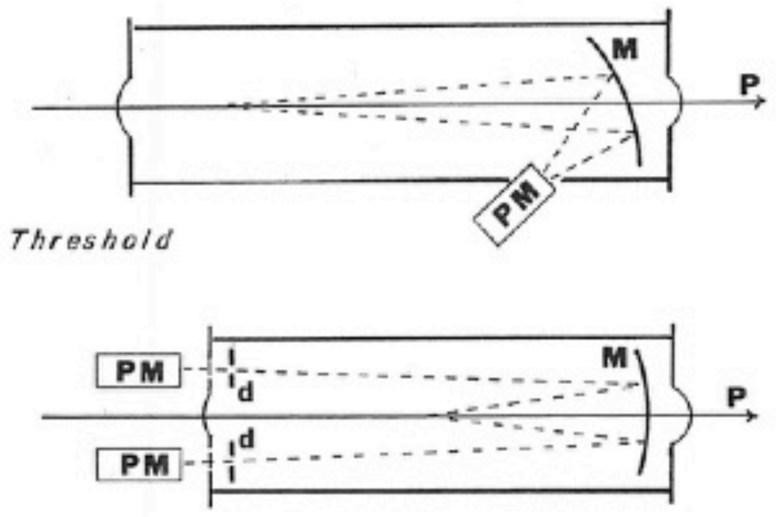
$p(\pi) = 0.08$	0.14	0.29	1.4 GeV



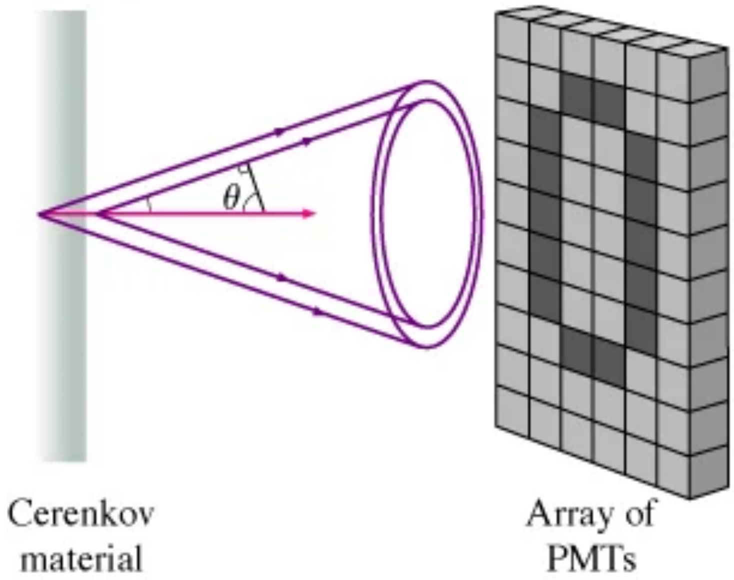
Cerenkov Radiation

The light can be collected in several ways:

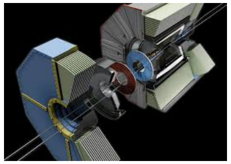
Measuring light yield:



Measuring Cerenkov angle (RICH):

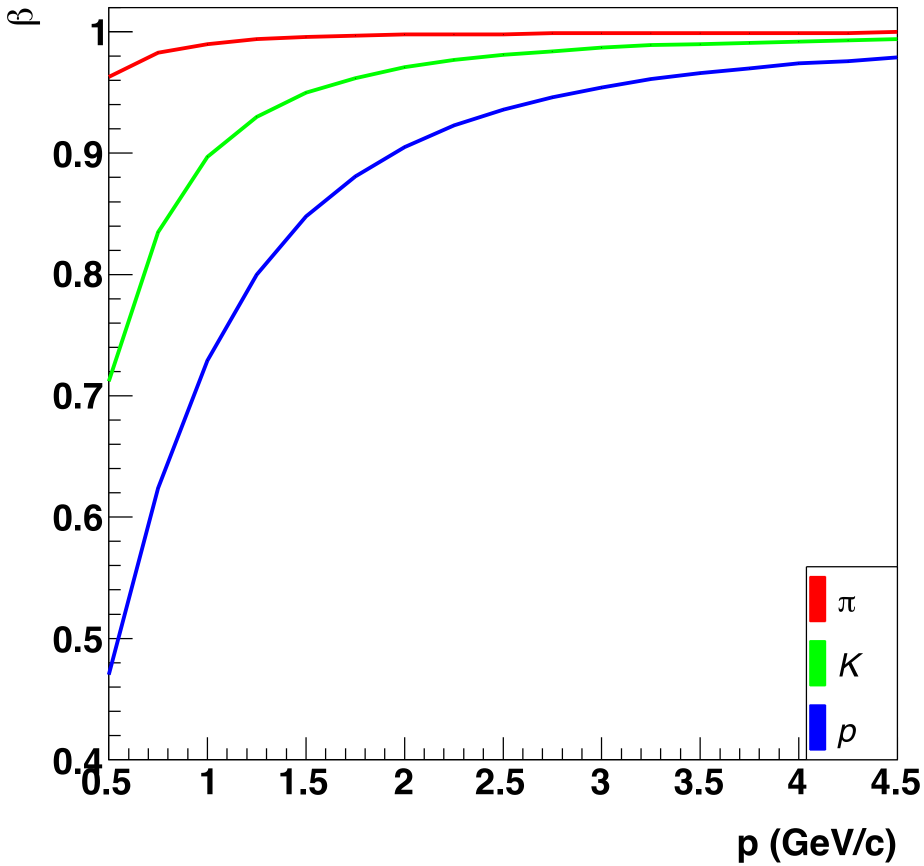


By measuring either light yield or θ_c , one measures β, the velocity of the charged particle. Given the momentum of the particle, i.e., as measured in a spectrometer (tracking detector in a magnetic field), one determines the mass (the particle identity): $m = p/(\gamma\beta)$

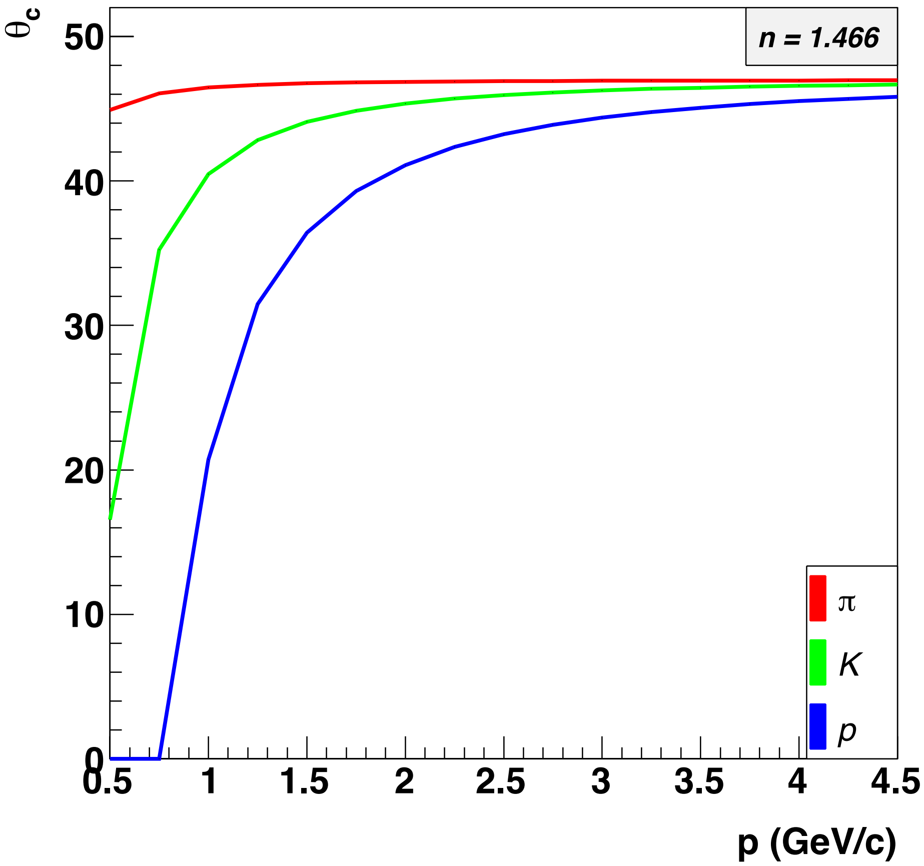


Cerenkov Radiation

Belle II (e^+e^-) momentum range:

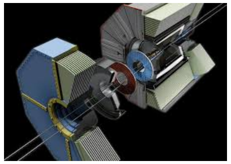


Cerenkov angle:



⇒ *for most of momentum range, β differs between π/K by only ~few %*

⇒ *for most of momentum range, θ_c differs between π/K by $\leq 2^o$ (34 mrad)*

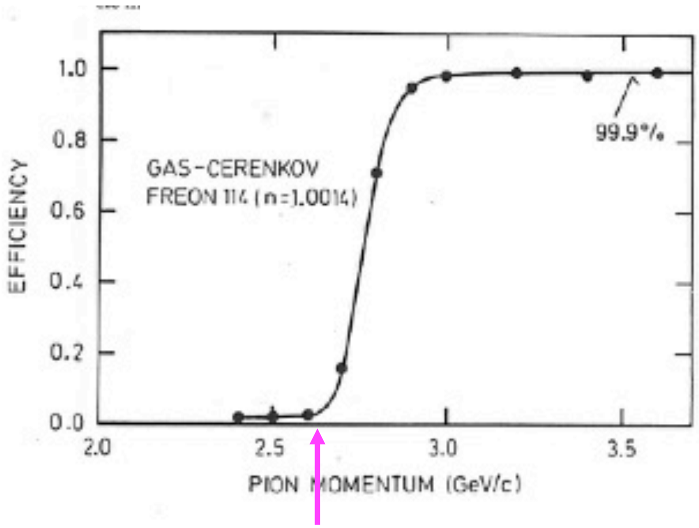


Cerenkov Radiation

Charged particles must be above the Cerenkov threshold (1/n) to be detected:

Freon 114: n = 1.0014, β_{thresh} = 0.9986, γ_{thresh} = 18.92,

⇒ $p_{thresh}(\pi)$= 2.637 GeV

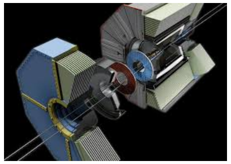


[from Fernow, *Introduction to Experimental Particle Physics*]

Most photons are emitted in the UV, which is hard to detect; but a generous number of photons are emitted in the visible, which matches well to mirrors, windows, and PMTs. The greater β, the greater θ_c , and the more light is radiated:

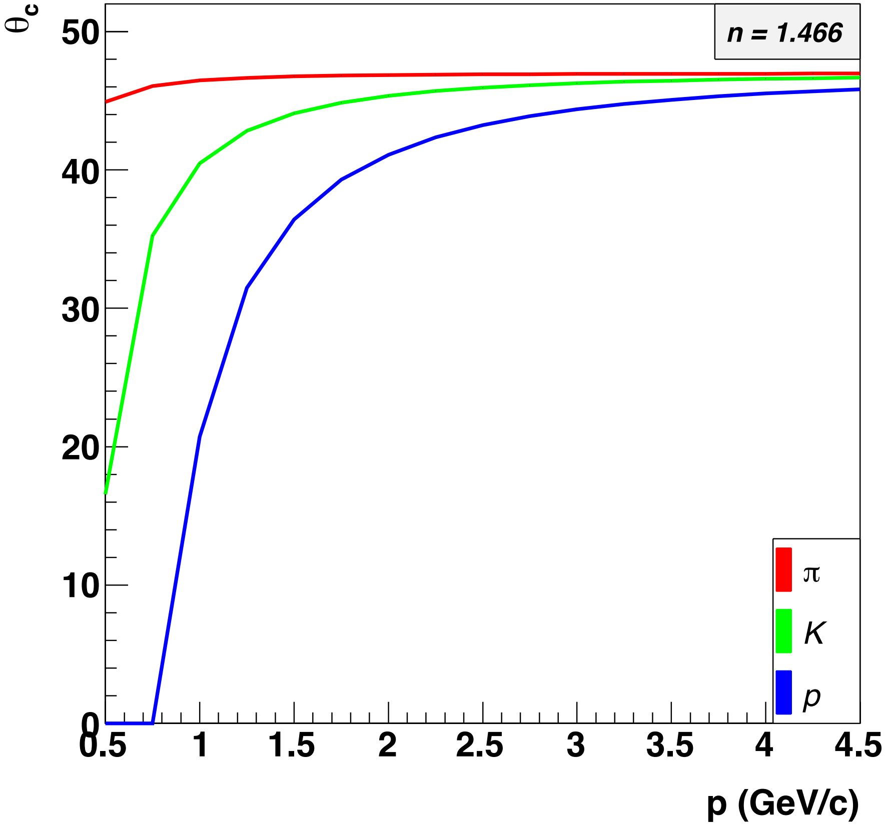
$$\begin{aligned}
\frac{dN}{dx\,d\lambda} &= 4\pi\alpha\frac{1}{\lambda^2}\left(1-\frac{1}{\beta^2n^2}\right)\\
\Rightarrow\quad \frac{dN}{dx} &= 2\pi\alpha\int_{n\beta}\left(1-\frac{1}{\beta^2n^2}\right)\frac{d\lambda}{\lambda^2}\\
&\approx 2\pi\alpha\sin^2\theta_c\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\\
&\approx 390\sin^2\theta_c \qquad (\lambda = 350-500\text{ nm})
\end{aligned}$$

Note:
detecting photons down to λ = 330 nm increases photon yield by 20% (390 → 470)

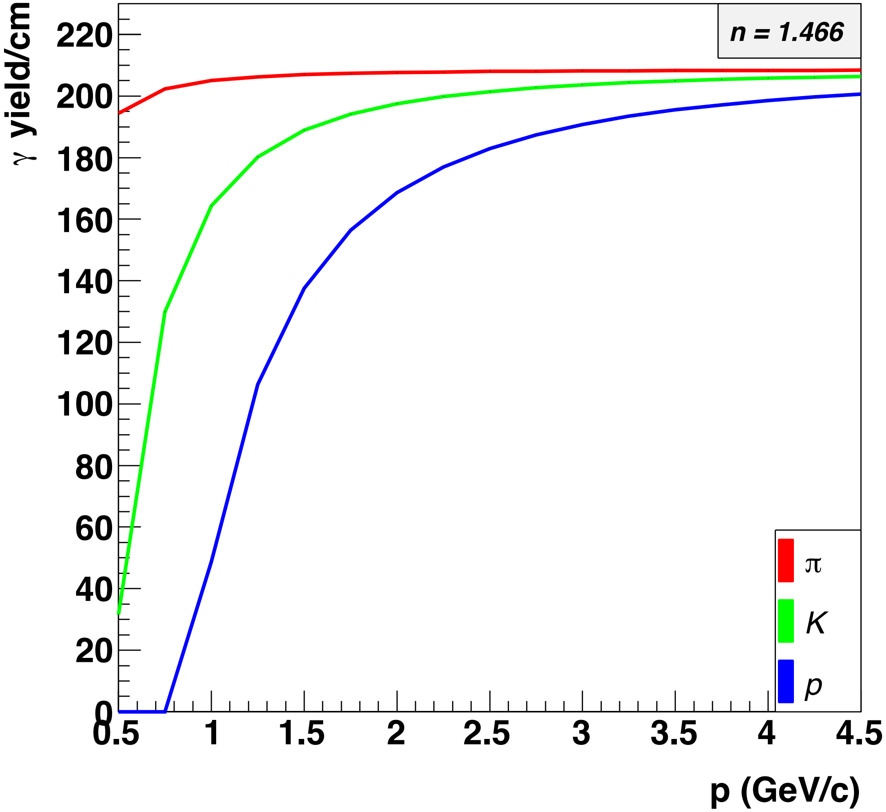


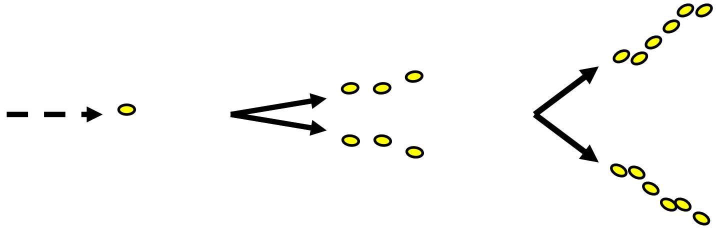
Cerenkov Radiation: Belle II quartz (n=1.466)

Cerenkov angle:

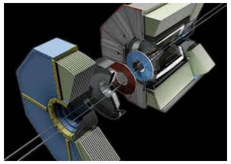


Photon yield per cm of radiator
(x 4 cm for 30^o tracks)



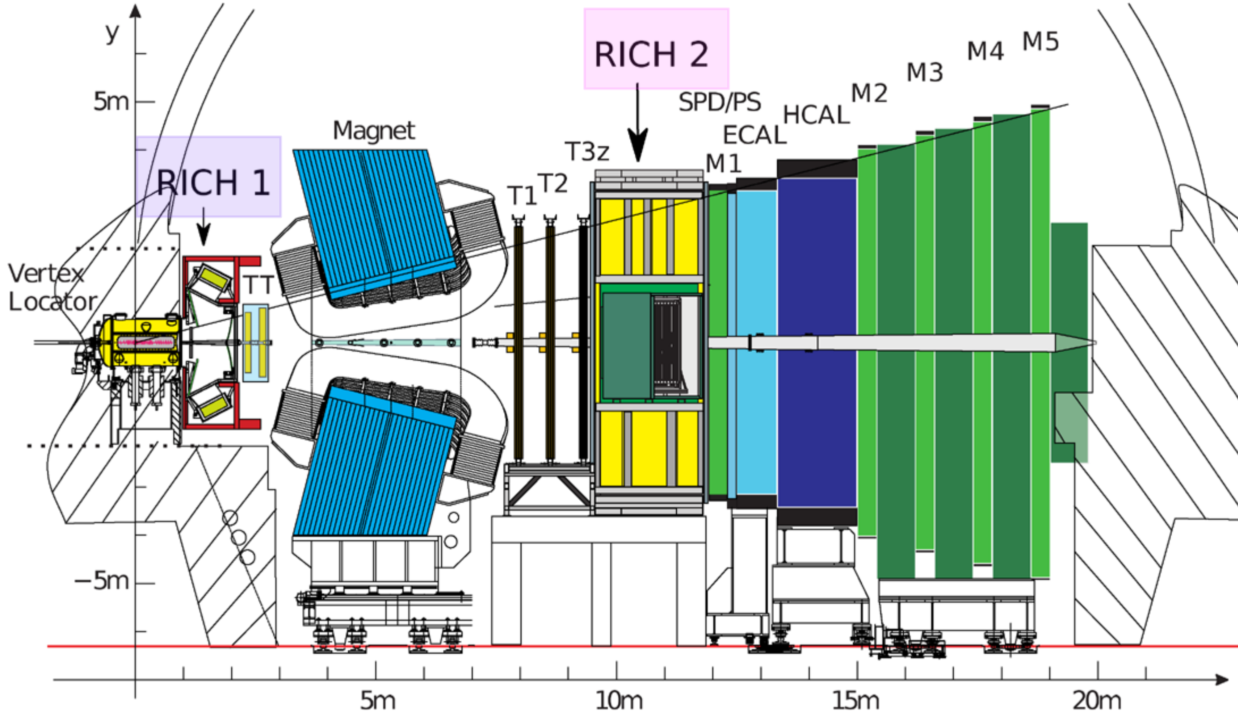


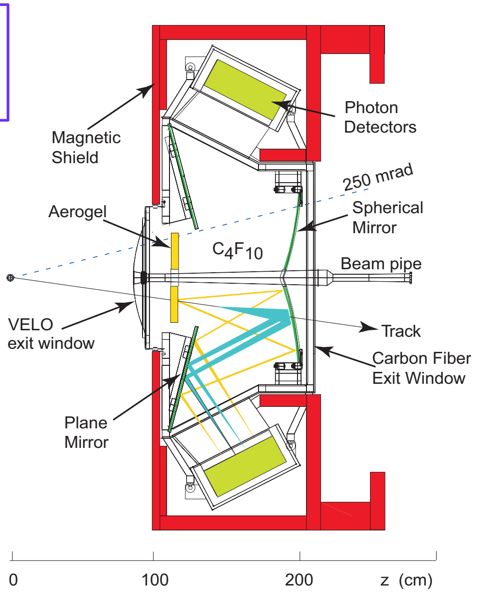
⇒ for most of momentum range, γ yield differs between π/K by ~ 5–15 γ/cm (+ Poisson fluctuations)



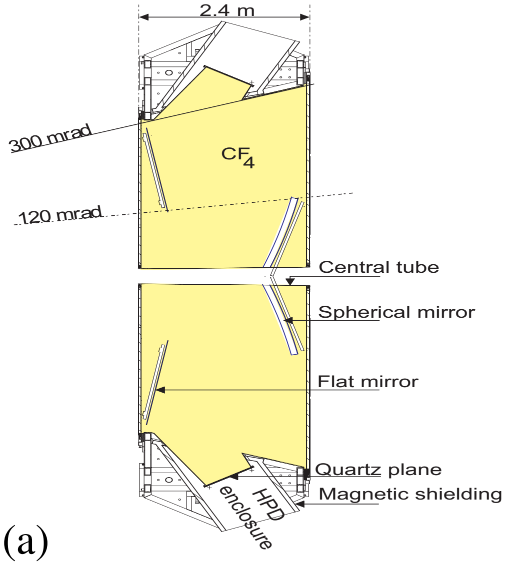
Cerenkov Radiation: LHCb

RICH 1: C_4F_{10}
($n = 1.0014$)

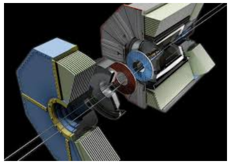




RICH 2: CF_4
($n = 1.0005$)



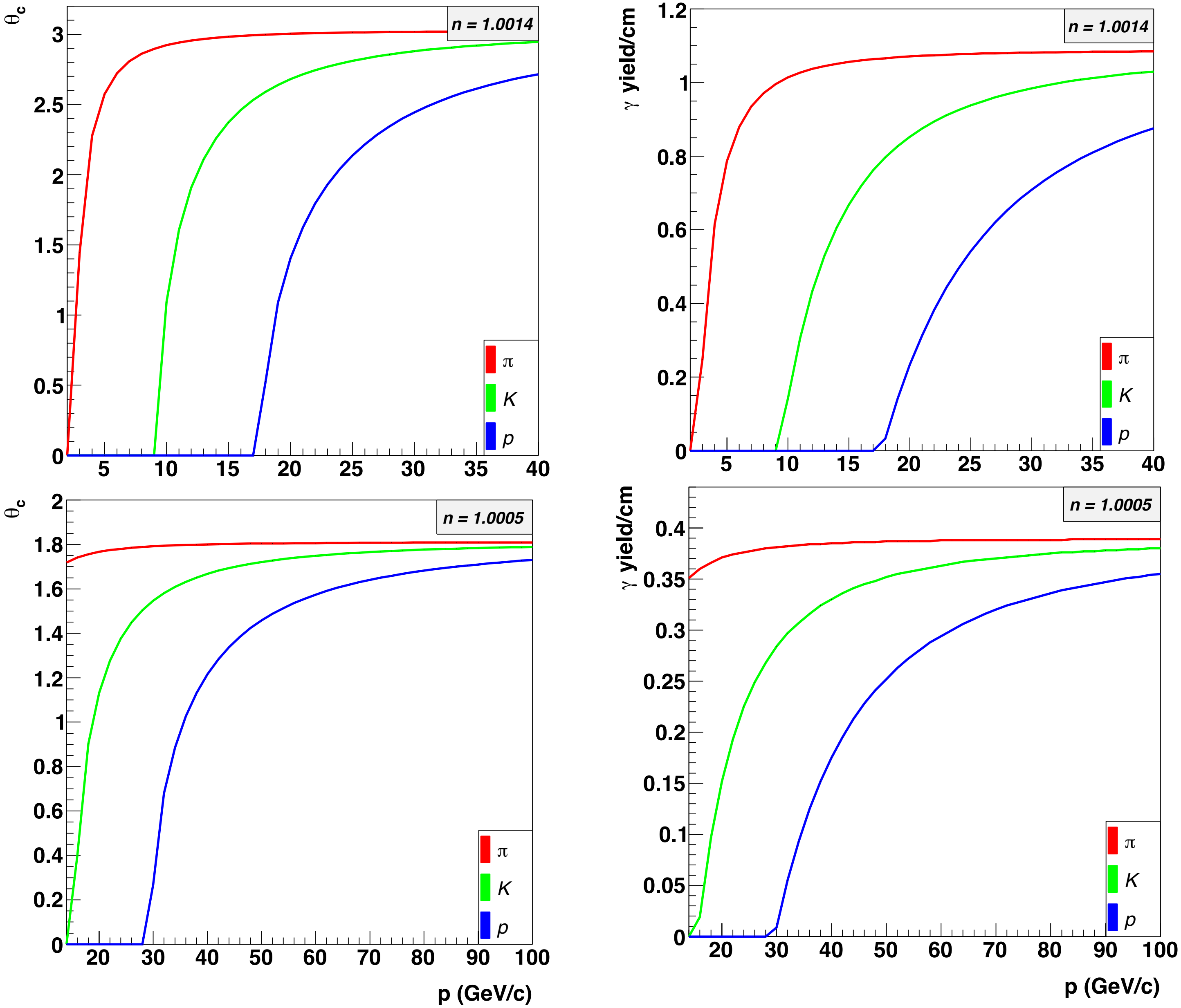
[more details: Adinolfi et al. (LHCb), EPJC 73, 2431 (2013)]



Cerenkov Radiation: LHCb

Cerenkov angle:

Photon yield per cm of radiator

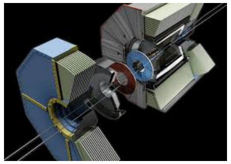


RICH 1: C_4F_{10}
($n = 1.0014$)

x 95 cm
= total γ

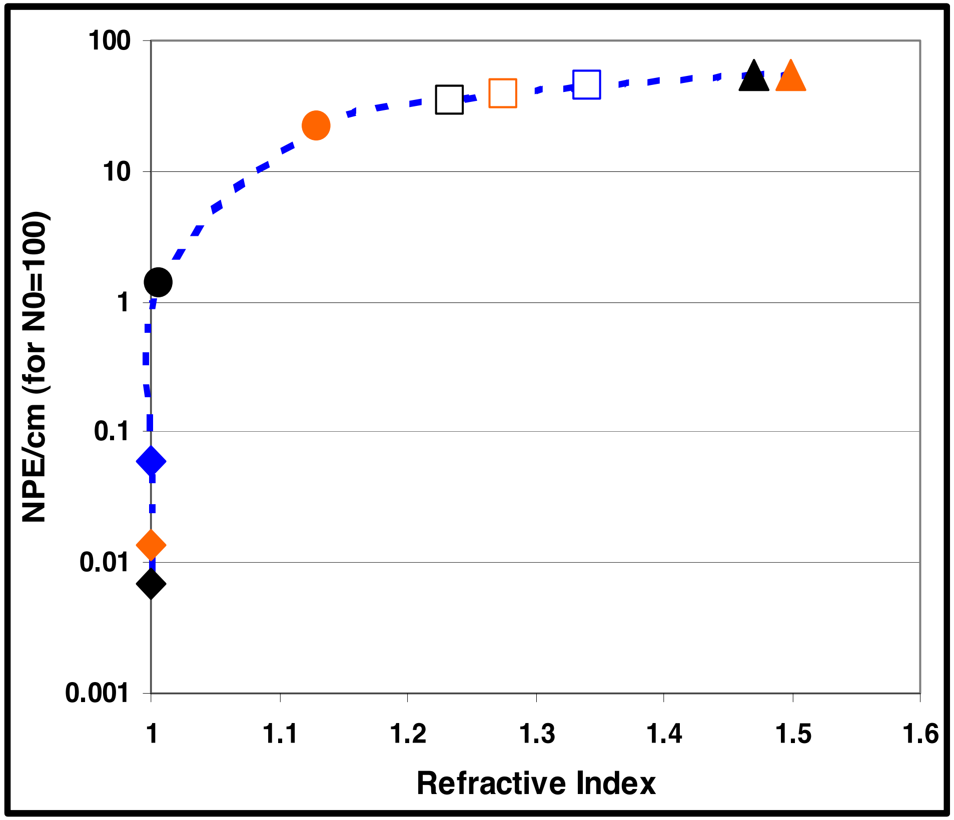
RICH 2: CF_4
($n = 1.0005$)

x 180 cm
= total γ

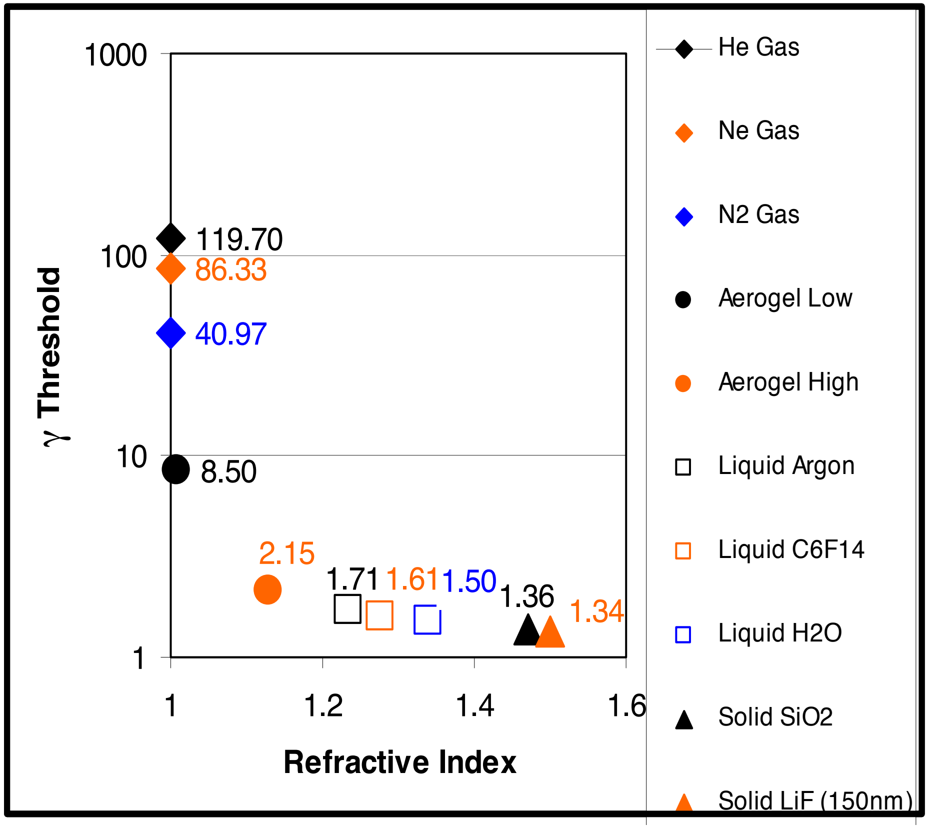


Cerenkov Radiators

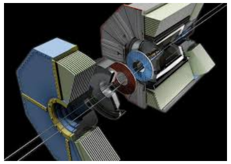
N_{PE}/cm versus Refractive Index for Various Radiators



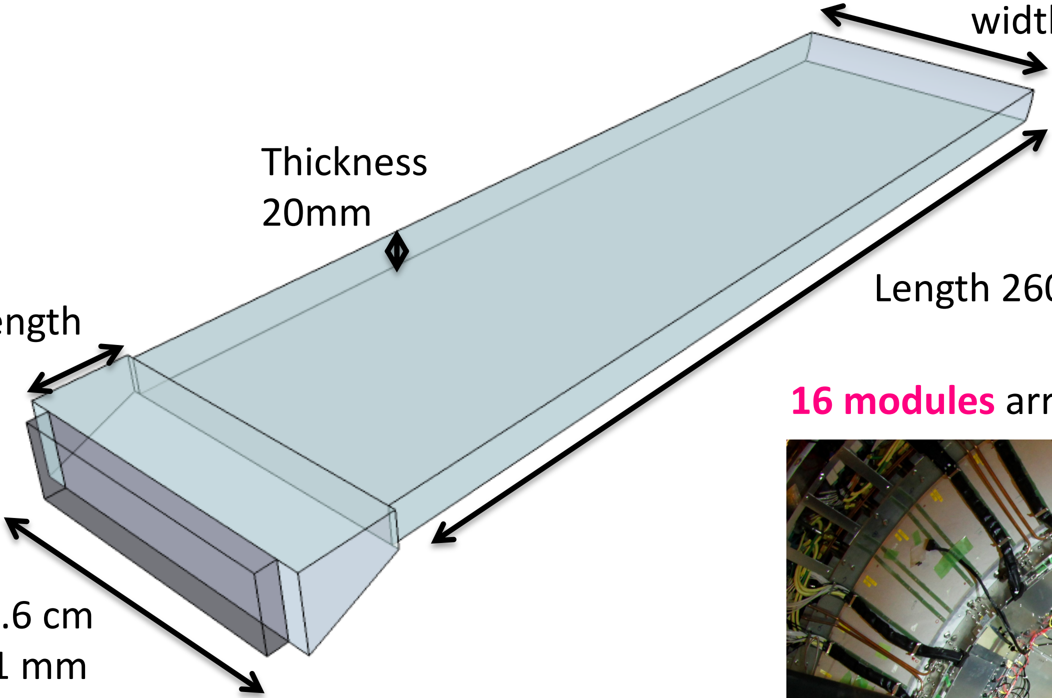
$\gamma_{threshold}$ versus Refractive Index for Various Radiators



[from Ratcliffe, *Imaging Rings in Ring Imaging Cherenkov Counters, presented at RICH 2002, Pylos, Greece*]



Belle II iTOP (“imaging time-of-propagation”) Detector



Bar/mirror
width 45 cm

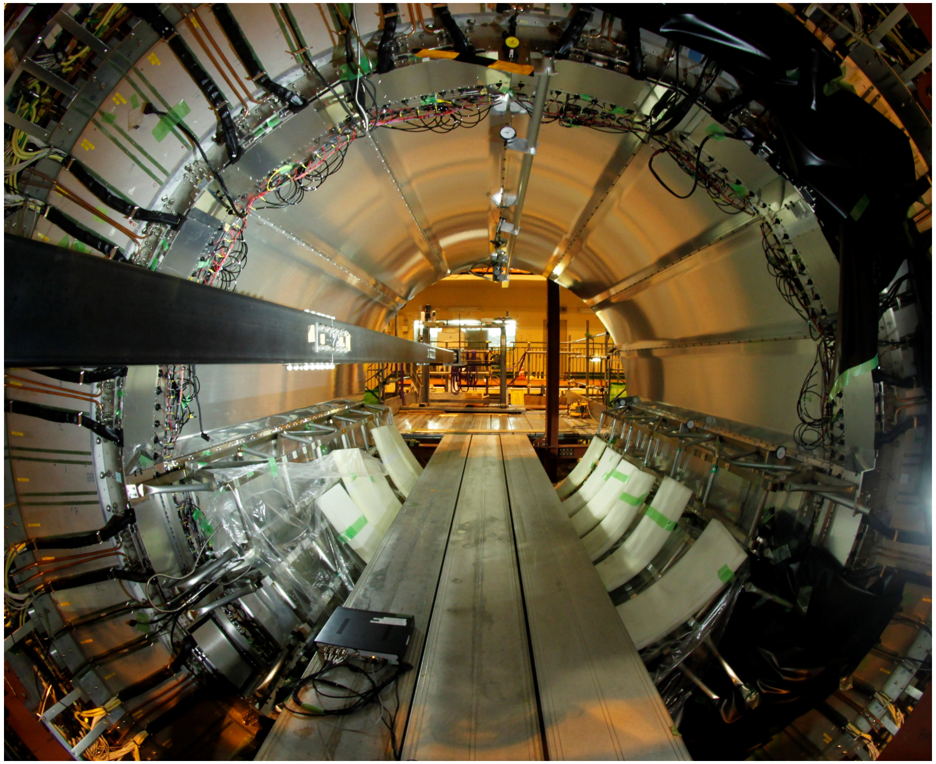
Thickness
20mm

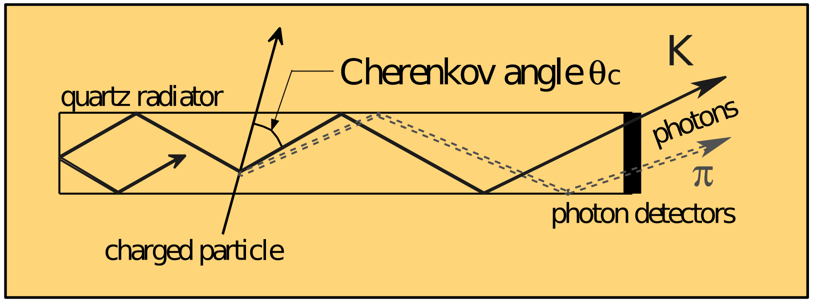
Length 260 cm

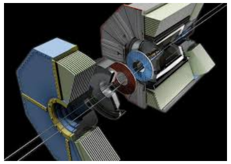
Prism length
10 cm

Prism width 45.6 cm
Prism height 51 mm
MCPPMT width 44.4 cm

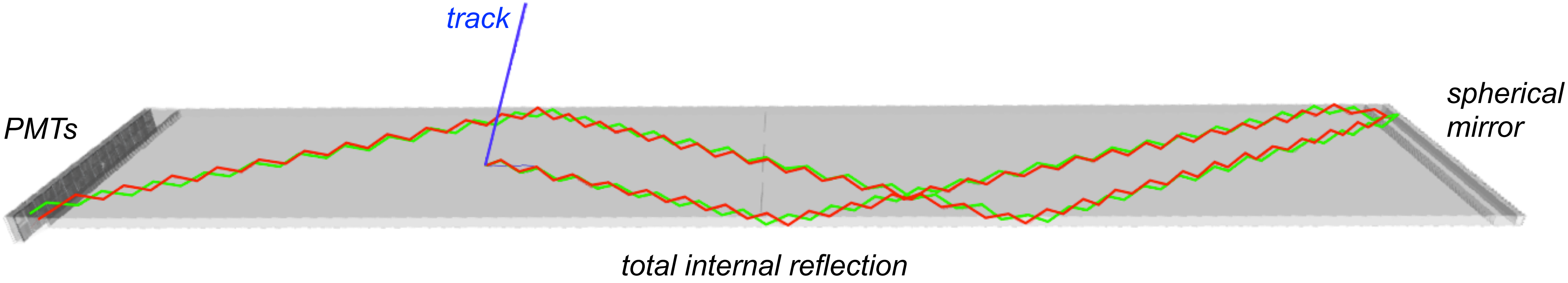
16 modules arranged azimuthally around beampipe:





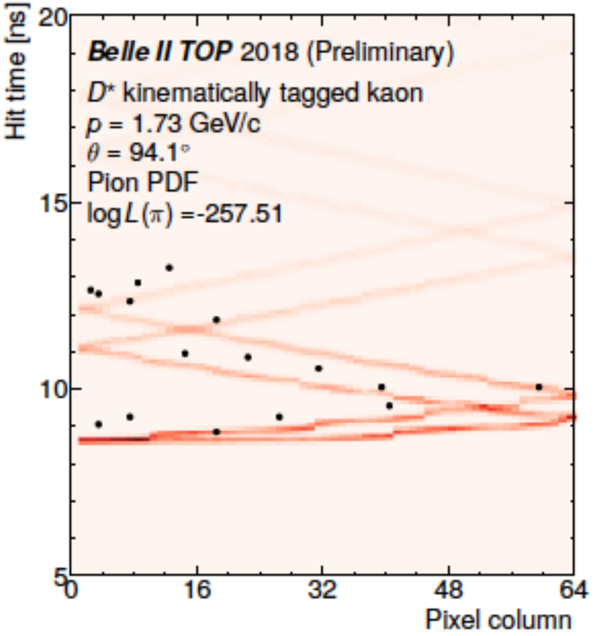


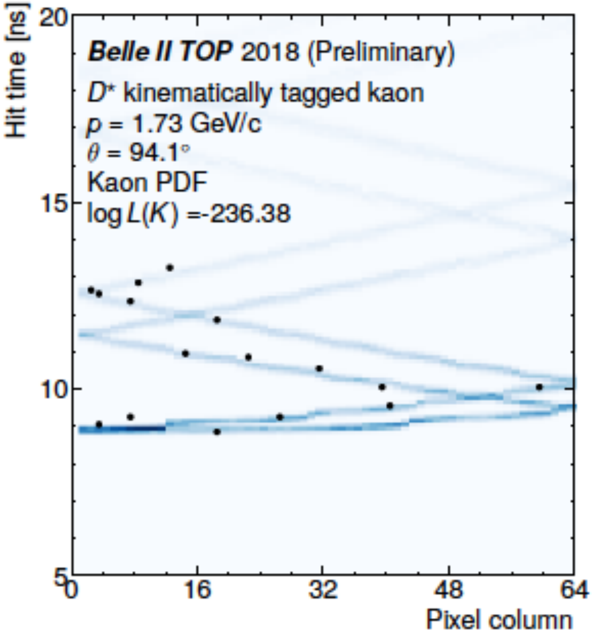
Belle II iTOP Detector: how it works

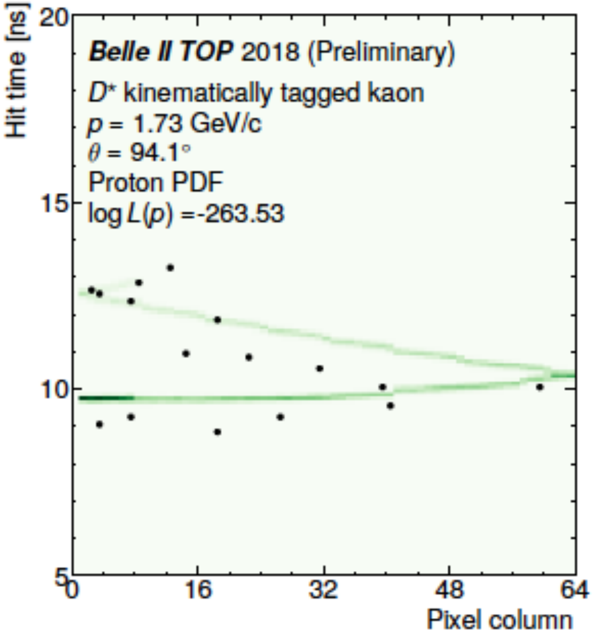


p= 1.7 GeV/c, θ_{polar} = 94° K^+ track:

best match:

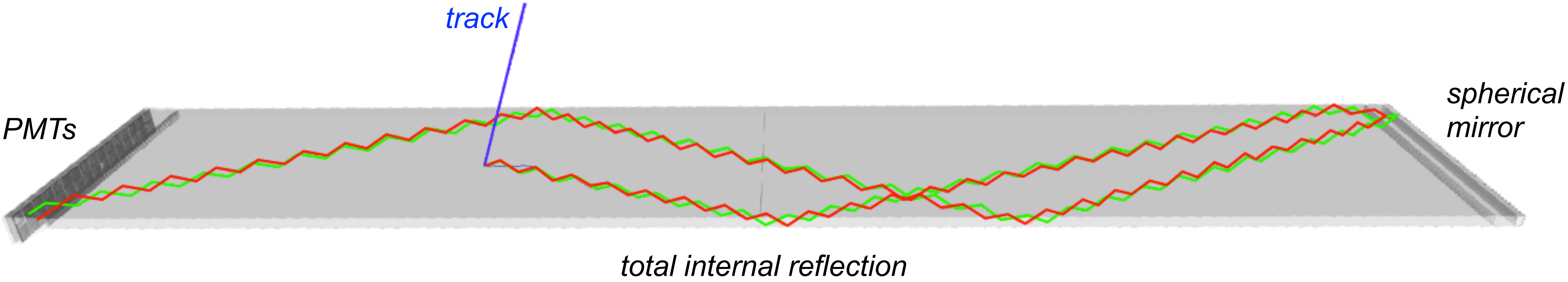


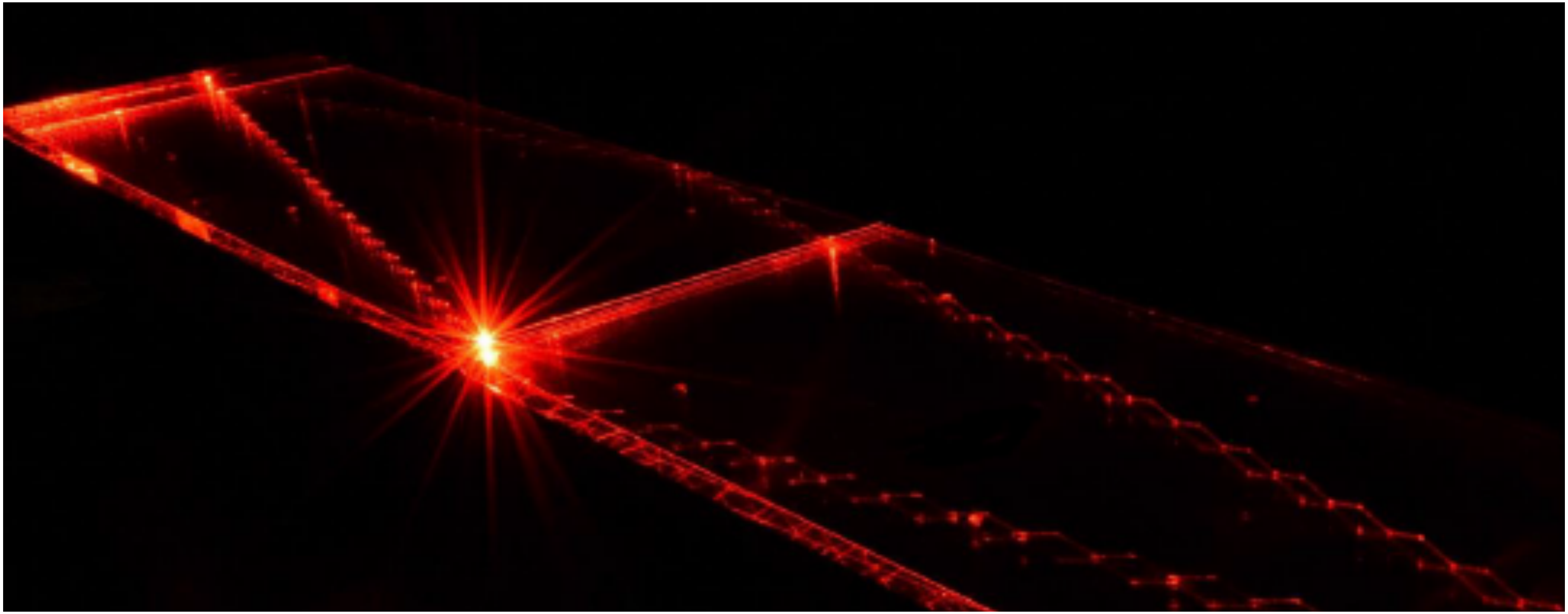




Note:
pions arrive earliest due to largest θ_c

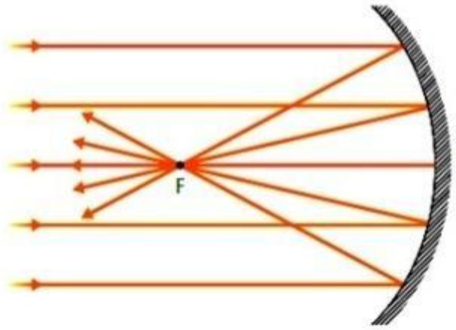
Belle II iTOP Detector: how it works



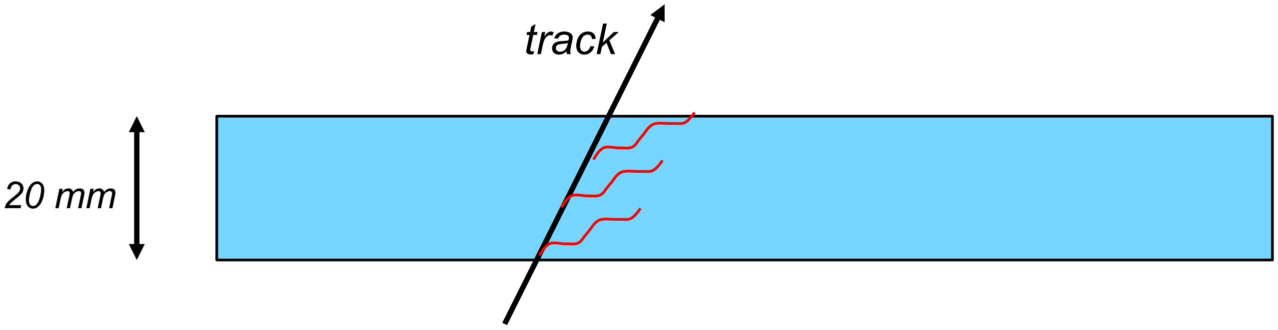


Belle II iTOP Detector: mirror focusing

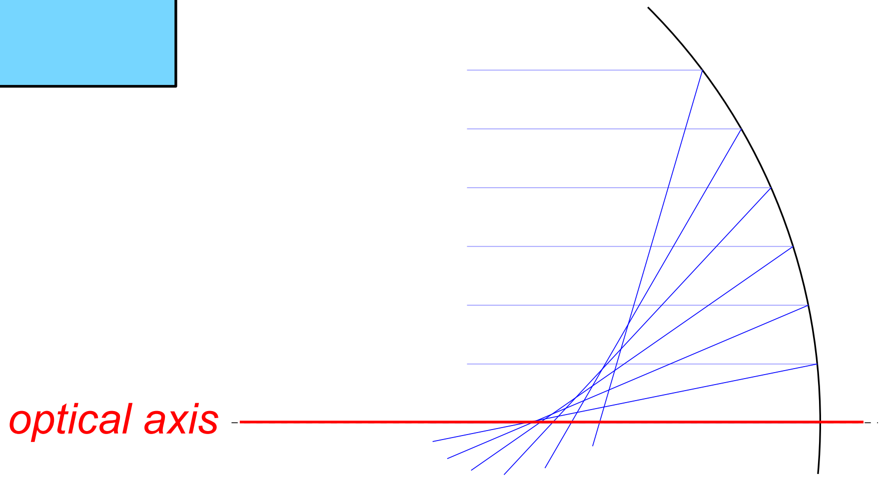
A spherical mirror focuses parallel rays to common point:

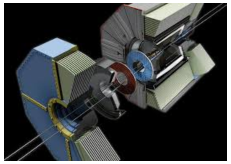


This can "remove" the thickness of the radiator bar:



But the mirror is not perfect:
there is spherical aberration:

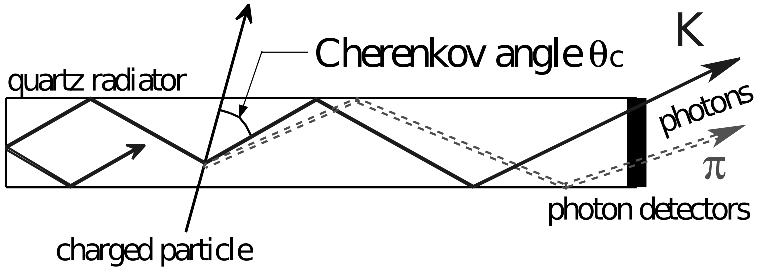




Belle II iTOP Detector: time-of-propagation

Time of propagation (TOP) depends on path length and group velocity:

$$v_g = \frac{c}{n_g}$$



This "group index" n_g differs from the "phase index" n that governs $\cos\theta_c = 1/(n\beta)$.

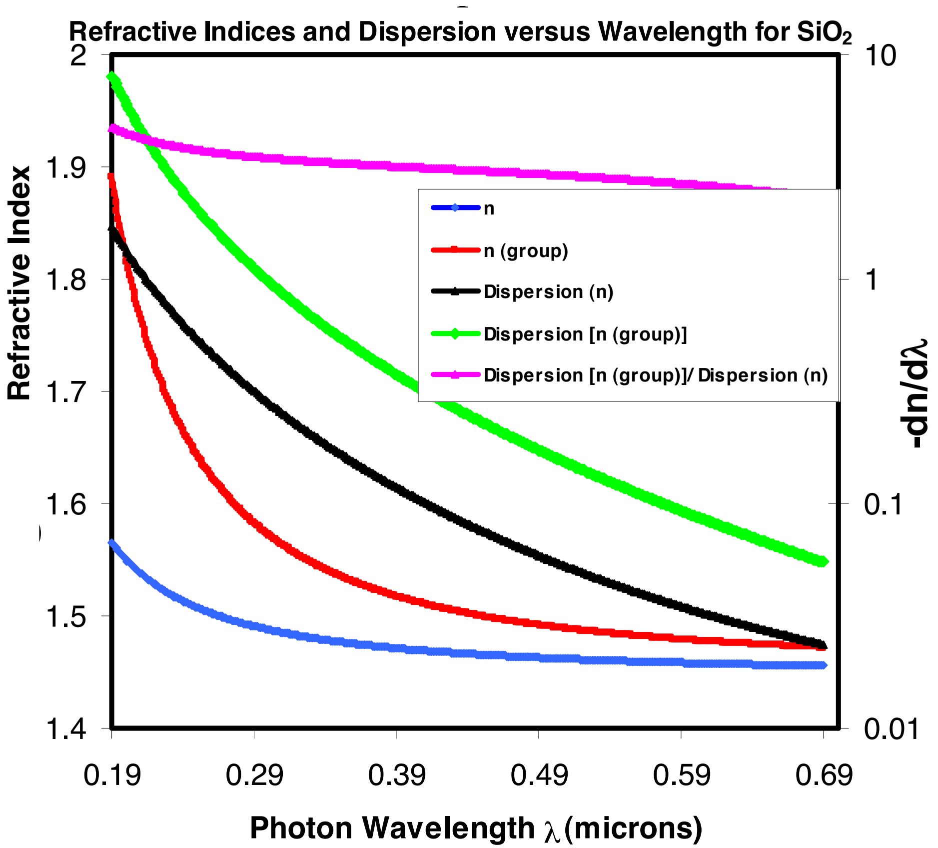
Also, the group index has much larger chromatic dispersion than the phase index:

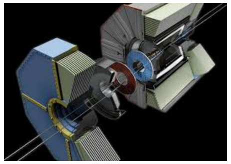
dispersion

$$n(\lambda) = n(\lambda_0) - \lambda \boxed{\frac{dn}{d\lambda}}$$

- the Cerenkov angle θ_c has very small (but non-zero) variation with photon wavelength: UV photons are emitted at slightly larger angles than IR photons

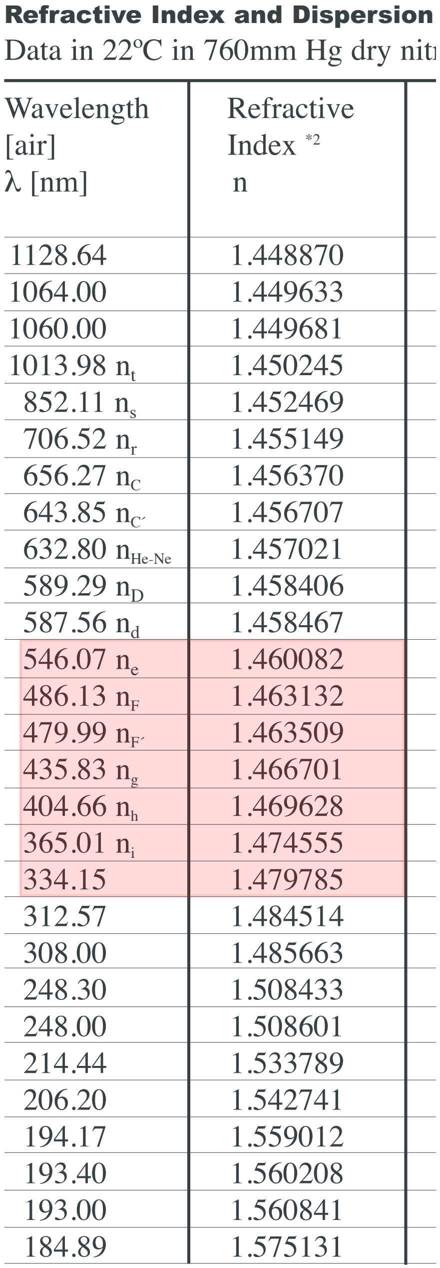
- the TOP has notable variation with photon wavelenth: UV photons propagate slower than IR photons; this degrades time resolution





Belle II iTOP Detector: time-of-propagation

Corning 7980
(quartz)



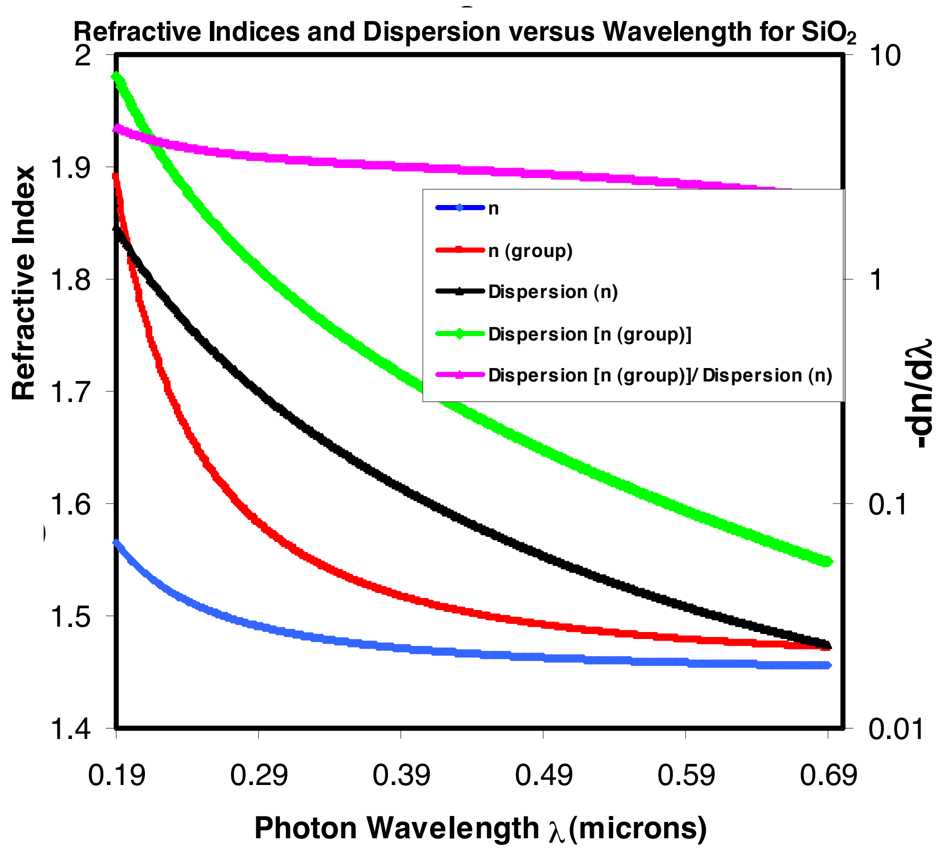
Refractive Index and Dispersion

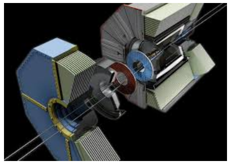
Data in 22ºC in 760mm Hg dry nit

Wavelength [air] λ [nm]	Refractive Index *2 n
1128.64	1.448870
1064.00	1.449633
1060.00	1.449681
1013.98 n_t	1.450245
852.11 n_s	1.452469
706.52 n_r	1.455149
656.27 n_C	1.456370
643.85 $n_{C'}$	1.456707
632.80 $n_{He\text{-}Ne}$	1.457021
589.29 n_D	1.458406
587.56 n_d	1.458467
546.07 n_e	1.460082
486.13 n_F	1.463132
479.99 $n_{F'}$	1.463509
435.83 n_g	1.466701
404.66 n_h	1.469628
365.01 n_i	1.474555
334.15	1.479785
312.57	1.484514
308.00	1.485663
248.30	1.508433
248.00	1.508601
214.44	1.533789
206.20	1.542741
194.17	1.559012
193.40	1.560208
193.00	1.560841
184.89	1.575131

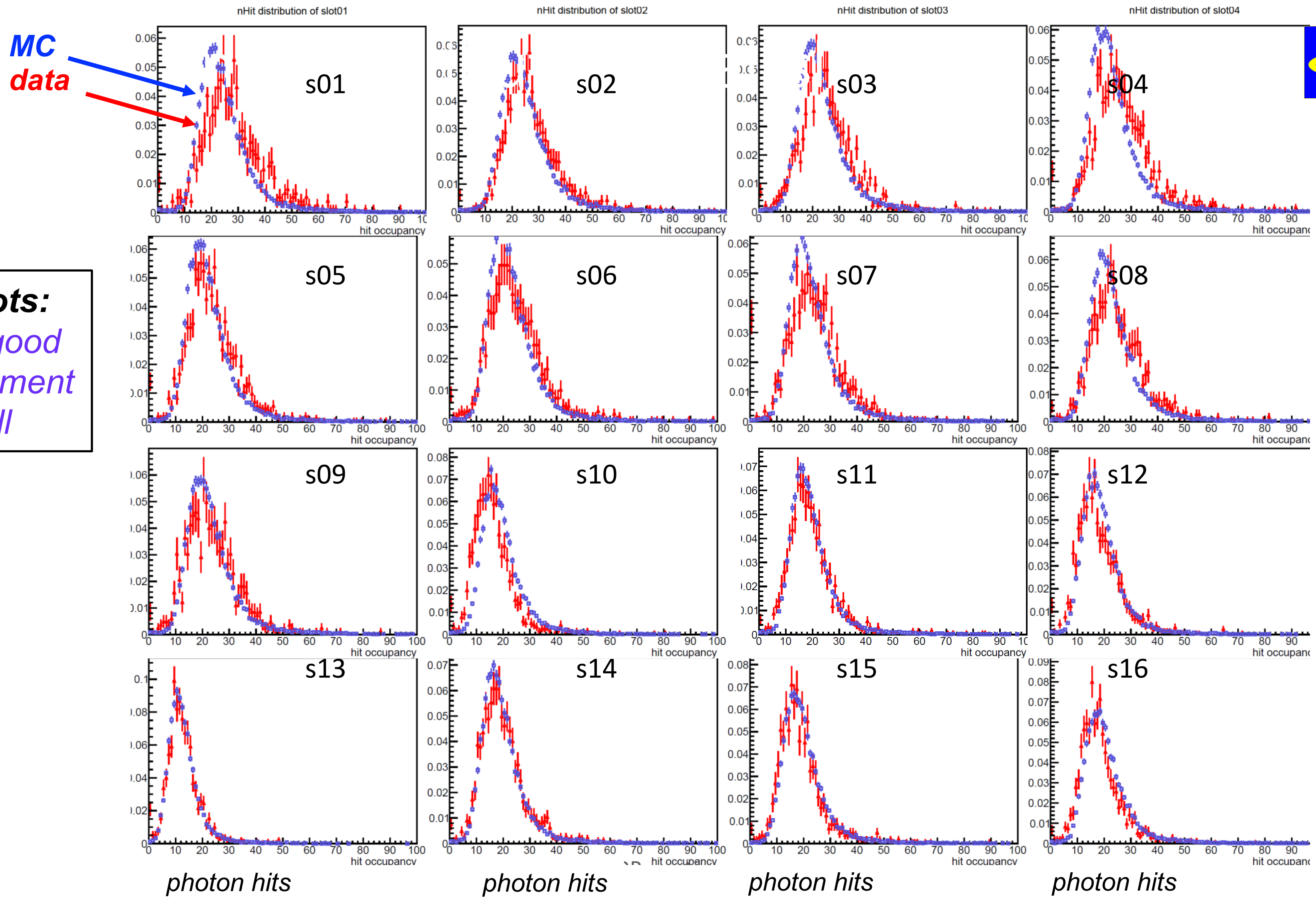
~1.4% effect for n
~2.6% effect for TOP

[from Ratcliffe, *Imaging Rings in Ring Imaging Cherenkov Counters, presented at RICH 2002, Pylos, Greece*]



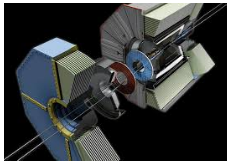


Belle II iTOP Detector: light yield



16 slots: *very good agreement overall*

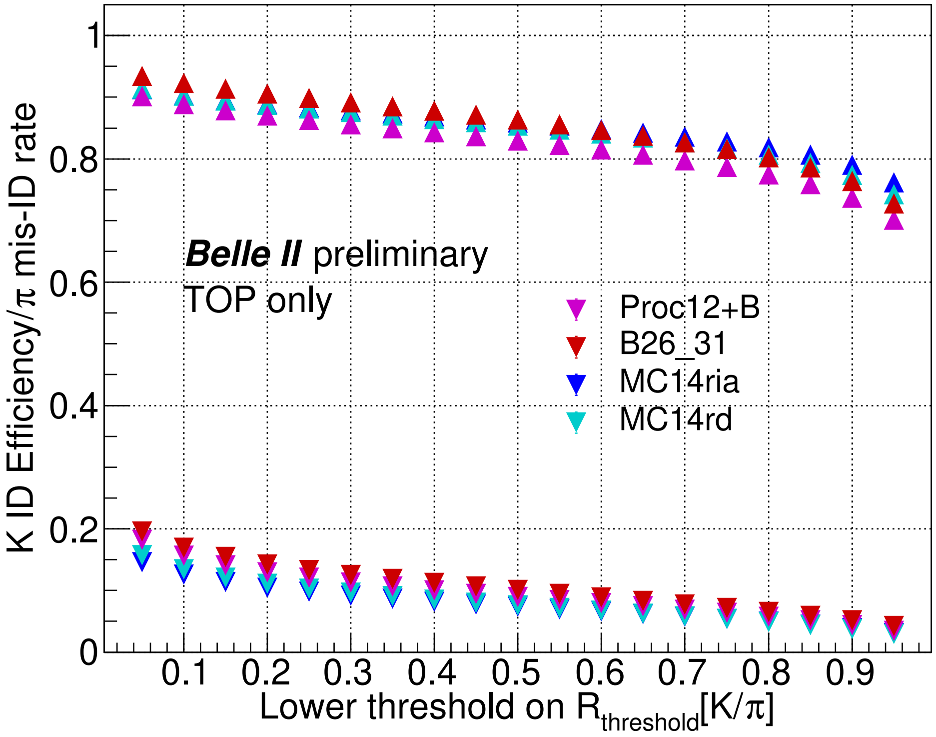
MC tuning includes measured quantum efficiency (~25%) and collection efficiency (~55%) of PMTs



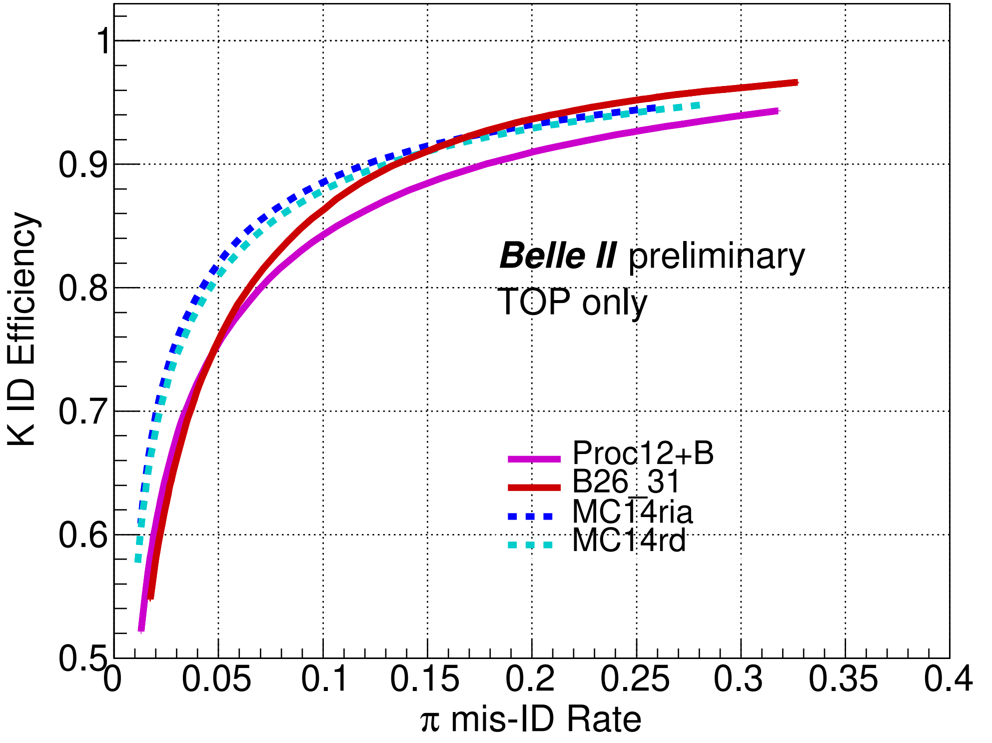
Belle II iTOP Detector: performance

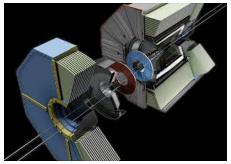
- *iTOP particle likelihood has a contribution from γ yield and a contribution from position + time (θ_c)*
- *Evaluate performance with $D^{*+}\to D^0(\to K^-\pi^+)\pi^+$ or $D^{*-}\to \overline{D}{}^0(\to K^+\pi^-)\pi^-$ decays*

Effic(K) = (# K tracks identified as K)/(# K tracks)
MisID(π) = (# π tracks identified as K)/(# π tracks)



"ROC" curve



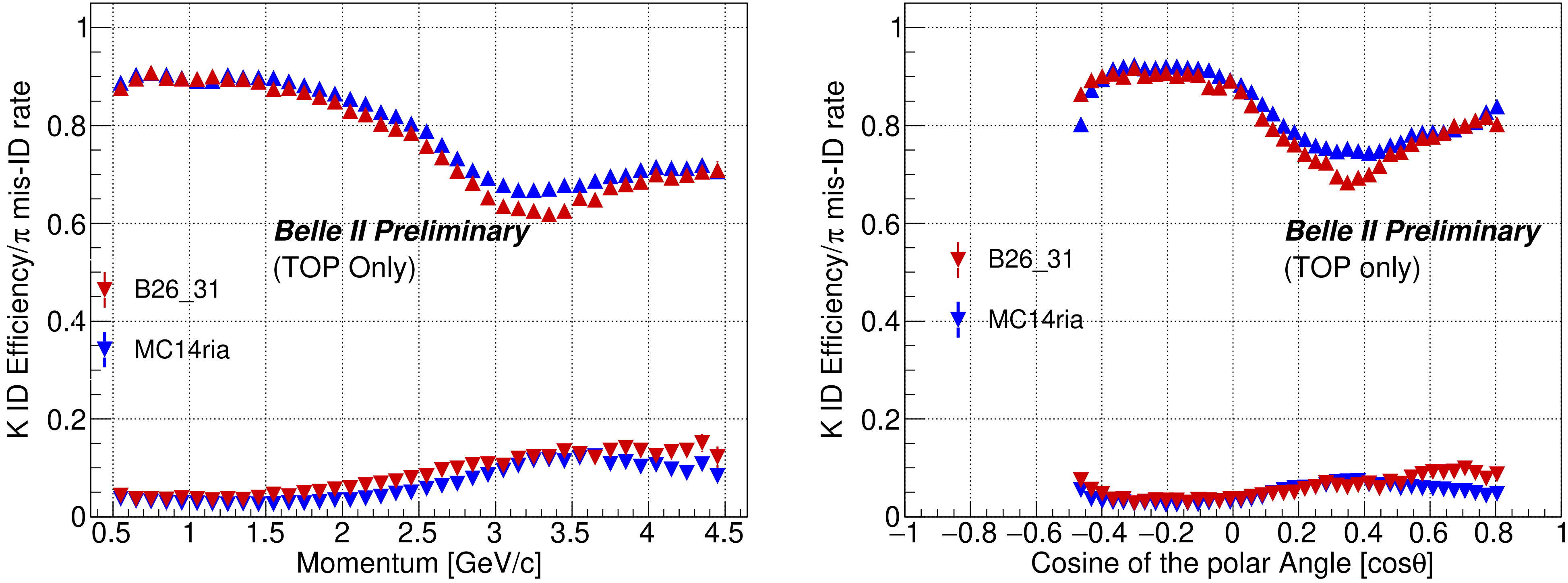


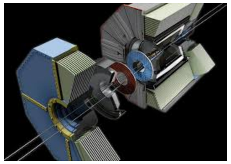
Belle II iTOP Detector: performance

- iTOP particle likelihood has a contribution from γ yield and a contribution from position + time (θ_c)
- Evaluate performance with $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+)\pi^+$ or $D^{*-} \rightarrow \overline{D}^0(\rightarrow K^+ \pi^-)\pi^-$ decays

Effic(K) = (# K tracks identified as K)/(# K tracks)
MisID(π) = (# π tracks identified as K)/(# π tracks)

$R_{K/\pi} > 0.8$





low momentum particle ID: dE/dx

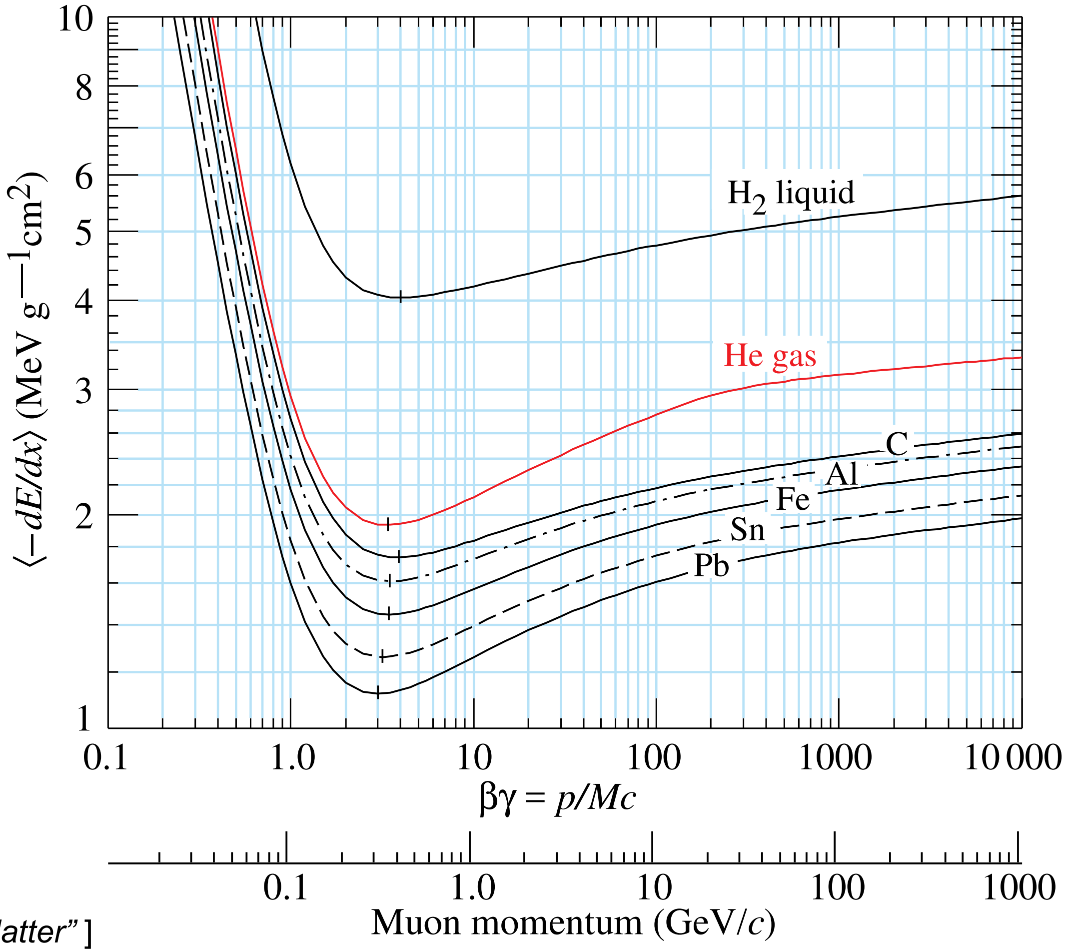
Bethe-Bloch formula (1933):

$$\left\langle -\frac{dE}{dx}\right\rangle = K\left(\frac{Z}{A}\right)\left(\frac{z^2}{\beta^2}\right)\left[\ln\left(\frac{2m\beta^2\gamma^2}{I}\right)-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

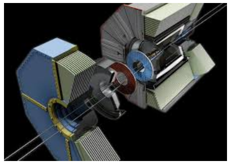
K = 0.307 MeV mol^{-1} cm^2

Complicated, but note:

- *depends on material only via (Z/A), which varies little over a range of materials*
- *depends on incident particle via z^2, i.e, higher z gives much more ionization*
- *also depends on $\beta\gamma$ of incident particle: broad minimum is at $\beta\gamma$ ~ 3, sharp drop at lower values, slow rise at larger values. This corresponds to ~2 MeV/(g/cm^2)*
- *does not depend on m of incident particle, only $\beta\gamma$ – and, knowing p, that is how one uses dE/dx for particle ID.*
- *the δ/2 term is a small correction (the "density effect")*



[from D. Groom, PDG Review *"Passage of Particles Through Matter"*]



low momentum particle ID: dE/dx

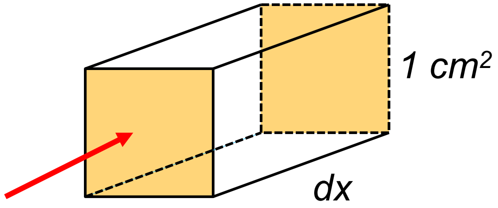
Bethe-Bloch formula (1933):

$$\left\langle -\frac{dE}{dx}\right\rangle = K\left(\frac{Z}{A}\right)\left(\frac{z^2}{\beta^2}\right)\left[\ln\left(\frac{2m\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

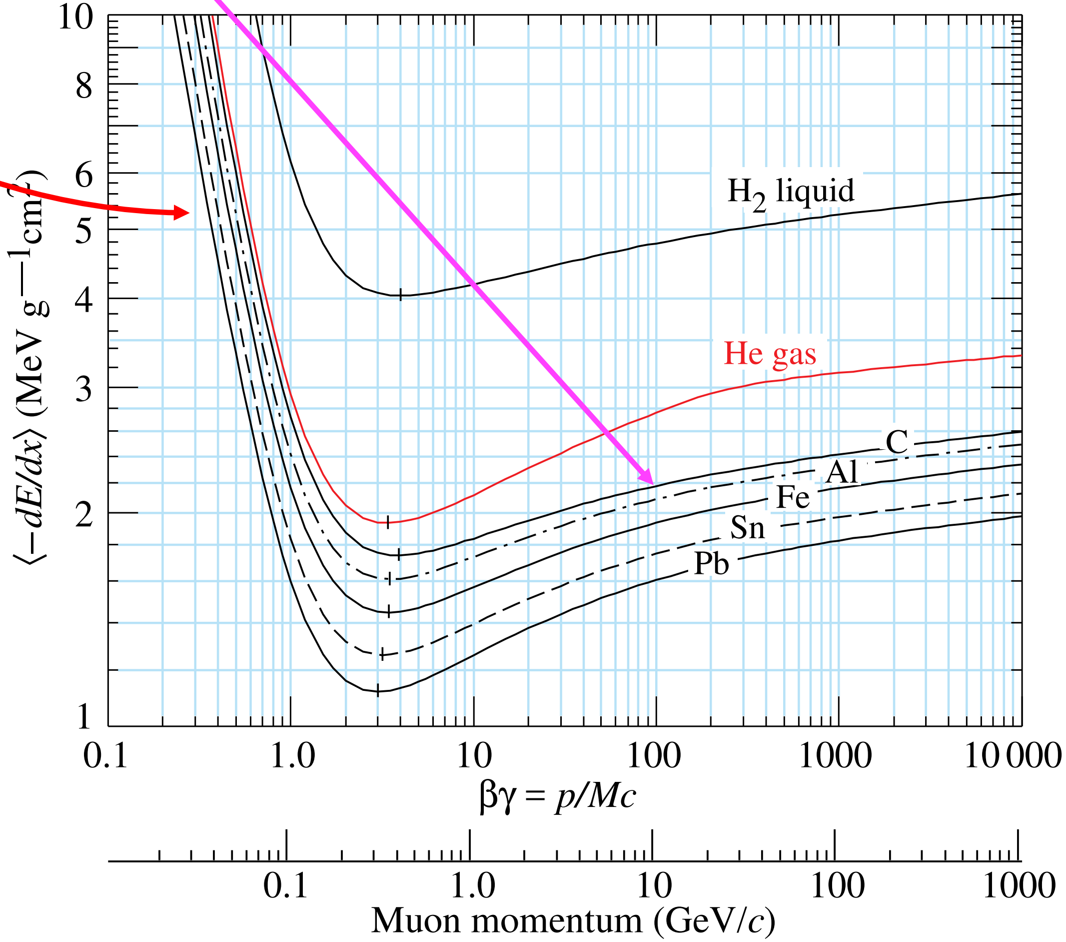
$K = 0.307$ MeV mol^{-1} cm^2

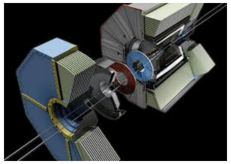
Finer points:

- denominator “dx” is a distance, but units are grams/cm^2 (not cm)



- $1/\beta^2$ drop is due to less time for incident particle to interact with electrons
- “relativistic rise” is due to greater range of electric field of incident particle, and greater maximum energy transfer
- when plotting vs. particle momentum, the $\beta\gamma$ curve gets shifted; shift depends on particle mass





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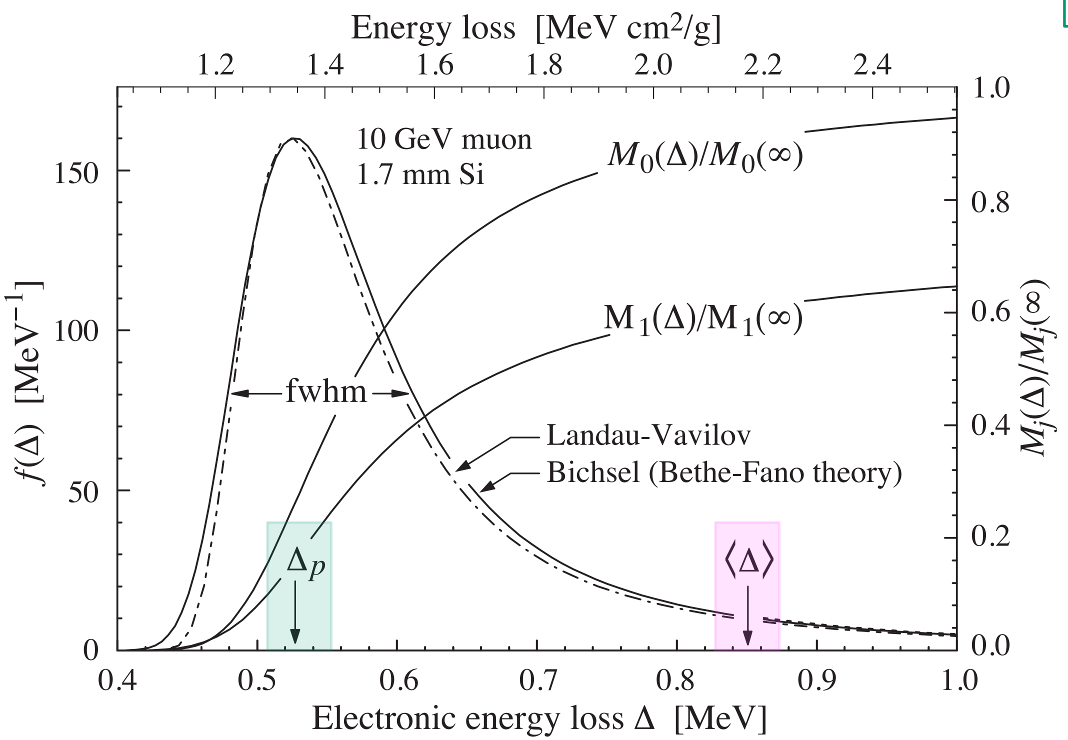
- *This formula gives only the* ***mean energy loss*** *– it is dominated by huge-energy-loss (tiny-impact-parameter) collisions, which liberate electrons (called "delta rays").*
- *⇒ PDG recommends using "**most probable energy loss**" formula for calculations*

adds ln($KZz^2x/(2A\beta^2 I)$) term



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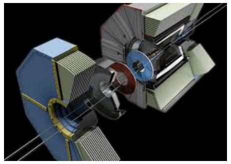
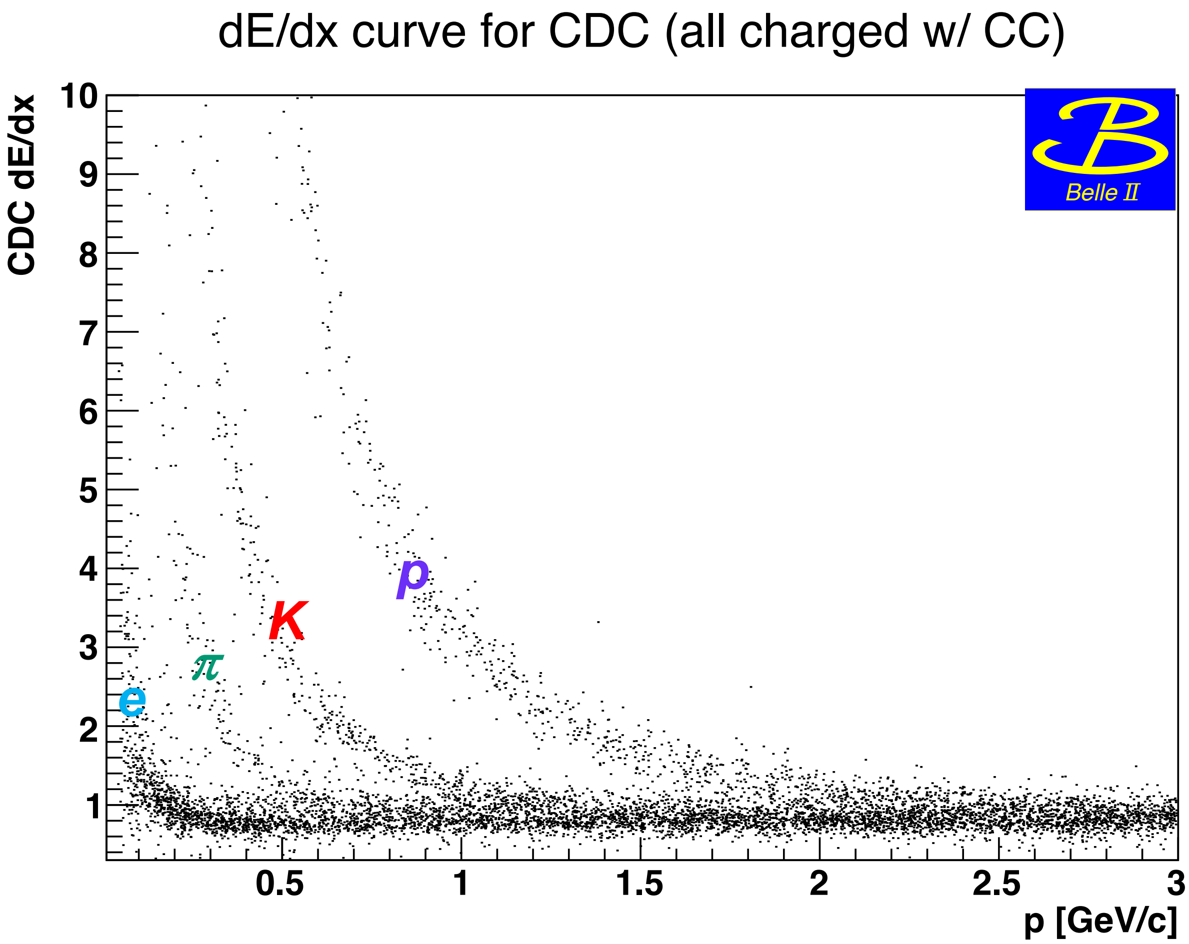
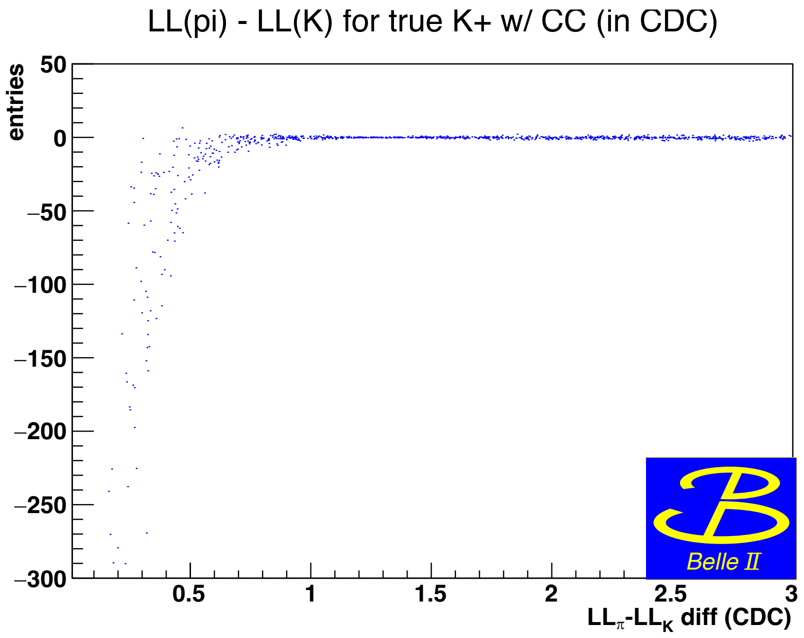


low momentum particle ID: dE/dx



dE/dx curve for CDC (all charged w/ CC)



LL(pi) - LL(K) for true K+ w/ CC (in CDC)

⇒ good π/K separation up to p ~1.1 GeV/c

Particle ID homework problem #1:

In the forward endcap region of Belle II is the ARICH:

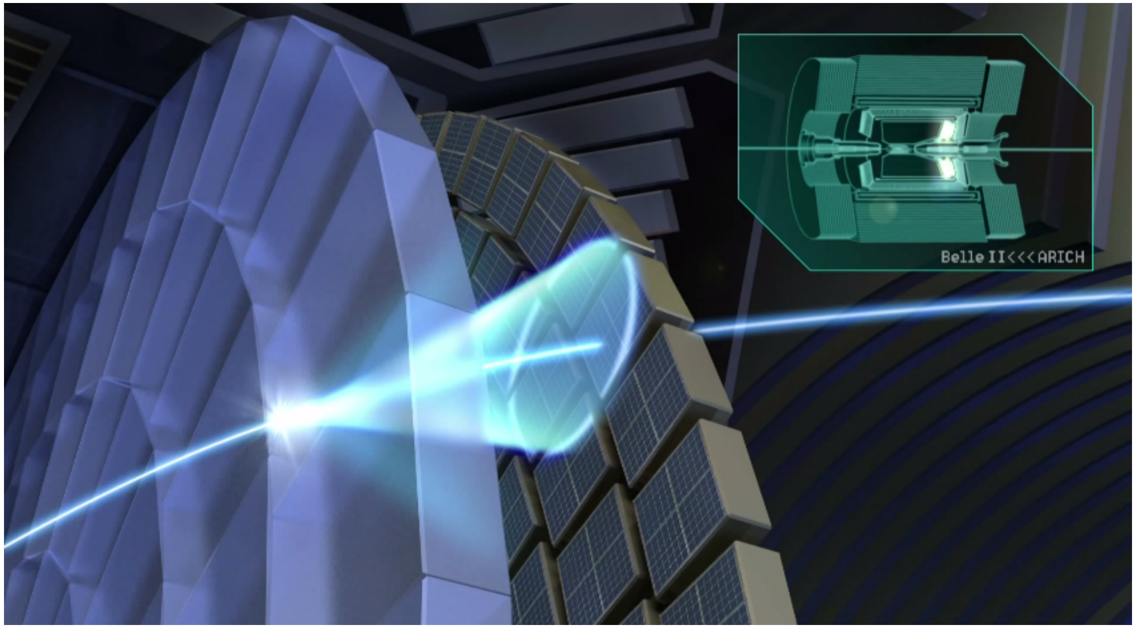
4.0 cm of aerogel radiator, followed by an array of finely segmented photodetectors. The separation is 20.0 cm (see figure) and n(aerogel) = 1.050.

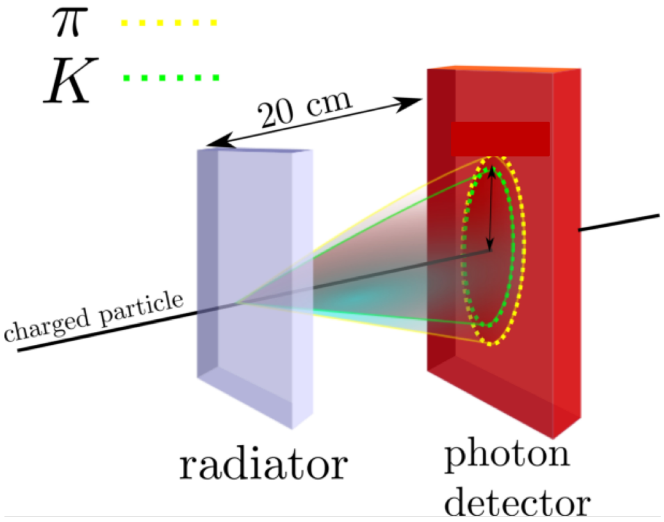
What is the difference in radii of the "Cerenkov rings" at the photodetectors for:

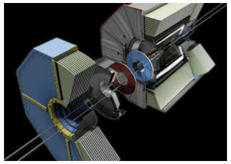
a) π^+ *and* K^+ *with p= 3.0 GeV/c?*

b) *for* π^+ *and* K^+ *with p= 4.0 GeV/c?*

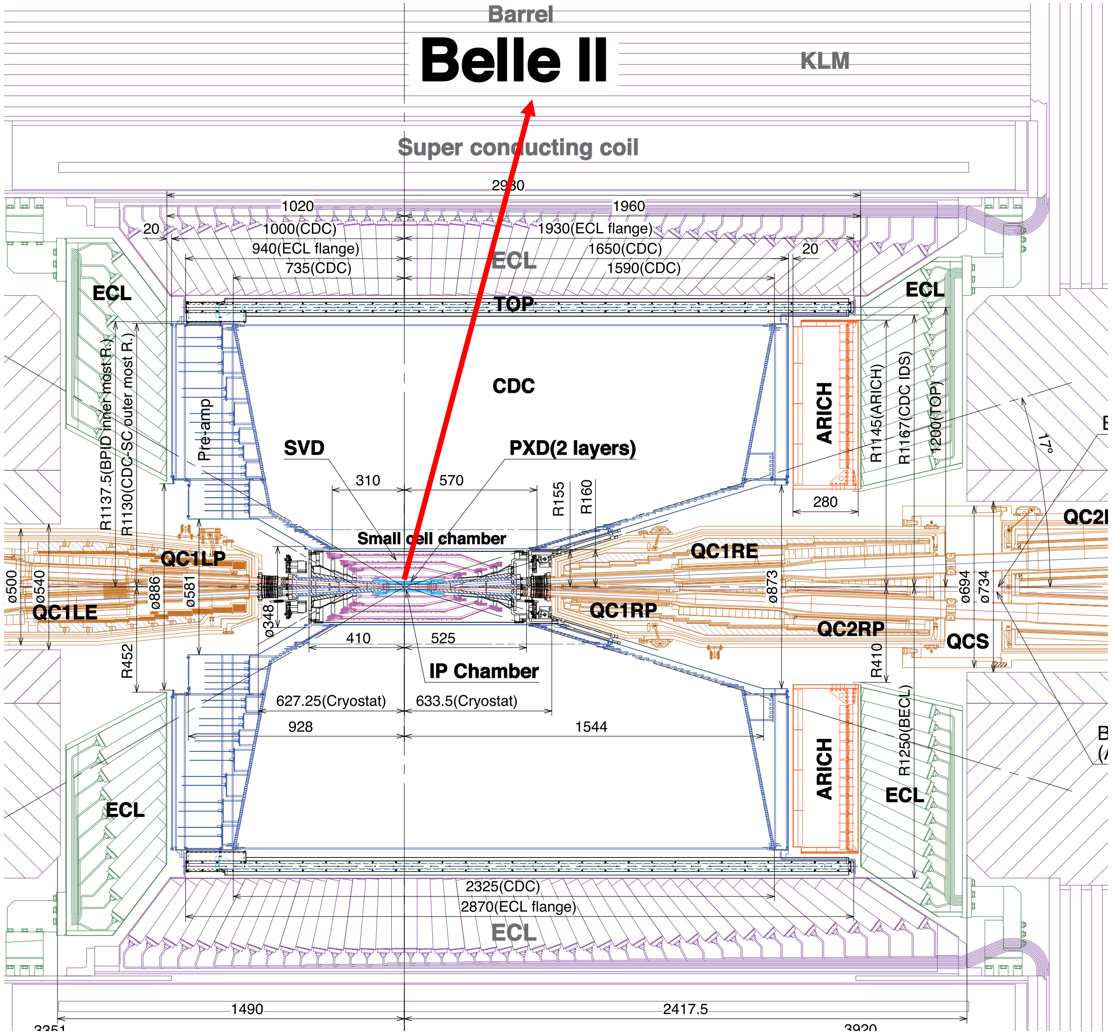
c) *what are the mean* γ *yields for these four cases?*







Particle ID homework problem #2:



For a μ^- to reach the KLM, it must pass through (at least) the following material:

a) ***iTOP quartz:*** *2.0 cm @ $\rho = 2.201\ \mathrm{g/cm^3}$*

b) ***ECL CsI crystal:*** *30 cm @ $\rho = 4.51\ \mathrm{g/cm^3}$*

c) ***magnet coil Alum.:*** *10 cm @ $\rho = 2.710\ \mathrm{g/cm^3}$*

d) ***KLM iron (1 layer):*** *4.7 cm @ $\rho = 7.874\ \mathrm{g/cm^3}$*

What is the minimum energy required for a "minimum-ionizing" μ^-

$$\langle -dE/dx \rangle \approx 2\ \mathrm{MeV / (g/cm^2)}$$

to reach the first scintillator layer of the KLM?