Requirements on detectors: example 1
B factory

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Contents

- Physics case for B factories / Super B factories
- Accellerator
- Detector

A little bit of history...

CP violation: difference in the properties of particles and their anti-particles – first observed in 1964 in the decays of neutral kaons.

M. Kobayashi and T. Maskawa (1973): CP violation in the Standard model – related to the weak interaction quark transition matrix

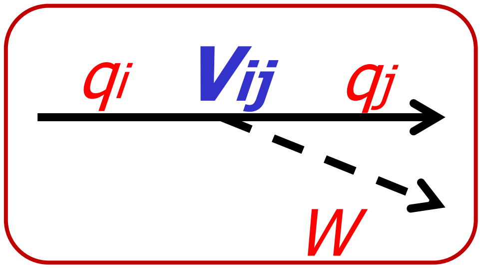
Their theory was formulated at a time when three quarks were known – and they requested the existence of three more!

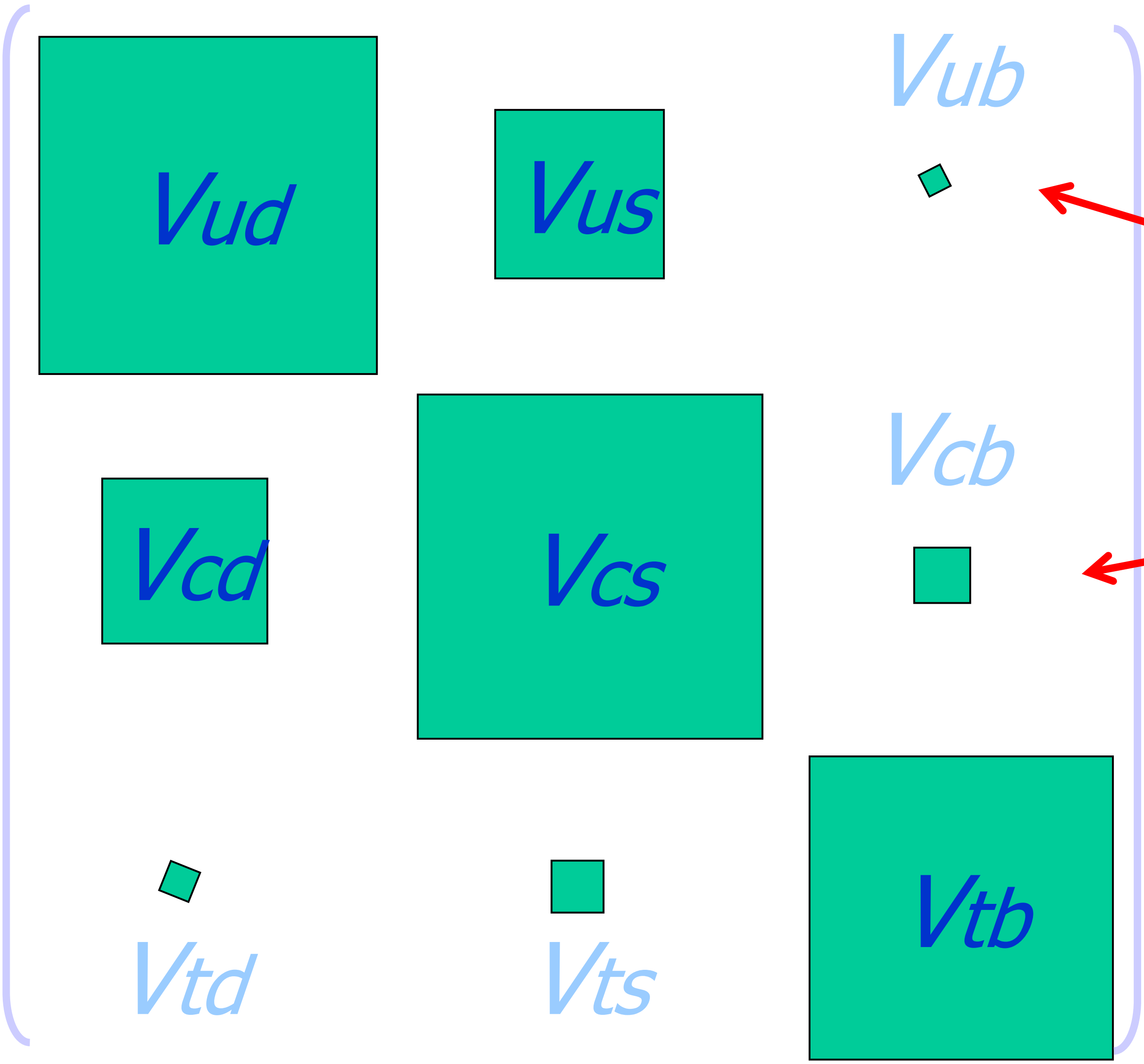
The last missing quark was found in 1994.

... and in 2001 two experiments – Belle and BaBar at two powerfull accelerators (B factories) - have further investigated CP violation and have indeed proven that it is tightly connected to the quark transition matrix

CKM - Cabibbo-Kobayashi-Maskawa (quark transition) matrix:

almost real and diagonal, but not completely!





Amplitude for the b → u transition

Amplitude for the b → c transition

CKM: unitary matrix
→relations of the type

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

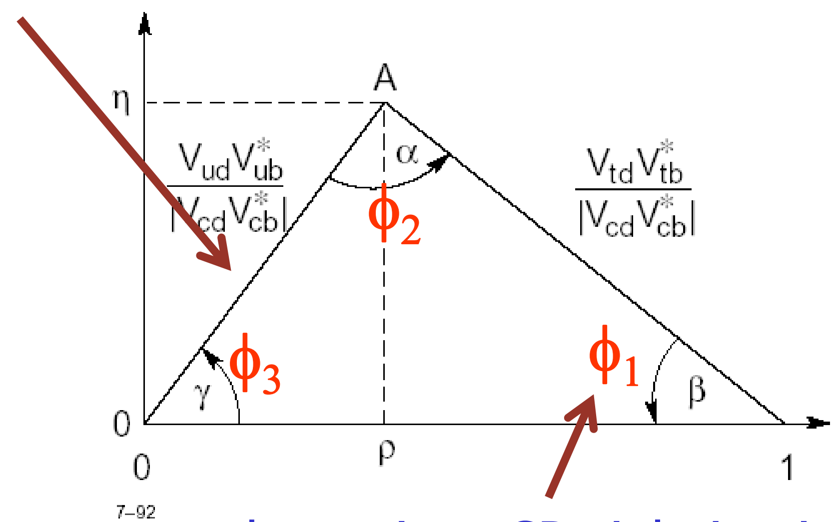
CKM matrix: determines charged weak interaction of quarks

Wolfenstein parametrisation: expand the CKM matrix in the parameter λ (=$\sin\theta_c$=0.22)

A, ρ and η: all of order one

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

determines probability of b→u transitions



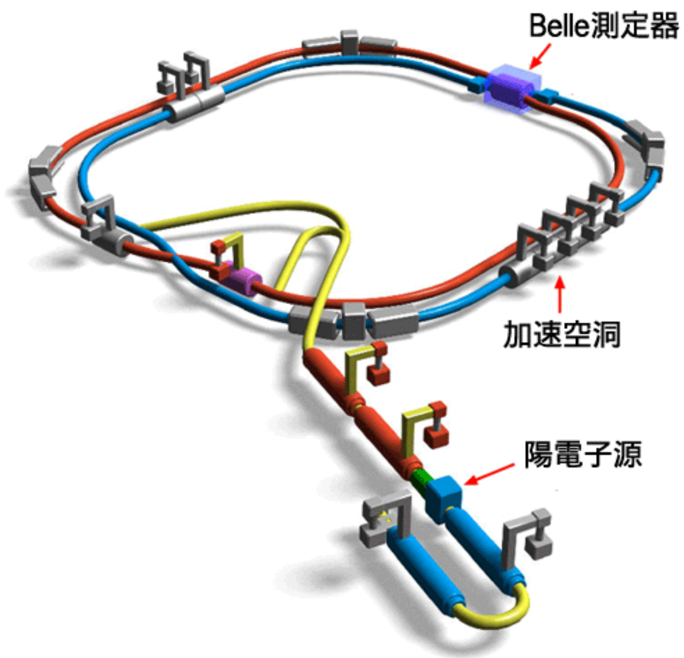
determines CP violation in B→J/ψ K_S decays

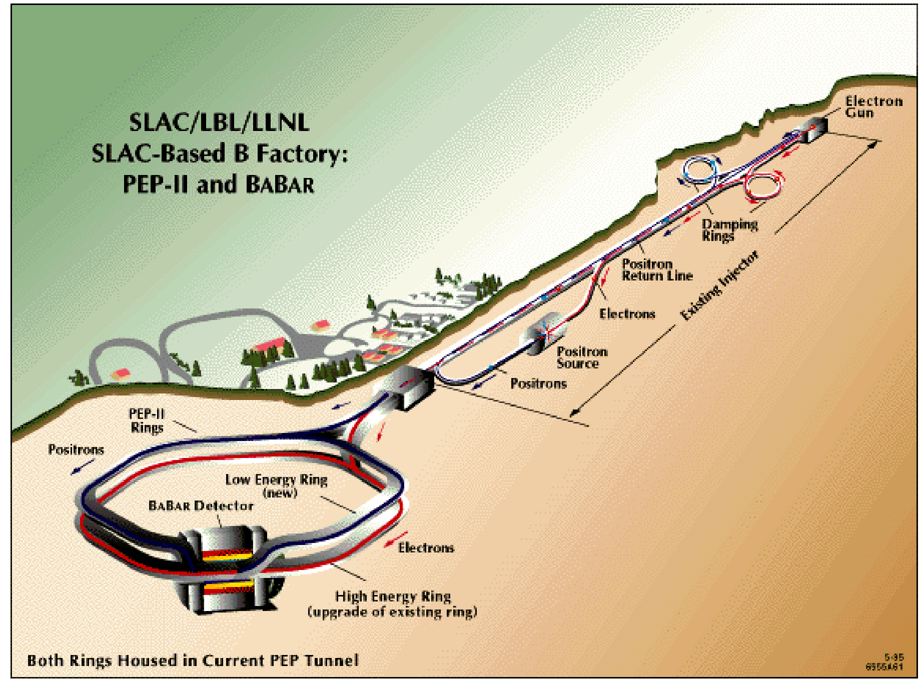
Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Goal: measure sides and angles in several different ways, check consistency →

Asymmetric B factories





$\sqrt{s}$=10.58 GeV

$e^+ \rightarrow \Upsilon(4S) \leftarrow e^-$

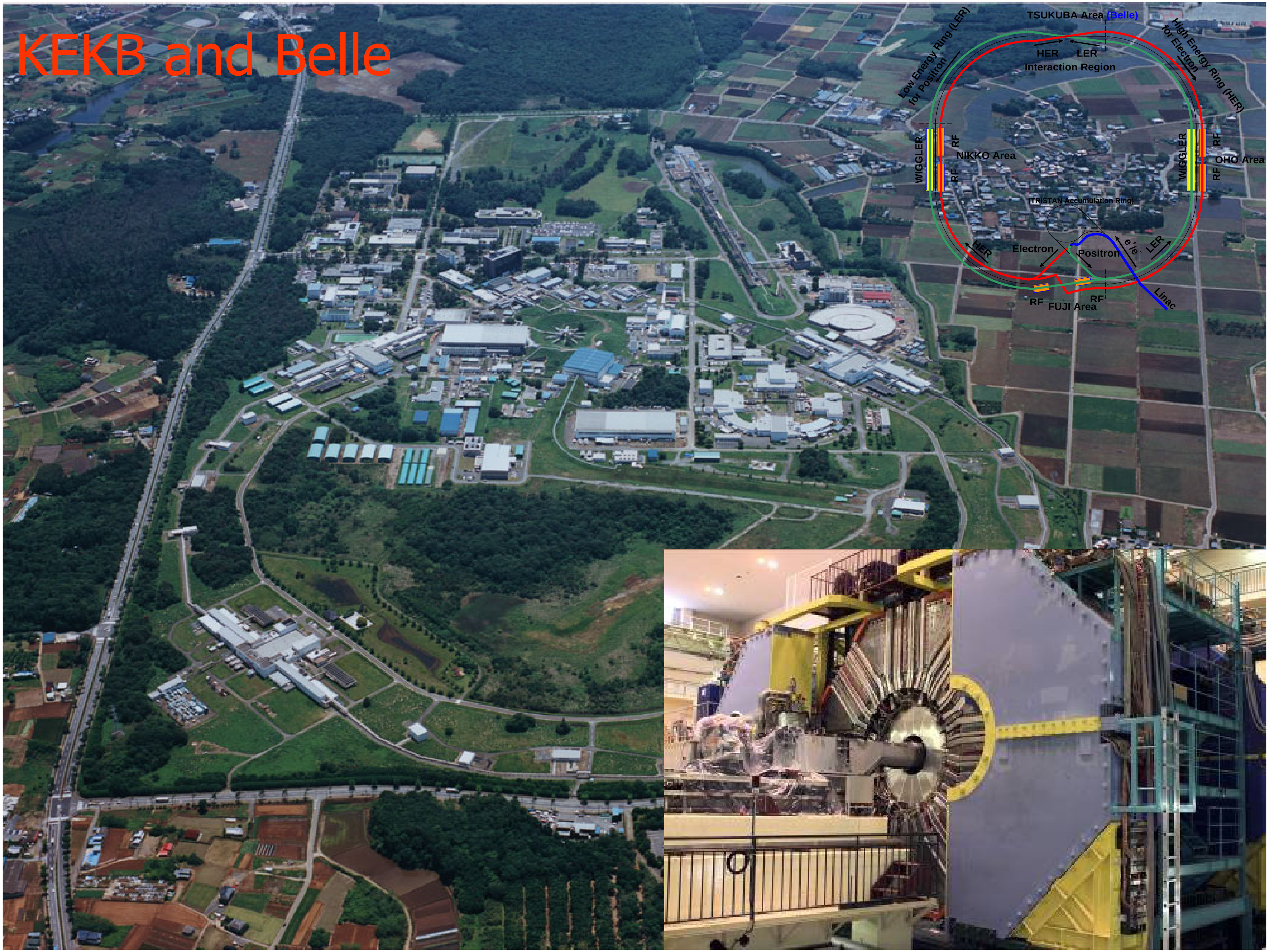
$\Upsilon(4S) \rightarrow B\,\bar{B}$

$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

BaBar $p(e^-)$=9 GeV $p(e^+)$=3.1 GeV $\beta\gamma$=0.56

Belle $p(e^-)$=8 GeV $p(e^+)$=3.5 GeV $\beta\gamma$=0.42

KEKB and Belle



How to design the experimental apparatus (‘spectrometer’)

To design a spectrometer with

- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

We have to understand what exactly we want to measure.

Spectrometer design: what do we want to measure? B factories: Time evolution in the B system

An arbitrary linear combination of the neutral B-meson flavor eigenstates, B and anti-B

$$a\left|B^0\right\rangle + b\left|\overline{B}^0\right\rangle$$

with a=a(t) and b=b(t), is governed by a time-dependent Schroedinger equation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a \\ b \end{pmatrix}$$

M and Γ are 2x2 Hermitian matrices. CPT invariance → $H_{11}=H_{22}$

$$M = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}, \Gamma = \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

diagonalize, solve →

Time evolution of B's

Time evolution in the B^0 in $\overline{B}^0$ basis:

$$\left| B^0_{phys}(t) \right\rangle = g_+(t) \left| B^0 \right\rangle + (q/p) g_-(t) \left| \overline{B}^0 \right\rangle$$
$$\left| \overline{B}^0_{phys}(t) \right\rangle = (p/q) g_-(t) \left| B^0 \right\rangle + g_+(t) \left| \overline{B}^0 \right\rangle$$

with

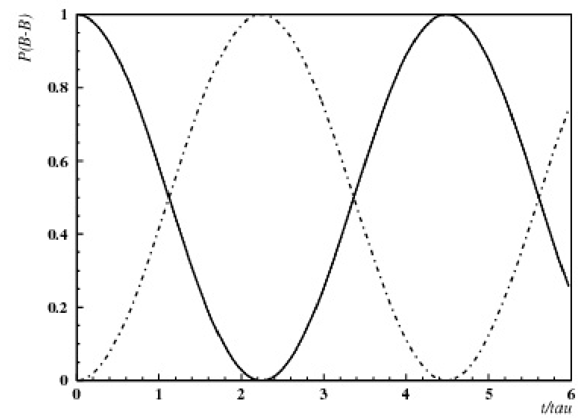
$$g_+(t) = e^{-iMt} e^{-\Gamma t/2} \cos(\Delta m t/2)$$
$$g_-(t) = e^{-iMt} e^{-\Gamma t/2} i \sin(\Delta m t/2)$$

$M = (M_H + M_L)/2$

If B mesons were stable ($\Gamma=0$), the time evolution would look like:

$$g_+(t) = e^{-iMt}\cos(\Delta m t/2)$$

$$g_-(t) = e^{-iMt} i \sin(\Delta m t/2)$$



→Probability that a B turns into its anti-particle

→beat in classical mechanics

$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

→Probability that a B remains a B

$$\left|\left\langle B^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |g_+(t)|^2 = \cos^2(\Delta m t/2)$$

→Expressions familiar from quantum mechanics of a two level system, neutrino mixing etc

CP violation: decay rate difference

Decay rate asymmetry:

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)}$$

Decay rate:

$$P(B^0 \to f_{CP}, t) \propto \left| \left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle \right|^2$$

Decay amplitudes vs time:

$$\left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle = g_+(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + (q/p) g_-(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}$$

$$\left\langle f_{CP} \middle| H \middle| \overline{B}^0_{phys}(t) \right\rangle = (p/q) g_-(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + g_+(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= (p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}$$

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP},t) - P(B^0 \to f_{CP},t)}{P(\overline{B}^0 \to f_{CP},t) + P(B^0 \to f_{CP},t)} =$$

CP violation: asymmetry in time evolution of B and anti-B

$$= \frac{\left|(p/q)g_-(t)A_{f_{CP}} + g_+(t)\overline{A}_{f_{CP}}\right|^2 - \left|g_+(t)A_{f_{CP}} + (q/p)g_-(t)\overline{A}_{f_{CP}}\right|^2}{\left|(p/q)g_-(t)A_{f_{CP}} + g_+(t)\overline{A}_{f_{CP}}\right|^2 + \left|g_+(t)A_{f_{CP}} + (q/p)g_-(t)\overline{A}_{f_{CP}}\right|^2} =$$

$$= \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1+|\lambda_{f_{CP}}|^2}$$

$$= C\cos(\Delta m t) + S\sin(\Delta m t)$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

Non-zero effect if Im(λ) ≠ 0, even if |λ| = 1

If |λ| = 1 →

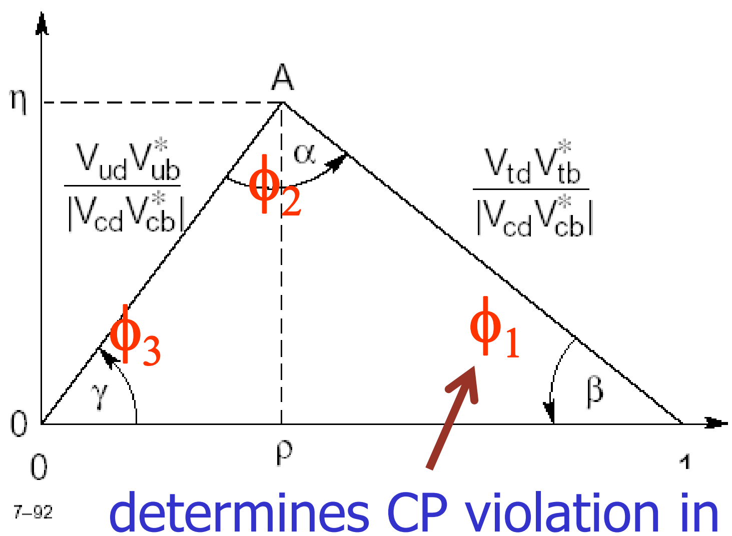
$$a_{f_{CP}} = -\mathrm{Im}(\lambda)\sin(\Delta m t)$$

Detailed derivation → backup slides

CP violation: related to the angles of the unitarity triangle

$$a_{f_{CP}} = -\mathrm{Im}(\lambda)\sin(\Delta m t)$$

$\mathrm{Im}(\lambda) = \sin 2\phi_1$ in $B \rightarrow J/\psi\ K_S$ decays!

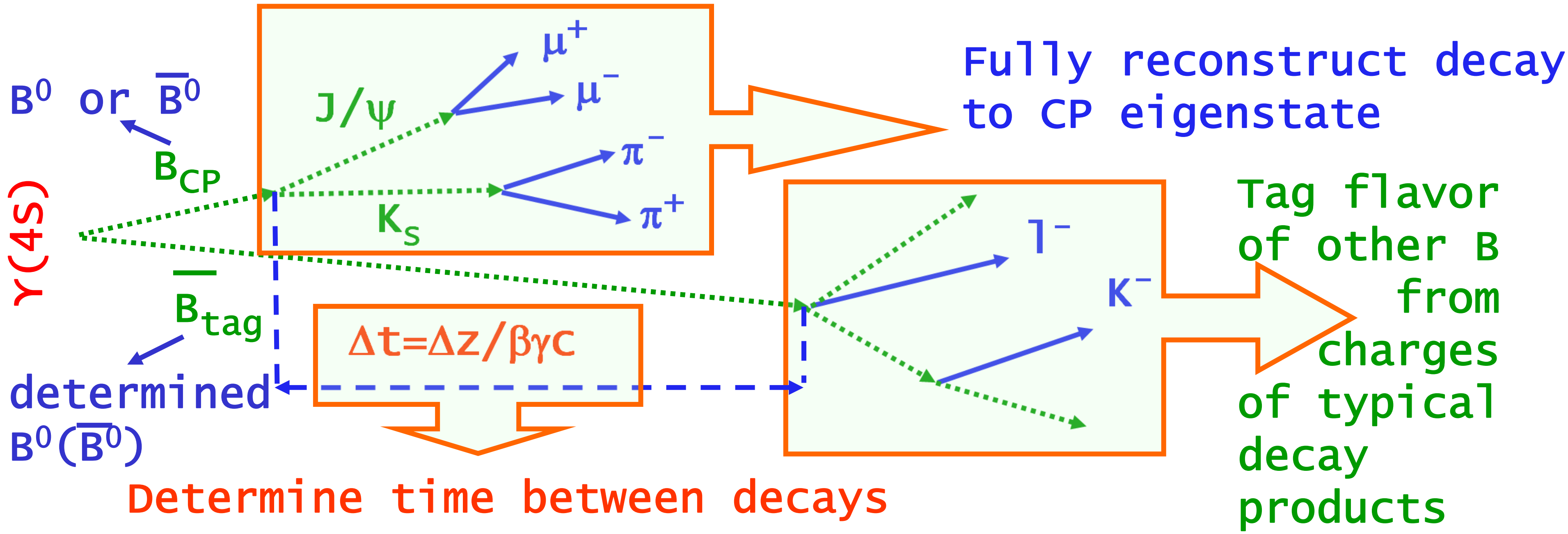


determines CP violation in $B \rightarrow J/\psi\ K_S$ decays

Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Typical measurement

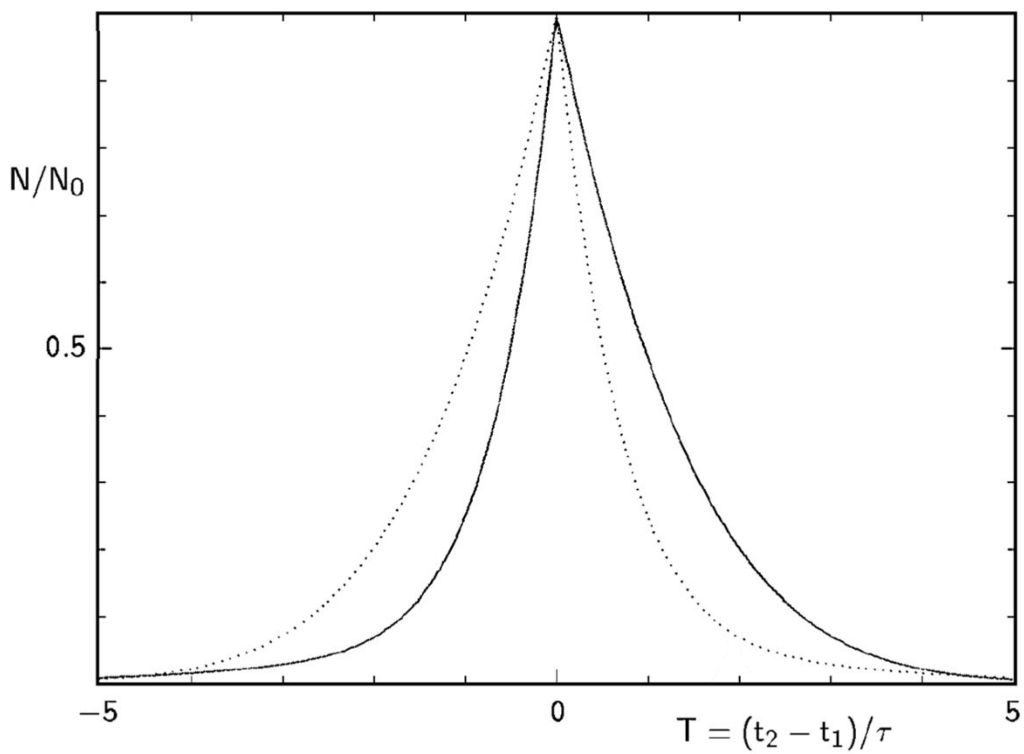


Experimental considerations

What kind of vertex resolution do we need to measure the asymmetry?

$$P(B^0(\overline{B}^0) \to f_{CP}, t) = e^{-\Gamma t}\left(1 \mp \sin(2\phi_1)\sin(\Delta m t)\right)$$

We are measuring this parameter



T = time difference of the two decays

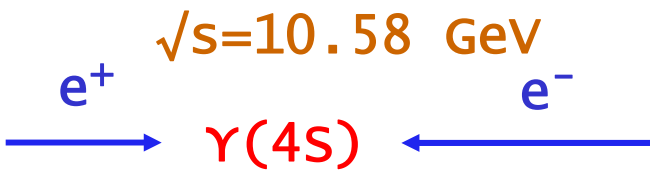
Want to distinguish the decay rate of B (dotted) from the decay rate of anti-B (full).

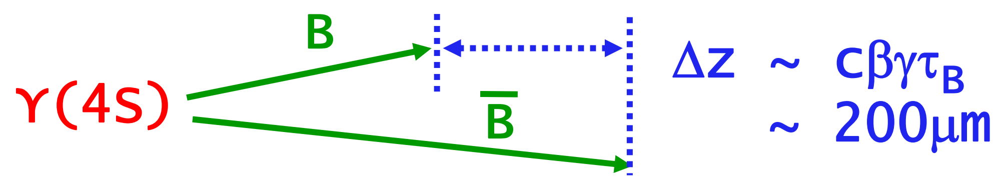
-> the two curves should not be smeared too much

Integrals are equal, time information mandatory!

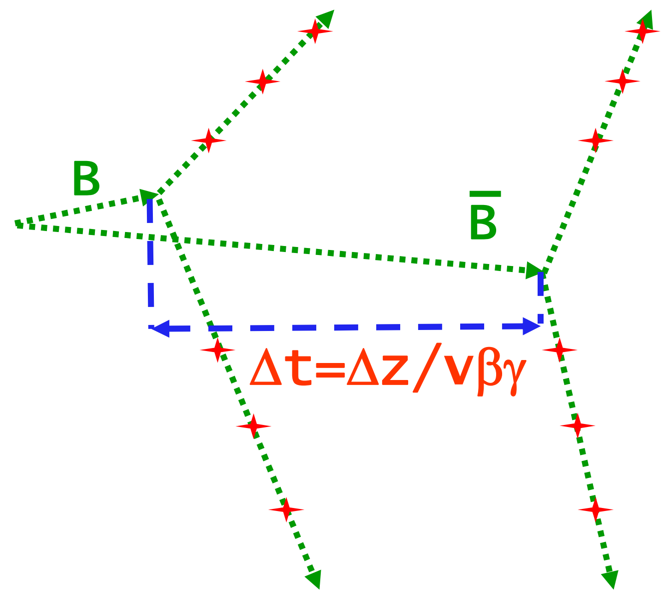
Asymmetric B factories: two beams have different energies so that c.m.s. is moving with velocity β

$\beta\gamma \sim 0.5$: why?





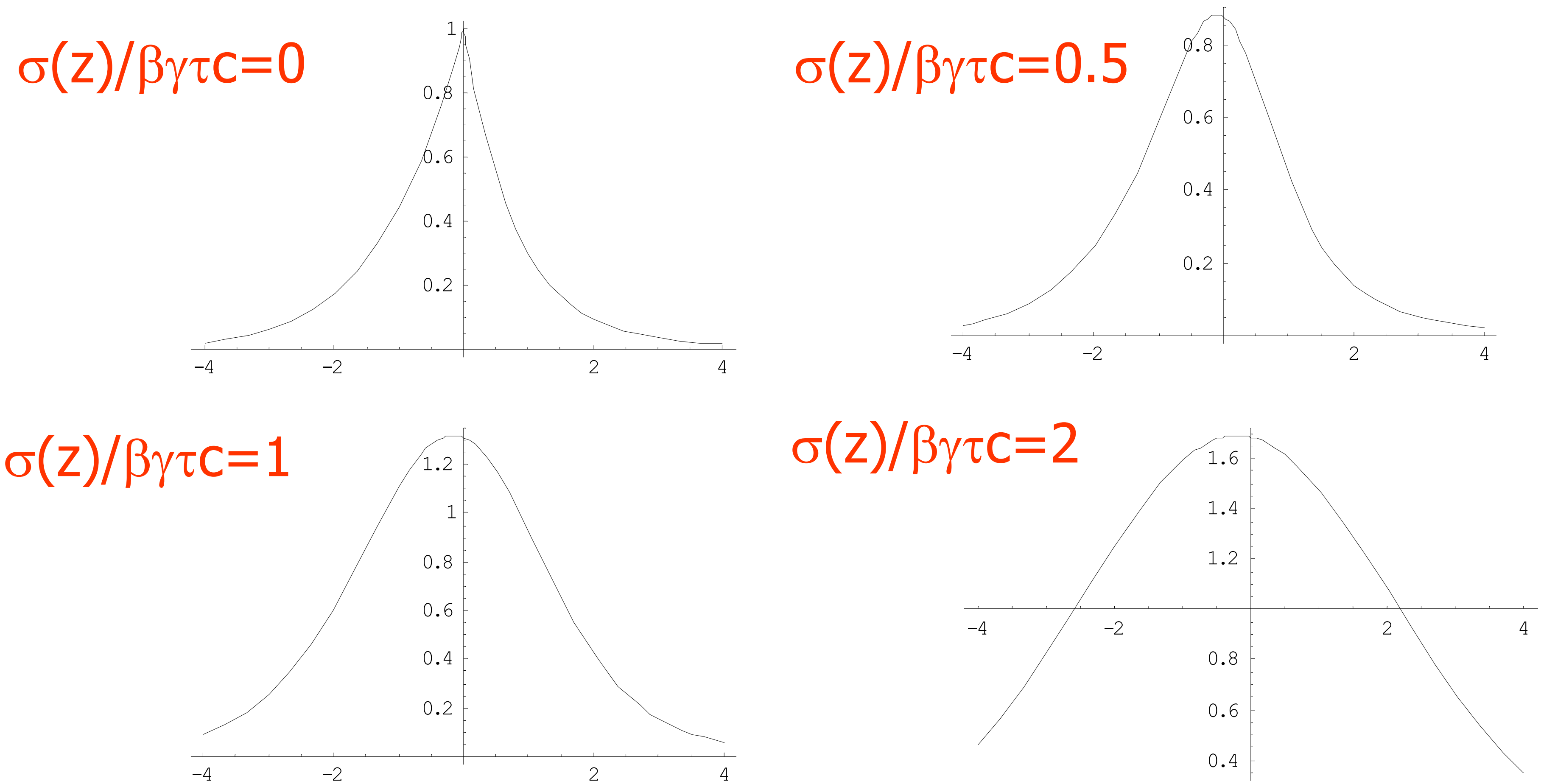
BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$



Decay point of a B (a crossing of extrapolated particle tracks) is measured with a finite precision $\sigma(z)$

Experimental considerations

B decay rate vs t for different vertex resolutions in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

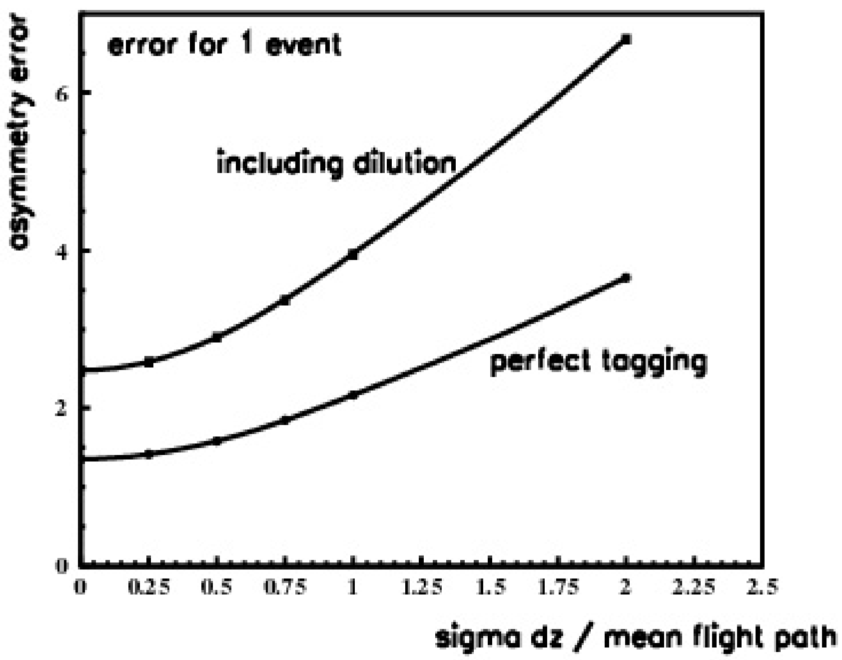


Measured distribution: convolution of P(t) and the resolution function (e.g., a Gaussian with $\sigma = \sigma(z)/\beta\gamma\tau c$)

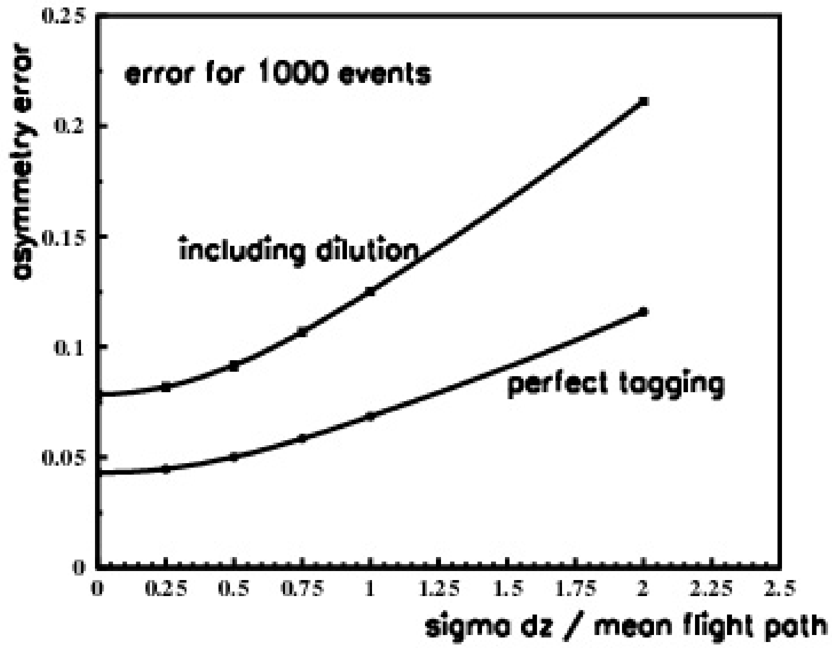
Experimental considerations

Error on $\sin 2\phi_1 = \sin 2\beta$ as a function of the vertex resolution in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

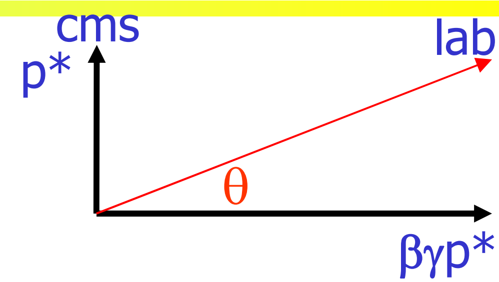
For 1 event



for 1000 events



Experimental considerations



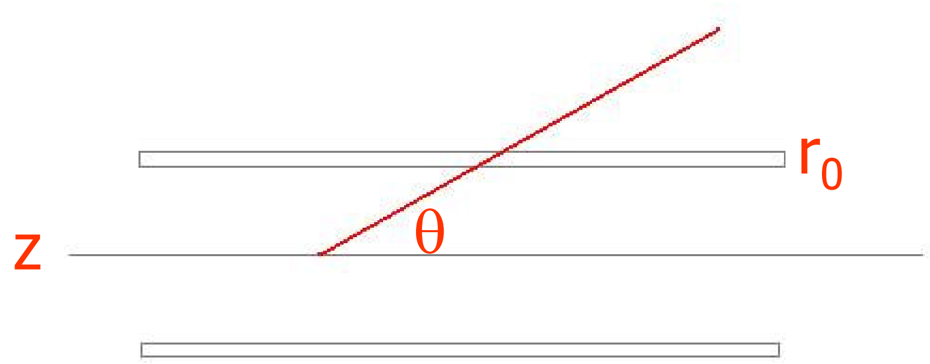
Choice of boost $\beta\gamma$:

Vertex resolution vs. path length

Typical B flight length: $z_B=\beta\gamma\tau c$

Typical two-body topology: decay products at 90^o in cms; at $\theta=\mathrm{atan}(1/\beta\gamma)$ in the lab

Assume: vertex resolution determined by multiple scattering in the beam pipe wall at r_0 (d: beam pipe thickness, X_0 radiation length of the material)



$$\sigma_\theta=15\ \mathrm{MeV}/p\ (d/X_0\sin\theta)^{1/2}$$

$$\sigma(z) = \sigma_\theta (dz/d\theta) = r_0\, \sigma_\theta /\sin^2\theta$$

$$\Rightarrow \sigma(z) \propto r_0(d/X_0)^{1/2}/\sin^{5/2}\theta$$

Experimental considerations

Choice of boost $\beta\gamma$:

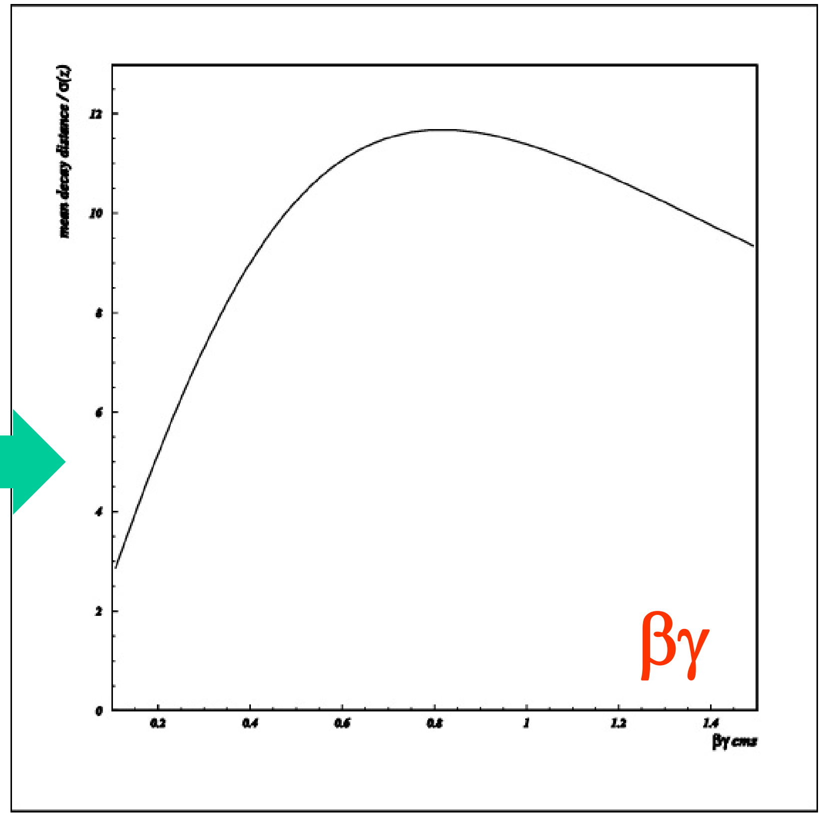
Maximize the ratio between the average flight path $\beta\gamma\tau c$ and the vertex resolution $\sigma(z)$

$\sigma(z) \propto r_0/\sin^{5/2}\theta$ with $\theta = \mathrm{atan}(1/\beta\gamma)$

$\beta\gamma\tau c/\sigma(z) \propto (1/r_0)\, \beta\gamma\tau c \sin^{5/2}\theta =$
$= (1/r_0)\, \beta\gamma\tau c \sin^{5/2}(\mathrm{atan}(1/\beta\gamma))$

Boost around $\beta\gamma=0.8$ seems optimal

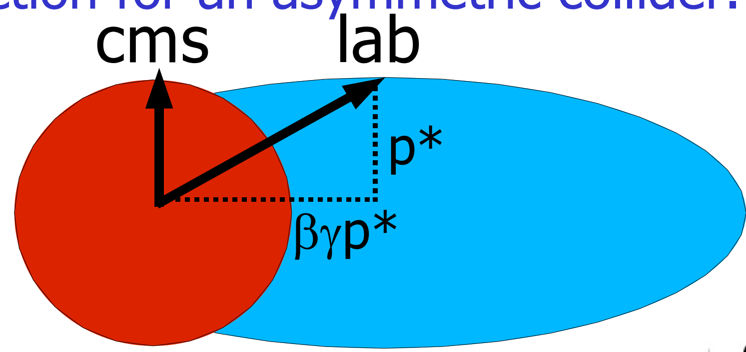
$\beta\gamma\tau c/\sigma(z)$



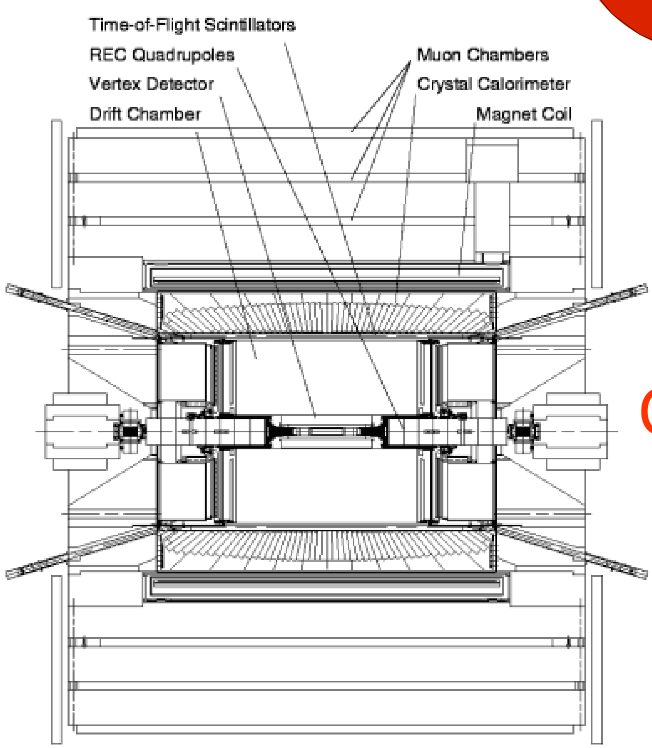
Not the whole story....

Experimental considerations

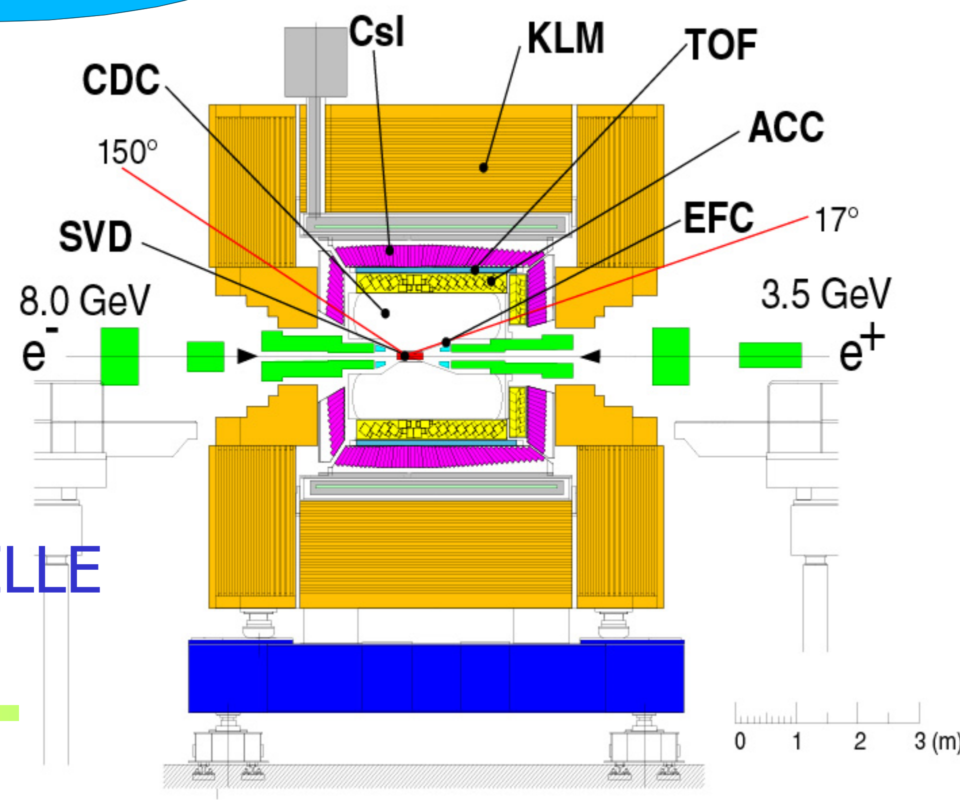
Detector form: symmetric for symmetric energy beams; extended in the boost direction for an asymmetric collider.



Exaggerated plot: in reality $\beta\gamma$=0.5



CLEO



BELLE

Experimental considerations

Which boost...

Arguments for a smaller boost:

- Larger boost -> smaller acceptance

(particles escape detection in the boosted direction in the region around the beam pipe) →

- Larger boost -> it becomes hard to damp the betatron oscillations of the low energy beam: less synchrotron radiation at fixed ring radius (same as the high energy beam)
- More Touschek (intra-beam) scattering for a lower energy beam

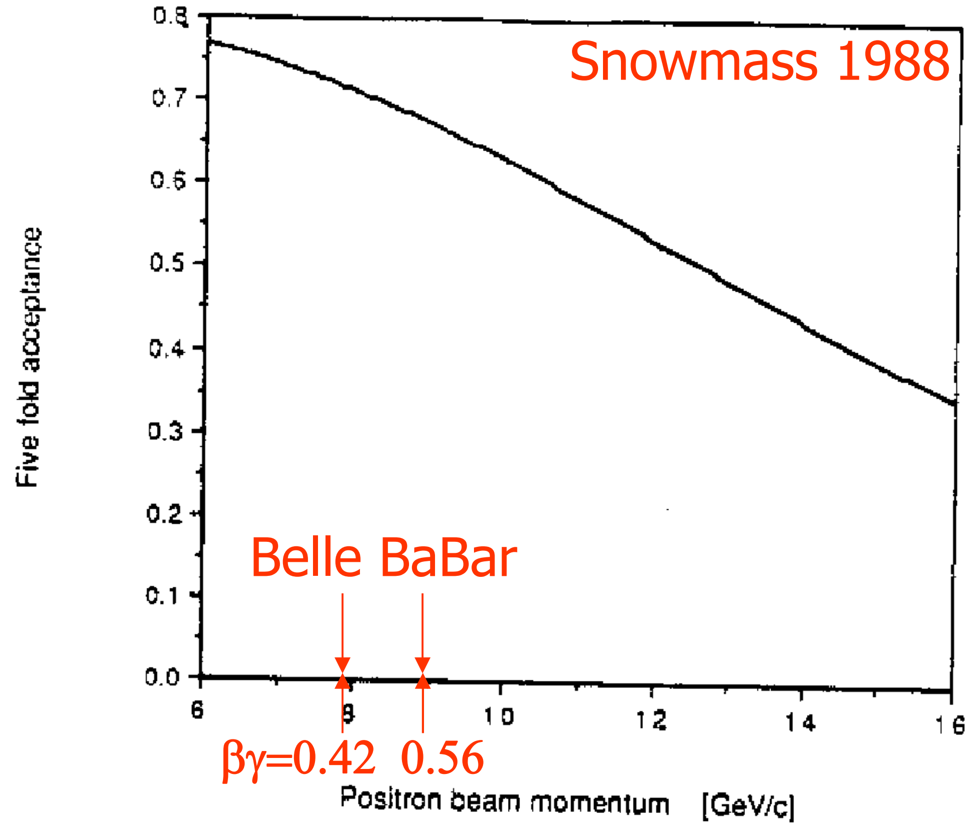
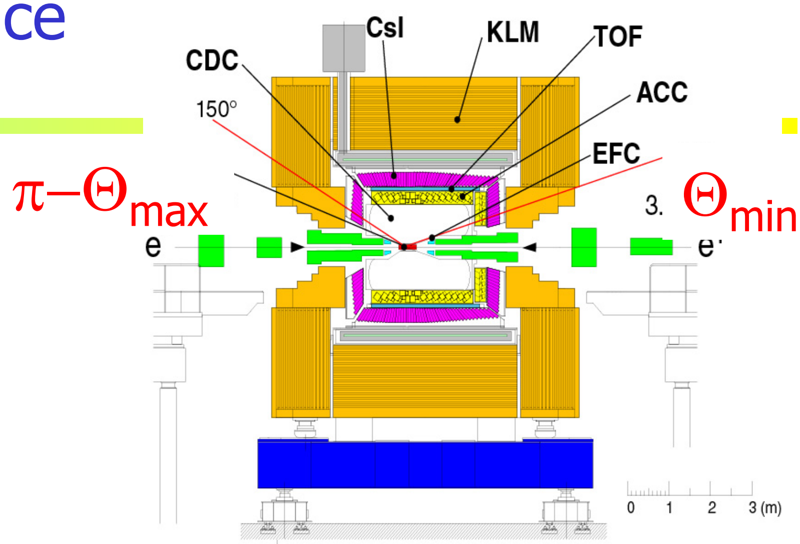
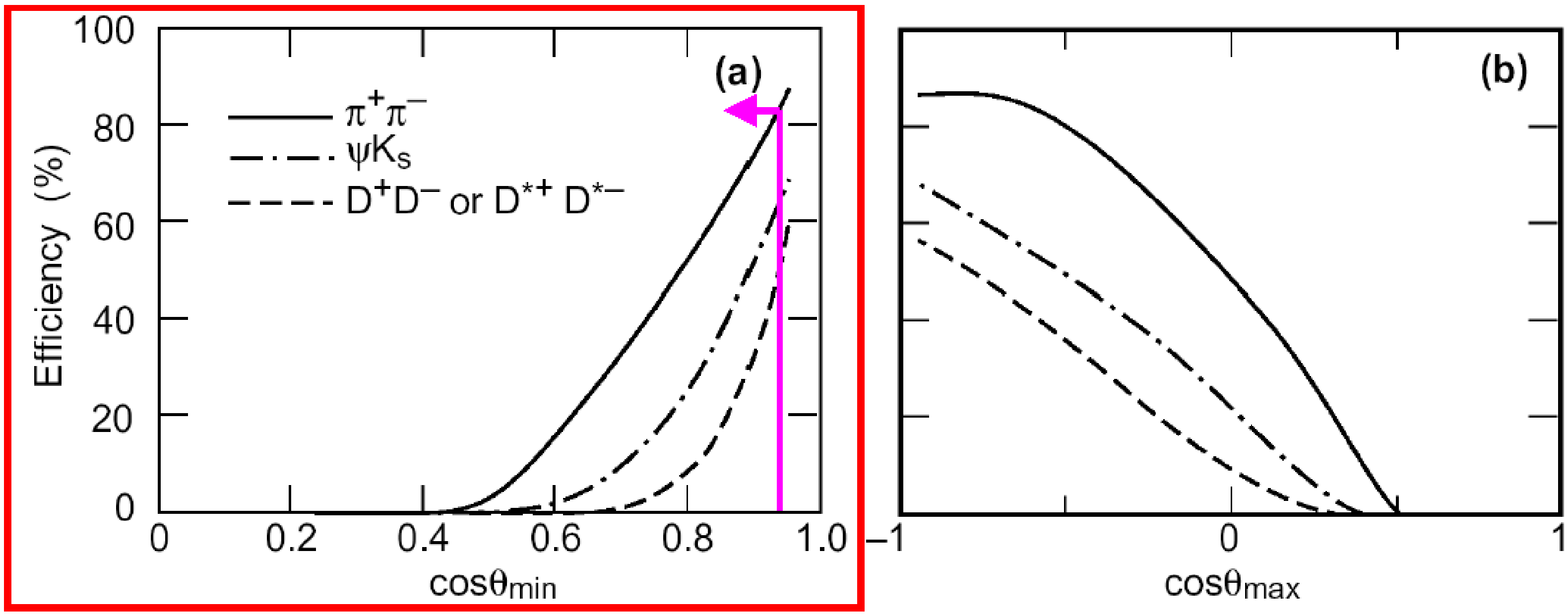


Figure 4. The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

Requirements: Geometric Acceptance





Angular coverage

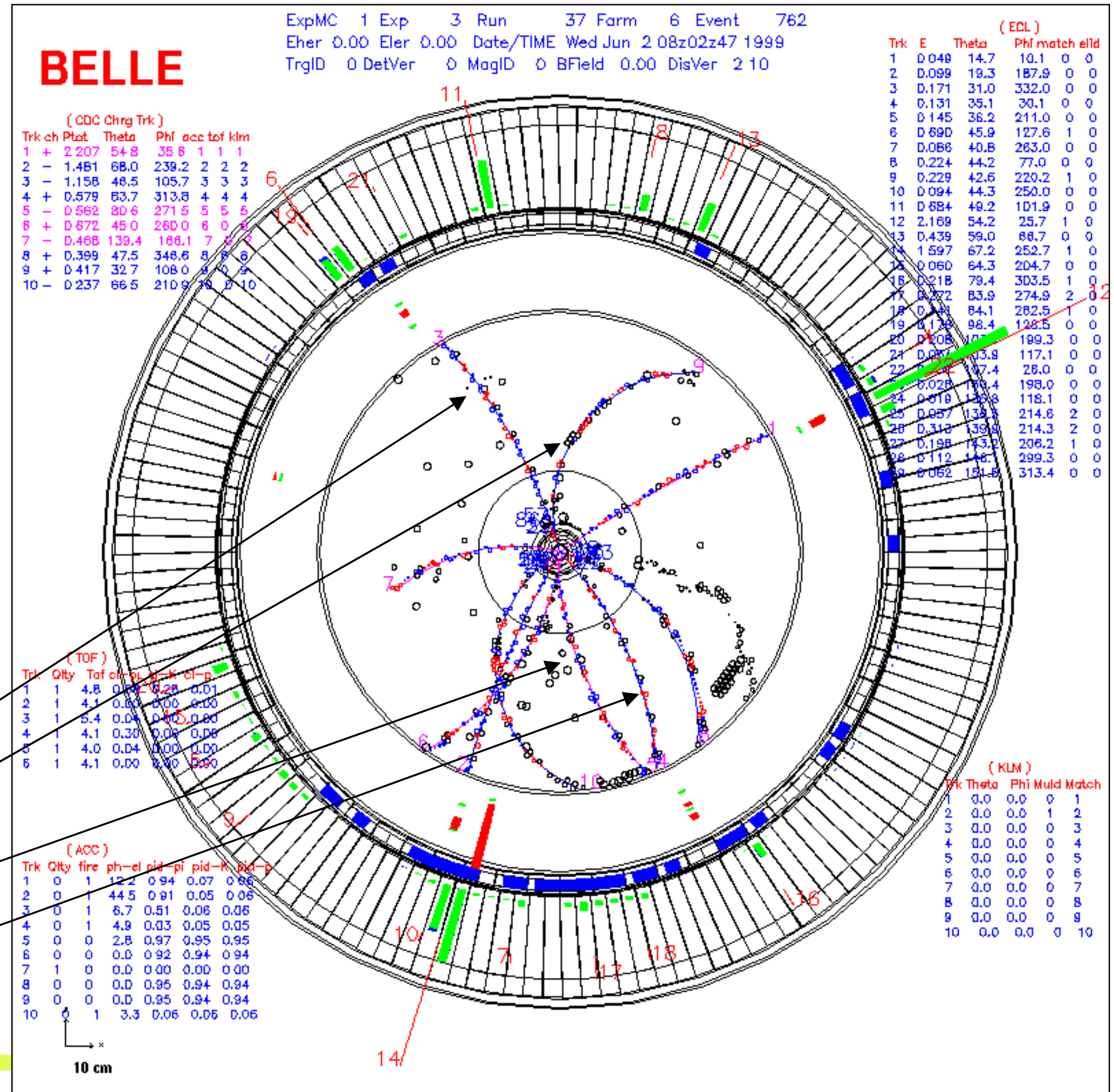
How to understand what happened in a collision?

Illustration on an example:

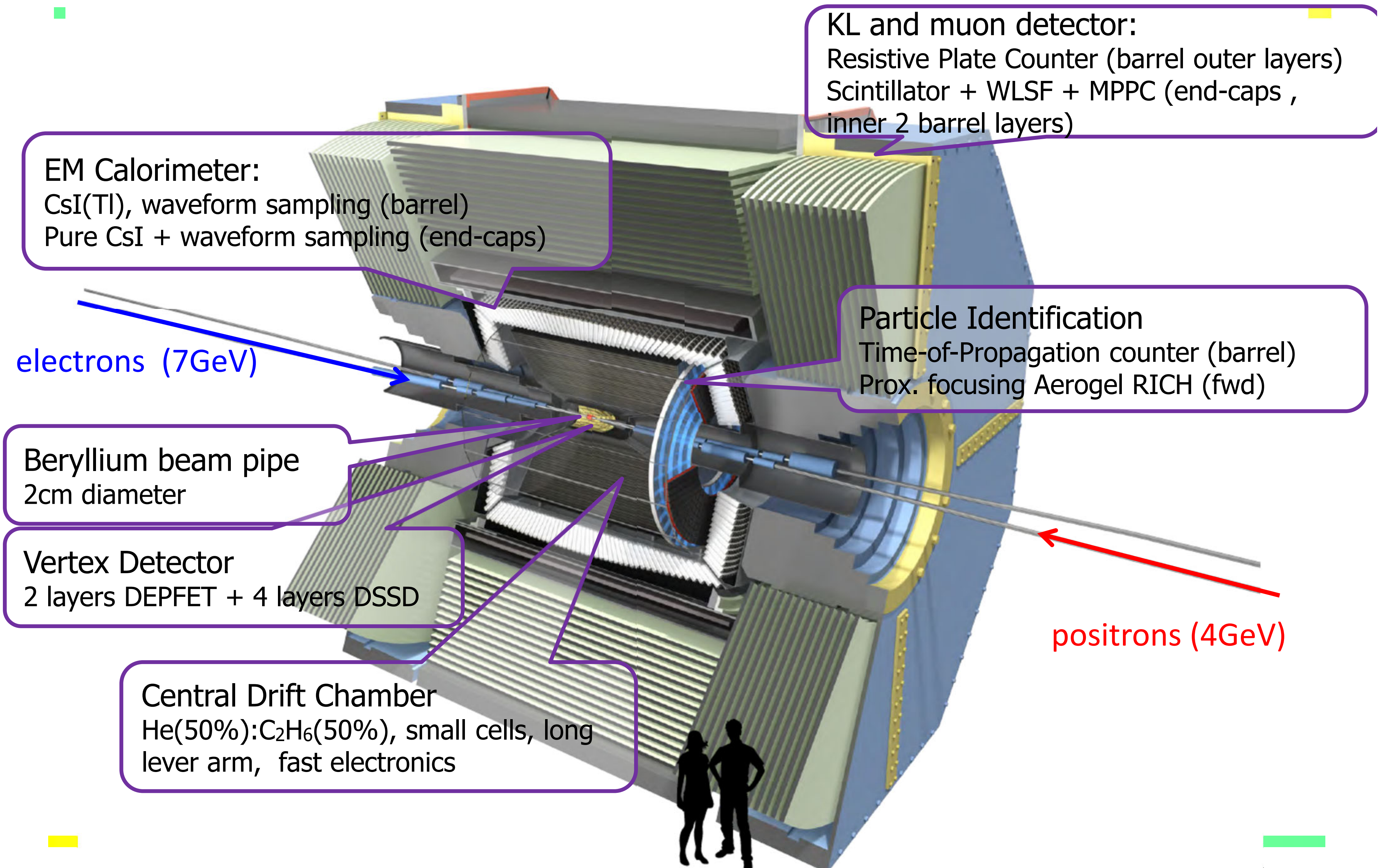
$B^0 \rightarrow K^0_S\, J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

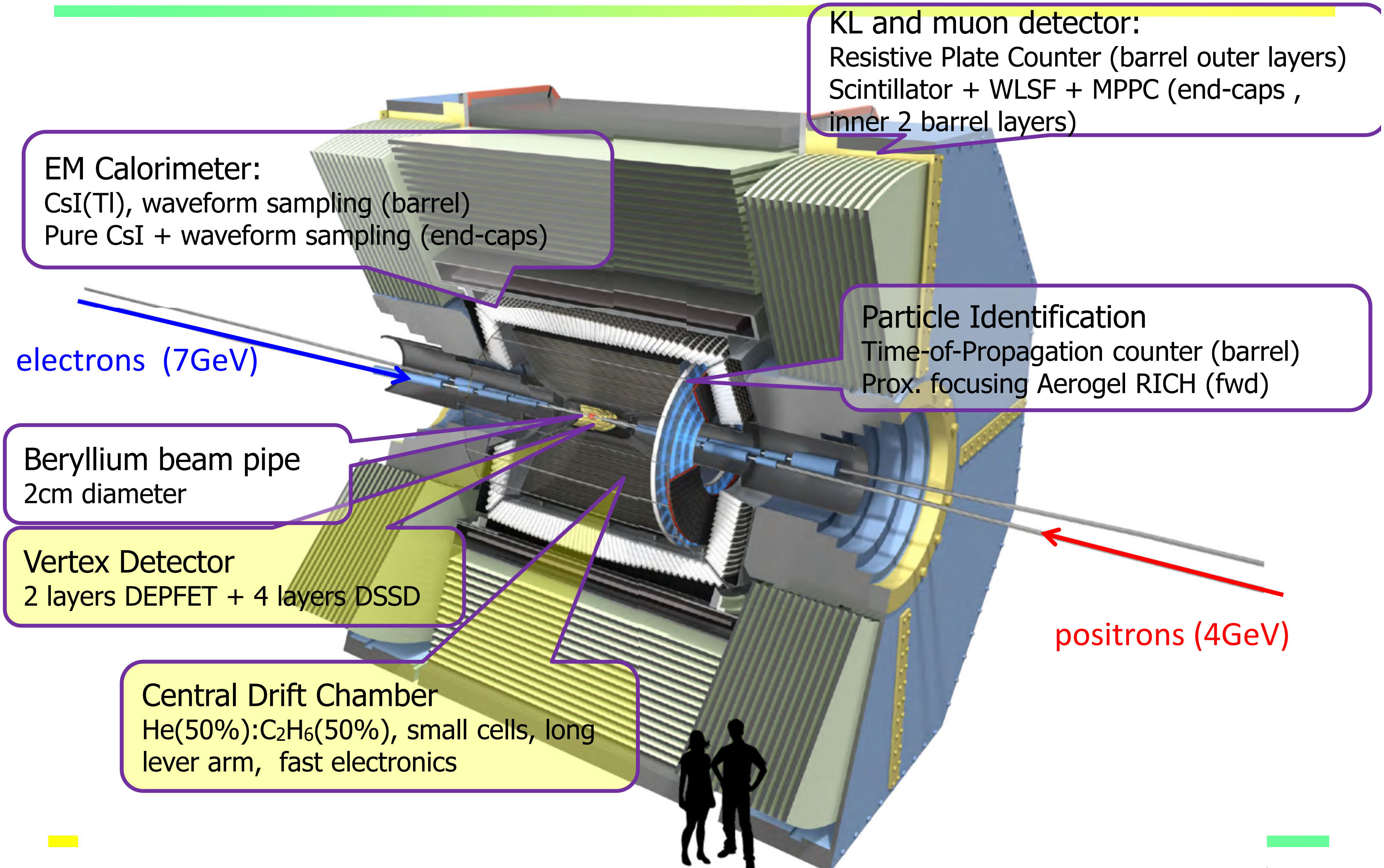
$J/\psi \rightarrow \mu^- \mu^+$

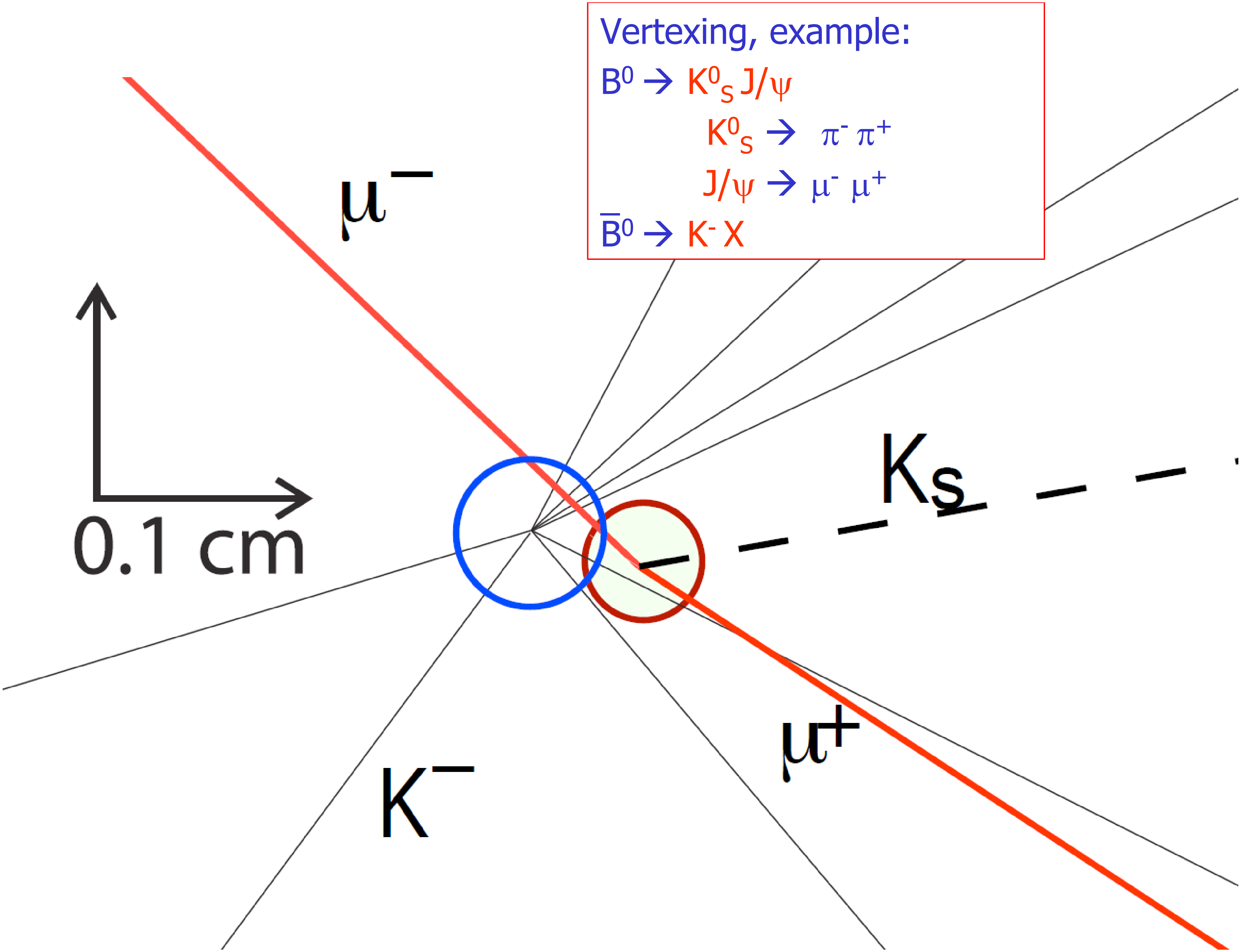


Belle II Detector



Tracking and vertex systems in Belle II

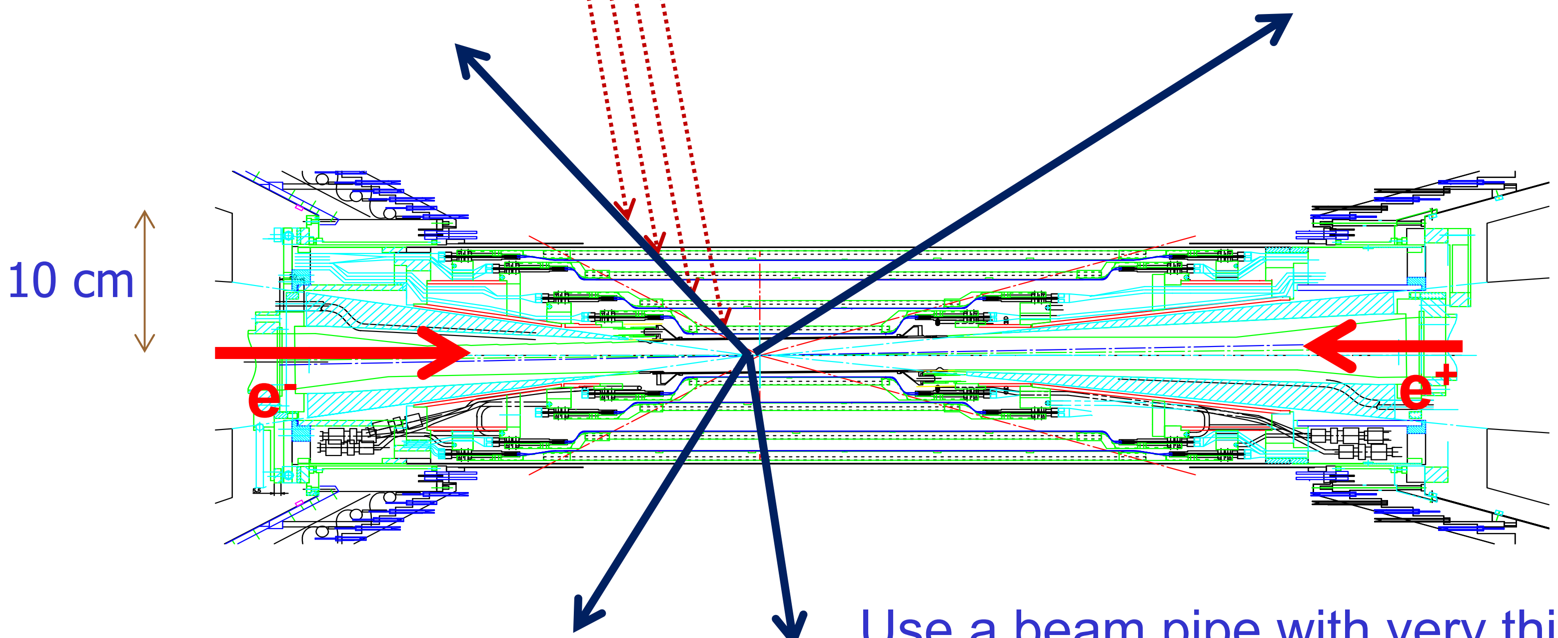




Vertexing, example:
$B^0 \rightarrow K^0_S J/\psi$
$K^0_S \rightarrow \pi^- \pi^+$
$J/\psi \rightarrow \mu^- \mu^+$
$\bar{B}^0 \rightarrow K^- X$
μ^-
0.1 cm
K_S
μ^+
K^-

Vertexing

Measure very accurately points on the track close to the interaction point



Use a beam pipe with very thin walls (and light material – long X_0) to reduce multiple scattering → **Be**

$\sigma(z) \propto r_0 (d/X_0)^{1/2} / \sin^{5/2}\theta$

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values $\gg$1 in brackets are for $(n-1)\times 10^6$ (gases).

Material	Z	A	$\langle Z/A\rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\vert_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({gℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	
Air (dry, 1 atm)			0.49919	61.3	90.1	36.62	(1.815)	(1.205)		78.80	
Shielding concrete			0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)			0.49707	64.6	96.5	28.17	1.696	2.230			

W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
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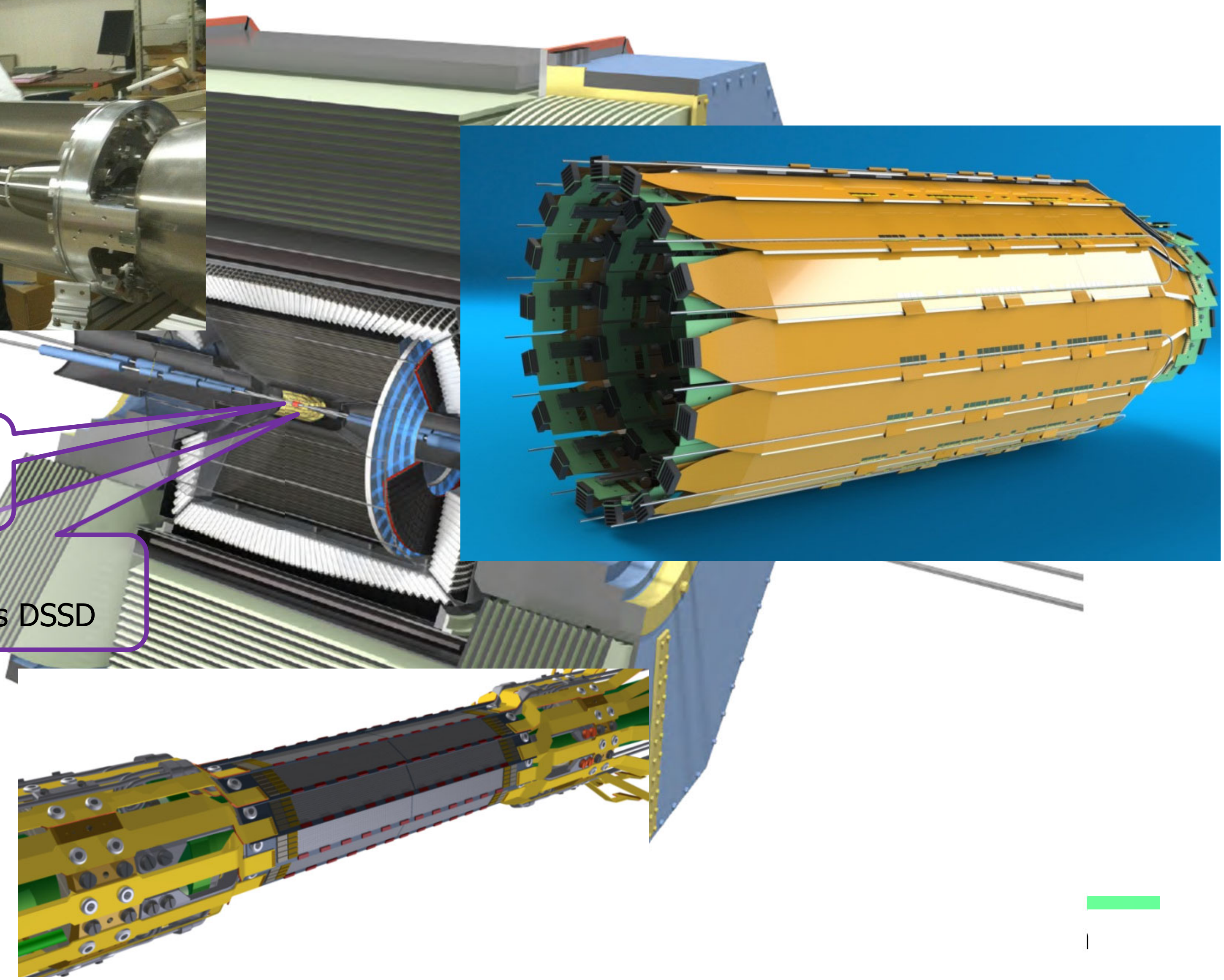
Shielding concrete			0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)			0.49707	64.6	96.5	28.17	1.696	2.230			
Lead glass			0.42101	95.9	158.0	7.87	1.255	6.220			
Standard rock			0.50000	66.8	101.3	26.54	1.688	2.650			
Methane (CH_4)			0.62334	54.0	73.8	46.47	(2.417)	(0.667)	90.68	111.7	[444.]
Ethane (C_2H_6)			0.59861	55.0	75.9	45.66	(2.304)	(1.263)	90.36	184.5	
Propane (C_3H_8)			0.58962	55.3	76.7	45.37	(2.262)	0.493(1.868)	85.52	231.0	
Butane (C_4H_{10})			0.59497	55.5	77.1	45.23	(2.278)	(2.489)	134.9	272.6	
Octane (C_8H_{18})			0.57778	55.8	77.8	45.00	2.123	0.703	214.4	398.8	
Paraffin ($CH_3(CH_2)_{n\approx 23}CH_3$)			0.57275	56.0	78.3	44.85	2.088	0.930			
Nylon (type 6, 6/6)			0.54790	57.5	81.6	41.92	1.973	1.18			
Polycarbonate (Lexan)			0.52697	58.3	83.6	41.50	1.886	1.20			
Polyethylene ($[CH_2CH_2]_n$)			0.57034	56.1	78.5	44.77	2.079	0.89			
Polyethylene terephthalate (Mylar)			0.52037	58.9	84.9	39.95	1.848	1.40			
Polyimide film (Kapton)			0.51264	59.2	85.5	40.58	1.820	1.42			
Polymethylmethacrylate (acrylic)			0.53937	58.1	82.8	40.55	1.929	1.19			1.49
Polypropylene			0.55998	56.1	78.5	44.77	2.041	0.90			
Polystyrene ($[C_6H_5CHCH_2]_n$)			0.53768	57.5	81.7	43.79	1.936	1.06			1.59
Polytetrafluoroethylene (Teflon)			0.47992	63.5	94.4	34.84	1.671	2.20			
Polyvinyltoluene			0.54141	57.3	81.3	43.90	1.956	1.03			1.58
Aluminum oxide (sapphire)			0.49038	65.5	98.4	27.94	1.647	3.970	2327.	3273.	1.77
Barium flouride (BaF_2)			0.42207	90.8	149.0	9.91	1.303	4.893	1641.	2533.	1.47
Bismuth germanate (BGO)			0.42065	96.2	159.1	7.97	1.251	7.130	1317.		2.15
Carbon dioxide gas (CO_2)			0.49989	60.7	88.9	36.20	1.819	(1.842)			[449.]
Solid carbon dioxide (dry ice)			0.49989	60.7	88.9	36.20	1.787	1.563	Sublimes at 194.7 K		
Cesium iodide (CsI)			0.41569	100.6	171.5	8.39	1.243	4.510	894.2	1553.	1.79
Lithium fluoride (LiF)			0.46262	61.0	88.7	39.26	1.614	2.635	1121.	1946.	1.39
Lithium hydride (LiH)			0.50321	50.8	68.1	79.62	1.897	0.820	965.		
Lead tungstate ($PbWO_4$)			0.41315	100.6	168.3	7.39	1.229	8.300	1403.		2.20
Silicon dioxide (SiO_2, fused quartz)			0.49930	65.2	97.8	27.05	1.699	2.200	1986.	3223.	1.46
Sodium chloride (NaCl)			0.55509	71.2	110.1	21.91	1.847	2.170	1075.	1738.	1.54
Sodium iodide (NaI)			0.42697	93.1	154.6	9.49	1.305	3.667	933.2	1577.	1.77
Water (H_2O)			0.55509	58.5	83.3	36.08	1.992	1.000(0.756)	273.1	373.1	1.33
Silica aerogel			0.50093	65.0	97.3	27.25	1.740	0.200	(0.03 H_2O, 0.97 SiO_2)		

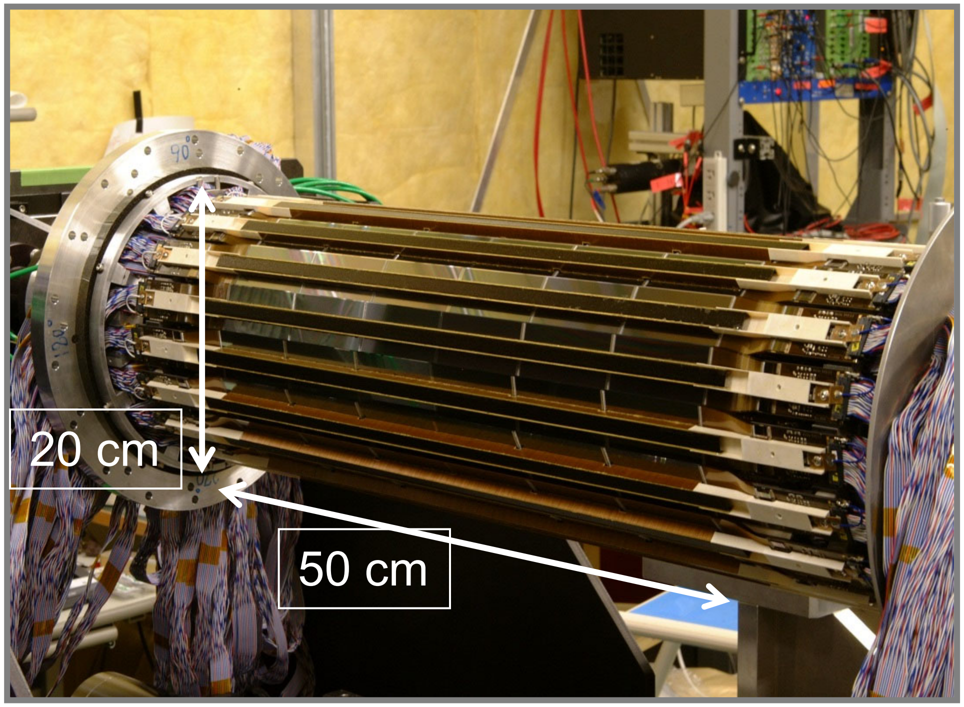
Belle II Detector – vertex region

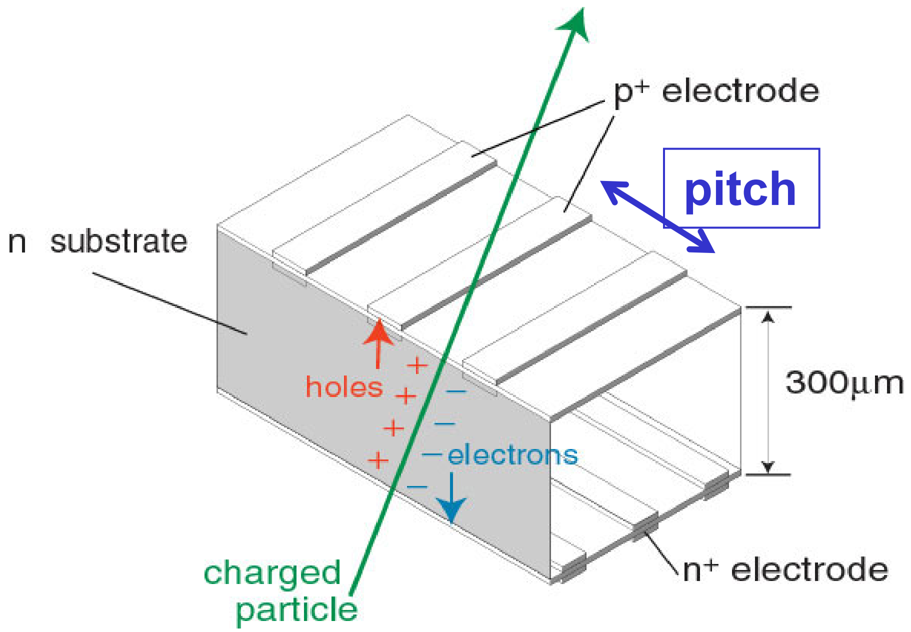


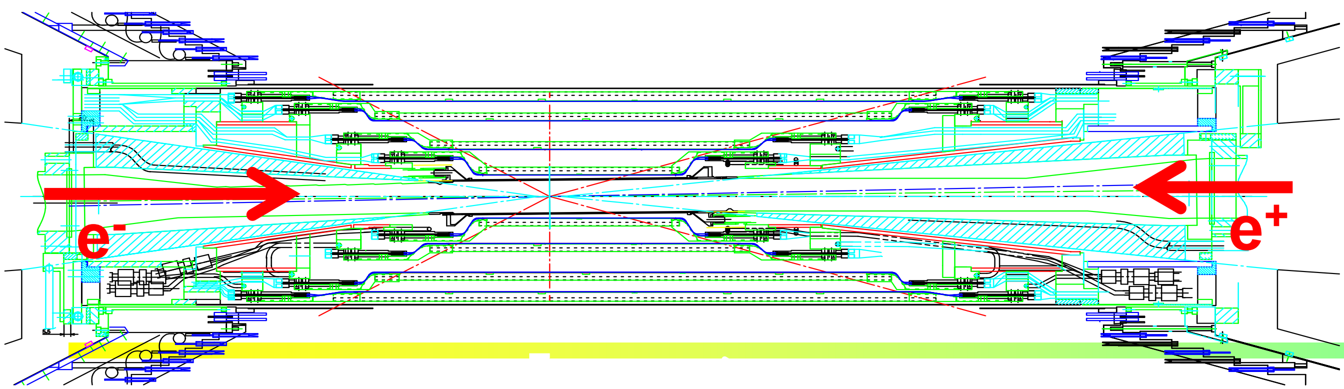
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Silicon vertex detector (SVD)







Two coordinates measured at the same time;

strip pitch: 50µm (75µm);

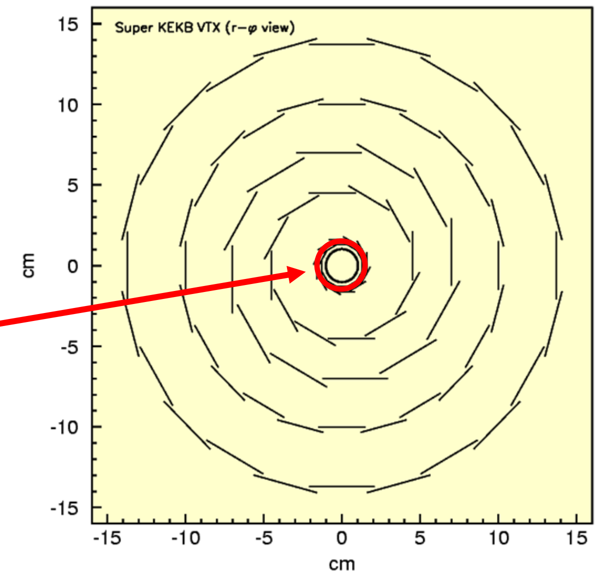
resolution 15µm (20µm).

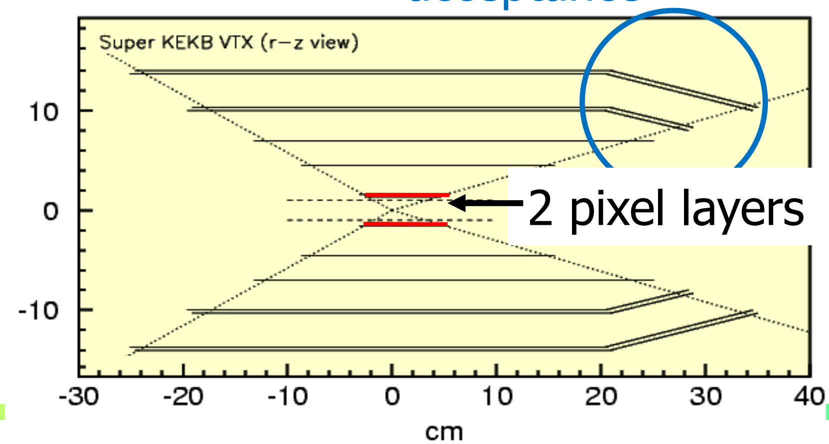
Belle II Vertex detector SVD+PXD

- Sensors of the innermost layers:

  Normal double sided Si detector (DSSD) → DEPFET Pixel sensors

- Configuration: 4 layers → 6 layers (outer radius = 8cm→14cm)
  - More robust tracking
  - Higher Ks vertex reconstruction efficiency
- Inner radius: 1.5cm → 1.3cm
  - Better vertex resolution





Pixel vertex detector PXD principle: DEPFET

p-channel FET on a completely depleted bulk

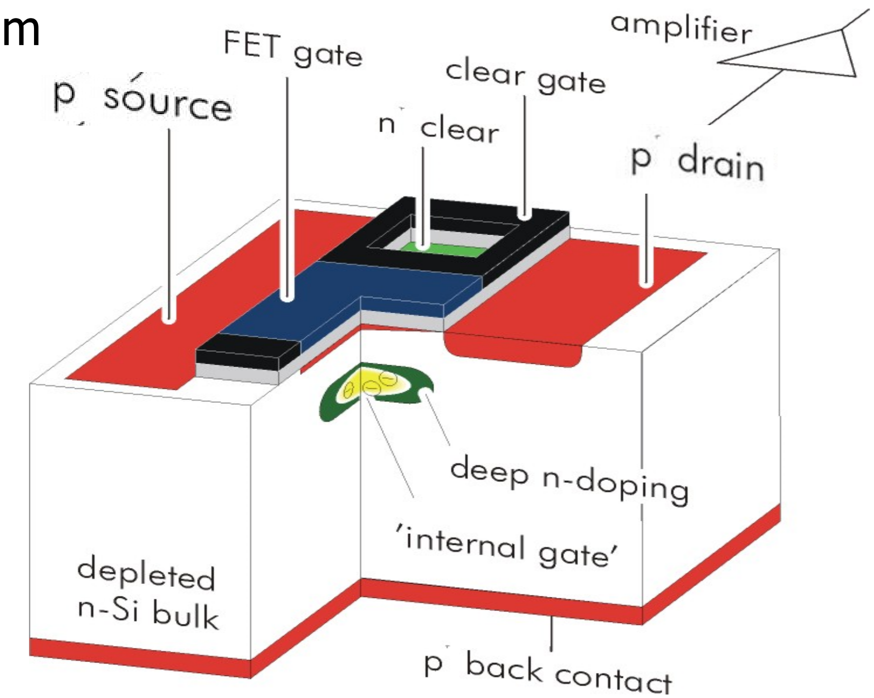
A deep n-implant creates a potential minimum for electrons under the gate ("internal gate")

Signal electrons accumulate in the internal gate and modulate the transistor current ($g_q \sim 400$ pA/e^-)

Accumulated charge can be removed by a clear contact ("reset")

Invented in MPI Munich

Depleted p-channel FET



Fully depleted:
→ large signal, fast signal collection

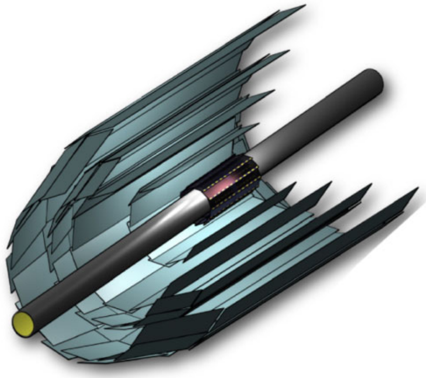
Low capacitance, internal amplification → low noise

Transistor on only during readout: low power

Complete clear → no reset noise

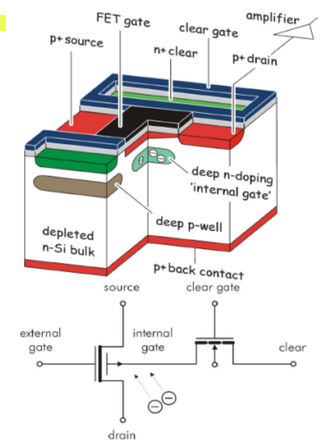
Vertex Detector

DEPFET:
http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

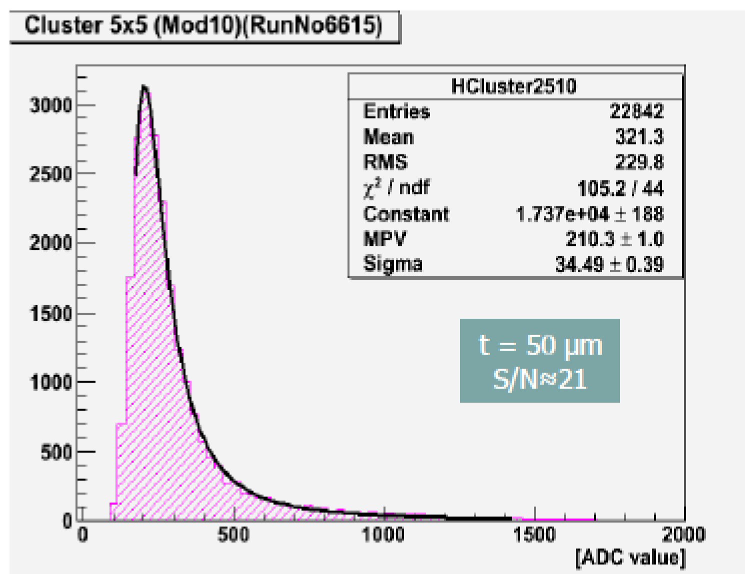


Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

DEpleted P-channel FET



Mechanical mockup of pixel detector



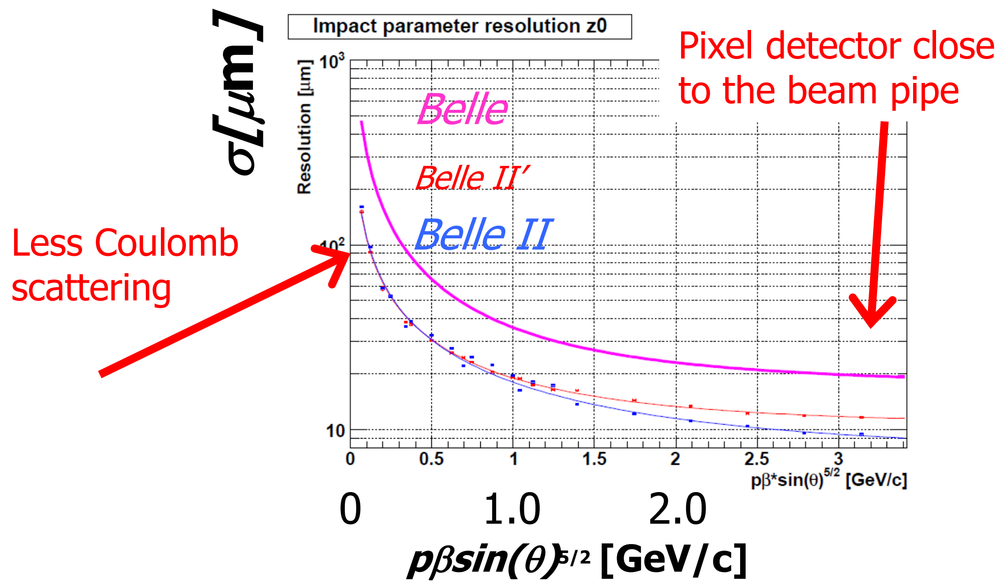
DEPFET pixel sensor

DEPFET sensor: very good S/N

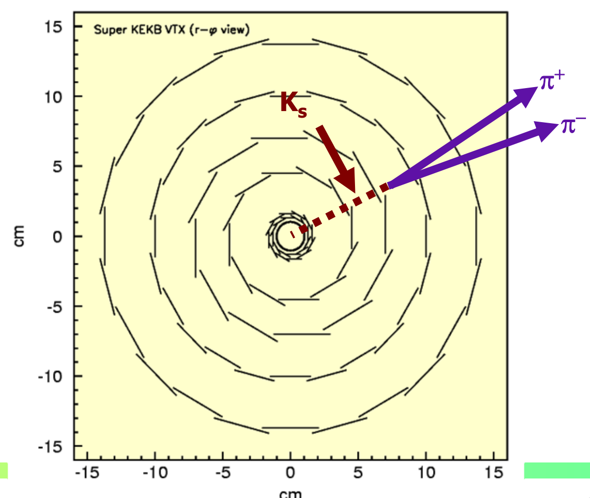
Expected performance

$$\sigma = a + \frac{b}{p\beta \sin^{\nu}\theta}$$

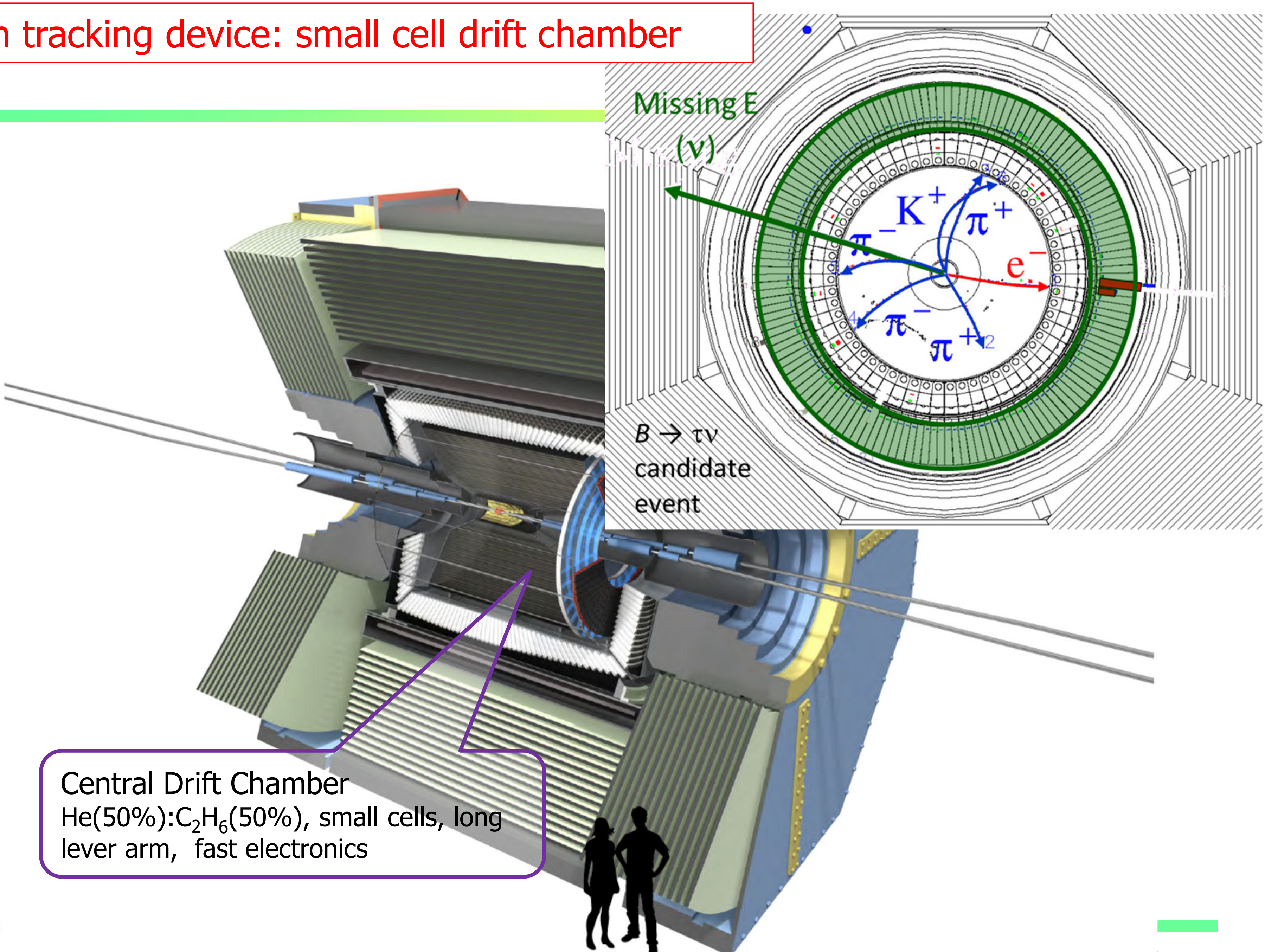
4 layers of silicons triop detectors → 2 layers of pixel detectors + 4 layers of silicons strip detectors: significant improvement in vertex resolution!



Larger detector volume → significant improvement in K_S reconstruction efficiency



Main tracking device: small cell drift chamber



Search for unstable particles which decayed close to the production point

How do we reconstruct final states that decayed to two stable particles?

From the measured tracks calculate the invariant mass of the system (i= 1,2):

$$Mc^2 = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2 c^2}$$

The candidates for the X→12 decay show up as a peak in the distribution on (mostly combinatorial) background.

How do we know it was precisely this reaction?

$B^0 \rightarrow K^0_S \, J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

$J/\psi \rightarrow \mu^- \mu^+$

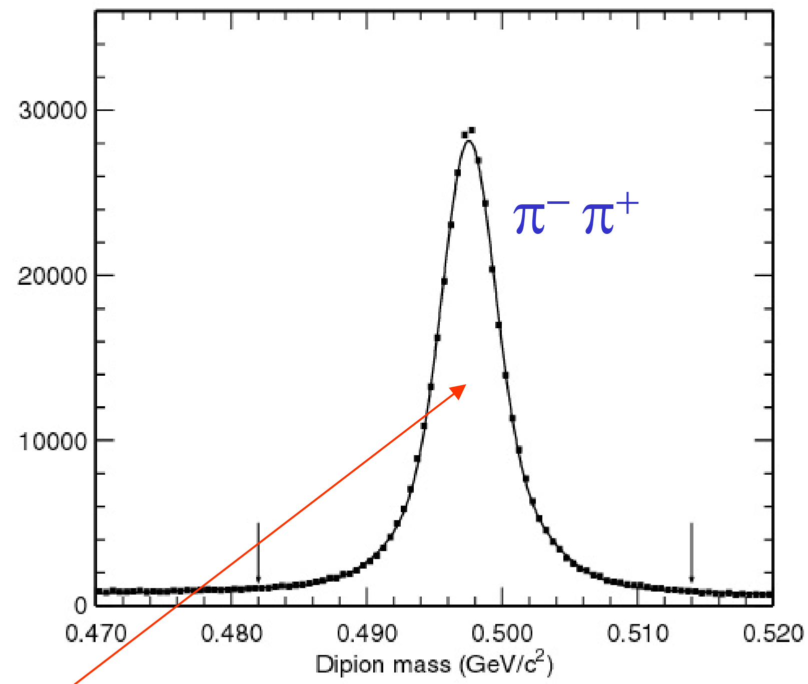
detect

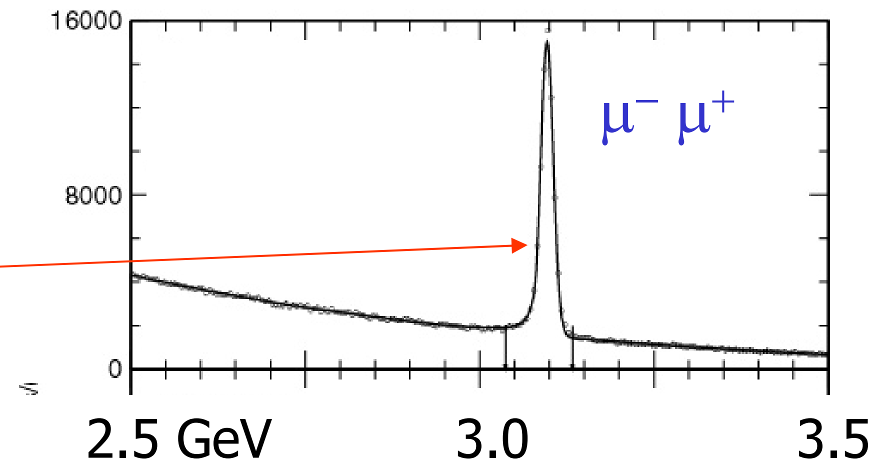
For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

$$M^2c^4=(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2$$

Mc^2 must be for K^0_S close to 0.5 GeV,

for J/ψ close to 3.1 GeV.





Rest in the histrogram: random coincidences (‘combinatorial background’)

Invariant mass resolution – momentum resolution

The name of the game: have as little background under the peak as possible without loosing the events in the peak (=reduce background and have a narrow peak).

$$Mc^2 = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2 c^2}$$

To understand the impact of momentum resolution, simplify the expression for the case where final state particles have a small mass compared to their momenta.

Example $J/\psi \rightarrow \mu^- \mu^+$

$M^2c^4 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 \rightarrow M^2c^4 = 2\, p_1\, p_2\, (1 - \cos\Theta_{12})$

N.B. mion mass of 104 MeV is much smaller than its momentum, 1.5 GeV/c

Resolution in invariant mass

$B^0 \rightarrow K^0_S J/\psi$, $K^0_S \rightarrow \pi^- \pi^+$, $J/\psi \rightarrow \mu^- \mu^+$

$M^2c^4 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2c^2 \rightarrow M^2c^4 = 2\, p_1\, p_2\, c^2\, (1 - \cos\Theta_{12})$

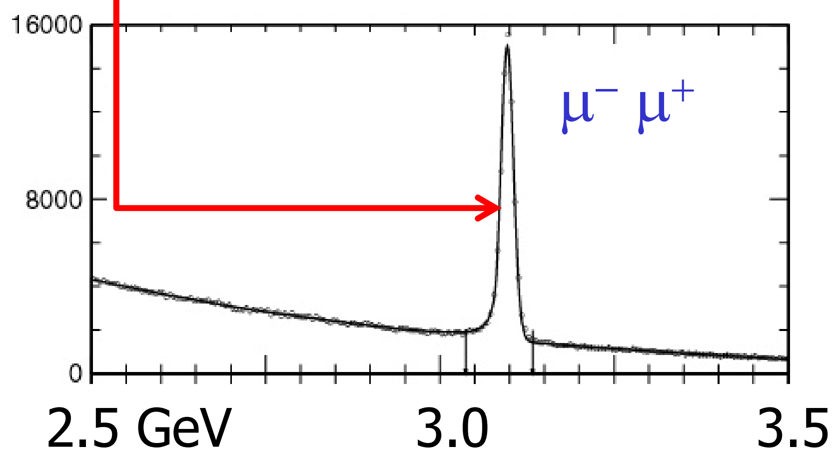
The J/ψ peak should be narrow to minimize the contribution of random coincidences ('combinatorial background')

The required resolution in Mc^2: about 10 MeV.

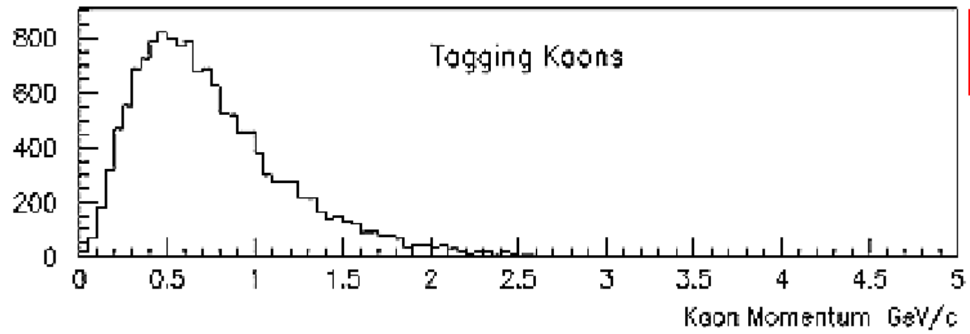
What is the corresponding momentum resolution?

For simplicity assume J/ψ is at rest $\rightarrow$
$\Theta_{12}=180^0$, $p_1=p_2=p=1.5$ GeV/c, $Mc^2=2pc$
$\rightarrow \sigma(Mc^2) = 2\, \sigma(pc)$ at $p=1.5$ GeV/c

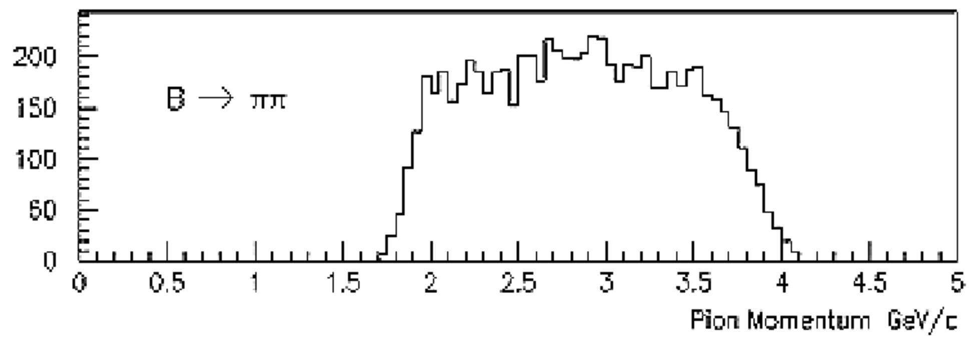
$\rightarrow \sigma(p)/p = 10$ MeV/2/1.5GeV = 0.3%



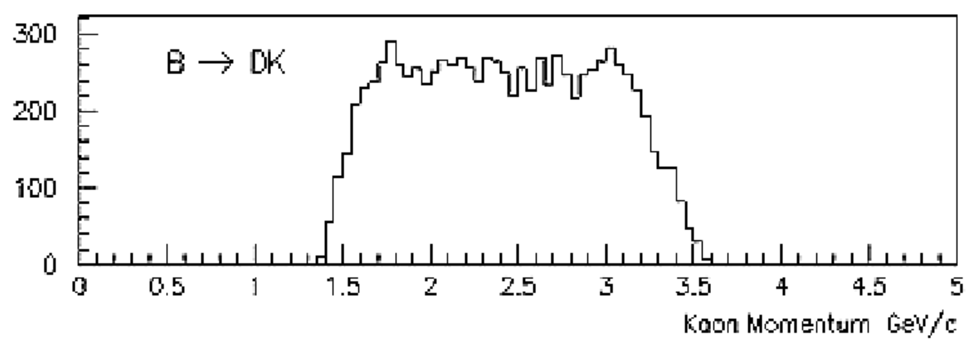
Requirements: momentum spectrum



Tagging Kaons



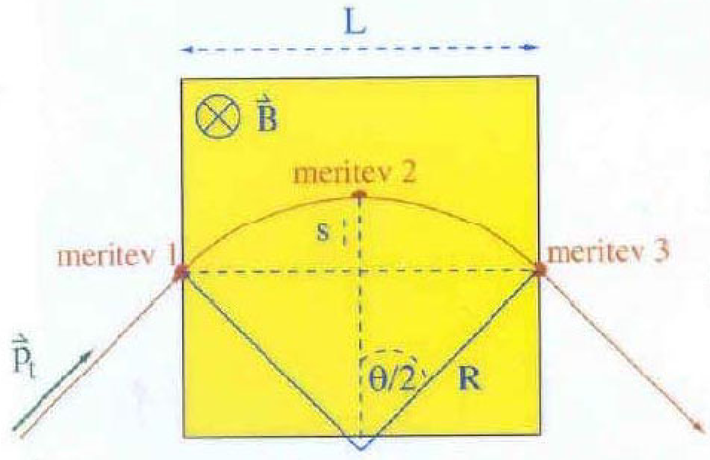
$B \to \pi\pi$



B → DK

From raw data to summary data
momentum measurement

Example of momentum determination:



$$p_t = q\,B\,R \Rightarrow R = \frac{p_t}{qB}$$

$$\sin\frac{\theta}{2} \approx \frac{\theta}{2} = \frac{L}{2R}$$

$$\cos\frac{\theta}{2} = \frac{R-s}{R} \Rightarrow s \approx R\frac{\theta^2}{8}$$

$$s = \frac{B\,L^2\,q}{8p_t}$$

if s determined by
3 measurement points:

$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\frac{\sigma(p_t)}{p_t} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)8p_t}{BL^2q}$$

for N measurement points:

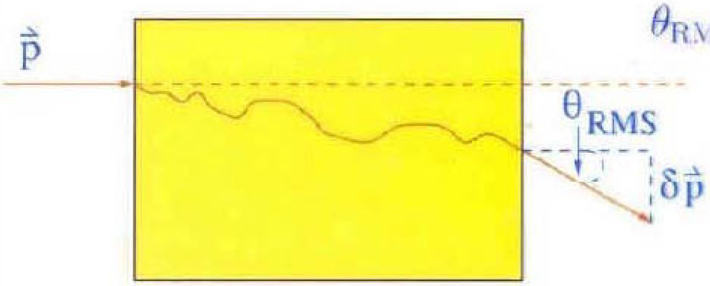
$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$

http://www-f9.ijs.si/~krizan/sola/nddop/slides/anpod_1213.pdf

From raw data to summary data

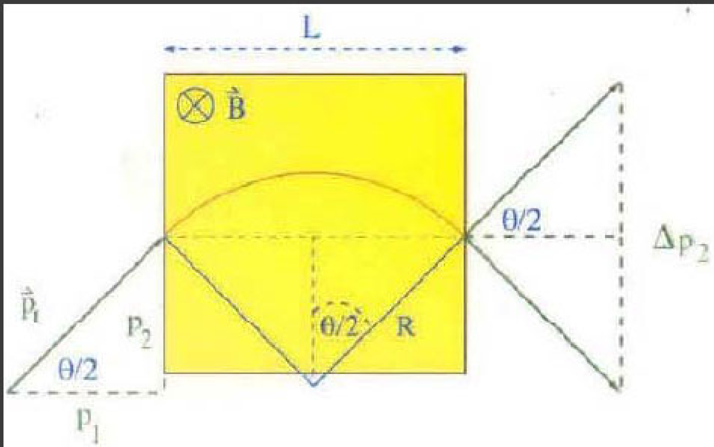
momentum measurement

Multiple scattering:



$$\theta_{\mathrm{RMS}} \approx \frac{13.6\mathrm{MeV}}{cp\beta}\sqrt{\frac{L}{X_0}}[1 + 0.038 \ln \frac{L}{X_0}]$$

$$\delta p = p \sin \theta_{\mathrm{RMS}}$$



$$\Delta p_2 = 2p_t \sin\frac{\theta}{2} \approx p_t\theta$$

$$\frac{\sigma(p_t)}{p_t} = \frac{\sigma(\Delta p_2)}{\Delta p_2}$$

$$\frac{\sigma(p_t)}{p_t} \approx \frac{p_t \sin\theta_{\mathrm{RMS}}}{p_t\theta} \approx \frac{\theta_{\mathrm{RMS}}}{\theta}$$

$$\frac{\sigma(p_t)}{p_t} \approx \frac{13.6\ \mathrm{MeV}}{qB\sqrt{LX_0}}$$

http://www-f9.ijs.si/~krizan/sola/nddop/slides/anpod_1213.pdf

eB = 0.3 (B/T) (1/m) GeV/c

Momentum resolution

Tracking system uncertainty

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$

eB = 0.3 (B/T) (1/m) GeV/c

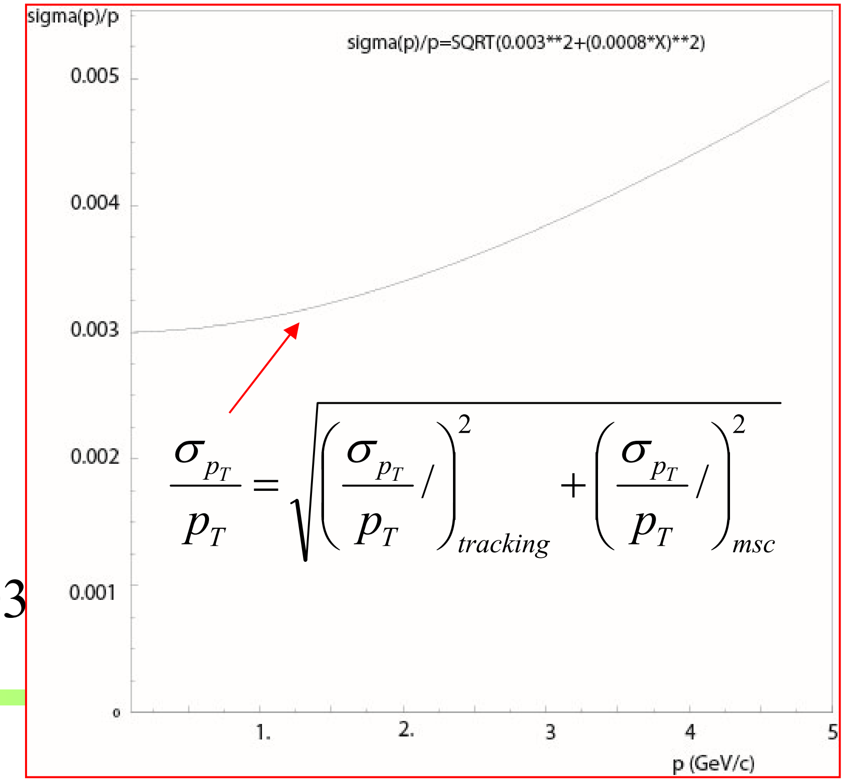
$$\frac{\sigma_{p_T}}{p_T} = p_T \frac{0.1\times10^{-3}m}{0.3(GeV/m)\times1.5\times1m^2}\sqrt{\frac{720}{54}} = \frac{p_T\times0.0008}{GeV}$$

For B=1.5T, L = 1m, σ_x = 0.1 mm
For p_T = 1 GeV: σ_{pT}/p_T = 0.08%
For p_T = 2 GeV: σ_{pT}/p_T = 0.16%

Uncertainty from multiple scattering

$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6MeV}{eB\sqrt{LX_0}}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6MeV}{0.3(GeV/m)\times1.5\sqrt{1m\times100m}} = 0.003$$

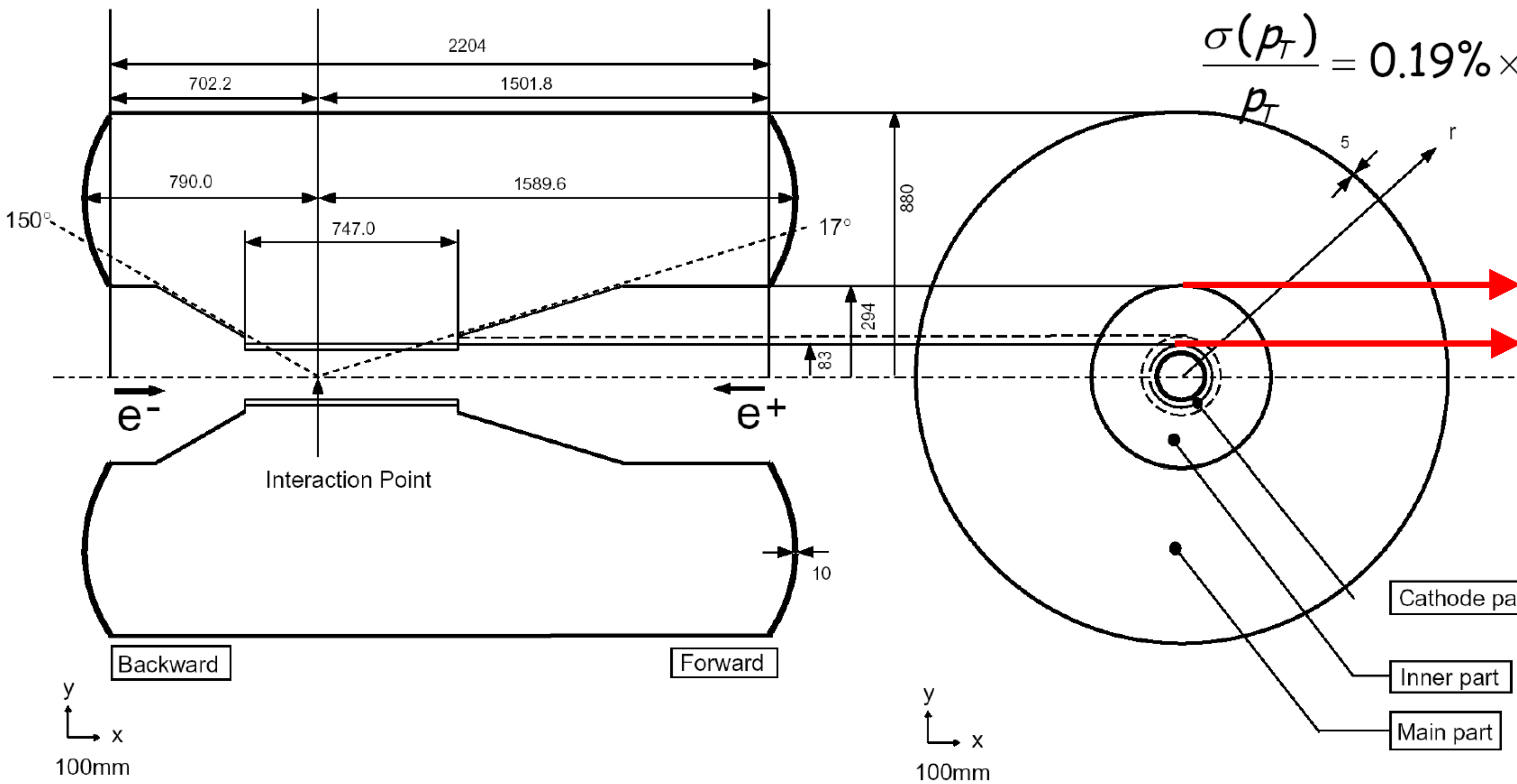


$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}/\right)^2_{tracking} + \left(\frac{\sigma_{p_T}}{p_T}/\right)^2_{msc}}$$

Tracking: Belle central drift chamber

- 50 layers of wires (8400 cells) in 1.5 Tesla magnetic field
- Helium:Ethane 50:50 gas, W anode wires, Al field wires, CF inner wall with cathodes, and preamp only on endplates
- Particle identification from ionization loss (5.6-7% resolution)

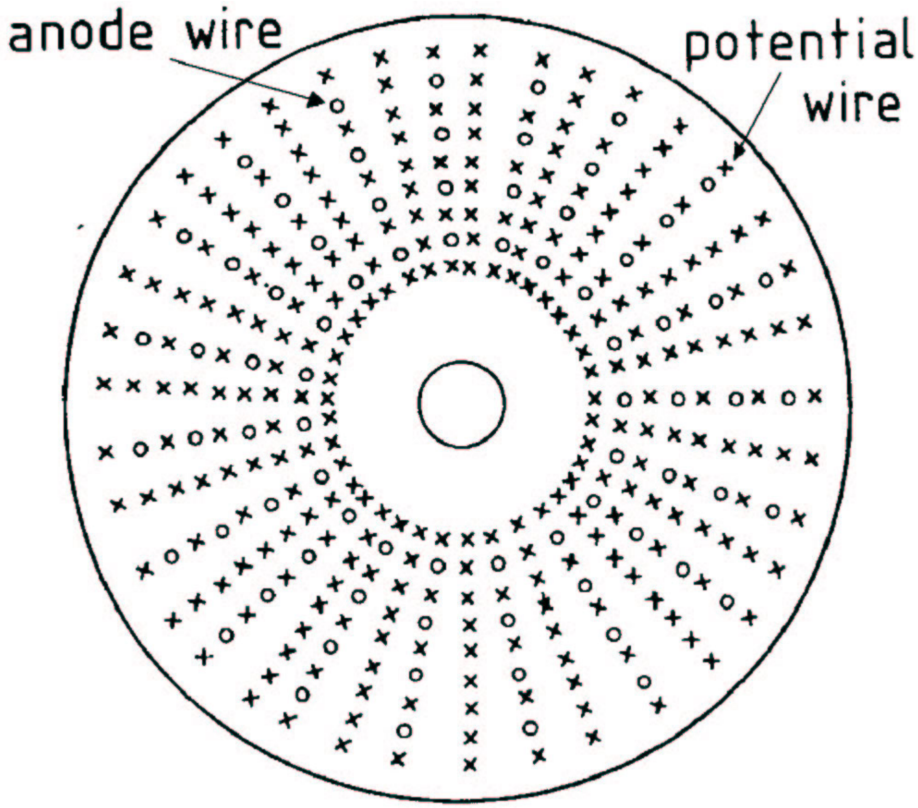
$$\frac{\sigma(p_T)}{p_T} = 0.19\% \times p_T \oplus \frac{0.30\%}{\beta}$$

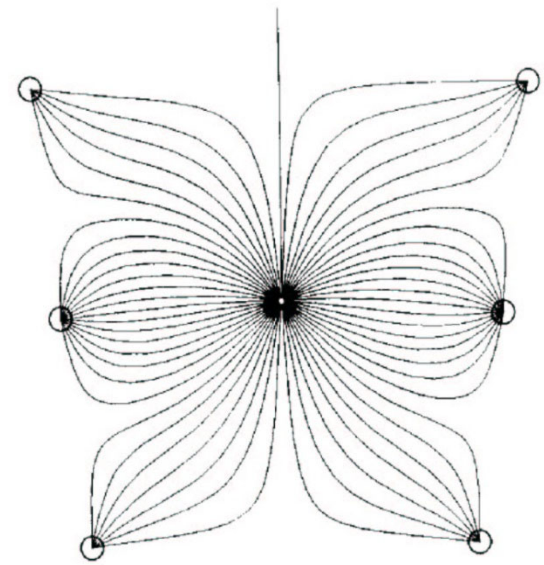


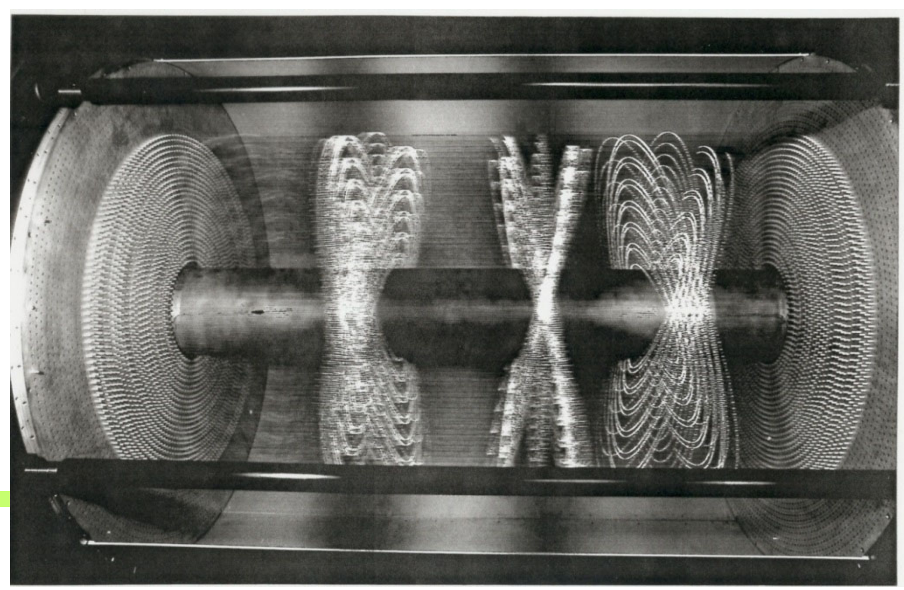
15 layers: 8.8-22.4 cm radius

Drift chamber with small cells

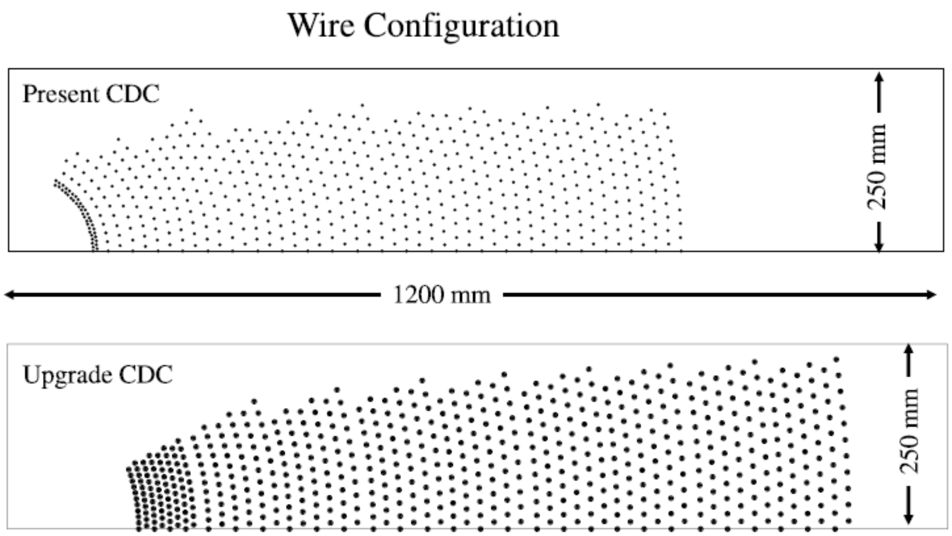
One big gas volume, small cells defined by the anode and field shaping (potential) wires

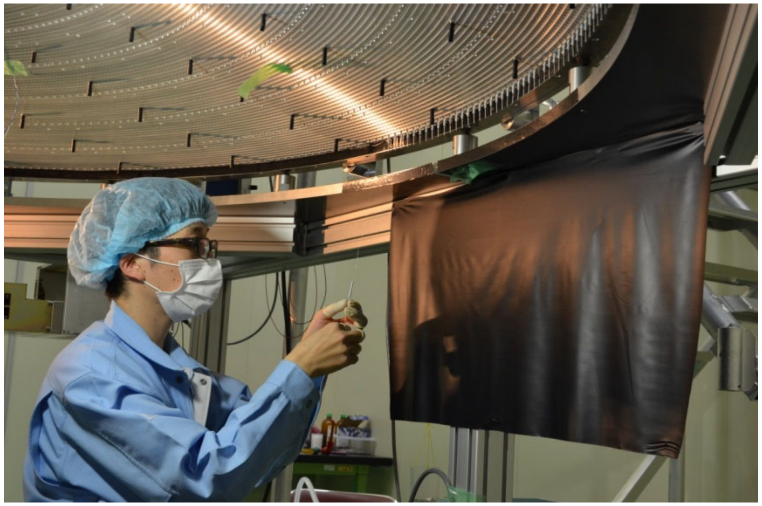






Belle II CDC

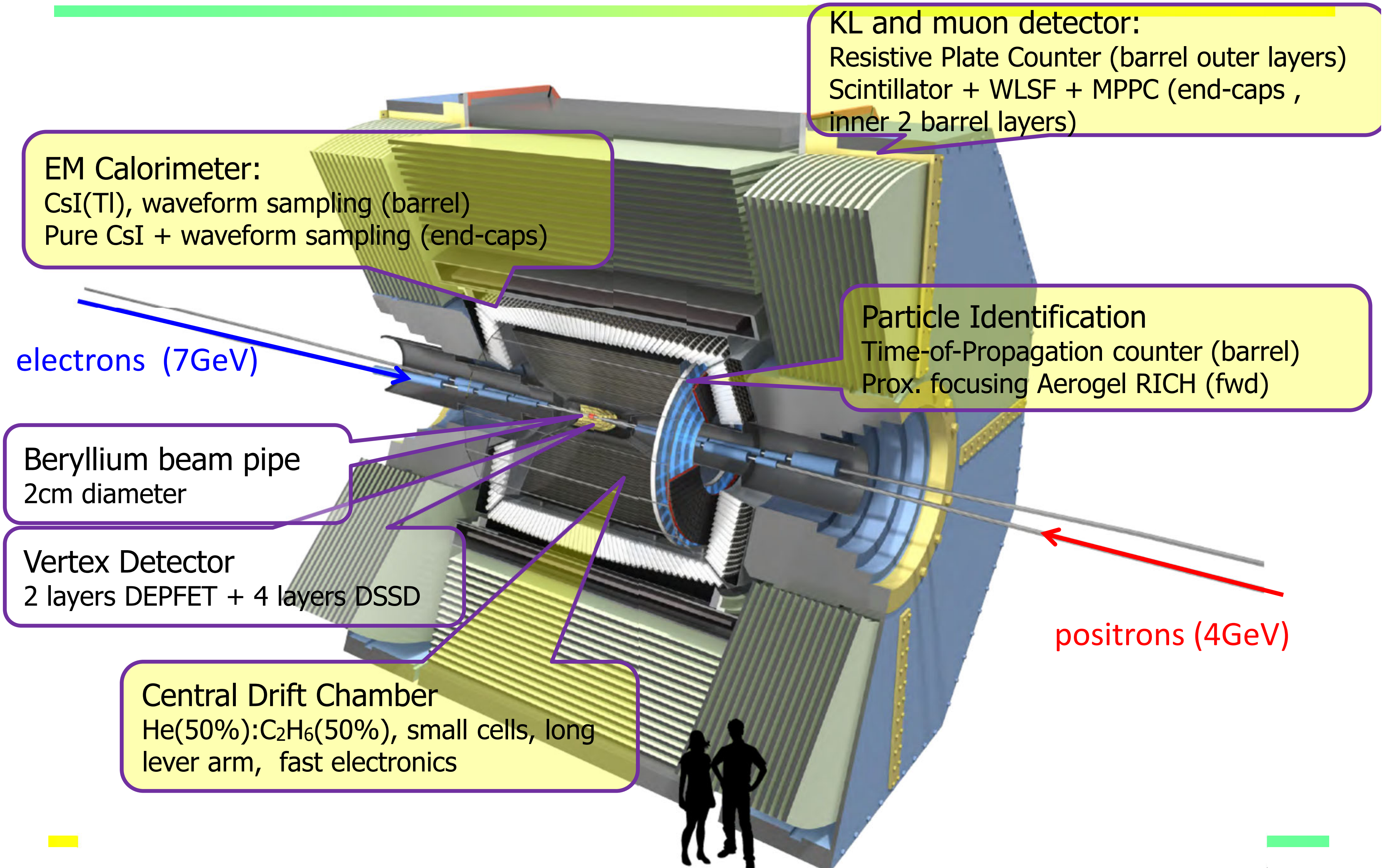




Wire stringing in a clean room

- thousands of wires,
- 1 year of work...

Particle identification systems in Belle II



Identification of charged particles

Particles are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$.

Momentum known (radius of curvature in magnetic field)

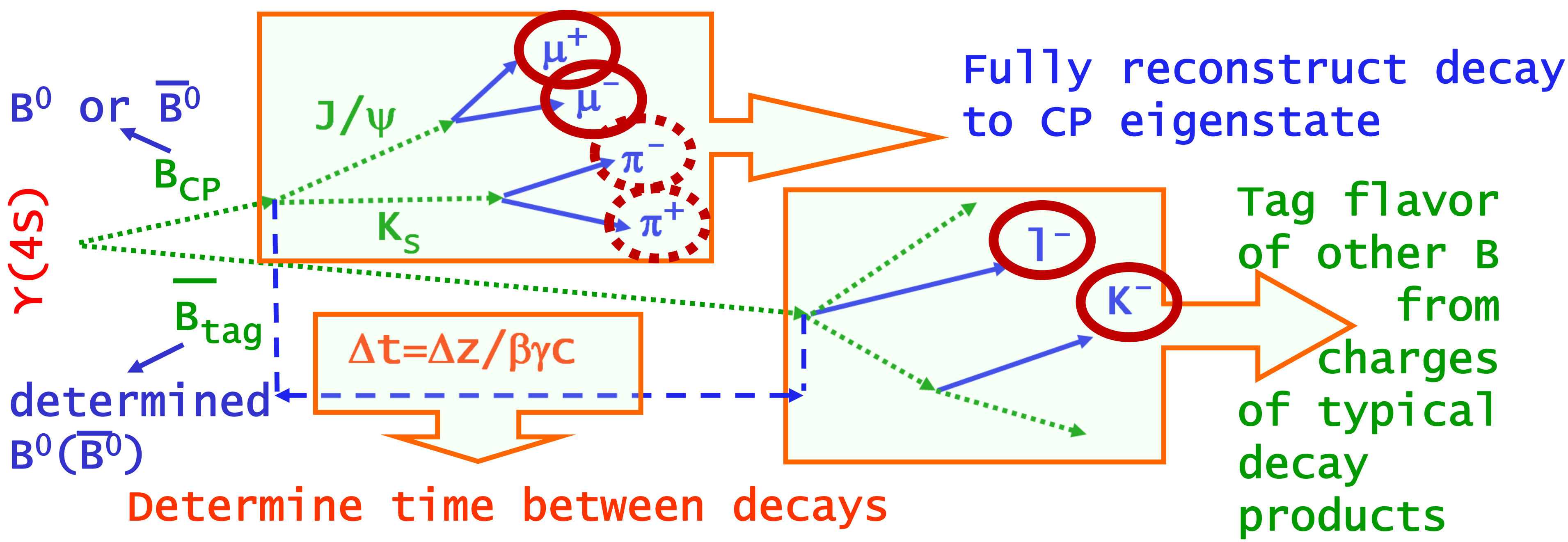
→Measure velocity:

- time of flight
- ionisation losses dE/dx
- Cherenkov angle
- transition radiation

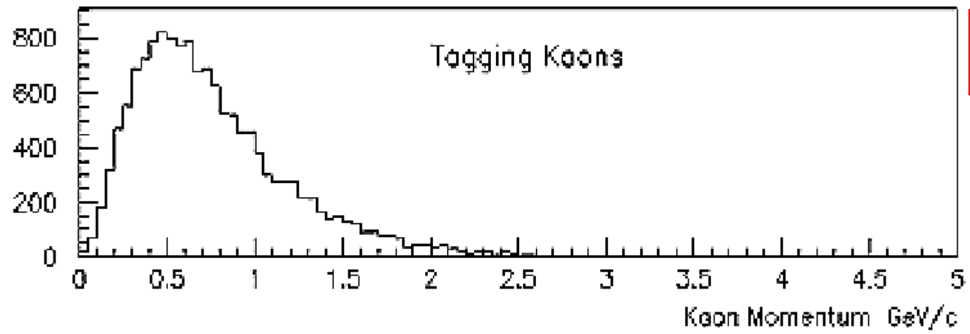
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

Reminder: where do we need identification?

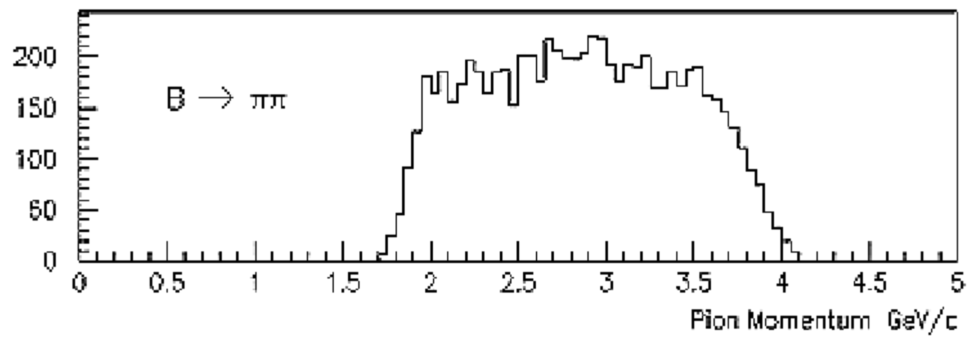


Requirements: Particle Identification



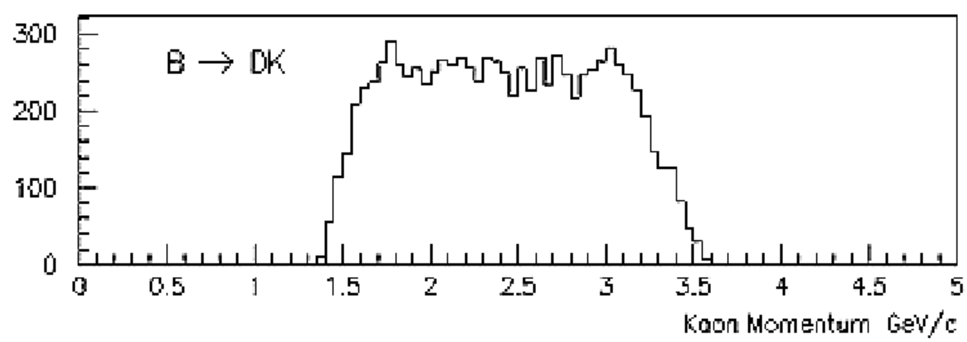
Tagging Kaons

Relatively soft, ms dominated for tracking



$B \to \pi\pi$

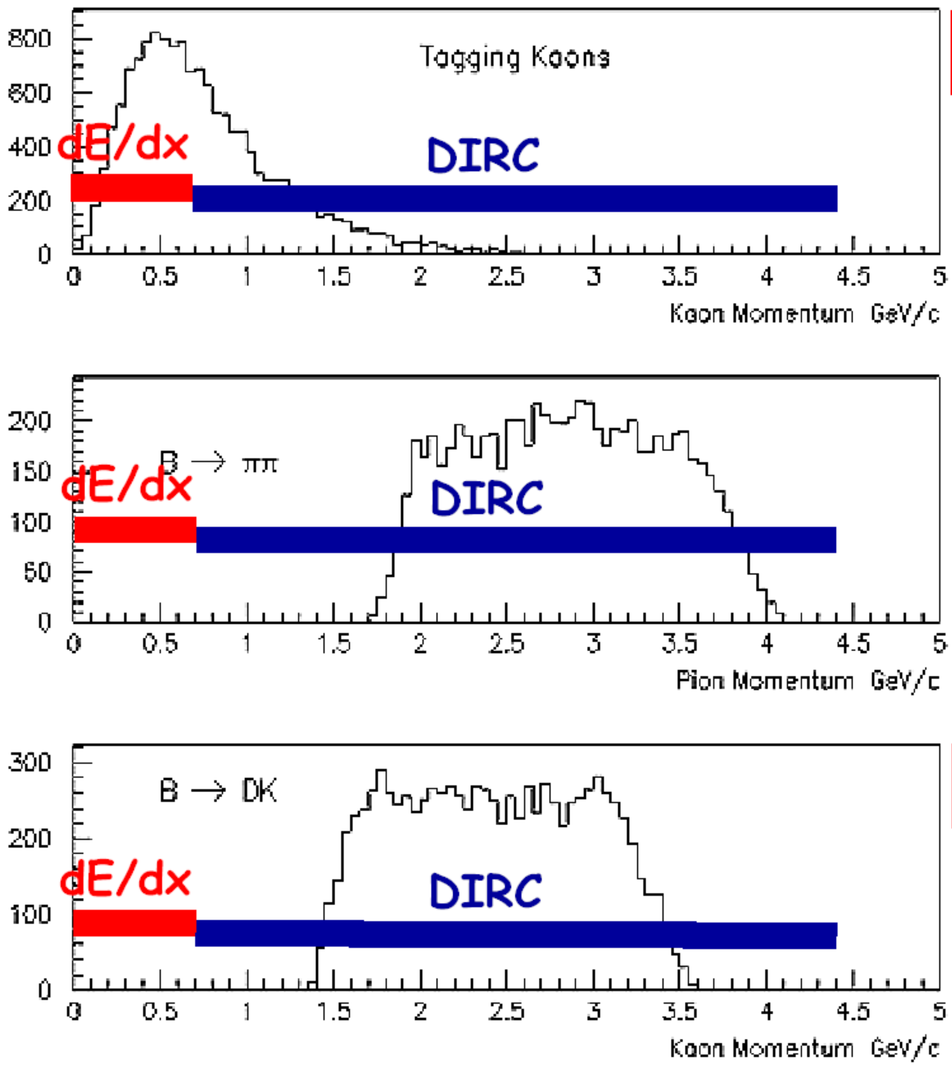
Requires dedicated PID



$B \to DK$

Requires dedicated PID

PID coverage of kaon/pion spectra

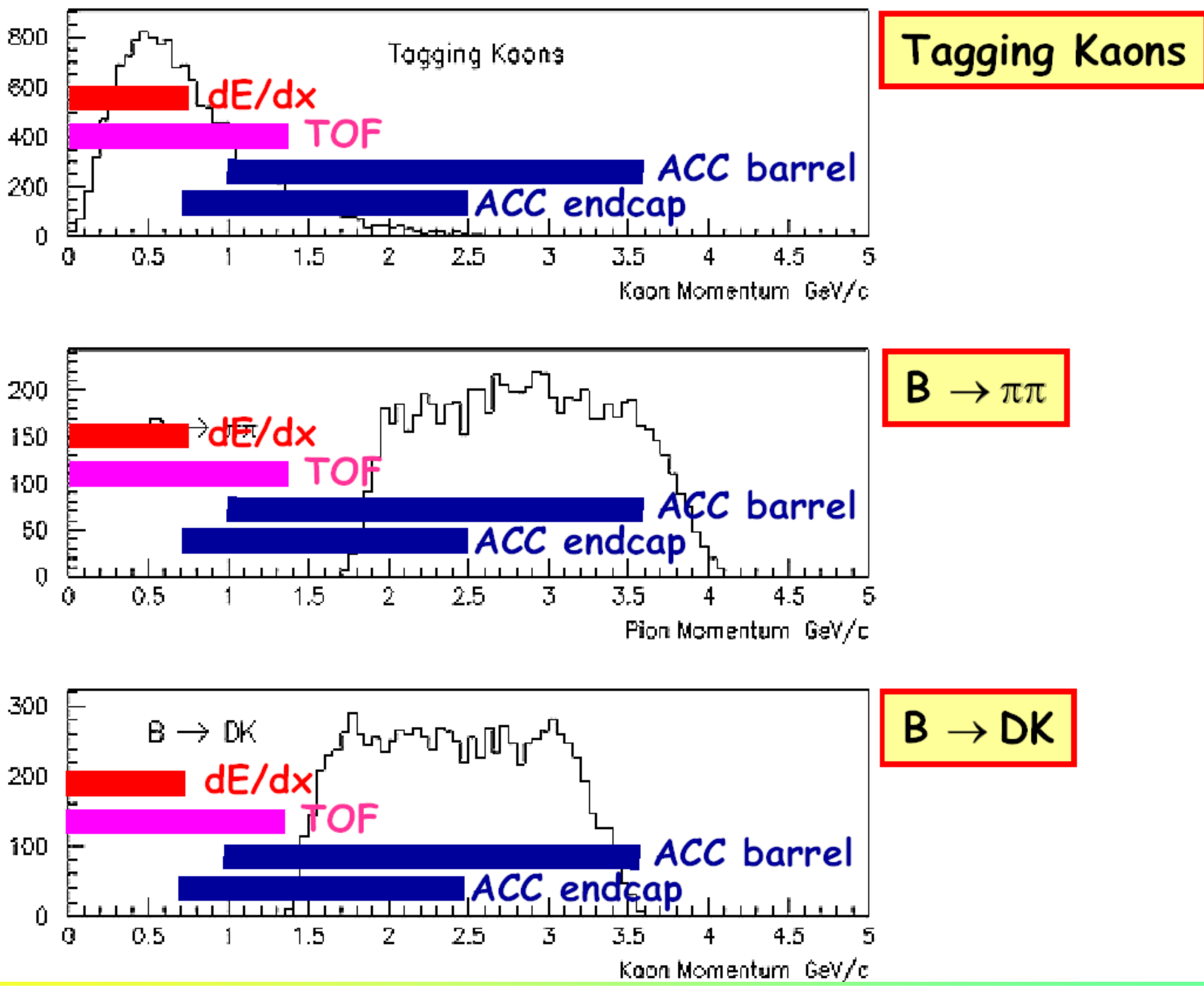


Tagging Kaons

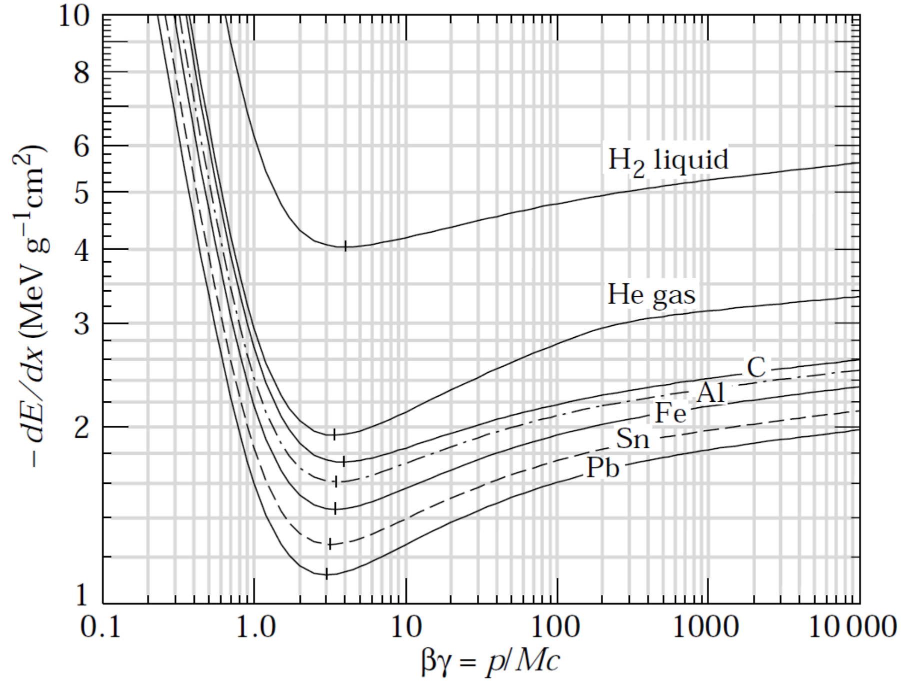
B → ππ

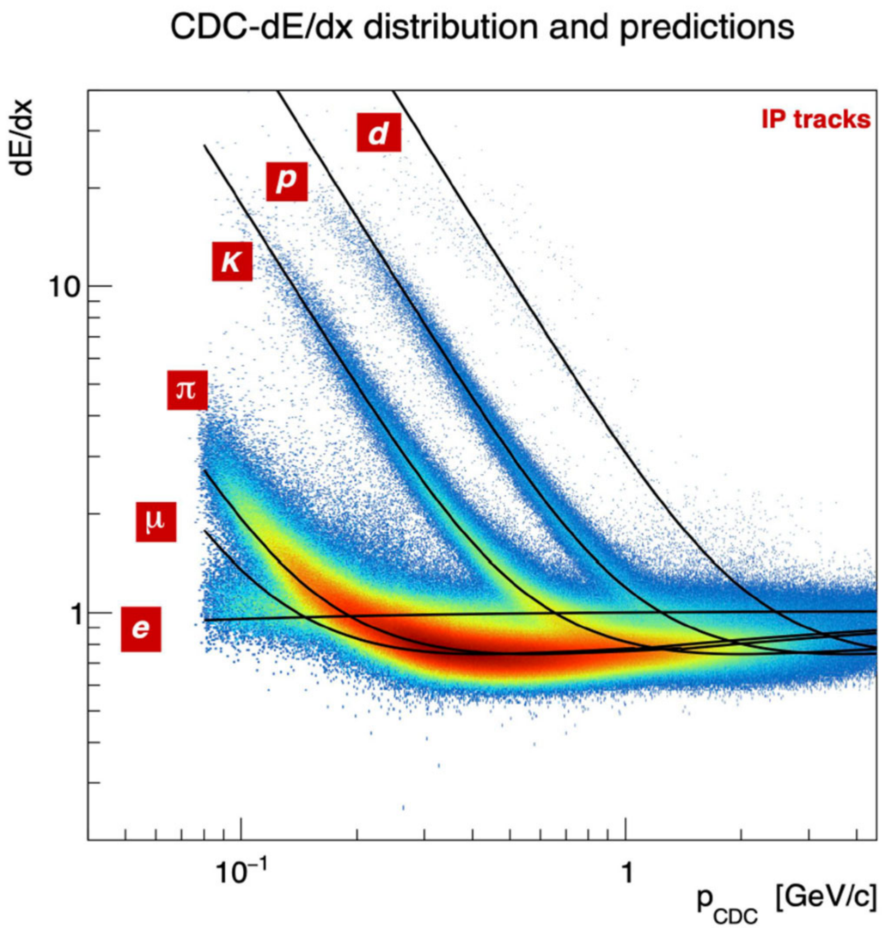
B → DK

PID coverage of kaon/pion spectra



Identification with the dE/dx measurement





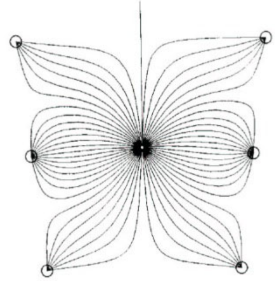
dE/dx is a function of velocity β

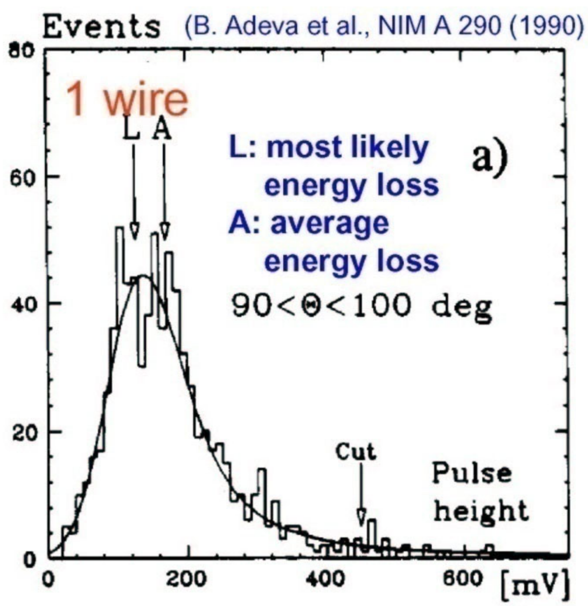
For particles with different mass the
Bethe-Bloch curve gets displaced
if plotted as a function of p

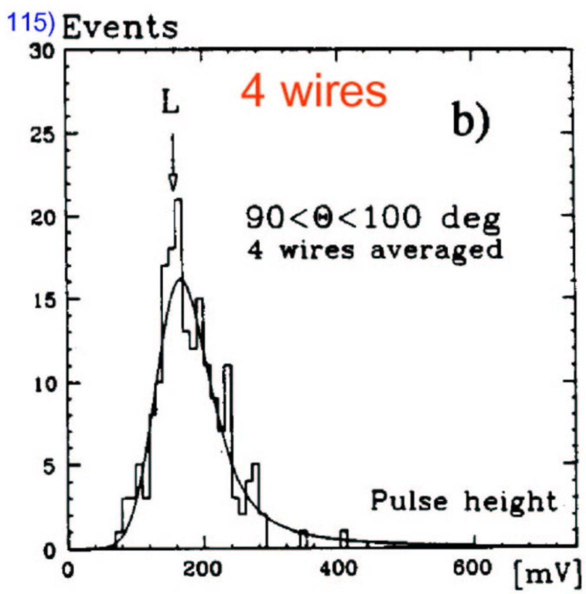
For good separation: resolution should be ~5%

Identification with dE/dx measurement

Problem: long tails (Landau distribution, not Gaussian) of a single measurement (one drift chamber cell)







Measure in each of the 50 drift chamber layers – use truncated mean (discard 30% largest values – from the tail).

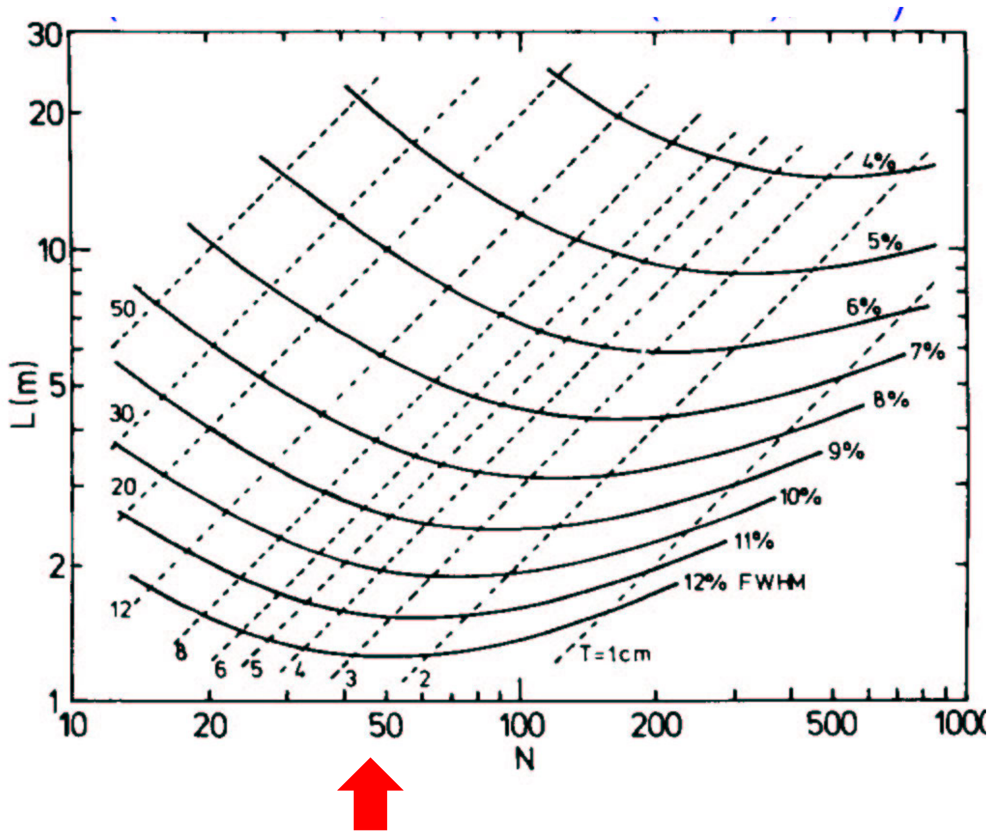
Identification with dE/dx measurement

Optimisation of the counter: length L, number of samples N, resolution (FWHM)

If the distribution of individual measurements were Gaussian, only the total detector length L would be relevant.

Tails: eliminate the largest 30% values → the optimum depends also on the number of samples.

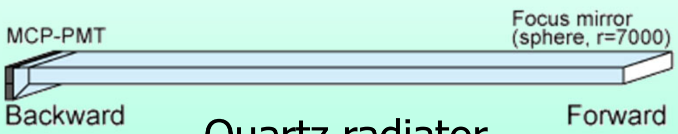
At about 1m path length: optimal number of samples: 50



FWHM: full width at half maximum = 2.35 sigma for a Gaussian distribution

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



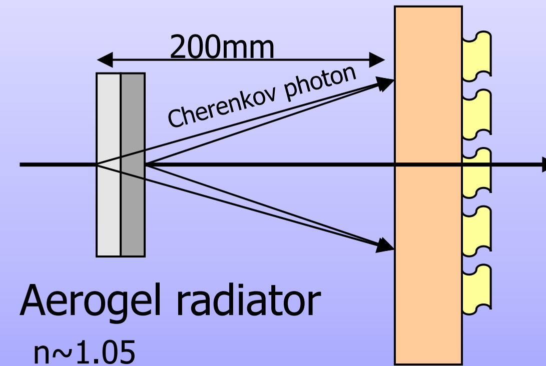
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

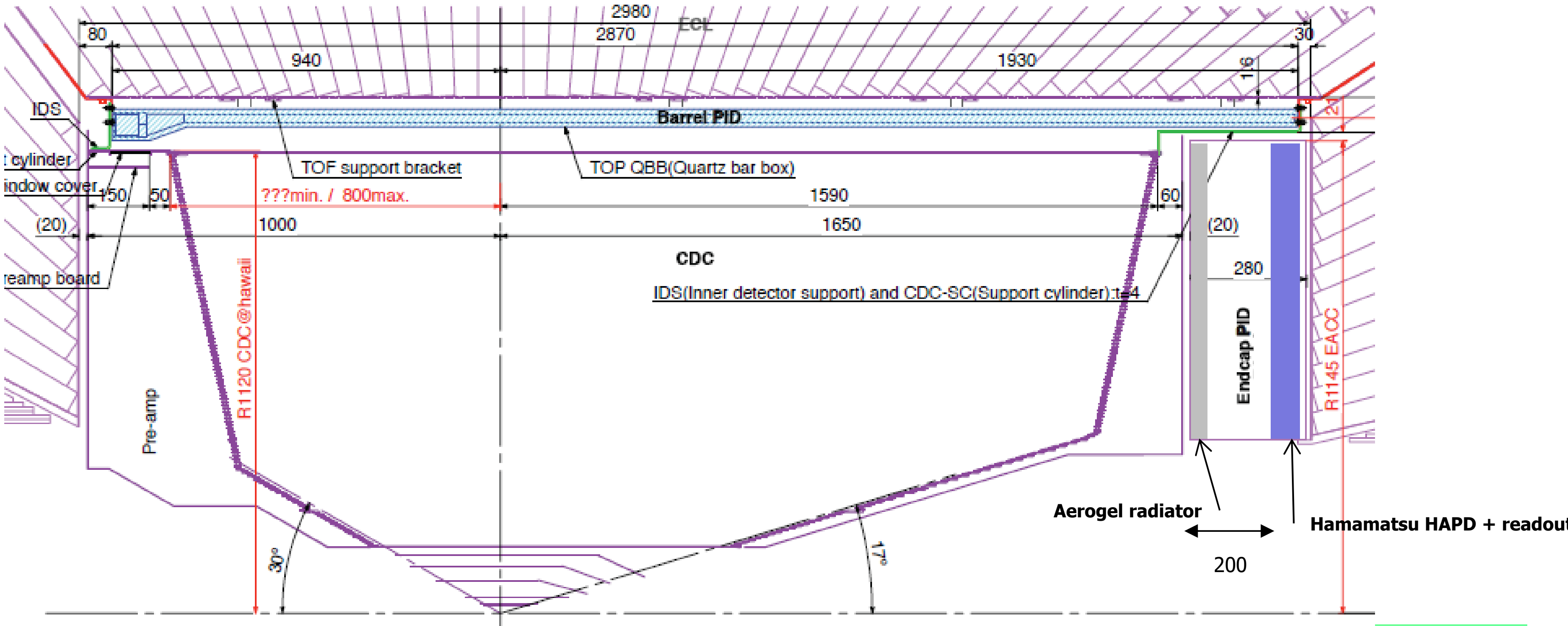
Endcap PID: Aerogel RICH (ARICH)



Aerogel radiator

n~1.05

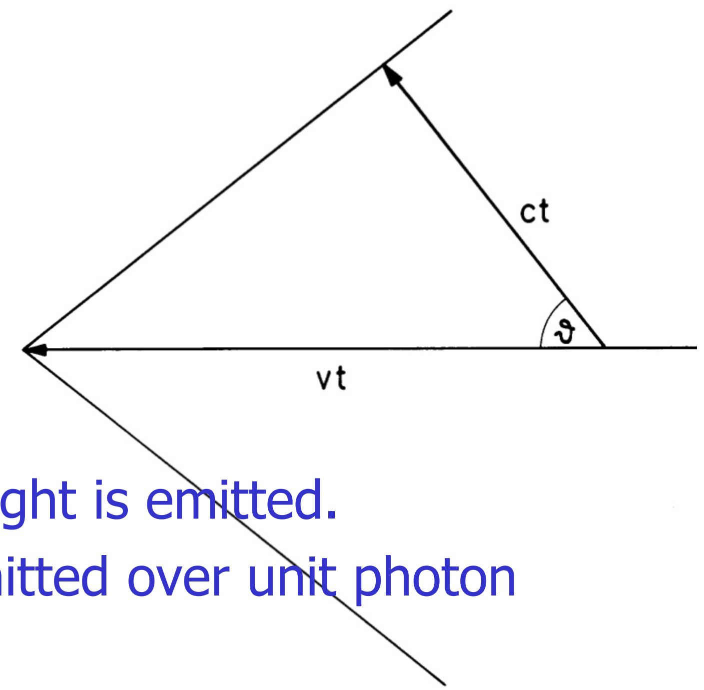
Hamamatsu HAPD
+ new ASIC



Cherenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle,

$\cos\theta = c/nv = 1/\beta n$



Two cases:

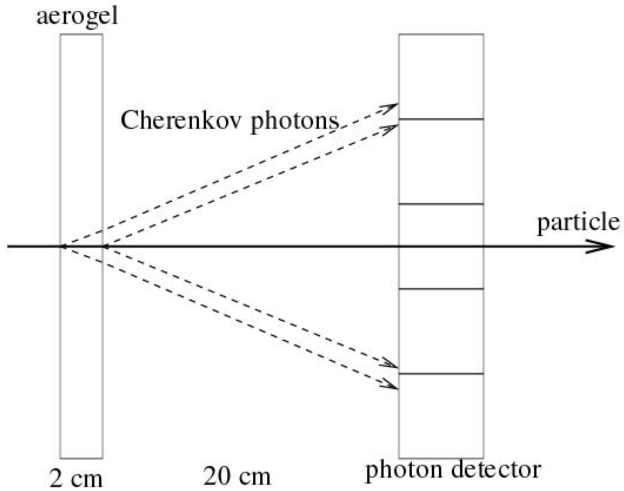
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

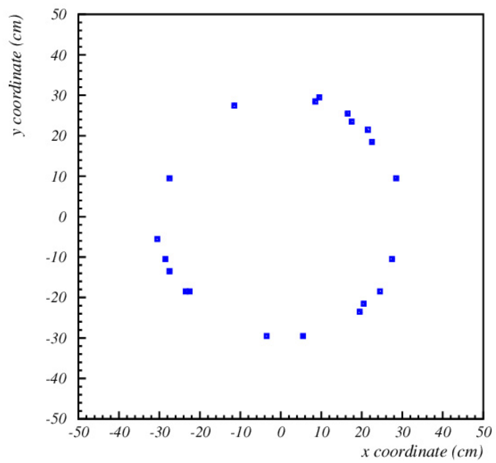
→ $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370(cm)^{-1}(eV)^{-1} L \sin^2\theta$$

→Few detected photons

Measuring the Cherenkov angle



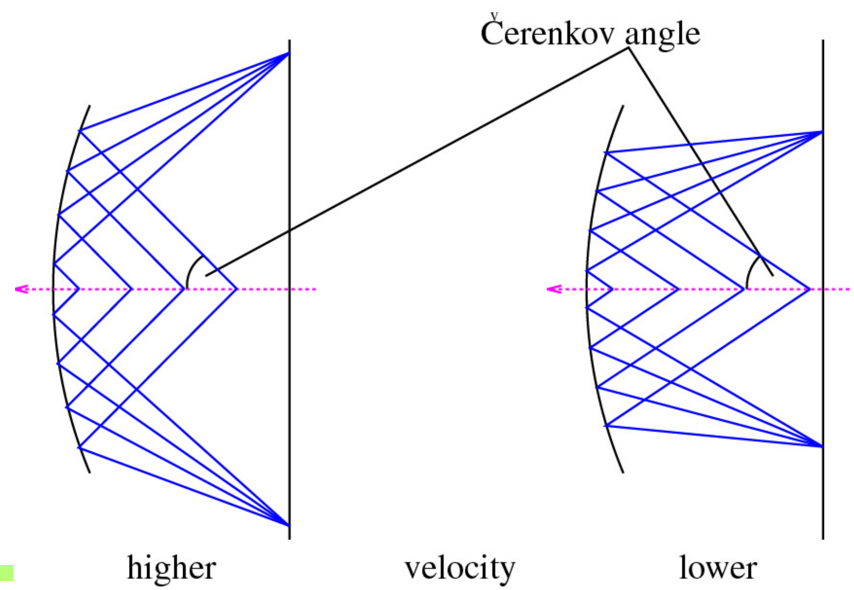


Idea: transform the direction into a coordinate → ring on the detection plane

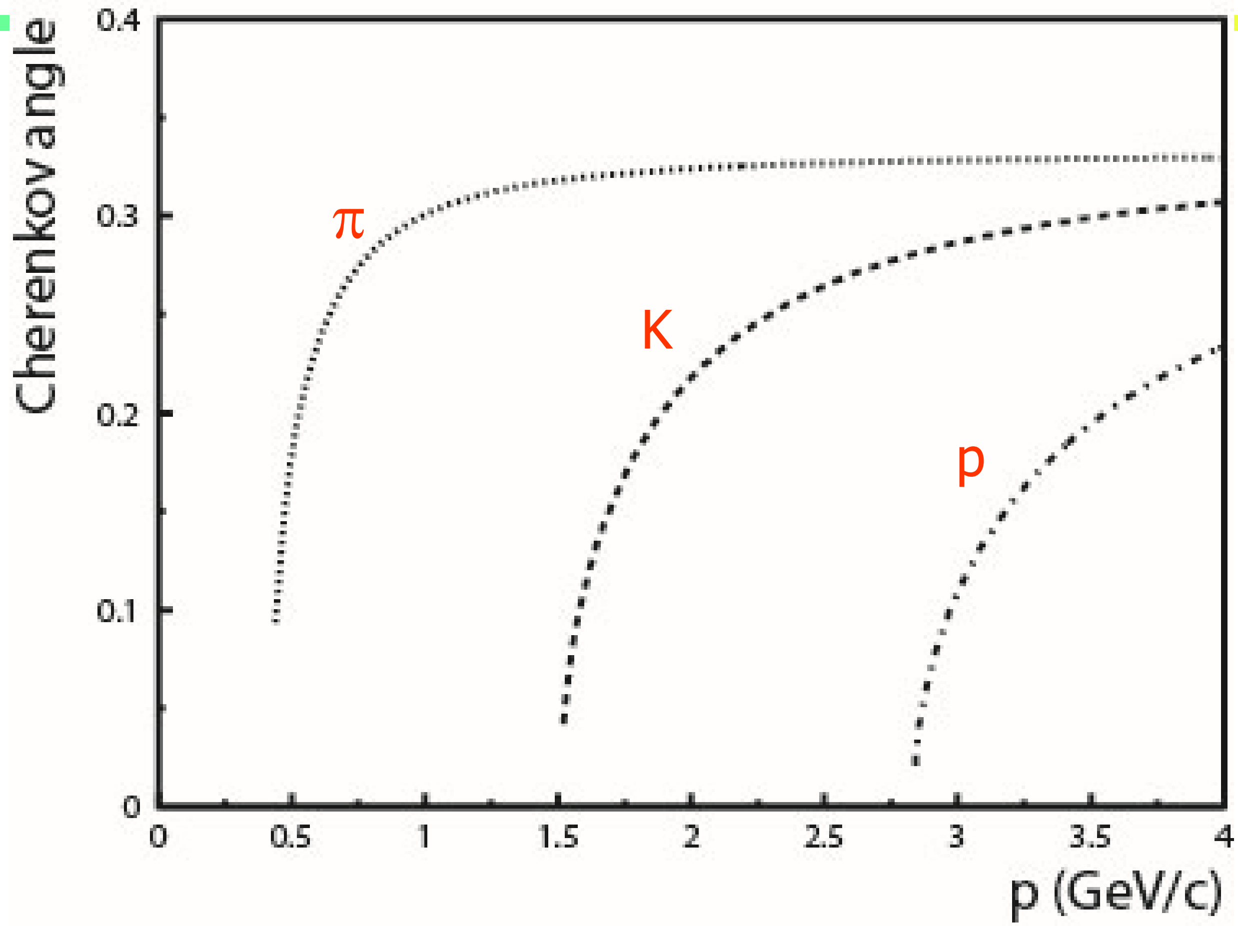
→ Ring Imaging Cherenkov (RICH) counter

Proximity focusing RICH

RICH with a focusing mirror



Measuring Cherenkov angle

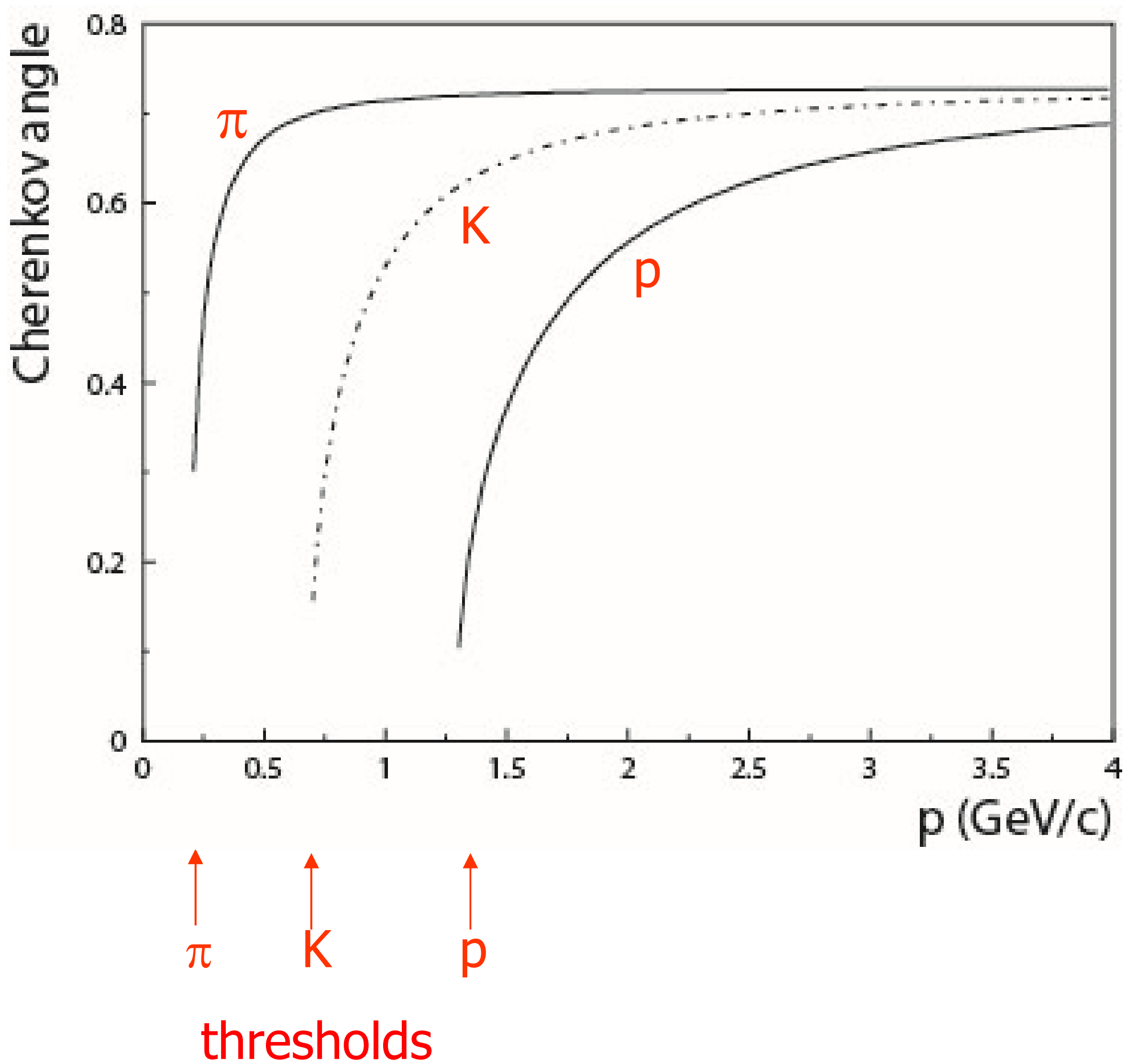


Radiator:
aerogel, n=1.06

π K p

thresholds

Measuring Cherenkov angle



Radiator:
quartz, n=1.46

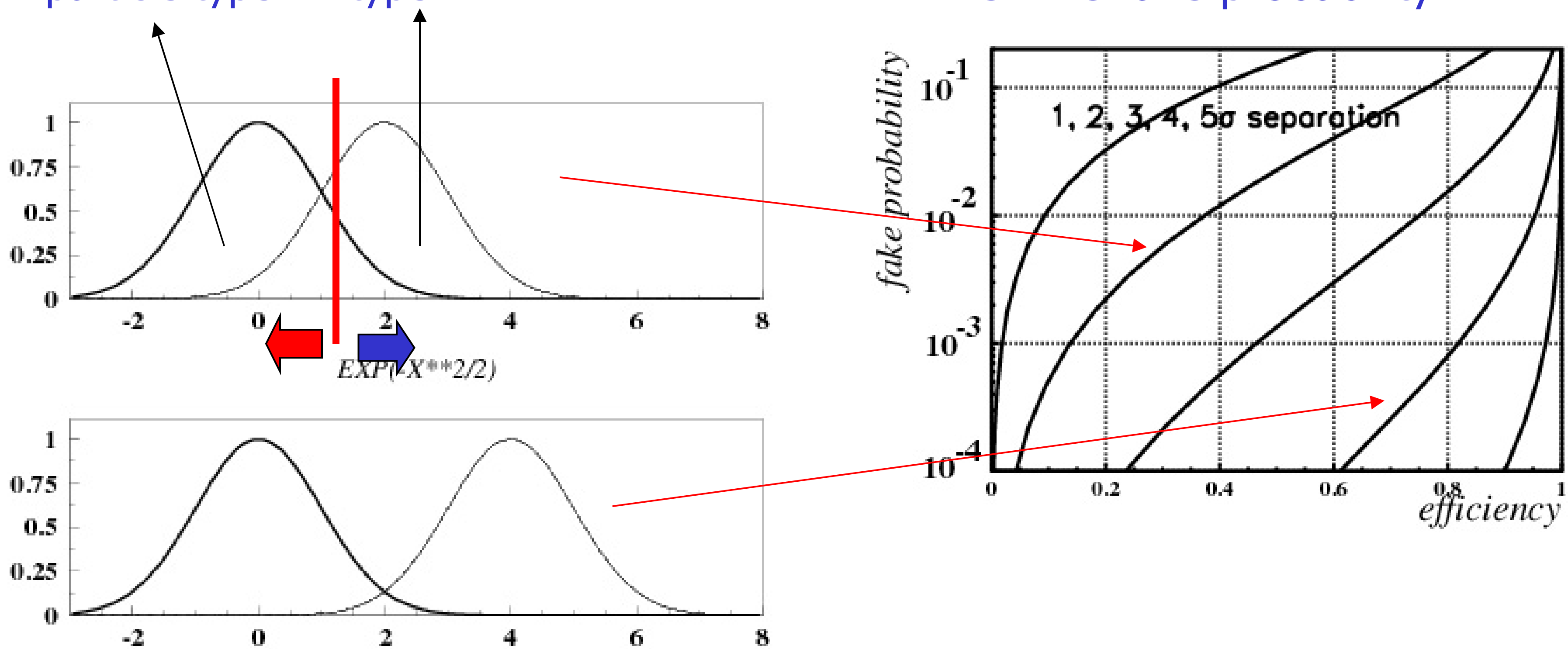
Efficiency and purity in particle identification

Efficiency and purity are tightly coupled!

Two examples:

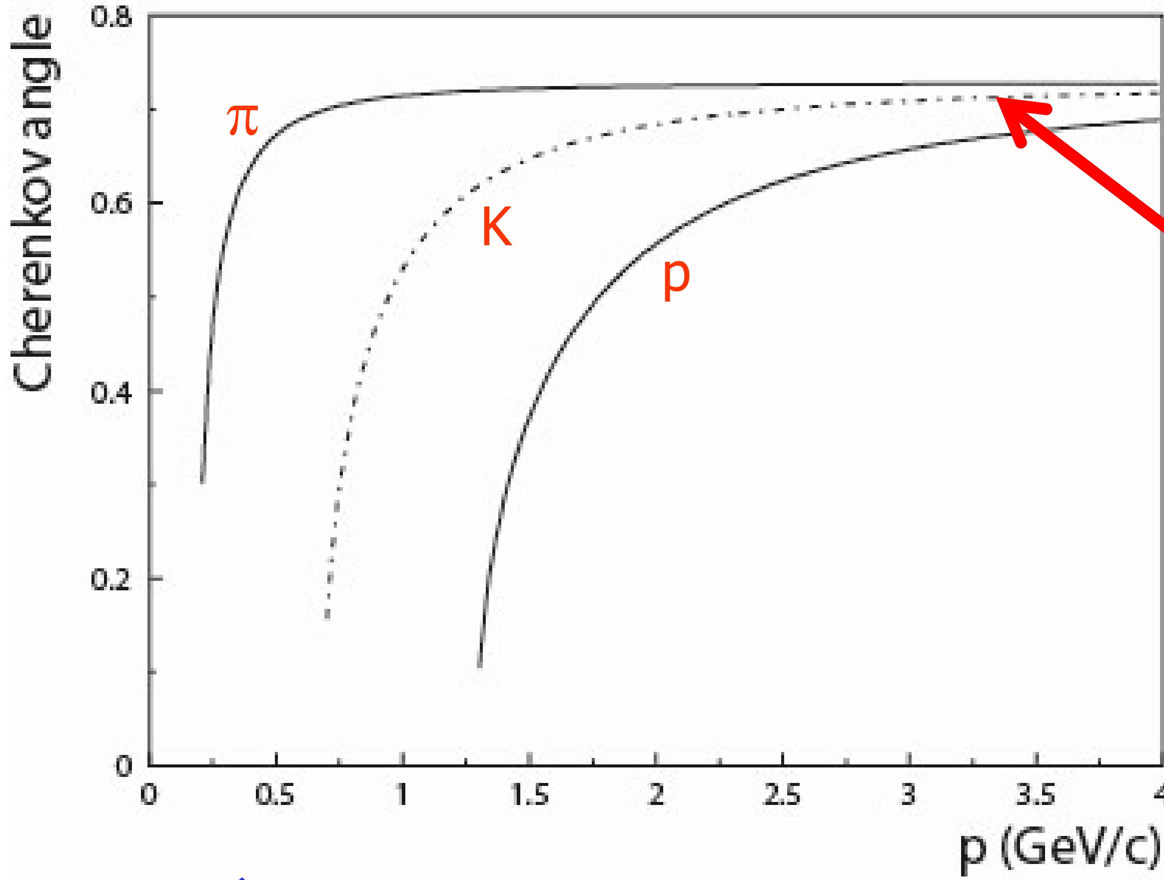
particle type 1 type 2

eff. vs fake probability



- any discriminating variable, e.g. Cherenkov angle

Measuring Cherenkov angle



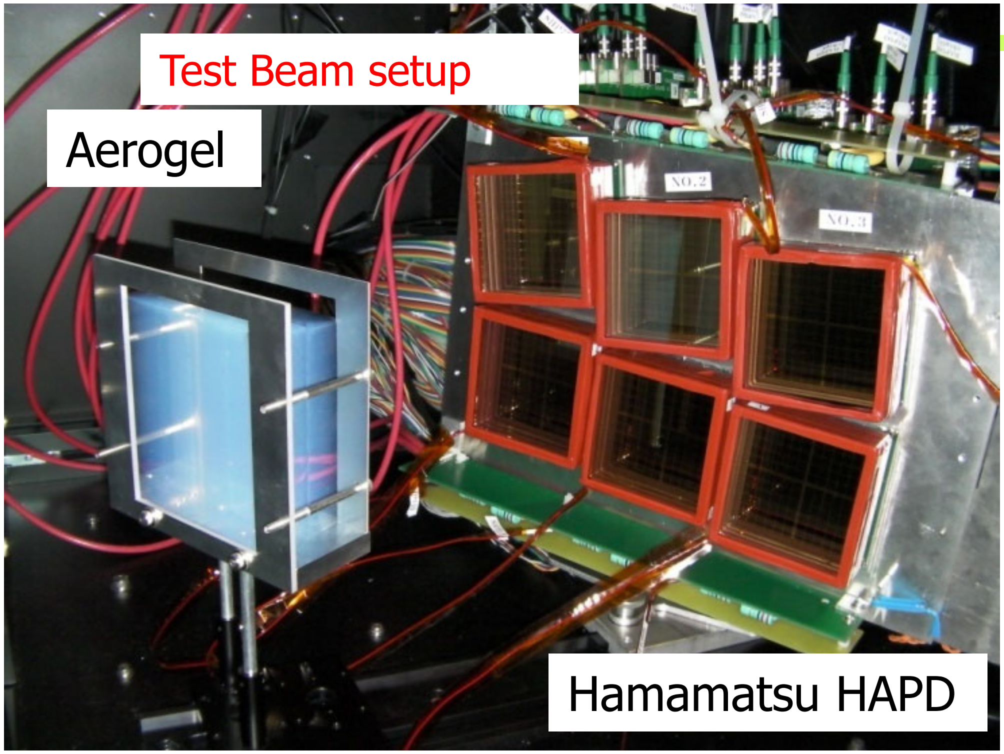
Radiator: quartz, n=1.06

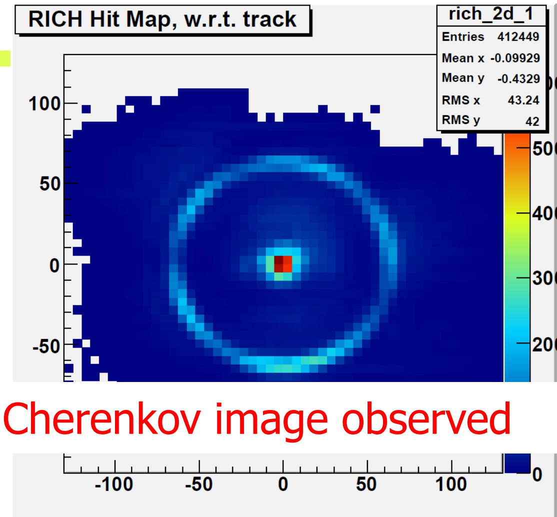
K/π overlap

P_{min} for K/π separation

P_{max} for K/π separation

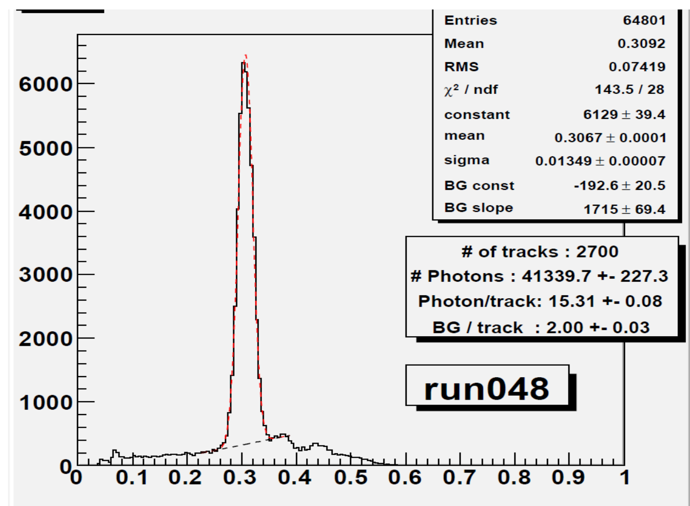
Aerogel RICH (endcap PID): larger particle momenta





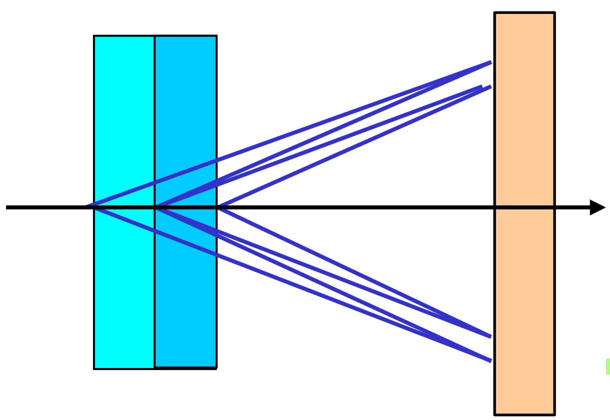
Clear Cherenkov image observed

Cherenkov angle distribution



RICH with a novel "focusing" radiator – a two layer radiator

Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.



6.6 σ π/K at 4GeV/c !

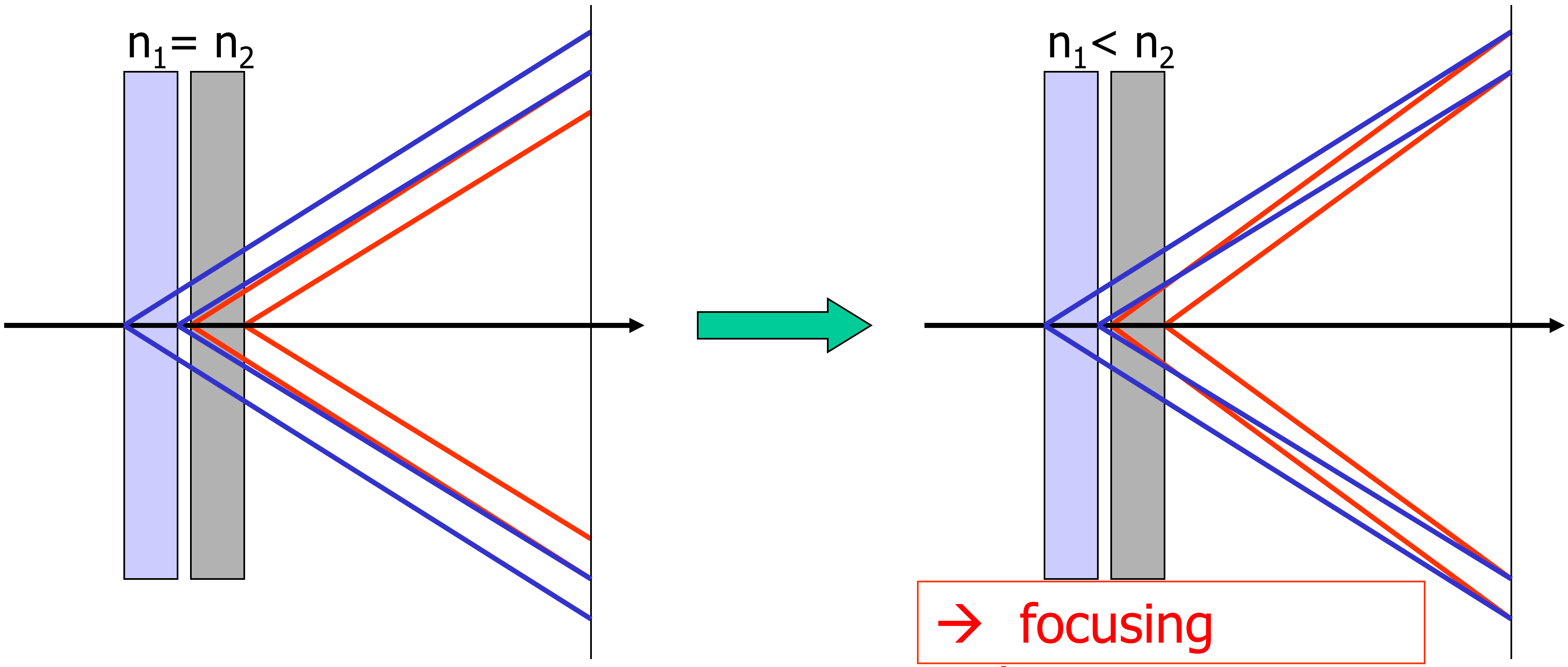
Peter Križan, Ljubljana

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: "focusing" configuration

normal

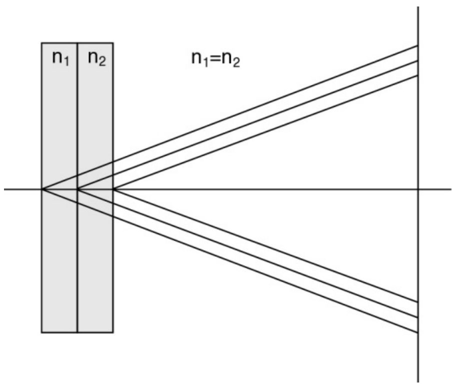


Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

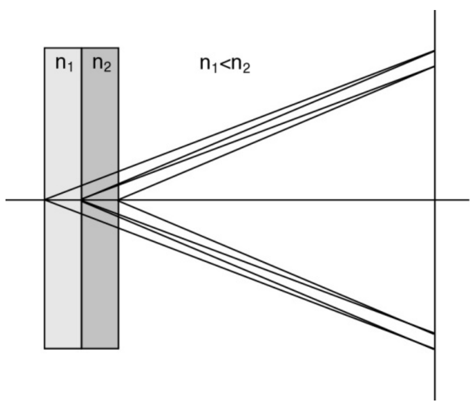
Focusing configuration – data

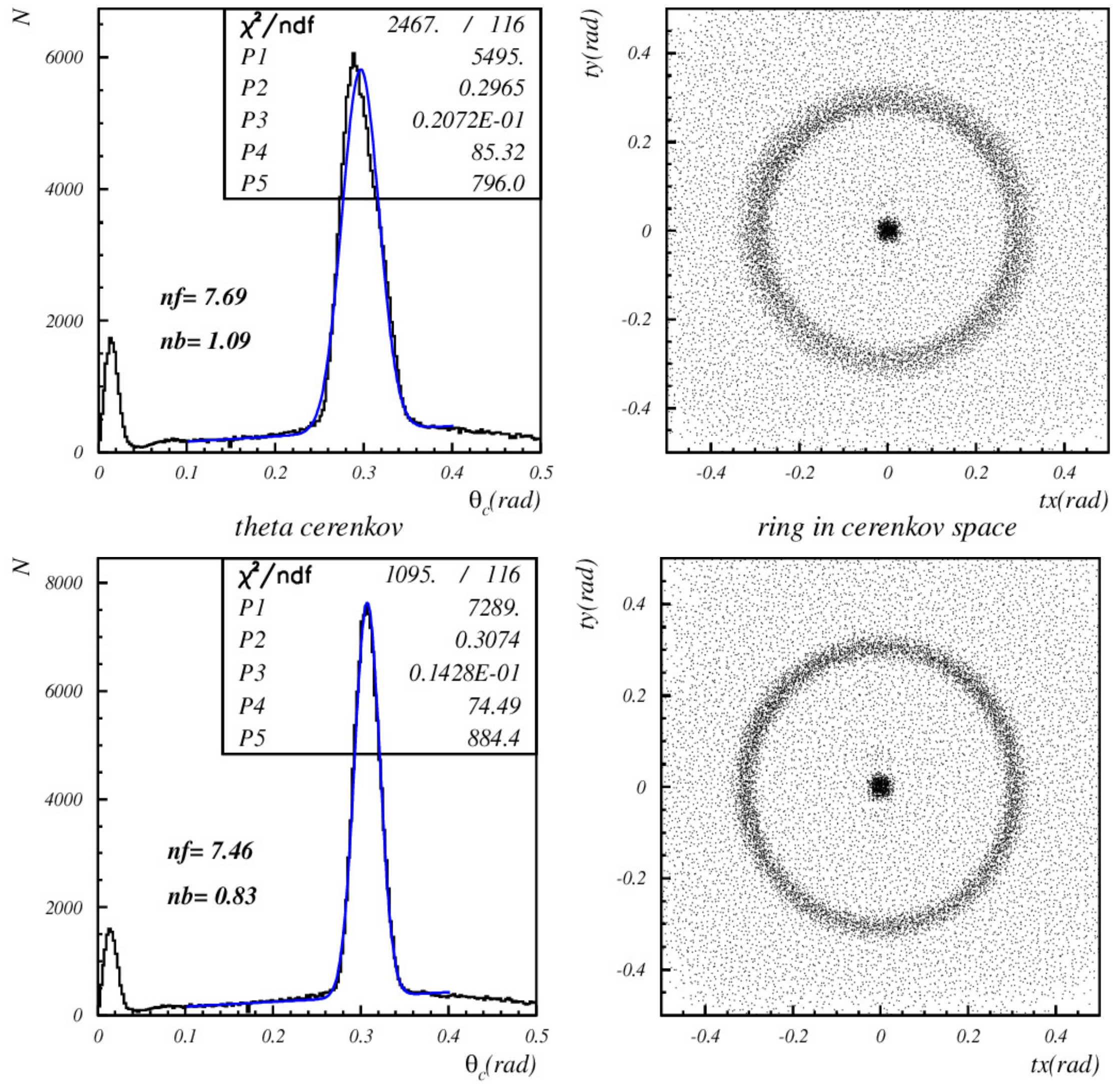
Increases the number of photons without degrading the resolution

4cm aerogel single index



2+2cm aerogel

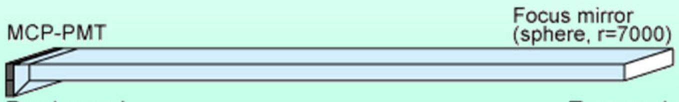




→NIM A548 (2005) 383

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



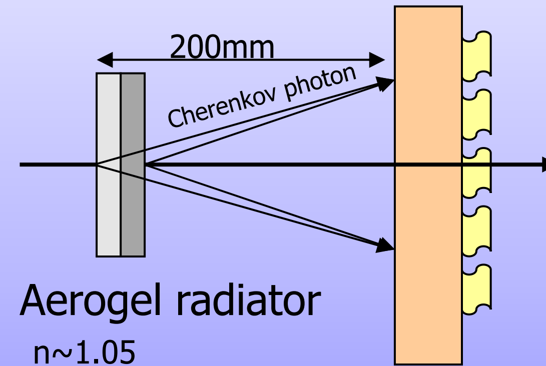
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

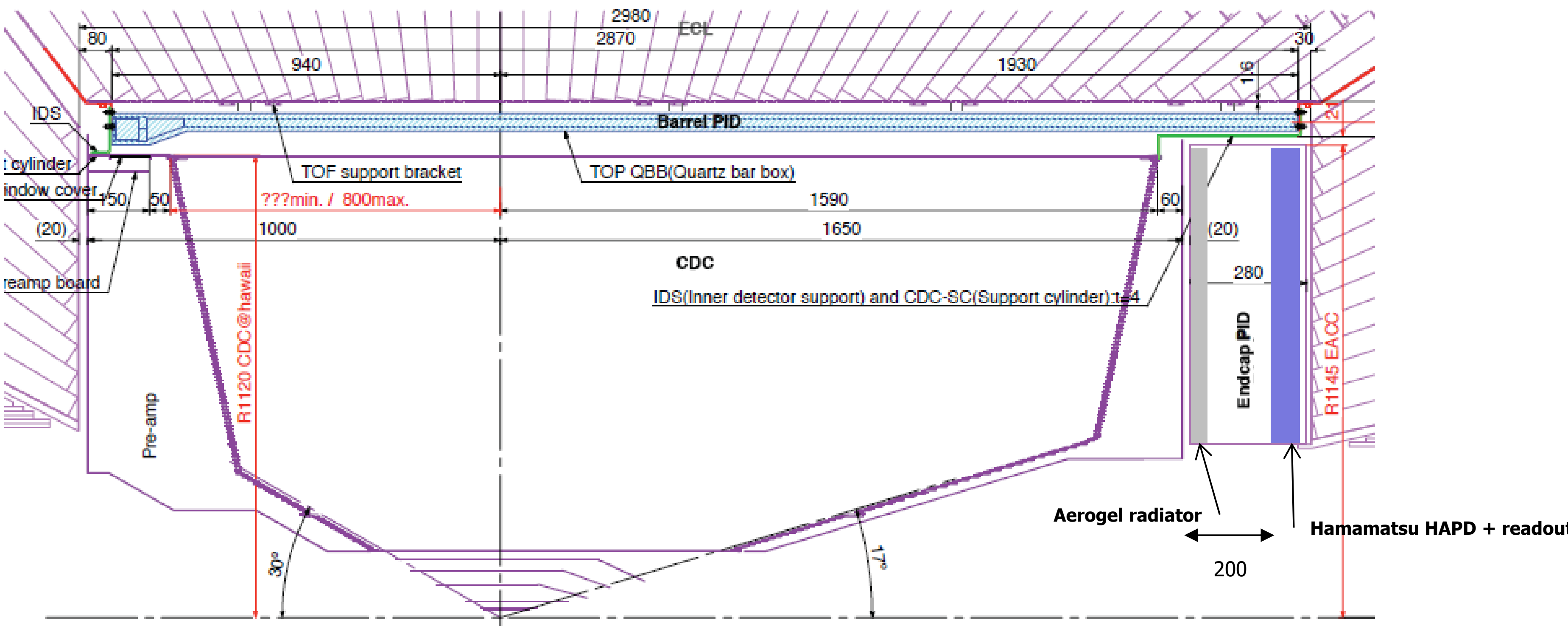
Endcap PID: Aerogel RICH (ARICH)



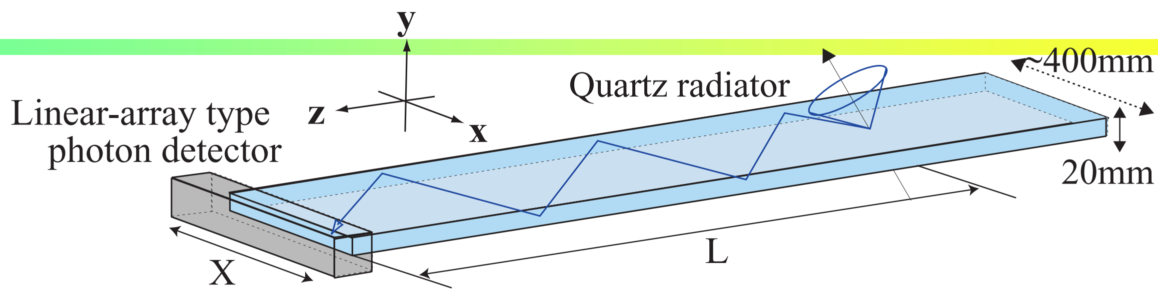
Aerogel radiator

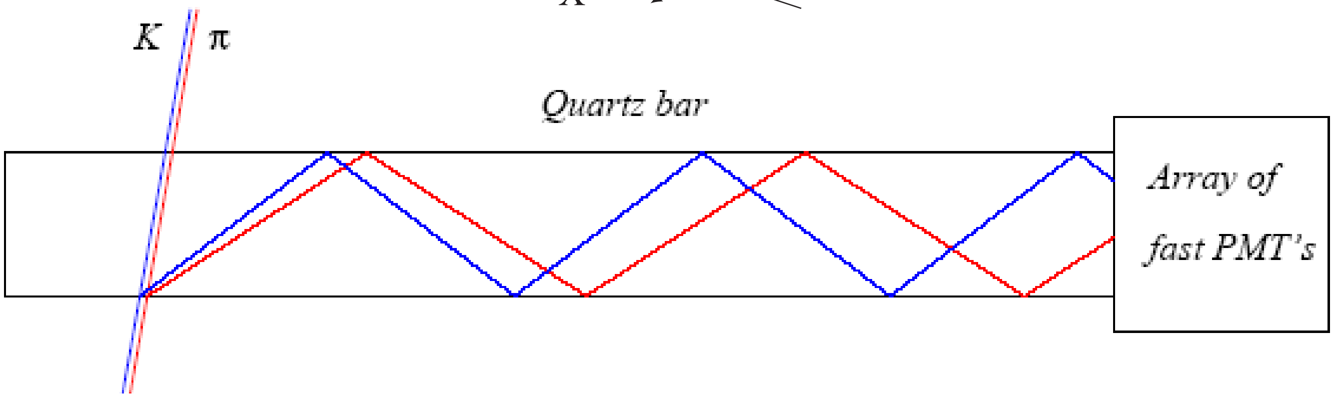
n~1.05

Hamamatsu HAPD
+ new ASIC

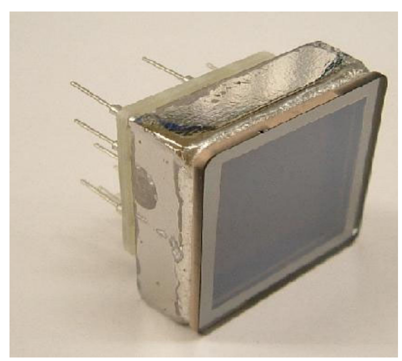


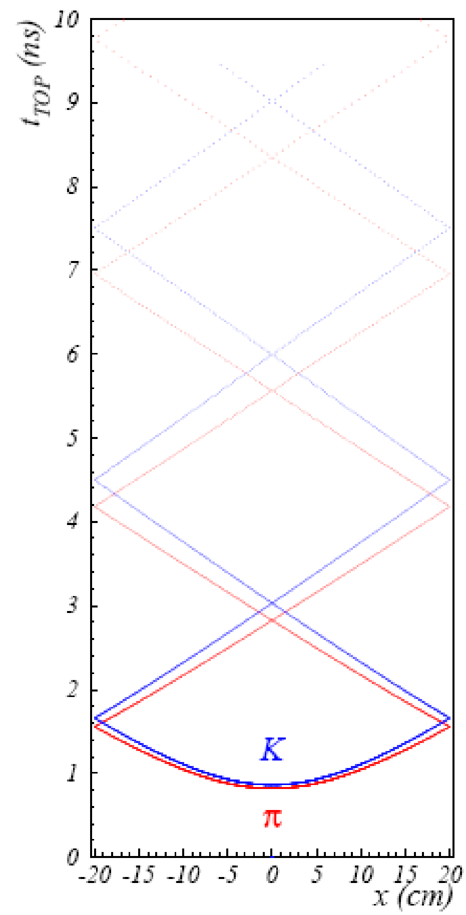
Belle II Barrel PID: Time of propagation (TOP) counter



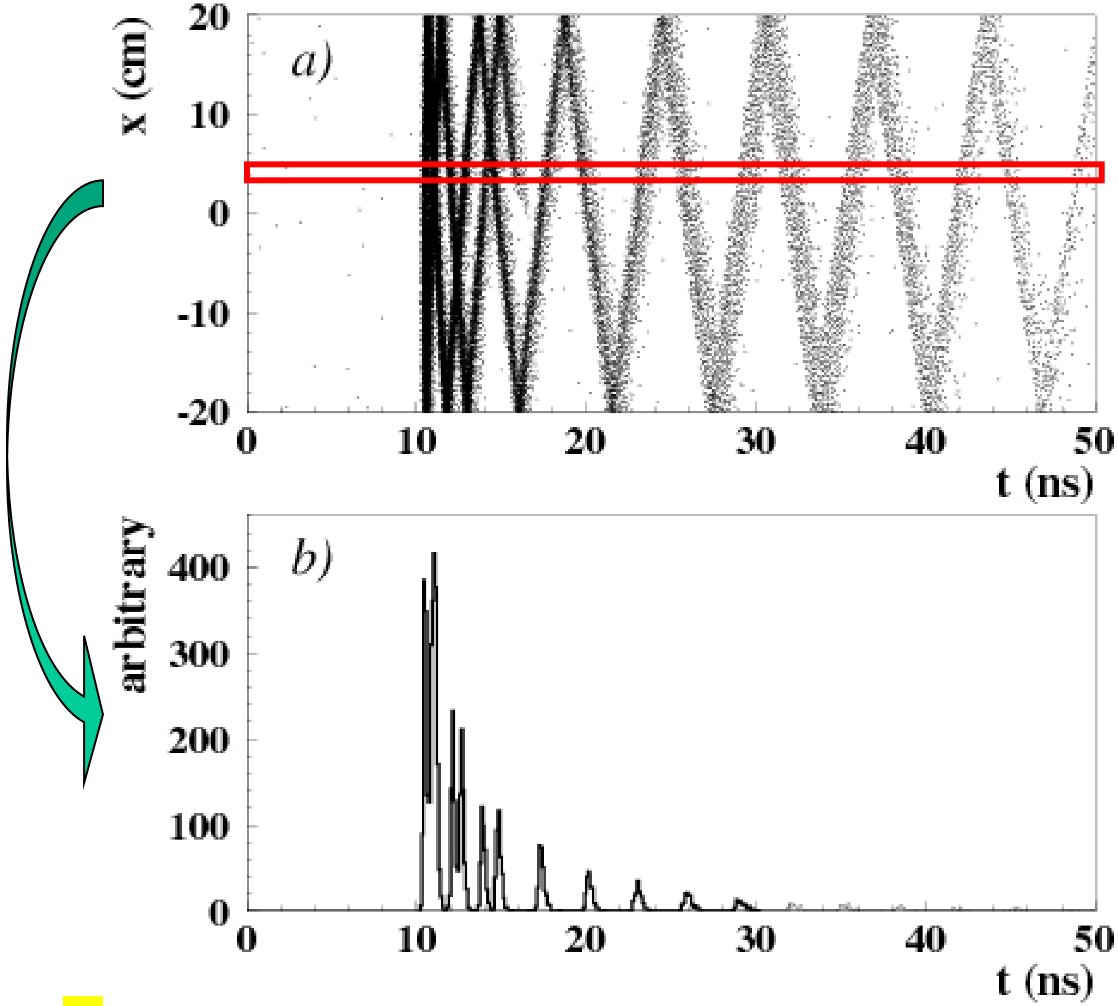


- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5



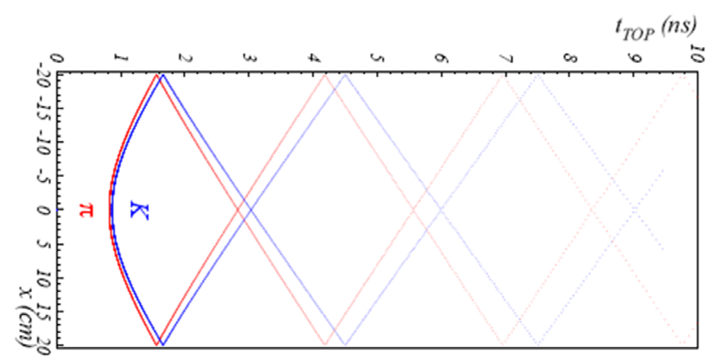


TOP image



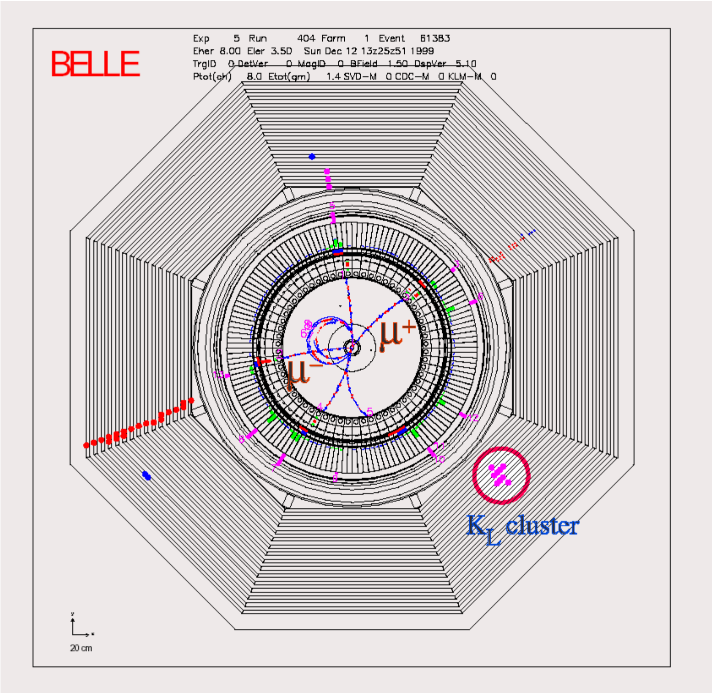
Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)



Muon (and K_L) detector

Separate muons from hadrons (pions and kaons): exploit the fact that muons interact only e.m., while hadrons interact strongly → need a few interaction lengths (about 10x radiation length in iron, 20x in CsI)



Detect K_L interaction (cluster): again need a few interaction lengths.

→ Put the detector outside the magnet coil, and integrate into the return yoke

Some numbers: 3.9 interaction lengths (iron) + 0.8 interaction length (CsI)

Interaction length: iron 132 g/cm^2, CsI 167 g/cm^2

$(dE/dx)_{min}$: iron 1.45 $MeV/(g/cm^2)$, CsI 1.24 $MeV/(g/cm^2)$ → ΔE_{min} = (0.36+0.11) GeV = 0.47 GeV → identification of muons above ~600 MeV

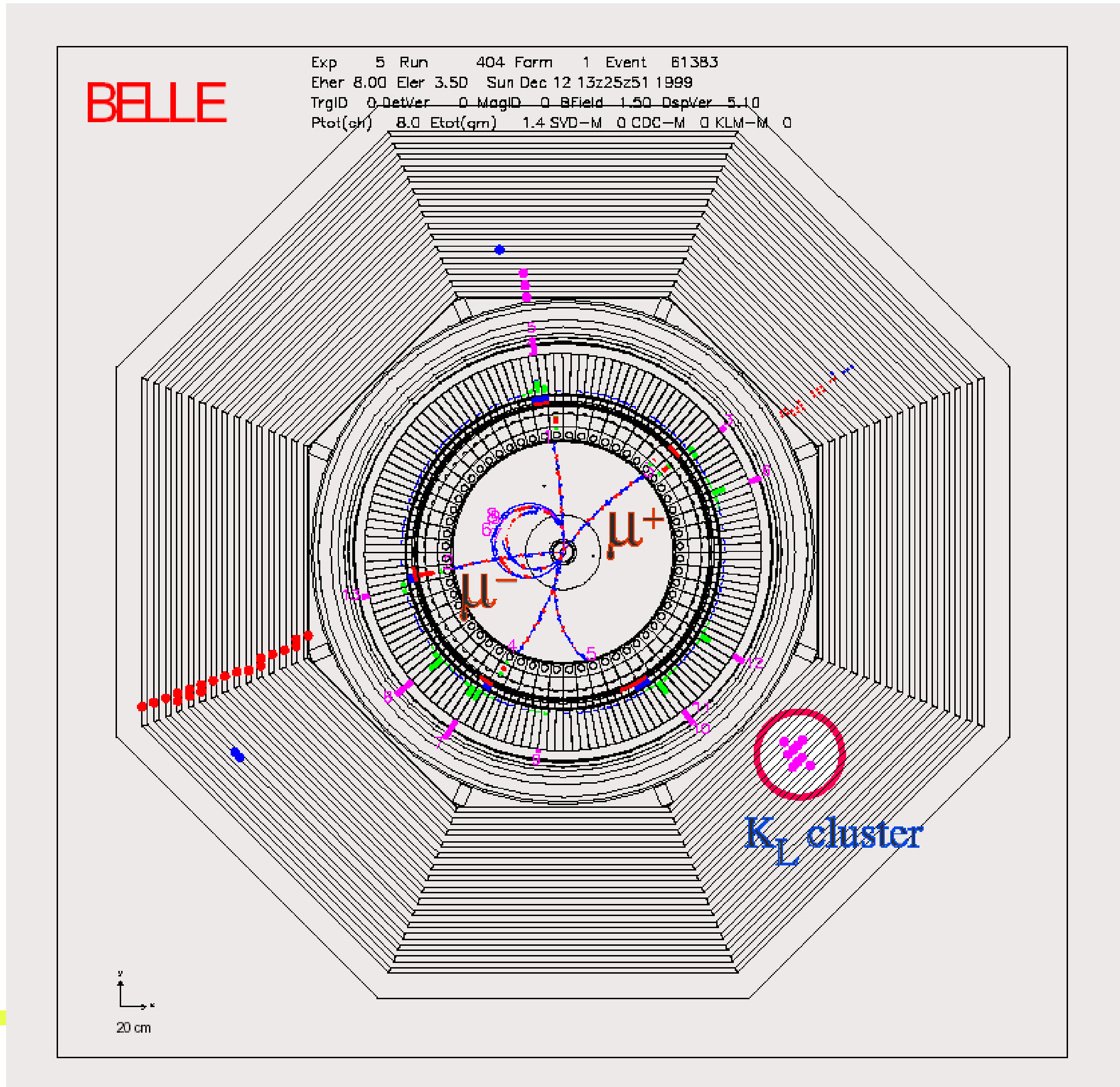
Muon and K_L detector

Example:

event with

- **two muons and a**
- **K_L**

and a pion that partly penetrated



Muon and K_L detector performance

Muon identification >800 MeV/c

efficiency

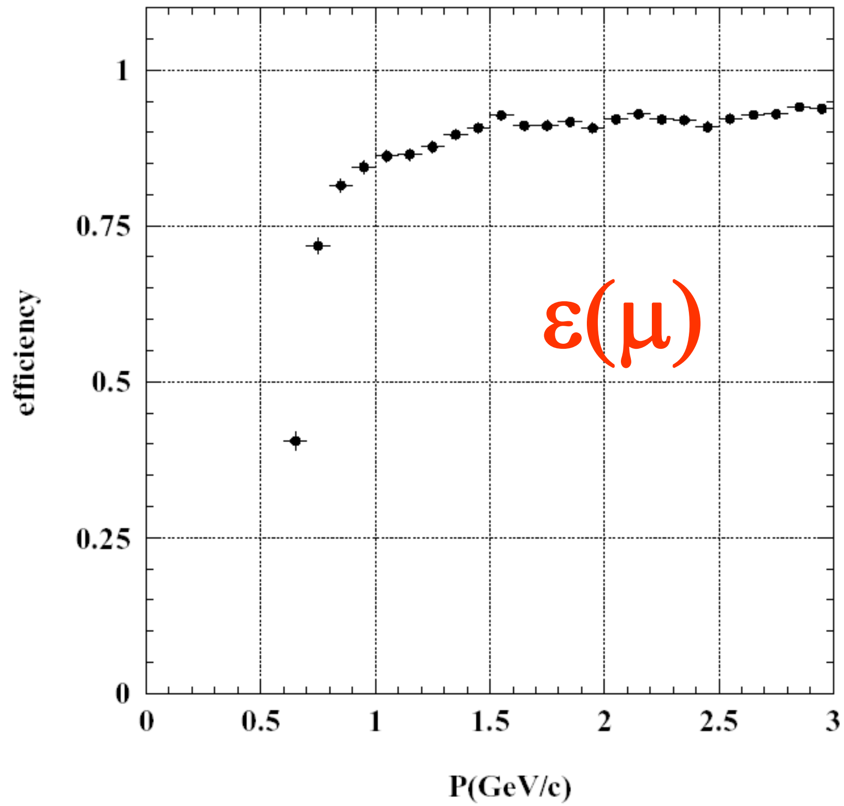


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

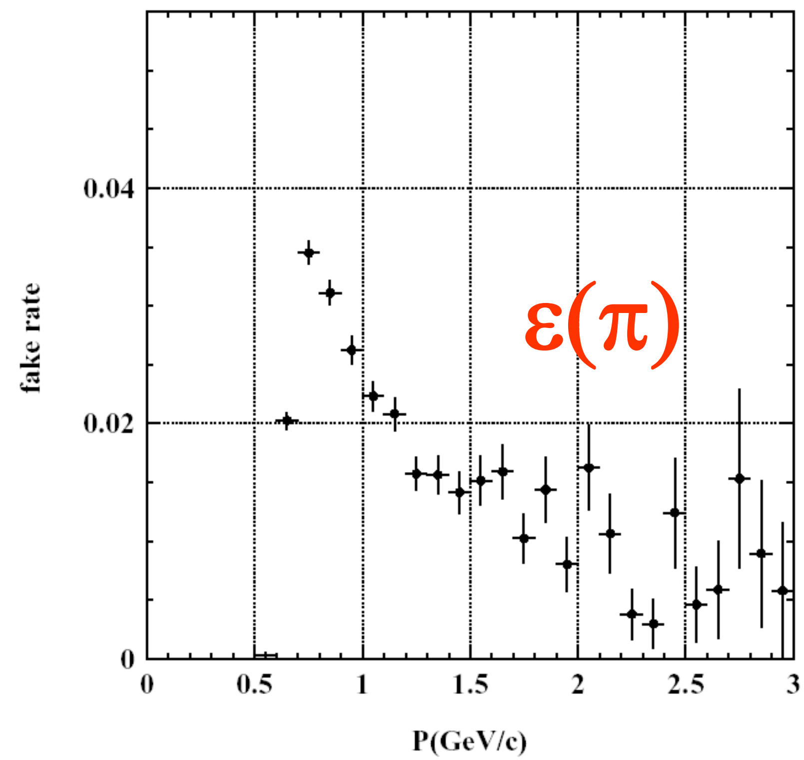


Fig. 110. Fake rate vs. momentum in KLM.

K_L detector performance

K_L detection: resolution in direction →

K_L detection: also with possible with electromagnetic calorimeter (0.8 interactin lengths)

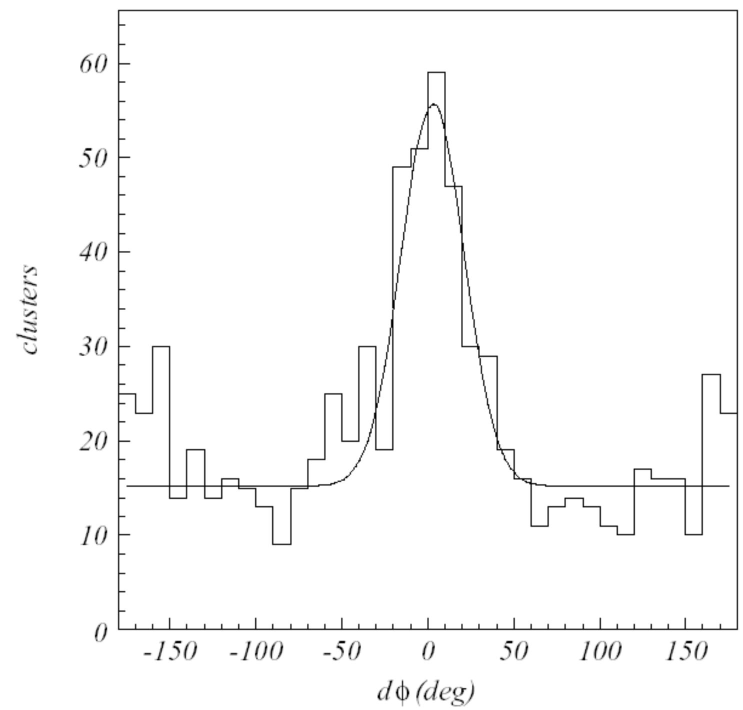
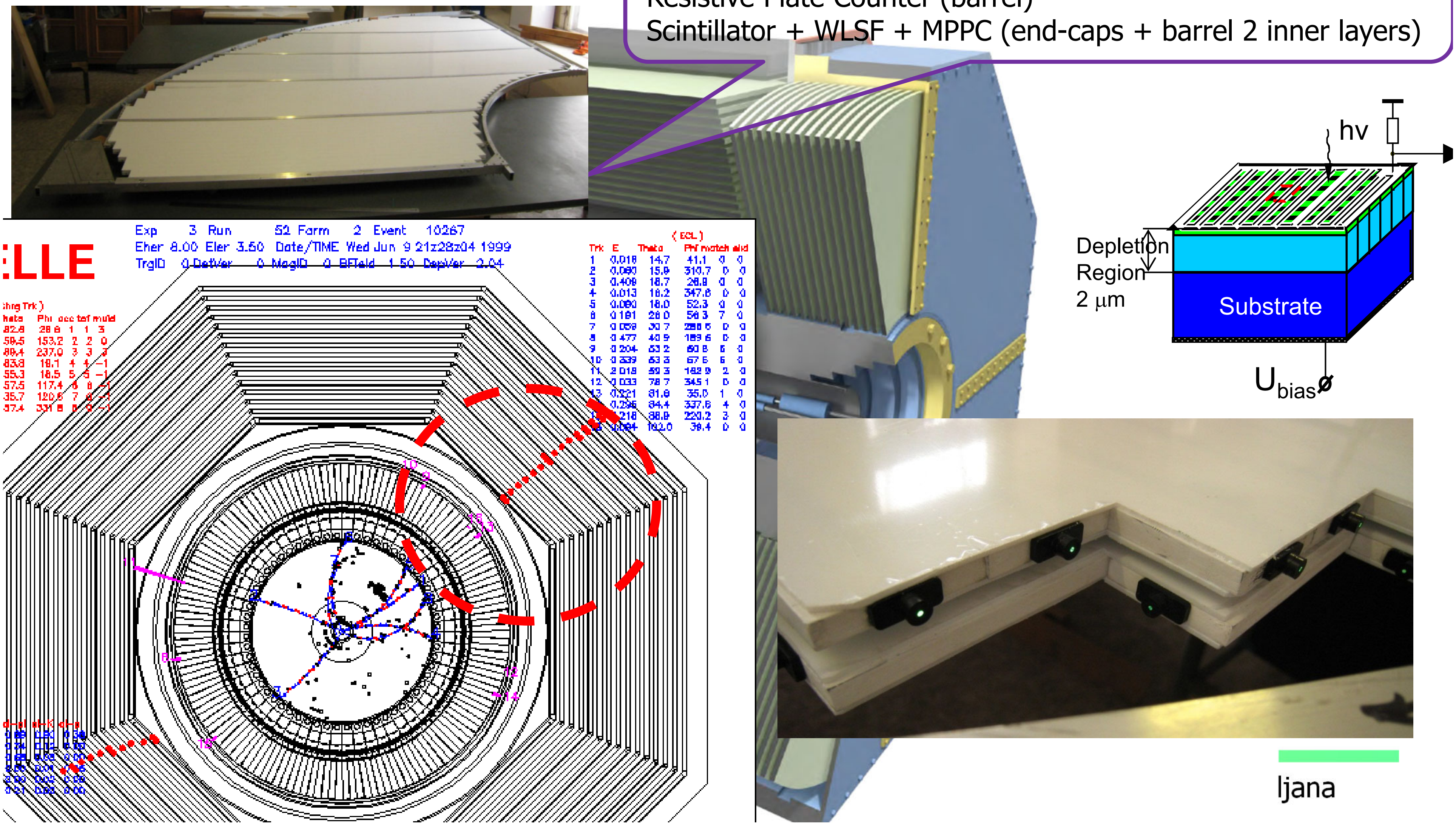


Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

Belle II, detection of muons and K_Ls: Parts of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

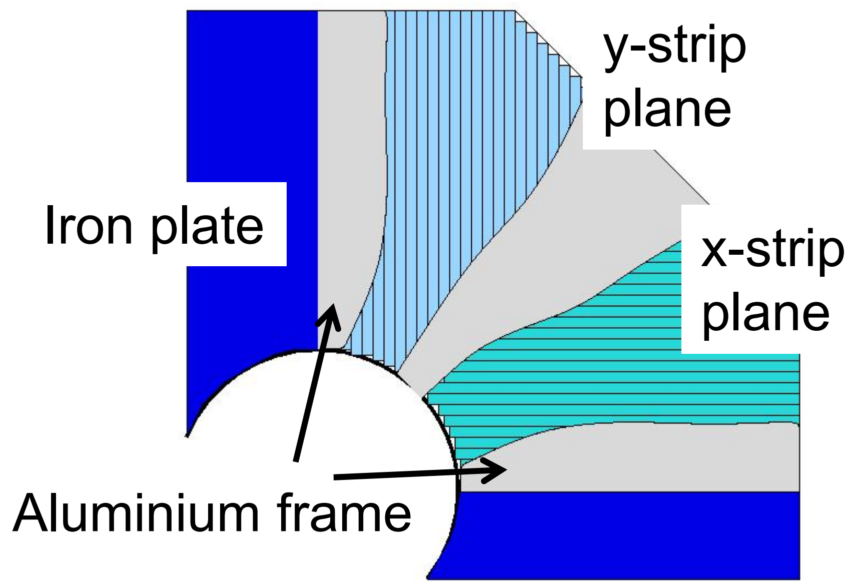
K_L and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps + barrel 2 inner layers)

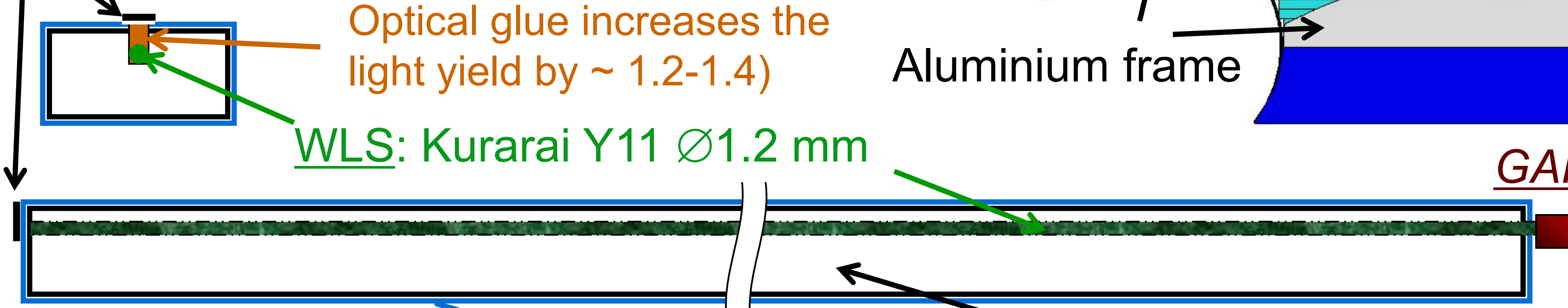


Muon detection system upgrade in the endcaps

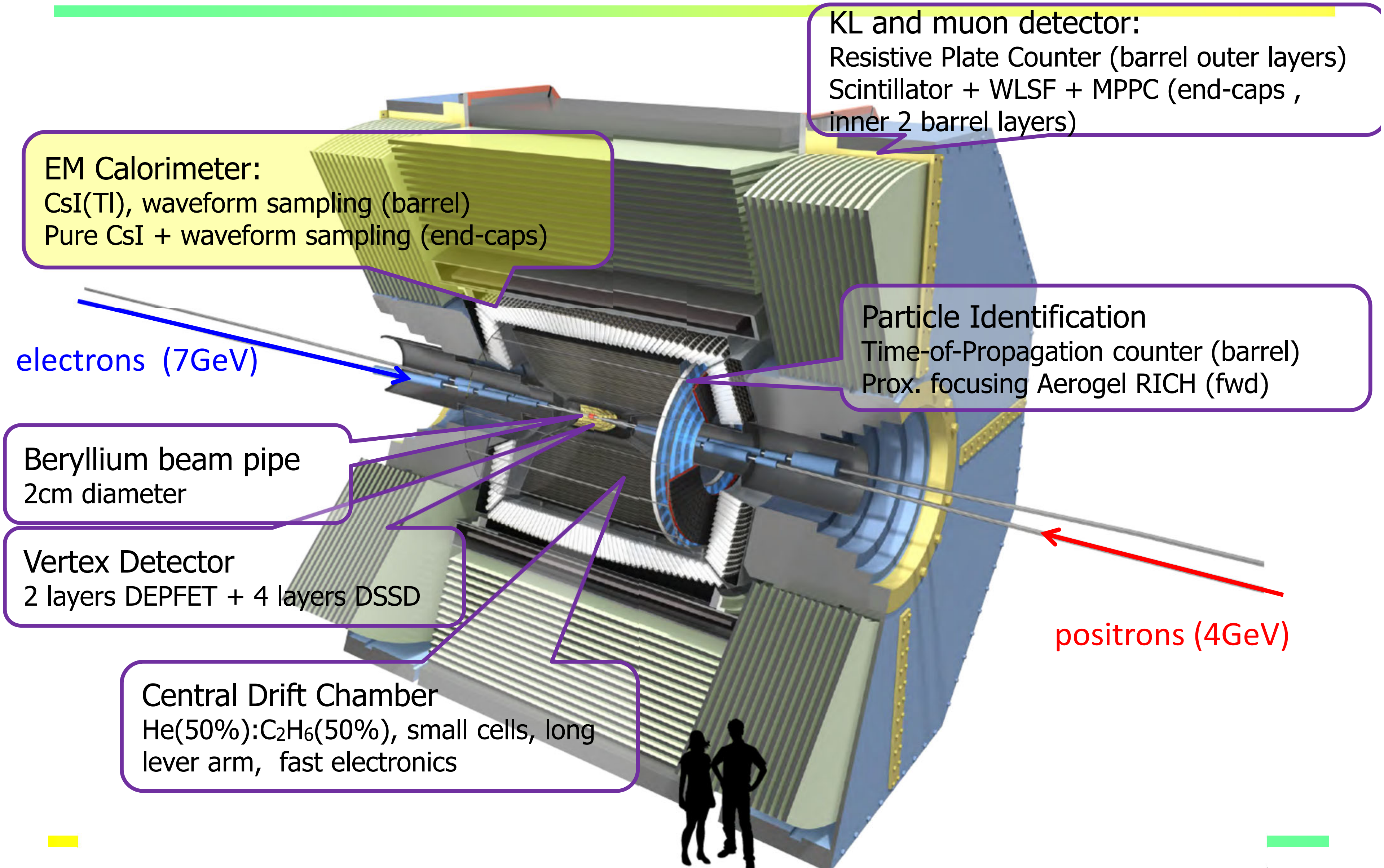
Scintillator-based KLM (endcap and two layers in the barrel part)

- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector
  (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%

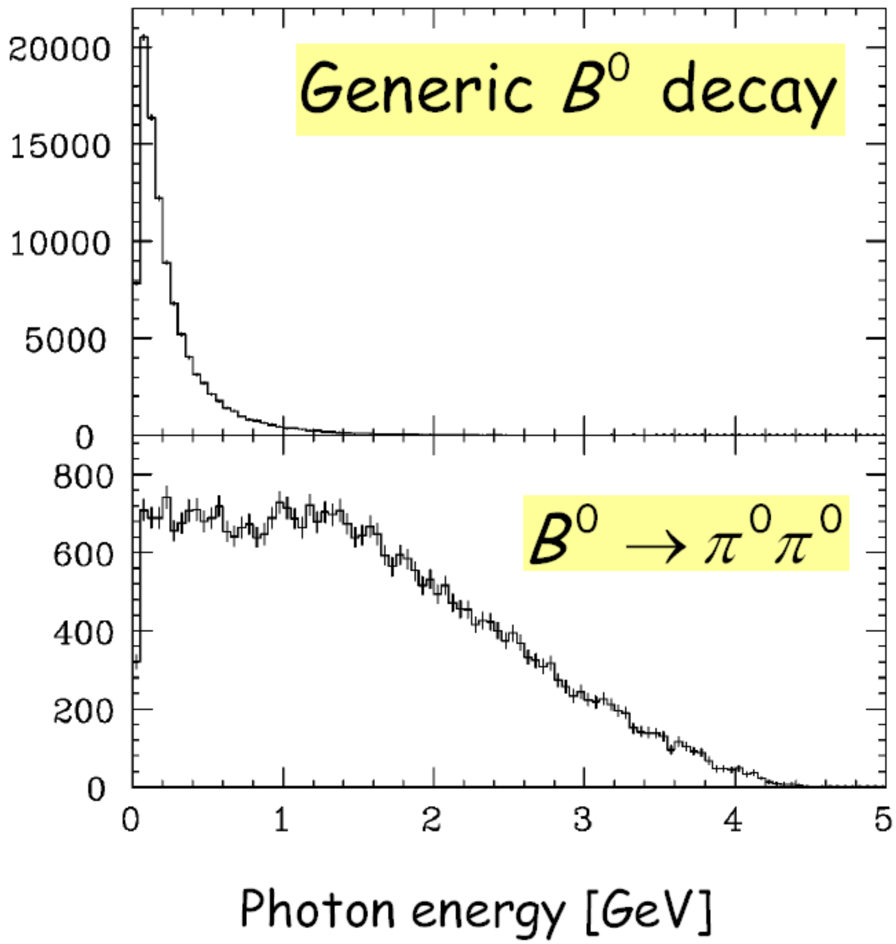


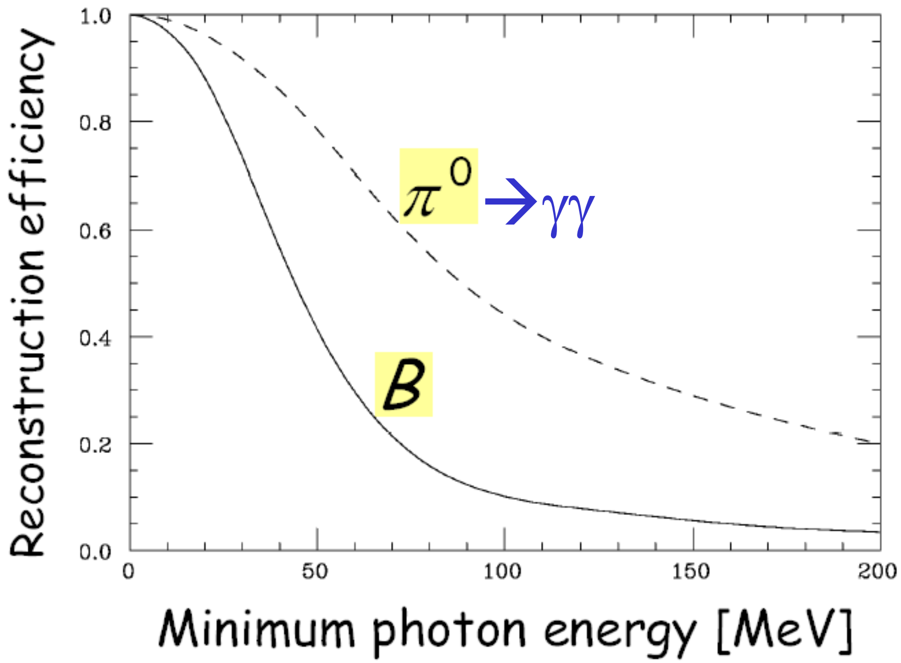


Calorimetry in Belle II



Requirements: Photons



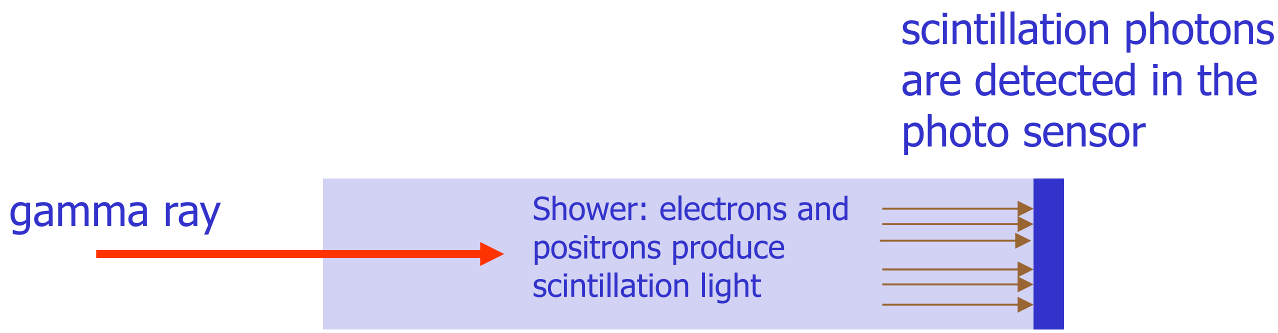


Requirements: Photons

$\pi^0 \rightarrow \gamma\gamma$ Need to reconstruct neutral pions from gamma pairs

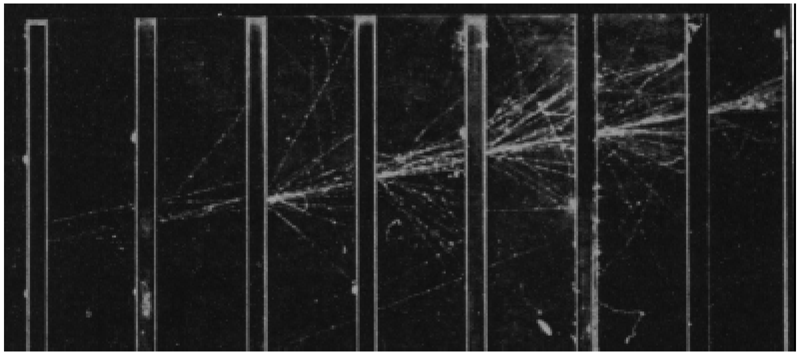
- Should also work for low energy gammas (photons)
- Excellent energy resolution

Detection of photons: scintillator crystal + photosensor

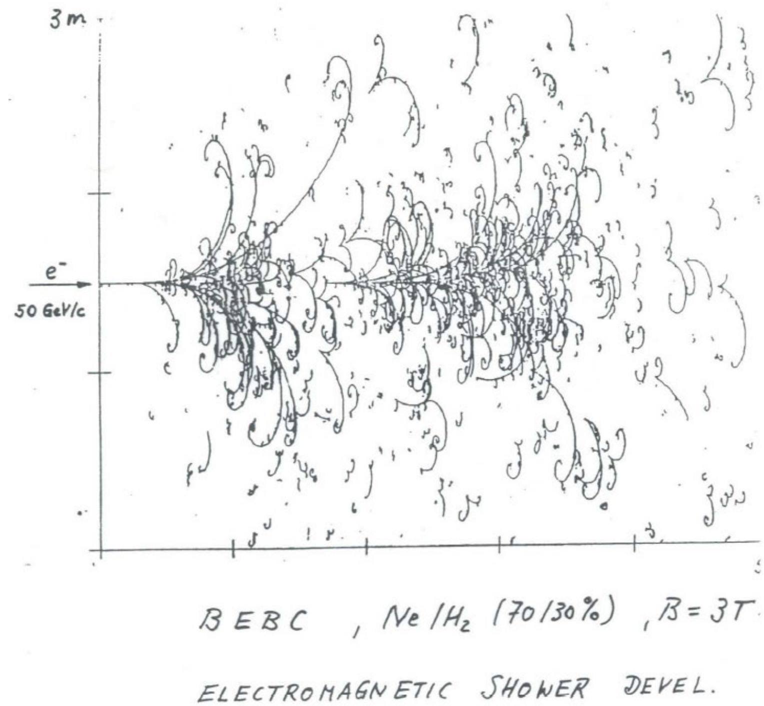


How does a shower develop? Gamma → e+e- pair production → bremstrahlung gammas → e+e- pair production → ….

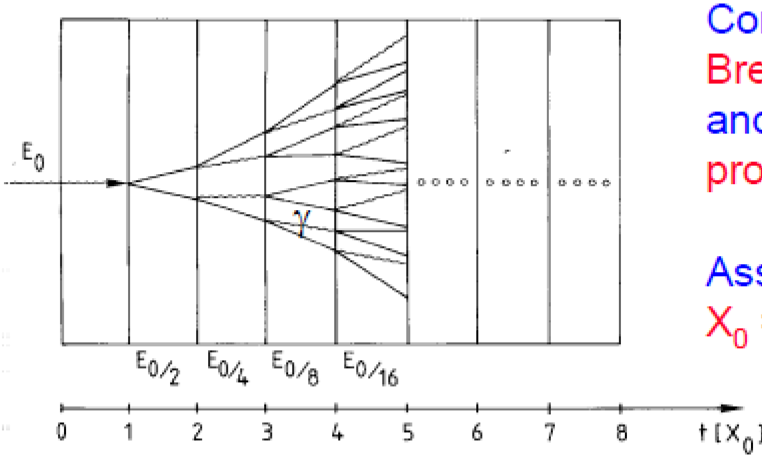
Electromagnetic Cascades (showers)



Electron shower in a cloud chamber with lead absorbers



Simple qualitative model



Consider only Bremsstrahlung and pair production.

Assume:
$X_0 = \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t) < E_c$

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \qquad N^{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect → absorption.

→ Calorimeter size depends only logarithmically on E_0

- Energy resolution of a calorimeter (intrinsic limit)

$$N^{total} \propto \frac{E_0}{E_c}$$

total number of track segments

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N)}{N} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E_0}}$$

holds also for hadron calorimeters

Also spatial and angular resolution scale like $1/\sqrt{E}$

Relative energy resolution of a calorimeter improves with E_0

More general:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term

Constant term

Inhomogenities
Bad cell inter-calibration
Non-linearities

→ Quality factor !

Noise term

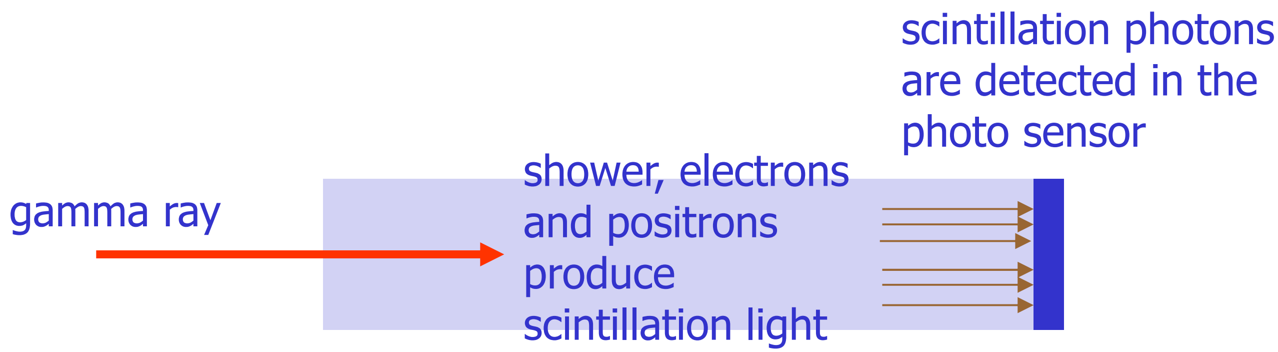
Electronic noise
radioactivity
pile up

Requirements: Photons

$\pi^0 \rightarrow \gamma\gamma$ Need to reconstruct neutral pions from gamma pairs

- Also gammas (photons) with low energy
- Excellent energy resolution

Detection of photons: scintillator crystal + photosensor



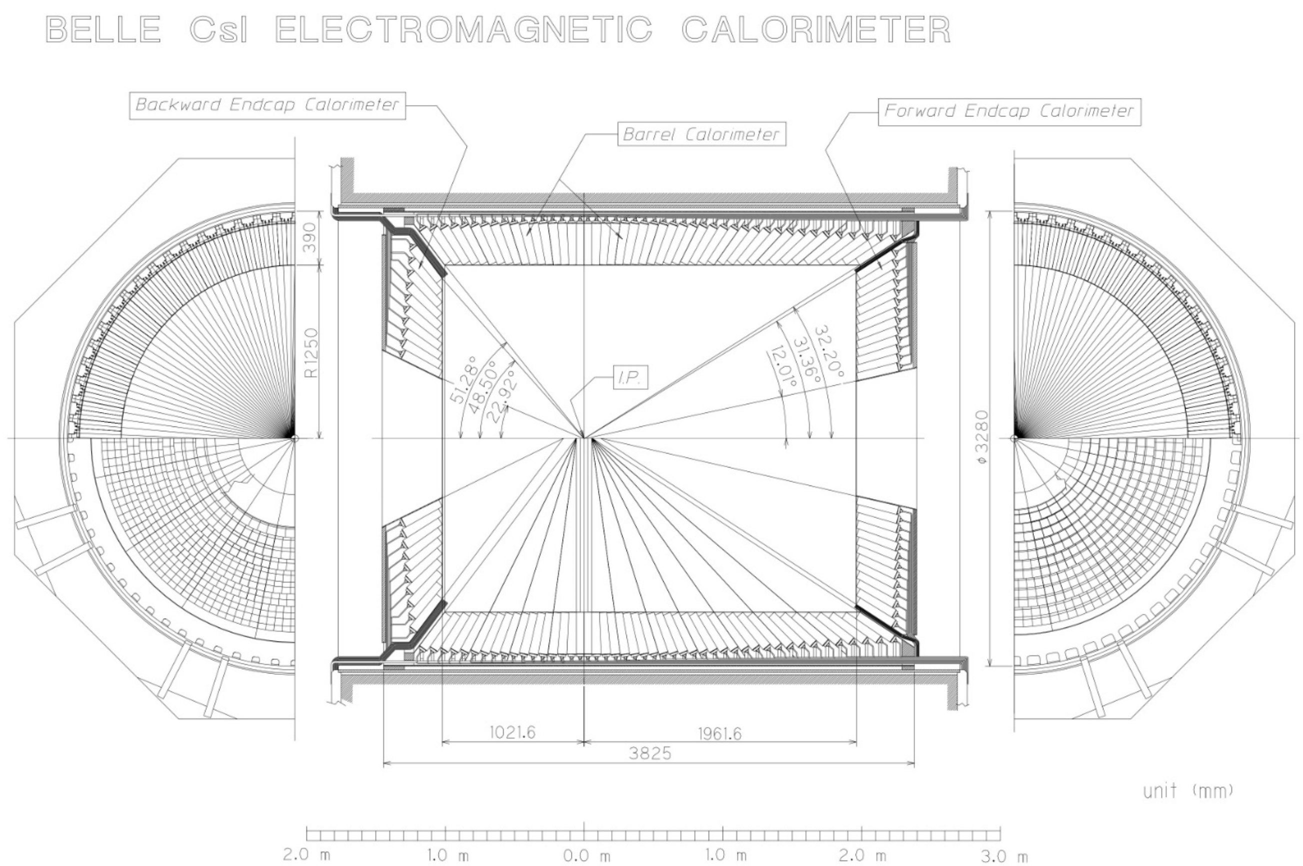
Need:
- High light yield (many scintillation photons) $\leftarrow \sigma(E)/E \propto N^{-1/2}$
- photo-sensor with low noise (noise spoils resolution)

Comparison of Inorganic Scintillators

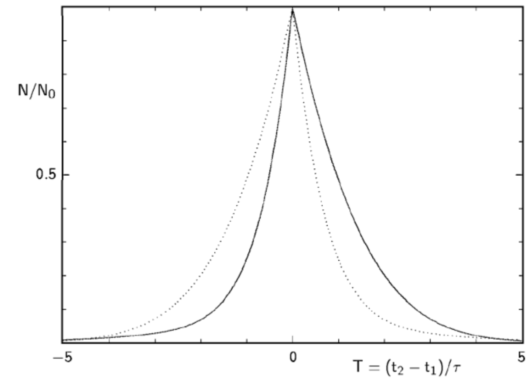
Scintillator material	Density (g/cm^3)	Radiation length	Refractive index	Wavelength at peak	Decay time	Light yield (Y/MeV)
NaI (Tl)	3.67	2.59 cm	1.78	410 nm	230 ns	4.1 x10^4
CsI (Tl)	4.51	1.86 cm	1.85	550 nm	800–6000 ns	6.6 x10^4
CsI (Na)	4.51	1.86 cm	1.80	420 nm	630 ns	4.0 x10^4
$LaBr_3$ (Ce)	5.3	1.88 cm	1.9	358 nm	35 ns	6.1 x10^4
$Bi_4Si_3O_{12}$ BSO	6.8	1.15 cm	2.06	480 nm	100 ns	0.2 x10^4
$Bi_4Ge_3O_{12}$ BGO	7.1	1.12 cm	2.15	480 nm	300 ns	0.9 x10^4
$CdWO_4$	7.9	1.1 cm	2.25	495 nm	5000 ns	2.0 x10^4
$YAlO_3$ (Ce) YAP	5.5	2.9 cm	1.94	350 nm	30 ns	2.1 x10^4
$Lu_3Al_5O_7$ (Ce) LuAG	7.4	1.4 cm	1.84	420 nm	40 ns	2.6 x10^4
Gd_2SiO_5 (Ce) GSO	6.7	1.4 cm	1.87	440 nm	60 ns	0.8 x10^4
$PbWO_4$	8.3	0.89 cm	1.82	425 nm	25 ns	0.05 x10^4

Calorimeter with CsI(Tl) crystals

Doping with tallium improves the light yield

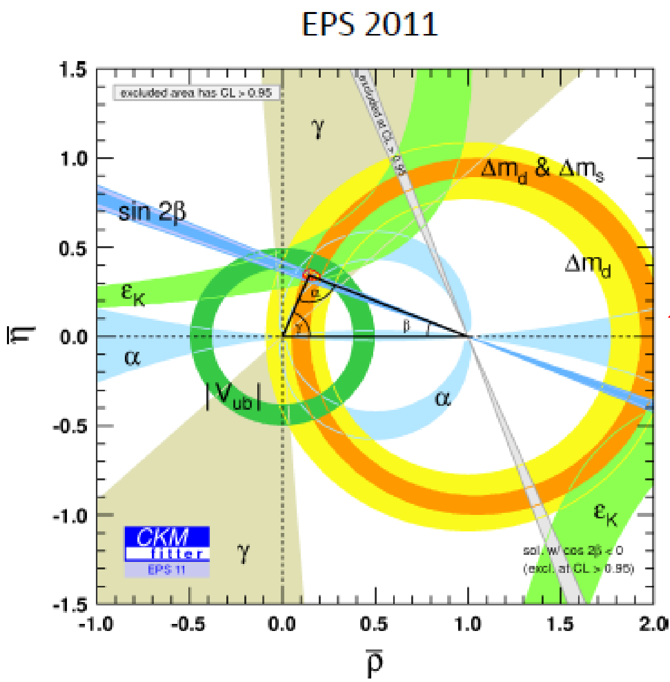


B factories, main result: CP violation in the B system

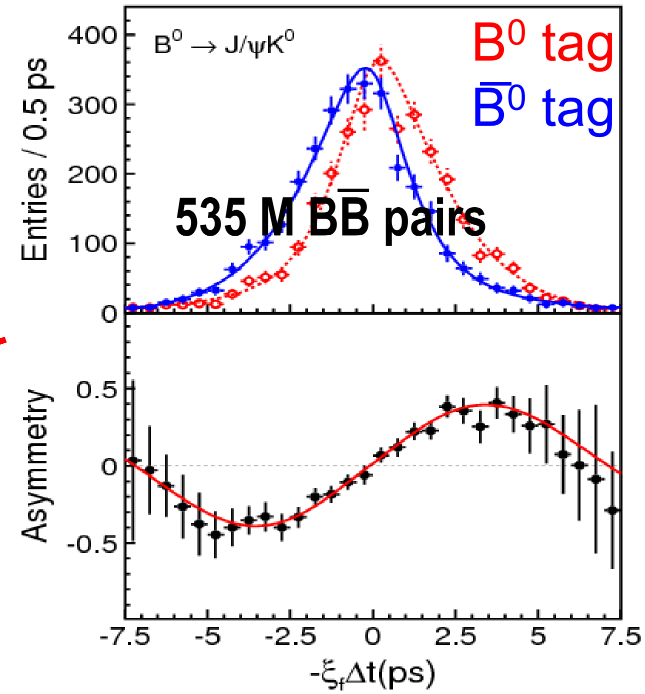


CP violation in B system: from the discovery (2001) to a precision measurement

sin2ϕ_1/sin2β from B→ J/psi K_S



sin2ϕ_1/sin2β

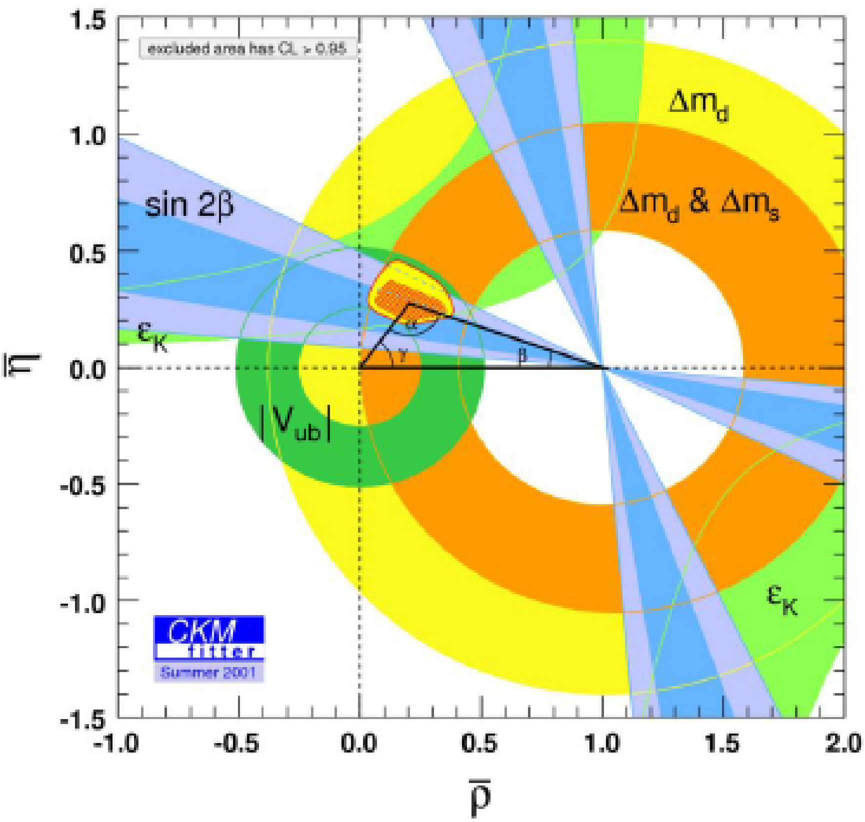


Constraints from many different measurements of angles and sides of the unitarity triangle → Remarkable agreement

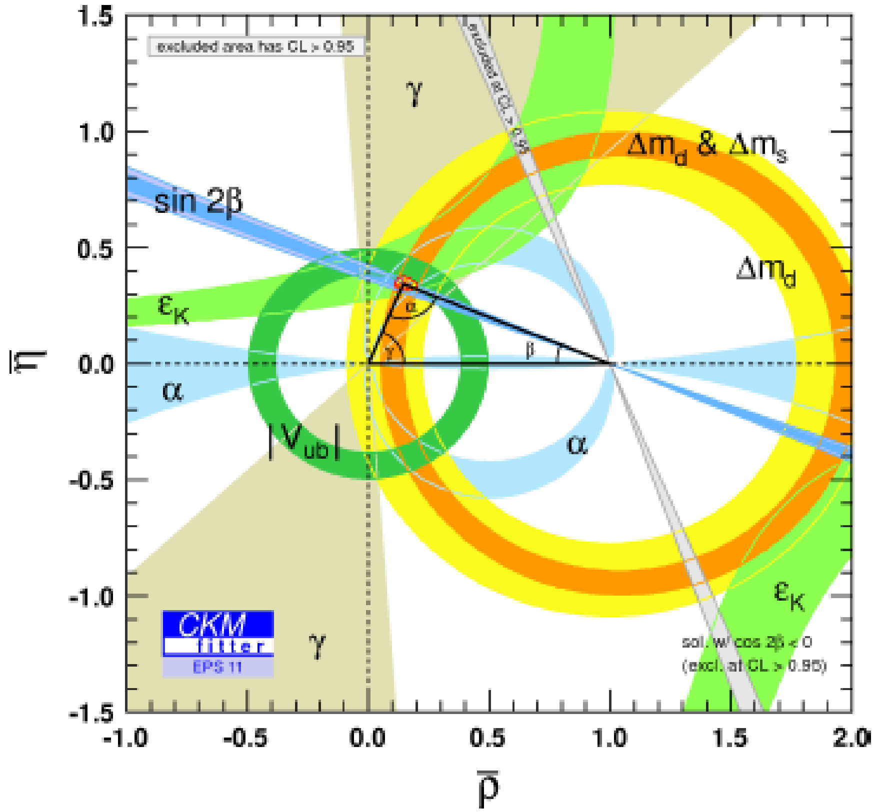
Unitarity triangle – 2011 vs 2001

CP violation in the B system: from the discovery (2001) to a precision measurement (2011).

EPS 2001

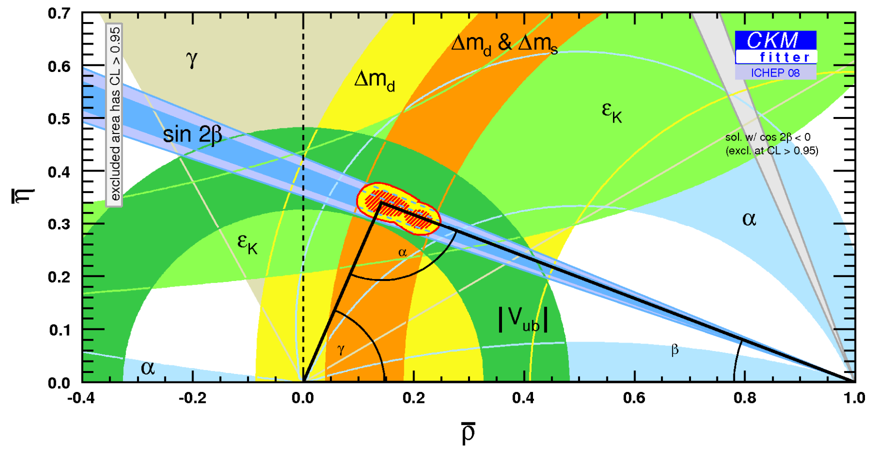


EPS 2011



KM's bold idea verified by experiment

Relations between parameters as expected in the Standard model →




→ Nobel prize 2008!

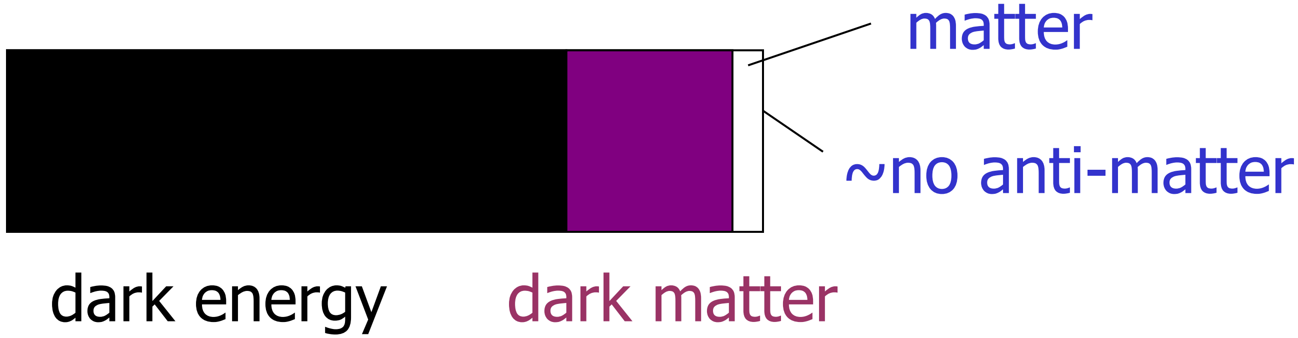
→ With essential experimental confirmations by BaBar and Belle! (explicitly noted in the Nobel Prize citation)

B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \to \tau\nu$, $D\tau\nu$)
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s\gamma$ branching fraction
- Study forward-backward asymmetry (A_{FB}) in $b \to s l^+ l^-$
- First look at the possible violation of lepton flavour universality
- Observation of D mixing
- Searches for rare τ decays
- Observation of new hadrons

The KM scheme is now part of the Standard Model of Particle Physics

- However, the CP violation of the KM mechanism is too small to account for the asymmetry between matter and anti-matter in the Universe (falls short by 10 orders of magnitude !)
- SM does not contain the fourth fundamental interaction, gravitation
- Most of the Universe is made of stuff we do not understand...



Two frontiers

Two complementary approaches to study shortcomings of the Standard Model and to search for the so far unobserved processes and particles (so called New Physics, NP). These are the **energy frontier** and the **intensity frontier** .

Energy frontier : direct search for production of unknown particles at the highest achievable energies.

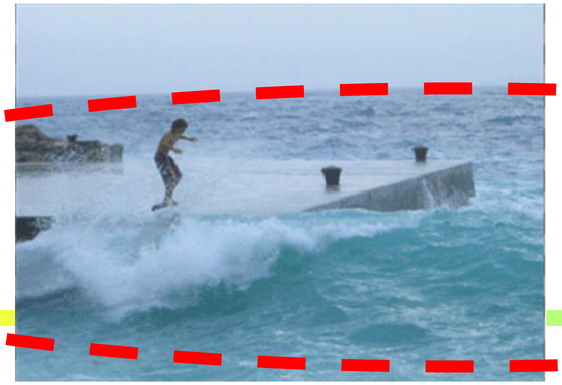
Intensity frontier : search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

→for this kind of studies, one has to investigate a very large number of reactions events → need accelerators with ultimate **intensity** (= luminosity)

Comparison of **energy** /**intensity** frontiers

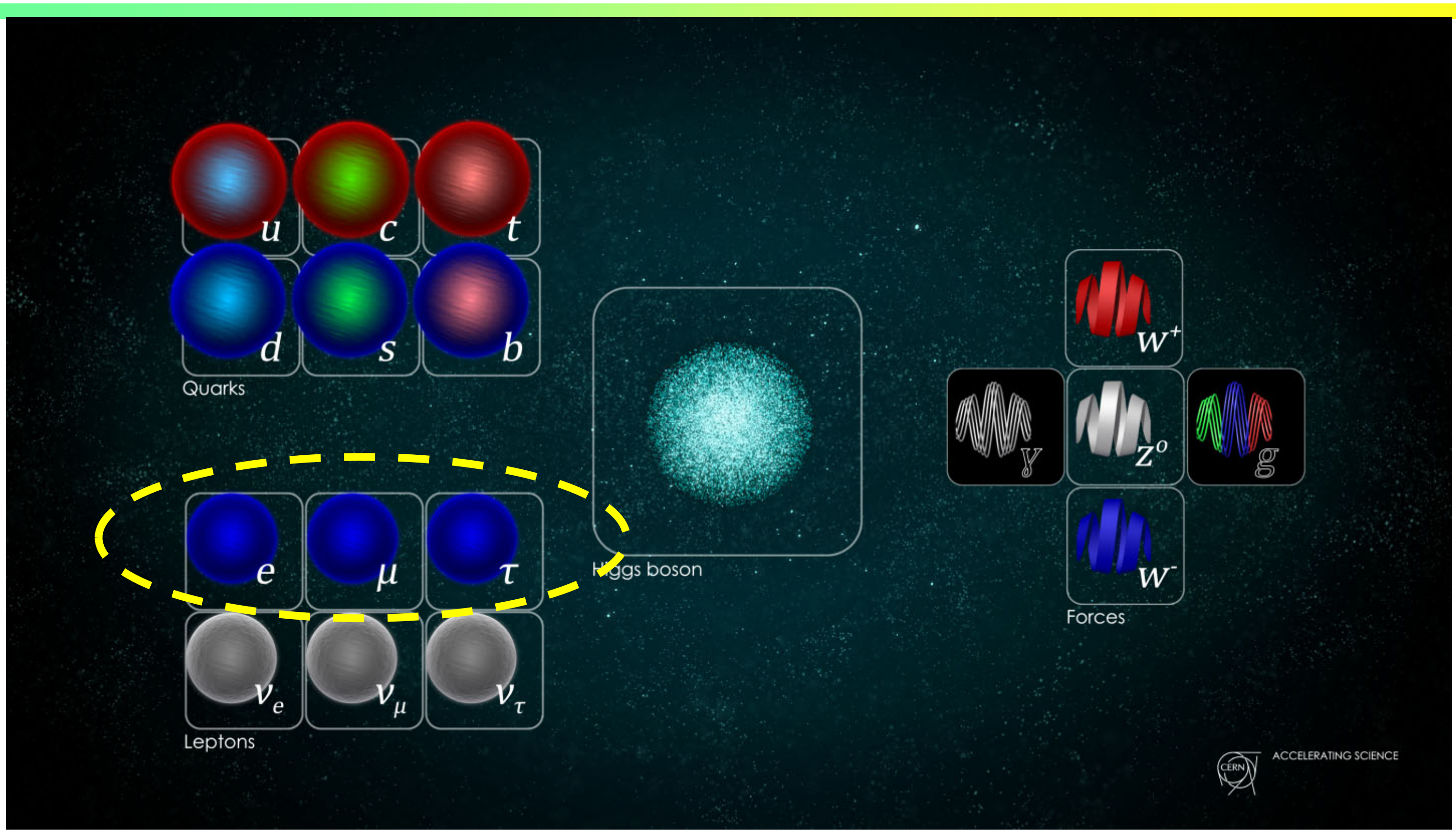
To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

Energy frontier (LHC)



Luminosity frontier (Belle and Belle II)

Standard Model: Lepton Flavour Universality

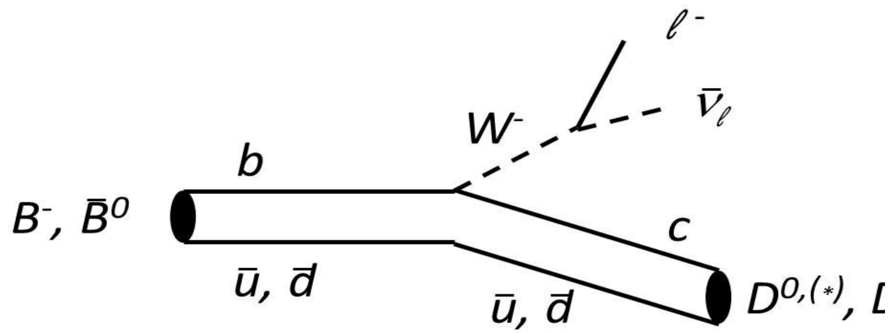


One of the cornerstones of the Standard model (verified by experiments): Lepton Flavour Universality (LFU) - interactions of leptons do not depend on their flavour

= e^-, μ^-, τ^- should behave in the same way

Anomalies in $B \to D^*\tau\nu$

Diagrams for the transition, mediated by the charged SM weak interaction



LFU → the rate for the transition (corrected for available phase space) should not depend on the lepton flavour

→ Same for electrons, muons and tau leptons

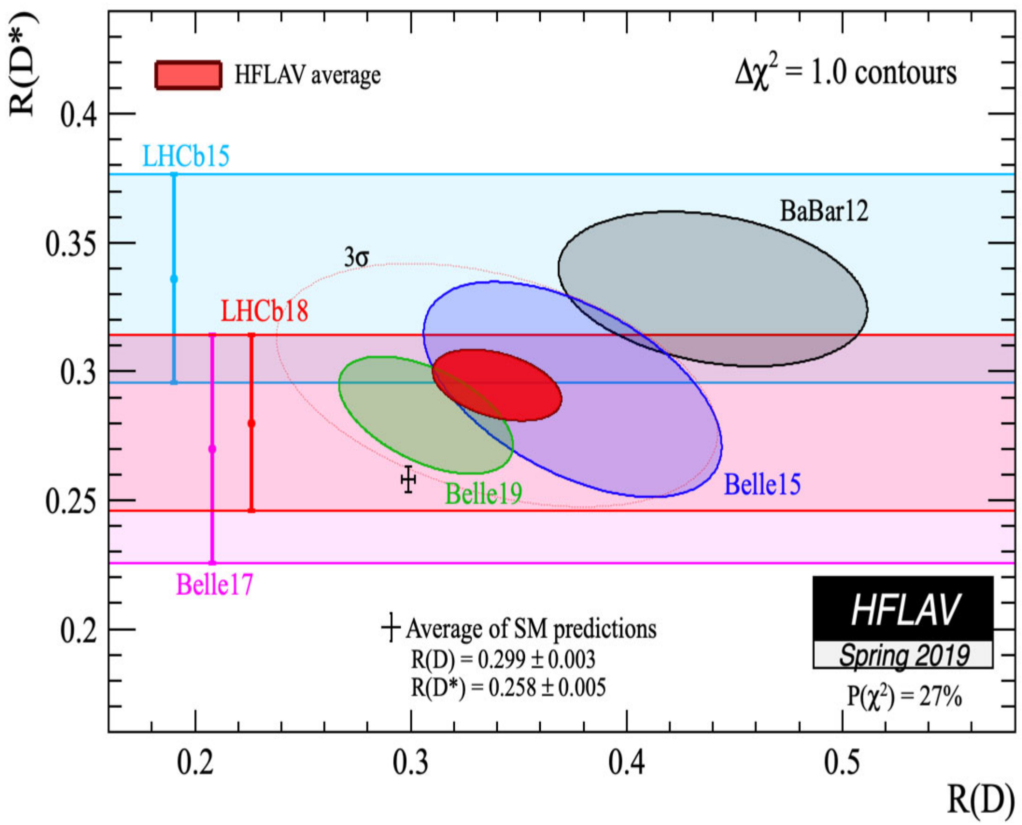
Compare the final state with a τ to the one with e or μ

Check the ratio of branching fractions $R(D^*) = Br(B \to D^*\tau\nu) / Br(B \to D^*l\nu)$

SM: $R(D^*) = 0.258 \pm 0.005$ vs. Experiment: $R(D^*) = 0.295 \pm 0.011 \pm 0.087$

(combined value of measurements of BaBar, Belle and LHCb collaborations)

Anomalies in $B \to D(*) \tau \nu$ decays



Measurements of R(D) and R(D*) compared to the SM predictions

Measurements of BaBar, Belle and LHCb collaborations

Similarly, for a D meson in the final state $R(D) = Br(B \to D\tau\nu) / Br(B \to Dl\nu)$

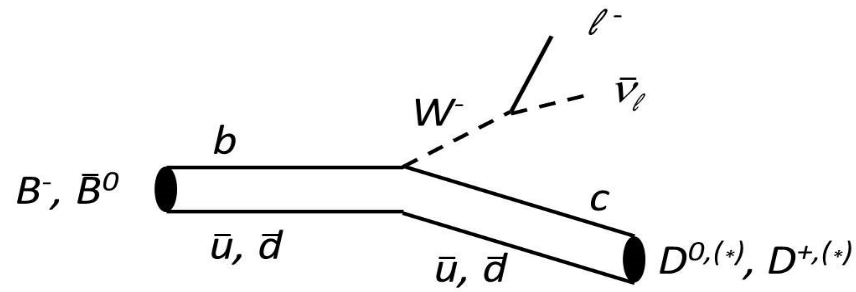
SM: $R(D) = 0.299 \pm 0.003$ vs. Experiment: $R(D) = 0.340 \pm 0.027 \pm 0.013$

Need more data!

If not a statistical fluctuation, what are possible interpretations?

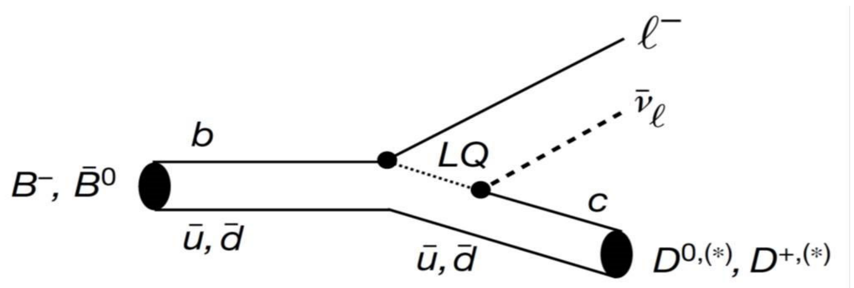
Diagrams for the $B \to D(*)\tau\nu$ transition:

mediated by the charged SM weak interaction



In addition:

a non-SM decay process involving leptoquarks



Other possibilities: an additional charged Higgs boson, and others

Need more data for any further conclusions! → the ball is on the experimental side.