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# Requirements on detectors: example 1

## B factory

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# Contents

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

## A little bit of history...

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**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**

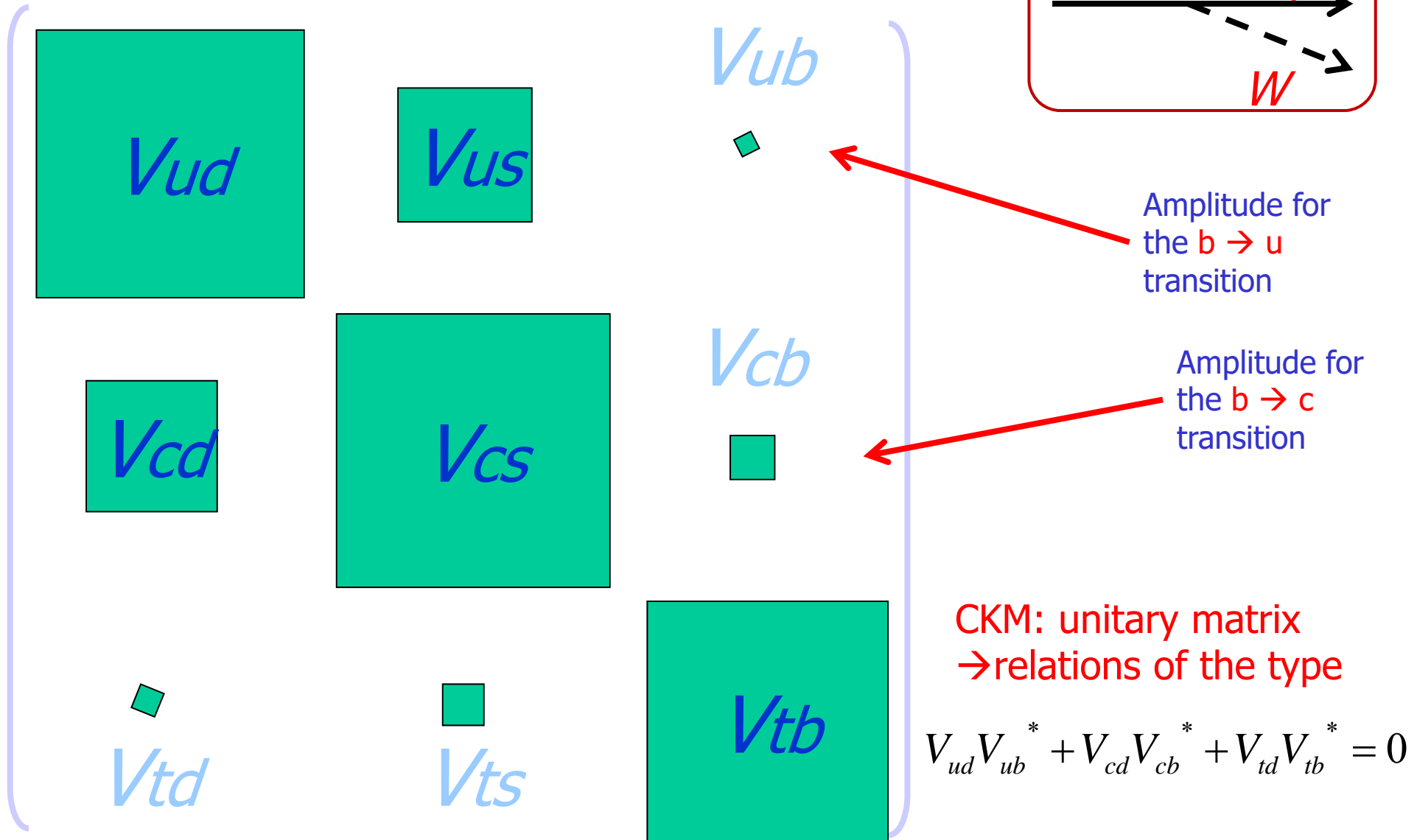
Their theory was formulated at a time when three quarks were known – and they requested the existence of three more!

The last missing quark was found in 1994.

... and in 2001 two experiments – Belle and BaBar at two powerful 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!



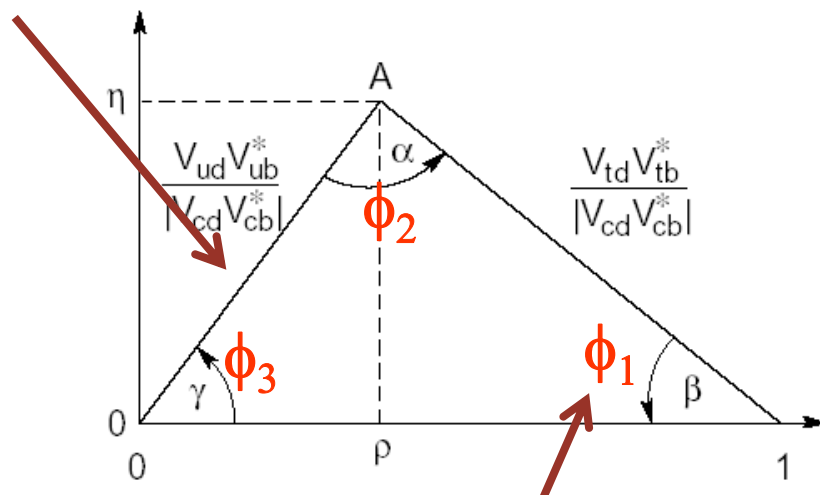
# CKM matrix: determines charged weak interaction of quarks

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

$A, \rho$  and  $\eta$ : 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  $b \rightarrow u$  transitions



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

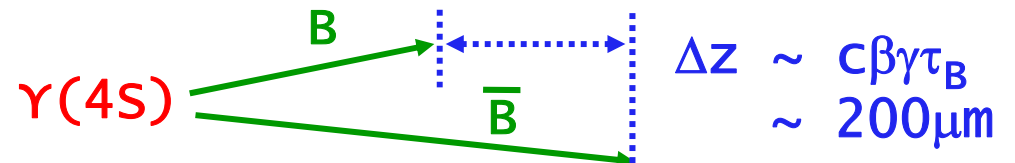
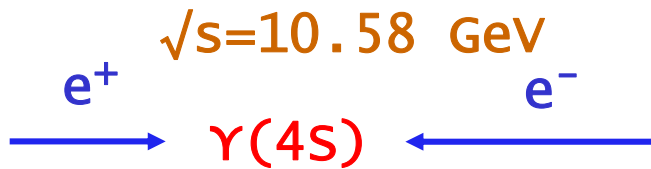
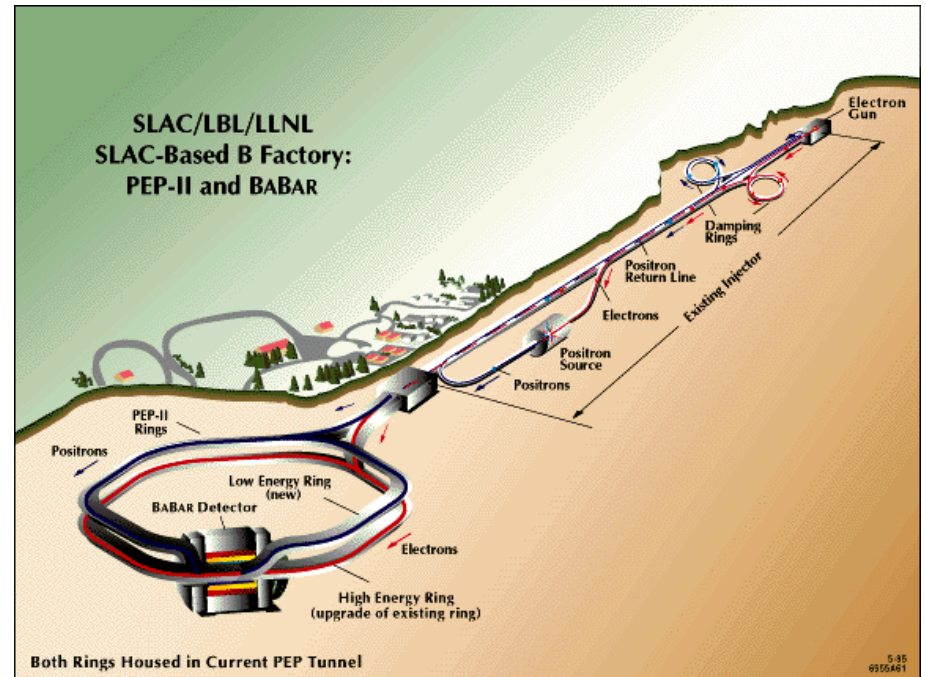
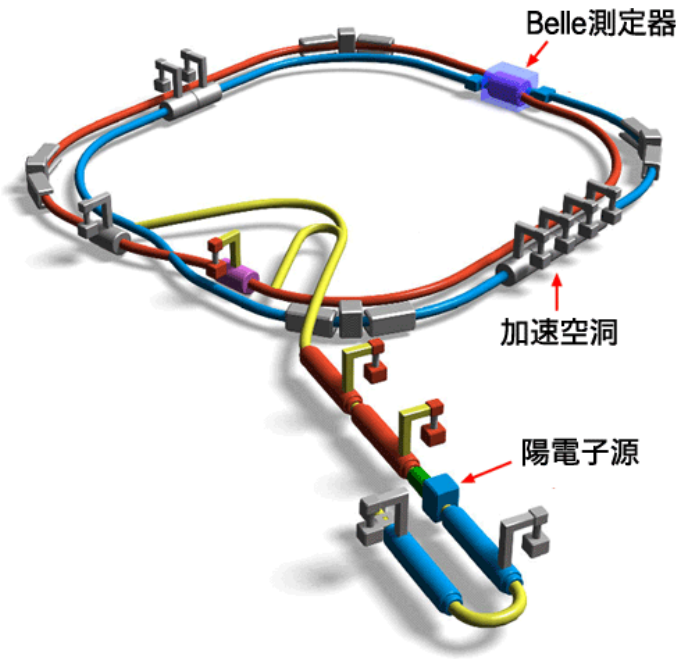
Unitarity condition:

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



Goal: measure sides and angles in several different ways, check consistency  $\rightarrow$

# Asymmetric B factories



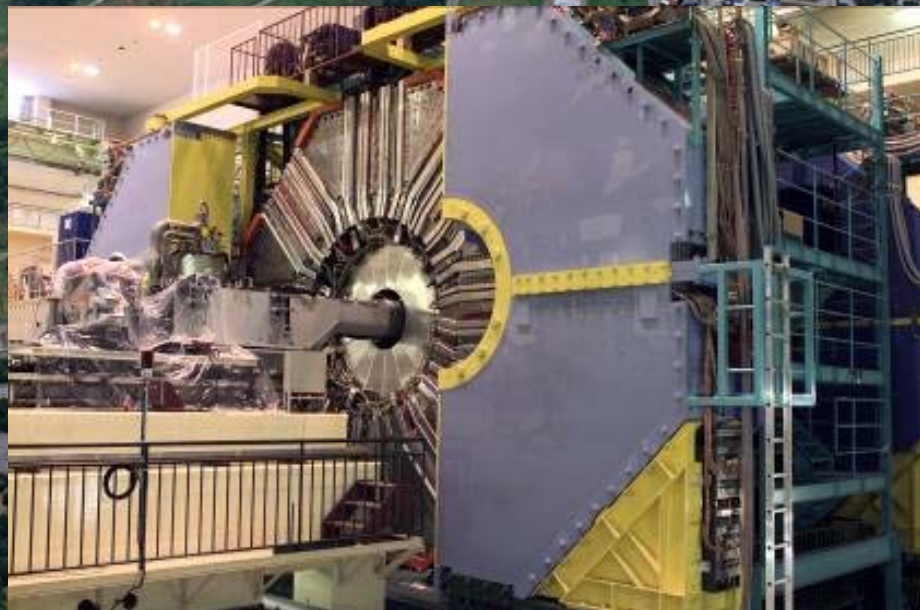
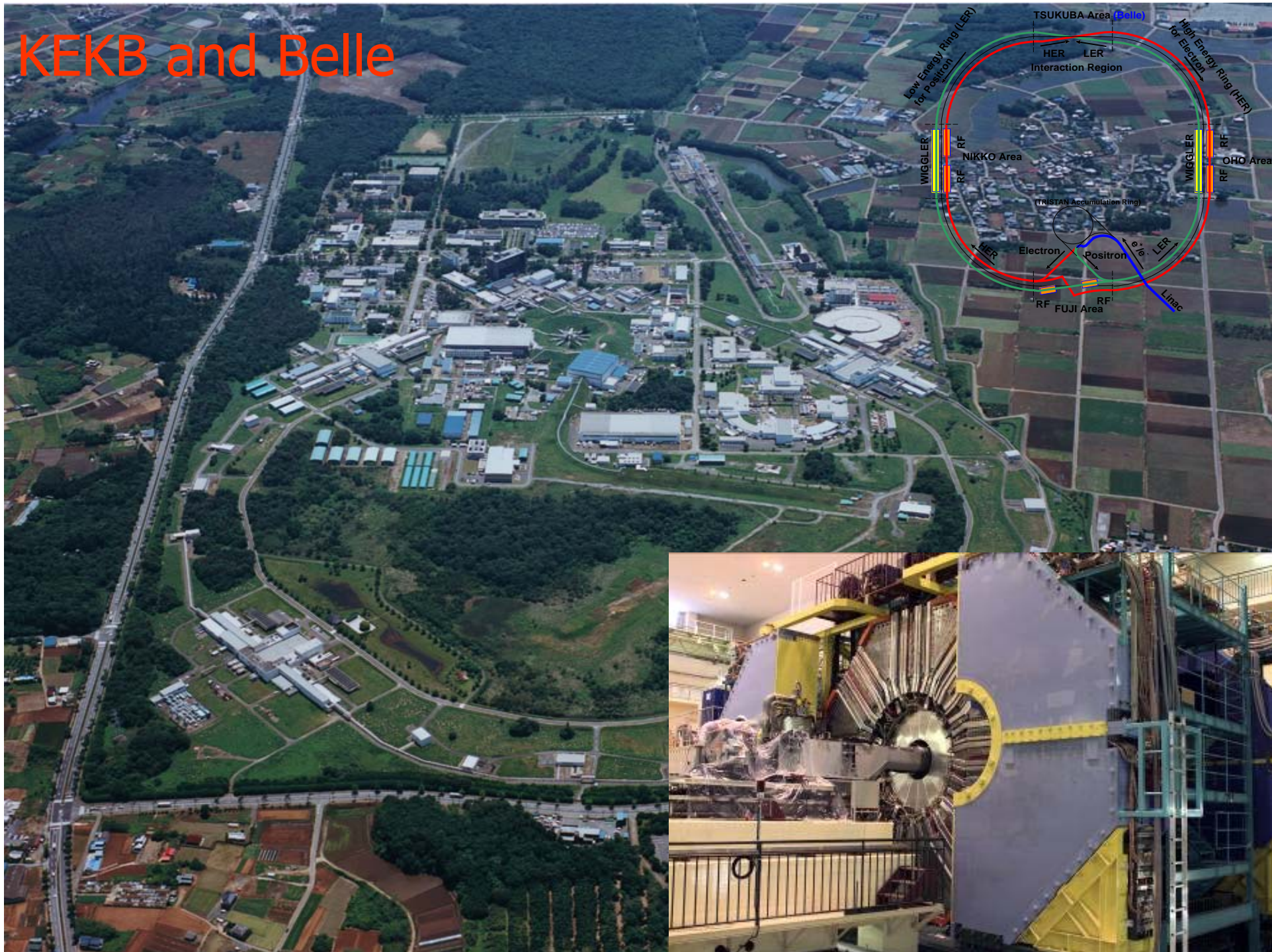
**BaBar**  $p(e^-) = 9 \text{ GeV}$   $p(e^+) = 3.1 \text{ GeV}$

$\beta\gamma = 0.56$

**Belle**  $p(e^-) = 8 \text{ GeV}$   $p(e^+) = 3.5 \text{ GeV}$

$\beta\gamma = 0.42$

# KEKB and Belle



# How to design the experimental apparatus ('spectrometer')

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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

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

$$a|B^0\rangle + b|\bar{B}^0\rangle$$

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

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

M and  $\Gamma$  are 2x2 Hermitian matrices. CPT invariance  $\rightarrow H_{11}=H_{22}$

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

diagonalize, solve  $\rightarrow$

# Time evolution of B's

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

$$\begin{aligned} |B_{phys}^0(t)\rangle &= g_+(t)|B^0\rangle + (q/p)g_-(t)|\bar{B}^0\rangle \\ |\bar{B}_{phys}^0(t)\rangle &= (p/q)g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle \end{aligned}$$

with

$$\begin{aligned} g_+(t) &= e^{-iMt} e^{-\Gamma t/2} \cos(\Delta mt / 2) \\ g_-(t) &= e^{-iMt} e^{-\Gamma t/2} i \sin(\Delta mt / 2) \end{aligned}$$

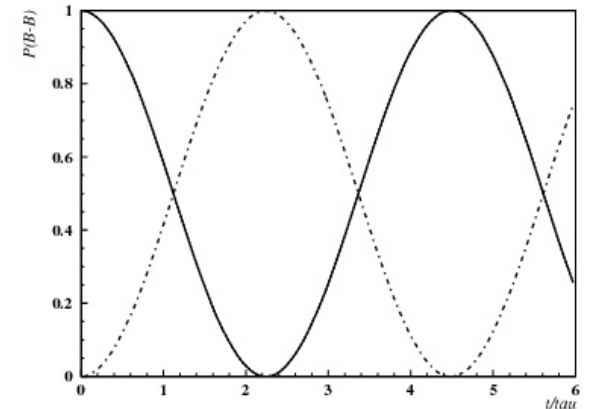
$$M = (M_H + M_L)/2$$

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

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

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



→Probability that a B turns into its anti-particle

→beat in classical mechanics

$$\left| \langle \bar{B}^0 | B_{phys}^0(t) \rangle \right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta mt / 2)$$

→Probability that a B remains a B

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

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

# CP violation: decay rate difference

Decay rate asymmetry:

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

Decay rate:  $P(B^0 \rightarrow f_{CP}, t) \propto \left| \langle f_{CP} | H | B_{phys}^0(t) \rangle \right|^2$

Decay amplitudes vs time:

$$\langle f_{CP} | H | B_{phys}^0(t) \rangle = g_+(t) \langle f_{CP} | H | B^0 \rangle + (q/p) g_-(t) \langle f_{CP} | H | \bar{B}^0 \rangle$$

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

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

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

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

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

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

$$= \frac{(1 - |\lambda_{f_{CP}}|^2) \cos(\Delta mt) - 2 \operatorname{Im}(\lambda_{f_{CP}}) \sin(\Delta mt)}{1 + |\lambda_{f_{CP}}|^2}$$

$$= C \cos(\Delta mt) + S \sin(\Delta mt)$$

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

Non-zero effect if  $\operatorname{Im}(\lambda) \neq 0$ , even if  
 $|\lambda| = 1$

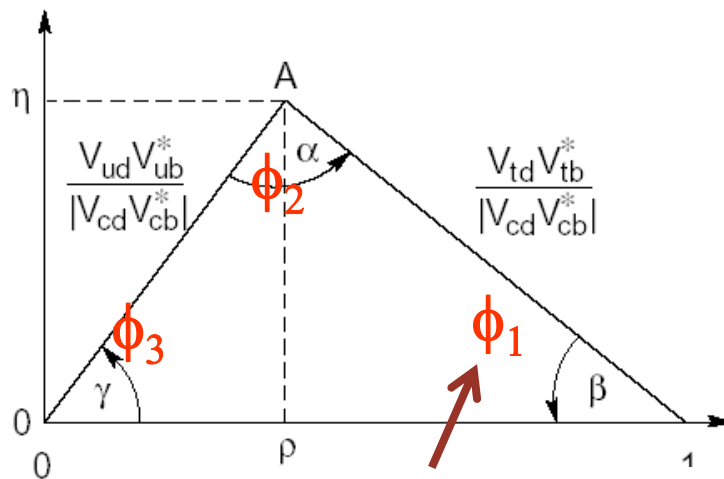
If  $|\lambda| = 1 \rightarrow$

$$a_{f_{CP}} = -\operatorname{Im}(\lambda) \sin(\Delta mt)$$

# CP violation: related to the angles of the unitarity triangle

$$a_{f_{CP}} = -\text{Im}(\lambda) \sin(\Delta mt)$$

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



7-92

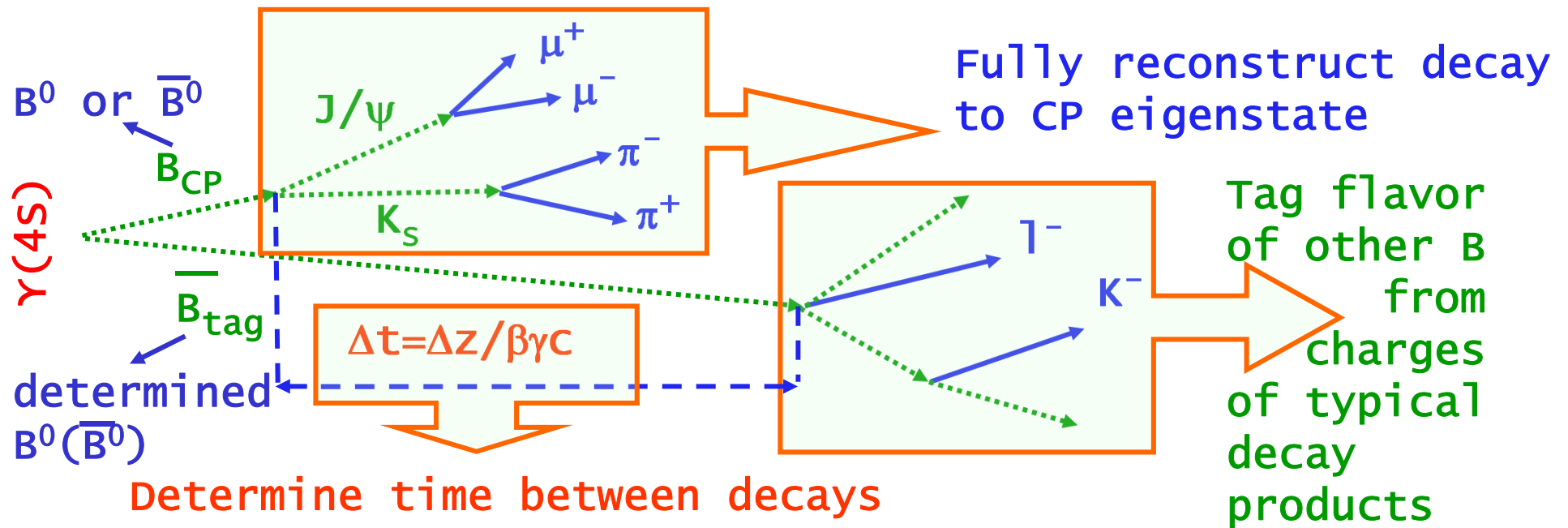
determines CP violation in  $B \rightarrow J/\psi K_S$  decays

Unitarity condition:

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



# Typical measurement

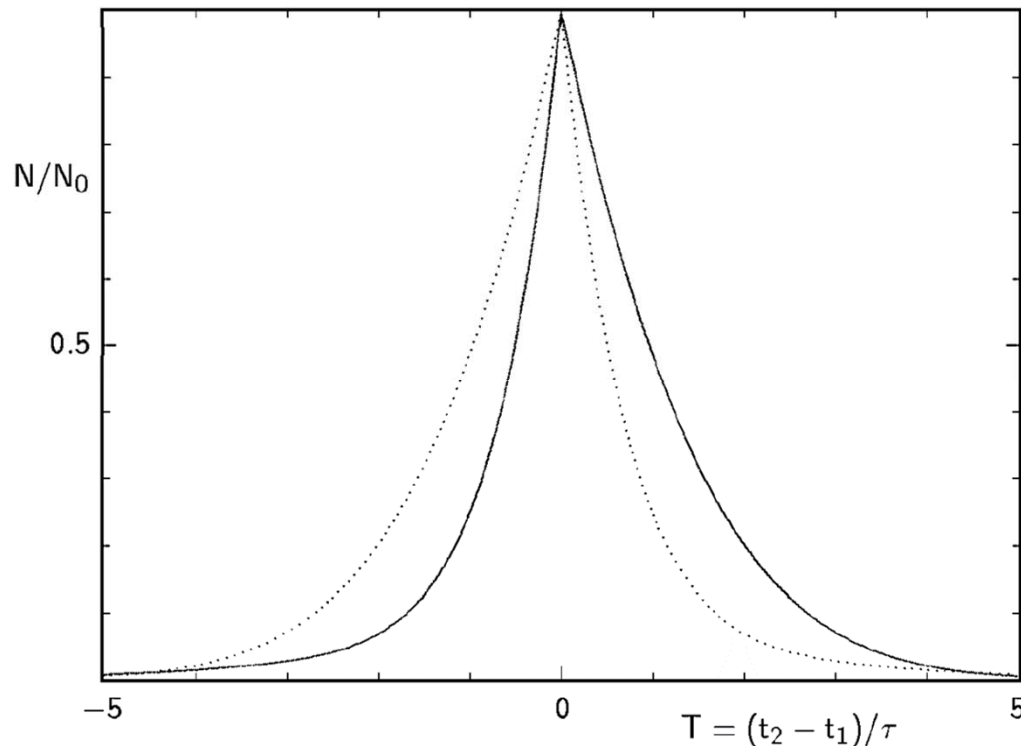


# Experimental considerations

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

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

↑ We are measuring this parameter



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

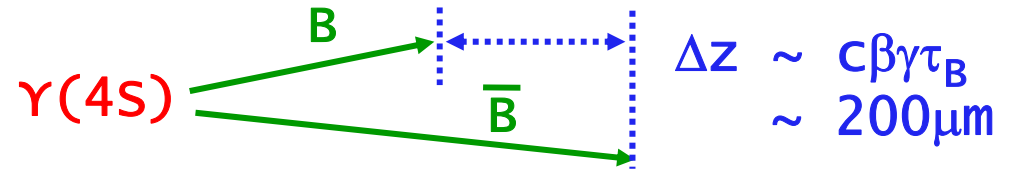
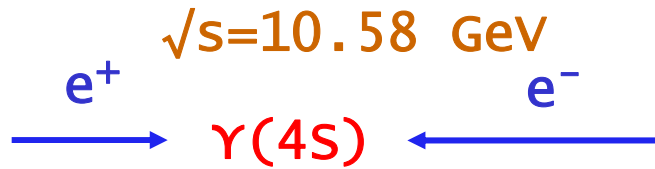
**Integrals are equal, time information mandatory!**

T = time difference of the two decays



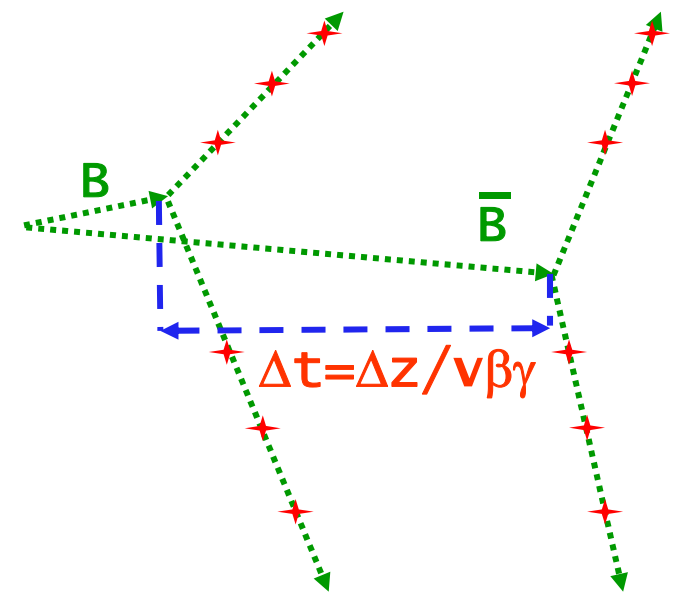
Asymmetric B factories: two beams have different energies so that c.m.s. is moving with velocity  $\beta$

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



BaBar	$p(e^-) = 9 \text{ GeV}$	$p(e^+) = 3.1 \text{ GeV}$
Belle	$p(e^-) = 8 \text{ GeV}$	$p(e^+) = 3.5 \text{ GeV}$

$\beta\gamma = 0.56$   
 $\beta\gamma = 0.42$

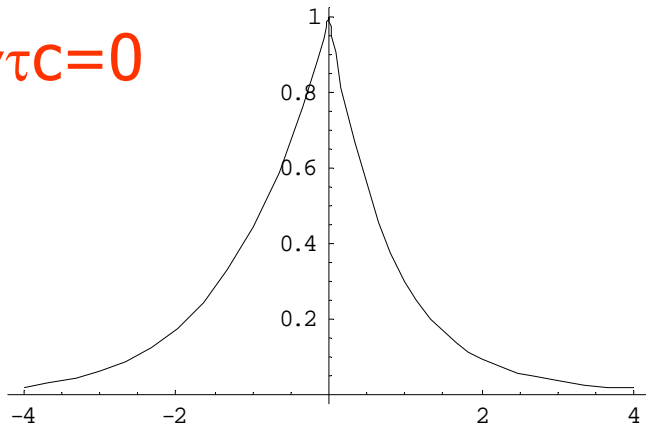


Decay point of a B (a crossing of extrapolated particle tracks) is measured with a finite precision  $\sigma(z)$

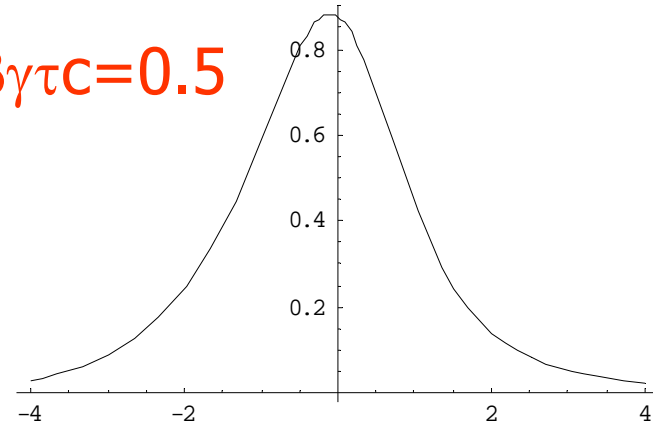
# Experimental considerations

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

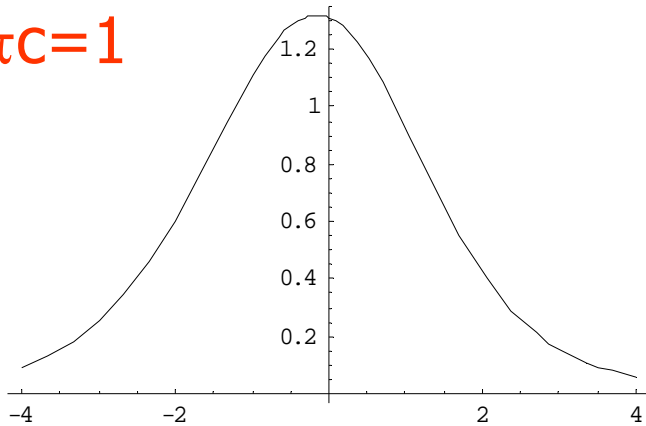
$$\sigma(z)/\beta\gamma\tau c = 0$$



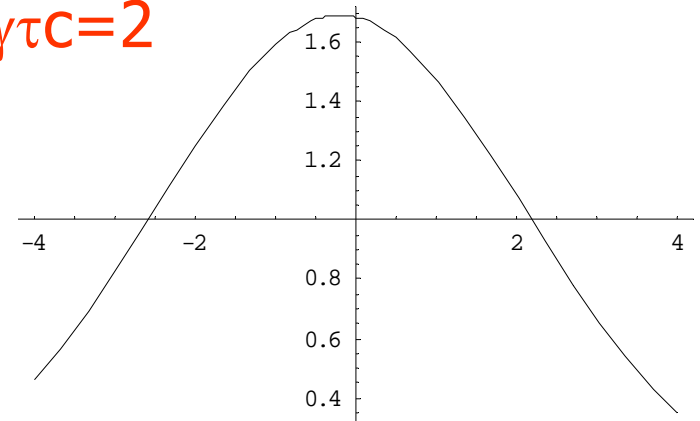
$$\sigma(z)/\beta\gamma\tau c = 0.5$$



$$\sigma(z)/\beta\gamma\tau c = 1$$



$$\sigma(z)/\beta\gamma\tau c = 2$$

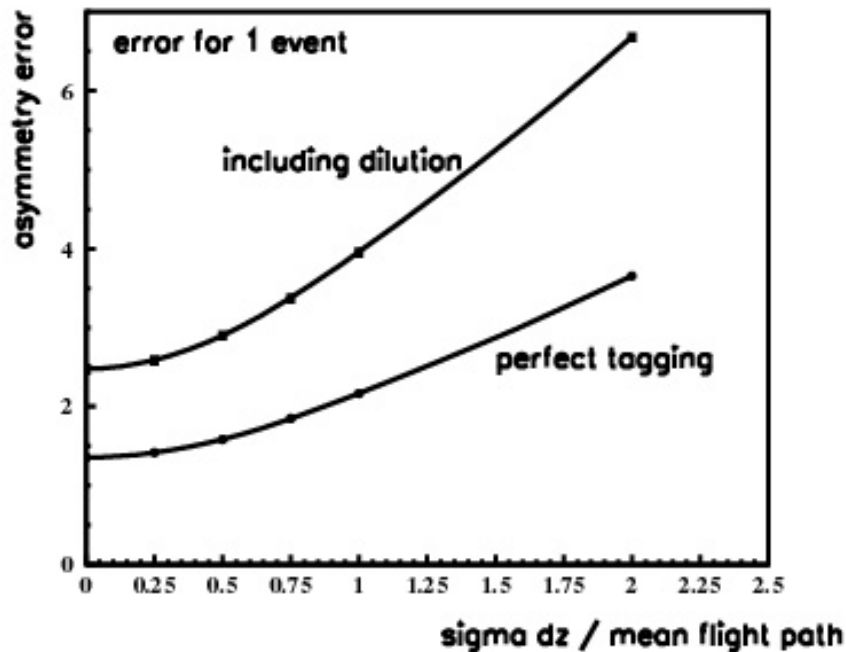


Measured distribution: convolution of  $P(t)$  and the resolution function (e.g., a Gaussian with  $\sigma = \sigma(z)/\beta\gamma\tau c$ )

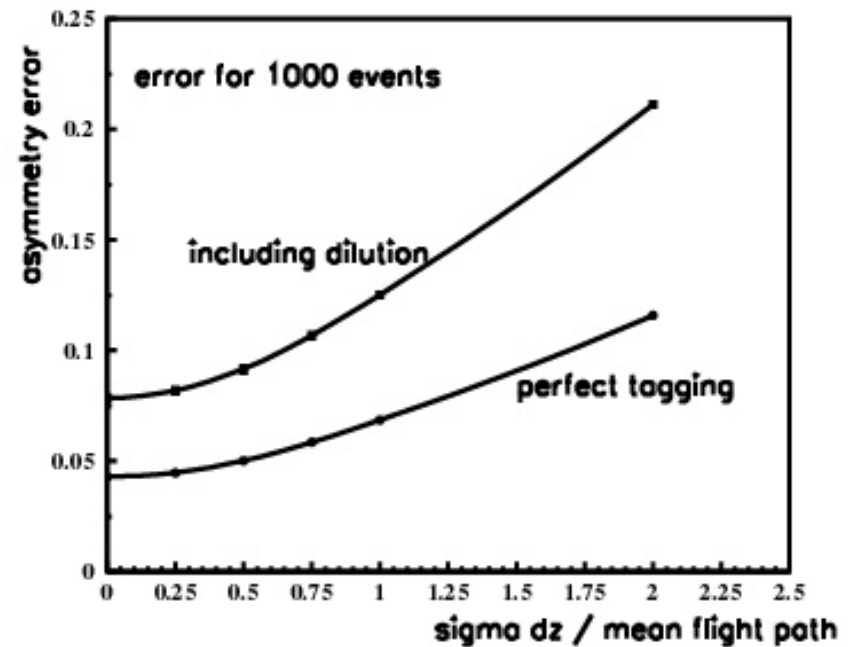
# Experimental considerations

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

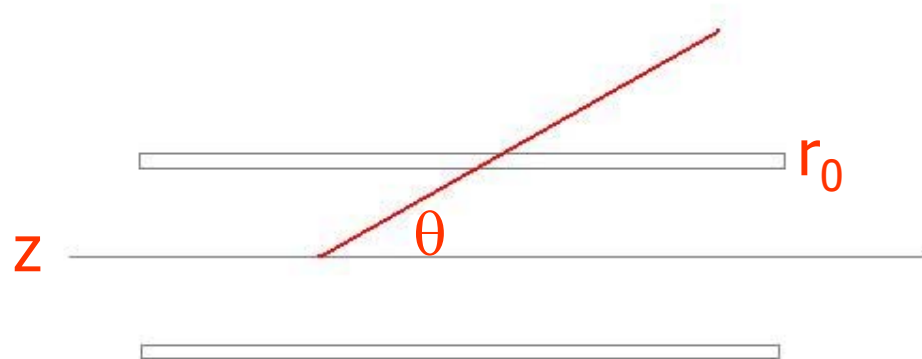
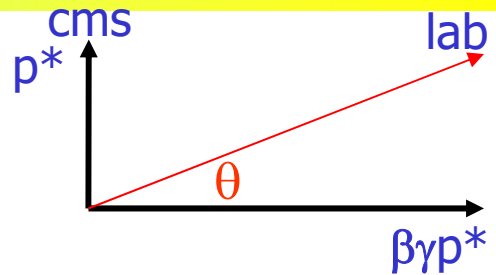
Choice of boost  $\beta\gamma$ :

Vertex resolution vs. path length

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

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



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

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

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

# Experimental considerations

Choice of boost  $\beta\gamma$ :

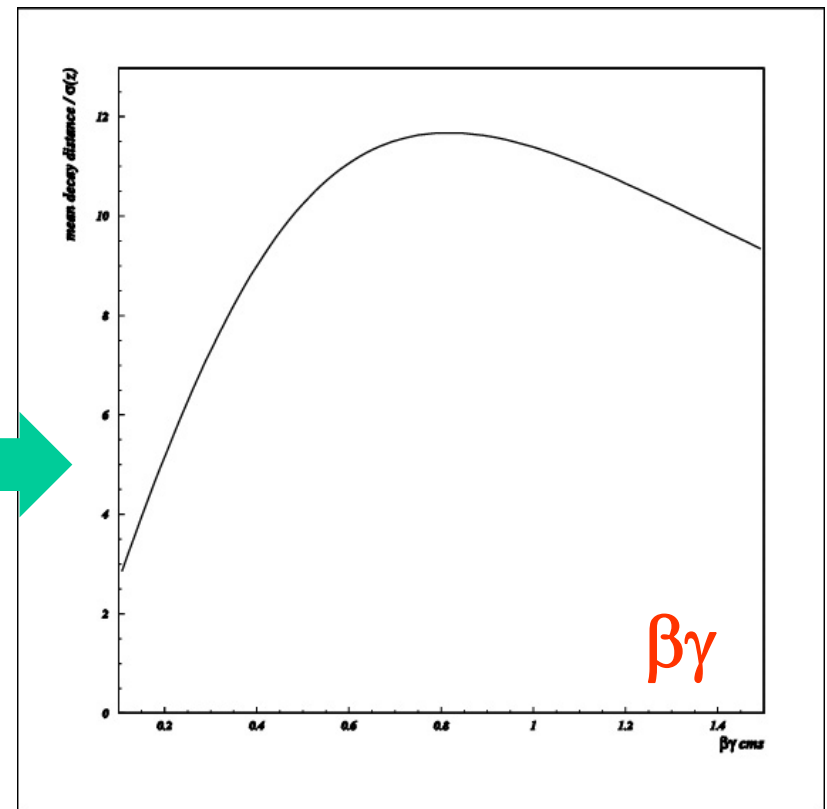
Maximize the ratio between the average flight path  $\beta\gamma\tau c$  and the vertex resolution  $\sigma(z)$

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

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

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

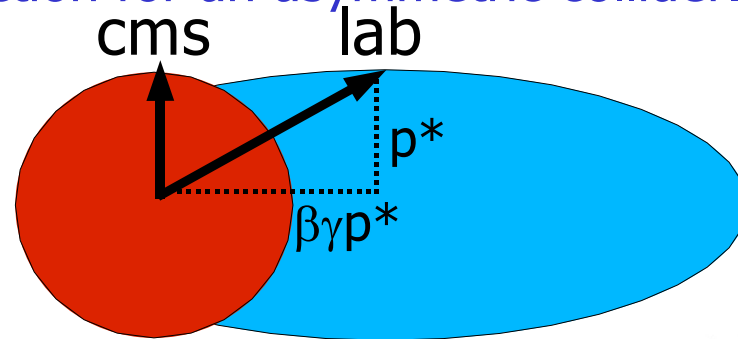
$\beta\gamma\tau c/\sigma(z)$



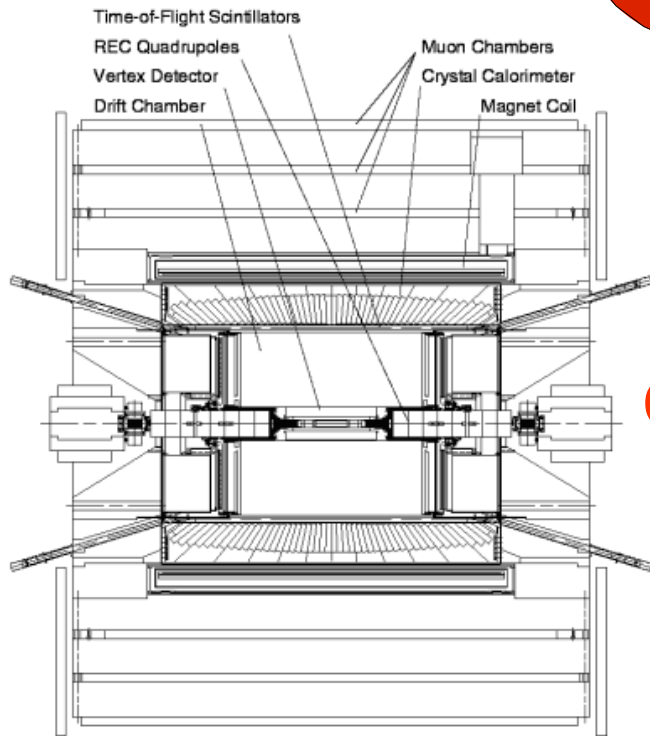
Not the whole story....

# Experimental considerations

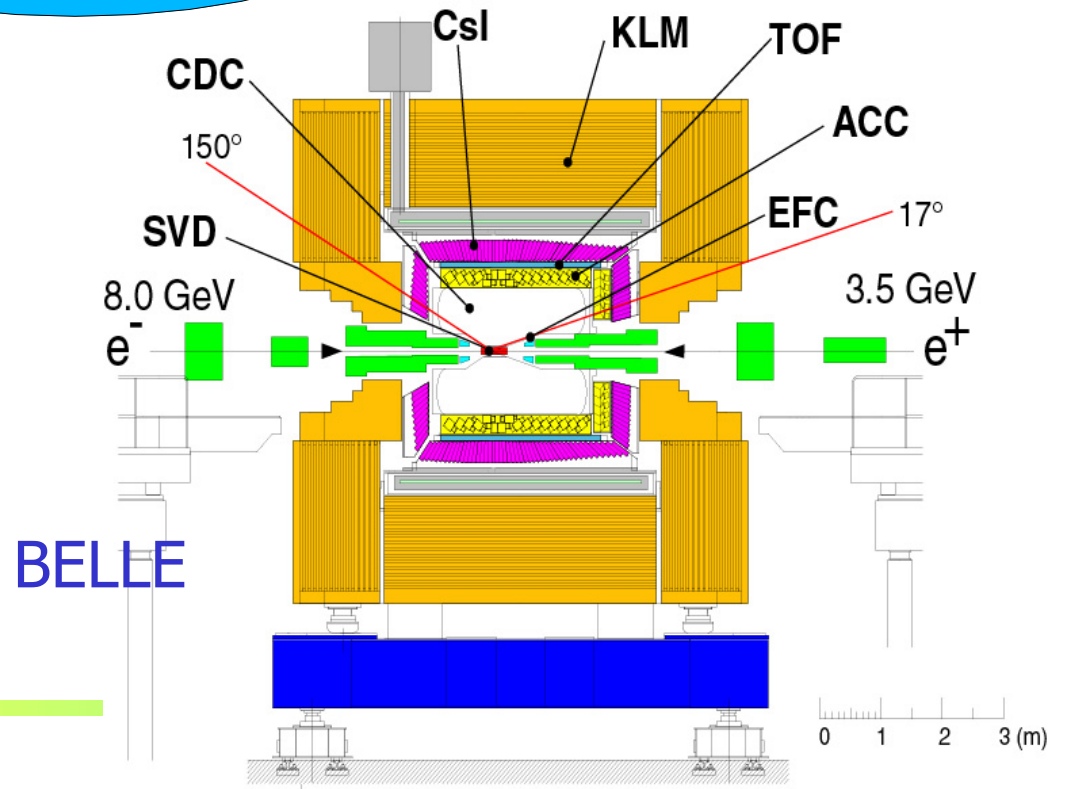
Detector form: symmetric for symmetric energy beams; extended in the boost direction for an asymmetric collider.



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



CLEO



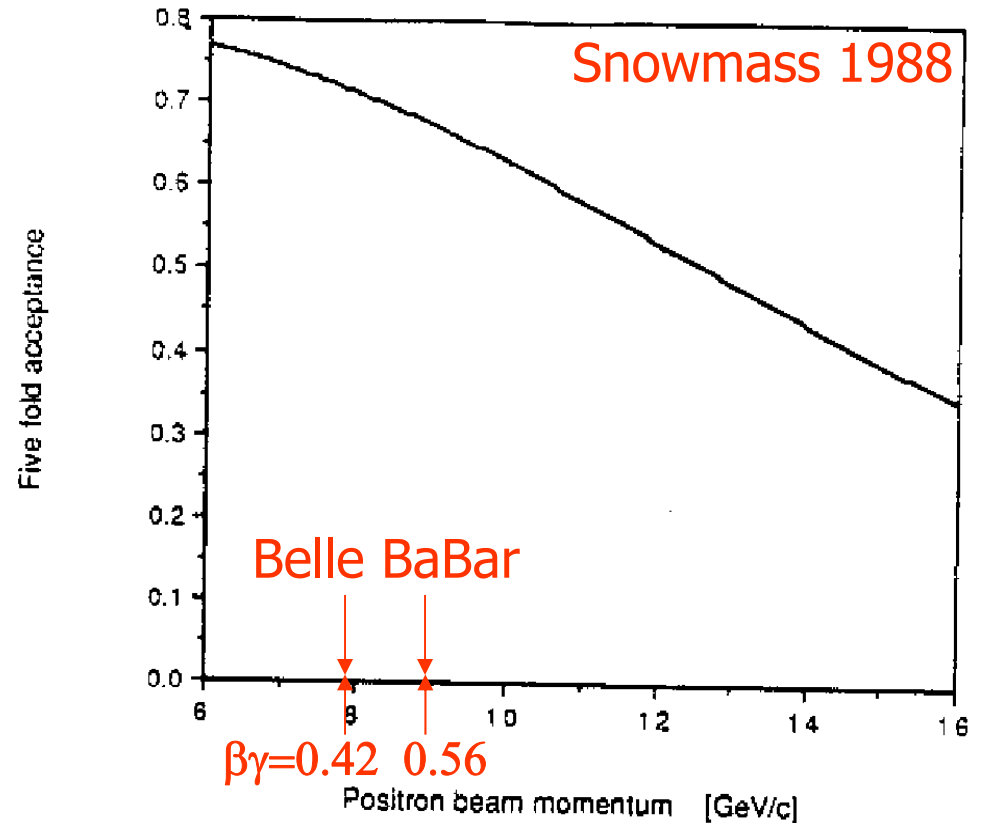
BELLE

# Experimental considerations

Which boost...

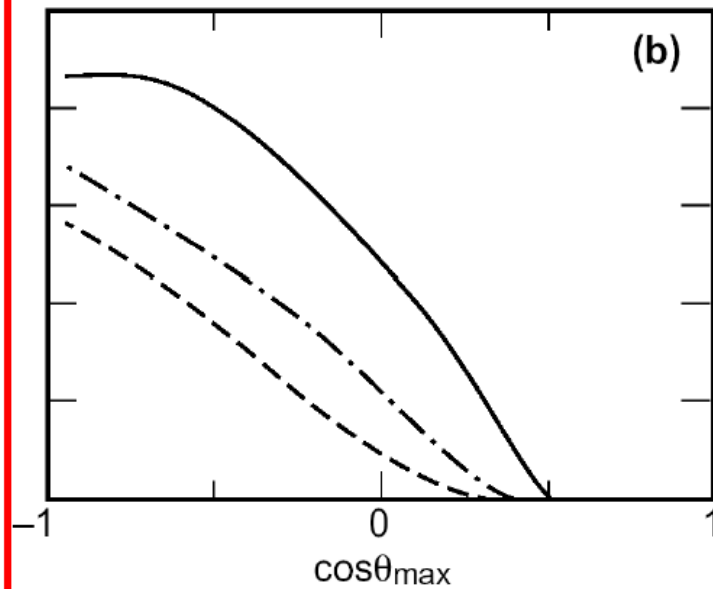
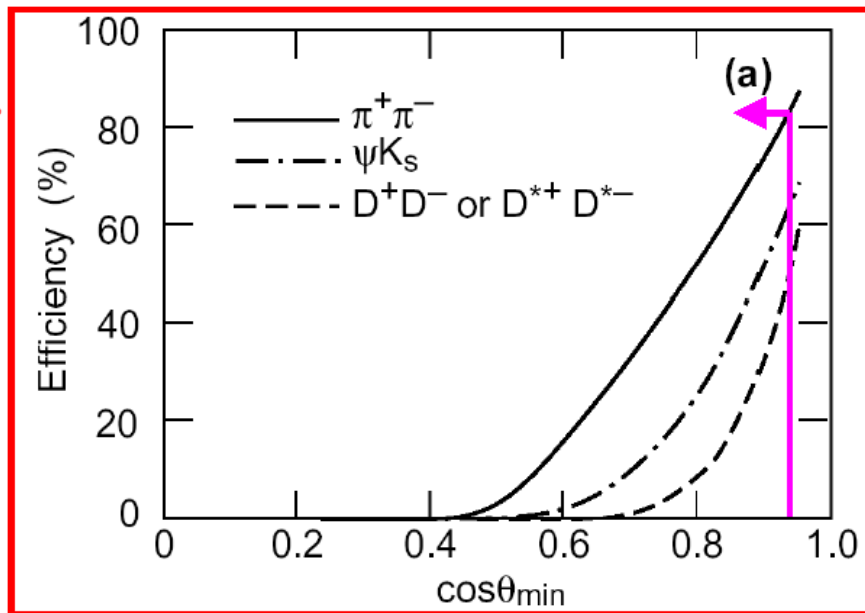
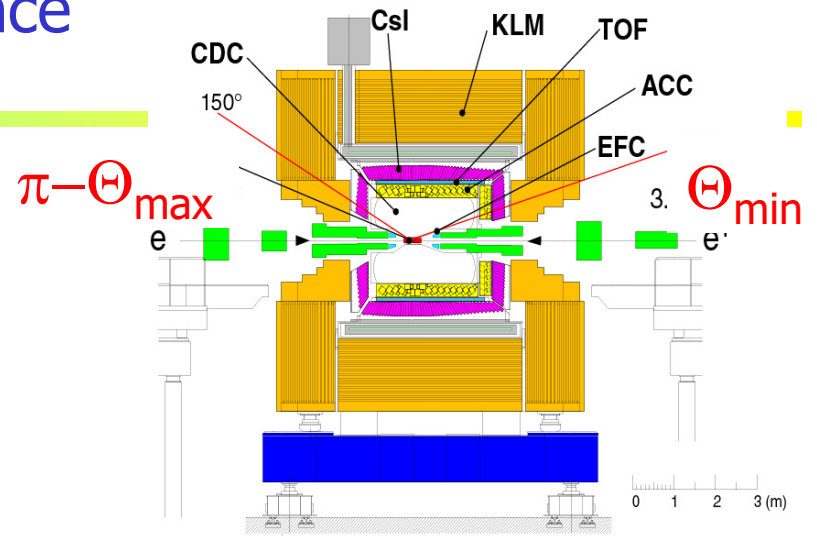
Arguments for a smaller boost:

- 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  $\Upsilon(4S)$ .

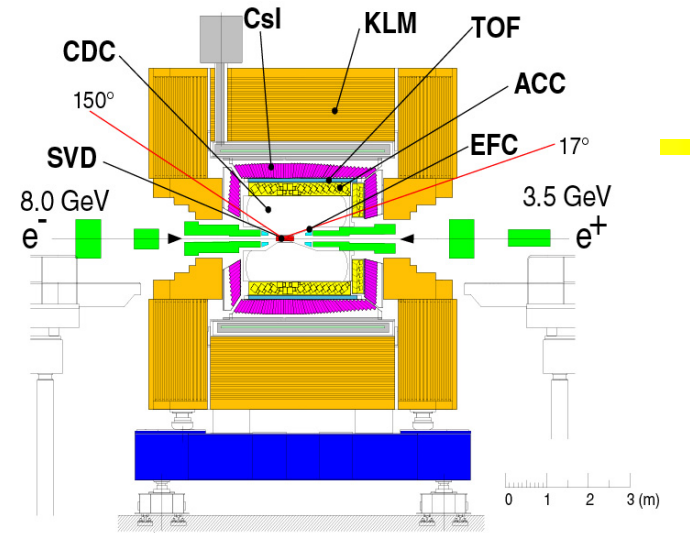
# Requirements: Geometric Acceptance



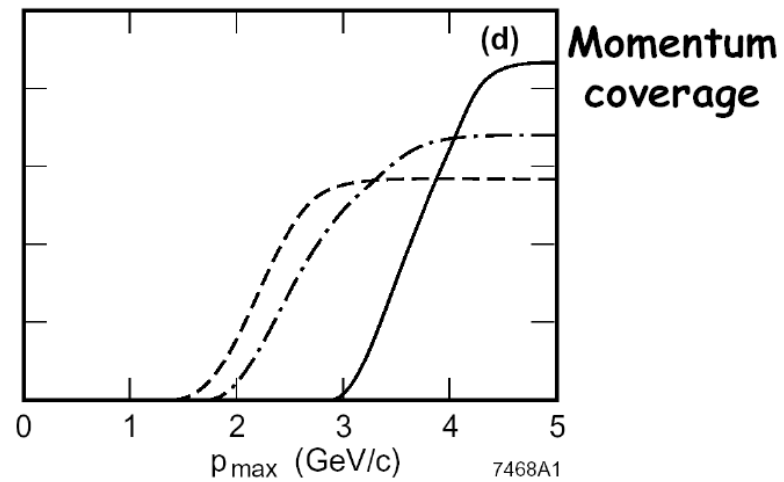
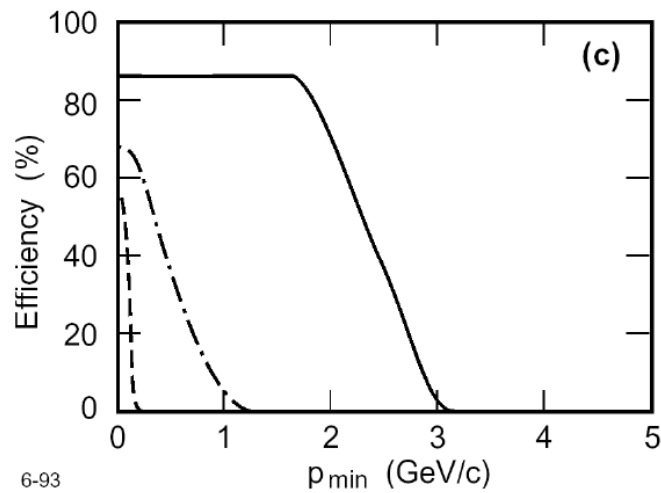
**Angular coverage**



# Requirements: momentum acceptance



- $\pi^+\pi^-$
- · -  $\psi K_S$
- - -  $D^+D^-$  or  $D^{*+}D^{*-}$



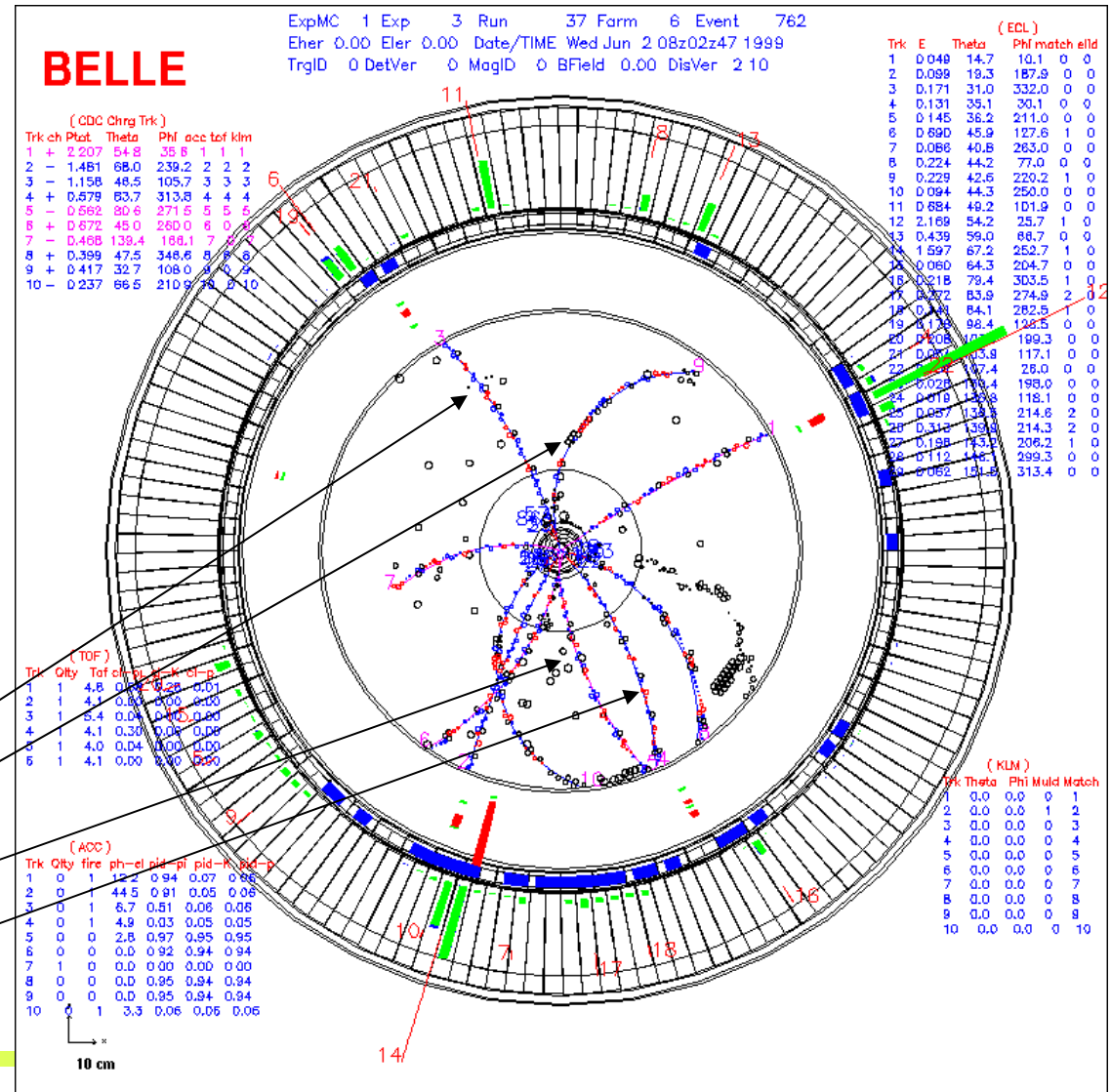
# How to understand what happened in a collision?

Illustration on an example:

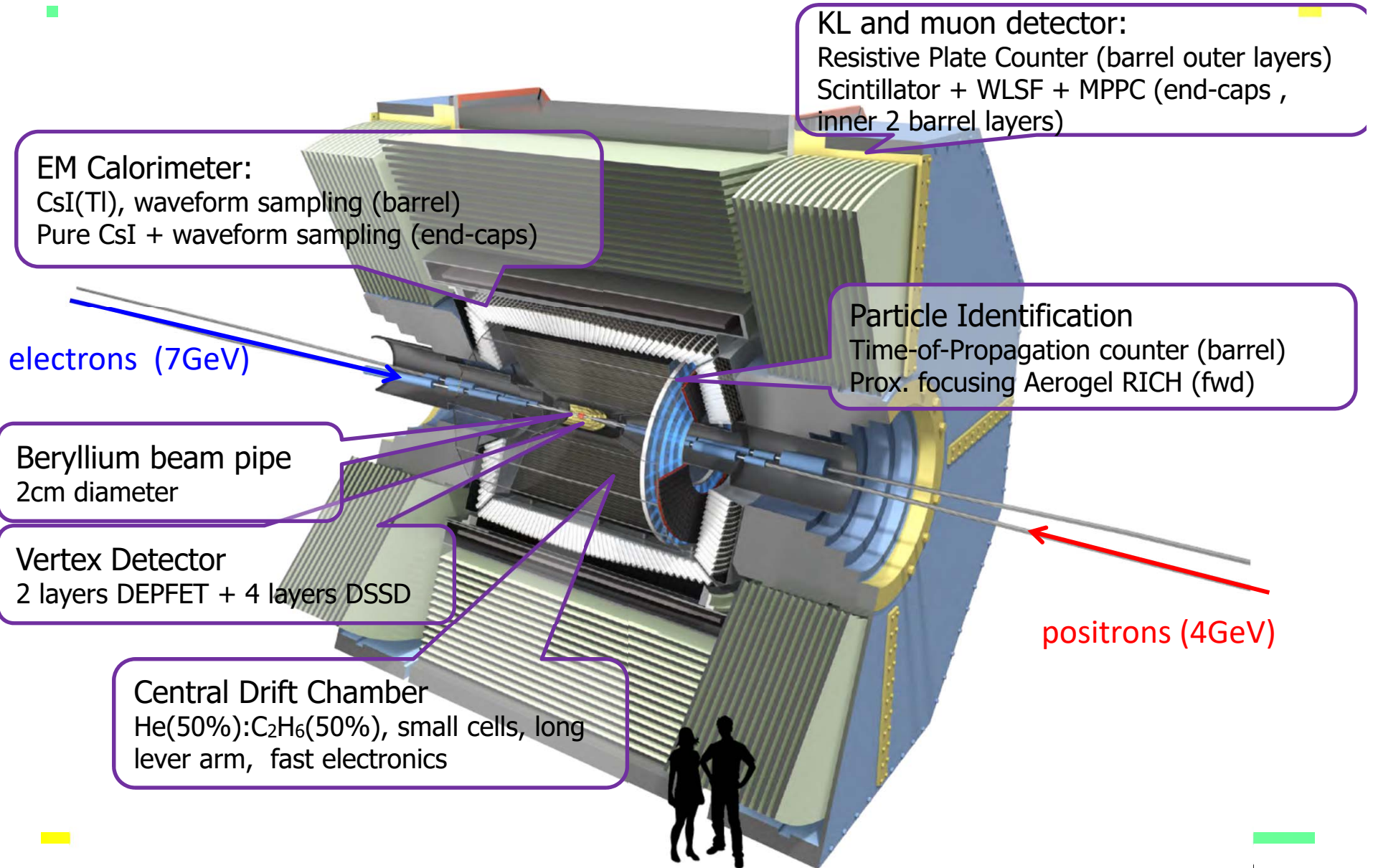
$$B^0 \rightarrow K_S^0 J/\psi$$

$$K_S^0 \rightarrow \pi^- \pi^+$$

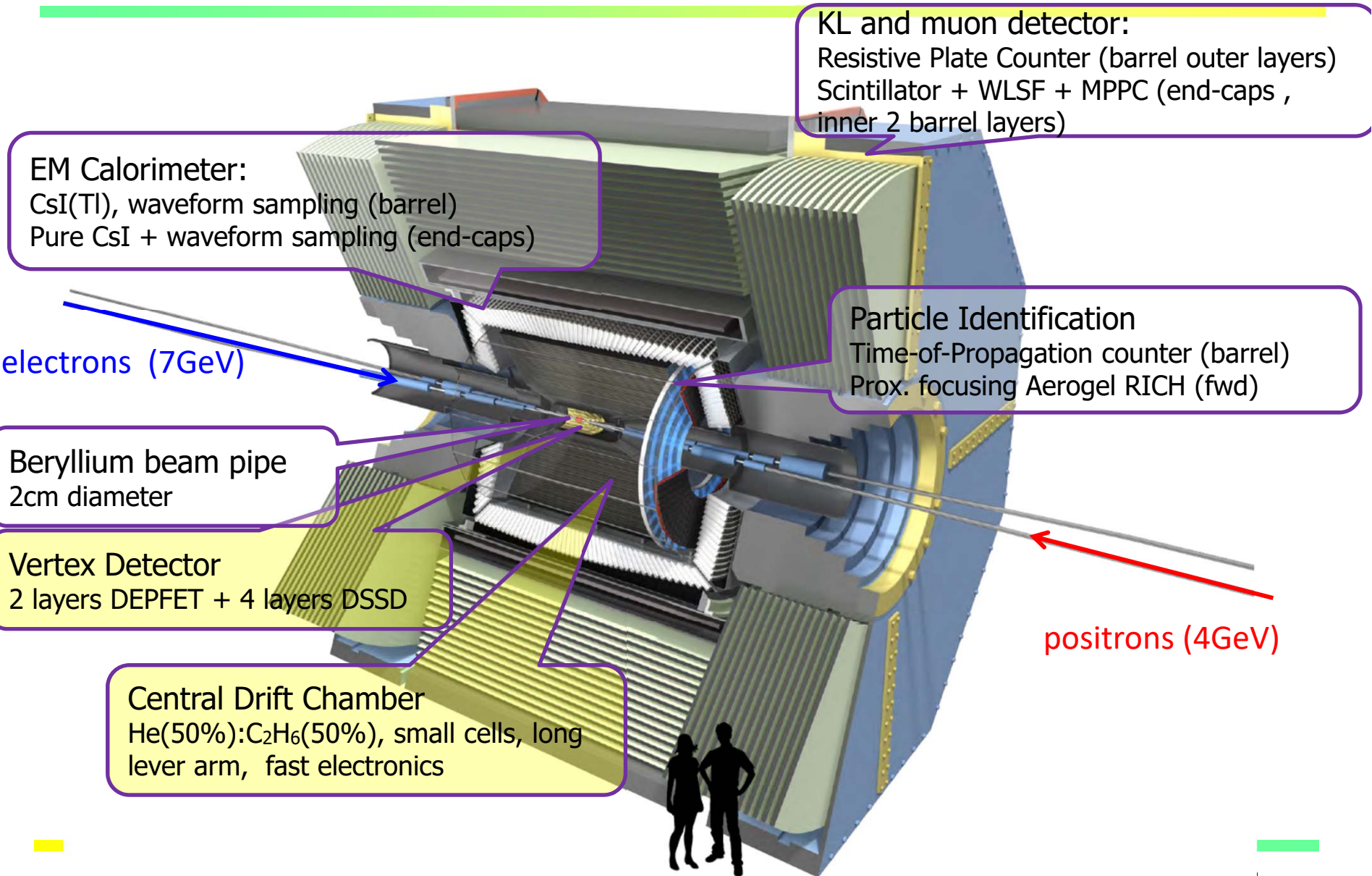
$$J/\psi \rightarrow \mu^- \mu^+$$



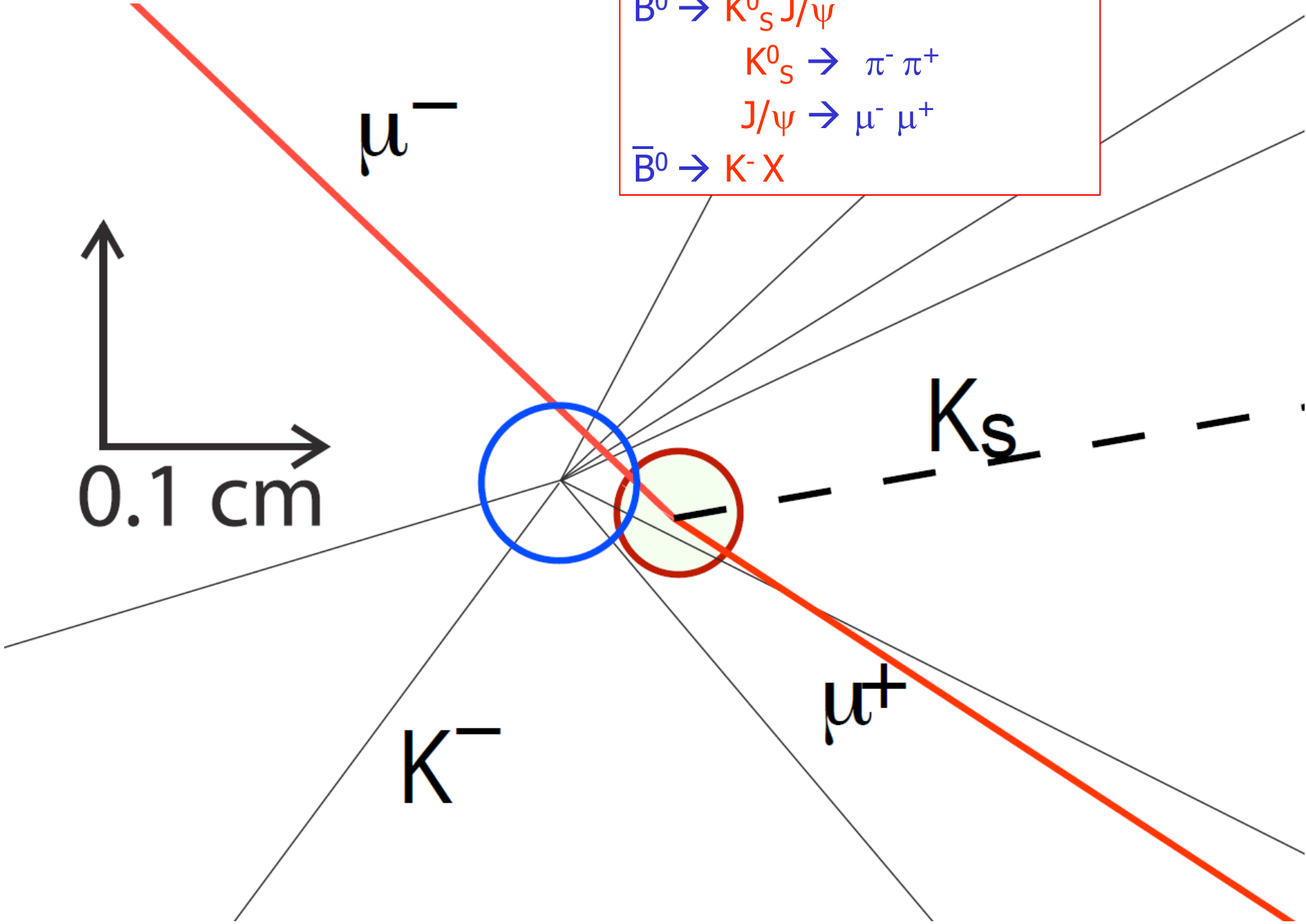
# Belle II Detector



# Tracking and vertex systems in Belle II

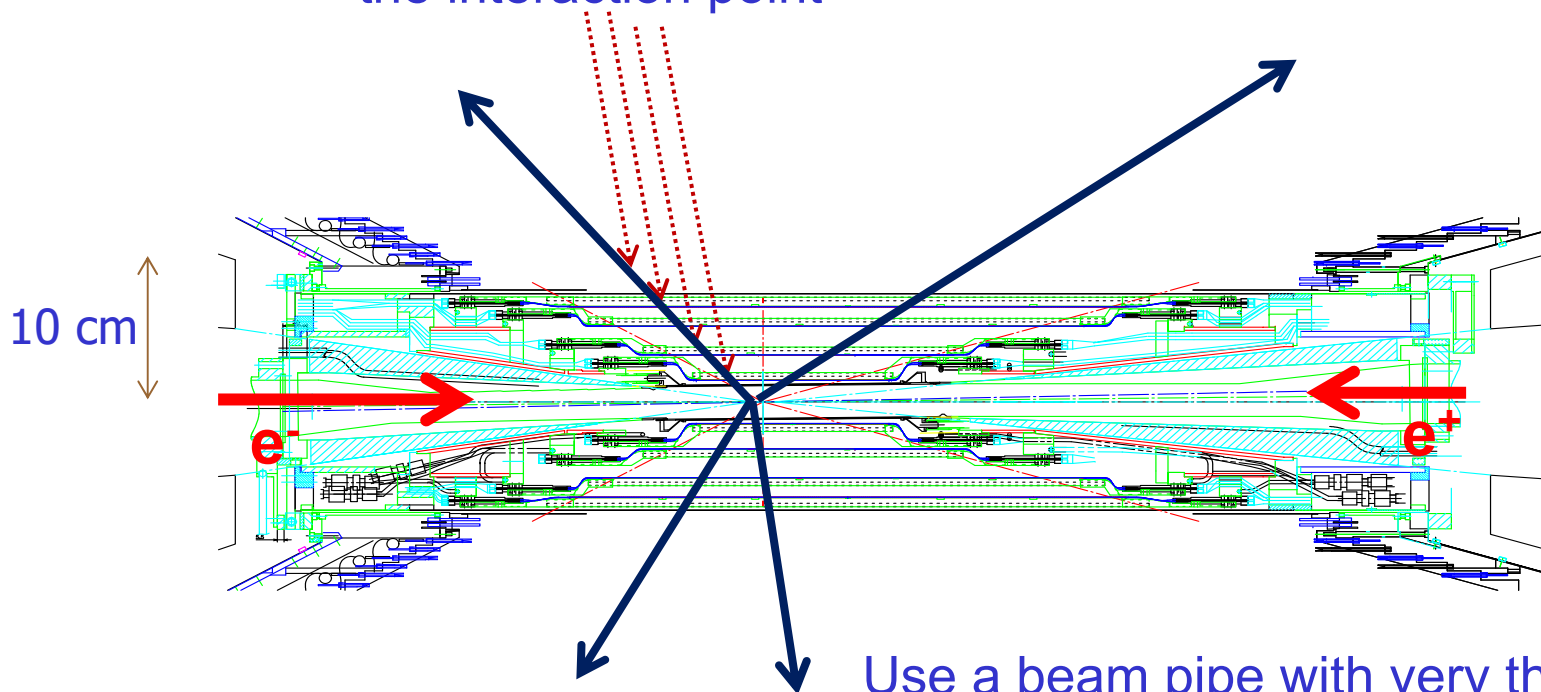


Vertexing, example:  
 $B^0 \rightarrow K_S^0 J/\psi$   
 $K_S^0 \rightarrow \pi^- \pi^+$   
 $J/\psi \rightarrow \mu^- \mu^+$   
 $\bar{B}^0 \rightarrow K^- X$



# 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

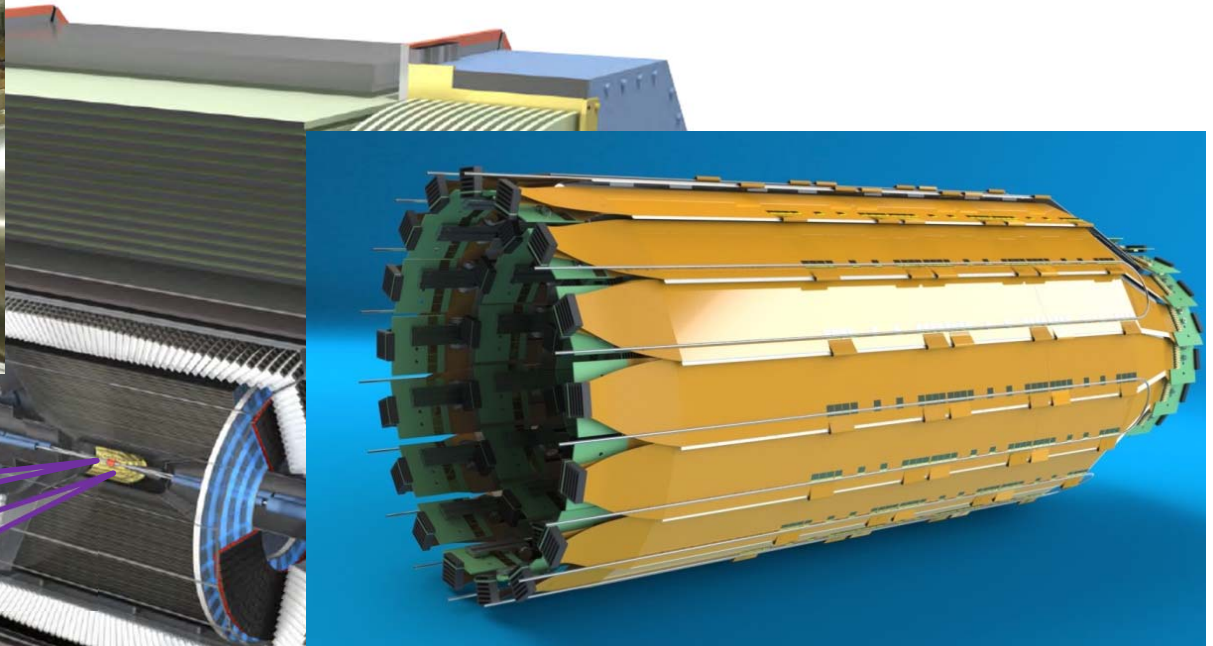
**Table 6.1** Abridged from [pdg.lbl.gov/AtomicNuclearProperties](http://pdg.lbl.gov/AtomicNuclearProperties) by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° 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 $\lambda_T$ {g cm <sup>-2</sup> }	Nucl.inter. length $\lambda_I$ {g cm <sup>-2</sup> }	Rad.len. $X_0$ {g cm <sup>-2</sup> }	$dE/dx _{\min}$ { MeV g <sup>-1</sup> cm <sup>2</sup> }	Density {g cm <sup>-3</sup> } ({gℓ <sup>-1</sup> })	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H <sub>2</sub>	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 <sub>2</sub>	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 <sub>2</sub>	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 <sub>2</sub>	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 <sub>2</sub>	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 <sub>2</sub>	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.	
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			
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 <sub>4</sub> )			0.62334	54.0	73.8	46.47	(2.417)	(0.667)	90.68	111.7	[444.]
Ethane (C <sub>2</sub> H <sub>6</sub> )			0.59861	55.0	75.9	45.66	(2.304)	(1.263)	90.36	184.5	
Propane (C <sub>3</sub> H <sub>8</sub> )			0.58962	55.3	76.7	45.37	(2.262)	0.493(1.868)	85.52	231.0	
Butane (C <sub>4</sub> H <sub>10</sub> )			0.59497	55.5	77.1	45.23	(2.278)	(2.489)	134.9	272.6	
Octane (C <sub>8</sub> H <sub>18</sub> )			0.57778	55.8	77.8	45.00	2.123	0.703	214.4	398.8	
Paraffin (CH <sub>3</sub> (CH <sub>2</sub> ) <sub>n</sub> ≈23CH <sub>3</sub> )			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 <sub>2</sub> CH <sub>2</sub> ] <sub>n</sub> )			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 <sub>6</sub> H <sub>5</sub> CHCH <sub>2</sub> ] <sub>n</sub> )			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 fluoride (BaF <sub>2</sub> )			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 <sub>2</sub> )			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 <sub>4</sub> )			0.41315	100.6	168.3	7.39	1.229	8.300	1403.		2.20
Silicon dioxide (SiO <sub>2</sub> , 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 <sub>2</sub> O)			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 <sub>2</sub> O, 0.97 SiO <sub>2</sub> )		

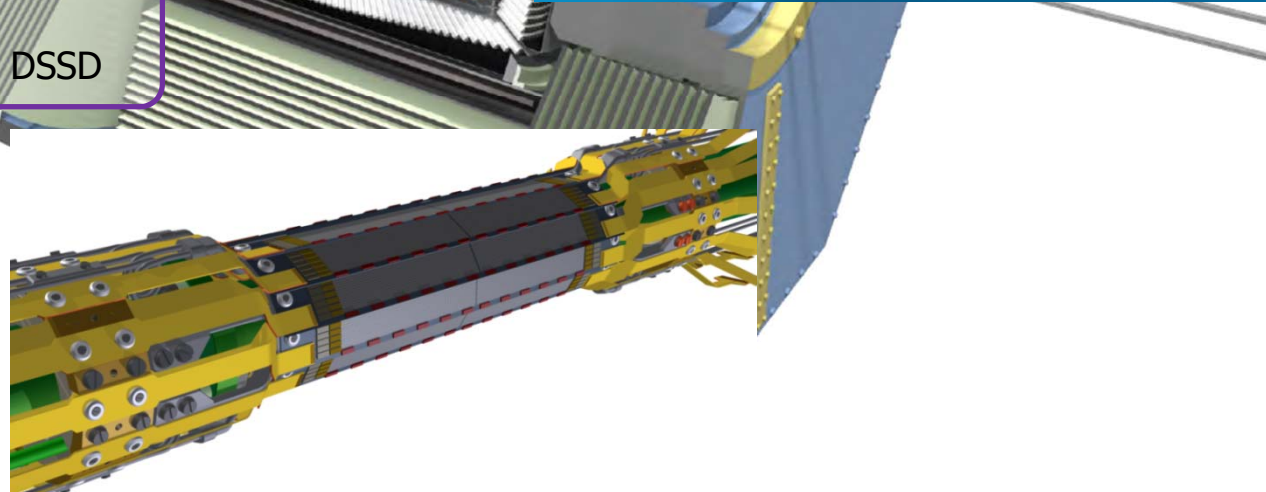


# Belle II Detector – vertex region

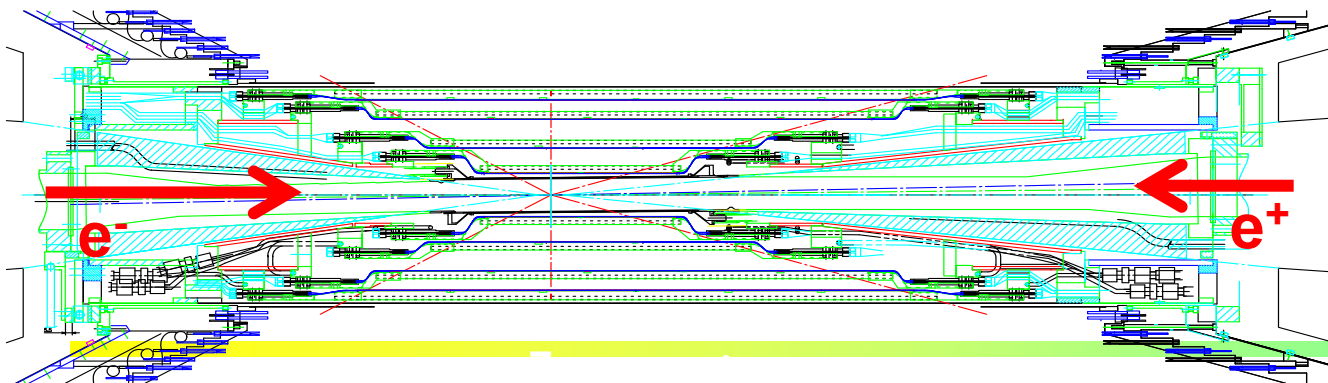
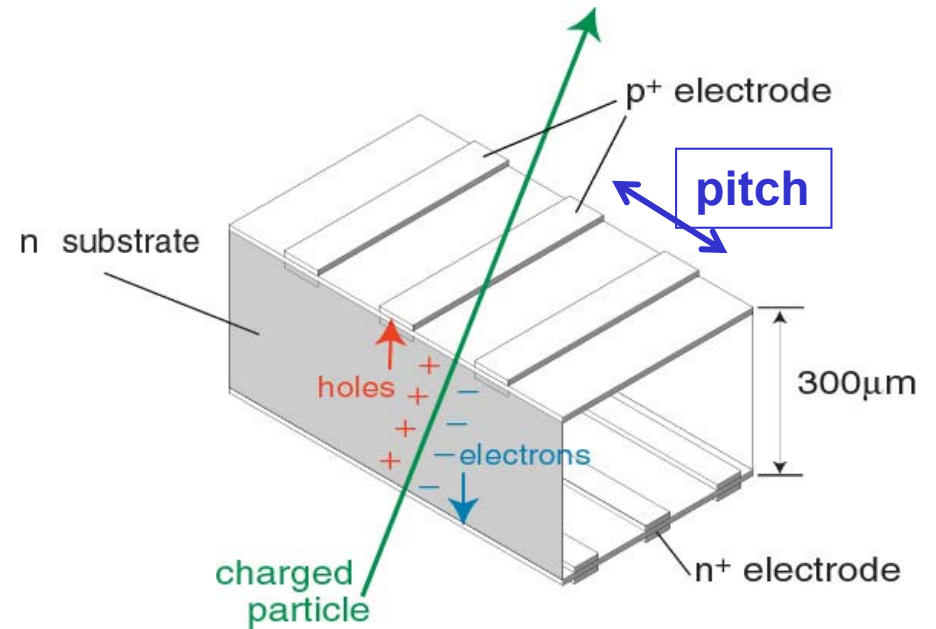
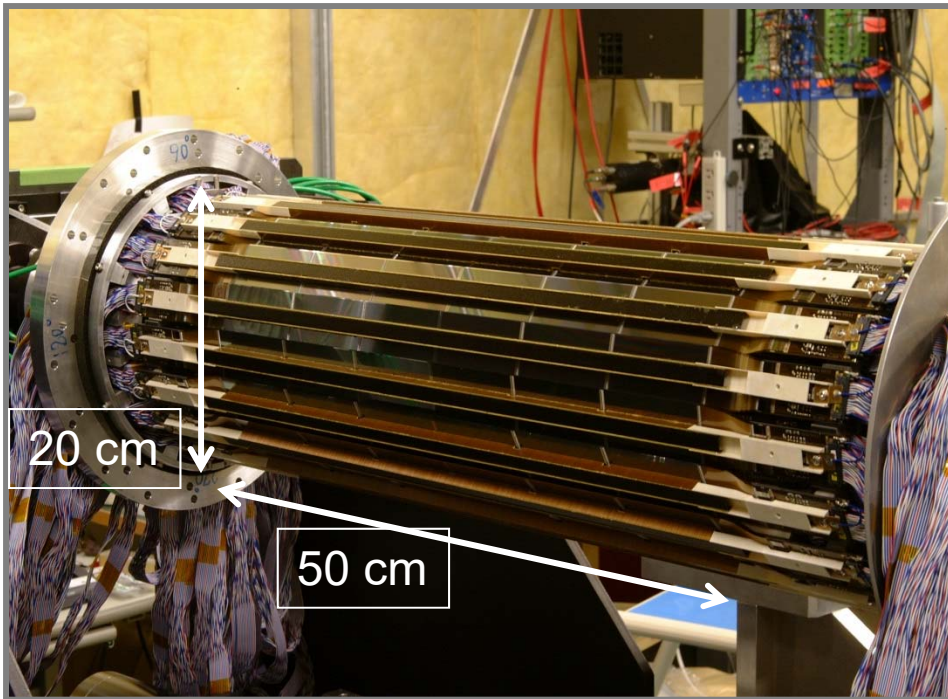


Beryllium beam pipe  
2cm diameter

Vertex Detector  
2 layers DEPFET + 4 layers DSSD



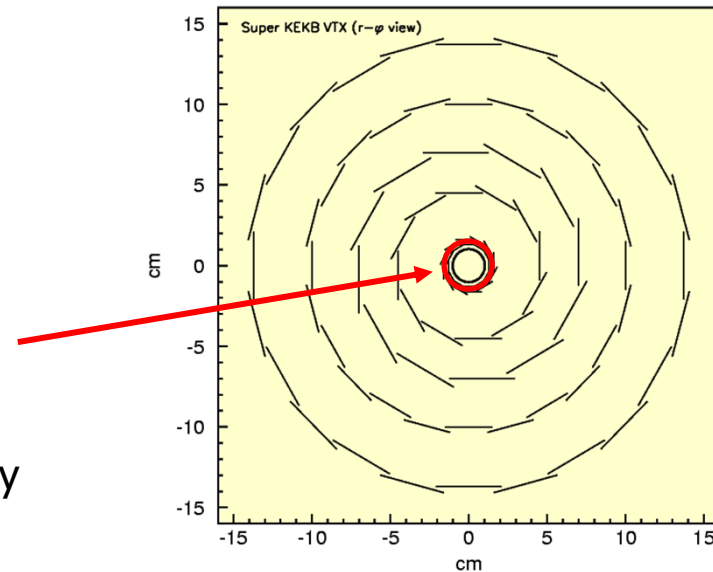
# Silicon vertex detector (SVD)



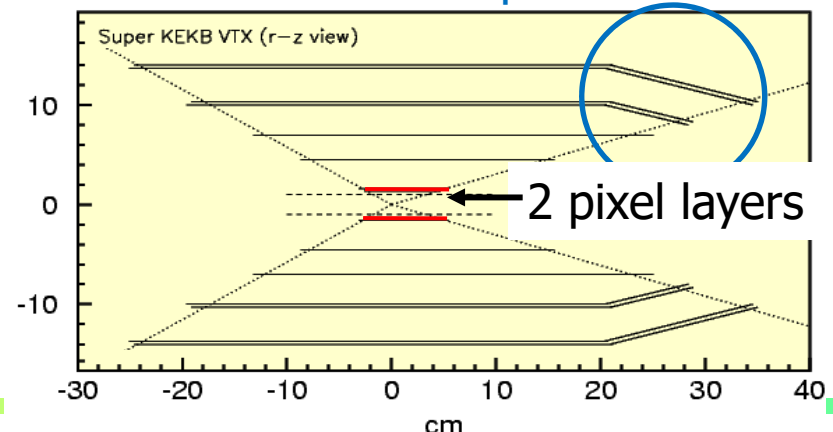
Two coordinates measured at the same time;  
strip pitch: 50μm (75μm);  
resolution 15μm (20μm).

# 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



Slant layer to keep the acceptance



# 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 ( $g_q \sim 400 \text{ pA/e}^-$ )

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

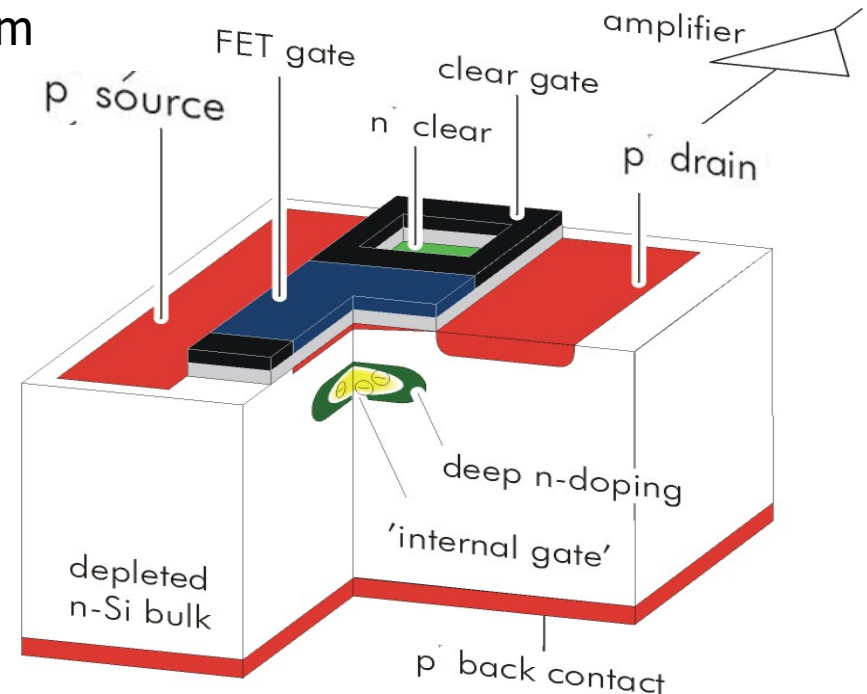
Invented in MPI Munich

Fully depleted:

→ large signal, fast signal collection

Low capacitance, internal amplification → low noise

## Depleted p-channel FET

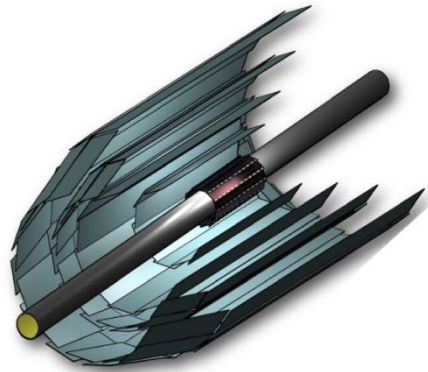


Transistor on only during readout:  
low power

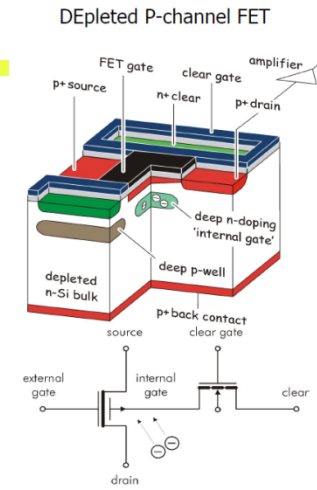
Complete clear → no reset noise

# Vertex Detector

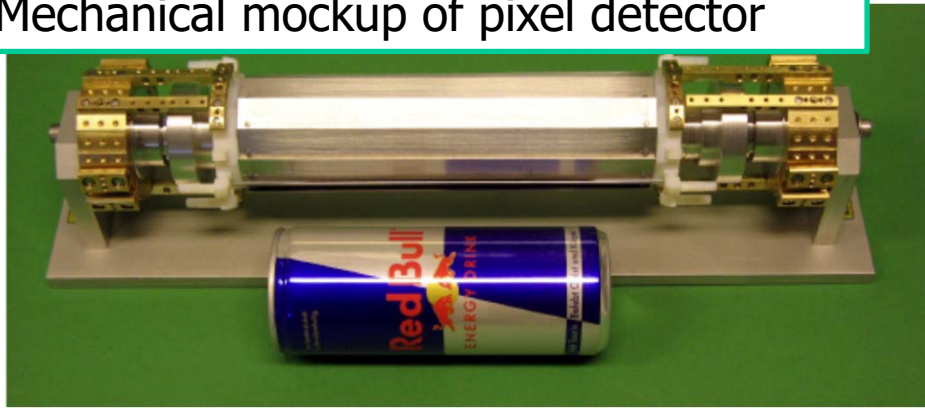
DEPFET:  
<http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome>



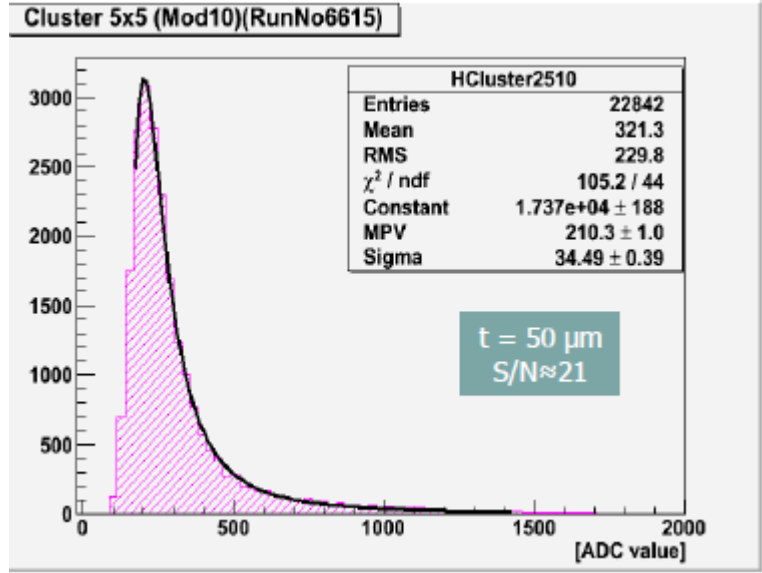
<b>Beam Pipe</b>	<b>r = 10mm</b>
<b>DEPFET</b>	
Layer 1	r = 14mm
Layer 2	r = 22mm
<b>DSSD</b>	
Layer 3	r = 38mm
Layer 4	r = 80mm
Layer 5	r = 115mm
Layer 6	r = 140mm



Mechanical mockup of pixel detector



DEPFET pixel sensor



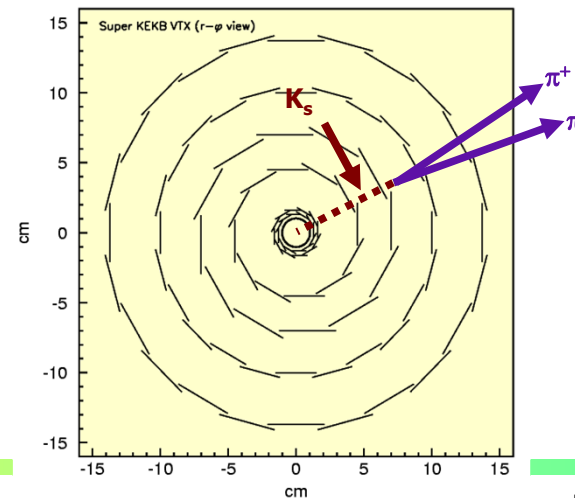
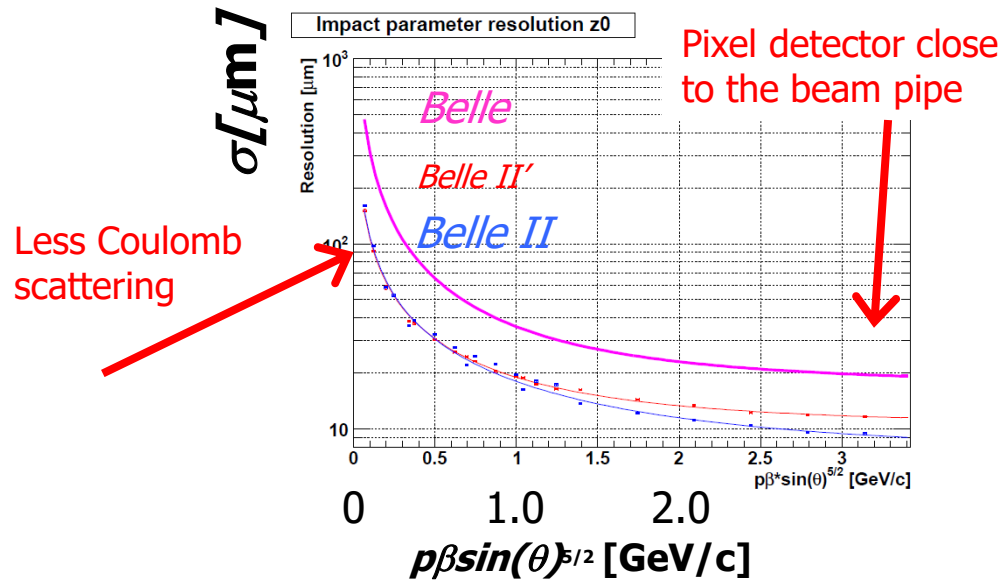
DEPFET sensor: very good S/N

# Expected performance

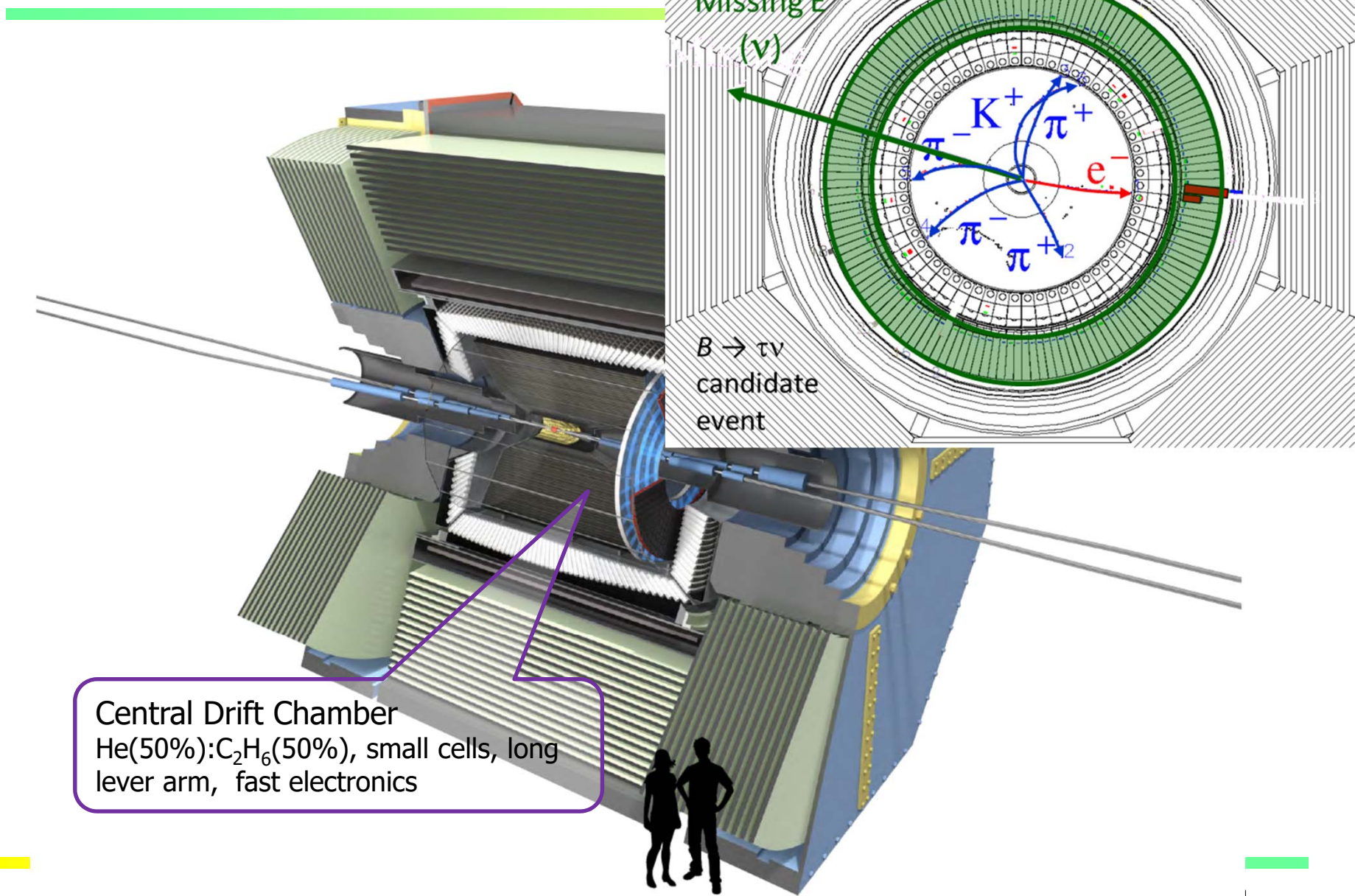
$$\sigma = a + \frac{b}{p\beta \sin^v \theta}$$

4 layers of silicons strip 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



Central Drift Chamber  
He(50%):C<sub>2</sub>H<sub>6</sub>(50%), small cells, long lever arm, fast electronics

# Search for unstable particles which decayed close to the production point

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

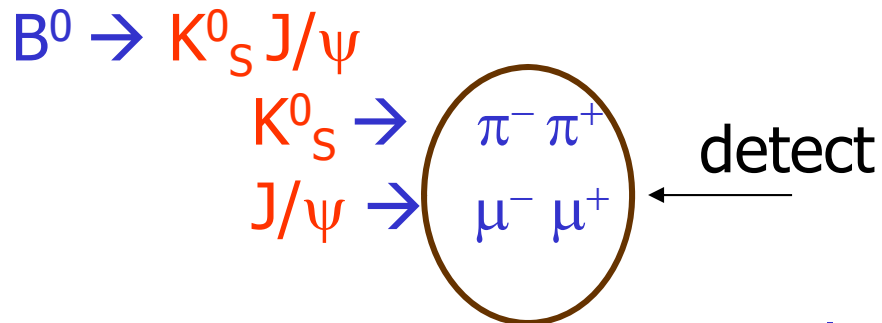
From the measured tracks calculate the invariant mass of the system ( $i= 1,2$ ):

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

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



# How do we know it was precisely this reaction?



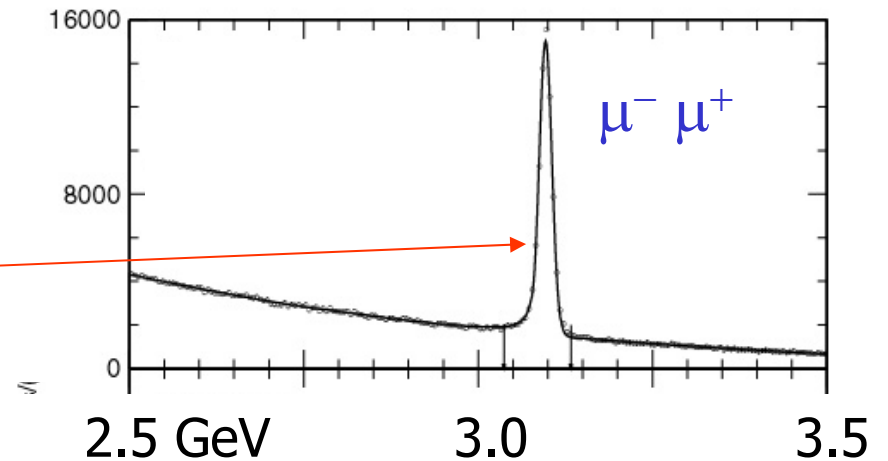
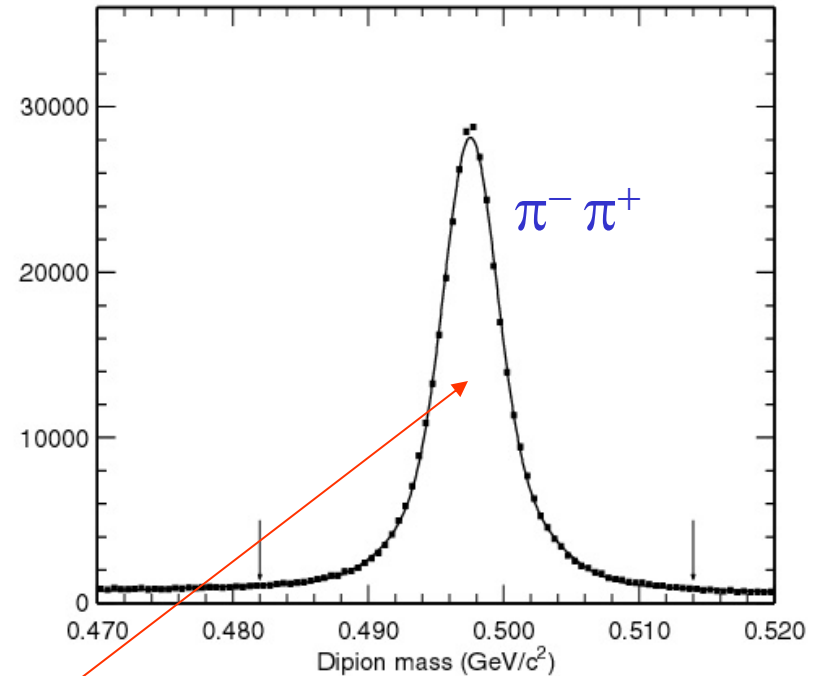
For  $\pi^- \pi^+$  in  $\mu^- \mu^+$  pairs we calculate the invariant mass:

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

$M c^2$  must be for  $K_S^0$  close to **0.5 GeV**,

for  $J/\psi$  close to **3.1 GeV**.

Rest in the histogram: random coincidences ('combinatorial background')



# Invariant mass resolution – momentum resolution

---

The name of the game: have as little background under the peak as possible without losing 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

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

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

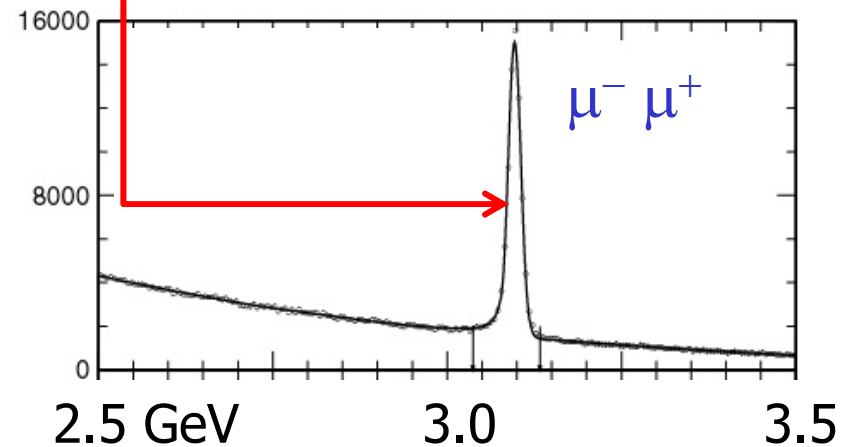
The  $J/\psi$  peak should be narrow to minimize the contribution of random coincidences ('combinatorial background')

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

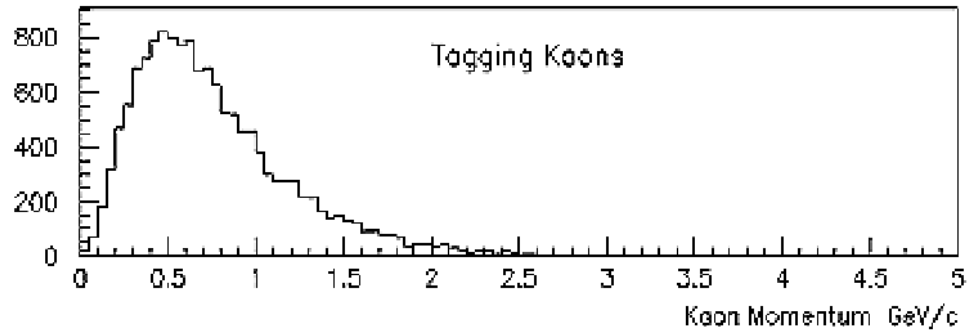
What is the corresponding momentum resolution?

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

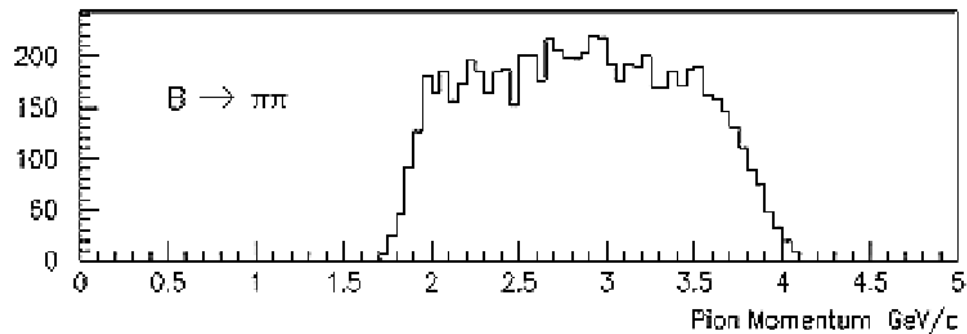
$\rightarrow \sigma(p)/p = 10 \text{ MeV}/2/1.5 \text{ GeV} = 0.3\%$



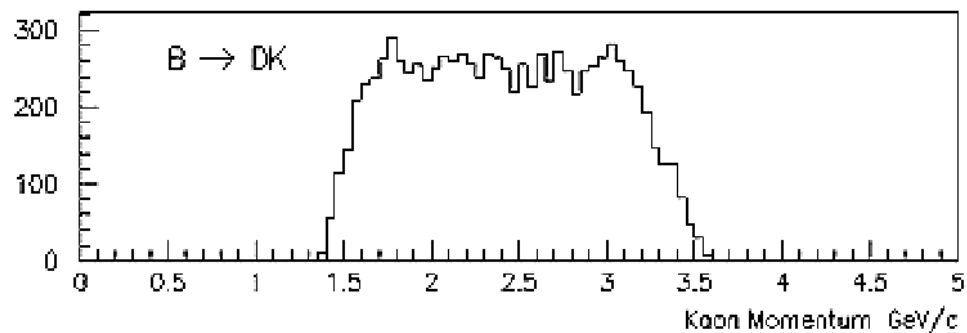
# Requirements: momentum spectrum



Tagging Kaons



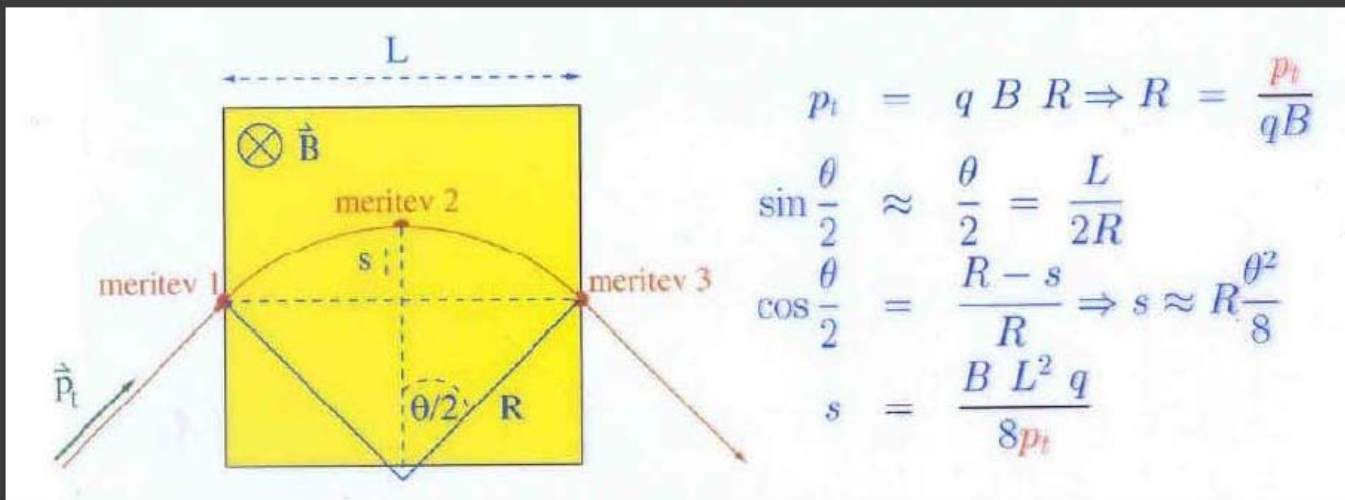
$B \rightarrow \pi\pi$



$B \rightarrow DK$

## From raw data to summary data momentum measurement

Example of momentum determination:



if  $s$  determined by  
3 measurement points:

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

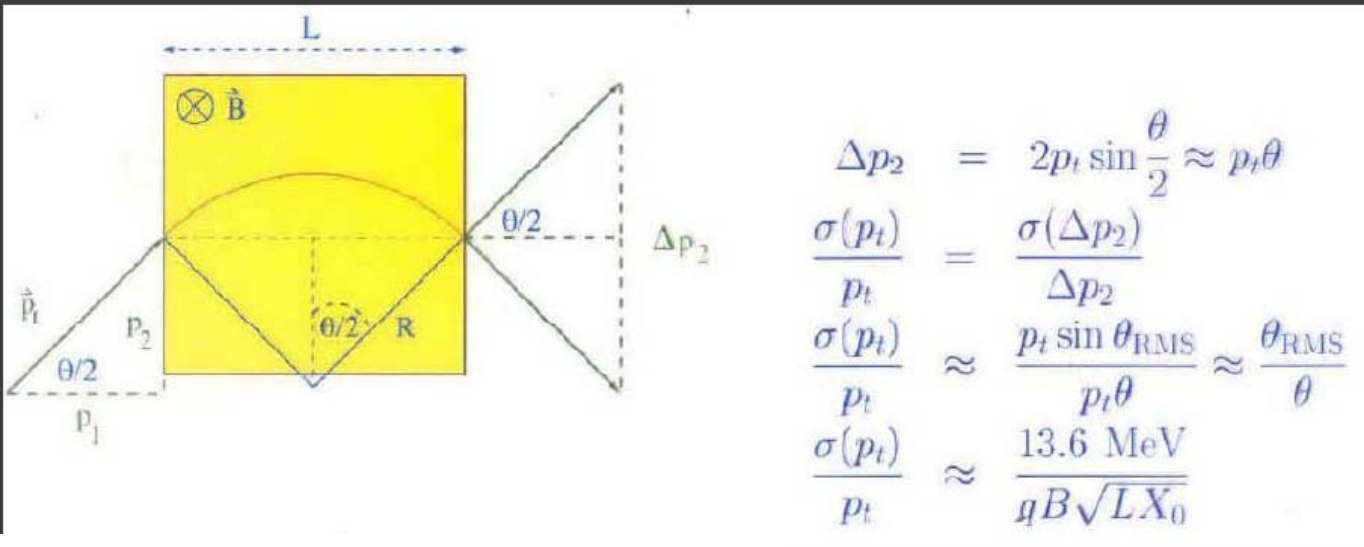
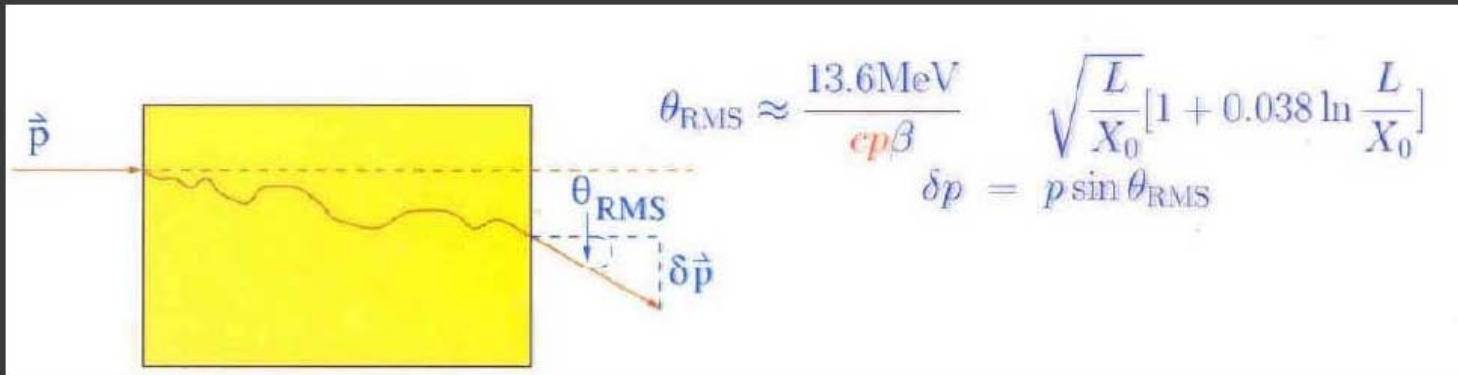
$$\frac{\sigma(p_t)}{p_t} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}} \sigma(x) 8 p_t}{B L^2 q}$$

for  $N$  measurement points:

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

## From raw data to summary data momentum measurement

Multiple scattering:



# Momentum resolution

Tracking system  
uncertainty

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

$$eB = 0.3 \text{ (B/T) (1/m) GeV/c}$$

$$\frac{\sigma_{p_T}}{p_T} = p_T \frac{0.1 \times 10^{-3} \text{ m}}{0.3(\text{GeV/m}) \times 1.5 \times 1 \text{ m}^2} \sqrt{\frac{720}{54}} = \frac{p_T \times 0.0008}{\text{GeV}}$$

For  $B=1.5\text{T}$ ,  $L = 1\text{m}$ ,  $\sigma_x = 0.1 \text{ mm}$

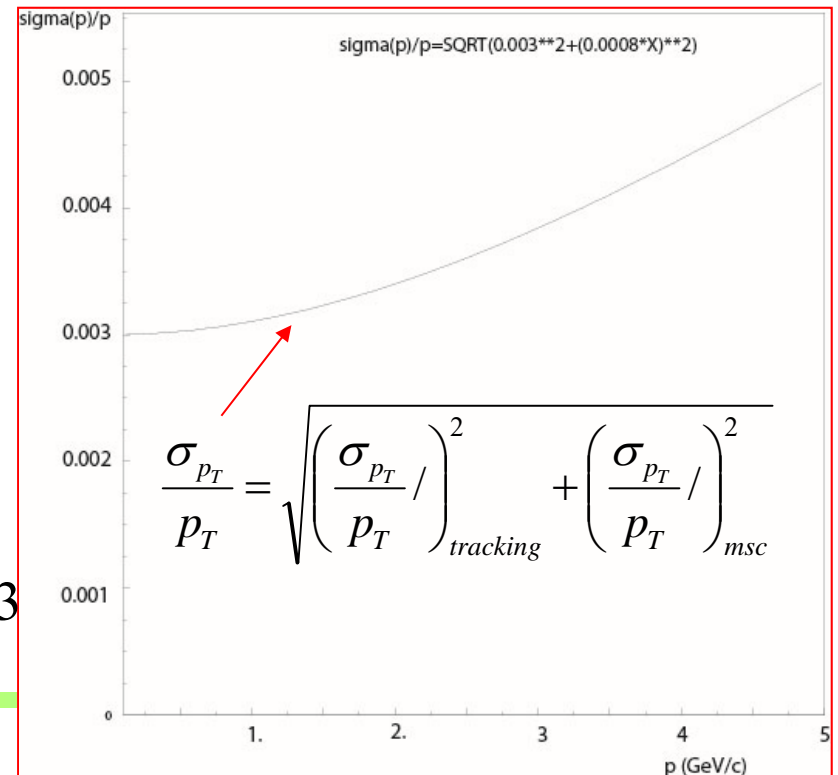
For  $p_T = 1 \text{ GeV}$ :  $\sigma_{p_T} / p_T = 0.08\%$

For  $p_T = 2 \text{ GeV}$ :  $\sigma_{p_T} / p_T = 0.16\%$

Uncertainty from multiple  
scattering

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

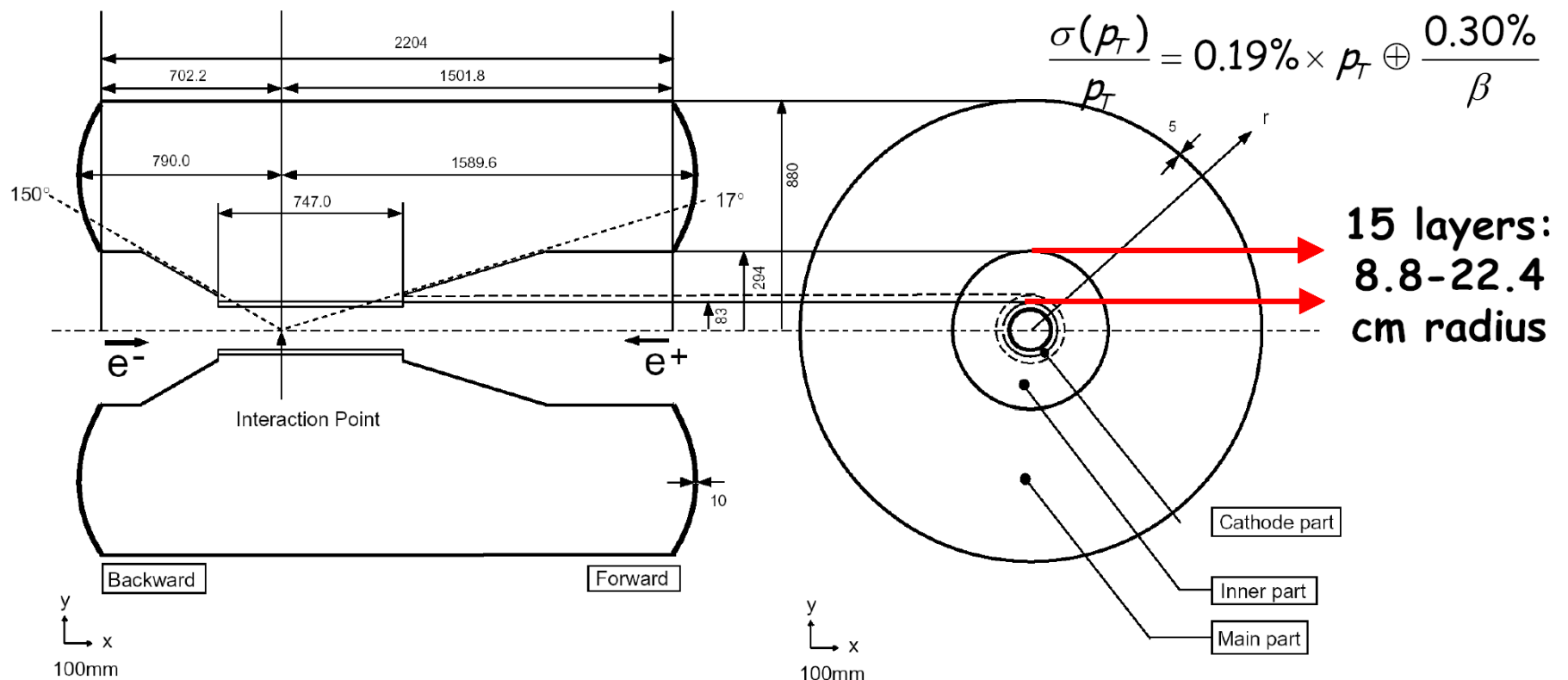
$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6 \text{ MeV}}{0.3(\text{GeV/m}) \times 1.5 \sqrt{1 \text{ m} \times 100 \text{ m}}} = 0.003$$



# Tracking: Belle central drift chamber



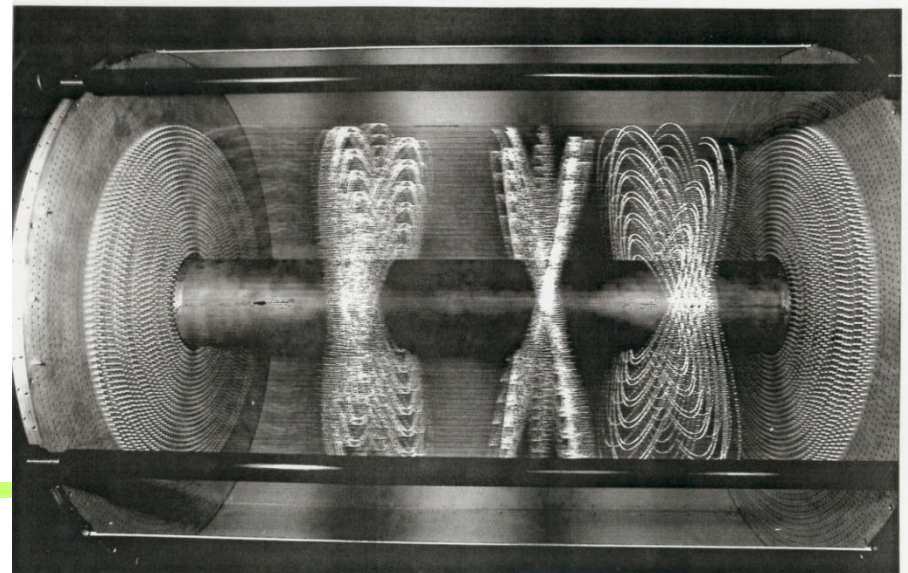
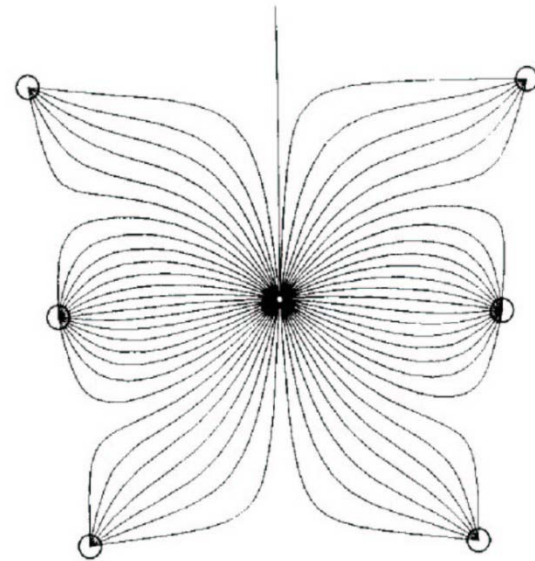
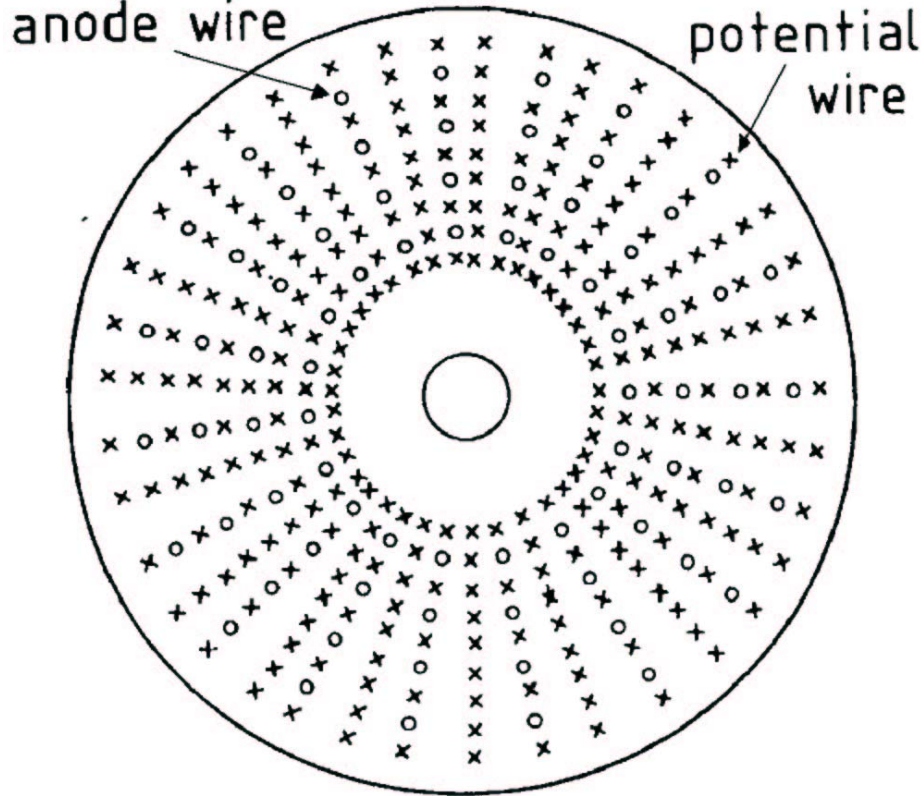
- 50 layers of wires (8400 cells) in 1.5 Tesla magnetic field
- Helium:Ethane 50:50 gas, W anode wires, Al field wires, CF inner wall with cathodes, and preamp only on endplates
- Particle identification from ionization loss (5.6-7% resolution)





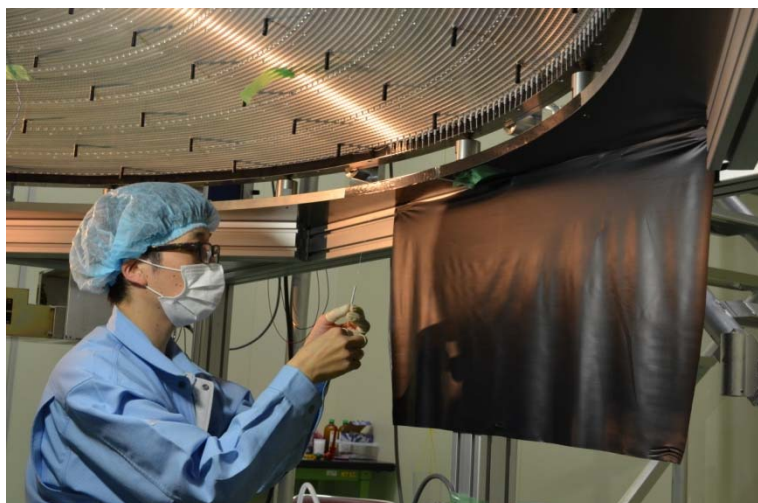
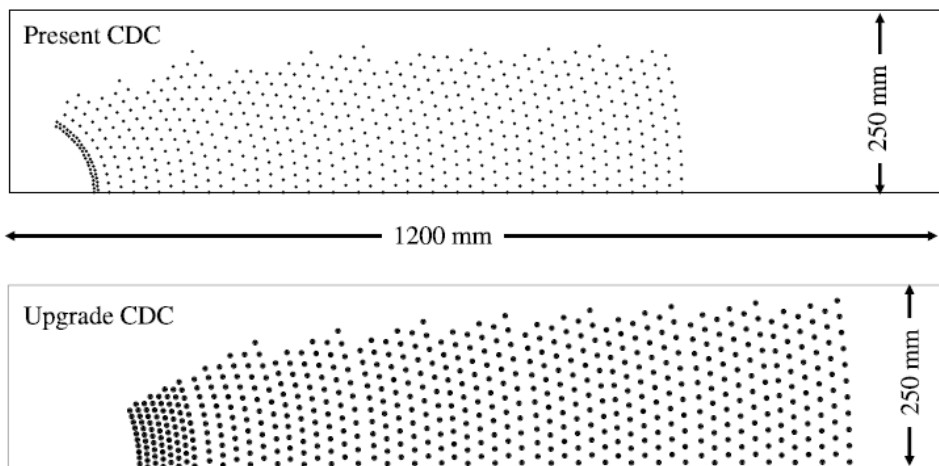
# Drift chamber with small cells

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



# Belle II CDC

## Wire Configuration

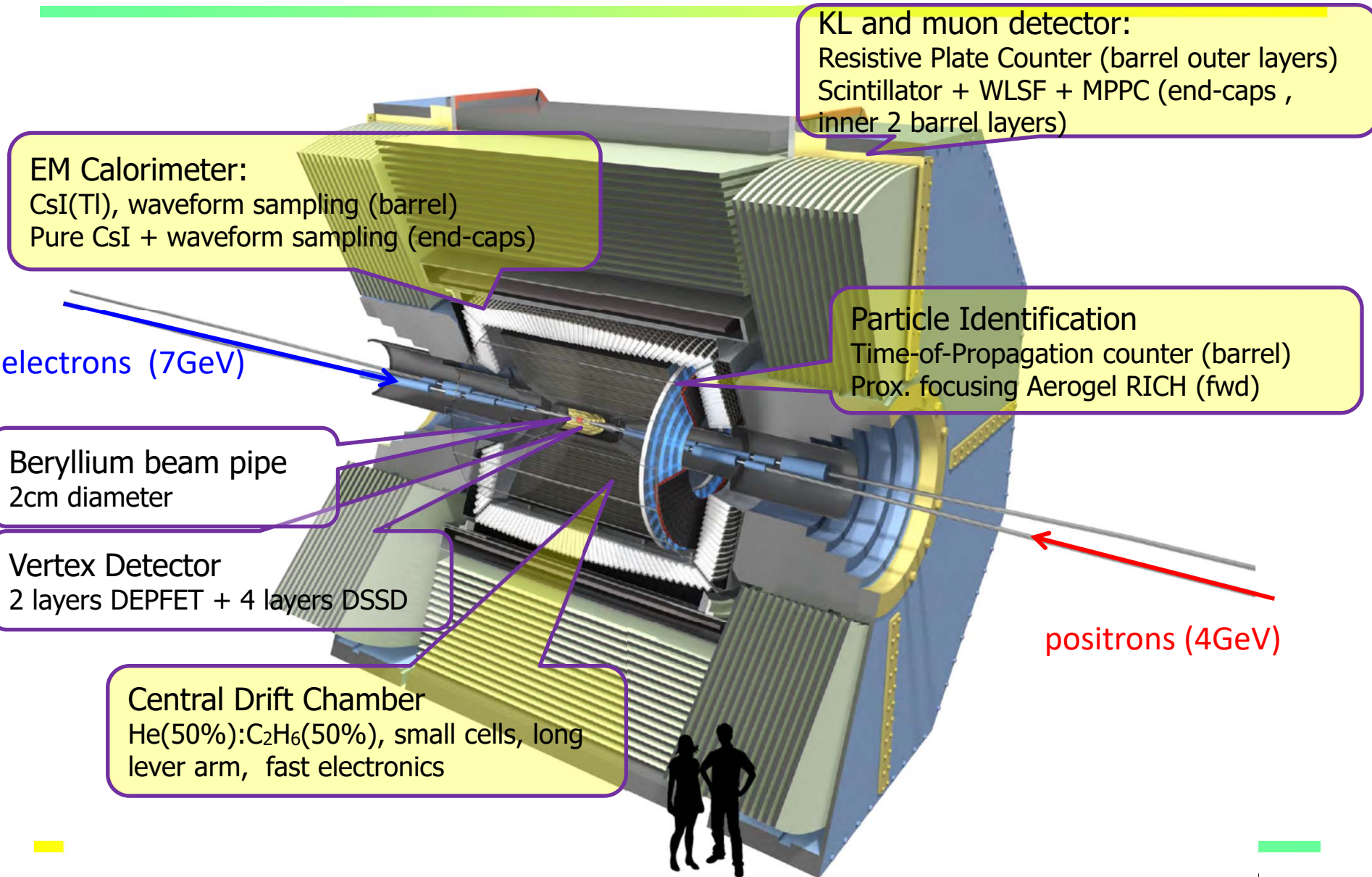


Wire stringing in a clean room

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



# Particle identification systems in Belle II



# Identification of charged particles

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

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

Momentum known (radius of curvature in magnetic field)

→ Measure velocity:

time of flight

ionisation losses  $dE/dx$

Cherenkov angle

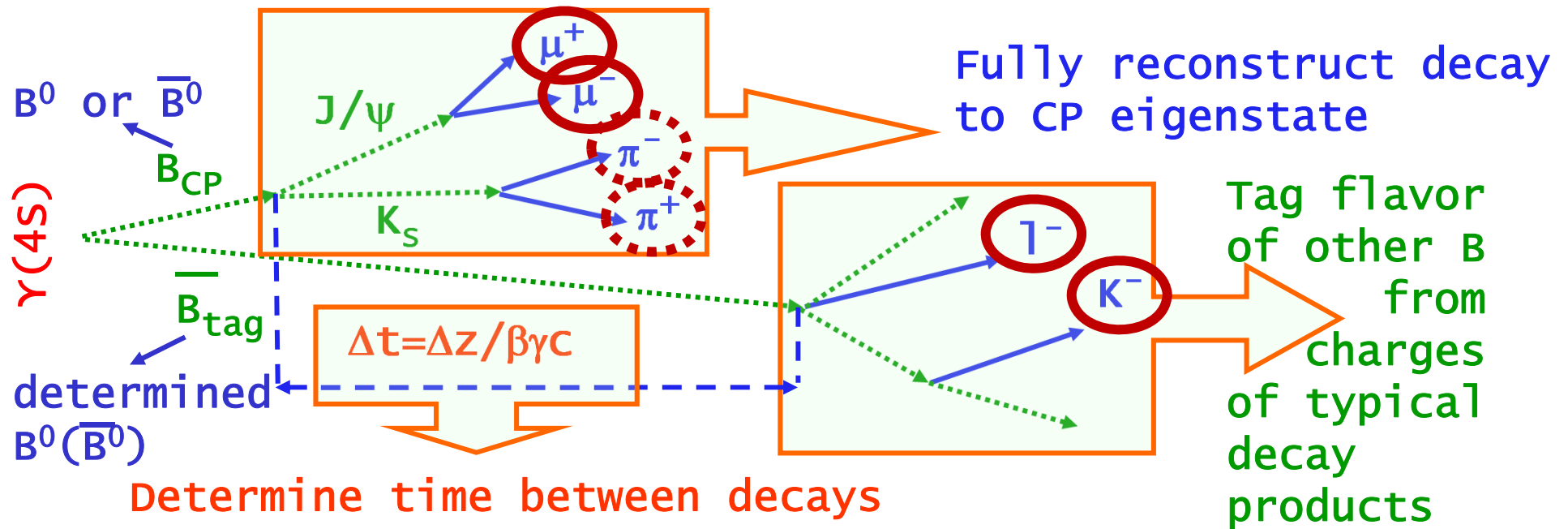
transition radiation

Mainly used for the identification of hadrons.

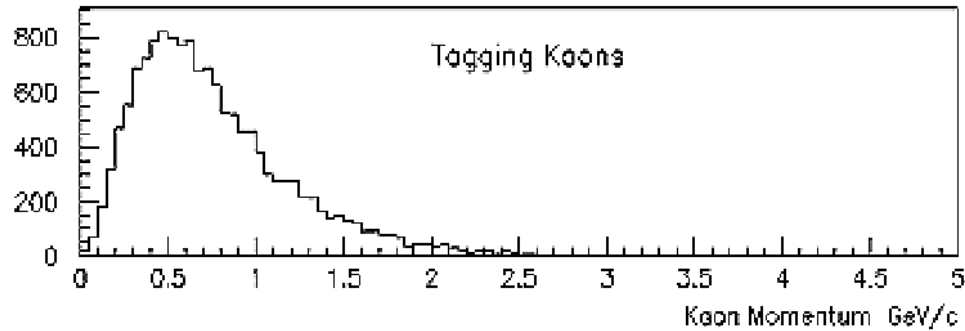
**Identification through interaction:** electrons and muons

---

# Reminder: where do we need identification?

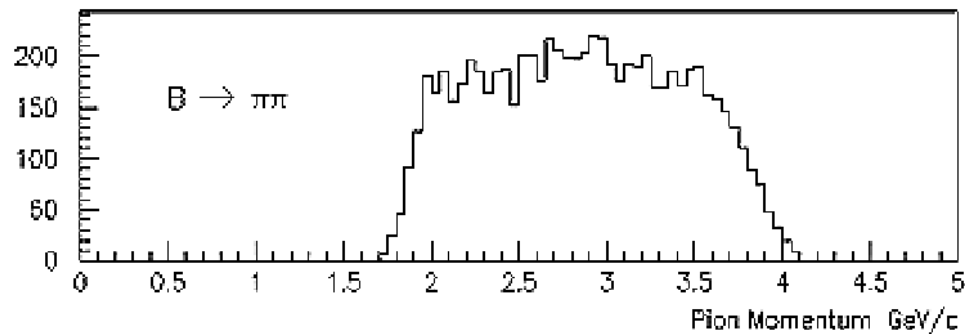


# Requirements: Particle Identification



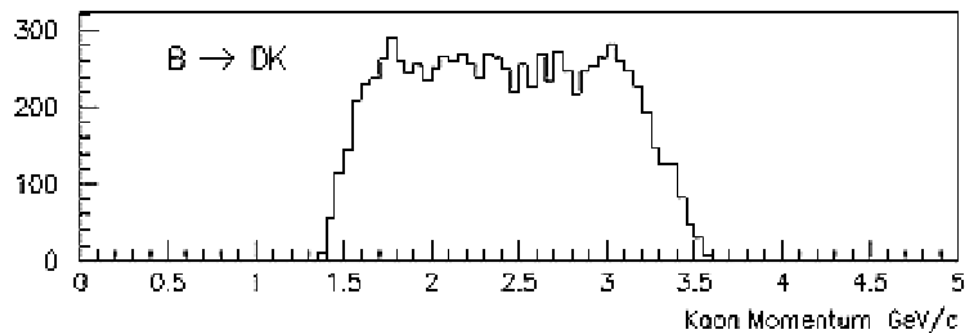
**Tagging Kaons**

Relatively soft,  
ms dominated  
for tracking



**$B \rightarrow \pi\pi$**

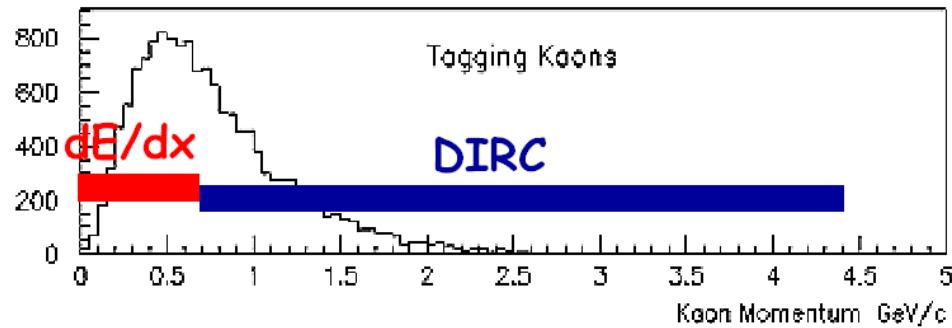
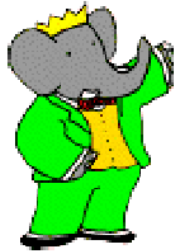
Requires  
dedicated PID



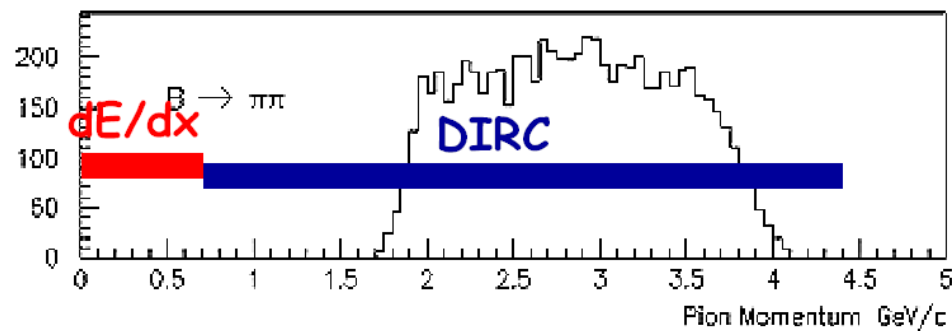
**$B \rightarrow DK$**

Requires  
dedicated PID

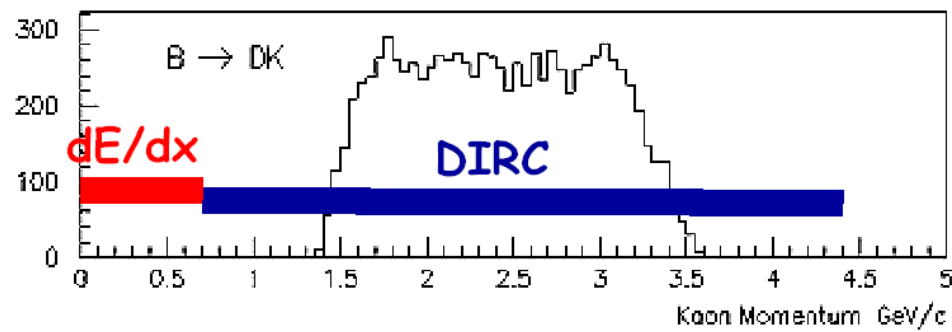
# PID coverage of kaon/pion spectra



Tagging Kaons

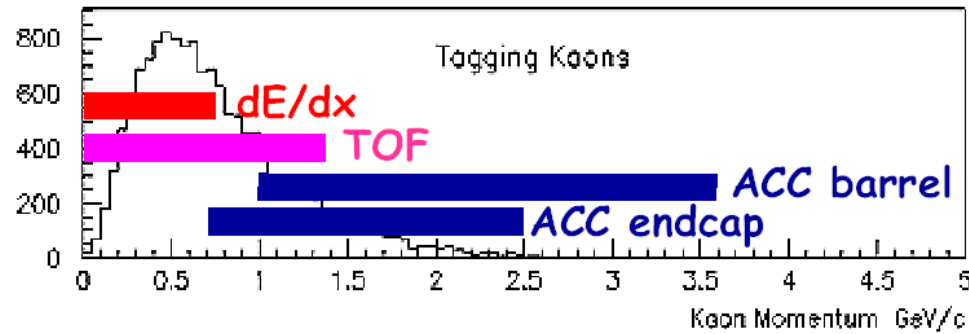


$B \rightarrow \pi\pi$

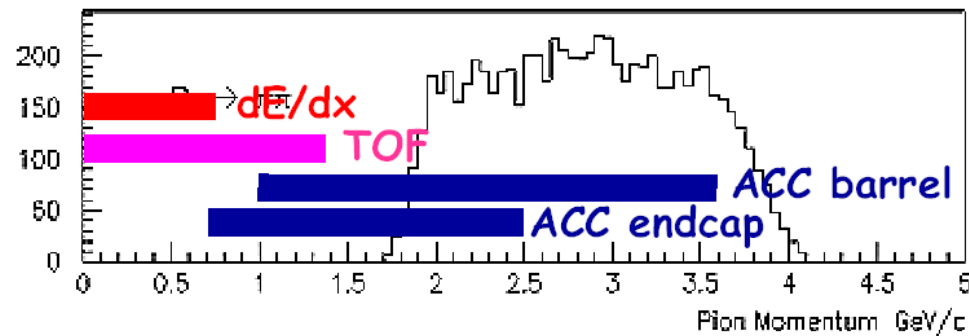


$B \rightarrow DK$

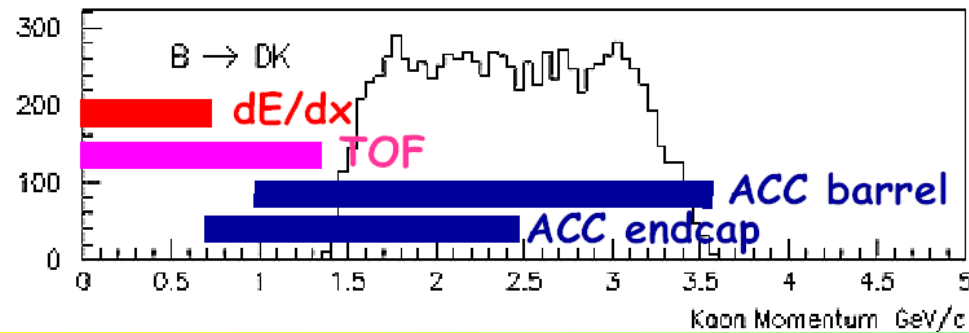
# PID coverage of kaon/pion spectra



Tagging Kaons



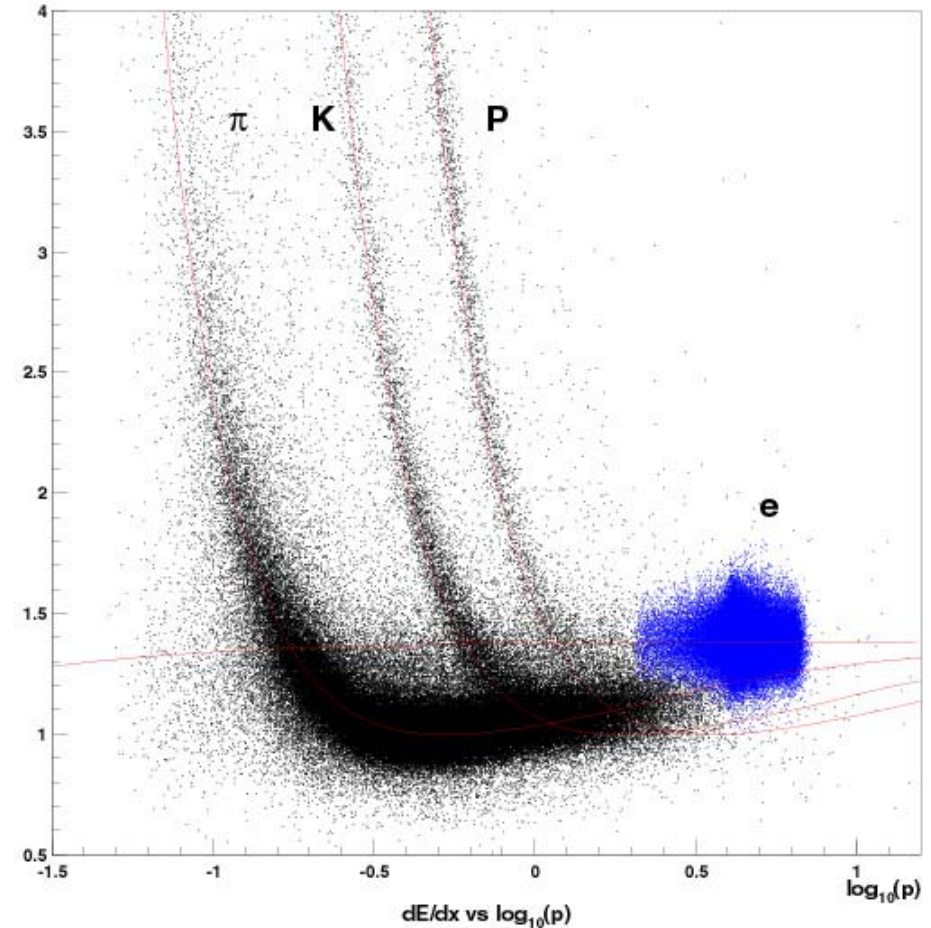
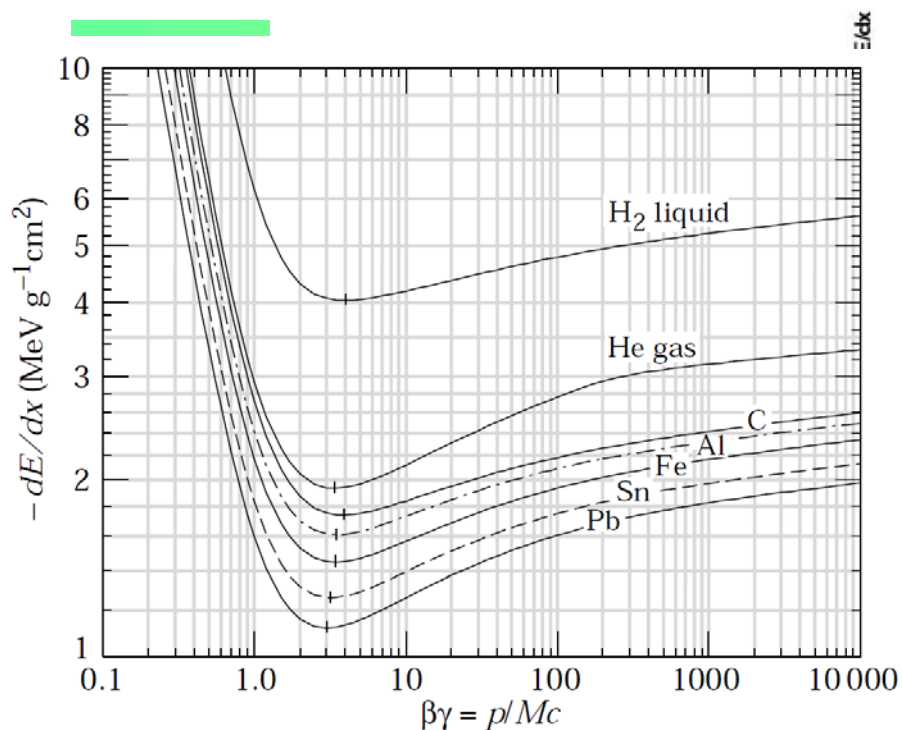
$B \rightarrow \pi\pi$



$B \rightarrow DK$



# Identification with the $dE/dx$ measurement

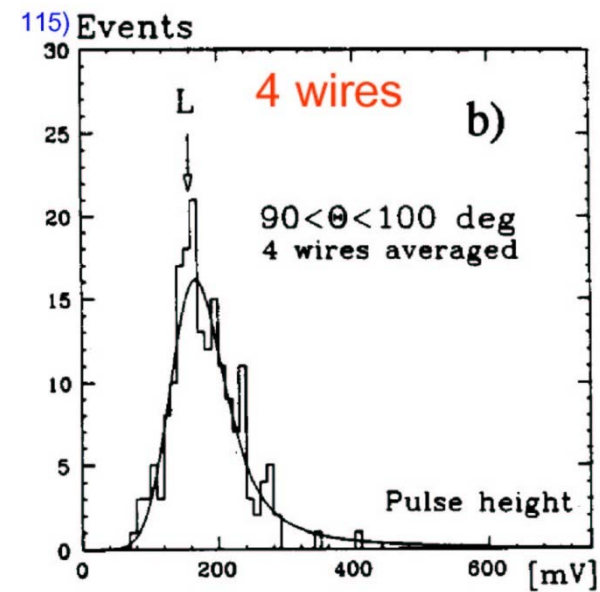
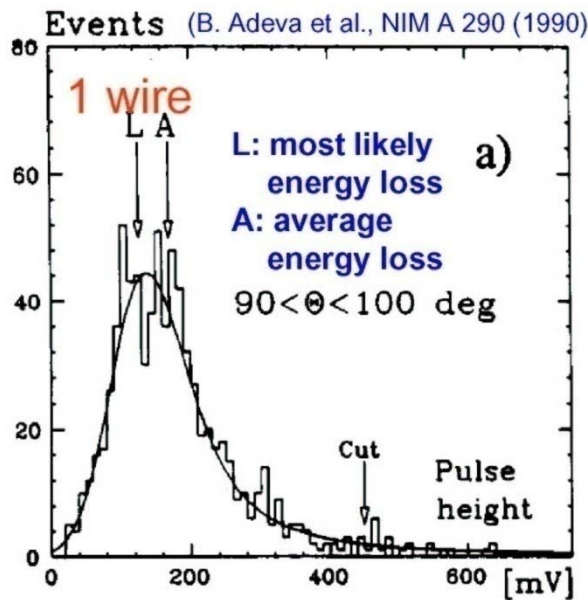
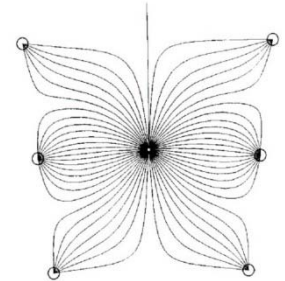


$dE/dx$  is a function of velocity  $\beta$   
For particles with different mass the  
Bethe-Bloch curve gets displaced  
if plotted as a function of  $p$

For good separation: resolution should be  $\sim 5\%$

# 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).

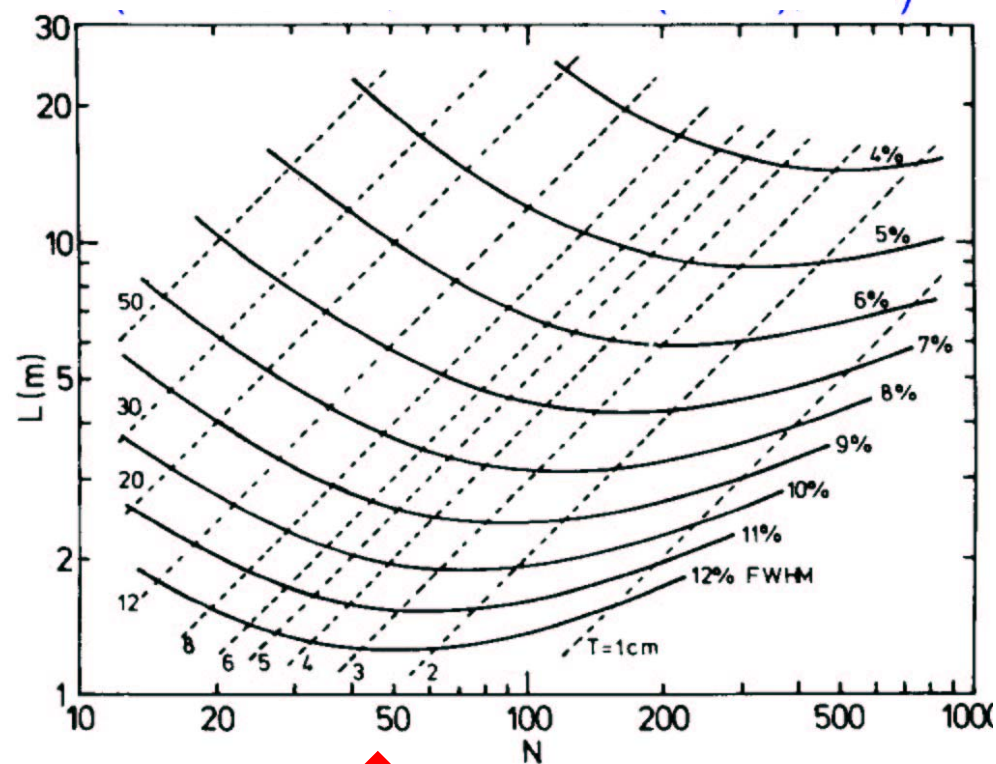
# Identification with $dE/dx$ measurement

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  $\rightarrow$  the optimum depends also on the number of samples.

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

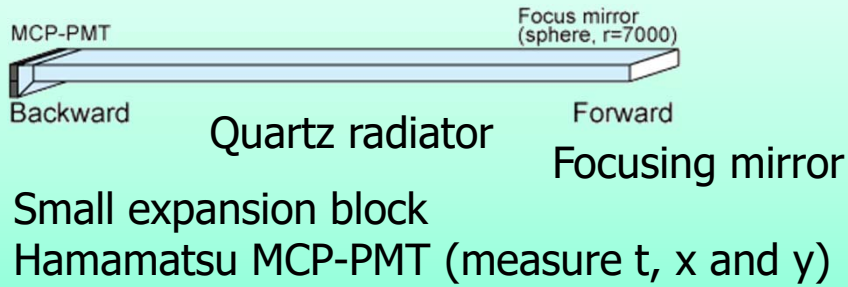


FWHM: full width at half maximum = 2.35 sigma for a Gaussian distribution

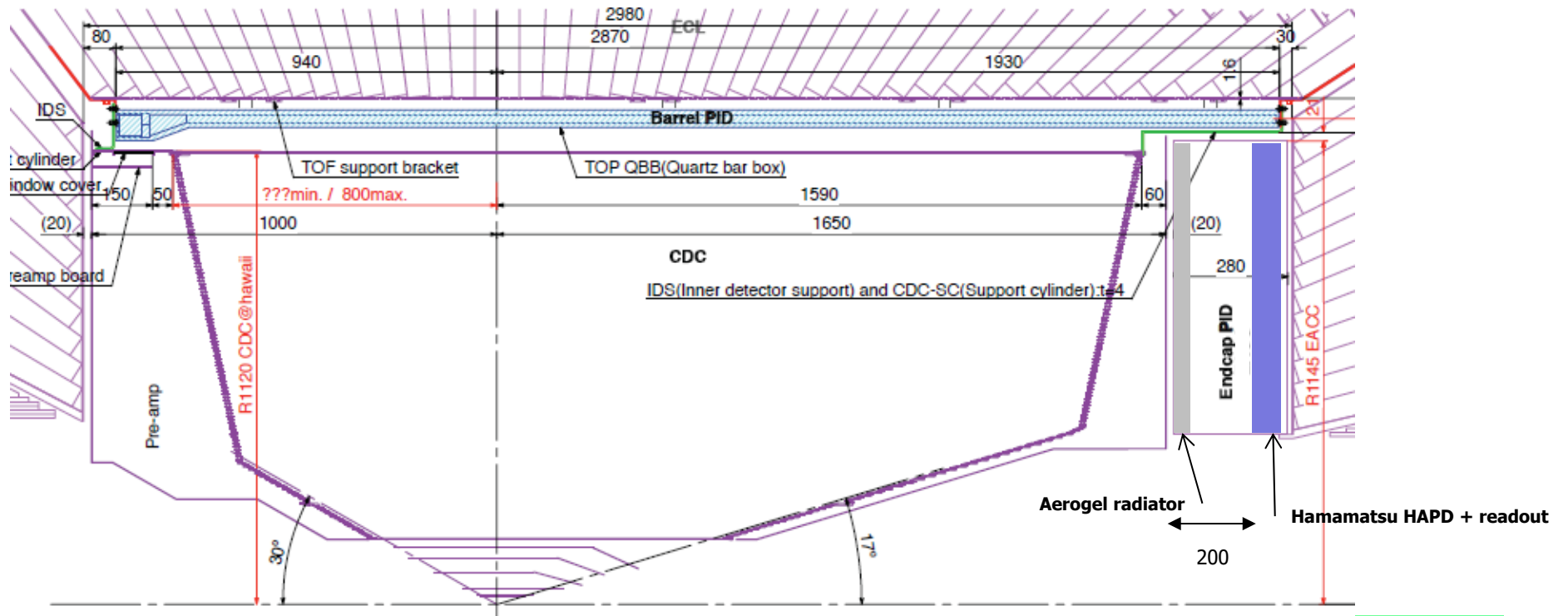
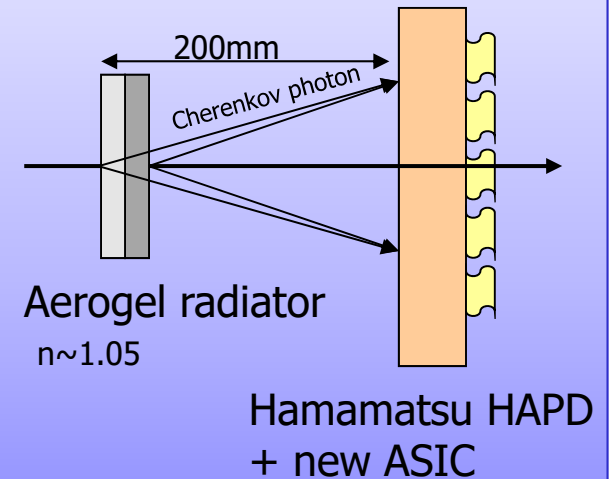


# Cherenkov detectors

## Barrel PID: Time of Propagation Counter (TOP)



## Endcap PID: Aerogel RICH (ARICH)



# Cherenkov radiation

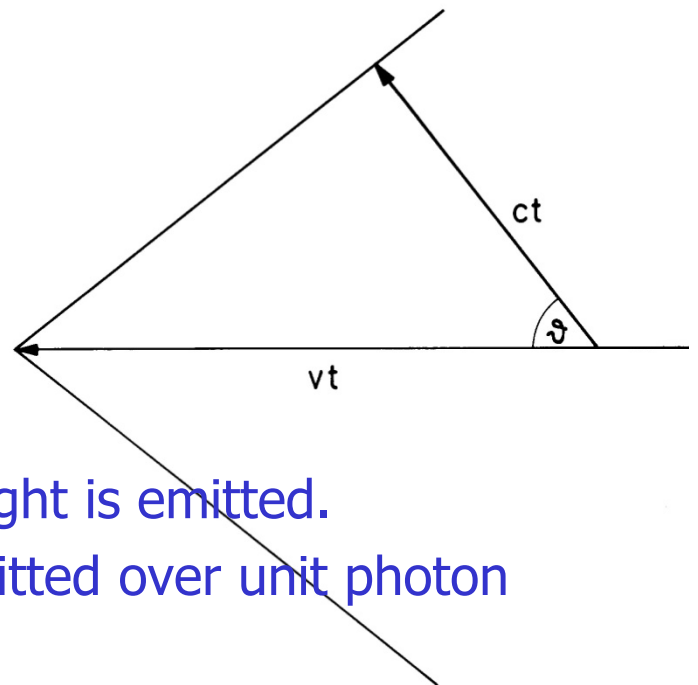
A charged track with velocity  $v = \beta c$  exceeding the speed of light  $c/n$  in a medium with refractive index  $n$  emits **polarized light** at a characteristic (Cherenkov) angle,

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

Two cases:

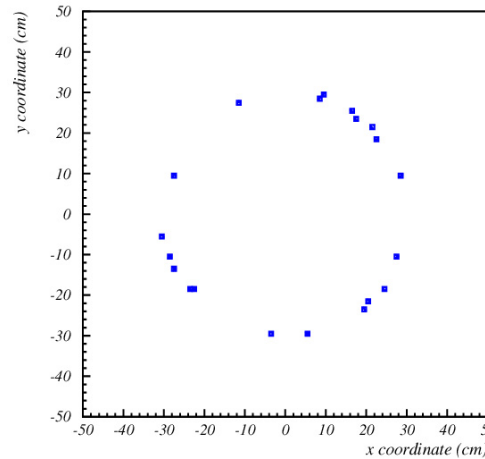
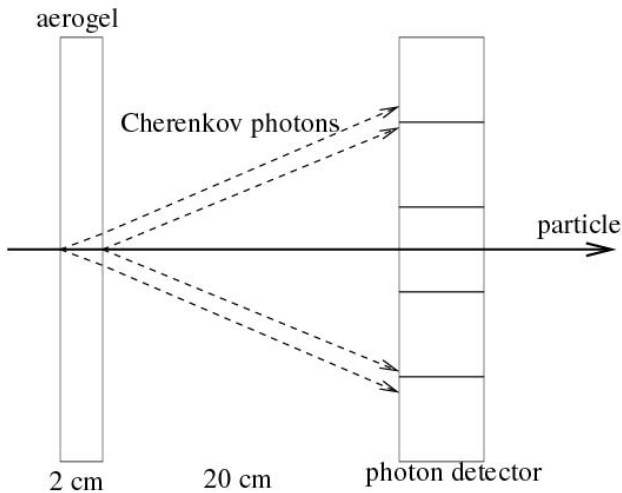
- $\beta < \beta_t = 1/n$ : below threshold **no** Cherenkov light is emitted.
- $\beta > \beta_t$ : the number of Cherenkov photons emitted over unit photon energy  $E = h\nu$  in a radiator of length  $L$ :

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



→ Few detected photons

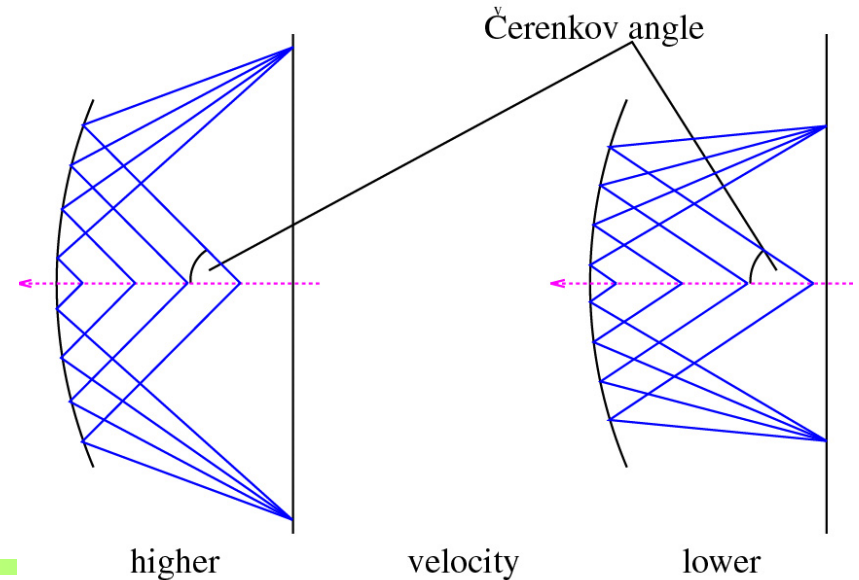
# Measuring the Cherenkov angle



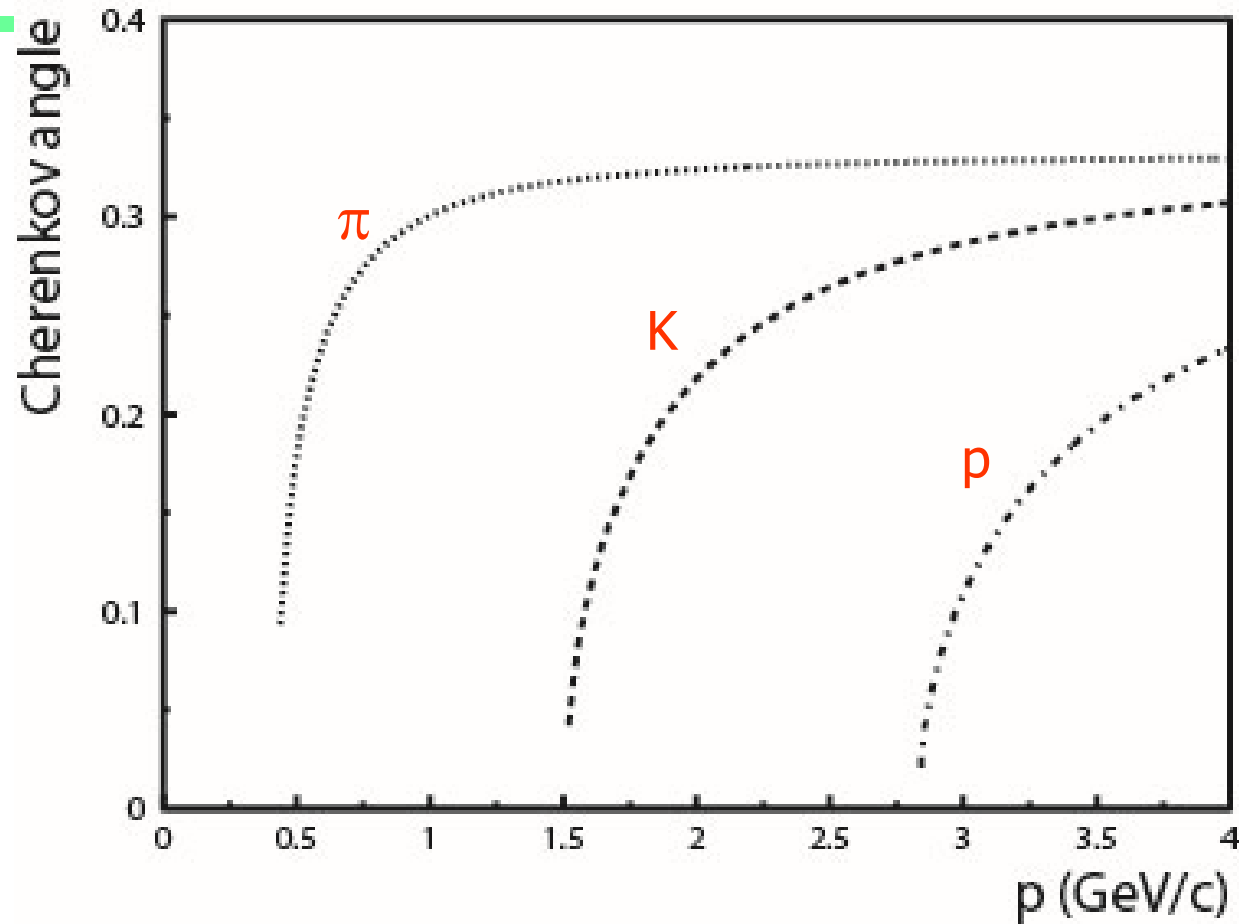
Idea: transform the **direction** into a **coordinate** → ring on the detection plane → **Ring Imaging Cherenkov (RICH) counter**

## Proximity focusing RICH

RICH with a focusing mirror



# Measuring Cherenkov angle



Radiator:  
aerogel,  $n=1.06$

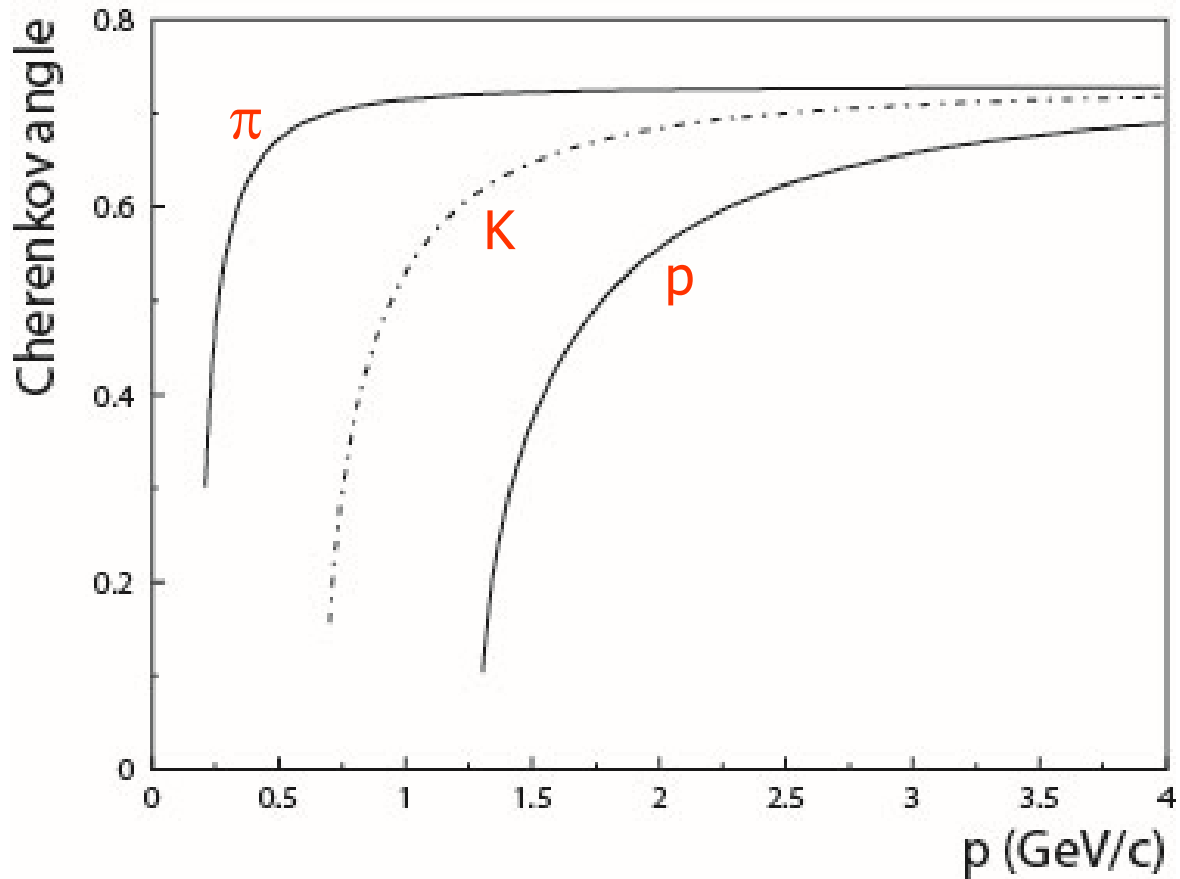
$\uparrow$   
 $\pi$

$\uparrow$   
K

$\uparrow$   
p

thresholds

# Measuring Cherenkov angle



Radiator:  
quartz,  $n=1.46$

$\pi$     $K$     $p$

thresholds

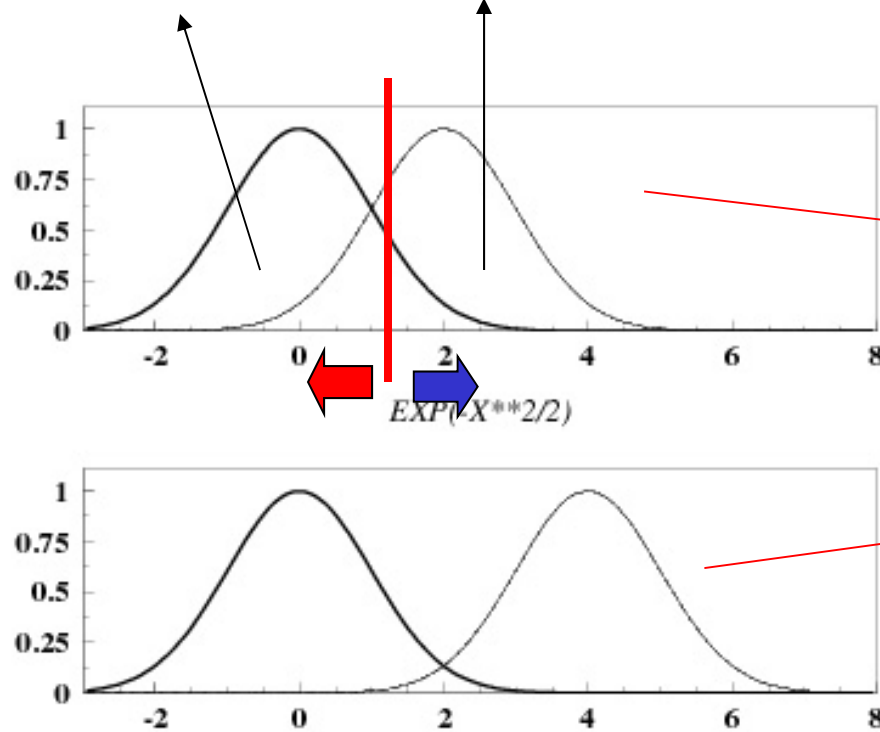


# Efficiency and purity in particle identification

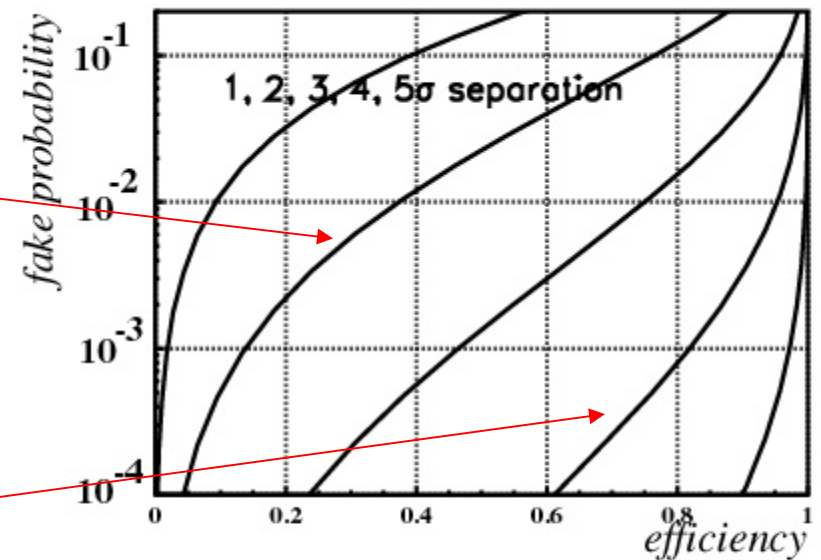
Efficiency and purity are tightly coupled!

Two examples:

particle type 1    type 2

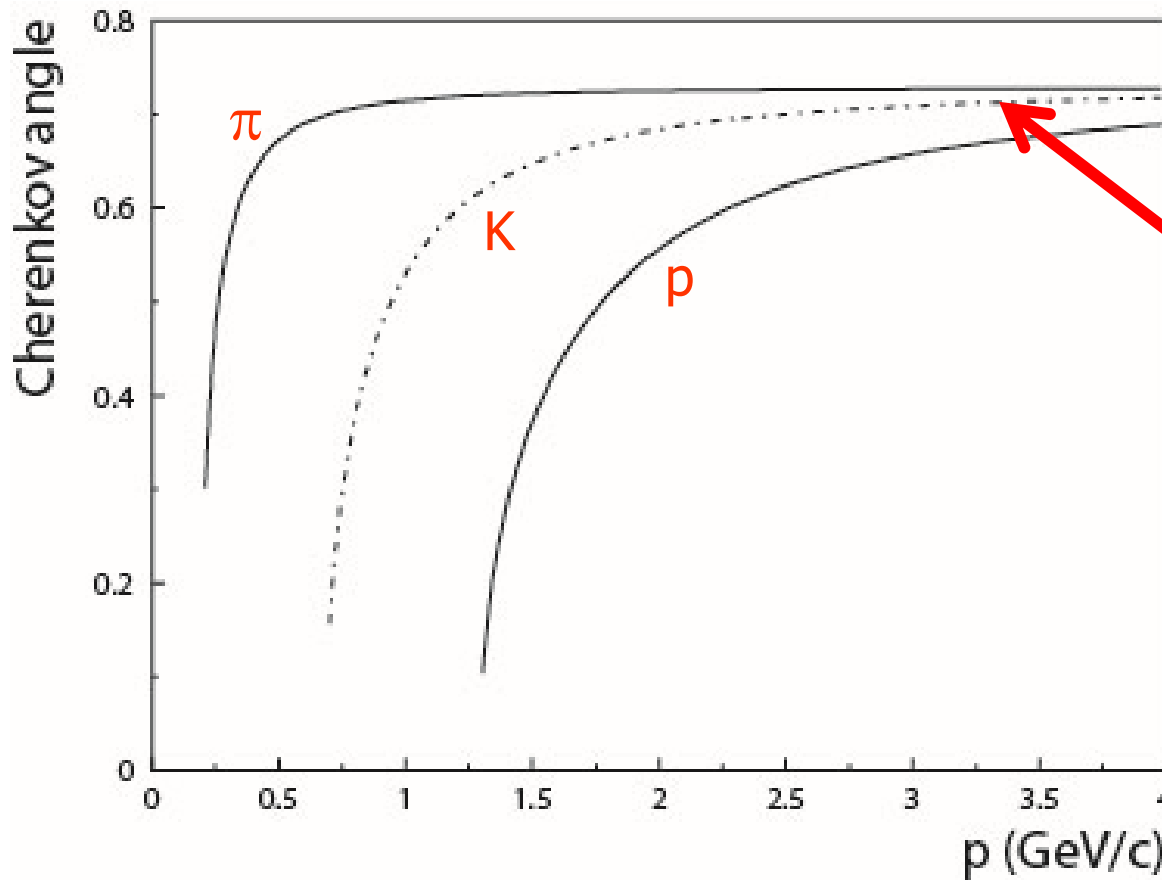


eff. vs fake probability



any discriminating variable, e.g.  
Cherenkov angle

# Measuring Cherenkov angle



Radiator:  
quartz,  $n=1.06$

K/ $\pi$  overlap

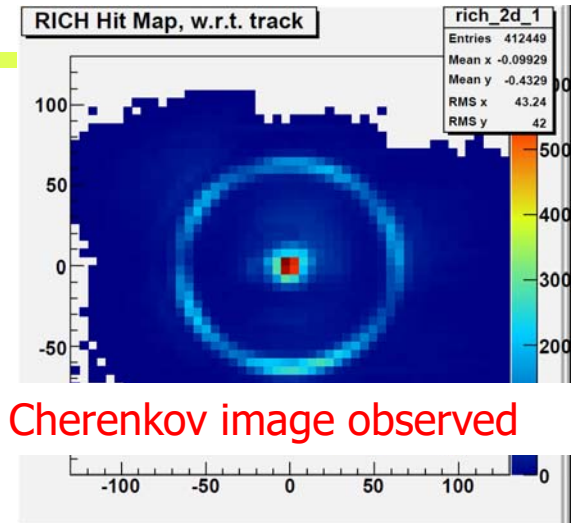
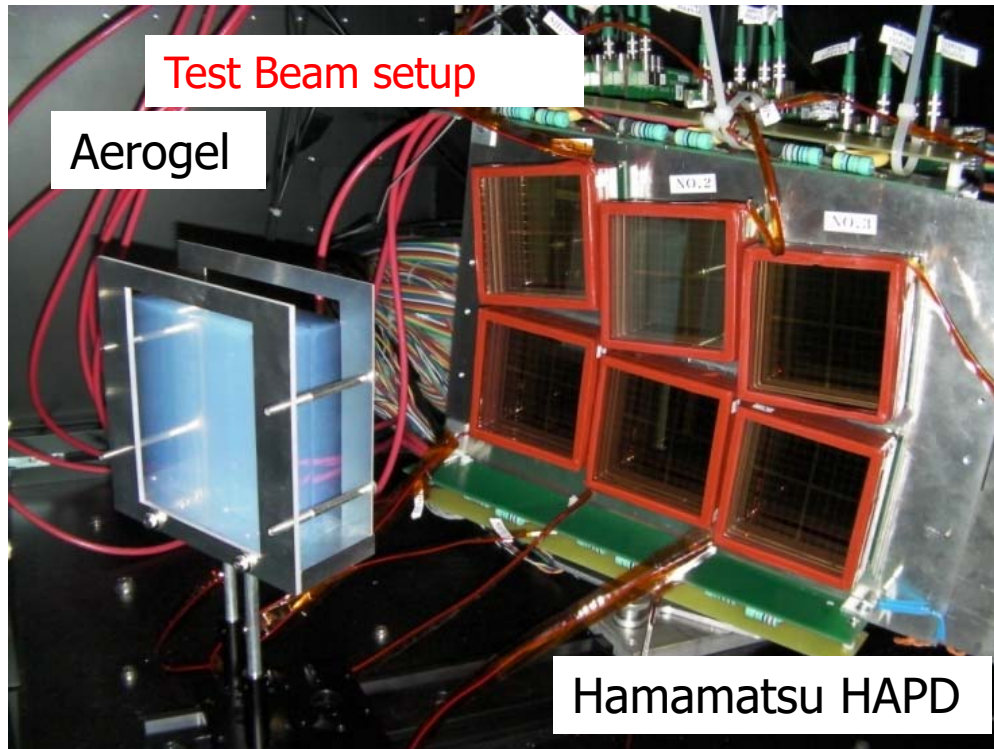


$P_{\min}$  for K/ $\pi$  separation



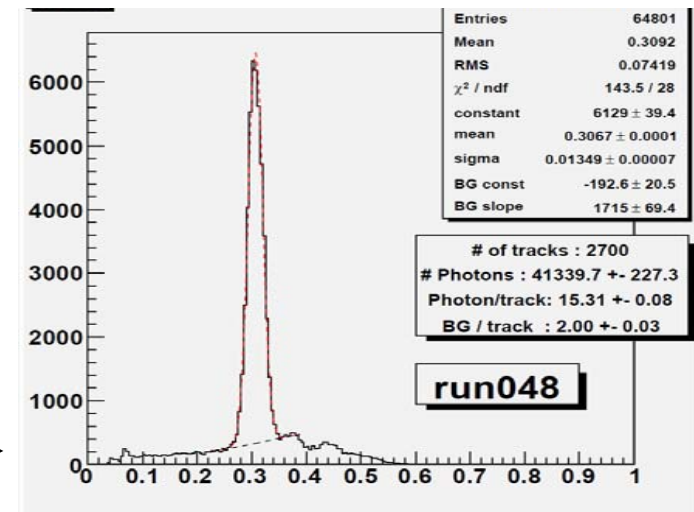
$P_{\max}$  for K/ $\pi$  separation

# Aerogel RICH (endcap PID): larger particle momenta



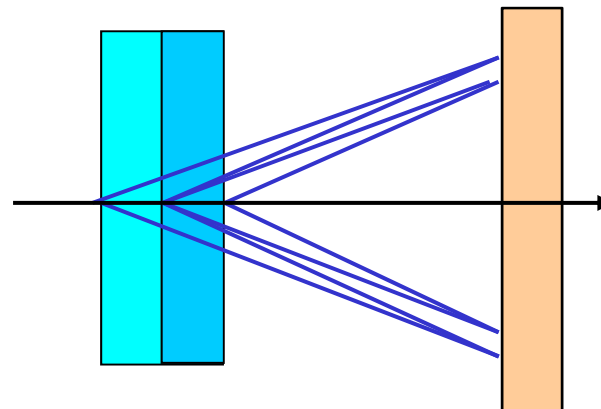
Clear Cherenkov image observed

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  $\sigma$   $\pi/K$  at 4GeV/c !**

Peter Križan, Ljubljana

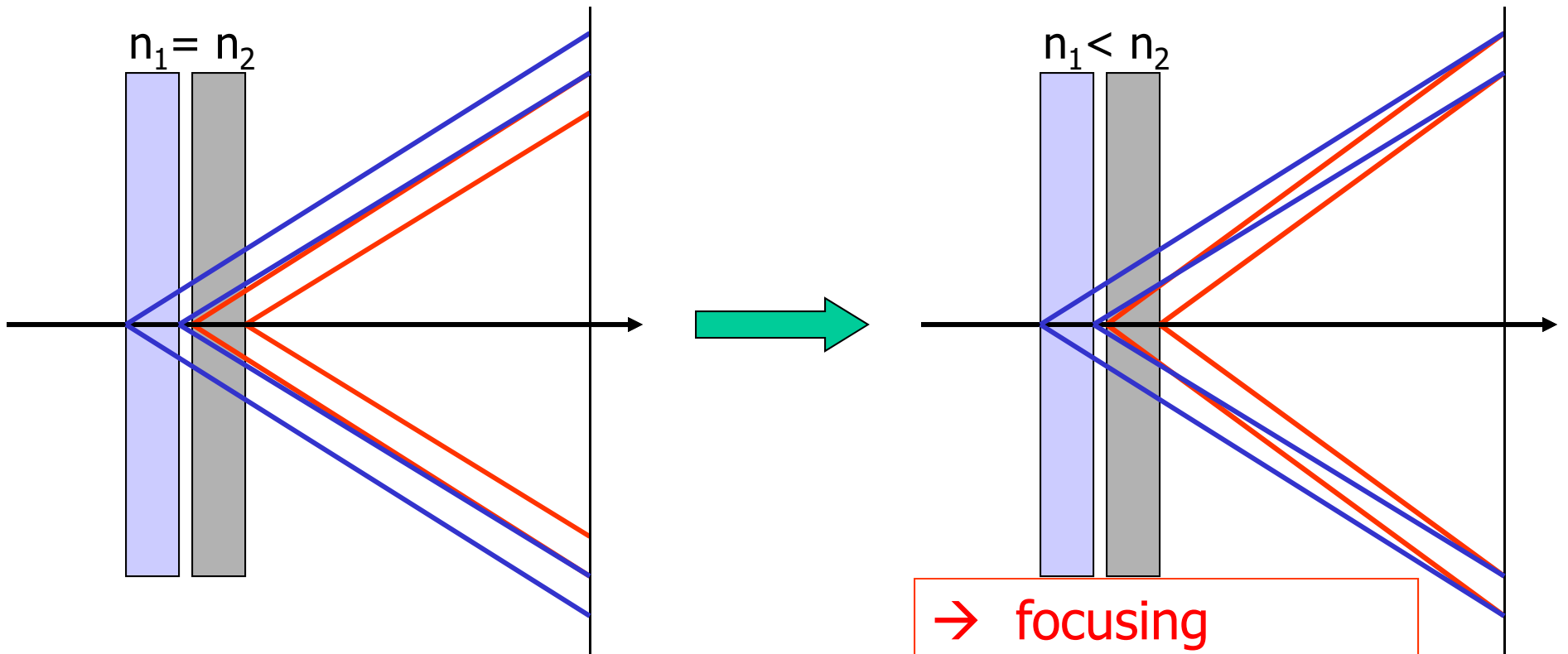


# Radiator with multiple refractive indices

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

→ stack two tiles with different refractive indices: “focusing” configuration

normal



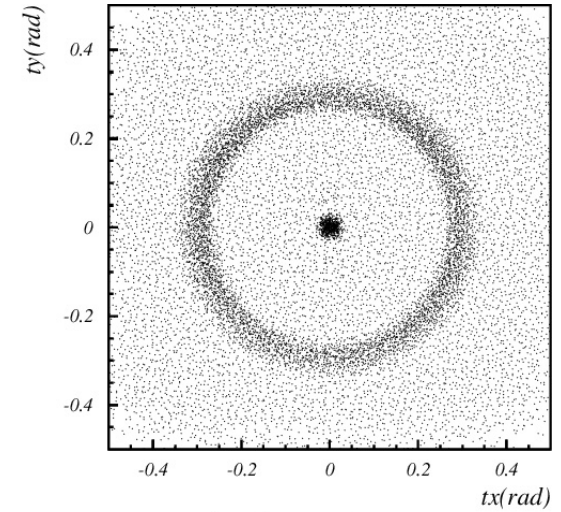
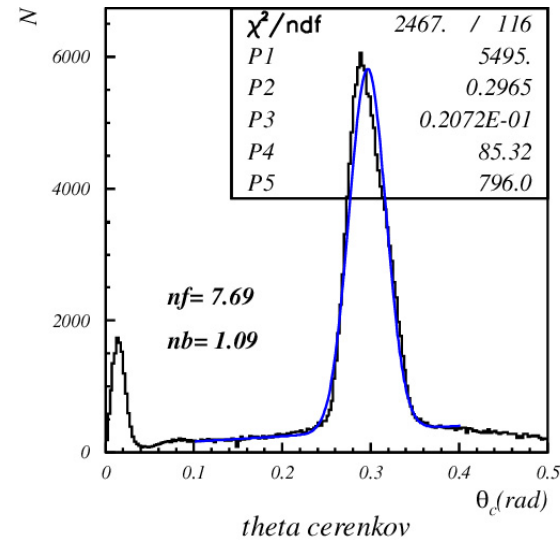
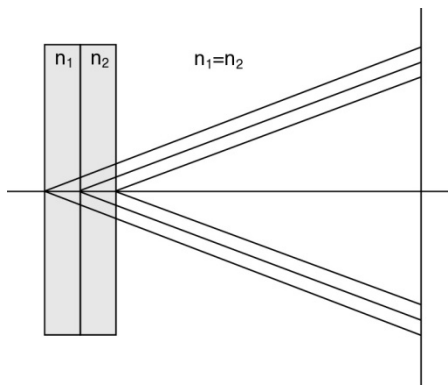
Such a configuration is only possible with aerogel (a form of  $\text{Si}_x\text{O}_y$ ) – material with a tunable refractive index between 1.01 and 1.13.



# Focusing configuration – data

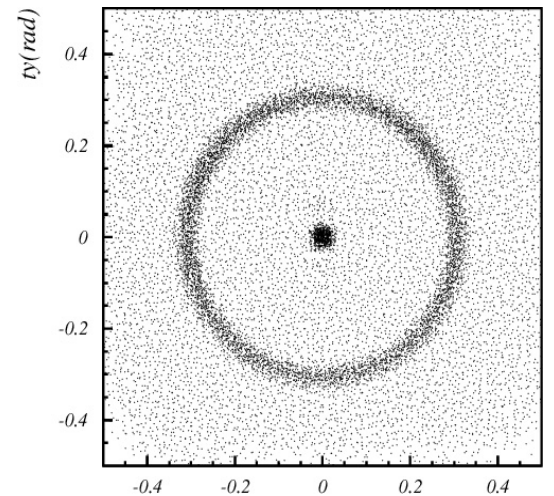
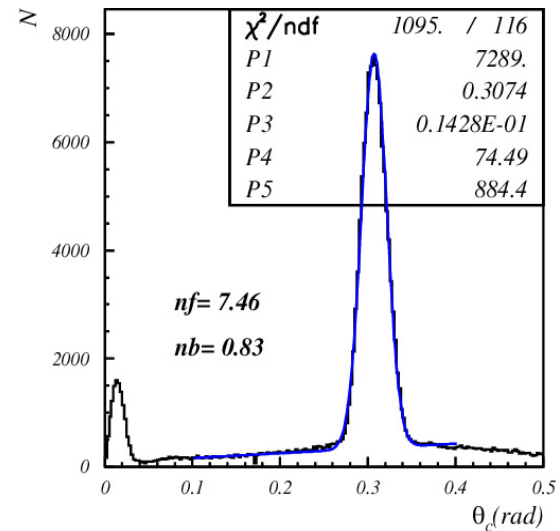
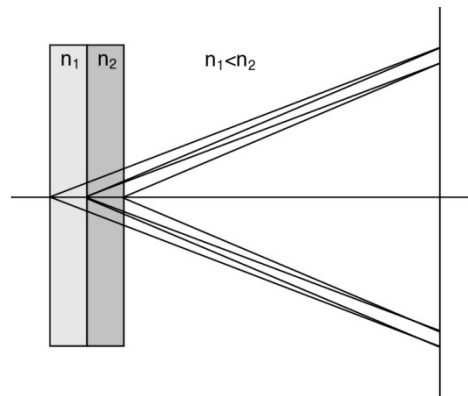
Increases the number of photons without degrading the resolution

## 4cm aerogel single index



ring in cerenkov space

## 2+2cm aerogel

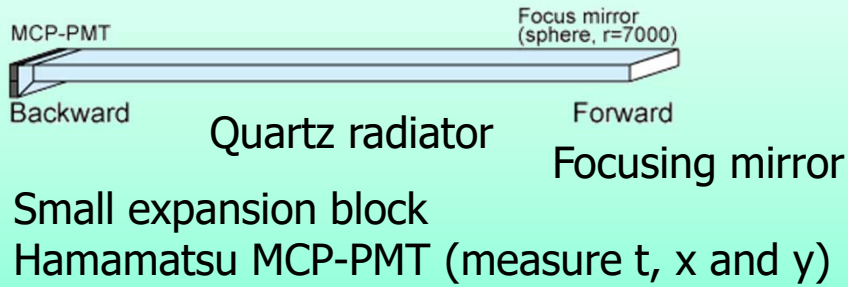


→ NIM A548 (2005) 383

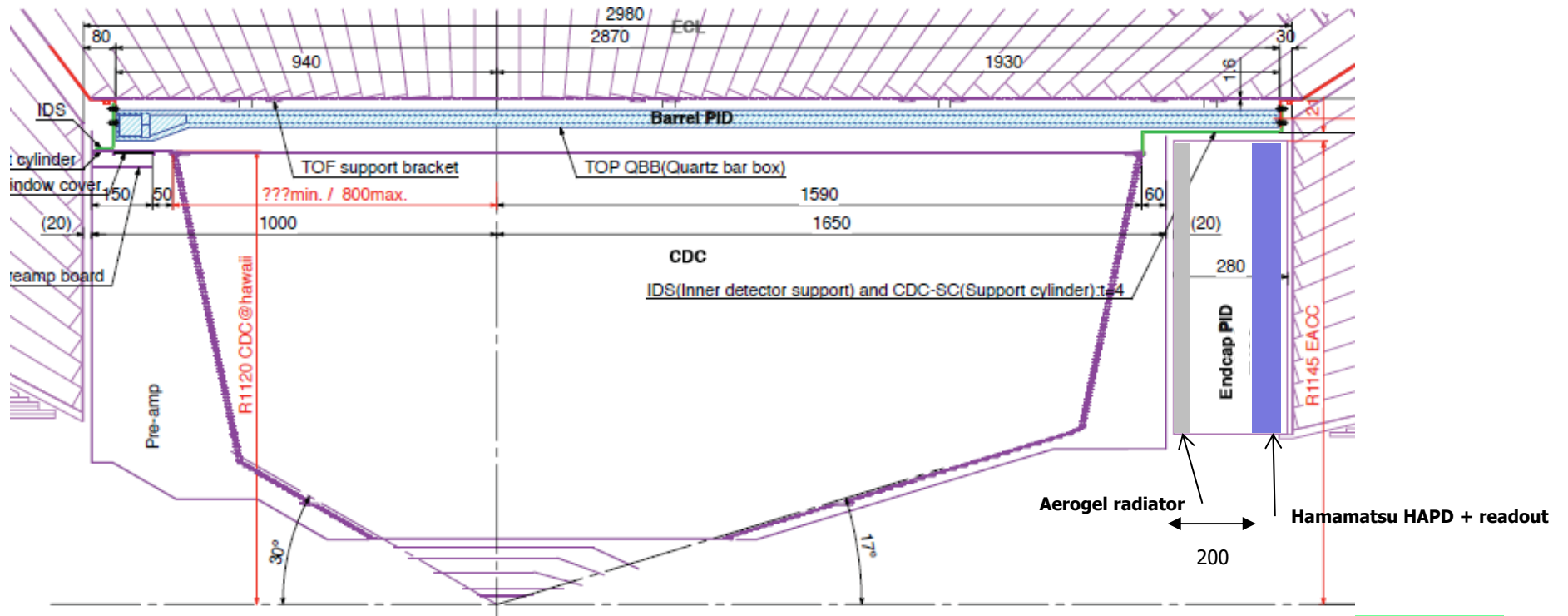
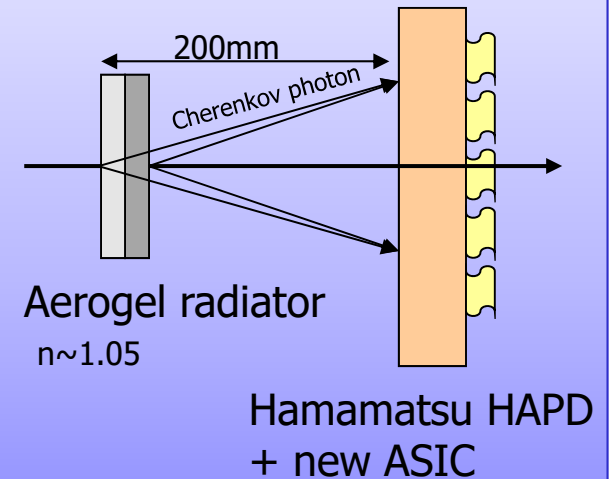


# Cherenkov detectors

## Barrel PID: Time of Propagation Counter (TOP)

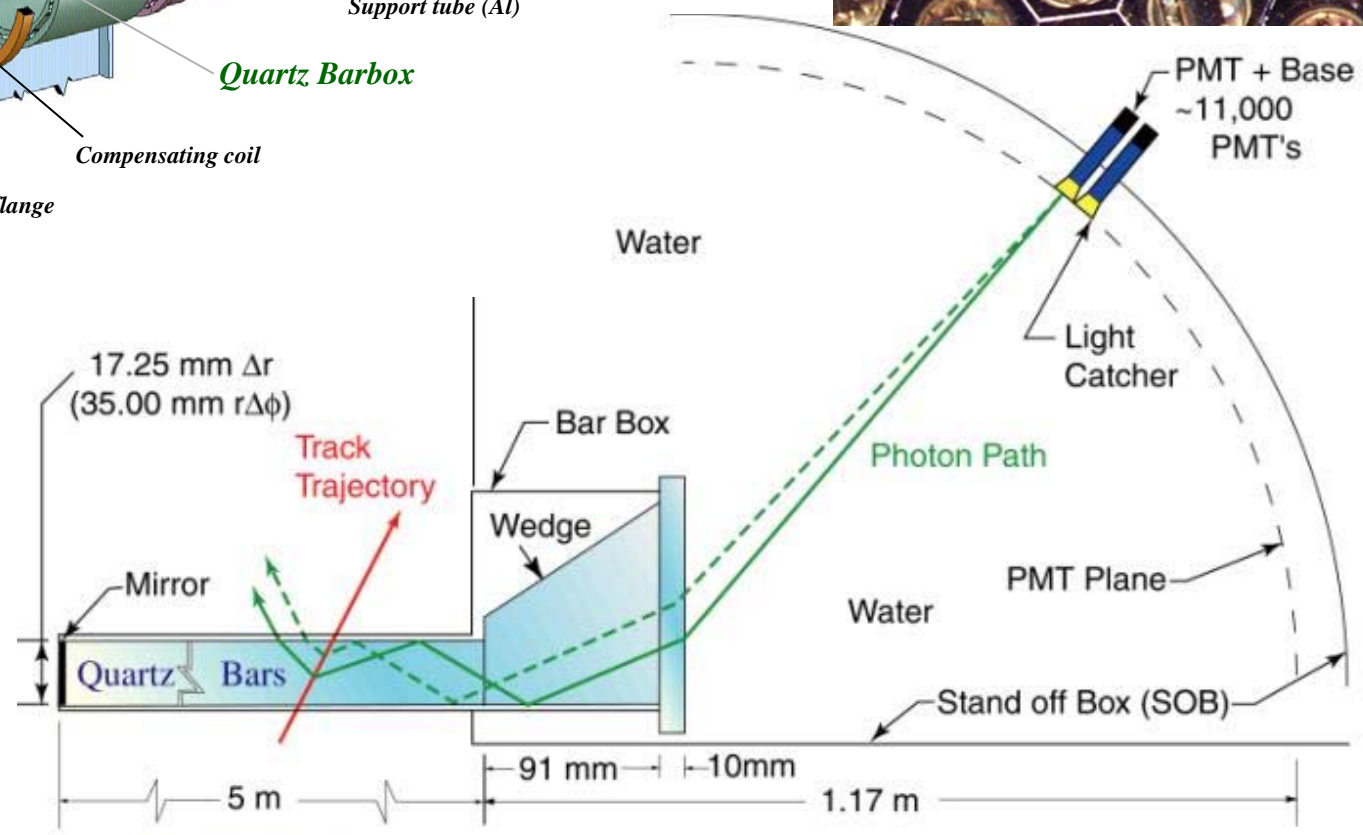
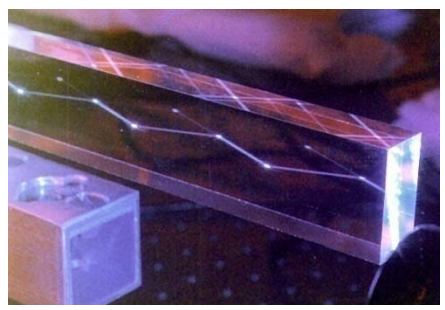
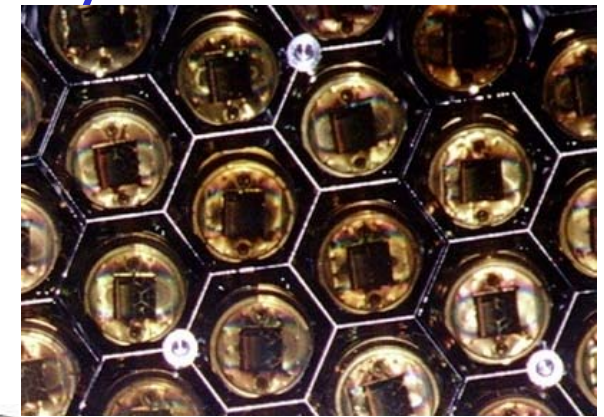
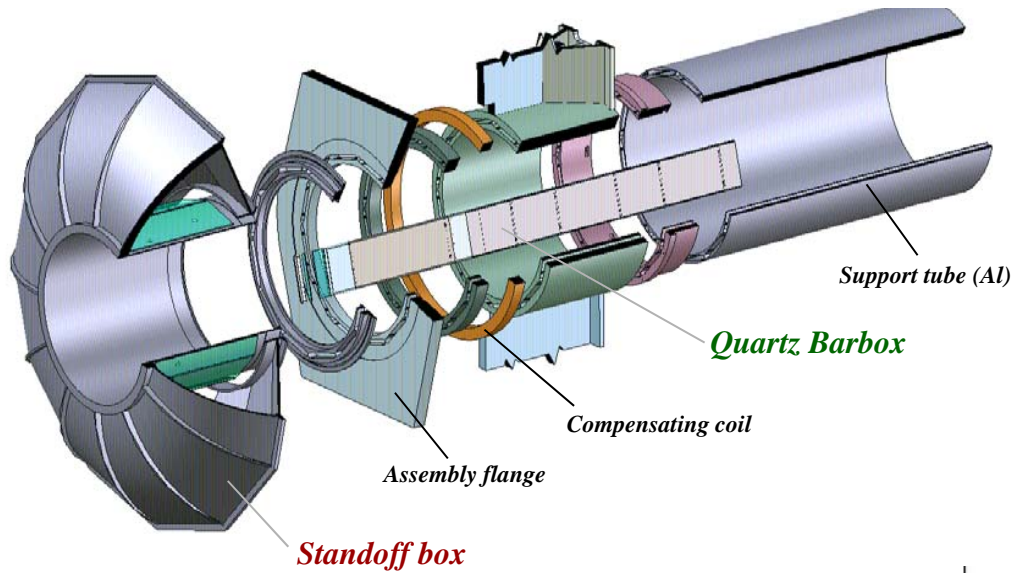


## Endcap PID: Aerogel RICH (ARICH)



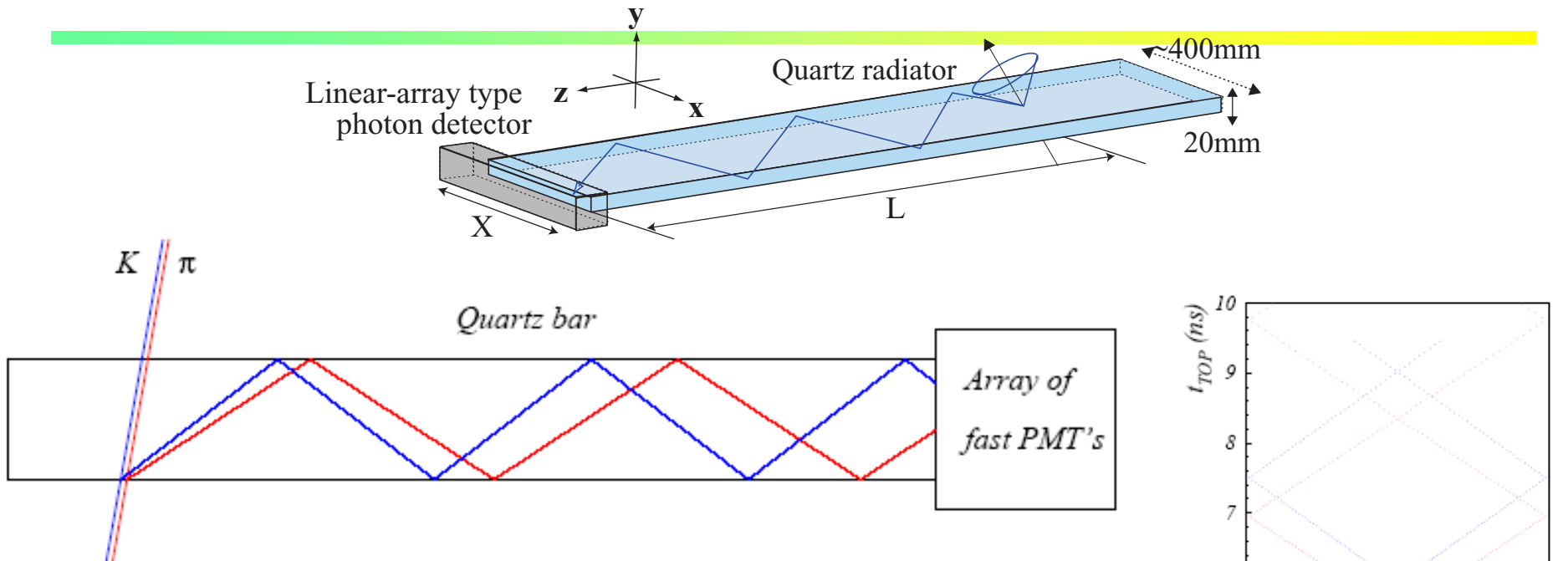
Peter Križan, Ljubljana

# DIRC (@BaBar) - detector of internally reflected Cherenkov light

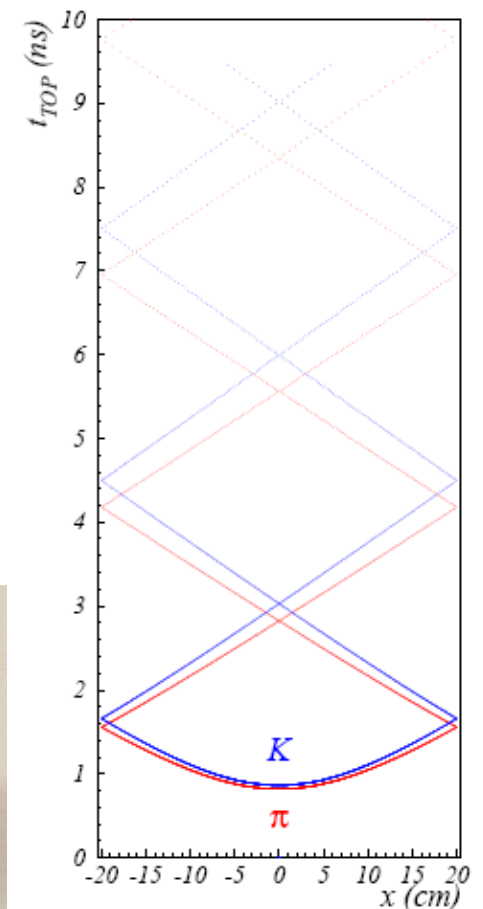
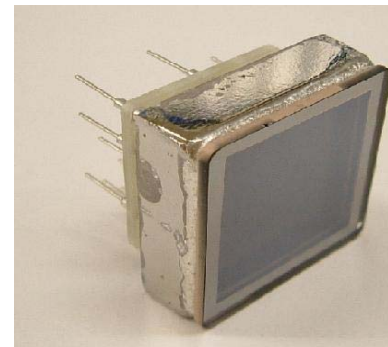


4 x 1.225 m Bars  
 glued end-to-end

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

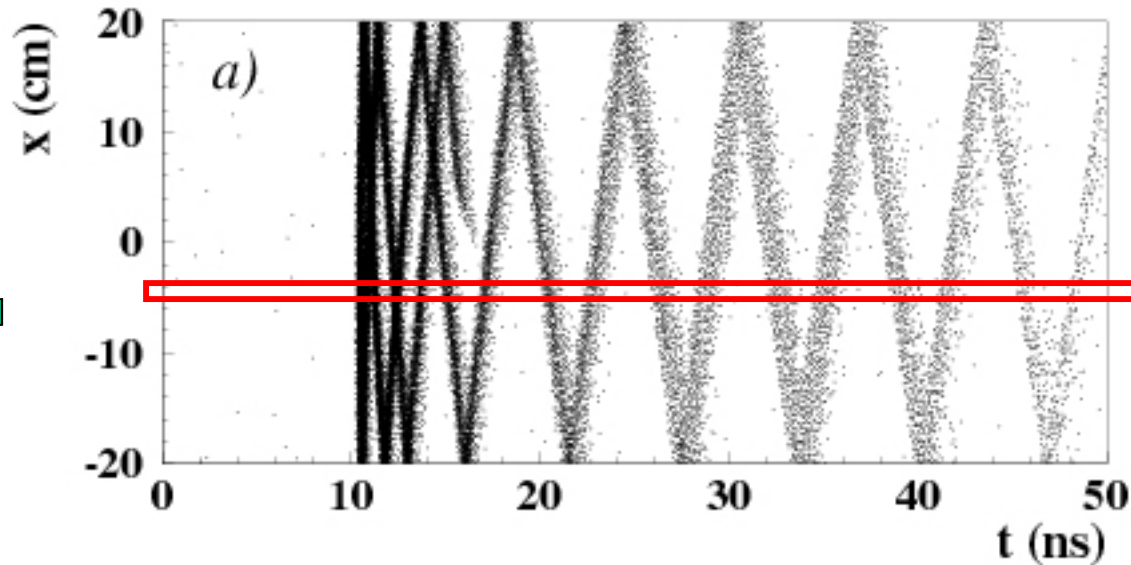


- Cherenkov ring imaging with **precise time measurement**.
- Device uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - **Photon detector (MCP-PMT)**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

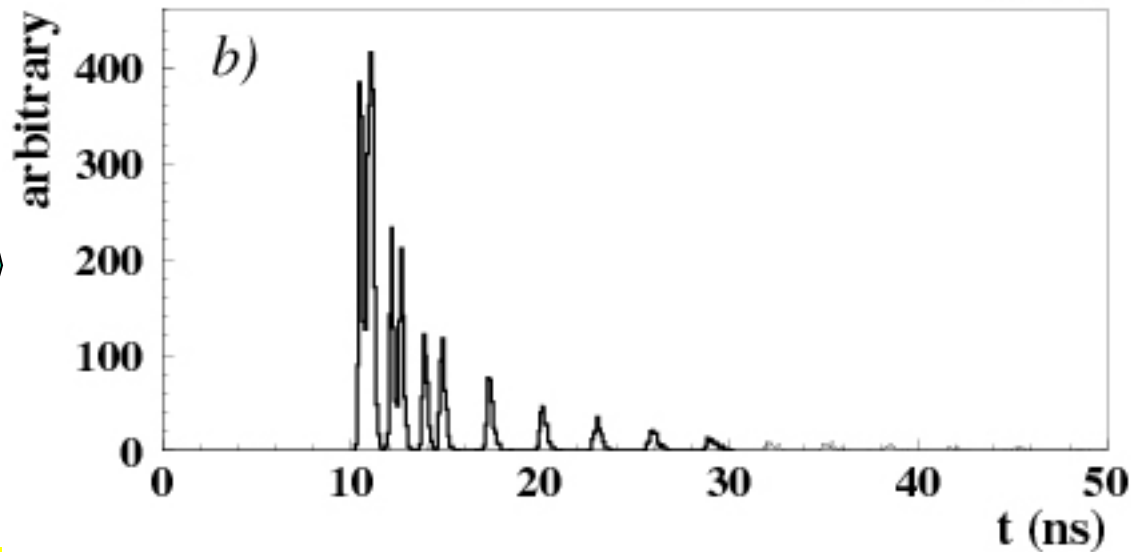




# TOP image



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



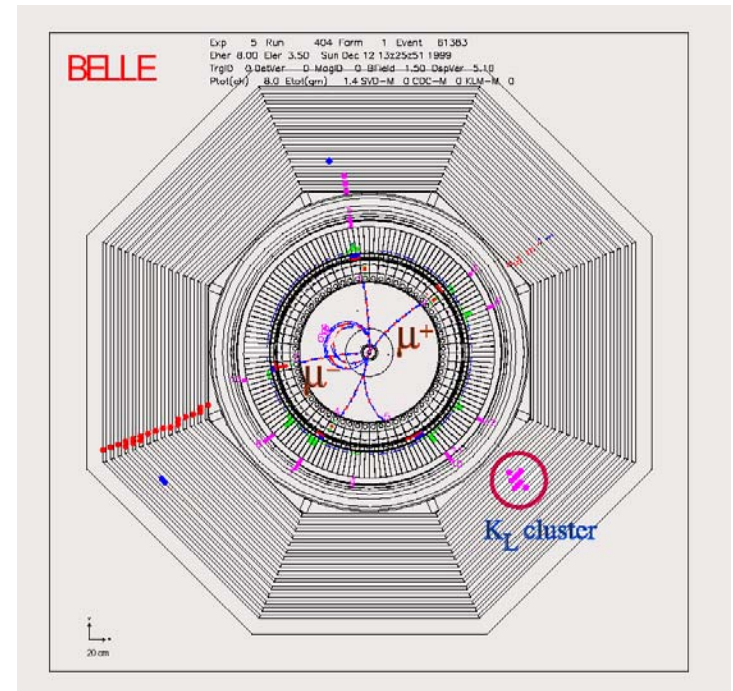
Time distribution of signals recorded by one of the PMT channels: different for  $\pi$  and  $K$  ( $\sim$ shifted in time)

# 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  $\rightarrow$  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.

$\rightarrow$  Put the detector outside the magnet coil, and integrate into the return yoke



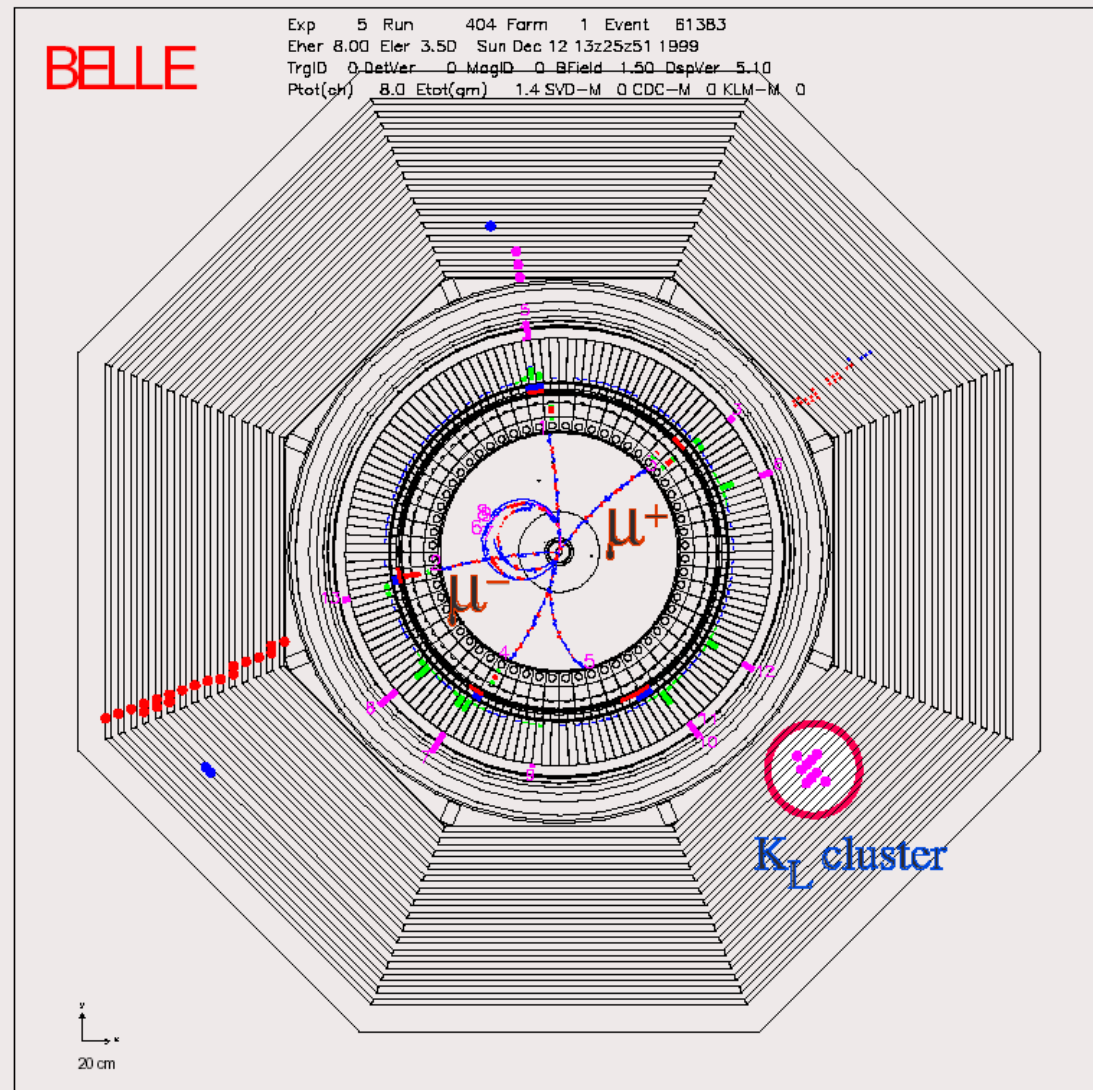
Some numbers: 3.9 interaction lengths (iron) + 0.8 interaction length (CsI)

Interaction length: iron 132 g/cm<sup>2</sup>, CsI 167 g/cm<sup>2</sup>

$(dE/dx)_{\min}$ : iron 1.45 MeV/(g/cm<sup>2</sup>), CsI 1.24 MeV/(g/cm<sup>2</sup>)  $\rightarrow \Delta E_{\min} = (0.36+0.11)$  GeV = 0.47 GeV  $\rightarrow$  identification of muons above  $\sim 600$  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

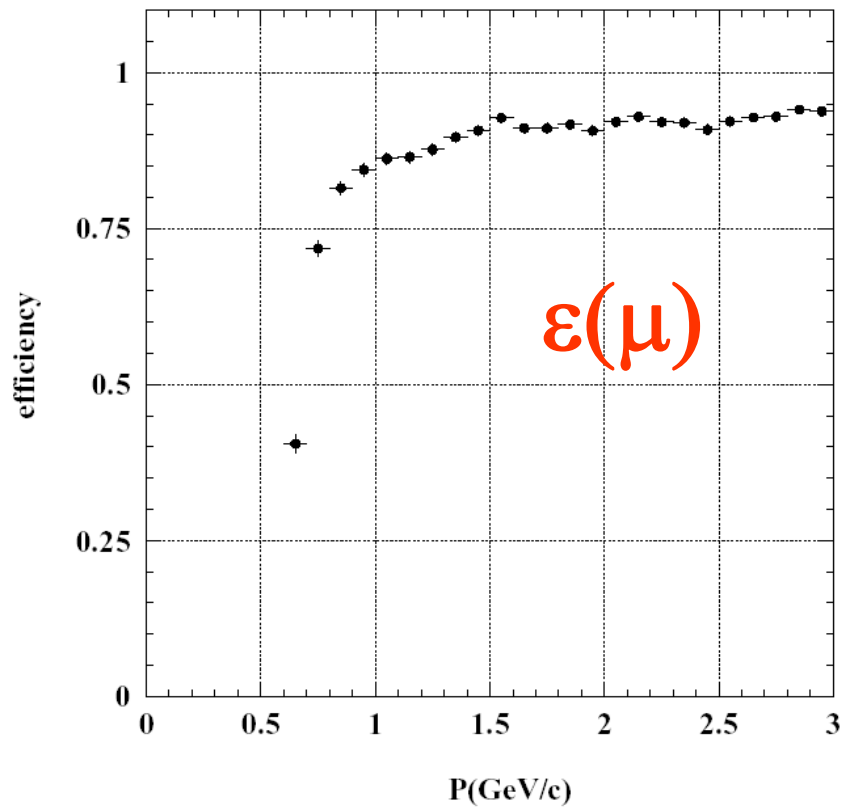


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

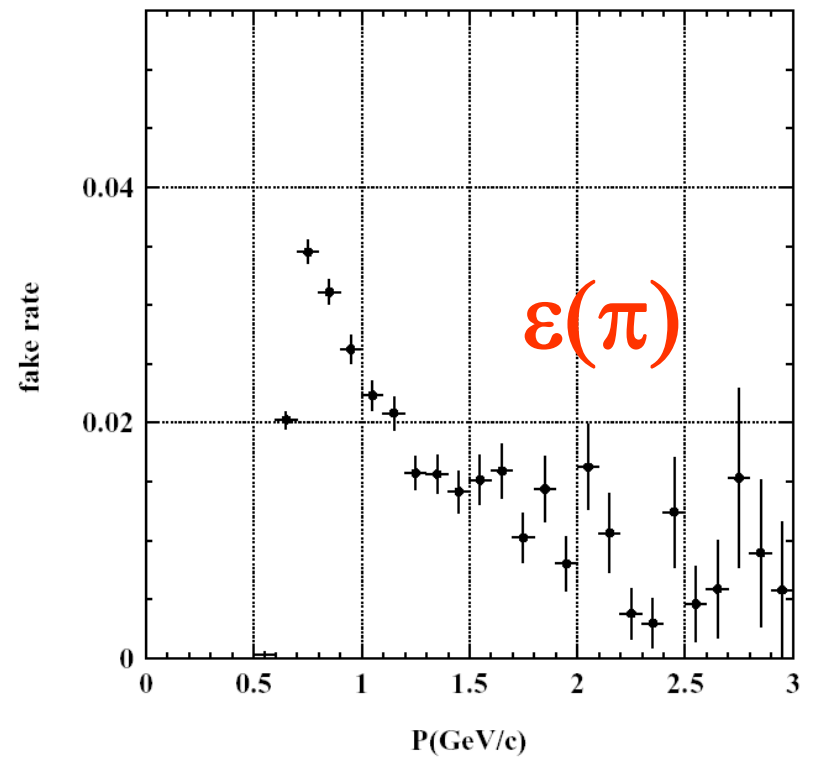


Fig. 110. Fake rate vs. momentum in KLM.

# $K_L$ detector performance

$K_L$  detection: resolution in direction →

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

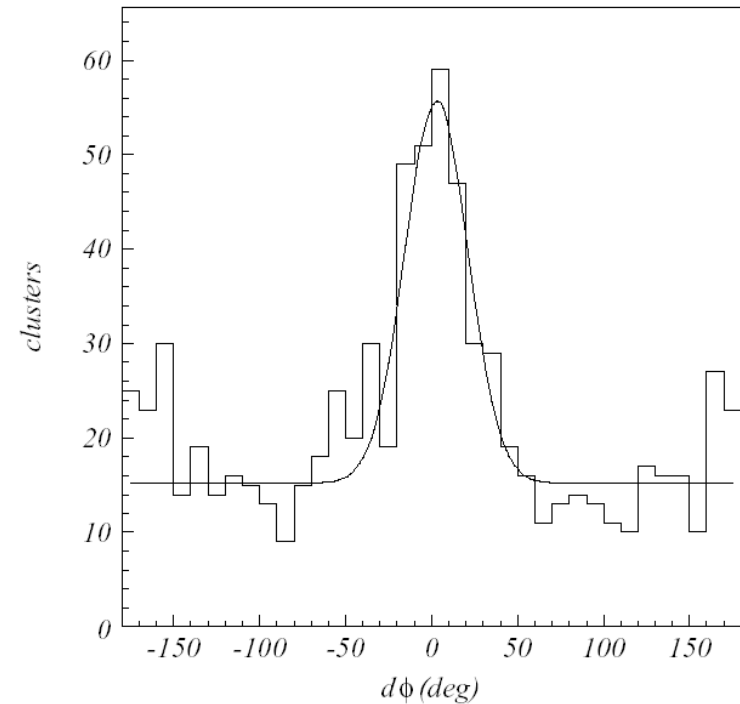
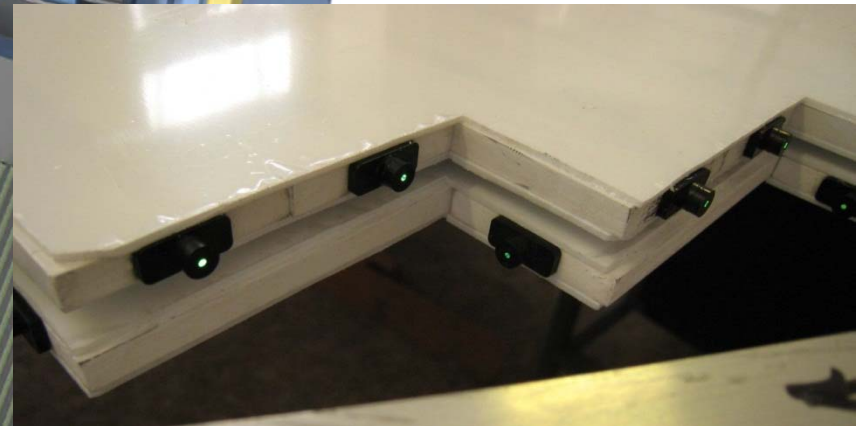
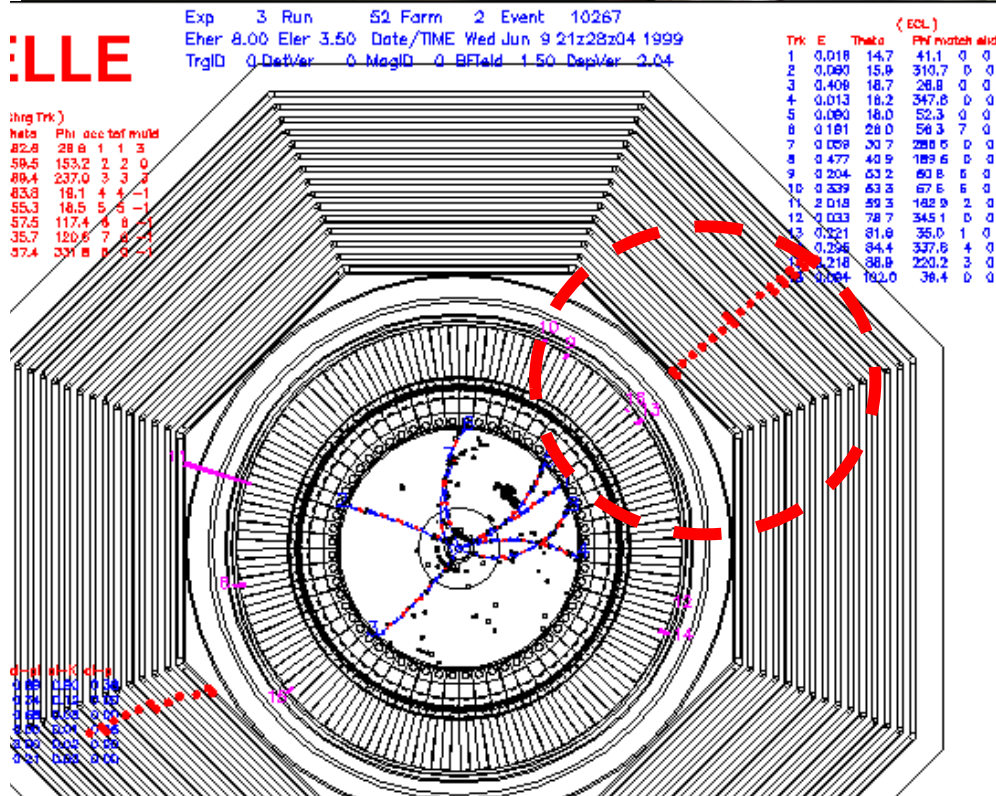
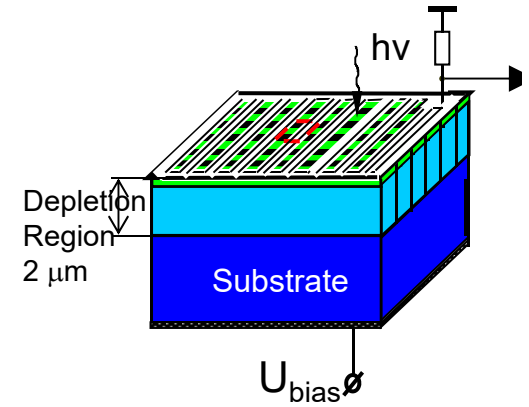
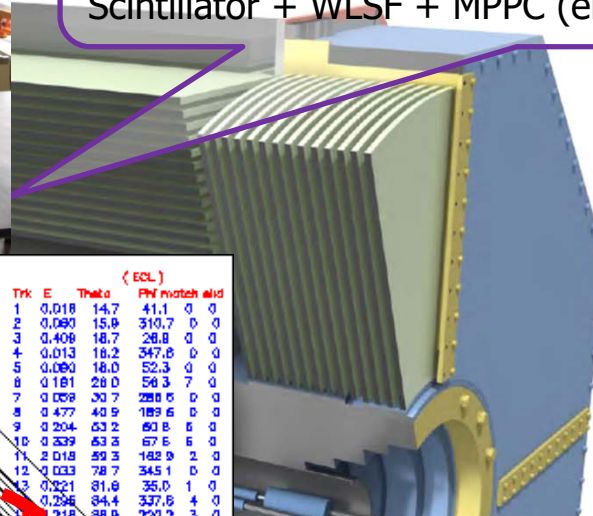
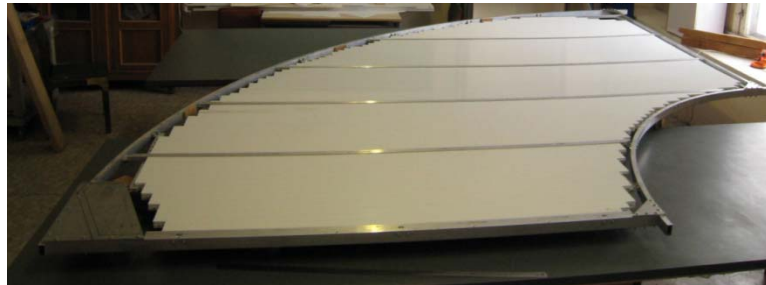


Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

Belle II, detection of **muons and  $K_L$ s**: 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)

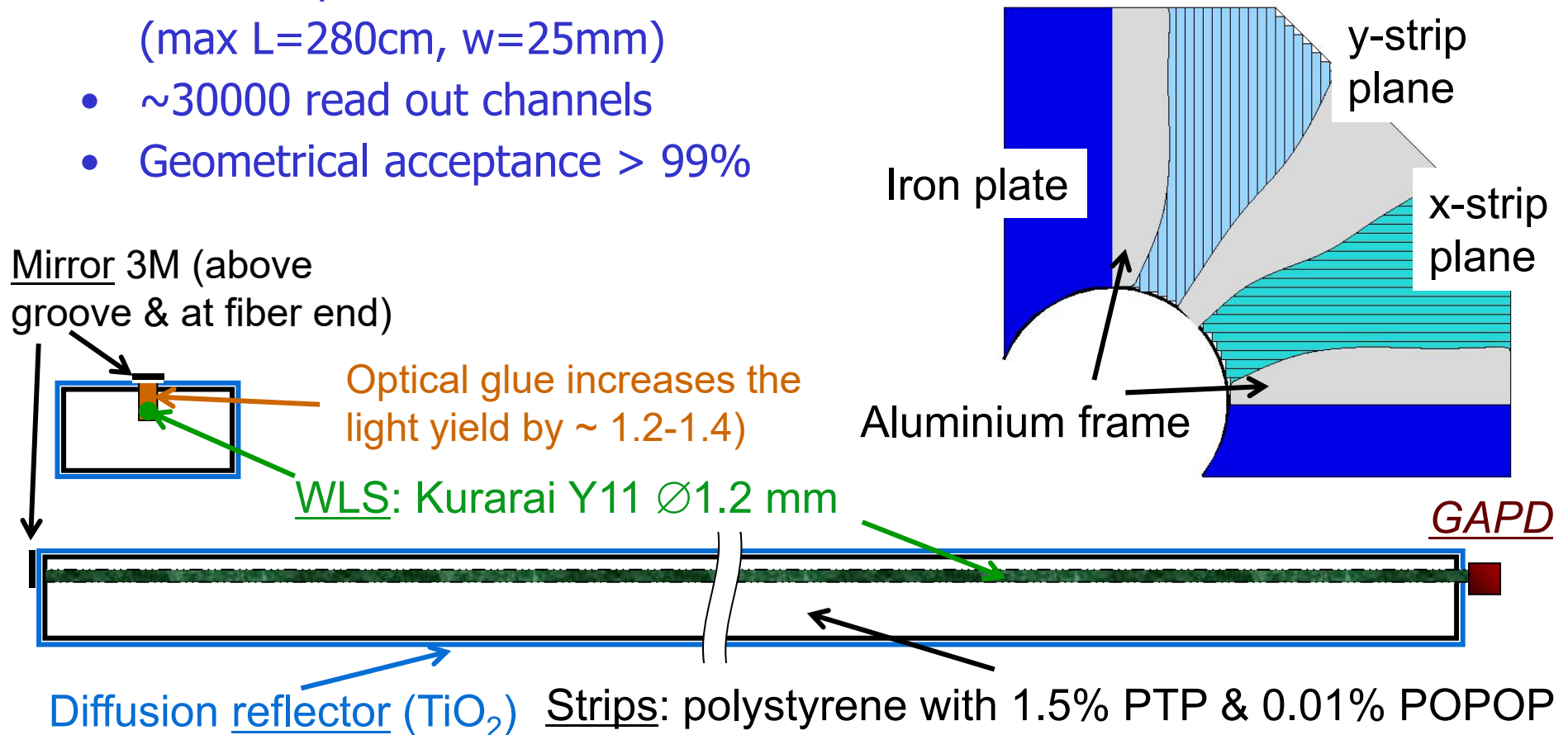


ljana

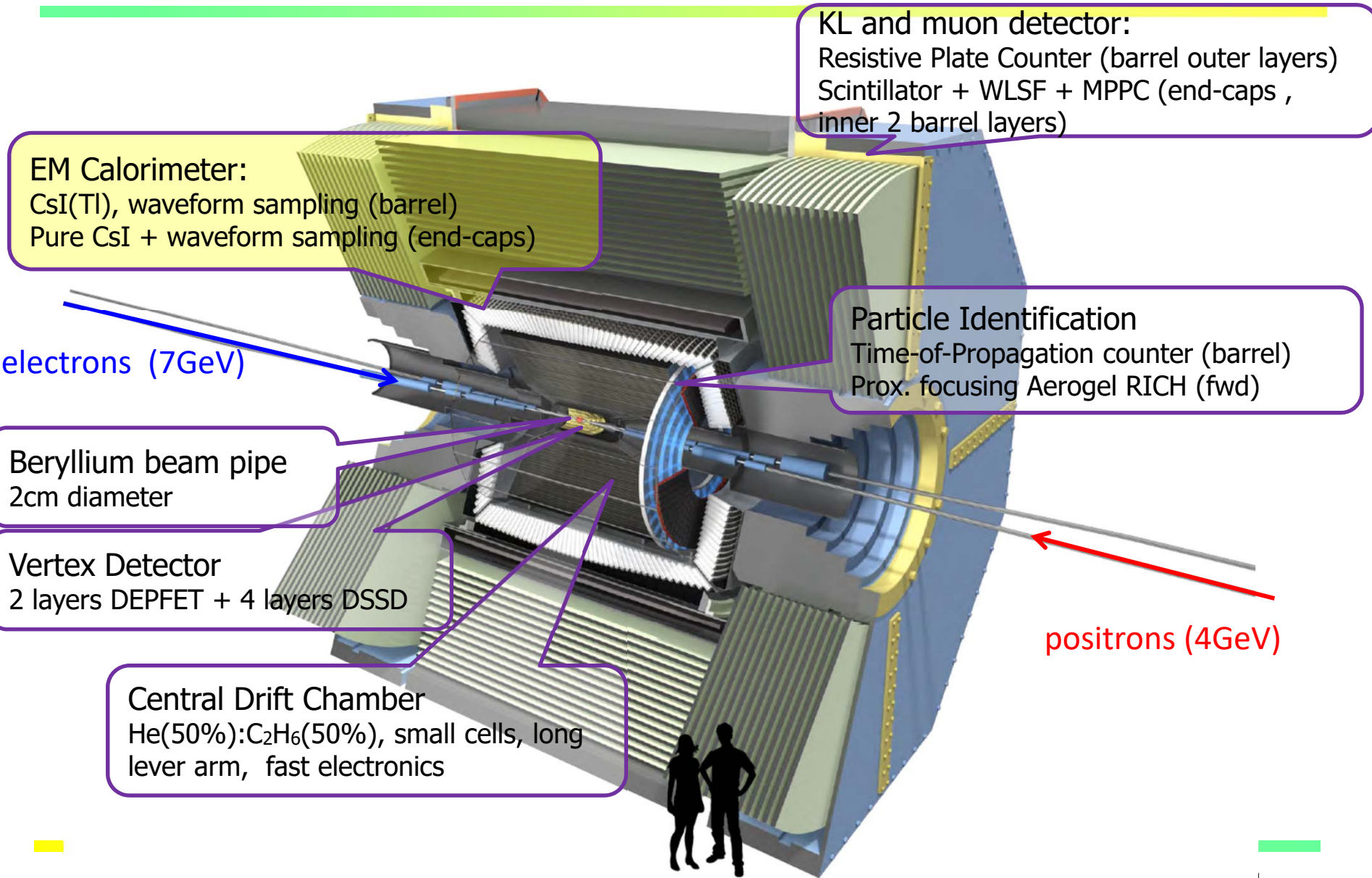
# Muon detection system upgrade in the endcaps

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)
- $\sim 120$  strips in one  $90^\circ$  sector (max  $L=280\text{cm}$ ,  $w=25\text{mm}$ )
- $\sim 30000$  read out channels
- Geometrical acceptance  $> 99\%$

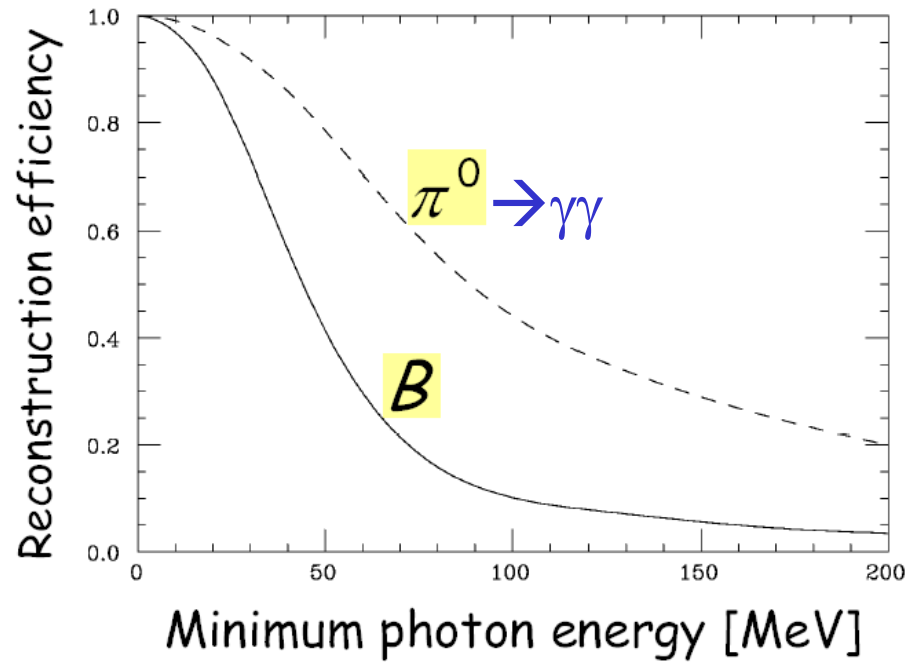
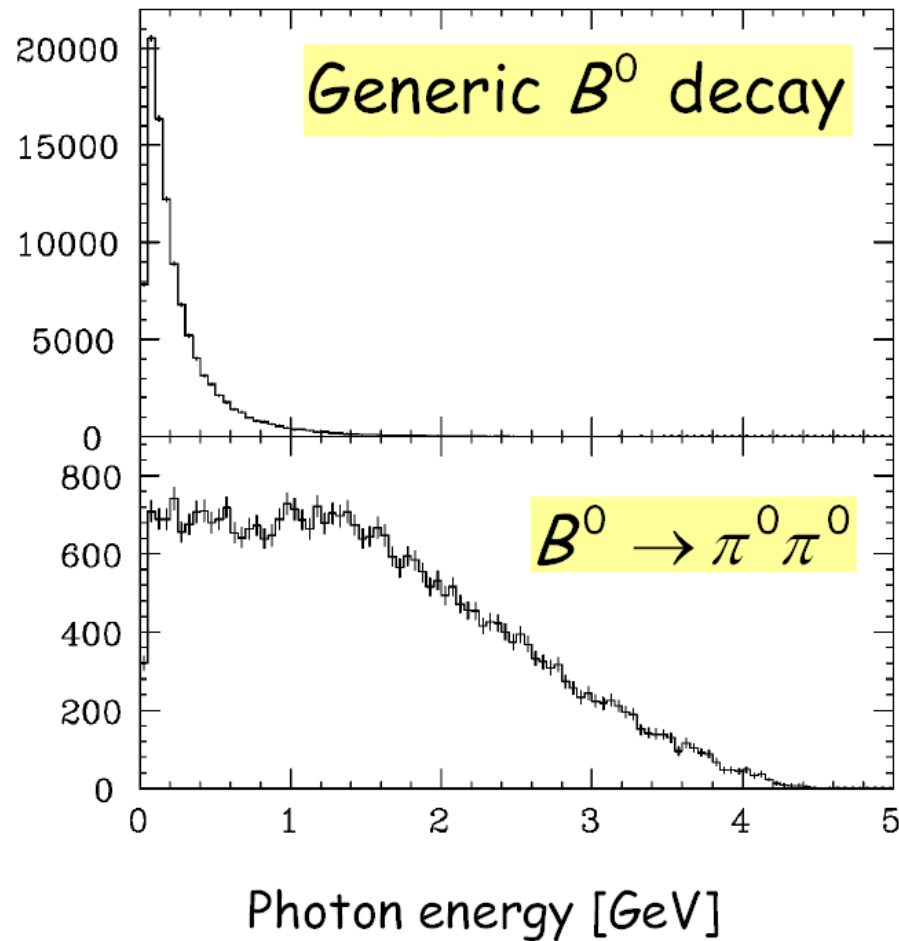


# Calorimetry in Belle II





# Requirements: Photons

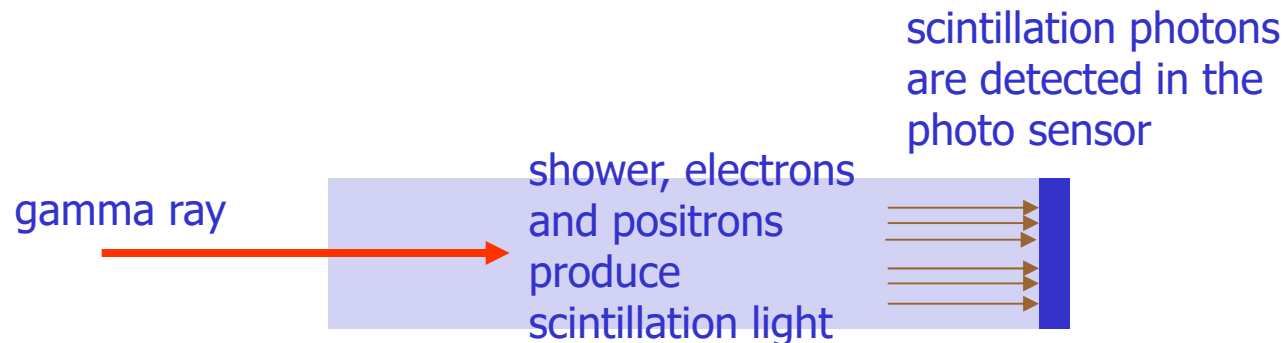


# Requirements: Photons

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

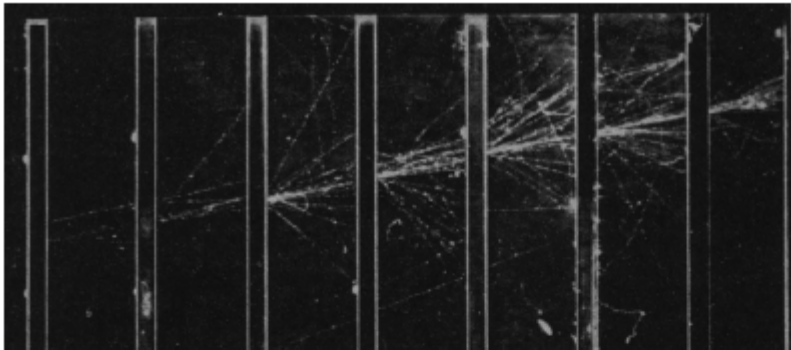
- Should also work for low energy gammas (photons)
- Excellent energy resolution

Detection of photons: scintillator crystal + photosensor

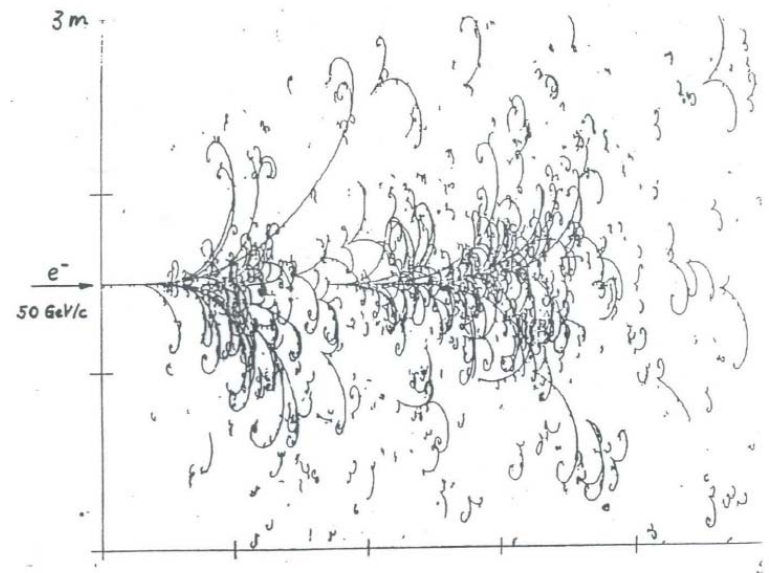


How does a shower develop? Gamma  $\rightarrow$  e+e- pair production  $\rightarrow$  bremsstrahlung gammas  $\rightarrow$  e+e- pair production  $\rightarrow$  ....

## Electromagnetic Cascades (showers)

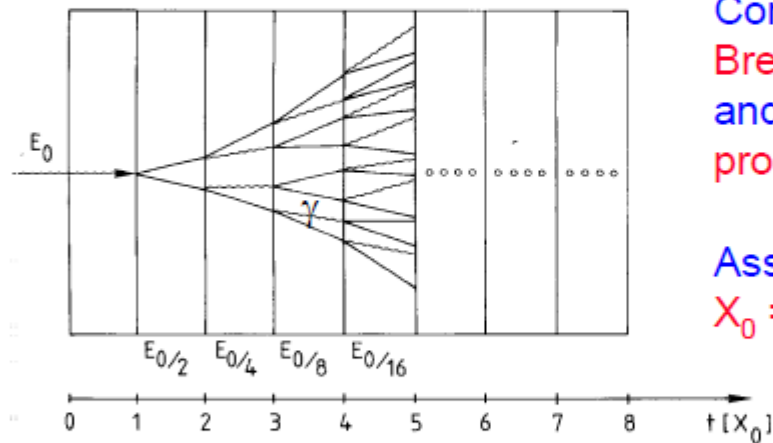


Electron shower in a cloud chamber with lead absorbers



B E B C , Ne / H<sub>2</sub> (70/30%) , B = 3T  
ELECTROMAGNETIC SHOWER DEVEL.

### Simple qualitative model



Consider only  
Bremsstrahlung  
and pair  
production.

Assume:  
 $X_0 = \lambda_{\text{pair}}$

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

Process continues until  $E(t) < E_c$

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

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

$\rightarrow$  Calorimeter size depends only logarithmically on  $E_0$

Peter Križan, Ljubljana

◆ Energy resolution of a calorimeter (intrinsic limit)

$$N^{total} \propto \frac{E_0}{E_c} \quad \text{total number of track segments}$$

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N)}{N} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E_0}} \quad \text{holds also for hadron calorimeters}$$

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

Noise term

Inhomogenities  
Bad cell inter-calibration  
Non-linearities

Electronic noise  
radioactivity  
pile up

Quality factor !

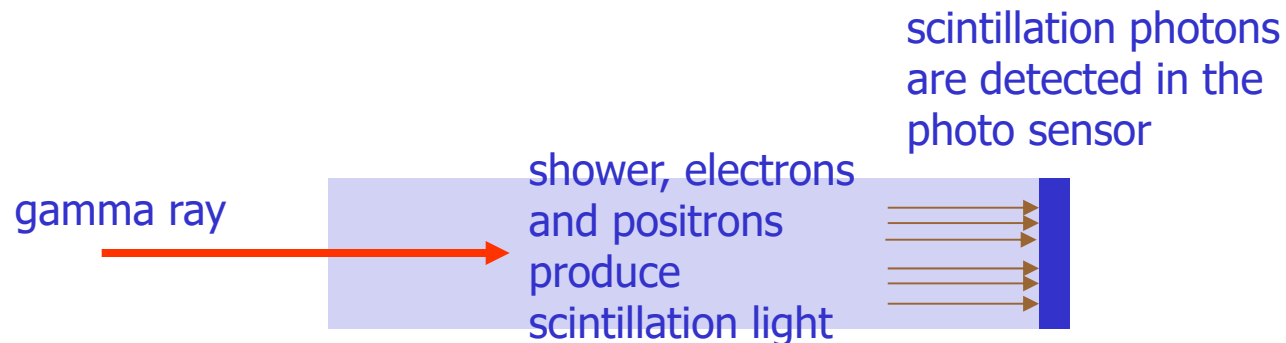
## Requirements: Photons



Need to reconstruct neutral pions from gamma pairs

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

Detection of photons: scintillator crystal + photosensor



Need:

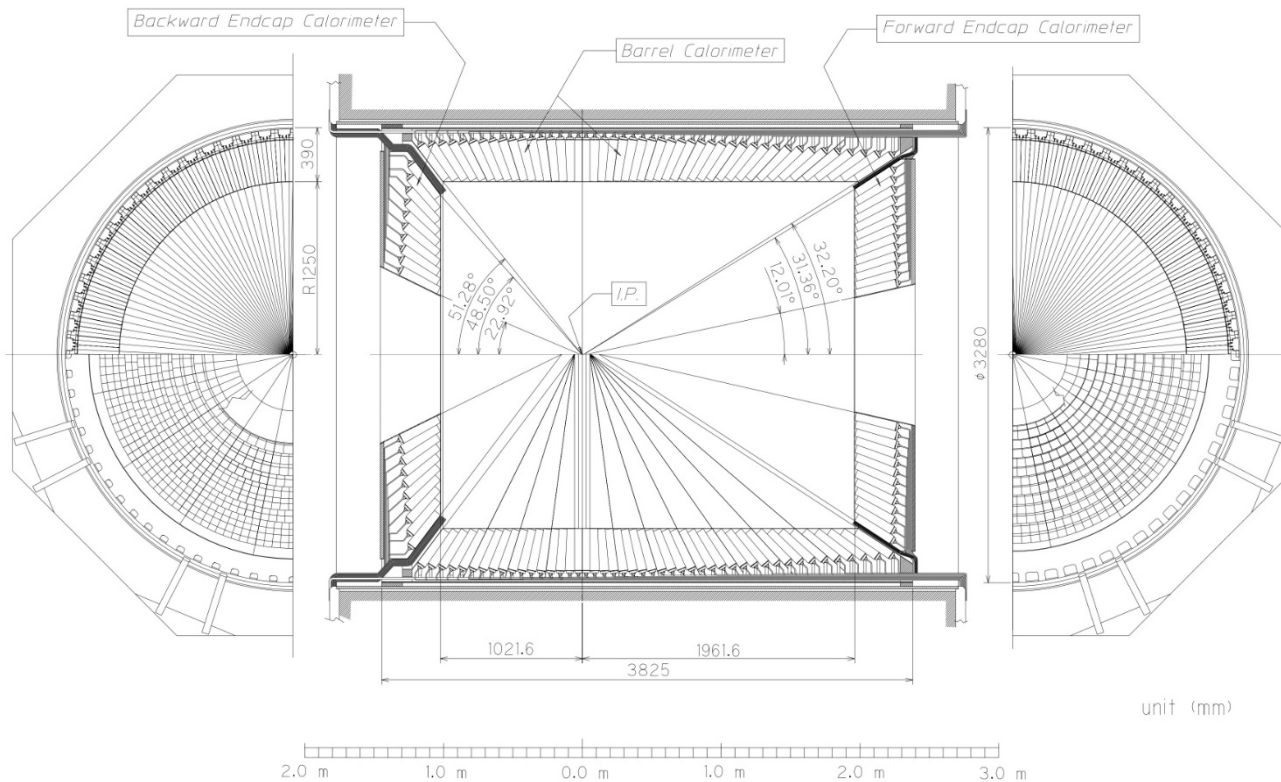
- High light yield (many scintillation photons)  $\leftarrow \sigma(E)/E \propto N^{-1/2}$
- photo-sensor with low noise (noise spoils resolution)

Scintillator material	Density (g/cm <sup>3</sup> )	Radiation length	Refractive index	Wavelength at peak	Decay time	Light yield (Y/MeV)
NaI (TI)	3.67	2.59 cm	1.78	410 nm	230 ns	4.1 x10 <sup>4</sup>
CsI (TI)	4.51	1.86 cm	1.85	550 nm	800–6000 ns	6.6 x10 <sup>4</sup>
CsI (Na)	4.51	1.86 cm	1.80	420 nm	630 ns	4.0 x10 <sup>4</sup>
LaBr <sub>3</sub> (Ce)	5.3	1.88 cm	1.9	358 nm	35 ns	6.1 x10 <sup>4</sup>
Bi <sub>4</sub> Si <sub>3</sub> O <sub>12</sub> <b>BSO</b>	6.8	1.15 cm	2.06	480 nm	100 ns	0.2 x10 <sup>4</sup>
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub> <b>BGO</b>	7.1	1.12 cm	2.15	480 nm	300 ns	0.9 x10 <sup>4</sup>
CdWO <sub>4</sub>	7.9	1.1 cm	2.25	495 nm	5000 ns	2.0 x10 <sup>4</sup>
YAlO <sub>3</sub> (Ce) <b>YAP</b>	5.5	2.9 cm	1.94	350 nm	30 ns	2.1 x10 <sup>4</sup>
Lu <sub>3</sub> Al <sub>5</sub> O <sub>7</sub> (Ce) <b>LuAG</b>	7.4	1.4 cm	1.84	420 nm	40 ns	2.6 x10 <sup>4</sup>
Gd <sub>2</sub> SiO <sub>5</sub> (Ce) <b>GSO</b>	6.7	1.4 cm	1.87	440 nm	60 ns	0.8 x10 <sup>4</sup>
PbWO <sub>4</sub>	8.3	0.89 cm	1.82	425 nm	25 ns	0.05 x10 <sup>4</sup>

# Calorimeter with CsI(Tl) crystals

Doping with tallium improves the light yield

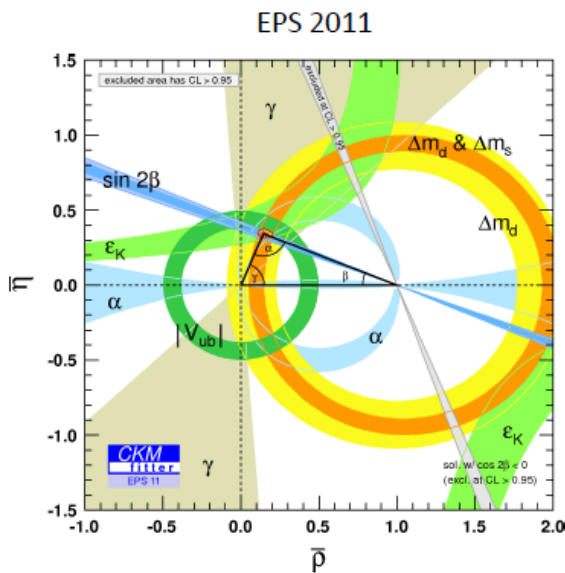
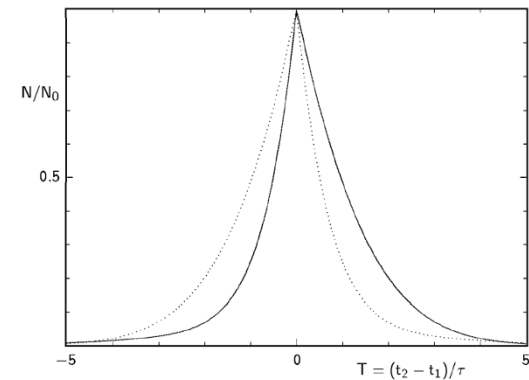
## BELLE CsI ELECTROMAGNETIC CALORIMETER



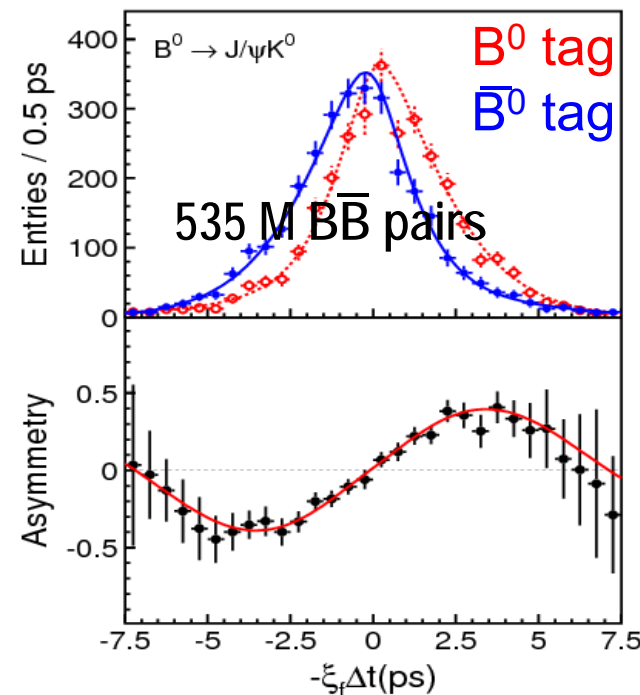
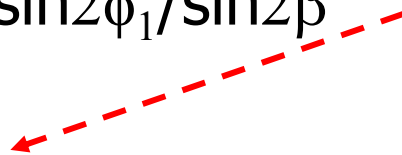
# B factories, main result: CP violation in the B system

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

$\sin 2\phi_1 / \sin 2\beta$  from  $B \rightarrow J/\psi K_S$



$\sin 2\phi_1 / \sin 2\beta$

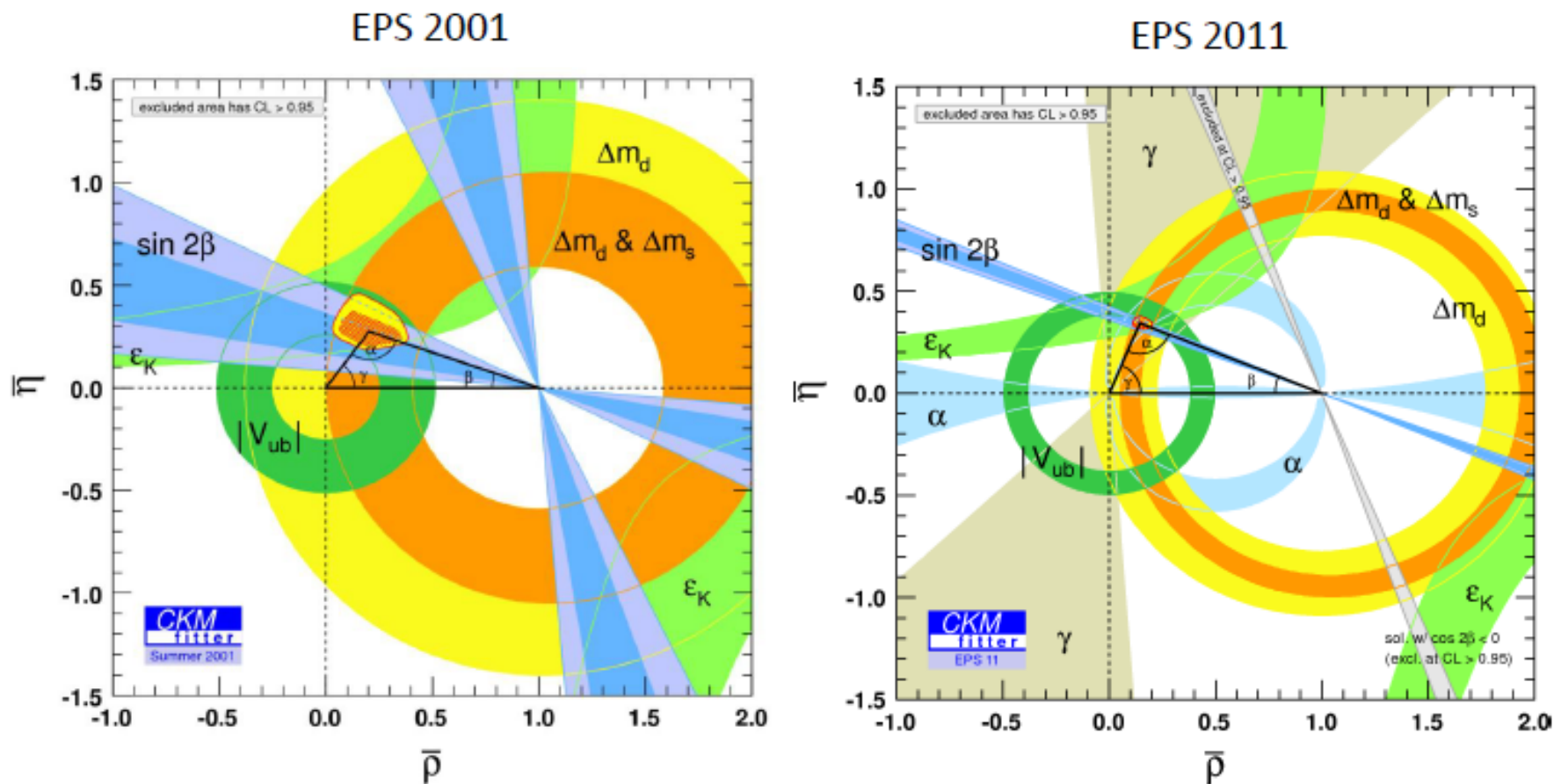


Constraints from many different measurements of angles and sides of the unitarity triangle  $\rightarrow$  **Remarkable agreement**



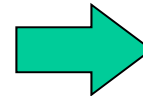
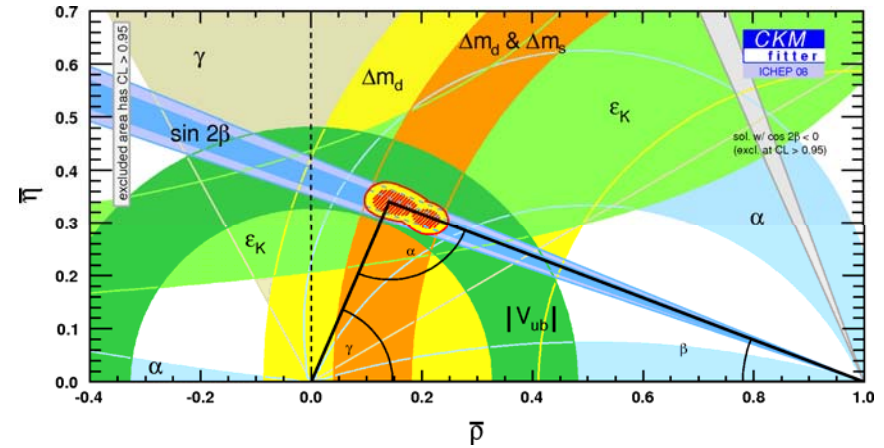
# Unitarity triangle – 2011 vs 2001

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

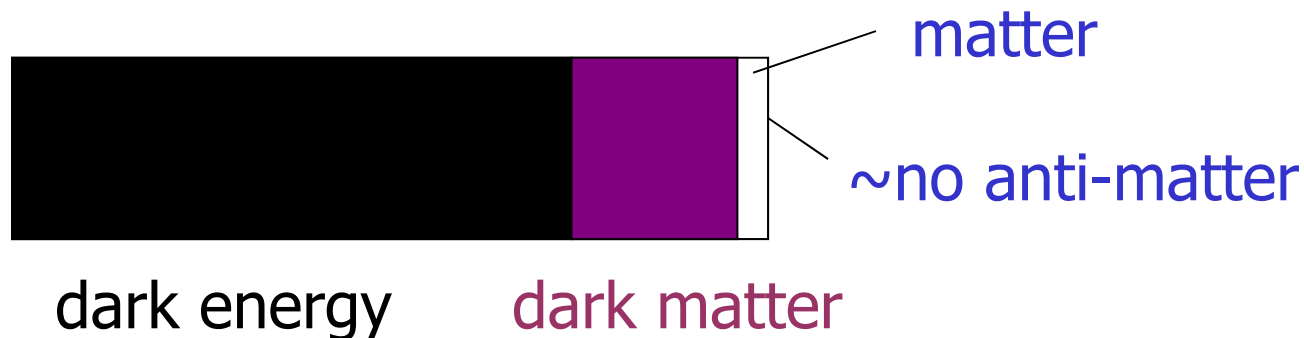
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- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g.,  $B \rightarrow \tau \nu$ ,  $D \tau \nu$ )
- $b \rightarrow s$  transitions: probe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

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

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- 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.

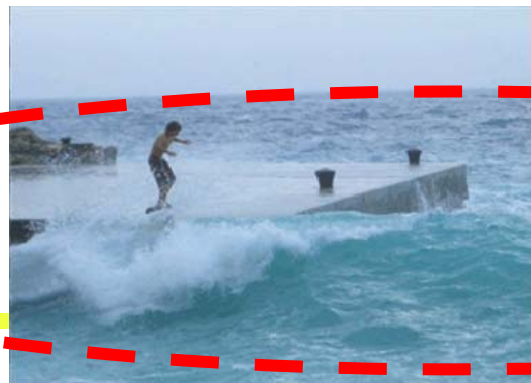
**Intensity frontier** : search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

→ 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.

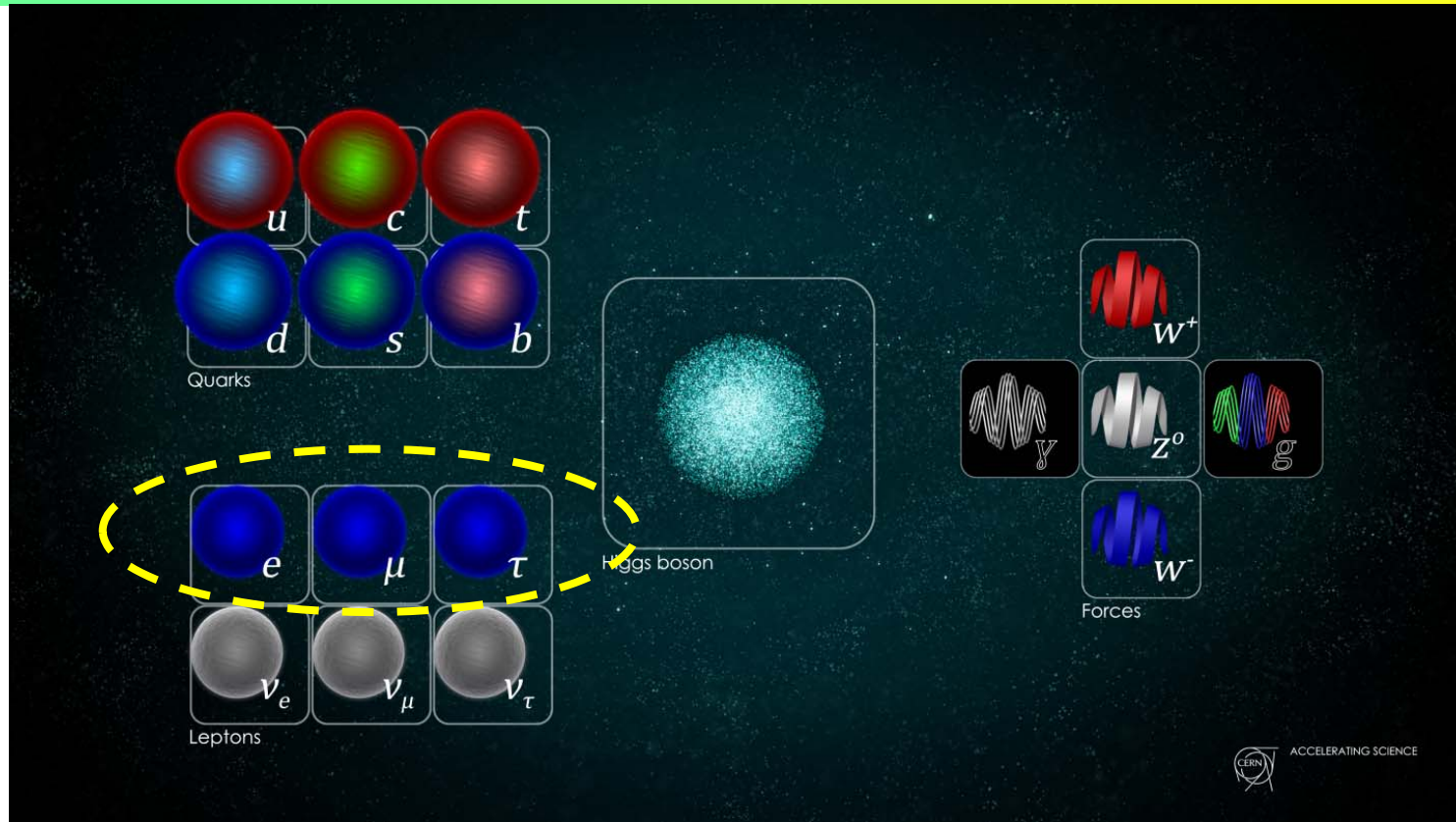
**Energy frontier (LHC)**



**Luminosity frontier  
(Belle and Belle II)**

Peter Križan, Ljubljana

# Standard Model: Lepton Flavour Universality



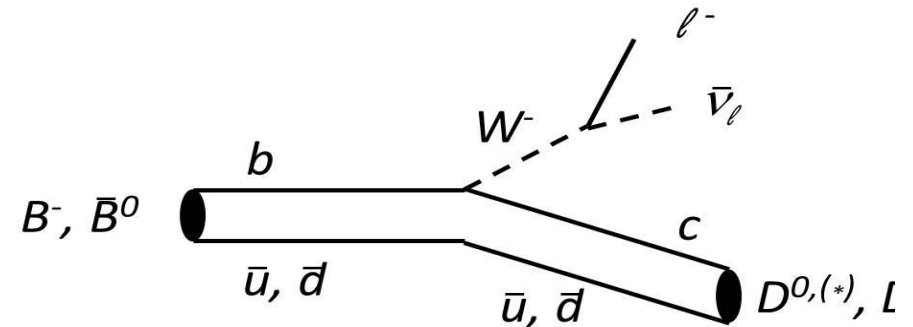
One of the cornerstones of the Standard model (verified by experiments):  
Lepton Flavour Universality (LFU) - interactions of leptons do not depend  
on their flavour

=  $e^-$ ,  $\mu^-$ ,  $\tau^-$  should behave in the same way

▪

# Anomalies in $B \rightarrow D^* \tau \nu$

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



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

$\rightarrow$  Same for electrons, muons and tau leptons

Compare the final state with a  $\tau$  to the one with e or  $\mu$

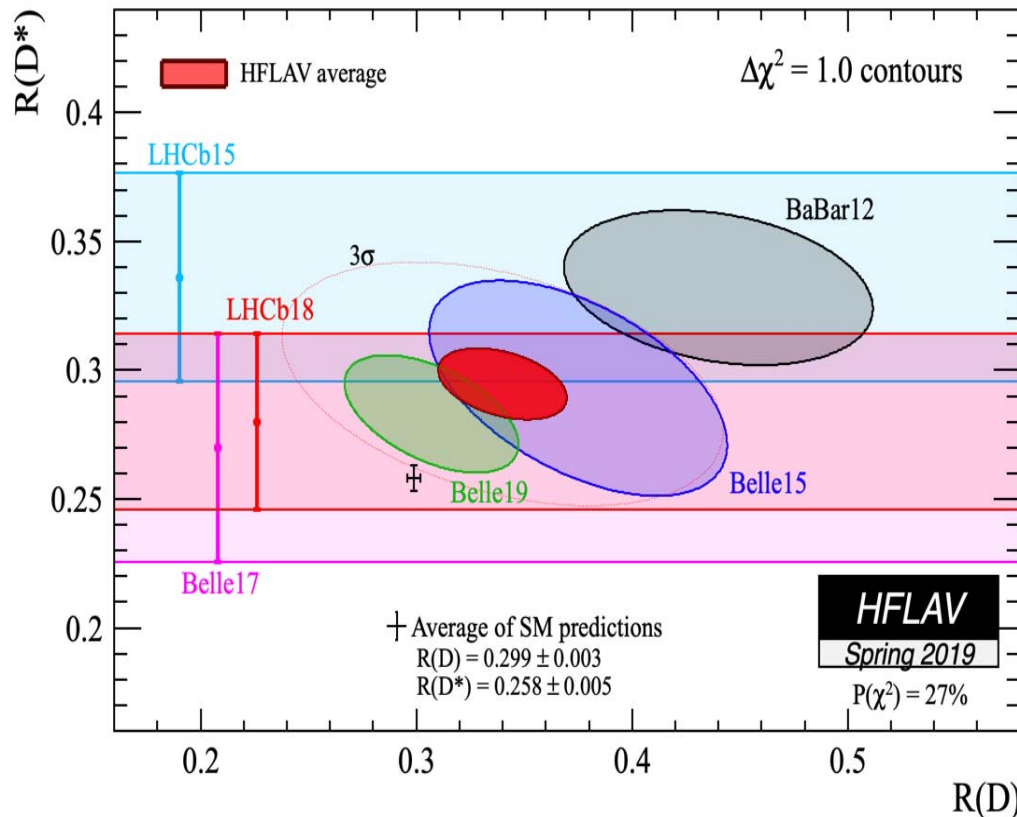
Check the ratio of branching fractions  $R(D^*) = \text{Br}(B \rightarrow D^* \tau \nu) / \text{Br}(B \rightarrow D^* l \nu)$

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 $B \rightarrow D(^*)\tau\nu$ decays



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

Measurements of BaBar, Belle and LHCb collaborations

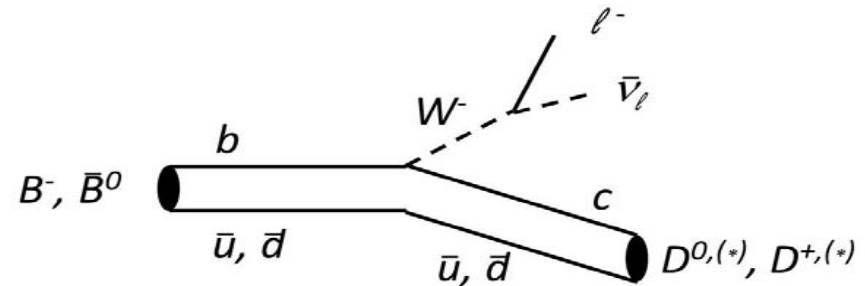
Similarly, for a D meson in the final state  $R(D) = \text{Br}(B \rightarrow D\tau\nu) / \text{Br}(B \rightarrow D\ell\nu)$   
 SM:  $R(D) = 0.299 \pm 0.003$  vs. Experiment:  $R(D) = 0.340 \pm 0.027 \pm 0.013$

Need more data!

# If not a statistical fluctuation, what are possible interpretations?

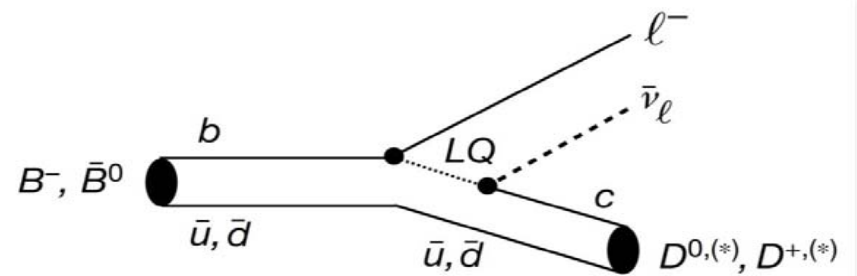
Diagrams for the  $B \rightarrow D^{(*)}\tau\nu$  transition:

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!  $\rightarrow$  **the ball is on the experimental side.**