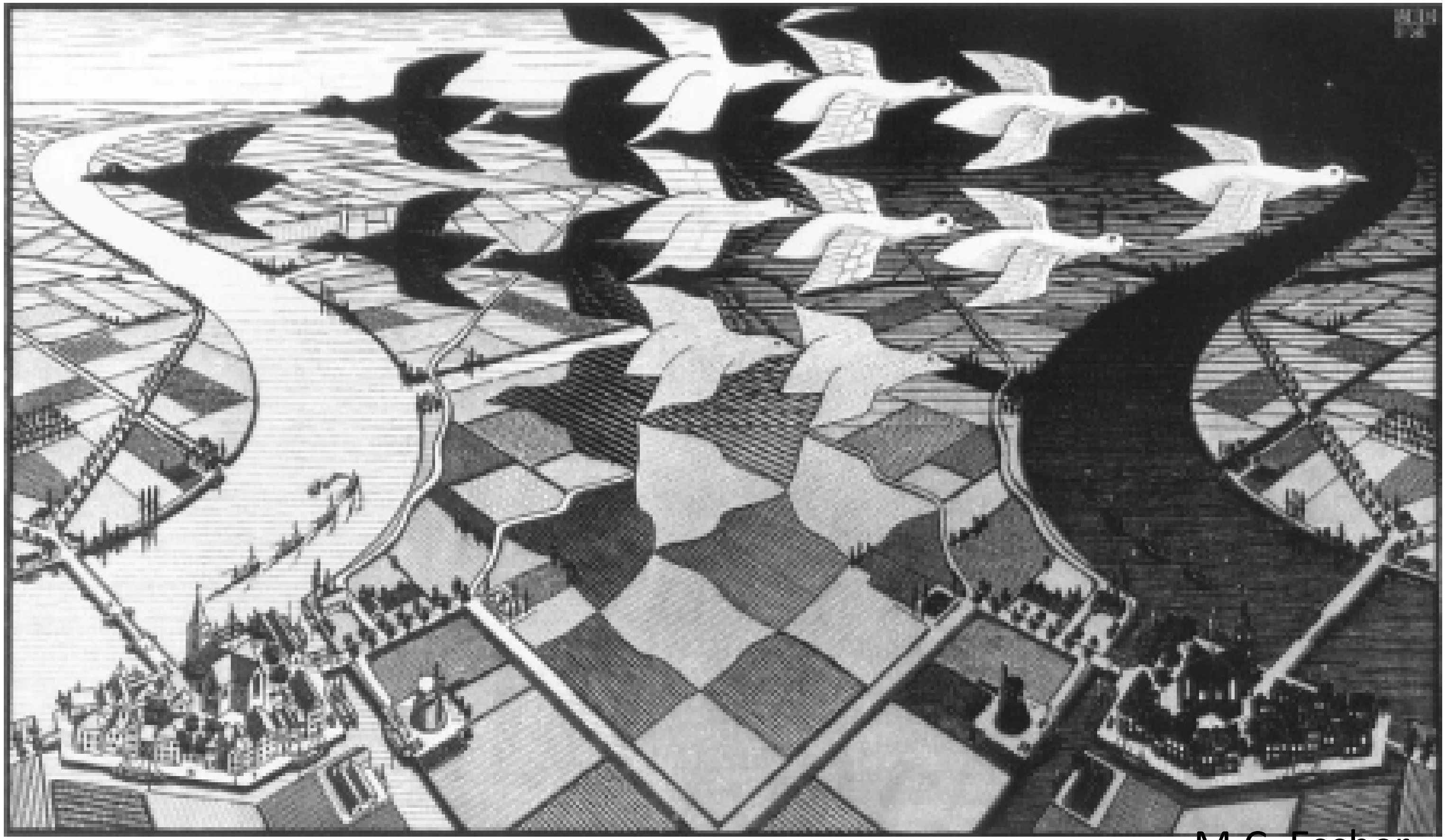
CP Violation

-- Lecture 5 --



M.C. Escher

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July-August, 2018

Summary of Lecture 4

- The Superweak model was a plausible explanation for the $K_L \rightarrow \pi^+\pi^-$ observation
  It predicted the phase of $\varepsilon = \phi_{SW} = \arctan(2\Delta M_K/\Delta\Gamma_K) \simeq 45^o$, in agreement with experiment, no other observable CPV processes, & a dull future for specialists in the field.

- Precise comparisons of the rates for $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^0\pi^0$ in high-statistics experiments exposed a direct CPV amplitude in $K_L \rightarrow \pi\pi$ decays, killing the Superweak model

- The measured Weak Interaction charge of the d-quark is 0.98 G_F, that for the s-quark is 0.21 G_F. These differences from G_F are due to quark-flavor mixing

- The non-existence of Flavor-Changing Neutral Currents was explained by the discovery of the charmed quark & Unitarity of the 4-quark flavor mixing matrix

- Kobayashi & Maskawa: a CP violating phase can be accommodated in the quark-flavor mixing matrix but only if there are 6 quark flavors (not 3, known in 1973)

- Three more quark-flavors are discovered: charm, bottom and top.

Today's topics

- Necessary conditions for observable KM-type CP violating asymmetries in B meson decays

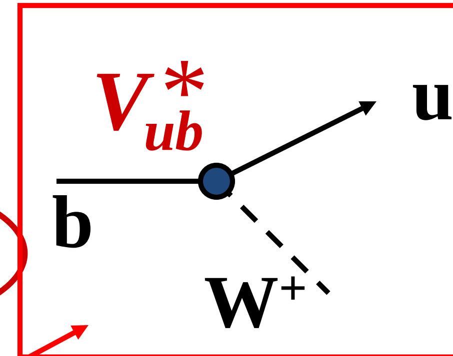
- Experimental tests of the KM model for CP violation

CKM matrix today

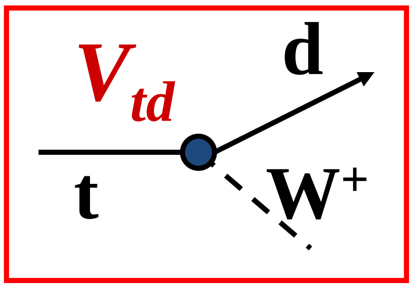
Cabbibo-**K**obayashi-**M**askawa

CPV phases are in the corners

$\phi_3\ (\gamma)$

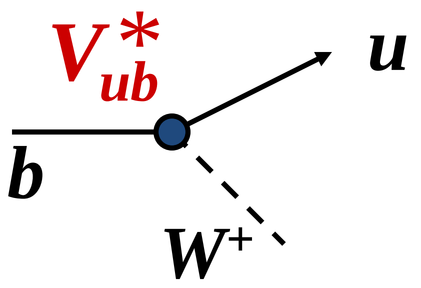


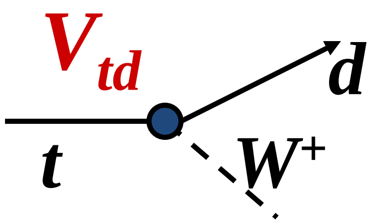
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$\phi_1\ (\beta)$

The challenge





Measure a complex phase for *b*→*u*

or in *t*→*d*

or, even better, both

KM model predicts large differences between B^0 and $\bar{B}^0$ decays

VOLUME 45, NUMBER 12 PHYSICAL REVIEW LETTERS 22 SEPTEMBER 1980

CP Nonconservation in Cascade Decays of *B* Mesons

Ashton B. Carter and A. I. Sanda
Rockefeller University, New York, New York 10021
(Received 2 June 1980)

Ikaros Bigi

Ichiro Sanda

Ashton Carter

NOTES ON THE OBSERVABILITY OF *CP* VIOLATIONS IN B DECAYS

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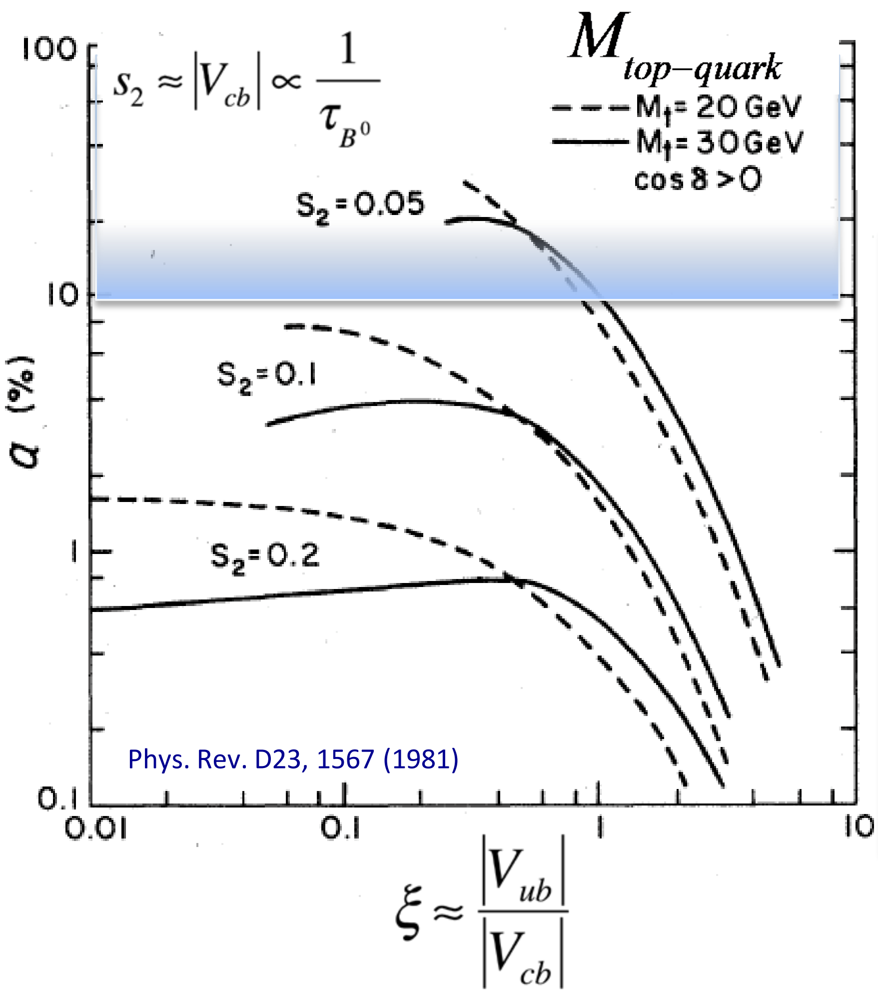
Sanda-Carter conditions

size of CPV $B^0(\overline{B}^0)$ decay asymmetry



Mixing freq: $\omega_{B^0 \leftrightarrow \overline{B}^0} \propto M_{t-quark}$

Carter-Sanda Conditions (for α≥10%):

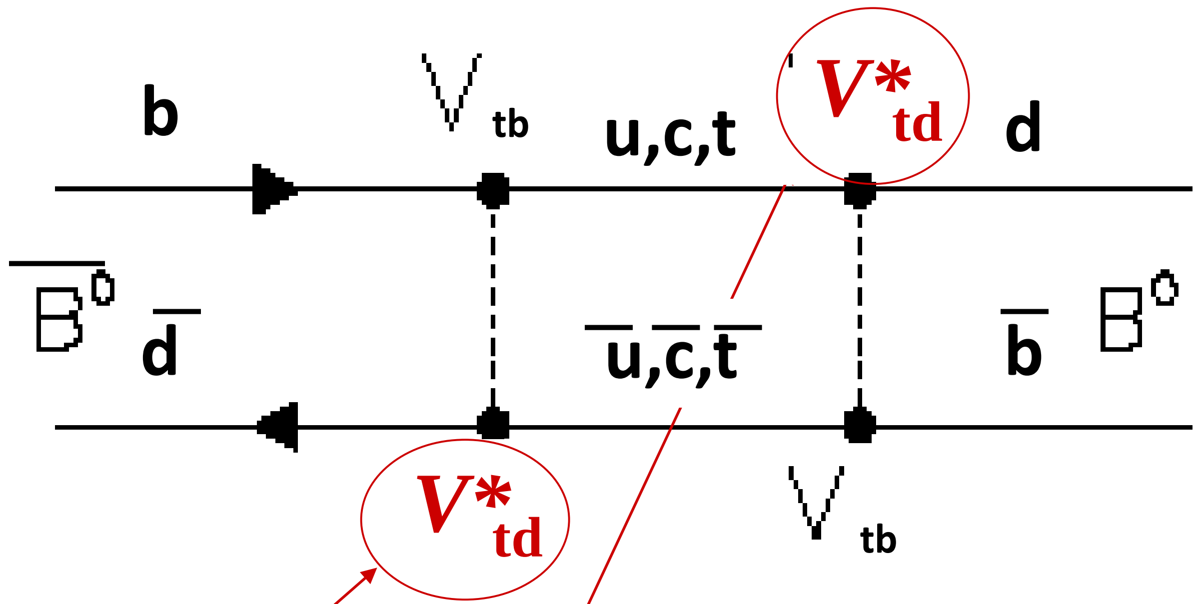
1) $M_t > 20 - 30$ GeV

2) $|V_{cb}| \leq 0.05 \Rightarrow \tau_{B0} > 1 \times 10^{-12}$ s

3) $|V_{ub}| < |V_{cb}|$

$B^0 \leftrightarrow \bar{B}^0$ mixing

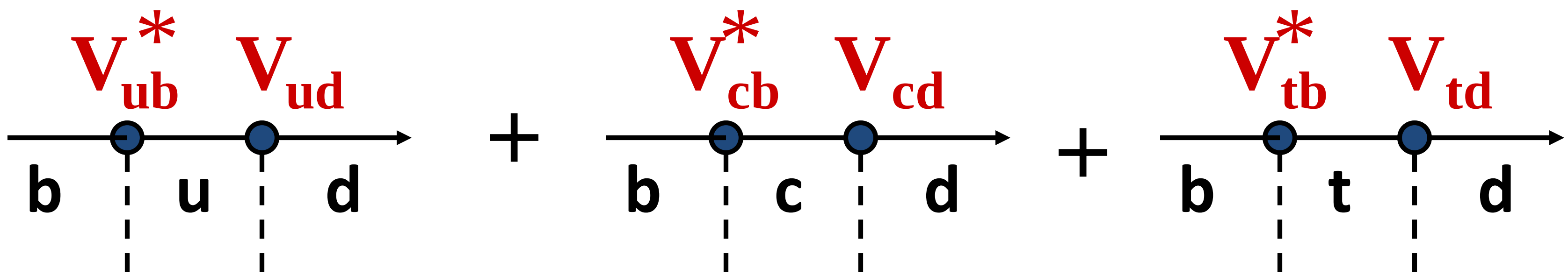
Essential element of the CPV measurement



These have a CPV phase: ϕ_1

(for B mesons, only short-distance terms are important)

b→d:



$$\mathcal{A} = V_{ub}^* V_{ud}\, f(m_u) + V_{cb}^* V_{cd}\, f(m_c) + V_{tb}^* V_{td}\, f(m_t)$$

amplitude for b→u,c,t→d mixing

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

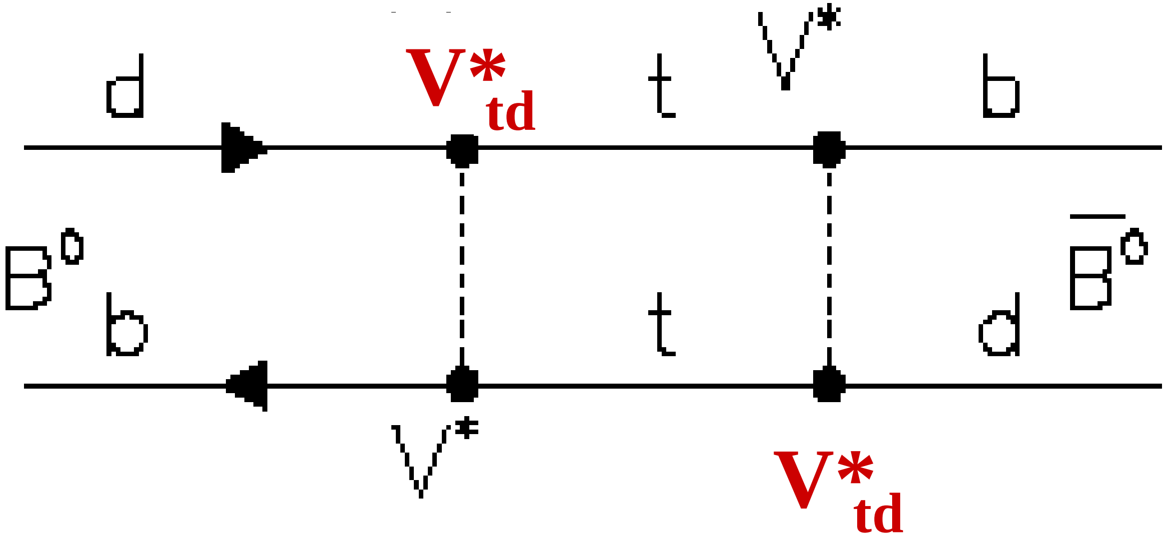
Unitarity relation

non-zero only if: $m_u \neq m_c \neq m_t$

Large m_t would overide GIM

if $m_t >> m_c$ & m_u: t-quark dominates

GIM cancellation is ineffective



$B^0 \leftrightarrow \overline{B}^0$ mixing would be fast

(and this would allows us to access V_{td}'s CPV phase)

$\overline{B}^0$—B^0 mixing discovered in Germany

ARGUS Experiment

PLB 192, 245 (1987)

$$e^+e^- \rightarrow B^0\overline{B}^0$$
$$\downarrow$$
$$B^0$$

$$M_t \geq 50 \text{ GeV}$$

Henning Schroeder
1945-2012

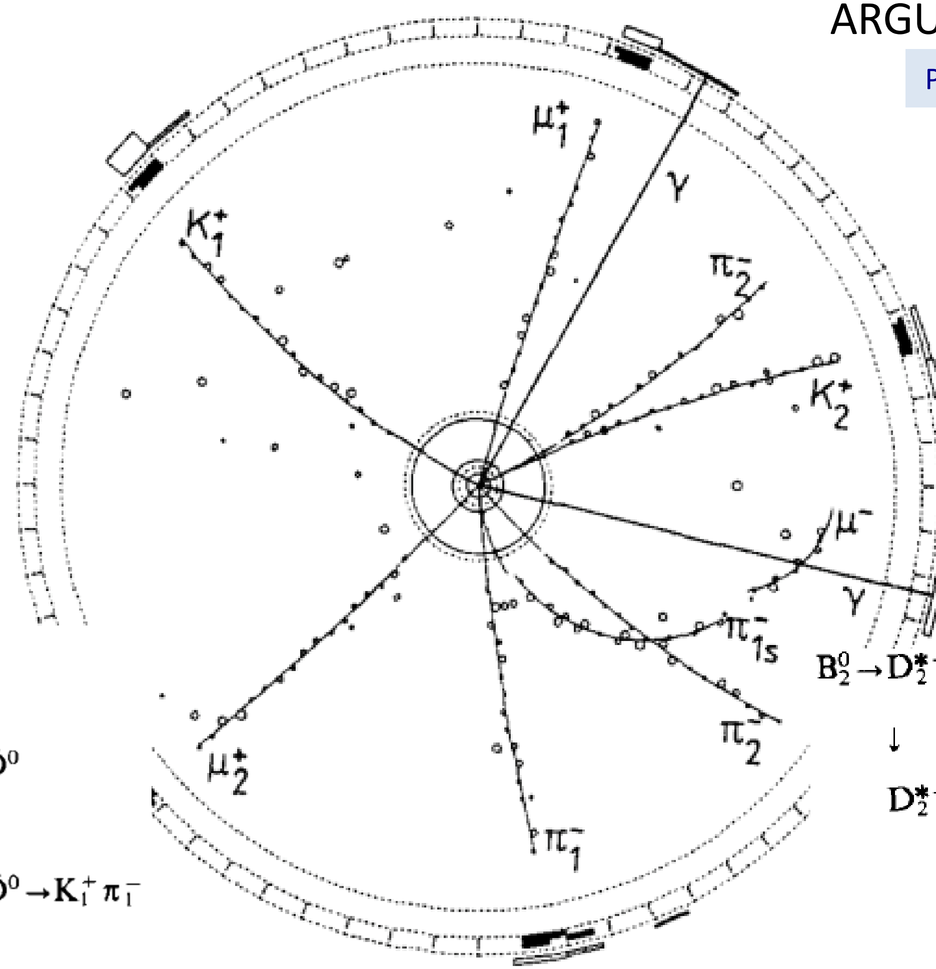
$B_1^0 \rightarrow D_1^{*-} \mu_1^+ \nu_1$

$\downarrow$

$D_1^{*-} \rightarrow \pi_1^- \bar{D}^0$

$\downarrow$

$\bar{D}^0 \rightarrow K_1^+ \pi_1^-$



$B_2^0 \rightarrow D_2^{*-} \mu_2^+ \nu_2$

$\downarrow$

$D_2^{*-} \rightarrow \pi^0 D^-$

$\downarrow$

$D^- \rightarrow K_2^+ \pi_2^- \pi_2^-$

Fig. 2. Completely reconstructed event consisting of the decay Υ (4S)$\rightarrow B^0B^0$.

m_t prediction from $B_d \leftrightarrow B_d$ mixing

PHYSICAL REVIEW D VOLUME 48, NUMBER 7 pg 3271 1 OCTOBER 1993

B_d^0-$\bar{B}_d^0$ mixing and the prediction of the top-quark mass in an independent particle potential model

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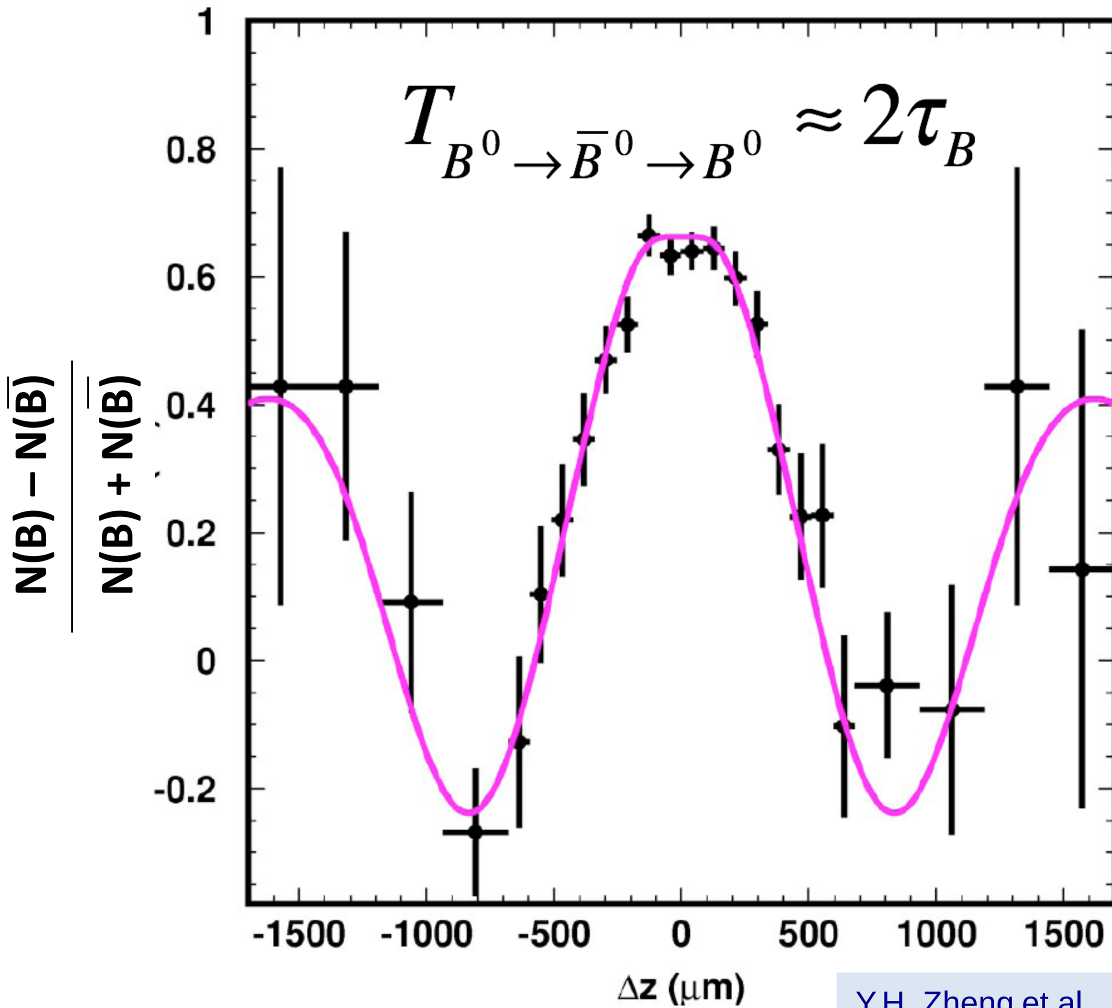
P. Das, A. R. Panda, and K. C. Roy
Physics Department, Kendrapara College, Kendrapara-754 211, India
(Received 22 December 1992; revised manuscript received 30 April 1993)

$$m_t = 167^{+16}_{-17} \text{ GeV}$$

PDG 2012: $m_t = 173.5 \pm 0.6 \pm 0.6$ GeV

Y.H. Zheng, PhD Thesis

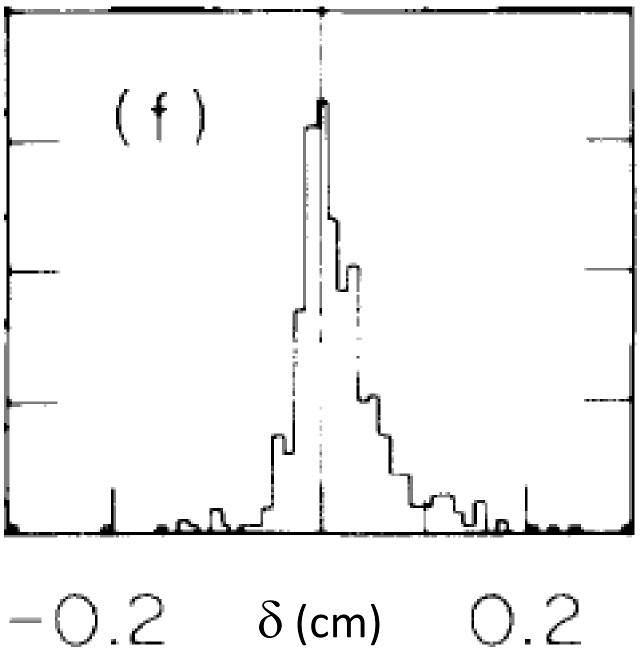


$M_t \approx 174$ GeV!

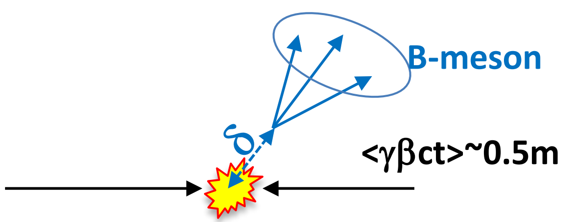
Y.H. Zheng et al., Phys Rev. D **67** 092004 (2003)

Long B-meson lifetime discovered at SLAC

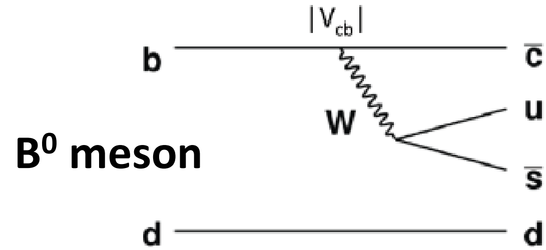
more B-decays with positive decay lengths



W. Ash et al., Phys. Rev. Lett. 58, 640 (1987)



<γβct>~0.5mm~resolution



$$\tau_B \propto \frac{1}{|V_{cb}|^2}$$

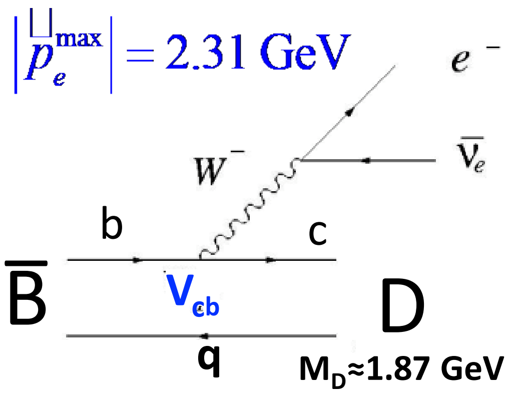
SLAC result in 1987:

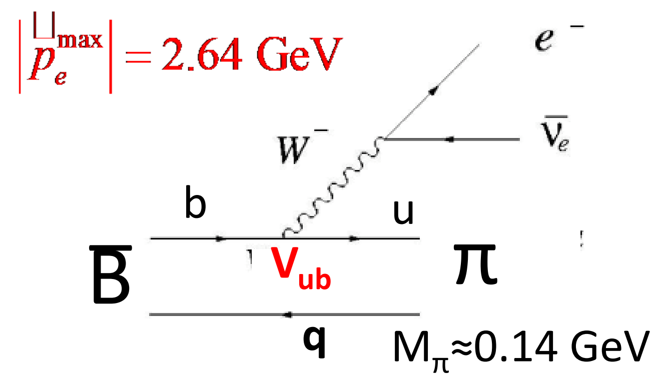
$$\tau_B = 1.2 \pm 0.2 \times 10^{-12} \text{ s}$$

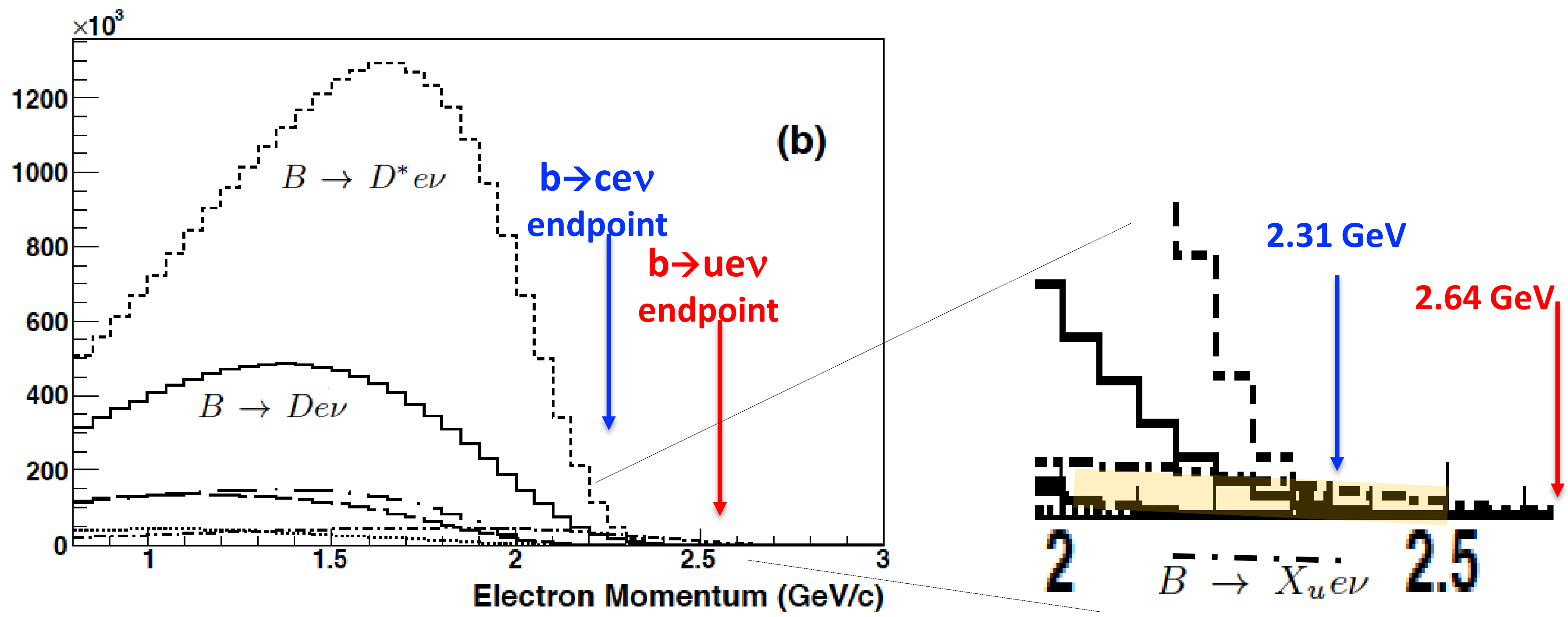
$$|V_{cb}| = 0.047 \pm 0.005$$

$$\text{latest results: } \tau_B = 1.52 \pm 0.01 \times 10^{-12} \text{ s}$$

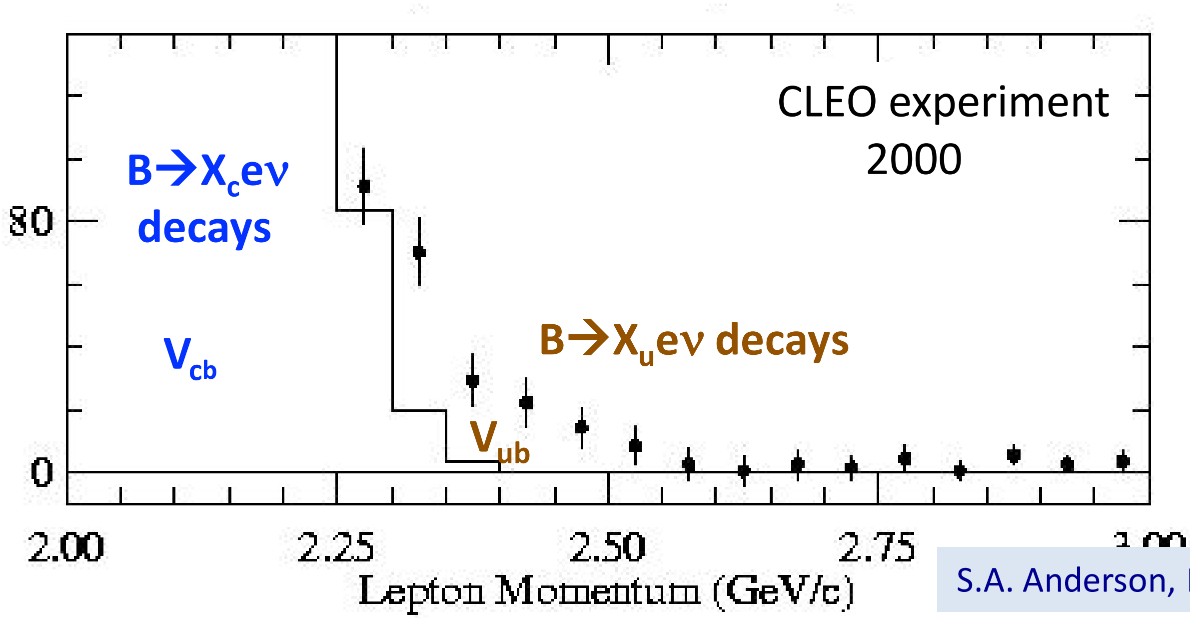
measure $|V_{ub}|/|V_{cb}|$ from $B \to X e^{\pm} \nu$ endpoint







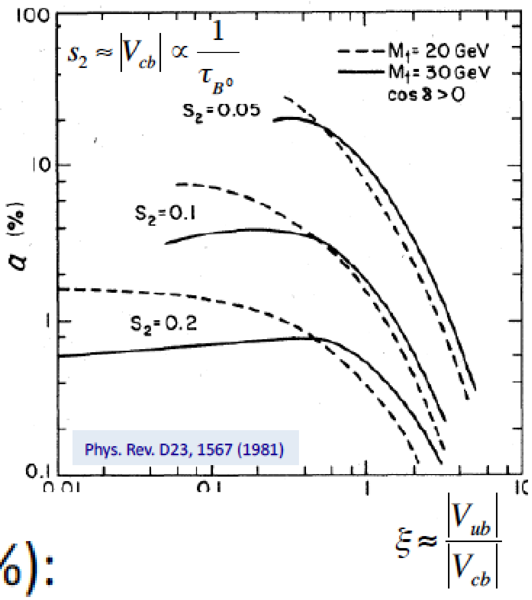
$|V_{ub}| = 0.0041 \pm 0.0009\ (\approx 0.1|V_{cb}|)$



S.A. Anderson, PhD thesis U. Minn (2002)

Carter-Sanda conditions are met!

size of CPV
$B^0(\bar{B}^0)$ decay
asymmetry



Conditions (for α≥10%):

1) $M_t > 20 - 30$ GeV

2) $|V_{cb}| \leq 0.05 \Rightarrow \tau_{B0} > 1 \times 10^{-12}$ s

3) $|V_{ub}| < |V_{cb}|$

Measurements (~1990)

ARGUS (DESY): $M_t \geq 130$ GeV

SLAC: $\tau_B = 1.2 \pm 0.2 \times 10^{-12}$ s, $|V_{cb}| < 0.047 \pm 0.005$

CLEO : $|V_{ub}| = 0.0041 \pm 0.0009 \approx 0.1 |V_{cb}|$

Ashton Carter in 2015

发表时间 18-02-2015 • 更改时间 18-02-2015 发表时间 02:37

阿什顿.卡特宣誓就任美国新任国防部长

作者：林兰

REUTERS/Gary Cameron

The Key

Use B^0 mesons

$B^0 = d\bar{b}$ $\bar{B}^0 = b\bar{d}$

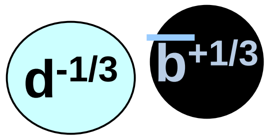
$B^0/\bar{B}^0$ similar to $K^0/\bar{K}^0$

小学课本

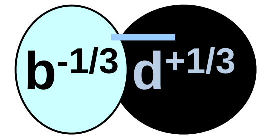
Primer on B mesons

Lesson 1: Basic properties

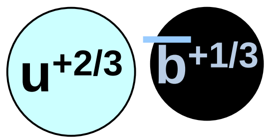
- **What are B mesons?**
  - $B^0 = d\,\bar{b}$



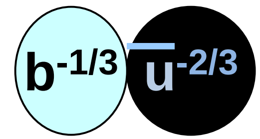
  - $B^0 = b\,\bar{d}$



  - $B^+ = u\,\bar{b}$



  - $B^- = b\,\bar{u}$



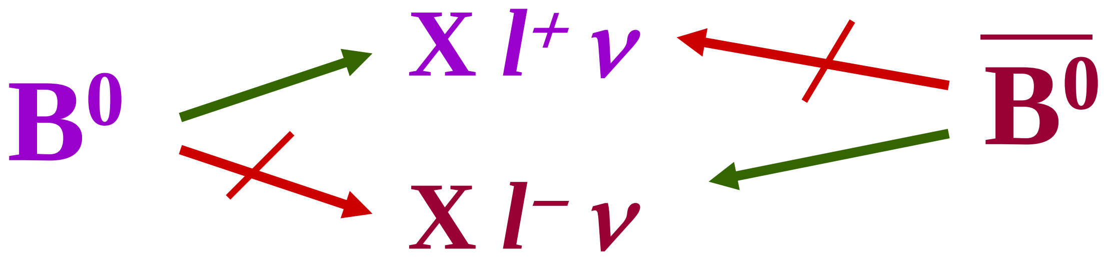
  - $J^{PC} = 0^{-+}$
  - $\tau = 1.5 \times 10^{-12}$ s ($c\tau \approx 450\ \mu$m)
- **How do they decay?**
  - usually to charm: $|b\to c|^2 / |b\to u|^2 \approx 100$
- **How are they produced?**
  - $e^+e^- \to \Upsilon(4S) \to B\,\bar{B}$ is the cleanest process

Lesson 2: "flavor-specific" B decays

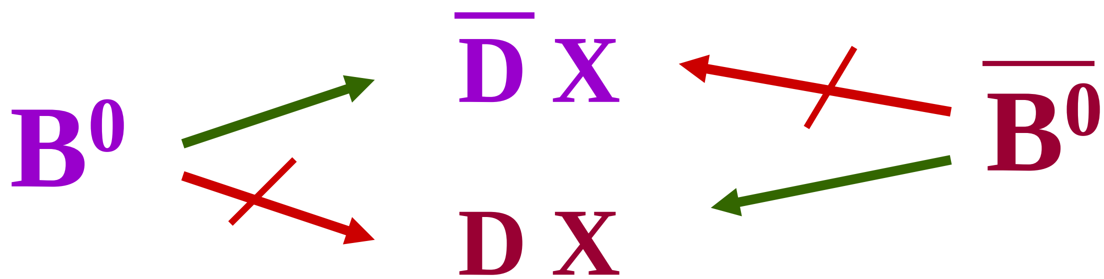
In >95% of B^0 decays:

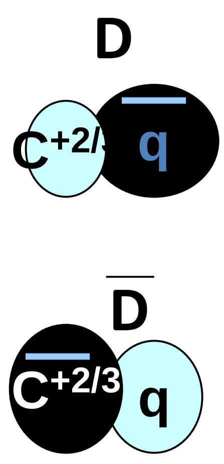
B^0 and $\overline{B}^0$ are distinguishable by their decay products

semileptonic decays:



hadronic decays:





Lesson 3: B → CP eigenstate decays

In 1~2% of B^0 decays:

final state is equally accessible from B^0 and $\overline{B^0}$

charmonium decays:

$B^0 \rightarrow J/\psi K_S \leftarrow \overline{B^0}$

$B^0 \rightarrow J/\psi K_L \leftarrow \overline{B^0}$

…

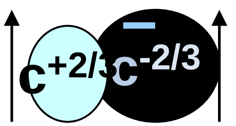
charmless decays:

$B^0 \rightarrow \pi^+\pi^- \leftarrow \overline{B^0}$

$B^0 \rightarrow K^+K^- \leftarrow \overline{B^0}$

…

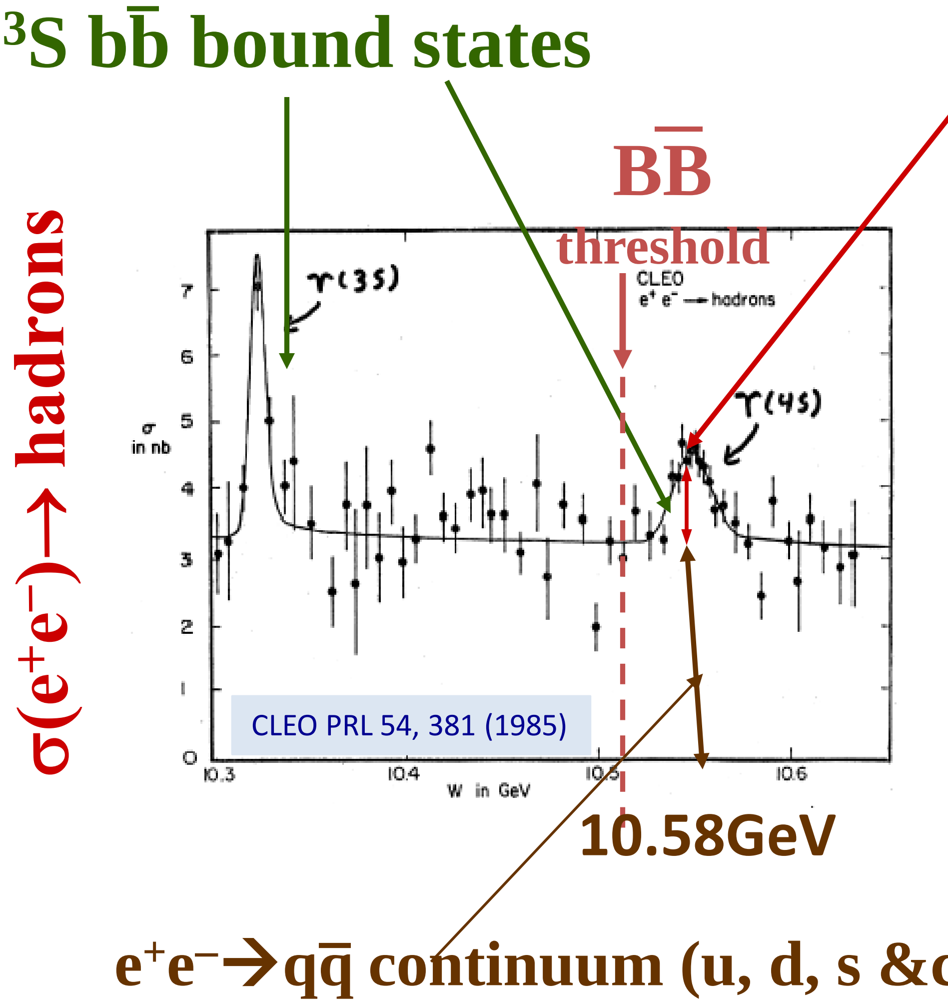
J/ψ



$J^{PC}=1^{--}$

CP=+

Lesson 4: The $\Upsilon(4S)$ resonance

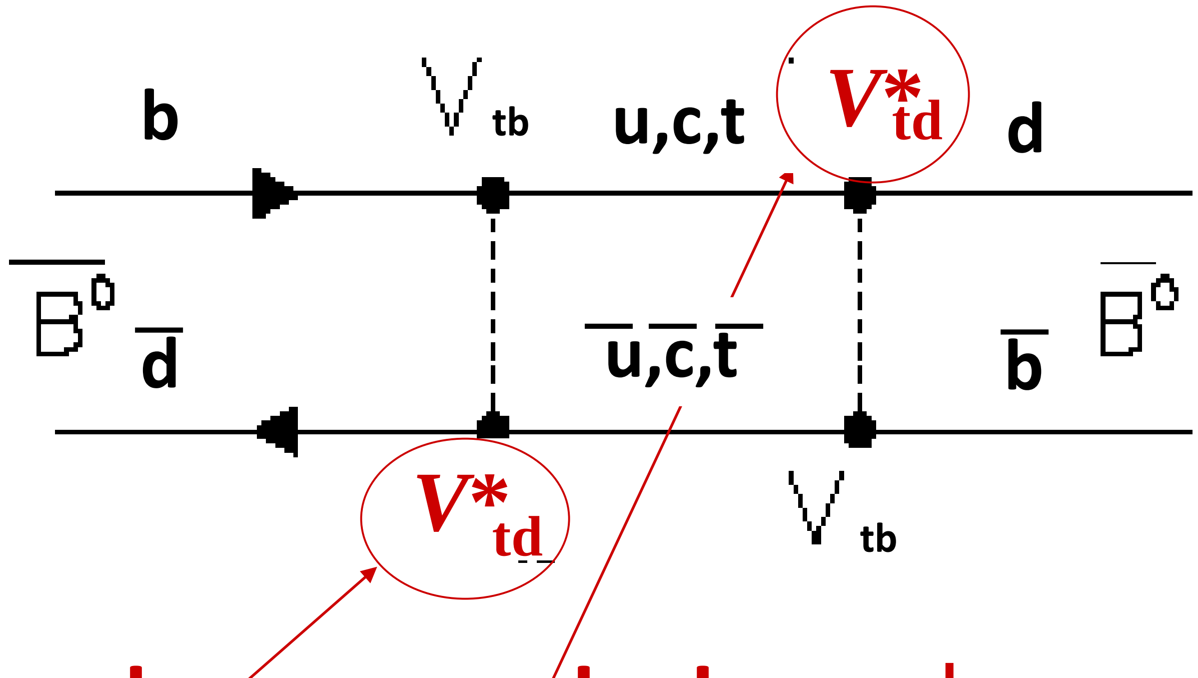


- $\sigma(e^+e^- \rightarrow B\bar{B}) \approx 1$nb
- $B^0\bar{B}^0/B^+B^- \approx 50/50$
- good S/N: (~1/3)
- $B\bar{B}$ and nothing else
- coherent 1^{--} P-wave

~95% flavor-specific decays; only a few % are CP-eigenstate decays

Lesson 5: $B^0 \leftrightarrow \bar{B}^0$ mixing

A B^0 can become a $\bar{B}^0$ (and vice versa)



These have a weak phase: ϕ_1

(in the $B\bar{B}$ system only short-distance terms are important)

The neutral B meson system

$$H = M - \frac{i}{2}\Gamma$$

Mass matrix Decay matrix

$$\langle B_j | H | B_i \rangle = \langle B_j | M | B_i \rangle - \tfrac{i}{2} \langle B_j | \Gamma | B_i \rangle = M_{ij} - \tfrac{i}{2}\Gamma_{ij} = X_{ij}$$

$$\begin{pmatrix} \langle B^0 | H | B^0 \rangle & \langle B^0 | H | \overline{B}^0 \rangle \\ \langle \overline{B}^0 | H | B^0 \rangle & \langle \overline{B}^0 | H | \overline{B}^0 \rangle \end{pmatrix} = \begin{pmatrix} M_{11} - \tfrac{i}{2}\Gamma_{11} & M_{12} - \tfrac{i}{2}\Gamma_{12} \\ M_{21} - \tfrac{i}{2}\Gamma_{21} & M_{22} - \tfrac{i}{2}\Gamma_{22} \end{pmatrix}$$

$\mathcal{CP}$T symmetry: $M_{11} = M_{22} \quad \Gamma_{11} = \Gamma_{22}$

no assumptions about $\mathcal{CP}$

Hermeticity: $X_{21} = M_{12}^* - \tfrac{i}{2}\Gamma_{12}^*$

$$H \Rightarrow \begin{pmatrix} M_{11} - \tfrac{i}{2}\Gamma_{12} & M_{12} - \tfrac{i}{2}\Gamma_{12} \\ M_{12}^* - \tfrac{i}{2}\Gamma_{12}^* & M_{11} - \tfrac{i}{2}\Gamma_{11} \end{pmatrix}$$

Schrodinger's Equation

-- allowing for CP violation and including decays --

to conform to the standard notation:

$$X_{21} = \mathcal{A}_{B^0 \to \bar{B}^0} = -ip^2 \quad \left(= M_{12}^* - \tfrac{i}{2}\Gamma_{12}^*\right)$$

$$X_{12} = \mathcal{A}_{\bar{B}^0 \to B^0} = -iq^2 \quad \left(= M_{12} - \tfrac{i}{2}\Gamma_{12}\right)$$

$$i\hbar \frac{\partial}{\partial t}\Psi(\mathrm{t}) = H\Psi(t)$$

$$\text{assume solutions of the form:} \quad \psi_i(t) = a_i e^{-i\lambda_i t}$$

Schrodinger's equation for energy eigenstates;

$$\begin{pmatrix} X_{11} & -ip^2 \\ -iq^2 & X_{11} \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t} = i\frac{\partial}{\partial t}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t}$$

$$\Rightarrow \begin{pmatrix} X_{11} - \lambda & -iq^2 \\ -ip^2 & X_{11} - \lambda_i \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} = 0$$

Solutions for Ψ(t)

eigenvalue equation:

$$\begin{vmatrix} X_{11}-\lambda_i & -iq^2 \\ -ip^2 & X_{11}-\lambda_i \end{vmatrix} = 0$$

eigenvalues | eigenstates

$$i=1: \quad \lambda_S = X_{11} + ipq; \quad |B_{"S"}\rangle = \tfrac{1}{\sqrt{p^2+q^2}}\left(p|B\rangle - q|\overline{B}^0\rangle\right)$$

$$i=2: \quad \lambda_L = X_{11} - ipq; \quad |B_{"L"}\rangle = \tfrac{1}{\sqrt{p^2+q^2}}\left(p|B\rangle + q|\overline{B}^0\rangle\right)$$

So far, experiment says

$$p \approx q \approx \tfrac{1}{\sqrt{2}} \quad \Rightarrow \quad \begin{aligned} |B_{"S"}\rangle &= |B_1\rangle = \tfrac{1}{\sqrt{2}}\left(|B^0\rangle + |\overline{B}^0\rangle\right) \\ |B_{"L"}\rangle &= |B_2\rangle = \tfrac{1}{\sqrt{2}}\left(|B^0\rangle - |\overline{B}^0\rangle\right) \end{aligned}$$

$$|B^0(t)\rangle = \tfrac{1}{\sqrt{2}}\left(|B_1\rangle e^{-i(M_1 - \frac{i}{2}\Gamma_1)t} + |B_2\rangle e^{-i(M_2 - \frac{i}{2}\Gamma_2)t}\right)$$

$$|\overline{B}^0(t)\rangle = \tfrac{1}{\sqrt{2}}\left(|B_1\rangle e^{-i(M_1 - \frac{i}{2}\Gamma_1)t} - |B_2\rangle e^{-i(M_2 - \frac{i}{2}\Gamma_2)t}\right)$$

$$\text{experiment}: \quad \Delta M_d = |M_1 - M_2| = 3.34 \pm 0.03 \times 10^{-10}\ \text{MeV}$$

$$\Gamma_{B^0} = (\Gamma_1 + \Gamma_2)/2 = (1.29 \pm 0.01)\Delta M_d$$

B^0(t) and $\overline{B}^0$(t) time dependence

$$\left|B^0(t)\right\rangle = \left(\left|B^0(0)\right\rangle\left(1+e^{i\Delta Mt}\right) + \left|\overline{B}^0\right\rangle\left(1-e^{i\Delta Mt}\right)\right)e^{-\Gamma_B t}$$

common phase

$$\left|\overline{B}^0(t)\right\rangle = \left(\left|\overline{B}^0(0)\right\rangle\left(1+e^{i\Delta Mt}\right) - \left|B^0\right\rangle\left(1-e^{i\Delta Mt}\right)\right)e^{-\Gamma_B t}$$

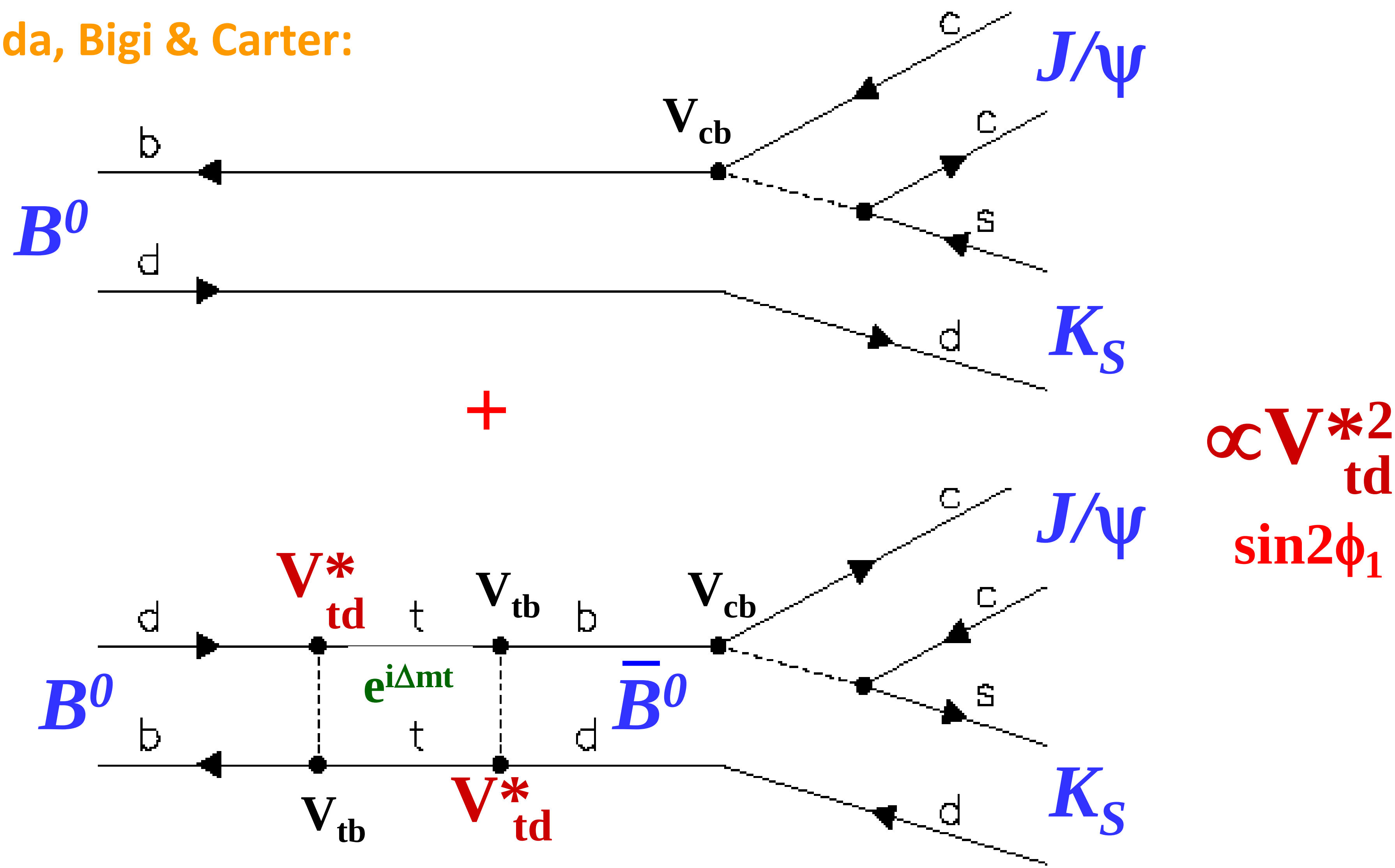
Can we measure ϕ_1?

- ✓ two processes: $B^0 \rightarrow f_{cp}$ & $B^0 \rightarrow \bar{B}^0 \rightarrow f_{cp}$
- ✓ weak phase: $2\phi_1$
- ✓ common phase: Δmt

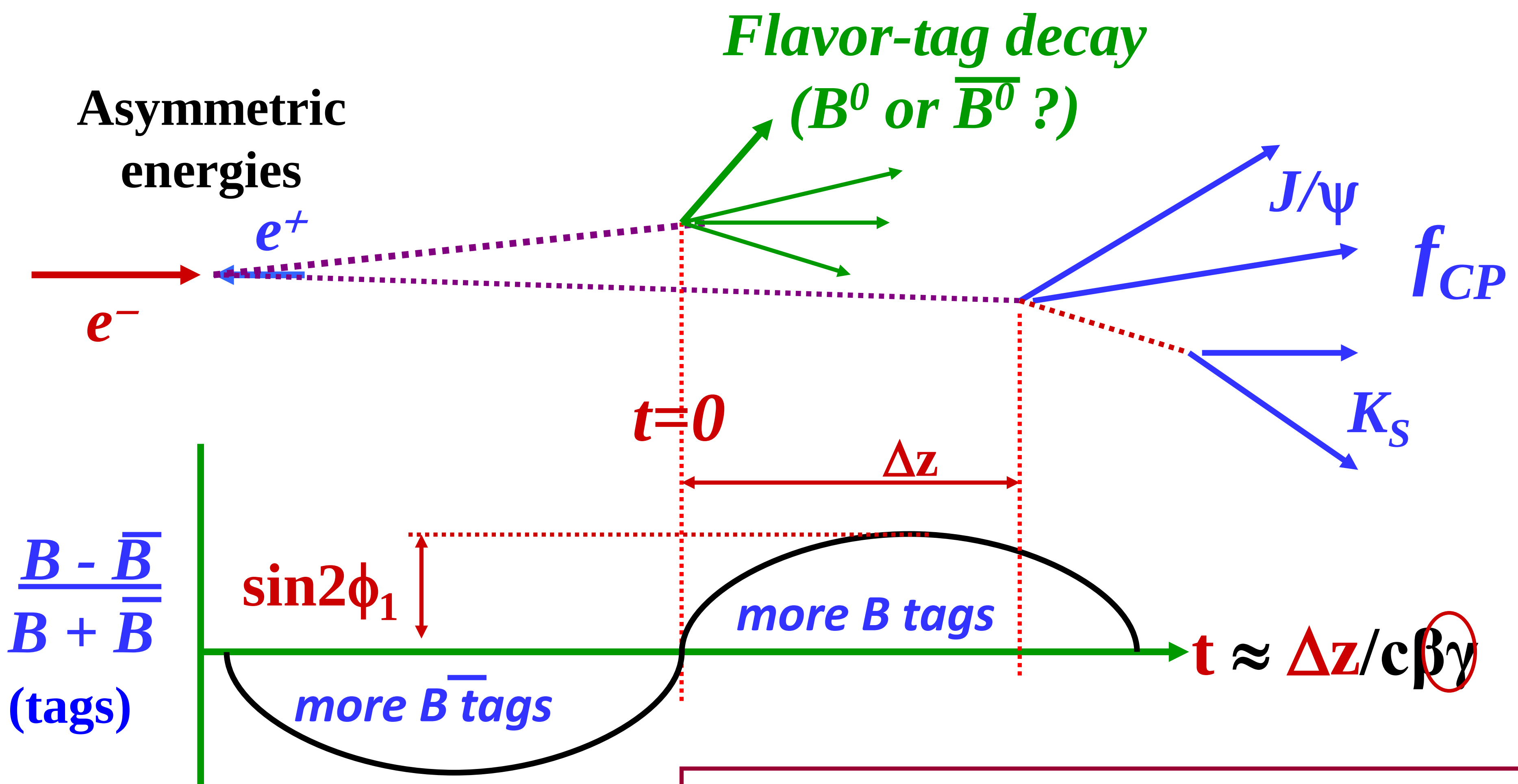
Yes!!

Interfere $B \to f_{CP}$ with $B \leftrightarrow \bar{B} \to f_{CP}$

Sanda, Bigi & Carter:



What do we measure?

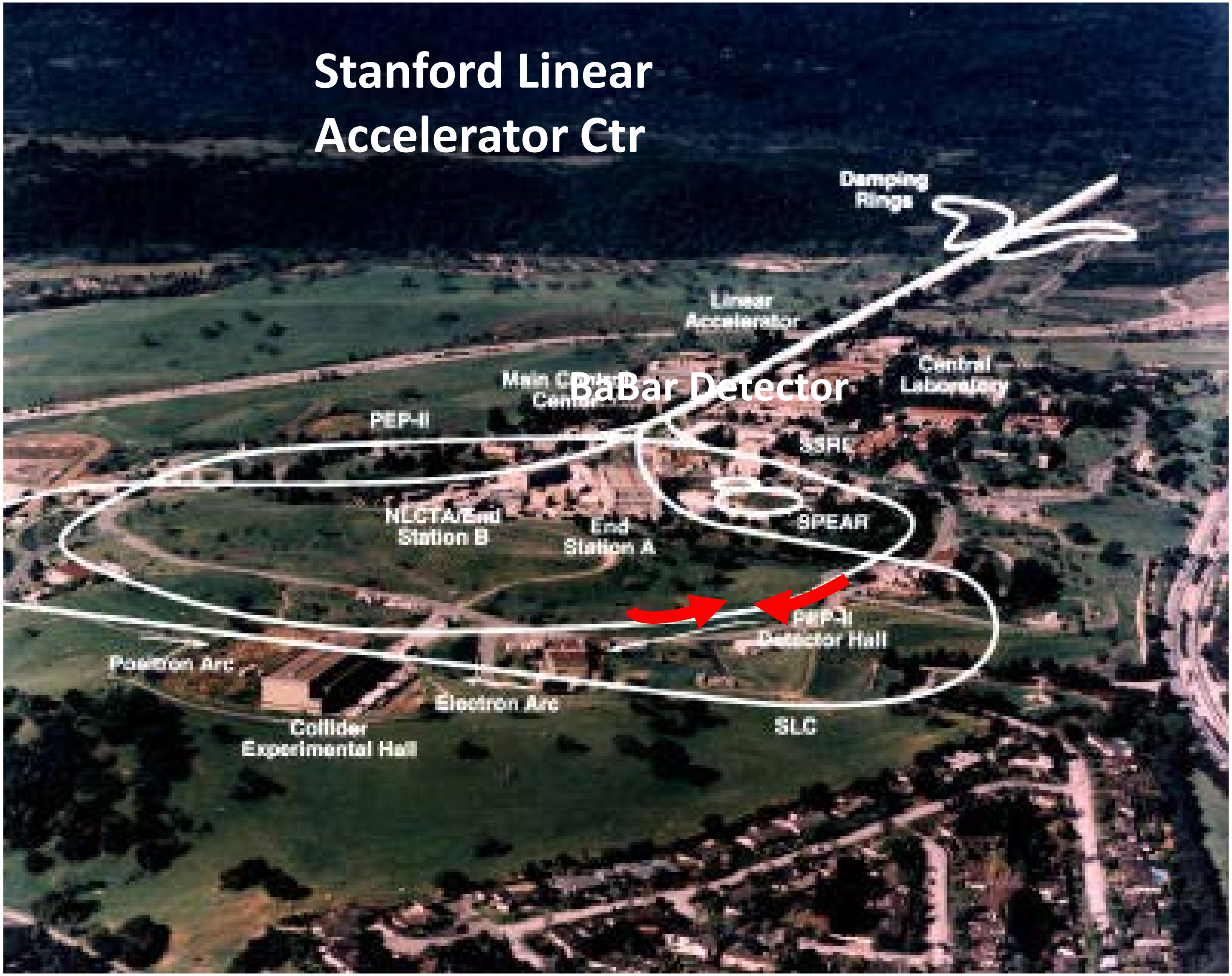


This is for CP=-1; for CP=+1, the asymmetry is opposite

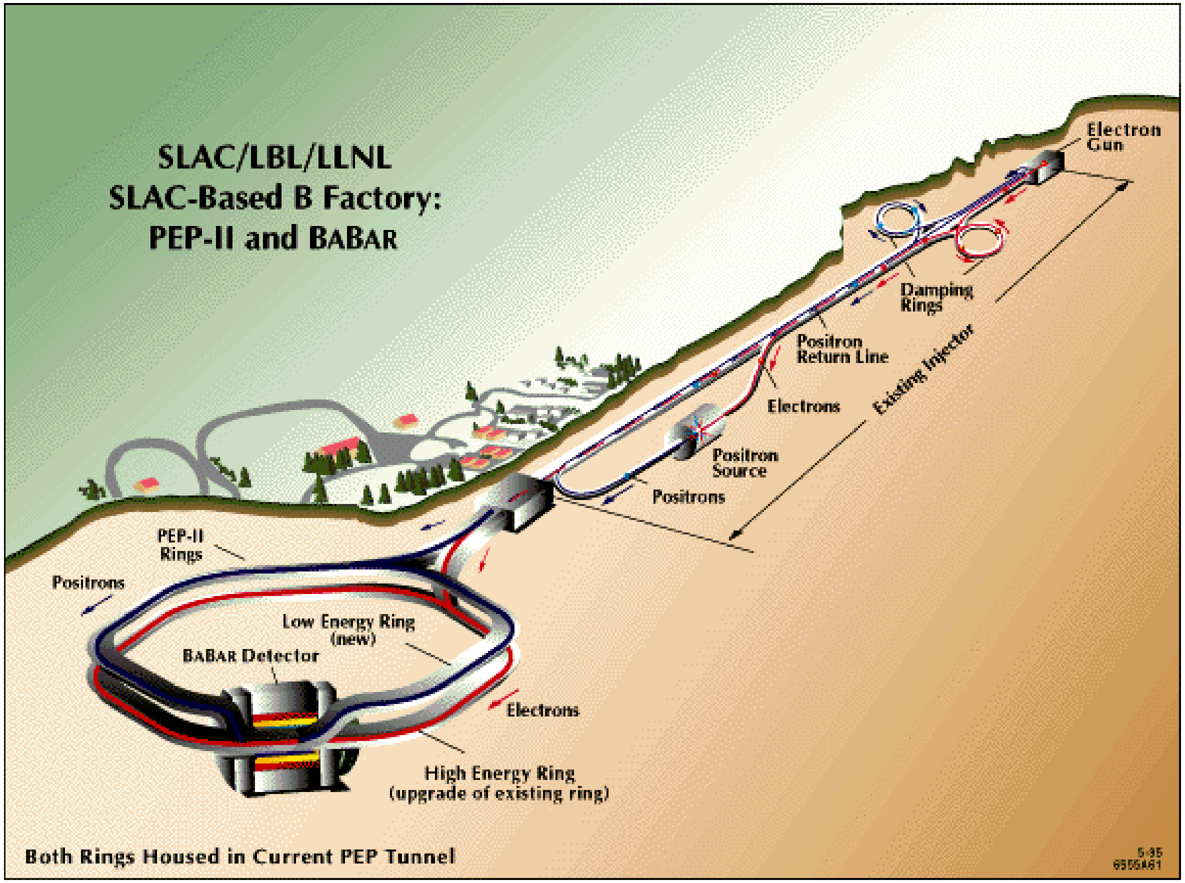
Requirements for CPV

- **Many B mesons**
  - "B-factory" & the $\Upsilon(4S)$ resonance
- **Reconstruct+isolate CP eigenstate decays**
  - Kinematic variables for signal +(*cont. bkg suppr+PID*).
- **"Tag" flavor of the other B**
- **Measure decay-time difference**
  - Asymmetric beam energies, high precision vertexing(Δz)
  - Likelihood fit to the Δt distributions

PEPII B factory in California



The PEPII Collider (magnetic separation)

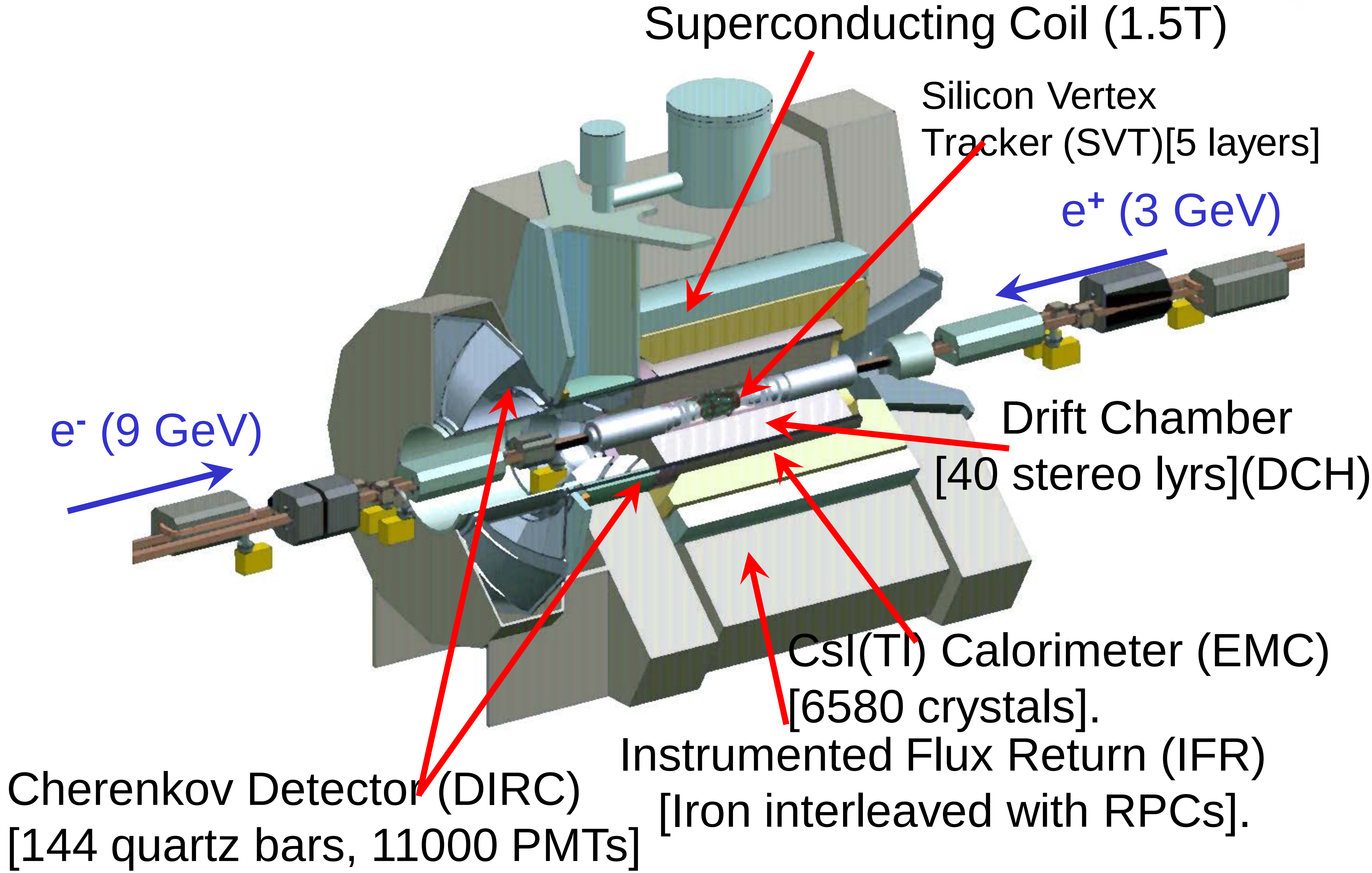


Int(L dt)=131 fb^{-1}

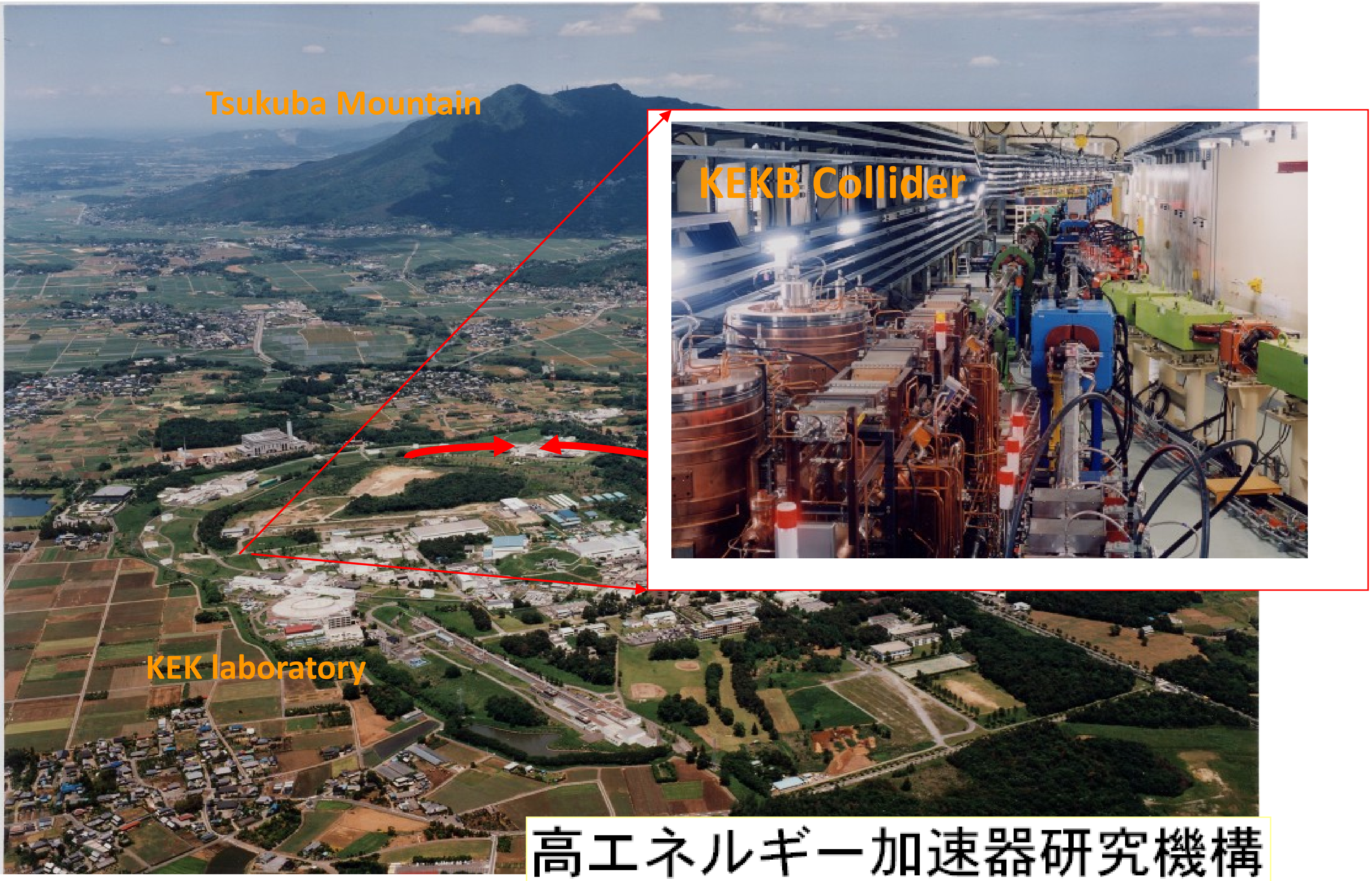
On resonance:113 fb^{-1}

9 x 3.0 GeV; L=(6.5 x 10^{33})/cm^2/sec

The BaBar Detector



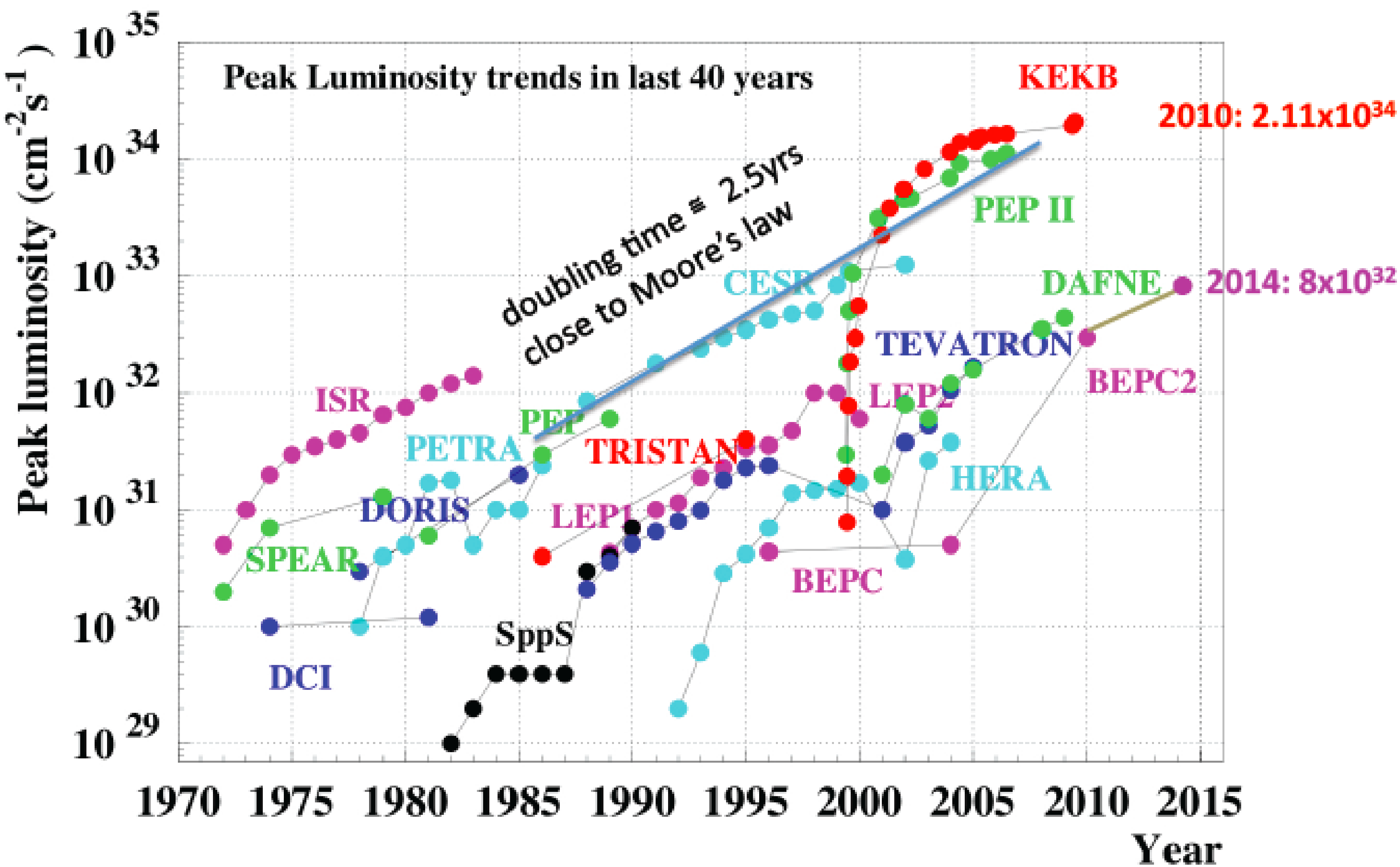
KEK laboratory in Japan

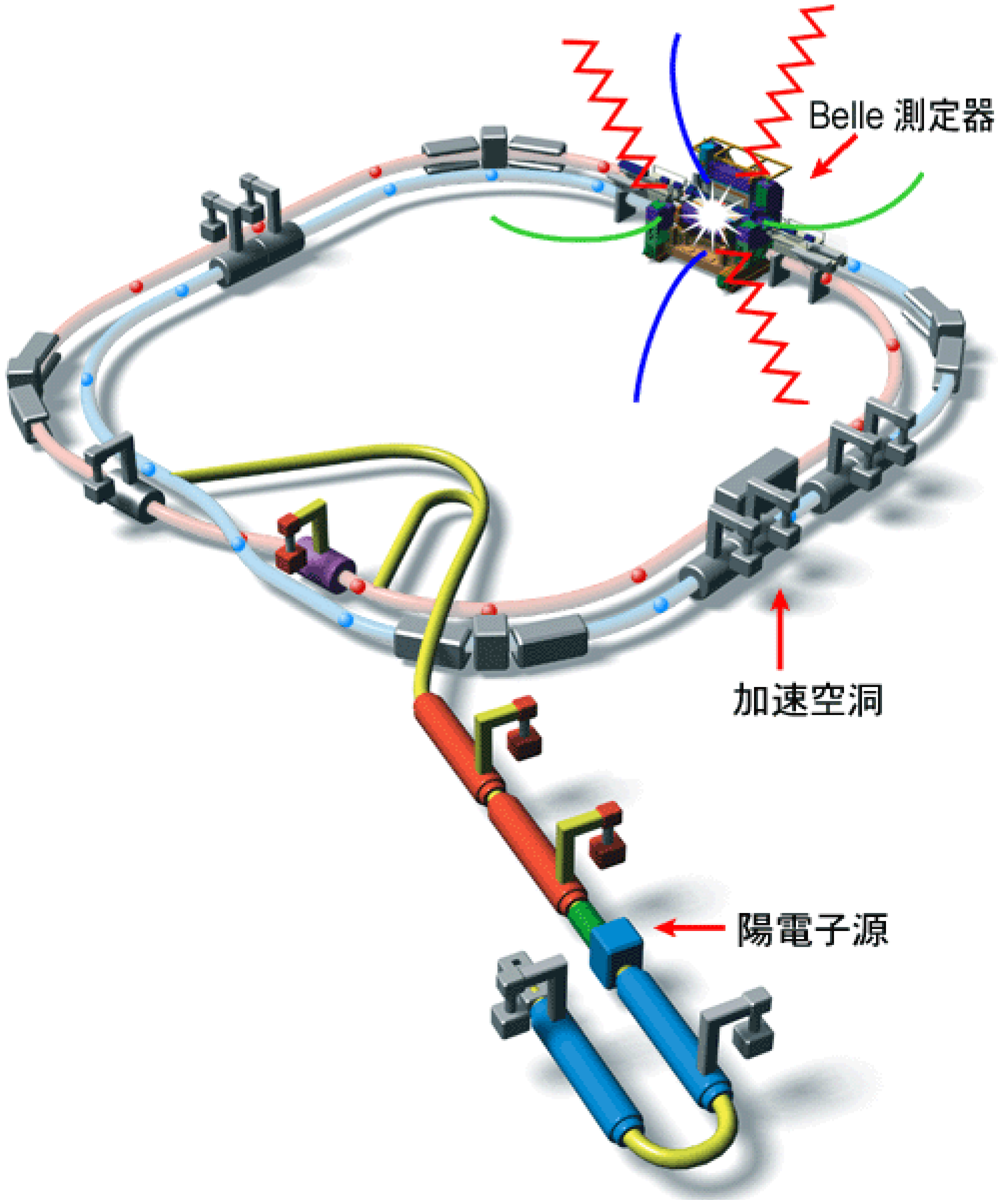


KEKB

- Two rings
  - e^+ : 3.5 GeV 1.5A
  - e^- : 8.0 GeV 1.1A
- E_{CM} : 10.58 GeV
- Luminosity:
  - target: 10^{34} cm^{-2} s^{-1}
  - actual: 2×10^{34} cm^{-2} s^{-1}
    - (~20 B's/s)

e^+e^- luminosity ~ $2^{(t/2.5yr)}$




Belle 測定器
加速空洞
陽電子源

Belle

A magnetic spectrometer based on a huge superconducting solenoid

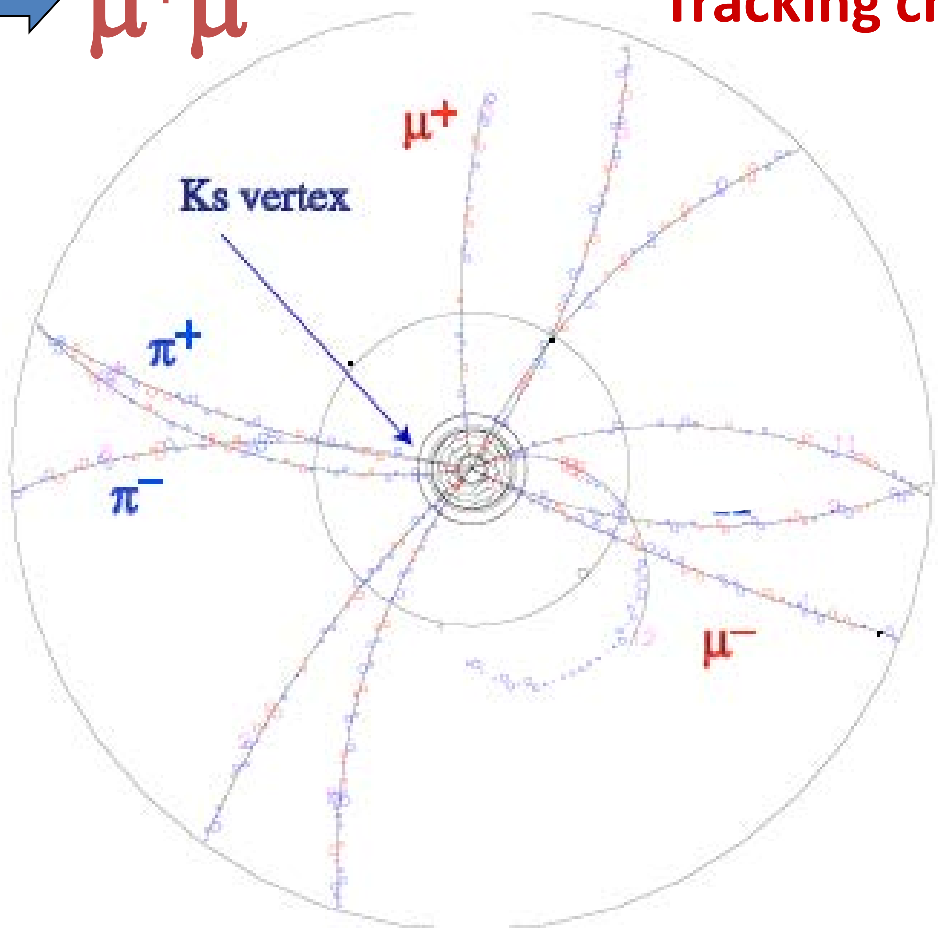
Step 2: Select events

$\bar{B}^0 \rightarrow J/\psi\ K_s$ **event**

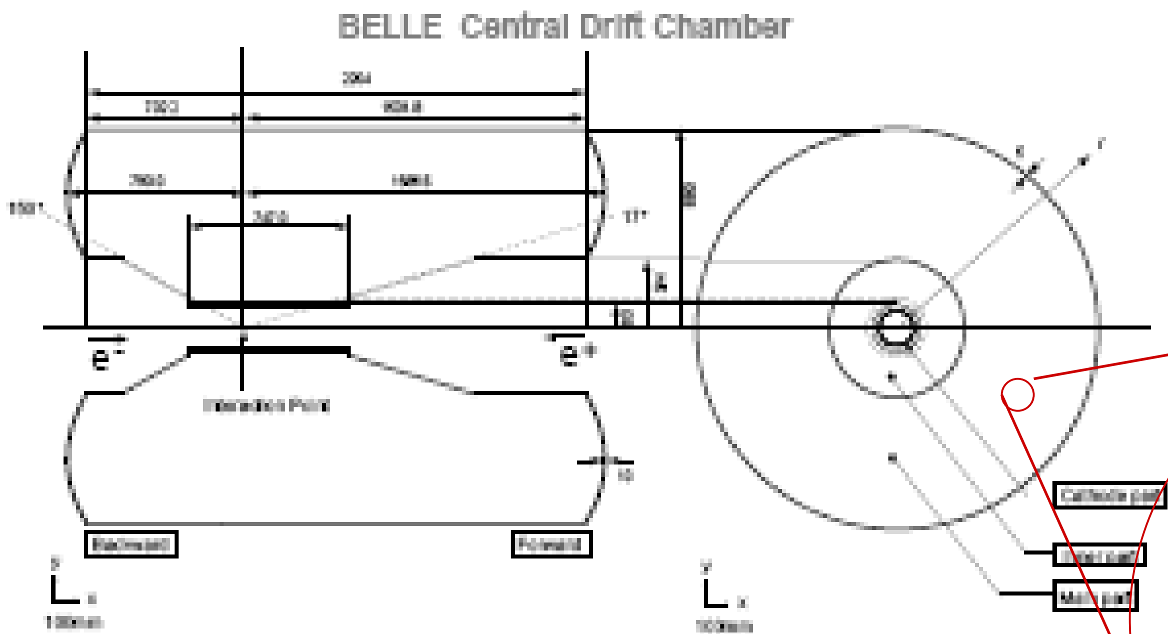
$K_s \rightarrow \pi^+\pi^-$

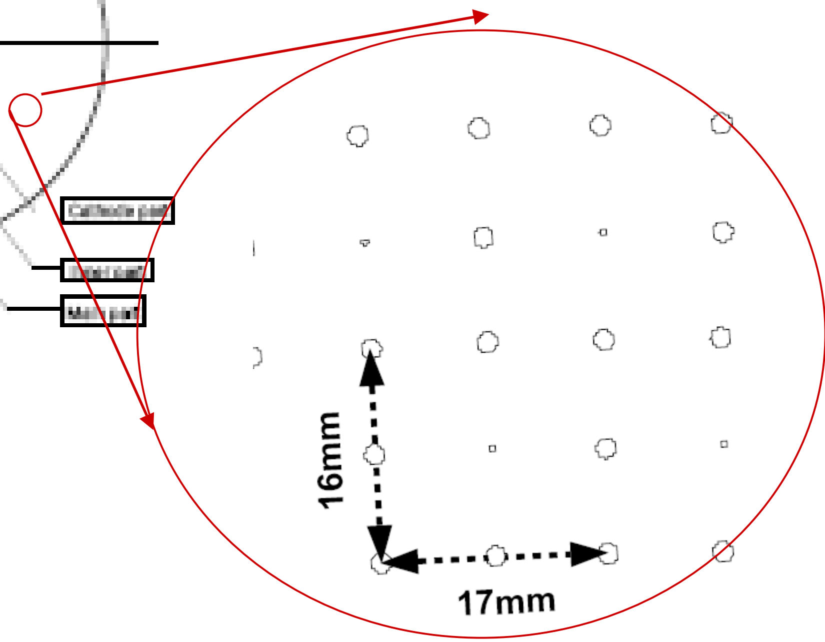
$J/\psi \rightarrow \mu^+\mu^-$

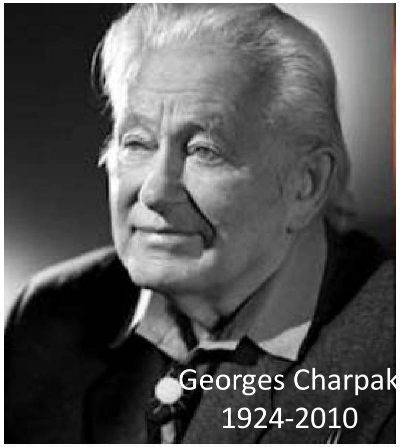
Tracking chamber only



Drift chamber for tracking & momentum measurement



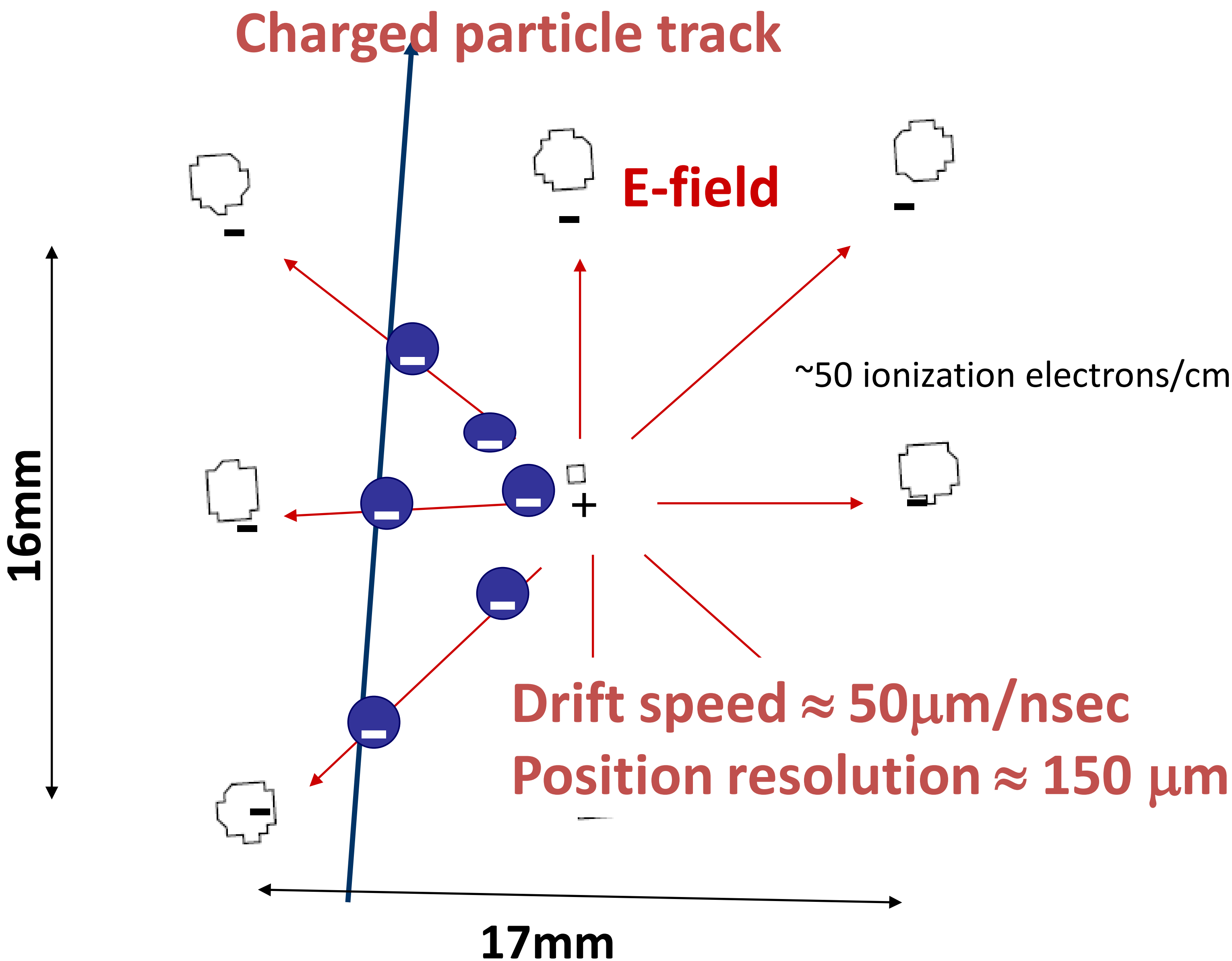




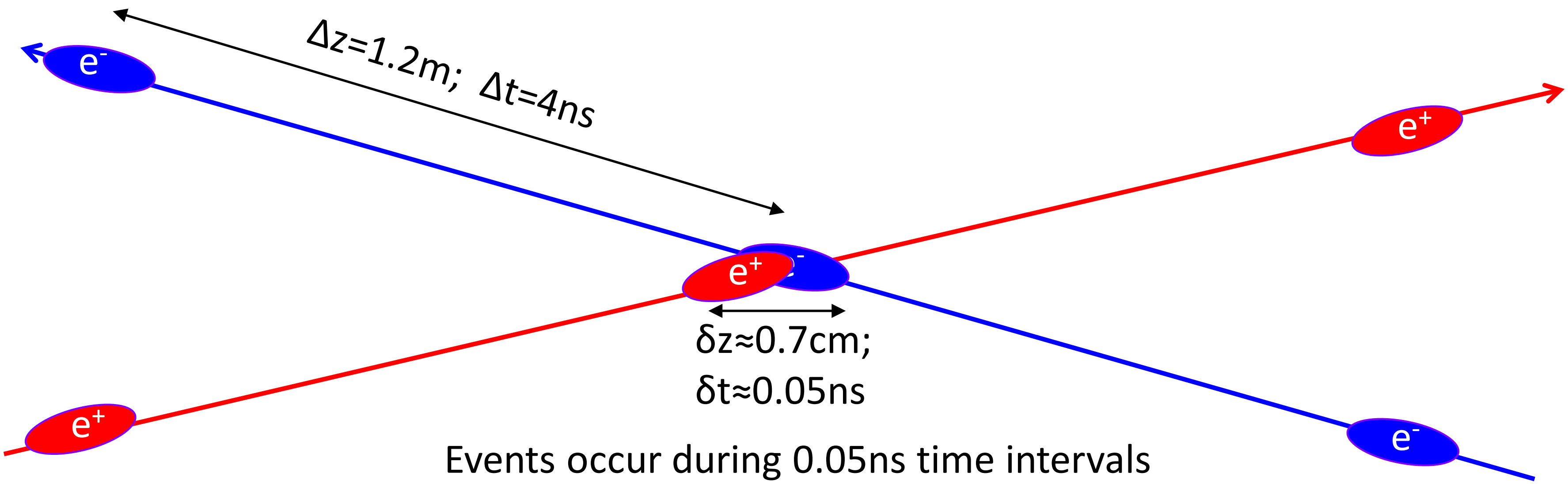
1992 Physics Nobel Prize

Belle drift chamber under construction

Drift chamber cell



Event-time structure

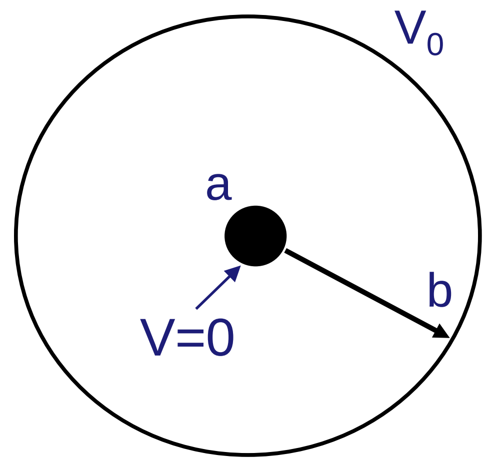


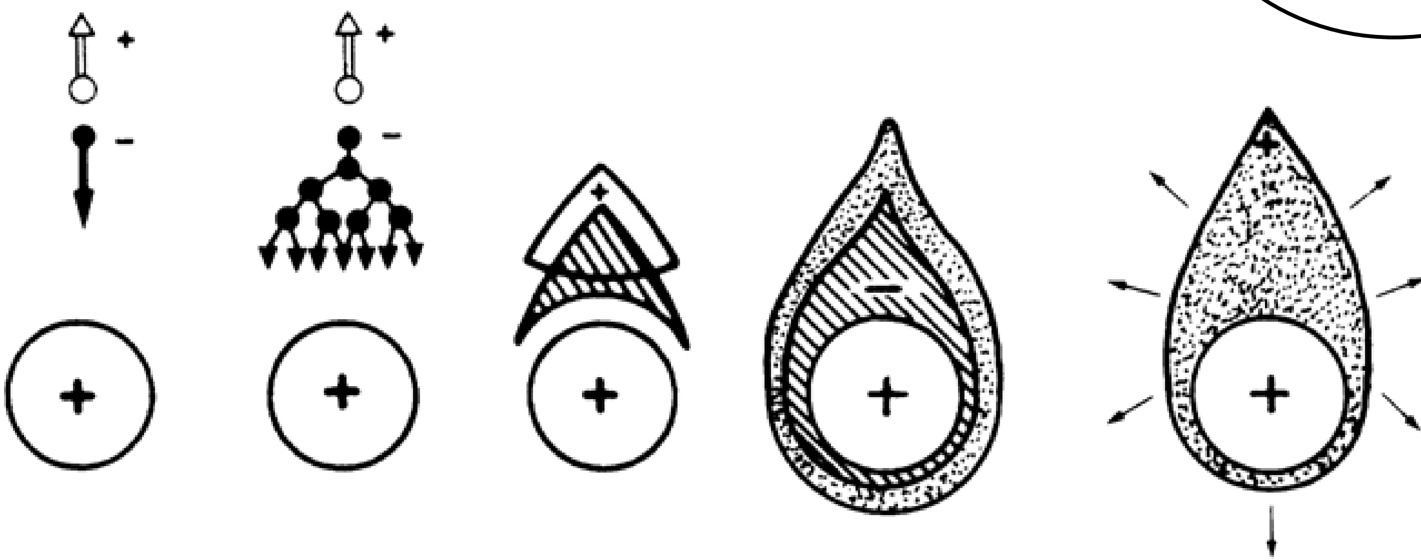
Events occur during 0.05ns time intervals separated by 4ns

It is not difficult to determine the time an event occurred (t_0) with <±0.5ns precision

Gas multiplication in a drift chamber

$$V(r) = V_0 \frac{\ln(r/a)}{\ln(b/a)}, \quad E(r) = \frac{V_0}{r\ln(b/a)}$$

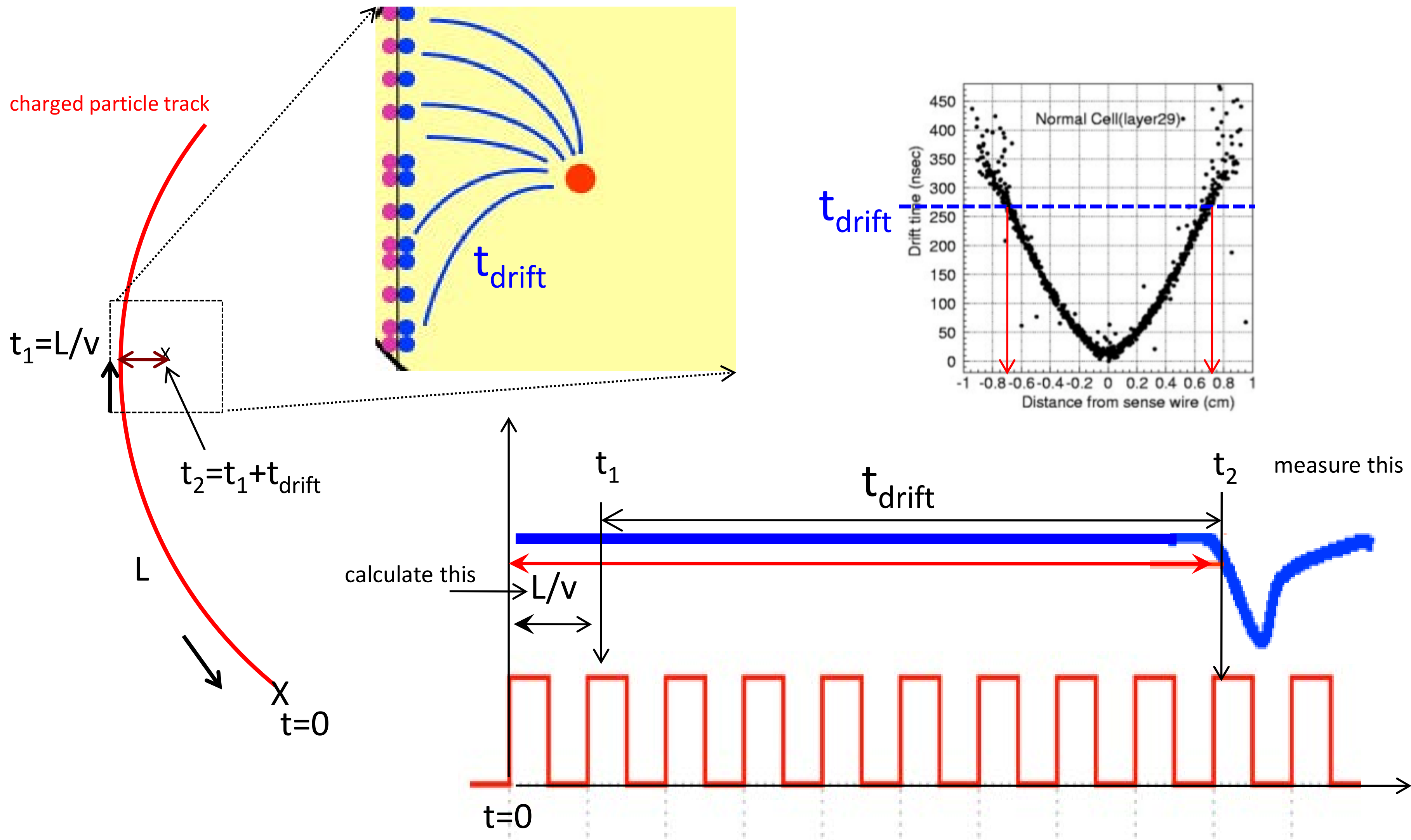




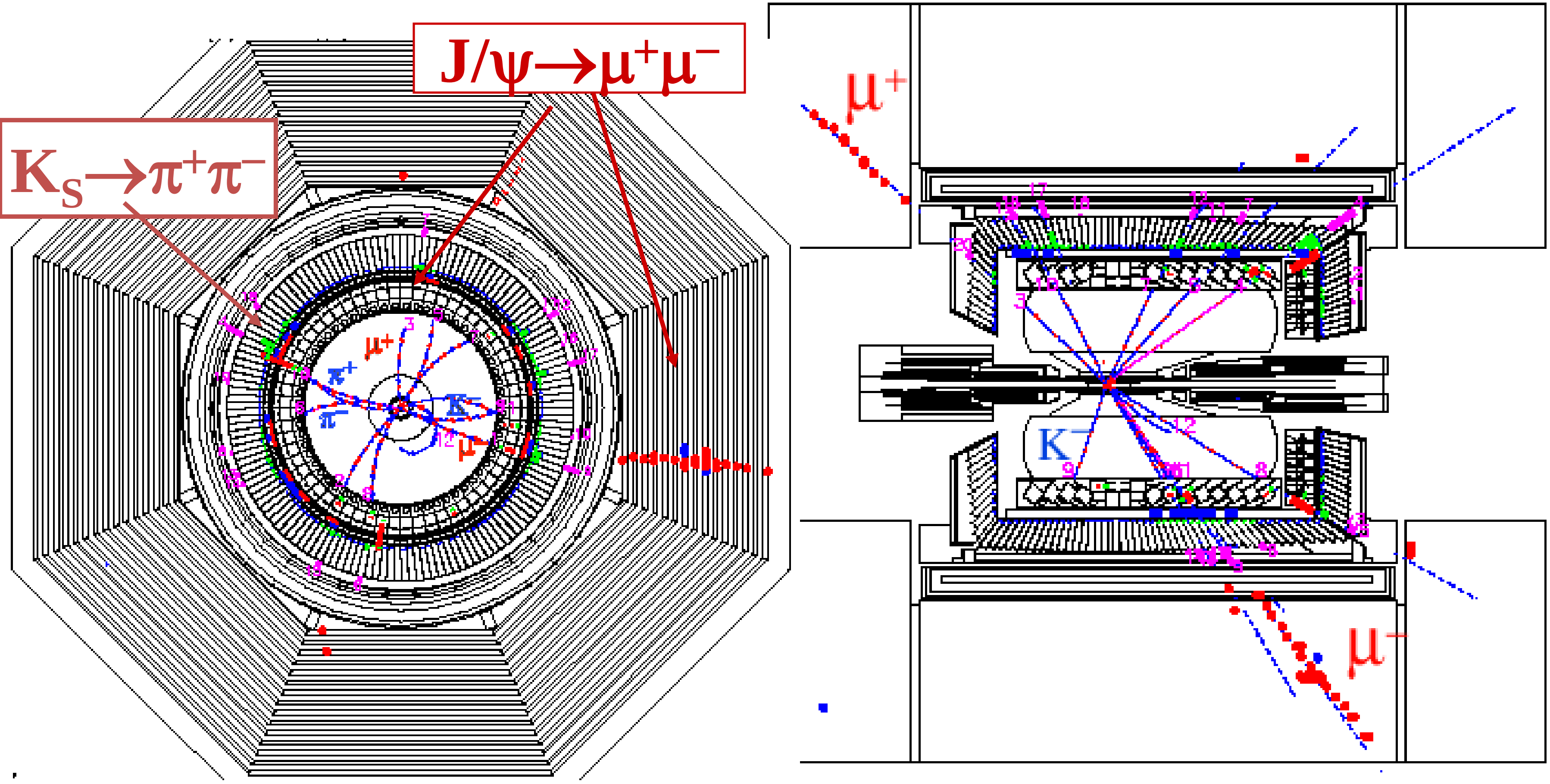
For V_0=2000V, b=2 cm a=20μm:
E-field at the wire≈150×10^3 V/cm

Gas gain ~ 10^5

Time vs drift distance

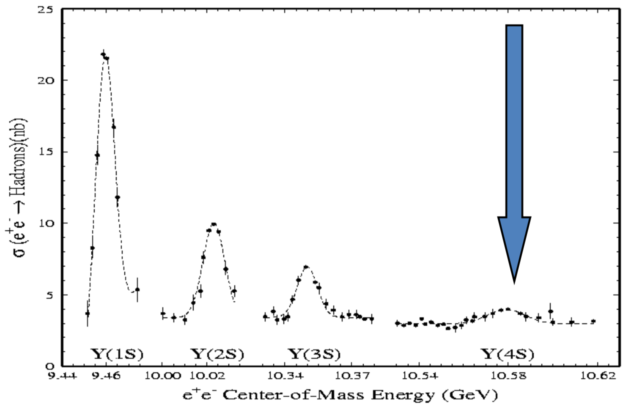


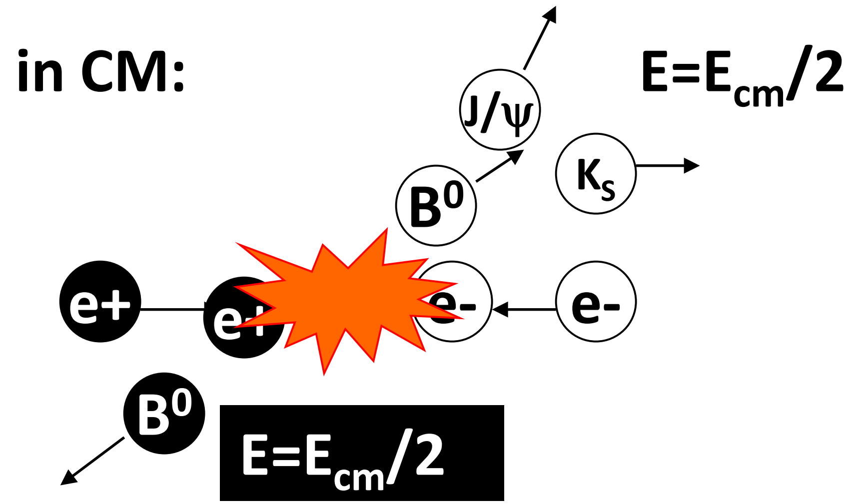
Same event in the entire Detector



$\bar{B}^0 \to J/\psi\, K_s$ event

Kinematic variables for the ϒ(4S)



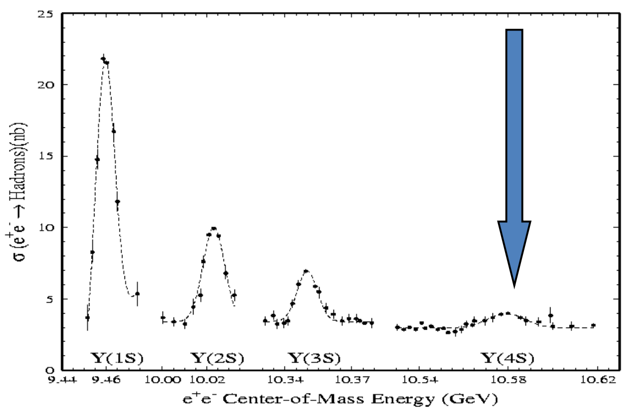


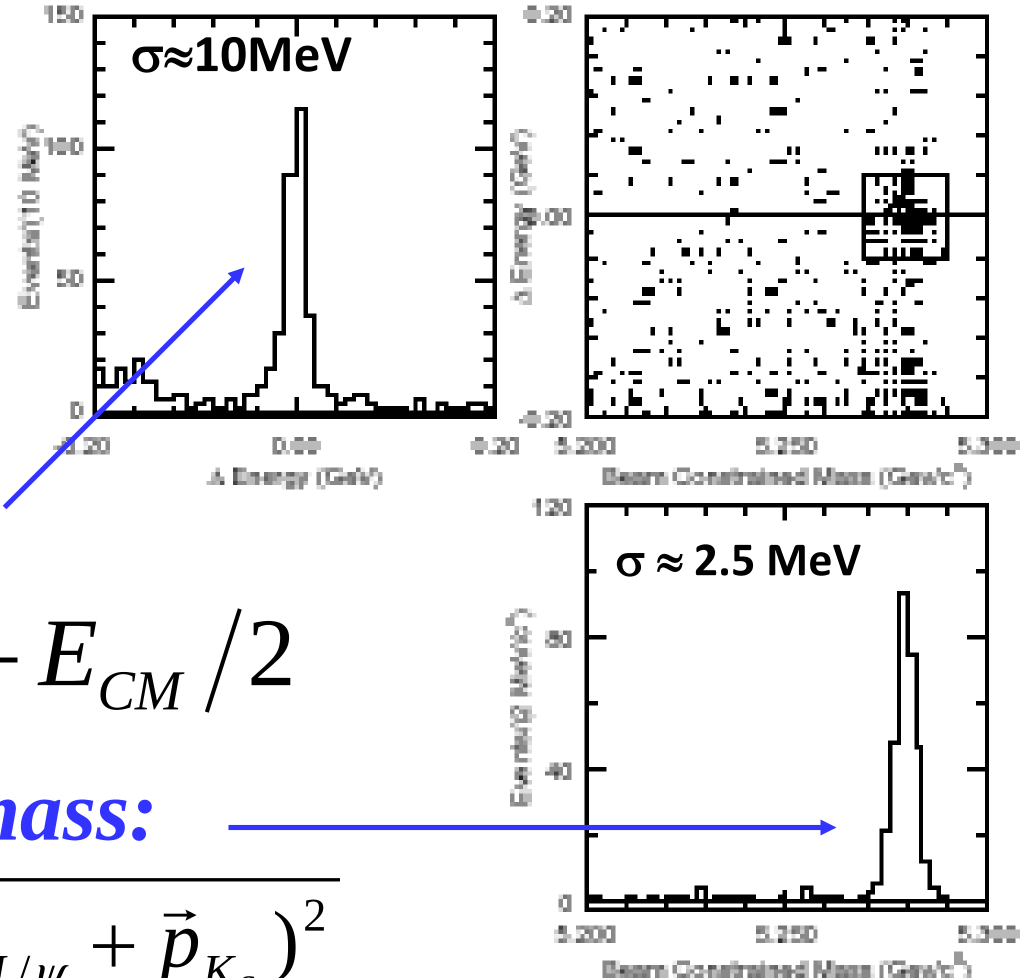
$$E_B \equiv E_{J/\psi} + E_{K_S} = E_{CM}/2$$

invariant mass: $$m_B = \sqrt{(E_{J/\psi} + E_{K_S})^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$

Beam-constrained mass: $$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$

Kinematic variables for the Υ(4S)





Energy difference:

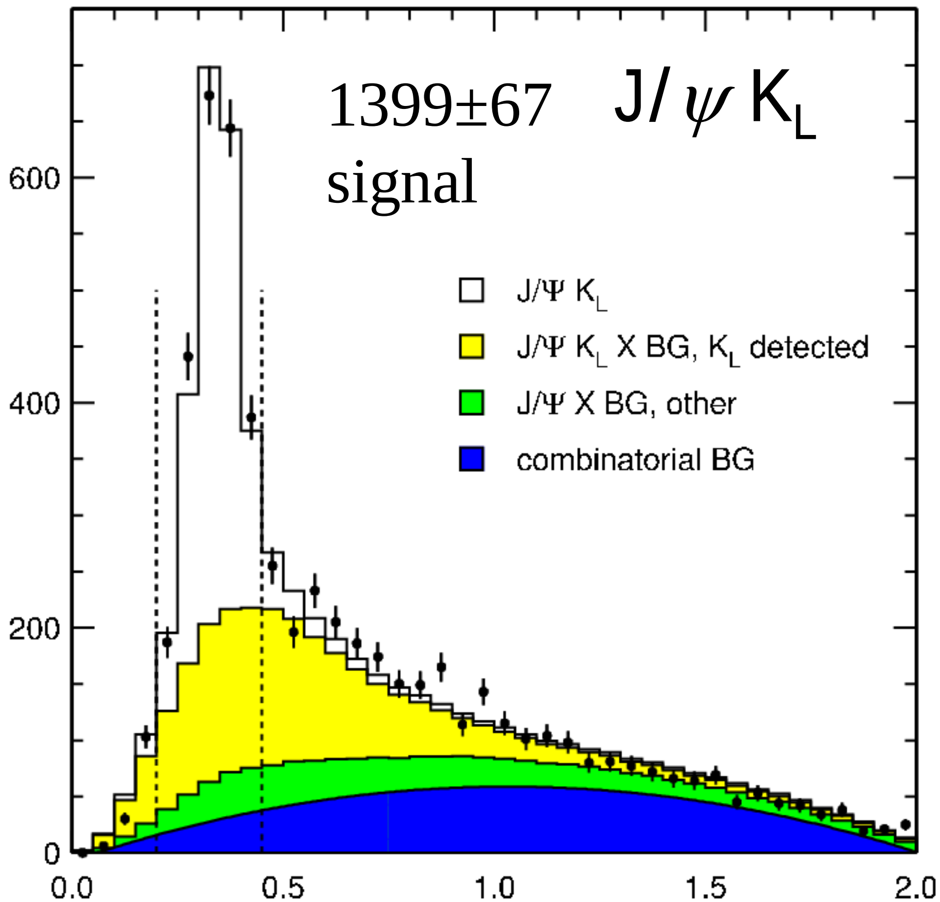
$$\Delta E \equiv E_{J/\psi} + E_{K_S} - E_{CM}/2$$

Beam-constrained mass:

$$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$

Signal purity≈98%

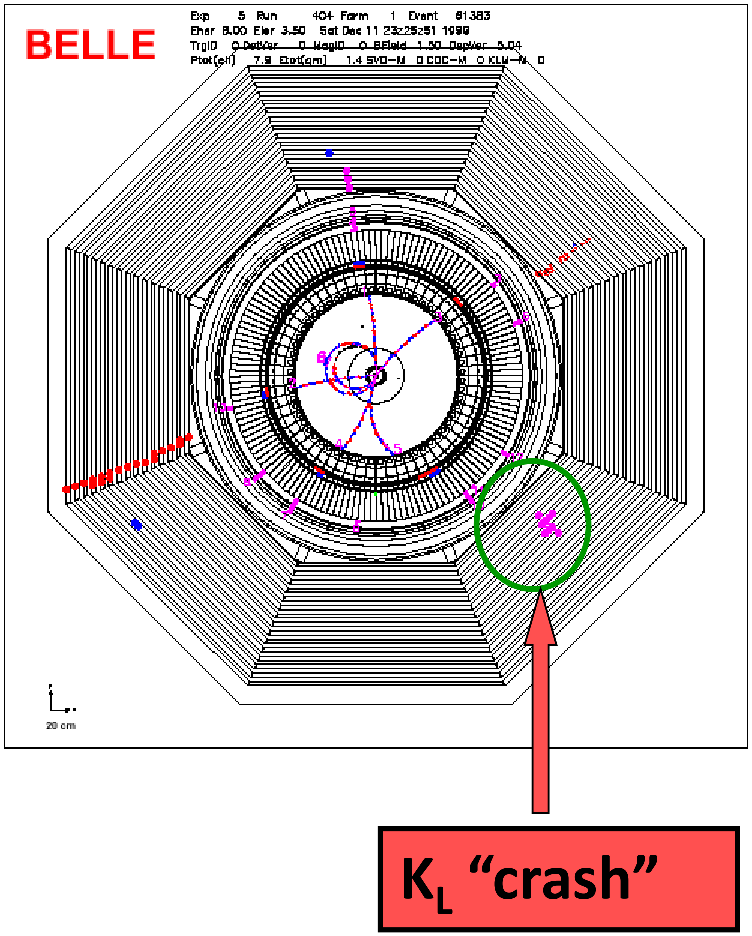
$B^0 \rightarrow \psi K_L$ signal event



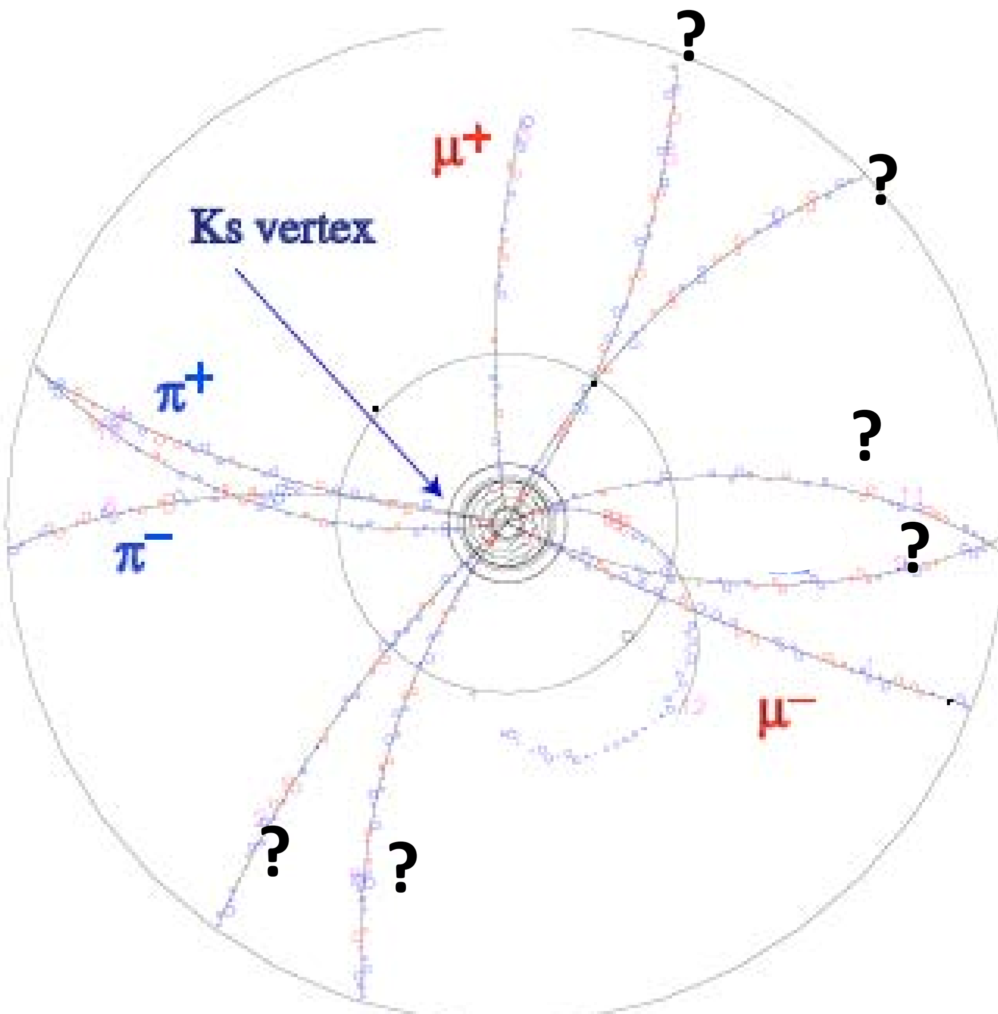
p_B^* (cms)

[2332 events with a purity of 0.60]

Event display



Step 3: Check the other tracks to see if the other meson is a B^0 or a $\overline{B}^0$



Flavor-tagging the other B

Figure of merit(Q)=ε(1-2 w)²: the 'effective" tagging efficiency

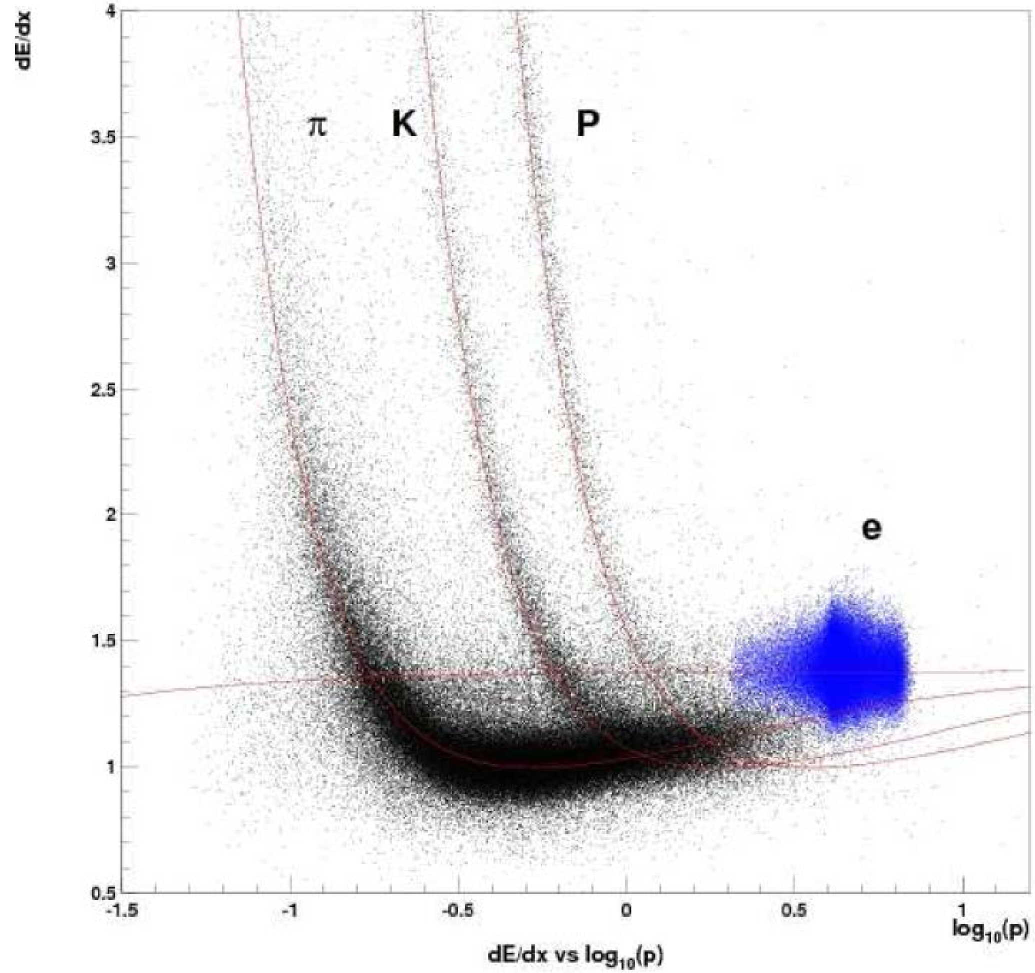
w=wrong-sign tags

- ***Inclusive Leptons:***
  - ***high-p l^-*** $b \rightarrow c\, l^- \nu$
  - ***intermediate-p l^+*** $\quad \hookrightarrow s\, l^+ \nu$
- ***Inclusive Hadrons:***
  - ***high-p π^-*** $B^0 \rightarrow \bar{D}^{(*)+} \pi^-,\ D^{(*)+} \rho^-$, etc., $\quad \rho^- \rightarrow \pi^- \pi^0$
  - ***low-p π^+*** $\quad \bar{D}^{(*)+} \rightarrow D^0 \pi^+$
  - ***intermediate-p K^-*** $\quad D^0 \rightarrow K^- X$

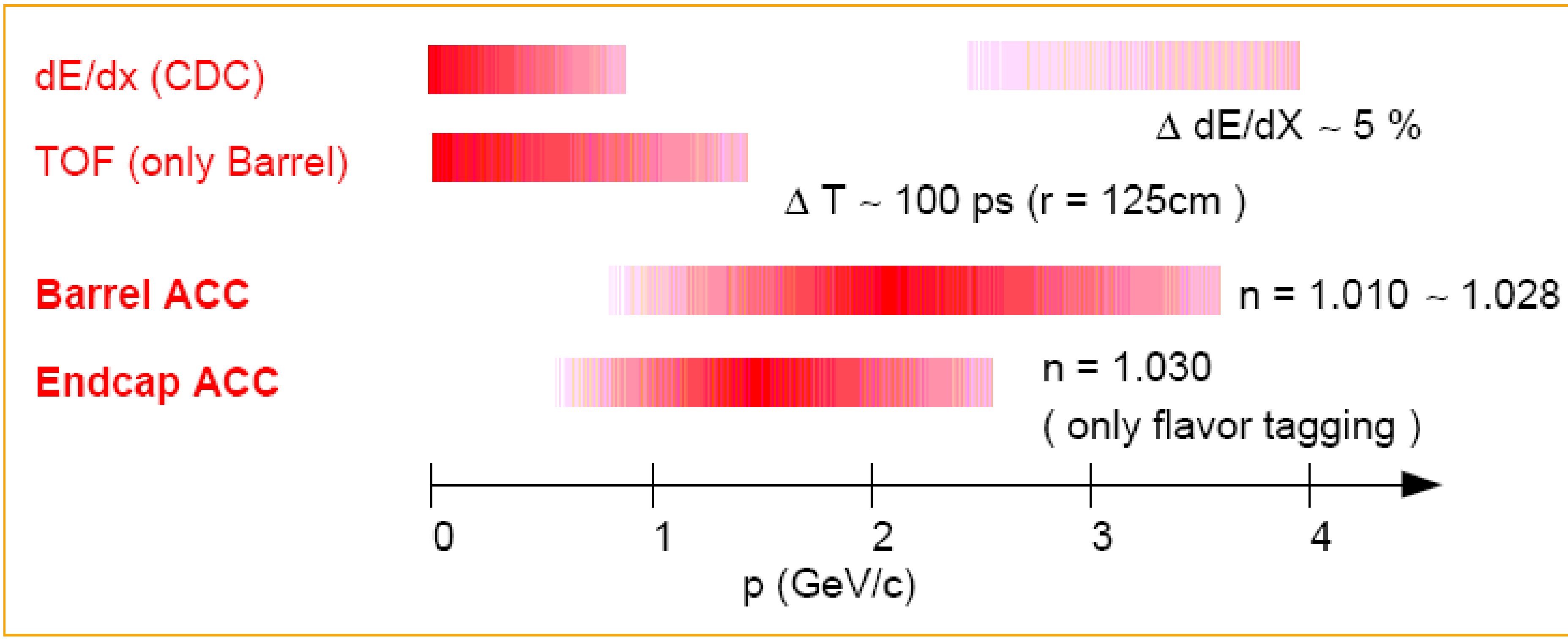
Belle: effective efficiency = 30 %

Distinguishing different particle types dE/dx

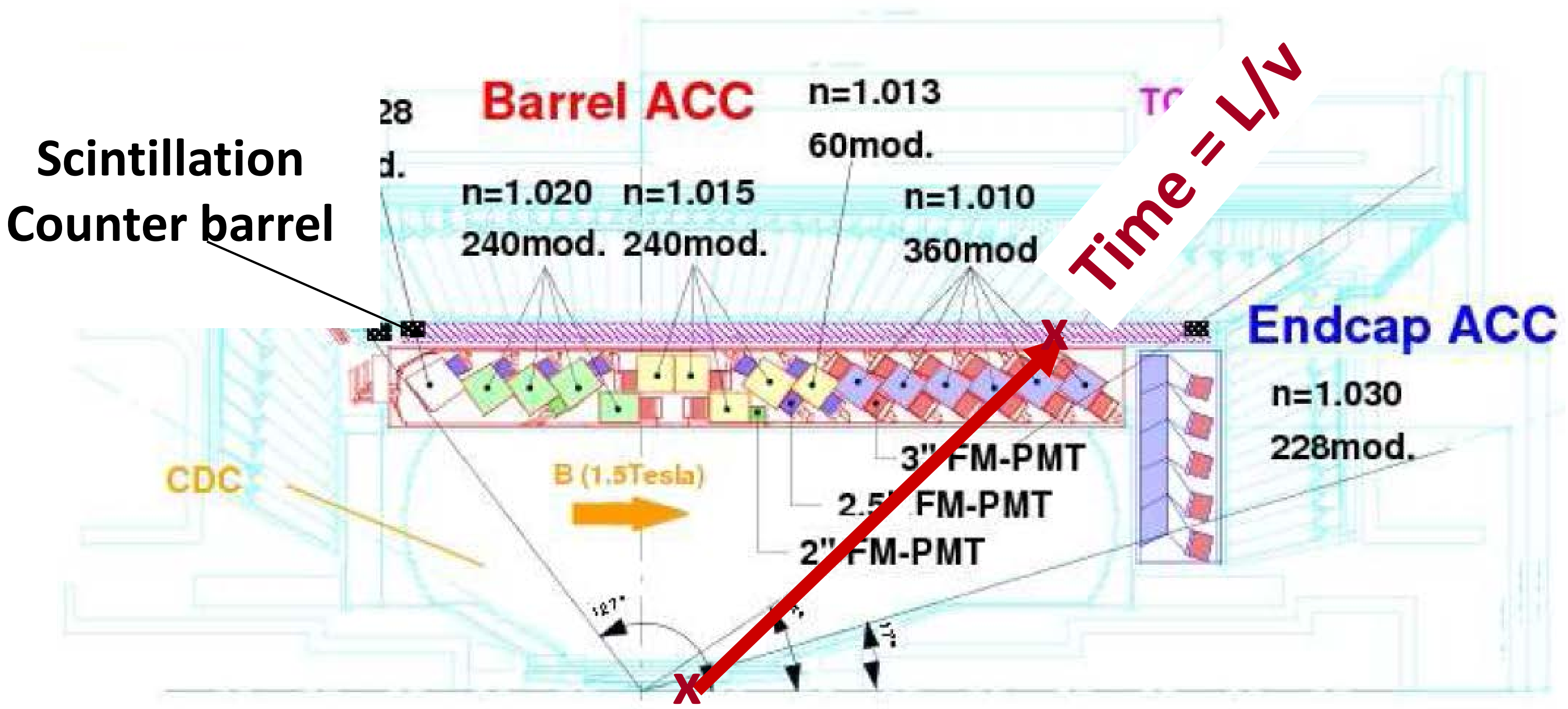
Ionization density in the drift chamber (dE/dx)



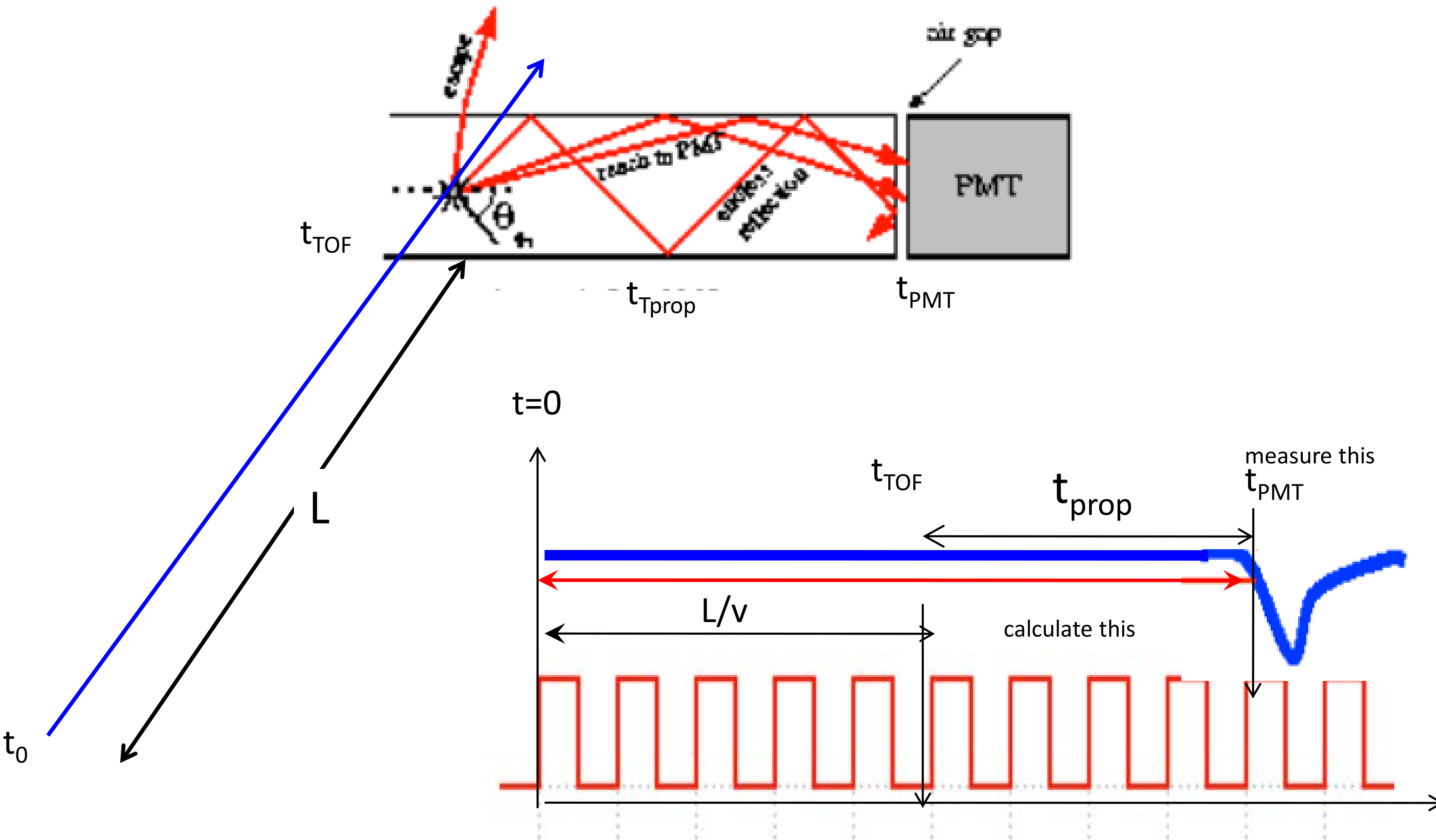
K meson identification from dE/dx, Cherenkov & TOF



Distinguishing different particle types (time-of-flight)



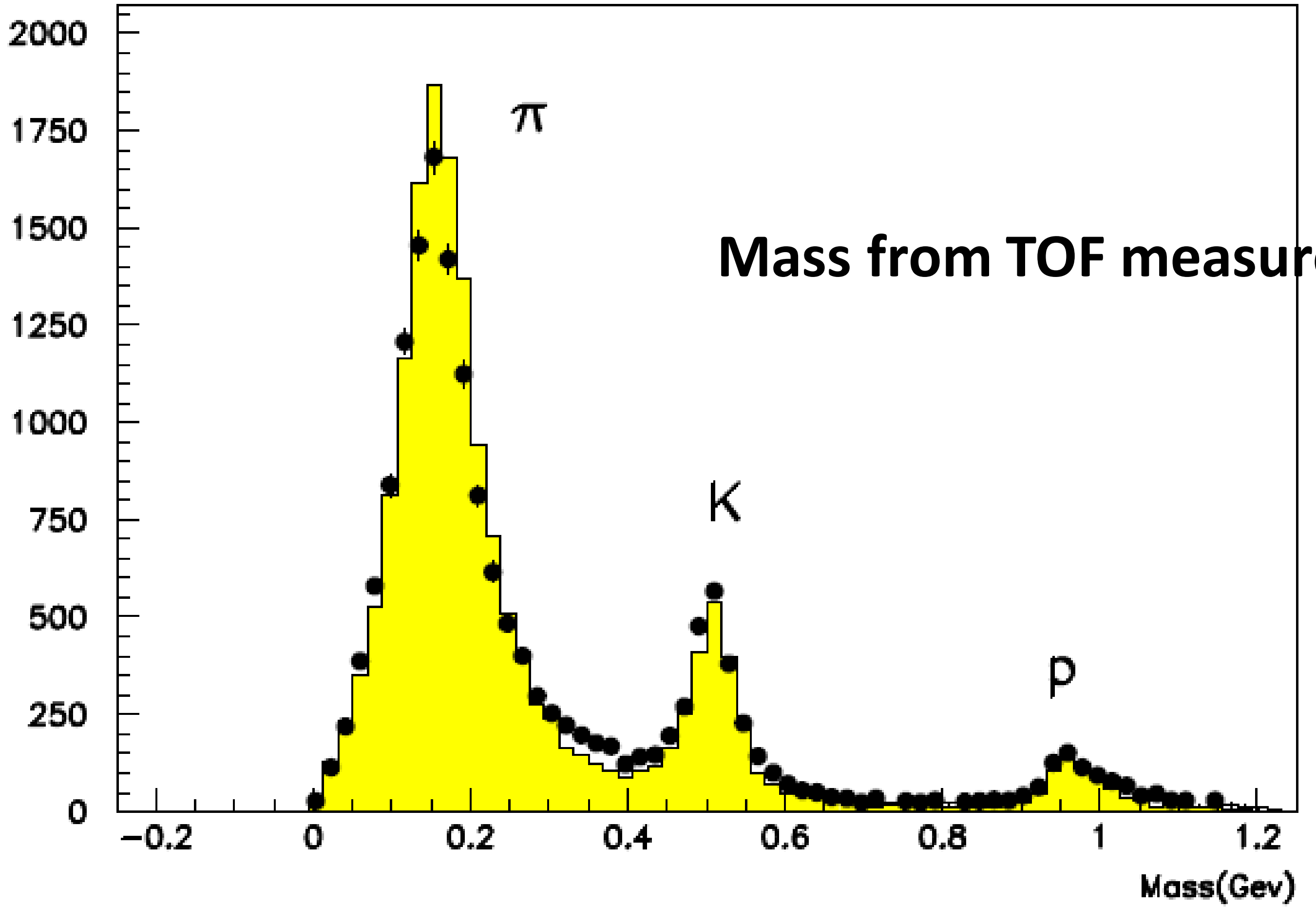
Time of flight measurement



here you use a much faster clock

TOF measurements of particle mass

Time = L/v ➔ $\beta = v/c = p/\sqrt{(p^2+m^2)}$ ➔ m



Mass from TOF measurements

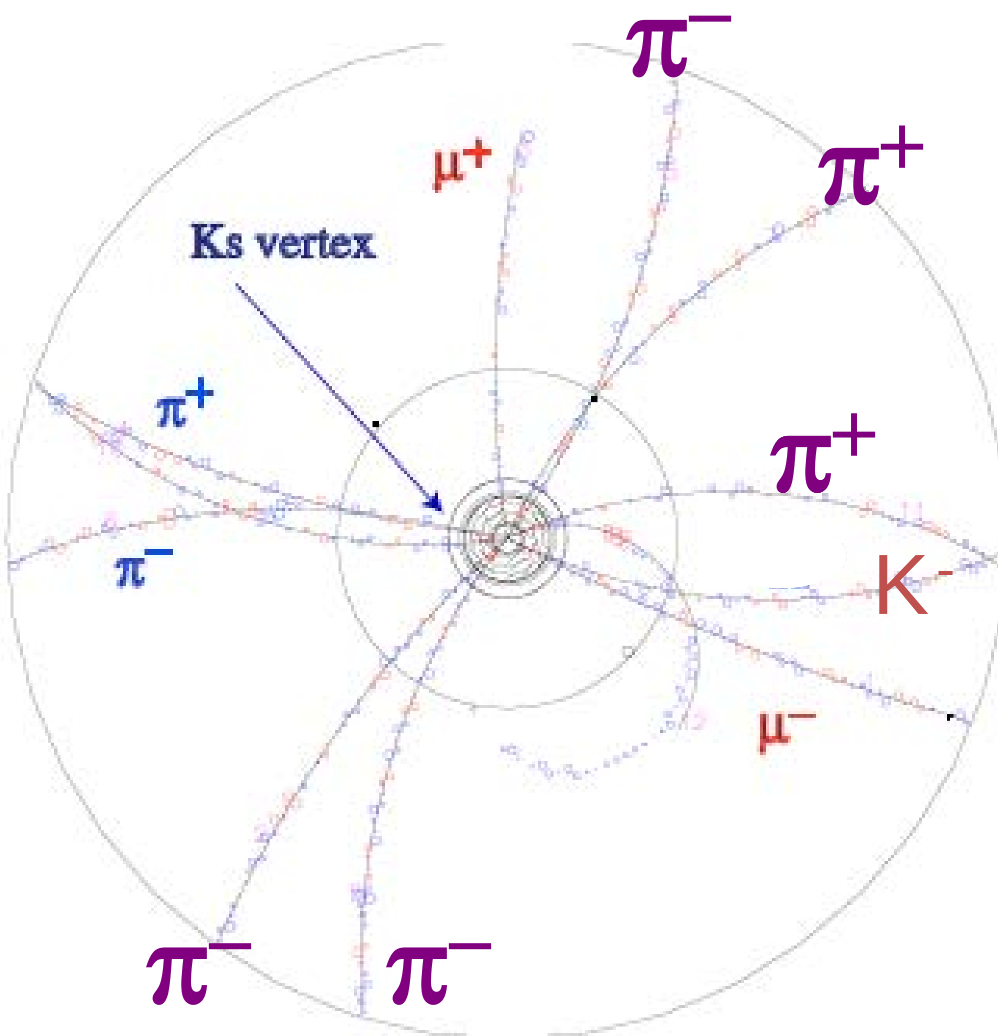
Identify the other tracks in the event

A K^- tag event means the other meson is (probably) a $\overline{B}^0$ (not a B^0)

$D \rightarrow K^-$ not K^+

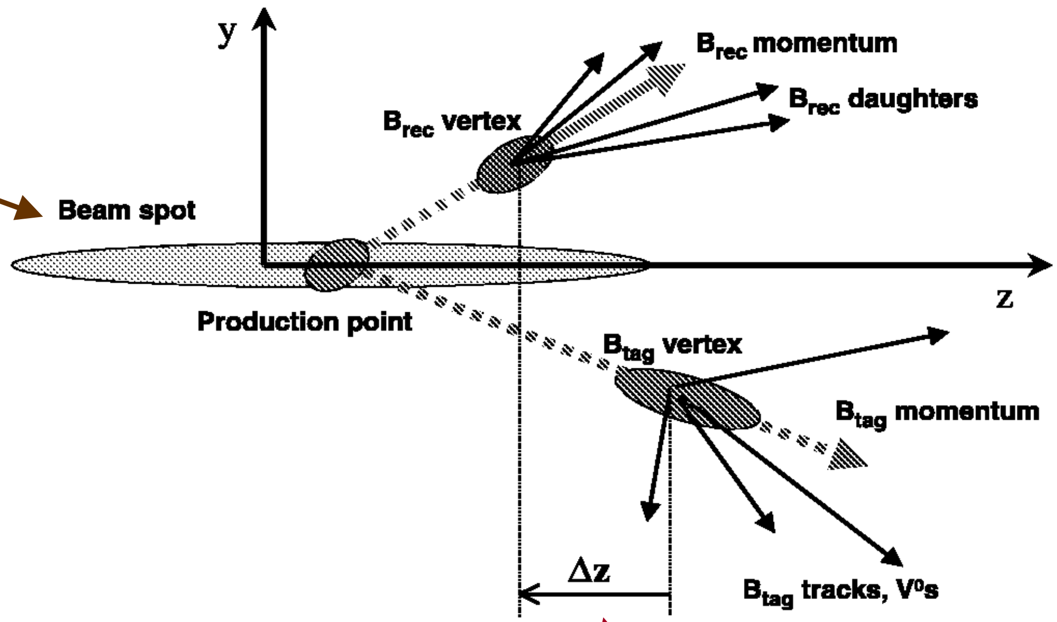
$\overline{D} \rightarrow K^+$ not K^-

$\overline{B} \rightarrow D >> B \rightarrow D$



Step 4. Find decay time difference

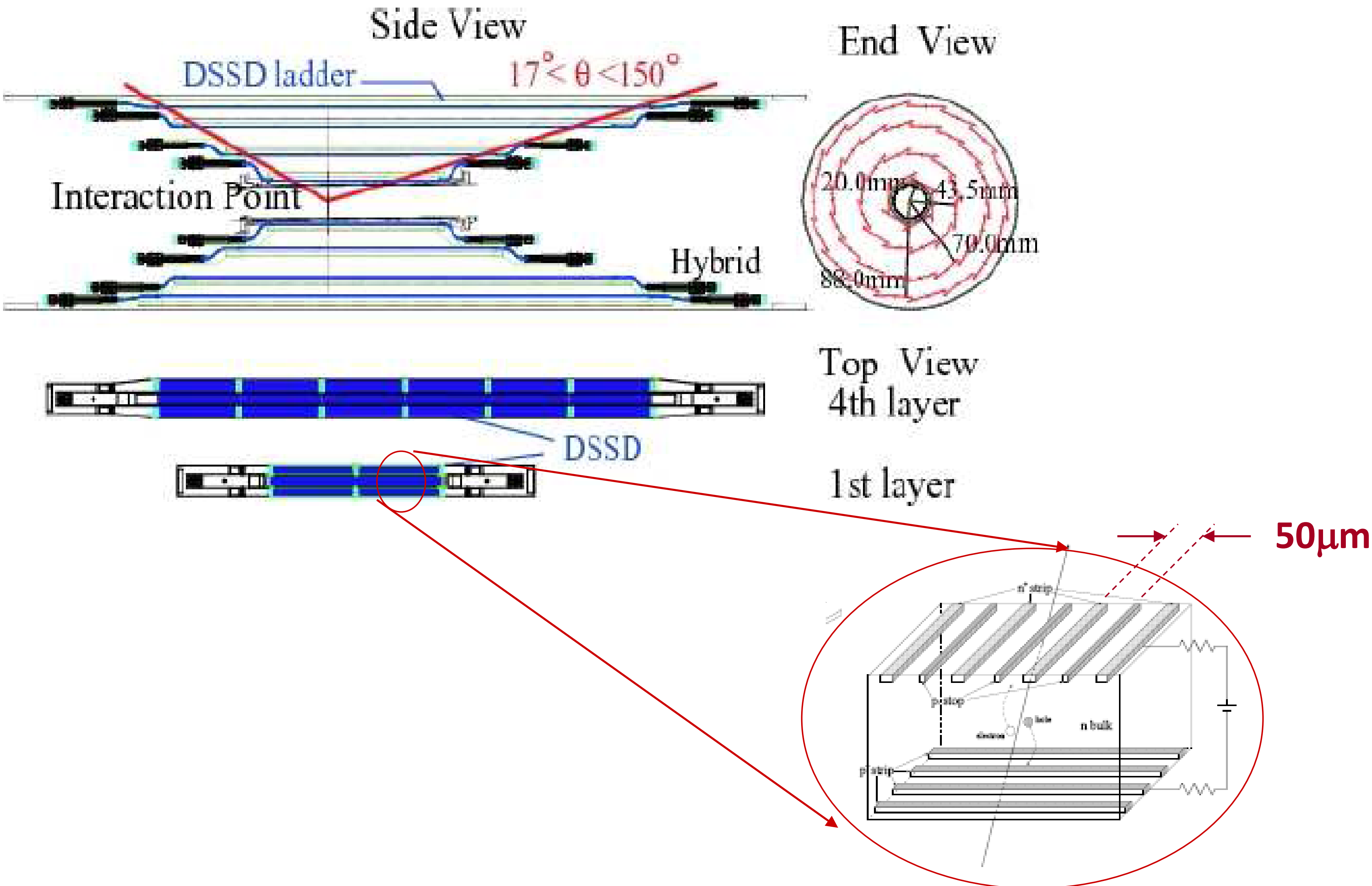
Beam spot: 110 μm x 5 μm x 0.35 cm



Silicon detectors measure Δz

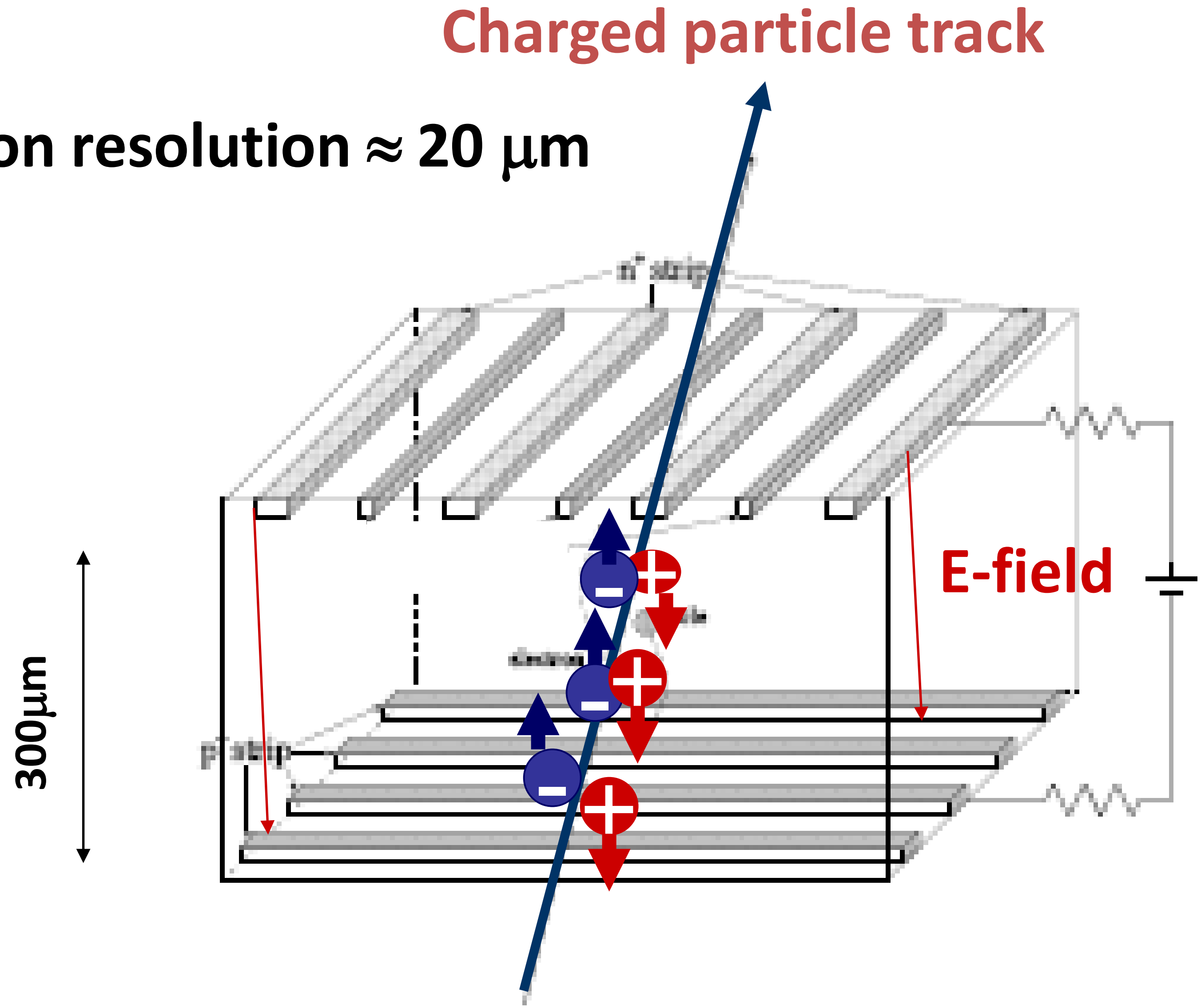
(typically ~200 μm)

Silicon vertex detector



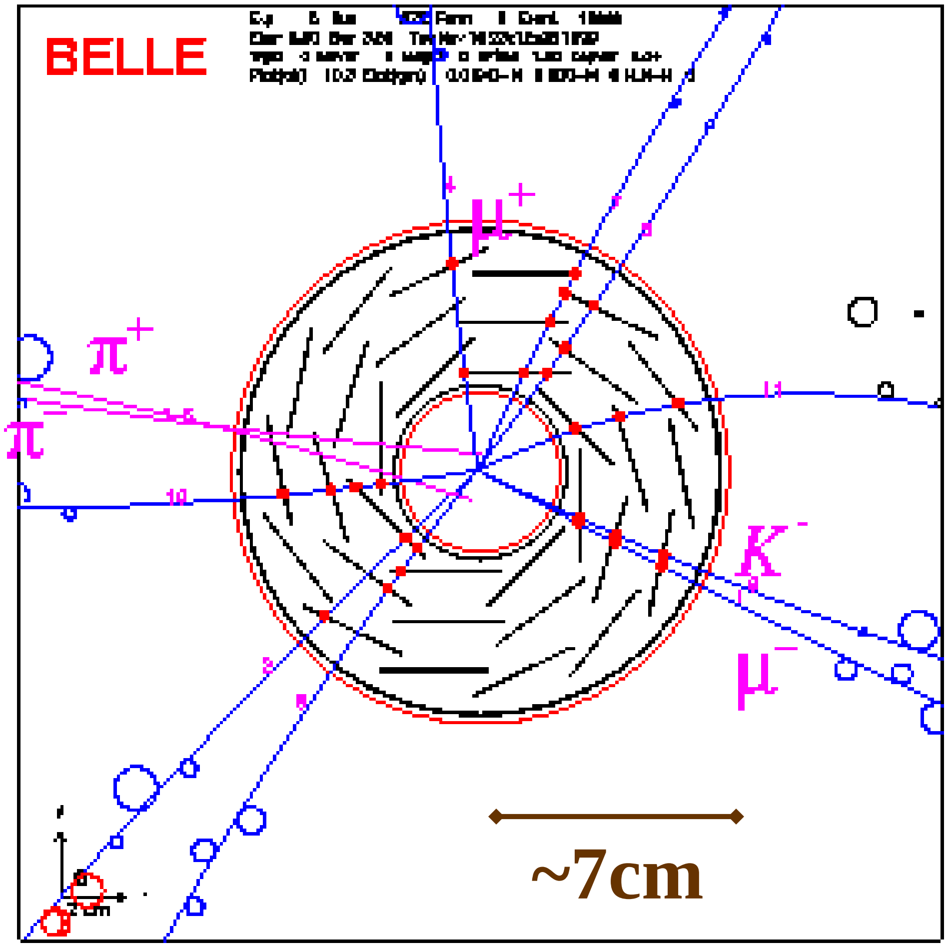
Silicon detector

position resolution ≈ 20 μm

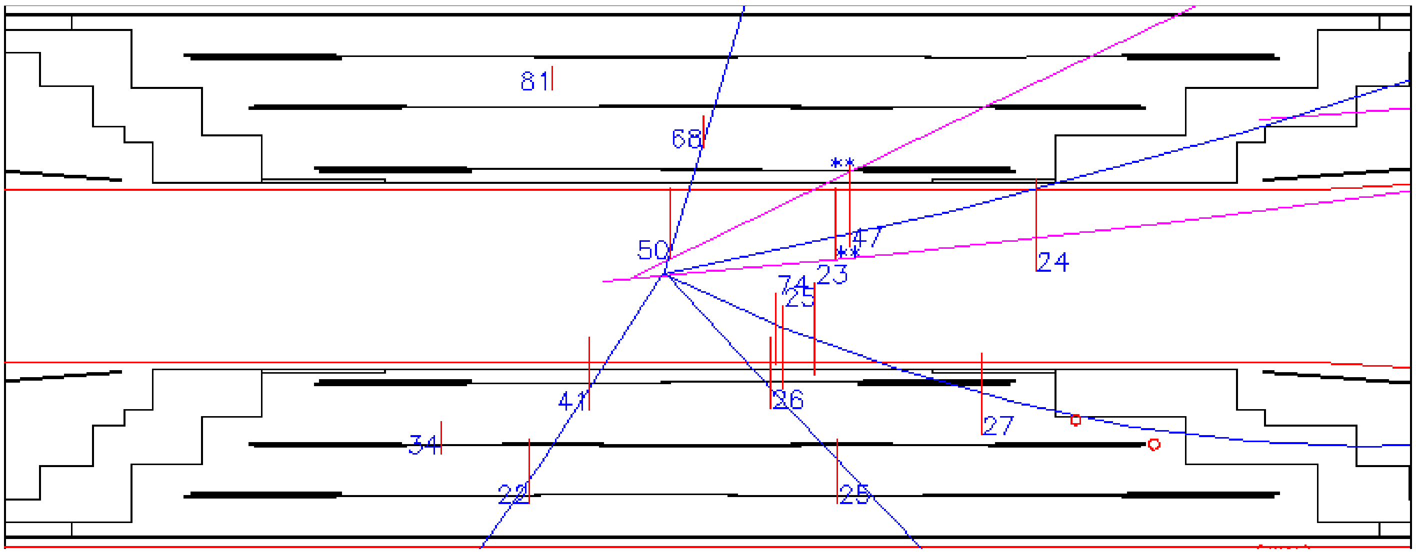


Magnified vertex

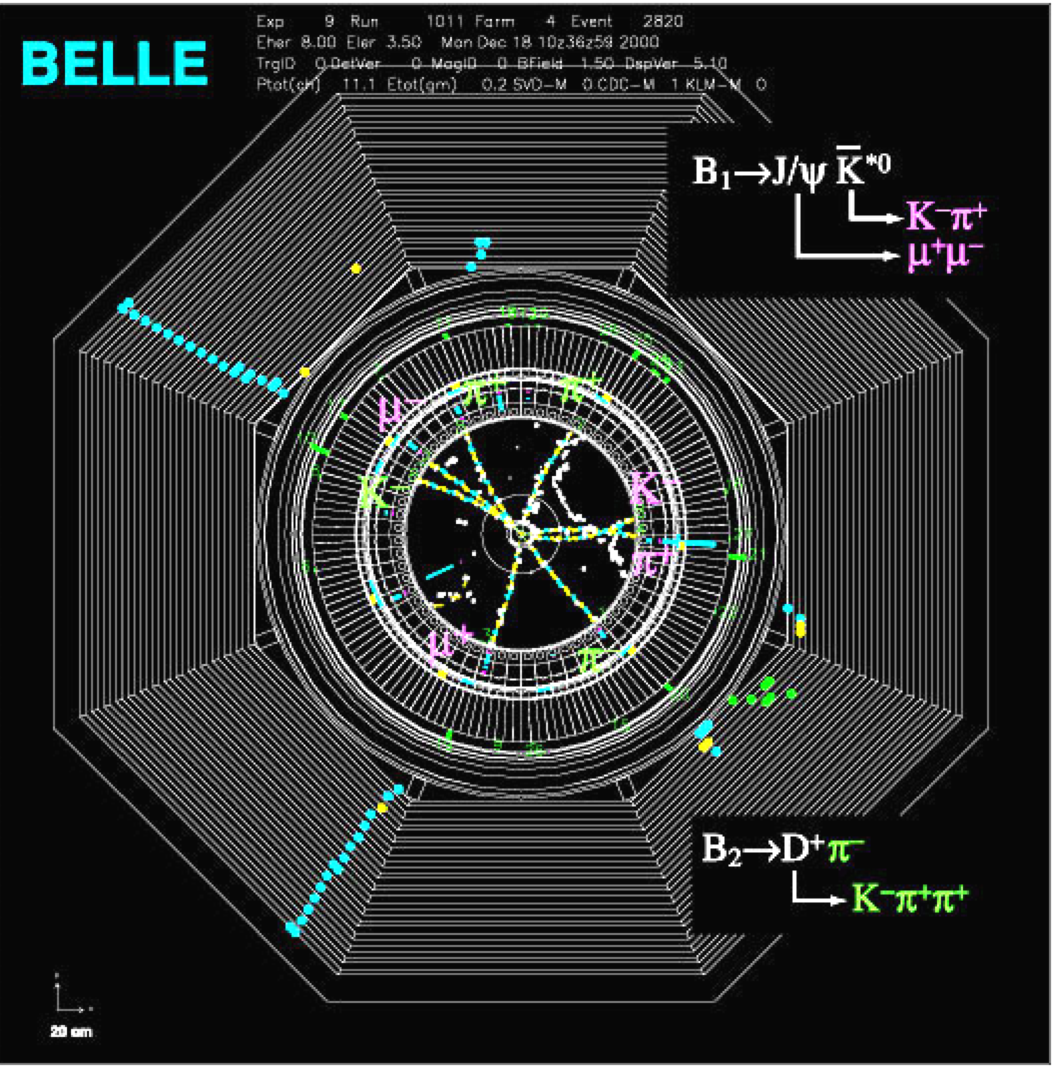
$K_s \rightarrow \pi^+\pi^-$

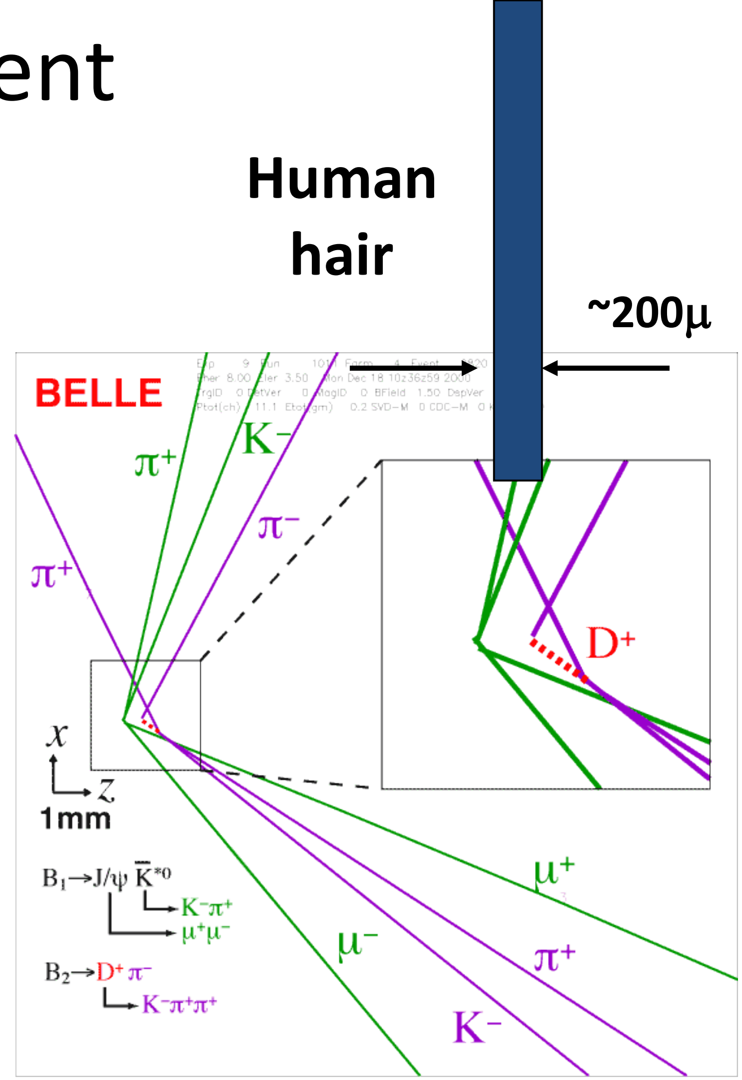


y-z vertices



A Fully-reconstructed Event





Event-by-event Likelihood

$$\mathcal{L}_i = \int \left(\left(1 - f_{bk} \right) \mathcal{P}_{sig} + f_{bk} \mathcal{P}_{bk} \right) \times \mathcal{R}(\Delta t - \Delta t') d\Delta t'$$

background frac

Sidebands & MC

resolution function
B-lifetime studies

b-flavor tag

PDG

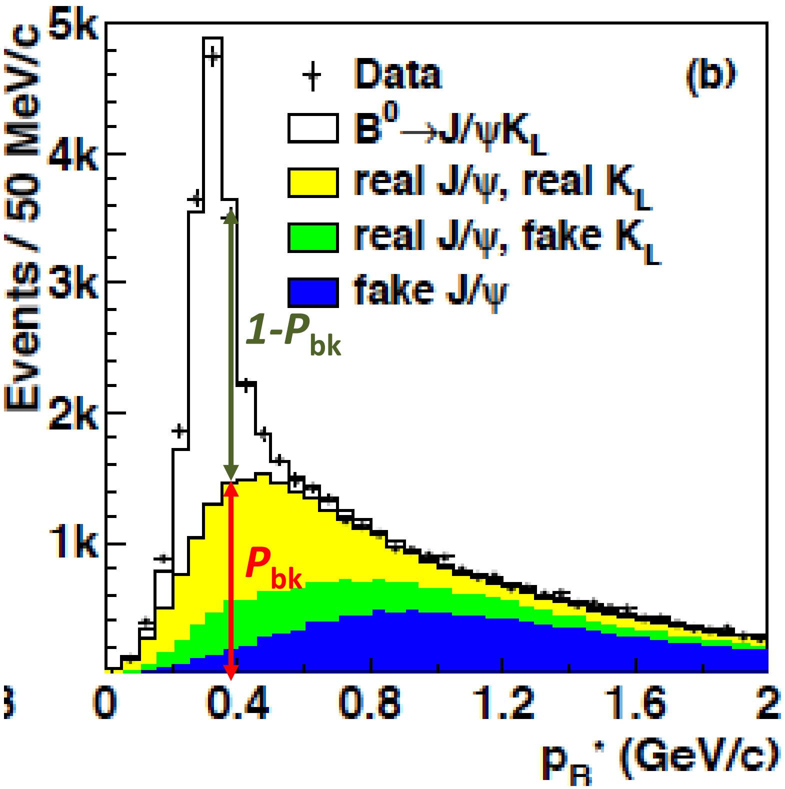
$$\mathcal{P}_{sig} = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B} (1 - \xi_f q (1 - 2w) \sin 2\phi_1 \sin \Delta m \Delta t)$$

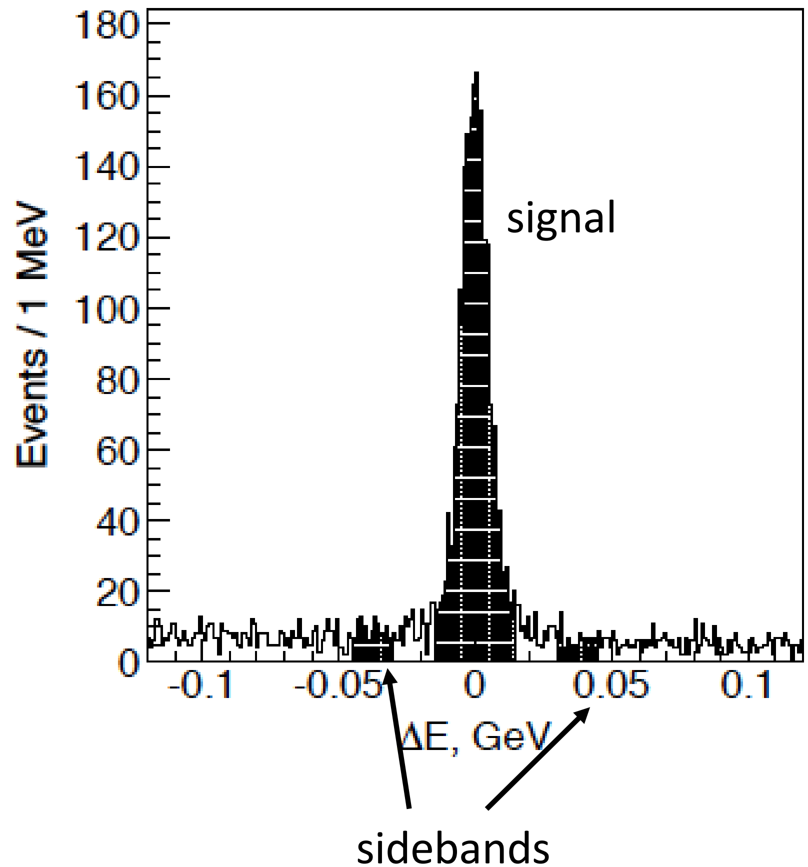
ξ_f = ±1 for CP = ±1

lone free parameter

wrong-tag frac.

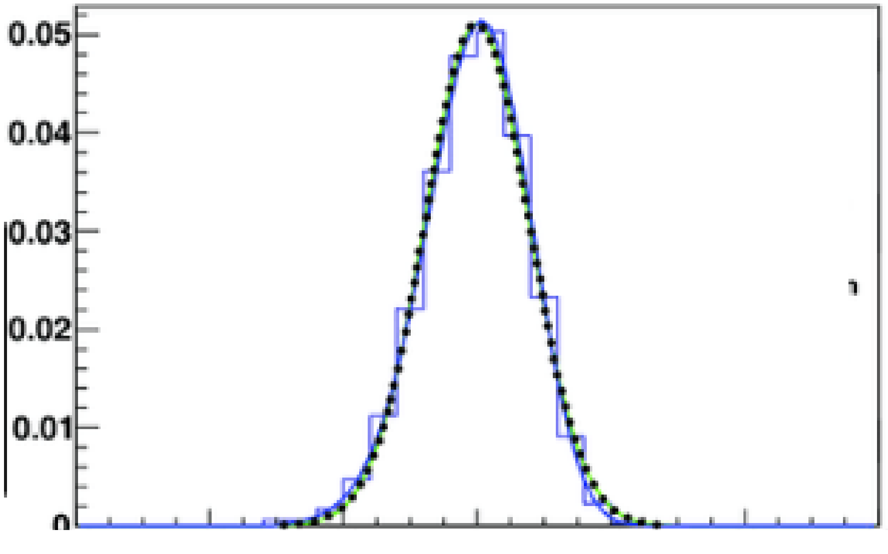
P_{bk}, sidebands, etc





Resolution function

$$\mathcal{R}(\delta t;\sigma_{\Delta t}) = f_{\rm core} h_G(\delta t;\delta_{\rm core}\sigma_{\Delta t}, S_{\rm core}\sigma_{\Delta t}) + f_{\rm tail} h_G(\delta t;\delta_{\rm tail}\sigma_{\Delta t}, S_{\rm tail}\sigma_{\Delta t}) + f_{\rm out} h_G(\delta t;\delta_{\rm out}, S_{\rm out}),$$



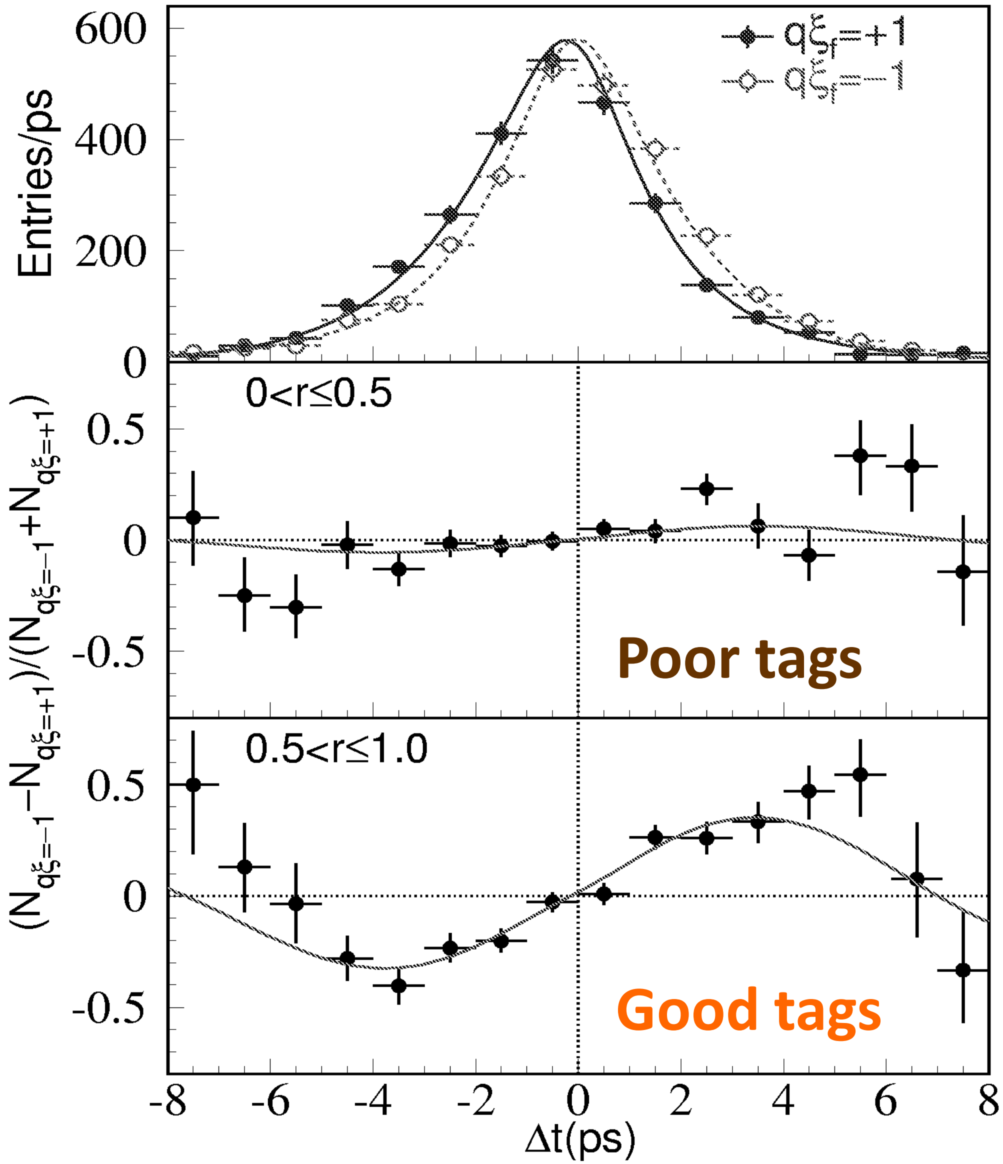
$\delta t_{meas} - \delta t_{true}$

$$h_G(\delta t;\delta,\sigma) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(\delta t-\delta)^2}{2\sigma^2}\right),$$

$\sin 2\phi_1$ measurement by Belle (2003)

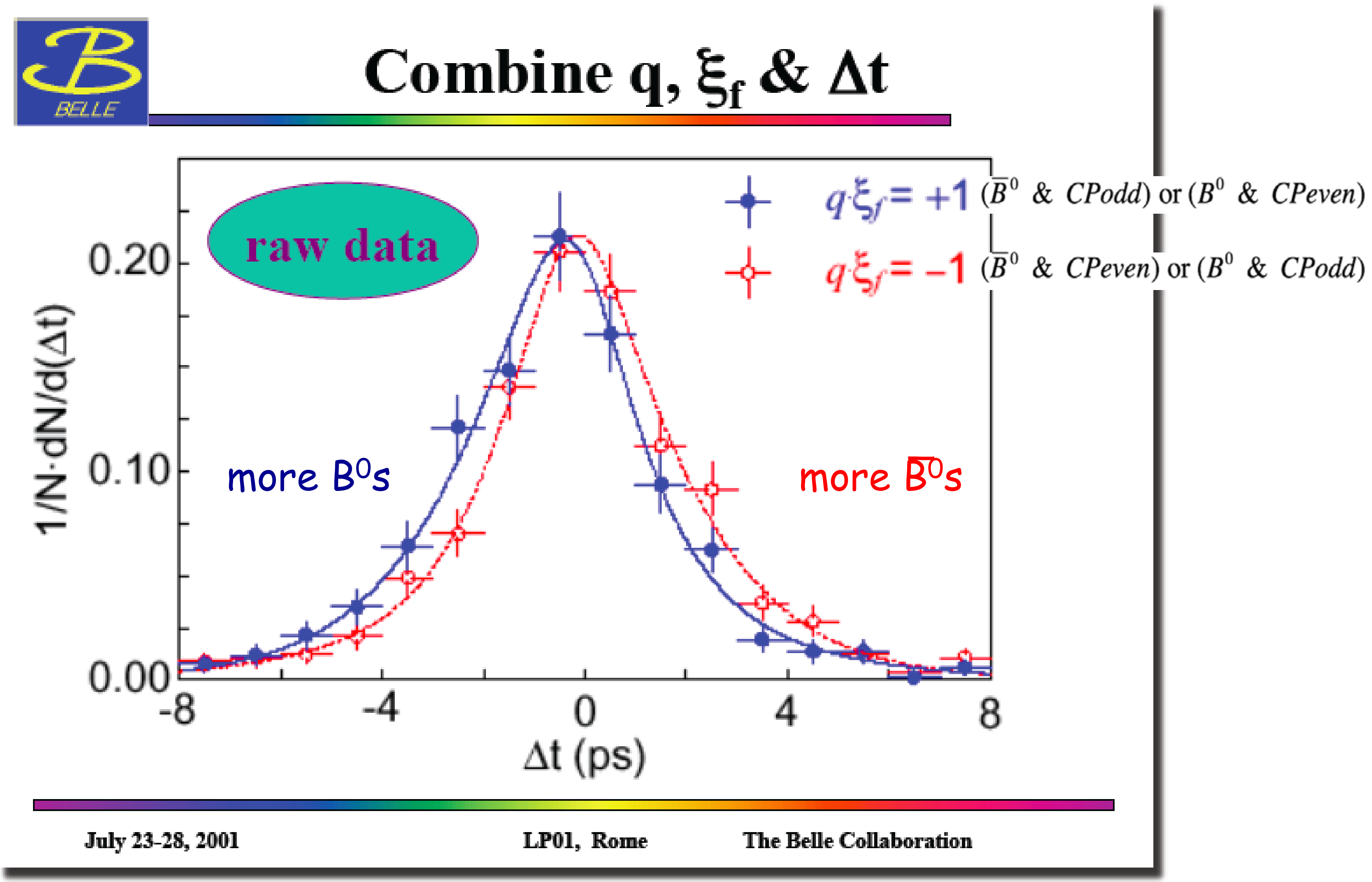
5417 evts

"Raw" asymmetry



CONF-0353

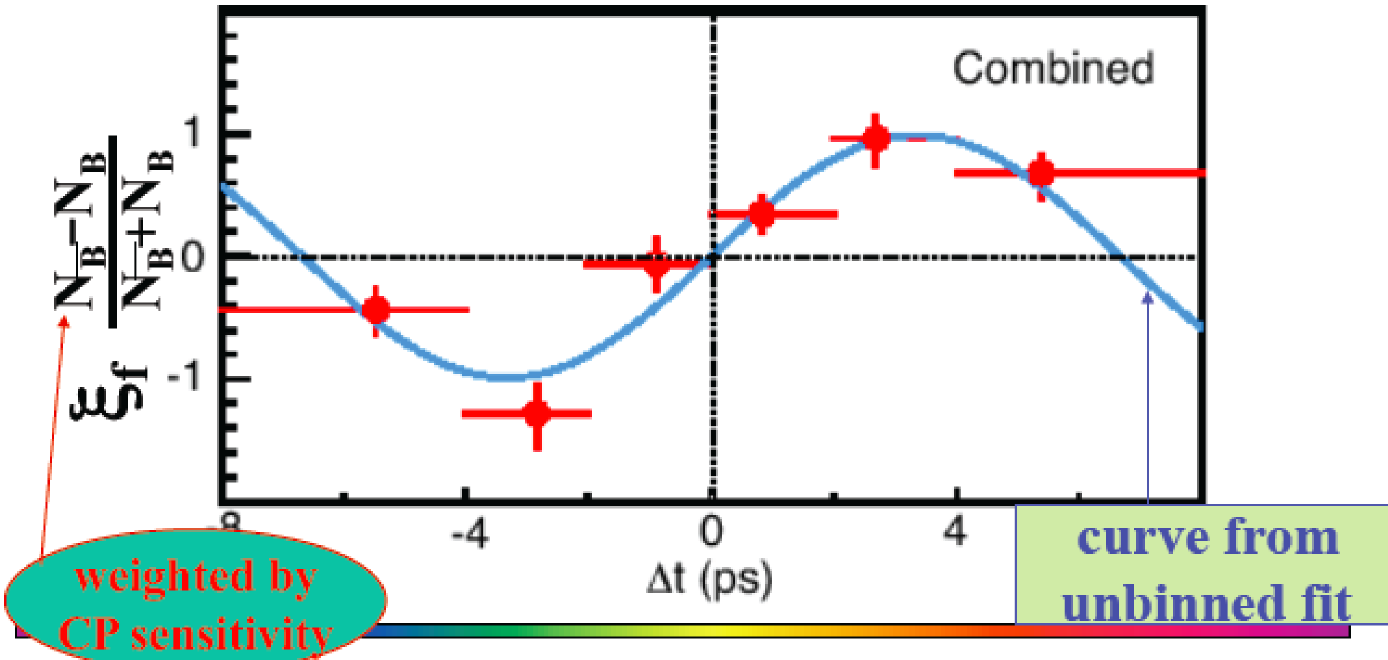
Belle results at LP-2001 Rome



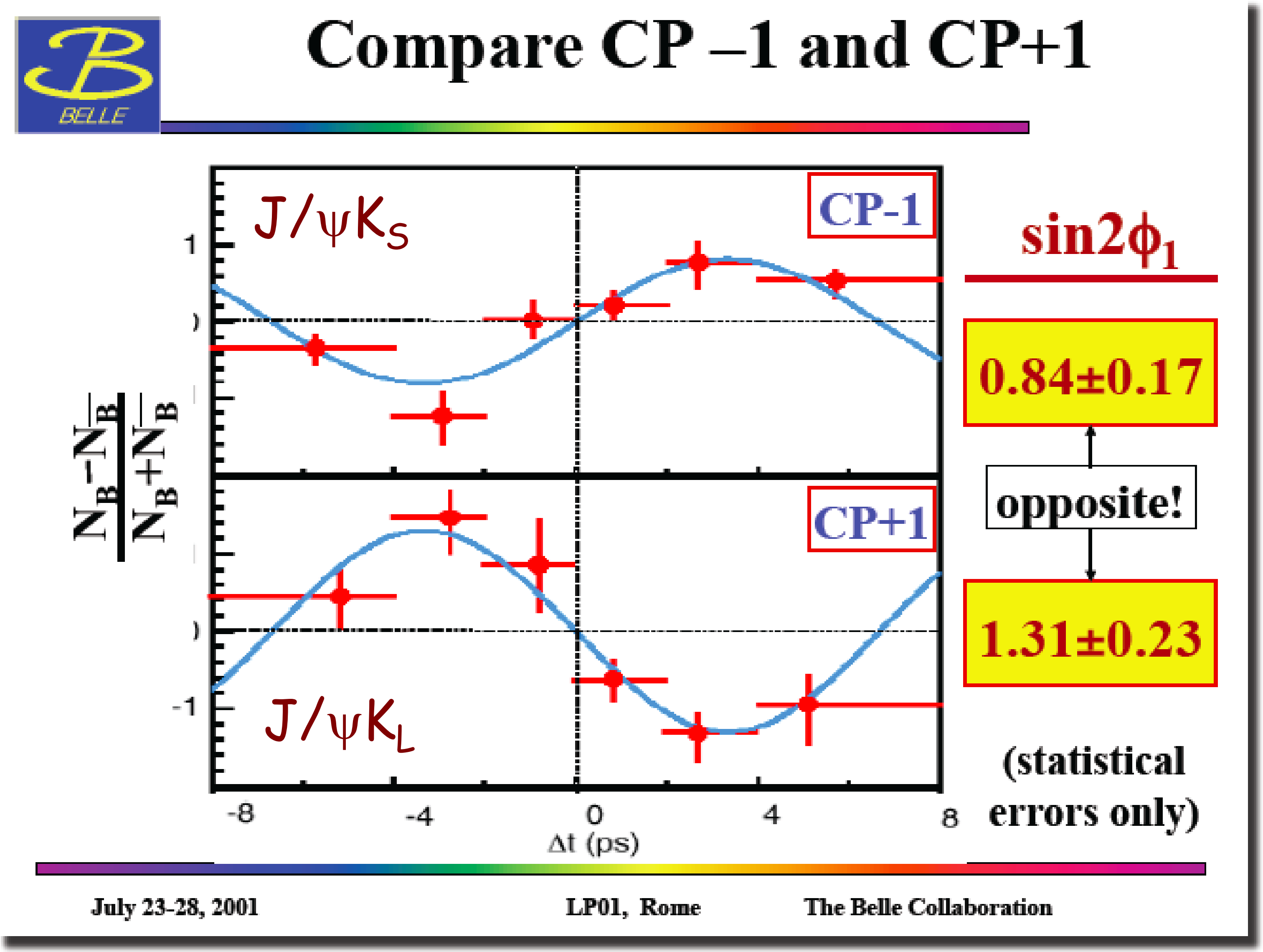
Belle Results LP-2001 Rome

$\sin 2\phi_1$ value that maximizes $\Pi_i L_i$

$\sin 2\phi_1 = 0.99 \pm 0.14$ (stat) ± 0.06(sys)



Belle Results LP-2001 Rome



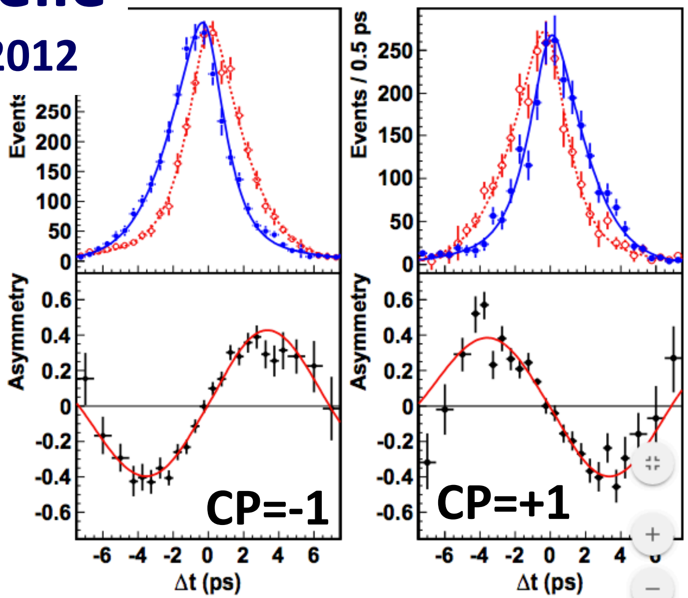
BaBar/Belle comparison (LP2001)

	BaBar	Belle
Integrated Luminosity	$23 fb^{-1}$	$33 fb^{-1}$
$K_S(\pi+\pi-)$ J/ψ events (purity)	316(96%)	457 (97%)
K_L J/ψ events (purity)	273(51%)	569 (61%)
Other CP modes	214	366
Effective tagging effic (w)	26%	27%
$\sin 2\phi_1$	0.59±0.14±0.05	0.99±0.14±0.06

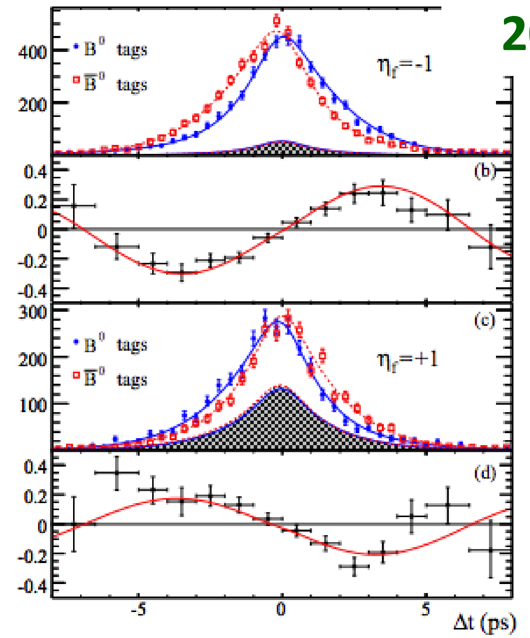
Weighted average: $\sin 2\phi_1 = 0.79 \pm 0.11$; $\phi_1 = 26^o \pm 5^o$

More recent results

Belle
2012

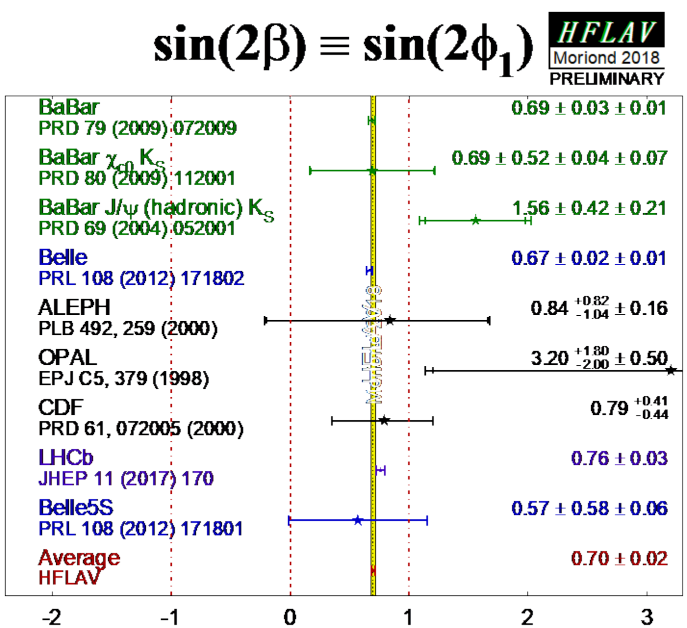


BaBar
2009

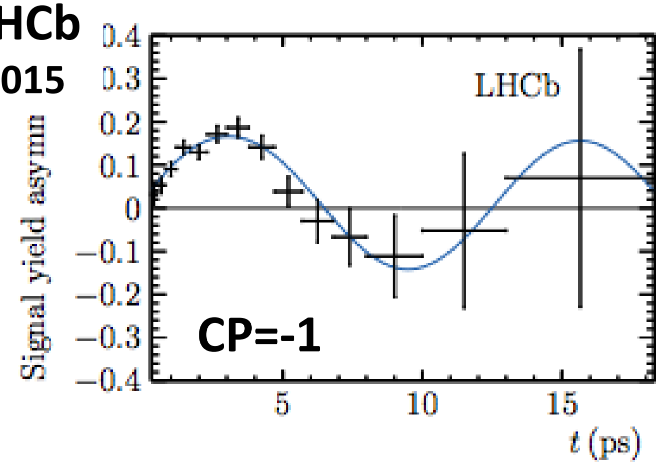


CP=-1

CP=+1



LHCb
2015

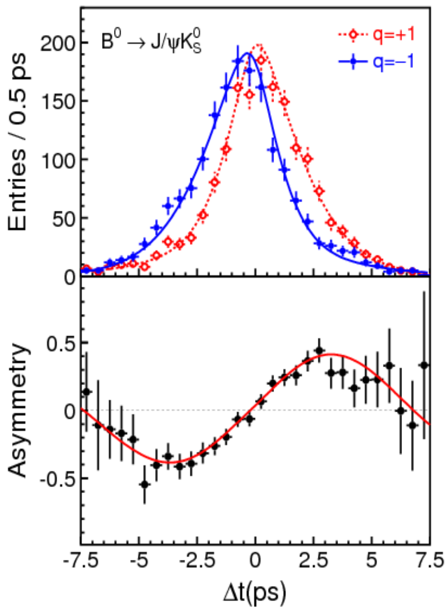


$\sin2\phi_1 = 0.699 \pm 0.017$

$\phi_1 = 22.2^0 \pm 0.7^0$

CP Violations seen in B meson decays

near their maximum possible values:



Consistent with KM-model-based prediction

Are these CPV asymmetries really due to a phase in the CKM matrix?

Summary of Lecture 5

- Carter and Sanda establishes conditions on M_t, $|V_{cb}|$ and $|V_{ub}|$ for producing measureable CP violating asymmetries in B meson decays.

- Experiments at DESY, SLAC and Cornell show that the Carter-Sanda conditions are met

- Experiments at KEK (Belle) and SLAC (BaBar) were designed to test the KM predictions for large, mixing-induced CP violation asymmetries in $B^0 \rightarrow K_S J/\psi$ and $K_L J/\psi$ decays

- Both experiments found CP violating asymmetries similar to the Carter-Sanda-Bigi KM-model-based predictions

- Unlike the K meson system, where the observed CP violating effects are small, the CP violating effects in B meson decay are large, near their maximum possible values ($\sin 2\phi_1 \approx 0.68$ *vs* a maximum possible value of 1).