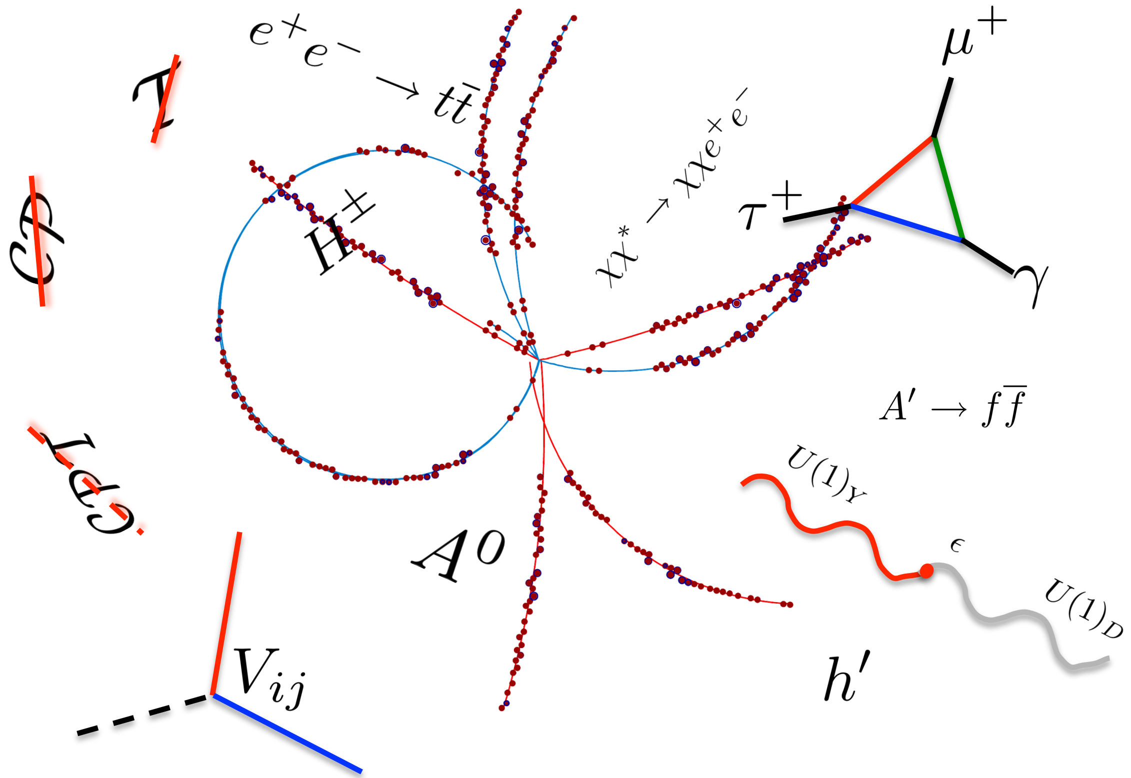
Queen Mary
University of London

Flavour Physics at e$^+$e$^-$ machines: Past/Present and Future



Adrian Bevan

IDPASC School, Valencia, May 2013

- There are three files:
  - 1) Introduction and formalism (this one)
  - 2) Results and future experiments
  - 3) Appendices

Preamble

OUTLINE
NOTES

Outline

These lectures will cover:

- Introduction
  - The B factories
  - CKM, and measuring CP asymmetries

- B Physics:
  - Unitarity triangle physics
    - CP violation measurements
      - The angles: $(\alpha, \beta, \gamma) = (\phi_2, \phi_1, \phi_3)$
      - Direct CP violation
      - Searching for new physics
    - Side measurements (result in brief)
  - Rare Decays

Outline

These lectures will cover:

- D Physics
  - Mixing, and CP violation potential
- Leptons
  - Tau charged LVF
- The Future:
  - Belle II and Super KEKB
  - A future linear collider (ILC/Higgs Factory/CLIC...)

Appendices cover

- More on α / Φ_2
- How does a global fit/new physics model constraint work?
- Nomenclature (main differences between BaBar & Belle).
- Testing T symmetry invariance in B decays.

Outline

These lectures will not cover:

- Sides of the unitarity triangle (not discussed in detail).
- Spectroscopy: X, Y, Z studies etc.
- Low mass new physics searches:
  - light (<10GeV) scalar Higgs or Dark matter searches.
  - Dark forces searches.
- B_s decays
- QCD physics
- As well as many other B, D and τ topics.

Notes

- The B factories have produced many excellent results (well over 800 papers combined).
  - Rather than show the results for both experiments for each measurement, I have selected results from either BaBar or Belle.
  - Where possible I show world average results based on the latest measurements.
  - I choose to use the α, β, γ convention for the Unitarity triangle angle measurements, and the S, C convention for time -dependent *CP* asymmetry measurements.
  - In general, charge conjugate modes are implied in discussions, unless referring specifically only to a particle or anti-particle decay mode/amplitude.
- BaBar and Belle, in collaboration with a number of theorists are finalising "*The Physics of the B Factories*", Ed. AB, B. Golob, T. Mannel, S. Prell and B. Yabsley (*with a long author list*). This will be available later in 2013, please refer to that for an extensive discussion of what has been achieved.

Introduction

NOTES:

- SEE LECTURES BY U. NIRSTE FOR GENERAL THEORETICAL ISSUES, SUCH AS NEUTRAL MESON MIXING.
- SEE LECTURES BY J. BERNABEU REGARDING T AND CPT NON-CONSERVATION FORMALISM.
- SEE LECTURES BY G. COWAN FOR DETAILS ON MULTIVARIATE METHODS USED.
- SEE LECTURES BY M-H. SCHUNE REGARDING RECENT RESULTS FROM LHCB.

ONLY A FEW KEY POINTS ARE RE-CAPPED HERE.

Introduction

- CP violation was discovered in 1964.
- Kobayashi and Maskawa proposed a model to accommodate CP violation (CPV) naturally.
  - Postulated three generations of particle.
  - One irreducible phase that can be used to manifest CPV in the SM.
  - This means that CPV in kaon, beauty, charm and top are related:
    - Measuring CPV in one system allows one to predict CPV in any other system.
    - Strange quark interactions dictated the level of CPV in the SM, and from these one could predict the levels expected in beauty.
    - The B Factories were build to test these predictions.

Introduction

- CP violation in the neutral kaon system is small:

$$|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$$
$$|\varepsilon'/\varepsilon| = (1.65 \pm 0.26) \times 10^{-3}$$

- CP violation was predicted to be large in some neutral B meson decays.
  - An O(1) effect was expected in $B^0 \to J/\psi K^0$ decays, manifest in a proper time-dependent distribution.

e.g. see I. I. Bigi and A. Sanda. Nucl.Phys. B193, 85 (1981).

- Difficult to study this via a symmetric energy machine, however details of a proposed method exists – but was never tested.

e.g. see K. Berkelman, Mod.Phys.Lett. A10 (1995) 165-172.

- A better solution was found, involving asymmetric energy colliders. This will be discussed shortly.

e.g. see P. Oddone. UCLA Linear- Collider BB Factory Concep. Design: Proceedings , 423– 446 (1987).

Introduction

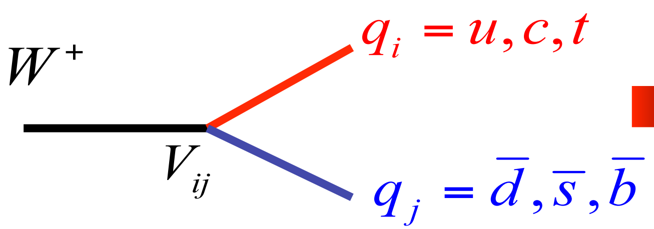
- B mesons were found to have a long life (1983), and to have a large mixing frequency (1987).

$$
\begin{aligned}
\tau_B &= (1.525 \pm 0.009)\, ps \\
\Delta\mathrm{m} &= (0.507 \pm 0.005)\, /ps
\end{aligned}
$$

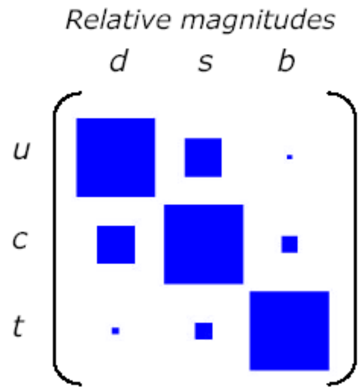
- Both physical features are required in order to be able to measure CP violation in B decays.

The CKM matrix

- Quarks change type in weak interactions:



$V =$



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

- We parameterise the couplings V_{ij} in the CKM matrix:

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

$\lambda \sim 0.22$

$A \sim 0.8$

$\rho \sim 0.2 - 0.27$

$\eta \sim 0.28 - 0.37$

- At the B factories we want to measure: $\bar{\rho} + i\bar{\eta} \equiv -\dfrac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$

$$\bar{\rho} \approx \rho(1-\lambda^2/2), \quad \bar{\eta} \approx \eta(1-\lambda^2/2)$$

- CKM expansions up to $O(\lambda^3)$ have been good enough to understand the broad picture of CP violation in B decays.

- If one wants to understand precision contributions, and in particular CP violation in charm, then one has to go to $O(\lambda^5)$.

- At this order the CKM matrix becomes

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta})+A\lambda^5(\bar{\rho}-i\bar{\eta})/2 \\ -\lambda+A^2\lambda^5[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-\bar{\rho}-i\bar{\eta}] & -A\lambda^2+A\lambda^4[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

- Remember that rephasing invariance means that if one associates a weak phase with a CKM matrix element – that association becomes convention dependent.
- Physical results are invariant of convention.

e.g. see AB, Inguglia, Meadows, PRD 84 (2011) 114009 for a discussion of what can be done with CP violation in charm decays in the future

- CKM expansions up to O(λ³) have been good enough to understand ... B decays.

- If one wants ... ns, and in particular C ... o go to O(λ⁵).

- At this order

$V_{CKM} = \Big(\; 1-\lambda^2/2 - \ldots \quad \ldots) + A\lambda^5(\bar{\rho} - i\bar{\eta})/2; \;\; -\lambda + A^2\lambda^5[1-\ldots \quad A\lambda^2; \;\; A\lambda^3[1-\bar{\rho} \ldots \quad \ldots - A^2\lambda^4/2 \; \Big) + \mathcal{O}(\lambda^6)$

- Remember t ... at if one associates ... ement – that association

- Physical res... are invariant of convention.

Note: any relationship between V_{ij} and a complex phase is model dependent statement. i.e. it is a statement that is true in a particular representation of the CKM matrix.

Physical observables are independent of the chosen phase convention, and so one should take care when discussing where the CP violating phase enters a particular decay mode. Invariants are related to the $|V_{ij}|$ and quartets of different V_{ij} terms.

Ususally experimentalists are sloppy and relate phases directly to a V_{ij}, in this case the Wolfenstein / Buras parameterisation is assumed.

e.g. see AB, Inguglia, Meadows, PRD 84 (2011) 114009 for a discussion of what can be done with CP violation in charm decays in the future

A brief history of CP violation: 1964-2001

- 1964:
  - Christensen, Cronin, Fitch and Turlay discover CP violation.
- 1967:
  - A. Sakharov: 3 conditions required to generate a baryon asymmetry:
    - Period of departure from thermal equilibrium in the early universe.
    - Baryon number violation.
    - C and CP violation.
- 1973:
  - Kobayashi and Maskawa propose a model of CP violation.

M. Kobayashi and T. Maskawa
Prog.Theor.Phys. **49**, 652–657 (1973)

- 1981:
  - I. Bigi and A. Sanda propose measuring CP violation in $B\to J/\psi K^0$ decays.

I. Bigi and A. Sanda Nucl.Phys.**B193** p85 (1981)

- 1987:
  - P. Oddone realizes how to measure CP violation: convert the PEP ring into an asymmetric energy e^+e^- collider.

Detector Considerations P. Oddone (LBL, Berkeley) . 1987
In the Proceedings of Workshop on Conceptual Design of a Test Linear Collider: Possibilities for a B Anti-B Factory, Los Angeles, California, 26-30 Jan 1987, pp 423-446.

- 1999:
  - BaBar and Belle start to take data. By 2001 CP violation has been established (and confirmed) by measuring $\sin 2\beta \neq 0$ in $B\to J/\psi K^0$ decays.

BaBar Collaboration, PRL **87**, 091801 (2001);
Belle Collaboration, PRL **87**, 091802 (2001).

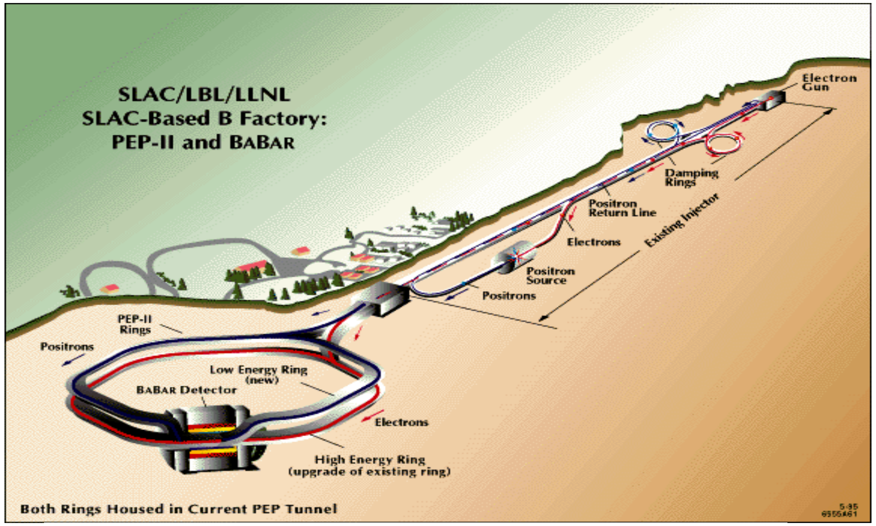
B Factory Facilities

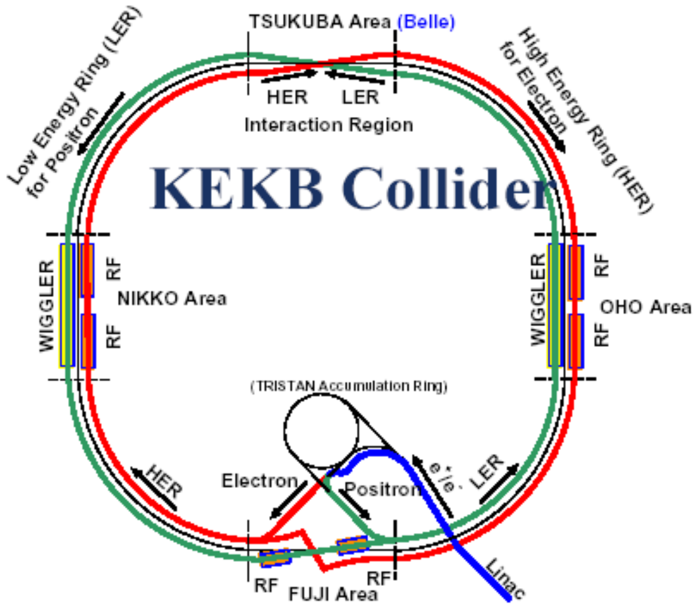
BABAR & PEP-II,
BELLE & KEKB

PEP-II and KEKB

PEP-II
- 9GeV e^- on 3.1GeV e^+
- Y(4S) boost: $\beta\gamma$=0.56

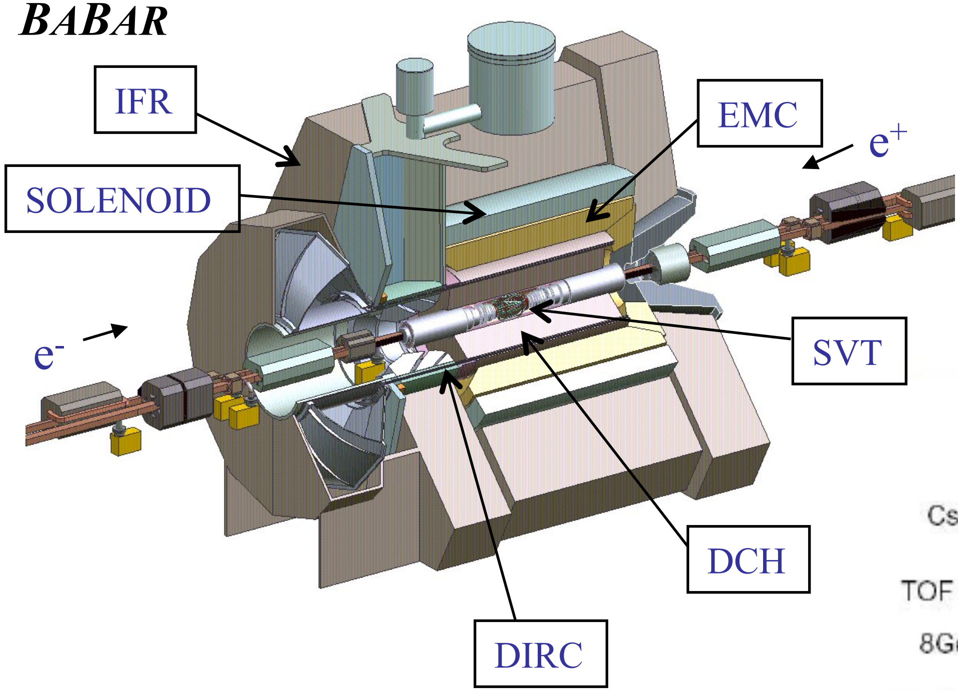
KEKB
- 8GeV e^- on 3.5GeV e^+
- Y(4S) boost: $\beta\gamma$=0.425





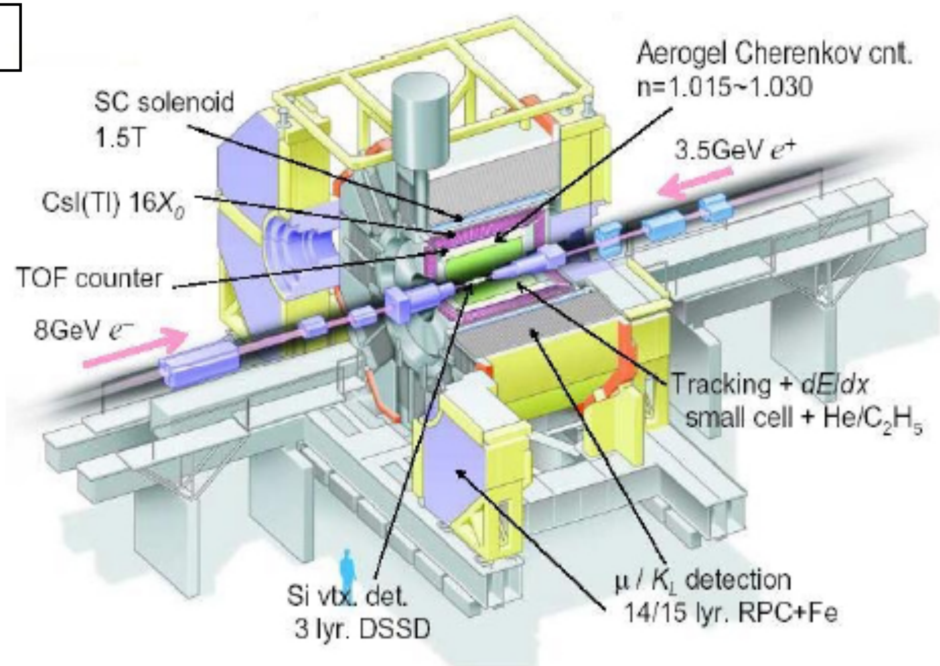
BABAR and Belle

BABAR



The differences between the two detectors are small. Both have:

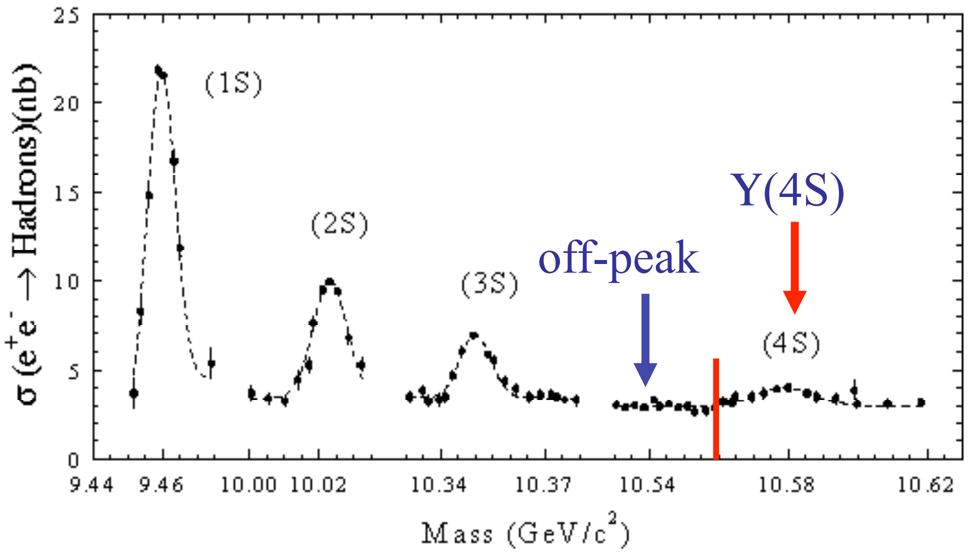
- Asymmetric design.
- Central tracking system
- Particle Identification System
- Electromagnetic Calorimeter
- Solenoid Magnet
- Muon/K^0_L Detection System
- High operation efficiency



How do we make B mesons?

- Collide electrons and positrons at $\sqrt{s}$=10.58 GeV/c^2

$e^+e^- \to$	Cross-section (nb)
$b\overline{b}$	1.05
$c\overline{c}$	1.30
$s\overline{s}$	0.35
$d\overline{d}$	0.35
$u\overline{u}$	1.39
$\tau^+\tau^-$	0.92
$\mu^+\mu^-$	1.16
e^+e^-	~ 40



many types of interaction occur.

- We're (only) interested in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ (for B physics).

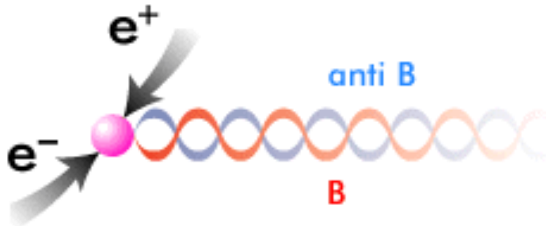
- Where

Most measurements assume equal production of charged and neutral B mesons, given that the measurement of this ratio is not significantly different from 0.5.

- The other processes constitute backgrounds for B physics.

How do we make B mesons?

- Pairs of B mesons are produced in P-wave entangled state:



$$\Psi = \frac{1}{\sqrt{2}}\left(B_1^0\overline{B}_2^0 - B_2^0\overline{B}_1^0\right)$$

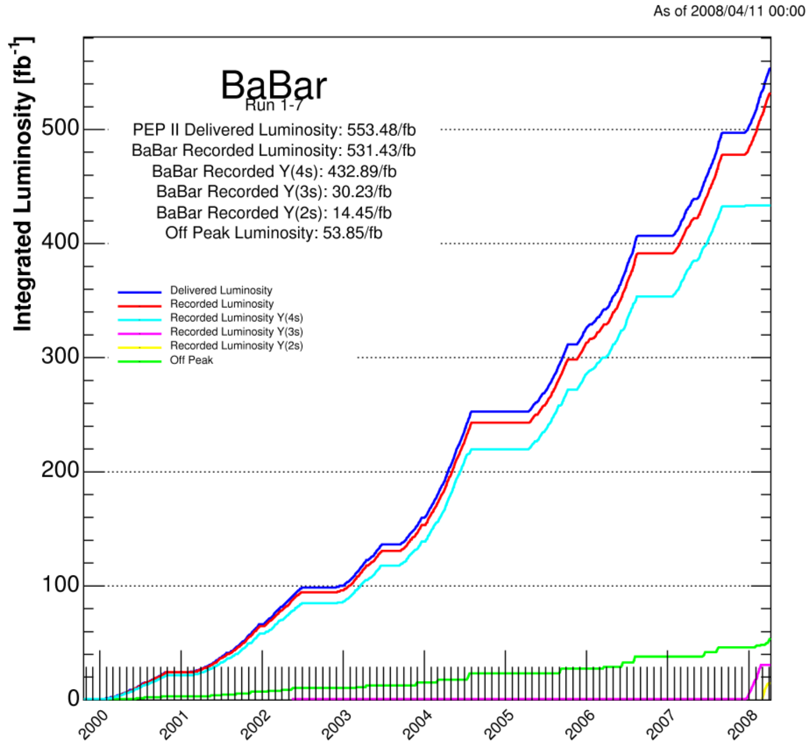
- The entangled state has several conseqences of relevance:
  - At the time one of the B mesons decays into a flavour specific final state, the other meson flavour can be inferred (as mixing is well known).
  - i.e. we can tag (with high efficiency) if a neutral B meson as a b or anti-b quark in it when performing CP violation tests.
  - We can also perform T and CPT symmetry tests.

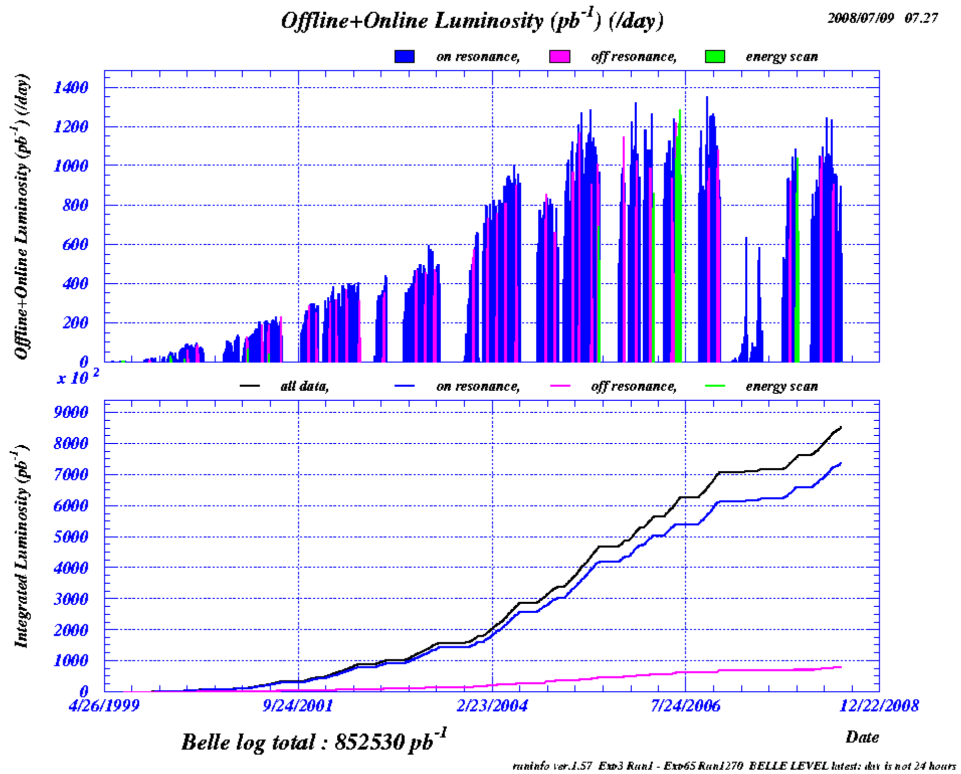
See lectures by Jose Bernabeu

- At the same time we get large numbers of D mesons and tau lepton pairs.
  - So the B Factories are really B, D and τ factories, and have made important contributions to these areas.
- The B Factories ran at other centre of mass (CM) energies as well. These extend the physics programme in a number of different ways – however those results are beyond the scope of these lectures.
- Data sets collected are summarised below.

Experiment	Resonance	On-peak Luminosity (fb^{-1})	Off-peak Luminosity (fb^{-1})
BaBar	$\Upsilon(4S)$	424.2	43.9
	$\Upsilon(3S)$	28.0	2.6
	$\Upsilon(2S)$	13.6	1.4
	Scan $> \Upsilon(4S)$	n/a	~4
Belle	$\Upsilon(5S)$	121.1	1.7
	$\Upsilon(4S)$ - SVD1	140.7	15.6
	$\Upsilon(4S)$ - SVD2	562.6	73.8
	$\Upsilon(3S)$	2.9	0.2
	$\Upsilon(2S)$	24.9	1.7
	$\Upsilon(1S)$	5.7	1.8
	Scan $> \Upsilon(4S)$	n/a	25.6

Data



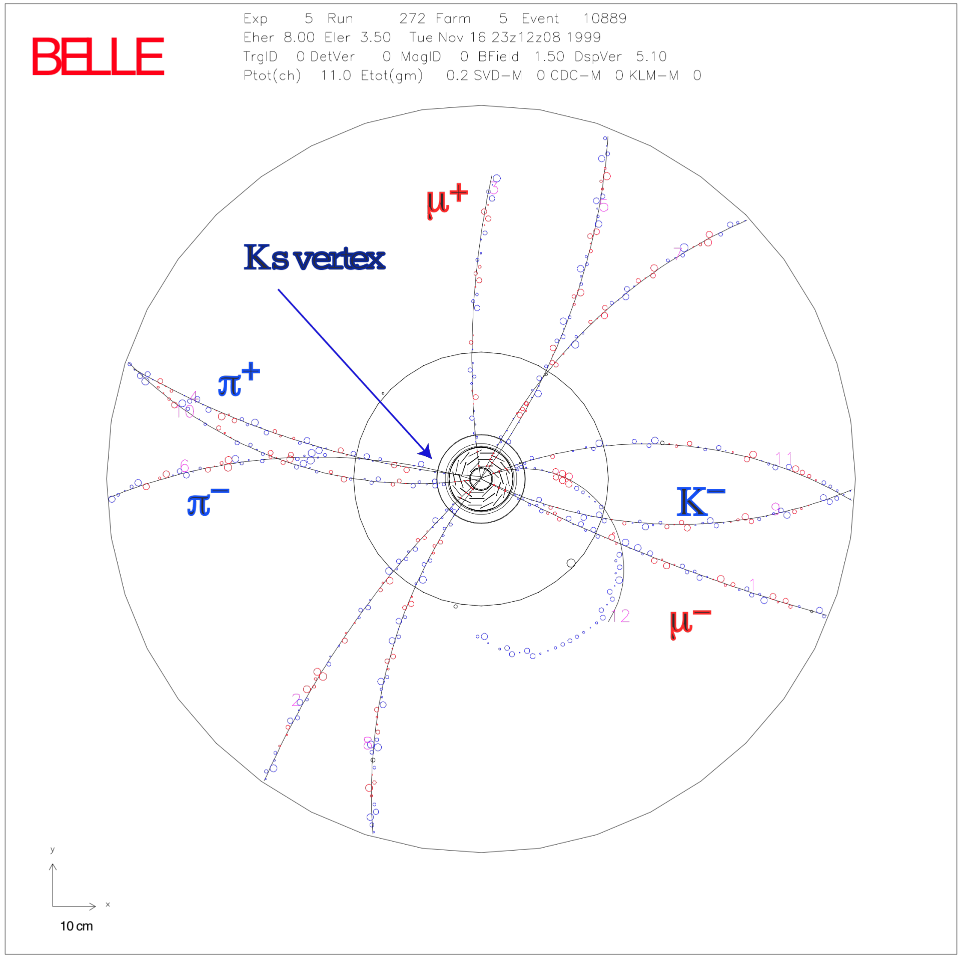


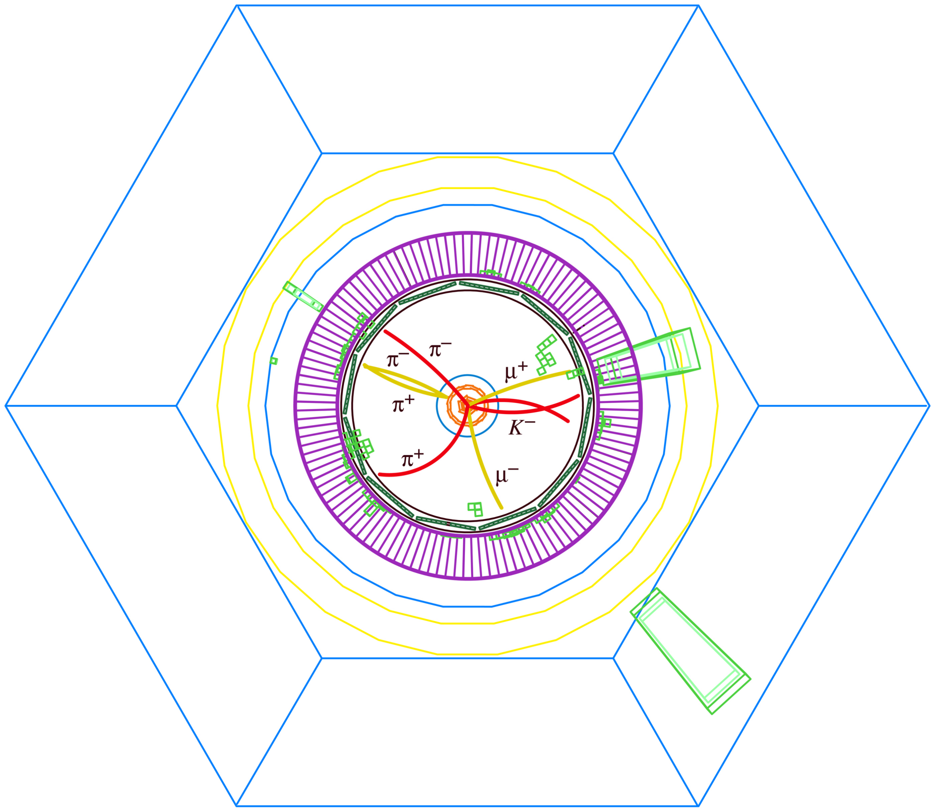
- The cumulative (BaBar+Belle) total number of recorded B mesons is over 1.2 billion.
- These are well reconstructed events, where one event occurs at a given time (i.e. no pile up problems to deal with; c.f. LHC).

What does an event look like?

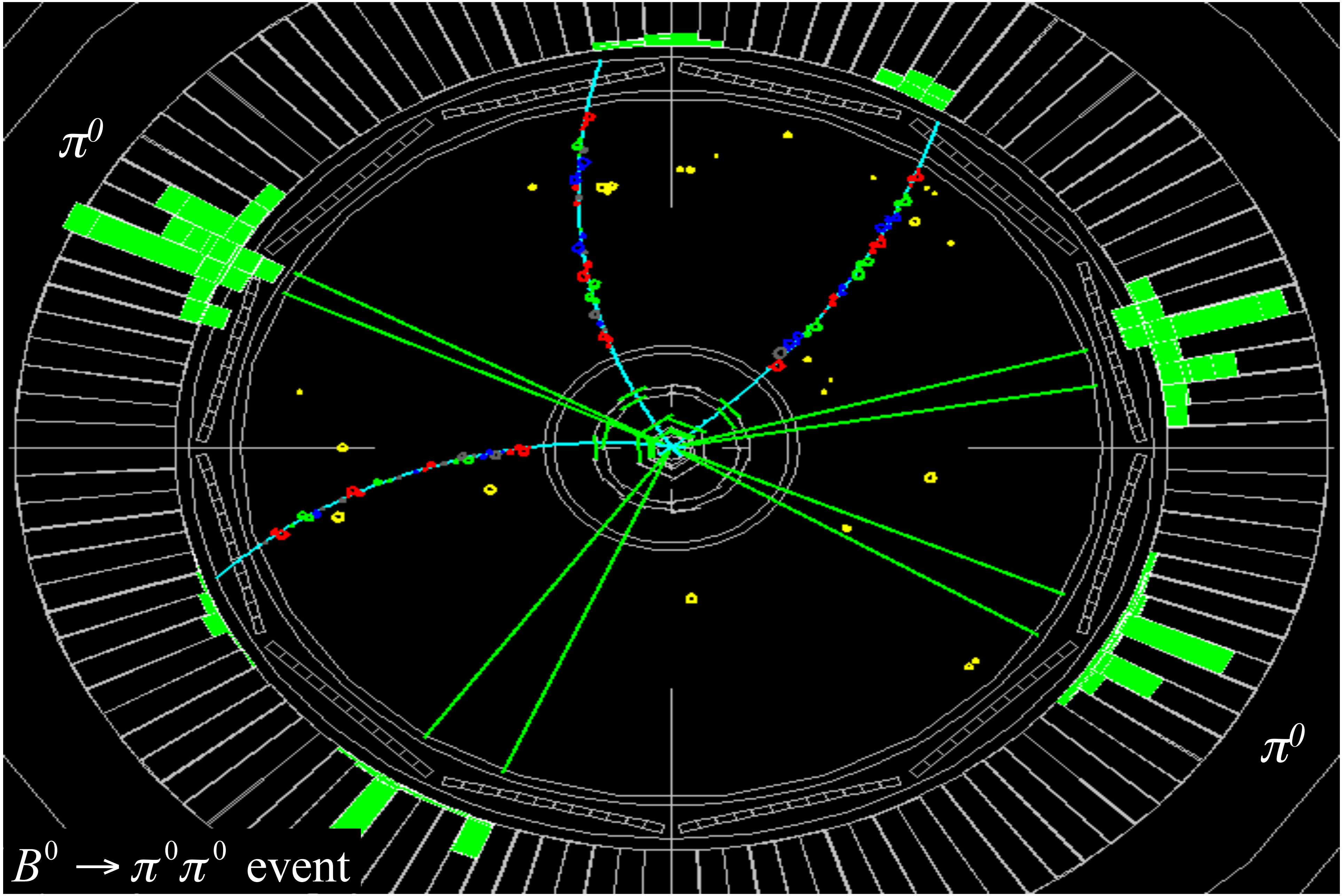
- A somewhat easier environment to work in than the LHC.

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





What does an event look like?

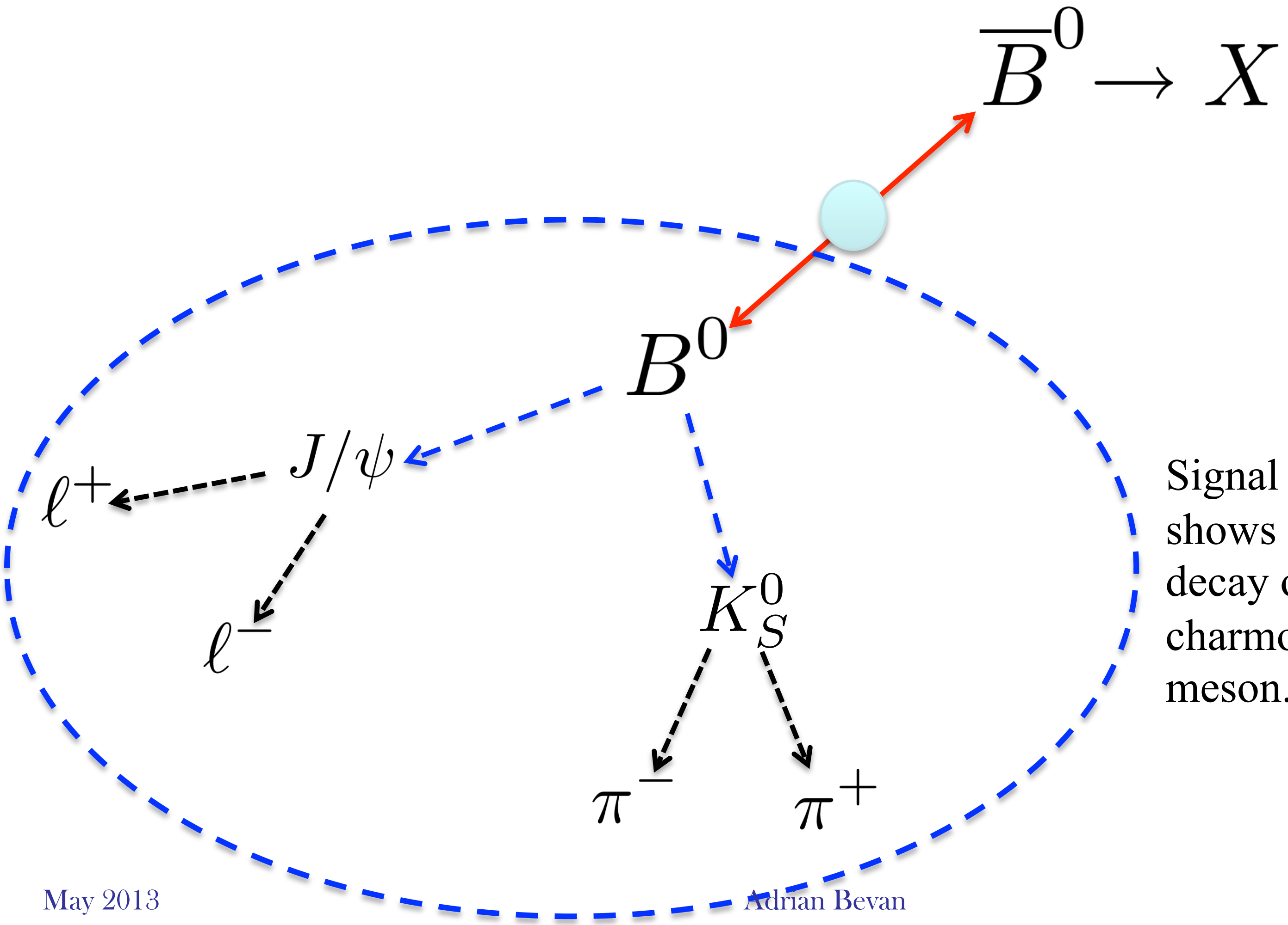


Techniques

GENERAL RECONSTRUCTION ISSUES

Isolating signal events

- A B event typically can be split into two hemispheres (in the CM frame): a signal side and an "other B" side. e.g.



Signal side, this example shows the golden mode decay of a B to a charmonium + a K_S meson.

Isolating signal events

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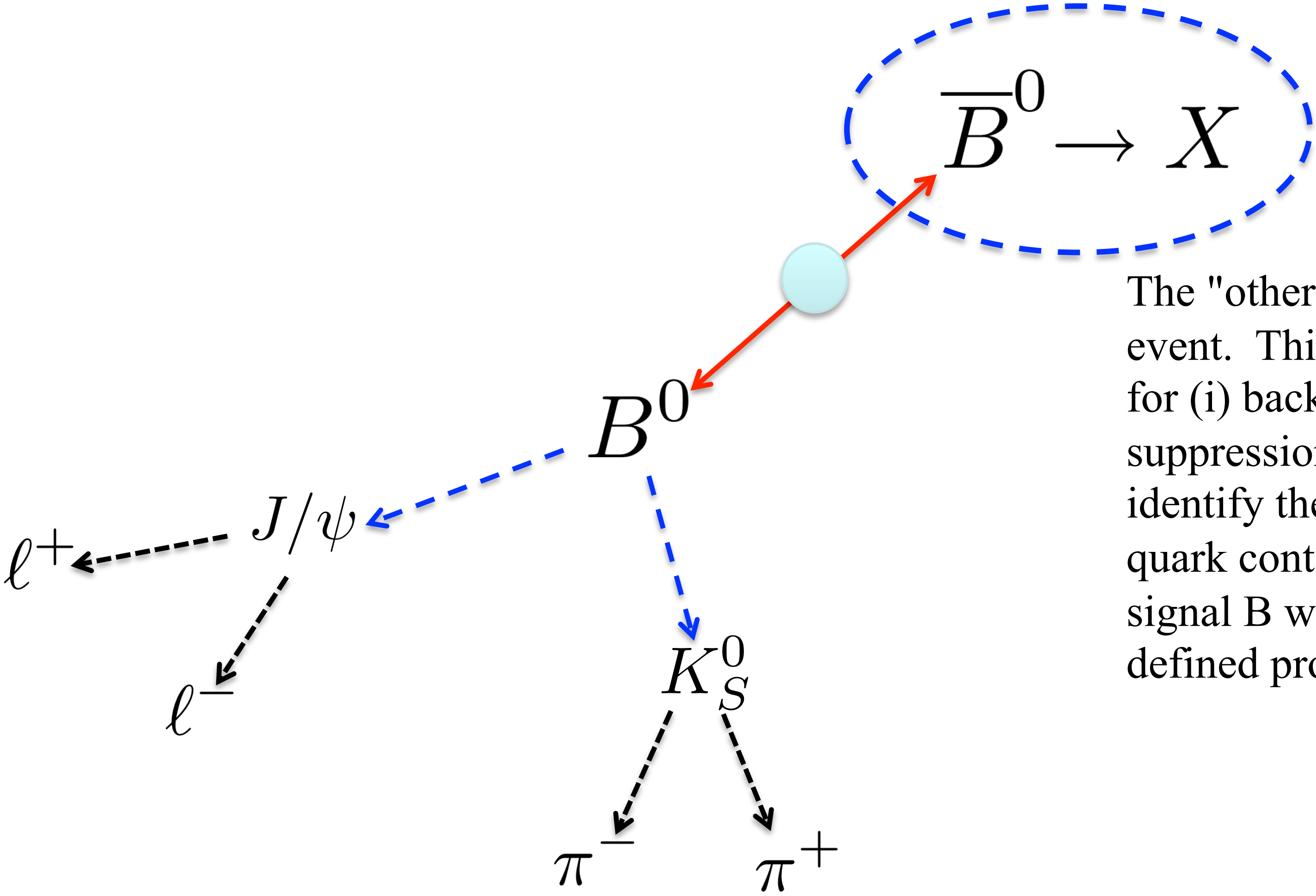


The "other" B in the event. This can be used for (i) background suppression, and (ii) to identify the underlying quark content of the signal B with some well defined probability.

Isolating signal events

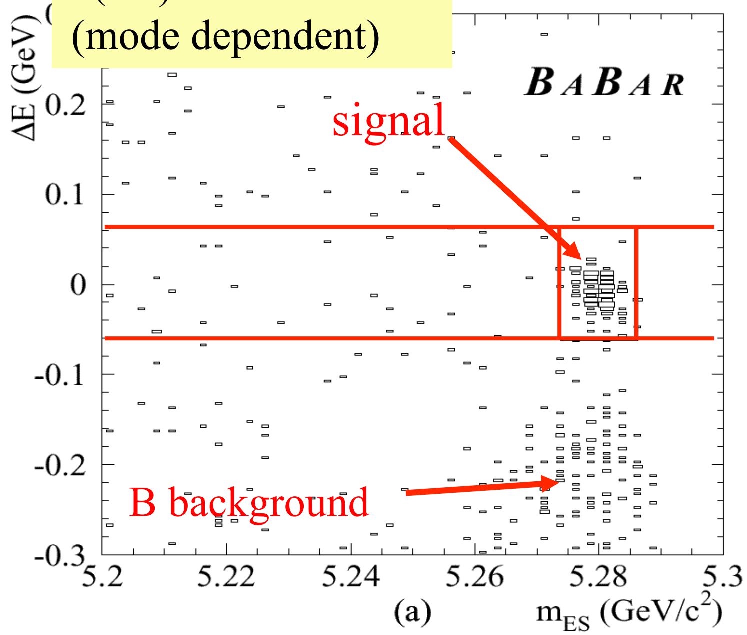
- Beam energy is known very well at an e^+e^- collider
  - Use an energy difference and effective mass to select events:

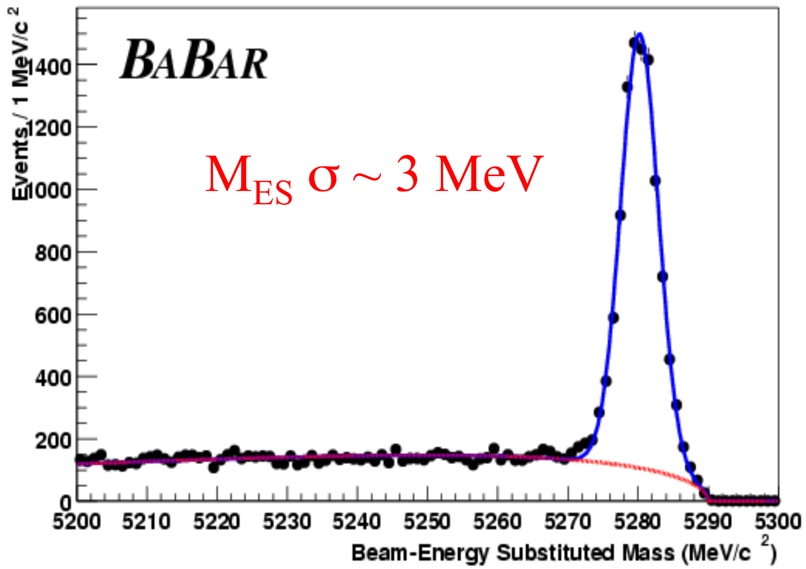
$$m_{ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2 / E_i^2 - \mathbf{p}_B^2},$$

- $\sqrt{s}$: beam energy in the CM frame.
- E_B^*: energy of $B_{\rm rec}$ in the CM frame.
- $\mathbf{p}_B$: momentum of $B_{\rm rec}$ in the lab frame.
- $(E_i, \mathbf{p}_i)$: four-momentum of the initial state in the lab frame.

These concepts apply to CLEO, BaBar, Belle (II) and can be extended to a future Linear collider/Higgs Factory Re: top.

$\sigma(\Delta E) \sim$ 15-80 MeV (mode dependent)





More background suppression

- Use the shape of an event to distinguish between $\Upsilon(4S) \rightarrow B\overline{B}$ and $e^+e^- \rightarrow q\overline{q}$.
- $\sqrt{s}$=10.58 GeV: compare m_{BB} = 10.56 GeV/c^2 with
  - m_{uu}, m_{dd}, m_{ss} ~ few to 100 MeV/c^2
  - m_{cc} ~ 1.25 GeV/c^2

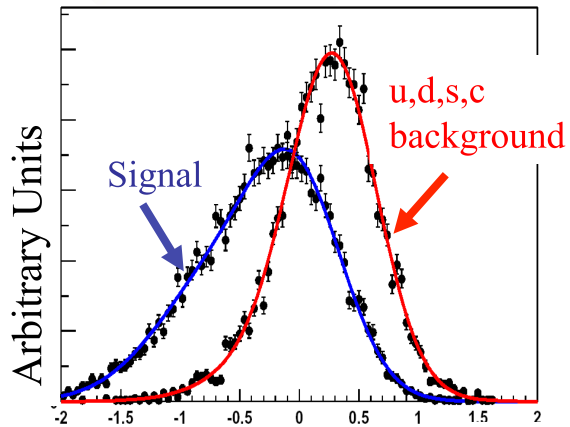
B-pair events decay isotropically

continuum (ee→q$\bar{q}$) events are 'jetty'

Analyses combine several event shape variables in a single discriminating variable: either Fisher or artificial Neural Network (usually a MLP).

Different papers have different approaches.

This allows for some discrimination between B and continuum events



Fisher Discriminant: $F = \sum_i \alpha_i x_i$

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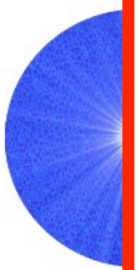
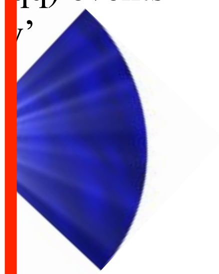
- √s=10.58 GeV: compare m_{BB} = 10.56 GeV/c^2 with
  - m_{uu}, m_{dd}, m_{ss} ~ few to 100 MeV/c^2
  - m_{cc} ~ 1.2…

B-pair events d…



…qq̄) events
…y'



See Lectures by Glen Cowan for details of other commonly used multivariate techniques.

The B factories used a range of techniques, including cut based analyses, maximum likelihood and χ^2 fits, Fisher discriminants, Neural Networks, Decision Trees (different variants), and likelihood ratios.

Analyses combine sev… variables in a single di… variable: either Fisher … Network (usually a MLP).

Different papers have different approaches.

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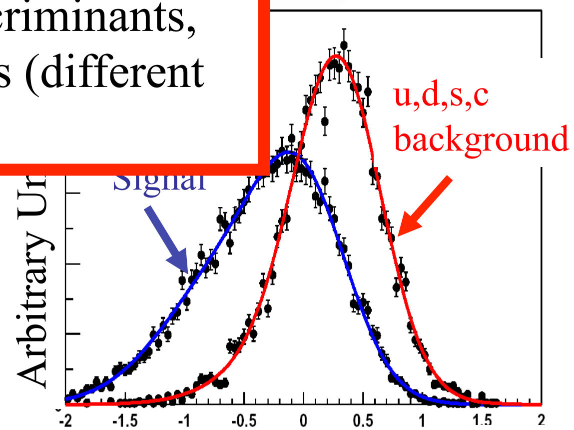


Fisher Discriminant: $F = \sum_i \alpha_i x_i$

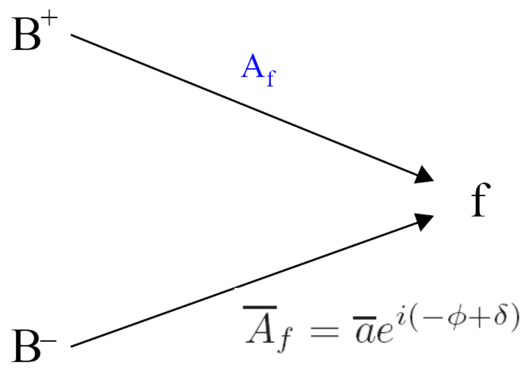
Techniques

TIME DEPENDENT METHODS

Time integrated CP asymmetries

- Charged B mesons do not oscillate.
- Measure a direct CP asymmetry by comparing amplitudes of decay:

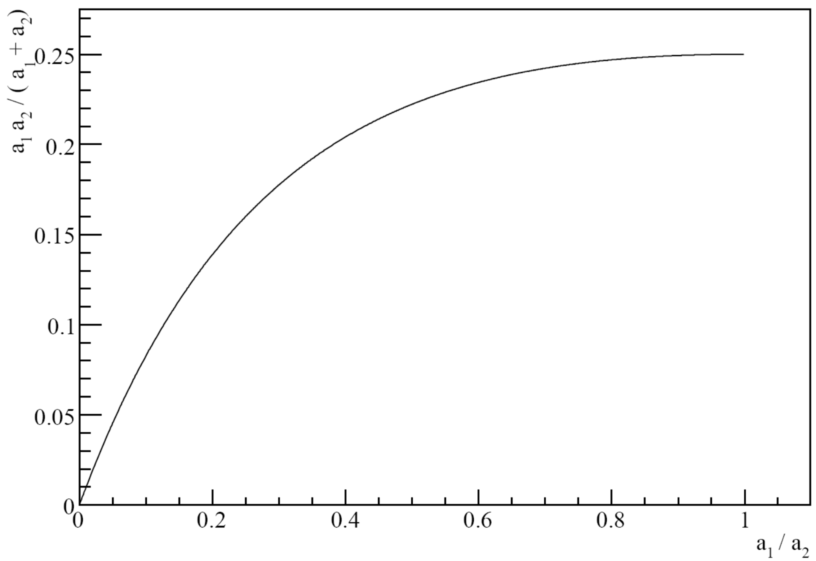
$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$



- Event counting exercise!
- With two (or more) amplitudes

$$A_1 = a_1 e^{i(\phi_1+\delta_1)}$$
$$A_2 = a_2 e^{i(\phi_2+\delta_2)}$$

see that we need different weak and strong phases to generate.

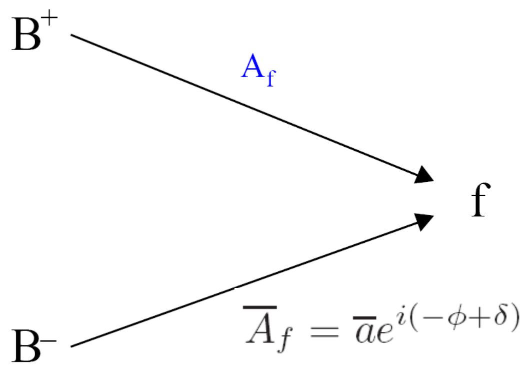


- A_{CP} is largest when $a_1 = a_2$.
- Need to measure δ!
- We can use this technique when studying neutral B mesons decaying to a self tagging final state.

Time integrated CP asymmetries

- Charged B mesons do not oscillate.
- Measure a direct CP asymmetry by comparing amplitudes of decay:

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$



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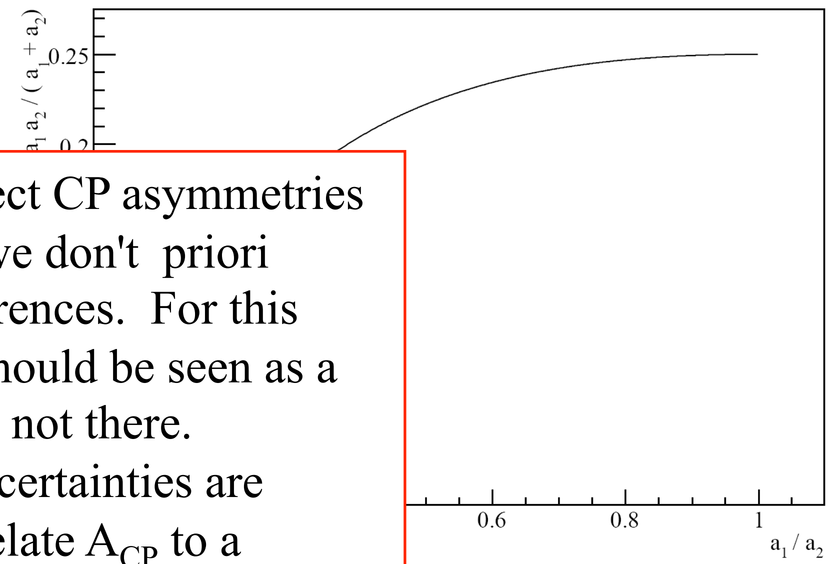
and strong phas

- A_{CP} is largest w

- Need to measu

- We can use this
neutral B meso

The problem with using direct CP asymmetries to constrain the SM is that we don't priori know the strong phase differences. For this reason direct CP violation should be seen as a binary test: it is there or it is not there. Generally large hadronic uncertainties are introduced when trying to relate A_{CP} to a measured weak phase.



Time-dependent CP asymmetries

- Ingredients of a time-dependent CP asymmetry measurement:
  - Isolate interesting signal B decay: B_{REC}.
  - Identify the flavour of the non-signal B meson (B_{TAG}) at the time it decays.
  - Measure the spatial separation between the decay vertices of both B mesons: convert to a proper time difference $\Delta t = \Delta z / \beta\gamma c$; fit for S and C.
- The time evolution of $B_{TAG} = B^0(\overline{B}^0)$ is

Note that Belle use a convention where C is replaced by $A_{CP} = -C$

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 \pm [-\eta_f S \sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)]\right\}.$$

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$$S = \frac{2\,\Im\lambda_{CP}}{1+|\lambda_{CP}|^2},$$

$$C = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2},$$

$$\sqrt{S^2+C^2} \leq 1$$

- **S** is related to CP violation in the interference between mixing and decay.
- **C** is related to direct CP violation.
- η_f is the CP eigenvalue of B_{REC}.

Time-dependent CP asymmetries

- Ingredients of a time-dependent CP asymmetry measurement:
  - Isolate interesting signal B decay: B_{REC}.
  - Identify the flavour of the non-signal B meson (B_{TAG}) at the time it decays.
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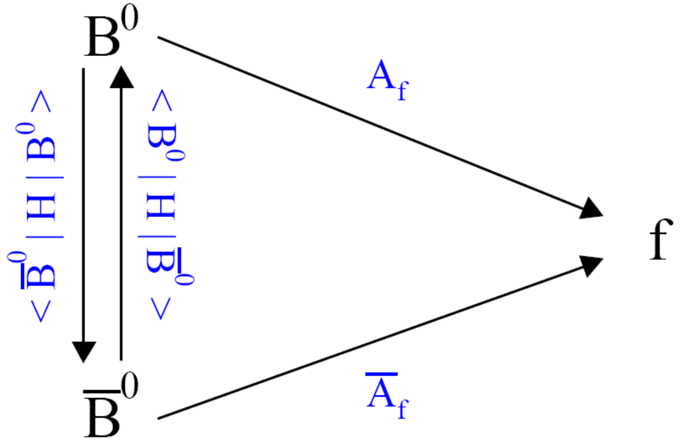

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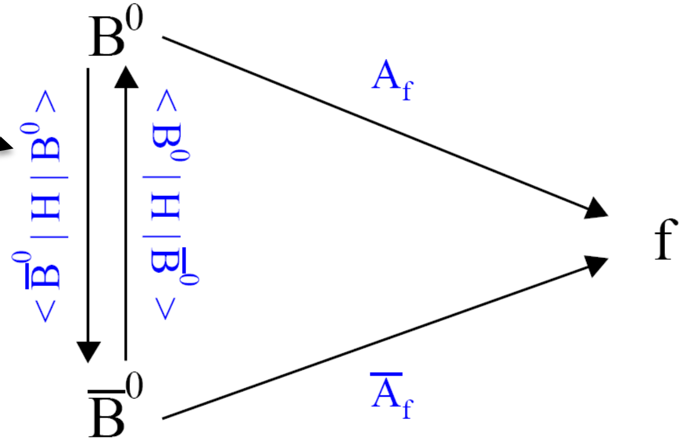

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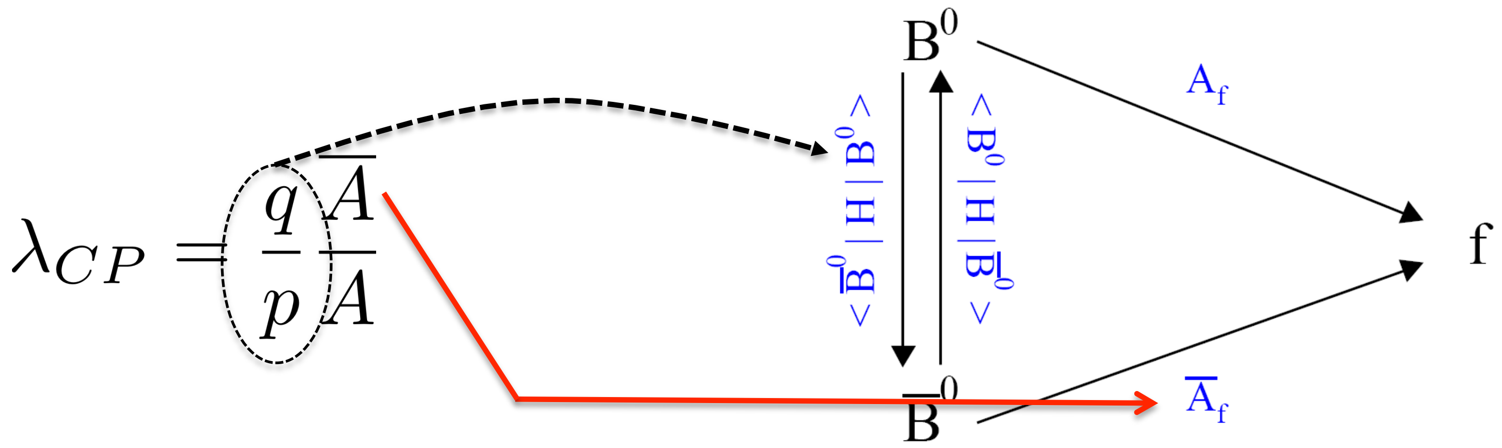

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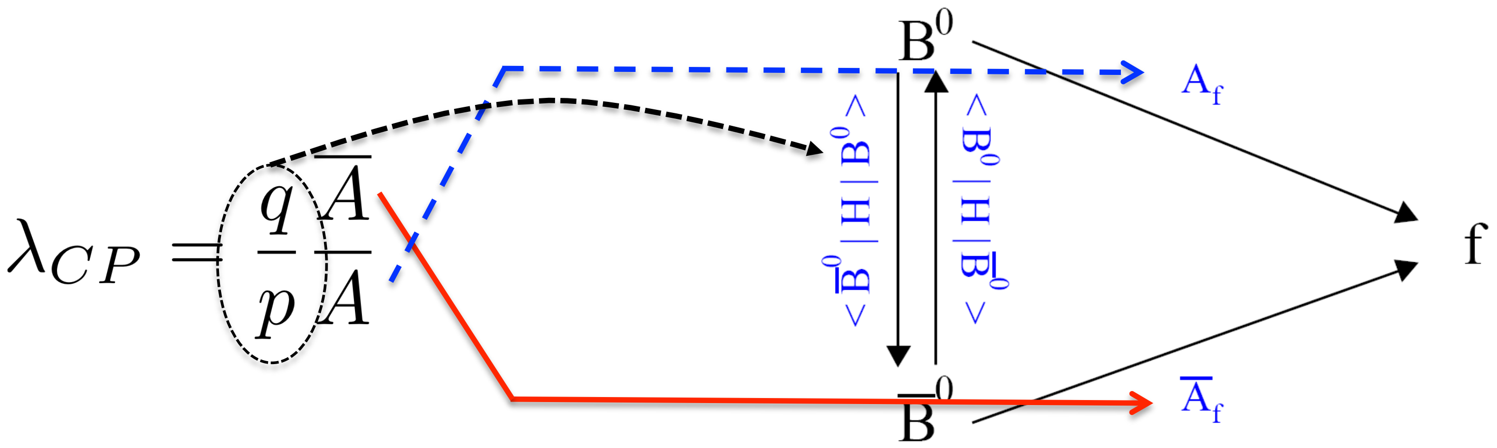
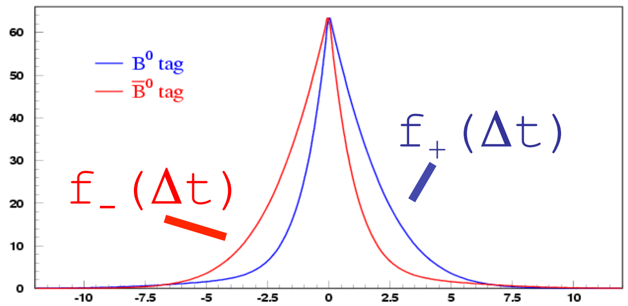


Time-dependent CP asymmetries

- Construct an asymmetry as a function of Δt:

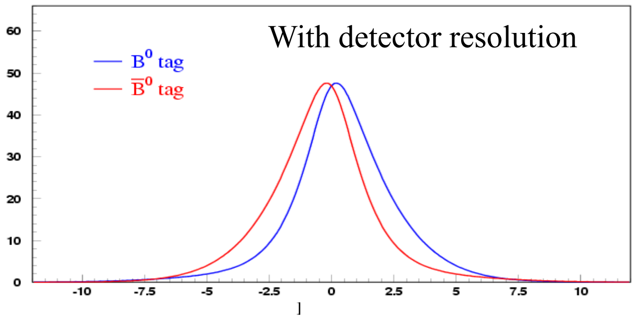
$$\mathcal{A}(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)}$$

$$\mathcal{A}(\Delta t) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$

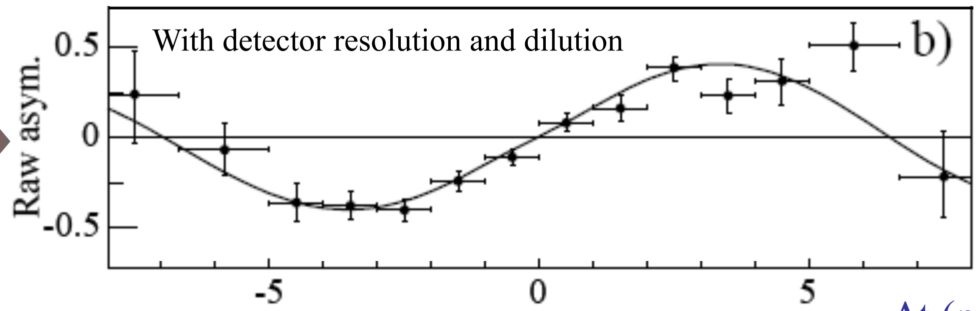


Experimental effects we need to include:

- Detector resolution on Δt.
- Dilution from flavor tagging (see later).



Δt (ps)



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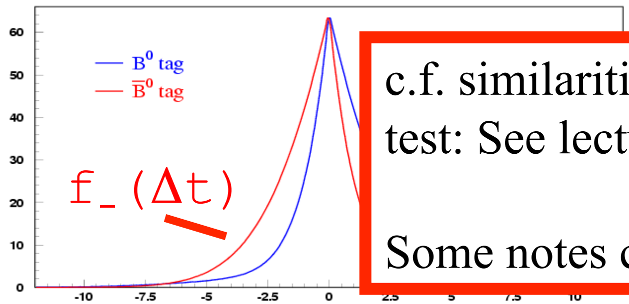

c.f. similarities with T-symmetry non-invariance test: See lectures by Jose Bernabeu.

Some notes can also be found in Appendix IV

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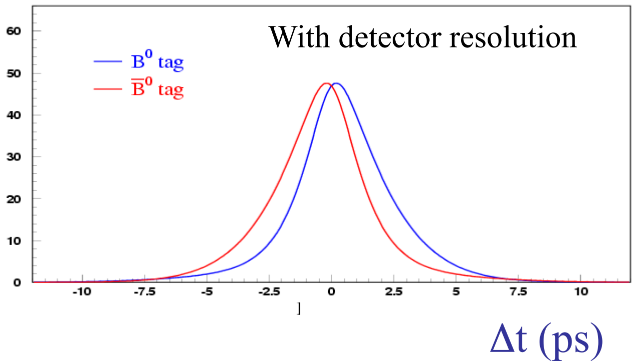
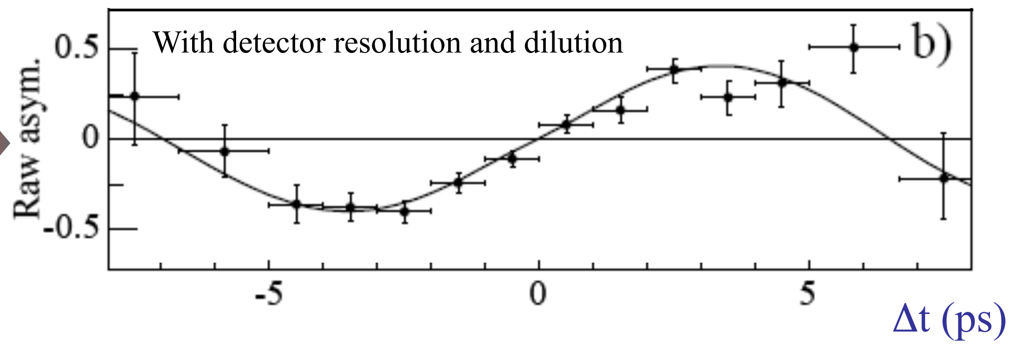
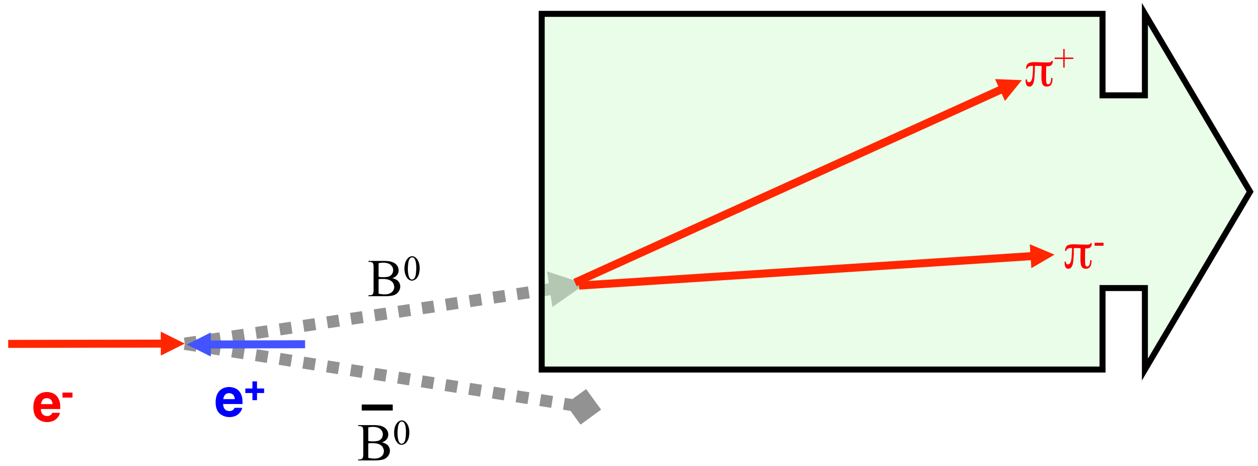
t.
ging (see later).





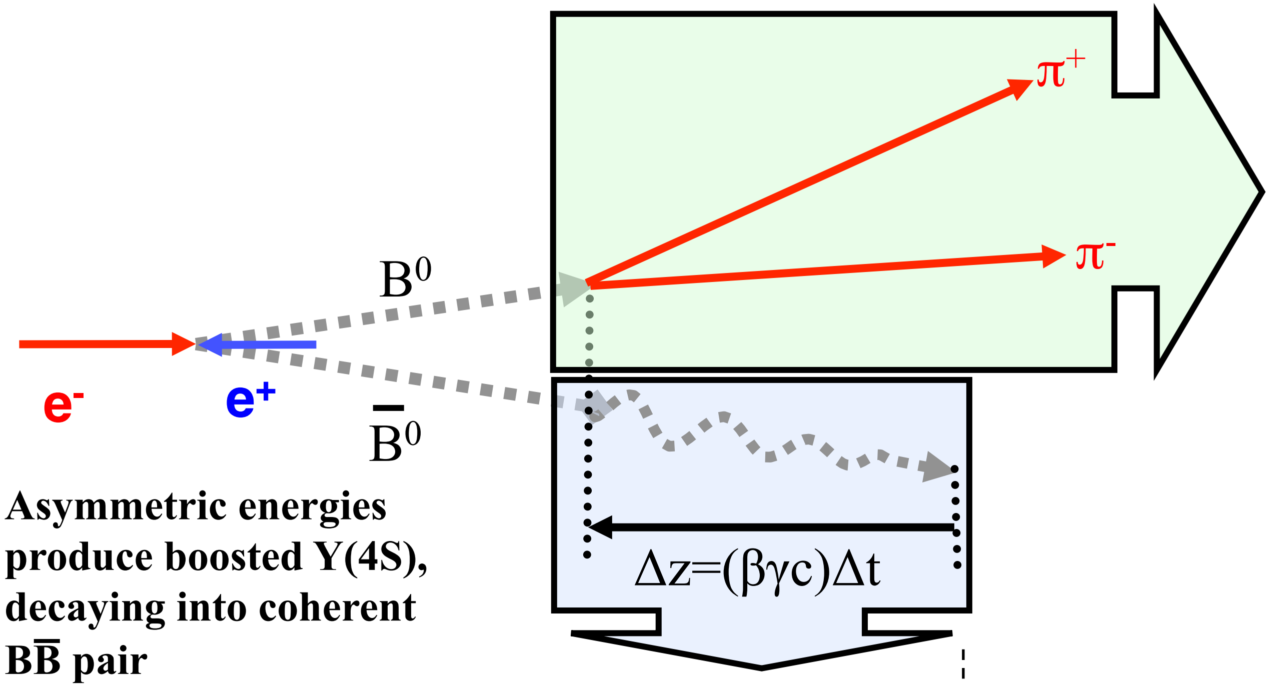
Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{REC})

Asymmetric energies produce boosted Y(4S), decaying into coherent $B\bar{B}$ pair

Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{REC})

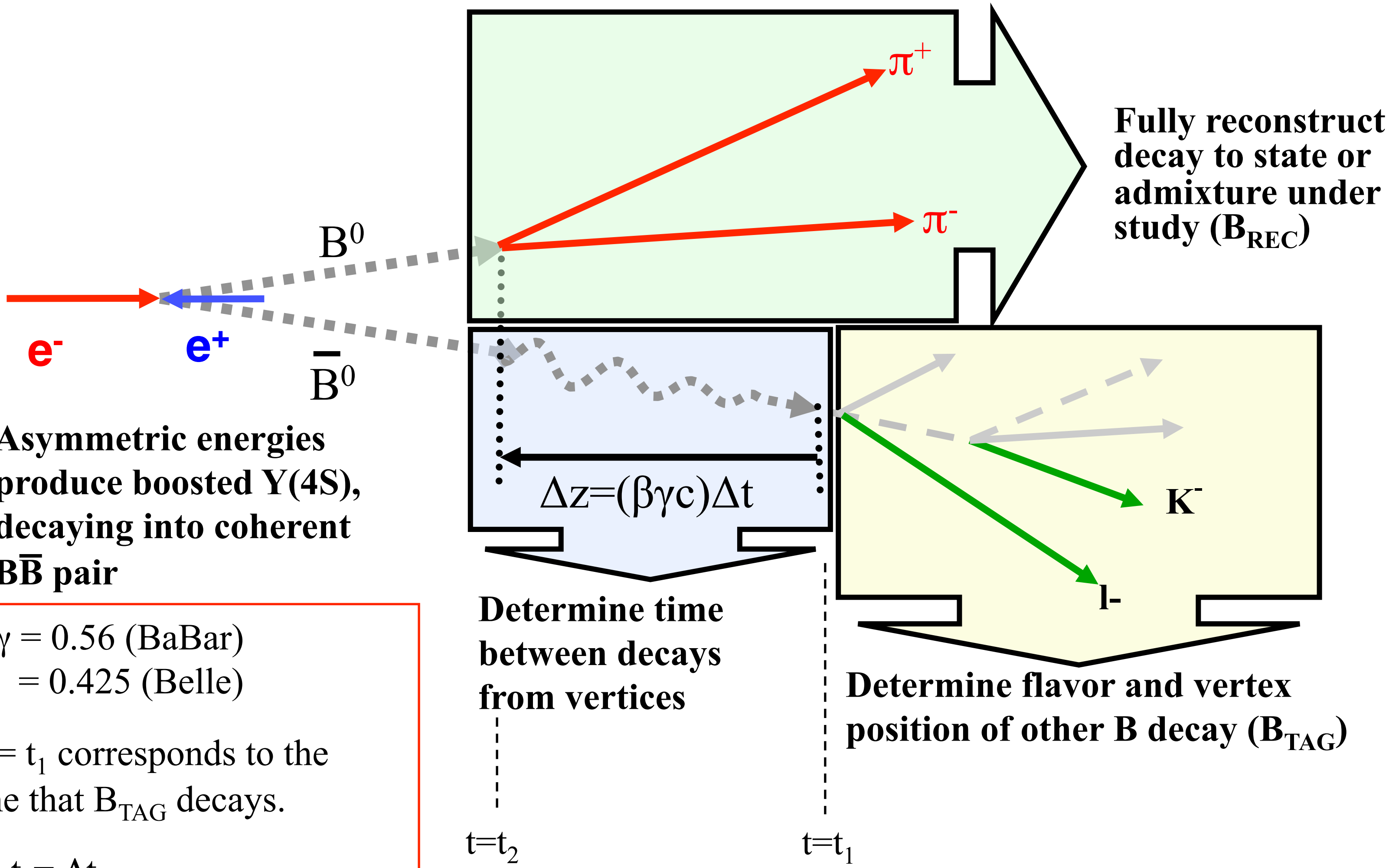
Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

- $\beta\gamma = 0.56$ (BaBar) $= 0.425$ (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

Determine time between decays from vertices

$t=t_2$ $t=t_1$

Measuring Δt



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- $\beta\gamma = 0.56$ (BaBar)
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- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

- Then fit the Δt distribution to determine the amplitude of sine and cosine terms.

Flavor tagging

- Don't always identify B_{TAG} flavor correctly: asymmetry diluted by $(1-2w)$
- ω is probability for assigning the wrong flavor (mistag probability).

$$N^{tag}_{B^0} = (1-\omega_{B^0})N_{B^0} + \omega_{B^0}N_{\overline{B}^0}$$

$$Q = \epsilon_{\rm tag}(1-2w)^2$$

$$\Delta\omega = \omega_{B^0} - \omega_{\overline{B}^0}$$

$$\omega = \frac{1}{2}(\omega_{B^0} + \omega_{\overline{B}^0})$$

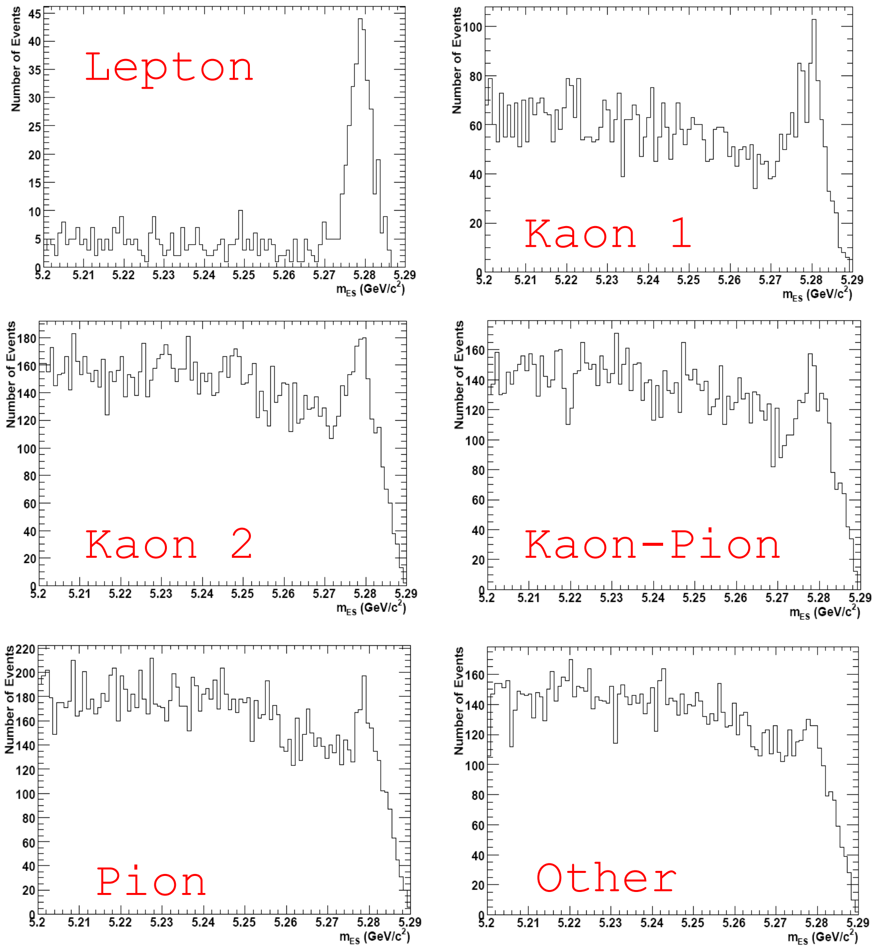
$N^{tag}_{B^0,\overline{B}^0}$ = the number of reconstructed events found in data

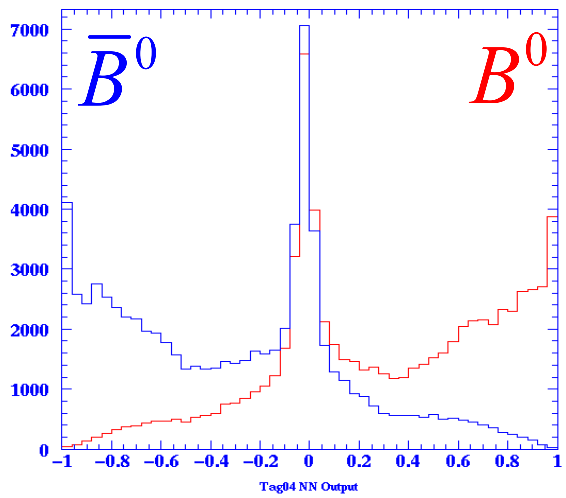
$N_{B^0,\overline{B}^0}$ = the true number of events (i.e. numbers obtained if ω = 0)

Flavor tagging

- Decay products of B_{TAG} are used to determine its flavor.
- At $\Delta t=0$, the flavor of B_{REC} is opposite to that of other B_{TAG}.
- B_{REC} continues to mix until it decays.
- Different B_{TAG} final states have different *purities* and different *mis-tag probabilities*.
- Can (right) split information by physical category or (below) use a continuous variable to distinguish particle and anti-particle.

BaBar's flavor tagging algorithm splits events into mutually exclusive categories ranked by signal purity and mis-tag probability. Belle opt to use a continuous variable output. These plots are for the 316fb^{-1} h^+h^- data sample.





Flavor tagging

- Don't always identify B_{TAG} flavor correctly: asymmetry diluted by $(1-2w)$
- ω is probability for assigning the wrong flavor (mistag probability).
- Effect is slightly different for B^0 and B^0 tags: $\Delta\omega$
- Define an effective tagging efficiency: $Q = \epsilon_{\rm tag}(1-2w)^2$
- Use a modified $f_{\pm}(\Delta t)$:

$$\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{(1\mp\Delta\omega)\pm(1-2\omega)\times[-\eta_f S\sin(\Delta m_d\Delta t)-C\cos(\Delta m_d\Delta t)]\}$$

Example: The BaBar tagging algorithm:

Category	$\epsilon_{\rm tag}$ (%)	ω (%)	$\Delta\omega$ (%)	Q (%)
Lepton	8.2 ± 0.1	3.2 ± 0.5	-0.2 ± 0.8	7.2 ± 0.2
Kaon I	11.3 ± 0.1	3.7 ± 0.7	1.1 ± 1.2	9.7 ± 0.3
Kaon II	17.3 ± 0.2	14.2 ± 0.7	-0.9 ± 1.1	8.8 ± 0.3
Kaon-Pion	13.4 ± 0.1	20.8 ± 0.8	0.5 ± 1.3	4.6 ± 0.3
Pion	13.8 ± 0.2	30.6 ± 0.8	4.1 ± 1.3	2.1 ± 0.2
Other	9.4 ± 0.1	40.1 ± 1.0	2.3 ± 1.5	0.4 ± 0.1
Untagged	26.8 ± 0.2	50.0 ± 0.0	–	0.0 ± 0.0
Total				32.7 ± 0.7

Belle does essentially the same thing, the only difference is in the way that flavour tagging information is used. For Belle a continuous variable is determined, based on the probability for an event to be a B candidate or not. The quark flavor b=+/−1 is then used to parameterise dilution for the ensemble of events.

Fitting for CP asymmetries

- Perform an extended un-binned ML fit in several dimensions (2 to 8).

$$\mathcal{L} = \frac{\exp(-\sum_j n_j)}{N!} \prod_i^N \sum_j n_j \mathcal{P}_j^i$$

  - $\mathcal{P}_j^i$ is the probability density function for the i^{th} event and j^{th} component (type) of event.
  - n_j is the event yield of the j^{th} component.
  - N is the total number of events.
  - Usually replicate the likelihood for each tagging category (BaBar) or include a variable in the fit that incorporates flavor tagging information (Belle).

- In practice we minimize $-\ln\mathcal{L}$ in order to obtain the most probable value of our experimental observables with a 68.3% confidence level (1σ error) using MINUIT.

- S and C (or A_{CP}) are observables that are allowed to vary when we fit the data.