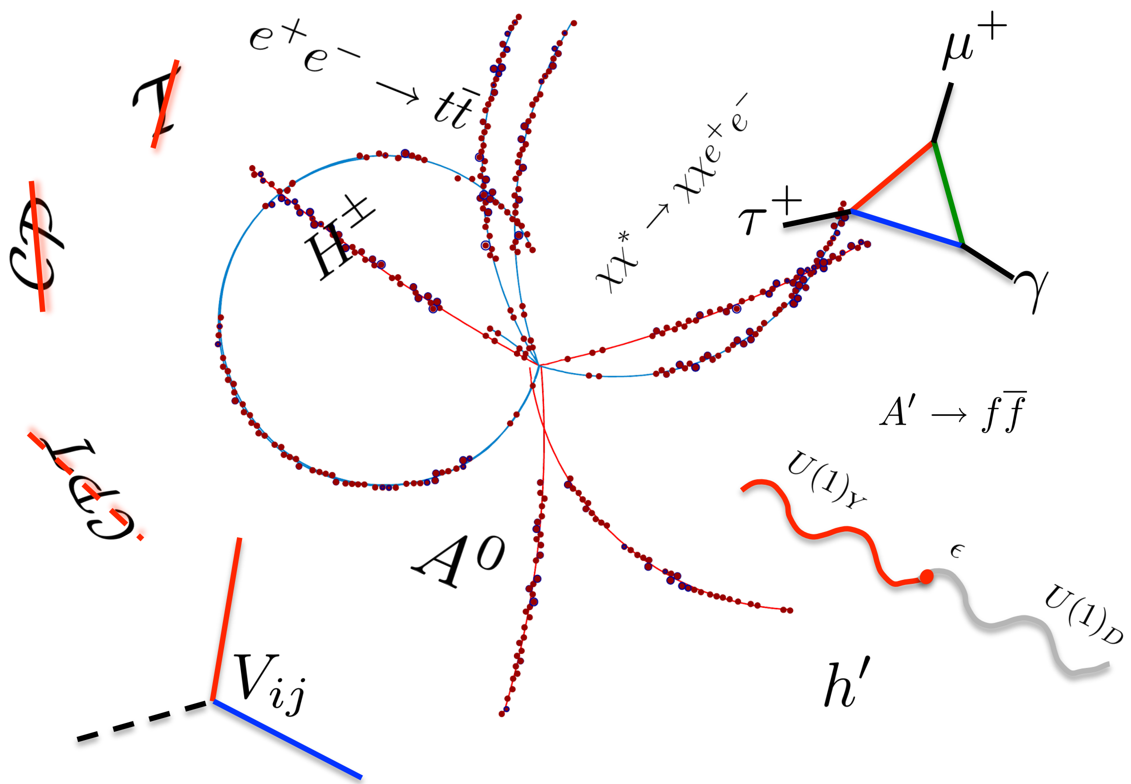
Flavour Physics at e⁺e⁻ machines: Past/Present and Future



Adrian Bevan

IDPASC School, Valencia, May 2013

Preamble

OUTLINE

NOTES

Outline

These lectures will cover:

- Introduction
  - The B factories
  - CKM, mixing, and measuring CP asymmetries
- B Physics:
  - Unitarity triangle physics
    - CP violation measurements
      - The angles: $(\alpha, \beta, \gamma) = (\phi_1, \phi_2, \phi_3)$
      - 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.
- 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:

$$
\begin{aligned}
|\varepsilon| &= (0.228 \pm 0.011) \times 10^{-3} \\
Re(\varepsilon'/\varepsilon) &= (1.65 \pm 0.26) \times 10^{-3}
\end{aligned}
$$

- 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

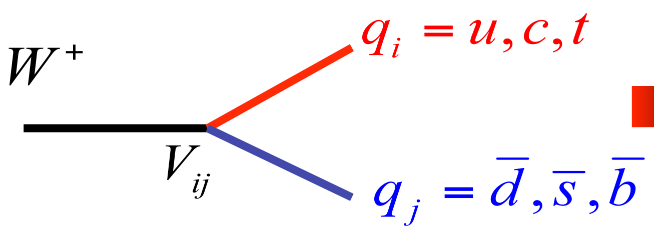
- B mesons were found to have a long life (1983), and to have a large mixing frequency (1987).

$$\tau_B = (1.525 \pm 0.009)\, ps$$
$$\Delta \text{m} = (0.507 \pm 0.005)\, /ps$$

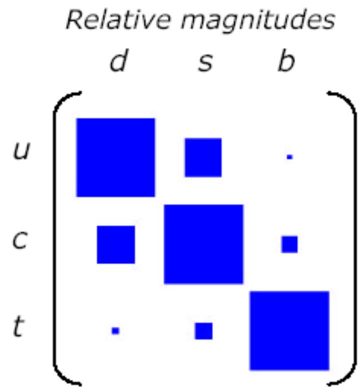
- Both physical features are required in order to be able to measure CP violation in B decays.

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(λ^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(λ^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.

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.

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

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

- Remember … at if one associates … ement – that association …
- Physical results are invariant of convention.

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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 $B \rightarrow J/\psi K^0$ 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 $B \rightarrow J/\psi K^0$ decays.

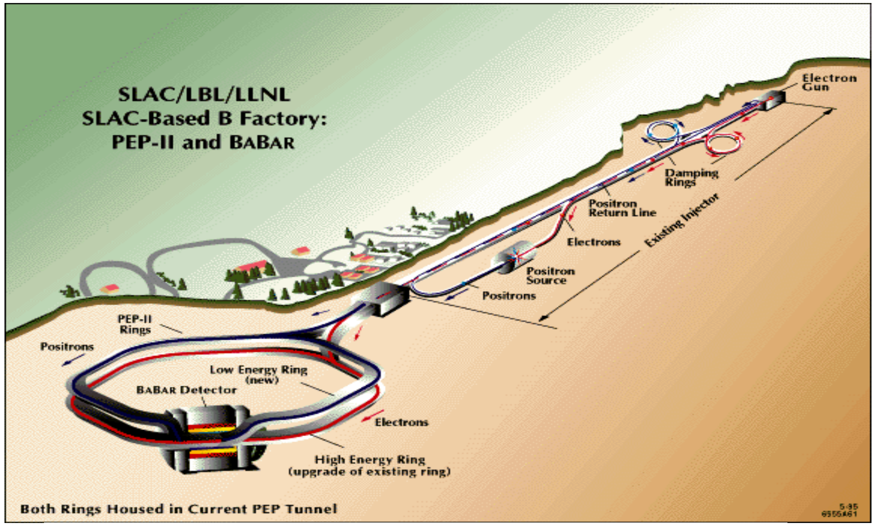
BaBar Collaboration, PRL **87**, 091801 (2001);
Belle Collaboration, PRL **87**, 091802 (2001).

B Factory Facilities

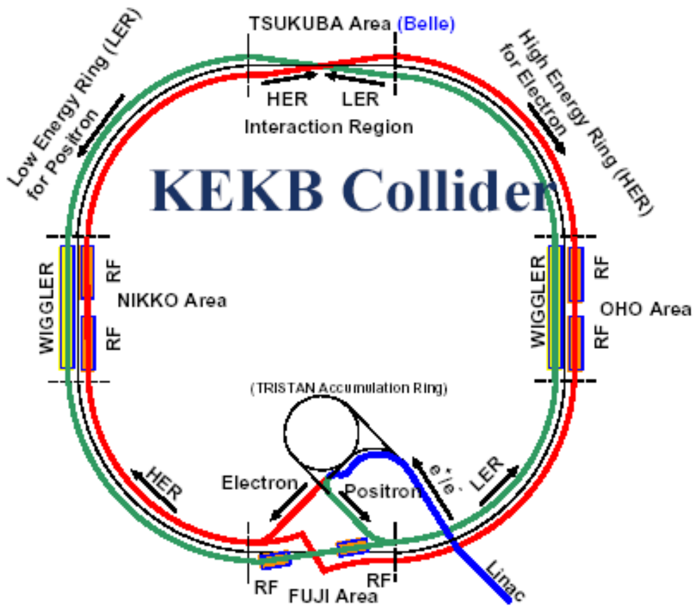
BABAR & PEP-II,
BELLE & KEKB

PEP-II and KEKB

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

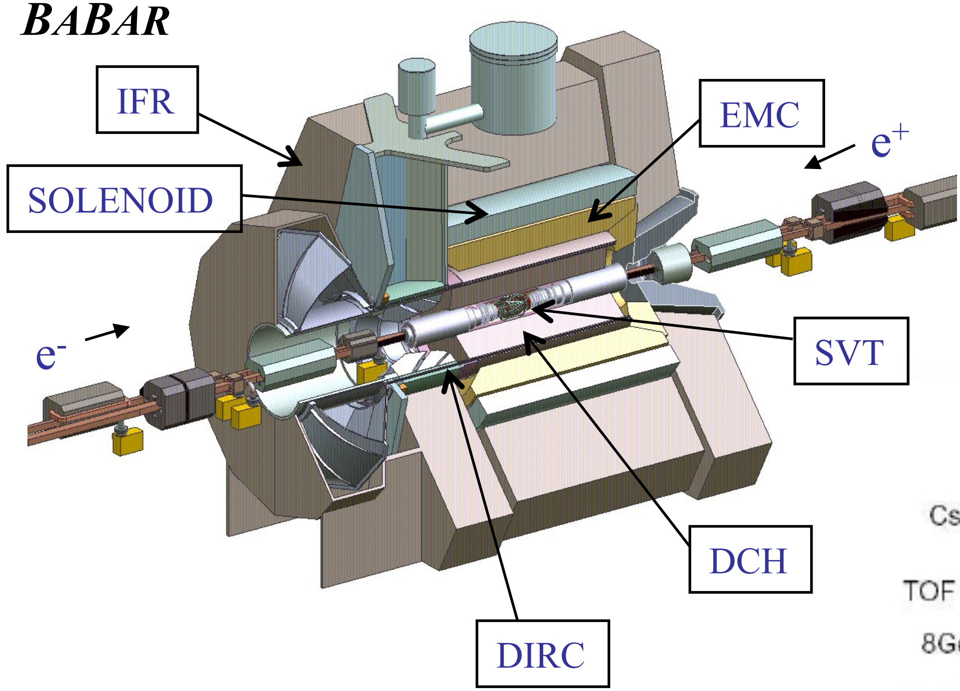


KEKB
- 8GeV e^- on 3.5GeV e^+
- Y(4S) boost: $\beta\gamma$=0.425



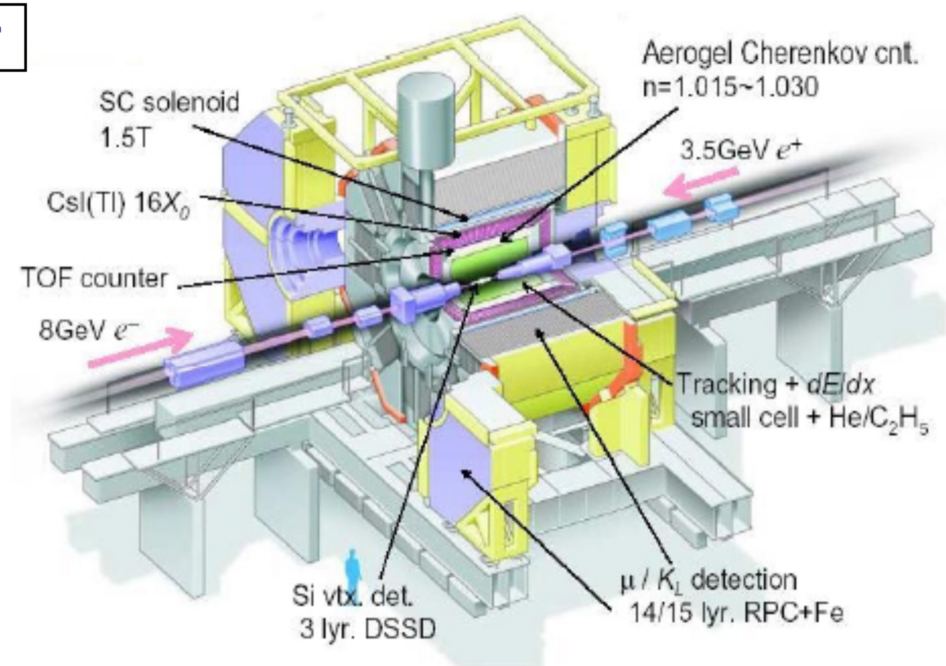
BaBar and Belle

BABAR



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

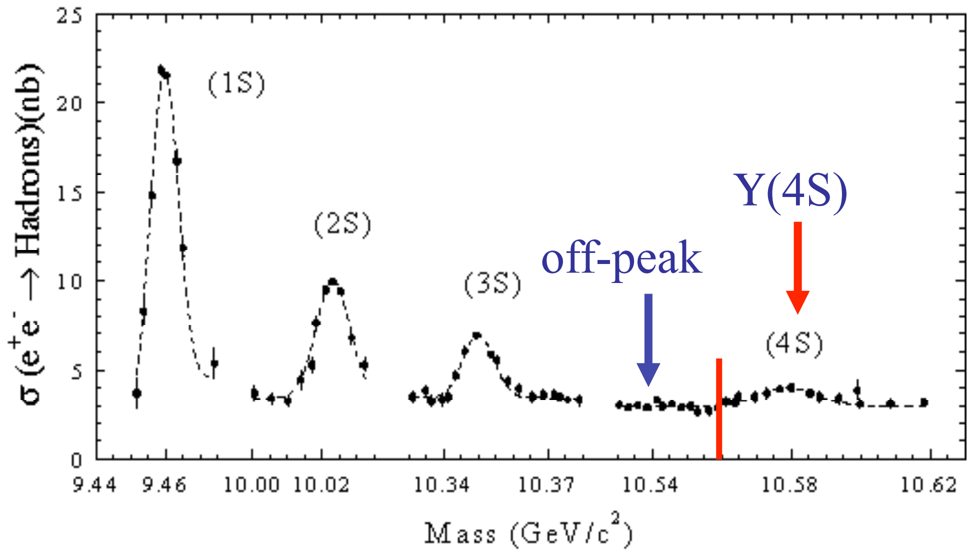
- Asymmetric design.
- Central tracking system
- Particle Identification System
- Electromagnetic Calorimeter
- Solenoid Magnet
- Muon/K^0_L Detection System
- High operation efficiency



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.

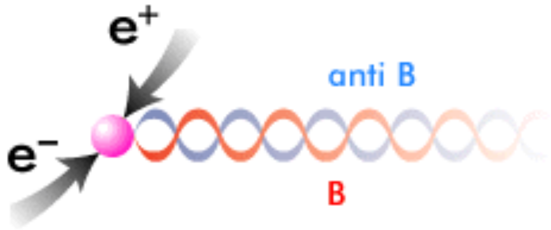
- We're (only) interested in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ (for B physics).
- Where $\dfrac{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)}{\mathcal{B}(\Upsilon(4S) \to B^+B^-)} \simeq 1$

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:



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

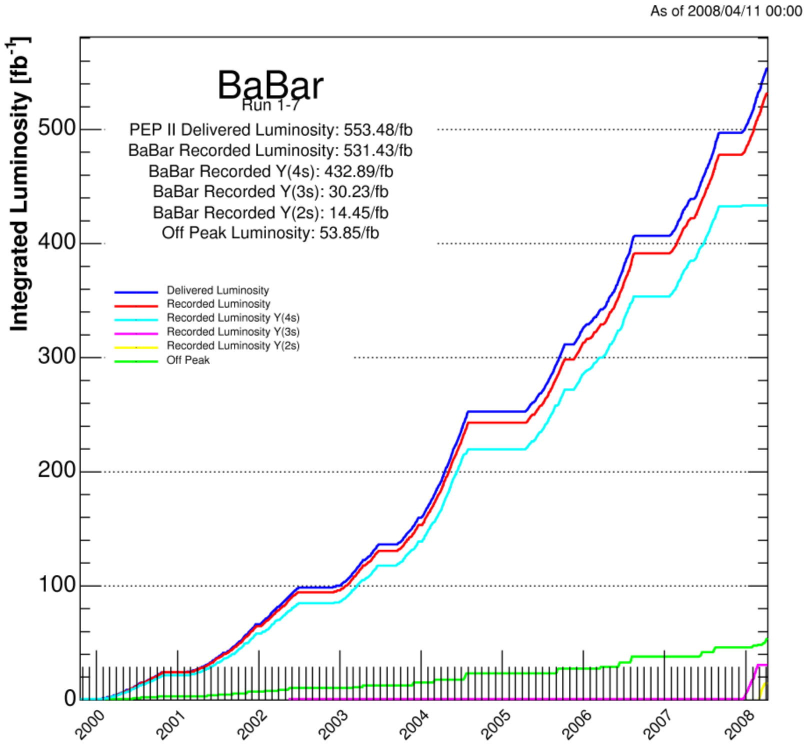
- The entangled state has several conseqences of relevance:
  - At the time one of the B mesons decays into a flavour specific final state, the other meson flavour can be inferred (as mixing is well known).
  - i.e. we can tag (with high efficiency) if a neutral B meson as a b or anti-b quark in it when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

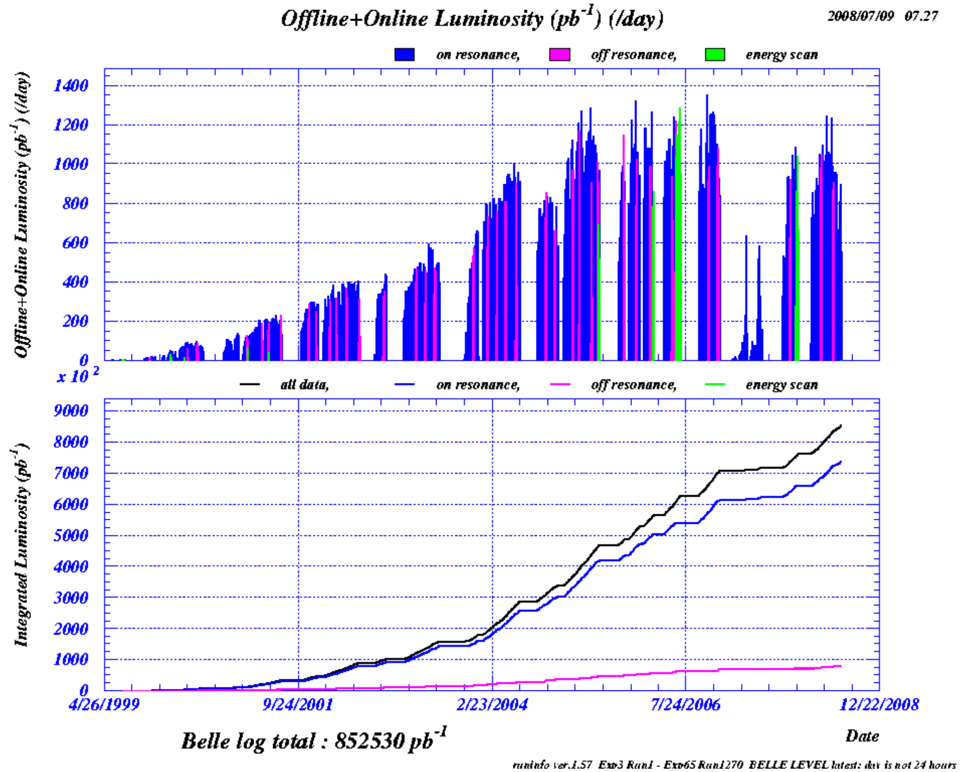
See lectures by Jose Bernabeu

- 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



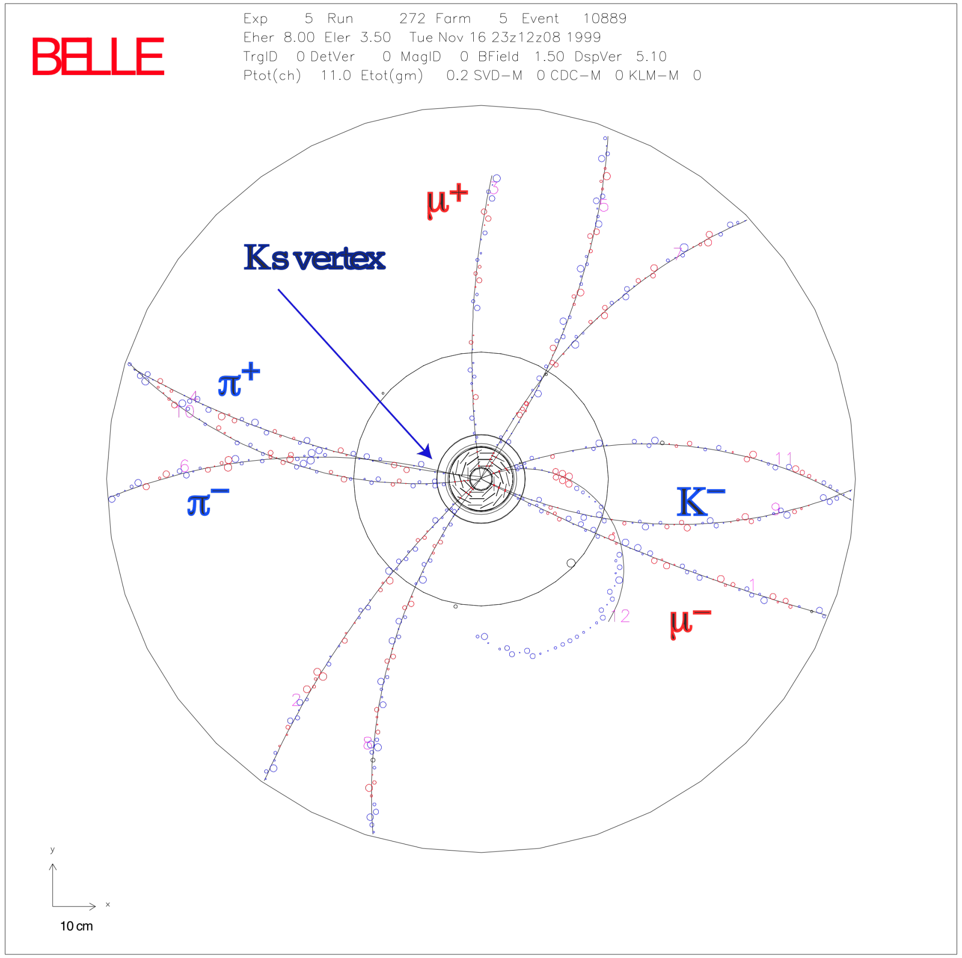


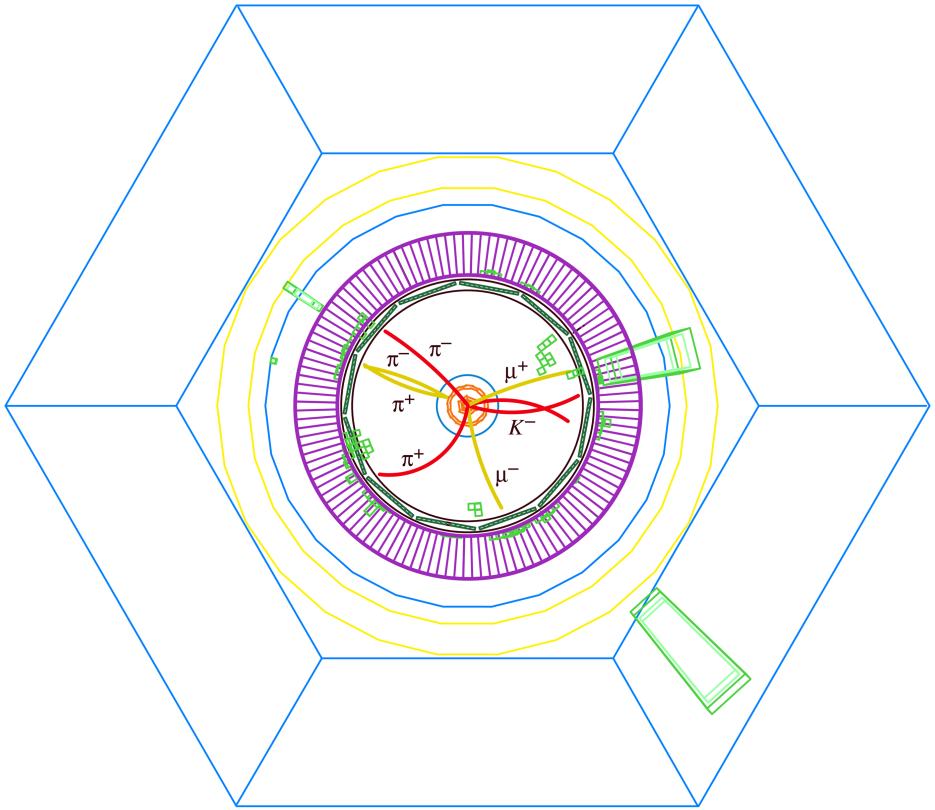
- The cumulative (BaBar+Belle) total number of recorded B mesons is over 1.2 billion.
- These are well reconstructed events, where one event occurs at a given time (i.e. no pile up problems to deal with; c.f. LHC).

What does an event look like?

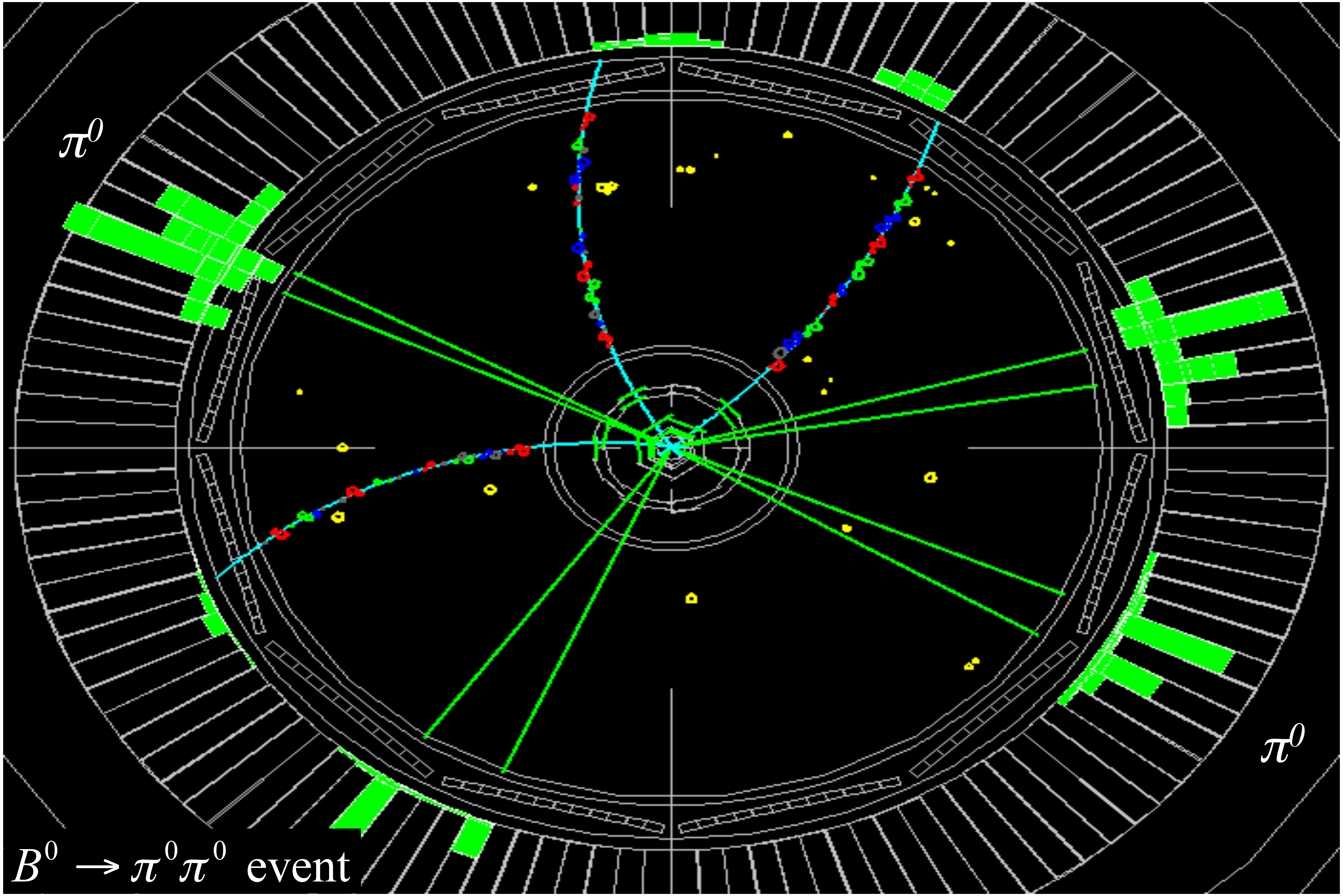
- A somewhat easier environment to work in than the LHC.

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





What does an event look like?

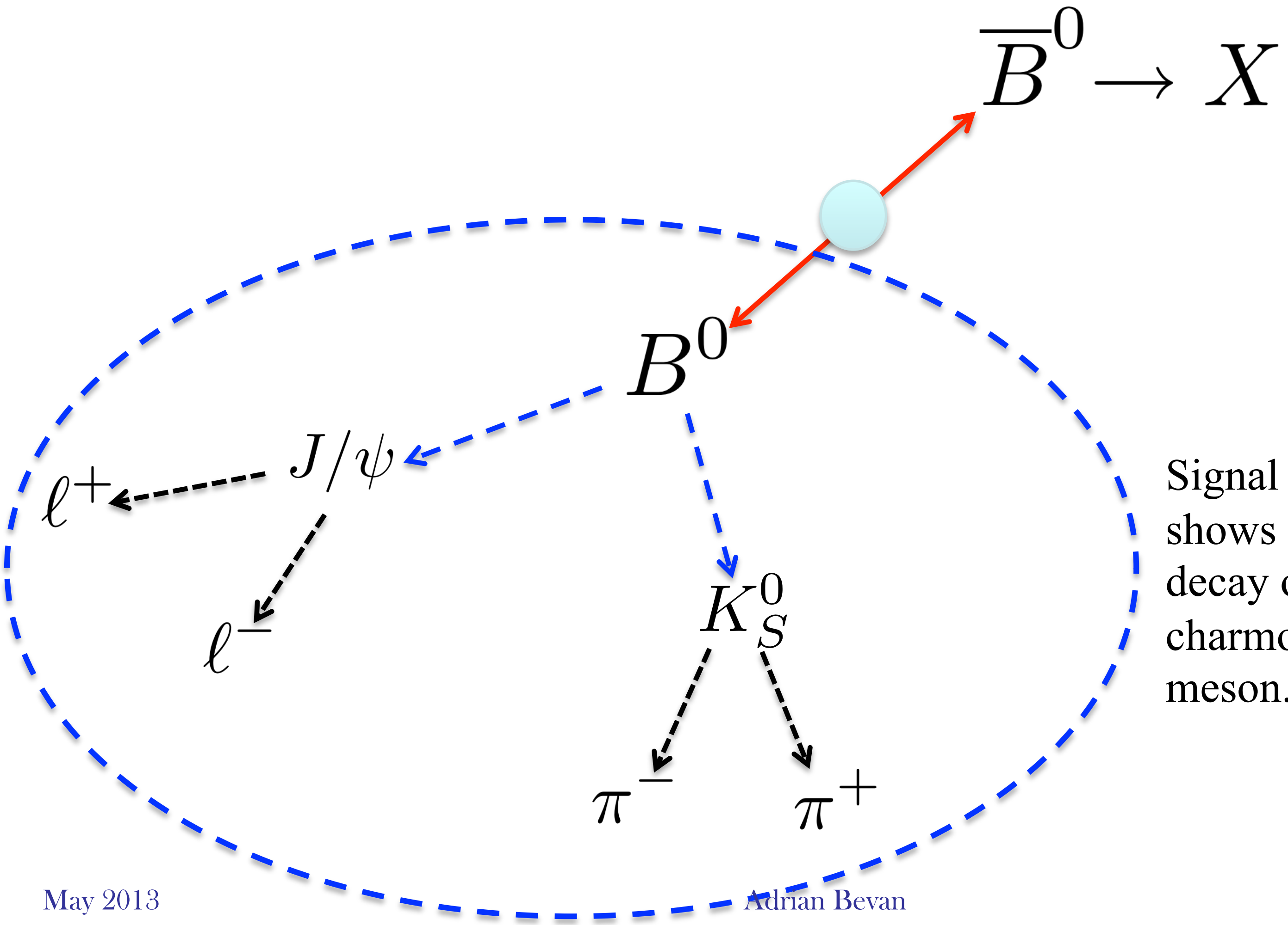


Techniques

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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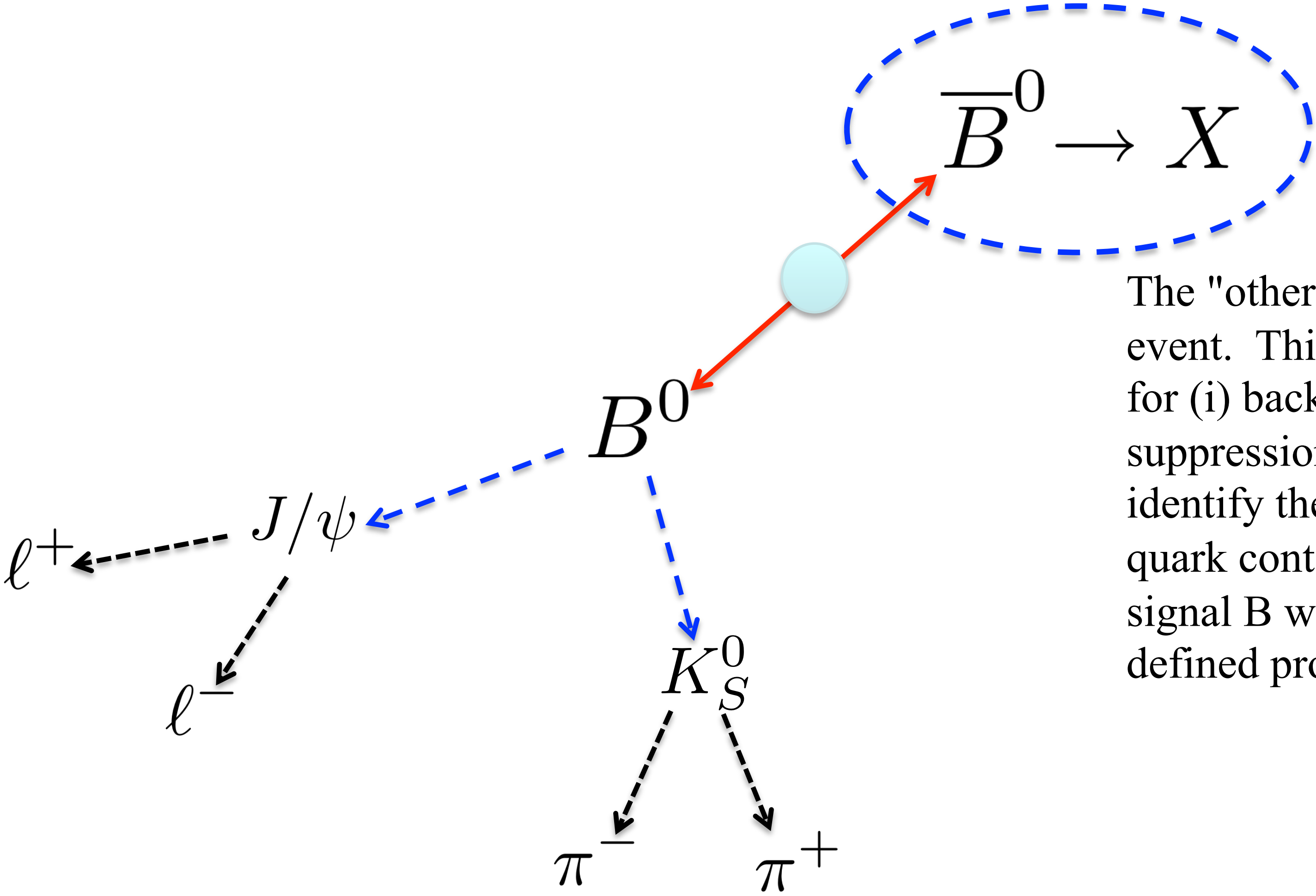


The "other" B in the event. This can be used for (i) background suppression, and (ii) to identify the underlying quark content of the signal B with some well defined probability.

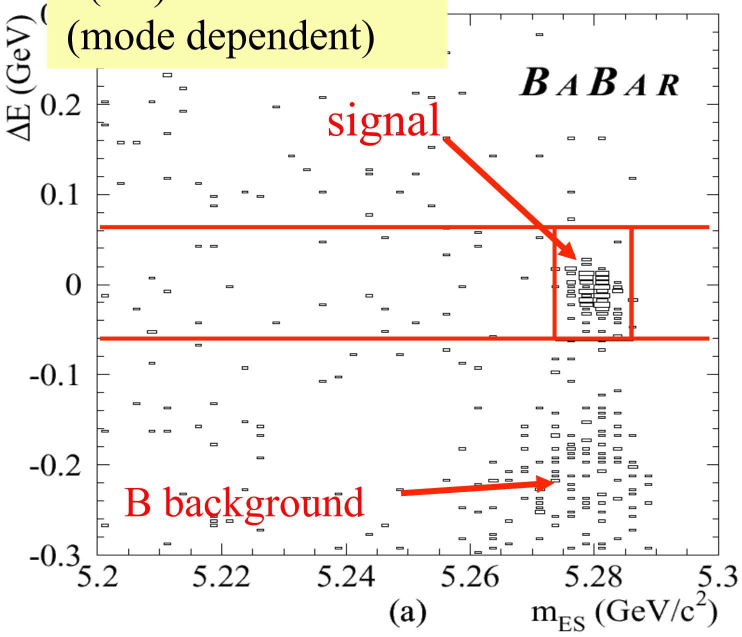
Isolating signal events

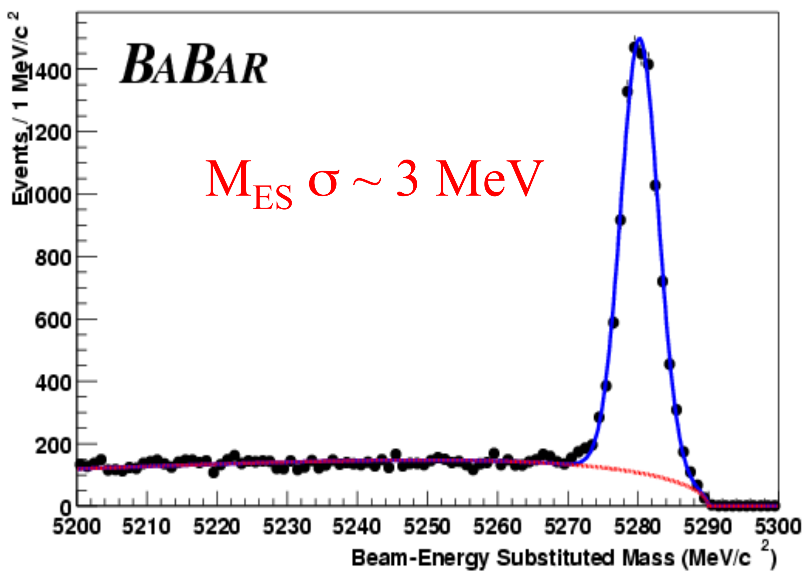
- Beam energy is known very well at an e^+e^- collider
  - Use an energy difference and effective mass to select events:

- $\sqrt{s}$: 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.

σ(ΔE)~ 15-80 MeV (mode dependent)



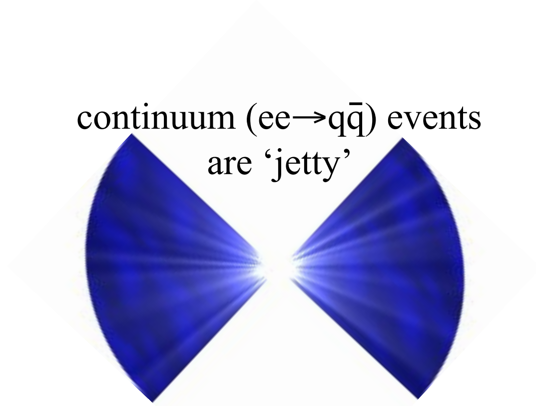


More background suppression

- Use the shape of an event to distinguish between $\Upsilon(4S) \to B\overline{B}$ and $e^+e^- \to q\overline{q}$.
- $\sqrt{s}$=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

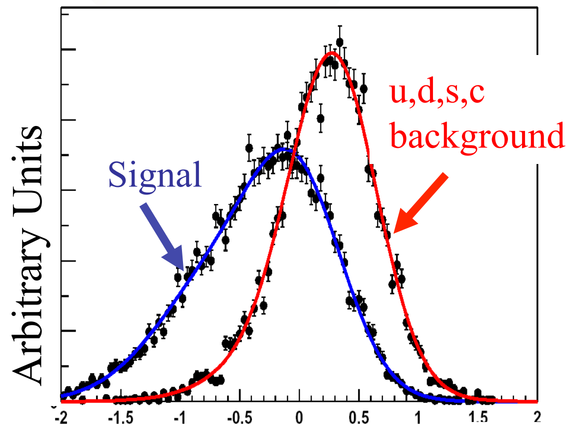
continuum (ee→q$\bar{q}$) events are ‘jetty’



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



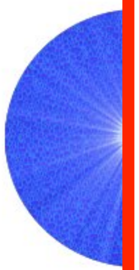
Fisher Discriminant: $F = \sum_i \alpha_i x_i$

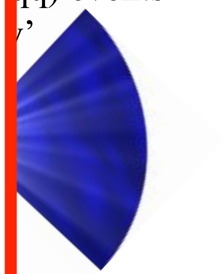
More background suppression

- Use the shape of an event to distinguish between $\Upsilon(4S) \to B\overline{B}$ and $e^+e^- \to q\overline{q}$.
- √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

q̄) events





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
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Different papers have different approaches.

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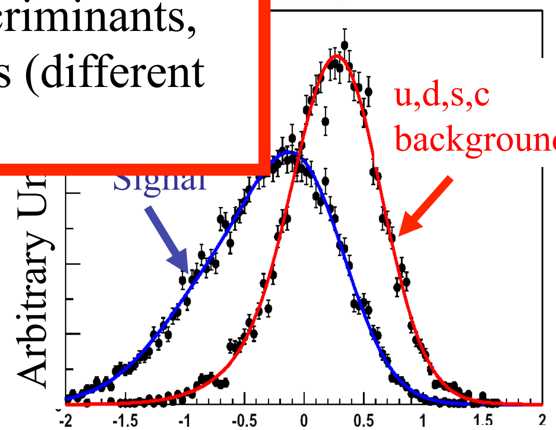


Fisher Discriminant: $F = \sum_i \alpha_i x_i$

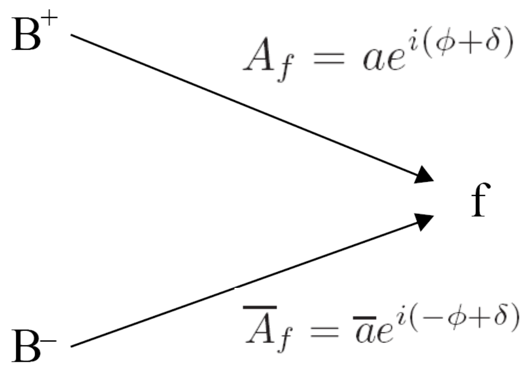
Techniques

TIME DEPENDENT METHODS

Time integrated CP asymmetries

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

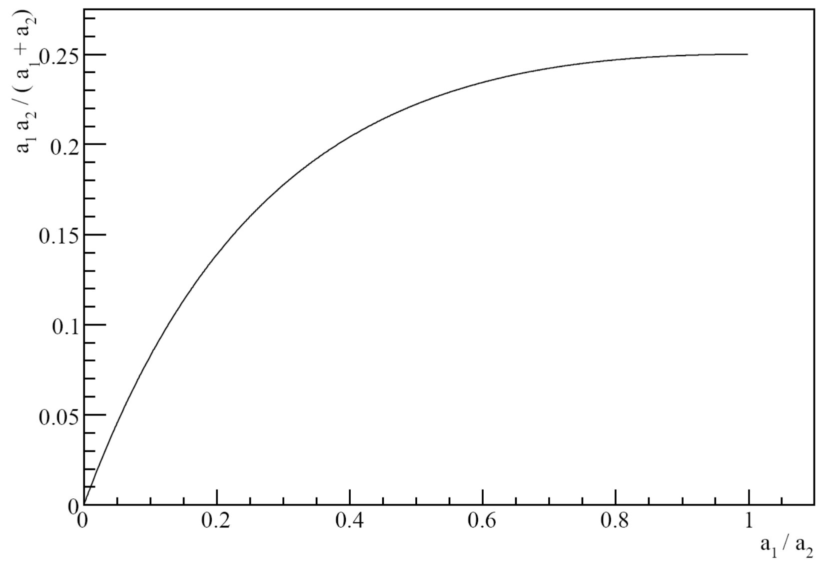
$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$



- 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.

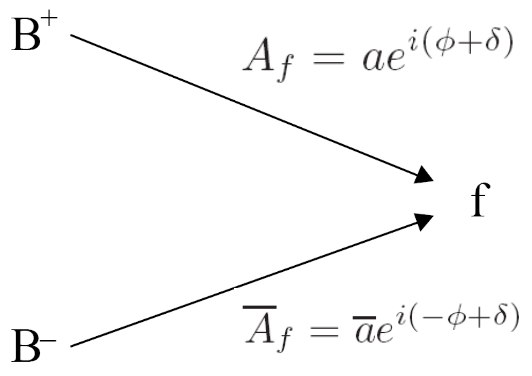


- A_{CP} is largest when $a_1 = a_2$.
- Need to measure δ!
- We can use this technique when studying neutral B mesons decaying to a self tagging final state.

Time integrated CP asymmetries

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

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



- Event counting exercise!
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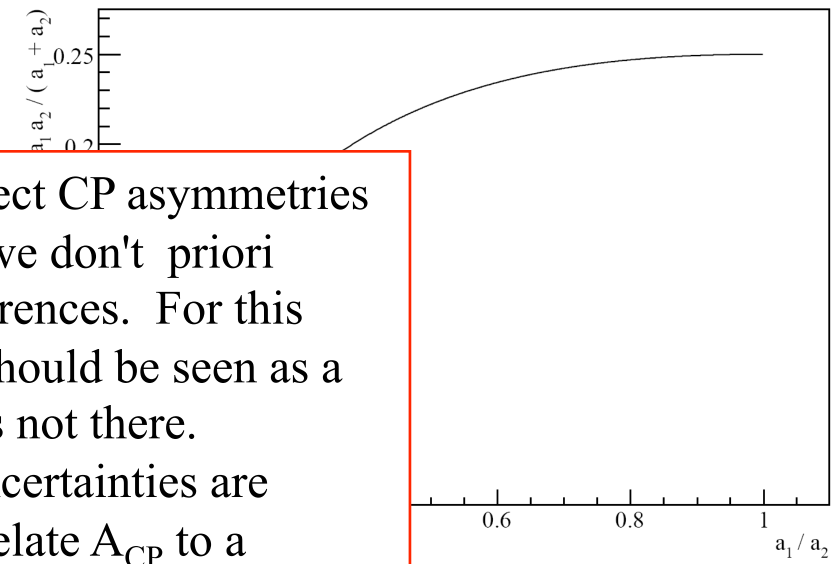
- A_{CP} is largest w
- Need to measu
- We can use this
neutral B meso



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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  - 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

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

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

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

- **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:
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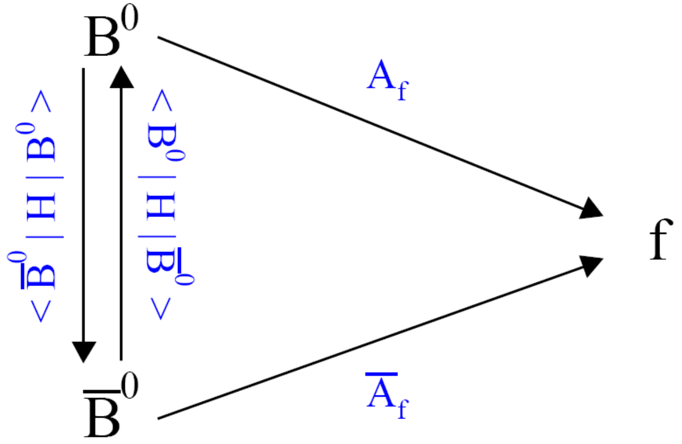

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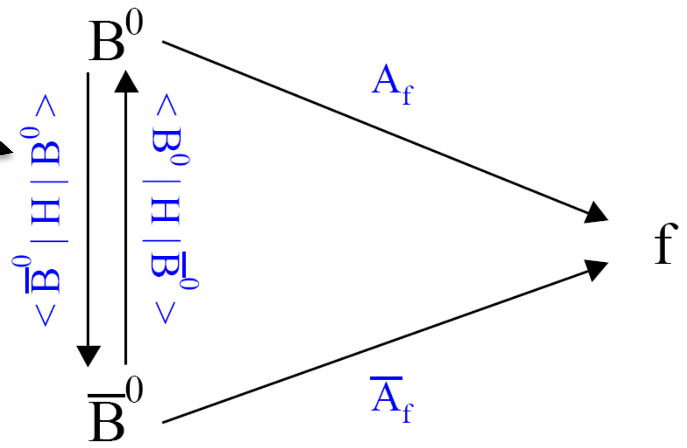

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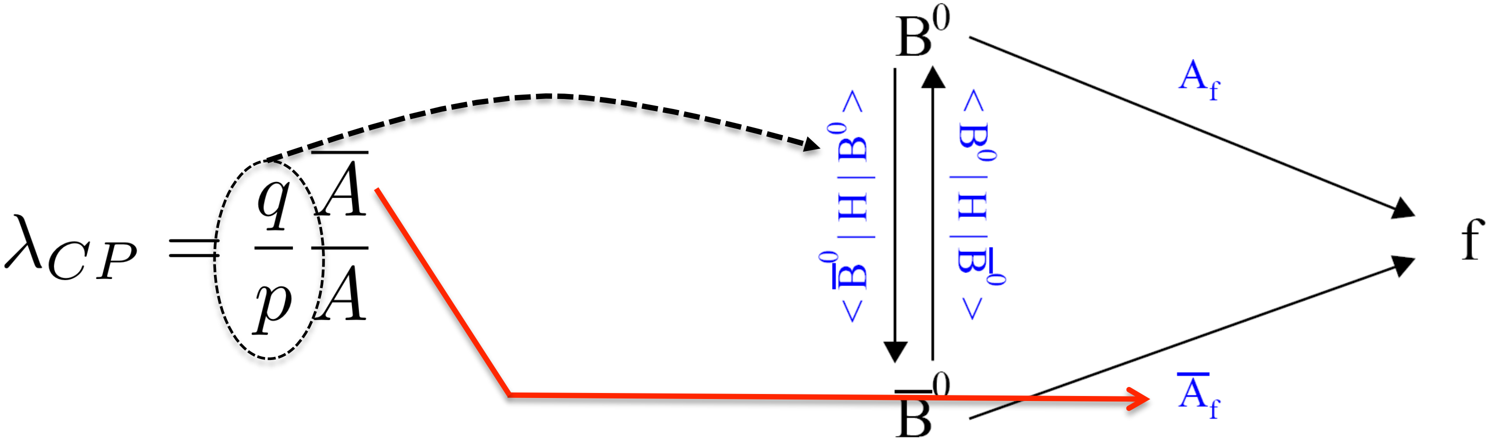

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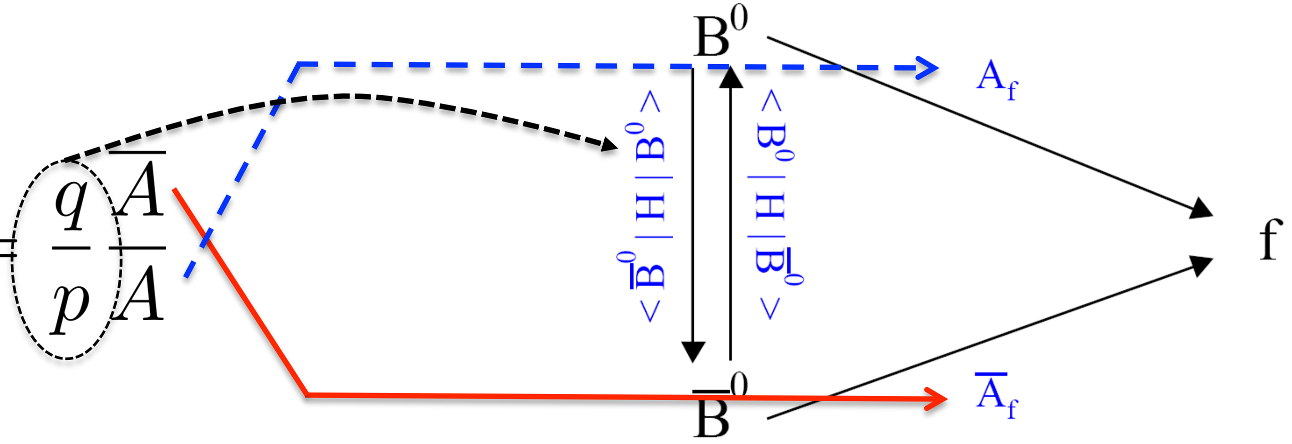
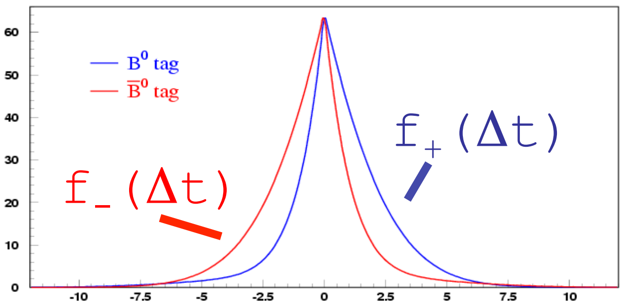


Time-dependent CP asymmetries

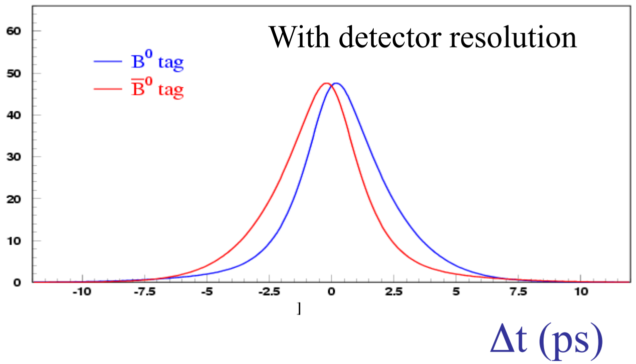
- Construct an asymmetry as a function of Δt:

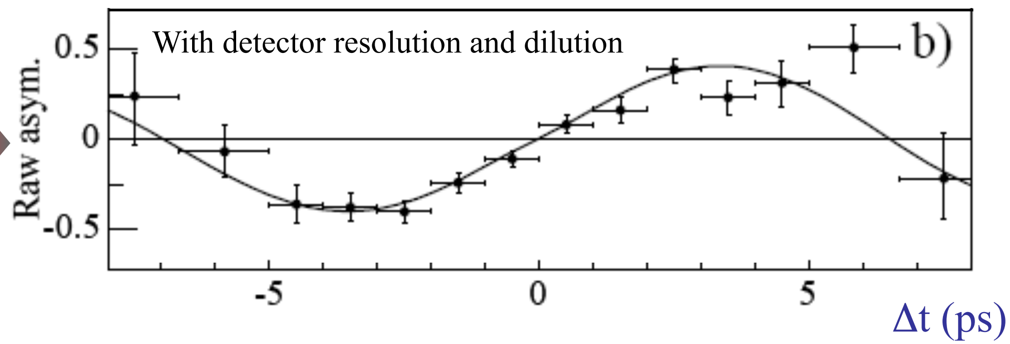
$$\mathcal{A}(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)}$$



Experimental effects we need to include:

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





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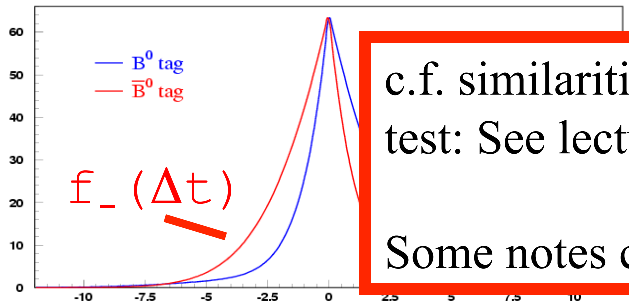
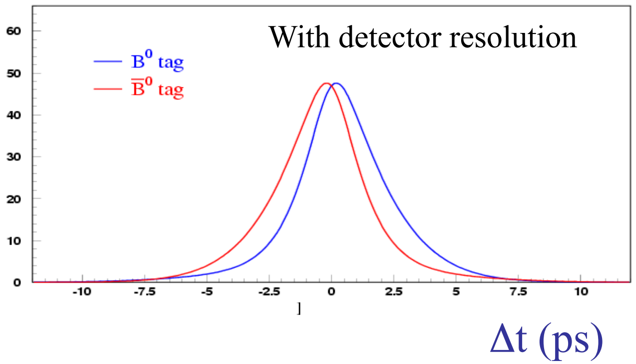
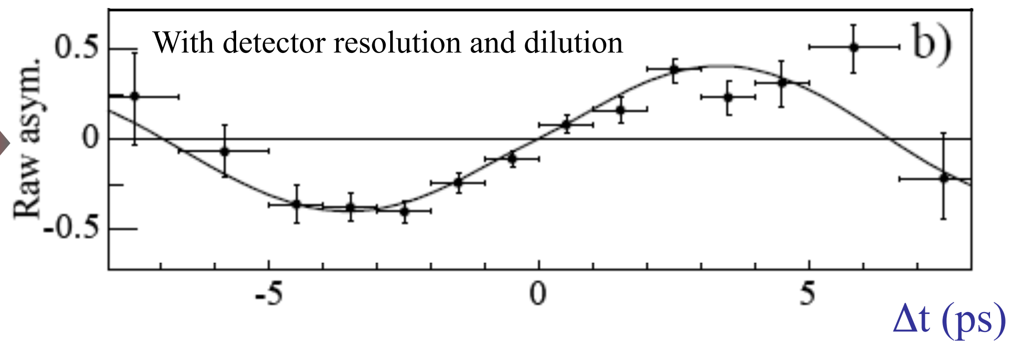


c.f. similarities with T-symmetry non-invariance test: See lectures by Jose Bernabeu.

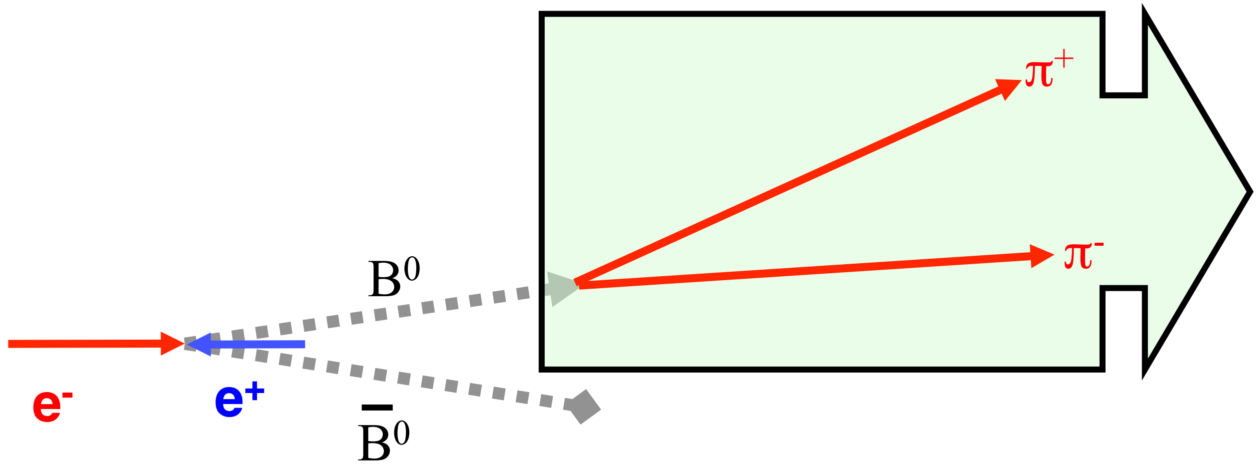
Some notes can also be found in Appendix IV

o include:
t.
ging (see later).





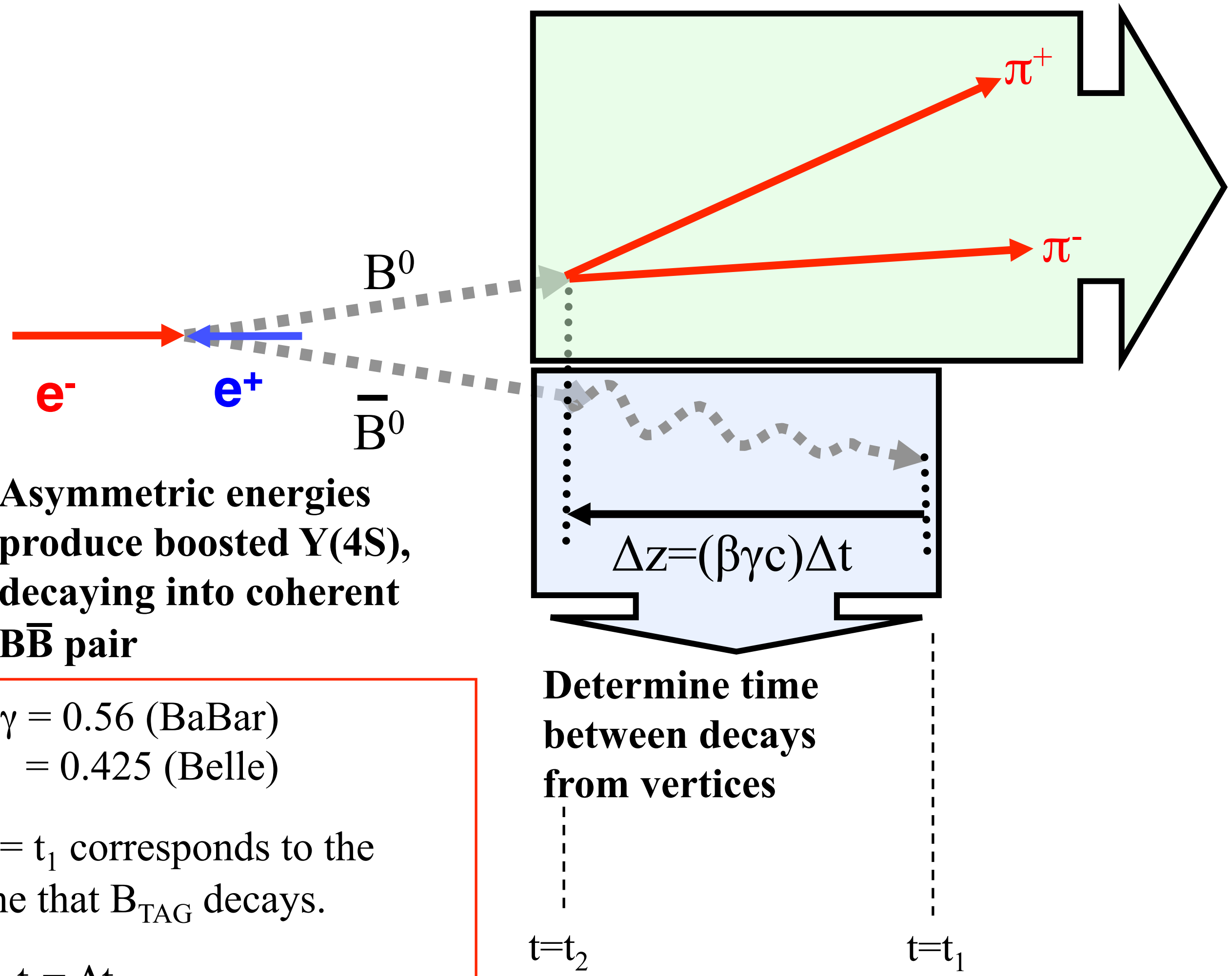
Measuring Δt



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

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

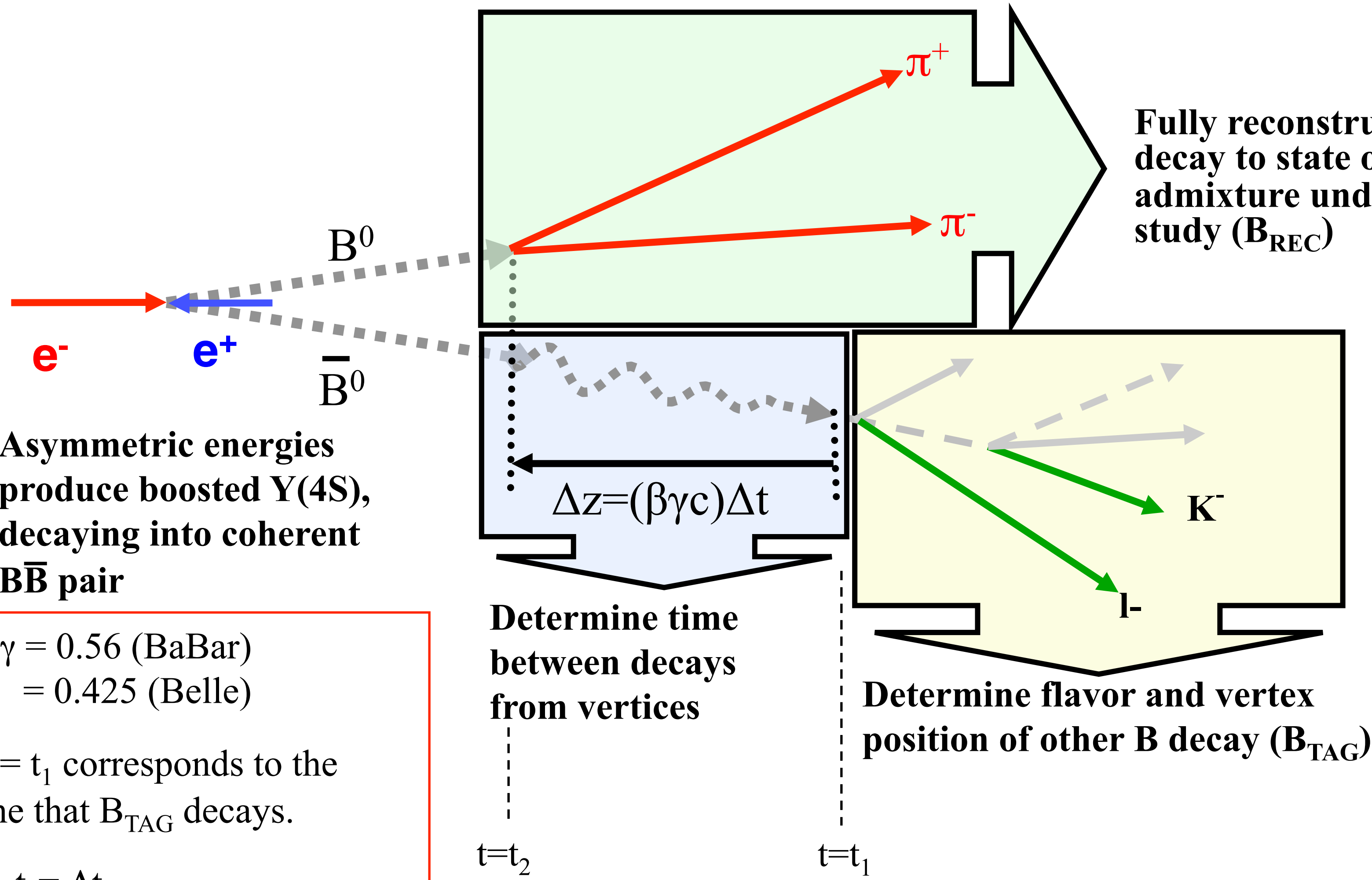
Measuring Δt



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

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

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).

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

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

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

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

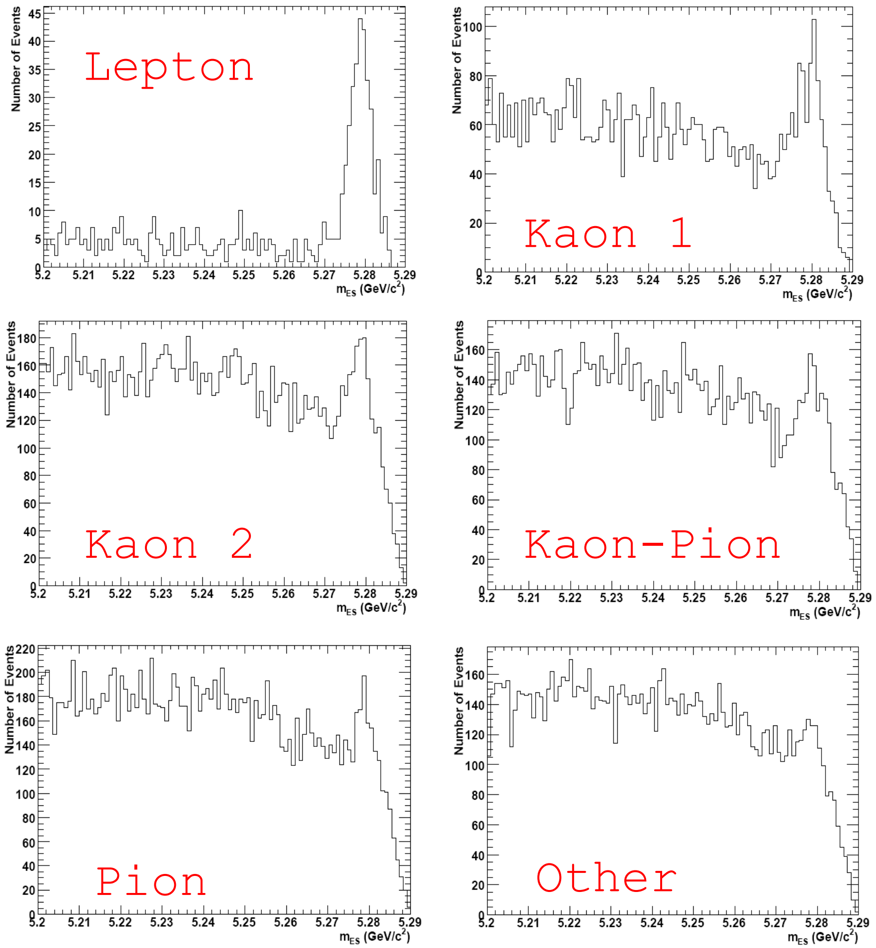
$N^{tag}_{B^0,\overline{B}^0}$ = the number of reconstructed events found in data

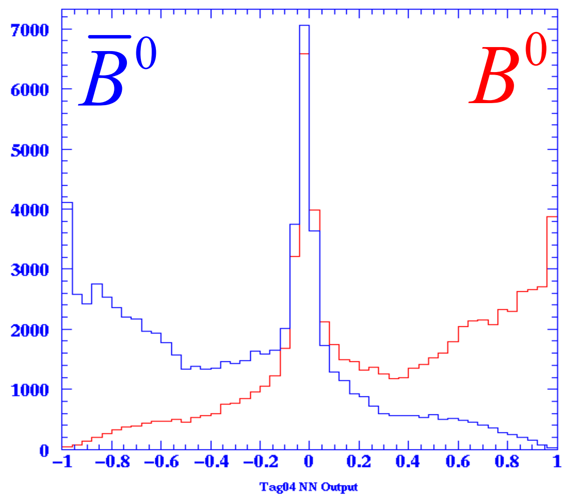
$N_{B^0,\overline{B}^0}$ = the true number of events (i.e. numbers obtained if ω = 0)

Flavor tagging

- Decay products of B_{TAG} are used to determine its flavor.
- At Δt=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: Δω
- Define an effective tagging efficiency: $Q = \epsilon_{\text{tag}}(1-2w)^2$
- Use a modified $f_{\pm}(\Delta t)$:

Example: The BaBar tagging algorithm:

Category	ϵ_{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.

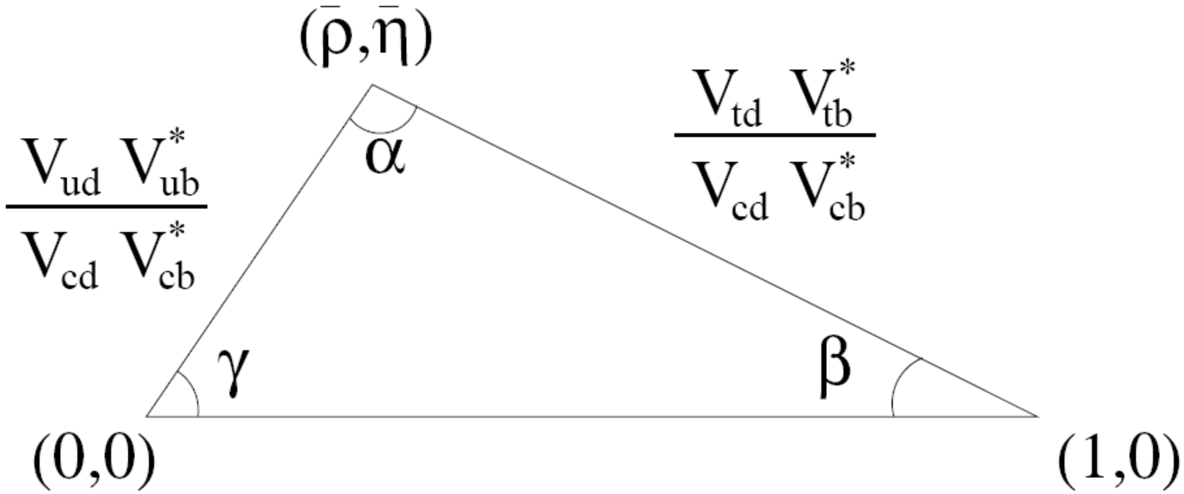
Physics: Quarks

B MESONS

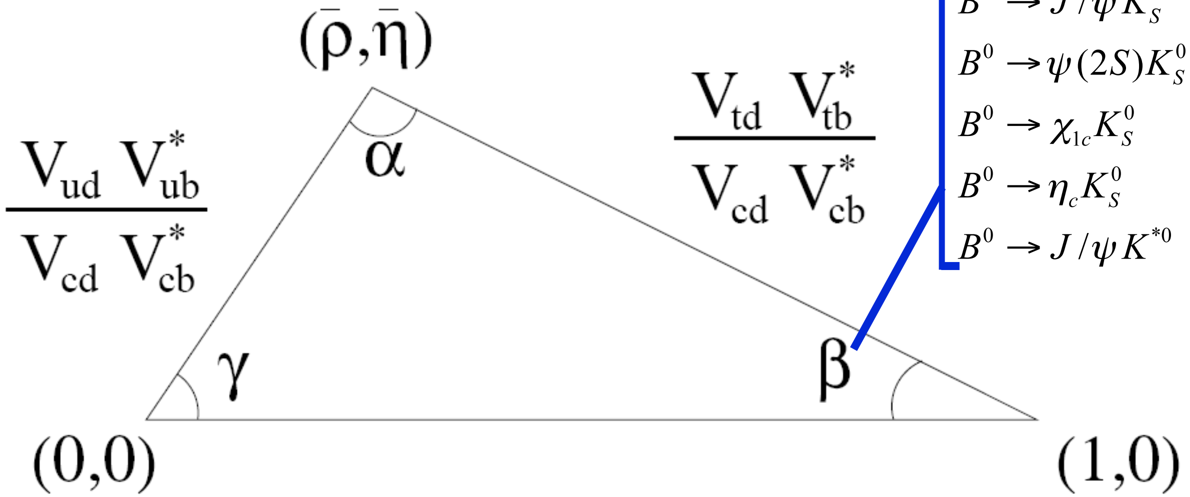
(i) Angles and sides of the Unitarity triangle

(ii) Rare decays

Angles of the Unitarity triangle



Theoretically clean (SM uncertainties ~10^{-2} [data driven method] to 10^{-3} [theoretical calculation]) tree dominated decays to Charmonium + K^0 final states.



$b \to c\bar{c}s$

$B^0 \to J/\psi K_L^0$

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

$B^0 \to \psi(2S) K_S^0$

$B^0 \to \chi_{1c} K_S^0$

$B^0 \to \eta_c K_S^0$

$B^0 \to J/\psi K^{*0}$

$B \to J/\psi \pi^0$

$B \to D^{(*)+} D^{(*)-}$

$B \to \eta' K^0$

$B \to \rho K^0$

$B \to \omega K^0$

$B \to \pi^0 K^0$

$B \to \phi K^{(*)0}$

$B \to KKK^0$

$B \to f^0(980) K^0$

⋮

CP violation: β

- Need to determine many parameters before we can extract S and C (and the angles of the triangle):
  - ω, Δω, ε_{TAG}, $\Delta\varepsilon_{TAG}$ for signal and for background.
  - Use a sample of fully reconstructed B decays to flavor specific final states to determine these parameters (B_{flav}).
  - Sample includes:

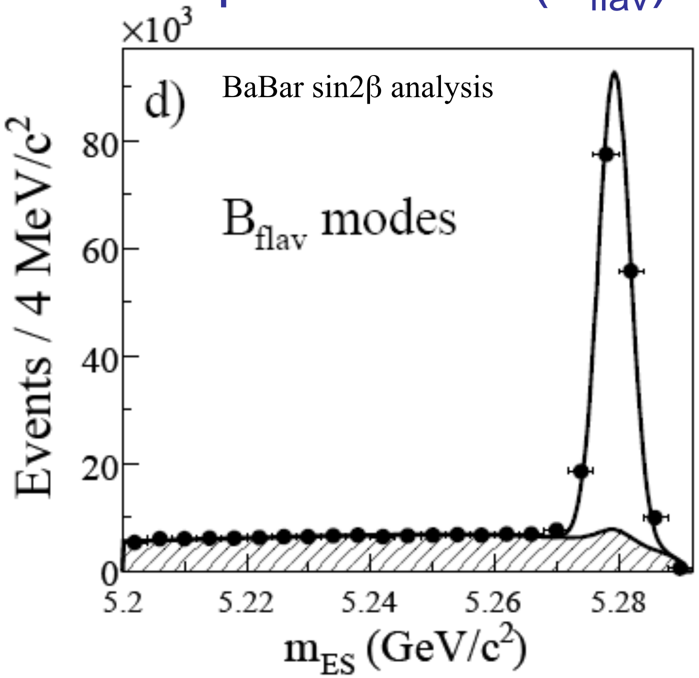
$B^0 \to D^{(*)-}\pi^+$

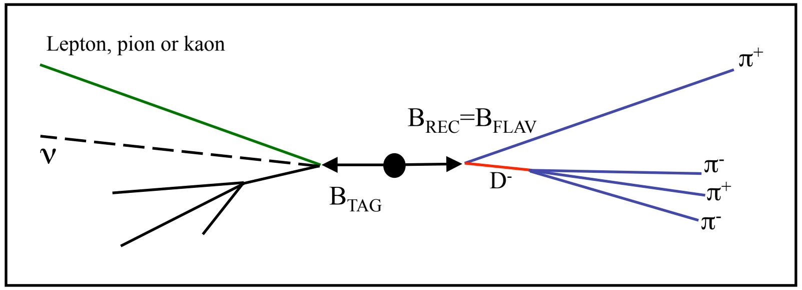
$B^0 \to D^{(*)-}\rho^+$

$B^0 \to D^{(*)-}a_1^+$

$B^0 \to J/\psi K^{*0},\ \ K^{*0} \to K^+\pi^-$

Background





This method to validate the tagging performance is used for all time-dependent CP asymmetry measurements.

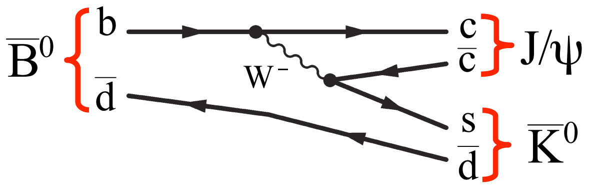
CP violation: β

- Measure S and C in several $b \to c\bar{c}s$ modes.

$$S = \sqrt{1 - C^2}\sin 2\beta$$

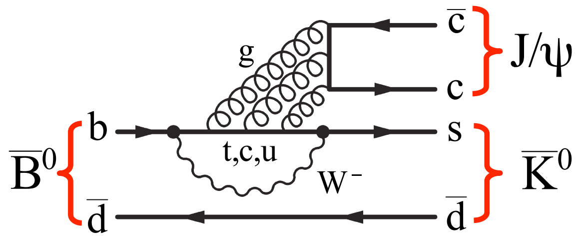
- Theoretically clean: Tree level process dominates:

$\eta_f = +1$



- Gluonic loop (penguin) is small:

$\eta_f = -1$



- Calculations suggest C<10^{-3}.

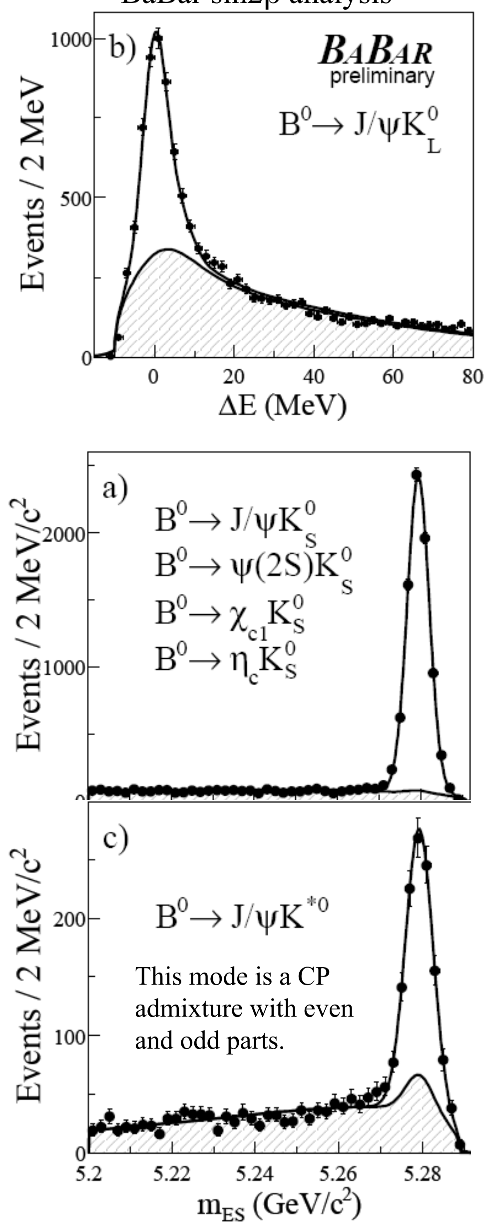
$\eta_f^{eff} \sim 0.5$

H. Li and S. Mishima, hep-ph/0610120.

H. Boos, J. Reuter, and T. Mannel, Phys. Rev. Lett. D **70**, 036006 (2006).

- Data driven methods constrain C<0.012.

BaBar sin2β analysis



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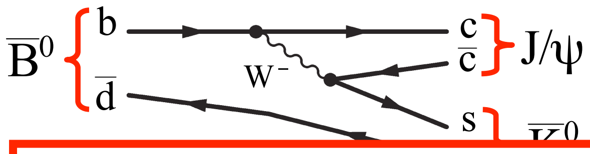

- Gluoni

Penguins are small in charmonium + K0 decays of a B meson, and so hadronic uncertainties from this source are negligible. It is likely for this to remain the case with the next generation of experiments.

- Calculations suggest C<10^{-3}.

$$\eta_f^{eff} \sim 0.5$$

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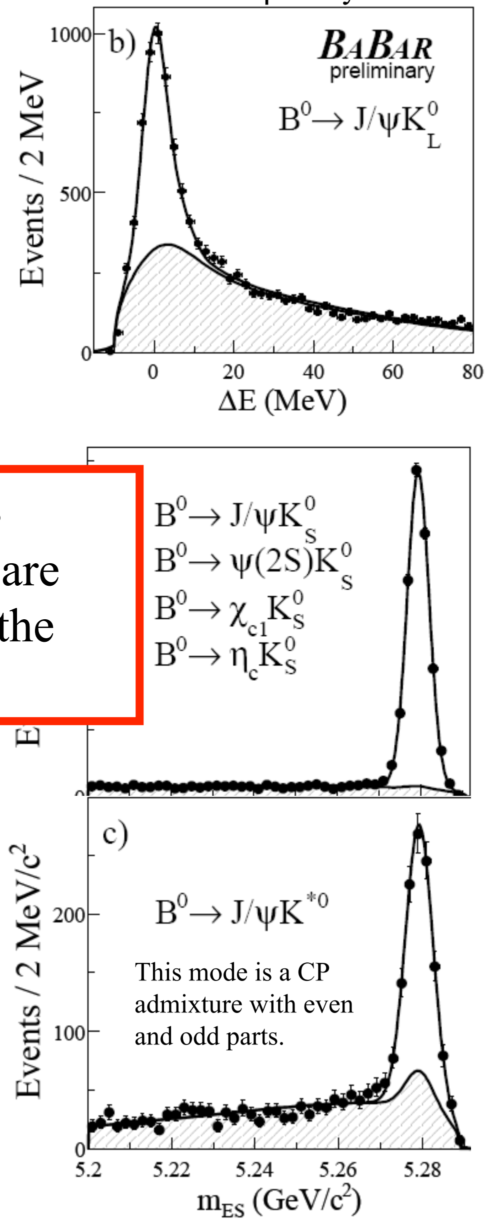
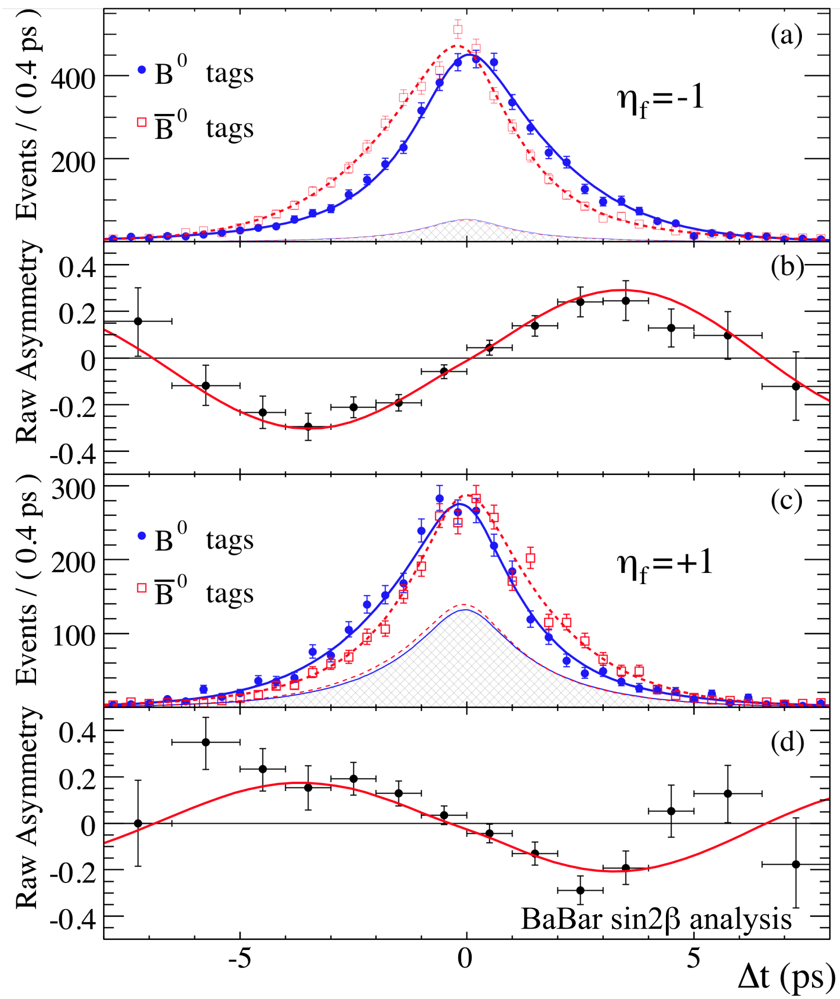


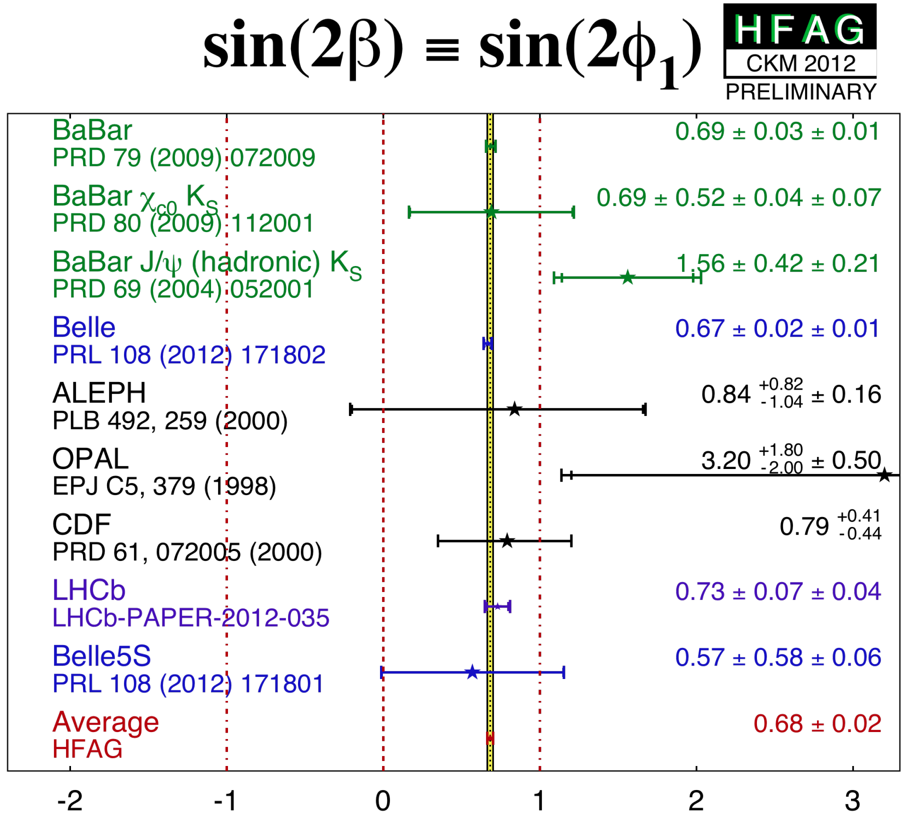
CP violation: β

- CP violating asymmetry is well established in these decays!



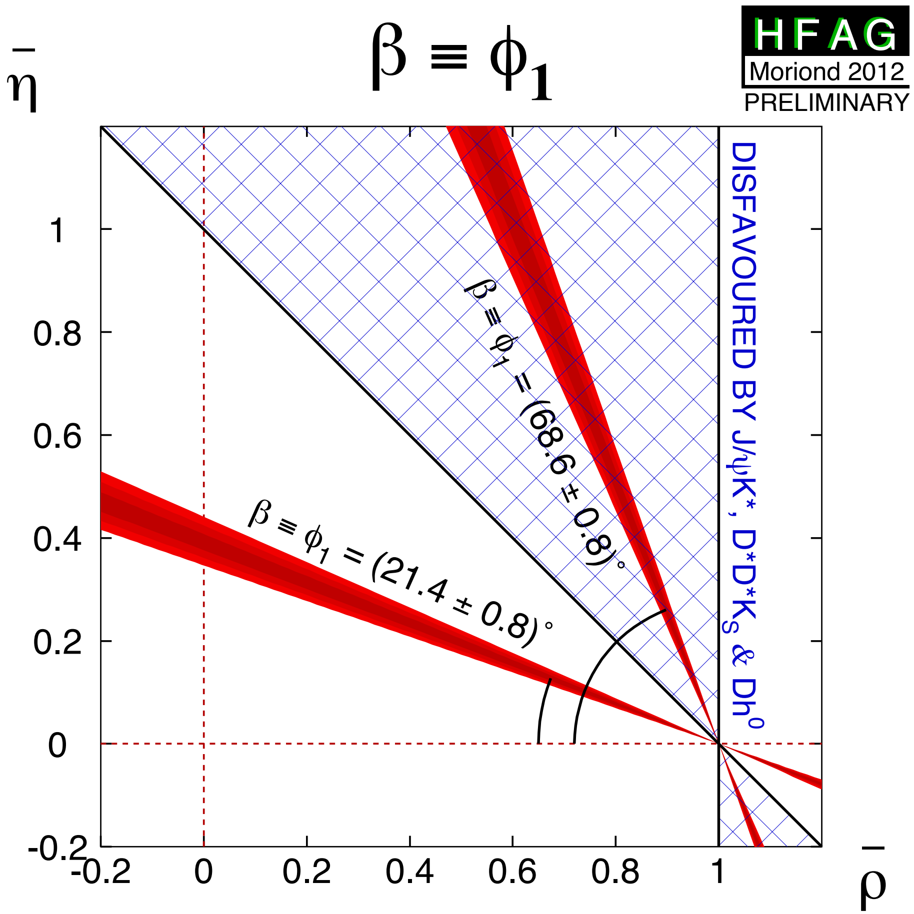
$$\sin 2\beta = (0.677 \pm 0.020)$$
(BaBar + Belle)

$\sin(2\beta) \equiv \sin(2\phi_1)$



BaBar and Belle still dominate the average value of sin2β

CP violation: β



- Four solutions exist in the ρ-η plane as we compute arcsin(2β).
- Additional measurements provide cos(2β) and help to resolve ambiguities.

- Theoretically clean CP violation measurements consistent with the Standard Model for:

$$B^0 \to J/\psi K_L^0$$
$$B^0 \to J/\psi K_S^0$$
$$B^0 \to \psi(2S) K_S^0$$
$$B^0 \to \chi_{1c} K_S^0$$
$$B^0 \to \eta_c K_S^0$$
$$B^0 \to J/\psi K^{*0}$$

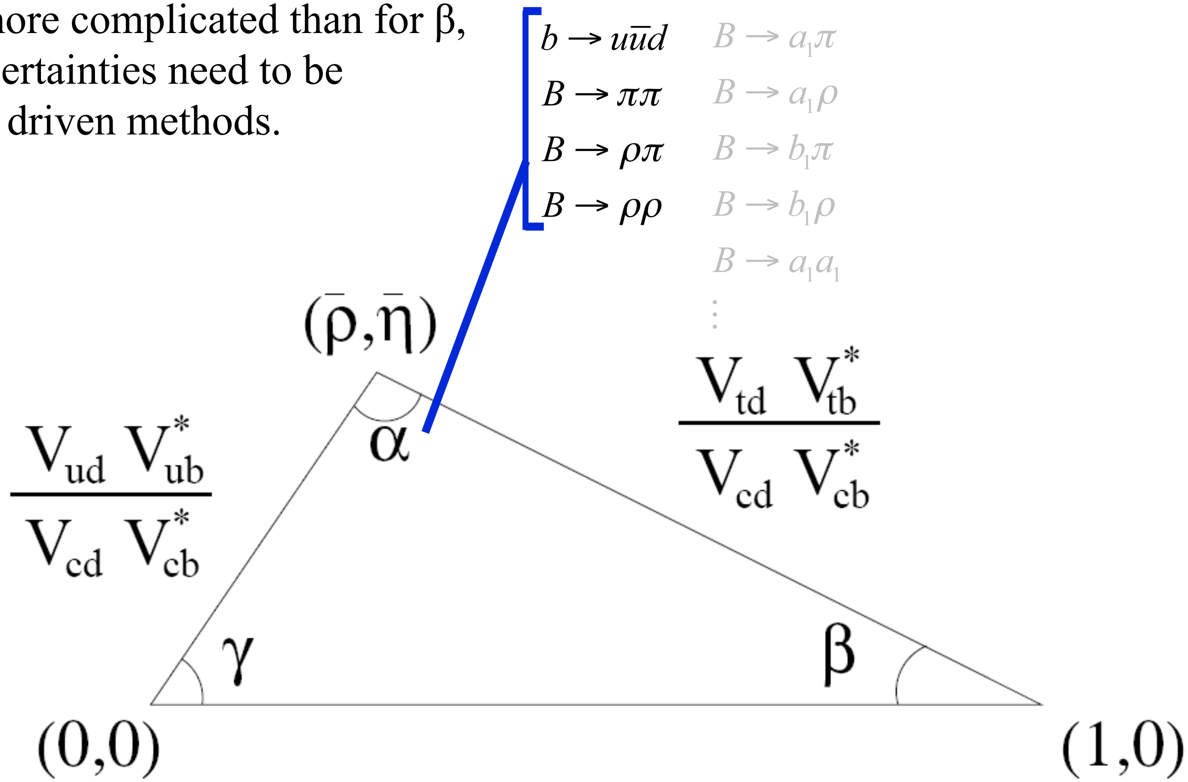
- Established technique for extracting S and C that can be used for other final sates.

- Measured S=sin2 β provides a reference point to search for New Physics (NP).

b→uūd transitions with possible loop contributions. Extract α using

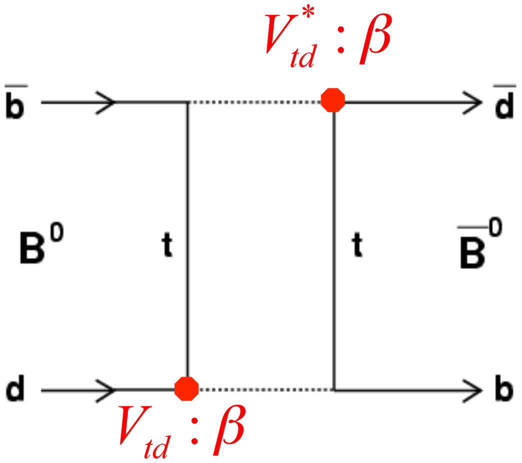
- SU(2) Isospin relations.
- SU(3) flavour related processes.

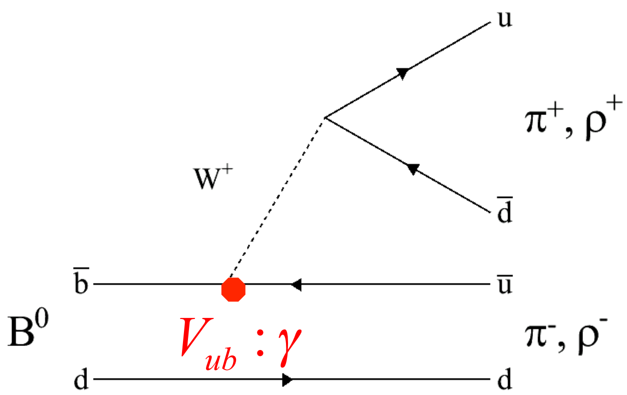
- Interpretation is more complicated than for β, where hadronic uncertainties need to be constrained by data driven methods.



CP violation: α

- Interference between box and tree results in an asymmetry that is sensitive to α in $B \to hh$ decays: $h=\pi, \rho, \ldots$
- Loop corrections are not negligible for α.





$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

- This scenario is equivalent to the measurement of sin2β in Charmonium decays … but nature is more complicated than this!

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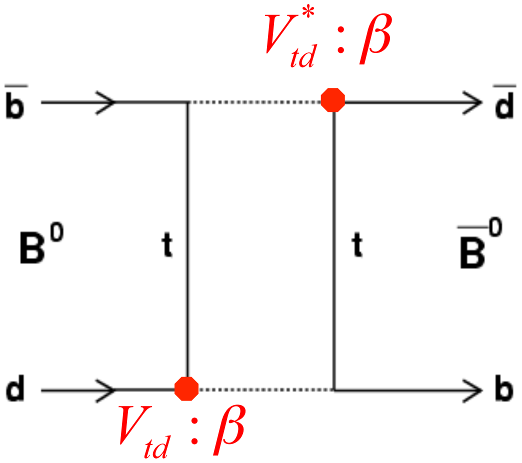
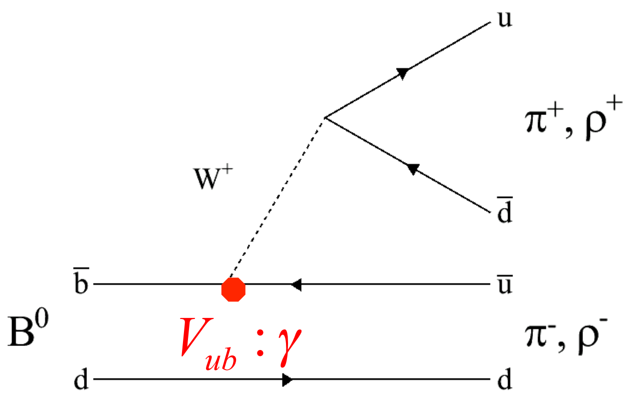
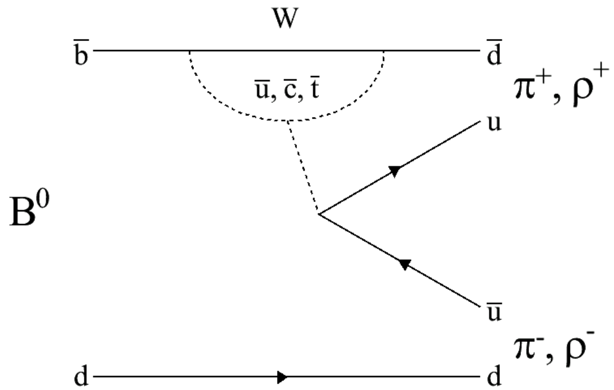
+Loops (penguins)







$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

- This scenario is equivalent to the measurement of sin2β in Charmonium decays … but nature is more complicated than this!

- Measure S $\propto \alpha_{eff}$.
- Need to determine $\delta\alpha=\alpha_{eff}-\alpha$ [P/T is different for each final state]

CP violation: α

- Interference between box and tree results in an asymmetry that is sensitive to α in $B\to hh$ decays: $h=\pi, \rho, \ldots$
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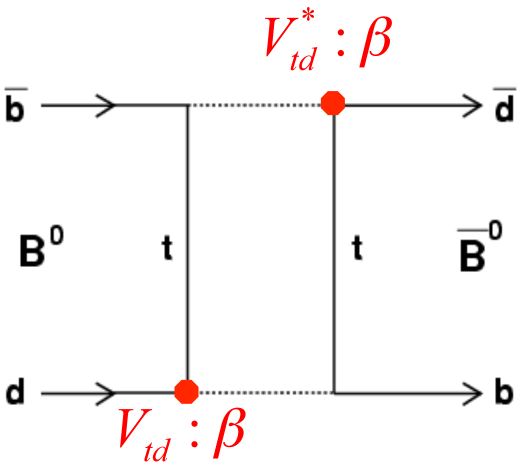

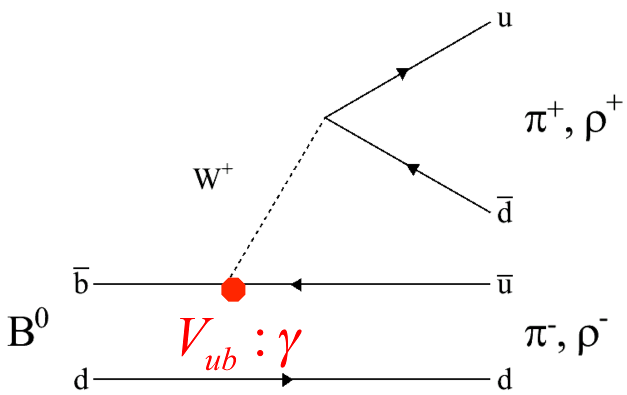

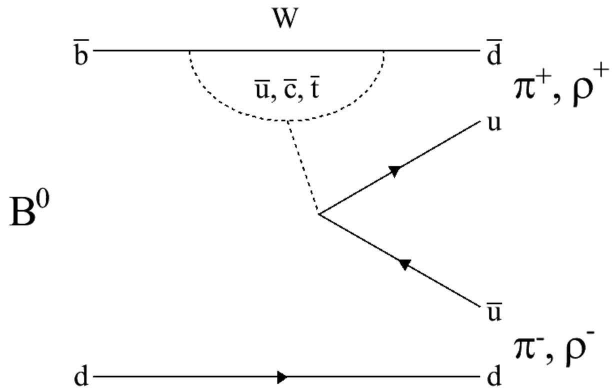

$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

- $\Delta I = 1/2$ operators yield penguin and tree amplitudes.
- $\Delta I = 3/2$ operators yield only tree amplitudes.
- Thus isospin is the key to understanding hadronic uncertainties in these decays.

Bounding penguins

- Several recipes describe how to bound penguins and measure alpha.
  - These are based on SU(2) or SU(3) symmetry.

SU(2)
(Isospin analysis)

(i.e. the assumed equivalence of *u* and *d* quark masses)

$\pi^+\pi^-$ and $\rho^+\rho^-$
Gronau-London
Isospin Triangles

- Use charged and neutral B decays to the hh final state to constrain the penguin contribution and measure alpha.

$\pi^{+/-}\rho^{-/+}$
Lipkin (et al.)
Isospin Pentagons

- Use charged and neutral B decays to the $\rho\pi$ final state to constrain the penguin contribution and measure alpha. Remove any overlapping regions in the Dalitz plot.

$\pi^{+/-}\pi^{-/+}\pi^0$
Snider-Quinn (et al.)
Fit Dalitz plot and extract parameters related to α

- Regions of the Dalitz plot with intersecting ρ bands are included in this analysis; this helps resolve ambiguities.

Bounding penguins

- Several recipes describe how to bound penguins and measure alpha.
  - These are based on SU(2) or SU(3) symmetry.

SU(2)

(i.e. the assumed equivalence

sses)

- Focus on extaction of α using these decays, as the 3 π analysis is not numerically robust with existing data samples.

- This robustness issue is discussed in some detail the recent BaBar paper: arXiv: 1304.3503. Some comments are given in Appendix I.

- Final states with neutral pions need to be used to constrain hadronic uncertainties: this angle is only measured (currently) by the B Factories.

$\pi^+\pi^-$ and $\rho^+\rho^-$
Gronau-London
Isospin Triangles

- Use charged and neutral B decays to the hh final state to constrain the penguin contribution and measure alpha.

π⁰

(et al.)

d extract

ted to α

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any overlapping regions in the Dalitz plot.

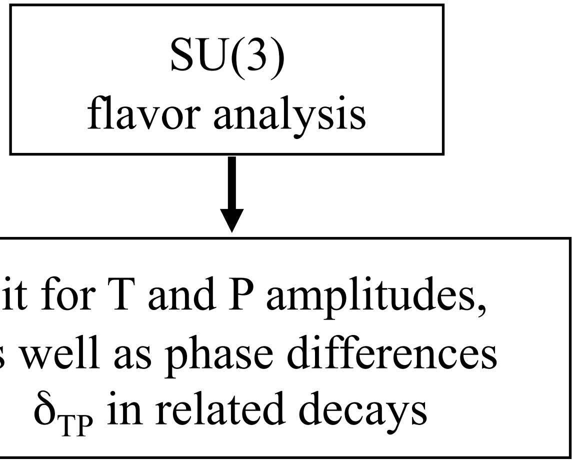
itz plot

bands

.

Bounding penguins

- Several recipes describe how to bound penguins and measure alpha.
  - These are based on SU(2) or SU(3) symmetry.



- Theoretical uncertainties tend to result in weaker constraints than the SU(2) analyses.
- No choice for decays like $B \rightarrow a_1\pi$, have to use SU(3) approach
- Exception exists for $B \rightarrow \rho^+\rho^-$: Use $K^{*0}\rho^+$ to constrain penguin contribution in $\rho^+\rho^-$ and measure α with better precision than SU(2).

Bounding penguins

- Several recipes describe how to bound penguins and measure alpha.
  - These are based on SU(2) or SU(3) symmetry.

SU(3)
flavor analysis

↓

Fit for T and P amplitudes,
as well as phase differences
δ_{TP} in related decays

For brevity, these approaches are not discussed – see the Appendix I.

- Theoretical uncertainties tend to result in weaker constraints than the SU(2) analyses.
- No choice for decays like $B \rightarrow a_1\pi$, have to use SU(3) approach
- Exception exists for $B \rightarrow \rho^+\rho^-$: Use $K^{*0}\rho^+$ to constrain penguin contribution in $\rho^+\rho^-$ and measure α with better precision than SU(2).

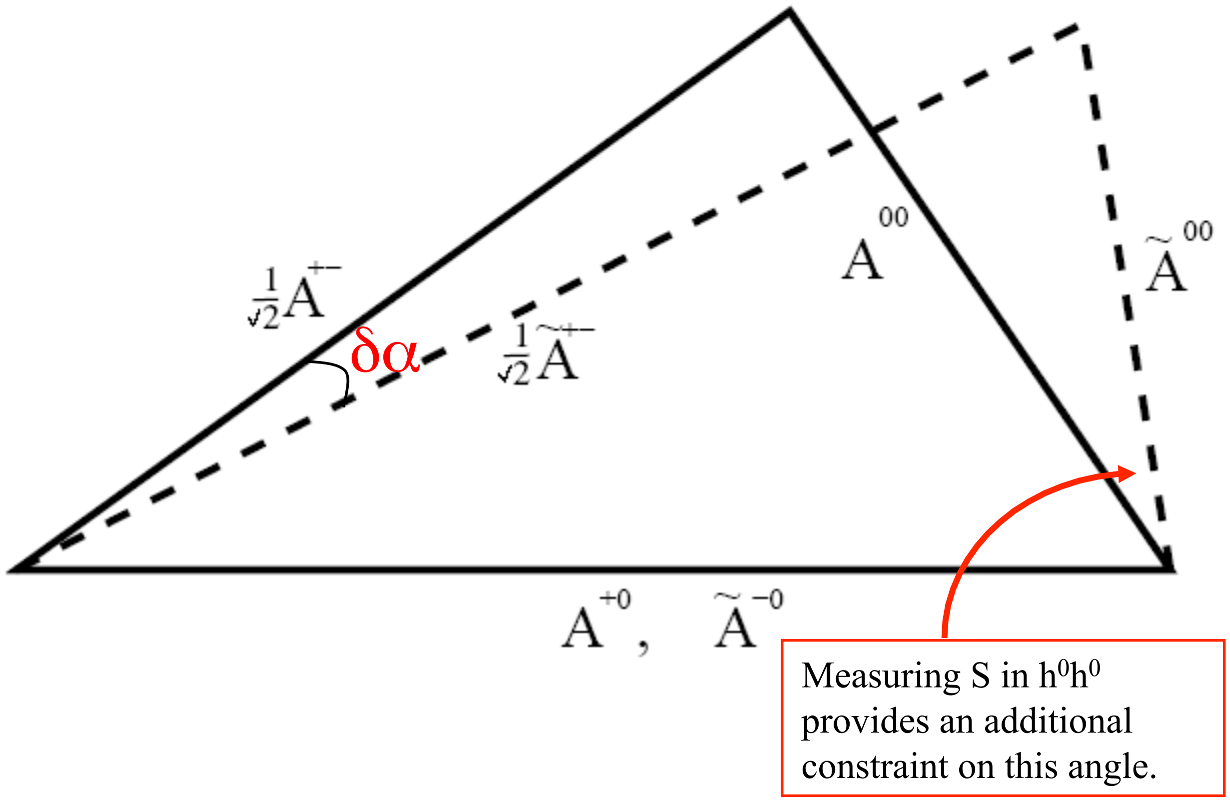
Isospin analysis

- Consider the simplest case: $B \to \pi\pi$ / $\rho\rho$ decays.

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}} \overline{A}^{+-} + \overline{A}^{00} = \overline{A}^{+0}$$

$\delta\alpha = \alpha_{eff} - \alpha$



For $\pi\pi$ & $\rho\rho$ require:

$\mathcal{B}(B^0 \to h^+h^-) + C.C.$

$\mathcal{B}(B^0 \to h^0h^0) + C.C.$

$\mathcal{B}(B^+ \to h^+h^0) + C.C.$

$S_{h^+h^-}$

- There are SU(2) violating corrections to consider, for example electroweak penguins, but these are much smaller than current experimental accuracy and can be incorporated into the Isospin analysis.

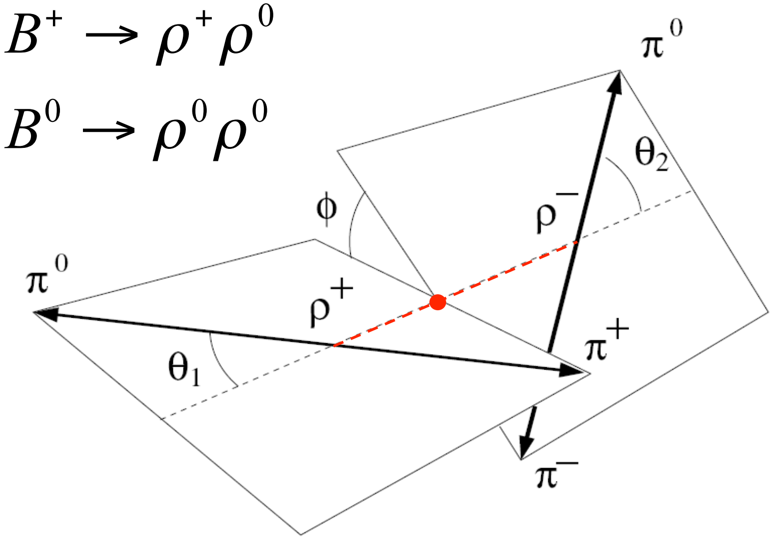
B→ρρ

- This is a decay of a B meson to two vector mesons.
- Requires a (simplified) angular analysis.
- Inputs from:

$$B^0 \to \rho^+\rho^-$$

$$B^+ \to \rho^+\rho^0$$

$$B^0 \to \rho^0\rho^0$$



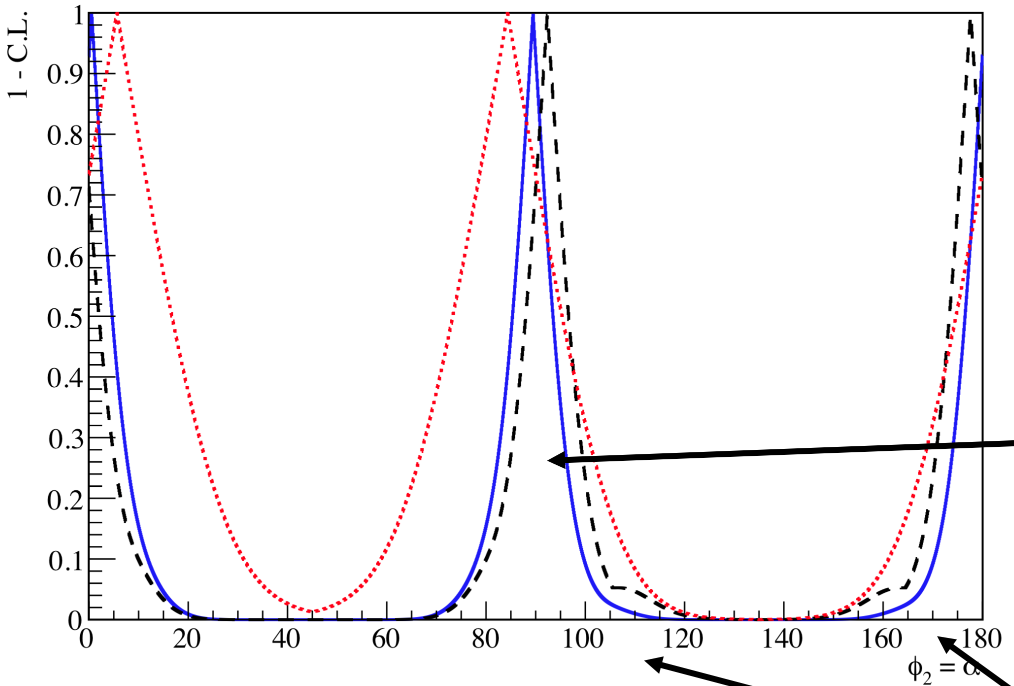
- We define the fraction of longitudinally polarised events as:

$$\frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}, = f_L.$$

- f_L ~ 1 for B→ρρ decays: this helps simplify extracting α.
- Can measure S^{00} as well as C^{00} to help resolve ambiguities.
- Finite width of the ρ is ignored in the α determination (see Falk et al.)

B→ρρ

- These results dominate our knowledge on α.



- BaBar.
- Belle.
- Combined.

Some features of this result:

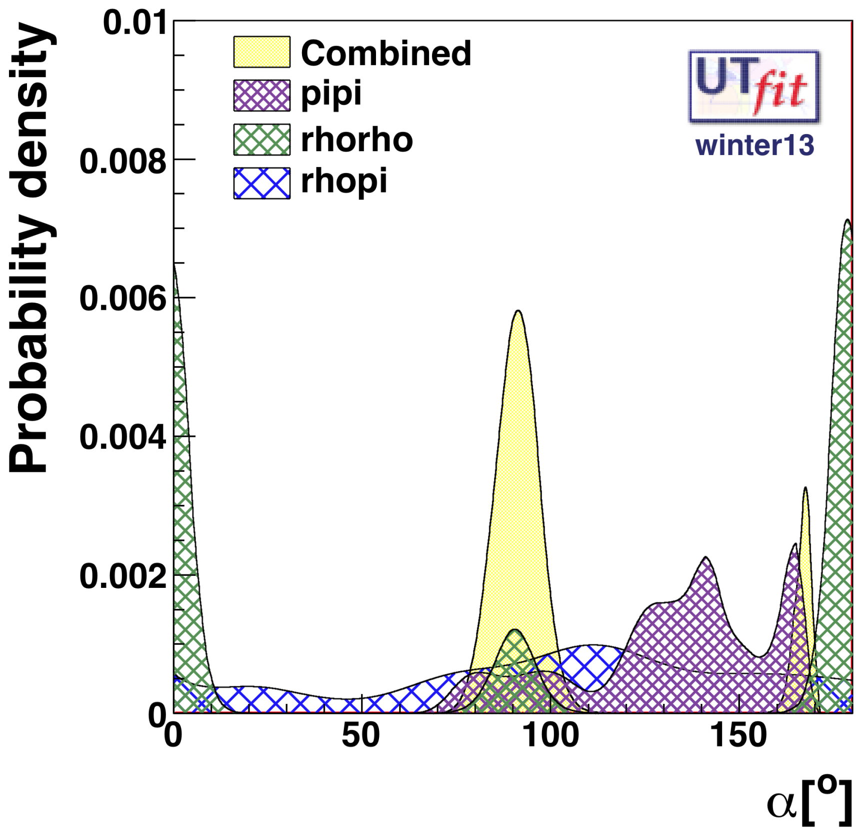
- Two of the solutions overlap near 90° and 180°.
- Ultimately we expect that the time-dependent CP asymmetry parameters measured in the $\rho^0\rho^0$ mode (S^{00} and C^{00}) will help resolve ambiguities. The effect can be seen as the bump at 110° and the mirror ~160°.
- There are two regions for α that are excluded:

$$\alpha \neq 45^\circ$$

$$\alpha \neq 130^\circ$$

CP violation: α

- One set of modes dominate our knowledge of α: B to ρρ decays
  - SU(3) can be used to provide an equivalent measurement with different theoretical uncertainties using B to $\rho^+\rho^-$ and K*ρ.



- Many modes are required to try and measure α precisely. Any deviation in measured values of could indicate new physics.

$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$

$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$$

Shown here

$$B \to \pi^+\pi^-\pi^0$$

$$B \to a_1\pi$$

$$B \to a_1\rho$$

...

Not shown: Need more data than currently available, and use SU(3) to extract α from final states with axial-vector mesons. These are related to hh modes above.

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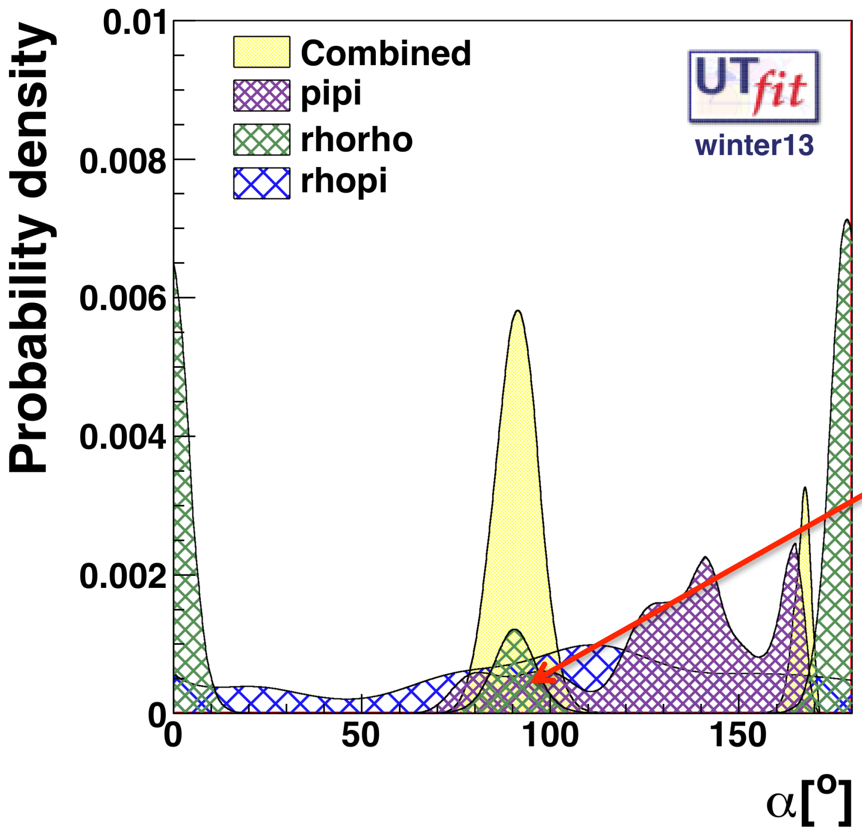

$$\alpha_{BF\,\mathrm{average}} = (88 \pm 5)^\circ$$

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$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$

$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0 \quad \text{Shown here}$$

$$B \to \pi^+\pi^-\pi^0$$

$$B \to a_1\pi$$

$$B \to a_1\rho$$

...

Not shown: Need more data than currently available, and use SU(3) to extract α from final states with axial-vector mesons. These are related to hh modes above.

$b \to c$ interfering with $b \to u$

$B \to D^{(*)}K^{(*)}$

$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)}\pi$

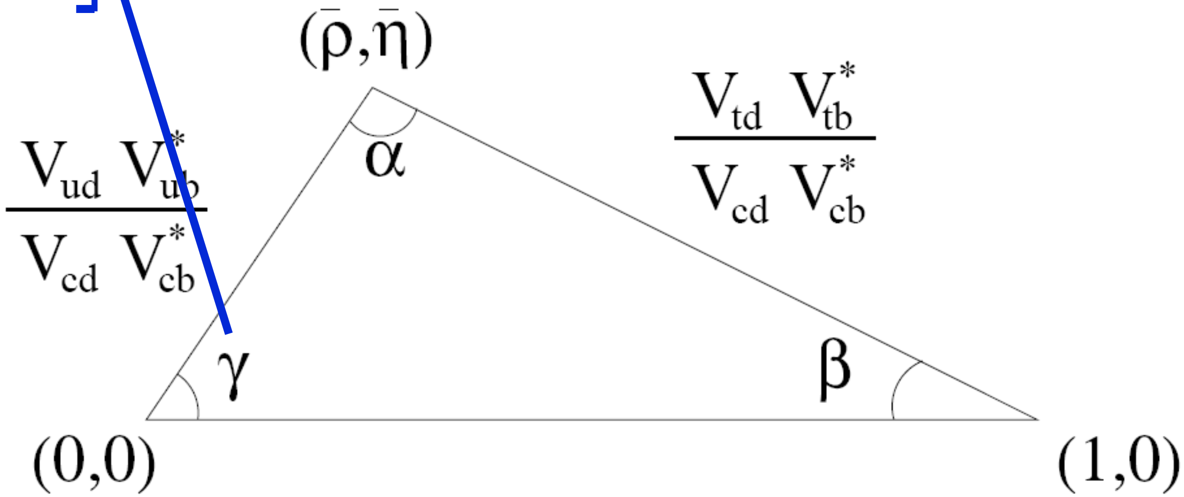
$B^0 \to D^{(*)}\rho$

+ *charmless*

Extract γ using $B \to D^{(*)}K^{(*)}$ final states using:

- GLW: Use CP eigen-states of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D \to K_s h^+ h^-$ decays.

Measurements using neutral D mesons ignore D mixing.



Measuring γ

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

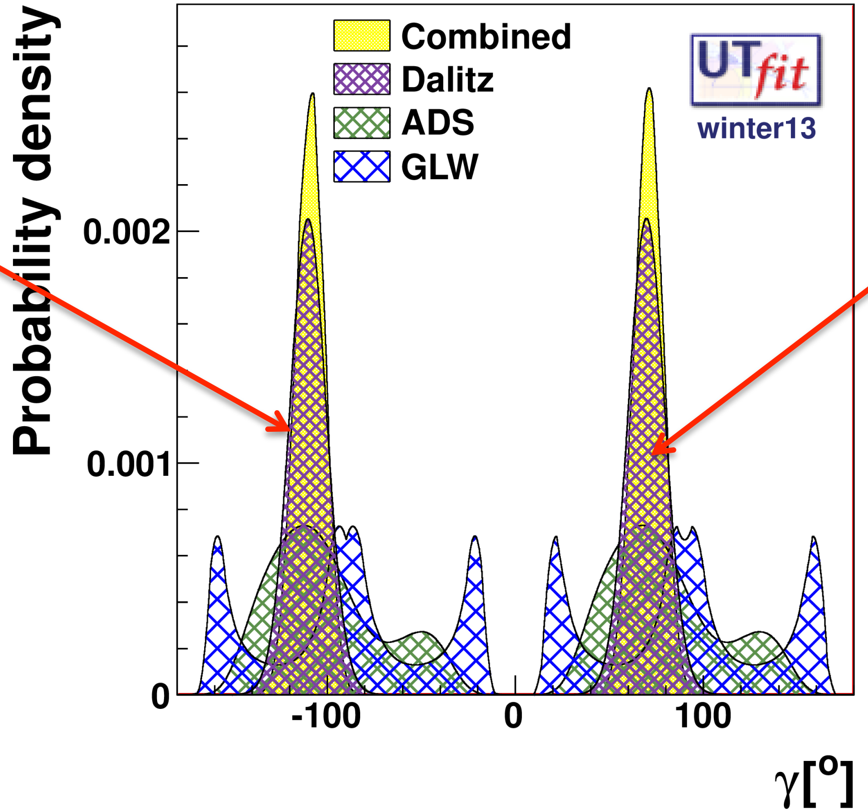
- Conceptually understanding how of the weak phase γ can be accessed in data is similar to α and β.
  - Two interfering amplitudes give rise to a dependence on the weak phase of interest. This is the result of interference between Cabibbo allowed vs Cabibbo suppressed contributions (different orders in λ in the decay amplitudes of interest).
  - One uses B decays to DK final states to extract information about the angle via one of three main methods:
    - ADS
    - GLW
    - GGSZ (or Dalitz method)
  - While it is possible to make theoretically clean measurements of this phase, these result from precision measurements of rare decays and the Dalitz method provides (currently) the best possible precision of all methods.

CP violation: γ

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

- In the long run the Dalitz method requires a binned measuremet of the strong phase difference in the $D \to K_S\pi^+\pi^-$ Dalitz plot – this is limited currently by CLEO data, however new results from BES III are expected soon.

$\gamma = (-109.0 \pm 7.8)^{\circ}$



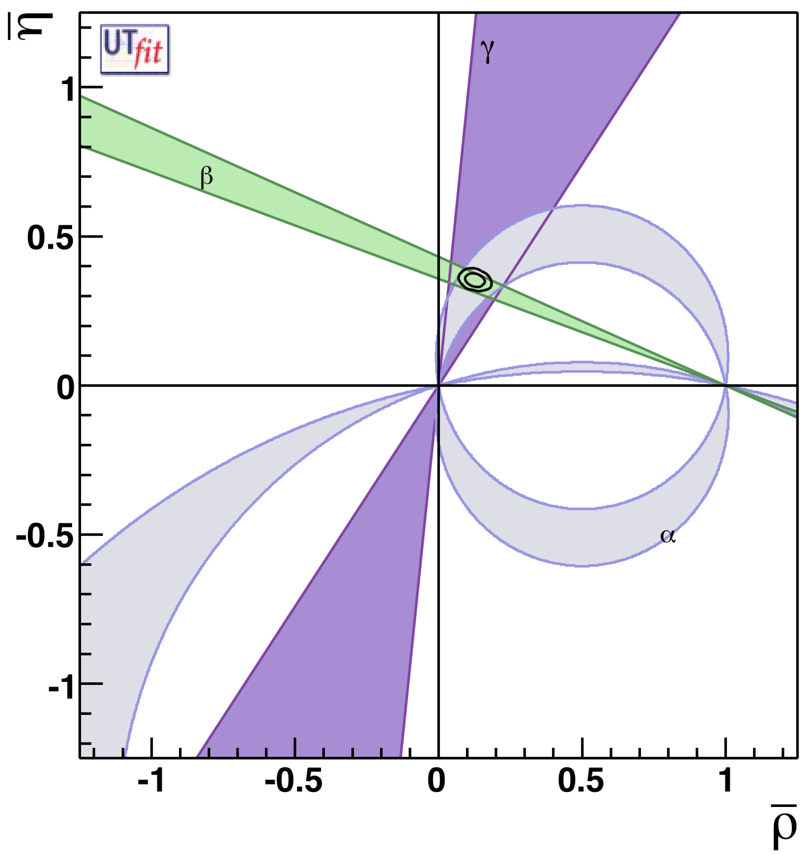
$\gamma = (70.8 \pm 7.8)^{\circ}$

- LHCb are also starting to make significant contriubutions to this measurement.

(Also see Appendix II)

What did we learn about the SM?

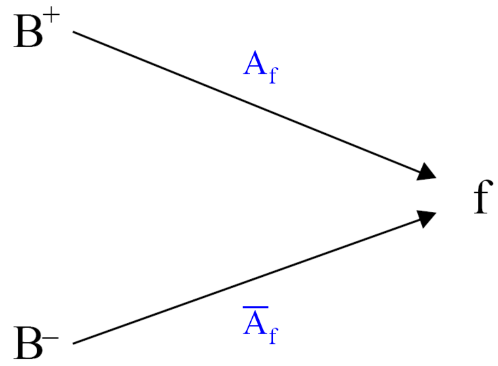
- Consider the angles measurements only (still dominated by the B Factories).



- Measurements of the angles (dominated by the precision on α and β)
  - Converge on a single point as predicted by the CKM matrix.
  - Are consistent with expectations from CPV in the kaon sector.
  - Establish the Kobayashi-Maskawa mechanism as a leading order description of CP violation in the quark sector of the SM.
  - Leave room for new physics to resolve the universal matter-antimatter asymmetry problem.

CP violation: Direct CP violation

- Recap from Introduction:
  - Number counting exercise: $A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$
  - Requires at least two amplitudes to interfere.
  - Amplitudes have to have different weak and strong phases. $A_{CP} \propto A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$



  - We are comparing A_f with $\overline{A}_f$.

  - Predictive power will be limited by our knowledge of weak phases and of the strong phase differences.
    - But there are many possible measurements that we can compare!

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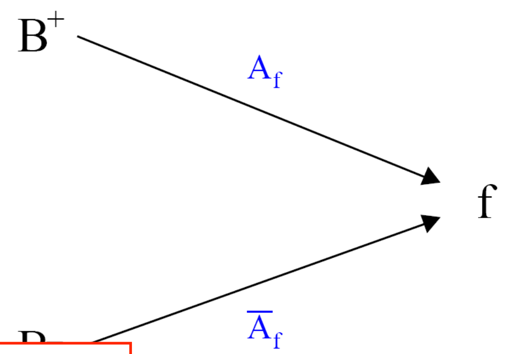

- We are comparing A_f with $\overline{A}_f$.

These are well defined in the SM, come from quartets of CKM matrix elements, thus depend on δ_{KM}.

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These strong phases can not be calculated accurately, and so present a problem when trying to interpret measurements.

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These amplitudes are calculable in an appropriate theoretical framework, for an assumed set of Feynman diagrams (or rather operators in the effective Hamiltonian).

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$\overline{A}_f$

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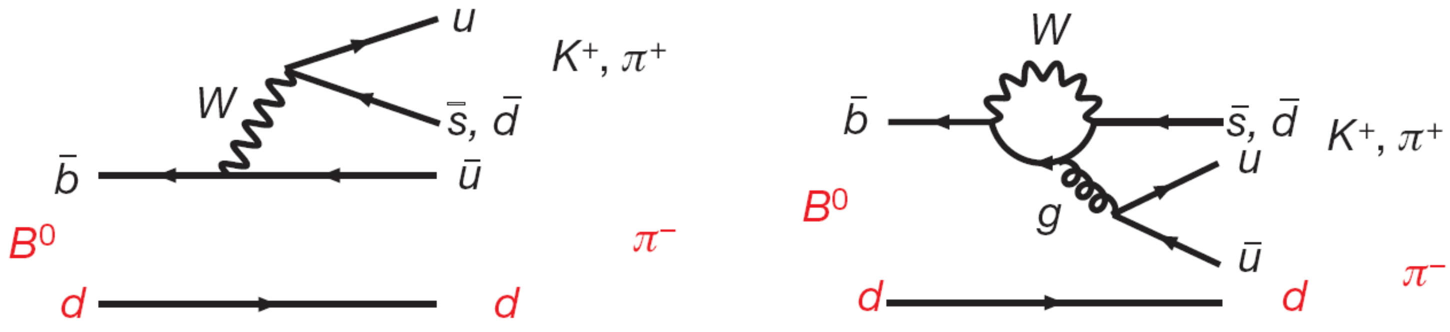
CP violation: Direct CP violation

- $B^0 \to K^\pm \pi^\mp$: Tree and gluonic penguin contributions

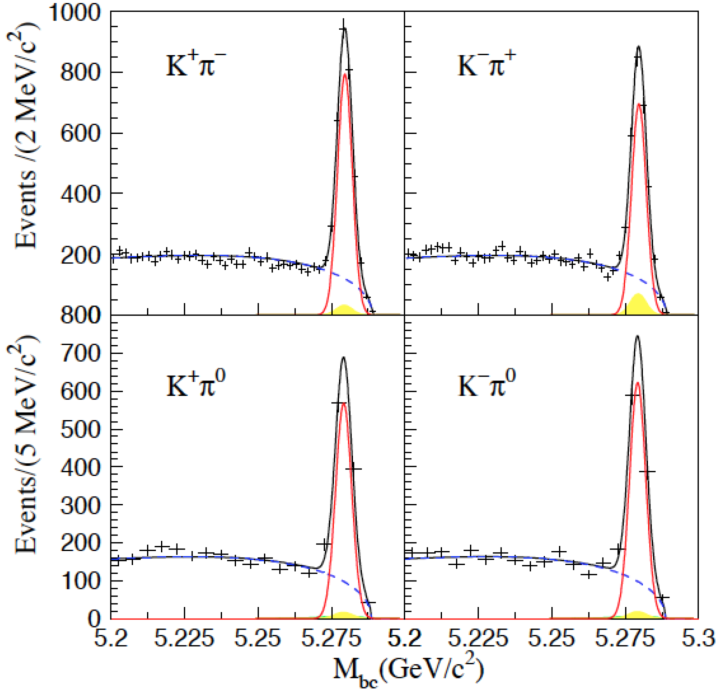


- Compute time integrated asymmetry

$$\mathcal{A}_{K^\pm\pi^\mp} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)}$$

$$A_{K^\pm\pi^\mp} = -0.069 \pm 0.014 \pm 0.007$$

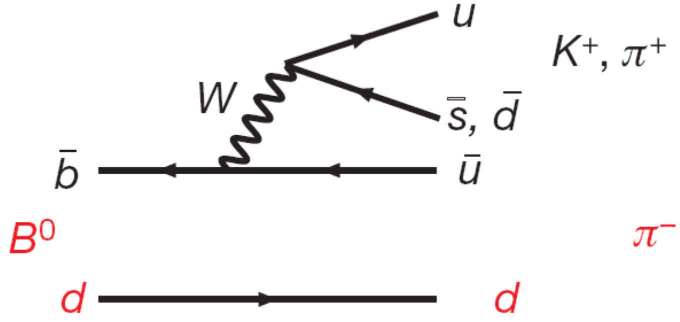
~7500 Kπ events reconstructed.

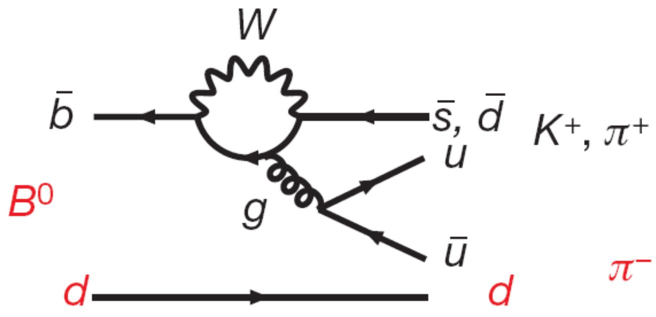


- Experimental results from Belle, BaBar, and CDF have significant weight in the world average of this CP violation parameter.
- Direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we can't use this to measure weak phases!

CP violation: Direct CP violation

- $B^0 \rightarrow K^{\pm}\pi^{\mp}$: Tree and gluonic penguin contributions





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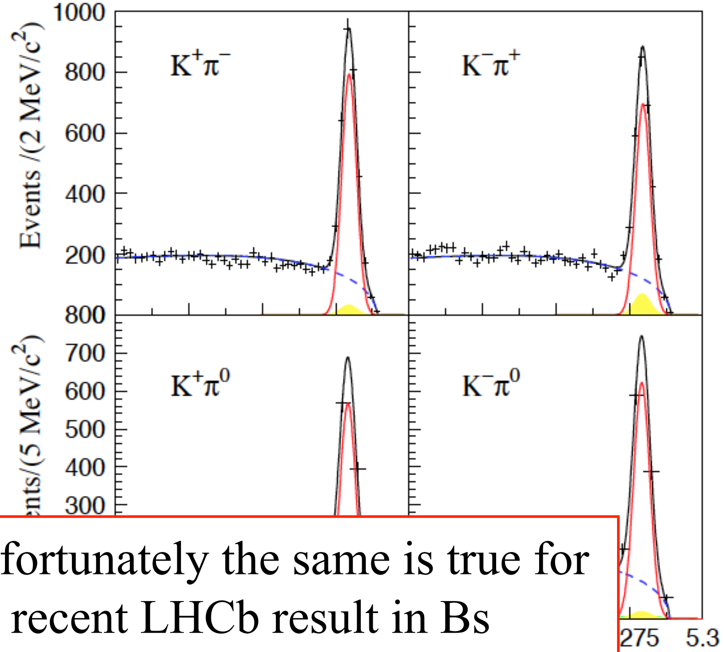
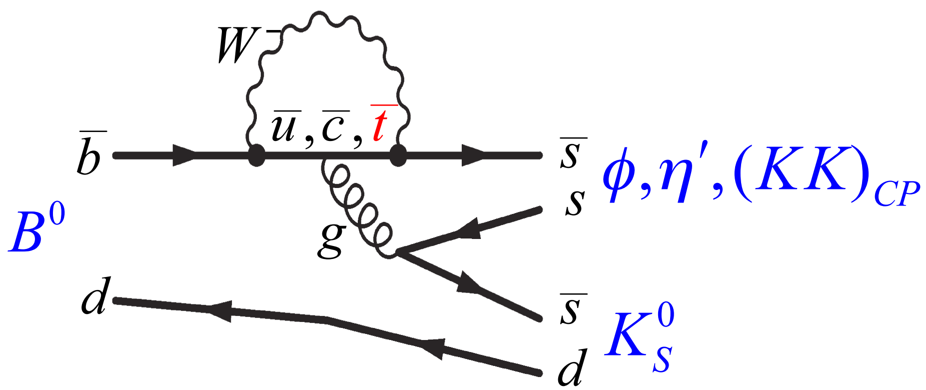


Unfortunately the same is true for the recent LHCb result in Bs decays to the same final state.

CP violation: Searching for new physics

- $\sin 2\beta$ has been measured to O(1°) accuracy in $b \to c\bar{c}s$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to $\sin 2\beta$ (loop dominated process).
  - Measure S precisely in that mode (S_{eff}).
  - Control the theoretical uncertainty on the Standard Model 'pollution' (ΔS_{SM}).
  - Compute $\Delta S = S_{meas} - S_{c\bar{c}s} - \delta S_{SM}$.
- In the presence of NP: $\Delta S_{NP} \neq 0$



- Many tests have been performed in:
  - B→d processes.
  - B→s processes.

• Unknown heavy particles can introduce new amplitudes that can affect physical observables of loop dominated processes.

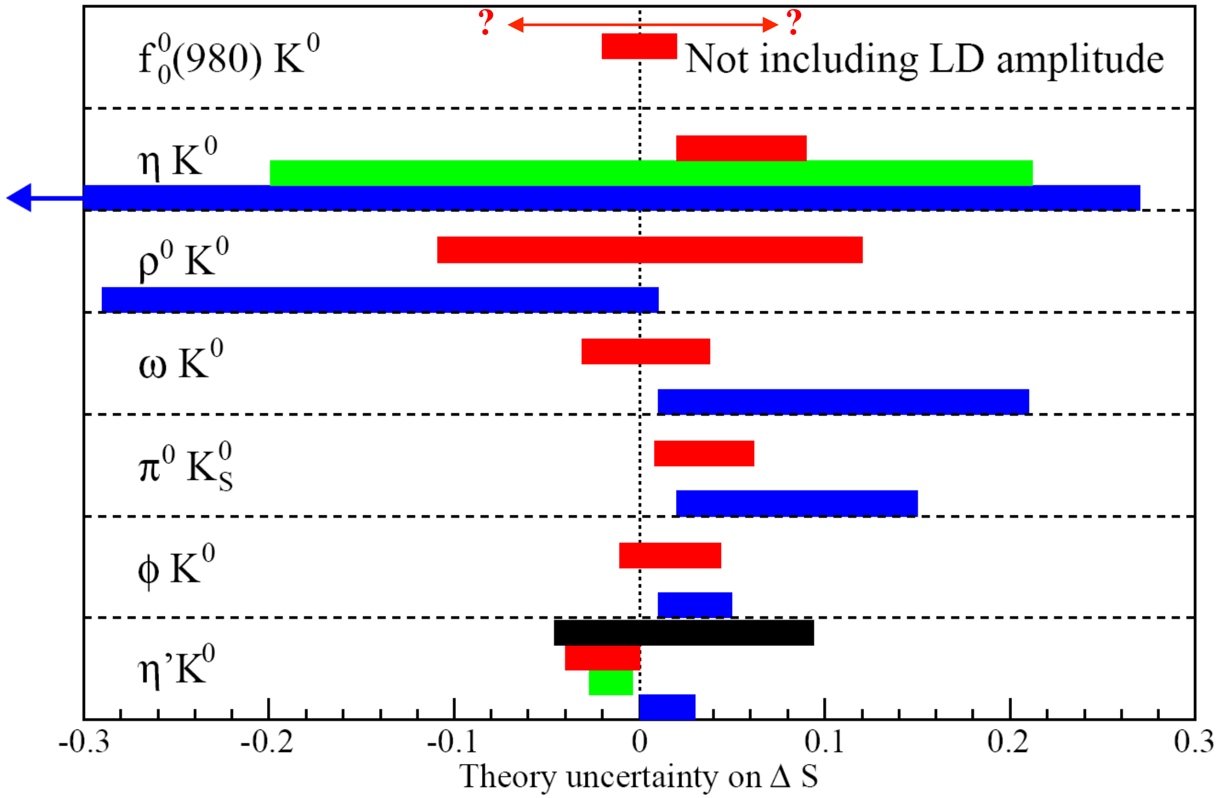
• Observables that might be affected include branching fractions, CP asymmetries, forward backward asymmetries … and so on.

• A successful search requires that we understand Standard Model contributions well!

SM uncertainties on ΔS

- To find NP we need to understand the SM contributions to a process.
  - Leading order term is expected to be the same as a SM weak phase.
  - Higher order terms including re-scattering, suppressed amplitudes, final state radiation and so on can modify our expectations.

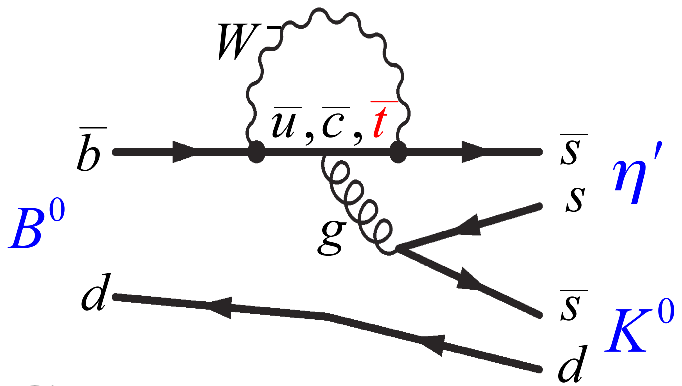
- Some channels are better understood than others.
- Sign of ΔS correction is mode dependent.
- Most precise ΔS correction is for $B^0 \to \eta' K^0$, where $\Delta S_{theory} \sim \pm 0.01$.
- Concentrate efforts on well understood channels.



QCDF Beneke, PLB**620**, 143 (2005)
SCET/QCDF, Williamson and Zupan, PRD**74**, 014003 (20
QCDF Cheng, Chua and Soni, PRD**72**, 014006 (2005)
SU(3) Gronau, Rosner and Zupan, PRD**74**, 093003 (2006)

$B \to \eta' K^0$

- Loop dominated b→s decay.



$$S = 0.59 \pm 0.07$$
$$C = 0.05 \pm 0.05$$

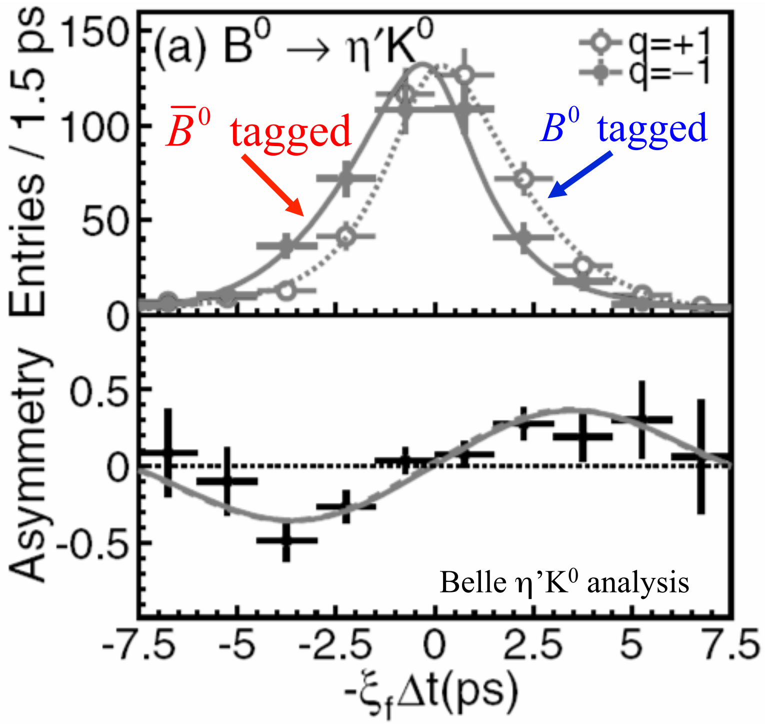
$$\Delta S = -0.077 \pm 0.075$$

- CP violation has been established in this decay channel by the B factories.
- Need at least 50 ab^{-1} of data to do a precision search for NP at the level of current theoretical uncertainties.

- Possible to measure S and C for both

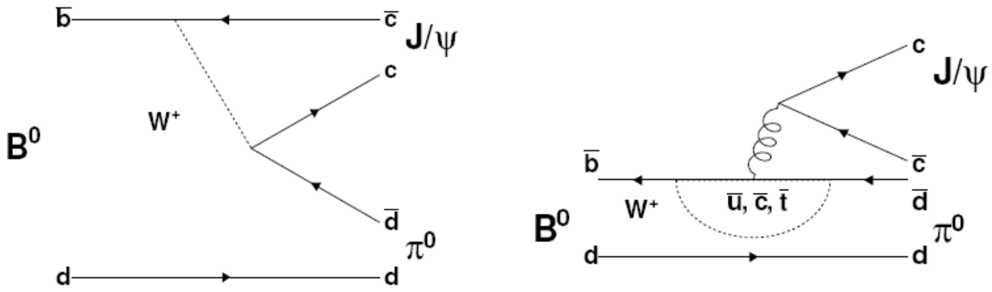
$$B^0 \to \eta' K^0_S \quad \text{(CP odd)}$$
$$B^0 \to \eta' K^0_L \quad \text{(CP even)}$$

- These asymmetries can be compared with the Charmonium reference measurement to calculate ΔS.



$B^0 \to J/\psi\pi^0$

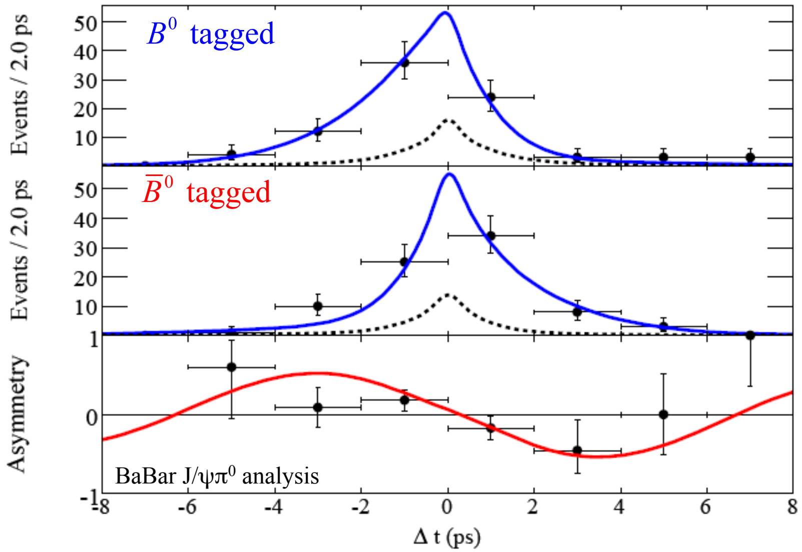
- Tree and penguin contributions: can be sensitive to NP.
- Alternatively, can be used to constrain SM uncertainties in the Charmonium β measurement.



- CP even final state:

$$S^{Tree}_{J/\psi\pi^0} = -S_{c\bar{c}s}$$

- CP violation observed in this decay.



$$S_{J/\psi\pi^0} = -0.93 \pm 0.15$$

$$C_{J/\psi\pi^0} = -0.10 \pm 0.13$$

$$\Delta S_{J/\psi\pi^0} = 0.23 \pm 0.15_{exp}$$

- Require a dataset of ~220ab^{-1} to make a 1% ΔS measurement in this channel.

Overview of ΔS measurements

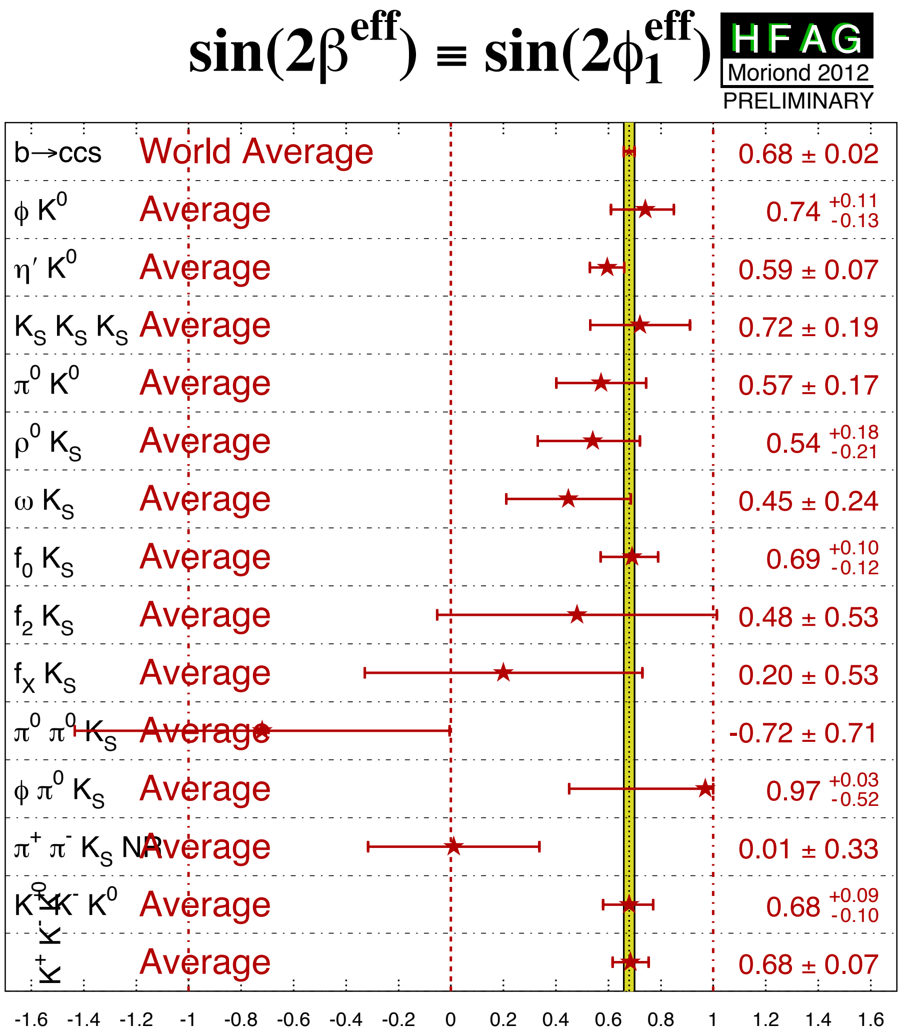
- Comparing sin2β in different physical processes, we see good agreement with the b→ccs reference point.

- Most of the b→s penguin channels have $\sin2\beta_{eff} < \sin2\beta$.
  - Could this be an indication of NP?
    - Insufficient statistics to tell.
  - Need to perform a mode-by-mode precision measurement in order to properly decouple Standard Model uncertainties from possible signals of NP.

- We need at least $50ab^{-1}$ to start performing measurements that will have comparable experimental and theoretical uncertainties in b→s penguin processes.

- Need ~$220ab^{-1}$ to do the same for b→d.

- Can start to do the same with α and γ once we have a precision measurement from one mode.



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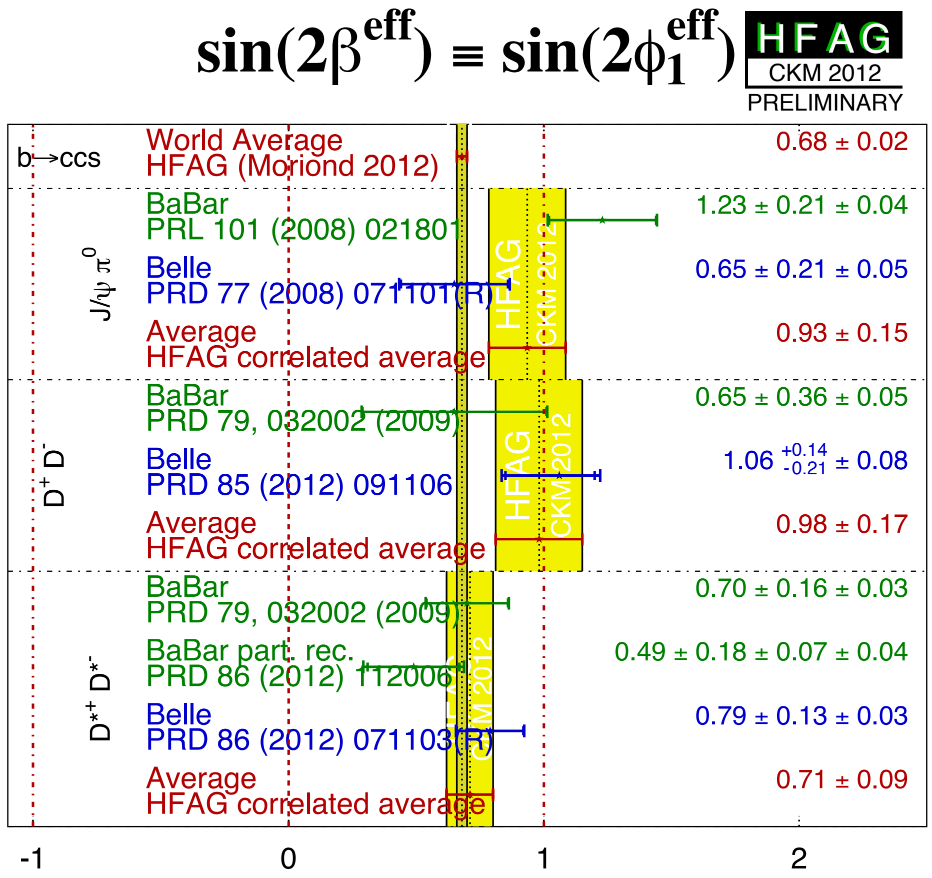


Sides of the Unitarity Triangle

This is a detailed and important topic, however unfortunately there is not time to discuss this in detail.

$b \to u l \nu$

$B \to \pi l \nu$

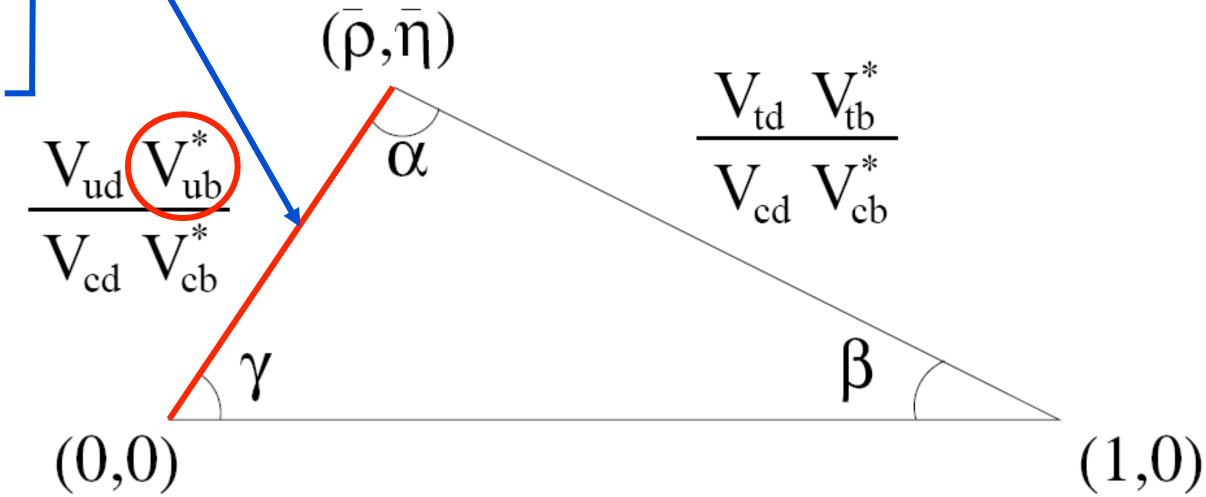
$B \to X_u l \nu$

$B \to \rho l \nu$

$B \to \omega l \nu$

⋮

- Use theory to relate partial branching fractions to V_{ub} for a given region of phase space.
- Several theoretical schemes available.



Sides of the Unitarity Triangle

This is a detailed and important topic, however unfortunately there is not time to discuss this in detail.

- Use theory to relate partial branching fractions to V_{cb} for a given region of phase space.

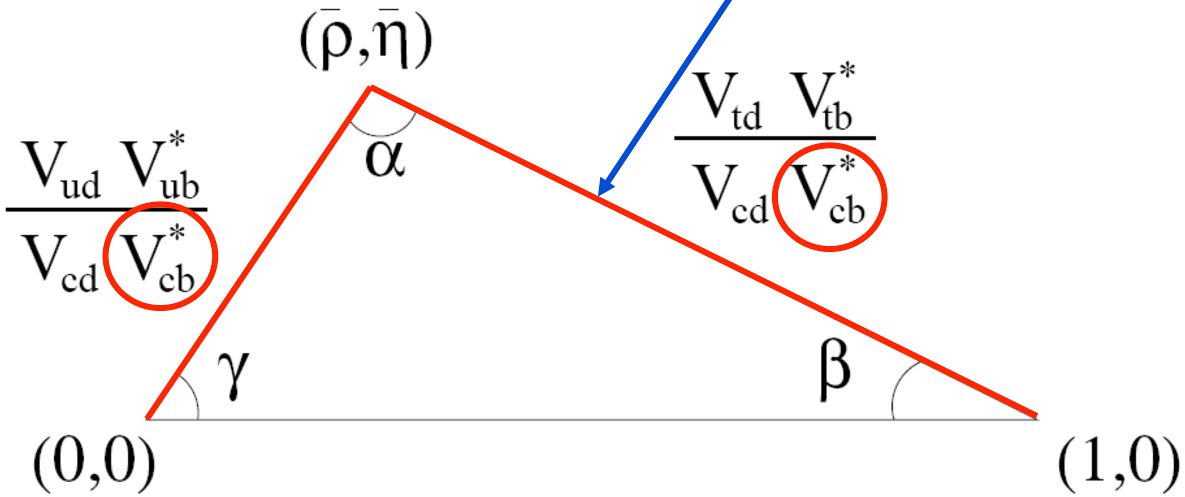
$b \to c l \nu$

$B \to D^{(*)} l \nu$

$B \to D X l \nu$

$B \to D^{**} l \nu$

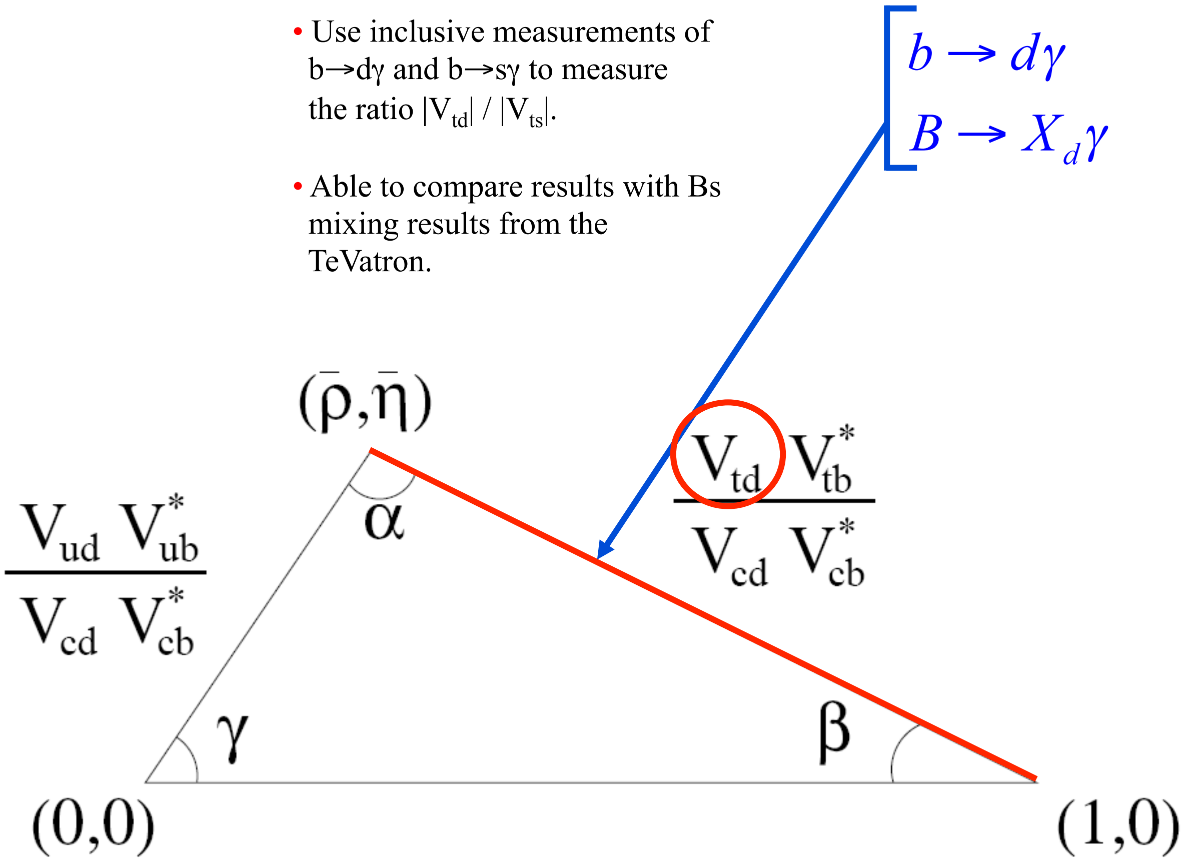
$\vdots$



Sides of the Unitarity Triangle

This is a detailed and important topic, however unfortunately there is not time to discuss this in detail.

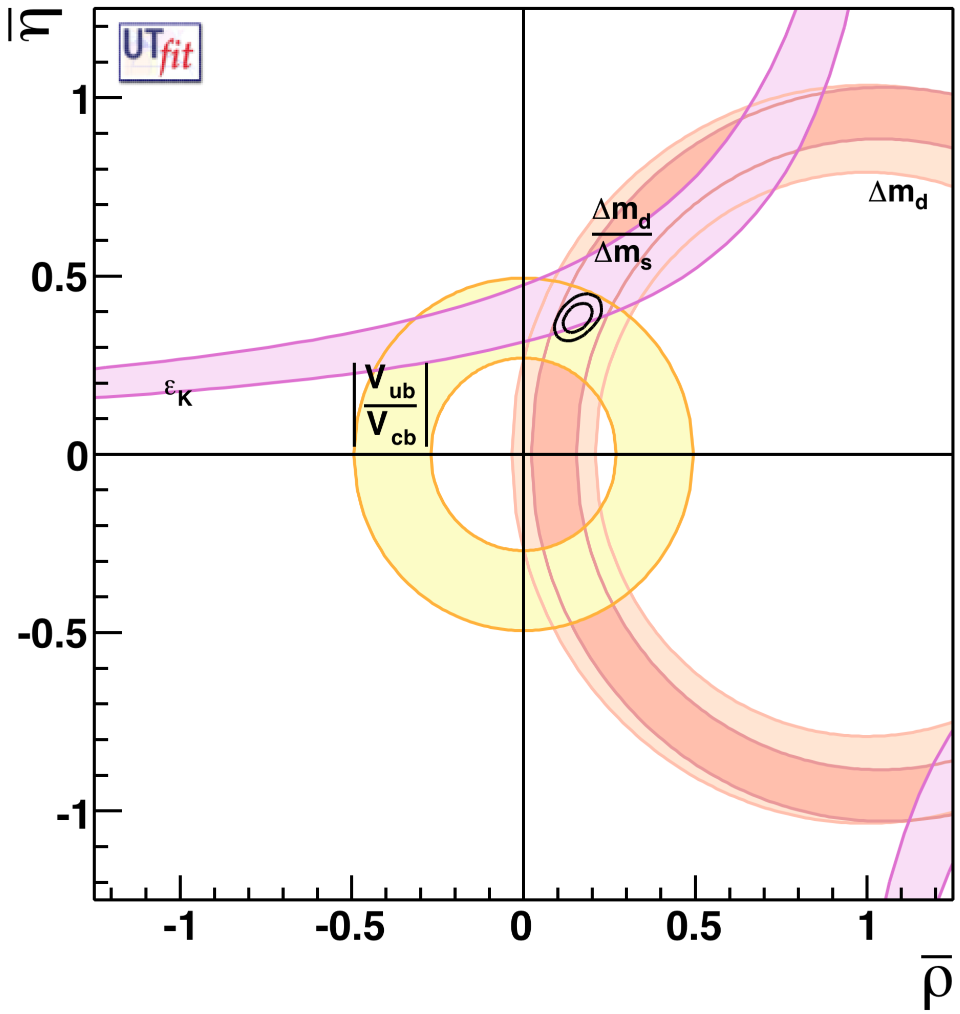
- Use inclusive measurements of b→dγ and b→sγ to measure the ratio $|V_{td}| / |V_{ts}|$.
- Able to compare results with Bs mixing results from the TeVatron.



(Also see Appendix II)

Sides of the Unitarity Triangle

- Annular constraints can be placed on the apex of the triangle

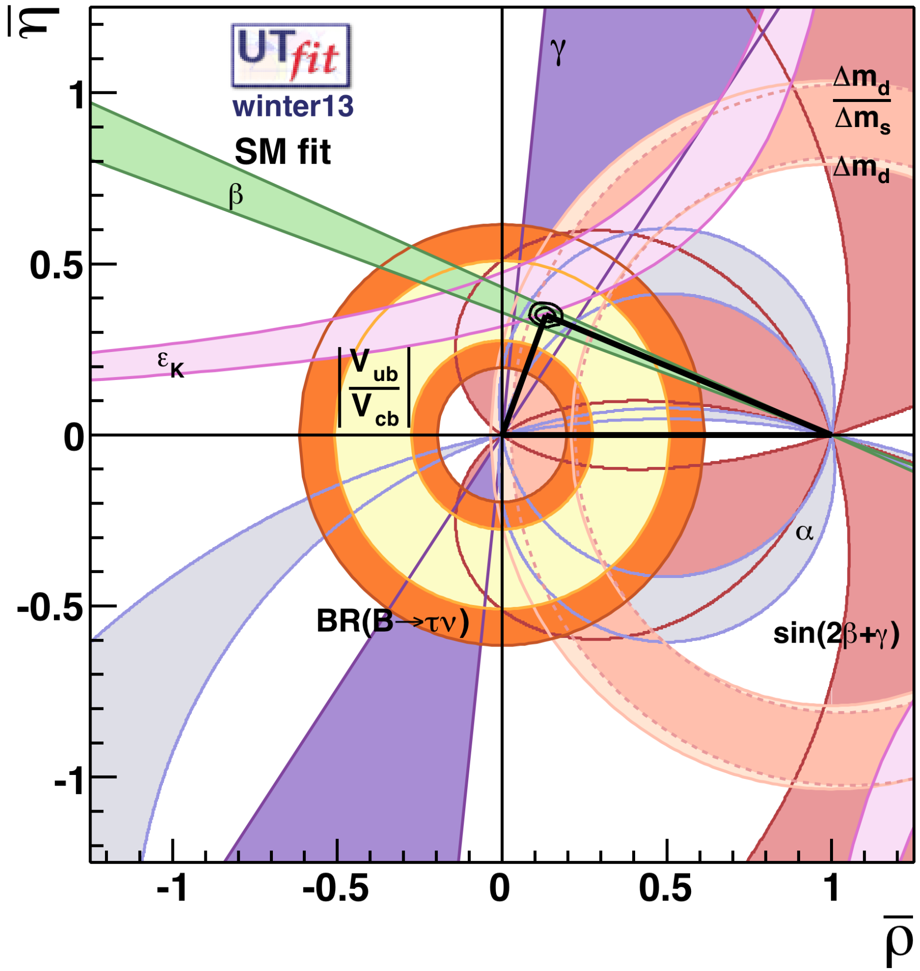


The results on V_{ub} and V_{cb} are compatible with mixing measurements, and CP violation in the kaon sector.

The big picture view

(Also see Appendix II)

- All constraints on the apex of the triangle are compatible.



$$A = 0.827 \pm 0.013$$
$$\lambda = 0.22535 \pm 0.00065$$
$$\rho = 0.136 \pm 0.021$$
$$\eta = 0.359 \pm 0.014$$

Similar results are obtained by other fitter collaborations.

See Appendix II for a brief introduction to how one can constrain a theoretical parameter using experimental observables.

Rare and forbidden B Decays

- These are probes for new physics.

- Different topologies can be used to constrain different features in the Lagrangian of different new physics models.

- In order to be sure that we understand any new physics found in the future, we should ensure that we perform a wide range of tests.
  - *Patterns of deviation from the standard model will tell us something about the detail of new physics, and help us go beyond saying that we have found something unexpected and we don't know what it is.*

  - *There are many interesting decays, I will just briefly mention B to $\tau\nu$, also see the appendix and the talk by Mary-Helene Schune.*

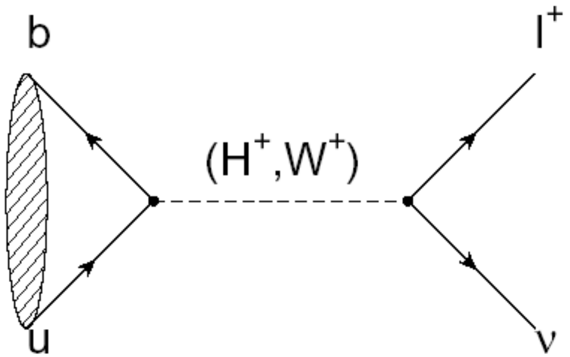
$B^{\pm} \to \tau^{\pm}\nu$

(Also see Appendix II)

- The decay $B^{\pm} \to \tau^{\pm}\nu$ has been measured, and can be compared with theoretical expectations.
- Measurement: $\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu) = (1.15 \pm 0.23) \times 10^{-4}$

- Standard Model expectation:

$$\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu)_{SM} = (1.01 \pm 0.29) \times 10^{-4}$$



In the Standard Model this channel is mediated by a W boson.

Beyond the Standard Model contributions from a charged Higgs particle can also be relevant.

$B^{\pm} \to \tau^{\pm}\nu$

(Also see Appendix II)

- The decay $B^{\pm} \to \tau^{\pm}\nu$ has been measured, and can be compared with theoretical expectations.
- Measurement: $\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu) = (1.15 \pm 0.23) \times 10^{-4}$
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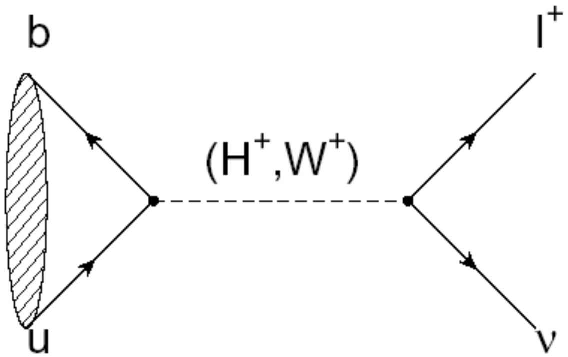
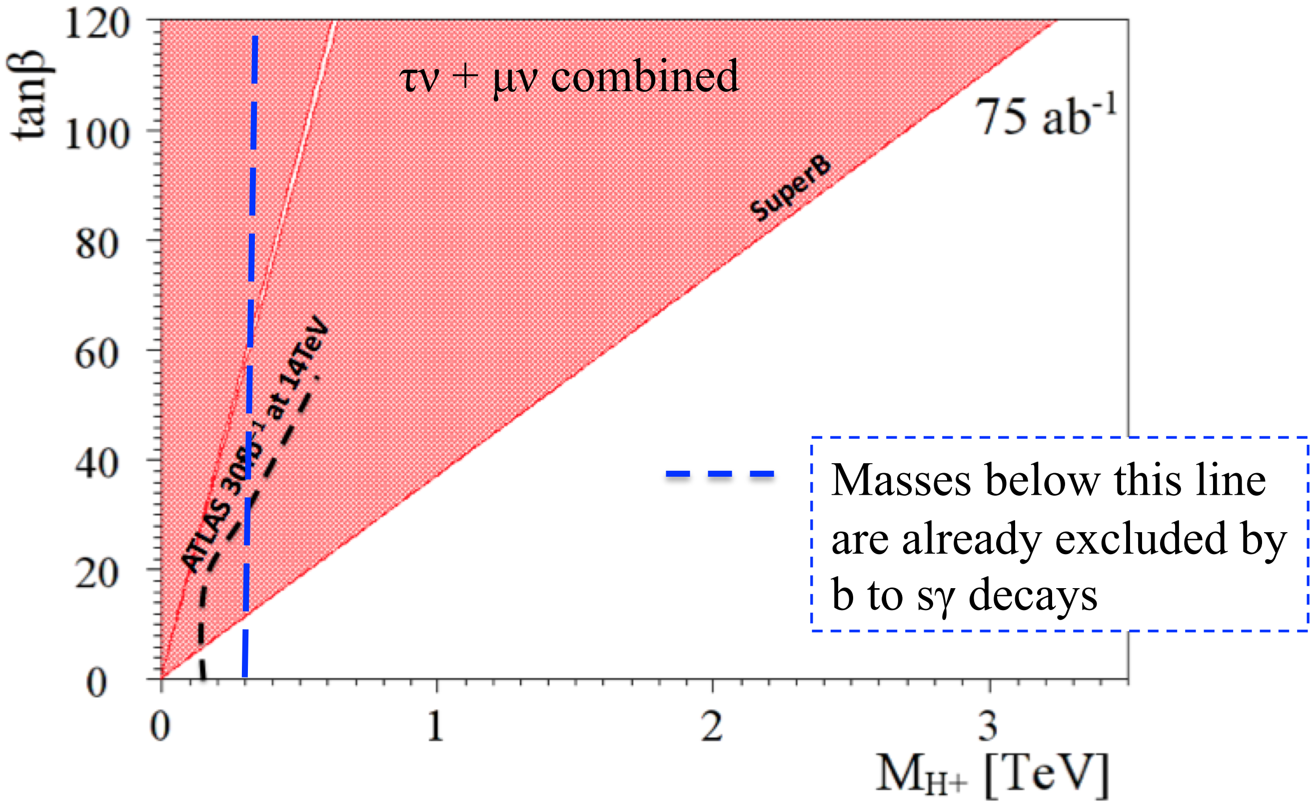


$$r_H = \frac{\mathcal{B}_{SM+NP}}{\mathcal{B}_{SM}}$$

For a simple extension of the Standard Model, called the type II 2 Higgs Doublet Model we know that r_H depends on the mass of a charged Higgs and another parameter, β.

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

- Looking forward one can estimate the kind of constraint on this model that can be made at Belle II.
  - Assume a measurement compatible with the SM.
  - The constraint for $50ab^{-1}$ is similar to that shown below.



Physics: Quarks

D MESONS

The quest for charm mixing

- Mixing is slow in charm: so instead of Δm and ΔΓ, we (usually) describe charm mixing with the parameters x and y, and Taylor expand the usual time-dependent formalism to obtain simplifications relevant for charm.

$$x = \frac{\Delta \mathrm{m}}{\Gamma} \qquad\qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

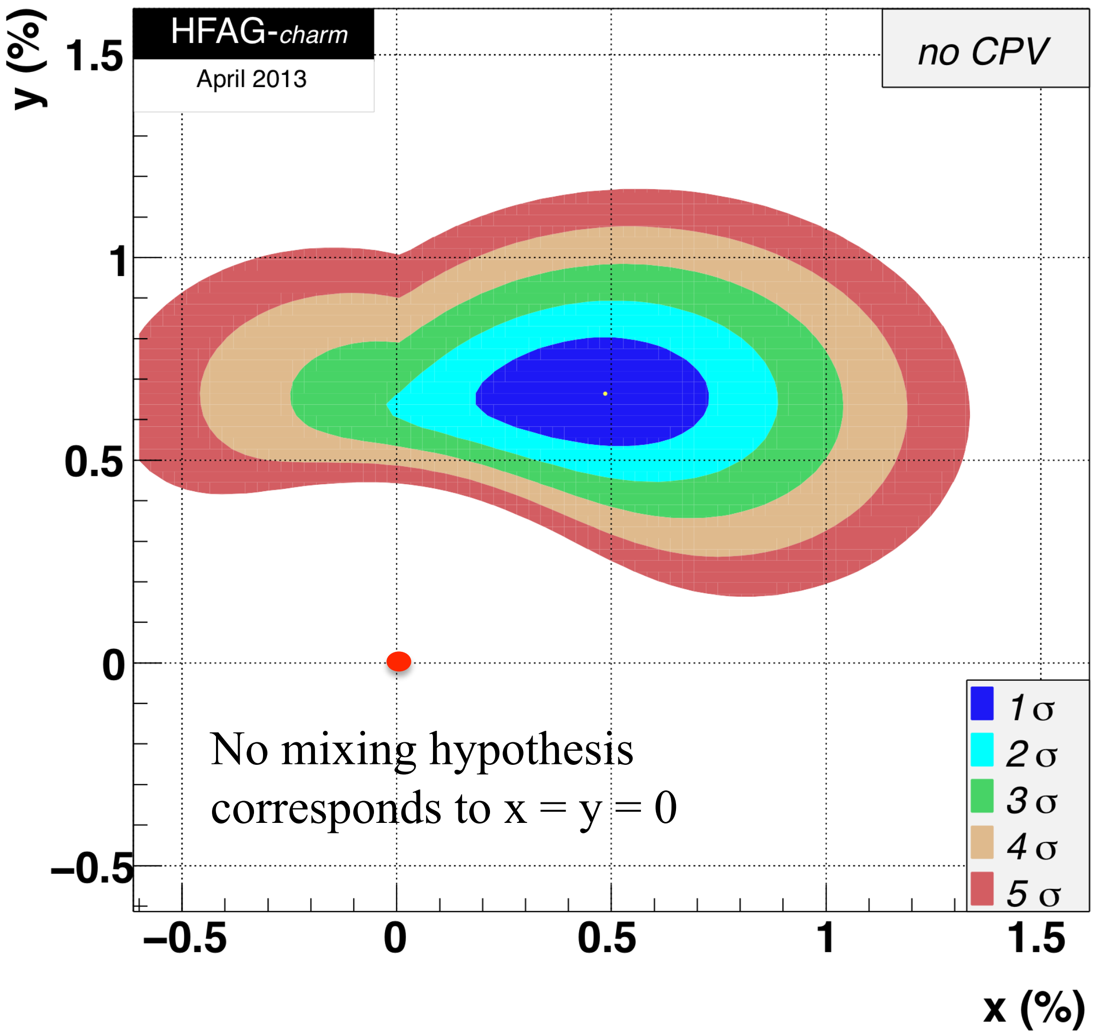
- Different final states can be used to explore mixing, often we study modes which have a strong phase difference that is important in the extraction of mixing parameters. These result in primed variables: x', y' that need to be extracted.

- N.B. While it is clear that the current formalism is good enough, one can expect that future measurements will eventually have sufficient statistics to require a more robust parameterisation.

- BaBar saw oscillations of charm mesons
- The combined BaBar, Belle, CLEO and the Tevatron combined were sufficient to establish charm mixing at the level of 5 sigma, but these results have recently been surpassed by an LHCb result that is the most significant observation of mixing in charm.

Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.49^{+0.17}_{-0.18}$	0.46 ± 0.18	$0.49^{+0.17}_{-0.18}$	[0.10, 0.81]
y (%)	0.66 ± 0.09	0.67 ± 0.09	0.74 ± 0.09	[0.56, 0.92]
δ (°)	$10.8^{+10.3}_{-12.3}$	$11.4^{+10.5}_{-12.7}$	$19.5^{+8.6}_{-11.1}$	[−9.6, 35.4]
R_D (%)	0.347 ± 0.006	0.347 ± 0.006	$0.350^{+0.007}_{-0.006}$	[0.337, 0.362]
A_D (%)	–	–	-2.6 ± 2.2	[−6.9, 1.7]
$\lvert q/p \rvert$	–	$1.04^{+0.07}_{-0.06}$	$0.69^{+0.17}_{-0.14}$	[0.44, 1.07]
ϕ (°)	–	$-1.6^{+2.4}_{-2.5}$	$-29.6^{+8.9}_{-7.5}$	[−44.6, −7.5]
$\delta_{K\pi\pi}$ (°)	$21.3^{+23.4}_{-23.8}$	$22.9^{+23.7}_{-24.0}$	$25.1^{+22.3}_{-23.0}$	[−20.6, 69.2]
A_π	–	–	0.16 ± 0.21	[−0.25, 0.57]
A_K	–	–	-0.16 ± 0.20	[−0.56, 0.23]
x_{12} (%)	–	0.46 ± 0.18	–	[0.10, 0.80]
y_{12} (%)	–	0.67 ± 0.09	–	[0.50, 0.85]
ϕ_{12}(°)	–	$4.8^{+9.2}_{-7.4}$	–	[−11.7, 35.9]

Current HFAG results (as of end April 2013)



Mixing in charm is interesting because:

(i) One can have CP violation in mixing.

(ii) One can explore CP violation in the interference between mixing and decay amplitudes.

(iii) There are a number of mixing and CP violation observables that could be affected by physics beyond the standard model.

CP Violation in charm

- The next generation of experiments will yield sufficient statistics to start to constrain time-dependent CP asymmetry parameters in the charm sector.
  - Data samples will be insufficient to measure a non-zero SM effect, but one can perform null tests.
  - Time-dependent measurements result in constraints on Imλ related to the KM phase in the CKM matrix.
  - Hadronic uncertainties will need to be understood.
  - This is an interesting area that is expected to develop in the coming decade.

Many authors have written on this topic in the last few years including AB et al.; Kagan et al. & Zupan et al.; Silvestrini et al; Bigi et al. A lot of the recent focus has been on time-integrated measurements, which in the short term showed promise.

A large number of probes available

- More generally there is a large number of charm decays to study CP violation in.
  - Direct CP violation is a good starting point, but hadronic uncertainties limit what can be learned from such measurements.
  - Time-dependent asymmetries are more interesting as we can constraint the weak phases in the SM.

$D^0 \to K^+K^-$
$D^0 \to K^0_S K^0_S$
$D^0 \to \pi^+\pi^-$
$D^0 \to \pi^0\pi^0$
$D^0 \to \rho^+\rho^-$
$D^0 \to \rho^0\rho^0$
$D^0 \to \phi\pi^0$
$D^0 \to \phi\rho^0$
$D^0 \to f^0(980)\pi^0$
$D^0 \to \rho^0\pi^0$
$D^0 \to a^0\pi^0$
$D^0 \to K^0_S K^0_S K^0_S$
$D^0 \to K^0_L K^0_S K^0_S$
$D^0 \to K^0_L K^0_L K^0_S$
$D^0 \to K^0_L K^0_L K^0_L$

$D^0 \to K^0_S\pi^0$
$D^0 \to K^0_S\omega$
$D^0 \to K^0_S\eta$
$D^0 \to K^0_S\eta'$
$D^0 \to K^0_S\pi^+\pi^-$ (NR)
$D^0 \to K^0_S\rho^0$
$D^0 \to K^0_S K^+K^-$ (NR)
$D^0 \to K^0_S\phi$
$D^0 \to K^0_S f^0$
$D^0 \to K^0_S a^0$

$D^0 \to K^0_L\pi^0$
$D^0 \to K^0_L\omega$
$D^0 \to K^0_L\eta$
$D^0 \to K^0_L\eta'$
$D^0 \to K^0_L\pi^+\pi^-$ (NR)
$D^0 \to K^0_L\rho^0$
$D^0 \to K^0_L K^+K^-$ (NR)
$D^0 \to K^0_L\phi$
$D^0 \to K^0_L f^0$
$D^0 \to K^0_L a^0$

AB, Inguglia, Meadows, PRD **84** 114009 (2011)

BaBar, Belle (II) and the LHC can study CPV via incoherent production.

An asymmetric τ-charm machine would have the benefit of a well defined initial state and high tagging Q.

Ultimately this will be a game of precision.
= systematic control

Physics: Leptons

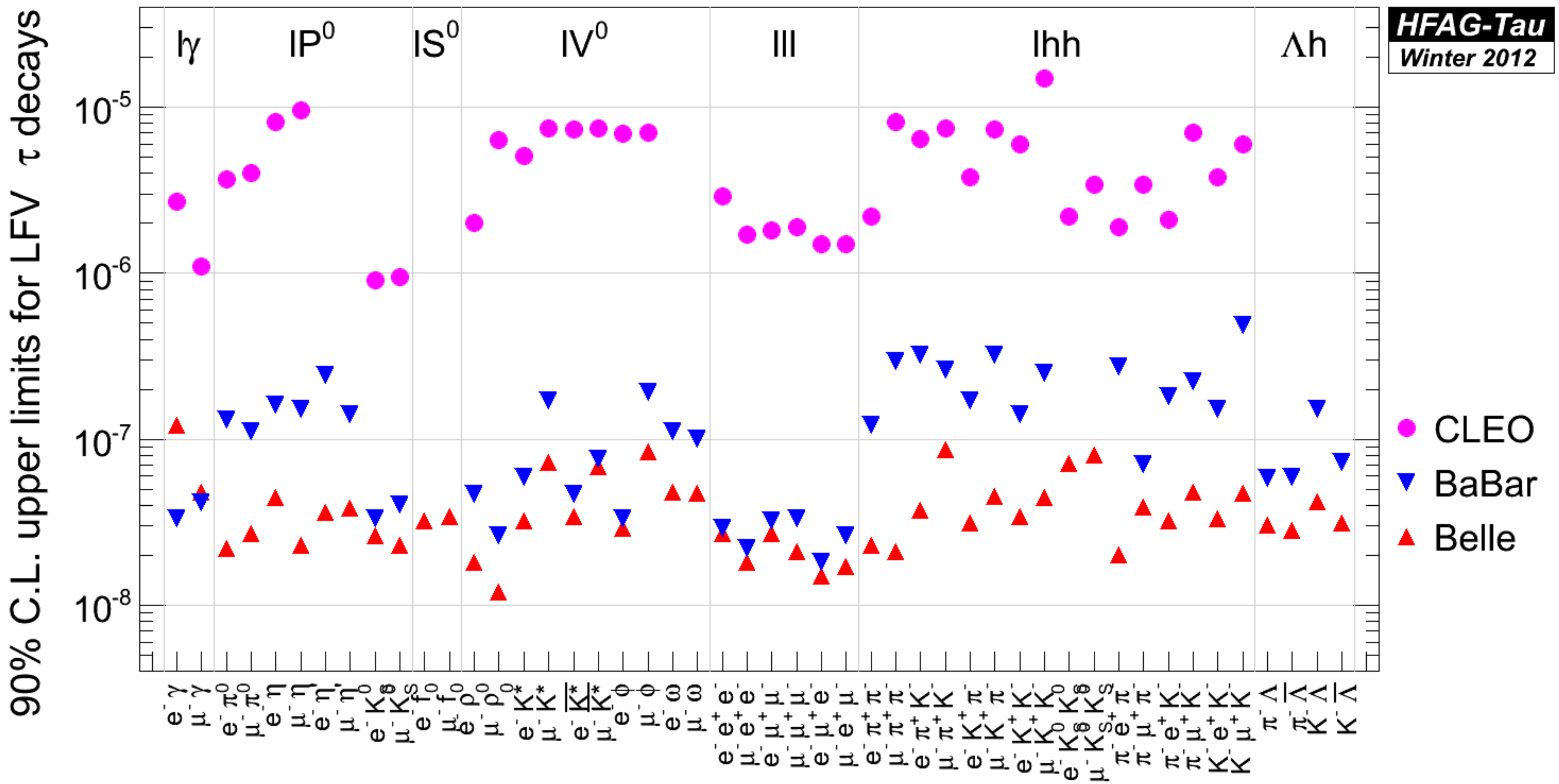
SEE THE LECTURES ON TAU PHYSICS BY J. PORTOLÉS, AND ON LEPTON FLAVOUR VIOLATION BY M. HIRSCH.

- The SM naturally has a low intrinsic level of charged lepton flavour violation (LFV) as a result of neutrino oscillations.
  - Such an effect would be un-observable with current or planned experiments.

$$\mathcal{B}_{SM}(\tau \to \mu\gamma) \simeq 10^{-54}$$

  - Many new physics scenarios include charged LVF couplings, which are able to enhance the expected level of many branching ratios up to the current experimental limits.
  - Experimentally a large number of potential channels remain background free, and improved sensitivity will scale by 1/N, whereas some modes have backgrounds and the scaling will be with the square root of increase in statistics from present day results.

- Current constraints on charged LFV decays from the B Factories:

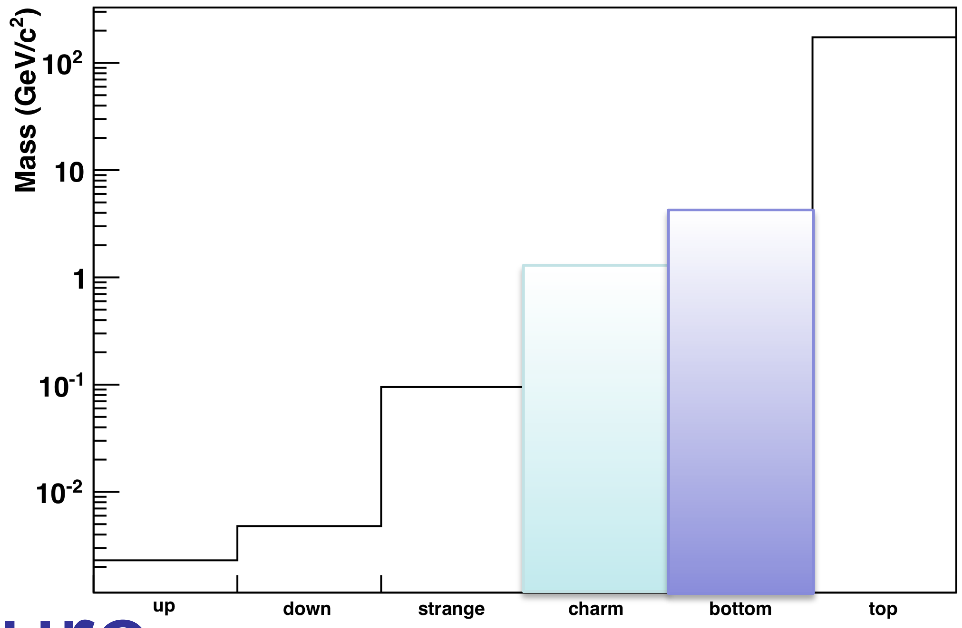


- The next generation of B Factories will allow for 1-2 order of magnitude improvements on these limits. for example:

  - Some decays such as $\tau \to \mu\gamma$ at the Υ(4S) scale with increase in statistics, as there is an irreducible physics background.

  - Some decays such as $\tau \to \mu\mu\mu$ scale with statistics as these are expected to be background free up to data samples of at least 75-100ab^{-1}.

  - A high-luminosity τ-charm experiment operating just above charm threshold, ψ(3770), would enable a background free measurement of $\tau \to \mu\gamma$.



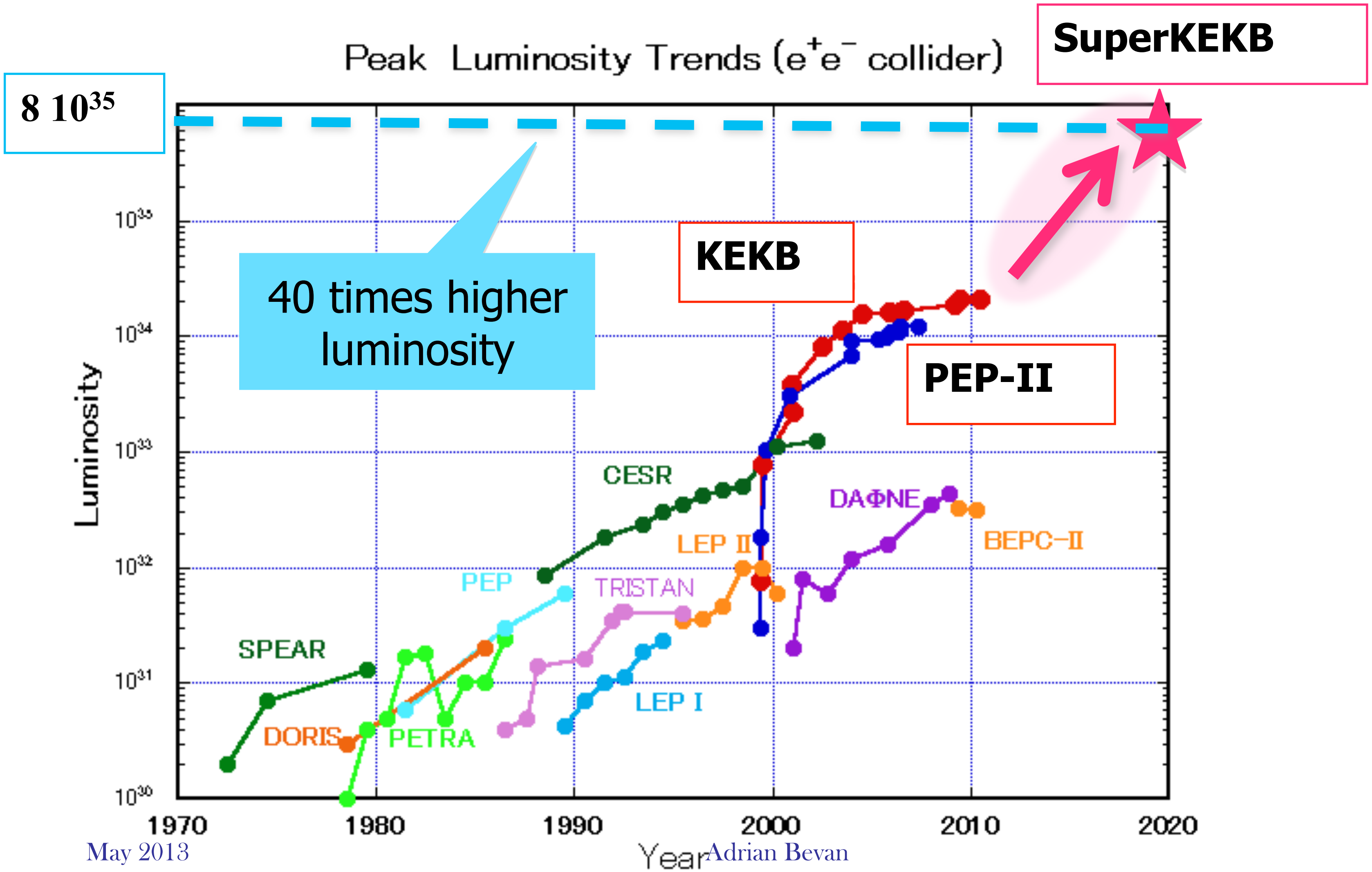
The (near) Future

The future of flavor physics will (in the long term) include precision top physics, studying billions of top quarks collected in hadronic and e^+e^- environments. Until that time, we must be content with studying the heaviest accessible up and down type quarks to learn about the subtleties of their interactions, and laying the groundwork required for precision top physics.

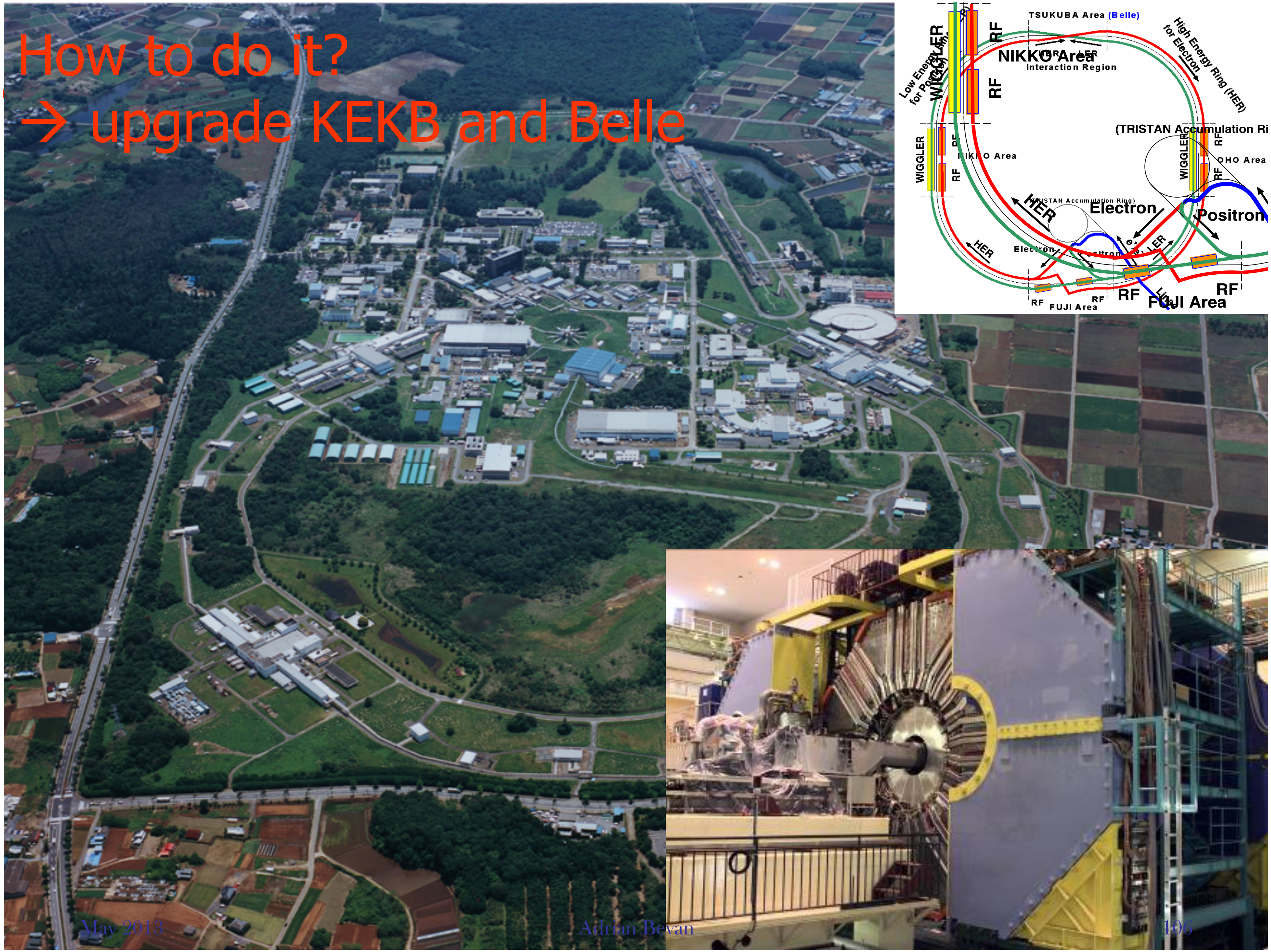
BELLE II AND SUPER KEKB

Thanks to Peter Krizan for up to date slides on the Belle II project.

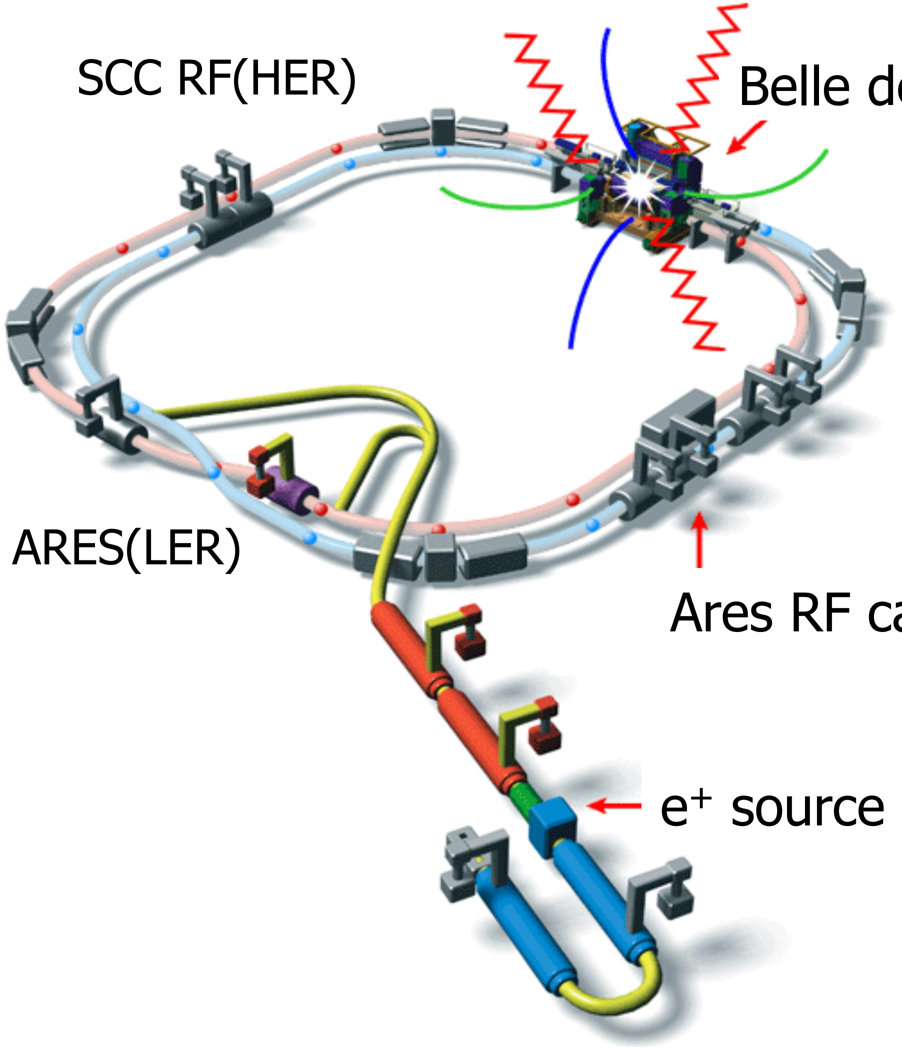
Need 50x more data →Next generation B-Factories



How to do it?
→ upgrade KEKB and Belle



The KEKB Collider & Belle Detector



- e^- (8 GeV) on e^+(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma$=0.425
- 22 mrad crossing angle
- Operating since 1999

Peak luminosity (WR!) :

2. 1 x 10^{34} $cm^{-2}s^{-1}$

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s
L > $1ab^{-1}$

Strategies for increasing luminosity

Lorentz factor

Beam current

Beam-beam parameter

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 - 1
(short bunch)

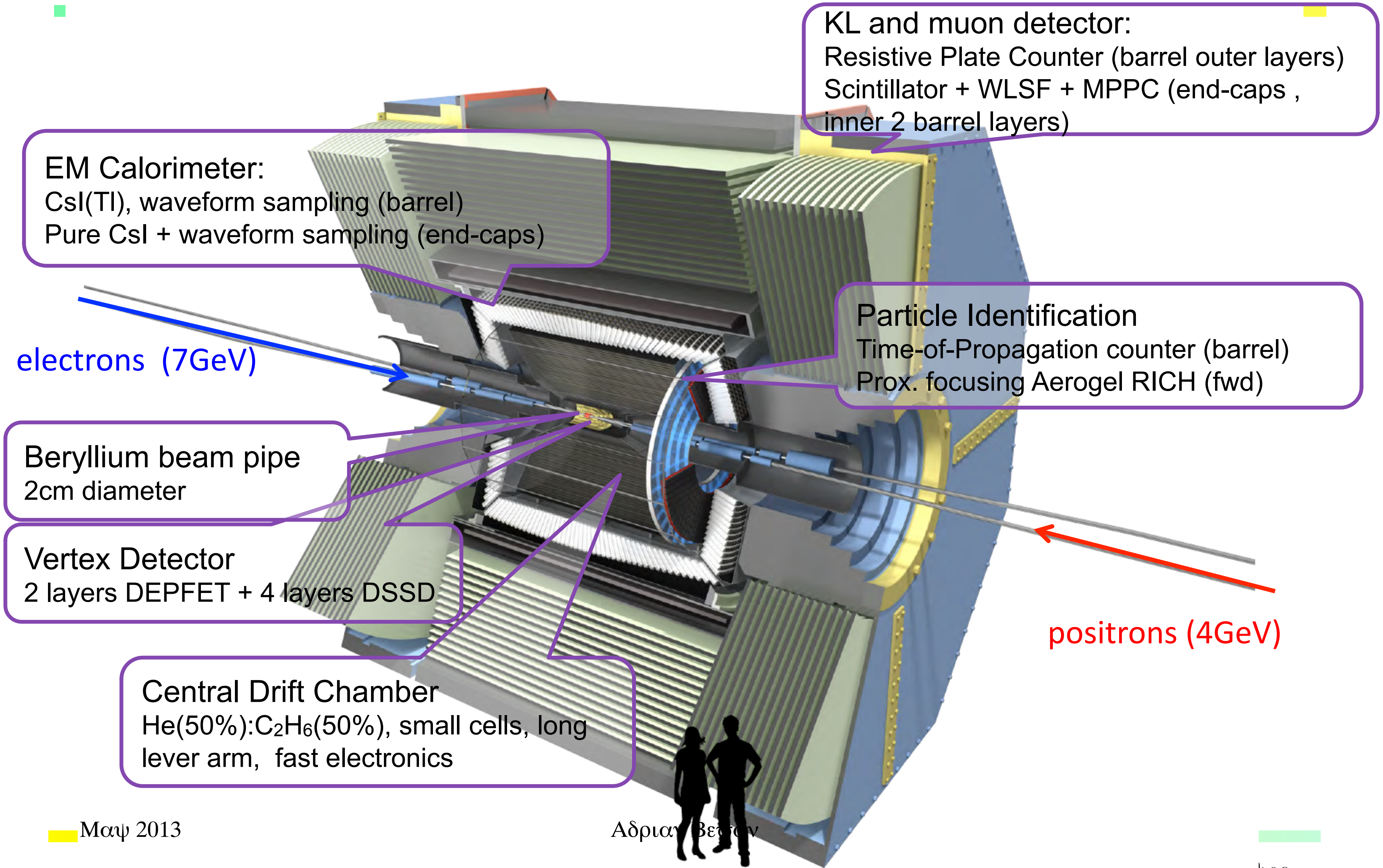
(1) Smaller b_y^*
(2) Increase beam currents
(3) Increase x_y

"Nano-Beam" scheme

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

Belle II Detector

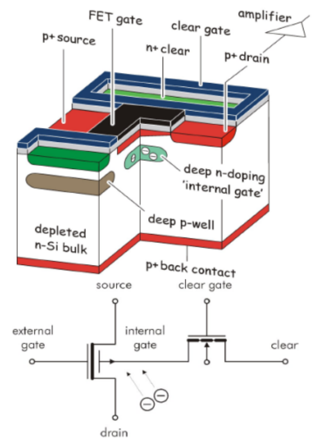


Vertex Detector

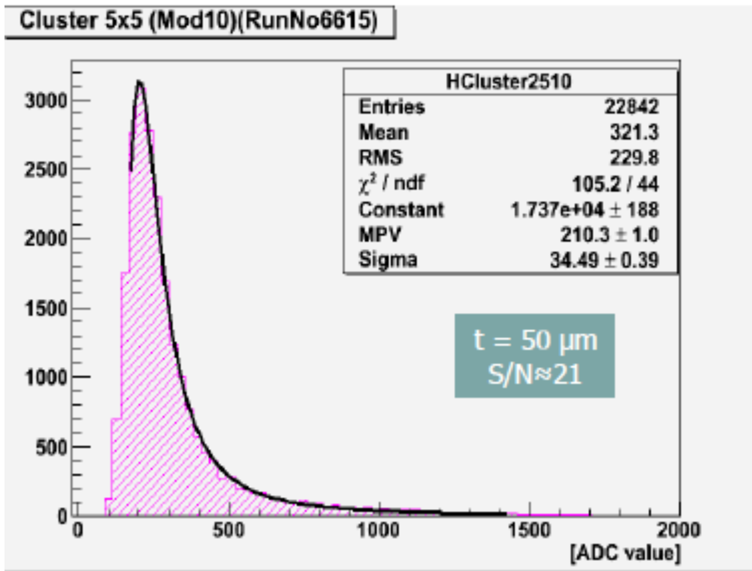
DEPFET:
http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

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

DEpleted P-channel FET



Mechanical mockup of pixel detector



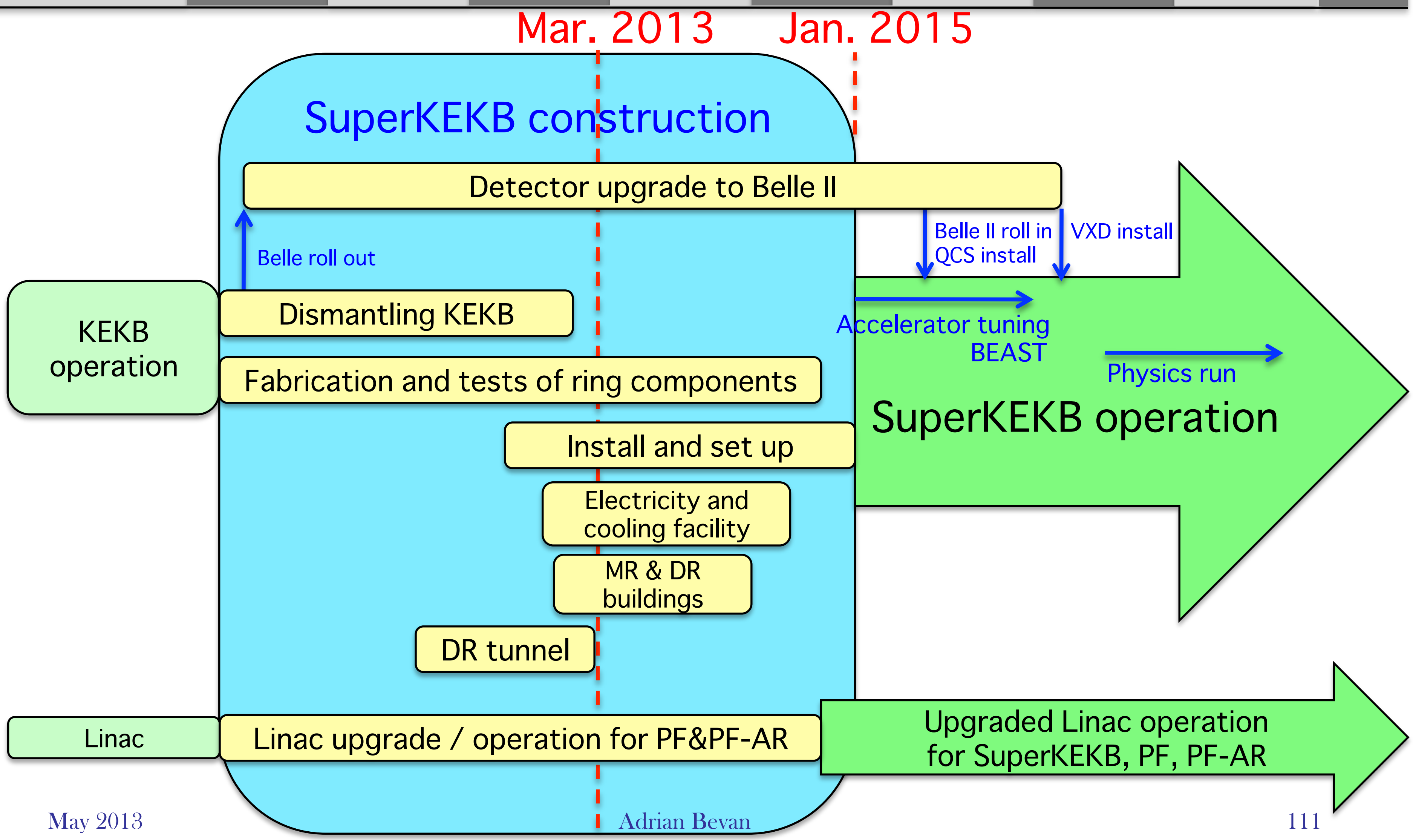
DEPFET pixel sensor

DEPFET sensor: very good S/N

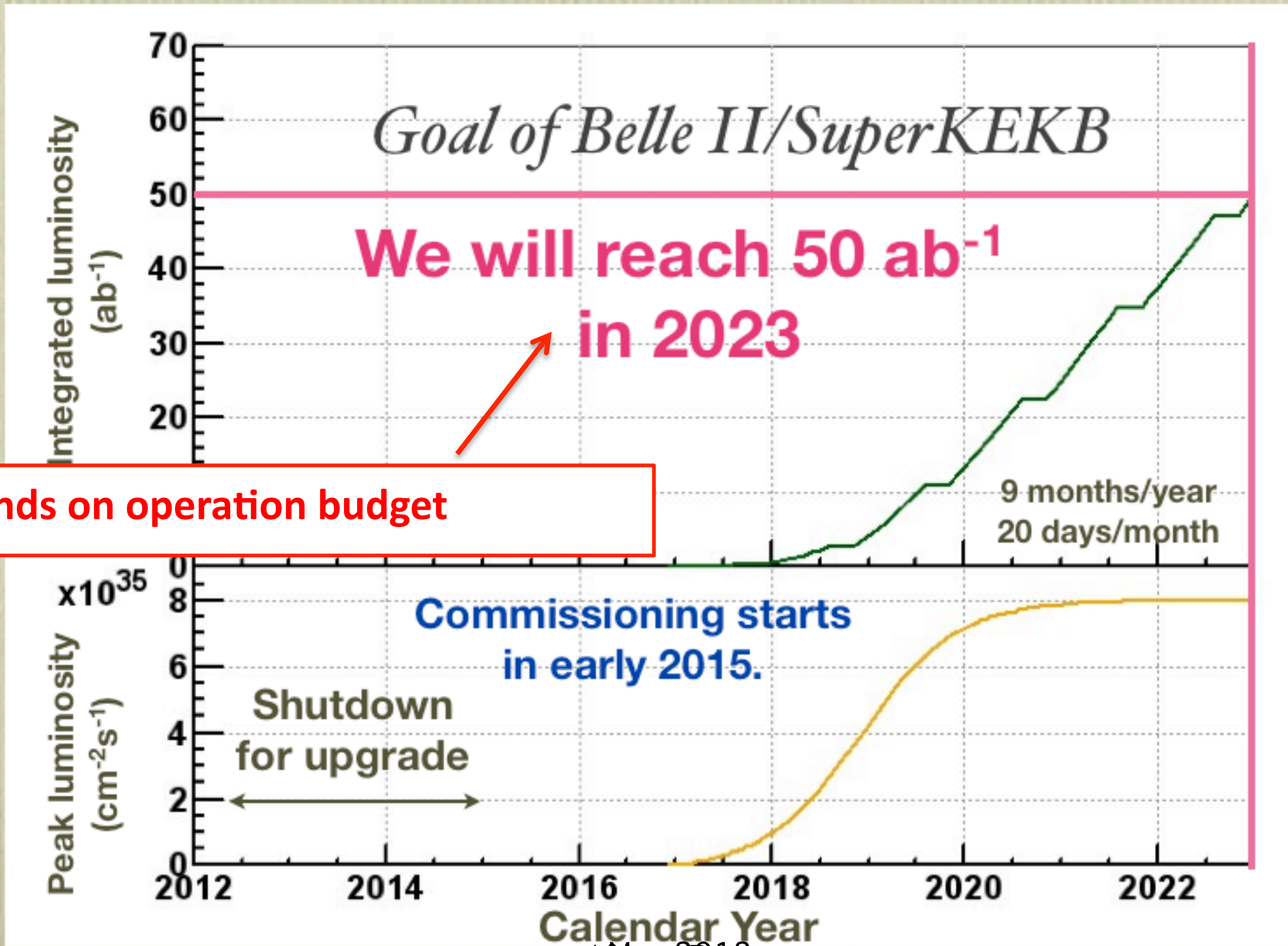
Peter Križan, Ljubljana

SuperKEKB/Belle II schedule

Calendar	2010	2011	2012	2013	2014	2015	2016	2017	···
Japan FY	2010	2011	2012	2013	2014	2015	2016	2017	··



SuperKEKB luminosity projection



Depends on operation budget

Physics overview

- Belle II will be able to perform many precision tests, the following are estimates of the sensitivities of key CKM related observables:

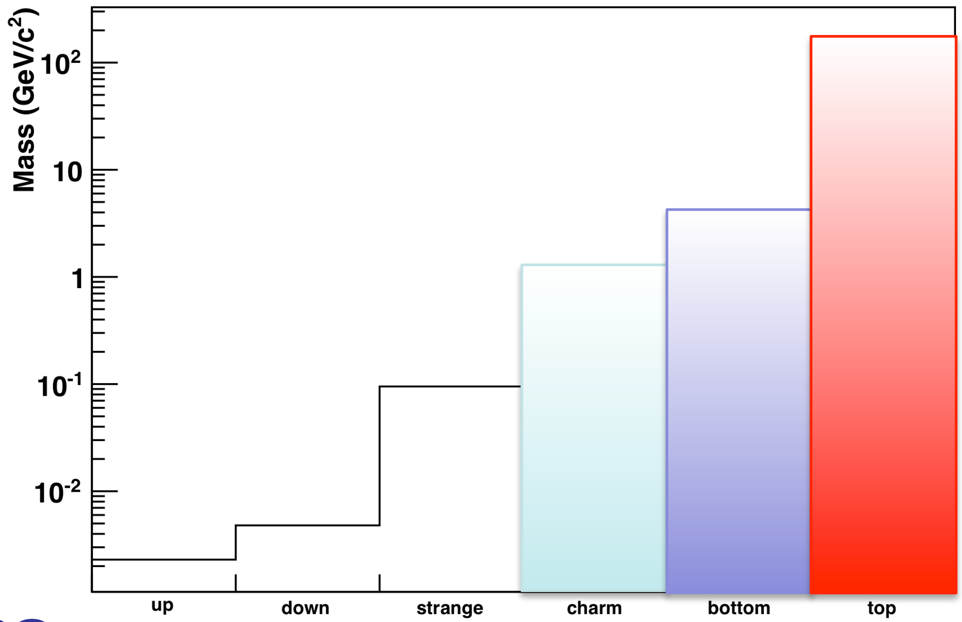
Observable/mode	Current now	Belle II (2023)	theory now
		$50\,\mathrm{ab}^{-1}$	
α from $u\bar{u}d$	6.1°	1°	$1-2^\circ$
β from $c\bar{c}s$ (S)	0.8° (0.020)	0.3° (0.007)	clean
S from $B_d \to J/\psi\pi^0$	0.21	0.021 (est.)	clean
γ from $B \to DK$	11°	1.5°	clean
$\lvert V_{cb}\rvert$ (inclusive) %	1.7	0.6 (est.)	dominant
$\lvert V_{cb}\rvert$ (exclusive) %	2.2	1.2 (est.)	dominant
$\lvert V_{ub}\rvert$ (inclusive) %	4.4	3.0	dominant
$\lvert V_{ub}\rvert$ (exclusive) %	7.0	5.0	dominant

- These results will enable a precision over-constraint of the CKM mechanism early next decade.

Physics overview

- Belle II will be able to perform many precision tests, the following are estimates of the sensitivities of key non-CKM related observables:

Observable/mode	Current B Factory now	Belle II (2023) $50\,\text{ab}^{-1}$	theory now
τ Decays			
$\tau \to \mu\gamma$ $(\times 10^{-9})$	< 44	< 5.0	
$\tau \to e\gamma$ $(\times 10^{-9})$	< 33	< 3.7 (est.)	
$\tau \to \ell\ell\ell$ $(\times 10^{-10})$	$< 150 - 270$	< 10	
$B_{u,d}$ Decays			
$\text{BR}(B \to \tau\nu)$ $(\times 10^{-4})$	1.64 ± 0.34	0.04	1.1 ± 0.2
$\text{BR}(B \to \mu\nu)$ $(\times 10^{-6})$	< 1.0	0.03	0.47 ± 0.08
$\text{BR}(B \to K^{*+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 80	2.0	6.8 ± 1.1
$\text{BR}(B \to K^{+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 160	1.6	3.6 ± 0.5
$\text{BR}(B \to X_s\gamma)$ $(\times 10^{-4})$	3.55 ± 0.26	0.13	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060	0.02	$\sim 10^{-6}$
$B \to K^*\mu^+\mu^-$ (events)	250^{a}	7-10k	-
$\text{BR}(B \to K^*\mu^+\mu^-)$ $(\times 10^{-6})$	1.15 ± 0.16	0.07	1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	7-10k	-
$\text{BR}(B \to K^*e^+e^-)$ $(\times 10^{-6})$	1.09 ± 0.17	0.07	1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14^{b}	0.03	-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280	7,000	-
$\text{BR}(B \to X_s\ell^+\ell^-)$ $(\times 10^{-6})^{c}$	3.66 ± 0.77^{d}	0.10	1.59 ± 0.11
S in $B \to K^0_S\pi^0\gamma$	-0.15 ± 0.20	0.03	-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07	0.02	± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.03	± 0.02
B^0_s Decays			
$\text{BR}(B^0_s \to \gamma\gamma)$ $(\times 10^{-6})$	< 8.7	$0.2 - 0.3$	0.4 - 1.0
A^s_{SL} $(\times 10^{-3})$	$-7.87 \pm 1.96\ ^{e}$	5. (est.)	0.02 ± 0.01
D Decays			
x	$(0.63 \pm 0.20\%$	0.04%	$\sim 10^{-2\ f}$
y	$(0.75 \pm 0.12)\%$	0.03%	$\sim 10^{-2}$ (see above).
y_{CP}	$(1.11 \pm 0.22)\%$	0.05%	$\sim 10^{-2}$ (see above).
$\lvert q/p \rvert$	$(0.91 \pm 0.17)\%$	3.0%	$\sim 10^{-3}$ (see above).
$\arg\{q/p\}$ $(^\circ)$	-10.2 ± 9.2	1.4	$\sim 10^{-3}$ (see above).



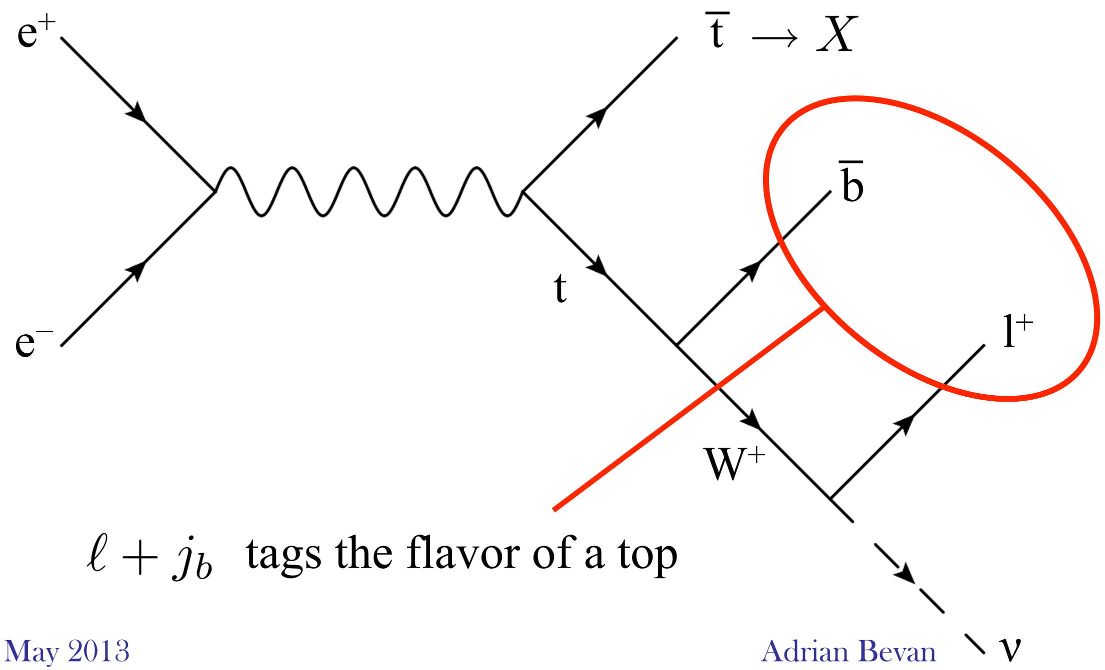
The (far) Future

The future of flavor physics will (in the long term) include precision top physics, studying billions of top quarks collected in hadronic and e^+e^- environments. Until that time, we must be content with studying the heaviest accessible up and down type quarks to learn about the subtleties of their interactions, and laying the groundwork required for precision top physics.

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

- A future linear collider operating at, or above top-pair production threshold has several advantages over the LHC for top physics:
  - Clean production environment
  - top-recoil reconstruction technique:
    - Reconstruct one top decay (e.g. $t \longrightarrow b\ell^{+}\nu$) and use the rest of the event to constrain the other top in the decay.



$\ell + j_b$ tags the flavor of a top

Use the charge of the lepton to tag the flavor of the tag top quark.

Infer the flavor of the *other* top.

No mixing to worry about, so flavor analysis of the *other* top decay is well defined. One needs to identify the state X, and accumulate many tops.

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

- Precision top physics is motivated by two goals:
  - Understanding the heaviest fermion known to us.
  - Using this as an interferometer to probe for new physics.
    - With large top-pair statistics, in the future one will be able to perform flavour measurements to complement results from kaon, B and D decays.
    - Results from the weak decay of strange quarks hinted at the existence of the c, b and t quarks. The top quark is the heaviest known particle, so precision top physics will play a role in understanding the behaviour of nature at higher scales, and extending our understanding of quark flavor.
    - If the LHC doesn't directly produce new heavy particles in pp collisions, perhaps studying top at a future linear collider will be the only way forward to learn a more complete theory of nature.

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

- Will there be a high energy e^+e^- collider? If so what will it be (i.e. what energy range etc.)?
- A CM energy at the $t\bar{t}$ production threshold will provide a clean sample of top quarks to study.
  - With sufficient statistics one can use rare processes to probe for new physics, test the CKM paradigm (unitarity of the CKM matrix etc).
  - Many similarities with the indirect tests being performed at the B Factories and motivating a high luminosity tau -charm factory.
  - However as top doesn't hadronize we can not use mixing to probe dynamics (i.e. there is no mixing as the top decays too quickly and doesn't form a bound meson).
  - Different effects will be important to probe CP violation, and low energy hadronic uncertainties will be replaced by jet fragmentation uncertainties.

Summary

Key Concepts

If you only pay attention to one slide – make sure it is this one.

- The following is true for rare decay searches for new physics AND CP violation:
  - Effects are maximal when amplitudes of similar magnitudes interfere.
  - You want to study experimentally well defined final states.
  - To interpret these one needs to have theoretical control of hadronic uncertainties.
  - A null, or non-null prediction from the standard model can be used to guide expectations.
    - Observed deviations from the standard model are model independent.
      - We don't have any significant guidance from experiment to drive developments in a particular direction.
    - In the absence of a *better idea*, we are left with testing benchmark models. The smallest set of benchmark models is that of the standard model itself.

- Flavour physics has taught us a lot about the fine detail of the Standard Model of particle physics.

- Two paradigms:
  - Study heaviest available quarks and leptons, to use rates and asymmetry observables search for new physics using benchmark models.
  - Place constraints on possible physics beyond the Standard Model via precision tests of SM observables.

- Some observables are able to test fundamental symmetries that may have deeper ramifications for our Universe: CP violation was discussed here, related T and CPT non-conservation tests are also important (see lectures at this school by J. Bernabeu).

- These results can't constrain the energy scale for new physics, but can constrain the ratio of coupling to scale.

- A number of discoveries have been made by the B Factories since 1999: highlights include:
  - CP violation in the interference between mixing and decay amplitudes (indirect CP violation) in B decays.
  - Direct CP violation (CP violation in decay) in B decays.
  - Discovery of new light particles: X(3872), Y(4260), D_{SJ}, etc.
  - Discovery of the ground state of the $b\bar{b}$ system: η_b
  - Evidence for charm mixing.
  - Observation of T-symmetry non-conservation in B decays.
- Conceptual advances include understanding that the CKM matrix provides the leading order description of CP violation in the Standard Model.
  - *This does not rule out possible new physics in CP violating observables.*

- Other notable advances:
  - Indirect constraints on new physics using B decays are (generally) model dependent.
  - The type-II 2HDM is the most recent scenario to be disfavoured at more than 3 σ.
  - Flavour constraints impose strong limits for model builders, in some cases going beyond the energy reach of the LHC.
  - If new physics is found at the LHC, then our experimental understanding of flavour has to come together with our theoretical understanding to explain why hints have not been seen already.
  - If the new physics scale is beyond the energy reach of the LHC, then flavour physics at a B (top) factory may be the best way forward to probe above the EW symmetry breaking scale.
    - One drawback with the last statement: We don't have a high luminosity top factory (yet).

THE END...

APPENDICES

APPENDIX I:

MORE ON α / Φ_2

APPENDIX II:

HOW DO I DO A GLOBAL FIT?
HOW DO I CONSTRAIN A NEW PHYSICS MODEL?

APPENDIX III:

CONVENTIONS

APPENDIX IV:

T VIOLATION IN B DECAY

Appendix I

- More on α / Φ_2
  - Some details regarding SU(3) and 3π determinations of α

Using SU(3)

(Appendix I)

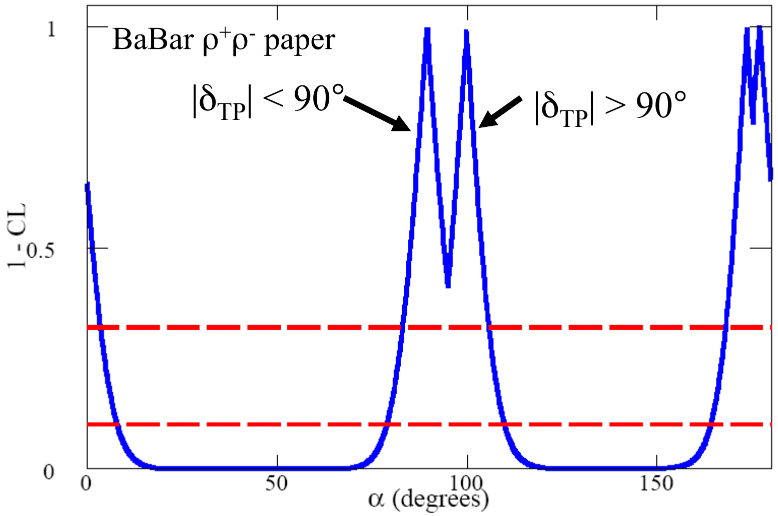
- Can relate the penguin contribution in $K^{*+}\rho^0$ to that in $\rho^+\rho^-$:

$$C_{\rm long} = \frac{2r\sin\delta_{\rm TP}\sin(\beta+\alpha)}{1-2r\cos\delta_{\rm TP}\cos(\beta+\alpha)+r^2},$$

$$S_{\rm long} = \frac{\sin 2\alpha + 2r\cos\delta_{\rm TP}\sin(\beta-\alpha) - r^2\sin 2\beta}{1-2r\cos\delta_{\rm TP}\cos(\beta+\alpha)+r^2}$$

$$\left(\frac{|V_{\rm cd}|f_\rho}{|V_{\rm cs}|f_{K^*}}\right)^2 \frac{\Gamma_{\rm L}(B^\pm \to K^{*0}\rho^+)}{\Gamma_{\rm L}(B^0 \to \rho^+\rho^-)} = \frac{Fr^2}{1-2r\cos\delta_{\rm TP}\cos(\beta+\alpha)+r^2}$$

$$F = 0.9 \pm 0.6$$



- If we assume that $|\delta_{\rm TP}| < 90°$:

$$\alpha = (89.8^{+7.0}_{-6.4})^\circ$$

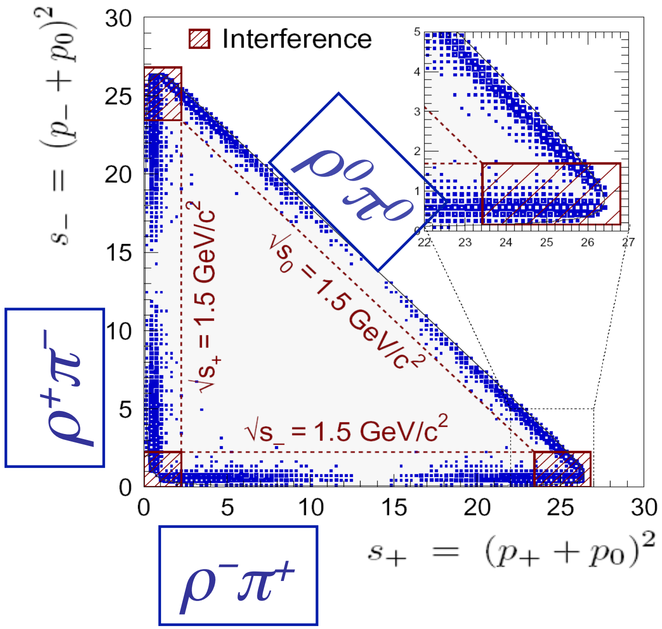
- Relaxing this assumption:

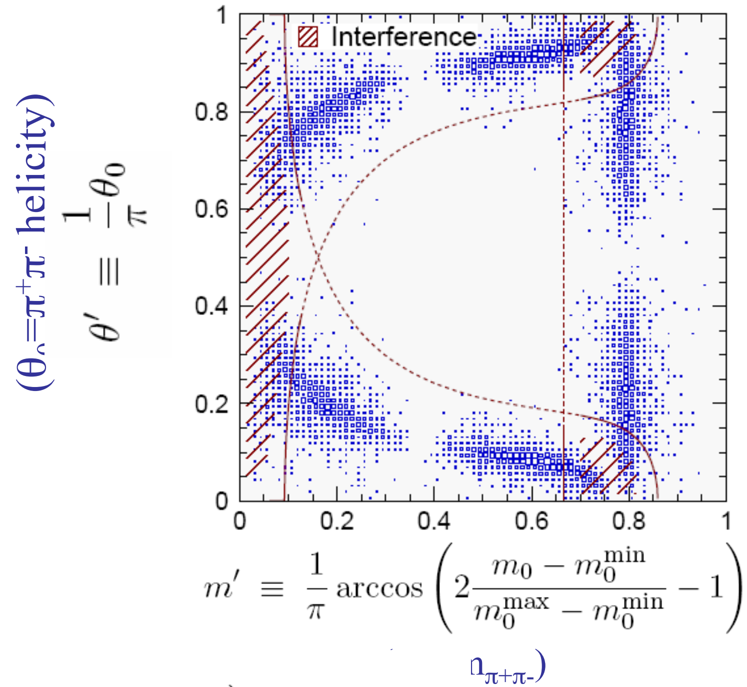
- Most precise determination of α!

M. Beneke, M. Gronau, J. Rohrer, and M. Spranger. *Phys. Lett. B* **638**, 68 (2006).

B→ρπ ($\pi^+\pi^-\pi^0$ Dalitz Plot) (Appendix I)

- Analyse a transformed Dalitz Plot to extract parameters related to α.
- Use the Snyder-Quinn method.





$$|\mathcal{A}_{3\pi}^{\pm}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[|\mathcal{A}_{3\pi}|^2 + |\overline{\mathcal{A}}_{3\pi}|^2 \mp \left(|\mathcal{A}_{3\pi}|^2 - |\overline{\mathcal{A}}_{3\pi}|^2\right)\cos(\Delta m_d \Delta t) \pm 2\mathrm{Im}\left[\overline{\mathcal{A}}_{3\pi}\mathcal{A}_{3\pi}^*\right]\sin(\Delta m_d \Delta t)\right],$$

- Fit the time-dependence of the amplitudes in the Dalitz plot:

B→ρπ ($\pi^+\pi^-\pi^0$ Dalitz Plot)

(Appendix I)

- The amplitudes are written in terms of Us and Is: 26 U and I parameters

$$|A_{3\pi}|^2 \pm |\overline{A}_{3\pi}|^2 = \sum_{\kappa\in\{+,0,-\}} |f_\kappa|^2 U_\kappa^\pm + 2\sum_{\sigma<\kappa\in\{+,0,-\}} \left(\mathrm{Re}\left[f_\kappa f_\sigma^*\right] U_\kappa^\pm - \mathrm{Im}\left[f_\kappa f_\sigma^*\right] U_{\kappa\sigma}^{\pm,\mathrm{Im}}\right)$$

$$\mathrm{Im}\left(\overline{A}_{3\pi} A_{3\pi}^*\right) = \sum_{\kappa\in\{+,0,-\}} |f_\kappa|^2 I_\kappa + \sum_{\sigma<\kappa\in\{+,0,-\}} \left(\mathrm{Re}\left[f_\kappa f_\sigma^*\right] I_{\kappa\sigma}^{\mathrm{Im}} + \mathrm{Im}\left[f_\kappa f_\sigma^*\right] I_{\kappa\sigma}^{\mathrm{Re}}\right)$$

- Which are related to CP conserving and CP violating observables:

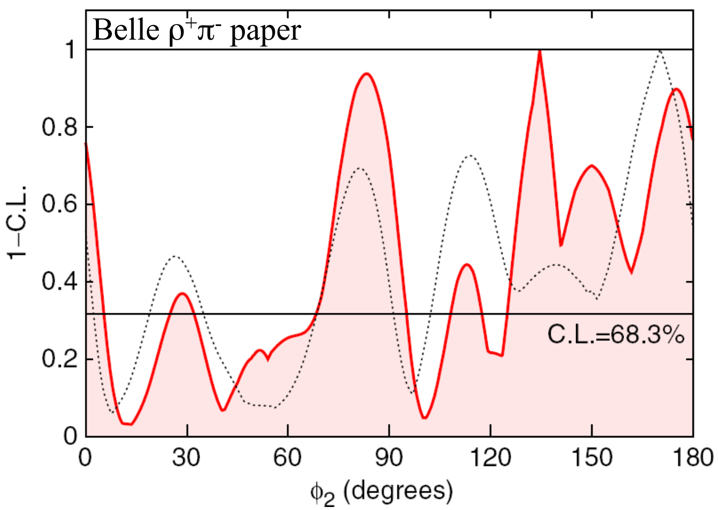
$$C = \frac{1}{2}\left(\frac{U_+^-}{U_+^+} + \frac{U_-^-}{U_-^+}\right) \quad S = \frac{I_+}{U_+^+} + \frac{I_-}{U_-^+}$$

$$\Delta C = \frac{1}{2}\left(\frac{U_+^-}{U_+^+} - \frac{U_-^-}{U_-^+}\right) \quad \Delta S = \frac{I_+}{U_+^+} - \frac{I_-}{U_-^+}$$

$$A_{CP} = \frac{U_+^+ - U_-^+}{U_+^+ + U_-^+}$$

CP violating observables

CP conserving observables



Some features of this result:

- No region is excluded at 3σ significance.
- A high statistics measurement will help resolve ambiguities in the measured value of α.
- Results from the Dalitz analysis, and the pentagon analysis (solid) are more stringent than using the Dalitz analysis alone.

BaBar Result

(Appendix I)

- The determination of U's and I's is numerically robust, as is the determination of the Quasi-2-body approximation parameters.

- Given current data samples, conversion of these results into a 1-CL constraint on α is not robust. There is a finite probability of obtaining the best fit value corresponding to something other than the true value of the angle.

  - See arXiv:1304.3503 for details.

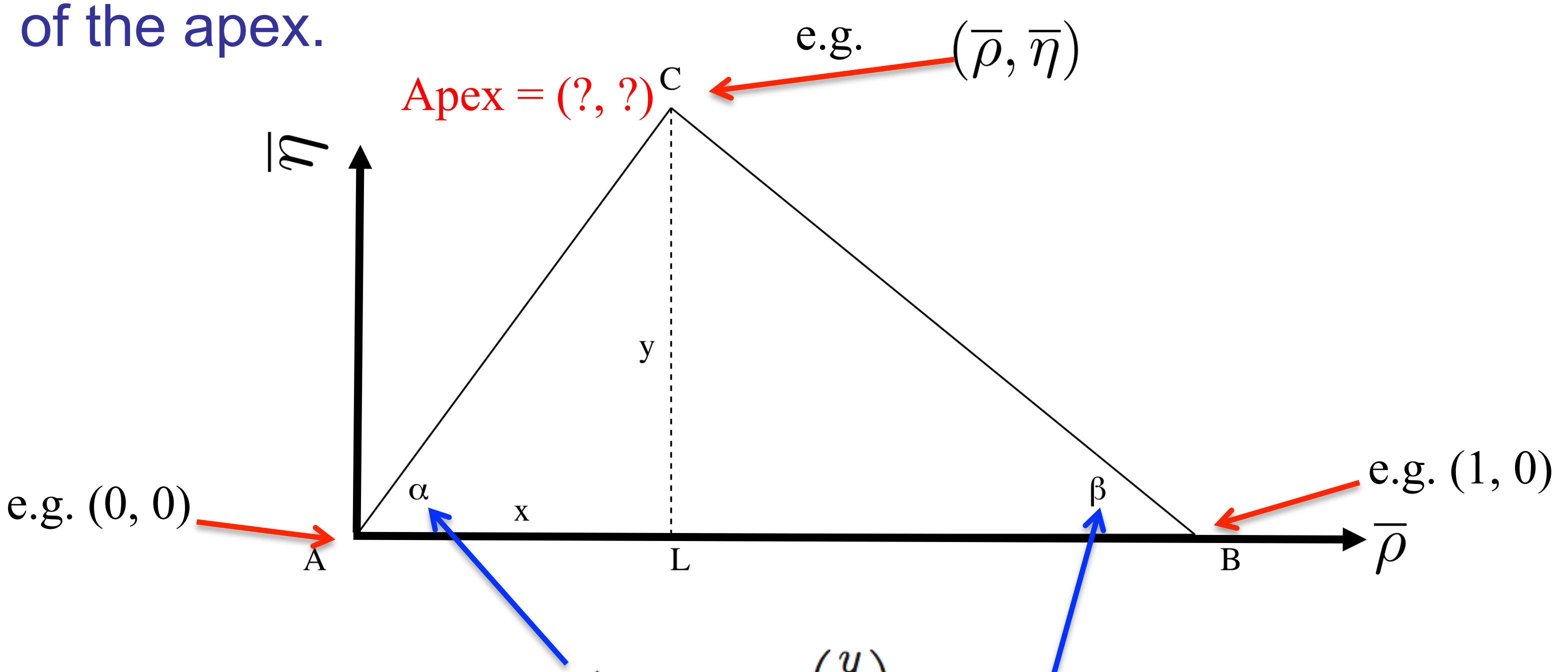
  - More data from Belle II is required to rectify this issue.

Appendix II

- How do I do a global fit?
  - There are three global fit groups:
    - CKM Fitter: http://ckmfitter.in2p3.fr/
    - UTfit: http://www.utfit.org/UTfit/
    - Unfit: arXiv:1301.5867 [Eigen et al.]
  - Two flavours of statistics:
    - Bayesian
      - Computational benefits, marginalize nuisance parameters, prior dependence etc.
    - Frequentist
      - "logical", but coverage needs to be understood, computationally expensive etc.
  - Many different inputs:
    - Theoretically straight forward (e.g. unitarity triangle angles)
    - Theoretically dependent (e.g. ε_K)
  - ... there is sufficient data to make meaningful global fits.

How do I do a global fit?

- The following illustrates how to locate the apex of a triangle with a known baseline. This is the equivalent of knowing two angles of the unitarity triangle, and determining an estimate of the apex.



$$\hat{\alpha} = \arctan\left(\frac{y}{x}\right),$$

$$\hat{\beta} = \arctan\left(\frac{y}{L-x}\right)$$

These examples are derived from the book "Statistical Data Analysis for the physical sciences", AB, Cambridge University Press (2013).

How do I do a global fit? Frequentist (Appendix II)

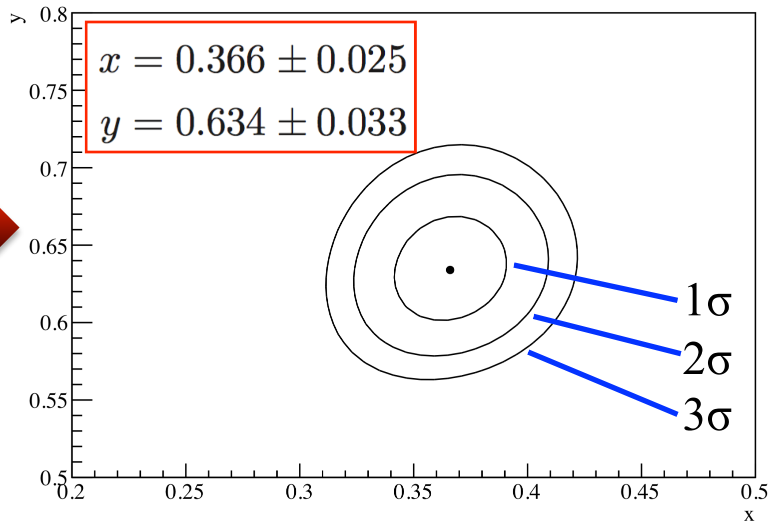
- Construct a X^2 from a number of constraints, and minimise this to obtain the most probable value, and an error ellipse (the confidence region) at some 1-CL value.

$$\chi^2 = \frac{(\alpha - \hat{\alpha})}{\sigma_\alpha^2} + \frac{(\beta - \hat{\beta})}{\sigma_\beta^2}$$

- For a given assumed *x* and *y* one can compute a value for the X^2, and then compute $P(X^2, \nu)$. From this one can obtain the desired result. e.g.

$$\begin{aligned} L &= 1 \\ \alpha &= (60 \pm 2)^\circ \\ \beta &= (45 \pm 2)^\circ \end{aligned}$$

$$\rho = \begin{pmatrix} 1.00 & -0.13 \\ -0.13 & 1.00 \end{pmatrix}$$



These examples are derived from the book "Statistical Data Analysis for the physical sciences", AB, Cambridge University Press (2013).

How do I do a global fit? Bayesian

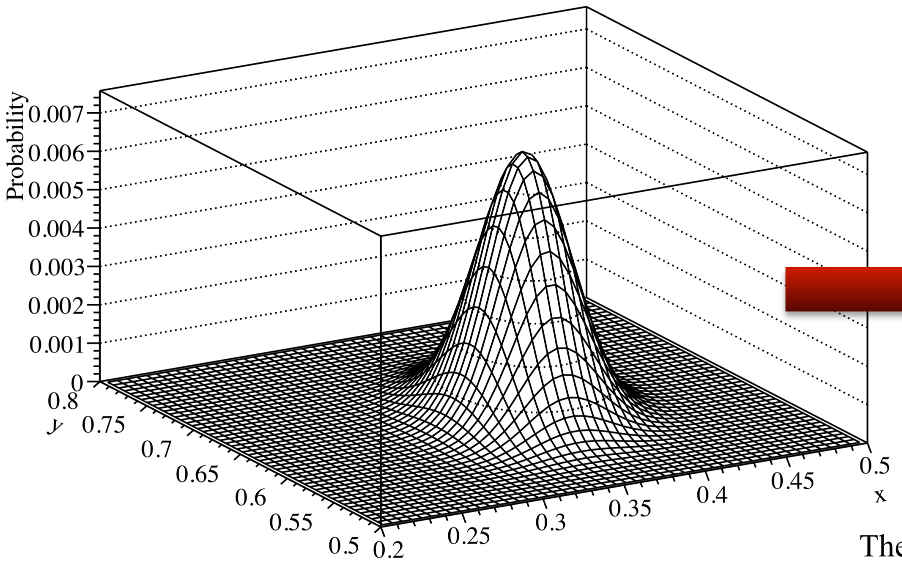
(Appendix II)

- Construct a priori probabilities (measurements = Gaussian?)
- Assume prior dependence
- Compute for a given (*x*, *y*)

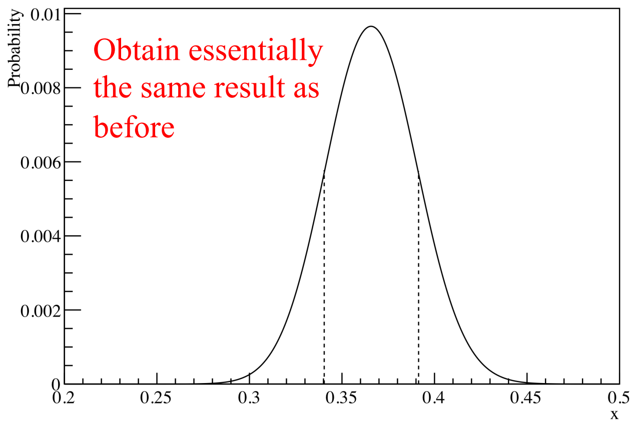
$$P(\hat{\alpha}|\alpha) = \frac{G(\hat{\alpha}, \alpha, \sigma_\alpha)P(\hat{\alpha})}{\int G(\hat{\alpha}, \alpha, \sigma_\alpha)d\underline{x}}$$

$$P(\hat{\beta}|\beta) = \frac{G(\hat{\beta}, \beta, \sigma_\beta)P(\hat{\beta})}{\int G(\hat{\beta}, \beta, \sigma_\beta)d\underline{x}}$$

$$\text{Probability} = P(\widehat{\alpha}|\alpha)P(\widehat{\beta}|\beta)$$



Integrate over variables/nuisance parameters to obtain marginal distribution for variable of interest



These examples are derived from the book "Statistical Data Analysis for the physical sciences", AB, Cambridge University Press (2013).

How do I do a global fit? Summary (Appendix II)

- Relatively straight forward to compute estimates for underlying parameters.
- Complications come into play when you have theoretical uncertainties, or a heavy theory input in converting an experimental observable into a theory parameter of interest.
- Both Frequentist and Bayesian approaches have issues that need to be addressed (in the case of Global CKM fits).
- With sufficient experimental data (i.e. precise enough measurements) the statistical approach taken should be (more or less) independent of the results obtained.
  - Differences in the way that theory uncertainties are treated may lead to differences in results.
  - Nuisance parameters and coverage may be issues for Frequentist treatment.
  - Prior dependence may be an issue for Bayesian treatment.

How do I constrain a new physics model?

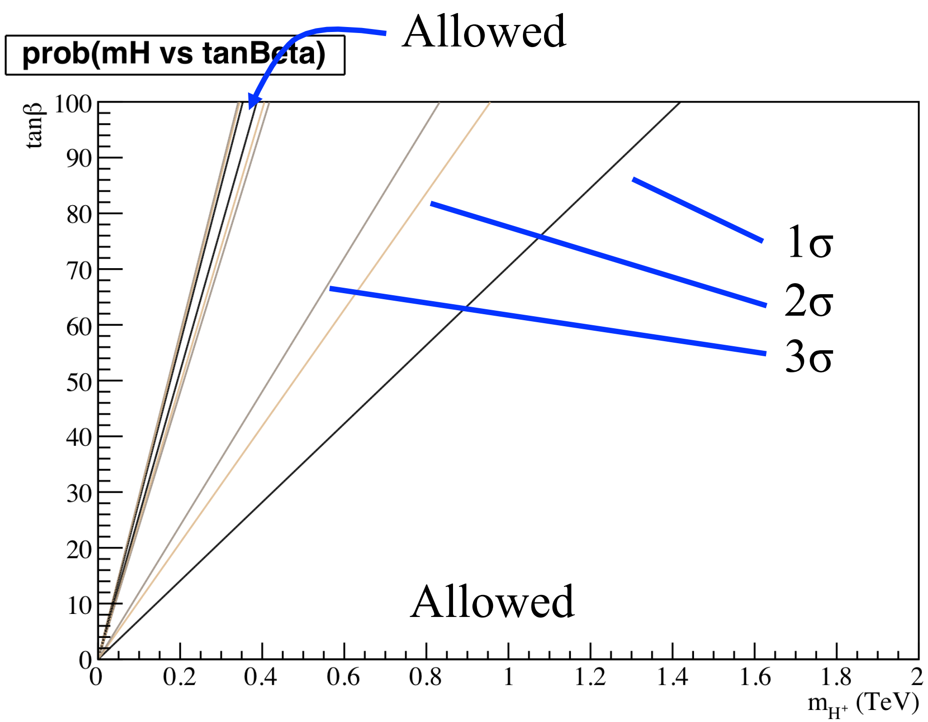
- These techniques can be applied to other scenarios in a straight forward way.
  - e.g. r_H for B decays into a lepton and neutrino final state, where the parameters fitted, or scanned through are tanβ and the charged Higgs mass in the case of a type-II 2HDM, and there is a single observable: r_H constraining these parameters.

ratio of Higgs vacuum expectation values

$$r_H = \left(1 - \frac{m_B^2}{m_{H+}^2}\tan^2\beta\right)^2$$

Charged Higgs mass

The ratio of branching ratios for SM+new physics, relative to the SM contribution.

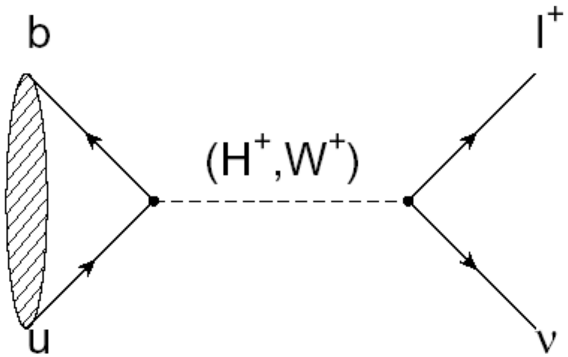


The problem

(Appendix II)

- The decay $B^{\pm} \to \tau^{\pm}\nu$ has been measured, and can be compared with theoretical expectations.
- Measurement: $\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu) = (1.15 \pm 0.23) \times 10^{-4}$
- Standard Model expectation:

$$\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu)_{SM} = (1.01 \pm 0.29) \times 10^{-4}$$



$$r_H = \frac{\mathcal{B}_{SM+NP}}{\mathcal{B}_{SM}}$$

For a simple extension of the Standard Model, called the type II 2 Higgs Doublet Model we know that r_H depends on the mass of a charged Higgs and another parameter, β.

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

What can we learn about m_H and tan β for this model?

- We can compute r_H from our knowledge of the measured and predicted branching fractions:

$$r_H = 1.14 \pm 0.40$$

- How can we use this to constrain m_H and tanβ?

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

Method 1: χ^2 approach

(Appendix II)

- Construct a χ^2 in terms of r_H

Calculate using

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

One has to select the parameter values.

From SM theory and experimental measurement

$$\chi^2 = \left(\frac{r_H - \widehat{r}_H(m_H, \tan\beta)}{\sigma_{r_H}}\right)^2$$

From SM theory and experimental measurement

Method 1: χ^2 approach

(Appendix II)

- For a given value of m_H and $\tan\beta$ you can compute χ^2.

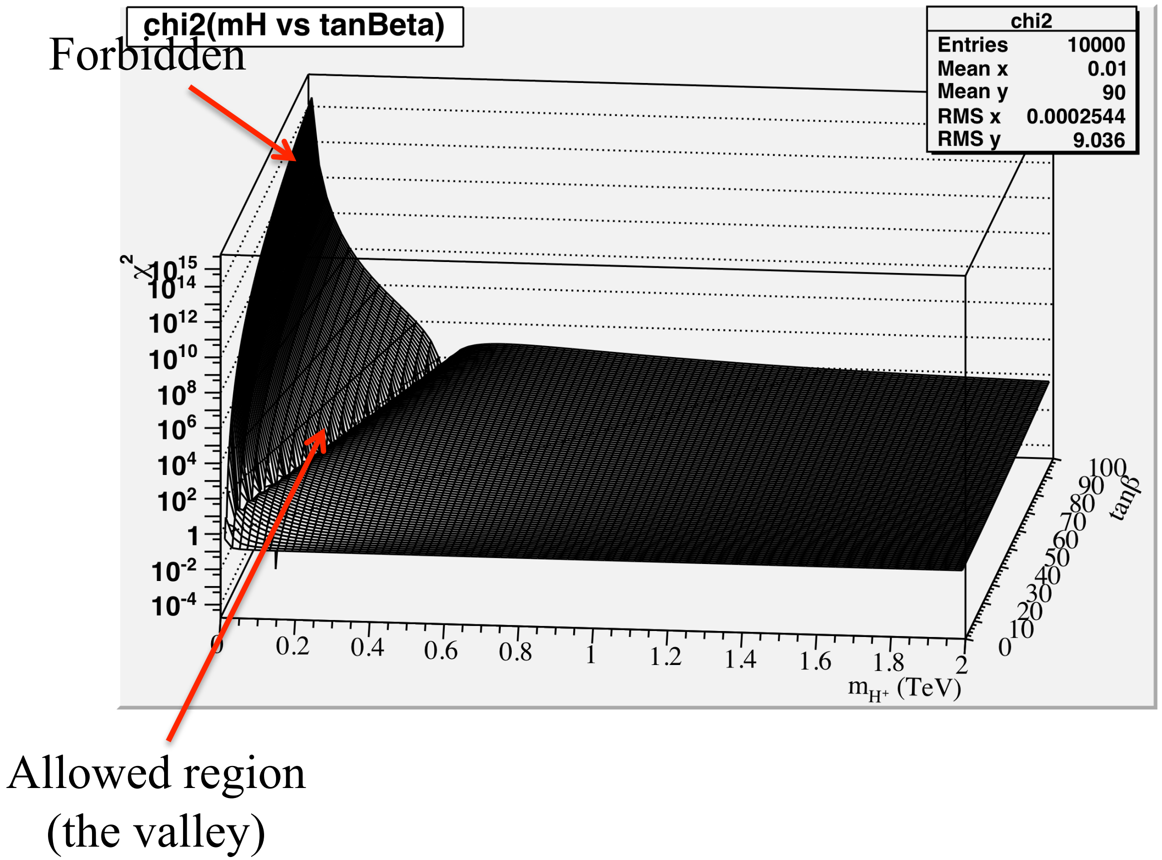
- e.g.

$$\begin{aligned} m_H &= 0.2\text{TeV} \\ \tan\beta &= 10 \\ \widehat{r}_H(m_H, \tan\beta) &= 0.93 \\ \chi^2 &= \left(\frac{1.14 - 0.93}{0.4}\right)^2 \\ &= 0.28 \end{aligned}$$

- So the task at hand is to scan through values of the parameters in order to study the behaviour of constraint on r_H.

Method 1: χ^2 approach

(Appendix II)



A large χ^2 indicates a region of parameter space that is forbidden.

A small value is allowed.

In between we have to decide on a confidence level that we use as a cut-off.

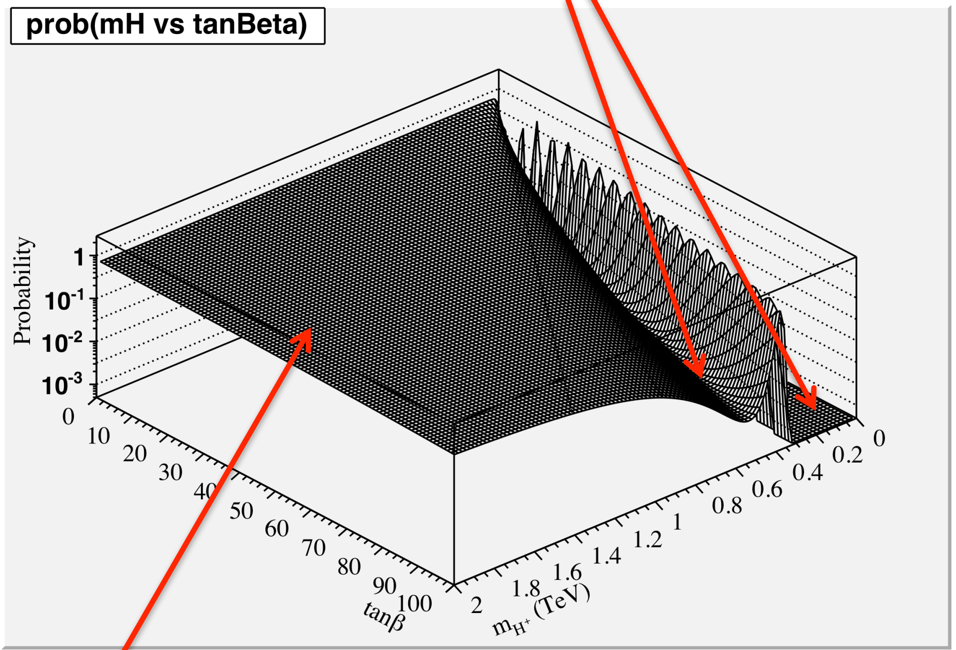
We really want to covert this distribution to a probability: so use the χ^2 probability distribution.

There are 2 parameters and one constraint (the data), so there are 2−1 degrees of freedom, i.e. ν=1

Method 1: χ^2 approach

(Appendix II)

Forbidden
(P ~ 0)



Allowed region
(P ~ 1)

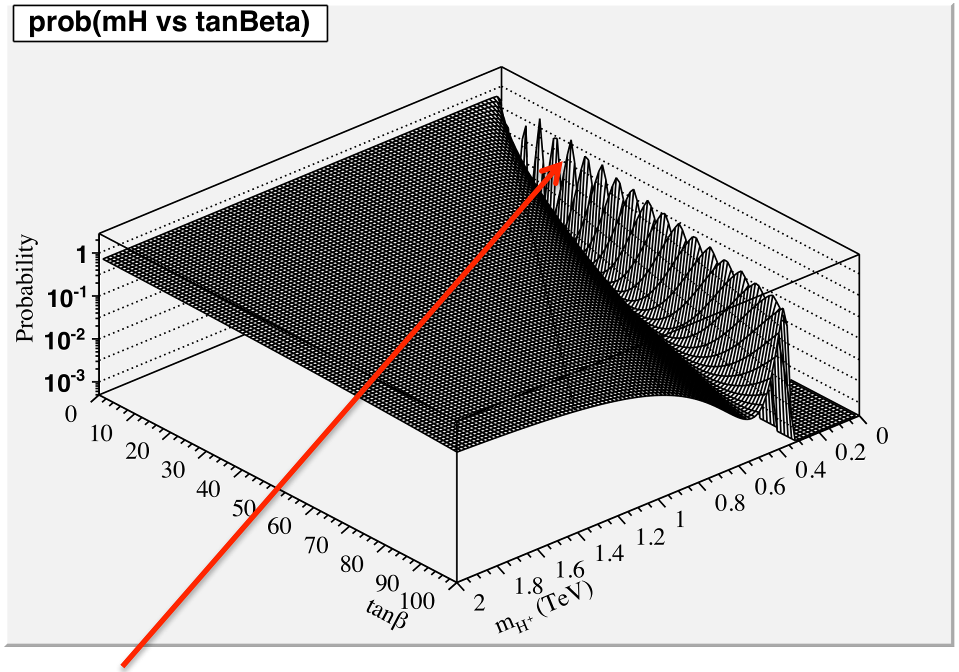
A value of P ~ 1 means that we have no constraint on the value of the parameters (i.e. they are allowed).

A small value of P, ~0 means that there is a very low (or zero) probability of the parameters being able to take those values (i.e. the parameters are forbidden in that region).

Typically one sets a 1−C.L. corresponding to 1 or 3 σ to talk about the uncertainty of a measurement, or indicate an exclusion region at that C.L.

Method 1: χ^2 approach

(Appendix II)



Artefact: a remnant of binning the data. For these plots there are 100 x 100 bins. As a result visual oddities can occur in regions where the probability (or χ^2) changes rapidly.
Solution: *finer binning!*

A value of P ~ 1 means that we have no constraint on the value of the parameters (i.e. they are allowed).

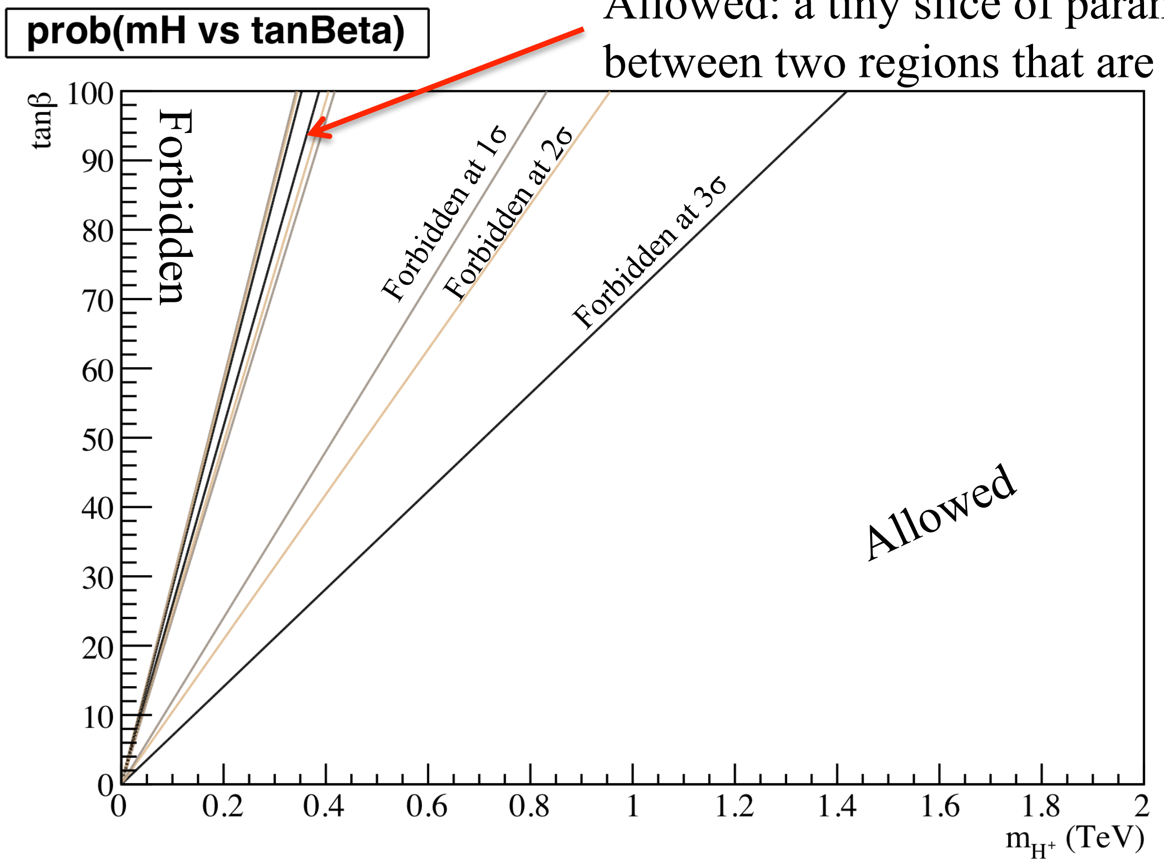
A small value of P, ~0 means that there is a very low (or zero) probability of the parameters being able to take those values (i.e. the parameters are forbidden in that region).

Typically one sets a 1−C.L. corresponding to 1 or 3 σ to talk about the uncertainty of a measurement, or indicate an exclusion region at that C.L.

Method 1: χ^2 approach

- A finer binning can be used to compute a 1-C.L. distribution. Here 1, 2 and 3σ intervals are shown.

Allowed: a tiny slice of parameter space is allowed between two regions that are forbidden



Appendix III

- Conventions
- This is a brief summary of conventions used on the different experiments for different (main) variable names.
- Unfortunately there is no uniformity to this process, and one has to get used to dual notations.

Description	*BABAR*	Belle
Unitarity Triangle angle	β	ϕ_1
Unitarity Triangle angle	α	ϕ_2
Unitarity Triangle angle	γ	ϕ_3
Beam constrained mass	m_{BC}	m_{ES}
Energy constrained mass	m_{ES}	m_{ES}
Energy difference	ΔE	ΔE
TDCPV sine coefficient	S	S
TDCPV cosine coefficient	C	$-A_{CP}$
Unassociated calorimeter energy	E_{EXTRA}	E_{ECL}

Appendix IV

- Testing T symmetry invariance
- This is a brief summary of results and ideas – see the lecture by J. Bernabeu for more details on the theoretical motivation.

http://www.economist.com/node/21561111

The Economist: 1st Sept 2012

The time-evolution of neutral meson systems is well understood, here one has to relate that information to T-conjugated pairs of decays in order to compute a T violating asymmetry.

A non-zero value of this asymmetry for any pair of T-conjugated decays would constitute T-symmetry non-invariance in that pairing.

Once can test the CKM matrix in a number of different ways using this approach.

Formalism

- Need to test a T conjugate process, and compare a state $|i\rangle$ to some other state $|f\rangle$

$$A_T = \frac{P(|i\rangle \to |f\rangle) - P(|f\rangle \to |i\rangle)}{P(|i\rangle \to |f\rangle) + P(|f\rangle \to |i\rangle)}$$

c.f. CP asymmetries constructed from CP conjugate processes.

- The problem resides in identifying a T conjugate pair of processes that can be experimentally distinguished.
- ... and which could be used to experimentally test T symmetry non-invariance.
  - Given strong and EM conservation we want to identify weak decays that can be transformed under T to a conjugate state that can also be studied.

Time-evolution

- Assuming ΔΓ=0 (good for B_d decays)

$$C^{\pm}_{\alpha,\beta} = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

Superscripts:
+ = normal ordering
− = T reversed ordering

$$S^{\pm}_{\alpha,\beta} = \frac{2Im\lambda}{1+|\lambda|^2}$$

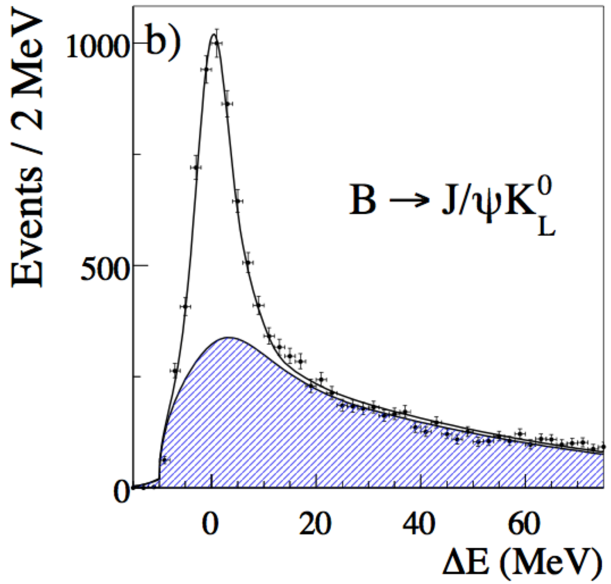
$$g^{\pm}_{\alpha,\beta}(\Delta t) \propto e^{-\Gamma\Delta t}\left[1 + C^{\pm}_{\alpha,\beta}\cos(\Delta m\Delta t) + S^{\pm}_{\alpha,\beta}\sin(\Delta m\Delta t)\right]$$

$$\alpha \in \{\ell^+, \ell^-\} \qquad \beta \in \{K_S, K_L\} \text{ i.e. } CP = \pm 1$$

- So one can relate the time-dependence to the weak structure of the decay (i.e. test the CKM formalism of the SM with an appropriate asymmetry observable).
- Need to account for mis-tag probability ω_α and detector resolution.

Event Selection: CP filters

- The same as for the sin2β CPV measurement in *Phys.Rev. D**79**:072009 (2009)*



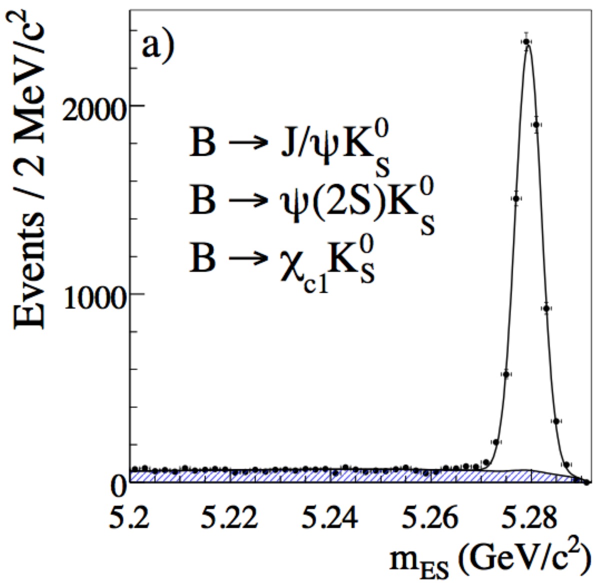
- CP even filter:

$$B \to J/\psi K_L$$

- CP odd filters:

$$\begin{aligned} B &\to J/\psi K_S \\ &\to \psi(2S) K_S \\ &\to \chi_{c1} K_S \end{aligned}$$

- Drop K* and η_c modes from the CP selection.



(Appendix IV)

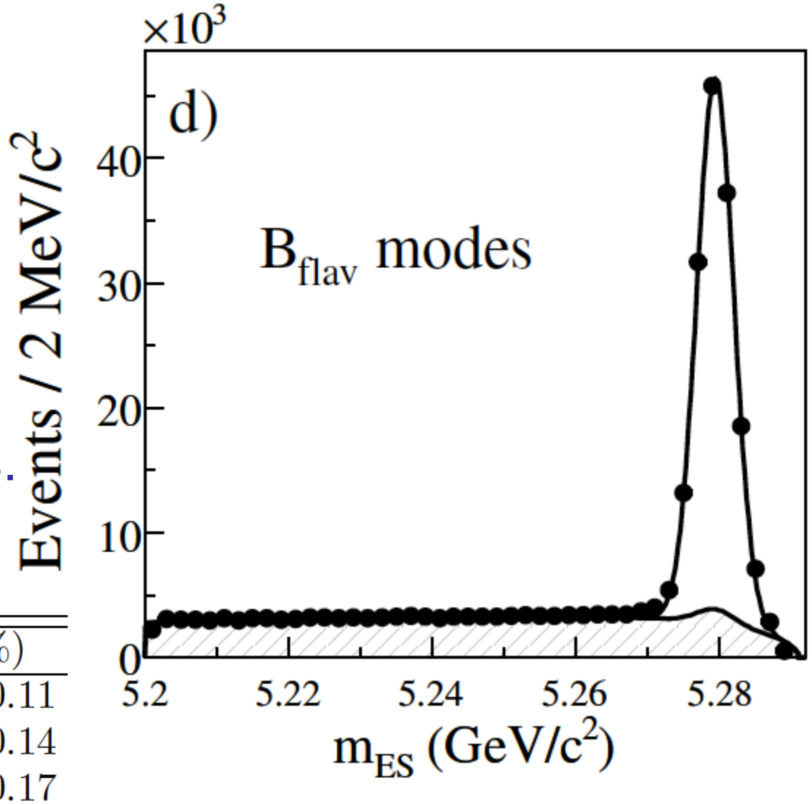
Event Selection: Flavor filters

- The same as for the sin2β CPV measurement in *Phys.Rev. D**79**:072009 (2009)*

- The set of "tag" modes used is:

$$B \rightarrow D^{(*)-}(\pi^+, \rho^+, a_1^+)$$

- which characterise "tag" performance and give the $B^0(\overline{B}^0)$ filter projections.

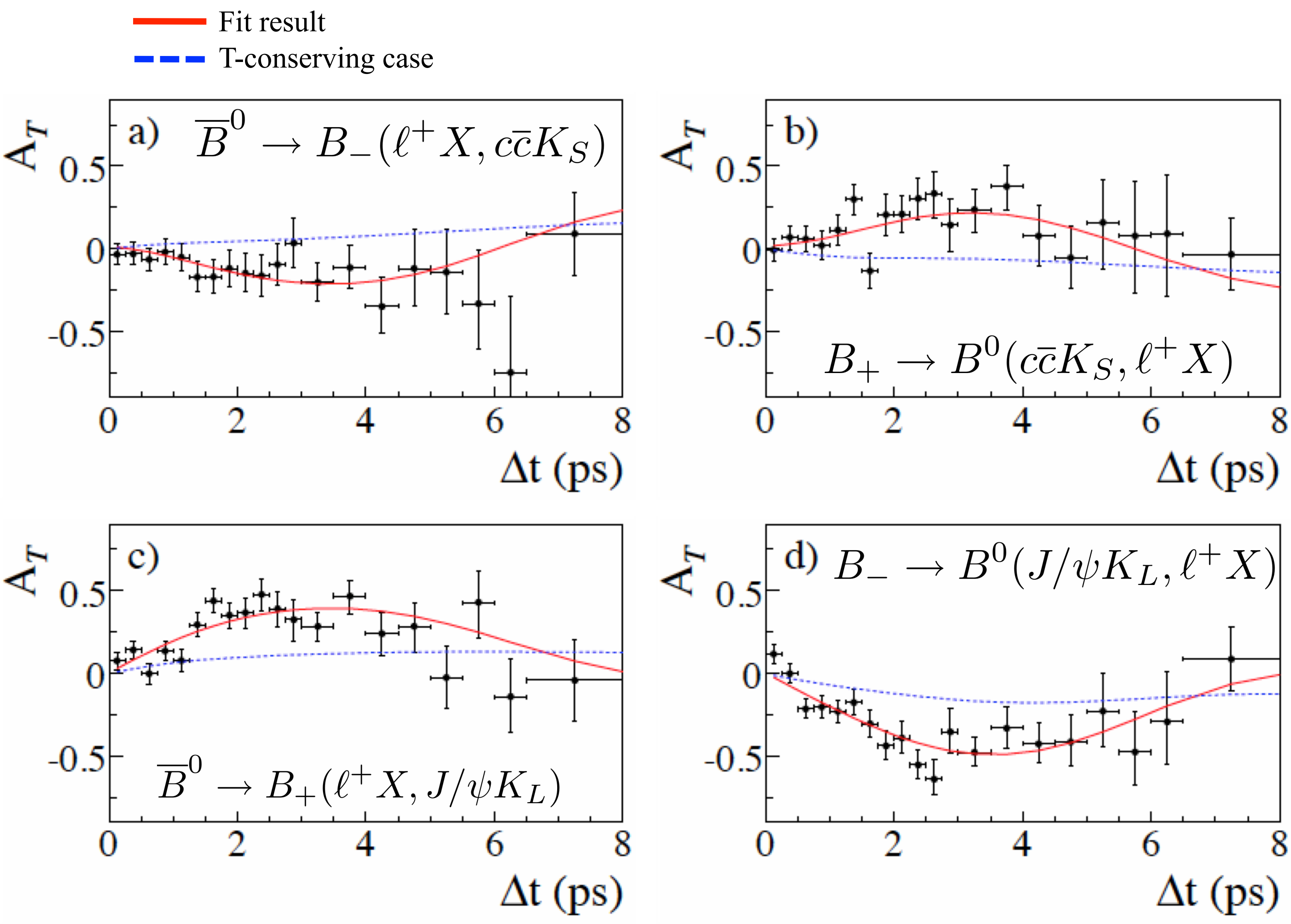


Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.96 ± 0.07	2.8 ± 0.3	0.3 ± 0.5	7.98 ± 0.11
Kaon I	10.82 ± 0.07	5.3 ± 0.3	-0.1 ± 0.6	8.65 ± 0.14
Kaon II	17.19 ± 0.09	14.5 ± 0.3	0.4 ± 0.6	8.68 ± 0.17
KaonPion	13.67 ± 0.08	23.3 ± 0.4	-0.7 ± 0.7	3.91 ± 0.12
Pion	14.18 ± 0.08	32.5 ± 0.4	5.1 ± 0.7	1.73 ± 0.09
Other	9.54 ± 0.07	41.5 ± 0.5	3.8 ± 0.8	0.27 ± 0.04
All	74.37 ± 0.10			31.2 ± 0.3

Overall
$Q = 31.2\%$

Experimental results

(Appendix IV)



Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Experimental results

(Appendix IV)

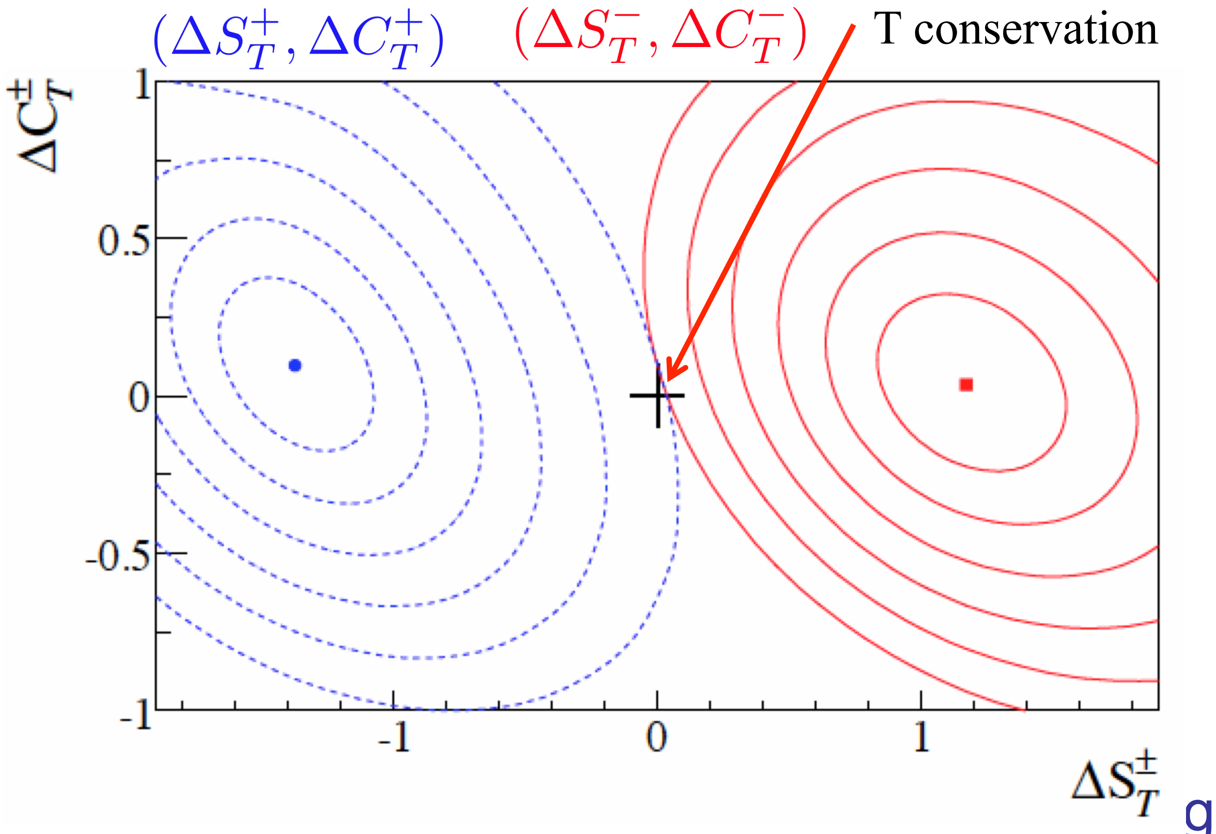
Parameter	Result
$\Delta S_T^+ = S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C^+_{\ell^-,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.04 \pm 0.14 \pm 0.08$
$\Delta S_{CP}^+ = S^+_{\ell^-,K_S^0} - S^+_{\ell^+,K_S^0}$	$-1.30 \pm 0.11 \pm 0.07$
$\Delta S_{CP}^- = S^-_{\ell^-,K_S^0} - S^-_{\ell^+,K_S^0}$	$1.33 \pm 0.12 \pm 0.06$
$\Delta C_{CP}^+ = C^+_{\ell^-,K_S^0} - C^+_{\ell^+,K_S^0}$	$0.07 \pm 0.09 \pm 0.03$
$\Delta C_{CP}^- = C^-_{\ell^-,K_S^0} - C^-_{\ell^+,K_S^0}$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S_{CPT}^+ = S^-_{\ell^+,K_L^0} - S^+_{\ell^+,K_S^0}$	$0.16 \pm 0.21 \pm 0.09$
$\Delta S_{CPT}^- = S^+_{\ell^+,K_L^0} - S^-_{\ell^+,K_S^0}$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C_{CPT}^+ = C^-_{\ell^+,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.14 \pm 0.15 \pm 0.07$
$\Delta C_{CPT}^- = C^+_{\ell^+,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.03 \pm 0.12 \pm 0.08$
$S^+_{\ell^+,K_S^0}$	$0.55 \pm 0.09 \pm 0.06$
$S^-_{\ell^+,K_S^0}$	$-0.66 \pm 0.06 \pm 0.04$
$C^+_{\ell^+,K_S^0}$	$0.01 \pm 0.07 \pm 0.05$
$C^-_{\ell^+,K_S^0}$	$-0.05 \pm 0.06 \pm 0.03$

- Observed level of T-violation balances CP violation.
- First direct measurement of T violation in B decays.
- Interpretation is unambiguous.

Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Experimental results

- Observation of T-violation can be seen in the following:



- Fit res g
Gaussian errors).

CL = 0.317, 4.55×10^{-2}, 2.70×10^{-3}, 6.33×10^{-5}, 5.73×10^{-7}, 1.97×10^{-9}

$-2\Delta\ln\mathcal{L}$ = 2.3, 6.2, 11.8, 19.3, 28.7, 40.1

Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Experimental results

(Appendix IV)

- Recall that $\Delta S^{\pm}$ are related to sin2β, so we can compare CP violation with T non-invariance for this parameter:

$$\Delta S^- \quad : \quad \beta_{SM} = (17.9^{+3.9}_{-3.6})^\circ$$

$$\Delta S^+ \quad : \quad \beta_{SM} = (21.6^{+3.2}_{-2.9})^\circ$$

- c.f. beta measured from the standard CP analysis:

$$S \quad : \quad \beta_{SM} = (21.7 \pm 1.2)^\circ$$

- As expected all results of β are in agreement with each other, however a more precise comparison of these results is called for.

This is my interpretation of the results.

- It was noted that one can remove the approximation that KL and KS are an orthonormal CP basis, by looking at B decays to two vector particle final states.

AB, Inguglia, Zoccali, **arXiv:1302.4191**

Backup slides

Recoil reconstruction

- Technique adapted from CLEO (for D mesons) and applied to B mesons. Similar approach can be taken for top quarks.

Full Reconstruction

Signal decay to detected particles

Hadronically reconstruct the tag final state of interest. Anything left must be from the other (signal) B in the final state.

Pro: Reconstruct whole event.

Con: Low efficiency (for B decays)

$$\epsilon \simeq 0.2 - 0.4\%$$

Signal decay includes neutrinos

Hadronically reconstruct the tag final state of interest.
Anything left must be from the other (signal) B in the final state.

Pro: Reconstruct visible energy in whole event.

Con: Low efficiency (for B decays), and missing neutrino (but this can be used as a kinematic variable to suppress background).

Recoil reconstruction

- Technique adapted from CLEO (for D mesons) and applied to B mesons. Similar approach can be taken for top quarks.

Partial Reconstruction

$$\epsilon \simeq 0.7\%$$

Reconstruct semi-leptonic B decays as a B meson "tag".

Pro: High reconstruction efficiency, and missing mass can be used as a discriminating variable.

Con: Higher background than full reconstruction approach, and event can't be fully reconstructed.

Recoil reconstruction

- Technique adapted from CLEO (for D mesons) and applied to B mesons. Similar approach can be taken for top quarks.

Partial Reconstruction

$$\epsilon \simeq 0.7\%$$

Reconstruct semi-leptonic B decays as a B meson "tag".

Pro: High reconstruction efficiency, and missing mass can be used as a discriminating variable.

Con: Higher background than full reconstruction approach, and event can't be fully reconstructed.

The efficiencies noted are typical values used in papers during the life of the B Factories. Recently more complicated hadronic and semi-leptonic tag algorithms have been used, with higher efficiencies.