YETI 2014: NU Flavours

These lectures concentrate on e^+e^- flavour physics experimental methodologies and results. Flavour physics results from the LHC and Tevatron are not included. See ATLAS, CDF, CMS, DØ, HERA-B and LHCb for more on flavour physics from hadron machines.

Recent results from BaBar and Belle

Some highlights…

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Overview

- The *B* Factories and their primary physics goal
- Rare decay constraints on new physics
- charged LFV and CPV
- The "Physics of the *B* Factories"
- The future...
- Summary
- Ancillary Material: Some technical details, and interesting topics are discussed in additional slides for you to study in your own time.

From 22 proposed e^+e^- *B* Factories, only 2 were built.*** These are situated at the KEK Laboratory in Tsukuba, Japan and at the SLAC National Accelerator Laboratory in Menlo Park, California.

THE *B* FACTORIES AND THEIR PRIMARY PHYSICS GOAL

*** Brief summaries of the many proposals can be found in:

D. Hitlin. “Asymmetric *B* factories”. In “Proceedings of the International School of Physics “Enrico Fermi”: CP Violation: From Quarks to Leptons, Varenna, Italy”, 2005, pages 553–567.

K. R. Schubert. “From ARGUS to *B*-meson factories”. In “ARGUS Symposium: 20 Years of *B* Meson Mixing”, 2007. doi: 10.3204/DESY-PROC-2008-01/e308.

- The discovery of CP violation in 1964 by Cronin, Fitch, Christensen and Turlay turned out to have profound implications:
  - CP violation in the kaon sector showed that sometimes (in weak decay) matter and antimatter behave differently.

Phys. Rev. Lett. **13**, 138–140 (1964)

  - Sakharov interpreted this phenomenon as a crucial ingredient to manifest a matter dominated universe:
    - Baryon number violation
    - A period of expansion in the early universe that is out of thermal equilibrium
    - C and CP violation

Pisma Zh. Eksp. Teor. Fiz. 5, 32–35 (1967).

  - Kobayashi and Maskawa proposed a 6 plet model (i.e. 6 quark model) to describe CP violation. This needed to be tested.

Prog.Theor.Phys. **49**, 652–657 (1973)

CKM Matrix (a brief reminder)

- We normally work in the convention defined by Buras (a modification of the Wolfenstein parameterisation).

- The Unitarity Triangle can be understood using a λ^3 expansion, however higher orders are required to probe the charm sector.

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

- Physical observables are convention independent, so we want to test invariants: the $|V_{ij}|$, quartets and so on.

- Bigi, Carter and Sanda wrote several seminal papers on how one might have large CP violation in *B* meson decay.

Nucl.Phys. B193, 85 (1981); Phys.Rev. D29, 1393 (1984); Phys.Rev.Lett. 45, 952 (1980); Phys.Rev. D23, 1567 (1981) .

- These required the measurement of either:
  - the proper time difference between the decay of a pair of entangled neutral *B* mesons created in the decay of an $\Upsilon(4S)$.
  - the proper time measurement from creation to decay of a neutral *B* meson.

- The (theoretically clean) golden channel was identified as

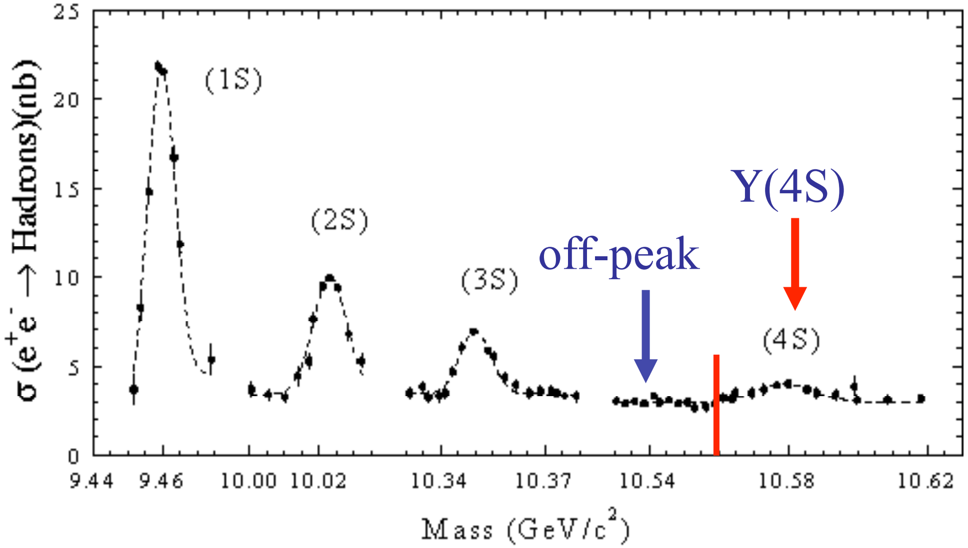
$$B \to J/\psi K^0_S$$

- Nice idea but:
  - How do you create tens of millions of *B* mesons?
  - How do you resolve the time differences using existing technology?

How do we make *B* mesons?

- Collide electrons and positrons at √s=10.58 GeV/c^2

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



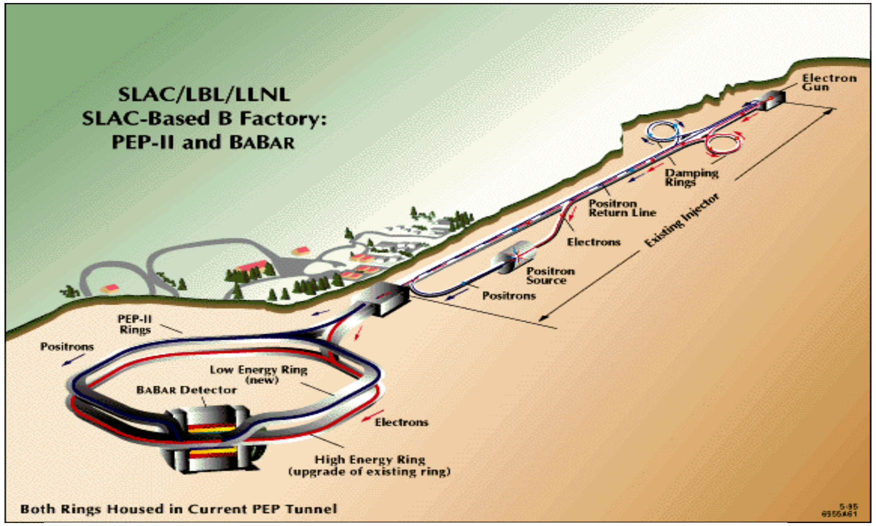
many types of interaction occur.

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

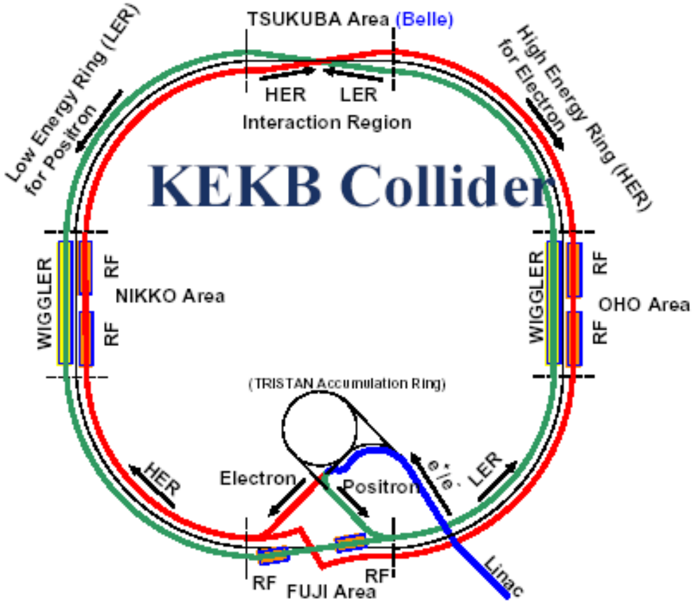
- Where $$\frac{\mathcal{B}(\Upsilon(4S) \rightarrow B^0\overline{B}^0)}{\mathcal{B}(\Upsilon(4S) \rightarrow B^+B^-)} \simeq 1$$

PEP-II and KEKB

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



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



The *B* Factories

Almost 900 papers from these collaborations

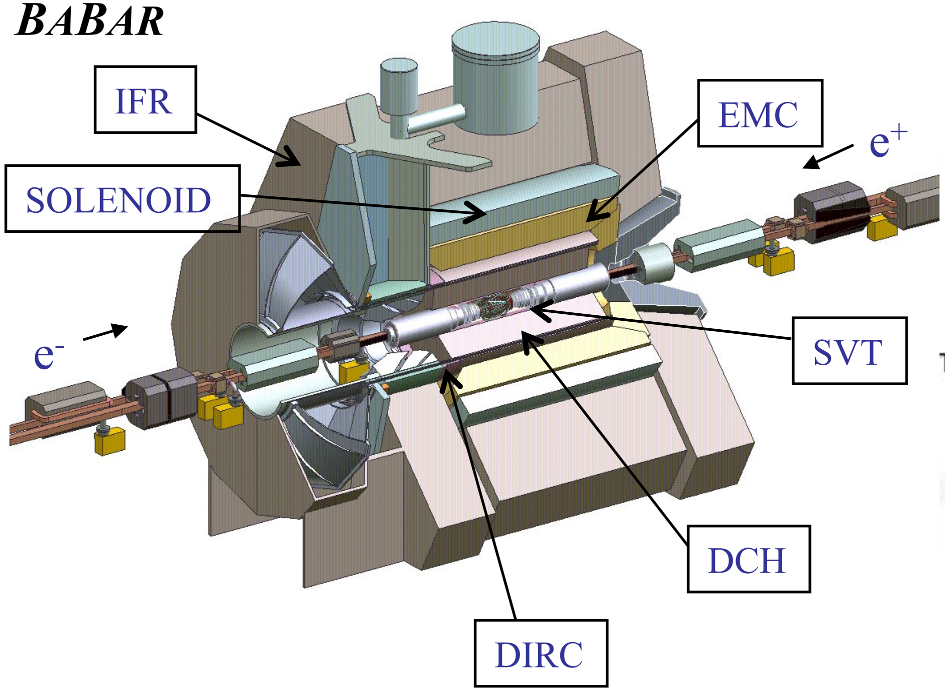
- Asymmetric energy e^+e^- colliders operating primarily at the $\Upsilon(4S)$.

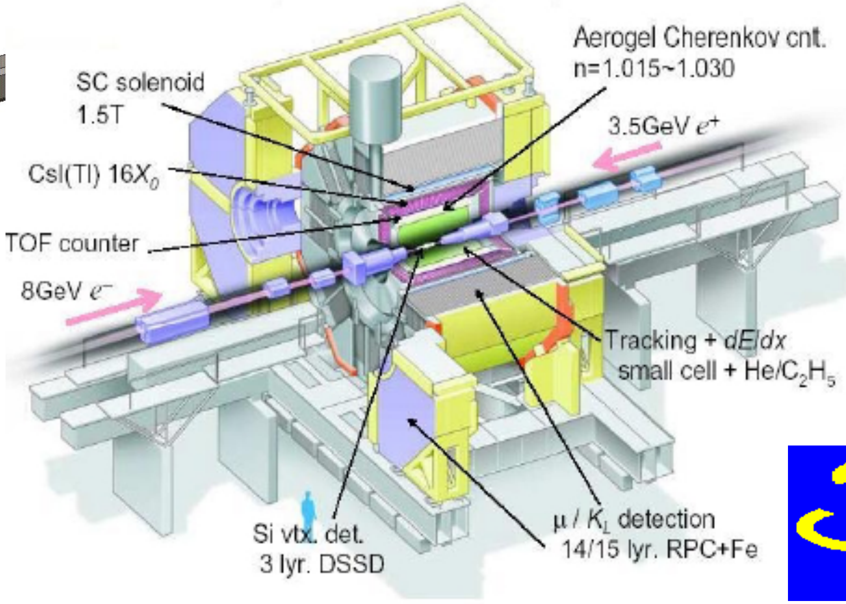
Differences between the experiments are small.
Both have:

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

BaBar:	425 fb^{-1}
Belle:	771 fb^{-1}

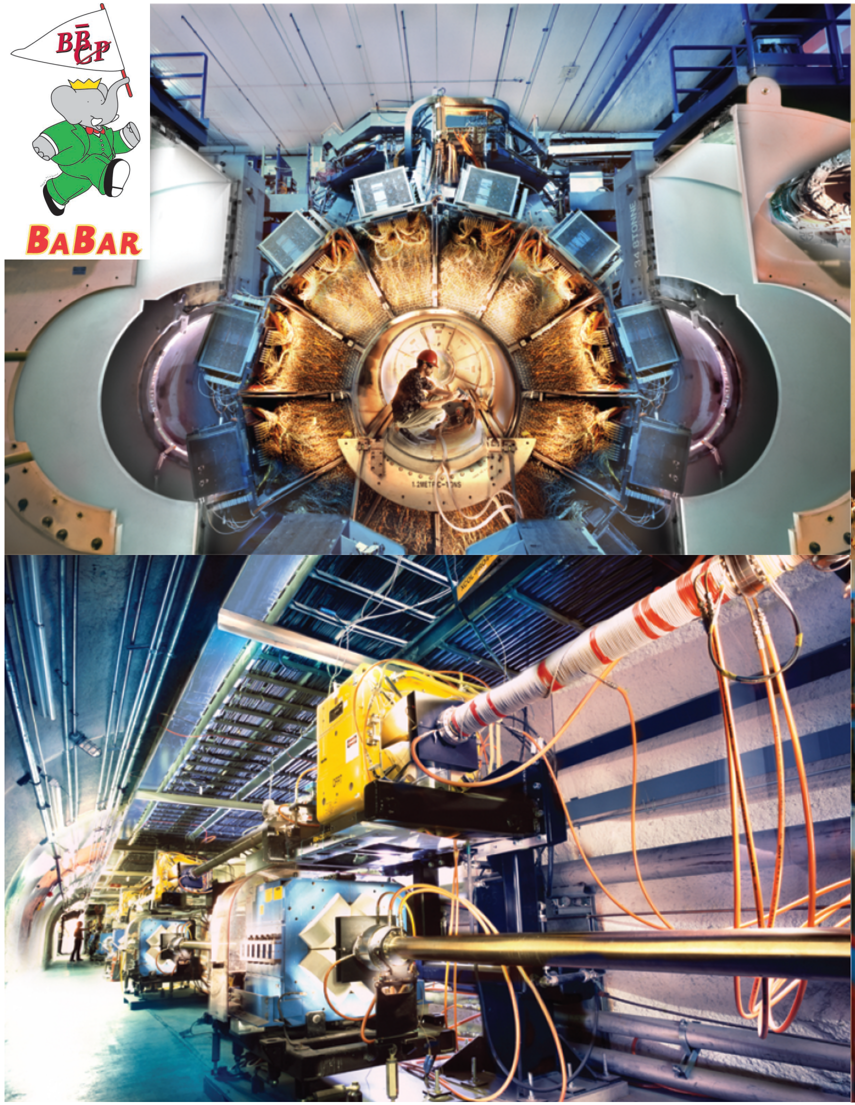
BABAR



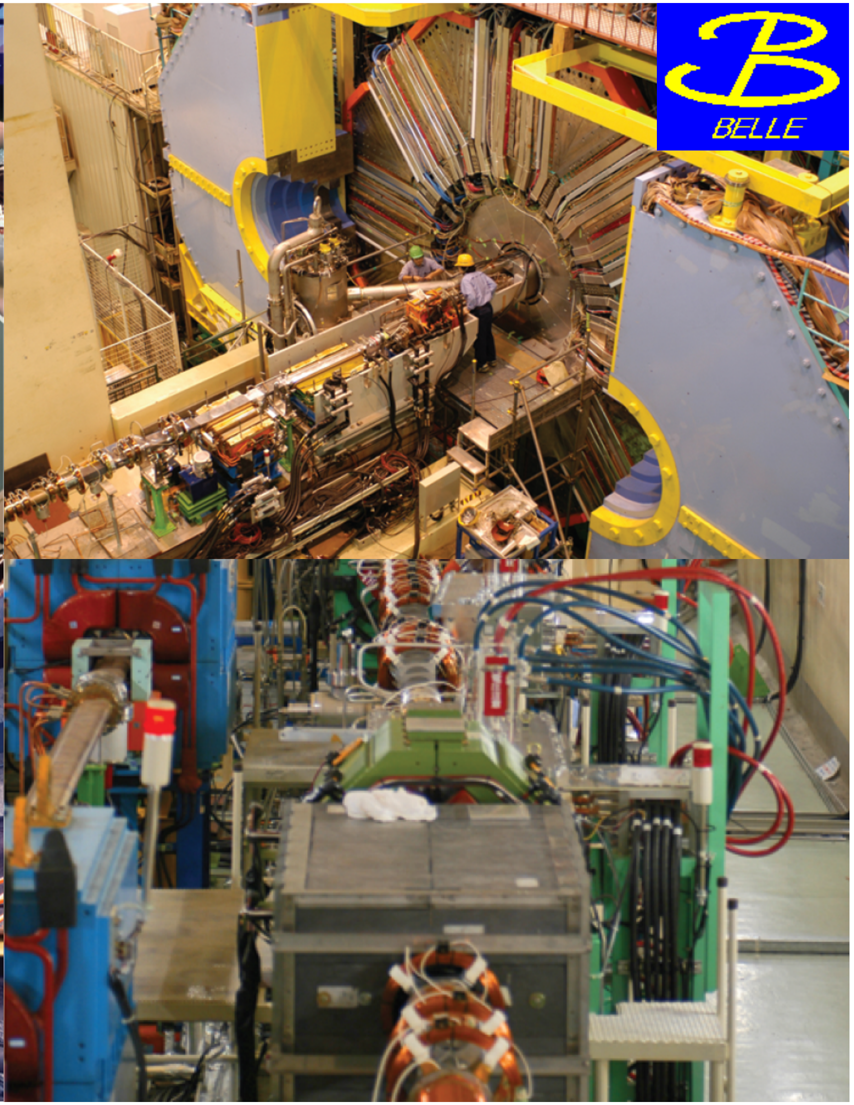


The *B* Factories

PEP-II and BaBar



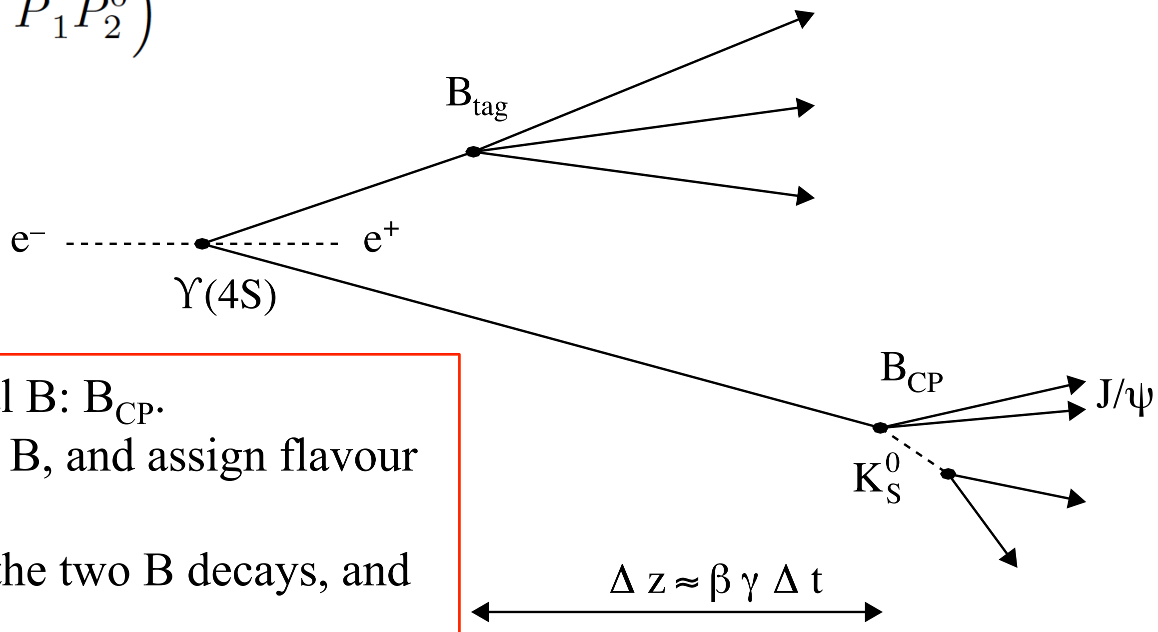
KEKB and Belle



Time-dependent methodology

- Recall that these B mesons are created in entangled pairs.

$$\Phi = \frac{1}{\sqrt{2}}\left(P_1^0 \overline{P}_2^0 - \overline{P}_1^0 P_2^0\right)$$



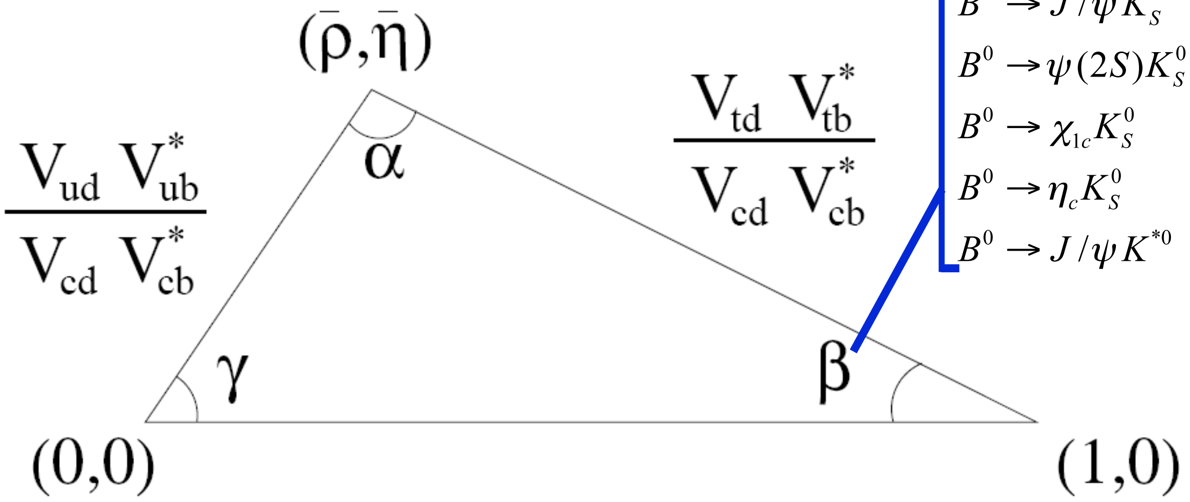
1. Reconstruct the signal B: B_{CP}.
2. Reconstruct the other B, and assign flavour tag: B_{tag}.
3. Compute vertices of the two B decays, and the difference Δz.
4. Convert Δz to Δt using knowledge of the CM boost relative tothe laboratory frame.
5. Fit the time-dependence, taking into account tagging dilution and resolution (see ancillary material at the end).

Equivalent measurements can be made for charm decays, see AB, G. Inguglia, and B. Meadows arXiv:1106.5075.

sin2β

Details of time-dependent CP analysis can be found in textbooks, and slides at the end of this lecture. Chapter 10 of the Physics of the B Factories is a good starting point to read up on this issue. Chapter 17.6 contains a detailed discussion of the measurement of $\beta=\Phi_1$.

Theoretically clean (SM uncertainties ~10^{-2} to 10^{-3}) tree dominated decays to Charmonium + K^0 final states.



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

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

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

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

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

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

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

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

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

$B \to \eta' K^0$

$B \to \rho K^0$

$B \to \omega K^0$

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

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

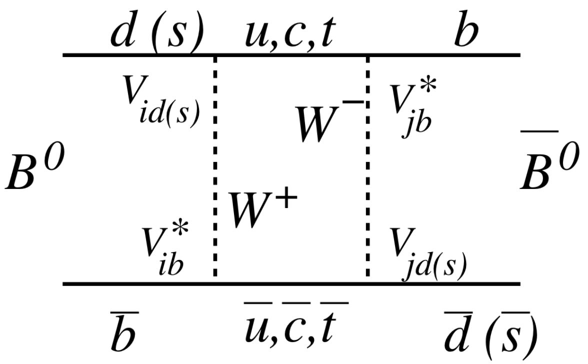
$B \to K K K^0$

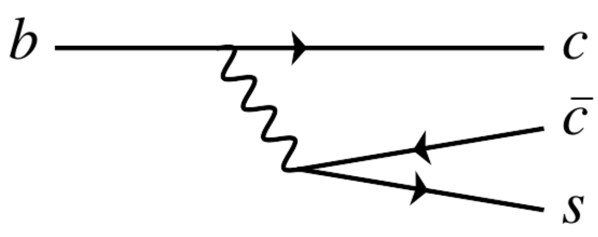
$B \to f^0(980) K^0$

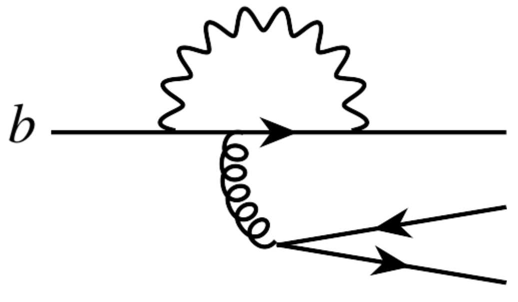
⋮

The golden modes

- Charmonium + K^0 decays are dominated by tree and mixing contributions. The penguin contribution to $\beta \sim 10^{-4}$.







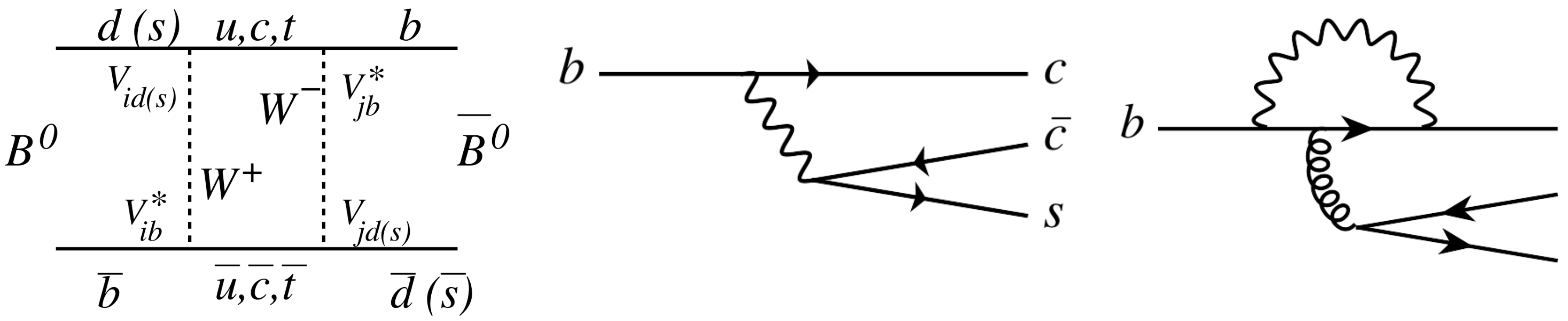
$$\mathcal{A}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$

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

	BABAR (Aubert, 2009a)				Belle (Adachi, 2012)			
Mode	N_{tag}	P	$-\eta_f S$	C	N_{tag}	P	$-\eta_f S$	C
$J/\psi K^0_S$	6750	95	$0.657 \pm 0.036 \pm 0.012$	$0.026 \pm 0.025 \pm 0.016$	13040	97	$0.670 \pm 0.029 \pm 0.013$	$0.015 \pm 0.021\ ^{+0.023}_{-0.045}$
$J/\psi K^0_L$	5813	56	$0.694 \pm 0.061 \pm 0.031$	$-0.033 \pm 0.050 \pm 0.027$	15937	63	$0.642 \pm 0.047 \pm 0.021$	$-0.019 \pm 0.026\ ^{+0.041}_{-0.017}$
$\psi(2S) K^0_S$	861	87	$0.897 \pm 0.100 \pm 0.036$	$0.089 \pm 0.076 \pm 0.020$	2169	91	$0.738 \pm 0.079 \pm 0.036$	$-0.104 \pm 0.055\ ^{+0.027}_{-0.047}$
$\chi_{c1} K^0_S$	385	88	$0.614 \pm 0.160 \pm 0.040$	$0.129 \pm 0.109 \pm 0.025$	1093	86	$0.640 \pm 0.117 \pm 0.040$	$0.017 \pm 0.083\ ^{+0.026}_{-0.046}$
$\eta_c K^0_S$	381	79	$0.925 \pm 0.160 \pm 0.057$	$0.080 \pm 0.124 \pm 0.029$				
$J/\psi K^{*0}$	1291	67	$0.601 \pm 0.239 \pm 0.087$	$0.025 \pm 0.083 \pm 0.054$				
All	15481	76	$0.687 \pm 0.028 \pm 0.012$	$0.024 \pm 0.020 \pm 0.016$	32239	79	$0.667 \pm 0.023 \pm 0.012$	$-0.006 \pm 0.016 \pm 0.012$

The golden modes

- Charmonium + K^0 decays are dominated by tree and mixing contributions. The penguin contribution to β~10^{-4}.



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

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

$$\boxed{S = \sin 2\beta}$$

$$\boxed{C \simeq 0}$$

	BABAR (Aubert, 2009a)				Belle (Adachi, 2012)			
Mode	N_{tag}	P	$-\eta_f S$	C	N_{tag}	P	$-\eta_f S$	C
$J/\psi K^0_S$	6750	9		026 ± 0.025 ± 0.016	13040	9	± 0.013	$0.015 \pm 0.021\,^{+0.023}_{-0.045}$
$J/\psi K^0_L$	5813	5		033 ± 0.050 ± 0.027	15937	6	± 0.021	$-0.019 \pm 0.026\,^{+0.041}_{-0.017}$
$\psi(2S)K^0_S$	861	87	$0.897 \pm 0.100 \pm 0.036$	$0.089 \pm 0.076 \pm 0.020$	2169	91	$0.738 \pm 0.079 \pm 0.036$	$-0.104 \pm 0.055\,^{+0.027}_{-0.047}$
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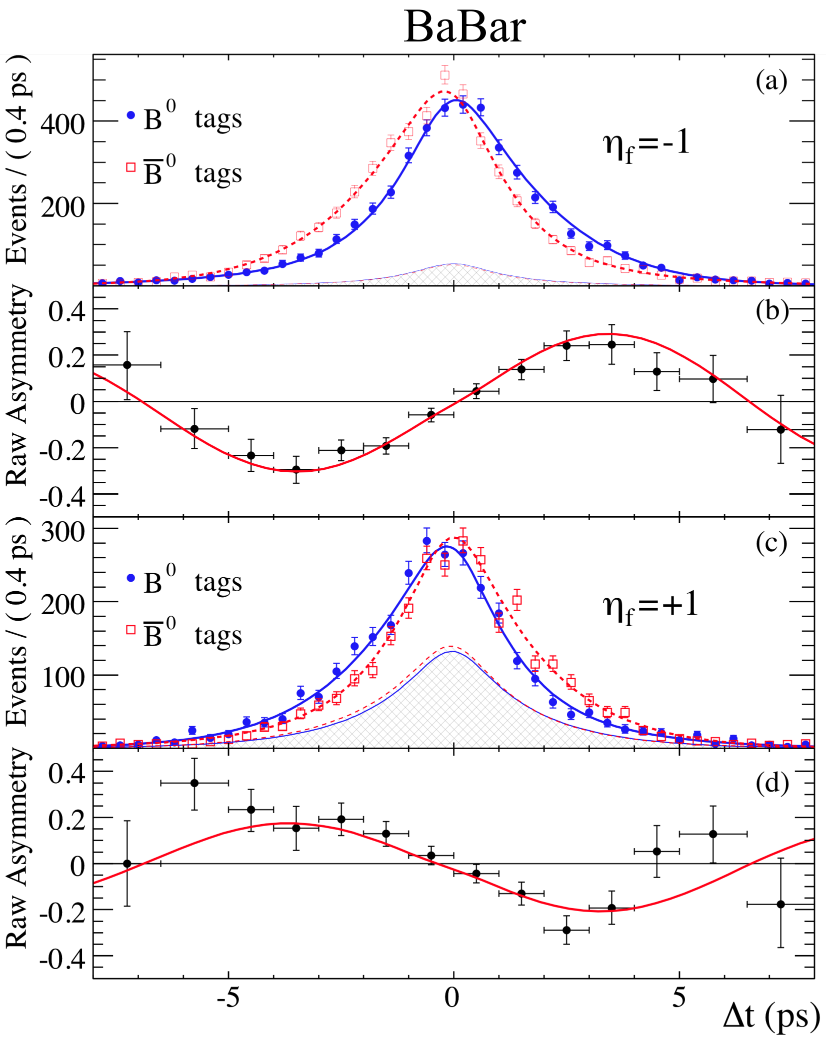
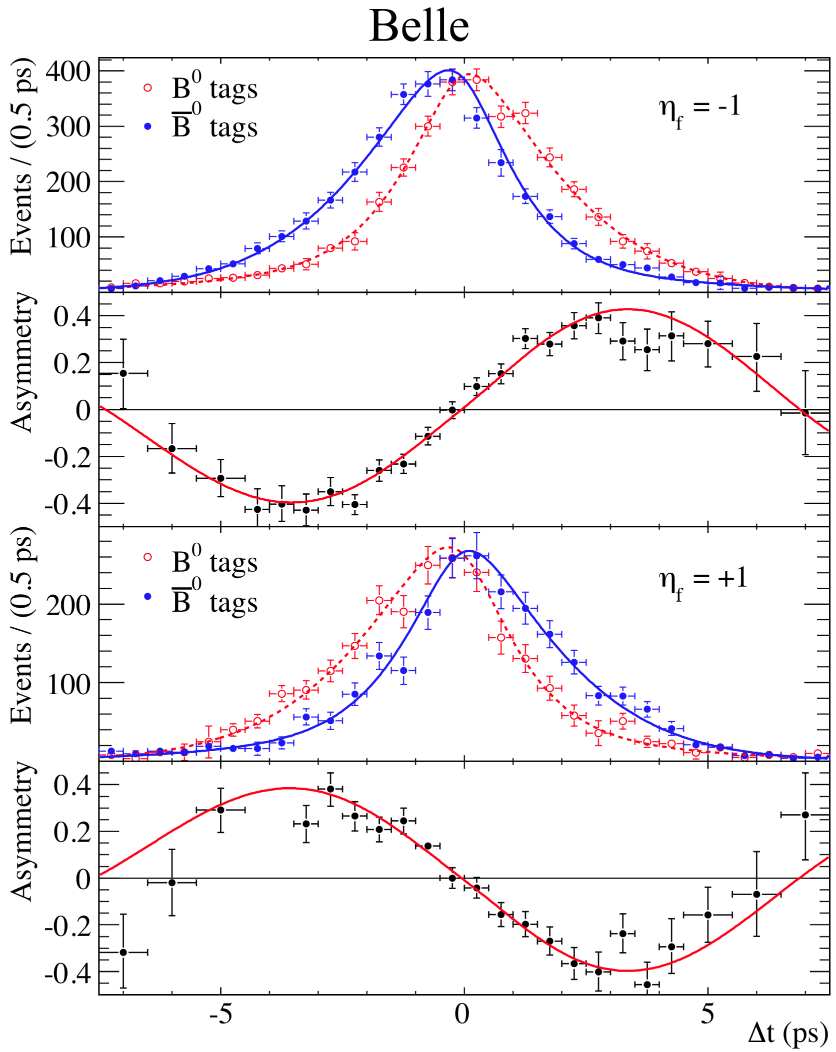




$$\sin 2\beta = \sin 2\phi_1 = 0.677 \pm 0.020$$

$$\beta = \phi_1 = (21.30 \pm 0.78)^\circ$$

$\sin 2\alpha_{\text{eff}}$ and α

Details of time-dependent CP analysis can be found in textbooks, and slides at the end of this lecture. Chapter 10 of the Physics of the B Factories is a good starting point to read up on this issue. Chapter 17.7 contains a detailed discussion of the measurement of $\alpha = \Phi_2$.

$b \to u\bar{u}d$ transitions with possible loop contributions. Extract α using

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

$b \to u\bar{u}d$

$B \to \pi\pi$

$B \to \rho\pi$

$B \to \rho\rho$

$B \to a_1\pi$

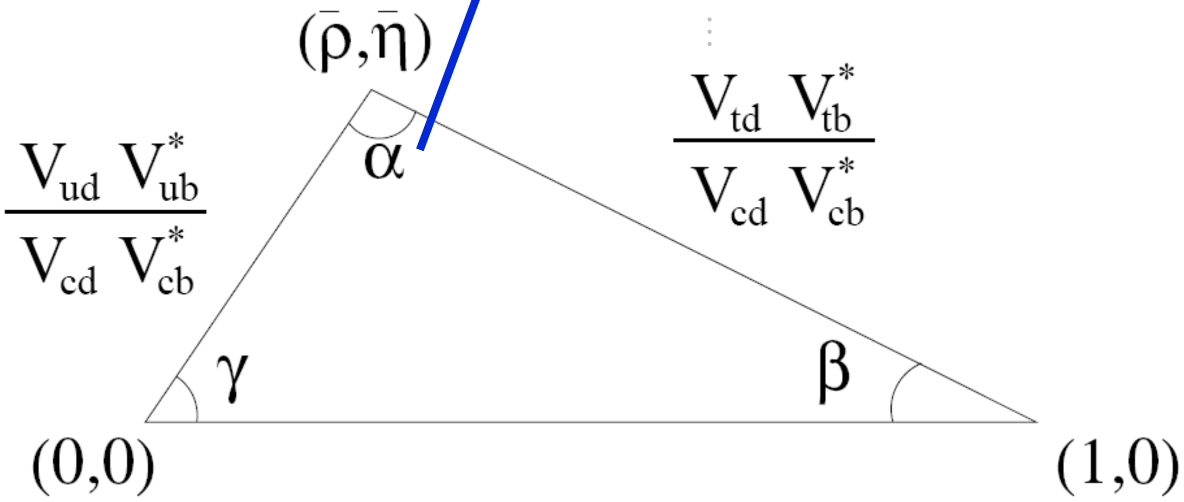
$B \to a_1\rho$

$B \to b_1\pi$

$B \to b_1\rho$

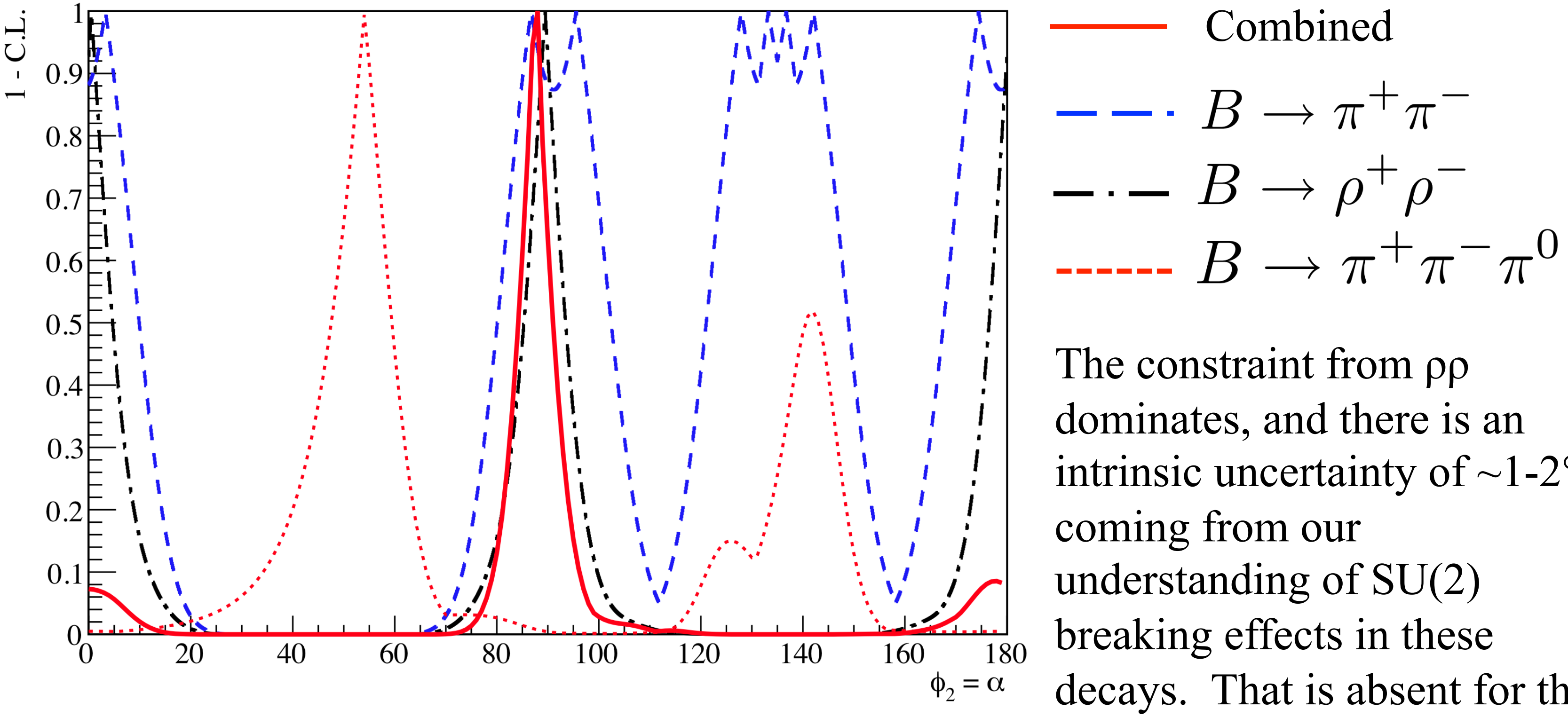
$B \to a_1 a_1$

$\vdots$



α

- This is all about how to constrain phase shifts from penguins, details are relegated to backup slides, here there is just the result:



The constraint from ρρ dominates, and there is an intrinsic uncertainty of ~1-2° coming from our understanding of SU(2) breaking effects in these decays. That is absent for the 3π time-dependent Dalitz plot analysis.

$$\alpha = \phi_2 = (87 \pm 5)^\circ.$$

*** Taken from Physics of the *B* Factories ed AB et al.**

γ

Details of the ADS, GLW and GGSZ methods to extract $\gamma=\Phi_3$ are commonly found, for example see Chapter 17.8 of the forthcoming Physics of the B Factories. Here I just show the bottom line.

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

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

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

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

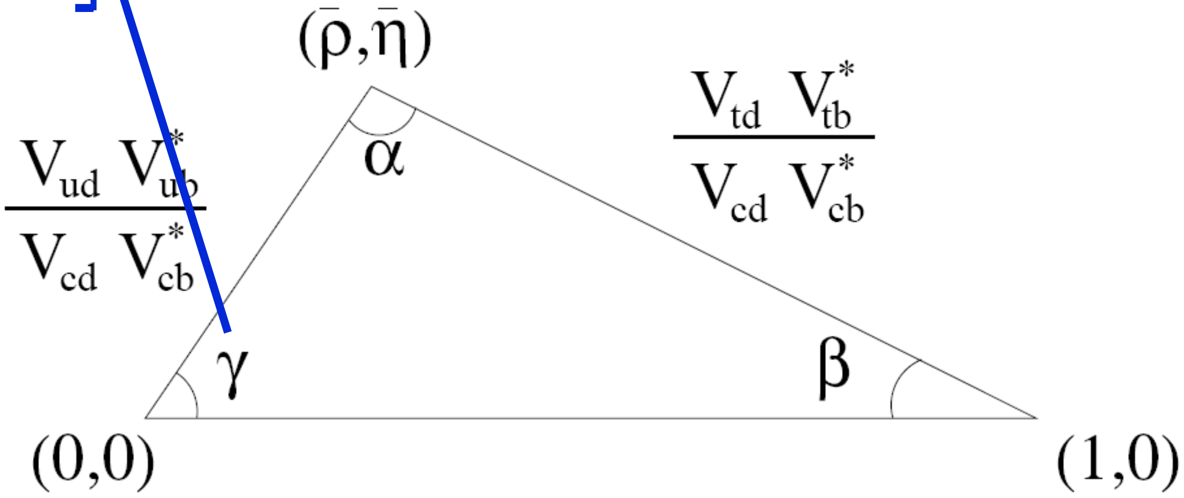
$B^0 \to D^{(*)}\rho$

$+$ *charmless*

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

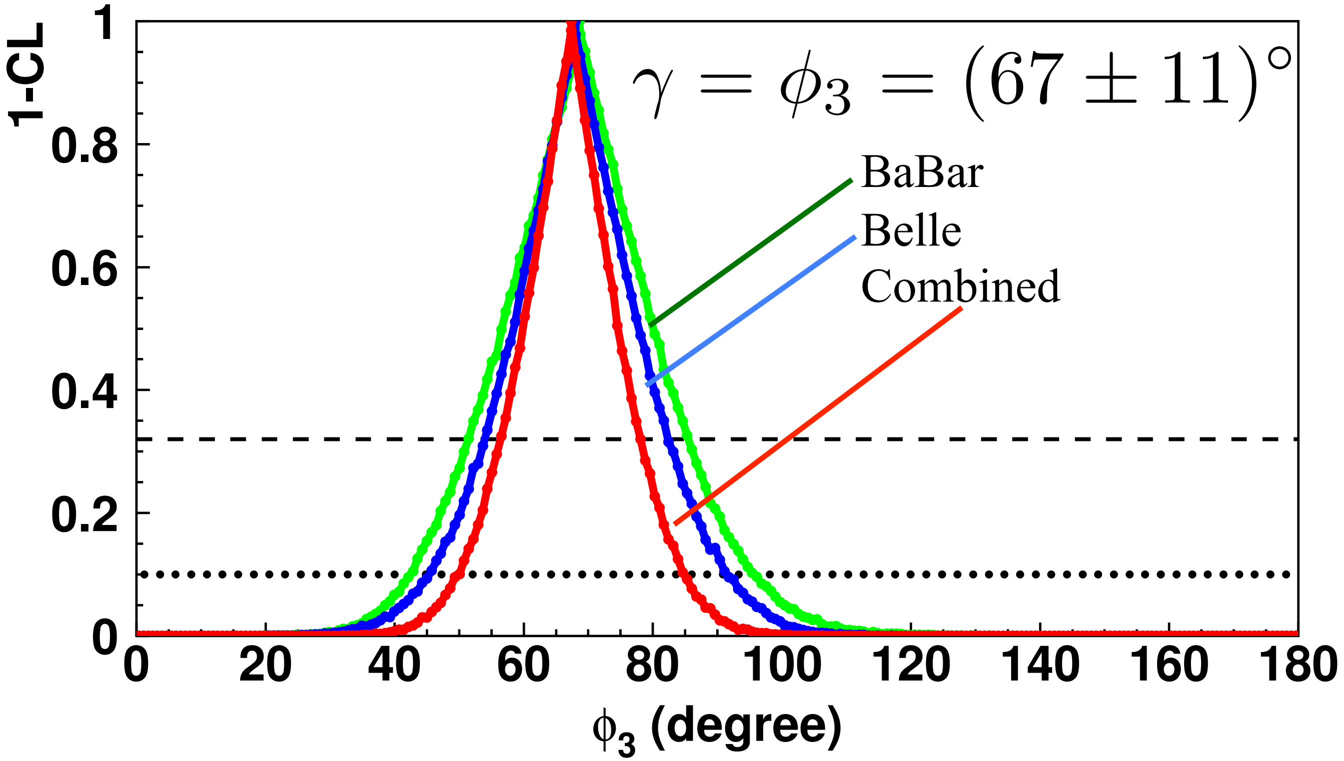
- GLW: Use CP eigen-states of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D\to K_s h^+h^-$ decays.

Measurements using neutral D mesons ignore D mixing.



γ

- As with α, there is no easy way to get a precision measurement of γ. The current methodology is to perform as many independent measurements and then determine γ from a global fit to those data.
- This will remain the case until the Belle II / LHCb upgrade era provides sufficient data for individual modes to provide 1° level precision.



*** Taken from Physics of the *B* Factories ed AB et al.**

Constraining the CKM Matrix

- There are three statistically distinct approaches that the global community works on:

CKM Fitter: (see tutorial this afternoon)
http://ckmfitter.in2p3.fr (hep-ph/0406184)
Frequentist inspired approach

Scan Method:
arXiv:1301.5867
Frequentist approach

UTfit:
http://www.utfit.org/UTfit/ (hep-ph/0501199)
Bayesian approach

If there is sufficient data to make a meaningful interpretation, then results obtained should be consistent.

Differences highlight either inadequate data, differences in the way theoretical uncertainties are treated or a mistake.

- UTfit and CKM fitter continually updated their analysis during the data taking phase of the *B* Factories.
- The Scan method results were originally given in the BaBar Physics Book, and the subsequent paper listed.

Constraining the CKM Matrix

- In summary the B Factories produced measurements of the angles of the Unitarity Triangle with the following precisions:

$$\begin{aligned}\beta &= \phi_1 = (21.30 \pm 0.78)^\circ \\ \alpha &= \phi_2 = (87 \pm 5)^\circ \\ \gamma &= \phi_3 = (67 \pm 11)^\circ\end{aligned}$$

- and the angles are consistent with a closed triangle:

$$\alpha + \beta + \gamma = (175 \pm 12)^\circ$$

- To improve upon this situation one needs:
  1. More precise measurements of γ: these are starting to be produced by LHCb.
  2. More precise measurements of α: Require Belle II.
- See the global fitter groups on the previous slide for more details on ways of combining data.

It is possible to construct CP, T and CPT asymmetries using pairs of entangled neutral B mesons. From these pairs one can test T symmetry non invariance (or motion reversal invariance[#]).

Results in kaon decays (e.g. see Kabir asymmetry) have been known for some time, and in 2012 BaBar discovered T violation in *B* decays.

T VIOLATION

Banuls & Bernabeu [PLB **464** 117 (1999); PLB **590** 19 (2000)]
Alverex & Szynkman [hep-ph/0611370]
Bernaneu, Martinez-Vidal, Villanueva-Perez [JHEP **1208** 064 (2012)]
AB, Inguglia, Zoccali, arXiv:1302.4191 [*B* and *D* decays]

[#] Following the nomenclature introduced by Klaus Schubert

- B Factory methodology: Entanglement is required in order to be able to construct a T-conjugate pair of scenarios. This comes from the wave function collapsing into the first or second time ordering:

$$\Phi = \frac{1}{\sqrt{2}}\left(P_1^0 \overline{P}_2^0 - \overline{P}_1^0 P_2^0\right)$$

- Hence one can compare rates of these two time orderings if we can identify T conjugate pairs of filters.

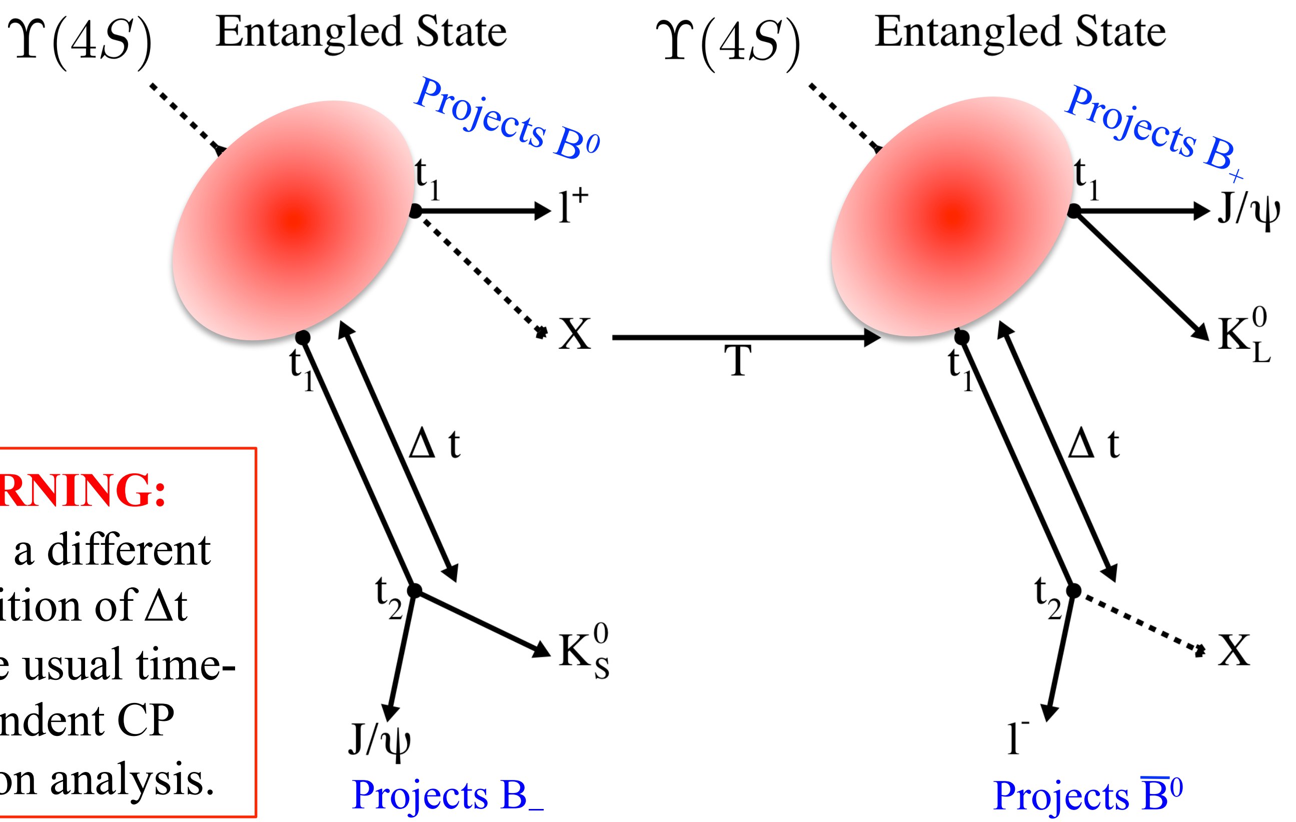
$$A_T = \frac{P(|i\rangle \to |f\rangle) - P(|f\rangle \to |i\rangle)}{P(|i\rangle \to |f\rangle) + P(|f\rangle \to |i\rangle)}$$

- Any two pairs of orthonormal basis vectors would do, but one uses flavour ($B^0, \overline{B}^0$) and CP filters (B_+, B_-) as these are experimentally "meaningful" projections.

Formalism

- What do we compare?
  - T conjugate pairs of *B* meson decays.

$$\overline{B}^0 \longrightarrow B_- \qquad\qquad B_- \longrightarrow \overline{B}^0$$



WARNING:
This is a different definition of Δt from the usual time-dependent CP violation analysis.

$$\Delta t = t_2 - t_1$$

- T-conjugate pairings:

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\overline{B}^0 \to B_-$	$(\ell^+ X, J/\psi K_S)$	$B_- \to \overline{B}^0$	$(J/\psi K_L, \ell^- X)$
$B_+ \to B^0$	$(J/\psi K_S, \ell^+ X)$	$B^0 \to B_+$	$(\ell^- X, J/\psi K_L)$
$\overline{B}^0 \to B_+$	$(\ell^+ X, J/\psi K_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K_S, \ell^- X)$
$B_- \to B^0$	$(J/\psi K_L, \ell^+ X)$	$B^0 \to B_-$	$(\ell^- X, J/\psi K_S)$

- Similarly CP and CPT conjugate parings can be defined (see Banuls & Bernabeu).

- Can study the time-evolution in the context of the "usual" B Factory time-dependent analysis methodology.

Time-evolution

- Assuming ΔΓ=0 (good for B_d decays)

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

Time-evolution

- Assuming ΔΓ=0 (good for B_d decays)

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

$$\alpha \in \{\ell^+, \ell^-\}$$

$$\beta \in \{K_S, K_L\} \text{ i.e. } CP = \pm 1$$

Time-evolution

- Assuming $\Delta\Gamma=0$ (good for B_d decays)

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

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

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

$$\alpha \in \{\ell^+, \ell^-\}$$

$$\beta \in \{K_S, K_L\} \text{ i.e. } CP = \pm 1$$

- 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.

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

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

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

$$\alpha \in \{\ell^{+}, \ell^{-}\}$$

$$\beta \in \{K_S, K_L\} \text{ i.e. } CP = \pm 1$$

- 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.

Time-evolution

- Physical distribution is

$$h^{\pm}_{\alpha,\beta}(\Delta t) \propto (1-\omega_\alpha)g^{\pm}_{\alpha,\beta}(\Delta t) + \omega_\alpha g^{\pm}_{\overline{\alpha},\beta}(\Delta t)$$

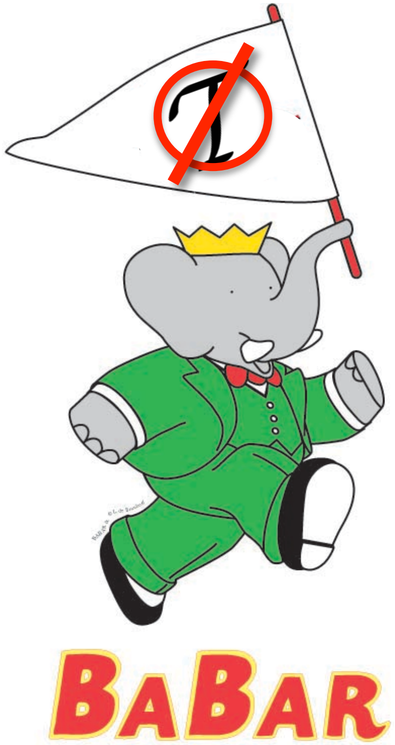
- In reality one has to account for detector resolution to obtain the asymmetry A_T.

$$A_T \simeq \frac{\Delta C_T^{\pm}}{2}\cos\Delta m\Delta t + \frac{\Delta S_T^{\pm}}{2}\sin\Delta m\Delta t$$

- In the SM (for the charmonium modes)

$$\Delta S_T^{\pm} = \mp 2\sin 2\beta$$

- Hence, expect $|\Delta S^{\pm}| \sim 1.4$, and similarly expect $\Delta C^{\pm} \sim 0$.


BABAR

Event Selection: CP filters

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

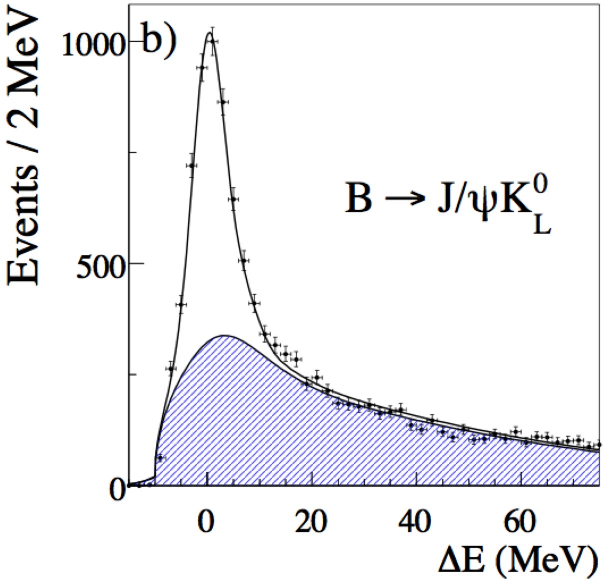
- CP even filter:

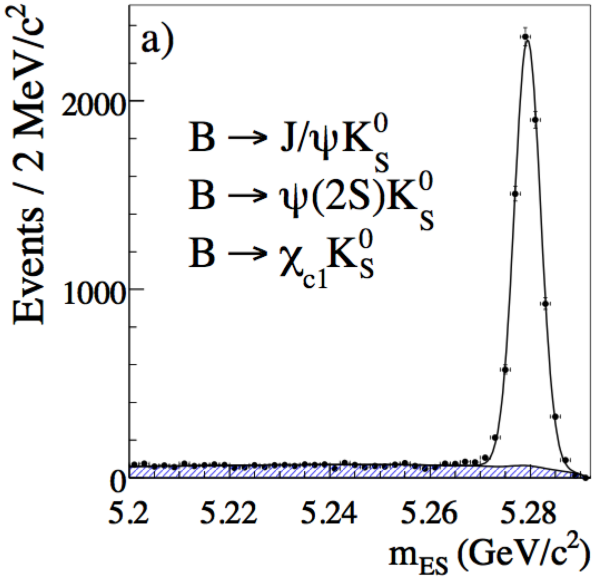
$$B \rightarrow J/\psi K_L$$

- CP odd filters:

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

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



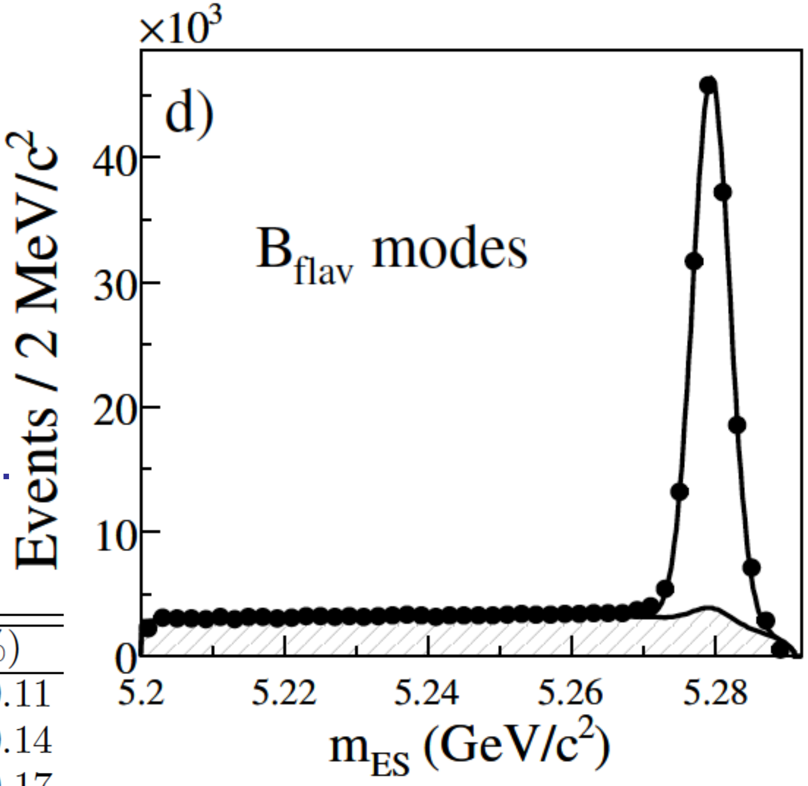


Event Selection: Flavor filters

- The same as for the sin2β CPV measurement in *Phys.Rev. D**79**:072009 (2009)*
- The set of "tag" modes used is:

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

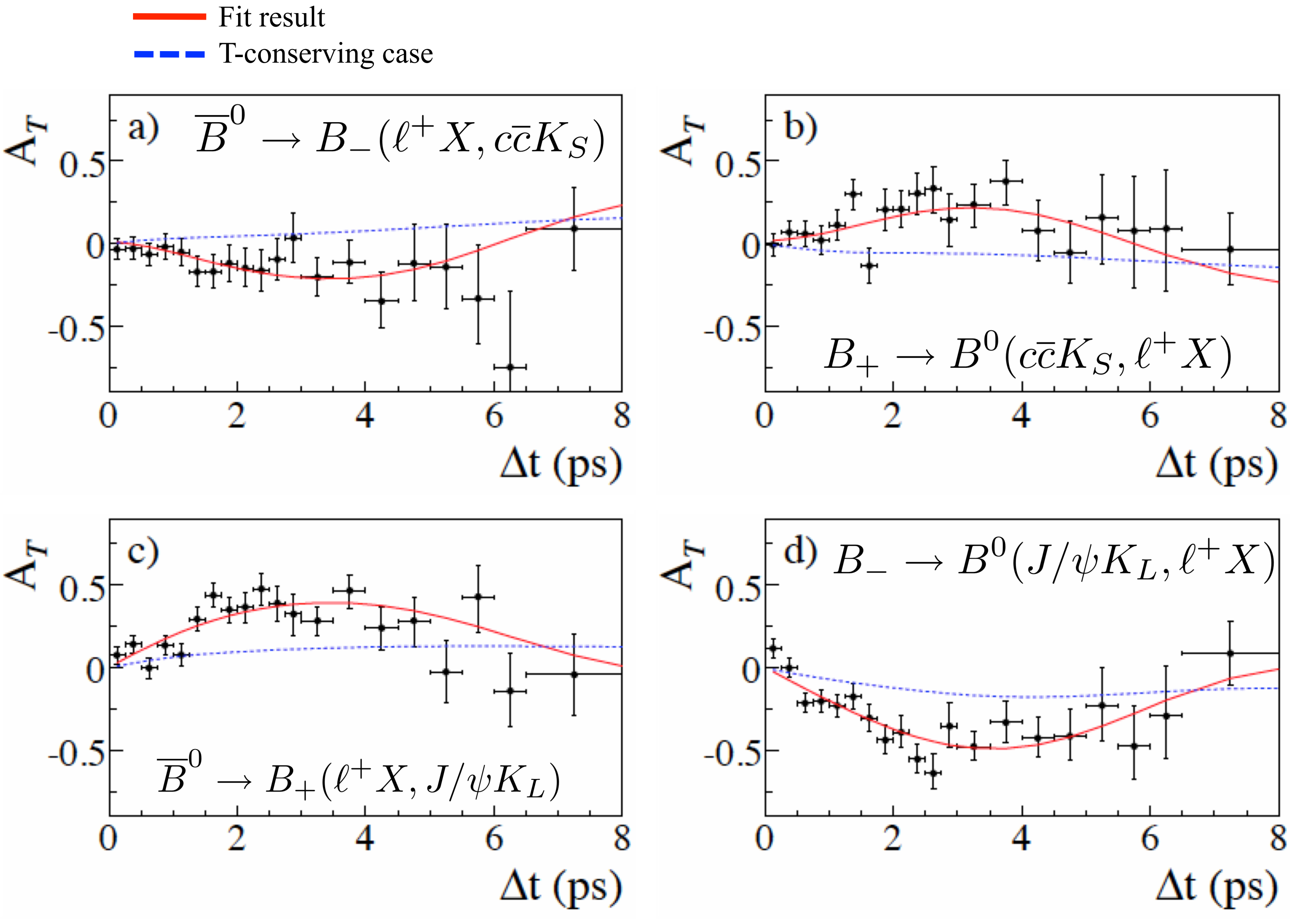
- which characterise "tag" performance and give the $B^0(\overline{B}^0)$ filter projections.



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



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

Experimental results

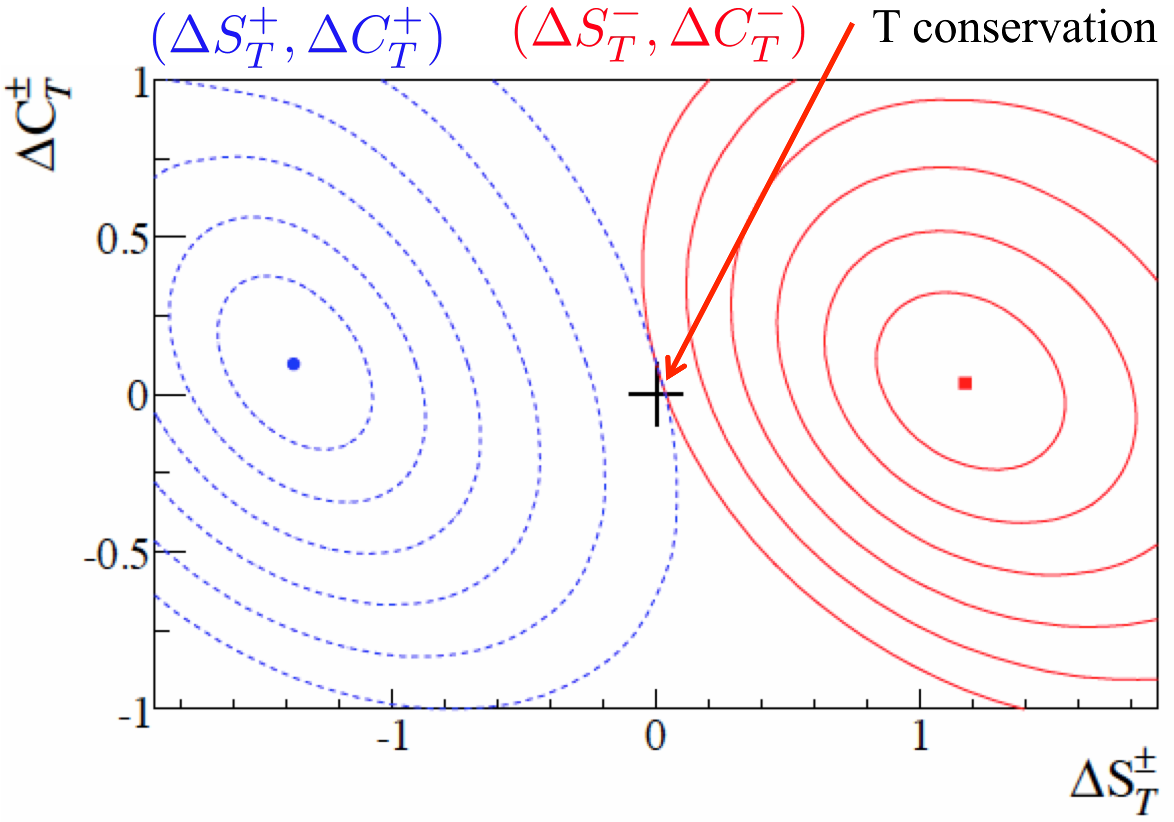
Parameter	Result
$\Delta S_T^+ = S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C^+_{\ell^-,K_L^0} -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

- Observed level of T -violation balances CP violation.
- First direct measurement of T violation in *B* decays.
- CP asymmetry is also evident (c.f. traditional measurements).
- CPT symmetry test is consistent with CPT conservation.

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

Experimental results

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



- Fit result is 14σ from the T conserving case (assuming 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

- Recall that ΔS± are related to sin2β, so we can compare CP violation with T non-invariance for this parameter:

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

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

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

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

- As expected all results of β are in agreement with each other, however a more precise comparison of these results is called for.
- 6 years after data taking stopped, novel measurements are still coming out of BaBar.
- arXiv:1302.4191 we outline a programme of similar measurements that can be made in *B* and *D* decays.

Experimental results

- Recall that ΔS± are related to sin2β, so we can compare CP violation with T non-invariance for this parameter:

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

Note: Need to avoid final states with strong interactions for these measurements. The strong interaction conserves T, and the weak interaction violates it, and it is important to know what you are measuring...

- arXiv:1302.4191 we outline a programme of similar measurements that can be made in *B* and *D* decays.

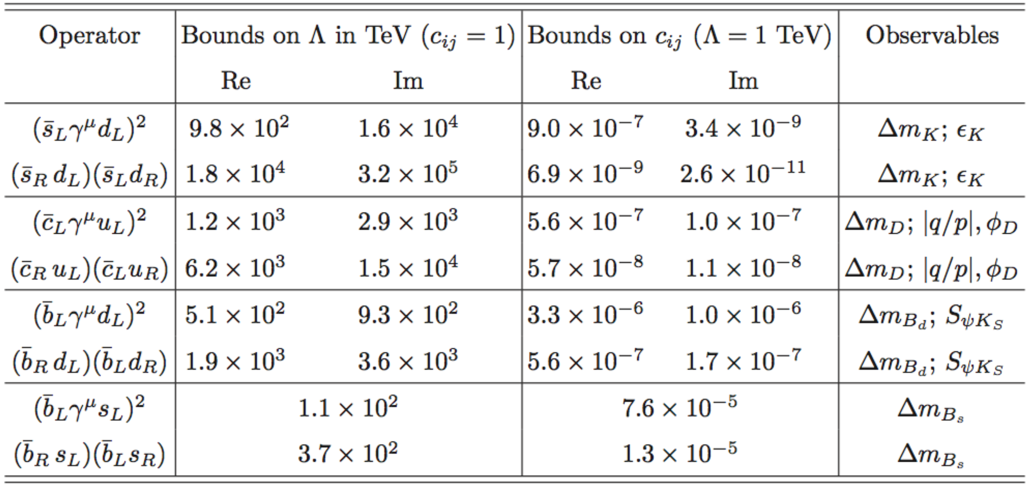
The intensity frontier is built on interferometry tests of rare Standard Model processes beating against some hypothetical new physics (or searches for Standard Model forbidden processes). Thus high energy scales are accessible via this route.

Rare decays can teach us about NP via their contribution to the interaction Lagrangian via: terms of order $\frac{c}{\Lambda^2_{NP}}$

(Semi-) RARE DECAY CONSTRAINTS ON NEW PHYSICS

What can we infer about Λ_{NP}?

- e.g. see arXiv:1002.0900 for a recent interpretation
  - The LHC has failed to find evidence for new physics, so we don't have a scale to set.
  - Flavor processes can be used to constrain $\frac{c}{\Lambda^2_{NP}}$.

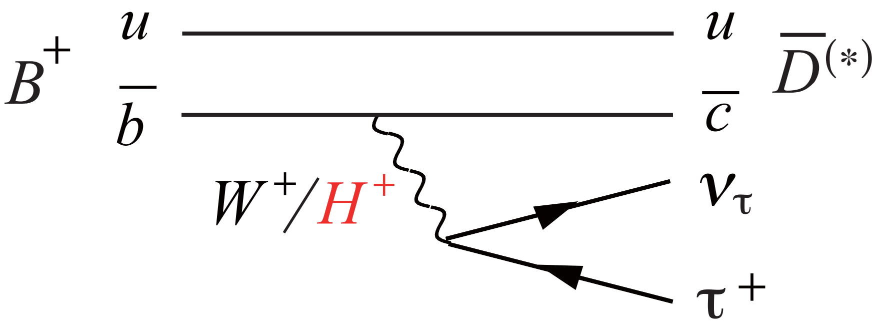


Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

  - For c~1, $\Lambda_{NP}<10^2 – 10^5$.
  - For Λ_{NP} c $<10^{-5}$ (very different from typical SM couplings).
  - i.e. we can constrain the c vs Λ^2 plane using certain rare decays.

Example: $B \to D^{(*)}\tau\nu$

- Analogous to $B \to \tau\nu$ this channel is sensitive to charged Higgs particles in the 2HDM/SUSY family of extensions of the SM.



- Measurement of the rate of these channels can be used to infer compatibility with the SM (or not), and constrain model parameters (such as tanβ[#] and m_H).

[#] The ratio of Higgs vacuum expectation values.

Example: $B \to D^{(*)}\tau\nu$

- The effective Hamiltonian for this decay is

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{\mathrm{qb}} \{[\overline{q}\gamma^{\mu}(1-\gamma_5)b][\overline{\tau}\gamma_{\mu}(1-\gamma_5)\nu_{\tau}] - \frac{M_b M_{\tau}}{M_B^2}\overline{q}[g_S + g_P\gamma_5]b[\overline{\tau}(1-\gamma_5)\nu_{\tau}]\} + \mathrm{h.c.}$$

- and the couplings g_s and g_p in MSSM are

$$g_S = g_P = \frac{M_B^2 \tan^2\beta}{M_H^2} \frac{1}{(1+\epsilon_0 \tan\beta)(1-\epsilon_{\tau}\tan\beta)}$$

- The decay rate depends on knowledge of form factors, which are model dependent; however experimentally one can take a ratio of τ to e, μ states to remove the form factor dependence.
- The experimental robustness is equally carefully thought out, minimising the dependence on observables that are not well understood by control sample verification of the Monte Carlo validation.

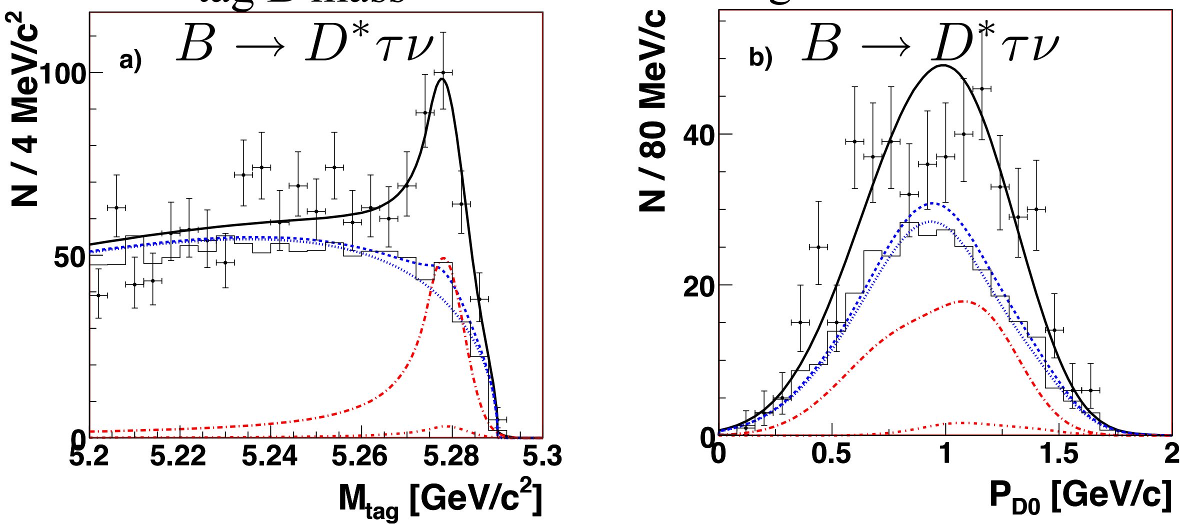
WARNING: There are many rare decay searches for new physics, but these two points are key (i) the observable should be theoretically clean and (ii) the experimental method should be as robust as possible. Otherwise any observed deviation from the SM will be dismissed as a problem with theory/analysis method, or both [e.g. see ΔA_{CP} measurements in charm].

Example: $B \rightarrow D^{(*)}\tau\nu$

- Thus we measure

$$\mathcal{R}_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}$$

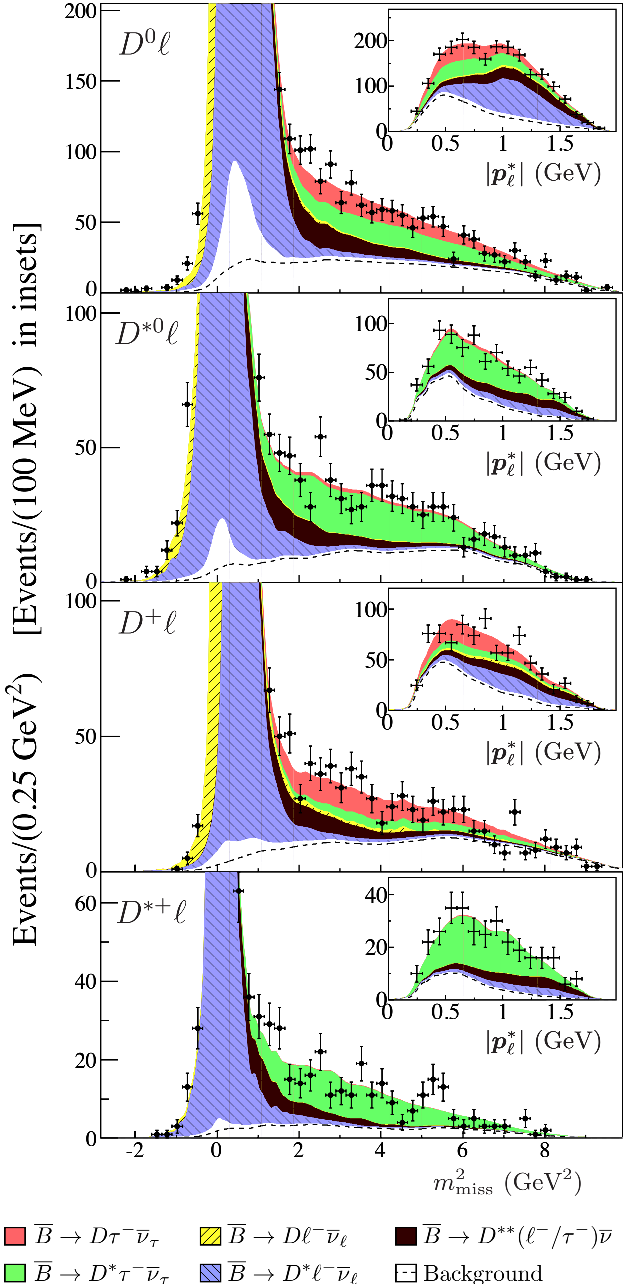
- To isolate these decays events are fully reconstructed, and the missing energy of the neutrino m_{miss} provides the most powerful discriminant against background.
- The tag B mass and $D^{(*)}$ momentum are also used.



tag B mass

signal D^0 momentum

Example: $B \to D^{(*)}\tau\nu$



- Isolation of the signal (red /green) depends on having a good understanding of the normalisation modes.
- The fit results, using an Isospin constraint are:

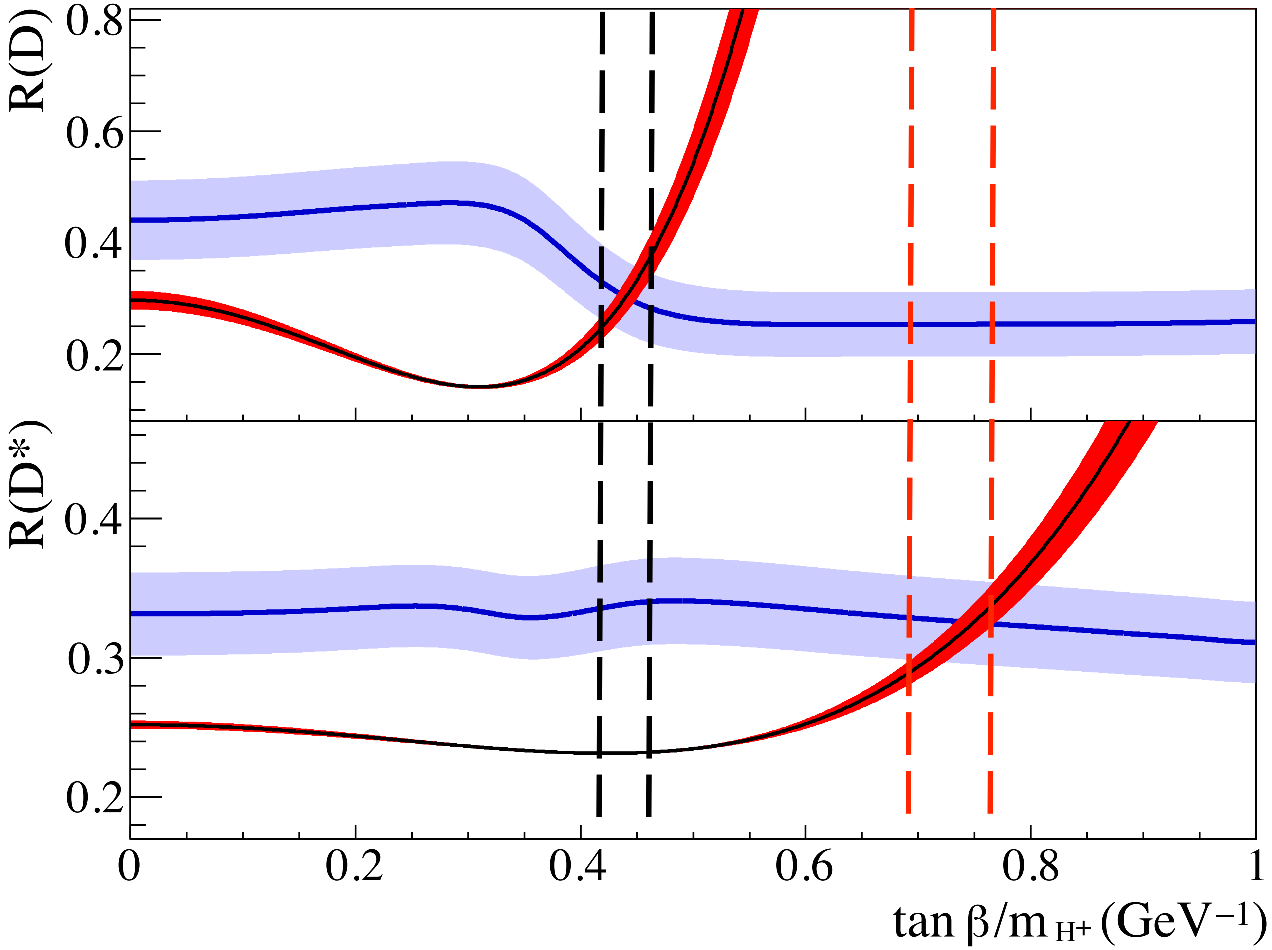
$$\mathcal{R}(D) \quad = \quad 0.440 \pm 0.058 \pm 0.042 \ [BaBar]$$

$$\mathcal{R}(D^*) \quad = \quad 0.332 \pm 0.024 \pm 0.018 \ [BaBar]$$

- A full breakdown of values obtained from the experiments (incl. no I-spin constraint) can be found at the end of these lectures.

Example: $B \rightarrow D^{(*)}\tau\nu$

- Constraining 2HDM (type II) using these modes is done as a function of the ratio of tanβ and m_H .



Preferred values of m_H/tanβ differ from each other by 3.4σ.

Equivalent constraints from B to τν prefer values of this ratio < 0.1.

The type II 2HDM variant is not consistent with flavour data; so here we provide important feedback to the LHC GPD programme.

CHARGED Lepton Flavour Violation (LFV)

LFV

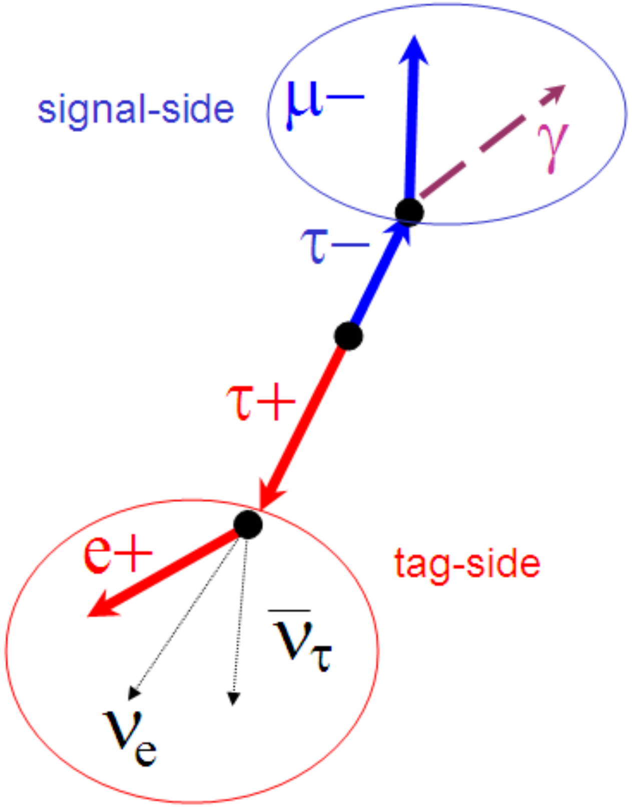
- Like CLEO before, the B Factories have surveyed a wide range of charged Lepton Flavour Violating decays.
  - Why? Quarks change flavour, neutrinos mix, so why can't a charged lepton change flavour. Many theories beyond the Standard Model allow for this.
- Methodology:
  - As with B mesons, a pair of τ leptons are created in collisions. Each have exactly half of the total energy of the CM system.
  - The charged lepton final states of interest don't have missing energy, e.g.

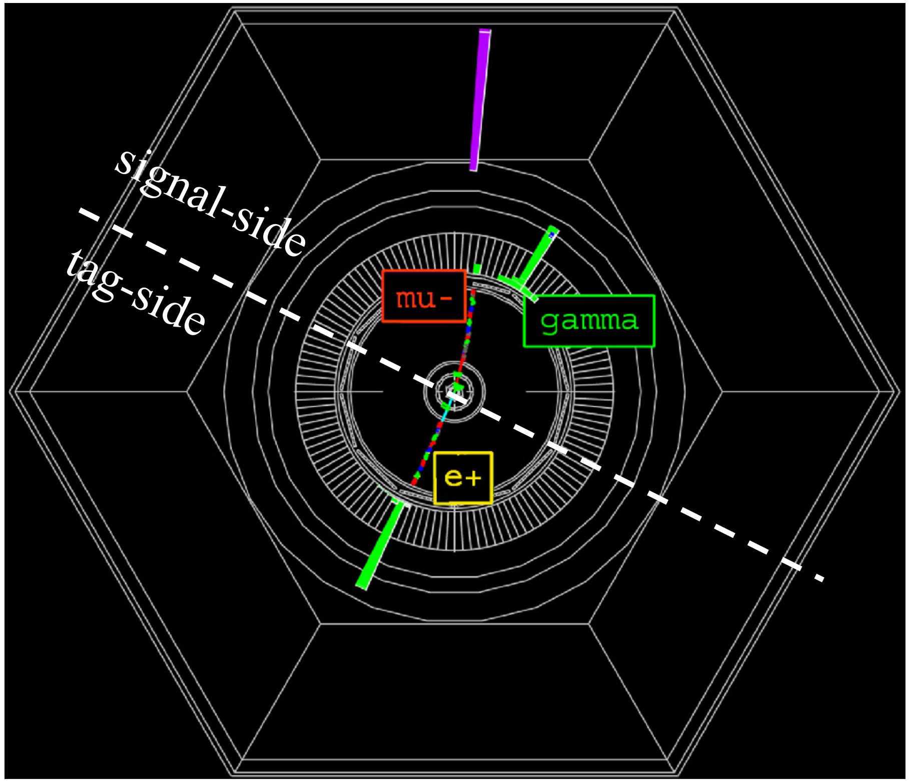
$$\tau^{\pm} \to \ell^{\pm}\gamma, \ell^{\pm}\ell^{\pm}\ell^{\mp}, \ldots$$

  - This provides a powerful kinematic constraint used to suppress combinatoric backgrounds.
  - Analyses are performed blind to avoid bias.

Example: $\tau^{\pm} \to \mu^{\pm}\gamma$

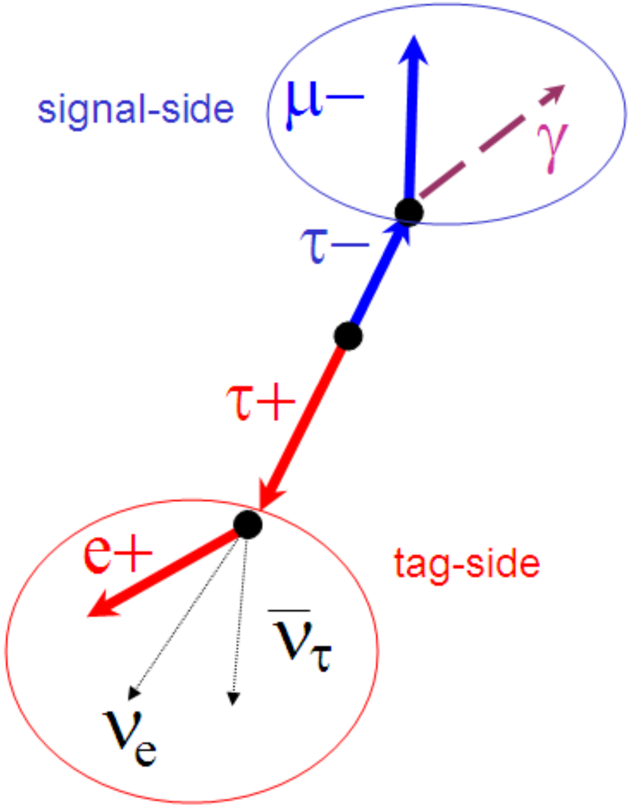
- The events are fully reconstructed, as shown below:

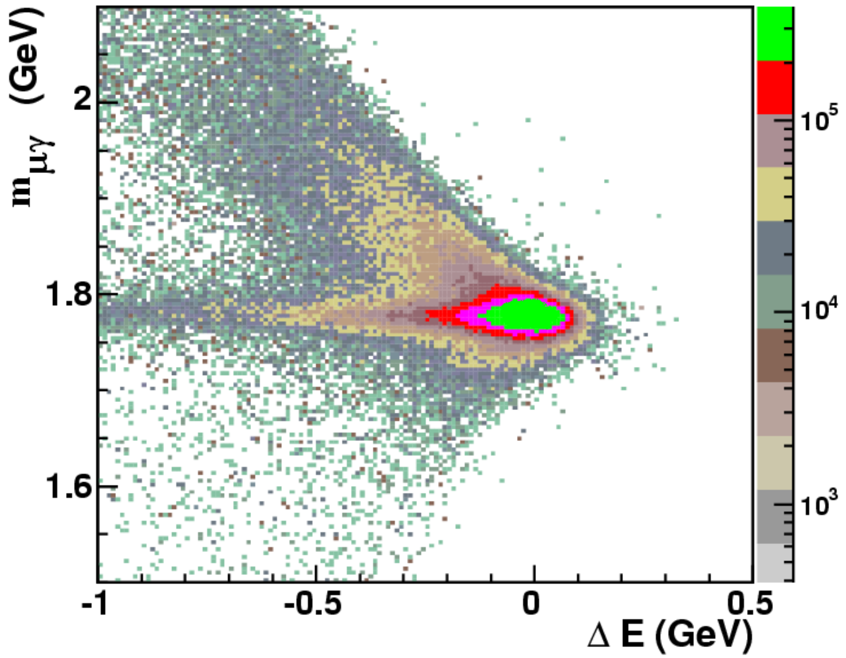




Example: $\tau^{\pm} \rightarrow \mu^{\pm}\gamma$

- The events are fully reconstructed, as shown below:



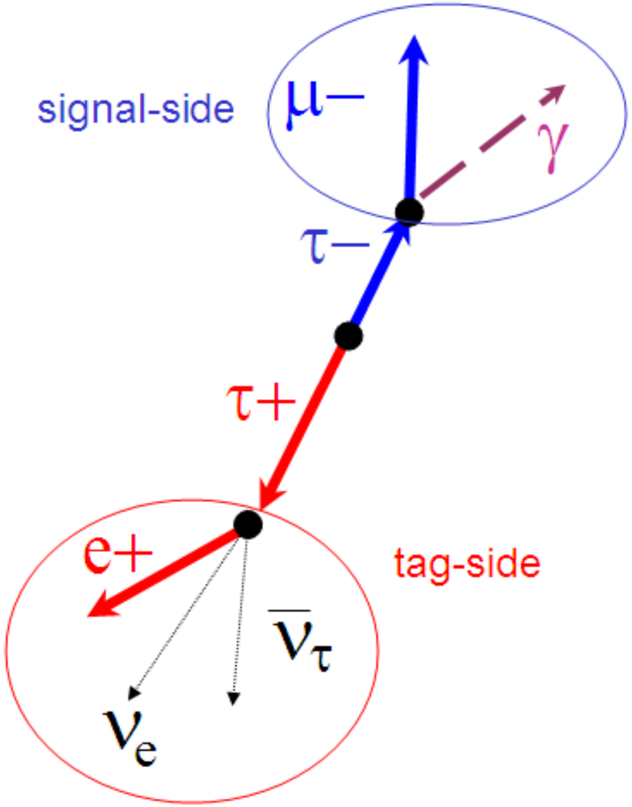


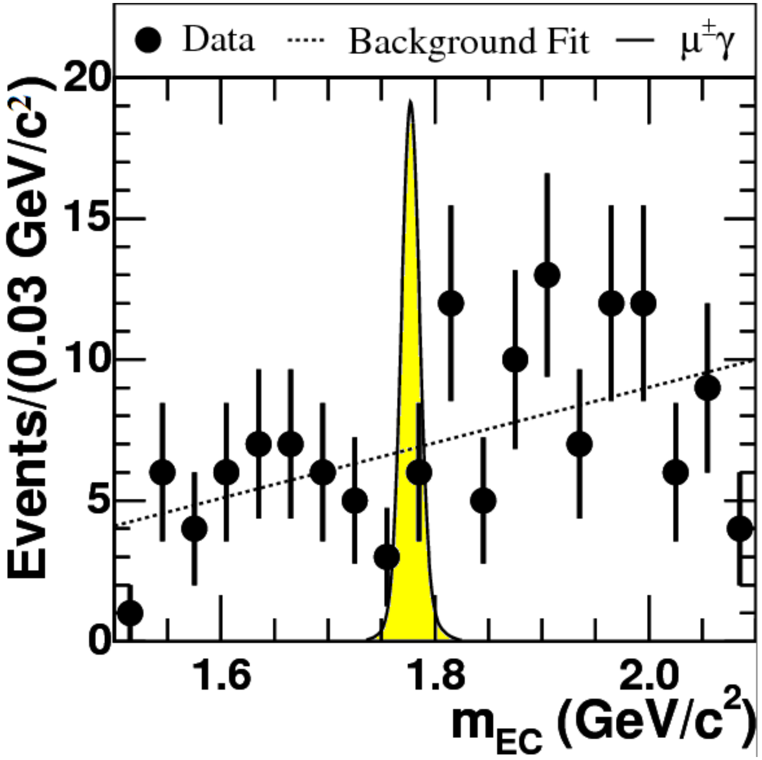
The plot on the right hand side shows the reconstructed τ mass and ΔE variable (the difference between the reconstructed τ energy and half of the total energy in the CM system. This is signal Monte Carlo, and it strongly peaks for m_τ~1.8 GeV and ΔE~0 GeV.

Combinatoric background will be spread across this plane, and mis-reconstructed τ events will peak away from the signal region. This mode should be background free up to ~50-100ab^{-1}.

Example: $\tau^{\pm} \to \mu^{\pm}\gamma$

- The events are fully reconstructed, as shown below:

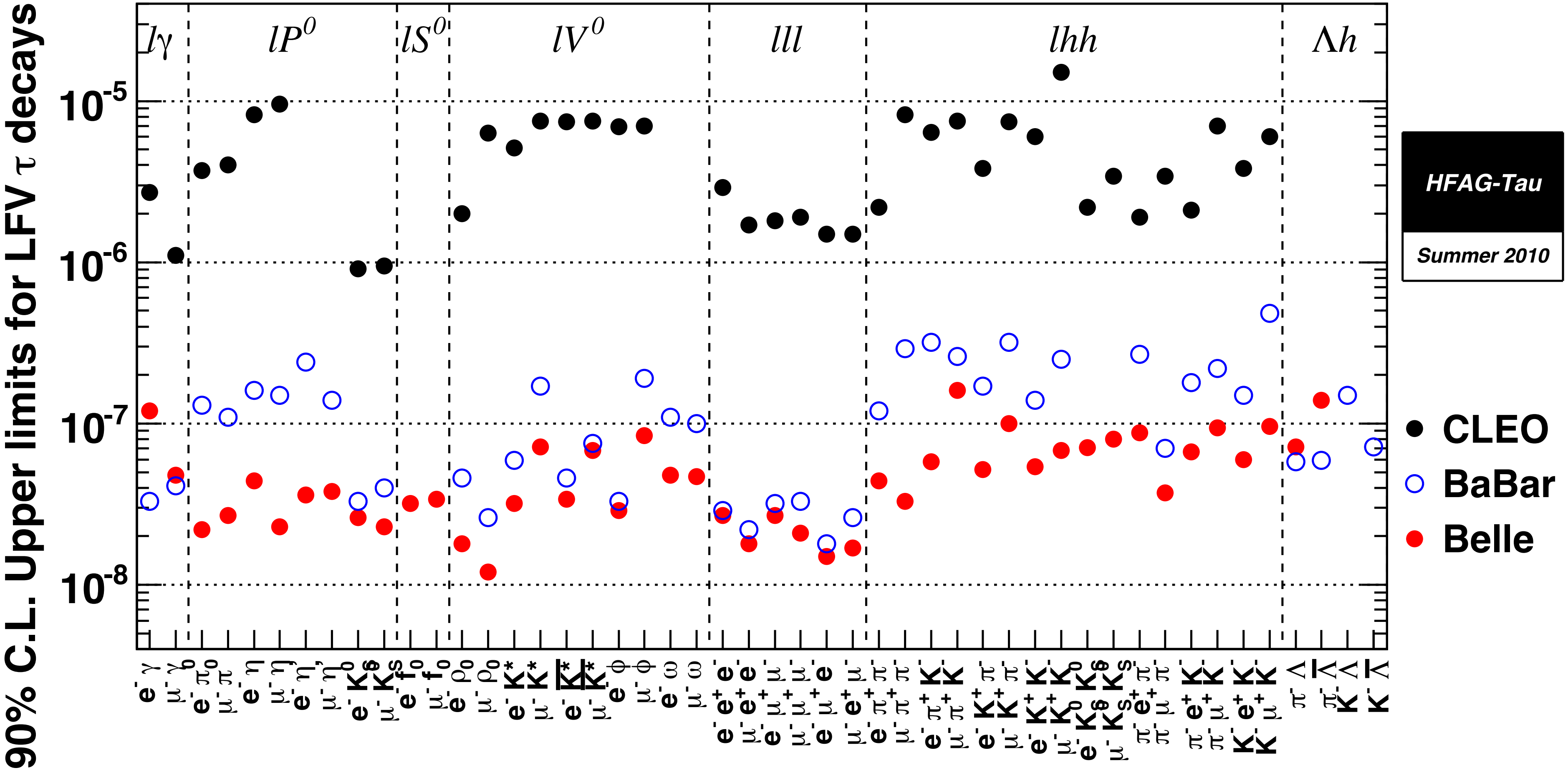


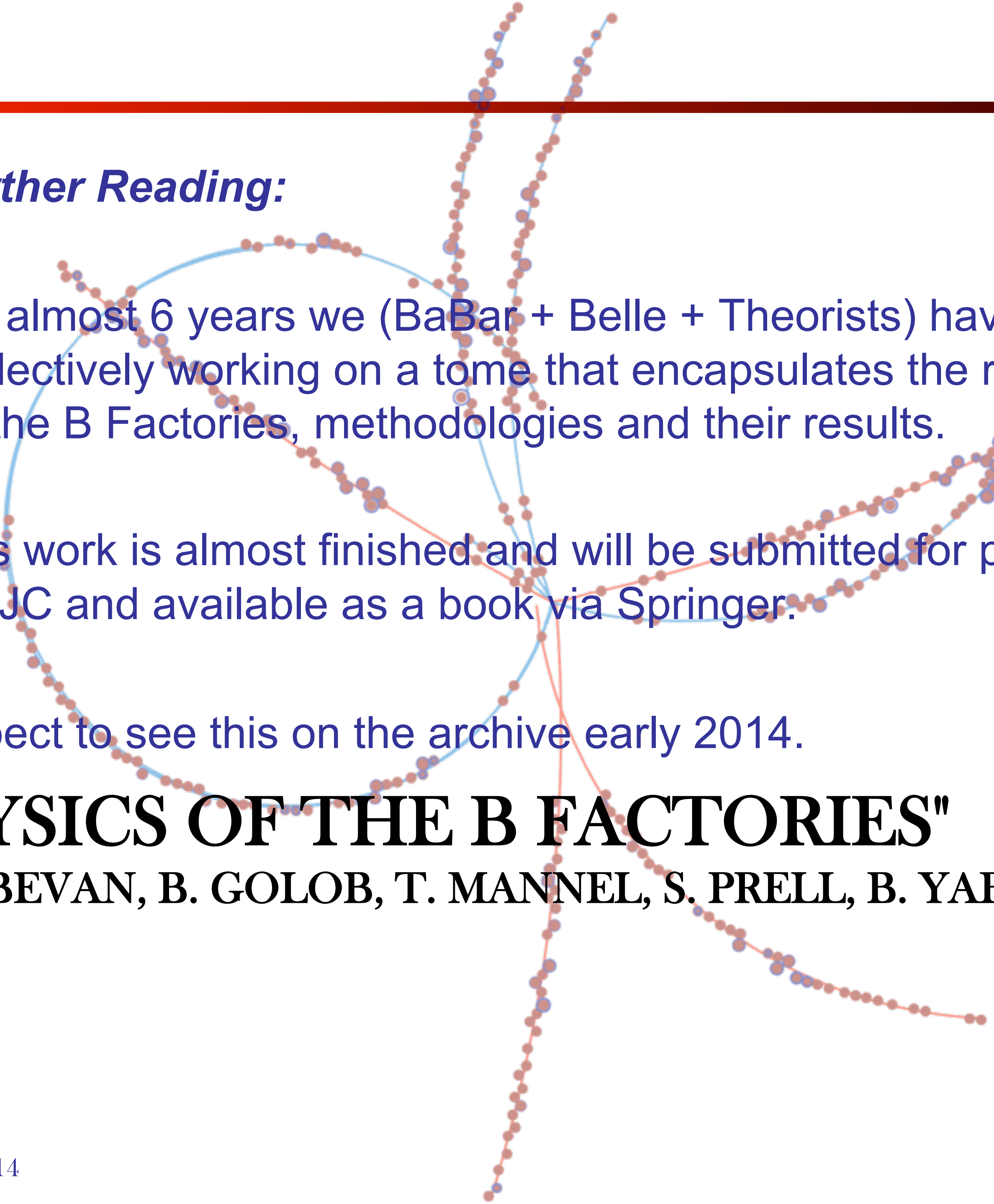


- The background is scattered away from the optimised signal region, and on unblinding a result consistent with no signal was found.

LFV

- A large number of searches have been performed, and no signals found.





Further Reading:

For almost 6 years we (BaBar + Belle + Theorists) have been collectively working on a tome that encapsulates the raison d'être of the B Factories, methodologies and their results.

This work is almost finished and will be submitted for publication in EPJC and available as a book via Springer.

Expect to see this on the archive early 2014.

"PHYSICS OF THE B FACTORIES"

ED A. BEVAN, B. GOLOB, T. MANNEL, S. PRELL, B. YABSLEY

THE FUTURE

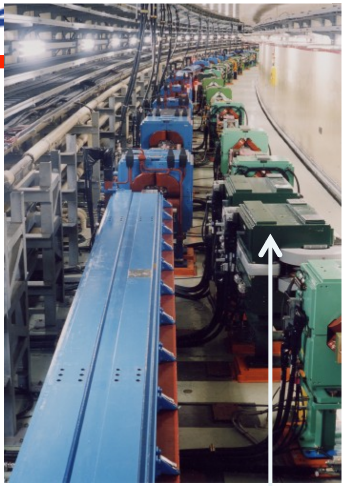
Belle II and Super KEKB

- The KEK based *B* Factory is being upgraded to a Super Flavor Factory.
  - Aim: accumulate 50ab^{-1} of data by ~2023 for precision flavour physics using an evolution of recent accelerator technology.

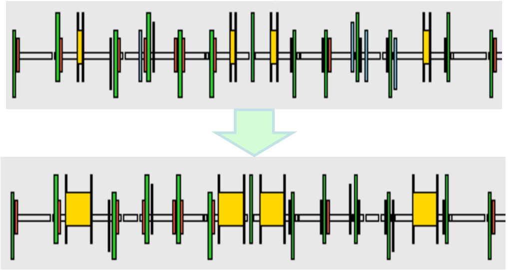
  - Construction is underway and data taking should commence next year.

C/O Peter Krizan

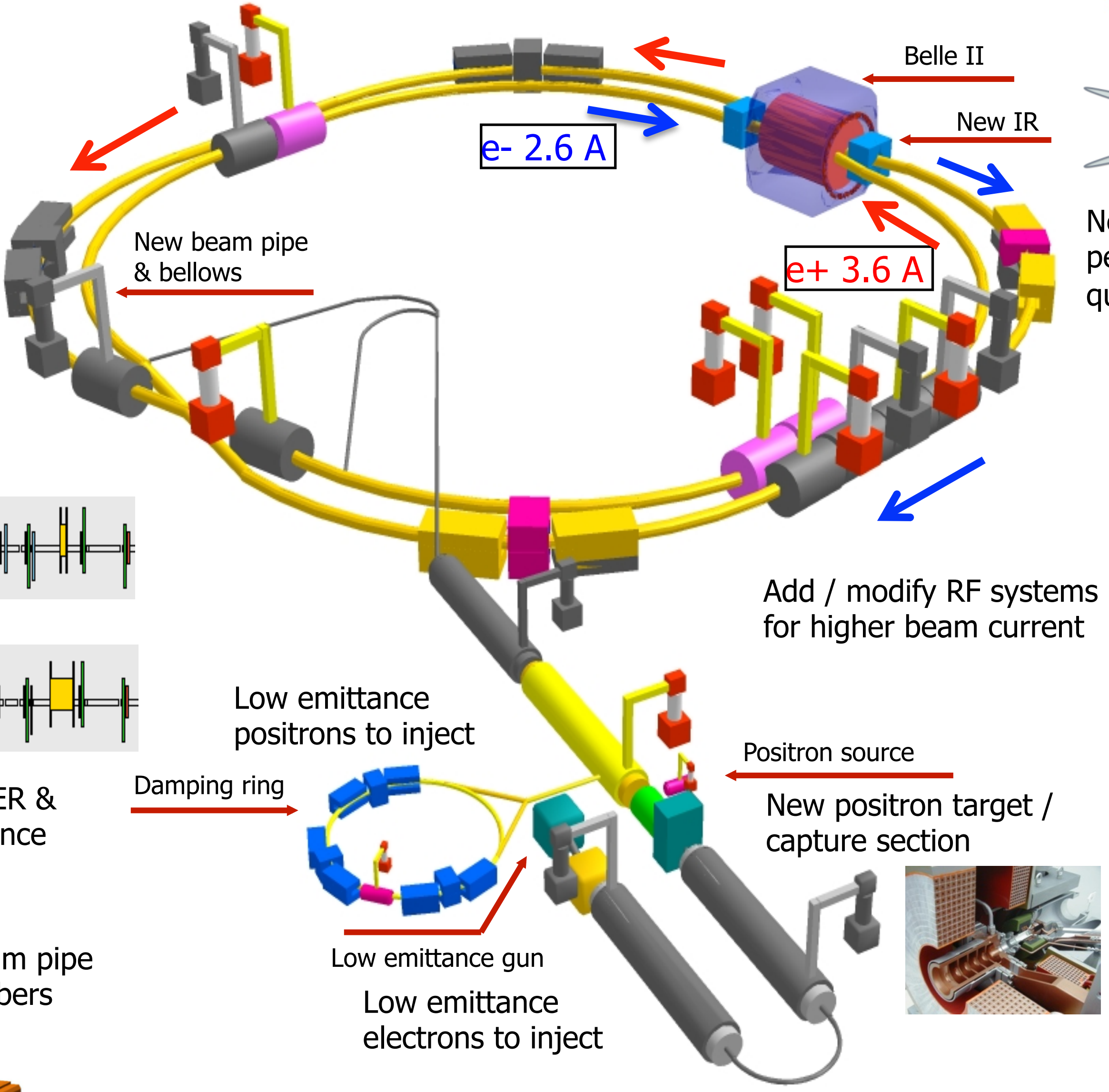
KEKB to SuperKEKB



Replace short dipoles
with longer ones (LER)



Redesign the lattices of HER &
LER to squeeze the emittance

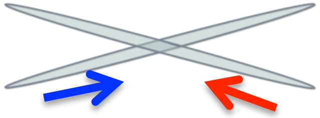


Low emittance
positrons to inject

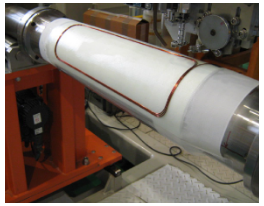
New positron target /
capture section

Low emittance
electrons to inject

Colliding bunches

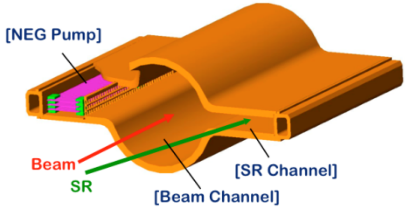


New superconducting /
permanent final focusing
quads near the IP



Add / modify RF systems
for higher beam current

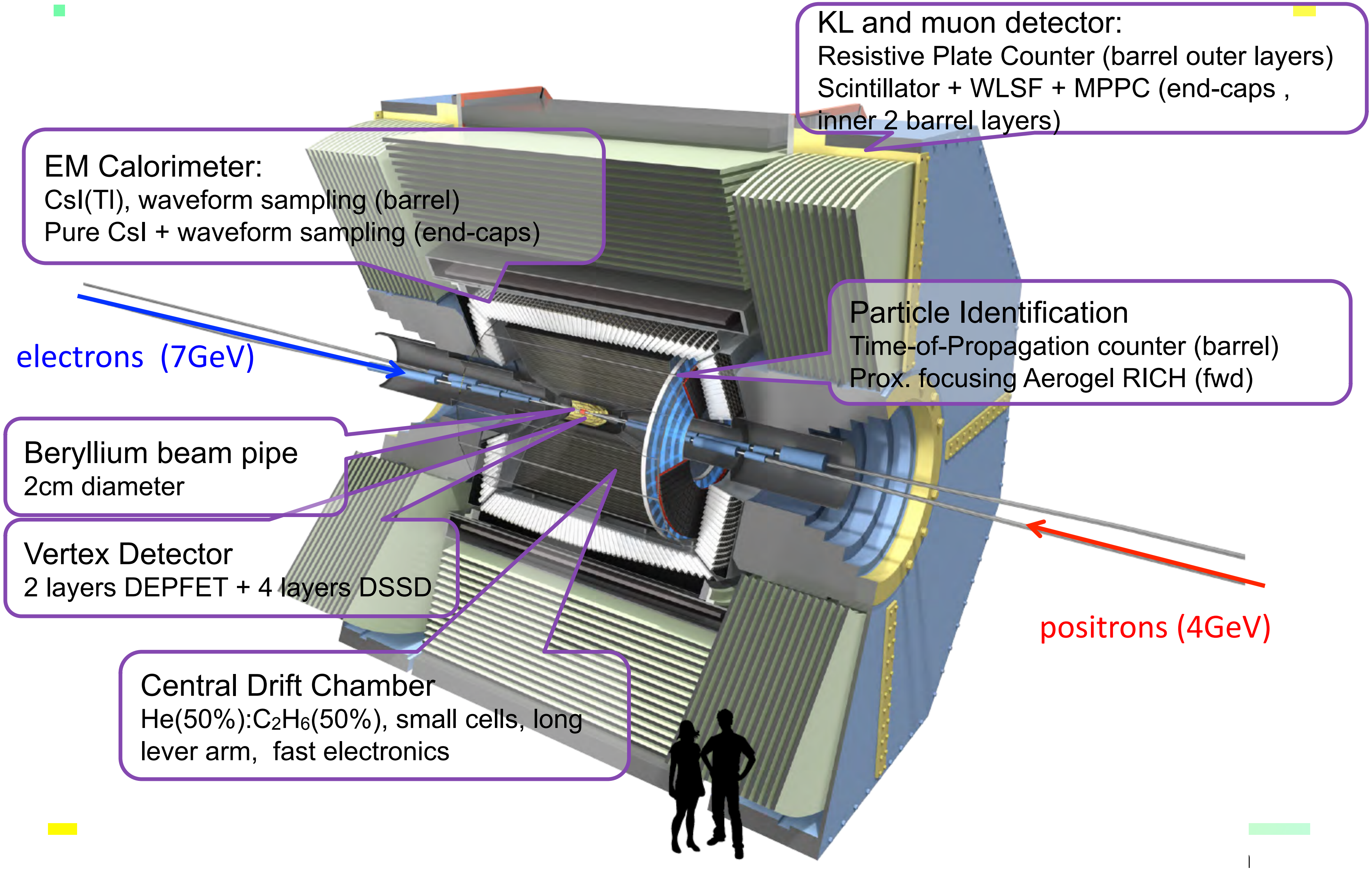
TiN-coated beam pipe
with antechambers



To obtain x40 higher luminosity

C/O Peter Krizan

Belle II Detector



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

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

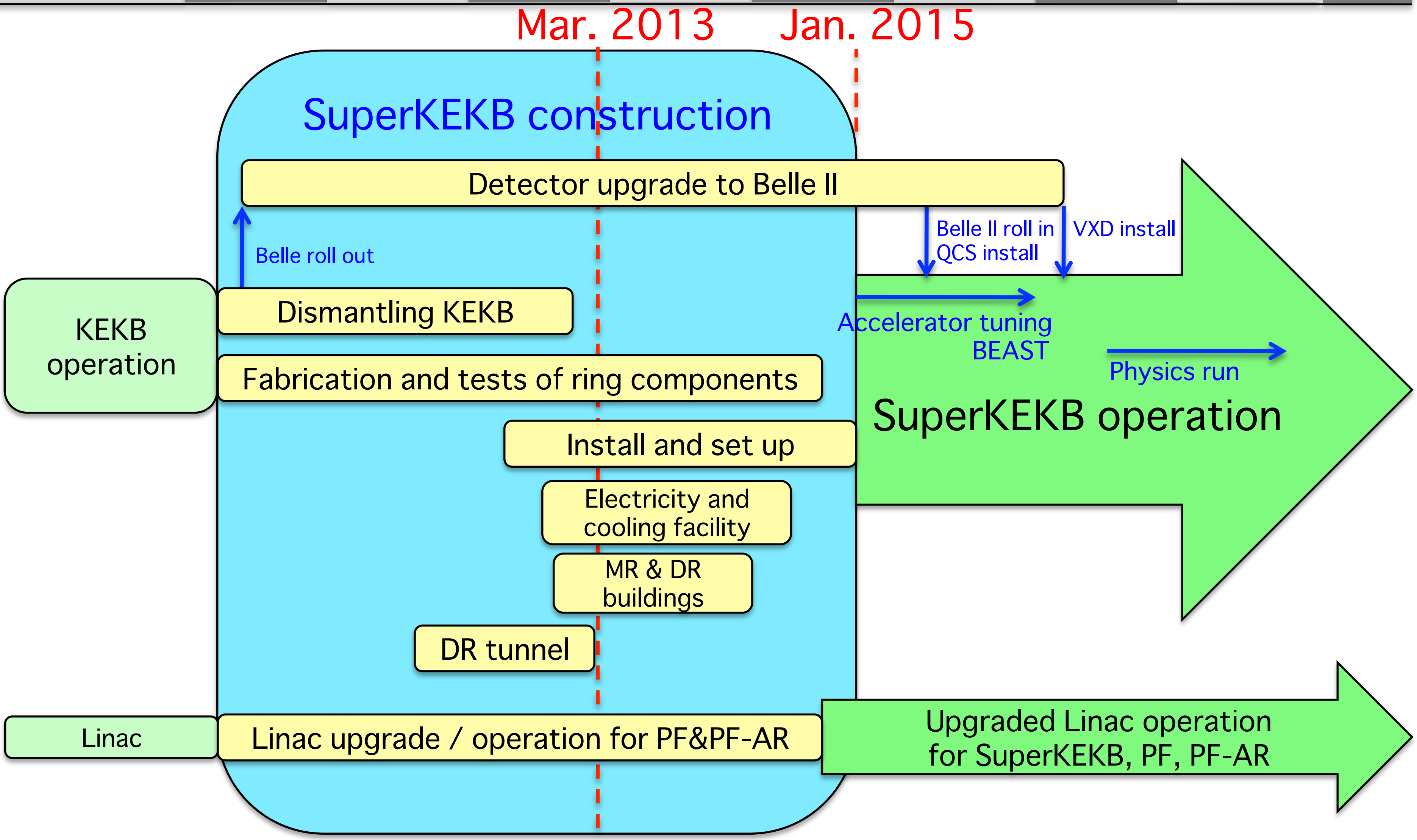
positrons (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

C/O Peter Krizan

SuperKEKB/Belle II schedule

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



Mar. 2013

Jan. 2015

SuperKEKB construction

Detector upgrade to Belle II

Belle roll out

Belle II roll in

QCS install

VXD install

KEKB operation

Dismantling KEKB

Fabrication and tests of ring components

Install and set up

Electricity and cooling facility

MR & DR buildings

DR tunnel

Accelerator tuning

BEAST

Physics run

SuperKEKB operation

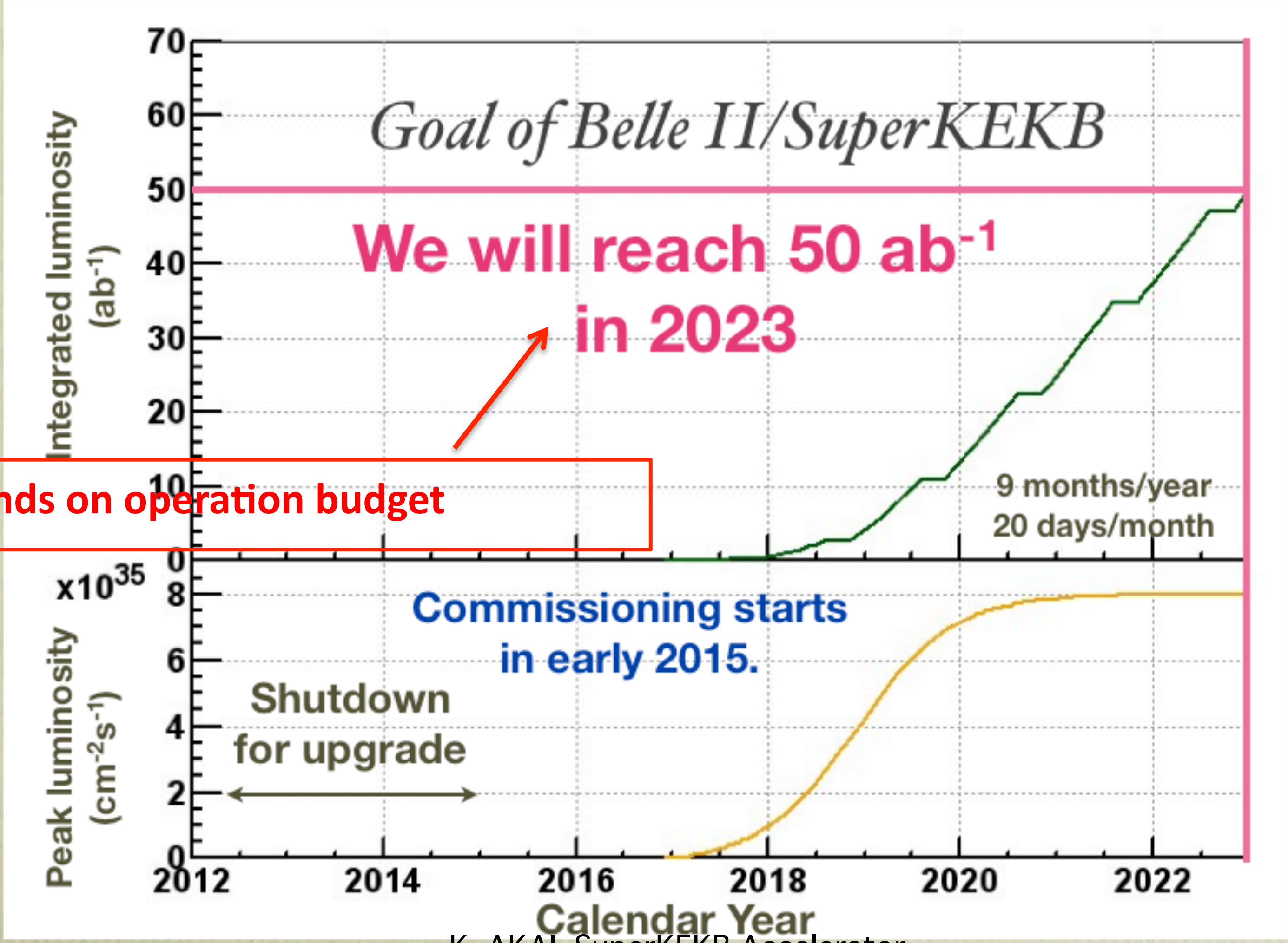
Linac

Linac upgrade / operation for PF&PF-AR

Upgraded Linac operation for SuperKEKB, PF, PF-AR

C/O Peter Krizan

SuperKEKB luminosity projection



Depends on operation budget

K. AKAI, SuperKEKB Accelerator Status, Nov. 12, 2012, 13th B2GM, KEK

SUMMARY

- The B Factories started to take data in 1999, and stopped at the end of the last decade.
  - They discovered CP violation in B_d and B_u systems, charm mixing and started a revival of charm meson spectroscopy that is a vibrant field at the LHC and further afield.
  - They developed analysis tools that are now common place in the community (RooFit/TMVA etc).

- Almost a thousand papers have been published from these experiments, with thousands of measurements having been made.

- A sample of more recent results has been given here.

- Anyone interested in learning more should take a look at the Physics of the *B* Factories book when it is released soon.

- The Belle II experiment is picking up where BaBar and Belle left off. Data taking should start in 2015.

and finally…

- July 10th marks the 50th anniversary of the submission of the 1964 discovery.
  - There will be a 2 day workshop at QMUL on the 10th and 11th July to celebrate CP violation measurements over the past (and next) five decades.

  - More information can be found at:

http://pprc.qmul.ac.uk/research/50-years-cp-violation

Technical details: luminosity, Belle II

Time-dependent CP violation measurements

Isospin analysis use for measuring the Unitarity Triangle angle α

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

Charm Mixing

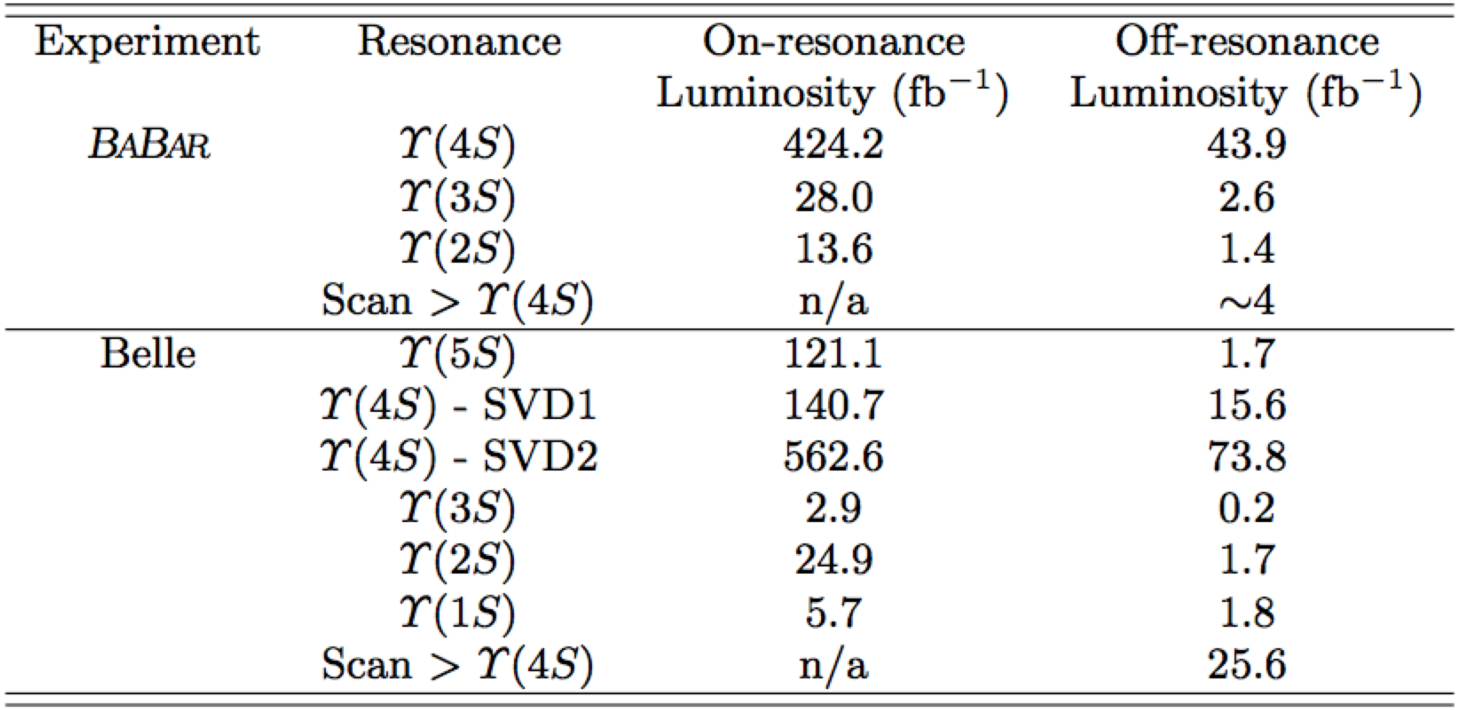
Dark Forces

ANCILLARY MATERIAL

TECHNICAL DETAILS

Integrated luminosity

- The following is a breakdown by energy of the integrated luminosity at the *B* Factories.*



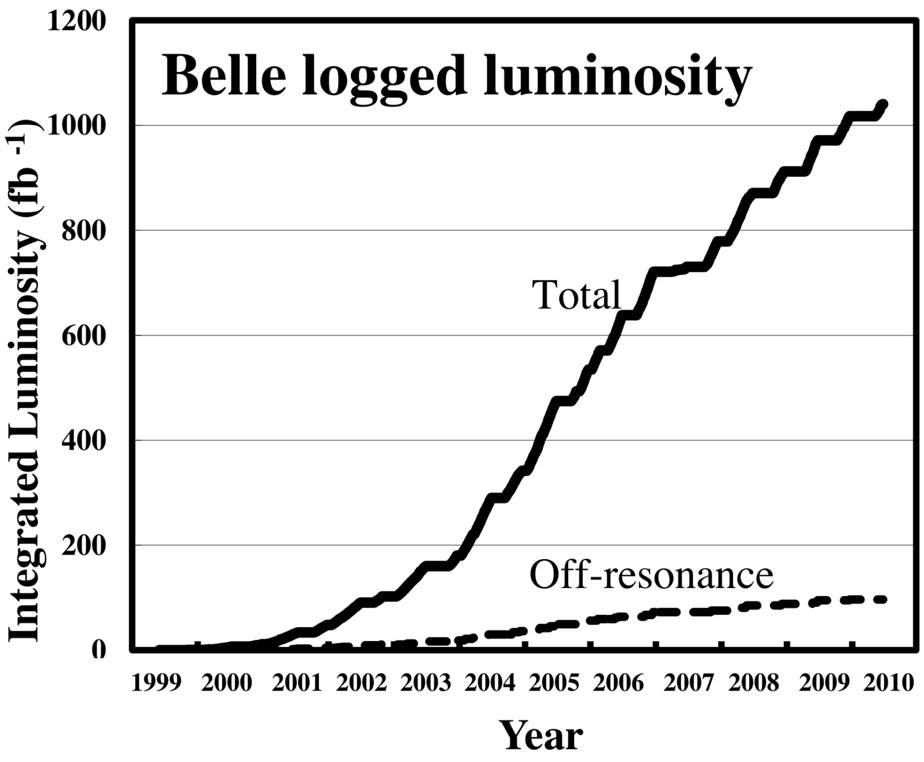
Experiment	Resonance	On-resonance Luminosity (fb^{-1})	Off-resonance Luminosity (fb^{-1})
BABAR	$\Upsilon(4S)$	424.2	43.9
	$\Upsilon(3S)$	28.0	2.6
	$\Upsilon(2S)$	13.6	1.4
	Scan $> \Upsilon(4S)$	n/a	$\sim$4
Belle	$\Upsilon(5S)$	121.1	1.7
	$\Upsilon(4S)$ - SVD1	140.7	15.6
	$\Upsilon(4S)$ - SVD2	562.6	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

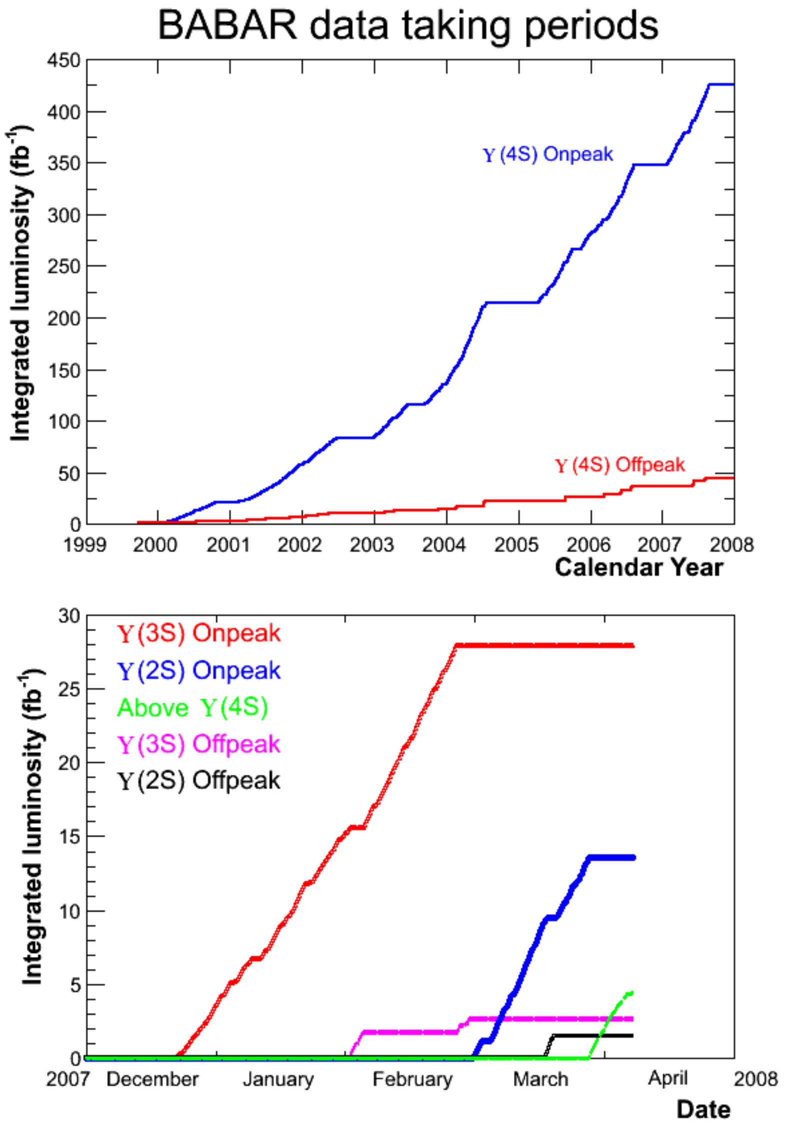
- A total of 1.2 billion pairs of *B* mesons recorded.

*** Taken from Physics of the *B* Factories ed AB et al.**

Integrated luminosity

- Profile as a function of time. *





*** Taken from Physics of the *B* Factories ed AB et al.**

Need 50x more data →Next generation B -factories

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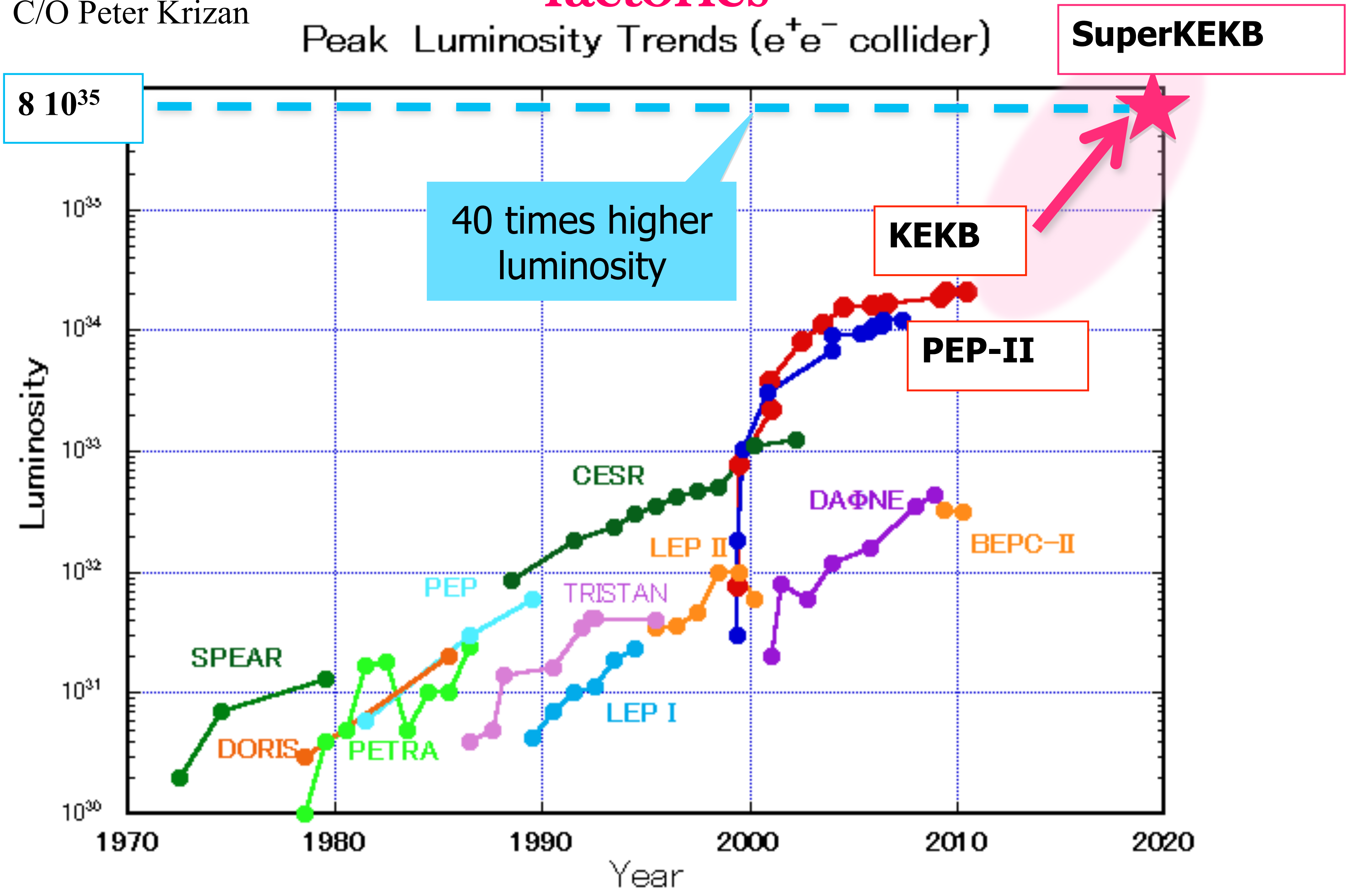
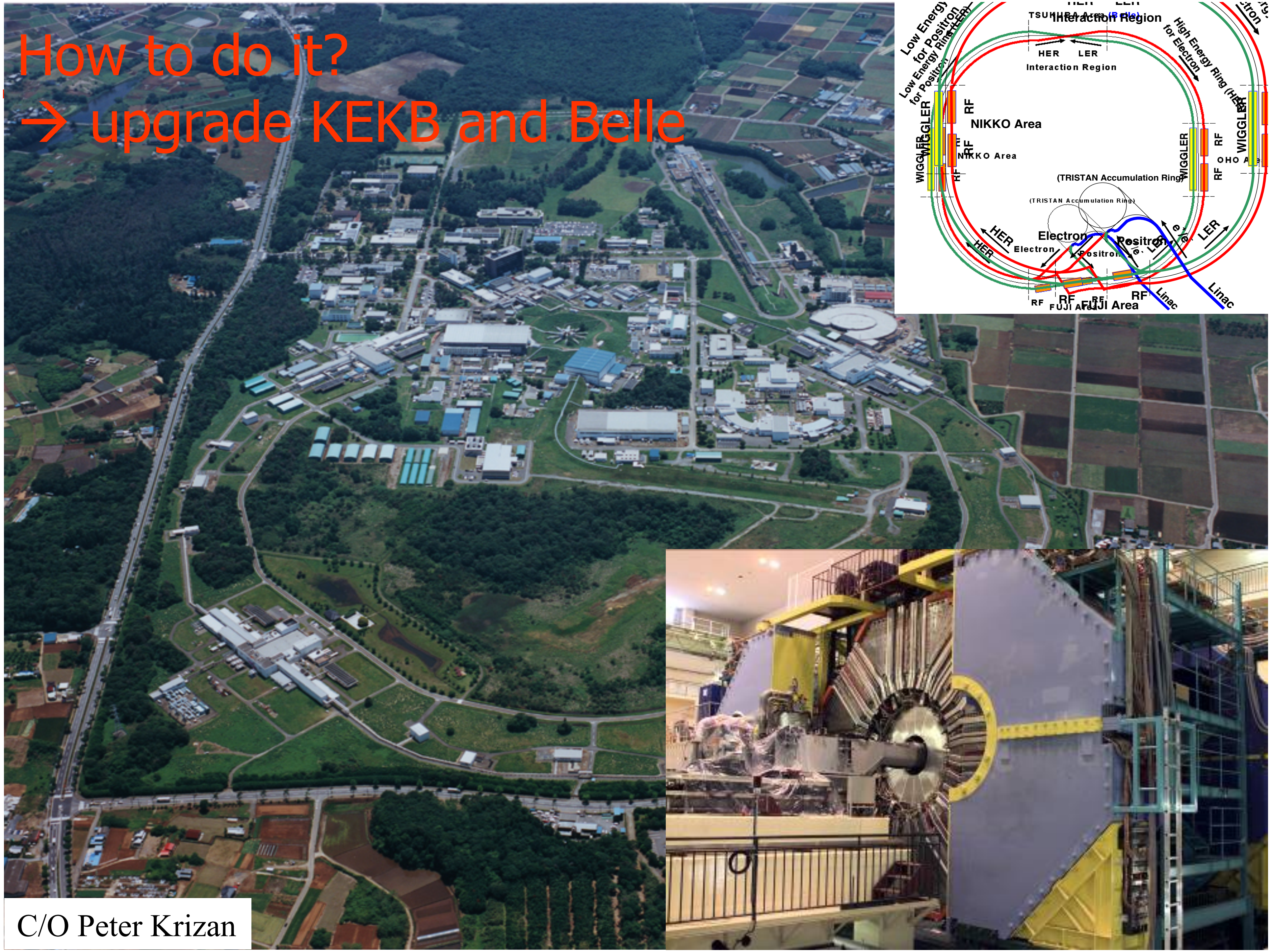


How to do it?
→ upgrade KEKB and Belle



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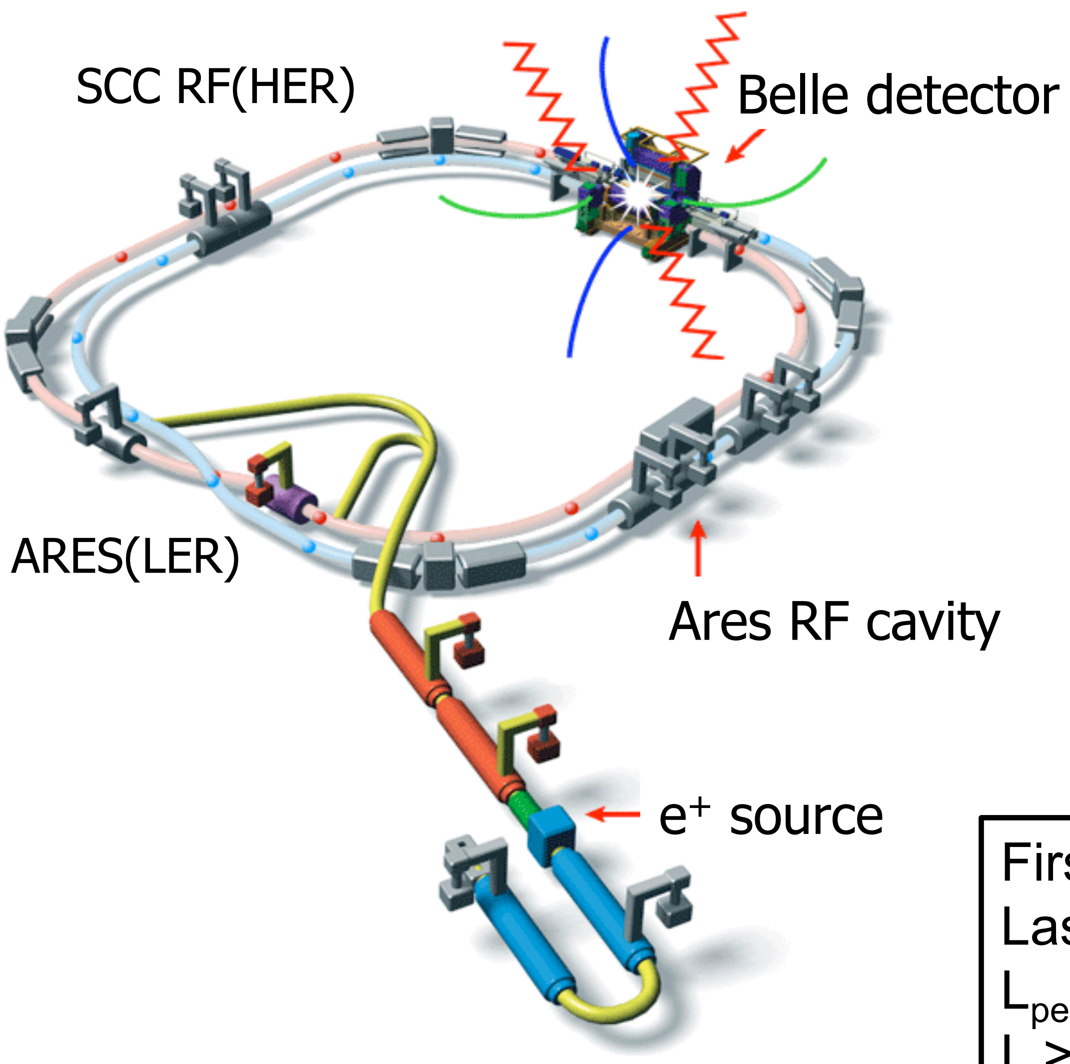
The KEKB Collider & Belle Detector



- 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!) :

$2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
$L_{peak} = 2.1\times10^{34}/\mathrm{cm}^2/\mathrm{s}$
$L > 1\mathrm{ab}^{-1}$

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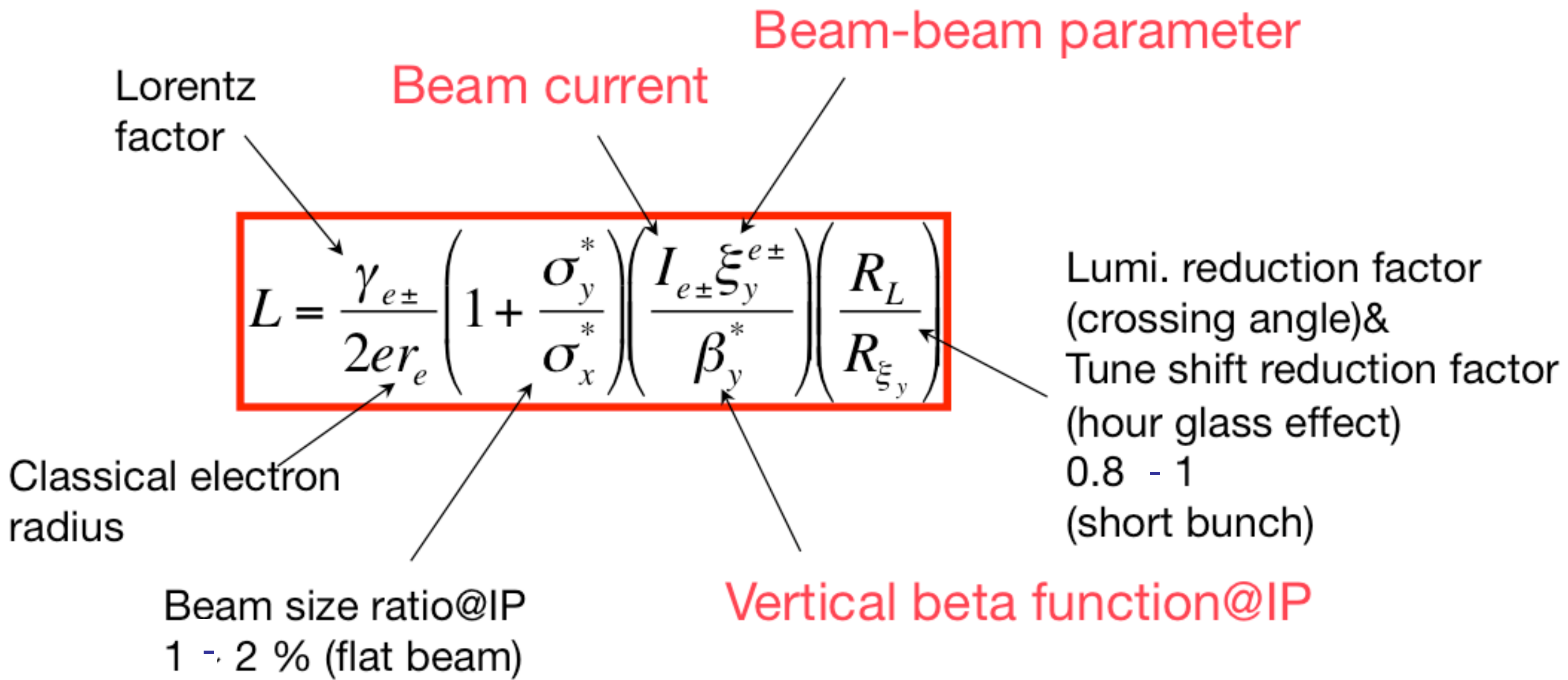
Strategies for increasing luminosity



Beam-beam parameter

Lorentz factor

Beam current

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

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

Classical electron radius

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

Vertical beta function@IP

(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

C/O Peter Krizan

Machine design parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

- **Nano-beams and a factor of two more beam current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of short lifetime for the LER

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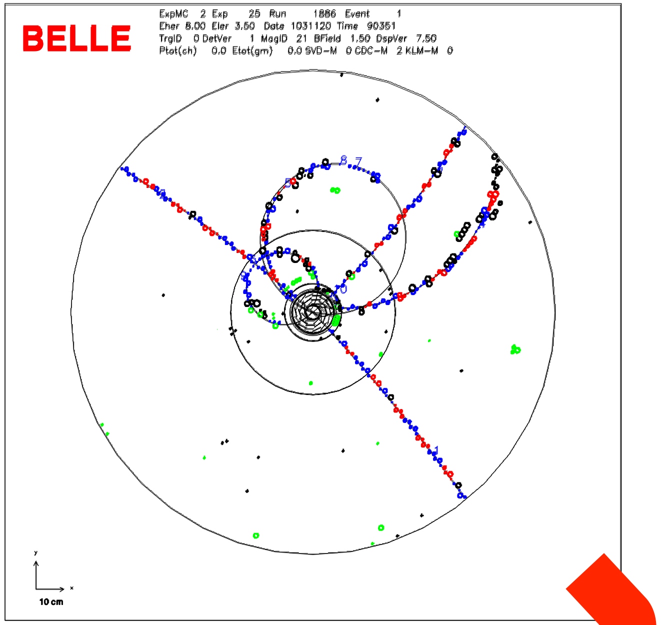
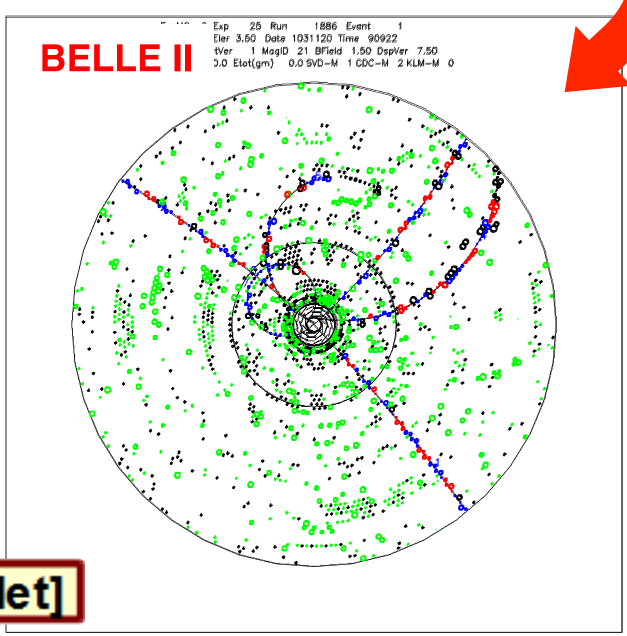
Need to build a new detector to handle higher backgrounds

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low *p* **m** identification ← **smm** recon. eff.
  - hermeticity ← **n** “reconstruction”





Have to employ and develop new technologies to make such an apparatus work!

→

C/O Peter Krizan

TDR published arXiv:1011.0352v1 [physics.ins-det]

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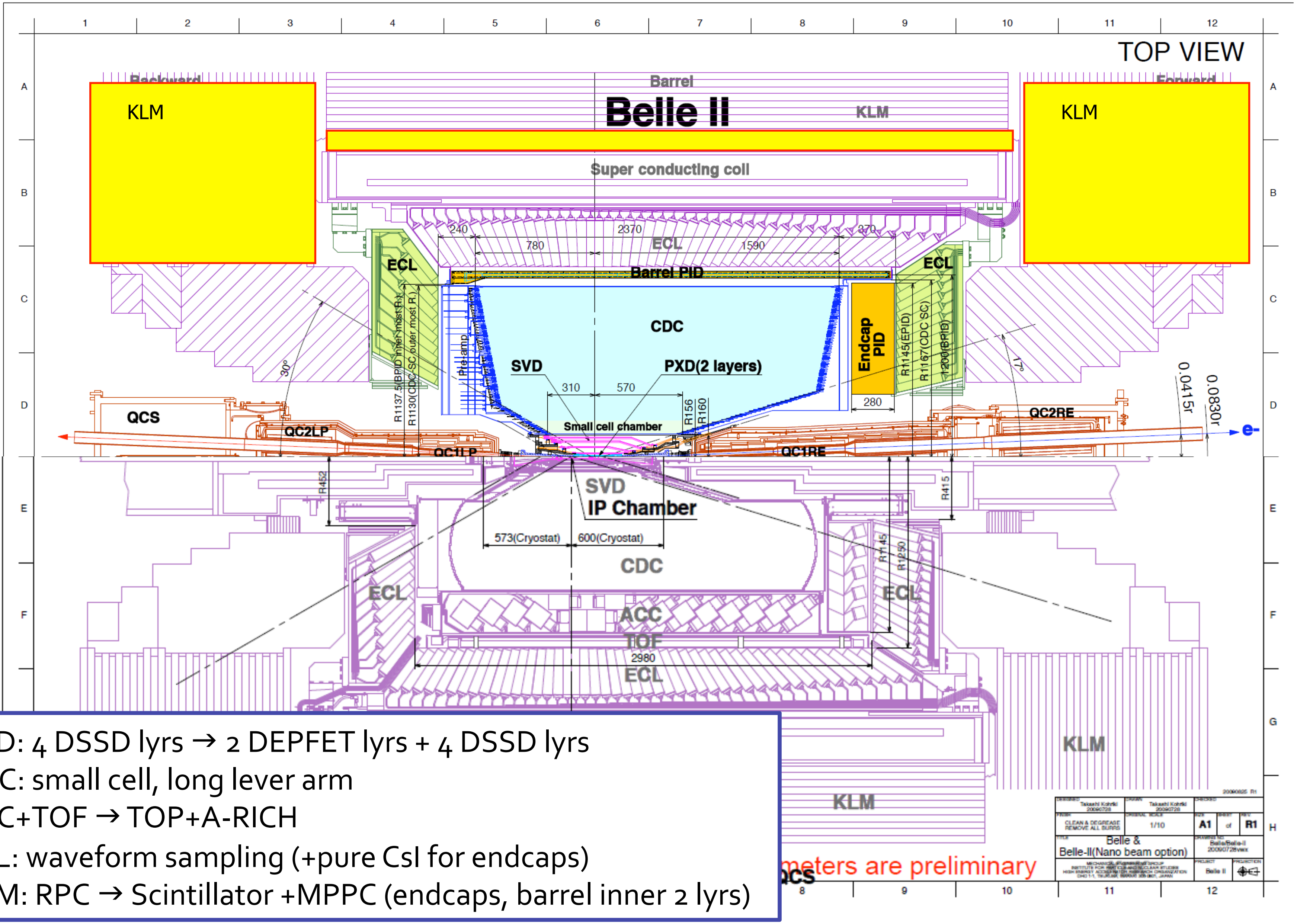
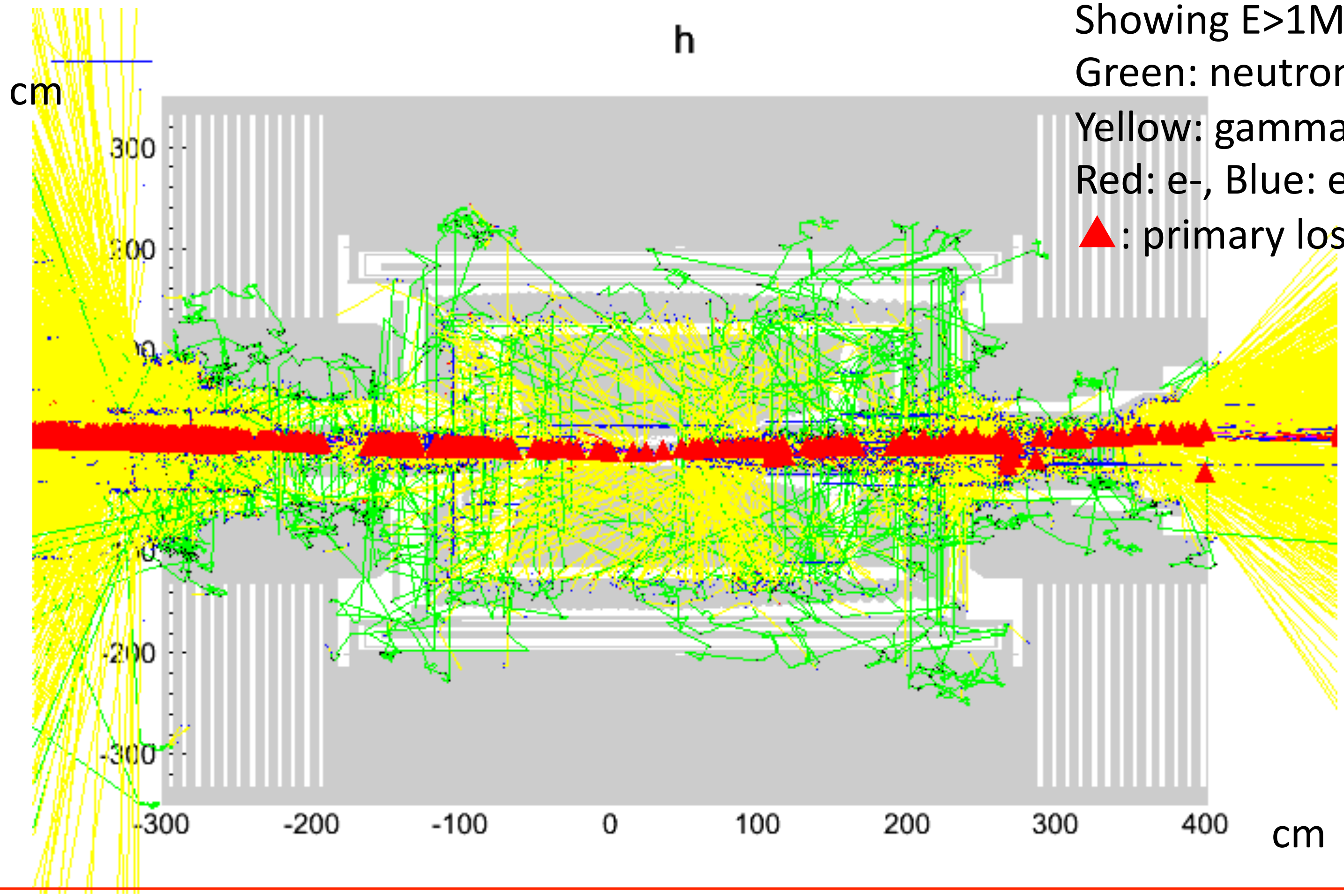
Belle II Detector (in comparison with Belle)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

Background event display

C/O Peter Krizan

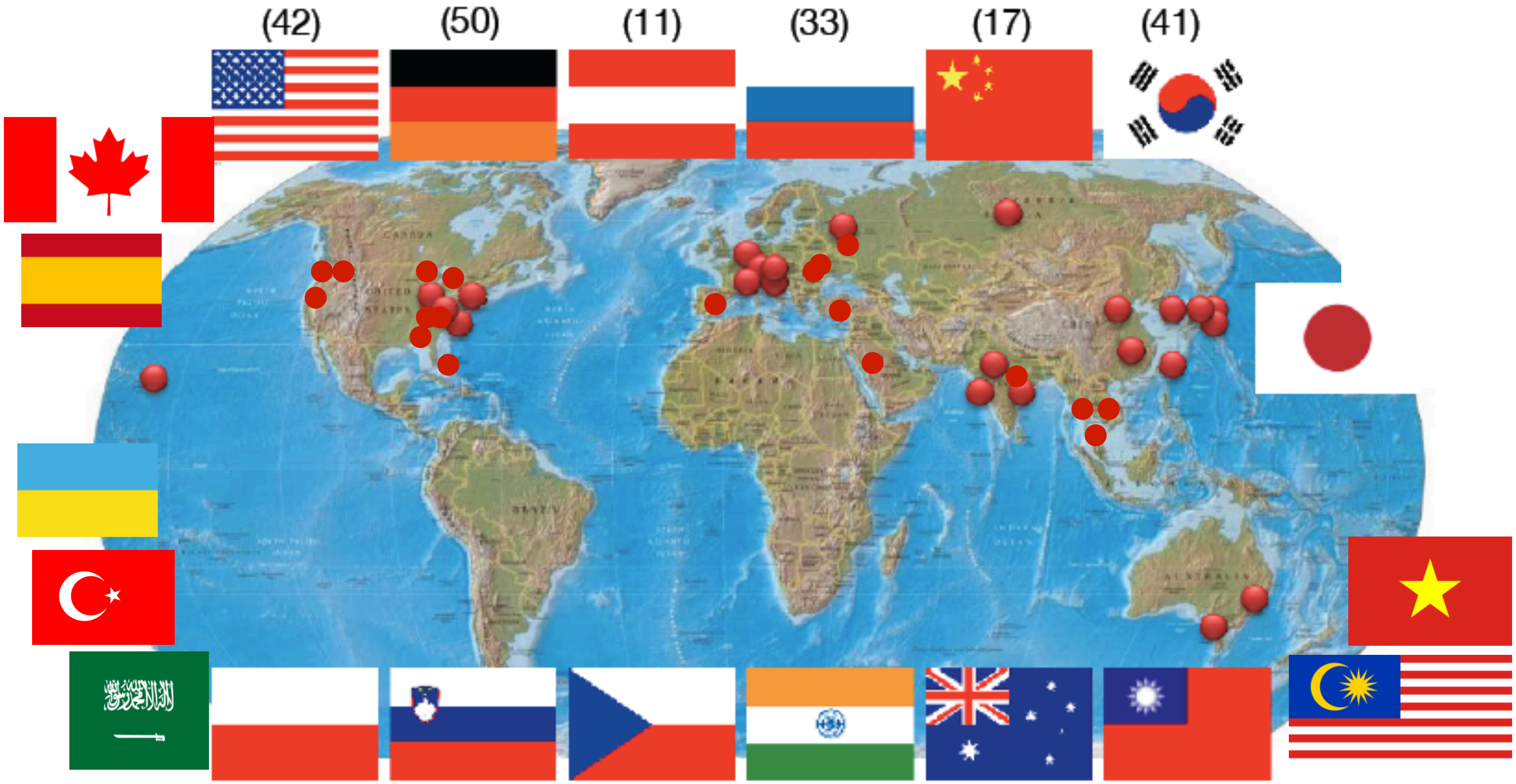


100ns
Showing E>1MeV
Green: neutron
Yellow: gamma
Red: e-, Blue: e+
▲: primary loss position

Neutrons: background hits in the muon and KL detection system (KLM) → reduce the efficiency of muon and KL detection → replace RPCs in the endcaps and 2 barrel layers.

The Belle II Collaboration

Addendum: A significant number of ex-SuperB have joined Belle II
and the number of collaborators is now more like ~600



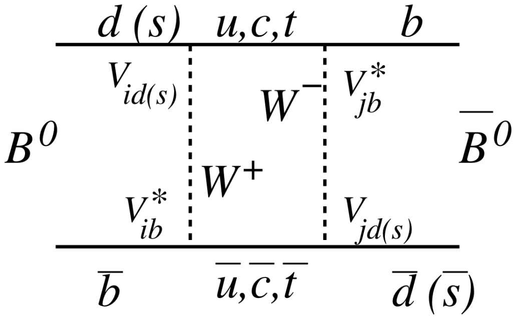
A very strong group of ~480 highly motivated scientists!

C/O Peter Krizan

TIME-DEPENDENT CP VIOLATION MEASUREMENTS

Time-dependent CP violation measurements

- One can start from an entangled pair of neutral mesons, which are exponentially decaying, and oscillating from particle to anti-particle, and derive formulae related to the decay probability for those mesons.
  - See for example Bigi & Sanda, Carter-Lavoura-Silvia etc.
- Mixing proceeds via:



- where the effective Hamiltonian is:

$$\mathcal{H}_{\text{eff}} = \mathbf{M} - \frac{i\mathbf{\Gamma}}{2}$$

$$= \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}\right]$$

Time-dependent CP violation measurements

- Ignoring detector effects, we have

$$\begin{aligned}
\Gamma(P^0(t) \to f) &\propto |\langle f|H_{\Delta F=1}|P^0(t)\rangle|^2 && (10.1.13)\\
&= e^{-\Gamma_1 t}|A_f|^2 \left[K_+(t) + |\lambda|^2 K_-(t) + 2\mathrm{Re}\left\{\lambda L^*(t)\right\}\right]\\
\Gamma(\overline{P}^0(t) \to f) &\propto |\langle f|H_{\Delta F=1}|\overline{P}^0(t)\rangle|^2 && (10.1.14)\\
&= e^{-\Gamma_1 t}|\overline{A}_f|^2 \left[K_+(t) + \frac{1}{|\lambda|^2} K_-(t) + 2\mathrm{Re}\left\{\frac{1}{\lambda} L^*(t)\right\}\right].
\end{aligned}$$

- Where λ is the observable of interest:

$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

where q and p are mixing parameters and

$$\begin{aligned}
A_f &= \langle f|H_{\Delta F=1}|P^0\rangle\\
\overline{A}_f &= \langle f|H_{\Delta F=1}|\overline{P}^0\rangle
\end{aligned}$$

In general the amplitude A will have a number of components, commonly we find tree, colour suppressed tree, W exchange and penguin topologies::

$$\begin{aligned}
A &= |T|e^{i\phi_T} + |CS|e^{i\phi_{CS}} + |W|e^{i\phi_W}\\
&\quad + \sum_{q=d,s,b} |P_q|e^{i\phi_q},
\end{aligned}$$

Time-dependent CP violation measurements

- We are interested in measuring the complex parameter λ,** and visually want to display the results in terms of a time-dependent asymmetry between particle and antiparticle state.

- But the formalism we start from is in terms of the proper time for a meson that is created at some known point in time. This is not the case for the B Factories as discussed earlier.... so we have to take a proper time difference for correlated production of neutral mesons. At ATLAS, CMS, LHCb and the Tevatron this is not necessary.
  - → The difference essentially boils down to a few sign flips in the formulae.

** There are a number of basis choices one can use, polar, cartesian, and if $\Delta\Gamma=0$ is a good approximation one can compactify the result in terms of $S = 2\mathrm{Im}\lambda / (1+|\lambda|^2)$ and $C = (1-|\lambda|^2) / (1+|\lambda|^2)$. The latter basis is commonly used as fit optimisations using this tend to be more numerically stable than the other bases. All are equivalent in the limit of high statistics where fit bias should not be an issue.

Time-dependent CP violation measurements

- For B_d decays we can assume that ΔΓ=0 (a more precise measurement of this physical parameter is required for future experiments). And we obtain a simple form for the time-dependence:

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}\sin(\Delta m_d \Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d \Delta t)\right],$$

- where f_+ and f_- are for B/B-bar, respectively.
- The asymmetry used to study these decays is:

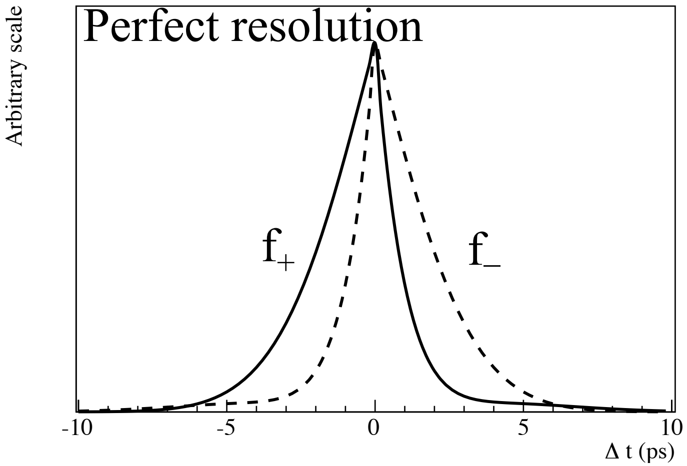
$$\mathcal{A}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)},$$

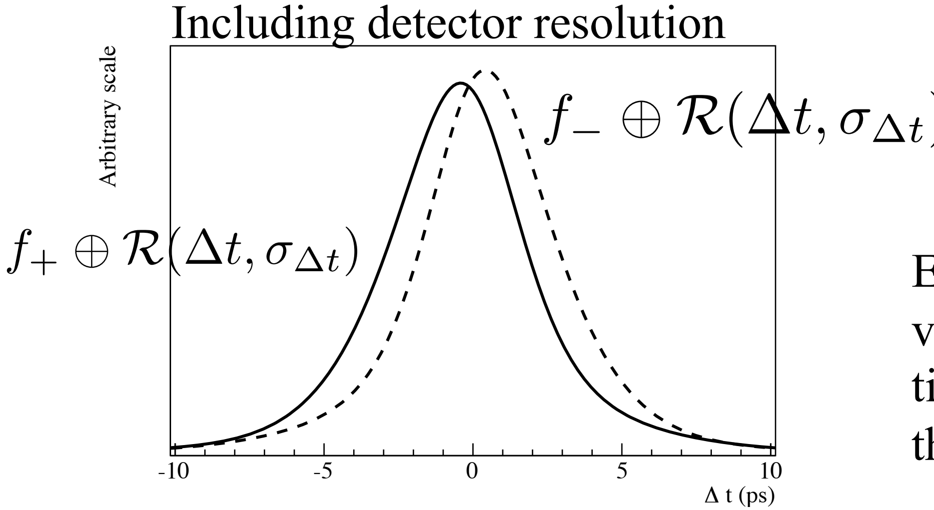
$$\mathcal{A}(\Delta t) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t).$$

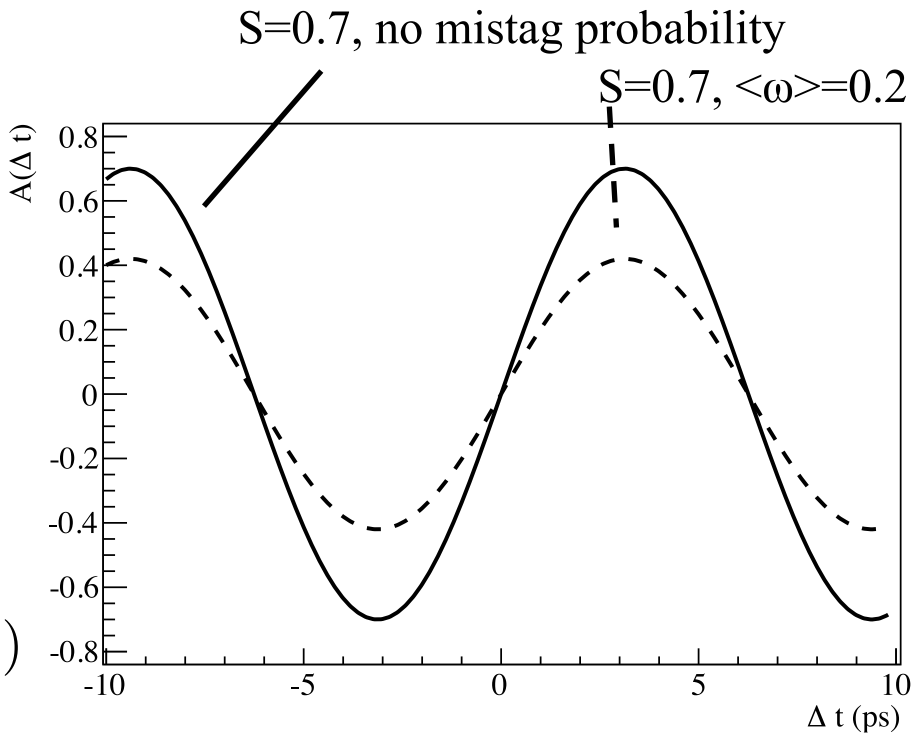
WARNING: This form follows the convention for a CP odd decay, such as J/ψKS. CP even final states have opposite sign coefficients for S and C.

Time-dependent CP violation measurements

- We need to account for (left) detector resolution, and (right) tagging efficiency. These two effects degrade our ability to measure λ.







Experiment design has to consider both precision vertexing (to control the resolution on proper time) and charged PID (to control uncertainties on the mis-tag probability; ω)

Isospin analysis required to constrain the phase shift from penguins with weak phases different to the leading order contributions in B to hh decays: i.e. constrain the difference between the measured value of α_{eff} and the fundamental CKM matrix invariant (quartet) phase α.

The methodology outlined by Gronau and London draws on knowledge of the $\Delta I=1/2$ rule in kaons, and has recently been studied in the context of D mesons by AB and Brian Meadows.

ISOSPIN ANALYSIS

$\pi\pi/\rho\rho$: Gronau and London, Phys. Rev. Lett. 65, 3381– 3384 (1990).
3π: Snyder and Quinn, Phys. Rev. D48, 2139–2144 (1993).

B to hh Isospin Analysis

- The problem: $\mathcal{A} = Te^{i\phi_T} + \sum_k P_k e^{i\phi_k}$
- If the weak phase of a penguin amplitude P_k matches that of the tree, then we absorb that term into the tree. The only thing that we care about is grouping amplitudes with a matching phase structure.
- Having done that we are left with the problem that penguin amplitudes are significant in B to hh decays, so we have to understand how the penguin shifts the phase of interest. e.g. for ππ decays:

$$\begin{array}{lcl} B^0 & \rightarrow & \pi^+\pi^- : A^{+-} \\ B^+ & \rightarrow & \pi^+\pi^0 : A^{+0} \\ B^0 & \rightarrow & \pi^0\pi^0 : A^{00} \end{array} \qquad \begin{array}{lcl} \overline{B}^0 & \rightarrow & \pi^+\pi^- : \overline{A}^{+-} \\ B^- & \rightarrow & \pi^-\pi^0 : \overline{A}^{-0} \\ \overline{B}^0 & \rightarrow & \pi^0\pi^0 : \overline{A}^{00} \end{array}$$

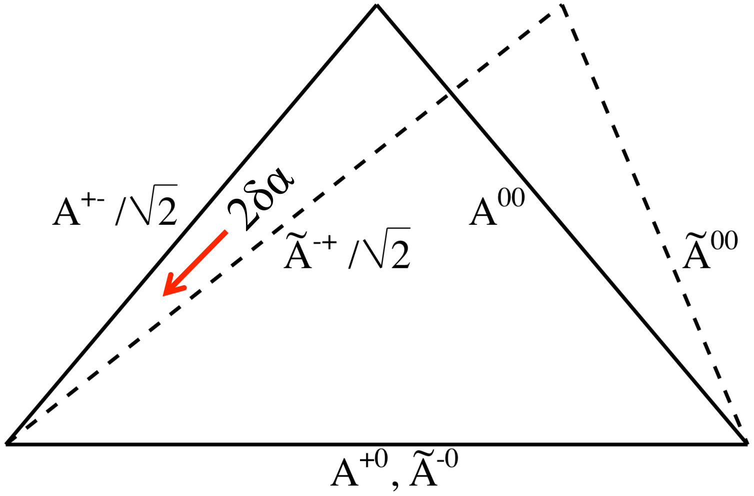
B to hh Isospin Analysis

- As with K and B decays the decays D to ππ are related by Isospin symmetry:

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

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

- Similarly on can extend to ρπ and ρρ decays, with the corresponding additional complexity.



e.g. see Gronau & London Phys. Rev. Lett. 65, 3381 (1990)

- Following from this it is straightforward to constrain the shift from penguins on the weak phase measurement that can be made in B to hh decays (h = π, ρ) using existing data.

B to hh Isospin Analysis

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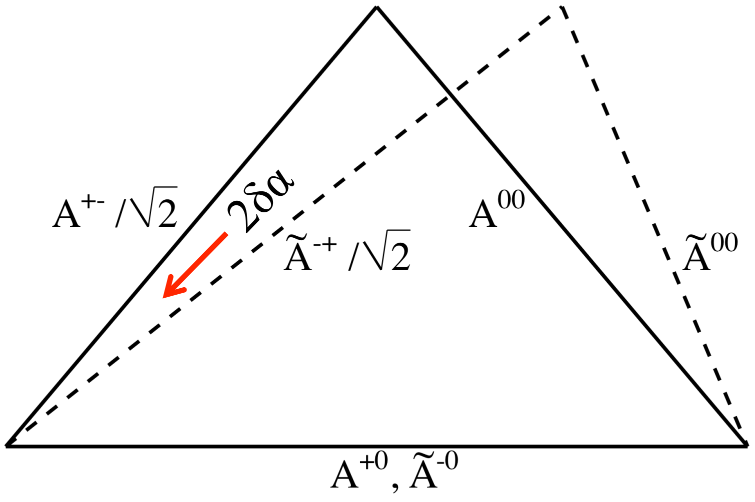


e.g. see Gronau & London Phys. Rev. Lett. 65, 3381 (1990)

• Similarly on can extend to ρπ and ρρ decays, with the corresponding additional complexity.

The bar notation is replaced by a tilde to represent an alignment convention according to the tree dominated ±0 mode.

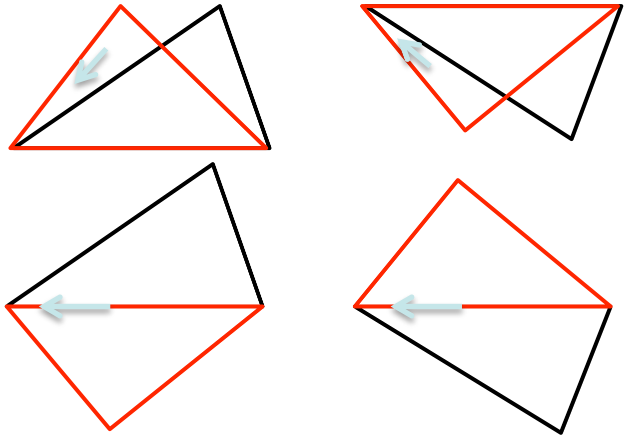
- Following … nstrain the shift from … surement that can b …) using existing data.

B to hh Isospin Analysis

- As with K and B decays the decays D to ππ are related by Isospin symmetry:

An ambuguity arises: we don't know the orientation of the triangles relative to each other.

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



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- Following from this it is straightforward to constrain the shift from penguins on the weak phase measurement that can be made in B to hh decays (h = π, ρ) using existing data.

B to hh Isospin Analysis

- Ambiguities in the measurement:
  - (S, C)   single valued numbers determined from the time-dependent anlalysis.**
  - Taking the arcsin results in (S, C) mapping onto an effective parameter, α_{eff}, with a four fold ambiguity.#
  - The isospin analysis used to convert α_{eff} α introduces a further four fold ambiguity from the orientation of the triangles.
  - In general many of these ambiguities overlap when converting (S, C) to α.

**The time-dependent analysis of the 3π Dalitz plot results in 26 bi-linear form factor co-efficients (U's and I's) that contain the weak phase information. Sometimes those are also translated into "quasi-2-body" parameters, including S and C in order to make a historical link back to initial analysis methodologies that were used circa 2002.

#This step is also equivelent to the four-fold ambiguity found in the sin2β measurement.

A breakdown of the measured values of R(D) and R(D*) for this decay mode as performed by the two experiments. Converting these results into constraints on a new physics model requires a good understanding of the efficiency of the NP model as a function of the charged Higgs mass. Currently this is only available for the BaBar result, however Belle are working on an update of their result, so we hope that there will be additional data included soon.

Unofficial averages push the significance of the exclusion of MSSM upward...

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

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

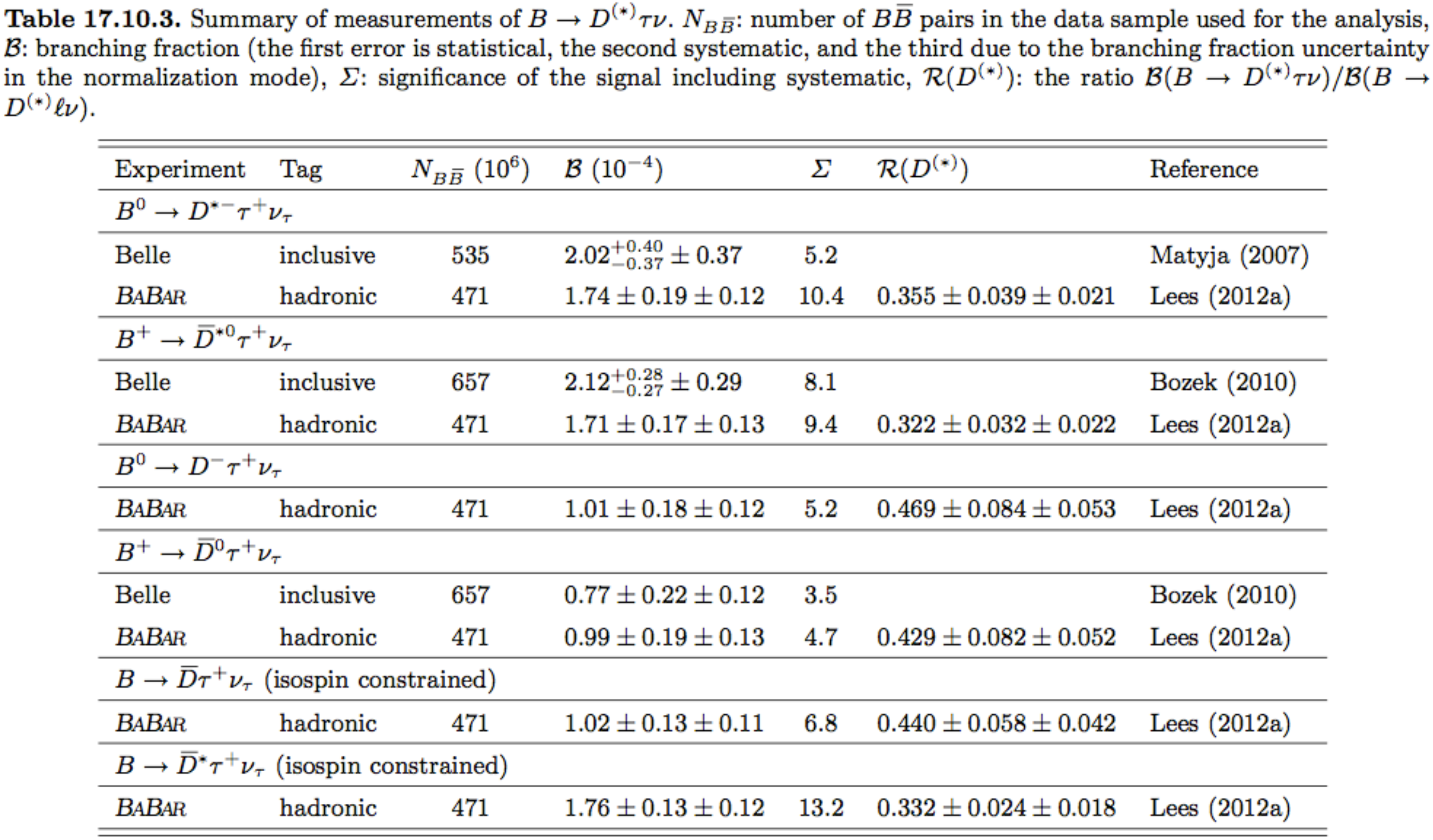


Table 17.10.3. Summary of measurements of $B \to D^{(*)}\tau\nu$. $N_{B\overline{B}}$: number of $B\overline{B}$ pairs in the data sample used for the analysis, $\mathcal{B}$: branching fraction (the first error is statistical, the second systematic, and the third due to the branching fraction uncertainty in the normalization mode), Σ: significance of the signal including systematic, $\mathcal{R}(D^{(*)})$: the ratio $\mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$.

Experiment	Tag	$N_{B\overline{B}}$ (10^6)	$\mathcal{B}$ (10^{-4})	Σ	$\mathcal{R}(D^{(*)})$	Reference
$B^0 \to D^{*-}\tau^+\nu_\tau$						
Belle	inclusive	535	$2.02^{+0.40}_{-0.37} \pm 0.37$	5.2		Matyja (2007)
BABAR	hadronic	471	$1.74 \pm 0.19 \pm 0.12$	10.4	$0.355 \pm 0.039 \pm 0.021$	Lees (2012a)
$B^+ \to \overline{D}^{*0}\tau^+\nu_\tau$						
Belle	inclusive	657	$2.12^{+0.28}_{-0.27} \pm 0.29$	8.1		Bozek (2010)
BABAR	hadronic	471	$1.71 \pm 0.17 \pm 0.13$	9.4	$0.322 \pm 0.032 \pm 0.022$	Lees (2012a)
$B^0 \to D^-\tau^+\nu_\tau$						
BABAR	hadronic	471	$1.01 \pm 0.18 \pm 0.12$	5.2	$0.469 \pm 0.084 \pm 0.053$	Lees (2012a)
$B^+ \to \overline{D}^0\tau^+\nu_\tau$						
Belle	inclusive	657	$0.77 \pm 0.22 \pm 0.12$	3.5		Bozek (2010)
BABAR	hadronic	471	$0.99 \pm 0.19 \pm 0.13$	4.7	$0.429 \pm 0.082 \pm 0.052$	Lees (2012a)
$B \to \overline{D}\tau^+\nu_\tau$ (isospin constrained)						
BABAR	hadronic	471	$1.02 \pm 0.13 \pm 0.11$	6.8	$0.440 \pm 0.058 \pm 0.042$	Lees (2012a)
$B \to \overline{D}^*\tau^+\nu_\tau$ (isospin constrained)						
BABAR	hadronic	471	$1.76 \pm 0.13 \pm 0.12$	13.2	$0.332 \pm 0.024 \pm 0.018$	Lees (2012a)

*** Taken from Physics of the *B* Factories ed AB et al.**

In 2007 BaBar published evidence for Charm Mixing using wrong sign decays. This followed the traditional methodology for searching for mixing.

A few weeks afterward Belle submitted a paper confirming this effect using measurements of y_{CP}.

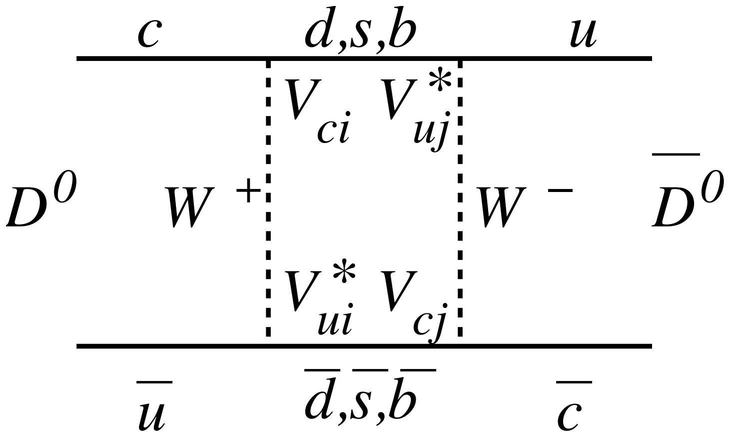
As with discovery of CP violation in B decays BaBar and Belle independently found charm mixing, presenting results at more or less the same time, and submitting papers within weeks of each other.

Charm Mixing

See chapter 19.2 of the Physics of the B Factories for more information.

Mixing formalism

- In general the mixing formalism parallels B and K decays, however the kinematics of charm lead to the possibility to make some approximations. This "simplifies" some of the equations after a Taylor expansion; but it does mean that the analysis methodology needs to evolve with increasing statistics.
  - [this parallels the history of observables used for B decay measurements as well]



Frequency of oscillation is encoded in x, and the lifetime difference between eigentates D_1 and D_2 is encoded in y.

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

WARNING: The relative strong phase between different determinations of x and y needs to be accounted for when combining results from different modes.

Mixing formalism

- One can compare the different neutral meson systems in terms of x and y:

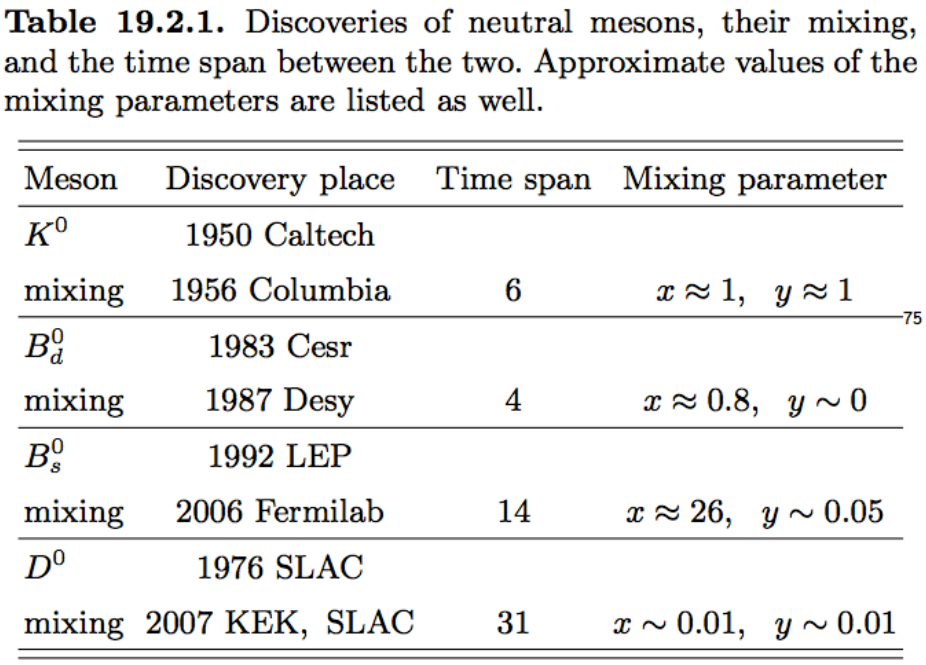
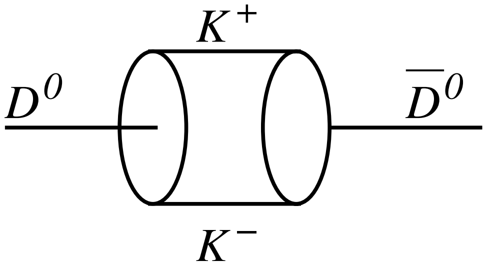


Table 19.2.1. Discoveries of neutral mesons, their mixing, and the time span between the two. Approximate values of the mixing parameters are listed as well.

Meson	Discovery place	Time span	Mixing parameter
K^0	1950 Caltech		
mixing	1956 Columbia	6	$x \approx 1, \quad y \approx 1$
B_d^0	1983 Cesr		
mixing	1987 Desy	4	$x \approx 0.8, \quad y \sim 0$
B_s^0	1992 LEP		
mixing	2006 Fermilab	14	$x \approx 26, \quad y \sim 0.05$
D^0	1976 SLAC		
mixing	2007 KEK, SLAC	31	$x \sim 0.01, \quad y \sim 0.01$

- Note: Unlike B decays, Charm can be affected by (hard to compute) long distance interactions.



Long distance contribution to charm mixing via K meson rescattering.

* **Taken from Physics of the *B* Factories ed AB et al.**

Wrong sign decay search

- Use decays to flavour specific final states, in this case the interference between Cabibbo allowed and suppressed states of $D^0 \to K^-\pi^+$ is the relevant process.
- The time-dependence of wrong sign decays is:

$$\frac{T_{\rm ws}}{e^{-\Gamma t}} \propto R_{\rm dcs} + \sqrt{R_{\rm dcs}} y' \, \Gamma t + \frac{x'^{\,2} + y'^{\,2}}{4} (\Gamma t)^2$$

$R_{\rm dcs}$ is the ratio of double Cabibbo suppressed (Wrong-Sign) to Cabibbo favoured (Right Sign) decays.

$$\begin{aligned} x' &= x \cos \delta_{K\pi} + y \sin \delta_{K\pi} \\ y' &= y \cos \delta_{K\pi} - x \sin \delta_{K\pi} \end{aligned}$$

This approximation is valid so long as higher order terms in x and y are not significant.

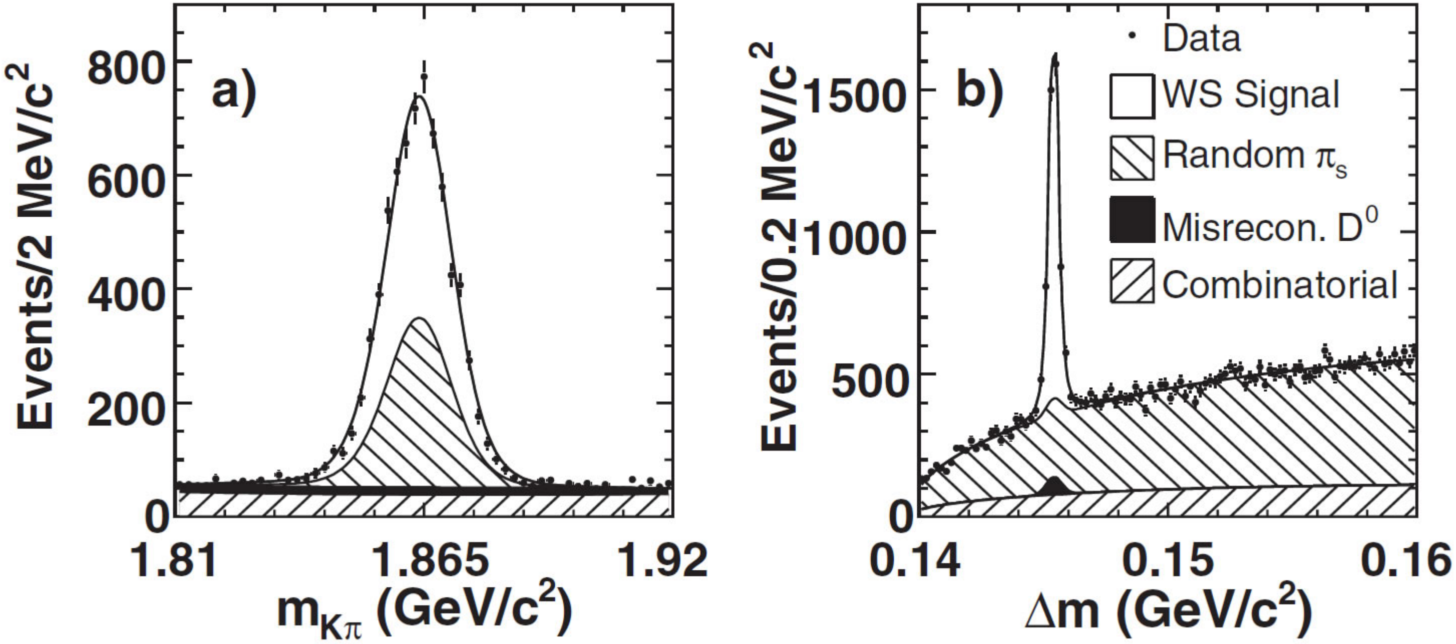
This assumes no CP violation.

$\delta_{K\pi}$ is a strong phase difference (a priori unknown, one must measure that)

Wrong sign decay search

- The selection of D mesons at the Y(4S) is via D* decays, where $D^{*\pm} \rightarrow D^0 \pi^{*\pm}$ provides a clean determination of signal via:
  - Kπ invariant mass (D^0 candidate mass)
  - The mass difference between the D and D* candidates.

Aubert et al. [BaBar Collaboration] Phys. Rev. Lett. 98, 211802 (2007)



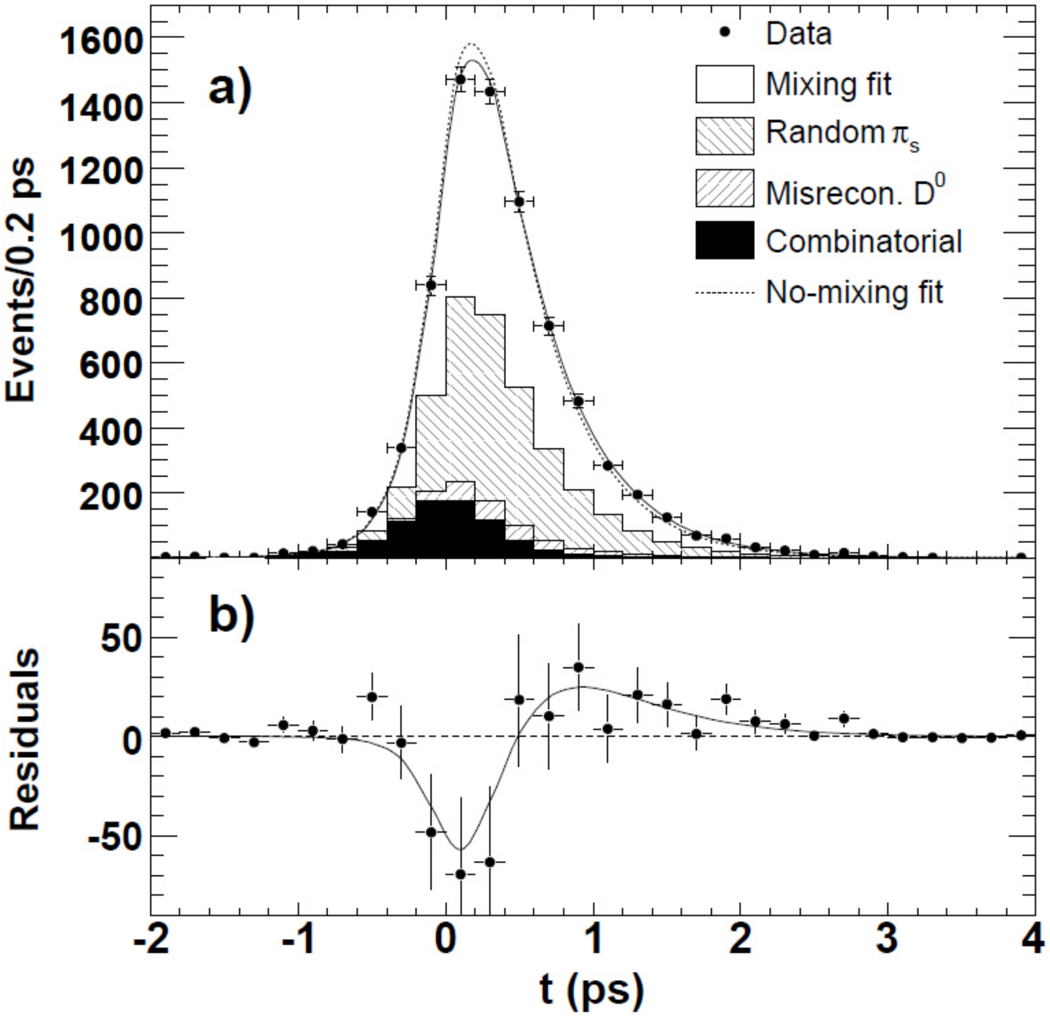
Wrong sign decay search

- Mixing is manifest in the proper time distribution.

• Negative values of t allow us to experimentally determine the resolution function for this observable in a straight forward way.

• The difference between decay times with and without mixing is evident in a subtle change of the t distribution.

• The reconstruction of t is based on the same principles as for the Δt distribution used for B decays; but is necessarily modified as a result of incoherent production.



Aubert et al. [BaBar Collaboration] Phys. Rev. Lett. 98, 211802 (2007)

y_{CP} measurement

- This is a study of lifetime differences between CP even and odd components of the neutral meson wave function.

Average lifetime of a D^0 meson

$$y_{CP} = \eta_{CP}\left(\frac{\tau_{FS}}{\tau_{CP}} - 1\right)$$

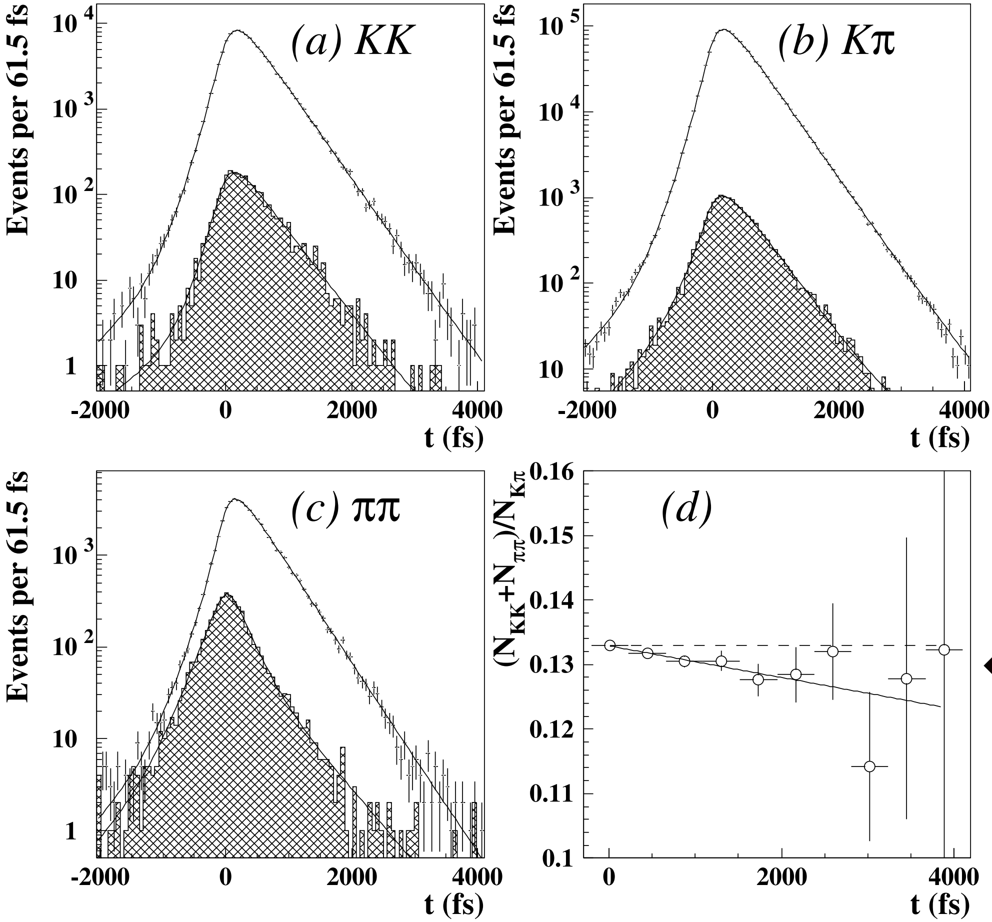
CP eigen value

Lifetime for the CP eigenstate (in the limit of no CP violation)

- A non-zero value for y_{CP} indicates mixing.
- Again we can study this in terms of decay rate as a function of t.

y_{CP} measurement

- This is a study of lifetime differences between CP even and odd components of the neutral meson wave function.

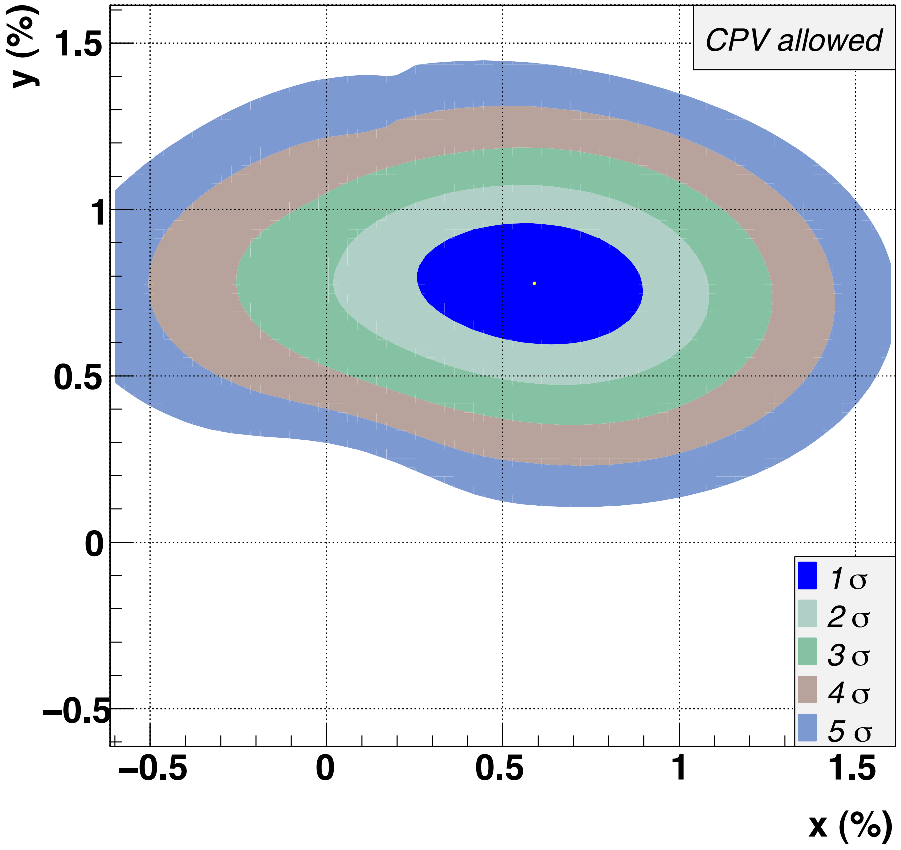


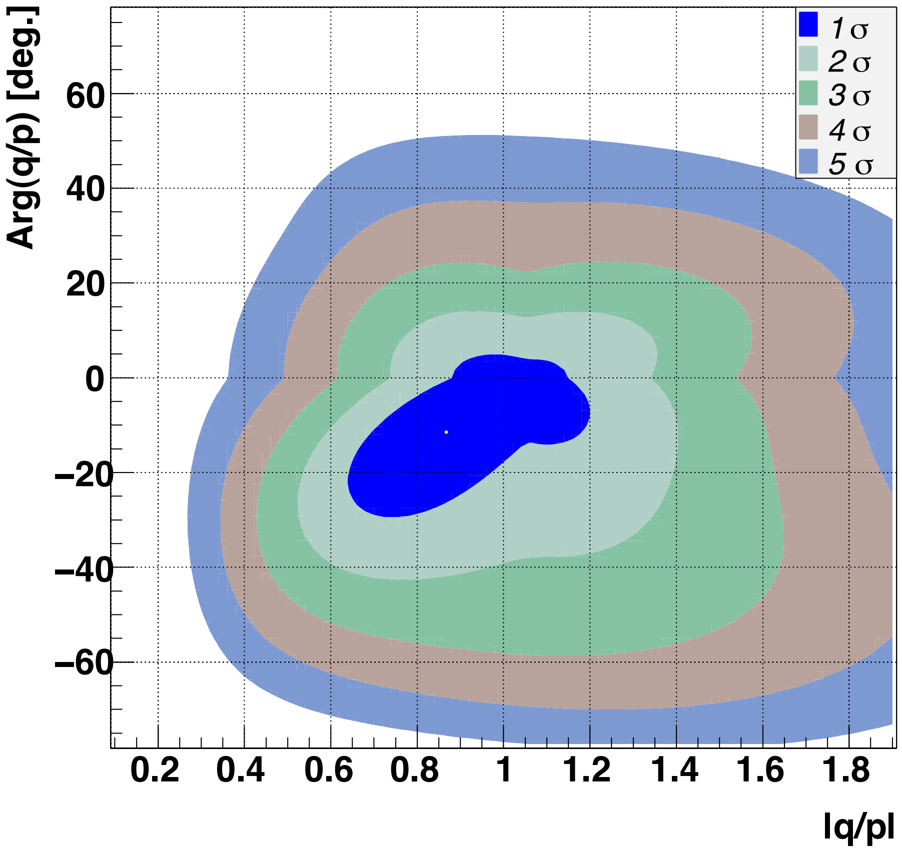
Mixing is evident in the distribution of the ratio of CP eigenstate decays normalised to Kπ deviating from a constant

Charm Mixing: what we learned from the B Factories

- The no-mixing hypothesis is disfavoured at the 10σ level, and

$$x = (0.59^{+0.21}_{-0.22})\%$$
$$y = (0.78 \pm 0.12)\%$$





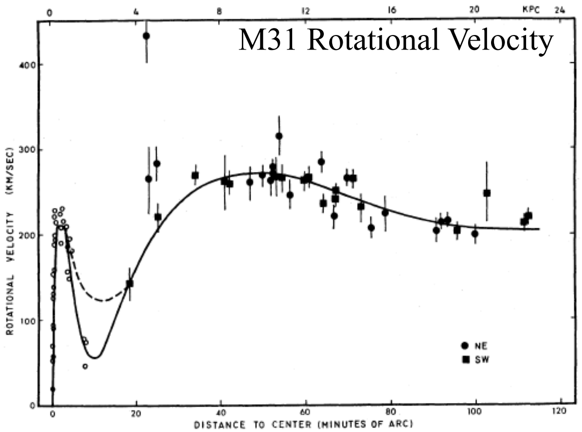
Constraints on more exotic models of new physics can also be placed at B Factories. Examples of this type of constraint are searches for dark photons and dark Higgs particles (see following slides).

There are also searches for light (few GeV) scalar Higgs particles that could be manifest in various SUSY-based new physics models that are performed using decays of the lighter Upsilon particles.

DARK FORCES

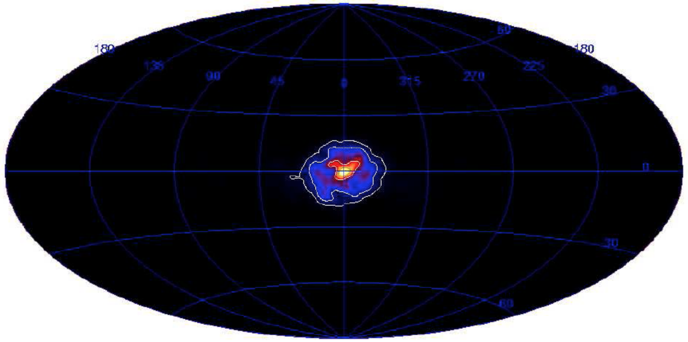
Dark Forces?

- Overwhelming astrophysical evidence for dark matter with several possibly related anomalies:
  - Rotational velocity of spiral galaxies,
  - Integral's 511 keV γ excess,
  - PAMELA/AMS-01/AMS-02 etc rising e^+ fraction, DAMA/LIBRA ,
  - PLANK/WMAP data ...

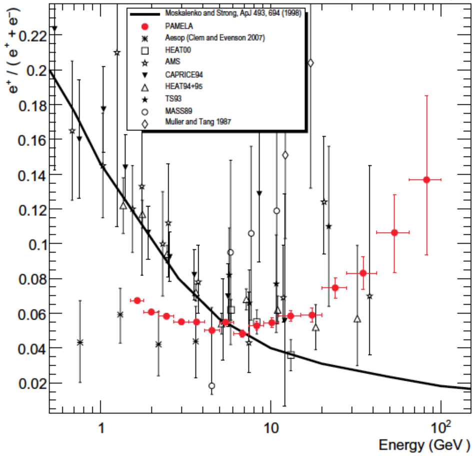

M31 Rotational Velocity

Rubin & Ford, APJ **159** 379-403 (1970)

INTEGRAL, Astron. Astrophys. **441** 513-532 (2005)



Fermi results now much more precise than PAMELA (see ICHEP 2012)



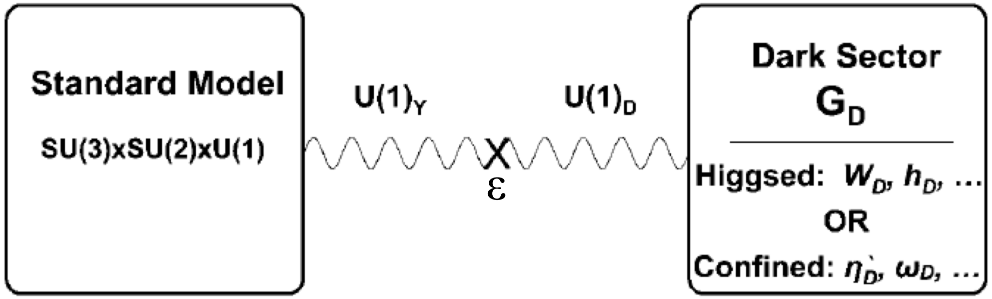
PAMELA, New J. Phys. 11 105023 (2009)

- This motivates ongoing searches for SUSY at the LHC and light scalars and dark sector particles at *B* Factories.

Dark Forces?

- The need for dark matter is well understood – but this is part of the solution.

e.g. R. Essig et al.
[PRD **80** 015003 (2009)]



MeV – 10 GeV low energy dark sector:

- MeV scale dictated by interpretation of INTEGRAL data:

$$\chi\chi \to e^+e^- \qquad \text{vs.} \qquad \chi\chi \to \chi\chi^* \to \chi\chi e^+e^-$$

- Natural dark sector mass scale of O(GeV) for ~TeV scale DM.

Interaction with SM matter through kinetic mixing ε, and we want to constrain the coupling g_D and/or ε.

- *B*, *D* and *K* Factories are a good place to look for dark forces.

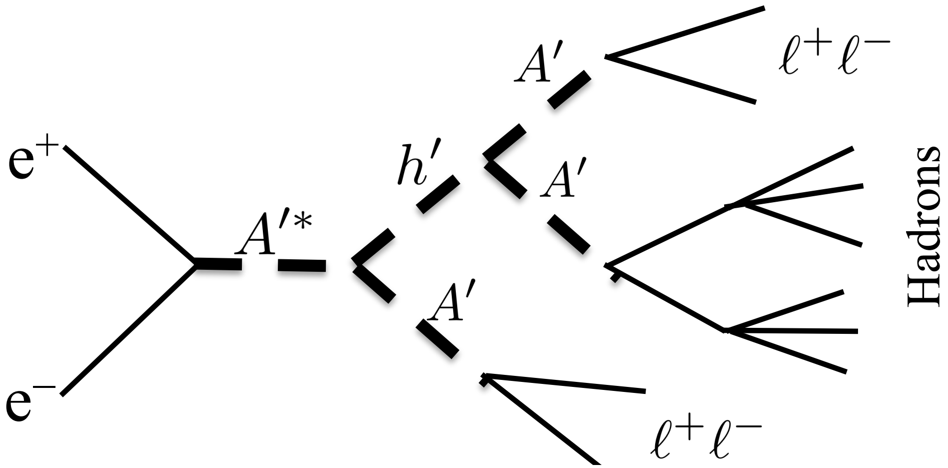
Dark Forces?

$$e^+e^- \to A'h'\,(h' \to A'A')$$

Accessible final states depend on mass of *A*'

Can search for dark Higgs (*h*') and dark photons (*A*').

e.g. see: PRL 108, 211801 (2012)

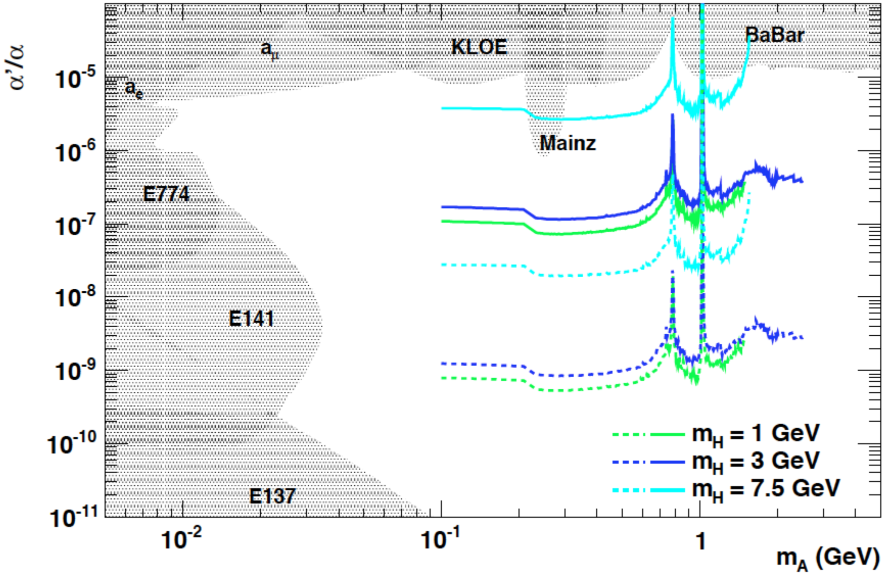


N. Arkani-Hamed et al.
[PRD **79** 015014 (2009)]

B. Batell et al.
[PRD **79** 115008 (2009)]
[PRD **80** 095024 (2009)]

Bjorken et al.
[PRD **80** 075018 (2009)]

R. Essig et al.
[PRD **80** 015003 (2009)]



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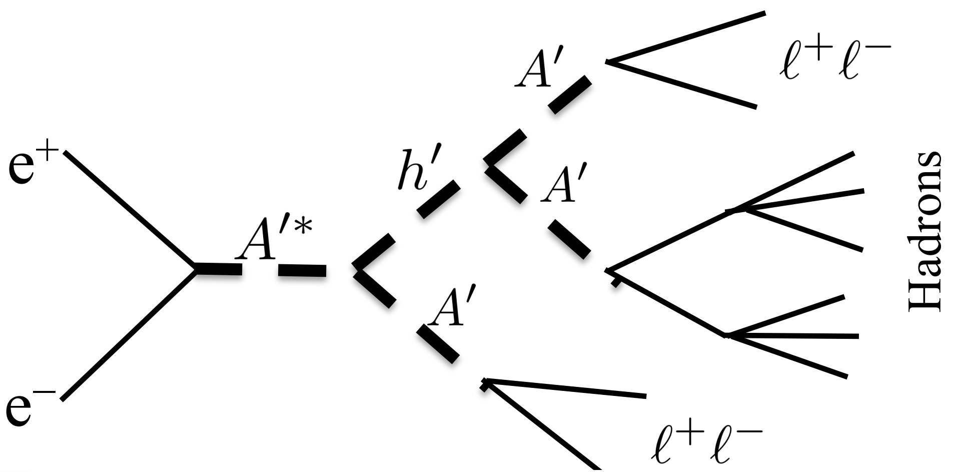

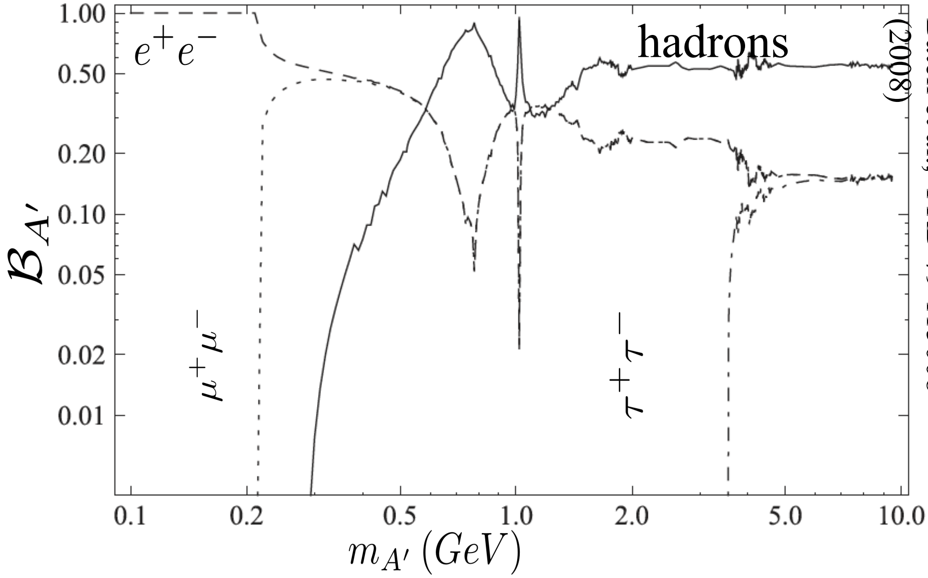

Batell et al., PRD 79 115008 (2008)