B-Physics Factories

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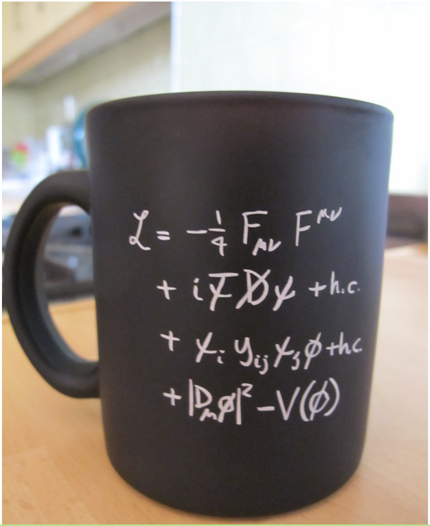
Introduction to Flavour Physics



Introduction to Flavour Physics

Gauge sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

- Describes gauge interactions of quarks and leptons
- Parametrized by **3 gauge couplings**

Higgs sector

$$+ |D_\mu \phi|^2 - V(\phi)$$

- Breaks electro-weak symmetry
- "Gives" mass to $W^{\pm}$ and Z bosons
- **2 free parameters**: Vacuum expectation value ($\sim$ 246 GeV) and Higgs mass

Flavour sector

$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$

- Quarks and leptons masses and mixing
- **22 free parameters** $\Rightarrow$ the most puzzling part of the Standard Model

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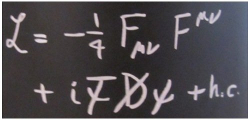

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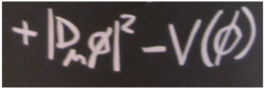

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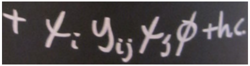

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Yukawa Lagrangian - before CKM Matrix Birth

- Yukawa coupling (for quarks here)

$$\mathcal{L}_Y = \bar{Q}_{L_i} Y^d_{ij} \phi^* u_{R_j} + \bar{Q}_{L_i} Y^d_{ij} \phi d_{R_j} + h.c.$$

- From flavour eigenstates to mass eigenstates = diagonalizing Y^d_{ij} and Y^u_{ij}:

$$V_{qL} Y^q V^{\dagger}_{qR} = M^q_{diag} \quad q_{L_i} = (V_{qL})_{ij} q^M_{L_i} \quad q_{R_i} = (V_{qR})_{ij} q^M_{R_i} \quad q = u, d$$

- Mass terms using $\phi = (v + H_0)/\sqrt{2}$:

$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} \bar{u}^M_{L_i} M^u_{diag} u^M_{R_j} + \frac{v}{\sqrt{2}} \bar{d}^M_{L_i} M^d_{diag} d^M_{R_j} + h.c. + \text{quark Higgs interaction}$$

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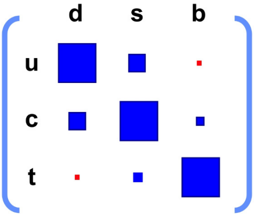
CKM Matrix Birth in Gauge Sector

- Charge current interaction

$$\mathcal{L}^{q}_{W^{\pm}} = -\frac{g}{\sqrt{2}}\bar{u}^{M}_{L_i}\gamma^{\mu}(V_{uL}V^{\dagger}_{dL})_{ij}d^{M}_{L_j}W^{+}_{\mu}$$

- The unitarity 3×3 matrix

$$V_{uL}V^{\dagger}_{dL} = V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Parametrization of the CKM matrix

- CKM is unitary matrix $\Rightarrow$ 18 parameters (9 complex elements)
- Only 4 are free

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\imath\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{\imath\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  - $s_{ij} = \sin\theta_{ij}$, $s_{ij} = \cos\theta_{ij}$
- Wolfenstein parametrization

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - \imath\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4\left(1 + 4A^2\right) & A\lambda^2 \\ A\lambda^3(1 - \rho - \imath\eta) & -A\lambda^2 + \frac{1}{2}A\lambda^4(1 - 2(\rho + \imath\eta)) & 1 - \frac{1}{2}A^4\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^5)$$

CP Violation in CKM Matrix

- Parity:

$$\hat{P}\psi(\mathbf{r}) = \psi(-\mathbf{r})$$

- Charge conjugation

$$\hat{C}\psi(\mathbf{r}) = \bar{\psi}(\mathbf{r})$$

- Time reversal

$$\hat{T}\psi(r,t) = \psi(r,-t)$$

- *CP* violated - δ parameter in CKM matrix:

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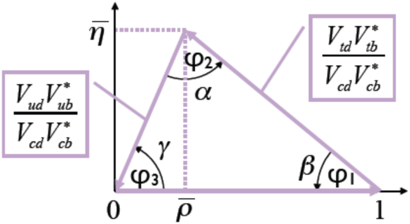
Unitarity Triangles

- Unitarity of CKM matrix leads to relations between matrix elements = **unitarity triangles**

$$\sum_{\alpha=u,c,t} V_{\alpha i} V^*_{\alpha j} = \delta_{ij}, \qquad \sum_{i=d,s,b} V_{\alpha i} V^*_{\beta i} = \delta_{\alpha\beta}.$$

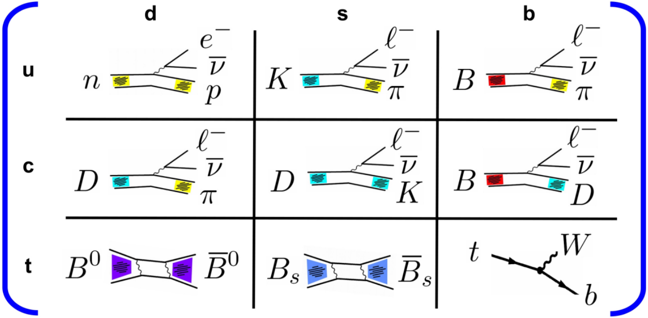
- Example:

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



Measuring the CKM Matrix

$V =$



Before "True" B-Factories - *b* quark

- *b* quark prediction: 1973 Makoto Kobayashi and Toshihide Maskawa (Nobel Prize in 2008)
- *b* quark name **bottom**: Haim Harari, 1975
- *b* quark discovery
  - Fermilab E288 experiment - Leon Lederman
  - 1977

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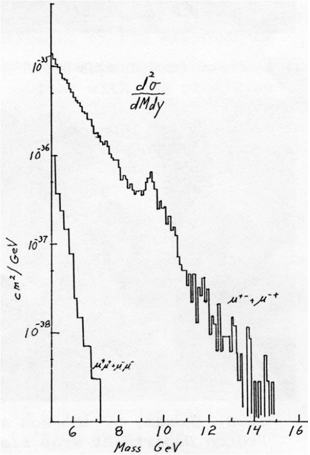
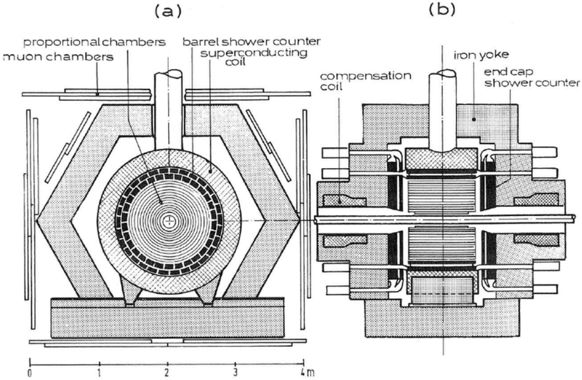


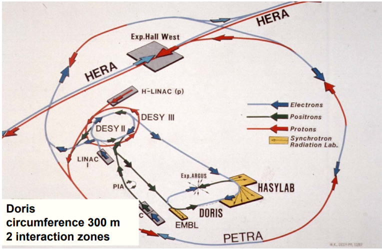
PLUTO - Way to B-Factories

- Constructed 1973-1974
- First electromagnetic superconductive solenoid in the world
- Y(9.46 GeV) confirmation, first gluon evidence (not discovery)



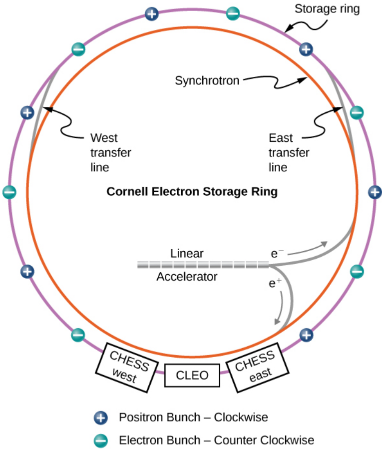
ARGUS - Way to B-Factories

- A Russian-German-United States-Swedish Collaboration
- DORIS (Doppel-Ring-Speicher = "double-ring storage") accelerator
- first place where the conversion of a B-meson into $\bar{B}$ was observed



CLEO - Way to B-Factories

- Cornell Electron Storage Ring (CESR)
- Collision energy: from 3.5 GeV to 12 GeV at its peak
- Initially measured the properties of the $\Upsilon(13S)$
  - Below the threshold for the *B* meson production
- In 1980s: spent time at the $\Upsilon(4S)$ energies
- Early 2000s: no longer competitive measurements of B mesons, back to $\Upsilon(1\text{-}3S)$ resonances

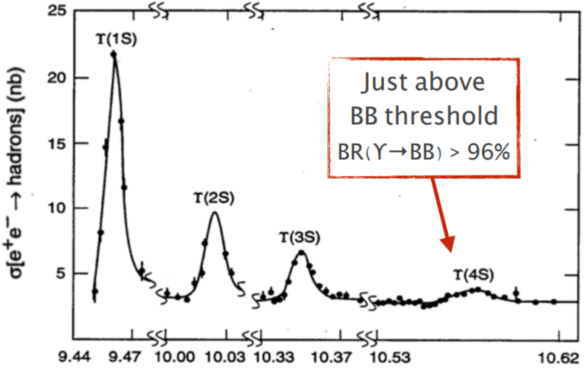


CLEO - Way to B-Factories

- CLEO I: 1979-1988
  - $\Upsilon(4S)$ discovery
- CLEO II: 1989-1999
  - FCNC decays $B^{+,0} \to K^{*+,0}\gamma$ and B mesons to two charmless mesons discovery
- CLEO III and CLEOc: 2000-2008
- **longest running experiment in the history of particle physics**

Requirements for a B Factory

- Usually, $b - \bar{b}$ created together ($\Upsilon(4S)$)
  - Both of them need to be detected and at least one reconstructed



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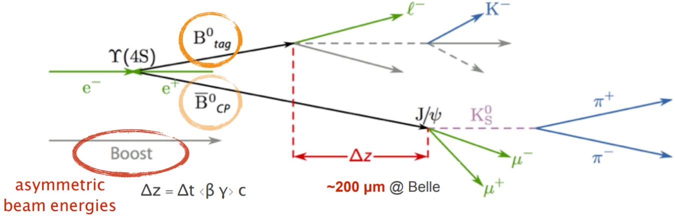

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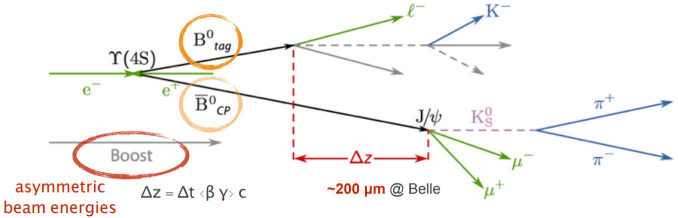
  - Asymmetric colliders ($E_{beam1} \neq E_{beam2}$)



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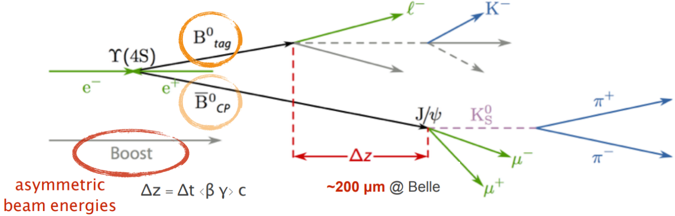

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  - e.g.: Branching ratio of $B^0 \to J/\psi K_S^0$ is 0.04% and $J/\psi \to l^+l^-$ is 12%
  - Millions of $B\bar{B}$ pairs needed $\to$: ~ 30 fb
- **High-resolution and large-coverage detector**
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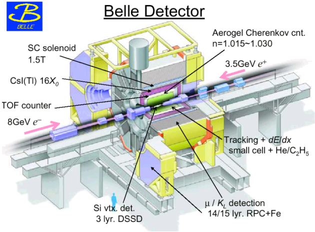
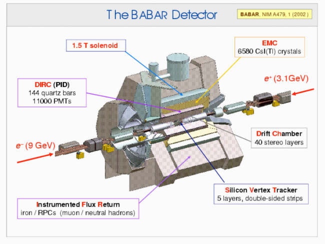
Heroes of the age of flavour

- **BaBar and Belle**: asymmetric beams, clean environment
- **CDF and D0**: general purpose, b-phys in hadron collision
- **ATLAS and CMS**: High p_{T} experiments, b-phys with dilepton final states
- **LHCb**: dedicated experiment for b- and c-physics at the LHC





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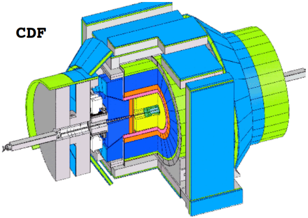

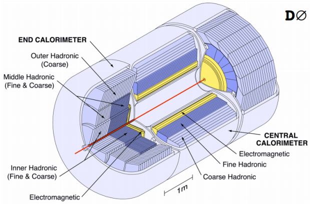

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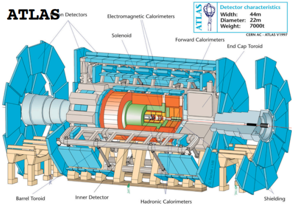

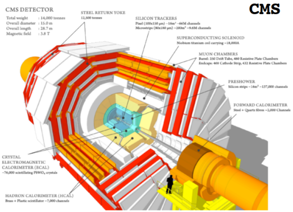

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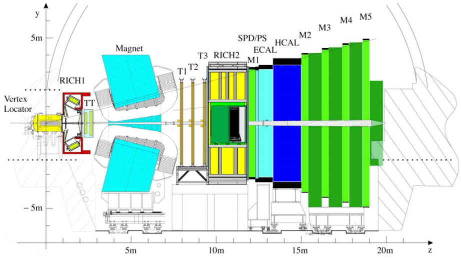
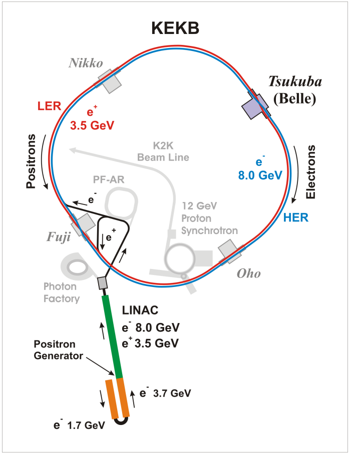


The Asymmetric B Factories

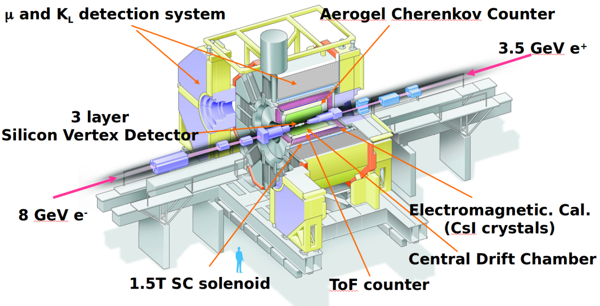
Belle



- Experiment operation: 1999–2010
- The High Energy Accelerator Research Organization (KEK) - Tsukuba, Ibaraki Prefecture, Japan
- $e^- e^+$ collisions ($E_{e^+} = 3.5$ GeV, $E_{e^-} = 8.0$ GeV)

Belle Detector

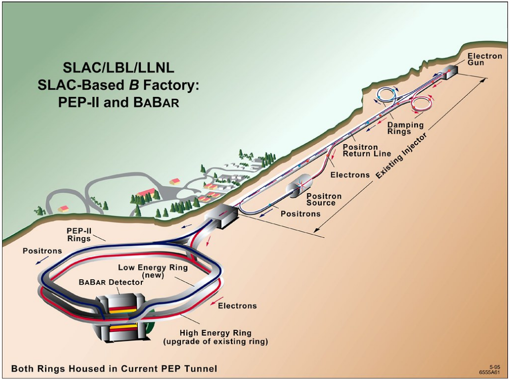
- A world-record luminosity of $2.1 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- More than $1\ \mathrm{ab}^{-1}$ of data over various bottomonium resonances
- The world largest sample of $\Upsilon(2S)$, $\Upsilon(4S)$, $\Upsilon(5S)$
- From $\Upsilon(4S) \to 772{\cdot}10^6$ of $B\bar{B}$ pairs



The Asymmetric B Factories

BABAR

- Experiment operation: 1999–2008
- Positron-Electron Project (PEP)
- e^-e^+ collisions ($E_{e^+} = 3.1$ GeV, $E_{e^-} = 9.0$ GeV)



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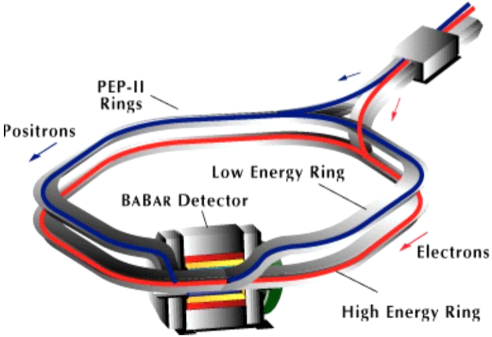

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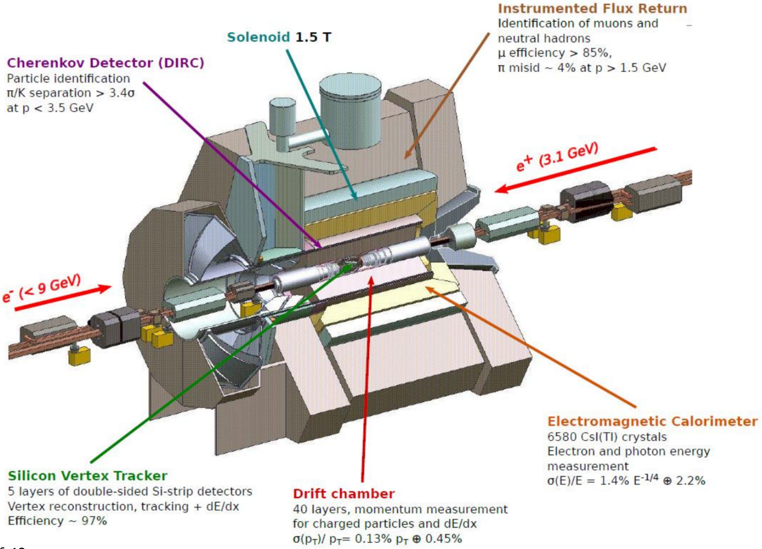
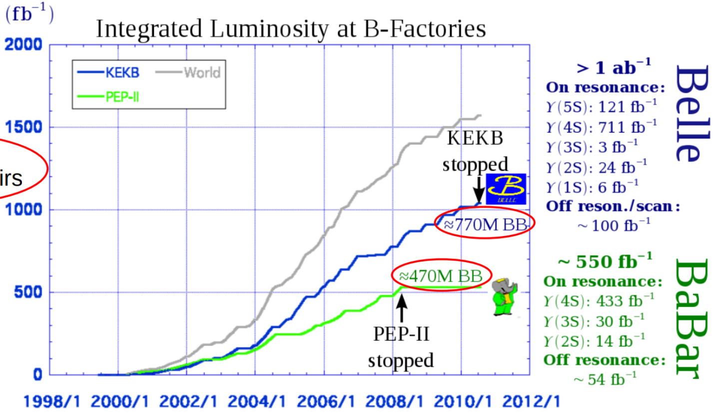
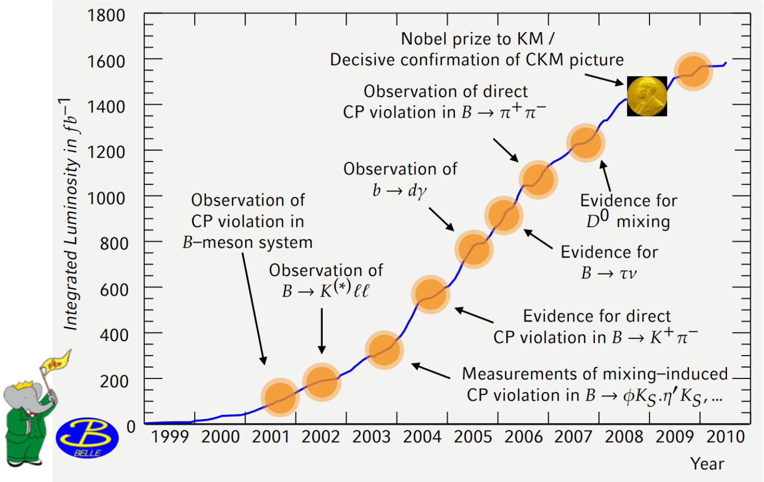


B-Physics Factories Luminosity

Total of
1240×10^6 BB pairs



B-Physics Factories Observations



B-Physics Factories Observations

Observation of CP violation in B-meson system

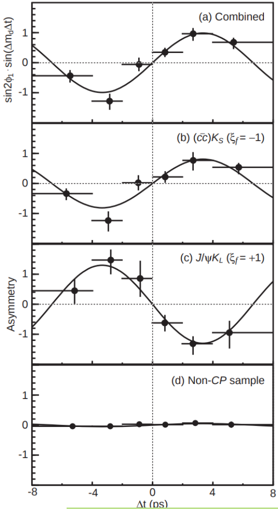
- Measuring time dependent CP asymmetry

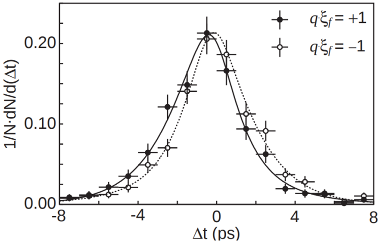
$$A_{CP}(\Delta t) = \frac{\Gamma\left(\bar{B}^0 \to f\right) - \Gamma\left(B^0 \to f\right)}{\Gamma\left(\bar{B}^0 \to f\right) + \Gamma\left(B^0 \to f\right)} = -n_f \sin(2\beta)\sin(\Delta m_d t)$$

- n_f: CP-eigenvalue of f
    - $n_f = -1$ for $J/\psi K^0_S$, $\psi(2S)K^0_S$
    - $n_f = +1$ for $J/\psi K^0_L$
- CKM unitarity triangle angle:

$$\sin 2\beta = 0.99 \pm 0.14 \pm 0.06$$

B-Physics Factories Observations

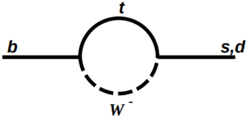




B-Physics Factories Observations

Observation of $b \to d\gamma$

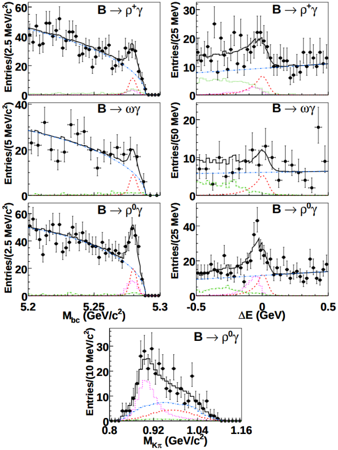
- SM: FCNC forbidden
- loop-induced FCNC possible ($b \to s$, $b \to d$) - penguin diagram
  - Radiative penguin decays: charged particle emits an external real photon
- Photon energy in $\Upsilon(4S)$ c.m.: $1.8 - 3.4\ \mathrm{GeV}$



$$\frac{\mathcal{B}(B \to (\rho,\omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = 0.0284 \pm 0.0050$$

- First measurement of the direct CP-violating asymmetry for $B^+ \to \rho^+\gamma$

Observation of $b \to d\gamma$



B-Physics Factories Observations

Evidence for D^0 mixing

- D system is the one that shows the smallest mixing
- Measuring the quantity

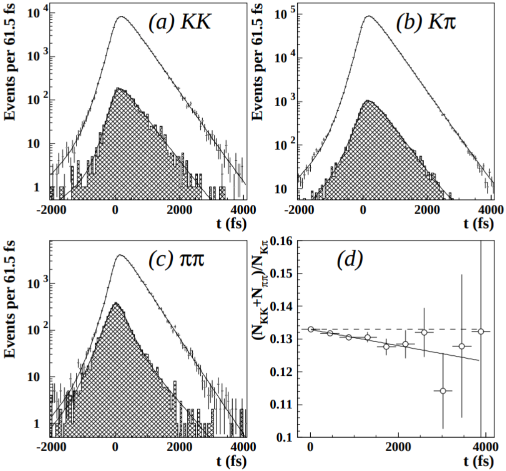
$$y_{CP} = \frac{\tau(D^0 \to K^- \pi^+)}{\tau(D^0 \to K^+ K^-)} - 1$$

- Can be shown:

$$y_{CP} = y \cos\phi - \frac{1}{2} A_M x \sin\phi$$

B-Physics Factories Observations

Evidence for D^0 mixing



B-Physics Factories Observations

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- Can be shown:

$$y_{CP} = y \cos\phi - \frac{1}{2} A_M x \sin\phi$$

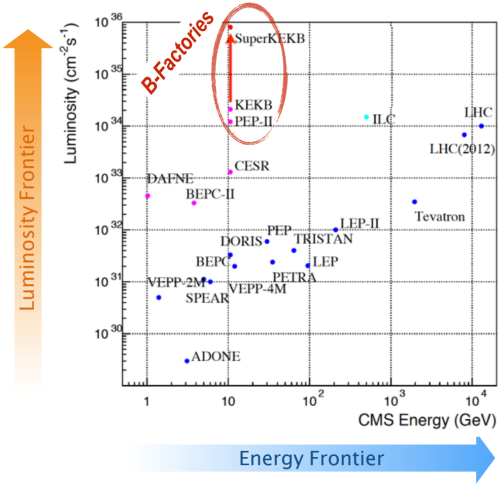
- Violation observed

$$y_{CP} = 0.0131 \pm 0.0032 \pm 0.0025$$

- Asymmetry also observed:

$$A = 0.0001 \pm 0.0030 \pm 0.0015$$

Next Generation *B* factories



Next Generation B factories

- Why we need higher luminosity?
  - target given by the physics community: 50 ab^{-1}
- If old KEKB used:
  - $2.1 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $0.3\ \mathrm{ab}^{-1}/\mathrm{year}$
  - 167 years
- How to get higher luminosity?

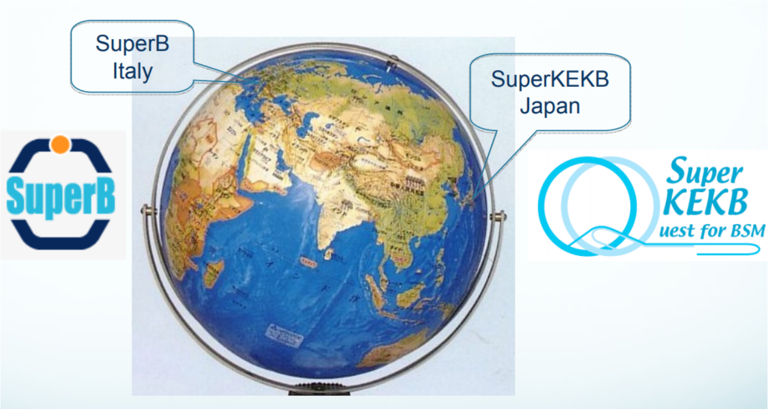
$$L = \frac{\gamma}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

  -
  - Beam size ratio, stored current, beam-beam parameter, β, geom. corrections (crossing angle)

Next Generation B factories

e^+ / e^-	KEKB	SuperKEKB
E [GeV]	3.5 / 8.0	4.0 / 7.0
I [A]	1.6 / 1.2	3.6 / 2.6
ξ	0.13 / 0.09	0.09 / 0.09
β^*_y [mm]	5.9 / 5.9	0.27 / 0.30
β^*_x [mm]	120 / 120	3.2 / 2.5
angle [mrad]	22	83
L [$cm^{-2}s^{-1}$]	2.1×10^{34}	80×10^{34}

Next Generation B factories



SuperKEKB/Belle II

SuperKEKB

- New e^+ source and e^- gun, powerful final quadrupoles

Belle II

- Reuse of the KEKB hardware as much as possible
- Minimum requirements: sustain Belle I performance
- Important improvements:
  - IP and secondary vertex resolution
  - K_S and π^0 reconstruction efficiency
  - PID in the encaps

SuperKEKB/Belle II

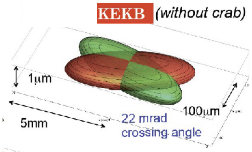
SuperKEKB

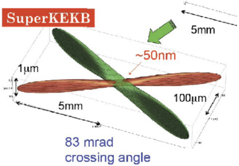
- New e^+ source and e^- gun, powerful final quadrupoles

Belle II

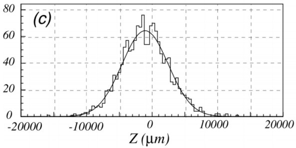
- Reuse of the KEKB hardware as much as possible
- Minimum requirements: sustain Belle I performance
- Challenges:
  - Higher occupancy, fake hits, noise
  - Radiation damage
  - Higher trigger rates: $0.5 \rightarrow 20\ \mathrm{kHz}$

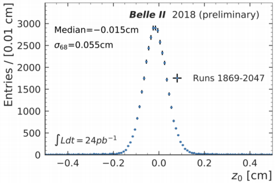
Collision with nano-beam





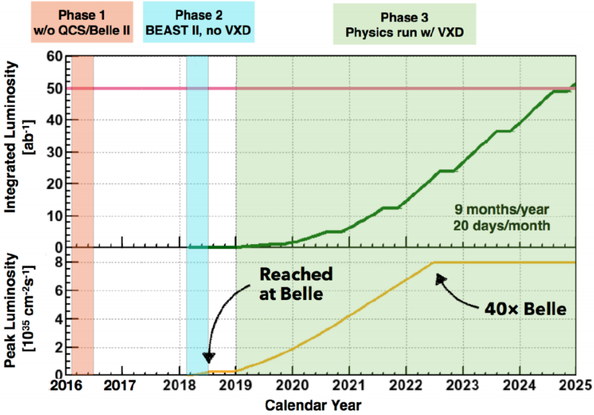
Belle case 1999 data



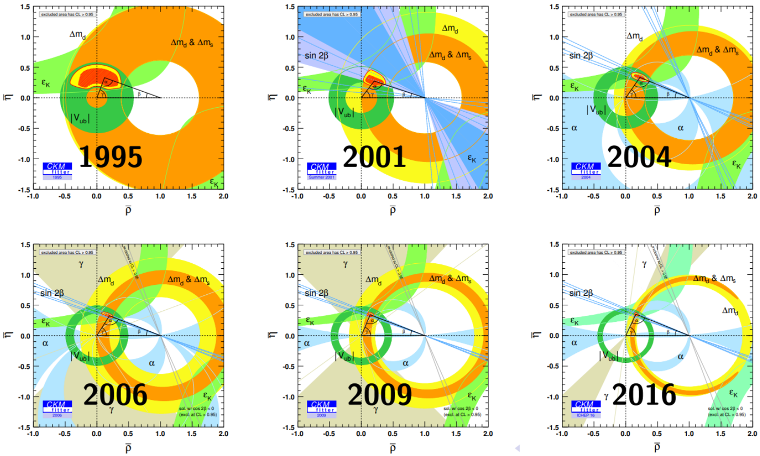


SuperKEKB/Belle II

Belle II

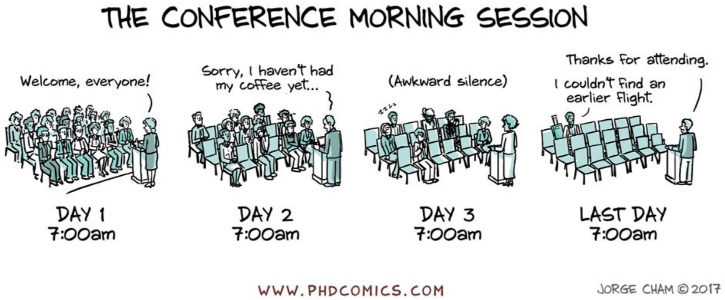


Summary


1995
2001
2004
2006
2009
2016
excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
|V_ub|
α
β
γ
CKM fitter
sol. w/ cos 2β < 0 (excl. at CL > 0.95)
$\bar{\rho}$
$\bar{\eta}$

Summary

- Role of flavour physics is important
- What properties B factories need?
- Belle and BABAR detectors and successes presented
- LHCb, ATLAS, CMS active, BelleII ramping up
- Still need to improve precision - NP?


THE CONFERENCE MORNING SESSION
Welcome, everyone!
DAY 1
7:00am
Sorry, I haven't had my coffee yet...
DAY 2
7:00am
(Awkward silence)
DAY 3
7:00am
Thanks for attending.
I couldn't find an earlier flight.
LAST DAY
7:00am
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Back-up

CP Violation

- Parity violated - is combination of $\mathcal{P}$ and $\mathcal{C}$ violated?
- Strong and EM interactions: $\mathcal{CP}$ conserved
- Weak interactions: $\mathcal{CP}$ violated:
  - Christenson, Cronin, Fitch and Turlay 1964
  - study of two neutral K mesons in the kaon decays, K_S^0 and K_L^0
  - if $\mathcal{CP}$ conserved:

$$K_S^0 \rightarrow 2\pi \qquad K_L^0 \rightarrow 3\pi$$

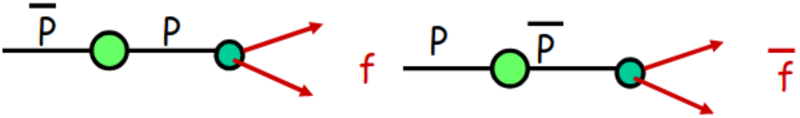
  - $K_L^0 \rightarrow 2\pi$ observed!!
  - $K^0\bar{K}^0$ oscillation, $\mathcal{CP}$ violated
- Three types of $\mathcal{CP}$ violation:
  - in decay
  - in mixing
  - in interference of mixing and decay

$\mathcal{CP}$ Violation in Mixing

- probability of oscillation from meson to anti-meson is different from the probability of oscillation from anti-meson to meson

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

- Mass eigenstates are not CP eigenstates
- Charged-current semileptonic neutral meson decays $M, \bar{M} \to l^{\pm}X$

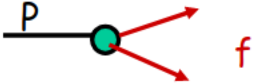


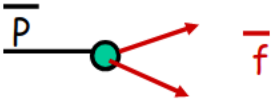
$\mathcal{CP}$ Violation in Decay

- decay amplitude of particle into the final state is different from the decay amplitude of its antiparticle into its final anti-state

$$\Gamma(M \to f) \neq \Gamma(\bar{M} \to \bar{f})$$

- In charged meson (and all baryon) decays, where mixing effects are absent, this is the only possible source of $\mathcal{CP}$ asymmetries

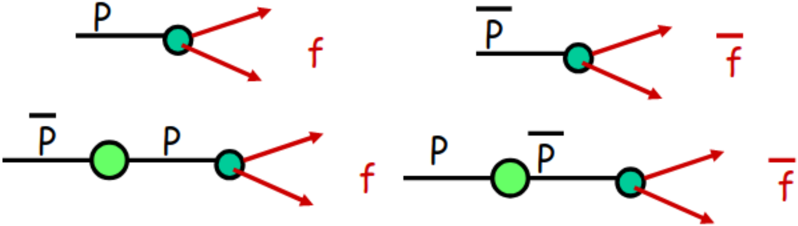




$\mathcal{CP}$ Violation in Interference of Mixing and Decay

- occurs in case both meson and antimeson decay into the same final state

$$M \to f \qquad M \to \bar{M} \to f$$



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