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University of Ljubljana
"Jožef Stefan" Institute

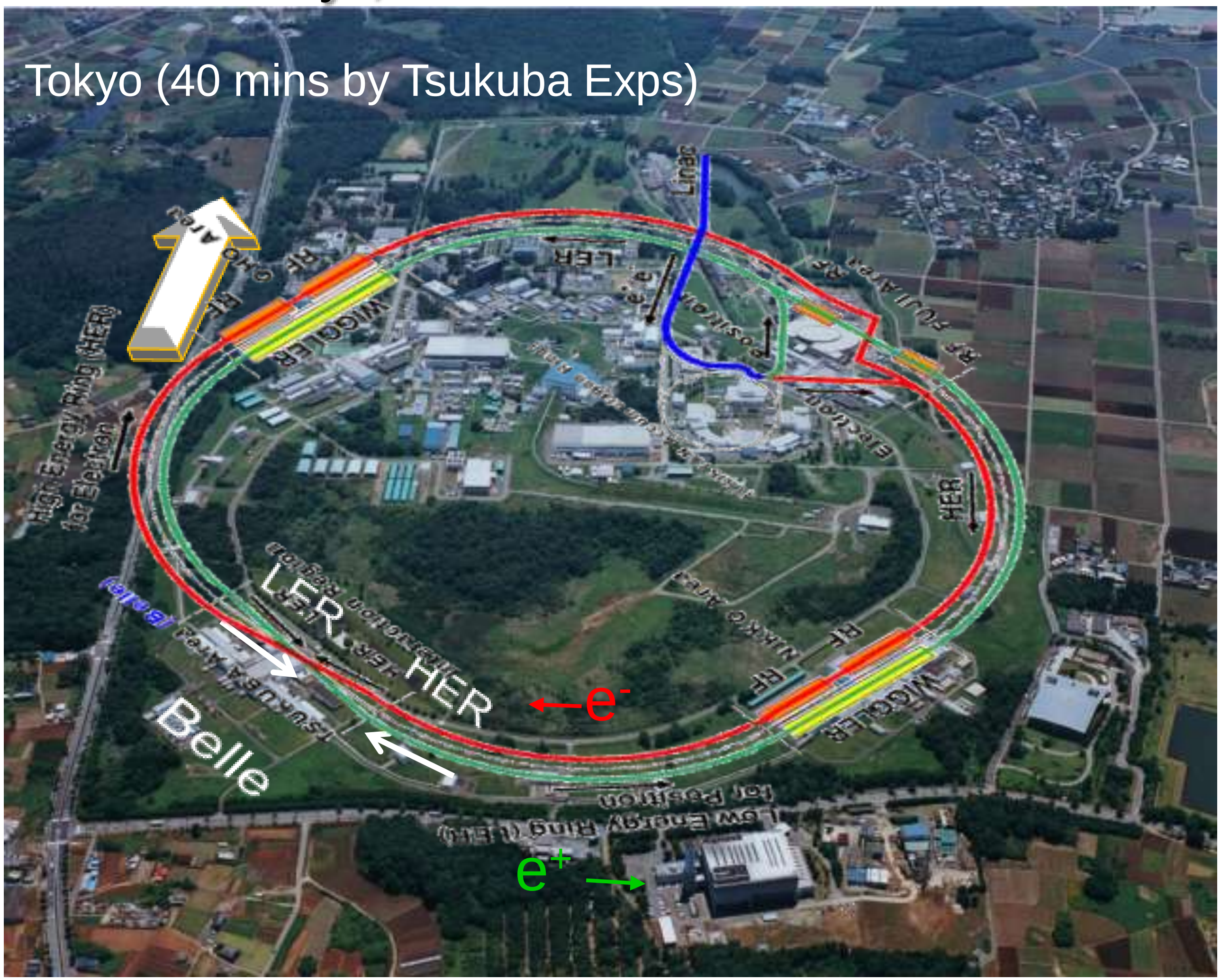
Fizikalni kolokvij Oddelka za fiziko FMF,
Ljubljana, December 2010

Introduction

Accelerator

"B-Factory", KEKB @ KEK

KEKB → accelerator
KEK → institute



KEKB:

e^- (HER): 8.0 GeV
e^+ (LER): 3.5 GeV

crossing angle:
22 mrad

$E_{CMS}=M(\Upsilon(4S))c^2$

$dN_f/dt = \sigma(e^+e^- \to f)\,\mathcal{L}$

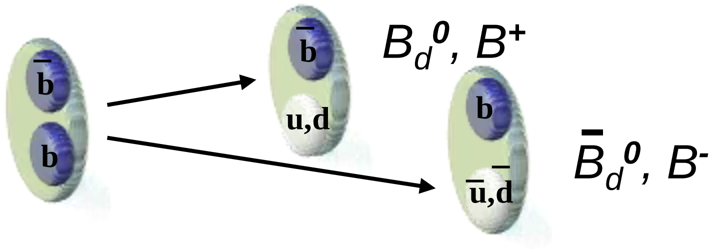
$\int_{1999}^{2010} \mathcal{L}dt = 1020\ fb^{-1}$

($1.02\ ab^{-1}$)

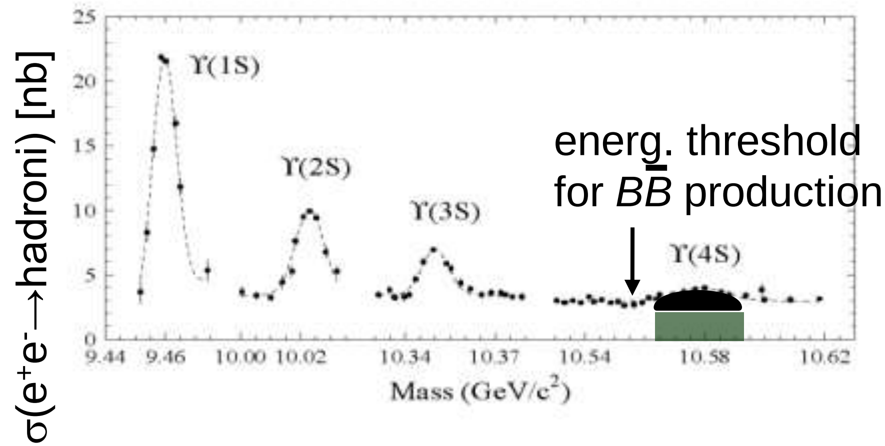
Accelerator

"B-Factory", KEKB @, KEK

$\Upsilon(4S)$



Belle $\int \mathcal{L} dt \approx 1020$ fb^{-1}



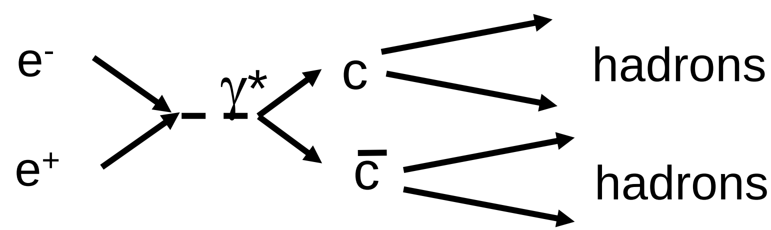
"on resonance" production

$e^+e^- \to \Upsilon(4S) \to B_d^0\bar{B}_d^0, B^+B^-$

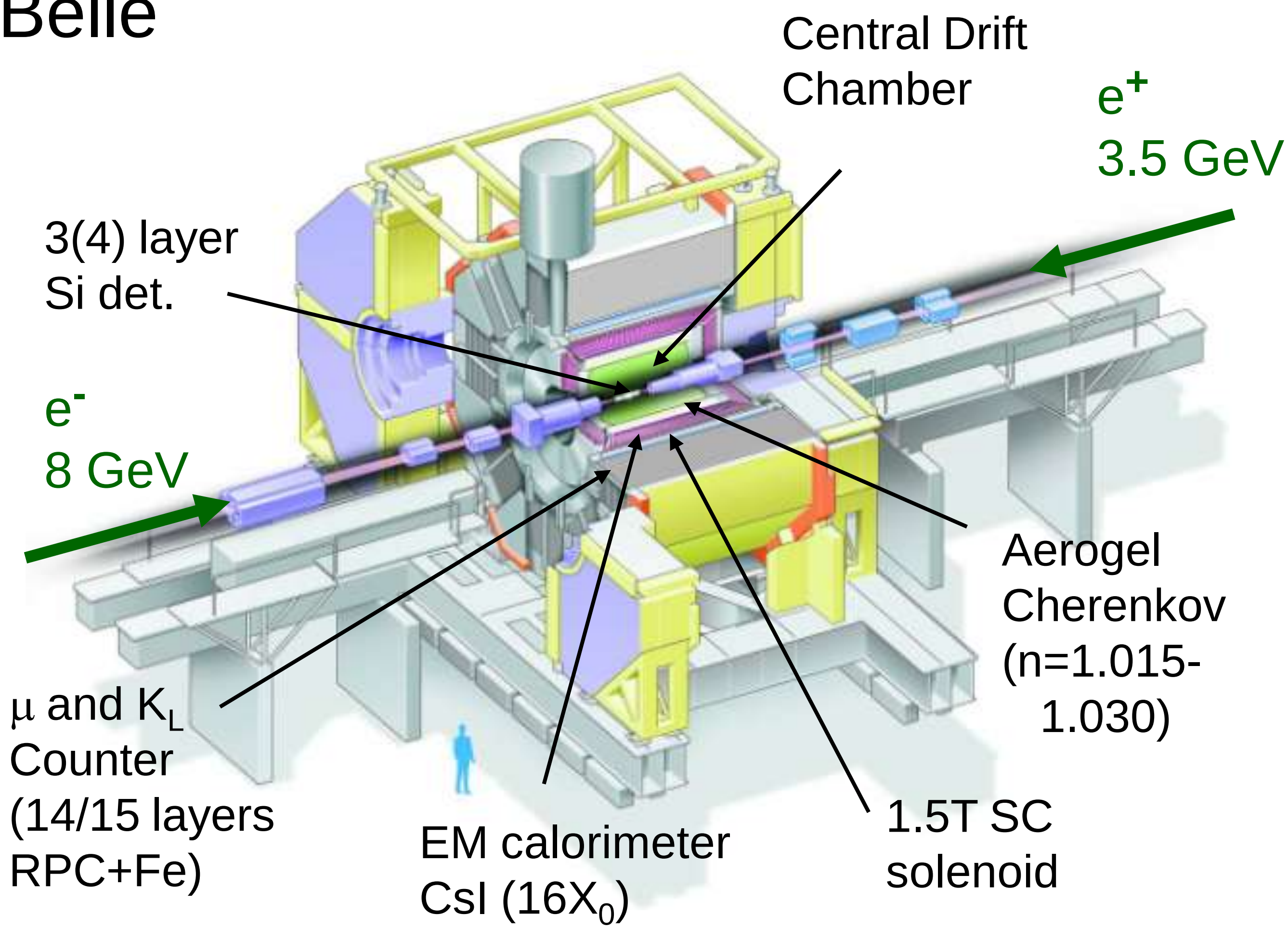
$\sigma(e^+e^- \to B\bar{B}) \approx 1.1$ nb (~10^9 $B\bar{B}$ pairs)

"continuum" production

$\sigma(e^+e^- \to c\,\bar{c}) \approx 1.3$ nb (~$1.3\text{x}10^9$ X_cY_c pairs)

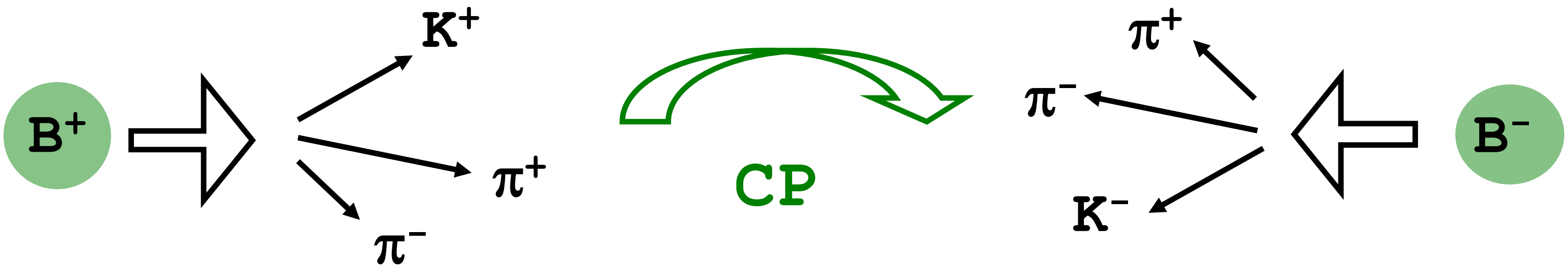


Detector Belle



B meson decay: $\sigma \sim 100\ \mu m$

Basic motivation



Why CP symmetry? → Why Universe evolved from symmetric state

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 0$$ to today's $$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \sim 10^{-10} - 10^{-9}$$?

"matter dominated" universe as observed for example by AMS 1

A. Sakharov, 1967: 3 necessary conditions for asymmetric universe evolution (received Nobel prize for peace in 1975):
baryon number violation, thermal non-equilibrium,
CP and C symmetry violation
(CPV)

A.D. Sakharov, Pisma Zh.Eksp.Teor.Fiz.5, 32 (1967) (1434 citations)

CPV is necessary condition for matter dominated universe

Basic motivation

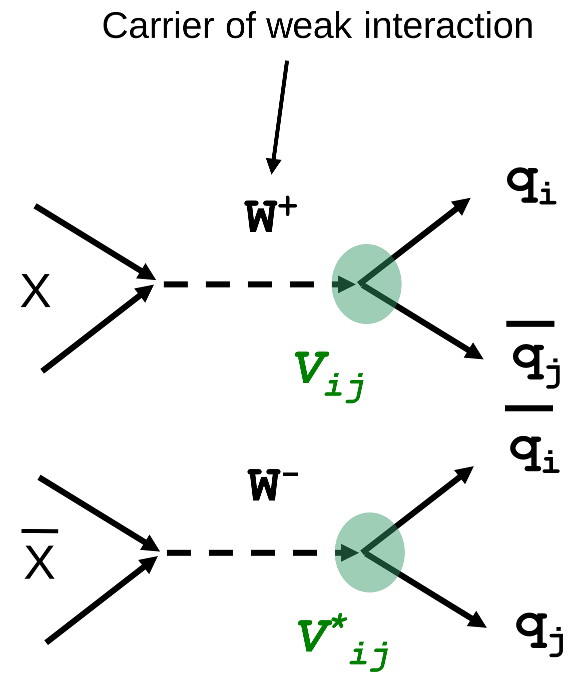
CP symmetry among particles (Standard Model):

Kobayashi-Maskawa mechanism:

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

Cabibbo-Kobayashi-Maskawa (CKM) matrix

M. Kobayashi, T. Maskawa, Prog.Th.Phys.49, 652 (1973) (6140 citations)



if $V_{ij}=V_{ij}^*$ ▶ SM Lagrangian $\mathscr{L}=\mathscr{L}_{CP}$ ▶

CP symmetry is conserved

if elements of CKM matrix complex ⇒ CPV

Basic motivation

Kobayashi-Maskawa mechanism:

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\phi} \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\phi} & -c_{12}s_{23} & c_{23}c_{13} \end{bmatrix}$$

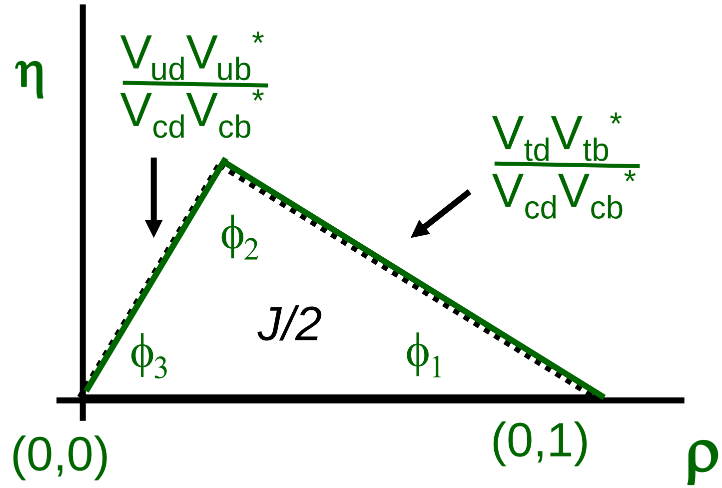
unitarity:

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

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \propto J$$

maximal possible value $J_{max} = \frac{1}{6\sqrt{3}} \approx 0.1$

exp. determined value $J_{meas} \approx 3 \cdot 10^{-5}$



$J_{meas} \Rightarrow$ baryon asymmetry of the universe $\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \sim 10^{-16}$

and not $\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-10} - 10^{-9}$

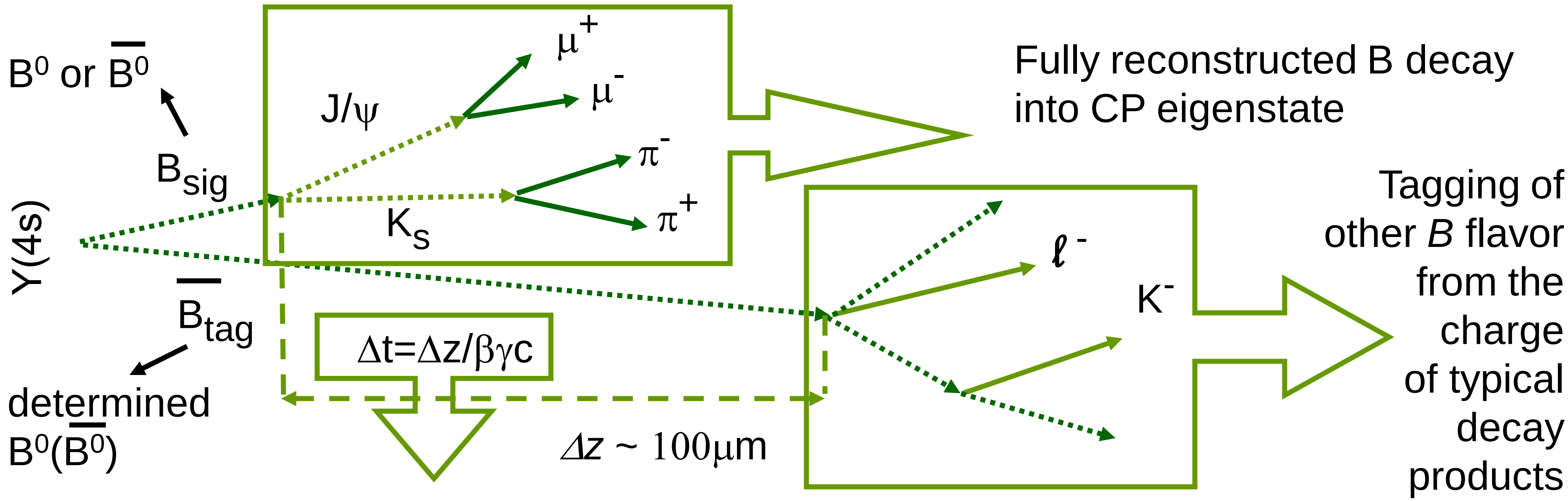
CPV as observed nowadays is too small to explain the matter asymmetry of the universe

Bread & butter

sin2ϕ_1

$$\varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

Method



Determination of the time between decays of two *B's*

sin2ϕ_1

Δt distribution for $\Upsilon(4S) \to B^0 \bar{B}^0 \to$ (e.g. $J/\psi K_s$) (X_{tag}):

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q \cdot \left[S_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t) \right] \right]$$

$q = \pm 1$: $B_{tag} = B^0, \bar{B}^0$

Δm_d: $B^0\bar{B}^0$ oscillation freq.

$S_f \neq 0$: time dependent CP violation (TCPV)

$\mathcal{A}_f \neq 0$: time independent CP violation (DCPV)

Why $S_f \neq 0$, $\mathcal{A}_f \neq 0$ means CPV?

$$A_{CP} = \frac{\mathcal{P}(\Delta t; B_{tag} = B^0) - \mathcal{P}(\Delta t; B_{tag} = \bar{B}^0)}{\mathcal{P}(\Delta t; B_{tag} = B^0) + \mathcal{P}(\Delta t; B_{tag} = \bar{B}^0)} = S_f \sin(\Delta m \Delta t) + \mathcal{A}_f \cos(\Delta m \Delta t)$$

B^0 and $\bar{B}^0$ behave differently!

SM: for $b \to c\bar{c}s$: $S=\sin 2\phi_1$, $A=0$

complex phase of CKM can be measured - for example - by study of Δt for $B^0\bar{B}^0$ pairs from $\Upsilon(4S)$

$sin2\phi_1$

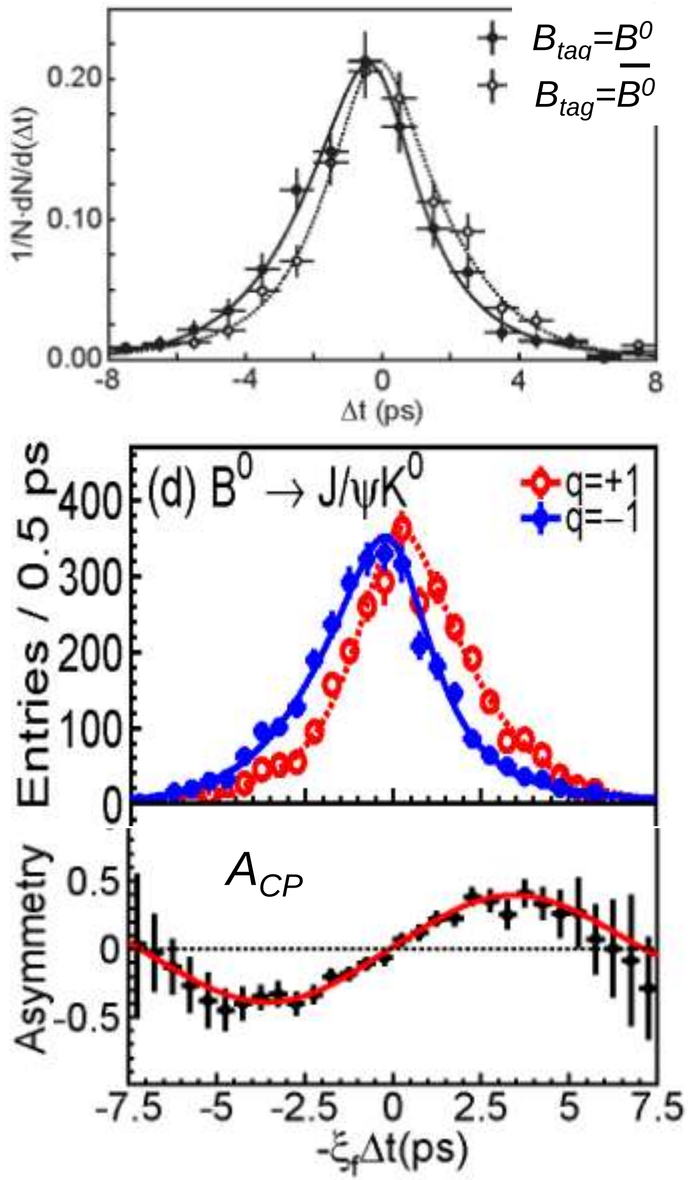
Results

one angle of unitarity triangle is measured with a great precision

Belle, PRD66, 032007 (2002)

significant measurement of TCPV in B^0 system; exp. evidence that CPV is indeed intrinsic property of weak interaction (CPV in K^0 - 1964)

$sin2\phi_1$=0.99 ± 0.14 ± 0.06



Belle, PRL98, 031802 (2008)

$sin2\phi_1$=0.642 ± 0.031 ± 0.017

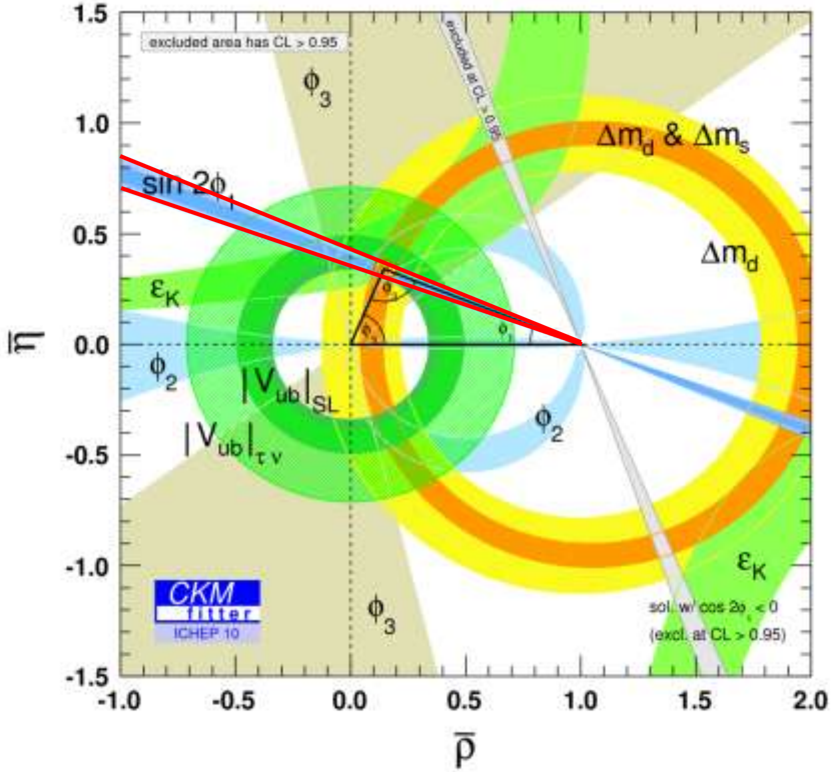
$sin2\phi_1$,1999-2010:
from free parameter of SM to precision measurement with accuracy ±3% (world average)

Verification of Kobayashi-Maskawa mechanism

$\phi_1 \neq 0 \quad \Rightarrow$ only established CPV in B^0 system;

KM mechanism: CPV in all processes arises from a single complex phase in CKM matrix; $\Rightarrow$ relation among CPV observables and magnitudes of CKM matrix elements in various processes

ϕ_1; $b \to c\bar{c}s$ ($B^0 \to J/\psi K_s$)



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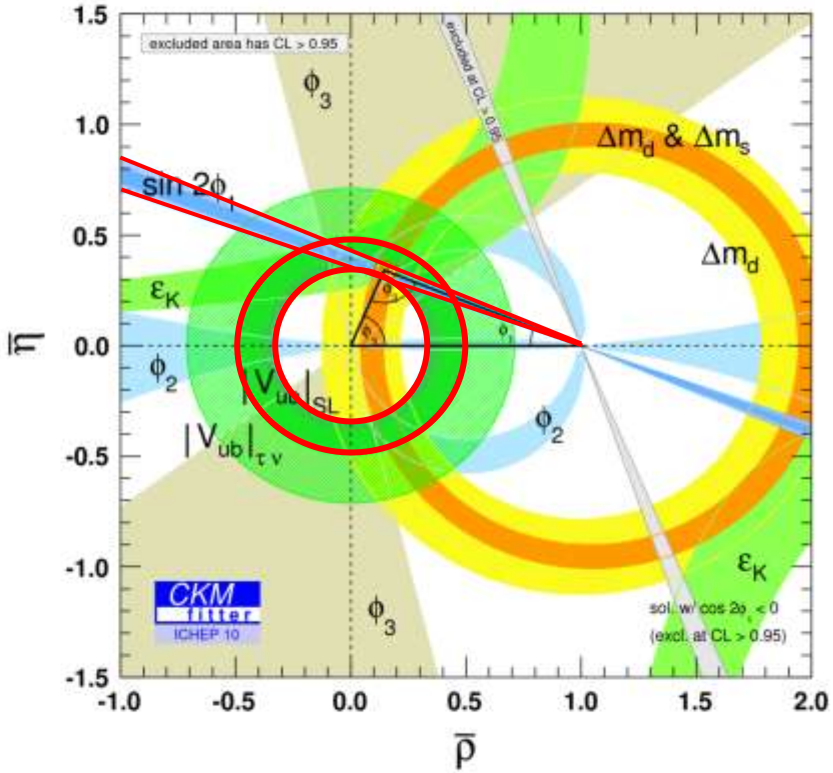
ϕ_1; $b \to c\bar{c}s$ ($B^0 \to J/\psi K_s$)

$|V_{ub}|$; $b \to \ell\nu u$ ($B^0 \to \pi \ell \nu$)

suppress 140x larger $b \to \ell\nu c$



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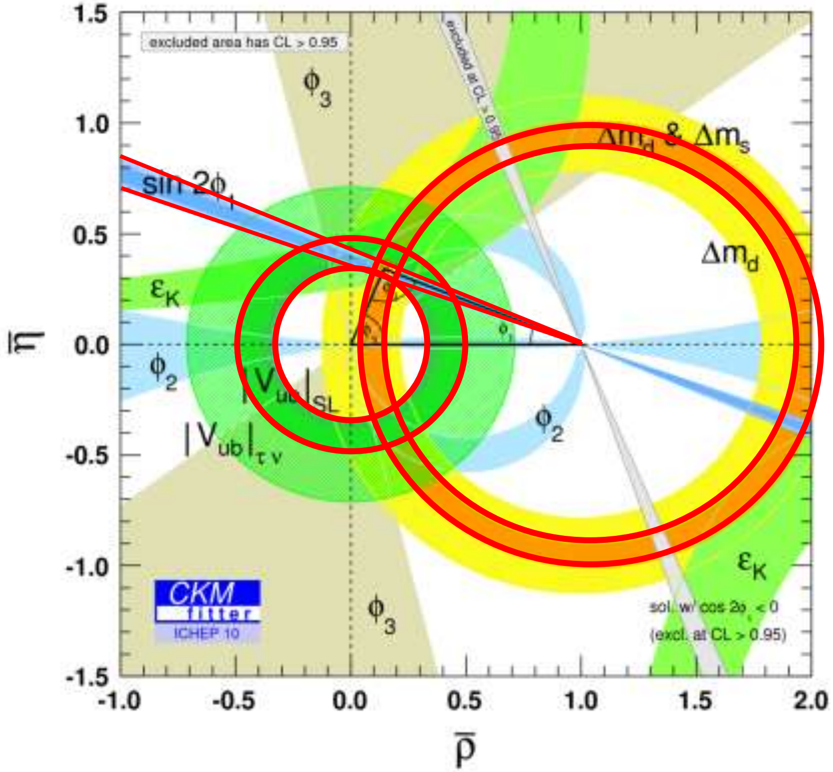
$\Delta m_d / \Delta m_s$; B^0_d/B^0_s oscillations

help from Tevatron



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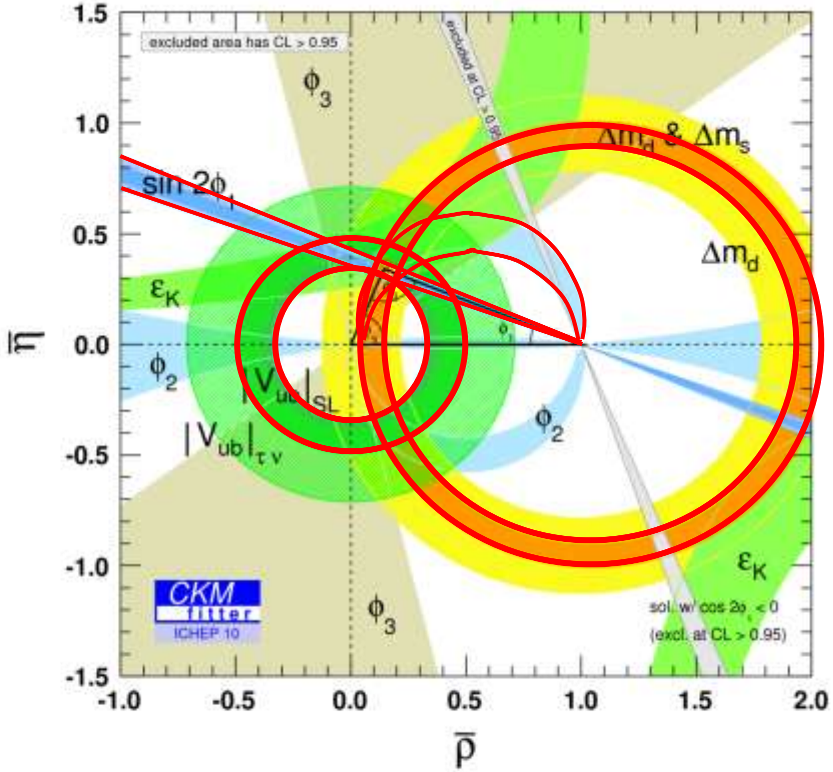
ϕ_2; $b \to u\bar{u}d$ ($B^{0,+} \to \pi\pi$)

measure all charge combinations



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help from Tevatron

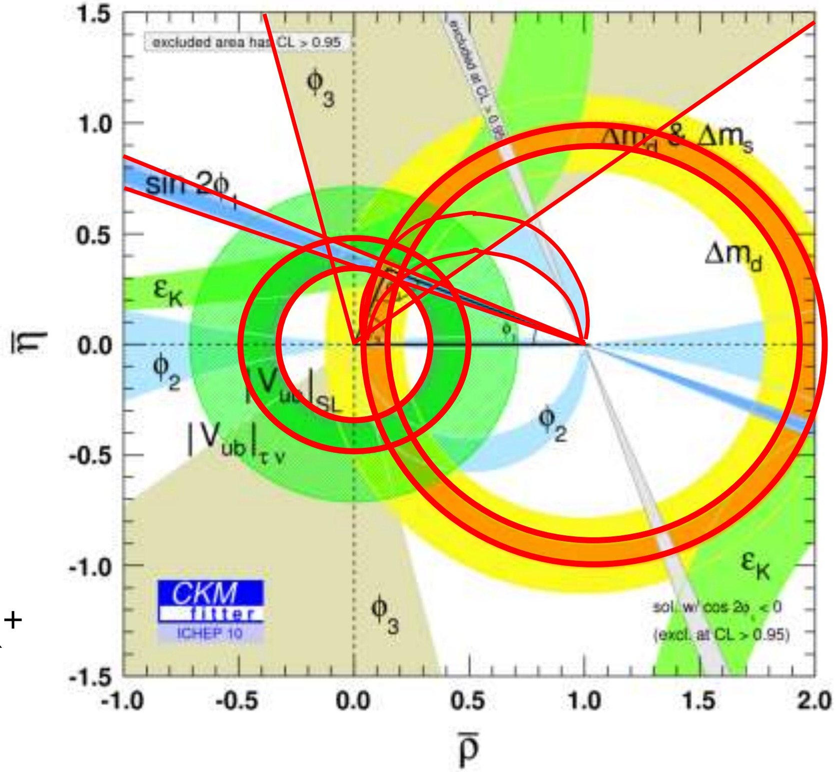
ϕ_2; $b \to u\bar{u}d$ ($B^{0,+} \to \pi\pi$)

measure all charge combinations

ϕ_3; $B^+ \to D^0(\to f_{com})\, K^+ / B^+ \to \bar{D}^0(\to f_{com})\, K^+$

($f_{com} = K_S\pi^+\pi^-$)

mutibody final state, special technique (Dalitz analysis)



Verification of Kobayashi-Maskawa mechanism

$\phi_1 \neq 0 \quad \Rightarrow$ only established CPV in B^0 system;

various measurements of variables related to CKM matrix agree very well

KM mechanism: CPV in all processes arises from a single complex phase in CKM matrix; ⇒ relation among CPV observables and magnitudes of CKM matrix elements in various processes

ϕ_1; $b \to c\bar{c}s$ ($B^0 \to J/\psi K_s$)

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suppress 140x larger $b \to \ell\nu c$

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help from Tevatron

ϕ_2; $b \to u\bar{u}d$ ($B^{0,+} \to \pi\pi$)

measure all charge combinations

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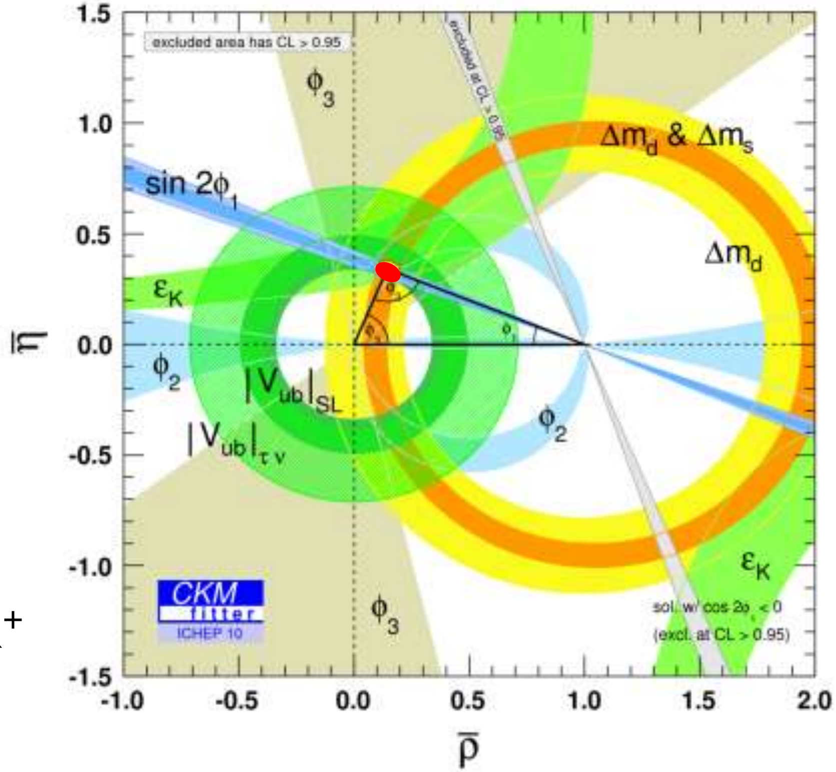


Verification of Kobayashi-Maskawa mechanism

Perhaps most valuable confirmation of the importance of B-factories (Belle + BaBar) measurements:

2008

"During the past decade, elementary particle physicists have measured Kobayashi and Maskawa's theory with great precision and found that it really does fit the data."

L. Brink, 2008 Nobel Prize presentation speech

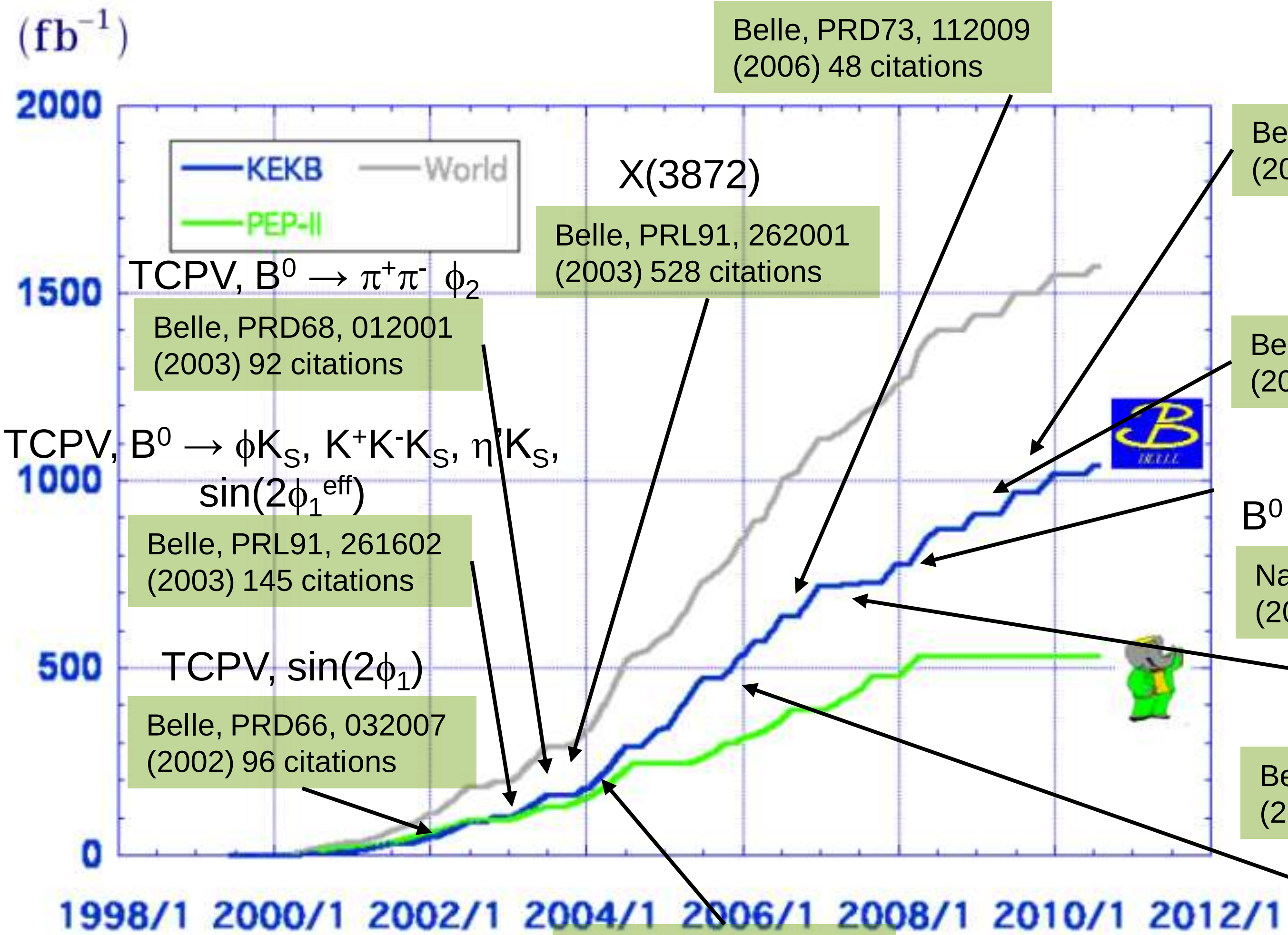
KEKB/Belle

May 1999 - July 2010

KEKB accelerator control room, July 2010: director general of KEK pressed the beam abort button of KEKB for the last time $\Rightarrow$ SuperKEKB

KM mechanism

Maj 1999 - July 2010



TCPV, $\sin(2\phi_1)$
Belle, PRD66, 032007 (2002) 96 citations

TCPV, $B^0 \to \pi^+\pi^-$ ϕ_2
Belle, PRD68, 012001 (2003) 92 citations

TCPV, $B^0 \to \phi K_S$, $K^+K^-K_S$, $\eta' K_S$, $\sin(2\phi_1^{eff})$
Belle, PRL91, 261602 (2003) 145 citations

X(3872)
Belle, PRL91, 262001 (2003) 528 citations

DCPV, $B^0 \to \pi^+\pi^-$, $K^+\pi^-$
Belle, PRL93, 021601 (2004) 117 citatov
Belle, PRL93, 191802 (2004) 137 citatov

ϕ_3, Dalitz analysis
Belle, PRD73, 112009 (2006) 48 citations

$B^+ \to \tau^+\nu$
Belle, PRL97, 251802 (2006) 199 citations

D^0 mixing
Belle, PRL98, 211803 (2007) 184 citations

DCPV difference, $B^0 \to K^+\pi^-$ in $B^+ \to K^+\pi^0$
Nature, 452, 332 (2008) 63 citations

$B \to K^*\ell^+\ell^-$
Belle, PRL103, 171801 (2009) 44 citations

$B^+ \to X_s \gamma$
Belle, PRL103, 241801 (2009) 15 citations

Cracks in SM dam?

Hints of inconsistencies

"During the past decade, elementary particle physicists have measured Kobayashi and Maskawa's theory with great precision and found that it really does fit the data."

L. Brink, 2008 Nobel Prize presentation speech

Really? How precisely?

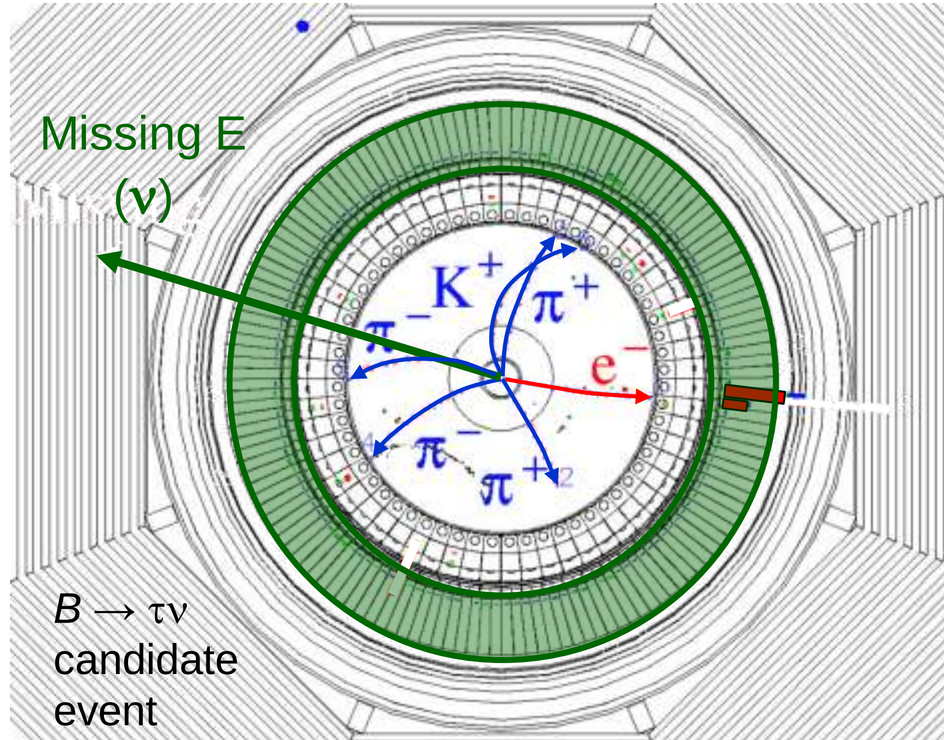
Cracks in SM dam?

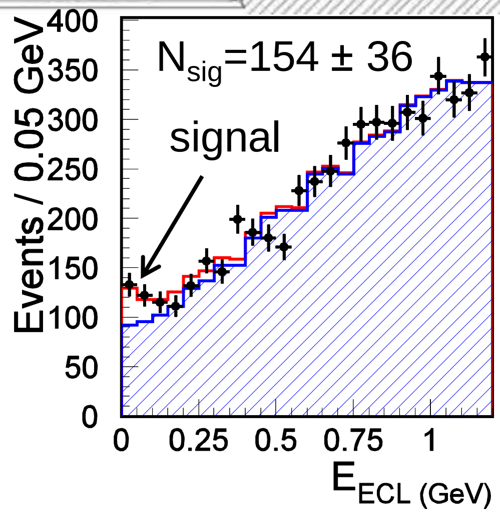
$B \rightarrow \tau\nu$

B leptonic decays

$\mathcal{B}(B \rightarrow \tau\nu)$
ν's escape detection!

method:
- fully reconstruct B_{tag} ($K^+\pi^-\pi^+\pi^-\pi^+$);
- search for tracks from $B_{sig}\rightarrow\tau\nu$ (e^-);
- no additional energy in EM calorim. (from π^0, γ, ...);
- signal at E_{ECL}~0





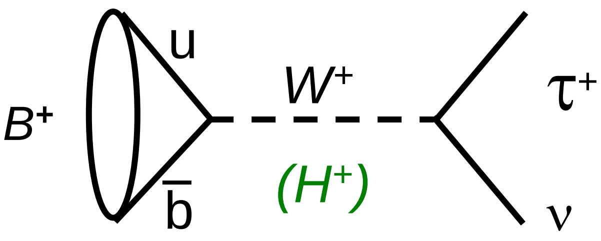
Belle, PRD82, 071101 (2010)

$$Br(B^+ \rightarrow \tau\nu) = (1.54 \pm^{0.38}_{0.37} \pm^{0.29}_{0.31}) \cdot 10^{-4}$$

Cracks in SM dam?

$B \to \tau\nu$

$\mathcal{B}(B \to \tau\nu)$: contribution of charged Higgs boson (in Minimal Suypersymmetric Standard Model)



Particles and processes not observed and not included in SM: "New Physics" (NP);

$\Delta E \Delta t \geq \hbar / 2$ Δt tiny →heavy particles can contribute virtually

tanβ: free parameter of MSSM

$$\mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}^{SM}(B^+ \to \tau^+\nu)\cdot(1-\frac{m_B^2}{m_H^2}\tan^2\beta)^2$$

$$\mathcal{B}(B^+ \to \tau\nu) = (1.64 \pm 0.34)\cdot 10^{-4}$$

Heavy Flavor Averaging Group,
http://www.slac.stanford.edu/xorg/hfag/

$$\mathcal{B}^{SM}(B^+ \to \tau\nu) = (0.76 \pm^{0.11}_{0.06})\cdot 10^{-4}$$

CKMFitter,
http://ckmfitter.in2p3.fr/

$$(1-\frac{m_B^2}{m_H^2}\tan^2\beta)^2 = 2.16 \pm 0.55$$

⇒ disagreement with SM;
uncertainty still large, need more data

contribution of NP can have observable effect in rare processes within the SM

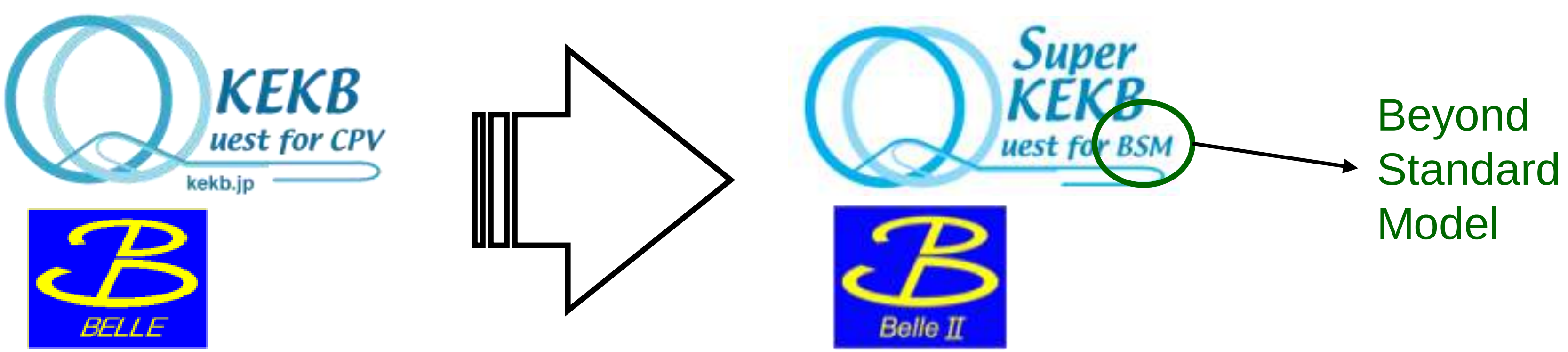
small hints of inconsistencies with the SM predictions were observed in several measurements

Way to proceed?

Kobayashi-Maskawa mechanism confirmed with accuracy available from existing B-factories;

hints of SM breakdown require at least one order of magnitude better accuracy;

$\sigma \propto 1/\sqrt{N} \Rightarrow \mathcal{O}(10^2)$ higher luminosity

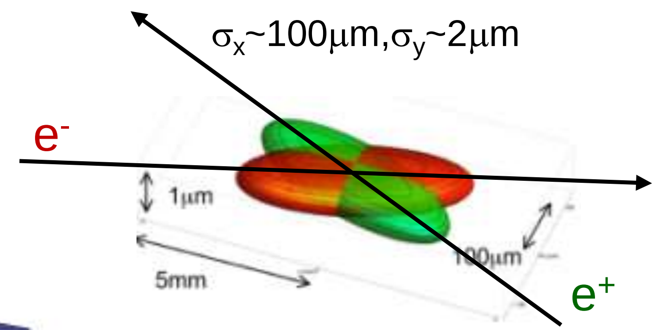


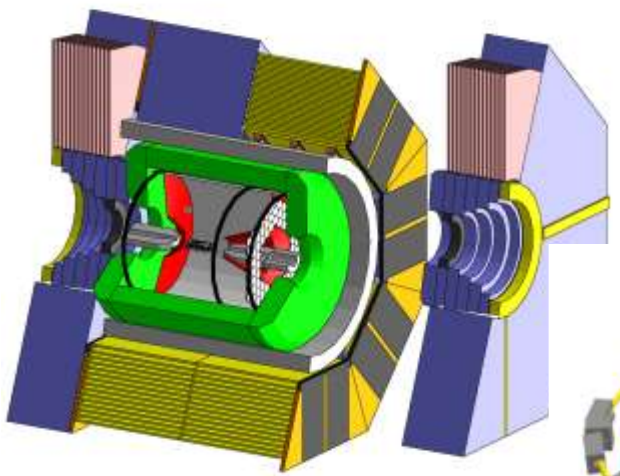
Way to proceed?

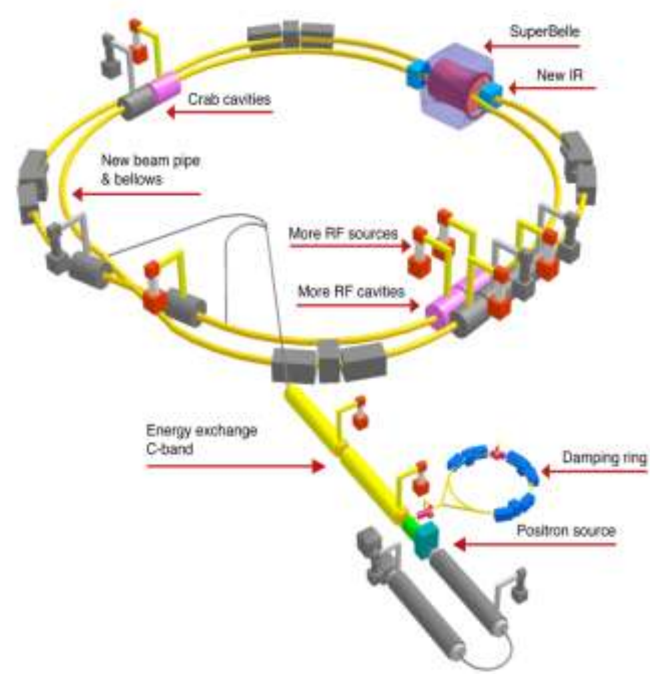
Super B Factories

two projects:
- SuperB, Frascati, Italy (new)
- SuperKEKB, KEK, Japan (upgrade)

squeezed (more “dense”) beams $\Rightarrow$ higher luminosity







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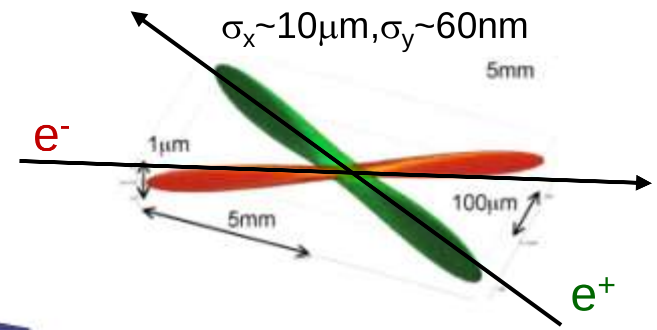
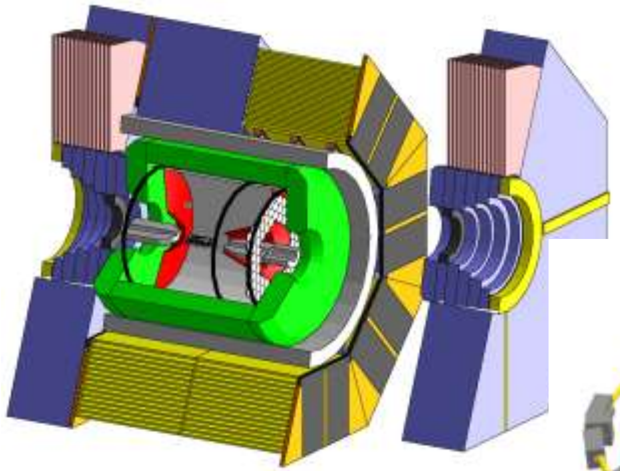
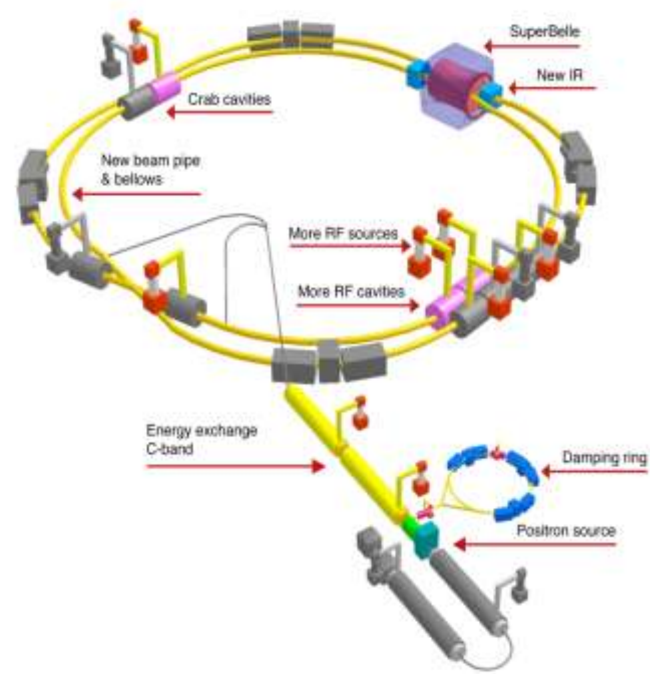
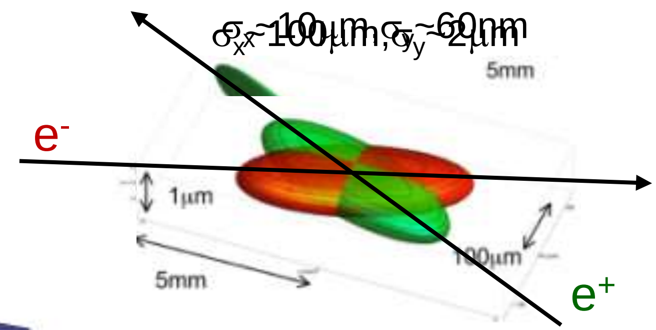


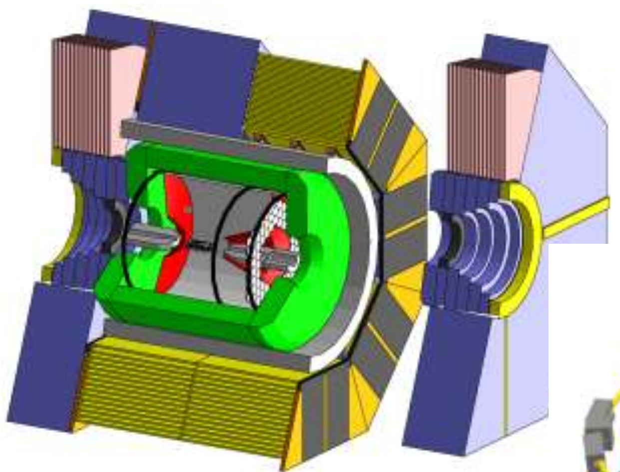




Super B Factories

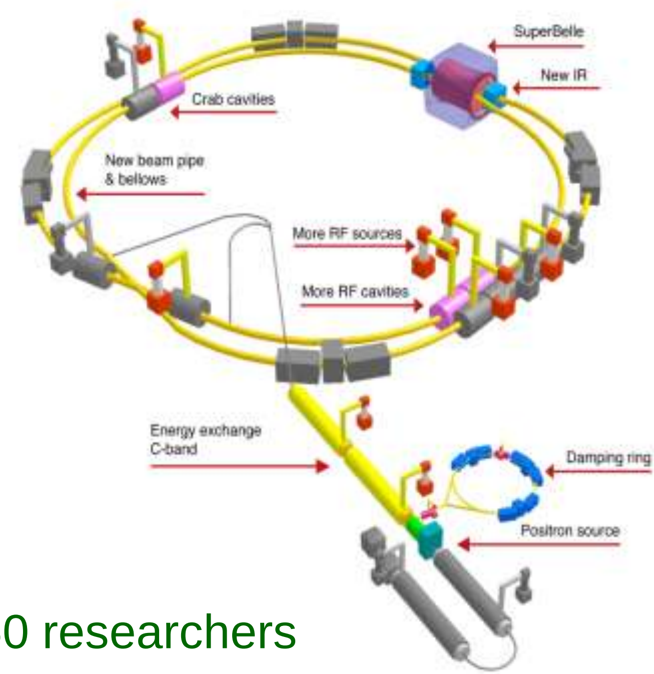


two projects:
- SuperB, Frascati, Italy (new)
- SuperKEKB, KEK, Japan (upgrade)



squeezed (more "dense") beams $\Rightarrow$ higher luminosity

current luminosity is a world record so far
$\Rightarrow$
large technological project



SuperKEKB:
upgrade of collider and detector (Belle II)

13 countries, 57 institutions, 360 researchers

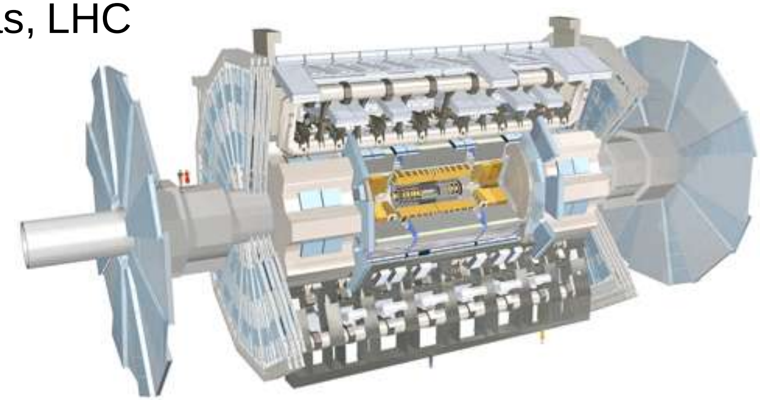
High energy/high precision

Two complementary approaches

high energy frontier

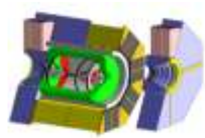
high precision frontier

Atlas, LHC



figures approx. to scale

Belle II, SuperKEKB



Search for production of unknown particles at highest achievable energies
LHC

Search for effect of unknown particles on processes very rare within the SM
SuperKEKB

High energy/high precision

Two complementary approaches

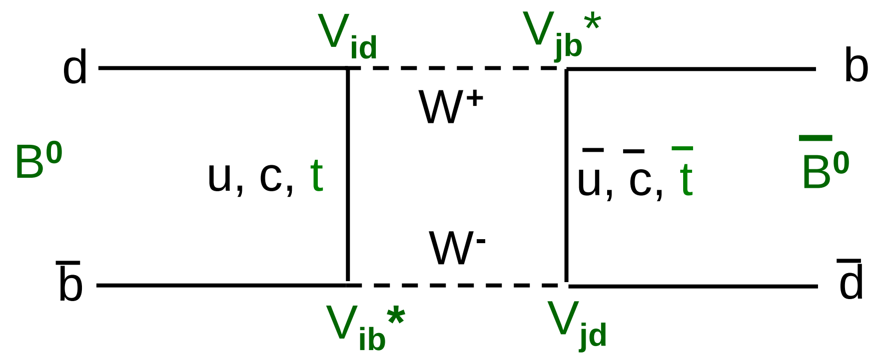
power of the precision measurements illustrated:

example of top quark discovery

predicted through the measurement of B_d^0-$\bar{B}_d^0$ oscillations;

also influences $\mathcal{B}_{Z\to\bar{b}b}$, precisely measured at LEP

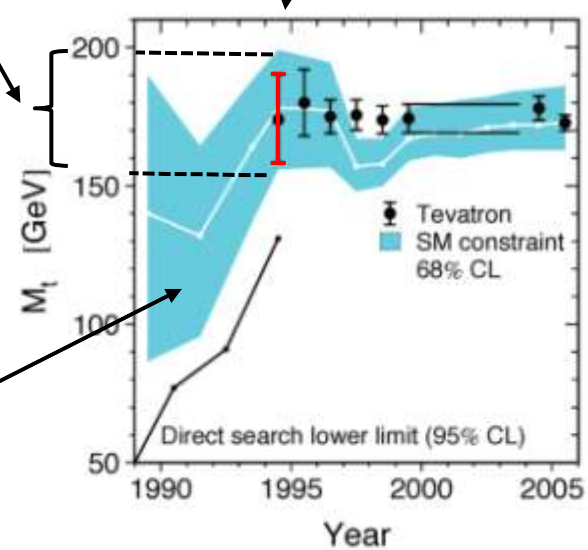
precise measurements can yield evidence of NP even if not observed directly



CDF, PRL74, 2626 (1995)

just before discovery we knew it should be here

it actually appeared here



m_t from $\mathcal{B}_{Z\to\bar{b}b}(m_t)$

Complementarity

Super B Factories/LHC

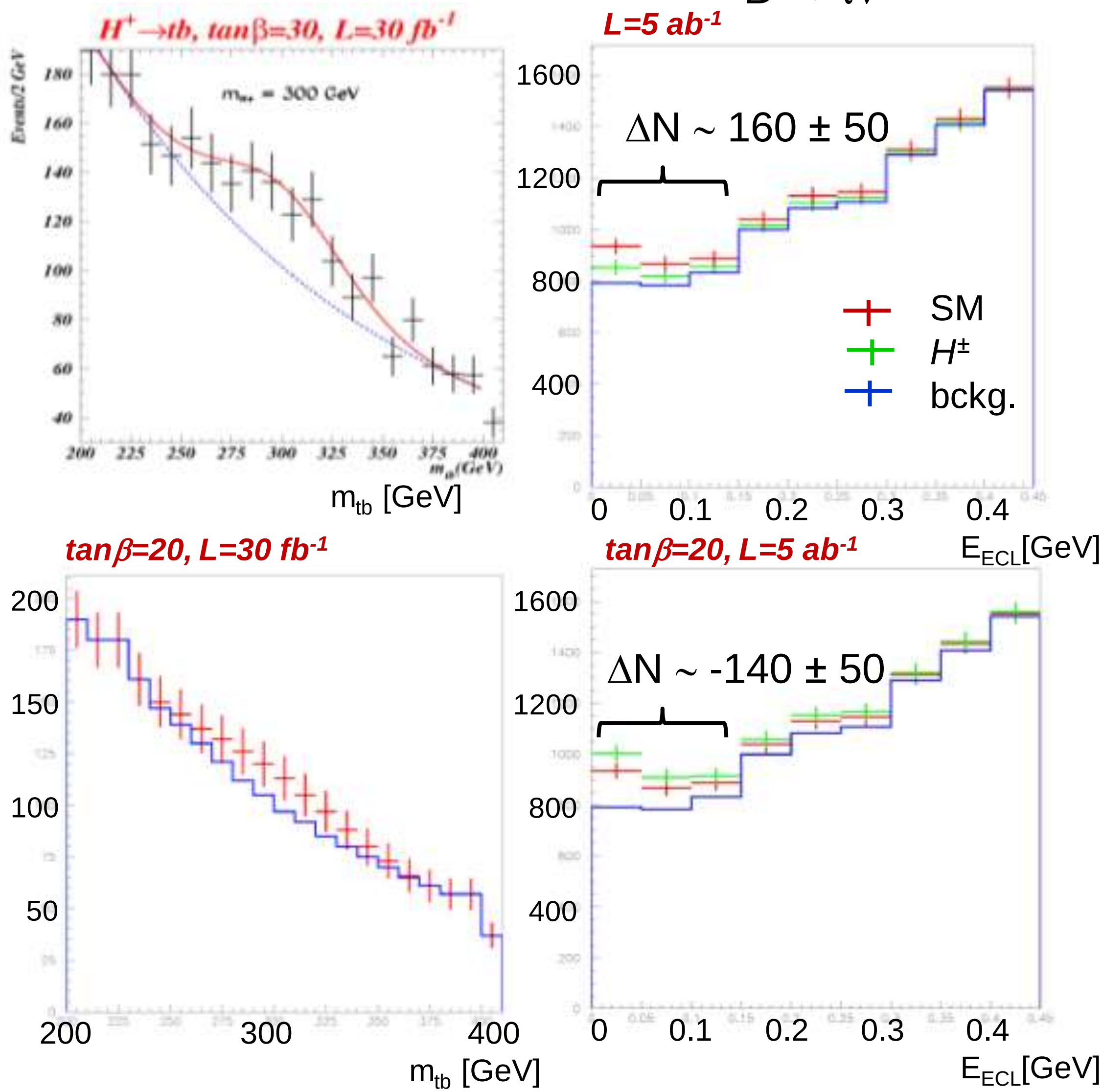
one example:
search for $H^\pm$ (MSSM);
$gb \to t\, H^\pm,\ H^\pm \to tb,\ t \to b\ell\nu$
signal of $H^\pm$ with m_H=300 GeV/c^2
and $\tan\beta$=30;
(free parameter of MSSM)

verification if signal indeed from $H^\pm$:
contribution of $H^\pm$ to $\mathcal{B}(B \to \tau\nu)$

$$\frac{\Gamma(B^+ \to \tau^+\nu)}{\Gamma^{SM}(B^+ \to \tau^+\nu)} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

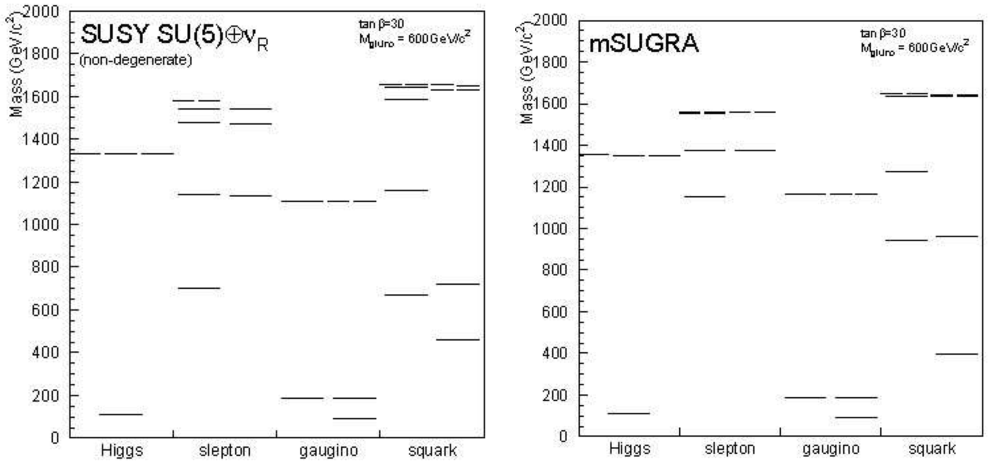
Atlas, reconstructed $H^\pm$ mass

Belle II, E_{ECL} in $B \to \tau\nu$



Complementarity

Super B Factories/LHC



further examples of identifying the nature of NP:

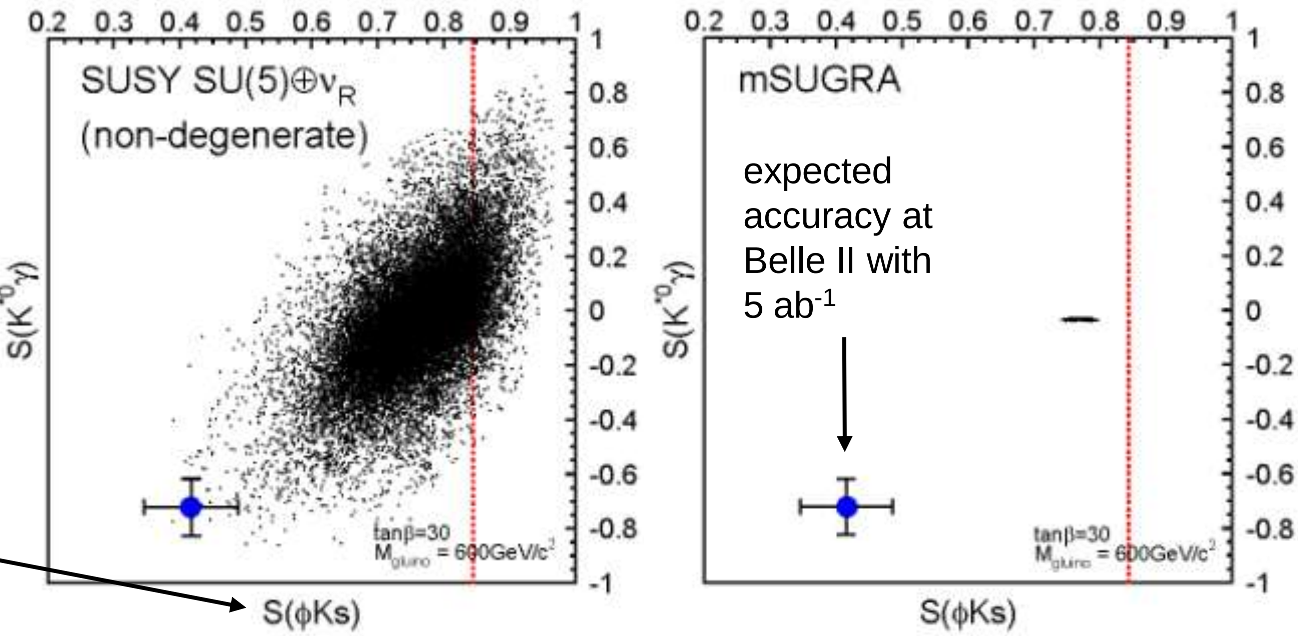
two NP models, mass spectrum of predicted new particles similar;

difficult to test model based on observed particles;

the contributions to observables measured at SuperKEKB differ

TCPV in $B^0 \to K^{*0}\gamma$

TCPV in $B^0 \to \phi K_s$



Quest for NP

Time line

Super KEKB/Belle II

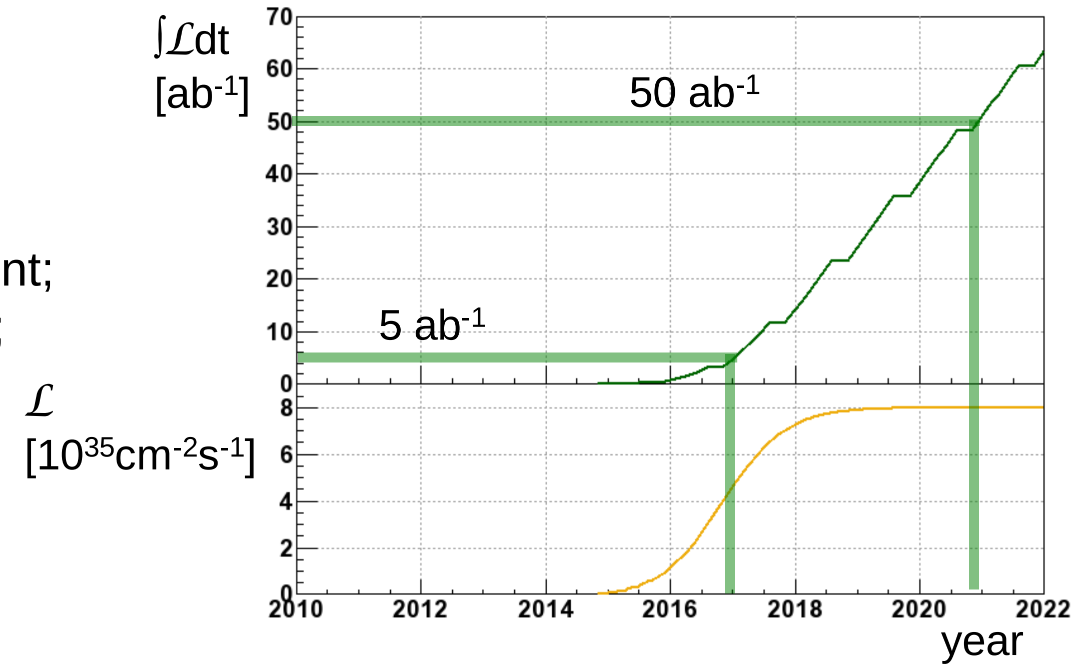
approved by Japanese government;
so far approved funding ~130 M$;

planned to start commissioning in 2nd half of 2014;

5 ab^{-1} at end of 2016;

50 ab^{-1} in 2021;

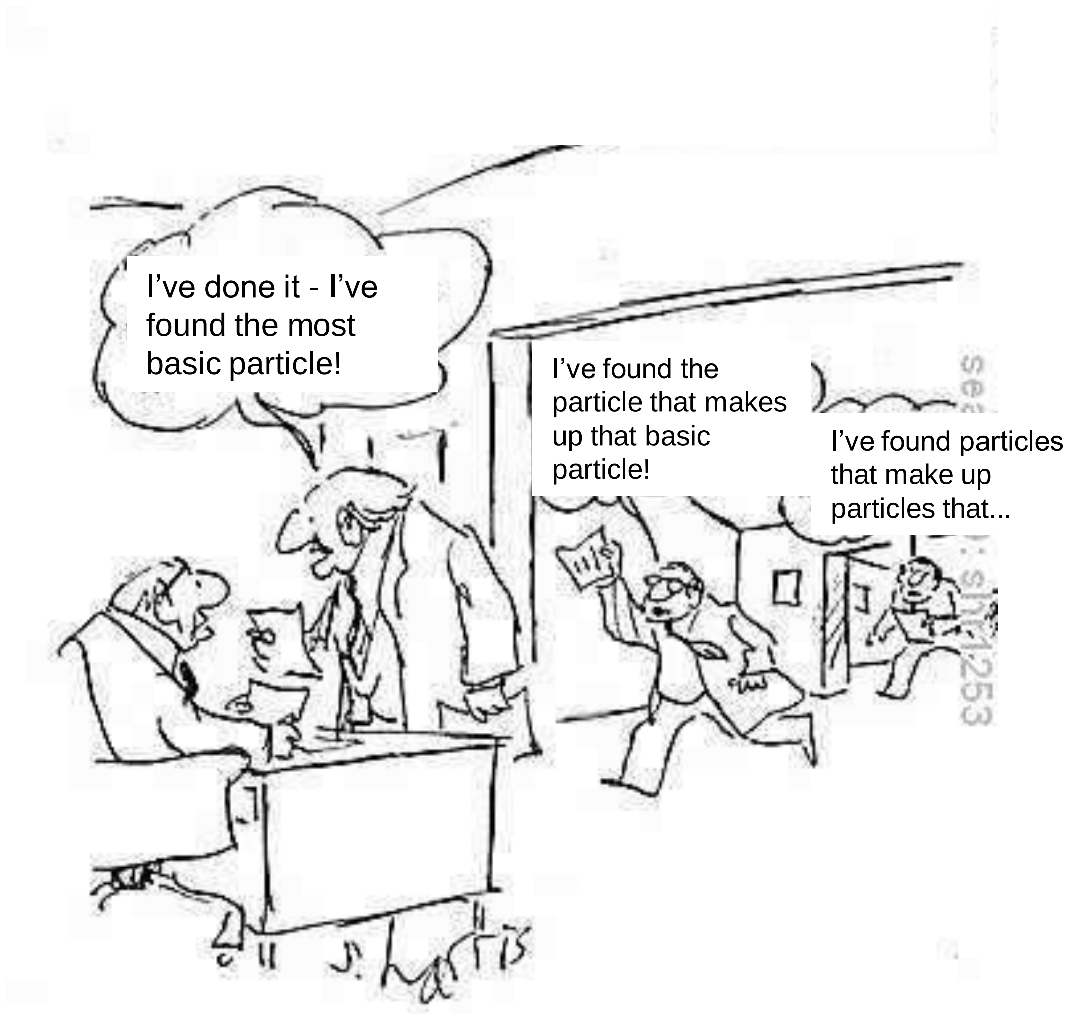
Belle II detector design/production ongoing with large European participation (~1/3 of collaboration)



Summary

- B Factories performance superseded expectations put forward before the start of operation
- Confirmation of KM mechanism; important spectroscopic results on new form of hadrons; several hints of inconsistencies of SM
- Super B Factories can provide complementary essential information on possible NP to LHC
- SuperKEKB/Belle II project is well on track, planned start of operation in 2014

Summary


I've done it - I've found the most basic particle!
I've found the particle that makes up that basic particle!
I've found particles that make up particles that...