CP Violation in the B sector

Marcello A. Giorgi
INFN & Universita' di Pisa

Italo's Fest

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OUTLINE

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- Validation of the CKM paradigm with CP Asymmetries in B meson decays.
- Still insufficient to explain the matter-antimatter unbalance in the universe.
- CP Violation adventure continues in quark and neutrino sector.
- A passion for Discrete Symmetries violation.

CPV from flavour mixing with 6 quarks (Kobayashi&Maskawa 1973)

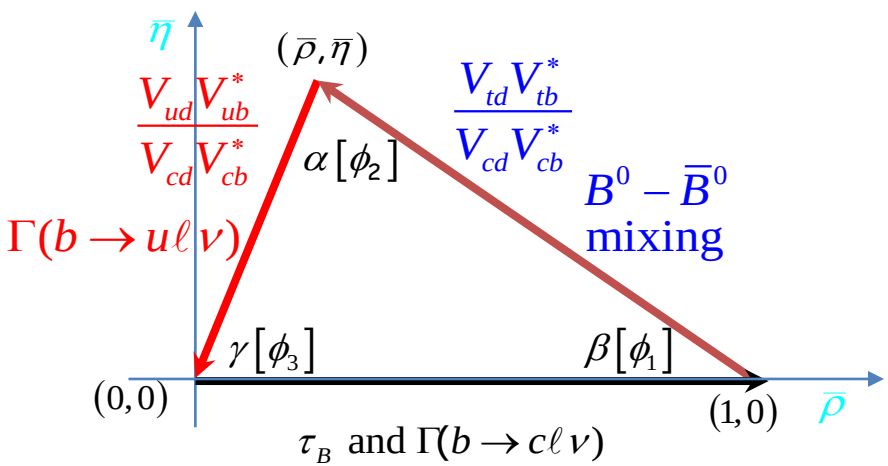
$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

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

9 - 5 = 3 + 1

- 9: U(3)
- 5: # of relative phases
- 3: O(3):real
- 1: Imaginary

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \boxed{i\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\boxed{i\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$



From 2 quark families : (rotation matrix in two dimensions with Cabibbo angle θ_C) to 3 quark families : mixing matrix with 3D rotation angles and one irreducible complex phase.

It explains indirect CP Violation in mixing for K->2 pions and allows prediction for direct CPV ($\varepsilon'/\varepsilon \neq 0$) and for many oservables related to CPV asymmetries in B decays.

M. Kobayashi and T. Maskawa, *CP Violation In The Renormalizable Theory Of Weak Interaction,* Prog. Theor. Phys. **49** (1973) 652

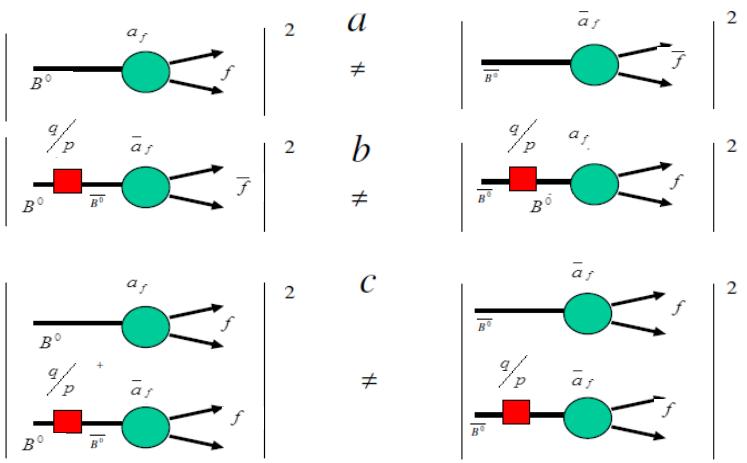
Towards validation of CKM

CP violation in B sector and the measurement of the Unitarity Triangle sides and angles has given a strong support to CKM.
This exploration inside the B sector required a strong effort to extract asymmetries in experiments at hadron machines where in the presence of large production cross section and huge background. A new kind of machines : the high luminosity e+ e- asymmetric colliders allowed a clean environment to study with high performance detectors (namely high precision silicon vertex trackers and optimal PID) the CP violation asymmetries in the interference between flavour mixing and decay amplitude.

dcCCPV in decay

dcCCPV in mixing

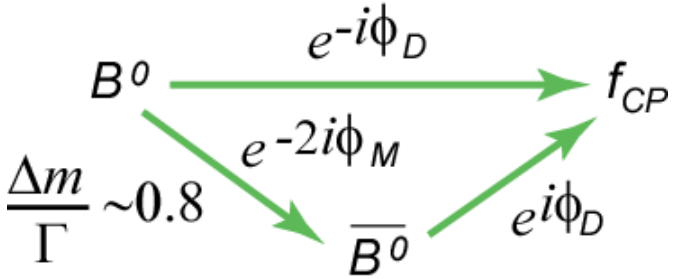
CPV in interference mixing-decay



Time dependent CP violation in *BB* system

Carter, Sanda Phys.Rev.Lett. 45, 952 (1980);
Phys.Rev. D23, 1567(1981)

Motivation for Asymmetric B Factories



$$A_{CP}(t) \equiv \frac{\Gamma(\overline{B^0} \to f_{CP}; t) - \Gamma(B^0 \to f_{CP}; t)}{\Gamma(\overline{B^0} \to f_{CP}; t) + \Gamma(B^0 \to f_{CP}; t)}$$

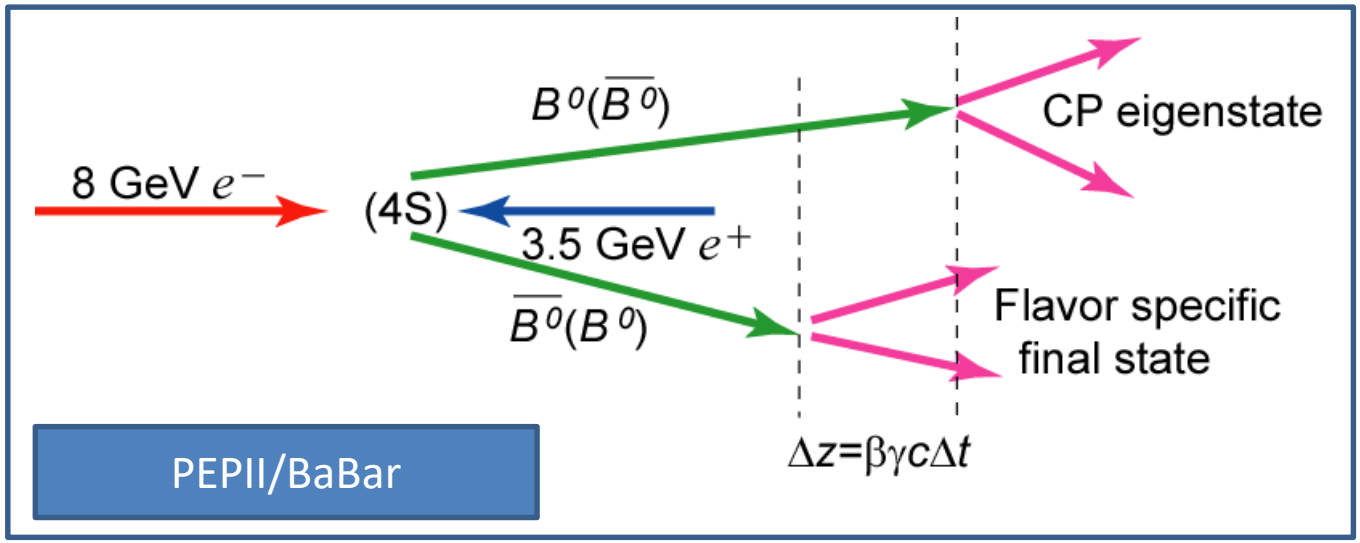
$$= A_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

Interference Mixing amplitude-Decay amplitude

$$A_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1}$$

$$S_f = \frac{2Im(\lambda_f)}{|\lambda_f|^2 + 1}$$

$$\lambda_f \equiv e^{-2i\phi_M} \frac{A(\overline{B} \to \overline{f})}{A(B \to f)}$$



Time dependent CP violation in *BB* system

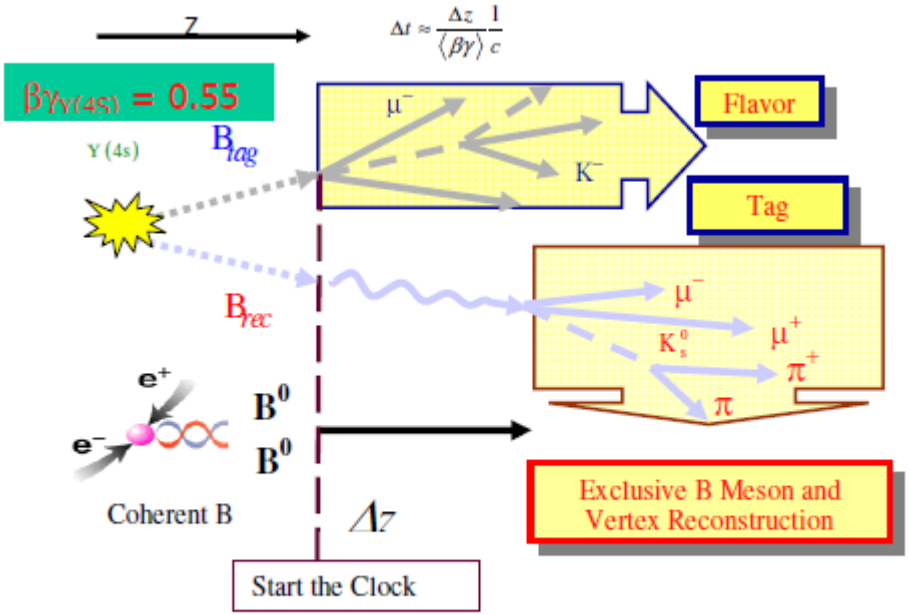


Fig. 1-1: Schematic view of the time dependent approach to the measurement of CP violation in the interference between mixing and decay amplitudes.

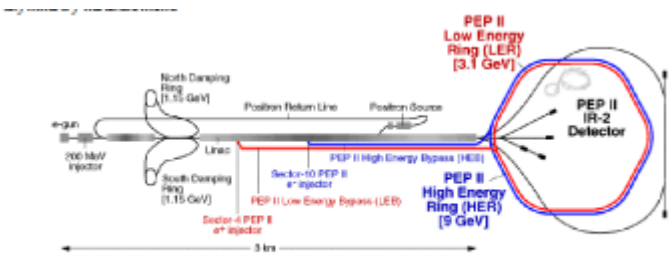
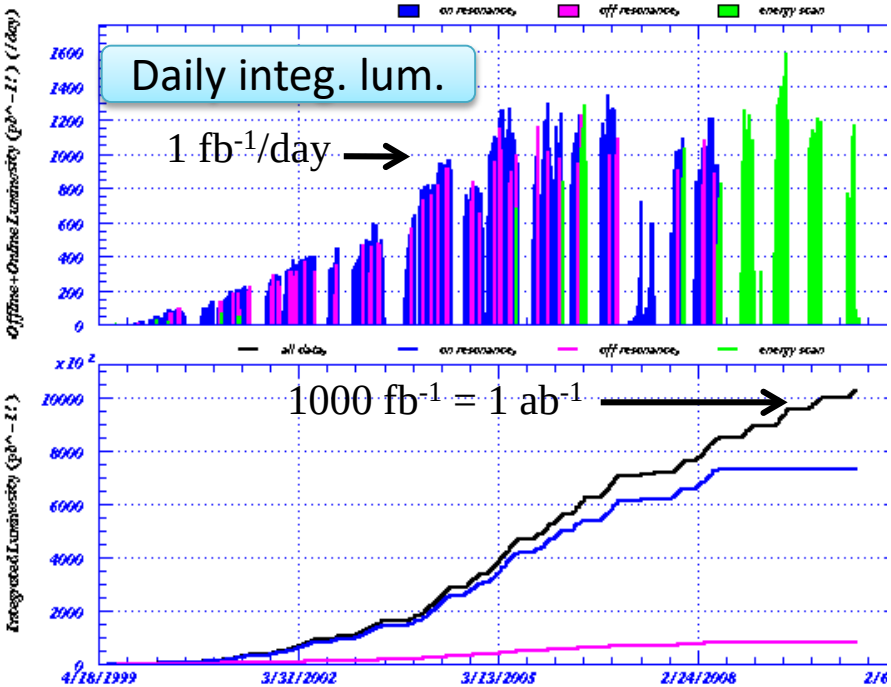


Fig. 4-1: PEPII Layout.

Fig. 5-2: View of the Silicon Vertex Tracker

PEPII and KEKB

KEKB $\mathscr{L}_{peak} = 2 \times 10^{34}/cm^2/s$



PEP-II Records

Last update: April 8, 2008

Peak Luminosity

12.069×10^{33} $cm^{-2}sec^{-1}$ — August 16, 2006

1722 bunches 2900 mA LER 1875 mA HER

Integration records of delivered luminosity

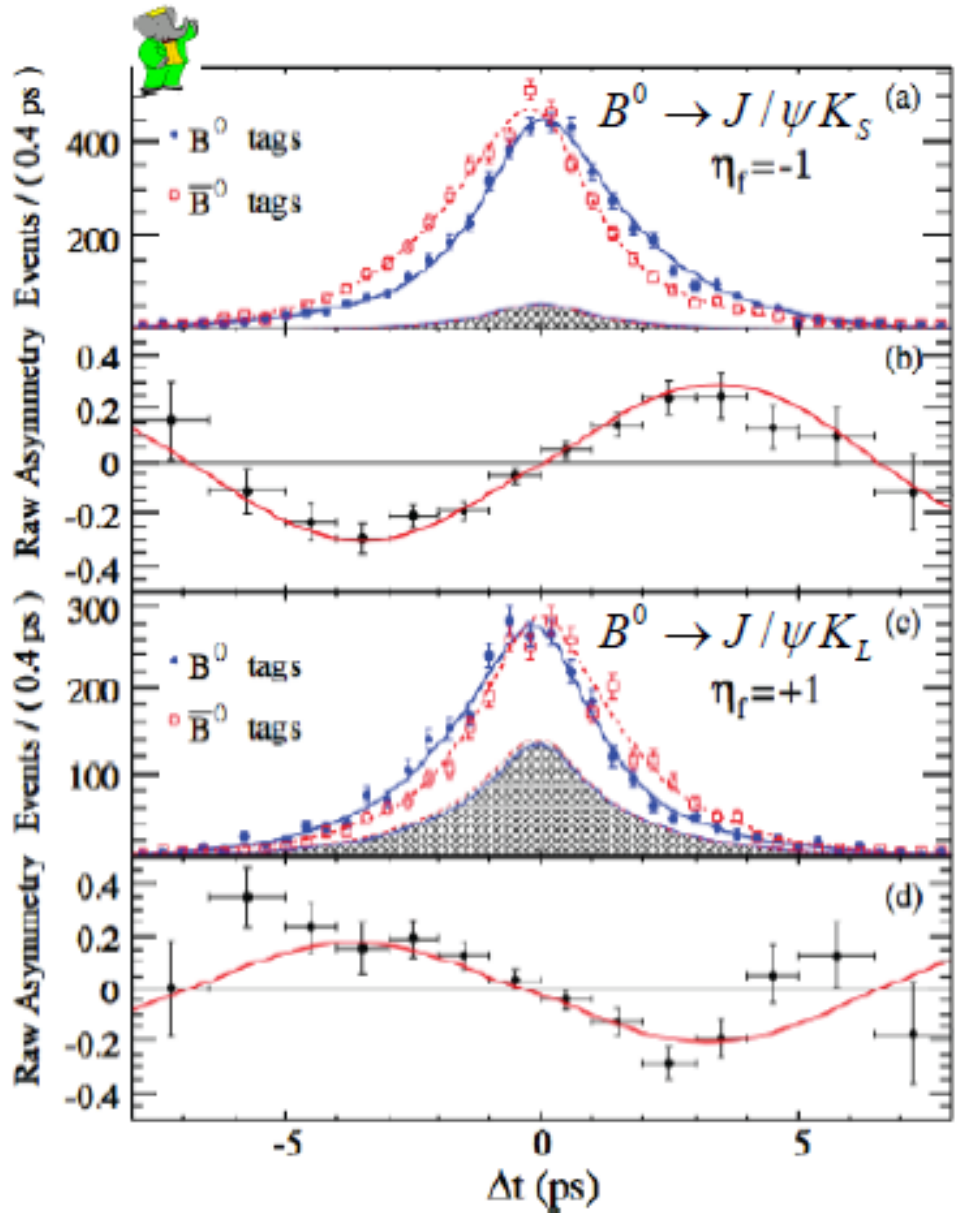
Best shift (8 hrs, 0:00, 08:00, 16:00)	339.0 pb^{-1}	Aug 16, 2006
Best 3 shifts in a row	910.7 pb^{-1}	Jul 2-3, 2006
Best day	858.4 pb^{-1}	Aug 19, 2007
Best 7 days (0:00 to 24:00)	5.411 fb^{-1}	Aug 14-Aug 20, 2007
Best week (Sun 0:00 to Sat 24:00)	5.137 fb^{-1}	Aug 12-Aug 18, 2007
Peak HER current	2069 mA	Feb 29, 2008
Peak LER current	3213 mA	Apr 7, 2008
Best 30 days	19.776 fb^{-1}	Aug 5 – Sep 3, 2007
Best month	19.732 fb^{-1}	August 2007
Total delivered	557 fb^{-1}	

PEP-II turned off April 7, 2008

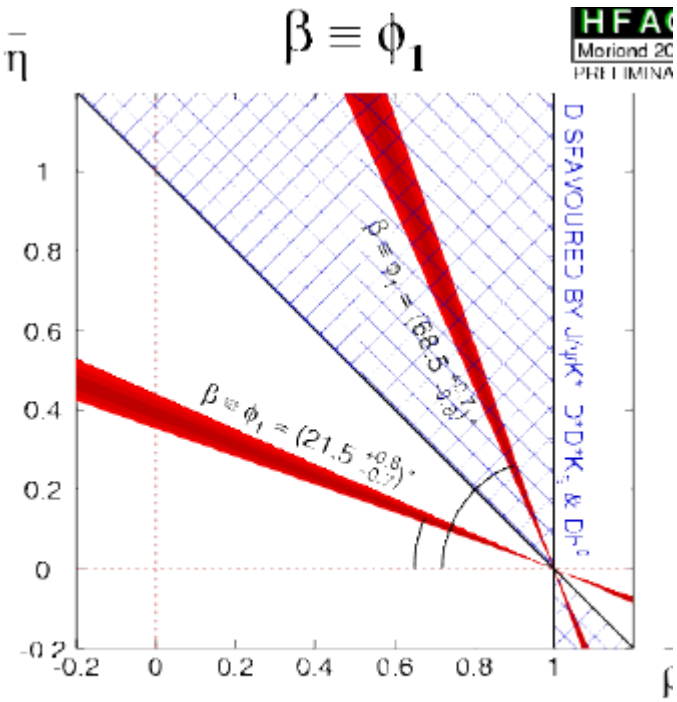
CP Violation Asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma(\overline{B^0} \to f_{CP}; t) - \Gamma(B^0 \to f_{CP}; t)}{\Gamma(\overline{B^0} \to f_{CP}; t) + \Gamma(B^0 \to f_{CP}; t)}$$

$$= A_f \cos(\Delta m t) - \xi_{CP}\, S_f \sin(\Delta m t)$$



2001:CKM validation from Babar and Belle *(PRL **89**(2002)201802)* *(PR **D 66** (2002)071102)*

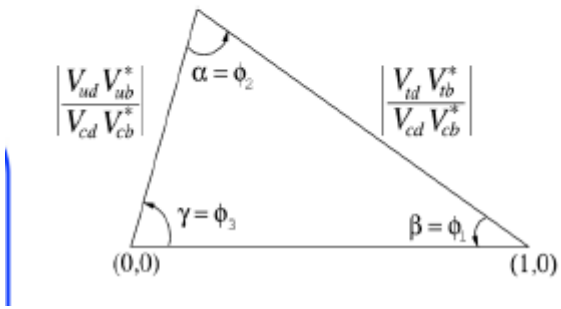


$$\varphi_1/\beta = (21.4 \pm 0.8)^\circ$$

$$V_{CKM} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array} \begin{array}{c} \\ u \\ c \\ t \end{array}$$

There are six unitarity conditions:
one has sides of comparable length

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



Results are all compatible with a single phase inside the flavour mixing matrix

14th anniversary of Direct CPV in B decay 2004

$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)}$$

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

BABAR PRL 93 (2004) 131801

$A_{CP} = -0.133 \pm 0.030 \pm 0.009$ **4.2σ**

Belle Confirmation at ICHEP04

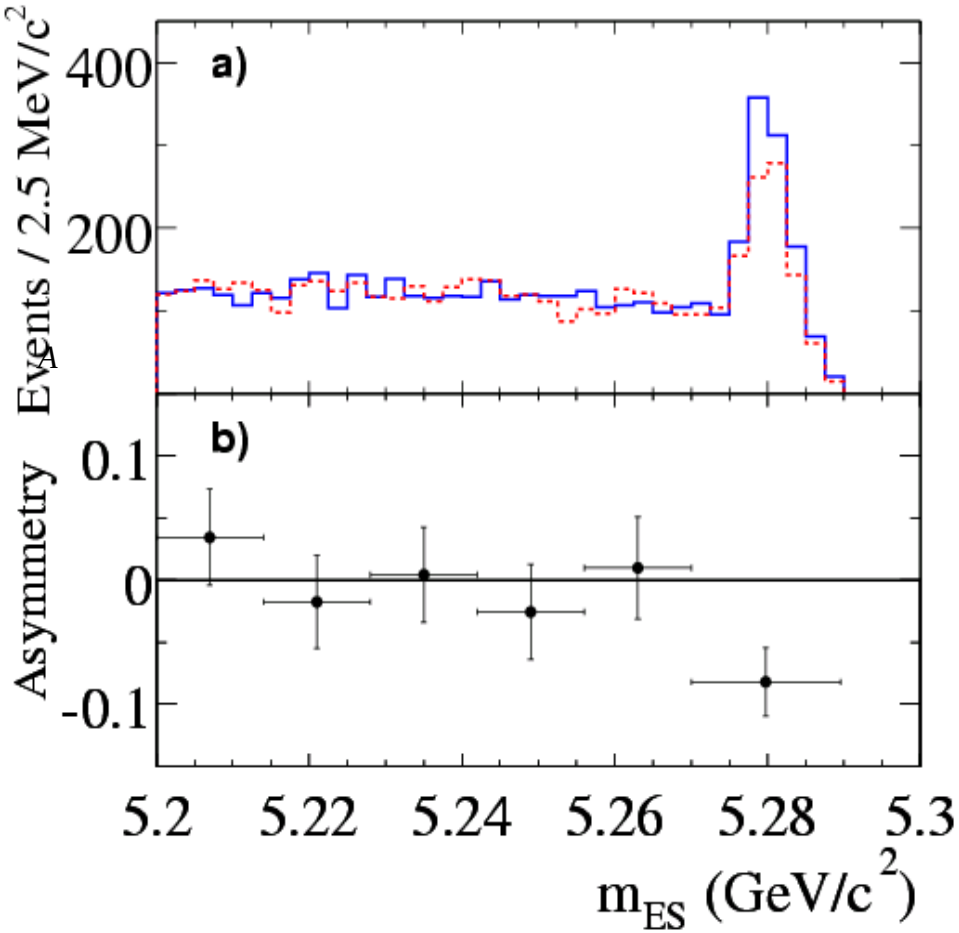
PRL 93 (2004) 191802

Signal (274M $B\bar{B}$ pairs): 2140 ± 53

$A_{CP} = -0.101 \pm 0.025 \pm 0.005$ **3.9σ**

Average $A_{CP} = -0.114 \pm 0.020$

Signal (227M $B\bar{B}$ pairs): 1606 ± 51



From Tevatron new constraints with Bs

Confirmation came also from Tevatron experiments CDF and D0, as in the In addition:

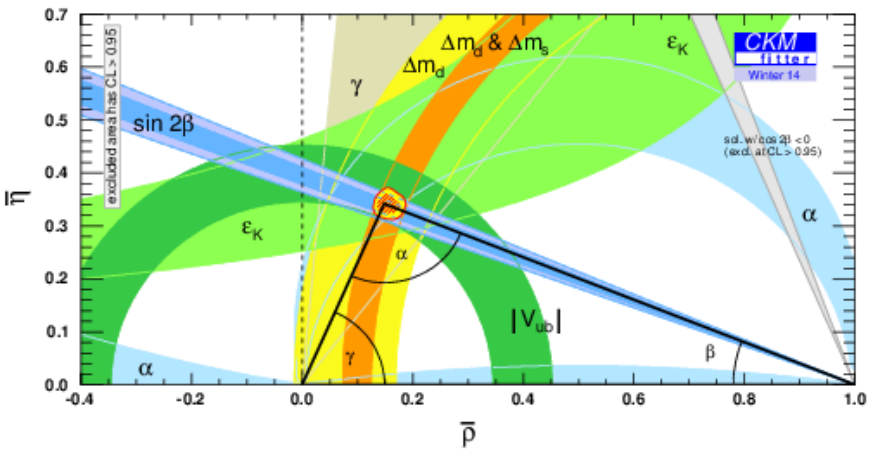
First double-sided 90% CL interval for Δm_s value was obtained by D0 collaboration

$$17 < \Delta m_s < 21\,\mathrm{ps}^{-1}$$

Measurement of Δm_s at 5σ level was performed by the CDF collaboration

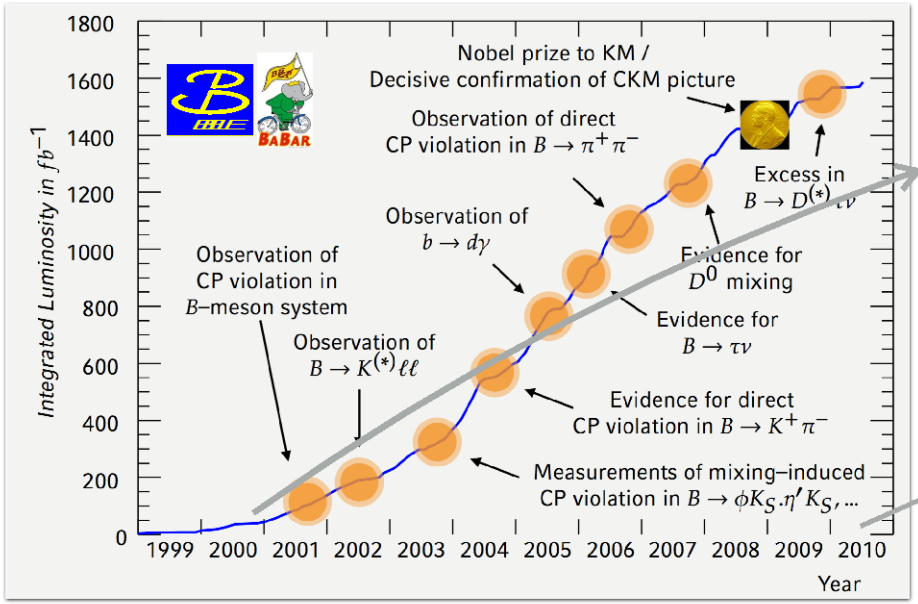
$$\Delta m_s = 17.77 \pm 0.10\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})\,\mathrm{ps}^{-1}$$

Then potting new constraints on CKM parameters:



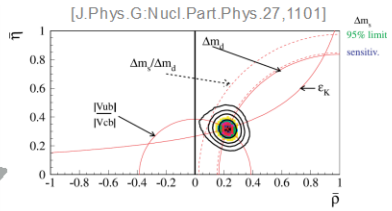
talk of G. Borissov. @ Queen Mary Workshop , July 2014

BaBar (PEPII@SLAC) and **Belle** (KEKB@KEK)



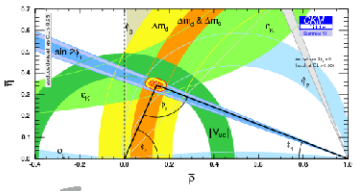
Unitarity Triangle @ 2000

[J.Phys.G:Nucl.Part.Phys.27,1101]



Unitarity Triangle @ 2011

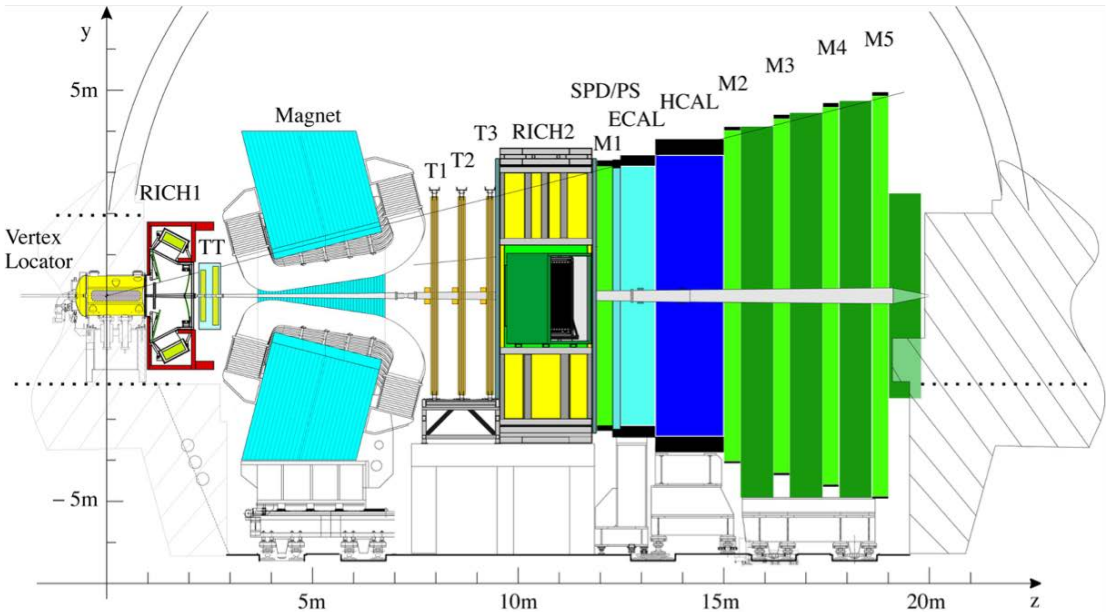
[CKM fitter]



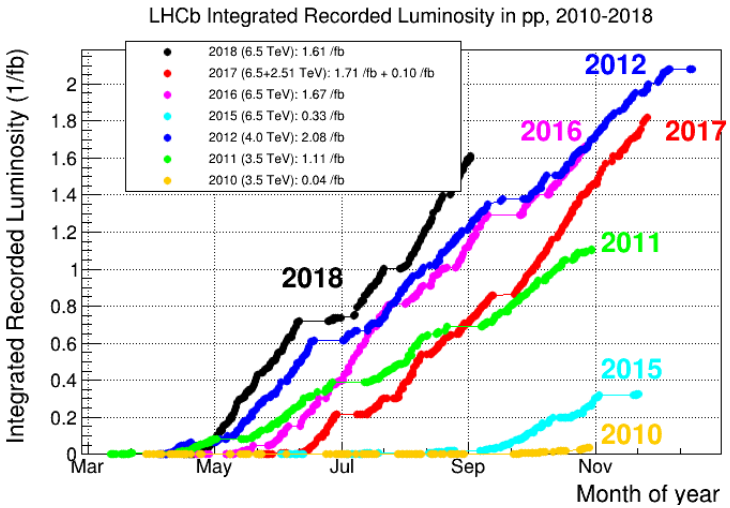
Confirmation of the Kobayashi-Maskawa mechanism of CPV.

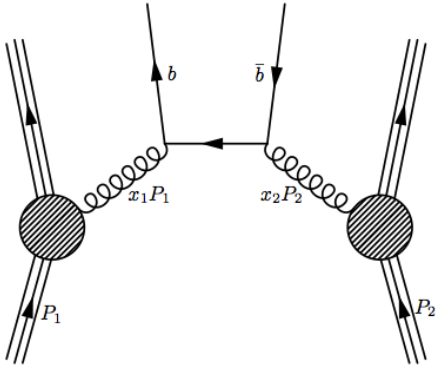
LHCb experiment at CERN

LHCb: dedicated heavy flavour physics experiment at LHC



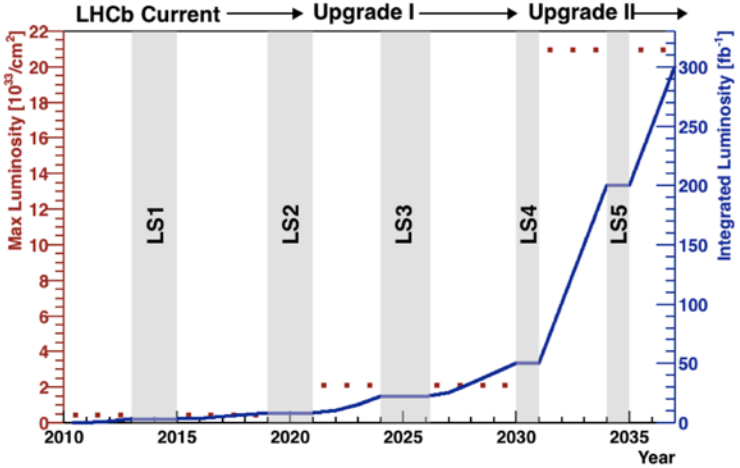
Collected >8 fb^{-1}



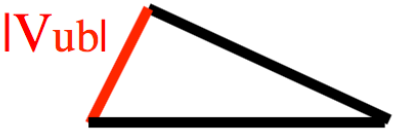


gluon-gluon fusion is the leading mechanism at LHCb

300 fb^{-1} after Upgrade II



$|V_{ub}/V_{cb}|$ results



2fb^{-1} data at 8 TeV - Nature Phys. 11 (2015) 743-747

Measure:

$$|V_{ub}|^2 = |V_{cb}|^2 \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>15\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7\mathrm{GeV}^2}} R_{FF}$$

world average	measured	LQCD [1]
$(39.5 \pm 0.8) \times 10^{-3}$	$(1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$	0.68 ± 0.07

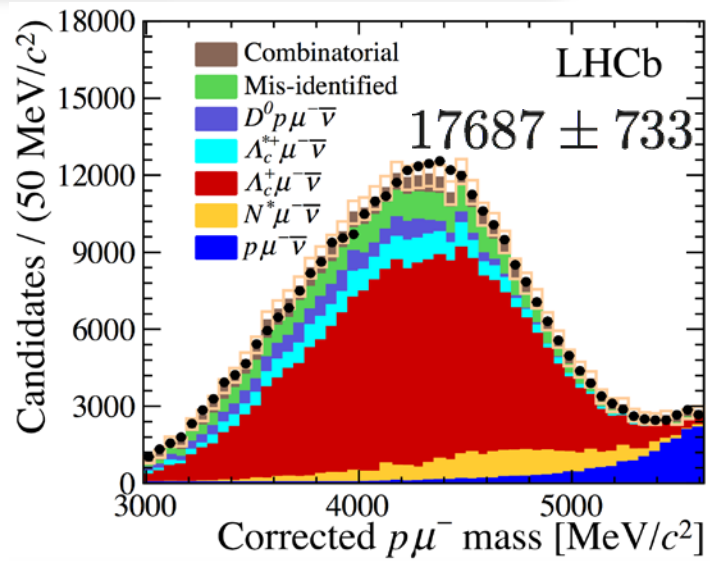
[1] W. Detmold, C. Lehner, and S. Meinel, arXiv:1503.01421

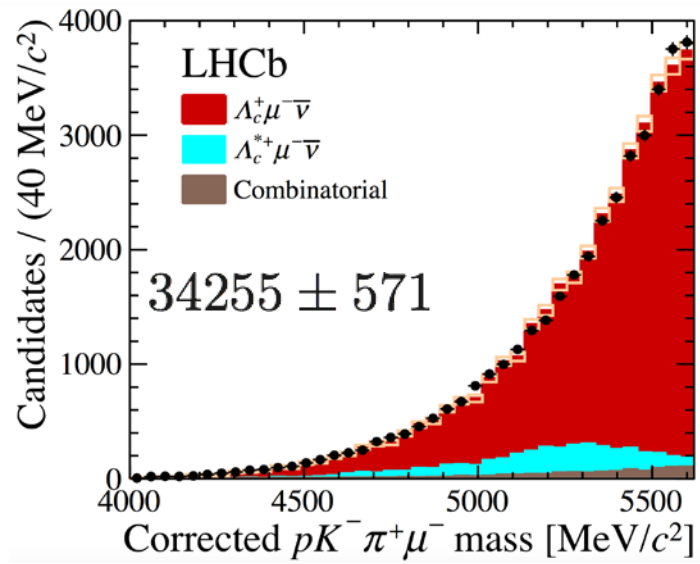
Most precise measurement

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$$

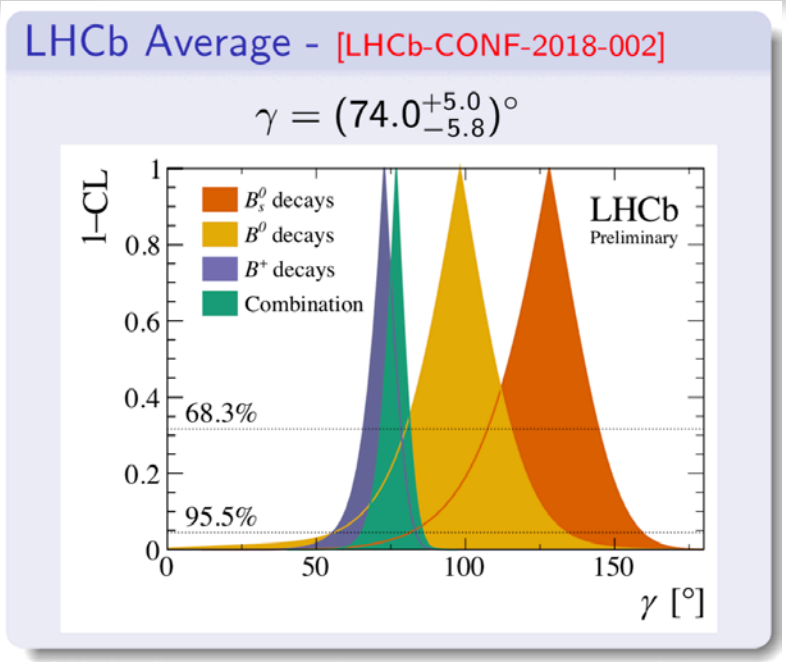
exp. LQCD $|V_{cb}|$

- Background contributions estimated using ad hoc control samples
- Largest exp. uncertainty from $\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$
- Important and independent determination of V_{ub} from B factories





CKM angle γ (source N.Neri)



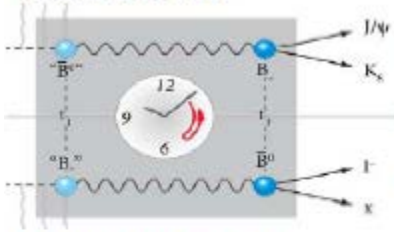
LHCb (8 fb^{-1}) γ = (74 $^{+5.0}_{-5.8}$)º from a combination of B→DK results.
Consistent with BaBar and Belle results.

Theory clean measurement

Oservation of direct T violation Babar 2012a lot of rumors on media

Physics: Particle Decays Point to an Arrow of Time

November 19, 2012



An experiment studying *B* meson decays makes a direct observation of time-reversal violation without relying on assumed relationships with other fundamental symmetries.

[Viewpoint on Phys. Rev. Lett. **109**, 211801

Read Article | More viewpoints

RESEARCH HIGHLIGHTS *Selections from the scientific literature*

BOTANY

Plant fertilization protein found

Fertilization in flowering plants is dependent on a protein that is secreted by the egg cell and activates incoming sperm.

Stefanie Sprunck at the University of Regensburg in Germany and her colleagues show that, in the model plant *Arabidopsis thaliana*, the arrival of sperm cells near the egg causes the release of a protein they call EGG CELL 1 (EC1). This triggers the redistribution of a second protein — one linked to fusion of the sex cells, or gametes — from inside the sperm to the sperm cell surface.

Sperm cells interacting with mutant *Arabidopsis* eggs that have faulty *ec1* genes failed to fuse, and the plant's pollen tubes continued to deliver sperm into the embryo sac. These results suggest that EC1 controls gamete fusion.

Science **328**, 1060–1063 (2012)

CLIMATE CHANGE

Carbon drop in snail shell shock

Free-swimming snails shrank all dimensions in response

PARTICLE PHYSICS

Time's arrow in B mesons

A cornerstone of the critical particle physics — the idea that not all processes run in the same way forwards in time as they do backwards — has been observed directly for the first time.

Members of the BaBar Collaboration traveled data from their experiment (pictured), which ran at the SLAC National Accelerator Laboratory in Menlo Park, California, from 1999 to 2008. The researchers identified B-meson decay chains that were time reversals of each other, and a comparison of the decay rates revealed a strong asymmetry. Earlier experiments have caught hints of time-reversal violation but failed to distinguish it clearly from violations of other fundamental symmetries.

Phys. Rev. Lett. **109**, 211801 (2012)

For a longer story on this research, see go.nature.com/258rwl

physics today

Time-reversal asymmetry in particle physics has finally been clearly seen

Bertram M. Schwarzschild

The Economist

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World politics | Business & finance | Economics | Science & technology | Culture | Blogs |

The arrow of time

Backward ran sentences...

To the relief of physicists, time really does have a preferred direction

Sep 1st 2012 | from the print edition

Like 323 Tweet 62

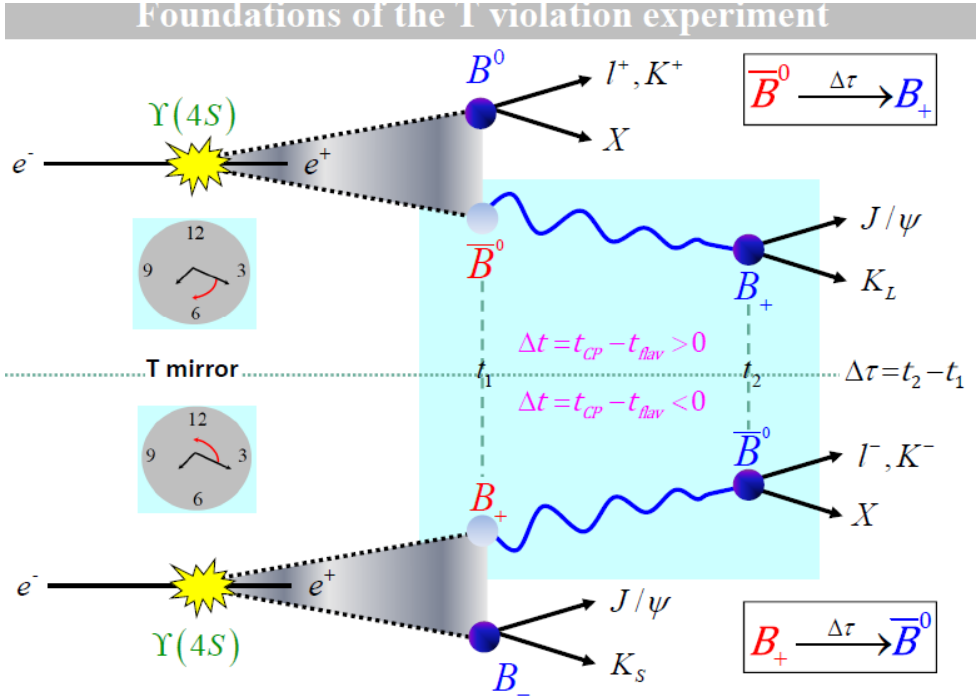
Time-reversal violation

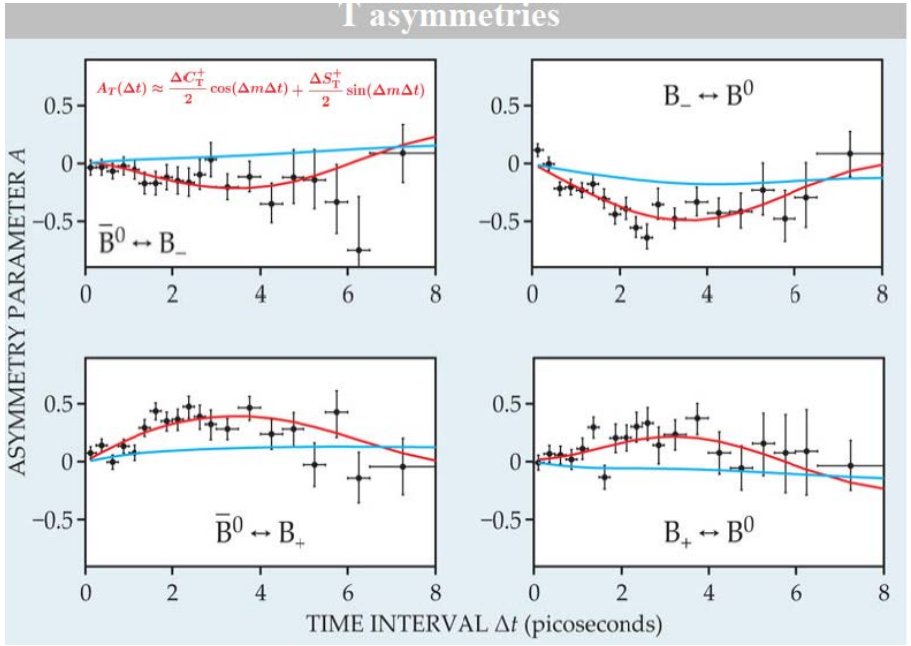
IOP A website from the Institute of Physics

physicsworld.com

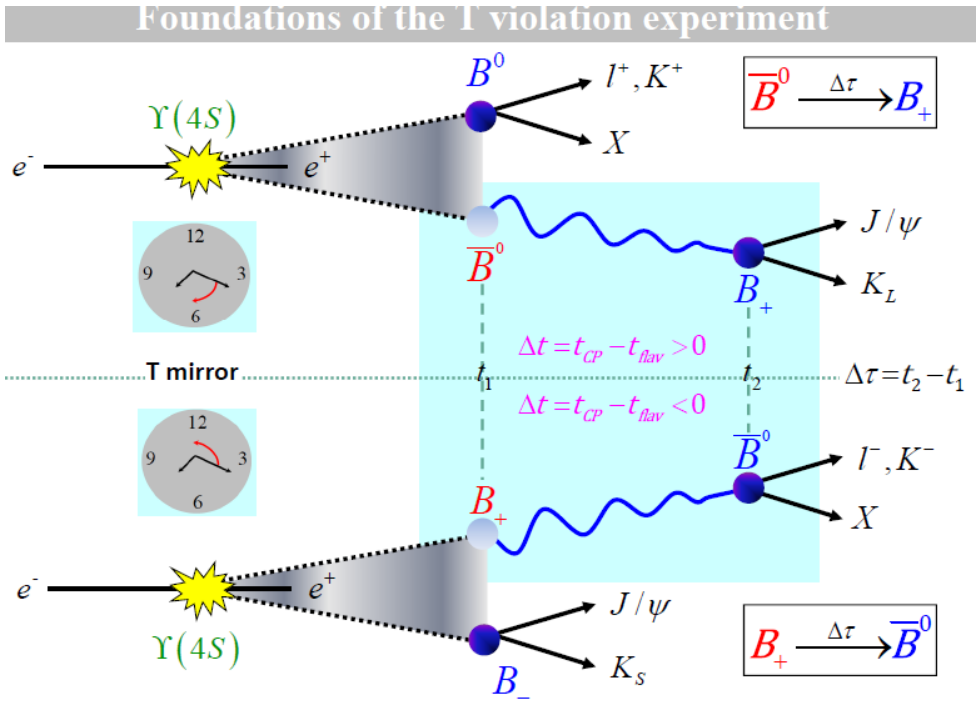
Physics World reveals its top 10 breakthroughs for 2012

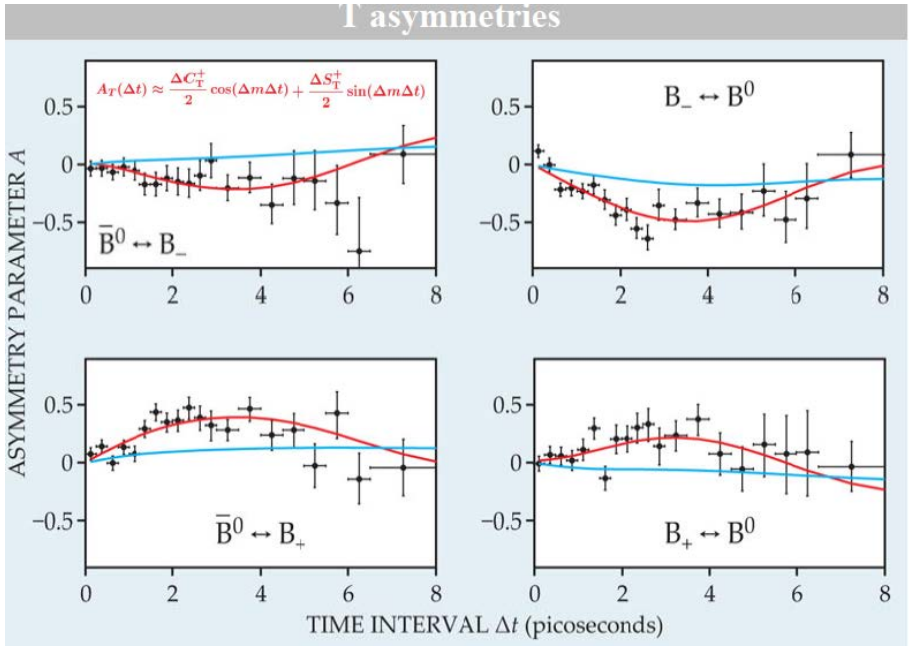
Observation of direct T violation Babar 2012





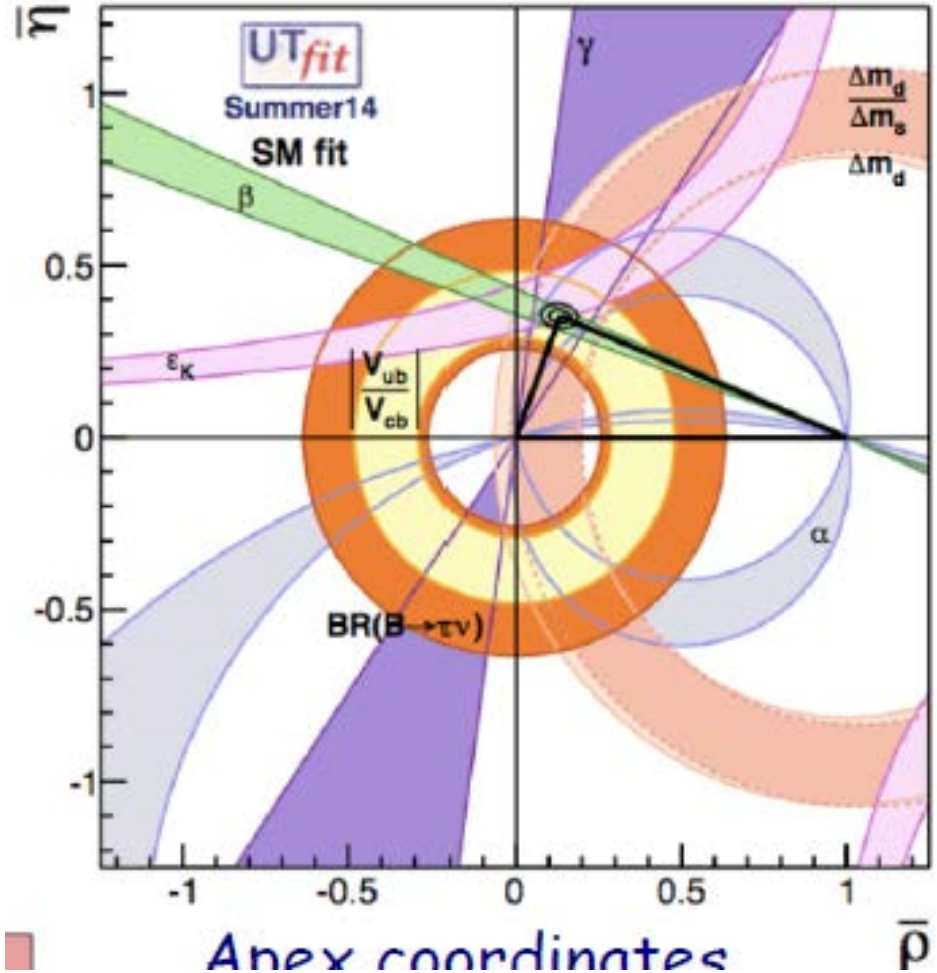
Observation of direct T violation Babar 2012



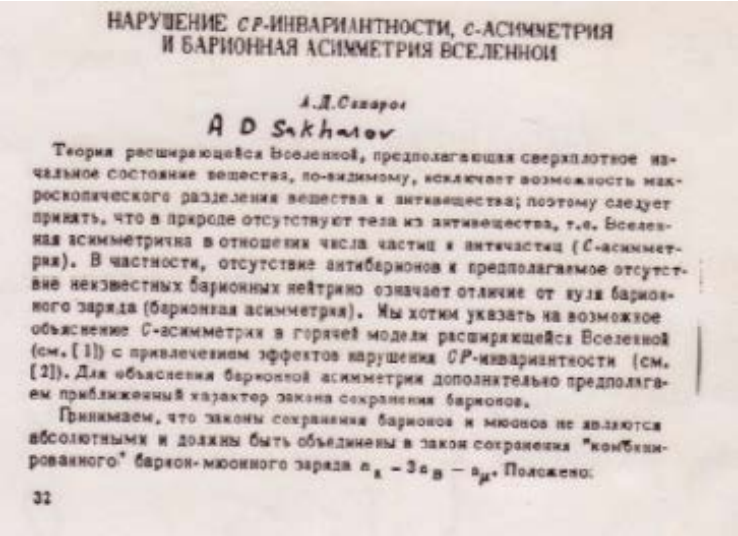


Everything compatible with what expected from CPT conservation

All data were in full agreement with CKM



The matter-antimatter puzzle



НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

A D Sakharov

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует принять, что в природе отсутствуют тела из антивещества, т.е. Вселенная асимметрична в отношении числа частиц и античастиц (*C*-асимметрия). В частности, отсутствие антибарионов и предполагаемое отсутствие неизвестных барионных нейтрино означает отличие от нуля барионного заряда (барионная асимметрия). Мы хотим указать на возможное объяснение *C*-асимметрии в горячей модели расширяющейся Вселенной (см. [1]) с привлечением эффектов нарушения *CP*-инвариантности (см. [2]). Для объяснения барионной асимметрии дополнительно предполагаем приближенный характер закона сохранения барионов.

Принимаем, что законы сохранения барионов и мюонов не являются абсолютными и должны быть объединены в закон сохранения "комбинированного" барион-мюонного заряда $n_B - 3n_B - n_\mu$. Положено:

32

The A. Sakharov conditions for the Matter-antimatter unbalance in the universe

:

- Baryon instability
- C violation and CP violation
- Thermo dynamical non-equilibrium

In Standard Model with CKM the Sakharov condition is met as C and CP ,but calculations show that it is STILL NOT sufficient to explain the matter-antimatter unbalance .

NEW CPV sources and new particles?

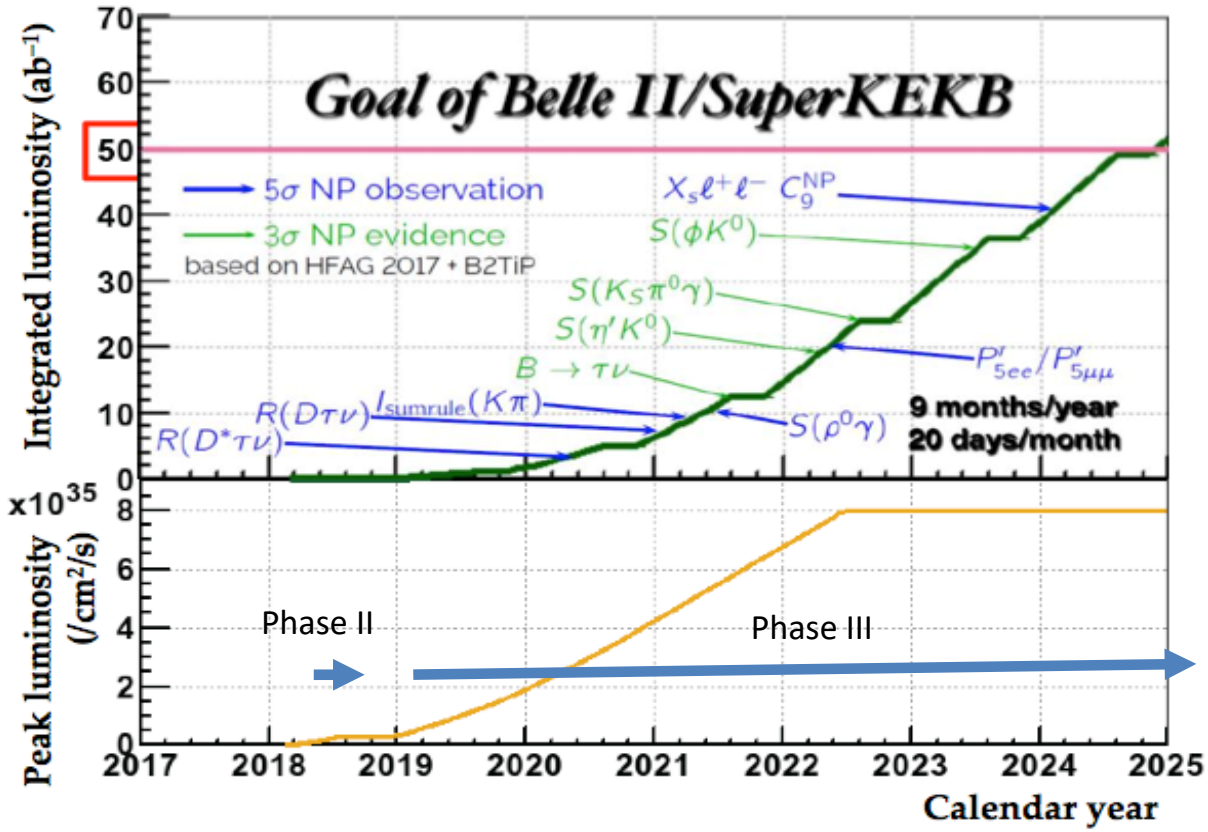
New experiments with hadrons and e+ e-

- BELLE II @ SuperKEKB, the upgraded machine at KEK is now starting with a very ambitious goal (50 ab^{-1}).
- Upgraded LHCb will in future run at an unprecedented luminosity (300 fb^{-1}).

Both the experiments will probe new physics BSM looking at precise measurements of CP asymmertries and very rare decays of b and c quarks and τ leptons.

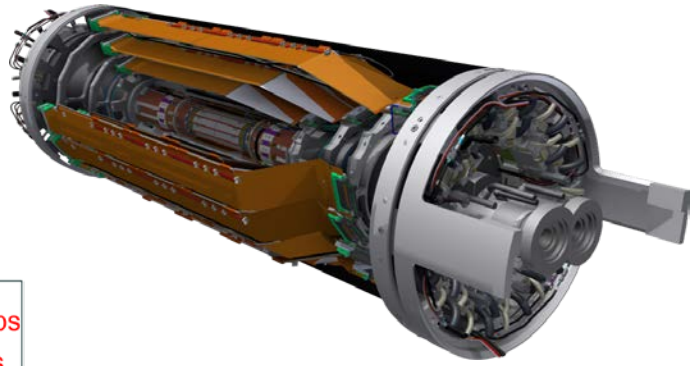
BEL LEII goals (source F.Forti)

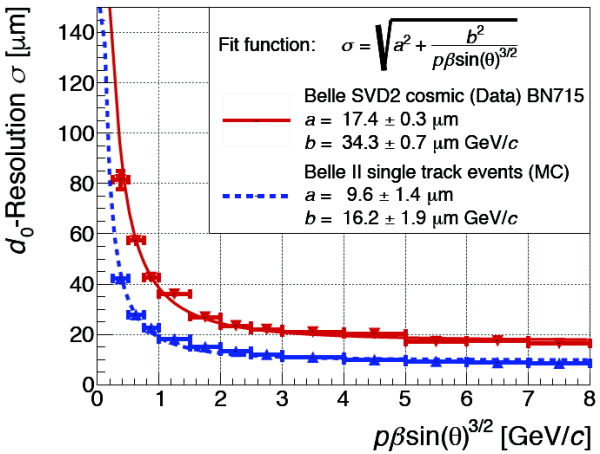
- Phase I (2016)
  - NO final focus; NO damping ring
  - Circulated both beams but no collisions;
  - Tune accelerator optics, etc.; vacuum scrubbing
  - Beam Background studies with dedicated BEAST II/1 detector
- Phase II (2018)
  - First collisions
  - Beam Commissioning
  - Background measurements with BEAST II/2
  - Physics run with Belle II without Vertex Detector
- Phase III (2019→)
  - Physics run

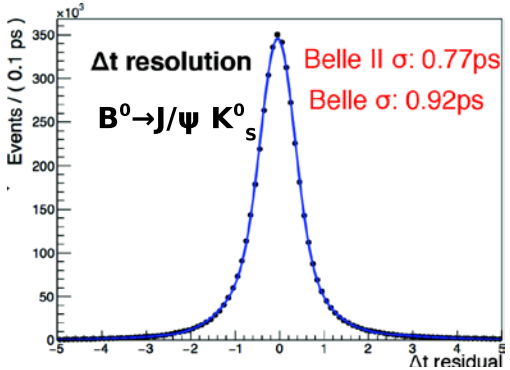


BELLE upgrades to BELLEII es:Vertex Detector (source F.Forti)

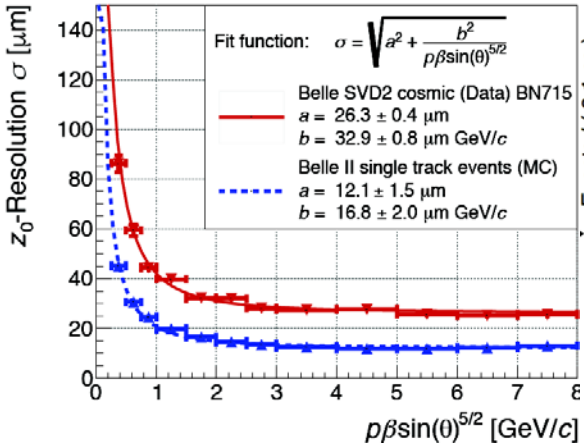
BaBar Vertex Detector



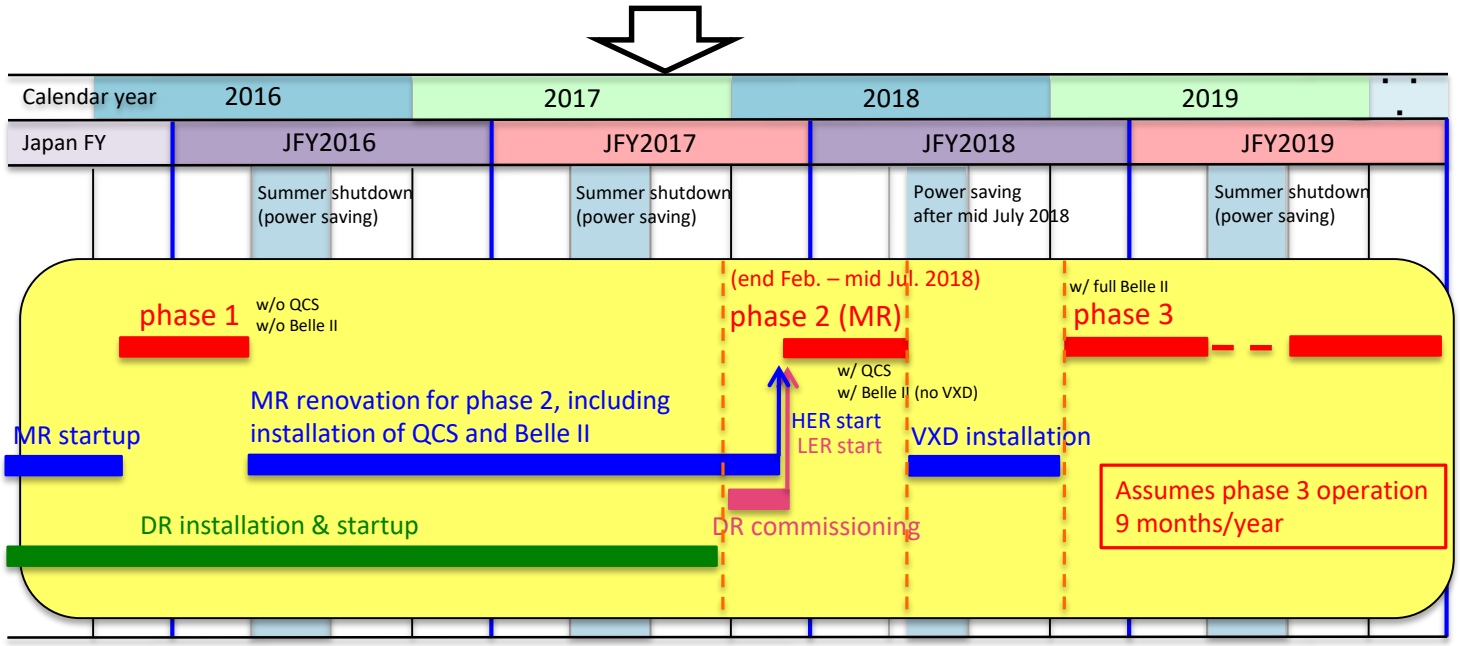




Significant improvements in vertex resolution w.r.t. Belle



SuperKEKB/Belle II schedule (source F.Forti)

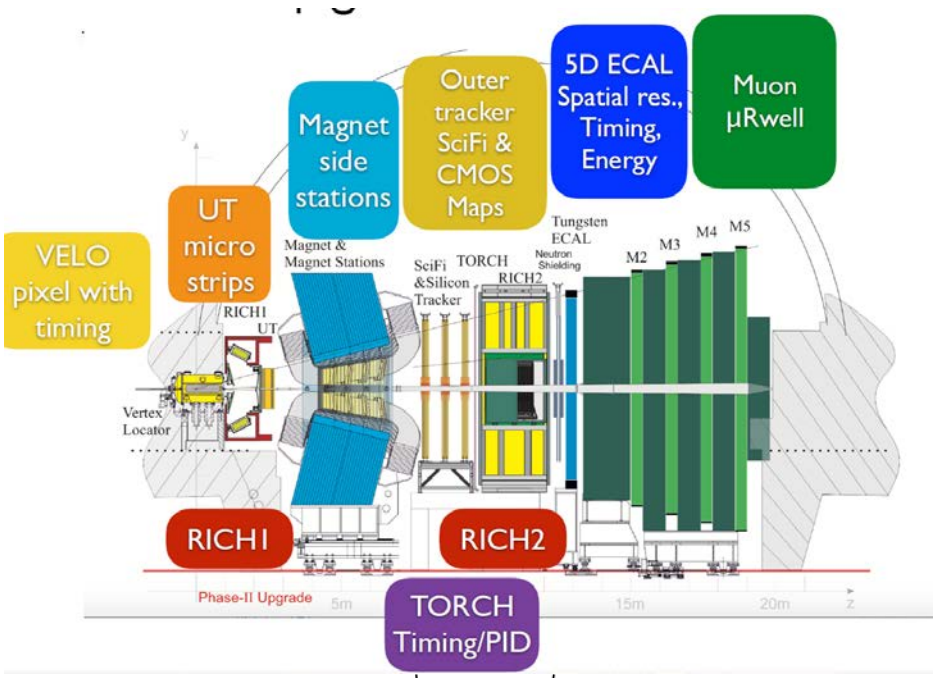


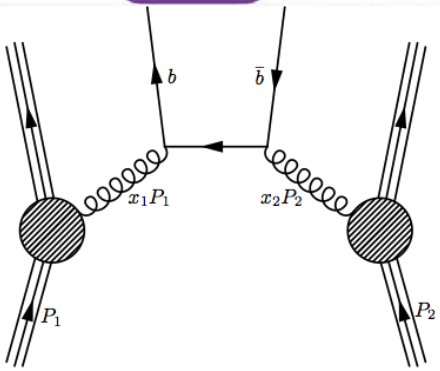
Phase 2 running concluded – 5 10^{33} luminosity reached

Deficit in JFY2018 operation funding may cause Phase III to start in Feb 2019 rather Jan 2019

LHCb upgrade (source N.Neri)

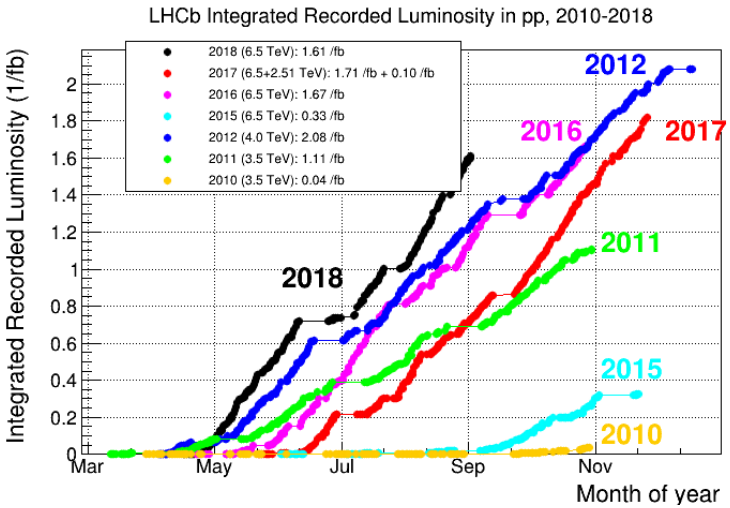
LHCb: dedicated heavy flavour physics experiment at LHC



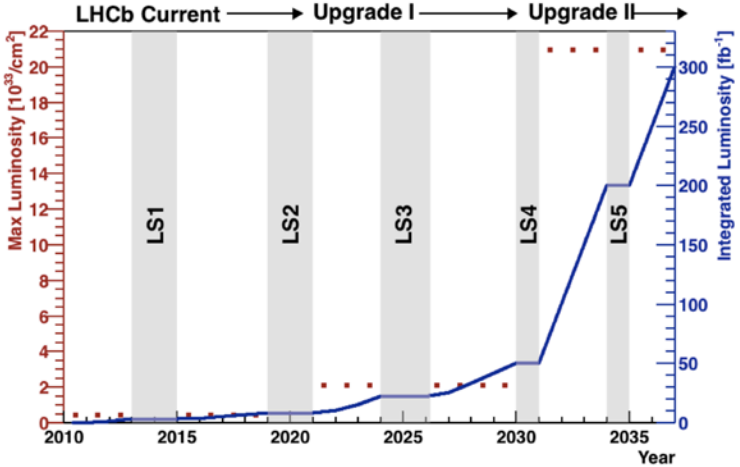


gluon-gluon fusion is the leading mechanism at LHCb

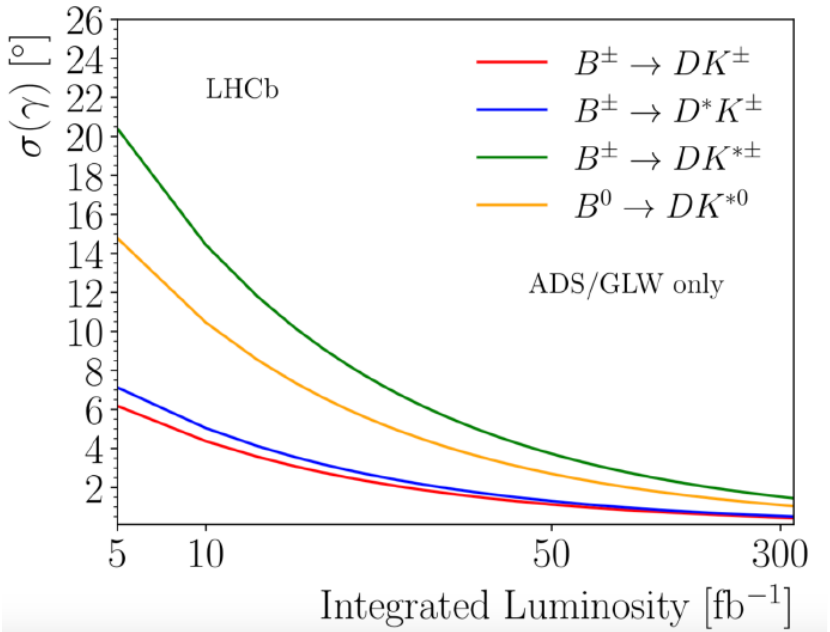
Collected >8 fb^{-1}

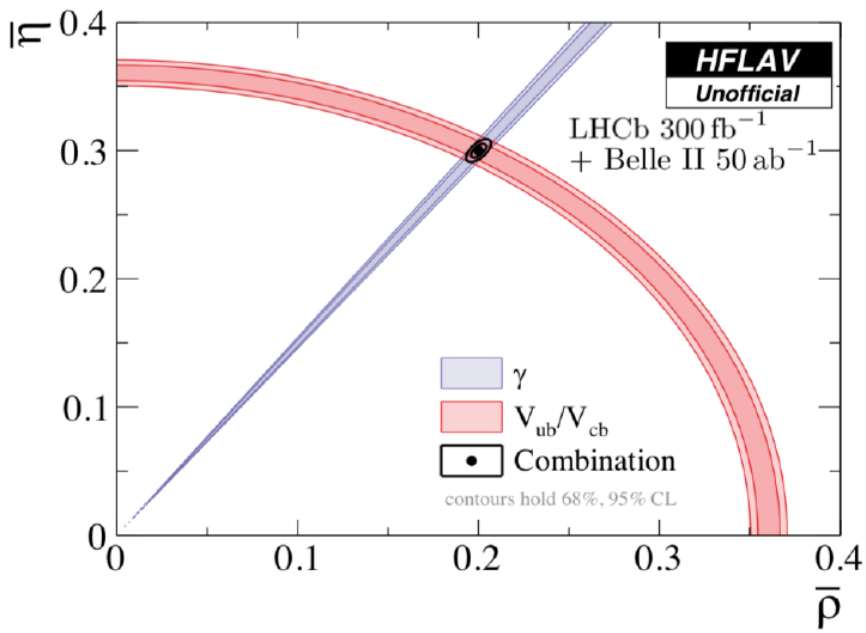


300 fb^{-1} after Upgrade II



LHCb ultimate γ sensitivity (source N.Neri)





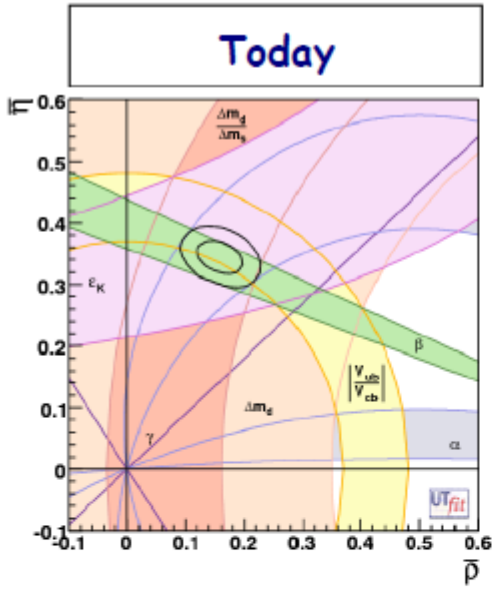
LHCb (8 fb^{-1}) γ = (74 $^{+5.0}_{-5.8}$)º from a combination of B→DK results.

Uncertainty down to 0.35º with 300 fb^{-1} after Upgrade II

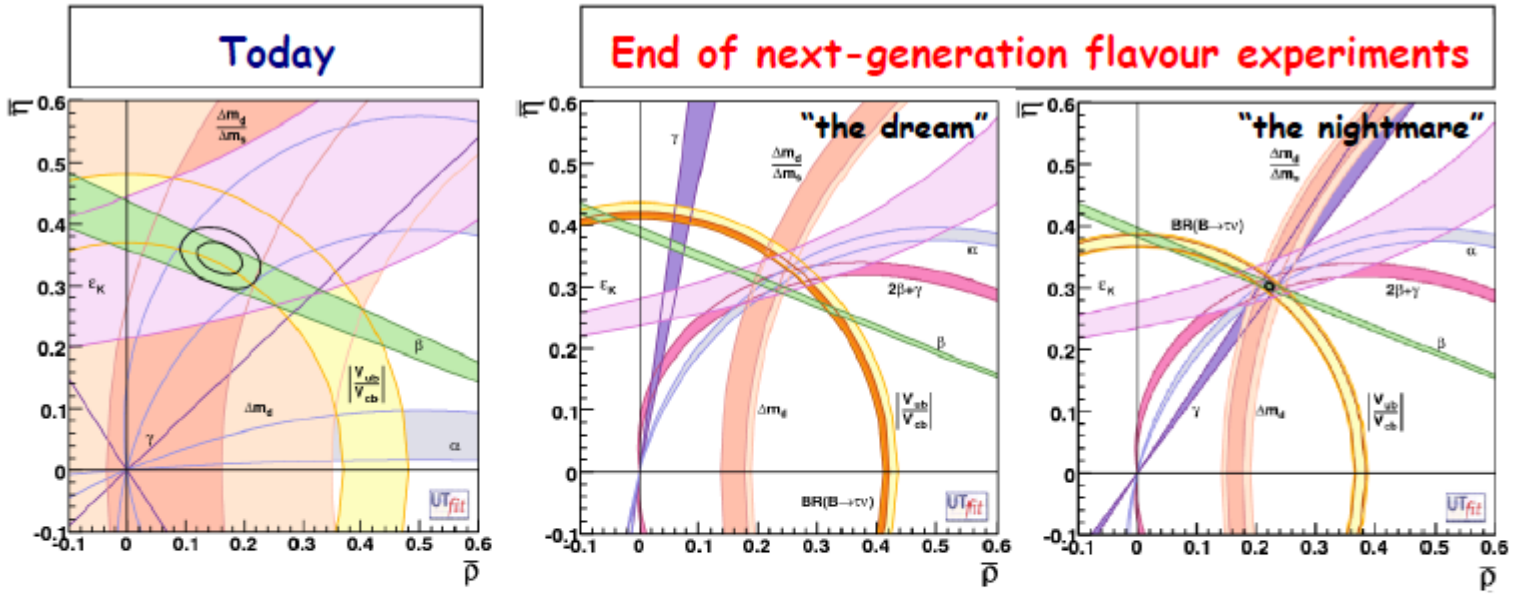
Towards future in CPV LHCb and Belle II @

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi\ell\nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c\ell\nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi\ell\nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K^0_S\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

Towards future with a continuous passion for discrete symmetries



Towards future with a continuous passion for discrete symmetries



Let's see if the dream come true…

Continuous passion for Discrete Symmetries

as it is for Italo!

Continuous passion for Discrete Symmetries

as it is for Italo!Since the beginning.
His work for the laurea thesis.

Demonstration of Parity Nonconservation in Hyperon Decay*†

F. Eisler, R. Plano, A. Prodell, N. Samios, M. Schwartz, and J. Steinberger, *Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York*
P. Bassi, V. Borelli, G. Puppi, G. Tanaka, P. Wolosche and V. Zoboli, *Istituto di Fisica, Bologna, Italy*
M. Conversi, P. Franzini, I. Mannelli, R. Santangelo, and V. Silvestrini, *Istituto di Fisica, Pisa, Italy*

and

D. A. Glaser, C. Graves, M. L. Perl, *University of Michigan, Ann Arbor, Michigan*

(Received October 21, 1957)

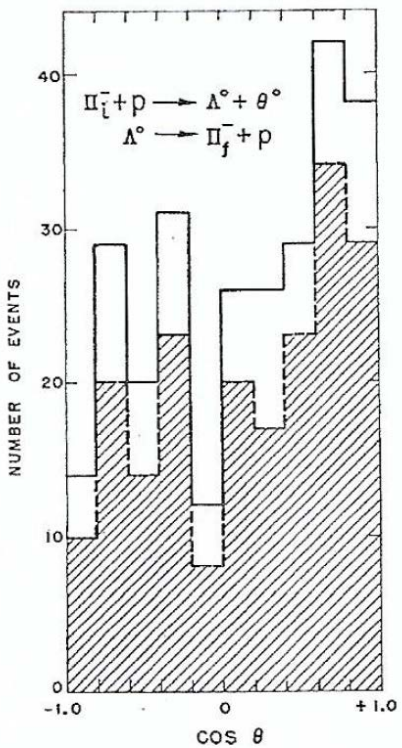


Fig. 1. Distribution in cosθ for process (1). The shaded area represents events for production angles in the center-of-mass range 30°–150°.