CP Violation in B-Mesons

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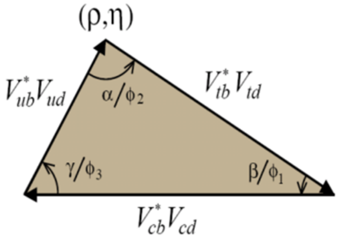
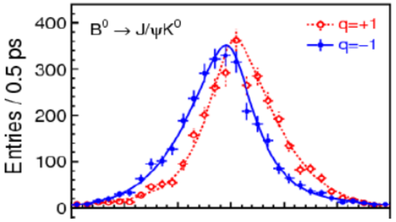
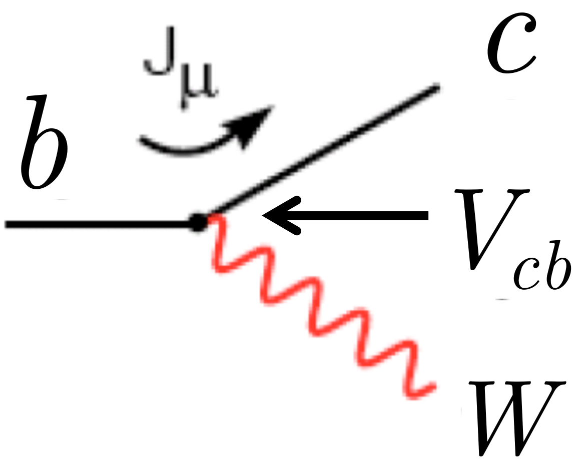
- Introduction: CP Violation in the Standard Model
- Direct CPV and CPV in Mixing
- Mixing-Induced CPV: Measuring the Angles of the UT
- Summary & Conclusions





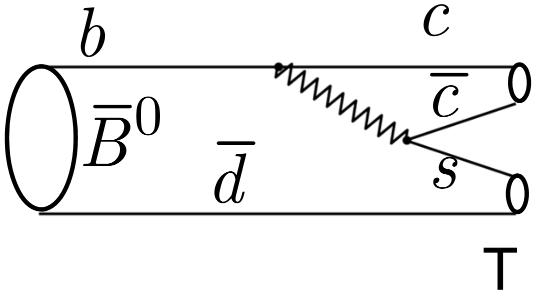
Changing Flavor: Trees, Penguins and ...

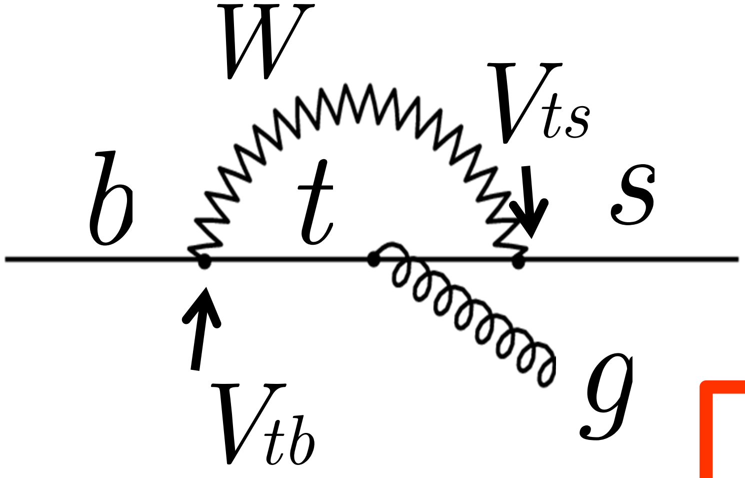


Flavor changing („charged current“) transitions proceed via a TREE DIAGRAM

first order

$$B^0(\overline{B}^0) \to J/\psi\, K_{S,L}$$

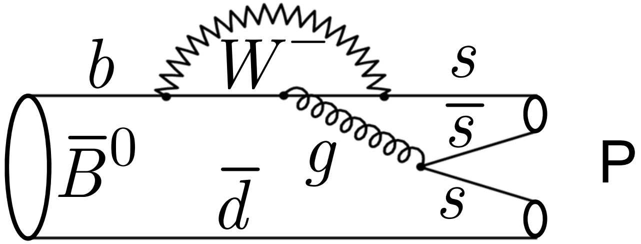




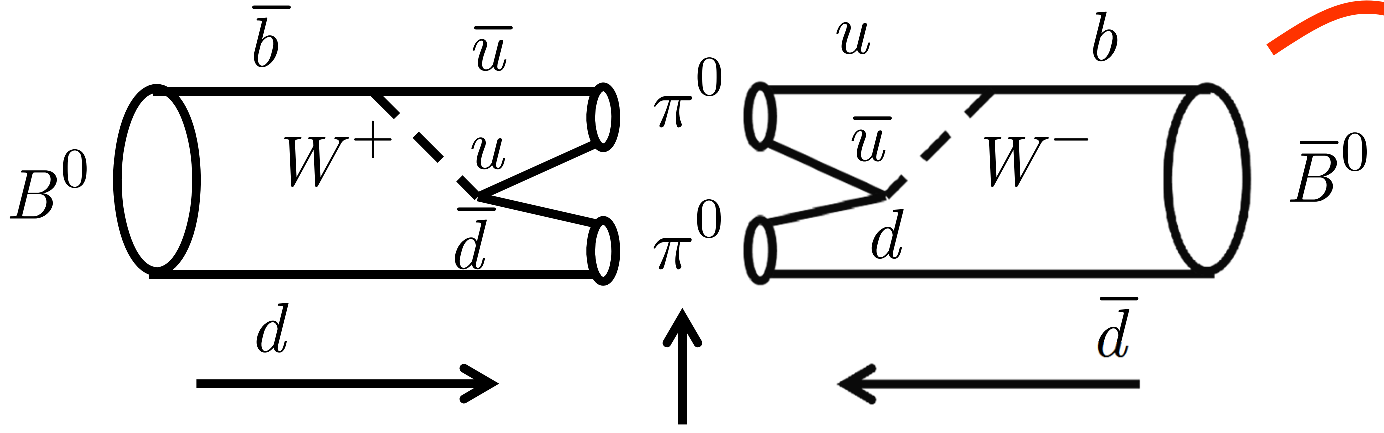
Flavor changing („neutral current“) transitions proceed via a PENGUIN DIAGRAM

second order

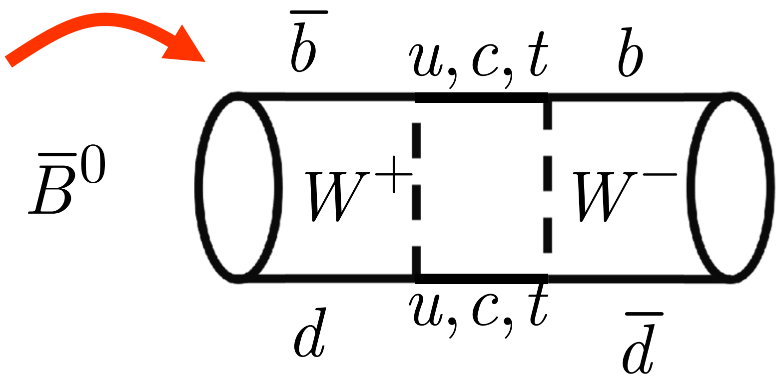
$$B^0(\overline{B}^0) \to \phi\, K_{S,L}$$



… Boxes: Matter-Antimatter Oscillations



same final state



„BOX DIAGRAM“

$$\boxed{\left\langle \bar{B}^0 \middle| B^0 \right\rangle \neq 0}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0(t) \\ \bar{B}^0(t) \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21}^* - \frac{i}{2}\Gamma_{21}^* & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} B^0(t) \\ \bar{B}^0(t) \end{pmatrix}$$

$$B_L = pB^0 + q\bar{B}^0$$

$$B_H = pB^0 - q\bar{B}^0$$

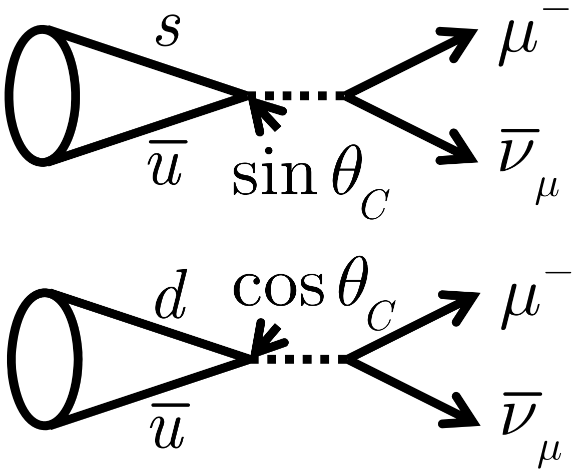
$$\left\langle B^0(t) \middle| \psi \right\rangle = a\left(e^{-iM_L t} + e^{-iM_H t}\right)$$

$$\left\langle \bar{B}^0(t) \middle| \psi \right\rangle = a\left(e^{-iM_L t} - e^{-iM_H t}\right)$$

The Origin of CP Violation in the SM

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

„flavor“ Matrix V: unitary „mass“



$$d' \approx \; d\cos\theta_C + s\sin\theta_C$$
$$s' \approx -d\sin\theta_C + s\cos\theta_C$$

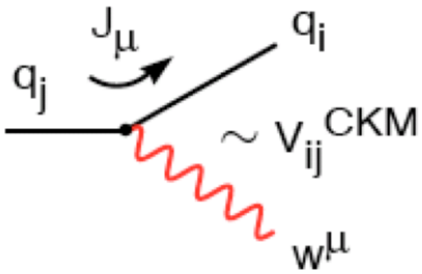
CP violation from Quark Mixing:
Extension of the Cabibbo-Matrix!

Mathematical reason: Matrix must have complex elements to violate CP:
only possible via n x n matrix with n > 2

Theory formulated in 1973 by Kobayashi & Maskawa
(Charm-, Bottom- and Top-Quark were not discovered yet!)

b-quark experiments have established the theory of K&M !

CKM Matrix and the Unitarity Triangle(s)



weak decays of hadrons (quarks change flavor) are described in the SM by the (unitary) CKM matrix

Cabibbo, Kobayashi, Maskawa

$$\lambda = \sin\theta_C$$

$$V^{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \enclose{circle}{i\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\enclose{circle}{i\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

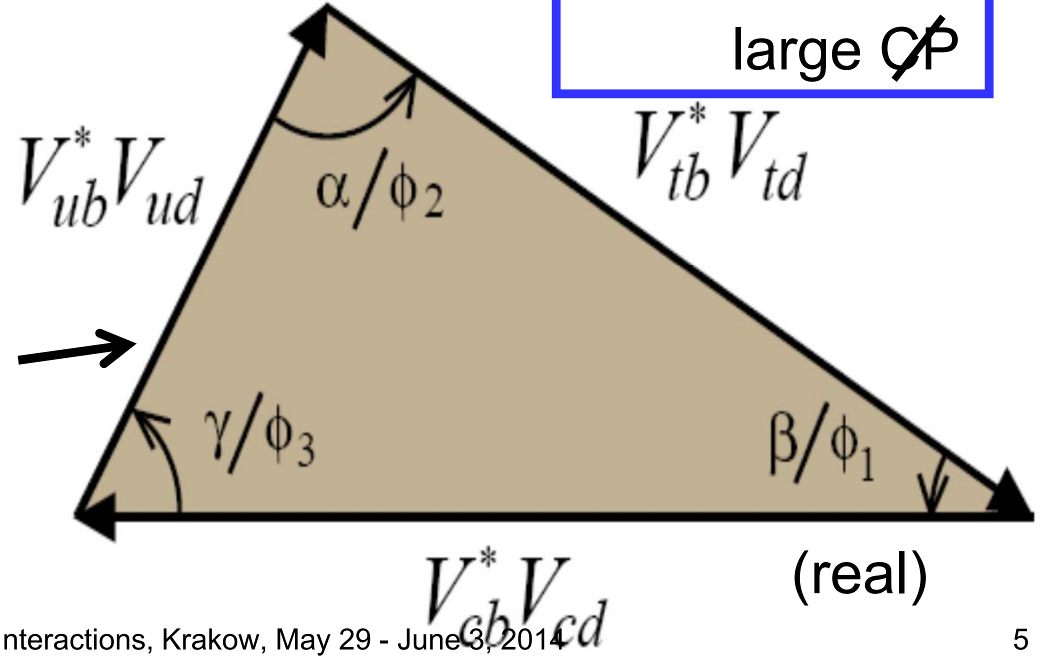
$$\boxed{V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0}$$

Triangle for K mesons

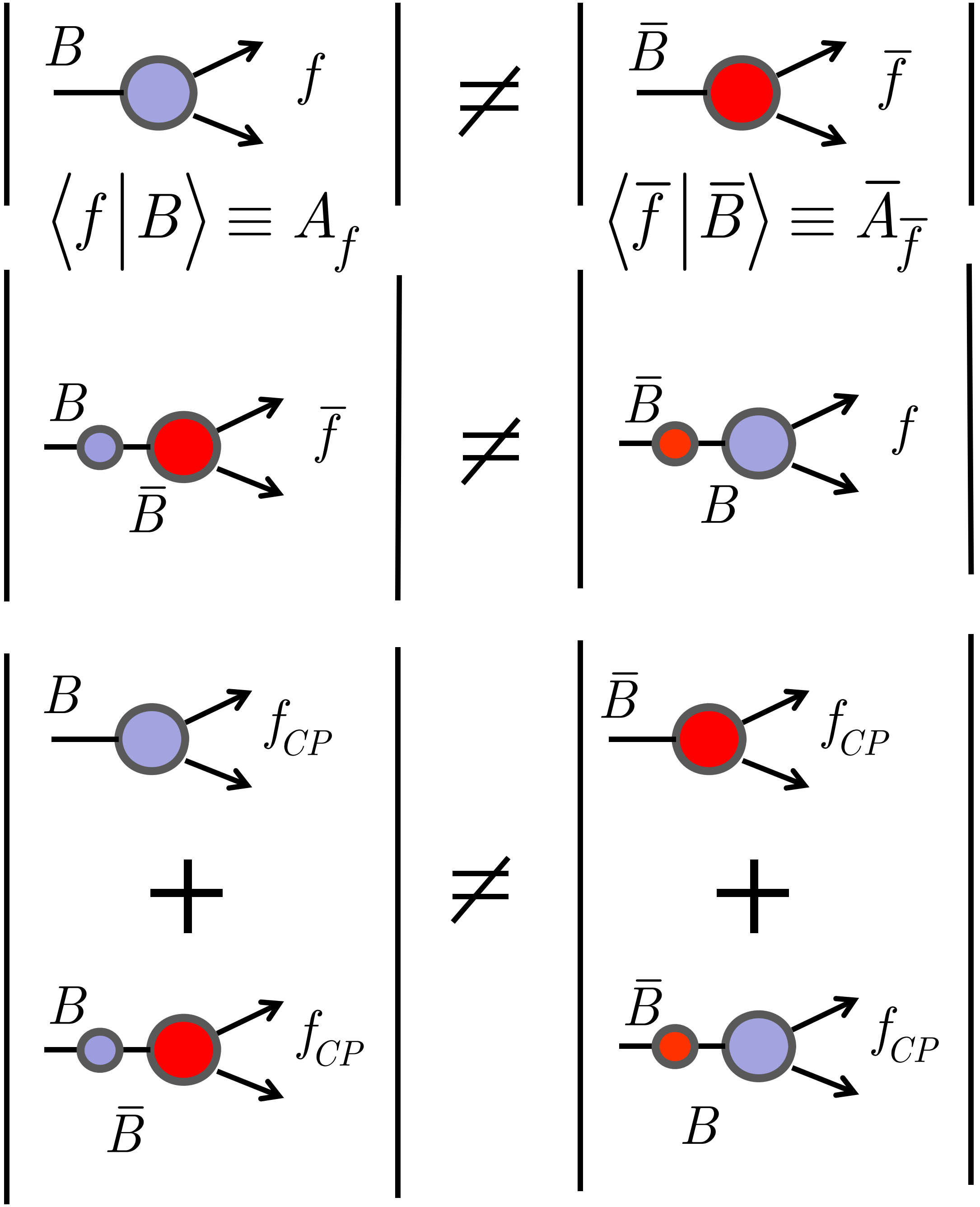
$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$

Triangle for B mesons

large angles =
large $\not{C}\!\!P$



Types of CP Violation in the B-System



$$\langle f | B \rangle \equiv A_f \qquad \langle \bar f | \bar B \rangle \equiv \bar A_{\bar f}$$

$$\left| \frac{\bar A_{\bar f}}{A_f} \right| \neq 1$$

direct CP violation

(charged and neutral B mesons)

$$\left| \frac{q}{p} \right| \neq 1$$

CP violation via mixing

(only neutral B mesons)

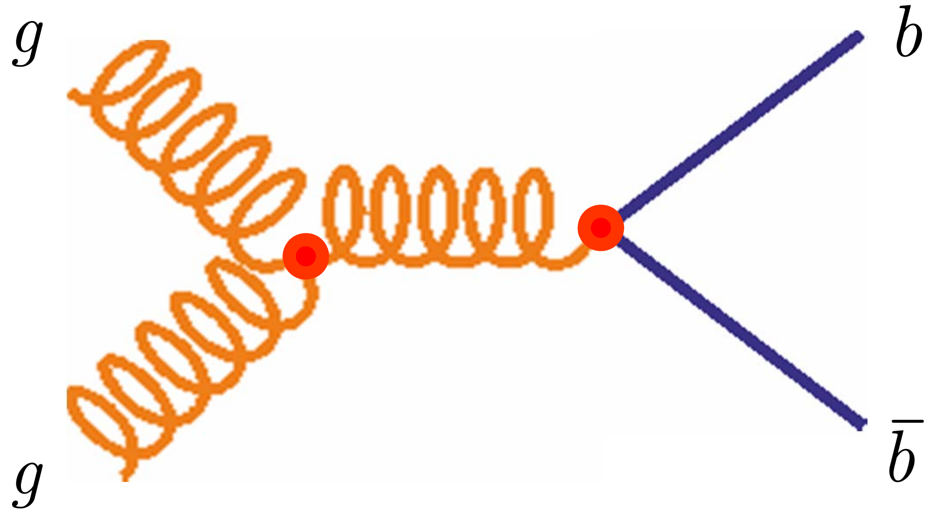
CP violation via interference between mixing and decay (“mixing-induced CPV”)

$$\mathrm{Im}\, \frac{q}{p} \frac{\bar A_f}{A_f} \neq 0$$

(only neutral B mesons)

Production Mechanisms of B-Mesons

B-mesons can be (easily) produced in pairs via the Strong Interaction:



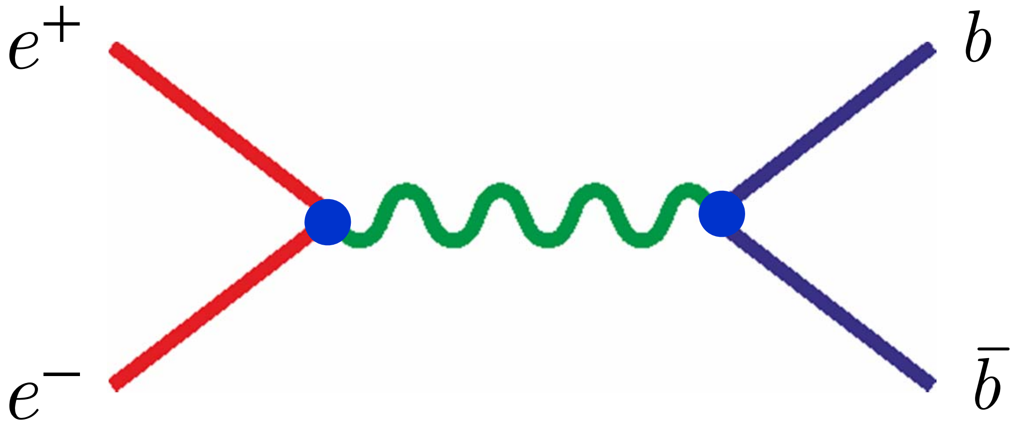
LHC:

ATLAS,
CMS,

LHCb

large cross section,
many B_d and B_s events,
but underlying
background in event

… or the Electromagnetic Interaction:



B Factories:

KEK (Belle)
PEP II (BaBar)

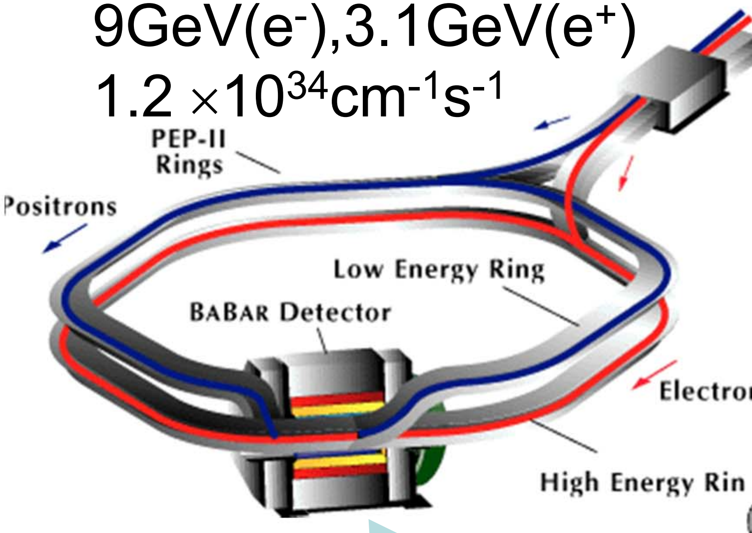
many clean
B_d events,

$N(B_d) >> N(B_s)$

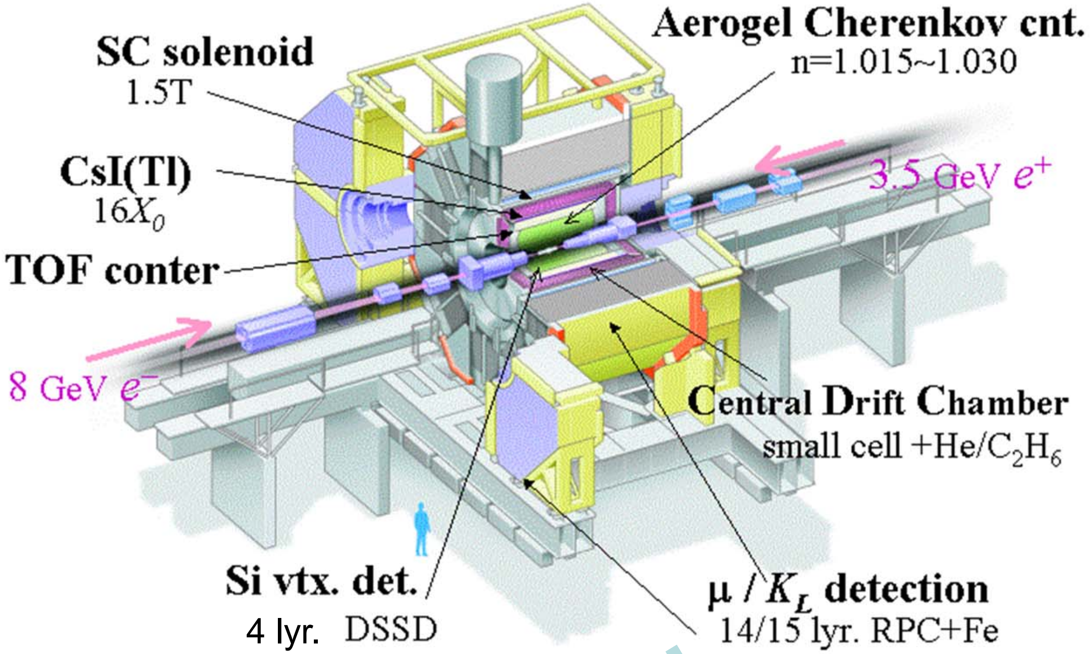
[Belle II @ SuperKEKB]

The Past B-Factories

PEP-II
9GeV(e^-),3.1GeV(e^+)
1.2 ×10^{34}cm^{-1}s^{-1}

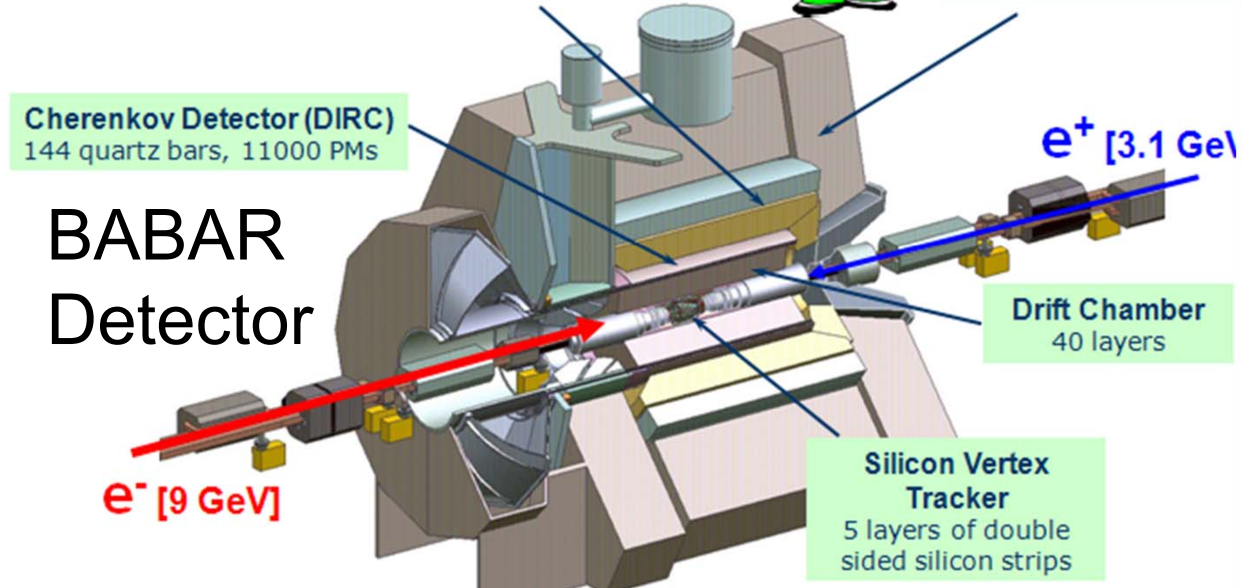


Belle Detector



Electromagnetic Calorimeter
6580 CsI crystals

trumented Flux Retur
layers of RPCs / LSTs



Cherenkov Detector (DIRC)
144 quartz bars, 11000 PMs

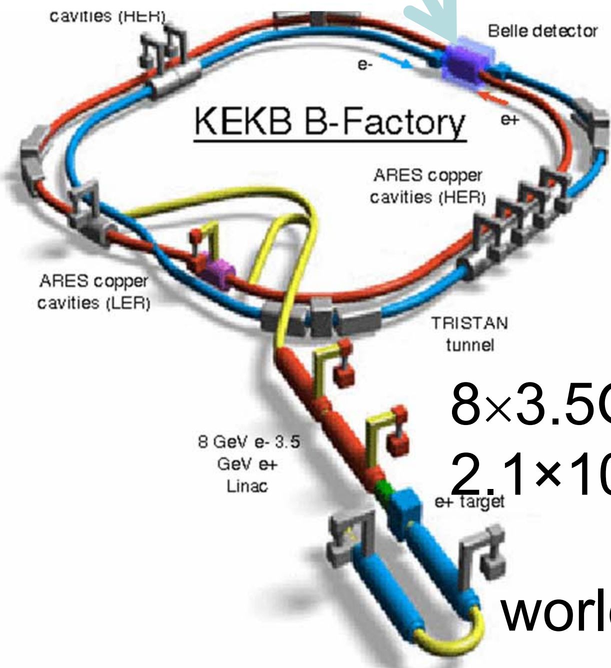
BABAR
Detector

e^+ [3.1 Ge

Drift Chamber
40 layers

Silicon Vertex Tracker
5 layers of double sided silicon strips

e^- [9 GeV]

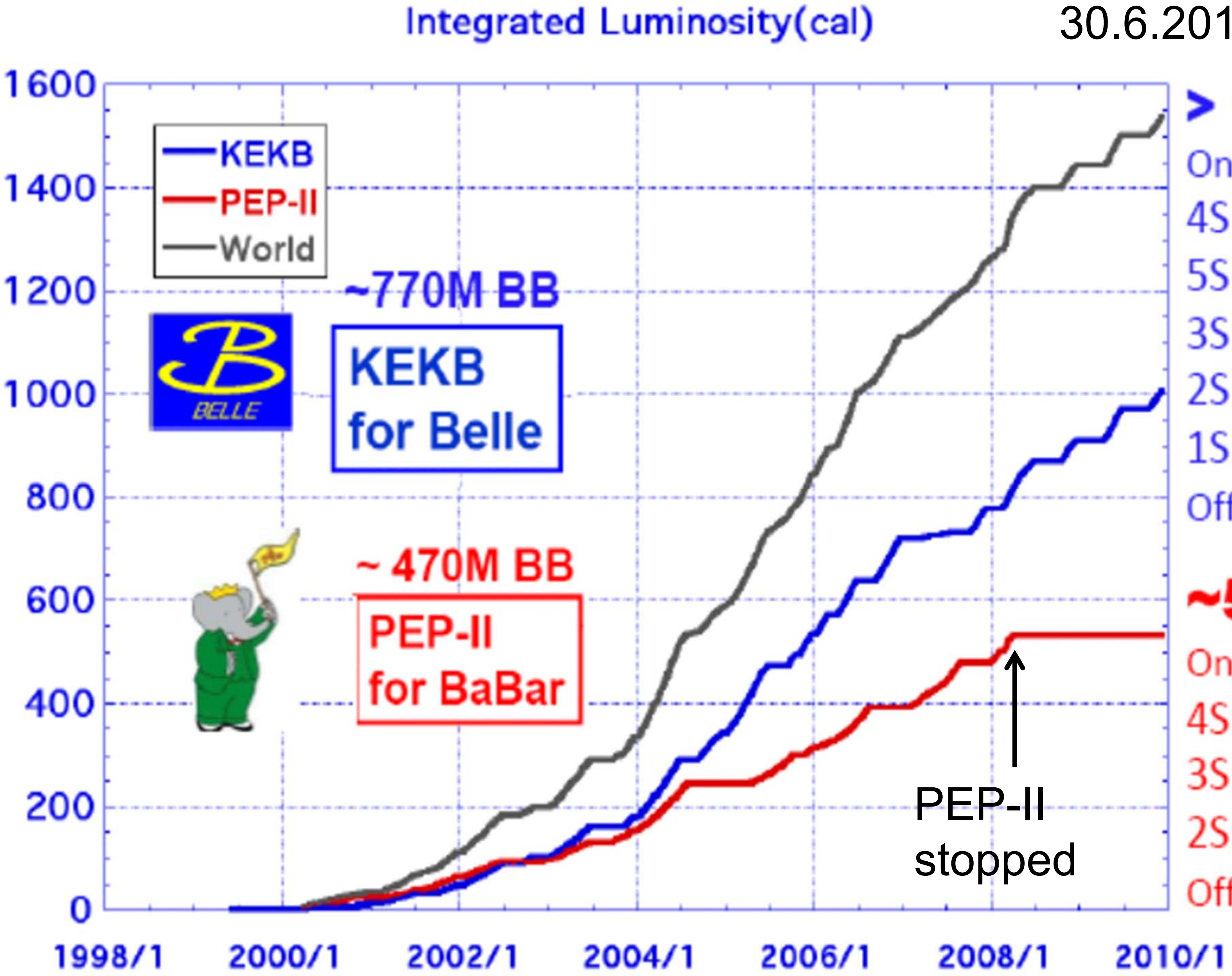


8×3.5GeV
2.1×10^{34}cm^{-2}s^{-1}

world record !

Luminosity accumulated at Past B-Factories

30.6.2010: KEKB stopped



PEP-II stopped

> 1.0 ab^{-1}

On-resonance samples:

4S: 711 fb^{-1}

5S: 121 fb^{-1}

3S: 3.0 fb^{-1}

2S: 24 fb^{-1}

1S: 5.7 fb^{-1}

Off-resonance: 87 fb^{-1}

~553 fb^{-1}

On-resonance samples:

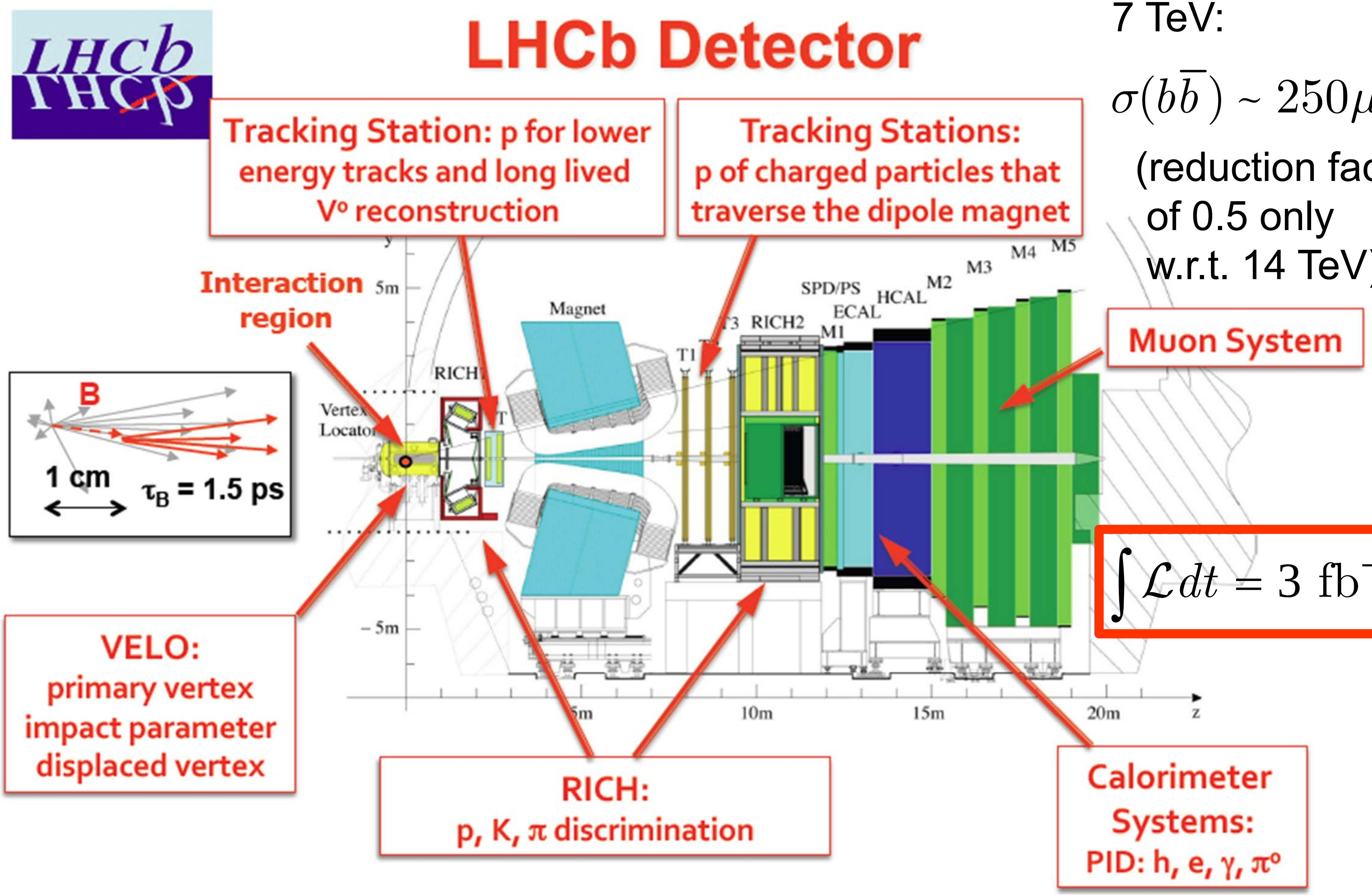
4S: 433 fb^{-1}

3S: 30 fb^{-1}

2S: 14 fb^{-1}

Off-resonance: 54 fb^{-1}

LHC Experiments: LHCb



Tracking Station: p for lower energy tracks and long lived V° reconstruction

Tracking Stations: p of charged particles that traverse the dipole magnet

Interaction region

Muon System

VELO: primary vertex impact parameter displaced vertex

RICH: p, K, π discrimination

Calorimeter Systems: PID: h, e, γ, π°

7 TeV:

$$\sigma(b\bar{b}) \sim 250\mu\text{b}$$

(reduction fact. of 0.5 only w.r.t. 14 TeV)

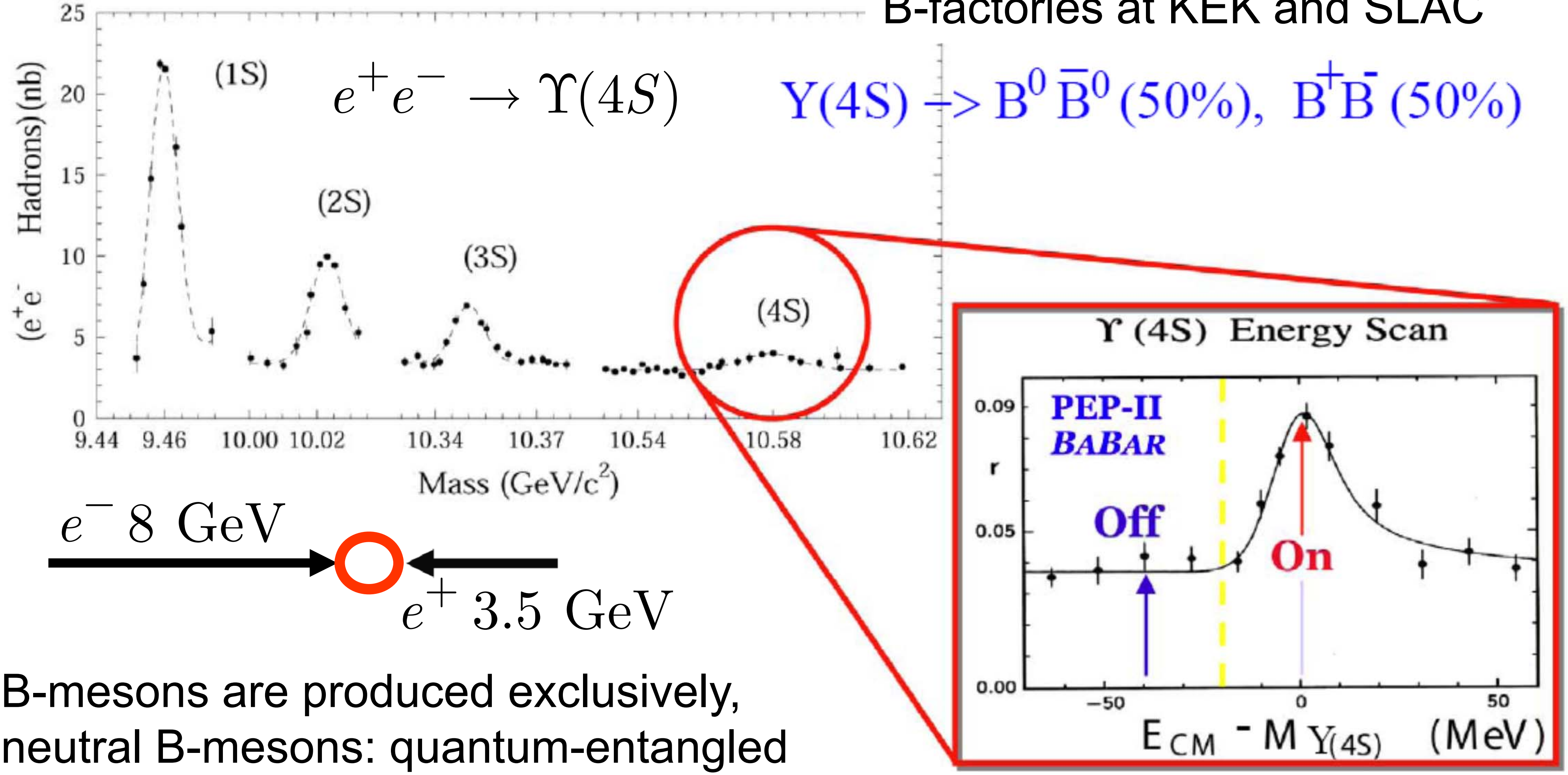
$$\boxed{\int \mathcal{L} dt = 3\ \text{fb}^{-1}}$$

B-Factories: Where do we Measure?

B-factories at KEK and SLAC

$e^+e^- \rightarrow \Upsilon(4S)$

Y(4S) -> $B^0\,\bar{B}^0$ (50%), B^+B^- (50%)



B-mesons are produced exclusively,
neutral B-mesons: quantum-entangled

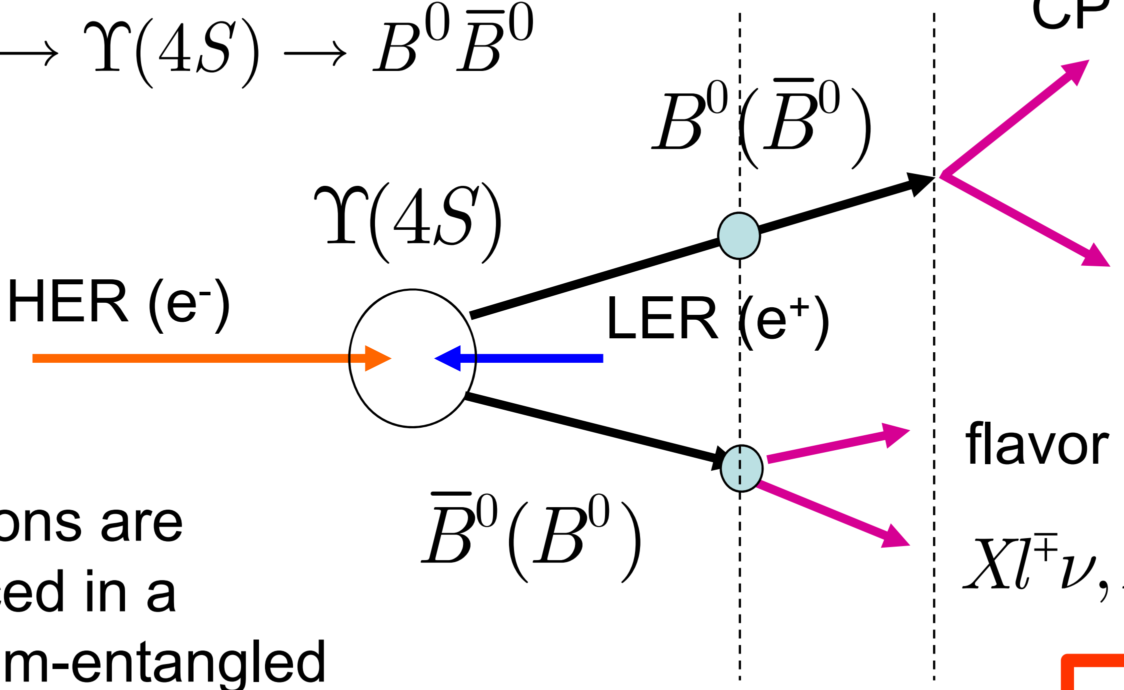
Beam energies are asymmetric:
both B‘s have the same Lorentz boost,
fly parallel in the lab system

background („continuum“)
below the resonance peak

The ~~CP~~ Observables: What do we measure?

B-Mesons: $\left|B^0\right\rangle = \left|\bar{b}d\right\rangle \quad \left|B^+\right\rangle = \left|\bar{b}u\right\rangle$

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$$



some state $f(\bar{f})$ or CP eigenstate, e.g.

$J/\psi K_S$ $CP = -1$ the „golden“ channel

flavor eigenstate

$X l^{\mp}\nu, D^{*\pm}X$ „flavor tagging“

B mesons are produced in a quantum-entangled state !

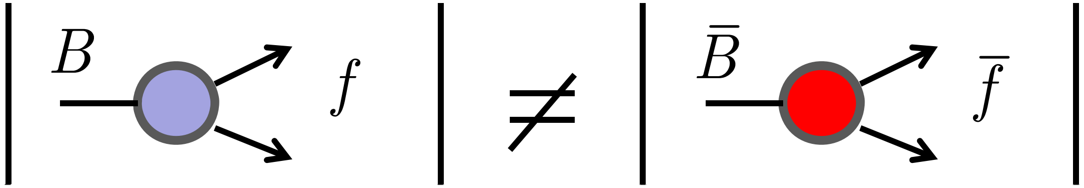
$$\Delta z = \beta\gamma c \Delta t$$

$$\boxed{\Delta t = t_{\mathrm{CP}} - t_{\mathrm{tag}}}$$

Asymmetric beam energies: translate decay time to decay length

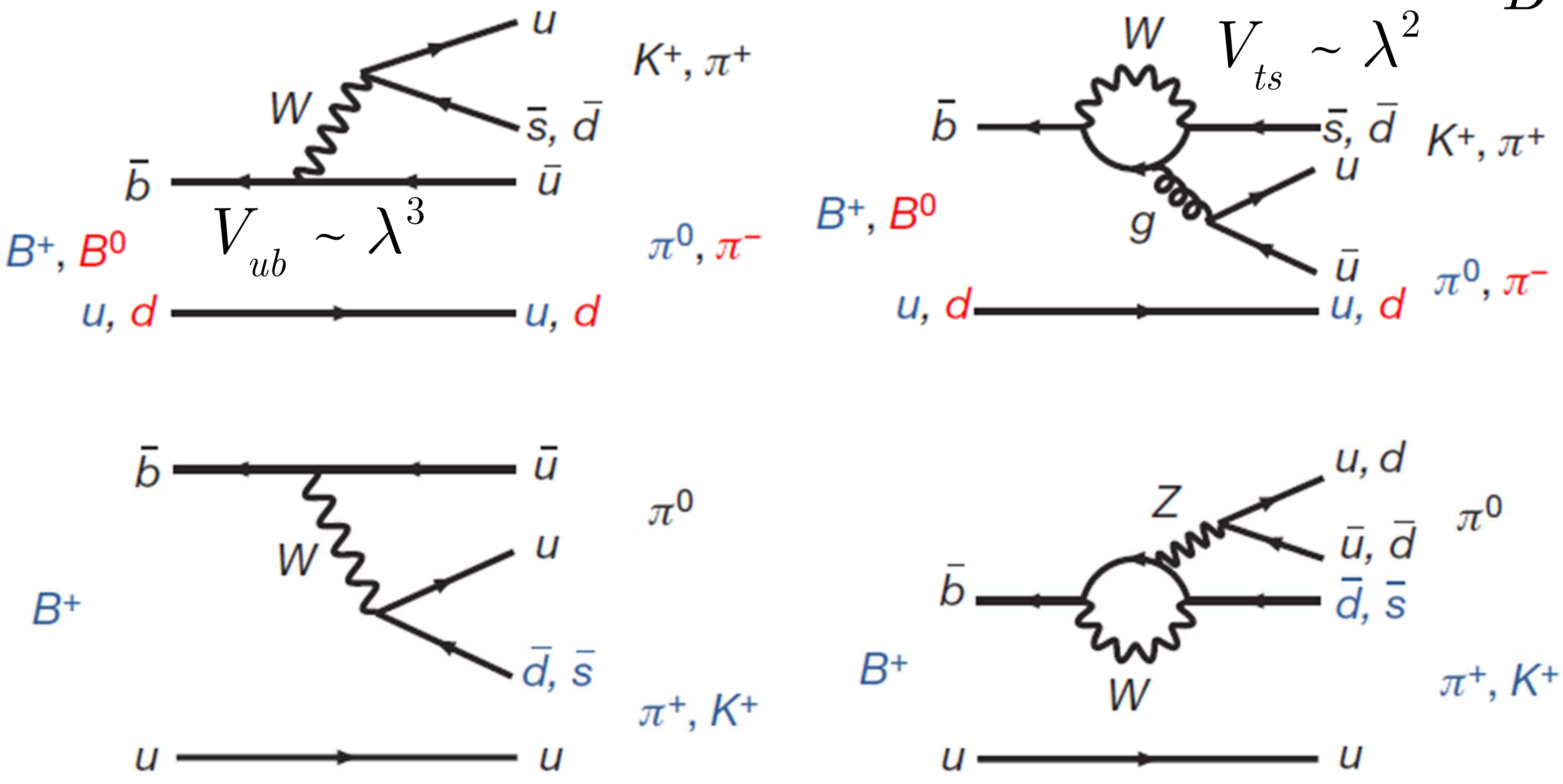
Δz ~ 150 μm → need excellent vertex detection

Direct CP Violation



Need two amplitudes of ~ similar magnitude, e.g.

$B \to K\pi$



$V_{ub} \sim \lambda^3$

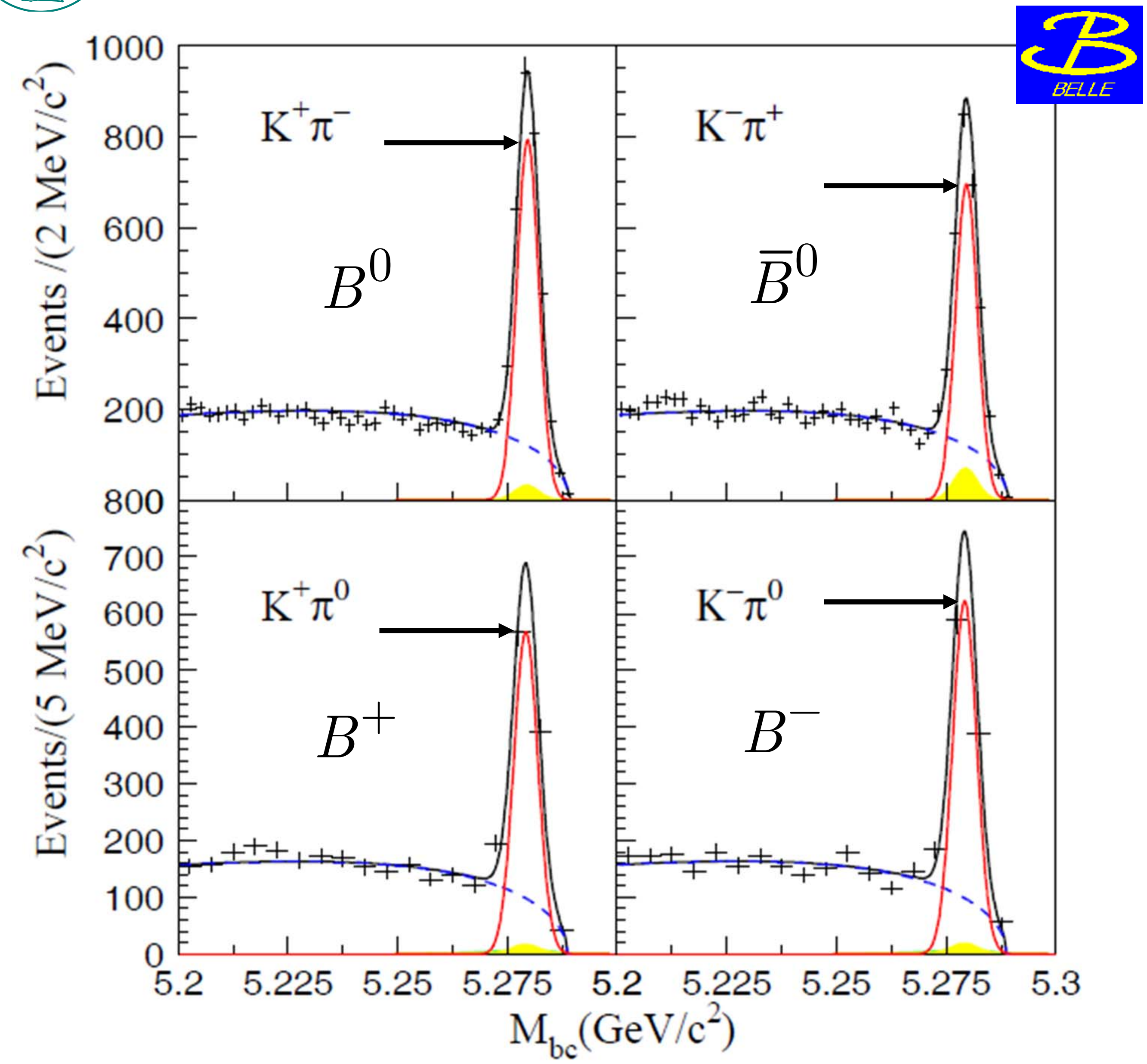
$V_{ts} \sim \lambda^2$

color-suppressed

build “CP Asymmetries”:
(integrated over time)

$$\mathcal{A}_{CP}(f) = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

Direct CP Violation in $B \rightarrow K\pi$



$A_{CP}(K^+\pi^-) < 0$

WA: -0.082 ± 0.006

(dominated by LHCb measurement)

$A_{CP}(K^+\pi^0) > 0$

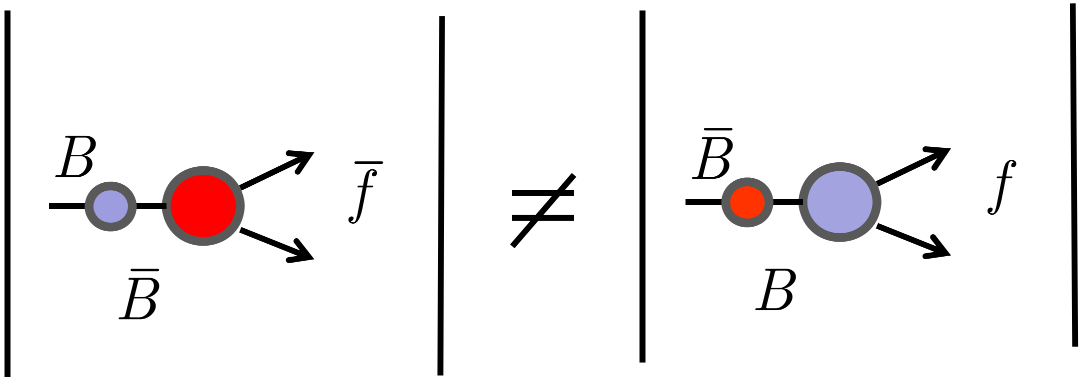
WA: $+0.040 \pm 0.021$

should be equal !

New Physics?

Nature 452, 332 (2008), PRD **87, 031103(R)** (2013)

CP Violation in Mixing



Select final state f
so that

$$B^0 \to f \not\leftarrow \bar{B}^0 \to \bar{f}$$

e.g.

$$\bar{B}^0 \to X l^- \bar{\nu} \not\leftarrow B^0$$

$$B^0 \to X l^+ \nu \not\leftarrow \bar{B}^0$$

look for semi-leptonic decays
with wrong-sign leptons

$$a_{sl}^{d,s} = \frac{\Gamma(\bar{B}^0 \to l^+ \mathrm{X}) - \Gamma(B^0 \to l^- \mathrm{X})}{\Gamma(\bar{B}^0 \to l^+ \mathrm{X}) + \Gamma(B^0 \to l^- \mathrm{X})} \simeq \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12}$$

SM: expect very small for B_d mesons,

and ~ 0 for B_s mesons

$$\phi_{12} = \arg(M_{12} / \Gamma_{12})$$

$$\phi_{12}^{s} \simeq 0.2^\circ$$

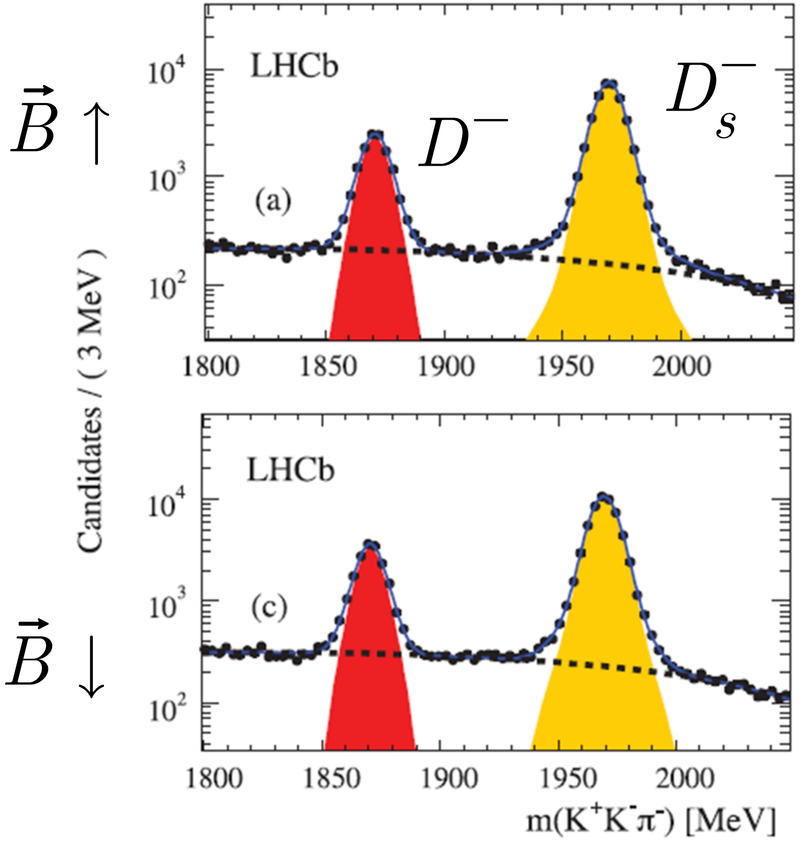
CP Violation in Mixing

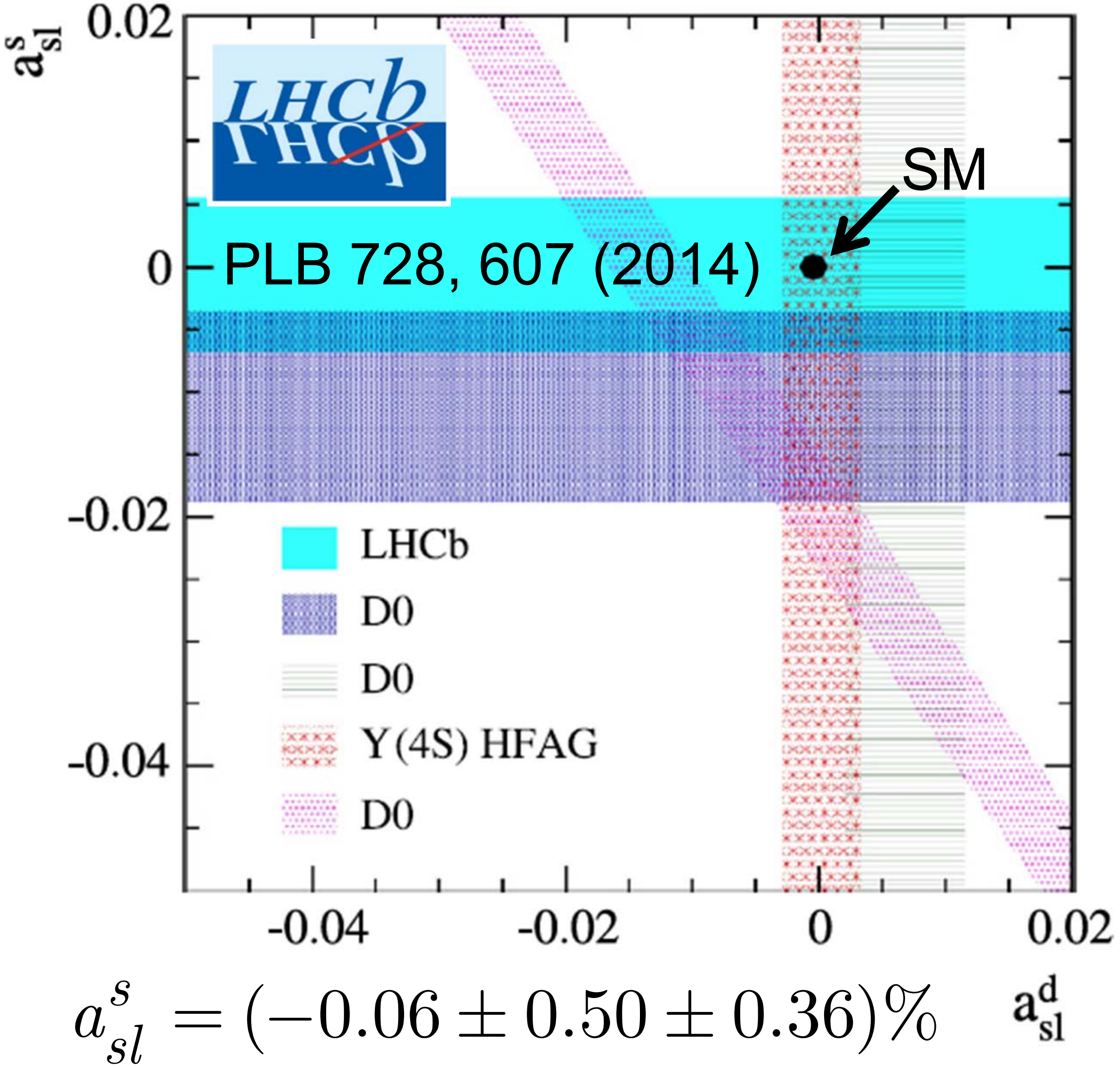
New measurement
by LHCb:

$$A_{\text{meas}} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)} = \frac{1}{2} a_{sl}^s$$

$$\overline{B}_s \to D_s^- X \mu^+$$

$$D_s^- \to \phi \pi^-$$





PLB 728, 607 (2014)

$$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

Mixing-Induced CP Violation

$$A = \left\langle f_{CP} \mid B^0 \right\rangle; \quad \bar{A} = \left\langle f_{CP} \mid \bar{B}^0 \right\rangle$$

f_{CP} : CP eigenstate
eigen value = ξ

$$\begin{tikzcd} B^0 \arrow[rr, "A"] \arrow[dr, dashed, "\frac{q}{p}"'] & & f_{CP} \\ & \bar{B}^0 \arrow[ur, dashed, "\bar{A}"'] & \end{tikzcd} \quad A_f \quad \neq \quad \begin{tikzcd} \bar{B}^0 \arrow[rr, "\bar{A}"] \arrow[dr, dashed, "\frac{p}{q}"'] & & f_{CP} \\ & B^0 \arrow[ur, dashed, "A"'] & \end{tikzcd}$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}}{A}$$

$$B_{L,H} = pB^0 \pm q\bar{B}^0$$

$$\mathcal{A}_{CP}(f,\Delta t) = \frac{\Gamma(\bar{B}^0 \to f;\Delta t) - \Gamma(B^0 \to f;\Delta t)}{\Gamma(\bar{B}^0 \to f;\Delta t) + \Gamma(B^0 \to f;\Delta t)}$$

$$\boxed{\Delta t = t_{CP} - t_{tag}}$$

„time-dependent CP asymmetry“

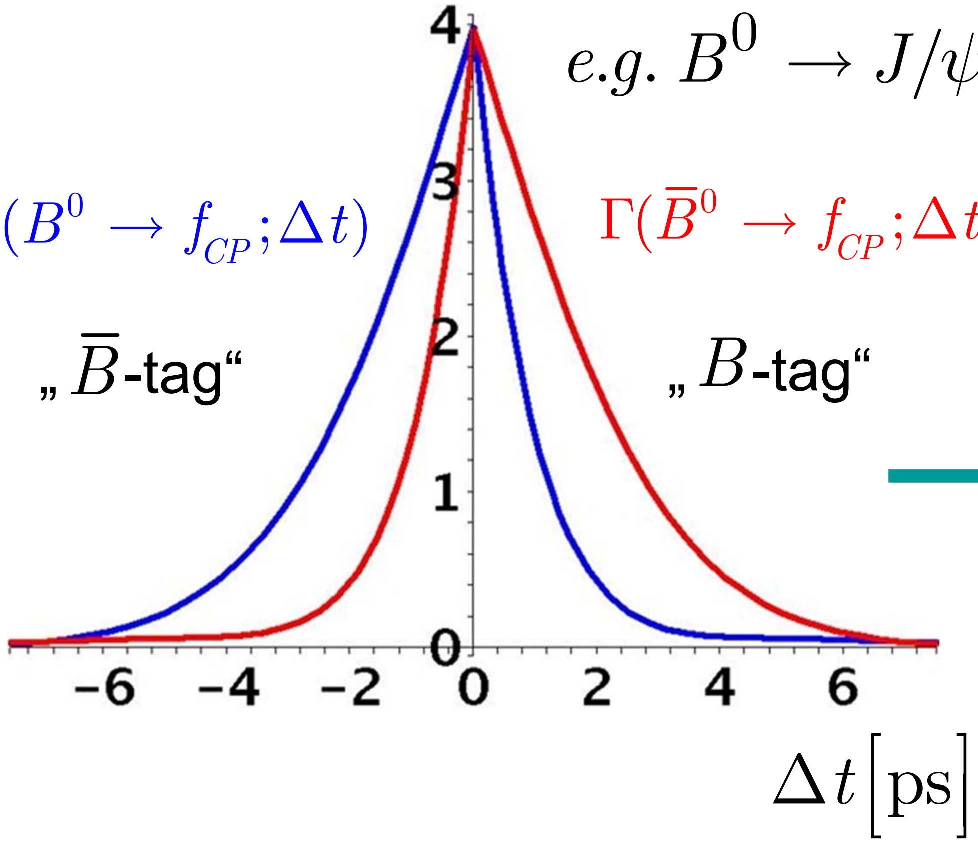
$$= \frac{\left|\lambda_f\right|^2 - 1}{\left|\lambda_f\right|^2 + 1}\cos\Delta M\Delta t + \frac{2\,\mathrm{Im}(\lambda_f)}{\left|\lambda_f\right|^2 + 1}\sin\Delta M\Delta t$$

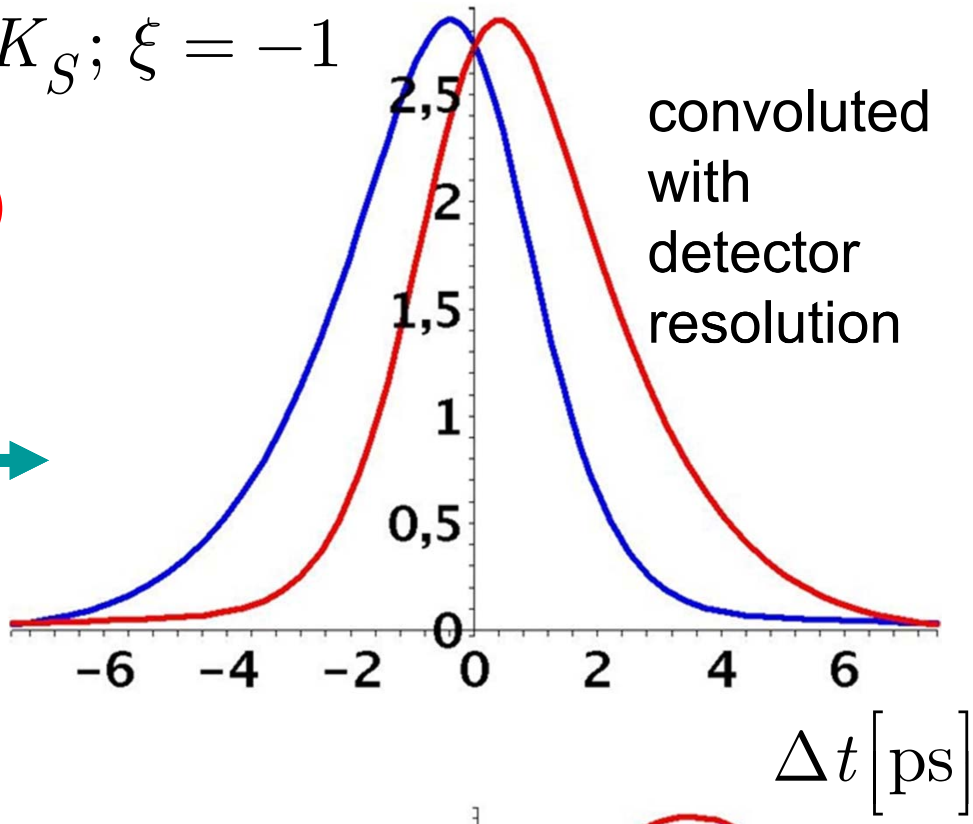
A_f „direct“

S_f „mixing-induced“

Time-Dependent CP-Asymmetries

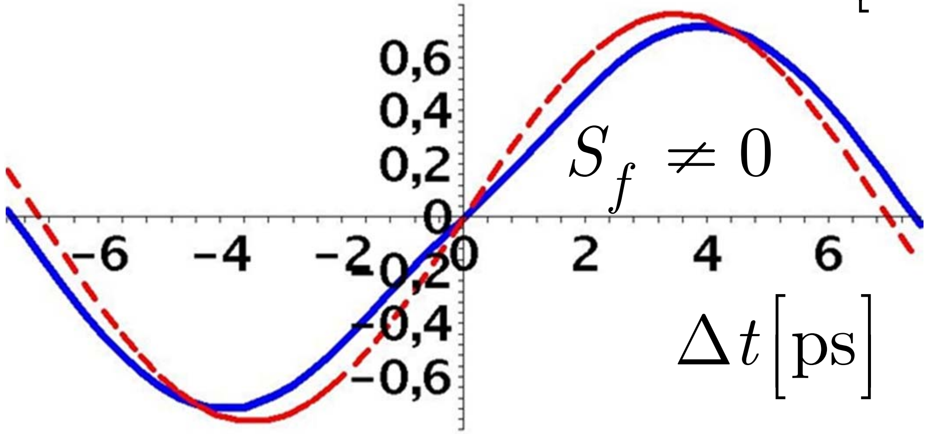
$e.g.\ B^0 \to J/\psi K_S;\ \xi = -1$





convoluted with detector resolution

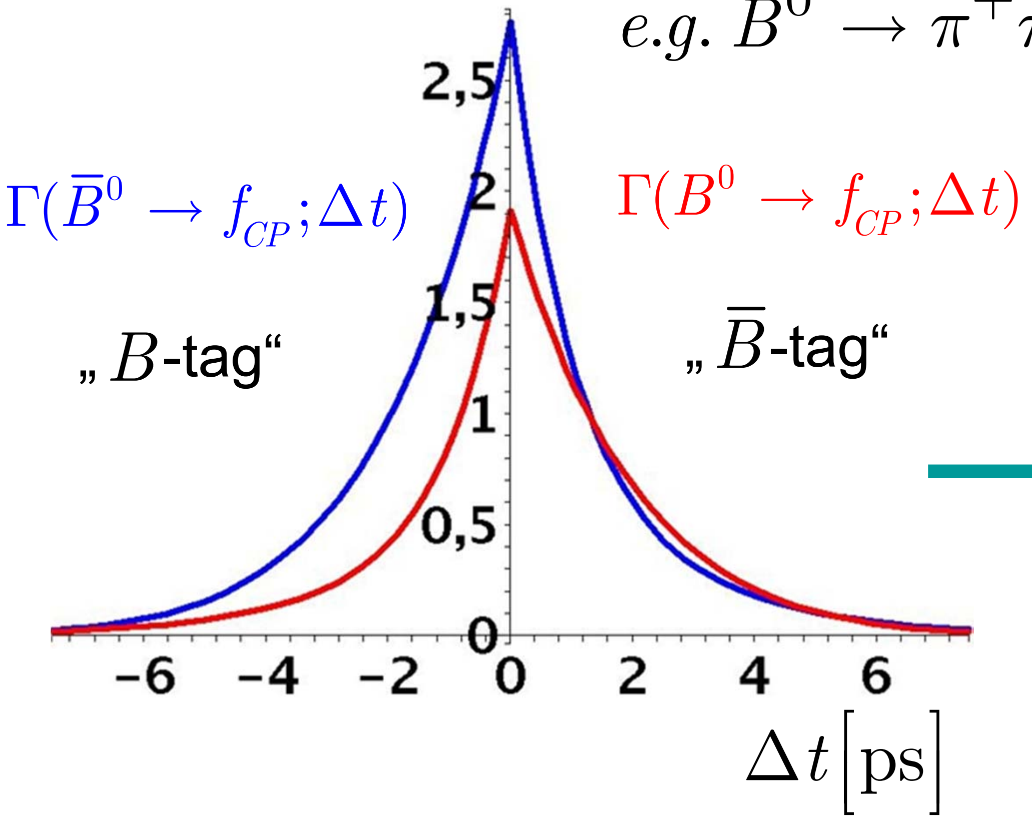
$$\mathcal{A}_{CP}(\Delta t) = \frac{N(\overline{B}^0,\Delta t) - N(B^0,\Delta t)}{N(\overline{B}^0,\Delta t) + N(B^0,\Delta t)}$$
$$= A_f \cos\Delta M\Delta t + S_f \sin\Delta M\Delta t$$

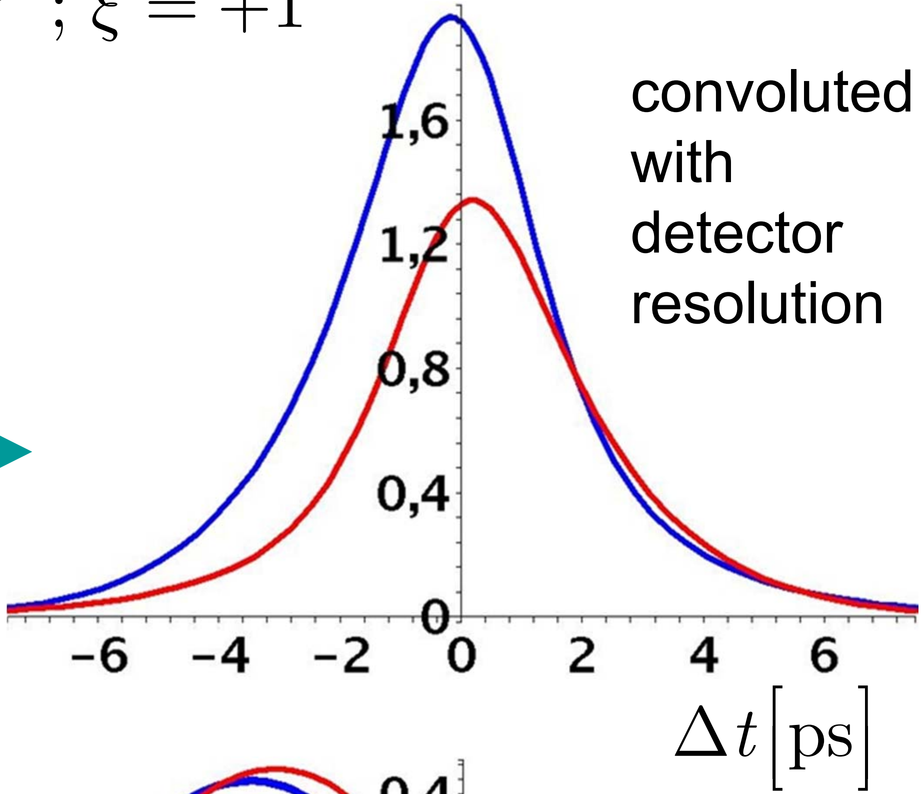


No direct CP violation: $A_f = 0$

Time-Dependent CP-Asymmetries

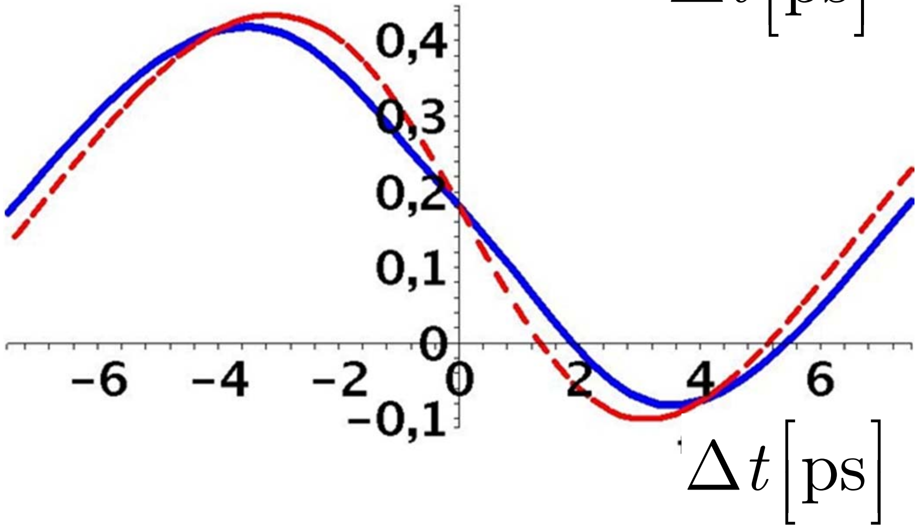
$e.g.\ B^0 \to \pi^+\pi^-;\ \xi = +1$





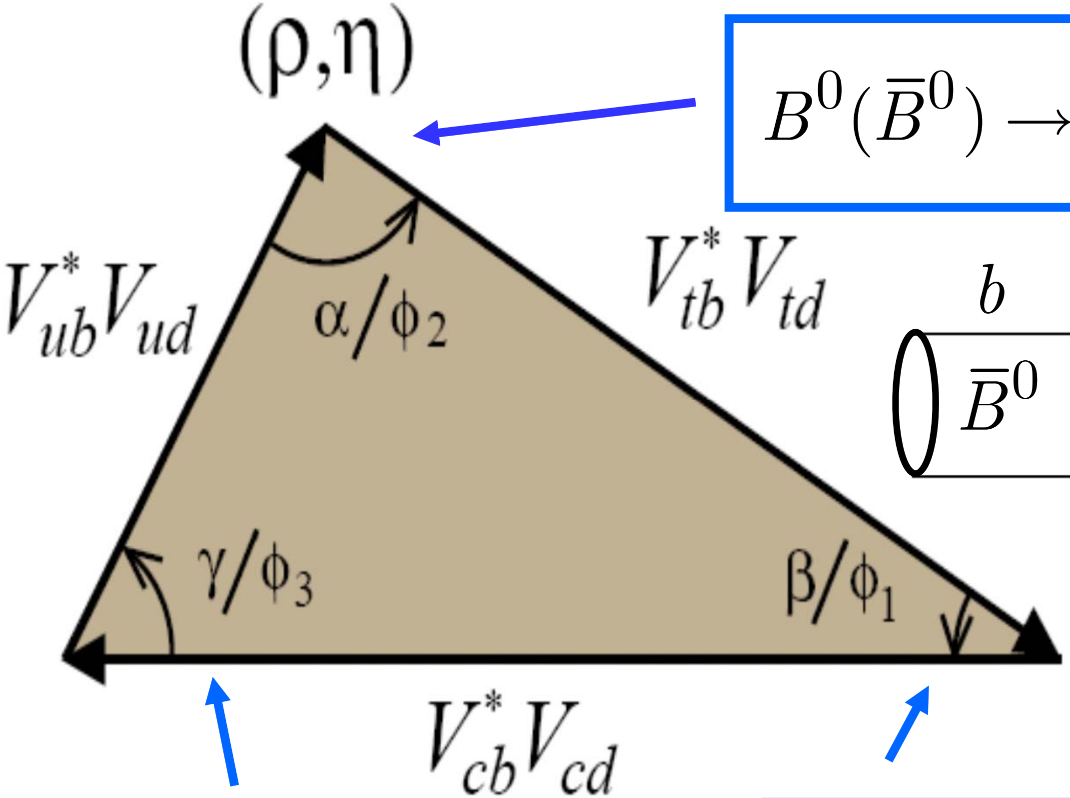
convoluted
with
detector
resolution

$$\mathcal{A}_{CP}(\Delta t) = \frac{N(\bar{B}^0,\Delta t) - N(B^0,\Delta t)}{N(\bar{B}^0,\Delta t) + N(B^0,\Delta t)}$$
$$= A_f \cos \Delta M \Delta t + S_f \sin \Delta M \Delta t$$



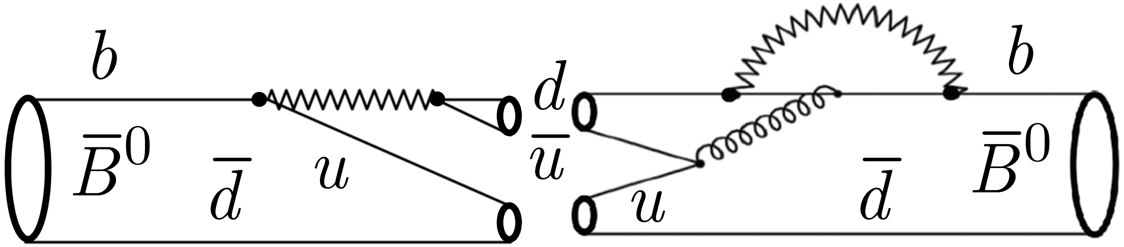
+ direct CP violation: $A_f \neq 0, S_f \neq 0$

Measuring the Angles Φ_1,Φ_2,Φ_3 (β,α,γ)



$$B^0(\bar{B}^0) \rightarrow \pi\pi, \rho\rho, \rho\pi, a_1\pi$$

$Br \sim 10^{-6}$

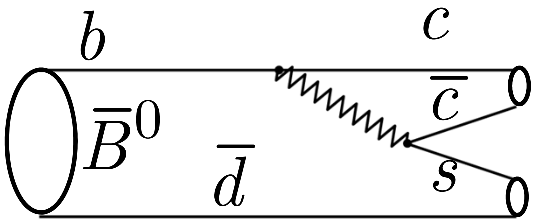


T ~ P

Tree (T) or Penguin (P) dominates

$Br \sim 10^{-4}$

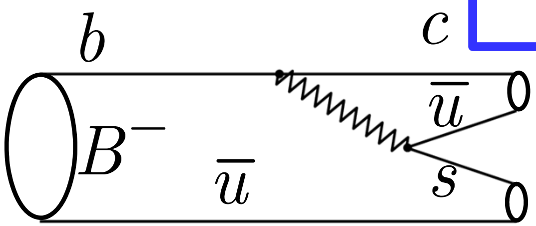
$$B^0(\bar{B}^0) \rightarrow J/\psi K_{S,L}$$
$$\rightarrow \phi K_{S,L}$$



T

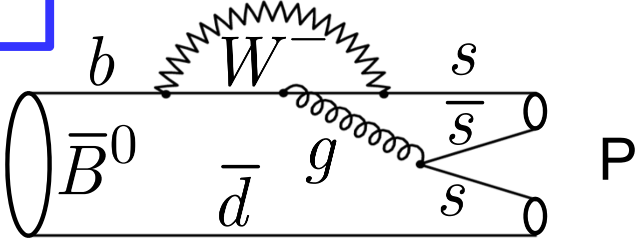
$$B^- \rightarrow DK^-, D \equiv \left[D^0/\bar{D}^0\right]$$

$Br \sim 10^{-5}$



T (only)

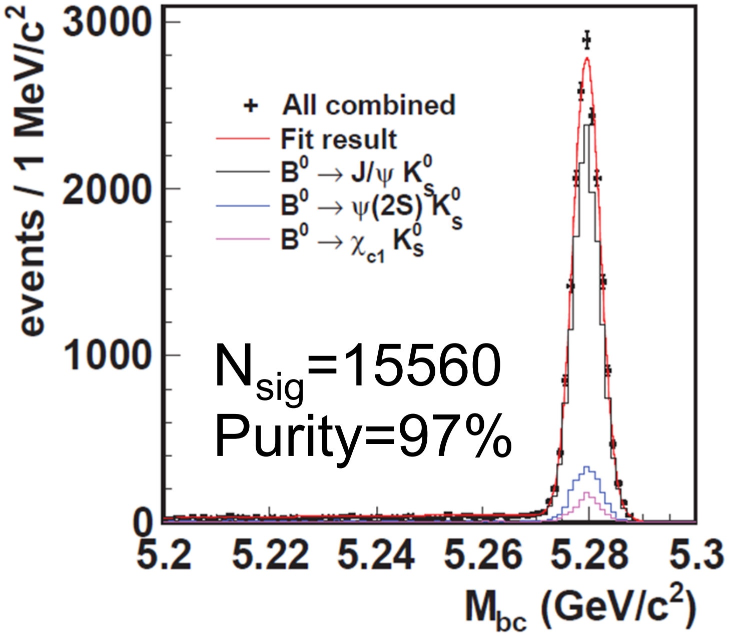
....



P

Measurement of ϕ_1 (β) in Charmonium K^0 modes

772MB$\bar{B}$



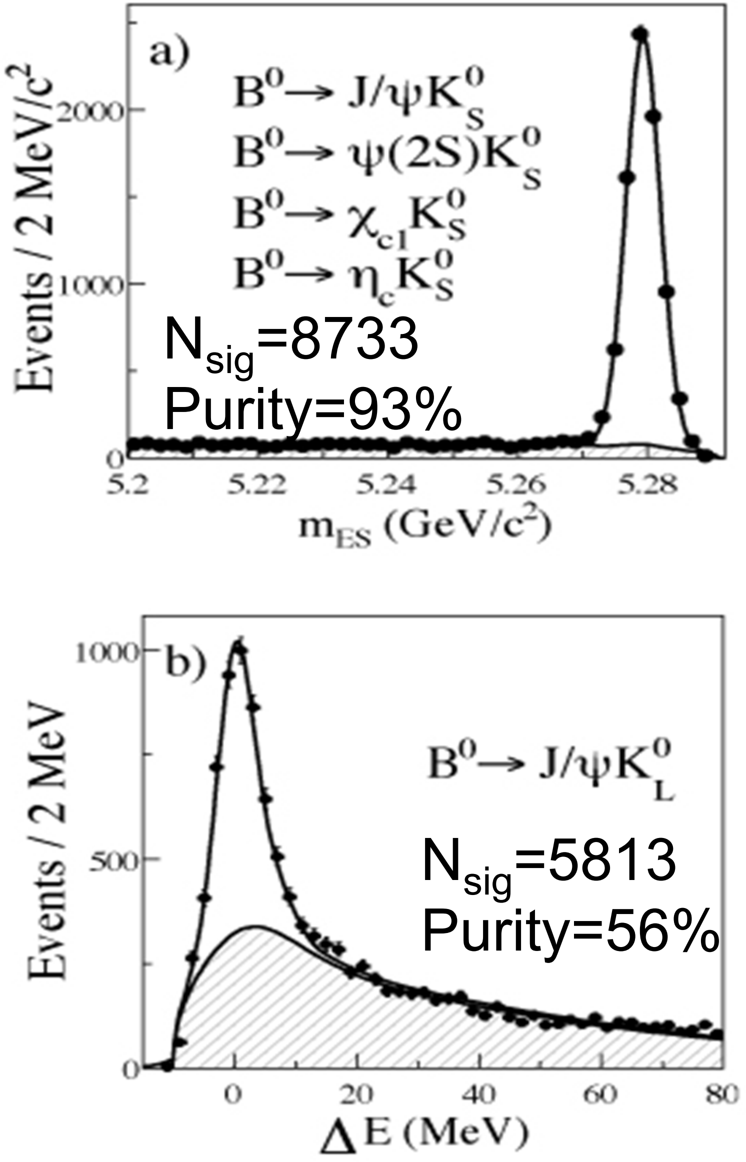
N_{sig}=15560
Purity=97%

Typical signal extraction:
reconstruct desired final state using

$$M_{bc} = \sqrt{\left(E^{*}_{beam}\right)^{2} - \left(p^{*}_{B^0}\right)^{2}}$$

$$\Delta E = E^{*}_{B^0} - E^{*}_{beam}$$

465MB$\bar{B}$

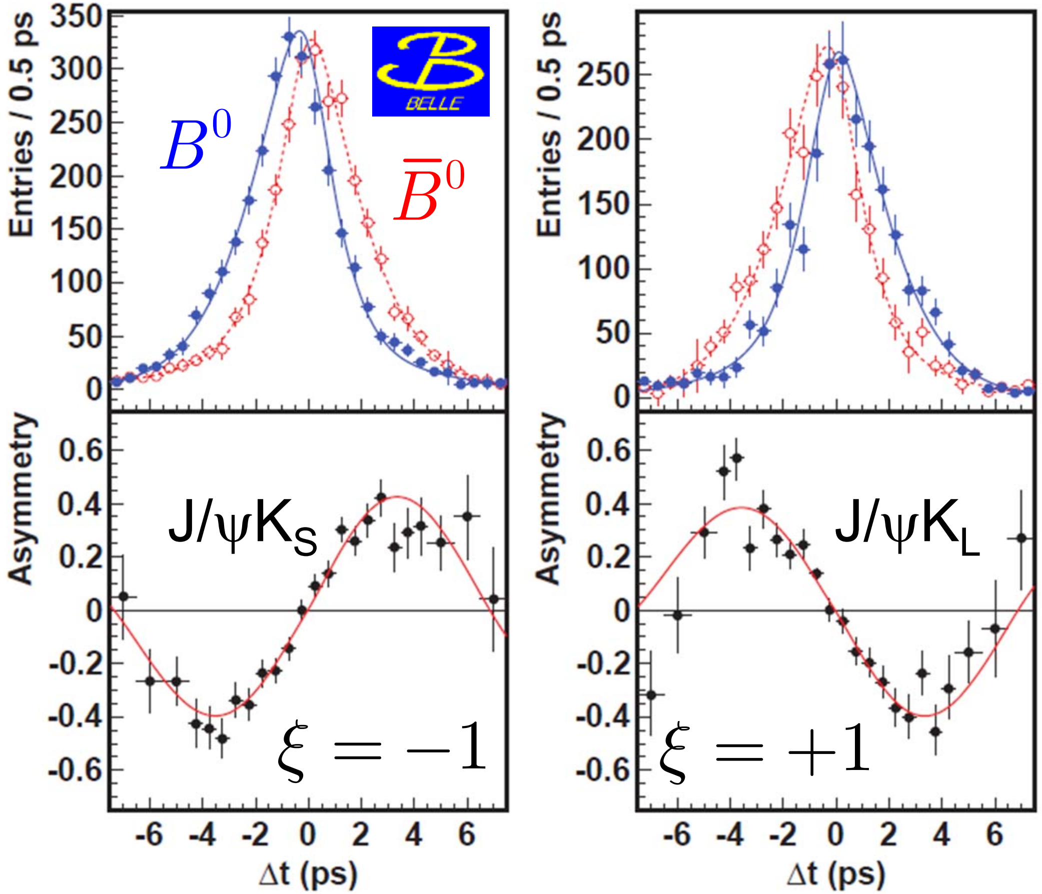


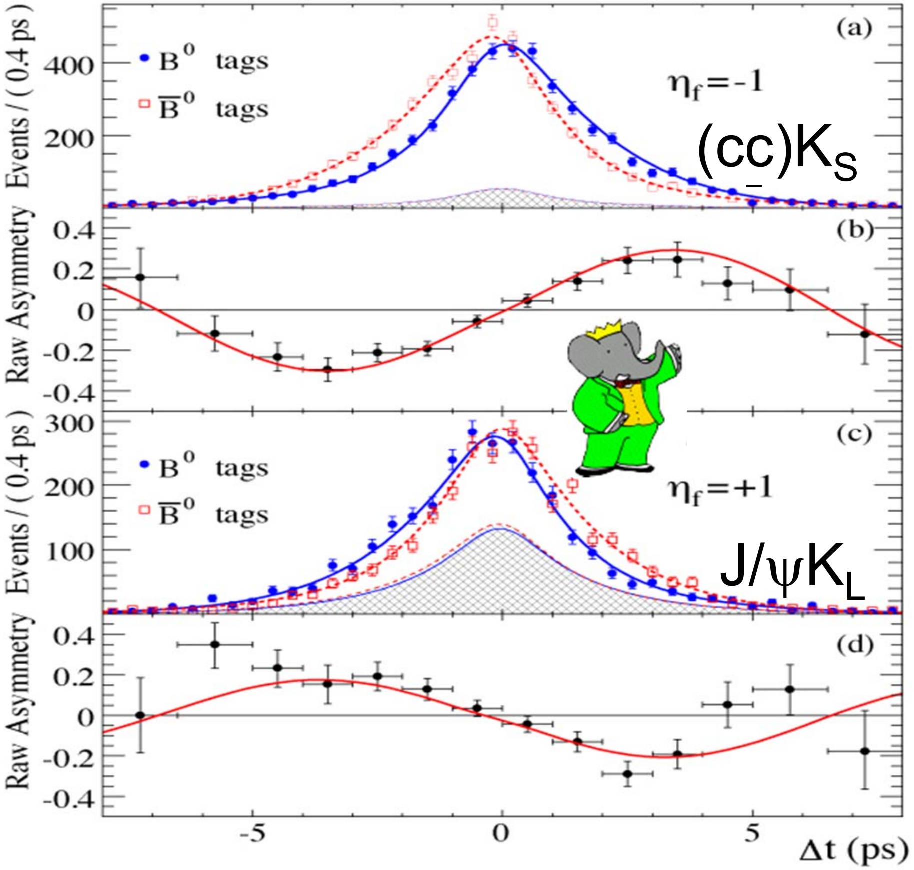
N_{sig}=8733
Purity=93%

N_{sig}=5813
Purity=56%

$E_B - E_{CM}/2$

Measurement of ϕ_1 (β) in Charmonium K^0 modes





$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$

$A_f = 0.006 \pm 0.016 \pm 0.012$

PRL108,171802(2012)

$\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$

$A_f = -0.024 \pm 0.020 \pm 0.016$

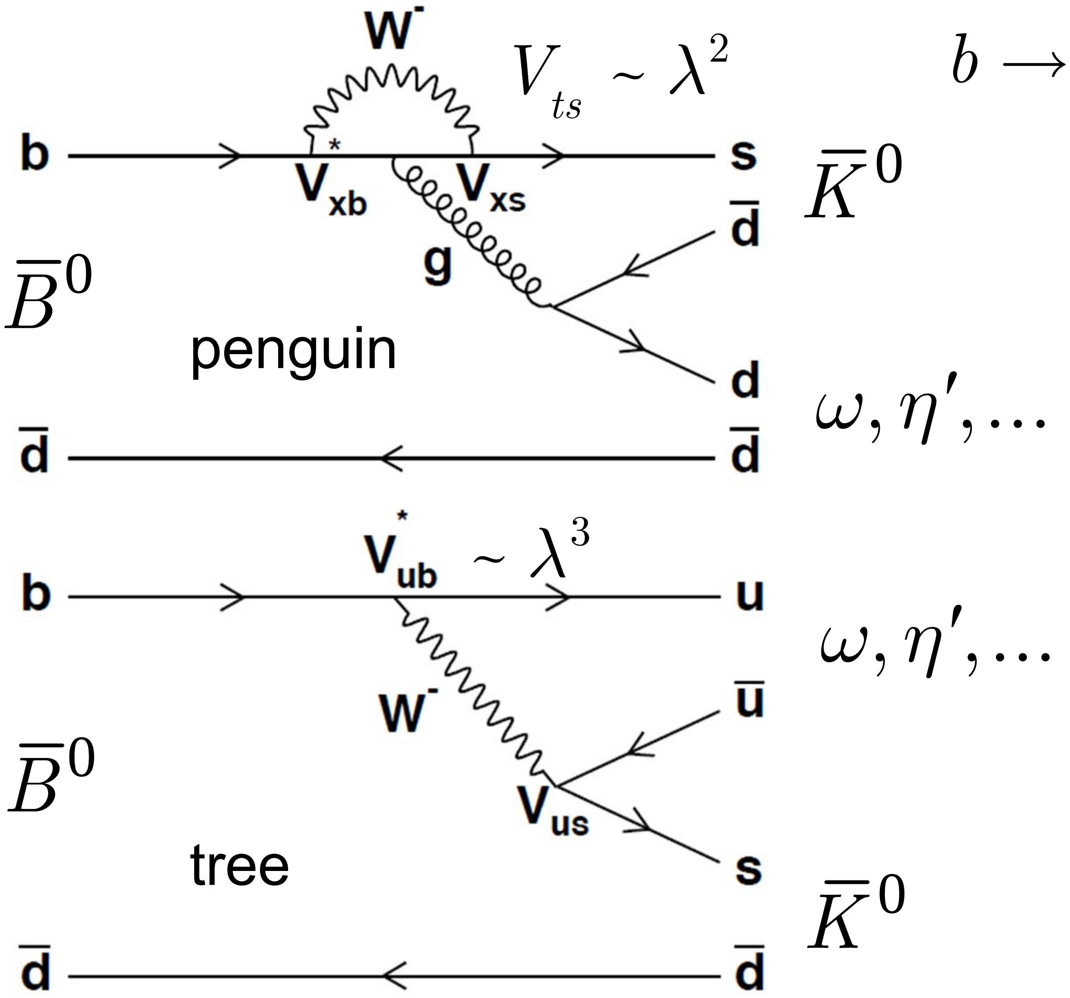
PRD79,072009(2009)

Excellent description by the Standard Model

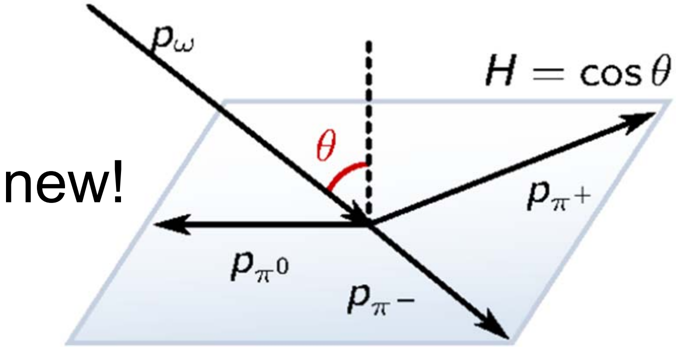
New Belle Results on Penguins: $B^0 \to \omega K_S$

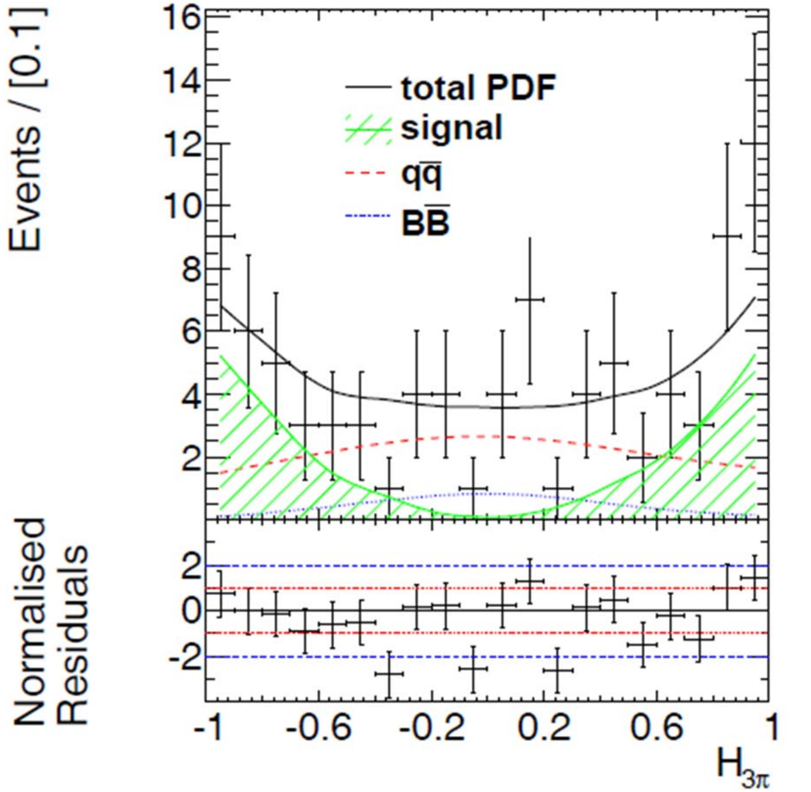
Physics reason: compare Φ_1 from penguins ~ Φ_1 from tree $b \longrightarrow c\bar{c}s$

$b \longrightarrow sq\bar{q}$



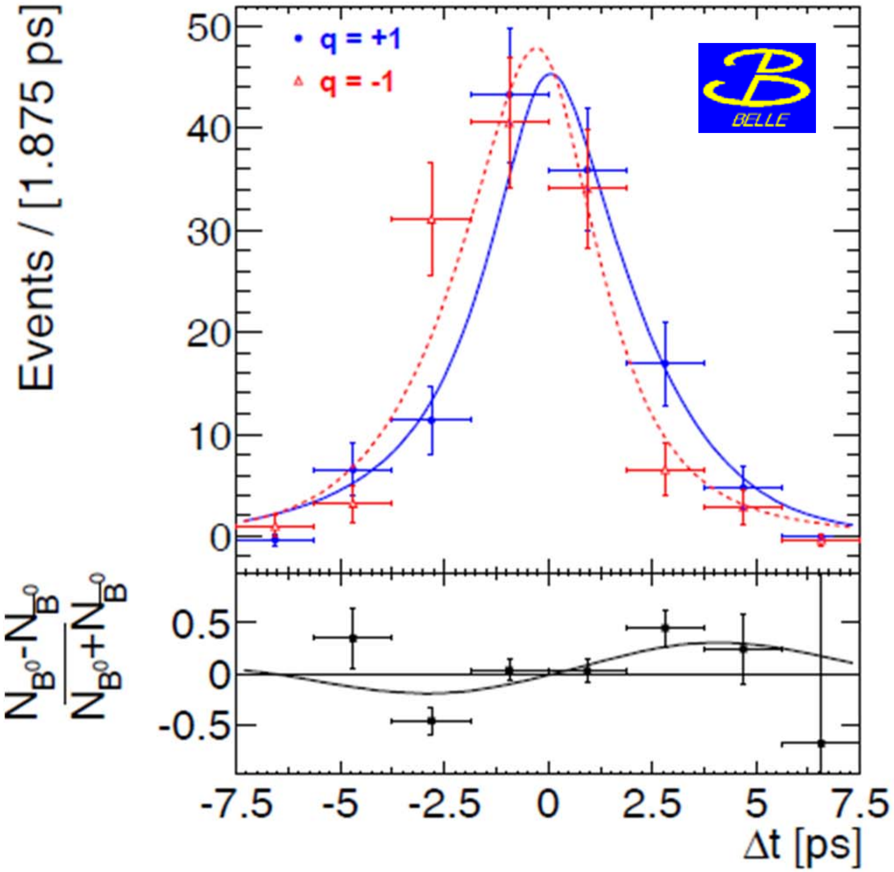
new!





Penguin-dominated, tree in addition
color- and Cabibbo-suppressed

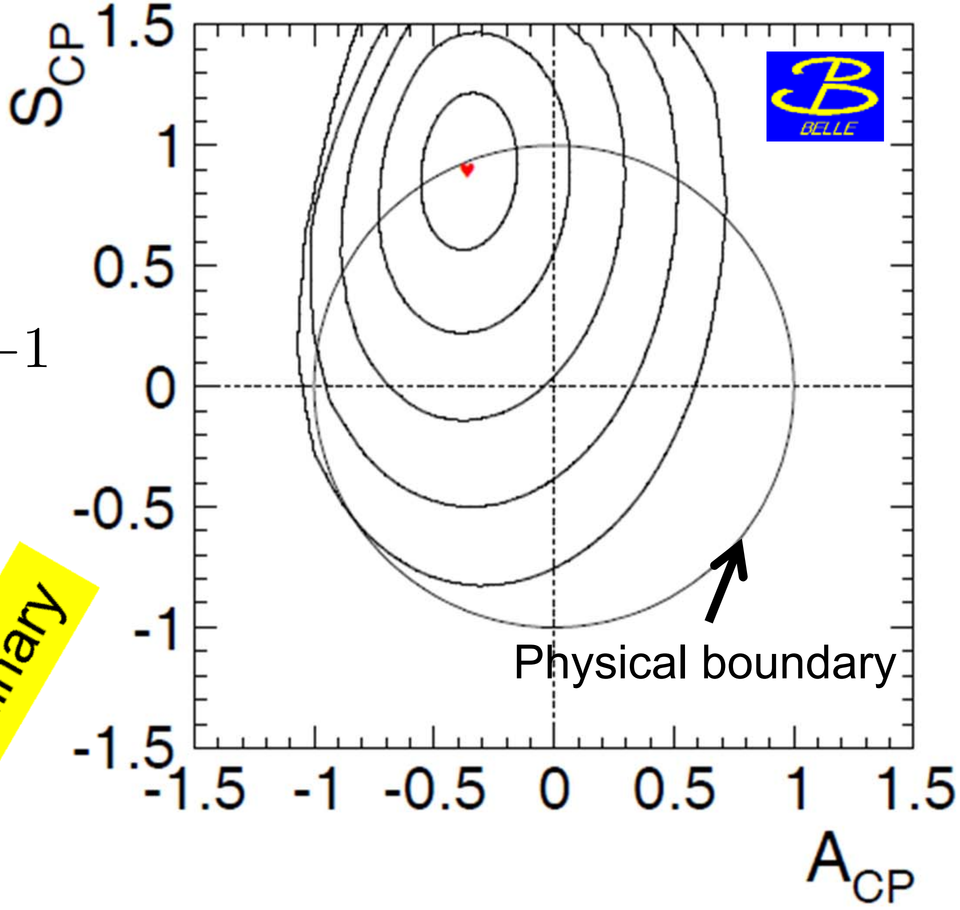
New Belle Results on Penguins: $B^0 \to \omega K_S$



arXiv 1311.6666

$$\xi_f = -1$$

preliminary



First evidence (3.1 σ) for CPV in this decay mode

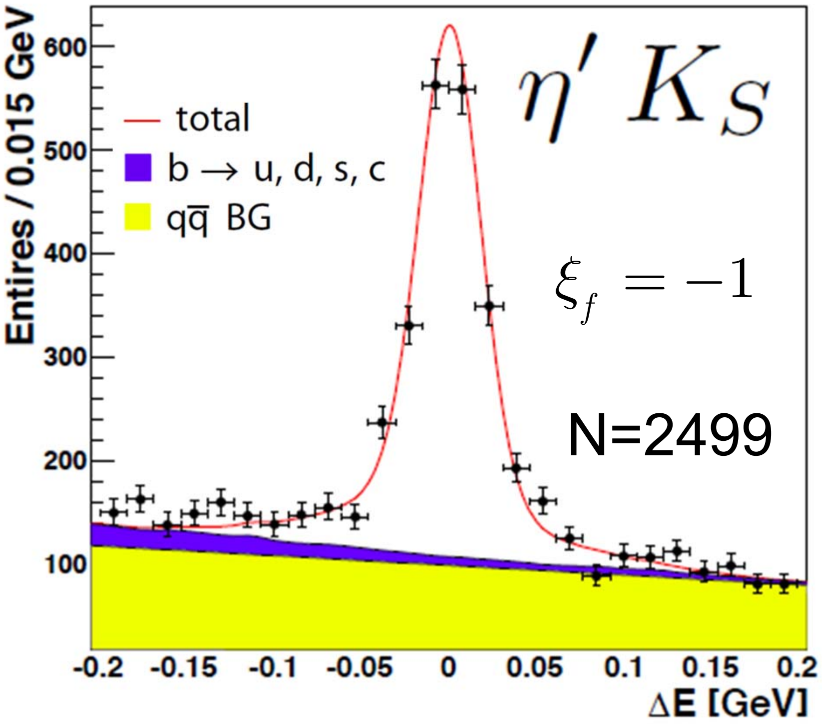
$$\mathcal{A}_{CP} = -0.36 \pm 0.19 \pm 0.05$$

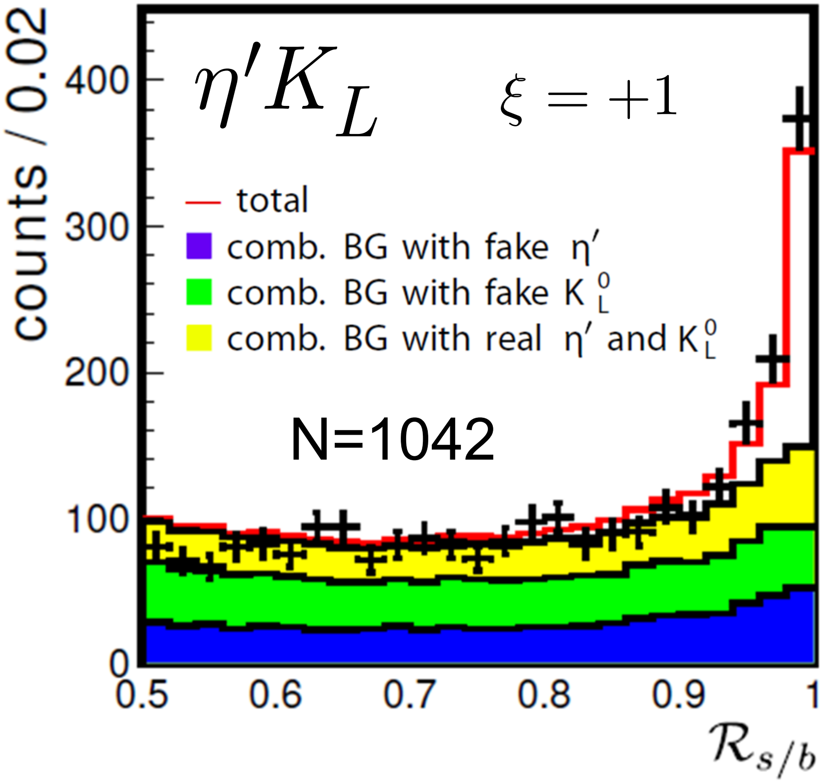
$$\mathcal{S}_{CP} = +0.91 \pm 0.32 \pm 0.05$$

SM: $\Delta = \mathcal{S}_{\omega K_s} - \sin 2\phi_1 \approx (0.1 - 0.2)$ consistent with SM !

New Belle Results on Penguins: $B^0 \to \eta' K^0$

Two analyses: $B^0 \to \eta' K_S (\xi = -1)$ and $B^0 \to \eta' K_L (\xi = +1)$



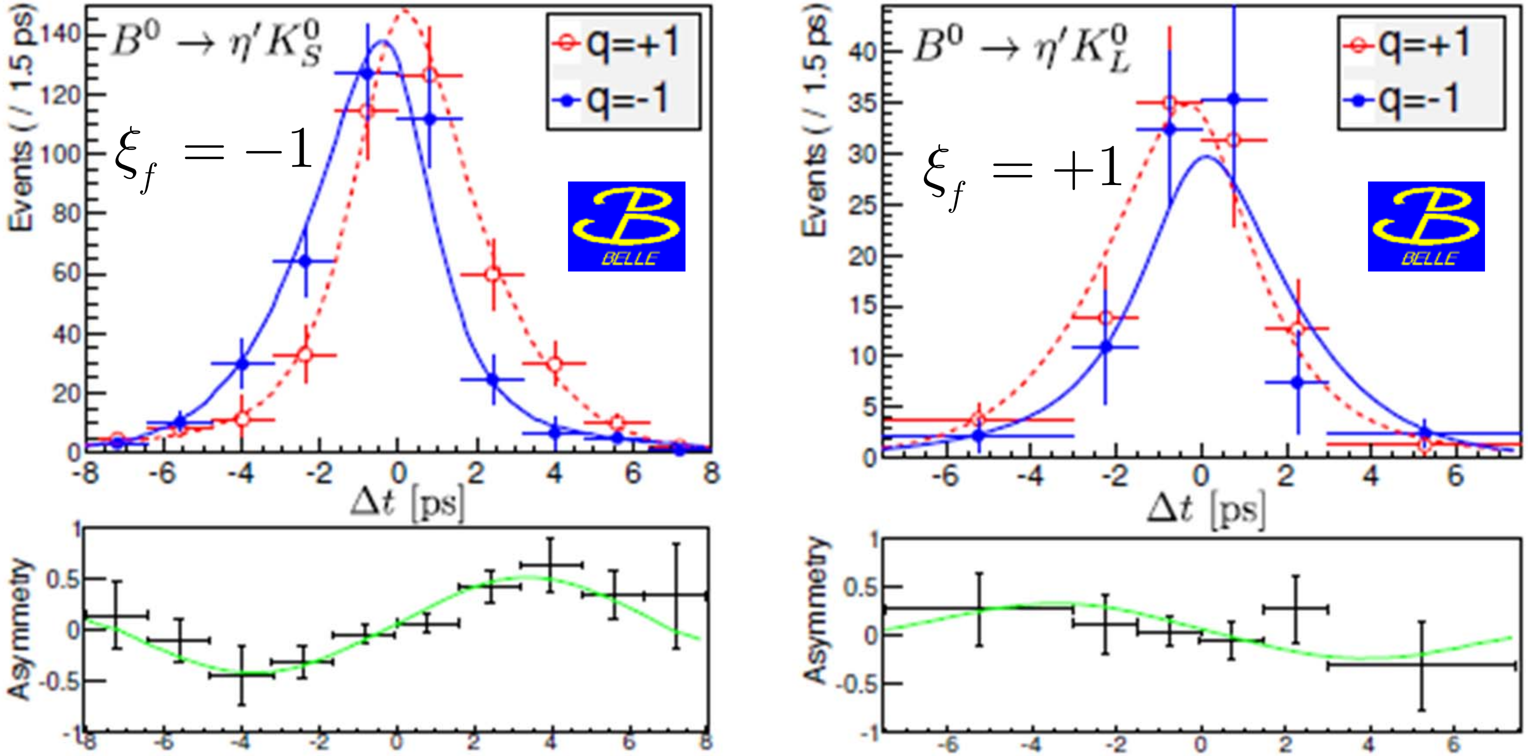


using M_{bc} and ΔE

only direction of the K_L known: cut on cms momentum of *B* meson

New Belle Results on Penguins: $B^0 \to \eta' K^0$

preliminary



Decay mode	$-\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$\eta' K^0_S$	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
$\eta' K^0_L$	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
$\eta' K^0$	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

Most precise penguin measurement so far, consistent with SM

Comparison of Tree and Penguins for ϕ_1 (β)

$b \longrightarrow c\bar{c}s$ tree

$b \longrightarrow sq\bar{q}$ penguins

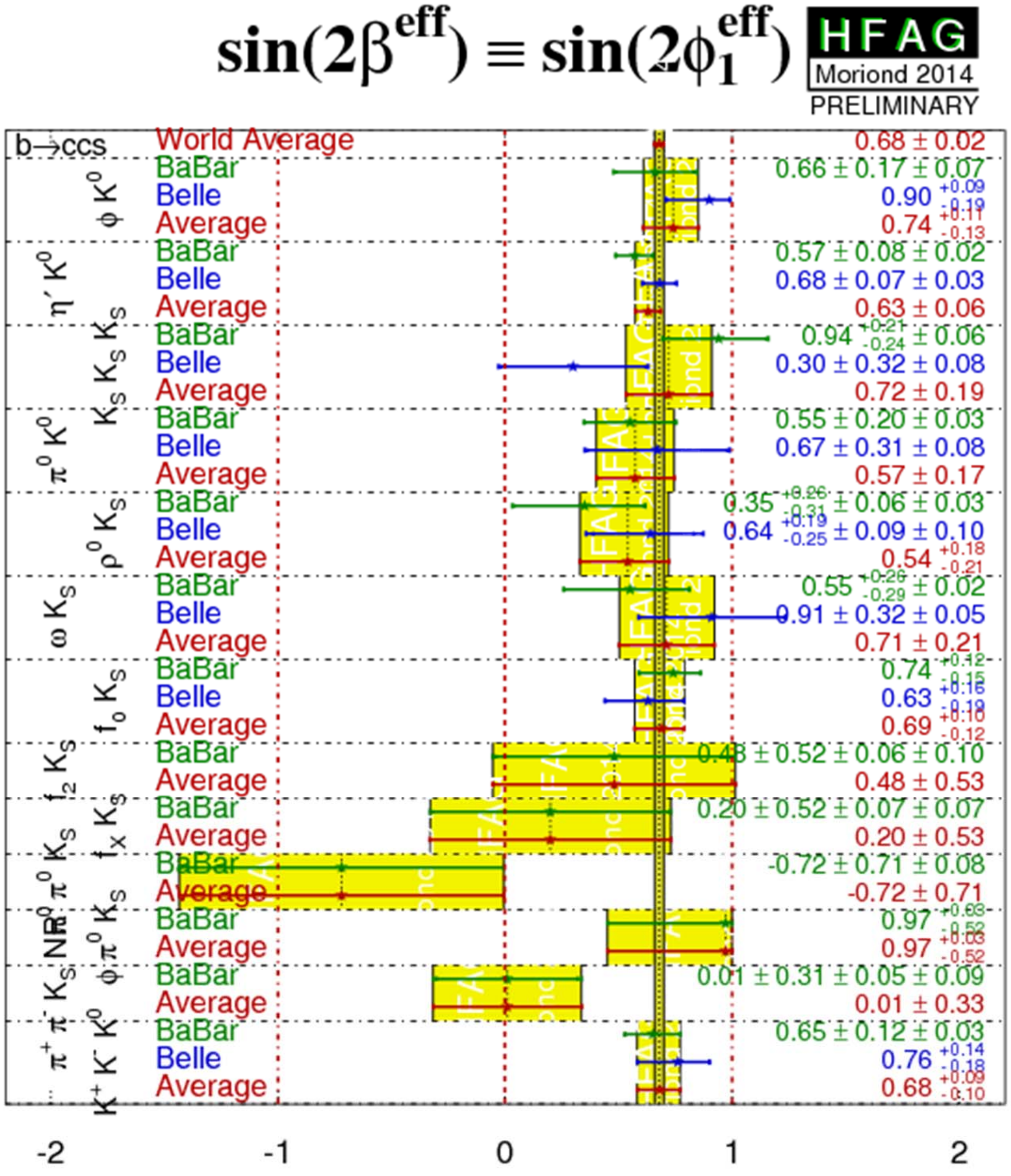
penguins from 2-body decays

penguins from Dalitz plot analysis

ϕ_1 from tree and penguins consistent

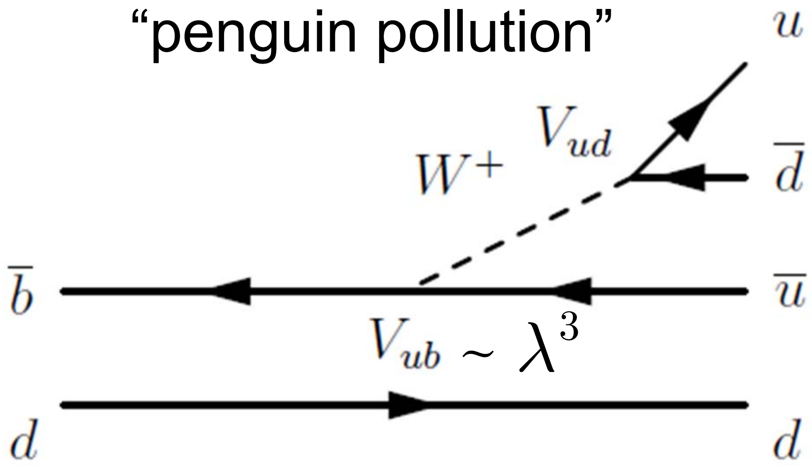
note: Theory would favor

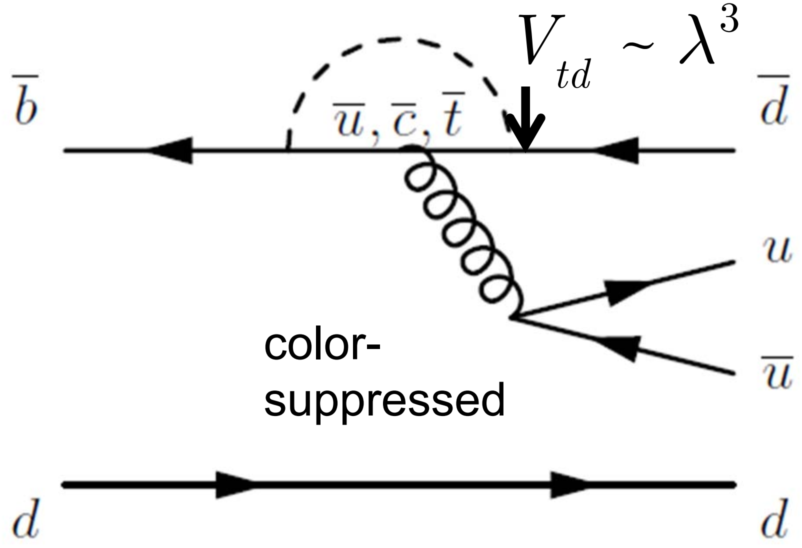
$$\phi_1^{eff} > \phi_1$$



Measuring the Angle Φ_2 (α) $B^0 \rightarrow \pi^+\pi^-$

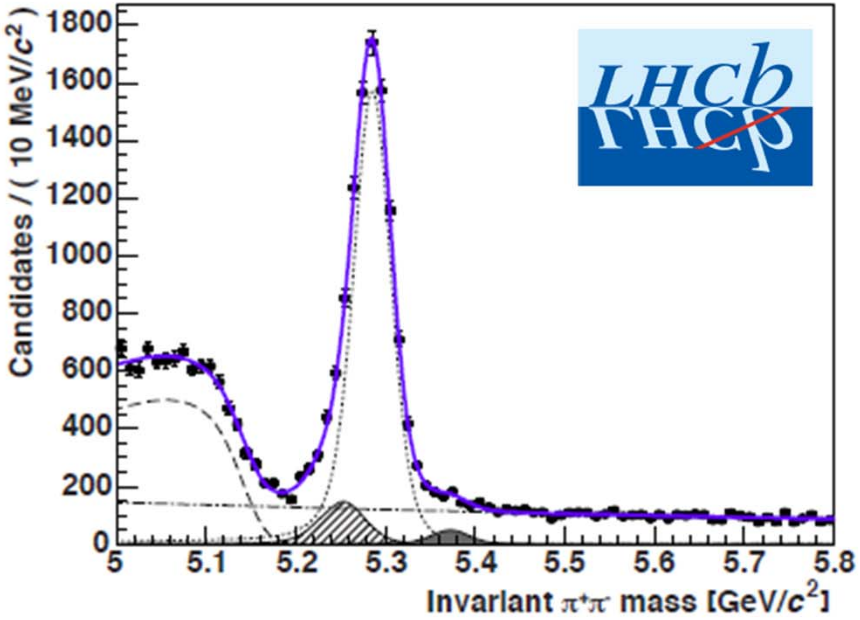
tree-dominated with
“penguin pollution”





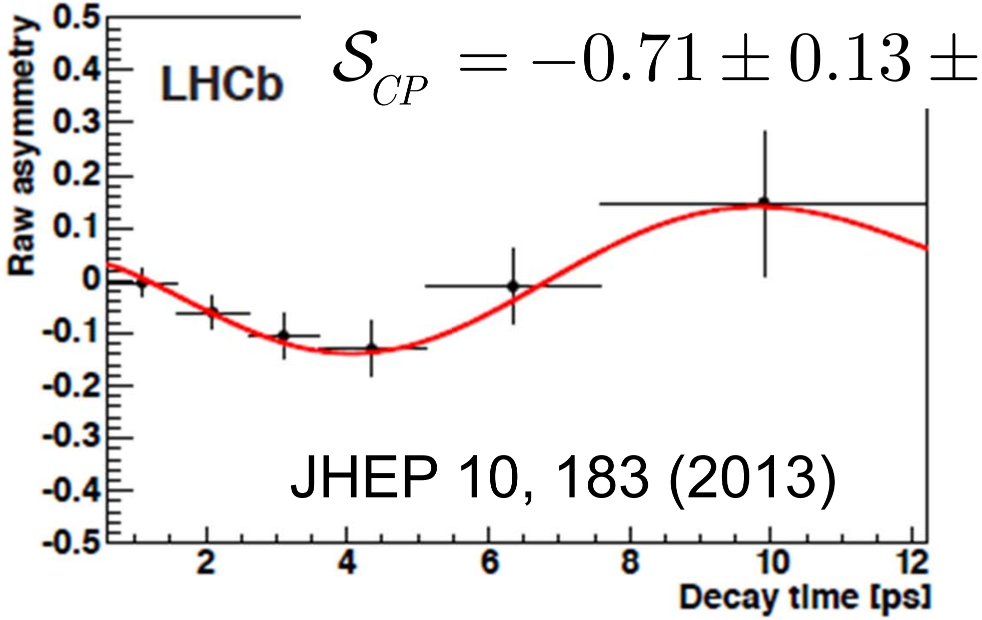
color-suppressed

flavor-tagging used



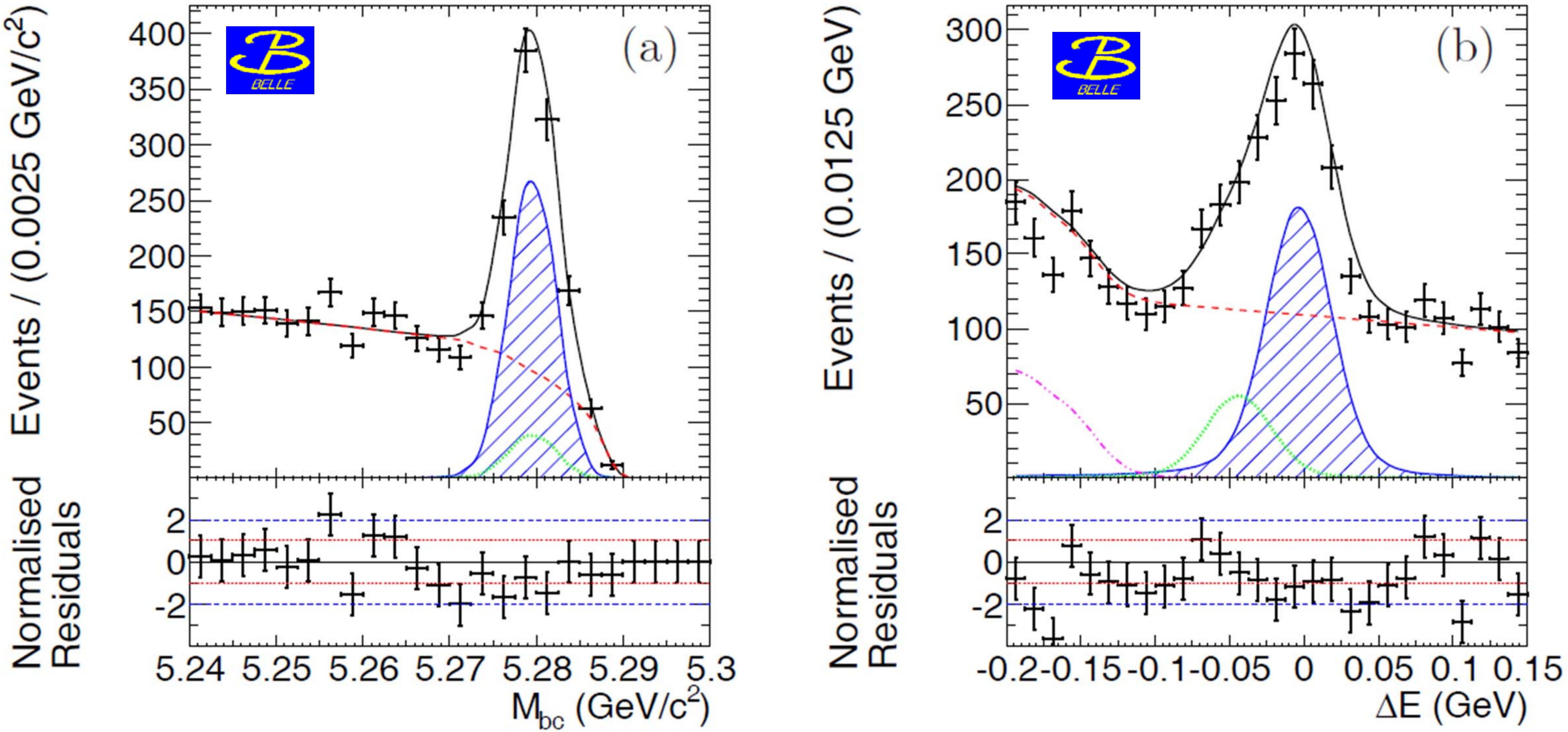
$$\mathcal{A}_{CP} = +0.38 \pm 0.15 \pm 0.02$$

$$\mathcal{S}_{CP} = -0.71 \pm 0.13 \pm 0.02$$



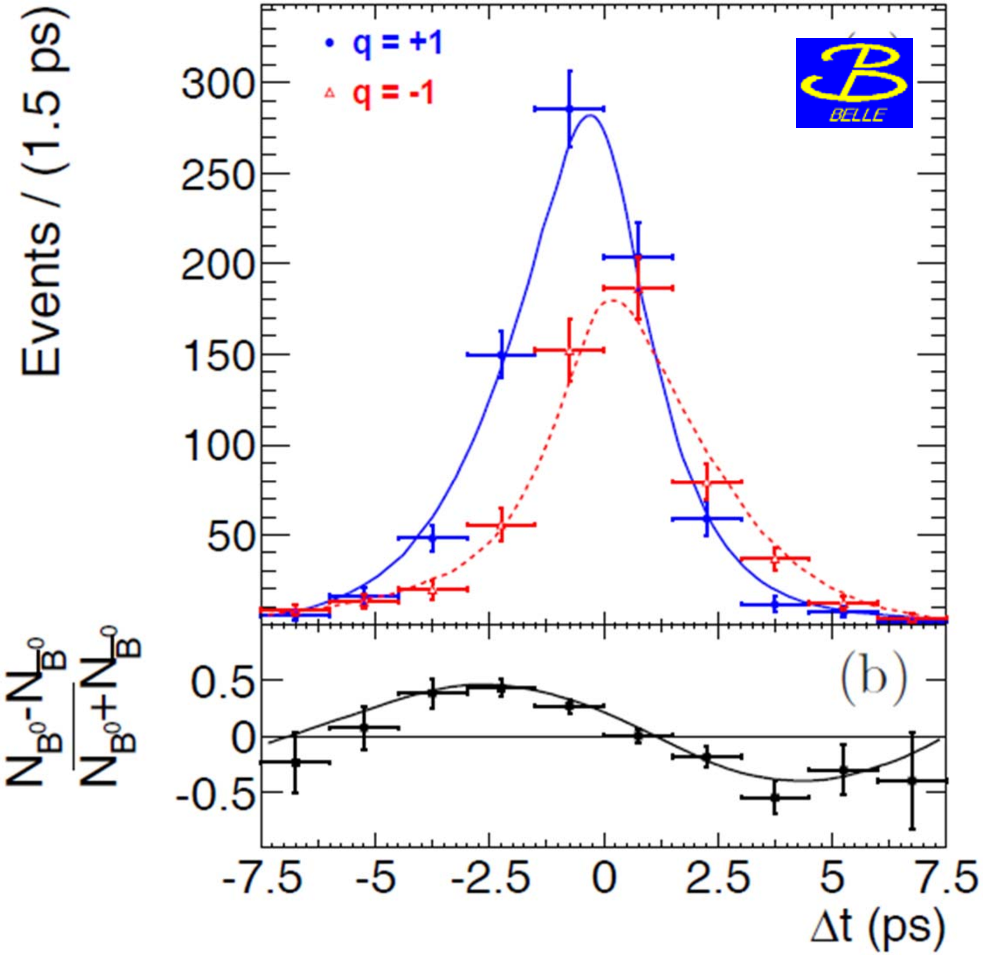
JHEP 10, 183 (2013)

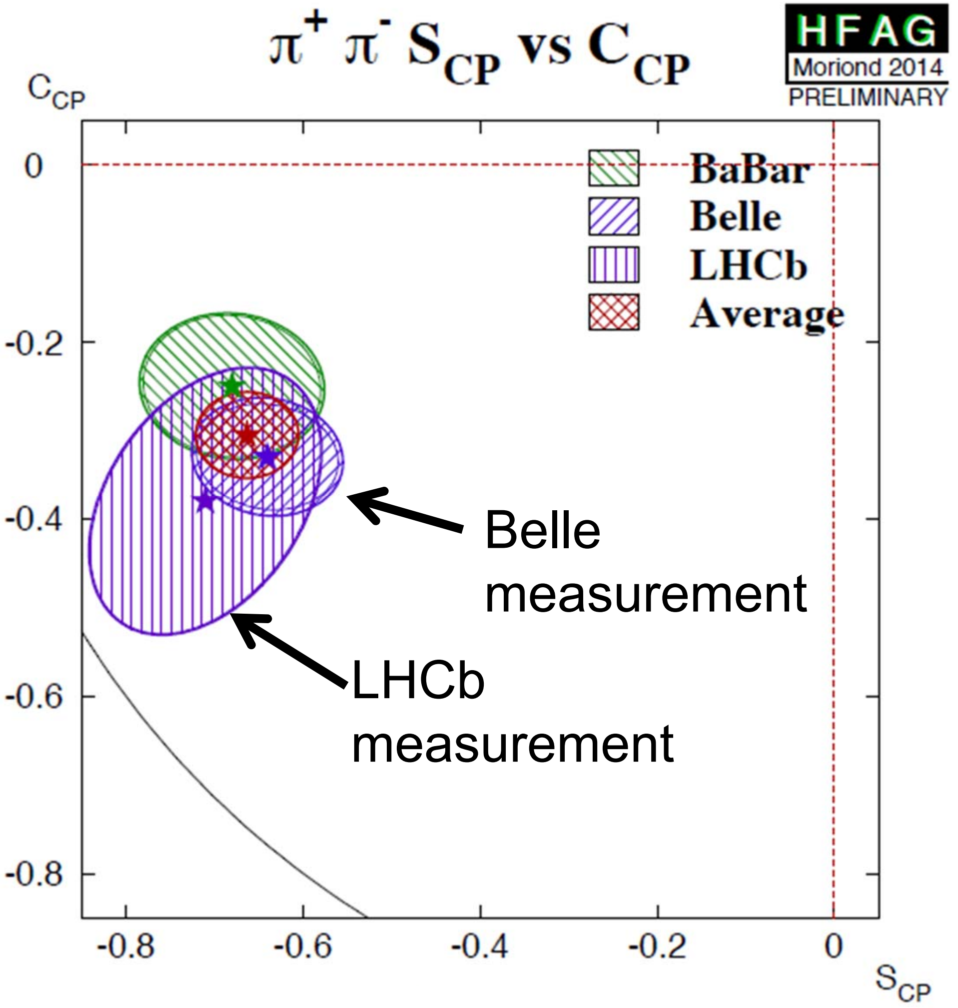
Measuring the Angle Φ_2 (α) $B^0 \to \pi^+\pi^-$



7-dim unbinned extended maximum likelihood fit:
+ part. ID ±, Fischer, Δt, flavor (including correlations)
to extract signal from huge BG (S=2.500, Cont=540.000)

Measuring the Angle Φ_2 (α) $B^0 \rightarrow \pi^+\pi^-$





Belle measurement

LHCb measurement

PRD 88, 092003 (2013)

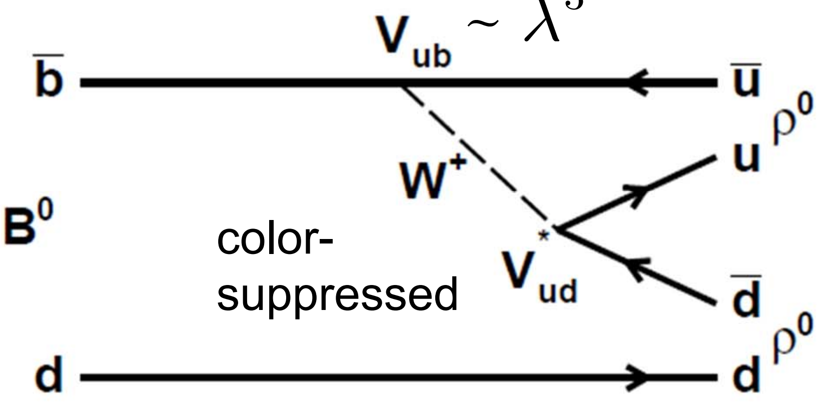
(most precise measurement so far)

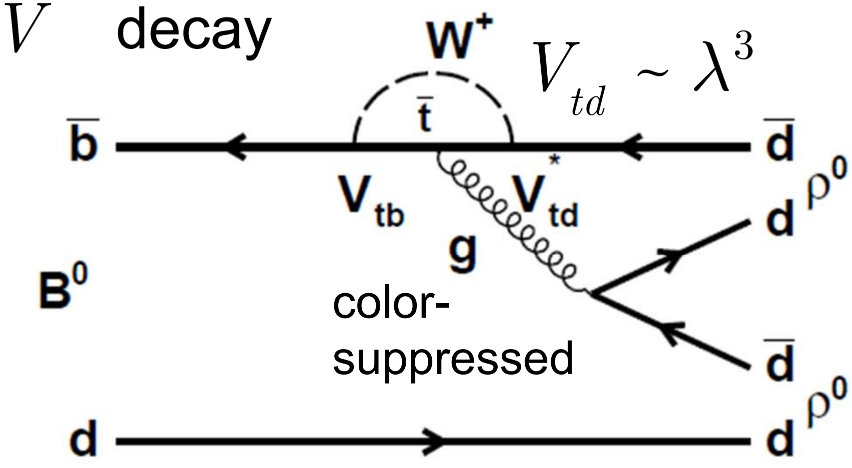
$$\mathcal{A}_{CP} = +0.33 \pm 0.08 \pm 0.03$$

$$\mathcal{S}_{CP} = -0.64 \pm 0.06 \pm 0.03$$

Measuring the Angle Φ_2 (α) $B^0 \to \rho^0 \rho^0$

$S \to VV$ decay

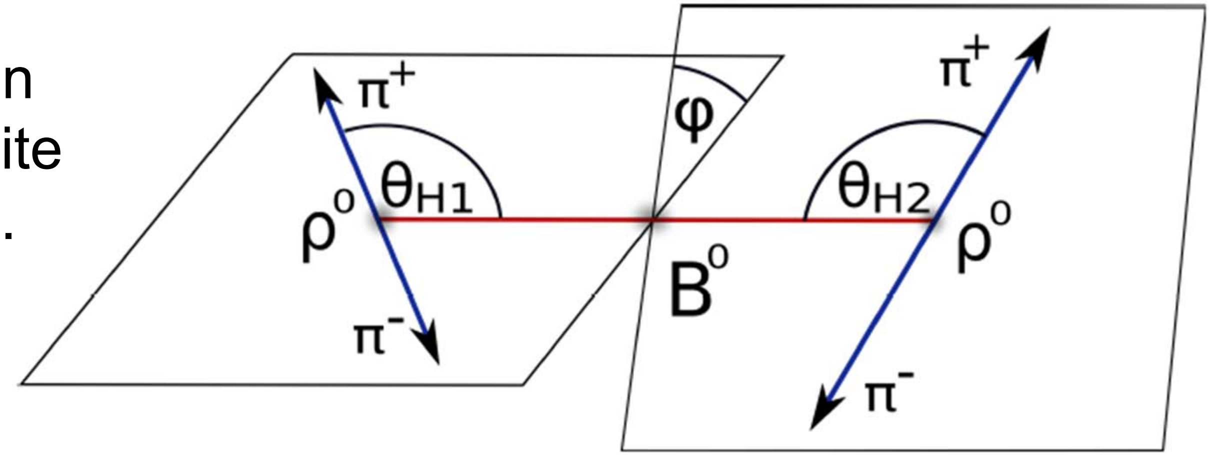




Very small branching ratio, large background from continuum

only longitudinally polarized ρ mesons in final state have definite CP eigenvalue (=+1).

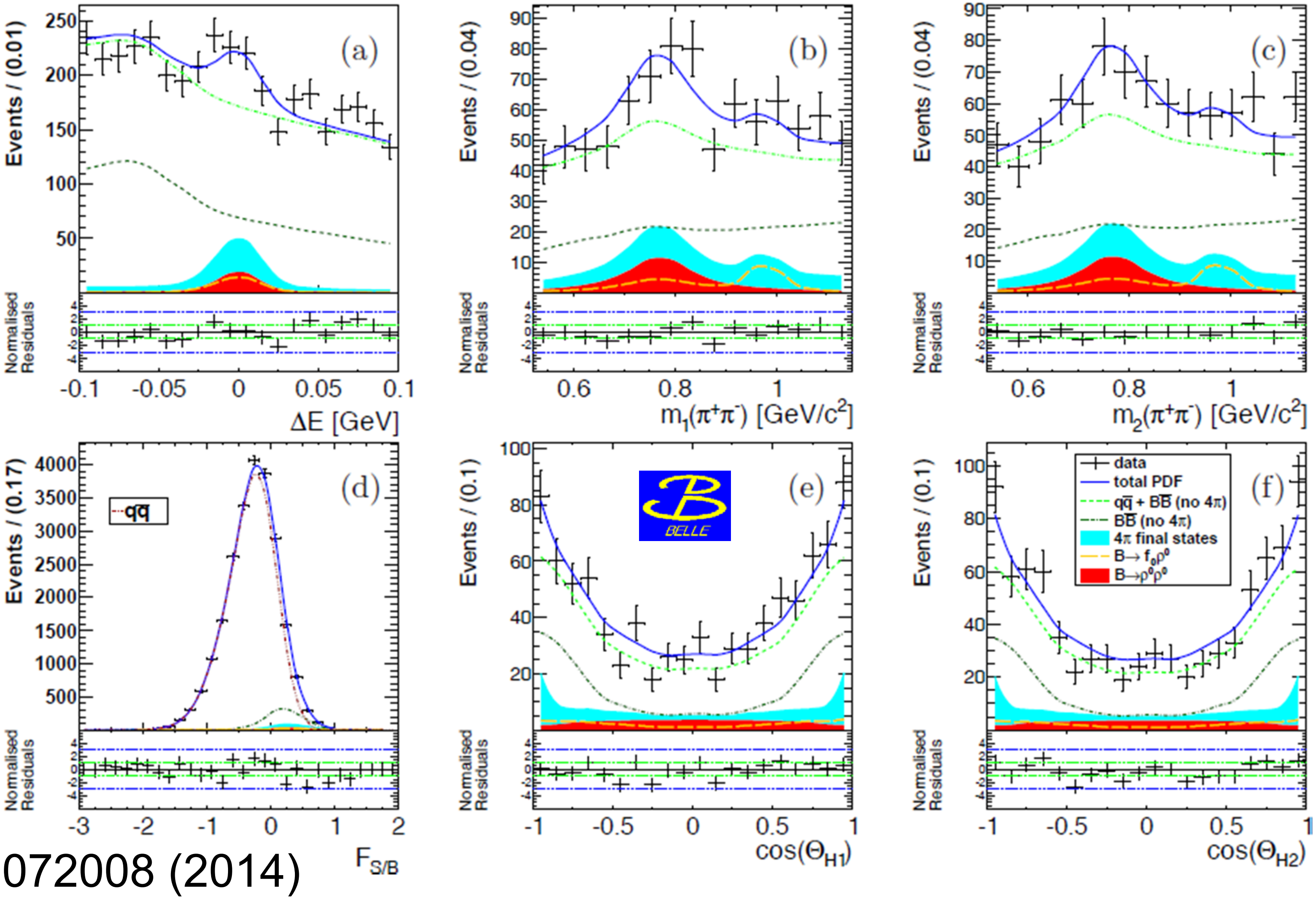
Helicity decay angle analysis required



Long. polarization of ρ^0 found by BaBar ~ 0.75 PRD 78, 071104 (2008)

Measuring the Angle Φ_2 (α) $B^0 \to \rho^0 \rho^0$

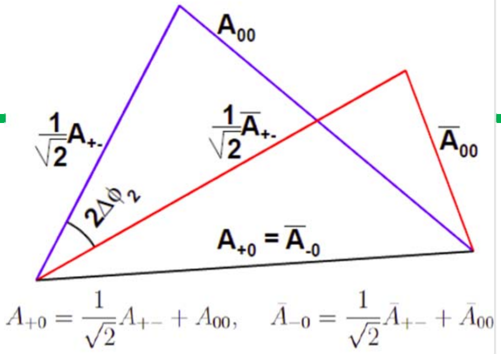
6-dim unbinned extended maximum likelihood fit:



PRD 89 072008 (2014)

First significant observation (3.4 σ) big “surprise” : $f_L = 0.21^{+0.18}_{-0.22} \pm 0.15$

Measuring the Angle Φ_2 (α)



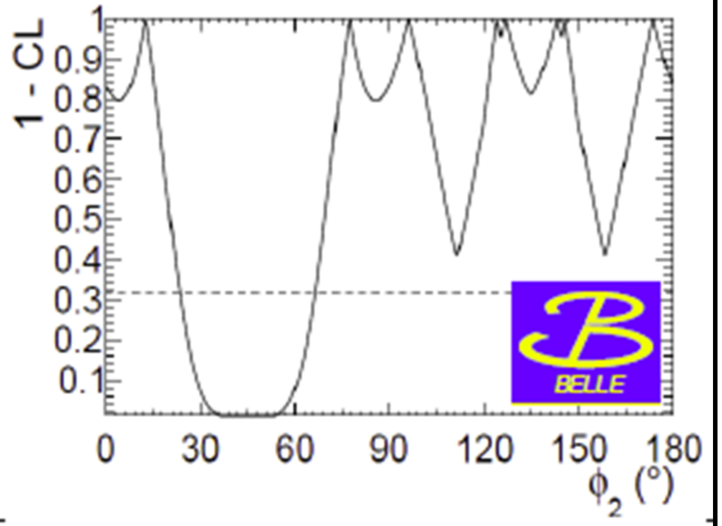
$A_{+0} = \frac{1}{\sqrt{2}}A_{+-} + A_{00}, \quad \bar{A}_{-0} = \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00}$

correct for penguin pollution via decay modes related by isospin (π and ρ)

$B \rightarrow \pi\pi$

$23.8^\circ < \phi_2 < 66.8^\circ$
is excluded @ 1σ C.L.

$B^0 \rightarrow \pi^+\pi^-$ 772M $B\bar{B}$ pairs used
$B^+ \rightarrow \pi^+\pi^0$ 772M $B\bar{B}$
$B^0 \rightarrow \pi^0\pi^0$ 275M $B\bar{B}$



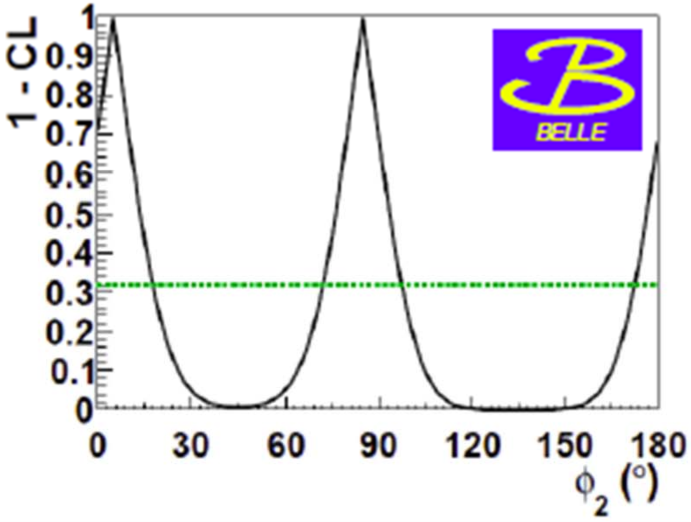
$B \rightarrow \rho\rho$

$\phi_2 = (84.9 \pm 12.9)^\circ \quad \Delta\phi_2 = (0.0 \pm 9.6)^\circ$

because Br($B \rightarrow \rho^0 \rho^0$) is so small:

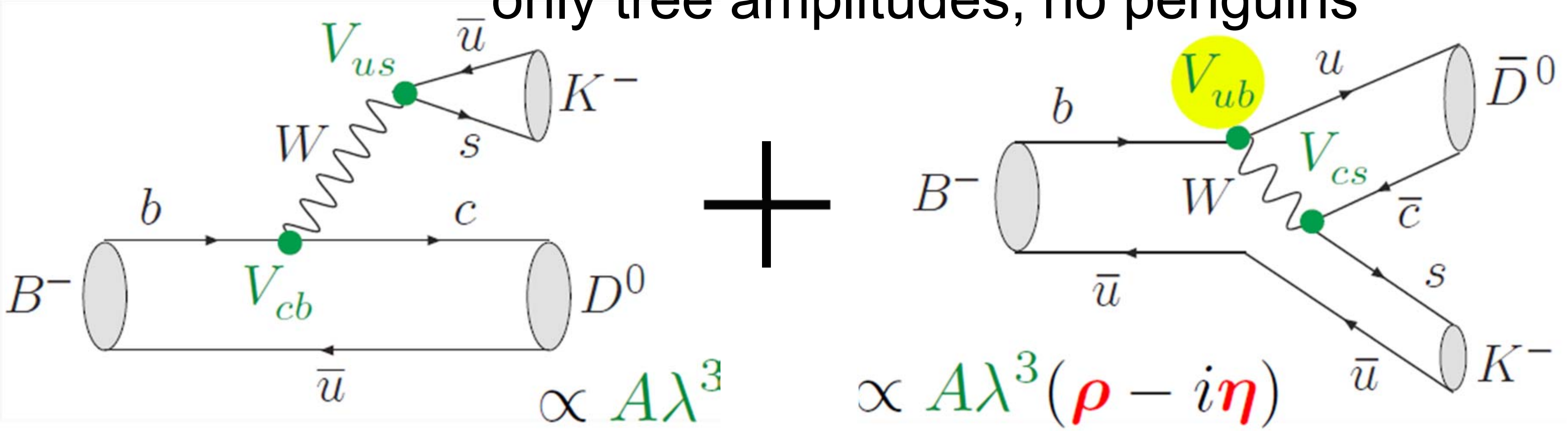
$$Br(B^0 \rightarrow \rho^0\rho^0) = (1.02 \pm 0.30 \pm 0.15) \times 10^{-6}$$

$B^0 \rightarrow \rho^0\rho^0$ 772M $B\bar{B}$ pairs used
$B^\pm \rightarrow \rho^\pm\rho^0$ 85M $B\bar{B}$
$B^0 \rightarrow \rho^+\rho^-$ 535M $B\bar{B}$



Measuring the Angle Φ_3 (γ) $B^- \to D^0 K^-$

only tree amplitudes, no penguins

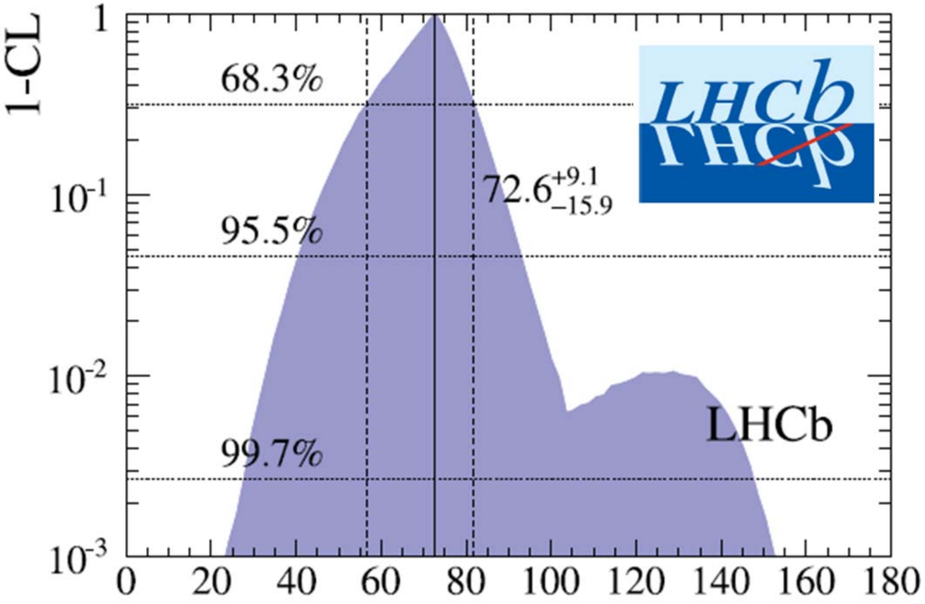


Uncertainty in Φ_3 depends on $r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| \approx 0.1$

LHCb: $\phi_3 = \left(72.6 \begin{matrix} +9.1 \\ -15.9 \end{matrix}\right)^\circ$

Belle: $\phi_3 = \left(68 \begin{matrix} +15 \\ -14 \end{matrix}\right)^\circ$
(arXiv 1301.2033)

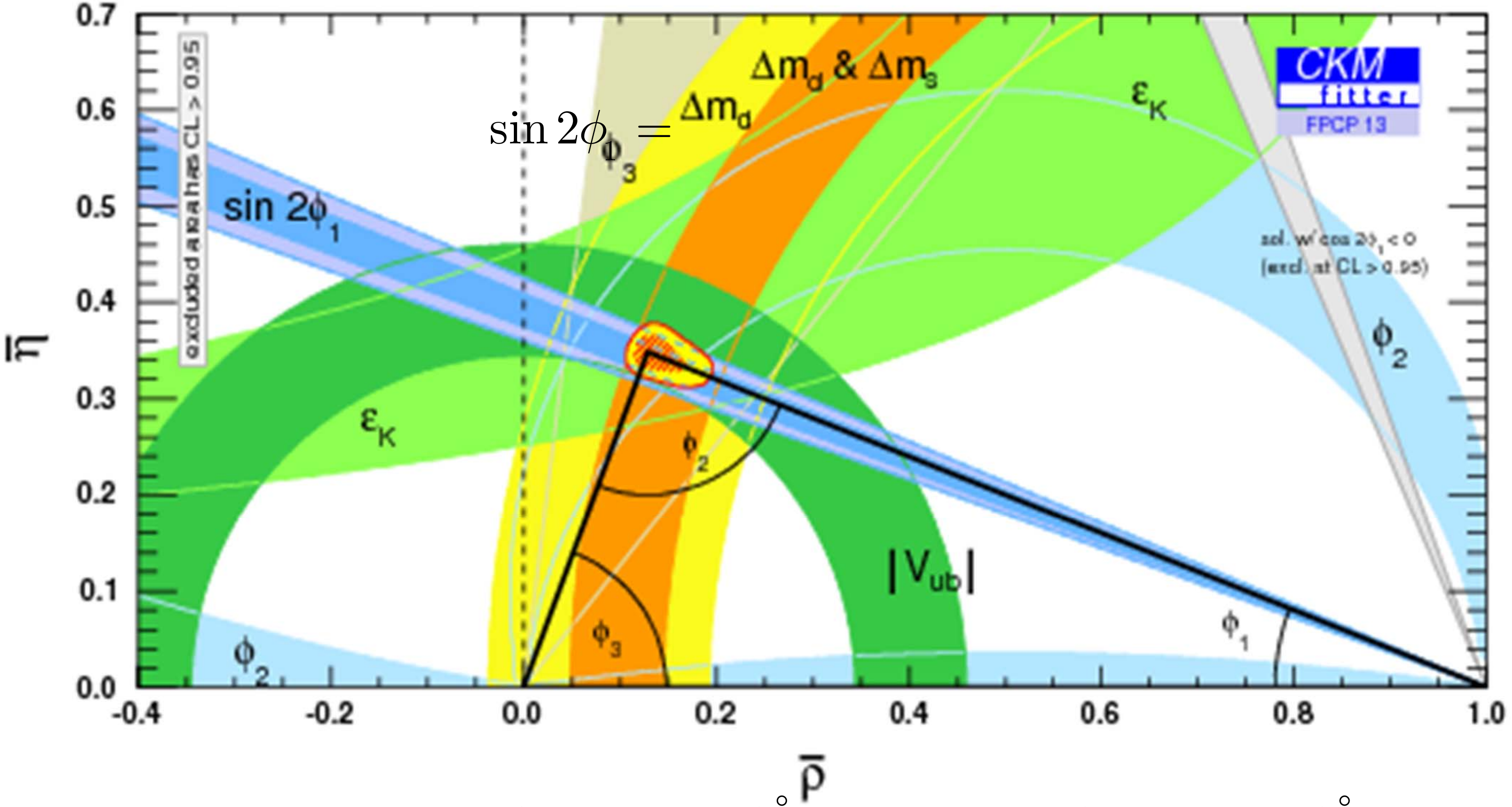
BaBar: $\phi_3 = \left(69 \begin{matrix} +17 \\ -16 \end{matrix}\right)^\circ$
(PRD 052015 (2013))



PLB 726, 151 (2013)

The Unitarity Triangle

SM nicely describes the CPV data



Global fit:

$$\phi_2(\alpha) = \left(85.4\,{}^{+4.0}_{-3.8}\right)^\circ \qquad \phi_3(\gamma) = \left(68.0\,{}^{+8.0}_{-8.5}\right)^\circ$$

Summary & Conclusions

- Data on CP violation in the B meson system (also D and K) are well described by the Standard Model via the CKM mechanism

- Some “tensions” exist, such as measurements of the sides of the B unitarity triangle, comparing V_{ub} (V_{cb}) from semileptonic exclusive and inclusive branching ratio measurements (not shown today)

- But: no single significant deviation (> 3 σ) seen,
  no sign of New Physics

- Analyses mostly still statistics limited (B factories),
  but also LHCb: 3 fb^{-1} on tape, not all analyzed yet, more data from 2016 onwards (14 TeV cms energy)

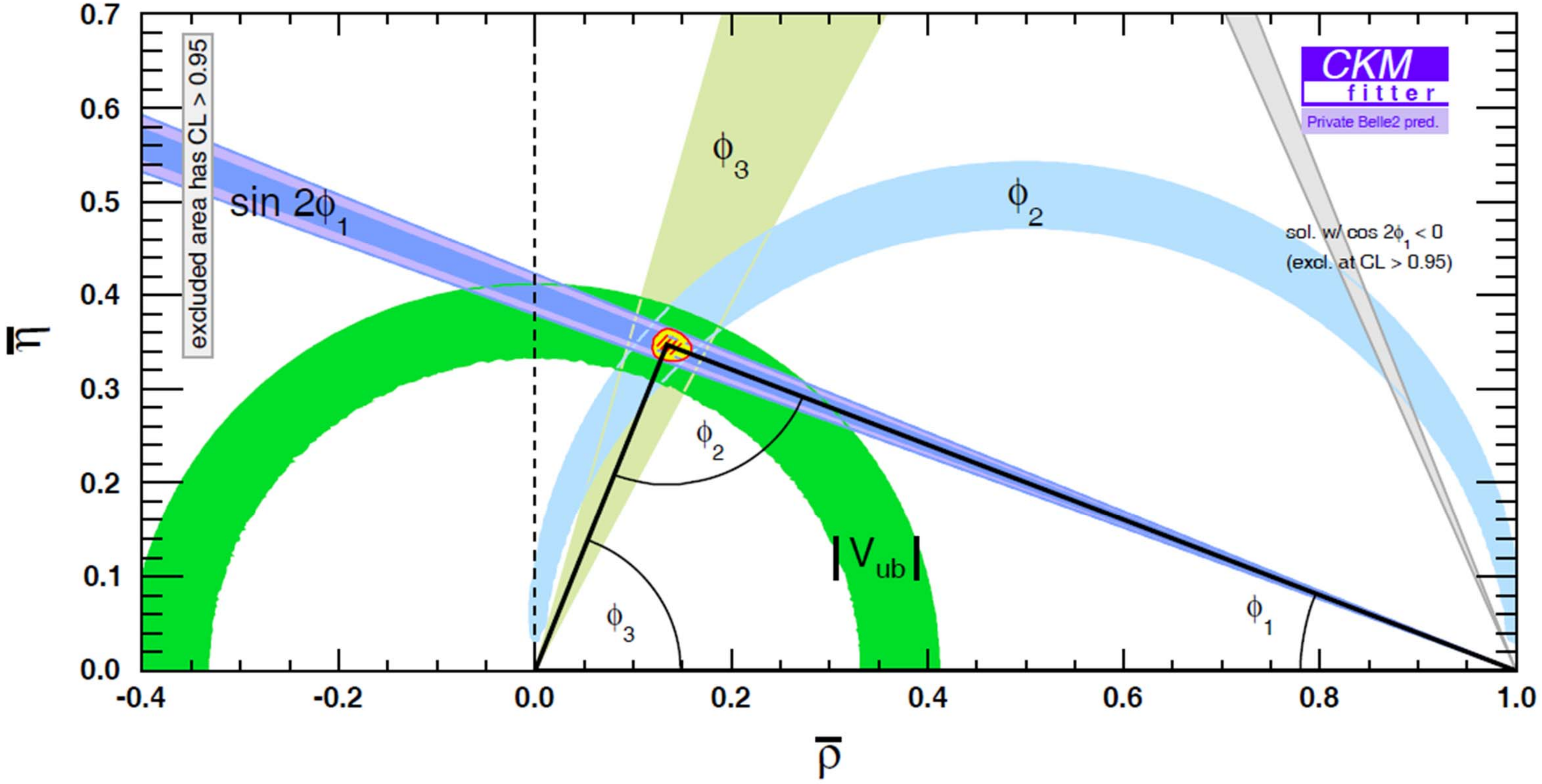
- Another big step yet to come: SuperKEKB and Belle II (2016)

- Exciting times ahead of us …

Backup

The Unitarity Triangle in the year 2023

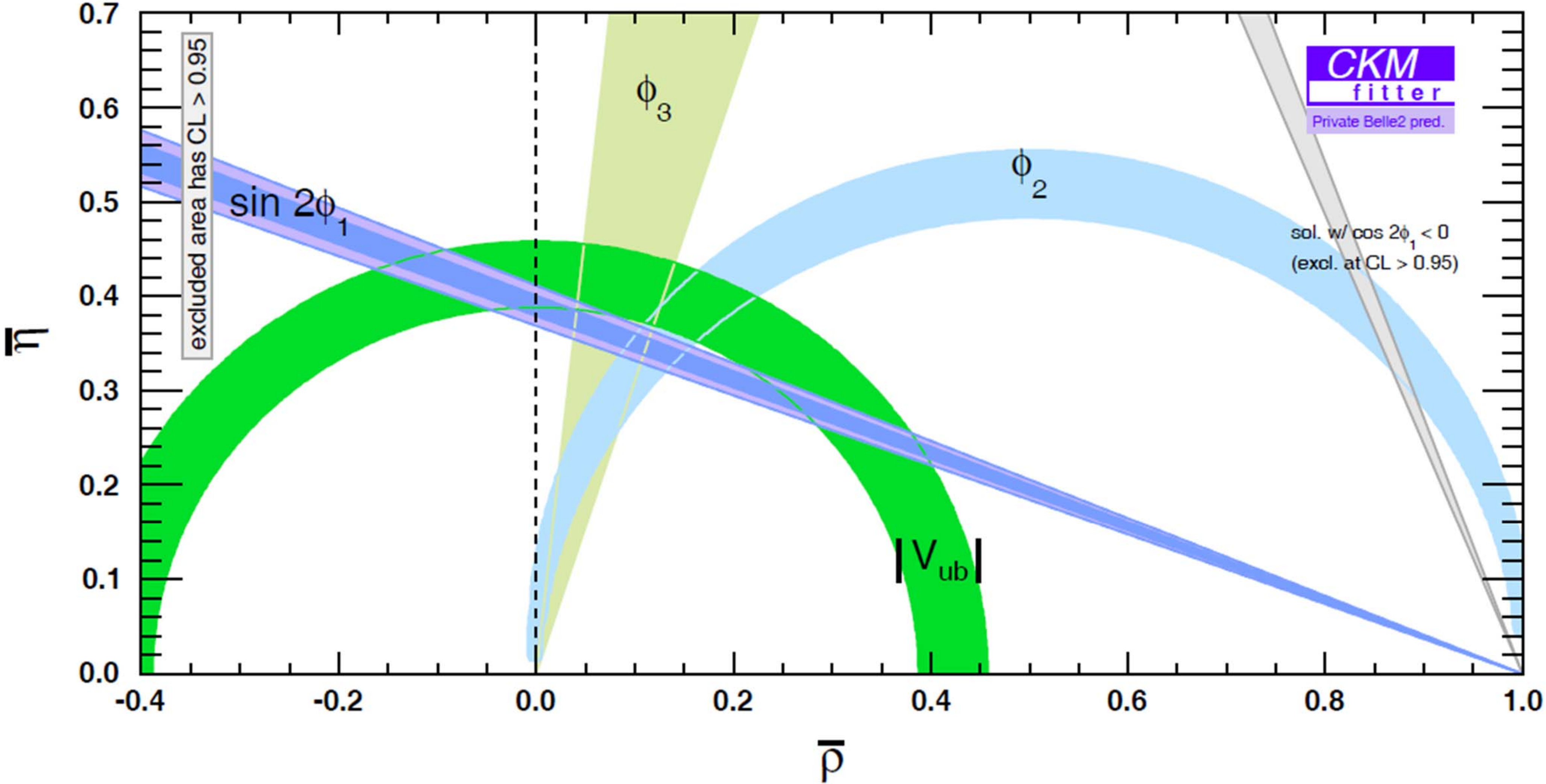
$$\int \mathcal{L} dt = 50 \text{ ab}^{-1}$$



SM correct   a nightmare …

The Unitarity Triangle in the year 2023

$$\int \mathcal{L}dt = 50\ \mathrm{ab}^{-1}$$



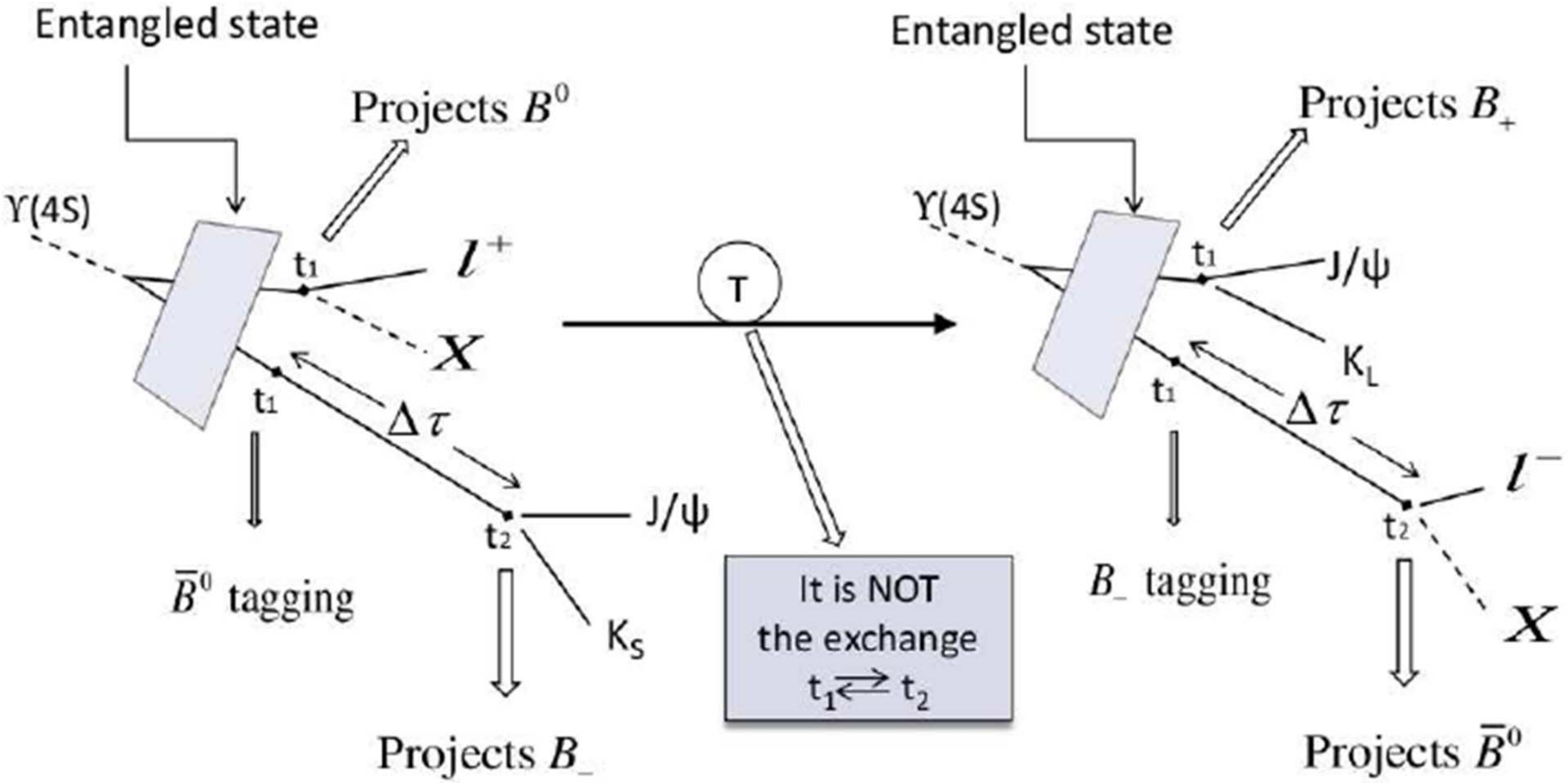
present tensions stay … … the dream !

New Measurement of TRV

$$\frac{1}{\sqrt{2}}\left(\left|\bar{B}^0\right\rangle\left|B^0\right\rangle-\left|B^0\right\rangle\left|\bar{B}^0\right\rangle\right) \qquad \frac{1}{\sqrt{2}}\left(\left|B_-\right\rangle\left|B_+\right\rangle-\left|B_+\right\rangle\left|B_-\right\rangle\right)$$

Flavor base

CP base: $\left|B_-\right\rangle=\left|J/\psi\, K_S\right\rangle;\left|B_+\right\rangle=\left|J/\psi\, K_L\right\rangle$

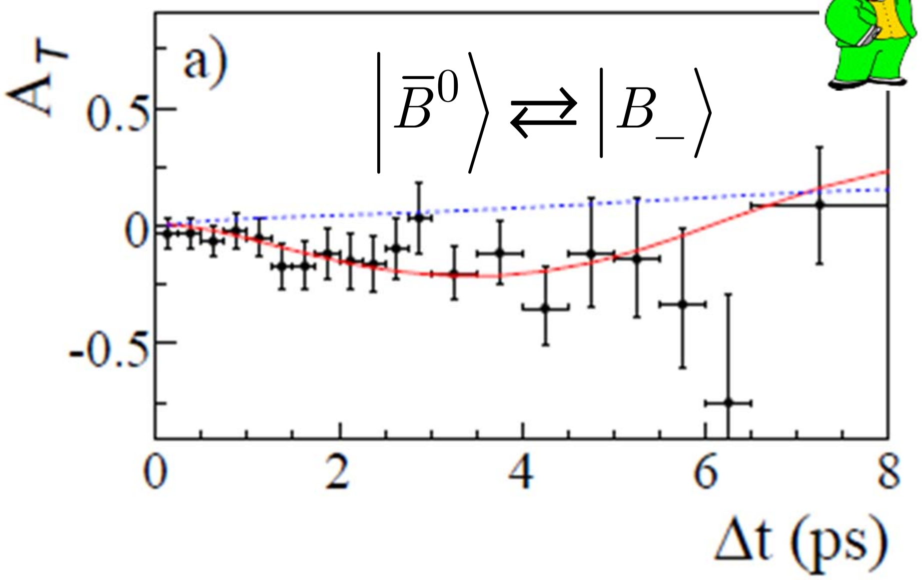


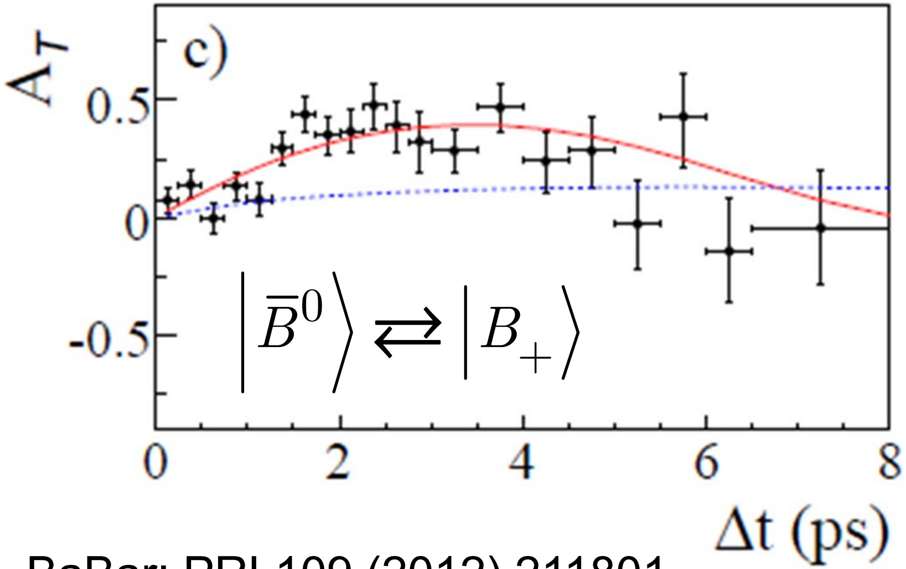
$$\boxed{\bar{B}^0 \xrightarrow{\Delta\tau} B_-}$$

J. Bernabeu et al.
JHEP08 (2012) 064

$$\boxed{B_- \xrightarrow{\Delta\tau} \bar{B}^0}$$

New Measurement of TRV (cont.)





BaBar: PRL109 (2012) 211801

$$\mathcal{A}_T(\Delta t) = \frac{N(K_L, l^-; \Delta t) - N(l^+, K_S; t')}{N(K_L, l^-; \Delta t) + N(l^+, K_S; t')}$$

$$\approx \frac{\Delta S}{2} \sin(\Delta m \Delta t)$$

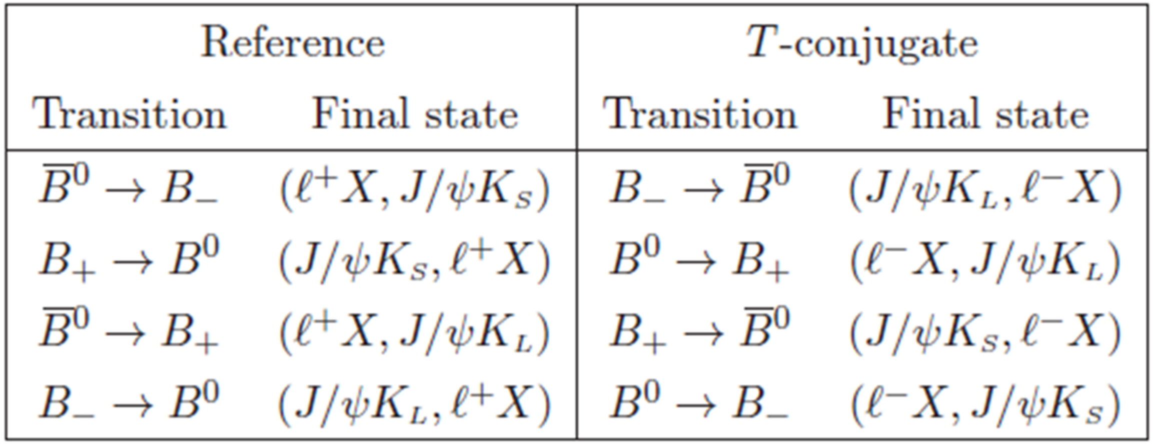
$$\Delta S_T^- = -1.17 \pm 0.18 \pm 0.11$$

$$\Delta S_T^+ = -1.37 \pm 0.14 \pm 0.06$$

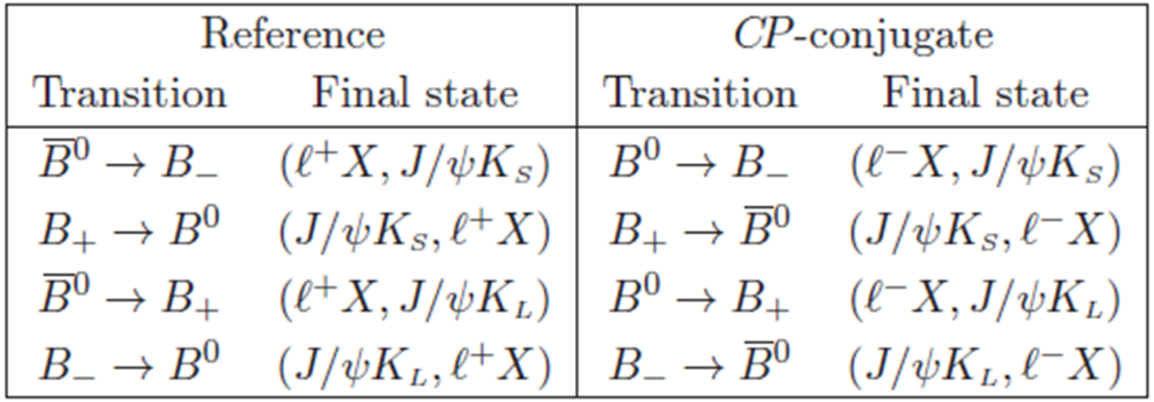
Standard Model:

$$\frac{\left|\Delta S\right|}{2} = \sin 2\beta$$

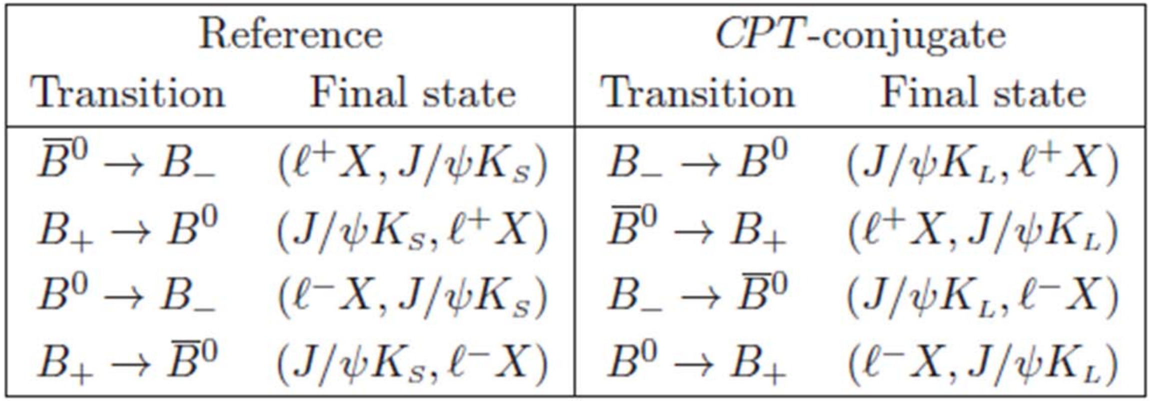
Tests of CP, T and CPT



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



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



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

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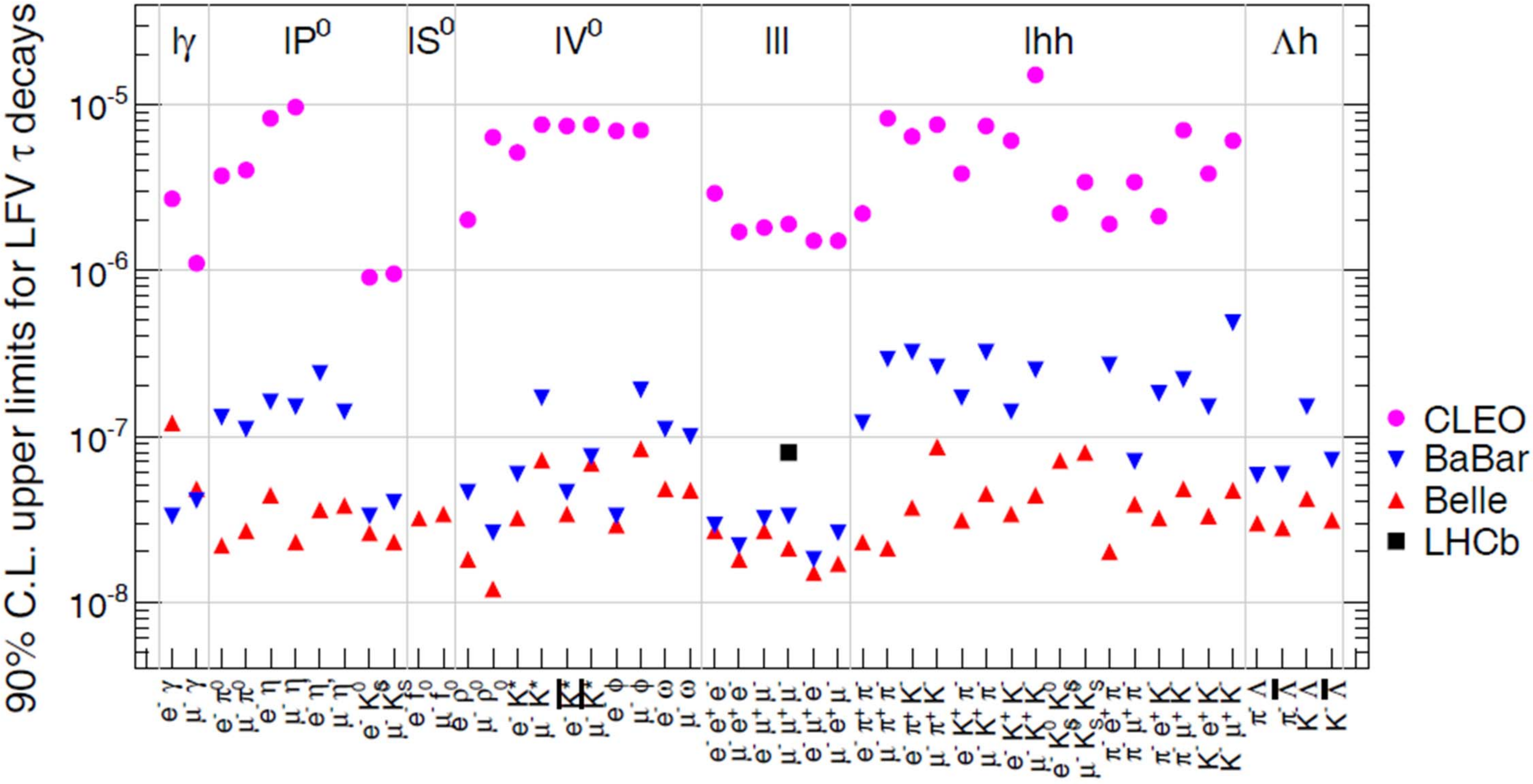
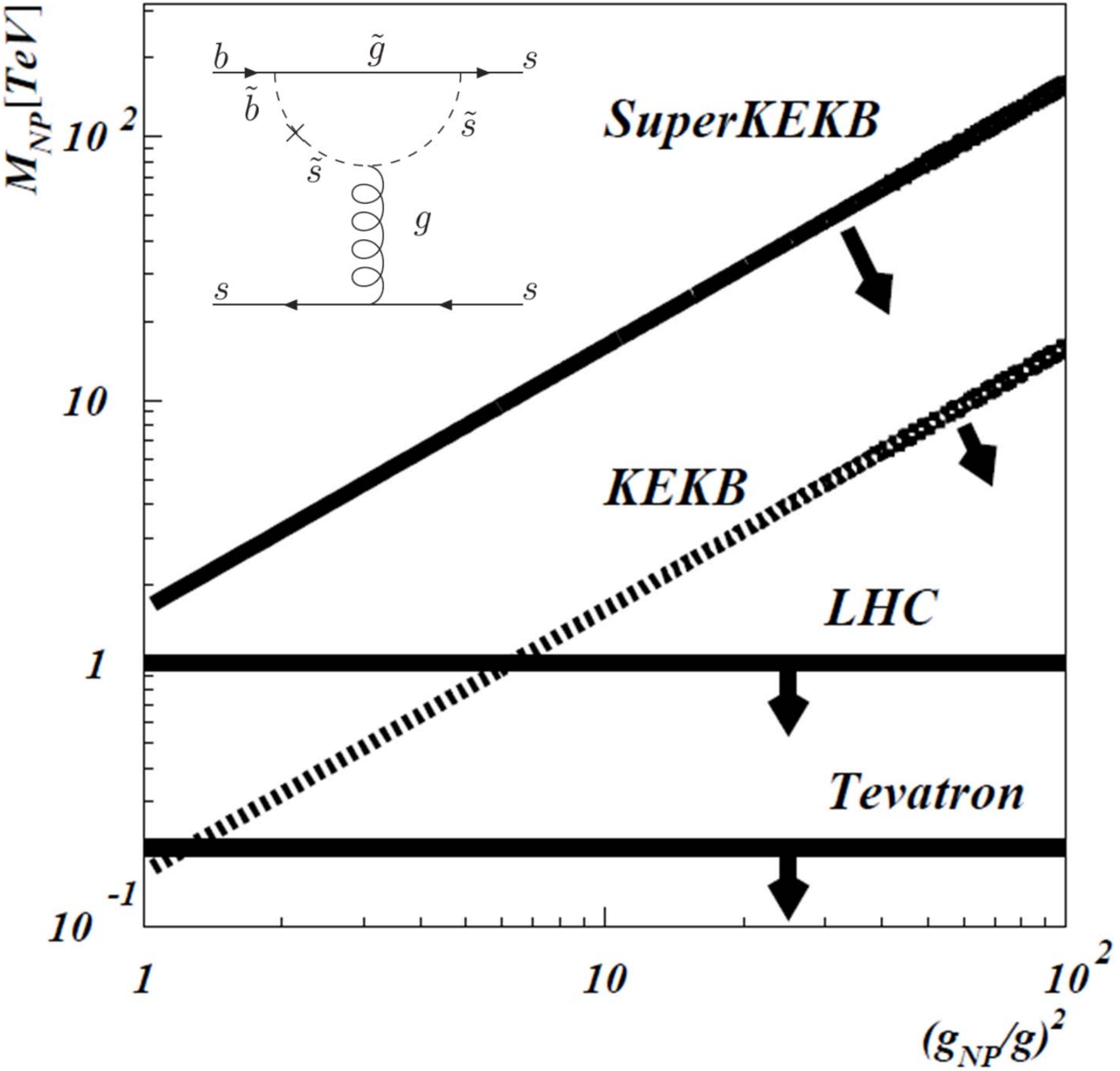
JHEP08 (2012) 064

Search for Lepton Flavor Violation

48 different LFV modes were studied at B-factories



Sensitivity to New Physics



Super Flavor Factories:

Indirect discovery of New Physics In quantum loops via high precision measurements, searching for deviations from the SM

complementary to the LHC