CPV and Angles of UT

K.Trabelsi
karim.trabelsi@kek.jp

Symmetries

Nature and its Law: ~ Symmetry = Beauty

P, C, T : most Fundamental Symmetry

P : Parity = Space inversion

C : Charge conjugate (Particle $\leftrightarrow$ Anti-particle; Quantum #)

[Lagrangian $\rightarrow$ Hermitian conjugate]

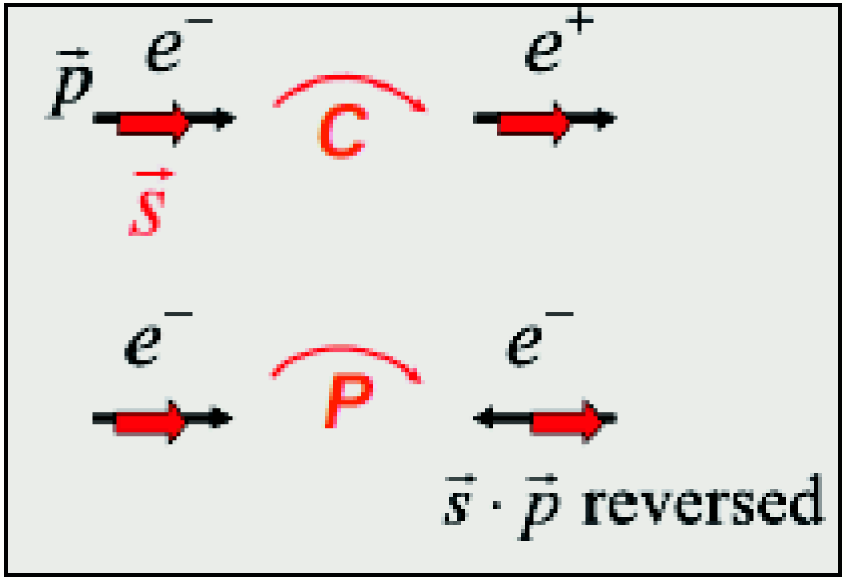
T : Time reversal [c-number $\rightarrow$ complex conjugate]

CPT Theorem

Lorentz invariant local quantum field theory $\rightarrow$ CPT symmetry

⇒ Particle $\leftrightarrow$ Anti-particle: Mass and Lifetime are identical

Charge conjugation, Parity, CP



- **CP = P** and **C** applied consecutively
- Charge conjugation (C)

  Change of all the charge quantum numbers into their opposite

  transforms a particle into its anti-particle

- Parity (P)

  Inversion of the spatial coordinates.

  $x \rightarrow -\vec{x}$ "Image in a mirror"

CP Violation ⇔ physics is not symmetric under CP transformation
⇔ **Experimental results in CP conjugate systems are not the same**

In the **Standard Model** of Particle Physics (SM):

- **C** and **P** are symmetries of strong and electromagnetic interactions.
- **C** and **P** symmetries are violated by weak interaction
- CP symmetry is **slightly violated by weak interaction**

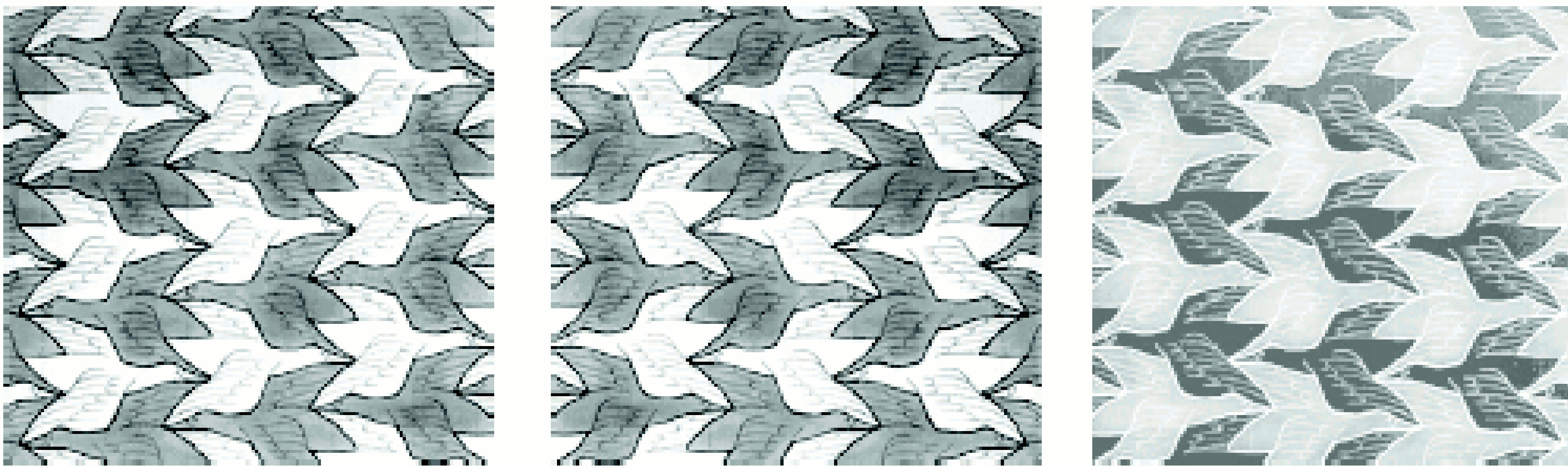
from E.Ben Haim

CP Violation with Escher's images

CP (anti-matter in a mirror)

P (mirror) C (anti-matter)

White geese fly right | White geese fly left | White geese fly right



Slight breaking of CP (look at the tails...)

Analogy to weak interaction in the Standard Model.

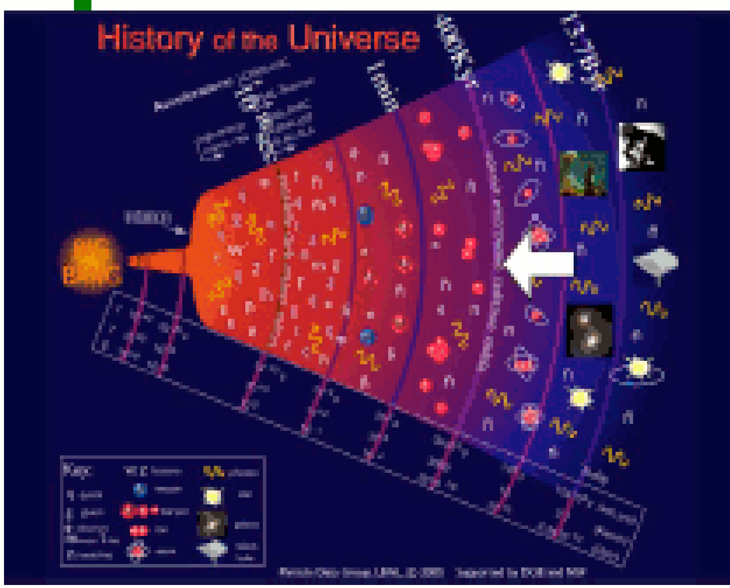
Why CPV is important ?

Difference between particle & anti-particle

(matter & anti-matter)

Universe: almost "matter" only (no anti-matter)

Big-Bang → N(particles) = N(anti-particles)



Sakhalov's 3 conditions (1967):

1. baryon number violation
2. **CP violation**
3. existence of non-equiblium

CPV is a key for Existence of Universe & us !

Andrei Sakharov (1921-1989)

But the CKM source of CPV orders of magnitude too small to explain the observed state of the universe!

discovery of CP violation

With simple quantum mechanics, one can show that in absence of CP violation:

$$
\begin{aligned}
CP|K_1\rangle &= \frac{1}{\sqrt{2}}(CP|K^0\rangle + CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) = +|K_1\rangle \\
CP|K_2\rangle &= \frac{1}{\sqrt{2}}(CP|K^0\rangle - CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle - |K^0\rangle) = -|K_2\rangle
\end{aligned}
$$

Final states CP eigenvalues are $+1$ $(\pi^+\pi^-)$ and -1 $(\pi^+\pi^-\pi^0)$. If CP is a conserved quantity, one then should have:

$$
\begin{aligned}
K_1 &\longrightarrow \pi\pi \\
K_2 &\longrightarrow \pi\pi\pi.
\end{aligned}
$$

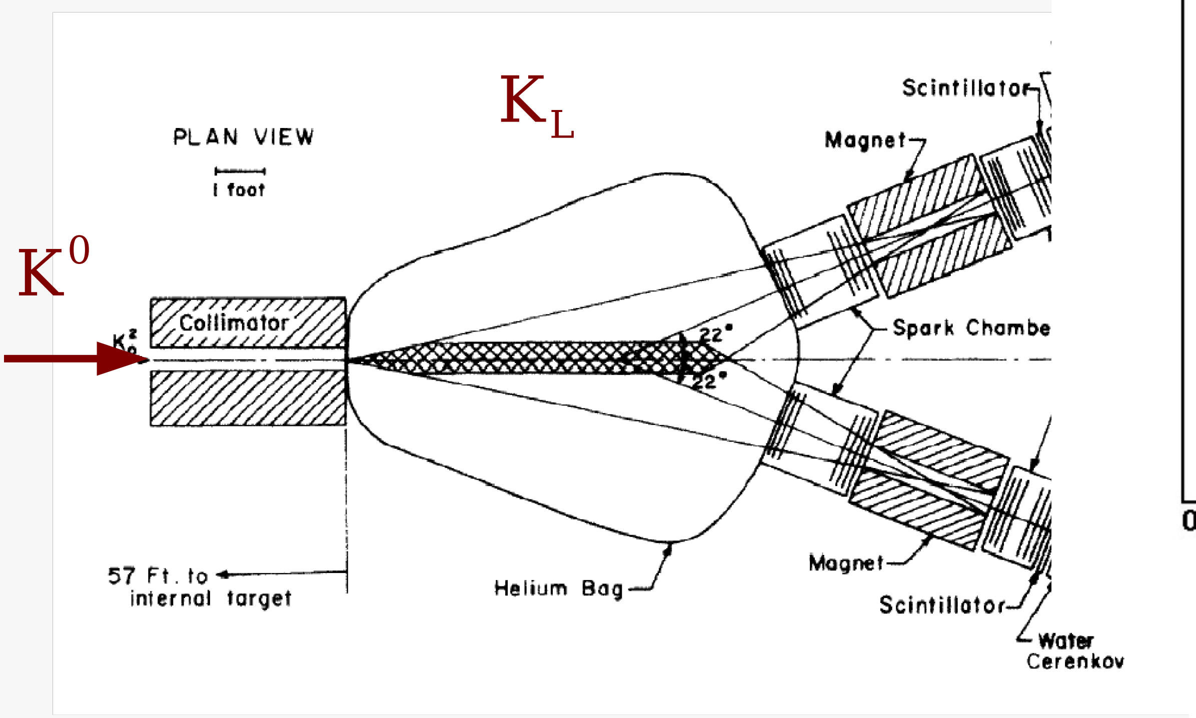
which well identify as K^0_S and K^0_L respectively.

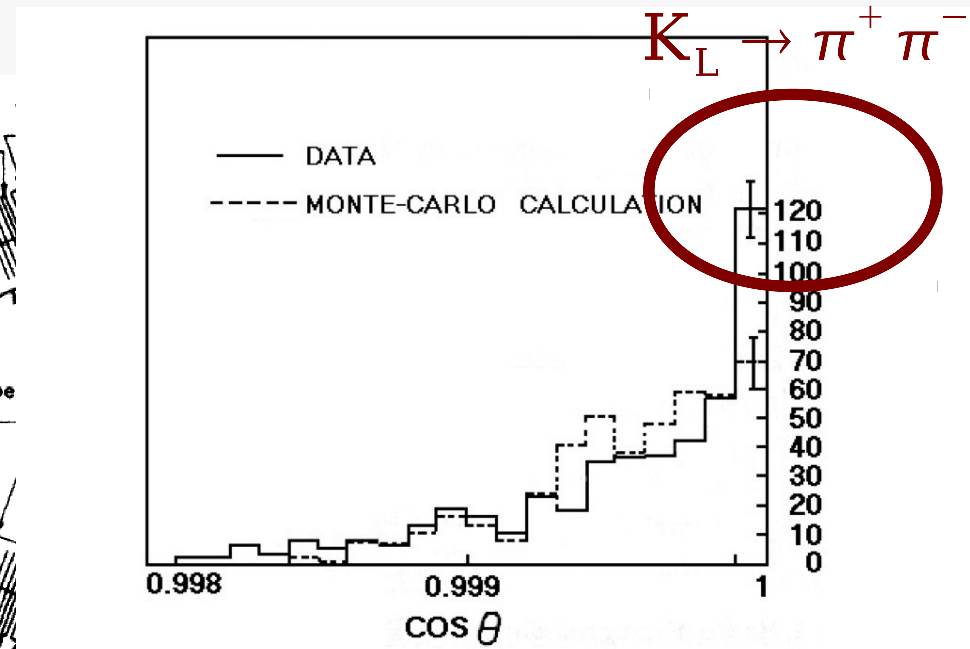
measuring K^0_L decays into two pions ?
$\Rightarrow$ proof that CP asymmetry is violated in weak interaction

discovery of CP violation

The CP violation in kaon system:
Christenson, Cronin, Fitch, Turlay, Phys. Rev. Lett. 13 (1964) 138.

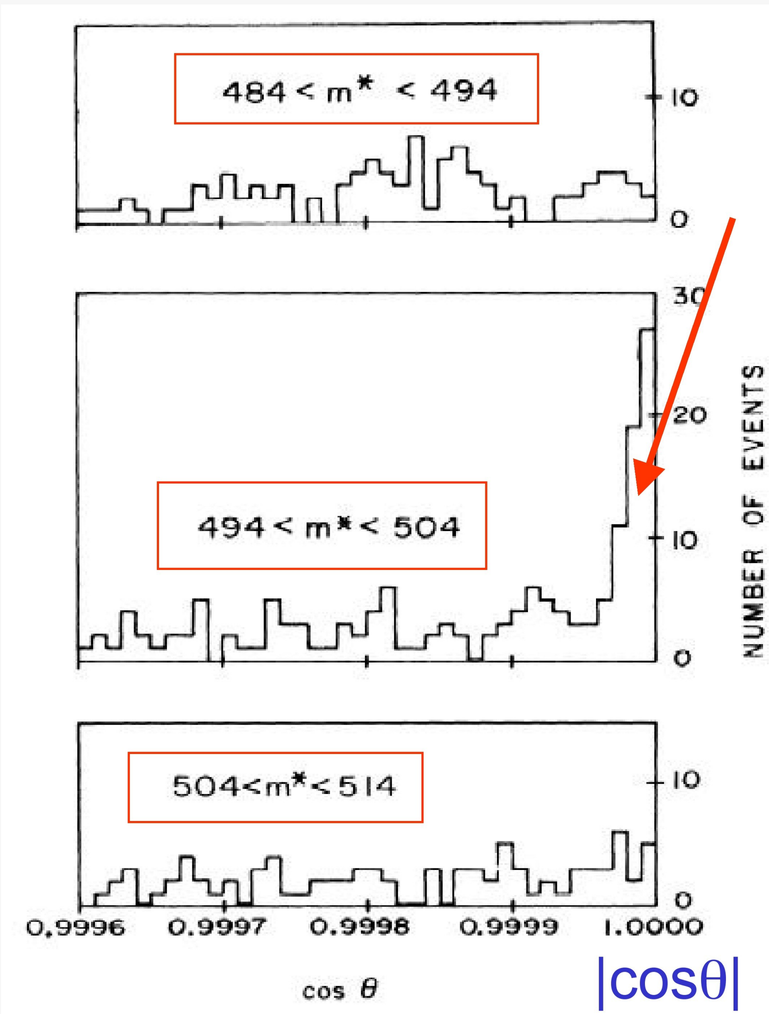
Far after the target, only K_L survives. They measured:





$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)}$$

discovery of CP violation



- Two body decay: in the K^0 center of mass system the two π are back to back: $|\cos\theta|=1$
- Today's more precise measurement for the ratio of amplitudes:

$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)} = (2.271 \pm 0.017)10^{-3}.$$

The unitarity triangle: introduction

The Higgs boson gives mass to bosons and fermions (quarks and leptons) through the Yukawa couplings but this is not the end of the story:

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger [\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5)V_{ij}d_j] + \text{h.c}$$

Once the mass matrix is diagonalized, it determines also how the mass and weak eigenstates are related. This is the CKM matrix. As for the masses, nothing is predicted except the mass matrix must be unitary and complex

$$\begin{pmatrix} u \\ s \\ b \end{pmatrix}_{EW} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} u \\ s \\ b \end{pmatrix}_{MASS}$$

The unitarity triangle: introduction

- Weak eigenstates are therefore a mixture of mass eigenstates, by the Cabibbo-Kobayashi-Maskawa elements V_{ij}: flavour changing charged currents between quark generations.

- This matrix is a 3×3 unitary, complex, and hence described by means of four parameters: 3 rotation angles and a phase. The latter makes possible the CP symmetry violation in the Standard Model.

- These four parameters are free parameters of the SM. As for electroweak precision tests, they must be measured with some redundancy and the SM hypothesis is to be falsified by a consistency test. We will review in this lecture this overall test. But let's define first the parameters.

Origin of CPV ?

Kobayashi-Maskawa Ansatz (1973)

Complex phase in the quark mixing matrix
→ source of CPV in Weak Interactions

KM-phase

Requires 3 (or more) generation of quarks

- only 3 quaks (u, d, s) were known at that time !
- All 6 quarks are now discovered

Essential ingredient of the Standard Model (SM)

The unitarity triangle: parameterization

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Consider the Wolfenstein parameterization as in EPJ C41: 1-131, 2005: unitary-exact and phase convention independent

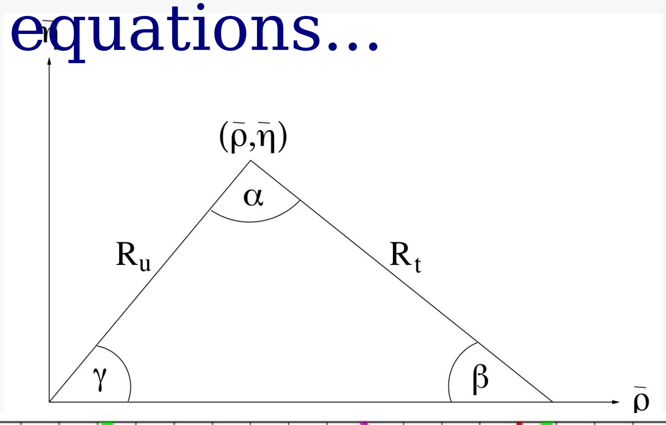
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad \text{and} \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- λ is measured from $|V_{ud}|$ and $|V_{us}|$ in superallowed beta decays and semileptonic kaon decays, respectively.
- A is further determined from $|V_{cb}|$, measured from semileptonic charmed B decays.
- The last two parameters are to be determined from angles and side measurements of the CKM unitarity triangle

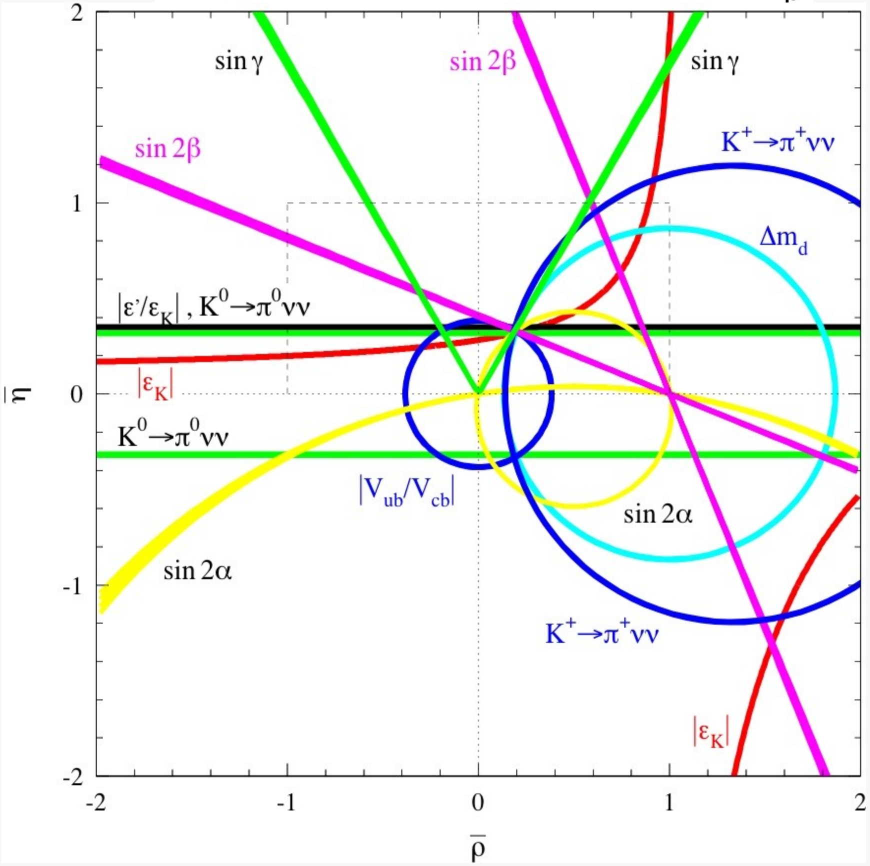
The unitarity triangle: representation

Unitarity $(U^{+}U)$ prescribes 6 complex equations...

An elegant way to represent the unitarity relations is to display them in the complex plane as the sum of three vectors:



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



The area of the triangle is half the Jarlkog invariant and measures the magnitude of the CP violation

$$J \sum_{\sigma\gamma=1}^{3} \epsilon_{\mu\nu\sigma}\epsilon_{\alpha\beta\gamma} = \mathrm{Im}(V_{\mu\alpha}V_{\nu\beta}V_{\mu\beta}^*V_{\nu\alpha}^*)\ ,$$

$$J = A^2\lambda^6\eta(1-\lambda^2/2) \simeq 10^{-5}$$

The unitarity triangle: definitions

- Sides and angles of the unitarity triangle
- Normalization given by the matrix element V_{cb}

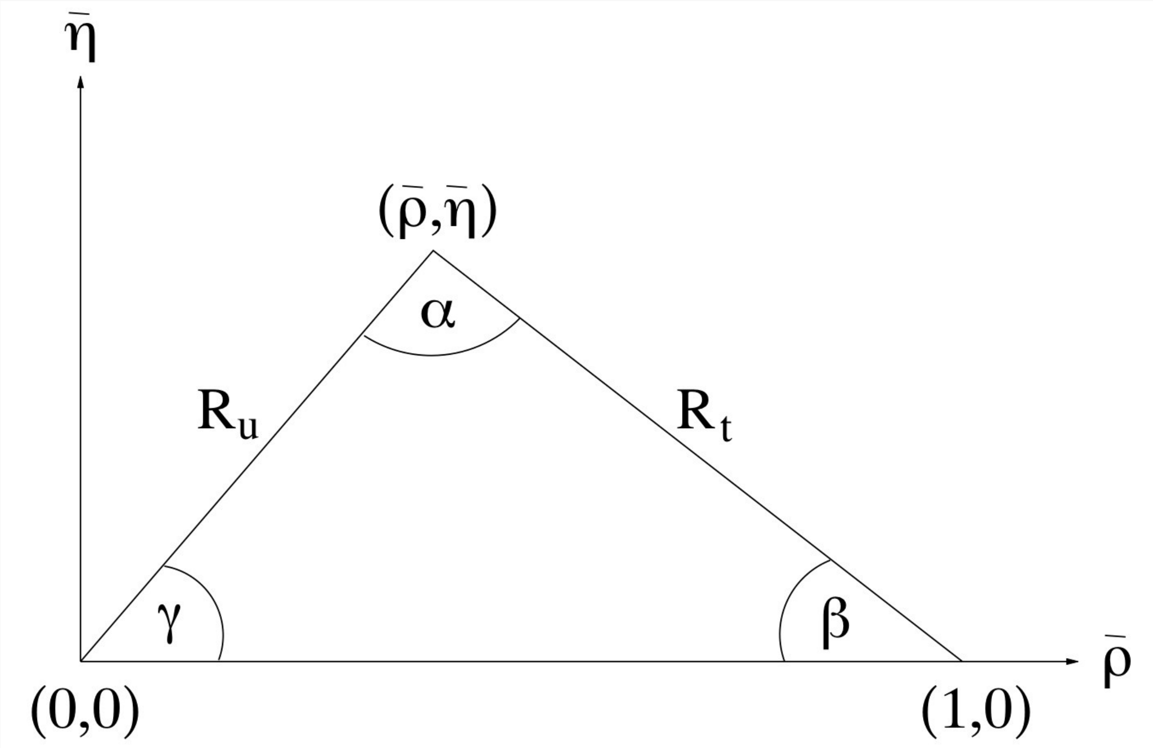
$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar{\rho}^2+\bar{\eta}^2}\,,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2}\,.$$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

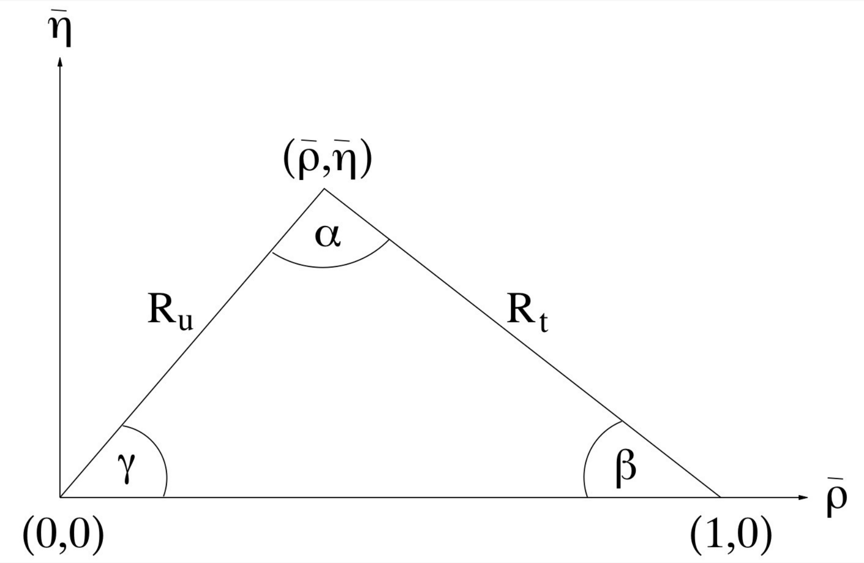


The unitarity triangle: definitions

- Sides of the unitarity triangle

Towards the experimental constraints:

$$\boxed{\begin{aligned} R_u &= \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar\rho^2+\bar\eta^2}\,, \\ R_t &= \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^2}\,. \end{aligned}}$$



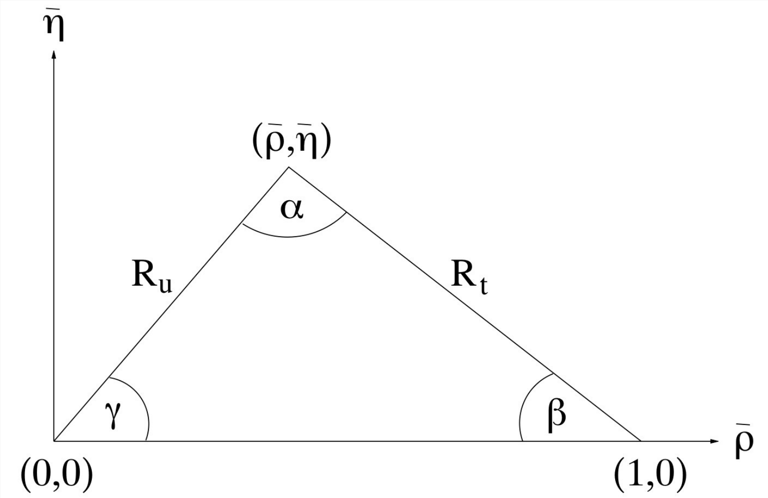
- R_u is measured by the matrix elements V_{ub} and V_{cb} extracted from the semileptonic decays of b-hadrons.
- R_t implies the matrix element V_{td} and hence can be measured from the mixing of B^0 mesons.

The unitarity triangle: definitions

- Angles of the unitarity triangle

Towards the experimental constraints:

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$
$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$



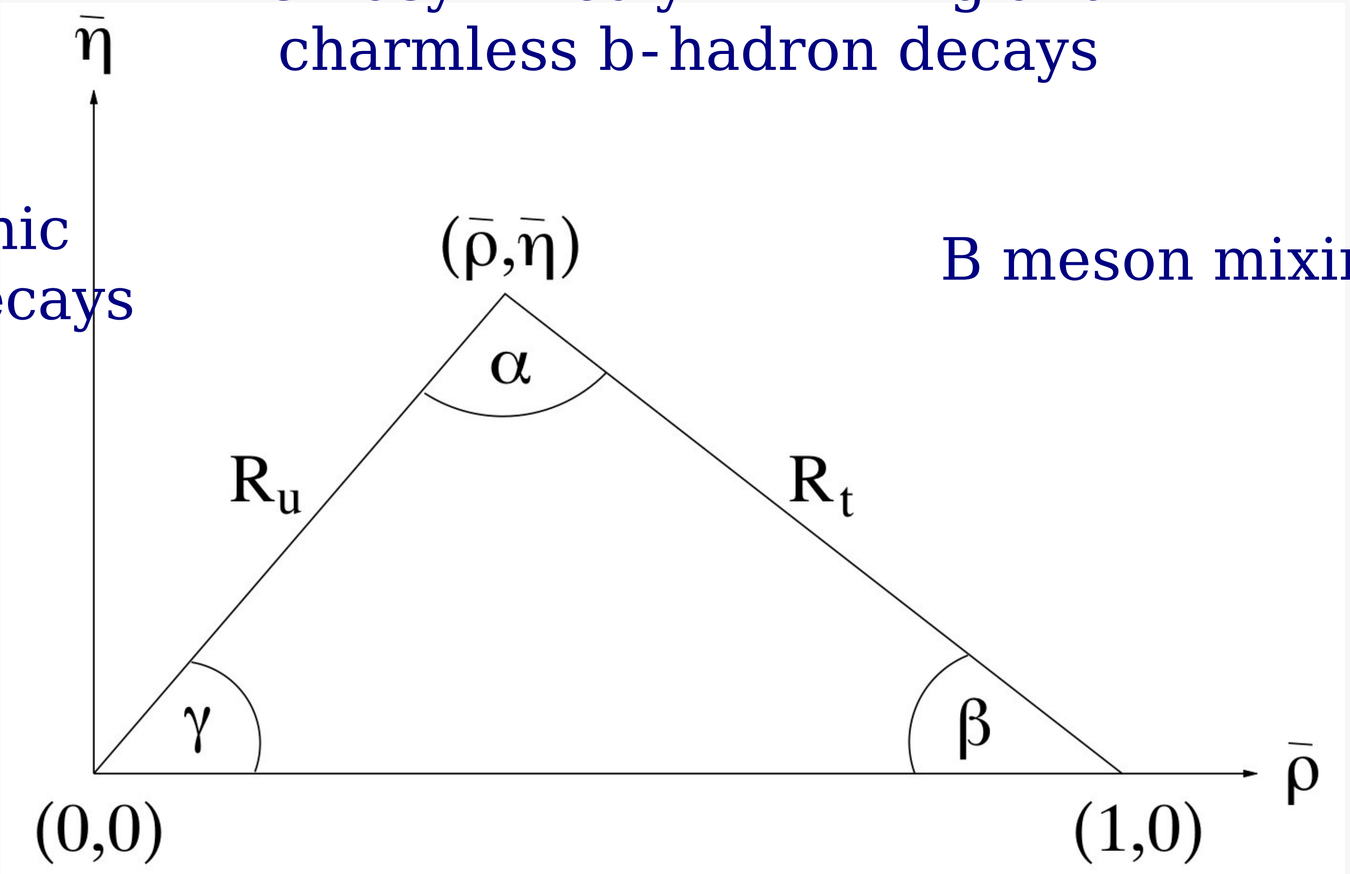
- The angle β/ϕ_1 is directly the weak mixing phase of B^0 mixing
- The angle γ is the weak phase at work in the charmless decays of b-hadrons
- The angle α is nothing else than $(\pi-\beta-\gamma)$ and can be exhibited in processes where both charmless decays and mixing are present

The unitarity triangle: measurements

CP asymmetry in mixing and charmless b-hadron decays

Semileptonic b-hadron decays

B meson mixing



CP asymmetry in charmless b-hadron decays

Overall normalization given by $|V_{cd}V_{cb}^*|$, hence semileptonic b decays

CP asymmetry in mixing processes

Angles

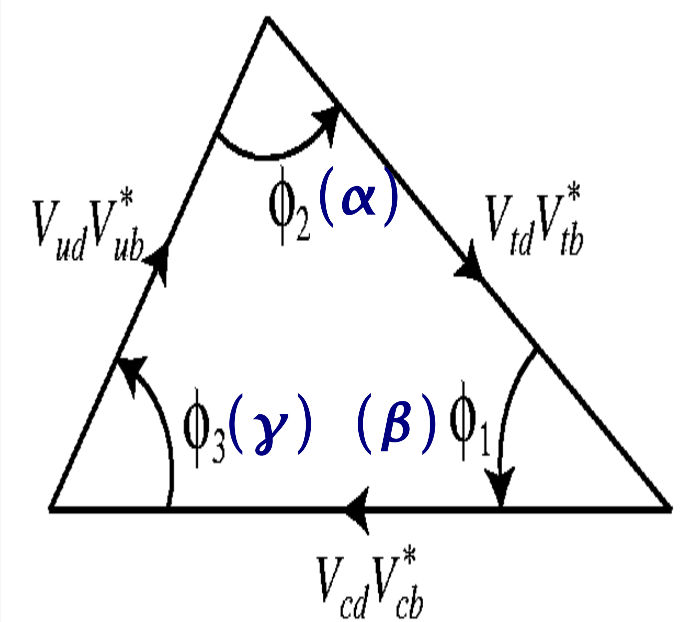
β , α and γ measurements

ϕ_1 , ϕ_2 and ϕ_3 measurements

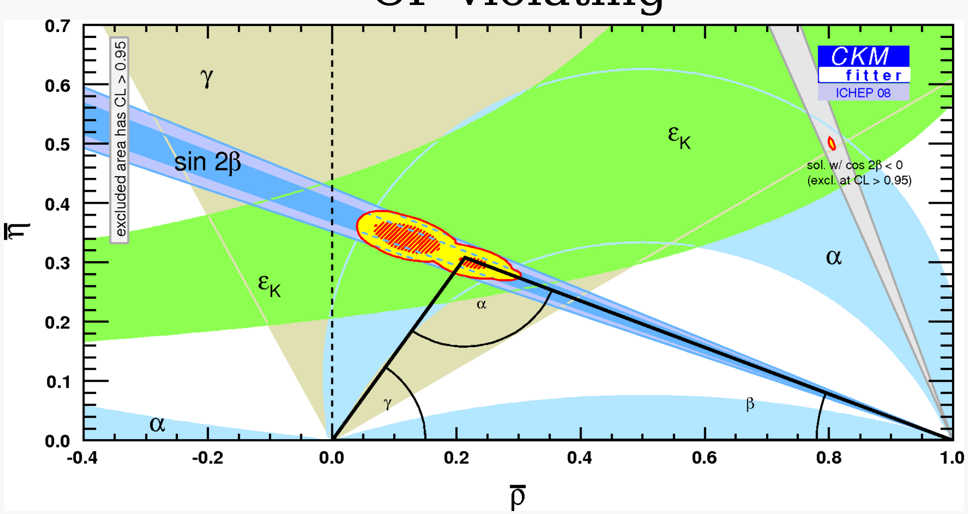
K.Trabelsi
karim.trabelsi@kek.jp

Motivations

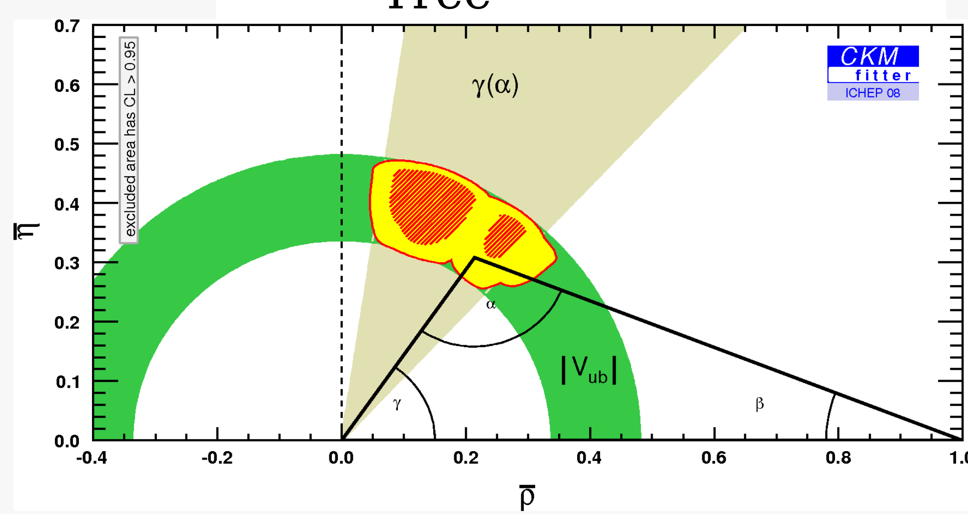
- Overconstrain the CKM matrix: measure fundamental parameters, constrain new physics effects
- Measure the 4 free paremeters in various ways:
  - CP conserving $\{|V_{us}|, |V_{cb}|, |V_{td}|, |V_{ub}|\}$
  - CP violating $\{\epsilon_K, \phi_s, \beta, \gamma\}$
  - Tree level $\{\ldots, \ldots, |V_{ub}|, \gamma\}$
  - Loop level $\{\ldots, \ldots, |V_{td}|, \beta\}$
  - …



CP violating



Tree

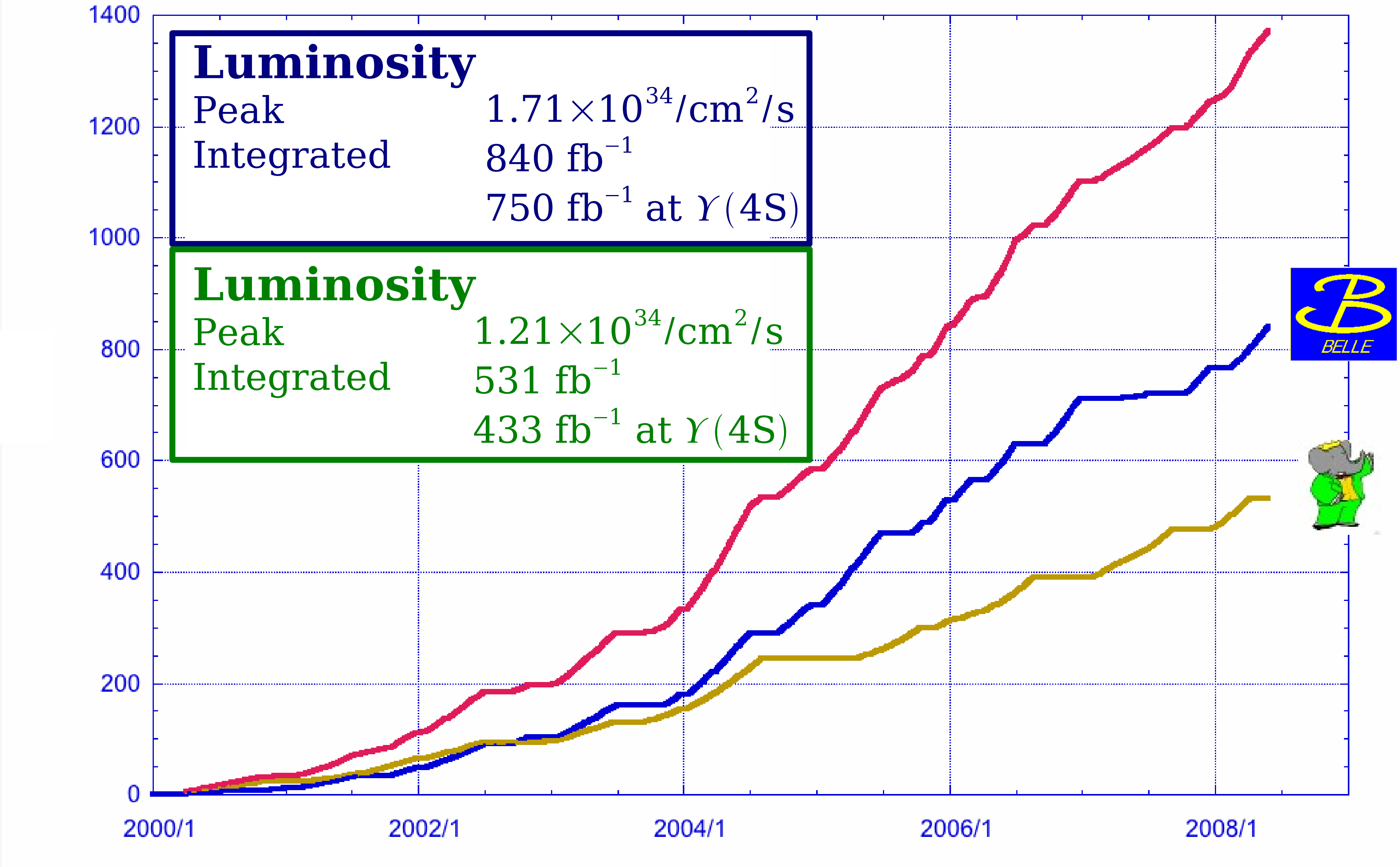


B factories: BaBar and Belle

$\Rightarrow$ experiments designed for ϕ_1 extraction !

Luminosity (fb^{-1})

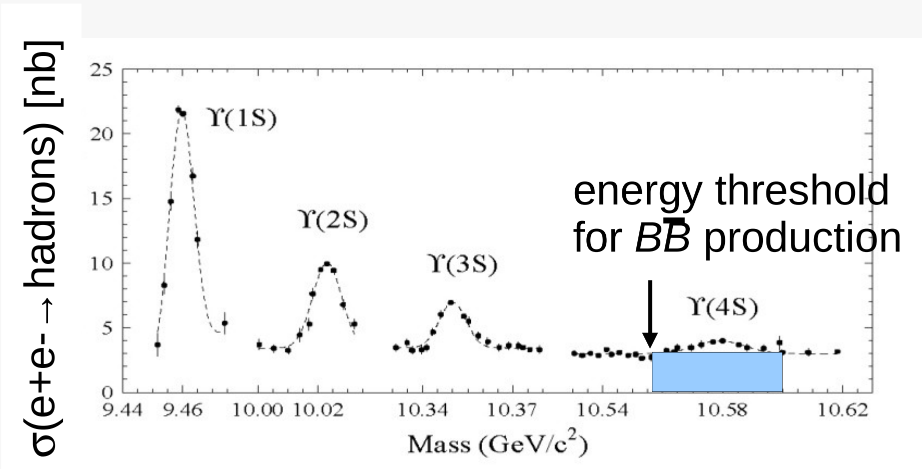
cumulated stat: $\sim$ **1400 fb^{-1} !!**

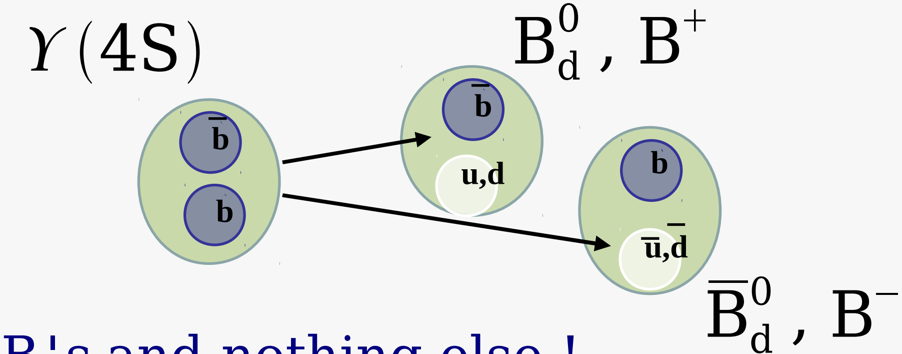


BaBar: $\sim 465\times10^6 B\bar{B}$ pairs = final sample

Belle: $\sim 657\times10^6 B\bar{B}$ pairs = max. current sample (final sample will probably be $\sim 800\times10^6 B\bar{B}$ pairs)

$\Upsilon(4S)$ B-factory





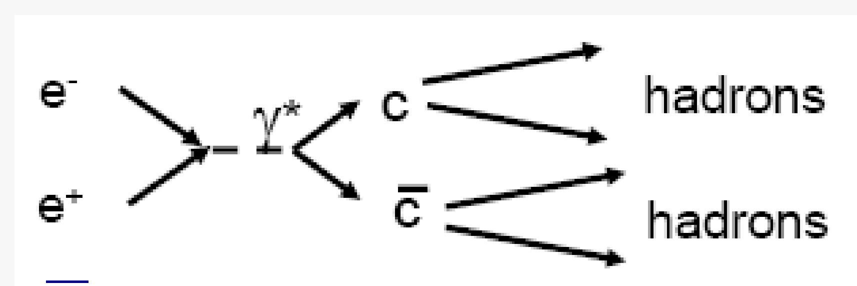
- 2 B's and nothing else !
- 2 B mesons are created simultaneously in a L=1 coherent state
  $\Rightarrow$ before first decay, the final states contains a B and a $\bar{B}$

''on resonance'' production

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

$$\sigma(e^+e^- \to B\bar{B}) \simeq 1.1\ \text{nb}\ (\sim 10^9\ B\bar{B}\ \text{pairs})$$

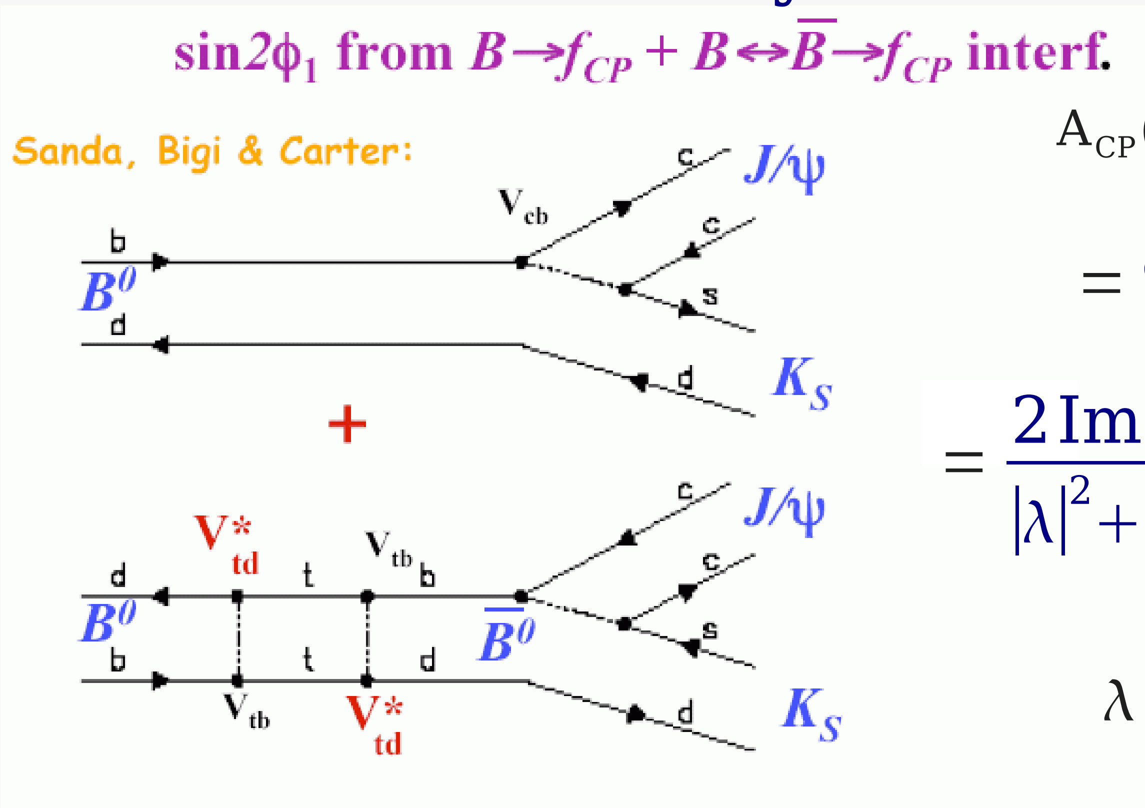
''continuum'' production



$$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3\ \text{nb}\ (\sim 1.3\times10^9\ X_c\bar{Y}_c\ \text{pairs})$$

$\tau\tau$ production also !

Time−dependent CP asymmetries in decays to CP eigenstates



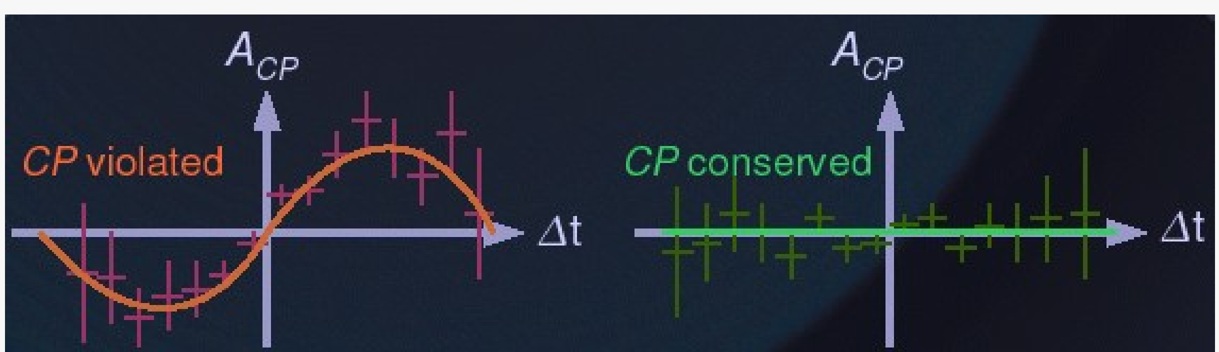
$$A_{CP}(f;t) = \frac{N(\overline{B}^0(t)\to f) - N(B^0(t)\to f)}{N(\overline{B}^0(t)\to f) + N(B^0(t)\to f)}$$

$$= \mathbf{S}\,\sin\Delta m_d t + \mathbf{A}\,\cos\Delta m_d t$$

$$= \frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1}\sin\Delta m_d t + \frac{|\lambda|^2-1}{|\lambda|^2+1}\cos\Delta m_d t$$

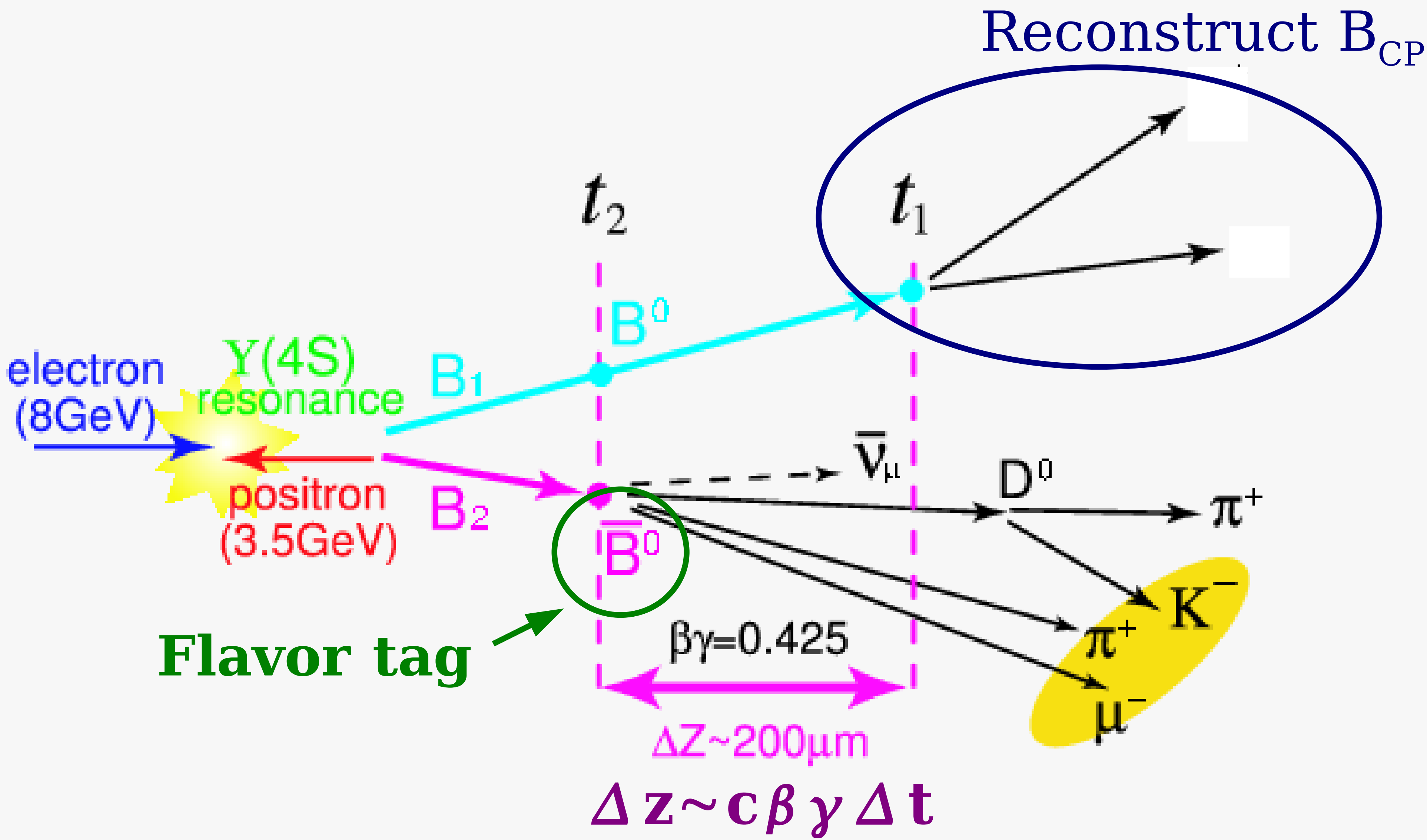
$$\lambda = \frac{q}{p}\,\frac{A(\overline{B}^0\to f)}{A(B^0\to f)} = e^{-i2\phi_i}\frac{\overline{A}_f}{A_f}$$

- $\mathbf{A} = 0$ and $\mathbf{S} = -\xi_f \sin 2\beta$ for $(c\bar{c})K_{S/L}$ $(\xi_f = \mp 1)$
- $\mathbf{A} = 0$ and $\mathbf{S} = \sin 2\alpha$ for $\pi^+\pi^-$ (if tree only)



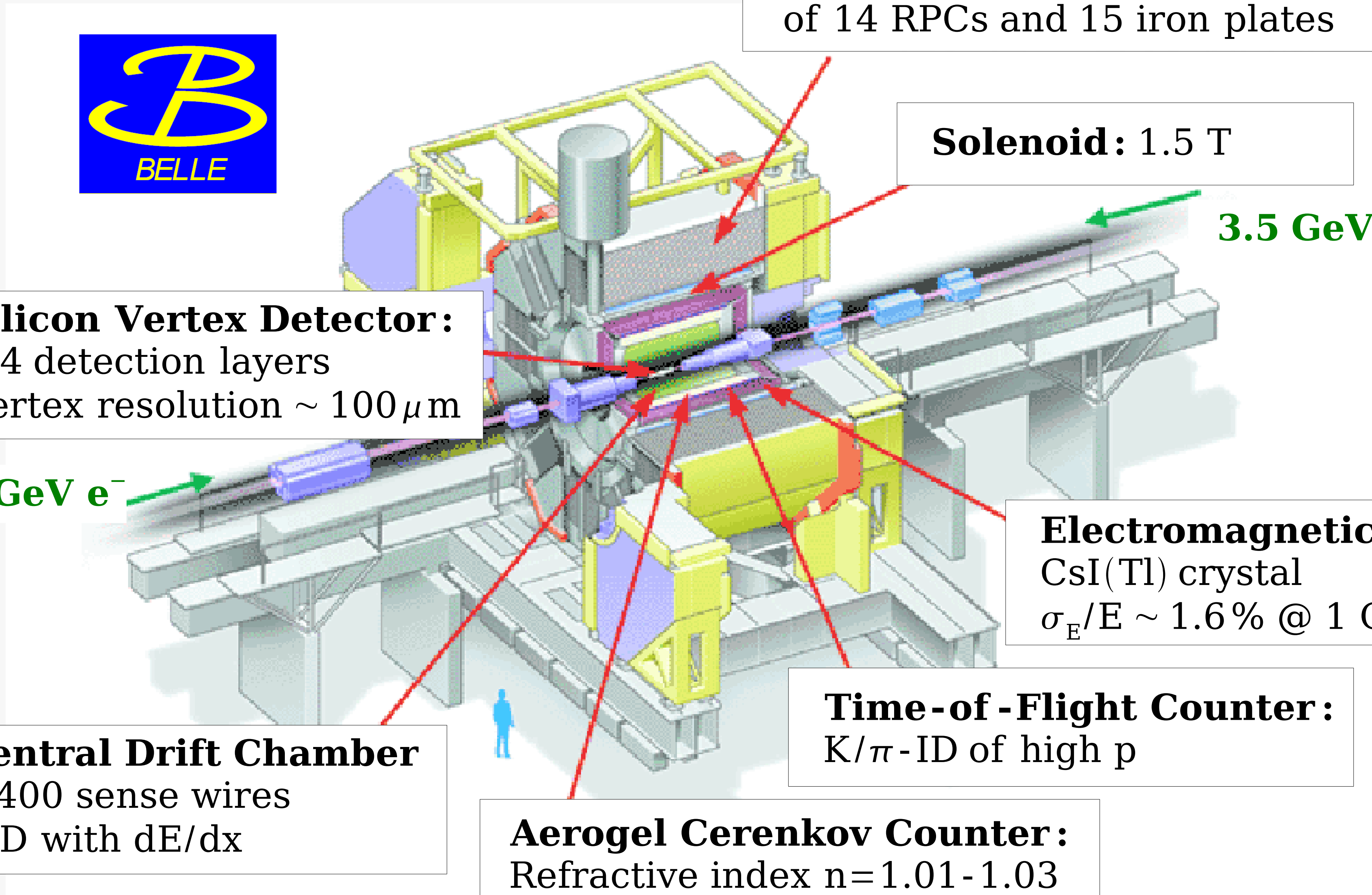
$$\mathbf{C} = -\mathbf{A}$$

Measuring the CP parameters **S** and **A**



$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left(1 + q\left(S\sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)\right)\right)$$

Belle in a nutshell

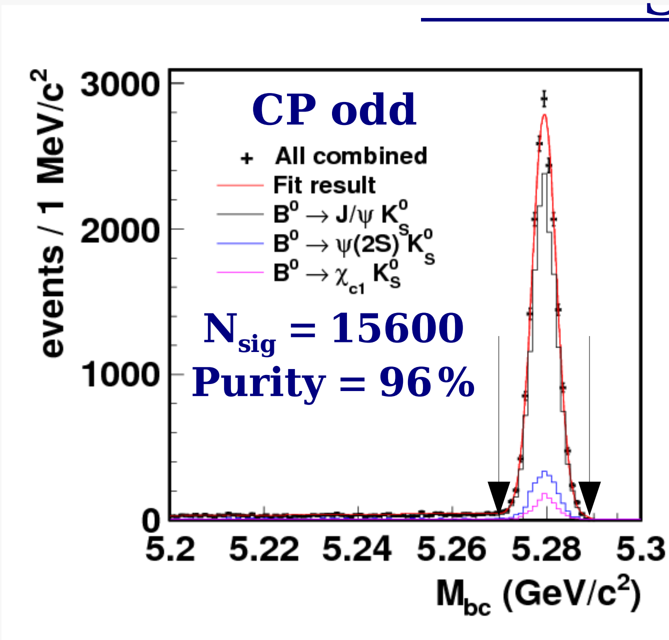


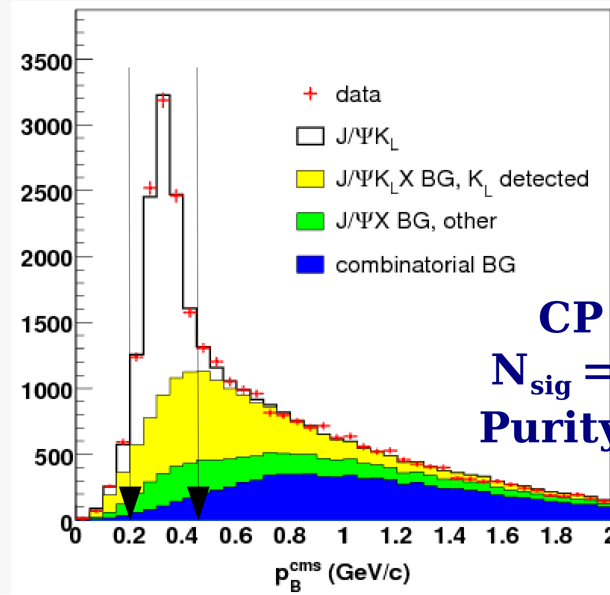
very stable detector, good particle identification, (kaon, pion, electron, muon),

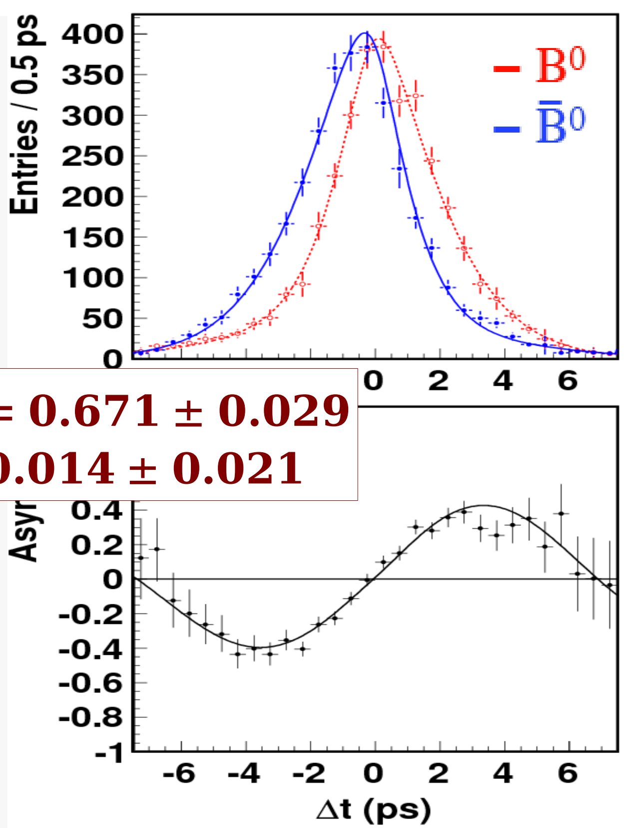
e^+e^- is a clean environment: excellent tracking, triggering, tagging...

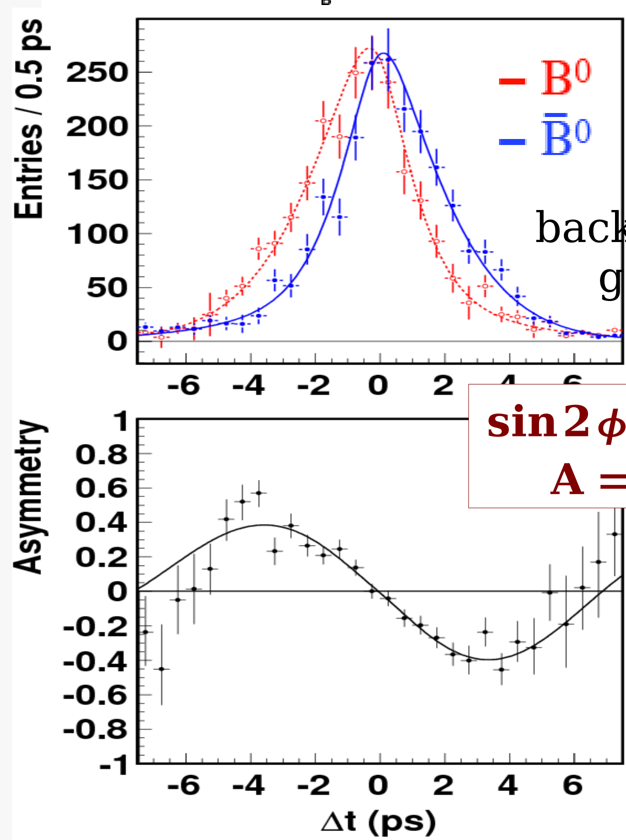
$c\bar{c}\,K_S$ and $J/\psi\,K_L$

$772\times10^6\ B\bar{B}$ pairs







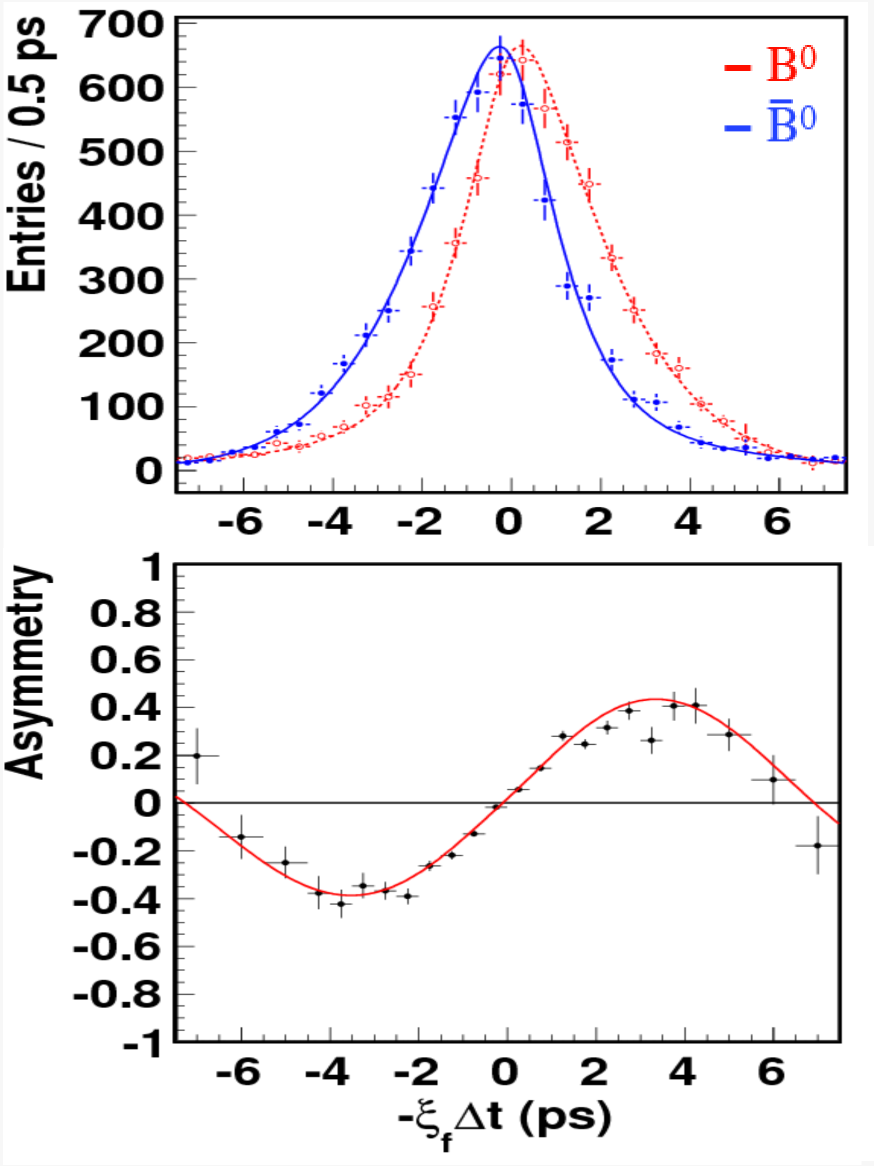


background subtracted
good tagged only

$\sin 2\phi_1 = 0.671 \pm 0.029$
$A = -0.014 \pm 0.021$

$\sin 2\phi_1 = 0.641 \pm 0.047$
$A = 0.019 \pm 0.026$

$\sin 2\phi_1$ in $(c\bar{c})K^0$ ... **772×10^6 $B\bar{B}$ pairs**

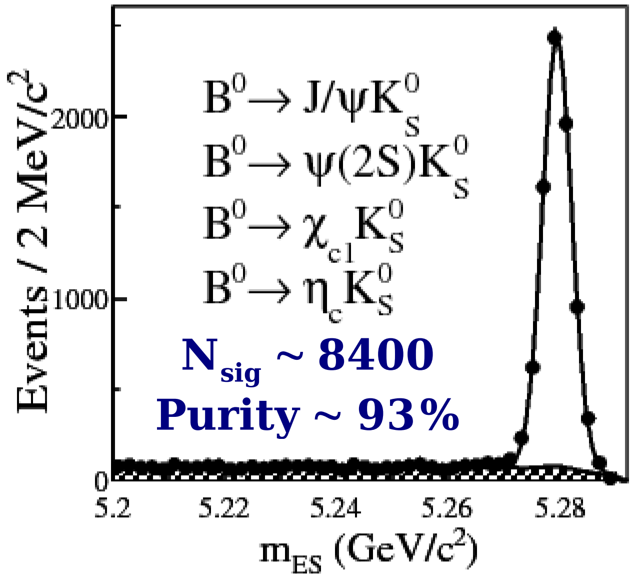


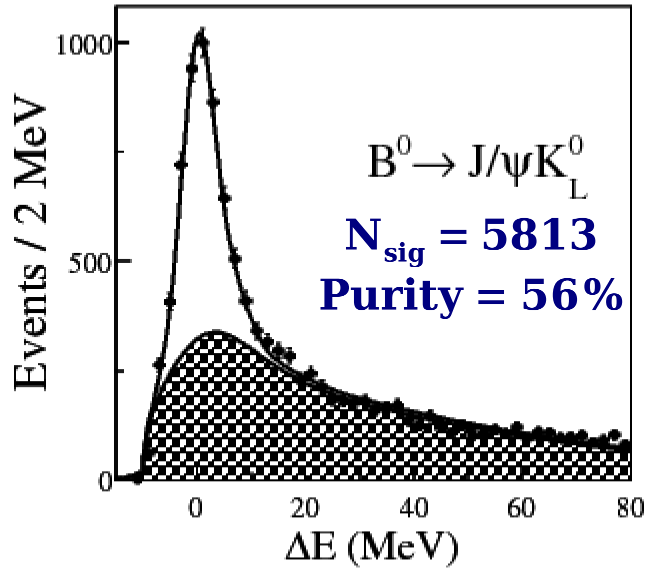
$$\boxed{\begin{array}{c} \sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013 \\ A = 0.007 \pm 0.016 \pm 0.013 \end{array}}$$

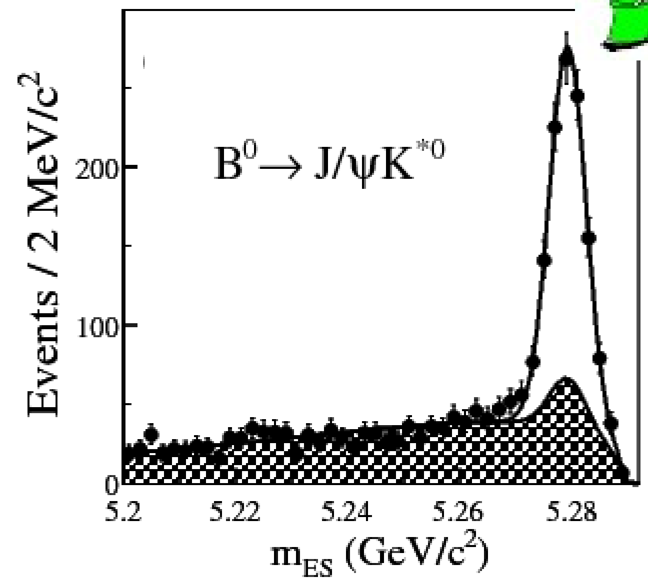
- World's most precise measurements
- anchor point of the SM
- still statistically limited !

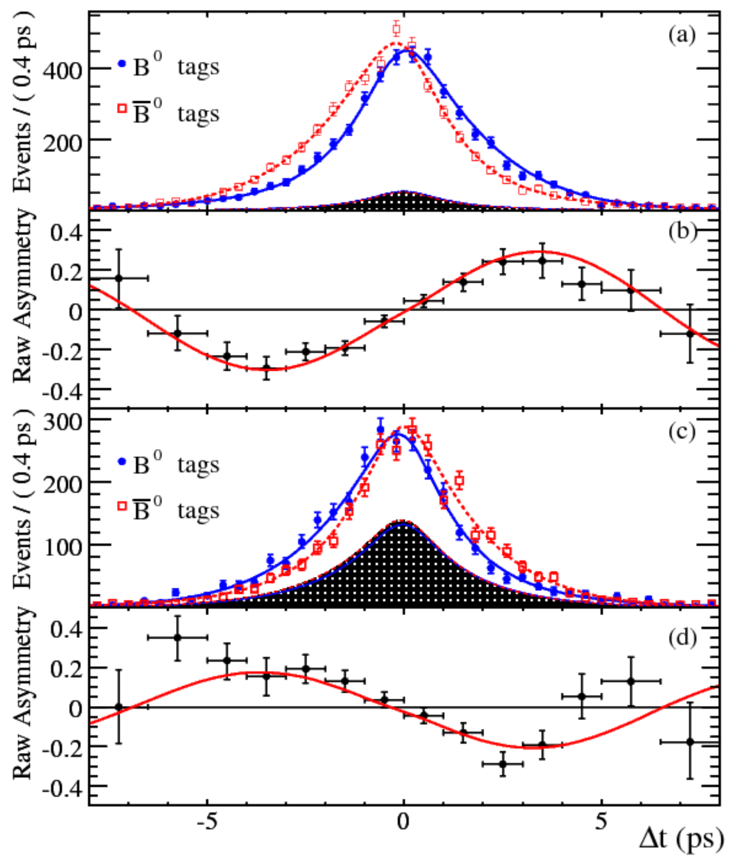
$\sin 2\beta$ in $(c\bar{c})\,K^{(*)0}$

465×10^6 $B\bar{B}$ pairs
[ArXiv:0902.1708]









Mode	$\sin 2\beta$
$J/\psi K_S$	$0.657 \pm 0.036 \pm 0.012$
$J/\psi K_L$	$0.694 \pm 0.061 \pm 0.031$
$J/\psi K^0$	**$0.666 \pm 0.031 \pm 0.013$**
$\psi(2S) K_S$	$0.897 \pm 0.100 \pm 0.036$
$\chi_{c1} K_S$	$0.614 \pm 0.160 \pm 0.040$
$\eta_c K_S$	$0.925 \pm 0.160 \pm 0.057$
$J/\psi K^{*0}$	$0.601 \pm 0.239 \pm 0.087$
$c\bar{c}K^{(*)0}$	**$0.687 \pm 0.028 \pm 0.012$**

Charmonium K^0 Systematics

Preliminary!

BELLE

Systematic errors:

	ΔS	ΔA
Vertexing	$^{+0.008}_{-0.009}$	± 0.008
Flavor tagging	$^{+0.004}_{-0.003}$	± 0.003
Resolution function	± 0.007	± 0.001
Physics parameters	± 0.001	< 0.001
Fit bias	± 0.004	± 0.005
$J/\psi K^0_S$ signal fraction	± 0.002	± 0.001
$J/\psi K^0_L$ signal fraction	± 0.004	$^{+0.000}_{-0.002}$
$\psi(2S) K^0_S$ signal fraction	< 0.001	< 0.001
$\chi_{c1} K^0_S$ signal fraction	< 0.001	< 0.001
Background Δt	± 0.001	< 0.001
Tag-side interference	± 0.001	± 0.008
Total	± 0.013	± 0.013

2011

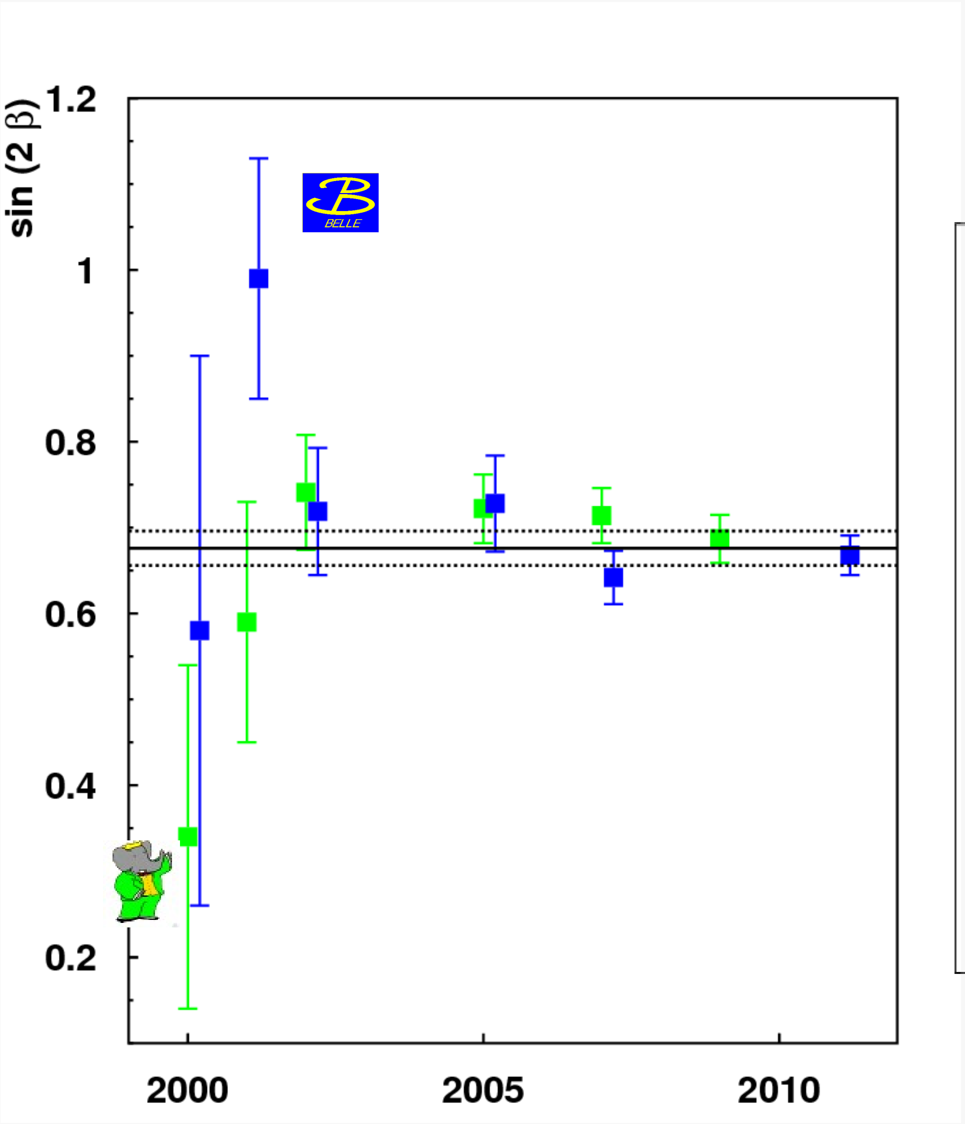
- Significant improvement in systematics: 0.017 → 0.013
- Better model for resolution function (decay mode independent)

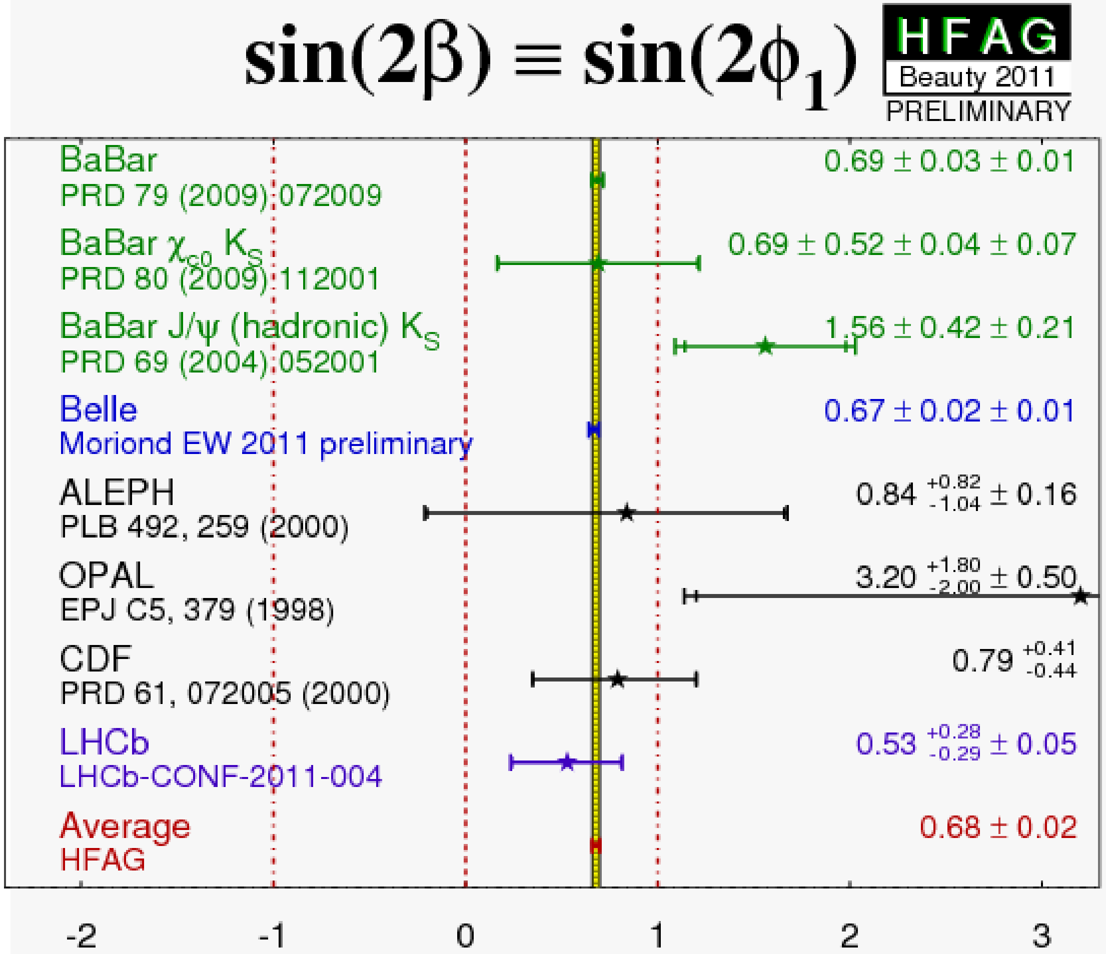
J/psi K0 systematic error

	dS	dA
Vertexing	0.012	0.009
(Ks:	0.013	0.021)
Flv tag	0.004	0.003
Res. func.	0.006	0.001
Phys.	0.001	0.001
Fit bias	0.007	0.004
Ks frac.	0.003	0.001
KL frac.	0.005	0.002
BG dt	0.001	0.001
T.S.I.	0.001	0.009
total	0.017	0.014

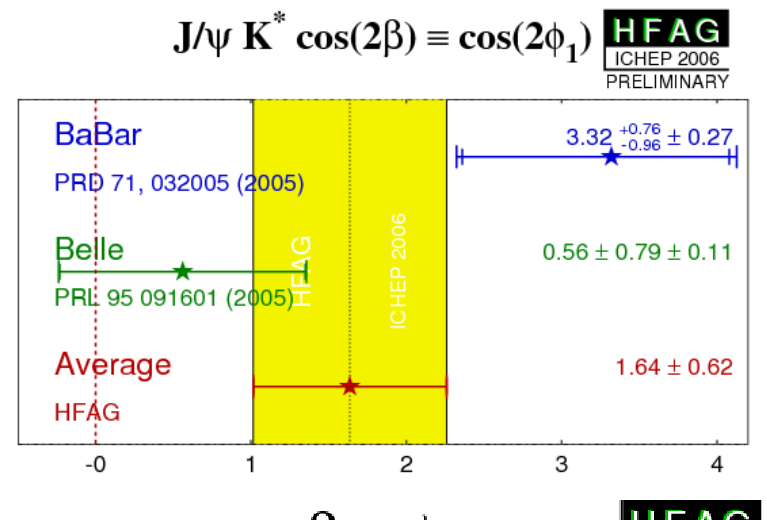
2006

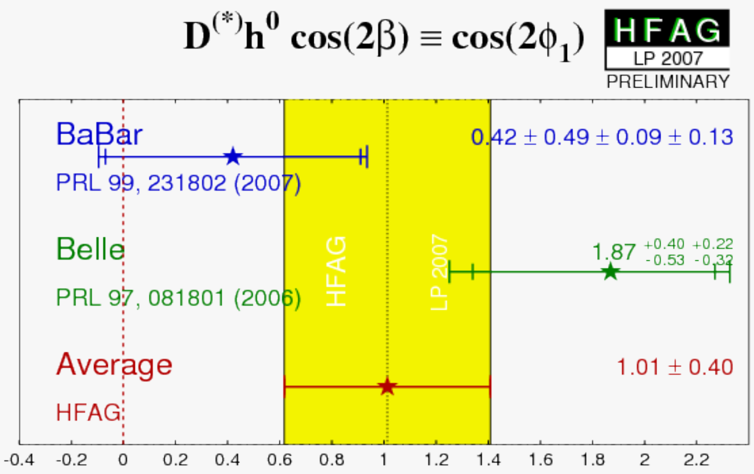
La raison d'être of the B factories

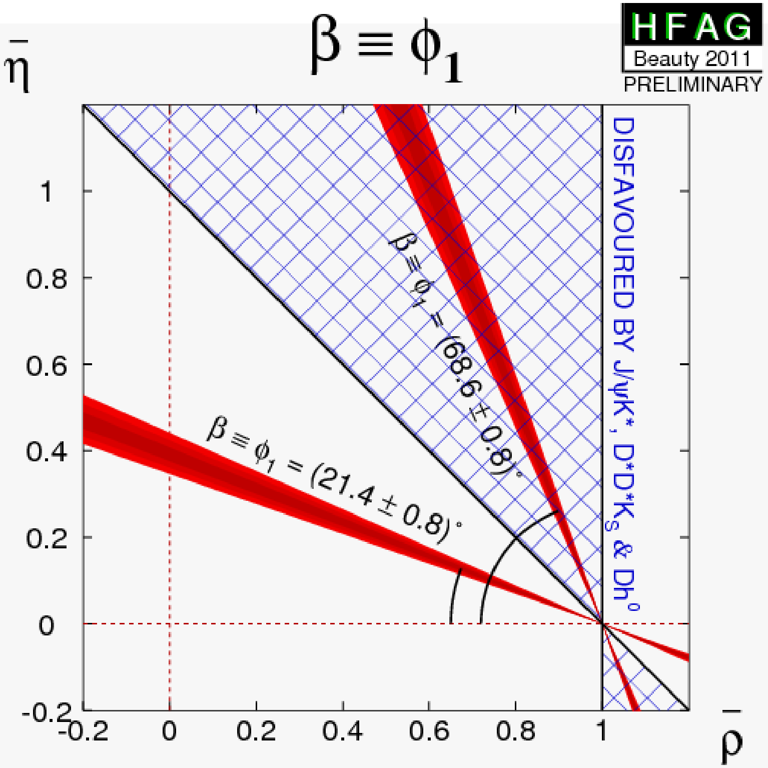




La raison d'être of the B factories







$$\boxed{\beta = (21.4 \pm 0.8)^{\circ}}$$

What is the source of CP violation ?

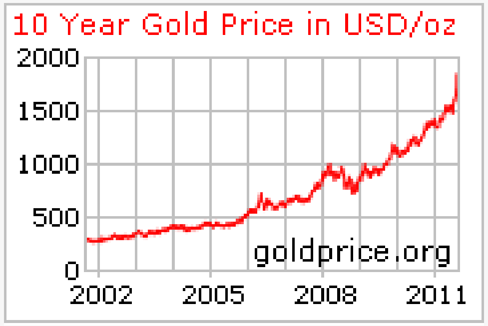
The Kobayashi-Maskawa phase is the source

Checking the quality of gold

LP2011 , T.Gershon

$B^0 \to J/\psi\, K_S$ is a golden mode for $\sin 2\phi_1$

Can check purity using flavour symmetries
- $B^0 \to J/\psi\, \pi^0$ (related by SU(3))
- $B^0{}_s \to J/\psi\, K_S$ (related by U spin)

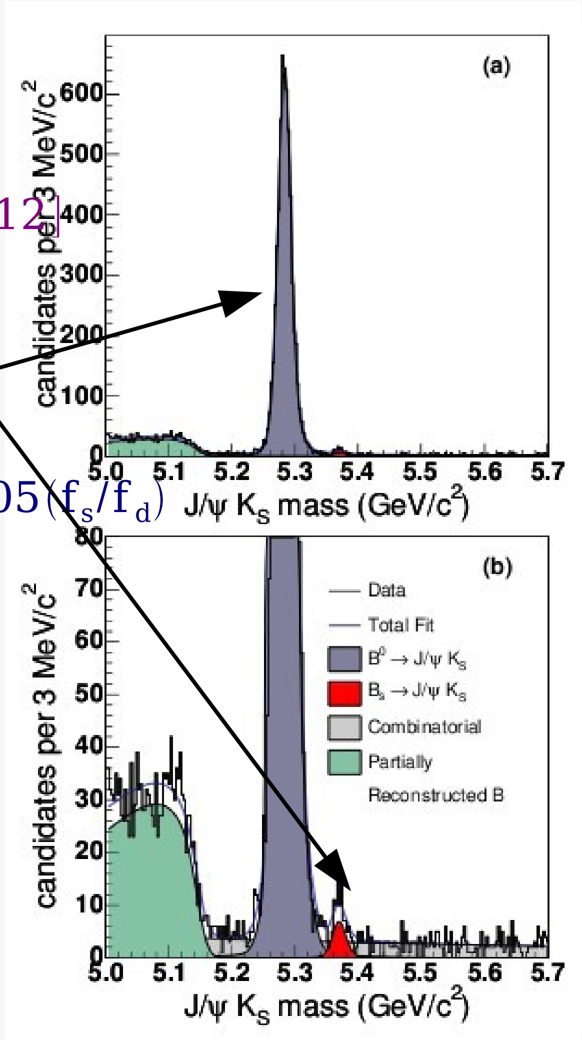


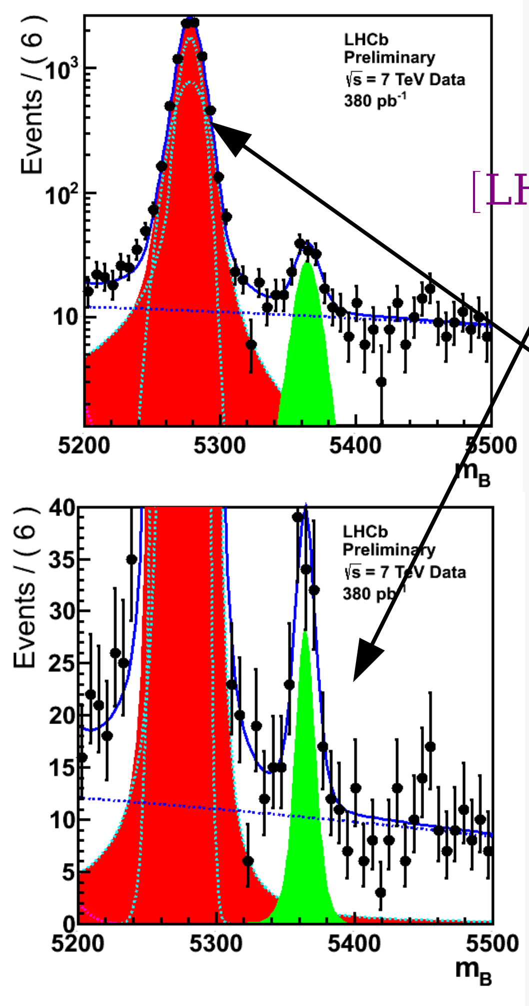
CDF

[PRD 83 (2011) 052012]

$$\frac{B(B_s \to J/\psi\, K_S)}{B(B \to J/\psi\, K_S)} =$$

$0.041 \pm 0.007\,(\mathrm{stat})$
$\pm\, 0.004\,(\mathrm{syst}) \pm 0.005\,(f_s/f_d)$





LHCb

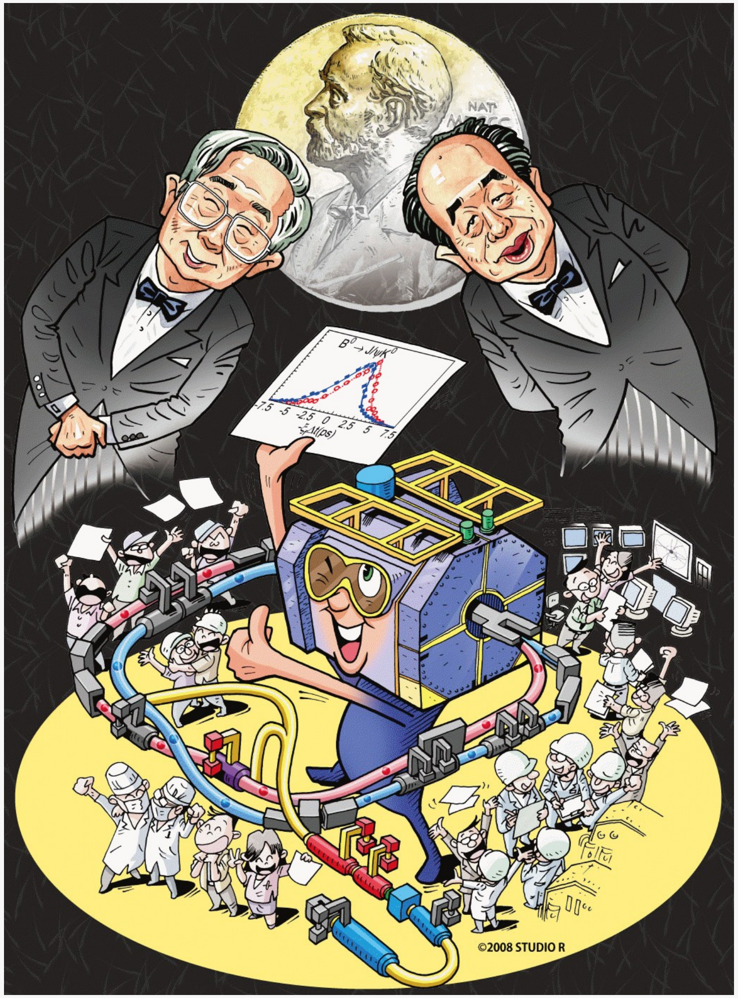
[LHCb−CONF−2011−048]

$$\frac{B(B_s \to J/\psi\, K_S)}{B(B \to J/\psi\, K_S)} =$$

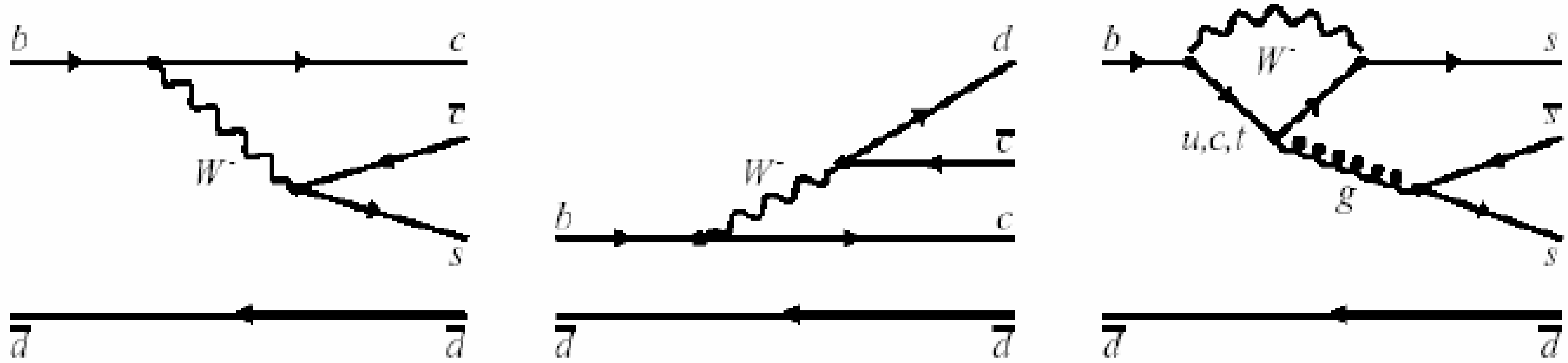
$0.038 \pm 0.006\,(\mathrm{stat})$
$\pm\, 0.002\,(\mathrm{syst}) \pm 0.003\,(f_s/$

Critical role of the B factories in
the verification of the KM hypothesis

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's



β in other modes



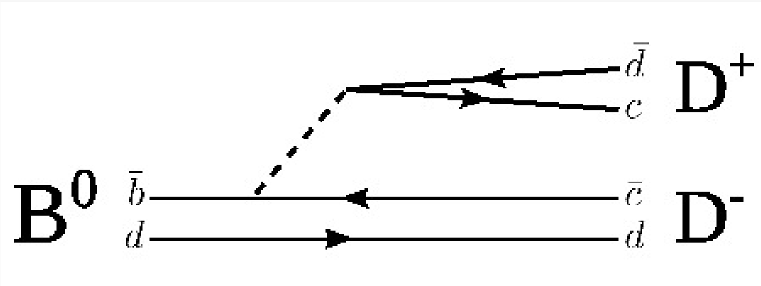
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0,$ $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$

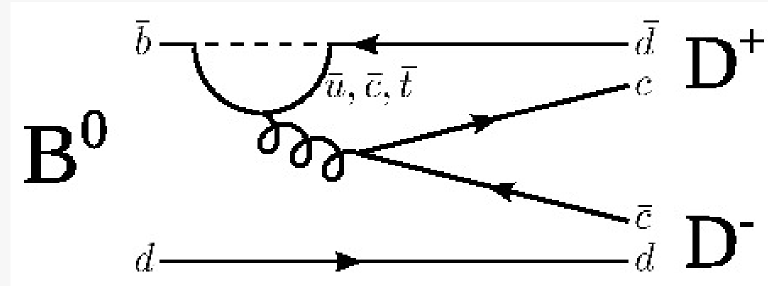
increasing tree diagram amplitude ←

increasing sensitivity to new physics →

possible new sources of CPV ?

Recent update of $B^0 \to D^+ D^-$ mode





772×10^6 $B\bar{B}$ pairs

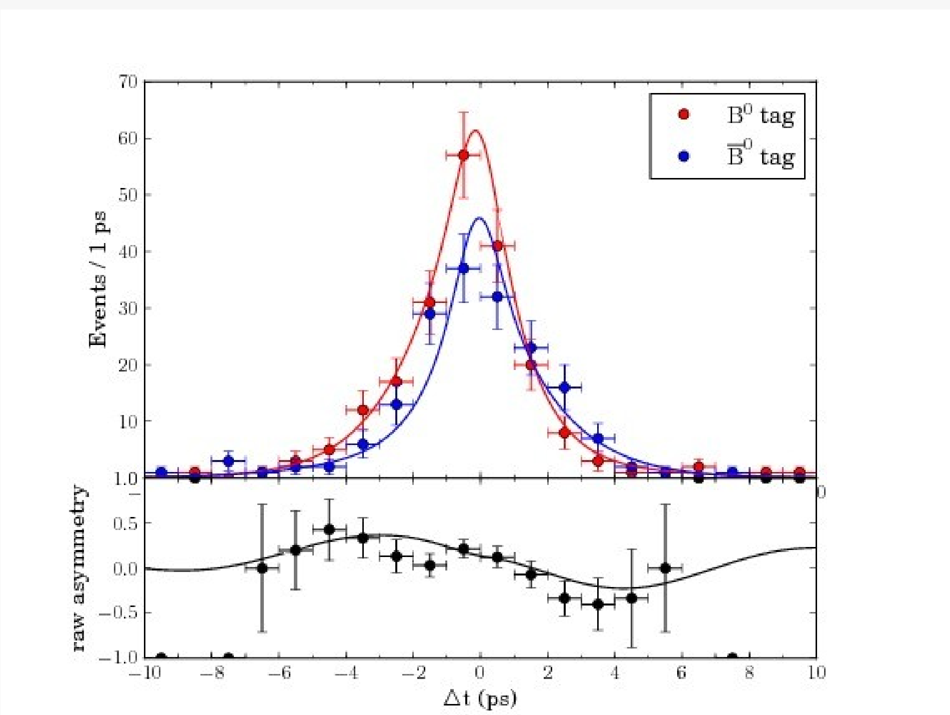
preliminary

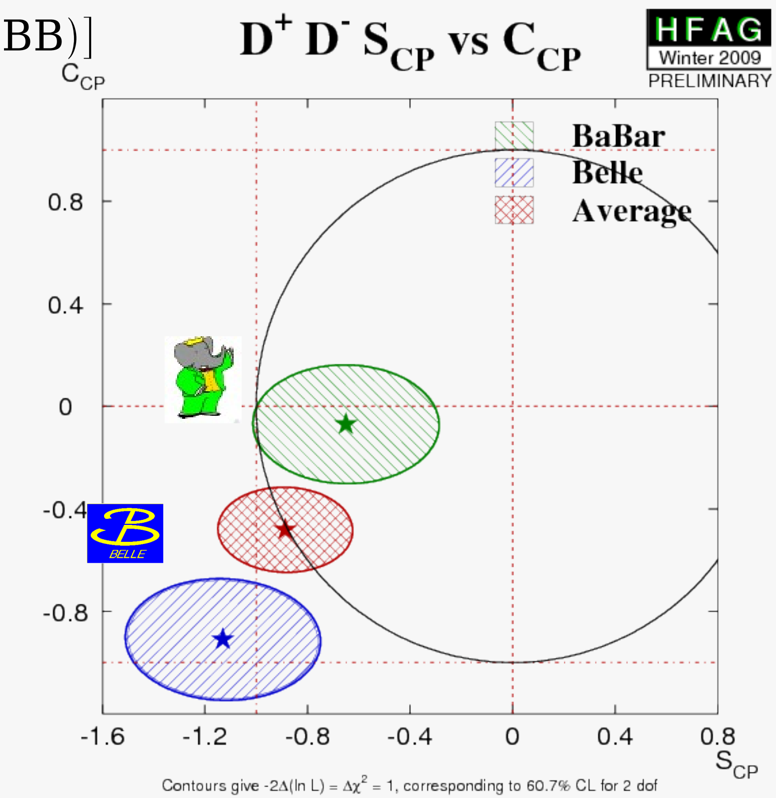
shown at EPS11

SM prediction: $S = -\sin 2\beta$ and $A = 0$ [Z.Z Xing, PRD61, 014010 (1999)]

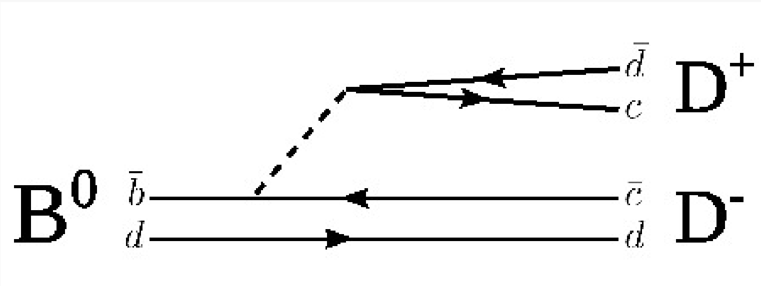
$$B^0 \to D^+ D^- \to (K^- \pi^+ \pi^+)(K^+ \pi^- \pi^-)$$
$$\to (K^- \pi^+ \pi^+)(K_S^0 \pi^-)$$

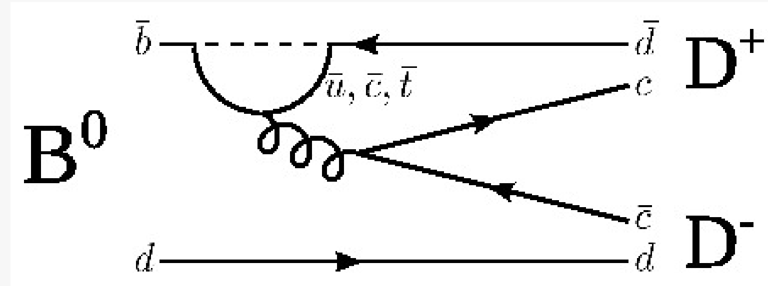
[> × 2 signal yield compared to previous analysis (535 MBB)]





Recent update of $B^0 \to D^+ D^-$ mode





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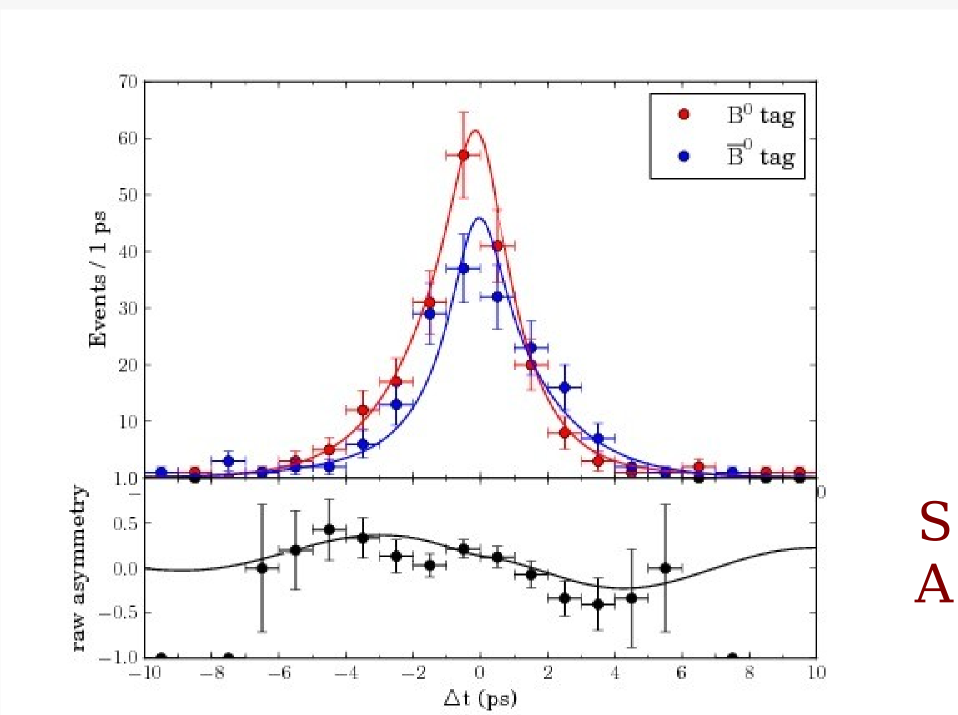
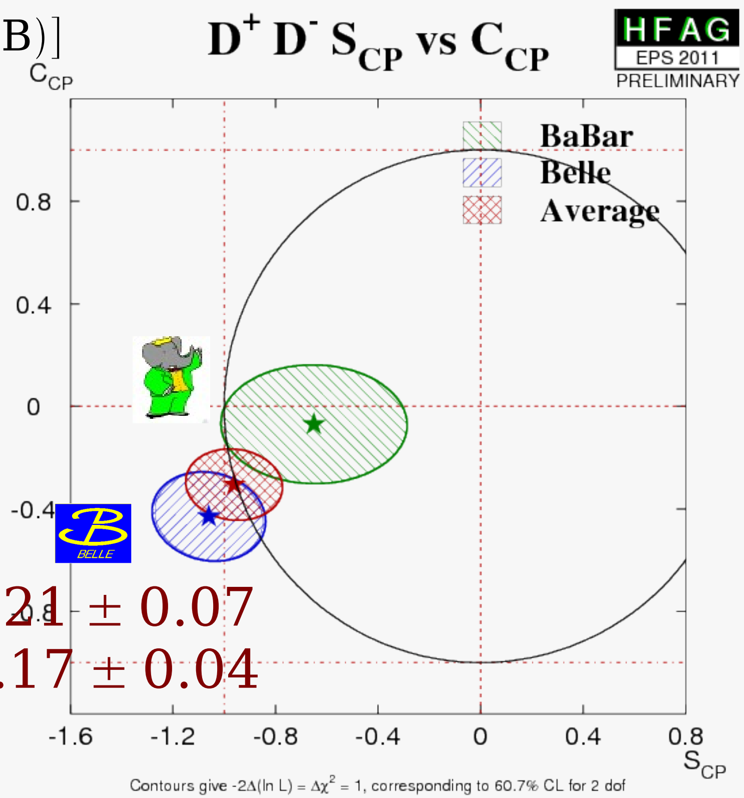
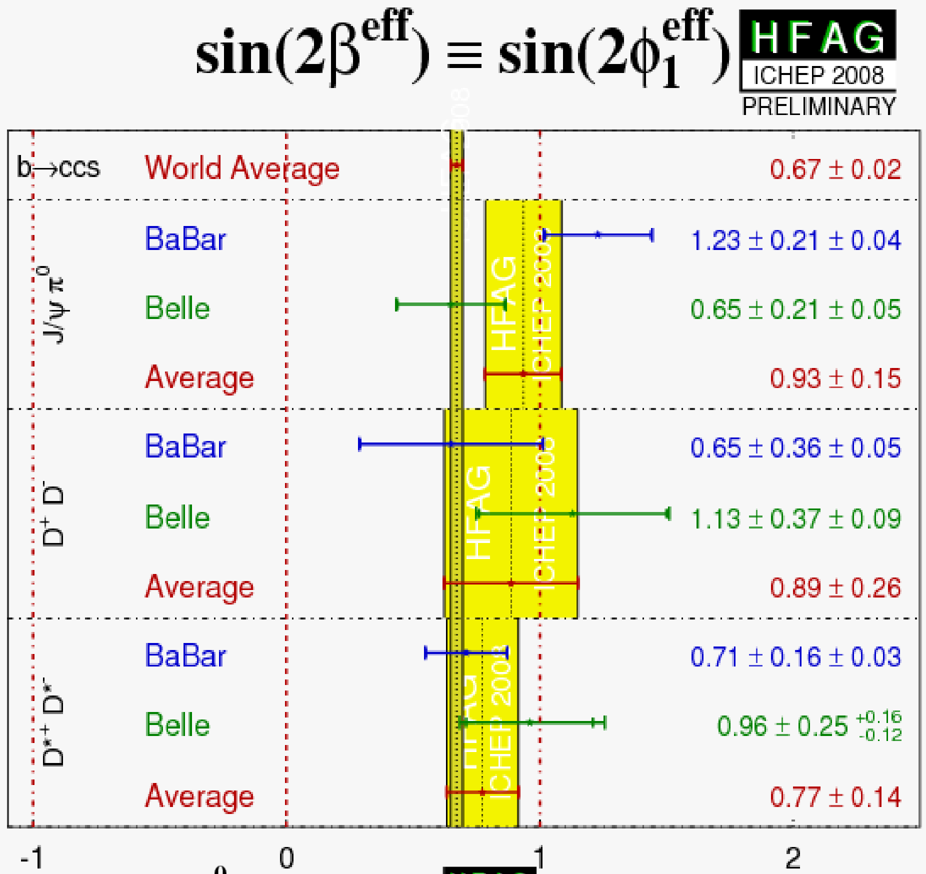
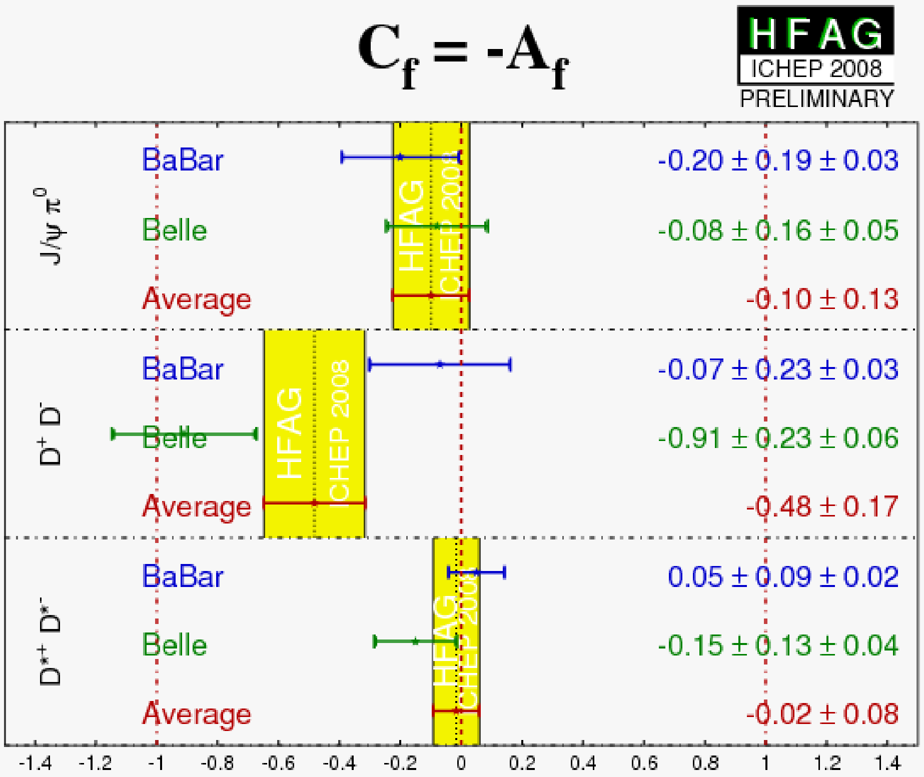


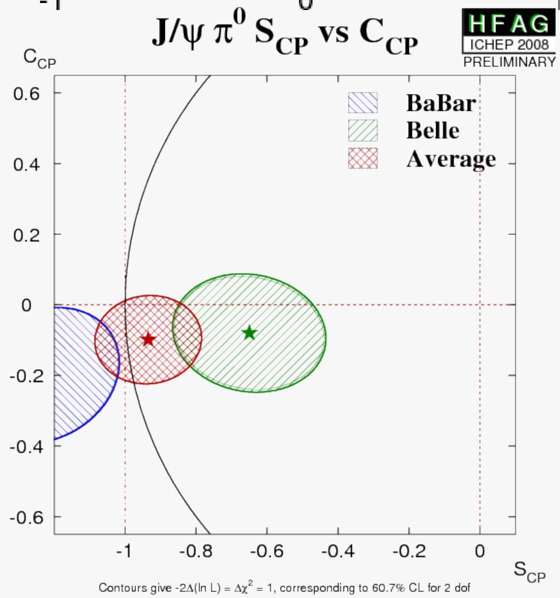


$$S = -1.06 \pm 0.21 \pm 0.07$$
$$A = +0.43 \pm 0.17 \pm 0.04$$

S and C in $b \to c\bar{c}d$ modes



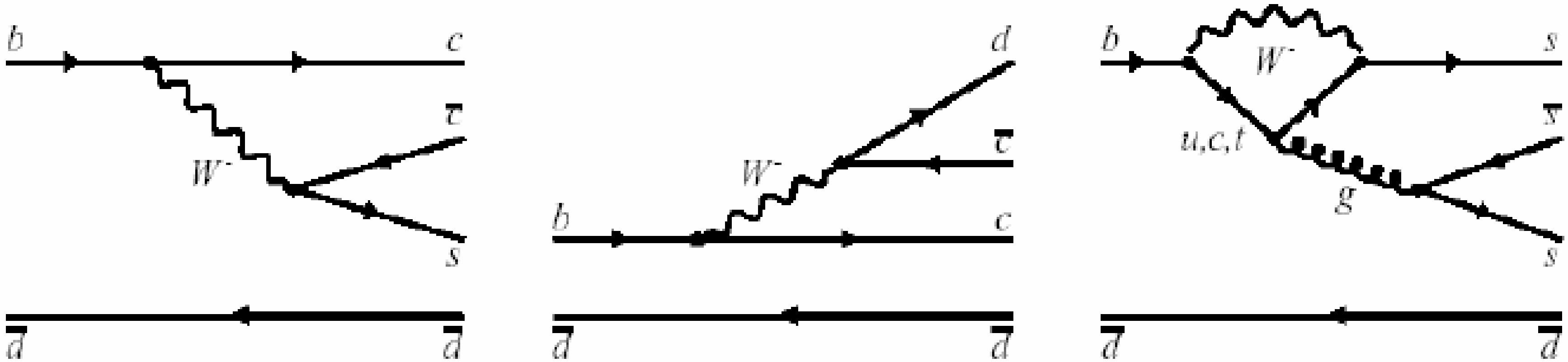




good agreement with $b \to c\bar{c}s$ modes result

$S = -\sin 2\beta, \; C = 0$

more info needed for C in D^+D^- mode



$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0,$ $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$

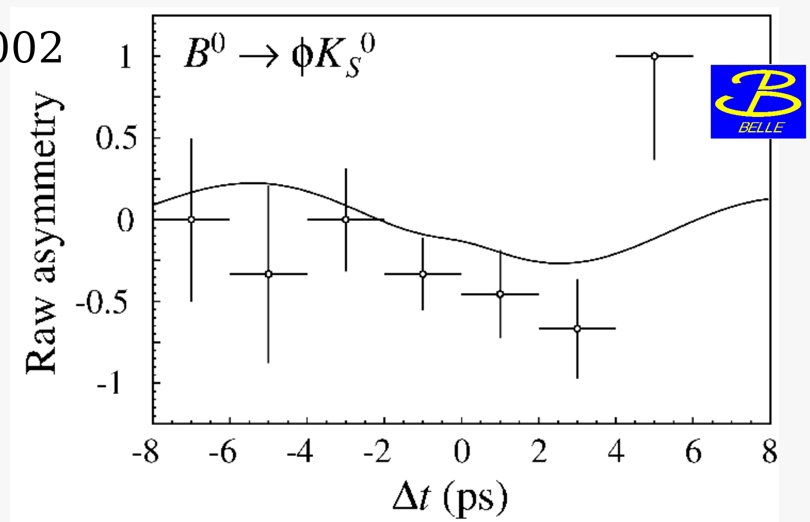
increasing tree diagram amplitude ←

increasing sensitivity to new physics →

first reported in Moriond EW 2002

$''\sin 2\beta'' = -0.73 \pm 0.64 \pm 0.22$

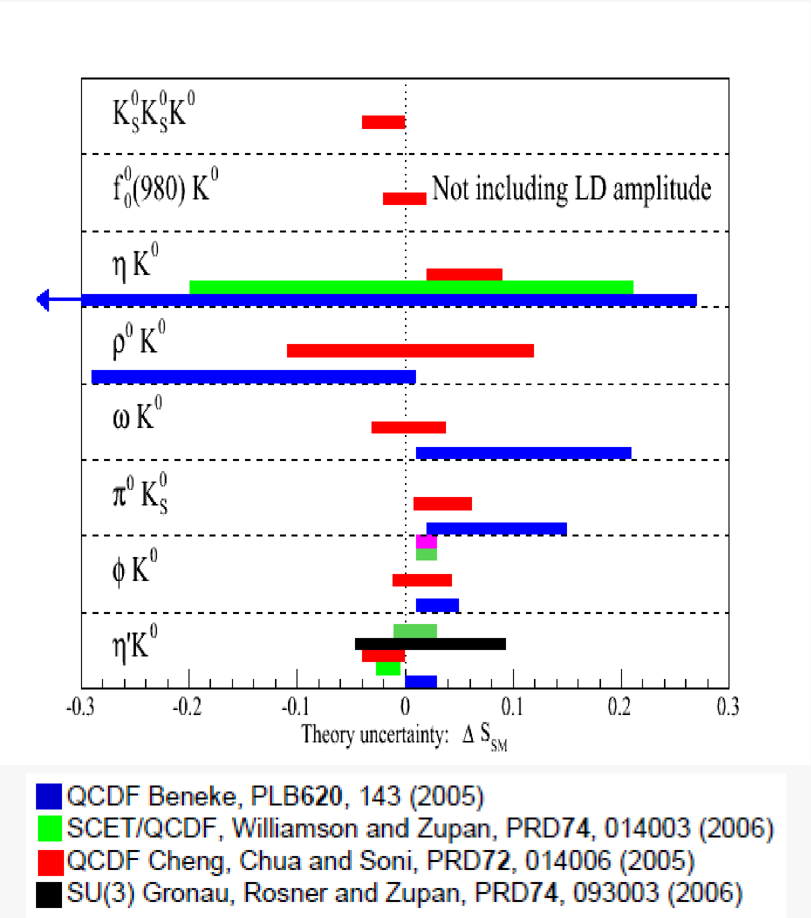
[PRD 67, 031102 (2003)]



"$\sin 2\phi_1$" from $b \to s$ penguins

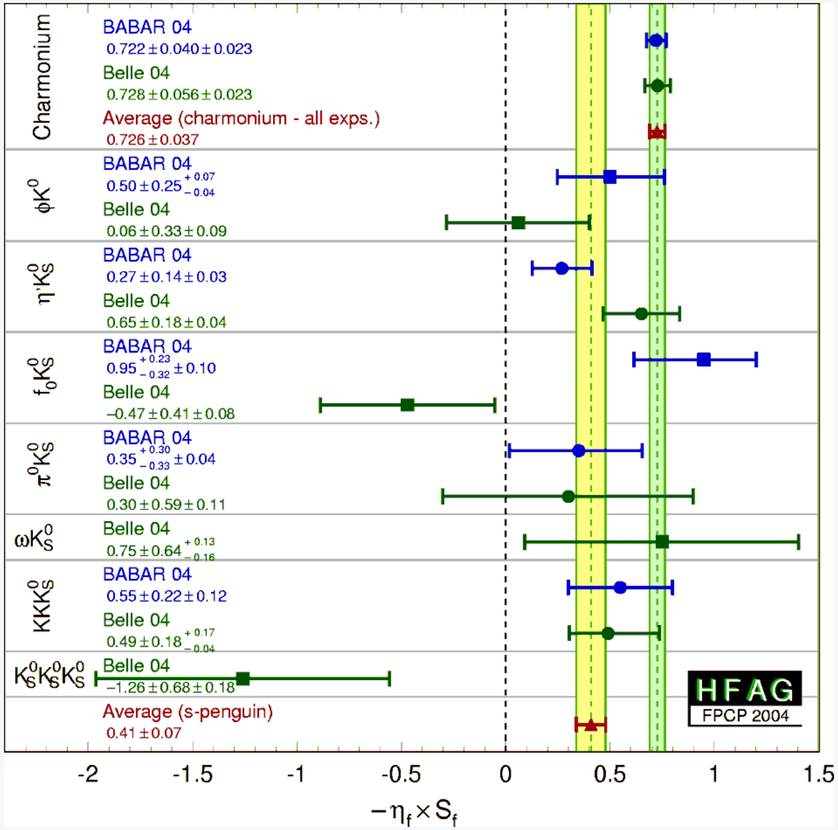
- dominant phase is the same as in $b \to c\bar{c}s$
- even in SM, possible deviations (tree pollution)
- New physics in the loop may cause deviation in the values of S and C

Theoretical prediction for ΔS



For most of the modes, theory predicts $\Delta S > 0$

In 2004:



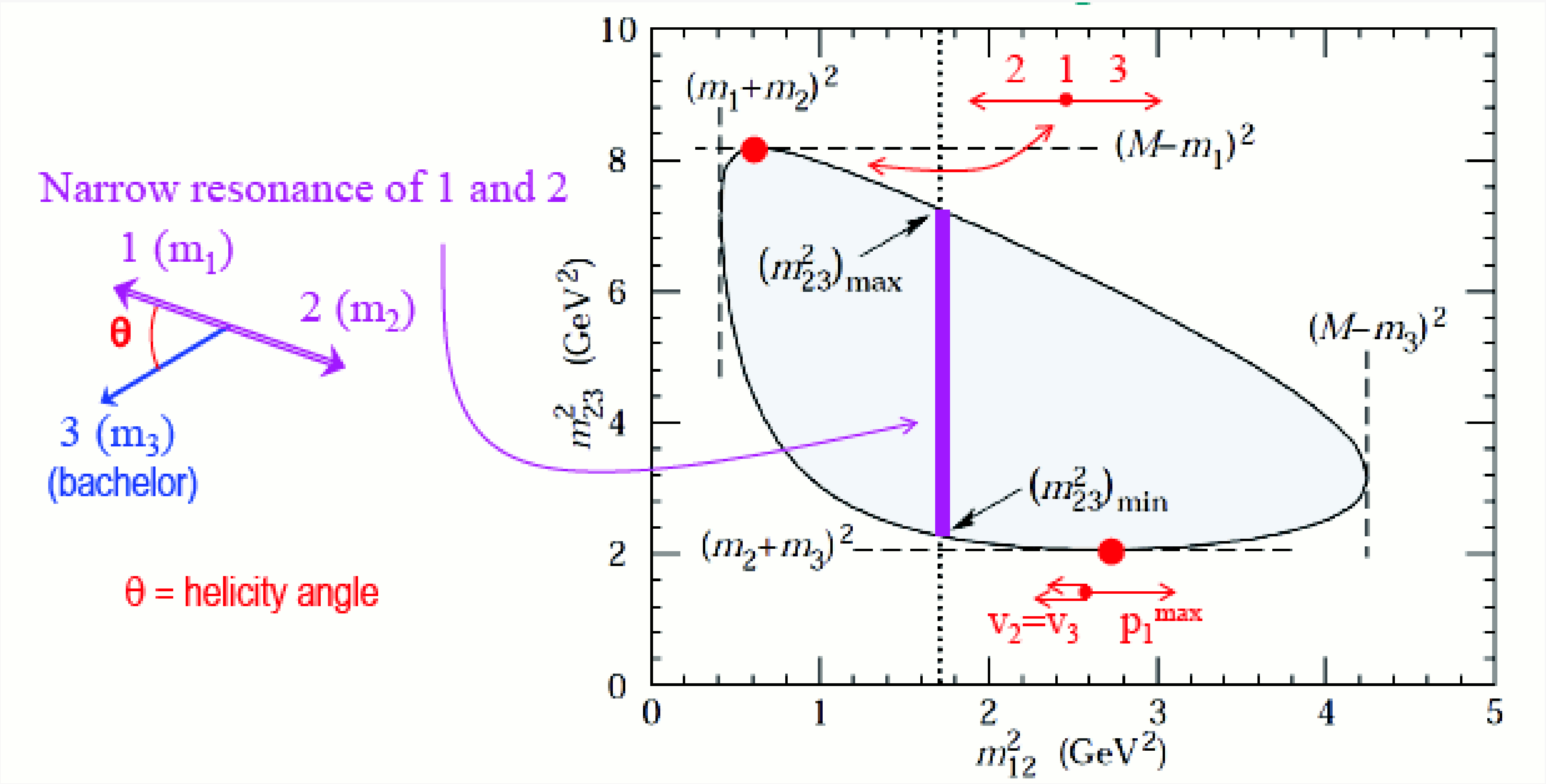
Tension between $\sin 2\phi_1$ from $b \to c\bar{c}s$ and $b \to q\bar{q}s$ $(\Delta S < 0)$

Dalitz plot

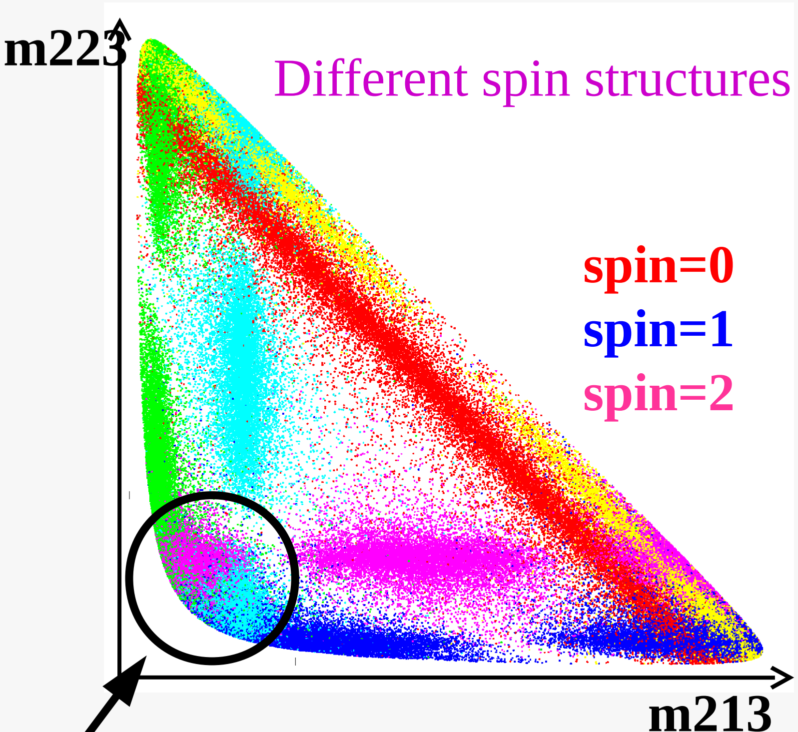
In 3-body decays spin-0 → 3 spin-0 (e.g. $B^0 \rightarrow \pi^+ \pi^- K^0_S$), there are only 2 meaningful degrees of freedom: usually taken to be squared invariant masses m^2_{ij}

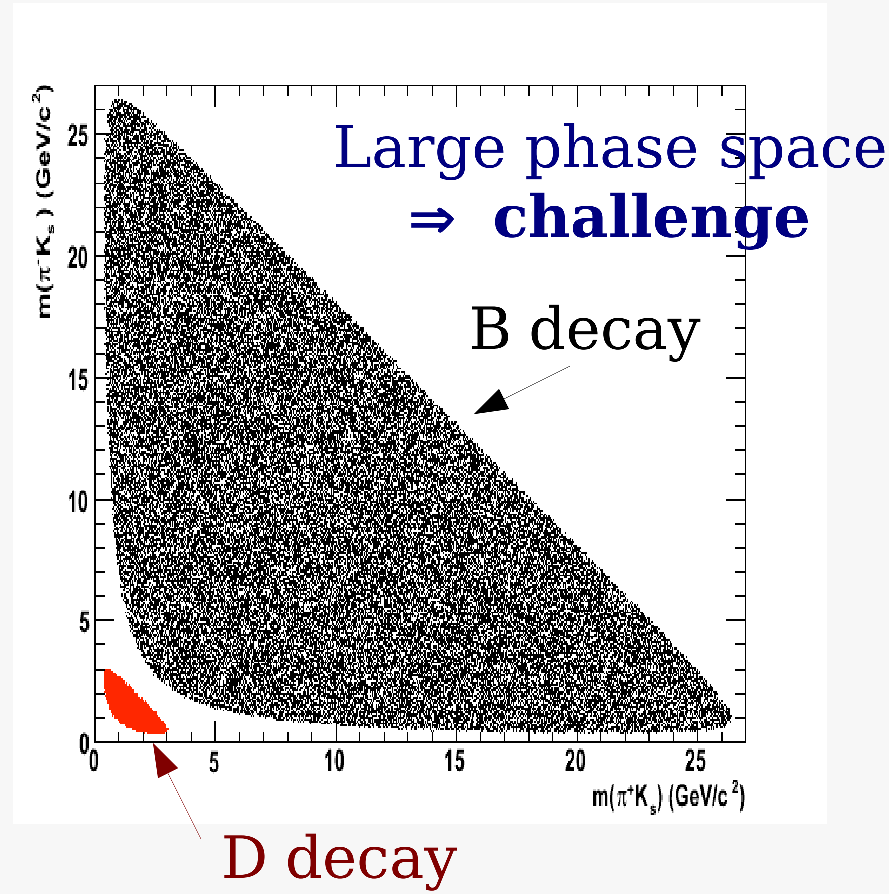
$$d\,m_{12}\,d\,m_{23} \propto \frac{d^3 p}{E}$$

Intermediate resonance ⇒ structure in the DP according to its mass and width



Dalitz plot





Superimposed resonant contributions:

- interference
- access to phases
  with no ambiguity such as $\sin 2\phi_1^{\mathrm{eff}} = \sin(\pi - 2\phi_1^{\mathrm{eff}})$

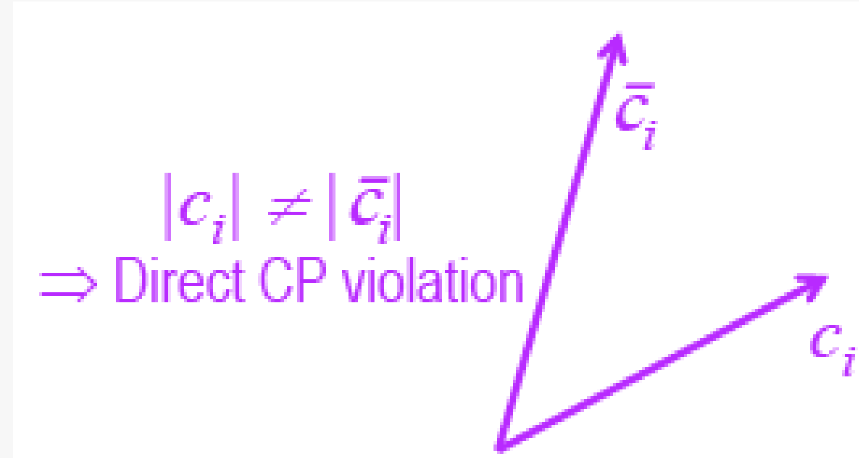
The isobar model

- Parameterization of intermediate state amplitudes
- In B decays:

$$A \sim \sum \underbrace{c_i}_{\text{complex}} \underbrace{F(m_{13}^2, m_{23}^2)}_{\text{e.g. Breit-Wigner}}$$

complex e.g. Breit-Wigner

(similar expression for $\bar{B}$ decays: $\bar{A}$)



- DP and Δt model:

$$\frac{d\Gamma\left(m_{13}^2, m_{23}^2, \Delta t, q_{tag}\right)}{d\Delta t\, dm_{13}\, dm_{23}} \propto e^{-|\Delta t|/\tau_{B^0}} \times \Big[\left(|A|^2 + |\bar{A}|^2\right) - q_{tag}\underbrace{\left(|A|^2 - |\bar{A}|^2\right)}_{\sim C}\cos(\Delta m_d \Delta t) + q_{tag}\underbrace{2\,\mathrm{Im}\left(\bar{A}A^* e^{-i2\beta}\right)}_{\sim S}\sin(\Delta m_d \Delta t)\Big]$$

Directly extracted parameters: isobar amplitudes c_i
Other parameters (S, C, A_{CP}, phases, BF) are computed from them

Dalitz-Plot Signal Model (an example: $B \to K_S \pi\pi$)

- Signal components:

  - $B^0 \to \rho^0(770)\, K^0_S$
  - $B^0 \to f_0(980)\, K^0_S$
  - $B^0 \to f_X(1300)\, K^0_S$
  - $B^0 \to f_2(1270)\, K^0_S$
  - $B^0 \to \chi_{c0}\, K^0_S$

  } $\pi^+\pi^-$ resonances

  - $B^0 \to K^*(892)\, \pi$
  - $B^0 \to K\pi$ S-wave

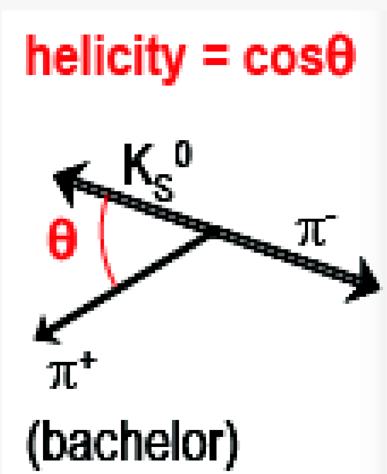
  } $K\pi$ resonances

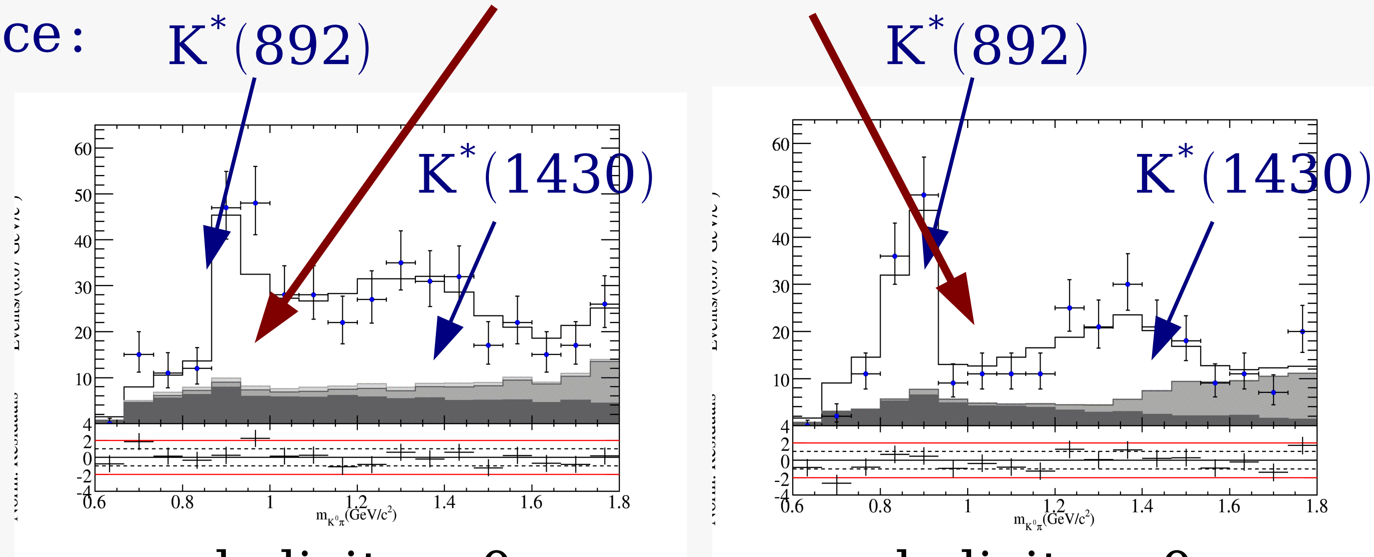
  - Non-resonant

interference

constructive destructive

- Example of interference:





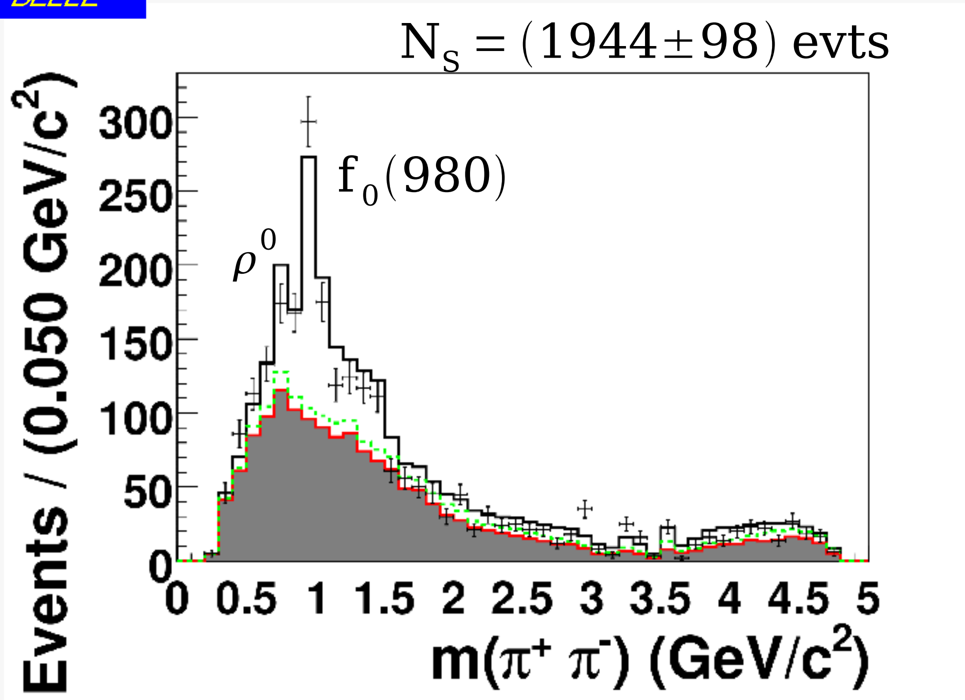
helicity > 0 helicity < 0

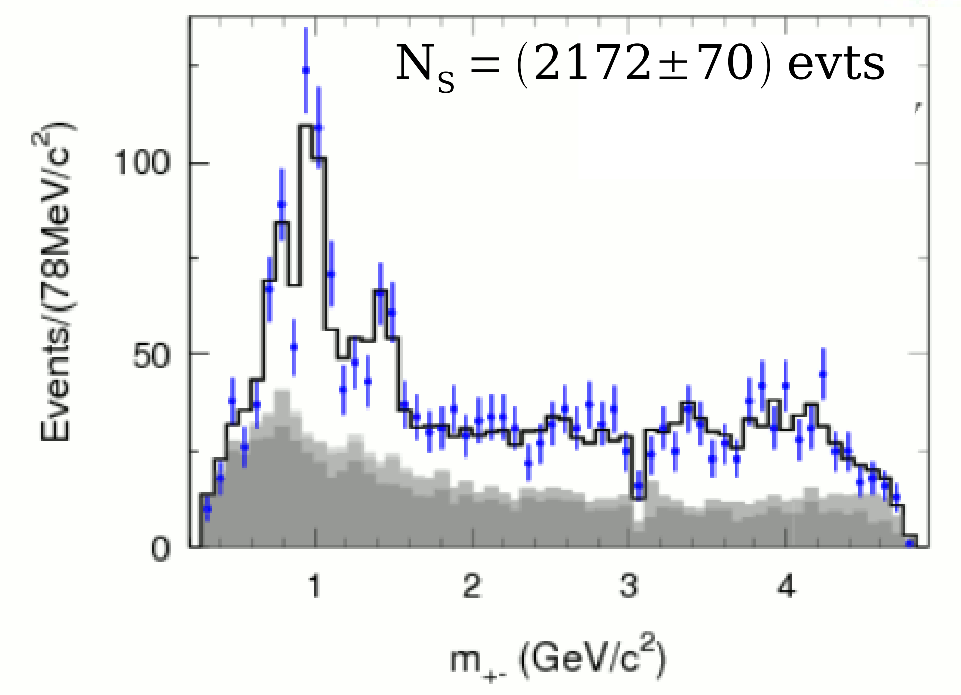
- multiple solutions: major issue in this method...
  (choice of the solution: external inputs...)

Time-dependent Dalitz plot analysis $K_S\pi^+\pi^-$

657×10^6 $B\bar{B}$ pairs
[ArXiv:0811.3665]

383×10^6 $B\bar{B}$ pairs
[ArXiv:0708.2097]





$\rho^0 K_S$

$$\beta_{\rm eff} = (20.0\,^{+8.6}_{-8.5} \pm 3.2 \pm 3.5)^\circ$$
$$A_{CP} = +0.03\,^{+0.23}_{-0.24} \pm 0.11 \pm 0.10$$

$$\beta_{\rm eff} = (19\,^{+10}_{-9} \pm 3 \pm 3)^\circ$$
$$A_{CP} = -0.02 \pm 0.27 \pm 0.08 \pm 0.06$$

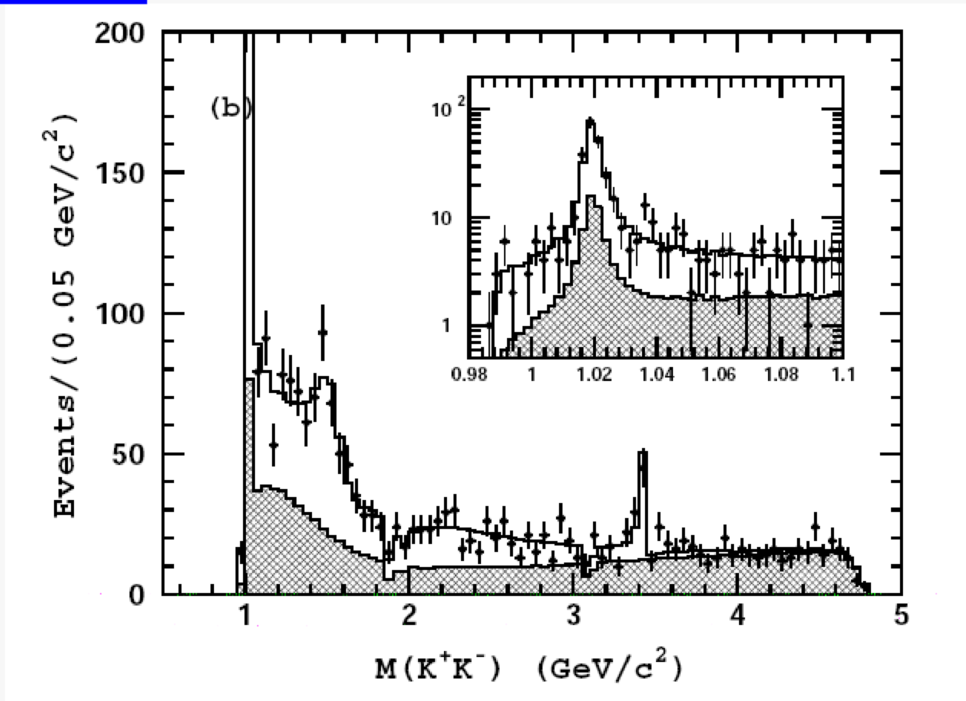
$f_0(980)K_S$

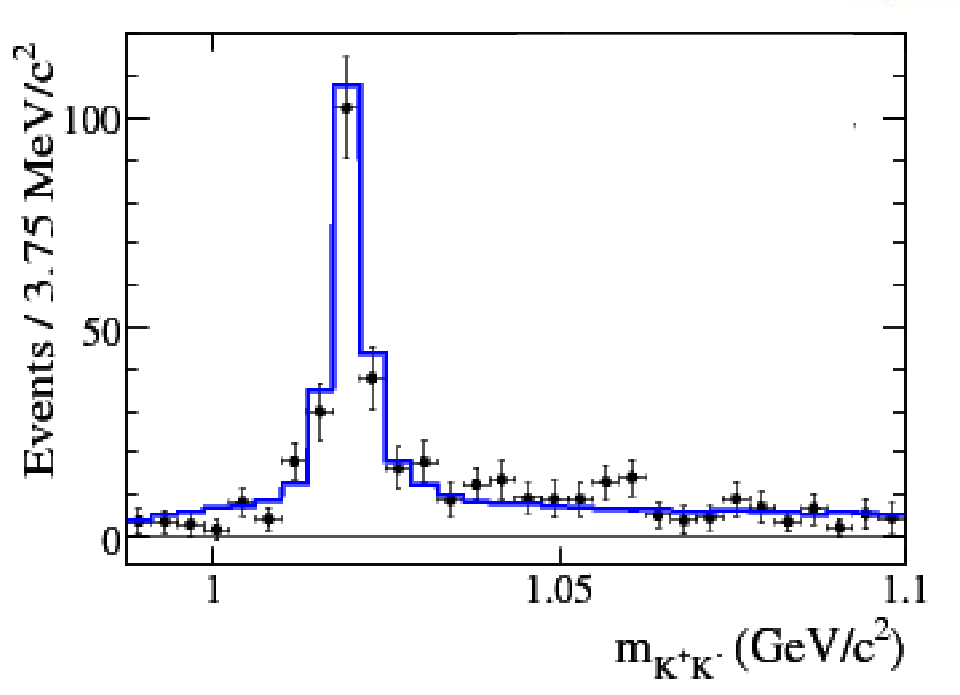
$$\beta_{\rm eff} = (12.7\,^{+6.9}_{-6.5} \pm 2.8 \pm 3.3)^\circ$$
$$A_{CP} = -0.06 \pm 0.17 \pm 0.07 \pm 0.09$$

$$\beta_{\rm eff} = (44\,^{+11}_{-10} \pm 3 \pm 4)^\circ$$
$$A_{CP} = -0.35 \pm 0.27 \pm 0.07 \pm 0.04$$

Time-dependent Dalitz plot analysis $K_S K^+ K^-$

465×10^6 $B\bar{B}$ pairs
[ArXiv:0808.0700]





ϕK_S

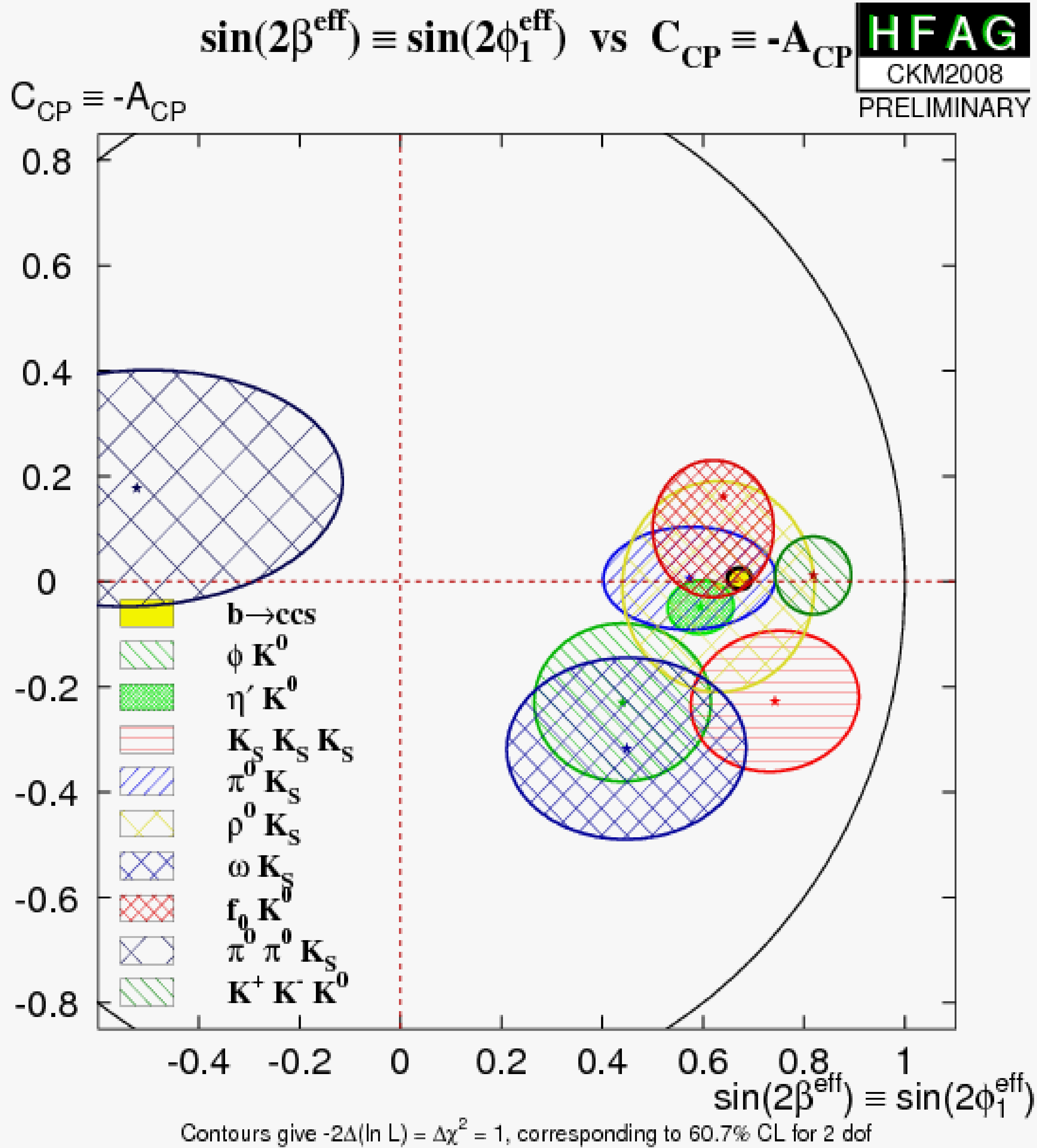
$$\beta_{\rm eff} = (21.2\ ^{+9.8}_{-10.4} \pm 2.0 \pm 2.0)^\circ$$
$$A_{CP} = +0.31\ ^{+0.21}_{-0.23} \pm 0.04 \pm 0.09$$

$$\beta_{\rm eff} = (7.7 \pm 7.7 \pm 0.9)^\circ$$
$$A_{CP} = +0.14 \pm 0.19 \pm 0.02$$

$f_0(980) K_S$

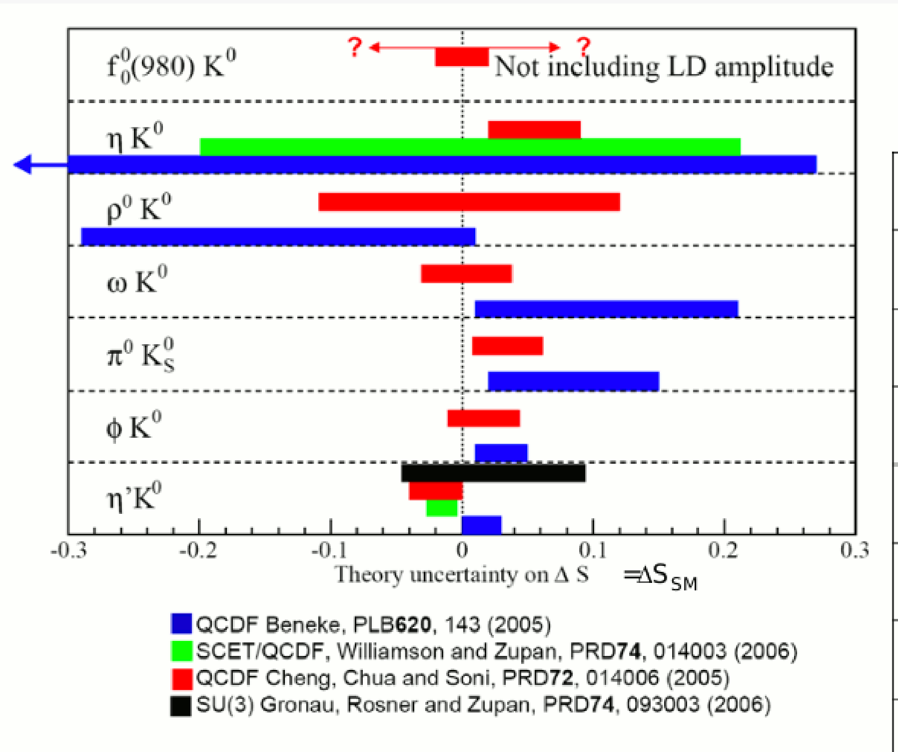
$$\beta_{\rm eff} = (28.2\ ^{+9.9}_{-9.8} \pm 2.0 \pm 2.0)^\circ$$
$$A_{CP} = -0.02 \pm 0.34 \pm 0.08 \pm 0.09$$

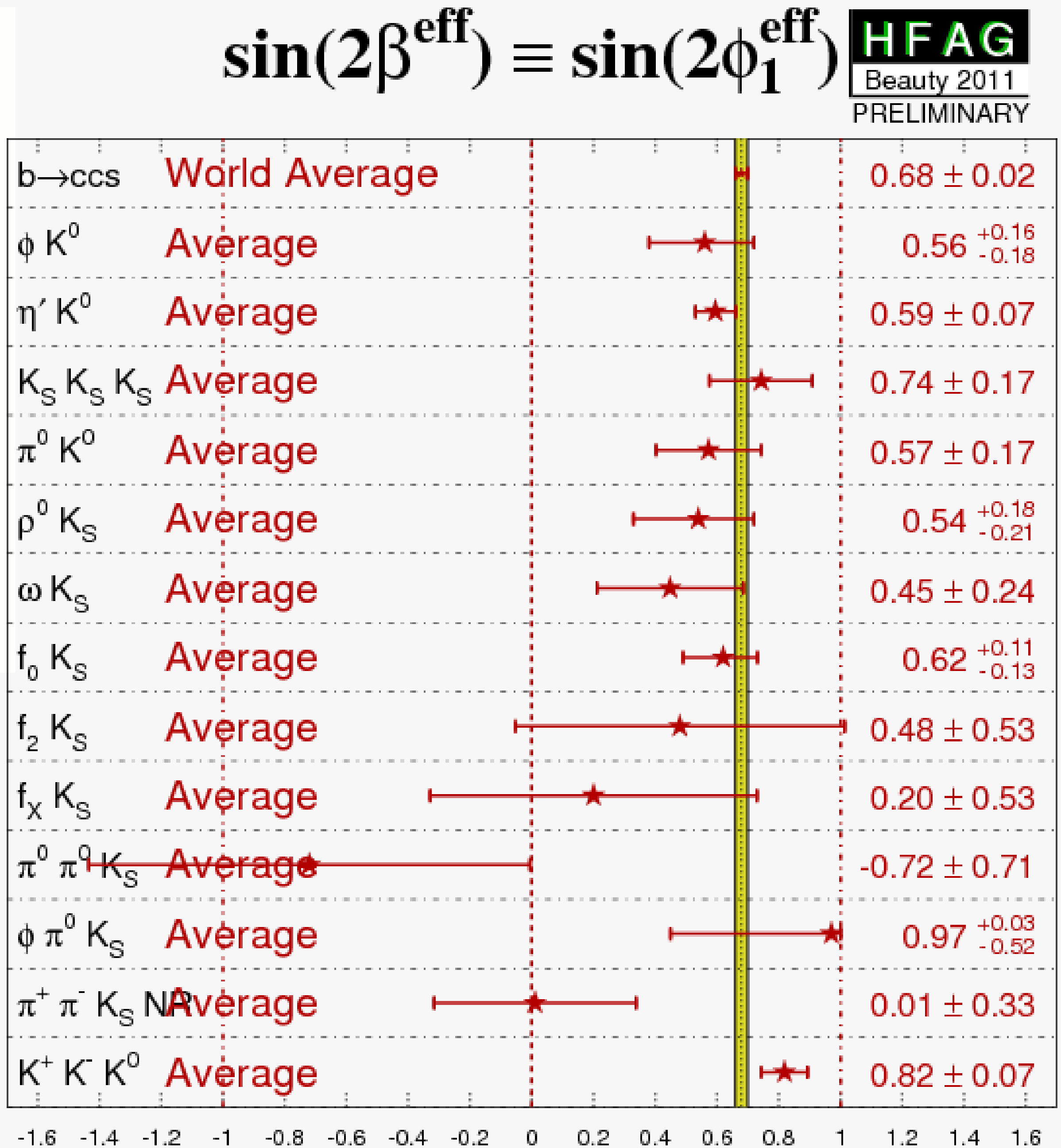
$$\beta_{\rm eff} = (8.5 \pm 7.5 \pm 1.8)^\circ$$
$$A_{CP} = +0.01 \pm 0.26 \pm 0.07$$



$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$ vs $C_{CP} \equiv -A_{CP}$
HFAG
CKM2008
PRELIMINARY
$C_{CP} \equiv -A_{CP}$
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$
$b \to ccs$
ϕK^0
$\eta' K^0$
$K_S K_S K_S$
$\pi^0 K_S$
$\rho^0 K_S$
ωK_S
$f_0 K^0$
$\pi^0 \pi^0 K_S$
$K^+ K^- K^0$
Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

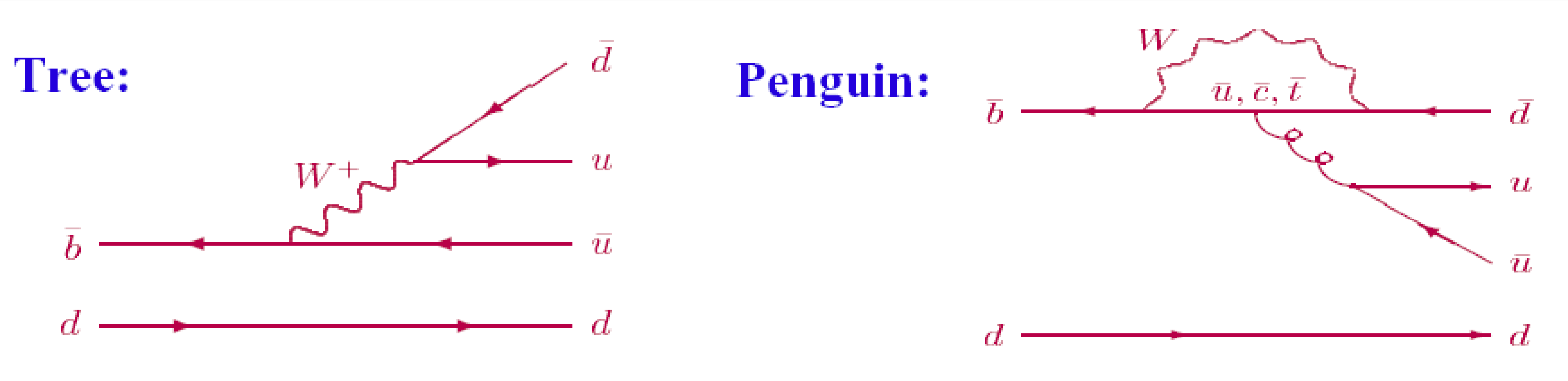
β with b→s penguins





More statistics crucial
for mode-by-mode studies

α determination



$$A(B^0 \to \pi^+ \pi^-) = T\, e^{i\gamma} + P\, e^{i\delta},\; r = |P|/|T|$$

$$\begin{aligned} A(t) &= S_{\pi^+\pi^-} \sin(\Delta m t) - C_{\pi^+\pi^-} \cos(\Delta m t) \\ &= \sqrt{1 - C^2_{\pi^+\pi^-}}\, \sin 2\alpha_{\text{eff}} \sin(\Delta m t) - C_{\pi^+\pi^-} \cos(\Delta m t) \end{aligned}$$

from time dependent CP, we can measure α_{eff}, but we want α !

expanding in r: $\boxed{\mathbf{S}_{\pi^+\pi^-} = \mathbf{\sin 2\alpha} + 2r \cos\delta \sin(\beta + \alpha) \cos 2\alpha + O(r^2)}$

time dependent decay width:

$$\Gamma(B^0(t)) \propto \Gamma_{\pi^+\pi^-} [1 + C_{\pi^+\pi^-} \cos \Delta m t - S_{\pi^+\pi^-} \sin \Delta m t]$$

3 measurables vs. 4 unknowns: T, r, δ, γ

$\to$ additional inputs required to determine the penguin pollution to fix r

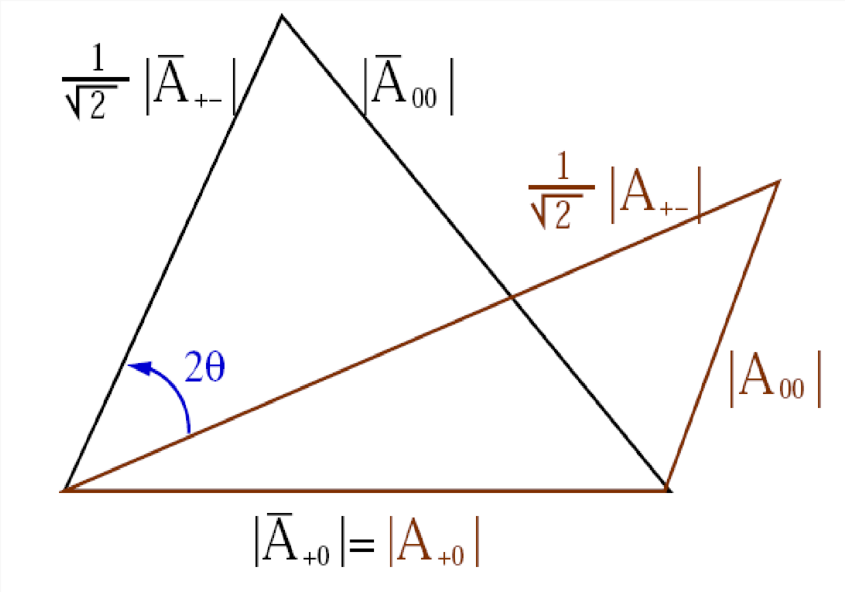
α determination with isospin analysis

[Gronau-London, PRL65, 3381 (1990)]

Isospin breaking (d and u charges different, $m_u \neq m_d$)

$$A_{+-} = A(B^0 \to \pi^+ \pi^-) = e^{-i\alpha}\, T^{+-} + P$$
$$\sqrt{2}\, A_{00} = \sqrt{2}\, A(B^0 \to \pi^0 \pi^0) = e^{-i\alpha}\, T^{00} + P$$
$$\sqrt{2}\, A_{+0} = \sqrt{2}\, A(B^+ \to \pi^+ \pi^0) = e^{-i\alpha}\, (T^{00} + T^{+-})$$

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



- neglecting EWP $\Rightarrow$ A_{+0} pure tree

  $|A_{+0}| = |\bar{A}_{+0}|$

$\Rightarrow$ $\Delta\alpha_{EWP} = (1.5 \pm 0.3 \pm 0.3)^o$

- $\pi^0 - \eta - \eta'$ and $\rho - \omega$ mixing [J.Zupan, hep-ph/0701004]

  (mass eigenstates do not coincide with isospin eigenstates)

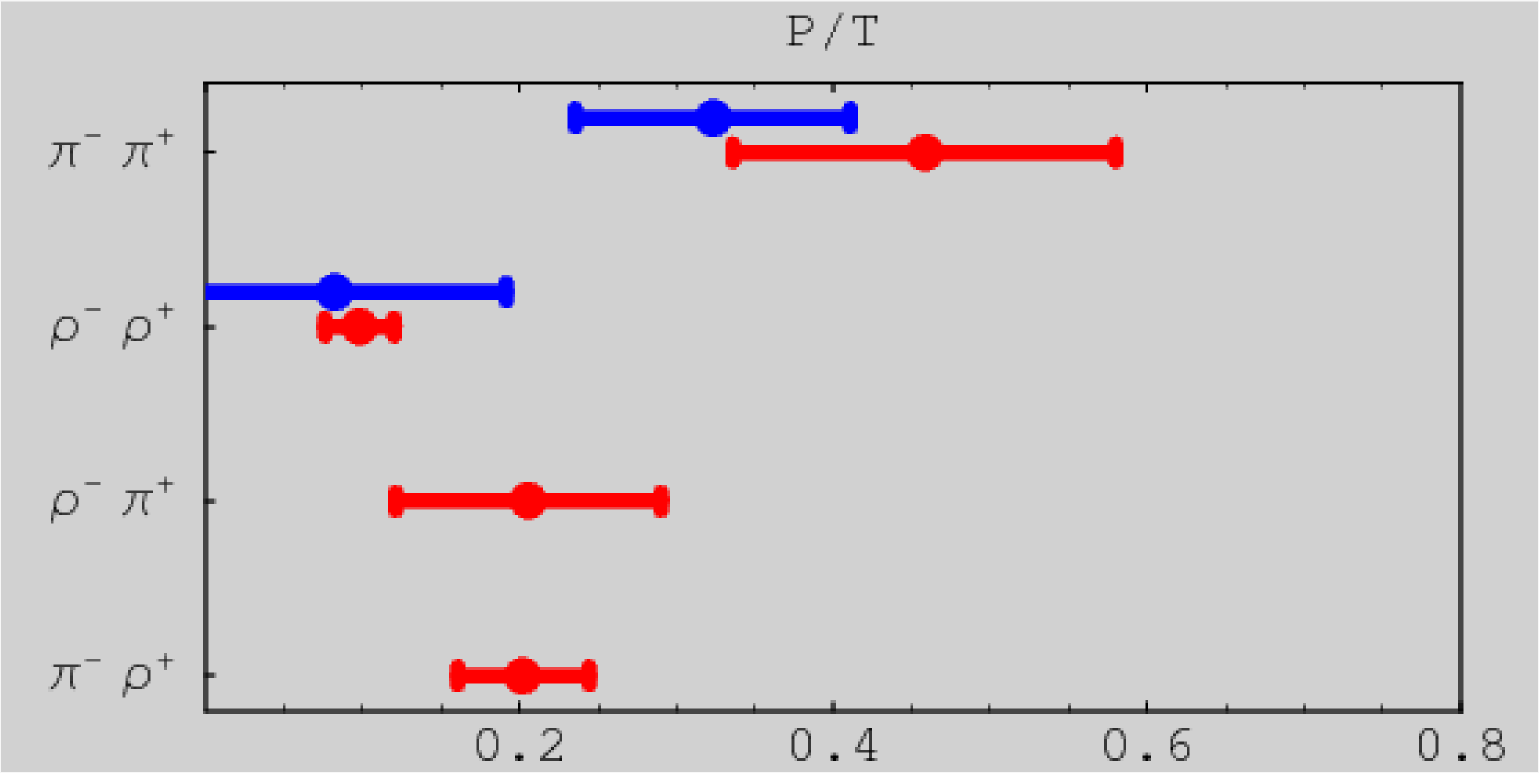
$\Rightarrow$ $|\Delta\alpha_{\pi\pi}^{\pi\text{-}\eta\text{-}\eta'}| < 1.6^o$

α can be resolved up to an 8-fold ambiguity ($\alpha \in [0, \pi]$)

Sizes of penguin-to-tree ratios r

hierarchy: $r(\pi^+\pi^-) > r(\rho^+\pi^-) \sim r(\rho^+\pi^-) > r(\rho^+\rho^-)$

larger r $\Rightarrow$ larger difference $\sin 2\alpha - \sin 2\alpha_{\rm eff}$



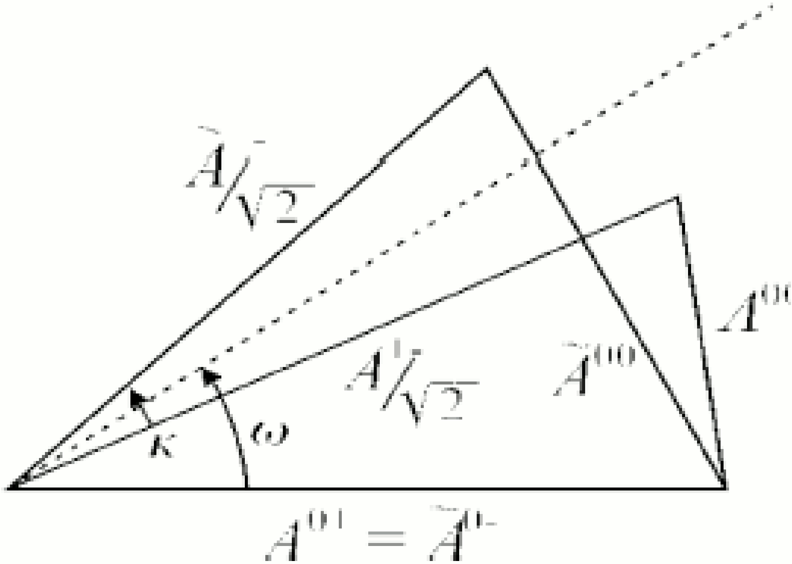
(blue) from isospin decomposition, (red) using SU(3)

Concrete example: B→$\pi\pi$ at Belle

Gronau and London,
PRL 65, 3381 (1990)

$$\frac{A(B^0\to\pi^+\pi^-)}{\sqrt{2}} + A(B^0\to\pi^0\pi^0) = A(B^+\to\pi^+\pi^0)$$
$$\frac{A(\overline{B}^0\to\pi^+\pi^-)}{\sqrt{2}} + A(\overline{B}^0\to\pi^0\pi^0) = A(B^-\to\pi^-\pi^0)$$

$$|A^{+-}_{\rm th}| = \sqrt{a^{+-}(1-\mathcal{A}_{\pi\pi})}$$
$$|\overline{A}^{+-}_{\rm th}| = \sqrt{a^{+-}(1+\mathcal{A}_{\pi\pi})}$$
$$|A^{0-}_{\rm th}| = |A^{0+}_{\rm th}| = \sqrt{a^{0+}}$$
$$|A^{00}_{\rm th}|^2 = \frac{|A^{+-}_{\rm th}|^2}{2} + |A^{0+}_{\rm th}|^2 - \sqrt{2}|A^{+-}_{\rm th}||A^{+0}_{\rm th}|\cos(\omega-\kappa/2)$$
$$|\overline{A}^{00}_{\rm th}|^2 = \frac{|\overline{A}^{+-}_{\rm th}|^2}{2} + |A^{0+}_{\rm th}|^2 - \sqrt{2}|\overline{A}^{+-}_{\rm th}||A^{+0}_{\rm th}|\cos(\omega+\kappa/2)$$
$$B^{\pi^+\pi^-}_{\rm th} = \left(|A^{+-}_{\rm th}|^2 + |\overline{A}^{+-}_{\rm th}|^2\right)/2 = a^{+-}$$
$$B^{\pi^0\pi^0}_{\rm th} = \left(|A^{00}_{\rm th}|^2 + |\overline{A}^{00}_{\rm th}|^2\right)/2$$
$$B^{\pi^0\pi^+}_{\rm th} = |A^{0+}_{\rm th}|^2(\tau_{B^\pm}/\tau_{B^0}) = a^{+0}\cdot(\tau_{B^\pm}/\tau_{B^0})$$
$$\mathcal{A}^{\pi^0\pi^0}_{\rm th} = \frac{|\overline{A}^{00}_{\rm th}|^2 - |A^{00}_{\rm th}|^2}{|\overline{A}^{00}_{\rm th}|^2 + |A^{00}_{\rm th}|^2}$$
$$\mathcal{A}^{\pi^+\pi^-}_{\rm th} = \mathcal{A}_{\pi\pi}$$
$$\mathcal{S}^{\pi^+\pi^-}_{\rm th} = \sqrt{1-\mathcal{A}'^2_{\pi\pi}}\,\sin(2\phi_2+\kappa)$$



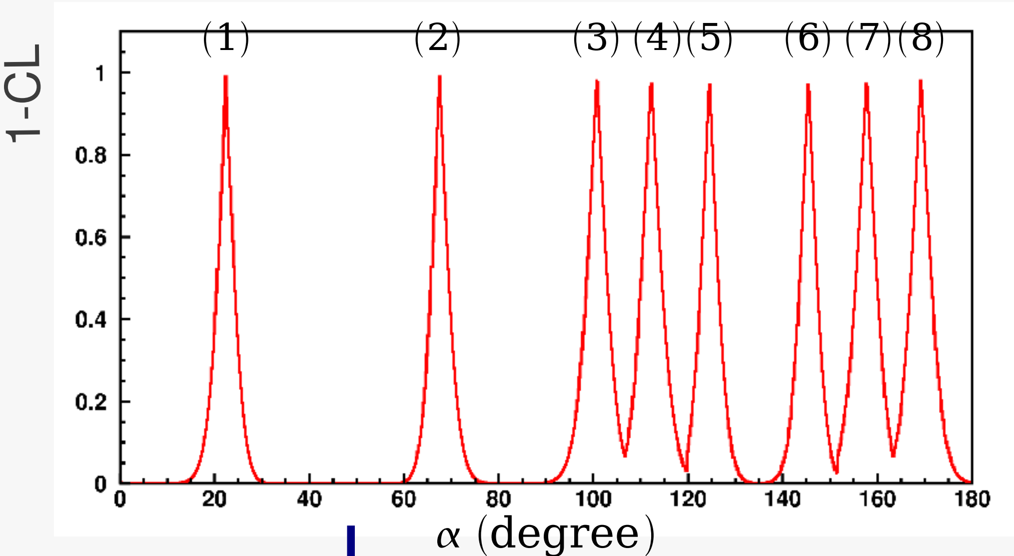
6 parameters + 6 observables
⇒ all determined

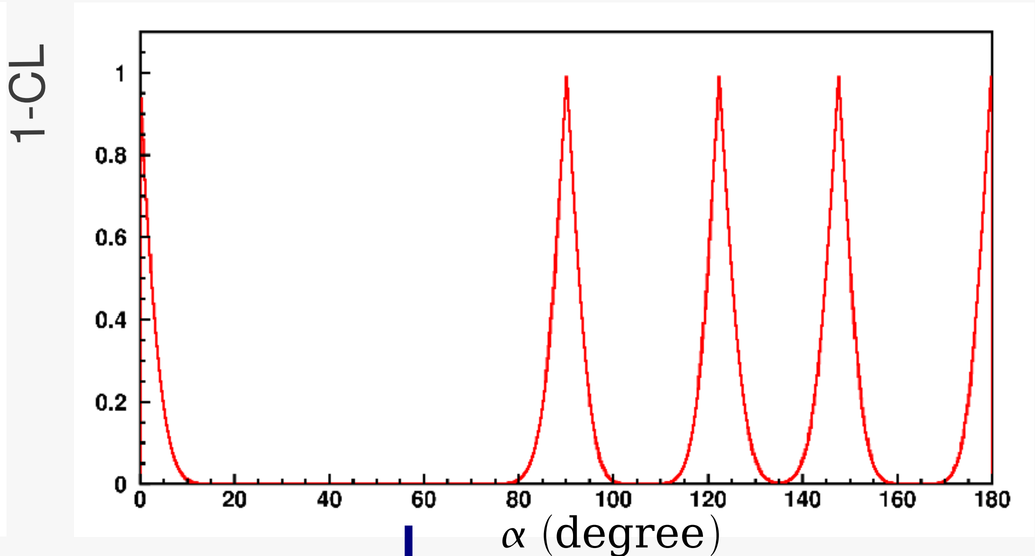
Some examples to illustrate α extraction

$Br(\pi^+\pi^-) = (5.0 \pm 0.2)\times 10^{-6}$
$Br(\pi^0\pi^0) = (1.5 \pm 0.1)\times 10^{-6}$
$Br(\pi^+\pi^0) = (3.5 \pm 0.2)\times 10^{-6}$
$C(\pi^+\pi^-) = -0.40 \pm 0.03$
$S(\pi^+\pi^-) = -0.50 \pm 0.04$
$C(\pi^0\pi^0) = -0.30 \pm 0.10$

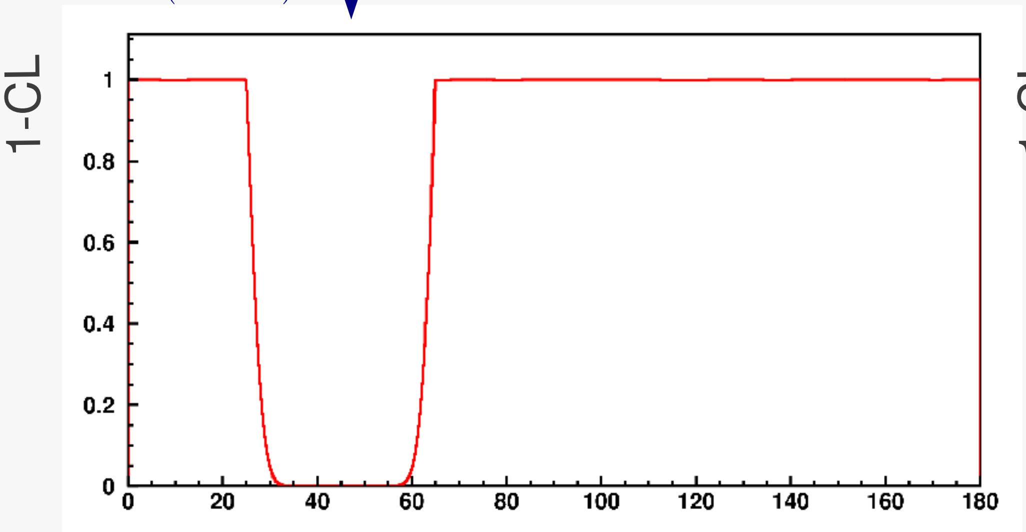
$\longrightarrow$

$\boxed{\begin{array}{l} Br(\pi^+\pi^-) = (2.0 \pm 0.2)\times 10^{-6} \\ Br(\pi^0\pi^0) = (0.5 \pm 0.1)\times 10^{-6} \end{array}}$
$Br(\pi^+\pi^0) = (3.5 \pm 0.2)\times 10^{-6}$
$C(\pi^+\pi^-) = -0.40 \pm 0.03$
$S(\pi^+\pi^-) = -0.50 \pm 0.04$
$C(\pi^0\pi^0) = -0.30 \pm 0.10$

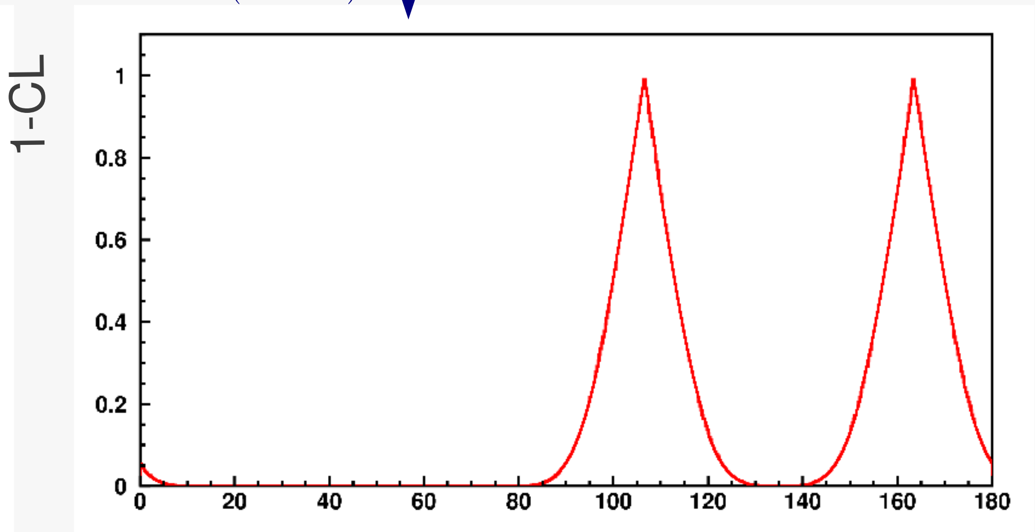




no $C(\pi^0\pi^0)$



no $C(\pi^0\pi^0)$



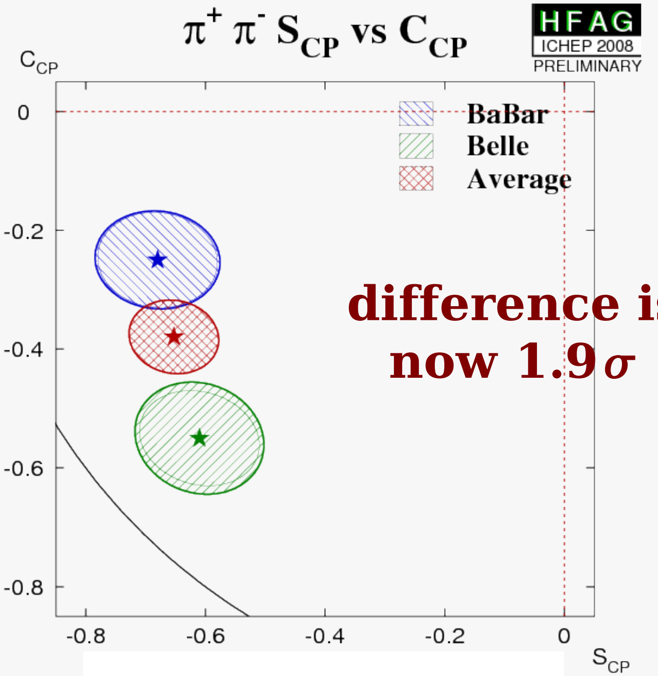
$\underline{\alpha}: \pi\pi$ system

$535 \times 10^6\ B\bar{B}$ **pairs**
PRL98, 221801(2007)

$$C = -0.55 \pm 0.08 \pm 0.05$$

$$S = -0.61 \pm 0.10 \pm 0.04$$

direct CPV @ 5.5σ

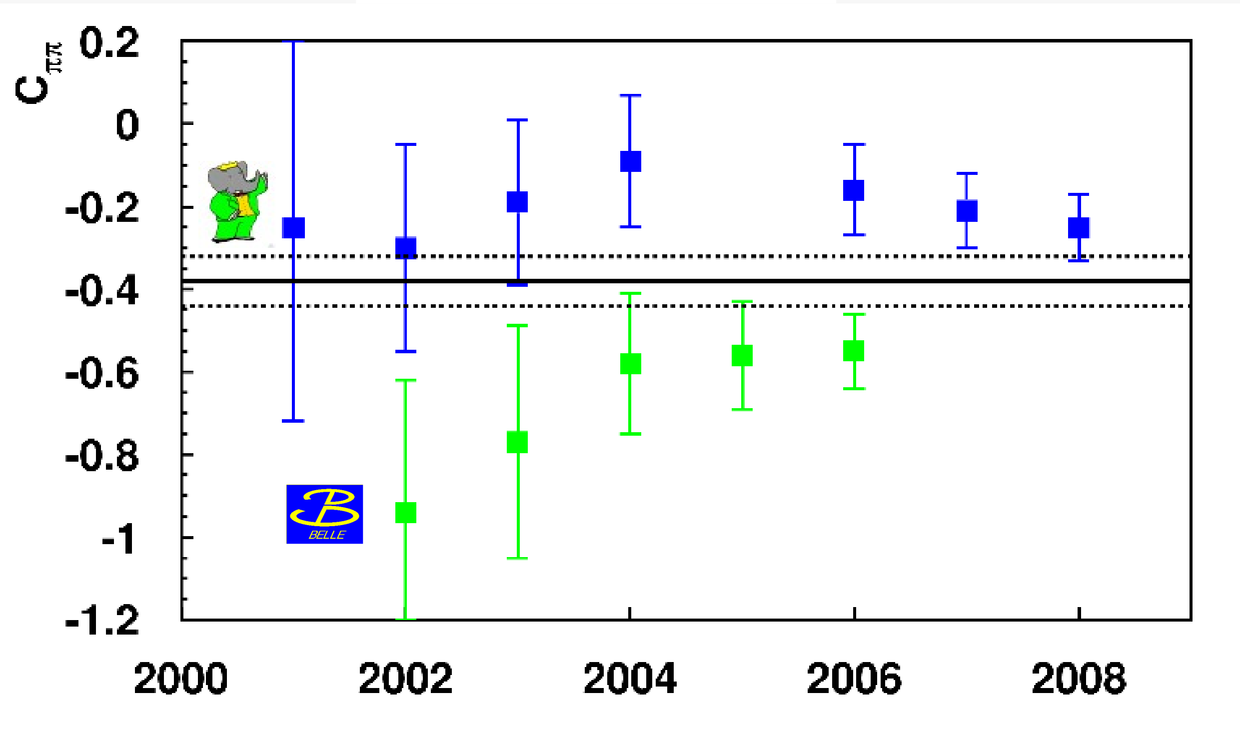


difference is now 1.9σ

$467 \times 10^6\ B\bar{B}$ **pairs**
ArXiv:0807.4226

$$C = -0.25 \pm 0.08 \pm 0.02$$

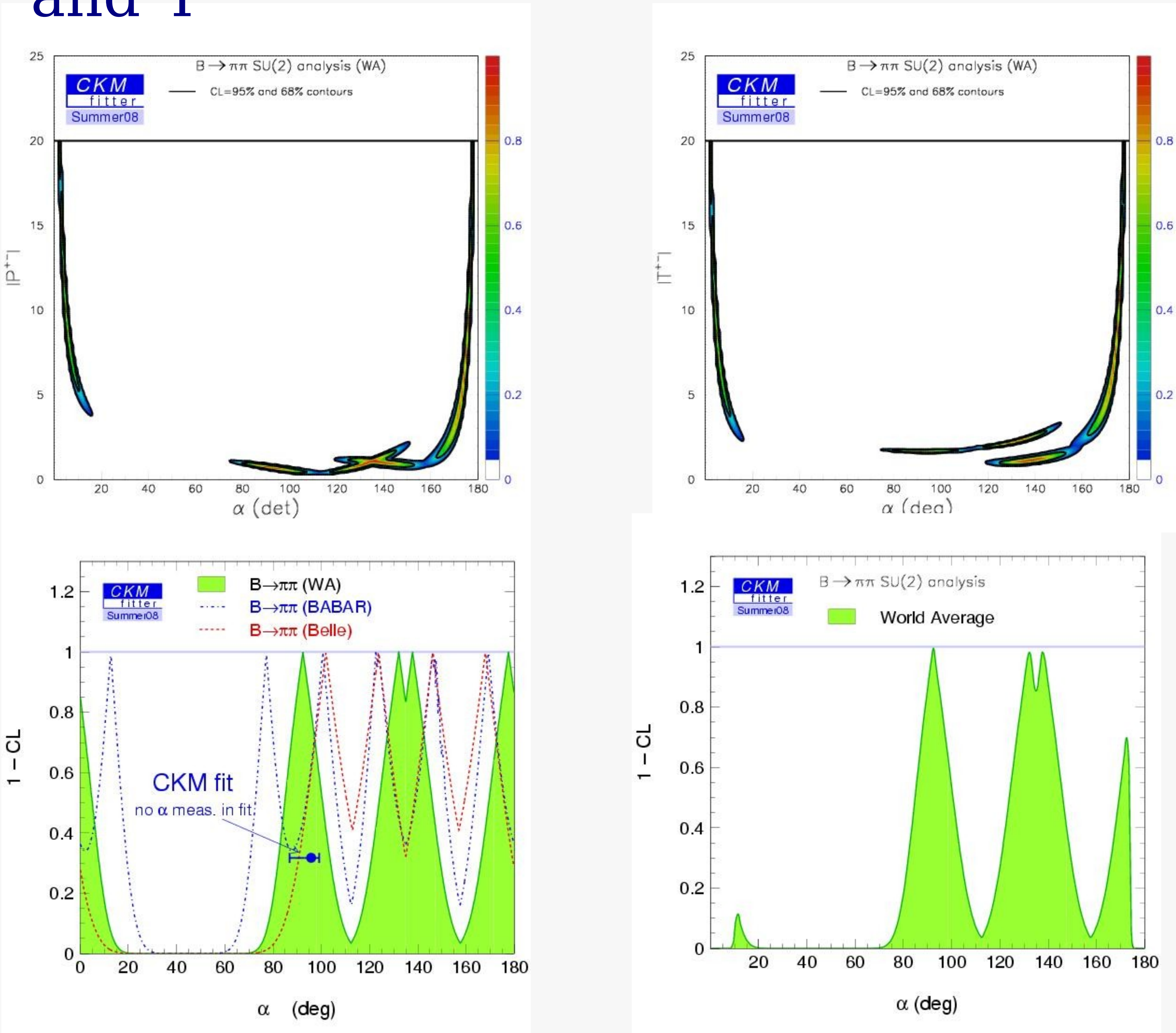
$$S = -0.68 \pm 0.10 \pm 0.03$$



Summary of $C_{\pi\pi}$

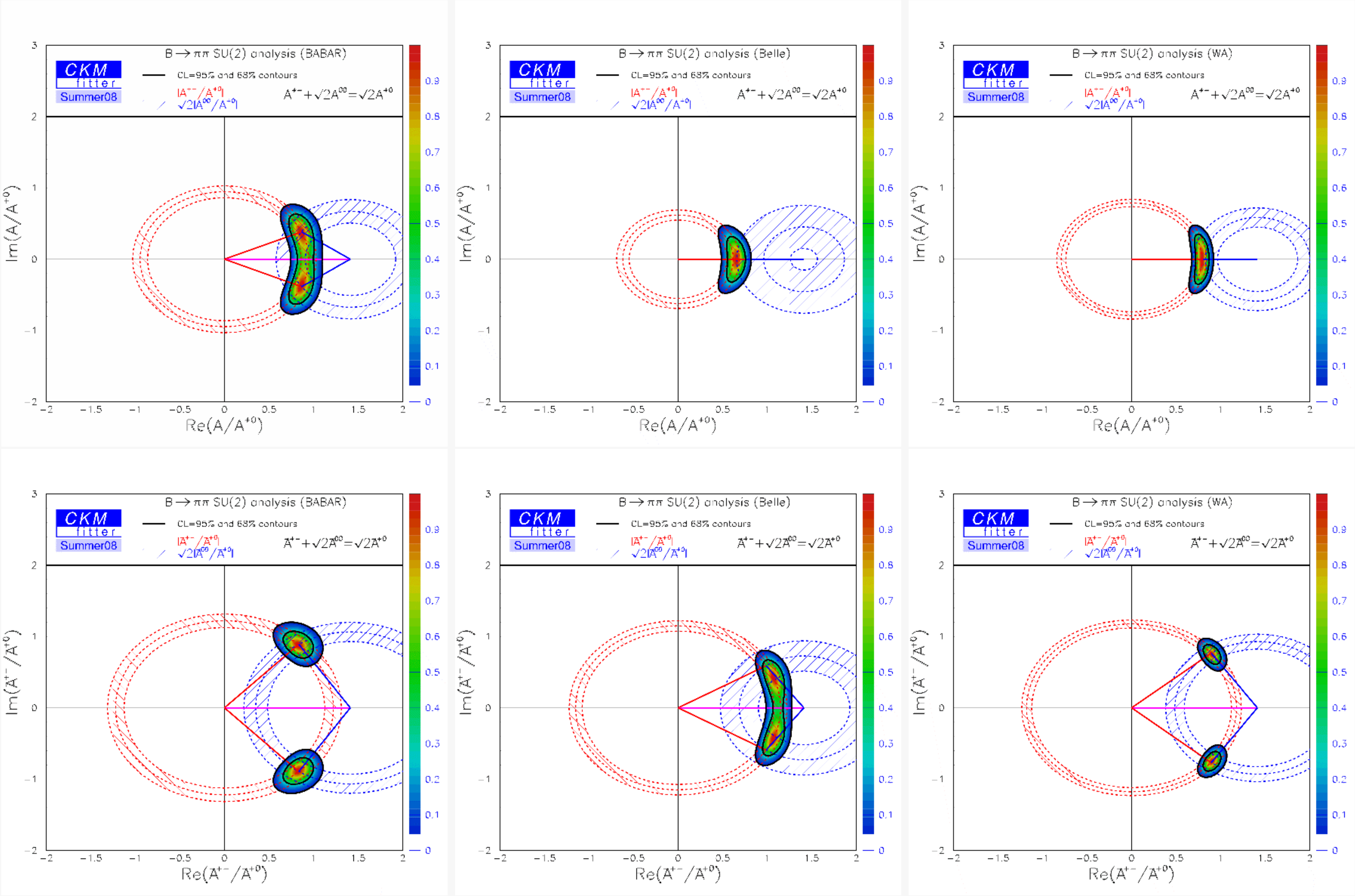
Year	BaBar	Belle	Difference
2001	$\mathbf{-0.25 \pm 0.45 \pm 0.14}$ PRD 65, 051502 (33M)		
2002	$\mathbf{-0.30 \pm 0.25 \pm 0.04}$ PRL 89, 281802 (88M)	$\mathbf{-0.94\,^{+0.25}_{-0.31} \pm 0.09}$ PRL 89, 071801 (45M)	
2003	$\mathbf{-0.19 \pm 0.19 \pm 0.05}$ preliminary LP2003 (123M)	$\mathbf{-0.77 \pm 0.27 \pm 0.08}$ PRD 68, 012001 (85M)	2.0σ
2004	$\mathbf{-0.09 \pm 0.15 \pm 0.04}$ PRL 95, 151803 (227M)	$\mathbf{-0.58 \pm 0.15 \pm 0.07}$ PRL 93, 021601 (152M)	3.2σ
2005		$\mathbf{-0.56 \pm 0.12 \pm 0.06}$ PRL 95, 101801 (275M)	2.3σ
2006	$\mathbf{-0.16 \pm 0.11 \pm 0.03}$ ArXiv:0607106 (347M)	$\mathbf{-0.55 \pm 0.08 \pm 0.05}$ PRL 98, 211801 (535M)	2.3σ
2007	$\mathbf{-0.21 \pm 0.09 \pm 0.02}$ PRL 99, 021603 (383M)		2.1σ
2008	$\mathbf{-0.25 \pm 0.08 \pm 0.02}$ ArXiv:0807.4226 (467M)		1.9σ

P and T



B → ππ SU(2) analysis (WA)
CKM fitter Summer08
CL=95% and 68% contours
|P+-|
α (deg)
|T+-|
B→ππ (WA)
B→ππ (BABAR)
B→ππ (Belle)
CKM fit
no α meas. in fit
1 – CL
α (deg)
B → ππ SU(2) analysis
World Average

Isospin triangles $B \to \pi\pi$ case



α: $\pi\pi$ system (6 observables for 6 parameters)

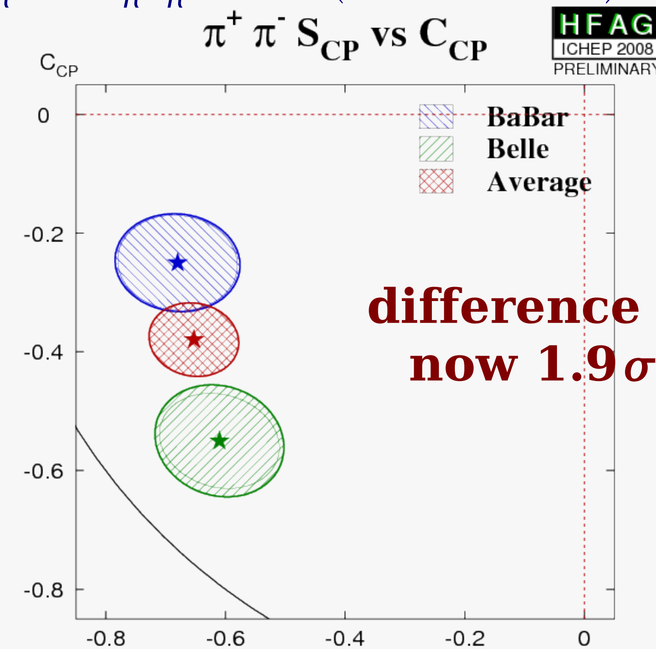
$Br(B\to\pi^+\pi^-)$, $S_{\pi^+\pi^-}$, $C_{\pi^+\pi^-}$, $Br(B\to\pi^+\pi^0)$, $Br(B\to\pi^0\pi^0)$, $C_{\pi^0\pi^0}$

535×10^6 $B\bar{B}$ pairs
PRL98, 221801(2007)

$C=-0.55\pm0.08\pm0.05$

$S=-0.61\pm0.10\pm0.04$

direct CPV @ 5.5σ

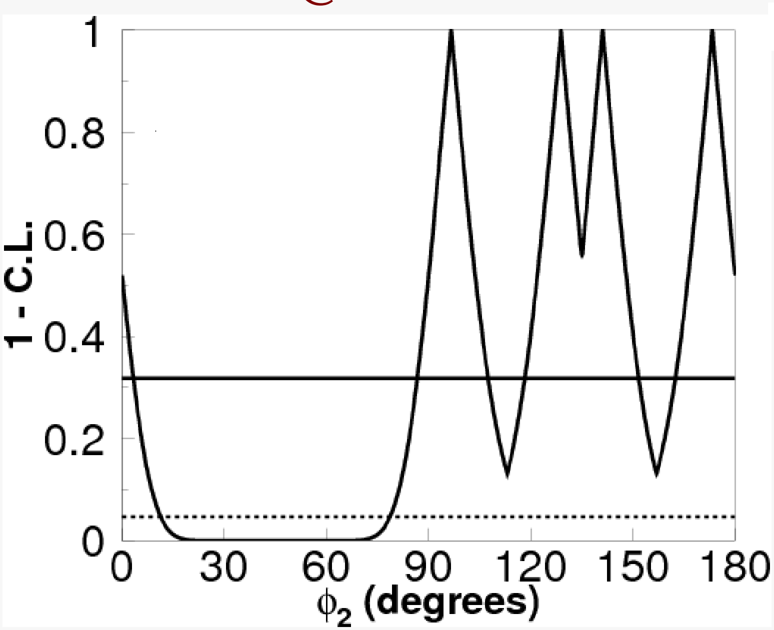


difference is now 1.9σ

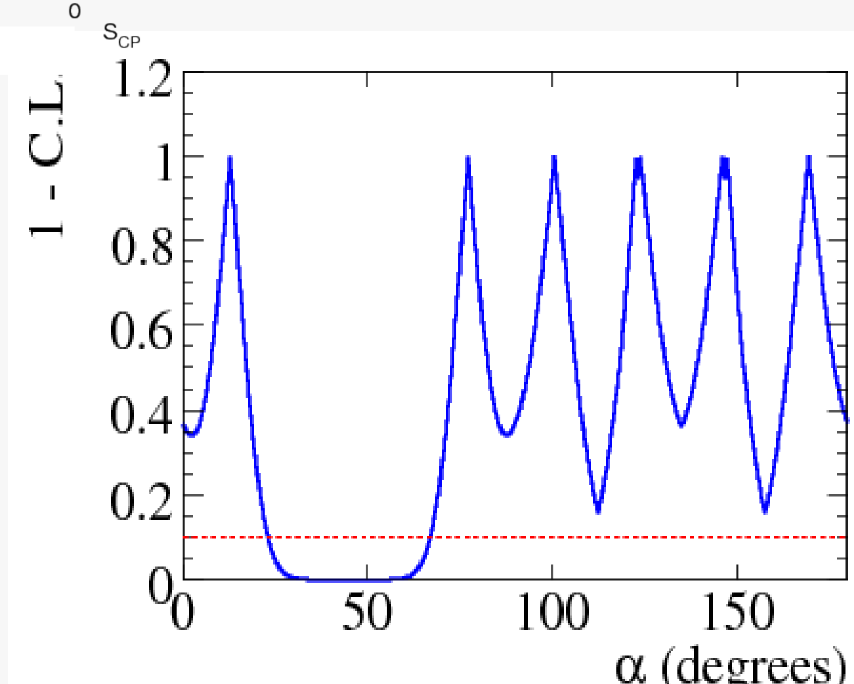
467×10^6 $B\bar{B}$ pairs
ArXiv:0807.4226

$C=-0.25\pm0.08\pm0.02$

$S=-0.68\pm0.10\pm0.03$



standard peak
$[86^\circ, 108^\circ]$ @ 68% C.L.

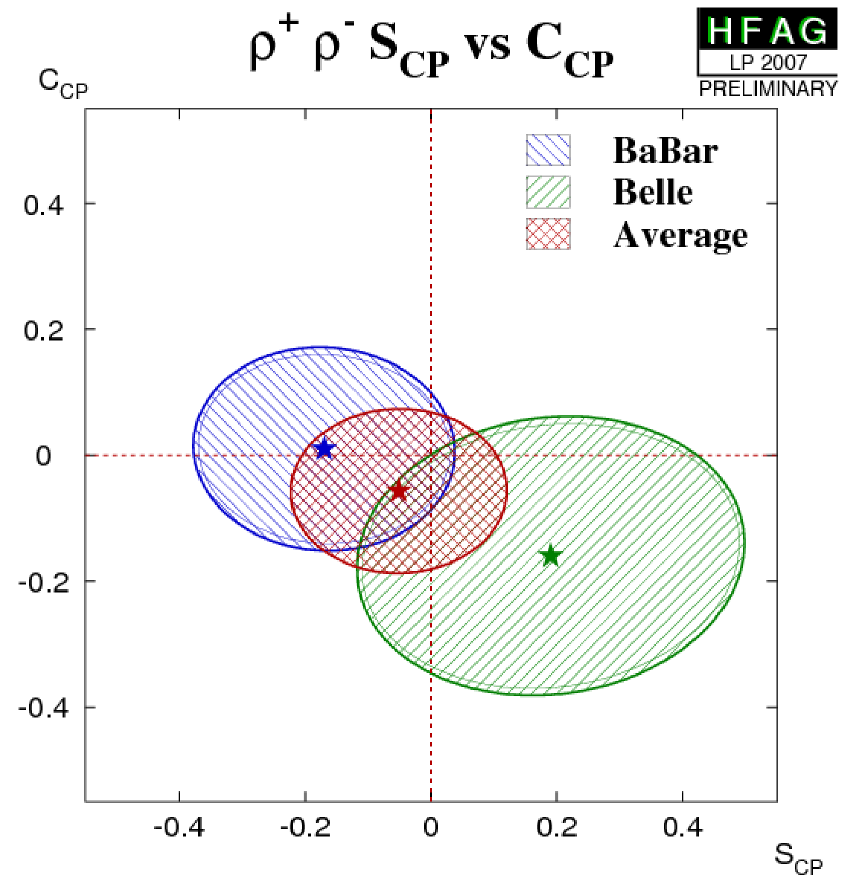


standard peak
$[71^\circ, 109^\circ]$ @ 68% C.L.

$\rho\,\rho$ system (5 observables for 6 parameters)

$(Br(B\to\rho^+\rho^-),\ S_{\rho^+\rho^-},\ C_{\rho^+\rho^-},\ Br(B\to\rho^+\rho^0),Br(B\to\rho^0\rho^0)) + f_L$

$\rho^+\rho^-$: ~ 100% longitudinally polarized (similar isospin analysis)



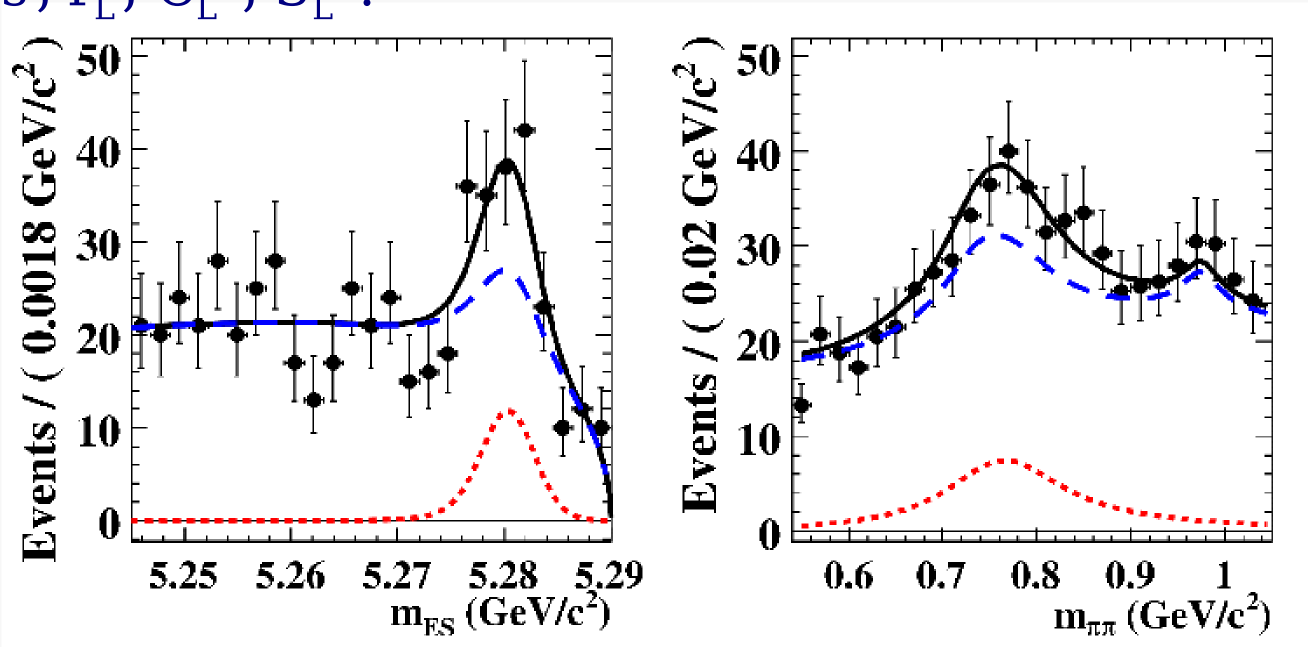
BaBar	Belle
387×10^6 $B\overline{B}$ pairs	**535×10^6 $B\overline{B}$ pairs**
PRD76, 052007(R)(2007)	**PRD76, 011104(R)(2007)**
$C=+0.01\pm0.15\pm0.06$	$C=-0.16\pm0.21\pm0.07$
$S=-0.17\pm0.20^{+0.05}_{-0.06}$	$S=+0.19\pm0.30\pm0.07$

$\rho^0\rho^0$ mode

465×10^6 $B\bar{B}$ pairs
[PRD78, 071104(R)]

10-dim fit to extract yields, f_L, C_L^{00}, S_L^{00}:

$N_S(\rho^0\rho^0) = 99^{+35}_{-34} \pm 15$
$(\Sigma = 3.1\ \sigma)$



$$\boxed{Br(B^0 \to \rho^0\rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}}$$

$N_S(\rho^0\pi^+\pi^-) = -12^{+39}_{-35} \pm 52$
$Br(B^0 \to \rho^0\pi^+\pi^-) < 8.7 \times 10^{-6}$ @ 90%C.L.

$N_S(4\pi^\pm) = 8^{+30}_{-25} \pm 6$
$Br(B^0 \to 4\pi^\pm) < 21.1 \times 10^{-6}$ @ 90%C.L.

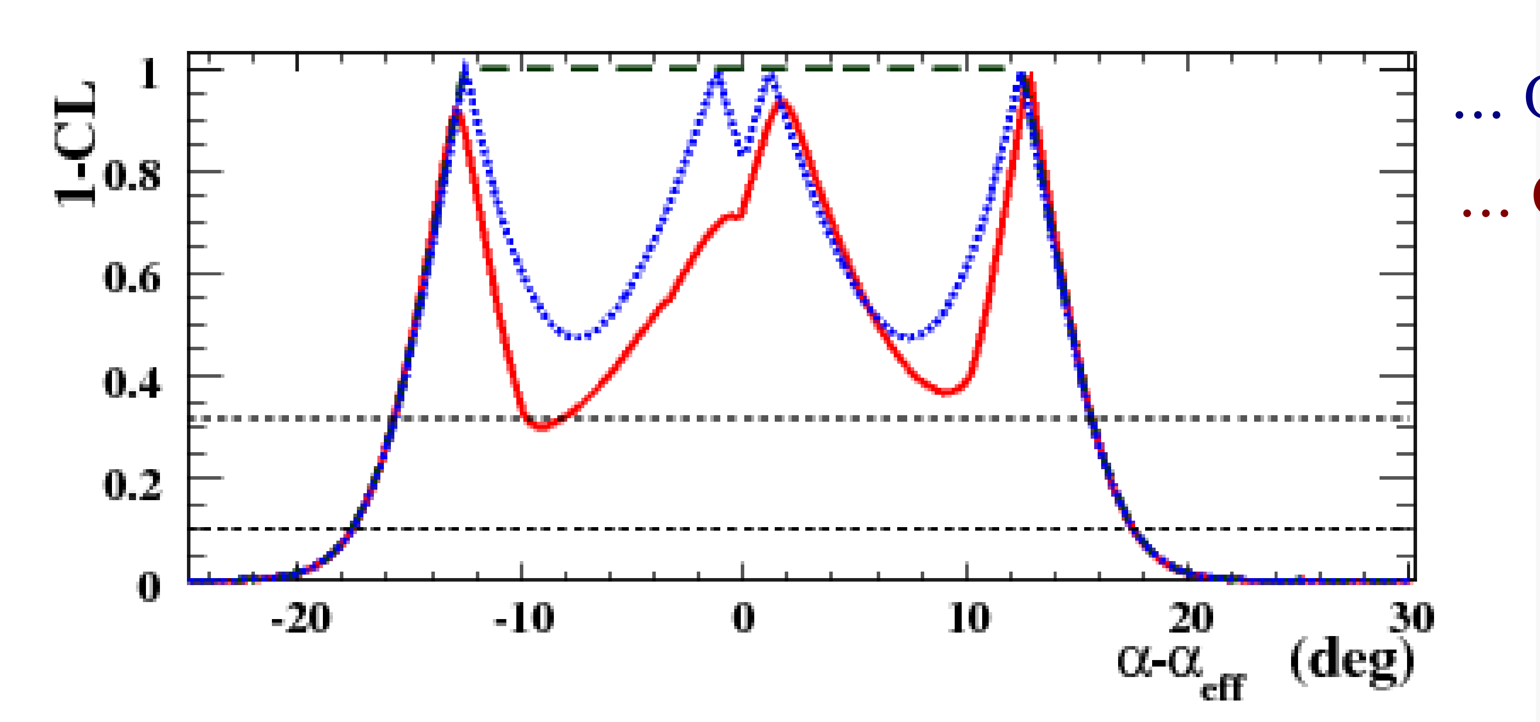
$\rho^0 \rho^0$ mode

465×10^6 $B\bar{B}$ pairs
[PRD78, 071104(R)]

$$f_L = 0.75\,^{+0.11}_{-0.14} \pm 0.04$$

$$S_L^{00} = 0.3 \pm 0.7 \pm 0.2 \quad C_L^{00} = 0.2 \pm 0.8 \pm 0.3$$

using $\rho^+\rho^-$: $f_L(\rho^+\rho^-)$, $Br(\rho^+\rho^-)$, S^{+-}, C^{+-} PRD76, 052007 (2007)
$\rho^+\rho^0$: $f_L(\rho^+\rho^0)$, $Br(\rho^+\rho^0)$ PRL97, 261801 (2006)
$\rho^0\rho^0$: $f_L(\rho^0\rho^0)$, $Br(\rho^0\rho^0)$ and ...

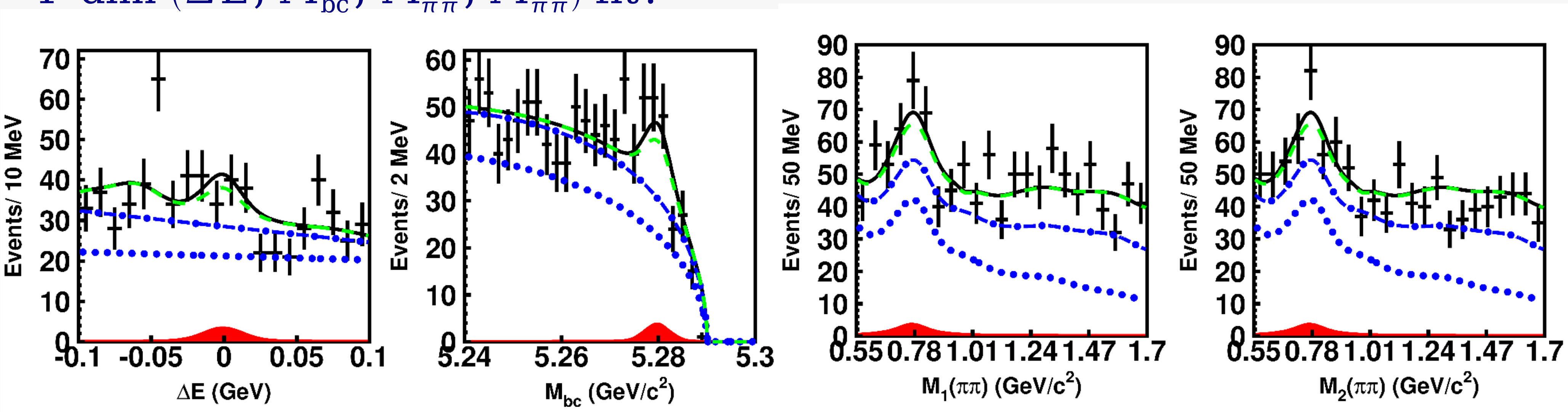


... C^{00}
... C^{00} & S^{00}

$\rho^0\rho^0$ mode

657×10^6 $B\overline{B}$ pairs
[PRD78, 111102(R)]

4-dim (ΔE, M_{bc}, $M_{\pi\pi}$, $M_{\pi\pi}$) fit:



$N_S(\rho^0\rho^0) = 24.5^{+23.6}_{-22.1}{}^{+10.1}_{-16.2}$ $(\Sigma = 1.0\ \sigma)$

$$\boxed{\begin{array}{c} Br(B^0 \to \rho^0\rho^0) < 1.0 \times 10^{-6} \text{ @ } 90\%\,C.L. \\ = (0.4 \pm 0.4^{+0.2}_{-0.3}) \times 10^{-6} \end{array}}$$

$N_S(\rho^0\pi^+\pi^-) = 113^{+67}_{-66} \pm 52$ $(\Sigma = 1.3\ \sigma)$

$Br(B^0 \to \rho^0\pi^+\pi^-) < 12.0 \times 10^{-6}$ @ 90%C.L.

$= (5.9^{+3.5}_{-3.4} \pm 2.7) \times 10^{-6}$

$N_S(4\pi^\pm) = 161^{+61}_{-59}{}^{+28}_{-25}$ $(\Sigma = 2.5\ \sigma)$

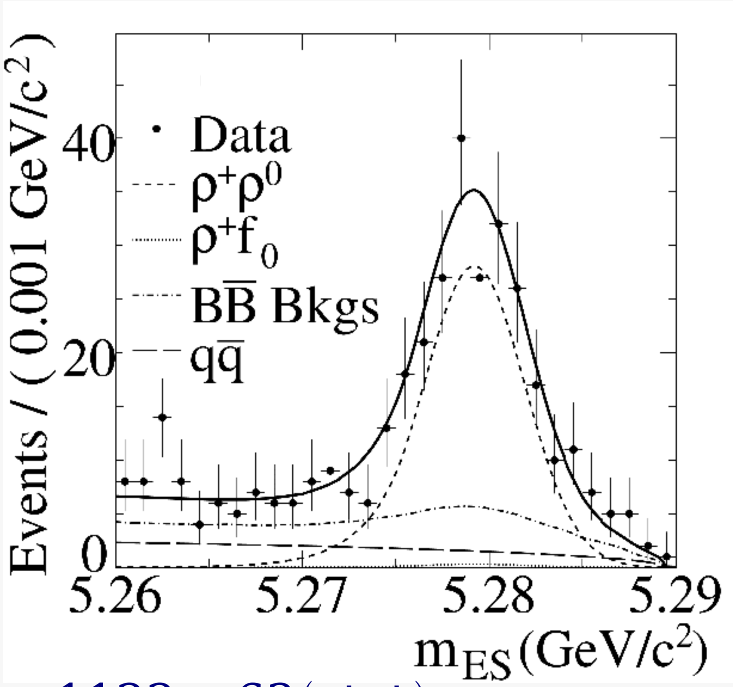
$Br(B^0 \to 4\pi^\pm) < 19.3 \times 10^{-6}$ @ 90%C.L.

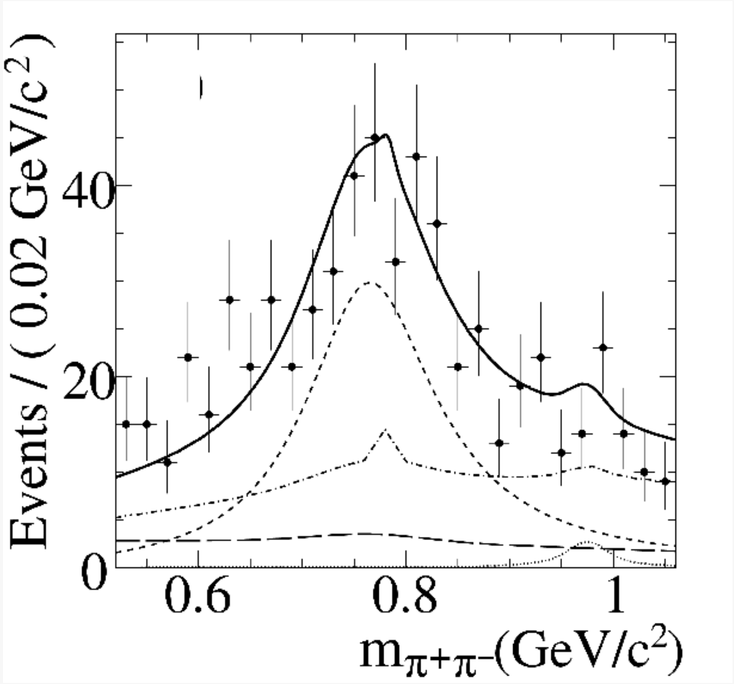
$= (12.4^{+4.7}_{-4.6}{}^{+2.1}_{-1.9}) \times 10^{-6}$

$Br(\rho^0\rho^0)$ is small ! SU(2) triangle even more squashed…

$\rho^+\rho^0$ mode

465×10^6 $B\bar{B}$ pairs
[ArXiv:0901.3522]





$N_S(\rho^+\rho^0) = 1122 \pm 63(\text{stat})$

$$Br(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$$

$$f_L = 0.950 \pm 0.015 \pm 0.006$$

Previous results:

232×10^6 $B\bar{B}$ pairs [PRL97, 261801 (2006)]

$Br(B^+ \to \rho^+\rho^0) = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$

$f_L = 0.905 \pm 0.042\ ^{+0.023}_{-0.027}$

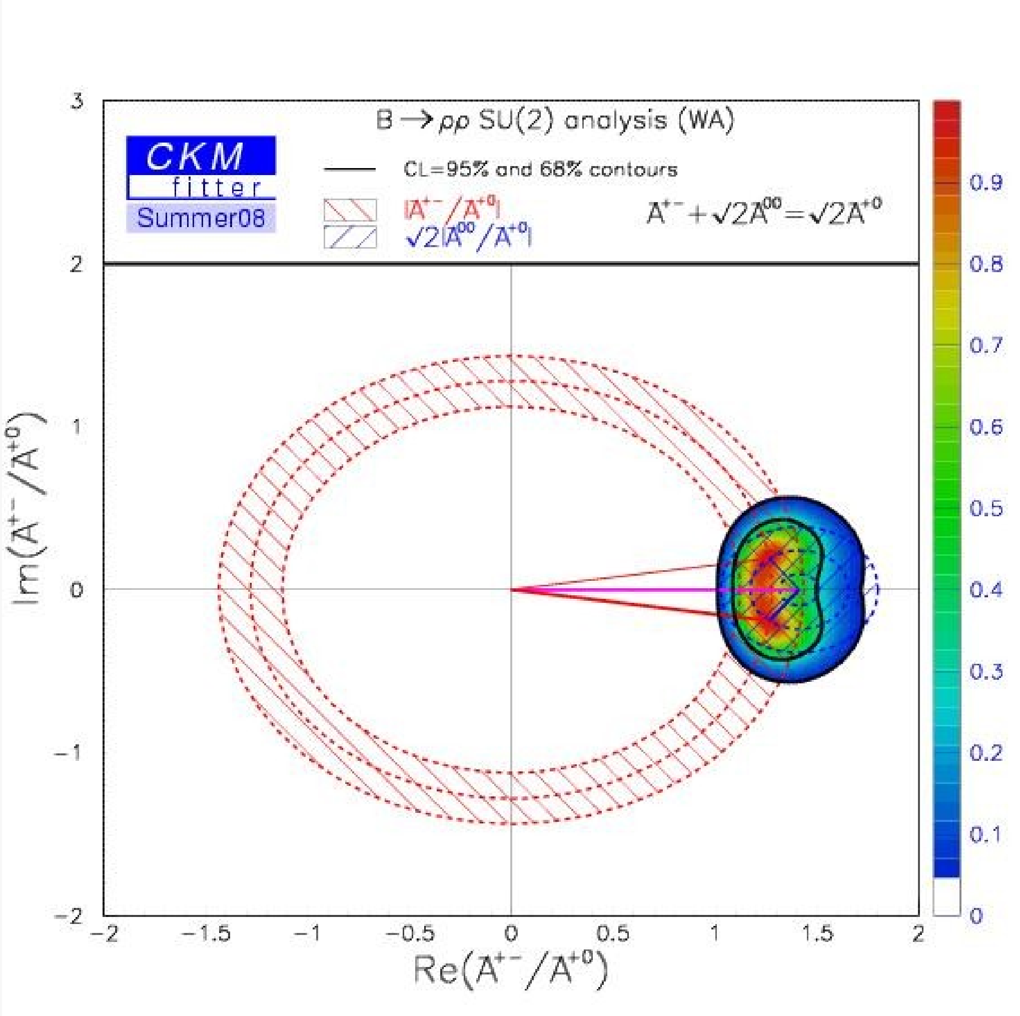
85×10^6 $B\bar{B}$ pairs [PRL91, 221801 (2003)]

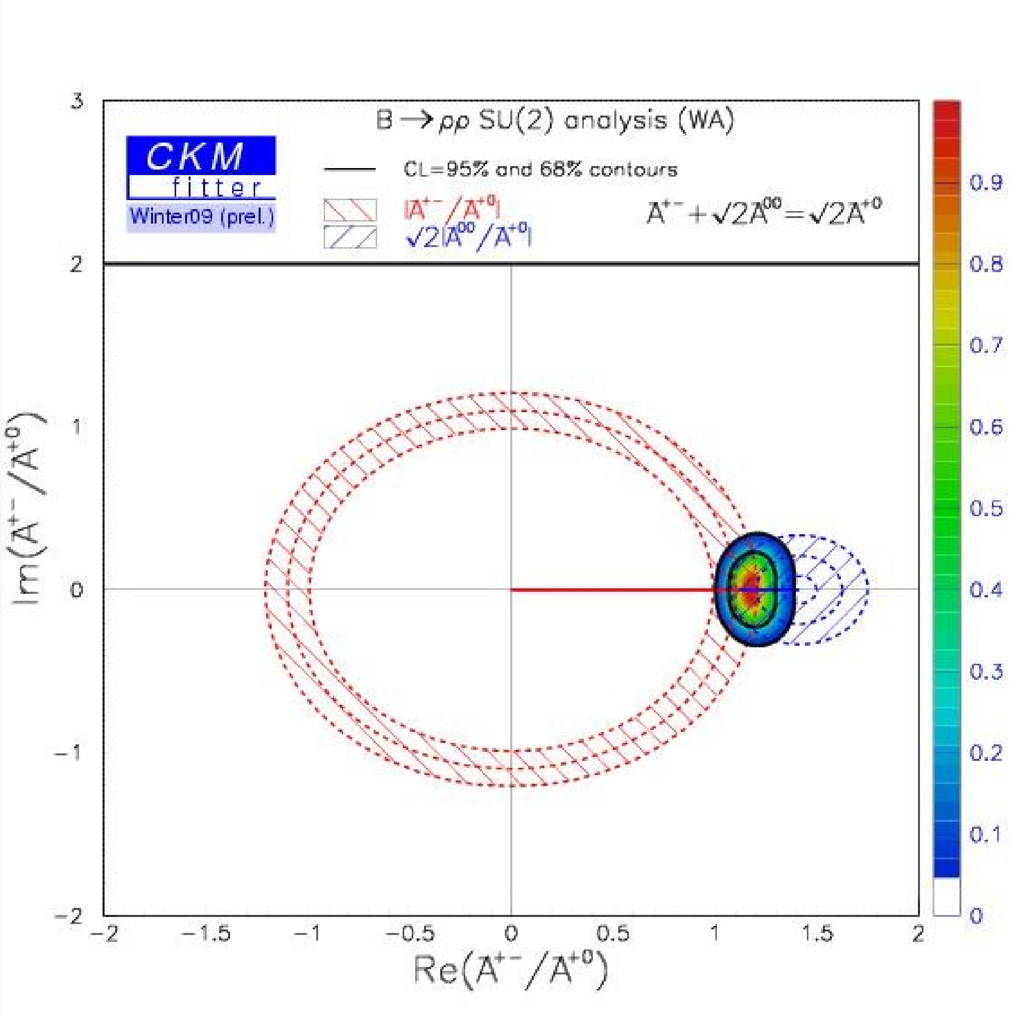
$Br(B^+ \to \rho^+\rho^0) = (31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$

$f_L = 0.948 \pm 0.106\ \pm 0.021$

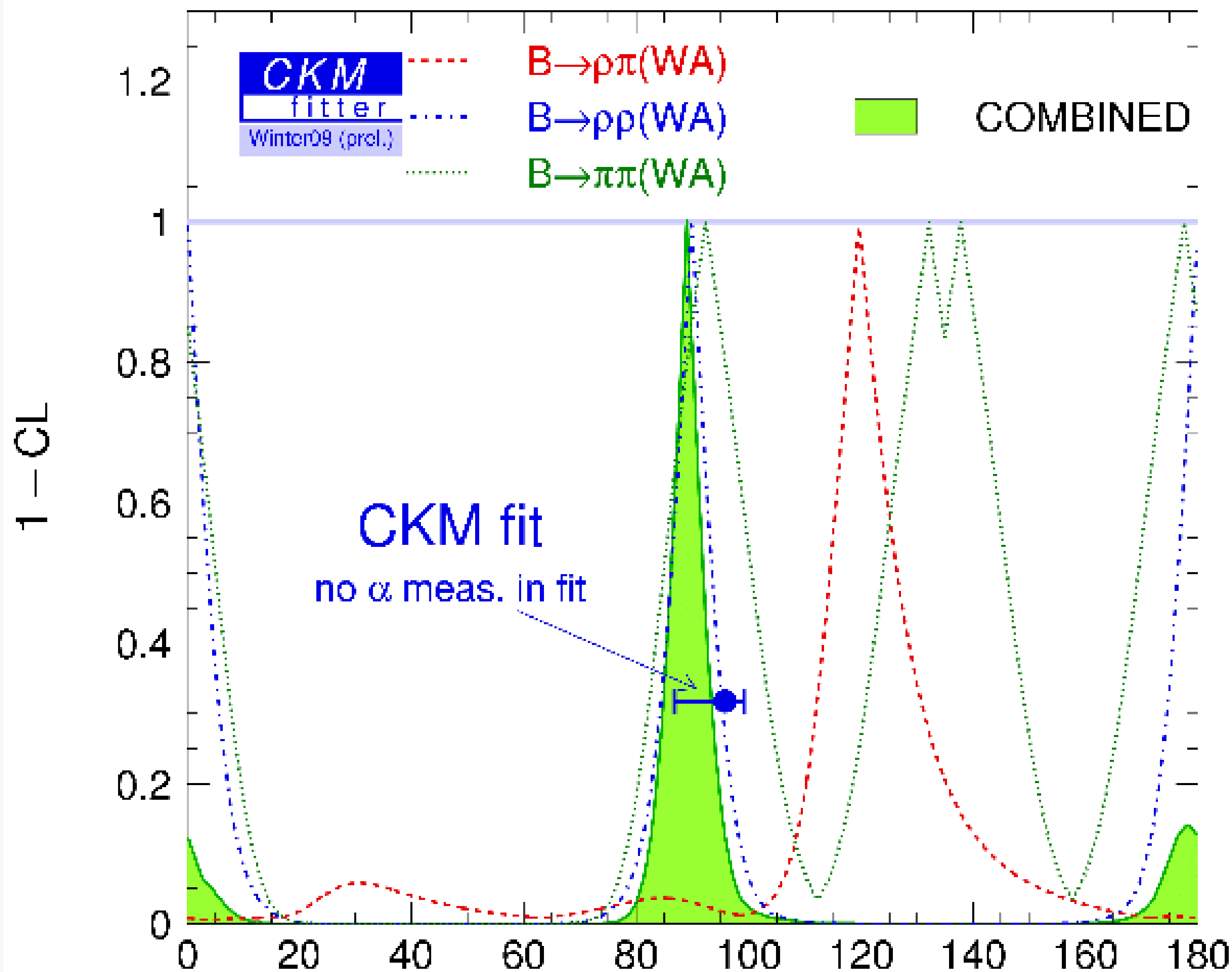
Isospin triangles (Summer 08 to Winter 09)

B → $\rho\,\rho$ case





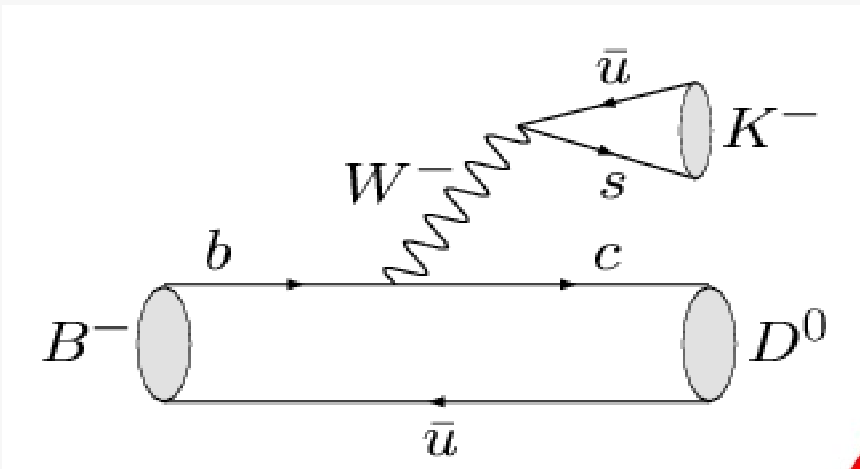
α determination



68% C.L. interval: $\alpha = (89.0^{+4.4}_{-4.2})^\circ$

γ measurements from $B^\pm \to DK^\pm$

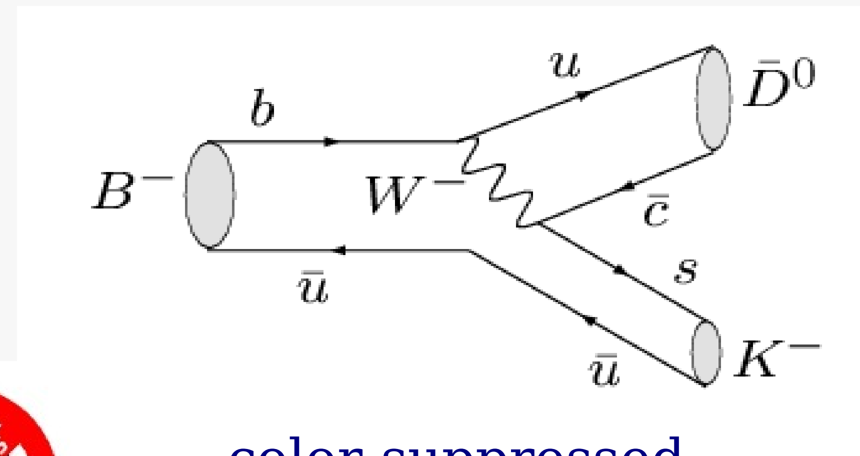
- Theoretically pristine $B \to DK$ approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$



color allowed

$B^- \to D^0 K^- \sim V_{cb} V^*_{us}$

$\mathbf{\sim A\lambda^3}$



color suppressed

$B^- \to \bar{D}^0 K^- \sim V_{ub} V^*_{cs}$

$\mathbf{\sim A\lambda^3(\rho + i\eta)}$

relative magnitude of suppressed amplitude is r_B

$$\boxed{r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V^*_{cs}|}{|V_{cb} V^*_{us}|} \times [\text{color supp}] = 0.1\text{-}0.2}$$

relative weak phase is γ, relative strong phase is δ_B

γ measurements from $B^{\pm} \to DK^{\pm}$

- Reconstruct D in final states accessible to both D^0 and $\overline{D}^0$
  - $D = D_{CP}$, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$

    GLW method (Gronau-London-Wyler)
  - $D = D_{sup}$, Doubly-Cabbibo suppressed decays as $K\pi$

    ADS method (Atwood-Dunietz-Soni)
  - Three-body decays as $D \to K_S\pi^+\pi^-$, $K_S K^+ K^-$

    GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

- Largest effects due to
  - charm mixing
  - charm CP violation

  negligible

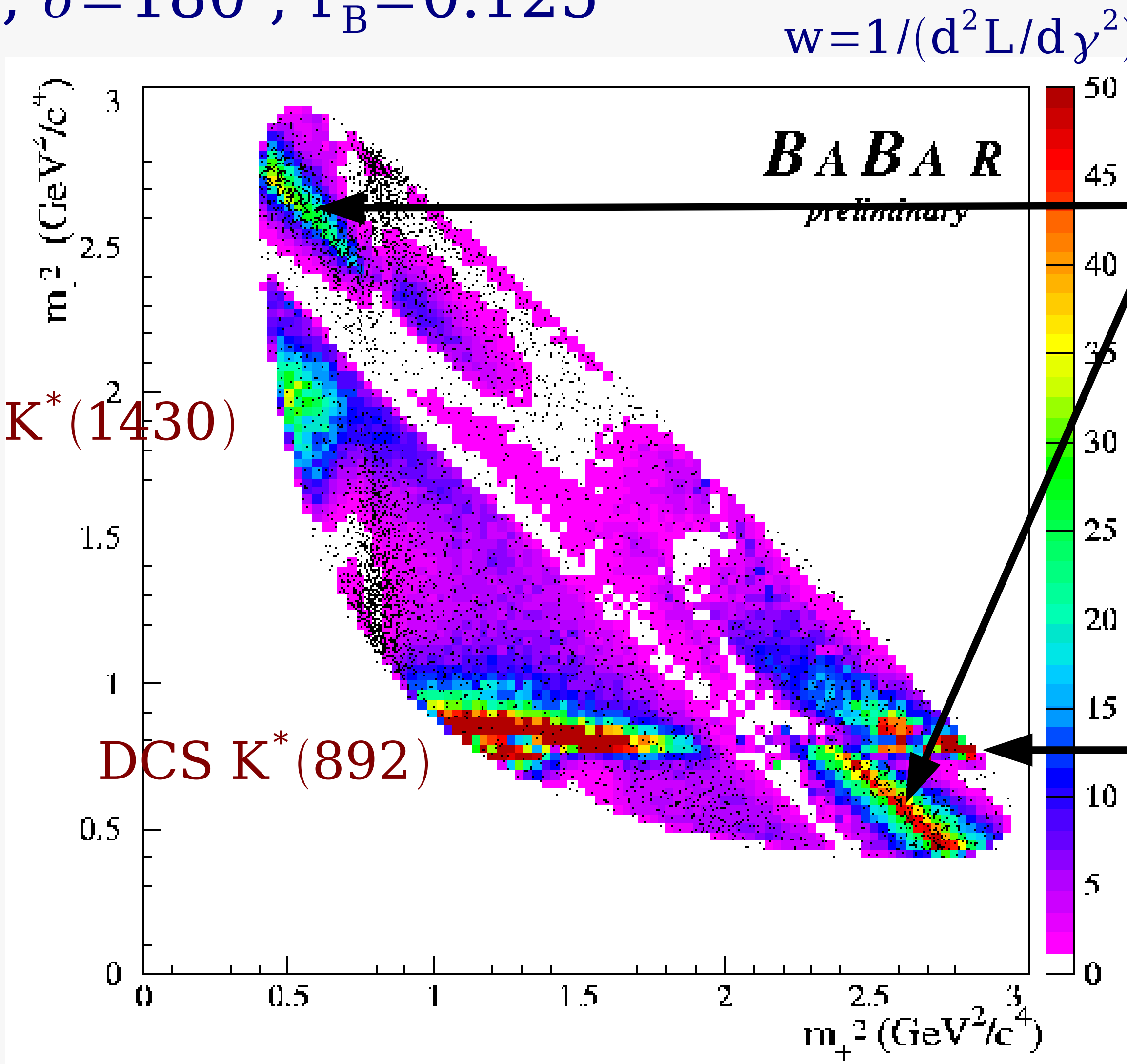
  Y.Grossman, A.Soffer, J.Zupan [PRD 72, 031501 (2005)]

- Different B decays (DK, D^*K, DK^*)
  - different hadronic factors (r_B, δ_B) for each

Sensitivity to γ

sensitivity to γ/ϕ_3 varies across the Dalitz plot

$\gamma=75^{\circ}$, $\delta=180^{\circ}$, $r_B=0.125$



DCS $K^*(1430)$

DCS $K^*(892)$

GLW like

Interference of

$B^- \to D^0 K^-$, $D^0 \to K^0_S \rho^0$

with

$B^- \to \overline{D}^0 K^-$, $\overline{D}^0 \to K^0_S \rho^0$

ADS like

Interference of

$B^- \to D^0 K^-$, $D^0 \to K^{*+} \pi^-$

with

$B^- \to \overline{D}^0 K^-$, $\overline{D}^0 \to K^{*+} \pi^-$

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

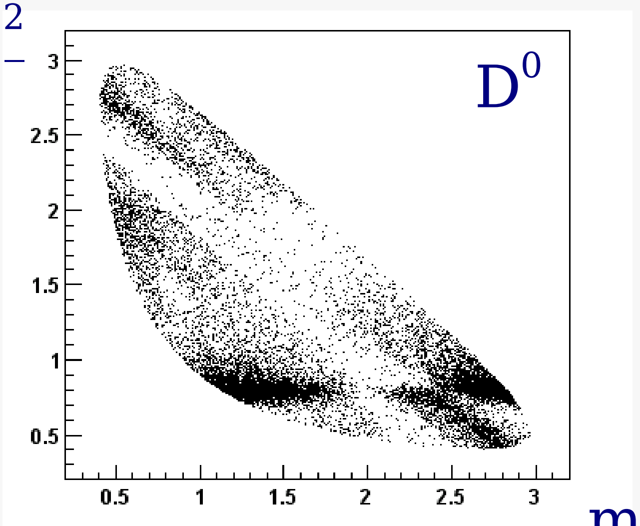
Reconstruction of three−body final states D^0, $\overline{D}^0 \to K_S \pi^+ \pi^-$

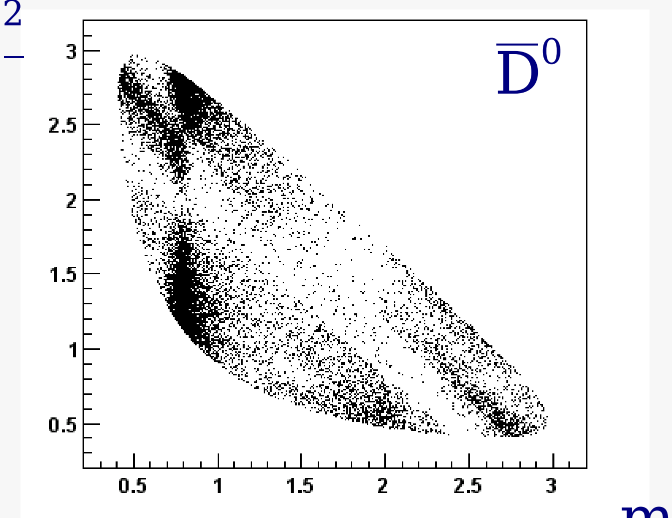
Amplitude for each Dalitz point is described as:

$$\overline{D}^0 \to K_S \pi^+ \pi^- \sim f(m_+^2, m_-^2)$$
$$D^0 \to K_S \pi^+ \pi^- \sim f(m_-^2, m_+^2)$$

$$B^+ \to (K_S \pi^+ \pi^-)_D K^+ : f(m_+^2, m_-^2) + r e^{i(\delta_B + \gamma)} f(m_-^2, m_+^2)$$

$m_- = M(K_S \pi^-)$
$m_+ = M(K_S \pi^+)$





$$B^- \to (K_S \pi^+ \pi^-)_D K^- : f(m_-^2, m_+^2) + r e^{i(\delta - \gamma)} f(m_+^2, m_-^2)$$

Simultaneous fit of B^+ and B^- to extract parameters r_B, ϕ_3 and δ_B

Note: 2 fold ambiguity on γ: $(\gamma, \delta_B) \to (\gamma + \pi, \delta_B + \pi)$

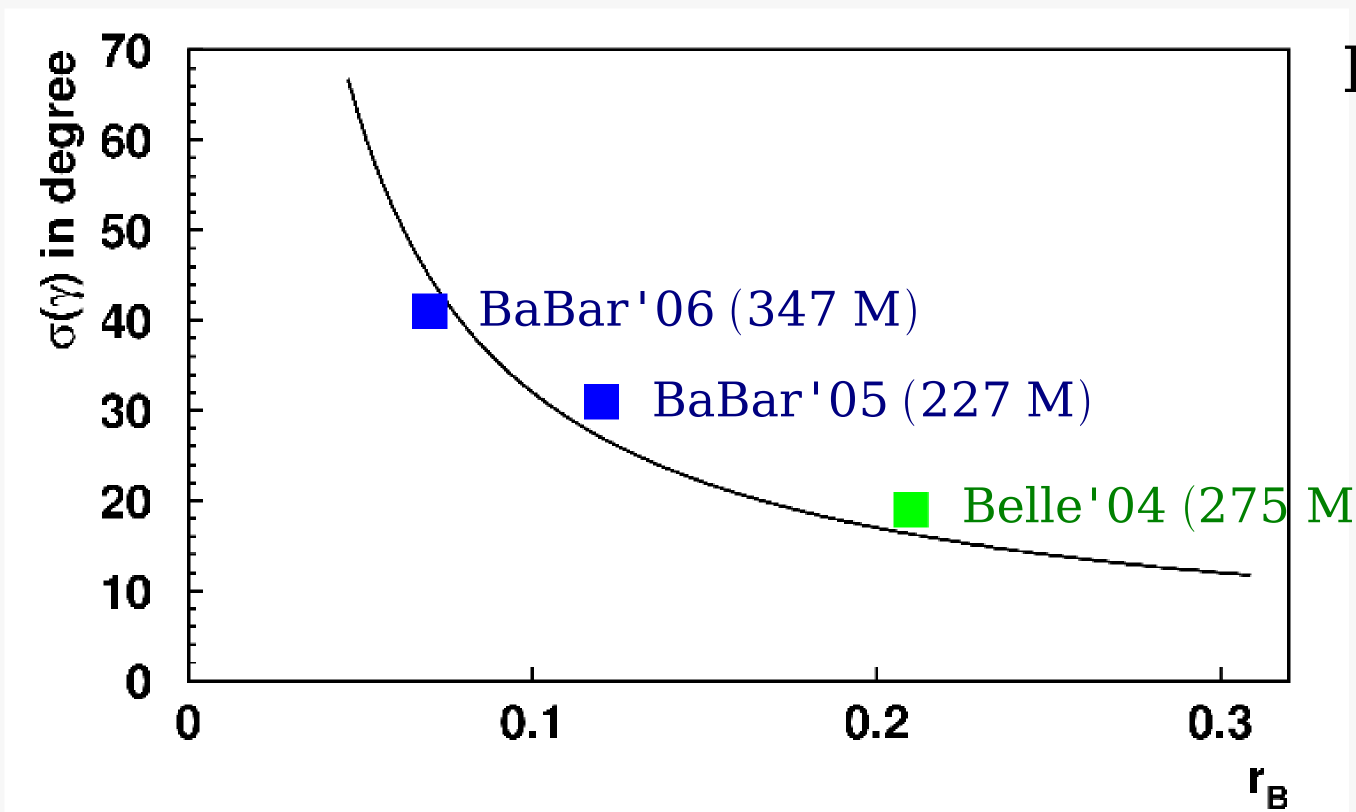
γ measurements from $B^{\pm} \to DK^{\pm}$ — r_B dependence

Dalitz $B \to D(K_S \pi\pi)K$

experimental inputs:

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$
$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

uncertainty on γ scales as $1/r_B$!



DK (stat only)

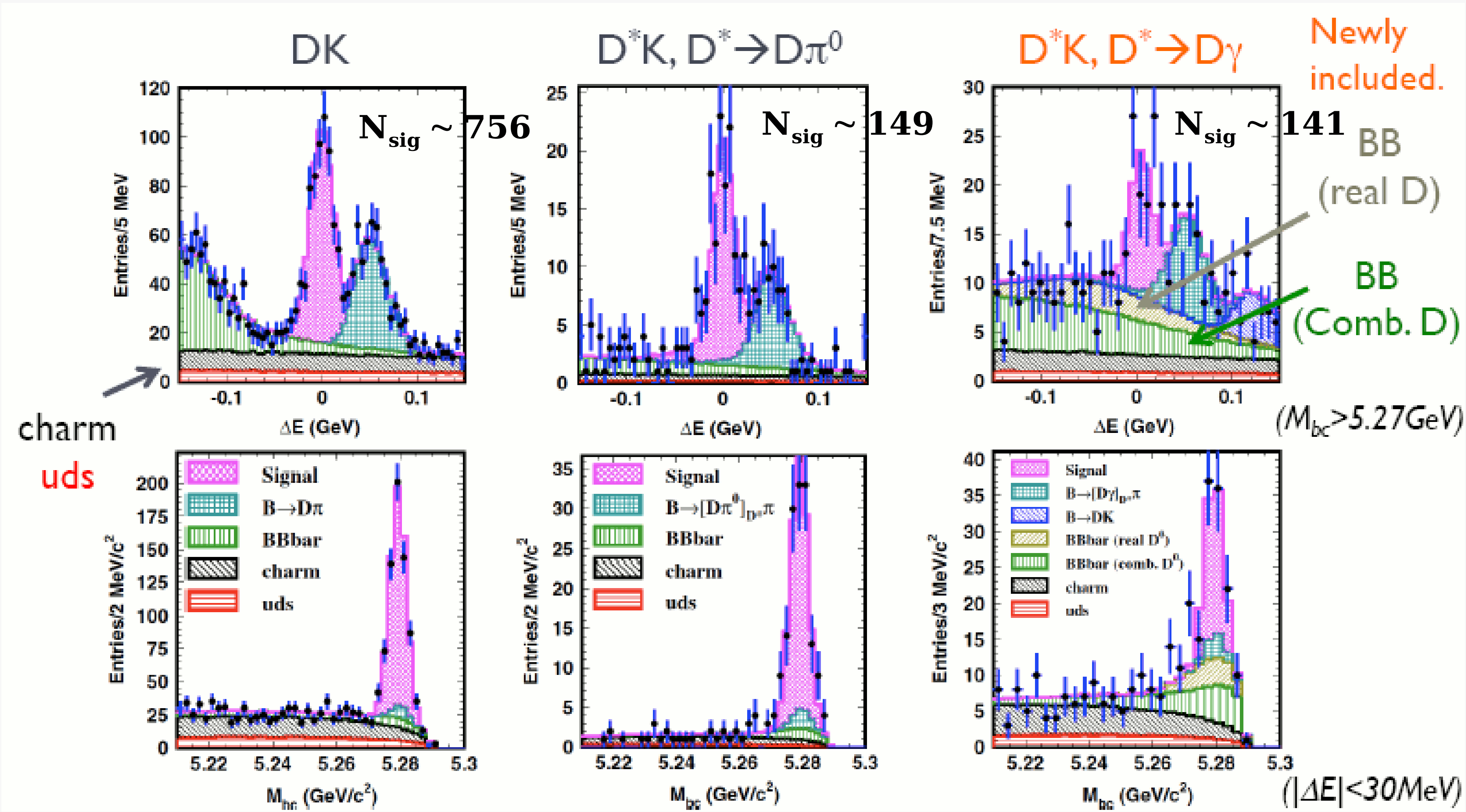
$\sigma(x_{\pm}) \sim 0.07$

$\sigma(y_{\pm}) \sim 0.08$

$B^- \to D^{(*)}(K_S\pi\pi)K^-$ Dalitz, ΔE and M_{bc} projections

$|\cos\theta_{thr}| < 0.8$ and $F > -0.7$

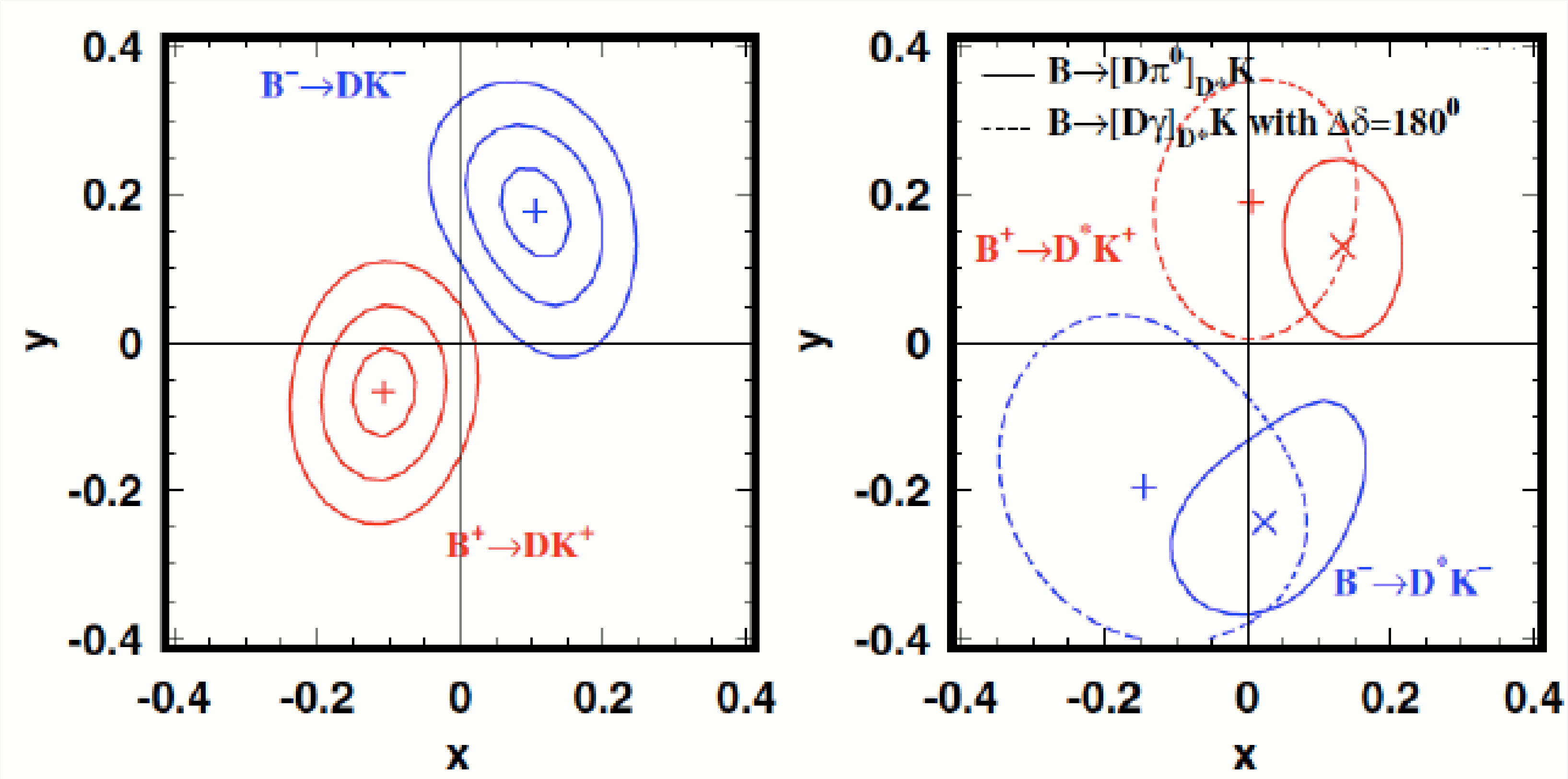
PRD 81, 112002 (2010)
657×10^6 $B\bar{B}$ pairs



γ measurement with $B \to D(K_S\pi\pi)K$

PRD 81, 112002 (2010)
657×10^6 $B\bar{B}$ pairs

$$x_\pm = r_B \cos(\delta_B \pm \gamma), \quad y_\pm = r_B \sin(\delta_B \pm \gamma)$$



$$\gamma = (80.8\,^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ \qquad \gamma = (73.9\,^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ$$

$$r_B = 0.161\,^{+0.040}_{-0.038} \pm 0.011\,^{+0.050}_{-0.010} \qquad r_B = 0.196\,^{+0.073}_{-0.072} \pm 0.013\,^{+0.062}_{-0.012}$$

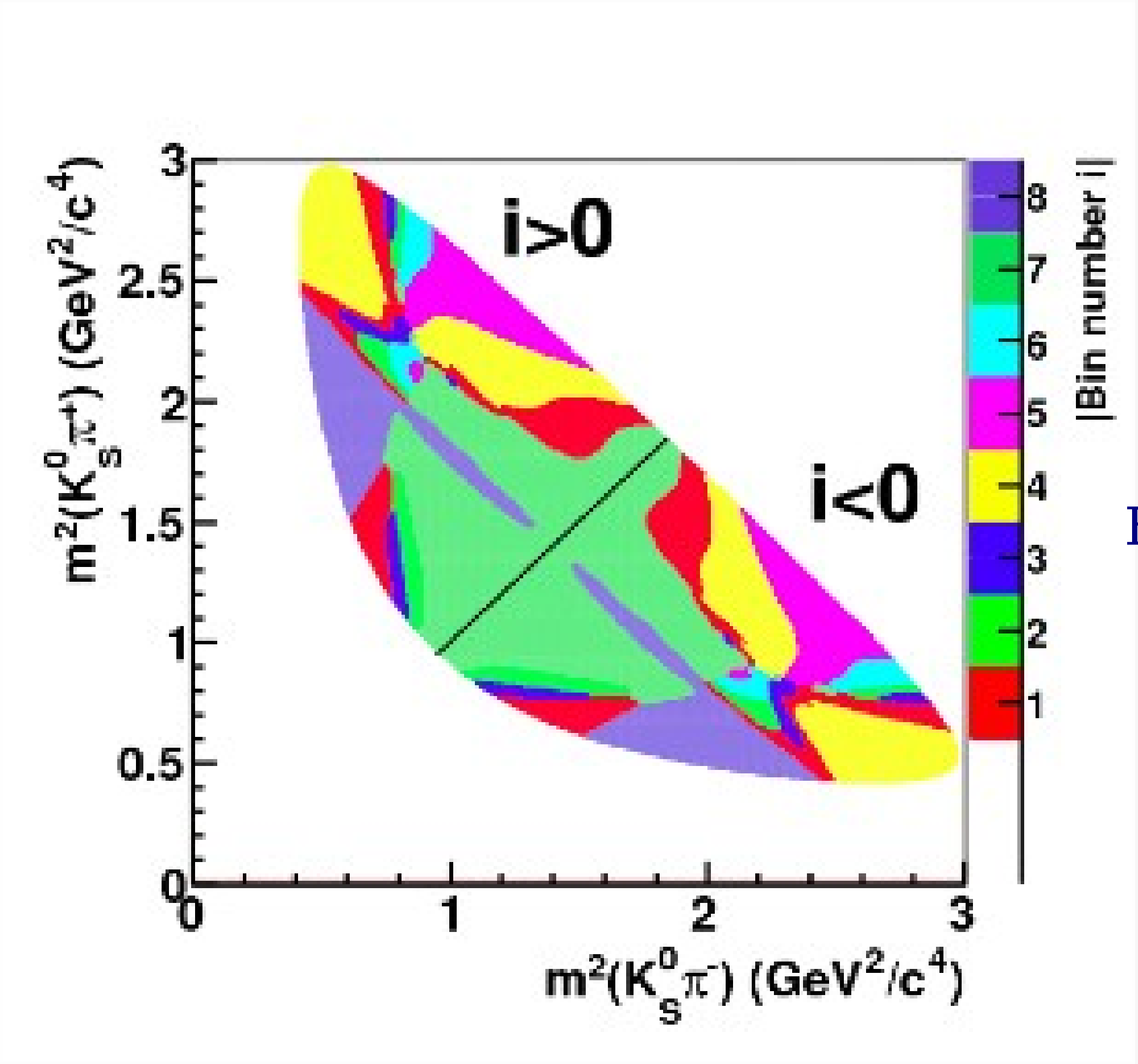
$$\delta_B = (137.4\,^{+13.0}_{-15.7} \pm 4.0 \pm 22.9)^\circ \qquad \delta_B = (341.7\,^{+18.6}_{-20.9} \pm 3.2 \pm 22.9)^\circ$$

combining both B modes (Dalitz): $\boldsymbol{\gamma = (78.4\,^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ}$

CPV significance is 3.5 standard deviations

(model-dependent error will limit viability of this approach)

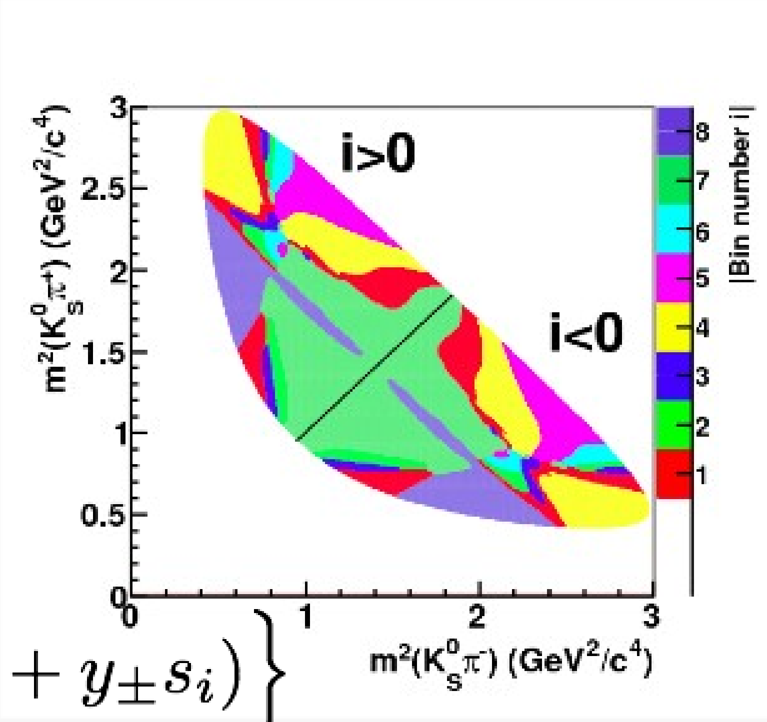
<u>Binned Dalitz method:</u> avoid the modeling error by ''optimal'' binning of the Dalitz plot



Bondar and Poluektov
EPJ C55, 51 (2008)

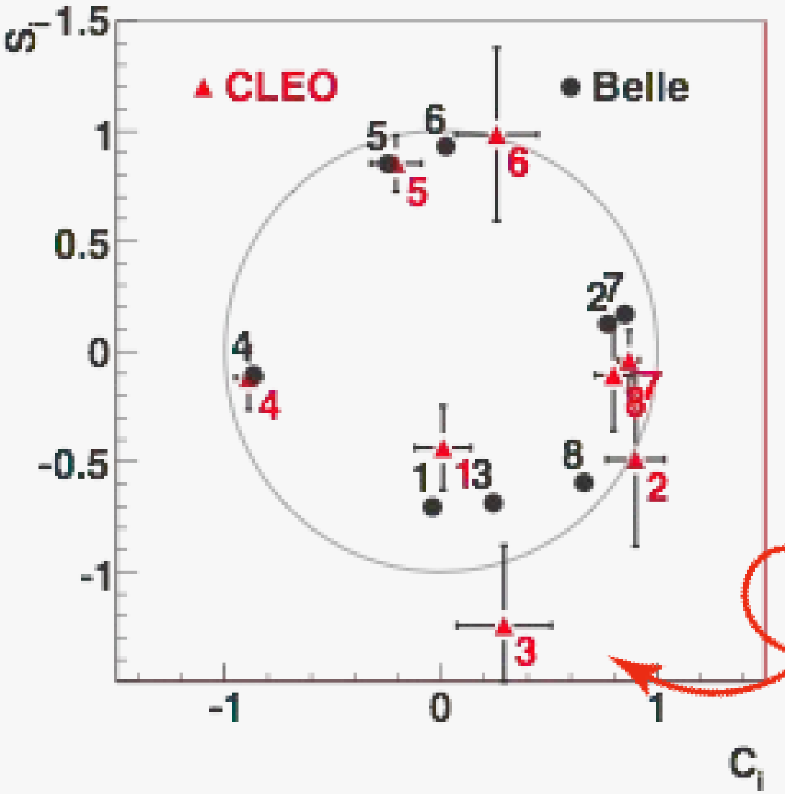
choice of bins guided by model, but extracted γ is not biased by this choice

Binned Dalitz method: minimize χ^2 in fit to all bins for each mode



Expected number of $B^\pm \to D K^\pm$ events in bin i is:

$$N_i^\pm = h\left\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i + y_\pm s_i)\right\}$$



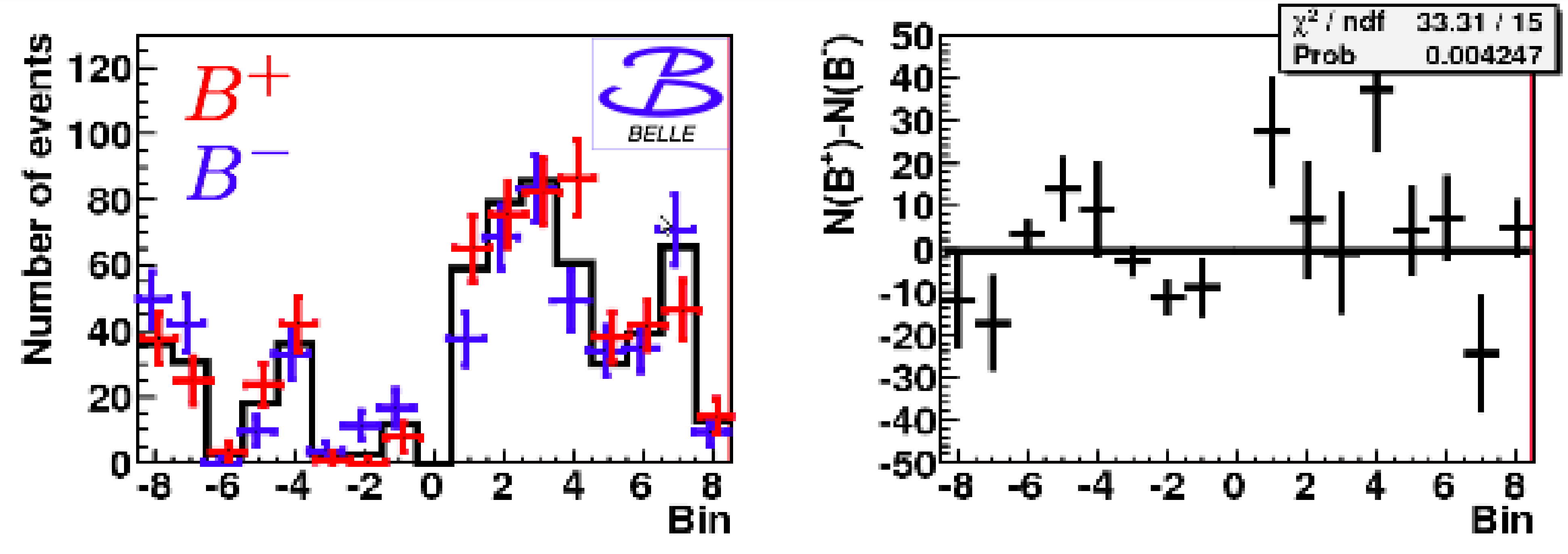
K_i is the # of events in bin i from a flavour-tagged sample ($D^{*\pm} \to D\pi^\pm$)

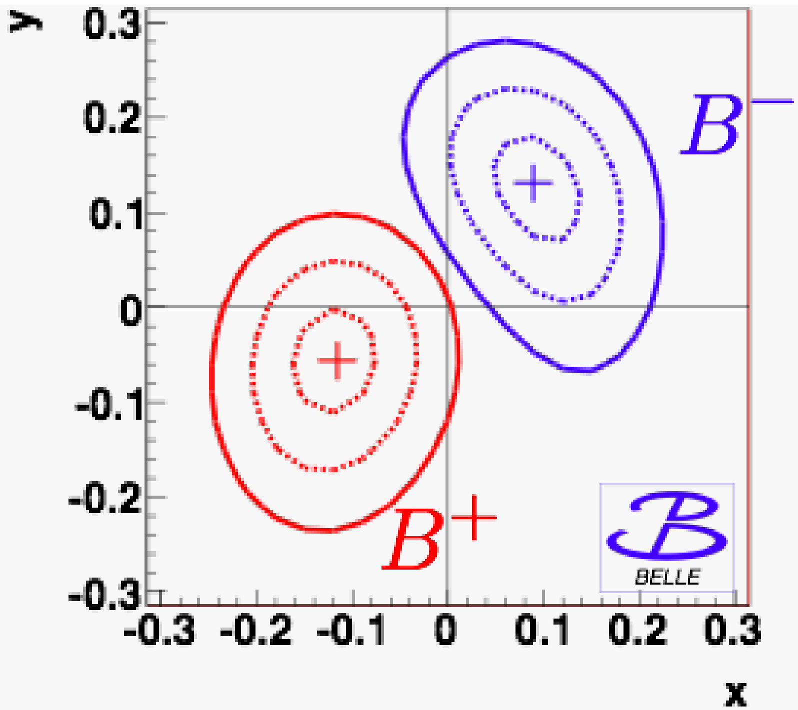
c_i and s_i contain information about the strong-phase difference in bin i

(use CLEO data for $\psi(3770) \to D^0\overline{D}^0$ here; can be measured by BES-III too)

Binned Dalitz method result in $B \to DK$ from 772 million events

arXiv:1106.4046





$$\gamma = (77.3\ ^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ$$

$$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$$

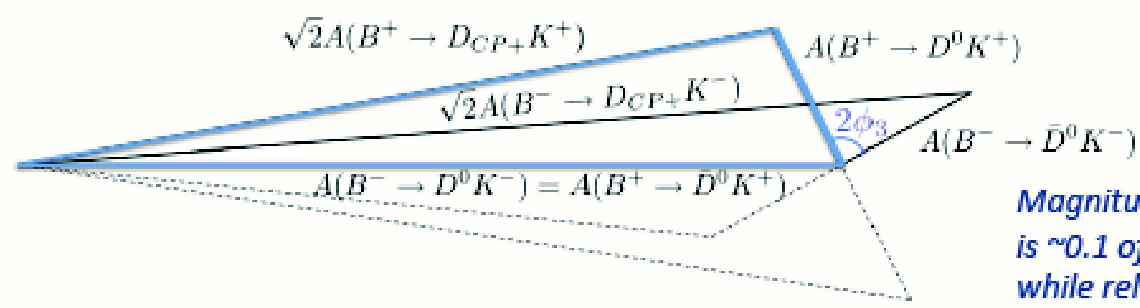
$$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ$$

uncertainty in c_i, s_i
from CLEO data
(can reduce using
future BES-III data)

GLW with $D_{CP}K$

D decays to CP eigenstates

➢ **Amplitude triangle:**



Magnitude of one side is ~0.1 of the others while relative magnitude of the others help ϕ_3 constraint.

Usually measured observables:

$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0K^-) + \mathcal{B}(B^+ \to \bar{D}^0K^+)}$$

$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}$$

Relation between $(A_{CP+}, A_{CP-}, R_{CP+}, R_{CP-})$ and (γ, r_B, δ_B)

$$\mathbf{A_{CP+}} = \frac{2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma} \qquad \mathbf{A_{CP-}} = \frac{-2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 - 2 r_B \cos\delta_B \cos\gamma}$$

$$\mathbf{R_{CP+}} = 1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma \qquad \mathbf{R_{CP-}} = 1 + r_B^2 - 2 r_B \cos\delta_B \cos\gamma$$

$\Rightarrow$ look for $R_{CP\pm} \neq 1$ and $A_{CP\pm} \neq 0$

$B \to Dh,\ D \to K\pi \ \to\ R_{D_{fav}}$

MC (case B)

$B \to D\pi$

$B \to DK$

$B\bar{B}$

continuum

$$\boxed{\begin{aligned}
N^{DK}_{\eta,\,KID>0.6} &= \frac{1}{2}\left(1-\eta A^{DK}\right) N^{D\pi}_{tot}\, R_{K/\pi}\, \epsilon \\
N^{DK}_{\eta,\,KID<0.6} &= \frac{1}{2}\left(1-\eta A^{DK}\right) N^{D\pi}_{tot}\, R_{K/\pi}\, (1-\epsilon) \\
N^{D\pi}_{\eta,KID>0.6} &= \frac{1}{2}\left(1-\eta A^{D\pi}\right) N^{D\pi}_{tot}\, \kappa \\
N^{D\pi}_{\eta,KID<0.6} &= \frac{1}{2}\left(1-\eta A^{D\pi}\right) N^{D\pi}_{tot}\, (1-\kappa)
\end{aligned}}$$

	kaon fake (1-ϵ)	kaon eff ϵ	pion eff (1-κ)	pion fake κ
MC	14.70 ± 0.06	85.41 ± 0.06	95.42 ± 0.03	4.47 ± 0.03 ⇐
data	15.86 ± 0.40	84.32 ± 0.39	92.13 ± 0.46	7.94 ± 0.31

Table 5: Efficiency and fake rate (in %) for kaon and pion, for data and MC. ϵ will be fixed in the fit but κ will be floated (see text for further explanations). These numbers are obtained after properly weighting the values provided by PID group for SVD1 and SVD2.

$\Rightarrow\ \kappa = (4.58 \pm 0.10)\%$ in the MC fit

$B \to Dh,\ D \to K\pi \ \to \ R_{D_{fav}}$

$$N^{DK}_{\eta,\ KID>0.6} = \frac{1}{2}\left(1-\eta A^{DK}\right) N^{D\pi}_{tot}\ R_{K/\pi}\ \epsilon$$

$$N^{DK}_{\eta,\ KID<0.6} = \frac{1}{2}\left(1-\eta A^{DK}\right) N^{D\pi}_{tot}\ R_{K/\pi}\ (1-\epsilon)$$

$$N^{D\pi}_{\eta,KID>0.6} = \frac{1}{2}\left(1-\eta A^{D\pi}\right) N^{D\pi}_{tot}\ \kappa$$

$$N^{D\pi}_{\eta,KID<0.6} = \frac{1}{2}\left(1-\eta A^{D\pi}\right) N^{D\pi}_{tot}\ (1-\kappa)$$

MC

$B \to D\pi$

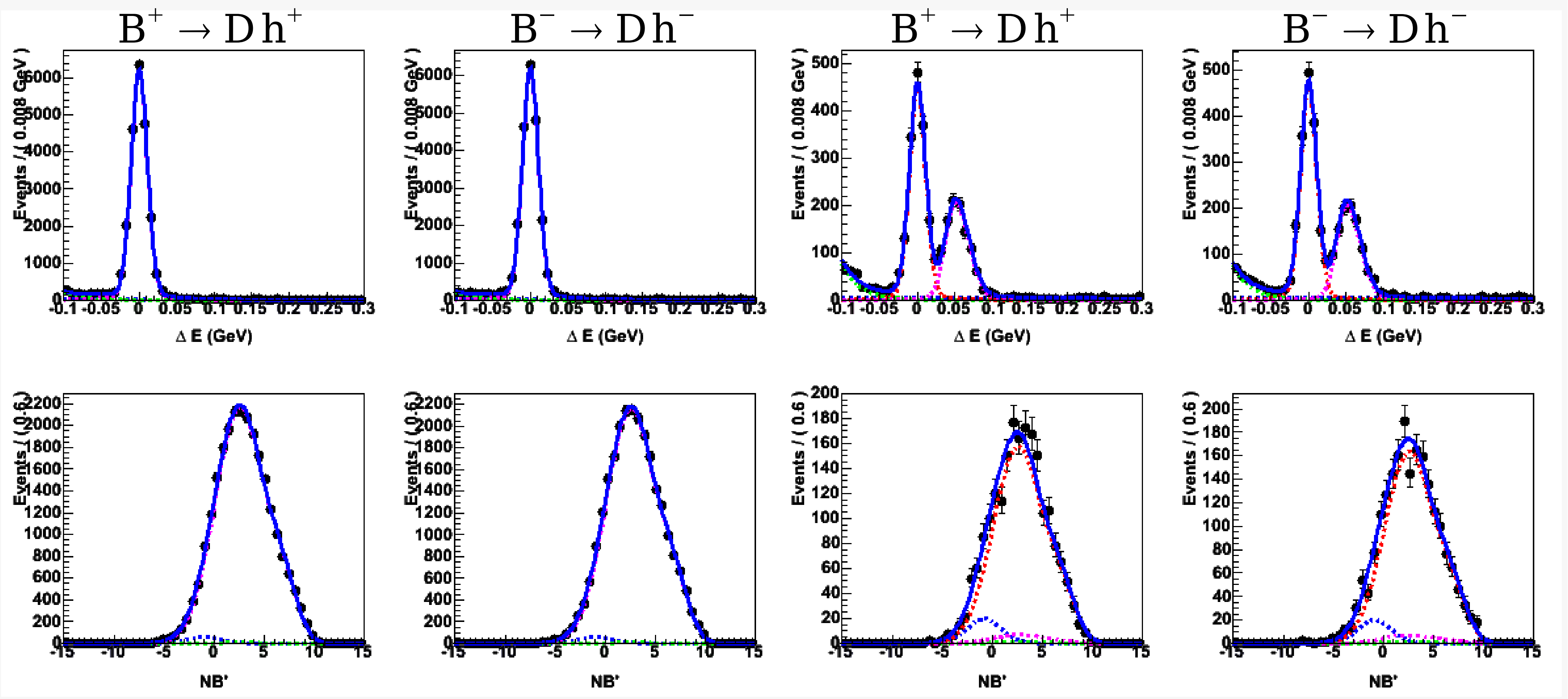
$B \to DK$

$B\overline{B}$

continuum

KID<0.6

KID>0.6



$B \to Dh,\ D \to K\pi \ \to \ R_{D_{fav}}$

data (772 $MB\bar{B}$)

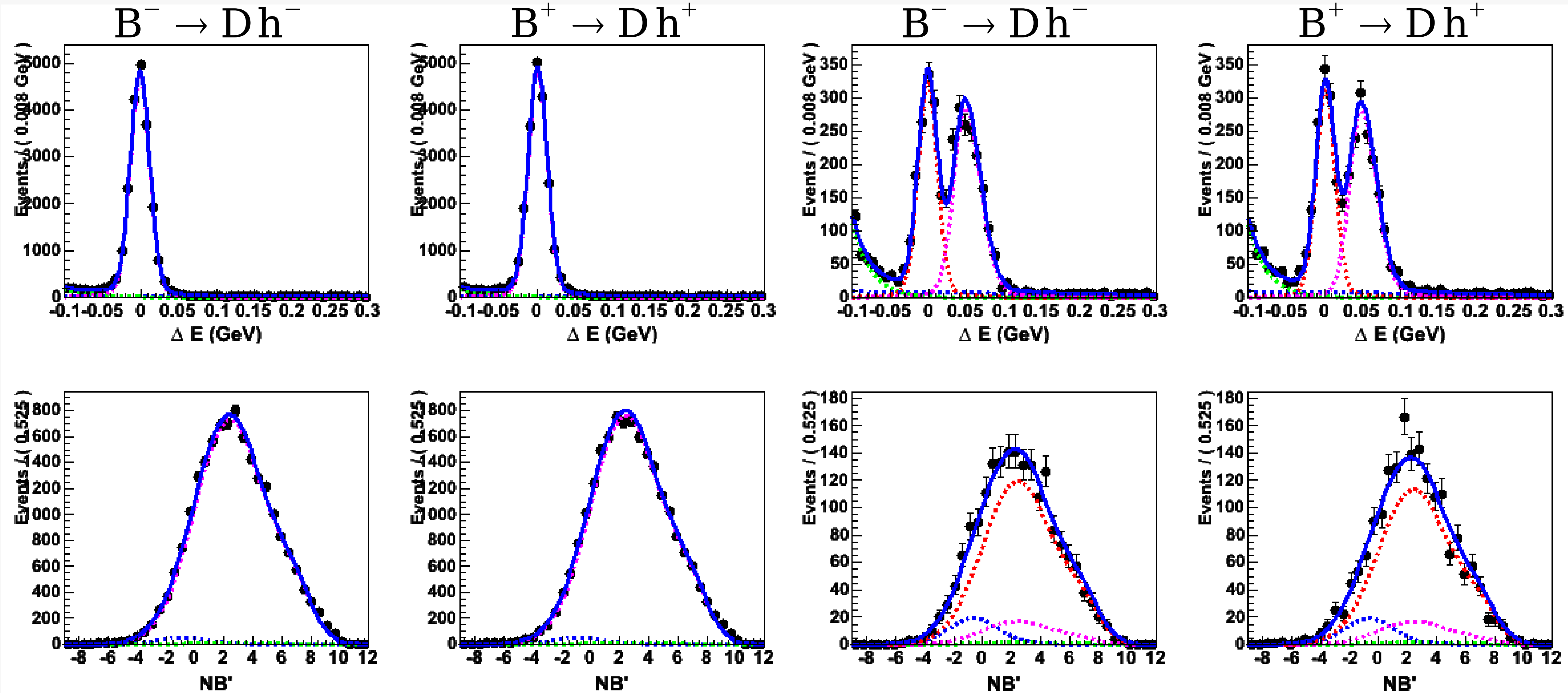
$B \to D\pi$

$B \to DK$

$B\bar{B}$

continuum

h is a pion candidate (KID<0.6)   h is a kaon candidate (KID>0.6)



$$\Rightarrow \ R_{D_{fav}} = (7.32 \pm 0.16)\%, \ \ A(DK) = (1.4 \pm 2.0)\%$$

$B \to Dh,\ D \to K\pi \ \to\ R_+$

data (772 $MB\bar{B}$)

$B \to D\pi$

$B \to DK$

$B\bar{B}$

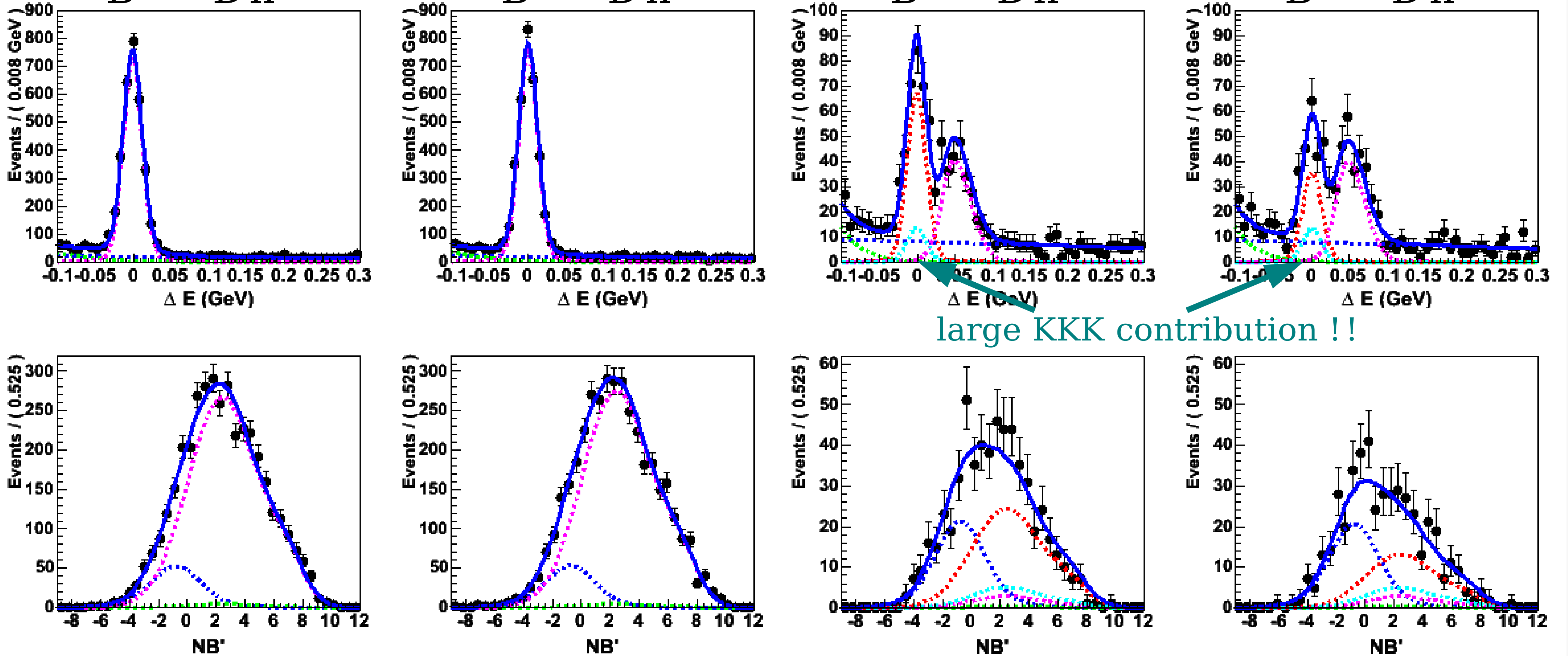
continuum

$D \to K^+K^-,\ \pi^+\pi^-$

Preliminary
LP 2011

h is a pion candidate (KID<0.6) h is a kaon candidate (KID>0.6)

$B^- \to Dh^-$ $B^+ \to Dh^+$ $B^- \to Dh^-$ $B^+ \to Dh^+$



$\Rightarrow\ R_{D_{CP+}} = (7.56 \pm 0.51)\%,\ \ A_{D_{CP+}} = (28.7 \pm 6.0)\%$

large asymmetry !!

$B \to Dh,\ D \to K\pi \ \to\ R_-$

data $(772\ MB\bar{B})$

$B \to D\pi$

$B \to DK$

$B\bar{B}$

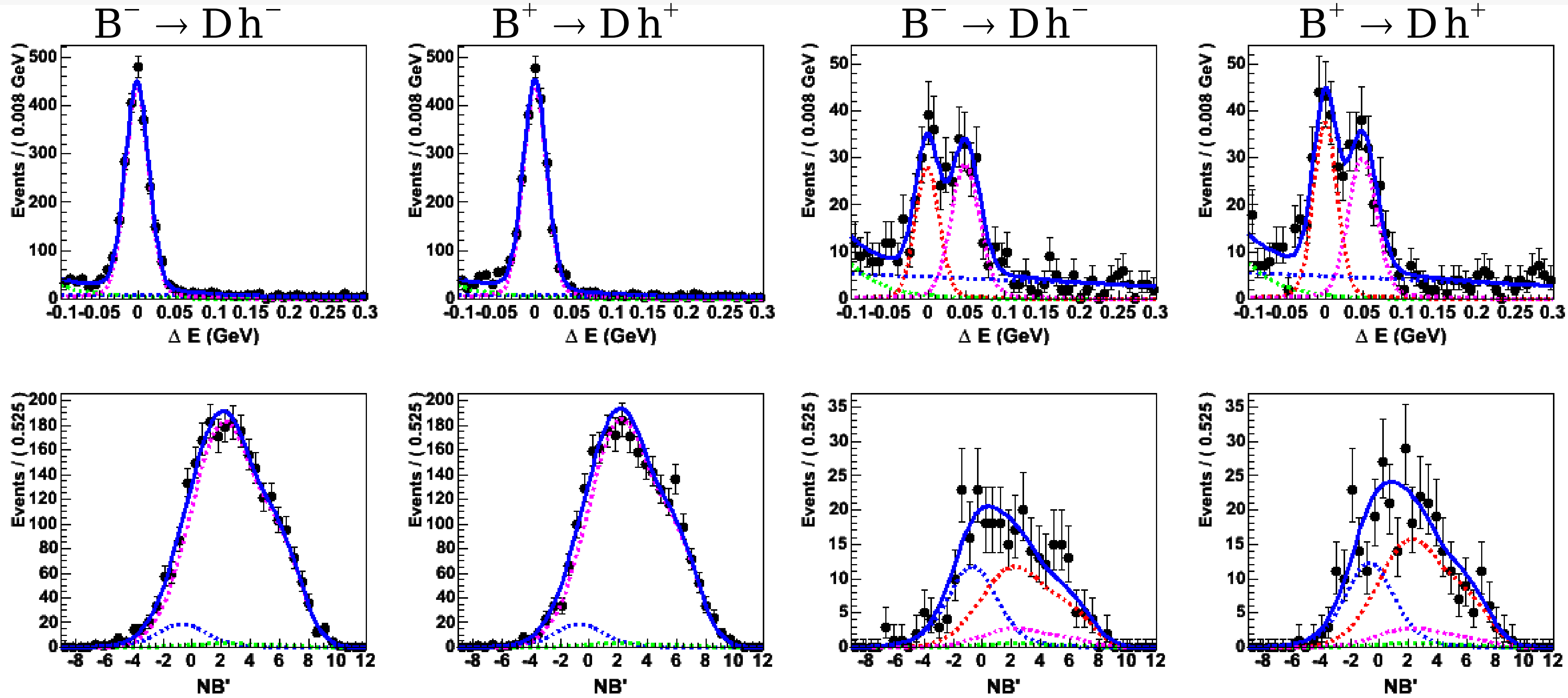
continuum

$D \to K_S\pi^0,\ K_S\eta(\gamma\gamma)$

Preliminary

LP 2011

h is a pion candidate (KID<0.6) h is a kaon candidate (KID>0.6)



$$\Rightarrow\ R_{D_{CP-}} = (8.29 \pm 0.63)\%,\quad A_{D_{CP-}} = (-12.4 \pm 6.4)\%$$

opposite asymmetry !!

GLW Results

Preliminary
LP 2011

Yields	$B \to D\pi$	$B \to DK$
$D \to K\pi$	50432 ± 243	3692 ± 83
$D \to KK, \pi\pi$	7696 ± 106	582 ± 40
$D \to K_S\pi^0, K_S\eta$	5745 ± 91	476 ± 37

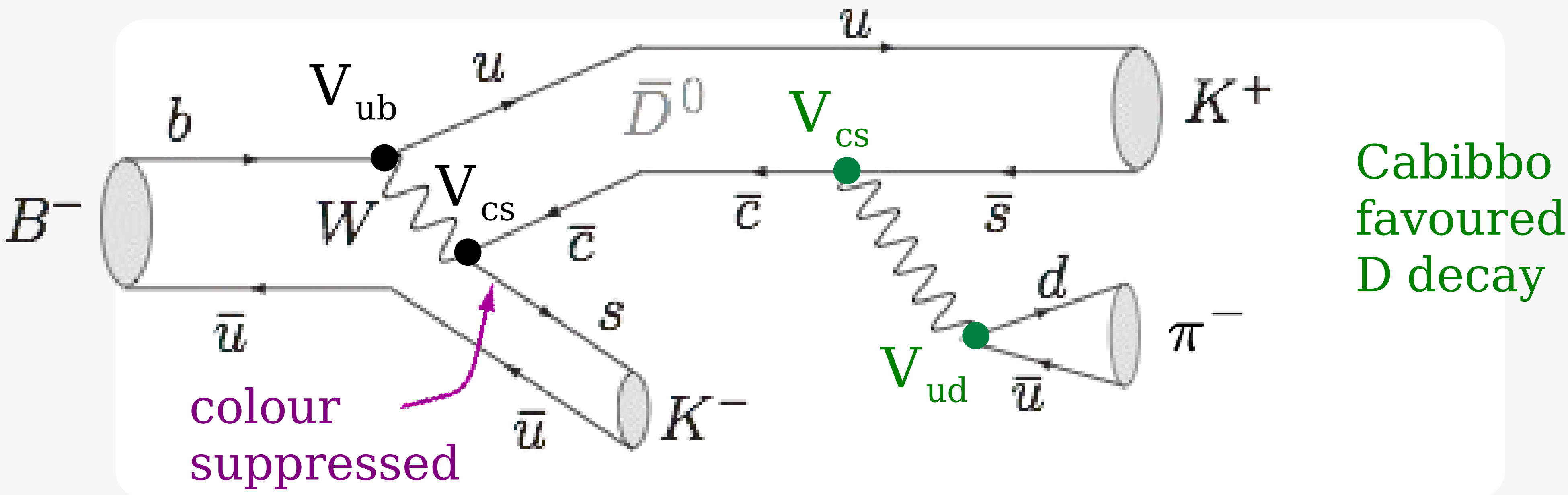
$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$
$$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$$

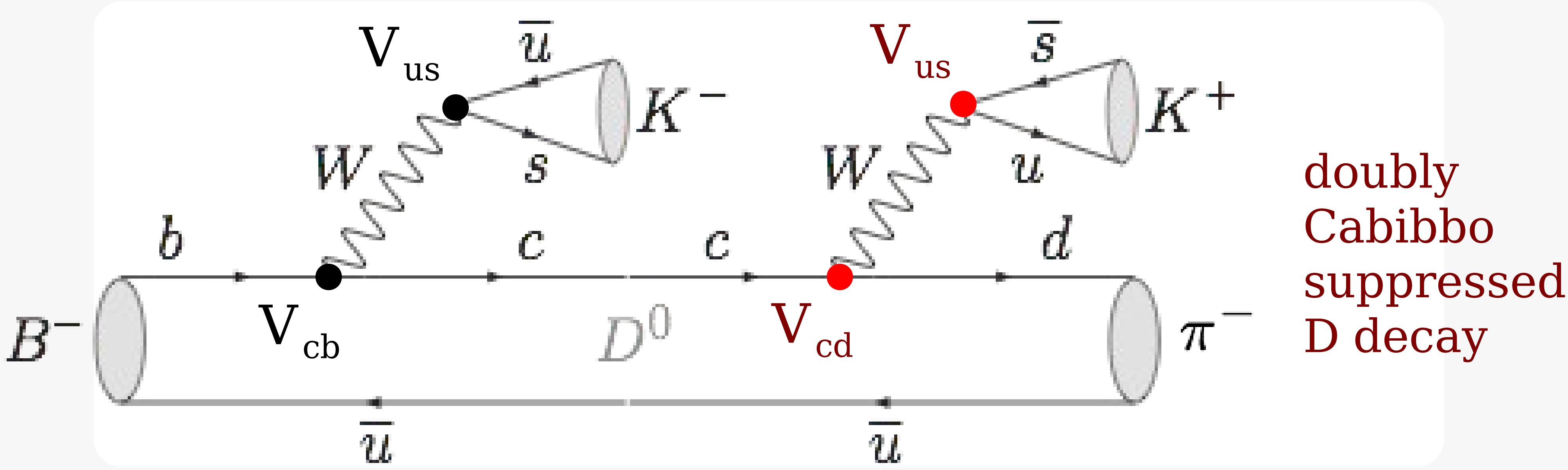
$$A_{CP+} = +0.29 \pm 0.06 \pm 0.02$$
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

systematics dominated by peaking background,
double ratio approximation

coming improvement: adding $K_S\omega$, $K_S\eta'$ for CP-odd modes
coming update: D^*K modes

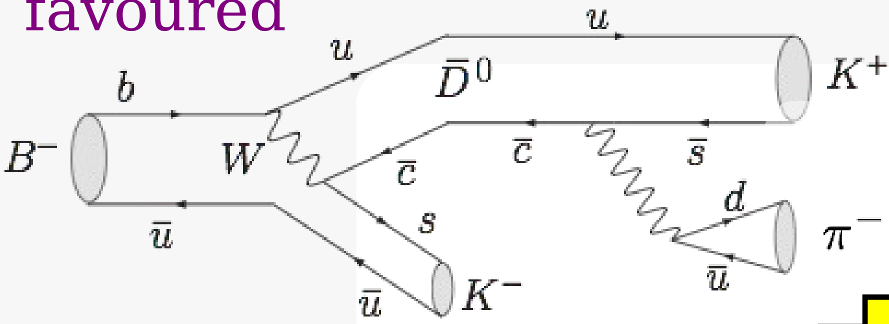
ADS method measures ϕ_3 via the interference in rare $B^- \to [K^+\pi^-]_D K^-$ decays



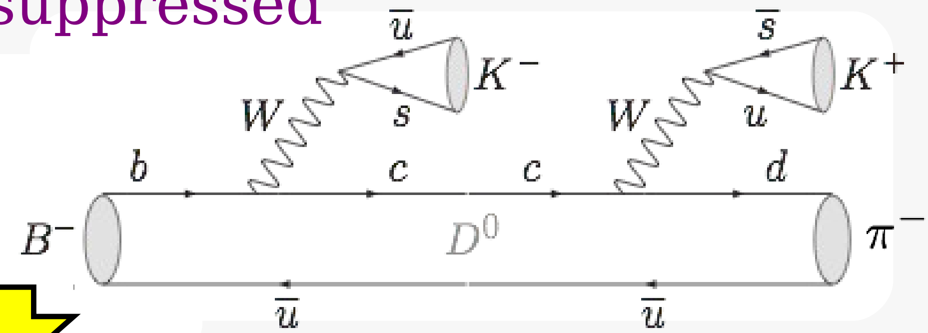


ADS rate and asymmetry (relative to the common decay):

favoured

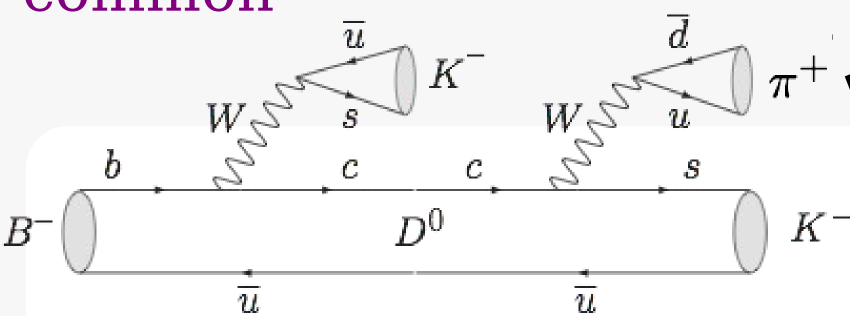


suppressed



$$\mathcal{R}_{DK} = \frac{\Gamma([K^+\pi^-]\,K^-) + \Gamma([K^-\pi^+]\,K^+)}{\Gamma([K^-\pi^+]\,K^-) + \Gamma([K^+\pi^-]\,K^+)}$$

common



$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3$$

$$\mathcal{A}_{DK} = \frac{\Gamma([K^+\pi^-]\,K^-) - \Gamma([K^-\pi^+]\,K^+)}{\Gamma([K^-\pi^+]\,K^-) + \Gamma([K^+\pi^-]\,K^+)}$$

$$= 2\, r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3 \,/\, \mathcal{R}_{DK}$$

where $r_D = \left| \frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(\bar{D}^0 \to K^+\pi^-)} \right| = 0.0613 \pm 0.0010$

$B^- \to DK^-,\ D \to K^+\pi^-$ ADS

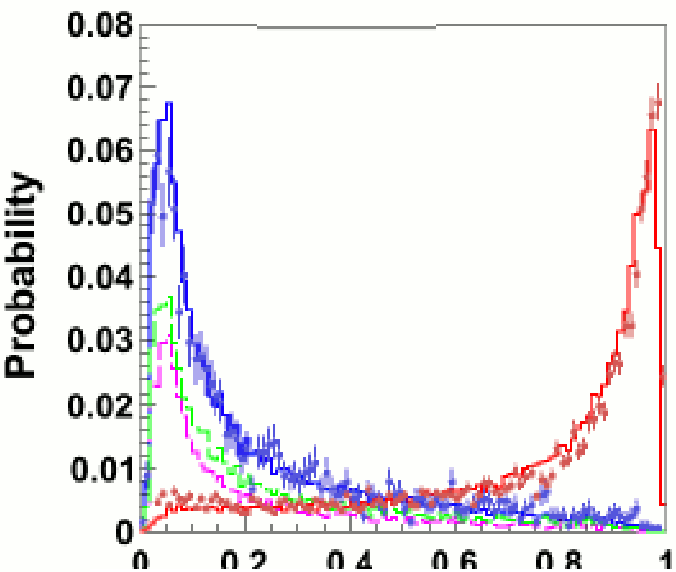
Main background is $e^+e^- \to q\bar{q}$ $(q=u, d, s, c)$ continuum

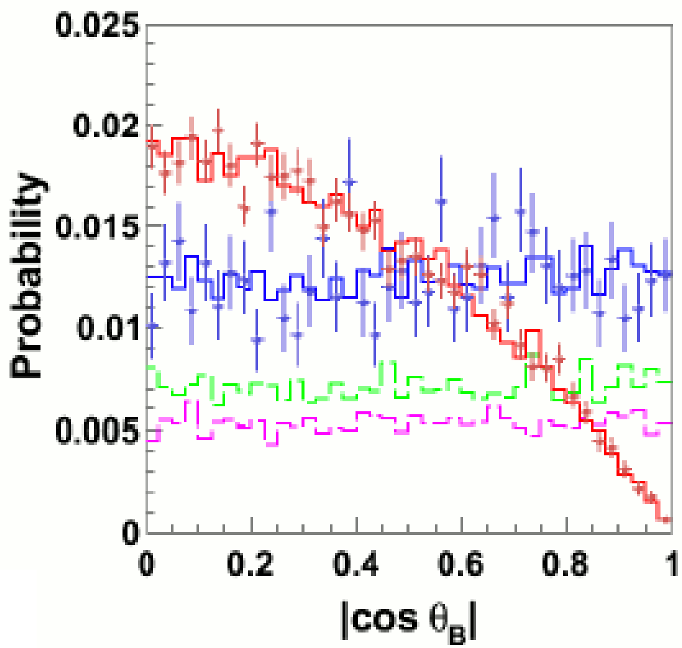
combine 10 variables with neural network:

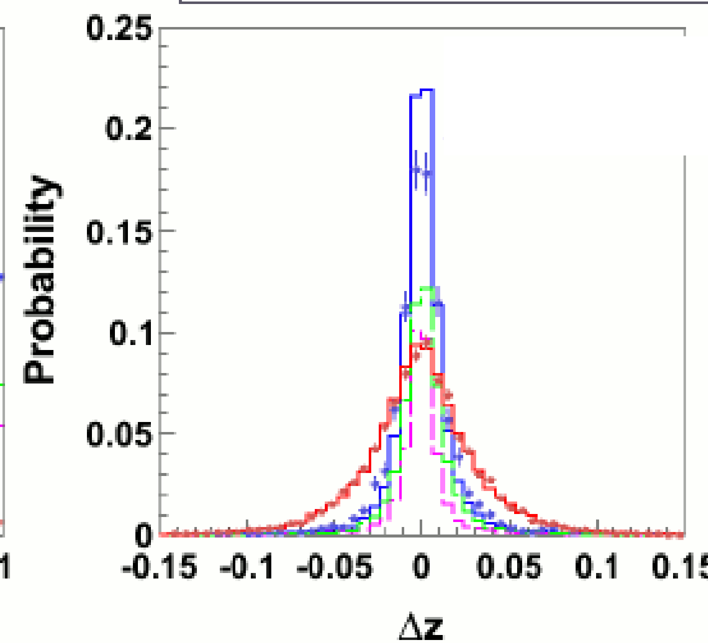
$B^- \to D\pi^-$
$\to K^-\pi^+$
M_{bc}-sideband

histogram: MC, dots: data
signal
qq = charm + uds

- Variables which have different distributions for signal and $q\bar{q}$ background are used.

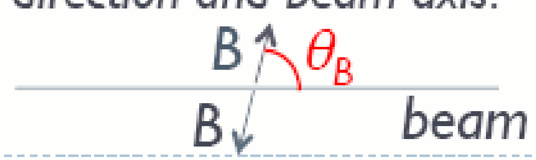




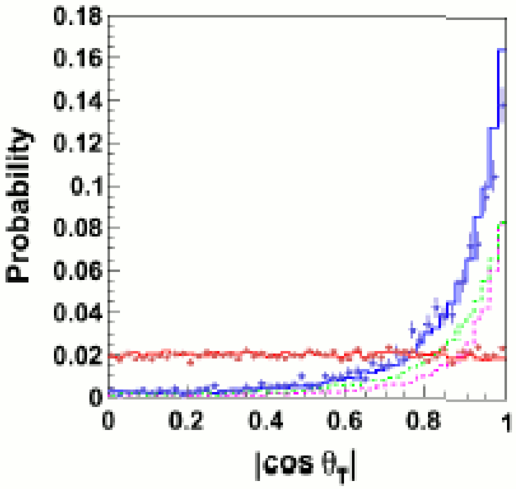


(Here, we use "old" package.)
(RooKSFW is also possible.)
Most powerful.

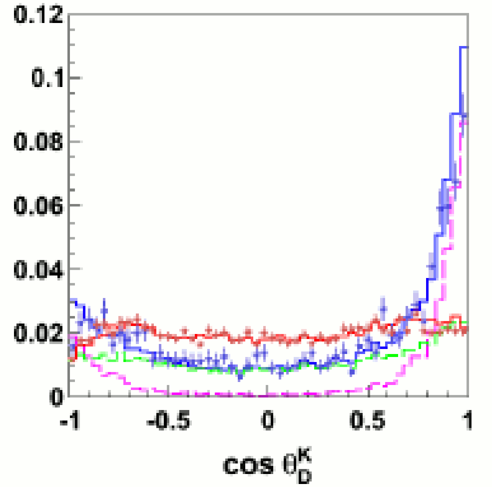
θ_B is angle between B-flight direction and beam axis.



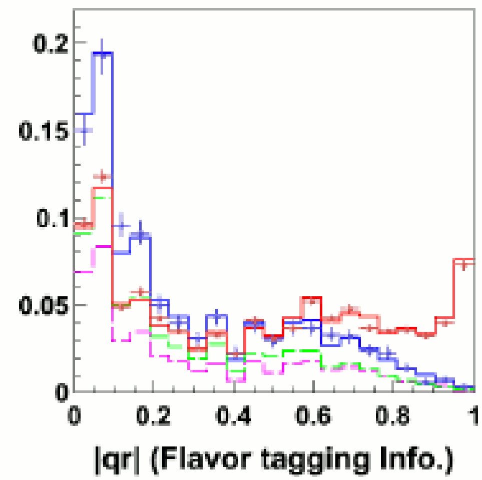
If tag is not possible, Δz = -999.
NB deals with as a δ-function.



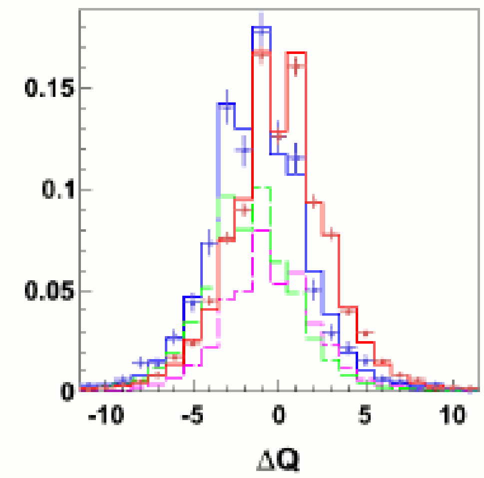
Angle between thrust axes of B decay and remainder.
No full correlation to LR(KSFW).



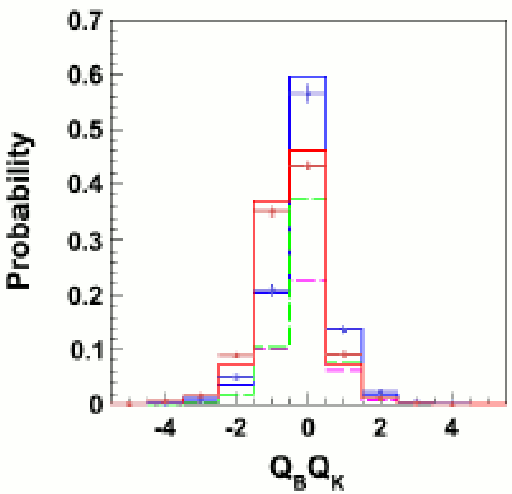
Decay angle of D →kπ.



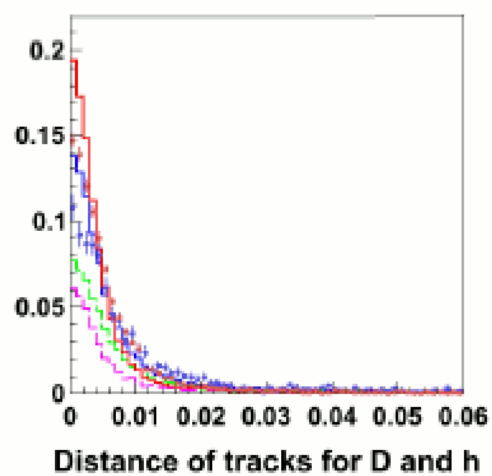
Flavor tagging Info. by MDLH. (NB possible.)



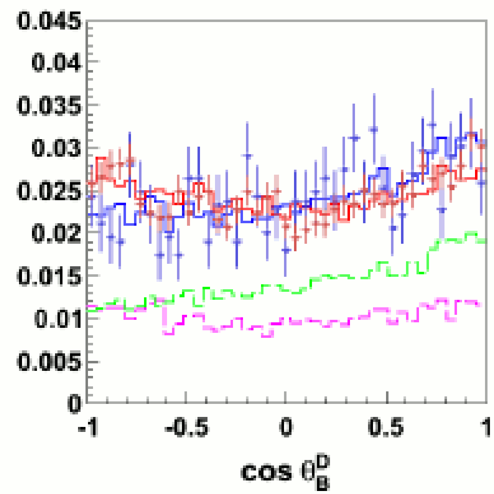
Difference of charges in D hemisphere and opposite hemisphere.



Product of charge of B and sum of charges for K not used in B reconstruction.



Distance of tracks for D and K.



Decay angle of B →DK.

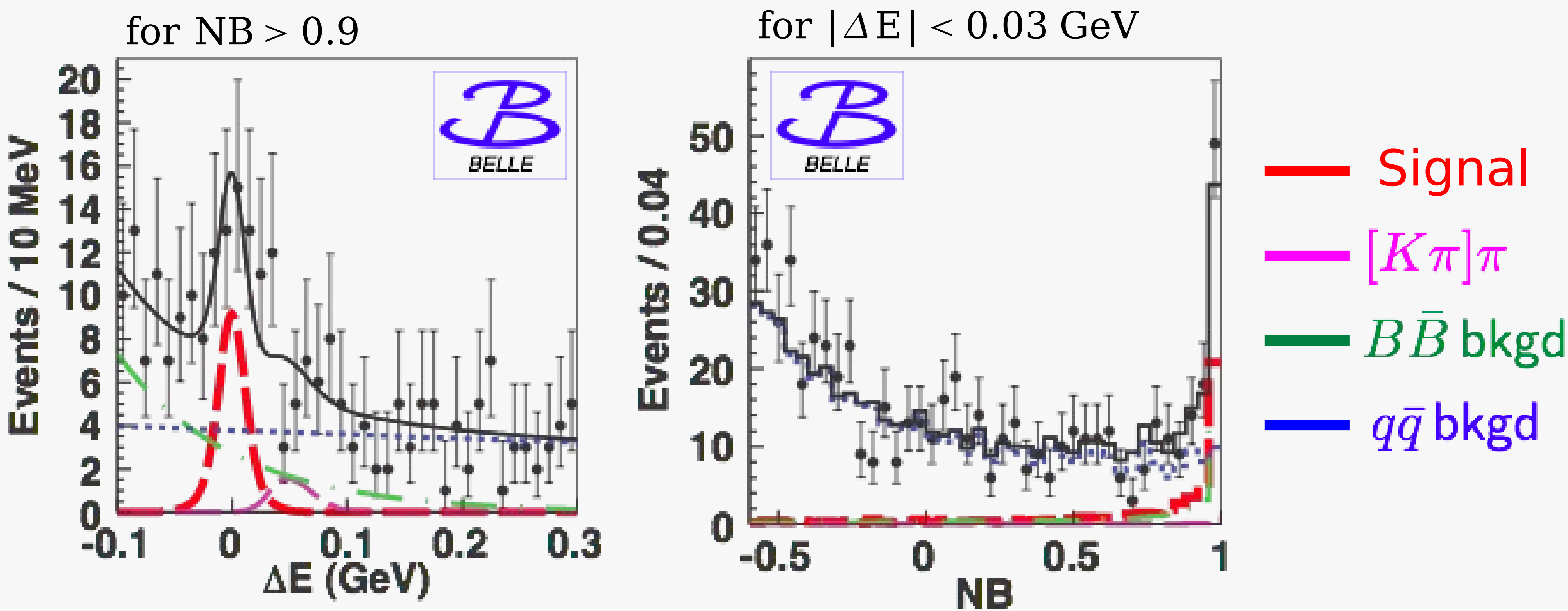
10 variables combined to obtain a single NN output (NB)

for example, at 99% bckg rej. signal eff. = 42% now becomes 60%

Yields for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\overline{B}$ events

PRL 106, 231803 (2011)

Fit ΔE and NB distributions together to extract signal



$56.0^{+15.1}_{-14.2}$ events

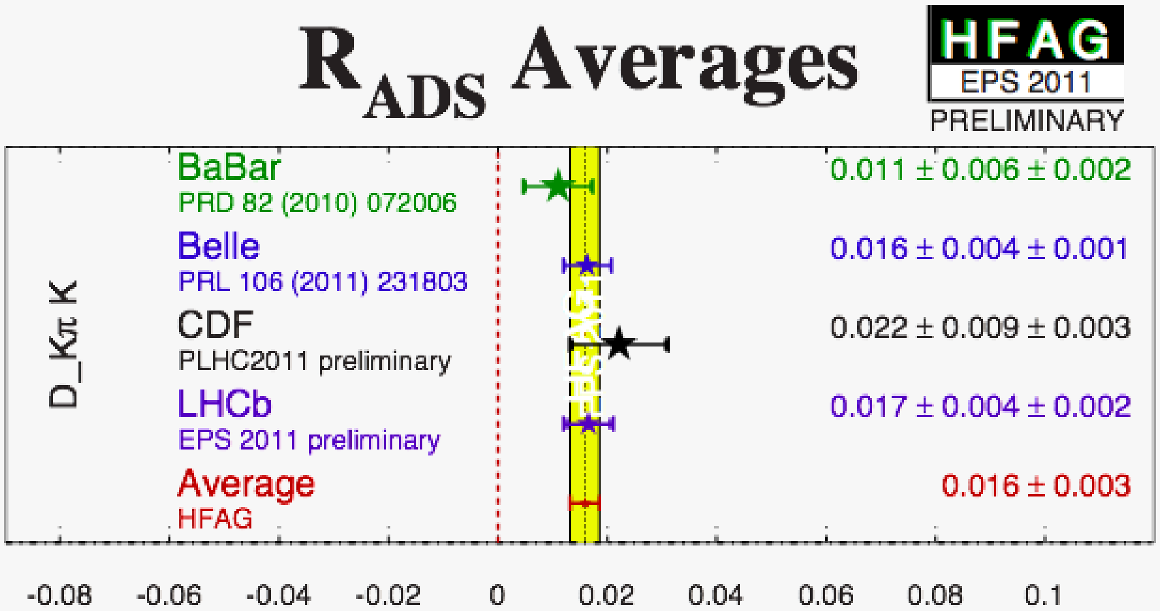
First evidence obtained with a significance of 3.8σ (including syst.)

$$\mathbf{R_{DK} = (1.63^{+0.44}_{-0.41}{}^{+0.07}_{-0.13}) \times 10^{-2}}$$

$$\mathbf{A_{DK} = -0.39^{+0.26}_{-0.28}{}^{+0.04}_{-0.03}}$$

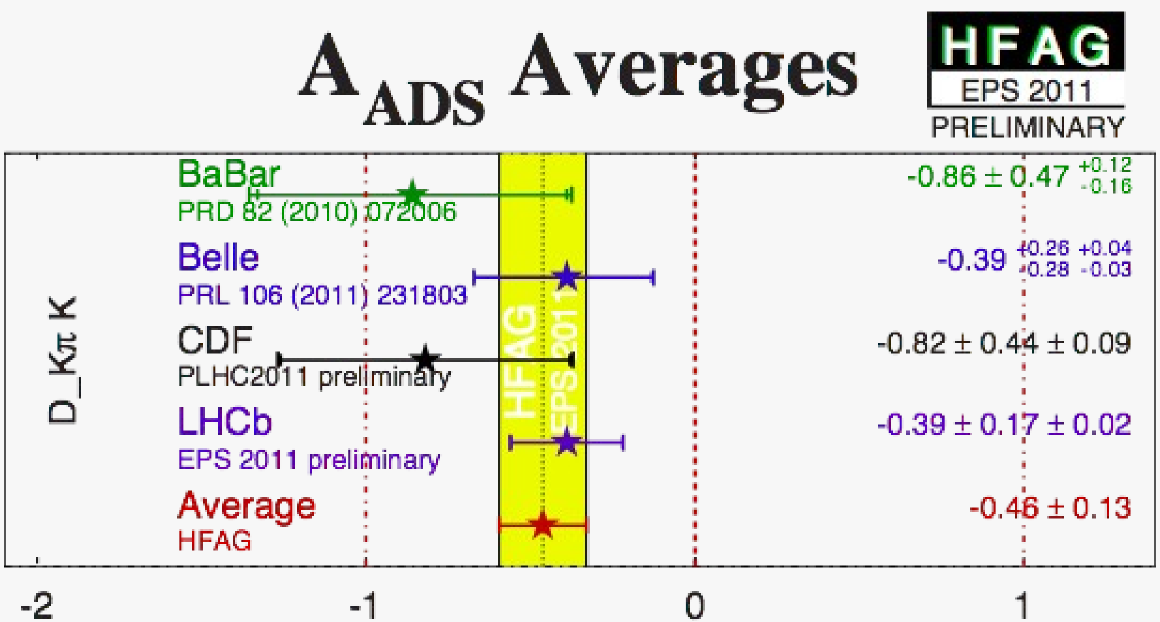
Results for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\bar{B}$ events

PRL 106, 231803 (2011)



$$\left(1.63\,^{+0.44}_{-0.41}\,^{+0.07}_{-0.13}\right) \times 10^{-2}$$

$\Rightarrow\ r_B \neq 0$



$$-0.39\,^{+0.26}_{-0.28}\,^{+0.04}_{-0.03}$$

First evidence for the ADS mode $B^- \to [K^+\pi^-]_{D^*}K^-$ from Belle 772 million $B\bar{B}$ events

Preliminary
LP 2011

study both modes: $D^* \to D\pi^0$, $D\gamma$:

Signal seen
with a significance of 3.5σ
for $D^* \to D\gamma$ mode

Ratio to favored mode:

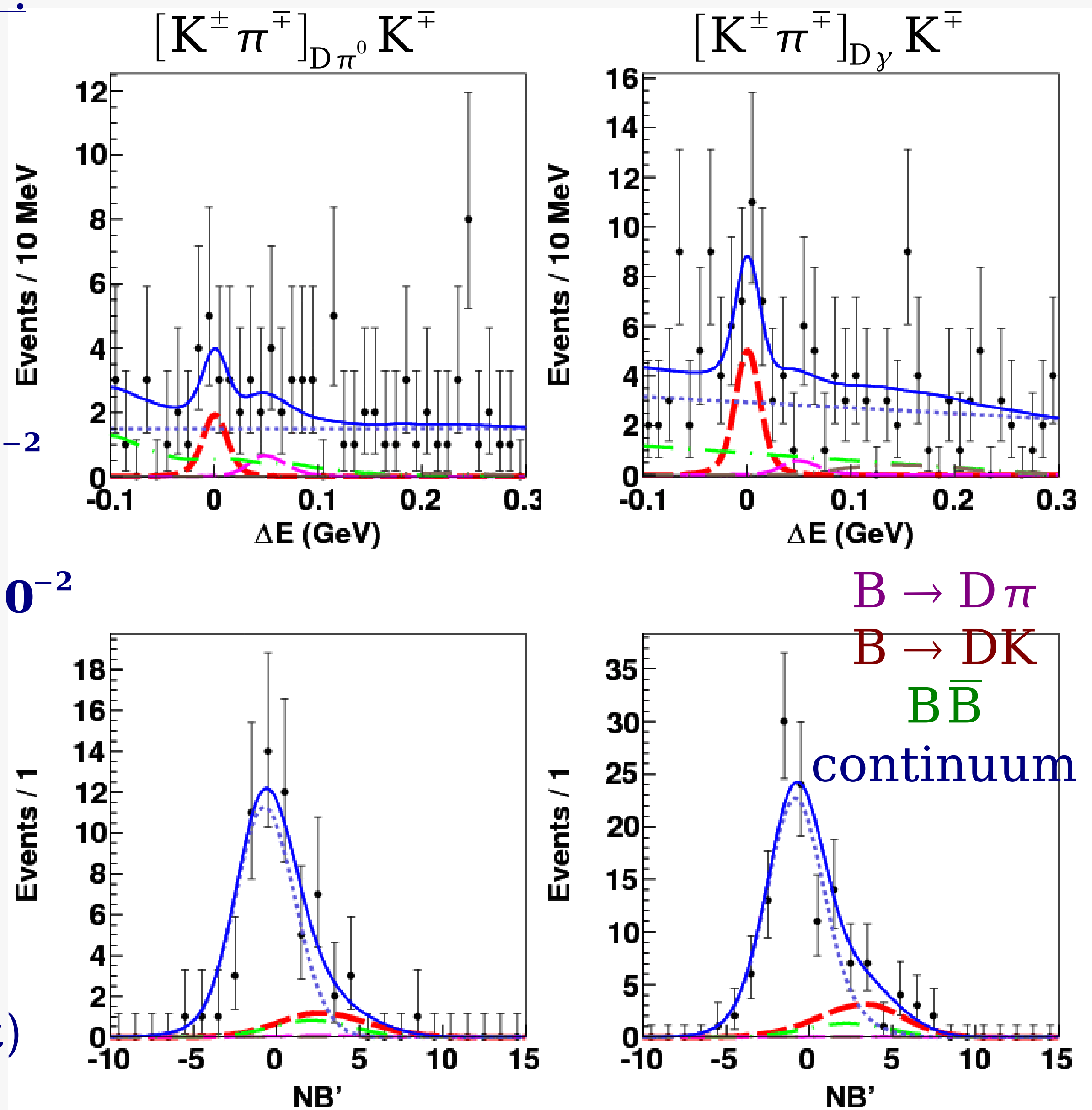
$$R_{D\pi^0} = (1.0\,^{+0.8}_{-0.7}(\text{stat})\,^{+0.1}_{-0.2}(\text{syst})) \times 10^{-2}$$

$$R_{D\gamma} = (3.6\,^{+1.4}_{-1.2}(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-2}$$

asymmetry:

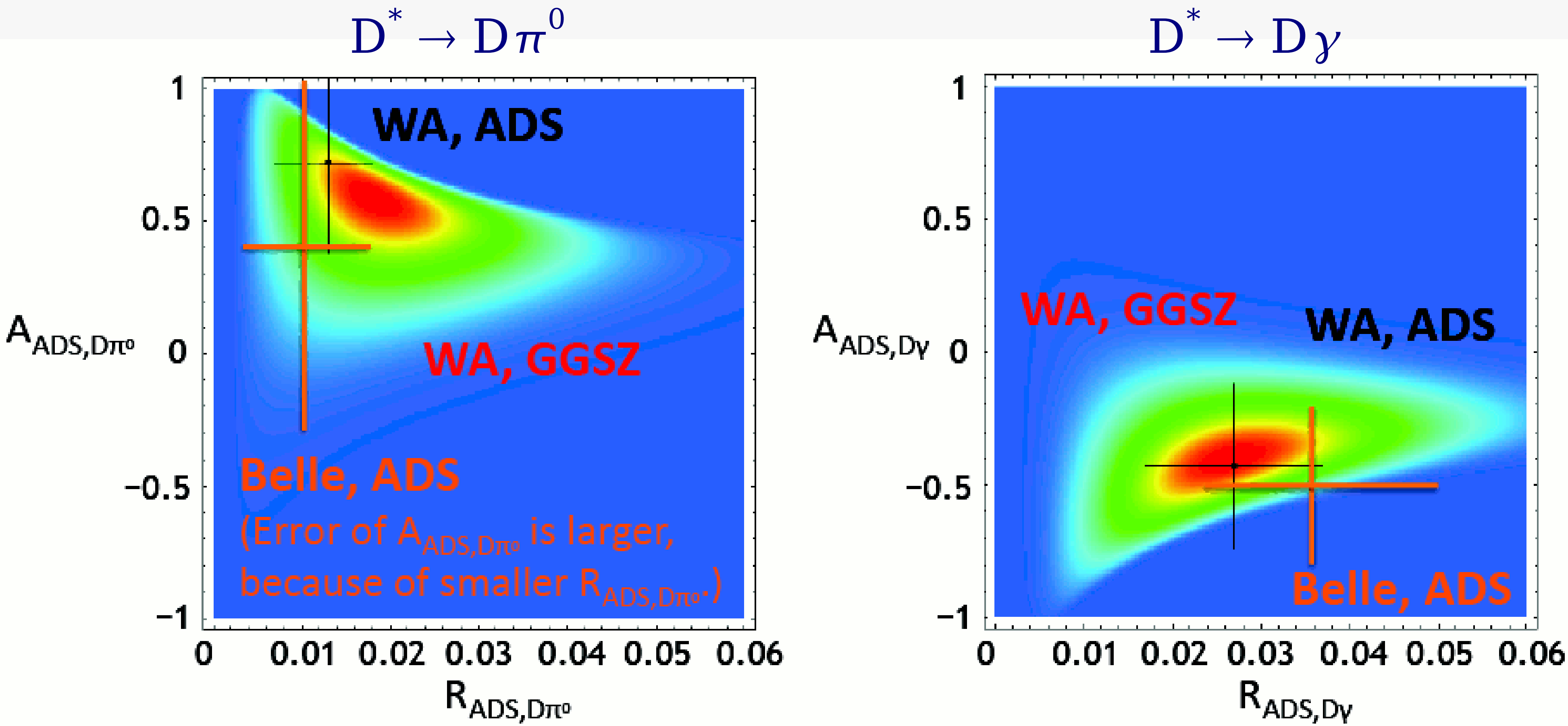
$$A_{D\pi^0} = 0.4\,^{+1.1}_{-0.7}(\text{stat})\,^{+0.2}_{-0.1}(\text{syst})$$

$$A_{D\gamma} = -0.51\,^{+0.33}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})$$



Comparison of the results obtained for D^*K with expectations

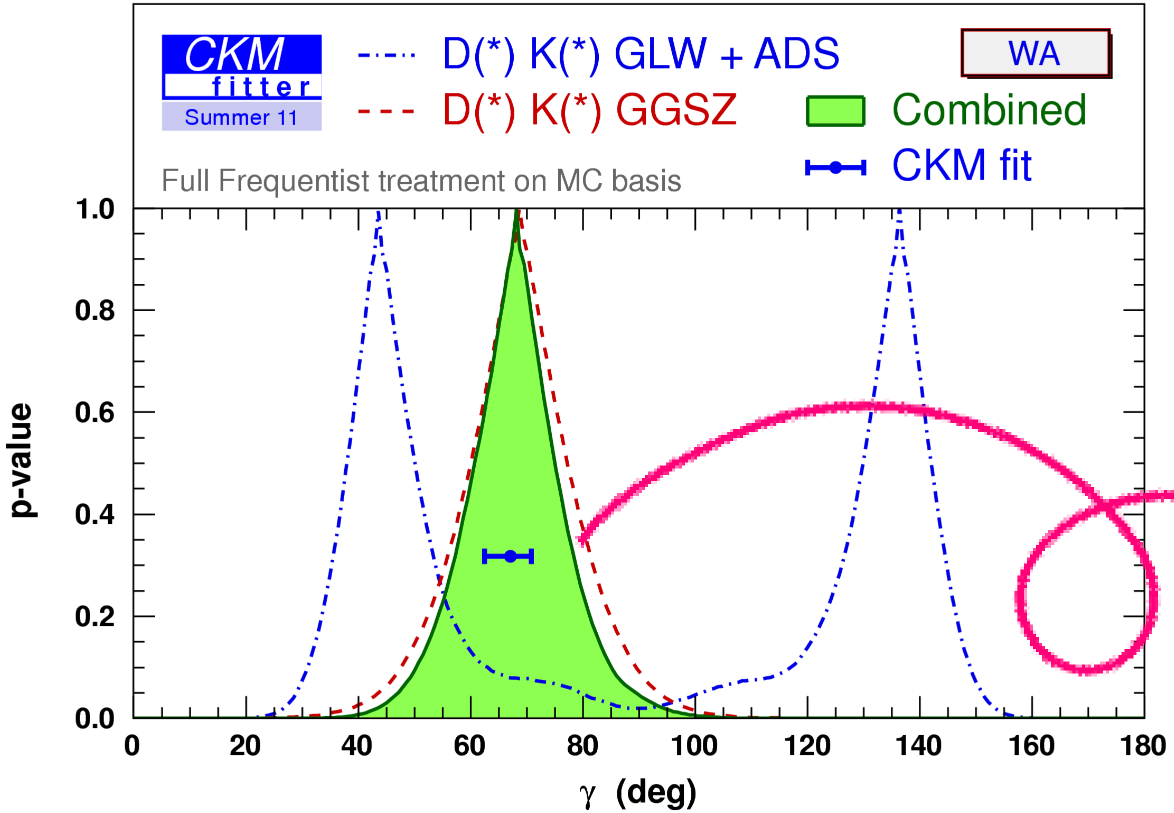
(where ''expectations'' are derived from the GGSZ observables)

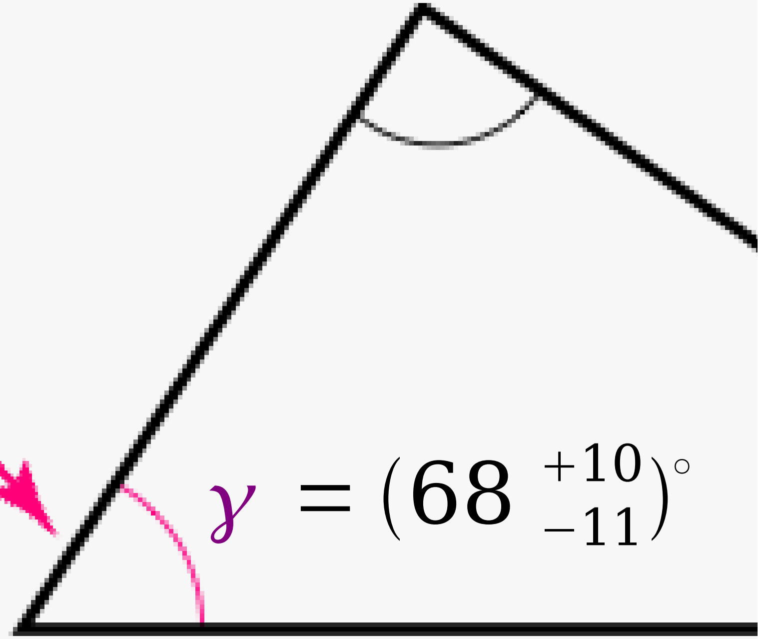


WA taken from HFAG 2011 summer.

Combined measurements for γ from all methods

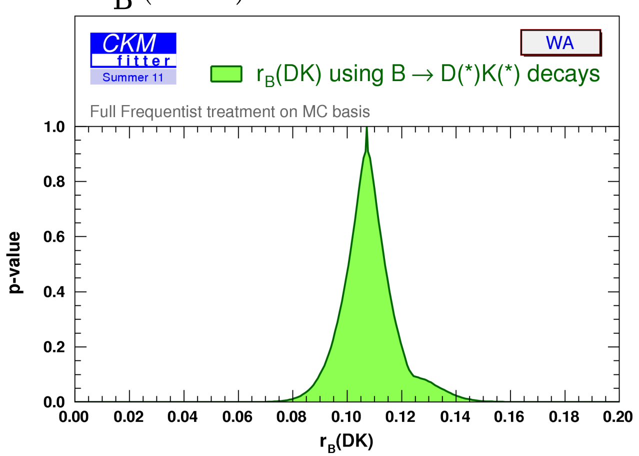
http://ckmfitter.in2p3.fr/



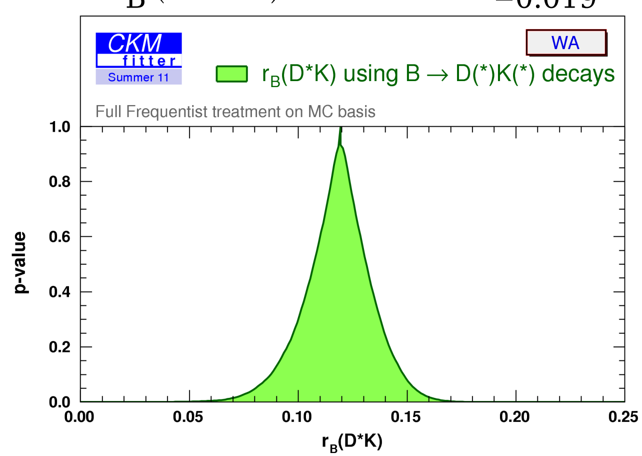


$$\gamma = (68\,^{+10}_{-11})^\circ$$

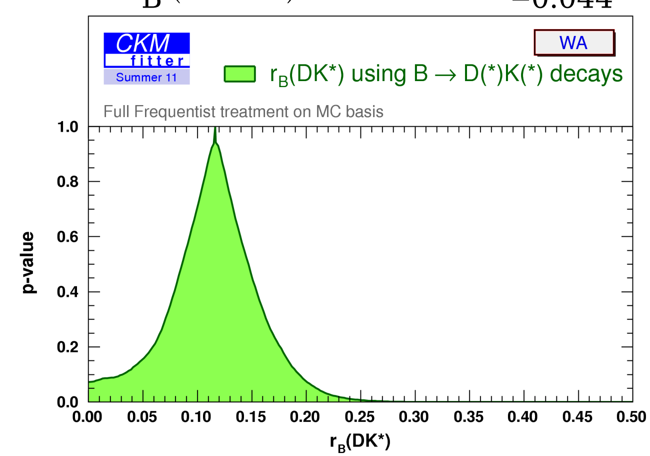
$r_B(DK) = 0.107 \pm 0.010$



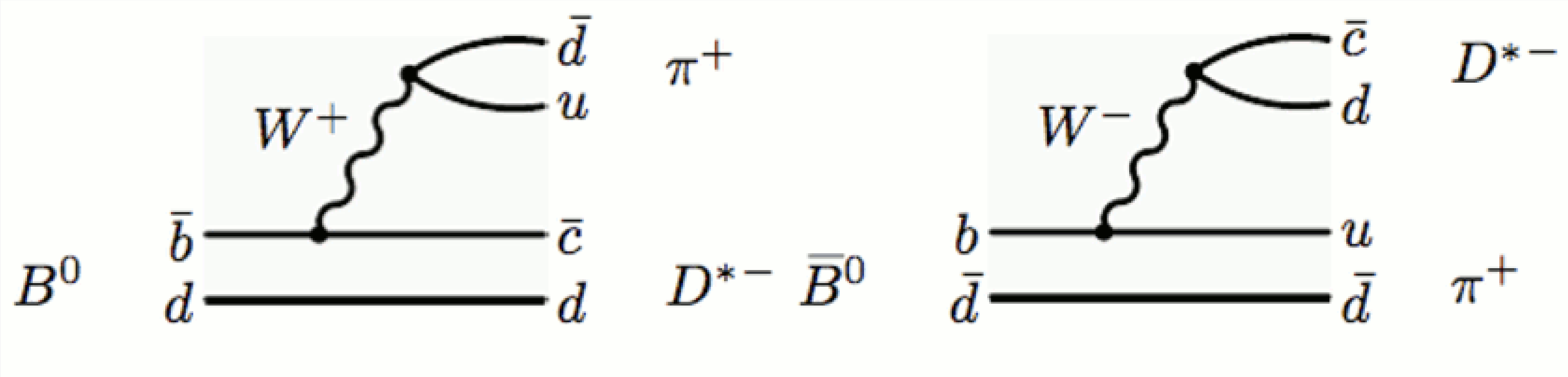
$r_B(D^*K) = 0.119\,^{+0.018}_{-0.019}$



$r_B(D^*K) = 0.116\,^{+0.045}_{-0.044}$



$r \sin(2\phi_1+\phi_3)$ from $B^0 \to D^{(*)}\pi$ decay



Use B flavor tag, measure time-dependent decay rates

$$P(B^0 \to D^{(*)\pm}\pi^{\mp}) = \frac{1}{8\tau_B} e^{-|\Delta t|/\tau_B} [1 \mp \mathbf{C} \cos(\Delta m \Delta t) - \mathbf{S}^{\pm} \sin(\Delta m \Delta t)]$$

$$P(\bar{B}^0 \to D^{(*)\pm}\pi^{\mp}) = \frac{1}{8\tau_B} e^{-|\Delta t|/\tau_B} [1 \pm \mathbf{C} \cos(\Delta m \Delta t) + \mathbf{S}^{\pm} \sin(\Delta m \Delta t)]$$

$$\mathbf{S}^{\pm} = -2 r \sin(2\phi_1 + \phi_3 \pm \delta_{D^{(*)}\pi}) \qquad \mathbf{C} = \frac{1-r^2}{1+r^2} \approx 1 \qquad r \approx 0.02$$

$\Rightarrow$ large stat available, small CP violation effect

- partial reconstruction helps increase statistics
- lepton tag (50196±286 signal evts)

657×10^6 $B\bar{B}$ pairs
[ArXiv:0809.3203]

$r\sin(2\phi_1+\phi_3)$ from $B^0 \to D^{(*)}\pi$ decay

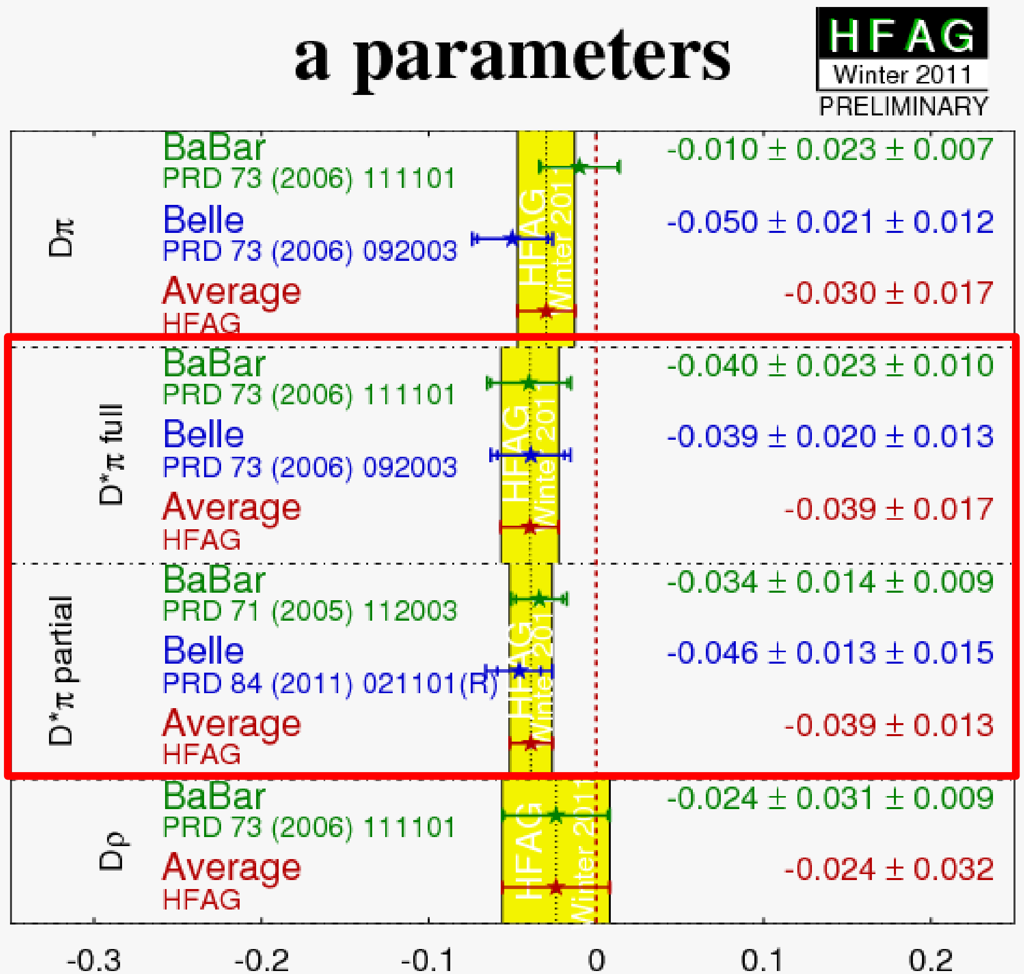
$657\times10^6\, B\bar{B}$ **pairs**
[PRD 84 (2011) 021101]

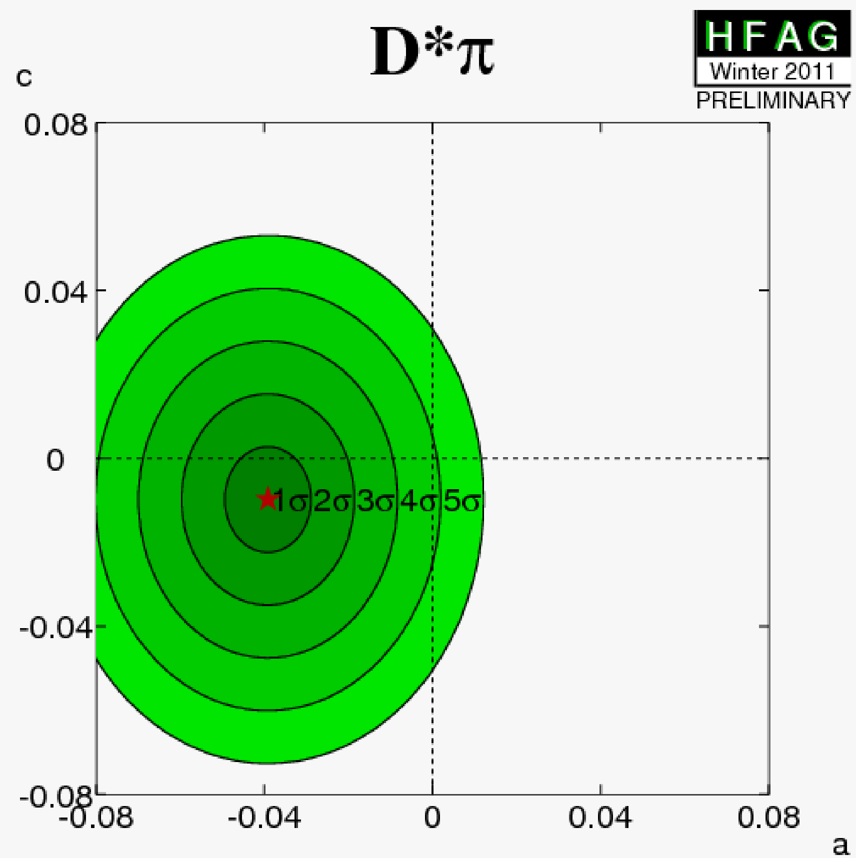
HFAG notation
$a = -(S^+ + S^-)/2$
$c = -(S^+ - S^-)/2$

$a = -0.046 \pm 0.013 \pm 0.015$
$c = -0.015 \pm 0.013 \pm 0.015$

significance of CPV is 2.6σ

summary for all measurements (partial and full)



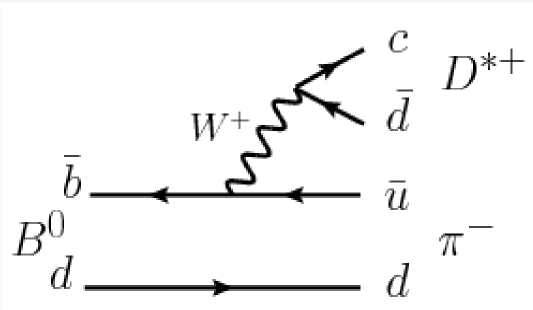


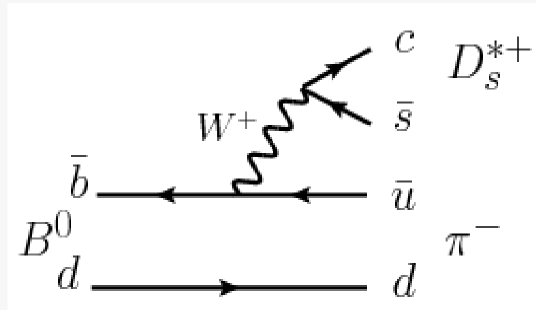
significance of CPV is $\sim 4\sigma$

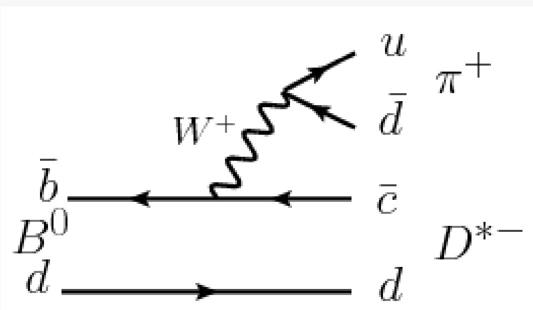
r using $B^0 \to D_s^{*+} \pi^-$ decay

$657 \times 10^6 B\bar{B}$ pairs
[PRD 81, 031101 (2010)]

1^{st} measurement in Belle

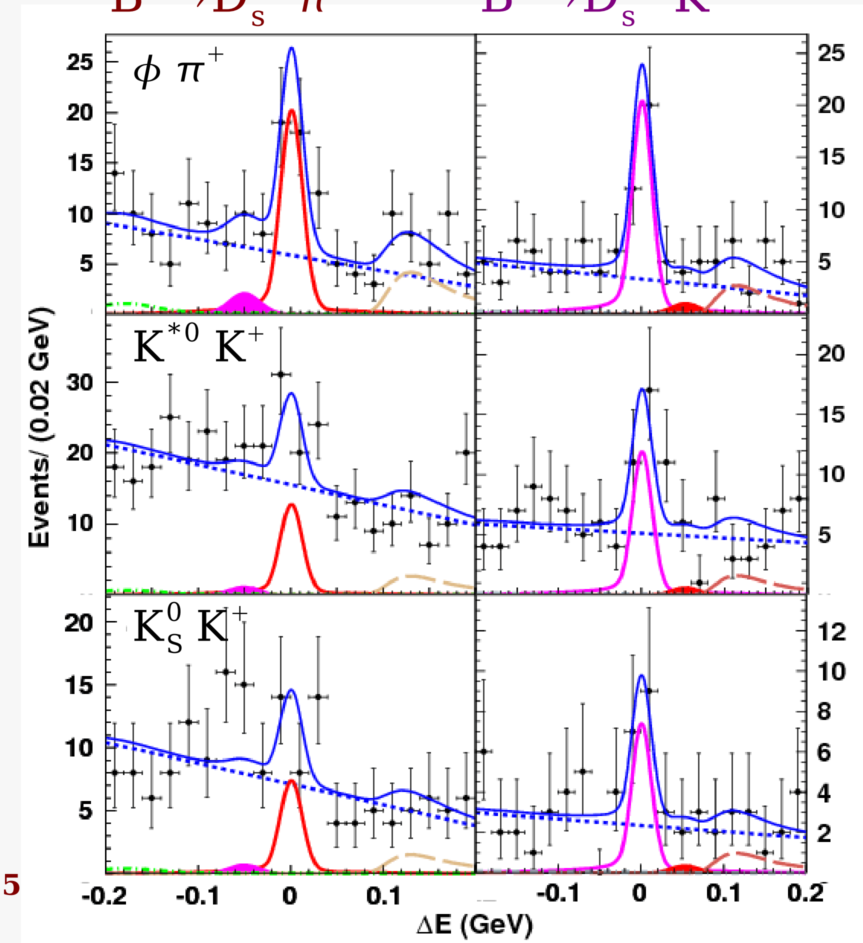






$$r = \tan\theta_C \left(\frac{f_{D^*}}{f_{D_s^*}}\right)\sqrt{\frac{Br(B^0 \to D_s^{*+}\pi^-)}{Br(B^0 \to D^{*-}\pi^+)}}$$

$B^0 \to D_s^{*+} \pi^-$ $\quad$ $B^0 \to D_s^{*-} K^+$



$\Sigma = 6.1\,\sigma$

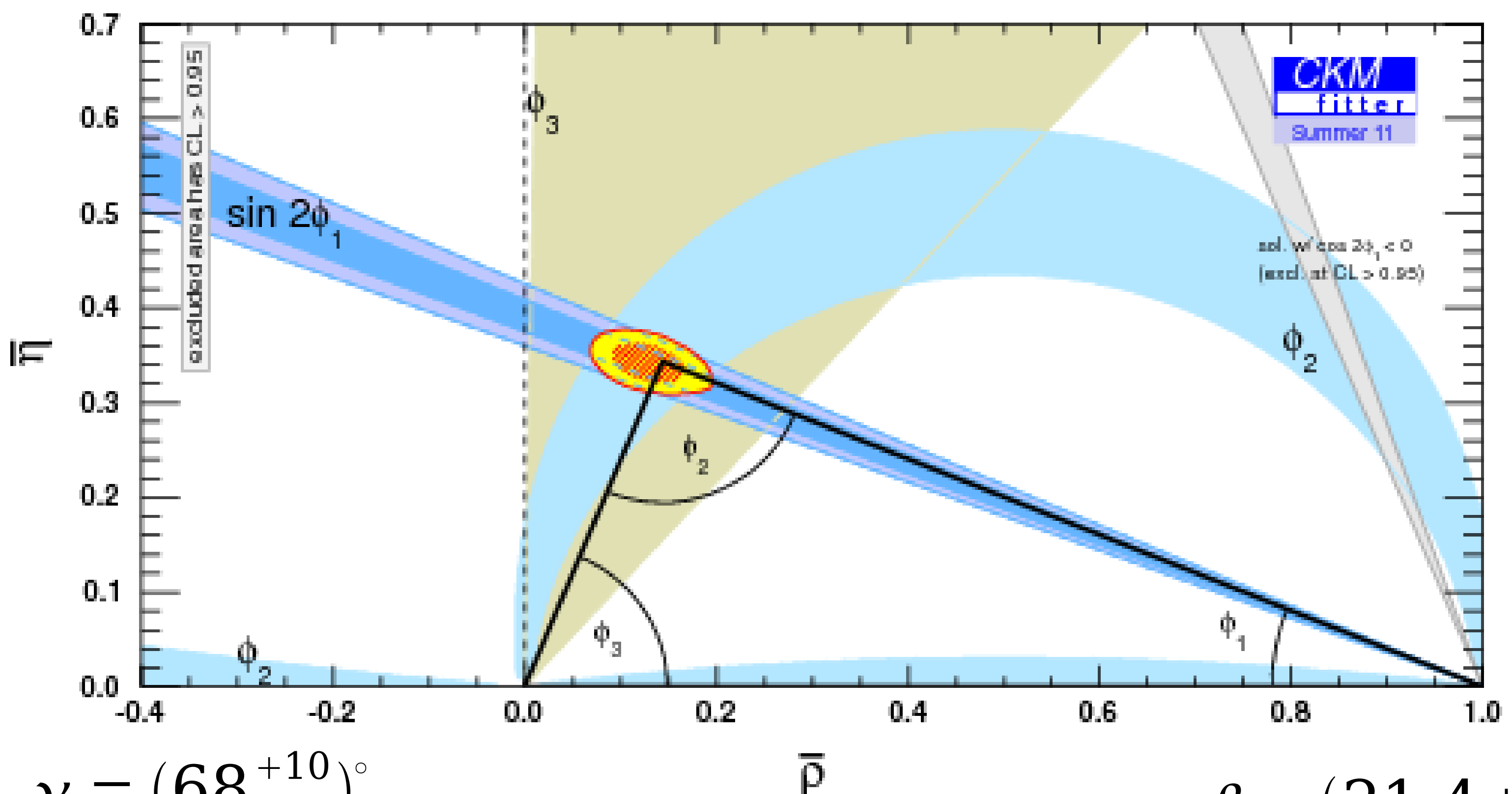
$Br(D_s^{*+}\pi^-) = (1.75 \pm 0.34 \pm 0.17 \pm 0.10) \times 10^{-5}$

$$\boxed{\mathbf{r = (1.58 \pm 0.15 \pm 0.10 \pm 0.03)\%}}$$

Summary

$$\alpha = (89.0^{+4.4}_{-4.2})^\circ$$

(WA, CKMfitter, Winter09)



$$\gamma = (68^{+10}_{-11})^\circ$$

(WA, CKMfitter)

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

(WA, HFAG, Winter11)