FLAVOR PHYSICS

(PART II: the *B* factories)

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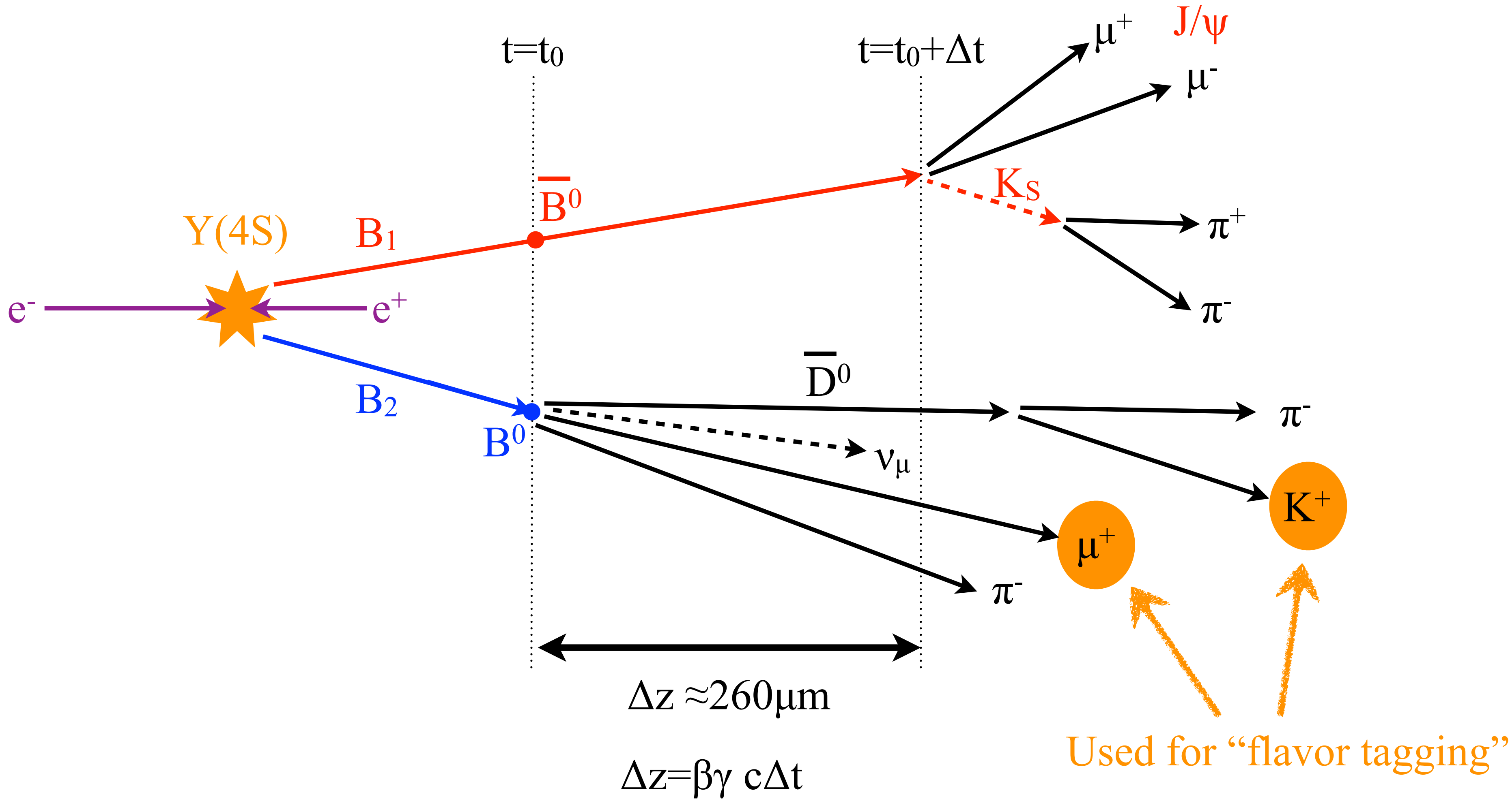
Flavor physics at the B Factories:

BELLE & BABAR

B Factory: requirements

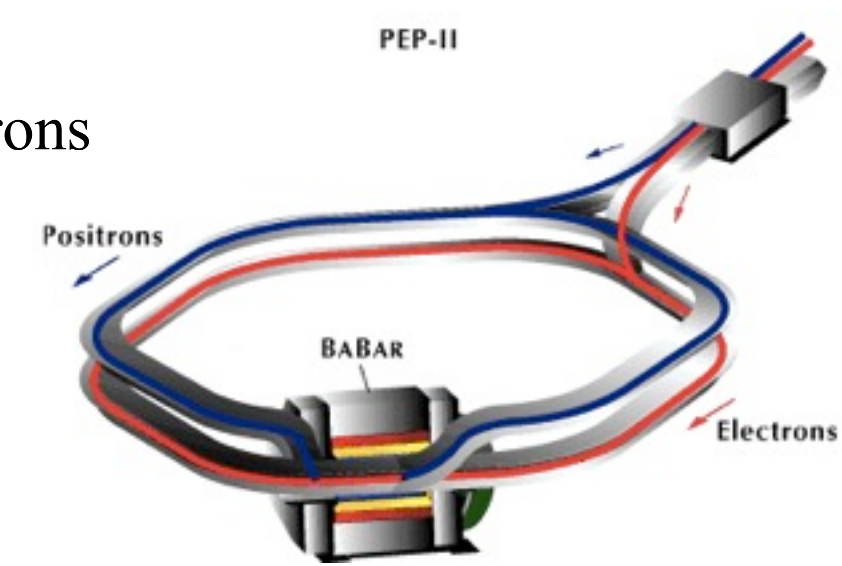
- Primary goal: measure "sin2β" in B^0 decays to $J/\psi K^0_S$
- Needed:
  - high-statistics sample of B^0 mesons
    => high-luminosity e^+e^- collider at the Υ(4S) resonance
  - full kinematical reconstruction of the signal events…
    … + efficient background rejection
    => 4π detector: tracking + calorimetry + particle ID
  - accurate lifetime measurement of the B^0 candidates
    => boosted Υ(4S) center-of-mass frame + excellent vertexing
  - efficient B-flavor tagging
    => excellent lepton and kaon identification capabilities

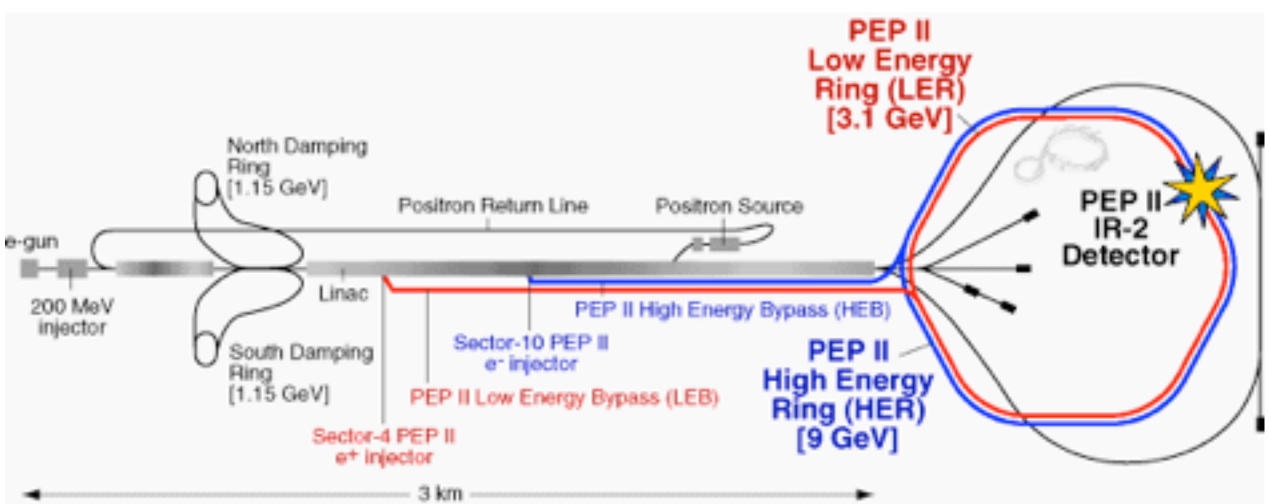
B^0 measurement principle at a B factory



PEP-II at SLAC

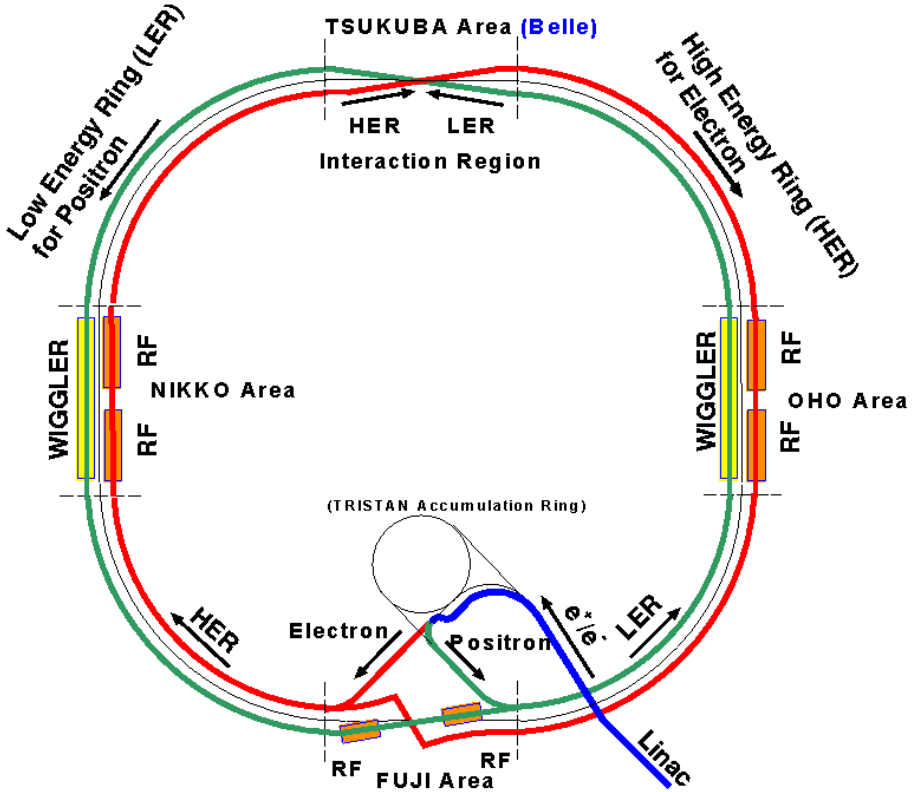
- PEP-II e^+e^- collider at Stanford Linear Accelerator Center
- 2.2km ring, 1658 bunches
- 9.0GeV electrons on 3.1GeV positrons
  => boost $\beta\gamma$=0.56
- Peak luminosity: $12x10^{33}cm^{-2}s^{-1}$
- Integrated luminosity: $553fb^{-1}$
- Operated until 2008



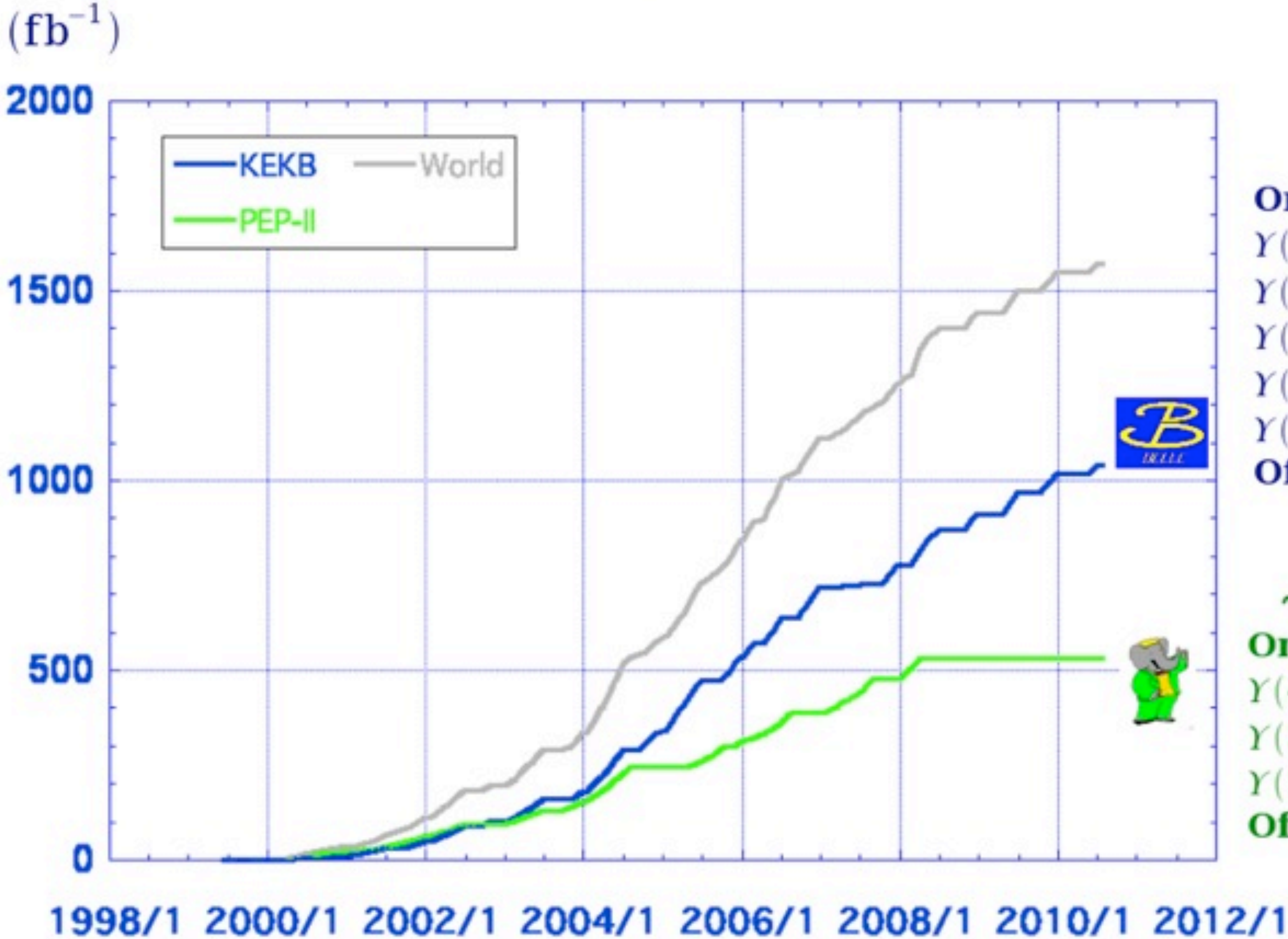


KEK-B at KEK

- KEK-B e^+e^- collider at KEK (Japan)
- 3km ring, 5120 bunches
- 8.0GeV electrons on 3.5GeV positrons
  => boost $\beta\gamma$=0.43
- Peak luminosity: $21x10^{33}cm^{-2}s^{-1}$
- Integrated luminosity: $1040fb^{-1}$
- Upgrading to Super-KEKB:
  - luminosity: $8x10^{35}cm^{-2}s^{-1}$
  - $50ab^{-1}$ by 2020



Luminosity at B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

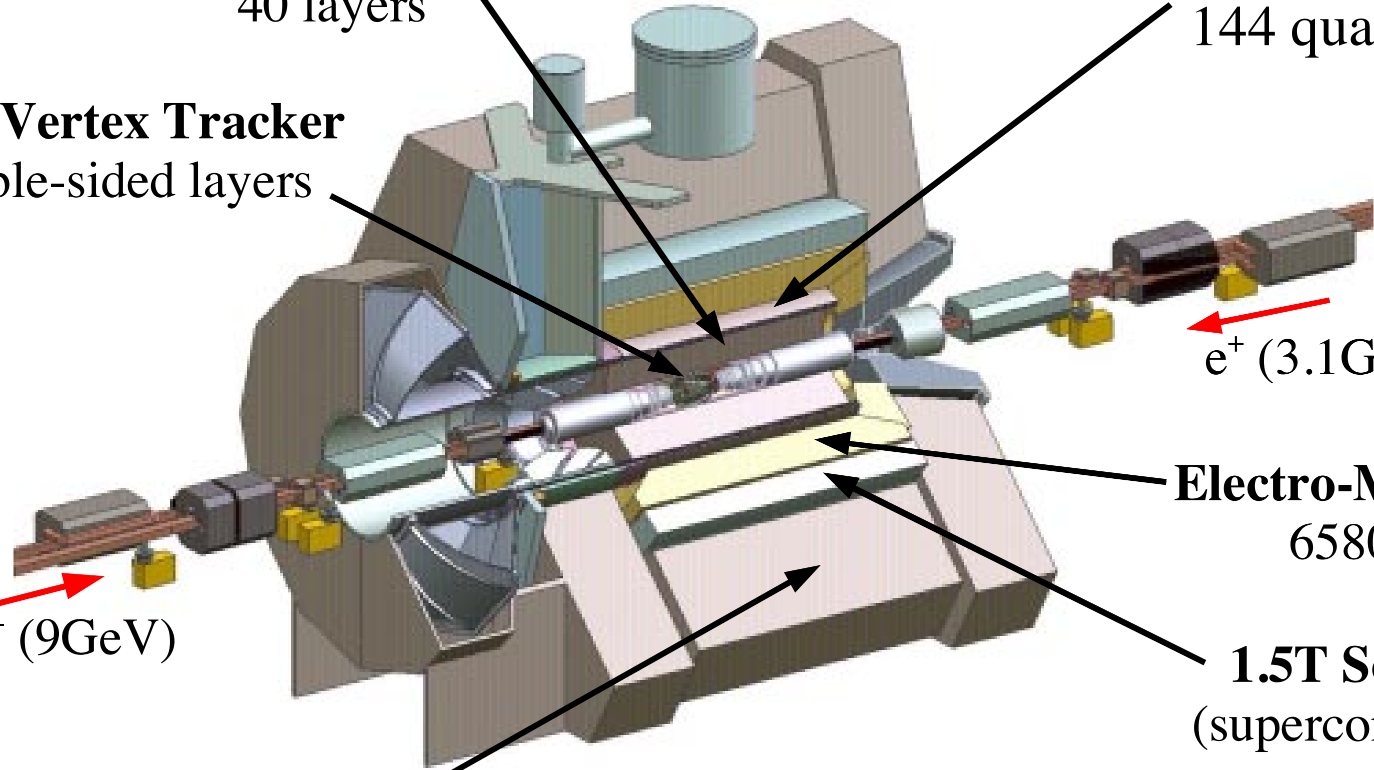
$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

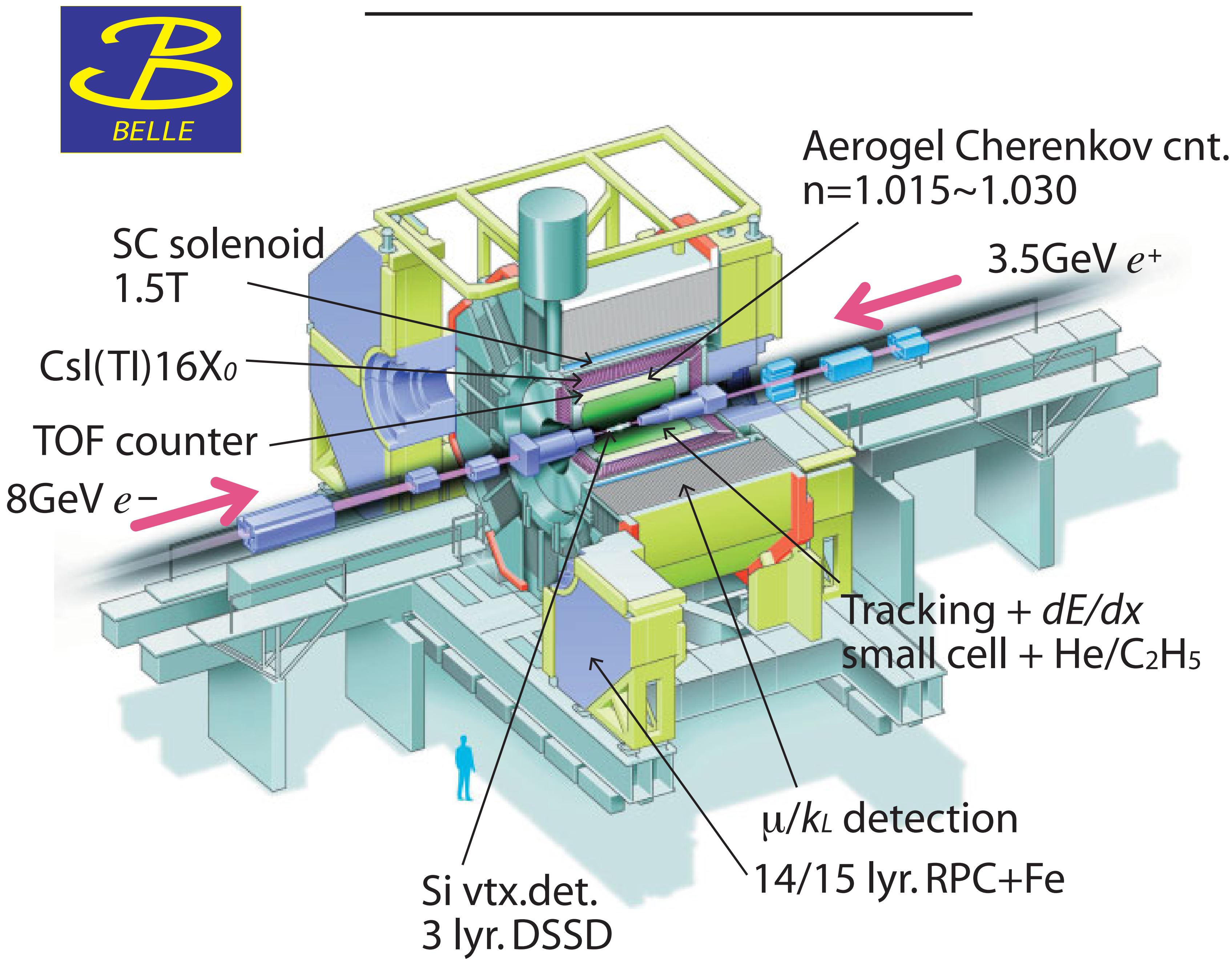
~ 54 fb^{-1}

BABAR detector



- Tracking: $\sigma(p_T)/p_T = 0.13\%\ p_T \oplus 0.45\%$
- DIRC: K/π separation $>3.5\sigma$ for p<3.5 GeV/c
- EMC: $\sigma_E/E = 2.3\%\ E^{-1/4} \oplus 1.9\%$

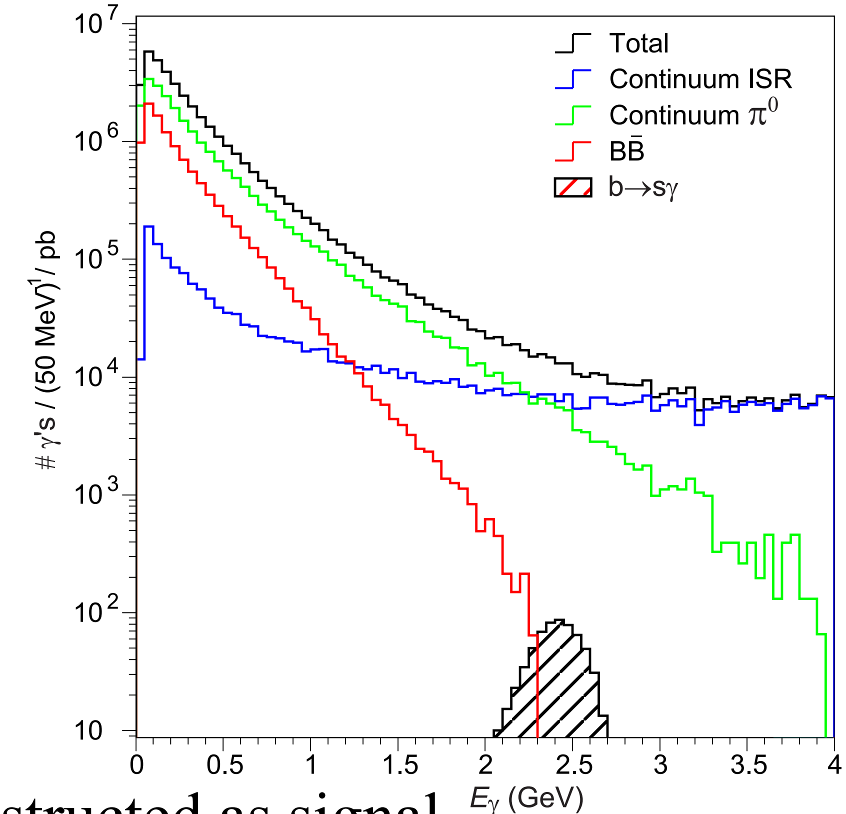
Belle Detector



Backgrounds at the Υ(4S)

- For B physics analyses, the dominant backgrounds are:

1. continuum background
   - $e^+e^- \rightarrow qq$, q=u,d,s,c
   - $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
2. combinatorial background
   - other decays of the Υ(4S) resonance
   - BB events (not signal), reconstructed as signal
     - e.g. B→ρπ reconstructed as B→ππ (“feed down”) or the opposite (“feed up”)
     - e.g. $B_1 \rightarrow D\pi$ and $B_2 \rightarrow D(\rightarrow K\pi)l\nu$ reconstructed as B→DK



Illustrative plot from CLEO b→sγ analysis

Variables for reconstruction of B mesons

A.Kinematic

- B mass
- B energy
- mass of daughter particles
- decay angle of daughter particles (when applicable)

B.Particle identification

- Cherenkov angle from ring-imaging Cherenkov detector
- Time-of-flight

C.Proper time

- decay time information from production and decay vertices

D.Event shape

- variables characterizing how jetty the event is
  (continuum is jetty, while $\Upsilon(4S) \rightarrow B\bar{B}$ events are isotropic)

B mass and energy

- B mass and energy
  - center of mass (CM) energy: $\sqrt{s}$=10.58GeV
  - E^* and p^* = B energy and momentum in CM

  Define: B mass calculated with energy fixed at the beam energy

$$m_{\mathrm{ES}} = \sqrt{\frac{1}{4}s - \mathbf{p}_B^{*2}}$$

  Define: Energy difference between the B and the beam energy

$$\Delta E = E_B^* - \frac{1}{2}\sqrt{s},$$

- Names for the B mass:
  - beam energy constrained mass m_{bc} (at Belle)
  - energy-substituted mass m_{ES} (at BABAR)

B mass and energy

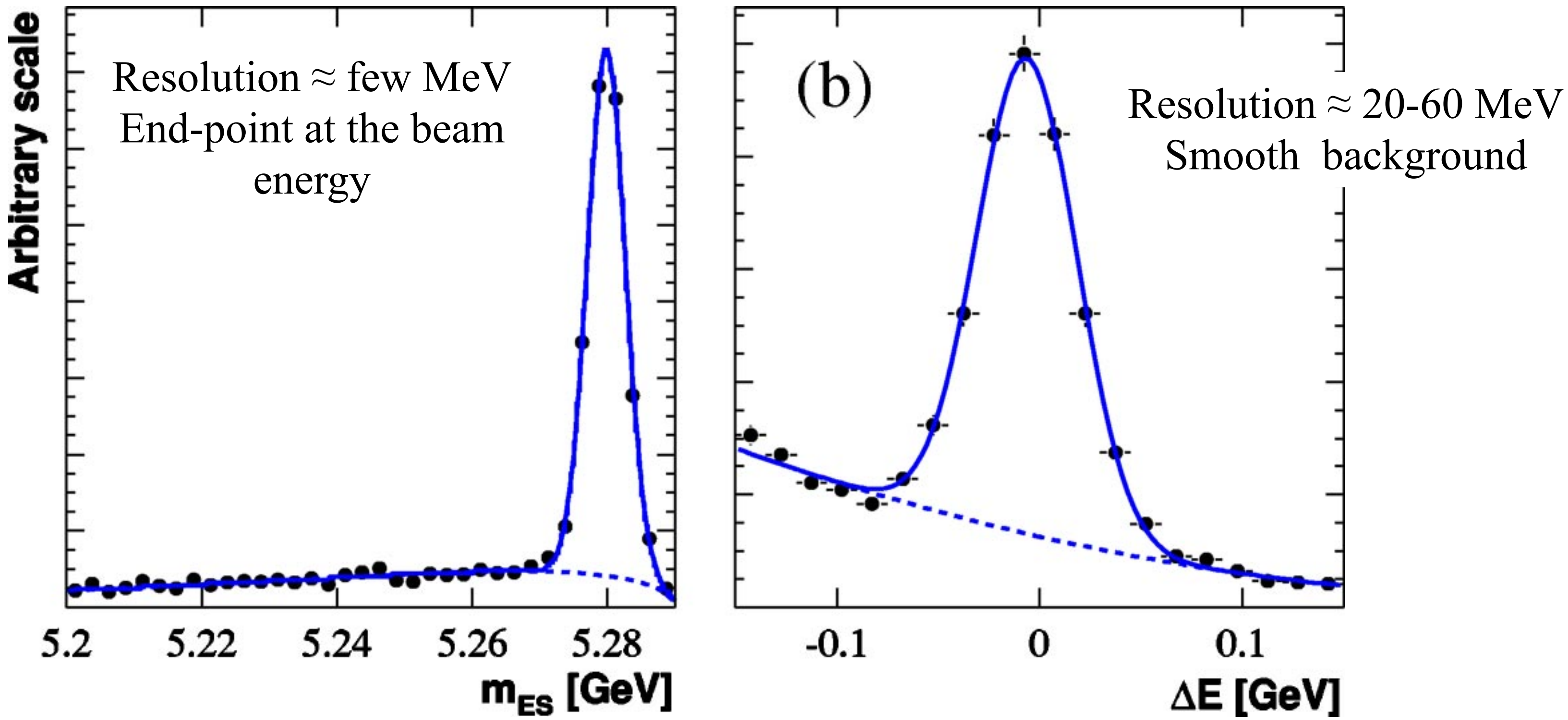
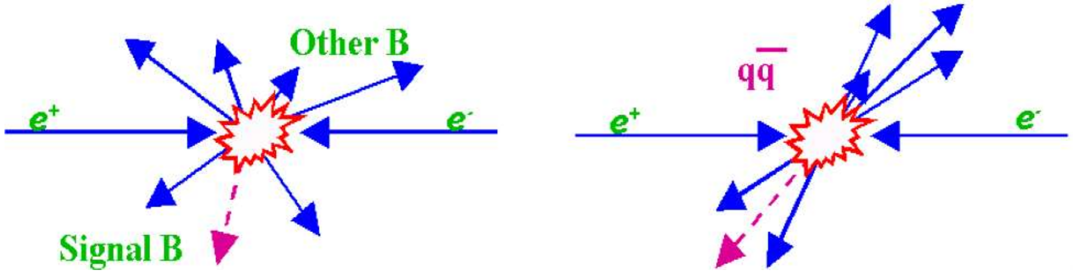
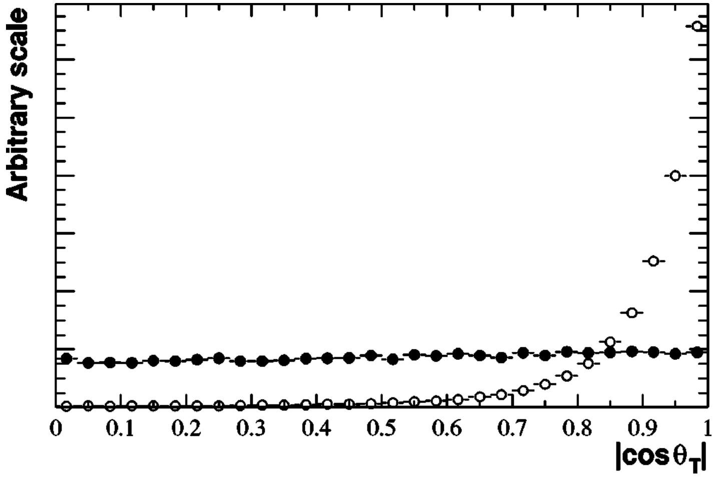


FIG. 7. Distributions of (a) m_{ES} and (b) ΔE from the $B^{-} \to \pi^{-} D^{0}$ data sample used to determine the small corrections to signal Monte Carlo PDF shapes.

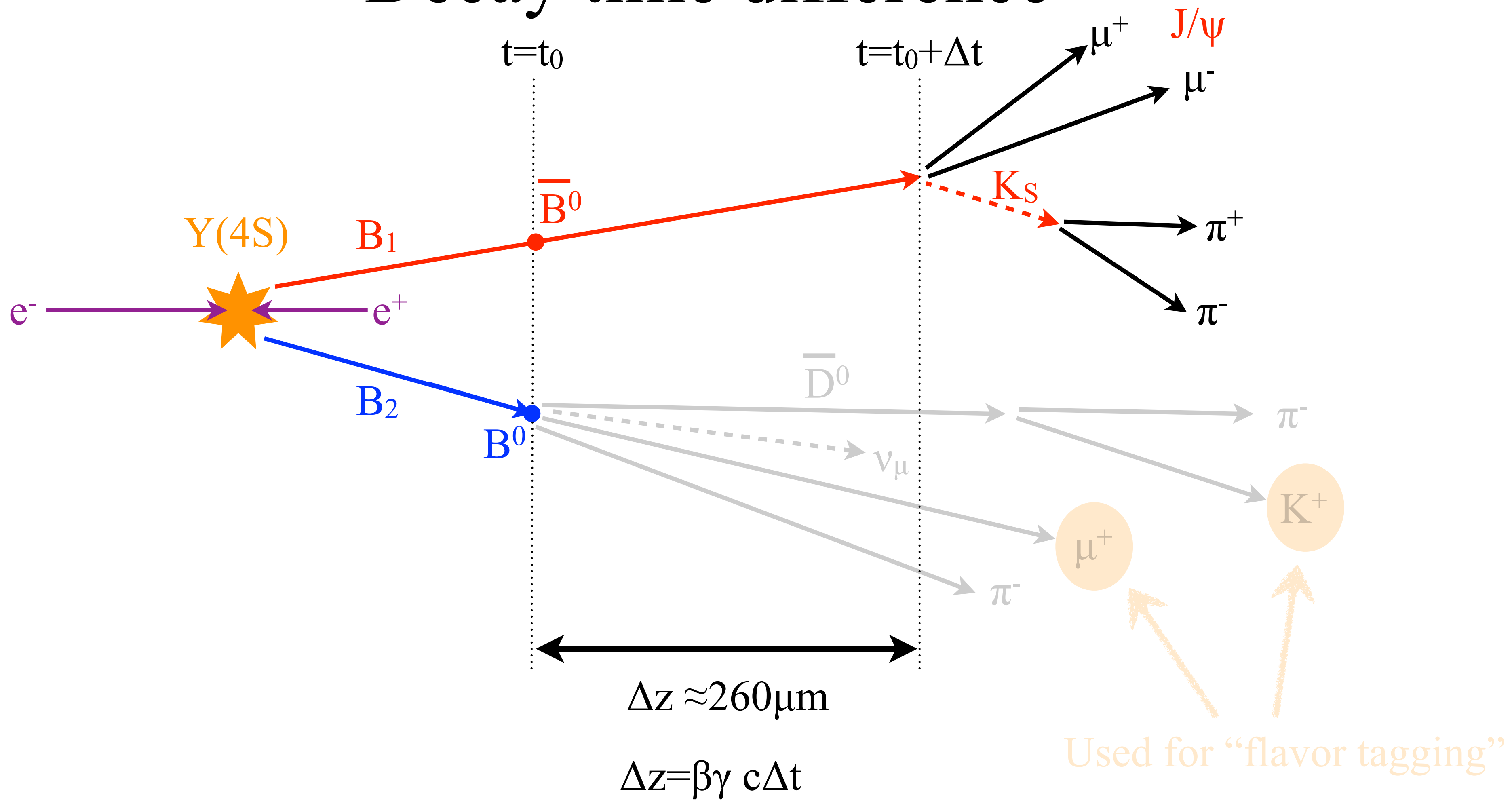
Event shape



- B mesons are produced (almost) at rest in Y(4S) CM
  => decay products are isotropic in CM frame
- the light quarks (u,d,s,c) in continuum events have high momentum
  => decay products are emitted along a main direction
- define the thrust axis as the axis that maximizes the sum of momenta projected on this axis
- the cosine of the angle θ_T of the thrust axis of the B candidate with respect to the thrust axis of the rest of the event is flat for signal, and sharply peaked at 1.0 for continuum

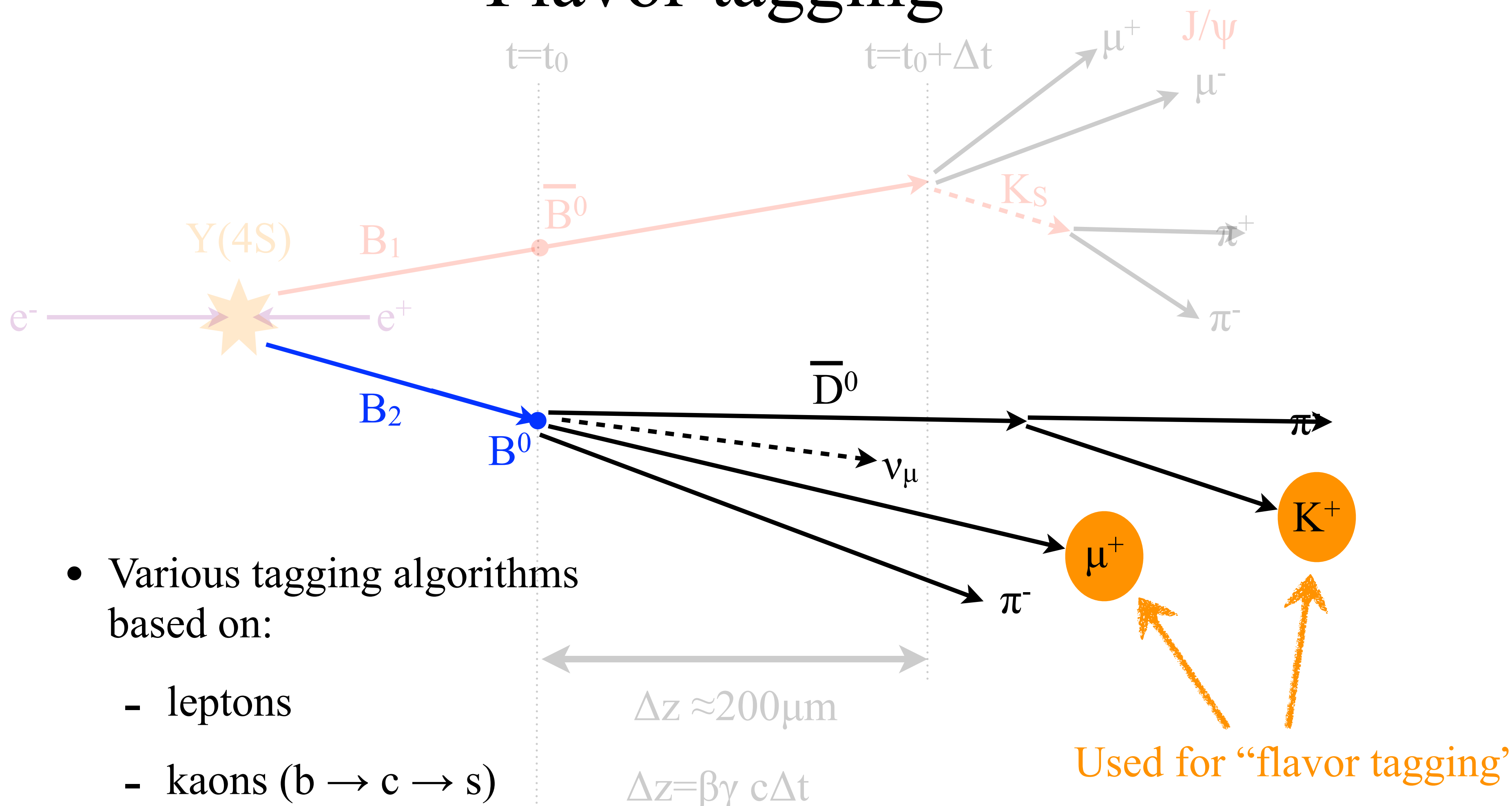


Decay time difference



- $\sigma(\Delta z)\approx 180\mu m$
- $\sigma(\Delta t)\approx 1.1ps$ (BABAR) & $1.4ps$ (Belle)

Flavor tagging



- Various tagging algorithms based on:
  - leptons
  - kaons ($b \rightarrow c \rightarrow s$)
  - other global event properties
- Combined in a neural network (BABAR) or likelihood (Belle)
- Mistag from effects such as opposite lepton sign in b or c quark decay

Tagging performance

- Tagging efficiency depends on
  - fraction of events for which tagging can be obtained: ε
  - probability to make wrong B flavor identification: p_w
- $D=1-2p_w$ is the dilution (1≡perfect identification; 0≡no flavor identification)

=> effective tagging power: $\varepsilon D^2 = \varepsilon(1-2p_w)^2$

Category		Efficiency ε (%)		Effect. dilution $\langle\mathcal{D}\rangle$ (%)		Tagging Power $\varepsilon\mathcal{D}^2$ (%)	
BaBar	Belle ($r\in$)	BaBar	Belle	BaBar	Belle	BaBar	Belle
Lepton	0.875–1	8.96 ± 0.07	14.4 ± 0.9	99.4 ± 0.3	97.0 ± 0.5	7.98 ± 0.11	13.5 ± 0.9
Kaon I	0.75–0.875	10.82 ± 0.07	9.8 ± 0.7	89.4 ± 0.3	78.2 ± 0.9	8.65 ± 0.3	6.0 ± 0.5
Kaon II	0.625–0.75	17.19 ± 0.09	10.7 ± 0.8	71.0 ± 0.4	68.4 ± 1.0	8.68 ± 0.17	5.0 ± 0.5
Kaon-Pion	0.5–0.625	13.67 ± 0.08	10.8 ± 0.8	53.4 ± 0.4	55.0 ± 1.1	3.91 ± 0.12	3.3 ± 0.4
Pion	0.25–0.5	14.18 ± 0.08	14.6 ± 0.9	35.0 ± 0.4	36.0 ± 0.8	1.73 ± 0.09	1.9 ± 0.2
Other	0–0.25	9.54 ± 0.07	39.7 ± 1.5	17.0 ± 0.5	7.2 ± 0.7	0.27 ± 0.04	0.2 ± 0.1
Total tagging power						31.2 ± 0.3	29.9 ± 1.2

Extraction of physics quantities

- Discriminating variables are generally combined in a maximum likelihood (ML) fit
  - use uncorrelated variables
    - correlated variables are combined into a NN or Fisher discriminant
  - extended ML fits are used for branching fraction measurements (N events, Y_j=yields, P^i_j=probability for event i and event category j)

$$\mathcal{L} = \frac{\exp(-\Sigma_j Y_j)}{N!} \prod_i^N \sum_j Y_j \mathcal{P}_j^i$$

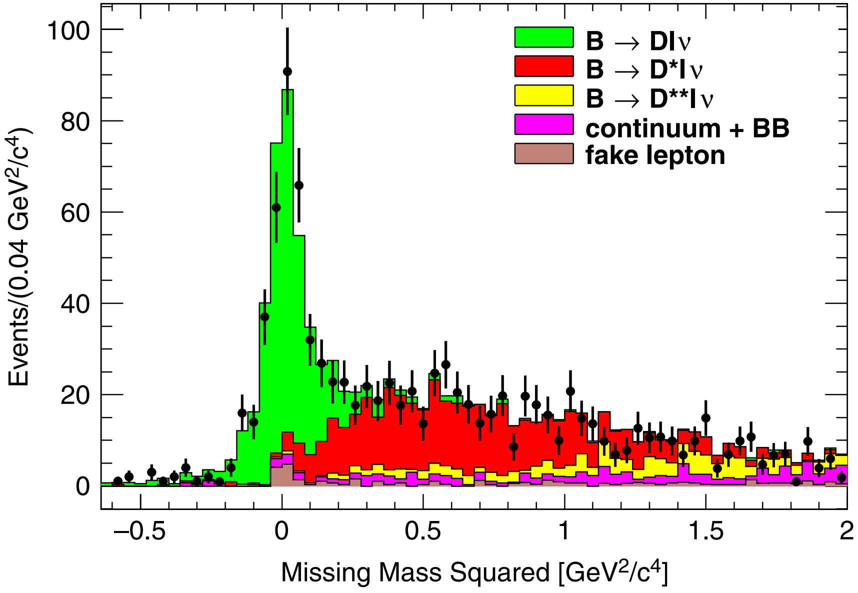
  - time-dependent fits are extensions of the above function
  - PDF parameters are determined from control samples, or left floating in the ML fit
  - up to O(100) free parameters in some ML fits!

Recoil technique

- Υ(4S)→BB => we can reconstruct one B meson (B_{reco}), and we know the momentum and direction of the other B (B_{sig})
  - this method gives a very clean sample of B_{sig} decays recoiling against the reconstructed B_{reco}
  - but the overall statistics is low

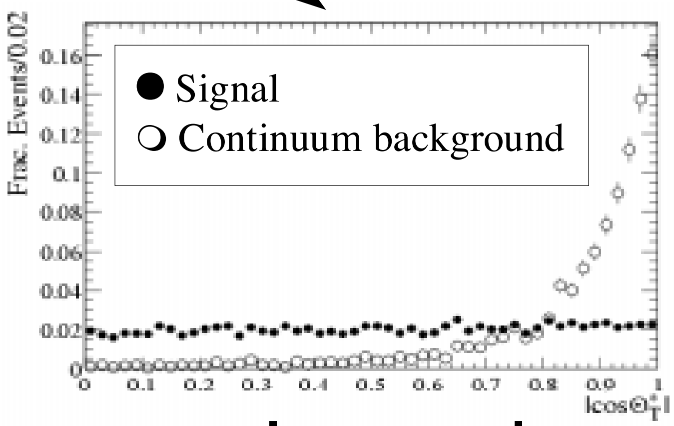
  =>Very useful to look for relatively abundant B decays, but which are subject to sizable backgrounds

- For example:
  - inclusive semileptonic B decays
  - $B^0 \to \nu\nu$ ("invisible" decay)
  - inclusive charmless b→sg



Analysis technique: summary

- Use Maximum Likelihood (ML) fit technique
- Use **kinematic**, **event shape** and **decay time** variables
- Apply loose cuts ⇒ keep side-bands for background fitting
- Main background: $e^+e^- \rightarrow q\bar{q}$ continuum ($q=u,d,s,c$)
  - Rejected with preliminary cut on thrust angle
- Extract from ML fit:
  - **signal yields**
  - **charge asymmetries**
  - **time dependent asymmetries**
  - **+ several parameters (PDFs, efficiencies, etc...)**
- Several crosschecks:
  - "toy MC"
  - control samples
  - etc...



$|\cos \Theta_{\text{thrust}}|$

Measurement of the angle β

Time-dependent asymmetry

- The asymmetry $A_f(t)$ can be written (assuming $\Delta\Gamma$=0 and |q/p|=1)

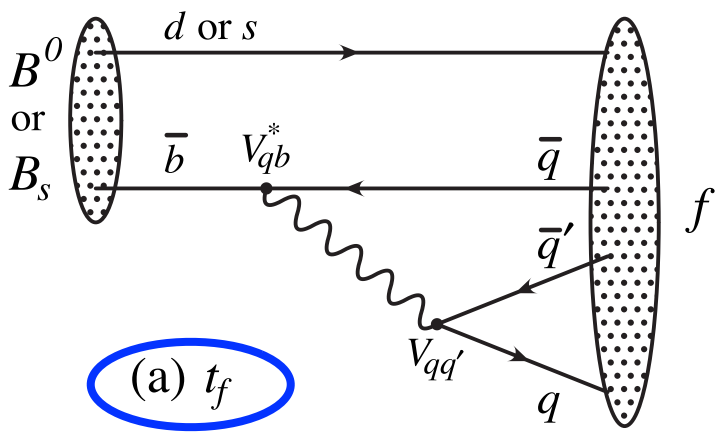
$$\mathcal{A}_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

where

$$S_f \equiv \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2} \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

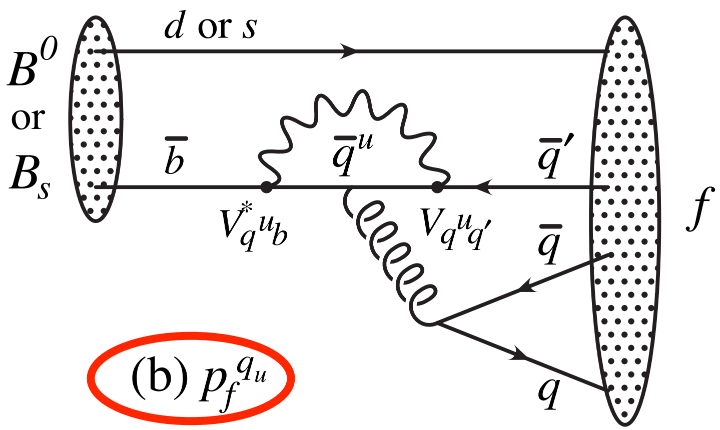
$$\lambda_f = e^{-i\phi_M}\left(\frac{\overline{A}_f}{A_f}\right)$$

Feynman diagrams for b→q$\bar{q}$q'



(a) t_f

Tree



(b) $p_f^{q_u}$

Penguin

Decay amplitudes

- For B→J/ψK$_S$ decays, the ratio $\overline{A}/A$ is

$$\frac{\overline{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{\left(V_{cb}V_{cs}^*\right) T_{\psi K} + \left(V_{ub}V_{us}^*\right) P_{\psi K}^u}{\left(V_{cb}^*V_{cs}\right) T_{\psi K} + \left(V_{ub}^*V_{us}\right) P_{\psi K}^u} \times \frac{V_{cd}^*V_{cs}}{V_{cd}V_{cs}^*}$$

Tree   Penguin   K^0 mixing

- For several B decays, determine the dominant phase in the decay amplitude, and the size of the next contribution

$\bar{b} \to \bar{q}q\bar{q}'$	$B^0 \to f$	$B_s \to f$	CKM dependence of A_f	Suppression
$\bar{b} \to \bar{c}c\bar{s}$	ψK_S	$\psi\phi$	$(V_{cb}^*V_{cs})T + (V_{ub}^*V_{us})P^u$	loop $\times\ \lambda^2$
$\bar{b} \to \bar{s}s\bar{s}$	ϕK_S	$\phi\phi$	$(V_{cb}^*V_{cs})P^c + (V_{ub}^*V_{us})P^u$	λ^2
$\bar{b} \to \bar{u}u\bar{s}$	$\pi^0 K_S$	K^+K^-	$(V_{cb}^*V_{cs})P^c + (V_{ub}^*V_{us})T$	λ^2/loop
$\bar{b} \to \bar{c}c\bar{d}$	D^+D^-	ψK_S	$(V_{cb}^*V_{cd})T + (V_{tb}^*V_{td})P^t$	loop
$\bar{b} \to \bar{s}s\bar{d}$	$\phi\pi$	ϕK_S	$(V_{tb}^*V_{td})P^t + (V_{cb}^*V_{cd})P^c$	$\lesssim 1$
$\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$	$\pi^0 K_S$	$(V_{ub}^*V_{ud})T + (V_{tb}^*V_{td})P^t$	loop

strongest suppression
=> negligible contribution from phase of V_{ub}
=> negligible weak phase in decay amplitude

Measurement of β in B^0 decays

- For $B \to J/\psi K_S$ and other $b \to ccs$ processes:

$$\lambda_{\psi Ks} = e^{-2i\beta} \Rightarrow S_{\psi Ks} = \sin 2\beta \quad \text{and} \quad C_{\psi Ks} = 0$$

  - correct to better than 1%

- For $B \to \varphi K_S$ and other $b \to sss$ processes:

$$\lambda_{\varphi Ks} = e^{-2i\beta} \Rightarrow S_{\varphi Ks} = \sin 2\beta \quad \text{and} \quad C_{\varphi Ks} = 0$$

  - correct to better than a few percents

- For $B \to \pi^+\pi^-$ and other $b \to uud$ processes:
  - the dominant decay amplitude contains the phase γ, and are therefore measuring $\sin(2\beta+2\gamma) = \sin(2\alpha)$

$B \to J/\psi K_S$

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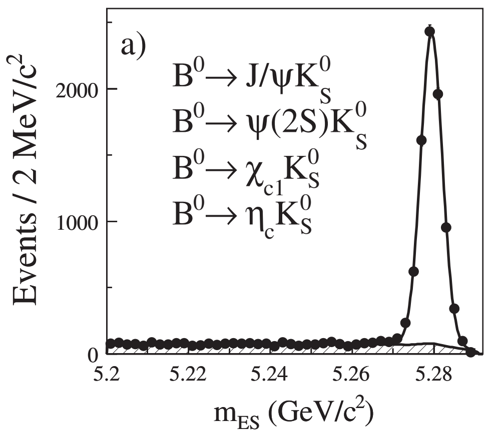

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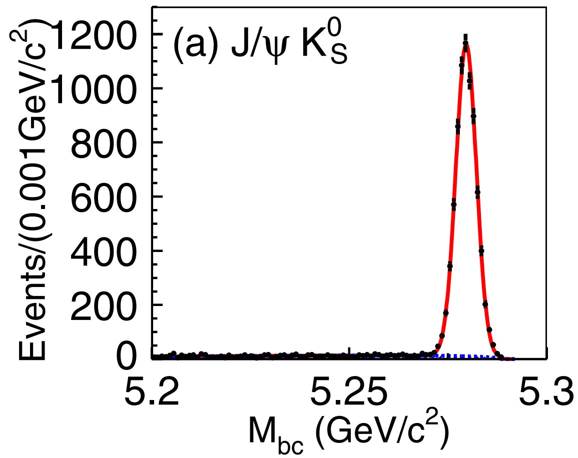
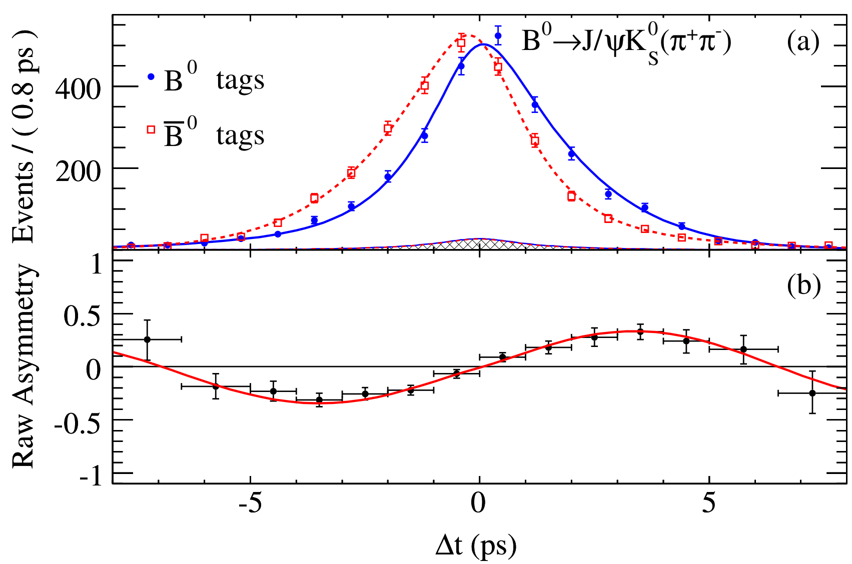
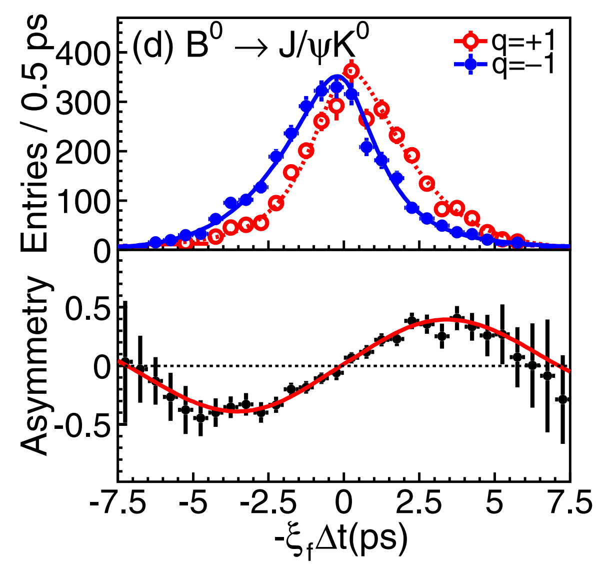
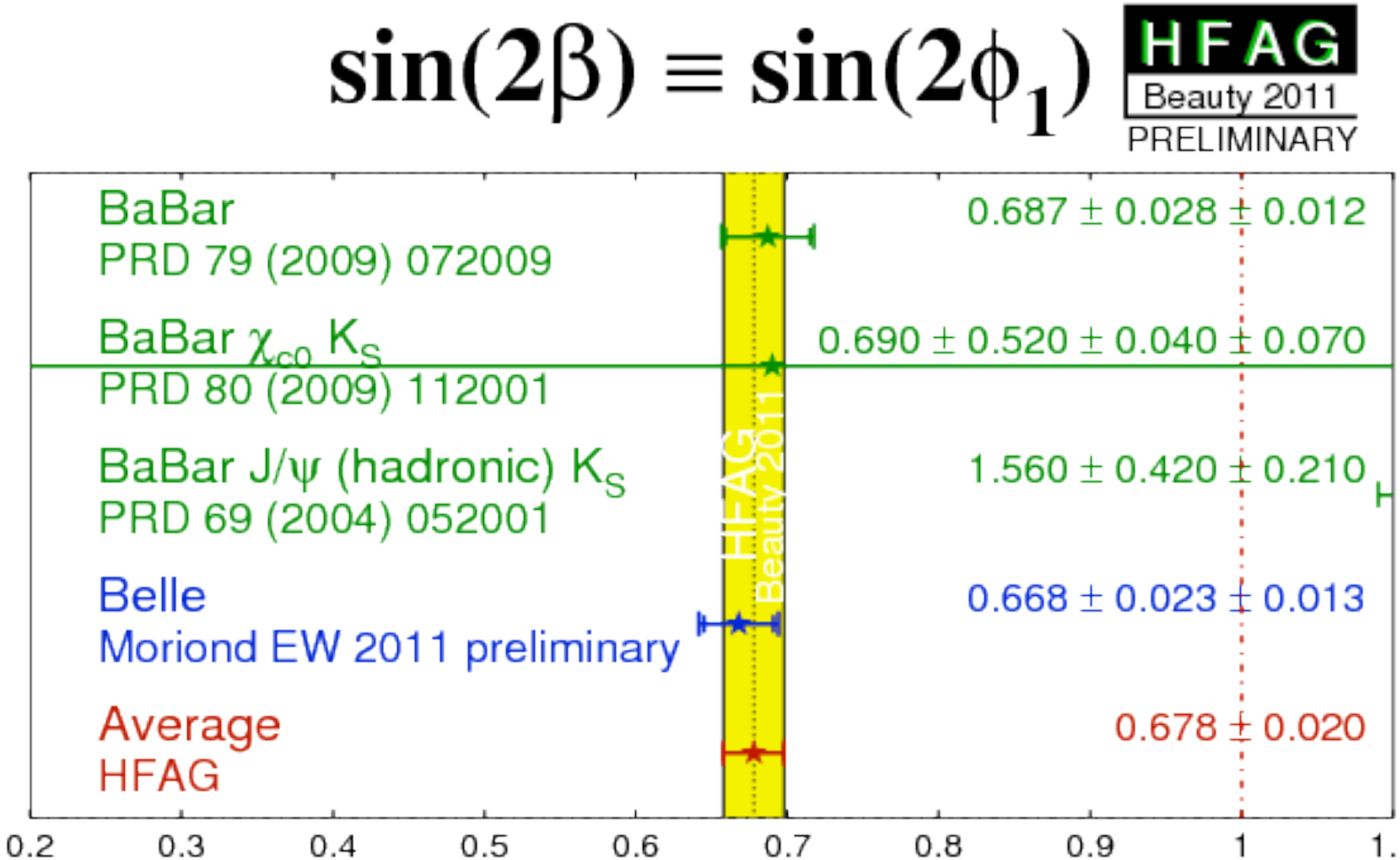






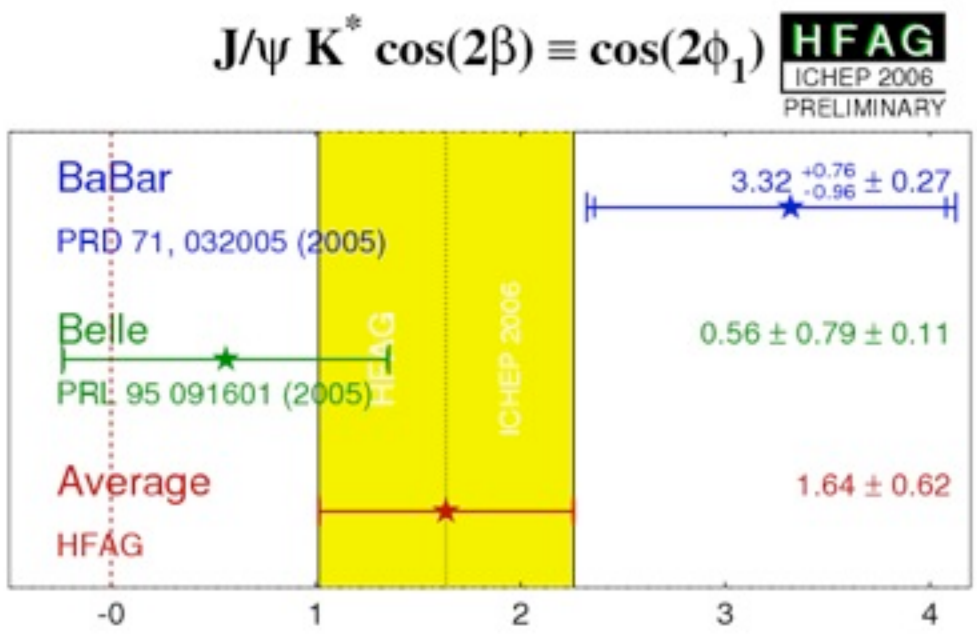
sin2β in b→ccs modes



$\cos 2\beta$

- Time-dependent angular analysis of $B^0 \to J/\psi K^{*0}$
  - interference between CP=+1 and CP=-1 amplitude => $\cos 2\beta$
- Results favor one of the solutions for the angle β

=> $\cos 2\beta > 0$



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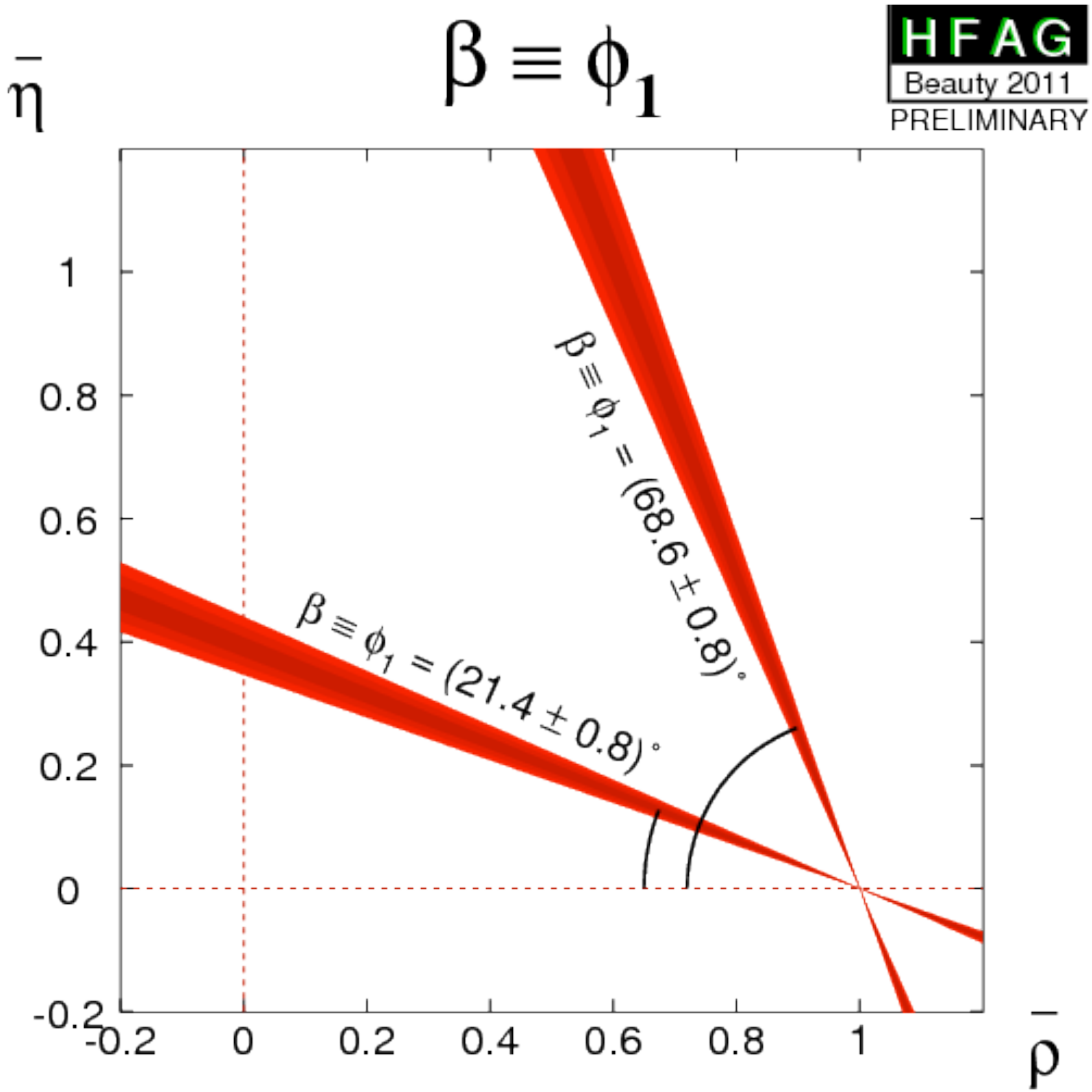
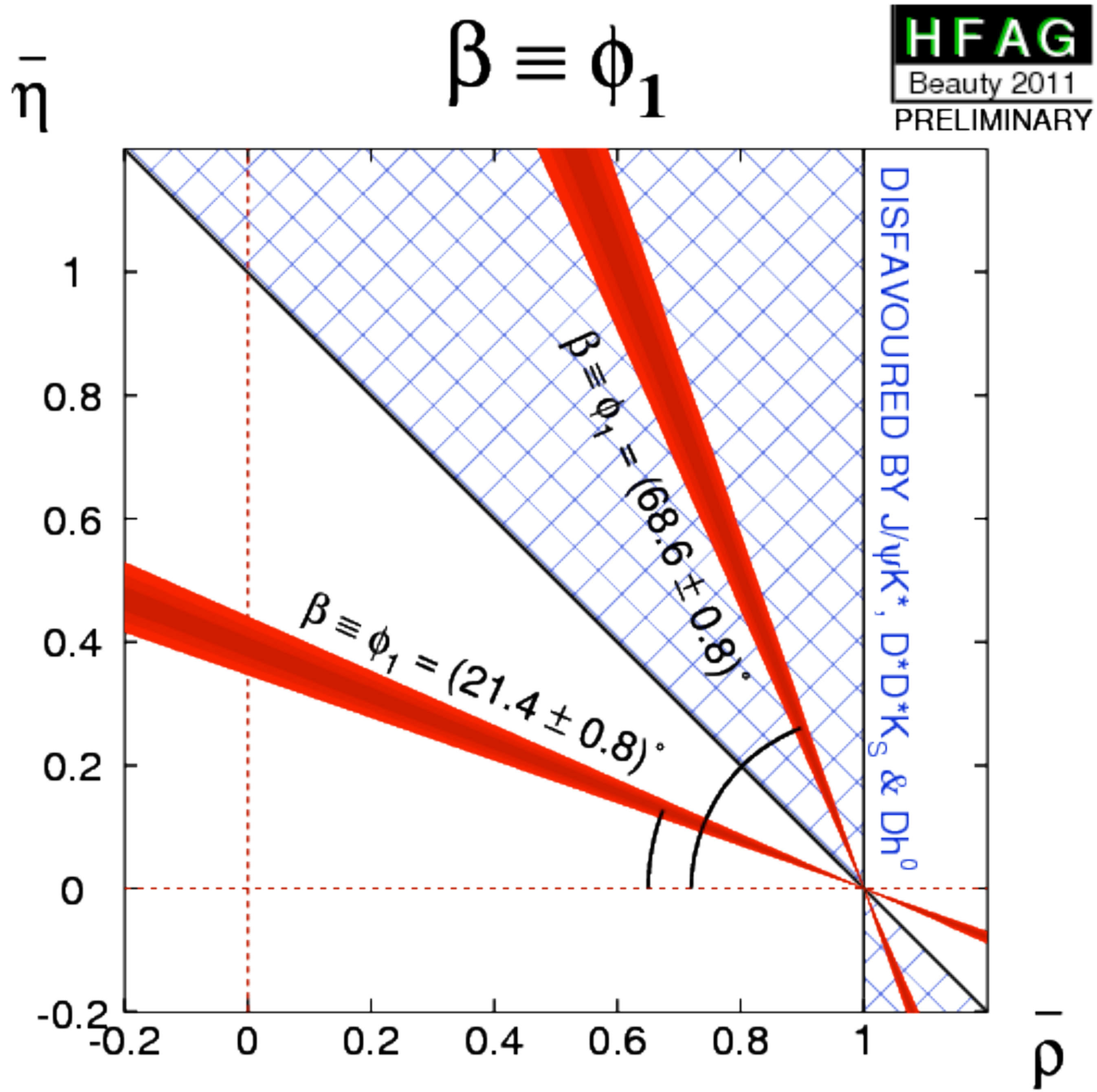


sin2β in b→ccs modes



sin2β in charmless penguin B^0 decays

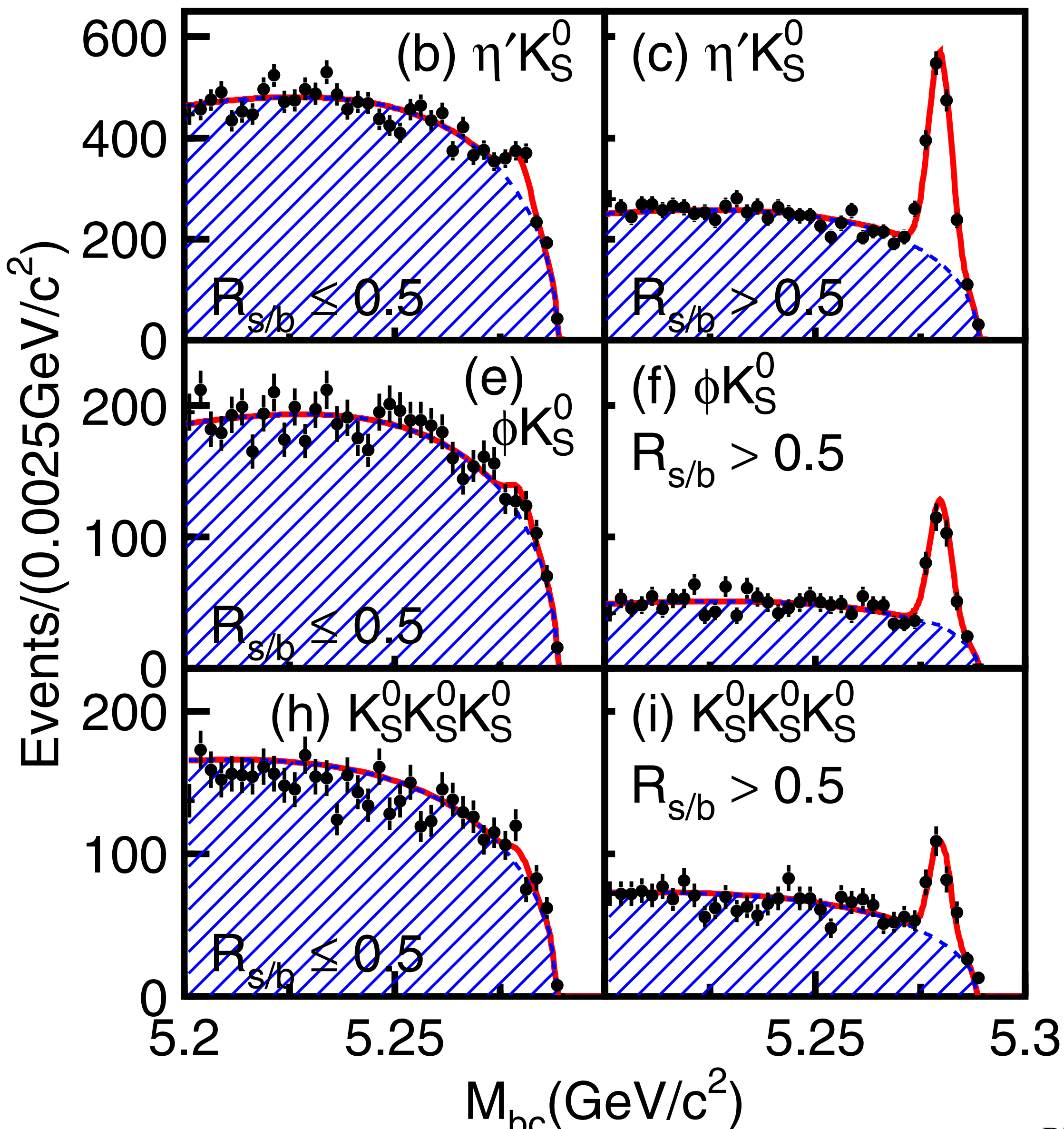
- Weak phase in the decay amplitudes can modify the measured asymmetry

=> $S = \sin 2\beta$ ➜ $S = \sin 2\beta^{eff}$

- Estimation of the value for $\Delta S = -\eta S_f - S_{ccs}$ from QCD
  - Table: prediction for $\sin 2\beta^{eff}$ for several modes:

$-\eta_f S_f$	QCDF[a]	pQCD[b]	SCET[c]
ϕK_S	$0.75^{+0.00}_{-0.04}$	0.71 ± 0.01	0.69
ωK_S	$0.85^{+0.03}_{-0.06}$	$0.84^{+0.03}_{-0.07}$	$0.50^{+0.05}_{-0.06}$ 0.80 ± 0.02
$\rho^0 K_S$	$0.64^{+0.03}_{-0.07}$	$0.50^{+0.10}_{-0.06}$	$0.85^{+0.04}_{-0.05}$ $0.56^{+0.02}_{-0.03}$
$\eta' K_S$	$0.74^{+0.00}_{-0.04}$	–	0.706 ± 0.008 0.715 ± 0.008
ηK_S	$0.79^{+0.02}_{-0.04}$	–	0.69 ± 0.16 0.79 ± 0.15
$\pi^0 K_S$	$0.79^{+0.02}_{-0.04}$	$0.74^{+0.02}_{-0.03}$	0.80 ± 0.03
$f_0(980) K_S$	$0.731^{+0.001}_{-0.001}$	–	–
$K^+K^-K_S$[e]	$0.728^{+0.009}_{-0.020}$	–	–
$K_S K_S K_S$	$0.719^{+0.009}_{-0.020}$	–	–
$K_S \pi^0 \pi^0$	$0.729^{+0.009}_{-0.020}$	–	–

m_{bc} in b→s penguin decays (BELLE)



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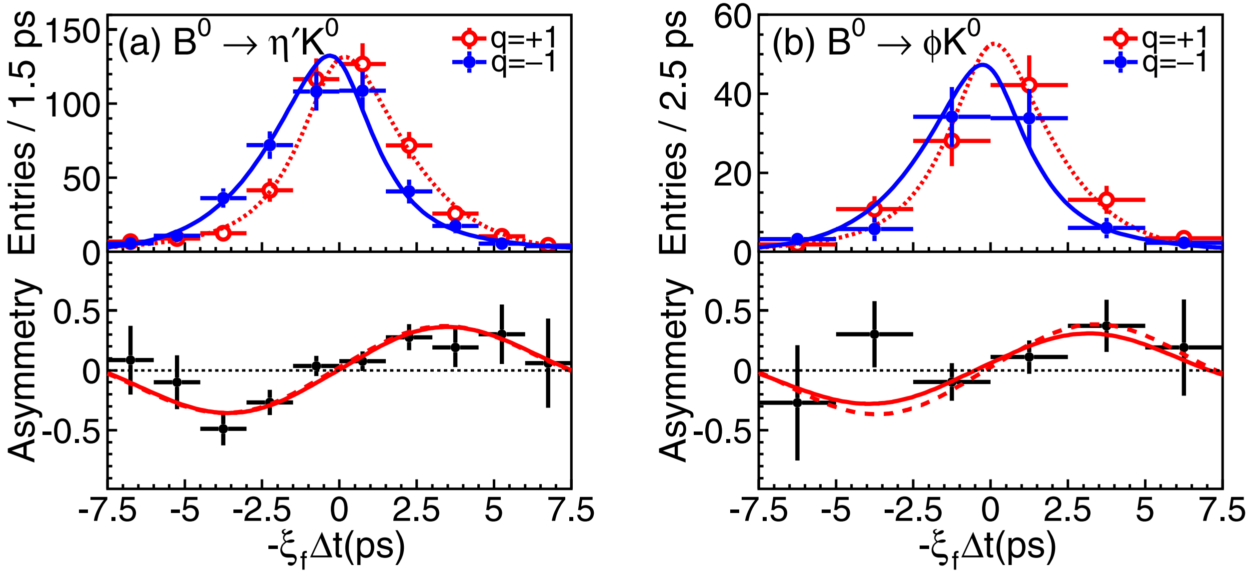
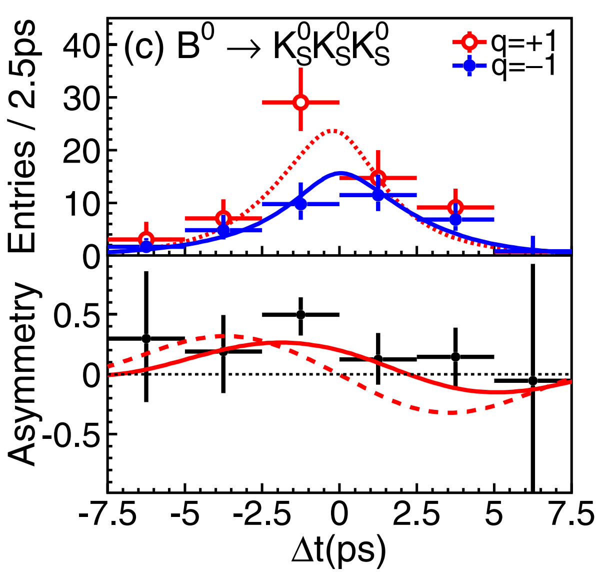
sin2β in b→s penguin decays (BELLE)





Mode	$\sin 2\phi_1^{\rm eff}$	$\mathcal{A}_f$
ϕK^0	$+0.50 \pm 0.21 \pm 0.06$	$+0.07 \pm 0.15 \pm 0.05$
$\eta' K^0$	$+0.64 \pm 0.10 \pm 0.04$	$-0.01 \pm 0.07 \pm 0.05$
$K_S^0 K_S^0 K_S^0$	$+0.30 \pm 0.32 \pm 0.08$	$+0.31 \pm 0.20 \pm 0.07$
$J/\psi K^0$	$+0.642 \pm 0.031 \pm 0.017$	$+0.018 \pm 0.021 \pm 0.014$

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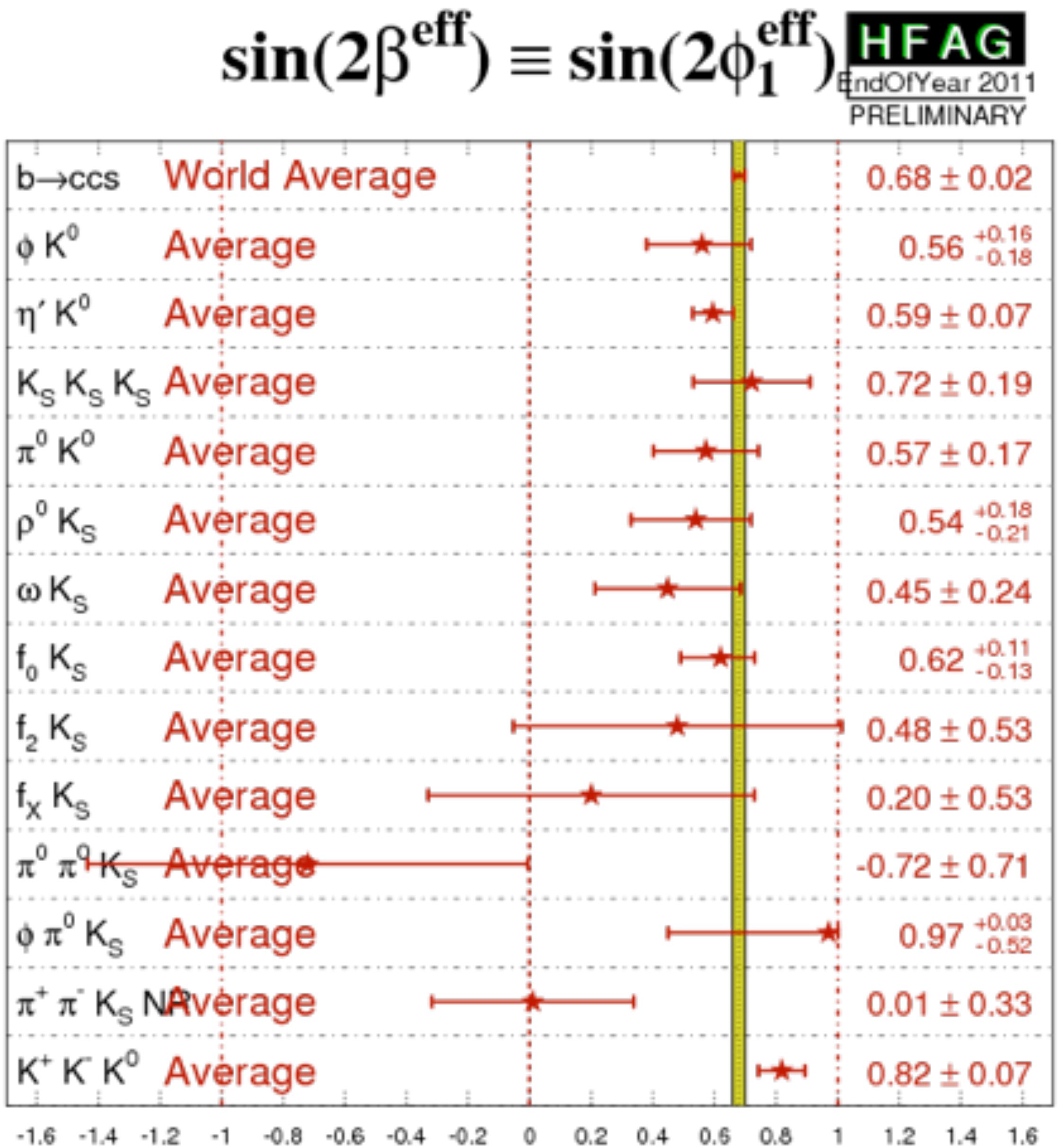
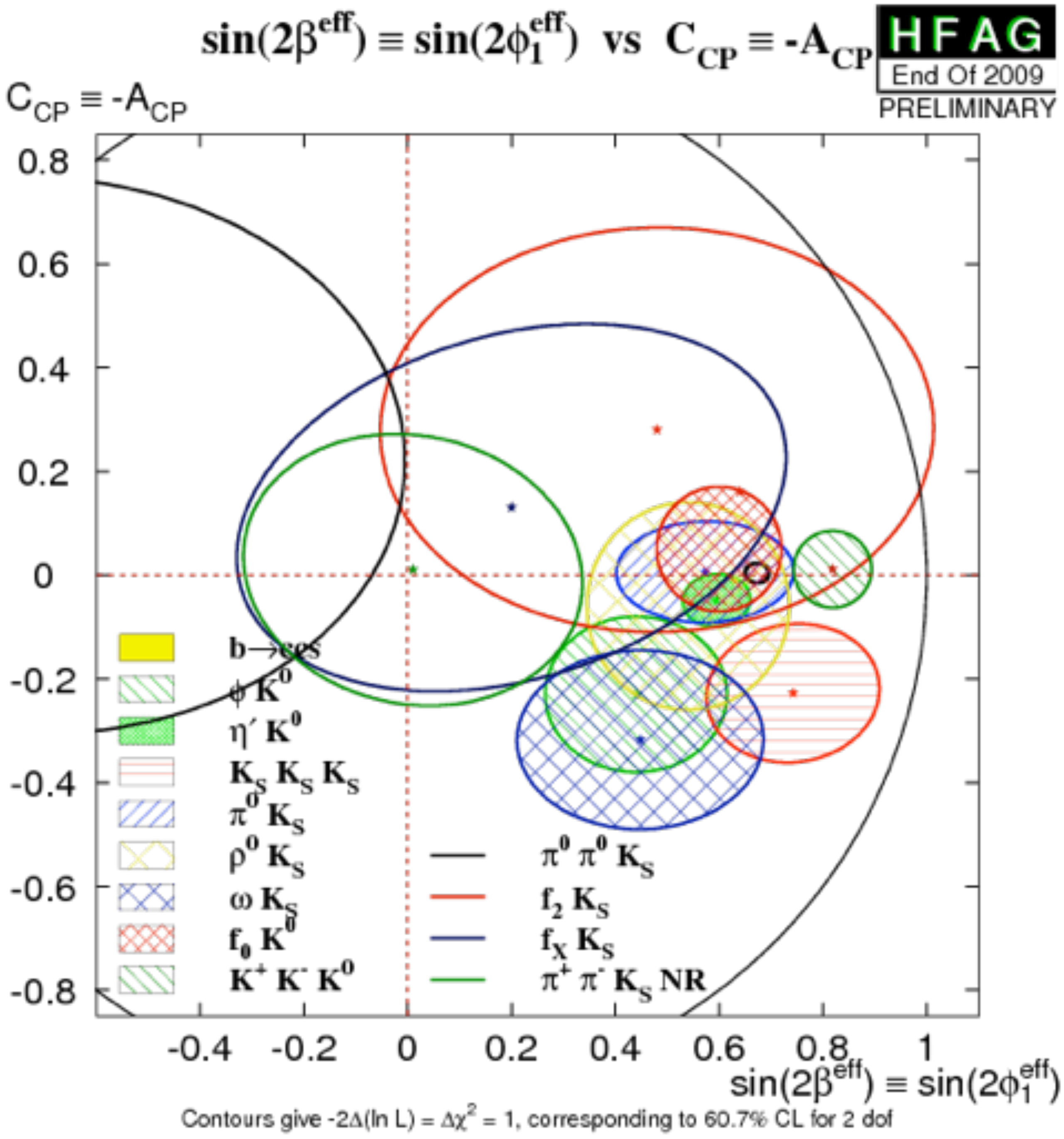
$\sin 2\beta^{eff}$ in b→s penguin decays: summary



$\sin 2\beta^{eff}$ in $b\rightarrow s$ penguin decays: C vs S



ΔS and the 2σ discrepancy

- Since around ~2005, the naïve average of $\sin 2\beta^{eff}$ in $b \rightarrow s$ penguin decays has been $\approx 2\sigma$ low relative to $\sin 2\beta$ measured in charmonium modes

- The average has slowly moved towards $\sin 2\beta$ with more data and more decay modes (regression to the mean?)

- QCD uncertainties are large, and no new physics can be invoked at this point

Year	$\sin 2\beta^{eff}$ naïve average
2005	0.50±0.06
2006	0.53±0.05
2007	0.56±0.05
2008	0.64±0.04
2009	0.62±0.04
2010-11	0.64±0.04

- More data, and more modes (B_s decays?) should help clarify the situation

$\sin(2\beta+\gamma)$

- B^0 decays to open charm are sensitive to $\sin(2\beta+\gamma)$
  - interference between
    - CKM-favored $b \to c$ decay amplitude A_{fav} (no weak phase)

      and

    - CKM-suppressed $b \to u$ decay amplitude A_{supp} (weak phase γ)
  - with and without mixing (phase 2β)

  => overall phase difference $2\beta+\gamma$
- Final states are not CP eigenstates. For example:
  - $B^0 \to D^- \pi^+$ (CKM-favored)
  - $B^0 \to D^+ \pi^-$ (CKM-suppressed)

$\sin(2\beta+\gamma)$

- Coefficient of the sine term in time-dependent asymmetry

$$S_f = -2r_f \sin(2\beta + \gamma - \delta_f)$$
$$S_{\bar{f}} = -2r_f \sin(2\beta + \gamma + \delta_f)$$

where

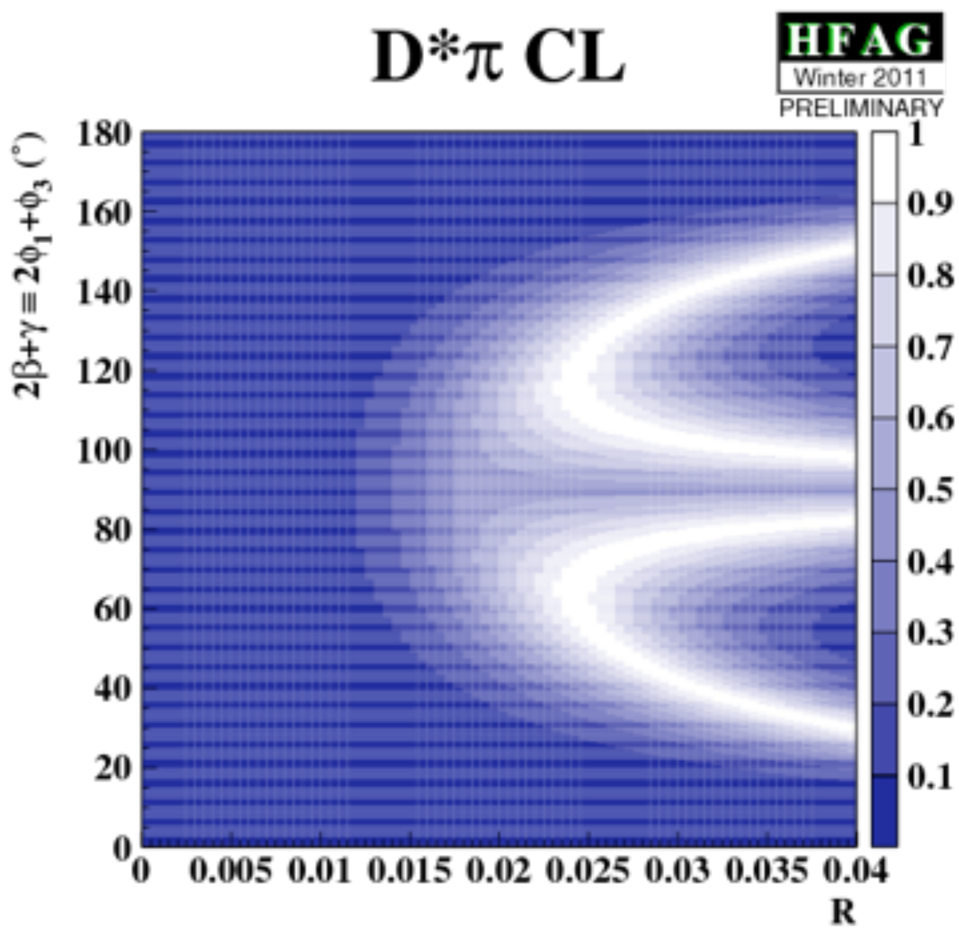
$$r_f = \left| \frac{A_{\mathrm{CKM-suppressed}}}{A_{\mathrm{CKM-favored}}} \right| \quad (\approx 0.01)$$

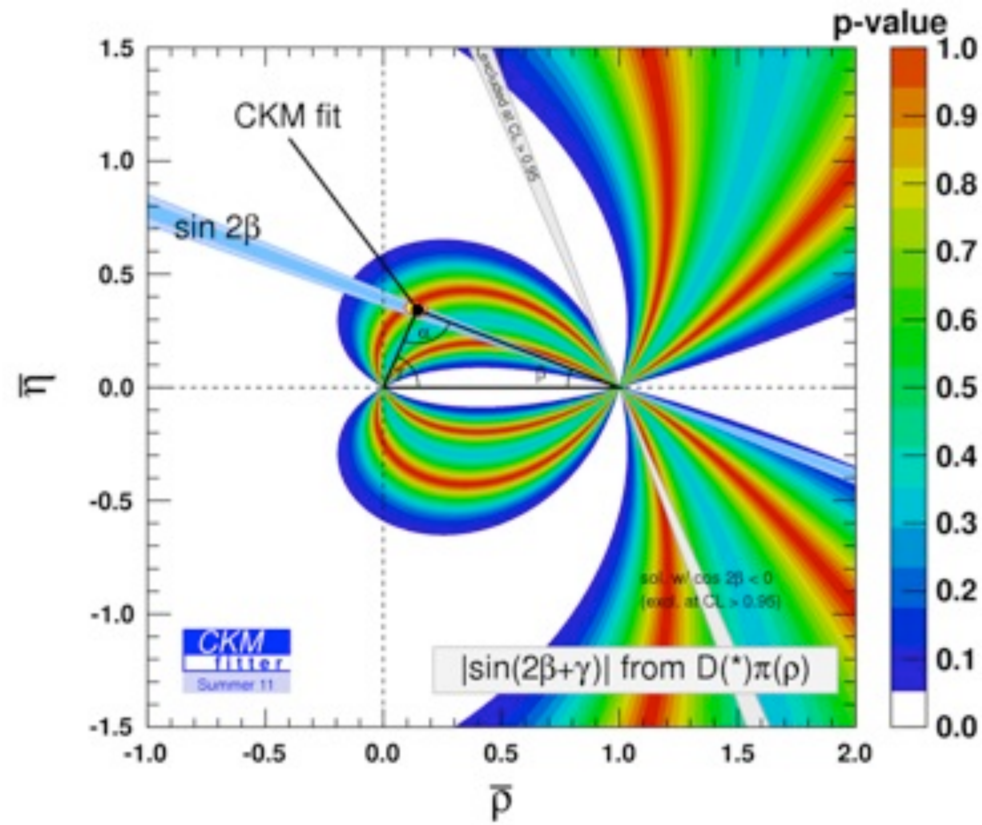
δ_f = strong phase

- Measure r_f in charged B decays, and use isospin relations
- Measure S_f and S_f => clean extraction of $(2\beta+\gamma)$ and δ_f

sin(2β+γ)

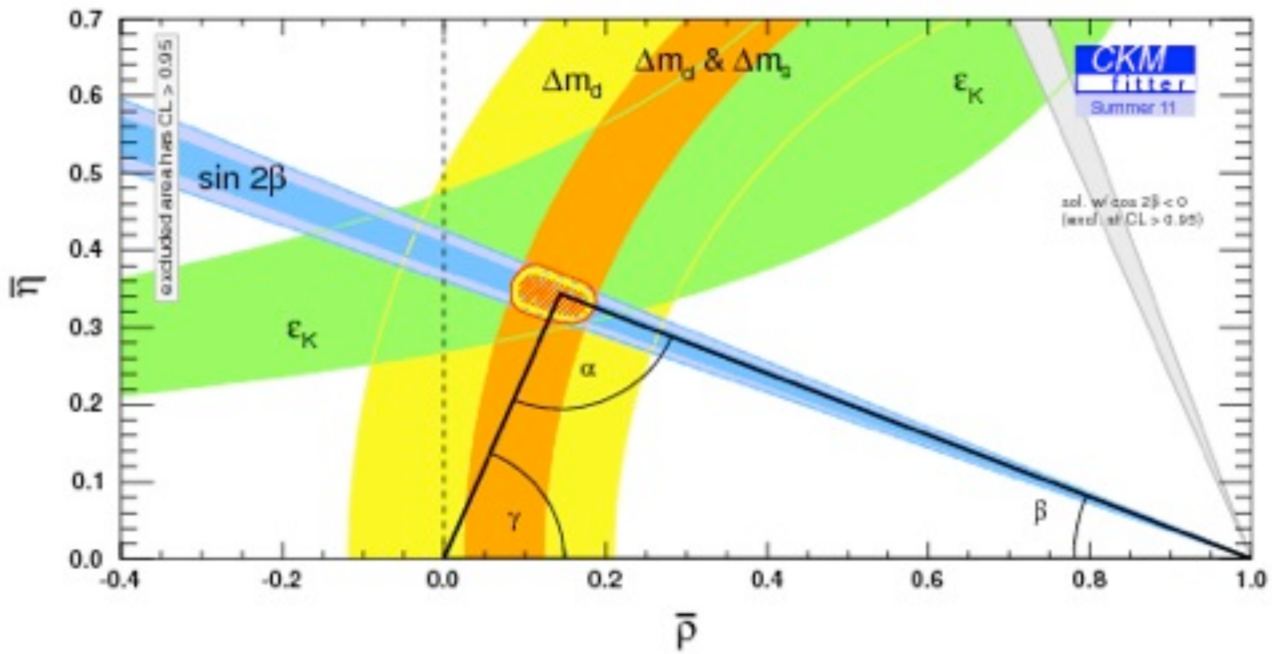
- The uncertainty on r_f is large
- In practice, we plot sin(2β+γ) as a function of r_f





Summary on angle β

- β is the most accurately measured CKM triangle property
- Several modes contribute to the measurement of β
  - $B \to (cc)K_S$ decays:
    - all consistent
    - with small theoretical uncertainties
  - $b \to s$ penguin decays:
    - inconsistencies at the level of 1-2σ
    - but large theoretical uncertainties



Measurement of the angle α

Measurement of α in B^0 decays

- Measure α in $B^0 \rightarrow \pi^+\pi^-$ and other $b \rightarrow u\bar{u}d$ processes:
  - the dominant decay amplitude contains the phase γ, and are therefore measuring the relative phase between $V^*_{tb}V_{td}$ and $V^*_{ub}V_{ud}$
- Problem in the decay amplitude:
  - the "penguin pollution" has another weak phase (β) than the dominant tree channel (γ)...
  - ...and is only suppressed at the loop level (and no additional CKM suppression)
- Solution:
  - determine the penguin amplitude from SU(3)-related decays:
    - $B^0(B^0) \rightarrow \pi^+\pi^-$, $B^\pm \rightarrow \pi^\pm\pi^0$ and $B^0(B^0) \rightarrow \pi^0\pi^0$
    - $B^0(B^0) \rightarrow \rho^+\rho^-$, $B^\pm \rightarrow \rho^\pm\rho^0$ and $B^0(B^0) \rightarrow \rho^0\rho^0$

sin*2α* in presence of penguin pollution (I)

- Define the ratio of the penguin over the tree amplitudes:

$$R_{PT} = \frac{|V_{tb}V_{td}|\,P^t_{\pi\pi}}{|V_{ub}V_{ud}|\,T_{\pi\pi}}$$

  - R_{PT} can be different for $\pi^+\pi^-$, $\pi^{\pm}\pi^0$ and $\pi^0\pi^0$
  - R_{PT} can also be defined for $\rho\rho$ final states

- The parameter λ can then be written as:

$$\lambda_{\pi\pi} = e^{2i\alpha}\left[\frac{1 - R_{PT}e^{-i\alpha}}{1 - R_{PT}e^{+i\alpha}}\right]$$

- The amplitude of the sine and cosine terms become:

$$S_{\pi\pi} \approx \sin 2\alpha + 2\mathcal{R}e(R_{PT})\cos 2\alpha \sin\alpha$$

$$C_{\pi\pi} \approx 2\mathcal{I}m(R_{PT})\sin\alpha$$

$\sin 2\alpha$ in presence of penguin pollution (II)

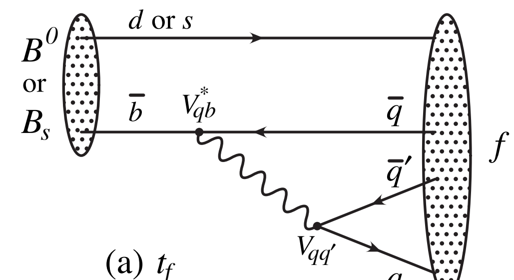
$$S_{\pi\pi} \approx \sin 2\alpha + 2\mathcal{R}e(R_{PT}) \cos 2\alpha \sin \alpha$$

$$C_{\pi\pi} \approx 2\mathcal{I}m(R_{PT}) \sin \alpha$$

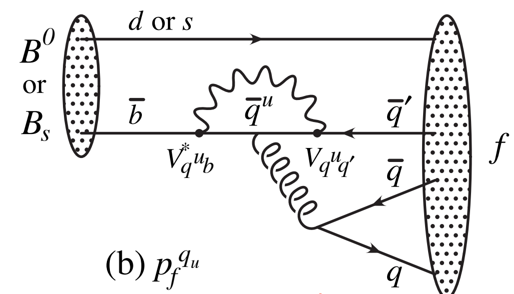
- Remarks:
  - if relative strong phase $\delta_{\text{strong}} = 0$ between $P_{\pi\pi}$ and $T_{\pi\pi}$
    => R_{PT} is real => $C_{\pi\pi} = 0$
    => the size of $C_{\pi\pi}$ is a measure of δ_{strong}
  - the measure of $\sin 2\alpha$ relies on the knowledge of R_{PT}
    => this is the problem of the “penguin pollution”
    - solution by Gronau and London, using isospin relations between measurable amplitudes

Gronau-London isospin analysis (I)

- The amplitudes for $B\rightarrow\pi\pi$ are related by isospin symmetry
- Pseudo-scalar B meson => $\pi\pi$ system must be in state $L=0$
- $L=0$ and Bose-Einstein symmetry
  => even isospin state ($I=0$ or $I=2$)
- Tree amplitude: $\Delta I = 1/2$ or $3/2$
  => $I=0$ or $I=2$ are possible
- $I_{gluon}=0$ => Penguin amplitude: $\Delta I = 1/2$
  => $I=0$ (and not $I=2$)
  - assume electroweak penguins can be neglected ($\Delta I=3/2$ allowed)
- Accessible isospin states:
  - $B^0(B^0)\rightarrow\pi^+\pi^-$ and $B^0(B^0)\rightarrow\pi^0\pi^0$ are $I=0$ or $I=2$
  - $B^{\pm}\rightarrow\pi^{\pm}\pi^0$ is $I=2$ only



$\Delta I = 1/2$ or $3/2$



$\Delta I = 1/2$

Gronau and London, Phys.Rev.Lett. 65 (1990) 3381

Gronau-London isospin analysis (II)

- $B \to \pi\pi$ amplitudes, including Clebsch-Gordan coefficients:

$$A(B^+ \to \pi^+\pi^0) = \tfrac{\sqrt{3}}{2} A_{3/2,2}$$
$$\tfrac{1}{\sqrt{2}} A(B^0 \to \pi^+\pi^-) = \tfrac{1}{\sqrt{12}} A_{3/2,2} - \sqrt{\tfrac{1}{6}} A_{1/2,0}$$
$$A(B^0 \to \pi^0\pi^0) = \tfrac{1}{\sqrt{3}} A_{3/2,2} + \sqrt{\tfrac{1}{6}} A_{1/2,0}$$

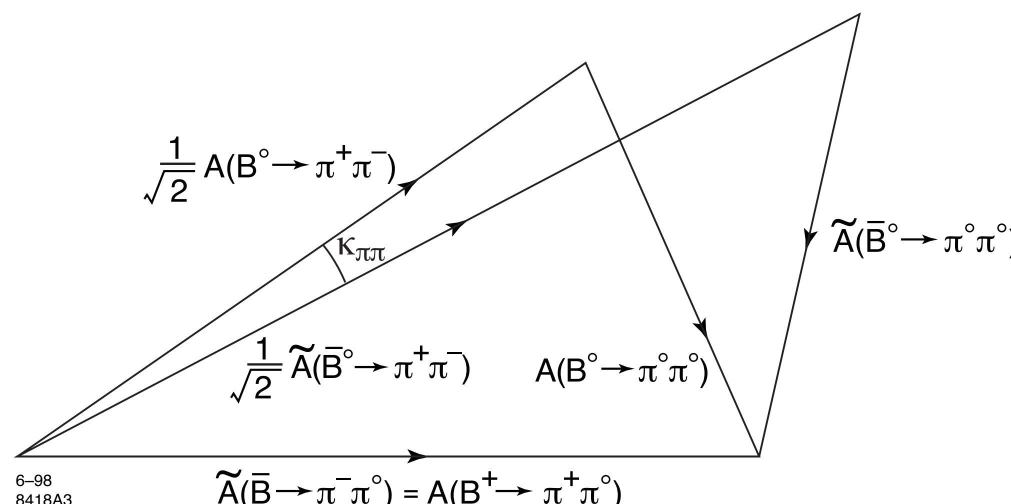
- Therefore, we have the relation

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

and its conjugate

$$\frac{1}{\sqrt{2}} \overline{A}^{+-} + \overline{A}^{00} = A^{-0}$$

=> build 2 triangles in the complex plane:



  - 6 sides can (in principle) be measured
  - and the angle κ be determined

Gronau and London, Phys.Rev.Lett. 65 (1990) 3381

Gronau-London isospin analysis (II)

- $B\to\pi\pi$ amplitudes, including Clebsch-Gordan coefficients:

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$$A(B^0 \to \pi^0\pi^0) = \frac{1}{\sqrt{3}} A_{3/2,2} + \sqrt{\frac{1}{6}} A_{1/2,0}$$

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$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

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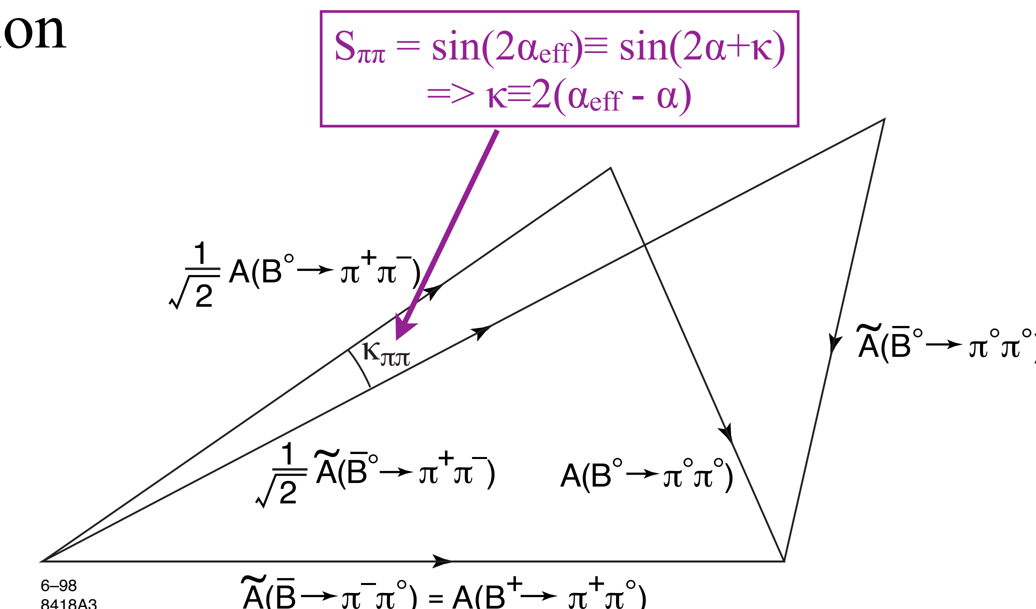
$$\frac{1}{\sqrt{2}} \overline{A}^{+-} + \overline{A}^{00} = A^{-0}$$

=> build 2 triangles in the complex plane:

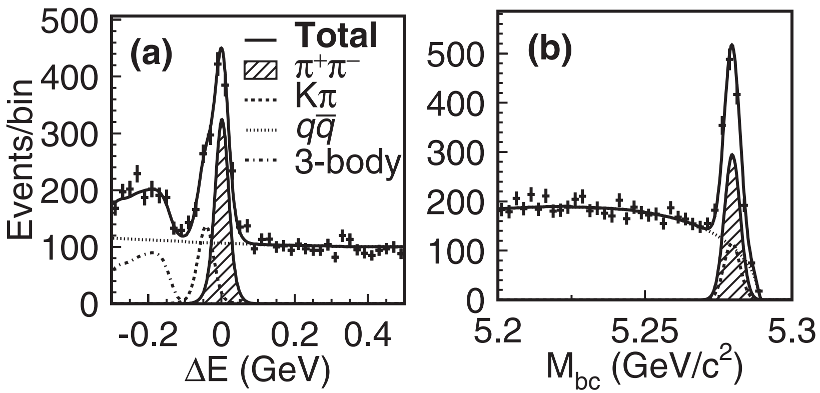


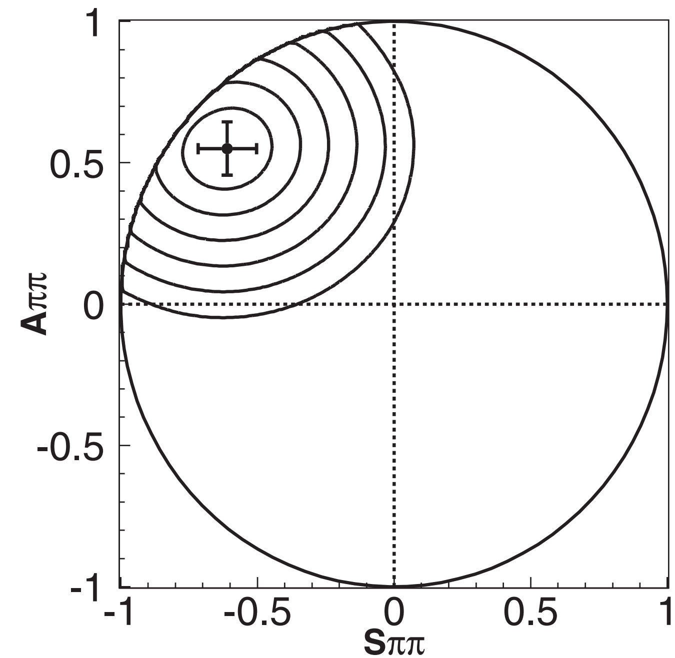
  - 6 sides can (in principle) be measured
  - and the angle κ be determined

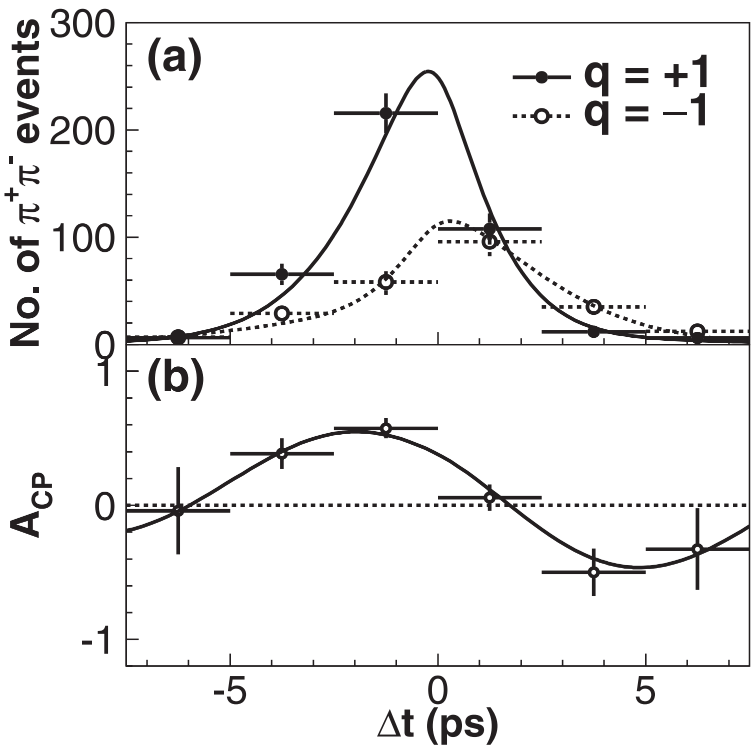
Gronau and London, Phys.Rev.Lett. 65 (1990) 3381

$B^0 \to \pi^+\pi^-$: Belle results

BELLE, PRL 98 (2007) 211801



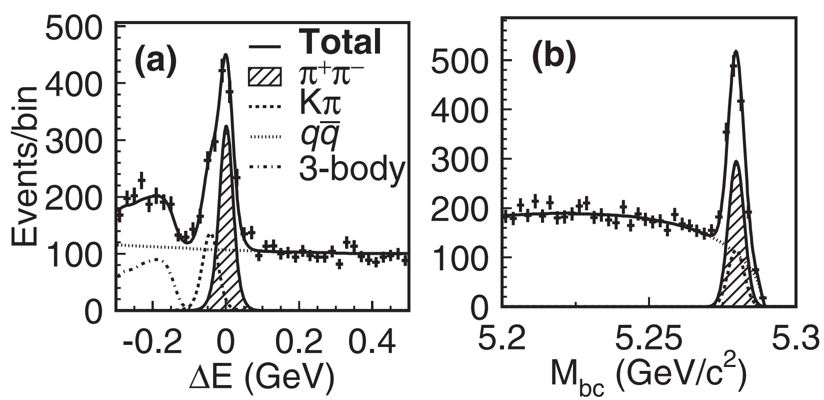


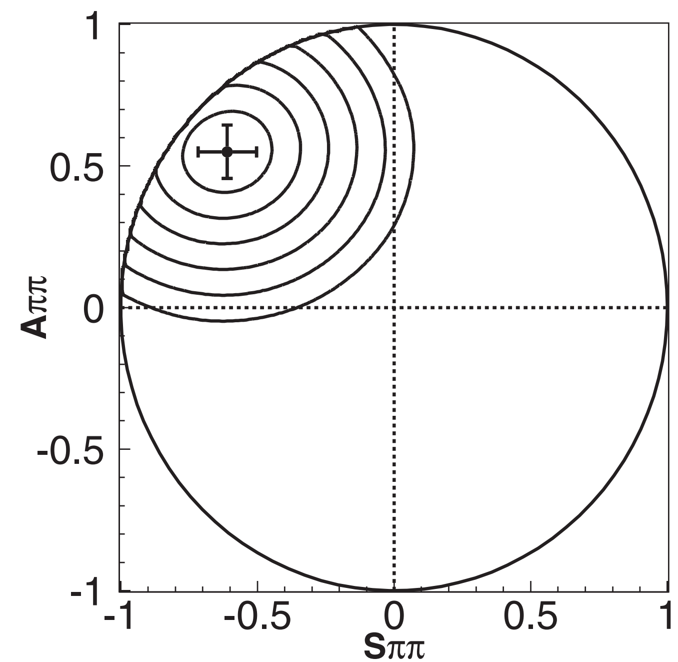


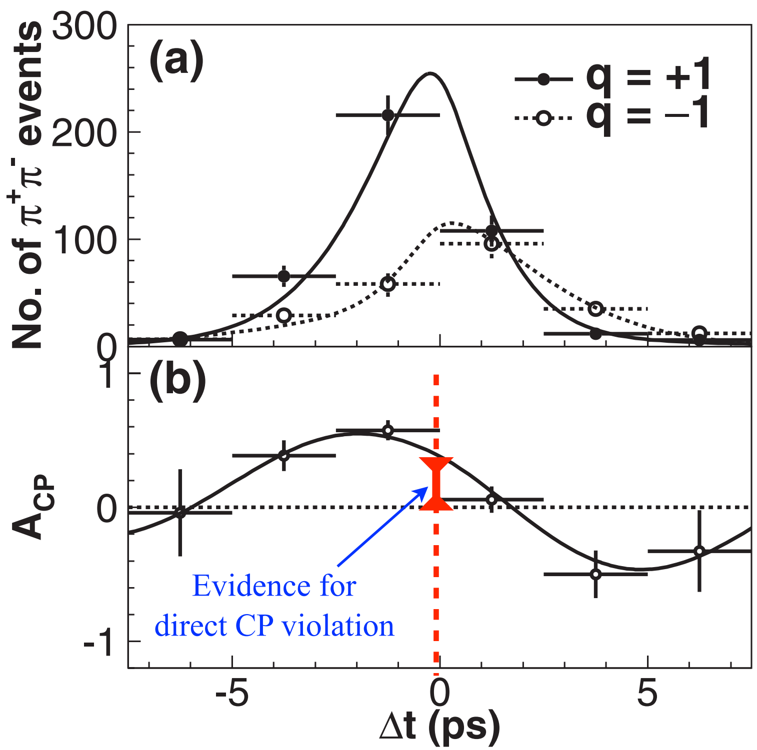
- Based on 535×10^6 $B\bar{B}$ pairs
- $S_{\pi\pi} = -0.61 \pm 0.10_{stat} \pm 0.04_{syst}$
- $A_{\pi\pi} = -C_{\pi\pi} = 0.55 \pm 0.08_{stat} \pm 0.05_{syst}$

$B^0 \rightarrow \pi^+\pi^-$: Belle results

BELLE, PRL 98 (2007) 211801





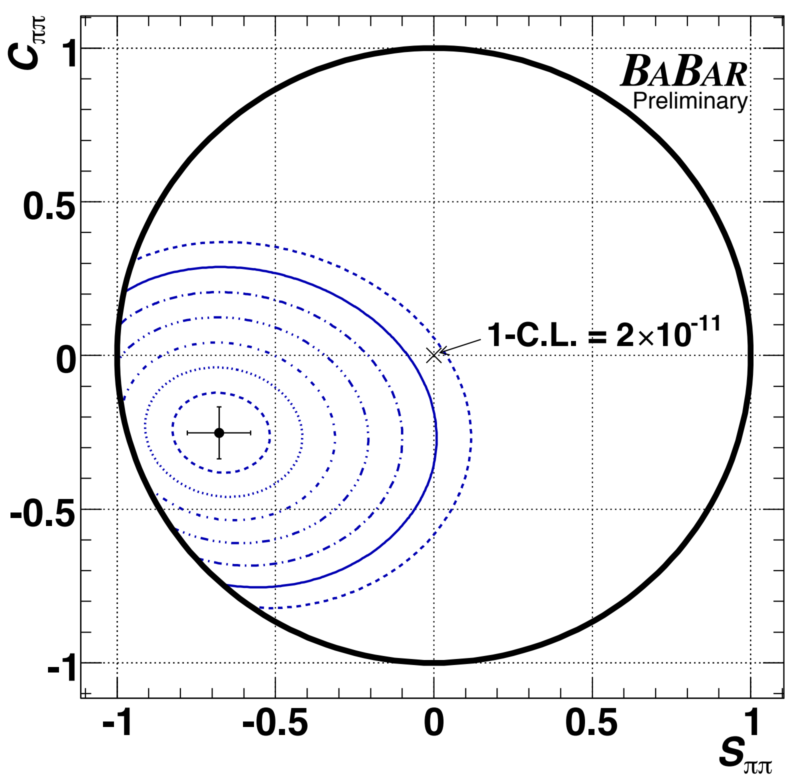


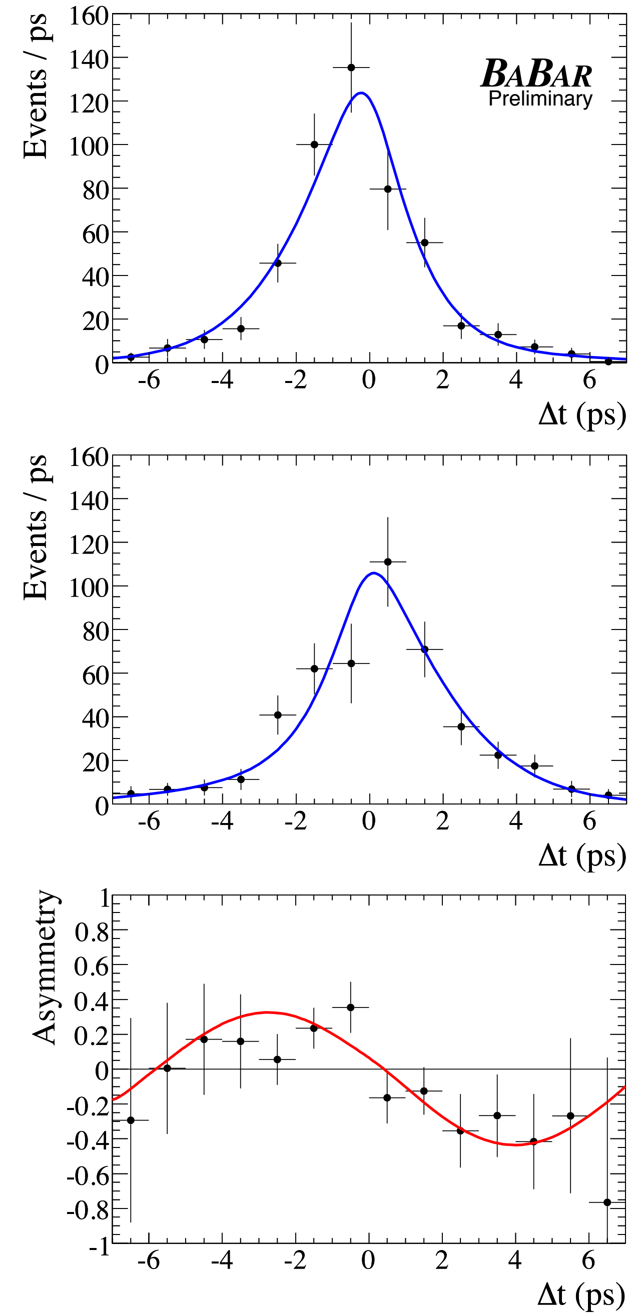
- Based on 535×10^6 $B\bar{B}$ pairs
- $S_{\pi\pi} = -0.61 \pm 0.10_{stat} \pm 0.04_{syst}$
- $A_{\pi\pi} = -C_{\pi\pi} = 0.55 \pm 0.08_{stat} \pm 0.05_{syst}$

$B^0 \rightarrow \pi^+\pi^-$: BABAR results

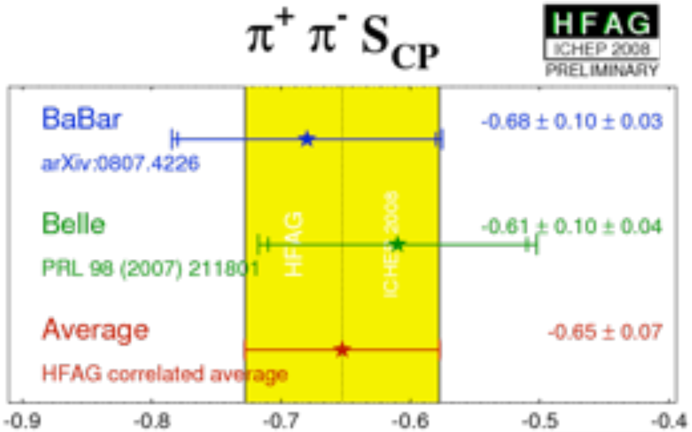
BABAR, arXiv:0807.4226

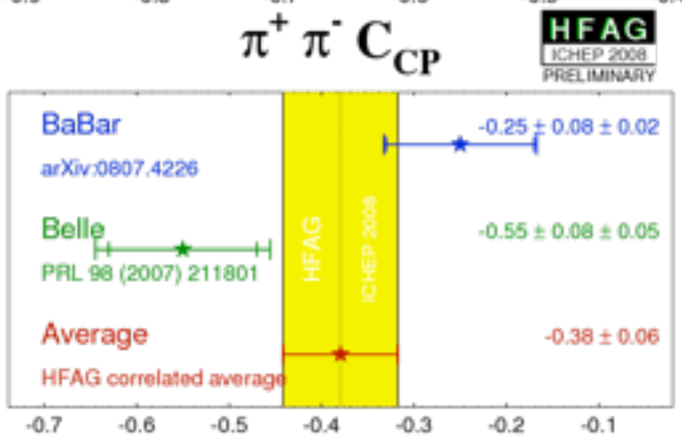
- Based on 467×10^6 BB pairs
- $S_{\pi\pi} = -0.68 \pm 0.10_{stat} \pm 0.03_{syst}$
- $C_{\pi\pi} = -0.25 \pm 0.08_{stat} \pm 0.02_{syst}$

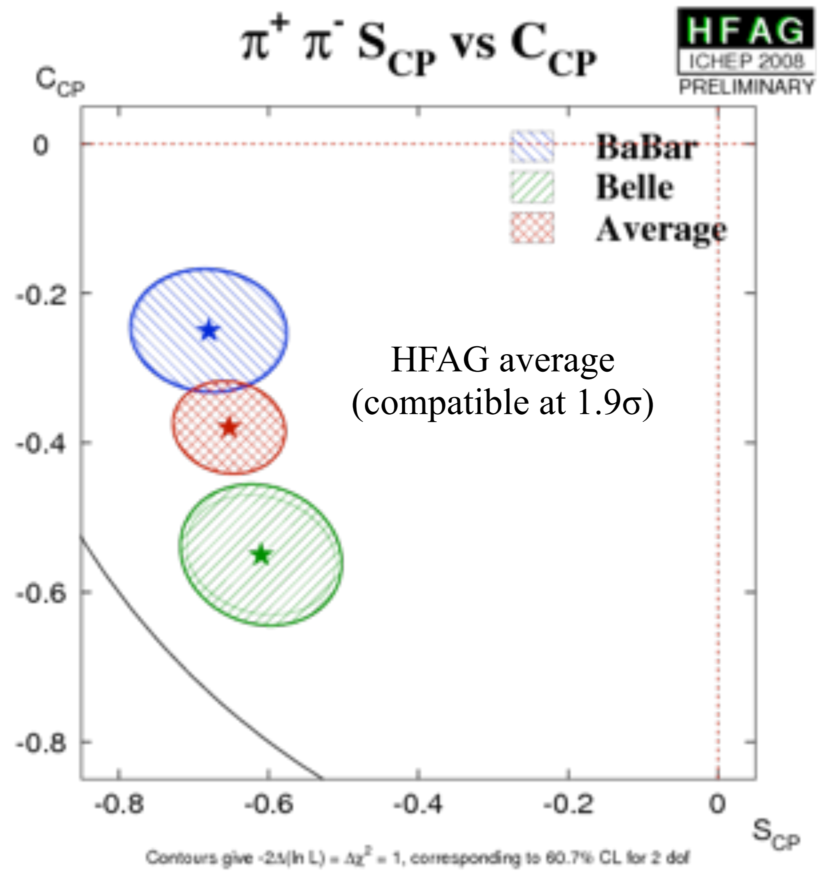




Combined $B^0 \rightarrow \pi^+\pi^-$ results







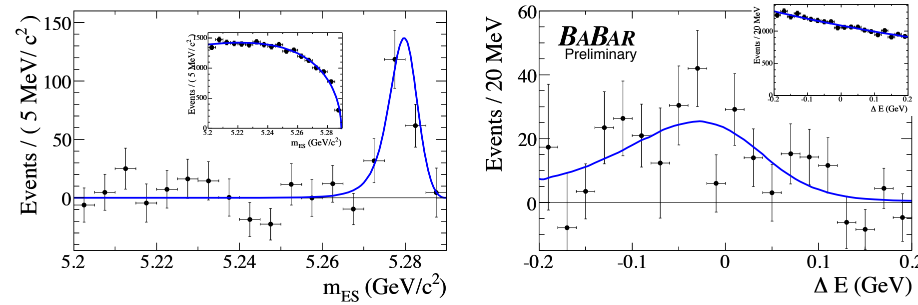
- $C \neq 0$ => non-zero strong phase between the tree and penguin amplitudes
- $sin2\alpha_{eff} = S/(1+C) = -1.05$
  => $\alpha_{eff} = sin^{-1}(-0.703)/2 = 135^o$ (+3 other solutions...)

Related $B\to\pi\pi$ modes

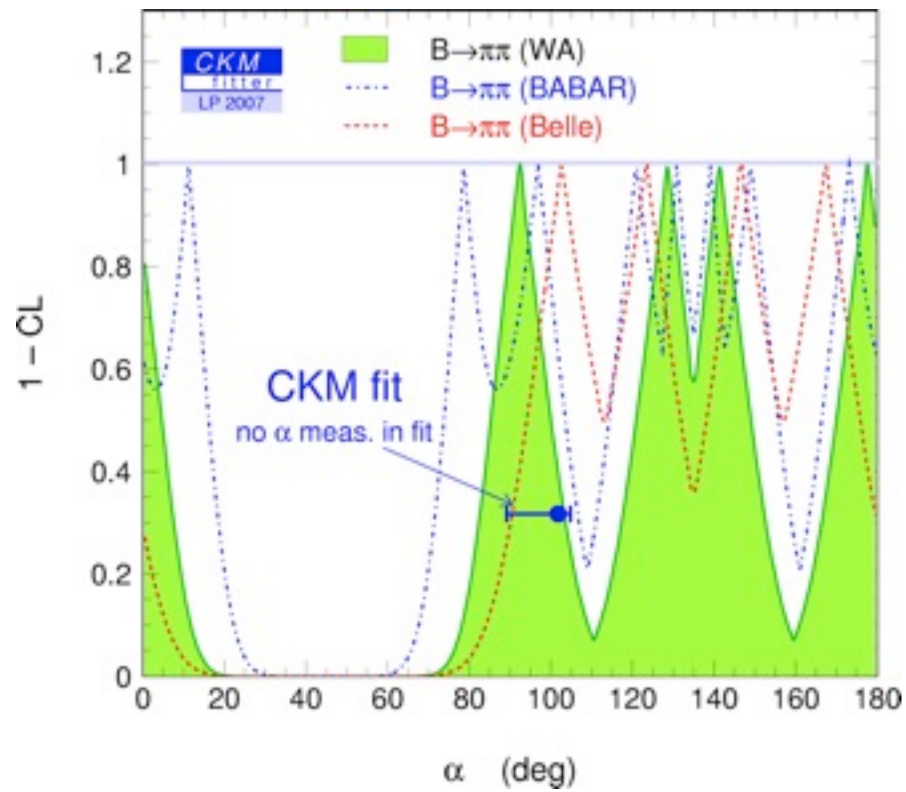
- Branching fractions + charge asymmetries:

$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.16 \pm 0.22) \times 10^{-6}$$
$$\mathcal{B}(B^\pm \to \pi^\pm\pi^0) = (5.59^{+0.41}_{-0.40}) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\pi^0) = 0.06 \pm 0.05$$
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.55 \pm 0.19) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.43^{+0.25}_{-0.24}$$

$B^0\to\pi^0\pi^0$ signal



- Combined result for α determined using method derived from global fit to isospin-related modes (CKMFitter group, 2007)
  - notice the 4-fold ambiguity
  - main uncertainty from relatively large $B^0\to\pi^0\pi^0$ branching fraction



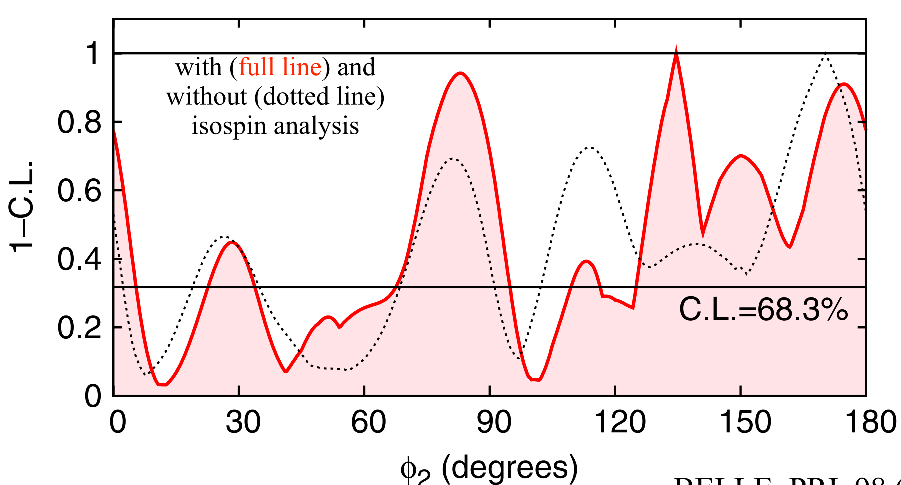
$B^0 \rightarrow \rho^+\pi^-$

- Snyder and Quinn (PRD 48 (1993) 2139) propose a time-dependent Dalitz plot analysis of $B^\pm \rightarrow \pi^\pm\pi^+\pi^-$ decays:
  - not a CP eigenstate! 4 decay rates: $B^+/B^- \rightarrow \pi^+\pi^+\pi^-/\pi^-\pi^+\pi^-$
  - determine the complex amplitudes and the UT angle α
  - fit the time- and Dalitz-plot-dependent decay rate:

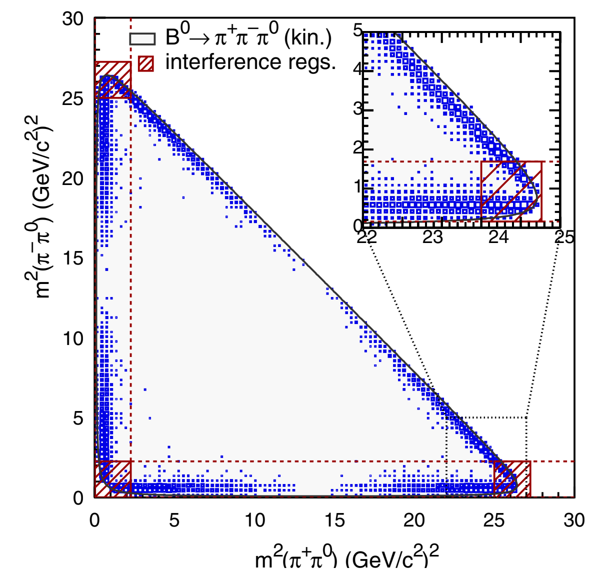
$$\frac{d\Gamma}{d\Delta t ds_+ ds_-} \sim e^{-|\Delta t|/\tau_{B^0}}\left\{(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2) - q_{\rm tag}(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2)\cos(\Delta m_d \Delta t) + q_{\rm tag} 2{\rm Im}\left[\frac{q}{p}A^*_{3\pi}\overline{A}_{3\pi}\right]\sin(\Delta m_d \Delta t)\right\}$$

  - determine 27 observable parameters!

- Belle and BABAR have applied this method



BELLE, PRL 98 (2007) 211801



BABAR, PRD 76 (2007) 012004

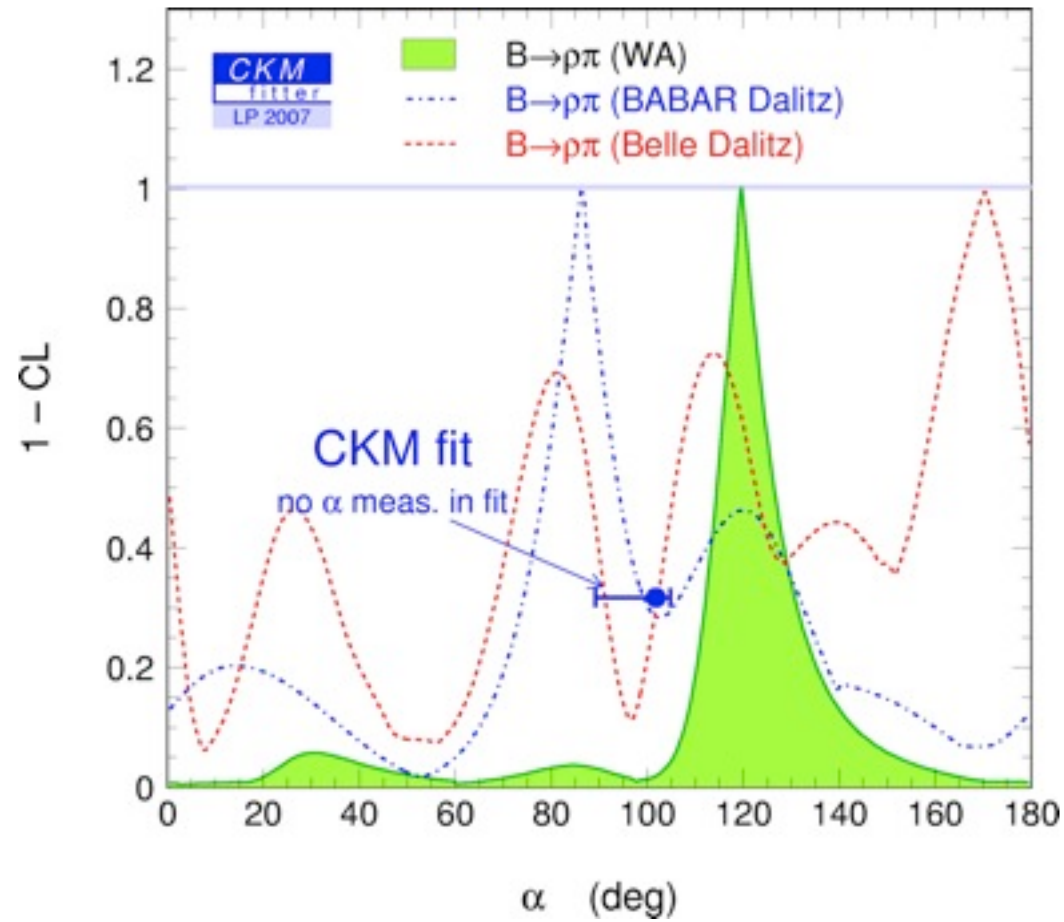
$B^0 \to \rho^+\pi^-$ combined results

- Combination of the results (CKMFitter group)
  - combine measured parameters from Belle and BABAR
  - use correlation matrices between parameters

TABLE IV. Correlation matrix of statistical uncertainties for the U and I coefficients. Since the matrix is symmetric, all elements above the diagonal are omitted.

	$N_{3\pi}$	I_0	I_-	I_{-0}^{Im}	I_{-0}^{Re}	I_+	I_{+0}^{Im}	I_{+0}^{Re}	I_{+-}^{Im}	I_{+-}^{Re}	U_0^-	U_0^+	$U_{-0}^{-,\mathrm{Im}}$
$N_{3\pi}$	1.00												
I_0	−0.02	1.00											
I_-	−0.04	−0.04	1.00										
I_{-0}^{Im}	−0.09	−0.11	0.28	1.00									
I_{-0}^{Re}	−0.03	0.28	−0.18	−0.15	1.00								
I_+	0.06	−0.04	−0.20	−0.21	0.17	1.00							
I_{+0}^{Im}	0.06	−0.03	−0.11	−0.14	0.09	0.38	1.00						
I_{+0}^{Re}	−0.17	0.30	0.18	0.17	−0.06	−0.35	−0.45	1.00					
I_{+-}^{Im}	0.09	0.11	0.14	−0.17	0.10	0.21	0.11	−0.03	1.00				
I_{+-}^{Re}	−0.24	0.04	0.36	0.28	−0.15	−0.46	−0.25	0.43	−0.01	1.00			
U_0^-	−0.03	0.07	0.08	−0.05	−0.11	−0.06	−0.02	0.13	0.09	0.15	1.00		
U_0^+	0.04	−0.02	0.20	0.32	−0.19	−0.24	−0.19	0.30	−0.13	0.35	0.11	1.00	
$U_{-0}^{-,\mathrm{Im}}$	0.01	0.13	−0.11	−0.14	0.42	0.14	0.08	−0.07	0.10	−0.13	−0.36	−0.18	1.00
$U_{-0}^{-,\mathrm{Re}}$	0.02	0.07	−0.05	−0.44	0.03	0.06	0.05	0.01	0.17	−0.06	0.04	−0.19	0.13
$U_{-0}^{+,\mathrm{Im}}$	0.07	0.18	−0.14	−0.39	0.21	0.22	0.18	−0.14	0.27	−0.26	0.03	−0.56	0.31
$U_{-0}^{+,\mathrm{Re}}$	−0.05	0.16	0.07	−0.21	0.07	−0.01	−0.01	0.14	0.25	0.08	0.09	−0.05	0.19
U_-^-	0.11	−0.01	−0.03	−0.06	0.01	0.01	0.02	−0.06	0.01	−0.08	−0.09	−0.08	0.12
U_-^+	−0.12	0.14	0.08	−0.02	0.08	−0.06	−0.06	0.22	0.06	0.20	0.11	0.18	0.10
$U_{+0}^{-,\mathrm{Im}}$	0.26	0.03	−0.17	−0.19	0.10	0.17	0.11	−0.20	0.08	−0.40	−0.26	−0.31	0.15
$U_{+0}^{-,\mathrm{Re}}$	0.13	−0.02	0.00	0.08	−0.18	−0.13	−0.23	0.07	−0.05	−0.05	−0.04	0.03	−0.11
$U_{+0}^{+,\mathrm{Im}}$	0.03	0.12	−0.17	−0.41	0.36	0.34	0.34	−0.31	0.25	−0.29	−0.02	−0.54	0.29
$U_{+0}^{+,\mathrm{Re}}$	0.23	−0.03	−0.16	−0.25	0.13	0.25	0.28	−0.49	0.16	−0.44	−0.12	−0.36	0.12
$U_{+-}^{-,\mathrm{Im}}$	−0.14	−0.04	0.03	0.15	−0.04	−0.08	−0.07	0.09	−0.11	0.19	0.01	0.13	−0.08
$U_{+-}^{-,\mathrm{Re}}$	−0.12	−0.10	−0.05	0.14	−0.05	−0.01	−0.04	−0.01	−0.20	0.07	−0.10	0.09	−0.04
$U_{+-}^{+,\mathrm{Im}}$	0.12	−0.20	−0.09	0.18	−0.21	−0.03	−0.01	−0.17	−0.18	−0.22	−0.17	0.02	−0.17
$U_{+-}^{+,\mathrm{Re}}$	−0.15	0.05	0.07	0.01	0.06	0.00	−0.03	0.12	0.22	0.13	0.10	0.10	0.03
U_+^-	−0.05	−0.01	0.00	0.05	−0.06	−0.07	−0.05	0.05	−0.03	0.04	−0.03	0.05	−0.04

	$U_{-0}^{-,\mathrm{Re}}$	$U_{-0}^{+,\mathrm{Im}}$	$U_{-0}^{+,\mathrm{Re}}$	U_-^-	U_-^+	$U_{+0}^{-,\mathrm{Im}}$	$U_{+0}^{-,\mathrm{Re}}$	$U_{+0}^{+,\mathrm{Im}}$	$U_{+0}^{+,\mathrm{Re}}$	$U_{+-}^{-,\mathrm{Im}}$	$U_{+-}^{-,\mathrm{Re}}$	$U_{+-}^{+,\mathrm{Im}}$	$U_{+-}^{+,\mathrm{Re}}$	U_+^-
$U_{-0}^{-,\mathrm{Re}}$	1.00													
$U_{-0}^{+,\mathrm{Im}}$	0.36	1.00												
$U_{-0}^{+,\mathrm{Re}}$	0.34	0.25	1.00											
U_-^-	0.19	0.06	0.03	1.00										
U_-^+	0.11	0.20	0.28	−0.13	1.00									
$U_{+0}^{-,\mathrm{Im}}$	0.07	0.22	−0.04	0.10	−0.16	1.00								
$U_{+0}^{-,\mathrm{Re}}$	−0.01	−0.08	−0.05	0.07	−0.05	0.32	1.00							
$U_{+0}^{+,\mathrm{Im}}$	0.22	0.56	0.17	−0.00	0.05	0.20	−0.25	1.00						
$U_{+0}^{+,\mathrm{Re}}$	0.08	0.23	0.02	0.11	−0.31	0.37	−0.06	0.41	1.00					
$U_{+-}^{-,\mathrm{Im}}$	−0.15	−0.20	−0.11	−0.27	−0.05	−0.15	−0.03	−0.12	−0.17	1.00				
$U_{+-}^{-,\mathrm{Re}}$	−0.12	−0.19	−0.21	0.08	0.02	−0.07	0.03	−0.16	−0.16	0.09	1.00			
$U_{+-}^{+,\mathrm{Im}}$	−0.22	−0.33	−0.35	0.06	−0.48	0.15	0.22	−0.33	0.12	0.10	0.12	1.00		
$U_{+-}^{+,\mathrm{Re}}$	0.03	−0.04	0.17	−0.02	0.10	−0.19	−0.19	0.05	−0.07	0.03	−0.15	−0.24	1.00	
U_+^-	−0.02	−0.03	−0.03	−0.07	0.11	0.14	0.30	−0.11	−0.11	0.18	0.20	0.02	−0.12	1.00



- Result: $\alpha = (120^{+11}_{-7})^o$

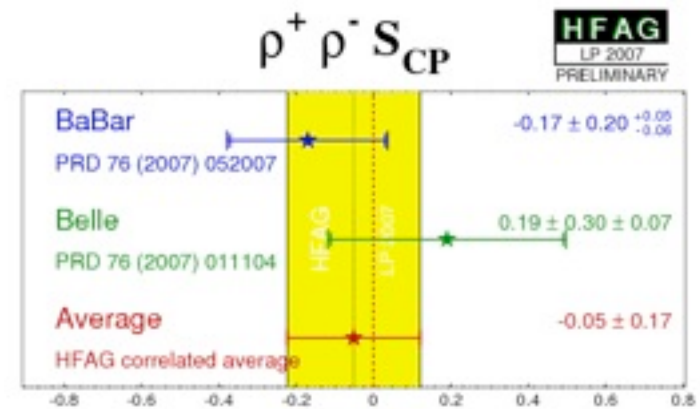
$B^0 \to \rho^+\rho^-$

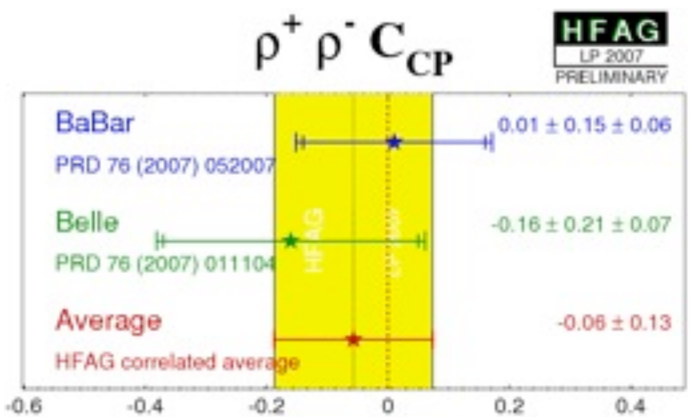
- $B^0 \to \rho^+\rho^-$ is sensitive to α (similar to $\pi^+\pi^-$ mode)
  - penguin amplitude separated using $B^\pm \to \rho^\pm\rho^0$ and $B^0 \to \rho^0\rho^0$
  - difference with $\pi^+\pi^-$: the rho meson is a vector
    => mixture of CP-odd and CP-even components in final state
    => thought to make the analysis difficult
- However
  1. the longitudinal polarization fraction f_L are measured to be close to unity => final state mostly CP-even!
  2. in addition, the branching fraction for $B^0 \to \rho^0\rho^0$ is small

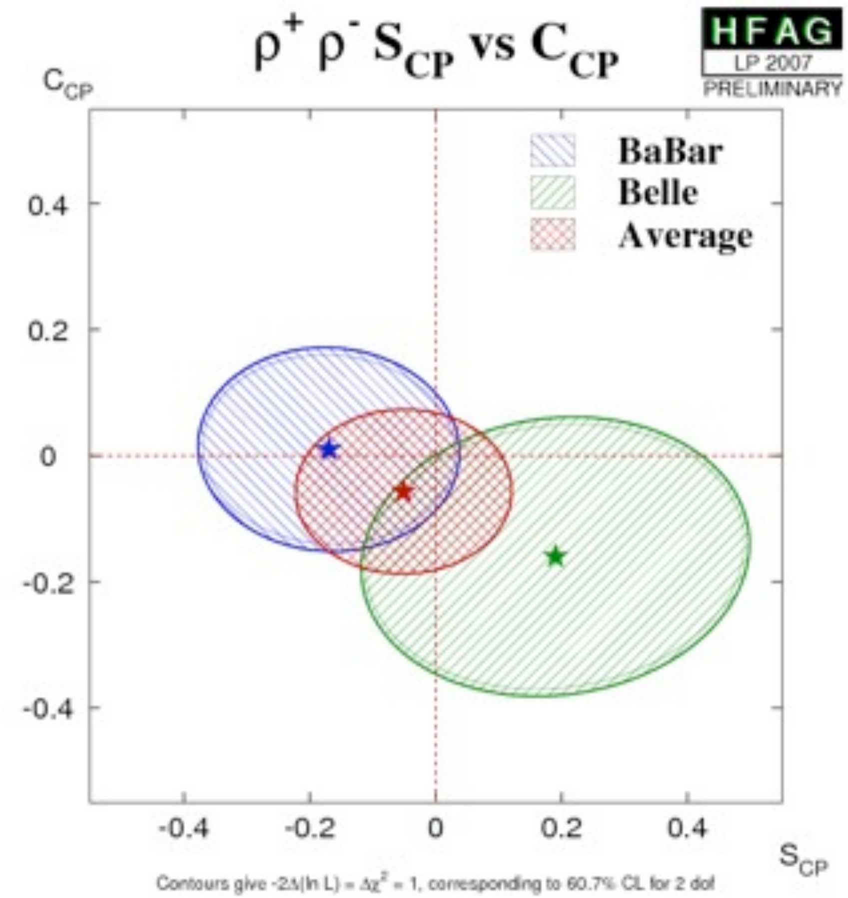
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (24.2^{+3.1}_{-3.2}) \times 10^{-6}$$
$$\mathcal{B}(B^\pm \to \rho^\pm\rho^0) = (24.0^{+1.9}_{-2.0}) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.73^{+0.27}_{-0.28}) \times 10^{-6}$$

=> the penguin amplitude is negligible
=> clean measurement of α! ($\alpha \approx \alpha_{eff}$)

$B^0 \to \rho^+\rho^-$ combined results



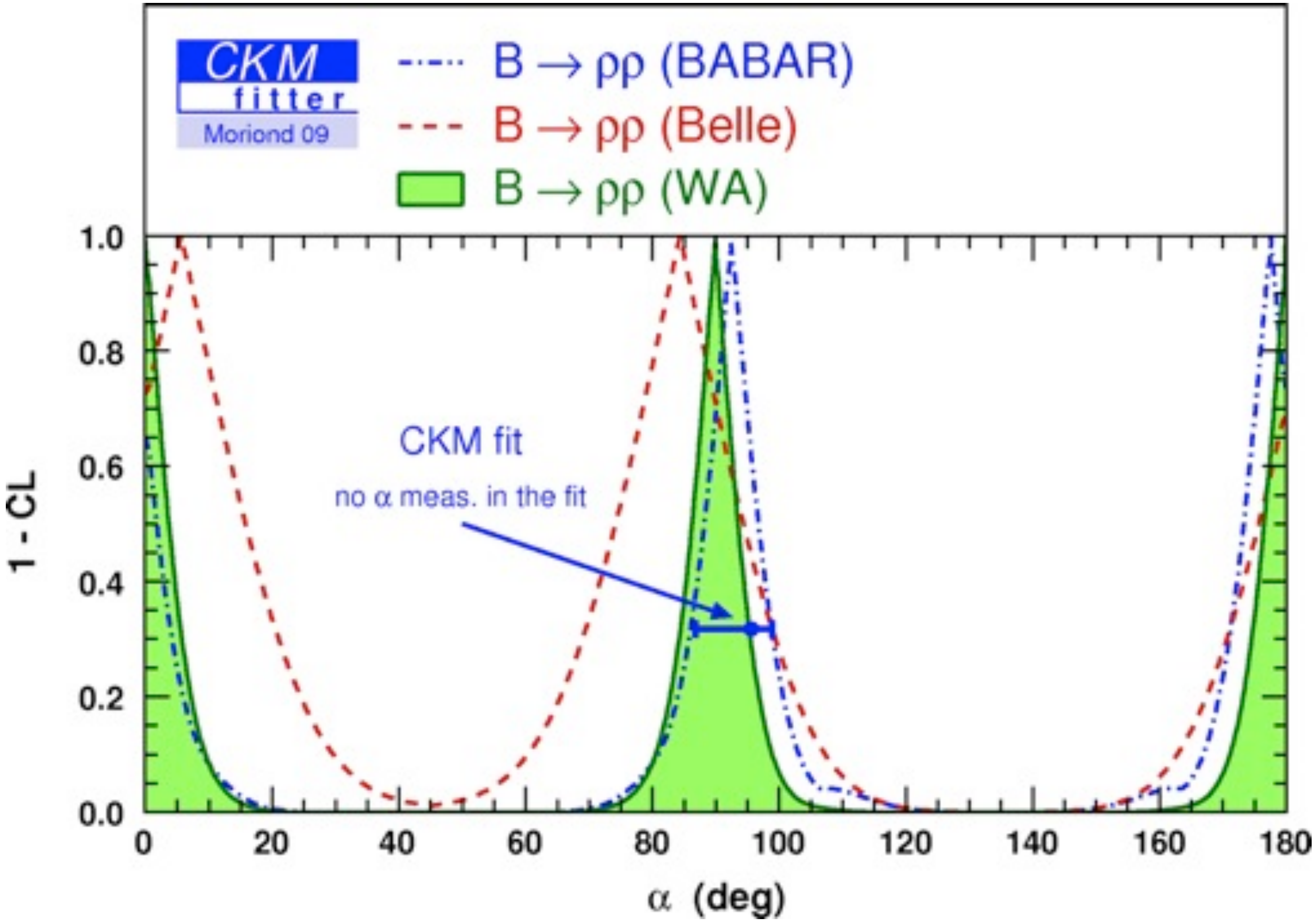




- $C \approx 0 \Rightarrow \sin 2\alpha_{eff} = S/(1+C) \approx S = -0.05$
- Penguin amplitude ≈ 0 => $\alpha_{eff} \approx \alpha$
  => $\alpha \approx \sin^{-1}(-0.05)/2 = 89^{o}$ (+3 other solutions...)

Angle α from $B^0 \to \rho^+\rho^-$

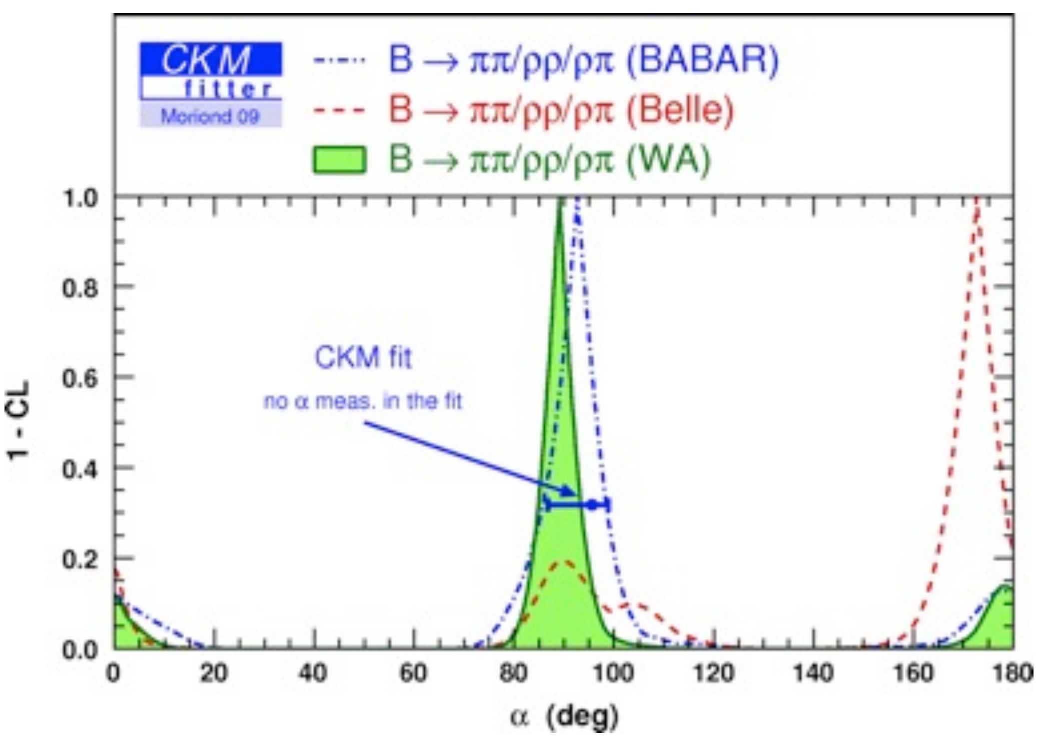
- Combined result for α (CKMFitter group)

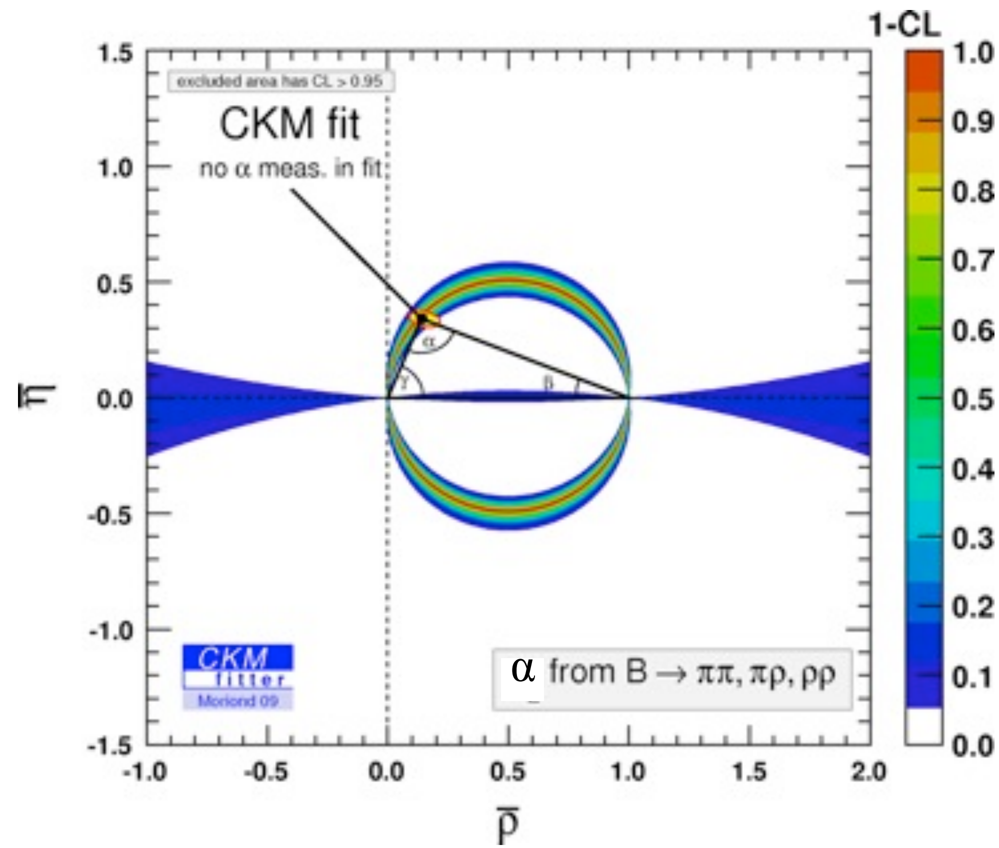


- Result: $\alpha = (89.9 \pm 5.4)^o$
  => most accurate measurement for α!!!

Summary on angle α

- The UT angle α is measured in several modes, most noticeably in $B \to \pi\pi$, $\rho\pi$, and $\rho\rho$
- Average from CKMFitter: $\alpha = (89.0^{+4.4}_{-4.2})^o$
  - compare to $\alpha = (97.5^{+1.6}_{-8.1})^o$ from indirect measurement

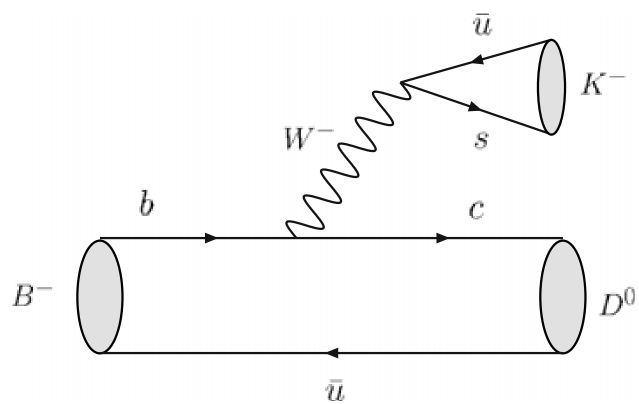




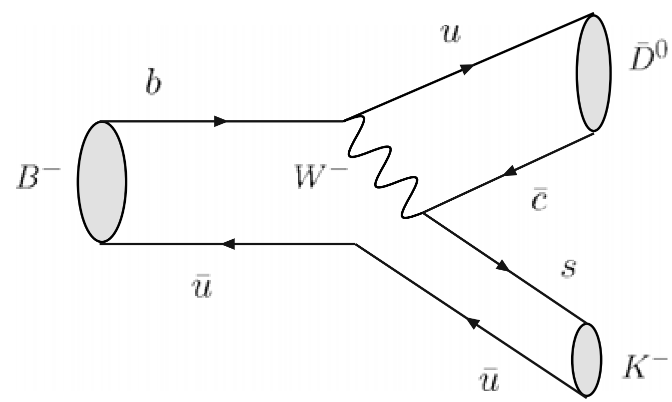
Measurement of the angle γ

Measurement of γ in B decays

- Measure γ, the relative phase between $V^{*}_{ub}V_{ud}$ and $V^{*}_{cb}V_{cd}$, in $B \rightarrow DK$ decays
  - exploit the interference between D^0 and $\overline{D^0}$ decays to a common CP eigenstate



no weak phase



weak phase of V_{ub} (=γ)

- Only UT angle measurable with tree processes only

Extracting γ from $B\to DK$ measurements

- Define the ratio of amplitudes

$$r_B e^{i\delta_B} = \frac{\mathcal{A}\left(B^+ \to D^0 K^+\right)}{\mathcal{A}\left(B^+ \to \overline{D}^0 K^+\right)}$$

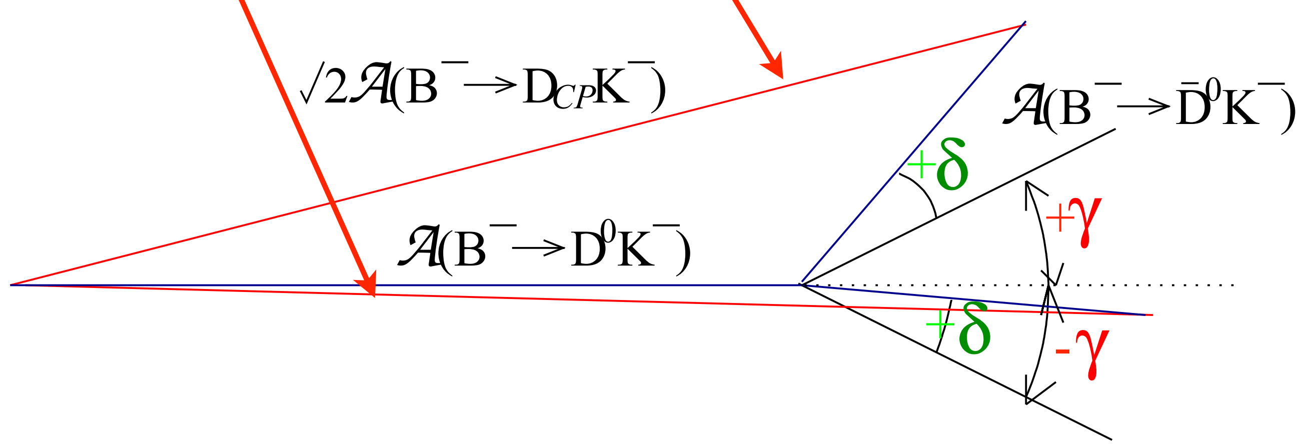
- Determine the decay rates to neutral D mesons in CP-even (D_1) and CP-odd (D_2) states

$$\mathcal{A}\left(B^- \to D_1 K^-\right) \propto \frac{1}{2}\left(1 + r_B e^{i(\delta_B-\gamma)}\right) \longrightarrow \Gamma\left(B^- \to D_1 K^-\right) \propto 1 + r_B^2 + 2r_B\cos\left(\delta_B - \gamma\right)$$

$$\mathcal{A}\left(B^- \to D_2 K^-\right) \propto \frac{1}{2}\left(1 - r_B e^{i(\delta_B-\gamma)}\right) \longrightarrow \Gamma\left(B^- \to D_2 K^-\right) \propto 1 + r_B^2 - 2r_B\cos\left(\delta_B - \gamma\right)$$

$$\mathcal{A}\left(B^+ \to D_1 K^+\right) \propto \frac{1}{2}\left(1 + r_B e^{i(\delta_B+\gamma)}\right) \longrightarrow \Gamma\left(B^+ \to D_1 K^+\right) \propto 1 + r_B^2 + 2r_B\cos\left(\delta_B + \gamma\right)$$

$$\mathcal{A}\left(B^+ \to D_2 K^+\right) \propto \frac{1}{2}\left(1 - r_B e^{i(\delta_B+\gamma)}\right) \longrightarrow \Gamma\left(B^+ \to D_2 K^+\right) \propto 1 + r_B^2 - 2r_B\cos\left(\delta_B + \gamma\right)$$



Extracting γ from $B \to DK$: remarks

- CP violating effects will be most visible for large r_B
  - r_B is typically 0.1-0.2
- Rate (Γ) measurements alone => $r_B \cos(\delta_B \pm \gamma)$
  => ambiguities in determination of γ
  - resolved in Dalitz plot analyses => $r_B \sin(\delta_B \pm \gamma)$
- Various methods:
  - "GLW" analyses
  - "ADS" analyses
  - Dalitz analyses

GLW analyses

Gronau and London, PLB 253 (1991) 483
Gronau and Wyler, PLB 265 (1991) 172

- Use D^0 decays to
  - $\pi^+\pi^-$, K^+K^- (CP even)
  - $K_S\pi^0$, $K_S\varphi$ (CP odd)
- Observables:
  - the asymmetry

$$\mathcal{A}_{1,2} \equiv \frac{\mathcal{B}(B^- \to D_{1,2}K^-) - \mathcal{B}(B^+ \to D_{1,2}K^+)}{\mathcal{B}(B^- \to D_{1,2}K^-) + \mathcal{B}(B^+ \to D_{1,2}K^+)} = \frac{2r_B \sin\delta' \sin\gamma}{1 + r_B^2 + 2r_B\cos\delta'\cos\gamma}$$

  - and the double ratio

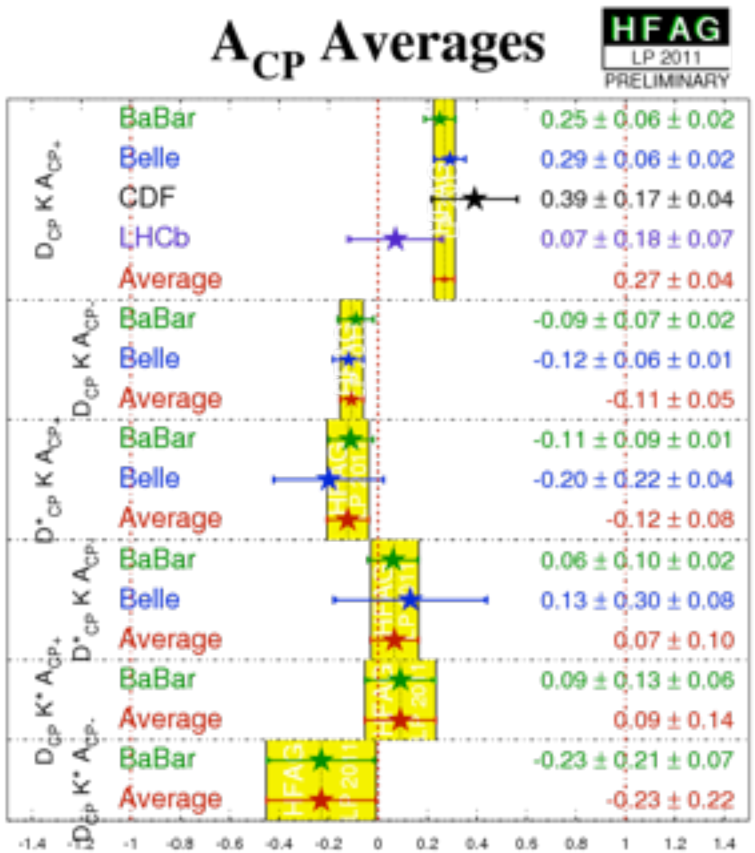
$$\mathcal{R}_{1,2} \equiv \frac{\mathcal{B}(B^- \to D_{1,2}K^-) + \mathcal{B}(B^+ \to D_{1,2}K^+)}{\mathcal{B}(B^- \to D^0K^-) + \mathcal{B}(B^+ \to D^0K^+)} = 1 + r_B^2 + 2r_B\cos\delta'\cos\gamma,$$

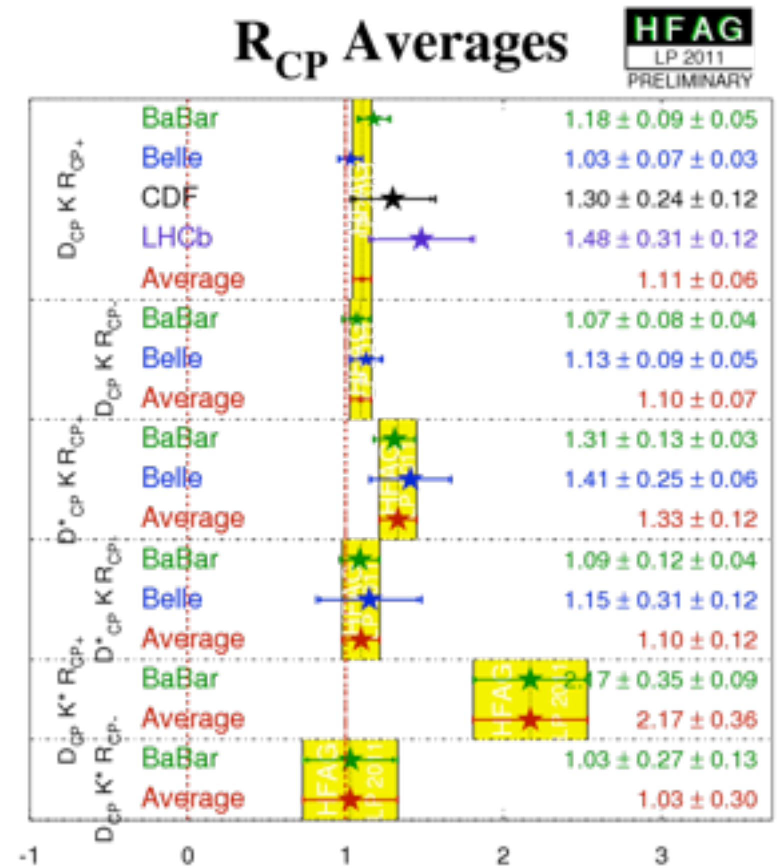
$$\delta' = \begin{cases} \delta_B & \text{for } D_1 \\ \delta_B + \pi & \text{for } D_2, \end{cases}$$

- Main difficulty:
  - small r_B => small measurable CP asymmetry

GLW analyses: results

- Belle, BABAR, CDF, and LHCb measured the asymmetries A and ratios R





ADS analyses

Atwood et.al., PRL 78 (1997) 3257
Atwood et.al., PRD 63 (2001) 036005

- To alleviate the problem of the small value of r_B , consider D^0 decays to $K^+\pi^-$ (and $K^-\pi^+$) such that:
  - suppressed B decay correspond to Cabibbo-allowed D^0 decay
  - and vice versa
    => interference from processes with similar amplitudes
    => larger CP violation is expected
- Observables:

$$\mathcal{R}_{ADS} = \frac{\mathcal{B}(B^\pm \to [K^\mp\pi^\pm]_D K^\pm)}{\mathcal{B}(B^\pm \to [K^\pm\pi^\mp]_D K^\pm)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma \cos\delta$$

$$r_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right| = 0.058 \pm 0.001$$

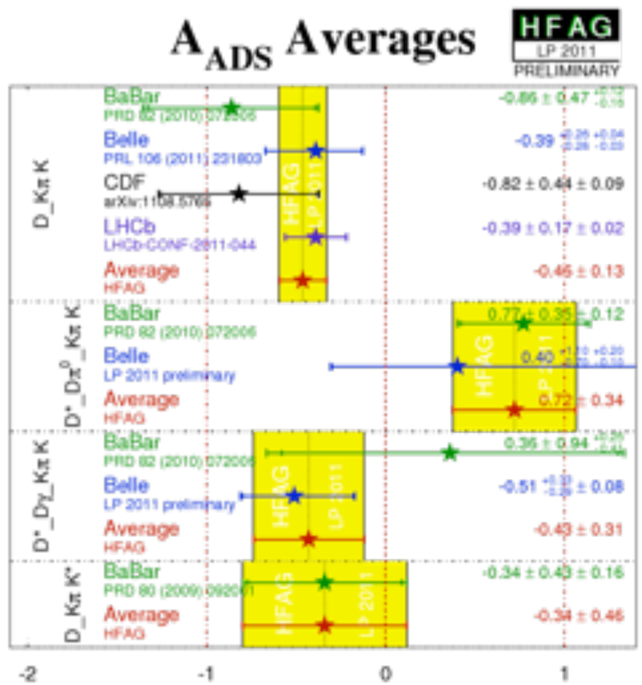
$$\delta = \delta_B + \delta_D$$

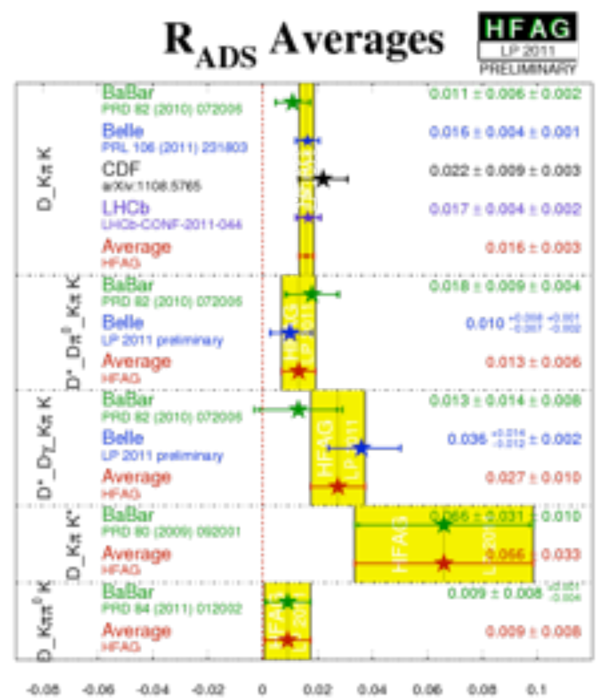
$$\mathcal{A}_{ADS} = \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) - \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)}$$

$$= \frac{2 r_B r_D \sin\gamma \sin\delta}{r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma \cos\delta}.$$

ADS analyses: results

- Results by Belle, BABAR, CDF, and LHCb





- Currently not sensitive to angle γ
  ...but useful constraint on r_B

$$r_B < 0.19 \text{ at } 90\% \text{ CL}$$

γ from Dalitz plot analyses

- $B \to D^0 K$ with $D^0 \to K_S \pi^+ \pi^-$
  - Dalitz plot analysis of the D^0 decay allows to determine all the information in a single mode
    => measure of γ with 2-fold ambiguity
- Evidence for direct CP violation from BABAR and Belle

BABAR

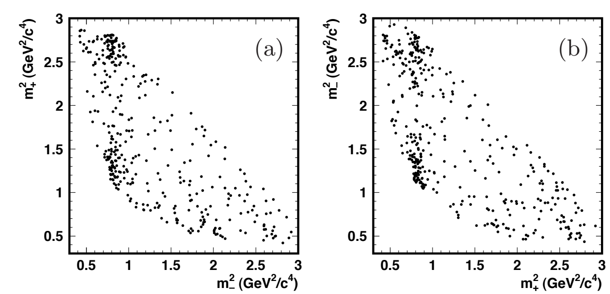
$$\gamma = (68 \pm 14 \pm 4 \pm 3)^o$$

Parameter	68.3% CL	95.4% CL
γ (°)	68^{+15}_{-14} $\{4, 3\}$	$[39, 98]$
r_B (%)	9.6 ± 2.9 $\{0.5, 0.4\}$	$[3.7, 15.5]$
r^*_B (%)	$13.3^{+4.2}_{-3.9}$ $\{1.3, 0.3\}$	$[4.9, 21.5]$
κr_s (%)	$14.9^{+6.6}_{-6.2}$ $\{2.6, 0.6\}$	< 28.0
δ_B (°)	119^{+19}_{-20} $\{3, 3\}$	$[75, 157]$
δ^*_B (°)	-82 ± 21 $\{5, 3\}$	$[-124, -38]$
δ_s (°)	111 ± 32 $\{11, 3\}$	$[42, 178]$

BABAR, arXiv:1005.1096

Belle

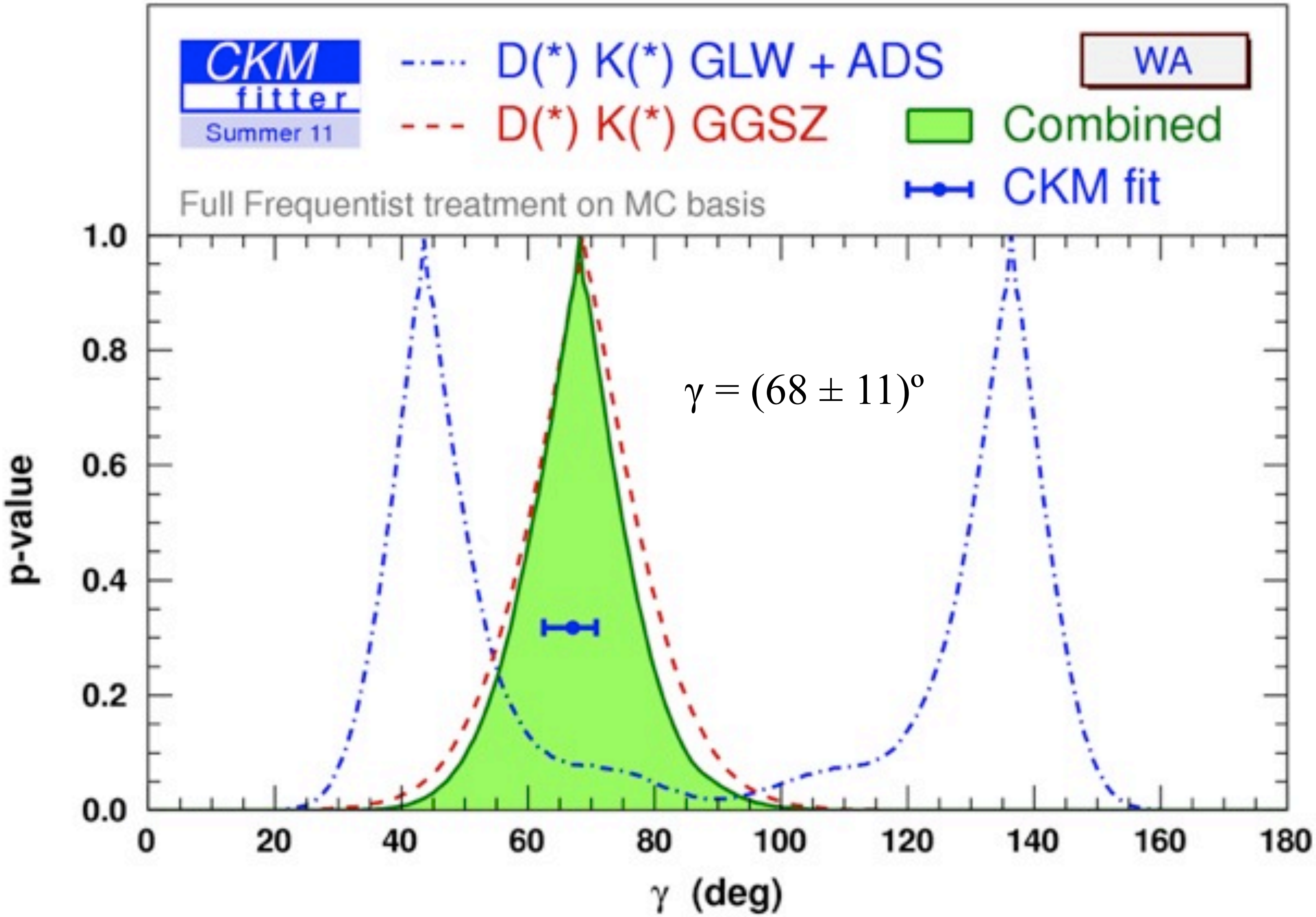
$$\gamma = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^o$$



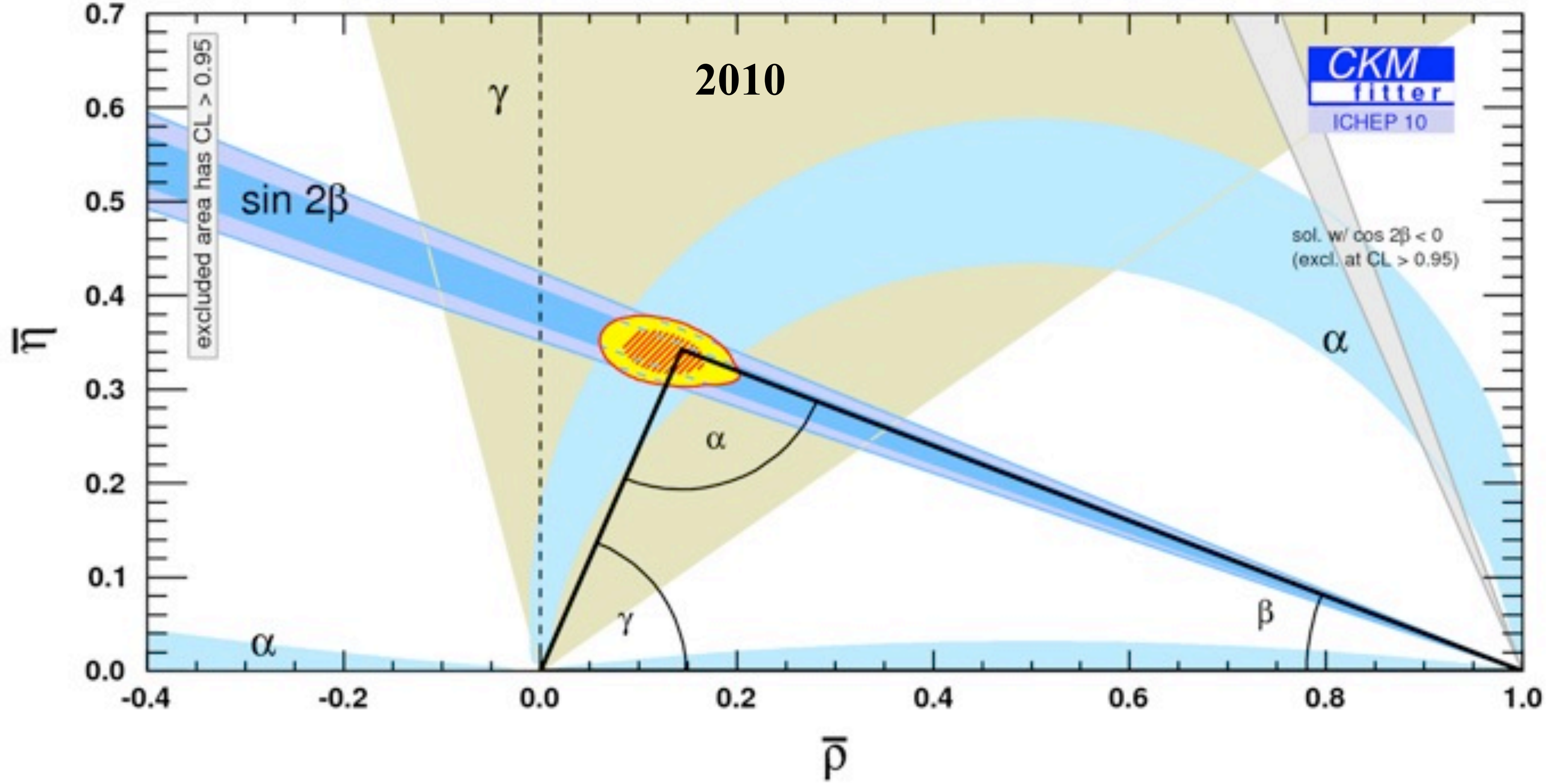
Parameter	1σ interval	2σ interval	Systematic error	Model uncertainty
ϕ_3	$(78.4^{+10.8}_{-11.6})^\circ$	$54.2^\circ < \phi_3 < 100.5^\circ$	3.6°	8.9°
r_{DK}	$0.160^{+0.040}_{-0.038}$	$0.084 < r_{DK} < 0.239$	0.011	$^{+0.050}_{-0.010}$
r_{D^*K}	$0.196^{+0.072}_{-0.069}$	$0.061 < r_{D^*K} < 0.271$	0.012	$^{+0.062}_{-0.012}$
δ_{DK}	$(136.7^{+13.0}_{-15.8})^\circ$	$102.2^\circ < \delta_{DK} < 162.3^\circ$	4.0°	22.9°
δ_{D^*K}	$(341.9^{+18.0}_{-19.6})^\circ$	$296.5^\circ < \delta_{D^*K} < 382.7^\circ$	3.0°	22.9°

BELLE, arXiv:1003.3360

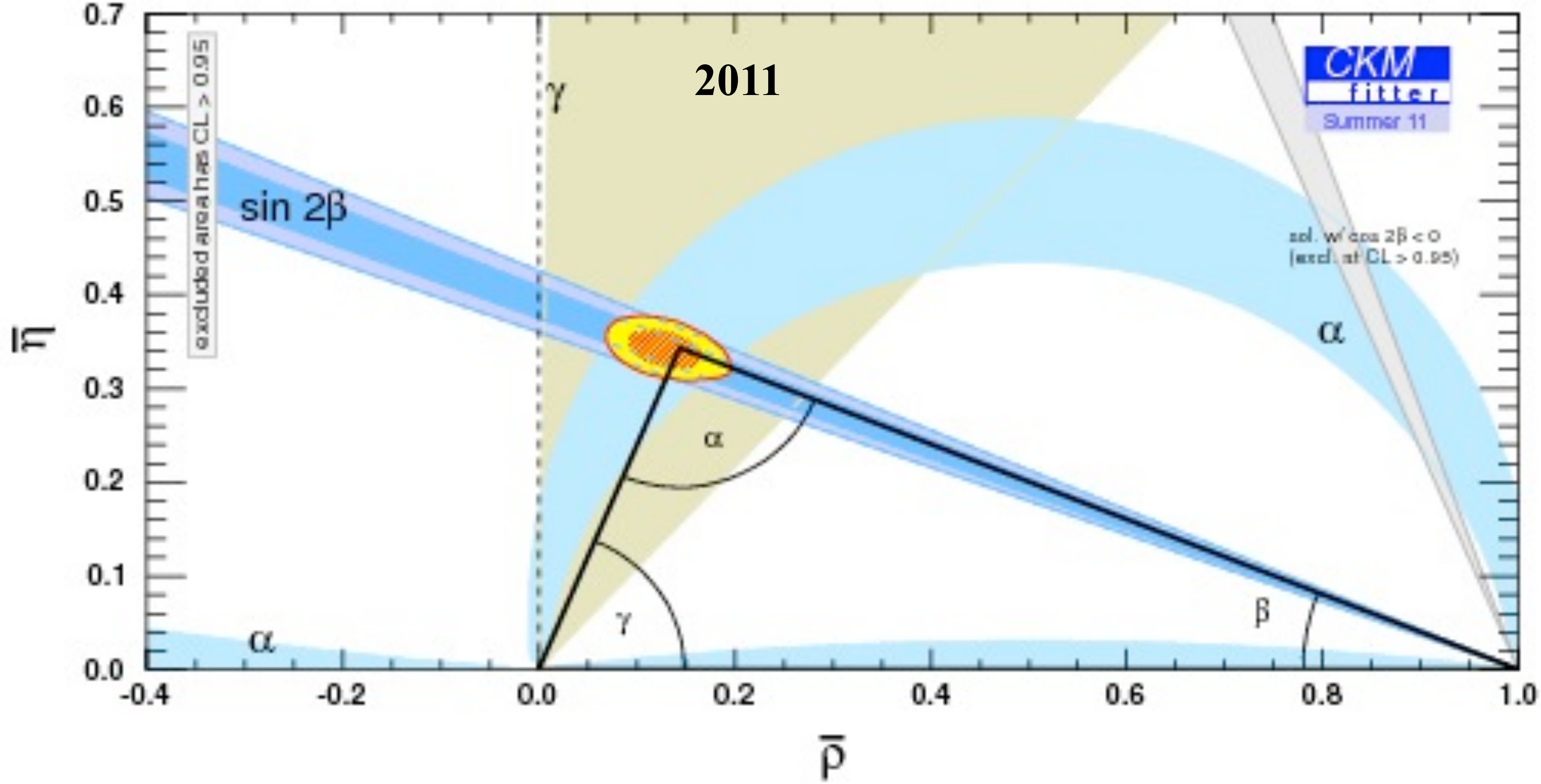
Summary on angle γ



Combined measurements of α, β, γ



Combined measurements of α, β, γ



Strong activity in the measurement of angle γ

Magnitude of the CKM elements V_{ub} and V_{cb}

CKM matrix element V_{ub} and V_{cb} in semileptonic decays

- The magnitude of $V_{(u/c)b}$ is measured in semileptonic decays
  - exclusive $B\to\pi l\nu$ and $B\to D^{(*)}l\nu$
  - inclusive $b\to ul\nu$ and $b\to cl\nu$
- For light leptons (e, μ), the decay rate for the process $H\to Pl\nu$ can be written as

CKM element

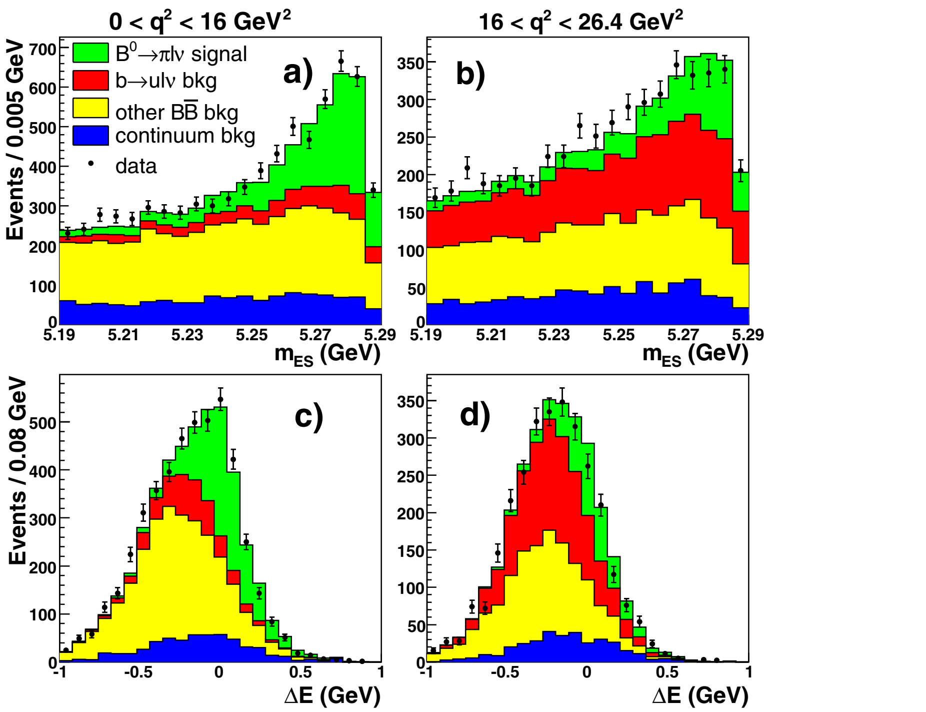
form factor

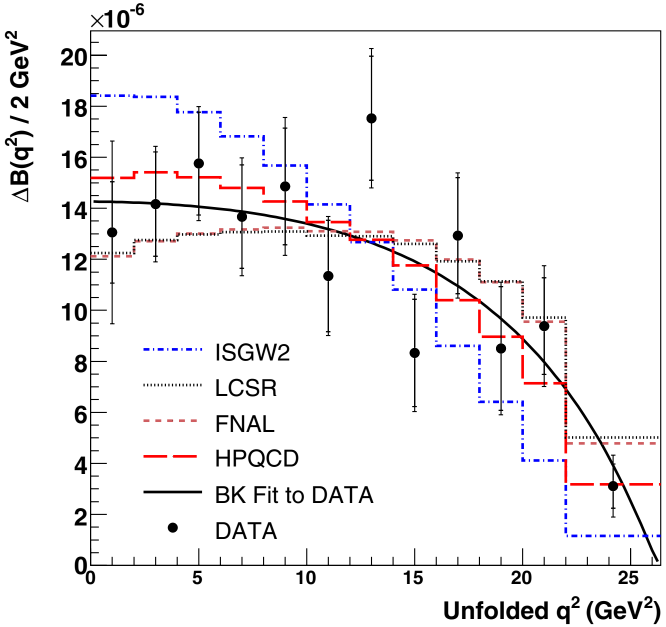
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{qQ}|^2}{192\pi^3 m_H^3}\left[(m_H^2+m_P^2-q^2)^2-4m_H^2m_P^2\right]^{3/2}|f_+(q^2)|^2$$

- Clean determination of the CKM matrix element from
  1. measurement of $d\Gamma/dq^2$
  2. theoretical calculation of the form factor $f_+(q^2)$ [e.g. Lattice QCD]
  3. determine $|V_{qQ}|$ from integration of the decay rate over the q^2 range

CKM element V_{ub}

- Measure $B \to \pi l \nu$ branching fraction and q^2 spectrum
- Extract signal from m_{ES}:ΔE distributions
- q^2 spectrum for signal
- Results:





$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.46 \pm 0.07_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-4}$$

$$|V_{ub}| = (4.1 \pm 0.2_{\rm stat} \pm 0.2_{\rm syst}{}^{+0.6}_{-0.4\rm FF}) \times 10^{-3}$$

BABAR, PRL 98 (2007) 091801

CKM element V_{ub} (Belle and BABAR)

- Many measurement of $B \to \pi l \nu$ branching fractions

	$\mathcal{L}$ (fb^{-1})	$\mathcal{B} \times 10^4$	$\Delta\mathcal{B}(q^2 < 16) \times 10^4$	$\Delta\mathcal{B}(q^2 > 16) \times 10^4$
BaBar no tag (π^-) [466]	206	$1.45 \pm 0.07 \pm 0.11$	$1.08 \pm 0.06 \pm 0.09$	$0.38 \pm 0.04 \pm 0.05$
CLEO no tag (π^-,π^0) [464]	16	$1.38 \pm 0.15 \pm 0.11$	$0.97 \pm 0.13 \pm 0.09$	$0.41 \pm 0.08 \pm 0.04$
BaBar sl. tag (π^-) [467]	348	$1.39 \pm 0.21 \pm 0.08$	$0.92 \pm 0.16 \pm 0.05$	$0.46 \pm 0.13 \pm 0.03$
Belle sl. tag (π^-) [471]	253	$1.38 \pm 0.19 \pm 0.15$	$1.02 \pm 0.16 \pm 0.11$	$0.36 \pm 0.10 \pm 0.04$
BaBar sl. tag (π^0) [467]	348	$1.80 \pm 0.28 \pm 0.15$	$1.38 \pm 0.23 \pm 0.11$	$0.45 \pm 0.17 \pm 0.06$
Belle sl. tag (π^0) [471]	253	$1.43 \pm 0.26 \pm 0.15$	$1.05 \pm 0.23 \pm 0.12$	$0.37 \pm 0.15 \pm 0.04$
BaBar had. tag (π^-) [468]	211	$1.07 \pm 0.27 \pm 0.19$	$0.42 \pm 0.18 \pm 0.06$	$0.65 \pm 0.20 \pm 0.13$
Belle had. tag (π^-) [472]	605	$1.12 \pm 0.18 \pm 0.05$	$0.85 \pm 0.16 \pm 0.04$	$0.26 \pm 0.08 \pm 0.01$
BaBar had. tag (π^0) [468]	211	$1.54 \pm 0.41 \pm 0.30$	$1.05 \pm 0.36 \pm 0.19$	$0.49 \pm 0.23 \pm 0.12$
Belle had. tag (π^0) [472]	605	$1.24 \pm 0.23 \pm 0.05$	$0.85 \pm 0.16 \pm 0.04$	$0.41 \pm 0.11 \pm 0.02$
Average		$1.36 \pm 0.05 \pm 0.05$	$0.94 \pm 0.05 \pm 0.04$	$0.37 \pm 0.03 \pm 0.02$

- ...and with other light resonances

Decay mode	$\mathcal{B} \times 10^4$	$\sigma_{stat} \times 10^4$	$\sigma_{syst} \times 10^4$
$B^+ \to \eta \ell^+ \nu$ (BaBar average) [469]	0.37	0.06	0.07
$B^+ \to \eta' \ell^+ \nu$ (CLEO no tag) [464][a]	2.66	0.80	0.56
$B^0 \to \rho^- \ell^+ \nu$ (average)	2.80	0.18	0.16
$B^+ \to \omega \ell^+ \nu$ (BaBar no tag) [469]	1.14	0.16	0.08

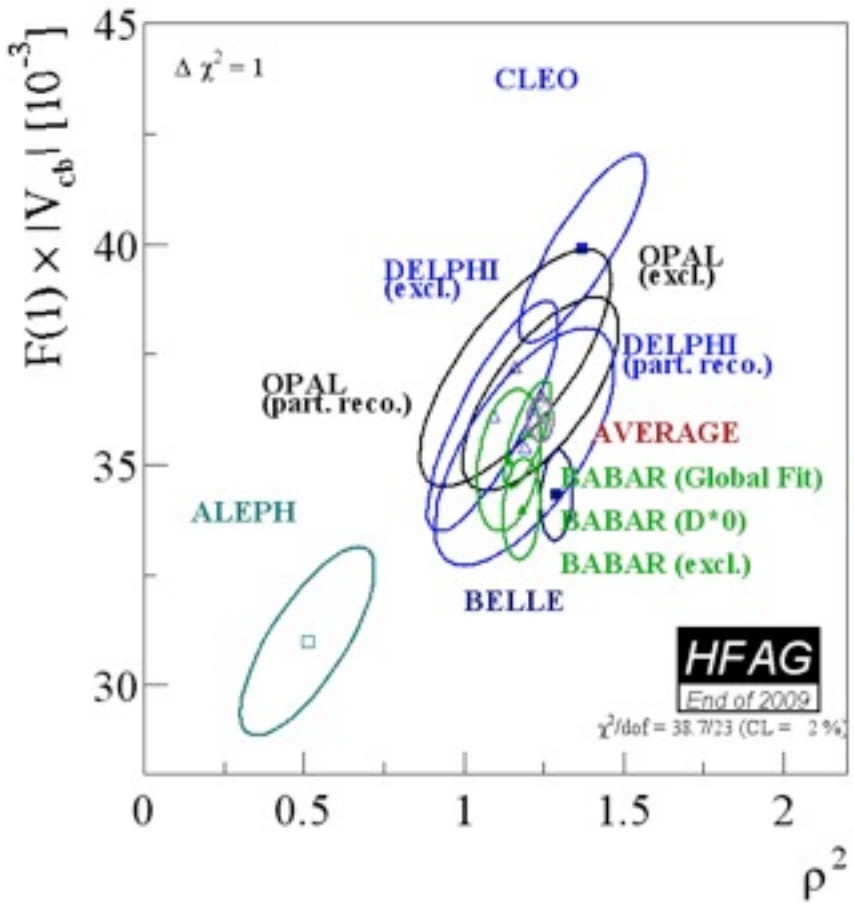
- $|V_{ub}|$ from exclusive decays yields:

$$|V_{ub}| = (3.38 \pm 0.36) \times 10^{-3}$$

CKM element V_{cb} from exclusive decays

- Measure $B \to D^{(*)} l\nu$ branching fraction and q^2 spectrum (similar to $B \to \pi l \nu$)
- Several measurements from
  - B factories
  - LEP
- Most accurate results from Belle and BABAR
- Average:

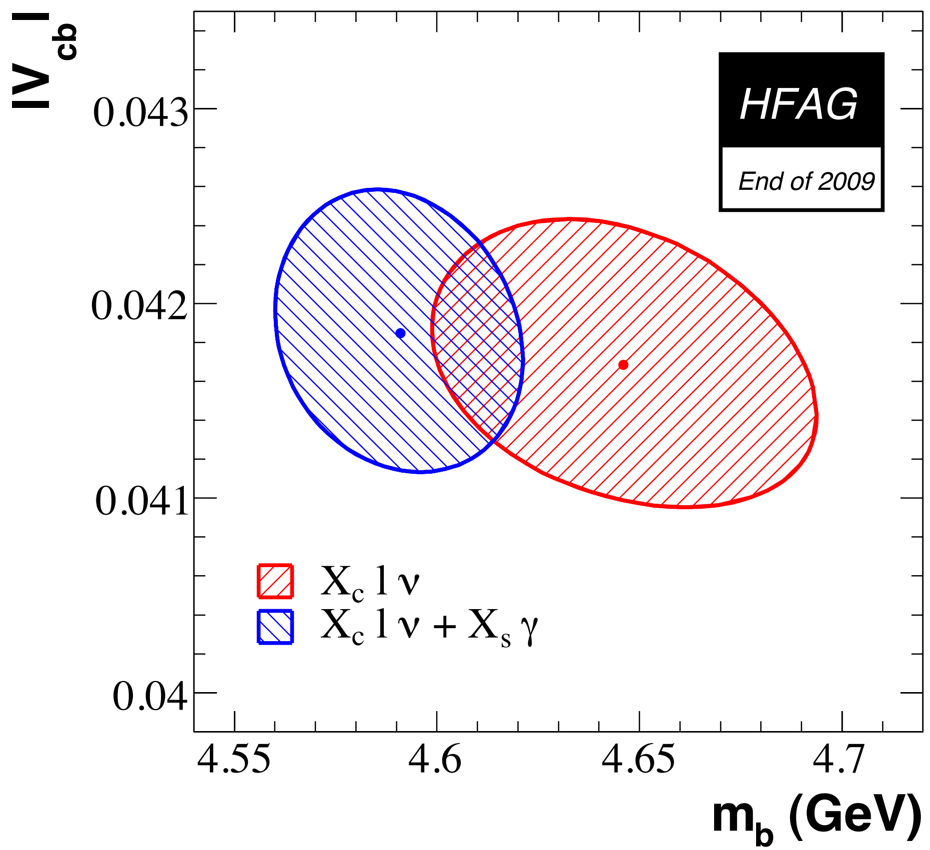
  $|V_{cb}| = (36.0 \pm 0.5) \times 10^{-3}$



CKM element V_{cb} from inclusive decays

- In inclusive measurements of $b \to c l \nu$, determine
  - branching fraction
  - lepton energy spectrum
- Global fit for V_{cb} and m_b
- Average:

$|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3}$



V_{ub} from leptonic $B^{\pm}\to\tau^{\pm}\nu_{\tau}$ decays

- The $B^{\pm}\to\tau^{\pm}\nu_{\tau}$ decay already occurs at the tree level
  - in SM
  - in new physics with extended Higgs sector

  => sensitivity to new physics
- From SM and Unitarity Triangle properties, expect

$$\mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} = (0.87 \pm 0.19) \times 10^{-4}$$

- In minimal flavor violation (MFV) supersymmetry models, define ratio of branching ratios (effective coupling $\varepsilon_0 \approx 10^{-2}$)

$$R_{P\ell\nu} = \frac{\mathcal{B}^{\mathrm{SM}}(P \to \ell\nu)}{\mathcal{B}^{\mathrm{SUSY}}(P \to \ell\nu)} = \left[1 - \left(\frac{m_P^2}{m_{H^{\pm}}^2}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right]^2$$

  - MSSM => O(10%) suppression relative to SM $BF(B\to\tau\nu)$

$B^{\pm}\rightarrow\tau^{\pm}\nu_{\tau}$ measurements

- At least 3 neutrinos in the final state ($B\rightarrow\tau\nu_{\tau}$, followed by (e.g.) $\tau\rightarrow\mu\nu_{\mu}\nu_{\tau}$) => use the recoil technique
  - reconstructed B (tagging B) as
    - semileptonic => high statistics, but non-negligible background
    - hadronic => cleaner, but lower statistics
  - on signal side:
    - reconstruct all visible particles
    - reject events with larger energy deposited in the calorimeter
- Belle and BABAR have observed the decay $B^{\pm}\rightarrow\tau^{\pm}\nu_{\tau}$:
  - Belle: $BF(B^{\pm}\rightarrow\tau^{\pm}\nu) = (1.54\pm0.38\pm0.30)\times10^{-4}$
  - BABAR: $BF(B^{\pm}\rightarrow\tau^{\pm}\nu) = (1.76\pm0.49)\times10^{-4}$
  - Average (HFAG): $BF(B^{\pm}\rightarrow\tau^{\pm}\nu) = (1.64\pm0.34)\times10^{-4}$

$B^{\pm}\rightarrow\tau^{\pm}\nu_{\tau}$: comparison to SM

- Average $B^{\pm}\rightarrow\tau^{\pm}\nu_{\tau}$ branching fraction:

$$\mathcal{B}(B \to \tau\nu)_{\text{exp}} = (1.64 \pm 0.34) \times 10^{-4}$$

- SM prediction:

$$\mathcal{B}(B \to \tau\nu)_{\text{SM}} = (0.87 \pm 0.19) \times 10^{-4}$$

- Difference = $(0.77 \pm 0.39)\times 10^{-4}$ => 2.0σ discrepancy
  - Remarks:
    - SM systematic uncertainty from lattice calculation is missing
    - experimental uncertainty is statistics dominated

    => new more data at next-generation B factory(ies)!

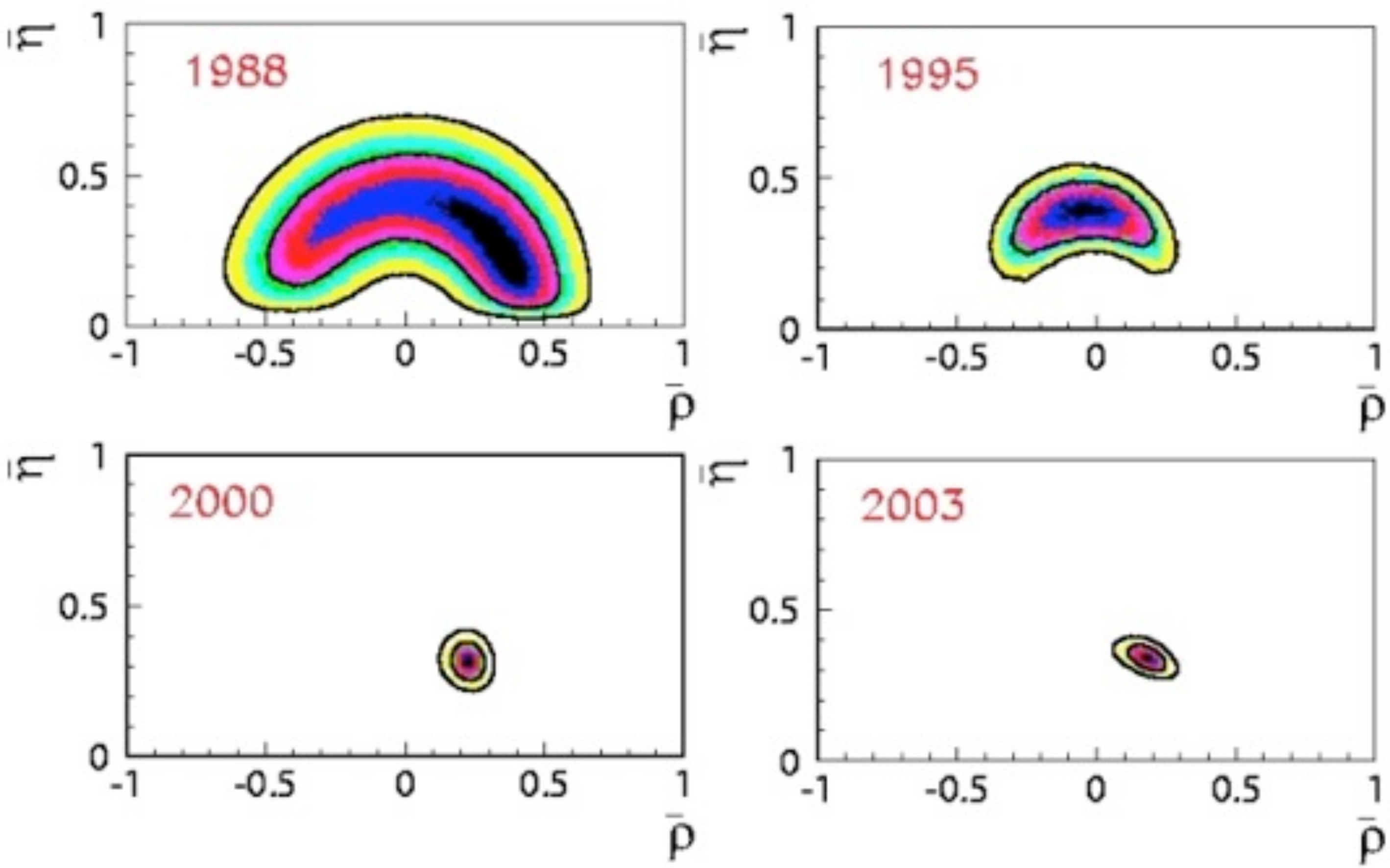
Global fits

Global fit strategy

- CKM matrix elements can be determined from global fit using all available measurements:
  - 4 parameters
  - 100's of measurements

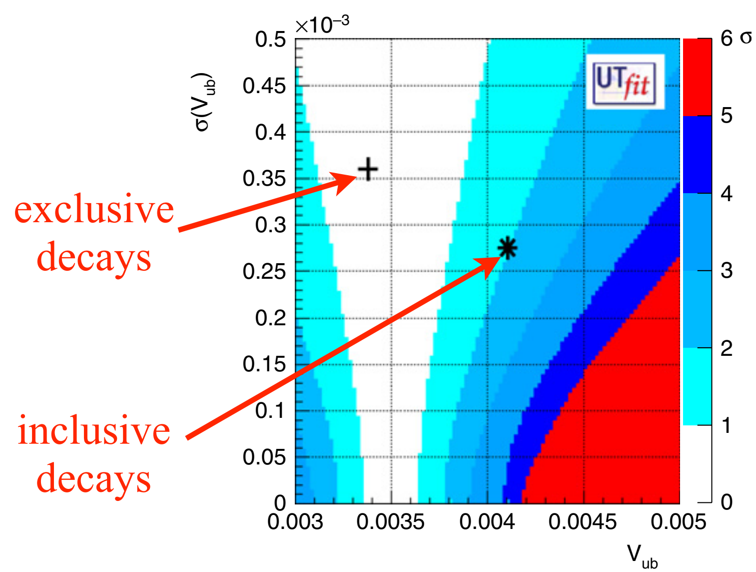
  => strong constraints on parameters
- Any discrepancy not explainable within the standard model would be a sign of new physics!
- Two main strategies:
  - frequentist
    - applied by the CKMFitter group [http://ckmfitter.in2p3.fr]
  - bayesian
    - applied by the UTFit group [http://www.utfit.org/UTfit]

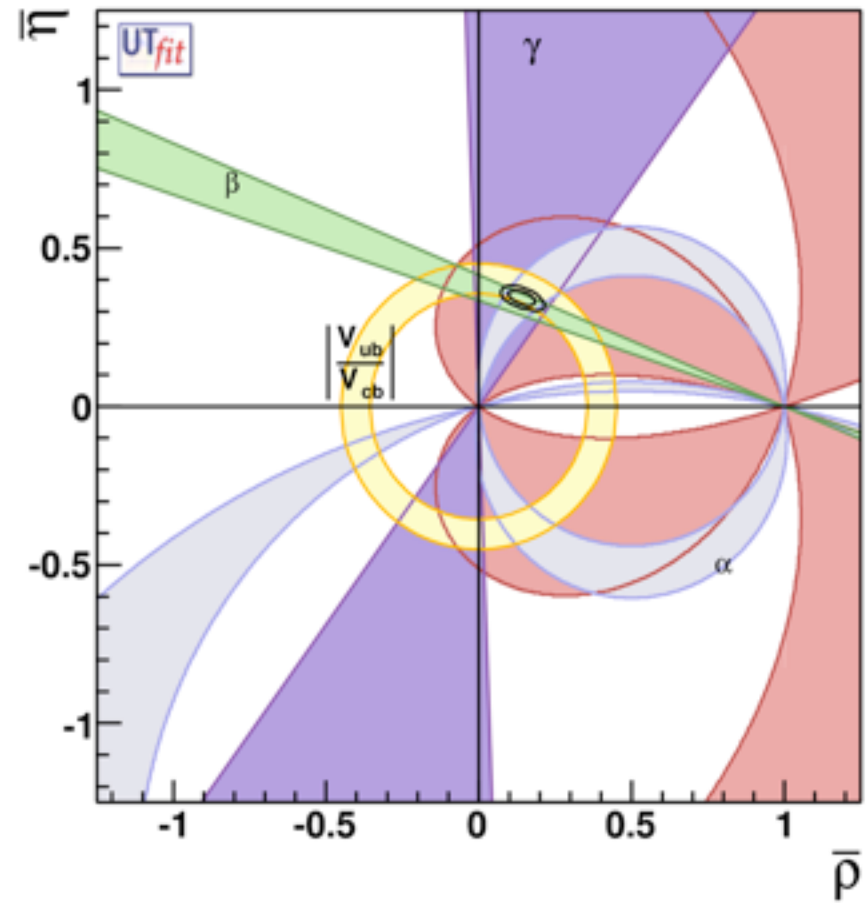
UTFit: evolution over time



UTFit: results 2010

- Overall very good agreement between measurements
  - small discrepancy between $|V_{ub}|$ measurements from inclusive and exclusive modes

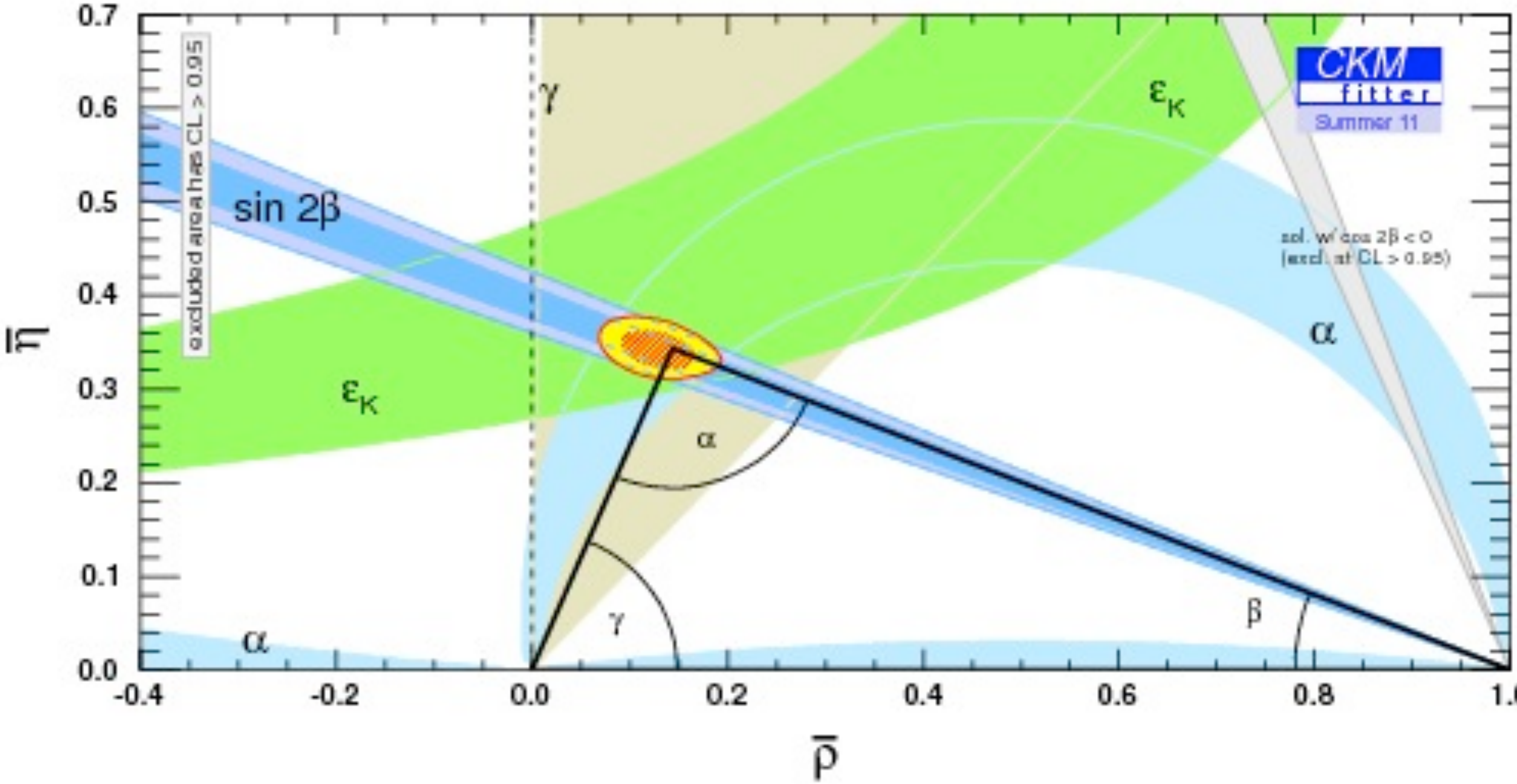




$$V_{CKM} = \begin{pmatrix} 0.97425 \pm 0.00015 & 0.22545 \pm 0.00065 & 0.00352 \pm 0.00011 e^{i(-67.7\pm4.4)} \\ -0.2253 \pm 0.00065 e^{i(-0.033\pm0.0016)} & 0.97342 \pm 0.00015 & 0.04099 \pm 0.00046 \\ 0.00854 \pm 0.00031 e^{i(-21.66\pm0.73)} & -0.04024 \pm 0.00045 e^{i(-1.04\pm0.048)} & 0.999154 \pm 1.8 \times 10^{-05} \end{pmatrix}$$

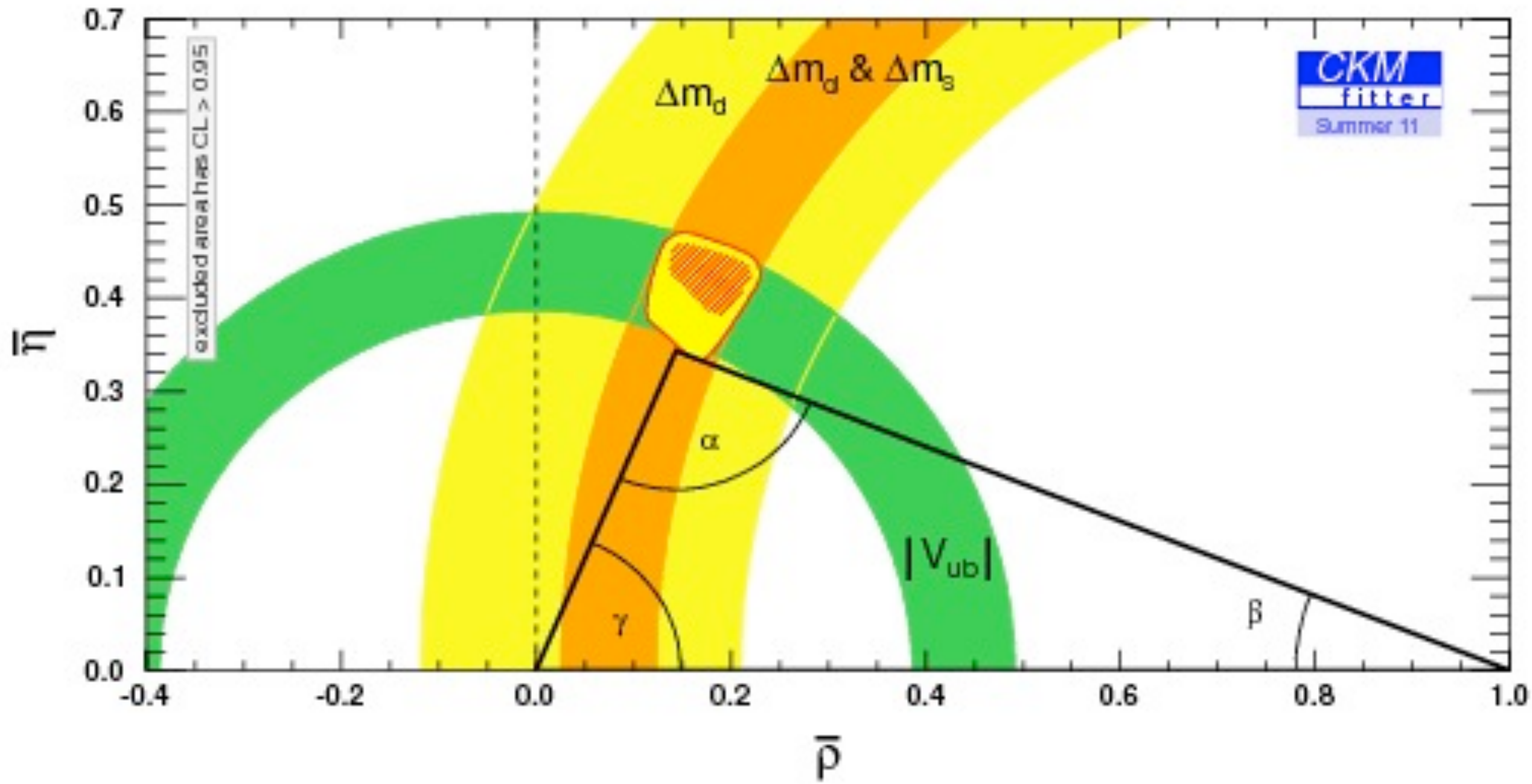
CKMFitter: CP violating quantities

α, β, γ, ε_K



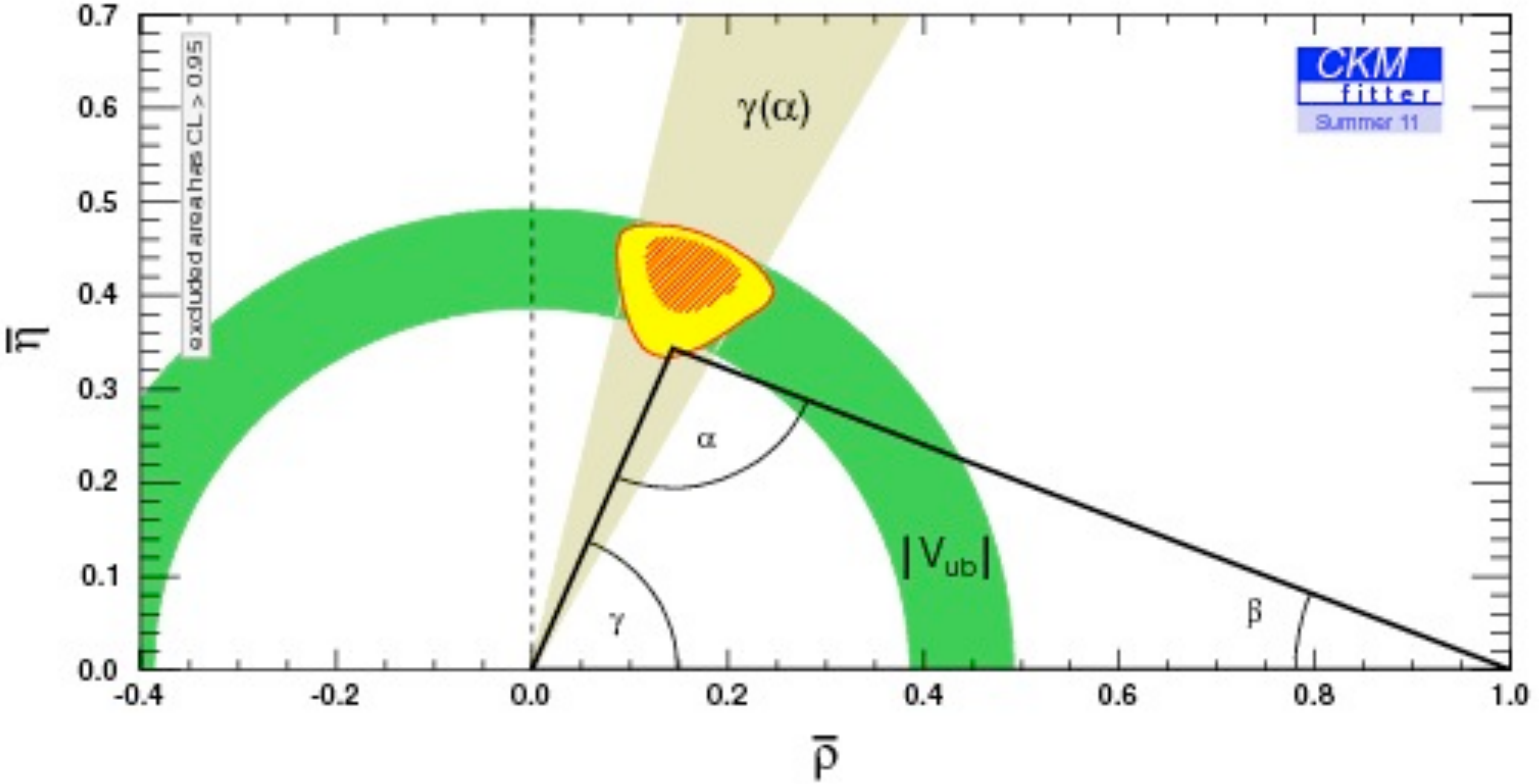
CKMFitter: CP conserved quantities

$|V_{ub}|$ (with $B\to\tau\nu$), Δm



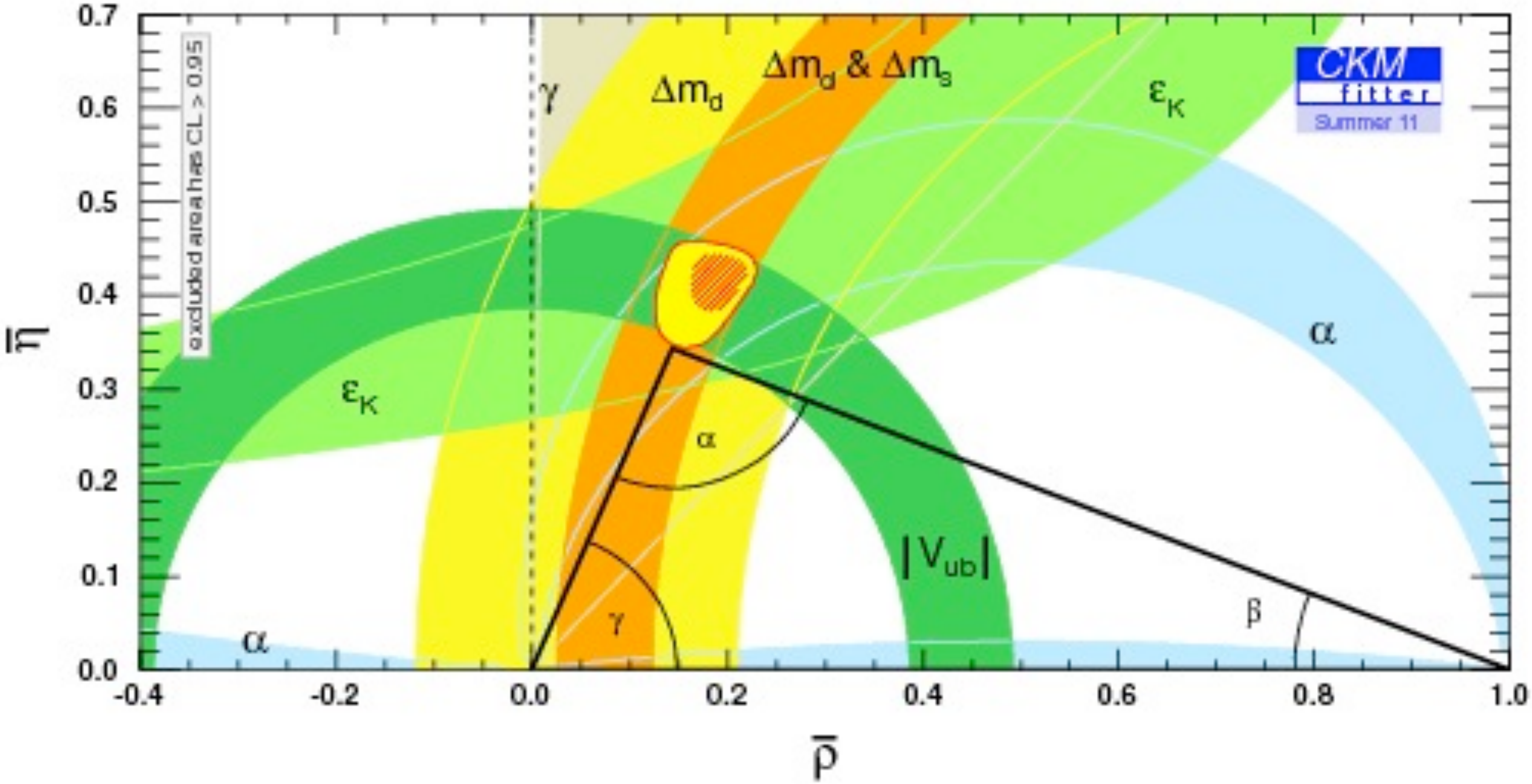
CKMFitter: tree quantities

$|V_{ub}|$, γ(from α and β)



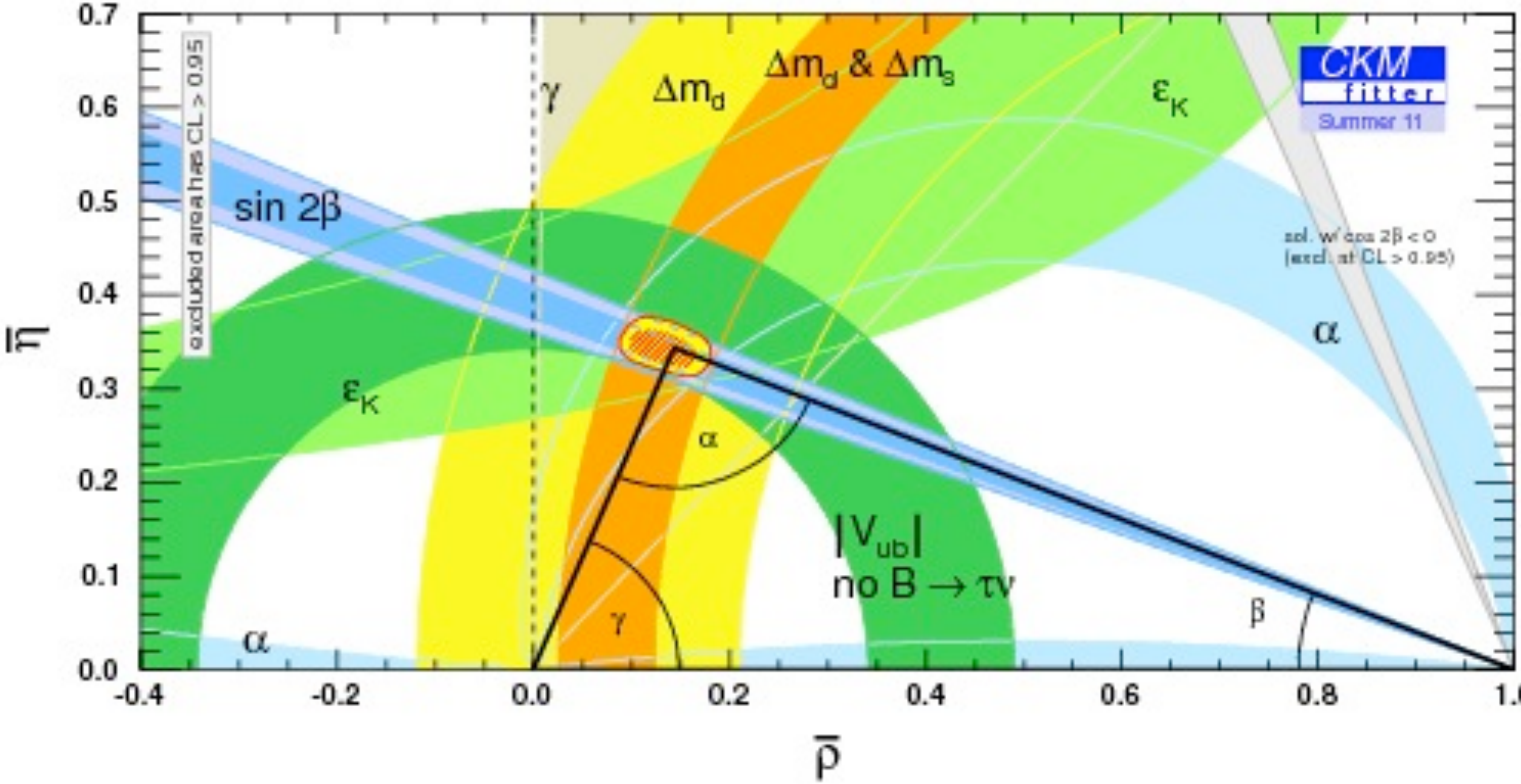
CKMFitter: global fit result

without sin2β, with B→τν



CKMFitter: global fit result

with sin2β, without B→τν



Comparison UTFit / CKMFitter

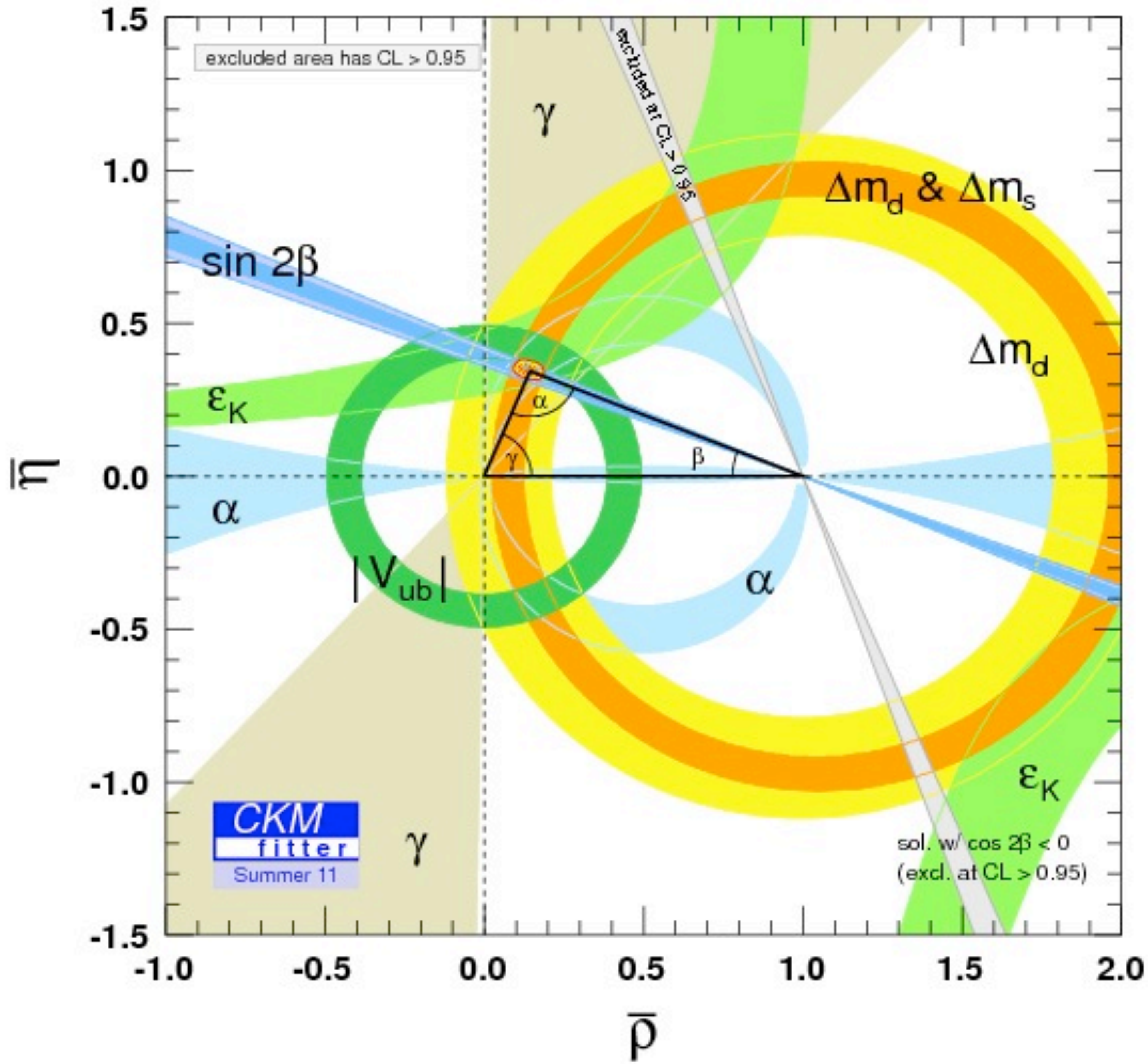
- Compare results from UTFit and CKMFitter groups

	UTFit	CKMFitter
$\bar{\rho}$	0.158 ± 0.021	$0.139^{+0.025}_{-0.027}$
$\bar{\eta}$	0.343 ± 0.013	$0.341^{+0.016}_{-0.015}$
A	0.802 ± 0.015	$0.812^{+0.010}_{-0.024}$
λ	0.2259 ± 0.0016	0.2252 ± 0.0008

$\alpha\,(^\circ)$	92.6 ± 3.2	$90.6^{+3.8}_{-4.2}$
$sin2\beta$	0.698 ± 0.019	$0.684^{+0.023}_{-0.021}$
$\gamma\,(^\circ)$	65.4 ± 3.1	$67.8^{+4.2}_{-3.9}$
$\|V_{\mathrm{ub}}\|$	0.00359 ± 0.0012	$0.00350^{+0.00015}_{-0.00014}$
$\|V_{\mathrm{cb}}\|$	0.0409 ± 0.0005	$0.04117^{+0.00038}_{-0.00115}$
$\|V_{\mathrm{td}}\|$	0.00842 ± 0.00021	$0.00859^{+0.00027}_{-0.00029}$

- The fitted values are all compatible within their uncertainties
- Both fitters agree on the tension between sin2β and B→τν

Summary



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
|V_ub|
α
ε_K
CKM
fitter
Summer 11
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$