Time-dependent CP violation in rare B decays

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On behalf of the *BABAR* and *Belle* Collaborations

FLAVOR PHYSICS & CP VIOLATION

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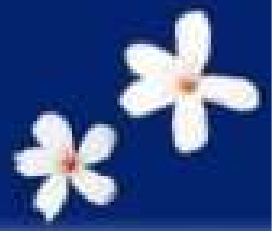

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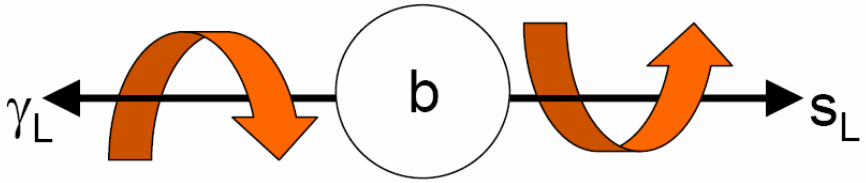
Outline

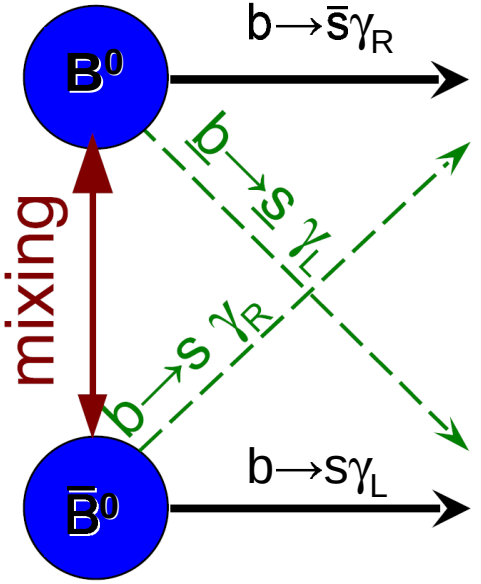
- **Rare penguin *B* decays : rationale and motivation**
- **Time-dependent study of radiative** $b \to s(d)\gamma$ **decays**
  - $B^0 \to K^*(K^0_S\pi^0)\gamma$, $B^0 \to \eta K^0_S\gamma$, $B^0 \to \rho^0\gamma$
- **Time-dependent study of penguin-dominated** $b \to q\bar{q}s$ **decays**
  - **A selection from the 9-mode list :**
    - $B^0 \to \eta' K^0_S$, $B^0 \to K^0_S\pi^+\pi^-$, $B^0 \to K^0_S K^+K^-$
  - **The global picture**
- **Perspectives and conclusions**

Time-dependent CP Violation in rare B decays : Motivation

- **FCNC processes are an excellent probe for BSM tests**
  - **Occur via loop-mediated amplitudes**
  - **Non SM amplitudes could contribute significantly**
- **We will discuss here two such processes**
  - **Radiative** $b \to s(d)\gamma$ **decays**
  - **Penguin-dominated charmless** $b \to q\bar{q}s$ **decays**
- **We concentrate in time-dependent CP studies**

Time-dependent study of $b\to s\gamma$ decays : Motivation





- **Radiated photon is almost completely polarised**
  - **"flavour-specific decay" :** $b\to s\gamma_L$ **and** $\bar{b}\to\bar{s}\gamma_R$
  - $B^0\leftrightarrow\bar{B}^0$ **interference can occur only through helicity flip**
- **Time-dependent CP asymmetry :**

$$A_{CP}(\Delta t)=\frac{\Gamma(\overline{B}^0(\Delta t)\to Xs\gamma_L)-\Gamma(B^0(\Delta t)\to Xs\gamma_R)}{\Gamma(\overline{B}^0(\Delta t)\to Xs\gamma_L)+\Gamma(B^0(\Delta t)\to Xs\gamma_R)}=S\sin\Delta m\Delta t-C\cos\Delta m\Delta t$$

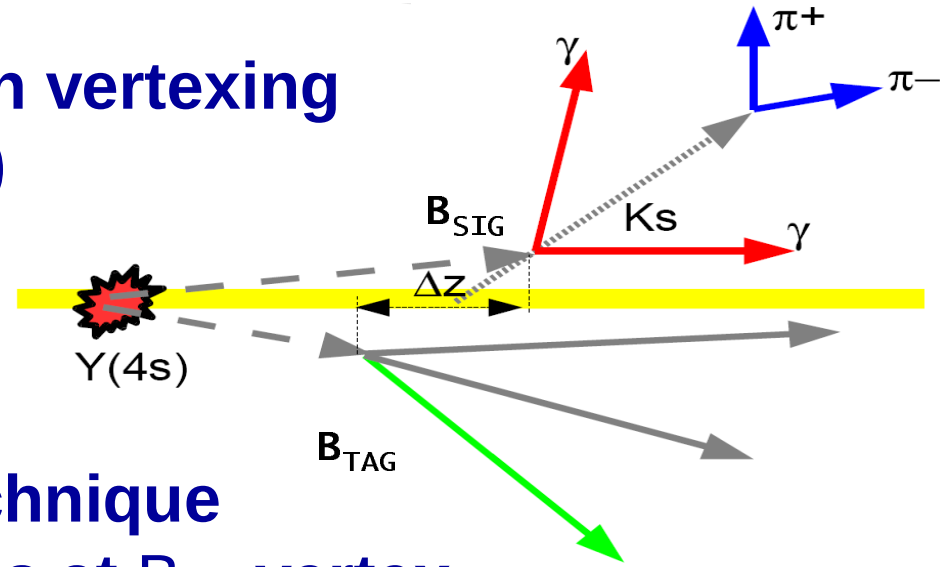
A

- **SM :** *S,C* **predicted to be very small**
  - *S* **sensitive to right/left polarisation rate** $S\sim -2m_s/m_b*\sin(2\beta)\sim -0.04$
- **A large CP asymmetry would be a clear indication of non-SM physics !**
- **Available modes :** $B^0\to K^*(K_s\pi^0)\gamma$ **(*BABAR* and *Belle*) ,** $B^0\to\eta K_s\gamma$ **(*BABAR*, new)**
- **Related mode :** $B^0\to\rho^0\gamma$ **(Belle)**

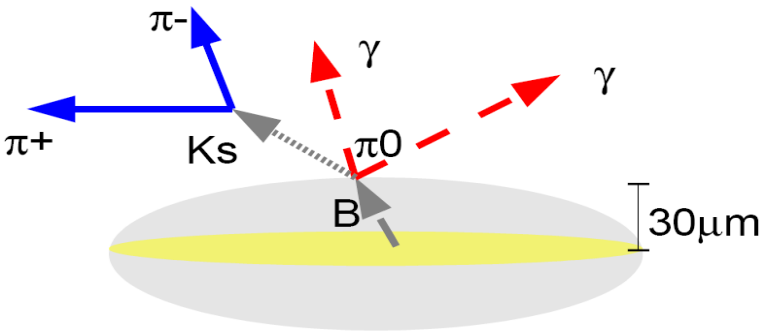
Time-dependent study of $b \to s\gamma$ decays : Vertexing

Δt measurement via Δz relies on vertexing of both B mesons (B_{sig} and B_{tag})

Example here : $B^0 \to K_S \pi^0$



Beam-spot constraining technique if no charged track originates at B_{sig} vertex



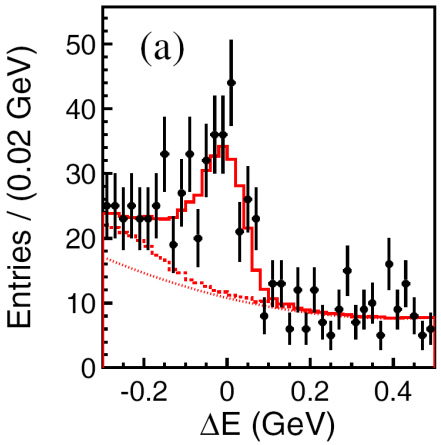
- **Extrapolate K_s flight to the beam spot**
- **Fit $\Upsilon(4S) \to B\bar{B}$ with kinematical constraint**
- **Validate using $B^0 \to J/\psi K_s$ control sample**

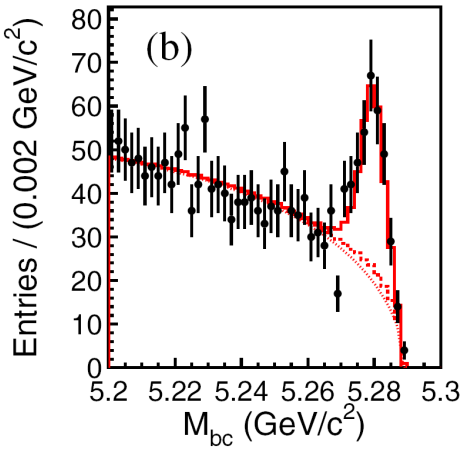
Well-established technique
Used in many neutral modes with one, two, three K_s

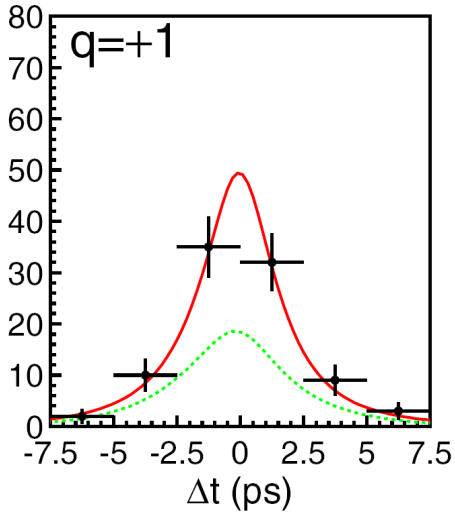
Belle : Time-dependent study of $B^0 \to K_S \pi^0 \gamma$

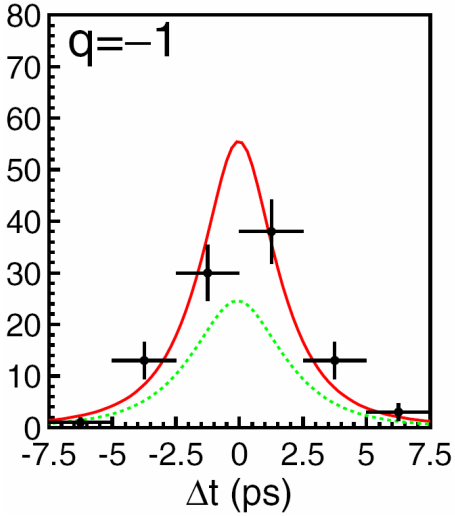
Variation of CP asymmetries along $m(K_S\pi^0)$ expected small

Check inside/outside the $K^*(892)$ range









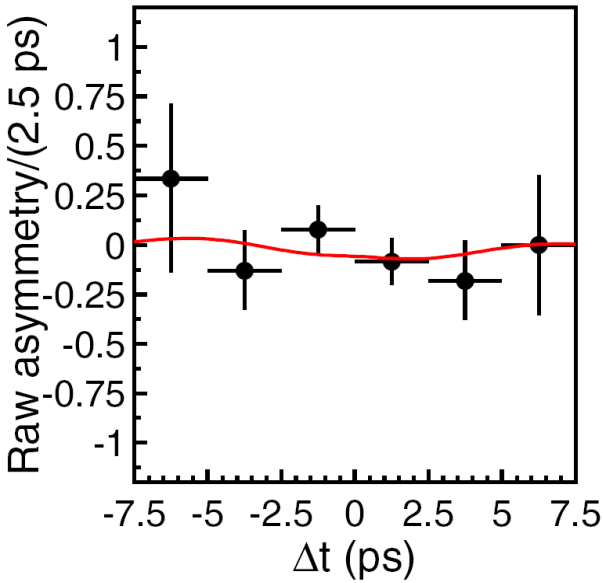
Belle, Phys. Rev. D74, 111104 (2006)
N(BB) = 535M

$$S = -0.10 \pm 0.31 \pm 0.07$$
$$A = -0.20 \pm 0.20 \pm 0.06$$

''Inclusive'' analysis,
$m(K_S\pi^0) < 1.8$ GeV/c^2

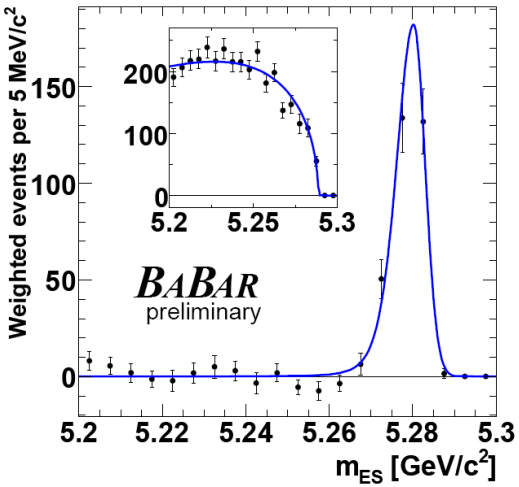
$$S = -0.32^{+0.36}_{-0.33} \pm 0.05$$
$$A = -0.20 \pm 0.24 \pm 0.05$$

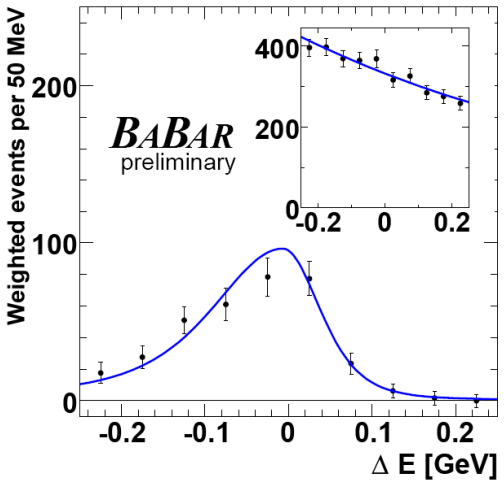
''K*(892)-only'' analysis,
$0.8 < m(K_S\pi^0) < 1.0$ GeV/c^2



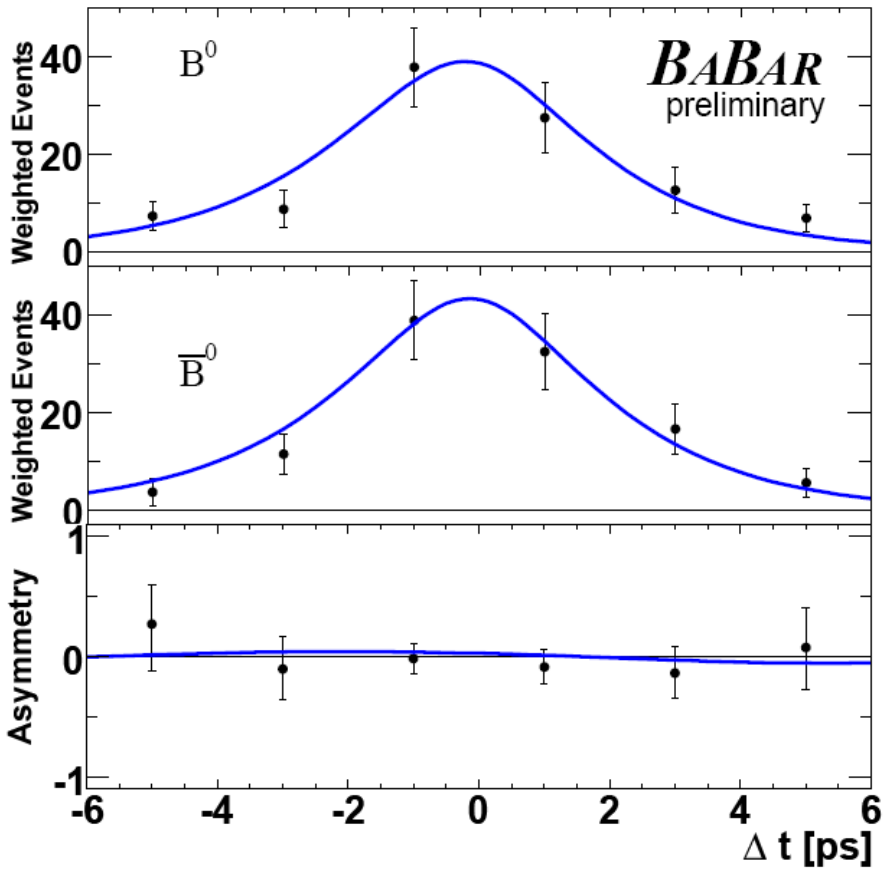
BABAR : Time-dependent study of $B^0 \to K_s\pi^0\gamma$

Variation of CP asymmetries along $m(K_s\pi^0)$ expected small
Check inside/outside the $K^*(892)$ range





M. Pivk, F. Le Diberder, "sPlots"
Nucl. Instrum. Meth. A555, 356 (2005)



$$S = -0.08 \pm 0.31 \pm 0.05$$

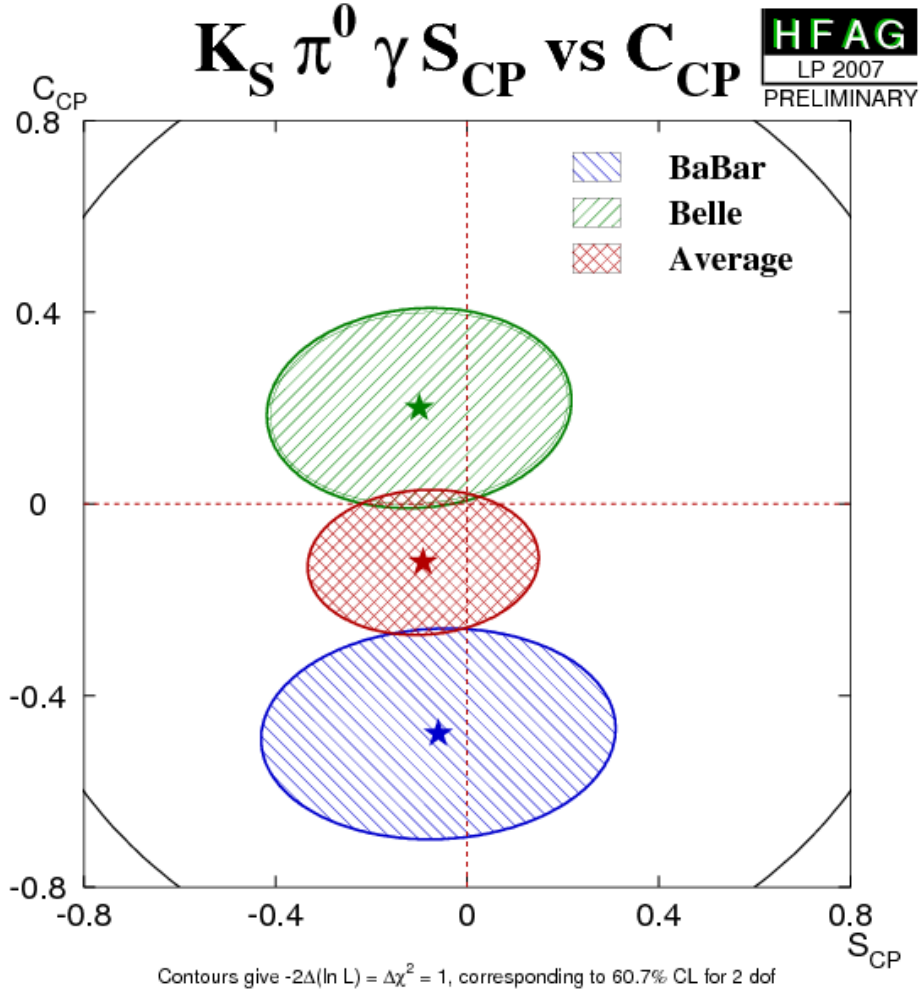
$$C = -0.15 \pm 0.17 \pm 0.03$$

PRELIMINARY

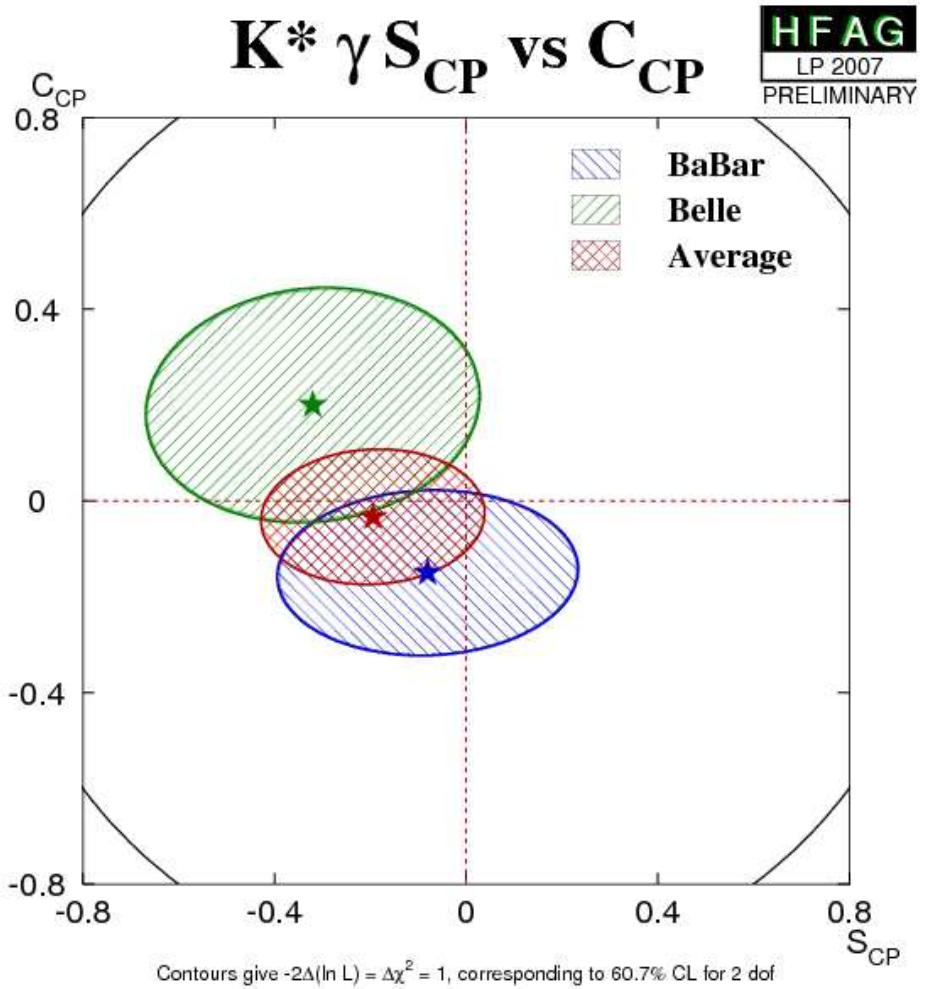
"K*(892)-only" analysis,
$0.8 < m(K_s\pi^0) < 1.0$ GeV/c²

BABAR, arXiv:0708.1614
N(BB) = 431M

Time-dependent study of $B^0 \to K_s \pi^0 \gamma$



''Inclusive'' analyses, $m(K_s\pi^0) < 1.8$ GeV/c^2



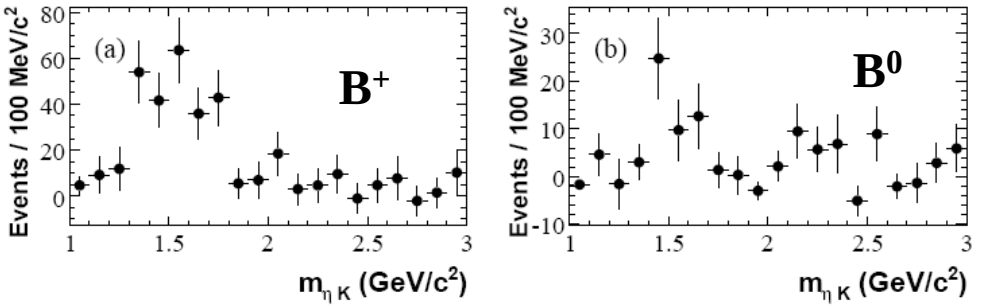
''K*(892)-only'' analysis, $0.8 < m(K_s\pi^0) < 1.0$ GeV/c^2

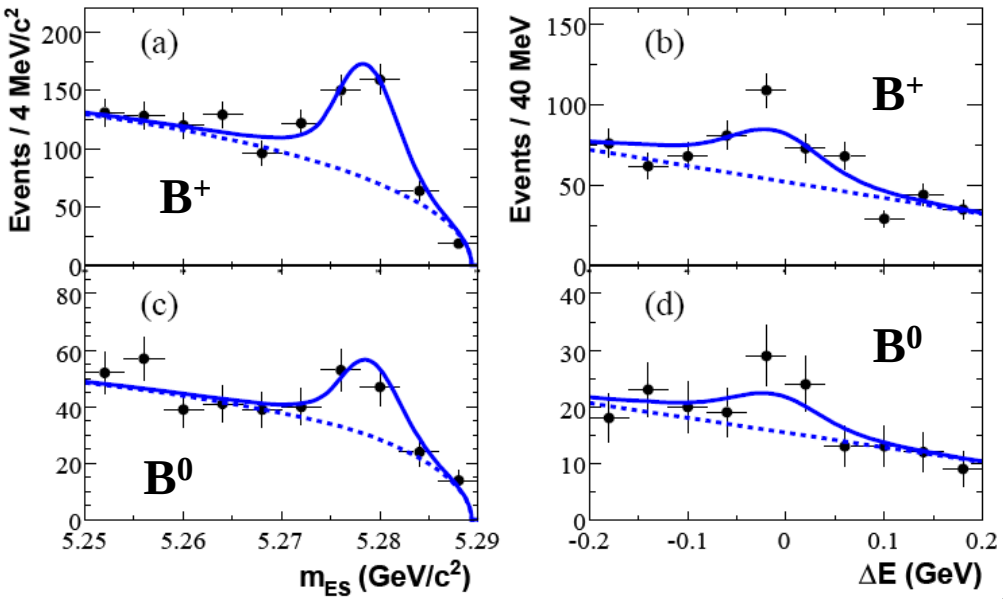
HFAG averages taking *(S,C)* correlations into account
Measurements compatible with CP conservation hypothesis

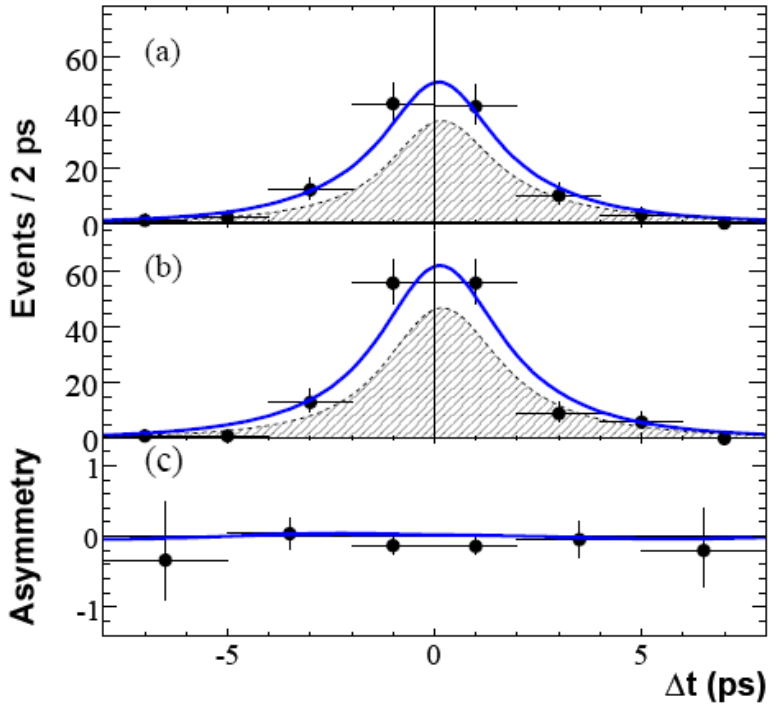
BABAR : Time-dependent study of $B^0 \to \eta K_S \gamma$ (new)

- **Combines $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi\pi^0$**
- **Beam-spot technique for $\eta \to \gamma\gamma$ events**
- **Signal significance : 3.9σ**
- **Uses the complete, final $\Upsilon(4S)$ sample**

- **Simultaneous control analysis : $B^+ \to \eta K^+ \gamma$**







$$BR = (7.1^{+2.1}_{-2.0} \pm 0.4) \times 10^{-6} \, (3.9\sigma)$$

$$S = -0.18^{+0.49}_{-0.46} \pm 0.12$$

$$C = -0.32^{+0.40}_{-0.39} \pm 0.07$$

PRELIMINARY

BABAR, arXiv:0804.XXXX

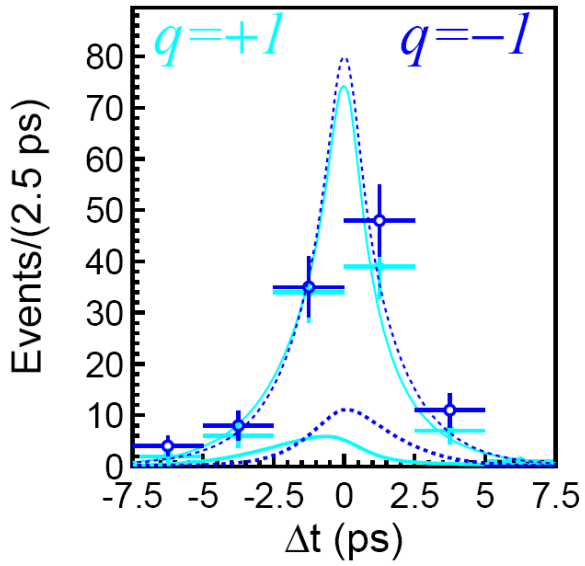
N(BB) = 465M

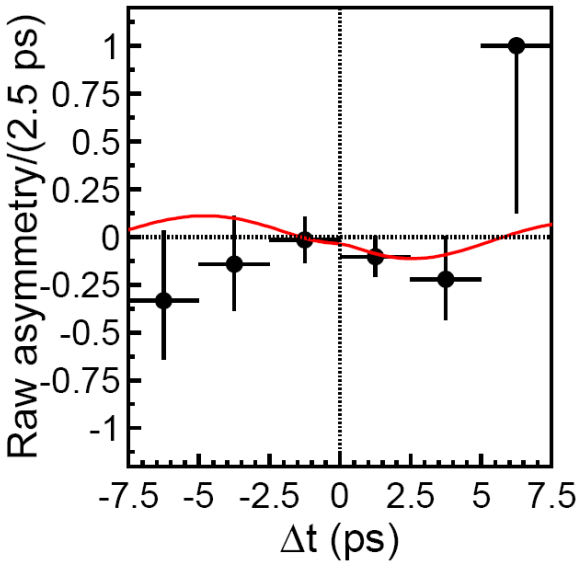
Belle : Time-dependent study of $B^0 \to \rho^0\gamma$

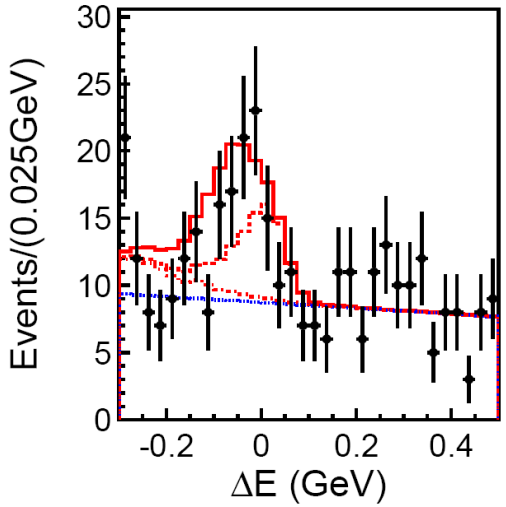
- **Photon polarisation suppresses $B^0 \leftrightarrow \bar{B}^0$ interference : expect *S* small**
- ***S* further suppressed by *CKM* cancellation (V_{td}) of mixing phase**
- **Experimental issue : $K^*\gamma$ background**

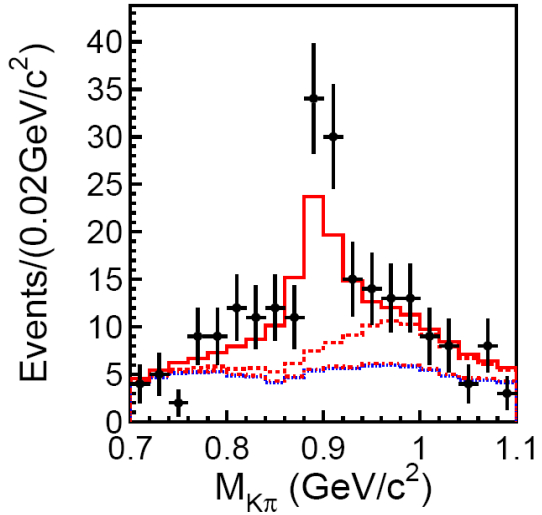
$$S = -0.83 \pm 0.65 \pm 0.18$$
$$A = -0.44 \pm 0.49 \pm 0.14$$

Belle, Phys. Rev. Lett. 100, 021602 (2008)
N(BB) = 535M





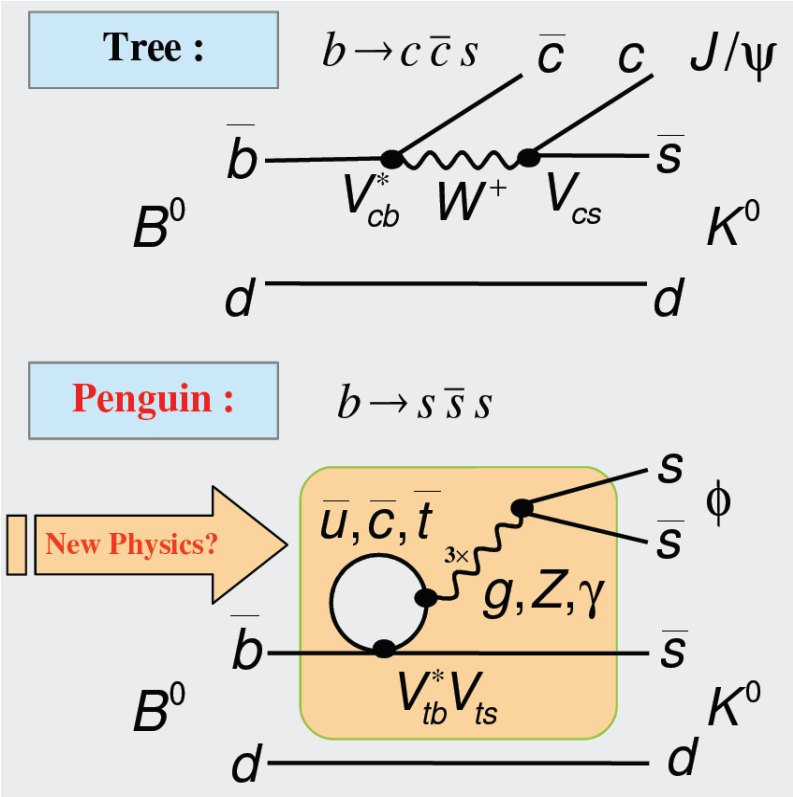




Summary : Time-dependent CP asymmetries in $b\to(s,d)\gamma$

- **Time-dependent analyses of three $b\to(s,d)\gamma$ modes have been performed by *BABAR* and/or *Belle***
  - $B^0 \to K^*(K^0_S\pi^0)\gamma$, $B^0 \to \rho^0\gamma$, $B^0 \to \eta K^0_S\gamma$
- **Measurements compatible with CP conservation**
  - **All measurements limited by statistics**
- **Other modes could be added**
- **Excellent physics case for *SuperB* and/or *Belle upgrade***
- ***Belle* has also studied $B_s\to\phi\gamma$ (BR only)**

b→sqq̄ penguins : loop-dominance



- b→scc̄ :
  - **"golden" modes for** sin2β
  - **tree-dominated decays**
  - **penguins carry same weak phase**
- b→sqq̄ :
  - **pure "internal" or "flavour-singlet" penguins**
  - **dominant phase, same CKM factors as** b→scc̄
  - **usually more than one phase involved**
  - **high mass scales involved in loops**
  - **non-SM contributions could contribute**

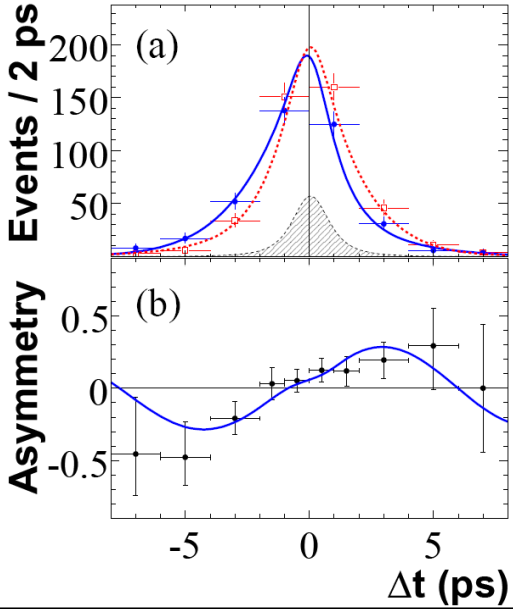
Standard Model	New Physics
$S_{c\bar{c}s} = S_{s\bar{s}s} + \Delta S_{SM} = \sin 2\beta$	$S_{c\bar{c}s} \neq \Delta S_{SM} + S_{s\bar{s}s}$
$C_{c\bar{c}s} \sim C_{s\bar{s}s} \sim 0$	$C_{c\bar{c}s} \neq C_{s\bar{s}s}$

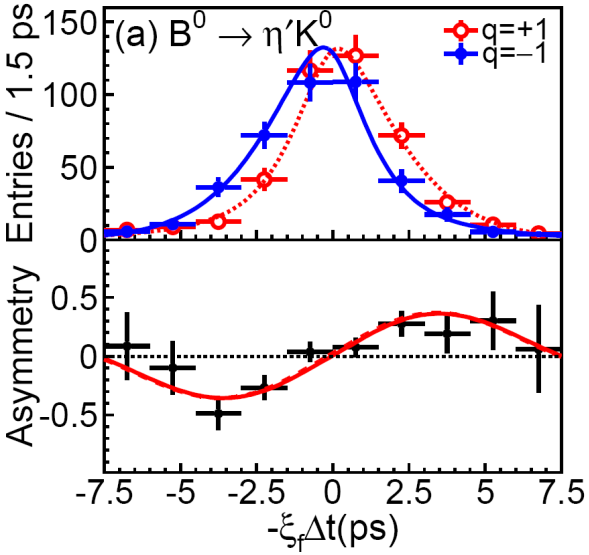
Theory issue : evaluate ΔS_{SM} for each mode
identify clean modes (with small ΔS_{SM})

Selected sample of $b\to sq\bar{q}$ *penguins :* $B^0\to\eta' K^0$

- **Experimentally clean :** **largest BR among the $b\to s$ penguin modes**
  kinematical identification of η'
  $\eta' K_L$ adds 50% more events
- **Theoretically clean : non-penguin contributions expected to be small**

- **First $b\to sq\bar{q}$ mode to establish CP violation; result agrees with $b\to sc\bar{c}$**





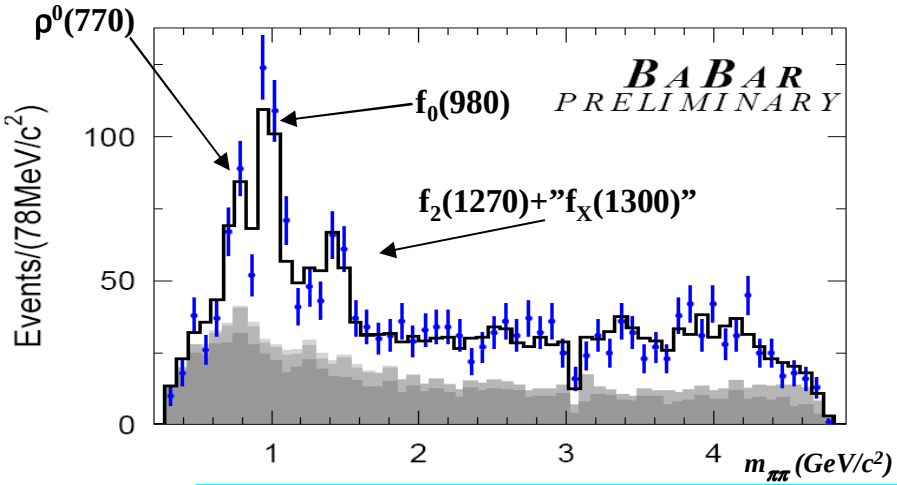
$$S = +0.58 \pm 0.10 \pm 0.03$$
$$C = -0.16 \pm 0.07 \pm 0.03$$
BABAR, Phys. Lett. 98, 031801 (2007)
N(BB) = 384 M

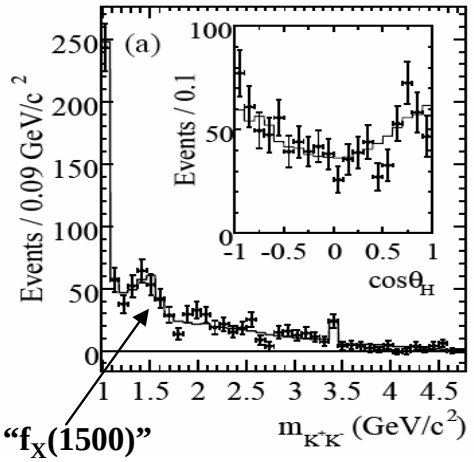
$$S = +0.64 \pm 0.10 \pm 0.04$$
$$C = +0.01 \pm 0.07 \pm 0.05$$
Belle, Phys. Lett. 98, 031802 (2007)
N(BB) = 535 M

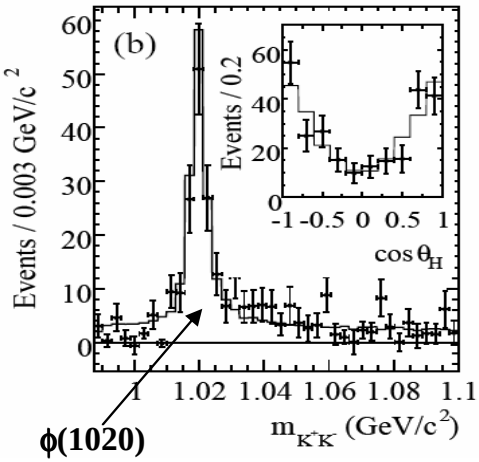
b→sq$\bar{q}$ *penguins : the time-dependent Dalitz analyses*

- **Time-dependent amplitude analyses of** $B^0 \to K^0_S \pi^+ \pi^-$ **and** $B^0 \to K^0_S K^+ K^-$
  - **Technically challenging :**
    - **3-D signal decay amplitude (DP + time)**
    - **several intermediate modes contribute**
  - **Weak phase** β_{eff} **directly extracted from isobar phases**
    - **counting-rate analyses access only to** $S=\sin 2\beta_{eff}$
    - **trigonometry ambiguities resolved by interference**
    - **intermediate modes related to** β_{eff} **include**
      - ϕK_S and $f_0 K_S$ **in** $B^0 \to K^0_S K^+ K^-$
      - $f_0 K_S$ and $\rho^0 K_S$ **in** $B^0 \to K^0_S \pi^+ \pi^-$
  - **Analyses yield several other interesting results**
    - **structrure of** $K\pi$ **S-wave , exotic** $\pi\pi$ **signal ("**f_X**" modes)**
    - **constraint on** (ρ,η) **via phases in** $B \to K^*(892)\pi$ **modes**
      - CPS, Phys. Lett. **B645**, 201 (2007)
      - GPSZ, Phys. Rev. **D75**, 014002 (2007)

b→sqq̄ *penguins : the time-dependent Dalitz analyses*

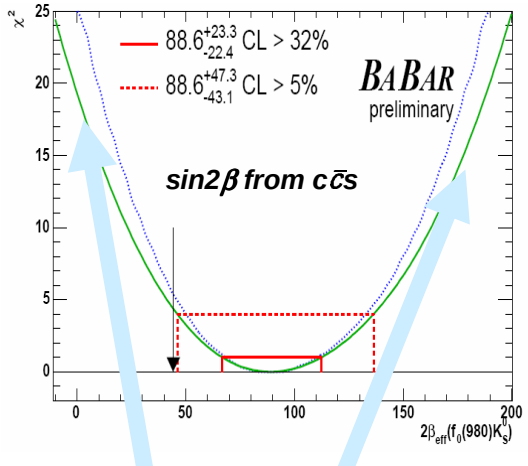


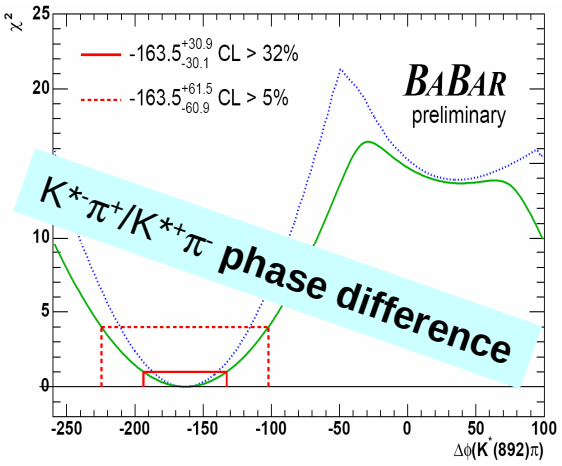


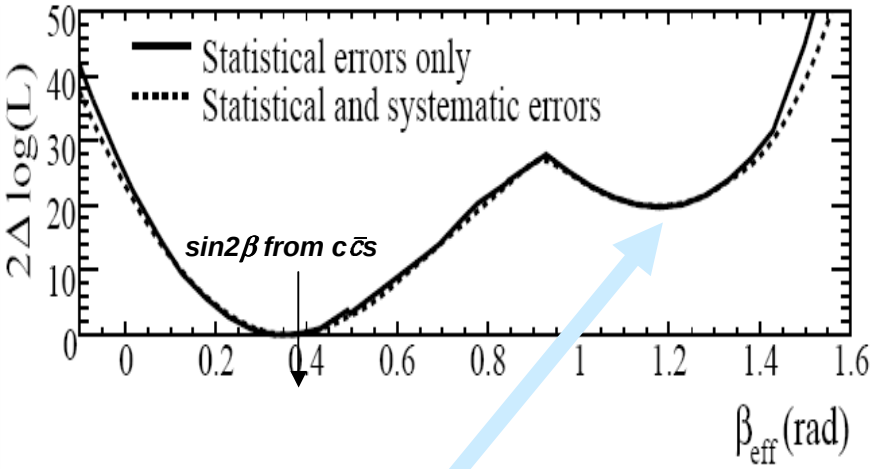


$B^0 \to K^0_S K^+ K^-$: BABAR, Phys. Rev. Lett. 99, 161802 (2007) N(BB) = 383 M

$B^0 \to K^0_S \pi^+ \pi^-$: BABAR, arXiv:0708.2097 N(BB) = 383 M



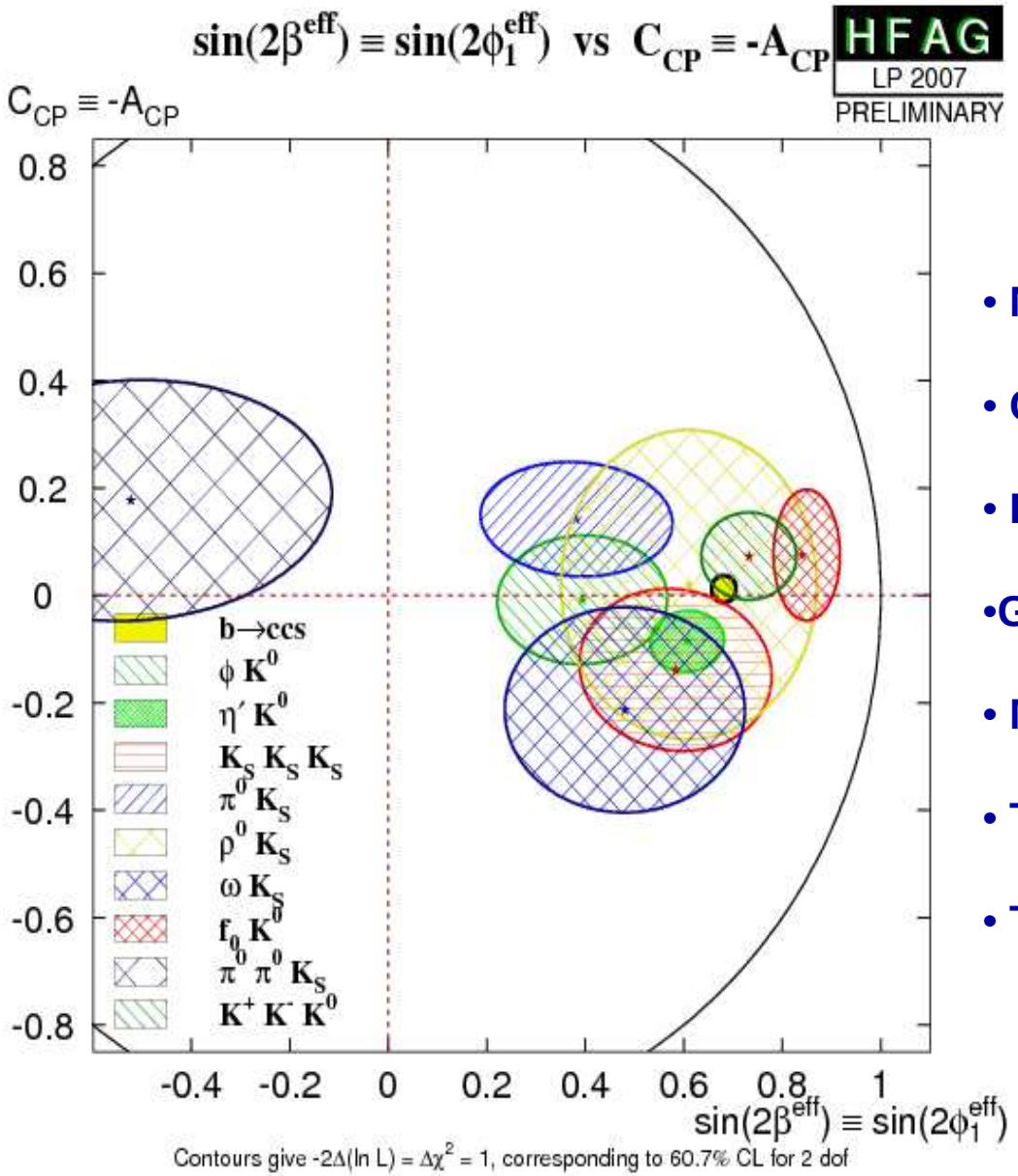




Non-gaussian result for f_0K_s
$2\beta_{eff} = 0$ (=180) ***excluded at*** 4.3σ ***(***3.9σ***)***

CP conservation excluded at 4.8σ **,**
mirror solution *excluded at* 4.5σ

b→sqq̄ *penguins : summary*



- **Nine modes in the b→sqq̄ family studied**
- **CP violation established in $B^0 \to \eta' K_S$**
- **Direct CP asymetries Compatible with zero**
- **Global agreement with golden b→scc̄**
- **Most values of *S* below b→scc̄ value**
- **Theoretical calculations predict *opposite* trend …**
- **To be followed …**

Time-dependent CP Violation in rare B decays : Conclusions

- **Radiative $b\to s(d)\gamma$ decays**
  - **Excellent probes for SM tests**
    - **CP asymmetries predicted small in the SM**
  - **B-factories are producing the first TD-analyses**
  - **Only accessible in a B-factory environment !**
- **Penguin-dominated charmless $b\to q\bar{q}s$ modes**
  - **Intense activity ongoing**
  - **CP violation established in $B^0\to\eta' K_S$**
  - **Dalitz analyses are challenging and promising**
  - **Interesting evolution of trends**
    - **Theory/experiment interplay required**
- **All these modes dominated by statistical uncertainties**

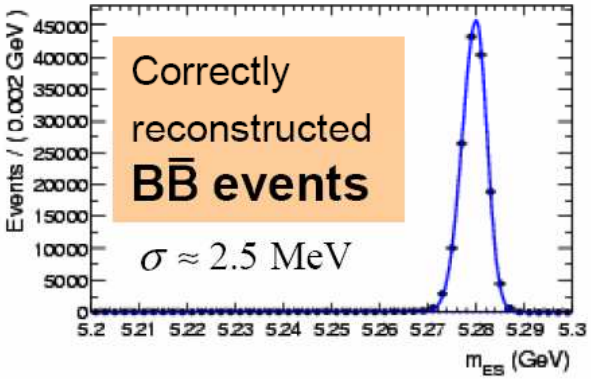
Spare Slides

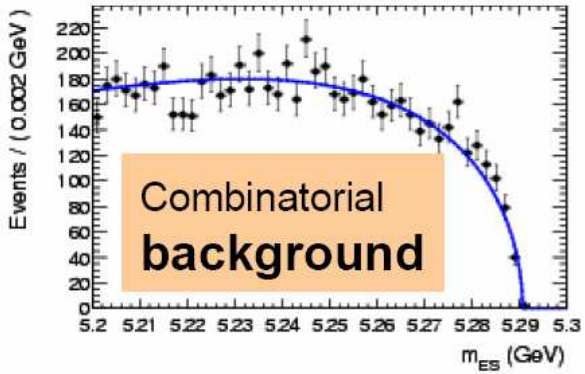
B Meson Reconstruction

Exploit kinematics of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for signal selection

Beam-energy substituted mass

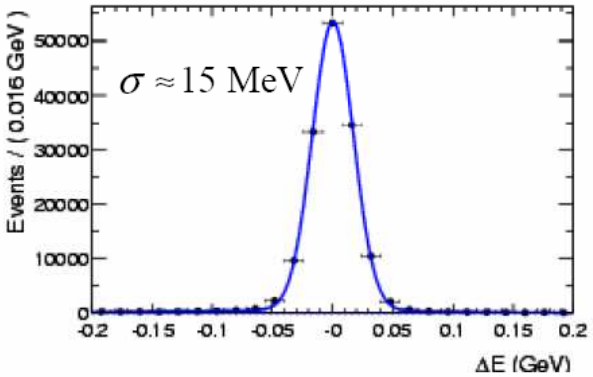
$$m_{ES} = \sqrt{E^{*}_{beam}{}^{2} - p^{*2}_{B}}$$

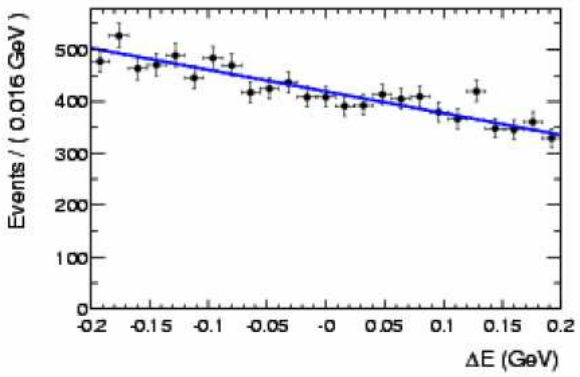




Energy difference

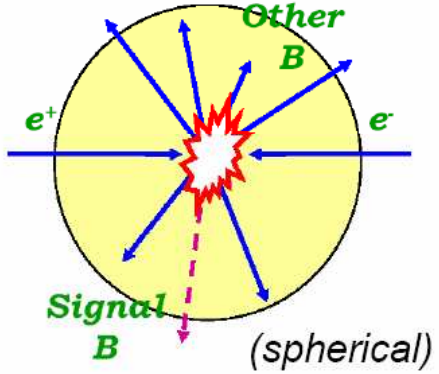
$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

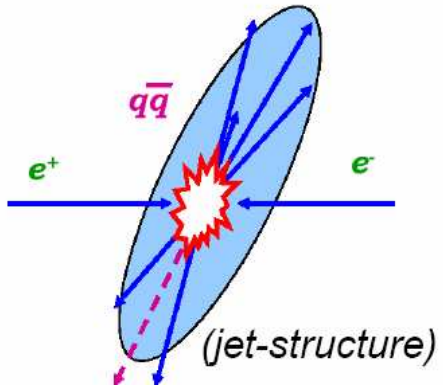




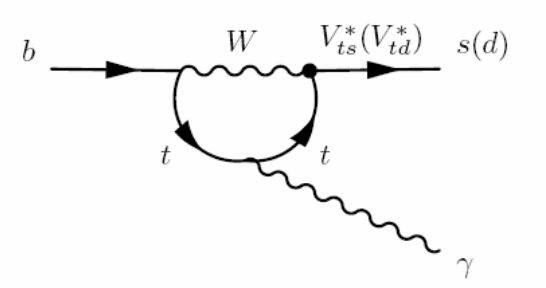
Event topology

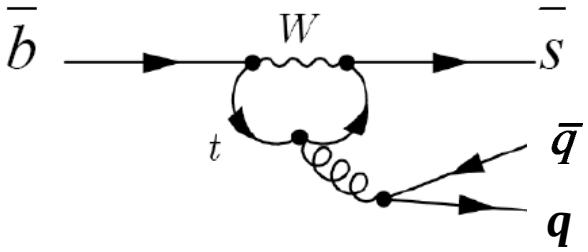
(multivariate methods)

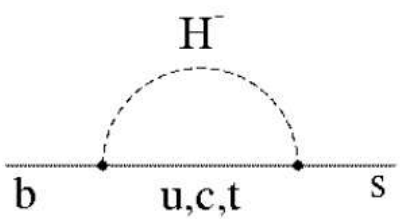


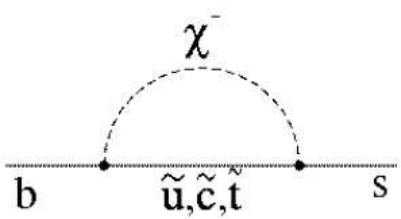


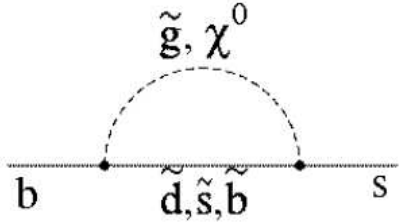
A few diagrams

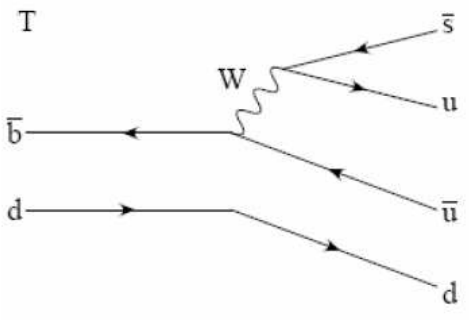


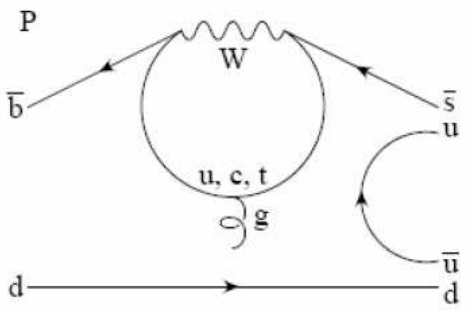












PDFs for time- and DP- dependence

Time Dalitz Plot and tagging Pdf

$$f(\Delta t, DP, q_{tag}) \propto (|A|^2 + |\overline{A}|^2)\frac{e^{-|\Delta t|/\tau}}{4\tau}\left(1 + q_{tag}\frac{2\,\mathrm{Im}[\overline{A}A^*]}{|A|^2+|\overline{A}|^2}\sin(\Delta m_d \Delta t) - q_{tag}\frac{|A|^2-|\overline{A}|^2}{|A|^2+|\overline{A}|^2}\cos(\Delta m_d \Delta t)\right)$$

Dalitz Plot Isobar Model

$$A(DP) = \sum a_j F_j(DP)$$
$$\overline{A}(DP) = \sum \overline{a}_j \overline{F}_j(DP)$$

shapes of intermediate states over DP

CP violation varies over the DP

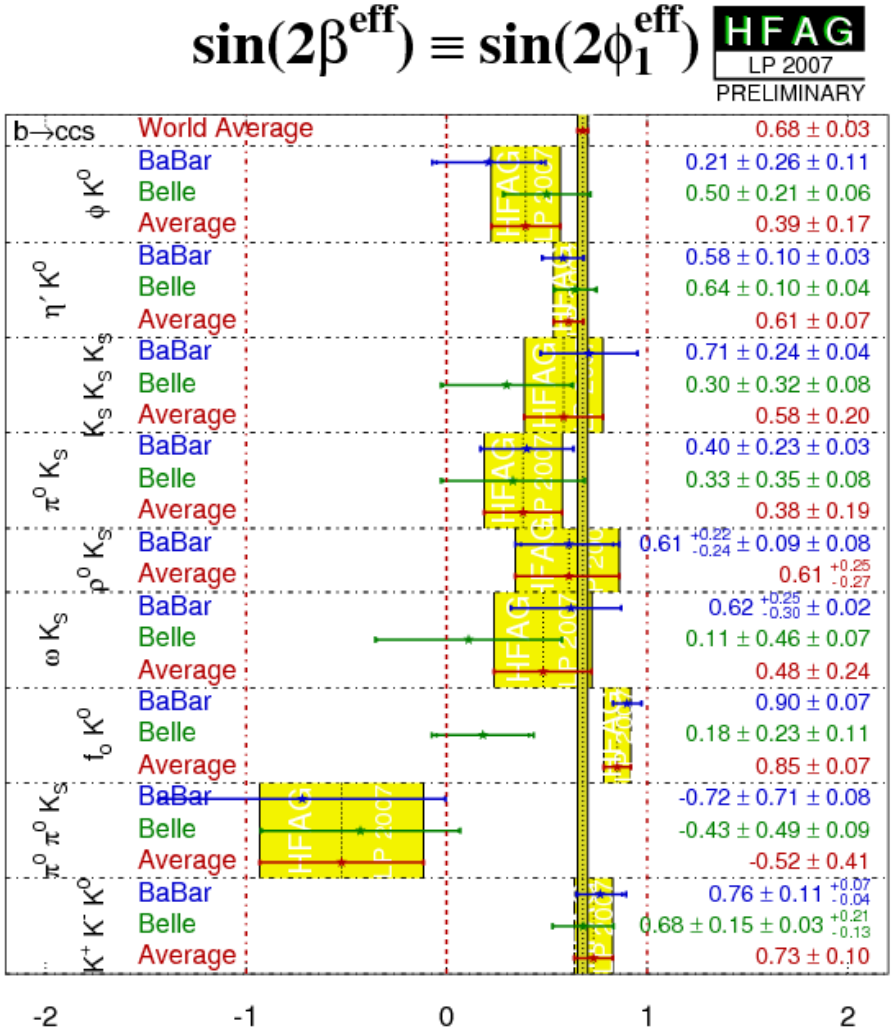
Amplitudes a_j and $\overline{a}_j$ determine DP interference pattern.

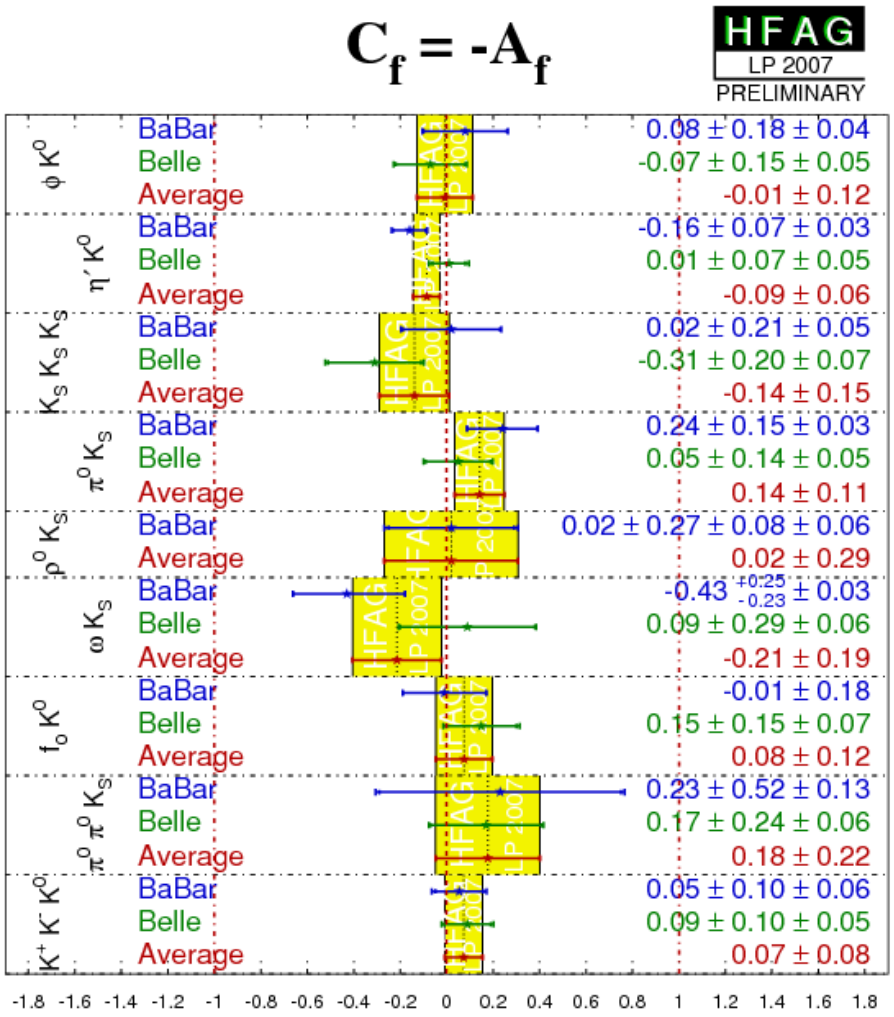
Time-Dependent CP Parameters:

$$C_j = \frac{|a_j|^2 - |\overline{a}_j|^2}{|a_j|^2 + |\overline{a}_j|^2} \qquad S_j = \frac{2\,\mathrm{Im}[\overline{a}_j a_j^*]}{|a_j|^2 + |\overline{a}_j|^2}$$

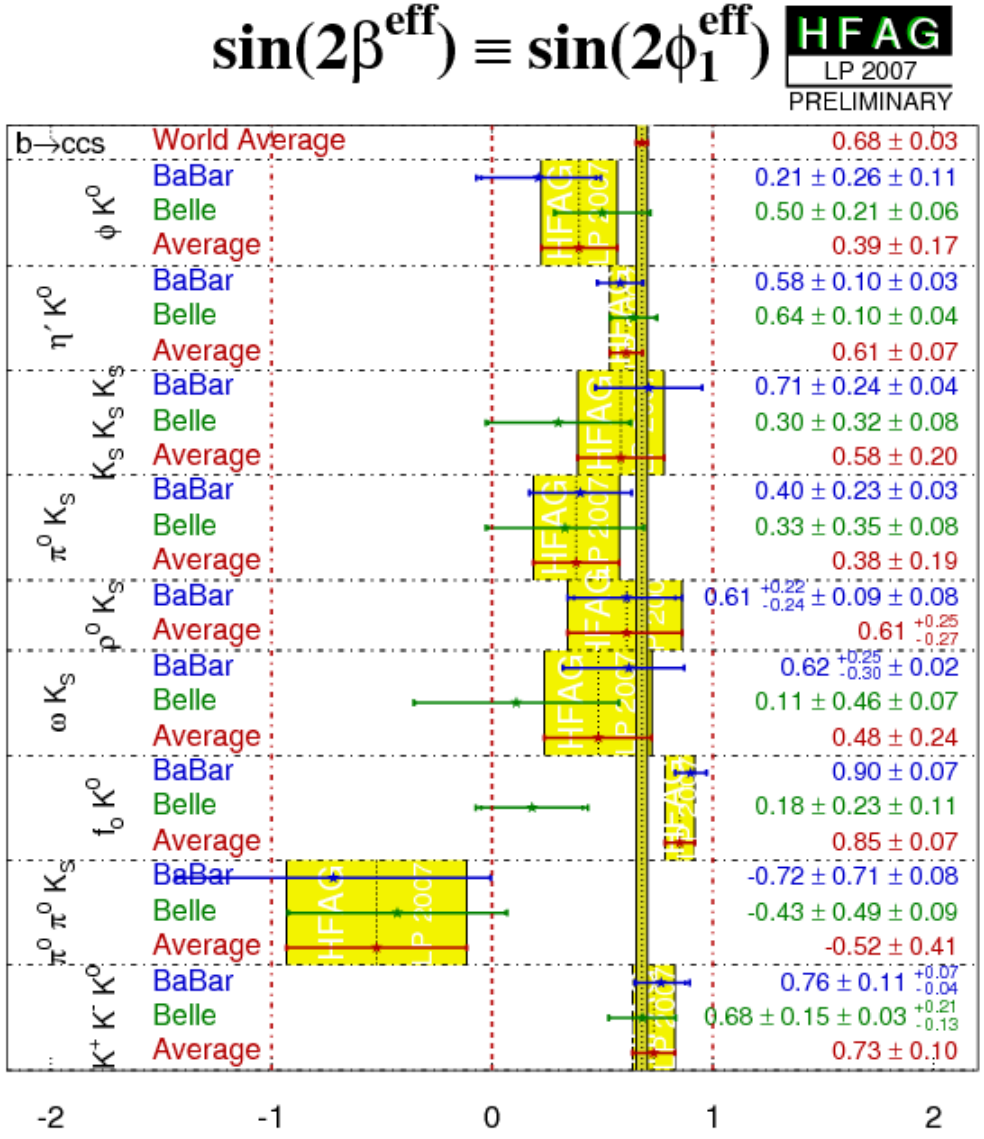
interference helps disentangling strong and weak phases, and thus raises the degeneracy in the time-dependent CP parameter S

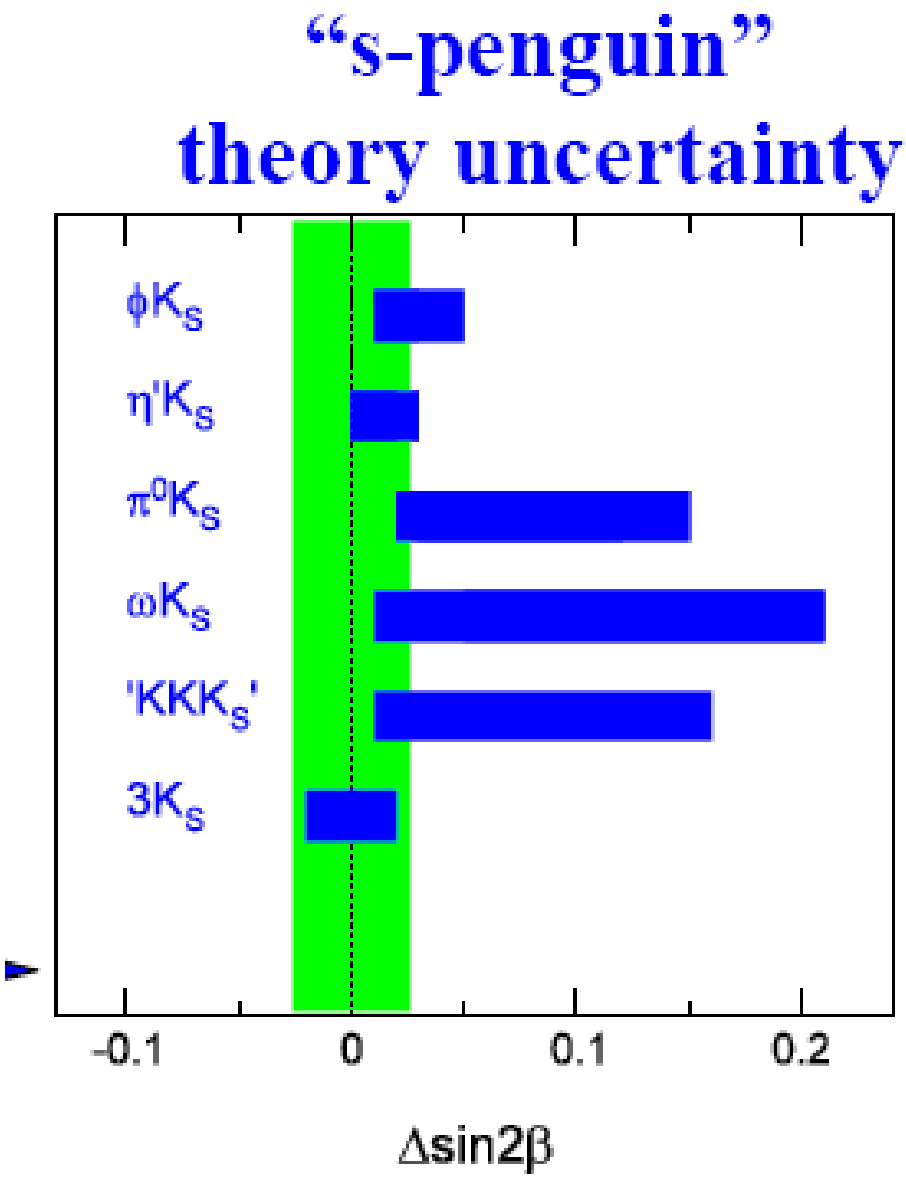
b→sqq̄ *penguins : summary*



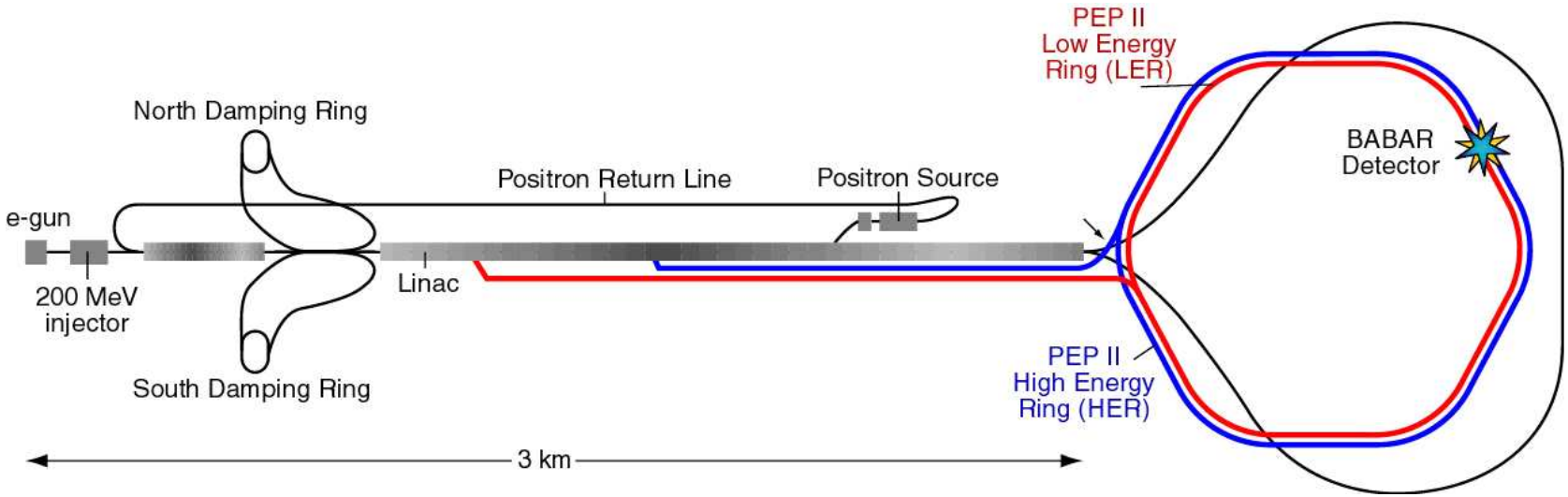


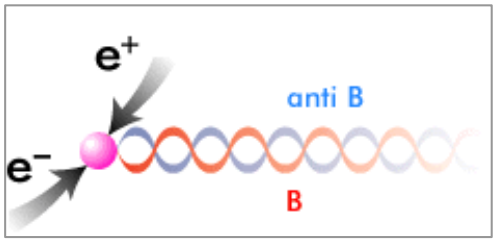
b→sqq̄ *penguins : summary*





Asymmetric B-Factories (e.g. PEP-II)





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

- coherent production of neutral *B* pairs
  → exploited for flavour tagging
- boost of $\Upsilon(4S)$ in the laboratory :
  → required for time-dependent *CP* measurements

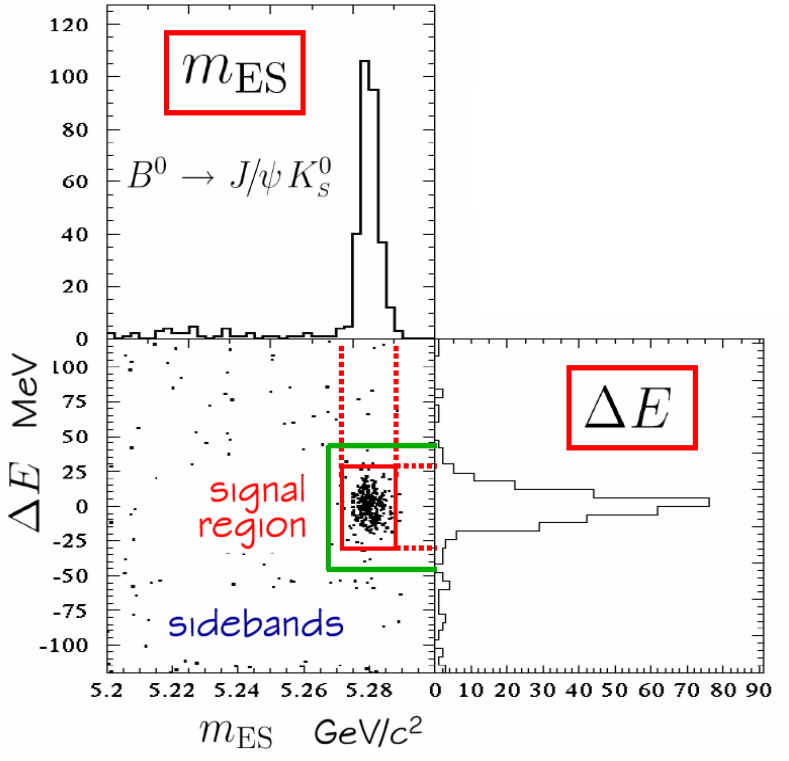
C.M. boost $\beta\gamma$:
~ 0.55 at PEP-II
~ 0.42 at KEK-B

Experimental technique: analysis

Use kinematical constraints at the Y(4S):

$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

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



Flavour tagging algorithm

- exploits charge correlations in B decay products

$$Q = \sum_i \varepsilon_i (1 - 2\omega_i)^2 \sim 0.3$$

$$\sigma_{stat} \sim 1/\sqrt{Q}$$

ε →Tagging efficiencies

ω→Mistag rate

Extract decay time difference Δt from vertexing

$$\gamma\beta\Delta t \sim \Delta z$$

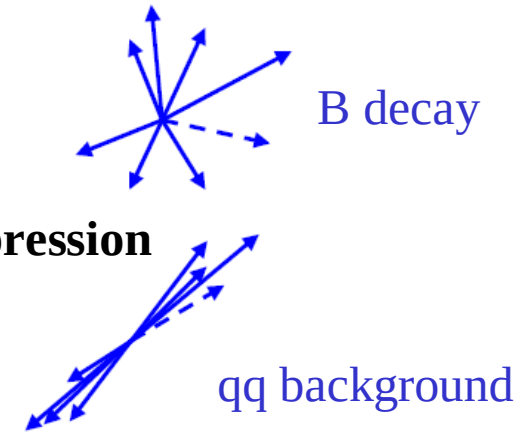
Perform unbinned maximum likelihood fits

- On signal-enriched samples with cuts on selection variables (Belle)
- On more inclusive samples with multivariate fits (BaBar)

$b \to s$ penguins : experimental challenges

Signal-to-background issues :

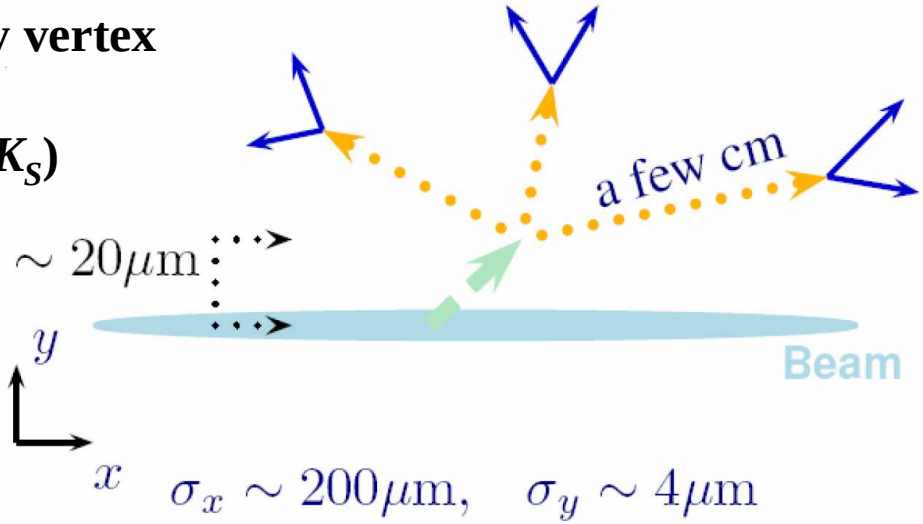
- **(very) small branching ratios, often below 10^{-5}**
- **Large backgrounds from $e^+e^- \to q\bar{q}$**
  - **event-shape discriminating variables for background supression**
- **Backgrounds from other *B* decays may be significant**
  - **Use WA measurements to estimate contamination**
  - **Add B-background information in ML fit**



Vertexing issues :

- **Some modes with no charged tracks from decay vertex**
  - **use beam-spot constraint**
  - **validate with control samples (i.e. $B^0 \to J/\psi K_S$)**

Beam-constraint vertexing in $B^0 \to K_S K_S K_S$:



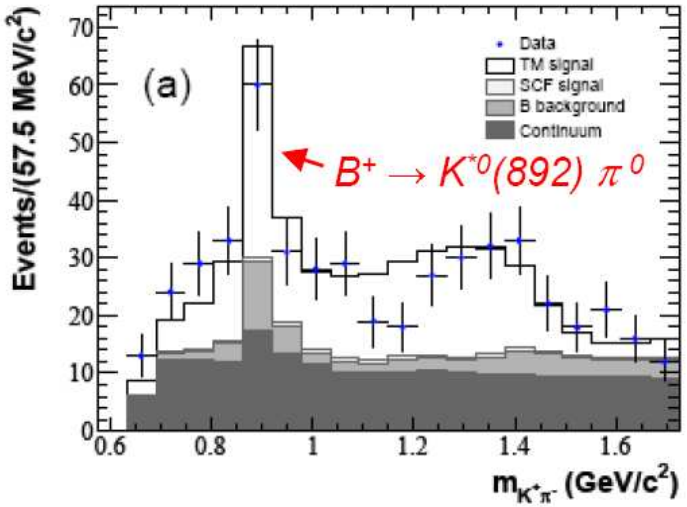
NEW!

Dalitz Analysis of $B^0 \to K^-\pi^+\pi^0$

232M $B\bar{B}$

$$BF(B^0 \to K^+\pi^-\pi^0) = (35.7^{+2.6}_{-1.5} \pm 2.2) \times 10^{-6}$$
$$A_{CP} = -0.03 \pm 0.05 \pm 0.06$$

BaBar, arXiv:0711.4417



- *Now BF($B^0 \to K^{*0}(892)\pi^0$) > 5σ significant*
- *No significant charge asymmetry in any resonant sub-decay*

	Branching Fraction (10^{-6})
$K^{*+}(892)\pi^-$	$12.6^{+2.7}_{-1.6} \pm 0.9$
$K^{*0}(892)\pi^0$	$3.6 \pm 0.7 \pm 0.4$
$(K\pi)^{*+}_0\pi^-$	$25.4^{+3.0+3.9}_{-3.7-3.0} \pm 4.7$
$(K\pi)^{*0}_0\pi^0$	$11.7^{+1.4+2.4}_{-1.3-1.7} \pm 3.2$
$\rho^-(770)K^+$	$8.0^{+0.8}_{-1.3} \pm 0.6$
N.R.	$4.4 \pm 0.9 \pm 0.5$

- *More data is needed to test phase differences for CP asymmetries*
- *CKM constraint from K*π BFs*

Gronau, Pirjol, Soni and Zupan, PRD 77, 057540 (2008)
Ciuchini, Pierini, Silvestrini, PRD 74, 051301 (2006)