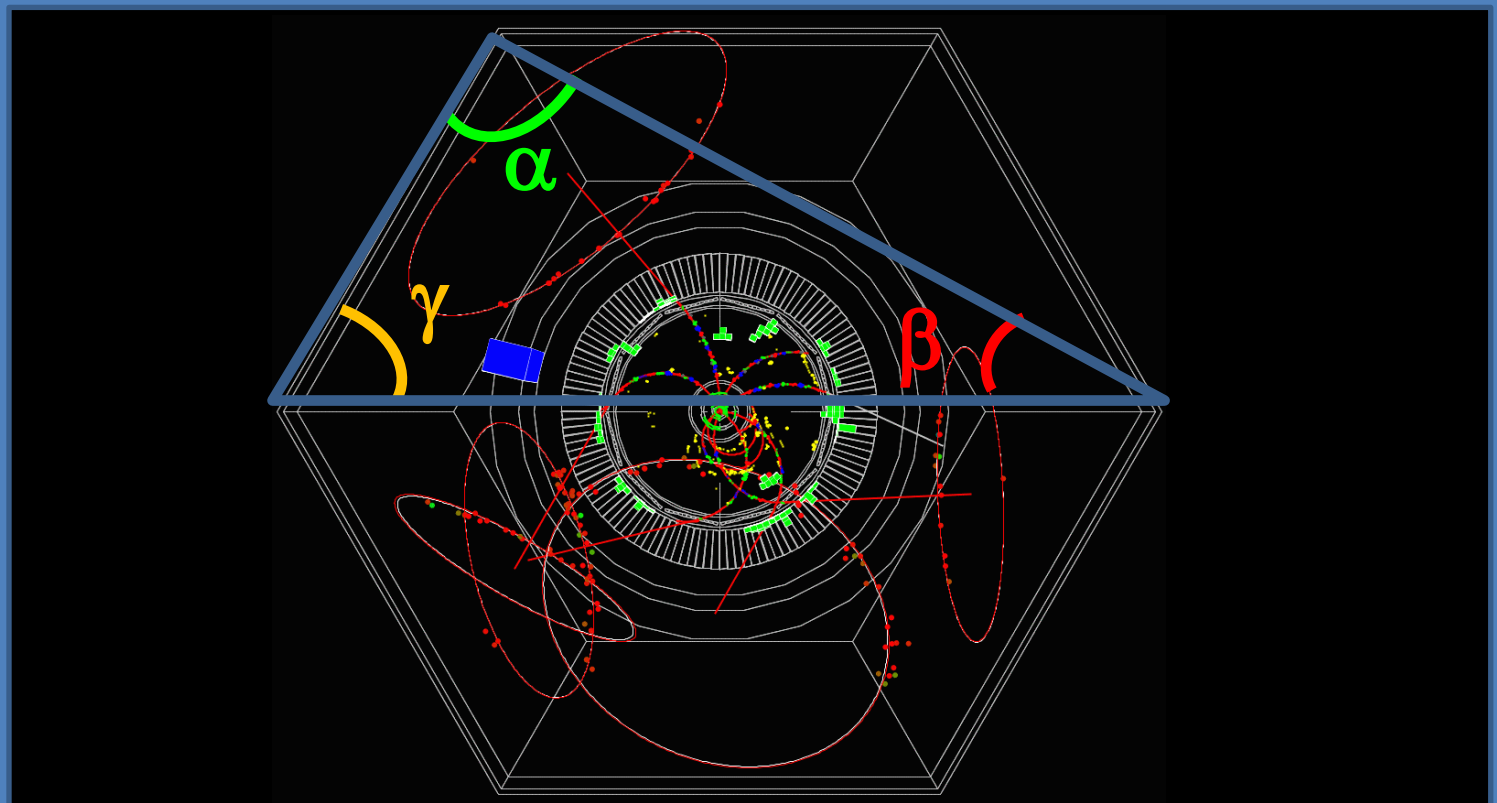
# Recent BABAR results on CP Violation in B decay analyses

**Arantza Oyanguren**
**(IFIC – Valencia)**
On behalf of the BaBar Collaboration

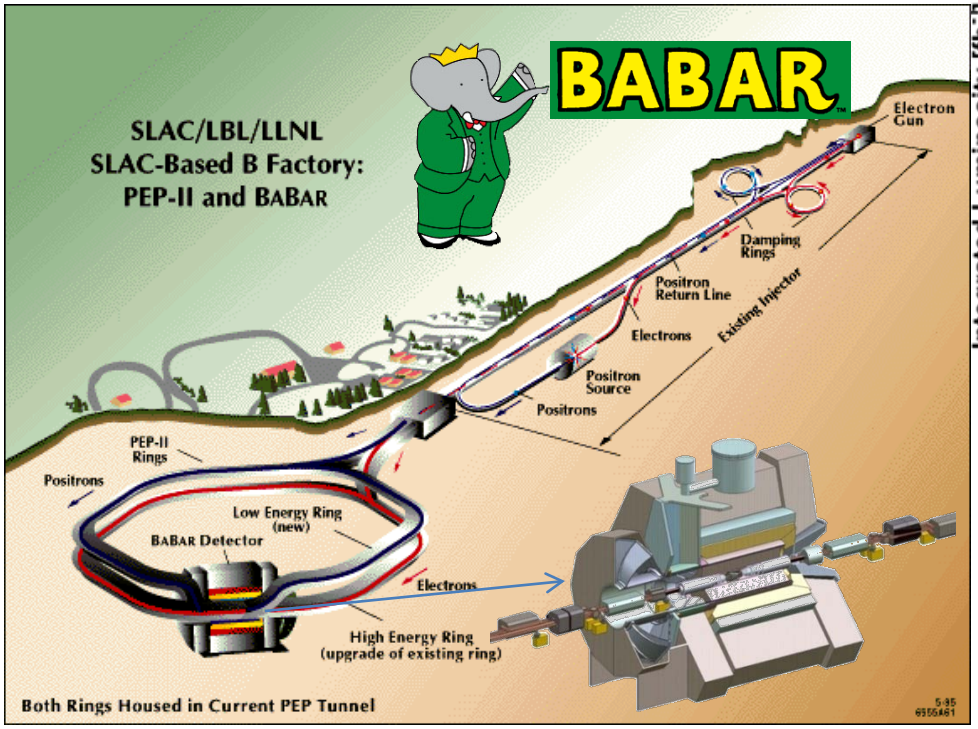
**DISCRETE 2012, Lisboa, Portugal**

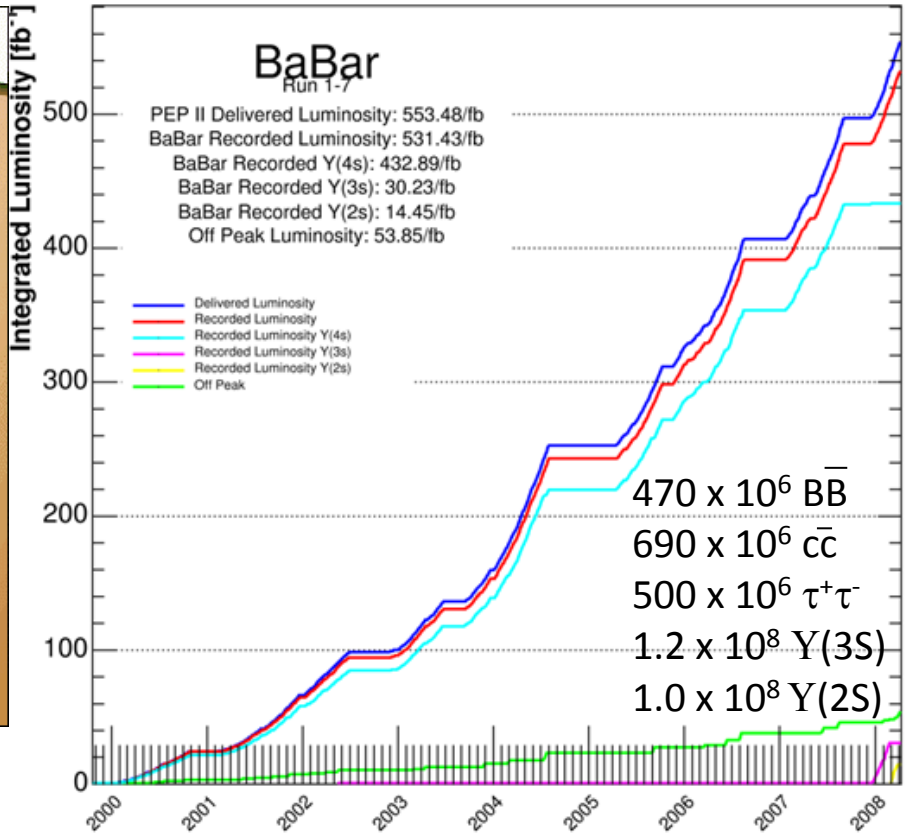


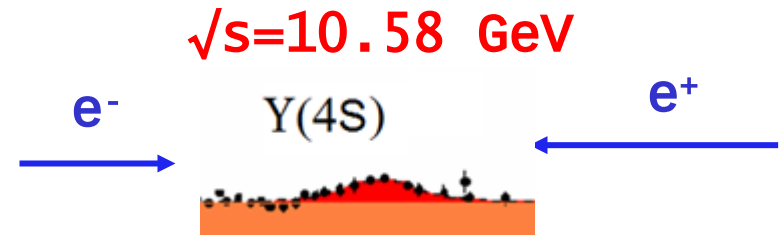
# Outline

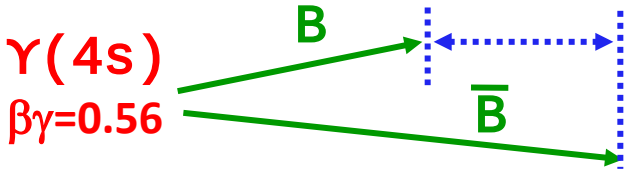
- Introduction
- Measurement of CP Violation in $B^0 \to D^{*+} D^{*-}$
- Measurement of CP Violation in $B^0 \to D^* \ell \nu$
- Recent results on $\alpha$ and $\gamma$ from BaBar
- Summary

# The BaBar experiment




$\Delta z \sim c\,\beta\gamma\,\tau_B \sim 260\mu m$

# CP Violation in B decays

$$\left|B_{L,H}\right\rangle = p\left|B^0\right\rangle \pm q\left|\overline{B}^0\right\rangle$$

$$A_f = \left\langle f\left|H\right|B^0\right\rangle$$

$$\overline{A_f} = \left\langle f\left|H\right|\overline{B}^0\right\rangle$$

- CP violation in decay

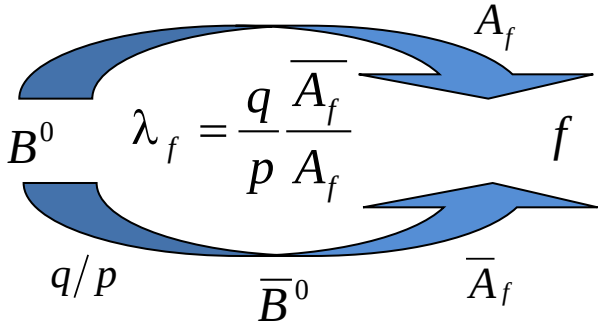
$$\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f}) \qquad \left|\frac{\overline{A_f}}{A_f}\right| \neq 1$$

- CP violation in mixing

$$\mathrm{P}(B^0 \to \overline{B}^0) \neq \mathrm{P}(\overline{B}^0 \to B^0) \qquad \left|\frac{q}{p}\right| \neq 1$$

- CP violation in interference

$$\Gamma(B^0(\to \overline{B}^0) \to f)(t) \neq \Gamma(\overline{B}^0(\to B^0) \to f)(t)$$



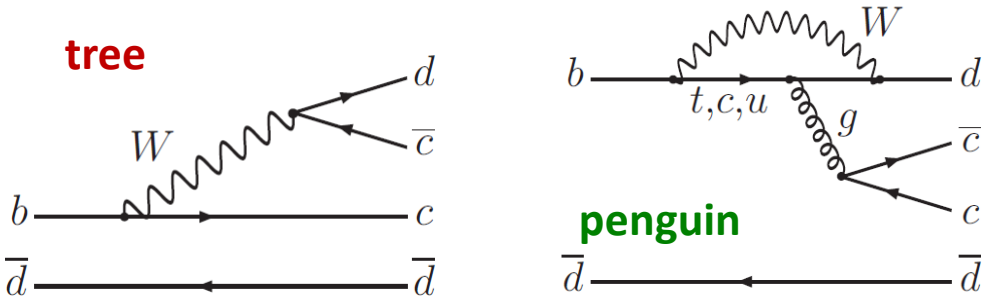

$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f}$$

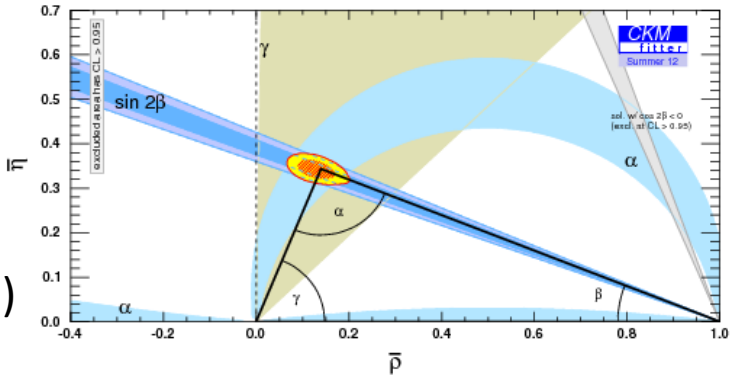
$$\left|\lambda_f\right| = 1$$

$$\mathrm{Im}\{\lambda_f\} \neq 0$$

# CPV in $B^0 \to D^{*+}D^{*-}$

- In Cabibbo suppressed $b \to (c\bar{c})d$ transitions (like $D^{*+}D^{*-}$), the color allowed tree amplitude gets a small contribution from penguin diagrams




→ **the Time Dependent (TD) CPV asymmetry is a measure of $S_{\eta=\pm1} \cong \eta \sin(2\beta)$** (the same as $\bar{b} \to (cc)s$ ($J/\psi K$))

- Penguin contributions lead to ~ few % corrections (models based on factorization and heavy quark symmetry) **[ Z. Xing, PL B443, 365 ('98), PRD61, 014010 ('99)]**

- Large deviation in $S_\eta$ from $b \to (c\bar{c})d$ and $b \to (c\bar{c})ds$ transitions ($D^{*+}D^{*-}$ and $J/\psi K$)

→ **New Physics**

**[ M. Gronau, J.L. Rosner and D. Pirjol, PRD78, 033011 ('08)]**
**[Y. Grossman and M.P. Worah, PLB395, 241 ('97)]**
**[R. Zwicky, PRD77, 036004 ('08)]**

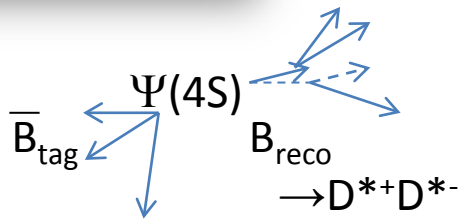
# CPV in $B^0 \to D^{*+}D^{*-}$

- The time-dependent decay rate for $B^0 \to D^{*+}D^{*-}$ produced at the $\Upsilon(4S)$ is given by

$$P_\eta^{S_{\rm tag}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_b}}{4\tau_b} \cdot [1 + S_{\rm tag}\, S_\eta \sin(\Delta m_d \Delta t) + S_{\rm tag}\, C \cos(\Delta m_d \Delta t)]$$

$$S_{\rm tag} = \begin{array}{l} +1\ (B^0_{\rm tag}) \\ -1\ (\overline{B}^0_{\rm tag}) \end{array} \qquad S_\eta = -\eta \frac{2\Im m(\lambda)}{1+|\lambda|^2} \qquad C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

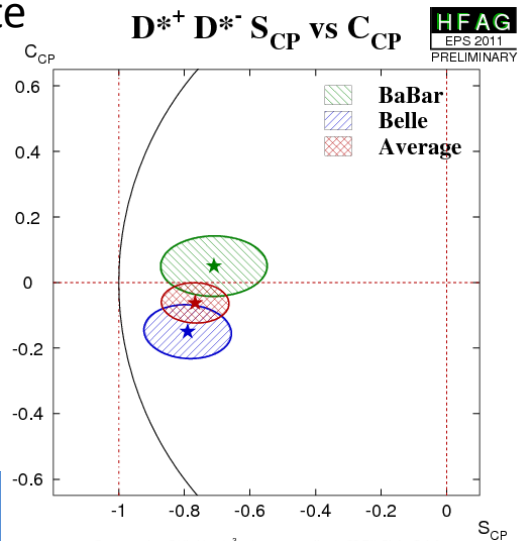
$$\begin{aligned} |B_L\rangle &= p|B\rangle + q|\overline{B}\rangle \\ |B_H\rangle &= p|B\rangle - q|\overline{B}\rangle \end{aligned} \qquad \lambda = \frac{q}{p}\frac{\overline{A}}{A}\ \begin{array}{l}(\overline{B}^0) \\ (B^0)\end{array}$$




$\tau_B$= averaged $B^0$ lifetime, $\Delta m_d$= $B^0\overline{B^0}$ mixing frecuency, $\Delta t = t_{B_{reco} \to D^{*+}D^{*-}} - t_{B_{tag}}$
and $\eta = \pm 1$ indicates the CP eigenvalue of the $B^0 \to D^{*+}D^{*-}$ final state

- The final state in $B^0 \to D^{*+}D^{*-}$ (VV) is an admixture of CP+ and CP- amplitudes

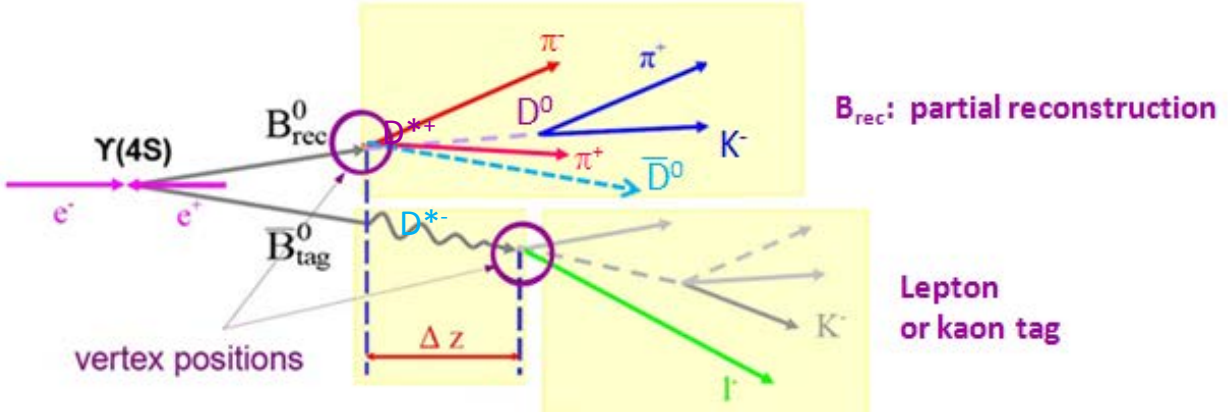
$\to$ need angular analysis to disentangle the two components
Done by BaBar and Belle using fully reconstructed events.
They measure the CP-odd fraction $R_\perp$ and the TD CP asymmetry $\to$



# CPV in $B^0 \to D^{*+}D^{*-}$

**BaBar, arXiv:1208.1282 [hep-ex], accepted by PRD**

- New analysis from BaBar using **partial reconstruction of the $B^0 \to D^{*+}D^{*-}$ decay**
  - ✓ 5 times more data compared to previous analyses using full reconstruction (almost independent samples)
  - ✘ penalty: higher background, larger systematic uncertainties




- 429 $fb^{-1}$ of On-peak BaBar data and 44.8 $fb^{-1}$ of Off-peak data (bkg studies)
- One B ($B_{tag}$) tagged with a lepton (**lepton tag**) or with a kaon (**kaon tag**)
- B ($B_{reco}$): fully reconstruct one D* decaying to $D^0\pi$, with the $D^0$ decaying to one of 4 modes: **$D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $K_s\pi\pi$** (reconstructed D*)
- Match this D* with a slow $\pi$ of opposite sign in the event (coming from the other D*)
- Select candidate if the kinematics is consistent with a $B^0$ decaying into a D* -$D^0\pi$ combination with a missing $D^0$

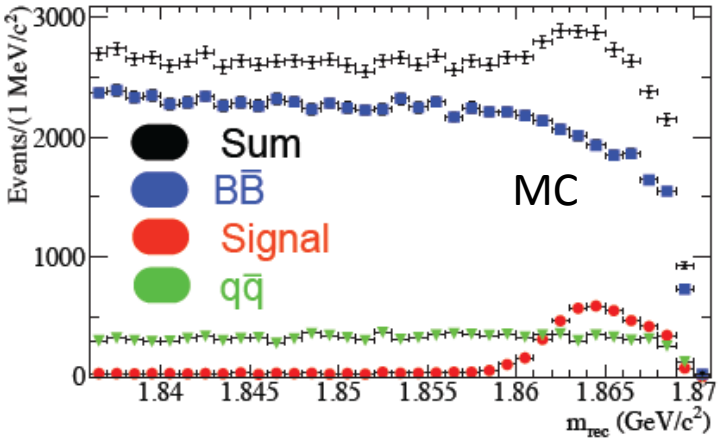
# CPV in $B^0 \to D^{*+}D^{*-}$

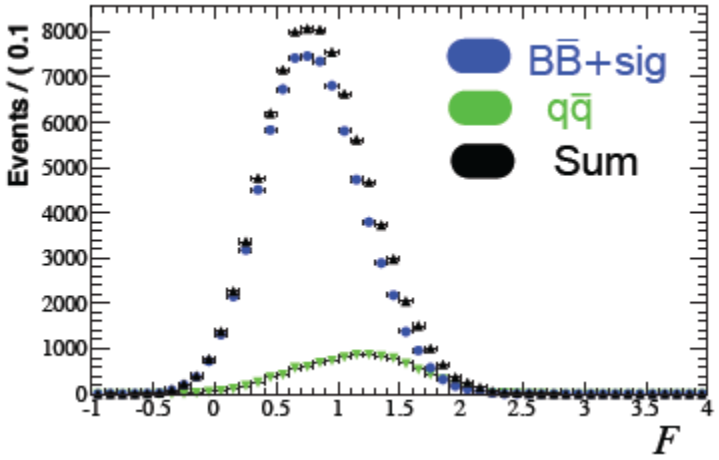
- Analysis method: two (main) unbinned maximum likelihood fits to data

**Kinematic fit:** signal and background characterization based on two variables:

→ The recoiling mass, $\mathbf{M_{rec}}$: mass of the non-reconstructed $D^0$

→ A **Fisher** discriminant based on the event shape




Bkg components:

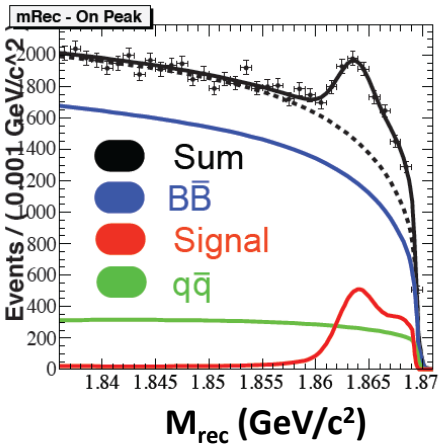
- Combinatorial (extracted from wrong sign sample)
- Light quarks (extracted from off-peak data)
- Peaking BB̄ (negligible)

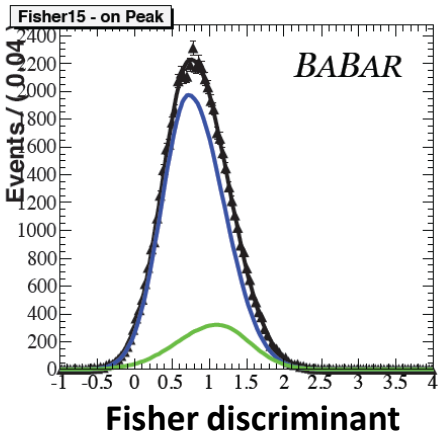
→ **Fit results: signal fraction and shape of signal and background PDFs**

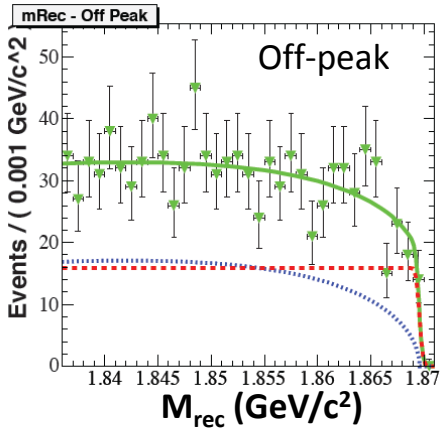
# CPV in $B^0 \to D^{*+}D^{*-}$

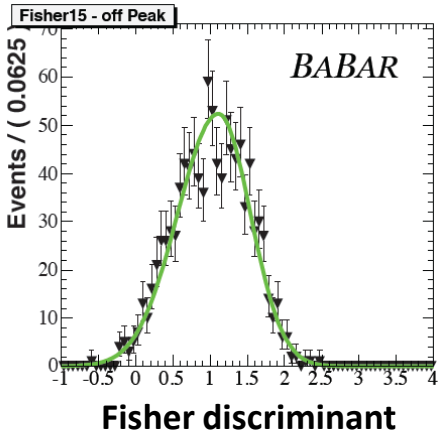
- Kinematic fit results:

**Kaon tag**



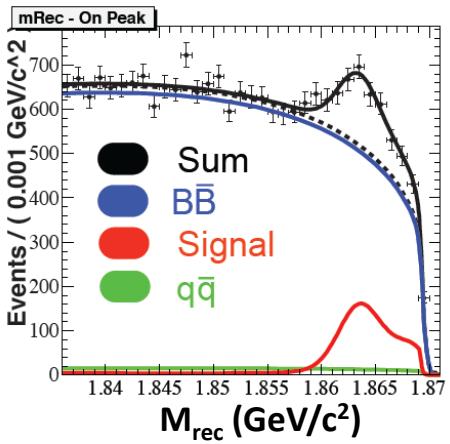



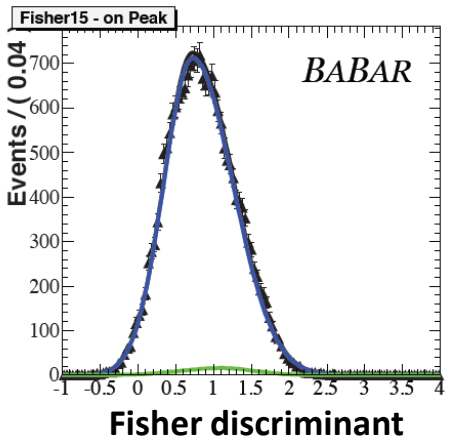



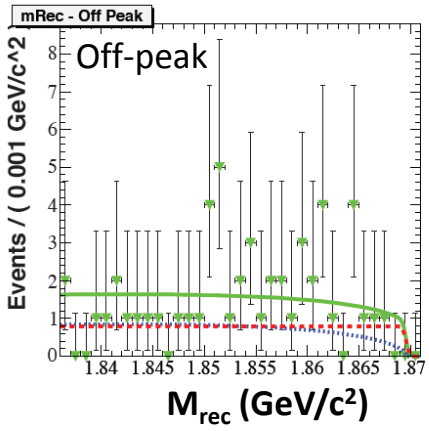



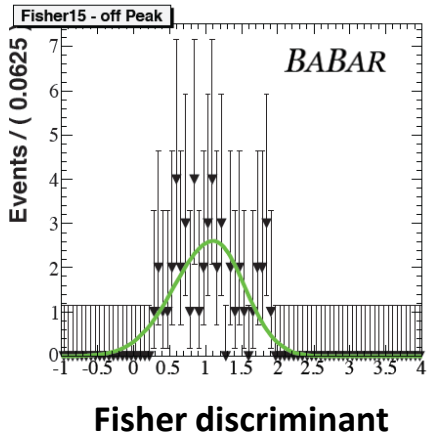

**3843 ± 397 signal events**

**Lepton tag**




**1129 ± 218 signal events**

# CPV in $B^0 \to D^{*+}D^{*-}$

- The kinematic fit is followed by a

**Time dependent fit:**

$\Delta t = \Delta z/\gamma\beta c$
from decay vertices
$\Delta z = z_{rec} - z_{tag}$

Kinematic fit: $M(M_{rec}) \times F(Fisher)$ x Time dependent fit: $T(\Delta t, \sigma_{\Delta t}, S_{tag}) \otimes R(\Delta t - \Delta t_{true}, \sigma_{\Delta t})$
Resolution function

→ **CP parameters, bkg and signal models and mistag probabilities**

- Mistag dilutes the CP parameters by a factor of $(1-2\omega)$ (obtained from a fit to signal MC)
- Additional dilution due to tagging tracks from missing $D^0$ $(1-\alpha)$, where $\alpha$ is the fraction of tags from the unreconstructed $D^0$ (reduced by applying a constraint around the $D^0$ direction and obtained from data with some input from MC)

→ $\omega$ mistag ~20% and ~10% for kaon and lepton tags respectively
→ $\alpha$ mistag ~12% and ~0% for kaon and lepton tags respectively

► Main systematics in the analysis are due to kinematic fit parameters and tagging dilution and interference with DCS decays

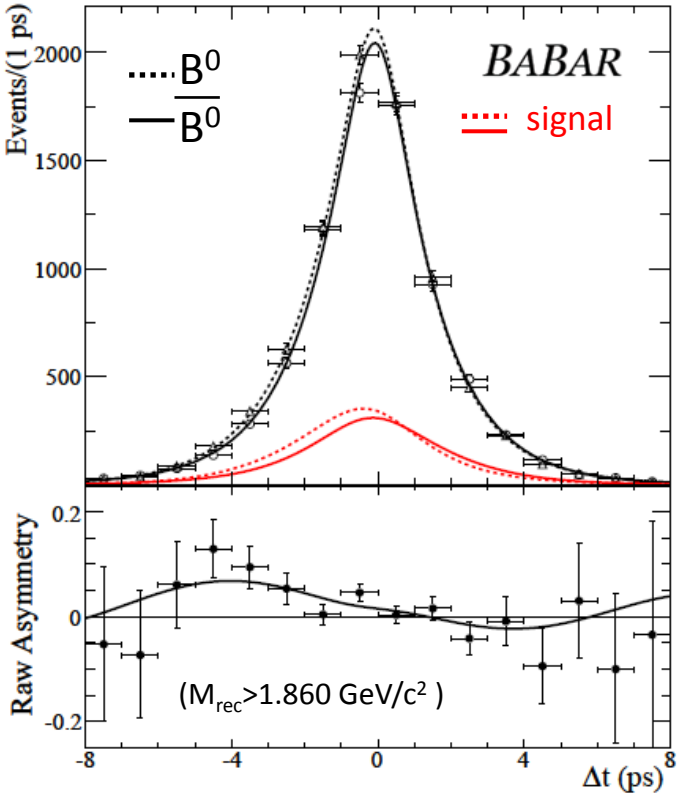
# CPV in $B^0 \to D^{*+}D^{*-}$

- Time-dependent fit results:

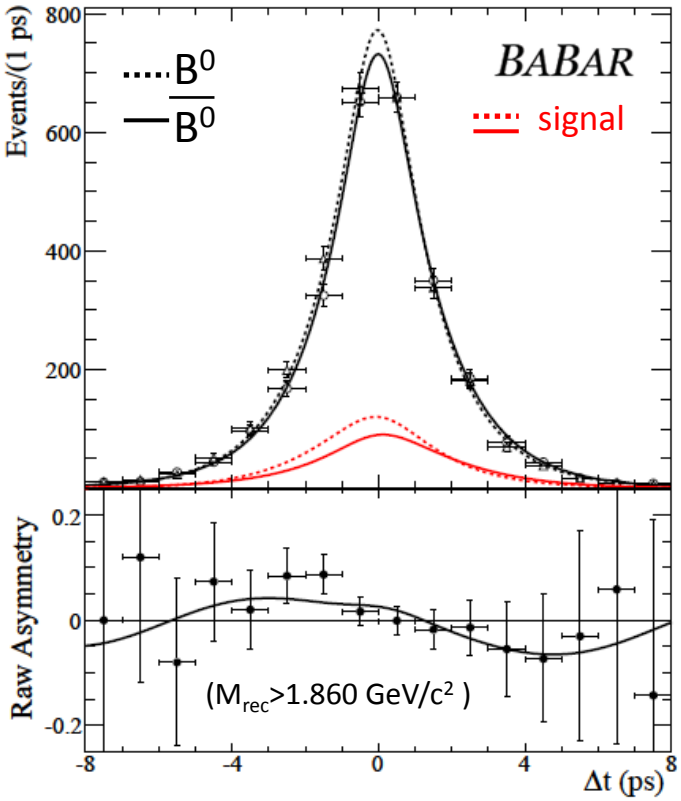
**Kaon tag**

$$A(\Delta t) = \frac{N_{S_{\rm tag}=1}(\Delta t) - N_{S_{\rm tag}=-1}(\Delta t)}{N_{S_{\rm tag}=1}(\Delta t) + N_{S_{\rm tag}=-1}(\Delta t)}$$

**Lepton tag**




$$C = +0.12 \pm 0.11$$
$$S = -0.42 \pm 0.16$$




$$C = +0.20 \pm 0.15$$
$$S = -0.21 \pm 0.20$$

# CPV in $B^0 \to D^{*+}D^{*-}$

- Combined result: kaon + lepton tags

$$\begin{aligned} C &= +0.15 \pm 0.09 \pm 0.04 \\ S &= -0.34 \pm 0.12 \pm 0.05 \end{aligned}$$

Neglecting penguin contributions:

$$\begin{aligned} C &= C_+ \\ S &= S_+ (1 - 2R_\perp) \end{aligned}$$

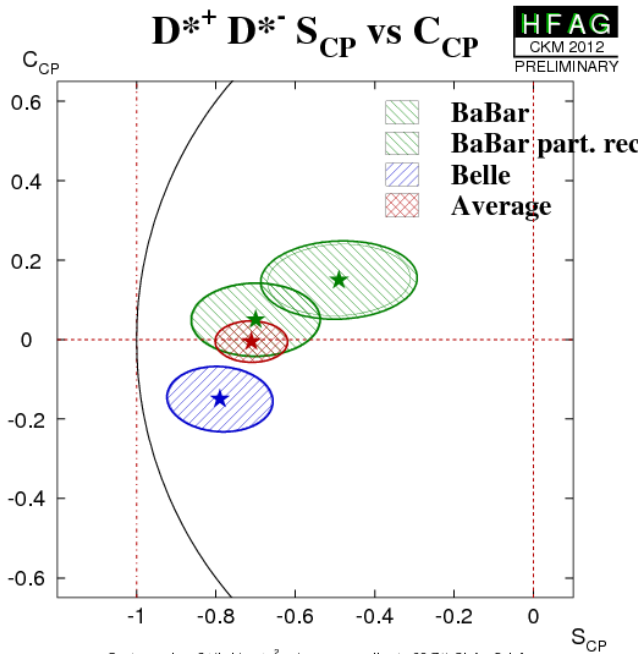
Dilution by the CP-odd component

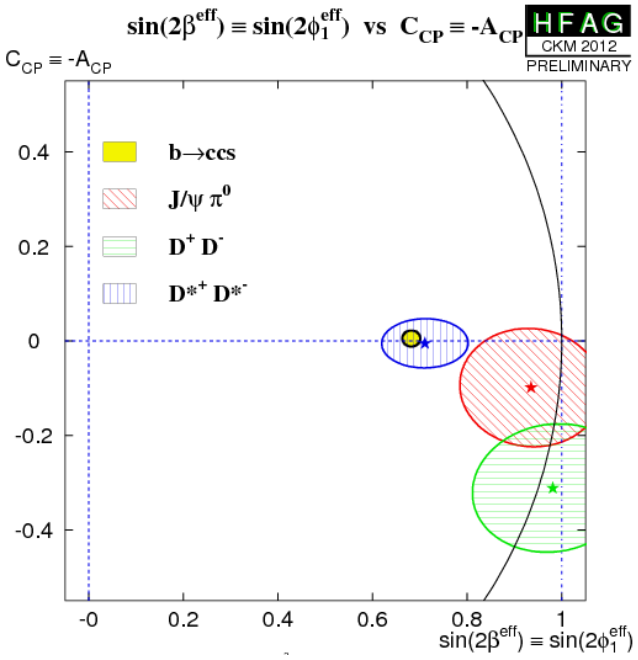
$R_\perp = 0.158 \pm 0.029$

BaBar PRD79,032002('09)

$$\begin{aligned} C_+ &= +0.15 \pm 0.09 \pm 0.04 \\ S_+ &= -0.49 \pm 0.18 \pm 0.07 \pm 0.04 \end{aligned}$$

**Compatible with previous BaBar and Belle results and with SM predictions**



# CPV in $B^0 \to D^* \ell \nu$

$$|B_L\rangle = p|B\rangle + q|\overline{B}\rangle$$
$$|B_H\rangle = p|B\rangle - q|\overline{B}\rangle$$

- In the SM the ratio $|q/p|=1$
  Including NLO QCD corrections: $\delta_{CP} = 1-|q/p| = (-2.96 \pm 0.67) \times 10^{-4}$
  **[M. Ciuchini et al, JHEP 0308,031('08)]**

**If $|q/p| \neq 1$ → CP Violation in mixing → sign of New Physics**

- If CP is violated in mixing, the semileptonic asymmetry $A_{SL}$ measured at flavour experiments

$$A_{sl}^q = \frac{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)} \neq 0$$

($A_{SL} = (1-|q/p|^4)/(1+|q/p|^4)$)
And $\phi$ (the CP violating phase) $\neq 0$

# CPV in $B^0 \to D^* \ell \nu$

$$A_{sl}^q = \frac{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}$$

- SM predictions **[Lenz, Nierste, arXiv:1102.4274 (2011))]**

  $A_{SL}$ $(B_d)$= $(-4.1 \pm 0.6)\times10^{-4}$ $\phi(B_d)=(-4.3 \pm 1.4)°$

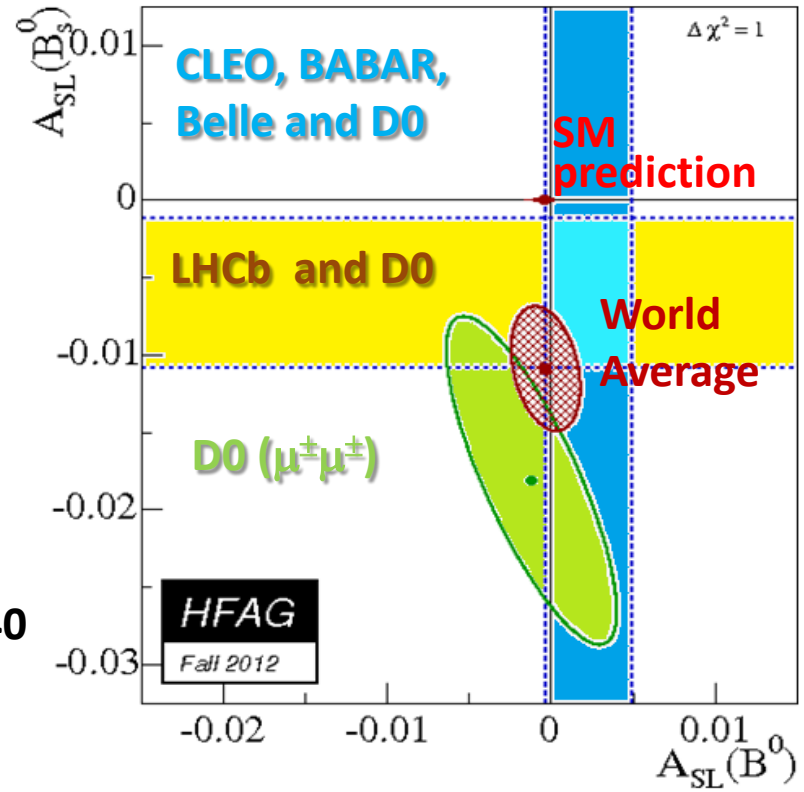
  $A_{SL}$ $(B_s)$= $(1.9 \pm 0.3)\times10^{-5}$ $\phi(B_s)=(0.22 \pm 0.06)°$

- Large deviation ($4\sigma$) observed by D0 in a dimuon asymmetry

- The HFAG averages of CLEO, BaBar, Belle, D0 and LHCb data:

**$B_d$: $|q/p| = 1.0002 \pm 0.0011$ $A_{SL}$ $-0.0003 \pm 0.0021$**
**$B_s$ : $|q/p| = 1.0055 \pm 0.0020$ $A_{SL} = -0.0109 \pm 0.0040$**

http://www.slac.stanford.edu/xorg/hfag/osc/fall_2012/



# CPV in $B^0 \to D^* \ell \nu$

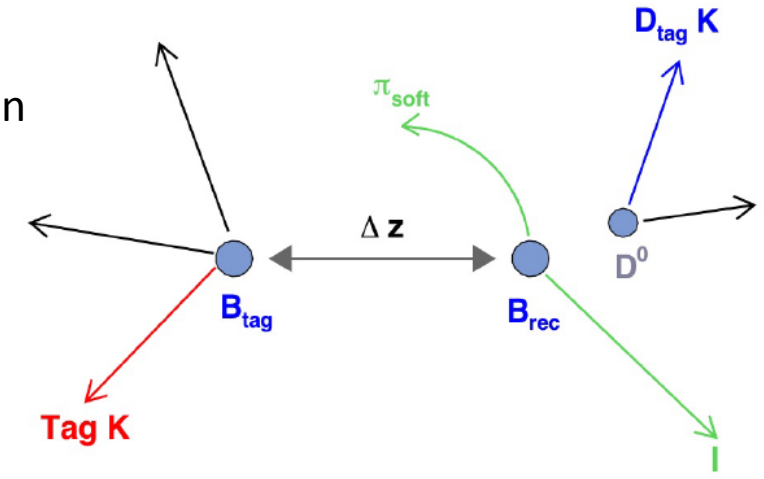
- New measurement of the semileptonic asymmetry $A_{SL}$ by BaBar using partial reconstruction of $B \to D^* \ell \nu$ and kaon tags

- 428 $fb^{-1}$ of On-peak BaBar data and 45 $fb^{-1}$ of Off-peak data (background studies)

- $B_{rec}$: lepton + soft pion from $D^* \to D^0 \pi$

- $B_{tag}$: kaon tag

- Mixing $\to$ same charge for the lepton and $K_{tag}$




**Semileptonic charge asymmetry:**

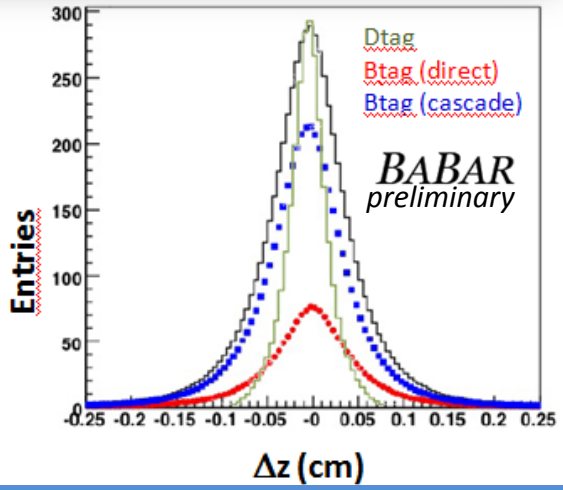
$$A_{SL} = \frac{N(\ell^+ K_T^+) - N(\ell^- K_T^-)}{N(\ell^+ K_T^+) + N(\ell^- K_T^-)}$$

- Two kaon tag categories: $D_{tag}$ (kaons from $D^0$ decay) and $K_{tag}$ (from $B_{tag}$), separated by $\Delta z = |z_{rec} - z_{tag}|$ and $\cos\theta_{K\ell}$

- The asymmetry observed in these samples are:

$$A(B_{tag}) \simeq A_{rec} + A_{tag} + \mathcal{A}_{SL}$$
$$A(D_{tag}) \simeq A_{rec} + A_{tag} + \chi_d \mathcal{A}_{SL} \qquad \chi_d = 0.1862 \pm 0.0023$$

- $D_{tag}$ is the main source of background but useful to disentangle physical and detector charge effects



# CPV in $B^0 \to D^* \ell \nu$

- Continuum and Combinatorial backgrounds suppressed by event shape variables and $\pi\ell$ Vertex Probability $\chi$

- Signal selected using the missing mass squared

$$\mathcal{M}_\nu{}^2 \equiv (E_{\rm beam} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$$

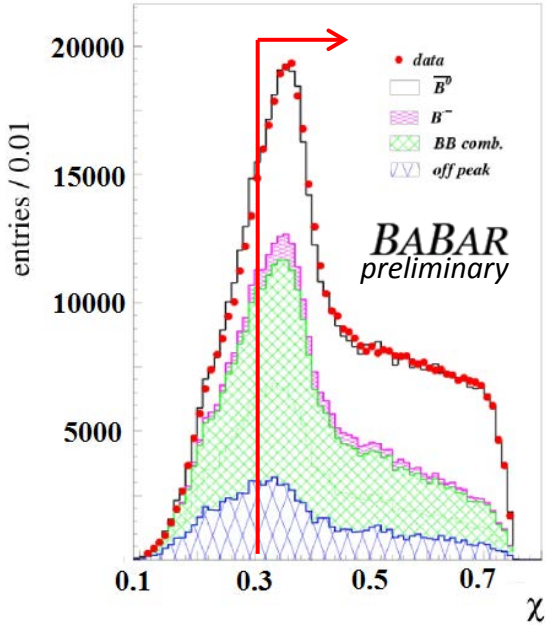
(assuming $p_B \sim 0$ and the D* direction from the soft $\pi$)

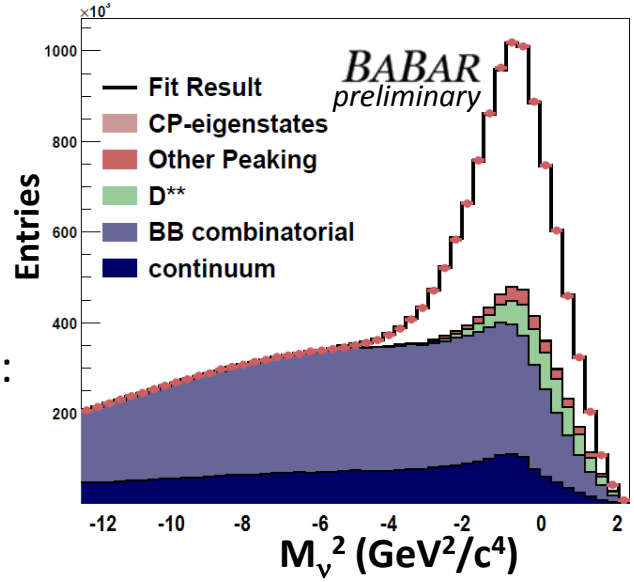
- Yield fitted on $M_\nu{}^2$ by floating D*, D** and combinatorial background using MC shapes, continuum fixed from off-peak data and small peaking from simulation

  $\to$ 6 x $10^6$ events selected in the signal region. (~30% of the total sample)

- $|q/p|$ from an Extended Maximum Likelihood Binned fit to the $\Delta t$ and $\cos(\theta_{K\ell})$ distributions of the 4 subsamples:

  Unmixed ($\ell^- K^+$ , $\ell^+ K^-$);
  Mixed ($\ell^+ K^+$, $\ell^- K^-$)



# CPV in $B^0 \to D^* \ell \nu$

$\Delta\Gamma=0$

**Unmixed samples:**

$$\mathcal{F}_{\bar{B}^0 B^0}(\Delta t') = \frac{\Gamma_0}{2(1+r'^2)} e^{-\Gamma_0|\Delta t'|} \left[ \left(1 + \left|\frac{q}{p}\right|^2 r'^2\right) \cosh(\Delta\Gamma\Delta t'/2) + \left(1 - \left|\frac{q}{p}\right|^2 r'^2\right) \cos(\Delta m_d \Delta t') - \left|\frac{q}{p}\right| (b+c) \sin(\Delta m_d \Delta t') \right]$$

**Mixed samples:**

$$\mathcal{F}_{\bar{B}^0 \bar{B}^0}(\Delta t') = \frac{\Gamma_0}{2(1+r'^2)} e^{-\Gamma_0|\Delta t'|} \left[ \left(1 + \left|\frac{p}{q}\right|^2 r'^2\right) \cosh(\Delta\Gamma\Delta t'/2) - \left(1 - \left|\frac{p}{q}\right|^2 r'^2\right) \cos(\Delta m_d \Delta t') - \left|\frac{p}{q}\right| (b-c) \sin(\Delta m_d \Delta t') \right] \left|\frac{q}{p}\right|^2$$

r', b, c are parameters resulting from interference between Cabibbo-Favoured and Doubly Cabibbo-Suppressed decays on the tag side

→ convoluted with the resolution function $\mathcal{R}(\Delta t, \Delta t')$

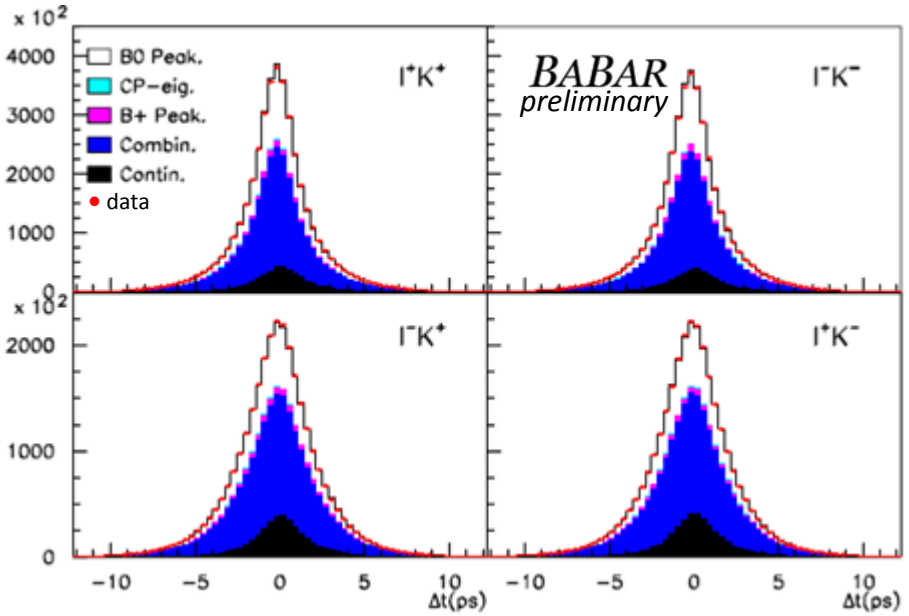
→ take into account mistag probabilities (different for $B_{tag}$ and $B_{rec}$)

→ disentangle $A_{tag}$ (tagging asymmetry($p_K$) ~1.4%) and $A_{rec}$ (reconstruction asymmetry ($\pi\ell$), ~ 0.3%) → $D_{tag}$

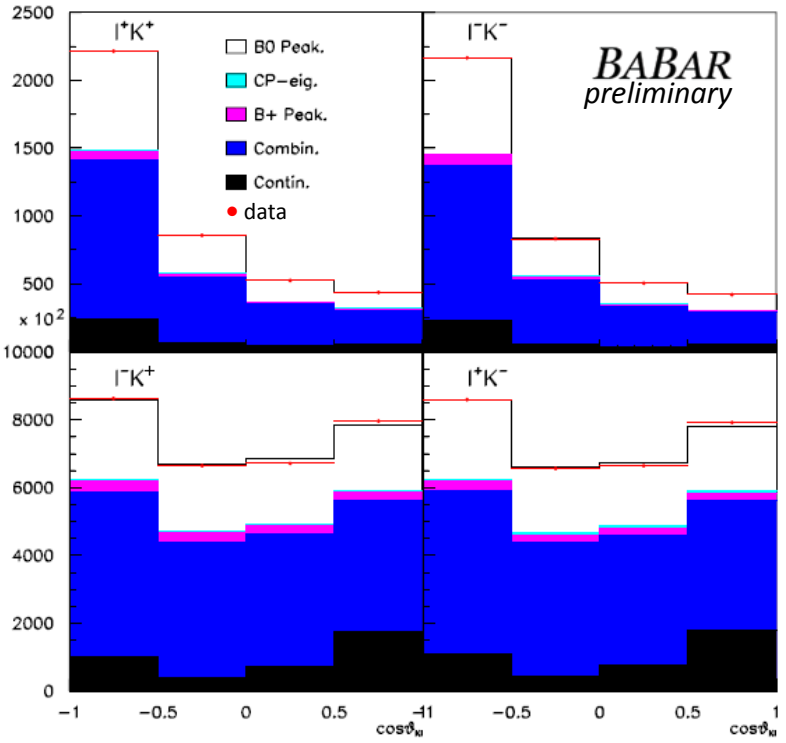
# CPV in $B^0 \to D^* \ell \nu$

- Results of the fit:

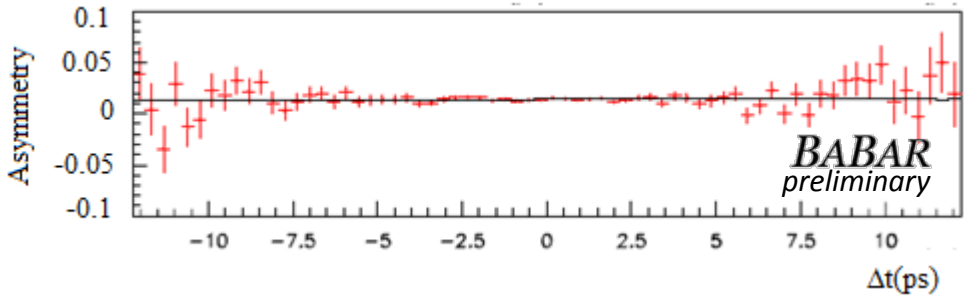
$\Delta t$ distributions




$\cos\theta_{K\ell}$ distributions




Raw $N(\ell^+K^+)/N(\ell^-K^-)$ Asymmetry




→ $|q/p|$-1 (blinded) + parameters describing signal and background samples

# CPV in $B^0 \to D^* \ell \nu$

- Results of the fit:

$$\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$$

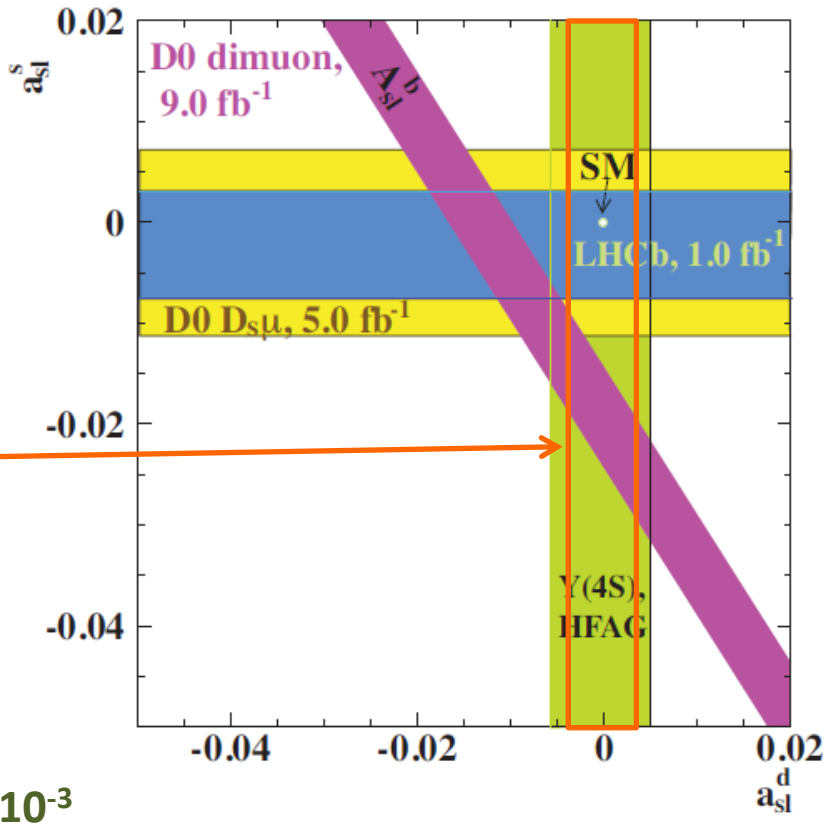
(after a small bias ~-0.04% correction)

► Main systematic coming from the sample composition

The semileptonic asymmetry:

$$\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$$

Compatible with previous results from B-factories and SM predictions




HFAG average @ $\Upsilon(4S)$: $|q/p|-1 = (0.2 \pm 2.8) \times 10^{-3}$

[arXiv:1207.1158v1 (2011)] $A_{SL} = (-0.05 \pm 0.56)\%$

# More BaBar results on CPV

- Measurement of CP Asymmetries and Branching Fractions in Charmless Two-Body B-Meson Decays to Pions and Kaons
[arXiv:1206.3525 [hep-ex]]

$$S_{\pi^+\pi^-} = -0.68 \pm 0.10 \pm 0.03$$
$$C_{\pi^+\pi^-} = -0.25 \pm 0.08 \pm 0.02$$
$$\mathcal{A}_{K^-\pi^+} = -0.107 \pm 0.016^{+0.006}_{-0.004}$$
$$C_{\pi^0\pi^0} = -0.43 \pm 0.26 \pm 0.05$$

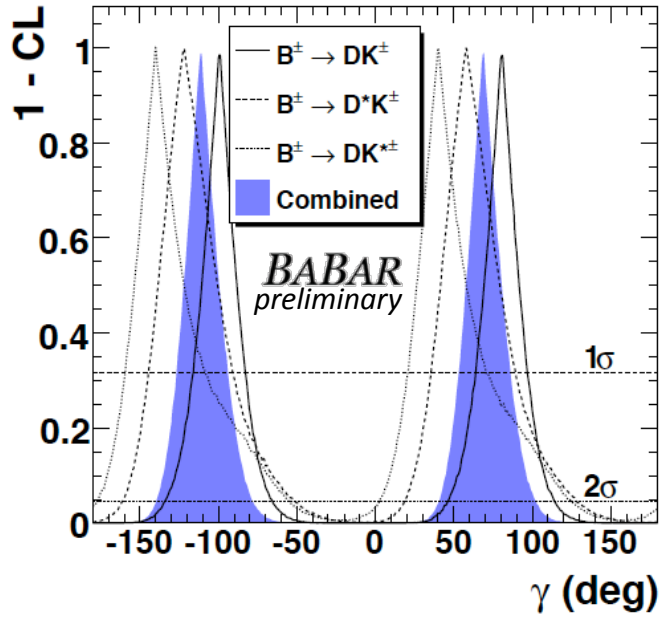
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^0\pi^0) = (10.1 \pm 0.6 \pm 0.4) \times 10^{-6}$$

**α ∈ [71°, 109°] (68% C.L.)**

- γ combination

(see J. Walsh talk this morning)

**γ = 69° $^{+17^\circ}_{-16^\circ}$ (68% C.L.)**



# Summary

● New precise measurements on CP violation in B decays using a partial reconstruction technique:

→ Partial reconstruction of $B^0 \to D^{*+} D^{*-}$ with lepton and kaon tags

$$\begin{aligned} C_+ &= +0.15 \pm 0.09 \pm 0.04 \\ S_+ &= -0.49 \pm 0.18 \pm 0.07 \pm 0.04 \end{aligned}$$

→ Partial reconstruction of $B^0 \to D^* \ell \nu$ with kaon tag

$$\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$$

$$\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$$

● Results in agreement with other measurements from B-factories and with SM predictions