Study of CP Asymmetry in $B^0 - \overline{B}^0$ Mixing Using Inclusive Dilepton Samples in BaBar

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Overview

- “Study of *CP* asymmetry in $B^0 - \overline{B}^0$ mixing with inclusive dilepton events”
  - Published by PRL in February

    Phys. Rev. Lett. 114, 081801 (2015)

  - Time-independent update of a 2006 BaBar analysis

    Phys. Rev. Lett. 96, 251802 (2006)

CP Violation In Mixing

- Neutral B mesons may transform into their anti-particles through the weak interaction
- Under the Standard Model (SM) the probabilities $\mathcal{P}(B^0 \to \overline{B}^0)$ and $\mathcal{P}(\overline{B}^0 \to B^0)$ may be different
  - This implies both *CP* and *T* violation
  - Such "*CP* violation in mixing" was first observed in the neutral kaon system, but has not yet been observed with B mesons
  - Within the SM, we expect *CP* violation in B-mixing on the order of 10^{-4}, but this could be altered by new physics in loops **arXiv:1008.1593 [hep-ph]**
- Prior to this analysis, the experimental average of CP asymmetry in $B^0 - \overline{B}^0$ mixing was $A_{CP} = (2.3 \pm 2.6) \times 10^{-3}$ **arXiv:1207.1158 [hep-ex]**
  - Average dominated by BaBar, Belle, and D0 experiments

CP Violation In Mixing II

- The neutral B system can be described using an effective hamiltonian so that:

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

where, assuming *CPT* symmetry, the mass eigenstates are:

$$|B_{L/H}\rangle = \frac{1}{\sqrt{p^2+q^2}}(p|B^0\rangle \pm q|\overline{B}^0\rangle)$$

and the probabilities for mixing and decay to a flavor-specific final state are:

$$\mathcal{P}(B^0 \to \overline{B}^0 \to \bar{f})(t) \quad \propto \quad |q/p|^2[\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)]$$
$$\mathcal{P}(\overline{B}^0 \to B^0 \to f)(t) \quad \propto \quad |p/q|^2[\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)]$$

  - If $|q/p| \neq 1$, then *CP* and *T* symmetry are violated

- Under these conventions, the CP/T asymmetry may be expressed as:

$$A_{CP} = \frac{\mathcal{P}(\overline{B}^0 \to B^0)(t) - \mathcal{P}(B^0 \to \overline{B}^0)(t)}{\mathcal{P}(\overline{B}^0 \to B^0)(t) + \mathcal{P}(B^0 \to \overline{B}^0)(t)} = \frac{1-|q/p|^4}{1+|q/p|^4} \simeq 2(1-|q/p|)$$

The BaBar Experiment

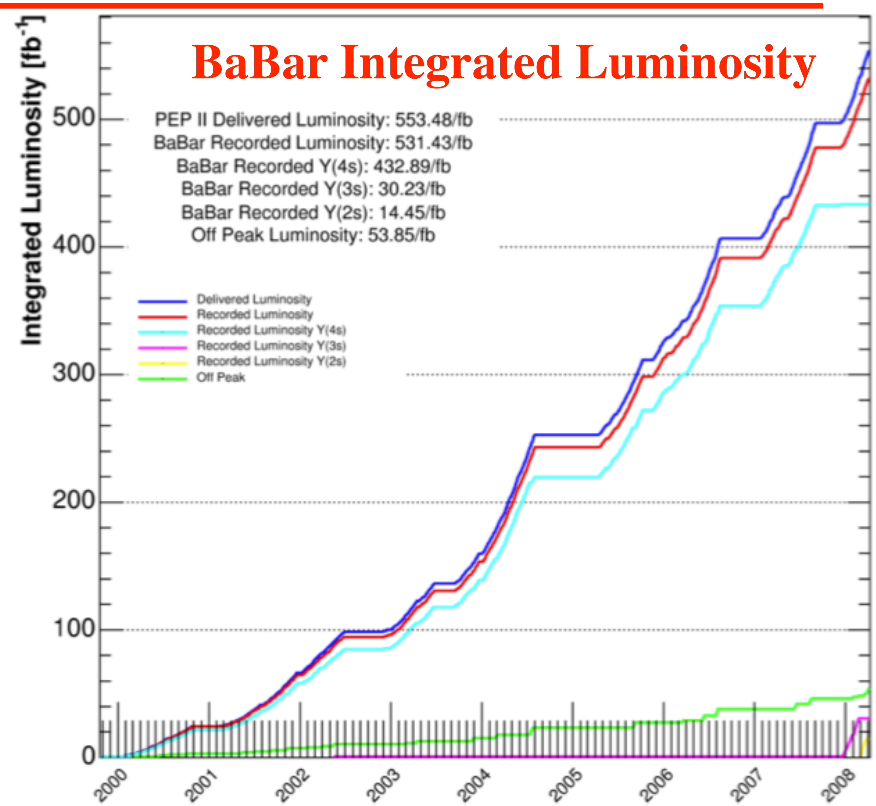
- Data collected by BaBar detector at SLAC National Accelerator Laboratory

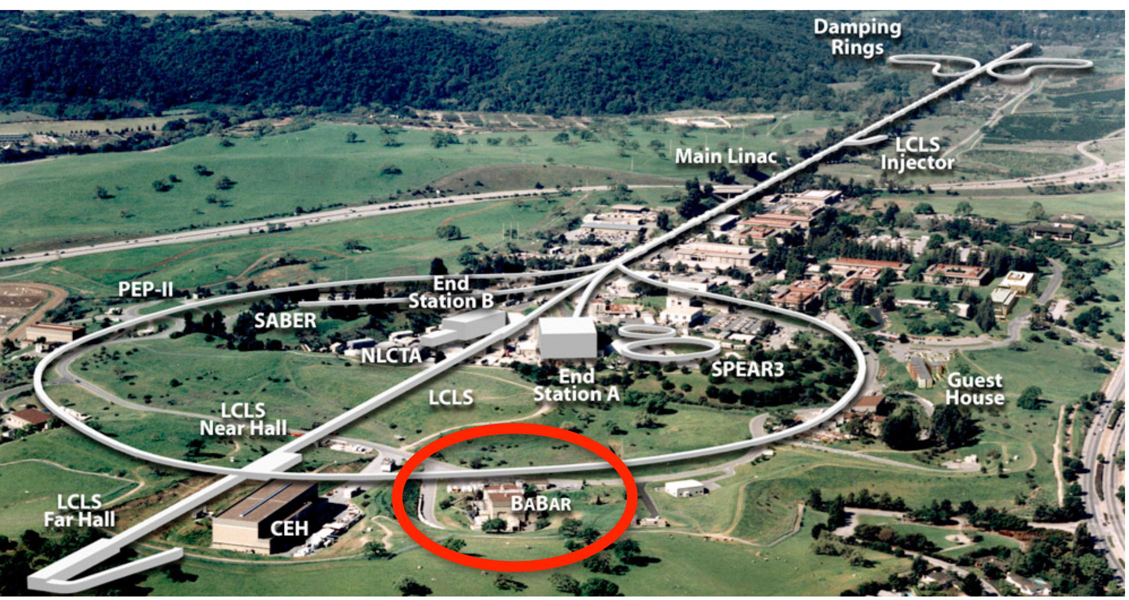
- Asymmetric-energy e^+ and e^- beams

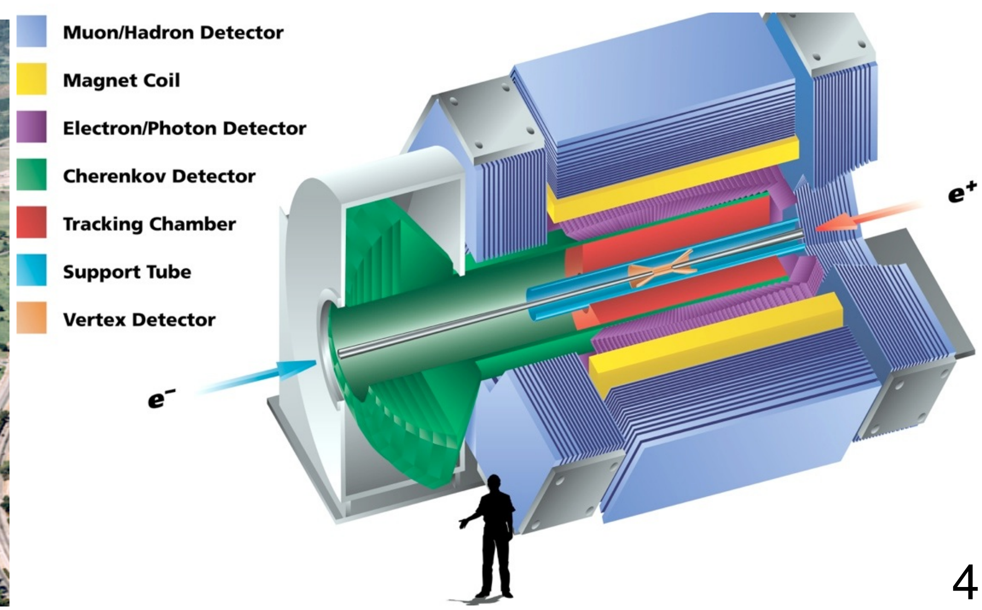
  $\Longrightarrow$ e^+e^- CM boosted in lab frame

- Our analysis uses the full dataset of $\sim 470 \times 10^6$ $B\overline{B}$ collected at the $\Upsilon(4S)$ resonance

- Neutral B mesons are produced as entangled pairs



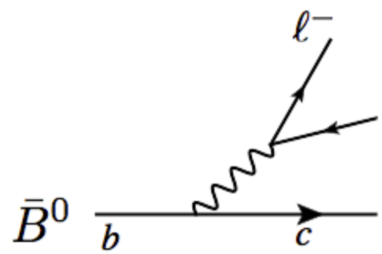




Dilepton Analysis

- For this analysis, we use semileptonic B decays where $\ell \in (e, \mu)$
  - The charge of the leptons provides the flavor of each B meson at the time it decayed
  - Mixing is indicated when the leptons from each B meson have the same charge:

$$\ell^+\ell^+ \implies \overline{B}^0 \to B^0$$
$$\ell^-\ell^- \implies B^0 \to \overline{B}^0$$
$$\ell^+\ell^- \implies \text{No mixing}$$



  - An inclusive analysis provides us with increased statistics

- Mixing Probabilities:

$$\mathcal{P}^{\pm\pm}(\Delta t) \propto e^{-\Gamma|\Delta t|}|q/p|^{\mp 2}[\cosh(\Delta\Gamma\Delta t/2) - \cos(\Delta m\Delta t)]$$
$$\mathcal{P}^{\pm\mp}(\Delta t) \propto e^{-\Gamma|\Delta t|}[\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m\Delta t)].$$

$$A_{CP} = \frac{\mathcal{P}(\Delta t)^{++} - \mathcal{P}(\Delta t)^{--}}{\mathcal{P}(\Delta t)^{++} + \mathcal{P}(\Delta t)^{--}} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2}.$$

Time-integrated probability

$$\mathcal{P}^{\pm\pm} \propto (1 \pm A_{CP})\chi_d$$
$$\mathcal{P}^{\pm\mp} \propto (1 - \chi_d)$$

mixing probability (→ χ_d)

$\chi_d = 0.774 \pm 0.006$

Analysis Strategy

- Taking into account the charge asymmetry a_{ℓ_j} (for lepton ℓ_j) in detector efficiency, and contributions from B^+B^- events:

$$\mathcal{P}^{\pm\pm} \propto (1 \pm a_{\ell_1} \pm a_{\ell_2} \pm A_{CP})\chi_d,$$
$$\mathcal{P}^{\pm\mp} \propto (1 \pm a_{\ell_1} \mp a_{\ell_2})(1 - \chi_d + r_B)$$

where $r_B = N_{B^+B^-}/N_{B^0\overline{B}^0}$

- Count 16 signal yields (two leptons ordered by CM p^*, each with two possible flavors e/μ and two possible charges +/-):

$$N^{\pm\pm}_{\ell_1\ell_2} = \frac{1}{2}N^0_{\ell_1\ell_2}(1 \pm a_{\ell_1} \pm a_{\ell_2} \pm A_{CP})\chi_d^{\ell_1\ell_2},$$
$$N^{\pm\mp}_{\ell_1\ell_2} = \frac{1}{2}N^0_{\ell_1\ell_2}(1 \pm a_{\ell_1} \mp a_{\ell_2})(1 - \chi_d^{\ell_1\ell_2} + r_B),$$

where $\chi_d^{\ell_1\ell_2}$ are effective mixing probabilities that take into account the slight efficiency difference between same-sign and opposite-sign samples

- Due to high correlations among a_{ℓ_j} and A_{CP}, we use an additional constraint based on "single lepton" events:

$$a_{\text{on}} = \alpha + \beta\chi_d A_{CP} + \gamma a_\ell \quad \text{(where } a_\ell \equiv (a_{\ell_1} + a_{\ell_2})/2\text{)}$$

Backgrounds

- We subtract a small background contribution from continuum $e^+e^- \to f\overline{f}(\gamma)$ events (where $f \in u, d, s, c, e, \mu, \tau$) using off-peak data

- The remaining background consists of $B\overline{B}$ events where at least one lepton candidate comes from a $B \to X \to \ell Y$ cascade, or from a hadron misidentified as a lepton

  - Including these contributions in the time-integrated signal yield equations we have:

$$M^{\pm\pm}_{\ell_1\ell_2} = \frac{1}{2}N^0_{\ell_1\ell_2}(1 + R^{\pm\pm}_{\ell_1\ell_2})\left[1 \pm a_{\ell_1} \pm a_{\ell_2} \pm \frac{1 + \delta_{\ell_1\ell_2}R^{\pm\pm}_{\ell_1\ell_2}}{1 + R^{\pm\pm}_{\ell_1\ell_2}}A_{CP}\right]\chi_d^{\ell_1\ell_2},$$

$$M^{\pm\mp}_{\ell_1\ell_2} = \frac{1}{2}N^0_{\ell_1\ell_2}(1 + R^{\pm\mp}_{\ell_1\ell_2})(1 \pm a_{\ell_1} \mp a_{\ell_2})(1 - \chi_d^{\ell_1\ell_2} + r_B),$$

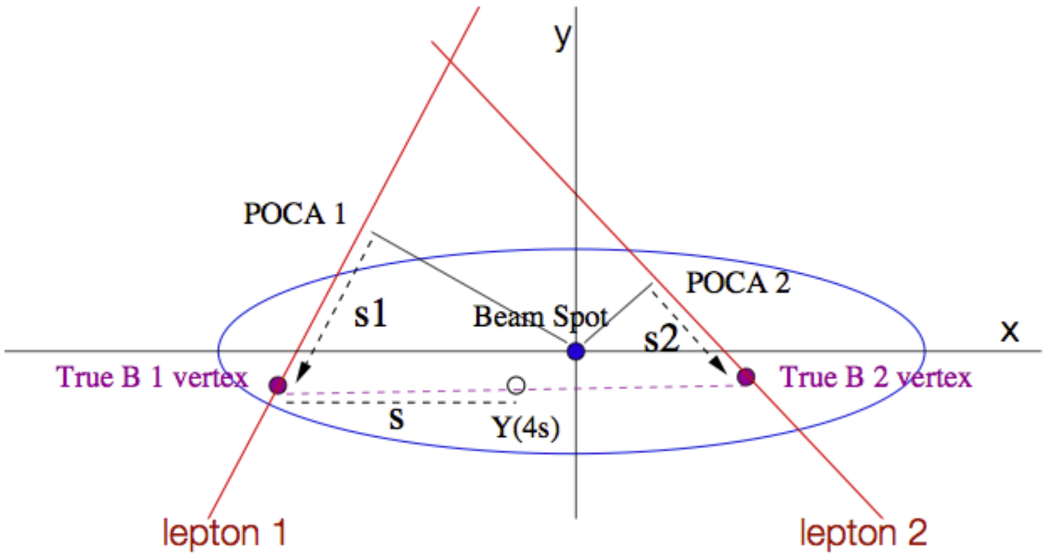
  where: $R^{\pm\pm}_{\ell_1\ell_2}$ and $R^{\pm\mp}_{\ell_1\ell_2}$ are bkg/sig ratios when $A_{CP} = 0$ and

  $\delta_{\ell_1\ell_2}$ is a dilution factor required because some same-sign background events have the right sign for a true mixed event and some do not

- Perform χ^2 fit using 8+8+1 equations to extract A_{CP}, 4 B^0 yields $N^0_{\ell_1\ell_2}$, 4 detector efficiency charge asymmetries a_{ℓ_j}, and 4 effective mixing probabilities $\chi_d^{\ell_1\ell_2}$

Event Selection

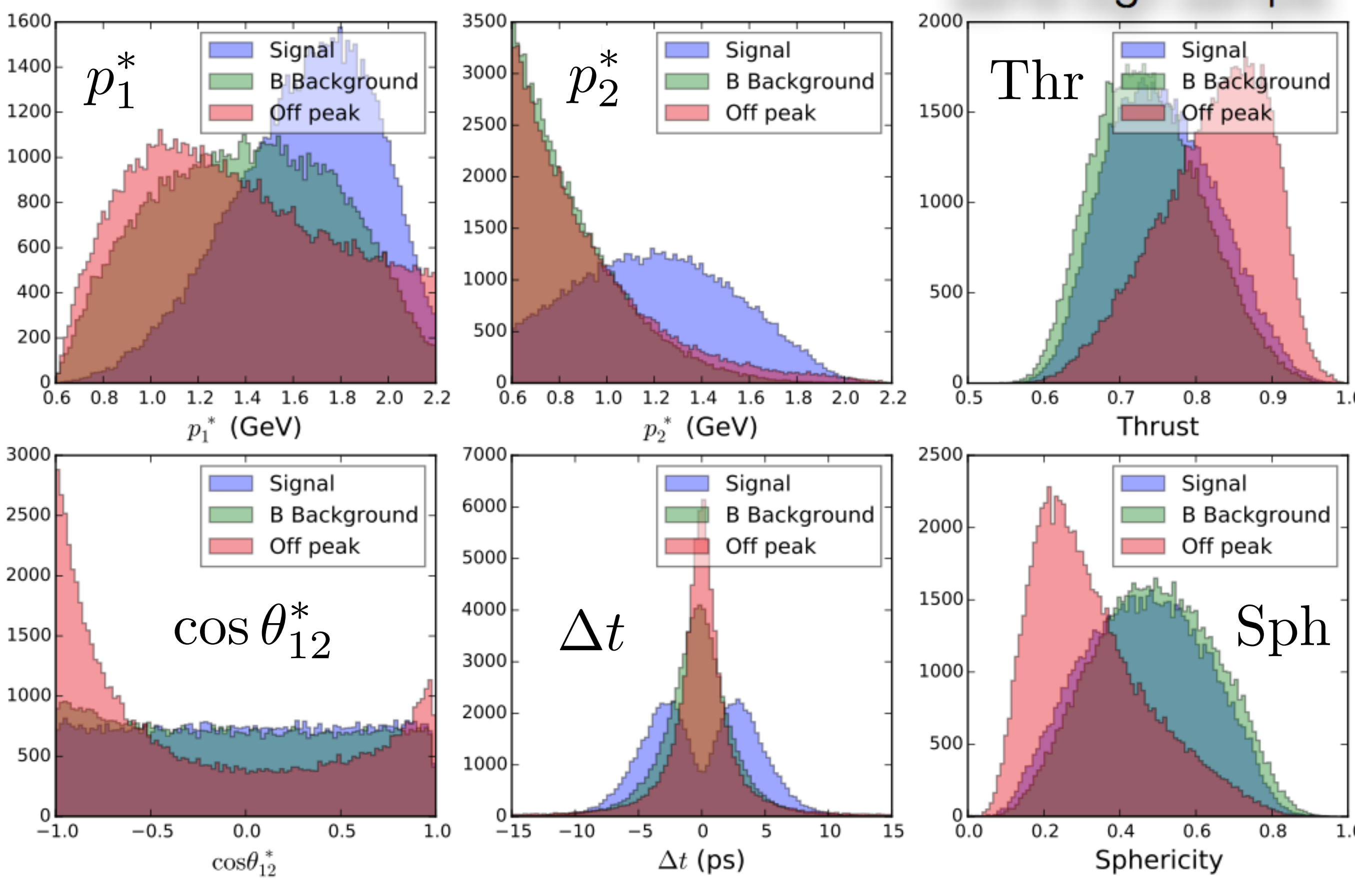
- Event shape consistent with a $B\overline{B}$ decay (at least 4 tracks, approximately isotropic)
- Two tracks with $p^* > 0.6$ GeV (or one for the single electron sample)
- Veto tracks consistent with photon conversion, or coming from J/ψ or $\psi(2S)$ meson
- Misc quality and fiducial cuts
- Calculate Δt from the separation along the collision axis of the two points-of-closest-approach (POCA) of the lepton tracks to the beam spot and the CM boost factor of ~0.56
  - Require $|\Delta t| < 15$ ps, $\sigma_{\Delta_t} < 3$ ps

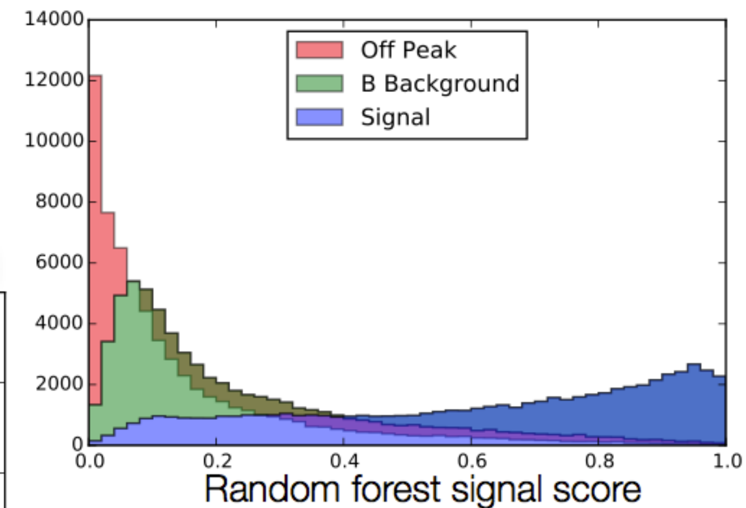


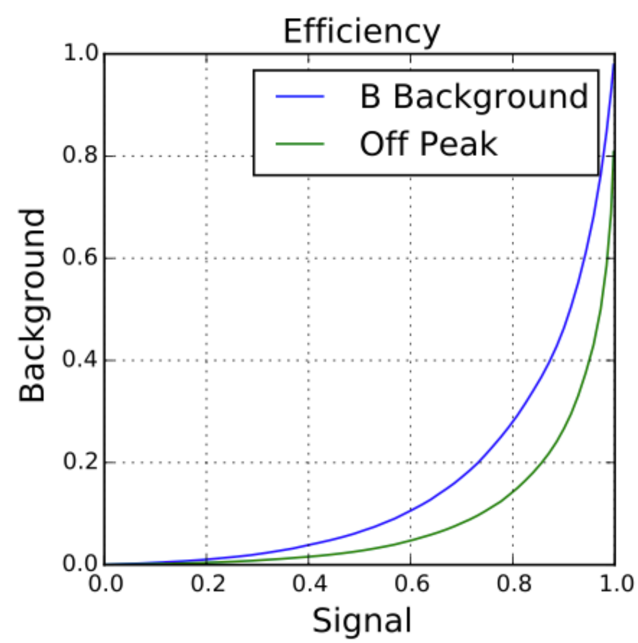
Multivariate Background Suppression

- Continuum and *B* backgrounds are suppressed using a random forest (RF) discriminator
- A separate, 8-variable RF is used for single-lepton
- Train on same-sign and opposite-sign samples separately:

same-sign sample



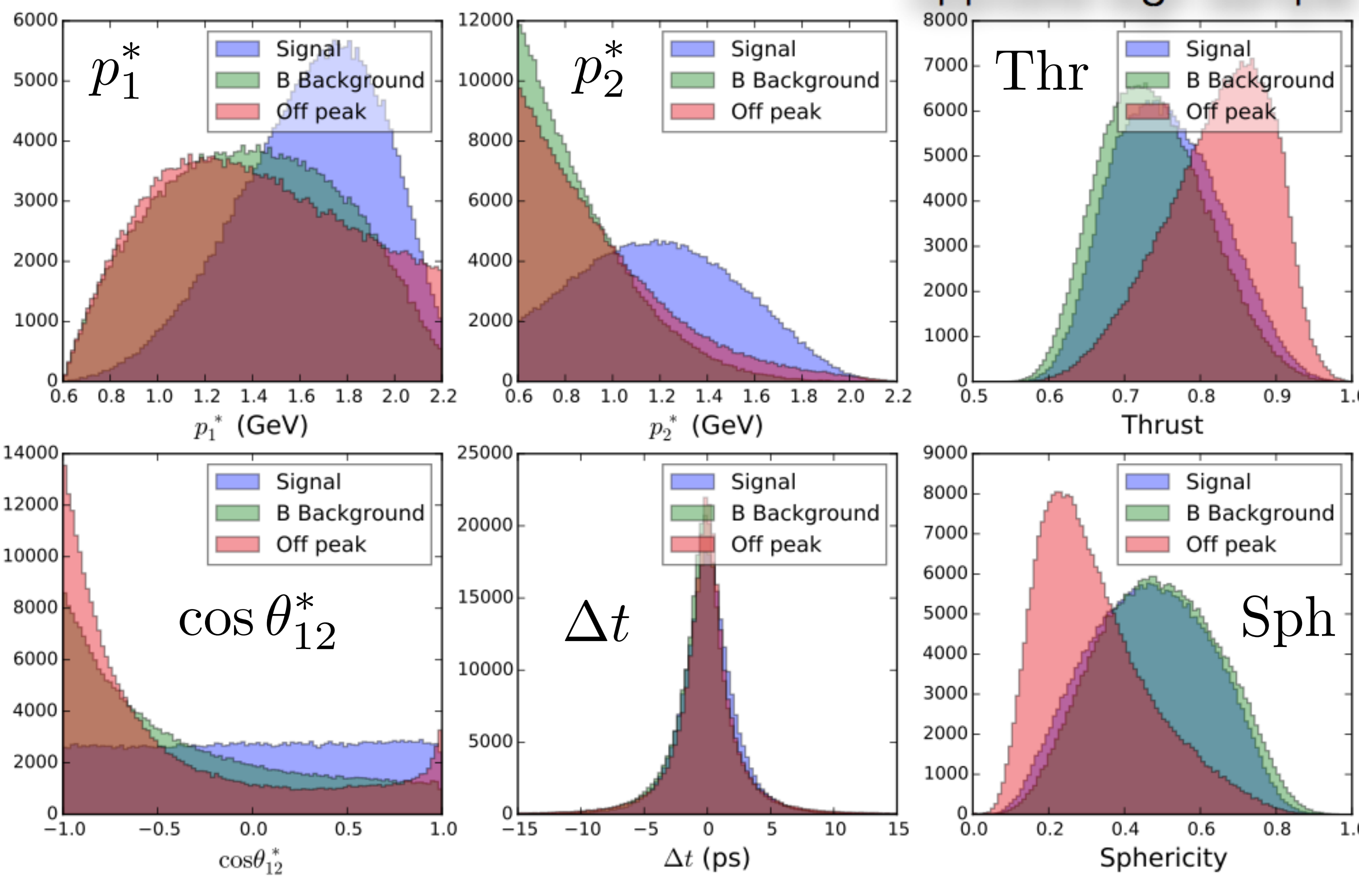


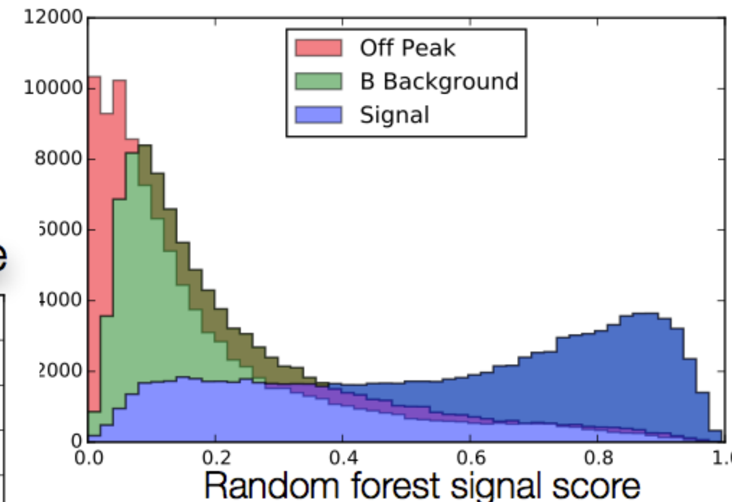


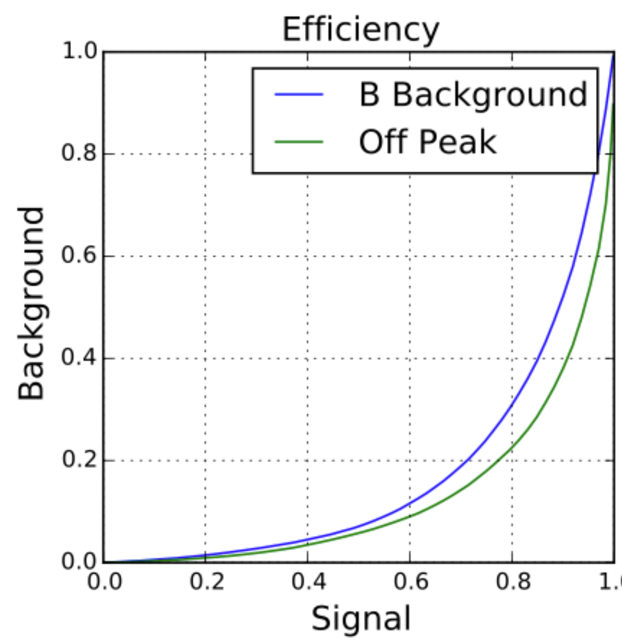
Multivariate Background Suppression II

- Continuum and *B* backgrounds are suppressed using a random forest (RF) discriminator
- A separate, 8-variable RF is used for single-lepton
- Train on same-sign and opposite-sign samples separately:

opposite-sign sample

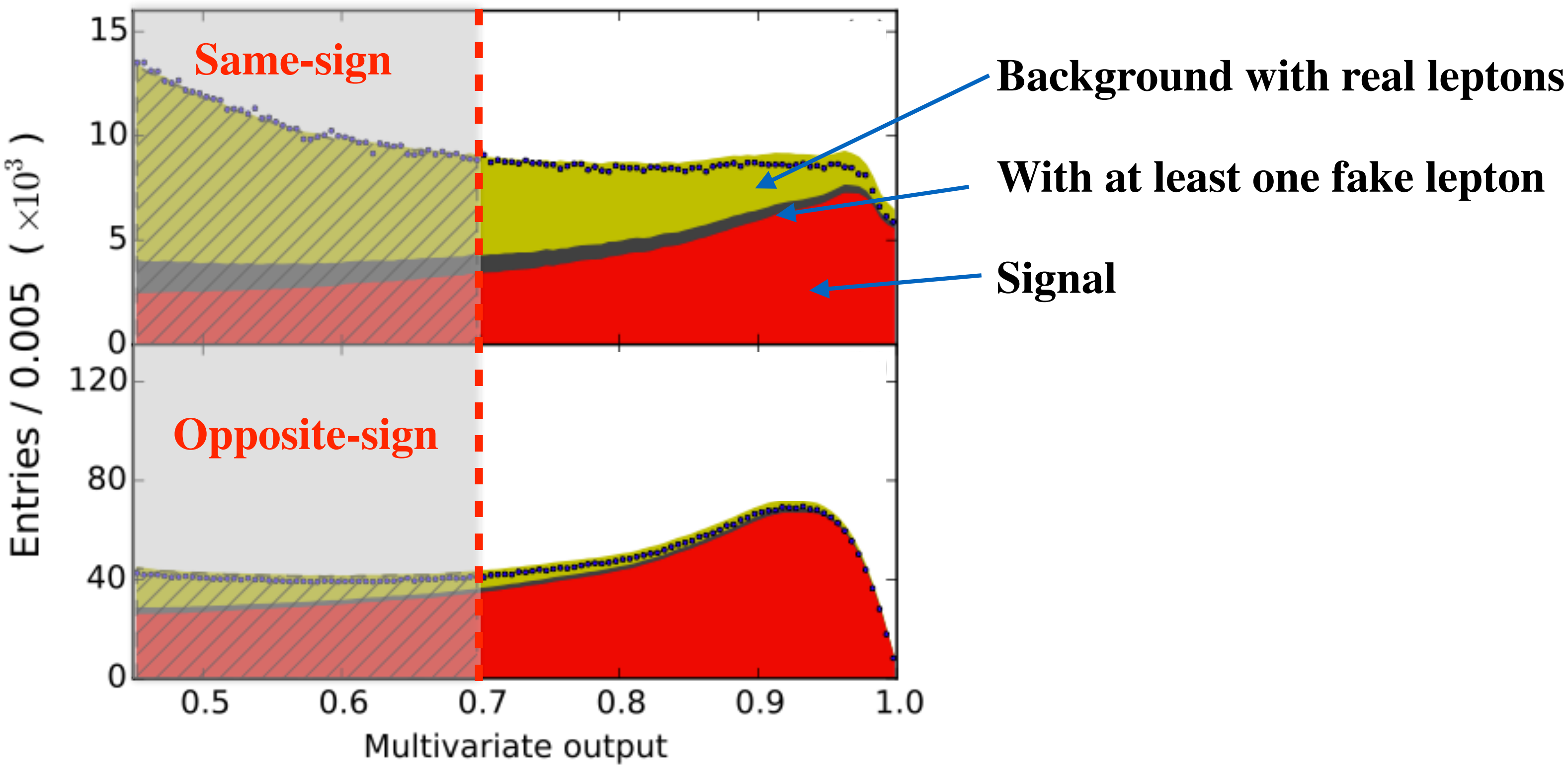






Final Selection

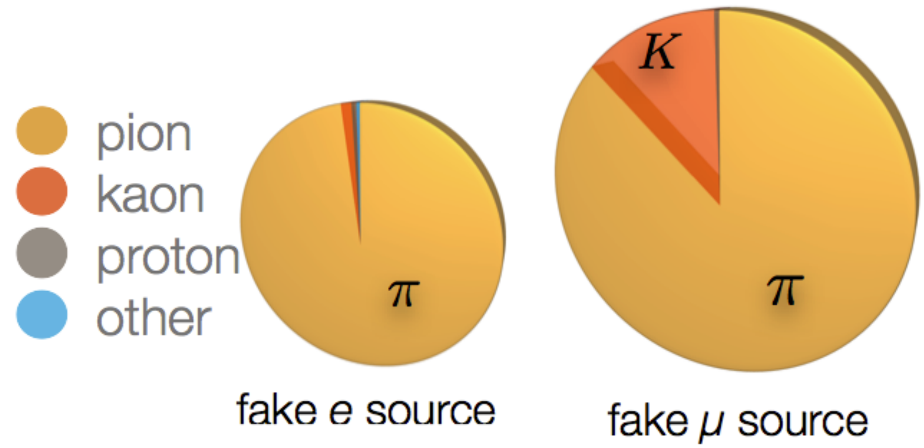
- RF Signal Probability Distribution



- Require multivariate (RF) output > 0.7
- After RF cuts, select 517 k same-sign events / 3196 k opposite-sign events from on-peak dilepton sample (and 85M single-electrons)
- 2.5% continuum background
- 35% (8%) $B\overline{B}$ background in same-sign (opposite-sign) sample

Fake Lepton Contributions

- Approx 0.1% of selected electrons and 3% of muons in dilepton samples are misidentified hadrons
    - 98% of misidentified electrons come from pions
    - 87% of misidentified muons come from pions and 12% from kaons



- To correct for differences in the muon misidentification rate between data and MC, we study clean kaon and pion samples from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
- For the electron misidentification rate correction, we use a larger pion control sample from $K^0_S \to \pi^+\pi^-$
- The ratios of the misidentification efficiencies between data and MC samples are used to scale the misidentified lepton components in MC

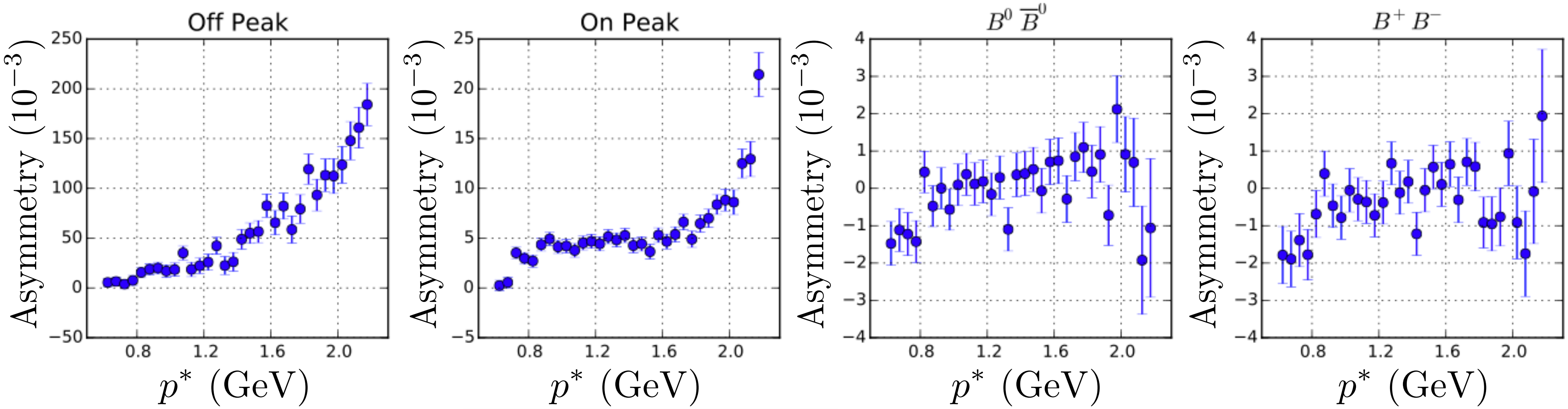
$$w^{\rm fake}_{\ell^\pm} = \sum_{h=K,\pi,p} f_{h\to\ell^\pm} \frac{\epsilon^{\rm data}_{h\to\ell^\pm}}{\epsilon^{\rm MC}_{h\to\ell^\pm}},$$

$$w^{\rm fake}_{\mu^+} = 0.792 \pm 0.012 \qquad w^{\rm fake}_{e^+} = 1.00 \pm 0.10$$

$$w^{\rm fake}_{\mu^-} = 0.797 \pm 0.013 \qquad w^{\rm fake}_{e^-} = 0.56 \pm 0.10$$

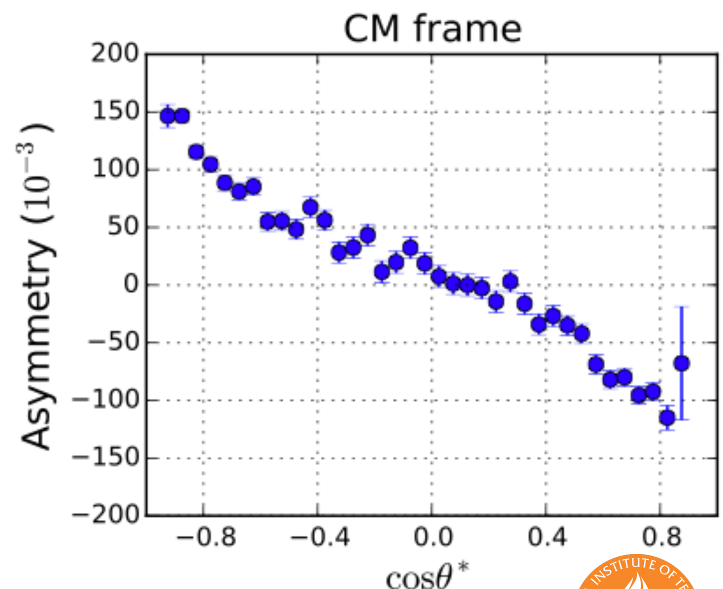
Single Electron Asymmetry

- Raw single-electron asymmetries:



$a_{\rm off} = (11.1 \pm 1.4) \times 10^{-3}$

$a_{\rm on} = (4.16 \pm 0.14) \times 10^{-3}$



- Larger off-peak asymmetry due to radiative Bhabha background and larger detector acceptance in backward (positron-beam) direction

Single Electron Constraint

- First, remove events probabilistically so that the single-electron momentum distribution matches the dilepton momentum distribution

- Then recalculate asymmetries and other values needed as inputs for single-electron constraint:
  - Data asymmetry: $a_{\text{on}} = (4.16 \pm 0.14) \times 10^{-3}$; $a_{\text{cont}} = (11.1 \pm 1.4) \times 10^{-3}$.
  - Continuum fraction: $f_{\text{cont}} = (10.315 \pm 0.016)\%$.
  - $B^0 \overline{B}^0$ fraction in $B\overline{B}$ component: $f_{B^0} = (48.5 \pm 0.6)\%$.
  - Cascade fractions: $f_{B^0}^{\text{casc}} = (19.778 \pm 0.006)\%$; $f_{B^\pm}^{\text{casc}} = (15.347 \pm 0.006)\%$.
  - Fake electron in $B\overline{B}$ component: $f_B^{\text{fake}} = (1.913 \pm 0.005) \times 10^{-3}$,
  - Fake electron asymmetry: $a_B^{\text{fake}} = 35\%$.
  - Direct-/cascade-electron asymmetry difference: $\delta_e^{\text{casc}} \equiv a_e^{\text{casc}} - a_e^{\text{dir}} = (-1.16 \pm 0.25) \times 10^{-3}$.
  - Cascade lepton mistag: $w^{\text{casc}} = (73.77 \pm 0.10)\%$.

- Based on these inputs to $a_{\text{on}} - \alpha = \beta \chi_d A_{CP} + \gamma a_e$, we have:

$$a_{\text{on}} - \alpha = (2.60 \pm 0.20) \times 10^{-3}$$

$$\beta \chi_d = 0.0573 \pm 0.0011$$

$$\gamma = 0.89513 \pm 0.00016$$

Systematic Uncertainties

- Summary of systematic uncertainties on A_{CP}:

Source	(10^{-3})
Generic MC bias correction	1.04
MC branching fractions	0.43
Misidentified lepton corrections in dilepton events	0.77
Misidentified e correction in single electron events	0.65
Neutral/charged B difference	0.74
Direct-/cascade e asymmetry difference	0.44
Direct-/cascade μ asymmetry difference	0.34
Background-to-signal ratios	0.68
Random forest cut efficiency	0.08
Total	1.90

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Direct-/cascade[illegible]	[illegible]
Background-to-[illegible]	[illegible]
Random forest [illegible]	[illegible]
Total	[illegible]

Fitting to generic MC generated with $A_{CP} = 0$ yields $A_{CP} = (-1.00 \pm 1.04) \times 10^{-3}$. We apply a correction based on this and treat the statistical uncertainty on the MC fit as a systematic uncertainty.

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Background-to-…	
Random forest…	
Total	

We correct the MC samples so that important branching fractions in the B decay chain are consistent with the world average. Most corrections are between 0.57 and 1.32. We estimate the systematic uncertainty by varying the corrections over their uncertainties.

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Random forest [illegible]	[illegible]
Total	[illegible]

The misidentified lepton systematics are estimated by varying the uncertainties of the corrections to e^+, e^-, μ^+ and μ^- individually.

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Total	[illegible]

In the single-electron MC sample, the electron charge asymmetry is slightly different for neutral B events vs. charged B events. These cannot be separated in data so we use the average asymmetry in the fit and apply a systematic uncertainty based on the change in A_{CP} after shifting the asymmetry in the signal component of the single-electron sample by half the charge asymmetry difference.

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Background-to-signal ratios	0.68
Random forest cut efficiency	0.08
Total	1.90

In the single-electron MC sample, we find a small difference in charge asymmetry between direct and cascade leptons. We shift the cascade lepton asymmetry to be the same as the direct lepton asymmetry and use the change in A_{CP} as a systematic uncertainty.

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Total	1.90

The background-to-signal ratios $R^{\pm\pm}_{\ell_1\ell_2}$ and $R^{\pm\mp}_{\ell_1\ell_2}$ (for $A_{CP} = 0$) are calculated from MC. We calculate a systematic for the ratios by varying them individually and taking the quadratic sum of the variation in A_{CP}.

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To take into account differences in the RF distribution between data and MC (the selection efficiency for $B\overline{B}$ dilepton events in MC is ~2% larger than for data), we shift the RF selection for the MC sample while keeping it the same for data until the selected MC events are reduced by up to 6%. We take the average change in A_{CP} as our systematic uncertainty.

Fit Results

- Final fit results (statistical errors only):

$$A_{CP} = (-3.9 \pm 3.5) \times 10^{-3}$$

N^0_{ee}	$N^0_{e\mu}$	$N^0_{\mu e}$	$N^0_{\mu\mu}$
430875 ± 515	365343 ± 429	458200 ± 480	268077 ± 391
χ_d^{ee}	$\chi_d^{e\mu}$	$\chi_d^{\mu e}$	$\chi_d^{\mu\mu}$
0.2248 ± 0.0006	0.1769 ± 0.0006	0.1754 ± 0.0005	0.2032 ± 0.0007
a_{e1}	a_{e2}	$a_{\mu 1}$	$a_{\mu 2}$
0.0034 ± 0.0006	0.0030 ± 0.0006	-0.0056 ± 0.0011	-0.0065 ± 0.0011

$$M^{\pm\pm}_{\ell_1\ell_2} = \frac{1}{2} N^0_{\ell_1\ell_2}(1 + R^{\pm\pm}_{\ell_1\ell_2})\left[1 \pm a_{\ell_1} \pm a_{\ell_2} \pm \frac{1 + \delta_{\ell_1\ell_2} R^{\pm\pm}_{\ell_1\ell_2}}{1 + R^{\pm\pm}_{\ell_1\ell_2}} A_{CP}\right]\chi_d^{\ell_1\ell_2},$$

$$M^{\pm\mp}_{\ell_1\ell_2} = \frac{1}{2} N^0_{\ell_1\ell_2}(1 + R^{\pm\mp}_{\ell_1\ell_2})(1 \pm a_{\ell_1} \mp a_{\ell_2})(1 - \chi_d^{\ell_1\ell_2} + r_B),$$

$$a_{\text{on}} = \alpha + \beta\chi_d A_{CP} + \gamma a_\ell,$$

	a_{e_1}	a_{e_2}	a_{μ_1}	a_{μ_2}
A_{CP}	-0.41	-0.47	-0.54	-0.51
a_{e_1}		-0.38	$+0.09$	$+0.39$
a_{e_2}			$+0.46$	$+0.15$
a_{μ_1}				$+0.43$

Asymmetry Correlations

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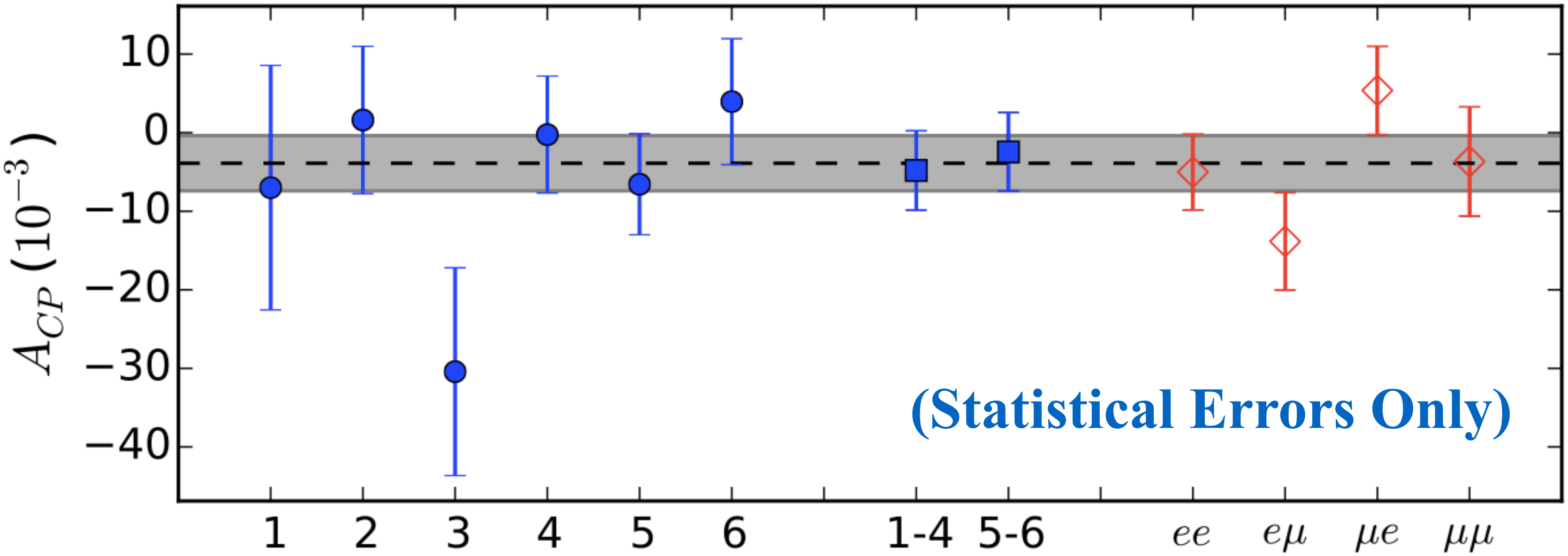
a_{e1}	a_{e2}	$a_{\mu 1}$	$a_{\mu 2}$
0.0034 ± 0.0006	0.0030 ± 0.0006	-0.0056 ± 0.0011	-0.0065 ± 0.0011

- CP Asymmetries divided by data-taking run and flavor combination:



Summary

- We measure the *CP* asymmetry:

  $$A_{CP} = (-3.9 \pm 3.5 \pm 1.9) \times 10^{-3}$$

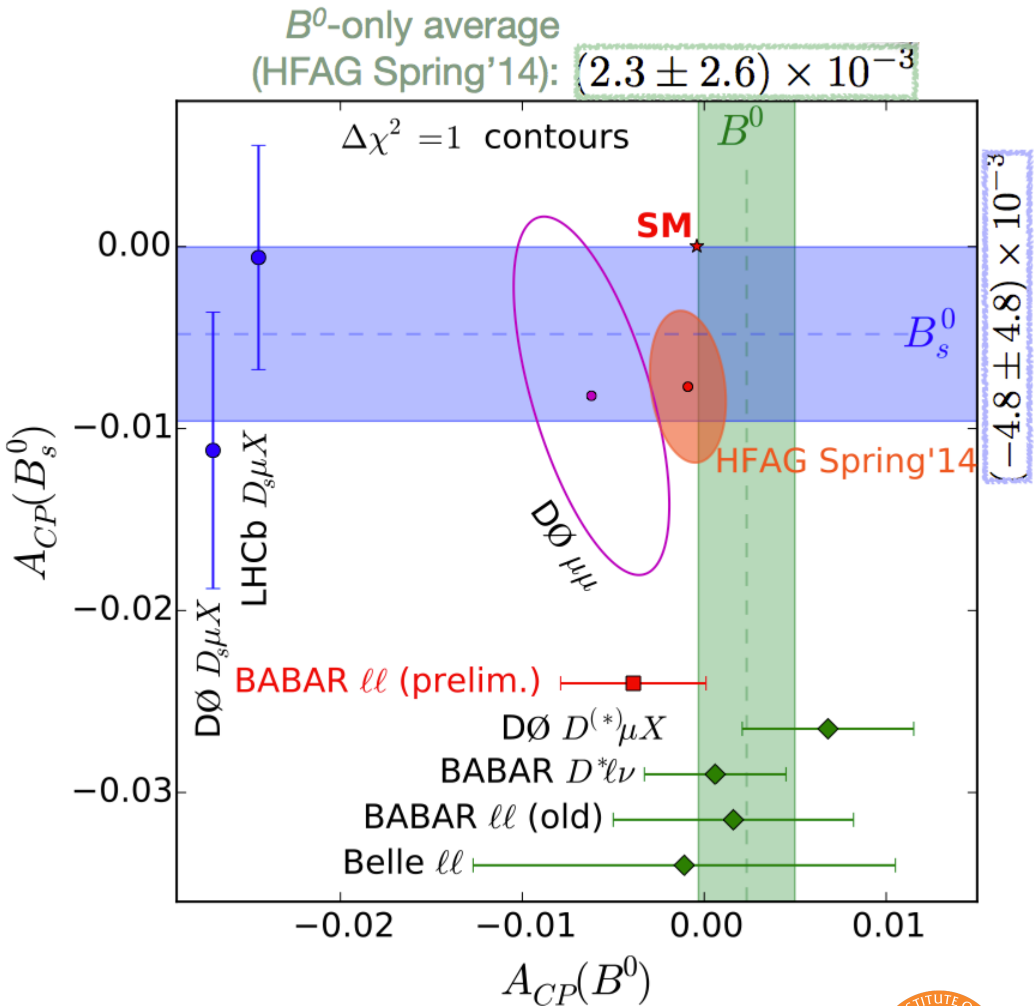
  in $B^0\!-\!\overline{B}^0$ mixing using inclusive dilepton decays at BaBar

- This result is consistent with the SM prediction and the world average

- It is also one of the most precise measurements to date

Measurements of *CP* Asymmetry in Neutral *B* Mixing Before This Measurement

(See next slide for updated results)



Summary

- We measure the *CP* asymmetry:

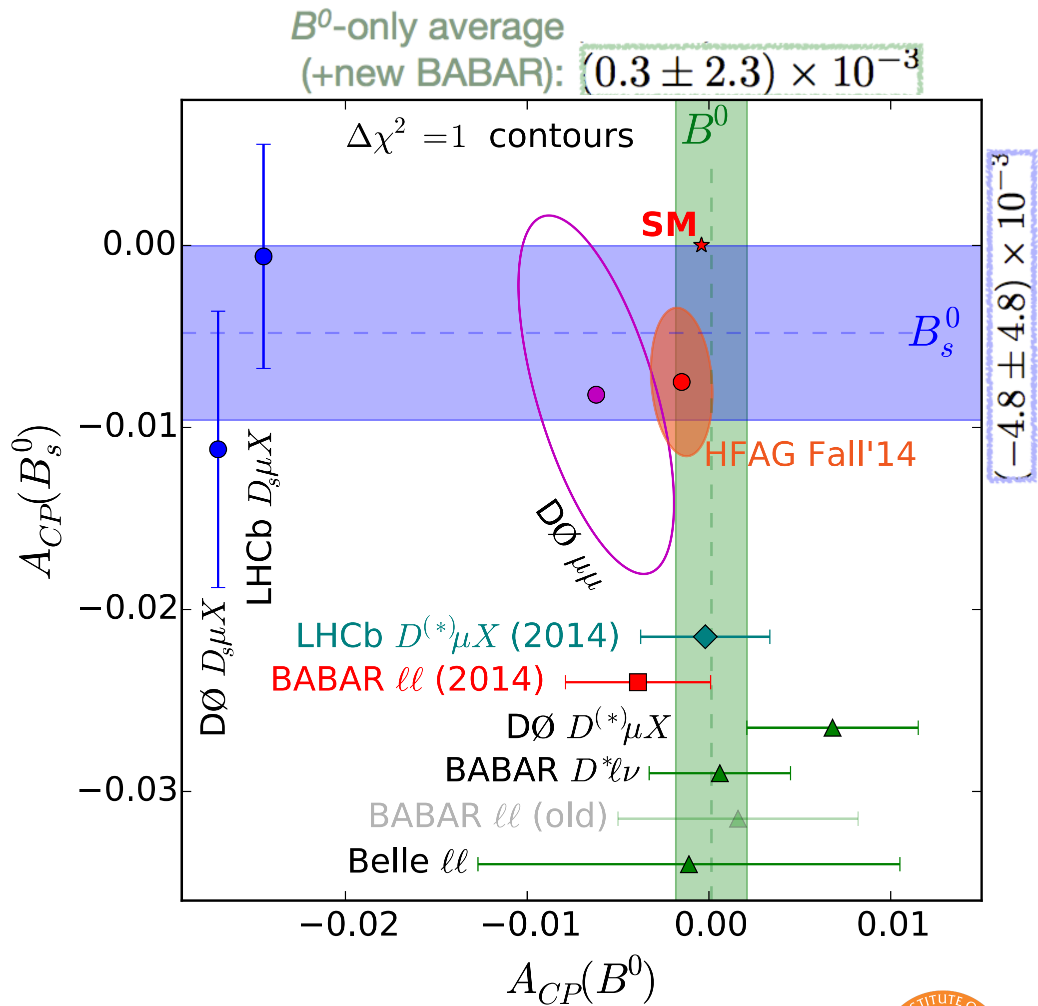
  $$A_{CP} = (-3.9 \pm 3.5 \pm 1.9) \times 10^{-3}$$

  in B^0–$\overline{B}^0$ mixing using inclusive dilepton decays at BaBar

- This result is consistent with the SM prediction and the world average

- It is also one of the most precise measurements to date

Measurements of *CP* Asymmetry in Neutral *B* Mixing Including This Measurement



Backup Slides

Event Yields

- Continuum-subtracted number of events:

	$\ell^+\ell^+$	$\ell^+\ell^-$	$\ell^-\ell^+$	$\ell^-\ell^-$
ee	$82\,303 \pm 320$	$426\,296 \pm 783$	$425\,309 \pm 782$	$81\,586 \pm 323$
$e\mu$	$55\,277 \pm 263$	$384\,552 \pm 684$	$378\,261 \pm 660$	$55\,878 \pm 264$
μe	$67\,399 \pm 290$	$467\,591 \pm 737$	$475\,363 \pm 744$	$67\,152 \pm 290$
$\mu\mu$	$47\,384 \pm 243$	$277\,936 \pm 619$	$278\,691 \pm 618$	$48\,145 \pm 247$