Mixing induced *CP* asymmetry in semileptonic *B*-meson decays at *BABAR*

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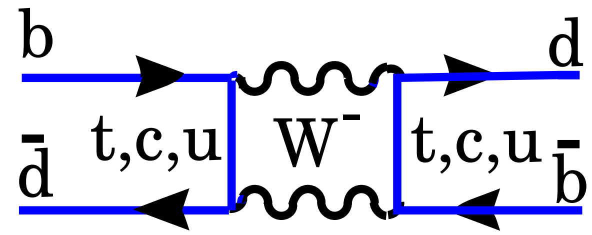
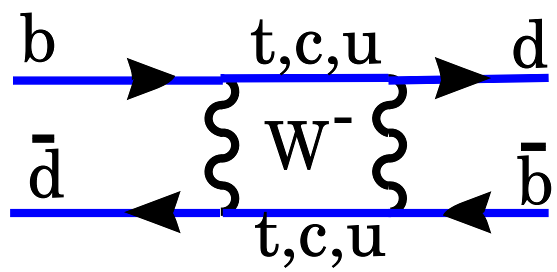
Neutral meson mixing

- In neutral meson systems, particle/antiparticle can couple to each other through weak interaction:

$$B^0_{d,s} \leftrightarrow \overline{B}^0_{d,s},\ D^0 \leftrightarrow \overline{D}^0,\ K^0 \leftrightarrow \overline{K}^0$$



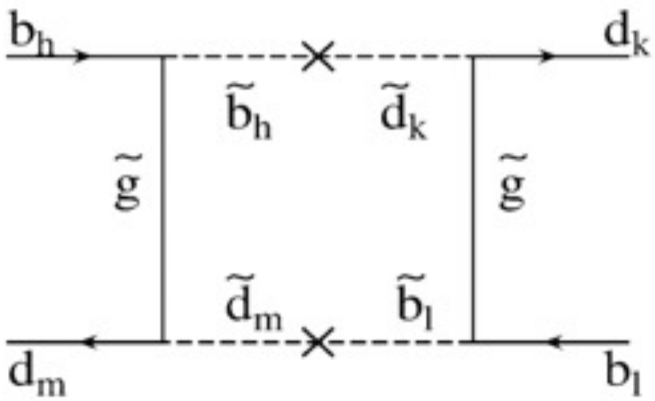


- Equation of a decaying particle : $B(t) = \exp[-imt - (\Gamma/2)t]$

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

  - ✦ Off-diagonal elements M_{12}, Γ_{12} in the matrix are non-trivial (and complex).

- Measurements of various aspects of mixing test the theory of weak interaction.
  - ✦ Mixing rate, decay rate difference, *CP* violation.
- New physics in the loops could alter these observables.

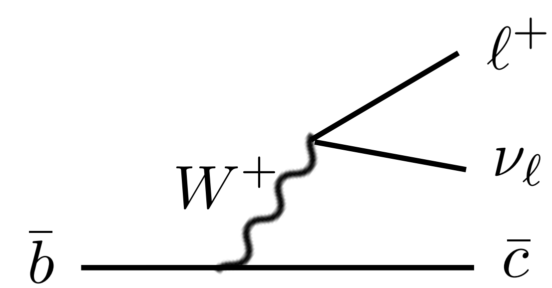


Mixing induced *CP* violation

- The eigenstates of the neutral *B* system are linear combinations of flavor states $|B^0\rangle$ and $|\overline{B}^0\rangle$

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

- For flavor specific final states: $B^0 \to f,\ \overline{B}^0 \to \bar{f};\ B^0 \not\to \bar{f},\ \overline{B}^0 \not\to f$
  - ✦ E.g., semileptonic decays: $B^0 \to X\ell^+\nu_\ell$
  - ✦ Assume no direct *CPV*: $|\langle f|B^0\rangle| = |\langle \bar{f}|\overline{B}^0\rangle|$
  - ✦ *CP* violation due to mixing:



$$A_{\rm sl} = \frac{\Gamma(\overline{B}^0(t=0)\to f) - \Gamma(B^0(t=0)\to \bar{f})}{\Gamma(\overline{B}^0(t=0)\to f) + \Gamma(B^0(t=0)\to \bar{f})} = \frac{1-|q/p|^4}{1+|q/p|^4} \simeq -2\left(\left|\frac{q}{p}\right| - 1\right) \simeq {\rm Im}\frac{\Gamma_{12}}{M_{12}}$$

$$\simeq \frac{\Delta\Gamma}{\Delta M}\tan\phi$$

$\overline{B}^0 \to B^0$, then decay to the "wrong sign" final state *f*.

CPV if $|q/p| \neq 1$

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Search/constrain new physics

- Standard Model prediction is small:

$$A_{\mathrm{sl}}^s = (1.9 \pm 0.3) \times 10^{-5}$$
$$A_{\mathrm{sl}}^d = -(4.1 \pm 0.6) \times 10^{-4}$$

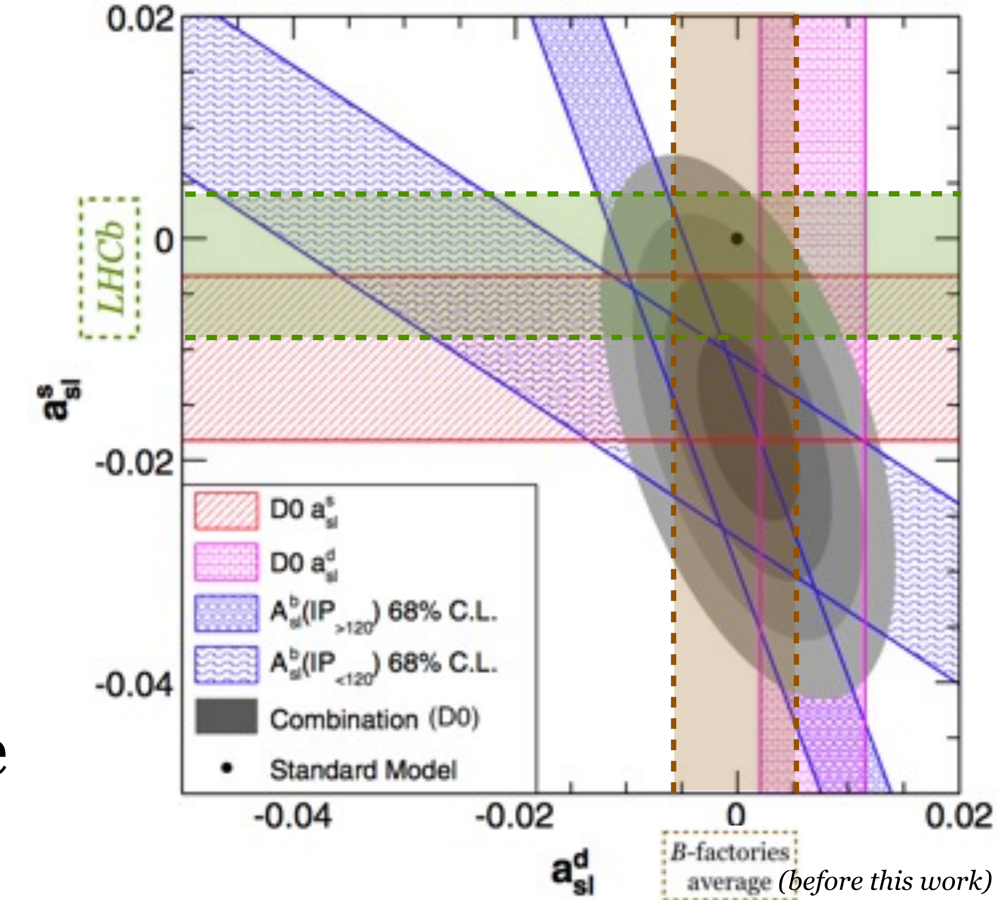
[Lenz, Nierste, arXiv:1102.4274 (2011)]

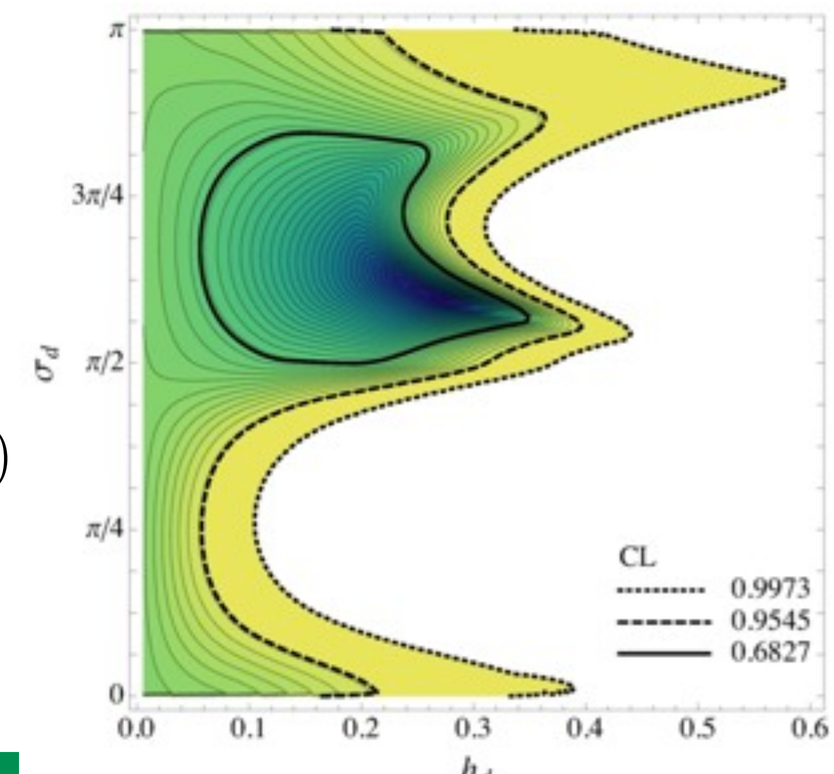
  - ✦ well below current experimental sensitivity ($\mathcal{O}(10^{-3})$).
  - ✦ observation of non-zero *CPV* would indicate new physics.
  - ✦ Some tension observed in D0 di-muon analysis

- Allowed new physics (model independent) parameter space is still sizable.

$$M_{12}^{d,s} = \left(M_{12}^{d,s}\right)^{\mathrm{SM}} \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

[Ligeti, et al. PRL 105, 131601 (2010)]



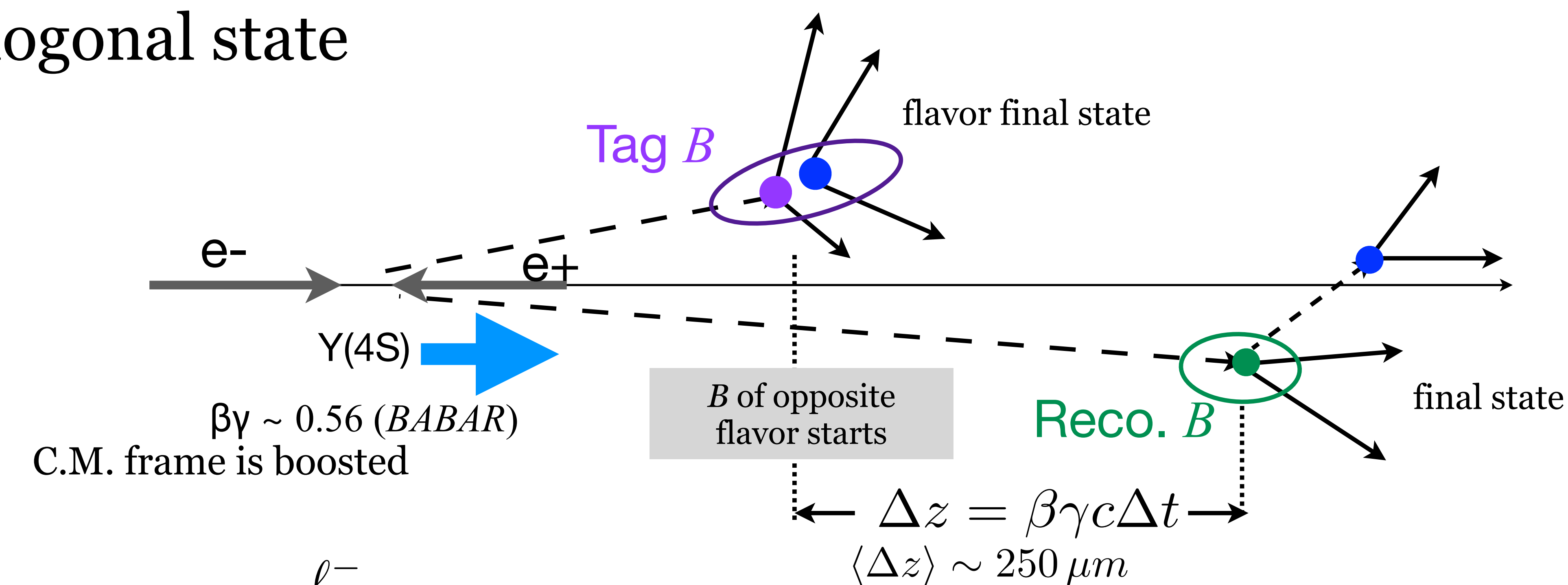


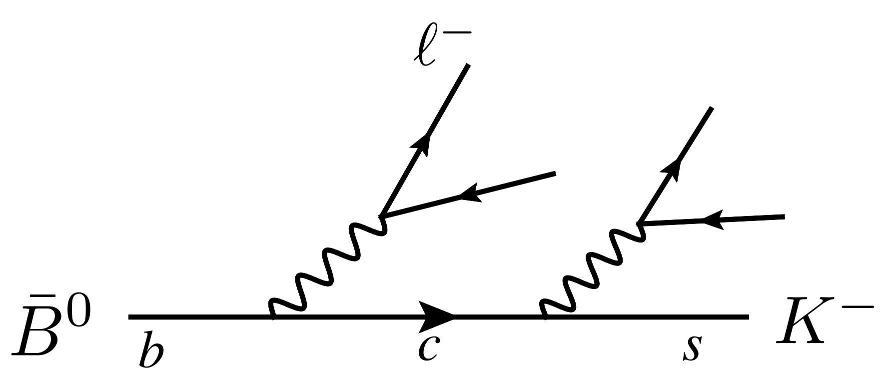
Experiment

- In B factories $\Upsilon(4S)$ are produced and decay to a pair of B mesons in a coherent L=1 antisymmetric quantum state

$$|i>= 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]$$

- Once one B decays to a basis state, the other projects to the orthogonal state





Charge of lepton or kaon indicates the flavor of the B at the time of decay.

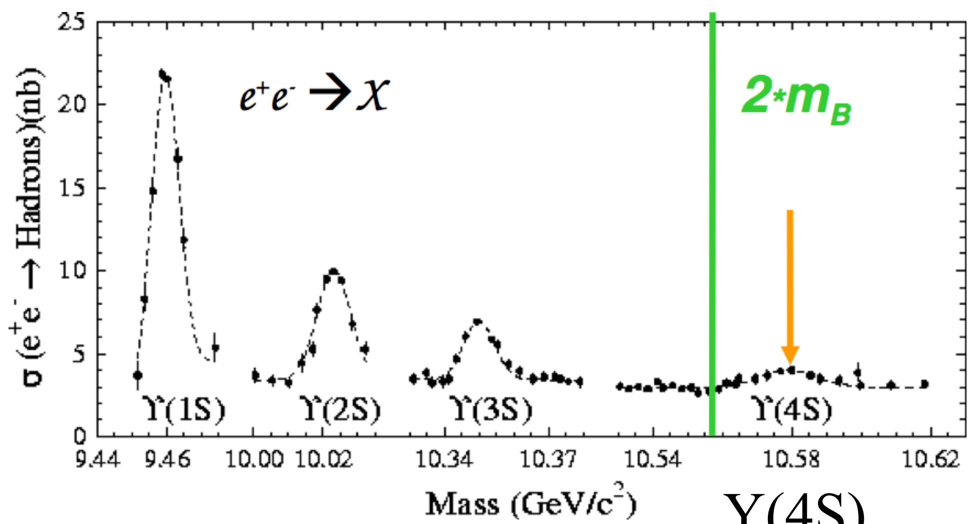
Experiment

- Reconstruct $B^0 \to \ell^+ \nu_\ell D^{*-}$ using a partial reconstruction technique.
- Find the flavor of the "tag *B*" using charged kaons in the rest of the event.
- The "wrong-sign" decays (via mixing) are identified by same-sign lepton-kaon combination:

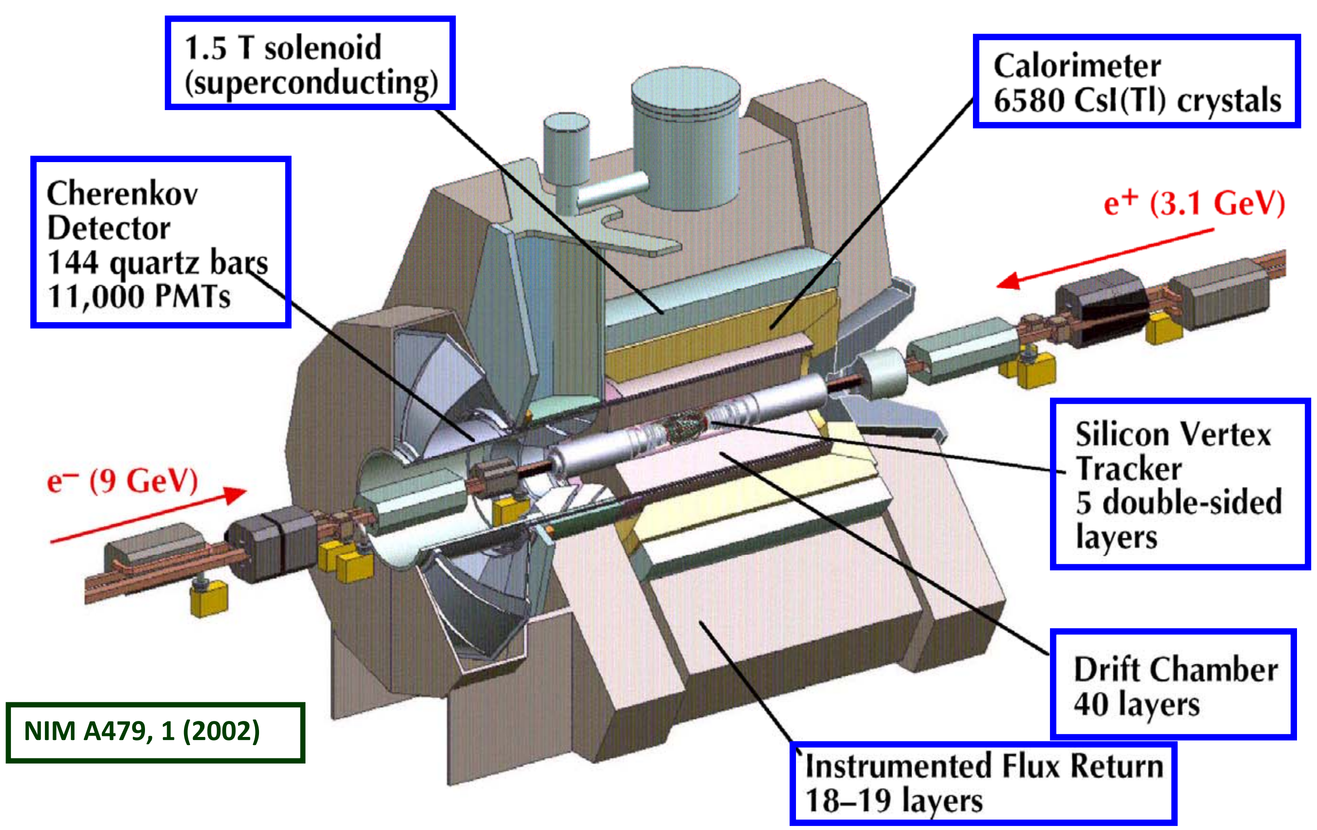
$$A_{\rm sl} = \frac{N(B^0 B^0) - N(\overline{B}^0 \overline{B}^0)}{N(B^0 B^0) + N(\overline{B}^0 \overline{B}^0)} = \frac{N(\ell^+ K^+) - N(\ell^- K^-)}{N(\ell^+ K^+) + N(\ell^- K^-)}$$

- Partial reconstruction gives higher efficiency than exclusive reconstruction, and better purity than inclusive lepton reconstruction.
- Kaon tag has a higher efficiency than lepton tag.
  - ✦ Somewhat higher mistag probability
  - ✦ Need to take care of interference due to doubly-Cabibbo-suppressed decay

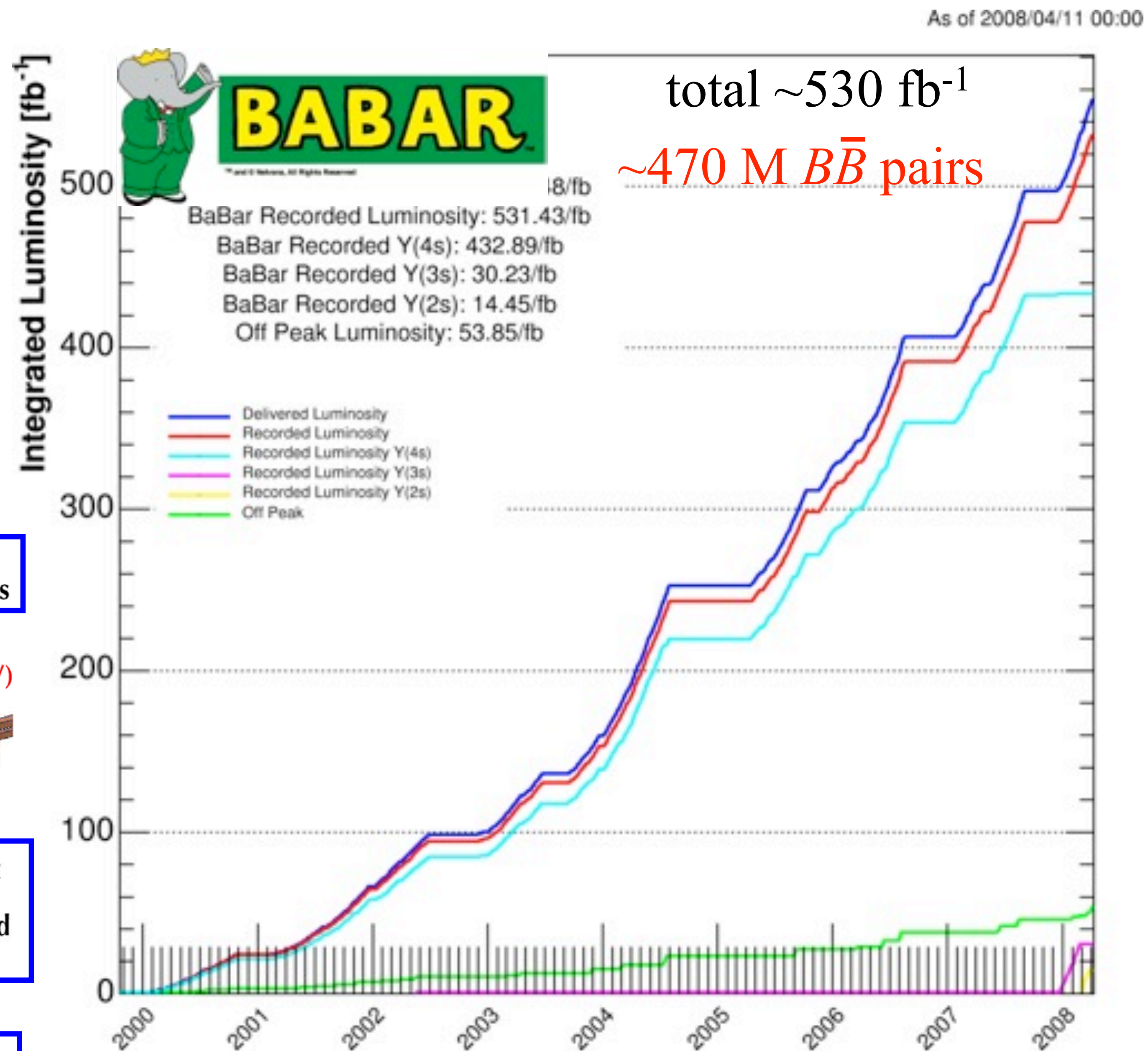
Dataset and detector



Υ(4S)



NIM A479, 1 (2002)

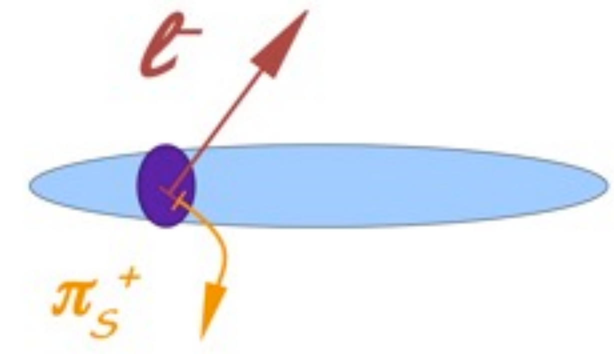


total ~530 fb^{-1}

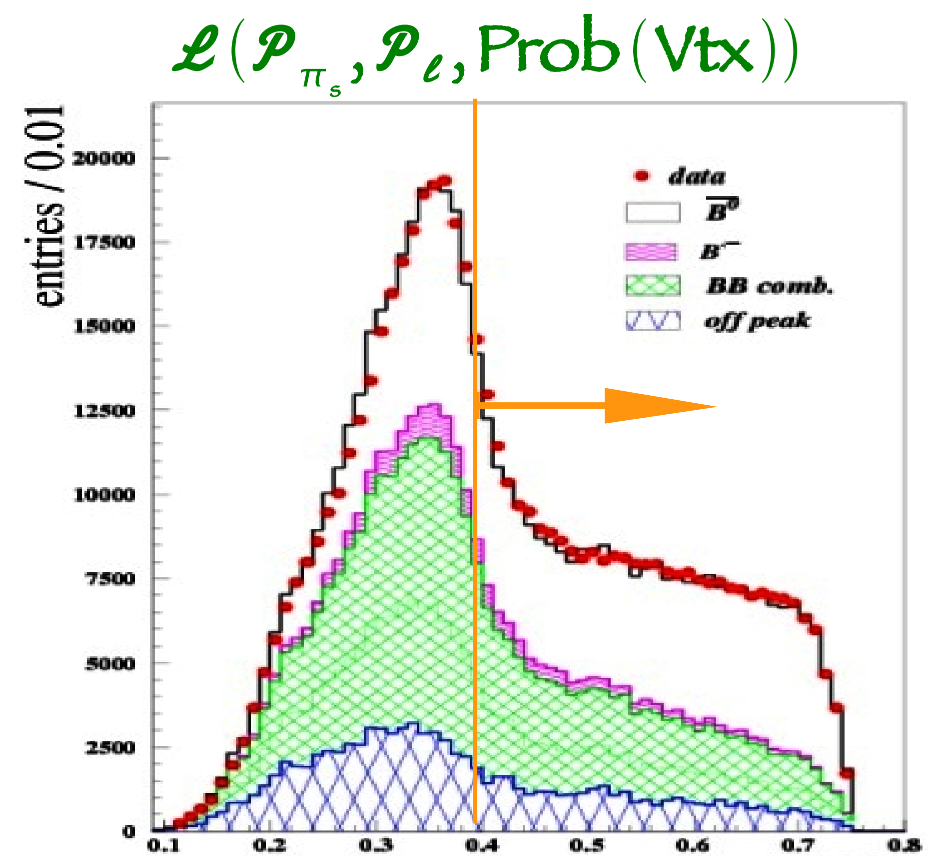
~470 M $B\bar{B}$ pairs

$B \to \ell \nu D^*$ partial reconstruction

- Use only lepton (e, μ) and the low momentum π_s of the opposite sign from $D^{*-} \to \pi_s^- \overline{D}^0$, ignoring the remaining products from charm.
- Assume B at rest in Υ(4S) frame.
- Approximate D^* direction using π_s: $\vec{p}_{D^*} = f(\vec{\pi_s})$
- Reconstruct B decay vertex using a beamspot constraint:



- Build a likelihood ratio function using lepton and pion momenta, and vertexing probability to reduce background.



$B \rightarrow \ell\nu D^*$ partial reconstruction

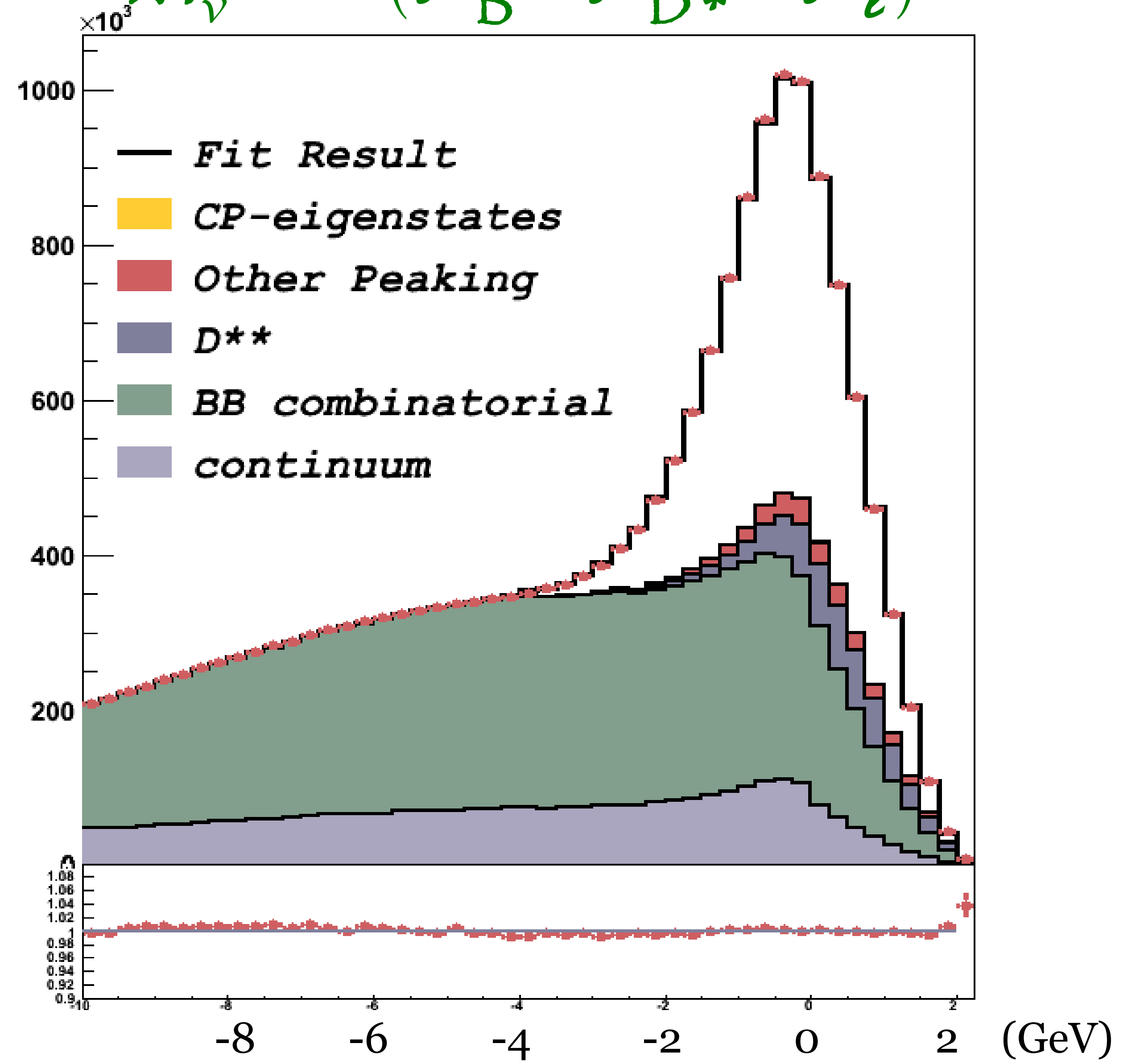
- Assume only the neutrino is not accounted for, and then calculate the missing neutrino mass
- Good signal

$$B^0 \rightarrow D^{*-}(X)\ell^+\nu_\ell$$
$$B^0 \rightarrow D^{*-}(X)\tau^+\nu_\tau;\ \tau^+ \rightarrow \ell^+\nu_\ell\bar{\nu}_\tau$$
$$B^0 \rightarrow D^{*-}h^+;\ \text{(misidentified)}$$

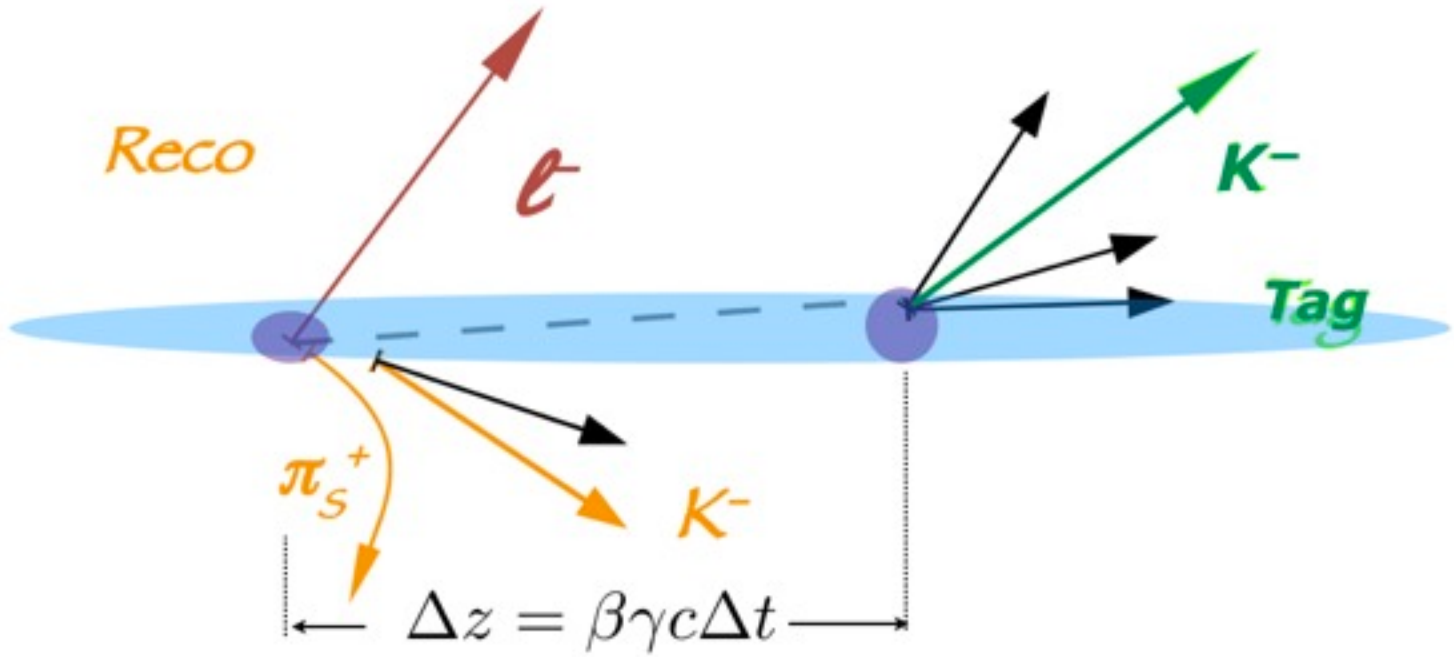
- Peaking but no B^o flavor info
  - ✦ double charm followed by charm semileptonic decay
  - ✦ charged B.
- Yield:

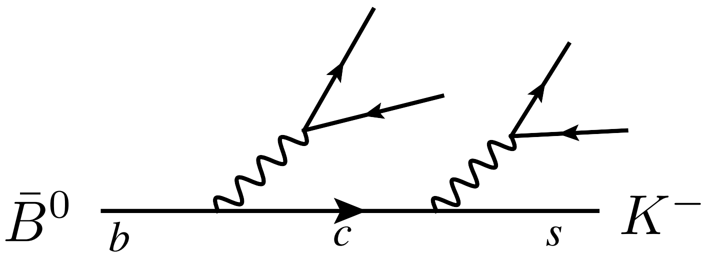
(5945 ± 7)×10³ peaking events

$$M_\nu^2 = (\mathcal{P}_B - \mathcal{P}_{D*} - \mathcal{P}_\ell)^2$$



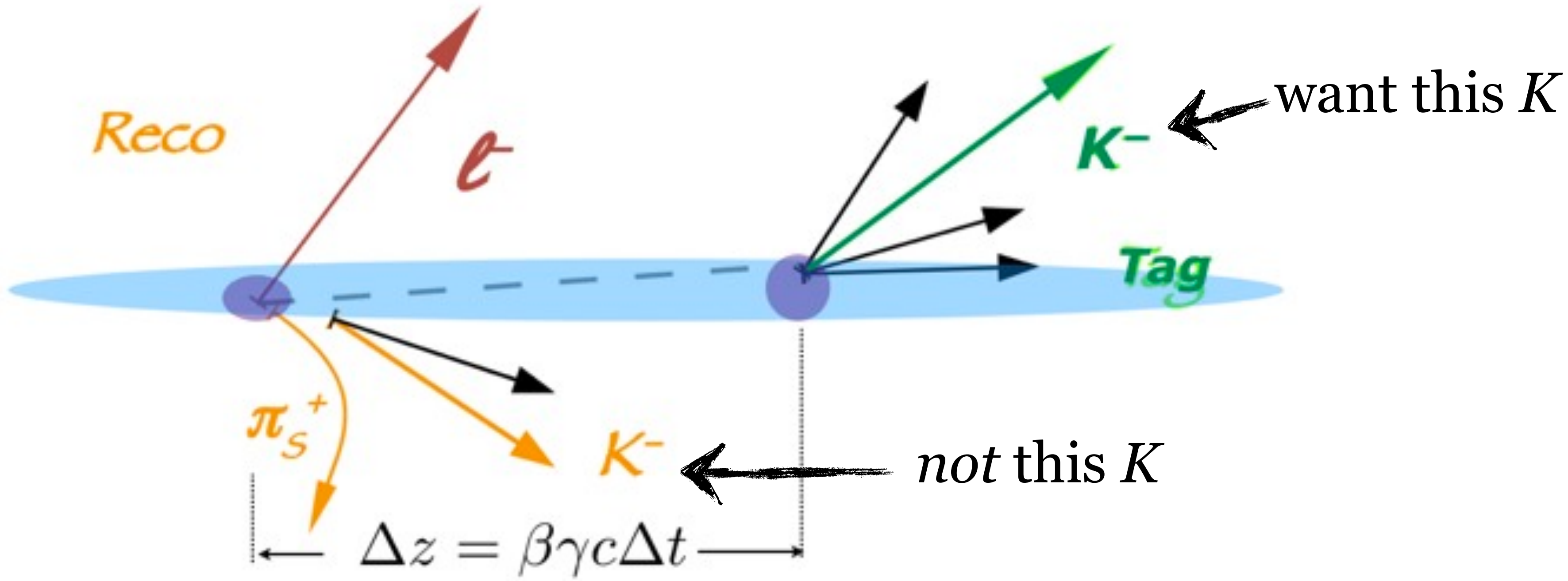
Kaon tag





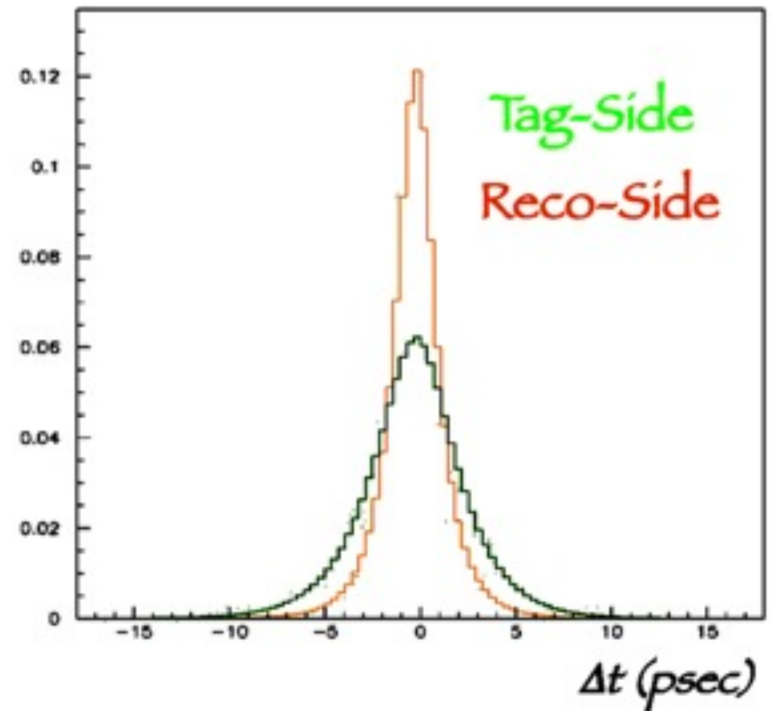
- Kaons are identified using ionization energy loss in the tracking devices and Cherenkov angles: ~85% efficiency, ~3% pion misidentification.
- Tag-*B* vertex is identified by intersecting kaon track with the beamspot.
- Define $\Delta t = \dfrac{z_{\text{reco.}} - z_{\text{tag}}}{\gamma\beta c}$, which should follow *B* decay distribution (plus some smearing from charm lifetime) for signal events.

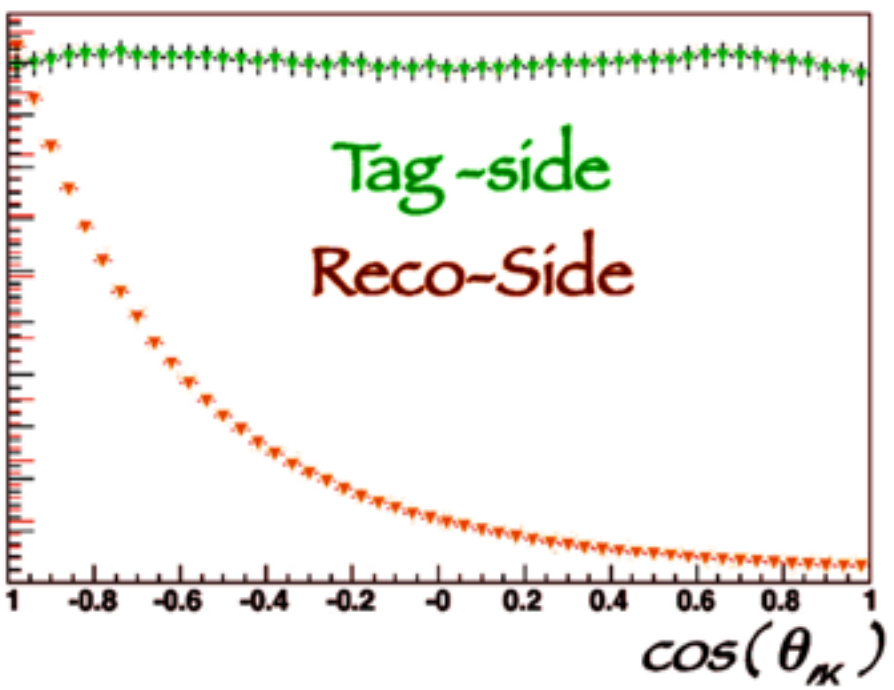
Kaon tag



- Kaon can also come from the reco. side, mimicking a mixed event.

Use Δt and angular correlation in the PDF to separate the two.





Contributing asymmetries

- Observed asymmetry has contributions from physics and detector.

- Observed asymmetry for same-sign signal events with tag-side kaon reflects (ℓ, π_s) *reconstruction charge asymmetry, kaon-id charge asymmetry, and physics* A_{sl}.
  - ✦ $A_{obs;K\text{-}tag} \simeq A_{\ell\pi} + A_K + A_{sl}$

- If kaon is from reco. side, then physics A_{sl} contribution is diluted by the mixing probability χ_d. (mixed and unmixed are equally likely to be reconstructed.)
  - ✦ $A_{obs;K\text{-}rec} \simeq A_{\ell\pi} + A_K + \chi_d A_{sl}$

- Asymmetry before kaon tagging $\frac{N(\ell^+\pi_s^-) - N(\ell^-\pi_s^+)}{N(\ell^+\pi_s^-) + N(\ell^-\pi_s^+)}$
  - ✦ $A_{obs;rec} \simeq A_{\ell\pi} + \chi_d A_{sl}$

- We have enough observables to determine all three $A_{\ell\pi}$, A_K, and A_{sl} from data simultaneously.

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$$\frac{N(\ell^+\pi_s^-) - N(\ell^-\pi_s^+)}{N(\ell^+\pi_s^-) + N(\ell^-\pi_s^+)}$$

- We have enough observables to determine all three $A_{\ell\pi}$, A_K, and A_{sl} from data simultaneously.

Signal physics model

- Without interference from doubly-Cabibbo-suppressed decays (DCSD) on the tag side, the underlying physics would be relatively simple:

opposite-sign/ unmixed

$$\begin{cases} \mathcal{F}_{\overline{B}^0 B^0}(\Delta t) = \dfrac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2}\left[\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m_d \Delta t)\right] \\ \mathcal{F}_{B^0 \overline{B}^0}(\Delta t) = \dfrac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2}\left[\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m_d \Delta t)\right] \end{cases}$$

same-sign/ mixed

$$\begin{cases} \mathcal{F}_{\overline{B}^0 \overline{B}^0}(\Delta t) = \dfrac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2}\left[\cosh(\Delta\Gamma\Delta t/2) - \cos(\Delta m_d \Delta t)\right]\left|\dfrac{q}{p}\right|^2 \\ \mathcal{F}_{B^0 B^0}(\Delta t) = \dfrac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2}\left[\cosh(\Delta\Gamma\Delta t/2) - \cos(\Delta m_d \Delta t)\right]\left|\dfrac{p}{q}\right|^2 \end{cases}$$

Signal physics model

- Including interference from doubly-Cabibbo-suppressed decays (DCSD) on the tag side.

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

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

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$$r' \sim \frac{\mathcal{A}(\bar{b} \to \bar{u}c\bar{d})}{\mathcal{A}(b \to c\bar{u}d)} \sim \mathcal{O}(\%)$$

$$b = 2r' \sin(2\beta+\gamma)\cos\delta'$$

$$c = -2r' \cos(2\beta+\gamma)\sin\delta'$$

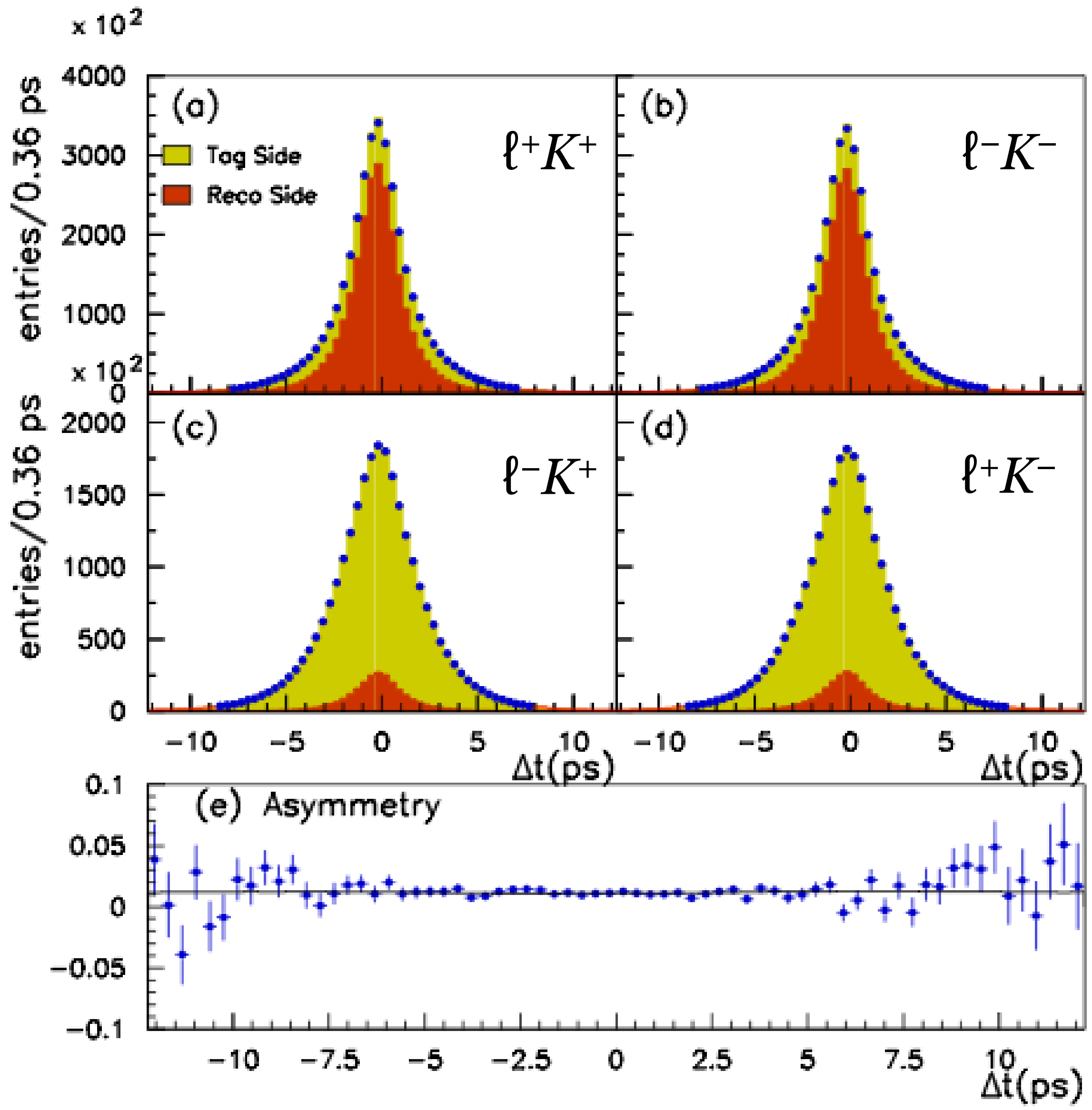
Fitting

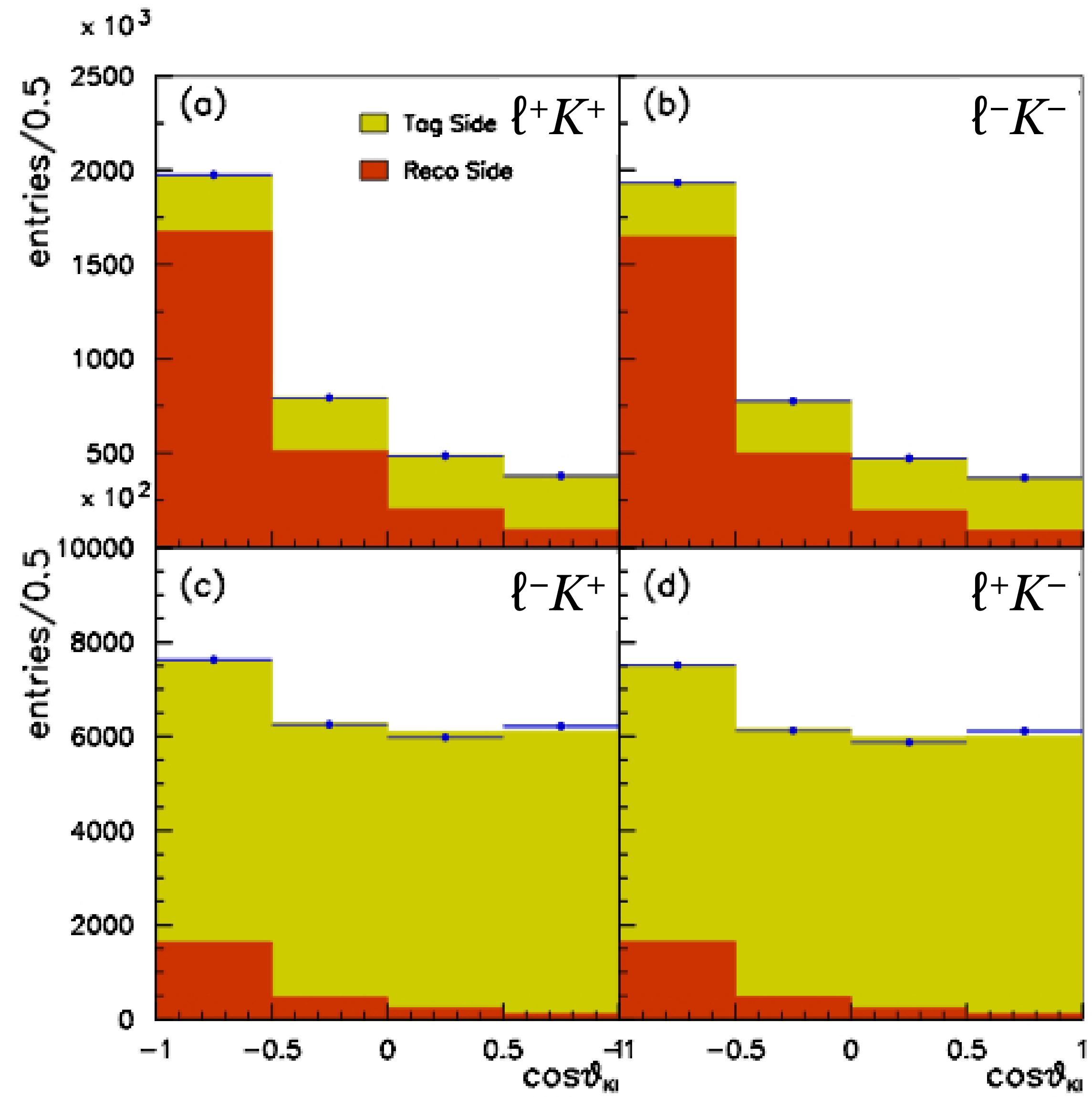
- Five variables (Δt, $\sigma_{\Delta t}$, $\cos\theta_{\ell K}$, M_ν^2, p_K) binned fit to separate signal to background, tag-side kaon from reco-side.
- Also include opposite-sign (unmixed) events ℓ^+K^-/ℓ^-K^+ to improve resolution and mis-tag parameters, etc.
- More than 100 free parameters:
  - ✦ A_{sl}, $A_{\ell\pi}$, A_K,
  - ✦ reco-side K fraction,
  - ✦ wrong tag fractions (charge dependent),
  - ✦ Doubly-Cabibbo-suppressed decay parameters,
  - ✦ Δt resolution parameters,
  - ✦ B lifetime, mixing rate, etc.

Result

$$A_{\rm sl} = (0.6 \pm 1.6^{+3.6}_{-3.2}) \times 10^{-3}$$

BABAR Preliminary





Result summary

- Lifetime and mixing rate consistent with the world average.
- A few per mille reconstruction asymmetry.
- Order of a percent kaon tag asymmetry.
- Fit to MC reproduces the generated value (also checked varying the generated value).

	Fit to Data	Fit to MC	MC value
$A_{\rm sl}$	$(0.6 \pm 1.6) \times 10^{-3}$	$(0.4 \pm 0.5) \times 10^{-3}$	0
$A_{e\pi_s}$	$(3.0 \pm 0.4) \times 10^{-3}$	$(9.7 \pm 0.2) \times 10^{-3}$	-
$A_{\mu\pi_s}$	$(3.1 \pm 0.5) \times 10^{-3}$	$(8.4 \pm 0.3) \times 10^{-3}$	-
A_K	$(13.7 \pm 0.3) \times 10^{-3}$	$(14.7 \pm 0.1) \times 10^{-3}$	-
τ_B^0	1.5535 ± 0.0019	1.5668 ± 0.0012	1.540
Δm_d	0.5085 ± 0.0009	0.4826 ± 0.0006	0.489

$$\Delta_{CP} = 1 - \left|\frac{q}{p}\right| \simeq \frac{1}{2} A_{\rm sl}$$

Source	$\sigma(\Delta_{CP})$
Peaking Sample Composition	$^{+1.50}_{-1.17} \times 10^{-3}$
Combinatorial Sample Composition	$\pm 0.39 \times 10^{-3}$
Δt Resolution Model	$\pm 0.60 \times 10^{-3}$
K_R Fraction	$\pm 0.11 \times 10^{-3}$
K_R Δt Distribution	$\pm 0.65 \times 10^{-3}$
Fit Bias	$^{+0.58}_{-0.46} \times 10^{-3}$
CP eigenstate Description	± 0
Physical Parameters	$^{+0}_{-0.28} \times 10^{-3}$
Total	$^{+1.88}_{-1.61} \times 10^{-3}$

Conclusions

$$A_{\rm sl} = (0.6 \pm 1.6^{+3.6}_{-3.2}) \times 10^{-3}$$

BABAR Preliminary
[accepted by PRL]

- Consistent with and more precise than previous *B* factories average $(-0.5\pm5.6)\times10^{-3}$.
- Competitive and complementary to similar measurements at hadron colliders.
- Result consistent with the Standard Model, no sign of *CP* violation in B_d mixing.
    - ✦ tension still exists in B_s mixing; *B* factories are not able to contribute to that measurement.