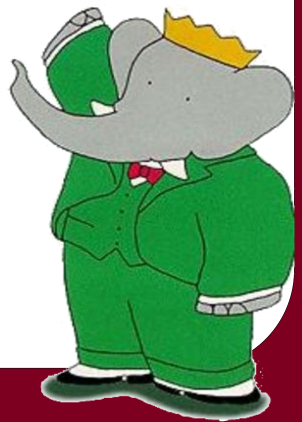
Recent BABAR results on T, CP AND CPT symmetries

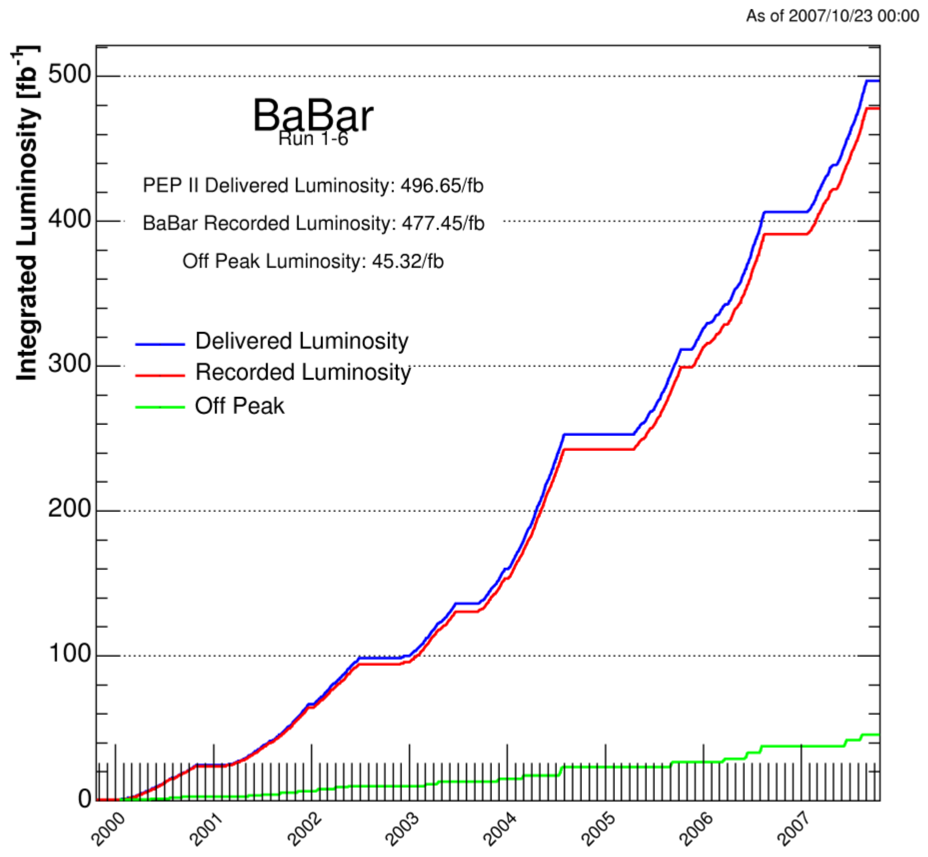
DESY Seminars:
Hamburg May 14th,
Berlin May15th



OUTLINE

- Introduction : reminder of a success
- First direct observation of T symmetry violation in the evolution and decay of the B^0 meson
- Search for mixing-induced CP violation with a new approach

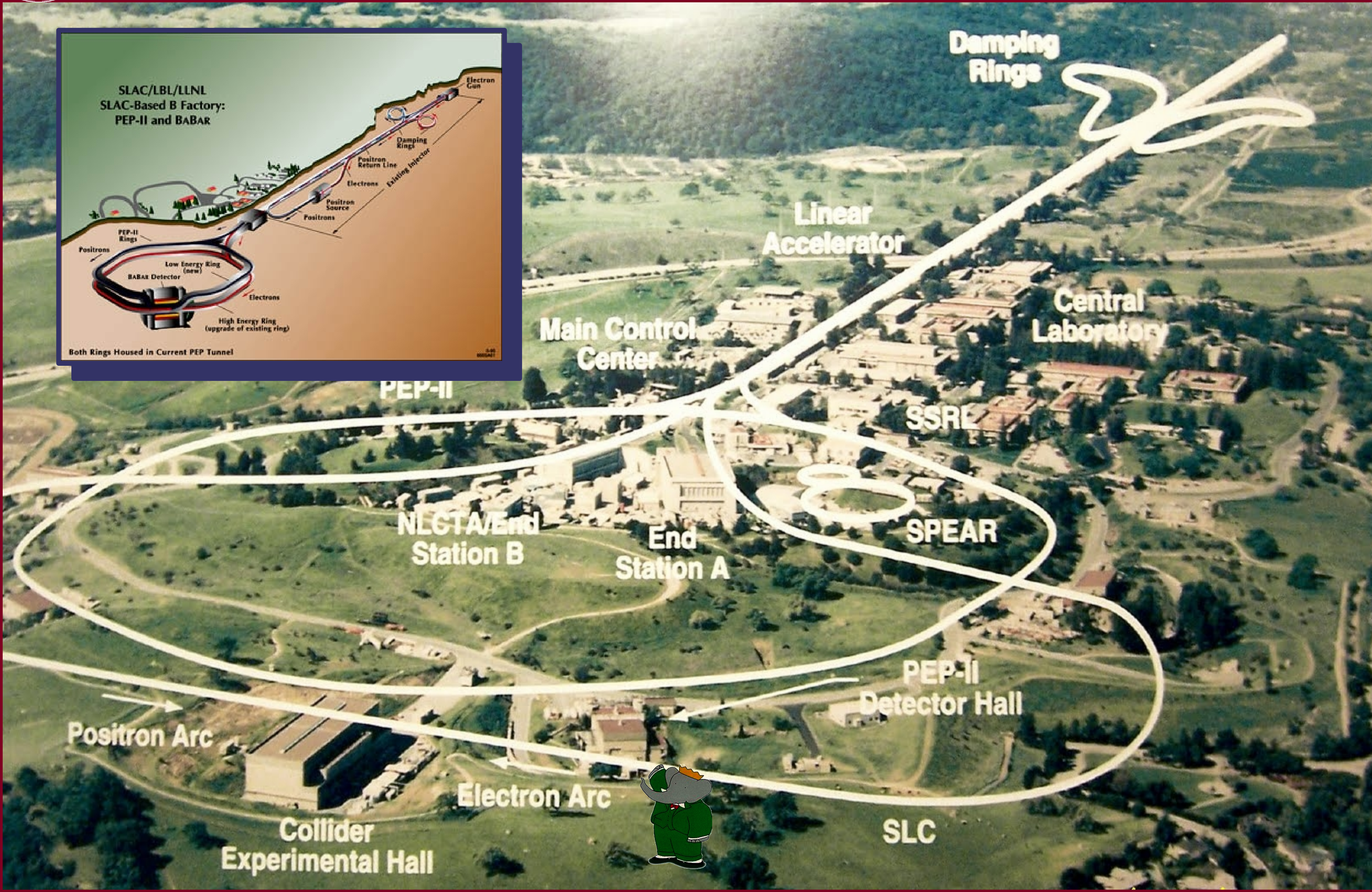
BaBar : history of a success



22/10/1999 -> 07/04/2008 :

- 530 fb^{-1} collected
- > 500 million $B\bar{B}$, $c\bar{c}$, $\tau\tau$ pairs
- 516 published papers

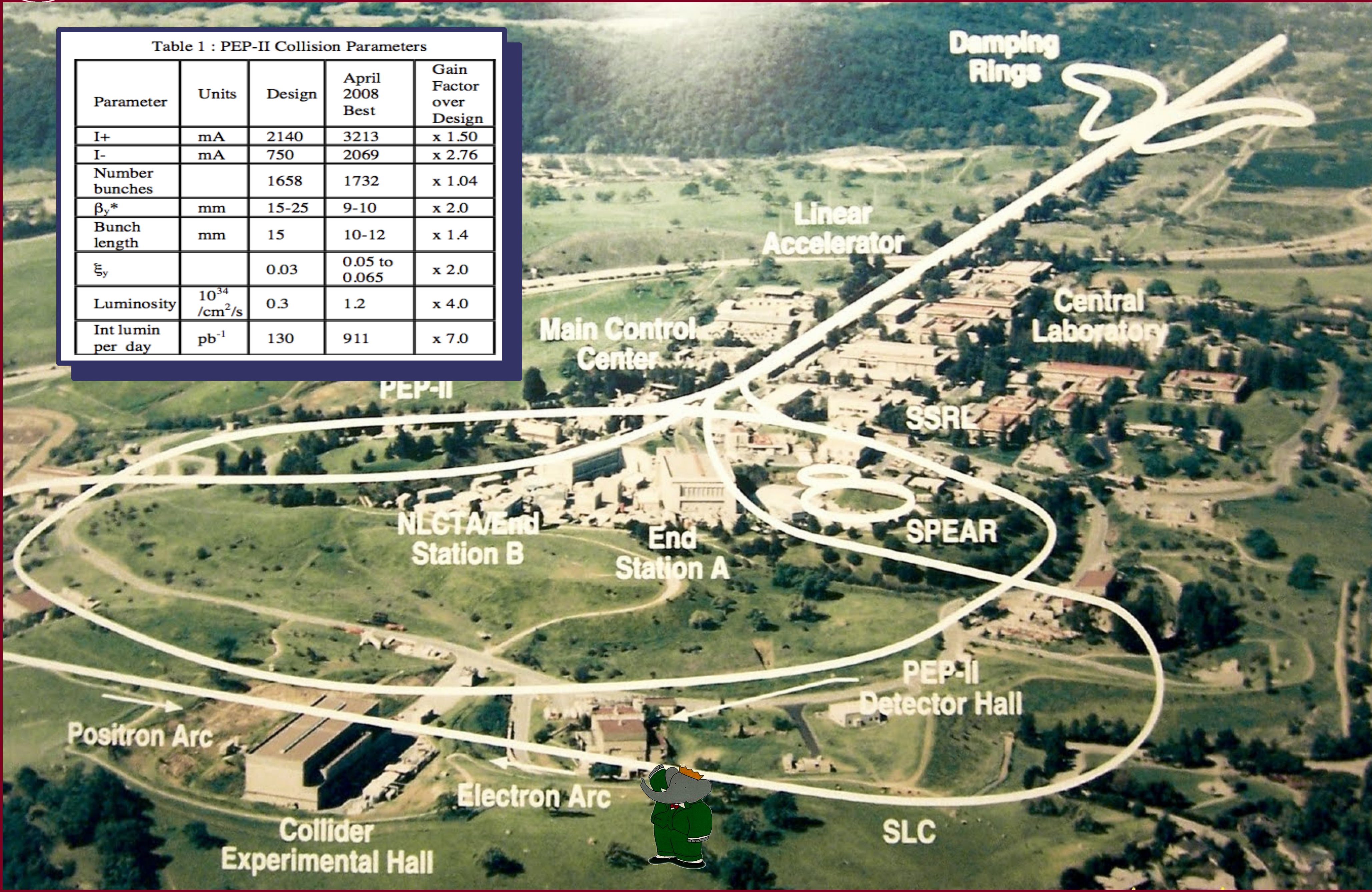
Tools for a success : the factory



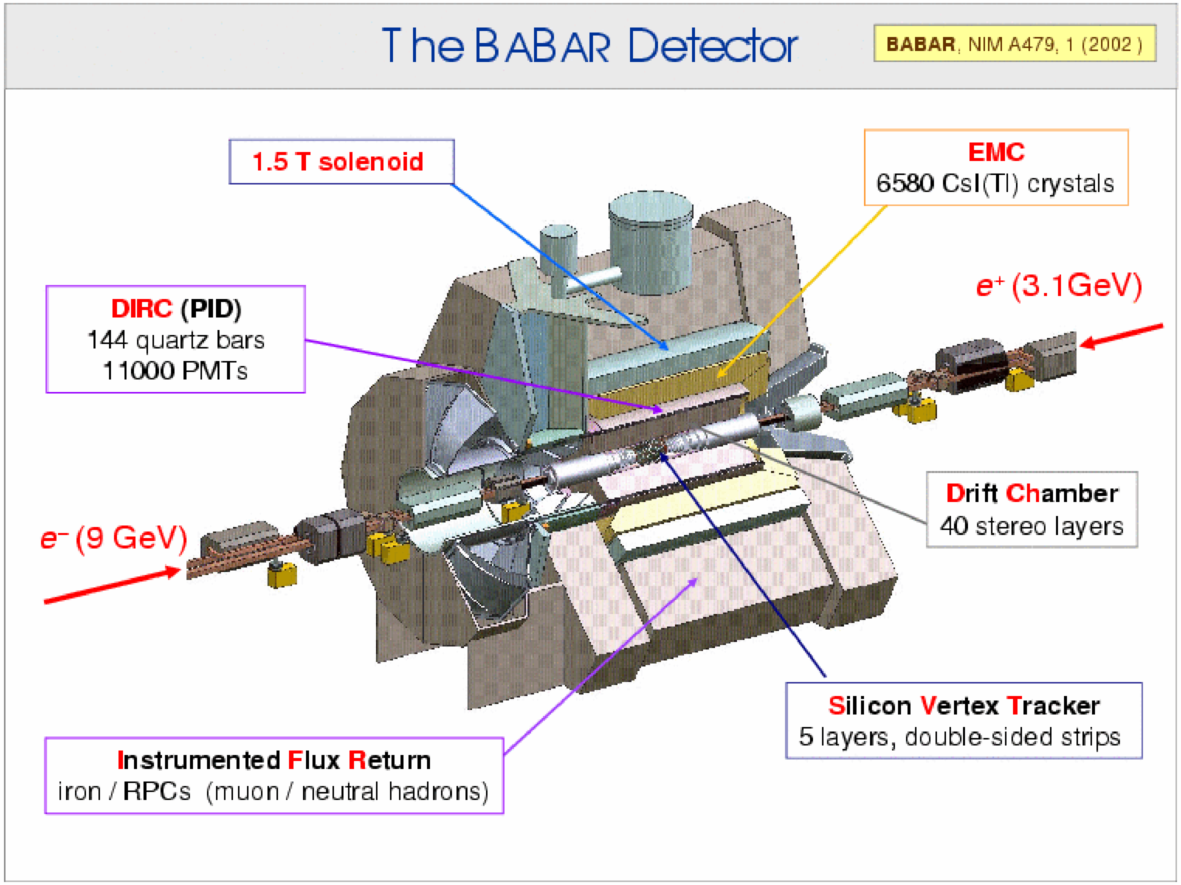
Tools for a success : the factory

Table 1 : PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3213	x 1.50
I-	mA	750	2069	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	10-12	x 1.4
ξ_y		0.03	0.05 to 0.065	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0



Tools for a success: the Detector



Silicon Vertex Tracker :

$$\sigma(\Delta Z)_{VERTEX} = 180\,\mu m$$

Tracking (SVT+DCH) :

$$\sigma(p_T)/p_T = (0.13\,p_T + 0.45)\%$$

PID (dE/dX + DIRC) :

$$\pi/K @ 4\sigma \quad (0.1 \rightarrow 4\,GeV)$$

EMC :

$$\sigma(E)/E = 2.3\,E^{-1/4} \oplus 1.85\%$$

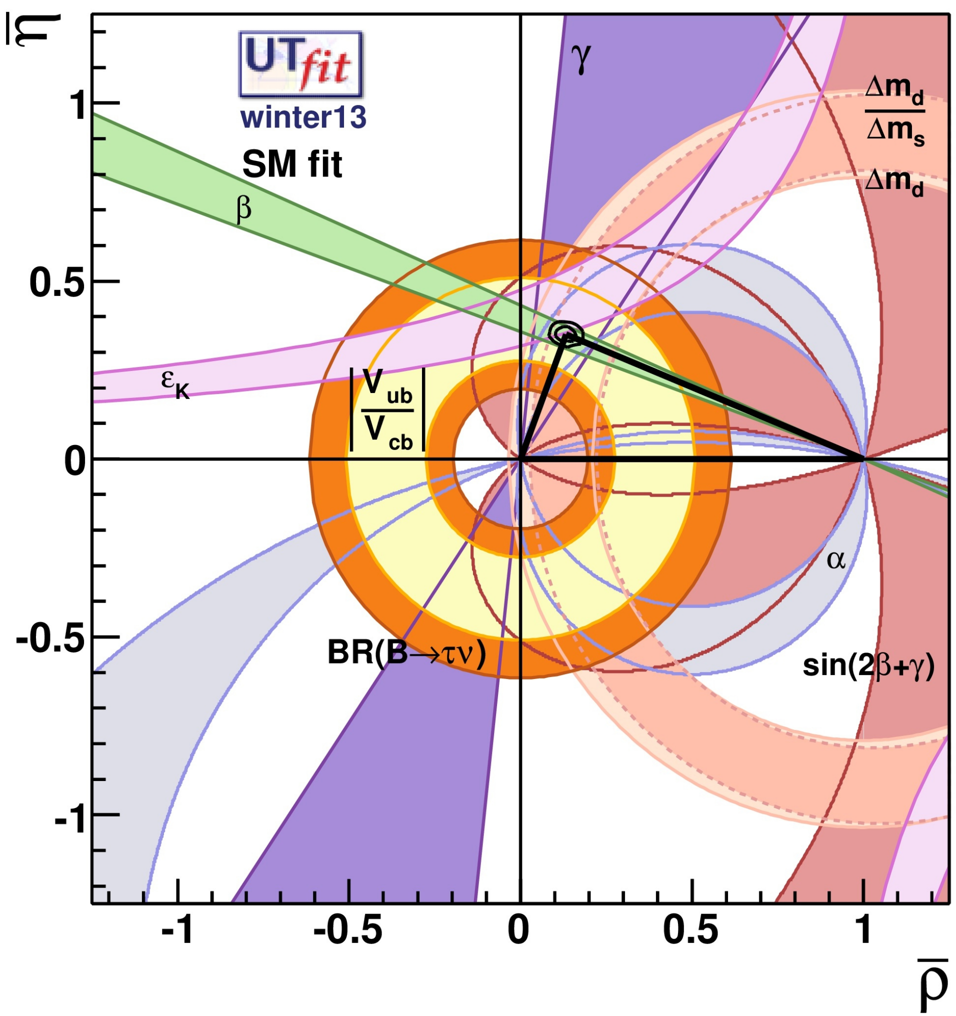
Instrumented Flux Return :

$$\epsilon_{\mu} \simeq 70\%$$

$$\epsilon_{\pi,K\rightarrow\mu} \simeq 2\%$$

θ, ϕ for hadron showers

Highlights: confirmation of CKM Pattern



- Fit to unitary triangle confirms Cabibbo-Kobayashi-Maskawa mechanism as sole source of CP-violation in hadron system evolution and decay

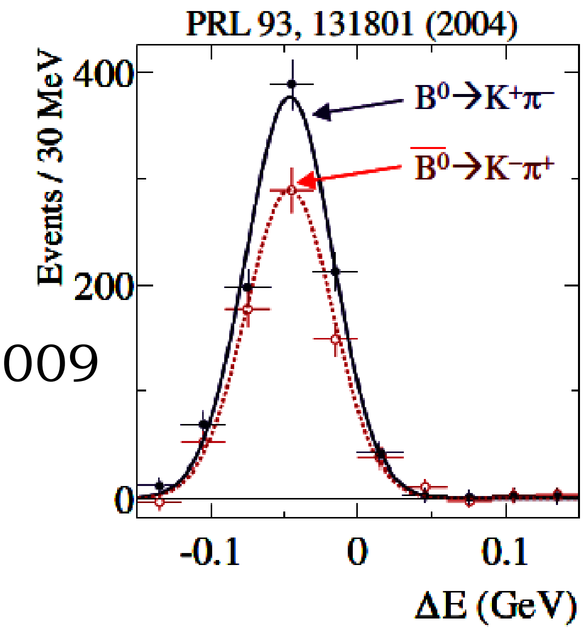
BaBar highlights on CP Violation

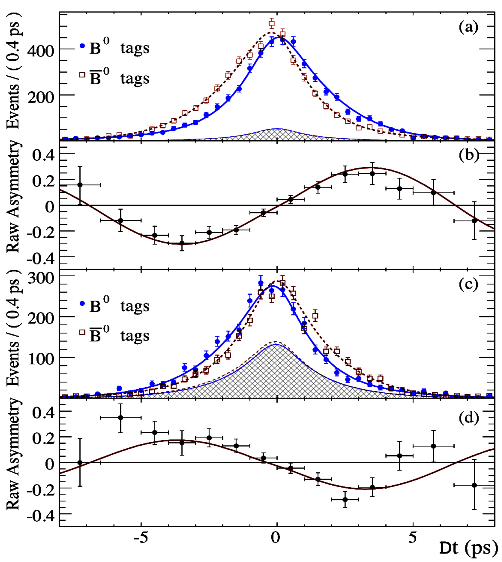
- First Observation of Direct CPV :

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

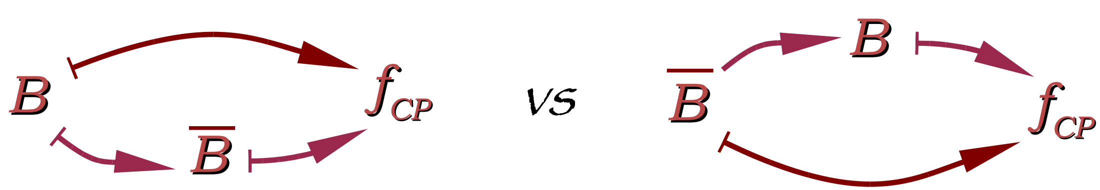
$$\frac{\Gamma(\overline{B}^0 \to K^- \pi^+) - \Gamma(B^0 \to K^+ \pi^-)}{\Gamma(\overline{B}^0 \to K^- \pi^+) + \Gamma(B^0 \to K^+ \pi^-)} = -0.133 \pm 0.030 \pm 0.009$$

PRL 93.131801





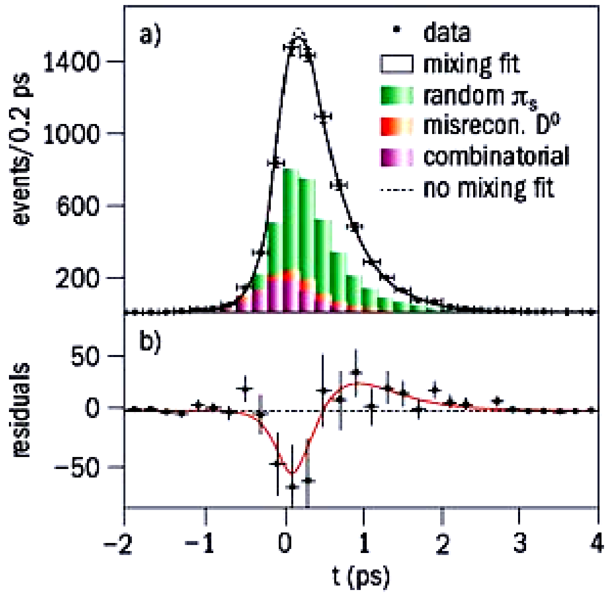
- CPV in interference of mixing and decay:



$$\sin(2\beta) = 0.666 \pm 0.031 \pm 0.013$$

PRD 79 (2009) 072009

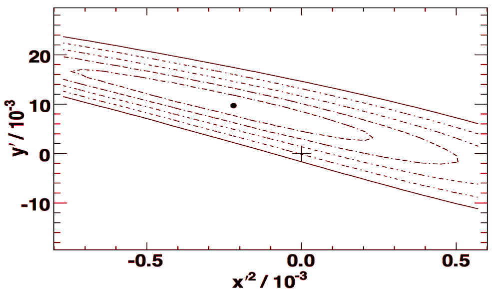
BABAR highlights on Mixing



First Observation of D^0 oscillation

$$x'^2 = [-0.22 \pm 0.30(stat.) \pm 0.21(syst.)] \times 10^{-3}$$

$$y' = [9.7 \pm 4.4(stat.) \pm 3.1(syst.)] \times 10^{-3}$$



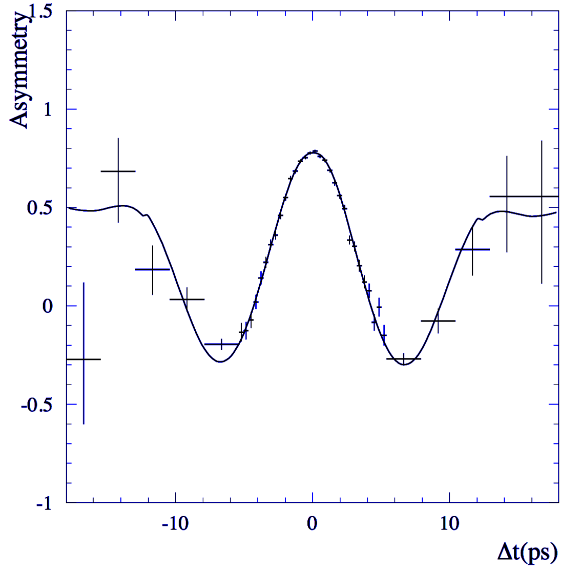
PRL 98, 211802

Precise measurement of B^0 oscillation frequency:

$$\tau_{B^0} = (1.504 \pm 0.013(stat)^{+0.018}_{-0.013}(syst))\,ps$$

$$\Delta m_d = (0.511 \pm 0.007(stat)^{+0.007}_{-0.006}(syst))\,ps^{-1}$$

PRD 73, 012004 (2006)



BABAR : the status

- Alive and well:
- Still 25 published papers in 2012
- plus 11 contributions (2012+2013) in reviewers hands
  - CPT in B mesons evolution and decay
  - CP in D mesons evolution and decay
  - rare B,D decays ;
  - τ lepton properties
  - search for light new particles ;
  - light hadron production in e^+e^- collisions ;
  - ...

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  - ...

Some open questions about CPT-V

- CP-*V* is well established
- CPT + CP-*V* ⇨ T Violation

  (1.a) Can we assert T Violation independently of CPT assumption ?

  (1.b) Can we test CPT in the B system ?
- CP in mixing has not yet been observed

  (2) Can we improve wrt existing measurements ?

PART I

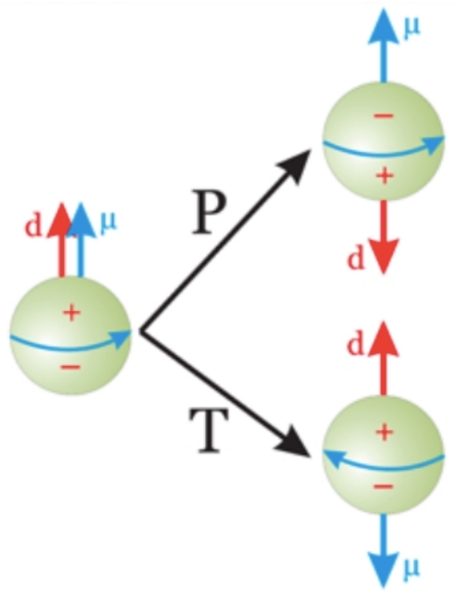
Discovering T-Violation

(and testing CPT)

T symmetry violation

- CP–Violation and CPT Theorem imply T-Violation in elementary systems
- Tests of T-V ignoring CPT-Th :
  - Electric Dipole Moment

$$\mathcal{D}_{Neutron} < 2.9 \cdot 10^{-28}\ em$$
$$\mathcal{D}_{electron} = 7 \pm 7 \cdot 10^{-29}\ em$$



  - $\nu_e \rightarrow \nu_\mu$ vs $\nu_\mu \rightarrow \nu_e$

    Needs long baseline, high ν flux

  - in particle decays :

    $|i\rangle \rightarrow |f\rangle$ vs $|f\rangle \rightarrow |i\rangle$

  - in the evolution and decay of neutral unstable mesons

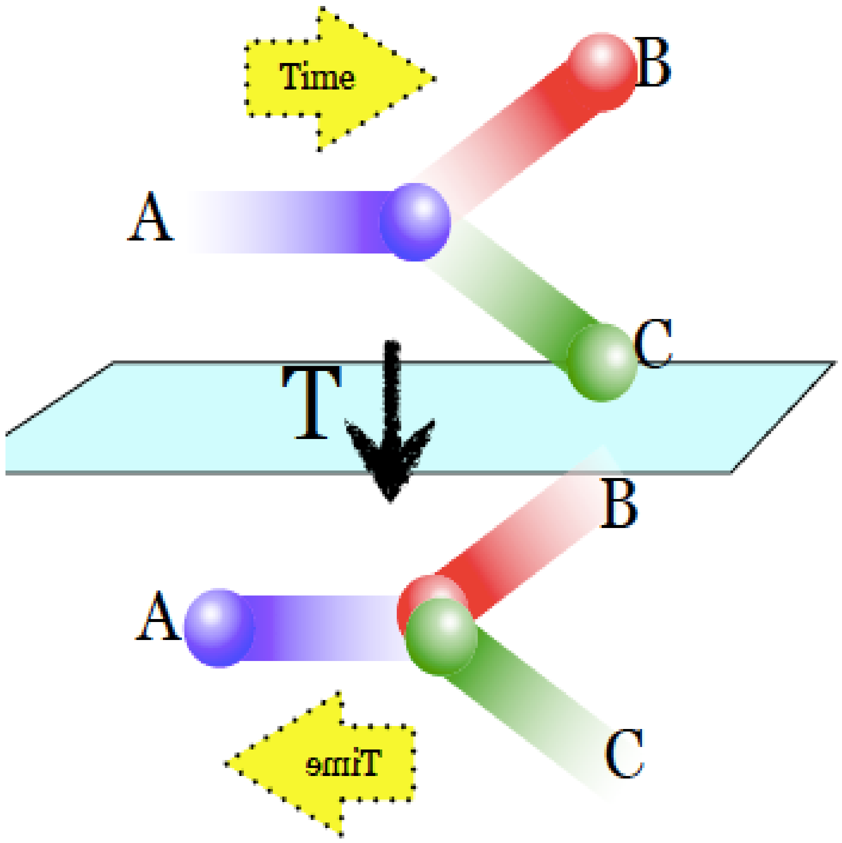
T Violation in Particle Decay

- Ideally compare two time-conjugate processes

$$\mathcal{A}(B^0 \rightarrow K^+ \pi^-)$$

vs

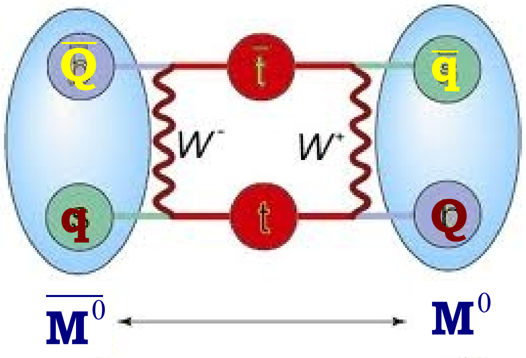
$$\mathcal{A}(K^+ \pi^- \rightarrow B^0)$$



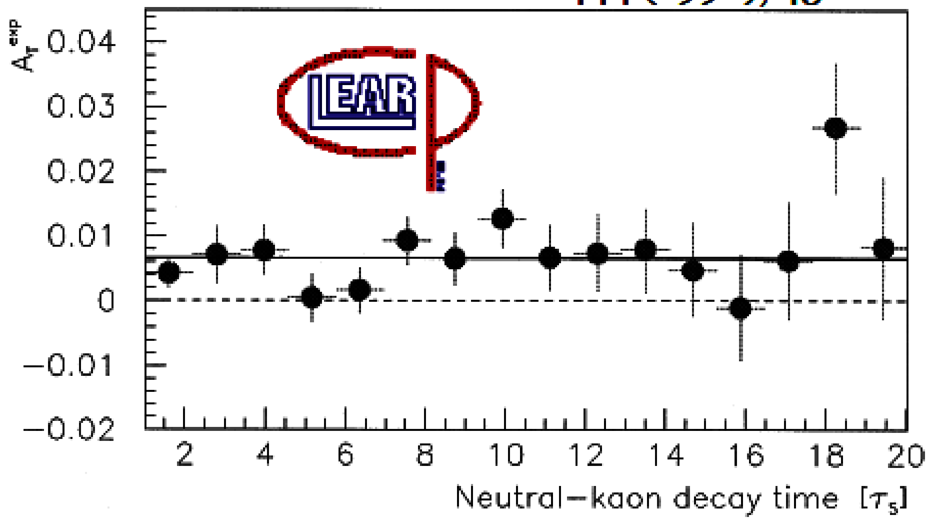
- Unfeasible :
  - collide K,π beams !
  - tiny effects
  - swamped by strong interactions

T-V in neutral meson oscillations

- Compare mixing rate for $M^0 \to \overline{M^0}$ vs $\overline{M^0} \to M^0$
- Make (wise) use of time information to assess the role of T-violation
- Sole result (before BABAR): 5 σ effect @ CPLEAR

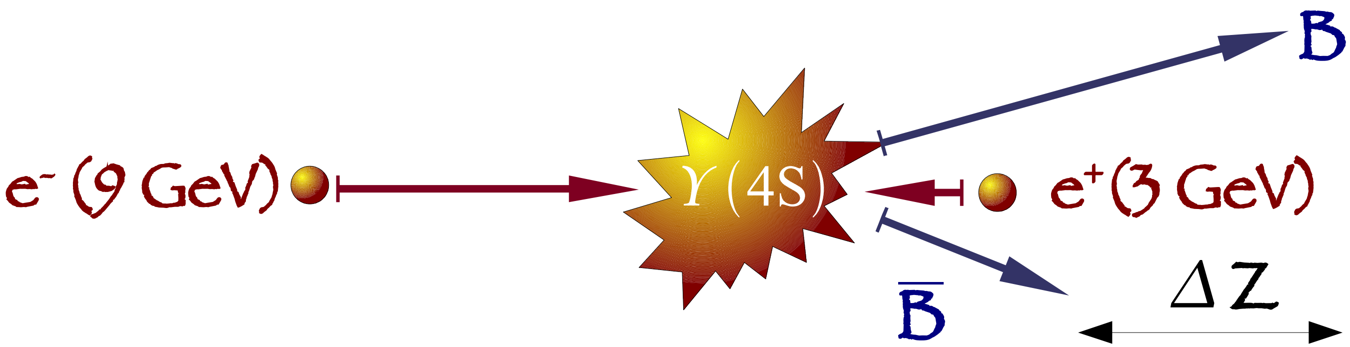


PLB444 (1998), 43



$$\left\langle \frac{R(\overline{K}^0_{t=0} \to e^+\pi^-\nu_{t=\tau}) - R(K^0_{t=0} \to e^-\pi^+\overline{\nu}_{t=\tau})}{R(\overline{K}^0_{t=0} \to e^+\pi^-\nu_{t=\tau}) + R(K^0_{t=0} \to e^-\pi^+\overline{\nu}_{t=\tau})} \right\rangle = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \times 10^{-3}$$

$e^+ e^- \to \Upsilon(4S) \to B\bar{B}$ @ BABAR



- Boosted beams ($\beta\gamma \approx 0.56$) allow measurement of proper time difference:

$$\langle \Delta Z \rangle \sim \beta\gamma\,\tau\, c \sim 250\ \mu m$$

- $M(4S) - 2M(B) \approx 10.5794 - 2 * 5.279 < m_\pi$

  - BB pair constitues an entangled quantum state, with same quantum numbers as $\Upsilon(4S)$
  - Small B momentum in the transverse direction (< 340 MeV), mesons are boosted along the beam line

Direct Measurement of T Violation

- In practice, exploit EPR entanglement in $B\bar{B}$ production at $\Upsilon(4S)$

$$e^+ e^- \to \Upsilon(4S) \to b\bar{b}$$

$$J^{PC} = 1^{--}$$

Direct Measurement of T Violation

- In practice, exploit EPR entanglement in $B\bar{B}$ production at $\Upsilon(4S)$

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

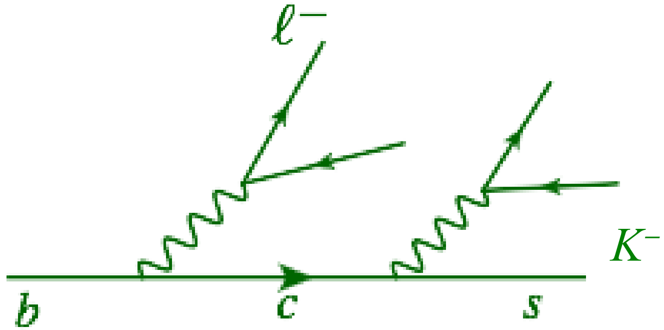
$J^{PC} = 1^{--}$

$$\rightarrow \frac{1}{\sqrt{2}}\left(|B^0(t_1)\overline{B^0}(t_2)\rangle - |B^0(t_2)\overline{B^0}(t_1)\rangle\right)$$

flavor eigenstate: $B^0 = \binom{\bar{b}}{d}$

- Flavor tagged with high efficiency by same means as CP analyses :

$$\overline{B^0} \rightarrow \ell^- X$$
$$\overline{B^0} \rightarrow K^- X$$
$$\overline{B^0} \rightarrow \pi^+_{soft} X, \ldots$$



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flavor eigenstate: $B^0 = (\bar{b}\, d)$

$$\rightarrow \frac{1}{\sqrt{2}}\left(|B_+(t_1)B_-(t_2)> - |B_+(t_2)B_-(t_1)> \right)$$

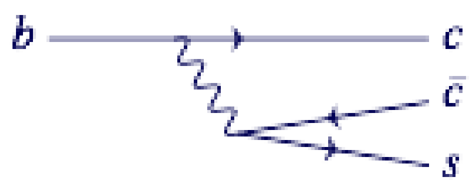
CP eigenstate: $CP|B_\pm> = \pm|B_\pm>$

- $B_{+,-}$ decay to CP +/- eigenstates (full reconstruction):

$$B_+ \rightarrow J/\psi K_L$$

$$B_- \rightarrow (c\bar{c})K_S$$

$(c\bar{c})$: $J/\psi, \psi(2S), \chi_{c1}$



Direct Measurement of T Violation

- In practice, exploit EPR entanglement in $B\bar{B}$ production at $\Upsilon(4S)$

$$e^+ e^- \to \Upsilon(4S) \to b\bar{b}$$

$J^{PC} = 1^{--}$

$$\to \frac{1}{\sqrt{2}}\left(|B^0(t_1)\overline{B^0}(t_2)> - |B^0(t_2)\overline{B^0}(t_1)>\right)$$

flavor eigenstate: $B^0 = (\bar{b}\ d)$

$$\to \frac{1}{\sqrt{2}}\left(|B_+(t_1)B_-(t_2)> - |B_+(t_2)B_-(t_1)>\right)$$

CP eigenstate: $CP|B_\pm> = \pm|B_\pm>$

- Perform 4 complementary tests:

$$B_+ \to B^0 \quad \text{vs} \quad B^0 \to B_+$$

$$B_- \to B^0 \quad \text{vs} \quad B^0 \to B_-$$

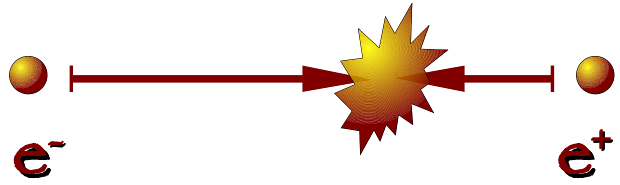
$$B_- \to \overline{B^0} \quad \text{vs} \quad \overline{B^0} \to B_-$$

$$B_+ \to \overline{B^0} \quad \text{vs} \quad \overline{B^0} \to B_+$$

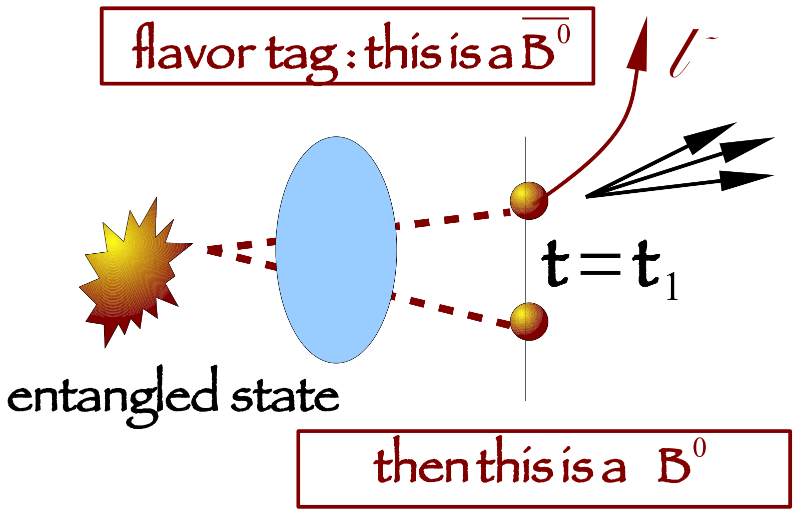
- ... plus INDEPENDENT tests of CPT and CP

T Analysis in a nutshell

boosted Υ(4S) ($\beta\gamma = 0.56$)

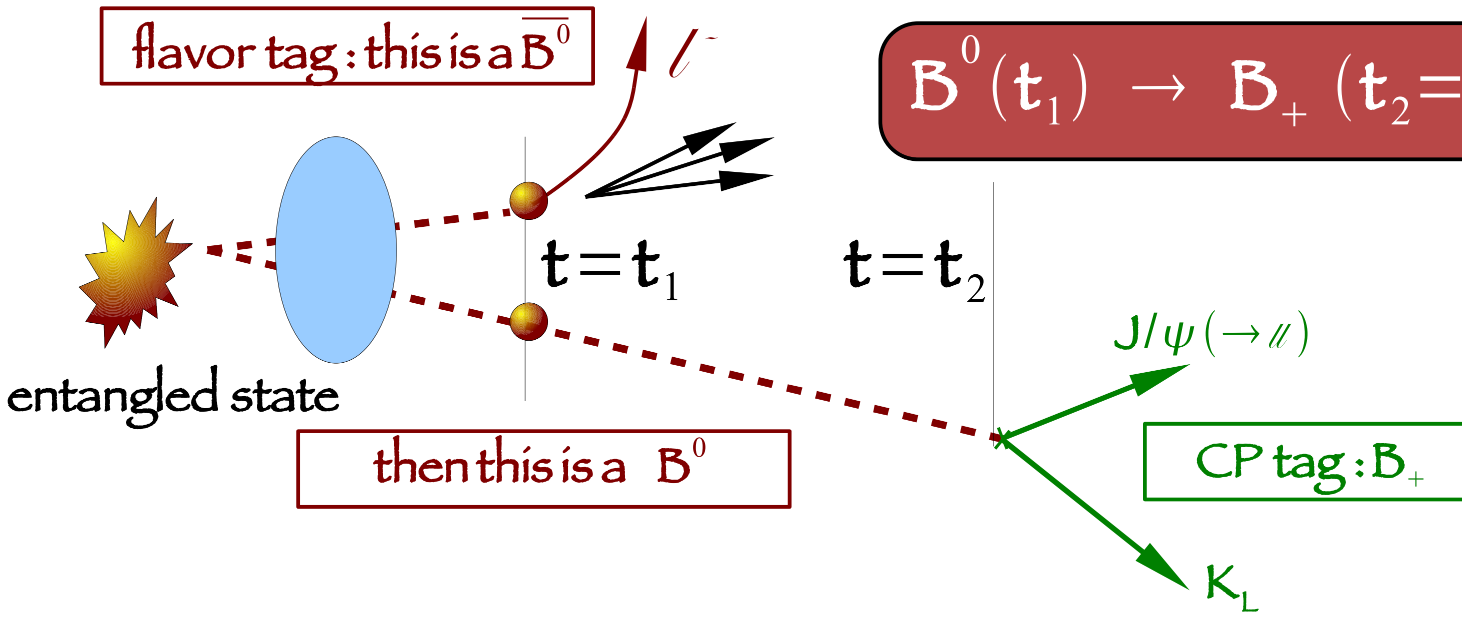


T Analysis in a nutshell

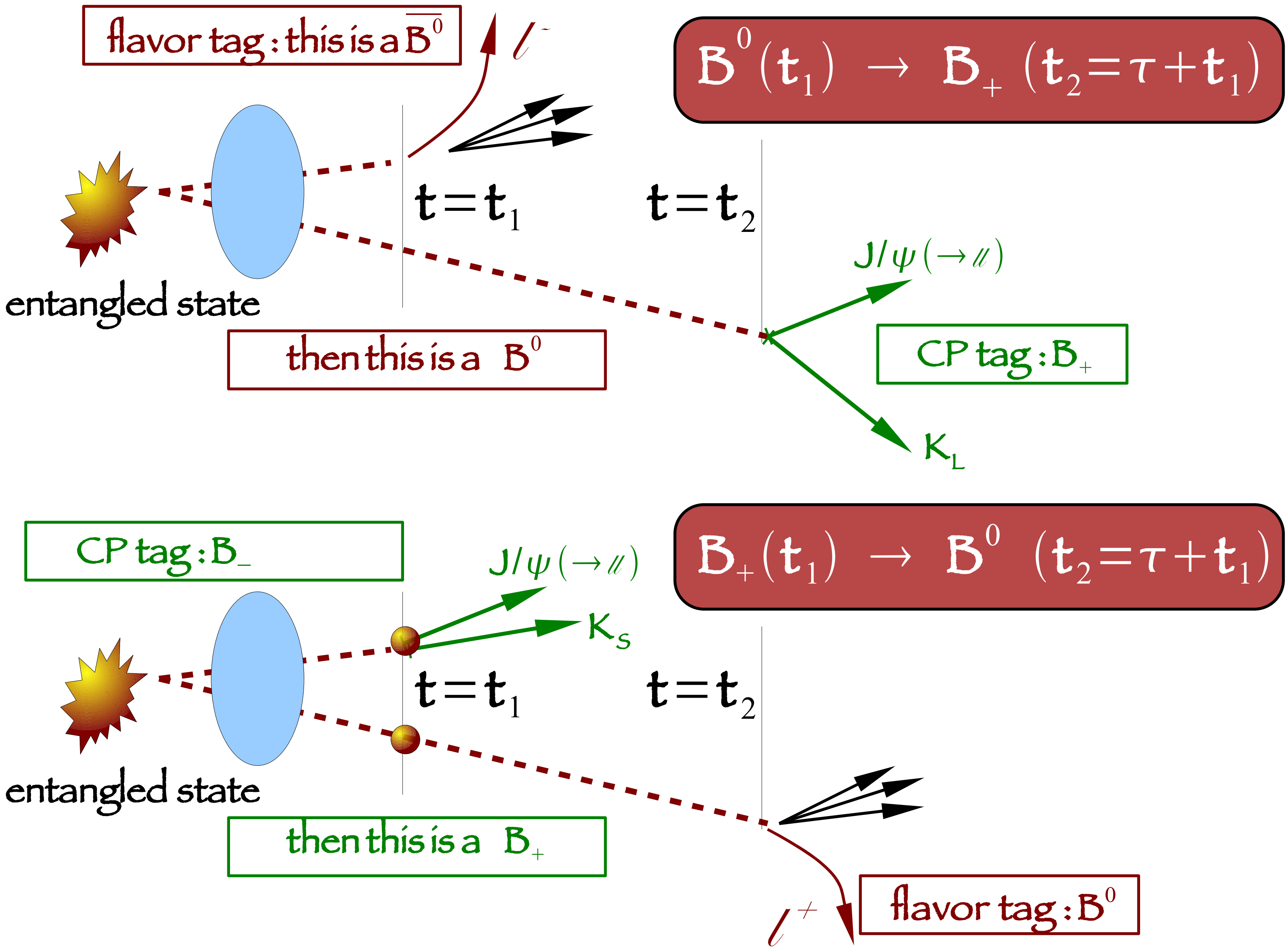


T Analysis in a nutshell

$$B^0(t_1) \rightarrow B_+\,(t_2 = \tau + t_1)$$



T Analysis in a nutshell



TV analysis steps

- Define $\Delta\tau = t(\text{flavor}) - t(CP)$
- Consider eight combinations (flavor x CP x sign of $\Delta\tau$)

$\alpha = B^0/\overline{B^0}$

$\beta = K_L/K_S$

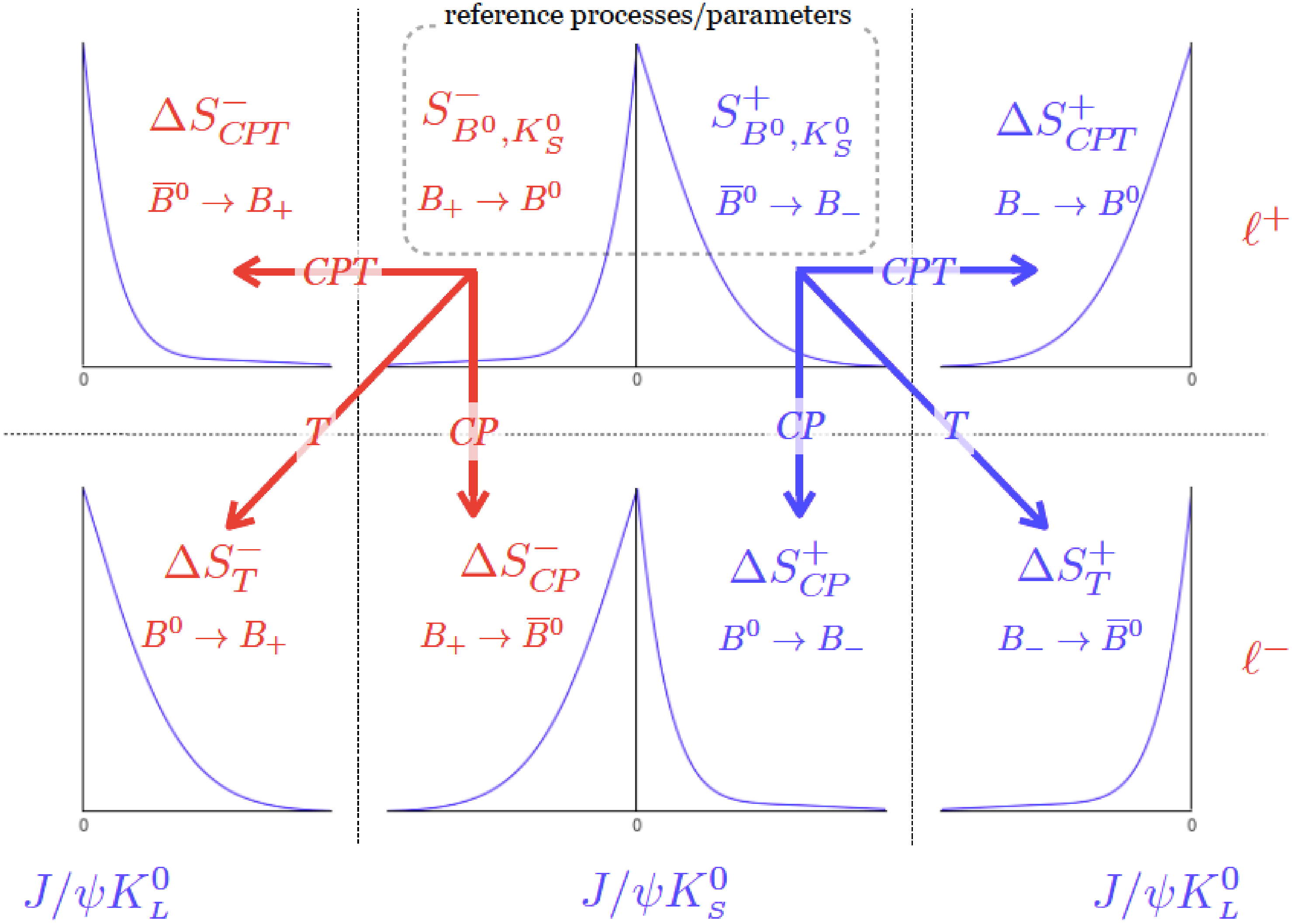
- Fit each with EPR-motivated function

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\ \mathcal{H}(\pm\Delta\tau)\ [1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)]$$

Heavyside step function

- $S^{+-}_{\alpha\beta}$, $C^{+-}_{\alpha\beta}$: fit parameters
  - T-Violation : $\Delta S^{\pm}_{T} = S^{\pm}_{\overline{B^0},K_L} - S^{\mp}_{B^0,K_S} \neq 0$
  - CP-Violation : $\Delta S^{-}_{CP} = S^{\pm}_{B^0,K_L} - S^{\mp}_{B^0,K_S} \neq 0$
  - CPT-Violation : $\Delta S^{-}_{CPT} = S^{\pm}_{B^0,K_S} - S^{\mp}_{\overline{B^0},K_S} \neq 0$
- Assuming CPT & CP fit results, expect :

$$S^{\pm}_{T,\alpha,\beta} = \pm\sin(2\beta)$$
$$\Delta S^{\pm}_{T} = 2\sin(2\beta)$$


reference processes/parameters
ΔS^-_{CPT}
$\overline{B}^0 \to B_+$
$S^-_{B^0,K^0_S}$
$B_+ \to B^0$
$S^+_{B^0,K^0_S}$
$\overline{B}^0 \to B_-$
ΔS^+_{CPT}
$B_- \to B^0$
ℓ^+
CPT
CPT
T
CP
CP
T
ΔS^-_T
$B^0 \to B_+$
ΔS^-_{CP}
$B_+ \to \overline{B}^0$
ΔS^+_{CP}
$B^0 \to B_-$
ΔS^+_T
$B_- \to \overline{B}^0$
ℓ^-
0
$J/\psi K^0_L$
$J/\psi K^0_S$
$J/\psi K^0_L$

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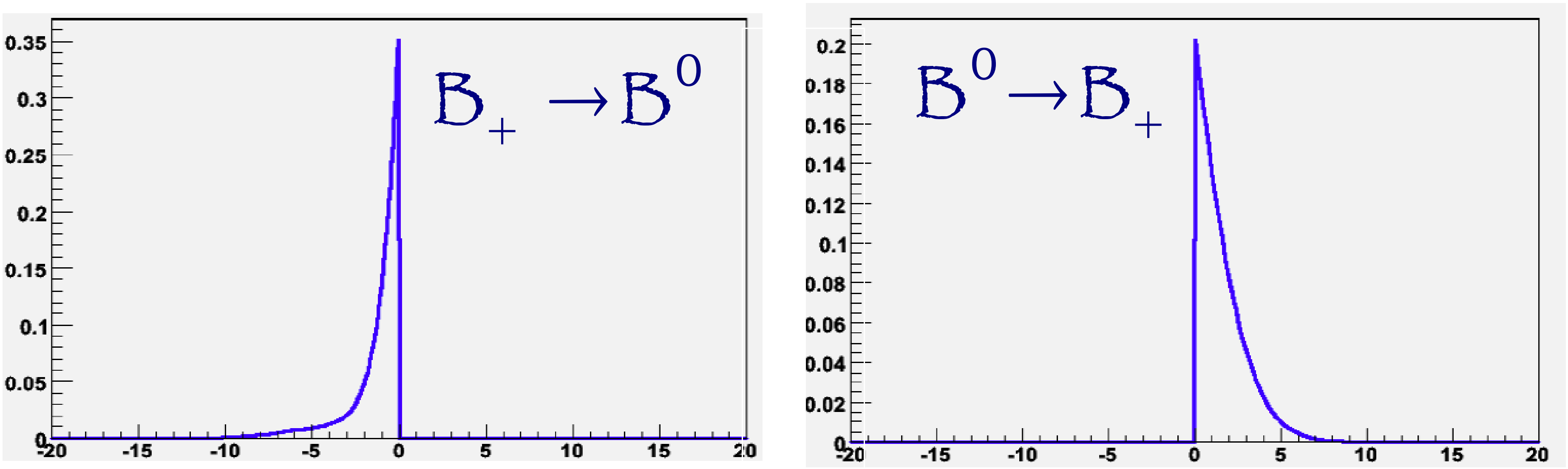
- Consider eight combinations (flavor (α) x CP(β) x sign of $\Delta\tau$)
- Fit each with EPR-motivated function

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\ \mathcal{H}(\pm\Delta\tau)\ [1+S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau)+C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)]$$

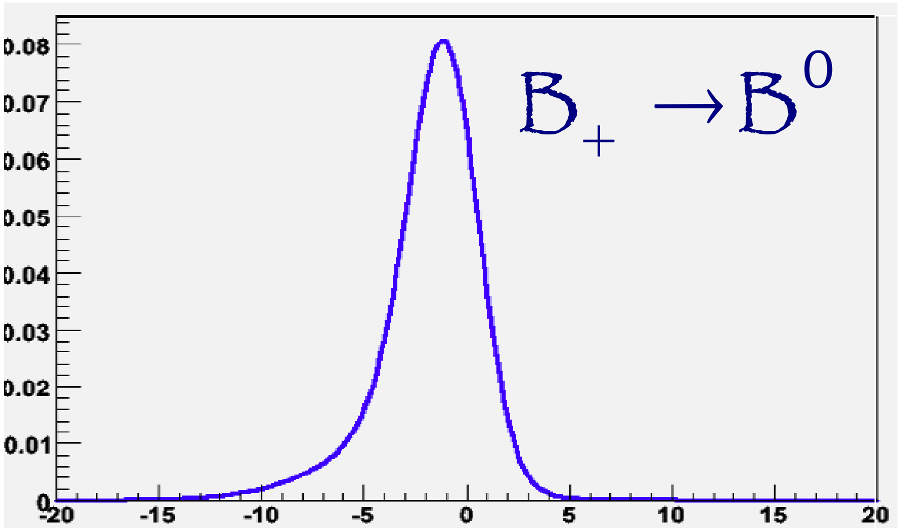
Heavyside step function

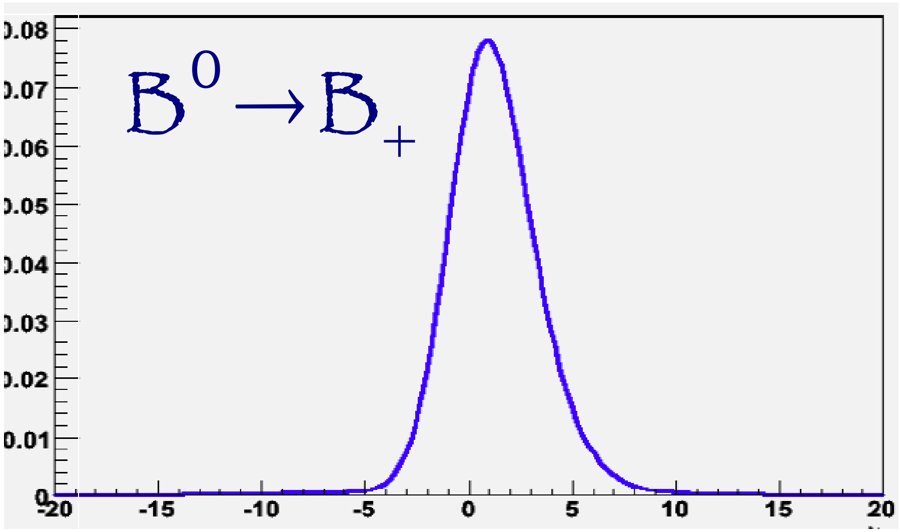


TV analysis steps : real data

- Need to account for finite $\Delta\tau$ resolution (parameters fitted in the data)

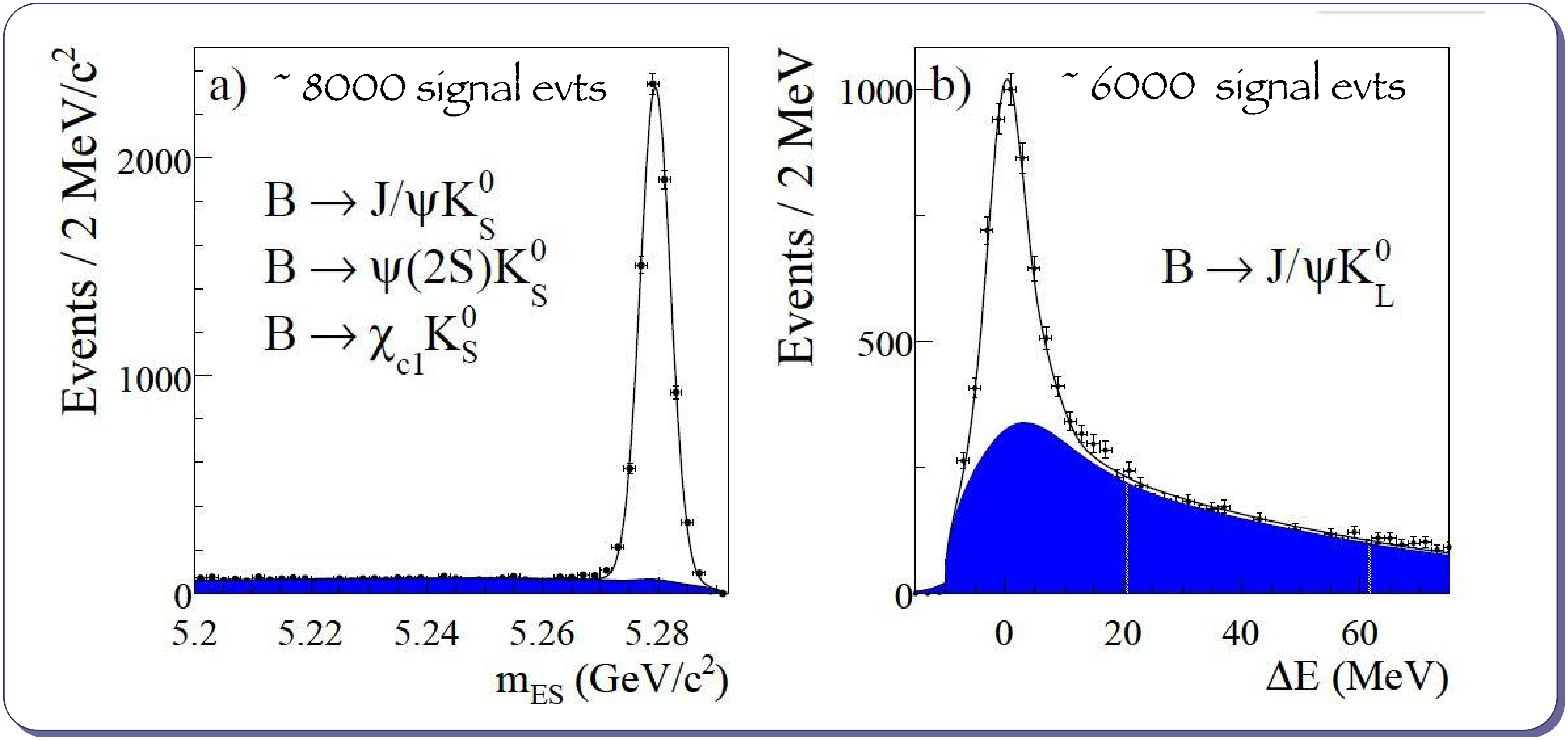
$$\mathcal{F}^{\pm}_{\alpha,\beta}(\Delta\tau) \propto g^{\pm}_{\alpha,\beta}(\Delta\tau')\times\mathcal{R}(\Delta\tau,\Delta\tau')$$





TV analysis steps : real data

- Need to account for finite $\Delta\tau$ resolution
- Need to account for background (mostly for $J/\psi\, K_L$)

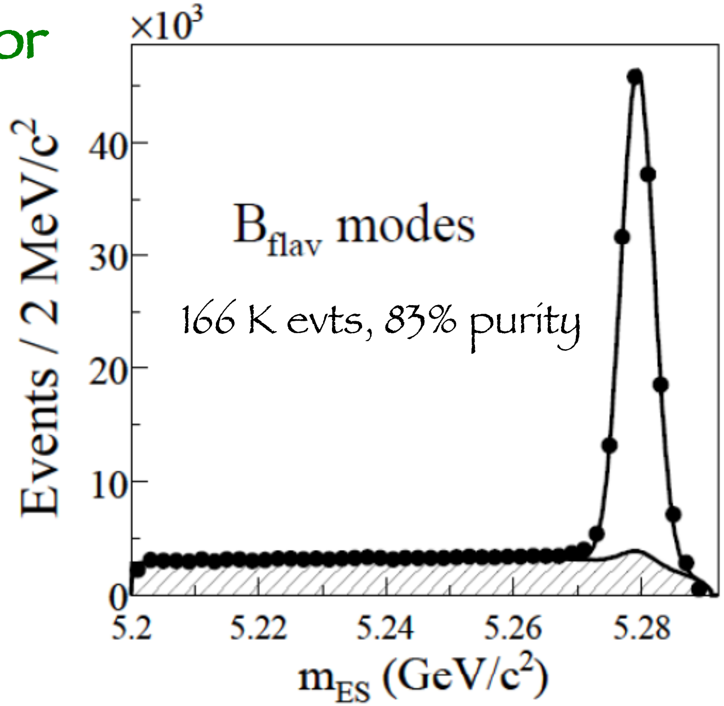


TV analysis steps : real data

- Need to account for finite $\Delta\tau$ resolution
- Need to account for background (mostly for $J/\psi\ K_L$)
- Need to account for dilution from wrong flavor tags
  - Tag-category dependent
  - Use samples of fully reconstructed flavor eigenstates ($D^{(*)}\pi, D^{(*)}K, J/\psi K^{(*)+}$ …)

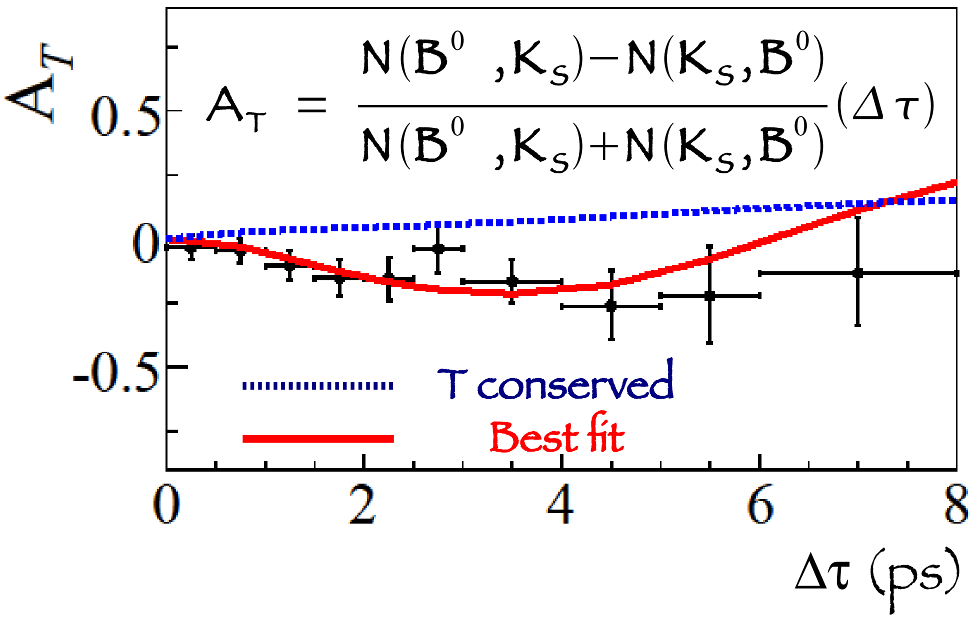
Category	ϵ_i (%)	w_i (%)	Δw_i (%)	Q_i (%)
Lepton	8.96 ± 0.07	2.8 ± 0.3	0.3 ± 0.5	7.98 ± 0.11
Kaon I	10.82 ± 0.07	5.3 ± 0.3	-0.1 ± 0.6	8.65 ± 0.14
Kaon II	17.19 ± 0.09	14.5 ± 0.3	0.4 ± 0.6	8.68 ± 0.17
KaonPion	13.67 ± 0.08	23.3 ± 0.4	-0.7 ± 0.7	3.91 ± 0.12
Pion	14.18 ± 0.08	32.5 ± 0.4	5.1 ± 0.7	1.73 ± 0.09
Other	9.54 ± 0.07	41.5 ± 0.5	3.8 ± 0.8	0.27 ± 0.04
All	74.37 ± 0.10			31.2 ± 0.3

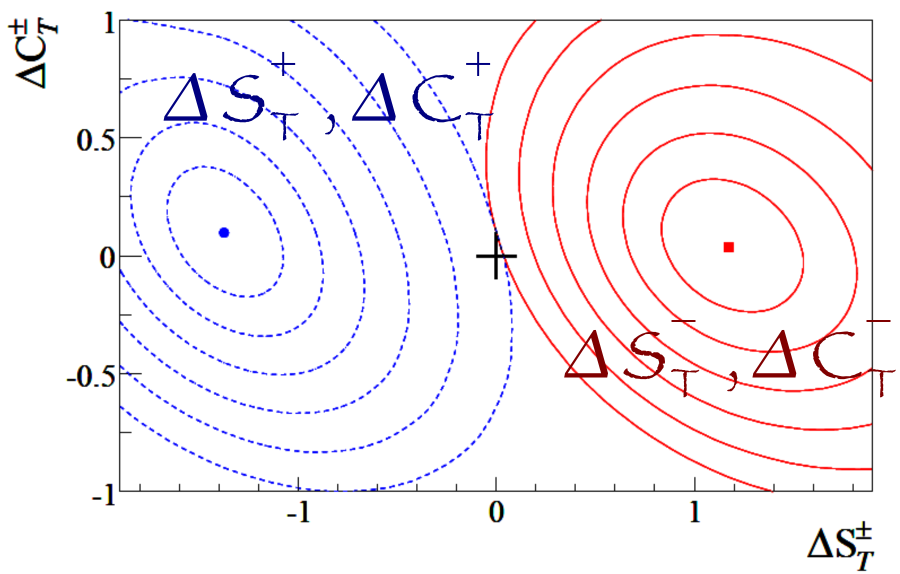
Large tagging power



T-V : RESULTS

Parameter	Final result
ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$
ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$
ΔC_T^+	$0.10 \pm 0.16 \pm 0.08$
ΔC_T^-	$0.04 \pm 0.16 \pm 0.08$
ΔS_{CP}^+	$-1.30 \pm 0.10 \pm 0.07$
ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$
ΔC_{CP}^+	$0.07 \pm 0.09 \pm 0.03$
ΔC_{CP}^-	$0.08 \pm 0.10 \pm 0.04$
ΔS_{CPT}^+	$0.16 \pm 0.20 \pm 0.09$
ΔS_{CPT}^-	$-0.03 \pm 0.13 \pm 0.06$
ΔC_{CPT}^+	$0.15 \pm 0.17 \pm 0.07$
ΔC_{CPT}^-	$0.03 \pm 0.14 \pm 0.08$
$S_{B^0,K_S^0}^+$	$0.545 \pm 0.084 \pm 0.06$
$S_{B^0,K_S^0}^-$	$-0.660 \pm 0.059 \pm 0.04$
$C_{B^0,K_S^0}^+$	$0.011 \pm 0.064 \pm 0.05$
$C_{B^0,K_S^0}^-$	$-0.049 \pm 0.056 \pm 0.03$





BaBar PRL 109, 211801 (2012)

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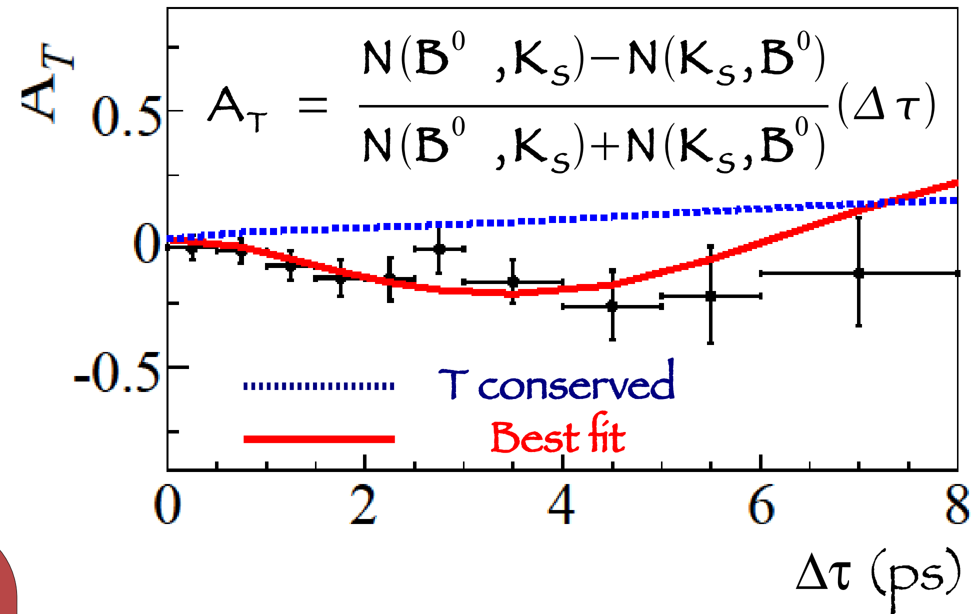
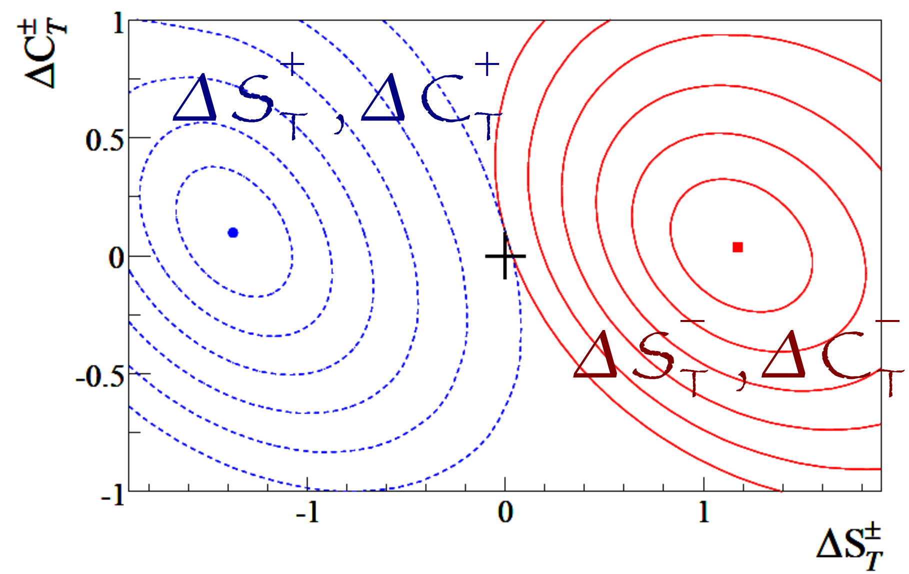
ΔC_T^+	$0.10 \pm 0.16 \pm 0.08$
ΔC_T^-	$0.04 \pm 0.16 \pm 0.08$
ΔS_{CP}^+	$-1.30 \pm 0.10 \pm 0.07$
ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$

First unambiguous observation of T-violation in B-Physics with 14 σ significance



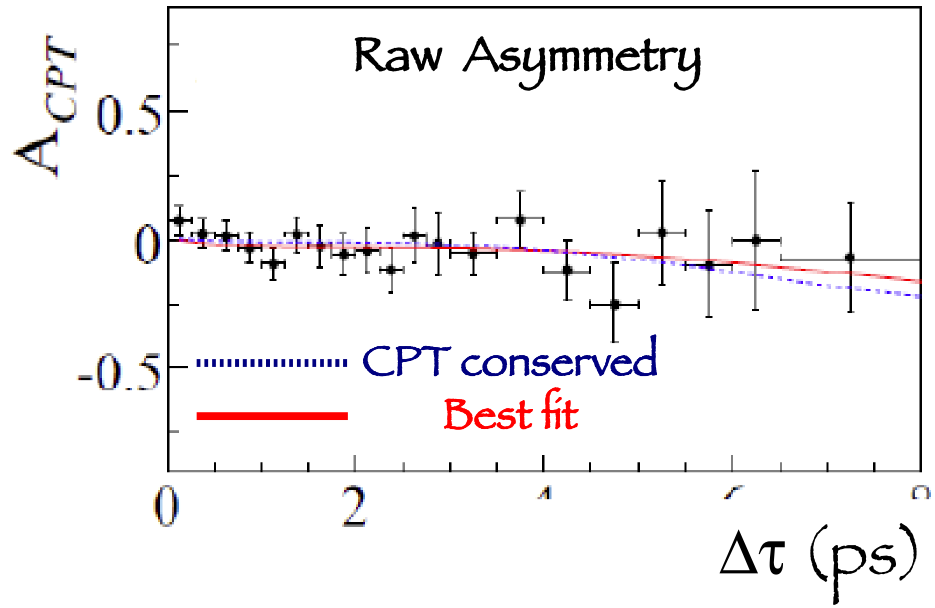


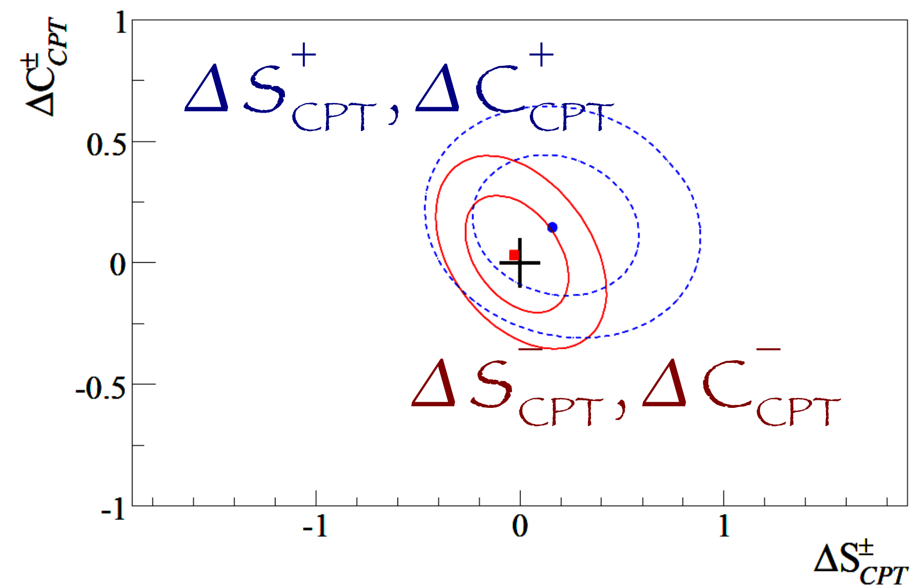
BABAR PRL 109, 211801 (2012)

CPT-V : RESULTS

Parameter	Final result
$\Delta S^{+}_{\mathrm{T}}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S^{-}_{\mathrm{T}}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C^{+}_{\mathrm{T}}$	$0.10 \pm 0.16 \pm 0.08$
$\Delta C^{-}_{\mathrm{T}}$	$0.04 \pm 0.16 \pm 0.08$
$\Delta S^{+}_{\mathrm{CP}}$	$-1.30 \pm 0.10 \pm 0.07$
$\Delta S^{-}_{\mathrm{CP}}$	$1.33 \pm 0.12 \pm 0.06$
$\Delta C^{+}_{\mathrm{CP}}$	$0.07 \pm 0.09 \pm 0.03$
$\Delta C^{-}_{\mathrm{CP}}$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S^{+}_{\mathrm{CPT}}$	$0.16 \pm 0.20 \pm 0.09$
$\Delta S^{-}_{\mathrm{CPT}}$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C^{+}_{\mathrm{CPT}}$	$0.15 \pm 0.17 \pm 0.07$
$\Delta C^{-}_{\mathrm{CPT}}$	$0.03 \pm 0.14 \pm 0.08$
$S^{+}_{\mathrm{B^0,K^0_S}}$	$0.545 \pm 0.084 \pm 0.06$
$C^{-}_{\mathrm{B^0,K^0_S}}$	$-0.049 \pm 0.056 \pm 0.03$

CPT is Conserved





BABAR PRL 109, 211801 (2012)

PART II

MIXING – INDUCED CPV

Mixing Induced CP-V

- B^0 mass eigenstates differ from flavor eigenstate:

$$|B_{L/H}> = \frac{1}{\sqrt{p^2+q^2}}[p|B^0> \pm q|\overline{B^0}>]$$

- $q = p = 2^{-1/2}$ <=> $B_{L/H}$ are CP eigenstates, CP is conserved

- CP asymmetry :

$$\mathcal{A}_{ll} = \frac{\Gamma(B^0(0)\to\overline{B}^0(t))-\Gamma(\overline{B}^0(0)\to B^0(t))}{\Gamma(B^0(0)\to\overline{B}^0(t))+\Gamma(\overline{B}^0(0)\to B^0(t))} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

- Standard Model : very tiny effect

$$\mathcal{A}_{ll}(B^0) = (-4.1\pm0.6)\cdot10^{-4}$$

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

$$\mathcal{A}_{ll}(B_s) = (1.9\pm0.3)\cdot10^{-5}$$

- Positive observation : DISCOVERY OF NEW PHYSICS

MIXING-INDUCED CPV

- Colliders : B produced in opposite flavor pairs
- Mixing : find two equal-flavor mesons at decay time
- CP asymmetry is usually measured through B semileptonic decays :

Negligible CP asymmetry in direct semileptonic decay (model independent)

$$\mathcal{A}_{\ell\ell} = \frac{N(B^0B^0) - N(\overline{B}^0\overline{B}^0)}{N(B^0B^0) + N(\overline{B}^0\overline{B}^0)} = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)}$$

- Consider also single – tag asymmetry:

$$\frac{N(B^0) - N(\overline{B}^0)}{N(B^0) + N(\overline{B}^0)} = \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)} = \chi_d \mathcal{A}_{\ell\ell}$$

MIXING-INDUCED CPV

- A new approach, pioneered by BABAR is here presented:
  - "Reco" 1st B : partial reconstruction of $B^0 \rightarrow \ell^+ \nu_\ell D^{*-}$
  - "Tag" 2nd B : use charged Kaons

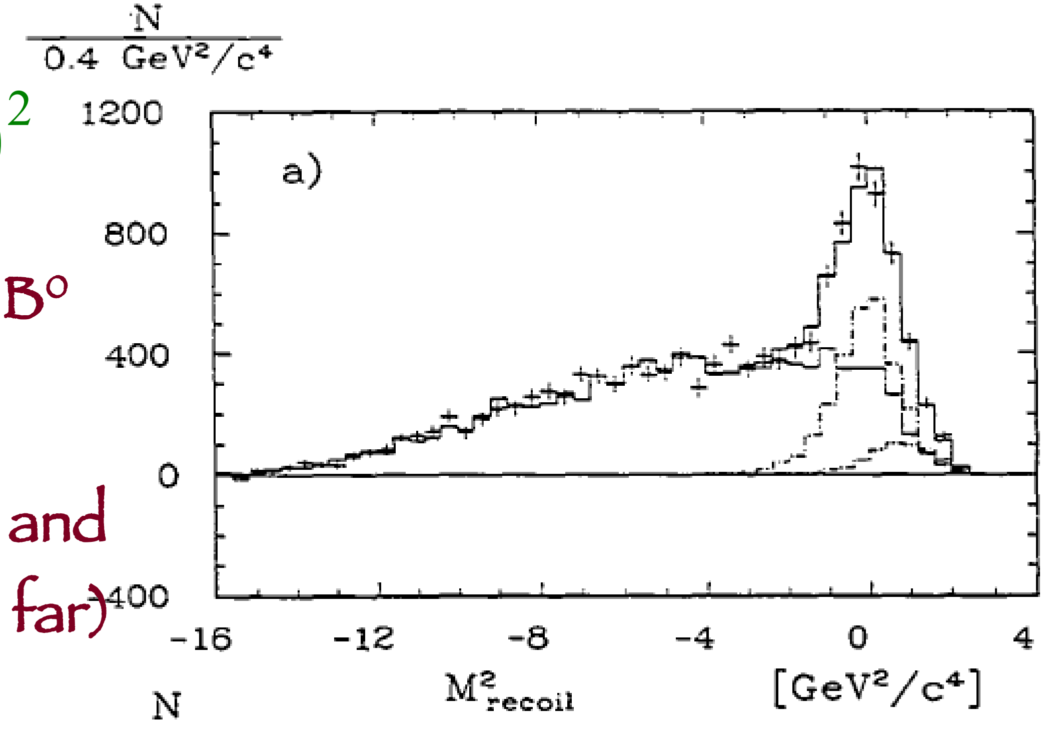
$$\mathcal{A}_{\ell\ell} = \frac{N(B^0 B^0) - N(\overline{B^0}\,\overline{B^0})}{N(B^0 B^0) + N(\overline{B^0}\,\overline{B^0})} = \frac{N(\ell^+ K^+) - N(\ell^- K^-)}{N(\ell^+ K^+) + N(\ell^- K^-)}$$

B -> D*ℓν Partial Reconstruction

- Use only ℓ and low momentum π_s from the decay $D^{*-} \rightarrow \pi_s^- \overline{D}^0$
- Assume B^0 at rest in Υ(4S) frame $\vec{P}_B \sim 0$
- Get D^* from π_s : $\vec{P}_{D*} = \vec{f}(\vec{P}_{\pi_s})$
- Compute missing mass from four momenta difference:

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

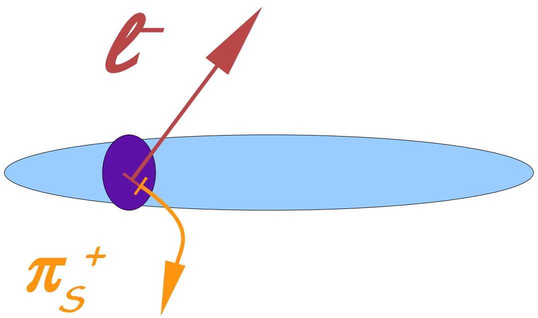
- ARGUS (1986) : first evidence of B^0 mixing at the Υ(4S) ...
- ... then CLEO, DELPHI, OPAL, and BABAR (4 published papers so far)

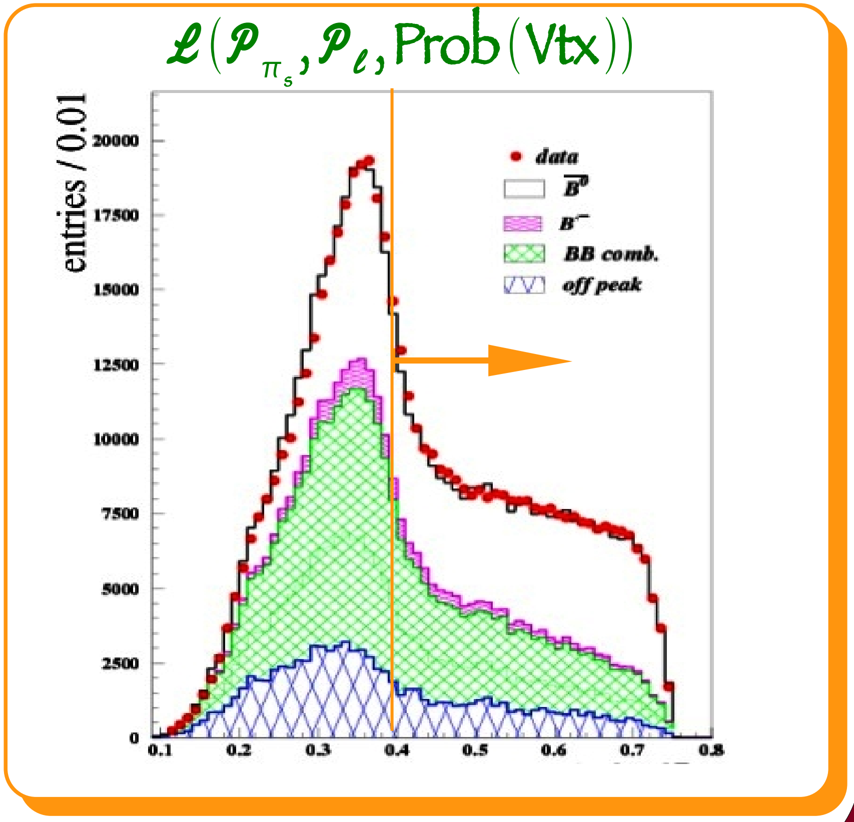


Partial Reco @BABAR

BABAR :

- B decay point intersecting beamspot, ℓ, π_s tracks
- Selection : likelihood ratio combining $p_\ell p_{\pi s}$, Prob(Vtx)
- Cut $\mathcal{L} > 0.4$



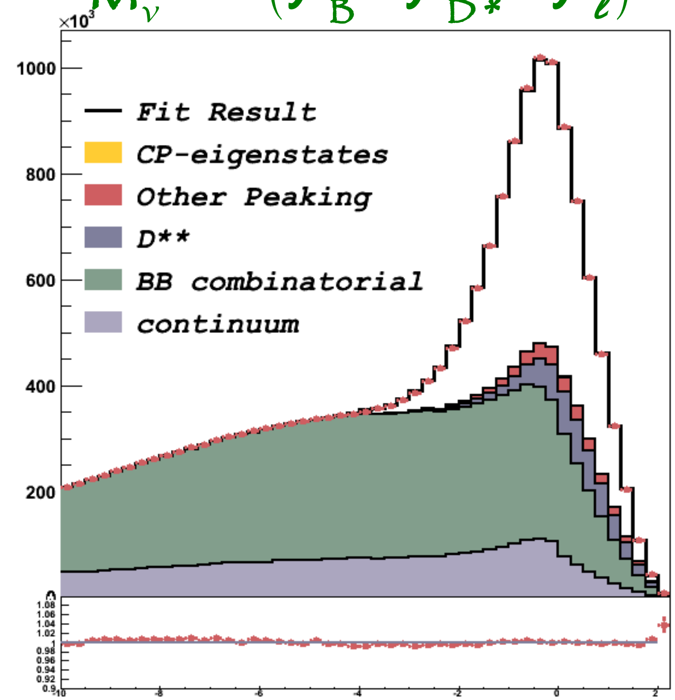


Sample composition:

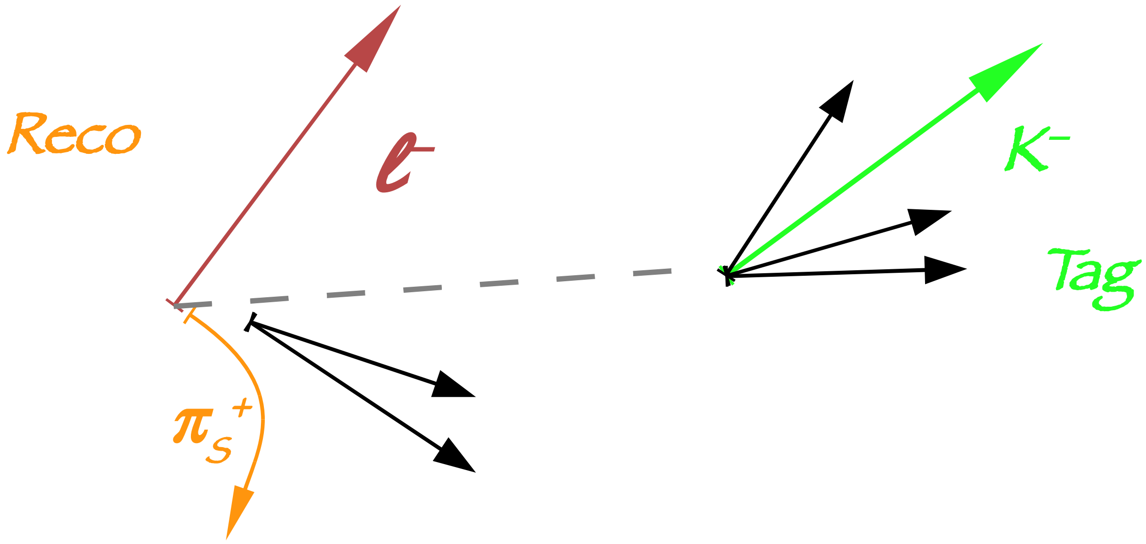
- continuum from rescaled off-peak events
- fit for BB combinatorial, peaking B^+, and peaking B^0 fractions assuming shapes from simulation
- combinatorial x-check in $\ell^+\pi_s^+$ sample

$(5370 \pm 6)\cdot 10^3$ Peaking Events

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

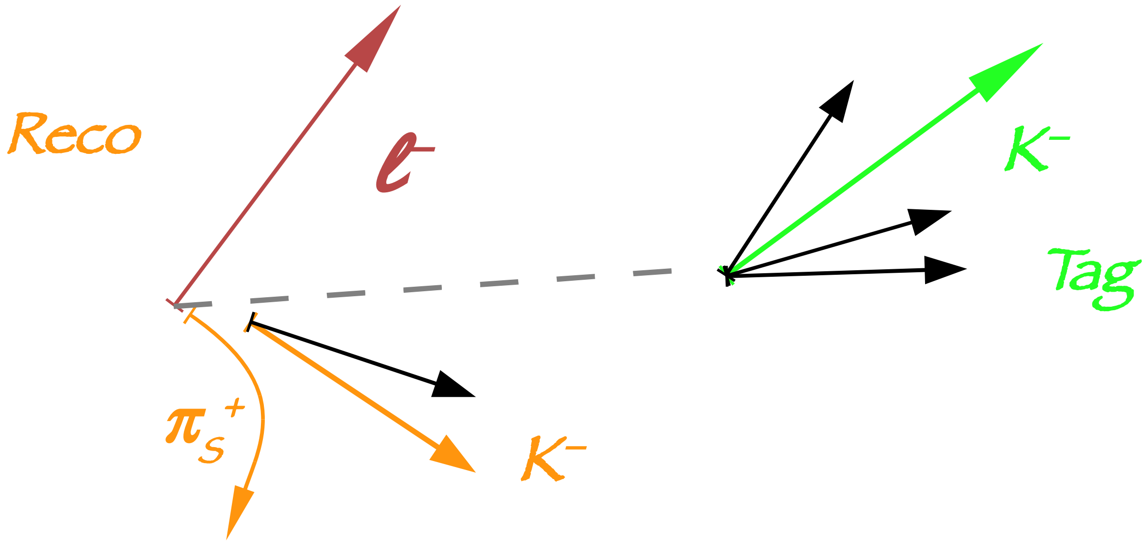


The Kaon Tag



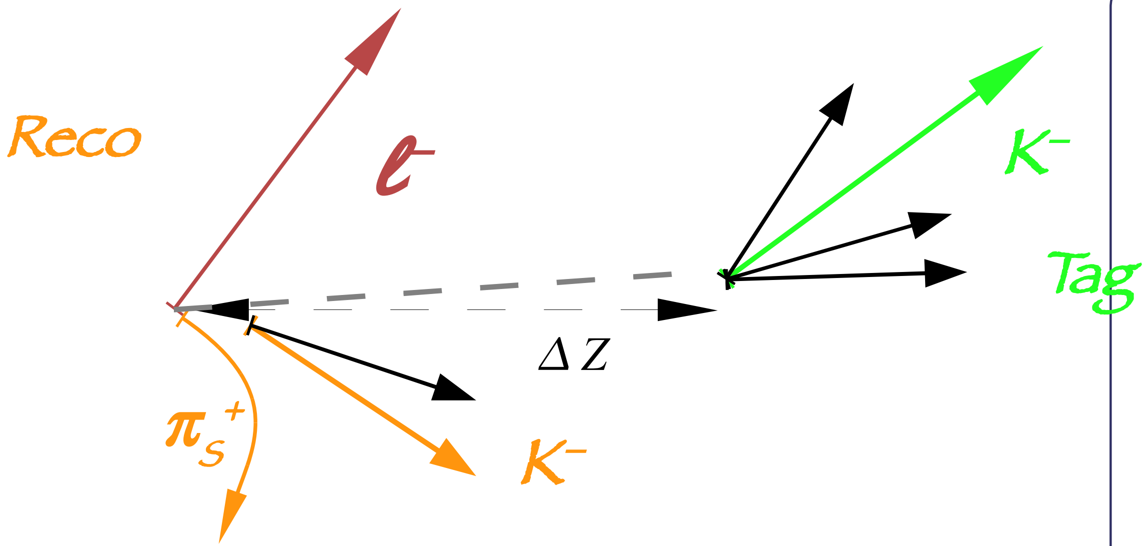
- K identified using dE/dX & Cherenkov with high purity
- Tag-B decay point from intersection of Kaon track and beamspot
- Define $\Delta Z = Z_{RECO} - Z_{TAG}$

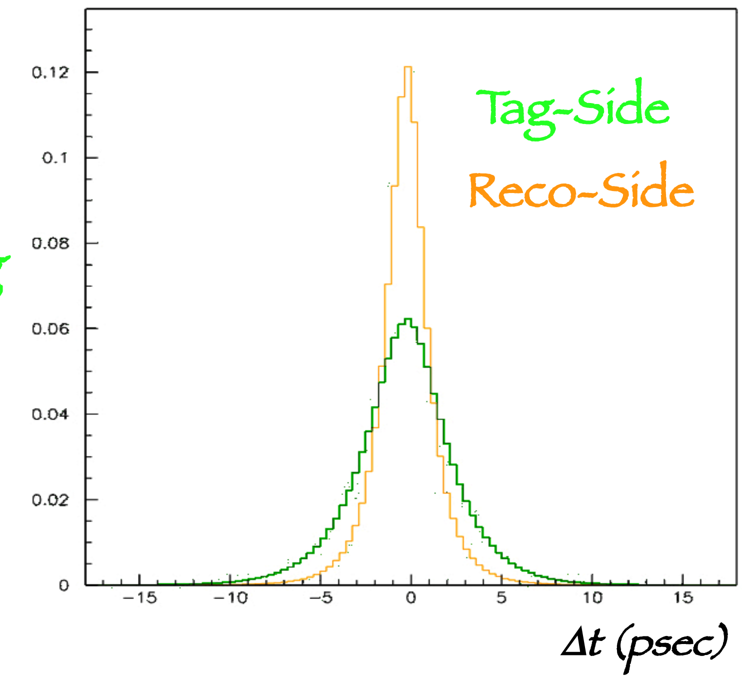
The Kaon Tag



- Equal charge Kaons also from the reco side, mimick a mixed event .

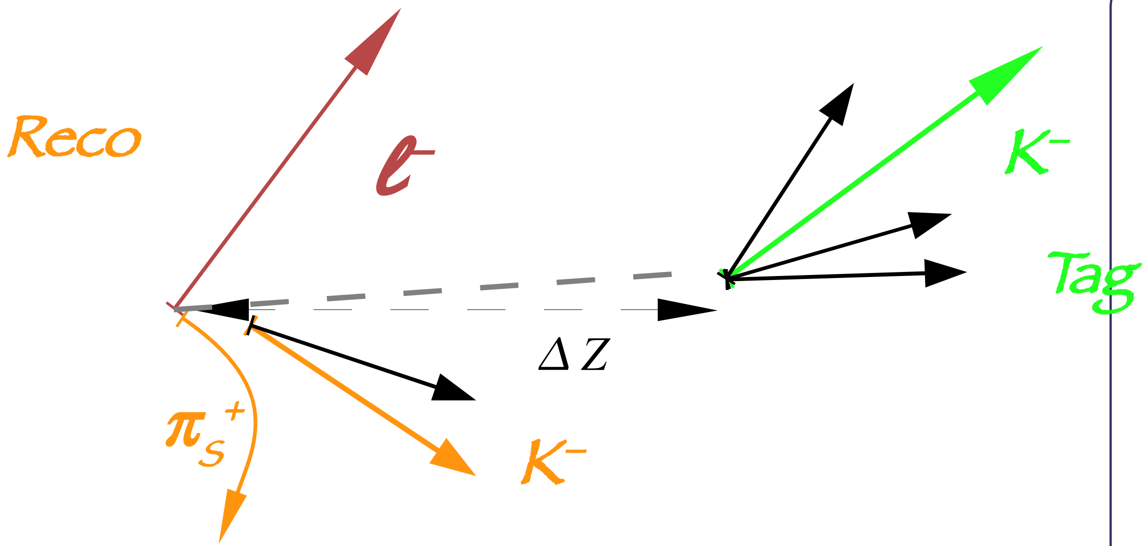
The Kaon Tag



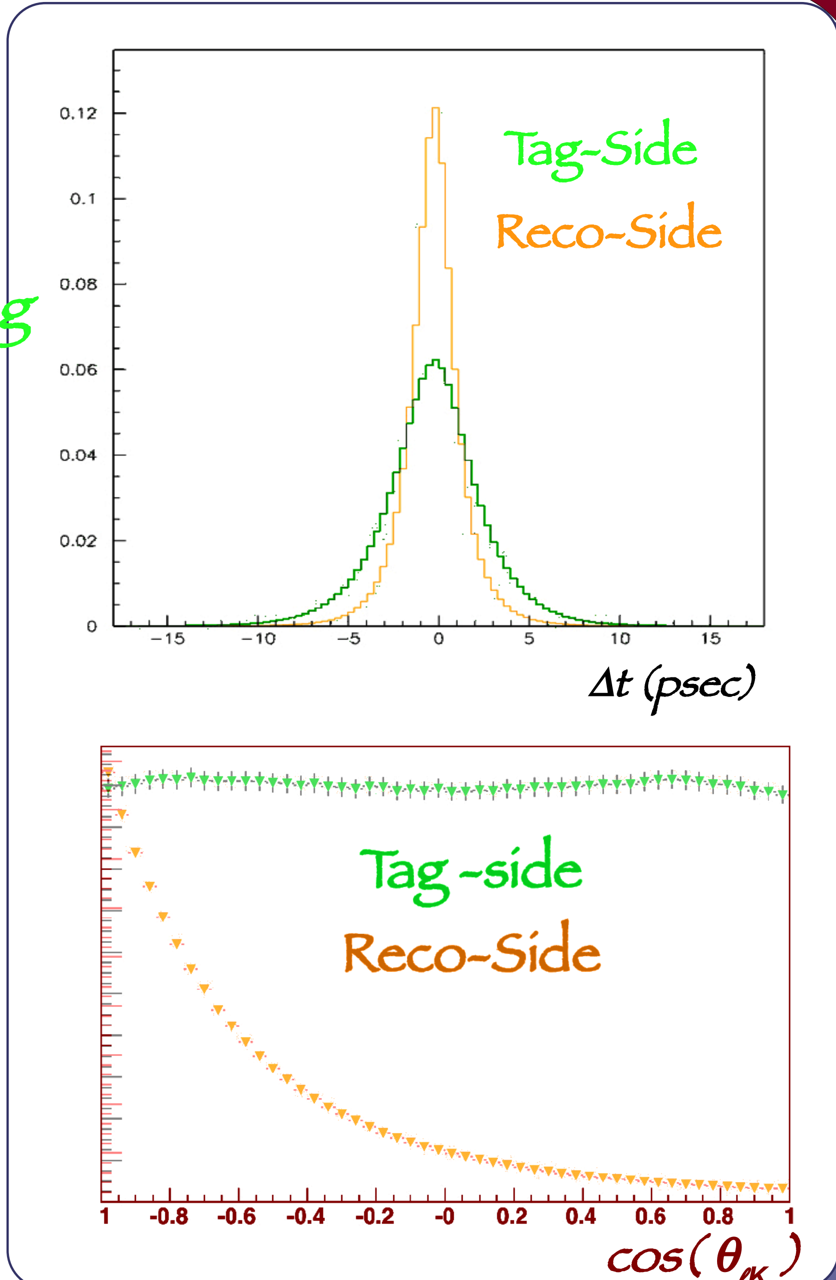


- Equal charge Kaons also from the reco side, mimick a mixed event .
- Separated *on statistical basis* by:
  - $\Delta t \approx (Z_\ell - Z_K)/(c\beta\gamma)$ (in the Lab)

The Kaon Tag

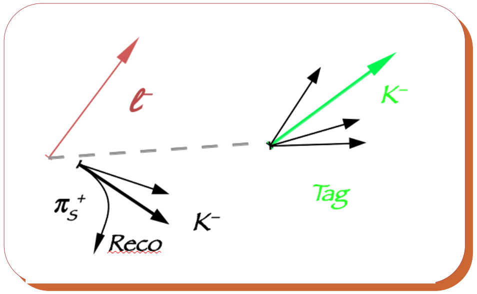


- Equal charge Kaons also from the reco side, mimick a mixed event .
- Separated *on statistical basis* by:
  - $\Delta t \approx (Z_\ell - Z_K)/(c\beta\gamma)$ (in the Lab)
  - $\cos(\theta_{\ell K})$ (in $\Upsilon(4S)$ rest frame)



Asymmetry

- Observed asymmetries for mixed reflect *RECO-side* charge asymmetry, *K*-id charge asymmetry and Physical asymmetry:



$$\mathcal{A}_{obs,K\text{-}Tag} \simeq \mathcal{A}_{Rec} + \mathcal{A}_{K} + \mathcal{A}_{\ell\ell}$$

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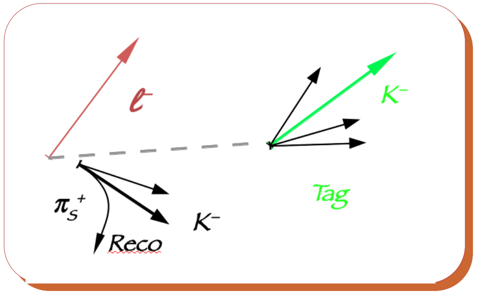
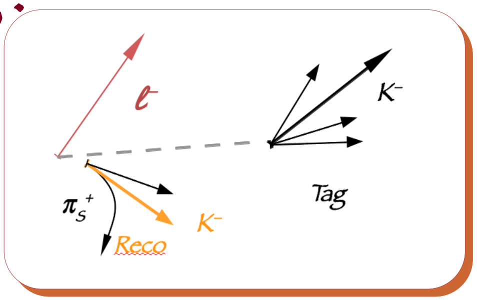


$$\mathcal{A}_{obs,K\text{-}Tag} \simeq \mathcal{A}_{Rec} + \mathcal{A}_K + \mathcal{A}_{\ell\ell}$$

- Kaons from reco side have tiny contribution from mixing :



$$\mathcal{A}_{obs,K\text{-}Rec} \simeq \mathcal{A}_{Rec} + \mathcal{A}_K + \chi_d\, \mathcal{A}_{\ell\ell}$$

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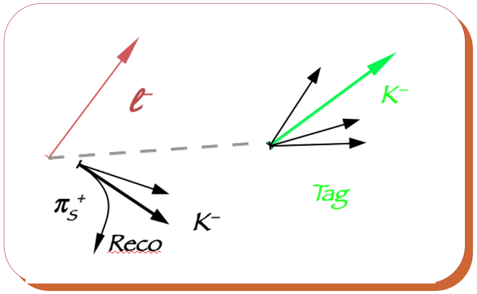

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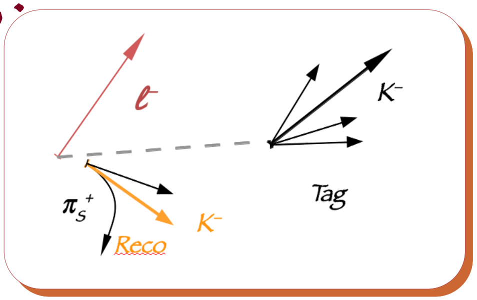

$$\mathcal{A}_{obs,K\text{-}Rec} \simeq \mathcal{A}_{Rec} + \mathcal{A}_{K} + \chi_d \mathcal{A}_{\ell\ell}$$

- Measure also single lepton asymmetry (before tagging) :

$$\mathcal{A}_{obs,Rec} = \frac{\ell^+ \pi_s^- - \ell^- \pi_s^+}{\ell^+ \pi_s^- + \ell^- \pi_s^+} \simeq \mathcal{A}_{Rec} + \chi_d \mathcal{A}_{\ell\ell}$$

Asymmetry

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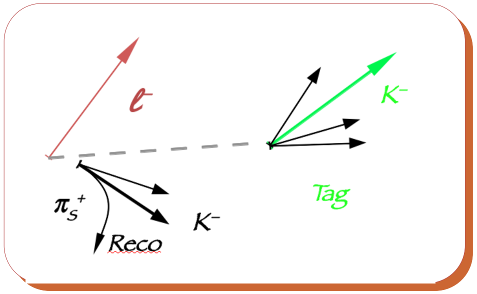

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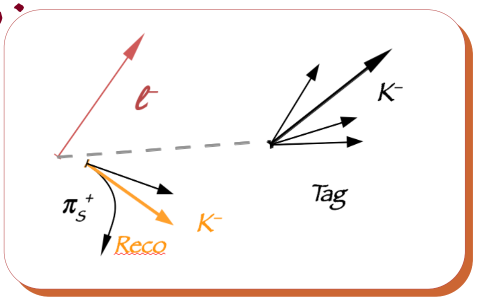

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- Measure also single lepton asymmetry (before tagging) :

$$\mathcal{A}_{obs,Rec} \simeq \mathcal{A}_{Rec} + \chi_d \mathcal{A}_{\ell\ell}$$

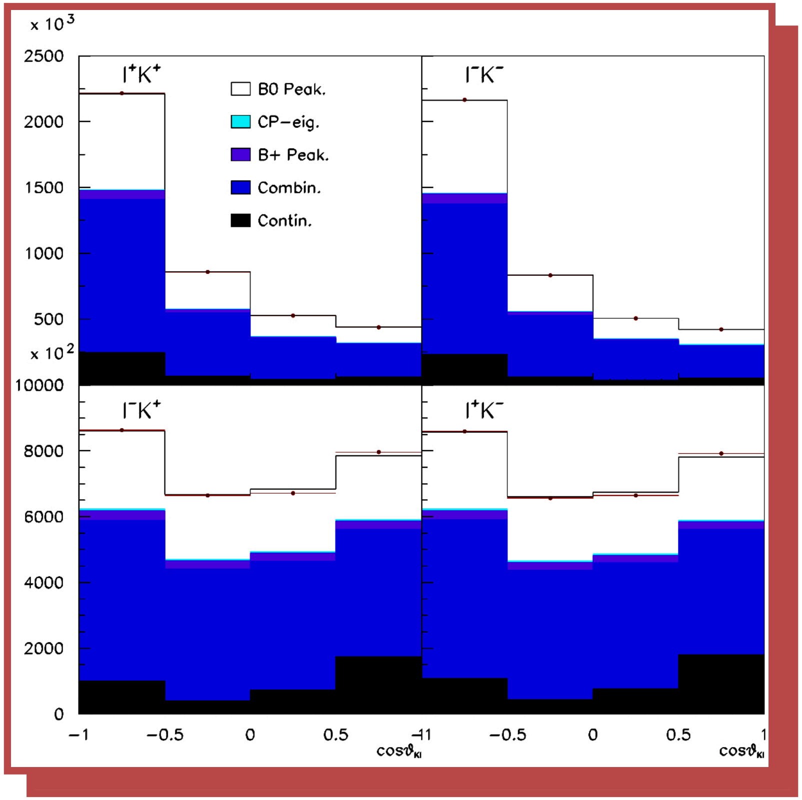
- Constrained system:

determine $\mathcal{A}_{\ell\ell}$ and main sources of systematic uncertainty from the data

MEASUREMENT

- 5D binned fit to (Δt, $\sigma(\Delta t)$, $\cos\theta_{\ell K}$, M_ν^2, p_K) space
- Use also opposite sign ℓ^+K^- / ℓ^-K^+ to improve precision on resolution parameters, mis-tagging etc.
- More than 100 free parameters:
  - $\mathcal{A}_{\omega}$, $\mathcal{A}_{REC}$, $\mathcal{A}_{K}$, K-Rec fraction, fraction of wrong tags (charge dependent), fraction of DCSC Kaons, ΔZ resolution parameters, ...

BABAR Preliminary



$\cos\theta_{\ell K}$

Peaking B0 PDF

- Four terms, one per each ℓK charge combination:

$\vec{j}=(\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}=\mathcal{PDF}$ for tag side K

$\mathcal{G}_{Kr}=\mathcal{PDF}$ for reco side K

ω = wrong charge tag frac.

$$\mathcal{G}_{\ell^+K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K) \times \{ (1-f^{++}_{Kr})[(1-\omega^+)\mathcal{G}_{B^0B^0}(\vec{j})+\omega^- \mathcal{G}_{B^0\overline{B^0}}(\vec{j})]+ f^{++}_{Kr}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j})+(1+\chi_d\mathcal{A}_{\ell\ell}) \}$$

$$\mathcal{G}_{\ell^-K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K) \times \{ (1-f^{--}_{Kr})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j})+\omega^+ \mathcal{G}_{\overline{B^0}B^0}(\vec{j})]+ f^{--}_{Kr}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j})+(1-\chi_d\mathcal{A}_{\ell\ell}) \}$$

Peaking B^0 PDF

- Four terms, one per each ℓK charge combination, including DETECTION asymmeties:

$\vec{j}=(\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}=$ PDF for tag side K

$\mathcal{G}_{Kr}=$ PDF for reco side K

ω = wrong charge tag frac.

$$\mathcal{G}_{\ell^+K^+}(\vec{j}) = \boxed{(1+\mathcal{A}_{rec})(1+\mathcal{A}_K)} \times \Big\{ (1-f^{++}_{Kr})\big[(1-\omega^+)\mathcal{G}_{B^0B^0}(\vec{j})+\omega^- \mathcal{G}_{B^0\overline{B^0}}(\vec{j})\big]+ f^{++}_{Kr}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j})+(1+\chi_d\mathcal{A}_{\ell\ell}) \Big\}$$

$$\mathcal{G}_{\ell^-K^-}(\vec{j}) = \boxed{(1-\mathcal{A}_{rec})(1-\mathcal{A}_K)} \times \Big\{ (1-f^{--}_{Kr})\big[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j})+\omega^+ \mathcal{G}_{\overline{B^0}B^0}(\vec{j})\big]+ f^{--}_{Kr}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j})+(1-\chi_d\mathcal{A}_{\ell\ell}) \Big\}$$

Peaking B⁰ PDF

$\vec{j}=(\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}$ = PDF for tag side K

$\mathcal{G}_{Kr}$ = PDF for reco side K

ω = wrong charge tag frac.

- Four terms, one per each ℓK charge combination,

... TAG-SIDE contributions:

$$\mathcal{G}_{\ell^+ K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K)\times$$

$$\boxed{\{\,(1-f_{Kr}^{++})[(1-\omega^+)\mathcal{G}_{B^0B^0}(\vec{j})+\omega^-\,\mathcal{G}_{B^0\overline{B^0}}(\vec{j})]+}$$

$$f_{Kr}^{++}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j})+(1+\chi_d\mathcal{A}_{\ell\ell})\,\}$$

$$\mathcal{G}_{\ell^- K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K)\times$$

$$\boxed{\{\,(1-f_{Kr}^{--})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j})+\omega^+\,\mathcal{G}_{\overline{B^0}B^0}(\vec{j})]+}$$

$$f_{Kr}^{--}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j})+(1-\chi_d\mathcal{A}_{\ell\ell})\,\}$$

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Peaking B⁰ PDF

$\vec{j}=(\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}$ = PDF for tag side K

$\mathcal{G}_{Kr}$ = PDF for reco side K

ω = wrong charge tag frac.

- Four terms, one per each ℓK charge combination and RECO-SIDE contributions:

$$\mathcal{G}_{\ell^+K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K) \times$$
$$\{ (1-f_{Kr}^{++})[(1-\omega^+)\mathcal{G}_{B^0B^0}(\vec{j})+\omega^- \mathcal{G}_{B^0\overline{B^0}}(\vec{j})]+$$
$$\boxed{f_{Kr}^{++}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j})+(1+\chi_d\mathcal{A}_{\ell\ell})} \}$$

$$\mathcal{G}_{\ell^-K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K) \times$$
$$\{ (1-f_{Kr}^{--})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j})+\omega^+ \mathcal{G}_{\overline{B^0}B^0}(\vec{j})]+$$
$$\boxed{f_{Kr}^{--}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j})+(1-\chi_d\mathcal{A}_{\ell\ell})} \}$$

Peaking B^0 Pdf – Tag Side

- $\cos\theta_{\ell K}$, M_ν^2, p_K : from simulation
- Δt: convolve resolution with Physics-motivated functions :

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

CP violation in the tag side :

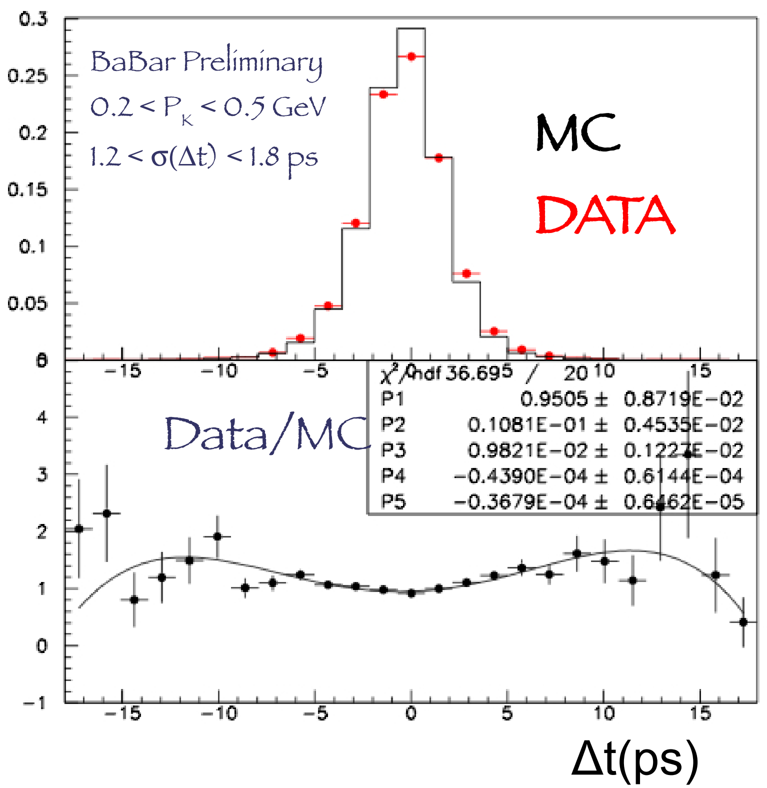
r'

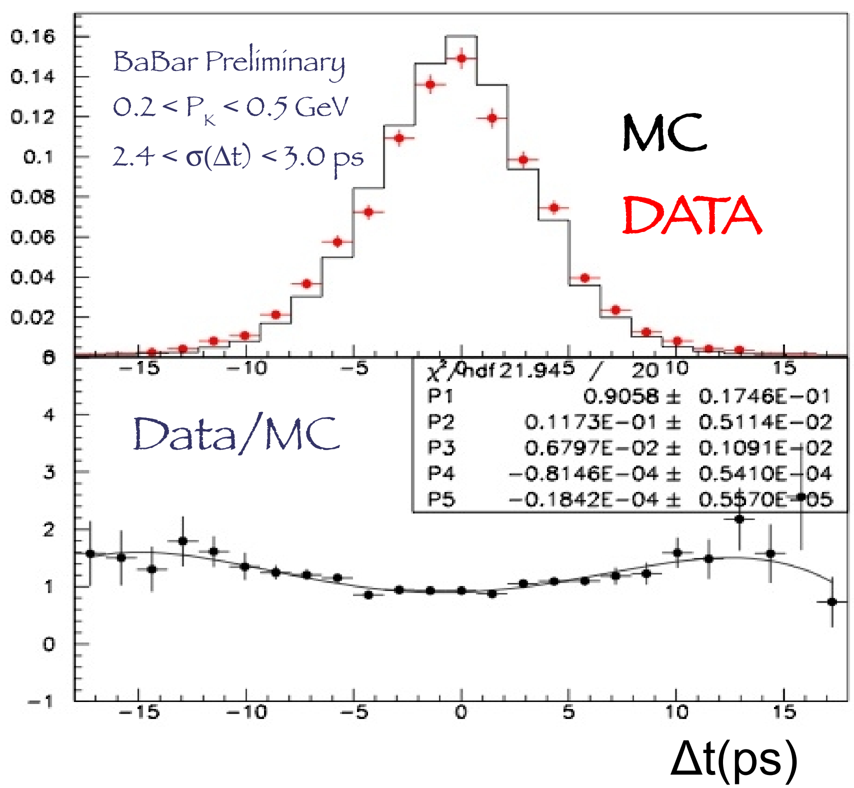
$b = 2r' \sin(2\beta+\gamma)\cos\delta'$,

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

Peaking B0 Pdf – Reco Side

- $\cos\theta_{\ell K}$, M_ν^2, p_K : from simulation
- Δt : use enriched Reco-side sample





Background PDF

- Combinatorial B^0 : similar to peaking B^0, many common parameters, including $|q/p|$ and detector asymmetries

- Peaking and combinatorial B^+ : same approach, use pure lifetime Δt PDF, helps constraining detector asymmetries, resolution parameters, etc.

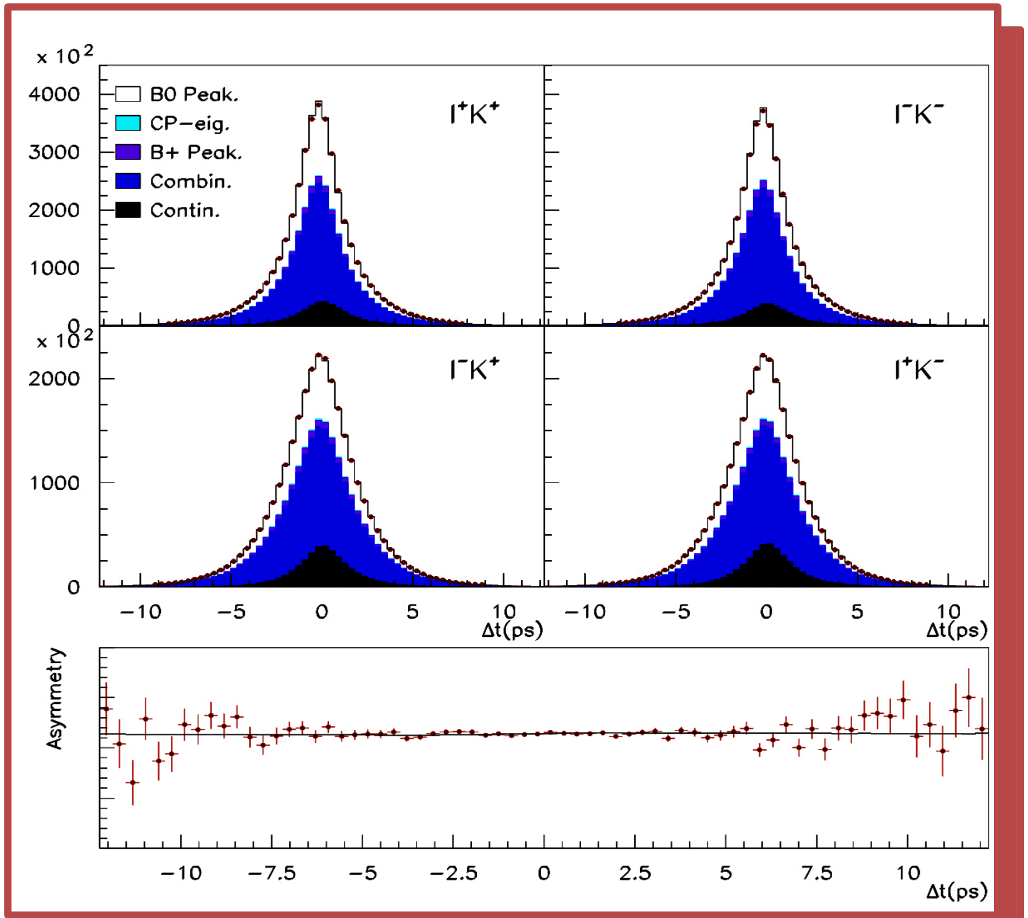
- Continuum : parameterized PDF from off-peak events

Results

$$\mathcal{A}_{\ell\ell} = (0.06 \pm 0.16^{+0.36}_{-0.32})\,\%$$

- No positive observation

BABAR Preliminary



Source	$\Delta\|q/p\|$
Peaking Sample Composition	$^{+1.17}_{-1.50} \times 10^{-3}$
Combinatoric Sample Composition	$\pm 0.39 \times 10^{-3}$
ΔT Resolution Model	$+0.60 \times 10^{-3}$
Dtag fraction	$\pm 0.11 \times 10^{-3}$
Dtag ΔT distribution	$\pm 0.65 \times 10^{-3}$
Fit Bias	$^{+0.46}_{-0.58} \times 10^{-3}$
CP-eigenstate description	—
Physical Parameters	$+0.28 \times 10^{-3}$
Total	$^{+1.61}_{-1.78} \times 10^{-3}$

Parameter	Fit to the data	Fit to the simulation	MC truth
δ_{CP}	$(0.29 \pm 0.84) \times 10^{-3}$	$(0.35 \pm 0.46) \times 10^{-3}$	0
$\mathcal{A}_{re}$	0.0030 ± 0.0004	0.0097 ± 0.0002	
$\mathcal{A}_{r\mu}$	0.0031 ± 0.0005	0.0084 ± 0.0003	
$\mathcal{A}_{K}$	0.0137 ± 0.0003	0.0147 ± 0.0001	
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

Results

BABAR Preliminary

$$\mathcal{A}_{\ell\ell} = (0.06 \pm 0.16^{+0.36}_{-0.32})\%$$

- Consistent and more precise than previous B-Factories average:

$$\mathcal{A}_{\ell\ell} = (-0.05 \pm 0.56)\%$$

Results

BABAR Preliminary

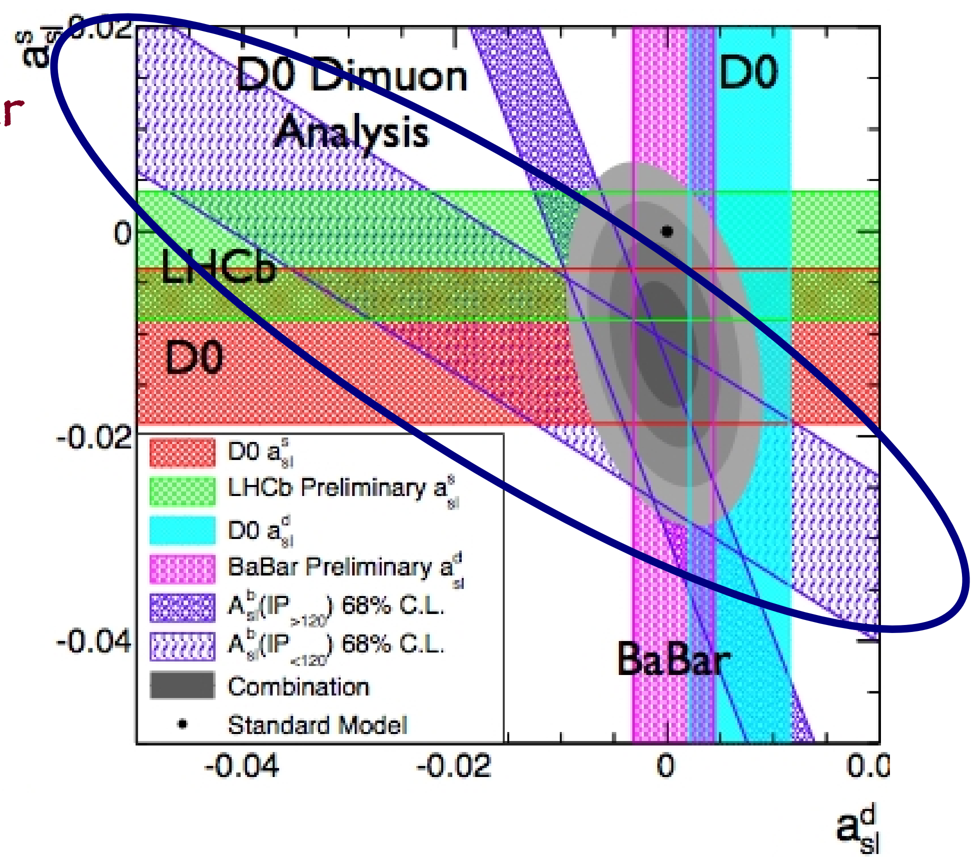
$$\mathcal{A}_{\ell\ell} = (0.06 \pm 0.16^{+0.36}_{-0.32})\%$$

- Consistent and more precise than previous B-Factories average:

$$\mathcal{A}_{\ell\ell} = (-0.05 \pm 0.56)\%$$

- Competitive and complementary to similar measurements at hadron colliders:

$$A_{\ell\ell} = C_d A^d_{\ell\ell} + C_s A^s_{\ell\ell} \quad (D\emptyset)$$



UNIVERSITÀ DEGLI STUDI DI PADOVA

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INFN

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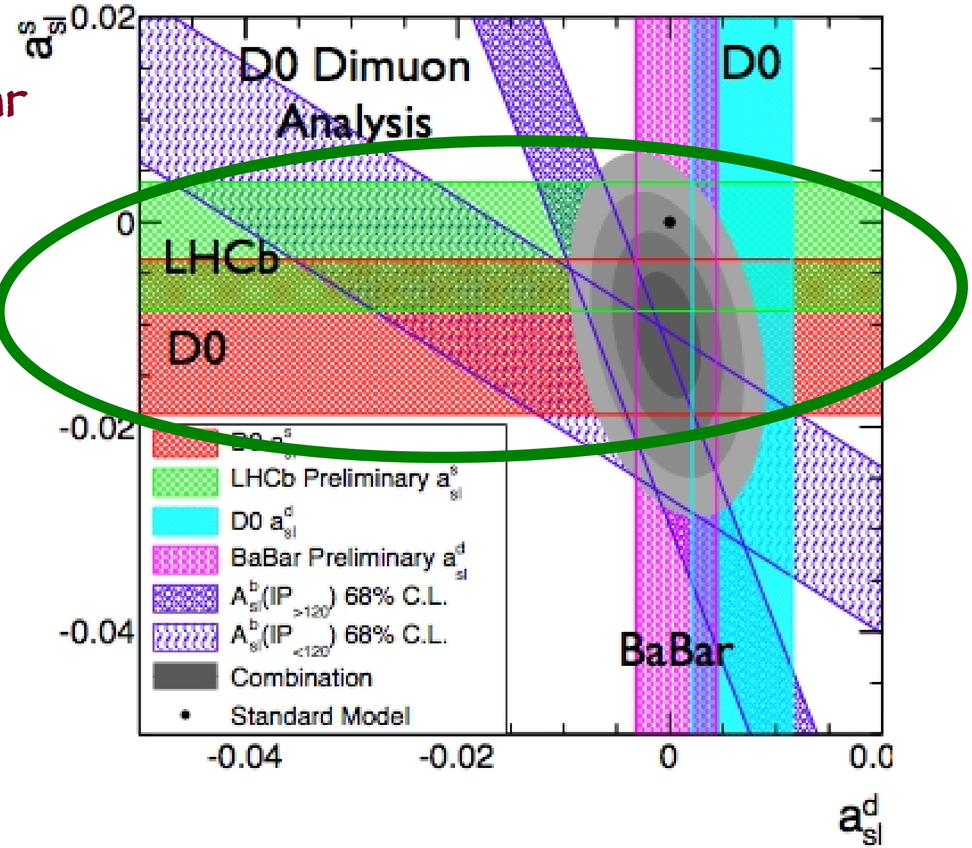

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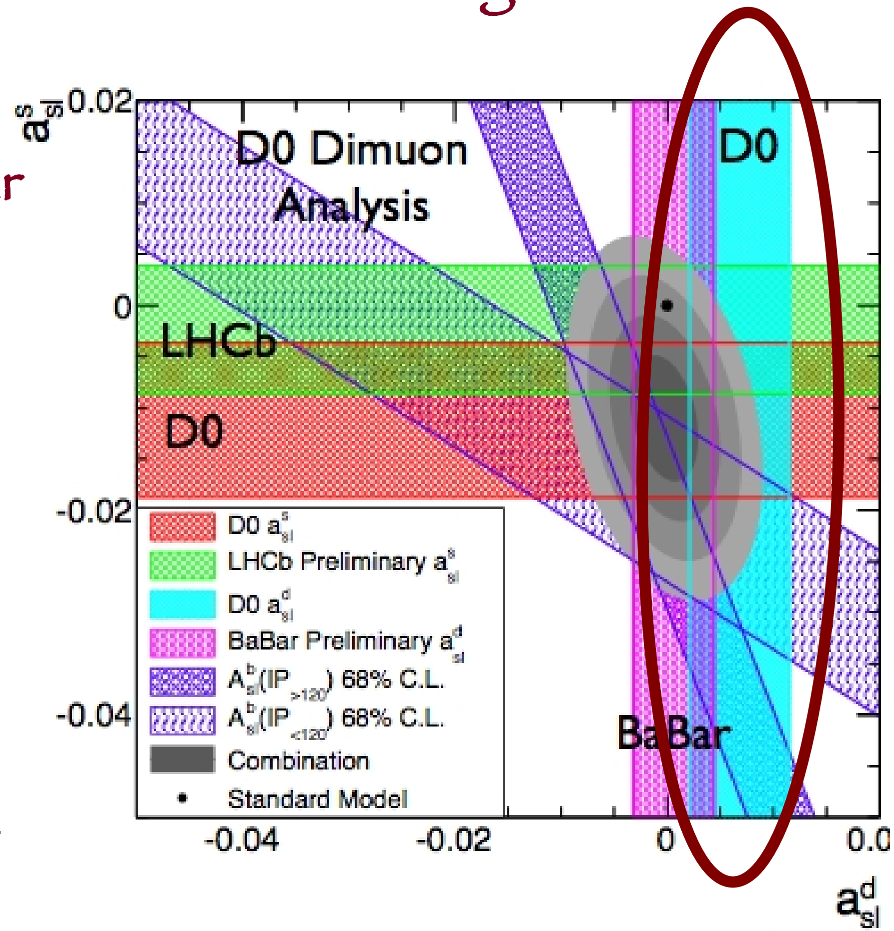
$$A_{\ell\ell}^s = \frac{(B_s \to D_s^- \ell^+ X) - (\overline{B}_s \to D_s^+ \ell^- X)}{(B_s \to D_s^- \ell^+ X) - (\overline{B}_s \to D_s^+ \ell^- X)}$$

$$A_{\ell\ell}^d = \frac{(B^0 \to D^{(*)+} \ell^+ X) - (\overline{B}^0 \to D^{(*)-} \ell^- X)}{(B^0 \to D^{(*)+} \ell^+ X) + (\overline{B}^0 \to D^{(*)-} \ell^- X)}$$



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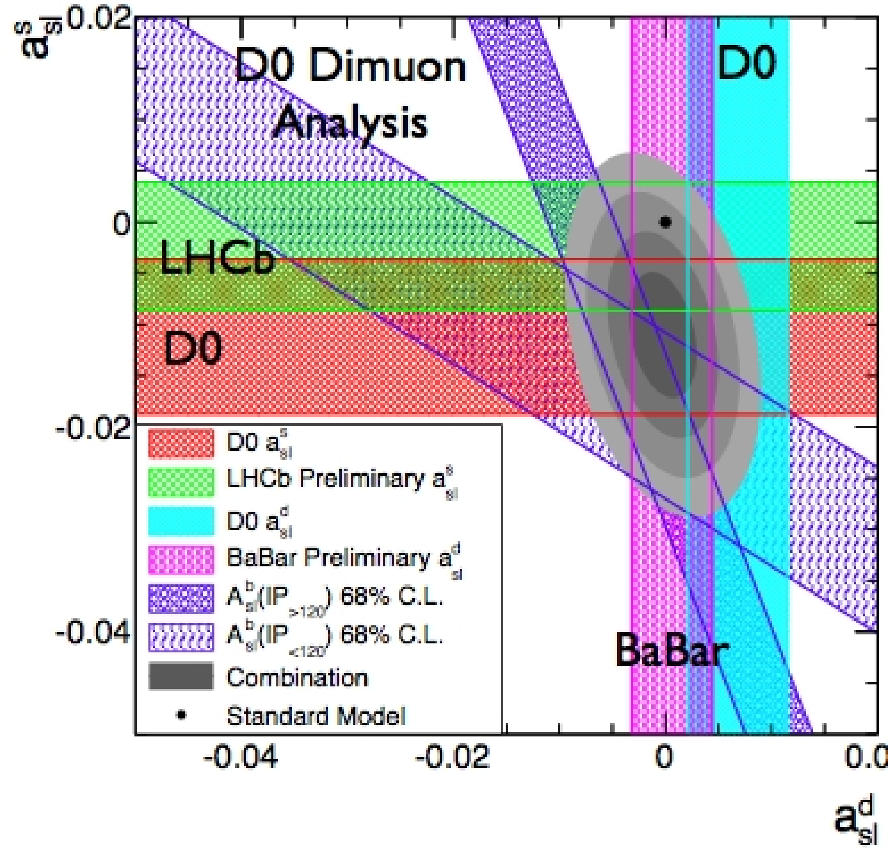
- Competitive and complementary to similar measurements at hadron colliders
- Contributing to world class precision in the determination of B-mixing CP asymmetries
- WA (grey) consistent with SM @ less than 2 σ



Conclusions

Five years after end running, BABAR has still glamour results on CP/T-Violation:

- First uncontroversial evidence of T-Violation in the *B*-meson system

http://www.economist.com/node/21561111

- Most stringent limit of mixing-induced CP-Violation in the evolution of B⁰ mesons

Backup

T-V in the PDG

e electric dipole moment		$<10.5 \times 10^{-28}$ $e$cm, CL = 90%
μ electric dipole moment		$(-0.1 \pm 0.9) \times 10^{-19}$ $e$cm
μ decay parameters		
transverse e^+ polarization normal to plane of μ spin, e^+ momentum		$(-2 \pm 8) \times 10^{-3}$
α'/A		$(-10 \pm 20) \times 10^{-3}$
β'/A		$(2 \pm 7) \times 10^{-3}$
Re(d_τ = τ electric dipole moment)		-0.220 to 0.45×10^{-16} $e$cm, CL = 95%
P_T in $K^+ \to \pi^0 \mu^+ \nu_\mu$		$(-1.7 \pm 2.5) \times 10^{-3}$
P_T in $K^+ \to \mu^+ \nu_\mu \gamma$		$(-0.6 \pm 1.9) \times 10^{-2}$
Im(ξ) in $K^+ \to \pi^0 \mu^+ \nu_\mu$ decay (from transverse μ pol.)		-0.006 ± 0.008
asymmetry A_T in K^0-$\overline{K}^0$ mixing		$\boxed{(6.6 \pm 1.6) \times 10^{-3}}$
Im(ξ) in $K^0_{\mu 3}$ decay (from transverse μ pol.)		-0.007 ± 0.026
$A_T(D^\pm \to K^0_S K^\pm \pi^+ \pi^-)$	[b]	$(-12 \pm 11) \times 10^{-3}$
$A_T(D^0 \to K^+ K^- \pi^+ \pi^-)$	[b]	$(1 \pm 7) \times 10^{-3}$
$A_T(D^\pm_s \to K^0_S K^\pm \pi^+ \pi^-)$	[b]	$(-14 \pm 8) \times 10^{-3}$
p electric dipole moment		$<0.54 \times 10^{-23}$ $e$cm
n electric dipole moment		$<0.29 \times 10^{-25}$ $e$cm, CL = 90%
$n \to p e^- \overline{\nu}_e$ decay parameters		
ϕ_{AV}, phase of g_A relative to g_V	[c]	$(180.018 \pm 0.026)^\circ$
triple correlation coefficient D	[d]	$(-1.2 \pm 2.0) \times 10^{-4}$
triple correlation coefficient R	[d]	0.008 ± 0.016
Λ electric dipole moment		$<1.5 \times 10^{-16}$ $e$cm, CL = 95%
triple correlation coefficient D for $\Sigma^- \to n e^- \overline{\nu}_e$		0.11 ± 0.10

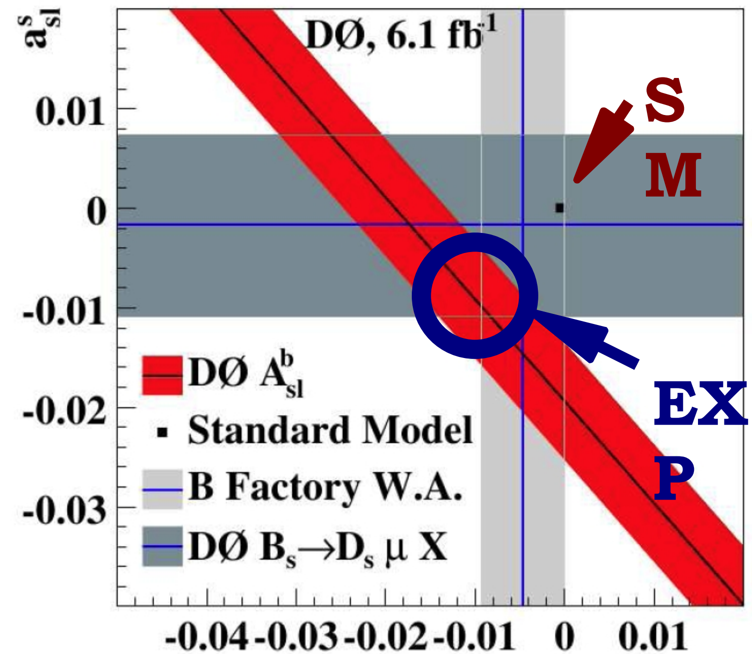
CPLEAR: PLB 444, 43 (1998)
Compares $K^0 \to \overline{K}^0$ with $\overline{K}^0 \to K^0$
Mixing rate.

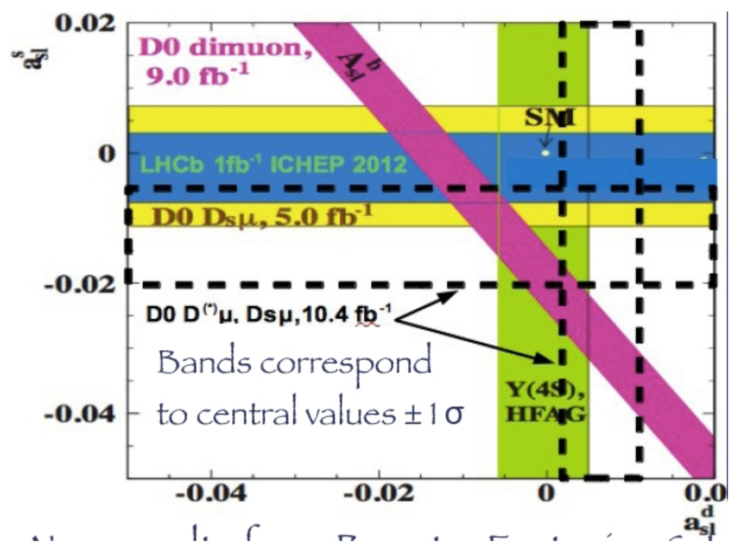
- Related by T *and* CP.
- Not time-dependent.
- Various criticisms.

BABAR:
PRD(RC)81, 111103 (2010)
PRD(RC) 84, 031103 (2011)
Triple products

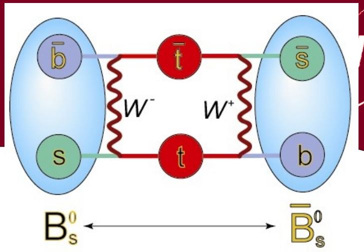
Dilepton Asymmetry @ colliders

- D0 claims large unexpected asymmetry in equal charge dilepton B decays at ICHEP 2010
- Lifetime analysis : effect connected to B_s mixing
- D0 and LHCb then measure asymmetry in the rates of $B_s \to D^{(*)}_s \mu \nu$ decays
- These measurements are consistent both with the SM and with D0 dilepton results





B^0 Mixing parameters



- Two-levels system evolution:

$$i\frac{d}{dt}\begin{pmatrix} B_q \\ \bar{B}_q \end{pmatrix} = \left[\begin{pmatrix} M_{11}^q & M_{21}^{q\,*} \\ M_{21}^q & M_{11}^q \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11}^q & \Gamma_{21}^{q\,*} \\ \Gamma_{21}^q & \Gamma_{11}^q \end{pmatrix}\right]\begin{pmatrix} B_q \\ \bar{B}_q \end{pmatrix}$$

- Mass eigenstates are related to flavor eigenstates by the relation:

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

- Where

$$\mathcal{A}_{ll} = \frac{1-|q/p|^4}{1+|q/p|^4} = \frac{\Gamma_{12}}{M_{12}}\sin\phi \qquad \left(\phi = -\mathrm{Arg}\frac{M_{12}}{\Gamma_{12}}\right)$$

- We have:

$$|q/p| = 1-(0.3^{+1.8}_{-2.0})\cdot 10^{-3} \qquad \textit{This Measurement}$$

$$|q/p| = 1+(0.2\pm 2.8)\cdot 10^{-3} \qquad \textit{Previous W.A.}$$