Recent results on T and CP Violation at *BABAR*

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects

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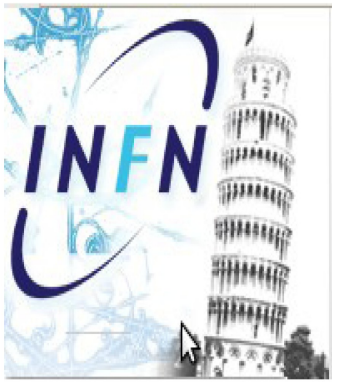
On behalf of the BABAR Collaboration



Outline

- Introduction
- Experiment overview
- Some recent highlights
  - **1st direct observation of T-Reversal violation (TRV) in B-mesons**
  - **CP violation (CPV) measurements in B-mesons**
    - CPV in B^0-mixing
    - Time-dependent Dalitz plot analysis of $B^0 \to (\rho\pi)^0$

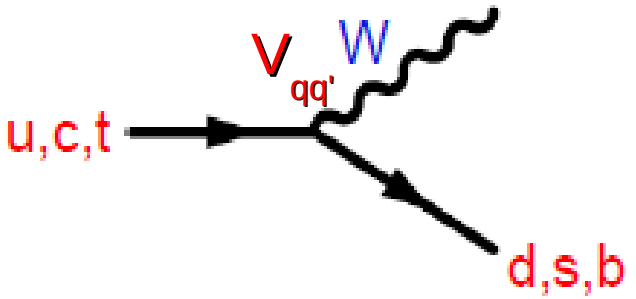
Introduction to CP and T Violation

CP and T Violation in the SM

Only source CPV in SM from CKM mechanism

Weak states **CKM Matrix** **Mass states**

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}$$



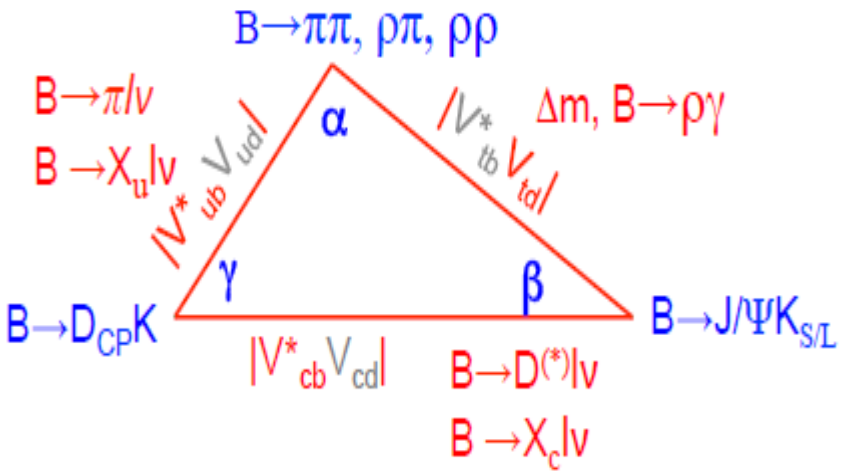
- **V_{CKM}:** 4 parameters, 3 real and a complex phase that introduces CPV in SM
- **V_{CKM} is unitarity:** 6 unitarity relations illustrated by 6 triangles.

Of particular interest for B_u and B_d is:

$$\alpha = -\arg(V_{tb}^* V_{td} / V_{ub}^* V_{ud})$$
$$\beta = -\arg(V_{cb}^* V_{cd} / V_{tb}^* V_{td})$$
$$\gamma = -\arg(V_{ub}^* V_{ud} / V_{cb}^* V_{cd})$$

Unitatiry Triangle (UT)

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



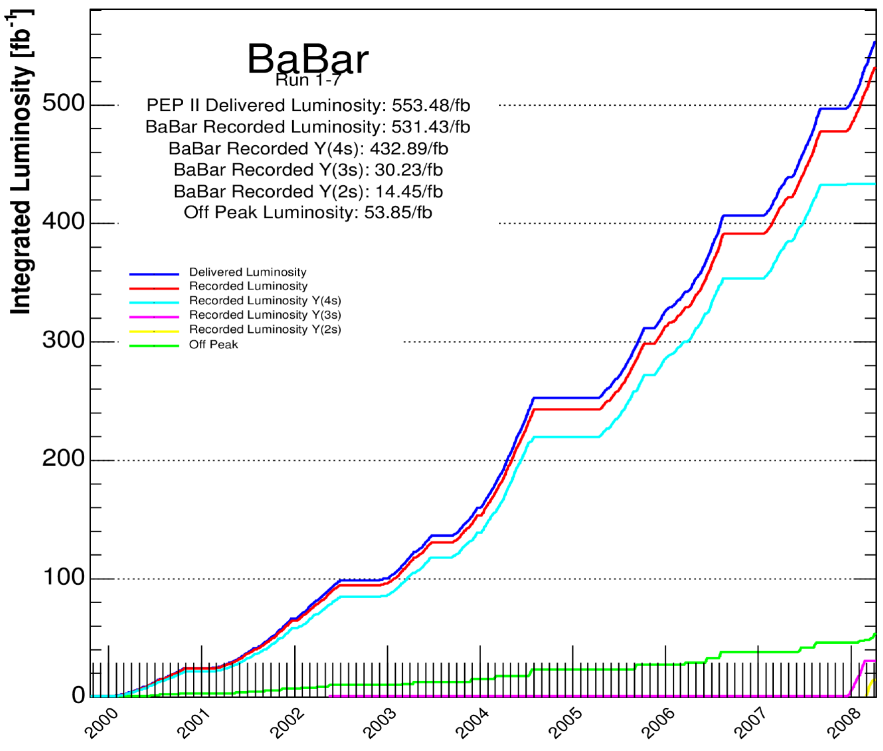
CKM and TRV

- CPT conservation: CPV implies TRV
- CKM is only source of TRV in SM

Experiment overview

BABAR Dataset

7 Runs over the course of 9 years



Over 500 submitted/published papers:

- CPV, CKM angles: α, β, γ
- Semi-Leptonic B decays: $|V_{ub}|$, $|V_{cb}|$
- B – B mixing: $|V_{td}|$
- D – D mixing
- Precision measurements, rare decays of B, charm hadrons, τ
- Spectroscopy, discovery of new states
- QCD
- Limits on new physics (NP)

30 publications in 2012

~471×10^6 B$\overline{\text{B}}$ (0.5 × Belle)

~690×10^6 c$\overline{\text{c}}$

~500×10^6 $\tau^+\tau^-$

~1.2×10^8 Υ(3S) (7 × Belle+CLEO)

~98×10^6 Υ(2S) (10 × CLEO)

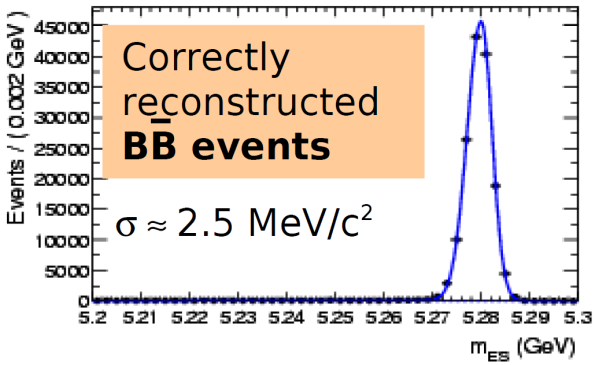
~18×10^6 Υ(1S) (from Υ(2S)→$\pi^+\pi^-\Upsilon$(1S))

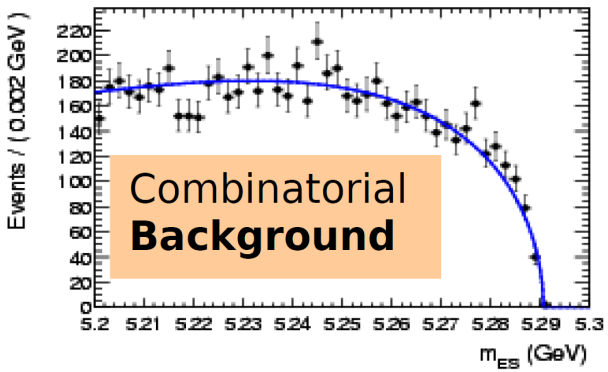
Experimental Issues

- Small S/B ratio, mostly continuum ($e^+e^- \to q\bar{q}$, $q \neq b$) background.
- Use kinematical and event-shape variables to discriminate:

Beam-energy substituted mass

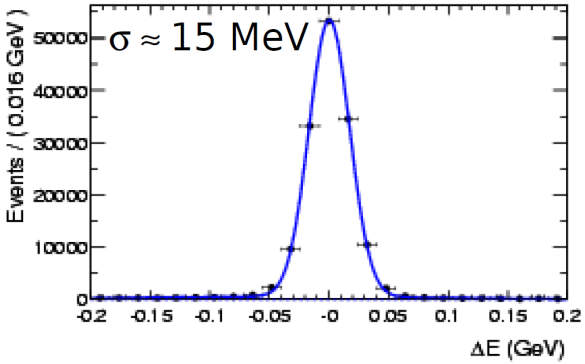
$$m_{ES} = \sqrt{E^{*}_{beam}{}^{2} - p^{*2}_{B}}$$

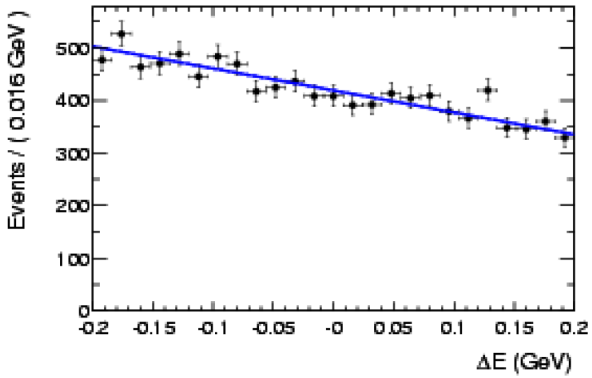




Energy difference

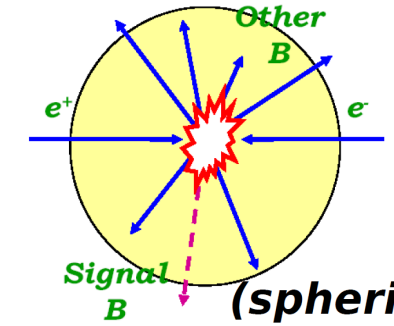
$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$



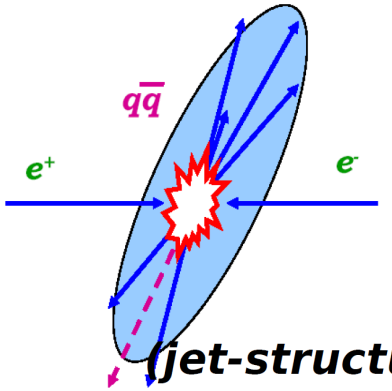


Event topology

(multivariate methods)



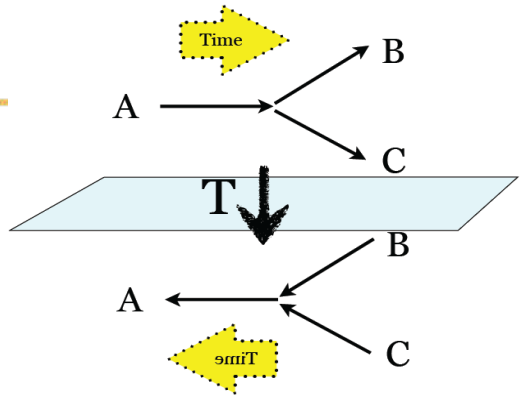
(spherical)



(jet-structure)

Observation of T-reversal Violation in B-meson decays

Time Reversal Violation



- **Time reversal is a discrete symmetry**
  - Exchanges |in> and |out> states, t → -t
  - No evidence of direct TRV in stable systems (e.g. EDM) or in unstable system
- **The CP and T symmetry transformations are connected via CPT theorem**
  - CPV observation ⇒ T violation
  - Does expected T-violation balance CPV exactly? ⇒ test of CPT
  - Can we observe direct T violation?
- **TRV in decays,** e.g. $\Gamma(B^0 \to K^+\pi^-) \neq \Gamma(K^+\pi^- \to B^0)$
  - Strong interaction will swamp the feeble weak process
- **TRV in mixing,** e.g. $R(\overline{K^0}_{t=0} \to e^+\pi^-\nu_{t=\tau}) \neq R(K^0_{t=0} \to e^-\pi^+\overline{\nu}_{t=\tau})$ **CPLEAR, PLB 444 (1998) 43**
  - CPV and TRV cannot be distinguished
- **TRV in interference between decays with and without mixing**
  - No motion reversal nor exchange of |in> → |out> states

Can we find processes that are achieved by T-reversal?

TRV measurement: The idea

- Use Einstein-Podolsky-Rosen entanglement @ $\Upsilon(4S)$ to overcome the problem of irreversibility
- $\Upsilon(4S)$ decay: use two sets of orthogonal states
  - Flavour eigenstates: $\overline{B^0}$ and B^0 $\Rightarrow$ $|i\rangle = \frac{1}{\sqrt{2}}\left[B^0(t_1)\overline{B}^0(t_2) - \overline{B}^0(t_1)B^0(t_2)\right]$
  - CP eigenstates: B_{CP+} and B_{CP-} $\Rightarrow$ $|i\rangle = \frac{1}{\sqrt{2}}\left[B_{CP+}(t_1)B_{CP-}(t_2) - B_{CP-}(t_1)B_{CP+}(t_2)\right]$

Method described in J. Bernabeu et al. arXiv: 1203.0171 [hep-ph]

- We can tag
  - Flavour eigenstate: e.g. use sign of prompt lepton in $B^0 \to l^+X$; $\overline{B^0} \to l^-X$ decays
  - CP eigenstate: reconstruct final state $J/\psi K^0_L$ or $J/\psi K^0_S$ which are CP+ and CP-, respectively

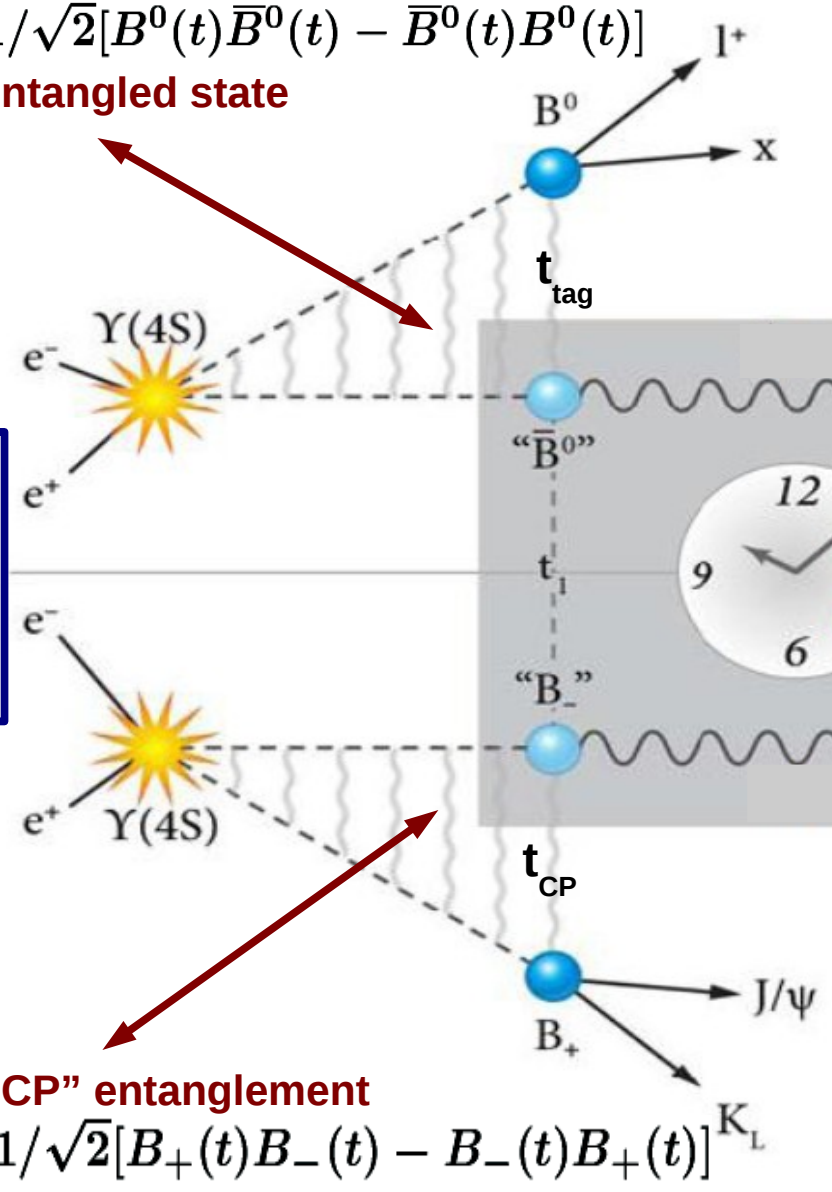
Look for the following transitions

Reference (X,Y) = (tag,CP)		T	T-transformed	
$B^0 \to B_+$	$(\ell^-, J/\psi K^0_L)$		$B_+ \to B^0$	$(J/\psi K^0_S, \ell^+)$
$B^0 \to B_-$	$(\ell^-, J/\psi K^0_S)$	$\longleftrightarrow$	$B_- \to B^0$	$(J/\psi K^0_L, \ell^+)$
$\overline{B}^0 \to B_+$	$(\ell^+, J/\psi K^0_L)$		$B_+ \to \overline{B}^0$	$(J/\psi K^0_S, \ell^-)$
$\overline{B}^0 \to B_-$	$(\ell^+, J/\psi K^0_S)$		$B_- \to \overline{B}^0$	$(J/\psi K^0_L, \ell^-)$

The Δt measurement and flavour/CP tagging technique

$|i\rangle = 1/\sqrt{2}[B^0(t)\overline{B}^0(t) - \overline{B}^0(t)B^0(t)]$

EPR entangled state



$\overline{B}^0 \to B_-$

$(\ell^+, J/\psi K_S^0)$

t_{tag} t_{CP} $\Delta t = t_{CP} - t_{tag} > 0$

$\Delta t = t_{CP} - t_{tag} < 0$

$B_- \to \overline{B}^0$

$(J/\psi K_L^0, \ell^-)$

$\beta\gamma = 0.56$ @ BaBar

$\Delta z = \beta\gamma c \Delta t$

$\langle \Delta z \rangle \approx 250 \mu m$

EPR "CP" entanglement

$|i\rangle = 1/\sqrt{2}[B_+(t)B_-(t) - B_-(t)B_+(t)]$

TRV measurement: The measurement

- Time-dependent decay rate ($\Delta t>0$)

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\left[1 + C^{\pm}_{\alpha,\beta}\cos(\Delta m\Delta\tau) + S^{\pm}_{\alpha,\beta}\sin(\Delta m\Delta\tau)\right]$$

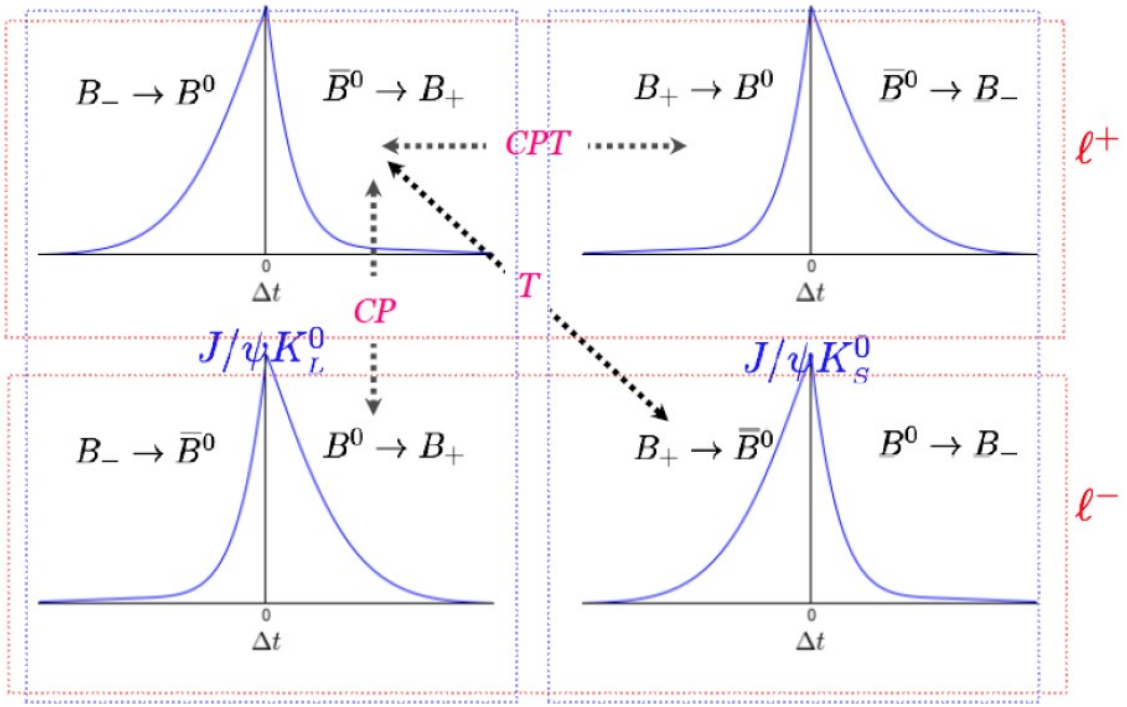
- $\alpha = B^0$ or $\overline{B^0}$
- $\beta = J/\psi K^0_S$ or $J/\psi K^0_L$
- $\pm$ = sign of $t_{CP} - t_{tag}$

8 {C,S} sets $\Rightarrow$ T,CP,CPT violating parameters

$\{\Delta C_{T,CP,CPT}, \Delta S_{T,CP,CPT}\}$

Decays with B^0 and $J/\psi K^0_S$ as reference

e.g. $\Delta S^-_T = S^+(l^-X, J/\psi K^0_L) - S^-(l^+X, J/\psi K^0_S)$ (similar of ΔC_T)



- In total can built
  - 4 independent T comparisons
  - 4 independent CP comparisons
  - 4 independent CPT comparisons
- T implies
  - Opposite Δt
  - Different reco states
  - Opposite flavour states

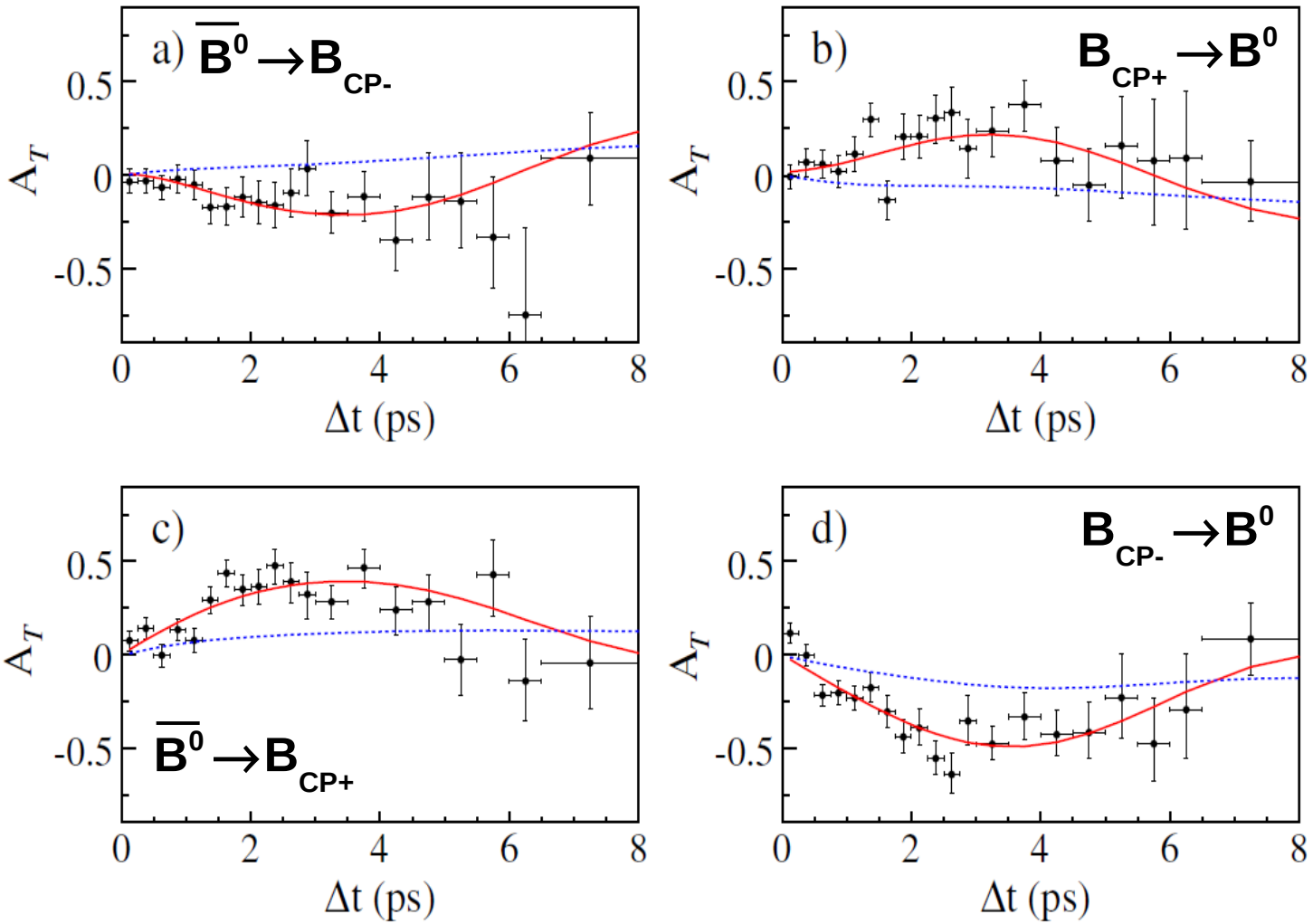
TRV measurement: Results on TRV

Phys. Rev. Lett. 109, 211801 (2012)

Dataset: 471×10^6 MBB

- Asymmetries of 4 transitions studied

$$A_T(\Delta t) = \frac{\Delta C_T^+}{2}\cos(\Delta m \Delta t) + \frac{\Delta S_T^+}{2}\sin(\Delta m \Delta t)$$

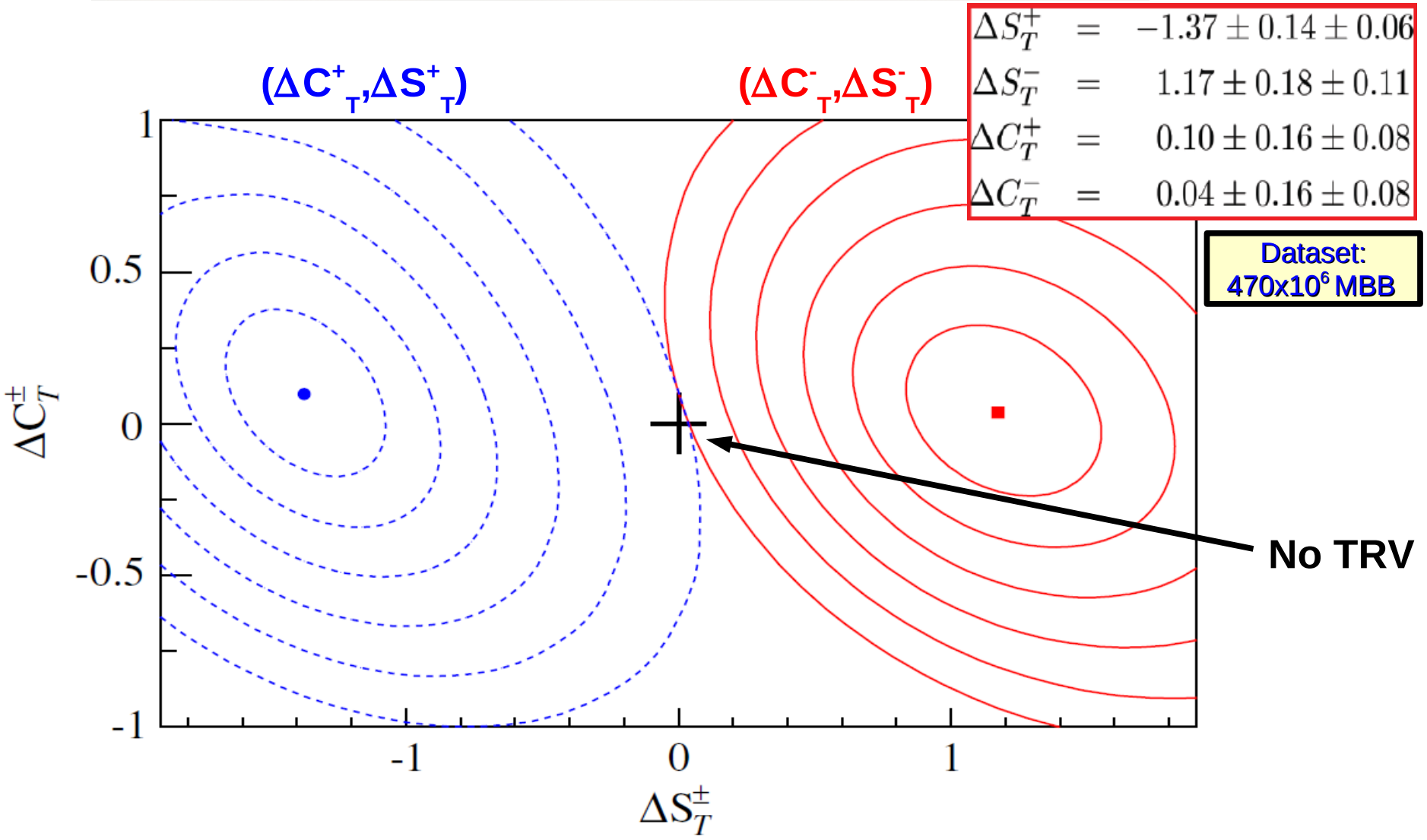


T conserved

Best fit

TRV measurement: Results on TRV

Phys. Rev. Lett. 109, 211801 (2012)



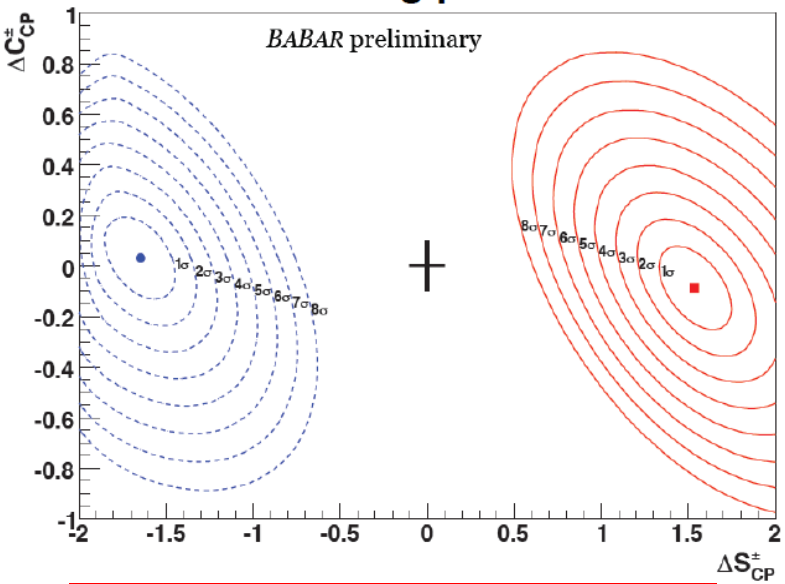
Time reversal violation with a significance of 14σ!! (syst. included)

TRV measurement: Results on CPV and CPTV

Phys. Rev. Lett. 109, 211801 (2012)

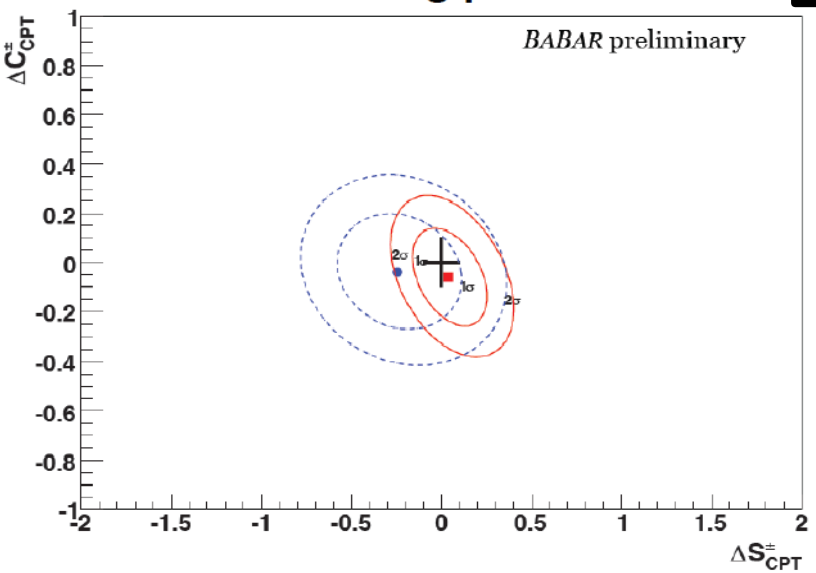
Dataset: 471x10^6 MBB

CP violating parameters



$$\Delta S^{+}_{CP} = -1.30 \pm 0.10 \pm 0.07$$
$$\Delta S^{-}_{CP} = 1.33 \pm 0.12 \pm 0.06$$
$$\Delta C^{+}_{CP} = 0.07 \pm 0.10 \pm 0.03$$
$$\Delta C^{-}_{CP} = 0.08 \pm 0.09 \pm 0.04$$

CPT violating parameters



$$\Delta S^{+}_{CPT} = 0.16 \pm 0.20 \pm 0.09$$
$$\Delta S^{-}_{CPT} = -0.03 \pm 0.13 \pm 0.06$$
$$\Delta C^{+}_{CPT} = 0.15 \pm 0.17 \pm 0.07$$
$$\Delta C^{-}_{CPT} = 0.03 \pm 0.14 \pm 0.08$$

- **Clear evidence of CPV (16.6σ)**
- **No evidence of CPT violation (0.33σ).**
  Consistent amount of T and CP violation

Latest CPV results in B-meson decays

B decays and CP Violation

By studying CPV in B decays can …

- Determine precisely Standard Model (SM) parameters
  - In particular CKM matrix elements
- May show New Physics (NP)
- Test QCD at low-q^2 (form factors)

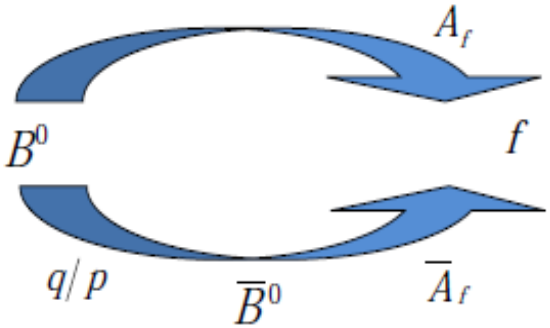
$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

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

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

Three types of CPV

- CPV in decay ⇒ $\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f})$ $\left|\frac{\overline{A_f}}{A_f}\right| \neq 1$
- CPV in mixing ⇒ $P(B^0 \to \overline{B}^0) \neq P(\overline{B}^0 \to B^0)$ $\left|\frac{q}{p}\right| \neq 1$
- CPV in interference ⇒ $\Gamma(B^0(\to \overline{B}^0) \to f)(t) \neq \Gamma(\overline{B}^0(\to B^0) \to f)(t)$



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

$$|\lambda_f| = 1$$

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

CPV in B^0-$\overline{B}^0$ mixing (1)

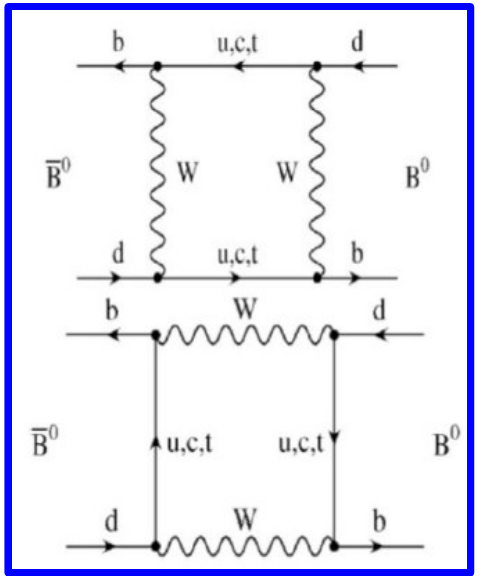
- Time independent CP asymmetry

$$a_{sl}^{d} = \frac{N(B^0,B^0) - N(\overline{B}^0,\overline{B}^0)}{N(B^0,B^0) + N(\overline{B}^0,\overline{B}^0)} = \frac{1-|q/p|^4}{1+|q/p|^4} \approx 2\left(1-|q/p|\right)$$

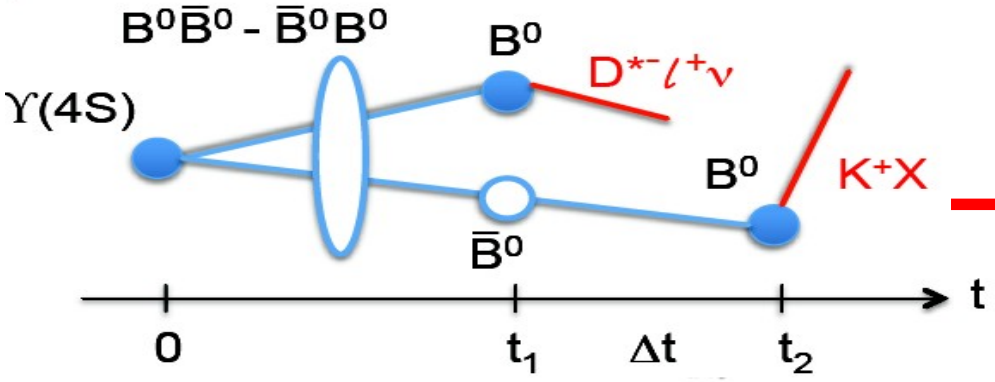
- Small effect in SM $a_{sl}^{SM}(B_d) = (-4.1 \pm 0.06) \times 10^{-4}$

Lenz, Nierste,1102:4274

New particles in the boxes could modify SM expectations



- Usual approach through semi-leptonic B decays (high yield but significant uncertainty from charge-asymmetry background)
- New approach
  - 1st B^0 from partial reconstruction: $B^0 \rightarrow D^{*-}l^+\nu$
  - 2nd B^0 tagged using charged kaons



$$A_{CP} = \frac{N\left(D^{*-}\ell^+\nu, K^+\right) - N\left(D^{*+}\ell^-\overline{\nu}, K^-\right)}{N\left(D^{*-}\ell^+\nu, K^+\right) + N\left(D^{*+}\ell^-\overline{\nu}, K^-\right)}$$

CPV in B^0-$\bar{B}^0$ mixing (2)

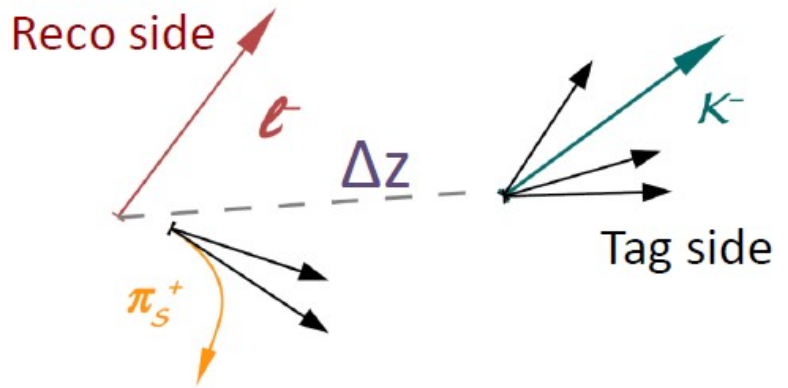
ArXiv: 1208.1282
BABAR preliminary

Dataset:
471×10^6 MBB

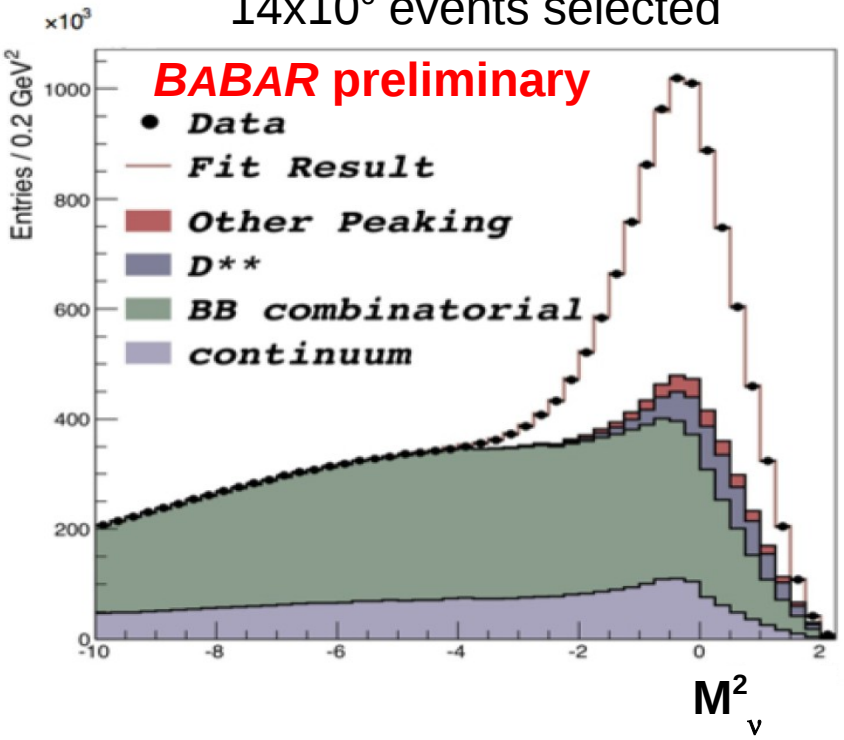
- Partial reconstruction using only the lepton ($e^{\pm}$,$\mu^{\pm}$) and soft π from $D^{*-} \rightarrow D^0 \pi^-$
- Kaon tagging: equal charge kaons from the reco side mimicking a mixed event distinguished using
  - $\Delta z = z(l) - z(K)$ (in the Lab frame)
  - $\cos(\theta_{Kl})$ (in the CM frame)
- Assume B^0 at rest in CM frame
- Compute missing mass from 4-momenta difference

$$M^2_\nu = (E_{beam}-E_{D^*}-E_\ell)^2-(P_{D^*}+P_\ell)^2=(P_B-P_{D^*}-P_\ell)^2$$

- A_{CP} extraction:
  - 4D binned fit to $\cos(\theta_{Kl})$, Δz, M^2_ν, p_K on 8 samples ($e^{\pm}K^{\pm}$,$\mu^{\pm}K^{\pm}$)



14×10^6 events selected



CPV in B^0-$\bar{B}^0$ mixing (3)

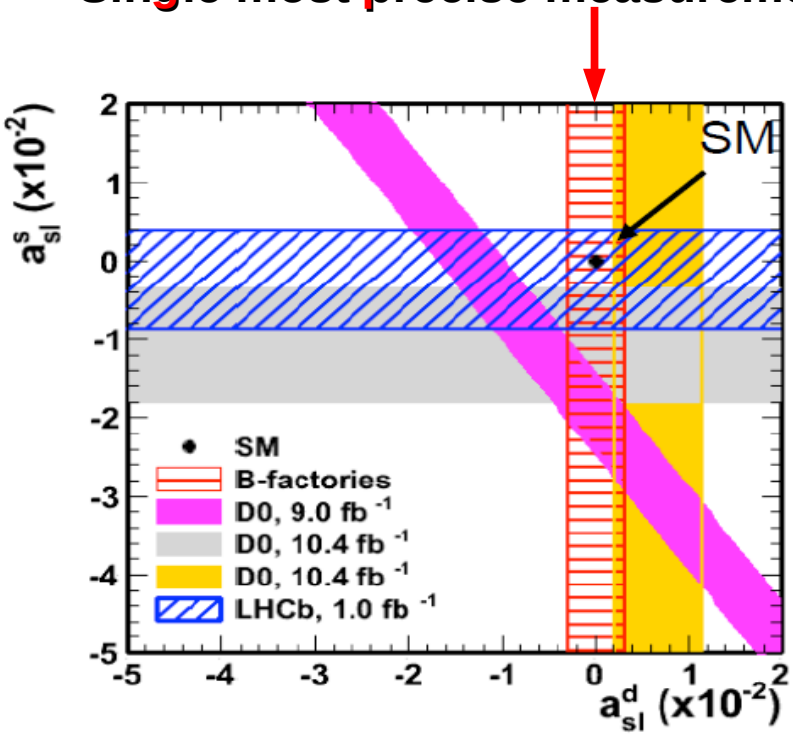
ArXiv: 1208.1282
BABAR preliminary

Dataset: 471x10^6 MBB

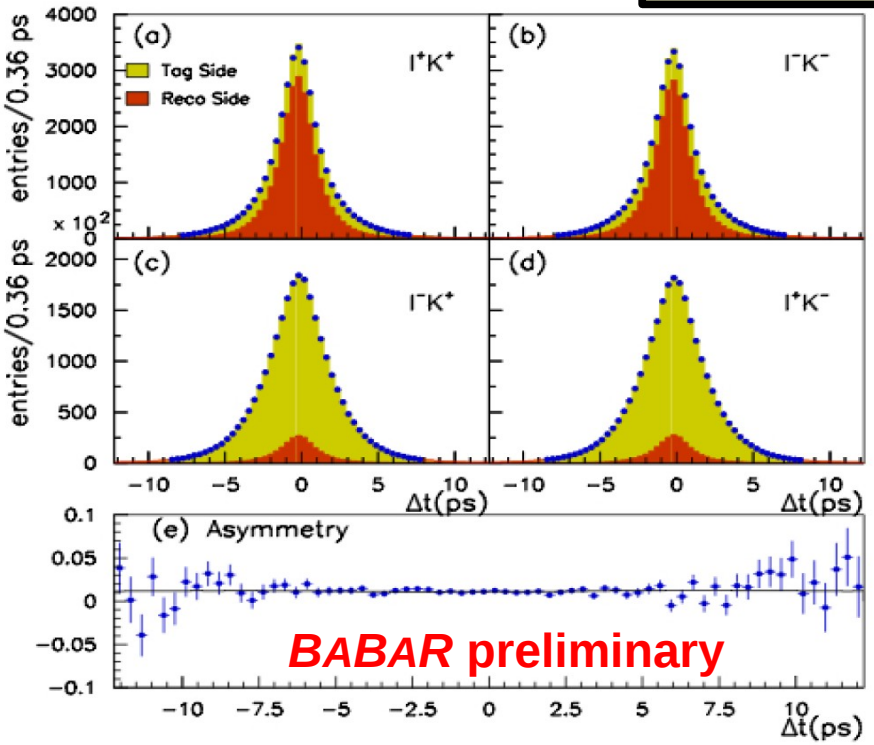
- Asymmetry measurement

$$a_{sl}^{d} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$$
$$1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$$

- Consistent with SM expectations
- Consistent with HFAG average
- **Single most precise measurement!**



Continuum subtracted data



$$C_d a_{sl}^d + C_s a_{sl}^s = (-0.79 \pm 0.17 \pm 0.09)\%$$

D0: PRD 84, 52007 (2011)

$$a_{sl}^s = (-1.12 \pm 0.74 \pm 0.17)\%$$

D0: PRL 110, 011801 (2013)

$$a_{sl}^d = (+0.68 \pm 0.45 \pm 0.14)\%$$

D0: PRD 86, 072009 (2012)

$$a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\%$$

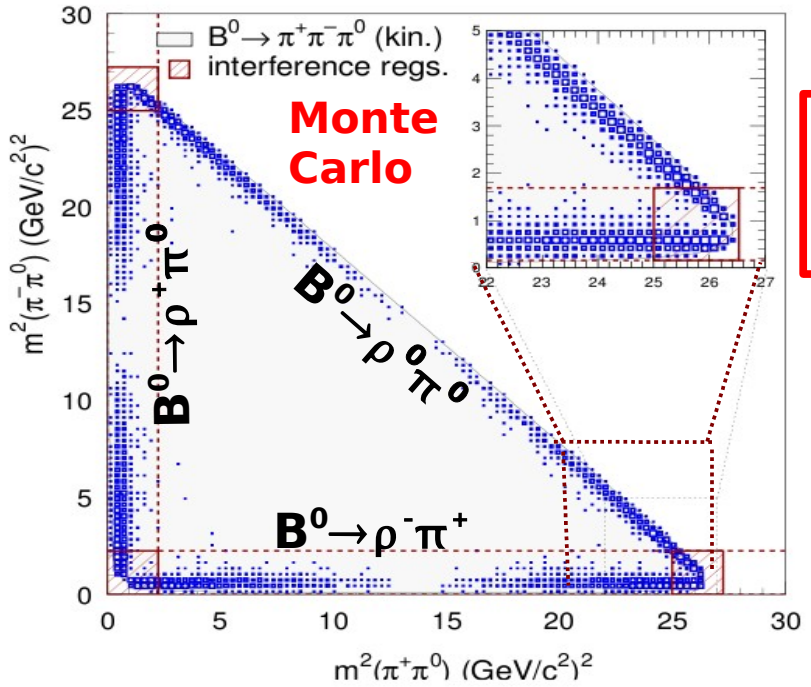
LHCb-CONF-2012-022

TD-Dalitz plot of $B^0 \to (\rho\pi)^0$ (1)

- $B^0 \to \pi^+\pi^-\pi^0$ CPV measurement
- Dominant decay $B^0 \to \rho^+\pi^-$ not a CP-eigenstate
- Complicated isospin relations: isospin pentagon including $B^0 \to \rho^+\pi^-/\rho^-\pi^+/\rho^0\pi^0$ and $B^+ \to \rho^+\pi^0/\rho^0\pi^+$ amplitudes
- Time-dependent amplitude analysis assuming isospin symmetry

  $\Rightarrow$ permits in principle unambiguous measurement of α-UT

Snyder and Quinn, PRD48:2139 (1993)



$$\overline{A}(\pi^+\pi^-\pi^0) = f_+\overline{A}(\rho^+\pi^-) + f_-\overline{A}(\rho^-\pi^+) + f_0\overline{A}(\rho^0\pi^0)$$
$$A(\pi^+\pi^-\pi^0) = f_+A(\rho^+\pi^-) + f_-A(\rho^-\pi^+) + f_0A(\rho^0\pi^0)$$

Interference between $\rho\pi$ resonances is used to disentangle weak and strong phases

$\Rightarrow$ direct access to α_{eff} no $\sin(2\alpha_{eff})$ ambiguity

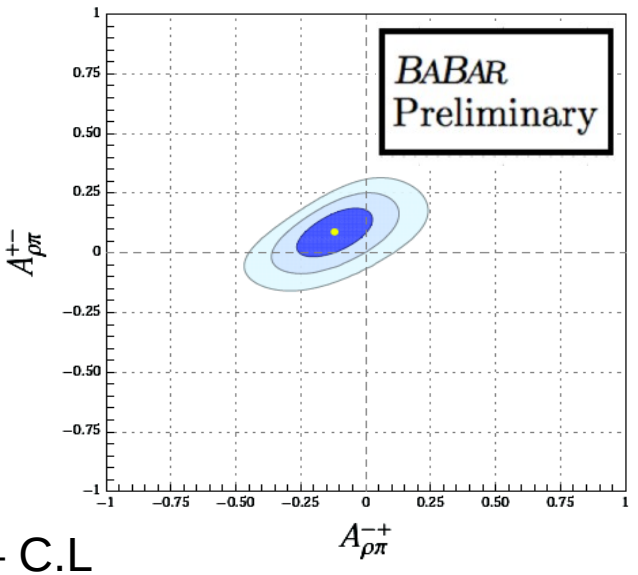
TD-Dalitz plot of $B^0 \to (\rho\pi)^0$ (2)

ArXiv: 1304.3503
BABAR preliminary

- New measurement with full BaBar dataset
- Direct CPV asymmetries

$$\mathcal{A}^{+-}_{\rho\pi} \equiv \frac{\Gamma(\overline{B}^0 \to \rho^-\pi^+) - \Gamma(B^0 \to \rho^+\pi^-)}{\Gamma(\overline{B}^0 \to \rho^-\pi^+) + \Gamma(B^0 \to \rho^+\pi^-)} = 0.09^{+0.05}_{-0.06} \pm 0.04$$

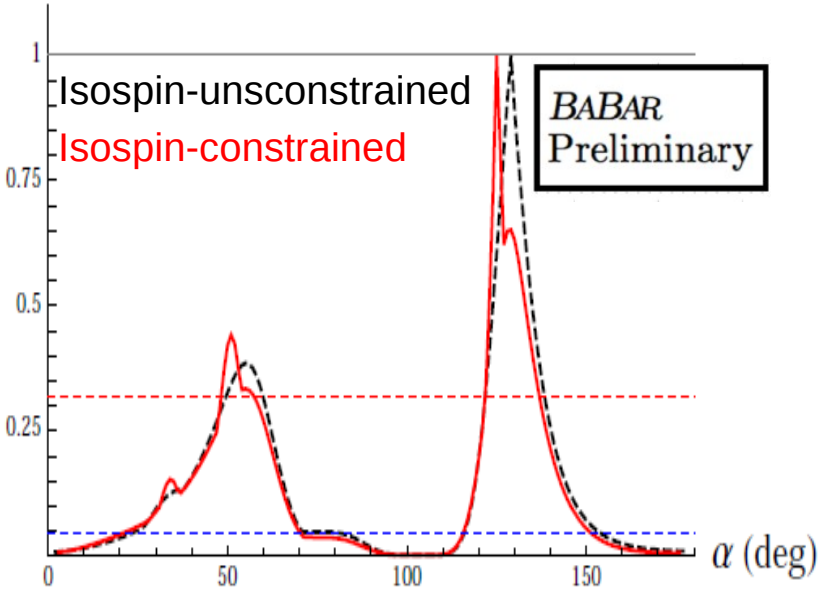
$$\mathcal{A}^{-+}_{\rho\pi} \equiv \frac{\Gamma(\overline{B}^0 \to \rho^+\pi^-) - \Gamma(B^0 \to \rho^-\pi^+)}{\Gamma(\overline{B}^0 \to \rho^+\pi^-) + \Gamma(B^0 \to \rho^-\pi^+)} = -0.12 \pm 0.08^{+0.04}_{-0.05}$$



no direct-CPV is $\Delta\chi^2$ 6.42 units from minimum

- Scan on α–UT
  - Importantly, studies find that α–scan is not robust with current statistics
    - Secondary solutions may be favoured due to statistical fluctuations
    - Problem disappears for higher S/B
  - Q2B parameters are reliable extracted
  - Analysis would benefit from increased dataset from high-luminosity experiments

$\Sigma \neq 1$ – C.L

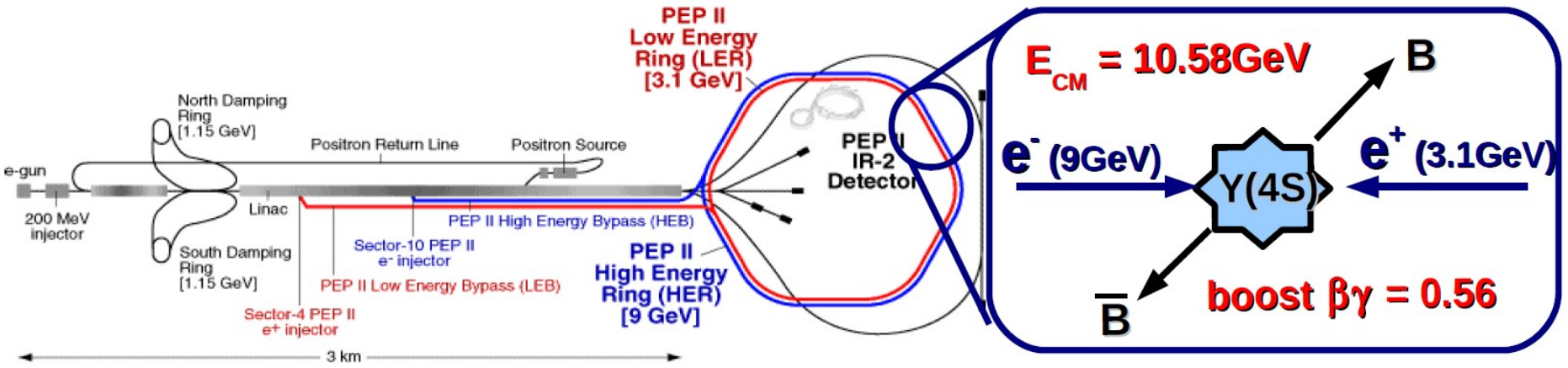


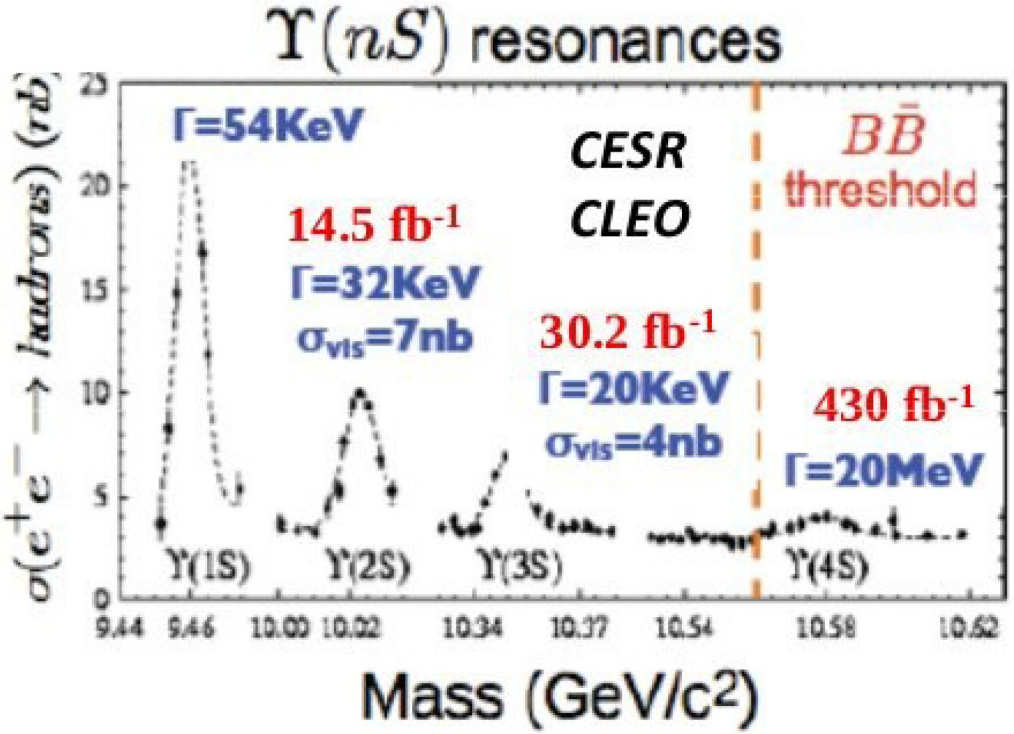
Conclusions

- *BABAR* last data collected in 2008, but collaboration still very active in producing very important results
- T reversal in B^0_d-$\overline{B}^0_d$ system is violated, supporting CPT invariance
  - **1st observation of TRV (14σ)**
  - Clear evidence of CPV (16.6σ) and no evidence of CPT
- New preliminary result of CPV in B^0-$\overline{B}^0$ mixing
  - $1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$ **Single most precise measurement!**
- New preliminary result on α-UT from $B^0 \to (\rho\pi)^0$
  - α-UT scan with current data not statistically robust. Analysis will benefit with higher data samples
- Stay tuned for more


Backup

PEP-II: a B factory at SLAC

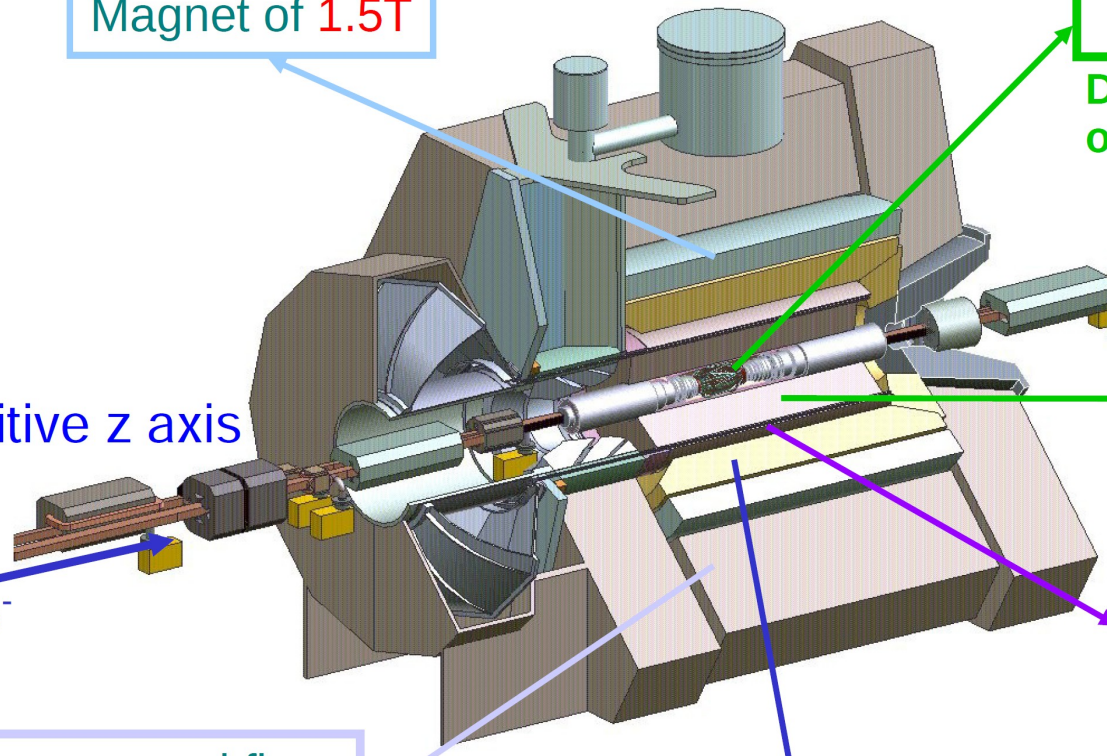




$e^+e^- \to$	Cross-Section (nb)
$b\bar{b}$	1.10
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

Important background for many analyses $e^+e^- \to q\bar{q}$ (q = u,d,s,c)

BABAR Detector



Magnet of 1.5T

Silicon Vertex Tracker (SVT)

Decay vertex reconstruction of tracks near from IP

e^+

Drift Chamber (DCH)

charged particles tracks deviation reconstruction: angles and momentum measurements.

positive z axis

e^-

Detector of Cherenkov light (DIRC)

Charged particles ID

K/π separation >2.5σ until 4GeV/c^2

Intrumented flux return (IFR)

$\mu^{+/-}$ Identification

Electromagnetic calorimeter (EMC)

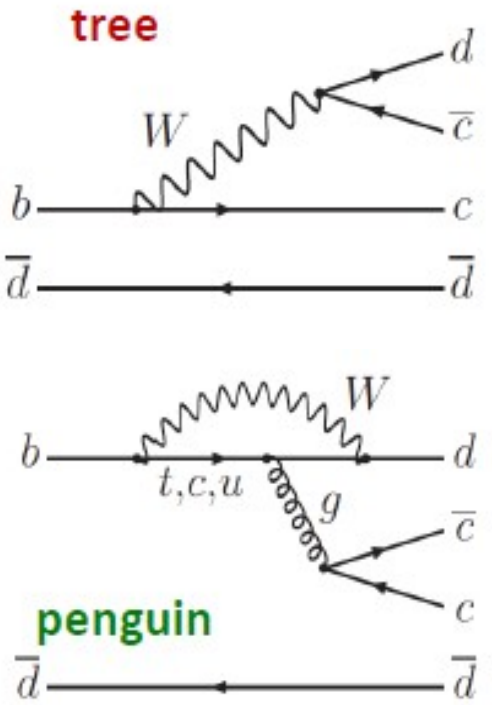
Detection of γ, e^- identification and $\pi^0 \rightarrow \gamma\gamma$ reconstruction, Measurements of Energy

CPV in $B^0 \to D^{*+}D^{*-}$ (1)

- In Cabibbo suppressed $b \to c\bar{c}d$ transitions (like $D^{*+}D^{*-}$), the color allowed tree amplitude gets small contribution from penguin diagrams
  - The time-dependent (TD) CPV asymmetry is a measurement of $S_\eta \approx \eta \sin(2\beta)$

    The same as $b \to (c\bar{c})s$ $J/\psi K$
- Penguin contributions lead to few percent corrections as predicted by models based on factorization and heavy quark symmetry

PL B443, 354 (1998)
PRD61, 014010 (1999)



- Large deviation of S_η from $b \to c\bar{c}d$ and $b \to (c\bar{c})s$ transitions ($D^{*+}D^{*-}$ and $J/\psi K$)

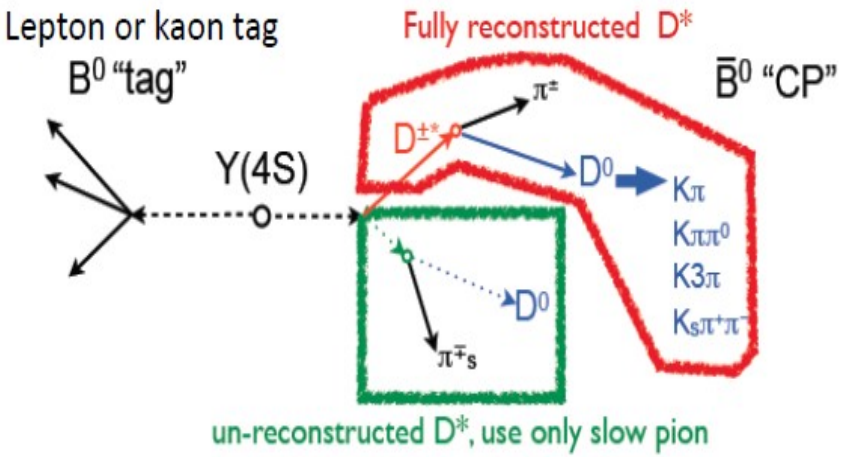
  $\Rightarrow$ Null test on new physics

PRD78, 033011 (2008)
PLB395, 241 (1997)
PRD77, 036004 (2008)

CPV in $B^0 \to D^{*+}D^{*-}$ (2)

Phys. Rev. D. 86, 112006 (2012)

- New analysis @ BaBar using partial reconstruction of $B^0 \to D^{*+}D^{*-}$ decay
  - ☺ 5x more statistics w.r.t previous analysis using full reconstruction
  - ☹ Higher backgrounds, larger systematics
- Selection:
  - B_{tag} flavour-tagged with lepton or Kaon
  - One fully rec. D* and one partially rec. using slow-π ($D^{*+} \to D^0\pi^+$)
  - Kinematics consistent with a B^0 decaying to a D* and missing D^0
  - Main discriminant variable is the missing D^0 reconstructed mass (m_{rec})



Time-dependent pdf

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

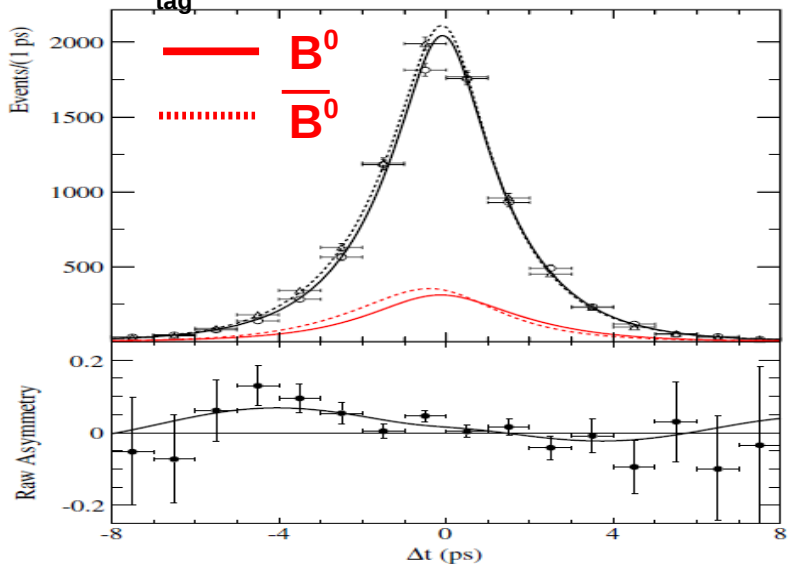
- VV final state: mixture of CP-even/odd
  - Due to partial reconstruction cannot do angular analysis to separate CP-even/odd
    ⇒ measure average C and S parameters
  - Use $R_\perp$ from fully reconstructed BaBar analysis (PRD79, 032002 (2009)) to relate
  - {C,S} to $\{C_+, S_+\}$ ⇒ $C = C_+$ and $S = S_+(1 - 2R_\perp)$

CPV in $B^0 \to D^{*+} D^{*-}$ (3)

Phys. Rev. D. 86, 112006 (2012)

Dataset: 471×10^6 MBB

B_{tag} tagged with Kaon



- The measurement:

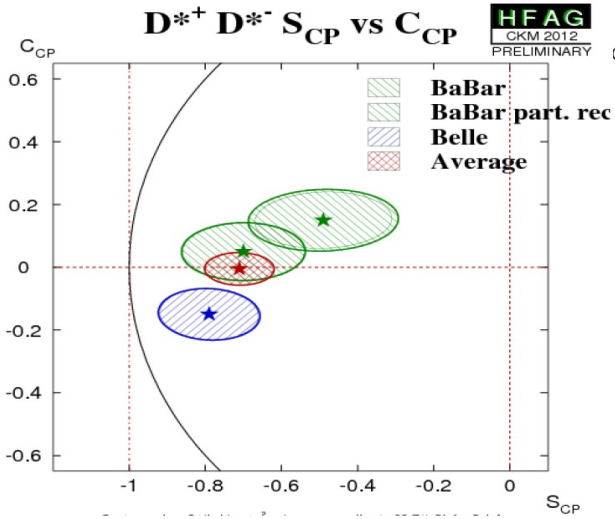
$C = +0.15 \pm 0.09 \pm 0.04$

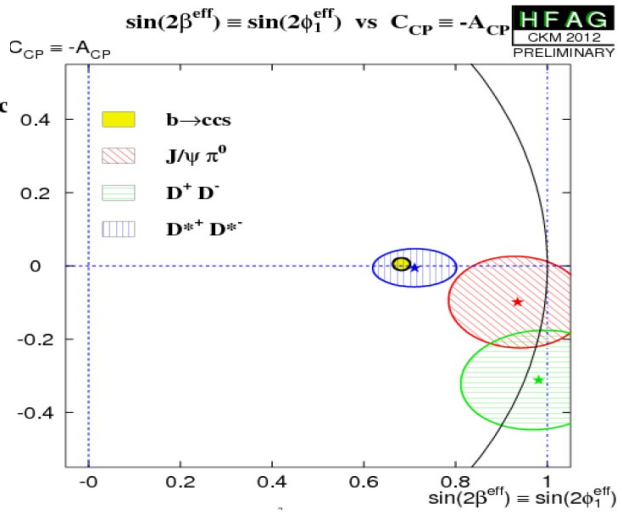
$S = -0.34 \pm 0.12 \pm 0.05$

- Using $R_\perp = 0.158 \pm 0.029$ get

$C_+ = +0.15 \pm 0.09 \pm 0.04$

$S_+ = -0.49 \pm 0.18 \pm 0.07 \pm 0.04(R_\perp)$





- Agreement with previous measurements
- Agreement with SM expectations