Recent Searches for BSM Physics at BaBar

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Pablo Picasso
Woman in Hat and Fur Collar (1937)
Museo Nacional d'Art de Catalunya, Barcelona

4 (of *Many*) Selected Recent BSM Search Results from BaBar

1) Observation of the rare decay $D^0 \rightarrow K^- \pi^+ e^+ e^-$

NEW: To be submitted to **Phys. Rev. Lett.**

2) Search for $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ decays

NEW: To be submitted to **Phys. Rev. D**

3) Measurement of $R(D^{(*)})$: Search for lepton universality violation in $B \rightarrow D^{(*)}\tau\nu$ / $D^{(*)}\ell\nu$

Phys. Rev. Lett. **109, 101802** (2012), and Phys. Rev. **D 88, 072012** (2013)

4) Search for beyond-SM *T*- and *CP*-violating effects in neutral *B* decays to **charmonium**

Phys. Rev. **D 94, 011101(R)** (2016) [arXiv:**1605.04545**]

1) Observation of the rare decay $D^0 \rightarrow K^- \pi^+ e^+ e^-$

NEW: To be submitted to **Phys. Rev. Lett.**

Observation of the rare decay $D^0 \to K^-\pi^+e^+e^-$

- While short-distance SM contributions to FCNC decays such as $D^0 \to K^-\pi^+e^+e^-$ should result in branching fractions of only approximately $O(10^{-9})$, long-distance SM contributions can push expected branching fractions up to the $O(10^{-6}$ or $10^{-7})$ range.

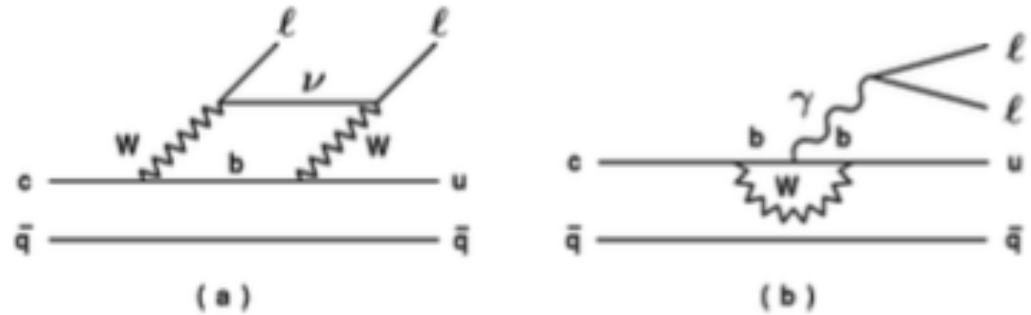


FIG. 1. Short distance contributions to FCNC decays in D mesons due to (a) box and (b) penguin diagrams.

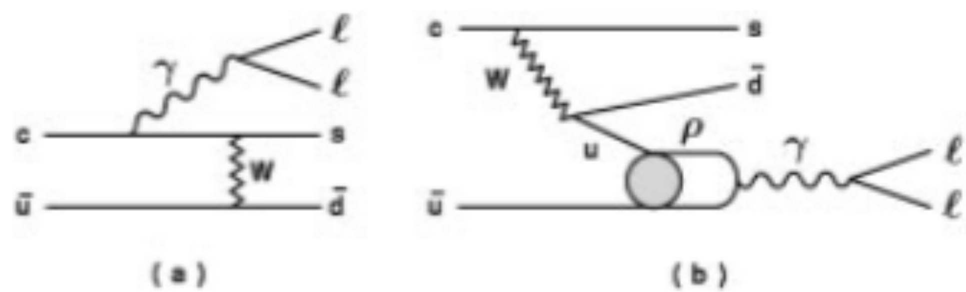


FIG. 2. Long distance contributions to FCNC decays in D mesons due to (a) photon pole amplitude and (b) vector meson dominance.

- FCNC MSSM models and *R*-parity violating models could, of course, push this expectation higher.

- LHCb has observed the decay $D^0 \to K^-\pi^+\mu^+\mu^-$:

LHC*b*:

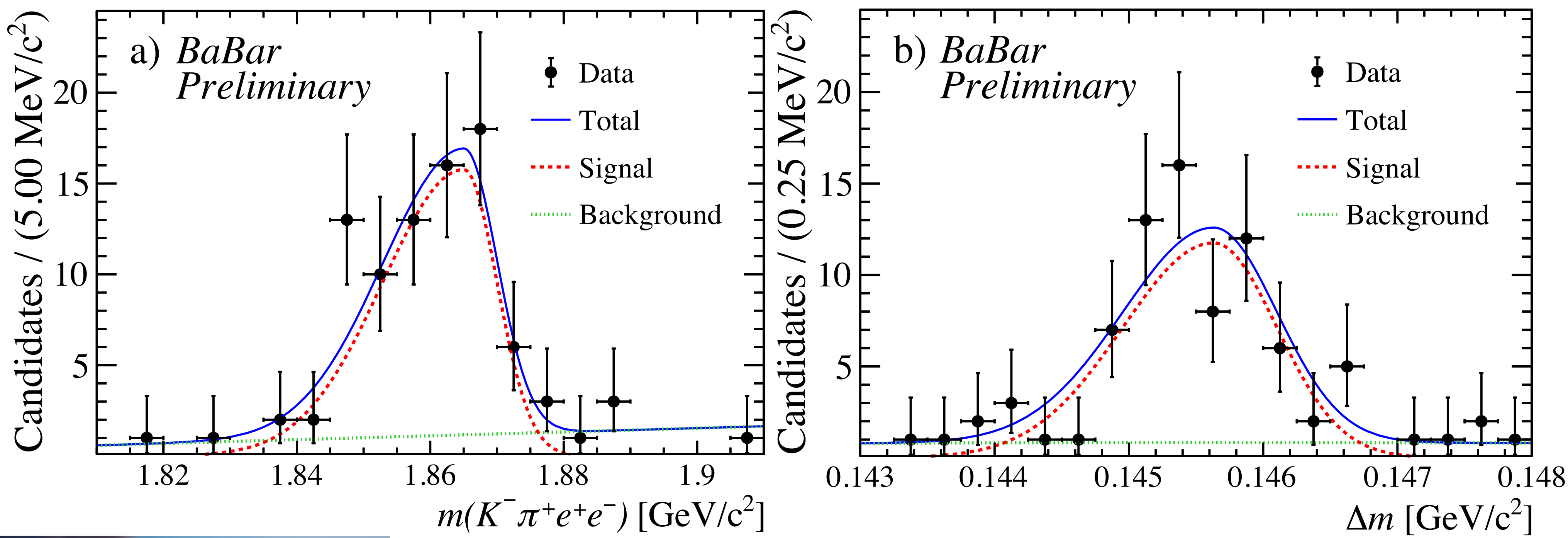
$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$$

(Phys. Lett. **B 757**, 558 (2016))

Observation of the rare decay $D^0 \to K^-\pi^+e^+e^-$

- In the full BaBar dataset, we reconstruct the decay $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+e^+e^-$, and we normalize to the well-measured mode $D^0 \to K^-\pi^+\pi^-\pi^+$. We also use the other well-measured modes $D^0 \to \pi^+\pi^-\pi^+\pi^-$ and $D^0 \to K^-\pi^+$ as cross-checks.
- We use unbinned maximum likelihood fits to bifurcated Gaussian distributions in $m(K^-\pi^+e^+e^-)$ and Δm ($\equiv m(D^{*+}) - m(K^-\pi^+e^+e^-)$) to extract the signal and the combinatorial background yields:

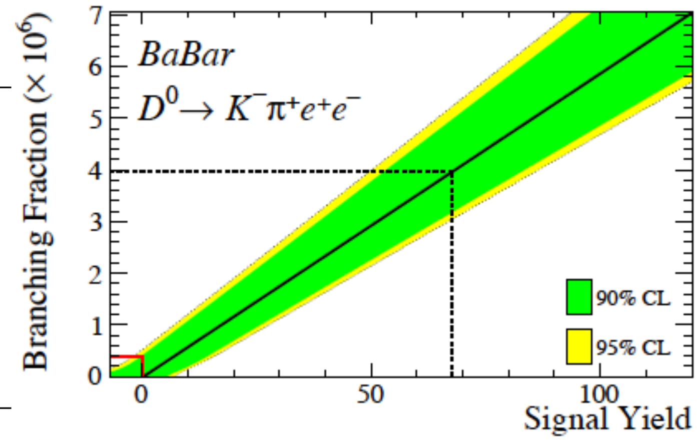
Fits to the $D^0 \to K^-\pi^+e^+e^-$ data sample for a) D^0 mass and b) Δm in the restricted phase space $0.675 < m(e^+e^-) < 0.875$ GeV/c^2



Observation of the rare decay $D^0 \to K^-\pi^+e^+e^-$

- Each candidate is weighted by its efficiency as a function of $m(K\pi)$ and $m(e^+e^-)$.
- The largest systematic uncertainties (3% and 2.2%) are from uncertainty on tracking efficiency and on PID efficiency respectively.

$m(e^+e^-)$ (GeV/c^2)	N_{sig} (cands.)	$\hat{\epsilon}_{\mathrm{sig}}$ (%)	$\mathcal{B}$ $(\times 10^{-6})$
$0.100-0.200$	175 ± 14	5.0 ± 0.2	-
> 0.100	308 ± 18	5.9 ± 0.2	-
> 0.200	134 ± 13	8.0 ± 0.2	$8.8 \pm 0.8 \pm 0.5 \pm 0.2$
$0.200-0.675$ or > 0.875	59 ± 9	6.4 ± 0.2	$4.8 \pm 0.7 \pm 0.3 \pm 0.1$
$0.675-0.875$	68 ± 9	8.9 ± 0.2	$3.95 \pm 0.53 \pm 0.16 \pm 0.08$



Uncertainties: Statistical ± Systematic ± Normalization $\mathcal{B}$.

NEW: To be submitted to **Phys. Rev. Lett.**

- We measure a branching fraction of:

$$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (\mathbf{4.0} \pm \mathbf{0.5} \pm \mathbf{0.2} \pm \mathbf{0.1}) \times 10^{-6},$$

where the first uncertainty is statistical, the second is systematic, and the third is from the uncertainty on the branching fraction of the $D^0 \to K^-\pi^+\pi^-\pi^+$ normalization mode.

(This is a similar central value as LHCb's $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$.)

2) Search for $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ decays

NEW: To be submitted to **Phys. Rev. D**

Search for $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ decays

- Charged lepton flavor conservation is a key part of the SM. (SM expectations for charged lepton flavor oscillations are unobservably small – but of course doesn't stop people from looking.)

- The branching fraction for $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ can be related to the branching fraction for $\mu^- \rightarrow e^-e^+e^-$ in a fairly model-independent way (Nussinov et al, PRD 63, 016003 (2001)). Both should be unobservably small in the SM, however various extensions including various SUSY models, leptoquarks, etc, can result in observable branching fractions. Decent limits exist for $\mu^- \rightarrow e^-e^+e^-$ (upper limits are presently in the 10^{-12} range [SINDRUM], and will improve [Mu3e , …]).

$$BR(\Upsilon \rightarrow e\mu) = BR(\mu \rightarrow eee)\frac{\Gamma(W \rightarrow e\nu)^2}{\Gamma(\Upsilon)\Gamma \rightarrow ee}(\frac{M_\Upsilon}{M_W})^6$$

S.Nussinov, et. al. PRD 63, 016003 (2001)

$$\mathrm{BF}(\mu \rightarrow eee) < 2\text{-}4 \times 10^{-8}$$

Bellgardt, et al., Nucl.Phys. B299 (1988)

$$\mathrm{BF}(\Upsilon \rightarrow ee) < 3\text{-}6 \times 10^{-3}$$

Belle PLB 660,154 (2008)

$$\mathrm{BF}(\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}) < \mathbf{2.5 \times 10^{-8}}$$

Calculated according to Nussinov

Search for $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ decays

- Existing experimental searches:

  No experimental measurement of the decay $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ yet!

Measurements	Results	CL (%)	Collaboration
$BF(\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp})$	$< 4.2 \times 10^{-6}$	90	J.P. Lees et al. PR D89 111102 (2014) [BaBar Collaboration]
$BF(\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp})$	$< 3.1 \times 10^{-6}$	90	
$BF(\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp})$	$< 20.3 \times 10^{-6}$	95	Love et al. PRL 101, 201601 (2008) [CLEO Collaboration]

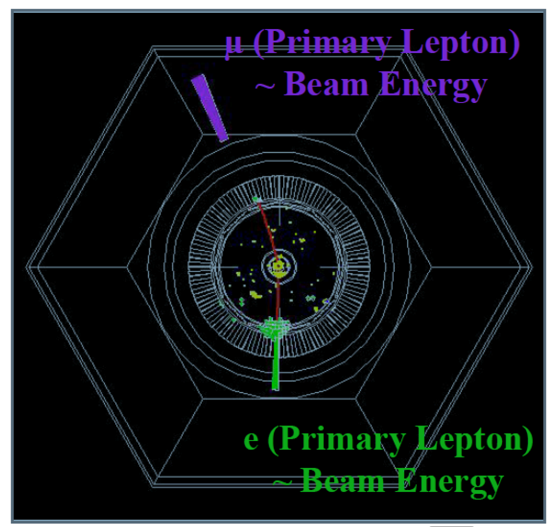
LEPTON FAMILY NUMBER (*LF*) VIOLATING MODES

$\Gamma(e^{\pm}\tau^{\mp})/\Gamma_{total}$ $\qquad \Gamma_{31}/\Gamma$

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<4.2	90	LEES	10B	BABR	$e^+e^- \rightarrow e^{\pm}\tau^{\mp}$

$\Gamma(\mu^{\pm}\tau^{\mp})/\Gamma_{total}$ $\qquad \Gamma_{32}/\Gamma$

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
< 3.1	90	LEES	10B	BABR	$e^+e^- \rightarrow \mu^{\pm}\tau^{\mp}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<20.3	95	LOVE	08A	CLEO	$e^+e^- \rightarrow \mu^{\pm}\tau^{\mp}$

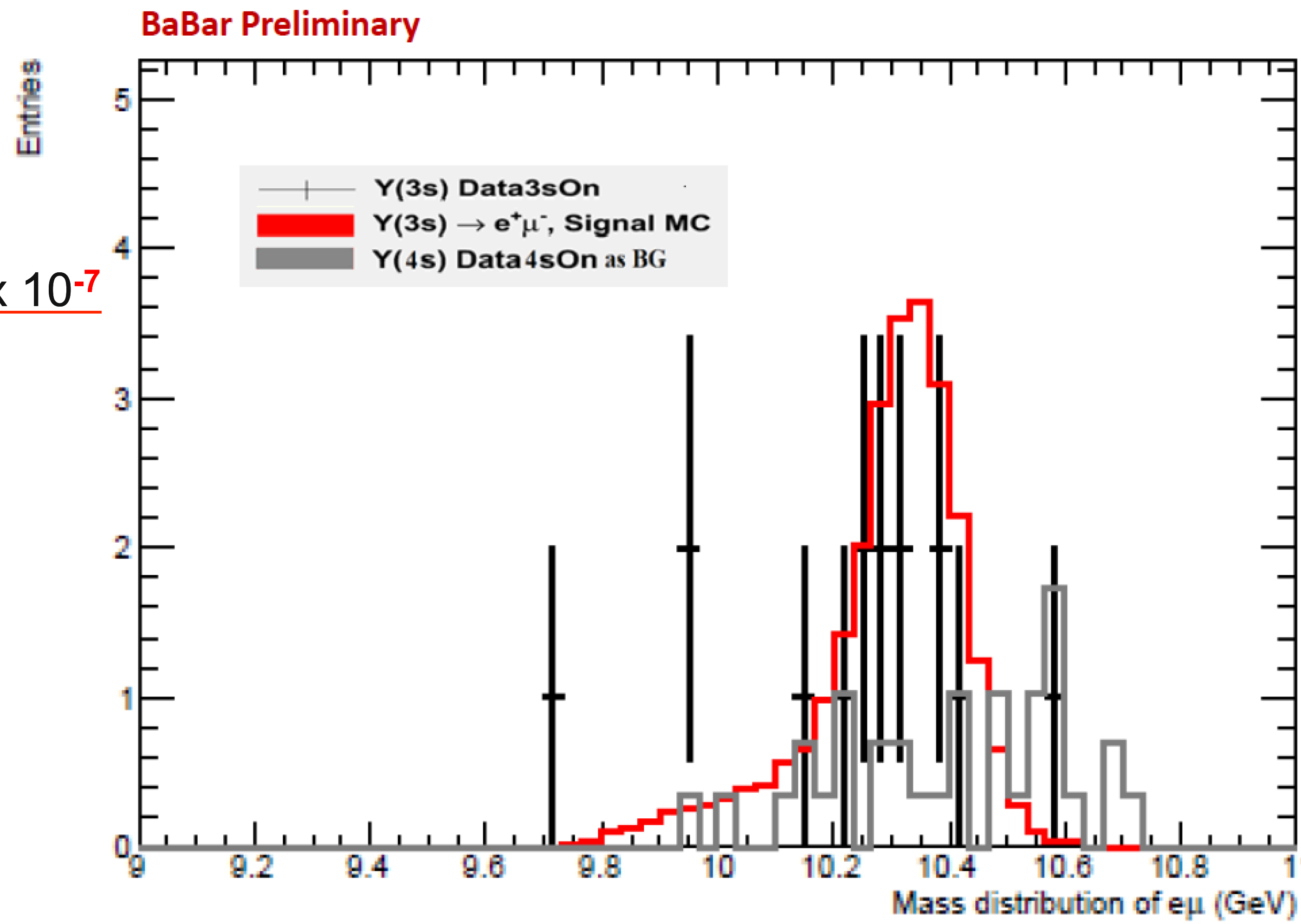


- Search for a single muon recoiling against a single electron each with kinetic energy (in the CM frame) approximately equal to ½ the $\Upsilon(3S)$ rest mass energy, and with the same center-of-mass boost as the beams:

Search for Υ(3S) → $e^{\pm}\mu^{\mp}$ decays

- In (117.7 ± 1.2) x 10^6 Υ(3S) events, we observe 15 candidates that pass all selection criteria, with an expected background of 12.2 ± 2.3 events.
- Given our signal efficiency of (23.4 ± 0.8)%, this allows us to set a limit of:

$\mathscr{B}(\Upsilon(3S) \to e^{\pm}\mu^{\mp}) < \mathbf{3.6} \times 10^{-7}$
at 90% CL



- Results to be submitted to PRD.

3) Measurement of $\boldsymbol{R}(\boldsymbol{D}^{(*)})$: Search for lepton universality violation in $\boldsymbol{B \to D^{(*)}\tau\nu}$ / $\boldsymbol{D^{(*)}\ell\nu}$

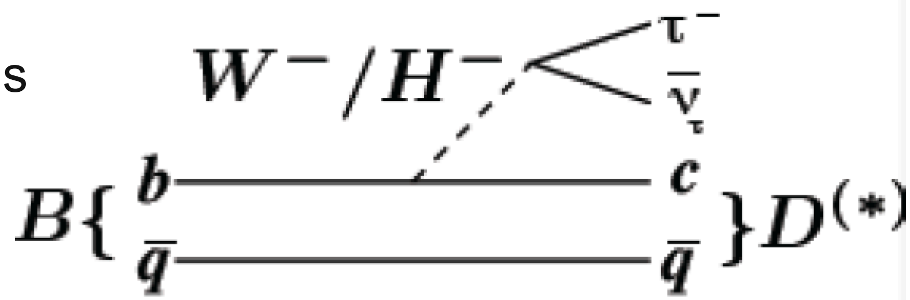
Phys. Rev. Lett. **109, 101802** (2012), and Phys. Rev. **D 88, 072012** (2013)

Measurement of $R(D^{(*)})$: $B \to D^{(*)}\tau\nu$ (and $B \to D^{(*)}\ell\nu$)

- Lepton flavor universality is a(nother) key part of the SM.

- Clearly, mass differences between the charged leptons do result in phase space availability differences that, in turn, result in differing branching fractions to decays that differ only by lepton flavor. However the **couplings** to the different leptons **must** always be the same in the SM.

- Theory results in fairly precise SM predictions for the branching fractions for $B \to D^{(*)}\ell\nu$ (including $B \to D^{(*)}\tau\nu$) – each of O(1-2%) with fractional uncertainties at around 7% of that level – and an even more precise SM prediction for the **ratio of branching fractions**:



$$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}\ell^+\nu_\ell)}$$

l = e, μ

for which the SM predicts:

$$R_{\rm SM}(D) = 0.297 \pm 0.017$$

$$R_{\rm SM}(D^*) = 0.252 \pm 0.03$$

(See, *e.g.*, Fajfer et al, Phys. Rev. D 85, 094025 (2012) and many others!)

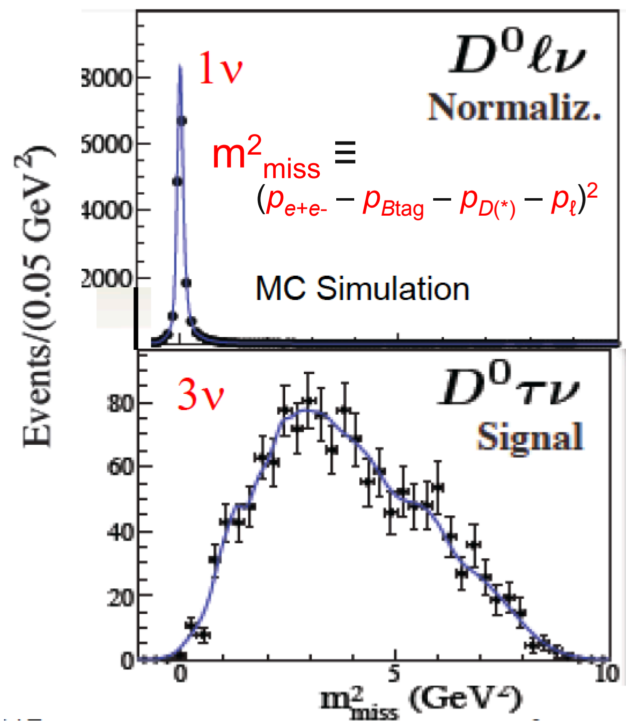
Measurement of $R(D^{(*)})$: $B \to D^{(*)}\tau\nu$ (and $B \to D^{(*)}\ell\nu$)

- These are extremely experimentally-challenging decays: $B \to D^{(*)}\tau\nu$ has unconstrained missing energy in the form of 2 or 3 neutrinos; and huge backgrounds from both other $B\bar{B}$ events (prominently featuring the particularly nasty $B \to D^{(*)}\tau\nu X$, where X can be many different things – as well as $B \to D^{(*)}D_S X$ with $D_S \to \tau\nu$), and from continuum.

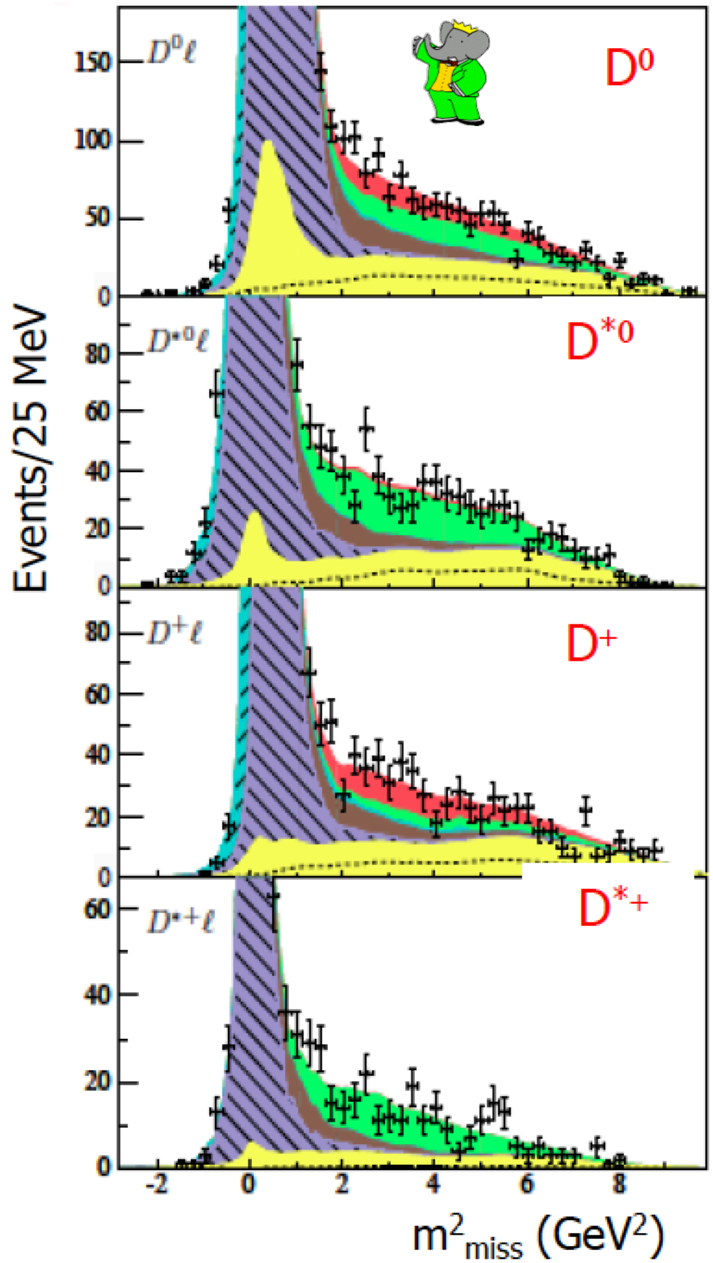
- We ameliorate these backgrounds by fully reconstructing the Υ(4S) event, except of course for the neutrinos. We use a clean, hadronically-reconstructed tag B sample for the other B in the event. Tau decays to μ and to e provide the cleanest τ sample.

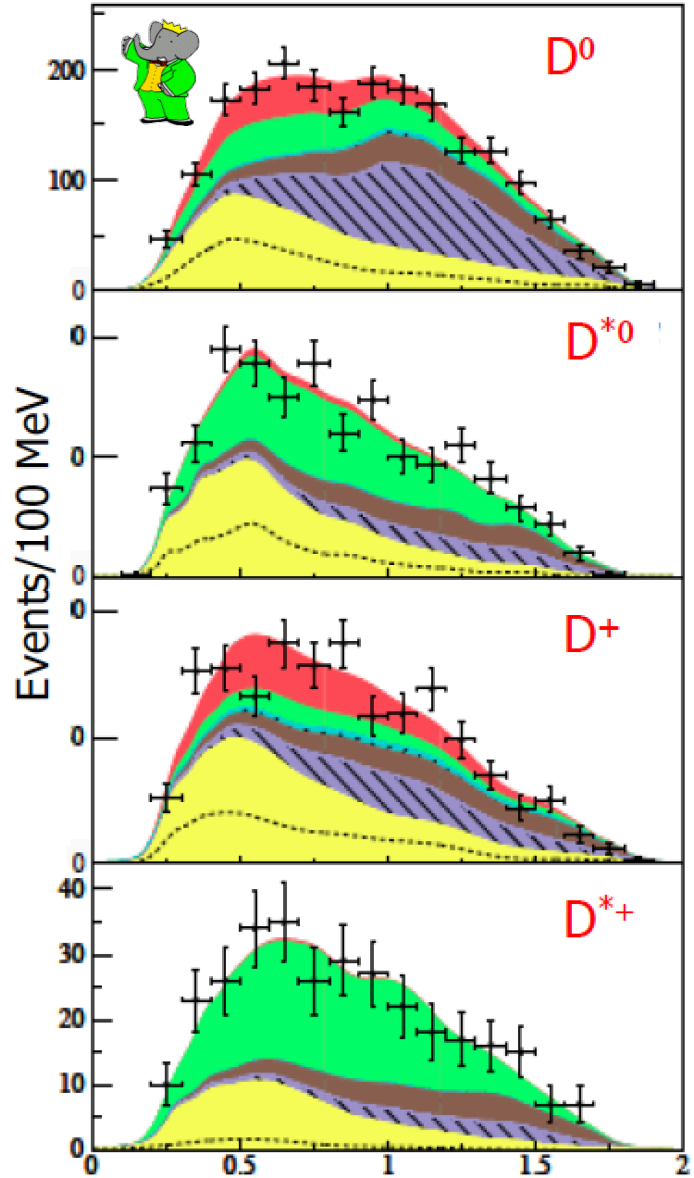
- We require no additional charged particles in the event, and we reduce backgrounds further via kinematic selections, and via utilizing a boosted decision tree to optimize background suppression.

- We use 4 separate $B \to D^{(*)}(\pi^0)\ell\nu$ data control samples for optimization studies and for MC corrections. We model the signal and backgrounds distributions with Keys PDFs. The unbinned 2-D maximum likelihood fit to data contains 22 free parameters.



Measurement of $R(D^{(*)})$: $B \rightarrow D^{(*)}\tau\nu$ (and $B \rightarrow D^{(*)}\ell\nu$)





- Fit results, combined using isospin relations:

$B \rightarrow D\,\tau\,\nu$

N_{signal}	489 ± 63
R(D)	0.440 ± 0.058
syst. error	± 0.042

$B \rightarrow D^*\,\tau\,\nu$

N_{signal}	888 ± 63
R(D*)	0.332 ± 0.024
syst. error	± 0.018

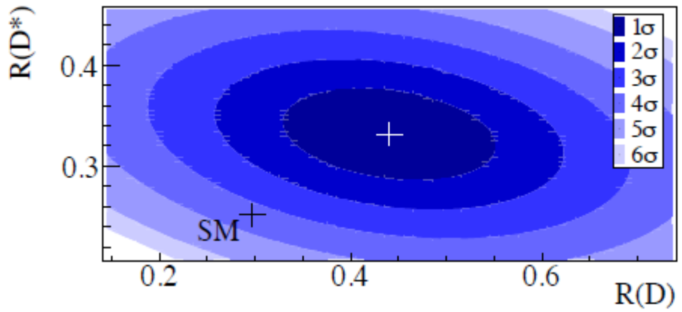
$D\tau\nu$, $D^*\tau\nu$, $D\ell\nu$, $D^*\ell\nu$, $D^{**}(\ell/\tau)\nu$ — Fitted yields

Bkg. — Fixed yield

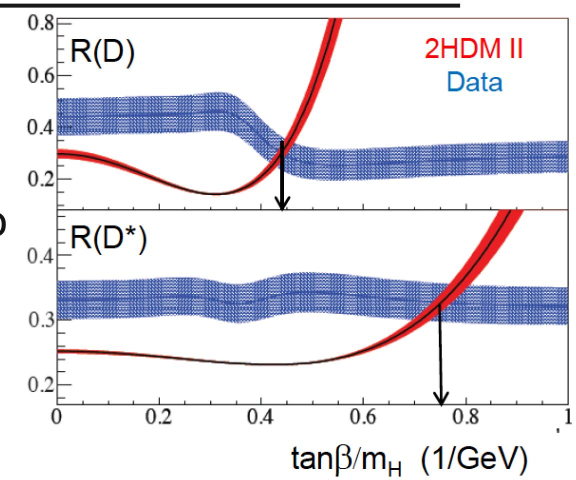
Phys. Rev. D 88, 072012 (2013)

Measurement of $R(D^{(*)})$: $B \to D^{(*)}\tau\nu$ (and $B \to D^{(*)}\ell\nu$)

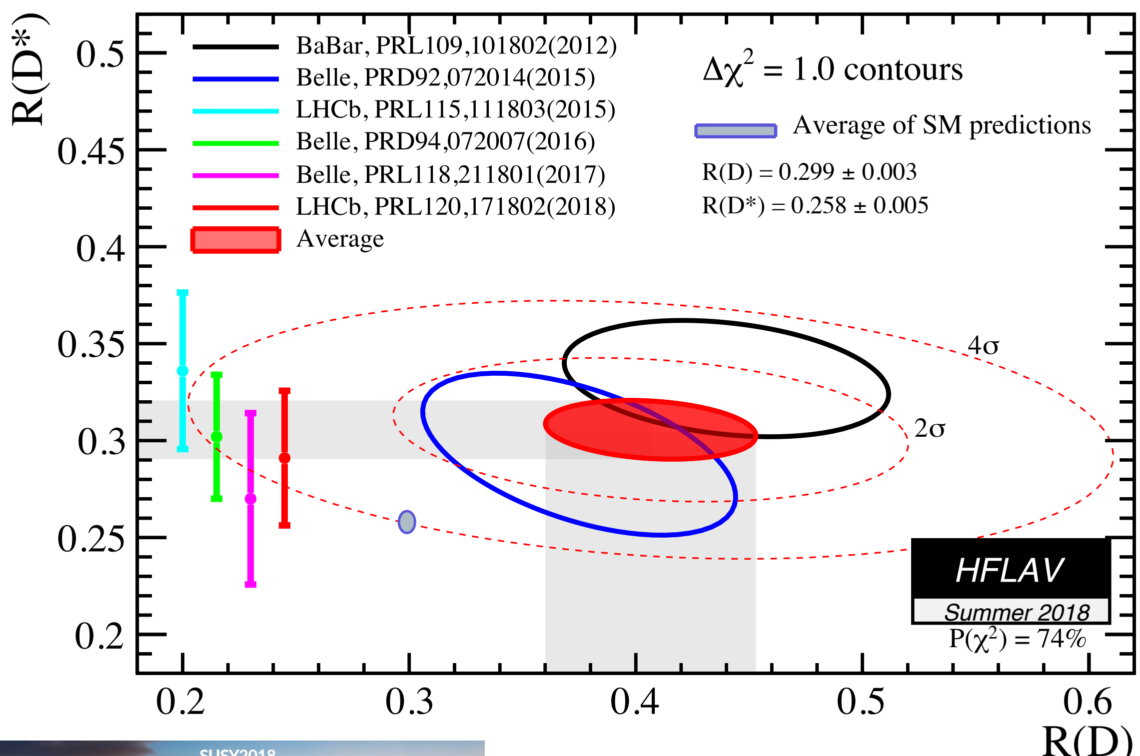
- Considering just this BABAR result alone, it is 3.4σ away from the SM prediction:

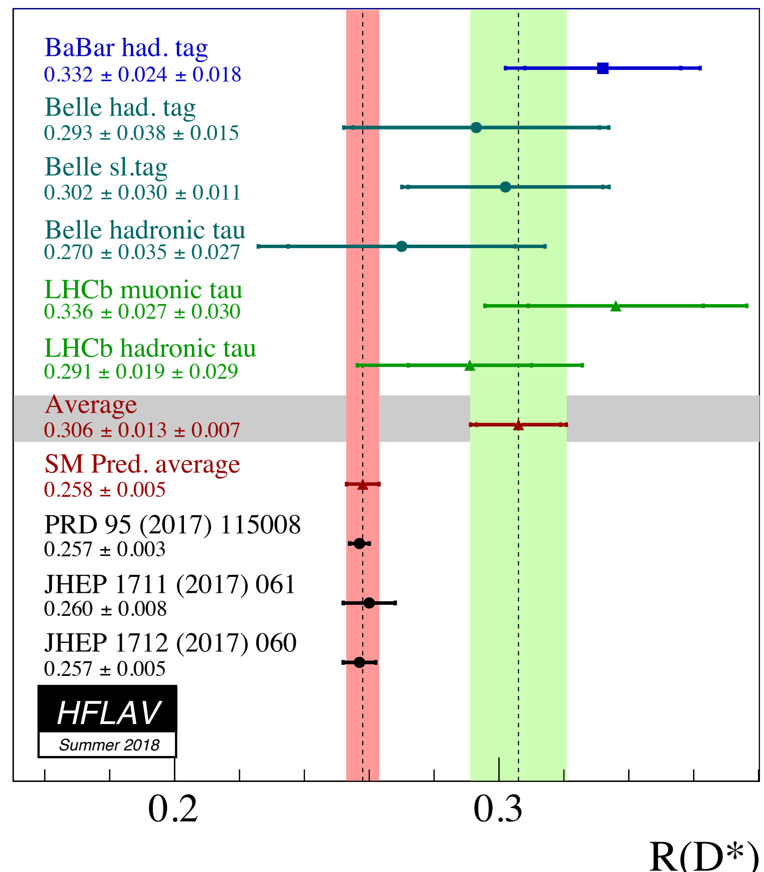


- But SUSY 2HDM models do not appear to resolve the discrepancy:

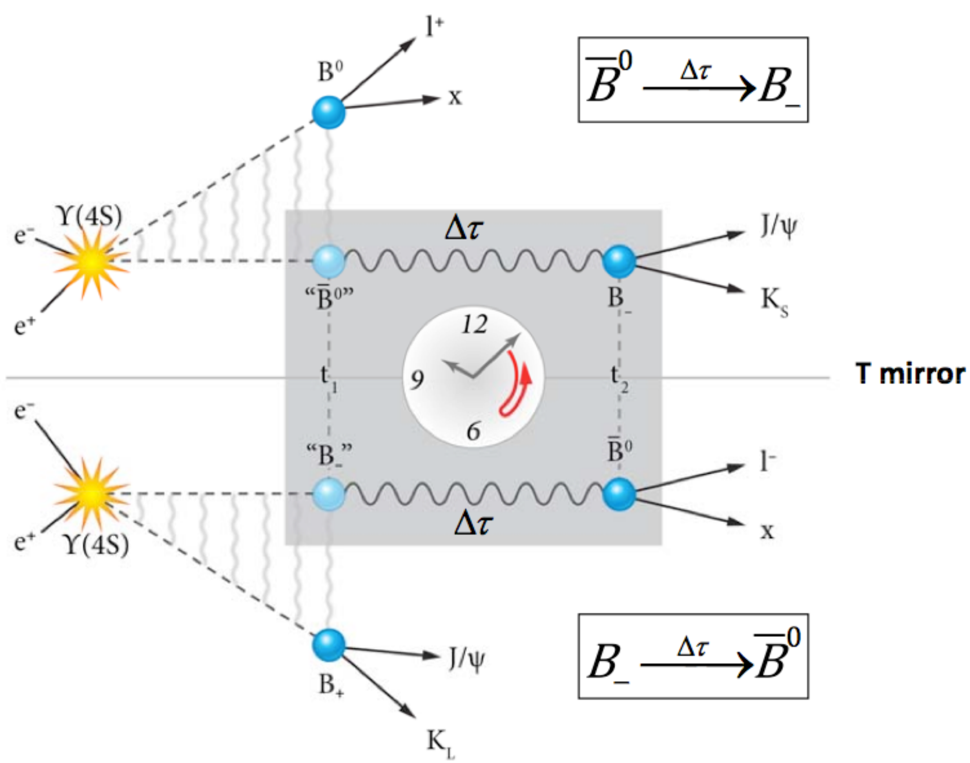


- Both Belle and LHCb have also confirmed deviations from SM expectations for $R(D^{(*)})$. This remains an unresolved anomaly for the SM:





4) Search for beyond-SM *T*- and *CP*- (and *CPT*-) violating effects in neutral *B* decays to charmonium



Phys. Rev. D 94, 011101(R) (2016) [arXiv:1605.04545]

Search for BSM *CP*- / *T*-violating effects in $\overset{(-)}{B}{}^0 \rightarrow$ charmonium

- This analysis separately measures ***T***- and ***CP***- (and, thus, ***CPT***-)violating effects in these events.

- Takes advantage of the fact that neutral ***B*** mesons are produced as entangled pairs in **Υ(4S)** decays:
  - Can be expressed in terms of either the **flavor** eigenstates B^0 and $\bar{B}^0$, or the ***CP*** eigenstates B_+ and B_-.

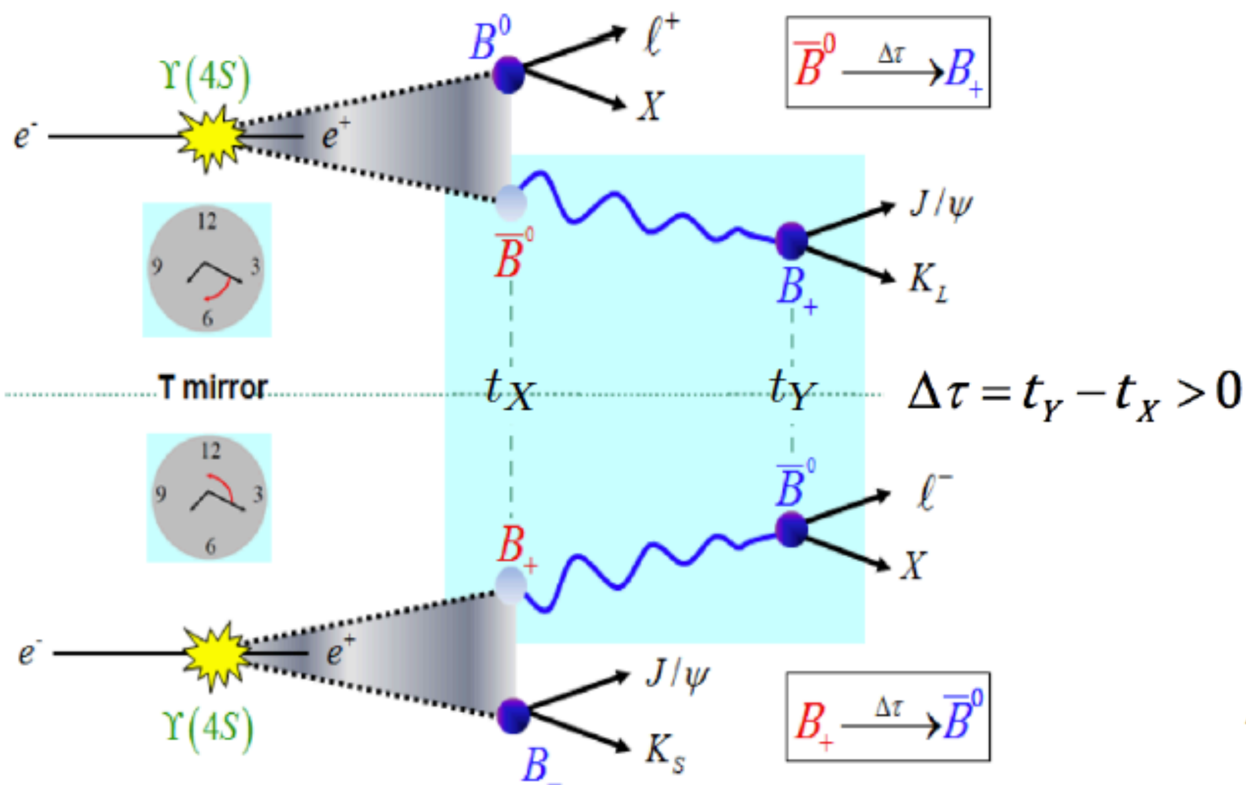
- The ***CP*** eigenstates B_+ and B_- are tagged by decays to $J/\psi K_L$ (*CP* even) and $J/\psi K_S$ (*CP* odd), respectively.

- **Flavor** eigenstates B^0 and $\bar{B}^0$ are tagged by semileptonic decays to ℓ^+X and ℓ^-X, respectively.

- Search for ***T*** violation by comparing rates for transitions from ***CP*** eigenstates → flavor eigenstates, with the transition rates for the time-reversed processes.

Search for BSM *CP*- / *T*-violating effects in $\overset{(-)}{B}{}^0 \rightarrow$ charmonium

- Example decay sequence:



$$\Delta t = t_{CP} - t_{\text{flav}}$$

Reference (X, Y)	***T-Transformed (X, Y)***
$B^0 \rightarrow B_+$ $(l^-, J/\psi K_L)$	$B_+ \rightarrow B^0$ $(J/\psi K_S, l^+)$
$B^0 \rightarrow B_-$ $(l^-, J/\psi K_S)$	$B_- \rightarrow B^0$ $(J/\psi K_L, l^+)$
$\bar{B}^0 \rightarrow B_+$ $(l^+, J/\psi K_L)$	$B_+ \rightarrow \bar{B}^0$ $(J/\psi K_S, l^-)$
$\bar{B}^0 \rightarrow B_-$ $(l^+, J/\psi K_S)$	$B_- \rightarrow \bar{B}^0$ $(J/\psi K_L, l^-)$

Reference: Physical Process
(X,Y): Reconstructed Final States

B_+, B_- — **tagged by** → $J/\psi K_L$, $J/\psi K_S$

Search for BSM *CP*- / *T*-violating effects in $\overset{(-)}{B}{}^0 \rightarrow$ charmonium

- Analysis performed using the following 4 assumptions:
  1) $\mathbf{A} \equiv A(B^0 \rightarrow c\bar{c}K^0)$ and $\bar{\mathbf{A}} \equiv A(\bar{B}^0 \rightarrow c\bar{c}\bar{K}^0)$ have a single weak phase.
  2) Assume B^0 does not decay to $c\bar{c}\bar{K}^0$ and $\bar{B}^0$ does not decay to $c\bar{c}K^0$.
  3) ***CP*** and ***T*** violation in $K^0 - \bar{K}^0$ mixing is negligible $\Rightarrow$ $K_S = \frac{K^0 + \bar{K}^0}{\sqrt{2}}$ and $K_L = \frac{K^0 - \bar{K}^0}{\sqrt{2}}$.
  4) Assume that $\Delta\Gamma$, the difference in decay widths of the B^0 **mass** eigenstates, B_H and B_L, is zero.

- We extract the parameter $|\bar{A}/A|$, which relates to ***CPT*** violation in decay amplitudes. (In the SM, $|\bar{A}/A| = 1$.)

- We also extract the real (*Re*) and imaginary (*Im*) parts of $\boldsymbol{z}$, where $\boldsymbol{z}$ is a separate ***CPT***-violating parameter, related to ***CPT*** violation in mixing amplitudes, and that specifically refers to the difference in the flavor-conserving amplitudes $B^0 \rightarrow B^0$ and $\bar{B}^0 \rightarrow \bar{B}^0$. (In the SM, both $Re(\boldsymbol{z}) = 0$ and $Im(\boldsymbol{z}) = 0$.)

Search for BSM *CP*- / *T*-violating effects in $\overset{(-)}{B}{}^0 \rightarrow$ charmonium

- Results:

$$|A/\bar{A}| = 0.999 \pm 0.023 \pm 0.017 \quad (1 \text{ in the SM})$$

- And:

$$Im(\mathbf{z}) = 0.010 \pm 0.030 \pm 0.013 \quad (0 \text{ in the SM})$$

$$Re(\mathbf{z}) = -0.065 \pm 0.028 \pm 0.014 \quad (0 \text{ in the SM})$$

Phys. Rev. D 94, 011101(R) (2016) [arXiv:1605.04545]

- The *Re*(***z***) result deviates from 0 by 2.1σ.

- The correlation coefficients are calculated to be:

	$\lvert\bar{A}/A\rvert$	$\mathrm{Im}(z)$	$\mathrm{Re}(z)$
$\lvert\bar{A}/A\rvert$	1.00	0.03	0.44
$\mathrm{Im}(z)$	0.03	1.00	0.03
$\mathrm{Re}(z)$	0.44	0.03	1.00

Statistical

	$\lvert\bar{A}/A\rvert$	$\mathrm{Im}(z)$	$\mathrm{Re}(z)$
$\lvert\bar{A}/A\rvert$	1.00	0.03	0.48
$\mathrm{Im}(z)$	0.03	1.00	−0.15
$\mathrm{Re}(z)$	0.48	−0.15	1.00

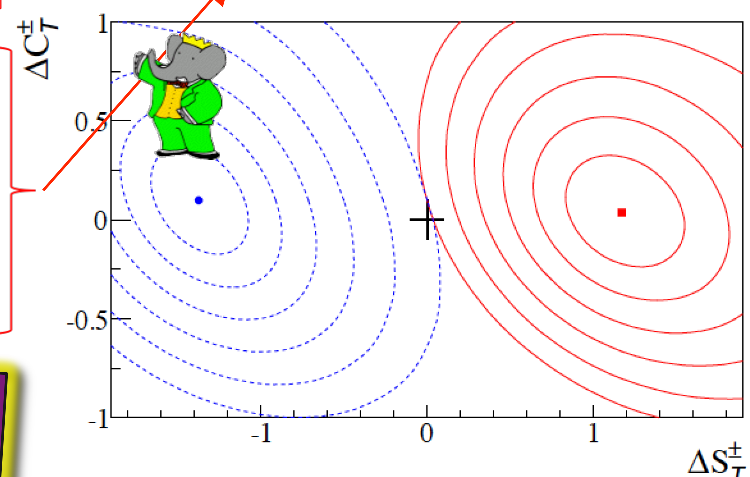
Systematic

Search for BSM *CP*- / *T*-violating effects in $\overset{(-)}{B}{}^0$ → charmonium

- We additionally determined earlier (back in 2012):

Parameter	Result	
$\Delta S_T^+ = S^-_{\ell-,K^0_L} - S^+_{\ell+,K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$	} = –2sin(2β)$_{SM}$ (–1.4)
$\Delta S_T^- = S^+_{\ell-,K^0_L} - S^-_{\ell+,K^0_S}$	$1.17 \pm 0.18 \pm 0.11$	} = +2sin(2β)$_{SM}$ (+1.4)
$\Delta C_T^+ = C^-_{\ell-,K^0_L} - C^+_{\ell+,K^0_S}$	$0.10 \pm 0.14 \pm 0.08$	} = 0_{SM}
$\Delta C_T^- = C^+_{\ell-,K^0_L} - C^-_{\ell+,K^0_S}$	$0.04 \pm 0.14 \pm 0.08$	
$\Delta S_{CP}^+ = S^+_{\ell-,K^0_S} - S^+_{\ell+,K^0_S}$	$-1.30 \pm 0.11 \pm 0.07$	} = –2sin(2β)$_{SM}$ (–1.4)
$\Delta S_{CP}^- = S^-_{\ell-,K^0_S} - S^-_{\ell+,K^0_S}$	$1.33 \pm 0.12 \pm 0.06$	} = +2sin(2β)$_{SM}$ (+1.4)
$\Delta C_{CP}^+ = C^+_{\ell-,K^0_S} - C^+_{\ell+,K^0_S}$	$0.07 \pm 0.09 \pm 0.03$	} = 0_{SM}
$\Delta C_{CP}^- = C^-_{\ell-,K^0_S} - C^-_{\ell+,K^0_S}$	$0.08 \pm 0.10 \pm 0.04$	
$\Delta S_{CPT}^+ = S^-_{\ell+,K^0_L} - S^+_{\ell+,K^0_S}$	$0.16 \pm 0.21 \pm 0.09$	} = 0_{SM}
$\Delta S_{CPT}^- = S^+_{\ell+,K^0_L} - S^-_{\ell+,K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$	
$\Delta C_{CPT}^+ = C^-_{\ell+,K^0_L} - C^+_{\ell+,K^0_S}$	$0.14 \pm 0.15 \pm 0.07$	
$\Delta C_{CPT}^- = C^+_{\ell+,K^0_L} - C^-_{\ell+,K^0_S}$	$0.03 \pm 0.12 \pm 0.08$	

All consistent with SM.



Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Summary

1) Observation of the rare decay $D^0 \to K\pi e^+e^-$

- $\mathcal{B}(D^0 \to K\pi e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$, a similar central value to LHCb's $\mathcal{B}(D^0 \to K\pi\mu^+\mu^-)$ result.

NEW!: To be submitted to **Phys. Rev. Lett.**

2) Search for $\Upsilon(3S) \to e^+\mu^-$ decays

- $\mathcal{B}(\Upsilon(3S) \to e^\pm\mu^\mp) < 3.6 \times 10^{-7}$ at 90% CL, consistent with SM – first limit on this decay mode.

NEW!: To be submitted to **Phys. Rev. D**

3) Measurement of $R(D^{(*)})$: Search for lepton universality violation in $B \to D^{(*)}\tau\nu$ / $D^{(*)}\ell\nu$

- BABAR first to see this anomaly, since confirmed by Belle + LHC*b*, and our combined $R(D^*)$ and $R(D)$ is still ~3.4σ away from SM predictions (with WA combination at the ~4σ [or more] level).

Phys. Rev. Lett. **109, 101802** (2012), & Phys. Rev. **D 88, 072012** (2013)

4) Search for beyond-SM ***T***- and ***CP***-violating effects in neutral ***B*** decays to **charmonium**

Phys. Rev. **D 94, 011101(R)** (2016) [arXiv:**1605.04545**]

- Direct measurements of ***T*** violation (separate from ***CP*** violation). Consistent with SM.

- Extremely active area: BABAR searches for BSM physics have resulted in many **SM confirmations** but also one or two **possible anomalies!**