Search for Invisible Dark Photon Decays at BABAR
+
New CP Violation Results from Combined BABAR+Belle Measurements

Markus Röhrken
California Institute of Technology

On behalf of the BABAR and Belle Collaborations

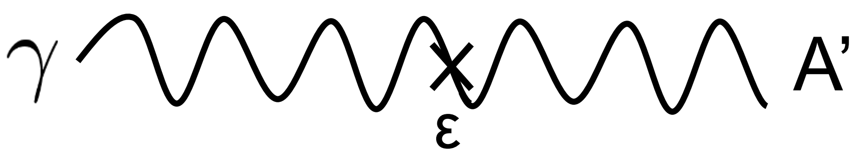
52nd Rencontres de Moriond - EW Interactions and Unified Theories
22nd of March 2017

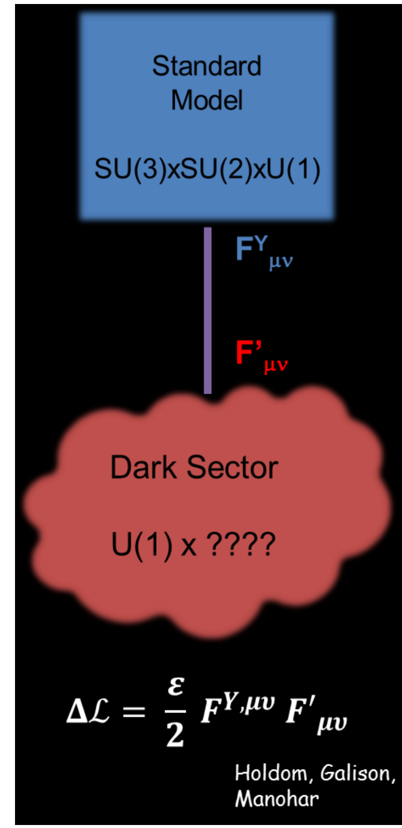
Caltech

BELLE

Search for Invisible Dark Photon Decays at *BABAR*

- Dark matter is an important open problem of modern physics.
- Dark sector models provide dark matter candidate alternatives to WIMPs and can exhibit a complex structure beyond that of the Standard Model (SM).
- The dark photon A' is the boson associated with an additional U(1)' gauge symmetry in the dark sector, and it is possibly light (sub-GeV).





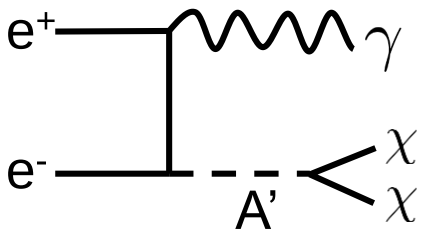
- There is a generic interaction of the form (kinetic mixing)

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

between the SM hypercharge Y and the U(1)' fields with a mixing strength ε.

Search for Invisible Dark Photon Decays at BABAR

- The dark photon will decay invisibly, if lighter dark sector states (dark matter candidates) exist:



- At e^+e^- colliders, one can search for $e^+e^- \rightarrow \gamma A'$ with $A' \rightarrow$ invisible by tagging the recoil photon in “single photon” events.

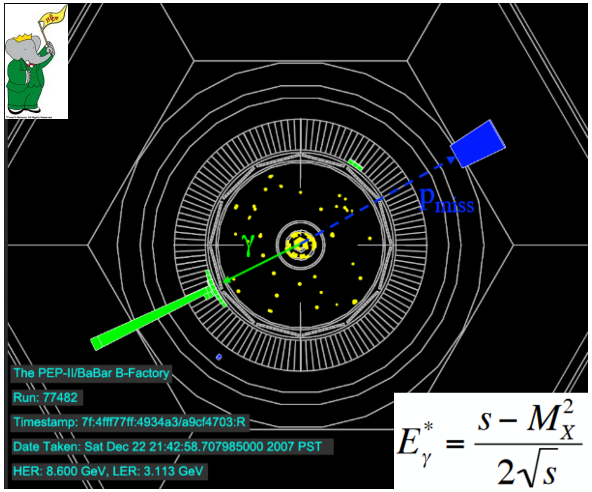
- BABAR collected about 53 fb^{-1} with dedicated single photon triggers during its last year of data taking, mostly at the Υ(2S) and Υ(3S) energies.

Analysis overview:

- Missing energy and momentum are the best signatures.

- Search strategy: Select single photon final states, then look for a bump in the missing mass M_X (or E_γ).

- Main background are $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \rightarrow \gamma e^+e^-$ with particles outside of the detector acceptance.

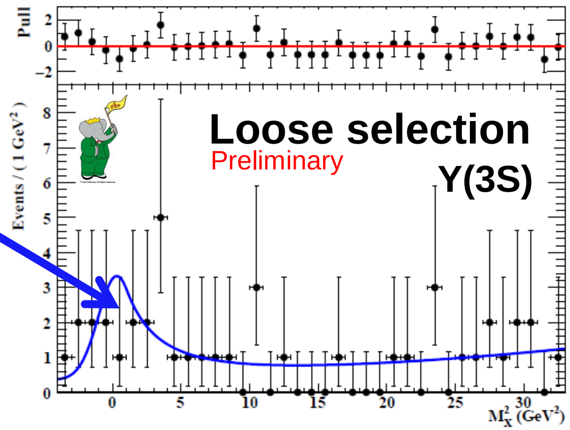


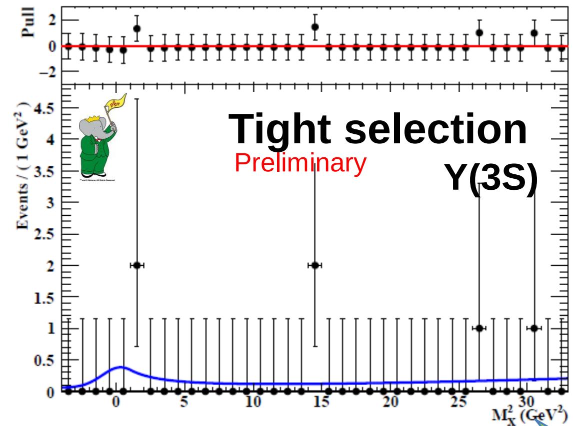
Search for Invisible Dark Photon Decays at BABAR

- The signal is extracted by simultaneous fits to the missing mass in independent regions of the data taken at the Υ(2S) and Υ(3S) energies.

- Examples of data distributions in the low-mass region:

Irreducible peaking background from $e^+e^- \to \gamma\gamma$

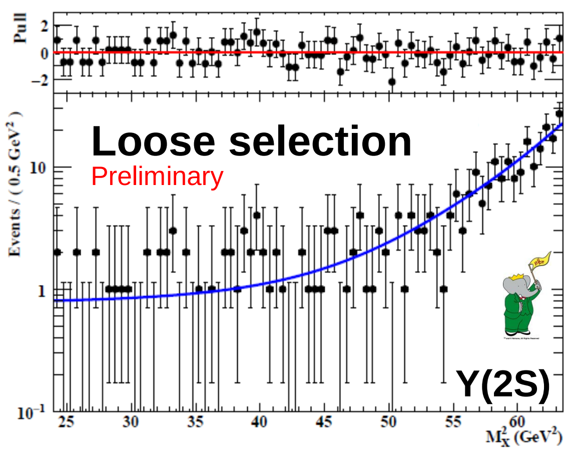


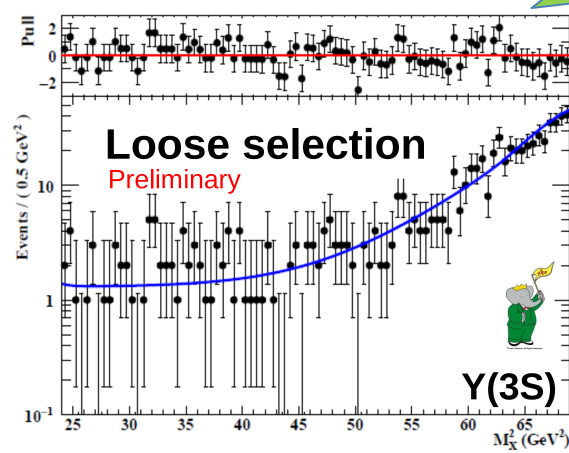


Blue: Background-only fit

- Examples of data distributions in the high-mass region:

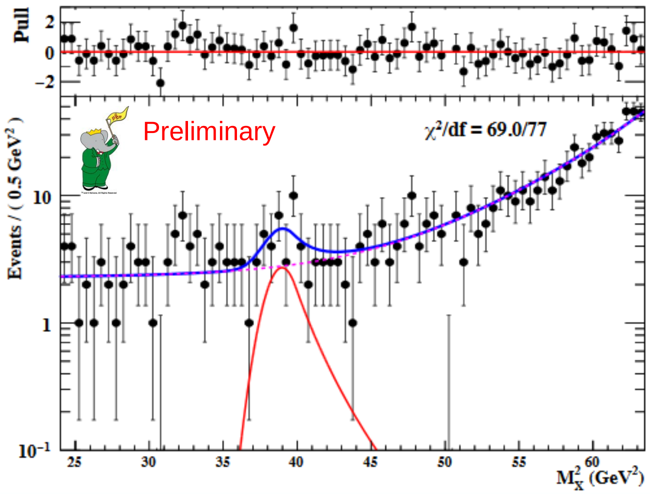
new result





Search for Invisible Dark Photon Decays at BABAR

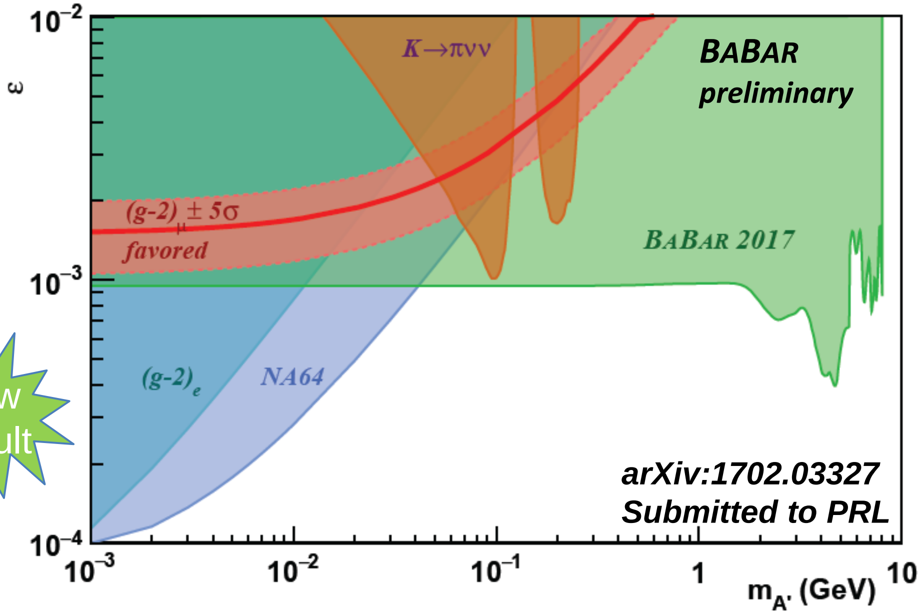
Most significant fit at $m_{A'}$ = 6.22 GeV



Local (global) significance: 3.1σ (2.6σ)
Global p-value: ≈1%

new result

Limits (90% CL) on the mixing parameter ε



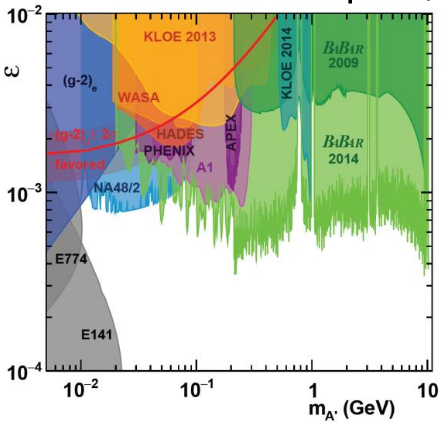
- No significant signal is observed.
- Upper limits on the mixing parameter ε as a function of $m_{A'}$ are estimated.

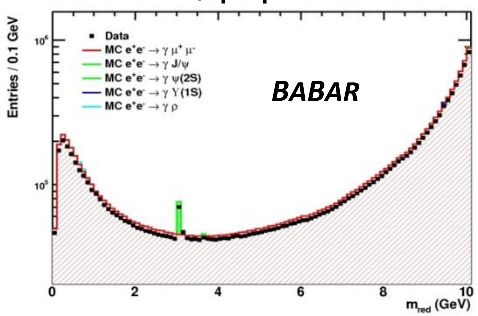
Large improvement over previous measurements.

Measurement rules out the entire region preferred by the $(g-2)_\mu$ anomaly.

Further Highlights of Light Dark Matter Searches at BABAR

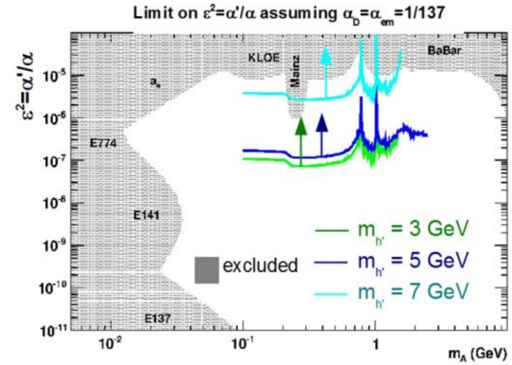
Search for dark photons in $e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-$





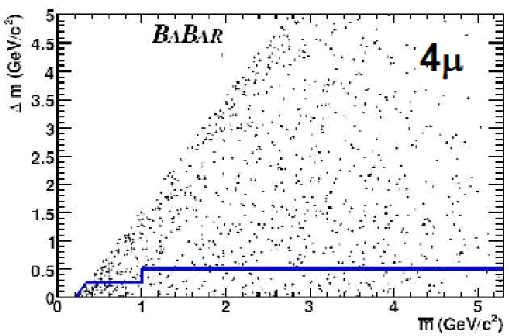
PRL 113 (2014) 201801
PRL viewpoint

Search for dark Higgs bosons in $e^+e^- \to h' A', h' \to A' A'$



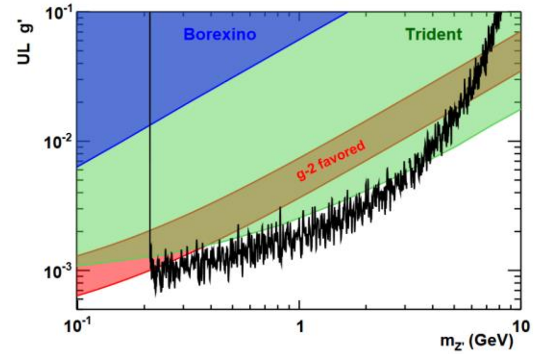
PRL 108 (2012) 211801

Search for dark bosons in $e^+e^- \to \gamma A' \to W' W'$



arXiv:0908.2821

Search for muonic dark force in in $e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-$

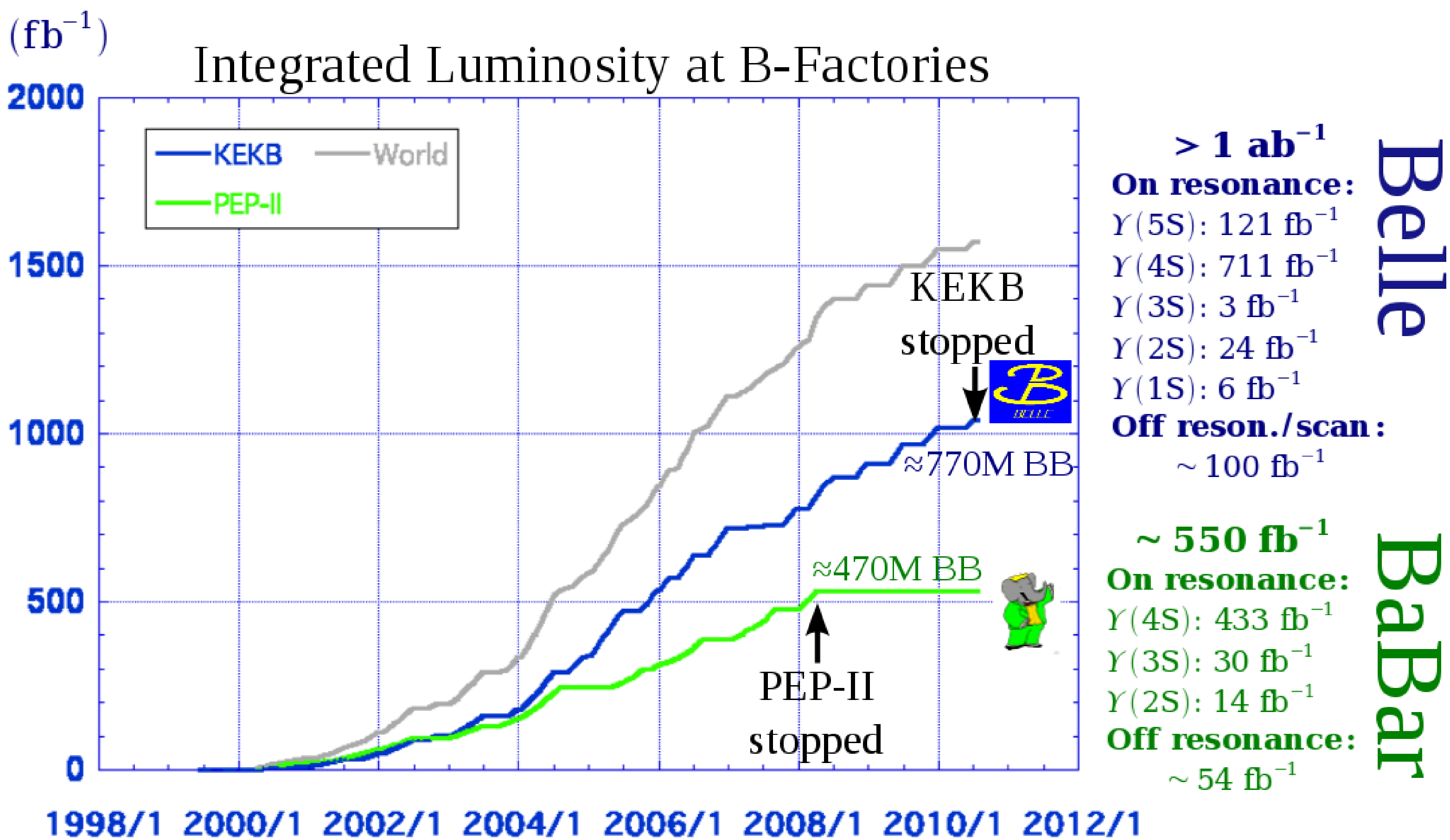


PRD 94 (2016) 011102

Further light dark matter searches are ongoing at BABAR.

Credit to Bertrand Echenard [echenard@caltech.edu]

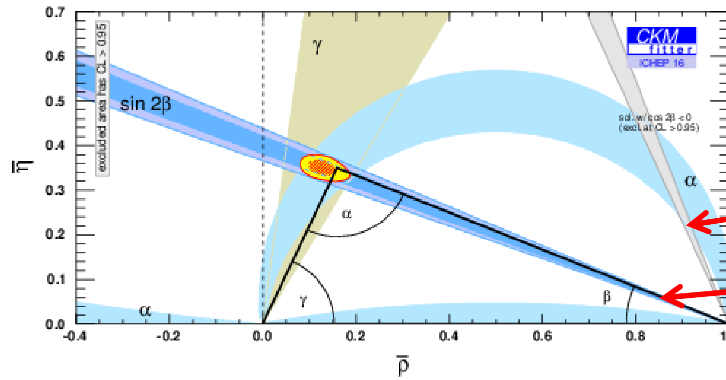
Combined BABAR+Belle Analysis of $B^0 \rightarrow D^{(*)}h^0$ decays



- Combined BABAR+Belle analyses to make full use of the about 1.1 ab^{-1} or ≈1240×10^6 BB collected on the Υ(4S).
- In a first BABAR+Belle analysis, we previously demonstrated the feasibility and the advantage of the joint approach [PRL **115**, 121604 (2015)].

Combined *BABAR*+Belle Analysis of $\mathrm{B}^0 \to \mathrm{D}^{(*)}\mathrm{h}^0$ decays

- The determination of the angle β of the Unitarity Triangle from sin(2β) [= sin(2ϕ_1)] measurements leads to a trigonometric ambiguity.

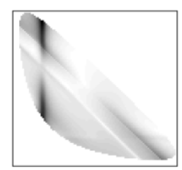


β=(π/2-21.9°)=68.1°

β=21.9°

- $\mathrm{B}^0 \to \mathrm{D}^{(*)}\mathrm{h}^0$ with $\mathrm{D} \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ decays enable to extract both sin(2β) and cos(2β):

$$|M_{B^0}(\Delta t)|^2 = \Big|$$  $$\times \cos(\Delta m \Delta t/2) - ie^{+2i\beta} \times$$  $$\times \sin(\Delta m \Delta t/2)\Big|^2$$

$$|M_{\bar{B}^0}(\Delta t)|^2 = \Big|$$  $$\times \cos(\Delta m \Delta t/2) - ie^{-2i\beta} \times$$  $$\times \sin(\Delta m \Delta t/2)\Big|^2$$

[A. Bondar, P. Krokovny, T. Gershon PLB **624** 1 (2005)]

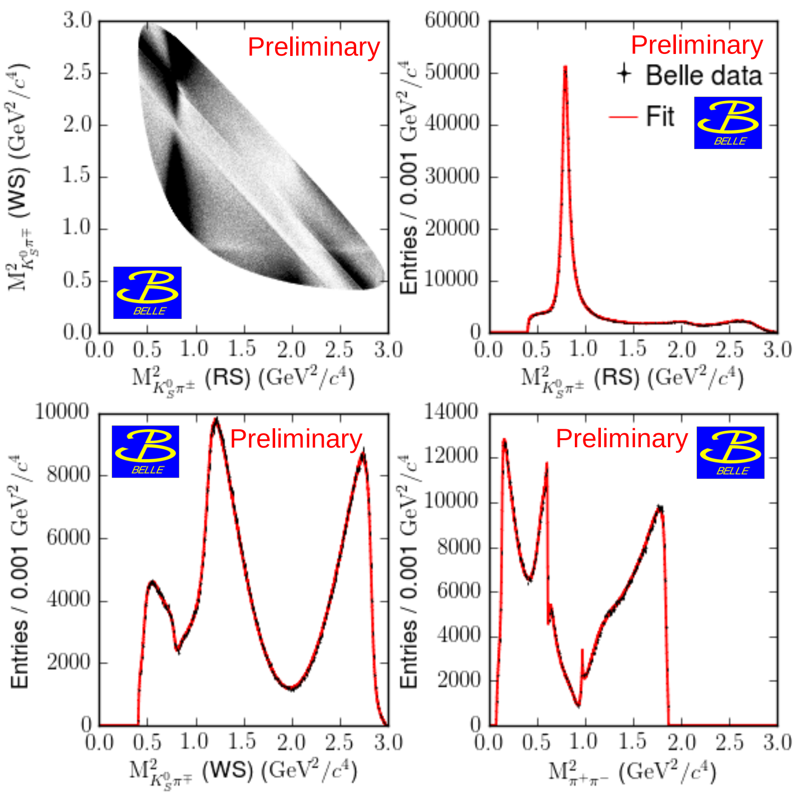
- Current best single experimental uncertainty on cos(2β) is ≈±0.36 [PRD 94 (2016) 052004]

→ Perform time-dependent Dalitz analysis combining *BABAR*+Belle data to improve the sensitivity on cos(2β).

Combined $B\small{A}B\small{AR}$+Belle Analysis of $\mathrm{B^0 \to D^{(*)} h^0}$ decays

- The $\mathrm{D \to K^0_S \pi^+ \pi^-}$ Dalitz model is directly obtained from flavor-tagged $\mathrm{e^+e^- \to c\bar{c}}$ data.

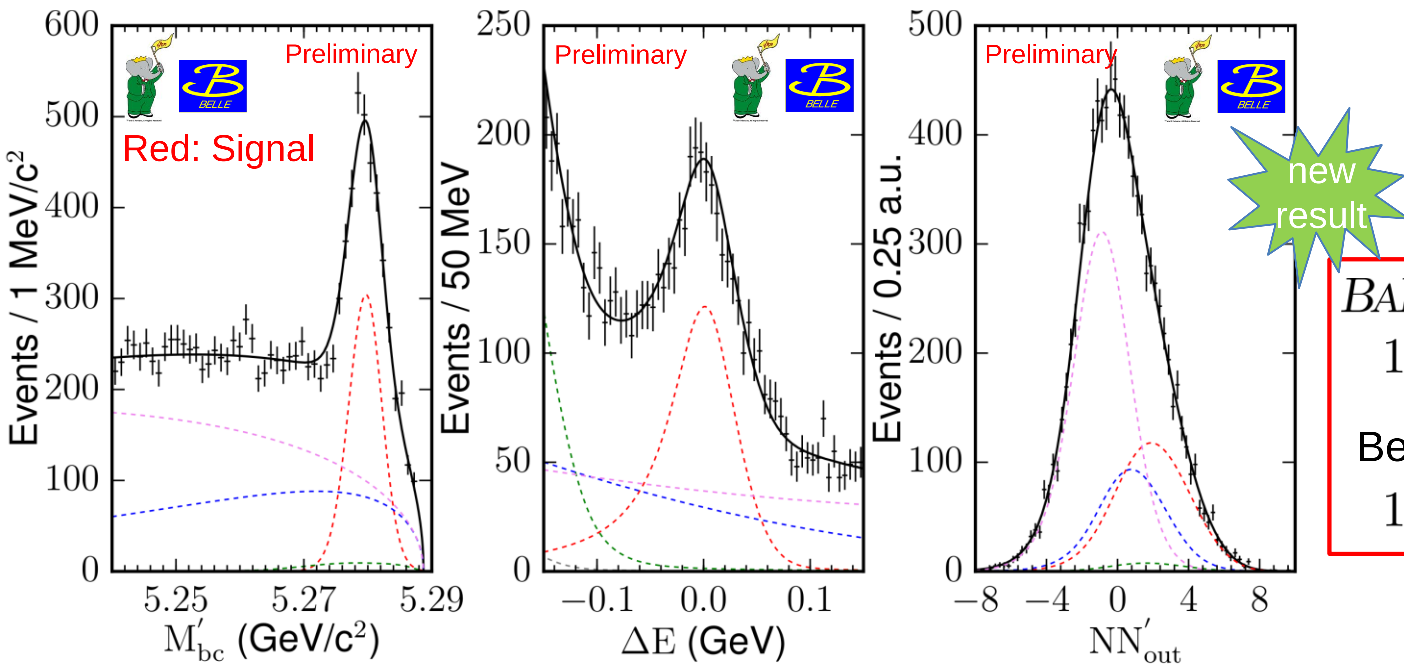
$$\boxed{\mathcal{A}_{D^0}(m_+^2, m_-^2) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} \underbrace{a_r e^{i\phi_r} \mathcal{A}_r(m_+^2, m_-^2)}_{\text{Isobar model for } L\neq 0} + \underbrace{\mathcal{A}_{K\pi_{L=0}}(s)}_{\text{LASS}} + \underbrace{F_1(s)}_{\text{K-matrix}}}$$



- The Dalitz model accounts for 14 intermediate two-body resonances.
- The K-matrix and LASS parameterizations are used to model the ππ and Kπ S-waves.
- The $\mathrm{D \to K^0_S \pi^+ \pi^-}$ Dalitz model extracted from $\mathrm{e^+e^- \to c\bar{c}}$ data is used to extract sin(2β) and cos(2β) from the $\mathrm{B^0}$ decay combining $B\small{A}B\small{AR}$+Belle data.

Combined *BaBar*+Belle Analysis of $\mathrm{B^0 \to D^{(*)}h^0}$ decays

- Reconstruct $\mathrm{B^0 \to D^{(*)}h^0}$ with $\mathrm{h^0}$ in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$
  $\mathrm{D \to K^0_S}\pi^+\pi^-$ and $\mathrm{D^{*0} \to D}\pi^0$.
- In total, 5 $\mathrm{B^0}$ decay modes are reconstructed.
- $\mathrm{e^+e^- \to q\bar{q}\ (q \in \{u, d, s, c\})}$ continuum background is identified by neural networks.
- Coherent analysis strategy, apply almost same selection on *BaBar* and Belle data.
- Extract signal by 3D fit of beam-constr. mass $\mathrm{M'_{bc}}$, energy-difference $\Delta\mathrm{E}$ and $\mathrm{NN'_{out}}$.



BaBar:
1129 ± 48 signal events

Belle:
1567 ± 56 signal events

Combined $B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.2em R}$+Belle Analysis of $\mathbf{B^0 \to D^{(*)} h^0}$ decays

- Perform measurement by maximizing the combined log-likelihood function:

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{B\kern-0.1em{\scriptscriptstyle A}\kern-0.1em B\kern-0.1em{\scriptscriptstyle A\kern-0.2em R}} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}}$$

- Physics PDFs are convoluted with specific resolution functions:

$$\mathcal{P}^{\mathrm{Exp.}} = \sum_{\mathrm{k}} \mathrm{f_k} \int \left[\mathrm{P_k}\left(\Delta \mathrm{t}'\right) \mathrm{R_k}\left(\Delta \mathrm{t} - \Delta \mathrm{t}'\right)\right] \mathrm{d}\left(\Delta \mathrm{t}'\right)$$

- Apply $B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.2em R}$ and Belle specific resolution models and flavor tagging algorithms.

- Apply common signal model:

$$\begin{aligned} \mathrm{P_{sig}}(\Delta \mathrm{t}) \propto & \left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right] \\ & \mp \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right) \cos(\Delta m \Delta t) \\ & \pm 2\eta_{h^0} \left(-1\right)^L \left[\mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right) \cos(2\beta) - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right) \sin(2\beta)\right] \sin(\Delta m \Delta t) \end{aligned}$$

$B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.2em R}$+Belle with 1.1 ab^{-1}: Preliminary

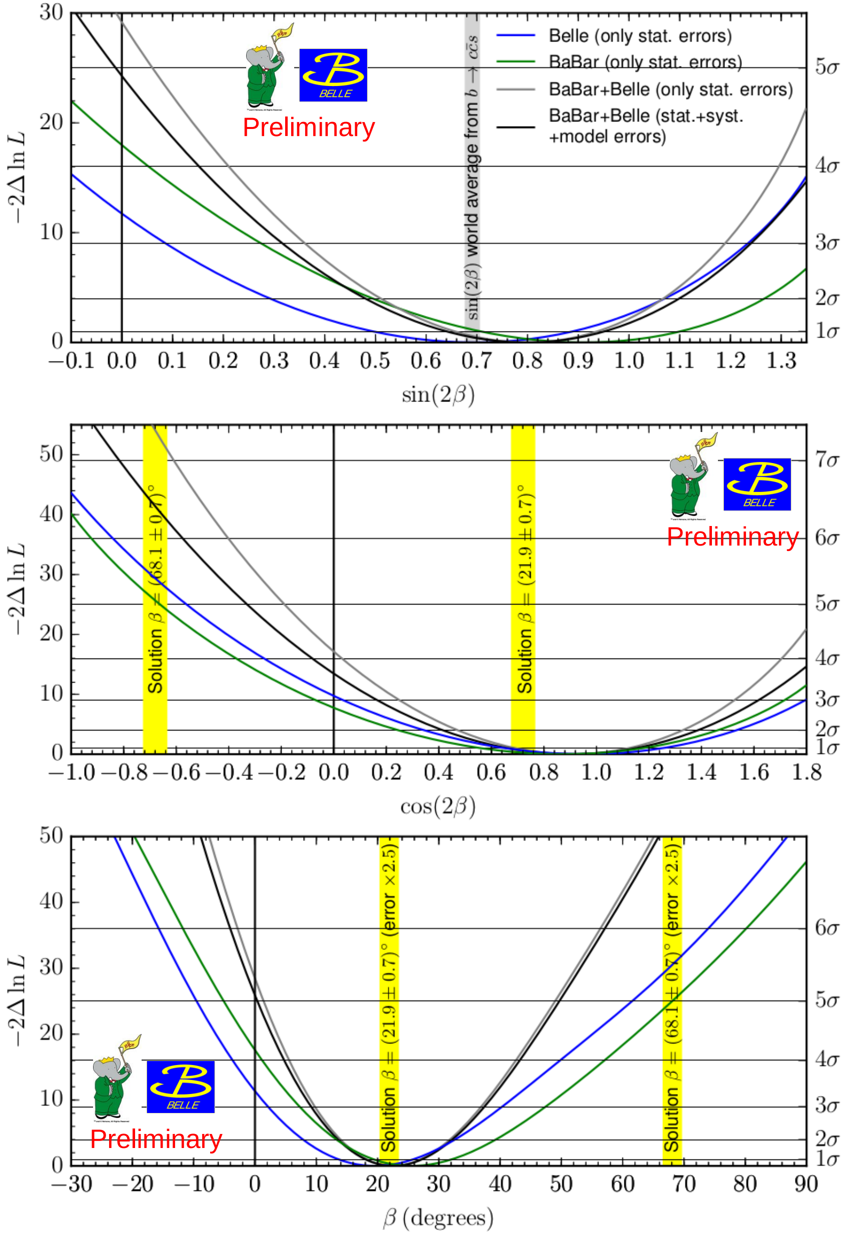
$$\sin(2\beta) = 0.80 \pm 0.14\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \pm 0.03\,(\mathrm{model})$$

$$\cos(2\beta) = 0.91 \pm 0.22\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.07\,(\mathrm{model})$$

$$\beta = (22.5 \pm 4.4\,(\mathrm{stat.}) \pm 1.2\,(\mathrm{syst.}) \pm 0.6\,(\mathrm{model}))^\circ$$

new result

Combined BaBar+Belle Analysis of $\mathrm{B^0 \to D^{(*)}h^0}$ decays



- First evidence for $\cos(2\beta) > 0$ (3.7σ)
- Direct exclusion of the 2nd solution

$$\pi/2 - \beta = (68.1 \pm 0.7)°$$

  of the CKM Unitarity Triangle (7.3σ)

  → Reduction of the trigonometric ambiguity of the CKM Unitarity Triangle
- Exclusion of $\beta = 0°$ (5.1σ)

  → Observation of CP violation in $\mathrm{B^0 \to D^{(*)}h^0}$ decays

new result

Summary

- Light dark sectors have recently emerged as a new possibility for dark matter and provide a rich phenomology.

- BABAR pioneered the low-energy, high-intensity collider searches in various dark sector signatures and continues to put stringent limits on the allowed parameter space.

- The BABAR and Belle experiments recently started performing measurements combining the about 1.1 ab^{-1} collected on the Υ(4S), which enables for an unprecedented sensitivity in time-dependent CP violation measurements.

- The most precise measurement of cos(2β), the exclusion of multifold solutions on the Unitarity Triangle and an observation of CP violation in $\mathrm{B}^0 \to \mathrm{D}^{(*)}\mathrm{h}^0$ decays have been reported.