Hadronic B/B_s decays at B factories – A story of trees and penguins

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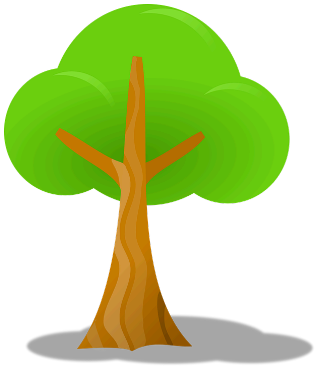
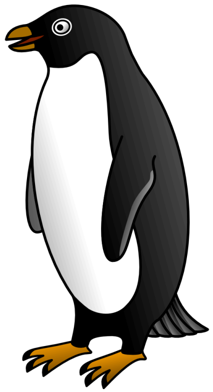
(On behalf of the Belle and BaBar Collaborations)

Why bother about them?

- These decays are mainly mediated by

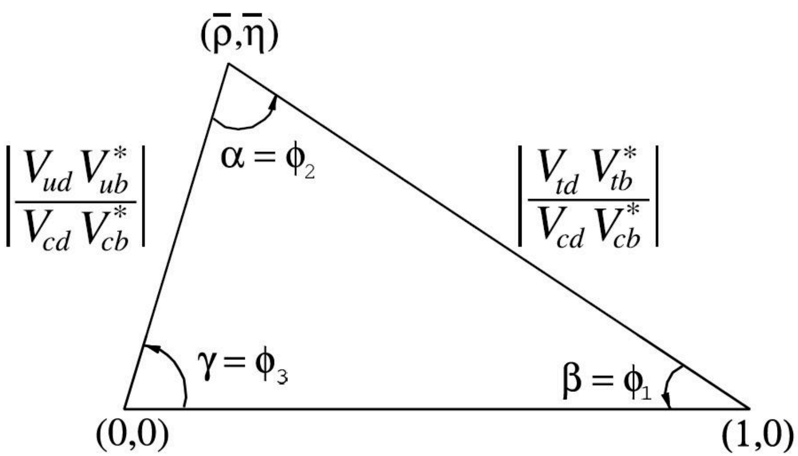
1) $b \to c$ Cabibbo favoured tree diagram
2) $b \to u$ Cabibbo suppressed tree and
   $b \to d, s$ penguin diagrams





- Measure three angles of the unitarity triangle

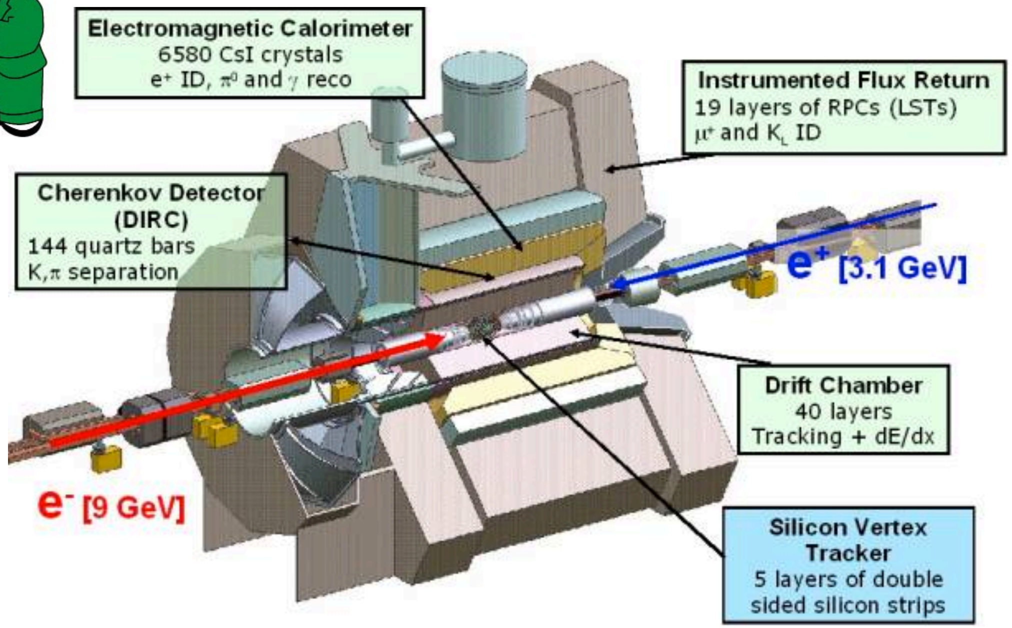
✧ β/ϕ_1 ($J/\psi K^0$, ϕK^0...) } Time-dependent CP violation
✧ α/ϕ_2 ($\pi\pi$, $\rho\rho$, $\rho\pi$...)
✧ γ/ϕ_3 ($D^{(*)}K^{(*)}$...) Direct CP violation

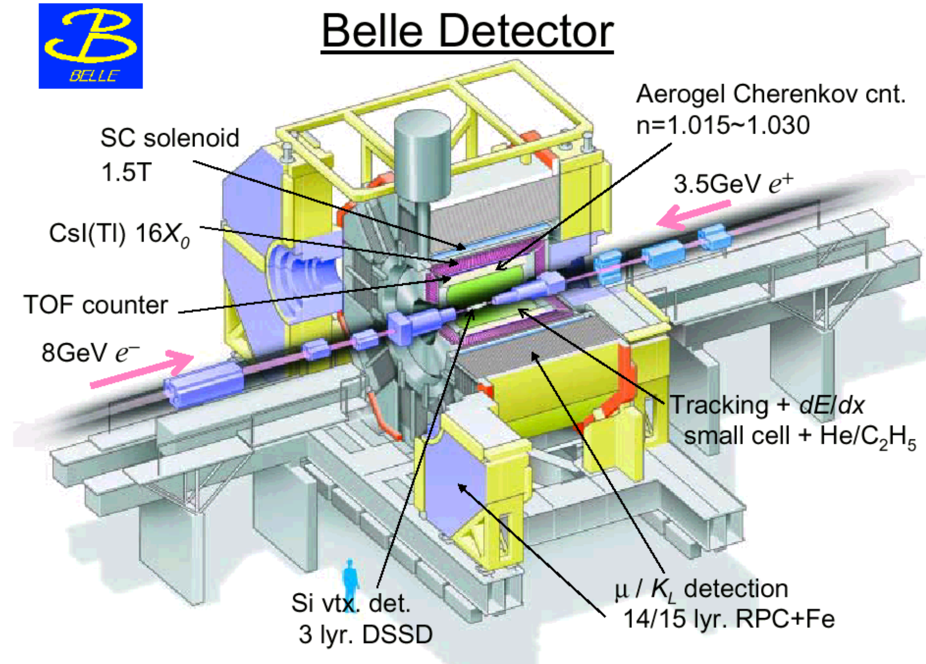


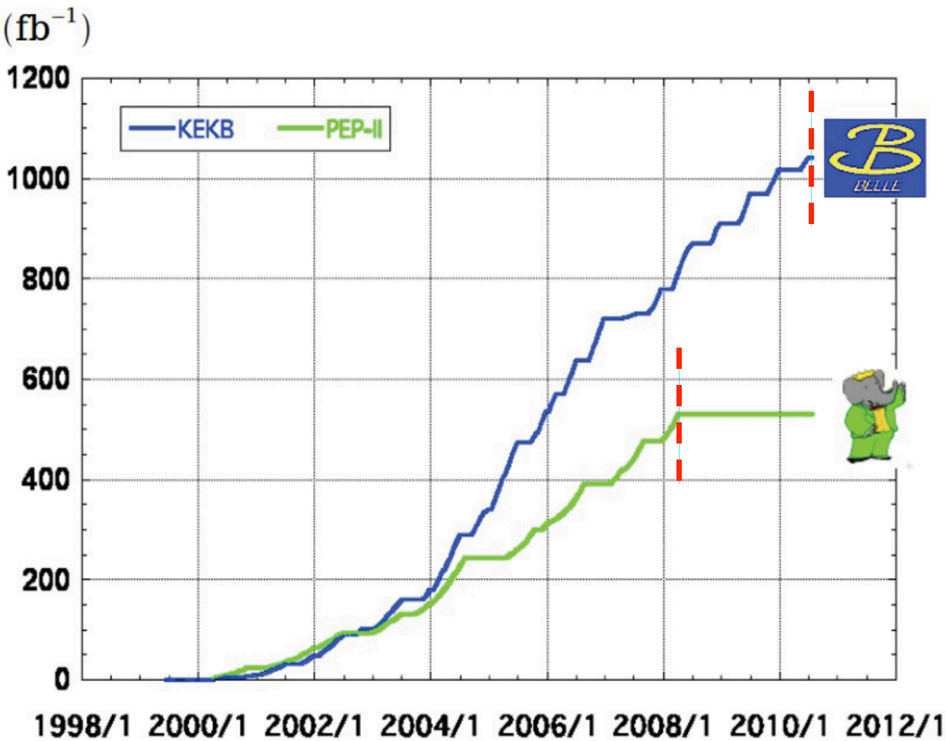
- Indirectly probe new physics (NP) especially via the study of second class of decays ➔ changed branching fraction (BF) and CP asymmetry w.r.t. the SM predictions

➢ Present a suite of recent results on hadronic B/B_s decays from Belle and BABAR

Experiments and dataset







> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~100 fb^{-1}

513.7 ± 1.8 fb^{-1}
On resonance:
$\Upsilon(4S)$: 424 fb^{-1}, 471 M
$\Upsilon(3S)$: 28 fb^{-1}, 122 M
$\Upsilon(2S)$: 14 fb^{-1}, 99 M
Off resonance:
48 fb^{-1}

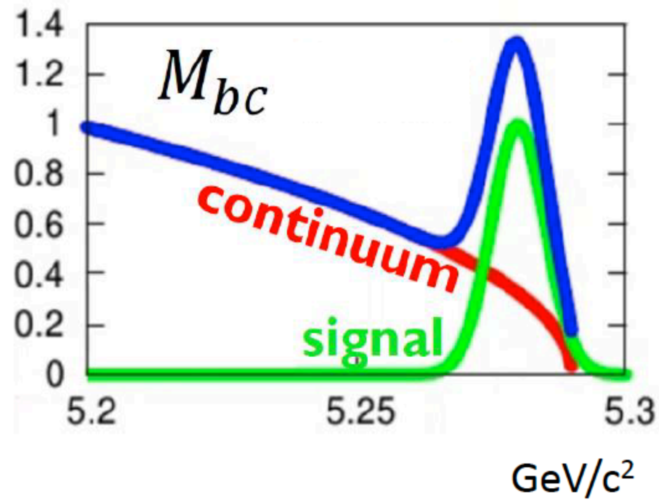
- Results based on full Υ(4S) dataset of Belle (772×10^6 $B\bar{B}$) and BABAR (471×10^6 $B\bar{B}$) as well as the unique Υ(5S) data from Belle (121 fb^{-1})

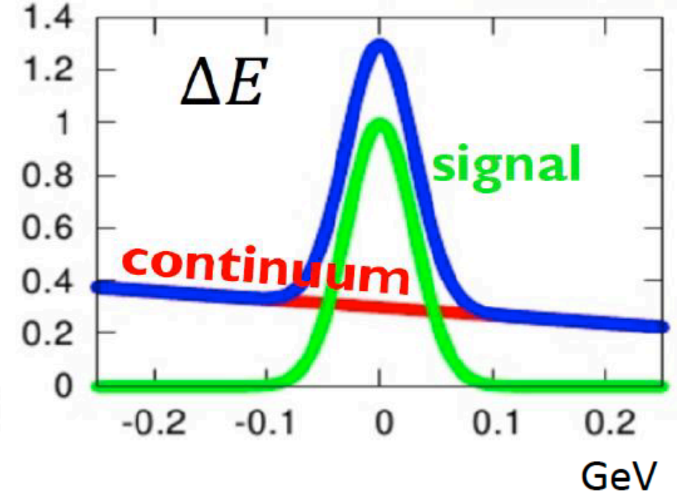
Analysis in a nutshell

- Kinematic reconstruction

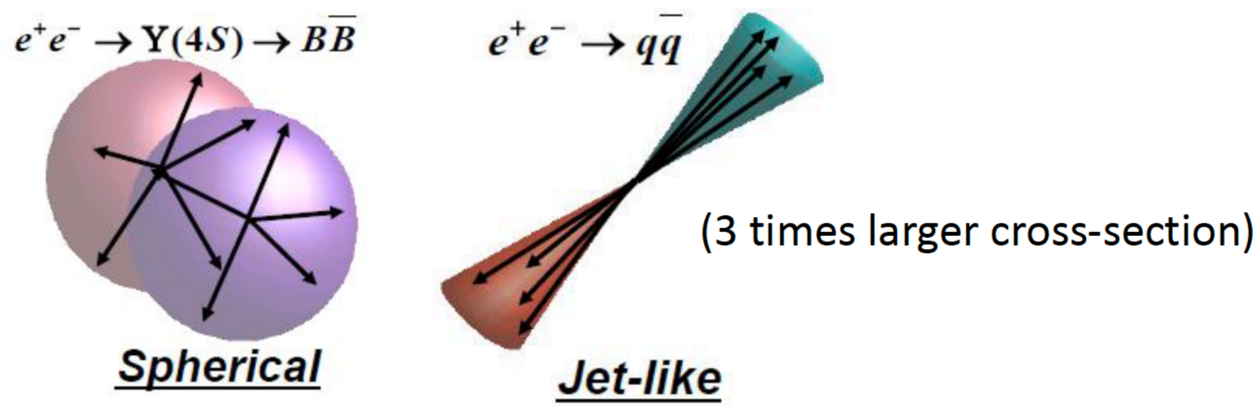
$$M_{bc} = \sqrt{E_{beam}^2 - |\sum_i \vec{p}_i|^2}$$

$$\Delta E = \sum_i E_i - E_{beam}$$

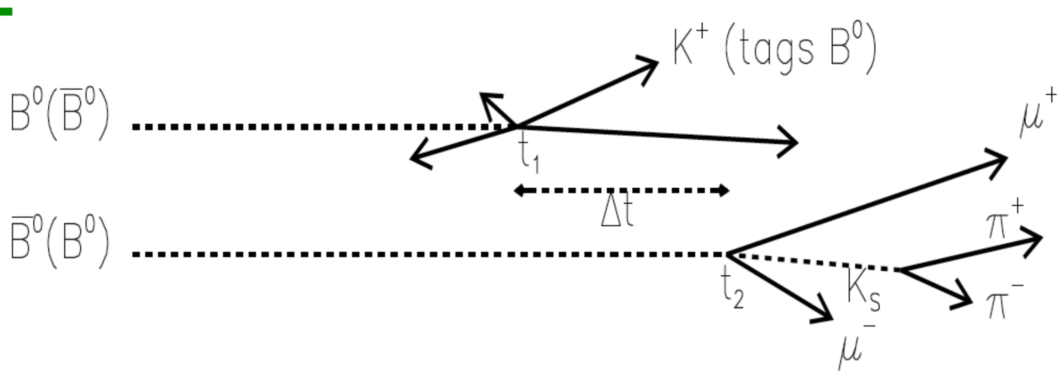




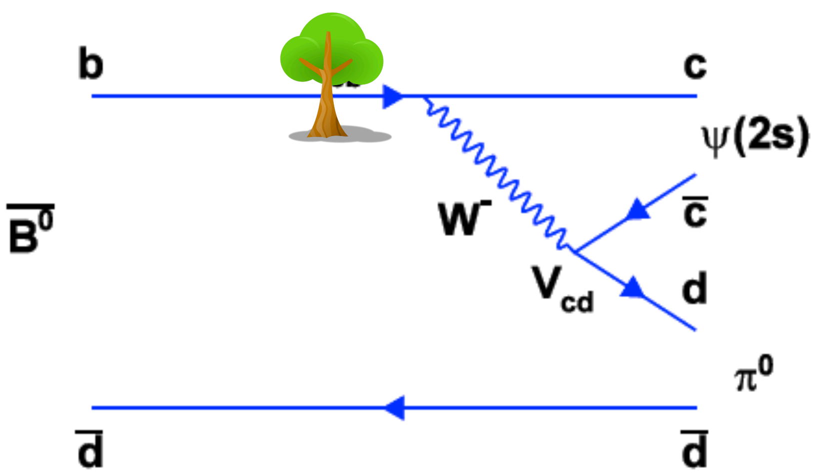
- Continuum suppression
  - Multivariate analyser (NN or LR) out of several event-shape variables
  - Translate NN_{out} to a more Gaussian-like distribution

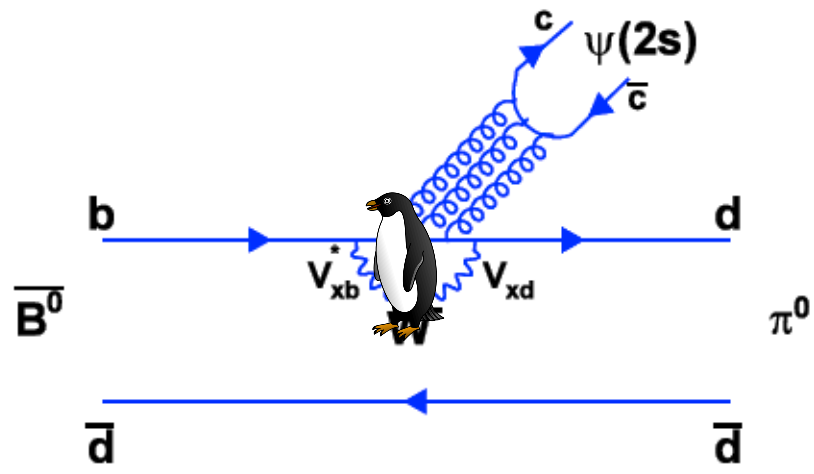


- Time-dependent CP violation study
  - Quantum entangled initial state
  - Excellent vertexing and tagging



First observation of $B^0 \to \psi(2S)\pi^0$





- The decay is sensitive to the UT angle ϕ_1
- In absence of penguin contribution, direct CP asymmetry $A_{CP} = 0$ and mixing-induced CP asymmetry $S_{CP} = -\sin(2\phi_1)$
- Possible NP contributions within the loop may lead to significant deviation of A_{CP} from zero or S_{CP} from the WA value of $\sin(2\phi_1)$
- Can also help constrain the penguin pollution in $b \to c\bar{c}s$ transitions

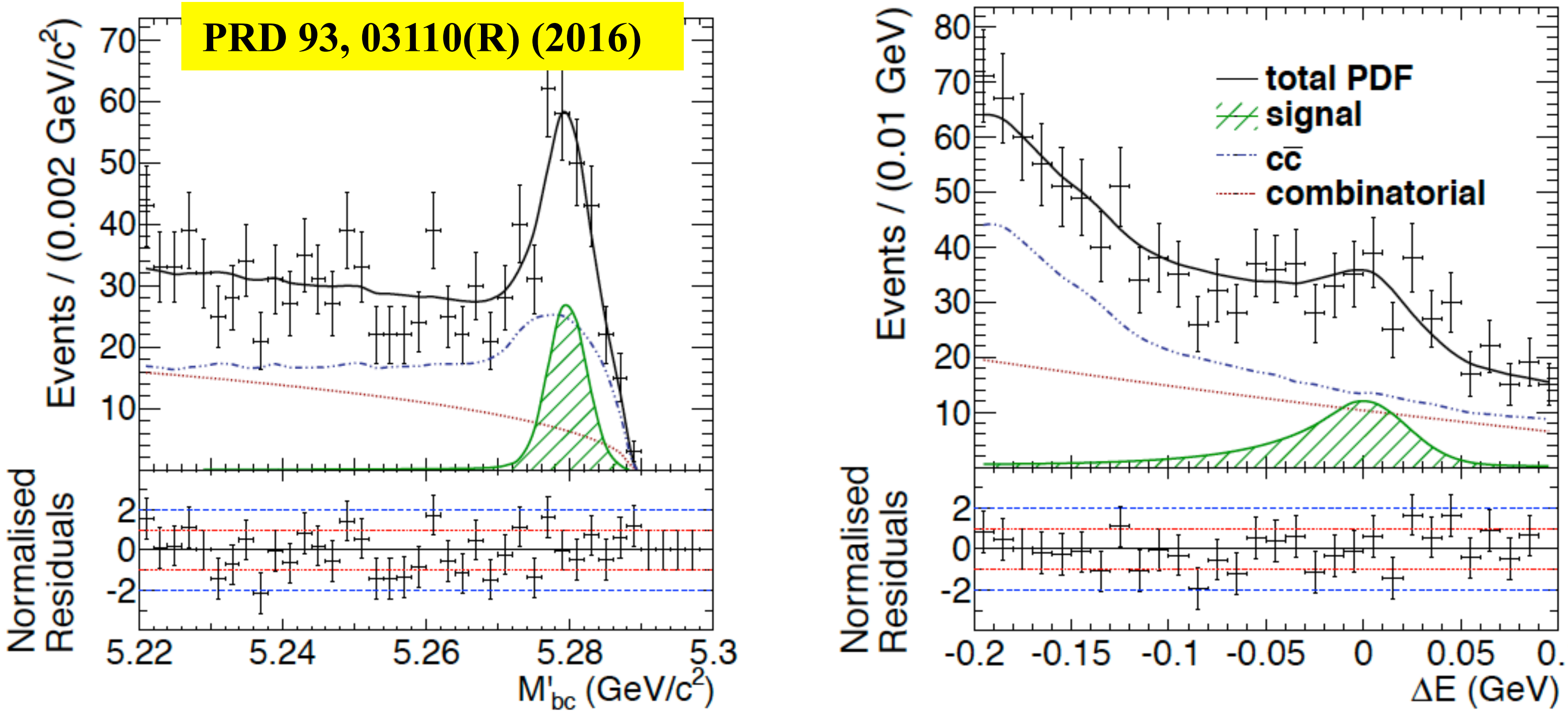
M. Ciuchini et al., PRL 95, 221804 (2005) **S. Faller et al., PRD 79, 014030 (2009)**

P. Frings et al., PRL 115, 061802 (2015)

First observation of $B^0 \to \psi(2S)\pi^0$

- Modified M_{bc} is obtained using precise E_{beam} and charged-track information in order to suppress correlation with ΔE

PRD 93, 03110(R) (2016)



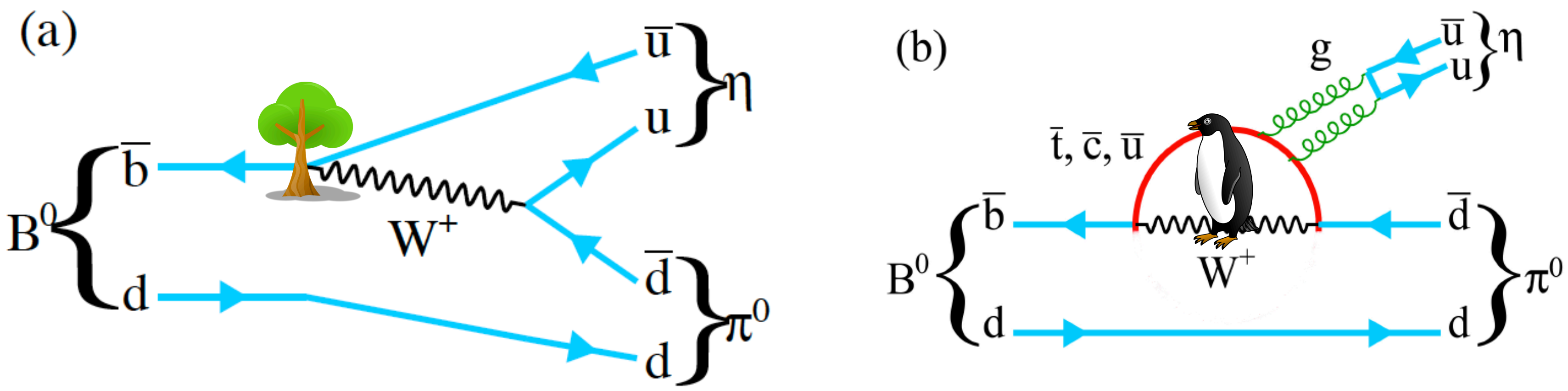
- Observed a signal yield of 85±12 with 7.2σ significance ➔ first observation

$$\boxed{BF(B^0 \to \psi(2S)\pi^0) = [1.17 \pm 0.17(stat) \pm 0.08(syst)]\text{x}10^{-5}}$$

- Consistent with the naïve expectation: $BF[B^0\to \psi(2S)\,\pi^0]/BF[B^0\to \psi(2S)\,K^0] = BF[B^0\to J/\psi\,\pi^0]/BF[B^0\to J/\psi\,K^0]$
- Opens up the possibility of time-dependent CP violation study at Belle II

Evidence for $B^0 \to \eta\pi^0$

- Highly suppressed decay: proceeds via $b \to u$ Cabibbo- and color-suppressed tree and $b \to d$ penguin diagrams



- Predicted BF: $(2\text{-}12)\times 10^{-7}$

A.R. Williamson et al., PRD 74, 014003 (2006) **H. Wang et al., NP B738, 243 (2006)**

- Can be used to limit isospin breaking effects on the value of UT angle $\sin(2\phi_2)$ obtained from $B \to \pi\pi$ decays

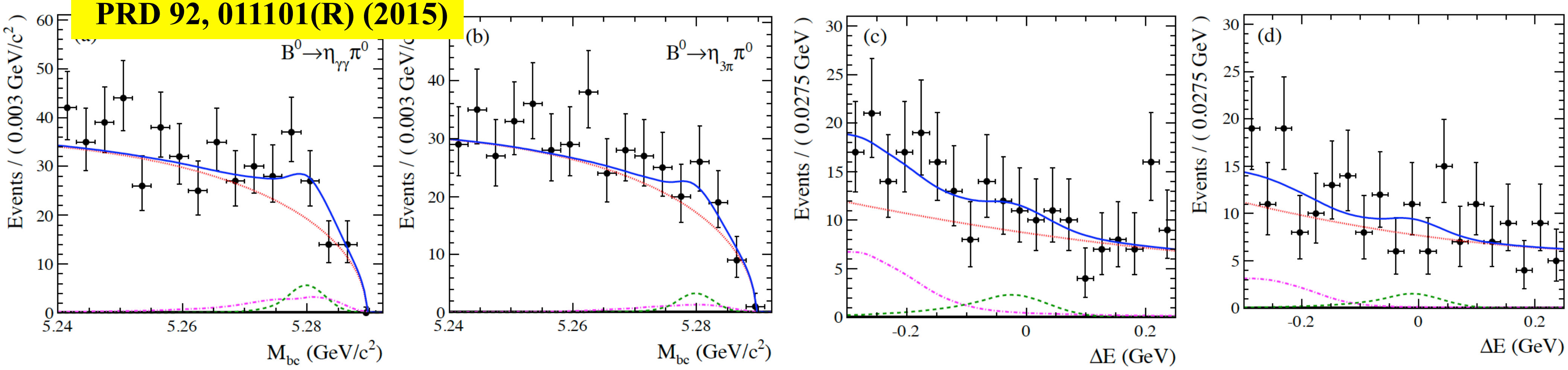
M. Gronau et al., PRD 71, 074017 (2005) **S. Gardner, PRD 72, 034015 (2005)**

- Can also help constrain the CP violation parameter governing time dependence in $B \to \eta' K^0$ decays

M. Gronau et al., PLB 596, 107 (2004) **PRD 74, 093003 (2006)**

Evidence for $B^0 \to \eta\pi^0$

PRD 92, 011101(R) (2015)



- First evidence: BELLE

$$\boxed{\left(4.1^{+1.7+0.5}_{-1.5-0.7}\right) \text{ x } 10^{-7}}$$

Mode	$Y_{\rm sig}$	$\epsilon(\%)$	$\mathcal{B}_\eta(\%)$	Significance	$\mathcal{B}(10^{-7})$
$B^0 \to \eta_{\gamma\gamma}\pi^0$	$30.6^{+12.2}_{-10.8}$	18.4	39.41	3.1	$5.6^{+2.2}_{-2.0}$
$B^0 \to \eta_{3\pi}\pi^0$	$0.5^{+6.6}_{-5.4}$	14.2	22.92	0.1	$0.2^{+2.8}_{-2.3}$
Combined				3.0	$4.1^{+1.7}_{-1.5}$

- 90% CL upper limit:

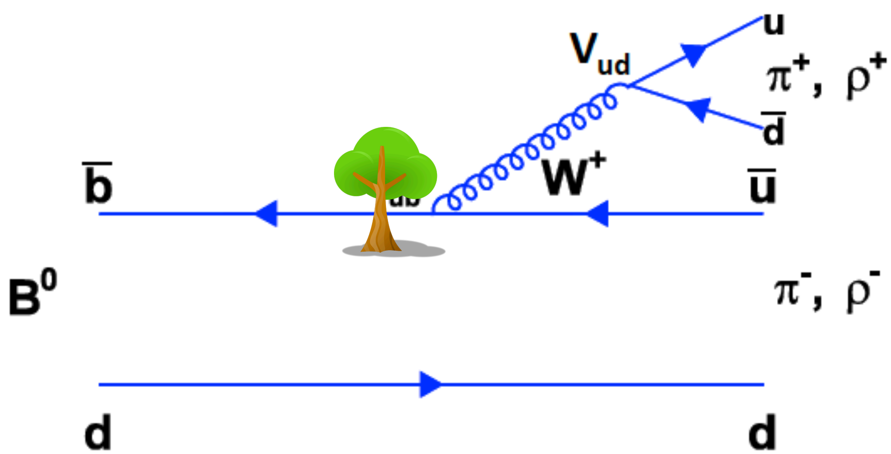
$$\boxed{6.5 \text{ x } 10^{-7}}$$

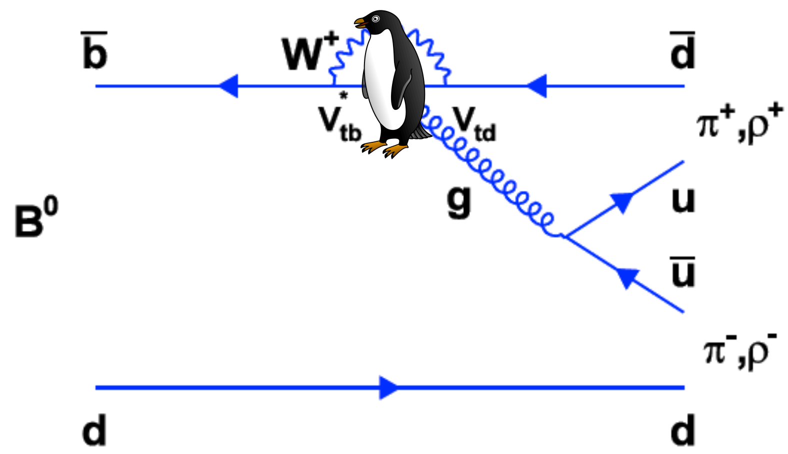
improves over the previous best limit from by a factor of 2 **PRD 78, 011107(R) (2008)**

- Isospin-breaking correction due to π-η-η' mixing (40% improvement over the previous value)

$$\boxed{\left|(\Delta\alpha - \Delta\alpha_0)_{\pi^0-\eta-\eta'}\right| < 0.97^0 \text{ at } 90\% \text{ CL}}$$

Study of $B^0 \to \rho^+\rho^-$ decays





- Proceeds dominantly via the $b \to u\bar{u}d$ transition and is thus sensitive to

$$\boxed{\phi_2 = \arg\left(-\frac{V_{td}\,V^*_{tb}}{V_{ud}\,V^*_{ub}}\right)}$$

- If tree only, then S_{CP} is directly related $\sin(2\phi_2)$ and $A_{CP} = 0$
- However, the penguin pollution can shift ϕ_2:

$$\boxed{S_{CP} = \sqrt{1 - A^2_{CP}}\,\sin(2(\phi_2 + \Delta\phi_2))}$$

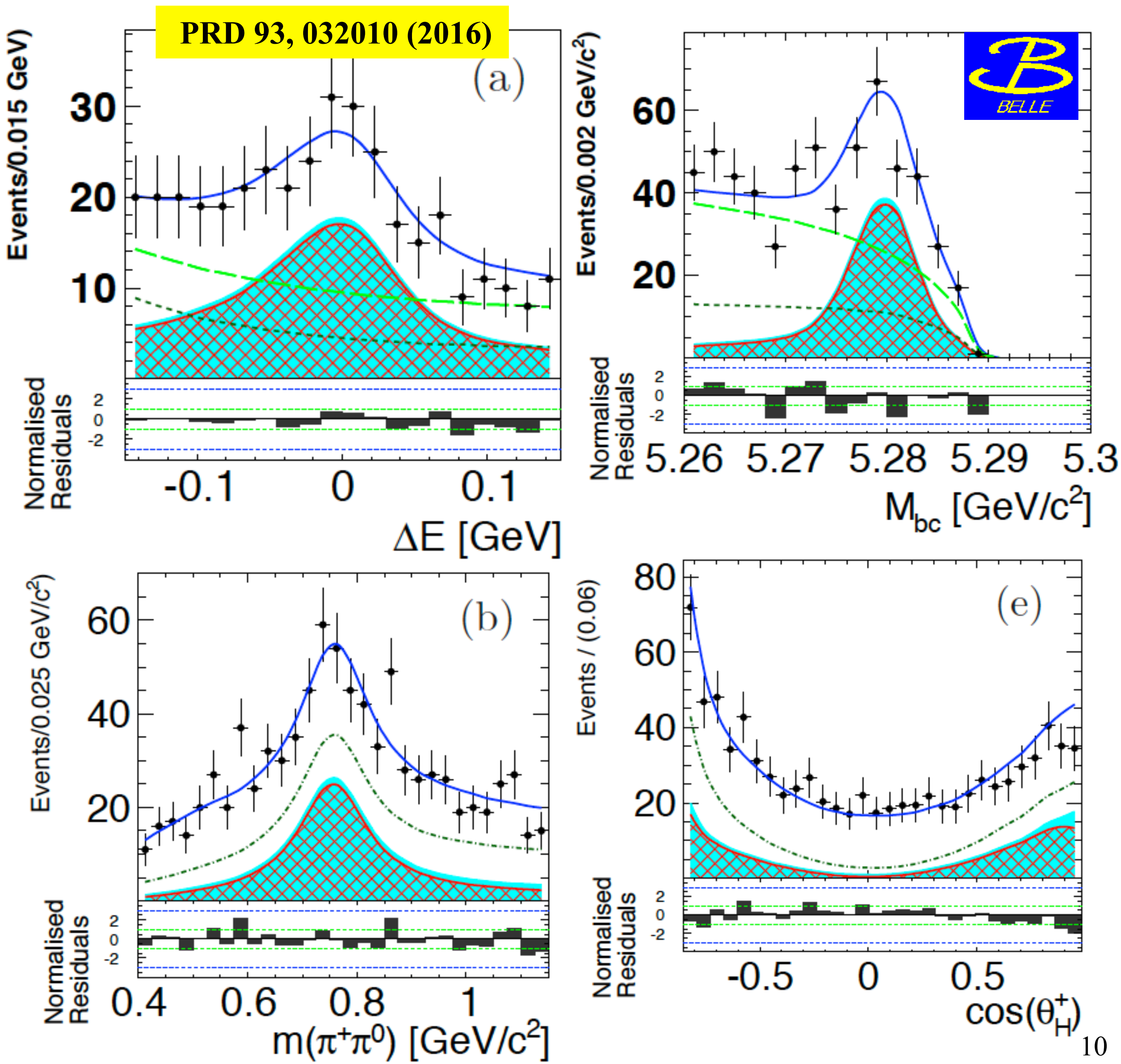
- $\Delta\phi_2$ can be extracted from an isospin analysis or SU(3) flavour symmetry

Gronau and London, PRL 65, 3381 (1990)

Beneke et al., PLB 638, 68 (2006)

Study of $B^0 \rightarrow \rho^+\rho^-$ decays

- 9D fit including M_{bc}, ΔE, Fisher, mass and helicity angle of ρ^+ and ρ^-, Δt and flavour tagging output



- Hashed (red) area: $B^0 \rightarrow \rho^+ \rho^-$ contribution
- Cyan: all 4π final states
- Dark green curve (short-dashed): non-peaking B background
- Bright green curve: total non-peaking background
- Dark green curve (dash-dotted): contributions from all $B\bar{B}$ decays

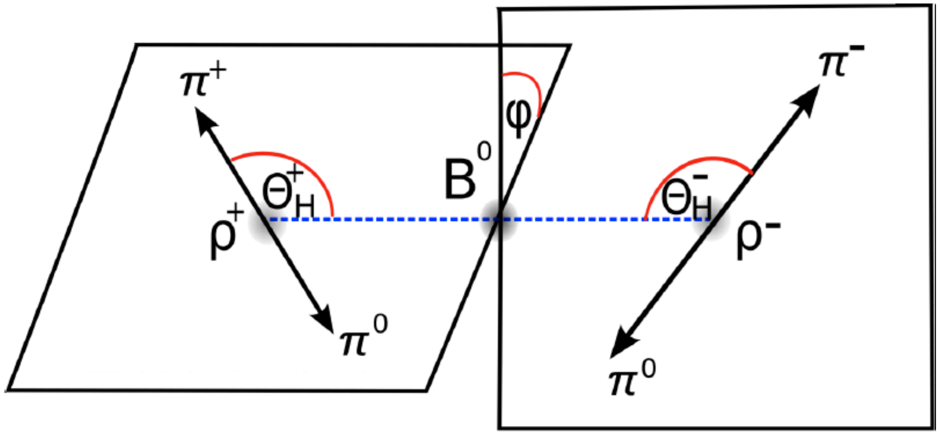
Results on $B^0 \to \rho^+\rho^-$ decays

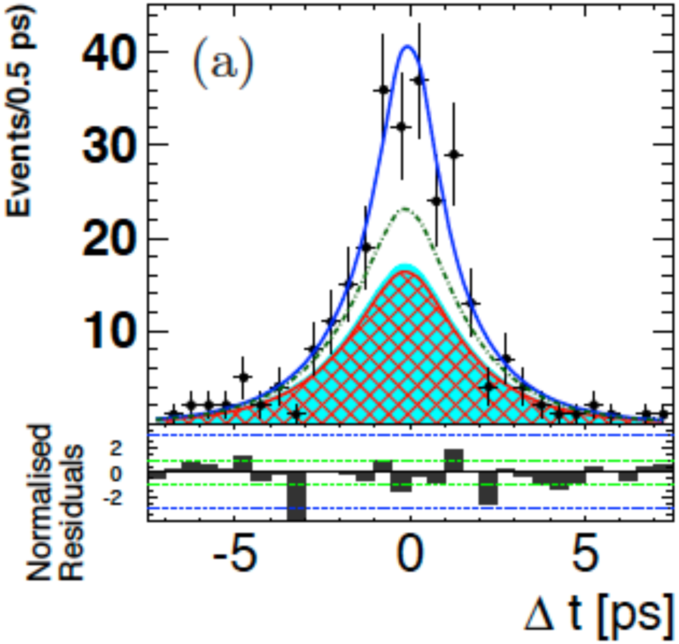
- Almost fully longitudinally polarized decay

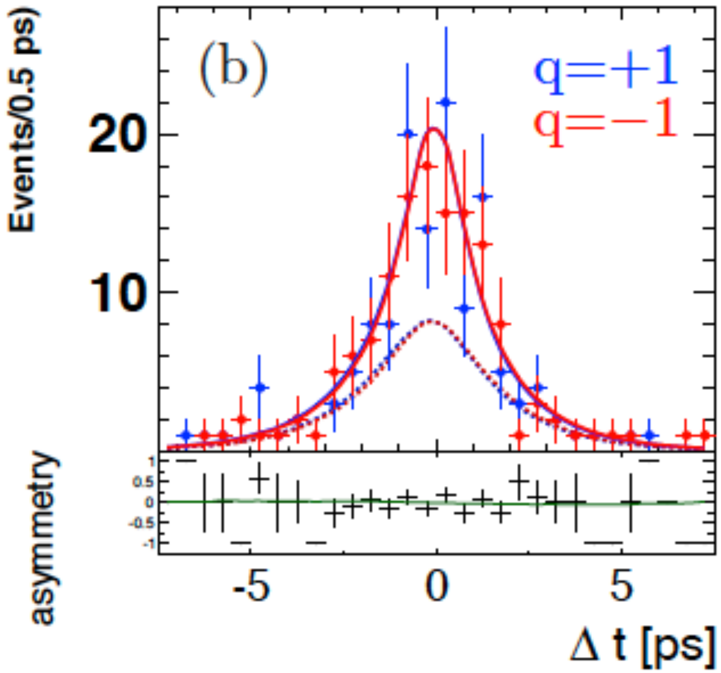
PRD 93, 032010 (2016)

$BF(B^0 \to \rho^+\rho^-) = (28.3 \pm 1.5 \pm 1.5)\mathrm{x}10^{-6}$
$f_L = 0.988 \pm 0.012 \pm 0.023$
$S_{CP} = -0.13 \pm 0.15 \pm 0.05$
$A_{CP} = 0.00 \pm 0.10 \pm 0.06$

772 M $B\bar{B}$

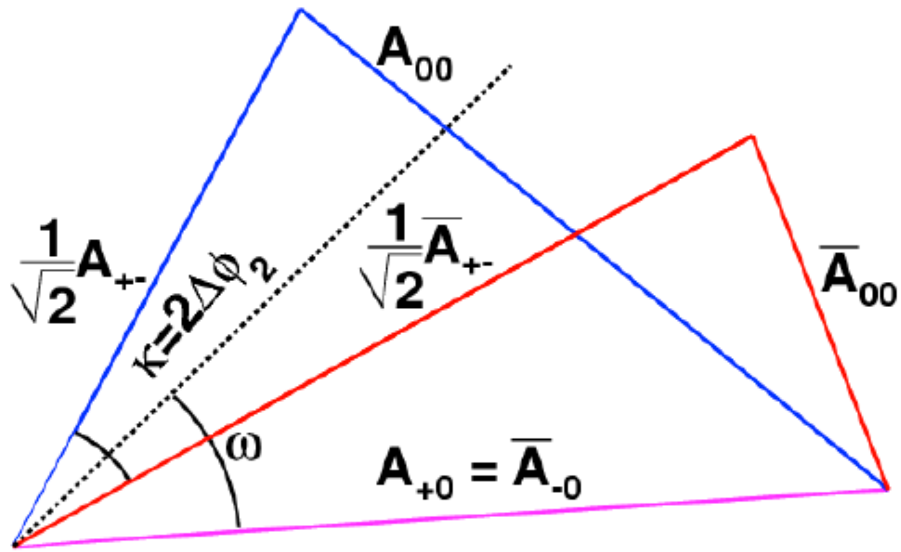






- Above plots are the projections of the fit result onto Δt
- A_{CP} is consistent with zero ➔ small penguin contribution

Implication for the UT angle ϕ_2



- Relations among various decay amplitudes:

$A_{+-}(B^0 \to \rho^+\rho^+)$ $\quad A_{+-} + \sqrt{2}A_{00} = \sqrt{2}A_{+0}$

$A_{00}(B^0 \to \rho^0\rho^0)$ $\quad \bar{A}_{+-} + \sqrt{2}\bar{A}_{00} = \sqrt{2}\bar{A}_{-0}$

$A_{+0}(B^0 \to \rho^+\rho^0)$ $\quad A_{+-}=\bar{A}_{-0}$ pure tree

Gronau and London, PRL 65, 3381 (1990)

- Performed an isospin analysis using previous Belle results on $\rho^+\rho^0$ and $\rho^0\rho^0$

PRL 91, 221801 (2003)

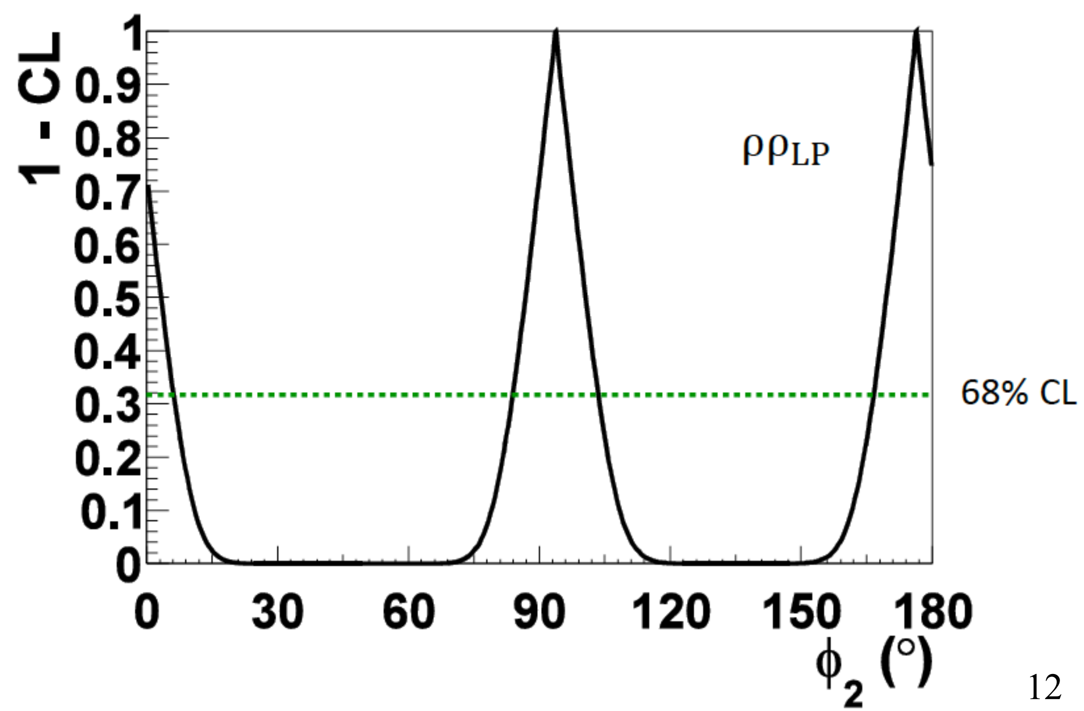
PRD 89, 072008 (2014)

- Two solution are found of which one consistent with other measurements:

$$\boxed{\phi_2 = (93.7 \pm 10.6)^0}$$

- The penguin contribution consistent with zero

$$\boxed{\Delta\phi_2 = (0.0 \pm 9.6)^0}$$

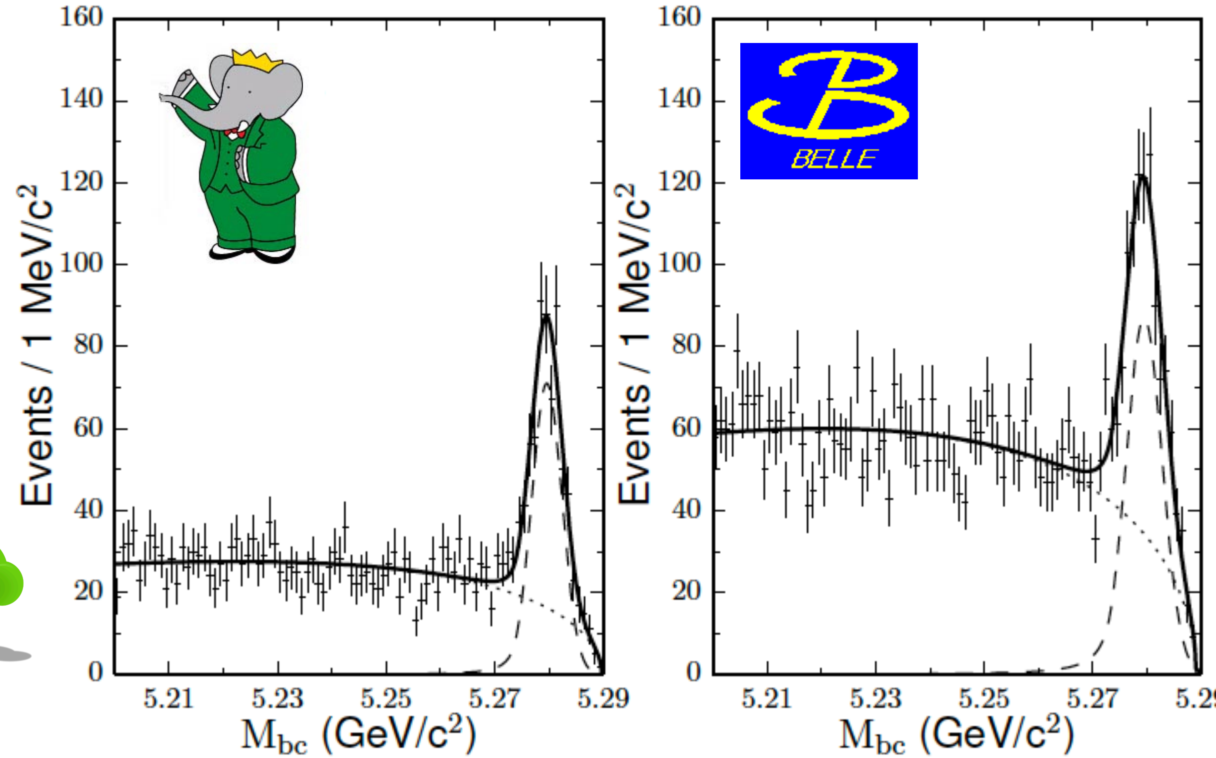


A joint Belle+BaBar analysis of $B^0 \to D^{(*)0}h^0$

- Both B-factory experiments use $b \to c\bar{c}s$ transition e.g., $J/\psi K^0$ to measure $\sin(2\phi_1)$

- Complementary and theory-wise clean approach is given by the $b \to c\bar{u}d$ transition, viz., $D^{(*)0}h^0$ where h^0 is a light hadron $\{\pi^0, \eta, \omega\}$

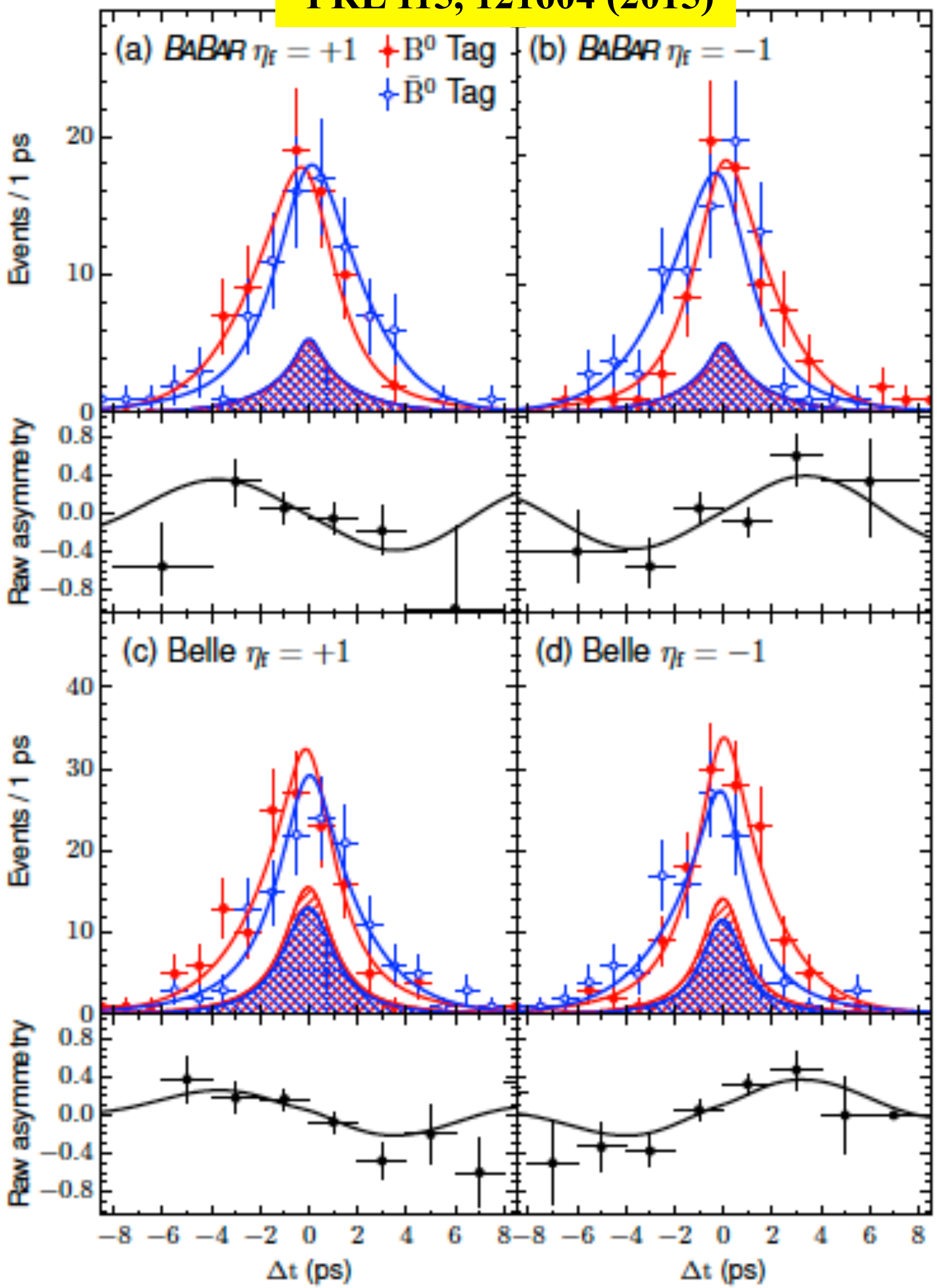
- First of its kind analysis is performed by combining the data from Belle and BaBar



Decay mode	BABAR	Belle
$\overline{B}^0 \to D_{CP}\pi^0$	241 ± 22	345 ± 25
$\overline{B}^0 \to D_{CP}\eta$	106 ± 14	148 ± 18
$\overline{B}^0 \to D_{CP}\omega$	66 ± 10	151 ± 17
$\overline{B}^0 \to D^*_{CP}\pi^0$	72 ± 12	80 ± 14
$\overline{B}^0 \to D^*_{CP}\eta$	39 ± 8	39 ± 10
$\overline{B}^0 \to D^{(*)}_{CP}h^0$ total	508 ± 31	757 ± 44

First observation of CP violation in $B^0 \to D^{(*)0}h^0$

PRL 115, 121604 (2015)



- Extract CPV parameters by maximizing the log-likelihood function

$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$
$$\mathcal{C} = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

- Establish CP violation at a significance of 5.4σ
- Consistent with the WA for $\sin(2\phi_1)$

- Systematics breakup:

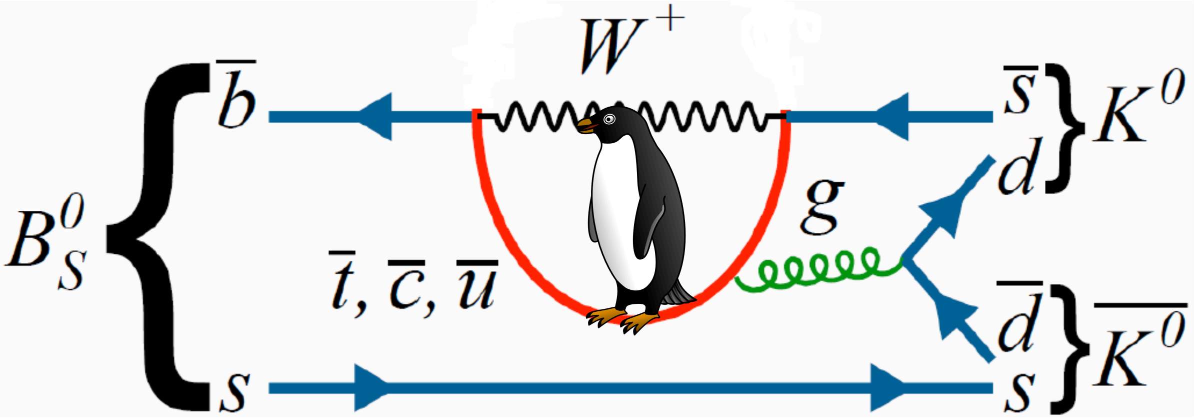
Source	$\mathcal{S}$	$\mathcal{C}$
Vertex reconstruction	1.5	1.4
Δt resolution functions	2.0	0.4
Background Δt PDFs	0.4	0.1
Signal purity	0.6	0.3
Flavor-tagging	0.3	0.3
Physics parameters	0.2	< 0.1
Possible fit bias	0.6	0.8
Peaking background	4.9	0.9
Tag-side interference	0.1	1.4
Total	5.6	2.5

First observation of $B_s \to K^0\overline{K}^0$

- All two-body B_s decays are observed but for the neutral combinations
- Predicted BF in the range of $(1.6\text{-}2.7)\times10^{-5}$

  C.H. Chen, PLB 520, 33 (2001)

  A. Ali et al., PRD 76, 074018 (2007)



- Non-SM particles and couplings could enhance the BF value up to 3.0×10^{-5}

  Q. Chang et al., J. Phys. G: Nucl. Part. Phys. 41, 105002 (2014)

- A_{CP} is not more than 1% in the SM, but can be an order of magnitude larger in presence of SUSY without changing its BF

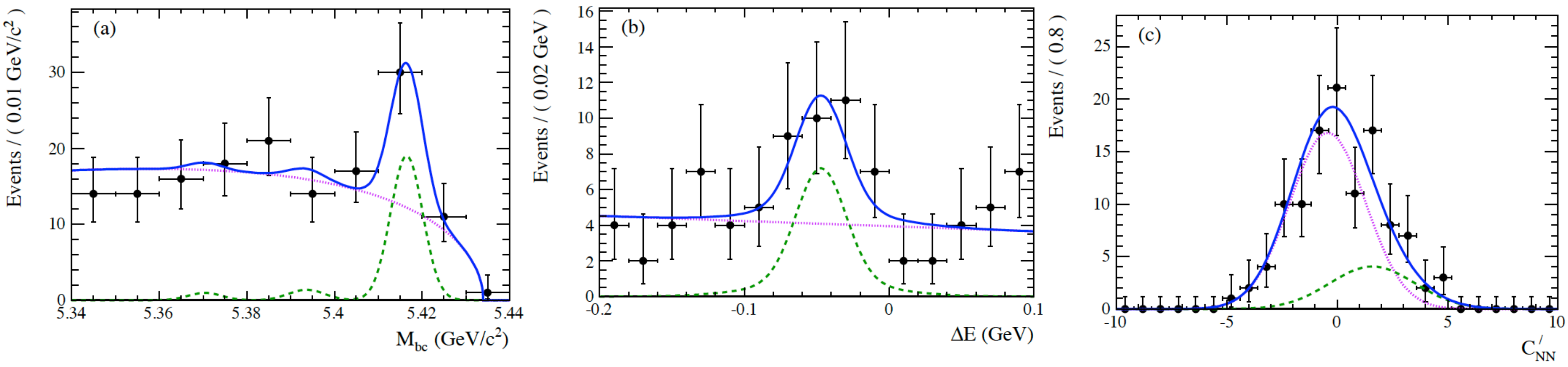
  A. Hayakawa et al., PTEP 2014, 023B04 **S. Baek et al., JHEP12 (2006) 019**

➢ Previous result: 90% CL limit on $BF(B_s \to K^0\overline{K}^0) < 6.6\times10^{-5}$ based on 23.6 fb^{-1}

PRD 82, 072007 (2010) BELLE

First observation of $B_s \to K^0 \overline{K}^0$

- ❑ 3D fit to extract the signal yield



- ❑ 29.0+8.5−7.6 signal events with a significance above 5 standard deviations including systematic uncertainty

$$\mathrm{BF}\,(B_s^0 \to K^0\,\overline{K}^0) = \left(19.6^{+5.8}_{-5.1}\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}) \pm 2.0\,\left(N_{B_s^0\,\overline{B}_s^0}\right)\right) \times 10^{-6}$$

PRL 116, 161801 (2016)

- ➢ Result is in agreement with the SM value
- ➢ Expect over 1000 of these decays at Belle II ➔ could perform a much higher sensitive search

Summary and Outlook

- ❑ Despite being in the tail mode (>5 years passed since their data taking), Belle and BaBar are producing high-quality physics results

- ❑ All results on hadronic B decays presented here are consistent with SM predictions

- ❑ With Belle II being very much in sight (2018), future looks brighter for flavour enthusiasts

Bright Futures

➢ See talks of J.-G. Shiu and M. Nayak

✧ One last slide

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TIFR, Mumbai

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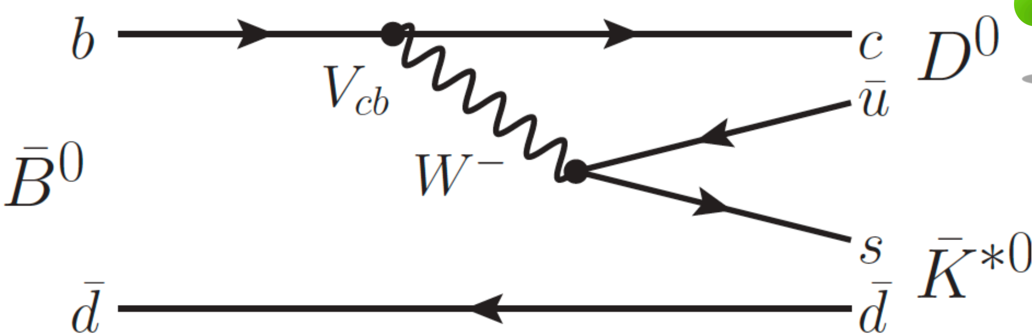
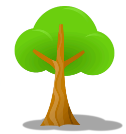
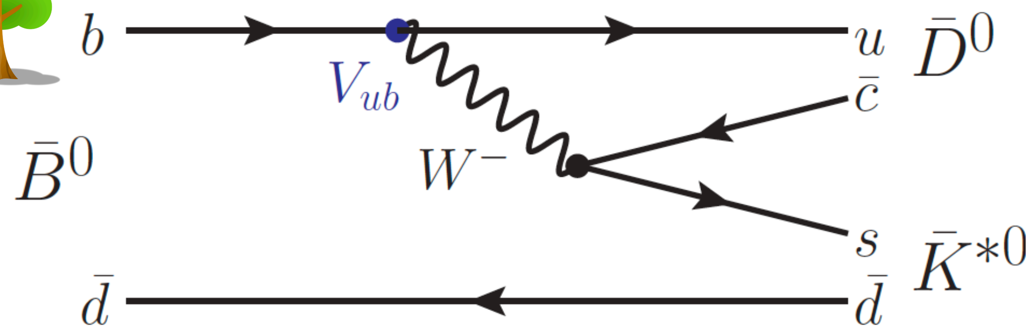
Image: https://en.wikipedia.org/wiki/Bandra-Worli_Sea_Link,Newscenter.phillips.com
Designed by Saurabh Sandilya

Bonus Materials

First model-independent analysis of $B^0 \rightarrow DK^{*0}$







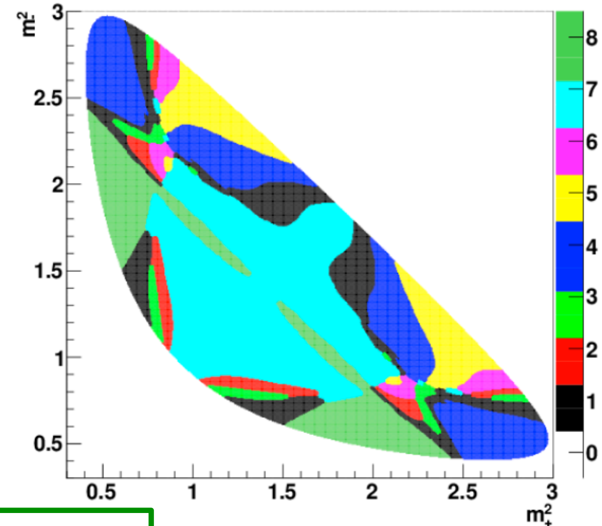
- Towards extraction of the UT angle ϕ_3, we measure the ratio of decay amplitudes of $B^0 \rightarrow D^0K^{*0}$ and $B^0 \rightarrow D^0K^{*0}$ with a model-independent (MI) study
- B-meson flavor is identified by the charged kaon coming from K^{*0}, while the (untagged) D mesons are reconstructed in the $K_S\pi^+\pi^-$ channel
- To model the strong dynamics of the decay, use:

Gronau, PLB 557, 198 (2003)

$$r_S^2 \equiv \frac{\Gamma(B^0 \to D^0 K^+ \pi^-)}{\Gamma(B^0 \to \bar{D}^0 K^+ \pi^-)} = \frac{\int \mathrm{d}p A^2_{b\to u}(p)}{\int \mathrm{d}p A^2_{b\to c}(p)} \qquad k e^{i\delta_S} \equiv \frac{\int \mathrm{d}p A_{b\to c}(p) A_{b\to u}(p) \mathrm{e}^{i\delta(p)}}{\sqrt{\int \mathrm{d}p A^2_{b\to c}(p) \int \mathrm{d}p A^2_{b\to u}(p)}}$$

> Here A is the magnitude of the amplitude of the given transition and δ is the relative strong phase across the $DK^+\pi^-$ Dalitz plot

Results from the MI analysis of $B^0 \to DK^{*0}$



- Amplitude of $B^0 \to DK^{*0}$, $D \to K_S\pi^+\pi^-$ over the DP:

$$A_B(m_+^2, m_-^2) = \bar{A} + r_S e^{i(\delta_S+\phi_3)} A$$

Subscript ± denotes the $K_S\pi^\pm$ combination, and A ($\bar{A}$) is the amplitude for $D = D^0$ ($\bar{D}^0$)

- Defining $x_\pm = r_S \cos(\delta_S \pm \phi_3)$ and $y_\pm = r_S \sin(\delta_S \pm \phi_3)$, the DP distribution density can be given by

$$\boxed{P_B = |A_B|^2 = |\bar{A} + r_S e^{i(\delta_S+\phi_3)} A|^2 = \bar{P} + r_S^2 P + 2k\sqrt{P\bar{P}}(x_+ C + y_+ S)}$$

- In the MI approach, expected number of events in the i^{th} bin of DP:

$$\boxed{N_i^\pm = h_B \left[K_{\pm i} + r_S^2 K_{\mp i} + 2k\sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i)\right]}$$

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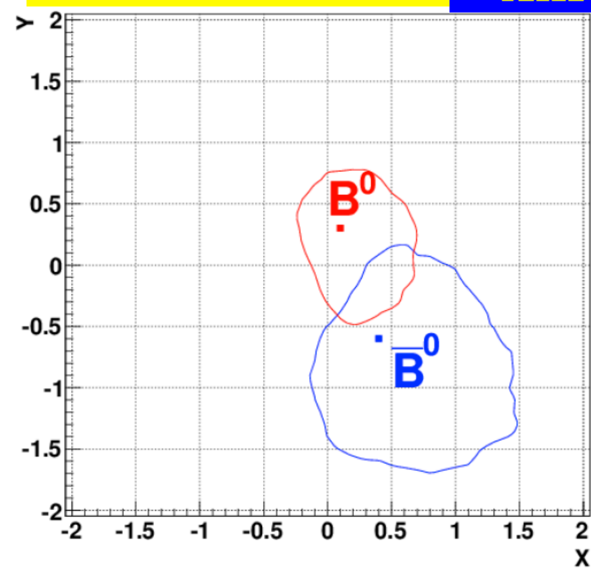
✧ K_i is no. events in the i^{th} bin of a flavor-tagged $D^0 \to K_S\pi^+\pi^-$ sample

✧ Strong-phase parameters c_i and s_i from CLEO

$$\begin{aligned}
x_- &= +0.4^{+1.0+0.0}_{-0.6-0.1} \pm 0.0 \\
y_- &= -0.6^{+0.8+0.1}_{-1.0-0.0} \pm 0.1 \\
x_+ &= +0.1^{+0.7+0.0}_{-0.4-0.1} \pm 0.1 \\
y_+ &= +0.3^{+0.5+0.0}_{-0.8-0.1} \pm 0.1 \\
r_S &< 0.87 \text{ at } 68\% \text{ C.L.}
\end{aligned}$$



➢ Last errors are due to the (c_i, s_i) precision