Charmless hadronic B decays from Belle

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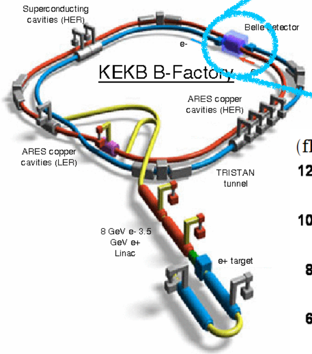
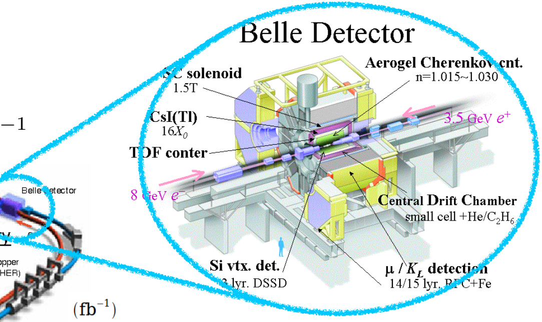
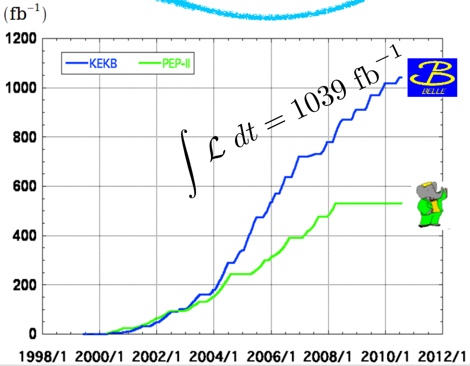
DPF 2013

16 countries
68 institutes
~400 members

$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$







> 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}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Motivation for rare B decays

- SM is a very good approx. for reality
  i.e. $A_{\text{Nature}} \simeq A_{\text{SM}}$ for most processes
- Need to look where A_{SM} is small, in order to be sensitive to NP
  * Study **rare decays**
  * Compare A_{Nature} with A_{SM},
    $\Rightarrow$ find new physics or learn new lessons!
- $b \to c$ decays take $\mathcal{O}(99\%)$ of all B decays
  The others ($b \to s,\ u,\ d$, or $b \to NP$) are *charmless* and *rare*.

Motivation for hadronic rare B decays

- Belle has excellent hadron identifications for $\pi^{\pm}$, π^0, $K^{\pm}$, K_S^0, p $(\bar{p})$ and for $\ell^{\pm}$ and γ, as well

  * Hadron ID facilities (Cherenkov, TOF, dE/dx for charged; EM Cal for π^0) are optimized for momentum ranges of the particles produced from B decays at Belle
  * Typically, $\epsilon \sim 90\%$ and $f \lesssim 10\%$ for charged hadrons
  * Also, very good performance for π^0

$\therefore$ Hadronic B decays (*incl.* π^0) can be reconstructed (*fully*) with high efficiency and purity $\Rightarrow$ experimentally, very clean!

- Charmless hadronic B decays usually have interference between $b \to u$ tree and $b \to s(d)$ penguin diagram processes

$\Rightarrow$ sensitive to CPV *Remember CKM is not sufficient for the CPV in our universe!*

- Some puzzles in rare hadronic B decays

  * "$K\pi$ puzzle" (Nature 452, 332 (2008); PRD 87, 031103(R) (2013))
  * "$V\,V$ puzzle" $f_L \sim 1$ (*or not*) in $B \to V\,V$ decays?

Outline

0. Motivations

1. $B^0 \to \phi K^*$

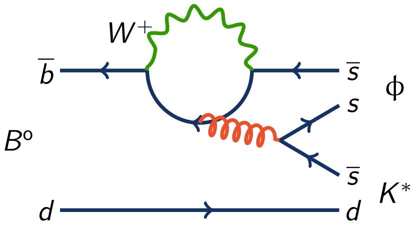
   * partial wave analysis for $J = 0,\ 1,\ 2$ states of K^*
   * search for CPV
   * arXiv:1308.1830, *submitted to PRD*

2. $B^0 \to K^+ K^- \pi^0$

   * first evidence of the decay
   * study of substructures
   * PRD **87**, 091101(R) (2013)

In both analyses, the full Belle data sample on the $\Upsilon(4S)$ resonance are used:
$\int \mathcal{L}\, dt \approx 711\ \mathrm{fb}^{-1},\ N_{B\overline{B}} = (772 \pm 11) \times 10^6$.

$B^0 \to \phi\, K^*$ – introduction



- Decays dominantly via $b \to s$ penguin process in the SM
  $\therefore$ negligible direct CPV in SM, i.e. a good place to look for CPV in NP

- $B \to V\, V \;\; \Rightarrow f_L \sim 1$ is expected by naive factorization hypothesis, *but*

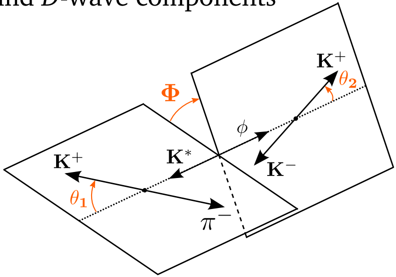
  $B^0 \to \phi\, K^*(892)^0 \quad f_L = 0.45 \pm 0.05 \pm 0.02$ Belle, PRL 94, 221804 (2005)
  $f_L = 0.494 \pm 0.034 \pm 0.013$ BaBar, PRD 78, 092008 (2008)

  $B^0 \to \phi\, K_2^*(1430)^0 \quad f_L = 0.901^{+0.046}_{-0.058} \pm 0.037$ BaBar, PRD 78, 092008 (2008)

$B^0 \to \phi\, K^*$ – analysis action plan

- Partial wave analysis of $B^0 \to \phi\, K^*$ with $K^* \to K^+\pi^-$ including
  - $J = 0$ (S-wave) $(K\pi)$ "scalar"
  - $J = 1$ (P-wave) $K^*(892)^0$ "vector"
  - $J = 2$ (D-wave) $K_2^*(1430)^0$ "tensor"
- Analysis, restricted to $M(K\pi) < 1.55$ GeV/c^2
  - LASS model for S-wave component (*incl.* $K_0^*(1430)$)
  - Rel. spin-dep. Breit-Wigner for P- and D-wave components
- Describe angular dist. in the helicity base, with angles $\theta_1,\ \theta_2,\ \Phi$
- Simultaneous fits to B^0 and $\overline{B}^0$ for CPV search

  $\Rightarrow$ extract 26 real parameters from the fits to 9 observables



$B^0 \to \phi\, K^*$ – physics parameters to extract

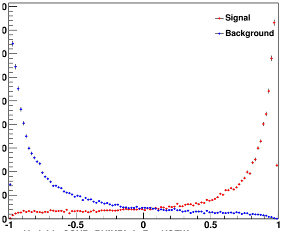
- $\exists$ 28 real parameters ($= 2 \times 2 \times 7$ complext amplitudes $A_0, A_{1\lambda}, A_{2\lambda}$; $\lambda = 0,\ \pm 1$), but overal phase can be fixed
- $\Delta\phi_{00} = (1/2)\arg(A_{00}/\bar{A}_{00})$ is only accessible in $B \to \phi K^0_S \pi^0$ CPV analysis; set $\Delta\phi_{00} = 0$ leaving only 26 parameters

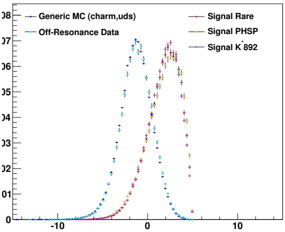
Parameter	Definition	$\phi(K\pi)^*_0$ $J=0$	$\phi K^*(892)^0$ $J=1$	$\phi K^*_2(1430)^0$ $J=2$
$\mathcal{B}_J$	$\frac{1}{2}(\bar{\Gamma}_J + \Gamma_J)/\Gamma_{\text{total}}$	$\mathcal{B}_0$	$\mathcal{B}_1$	$\mathcal{B}_2$
f_{LJ}	$\frac{1}{2}(\lvert\bar{A}_{J0}\rvert^2/\sum\lvert\bar{A}_{J\lambda}\rvert^2 + \lvert A_{J0}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2)$	–	f_{L1}	f_{L2}
$f_{\perp J}$	$\frac{1}{2}(\lvert\bar{A}_{J\perp}\rvert^2/\sum\lvert\bar{A}_{J\lambda}\rvert^2 + \lvert A_{J\perp}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2)$	–	$f_{\perp 1}$	$f_{\perp 2}$
$\phi_{\parallel J}$	$\frac{1}{2}(\arg(\bar{A}_{J\parallel}/\bar{A}_{J0}) + \arg(A_{J\parallel}/A_{J0}))$	–	$\phi_{\parallel 1}$	$\phi_{\parallel 2}$
$\phi_{\perp J}$	$\frac{1}{2}(\arg(\bar{A}_{J\perp}/\bar{A}_{J0}) + \arg(A_{J\perp}/A_{J0}) - \pi)$	–	$\phi_{\perp 1}$	$\phi_{\perp 2}$
δ_{0J}	$\frac{1}{2}(\arg(\bar{A}_{00}/\bar{A}_{J0}) + \arg(A_{00}/A_{J0}))$	–	δ_{01}	δ_{02}
$\mathcal{A}_{CPJ}$	$(\bar{\Gamma}_J - \Gamma_J)/(\bar{\Gamma}_J + \Gamma_J)$	$\mathcal{A}_{CP0}$	$\mathcal{A}_{CP1}$	$\mathcal{A}_{CP2}$
$\mathcal{A}^0_{CPJ}$	$\frac{\lvert\bar{A}_{J0}\rvert^2/\sum\lvert\bar{A}_{J\lambda}\rvert^2 - \lvert A_{J0}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}{\lvert\bar{A}_{J0}\rvert^2/\sum\lvert\bar{A}_{J\lambda}\rvert^2 + \lvert A_{J0}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}$	–	$\mathcal{A}^0_{CP1}$	$\mathcal{A}^0_{CP2}$
$\mathcal{A}^\perp_{CPJ}$	$\frac{\lvert\bar{A}_{J\perp}\rvert^2/\sum\lvert\bar{A}_{J\lambda}\rvert^2 - \lvert A_{J\perp}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}{\lvert\bar{A}_{J\perp}\rvert^2/\sum\lvert\bar{A}_{J\lambda}\rvert^2 + \lvert A_{J\perp}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}$	–	$\mathcal{A}^\perp_{CP1}$	$\mathcal{A}^\perp_{CP2}$
$\Delta\phi_{\parallel J}$	$\frac{1}{2}(\arg(\bar{A}_{J\parallel}/\bar{A}_{J0}) - \arg(A_{J\parallel}/A_{J0}))$	–	$\Delta\phi_{\parallel 1}$	$\Delta\phi_{\parallel 2}$
$\Delta\phi_{\perp J}$	$\frac{1}{2}(\arg(\bar{A}_{J\perp}/\bar{A}_{J0}) - \arg(A_{J\perp}/A_{J0}) - \pi)$	–	$\Delta\phi_{\perp 1}$	$\Delta\phi_{\perp 2}$
$\Delta\delta_{0J}$	$\frac{1}{2}(\arg(\bar{A}_{00}/\bar{A}_{J0}) - \arg(A_{00}/A_{J0}))$	–	$\Delta\delta_{01}$	$\Delta\delta_{02}$

$B^0 \to \phi K^*$ – experimental observables

- Reconstruct $B^0 \to \phi K^*$ with $\phi \to K^+K^-$ and $K^* \to K^+\pi^-$
- 9D fit to B^0 and $\overline{B}^0$
  - * $M_{\rm bc},\ \Delta E$ – the two most characteristic variables for B decays
  - * $M_{KK},\ M_{K\pi}$
  - * $C'_{\rm NB}$ – neural network output for continuum suppression
  - * $\theta_1,\ \theta_2,\ \Phi$ – the three helicity angles
  - * Q – charge of K from K^*

$$C_{\rm NB} \Longrightarrow C'_{\rm NB} = \ln\left(\frac{C_{\rm NB}}{1 - C_{\rm NB}}\right)$$





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  - * $C'_{\rm NB}$ – neural network output for continuum suppression
  - * $\theta_1,\ \theta_2,\ \Phi$ – the three helicity angles
  - * Q – charge of K from K^*
- 3 components included in the fit
  - * Signal
  - * peaking background from $B^0 \to f_0(980)K^*(892)^0$
  - * combinatorial bkgd. (= continuum + other $B\overline{B}$)

$B^0 \to \phi\, K^*$ – Results

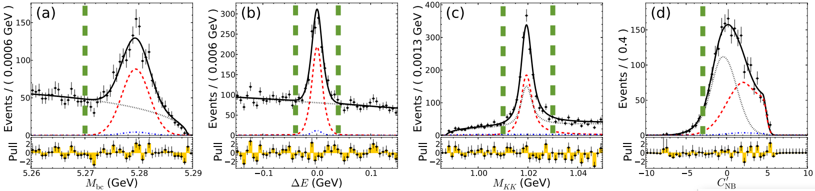


FIG. 4: Projections onto the observable (a) $M_{\rm bc}$, (b) ΔE, (c) M_{KK}, and (d) $C'_{\rm NB}$ for $B^0 \to \phi(K^+\pi^-)^*$ and
combined. The data distributions are shown by black markers with error bars whereas the overall fit funct

Total PDF
Continuum
$B^0 \to f_0\ K^*$
$B^0 \to \phi\ K^*$

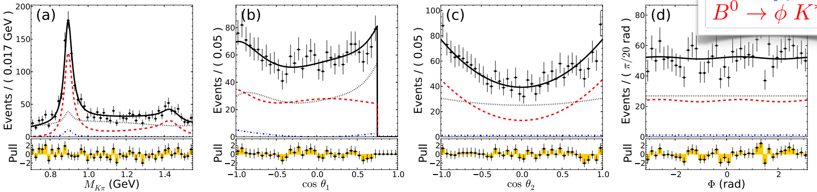


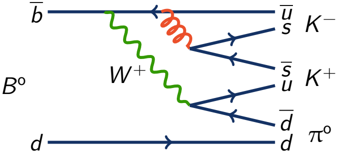
FIG. 5: Projections onto the observables (a) $M_{K\pi}$, (b) $\cos\theta_1$, (c) $\cos\theta_2$, and (d) Φ for $B^0 \to \phi(K^+\pi^-)^*$ and $\bar{B}^0 \to \phi(K^-\pi^+)^*$
combined. The data distributions are shown by black markers with error bars whereas the overall fit function, combinatorial

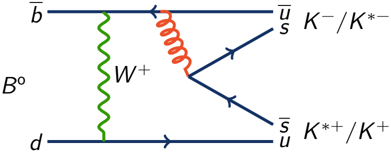
$B^0 \to \phi K^*$ – Results

Parameter	$\phi(K\pi)^*_0$ $J=0$	$\phi K^*(892)^0$ $J=1$	$\phi K^*_2(1430)^0$ $J=2$
FF_J	$0.273 \pm 0.024 \pm 0.021$	$0.600 \pm 0.020 \pm 0.015$	$0.099^{+0.016}_{-0.012} \pm 0.018$
f_{LJ}	$\cdots$	$0.499 \pm 0.030 \pm 0.018$	$0.918^{+0.029}_{-0.060} \pm 0.012$
$f_{\perp J}$	$\cdots$	$0.238 \pm 0.026 \pm 0.008$	$0.056^{+0.050}_{-0.035} \pm 0.009$
$\phi_{\parallel J}$ (rad)	$\cdots$	$2.23 \pm 0.10 \pm 0.02$	$3.76 \pm 2.88 \pm 1.32$
$\phi_{\perp J}$ (rad)	$\cdots$	$2.37 \pm 0.10 \pm 0.04$	$4.45^{+0.43}_{-0.38} \pm 0.13$
δ_{0J} (rad)	$\cdots$	$2.91 \pm 0.10 \pm 0.08$	$3.53 \pm 0.11 \pm 0.19$
$\mathcal{A}_{CPJ}$	$0.093 \pm 0.094 \pm 0.017$	$-0.007 \pm 0.048 \pm 0.021$	$-0.155^{+0.152}_{-0.133} \pm 0.033$
$\mathcal{A}^0_{CPJ}$	$\cdots$	$-0.030 \pm 0.061 \pm 0.007$	$-0.016^{+0.066}_{-0.051} \pm 0.008$
$\mathcal{A}^\perp_{CPJ}$	$\cdots$	$-0.14 \pm 0.11 \pm 0.01$	$-0.01^{+0.85}_{-0.67} \pm 0.09$
$\Delta\phi_{\parallel J}$ (rad)	$\cdots$	$-0.02 \pm 0.10 \pm 0.01$	$-0.02 \pm 1.08 \pm 1.01$
$\Delta\phi_{\perp J}$ (rad)	$\cdots$	$0.05 \pm 0.10 \pm 0.02$	$-0.19 \pm 0.42 \pm 0.11$
$\Delta\delta_{0J}$ (rad)	$\cdots$	$0.08 \pm 0.10 \pm 0.01$	$0.06 \pm 0.11 \pm 0.02$
N_J (events)	$303 \pm 29 \pm 25$	$668 \pm 34 \pm 24$	$110^{+18}_{-14} \pm 20$
$\epsilon_{\mathrm{reco},J}$ (%)	28.7 ± 0.1	26.0 ± 0.1	16.3 ± 0.1
ϵ_J (%)	9.4 ± 0.1	8.5 ± 0.1	2.6 ± 0.1
$\mathcal{B}_J$ (10^{-6})	$4.3 \pm 0.4 \pm 0.4$	$10.4 \pm 0.5 \pm 0.6$	$5.5^{+0.9}_{-0.7} \pm 1.0$

- *BF and polarization parameters are consistent with existing results*
- *all CPV parameters are consistent with zero direct CPV*

$B^0 \to K^+K^-\pi^0$ – introduction





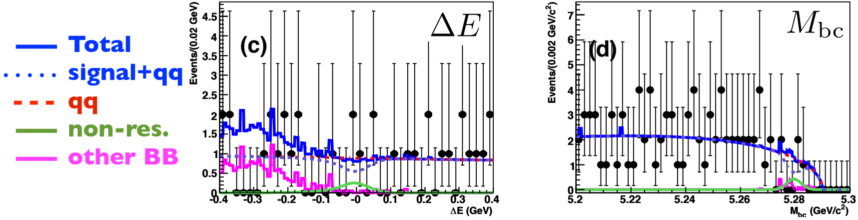
- Decays occur via $b \to u$ color-suppressed or W exchange diagrams
  $\therefore$ strongly suppressed in SM

$$\mathcal{B}_{\rm SM}(B^0 \to K^{*\pm}K^{\mp}) \lesssim \mathcal{O}(10^{-7}), \;\; \mathcal{B}_{\rm SM}(B^0 \to \phi\pi^0) \sim \mathcal{O}(10^{-9})$$

- Existing limit:
  $\mathcal{B}(B^0 \to K^+K^-\pi^0) < 1.9 \times 10^{-5}$ by CLEO (PRL 89, 251801 (2002))
- No experimental information on resonance substructures are available
  e.g. $K^*(892)^{\pm}K^{\mp}$, $K_0^*(1430)^{\pm}K^{\mp}$, $f_0(980)\pi^0$

Reminder – *a related result*

$B^0 \to \phi\pi^0$ PRD 86, 031102(R), (2012)

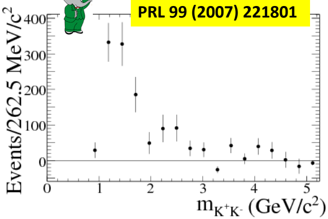


$$\mathcal{B}(B^0 \to \phi\pi^0) < 1.5 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

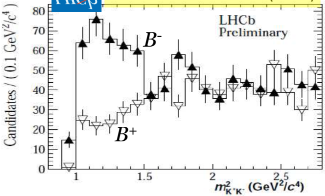
some puzzles in $M_{K^+K^-}$

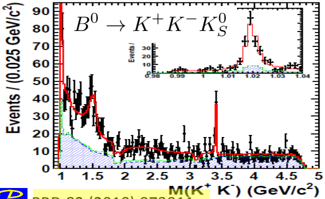
$B^\pm \to K^+K^-\pi^\pm$

PRL 99 (2007) 221801

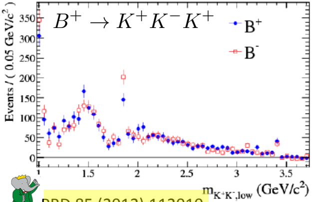


LHCb-CONF-2012-028 (2012)





PRD 82 (2010) 073011

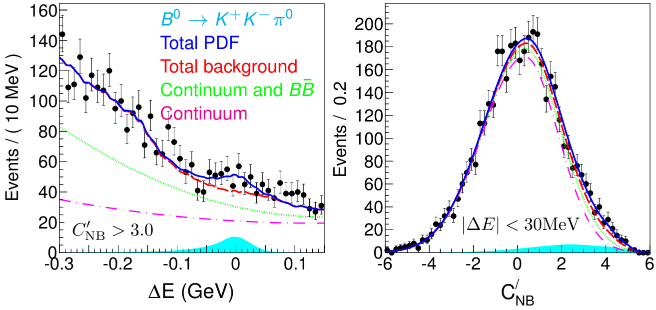


PRD 85 (2012) 112010

A peak at $M_{KK} \sim 1.5$ GeV/c^2? $A_{CP} \neq 0$ in the LHCb result?

$B^0 \to K^+K^-\pi^0$ – Results

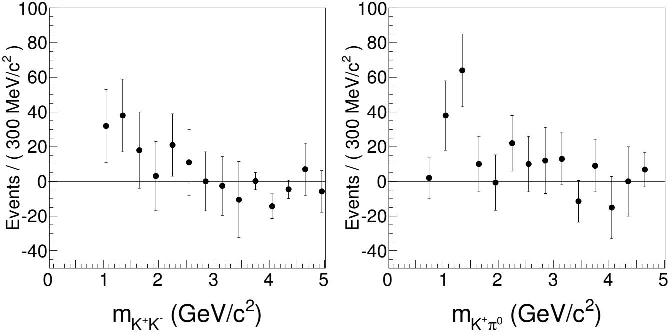
- Neural-net-based suppression of $e^+e^- \to q\bar{q}$ continuum $\Rightarrow C'_{\rm NB}$
- Select $\pm 3\sigma$ region of $M_{\rm bc}$: $5.271 < M_{\rm bc} < 5.287$ GeV/c^2
- 2D fit on ΔE and $C'_{\rm NB}$ with the components:



$$N_{\rm sig} = 299 \pm 83, \quad \mathcal{B}(B^0 \to K^+K^-\pi^0) = (2.17 \pm 0.60 \pm 0.24) \times 10^{-6} \quad (3.5\sigma)$$

First evidence!

$B^0 \to K^+K^-\pi^0$ – Resonance substructure?



- Signal yields fitted in $M_{K^+K^-}$ and $M_{K^+\pi^0}$ bins
- Nothing definitely stated about $M_{KK} \sim 1.5\mathrm{GeV}/c^2$ structure observed by BaBar and LHCb
- Excess of events in $M_{K^+\pi^0} \sim 1.4\mathrm{GeV}/c^2$
  Amplitude analysis with much more statistics is required $\Rightarrow$ Belle II

Closing words

- Partial wave analysis of $B^0 \to \phi\, K^*$ and search for CPV
  - * BF and polarizations consistent with existing results

    $\mathcal{B}(B^0 \to \phi\,(K\pi)^*_0) = (4.3 \pm 0.4 \pm 0.3) \times 10^{-6}$
    $\mathcal{B}(B^0 \to \phi\, K^*(892)^0) = (10.4 \pm 0.5 \pm 0.5) \times 10^{-6}$
    $\mathcal{B}(B^0 \to \phi\, K^*_2(1430)^0) = (5.5^{+0.9}_{-0.7} \pm 0.7) \times 10^{-6}$

    $f_L = 0.499 \pm 0.030 \pm 0.018 \quad (\phi\, K^*)$
    $f_L = 0.918^{+0.029}_{-0.060} \pm 0.012 \quad (\phi\, K^*_2(1430)^0)$
  - * No evidence for *CP* violation
- $B^0 \to K^+K^-\pi^0$
  - * First evidence with 3.5σ significance

    $\mathcal{B}(B^0 \to K^+K^-\pi^0) = (2.17 \pm 0.60 \pm 0.24) \times 10^{-6}$
  - * No definite statement on the substructures $\Rightarrow$ **Belle II**
    $\to$ *Sven Vahsen's talk tomorrow @ QLF-I*