

# Measurements of electroweak penguin and leptonic $B_{(s)}$ decays at Belle

ICHEP 2016

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*for the Belle Collaboration*

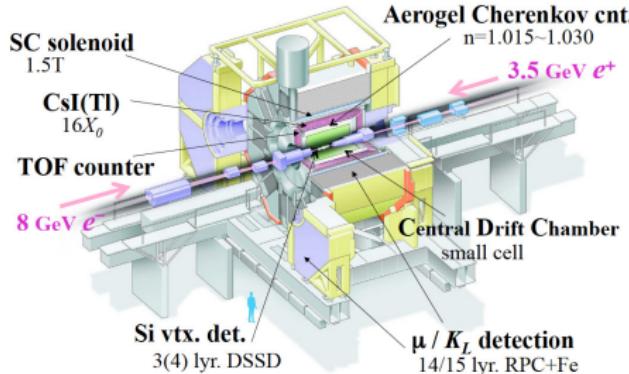


Institute of High Energy Physics  
Austrian Academy of Sciences

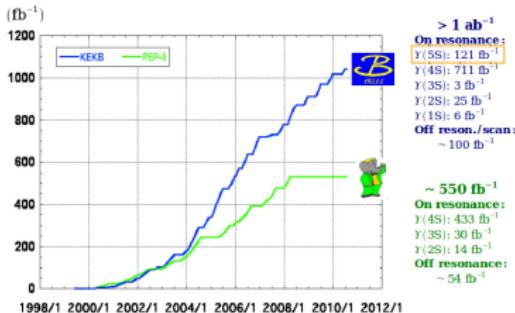
FWF Project  
P26794-N20

August 6th, 2016

# The Belle experiment



## Integrated luminosity of B factories



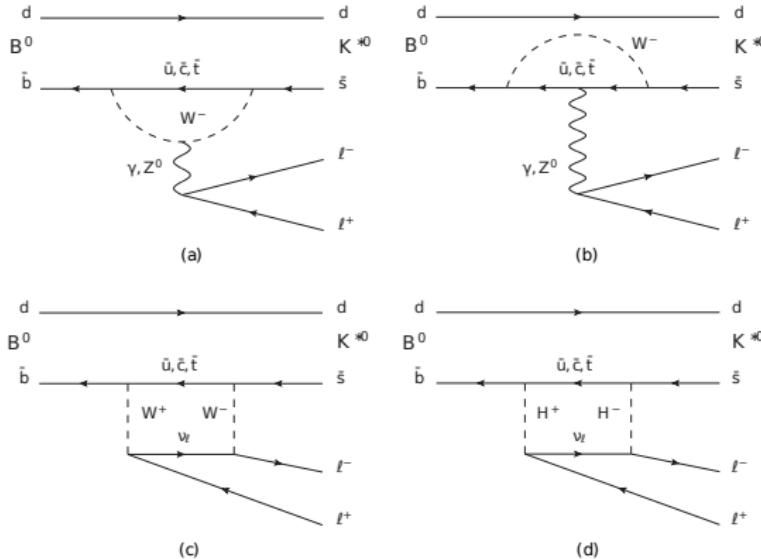
## Data sample:

- $711 \text{ fb}^{-1}$  @  $\Upsilon(4S)$   
 $\rightarrow 772 \times 10^6 B\bar{B}$  pairs
- $121.4 \text{ fb}^{-1}$  @  $\Upsilon(5S)$   
 $\rightarrow 7.1 \times 10^6 B_s\bar{B}_s$  pairs

## Outline:

- Angular analysis  
 $B^0 \rightarrow K^*(892)^0 \ell^+\ell^-$
- $B_s^0$  hadronic tag

# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Introduction



Belle Collaboration conference

paper arXiv:1604.04042 [hep-ex]

- a, b and c: SM processes
- d: non-SM with charged Higgs

LHCb reports  $3.4\sigma$  deviation from Standard Model prediction in angular distribution of  $B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-$

JHEP 02, 104 (2016), arXiv:1512.04442 [hep-ex]



# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Reconstruction

## charged tracks:

- distance to IP required to be  $|dr| < 1.0 \text{ cm}$  and  $|dz| < 5.0 \text{ cm}$
- particle identification based on CDC, TOF, ACC, ECL and KLM information

## B meson candidates:

- $\Delta E = E_B^* - E_{\text{beam}}$  and  
 $M_{bc} = \sqrt{E_{\text{beam}}^2 - (p_B^*)^2}$
- $-0.1 \text{ } (-0.05) \text{ GeV} < \Delta E < 0.05 \text{ GeV}$  for  $\ell = e$  ( $\ell = \mu$ ) and  
 $5.22 \text{ GeV} < M_{bc} < 5.3 \text{ GeV}$

## $K^{*0} \rightarrow K^+ \pi^-$ :

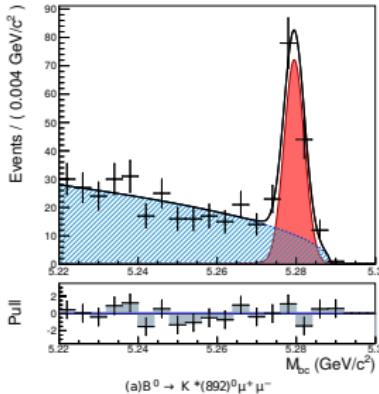
- invariant mass  
 $0.6 \text{ GeV} < M_{K^*} < 1.4 \text{ GeV}$

## Background suppression:

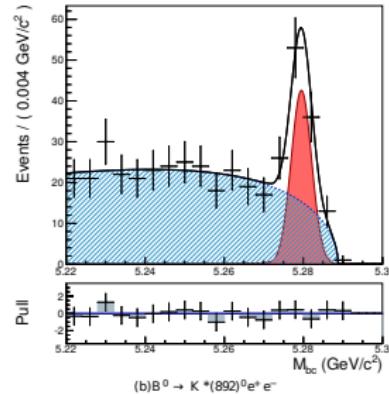
- $B^0 \rightarrow K^{(*)} J/\psi$  and  
 $B^0 \rightarrow K^{(*)} \psi(2S)$  vetoed by selection on  $M_{\ell^+ \ell^-}$
- Neural networks used sequentially from bottom to top of the decay chain, transferring network output

# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Signal extraction

- unbinned extended maximum likelihood fit
- signal: Crystal Ball function
- background: Argus function



(a)  $B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-$



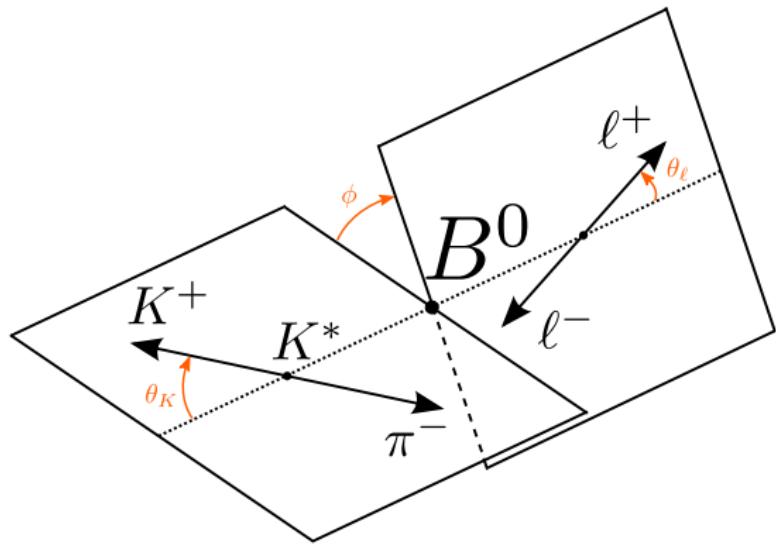
(b)  $B^0 \rightarrow K^*(892)^0 e^+ e^-$

Bin	$q^2 [\text{GeV}^2]$	signal	background
0	1.00 – 6.00	$49.5 \pm 8.4$	$30.3 \pm 5.5$
1	0.10 – 4.00	$30.9 \pm 7.4$	$26.4 \pm 5.1$
2	4.00 – 8.00	$49.8 \pm 9.3$	$35.6 \pm 6.0$
3	10.09 – 12.90	$39.6 \pm 8.0$	$19.3 \pm 4.4$
4	14.18 – 19.00	$56.5 \pm 8.7$	$16.0 \pm 4.0$
total	total range	$118 \pm 12$	$69 \pm 12$

# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Angular analysis

$\theta_\ell$ : angle between direction of  $\ell^+$  ( $\ell^-$ ) and opposite direction of  $B$  ( $\bar{B}$ ) in rest frame of dilepton system

$\theta_K$ : angle between direction of kaon and opposite direction of  $B$  ( $\bar{B}$ ) in  $K^*$  rest frame



definitions follow JHEP 08, 131 (2013)

$\phi$ : angle between decay plane formed by  $\ell^+ \ell^-$  and  $K^*$  decay plane

# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Angular observables

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \right.$$

$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$

$$\begin{aligned} &+ \frac{1}{4}(1-F_L)\sin^2\theta_K \cos 2\theta_\ell \\ &- F_L\cos^2\theta_K \cos 2\theta_\ell + S_3\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi \\ &+ S_4\sin 2\theta_K \sin 2\theta_\ell \cos\phi + S_5\sin 2\theta_K \sin\theta_\ell \cos\phi \\ &+ S_6\sin^2\theta_K \cos\theta_\ell + S_7\sin 2\theta_K \sin\theta_\ell \sin\phi \\ &\left. + S_8\sin 2\theta_K \sin 2\theta_\ell \sin\phi + S_9\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right] \end{aligned}$$

- $F_L$  and  $S_i$  functions of  $q^2$
- eight free parameters

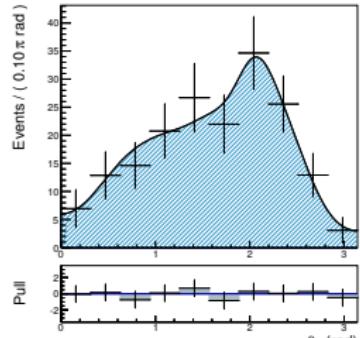
$$P'_5, S_5 : \begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

## Folding technique:

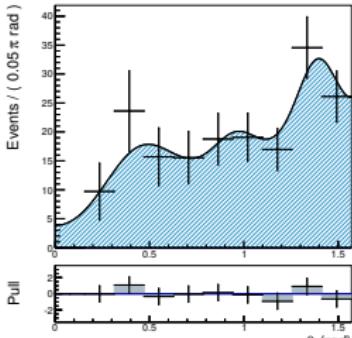
- not enough statistics to perform eight-dimensional fit
- use symmetries of  $\sin$  and  $\cos$  to cancel terms
- reduce number of free parameters to 3:  $F_L$ ,  $S_3$  and  $S_i$  or  $P'_i$

JHEP 01, 019 (2009) / JHEP 1305, 137 (2013) / Phys. Rev. Lett. 111, 191801 (2013) / Cian, Track Reconstruction Efficiency and Analysis of  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  at the LHCb Experiment, Ph.D. thesis, University of Zurich (2013)

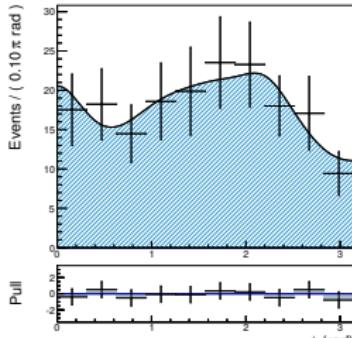
# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Fit projections



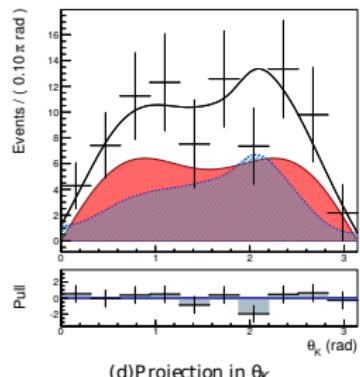
(a)Projection in  $\theta_K$



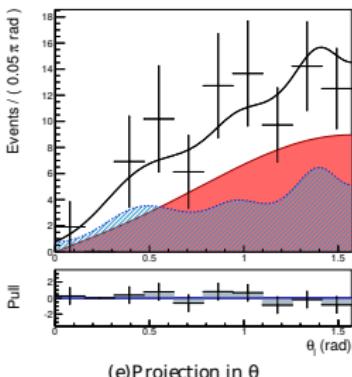
(b)Projection in  $\theta$



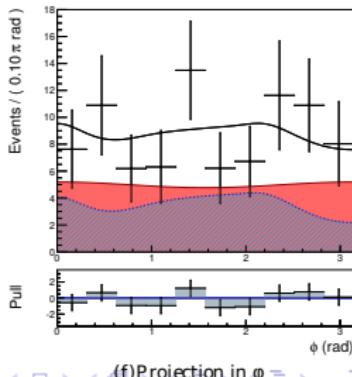
(c)Projection in  $\phi$



(d)Projection in  $\theta_K$

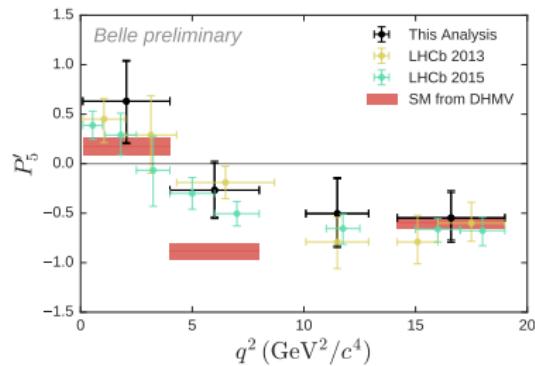
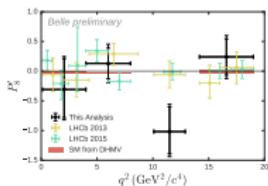
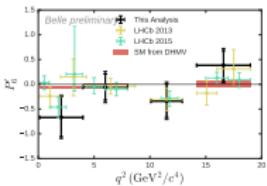
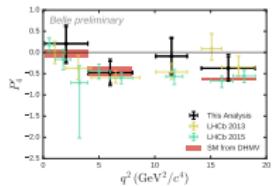


(e)Projection in  $\theta$



(f)Projection in  $\phi$

# $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$ : Results

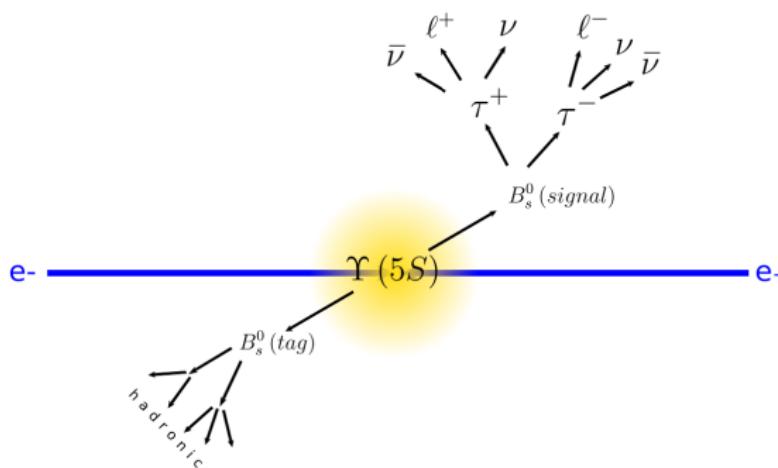


- results consistent with LHCb
- $P'_5$  shows  $2.1\sigma$  deviation from DHMV SM prediction in  $4.0 \text{ GeV}^2 < q^2 < 8.0 \text{ GeV}^2$
- published as Belle conference paper [arXiv:1604.04042 \[hep-ex\]](https://arxiv.org/abs/1604.04042)

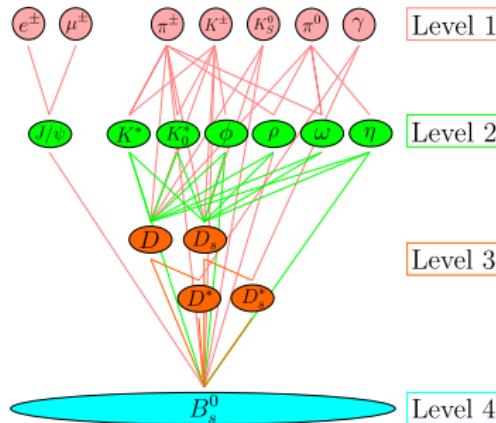
# $B_s^0$ hadronic tag: Introduction

- Belle experiment very successful with hadronic  $B_s^0$  decay modes
- however, neutrinos in (leptonic and semi-leptonic) final states not detected
- hadronic tagging already applied successfully on  $\Upsilon(4S)$  data

*Nucl. Instrum. Meth. A 654, 432-440 (2011)*



# $B_s^0$ hadronic tag: Software architecture



$B_s^0$  tag includes

- $> 5000$  exclusive  $B_s^0$  decay modes
- $> 100$  neural networks (NN); one for every particle and each decay mode

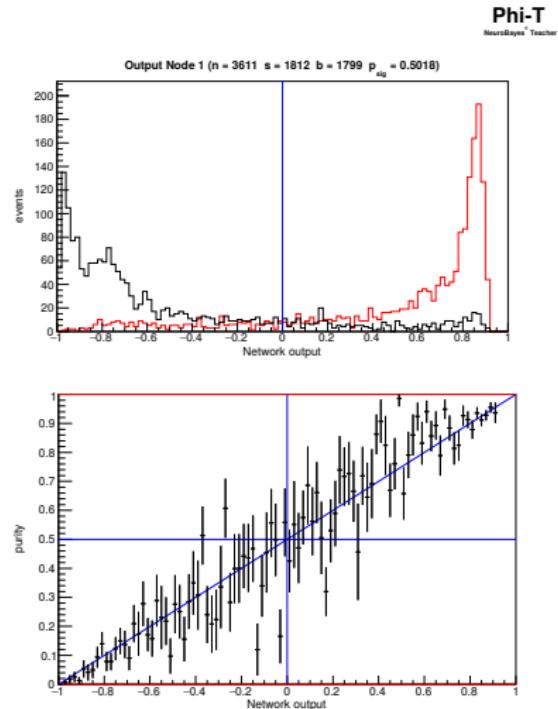
## selection criteria

- **Level 1:** particle identification for charged tracks; NN and energy cut on  $\gamma$  candidates; reconstruction of  $K_S^0 \rightarrow \pi^+ \pi^-$ ,  $\pi^0 \rightarrow \gamma \gamma$
- **Level 2 and 3:** cuts on invariant mass and NN output
- **Level 4:**
  - $-0.3 \text{ GeV} \leq \Delta E \leq 0.3 \text{ GeV}$
  - $M_{bc} \geq 5.2 \text{ GeV}$

# $B_s^0$ hadronic tag: Neural Networks

## Network training and output selection:

- important training variables: likelihood values from particle identification, network output of daughter particles,  $\Delta E$
- selection on network output for  $\gamma$  and level 2 particles optimized with  $FoM = \frac{S}{\sqrt{S+B}}$
- soft requirements on network output on level 3, no restrictions on level 4



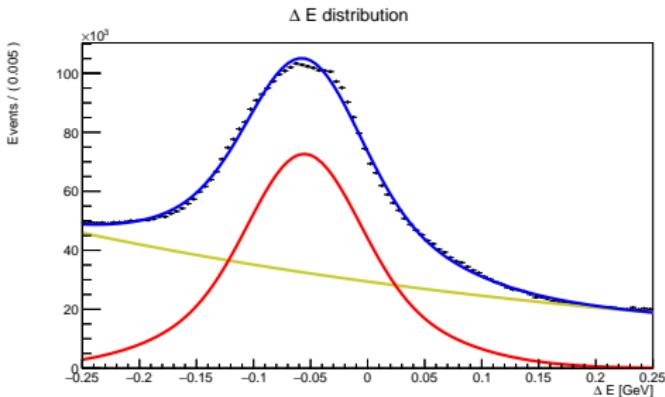
upper plots valid for  $B_s^0 \rightarrow D_s^* - \pi^+$

# $B_s^0$ hadronic tag: Efficiency

PRELIMINARY

## tag selection:

- network output for  $B_s^0$  daughter particles  $\geq 0$
- network output for  $B_s^0$  candidate  $\geq -0.5$
- $M_{bc} \geq 5.35 \text{ GeV}$
- event shape variable  $R_2 \leq 0.4$



- signal: double gaussian, same mean, different width
- background: exponential function

## Efficiency determination (work in progress)

2258340 signal events corresponding to  $\epsilon = 0.68\%$

# Summary

Angular analysis  $B^0 \rightarrow K^*(892)^0 \ell^+ \ell^-$  arXiv:1604.04042  
[hep-ex]

- results in agreement with LHCb studies
- eight free parameters for angular analysis
- folding technique reduces number of parameters to three without losing experimental sensitivity
- $P'_5$  shows  $2.1\sigma$  deviation from DHMV SM prediction in  $4.0 \text{ GeV}^2 < q^2 < 8.0 \text{ GeV}^2$

$B_s^0$  hadronic tag:

- hierarchical architecture with  $> 5000$   $B_s^0$  decay modes and  $> 100$  neural networks
- efficiency  $\epsilon = 0.68\%$  (**preliminary**, work in progress)
- opens field for new  $B_s^0$  analyses

Thank you for your  
attention.

# Backup

$$P'_4, S_4 : \begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \phi \rightarrow \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

$$P'_5, S_5 : \begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

$$P'_6, S_7 : \begin{cases} \phi \rightarrow \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \rightarrow -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

$$P'_8, S_8 : \begin{cases} \phi \rightarrow \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \rightarrow -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \rightarrow \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

