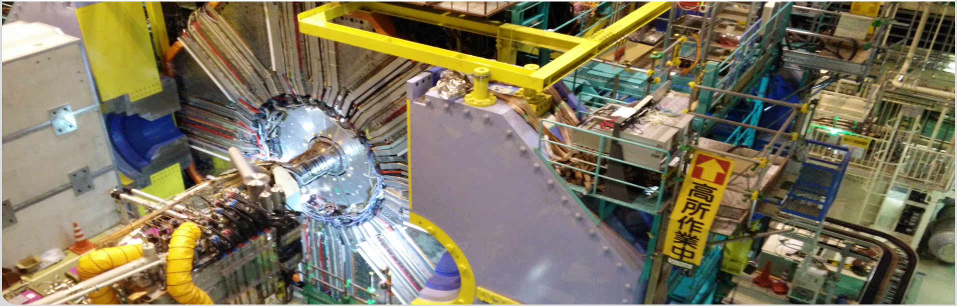
Karlsruhe Institute of Technology

$B^+ \to \ell^+ \nu_\ell \gamma$ at Belle

10th International Workshop on the CKM Unitarity Triangle

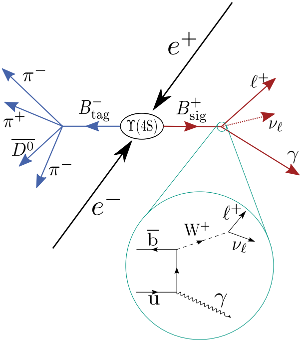
Moritz Gelb for the Belle Collaboration | 19.09.2018

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (ETP)



Introduction

- B meson pair is produced at the $\Upsilon(4S)$ resonance with no additional particles
- Measurement of missing energy modes possible
- New *tagging algorithm* for Belle II developed[a]
- Opposite B meson can now be reconstructed with higher efficiency compared to the Belle approach
- New method applied to (converted) Belle MC/data and later Belle II
- Update of the Belle hadronically tagged $B^+ \to \ell^+ \nu_\ell \gamma$ analysis[b]
- Determination of the first inverse moment λ_B of the light-cone distribution amplitude of the B meson



[a] arXiv:1807.08680 (2018)
[b] Phys. Rev. D 91, 112009 (2015)

The Decay $B^+ \to \ell^+ \nu_\ell \gamma$

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 m_B^4 |V_{ub}|^2}{48\pi^2} x_\gamma^3 (1 - x_\gamma)[F_A^2 + F_V^2]$$

Form Factors (valid for large photon energies)

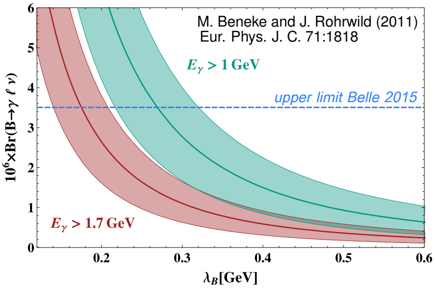
$$F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2}\right]$$

$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma}\right]$$

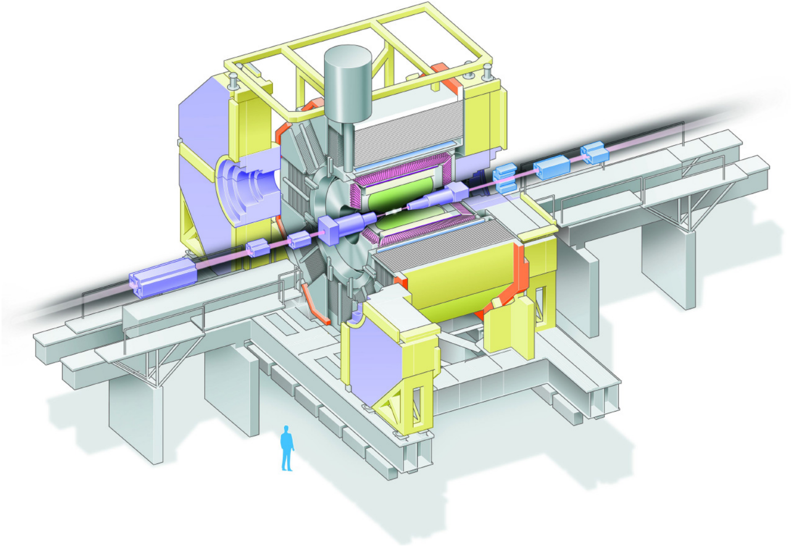
Previous Belle result (2015):

$$\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma) < 3.5 \cdot 10^{-6}$$

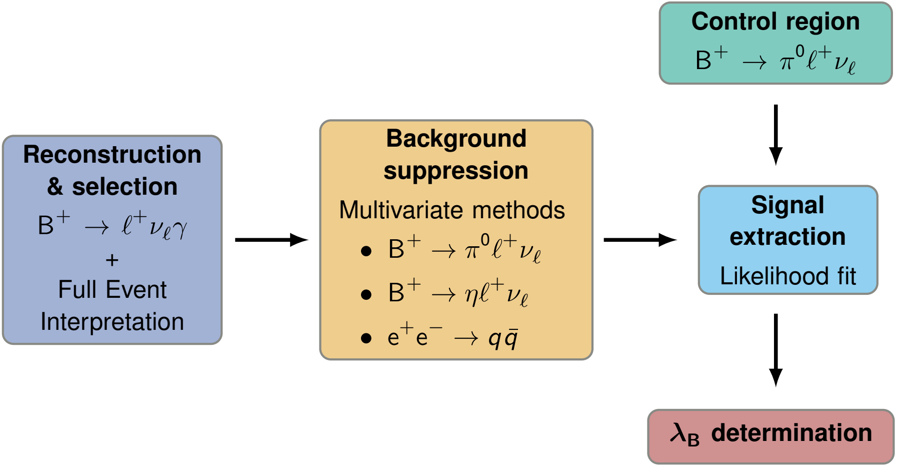
Method	λ_B (GeV)
QCD factorization	≈ 0.2
QCD sum rules	0.46 ± 0.11
BaBar (2009) (90% C.L.)	> 0.115
Belle (2015) (90% C.L.)	> 0.238



The Belle Detector

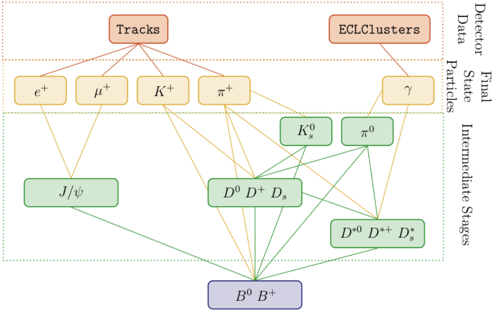


Analysis Strategy



The Tagging Algorithm: Full Event Interpretation

- Hierarchical reconstruction of $\mathrm{B}_{\mathrm{tag}}$ with a network of classifiers
- Successor of the Belle Full Reconstruction (FR)
- Training and application
- **Hadronic** and semi-leptonic tag modes
- *Generic FEI:*
  1) FEI trained and applied on full event
  2) Signal selection
- ***Signal-specific FEI*** *(new):*
  1) Signal selection
  2) FEI trained and applied on **rest-of-event** $\rightarrow$ trained on specific event topology
- Each $\mathrm{B}_{\mathrm{tag}}$ candidate has an assigned probability P_{FEI}



Tagging efficiency on MC

Tag	FR[1]	gen. FEI Belle	gen. FEI Belle II
Hadronic B^+	**0.28%**	**0.76%**	0.66%
SL B^+	0.67%	1.80%	1.45%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^0	0.63%	2.04%	1.94%

[1] Belle Full Reconstruction algorithm.

Calibration of the Tagging Algorithm

Why calibration?

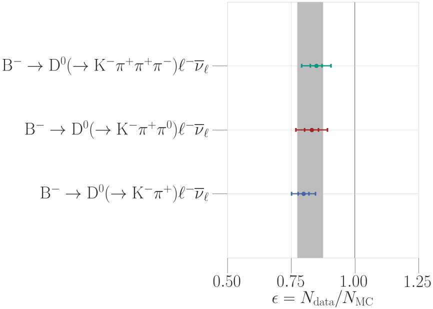
Difference in tagging efficiency on data and MC:

- Hadronic branching ratios
- Dynamics of hadronic decays
- Detector simulation
- ...

Procedure

1) Reconstruct B_{sig} in well-known channel
2) Apply tagging algorithm
3) Extract the number of events on MC and data via a fit on M^2_{miss}
4) Calculate the correction factor for calibration channel:

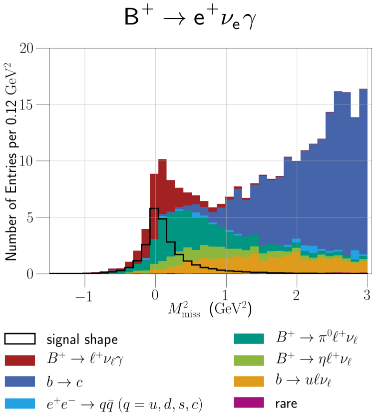
$$\epsilon = \frac{N_{Data}}{N_{MC}}$$

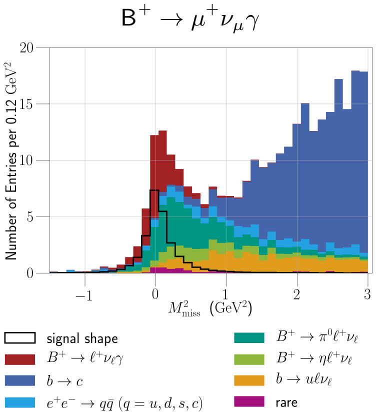


$$\epsilon = \mathbf{0.825 \pm 0.014 \pm 0.049}$$

ϵ incorporates all corrections on the tag-side B_{tag}.

Missing Mass – MC Expectation





Signal simulated with $\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)_{E_\gamma > 1.0\,\mathrm{GeV}} = 5 \times 10^{-6}$

Increased signal reconstruction efficiency by a **factor of 3** compared to previous Belle analysis – without increasing the background.

Improved Measurement Strategy

Improved measurement strategy

To **constrain the peaking background** from $B^+ \to \pi^0 \ell^+ \nu_\ell$ decays in the analysis we fit an additional sample of reconstructed $B^+ \to \pi^0 \ell^+ \nu_\ell$ decays.
We have two samples:

- $B^+ \to \ell^+ \nu_\ell \gamma$ selection (nominal analysis)
- $B^+ \to \pi^0 \ell^+ \nu_\ell$ selection (control region)

In addition we can use the extracted $\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell)$.

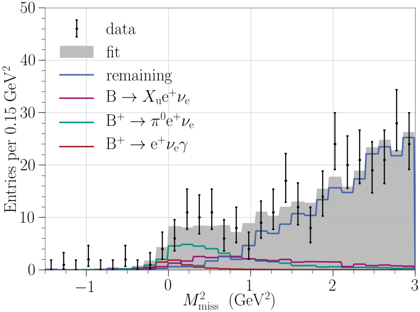
Two parameters

$$\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma)_{E_\gamma > 1.0\,\mathrm{GeV}} \quad \text{and} \quad \mathcal{R}_\pi = \frac{\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma)_{E_\gamma > 1.0\,\mathrm{GeV}}}{\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell)} \tag{1}$$

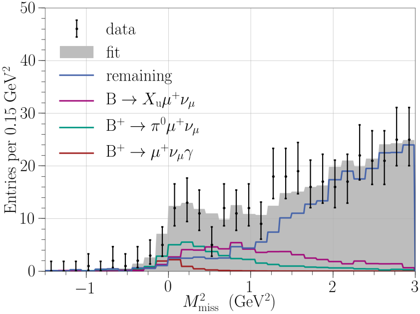
This allows to extract λ_B independent of $|V_{ub}|$. In addition, some systematics cancel in the ration $\mathcal{R}$.

Fit on Data

$B^+ \to e^+\nu_e\gamma$



$B^+ \to \mu^+\nu_\mu\gamma$



ℓ	$\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell)$ (10^{-5})	σ	$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)$ (10^{-6})	σ
e	$8.3^{+0.9}_{-0.8} \pm 0.9$	8.0	$1.7^{+1.6}_{-1.4} \pm 0.7$	1.1
μ	$7.5 \pm 0.8 \pm 0.6$	9.6	$1.0^{+1.4}_{-1.0} \pm 0.4$	0.8
e, μ	**$7.9 \pm 0.6 \pm 0.6$**	**12.6**	**$1.4 \pm 1.0 \pm 0.4$**	**1.4**

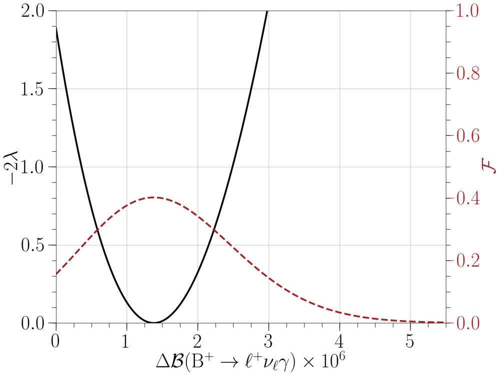
Previous results for $B^+ \to \pi^0\ell^+\nu_\ell$

	$\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell)$ $(\times 10^{-5})$
Belle excl. (2013)	$8.0 \pm 0.8 \pm 0.4$
PDG	7.80 ± 0.27

Limit Calculation

Bayesian Limit

$$0.9 = \frac{\int_0^{\Delta\mathcal{B}_{\text{limit}}} \mathcal{L}_{\text{PDF}}(\Delta\mathcal{B})\, d\Delta\mathcal{B}}{\int_0^{\infty} \mathcal{L}_{\text{PDF}}(\Delta\mathcal{B})\, d\Delta\mathcal{B}}$$



ℓ	$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)$ limit $\left(10^{-6}\right)$ @90% C.L.		
	BaBar (2009)	Belle (2015)	**This work**
e	-	< 6.1	$<$ **4.3**
μ	-	< 3.4	$<$ **3.4**
e, μ	< 14	< 3.5	$<$ **3.0**

Systematics

Source	$\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell)$ in 10^{-5}	$\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma)$ in 10^{-6}
$N_{B\overline{B}}$	± 0.11	± 0.02
LID efficiency	± 0.16	± 0.02
Tracking efficiency	± 0.03	± 0.0
Calibration	± 0.49	± 0.09
Reconstructed tag channel	± 0.01	± 0.14
Peaking background BDT	± 0.02	± 0.24
PDF templates	± 0.08	± 0.18
$B \to X_u \ell^+ \nu_\ell$	± 0.02	± 0.07
Reconstruction efficiency	± 0.20	± 0.01
Signal model	± 0.0	± 0.03
BCL model	± 0.25	± 0.01
Combined	$\pm$**0.62**	$\pm$**0.36**

Systematic uncertainties are directly incorporated into the likelihood.

Extraction of λ_B

$$R_\pi = \frac{\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)}{\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell)} = \frac{\Delta\Gamma(\lambda_B)}{\Gamma(B^+ \to \pi^0\ell^+\nu_\ell)}$$

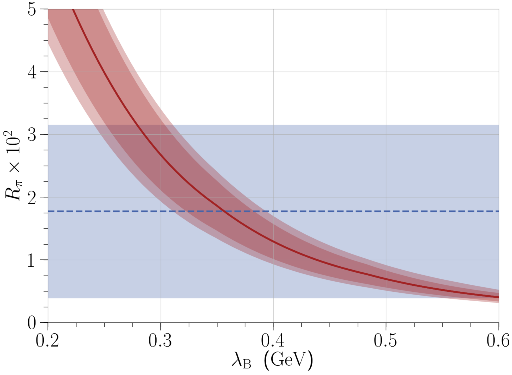
$$R_\pi^{\text{meas}} = (1.7 \pm 1.4) \times 10^{-2}$$

	λ_B (GeV)
Model I	$0.36^{+0.25}_{-0.08}{}^{+0.03}_{-0.03}$
Model II	$0.38^{+0.25}_{-0.06}{}^{+0.05}_{-0.08}$
Model III	$0.32^{+0.24}_{-0.07}{}^{+0.05}_{-0.08}$

based on:

Beneke et al., JHEP 07:154 (2018)

HFLAV, Eur. Phys. J., C77:895, (2017)

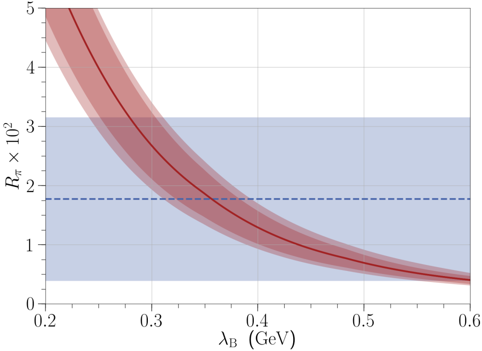


Two one-sided limits (@90% C.L.)

$\lambda_B > 0.24$ GeV and $\lambda_B < 0.68$ GeV

Conclusion

- First application of new tagging algorithm for Belle II.
- Updated results for $B^+ \to \ell^+ \nu_\ell \gamma$
- Improved method for λ_B extraction.
- Results will be published soon.



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