Karlsruhe Institute of Technology

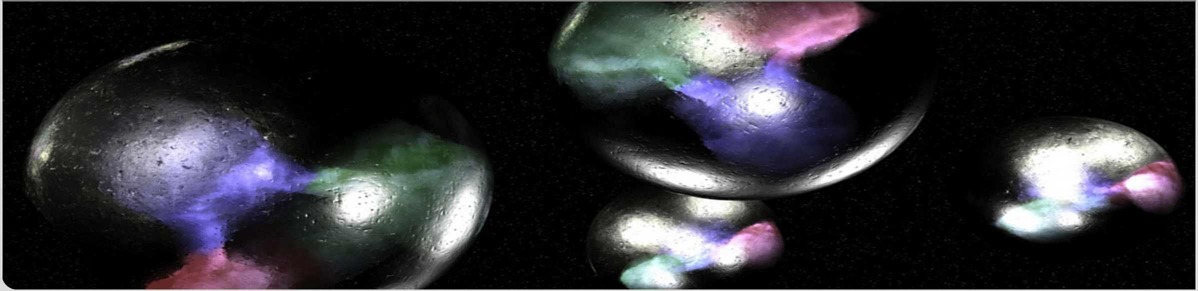
BELLE Belle II

$B^+ \to \ell^+\nu_\ell\gamma$ at Belle and prospects of $B^+ \to \ell^+\nu_\ell(\gamma)$

6th KEK Flavor Factory Workshop

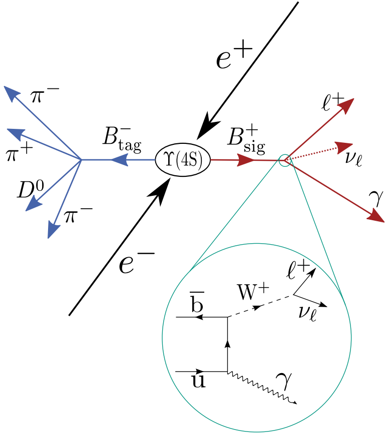
Felix Metzner | 15th February 2019

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)



Introduction

- B meson pairs are 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



This Analysis: M. Gelb, F. U. Bernlochner, P. Goldenzweig, F. Metzner *et al.* (The Belle Collaboration) Phys. Rev. D 98, 112016 (2018)

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

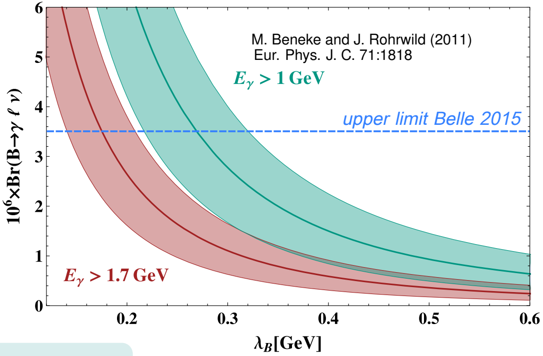
The Decay $B^+ \to \ell^+ \nu_\ell \gamma$

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

with $x_\gamma = 2E_\gamma / m_B$

Previous Belle result (2015):

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



Form Factors (valid for large photon energies)

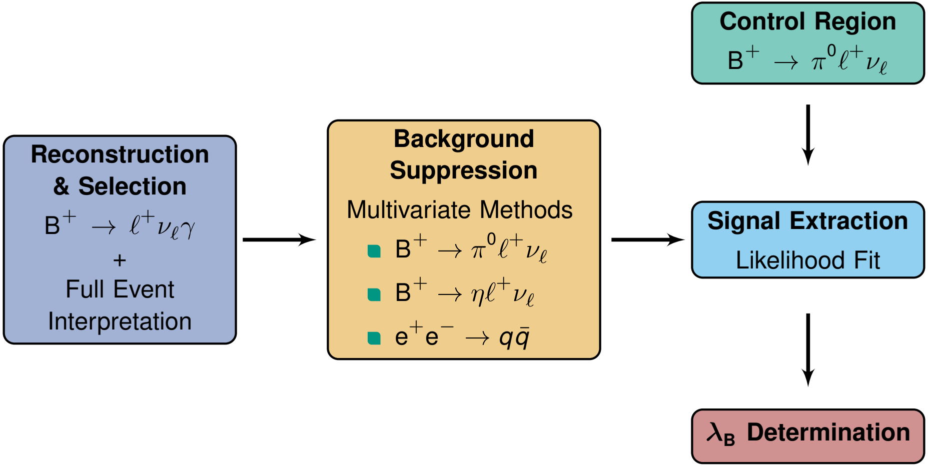
$$F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2}\right]$$

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

Method	λ_B (GeV)
QCD factorization	≈ 0.2
QCD sum rules	0.46 ± 0.11
BaBar (2009)[a]	> 0.115
Belle (2015)[b]	> 0.238

a: Phys. Rev. D 80, 111105 (2009)
b: Phys. Rev. D 91, 112009 (2015)

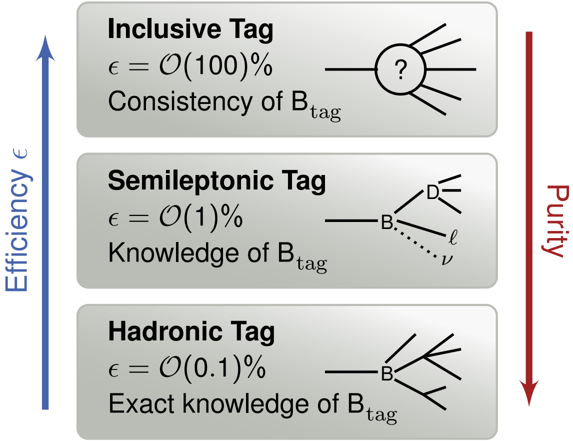
Analysis Strategy



Tag-Side B-Meson Reconstruction

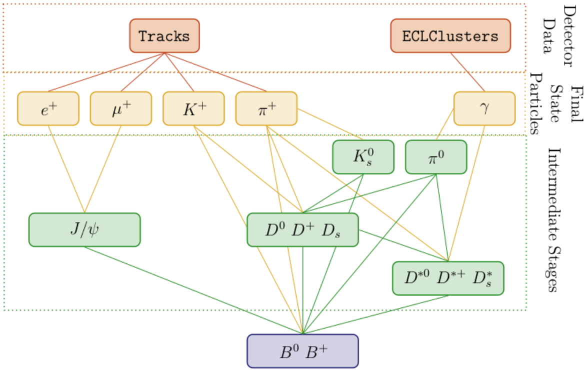
Analysis of **missing energy mode** relies on

- reconstruction of second **B $_{\text{tag}}$ meson**
- in **hadronic** decay channels



The Tagging Algorithm: Full Event Interpretation

- Hierarchical reconstruction of B_{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 B_{tag} candidate has an assigned probability P_{FEI}



B–Tagging efficiency ϵ on MC

Tag	FR[a]	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%

a: Belle Full Reconstruction algorithm.

Calibration of the Tagging Algorithm

Why calibration?

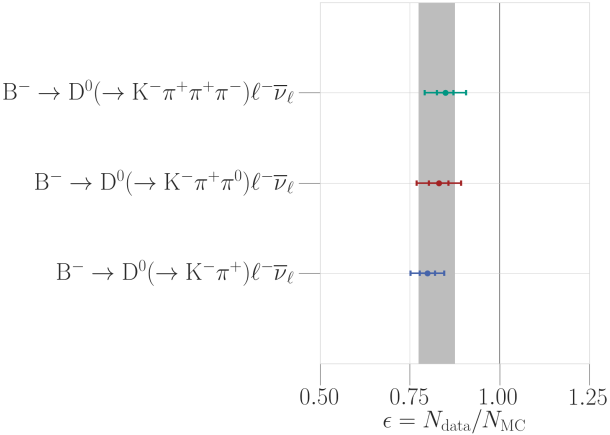
Difference in tagging efficiency on data and MC:

- 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 of the M^2_{miss} distribution
4) Calculate the correction factor for calibration channel:

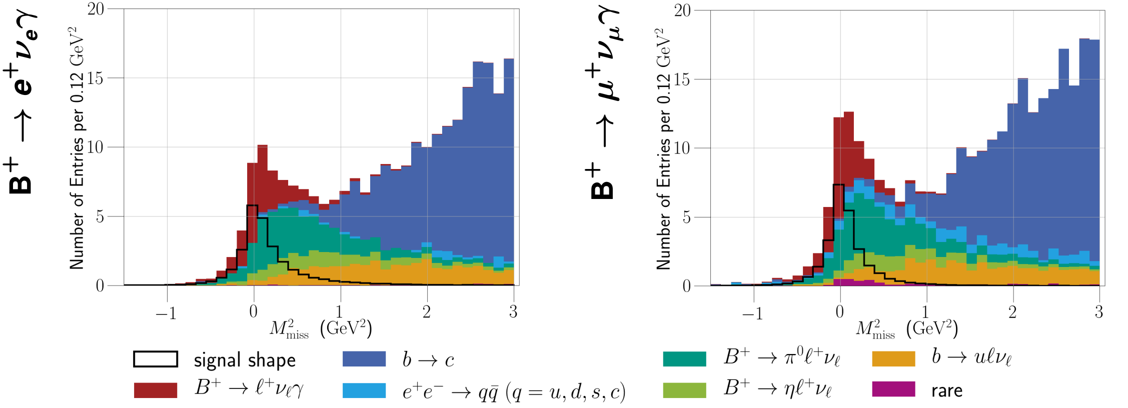
$$\epsilon = \frac{N_{Data}}{N_{MC}}$$



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

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

Missing Mass — MC Expectation



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

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

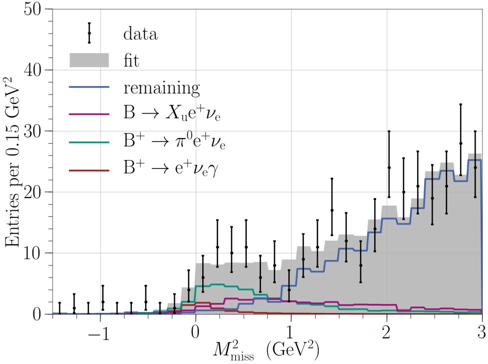
Measure two quantities:

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

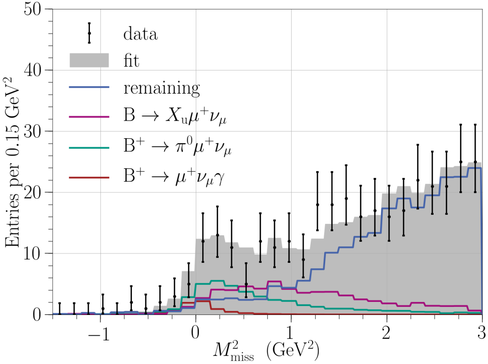
This allows to extract λ_B independent of $|V_{ub}|$. In addition, some systematics cancel in the ration $\mathcal{R}$.

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.[a]	$8.0 \pm 0.8 \pm 0.4$
PDG	7.80 ± 0.27

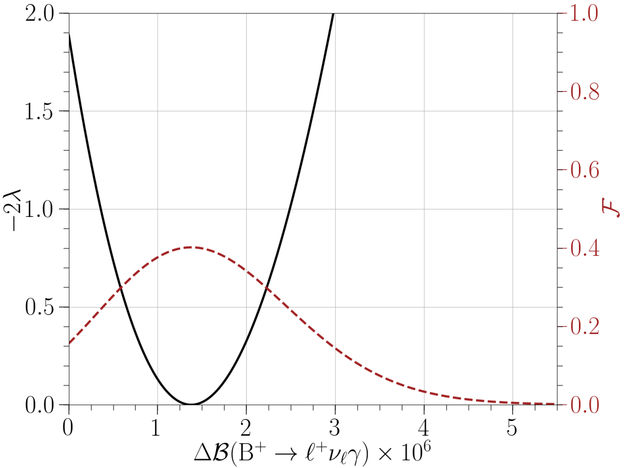
a: *Sibidanov et al.*, Phys. Rev. D 88, 032005 (2013)

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



Limits are estimated with total systematic error.

a: Phys. Rev. D 80, 111105 (2009)
b: Phys. Rev. D 91, 112009 (2015)

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}
Multiplicative	$N_{B\overline{B}}$	Common	± 0.11	± 0.02
	LID Efficiency	Common	± 0.16	± 0.02
	Tracking Efficiency	Common	± 0.03	± 0.00
	Calibration	Specific	± 0.49	± 0.09
	Reconstruction Efficiency	Specific	± 0.20	± 0.01
Additive	Reconstructed Tag Channel	Specific	± 0.01	± 0.14
	Peaking Background BDT	Specific	± 0.02	± 0.24
	PDF Templates	Specific	± 0.08	± 0.18
	$B \to X_u \ell^+ \nu_\ell$	Specific	± 0.02	± 0.07
	Signal Model	Specific	± 0.00	± 0.03
	BCL Model	Specific	± 0.25	± 0.01
	Combined		$\pm$**0.62**	$\pm$**0.36**

Systematic uncertainties are directly incorporated into the likelihood.

Extraction of λ_B

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

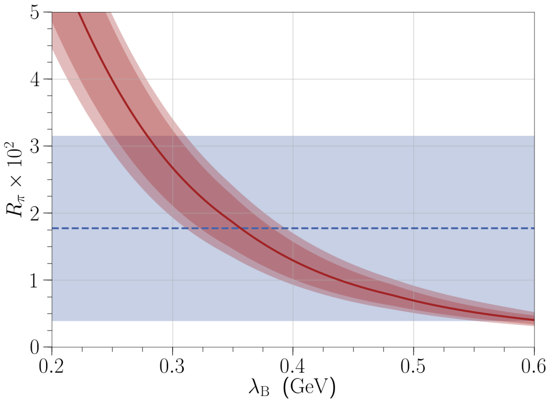
$$R_\pi^{\text{measured}} = (1.7 \pm 1.4) \times 10^{-2}$$

	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 theoretical input from:

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

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



$\lambda_B > 0.24$ GeV @ 90% C.L.

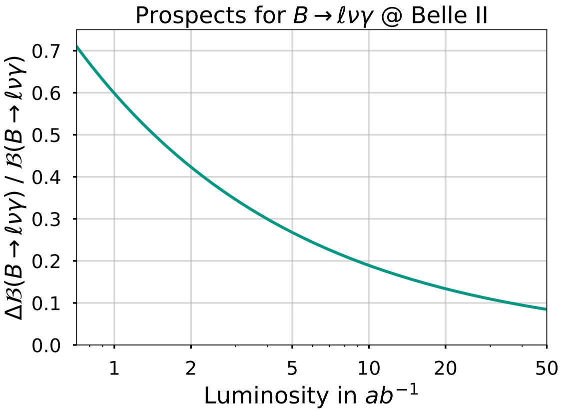
Result of Belle (2015) was $\lambda_B > 0.238$ GeV

Prospects of $B^+ \to \ell^+ \nu_\ell \gamma$ at Belle II

Analysis is **statistically limited**.

$\Rightarrow$ **Extrapolation for Belle II**:

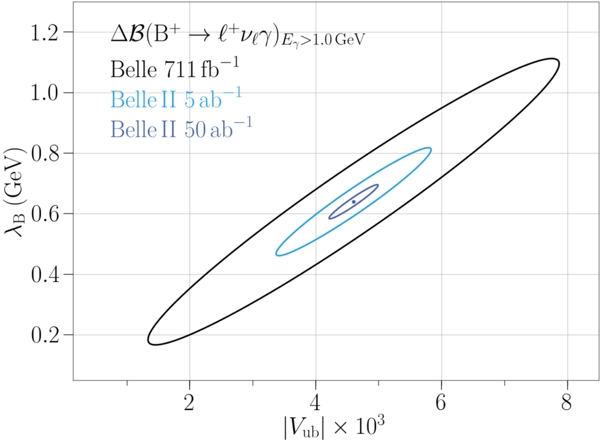
- scale statistical uncertainty with luminosity: $\sqrt{711\ \text{fb}^{-1}/\mathcal{L}}$
- unchanged central value
- unchanged systematic uncertainty



Prospects of $B^+ \to \ell^+ \nu_\ell \gamma$ at Belle II

$\Rightarrow$ Estimate improved statistical uncertainties for the full analysis

$\Rightarrow$ Propagate results to V_{ub} and λ_B



$B^+ \to \mu^+\nu_\mu$ at Belle
and
Prospects for Belle II

$B^+ \to \mu^+\nu_\mu$ at Belle

Rare decay with SM expectation of

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) \approx \mathcal{O}(10^{-7}).$$

Latest result (Belle 2018):

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = (6.46 \pm 2.22 \pm 1.6) \times 10^{-7}$$

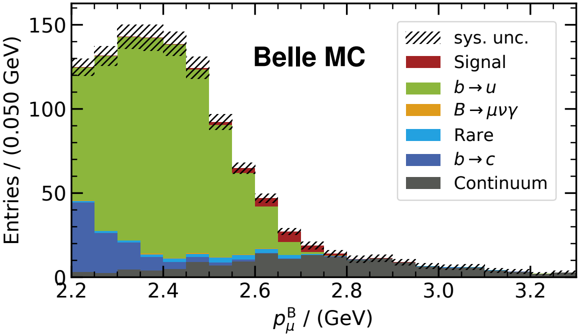
Phys. Rev. Lett 121, 031801 (2018)

$\Rightarrow$ Requires high reconstruction efficiency!

Clean signature of **two-body decay** of B_{sig}

$\Rightarrow$ $\boldsymbol{p_\mu^B = m_B/2 \approx 2.64}$ **GeV**

in the B_{sig} rest frame



$\Rightarrow$ **Experimental access to CKM matrix element V_{ub}**

$\Rightarrow$ **Sensitive to New Physics (e.g. 2HDM, Sterile Neutrinos)**

$B^+ \to \mu^+ \nu_\mu$ at Belle

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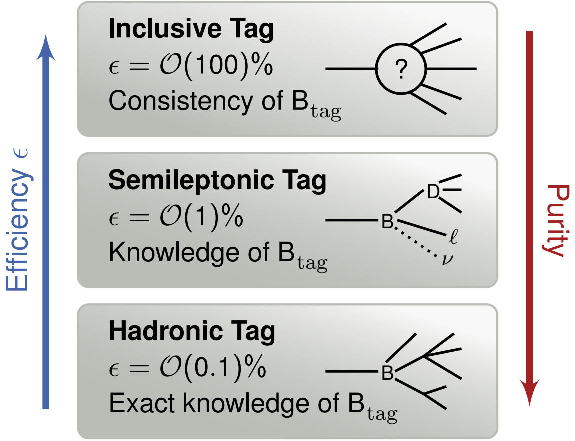
To provide a sufficiently high reconstruction efficiency a **inclusive B-tagging** algorithm is applied.

Knowledge of the B_{tag} meson's momentum allows to boost into the B_{sig} rest frame.



Prospects of $B^+ \to \mu^+\nu_\mu$ at Belle II

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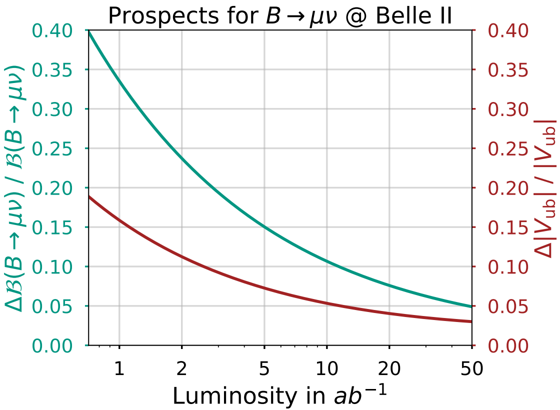
Based on these new results we make **predictions** for the relative uncertainties of

- $\mathcal{B}(B^+ \to \mu^+\nu_\mu)$ and
- V_{ub}

for this statistically limited decay mode, assuming

- unchanged central values and
- 3% irreducible systematic uncertainty

by scaling reducible σ with $\sqrt{711\,\text{fb}^{-1}/\mathcal{L}}$ and propagating the effect to V_{ub}.



$\Delta\lvert V_{ub}\rvert / \lvert V_{ub}\rvert$	@ Belle	@ Belle II 5 ab^{-1}	@ Belle II 50 ab^{-1}
$B^+ \to \mu^+\nu_\mu$	19%	7.3%	3.0%
$B^+ \to \pi^0\ell^+\nu_\ell$	4.3%	2.0%	1.5%

Summary

- First application of (signal-specific) FEI.
- Improved upper 90% C.L. limit. for $B^+ \to \ell^+ \nu_\ell \gamma$
- Improved method for λ_B extraction!

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	$< \mathbf{4.3}$
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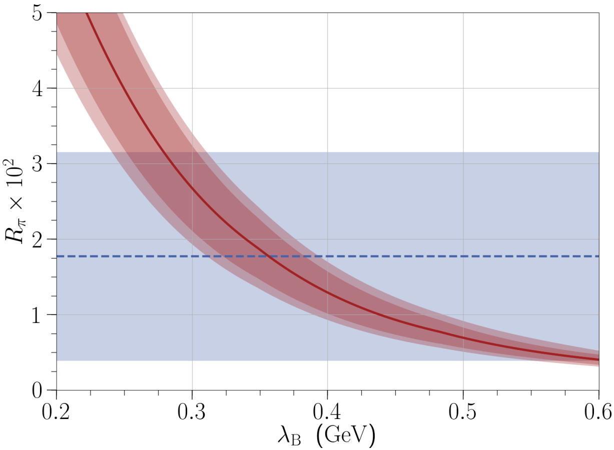
	λ_B (GeV)
QCD factorization	≈ 0.2
QCD sum rules	0.46 ± 0.11
BaBar	> 0.115
Belle (2015)	> 0.238
This work	$> \mathbf{0.24}$



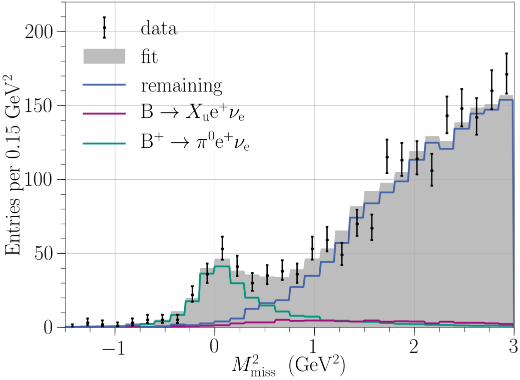
By utilizing the new Belle II software and the B2BII conversion package, we can

- still squeeze out new results from the Belle data set and
- get the analysis software warmed up for Belle II data.

Thank You for Your attention!

Backup — Fit on Data for $B^+ \to \pi^0 \ell^+ \nu_\ell$

$B^+ \to \pi^0 e^+ \nu_e$



$B^+ \to \pi^0 \mu^+ \nu_\mu$