MITP
SCIENTIFIC
PROGRAM

Flavourful Opportunities in Semileptonic B Decays:

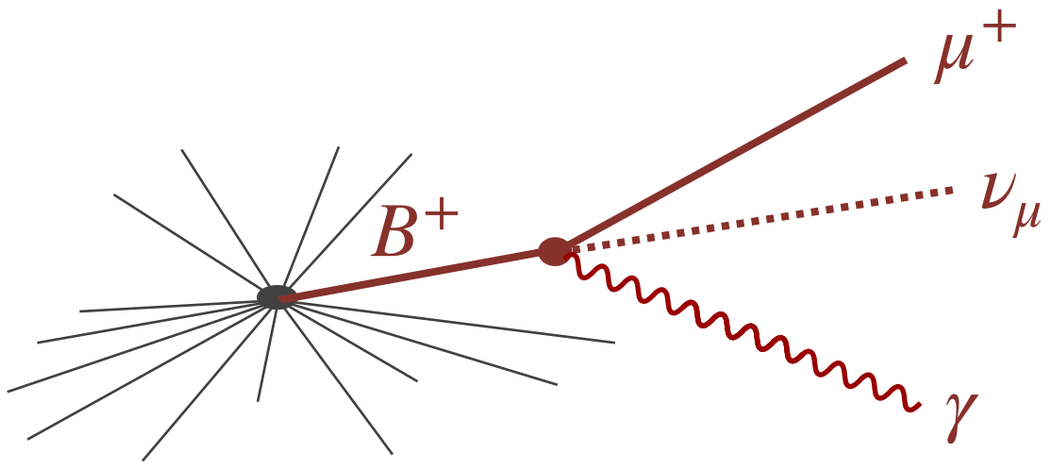
Connecting Theory and Experiment

July 6 – 17, 2026

https://indico.mitp.uni-mainz.de/event/448/

Mainz Institute for Theoretical Physics

Radiative leptonic decays and the B-meson LCDA



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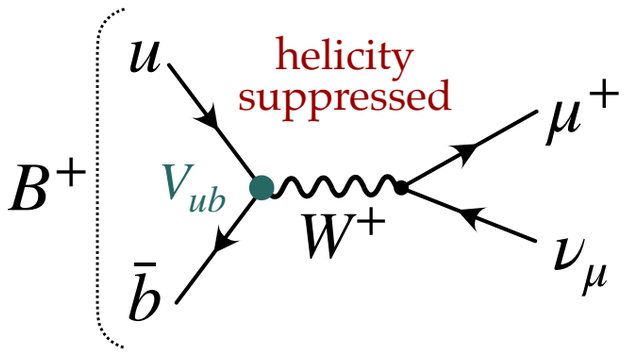
July 16th 2026

$B^+ \to \mu\nu\gamma$: **why?**



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

Suppressed by V_{ub} + helicity m_ℓ^2/m_B^2

Very precise prediction (just f_B)

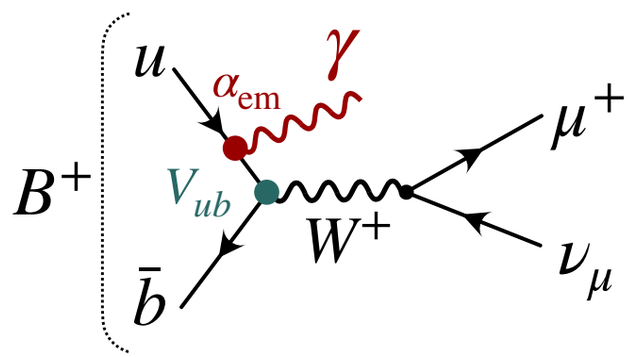
Theory: BR $= (3.8 \pm 0.4) \times 10^{-7}$

Belle+Belle2: BR $= (4.4 \pm 2.1) \times 10^{-7}$

Phys.Rev.D 113 (2026) 11, 112012

Test the SM

measure V_{ub},
search for H^+, LQ



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

Suppressed by V_{ub} + ~~helicity~~ + α_{em}

Depends on $B \to \gamma$ form factors

Theory: BR $= \mathcal{O}(10^{-6})$

Belle: BR $< 3.0 \times 10^{-6}$ at 90% CL

Study B^+ meson

to improve predictions
for other channels

$B^+ \to \ell^+ \nu\gamma$ differential rate

- The differential decay rate can be parametrized with E_γ and $\cos\theta_\ell$
- When integrating over $\cos\theta_\ell$ it reads:

Includes FSR term

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{\text{em}} G_F^2 |V_{ub}|^2}{6\pi^2} m_B E_\gamma^3 \left(1 - \frac{2E_\gamma}{m_B}\right) \left[|F_V|^2 + |\hat{F}_A|^2 \right]$$

With $F_{V(A)}$ the (axial-)vector form factors that depend on:

$$F_{V,A}\left(E_\gamma\right) = \frac{e_u f_B m_B}{2E_\gamma \lambda_B(\mu)} R\left(E_\gamma, \mu\right) + \left[\xi\left(E_\gamma\right) \pm \Delta\xi\left(E_\gamma\right)\right]$$

Tree level factorisation, depends on $1/\lambda_B$

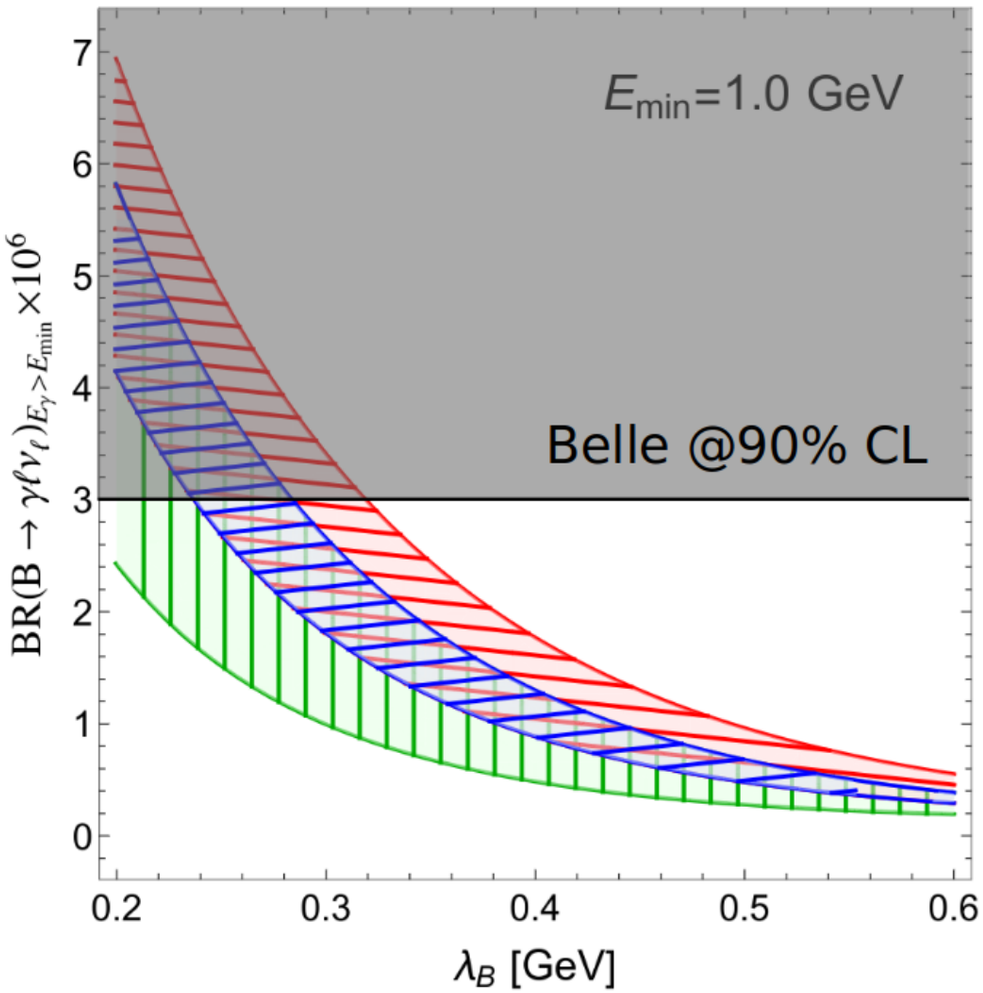
Depends weakly on LCDA shape

Power suppressed by $1/m_b$ and $1/2E_\gamma$

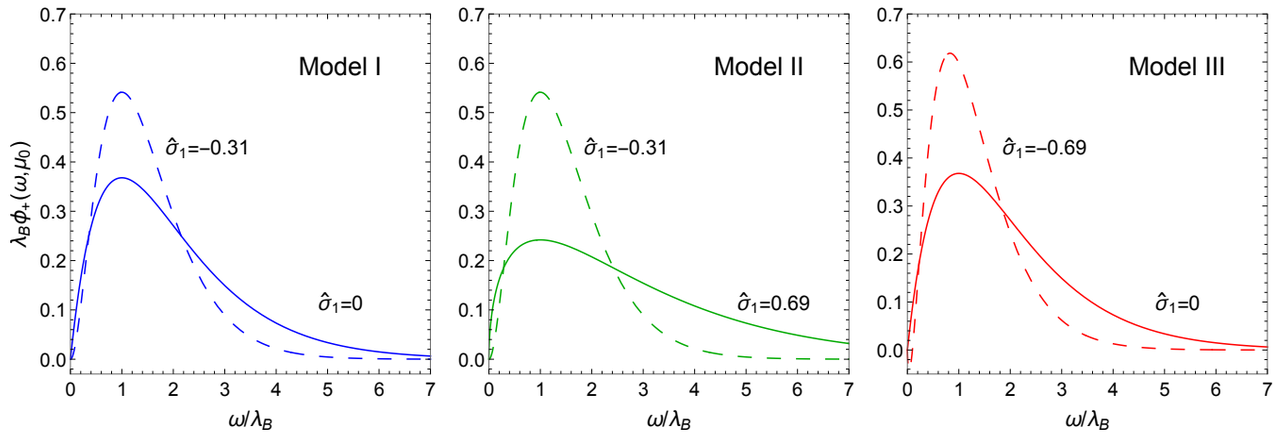
N.B.: Power corrections blow up for $E_\gamma < 1.5$ GeV

Extracting λ_B from $B \to \ell \nu \gamma$

M.Beneke et al JHEP 07 (2018) 154



LCDA shape depends mainly on value of $\hat{\sigma}_1$
which enters the BR within $R(E_\gamma, \mu)$



D.van Dyk et al JHEP 10 (2022) 162
LCDA parametrisation with expansion
that keeps truncation error under control

The B meson LCDA and λ_B

- Inside the B^+ meson: b quark at rest, u quark has momentum ω along the light-cone
- The $\phi_+(\omega, \mu)$ light-cone distribution amplitude (LCDA) is the amplitude to find the u quark with momentum ω
- Any b-quark decay in QCD factorization is convoluted with this soft **universal** function (same for any exclusive B decay)
- The LCDA is mainly characterized by its first inverse moment

$$\lambda_B^{-1}(\mu) = \int_0^\infty \frac{d\omega}{\omega} \phi_+(\omega, \mu)$$

- The parameter λ_B is very poorly known (0.2-0.6 GeV) although Lattice calculations are being developed (see 2302.01298, 2306.05904, 2308.07033, 2605.10946, …)

Form factors and LCDA

- B form factors predictions are key
  - Lattice QCD: robust, but slow and hard to do at low q^2
  - LCSR: broader reach, real caveats, but often the only option
- The B-meson LCDA (esp. λ_B) is a recurring bottleneck
  - B-meson LCSR: dominant parametric uncertainty (B→π, K, ϱ, Λ_b→p)
  - QCD factorisation for nonleptonic decays (B→$\pi\pi$, Kπ, …)
  - Feeds exclusive $|V_{ub}|$ (and $|V_{cb}|$)

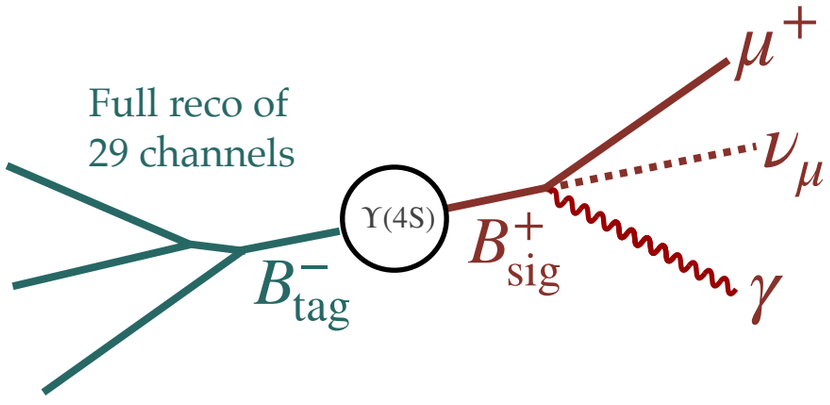
MITP discussion session

Ingredients of b2sll theory

- **ingredient #1: parametrisation of the local FFs: solid**
- **ingredient #2: values of the local FFs: not solid yet, but improvable (B->K: soon, B->φ: ?, B->Kπ: in design phase, B->K*(NWA): fogettaboutit…)**
- **ingredient #3: parametrisation of the nonlocal FFs**
  - **q2-expansion(small q2 far below J/psi only)**
  - **z-expansion(q2 < 4MD^2)**
- **ingredient #4: values of the nonlocal FFs**
  - **OPE leading power (LP): purely partonic**
  - **OPE next-to-leading power (NLP):**
  - **real parts: start at 1-loop (order alpha_s^0); 2-loop results are known at LP**
  - **imaginary parts: start at 2-loop (order alpha_s^1)**
  -

$B^+ \to \mu\nu\gamma$: **how?**

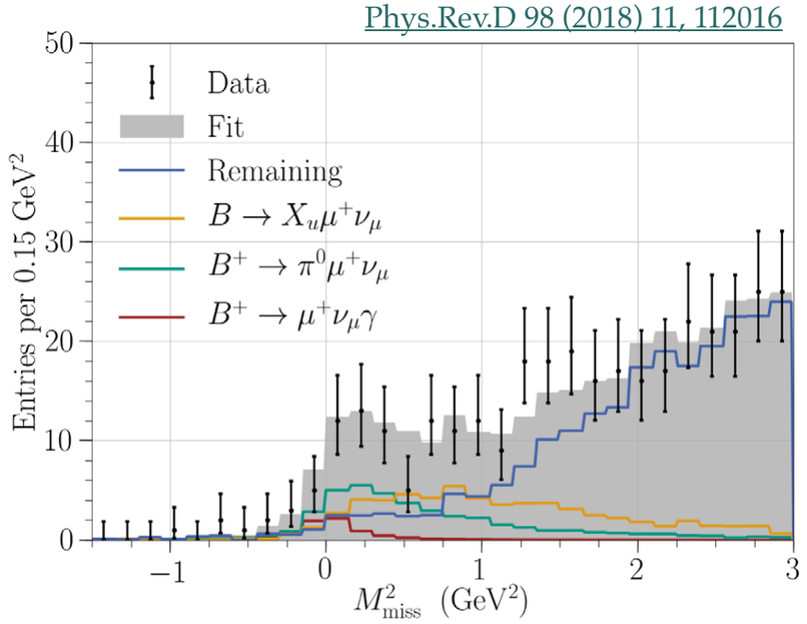
Method @Belle



- Full reco of B_{tag} $\varepsilon \simeq 0.8\,\%$

$$p_{B_{\text{sig}}} = \left(\frac{\sqrt{s}}{2}, -\vec{p}_{B_{\text{tag}}}\right) \qquad M^2_{\text{miss}} = p^2_\nu = \left(p_{B_{\text{sig}}} - p_\ell - p_X\right)^2$$

Phys.Rev.D 98 (2018) 11, 112016



$B^+ \to \mu\nu\gamma$: **how?**

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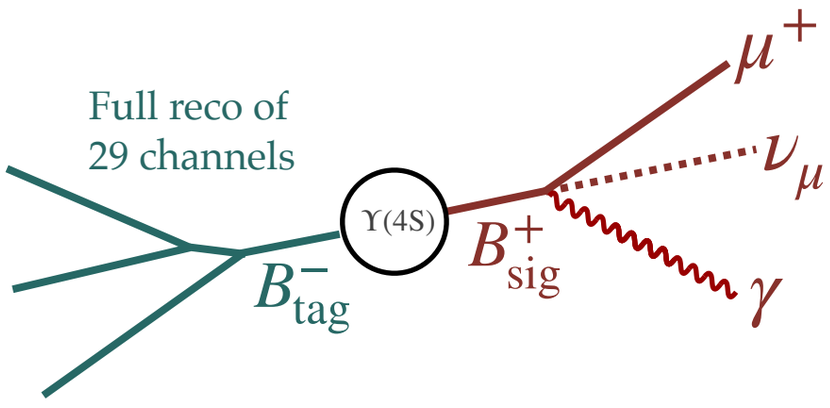

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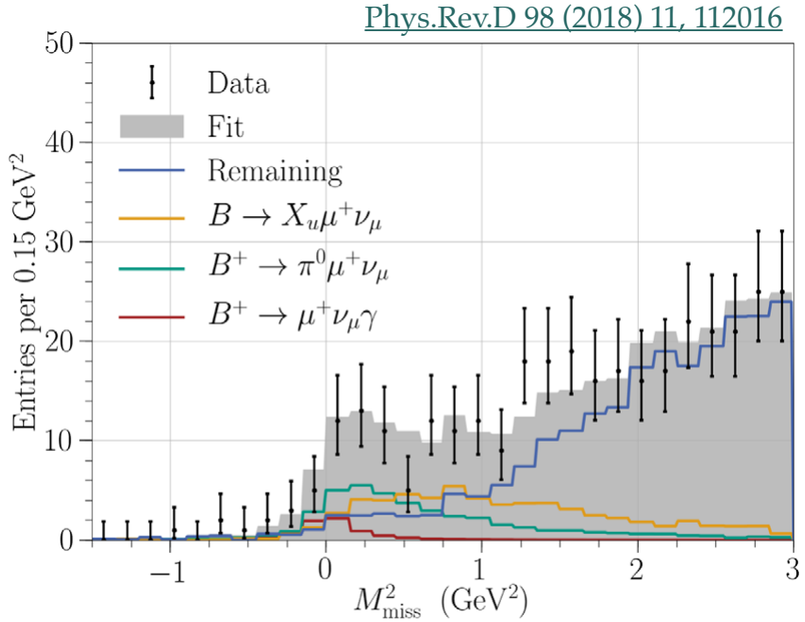
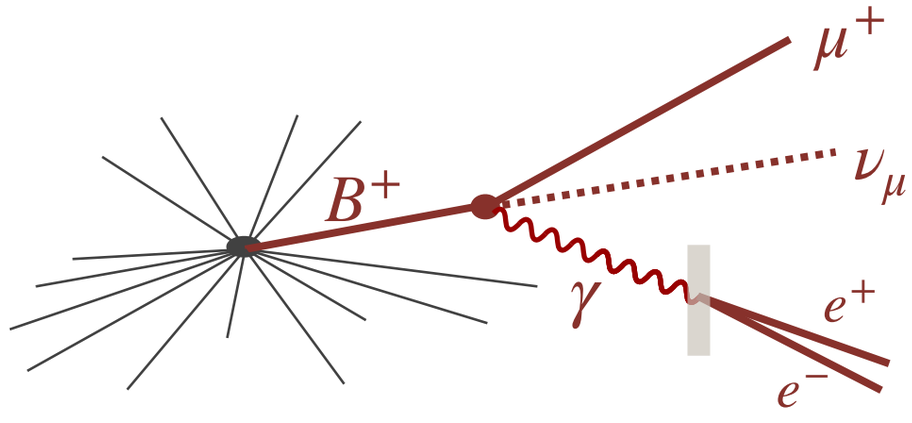


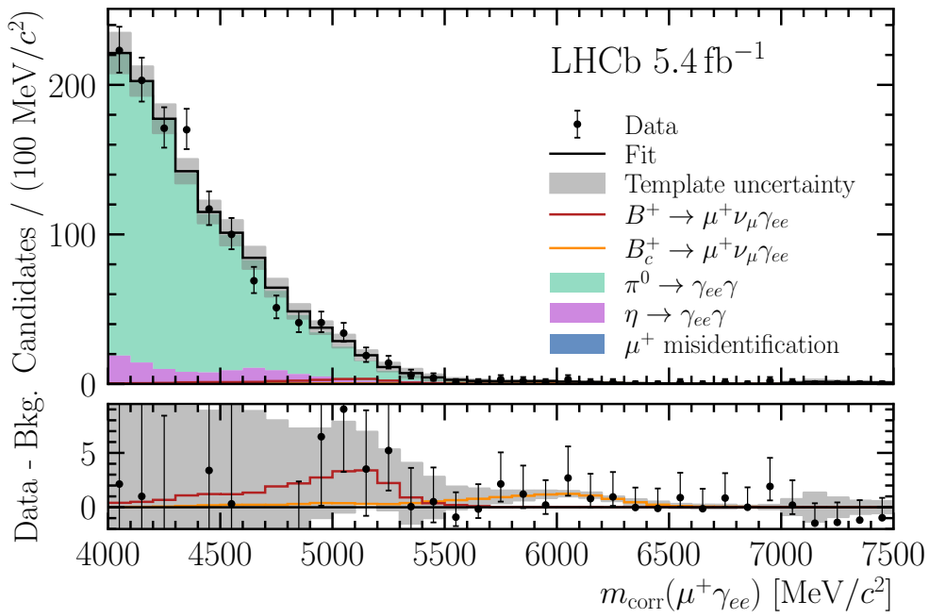
Method @LHCb



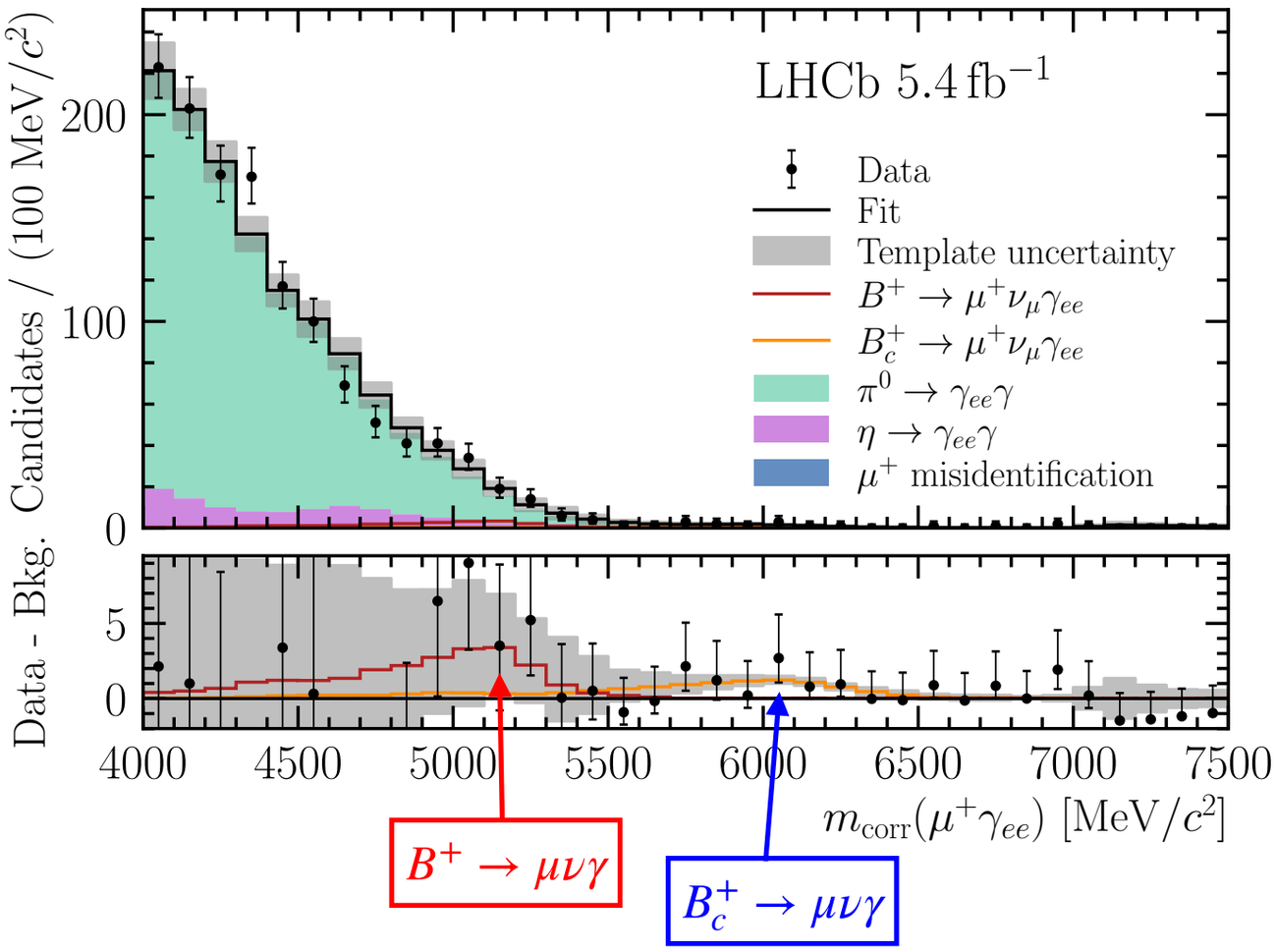
- γ conversion in material (7%)
  → get B^+ displaced vertex

$$m_{\text{corr}} = \sqrt{m^2_{\text{visible}}\left(\mu^+\gamma_{ee}\right) + p^2_\perp} + p_\perp$$

NEW!! arXiv:2607.12825



Also $B_c^+ \to \mu\nu\gamma$ in LHCb



Theoretical predictions:

$$BR(B_c^+ \to \mu^+\nu\gamma) \sim [2,\ 8] \times 10^{-5}$$

[19] Chiladze, Falk, Petrov, PRD 60 (1999) 034011, hep-ph/9811405
[20] Colangelo, De Fazio, MPLA 14 (1999) 2303, hep-ph/9904363
[21] Chang, Lu, Wang, Zong, PRD 60 (1999) 114013, hep-ph/9904471
[22] Barik, Naimuddin, Dash, Kar, PRD 78 (2008) 114030
[23] Wang, Zhu, EPJC 75 (2015) 360, arXiv:1501.04493

- Can also search for $B_c^+ \to \mu\nu\gamma$
  - Never been searched for!
  - Useful to study B_c^+ meson structure? The only weakly decaying meson composed of two heavy quarks.
  - Expect similar rate as B^+ due to

$$\frac{f_c}{f_u} \simeq \frac{|V_{ub}|^2}{|V_{cb}|^2}$$

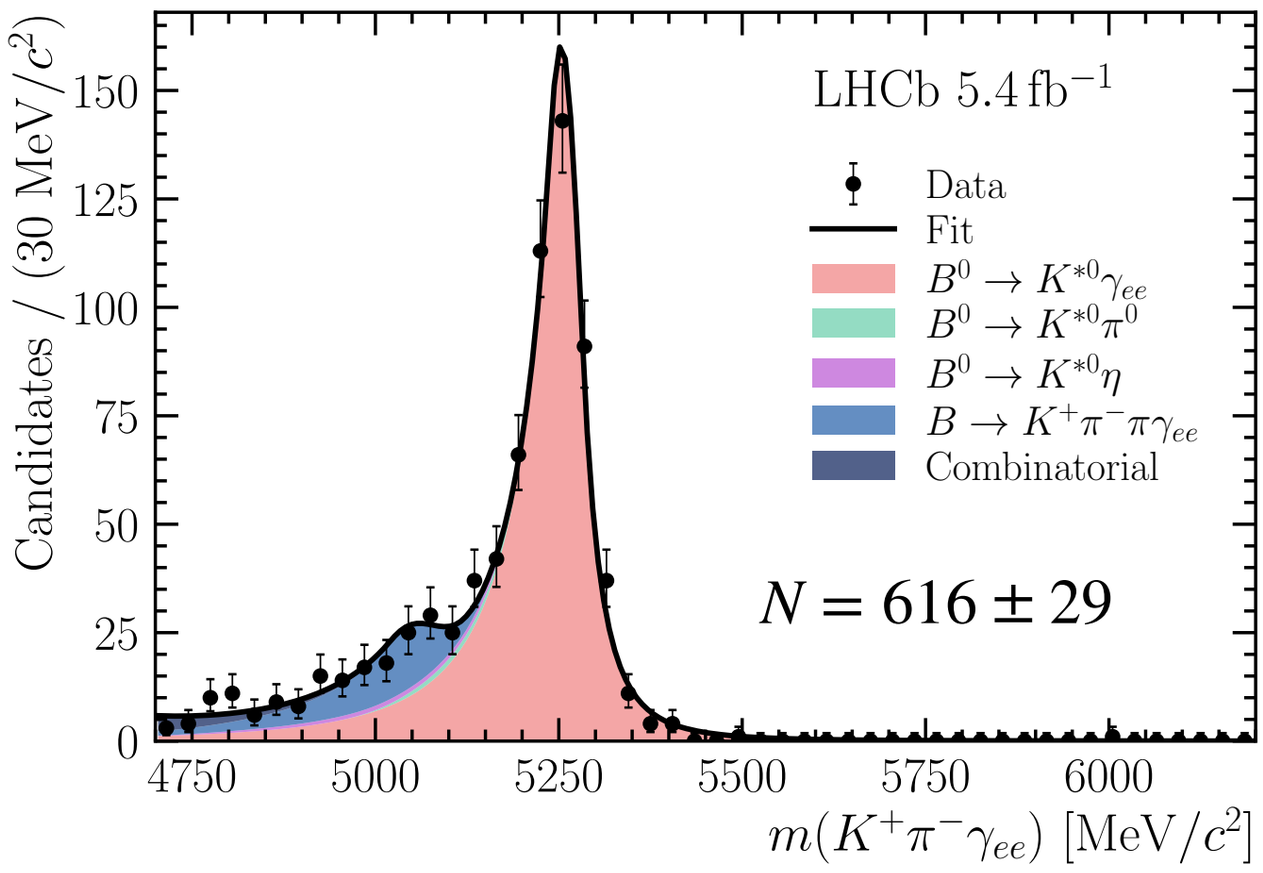
  - 10x lower efficiency due to $\tau(B_c^+) \simeq 0.3 \times \tau(B^+)$
  - Much lower background under the peak — a **future dedicated search could greatly improve sensitivity**

Dataset and selection

- Run 2 pp data (2016–2018), $\sqrt{s} = 13$ TeV, 5.4 fb^{-1}
- Hardware trigger based on high-p_T muon or electron
- Three classifiers against the main background sources:
  - XGBoost vs combinatorial (topology, kinematics, vertex quality);
  - XGBoost anti-π^0 (γ_eeγ_calo mass, cone multiplicity, p_T asymmetry); Also, no bremmstrahlung recovery used to avoid adding back the energy of the other γ from the π^0
  - Isolation BDT vs partially reconstructed B decays based on nearby tracks
  - working point optimized on the expected UL: 98% background rejection at 22% (8%) efficiency for B^+ (B_c^+)

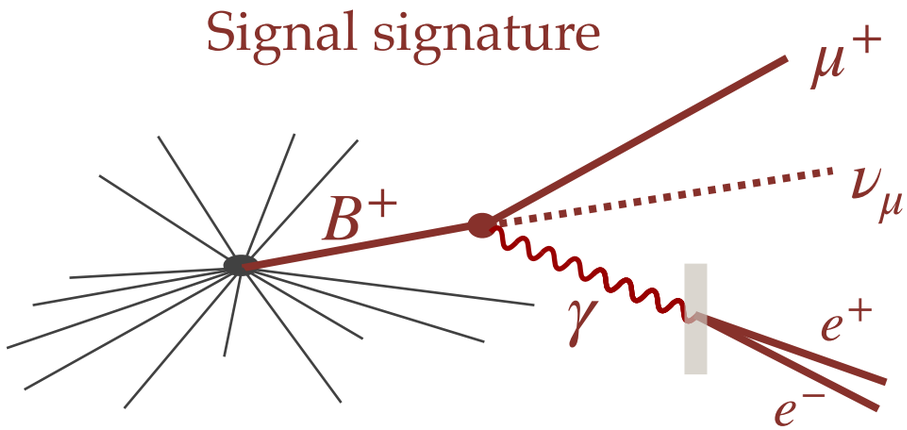
Normalisation

- Normalised to $B^0 \to K^{*0}\gamma_{ee}$
- BR known with 6% uncertainty
- Cancels systematics related to γ_{ee} conversion
- Photon has similar energy spectrum



Background modelling

- Main backgrounds:
  1. $B^+ \to \mu^+ \nu \pi^0$ with BR=7.8×10^{-5}
  2. $B \to \mu^+ \nu \pi^0(X)$ and $B \to \mu^+ \nu \eta(X)$
  3. Random combinations of μ^+ and π^0/η
  4. $B \to h^+ \pi^0(X)$ and $B \to h^+ \eta(X)$
  5. Random combinations of h^+ and π^0/η
  6. $B \to X h^+ \gamma_{ee}$ from $b \to s\gamma$ (rare)
  7. Random combinations of h^+ and γ_{ee}
  8. Random combinations of μ^+ and γ_{ee}
  9. Fake conversion γ_{ee}



Background modelling

- Main backgrounds:

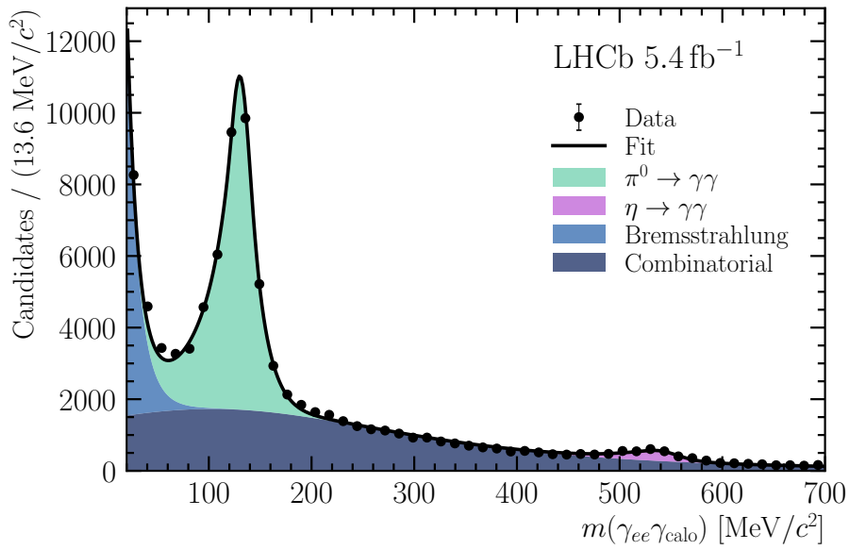
$\pi^0/\eta \to \gamma_{ee}\gamma$

1. $B^+ \to \mu^+\nu\pi^0$ with BR=7.8×10^{-5}
2. $B \to \mu^+\nu\pi^0(X)$ and $B \to \mu^+\nu\eta(X)$
3. Random combinations of μ^+ and π^0/η
4. $B \to h^+\pi^0(X)$ and $B \to h^+\eta(X)$

μ^+ misID

5. Random combinations of h^+ and π^0/η
6. $B \to Xh^+\gamma_{ee}$ from $b \to s\gamma$ (rare)
7. Random combinations of h^+ and γ_{ee}
8. Random combinations of μ^+ and γ_{ee}
9. Fake conversion γ_{ee}

Model using pure sample of $\pi^0_{\gamma_{ee}}$ and $\eta_{\gamma_{ee}}$ from data



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Model using data control sample with no μ ID

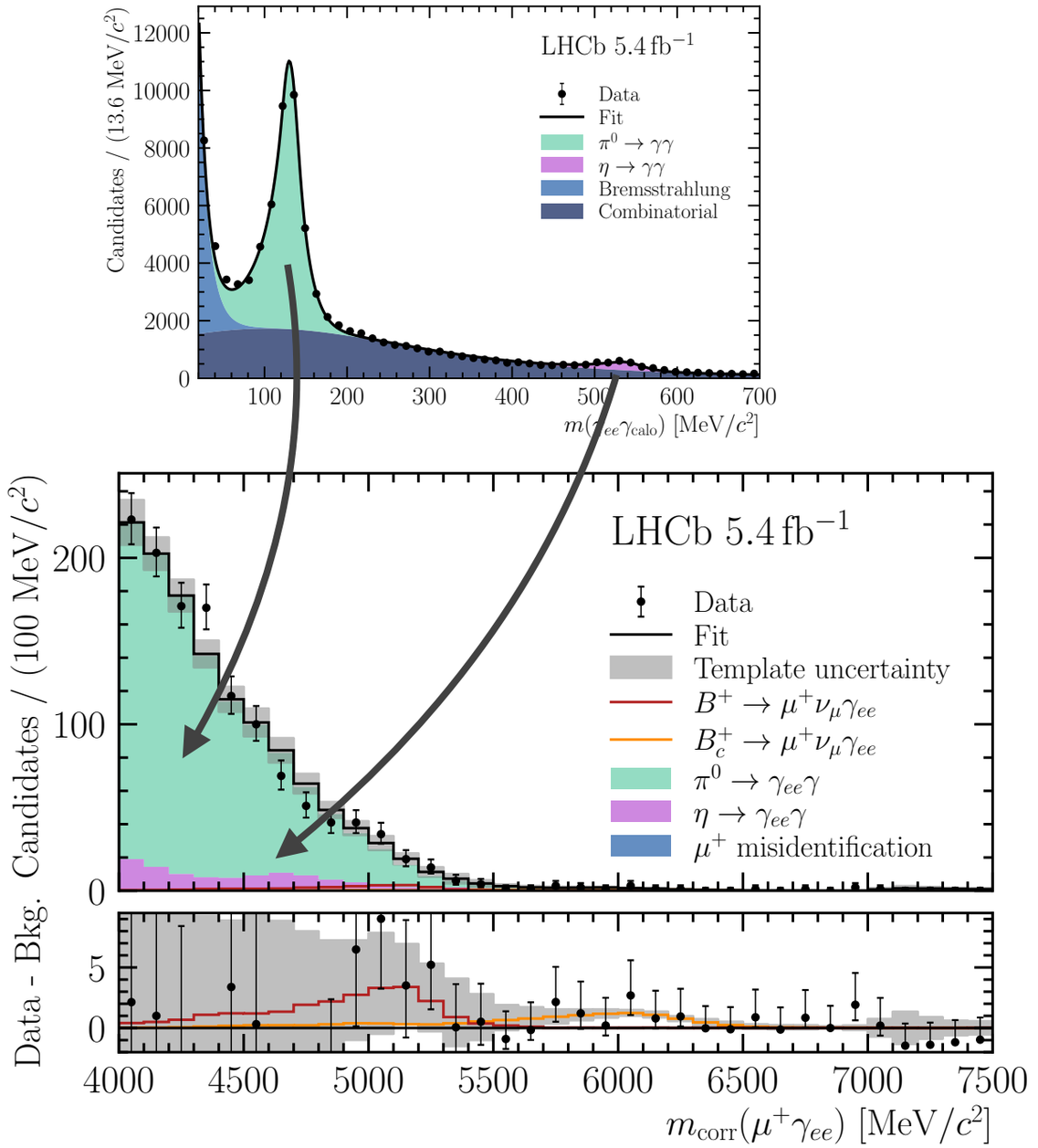
Negligible after BDT

Negligible thanks to $m(ee) < 10$ MeV and double charge in VELO

Modelling bkg from π^0 and η

~data-driven bkg modelling

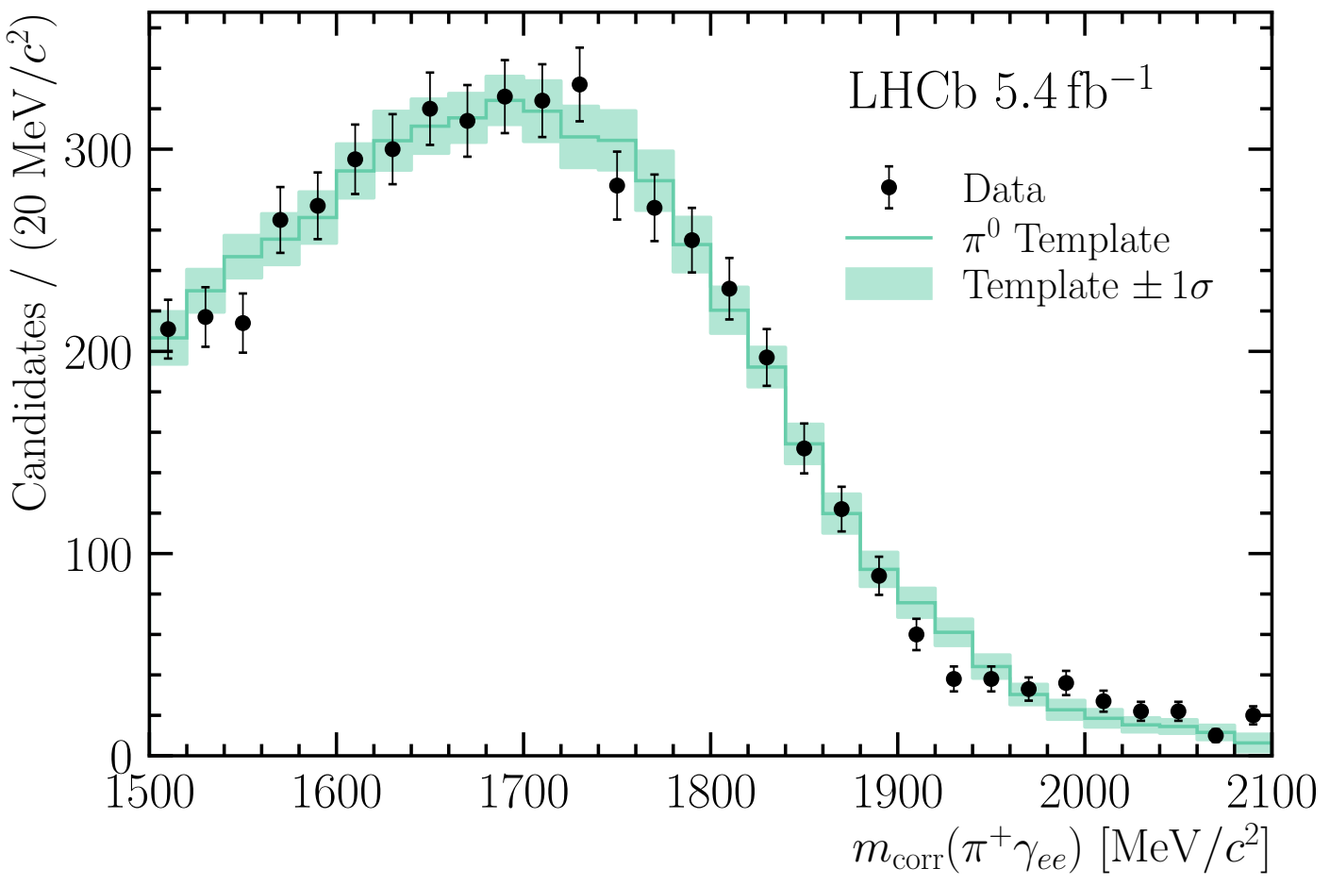
- Procedure to get m_{corr} template for π^0/η
  - Search for additional γ_{calo}
  - Fit π^0 and η peaks (in momentum bins)
  - Get pure π^0 and η samples using sPlot
  - Unfold efficiency of finding γ_{calo} using correction map **obtained from MC**
  - Get m_{corr} template for all bkg's from π^0 and η



Modelling bkg from π^0 and η

- **Independent closure test**
  - Use high-stat $D^0 \to K\pi\gamma_{ee}$ candidates
  - Channel dominated by $D^0 \to K\pi\pi^0$
  - Pure sample of $\pi^0 \to \gamma_{ee}\gamma$ selected only with γ_{ee}
  - Get $m(K\pi\gamma_{ee})$ template using same procedure

Template obtained from sPlotted π^0 peak



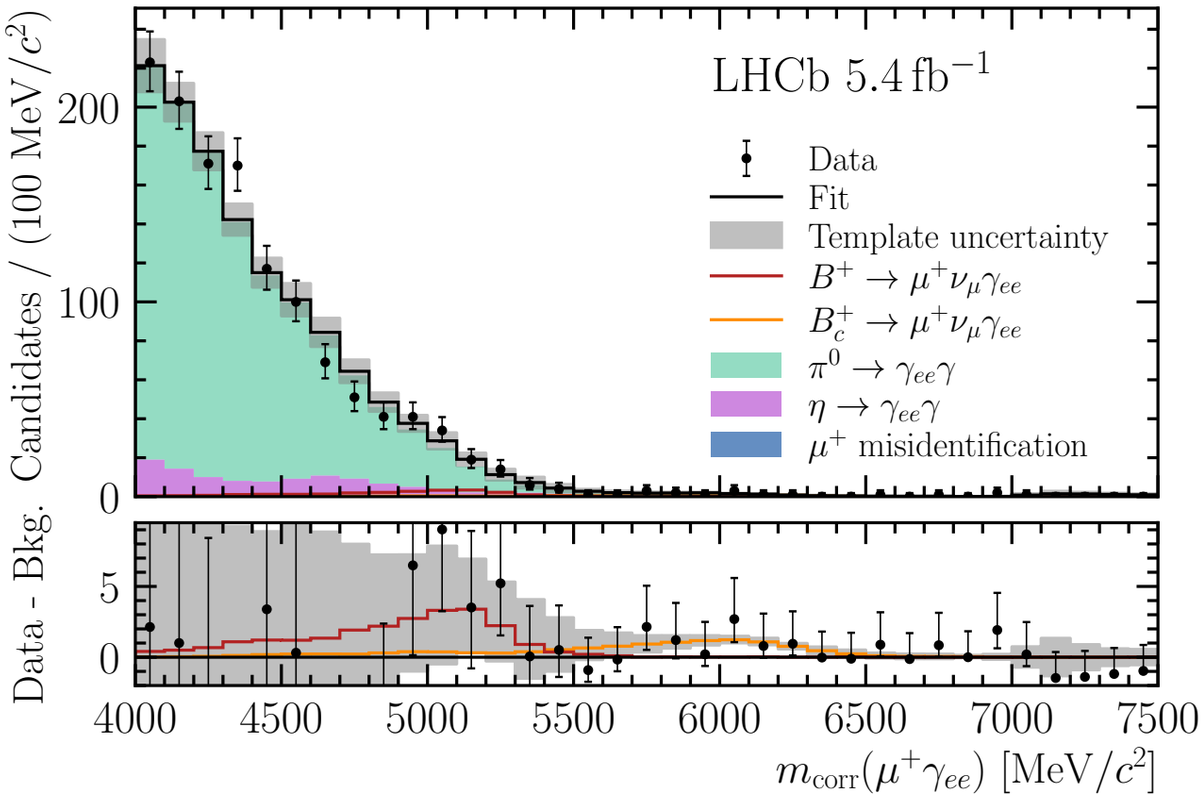
Pseudo corrected mass
taking into account lost kaon

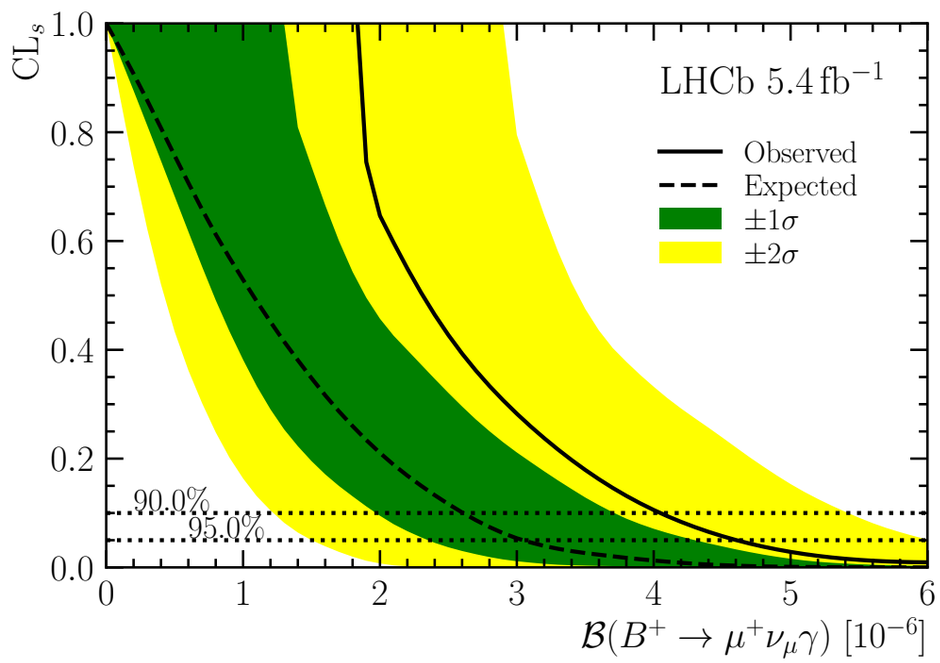
Mass fit and result

- Binned ML fit to m_{corr}
- Template statistics propagated with per-bin nuisance parameters
- No significant excess:
  - $N(B^+ \to \mu\nu\gamma) = 32 \pm 24$,
  - $N(B_c^+ \to \mu\nu\gamma) = 13^{+6}_{-5}$
  - 10% anticorrelated
- 90% CL limits with CLs using pseudoexperiments

$$\mathcal{B}\left(B^+ \to \mu^+\nu_\mu\gamma\right)_{E_\gamma^*>1\text{GeV}} < 4.0 \times 10^{-6}$$

$$\mathcal{B}\left(B_c^+ \to \mu^+\nu_\mu\gamma\right)_{E_\gamma^*>1\text{GeV}} < 1.6 \times 10^{-3}$$



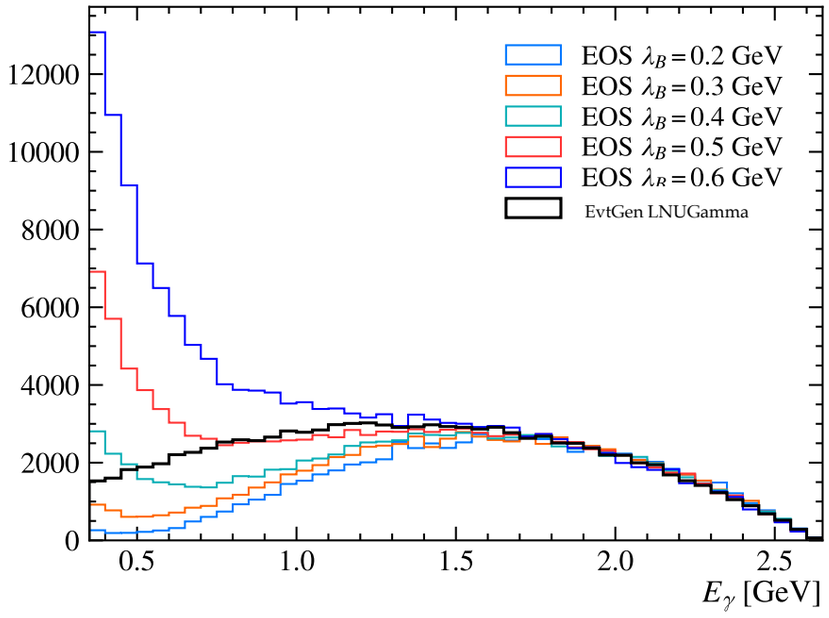


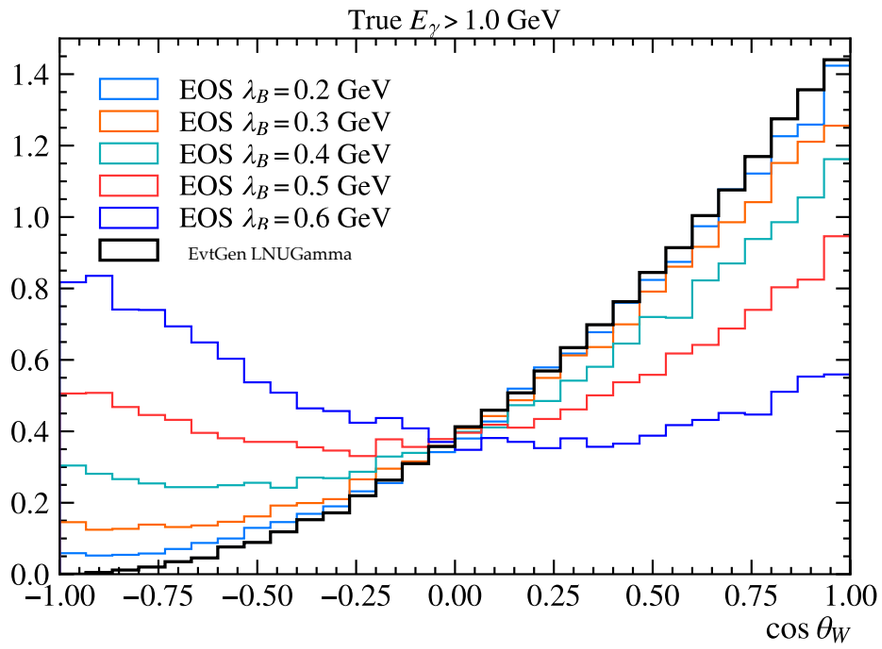
Systematic uncertainties

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu\gamma)_{E^*_\gamma>1\,\mathrm{GeV}} = (1.9 \pm 1.5 \pm 0.8 \pm 0.1) \times 10^{-6},$$
$$\mathcal{B}(B_c^+ \to \mu^+\nu_\mu\gamma)_{E^*_\gamma>1\,\mathrm{GeV}} = (9.8^{+4.6}_{-3.8} \pm 1.8 \pm 2.4) \times 10^{-4},$$

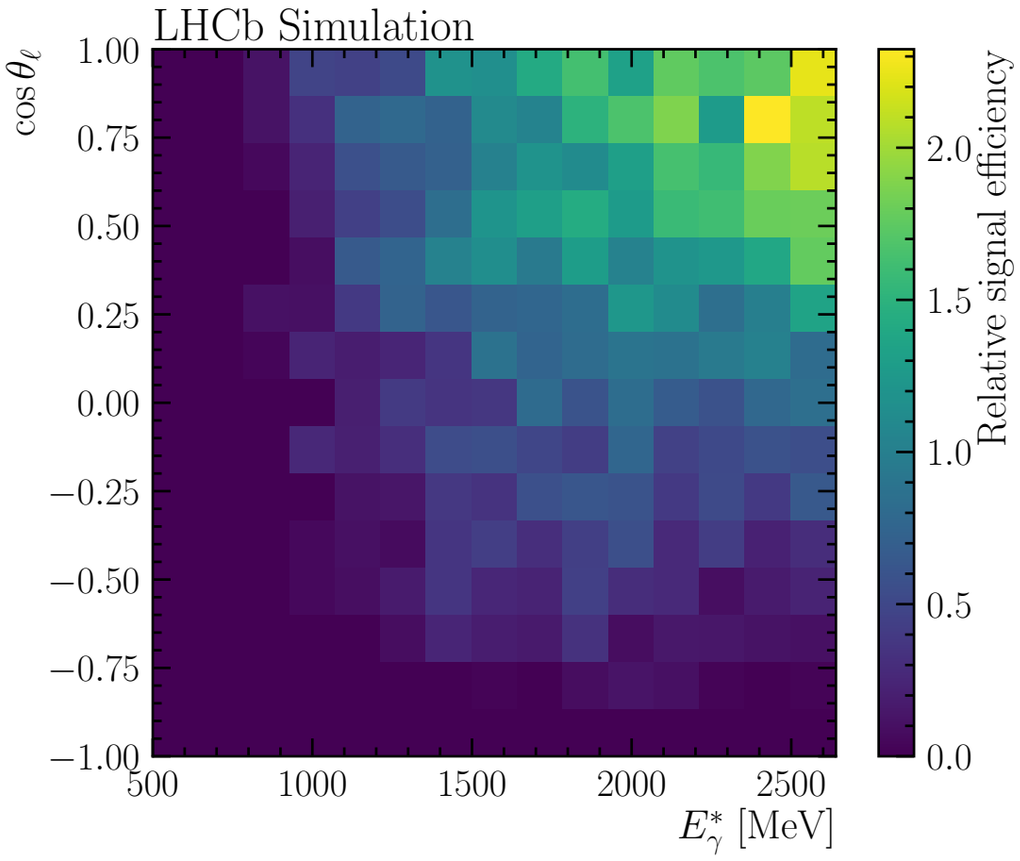
Source	$\mathcal{B}(B^+)$ $[10^{-6}]$	$\mathcal{B}(B_c^+)$ $[10^{-4}]$
$\pi^0/\ \eta$ background model	0.76	1.01
Signal model	0.21	0.92
Fit bias	0.05	0.23
Muon misidentification	0.07	0.63
Efficiency calibration	0.06	0.32
Selection efficiency	0.02	0.10
Simulation sample size	0.07	0.74
Normalization yield	0.09	0.46
$\mathcal{B}(B^0 \to K^*(892)^0\gamma)$ [46]	0.11	0.59
f_d/f_c [51]	–	2.33
Total systematic	0.80	1.79
Total external	0.11	2.40

Model dependence





- LCDA model can change significantly spectrum at low E_γ and A_{FB}
- Limited impact on mass signal shape folded into measurement
- Model dependence of the efficiency left for interpretation: maps provided
- Small efficiency below 1.5 GeV means lower sensitivity to region where QCD factorization breaks



Comparison with Belle

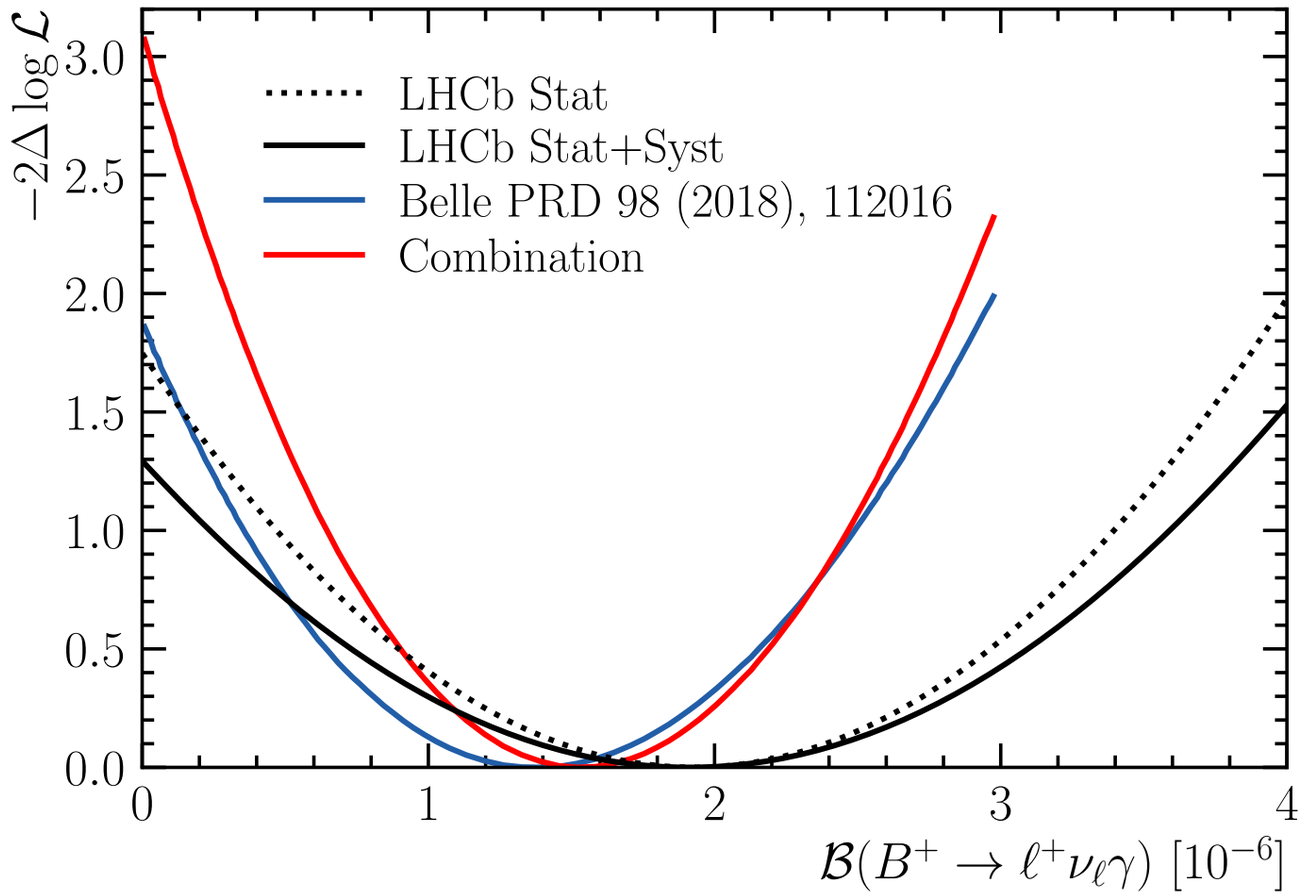
$$\mathcal{B}\left(B^+ \to \mu^+\nu_\mu\gamma\right)^{\text{LHCb}}_{E^*_\gamma>1\text{GeV}} < 4.0\times10^{-6}$$

Averaged over $\ell = e, \mu$

$$\mathcal{B}\left(B^+ \to \ell^+\nu_\mu\gamma\right)^{\text{Belle}}_{E^*_\gamma>1\text{GeV}} < 3.0\times10^{-6}$$

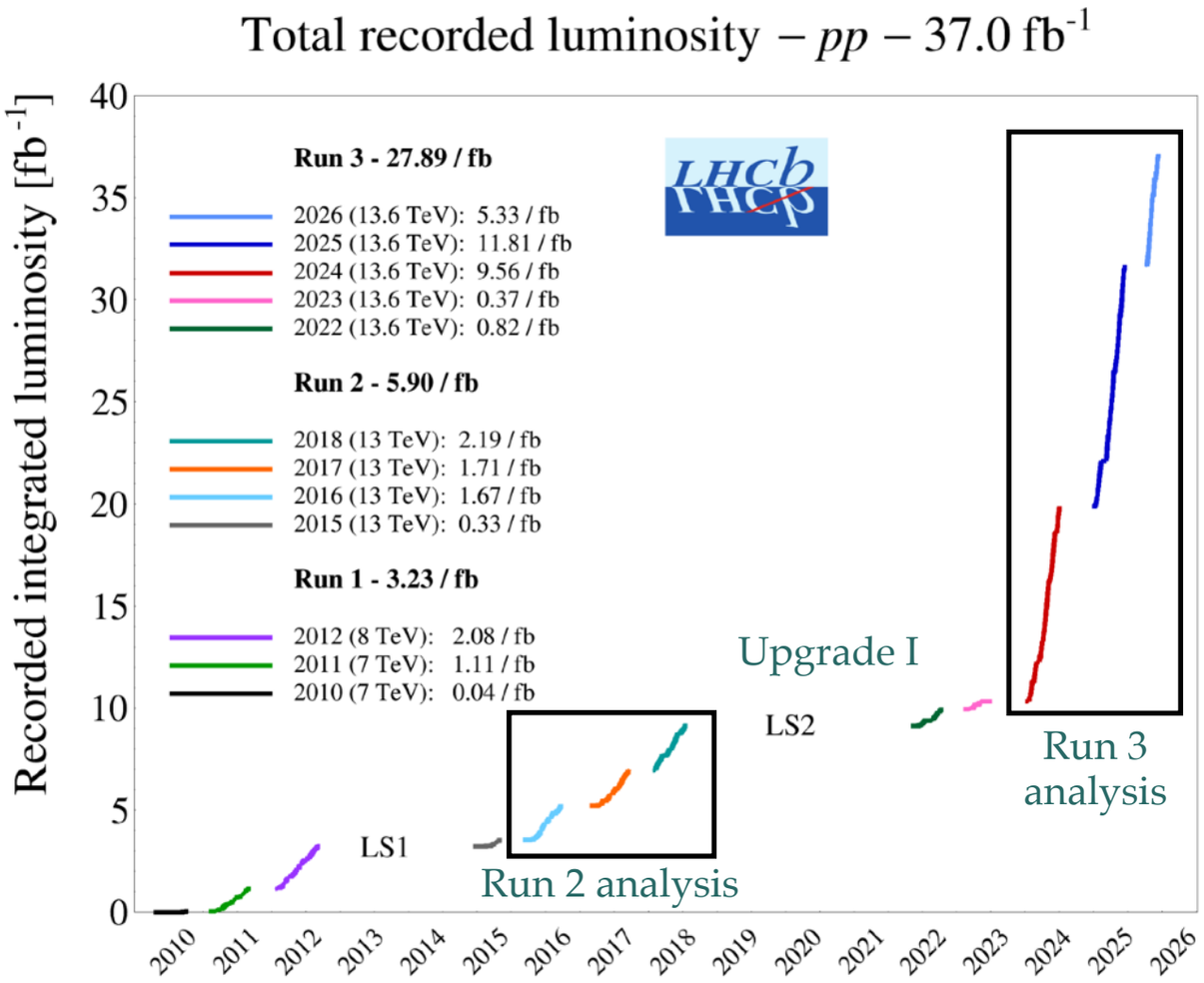
- LHCb was not expected to provide input on $B^+ \to \ell\nu\gamma$
- LHCb Run 2 result (5.4/fb) demonstrates a sensitivity close to Belle result (which was using improved hadronic tagging)
- Results perfectly compatible

Belle, *Phys.Rev.D* 98 (2018) 11, 112016
LHCb, arXiv:2607.12825

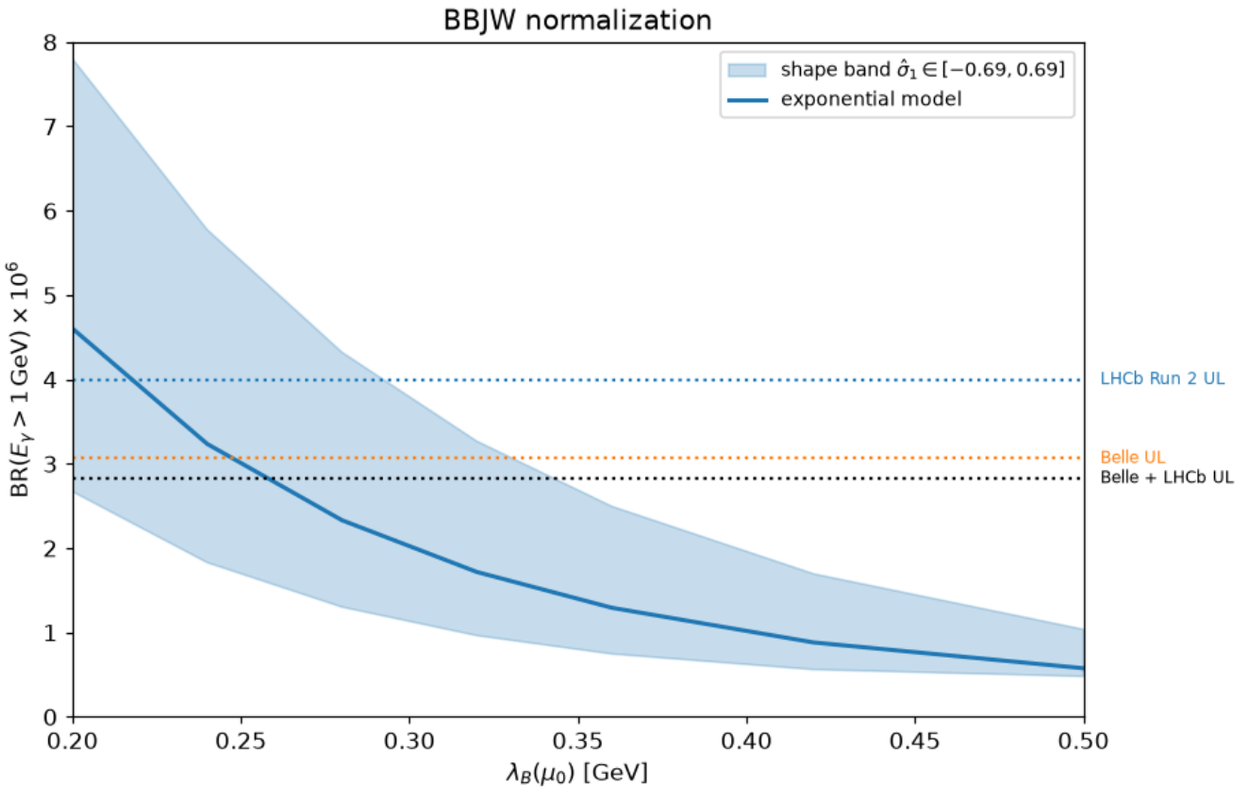


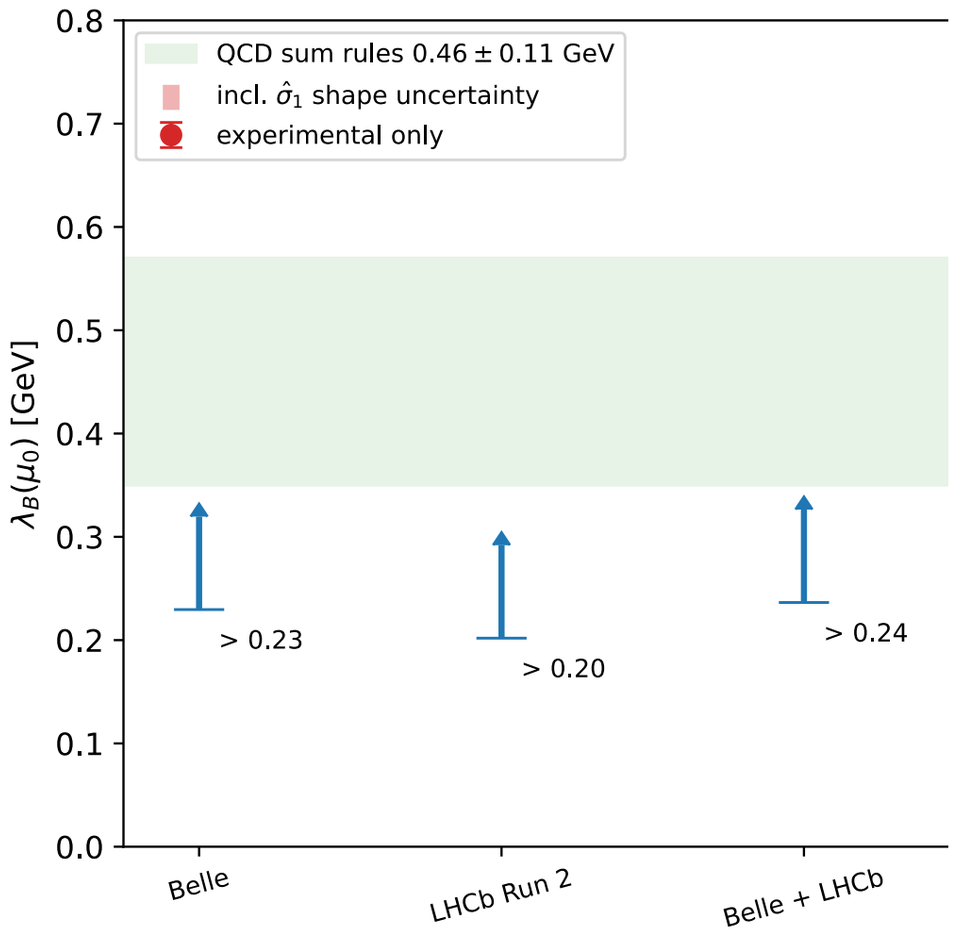
Run 3 potential

- LHCb upgraded and collected data in Run 3 with × 5 higher rate
- Upgraded to software trigger
  - no hardware trigger bottleneck for electrons
  - Dedicated software trigger for $B \to \mu\nu\gamma_{ee}$ and $B \to e\nu\gamma_{ee}$
  - Analysis WIP, first observation at reach (?)

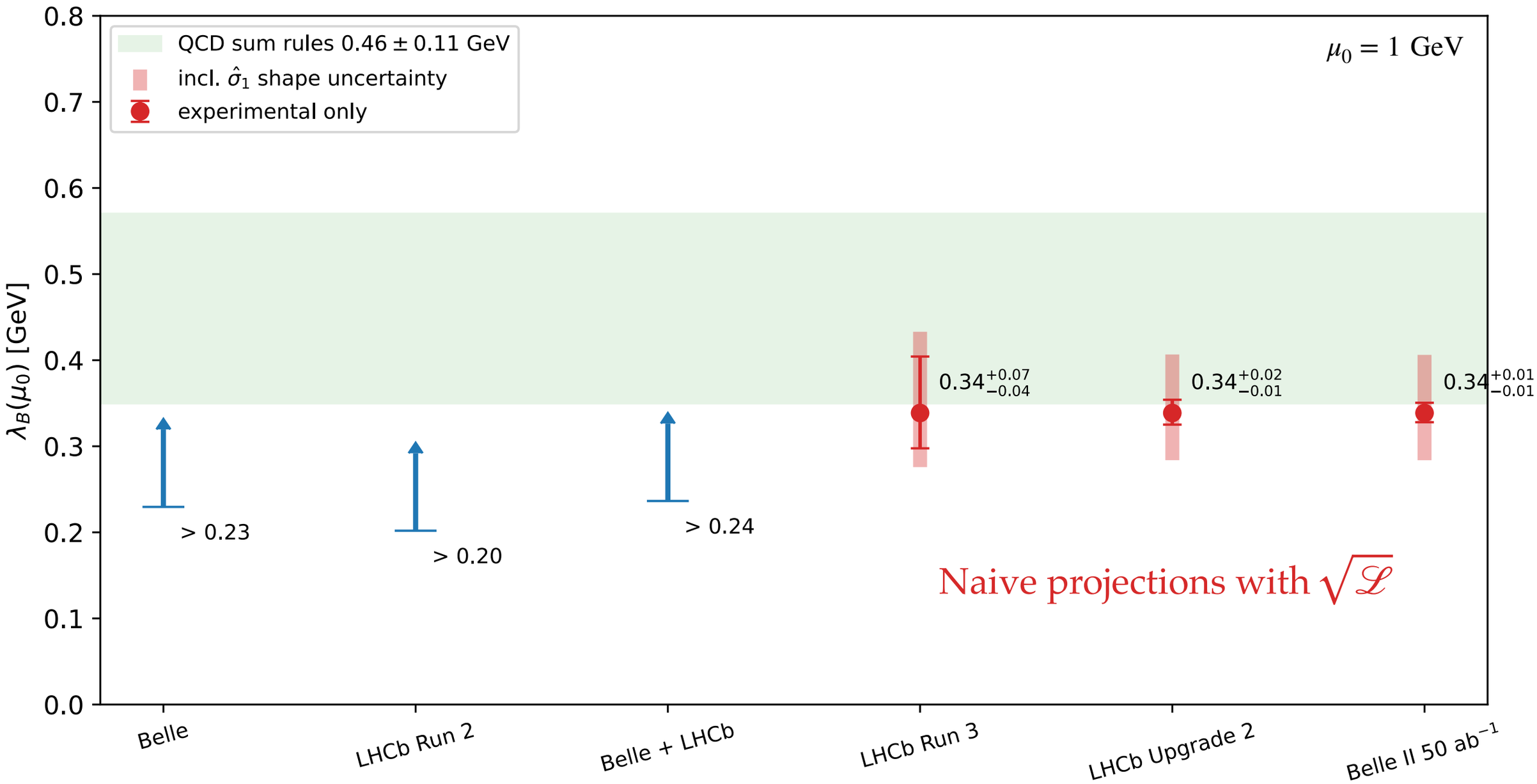


Simplified interpretation as λ_B





Naive projections



Naive projections with $\sqrt{\mathscr{L}}$

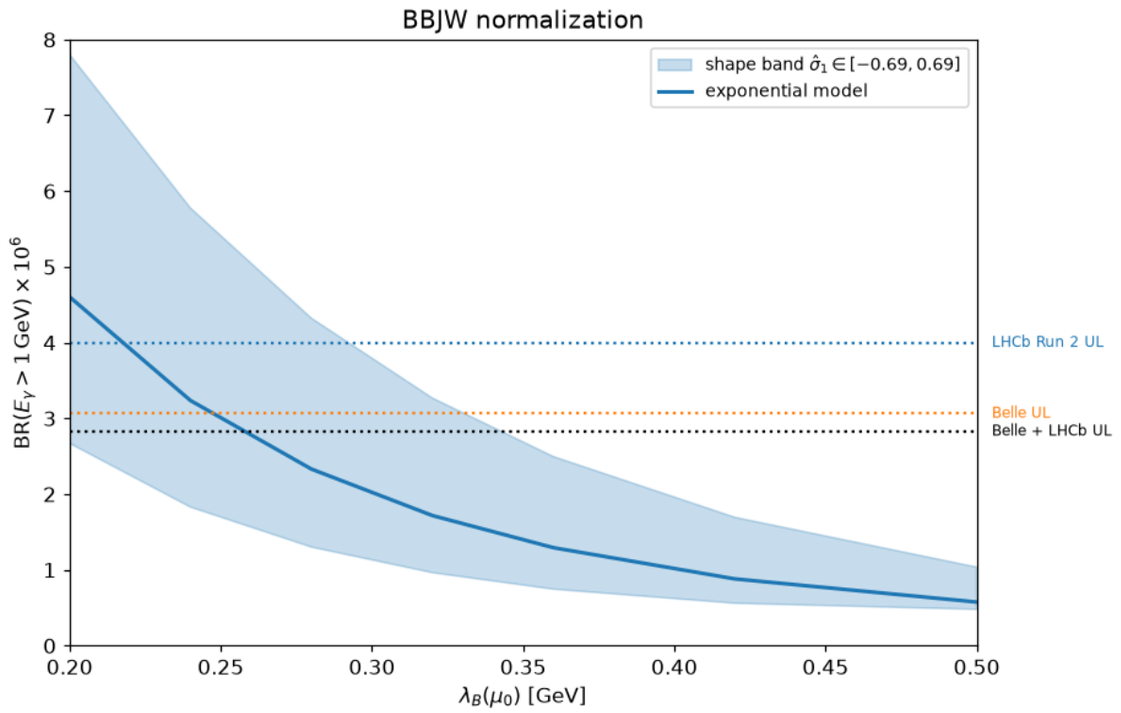
+potentially measure $d\Gamma/dE_\gamma$

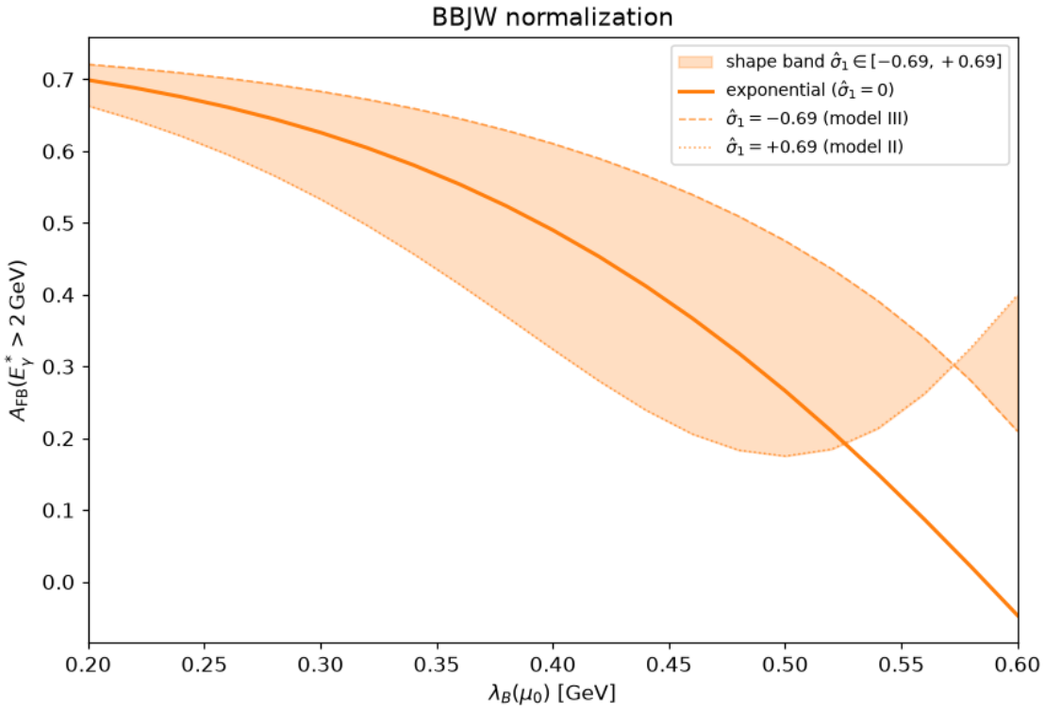
Measuring a_{FB}?

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{\mathrm{em}} G_F^2 |V_{ub}|^2}{6\pi^2} m_B E_\gamma^3 \left(1 - \frac{2E_\gamma}{m_B}\right)\left[|F_V|^2 + |\hat{F}_A|^2\right]$$

$$a_{\mathrm{FB}}(E_\gamma) = \frac{3}{2} \frac{\mathrm{Re}\, F_V \hat{F}_A^*}{|F_V|^2 + |\hat{F}_A|^2}$$

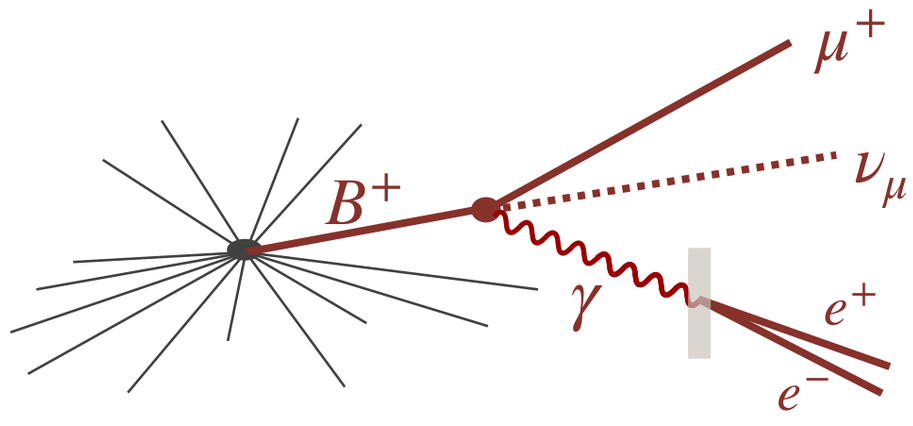
- The forward-backward asymmetry a_{FB} is sensitive to λ_B and the LCDA shape and it is insensitive to the normalisation of the form factors
- Better sensitivity than BR for large λ_B
- Probably very hard to measure due to background modelling in $\cos\theta_\ell$



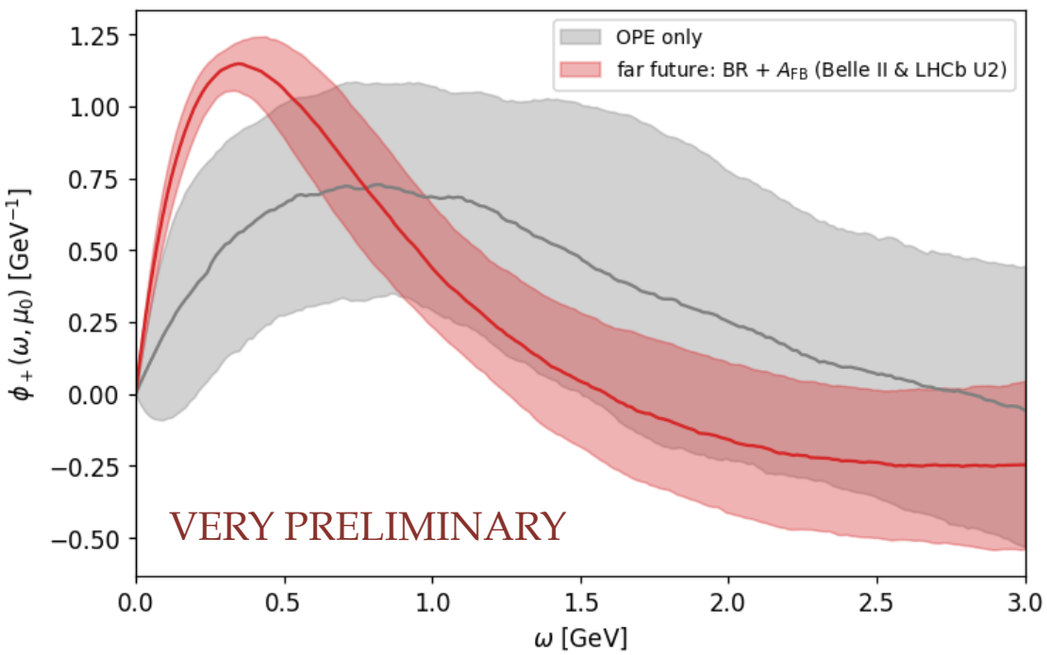


Conclusions

- First search for $B^+ \to \mu^+\nu\gamma$at a hadron collider and first ever experimental investigation of $B_c^+ \to \mu^+\nu\gamma$ ever, enabled by photon conversions technique
- $\mathcal{B}(B^+ \to \ell^+\nu\gamma) < 4.0 \times 10^{-6}$ at 90% CL is competitive with Belle and close to SM
- $\mathcal{B}(B_c^+ \to \ell^+\nu\gamma) < 1.6 \times 10^{-3}$ is 20–80 times higher than SM predictions
- The published likelihoods + efficiency maps make the result reinterpretable for any LCDA model
- **Outlook**: LHCb Run 3 has a chance of first observation and a λ_B experimental determination
- **Farther future**: Belle II 50 ab^{-1} and LHCb Upgrade 2 reach ~5% on λ_B, with potential for $d\Gamma/dE_\gamma$ and a first a_{FB} measurement → measure full LCDA

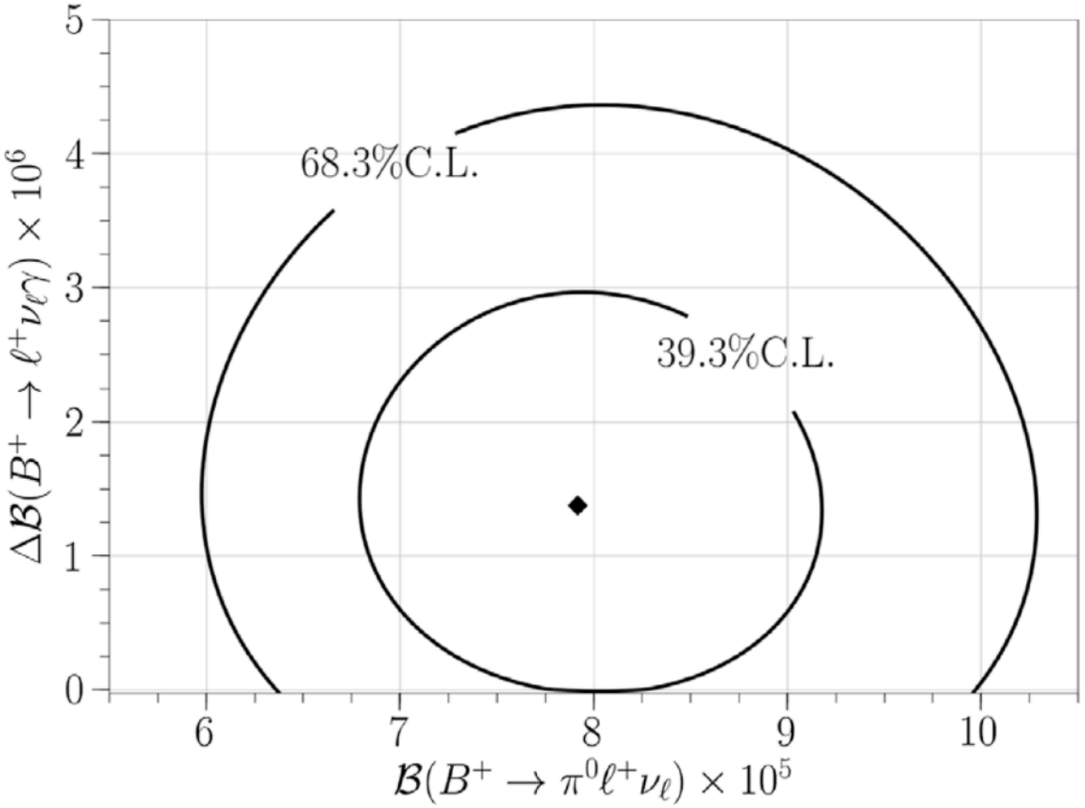


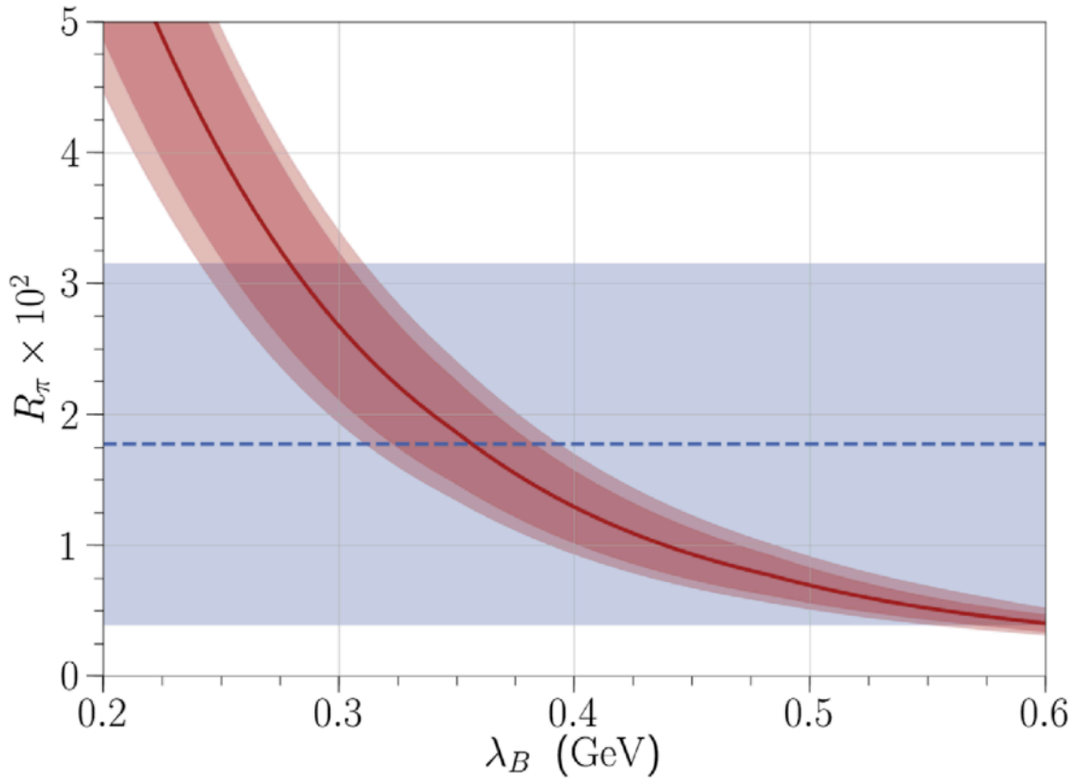
EOS study inspired by P.Lughausen PhD thesis (Ch 4)



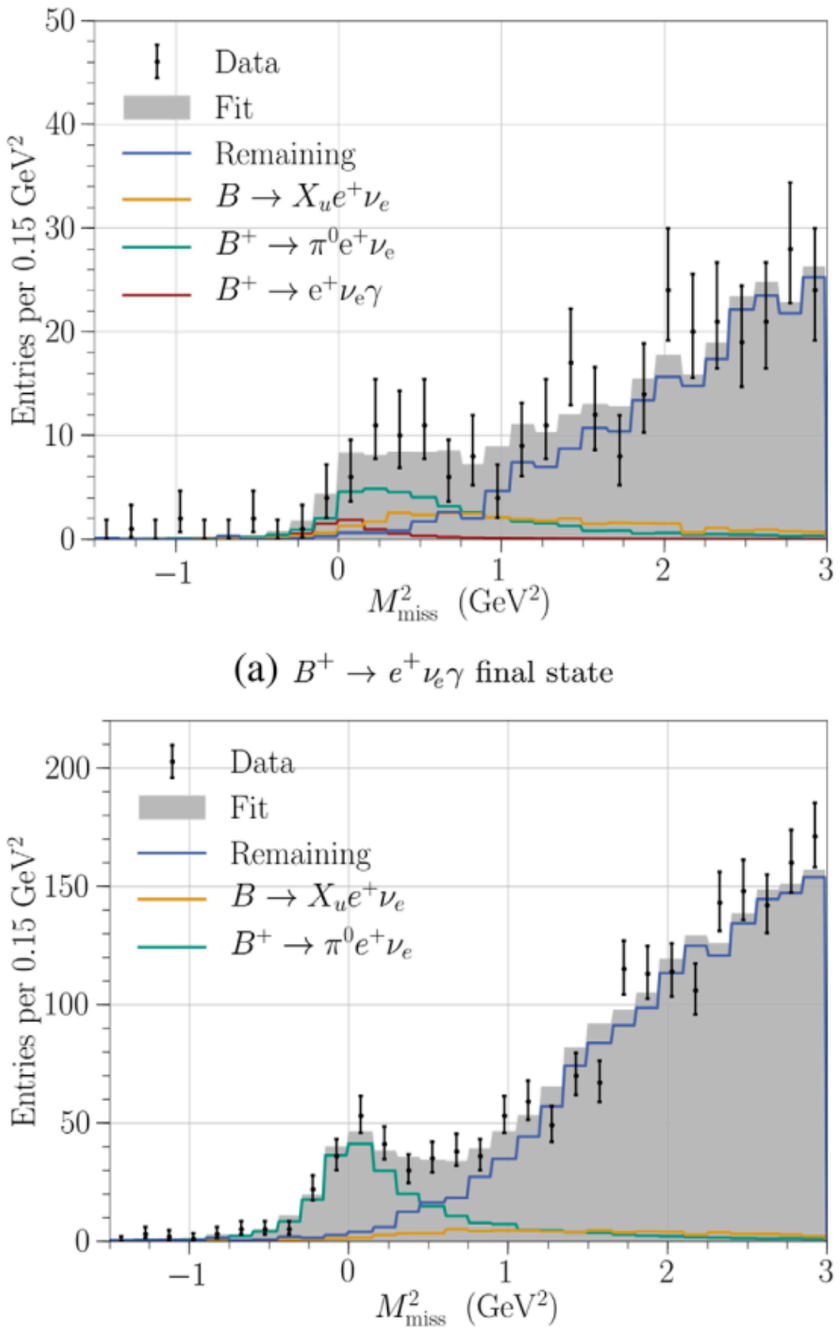
Backup

Belle measurement

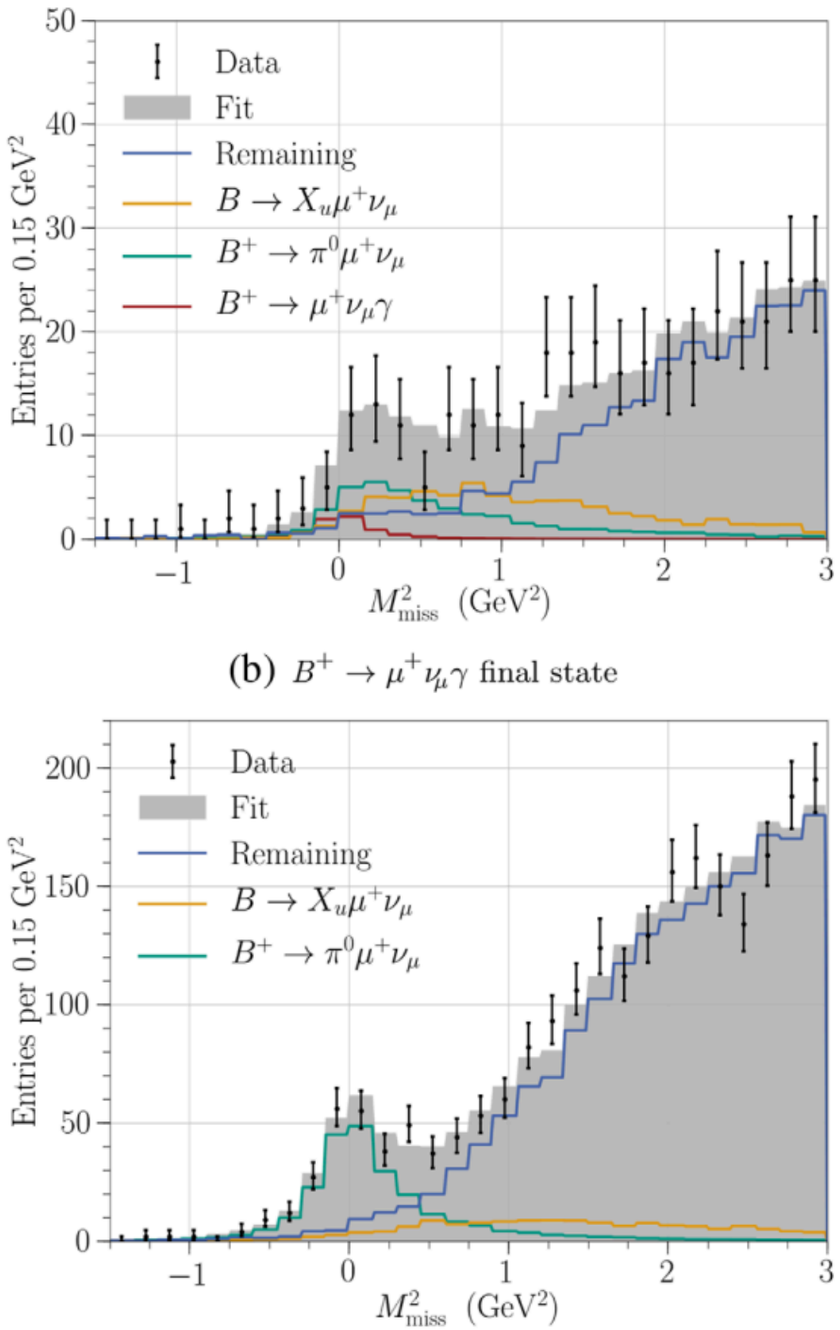




Belle measurement



(a) $B^+ \to e^+ \nu_e \gamma$ final state



(b) $B^+ \to \mu^+ \nu_\mu \gamma$ final state

(c) $B^+ \to \pi^0 e^+ \nu_e$ final state

(d) $B^+ \to \pi^0 \mu^+ \nu_\mu$ final state