Search for $B \to \ell \bar{\nu}_\ell \gamma$ with Belle & (naive) Prospects with Belle II

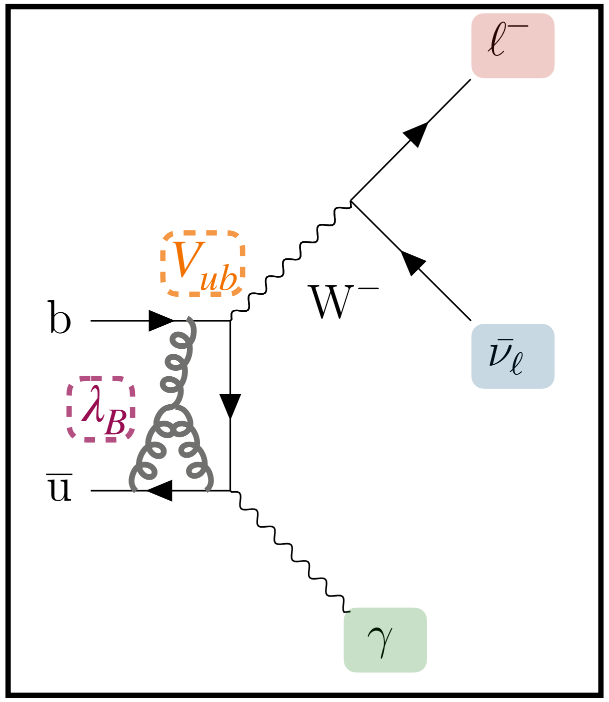
Based on Phys. Rev. D 98, 112016 (2018) and

Thesis of Dr. Moritz Gelb https://publish.etp.kit.edu/record/21546

Florian Bernlochner (florian.bernlochner@uni-bonn.de)

Setting the Scene

Why : Access to λ_B and also in principle $|V_{ub}|$



How : Exploit experimental signature

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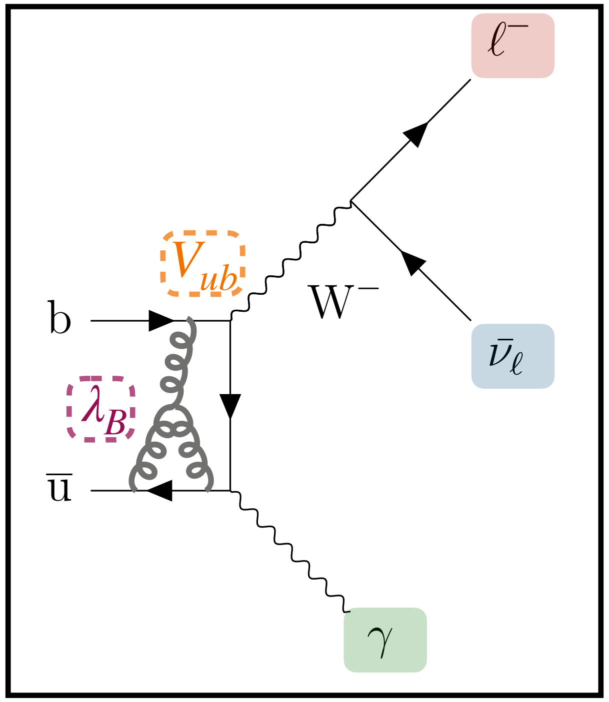

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High momentum lepton → Other processes do as well, e.g. $B \to X_u \ell \bar{\nu}_\ell$; need good PID

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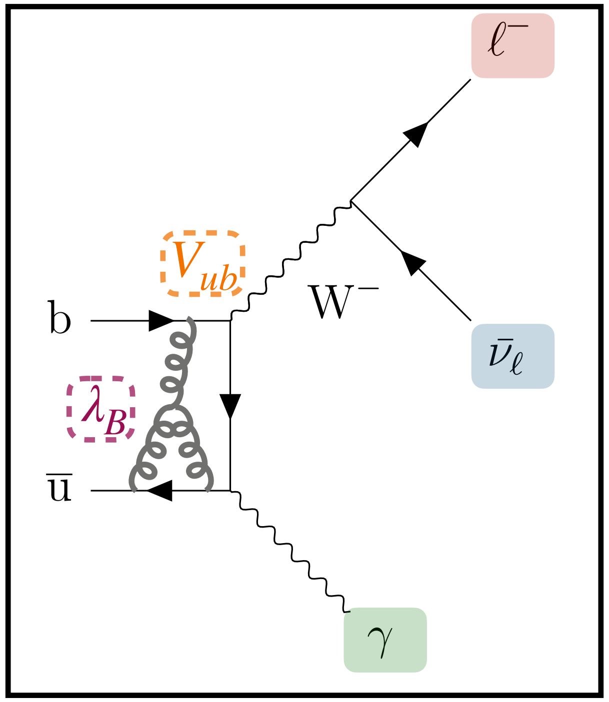

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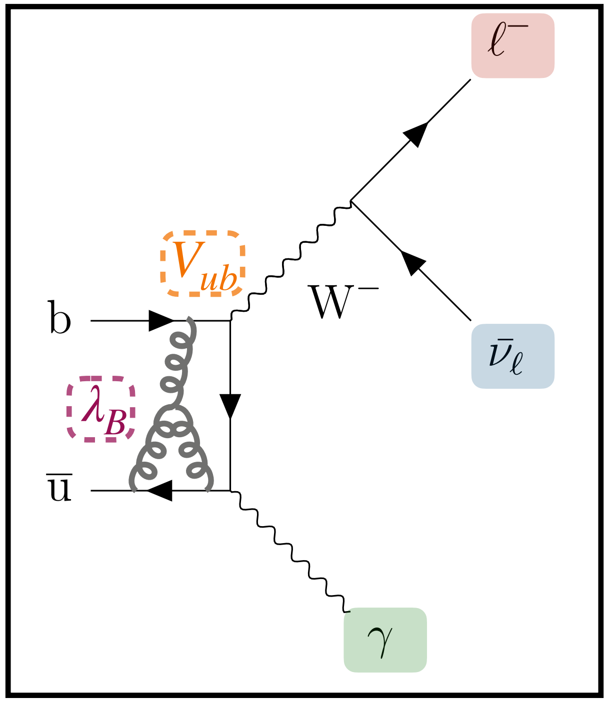

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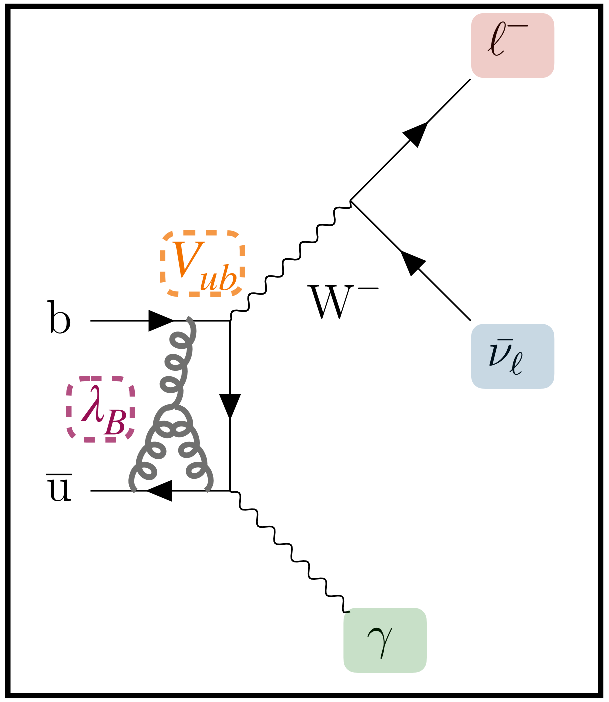

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Missing Energy	→	Need information about rest of event (ROE)
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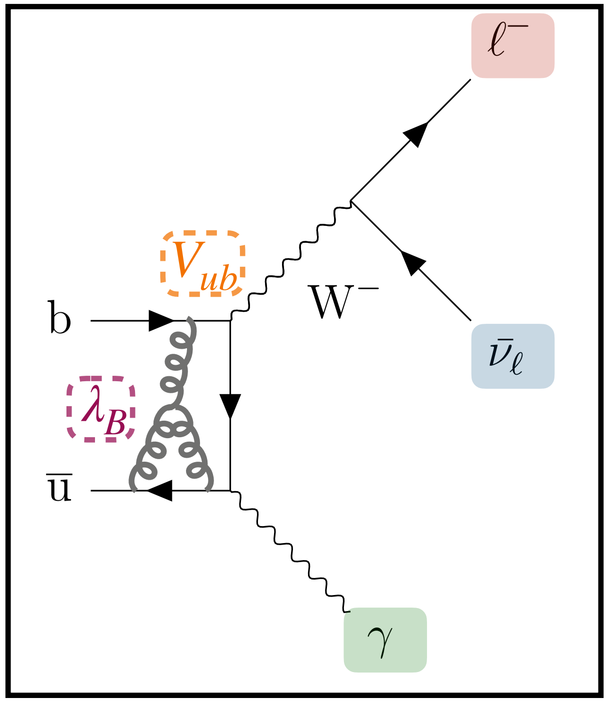
Other considerations: low BF ~ 10^{-6}

Important Backgrounds : $B \to [\pi^0 \to]\gamma\gamma\ell\bar{\nu}_\ell$ $B \to [\eta \to]\gamma\gamma\ell\bar{\nu}_\ell$

Search uses full Belle data set of 711/fb, will talk a bit about Belle II prospects later

Looking back



Status before this Measurement

Experiment	Data set (fb^{-1})	Limit 90% C.L. (10^{-6})	Comment
CLEO (1997) [15]	2.5	$\mathcal{B}(\mathrm{B}^+ \to e^+\nu_e\gamma) < 52$	–
		$\mathcal{B}(\mathrm{B}^+ \to \mu^+\nu_\mu\gamma) < 200$	–
BaBar (2009) [2]	423	$\mathcal{B}(\mathrm{B}^+ \to e^+\nu_e\gamma) < 17$	model-independent
		$\mathcal{B}(\mathrm{B}^+ \to \mu^+\nu_\mu\gamma) < 24$	model-independent
		$\mathcal{B}(\mathrm{B}^+ \to \ell^+\nu_\ell\gamma) < 15.6$	model-independent
		$\Delta\mathcal{B}(\mathrm{B}^+ \to \ell^+\nu_\ell\gamma) < 14$	with $E_\gamma > 1\,\mathrm{GeV}$
Belle (2015) [1]	711	$\Delta\mathcal{B}(\mathrm{B}^+ \to e^+\nu_e\gamma) < 6.1$	with $E_\gamma > 1\,\mathrm{GeV}$
		$\Delta\mathcal{B}(\mathrm{B}^+ \to \mu^+\nu_\mu\gamma) < 3.4$	with $E_\gamma > 1\,\mathrm{GeV}$
		$\Delta\mathcal{B}(\mathrm{B}^+ \to \ell^+\nu_\ell\gamma) < 3.5$	with $E_\gamma > 1\,\mathrm{GeV}$

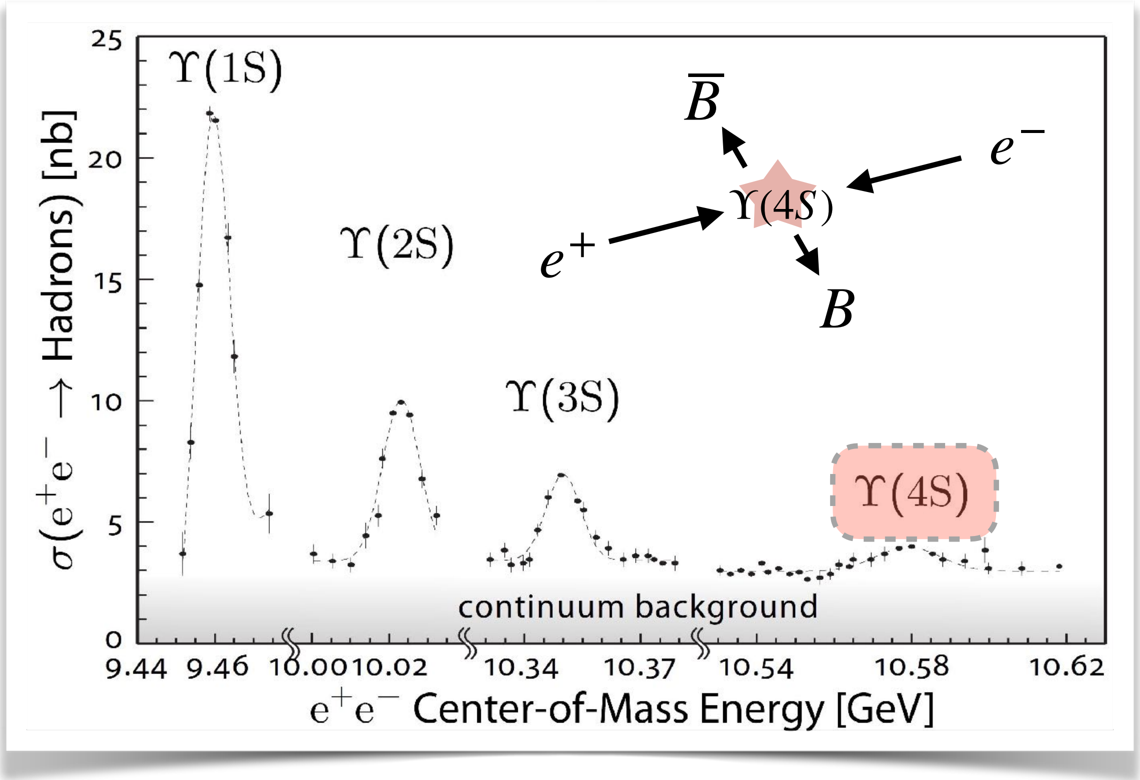
→

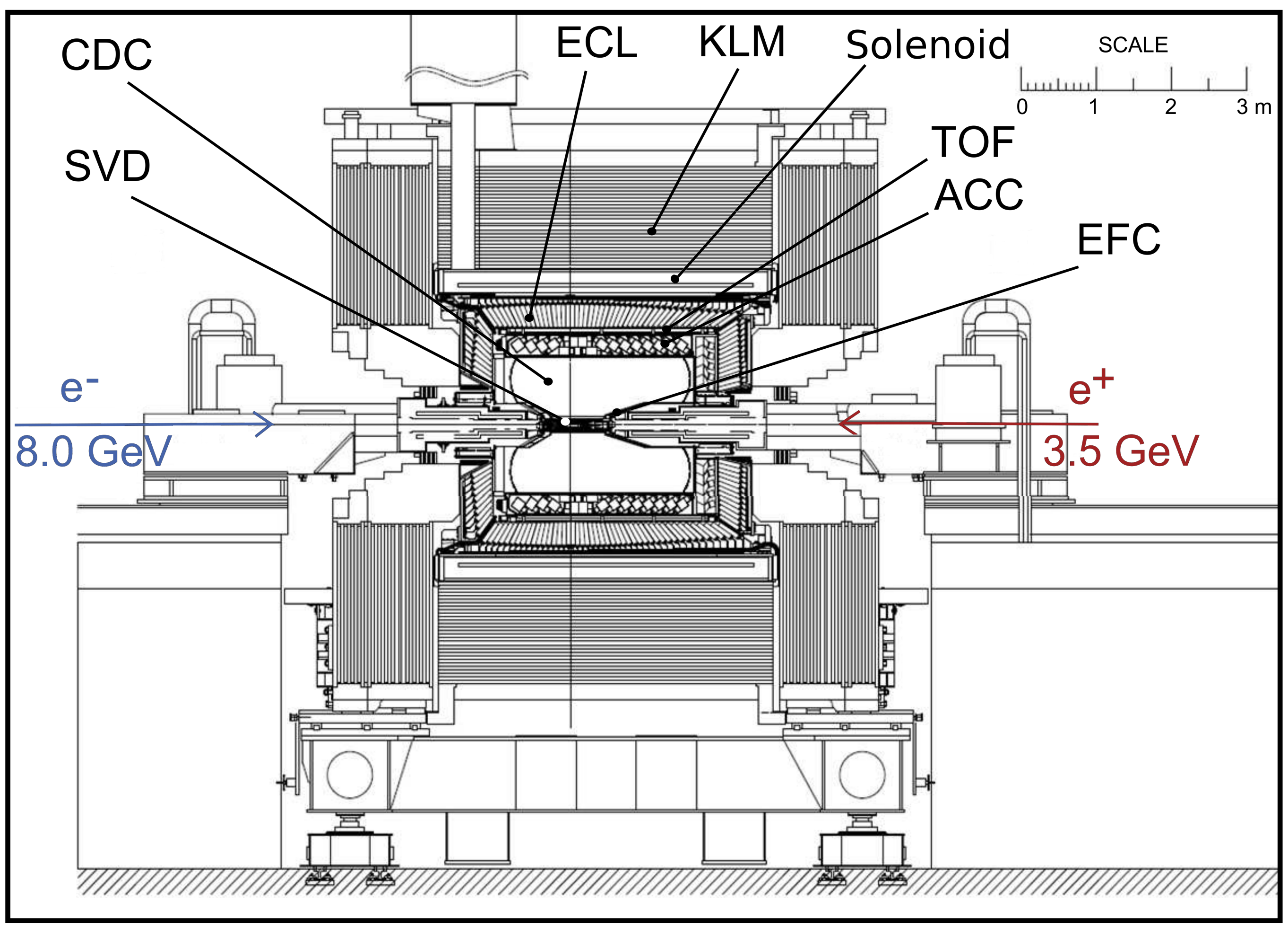
	$B^+ \to e^+\nu_e\gamma$	$B^+ \to \mu^+\nu_\mu\gamma$	Combined
N_{New}	24.8	25.7	50.5
$N_{\mathrm{Published}}$	8.0	8.7	16.5

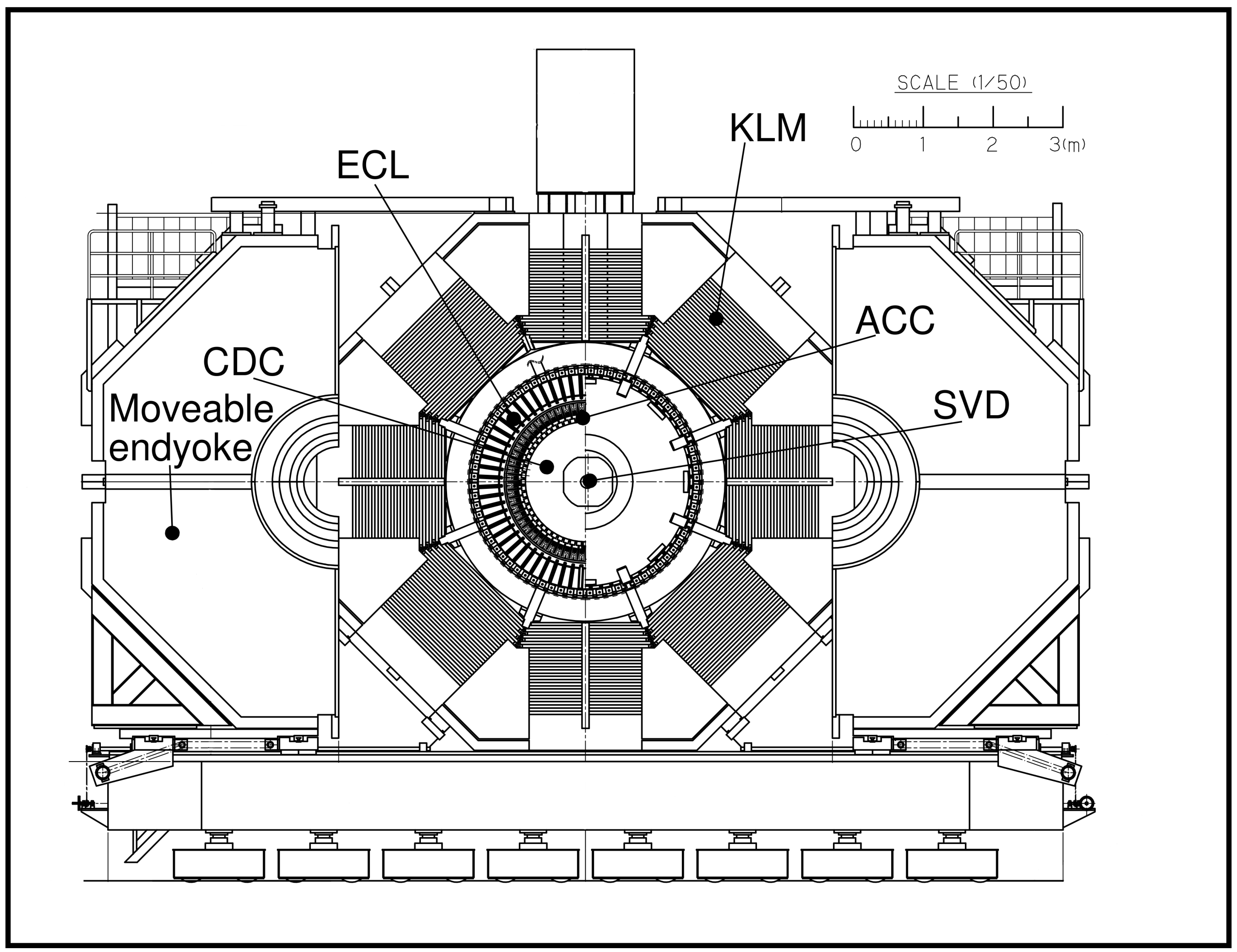
New analysis strategy : **factor ~ 3 higher signal efficiency**

Belle accumulated significant data set on the $\Upsilon(4S) = \langle b\bar{b} \rangle$.

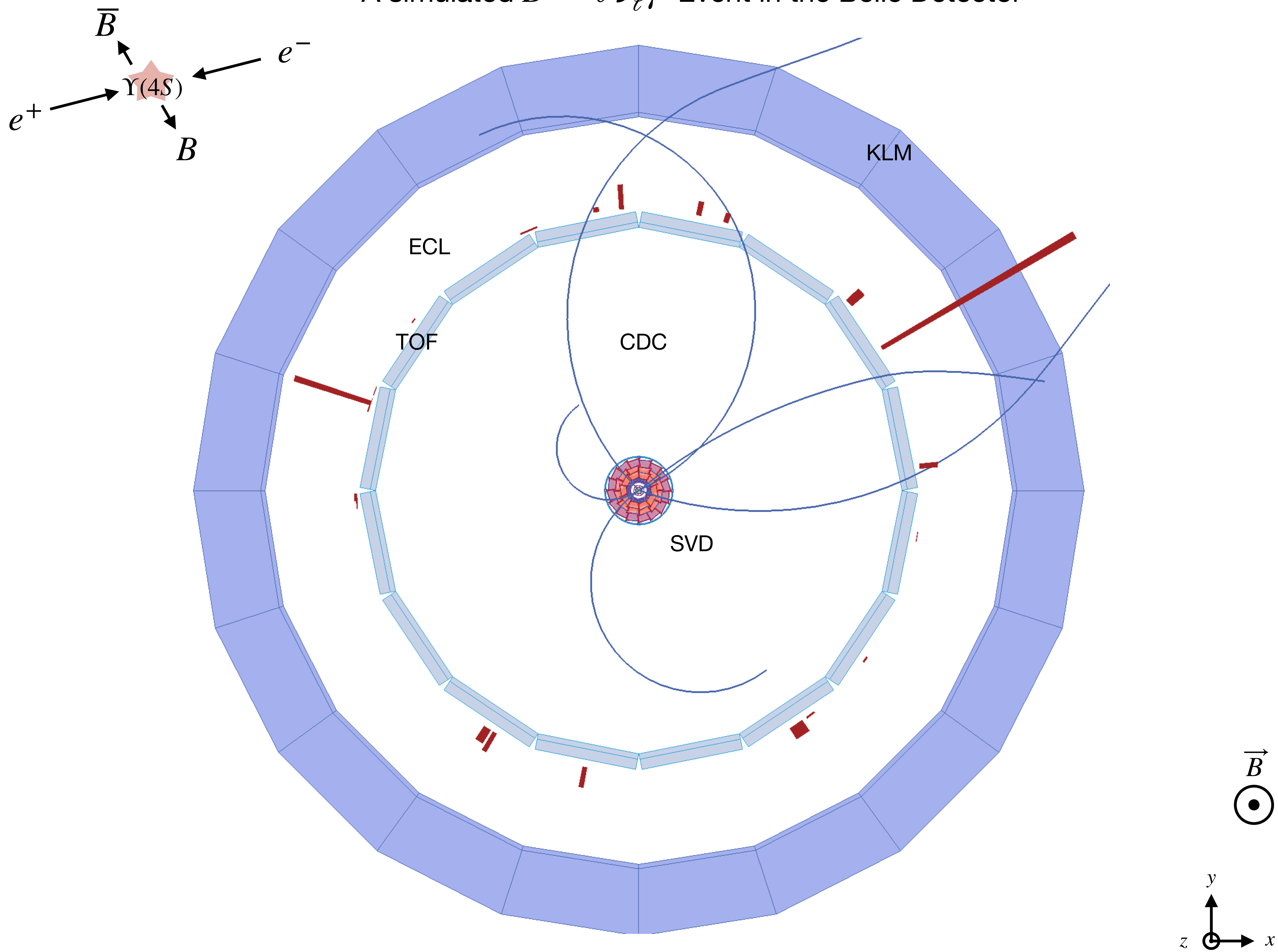
Detector has near 4π coverage, fine EM calorimeter & PID capabilities

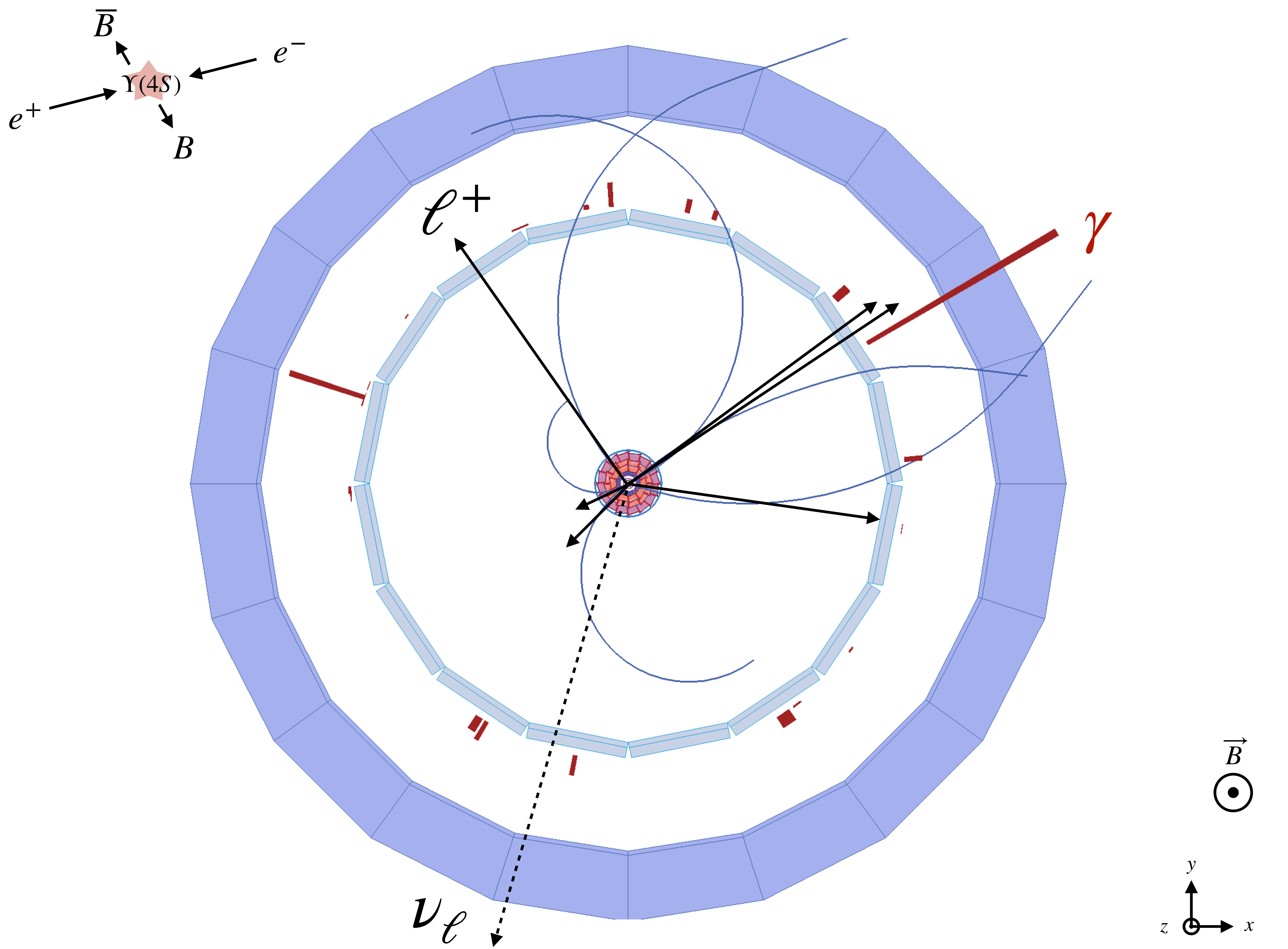






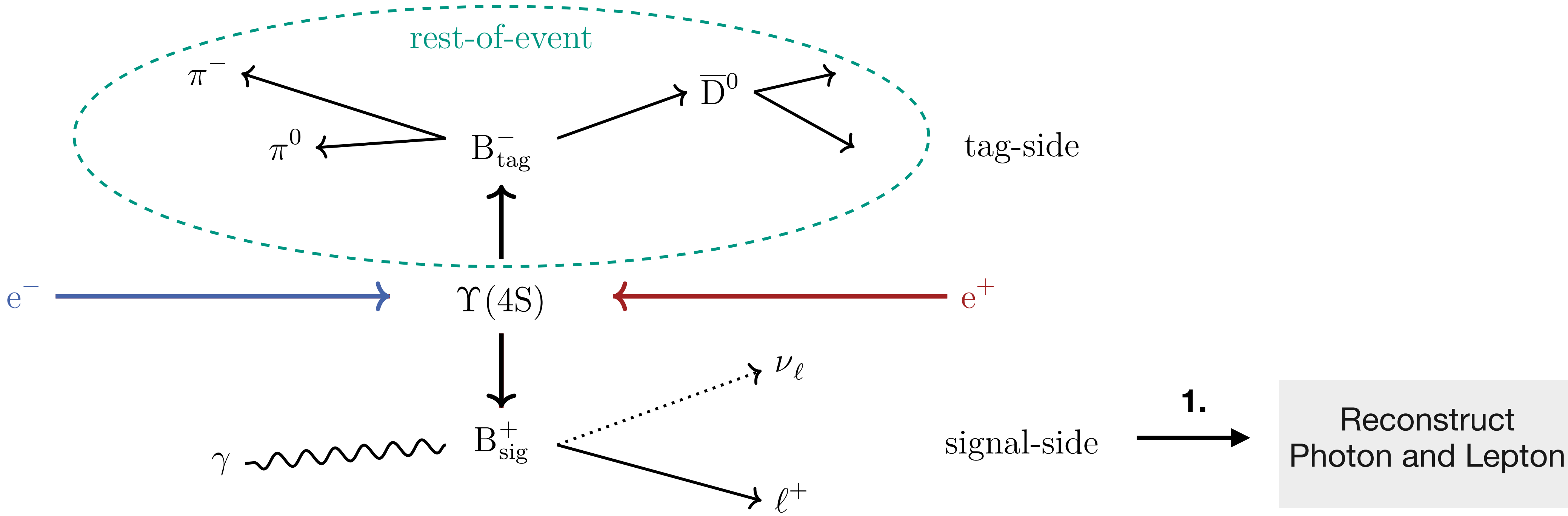
A simulated $B \to \ell \bar{\nu}_\ell \gamma$ Event in the Belle Detector





$\overline{B}$
e^-
$\Upsilon(4S)$
e^+
B
ℓ^+
γ
ν_ℓ
$\vec{B}$
y
z
x

Analysis in a nutshell



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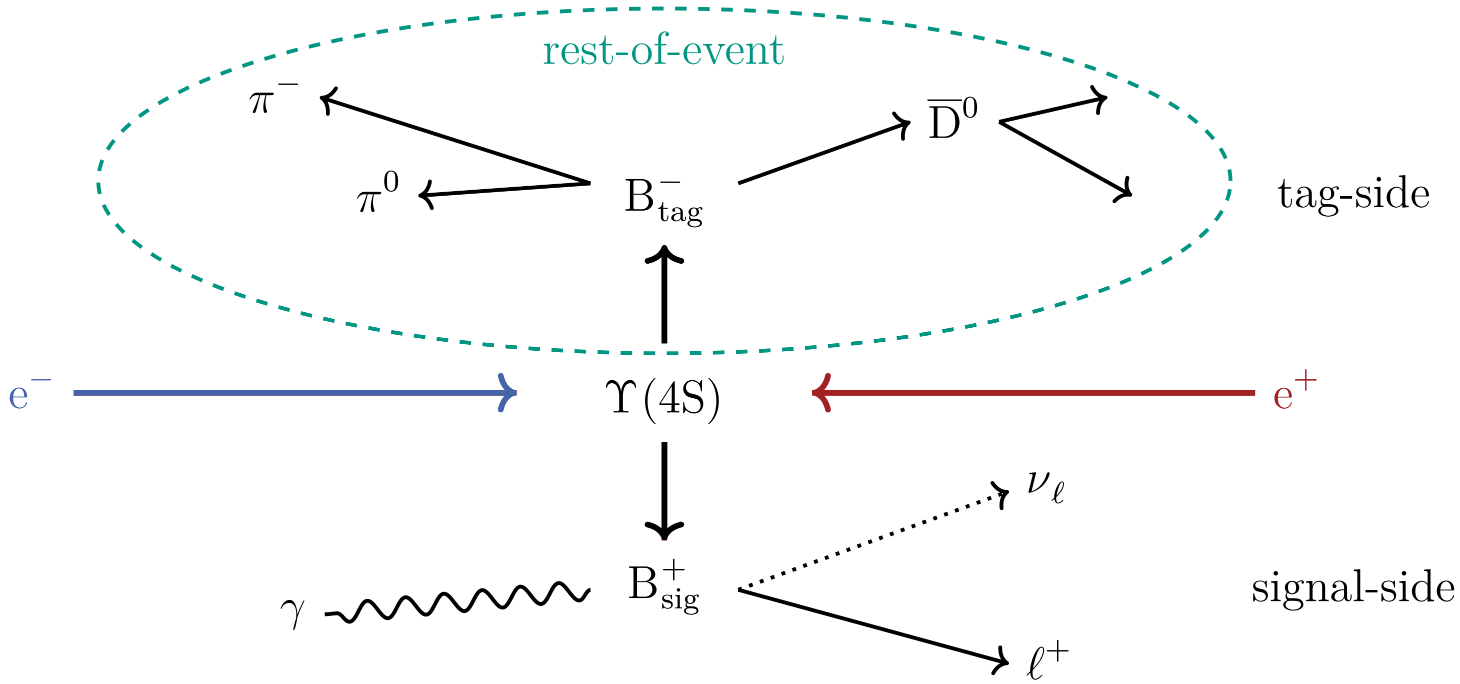

2. Reconstruct in hadronic modes

= no unassigned particles

1. Reconstruct Photon and Lepton

No additional unassigned particles allowed

'completeness constraint'

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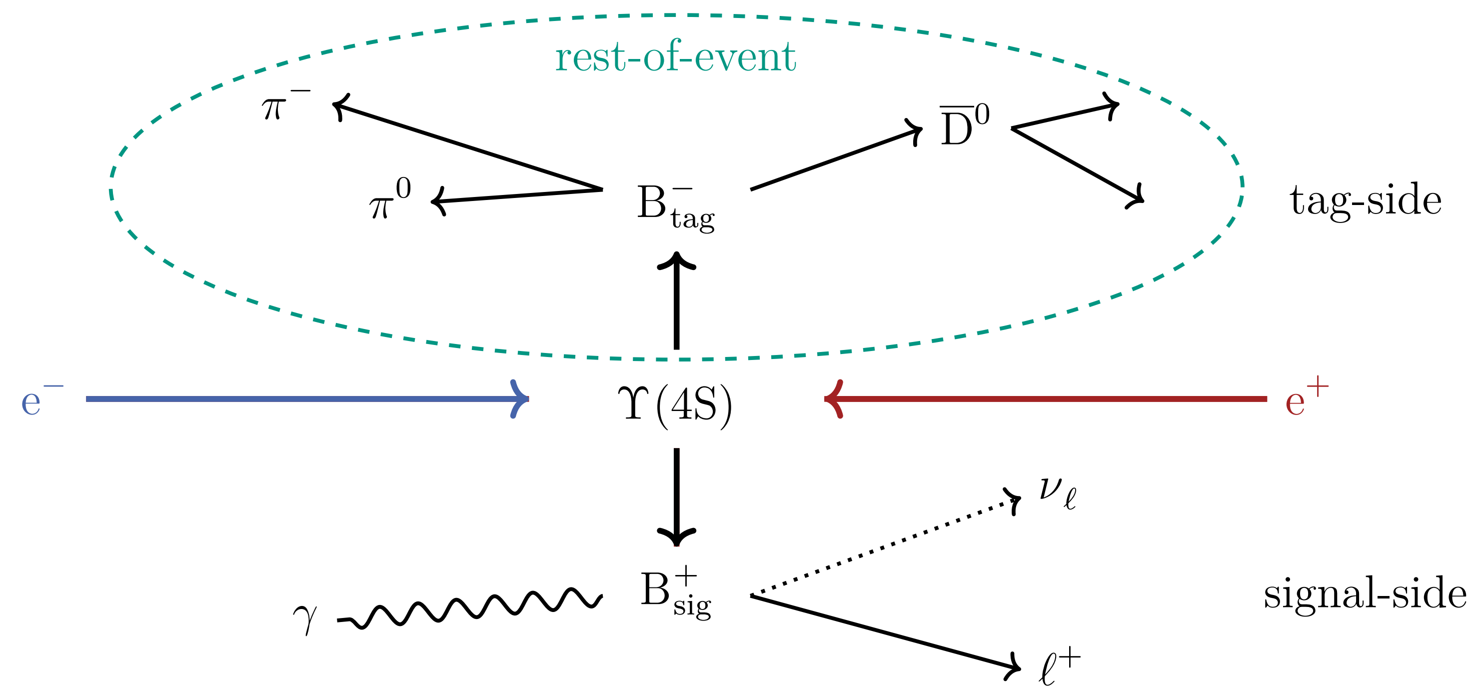

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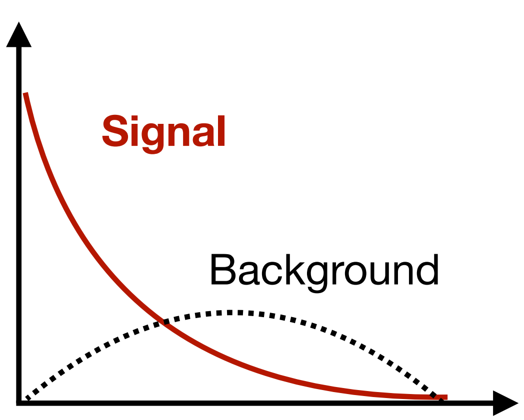
3. Veto against events with large **unassigned** neutral energy depositions



$$E_{\mathrm{ECL}} = \sum E_{\mathrm{cluster}}$$

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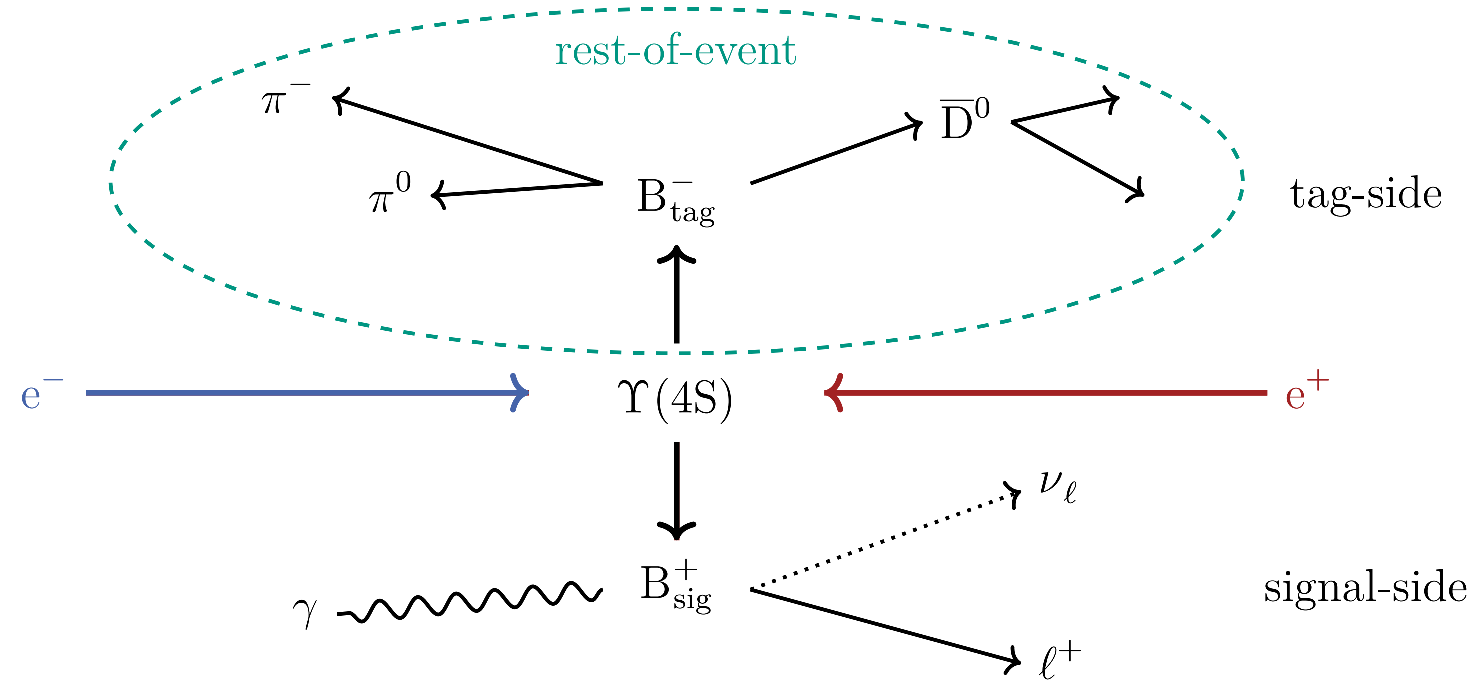

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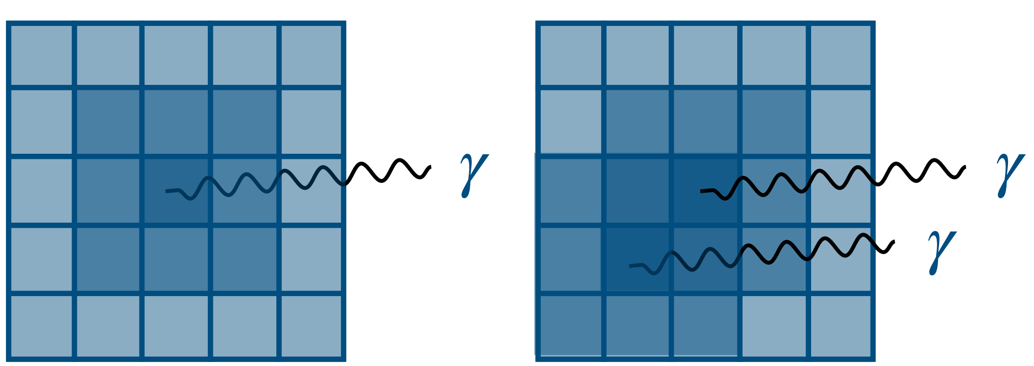
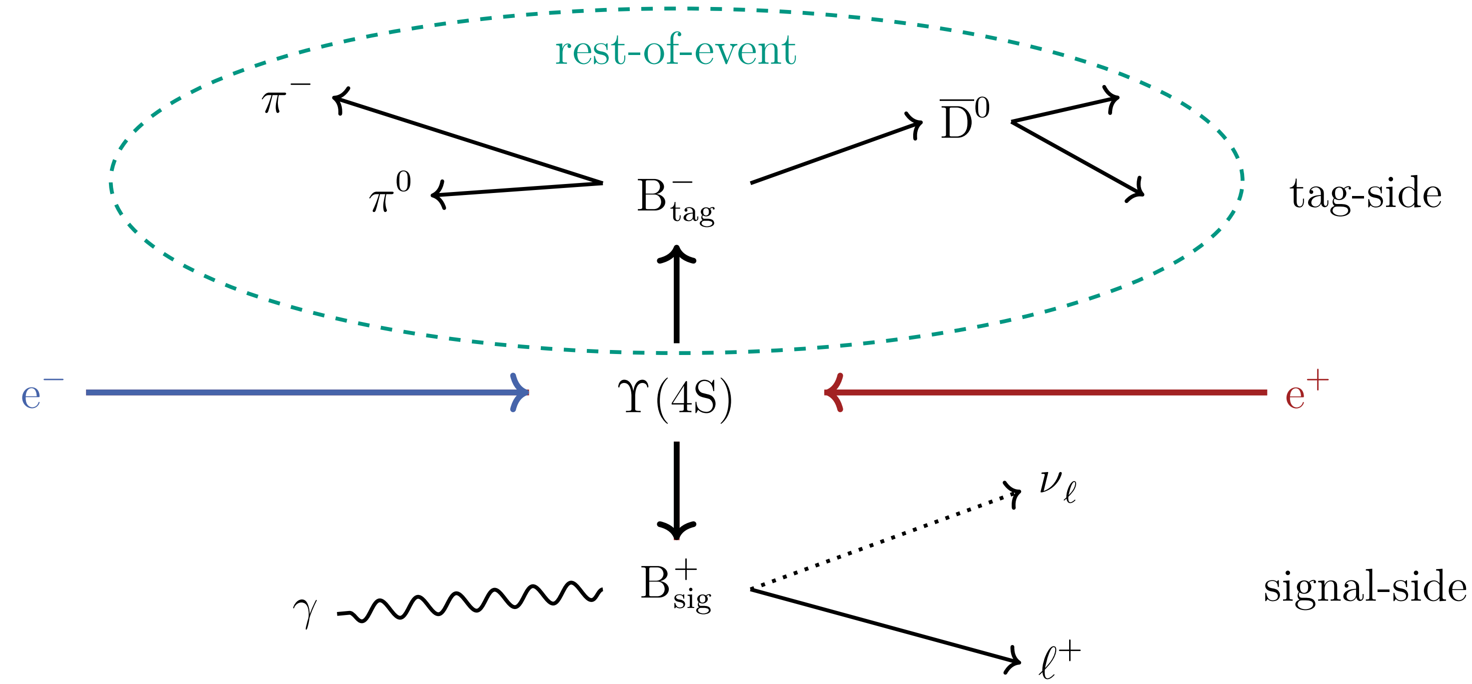
4. Use calorimeter granularity to veto against **collimated** $\gamma\gamma$



$$E9E25 = \frac{\sum_{3x3} E_i}{\sum_{5x5} E_i}$$

→ Close to 1 = **narrow** EM shower (cut : 0.9)

Analysis in a nutshell



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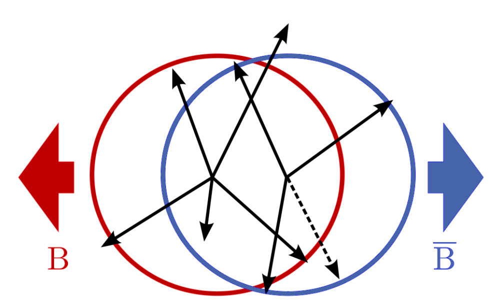
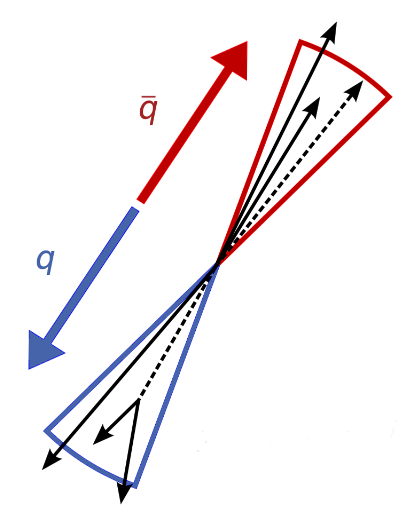
5. Use event information to further suppress backgrounds





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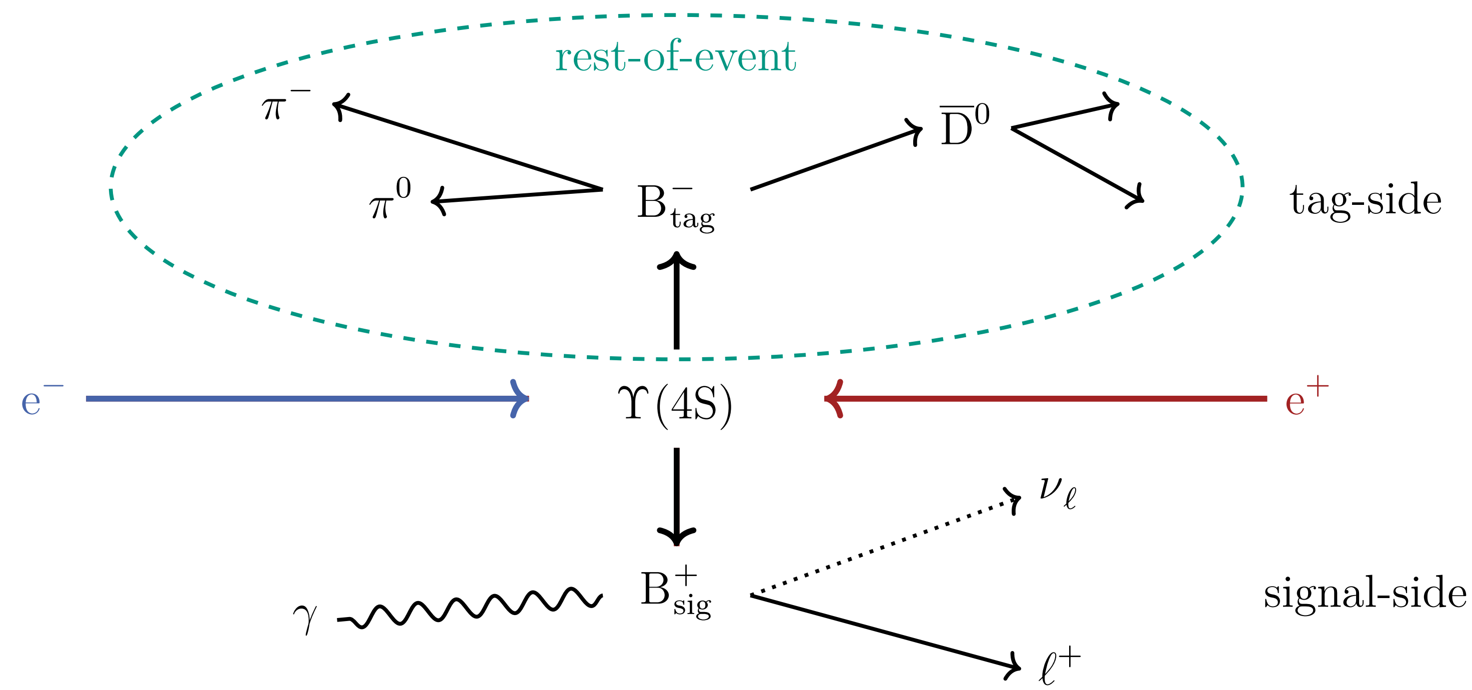

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6. Explicitly reconstruct dominant peaking background to constrain its presence

$$B \to [\pi^0 \to]\gamma\gamma\ell\bar{\nu}_\ell$$

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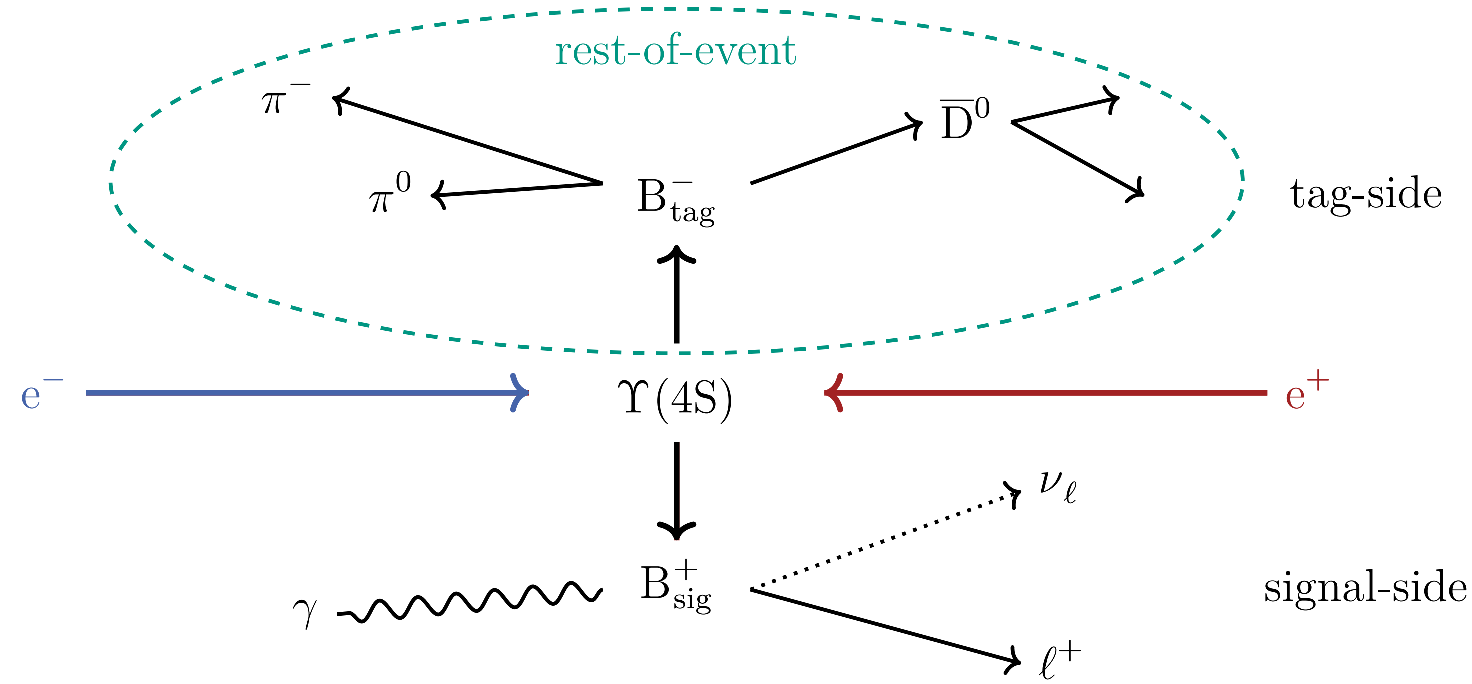

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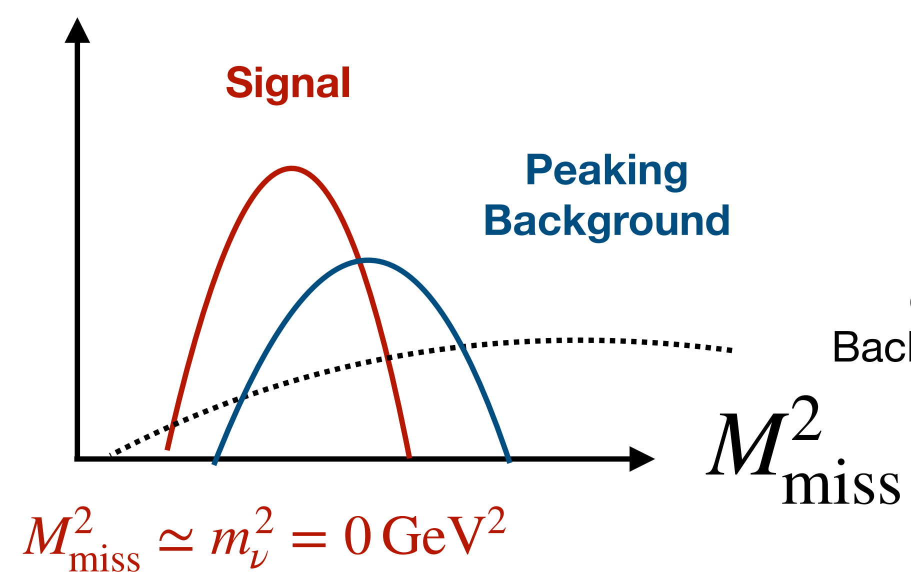
No additional unassigned particles allowed



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4. Use calorimeter granularity to veto against **collimated** $\gamma\gamma$

5. Use event information to further suppress backgrounds

6. Explicitly reconstruct dominant peaking background to constrain its presence

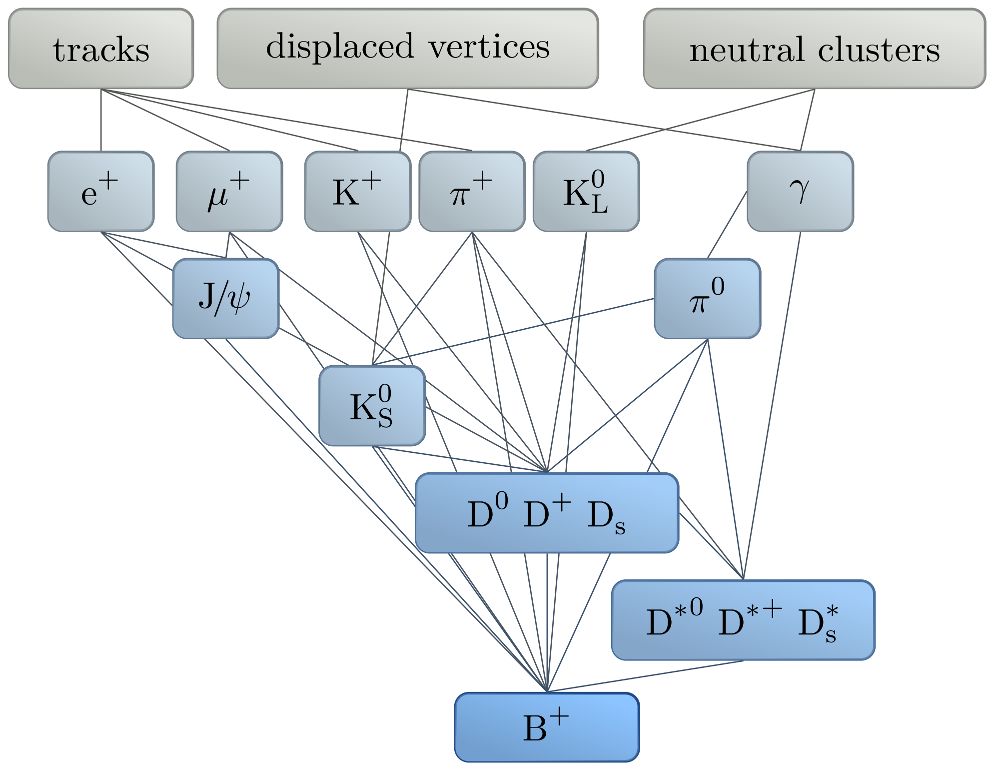
7. Fit $M^2_{\mathrm{miss}} = (p_{\mathrm{B_{sig}}} - p_\ell - p_\gamma)^2$ and discover or set limits

$$= \left(\begin{pmatrix} \frac{E_{\mathrm{CMS}}}{2c} \\ -\vec{p}_{\mathrm{B_{tag}}} \end{pmatrix} - p_\ell - p_\gamma \right)^2, \quad \simeq m^2_\nu$$

Hadronic Tagging

Reconstruct second B using a hierarchical reconstruction approach — the so-called **Full Event Interpretation**

arXiv:1807.08680 [hep-ex]



Stage 0 Collection of final state particles reconstructed from clusters and tracks.

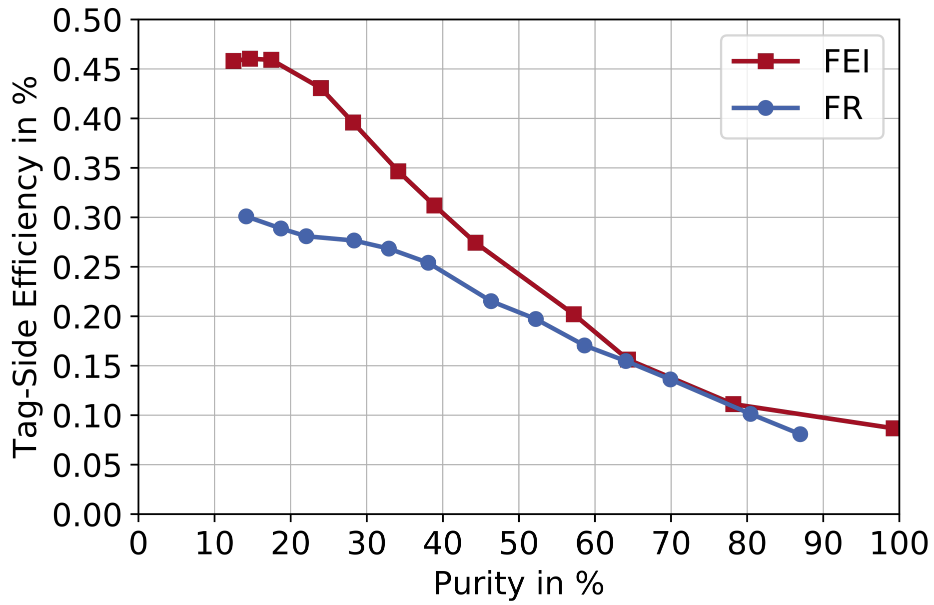
Stage 1 Reconstruction of π^0 and J/ψ candidates.

Stage 2 Reconstruction of K^0_S candidates.

Stage 3 Reconstruction of D candidates.

Stage 4 Reconstruction of D^* candidates.

Stage 5 Reconstruction of B candidates.

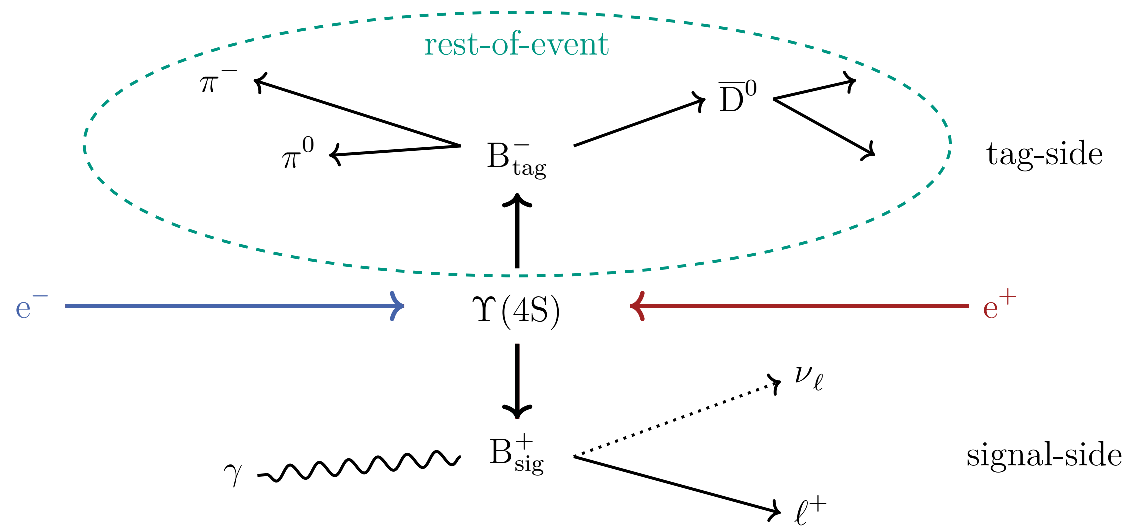


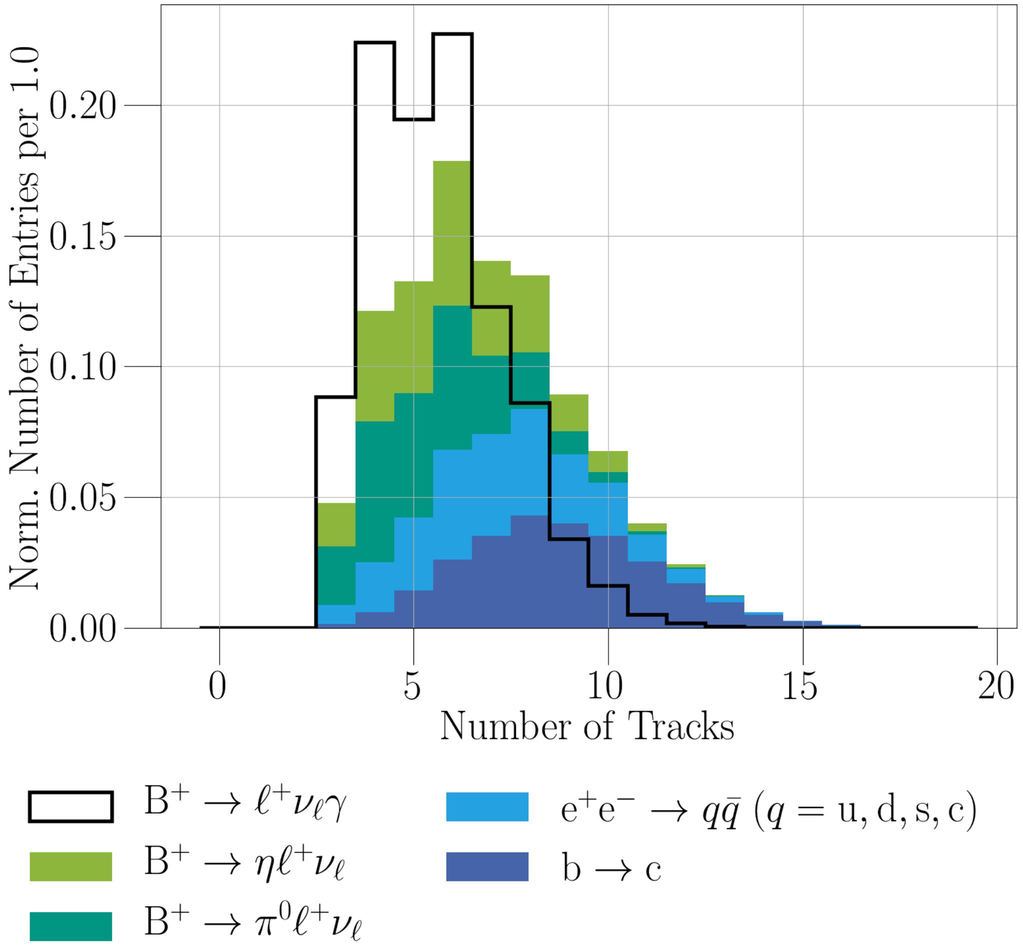
Algorithm beats previous multivariate algorithm, especially using **low purity** modes in terms of efficiency

Output : Single classifier output that quantifies the quality of the tag-candidate

Challenge : Calibration of efficiencies

Event **signature very** different from two high-multiplicity B meson decays



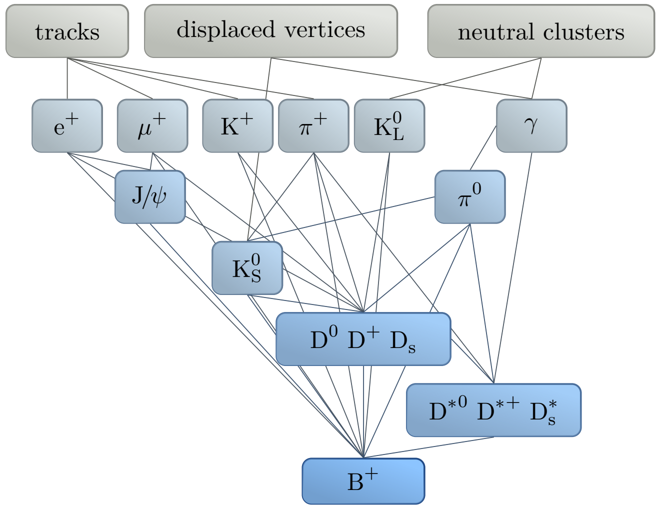


Usually train the FEI using **generic** MC (using $\Upsilon(4S) \to B\overline{B}$ decays into every final state)

Here we exploit the above and produce a **specific training** to boost the efficiency

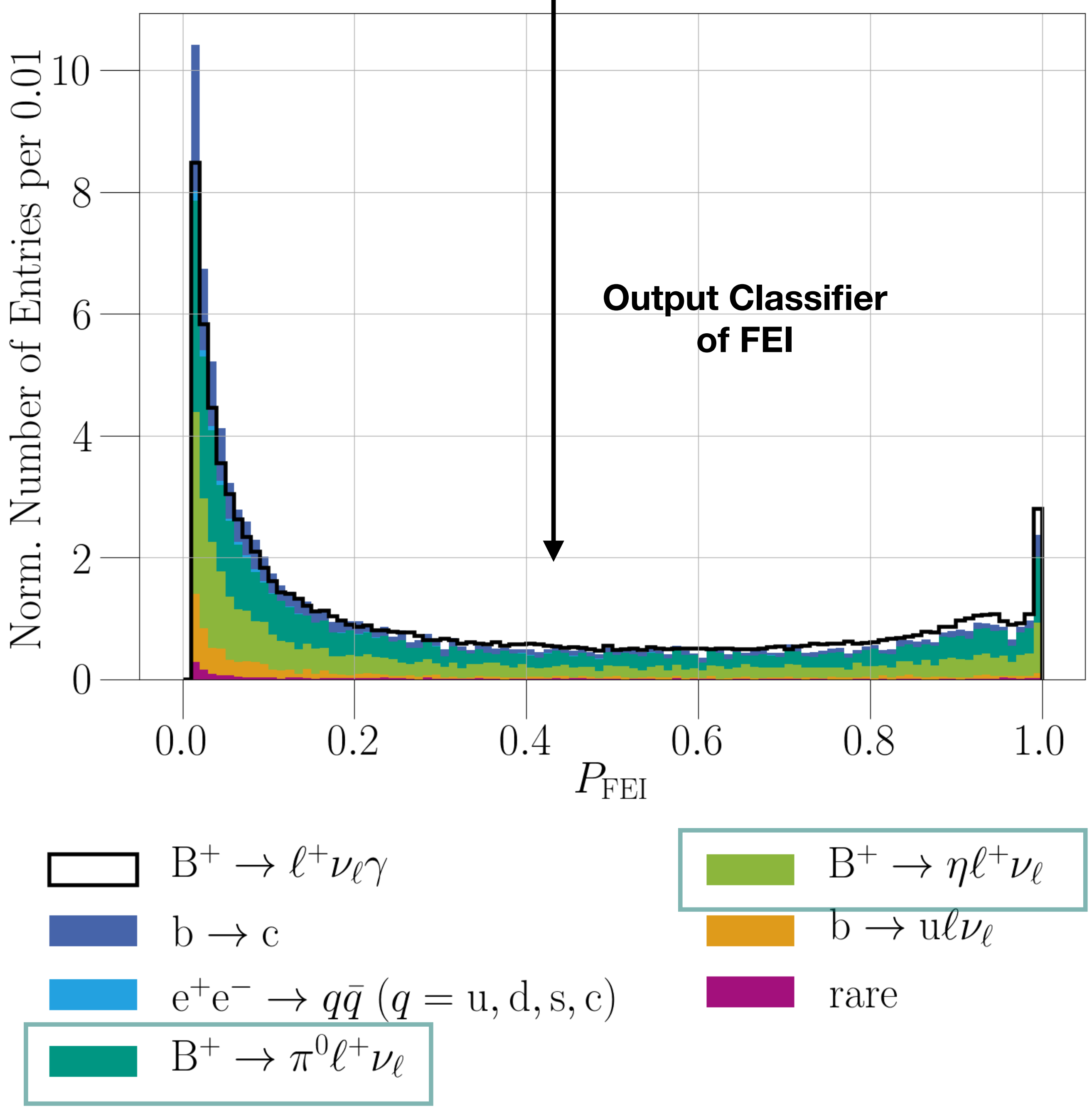
Tagging algorithm	Reconstructed $\Upsilon(4S)$ candidates (%)	
	Electron	Muon
Generic FEI	1.50	1.63
Signal-specific FEI	1.80	1.95

Tag Side



Signal Side

Sample	Variable	Cut
$B^+ \to \ell^+\nu_\ell\gamma$	eID	> 0.8
	$muID$	> 0.8
	E_γ	$> 1.0\,\mathrm{GeV}$
	M_B	$\in (1.0, 6.0)\,\mathrm{GeV}$
$B^+ \to \pi^0\ell^+\nu_\ell$	eID	> 0.8
	$muID$	> 0.8
	p_ℓ	$\geq 300\,\mathrm{MeV}$
	M_{π^0}	$\in (115, 152)\,\mathrm{MeV}$
	M_B	$\in (1.0, 6.0)\,\mathrm{GeV}$



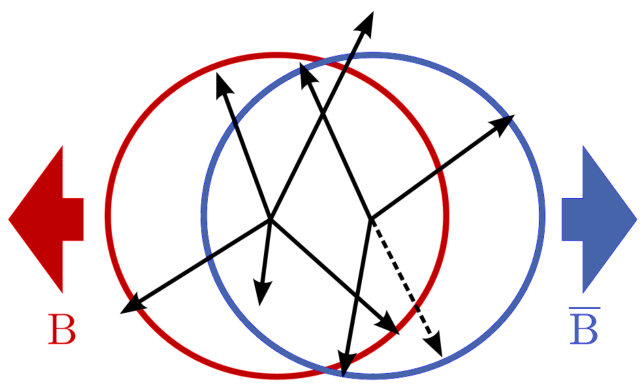
Additional Cuts

Variable	Cut
M	$\in [7.5, 10.5]\,\mathrm{GeV}$
ΔE	$\in [-0.15, 0.1]\,\mathrm{GeV}$
M_{bc}	$\in [5.27, 5.29]\,\mathrm{GeV}$
E_{ECL}	$\leq 0.9\,\mathrm{GeV}$
M^2_{miss}	$\in (-1.5, 3.0)\,\mathrm{GeV}^2$
$E9E25_\gamma$	> 0.9
P_{FEI}	> 0.01
Remaining N_{tracks}	$= 0$

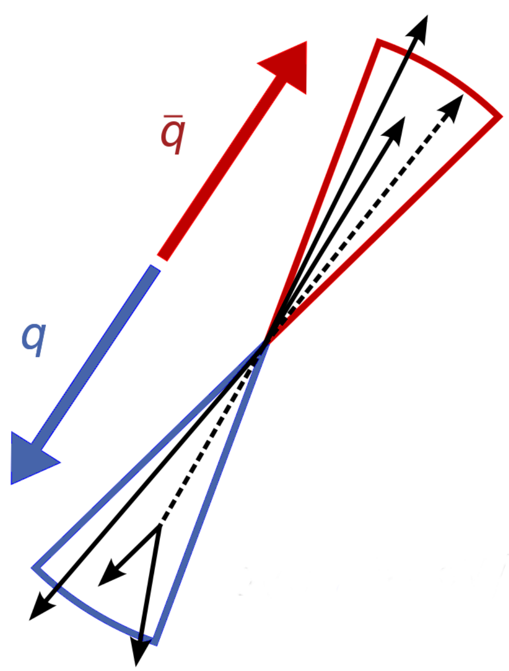
Large amount of peaking background left

Some Continuum left

Continuum Suppression



vs.



T_B, T_{ROE} The magnitude of the thrust of the B_{sig} candidate and the ROE, respectively. The thrust T is calculated from the momenta $\vec{p}_i$ of the final state particles as

$$T = \frac{\sum_i^N |\vec{T}\vec{p}_i|}{\sum_i^N |\vec{p}_i|}, \tag{5.3}$$

where $\vec{T}$ denotes the direction of the maximal total momentum.

$\cos\theta_{B,z}$, $\cos\theta_{B,ROE}$ The angle between the thrust axis of the daughter particles of the B_{sig} candidate and the z-axis and the ROE, respectively. As stated above, continuum events are more jet-like and so large angles are expected between the B_{sig} candidate and its ROE. The distribution is uniform for $B\bar{B}$ events.

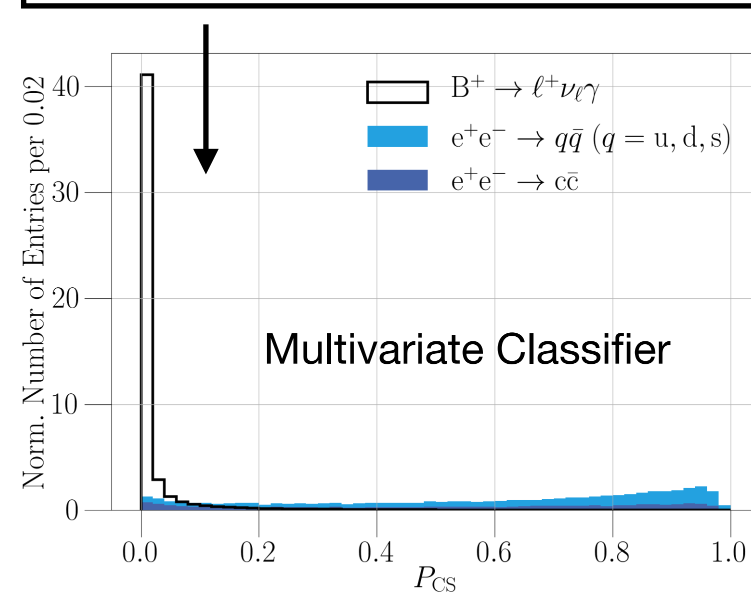
R2 To characterize the event shape by energy and momentum flow in the event the so-called Fox-Wolfram Moments were developed [45]. The moments are calculated as

$$H_l = \sum_{i,j}^{N} \frac{|\vec{p}_i|\,|\vec{p}_j|}{s} P_l(\cos(\phi_{ij})), \tag{5.4}$$

where N is the number of particles in the event, s is the squared center-of-mass energy, $\vec{p}_x$ is the momentum of the particle x, ϕ_{ij} is the angle between the particles i and j, and P_l is the l-th Legendre polynomial. The reduced Fox-Wolfram Moment $R2$ is defined as the ratio $R2 = H_2/H_0$.

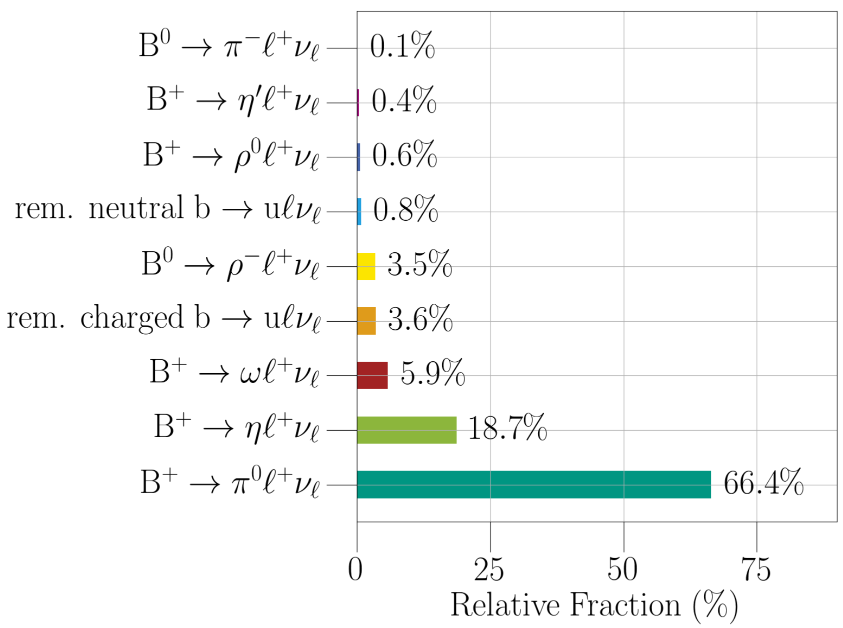
Kakuno-Super-Fox-Wolfram Moments The improved Fox-Wolfram-Moment were developed by the Belle collaboration [23, p.114]. In total there are 17 such moments.

Cleo Cones In the 90's the CLEO Collaboration introduced the so-called Cleo Cones. Nine cones in 10° steps around the B_{sig} thrust axis are defined. Within these intervals the momentum flow is calculated as the scalar sum of the final state particles pointing in the interval [46].



Peaking Background Suppression

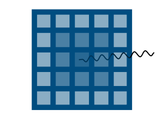
1st Step: Look for π^0 candidates



2nd Step: Look at global properties to veto $B \to \gamma\gamma\ell\bar{\nu}_\ell$

ECL cluster hits Number of hits associated to the ECL cluster used for the signal-side photon reconstruction.

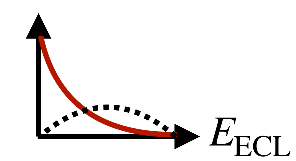
E9E25 Ratio of energies in inner 3x3 and 5x5 cells of the ECL cluster.



ECL cluster LAT Lateral distribution of the ECL cluster.

$\boldsymbol{\theta_{\gamma,p_{\text{miss}}}}$ Angle of the signal-side photon and the missing momentum $\vec{p}_{\text{miss}}$ in the rest frame of the B_{sig} candidate.

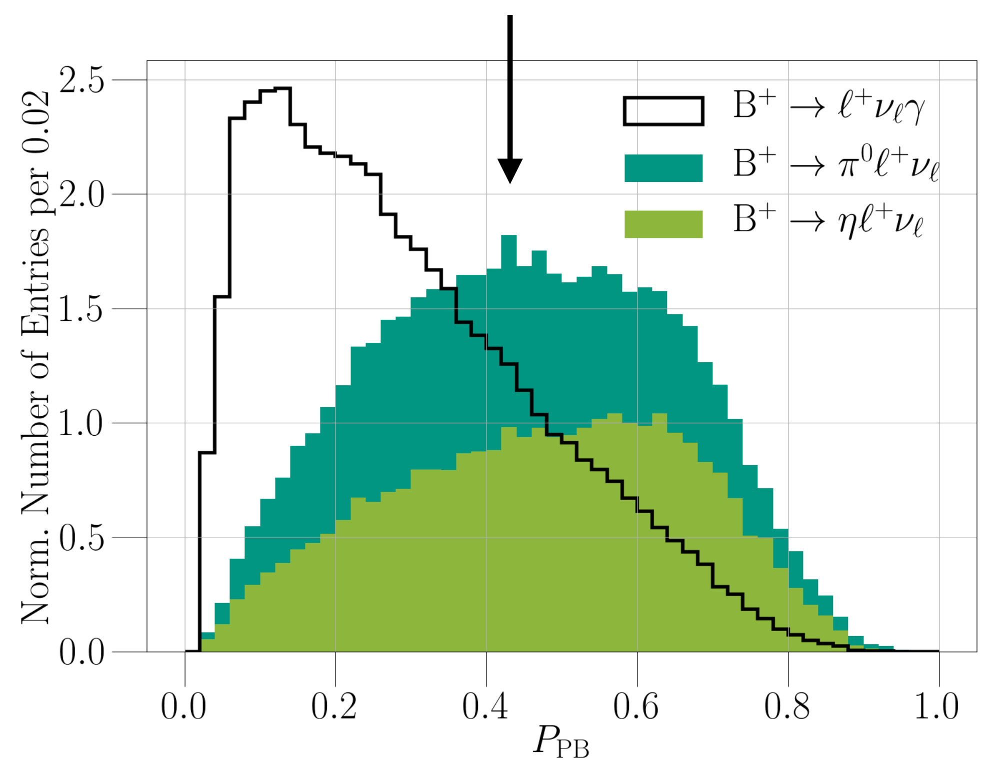
$\boldsymbol{E_{\text{ECL}}}$ The extra energy.



Energy asymmetry Energy asymmetry of the daughter particles of the B_{sig} candidate calculated as

$$A = \frac{E_\ell E_\gamma}{E_\ell + E_\gamma}. \tag{5.5}$$

where i denotes a daughter particle. The variable reveals the asymmetry in the energy distribution of the lepton and photon candidate.



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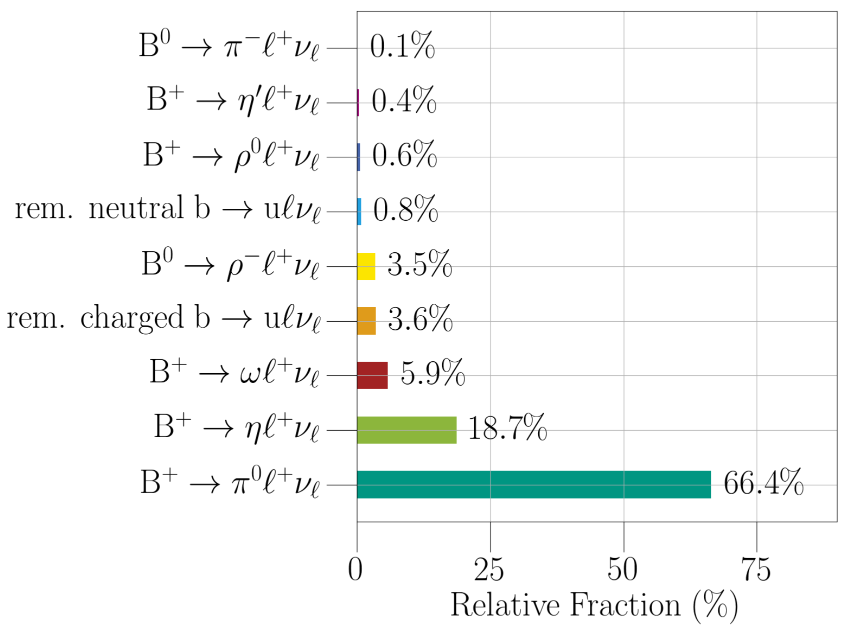

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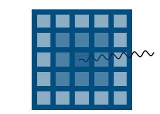

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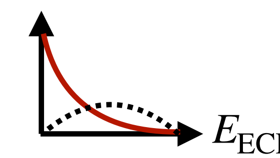

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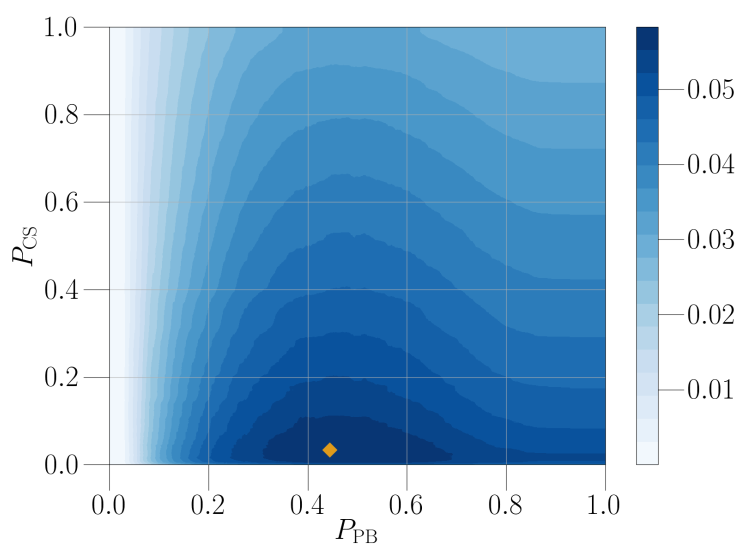
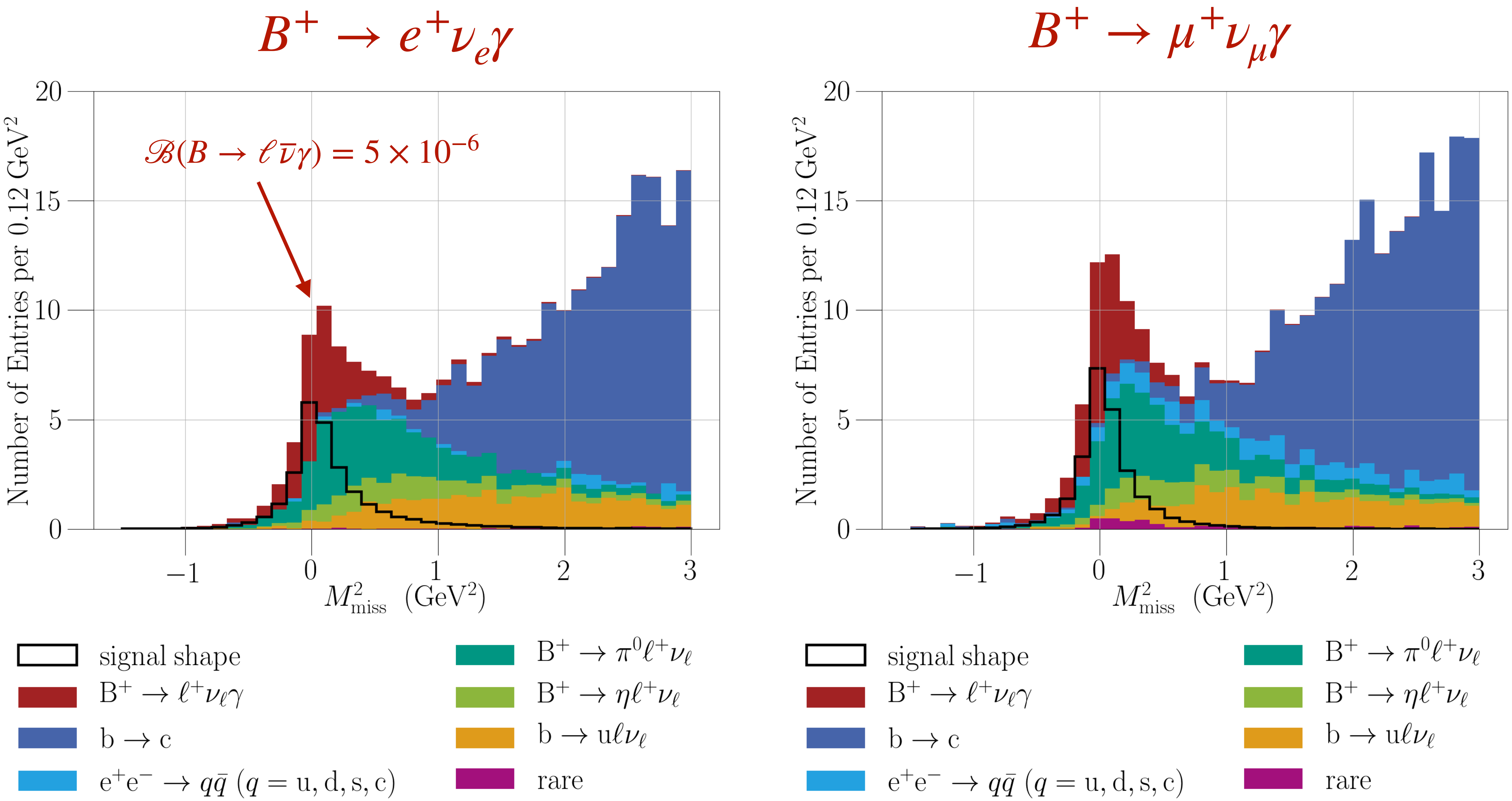
Where to cut? Global optimization



	Signal efficiency	Background rejection					
	$B^+ \to \ell^+ \nu_\ell \gamma$	Rare	$b \to u \ell \nu_\ell$	$B^+ \to \eta \ell^+ \nu_\ell$	$B^+ \to \pi^0 \ell^+ \nu_\ell$	$e^+ e^- \to q\bar{q}$	$b \to c$
E9E25	0.960	0.080	0.050	0.040	0.080	0.20	0.080
$\theta_{\nu\gamma}$	1.000	0.150	0.010	0.020	0.020	0.14	0.010
$M_{\rm bc}$	0.780	0.820	0.750	0.410	0.370	0.87	0.780
$M_\pi$veto	0.960	0.290	0.450	0.080	0.680	0.43	0.430
$P_{\rm CS}$	0.860	0.630	0.340	0.200	0.210	0.95	0.460
$P_{\rm PB}$	0.860	0.700	0.380	0.440	0.430	0.63	0.520
$P_{\rm FEI}$	0.640	0.650	0.590	0.440	0.430	0.68	0.650
Comb.	**0.406**	**0.992**	**0.972**	**0.839**	**0.911**	**0.99**	**0.989**

After **final** selection :



More things to check prior unblinding:

Tagging efficiency needs to be calibrated

Reconstruct $B^+ \to \pi^0\ell^+\nu_\ell$ as control mode

Tagging Calibration

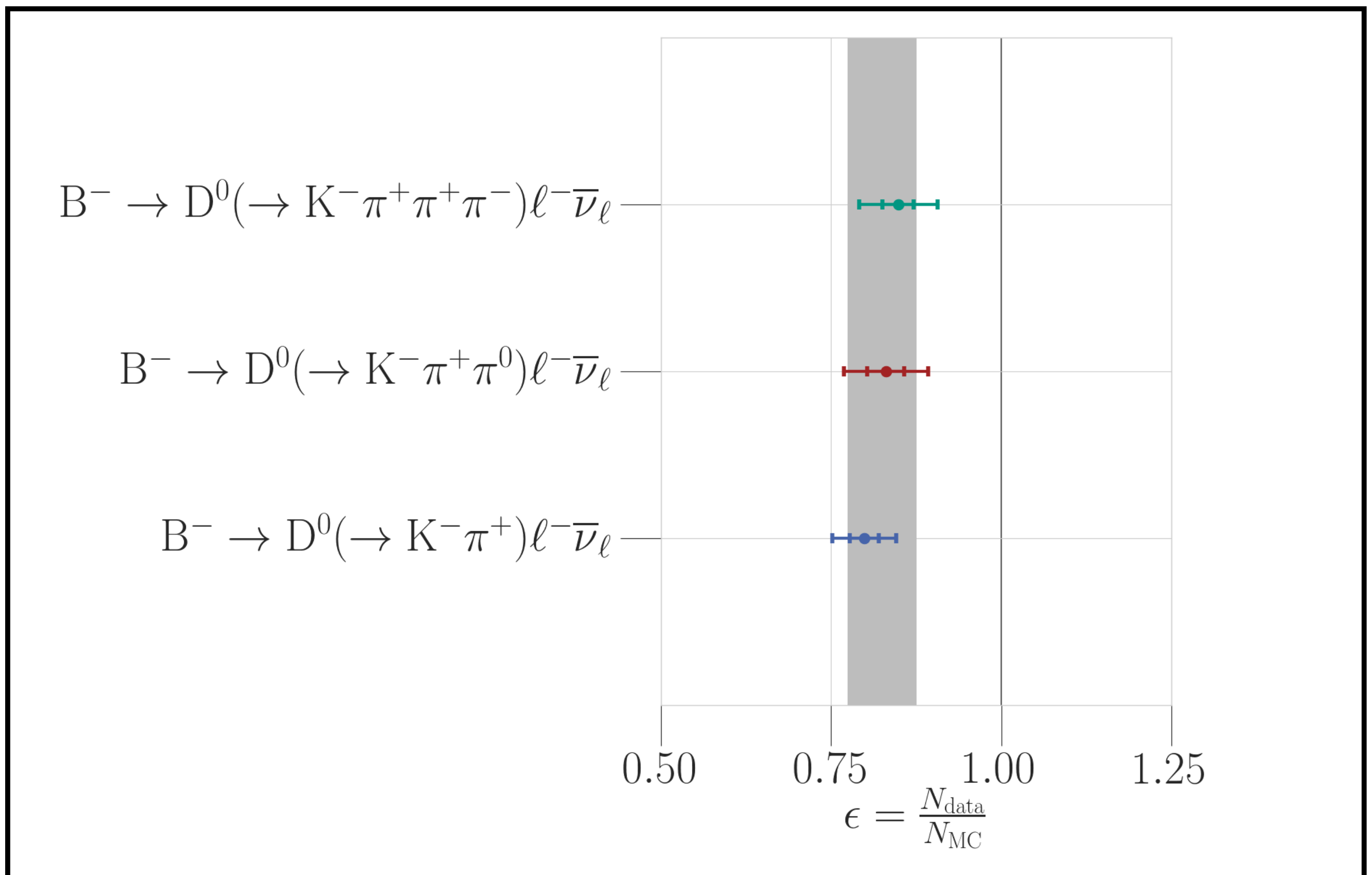
Idea: combine standard candle and well measured validation channel

$$\mathrm{B}^- \to \mathrm{D}^0(\to \mathrm{K}^-\pi^+)\,\ell^-\bar{\nu}_\ell$$

$$\mathrm{B}^- \to \mathrm{D}^0(\to \mathrm{K}^-\pi^+\pi^0)\,\ell^-\bar{\nu}_\ell$$

$$\mathrm{B}^- \to \mathrm{D}^0(\to \mathrm{K}^-\pi^+\pi^+\pi^-)\,\ell^-\bar{\nu}_\ell$$

$$\longrightarrow \quad \epsilon_c = \frac{N_c^{\mathrm{data}}}{N_c^{\mathrm{MC}}},$$



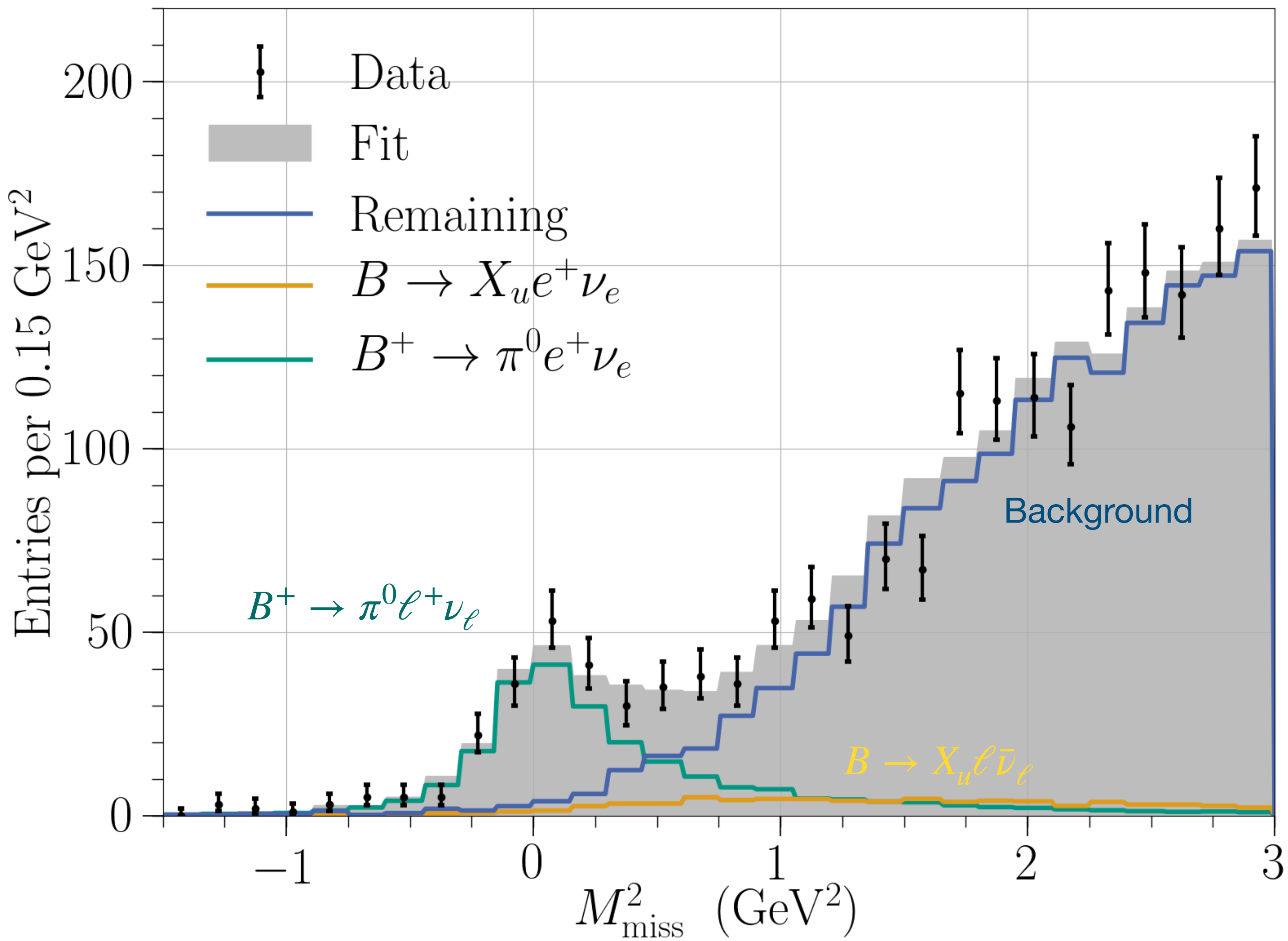
Average efficiency correction:

$$\epsilon_{\mathrm{all}} = \frac{N_{\mathrm{data}}}{N_{\mathrm{MC}}} = 0.825 \pm 0.014 \, \pm 0.049,$$

Also tested tag-side composition

Tagging Calibration Validation

Validation : Determine $B^+ \to \pi^0 \ell^+ \nu_\ell$ BF via binned NLL fit in M^2_{miss}



$$\mathscr{B}(B^+ \to \pi^0 \ell^+ \nu_\ell) = \left(7.8 \pm 0.6\right) \times 10^{-5}$$

$$\mathscr{B}_{\text{PDG}}(B^+ \to \pi^0 \ell^+ \nu_\ell) = (7.80 \pm 0.27) \times 10^{-5}$$

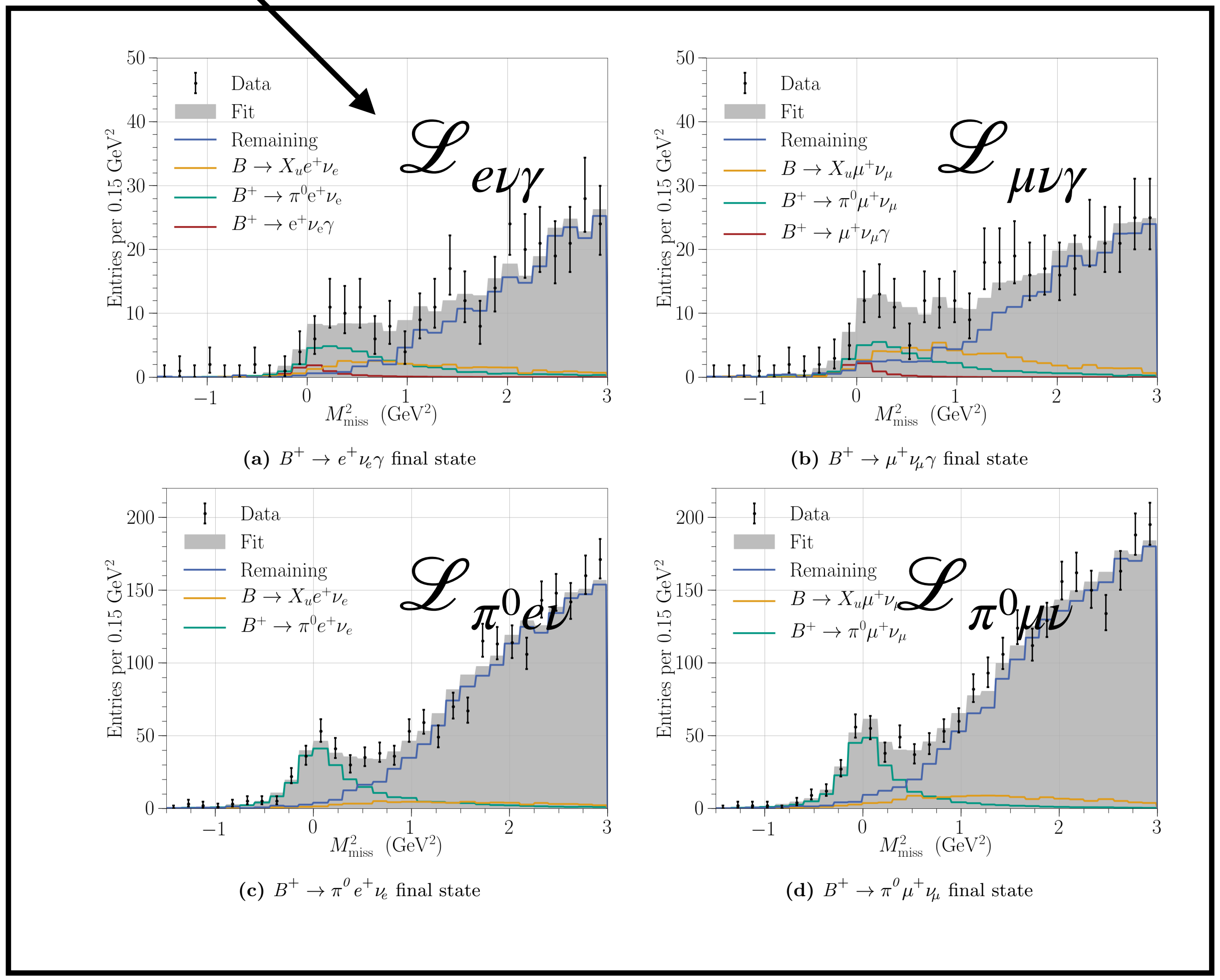
Final Fit & Systematic Uncertainties

Binned NLL fit with 4 categories: $$\mathcal{L} = \prod_c \mathcal{L}_c \times \prod_k^{\text{syst}} \mathcal{G}(\theta_k)$$

Systematic uncertainties incorporated via **Nuisance Parameters**

Mult. : $$\nu_j\, f_{ij} \to \nu_j\, f_{ij} \times \prod_k^{\text{syst}} \left(1 + \theta_k \epsilon_{ijk}\right),$$

Additive : $$\nu_j\, f_{ij} \to \nu_j\, f_{ij} + \sum_k^{\text{syst}} \theta_k \epsilon_{ijk},$$

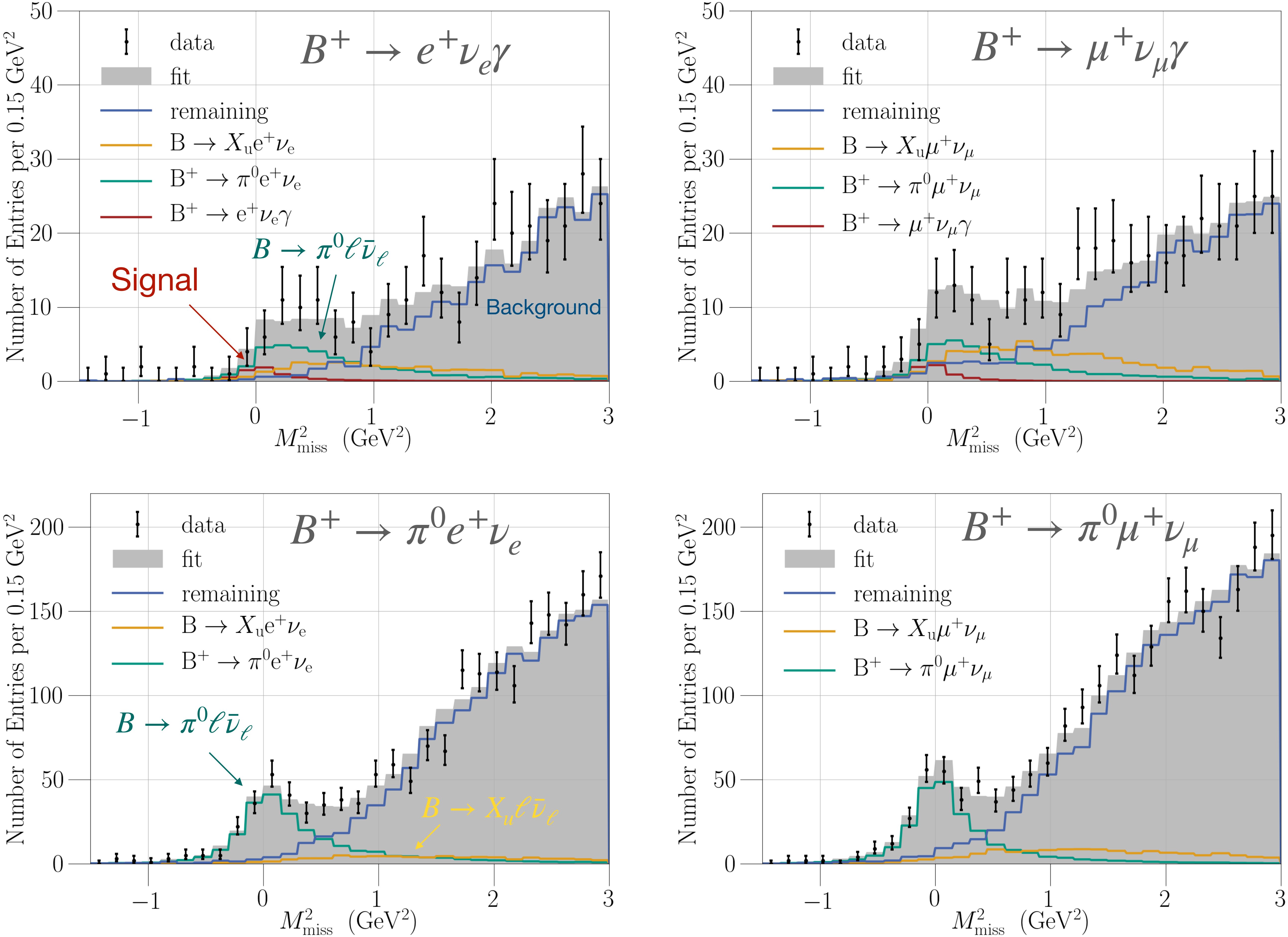


(a) $B^+ \to e^+ \nu_e \gamma$ final state
(b) $B^+ \to \mu^+ \nu_\mu \gamma$ final state
(c) $B^+ \to \pi^0 e^+ \nu_e$ final state
(d) $B^+ \to \pi^0 \mu^+ \nu_\mu$ final state

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}
Calibration	± 0.49	± 0.09
Reconstruction efficiency	± 0.20	± 0.01
$\mathcal{L}_{\text{LID}}$ efficiency	± 0.16	± 0.02
$N_{B\bar{B}}$	± 0.11	± 0.02
Tracking efficiency	± 0.03	± 0.0
Peaking background BDT	± 0.02	± 0.24
PDF templates	± 0.08	± 0.18
BCL model	± 0.25	± 0.01
Reconstructed tag channel	± 0.01	± 0.14
$B \to X_u \ell^+ \nu_\ell$	± 0.02	± 0.07
Signal model	± 0.00	± 0.03
Combined	**± 0.62**	**± 0.36**

ca. **2% and 1.8%**

(leading errors: **calibration, Bkg suppression, MC stat.**)



$B^+ \to e^+\nu_e\gamma$
data
fit
remaining
$B \to X_u e^+\nu_e$
$B^+ \to \pi^0 e^+\nu_e$
$B^+ \to e^+\nu_e\gamma$
Signal
$B \to \pi^0\ell\bar{\nu}_\ell$
Background
Number of Entries per 0.15 GeV^2
$M^2_{\rm miss}$ (GeV^2)
$B^+ \to \mu^+\nu_\mu\gamma$
$B \to X_u \mu^+\nu_\mu$
$B^+ \to \pi^0 \mu^+\nu_\mu$
$B^+ \to \mu^+\nu_\mu\gamma$
$B^+ \to \pi^0 e^+\nu_e$
$B \to X_u\ell\bar{\nu}_\ell$
$B^+ \to \pi^0 \mu^+\nu_\mu$

Result

$$\Delta\,\mathcal{B} = \frac{N_{\mathrm{sig},i}}{\epsilon_i \cdot 2 \cdot \mathcal{B}(\Upsilon(4S) \to \mathrm{B}^+\mathrm{B}^-) \cdot N_{\mathrm{B\bar{B}}}},$$

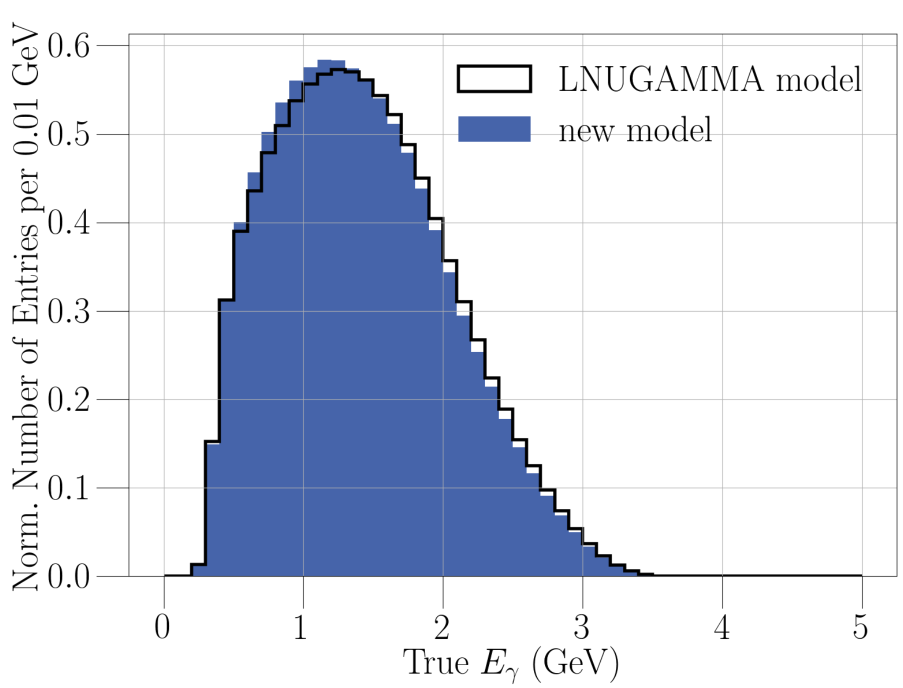
Efficiency to maps yields to partial BF with $E_\gamma > 1\,\mathrm{GeV}$

Studied **two signal** models:

G. P. Korchemsky, D. Pirjol, and T.-M. Yan. Radiative leptonic decays of B mesons in QCD. *Phys. Rev. D*, 61:114510, May 2000. URL https://link.aps.org/doi/10.1103/PhysRevD.61.114510. — ‘LNUGAMMA’

M. Beneke and J. Rohrwild. B meson distribution amplitude from $B \to \gamma\ell\nu$. *The European Physical Journal C*, 71(12):1818, Dec 2011. URL https://doi.org/10.1140/epjc/s10052-011-1818-8. — ‘New model’

Use difference as systematic error in efficiency calculation



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}
Calibration	±0.49	±0.09
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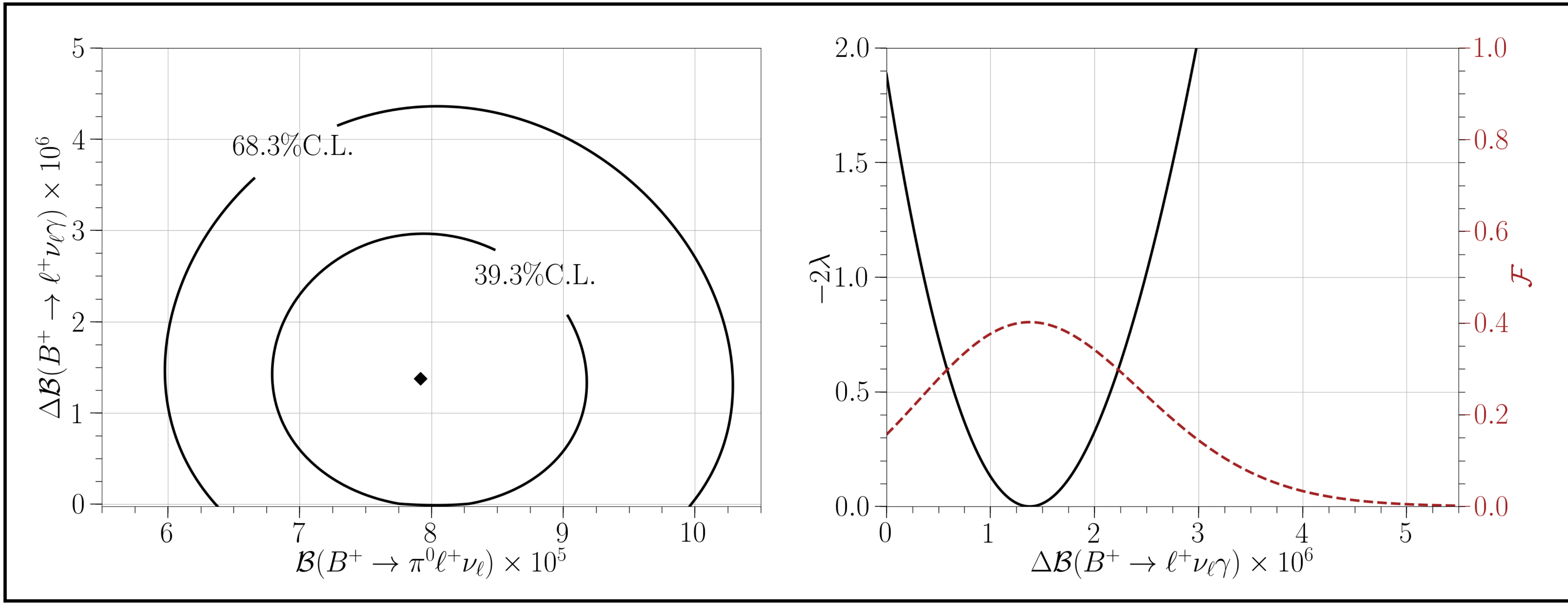
$B \to X_u \ell^+ \nu_\ell$	±0.02	±0.07
Signal model	±0.00	±0.03
Combined	$\pm$**0.62**	$\pm$**0.36**

Result

$$\Delta\,\mathcal{B} = \frac{N_{\mathrm{sig},i}}{\epsilon_i \cdot 2 \cdot \mathcal{B}(\Upsilon(4S) \to \mathrm{B}^+\mathrm{B}^-) \cdot N_{\mathrm{B\bar{B}}}},$$

Find: $\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) = (1.4 \pm 1.0 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell) = (7.9 \pm 0.6 \pm 0.6) \times 10^{-5}$,

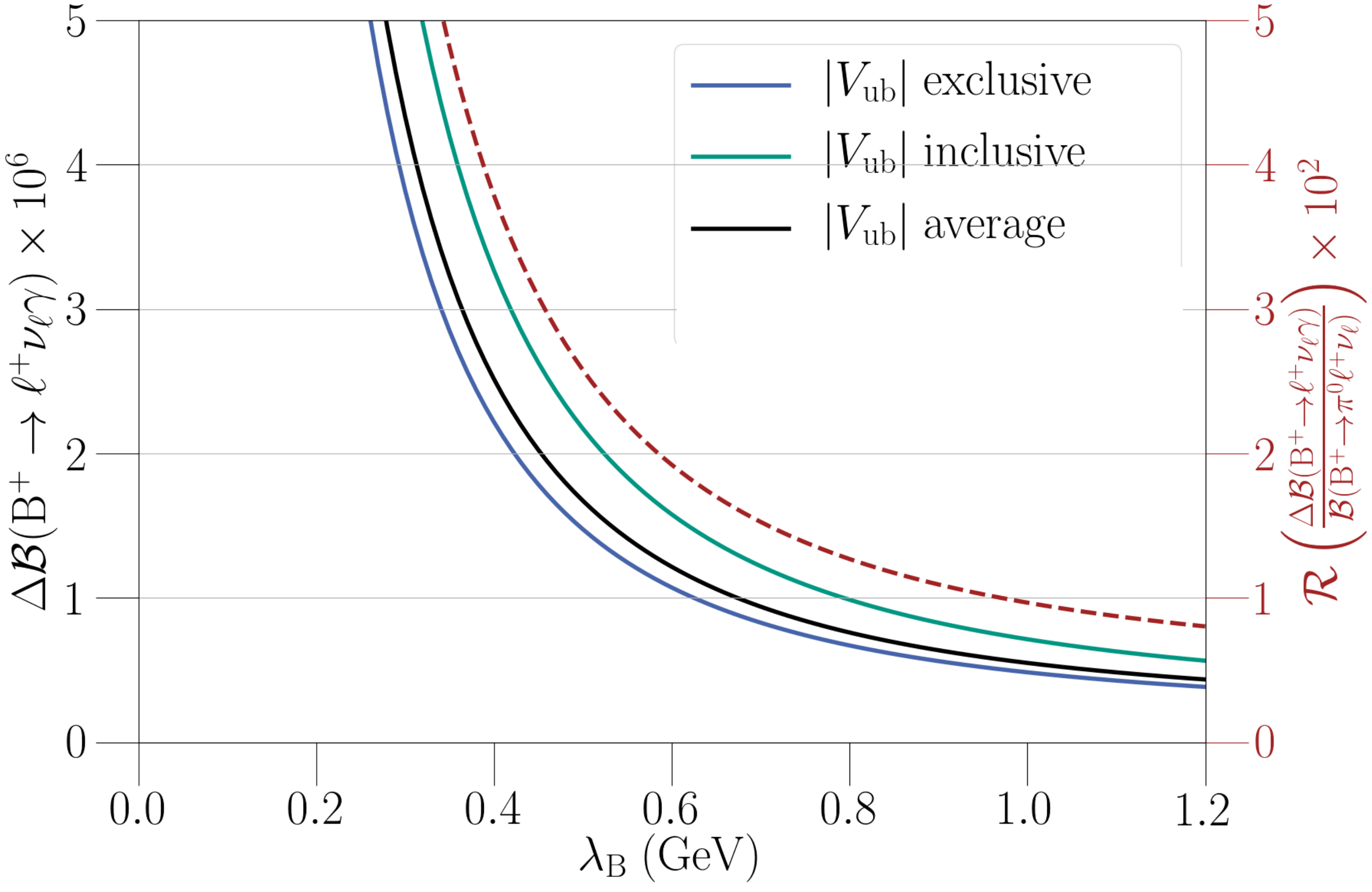


ℓ	$\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell)$ (10^{-5})	σ	$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)$ (10^{-6})	σ
e	$8.3^{+0.9}_{-0.8} \pm 0.9$	8.0	$1.7^{+1.6}_{-1.4} \pm 0.7$	1.1
μ	$7.5^{+0.8}_{-0.8} \pm 0.6$	9.6	$1.0^{+1.4}_{-1.0} \pm 0.4$	0.8
e, μ	$7.9^{+0.6}_{-0.6} \pm 0.6$	12.6	$1.4^{+1.0}_{-1.0}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

	$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)$ limit (10^{-6})		
ℓ	BaBar [35]	Belle [11]	This work
e	-	< 6.1	< 4.3
μ	-	< 3.4	< 3.4
e, μ	< 14	< 3.5	< 3.0

Solving for λ_B

Usual approach: Use measured partial BF and $|V_{ub}|$ to solve for λ_B



Solving for λ_B

Our new idea:

M. Beneke (Munich, Tech. U.), V.M. Braun (Regensburg U.), Yao Ji (Regensburg U.), Yan-Bing Wei (Munich, Tech. U. and Beijing, Inst. High Energy Phys.)

JHEP 07 (2018) 154, 1804.04962 [hep-ph]

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

← Independent of $|V_{ub}|$

Measure

HFLAV BCL Fit (with FLAG input)

$$\Gamma(B^+ \to \pi^0 \ell^+ \nu_\ell) = |V_{ub}|^2 \times (2.4 \pm 0.2) \times 10^{-12}\ \text{GeV}.$$

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

some systematics cancel

Solving for λ_B

Paper has 3 different models for the LCDA

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

Our new idea:

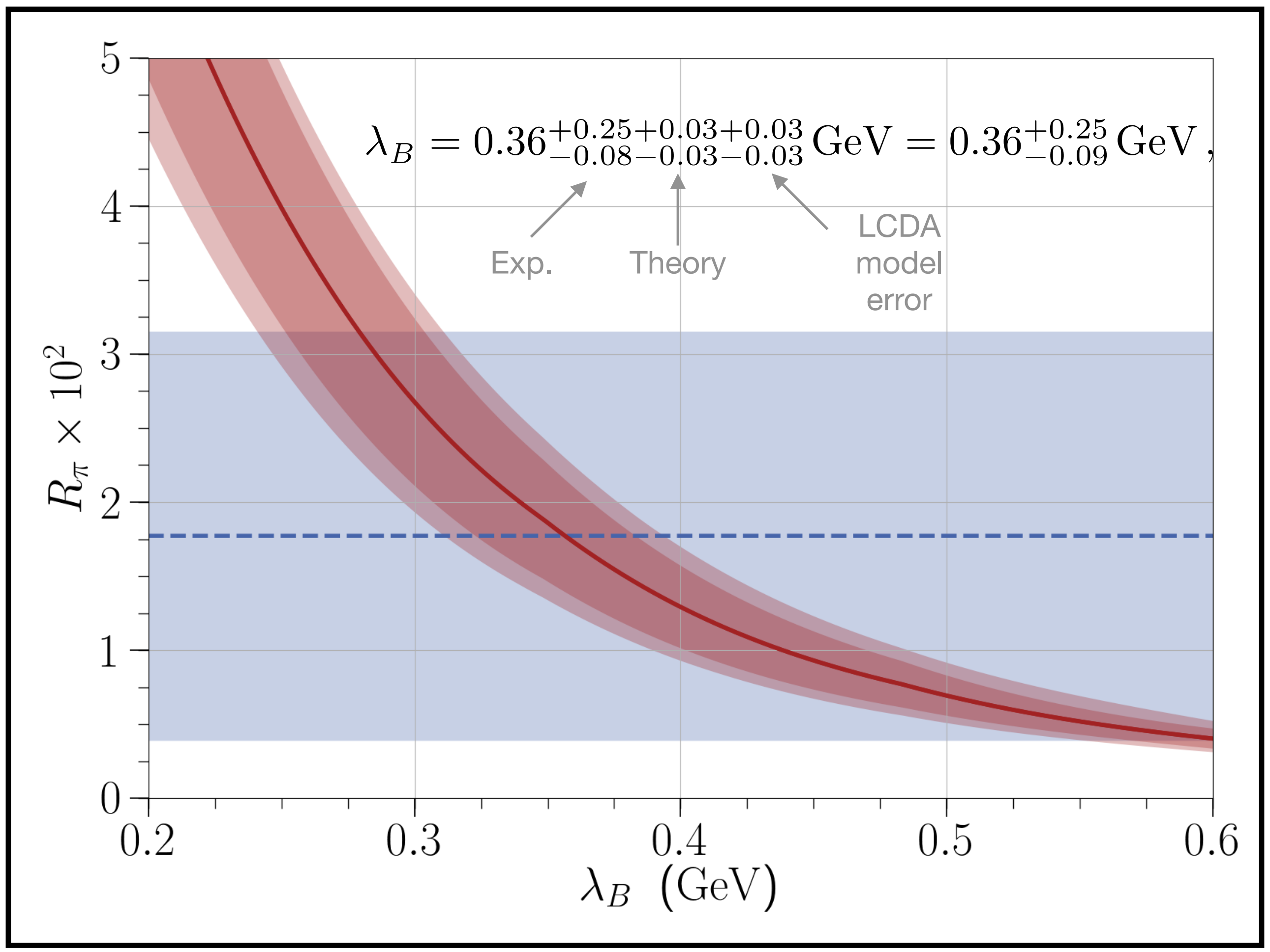
M. Beneke (Munich, Tech. U.), V.M. Braun (Regensburg U.), Yao Ji (Regensburg U.), Yan-Bing Wei (Munich, Tech. U. and Beijing, Inst. High Energy Phys.)

JHEP 07 (2018) 154, 1804.04962 [hep-ph]

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

Measure

HFLAV BCL Fit (with FLAG input)



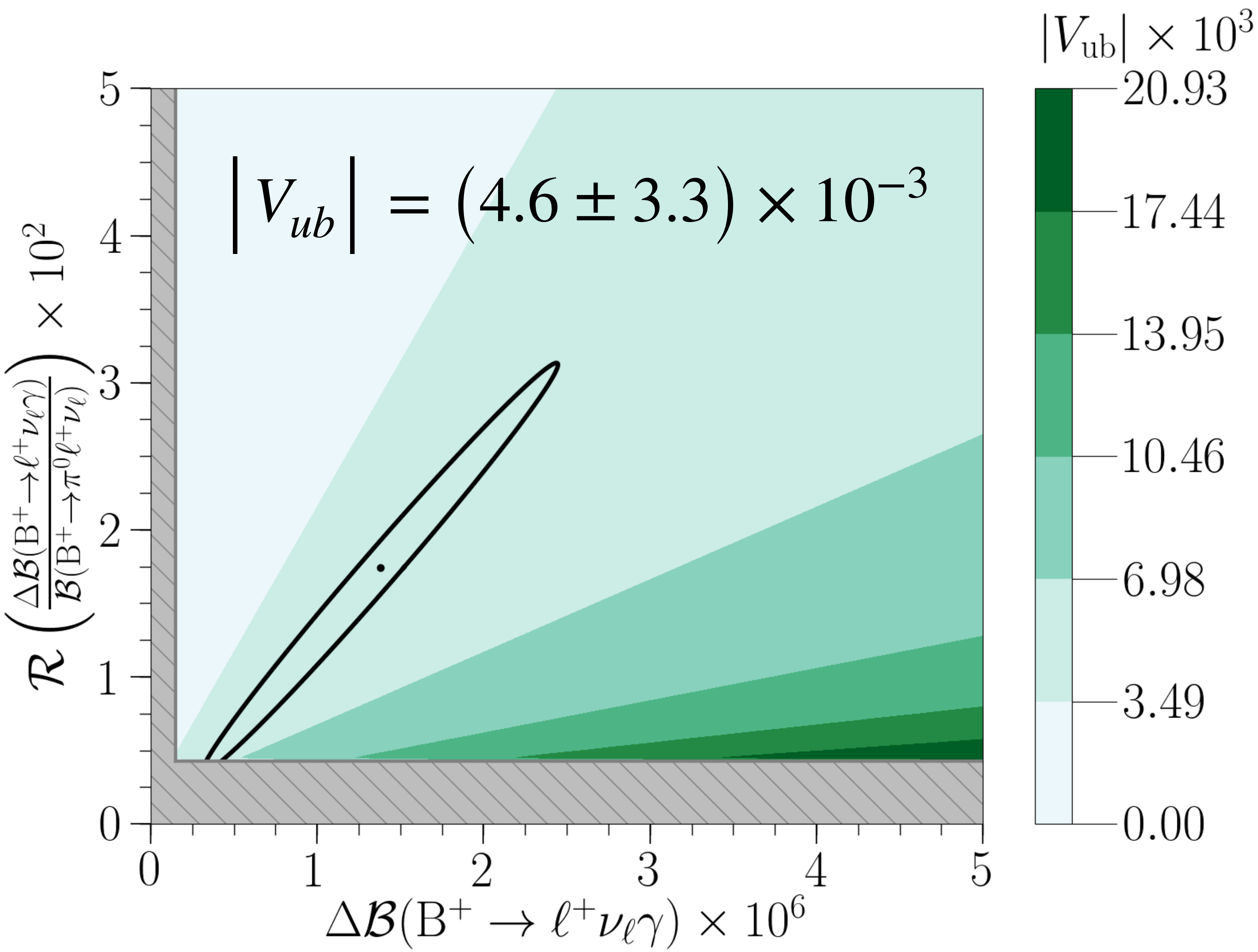
→

90% CL limit of :

$\lambda_B > 0.24\,\text{GeV}$

Only for the brave: $|V_{ub}|$

Can also use $R_\pi : \Delta\mathcal{B}(\mathcal{B} \to \ell\bar{\nu}_\ell\gamma)$ to simultaneously solve for $\lambda_B : |V_{ub}|$



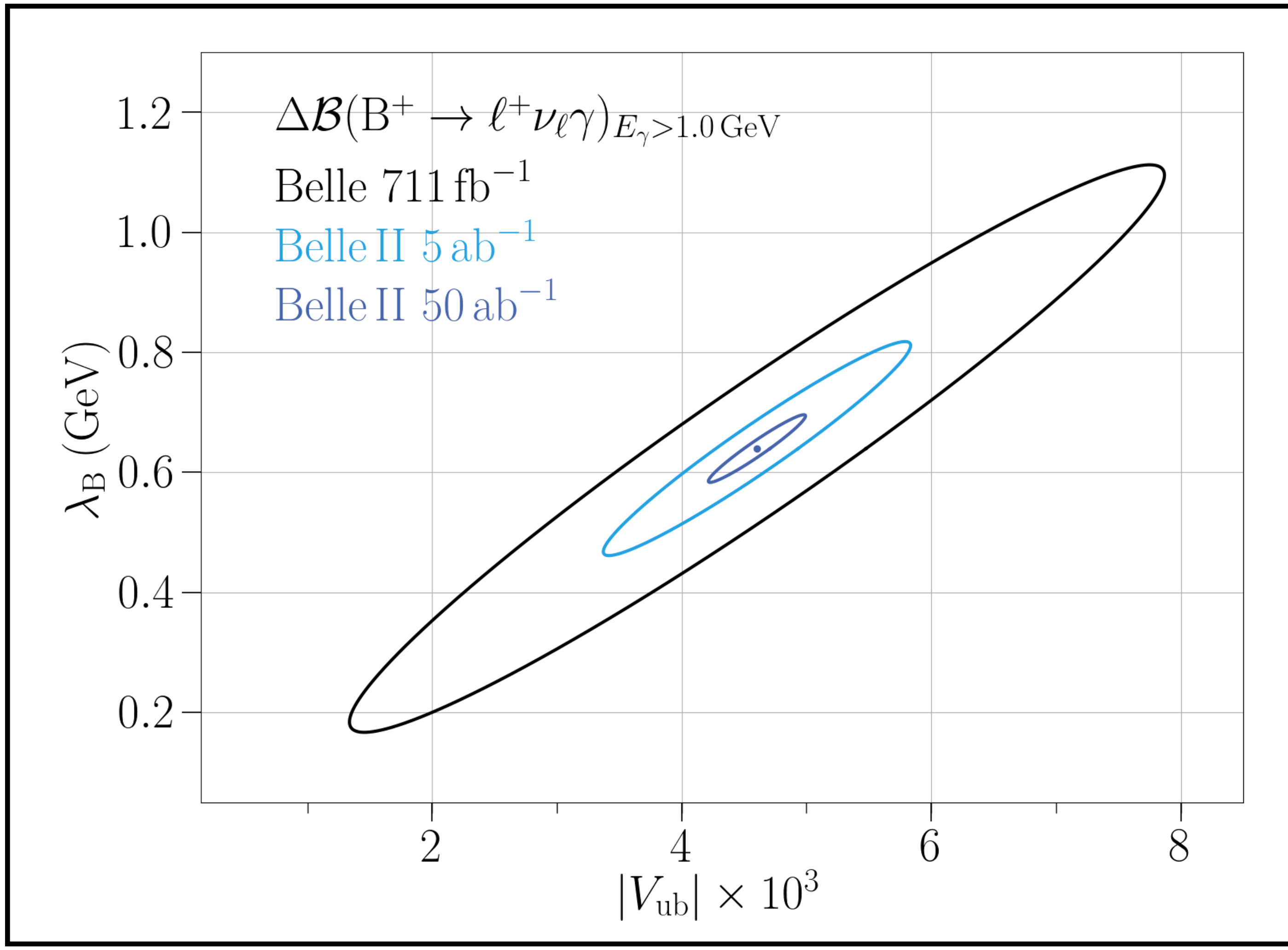
Looking Forward to Belle II

The future: **Belle II**

Naive **luminosity** scaling of stat. error

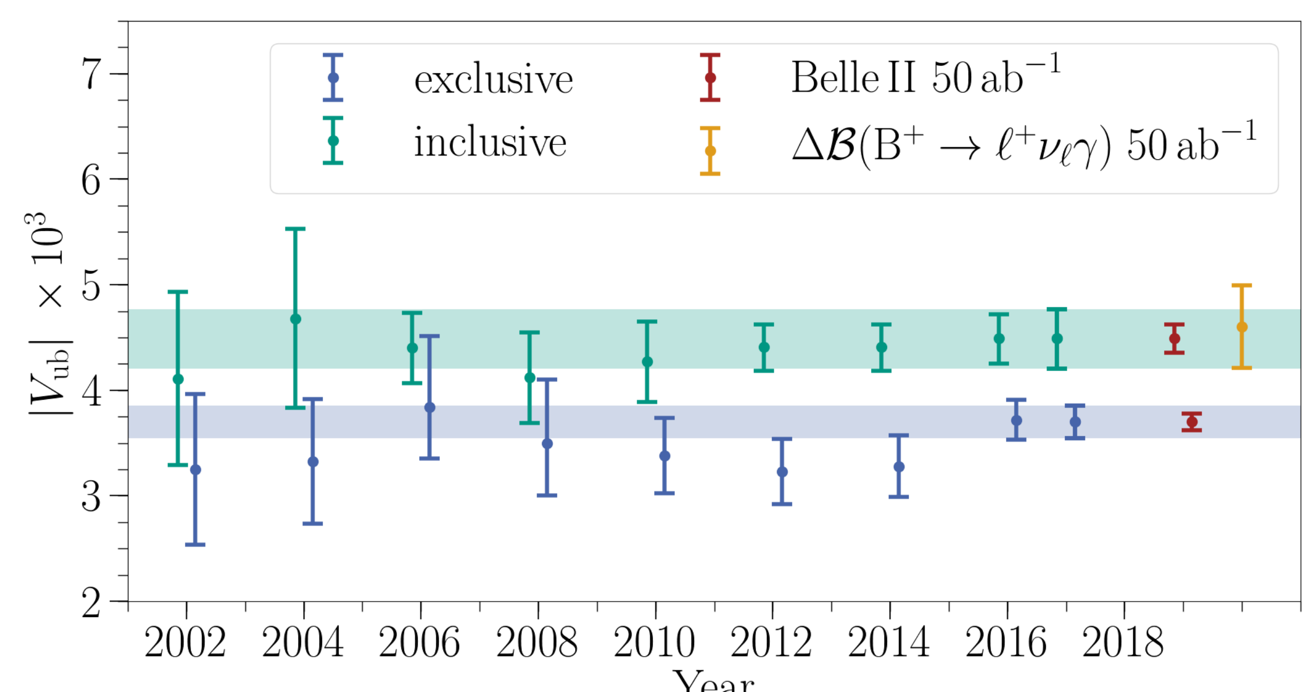
(sig. with respect to found central value)

	Belle 711 fb^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
Stat. uncertainty	$\pm 71\%$	$\pm 27\%$	$\pm 9\%$
Significance	1.3σ	3.3σ	6.4σ



Precise determinations of λ_B possible (~ 50 MeV), but $|V_{ub}|$ precision limited to ~8% in simultaneous determination

Experimental limitation about **4.5%** if λ_B known from theory



Looking Forward to Belle II

The future is hard to predict .. picture could change **if**

- Progress on tagging is made (and with inclusion of SL tagging)

- Better control and rejection of $B \to \gamma\gamma\ell\bar{\nu}_\ell$

- Better control and rejection of $B \to X_u\ell\bar{\nu}_\ell$

- Better rejection on collimated photons; more data will allow to explore this data driven with e.g. hadronic decays

- Input on λ_B from theory (no simultaneous determination)

- Simultaneous analyses with $B \to \gamma^*\ell\bar{\nu}_\ell$

- Differential Measurements as a function of q^2/E_γ etc.

Backup

Florian Bernlochner (florian.bernlochner@uni-bonn.de)

Beware of old MC — it might bite you

Fixed a mean bug in $B \to \pi \ell \bar{\nu}_\ell$ MC that affected old measurement :