Search for $B \to K^{(*)}\nu\bar{\nu}$ decays at Belle II

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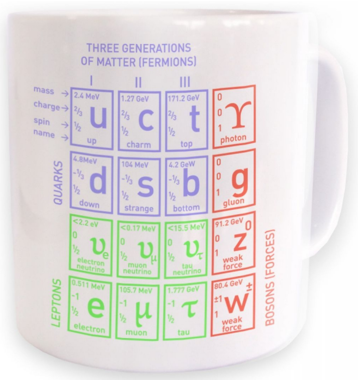
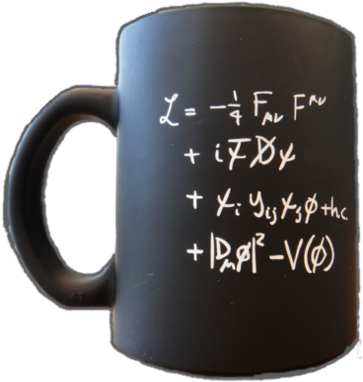
HDR defense – 10 September 2026

The Standard Model of particle physics

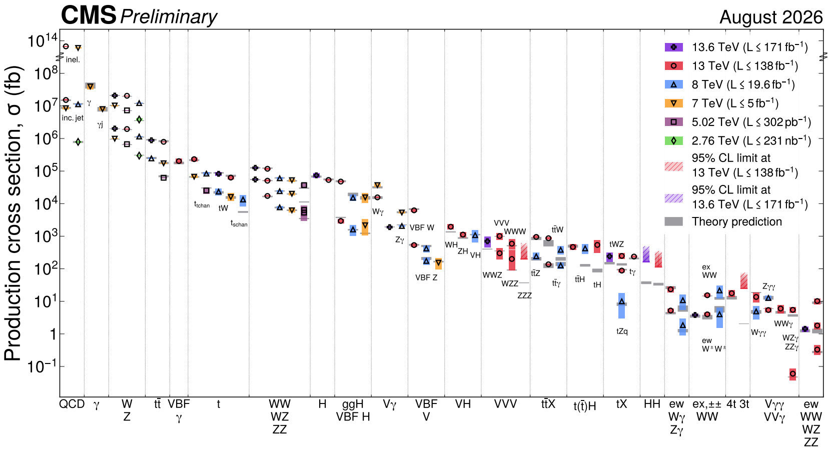
$$SU(3) \times SU(2) \times U(1)$$



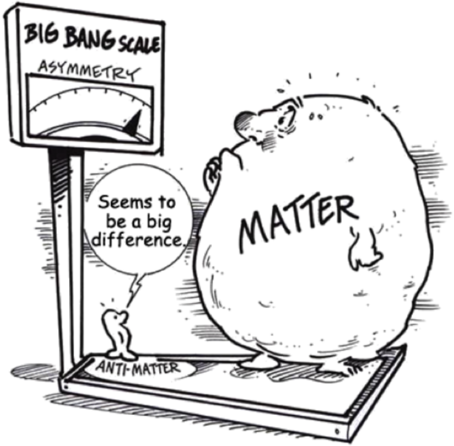


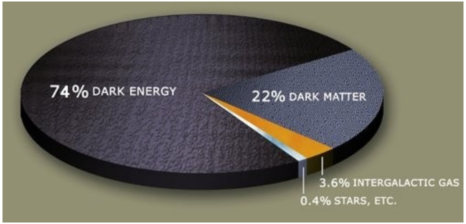
18 free parameters (3 force couplings, 2 from the Higgs potential and 13 from Yukawa couplings) + 7 or more for neutrinos masses

The Sandard Model of particle physics is very successful ...



... but it is known to be incomplete





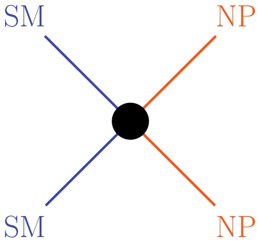
Two paths to discovery

Direct

Indirect

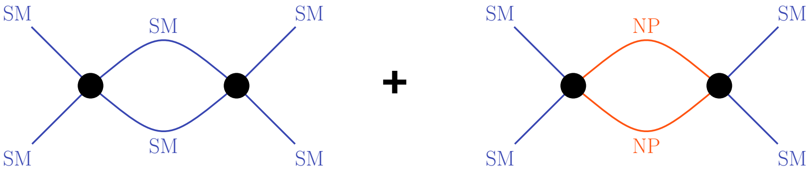
Two paths to discovery

Direct detection



Limited by the centre of mass energy of the accelerator

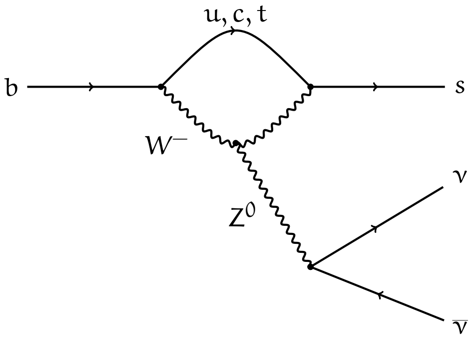
Loop effects



High mass particles can enter the loop ($\Delta E \Delta t \geqslant \hbar/2$)

$b \to s\nu\bar{\nu}$ transitions

- Known with high accuracy in the SM
- New physics could modify significantly the rate
- Possible to recast to look for $B^+ \to K^+X_{dark}$



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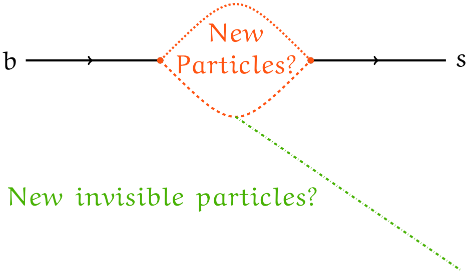


Outlook

1. Theoretical introduction
2. Belle II
3. Evidence of $B^+ \to K^+ \nu\bar{\nu}$
4. GraFEI
5. Search for $B^+ \to K^+$ axion
6. Future prospects

Theoretical introduction

Theoretical prediction

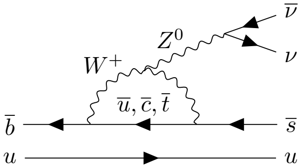
- Flavour changing neutral current
- Express in terms of effective field Theory

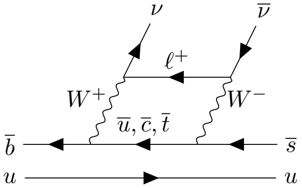
$$\mathcal{L}_{\text{eff}}^{b\to s\nu\bar{\nu}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_a \mathcal{C}_a \mathcal{O}_a + \text{h.c.}$$

- Two operators at dimension 6

$$\mathcal{O}_L \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$
$$\mathcal{O}_R \propto (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

- In Standard Model only C_L present





Theoretical prediction

[Allwicher, Becirevic, Piazza, Rosauro-Alcaraz, Sumensari, '23]

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) \propto |f_+^K(q^2)|^2 |C_L + C_R|^2$$

$$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu}) \propto |V(q^2)|^2 |C_L + C_R|^2 + (|A_1(q^2)|^2 + |A_{12}(q^2)|^2)|C_L - C_R|^2$$

$$\mathcal{B}(B^0 \to K^{(*)0} \nu\bar{\nu}) = \frac{\tau_{B^+}}{\tau_{B^0}} \mathcal{B}(B^+ \to K^{(*)+} \nu\bar{\nu})$$

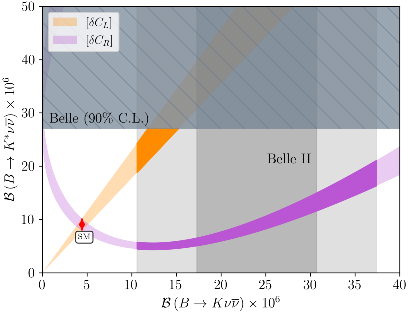
f_+^K, V, A_1 and A_{12} are form factors

Complementary constraints from $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$

Standard Model prediction

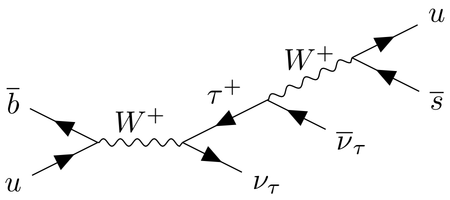
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (4.44 \pm 0.30) \times 10^{-6}$$

$$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu}) = (9.8 \pm 1.4) \times 10^{-6}$$



Non pertubative contribution

- Non pertubative contribution from τ decays
- A bit more than 10% of perturbative component
- Considered an irreducible background

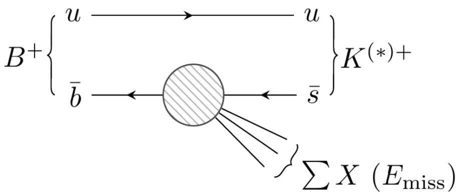


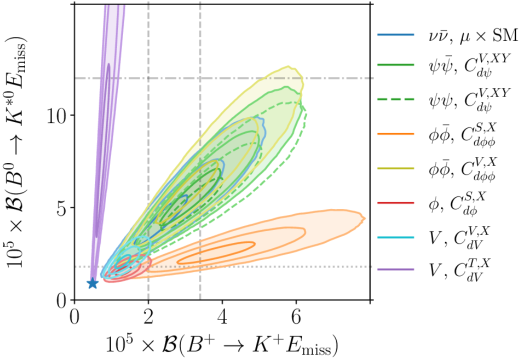
$$\mathcal{B}(B^+ \to (\tau^+ \to K^+\overline{\nu})\nu) = (6,28 \pm 0,06) \times 10^{-7},$$
$$\mathcal{B}(B^+ \to (\tau^+ \to K^{*+}\overline{\nu})\nu) = (1,07 \pm 0,10) \times 10^{-6}.$$

Sensitivity to $b \to s\, E_{\text{miss}}$

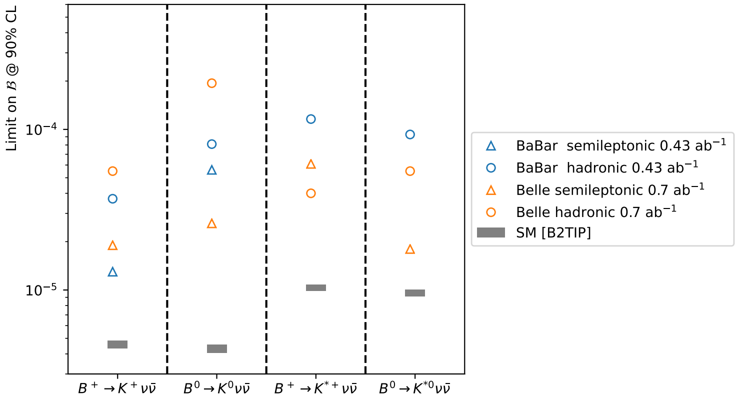
[Bolton, Fajfer, Kamenik, Novoa-Brunet, ’24, ’25]

- Neutrinos not observed directly: sensitive to any $b \to s\, E_{\text{miss}}$
- Single or multiple missing particles with different spin possible
- Again complementary constraints from K and K^*





No $b \to s\nu\overline{\nu}$ transitions observed before the start of my work

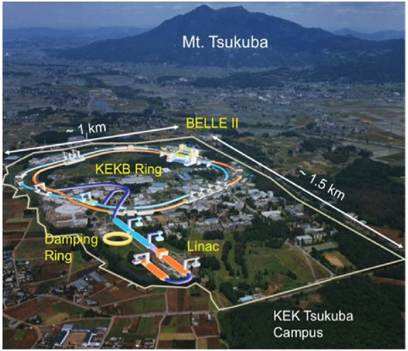


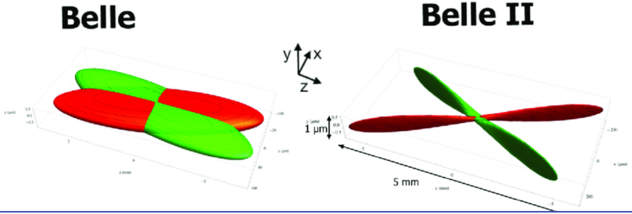
But limits close to expected values ... opportunity for Belle II

Belle II

Belle II @ SuperKEKB

- Multi-purpose detector successor of Belle @ KEKB
- Electron-positron beams with asymmetric energy (7 and 4 GeV): boost $\beta\gamma = 0.28$
- Plan to collect about 50 ab^{-1} of collisions at the $\Upsilon(4S)$ mass (10.58 GeV)

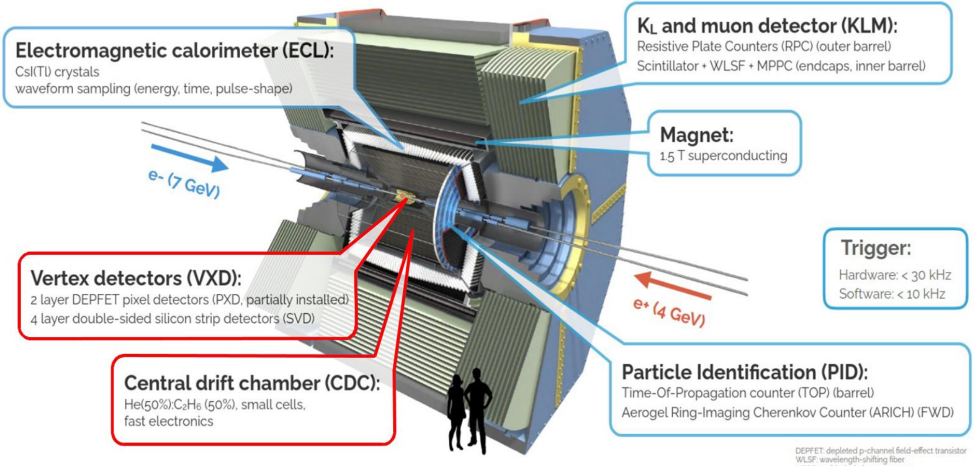




- $\mathcal{L} \propto 1/\beta_y^*$
- β_y^*: 5.9 mm (KEKB) $\rightarrow$ 0.3 mm (SuperKEKB)
- $\mathcal{L} \sim 6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Belle II

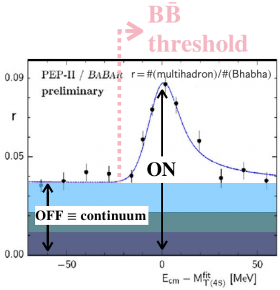
Ensure equal/better performance than Belle (tracking, vertexing, PID, calorimeter resolution) in an harsher environment (higher beam background, higher trigger rate: 0.5 kHz → 30 kHz)

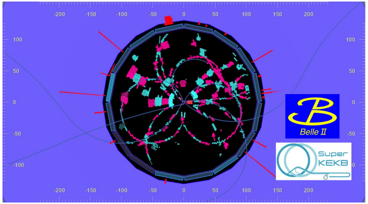


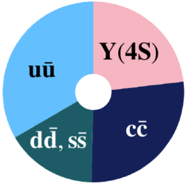
DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

Advantages of an $e^+ e^-$ flavour factory

- Known initial kinematics and good hermeticity
  - possible to fully reconstruct events with invisible particles
- Clean environment (average 11 tracks per event)
  - efficient detection of neutrals (γ, π^0, η, ...)
- Run at the $\Upsilon(4S)$ mass just above $B\bar{B}$ threshold
  - Relatively low background
  - Data off-resonance provide control sample without $B\bar{B}$



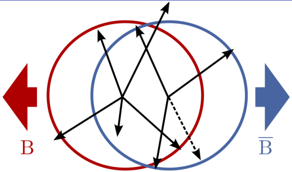




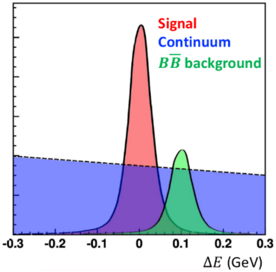
Hadronic cross-section
@ $\sqrt{s} = 10.58$ GeV

Tools at an $e^+ e^-$ flavour factory

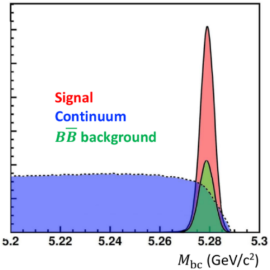
- Optimised variables to exploit information on initial kinematics
- Exploit different event shape to separate $B\bar{B}$ from continuum background



$$\Delta E = E_B^* - \sqrt{s}/2 \qquad M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{\,*2}|}$$

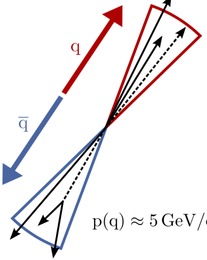


Expected $\Delta E \simeq 0$



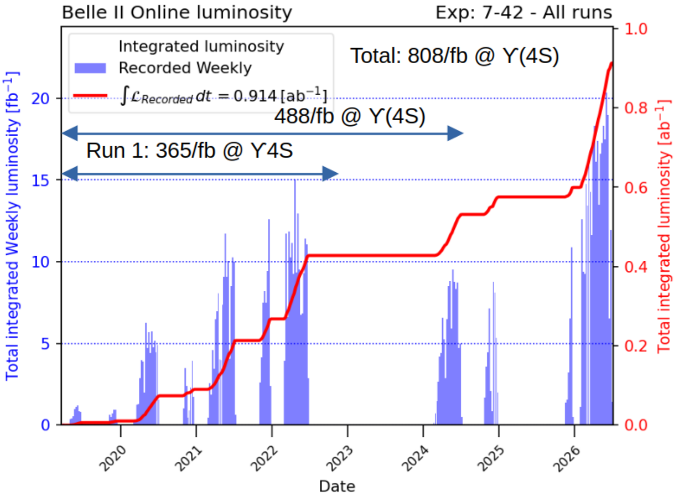
Expected $M_{bc} \simeq m_B$

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$



$e^+e^- \to q\bar{q} \quad (q \in \{u, d, s, c\})$

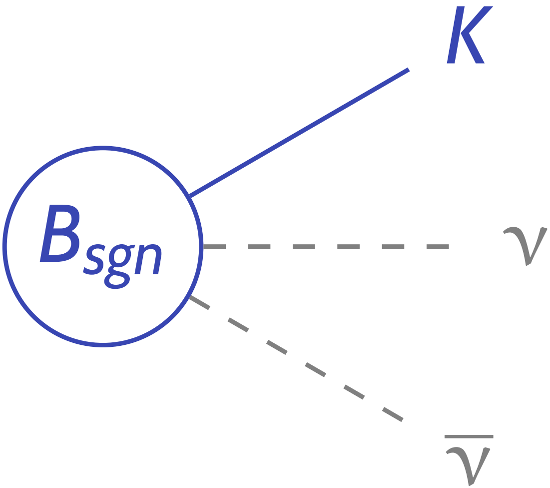
Belle II current dataset



Record instantaneous luminosity: 5.32×10^{34} cm^{-2} s^{-1} with $\beta_y^* = 0.9$ mm

The reconstruction challange

We want to study decays with particles that we do not reconstruct like neutrinos

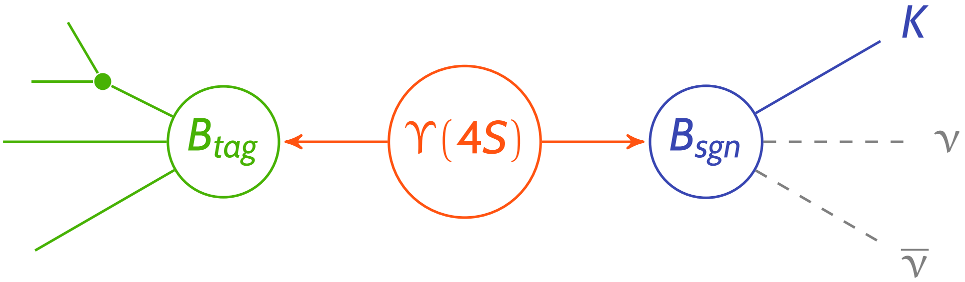


The strategy

Reconstruct all the rest and infer what is missing

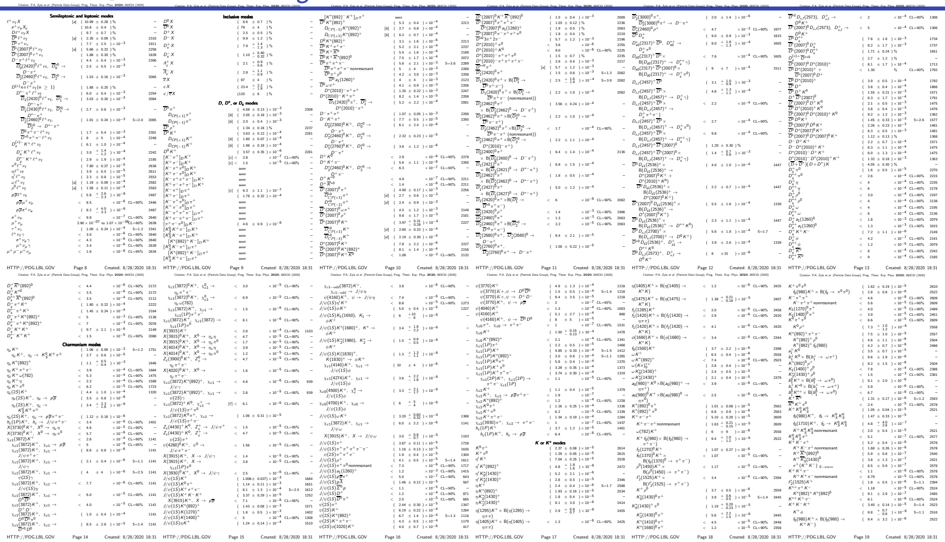
What does it mean at Belle II

What does it mean at Belle II



What does it mean at Belle II

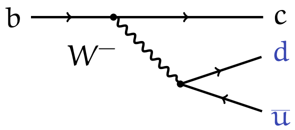
Possible decays of the B_{tag}



Tagging strategies

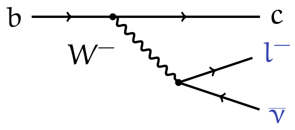
Tagged approach

Hadronic tag



- Reconstruct fully hadronic decays of B (mainly $B \to D^{(*)} n\pi$)
- Efficiency$\sim$ 0.1%
- Full kinematic constraint

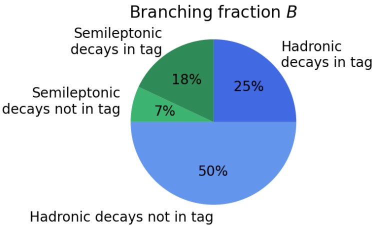
Semileptonic tag



- Reconstruct $B \to D^{(*)} l\nu$
- Efficiency$\sim$ 1%
- Partial kinematic constraint due to neutrino

Inclusive approach

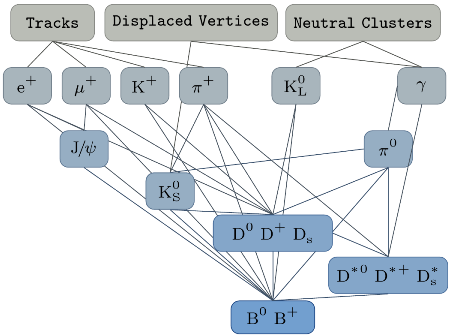
- Reconstruct signal first
- Check consistency of the rest with B_{tag}
- High efficiency, low purity

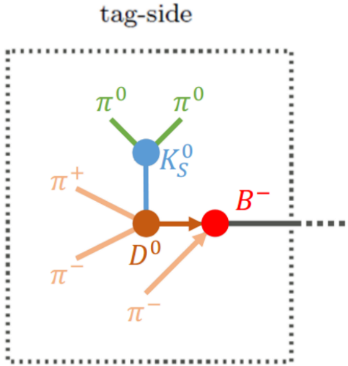


Full Event Interpretation

[Comput. Softw. Big Sci. 3, 6 (2019)]

- 6 levels of BDT to reconstruct sequentially the intermediate decays
- More that 10 000 decays considered
- $\mathcal{O}(1\%)$ efficiency





Evidence of $B^+ \to K^+ \nu\bar{\nu}$

[Phys. Rev. D 109, 112006 (2024)]

In collaboration with colleagues from Perugia and Desy

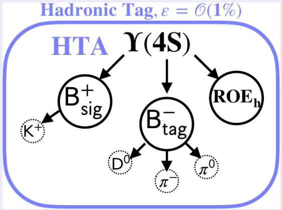
Collaborators@IPHC: Léonard Polat, Lucas Martel and Jacopo Cerasoli

Analysis's strategy

[Phys. Rev. D 109, 112006 (2024)]

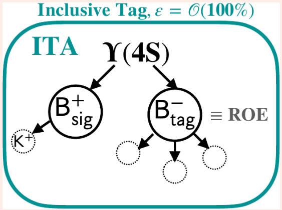
Hadronically tagged analysis (HTA)

- Select first tag B decaying hadronically
- Request only signal and B_{tag} in the event
- One BDT to reject background
- Total efficiency $\sim 0.4\%$, purity $\sim 3.5\%$
- Fit BDT output



Inclusive tagged analysis (ITA)

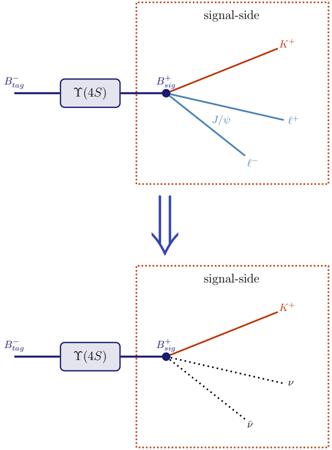
- Select first signal kaon that minimises q^2_{rec} (computed as K^+ recoil)
- Two consecutive BDTs
- Total efficiency $\sim 8\%$, purity $\sim 0.8\%$
- Binned fit to q^2_{rec} and second BDT output



Control samples

[Phys. Rev. D 109, 112006 (2024)]

- Analysis relies on simulation for background suppression and background templates for the fit
- Simulation corrected and validated via several control samples

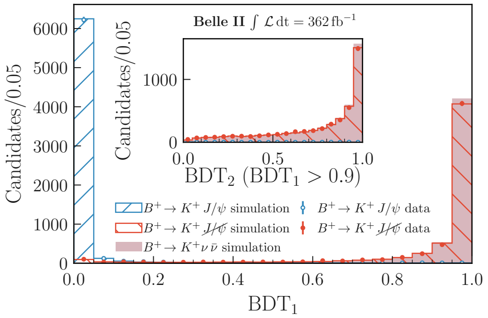


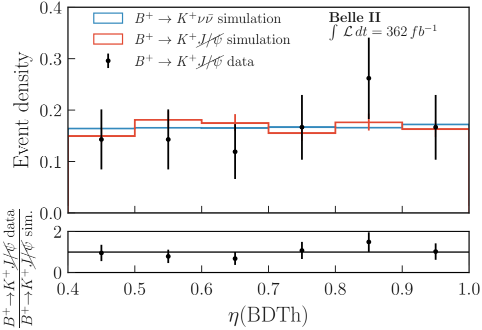
- offres: to control continuum background
- pion-enriched: select pion instead of signal kaon
- wrong-charge: $B^+_{sgn}B^+_{tag}$ or $B^-_{sgn}B^-_{tag}$, only for HTA
- embedding: $B^+ \to J/\psi K^+$, removing J/ψ and correcting the kaon kinematics to match the signal

Signal validation

[Phys. Rev. D 109, 112006 (2024)]

- Total efficiency corrected and validated with embedding control sample
  - Data/MC efficiency ratio = 1.00 ± 0.03 for ITA and 0.67 ± 0.06 for HTA
  - Use calibration factor and propagate uncertainty to the fit
- Kaon ID selection corrected with $B^+ \to \overline{D}^0(\to K^+\pi^-)\pi^+$ and validated with $B^+ \to \overline{D}^0(\to K^+\pi^-)K^+$

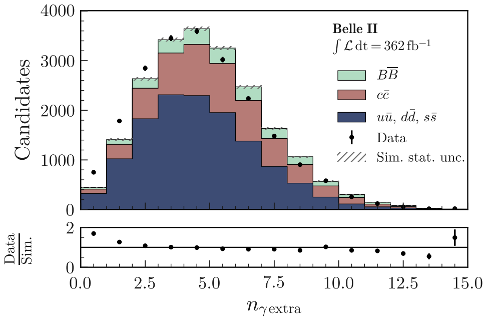


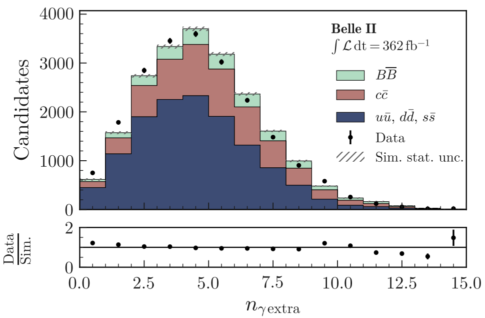


Background corrections and validation

[Phys. Rev. D 109, 112006 (2024)]

- Correct continuum for data/MC differences in normalisation and shape with offres control sample
- Correct shape extra energy distribution of HTA (most important variable in BDT) with wrong-charge control sample, validate and assign systematics from pion-enriched control sample

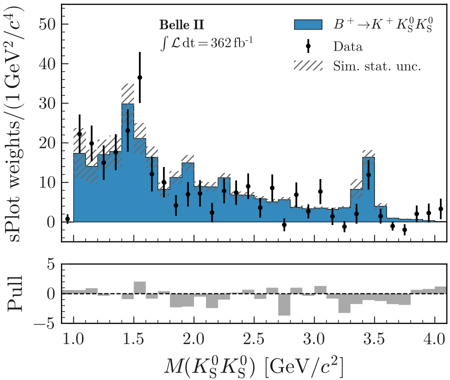




Background corrections and validation

[Phys. Rev. D 109, 112006 (2024)]

- Propagate uncertainties on main B branching fractions to the fit
- Size of $B \to X_c(K_L^0 X)$ corrected using pion-enriched sideband
- Modelling of K_L^0 detection efficiency in the calorimeter corrected using $e^+e^- \to \gamma\phi(\to K_S^0 K_L^0)$
- Fix kinematic distribution of $B^+ \to K^+ K_L^0 K_L^0$ from $B^+ \to K^+ K_S^0 K_S^0$ and of $B^+ \to K^+ n\bar{n}$ from $B^+ \to K^+ p\bar{p}$
- Background components in the fit are free to vary within statistical uncertainties obtained from control samples ($\sim$ 50%)

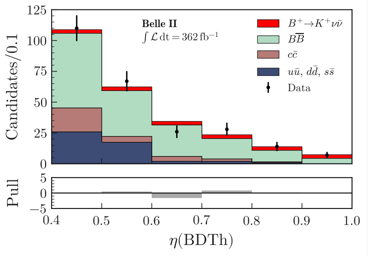


Results

[Phys. Rev. D 109, 112006 (2024)]

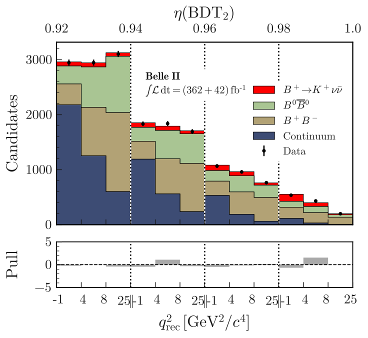
HTA

- $\mathcal{B} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$
- 1.1σ significance
- 0.6σ deviation from SM



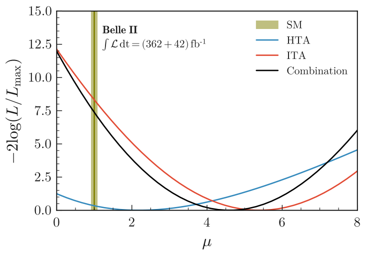
ITA

- $\mathcal{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$
- 3.5σ significance
- 2.9σ deviation from SM



Combination

- 1.2σ agreement between ITA and HTA, 2% common events
- $\mathcal{B} = (2.3 \pm 0.5^{+0.5}_{-0.5}) \times 10^{-5}$
- 3.5σ significance
- 2.7σ deviation from SM



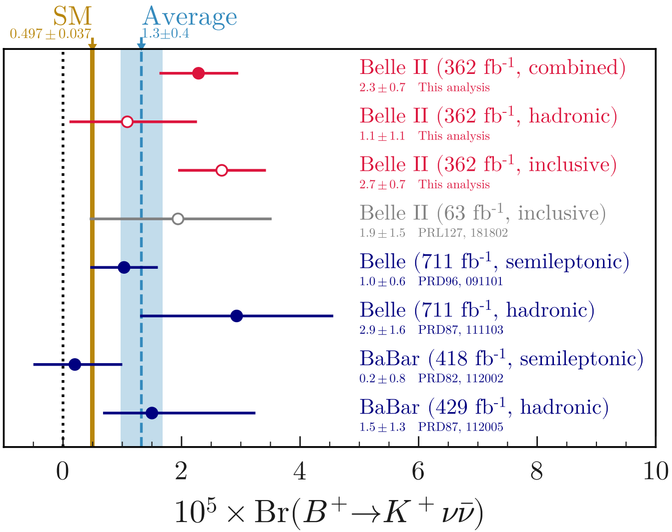
Precision on $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ [Phys. Rev. D 109, 112006 (2024)]

- Precision competitive with previous searches
- Belle II ITA provides best precision per luminosity
- Belle II HTA has better precision with less luminosity than other HTA searches

Analyse $B^+ \to K^+\nu\bar{\nu}$	Incertitude $[10^{-6}]$	Incertitude pour 365 fb^{-1} $[10^{-6}]$
BaBar HTA	12.9	14.0
BaBar STA	7.5	8.0
Belle HTA	16.8	23.5
Belle STA	5.8	8.1
Belle II HTA	10.7	10.7
Belle II ITA	7.1	7.1

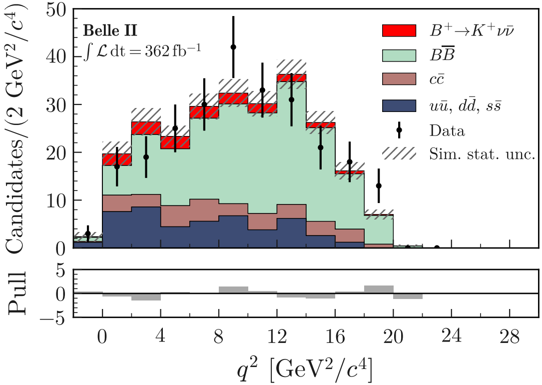
Status now

- Intriguing tension between experimental results and SM prediction
- Pletora of new physics models proposed to explain this tension
- Semileptonic analyses from Belle and BaBar seems in better agreement with prediction

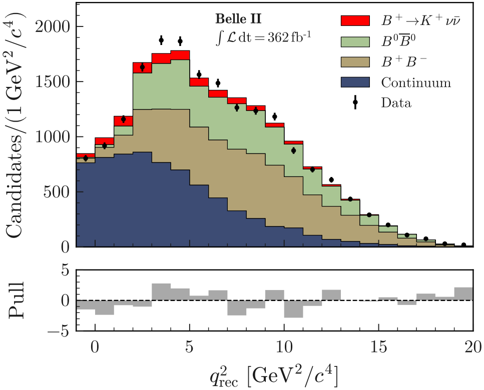


Post-fit q^2 projection

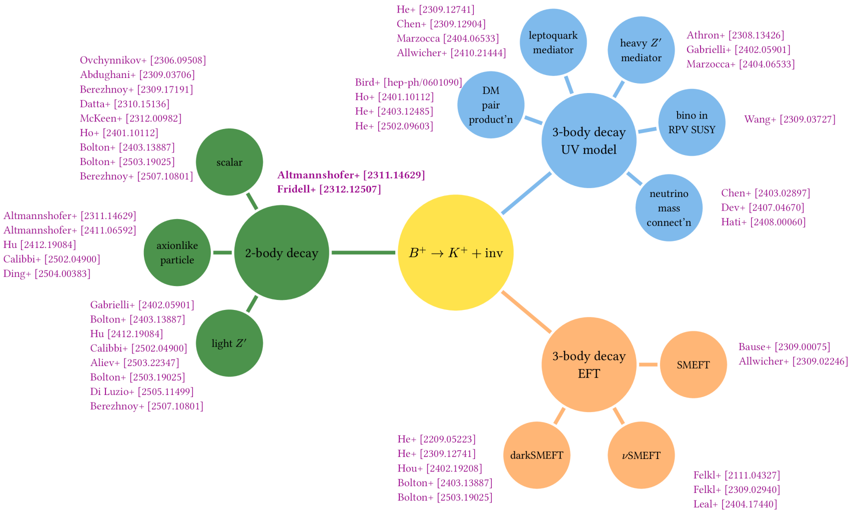
HTA



ITA



Many possible New Physics explanations [M. Schmidt, 2025 Belle II Physics Week]



GraFEI

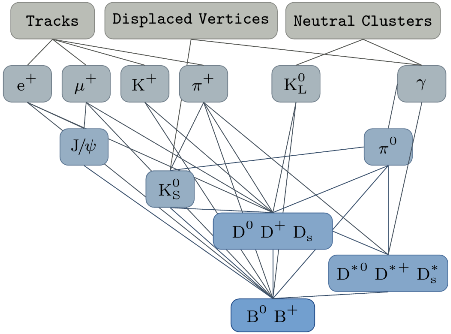
[Mach. Learn.: Sci. Technol 3, 035012 (2022), EPJ Web Conf. 337, 01265 (2025)]

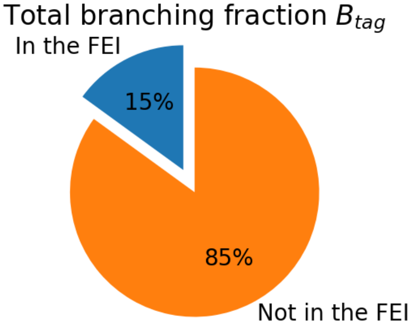
In collaboration with colleagues from Karlsruhe and Bonn

Collaborators@IPHC: Ilias Tsaklidis, Arthur Thaller, Jacopo Cerasoli, Corentin Santos and Merna Abumusabh

Drawbacks FEI

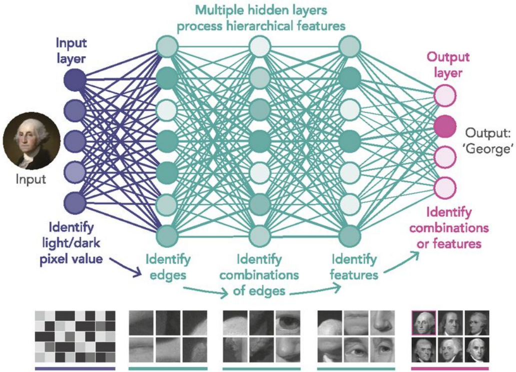
- 6 stages are disconnected
- Possible sub-decays are hard-coded



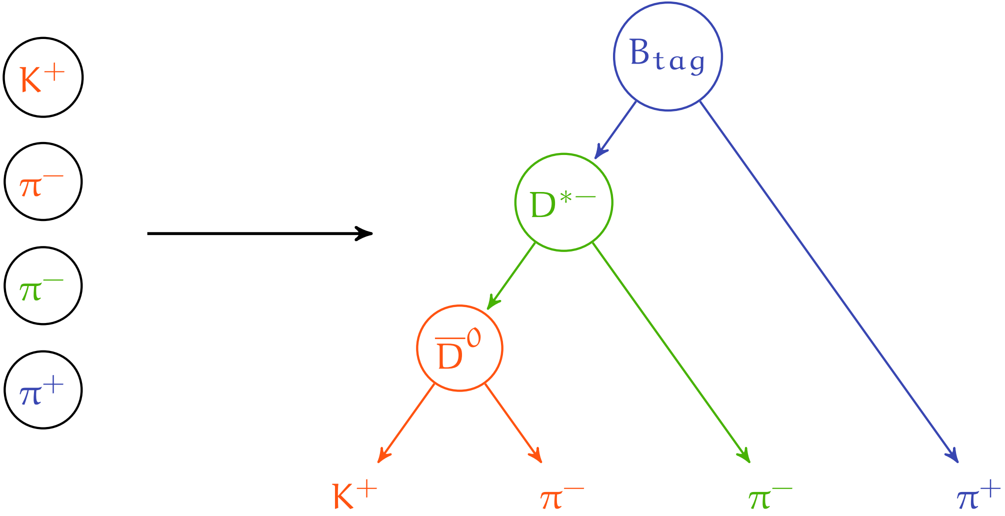


Deep learning

- Deep learning extracts autonomously the high level features without the need of experts intervention
- Successful for complex problems with hierarchical data (image recognition, natural language processing, web searches, ...)



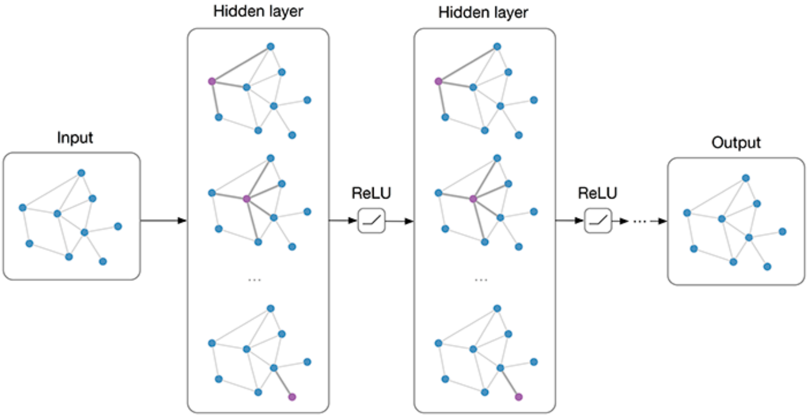
The goal: reconstruct a generic decay from its final state particles



Graph networks

Particles in a decay

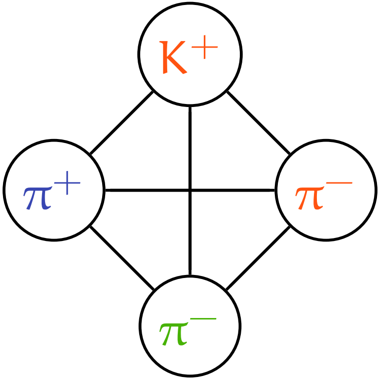
- Do not have a fixed number
- Do not have a clear ordering (symmetric under permutations)
- Can be described by a graph → use graph neural networks



Input graph

Fully connected graph of final state particles with features associated to

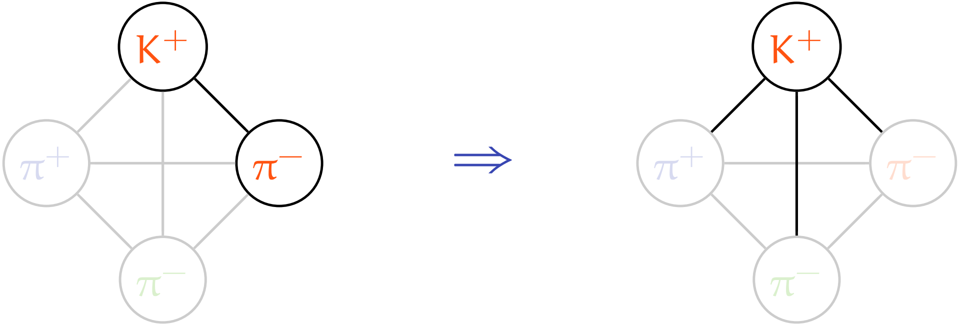
- Nodes: quantities associated to the particles (e.g. p_T, p_z, r, z, charge, PID information, ...)
- Edges: relations between the particles (e.g. angle between tracks, distance of closest approach, ...)
- Global: (optional): features related to the whole event e.g. position interaction point, ...



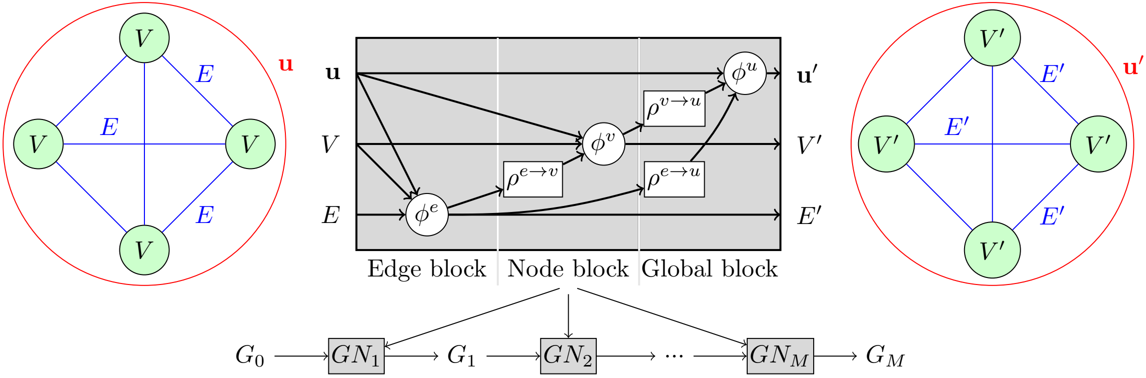
Graph neural network block

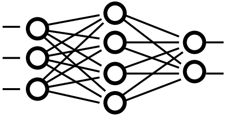
In each graph neural network block

- Update edge features with information from features current edge and connected nodes
- Update node features with information from node and average of updated edge features
- Global features, if present, taken into account in update edges and nodes and updated at the end using averages of all nodes and edges



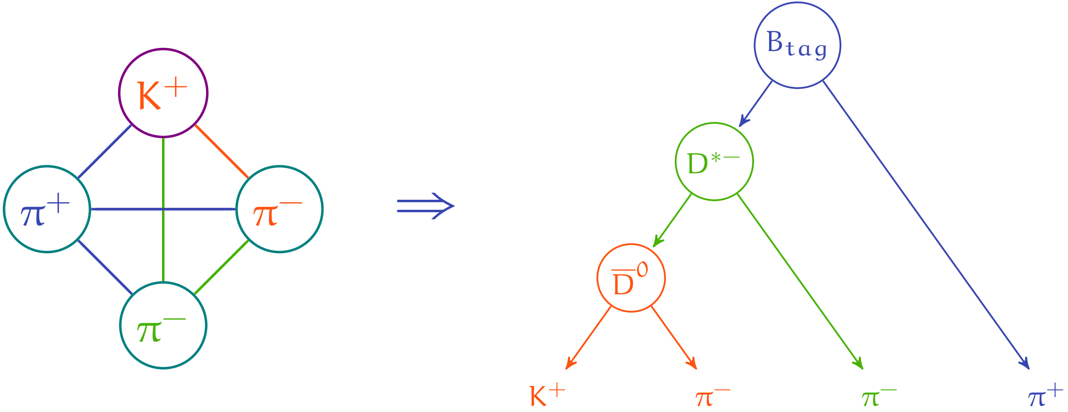
Chain several graph neural network blocks



$\phi =$  , $\rho = \frac{1}{N}\sum_{i=1}^{N} x_i$

From final graph extract decay tree

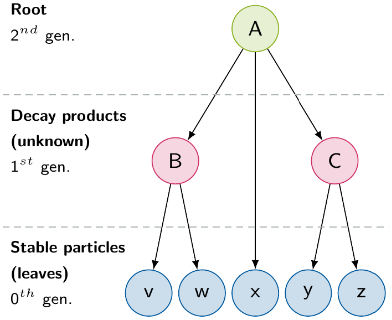
- Particle identity using node features
- Structure of decay tree using edge features



Lowest Common Ancestor Matrix

[Mach. Learn.: Sci. Technol 3, 035012 (2022)]

- Rows and columns are final state particles
- LCA: Elements are Lowest Common Ancestor
  - Prior knowledge of intermediate particles needed
- LCAG: Elements are the generation of Lowest Common Ancestor
  - No prior knowledge of intermediate particles needed



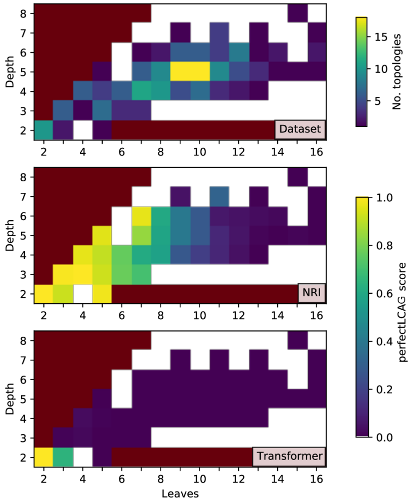
v	v	B	A	A	A
w	B	w	A	A	A
x	A	A	x	A	A
y	A	A	A	y	C
z	A	A	A	C	z

v	0	1	2	2	2
w	1	0	2	2	2
x	2	2	0	2	2
y	2	2	2	0	1
z	2	2	2	1	0
	v	w	x	y	z

Proof of concept

[Mach. Learn.: Sci. Technol 3, 035012 (2022)]

- Toy dataset with 200 different phase-space topologies
- Train graph neural network and transformer on 2000 events for topology
- Transformer has poor performance
- Graph neural network predicts correctly decays with less up to 8 generations:
  - 92.5% if up to six final state particles
  - 59.7% if up to ten final state particles

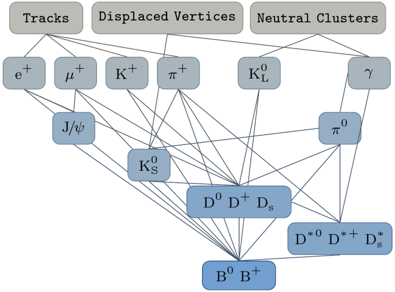


Lowest Common Ancestor Step Matrix

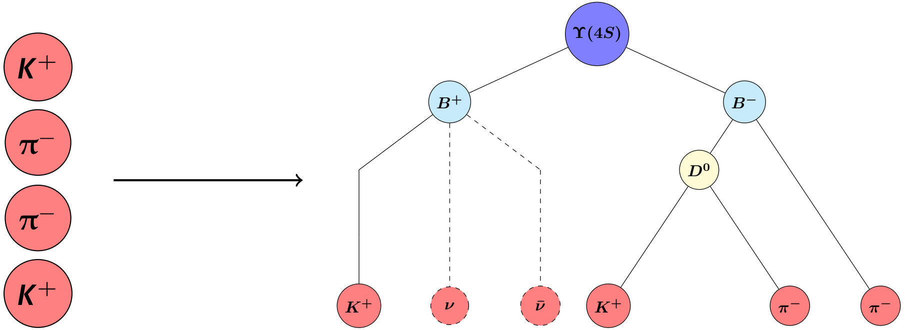
Drawbacks Lowest Common Ancestor Generation Matrix

- Matrix can be very deep and hard to predict
- Possible interference between decays with same final state particle not considered

Do not consider short-lived resonances and assign to particles a class (0 to 6) inspired by FEI step

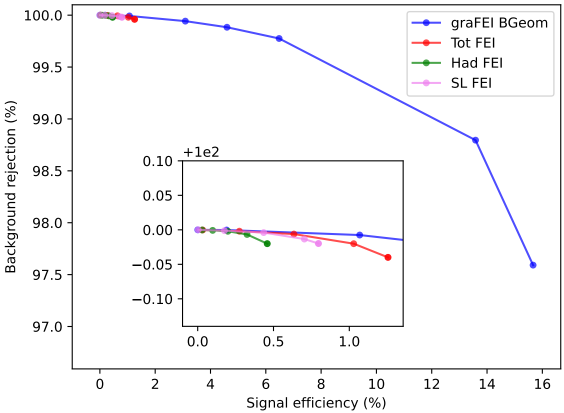


- Based on a deep graph neural network
- Reconstructs the $\Upsilon(4S)$ decay via the final state particles
- Trained over $\Upsilon(4S)$ decays $\longrightarrow$ No need to hard-code decay channels



Performance of GraFEI

- Significant improvement over the FEI
- Max efficiency 16% for GraFEI vs 1% for FEI
- Possible better efficiency by more than a factor 2 for same background rejection
- Now included in Belle II software and publicly available on GitHub

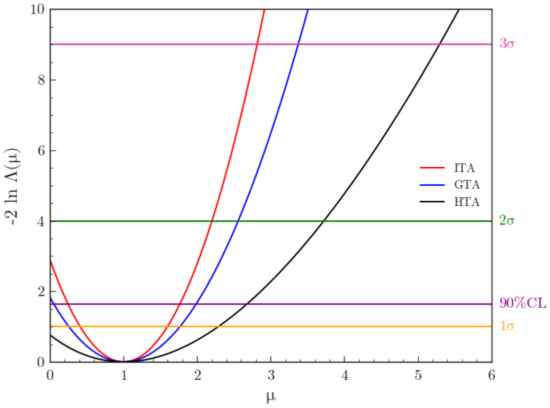


Comparison graFEI vs HTA and ITA

[EPJ Web Conf. 337, 01265 (2025)]

- Prototyped $B^+ \to K^+ \nu\bar{\nu}$ search with HTA strategy but using graFEI instead of FEI
- Considered only statistical uncertainties
- Better efficiency than HTA and better purity than ITA
- Twice better than HTA, 20% worse than ITA (but not optimised)

	$\varepsilon\,[\%]$	$\mathcal{P}^{\mathrm{sig}}\,[\%]$
HTA	0.4	3.5
ITA	8	0.8
GTA	**2.7**	**1.3**



Conclusions GraFEI

- Encouraging results but no breakthrough with respect to ITA
- Relies on good simulation (if not under-performance and systematics)
- New architectures could provide further improvements

Search for $B^+ \to K^+$ axion

[Phys. Rev. Res. 8, 023129 (2026)]

In collaboration with colleagues from Annecy and Orsay
Collaborators@IPHC: Merna Abumusabh

Motivations

[Phys. Rev. Res. 8, 023129 (2026)]

Axions and ALPs

- Axions are hypothetical light pseudoscalar particles that solve strong CP problem
- Link between mass and decay constant: $m_a \propto 1/f_a$ (f_a Peccei-Quinn scale)
- Axion like particles (ALPs) similar to axions but without this link
- Axions and ALPs are possible dark matter candidates

Possible to recast $B^+ \to K^+ \nu\bar{\nu}$ search as a search for $B^+ \to K^+ a$

- $B^+ \to K^+ a$ is a two body decay: q^2 distribution peaking at m_a^2
- For QCD axion $m_a \sim 0$

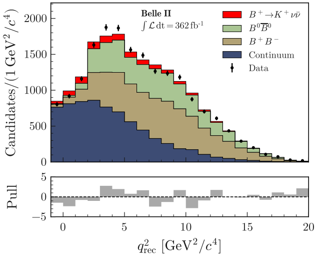
$$\mathcal{B}(B^+ \to K^+ a) \propto |f_+^K(m_a^2)|^2 |(F_V)_{sb}|^2$$

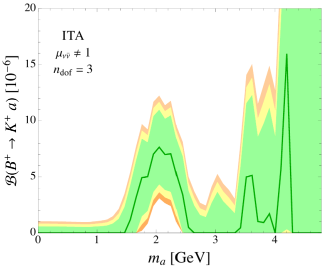
$(F_V)_{sb} = 2f_a/(k_V)_{sb}$ Peccei-Quinn scale rescaled to coupling between axion and b and s quarks

Reinterpretation

[Phys. Rev. Res. 8, 023129 (2026)]

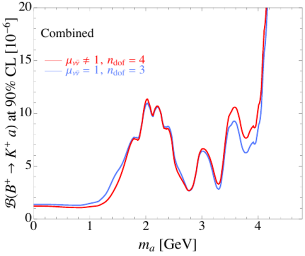
- Fit post-fit q^2_{rec} distribution with 3 components
  - $B^+ \to K^+ a$
  - $B^+ \to K^+ \nu\overline{\nu}$
  - Background (shape taken from distribution)
- Translate known theoretical q^2 shape into q^2_{rec} for $B^+ \to K^+ a$ and $B^+ \to K^+ \nu\overline{\nu}$
- Gaussian constrain background
- Two options for $\mathcal{B}(B^+ \to K^+ \nu\overline{\nu})$
  - Fixed to Standard Model value
  - Free to value
- Consider both ITA and HTA
- Set upper limit on $\mathcal{B}(B^+ \to K^+ a)$ and corresponding lower limit on $|(F_V)_{sb}|$





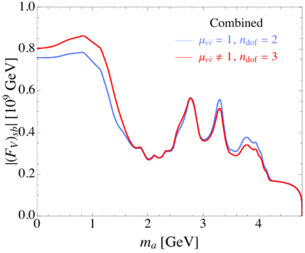
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$ fixed to Standard Model value

- $\mathcal{B}(B^+ \to K^+ a) < 1.4 \times 10^{-6}$
- $|(F_V)_{sb}| > 7.6 \times 10^8$ GeV



$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$ free to vary

- $\mathcal{B}(B^+ \to K^+ a) < 1.2 \times 10^{-6}$
- $|(F_V)_{sb}| > 8.0 \times 10^8$ GeV



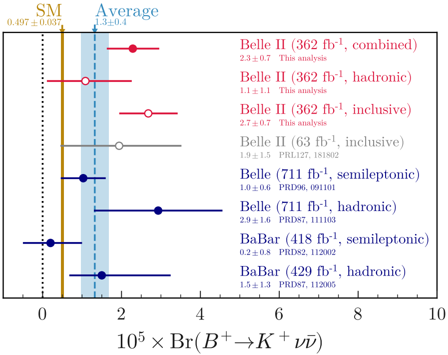
Best lower limit on $|(F_V)_{sb}|$

Future prospects

In collaboration with colleagues from Perugia and Bonn
Collaborators@IPHC: Corentin Santos and Merna Abumusabh

Motivations for semileptonic-tag analysis

- Important to look for $B^+ \to K^+\nu\bar{\nu}$ in a complementary way
- $B \to K^*\nu\bar{\nu}$ provides complementary information
- Past semileptonic tagged analysis had sensitivities in the same ballpark than ITA



Analyse $B^+ \to K^+\nu\bar{\nu}$	Incertitude pour 365 fb^{-1} [10^{-6}]
BaBar HTA	14.0
BaBar STA	8.0
Belle HTA	23.5
Belle STA	8.1
Belle II HTA	10.7
Belle II ITA	7.1

Analysis's strategy

Similar strategy than HTA

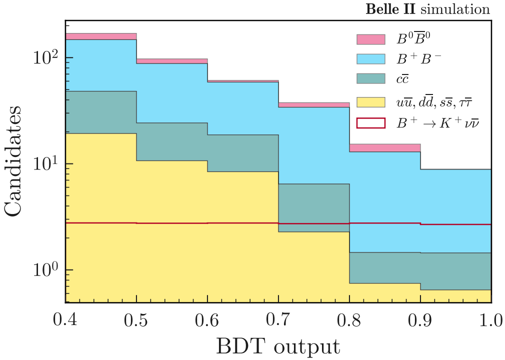
- Select first tag B decaying semileptonically to $B_{tag} \to D^{(*)} l\nu$
- Request only signal and Btag in the event
- Fit BDT output
- Corrections and systematics obtained from control samples

Key differences

- Look for $B^{+} \to K^{+}\nu\bar{\nu}$ and $B^{0} \to K^{*0}\nu\bar{\nu}$
- Improved simulation (run dependent)
- Correct all background branching fractions to latest PDG value
- Use extra-track control sample (allow one or more low-quality tracks)

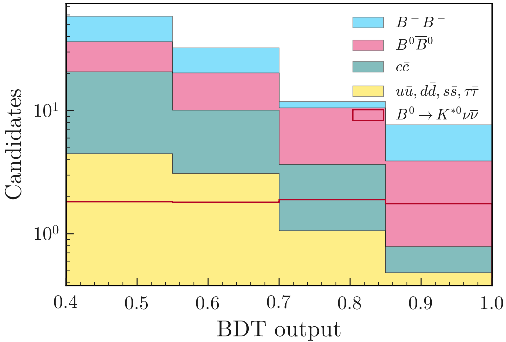
Expected results

$B^+ \to K^+ \nu\bar{\nu}$



$$\sigma_{\mathcal{B}}^{\text{expected}} \sim 5 \times 10^{-6}$$

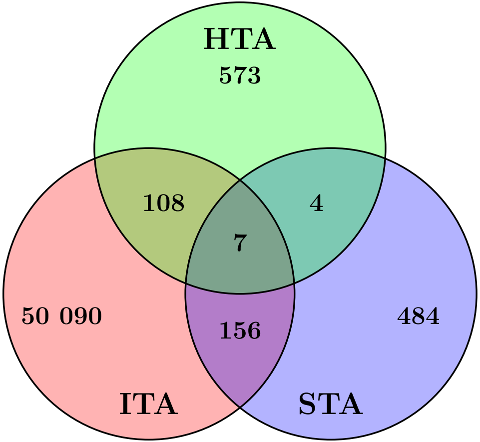
$B^0 \to K^{*0} \nu\bar{\nu}$



$$\sigma_{\mathcal{B}}^{\text{expected}} \sim 20 \times 10^{-6}$$

More details will follow in Corentin's and Merna's PhD defense ;-)

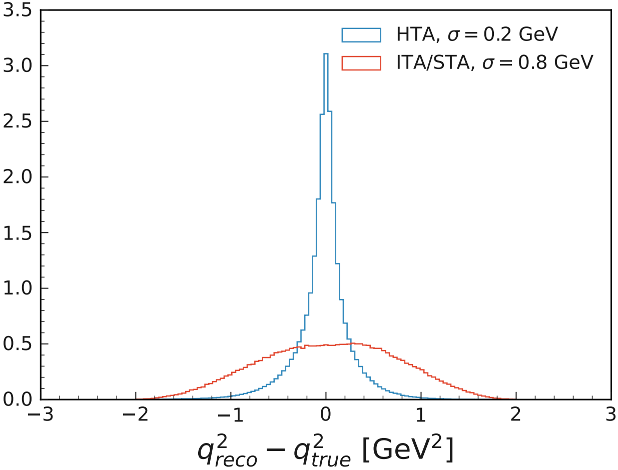
Longer term perspectives: combine different tagging strategies



Number of expected events with 1 ab^{-1}

Longer term perspectives: dedicated two-body search

HTA has 4 times better q^2 resolution that ITA and STA:



Conclusion

- Developed GraFEI to generically reconstruct B decays that shows improvements over the FEI
- First evidence of $B^+ \to K^+ \nu\bar{\nu}$ with 2.7σ tension over Standard Model prediction
- Now focus on confirming the results with a complementary analysis and adding new decay modes

BACKUP

Expected efficiency and purity semileptonic search

Analyse $B^+ \to K^+\nu\bar{\nu}$	Efficacité	Pureté
BaBar HTA	0.04%	17%
BaBar STA	0.16%	35%
Belle HTA	0.05%	5%
Belle STA	0.2%	5%
Belle II HTA	0.4%	3.5%
Belle II ITA	8%	0.8%
Belle II STA	0.7%	5%
Belle II STA $B^0 \to K^{*0}\nu\bar{\nu}$	0.2%	5%

Systematics HTA

[Phys. Rev. D 109, 112006 (2024)]

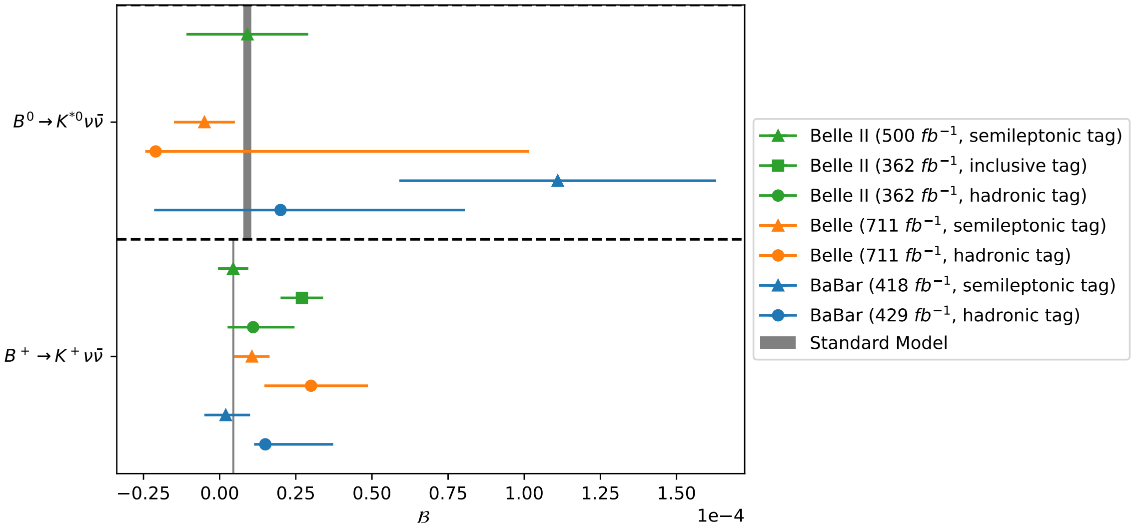
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background		Global, 1	30%	0.91
Normalization of continuum background		Global, 2	50%	0.58
Leading B-decay branching fractions		Shape, 3	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+K^0_LK^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \to D^{**}$		Shape, 1	50%	< 0.01
Branching fraction for $B^+ \to K^+n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \to K^0_LX$	$+30\%$	Shape, 1	10%	0.03
Continuum-background modeling, BDT$_\mathrm{c}$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\overline{B}$		Global, 1	1.5%	0.07
Track finding efficiency		Global, 1	0.3%	0.01
Signal-kaon PID	p, θ dependent $O(10–100\%)$	Shape, 3	$O(1\%)$	< 0.01
Extra-photon multiplicity	$n_{\gamma\mathrm{extra}}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K^0_L efficiency		Shape, 1	17%	0.31
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency		Shape, 6	16%	0.42
Simulated-sample size		Shape, 18	$O(1\%)$	0.60

Systematics ITA

[Phys. Rev. D 109, 112006 (2024)]

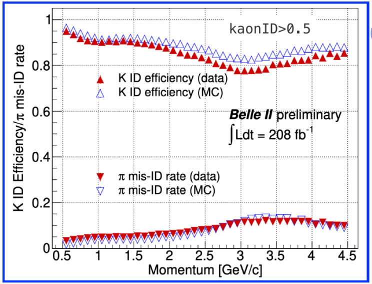
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background		Global, 2	50%	0.90
Normalization of continuum background		Global, 5	50%	0.10
Leading B-decay branching fractions		Shape, 6	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \to D^{**}$		Shape, 1	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \to K^0_L X$	$+30\%$	Shape, 1	10%	0.14
Continuum-background modeling, $\mathrm{BDT_c}$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity		Global, 1	1%	< 0.01
Number of $B\overline{B}$		Global, 1	1.5%	0.02
Off-resonance sample normalization		Global, 1	5%	0.05
Track-finding efficiency		Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10–100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy		Shape, 1	0.5%	0.08
Hadronic energy	-10%	Shape, 1	10%	0.37
K^0_L efficiency in ECL	-17%	Shape, 1	8.5%	0.22
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency		Global, 1	3%	0.03
Simulated-sample size		Shape, 156	$O(1\%)$	0.52

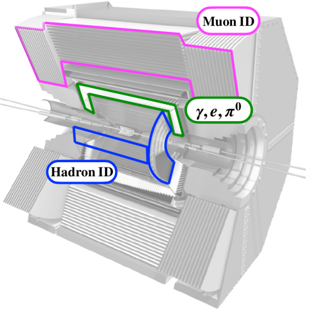
Expected results semileptonic $B \to K^{(*)}\nu\bar{\nu}$ search

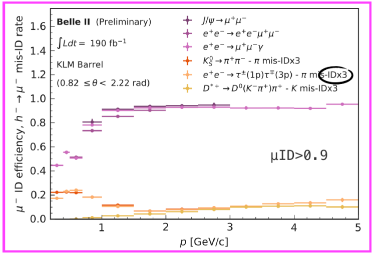


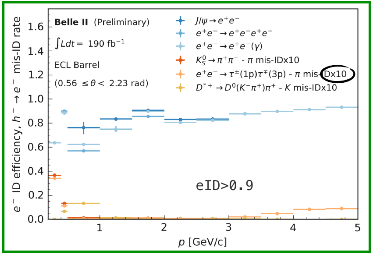
Key Belle II performance

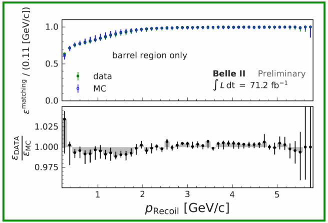
- Good kaon identification in full momentum range
  - $\varepsilon(K) \sim 90\%, \pi \to K \sim 6\%$
- High photon efficiency
  - $\varepsilon(\gamma) \sim 90\%$ ($p > 1.5$ GeV)
- Good lepton ID performance
  - $\varepsilon(\mu) \sim 90\%, \pi \to \mu \sim 7\%$
  - $\varepsilon(e) \sim 86\%, \pi \to e \sim 0.4\%$











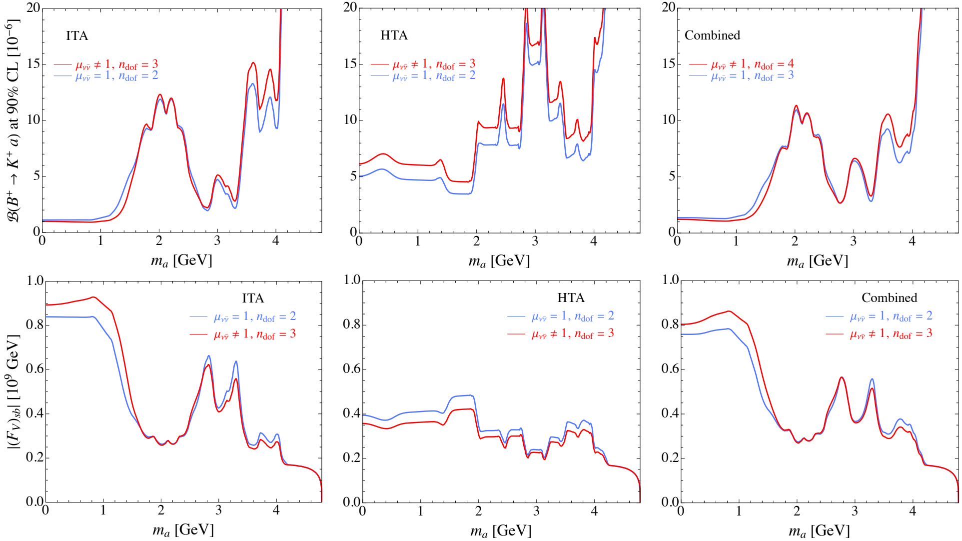
Limits $B^+ \to K^+ a$

[Phys. Rev. Res. 8, 023129 (2026)]

	ITA	HTA	Combined
$\mu_{\nu\bar{\nu}} = 1$	$n_{\text{dof}} = 2$ $\mathcal{B}_a < 1.1 \times 10^{-6}$ $\lvert(F_V)_{sb}\rvert > 8.4 \times 10^8$ GeV	$n_{\text{dof}} = 2$ $\mathcal{B}_a < 5 \times 10^{-6}$ $\lvert(F_V)_{sb}\rvert > 4 \times 10^8$ GeV	$n_{\text{dof}} = 3$ $\mathcal{B}_a < 1.4 \times 10^{-6}$ $\lvert(F_V)_{sb}\rvert > 7.6 \times 10^8$ GeV
$\mu_{\nu\bar{\nu}} \neq 1$	$n_{\text{dof}} = 3$ $\mathcal{B}_a < 1.0 \times 10^{-6}$ $\lvert(F_V)_{sb}\rvert > 8.9 \times 10^8$ GeV	$n_{\text{dof}} = 3$ $\mathcal{B}_a < 6 \times 10^{-6}$ $\lvert(F_V)_{sb}\rvert > 4 \times 10^8$ GeV	$n_{\text{dof}} = 4$ $\mathcal{B}_a < 1.2 \times 10^{-6}$ $\lvert(F_V)_{sb}\rvert > 8.0 \times 10^8$ GeV

Upper limits $B^+ \to K^+ a$

[Phys. Rev. Res. 8, 023129 (2026)]



Fit results $B^+ \to K^+ a$

[Phys. Rev. Res. 8, 023129 (2026)]