Based on arXiv 2607.25607

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Search for $B^0 \to K_S^0 \tau^+ \tau^-$

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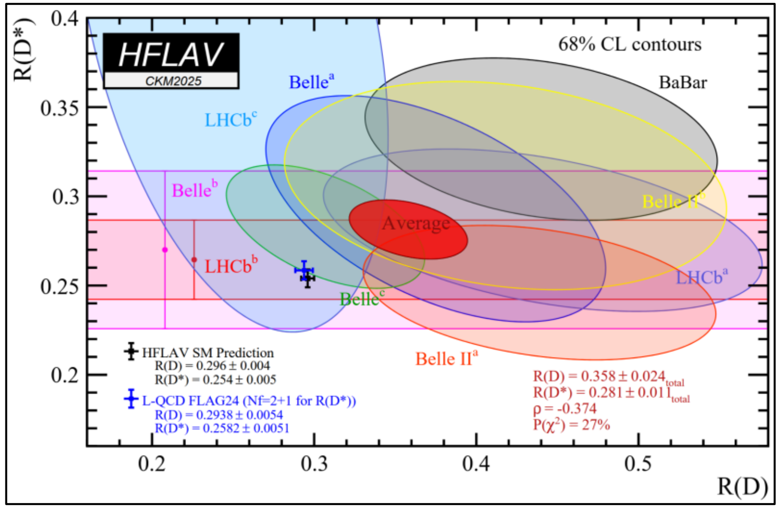
Motivation

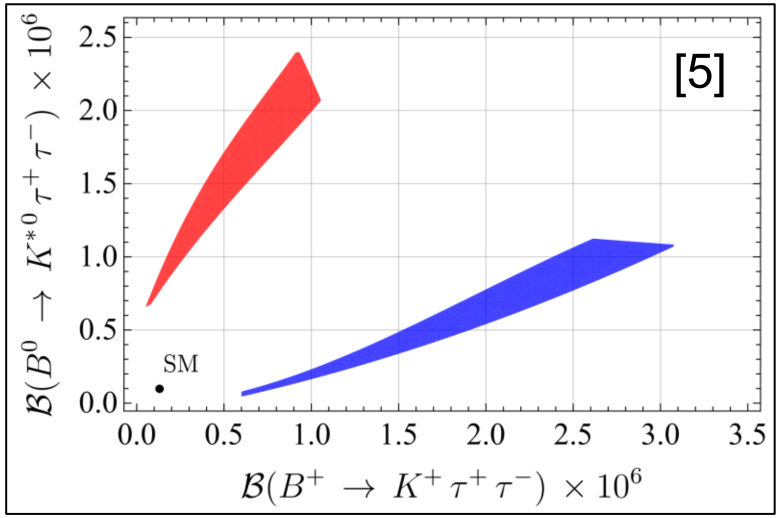
- $b \to s\tau\tau$ transitions occur only in loop level as FCNC
  SM expected BF $\mathcal{O}(10^{-7})$ [1]
- Non-SM particles could modify decay properties
- Correlations with $R_{D^{(*)}}$ [2] suggest large enhancements to SM BF $\mathcal{O}(10^2$ - $10^3)$ [3]

$$C_9^{\tau\tau} = -C_{10}^{\tau\tau} \sim -\frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{SM}}} - 1\right)$$

- Excess in $B^+ \to K^+\nu\bar{\nu}$, combined with $R_{K^{(*)}}$ constraints, suggests LFU violation in τ's [4,5]

HFLAV





[1]PRD107,119903(2023) [2]PRL120,181802(2018) [3]PRD105,113007(2022) [4]PLB848,138411(2023) [5]arXiv:2309.00075

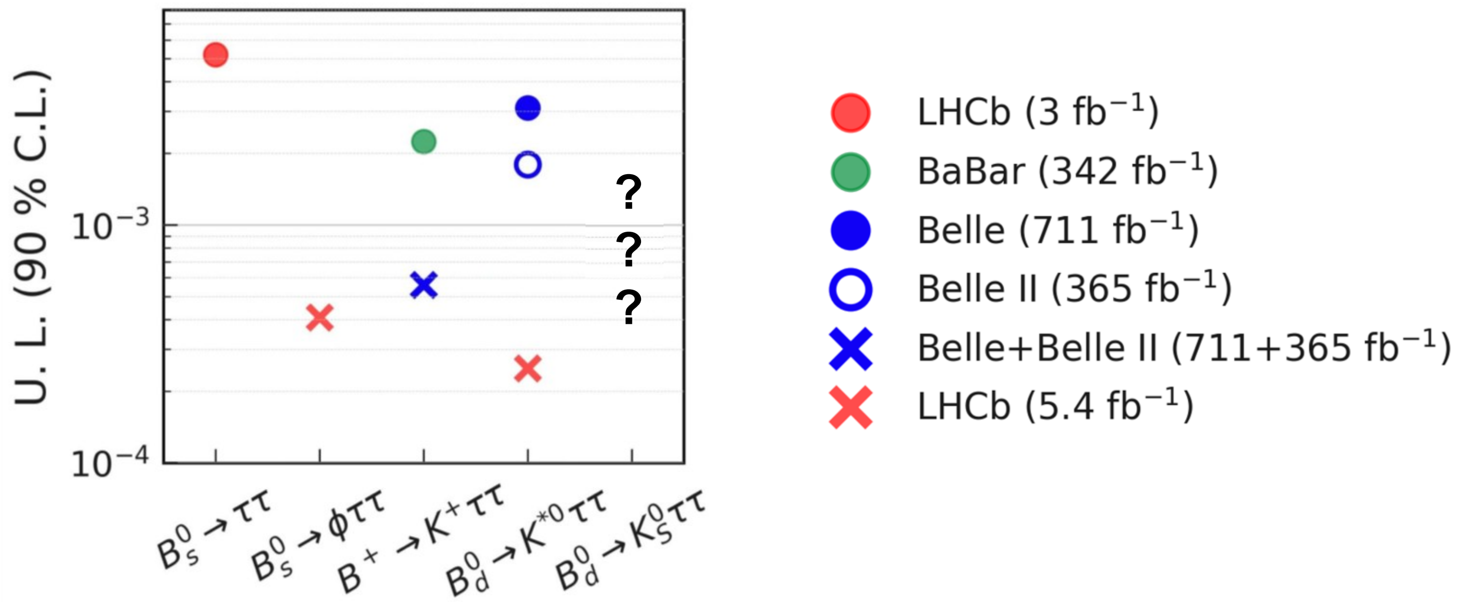
Experimental Status

Before 2025, very few experimental results and upper limits ~ $\mathcal{O}(10^{-3})$ on $B \to K^{(*)}\tau\tau$

- Belle II $B^0 \to K^{*0}\tau\tau$ result improved over Belle (×2)
- New $B^+ \to K^+\tau\tau$ (Belle and Belle II) result
- First direct search at LHCb for $B^0 \to K^{*0}\tau\tau$
- <u>No experimental input for $B^0 \to K^0\tau\tau$</u>

Limits for $B \to K_P\tau\tau$ and $B \to K_V\tau\tau$ provide complementary information in constraining BSM physics

P = pseudoscalar **V = vector**



PRL 118 (2017) 25, 251802

PRL 118 (2017) 3, 031802

PRD 108 (2023) 1, L011102

PRL 135, 151801 (2025)

PRL 137 (2026) 5, 051805

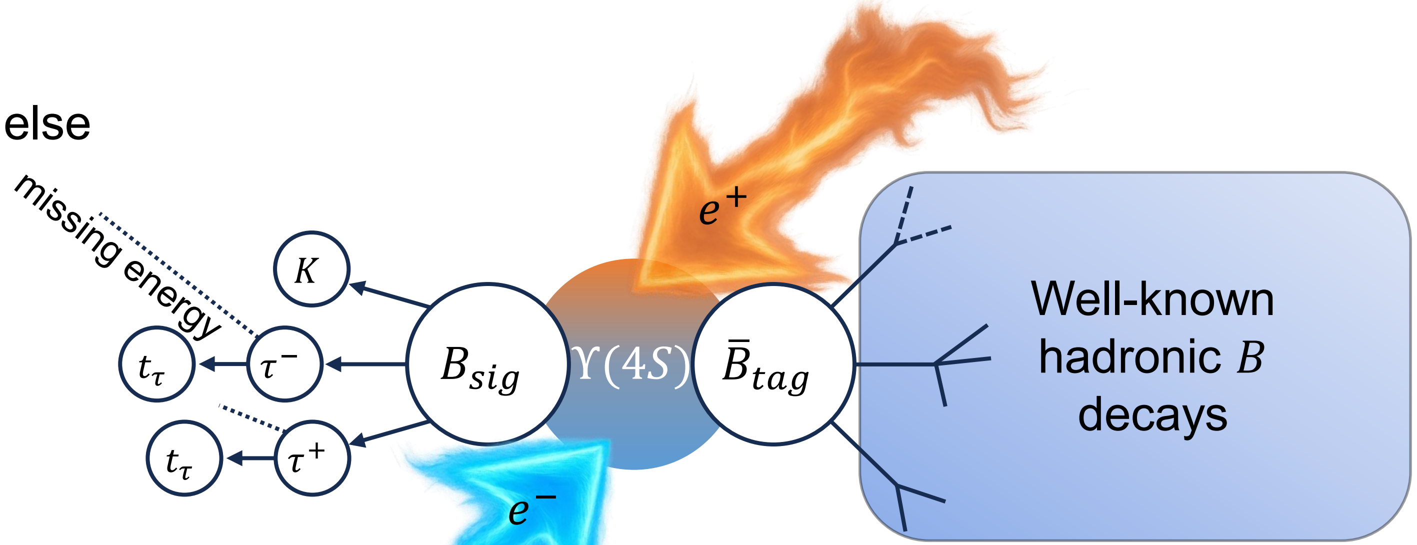
PRL 136 (2026) 181802

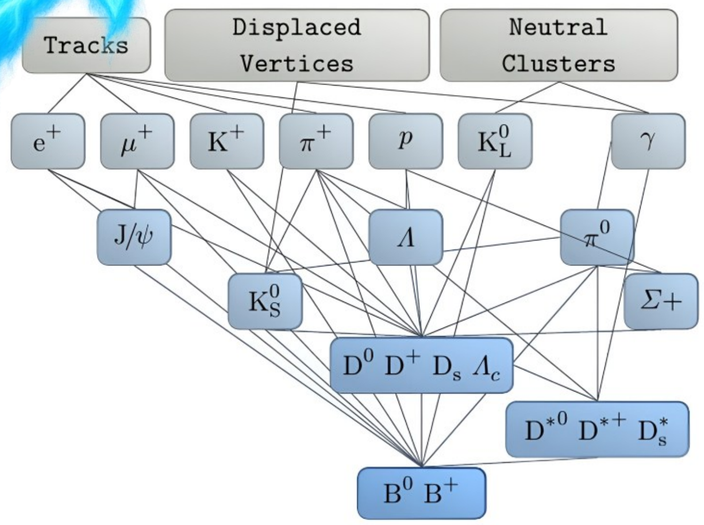
Hadronic B-Tagging

- At $\Upsilon(4S)$ we have just **two B mesons** and nothing else
- MVA-based **B-tagging** algorithm with hierarchical approach, called Full Event Interpretation (FEI) is used to exclusively reconstruct the **non-signal B meson ($\bar{B}_{tag}$)** in $\mathcal{O}(10^4)$ decay chains
- This tagging technique has a rather low efficiency of $\mathcal{O}(0.1\%)$, but also comes with a **high purity** of $\mathcal{O}(10\%)$
- FEI-reconstructed **tag B meson** allows for kinematic and flavor inference on the **signal B meson** through the $\Upsilon(4S)$ constraint

⇒ **No missing energy in the tag side**

Crucial for signatures with neutrinos

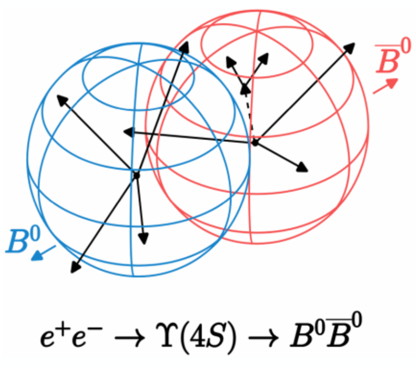


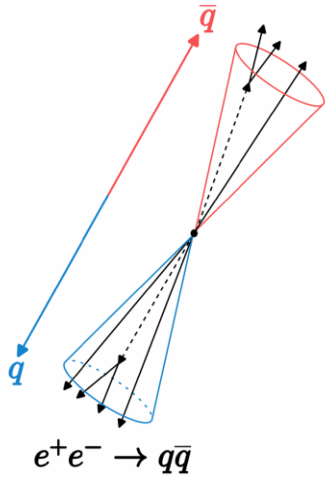


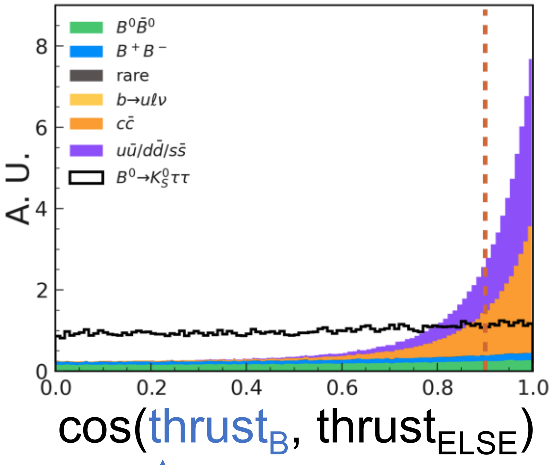
Comput Softw Big Sci 3, 6 (2019)

Hadronic B-Tagging

- With hadronic B-tagging the $q\bar{q}$ background is generally minor
- Reduced further with event-shape information



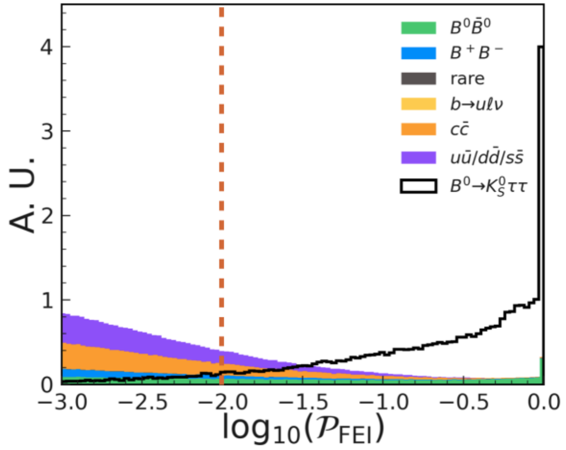


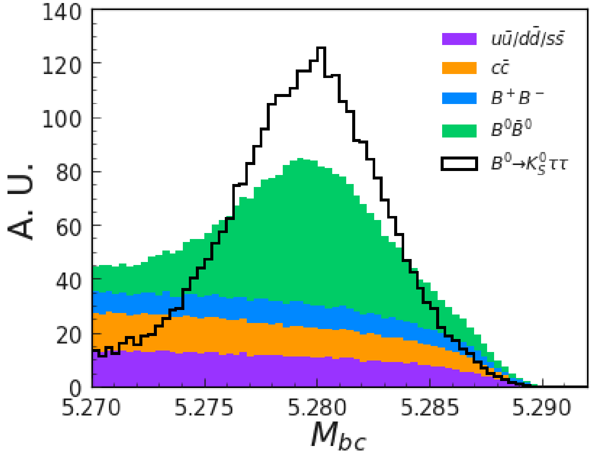


accessed with B-tagging

Minimal requirements on tag-side correctness score ($\mathcal{P}_{FEI}$) and beam-constrained mass (M_{bc}) act as a **powerful filter against misreconstructed events**

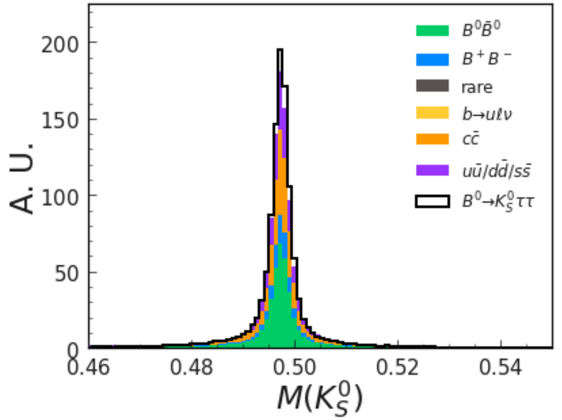
$$M_{bc}c^2 = \sqrt{s/4 - p_{B_{tag}}^{*2}c^2}$$



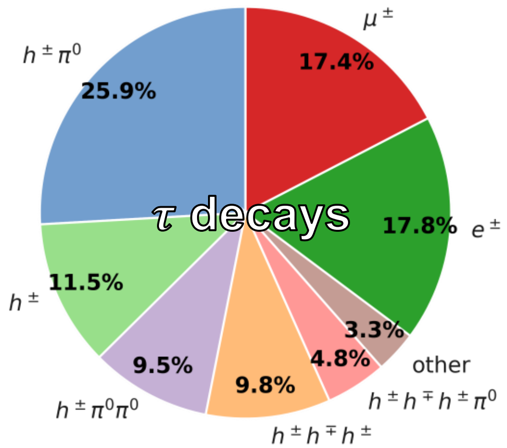


High tag reliability as a way to **isolate signal side** and study its properties

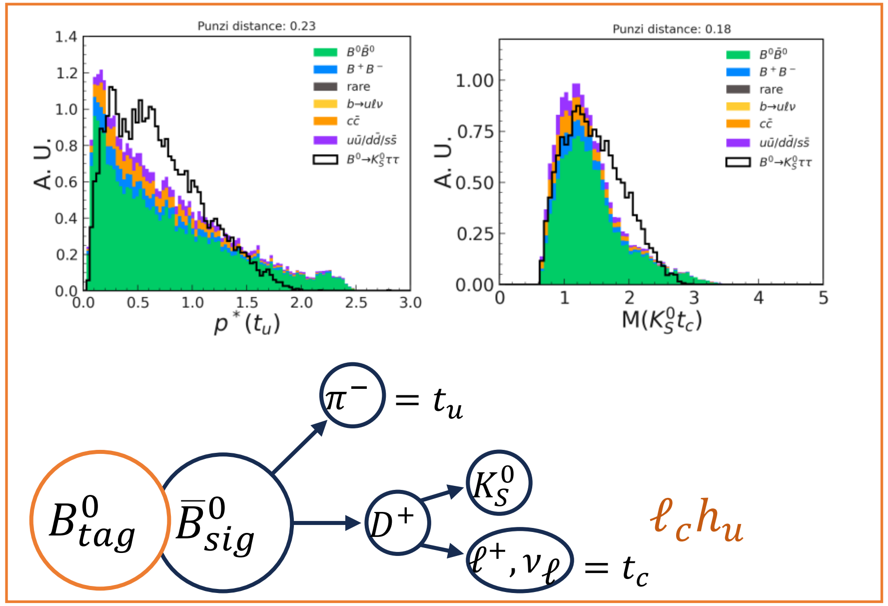
Signal Selection

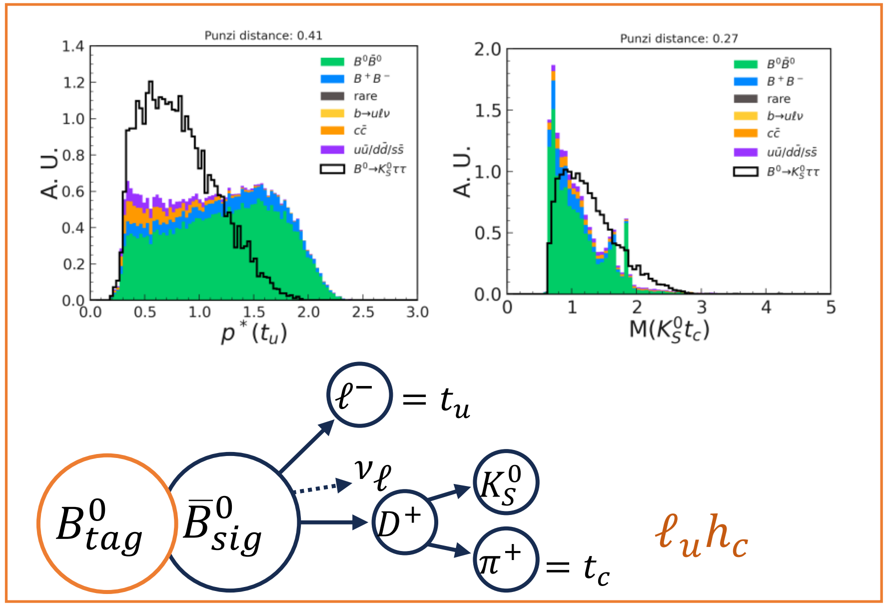


- K_S^0 is reconstructed as (usually displaced) $\pi^+\pi^-$ vertex with quality criteria imposed
- Reconstruct τ leptons through decays to a **single charged particle t_τ (~85%)**



- 10 possible final-state combinations follow a rank-based order of **category assignment**
- Use **flavor of B_{tag}** for more efficient background suppression
- **5 orthogonal categories** with different purity/sensitivity

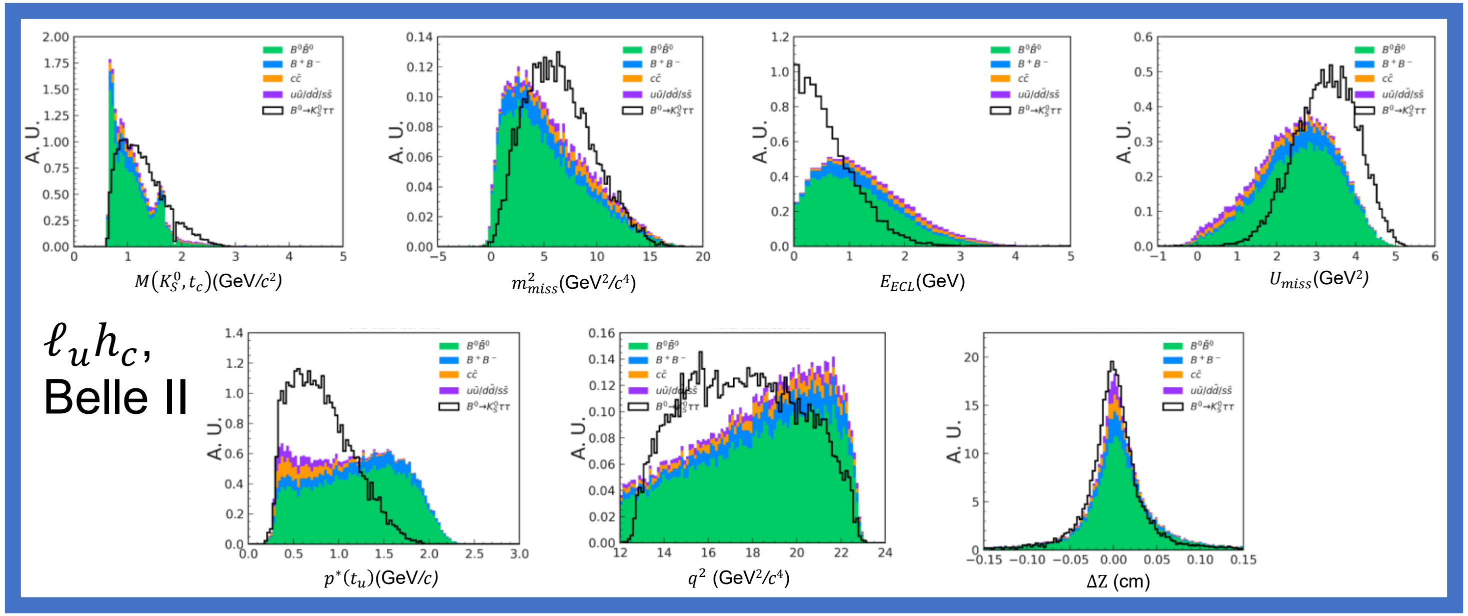


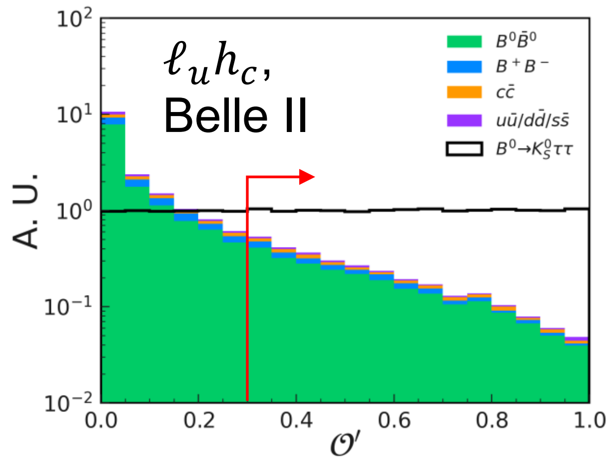


$\tau\bar{\tau}$ final state	Category
$\mu\ \mu$	$\ell\ell$
$e\ \mu$	
$e\ e$	
$\mu\ \rho$	$\rho\ell$
$e\ \rho$	
$\mu\ h$	$\ell_c h_u, \ell_u h_c$
$e\ h$	
$\rho\ \rho$	$\ell 0$
$\rho\ h$	
$h\ h$	

Background Suppression

- Multivariate classification – combining **multiple discriminating observables** into a single measure of how signal-like an event is
- Classifier based on boosted decision trees (BDT) **assigns a score $\mathcal{O}'$** to each event
- An independent classifier is tailored for each category in Belle and Belle II





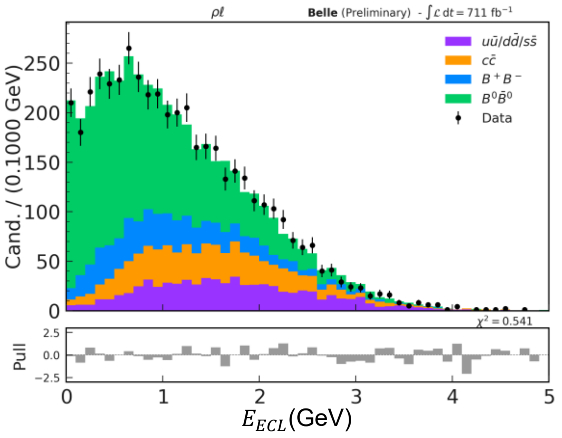
- We impose a minimal requirement on the BDT score output (**$\mathcal{O}'$>0.3**) to define the signal extraction region
- We achieve >80% background rejection at 70% signal efficiency for every category

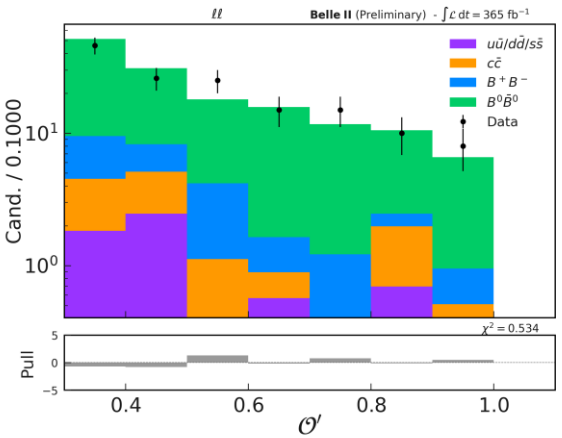
Validation

① **Off-resonance** (collision energy sideband)

- 60 MeV below $\Upsilon(4S)$ production threshold
- Only $q\bar{q}$ backgrounds

Bad B_{tag}, good K_S^0

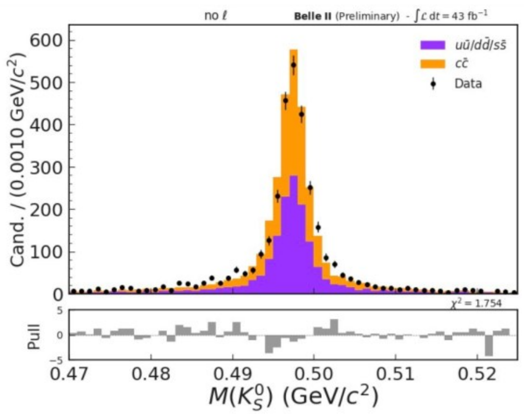


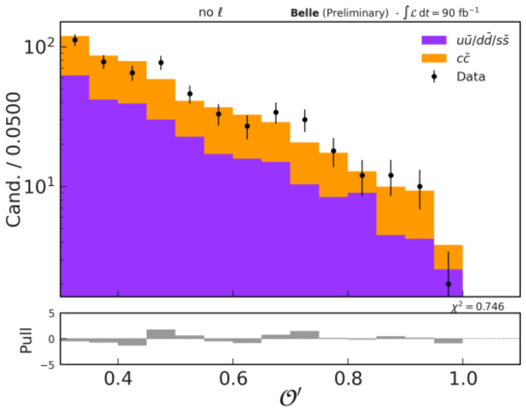


③ M_{bc} sideband

- Depleted in good B_{tag} candidates
- Suitable to estimate $q\bar{q}$ and $B\bar{B}$ combinatorics

Bad B_{tag}, good K_S^0

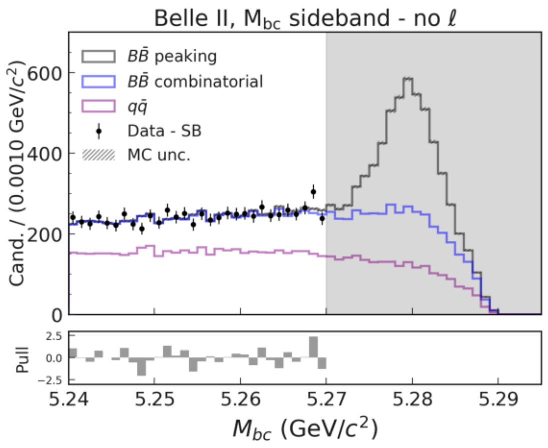


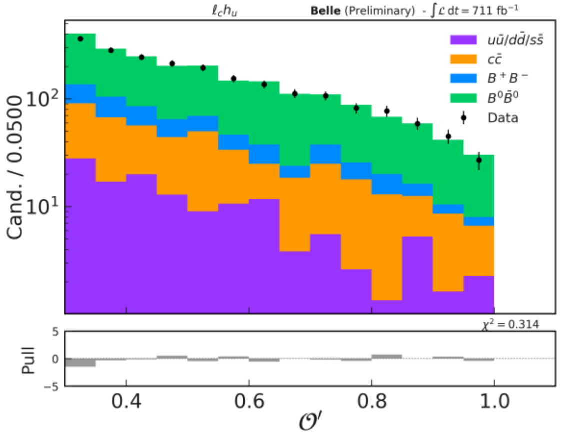


② K_S^0 sideband

- Off-peak invariant mass + inverted quality criteria
- Good proxy for general backgrounds

Good B_{tag}, bad K_S^0





Systematic Uncertainties

The result is statistically limited but a careful assessment of the systematic uncertainties is necessary

- Limited simulation sample size
- External inputs
- Efficiency calibrations
- Dedicated measurements

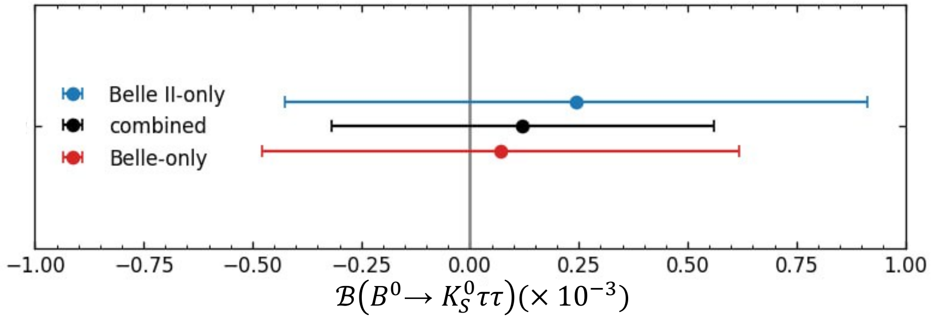
Source	Uncertainty type, parameters	Applied to
MC statistics	Uncorrelated shape, 140	All
Leading B-decay branching fractions	Correlated shape, 140	$B\bar{B}$
$D \to K_L^0$ modeling	Correlated shape, 2	$B\bar{B}$
f_{00}	Correlated shape, 1	$B\bar{B}$, signal
Luminosity uncertainty	Normalization, 2	$q\bar{q}$
χ_d	Correlated shape, 1	$B\bar{B}$, signal
Leading τ-decay branching fractions	Correlated shape, 10	signal
Number of $\Upsilon(4S)$	Normalization, 2	$B\bar{B}$, signal
Signal form factor	Correlated shape, 1	signal
Tracking efficiency	Correlated Shape, 2	All
FEI efficiency	Correlated shape, 2	$B\bar{B}$, signal
Lepton ID	Correlated shape, 6	All
π^0 efficiency	Correlated shape, 2	All
K_S^0 efficiency	Correlated shape, 2	All
$q\bar{q}$ normalization	Normalization, 4	$q\bar{q}$
Signal efficiency uncertainty	Normalization, 2	signal
Combinatorial $B_{\rm tag}^0$ normalization	Correlated shape, 10	$B\bar{B}$

Nuisance parameters related to each source are implemented directly into the signal extraction model

Signal Extraction

- Binned maximum-likelihood fit to $\mathcal{O}'$
- We observe no significant signal

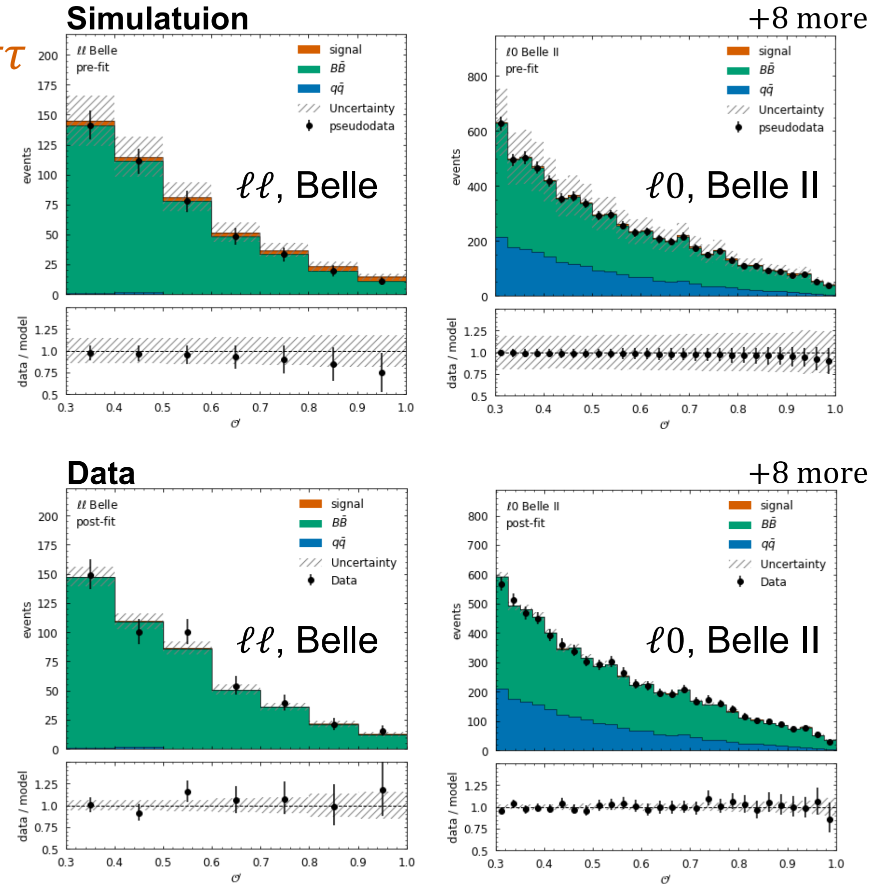
$$\mathcal{B}(B^0 \to K_S^0 \tau\tau) = [0.12 \pm 0.33\,(stat.) \pm 0.29\,(syst.)] \times 10^{-3}$$



Signal $B^0 \to K_S^0 \tau\tau$

$B\overline{B}$ background

$q\overline{q}$ background



- We set an upper limit on $\mathcal{B}(B^0 \to K_S^0 \tau\tau)$ using CLs method

$\mathcal{B}(B^0 \to K_S^0 \tau\tau) < 0.83 \times 10^{-3}$ at 90% Confidence Level

Limit $\times\ 10^{-3}$	**Expected**	**Observed**
Belle	1.12	1.31
Belle II	0.95	1.01
Combined	0.74	**0.83**

- No tensions in the nuisance parameter pulls
- Dominant systematic uncertainties:
  - Leading B-decay branching fractions (0.20×10^{-3})
  - Simulation sample size (0.18×10^{-3})

Isospin Average

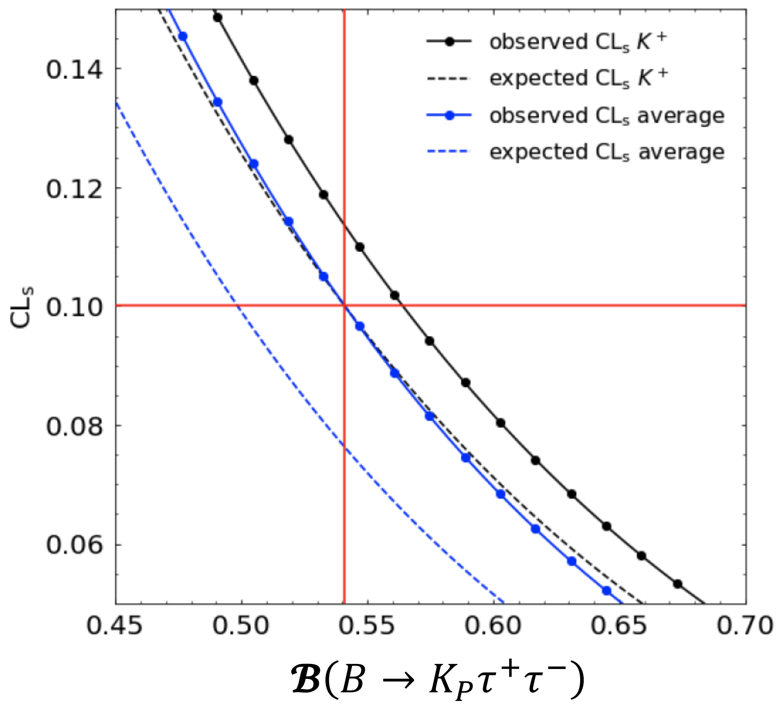
- We perform isospin average for $B^+ \to K^+\tau^+\tau^-$ and $B^0 \to K_S^0\tau^+\tau^-$.
- Both are pseudo-scalars ↔ BSM physics should act in a same way.

- We perform a fit to joint likelihood with a single parameter of interest:

$$\mathcal{B}(B \to K\tau^+\tau^-) \equiv \mathcal{B}(B^+ \to K^+\tau^+\tau^-) = 2\frac{\tau_{B^+}}{\tau_{B^0}}\mathcal{B}(B^0 \to K_{\mathrm{S}}^0\tau^+\tau^-)$$

- Correlations of systematic uncertainties is taken into account.

	$\mathcal{B}(\times 10^{-3})$	observed (expected) $\times 10^{-3}$ Upper Limit $\times 10^{-3}$
$B^0 \to K_S^0\tau\tau$	0.12 ± 0.44	0.83 (0.74)
$B^+ \to K^+\tau\tau$	0.04 ± 0.30	0.56 (0.54)
Combination	0.06 ± 0.28	0.54 (0.50)



Interpretation

- If we consider the effective parametrization:

$$\mathcal{H}_{\text{eff}}(b \to s\ell\ell) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i^\ell \mathcal{O}_i^\ell + \text{h.c.}$$

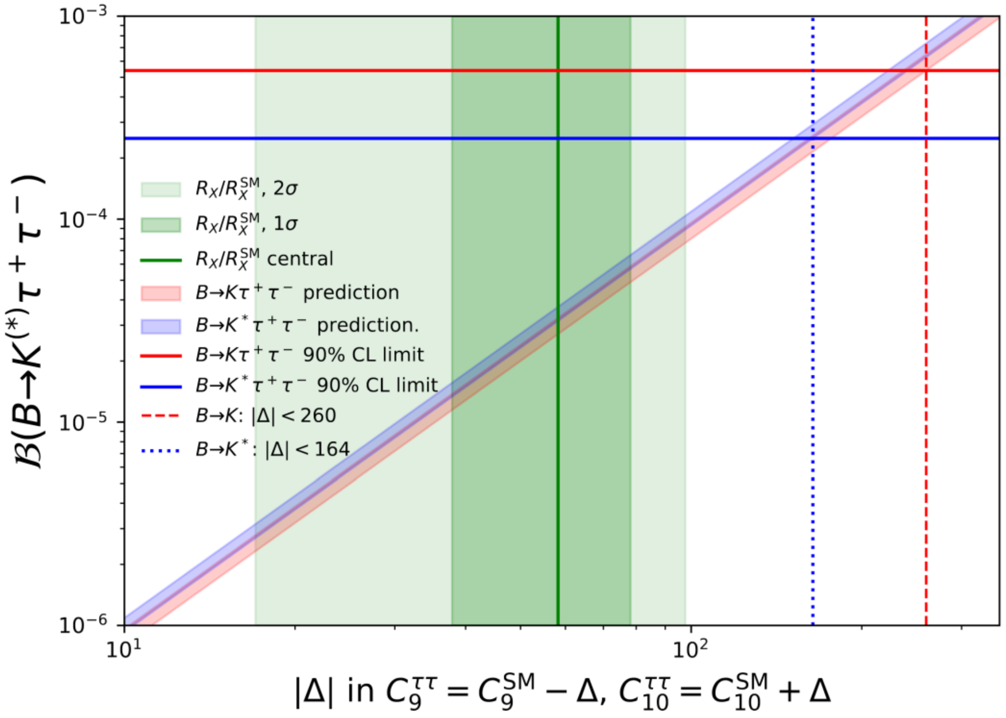
- And introduce new **heavy degree of freedom** Δ into Wilson coefficients $\mathcal{C}_9^\tau$ and $\mathcal{C}_{10}^\tau$:

$$C_9^\tau = C_9^{\text{SM}} - \Delta, \qquad C_{10}^\tau = C_{10}^{\text{SM}} + \Delta$$ [PRL **120**, 181802]

- With a relation of Δ to an **observed flavor anomaly**:

$$\Delta = \frac{2\pi}{\alpha} \frac{V_{cb}}{V_{tb} V_{ts}^*} \left(\sqrt{\frac{R_X}{R_X^{\text{SM}}}} - 1 \right)$$

- We can put a constraint on it using our measurement.



- We need an <u>order of magnitude in sensitivity</u> on $\mathcal{B}(B \to K\tau\tau)$ to start excluding existing flavor anomalies.

Conclusion

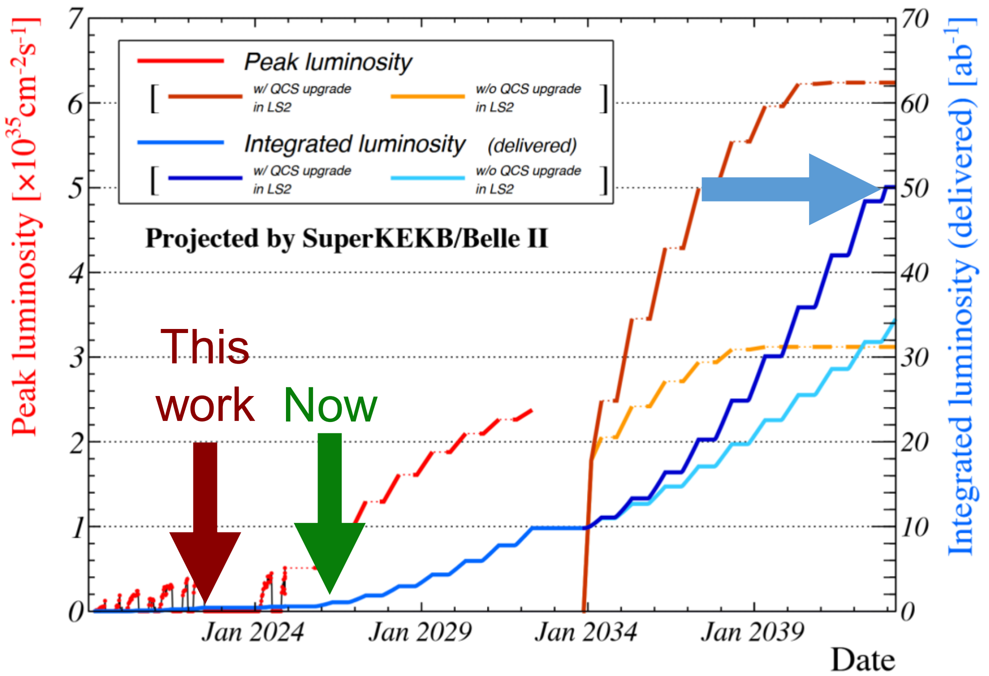
- **First search** for $B^0 \to K_S^0 \tau\tau$
  - Hadronic B-tagging
  - Belle + Belle II datasets
- No significant signal is observed

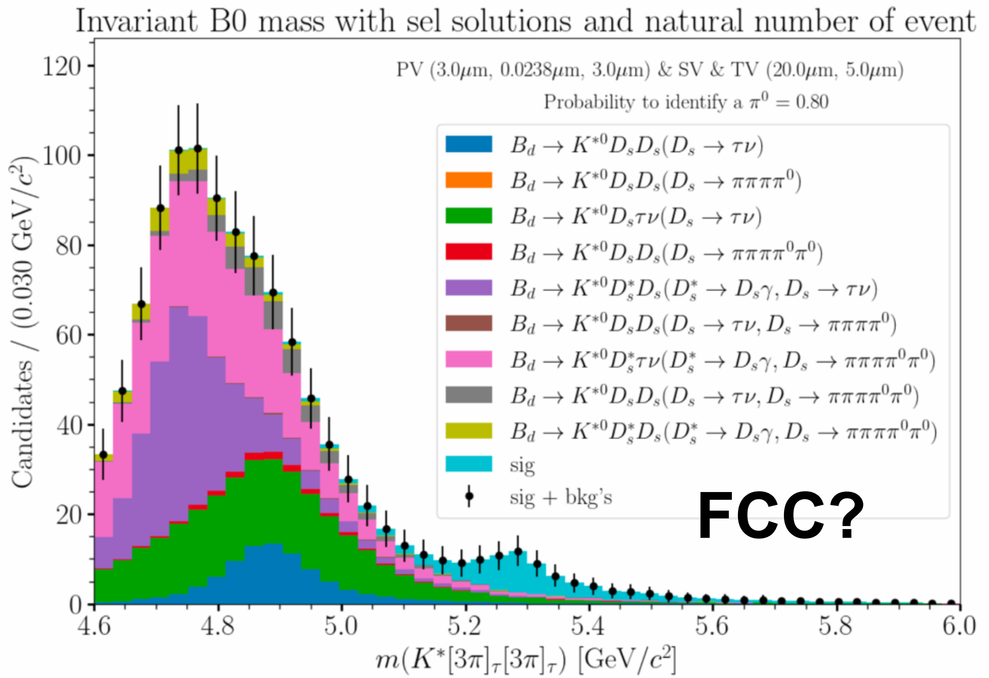
== best and only upper limit.

- Isospin average (also first in $b \to s\tau\tau$ sector) provides the **most stringent constraint to date** on $b \to s\tau\tau$ transitions involving a pseudoscalar kaon in the final state
- Paper related to this work is submitted to JHEP and available on arXiv: 2607.25607
- Positive feedback from the referees
- Come to my defense on October 5 to listen to the same talk

Prospects

- Belle II has accumulated the **largest $\Upsilon(4S)$ dataset** to date.
  - Nearly tripled the Belle II dataset used in this analysis and surpassed Belle dataset.
- **Increase efficiency** → Add τ channels when not explored already, **improved hadronic or alternative B-tagging approaches** (semileptonic, inclusive).
  - Semileptonic B-tagging has nearly four times higher signal efficiency for B^0.
- **Reduce systematic uncertainties**: many of statistical nature; improve reconstruction, modelling.





Backup

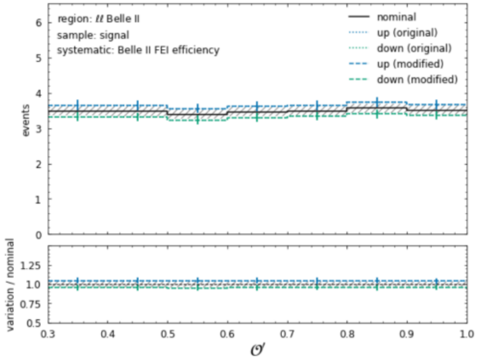
Systematic Uncertainties

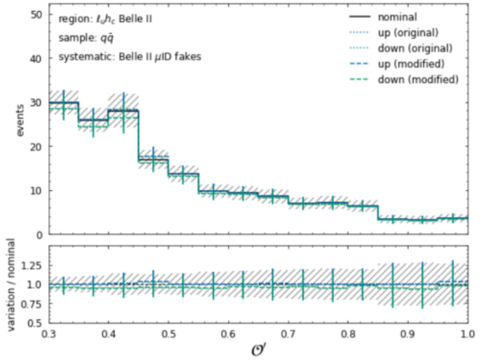
$\times 10^{-3}$

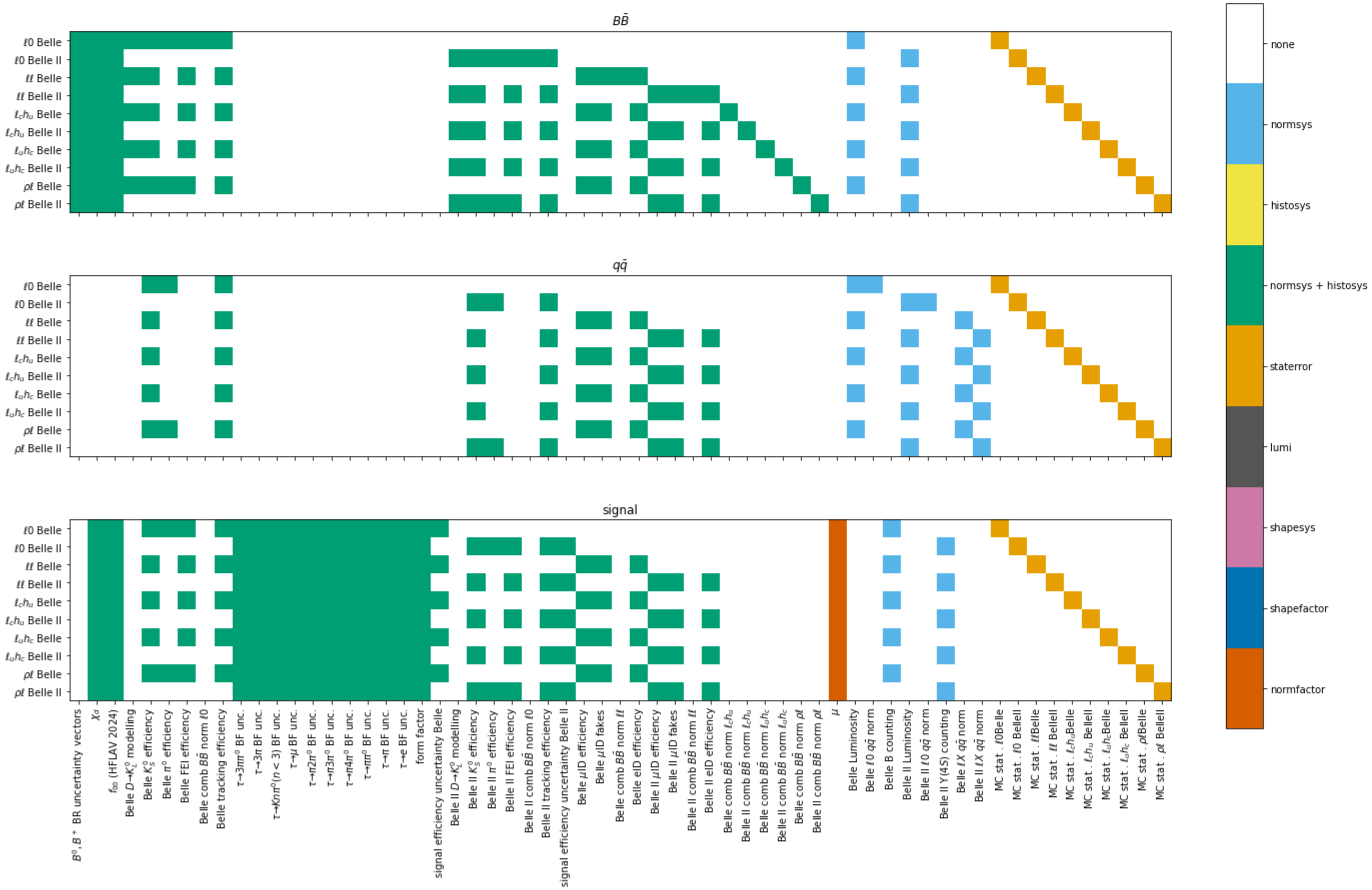
Source	**Uncertainty type, parameters**	σ_μ
Leading B-decay branching fractions	Correlated shape, 140	0.20
MC statistics	Uncorrelated shape, 140	0.18
B-tagging efficiency	Correlated shape, 2	0.06
Combinatorial B^0_{tag} normalization	Correlated shape, 10	0.05
$D \to K^0_L$ modeling	Correlated shape, 2	0.05
Lepton ID	Correlated shape, 6	0.03
f_{00}	Correlated shape, 1	0.02
Signal efficiency uncertainty	Normalization, 2	0.02
π^0 efficiency	Correlated shape, 2	0.02
$q\bar{q}$ normalization	Normalization, 4	0.02
Signal model	Correlated shape, 1	0.01
K^0_S efficiency	Correlated shape, 2	< 0.01
Number of $\Upsilon(4S)$	Normalization, 2	< 0.01
Luminosity uncertainty	Normalization, 2	< 0.01
Tracking efficiency	Correlated shape, 2	< 0.01
Leading τ-decay branching fractions	Correlated shape, 10	< 0.01
χ_d	Correlated shape, 1	< 0.01
Total		**0.29**

Systematic Uncertainties

- All the main systematics are included into the fit model, in such a way that the yields and the shapes of the templates are allowed to vary within the uncertainties of a given systematic source.







- **Normsys**: Normalisation uncertainties
  - $\rightarrow q\bar{q}$, total luminosity, N_{BB}
- **Histosys**: (nominal, up, down templates), corr. shapes
  - $\rightarrow$ All the main corrections + BB_{comb}, χ_d, f_{00}, BF
- **MC statistical uncertainties**
- **Norm factor** (POI)

- Each entry on the X axis in the modifier grid corresponds to 1 nuisance parameter.
- Exceptions:
  - POI = not a nuisance parameter.
  - Staterrors and leading B-decay uncertainties – total number of NP equals to number of bins.