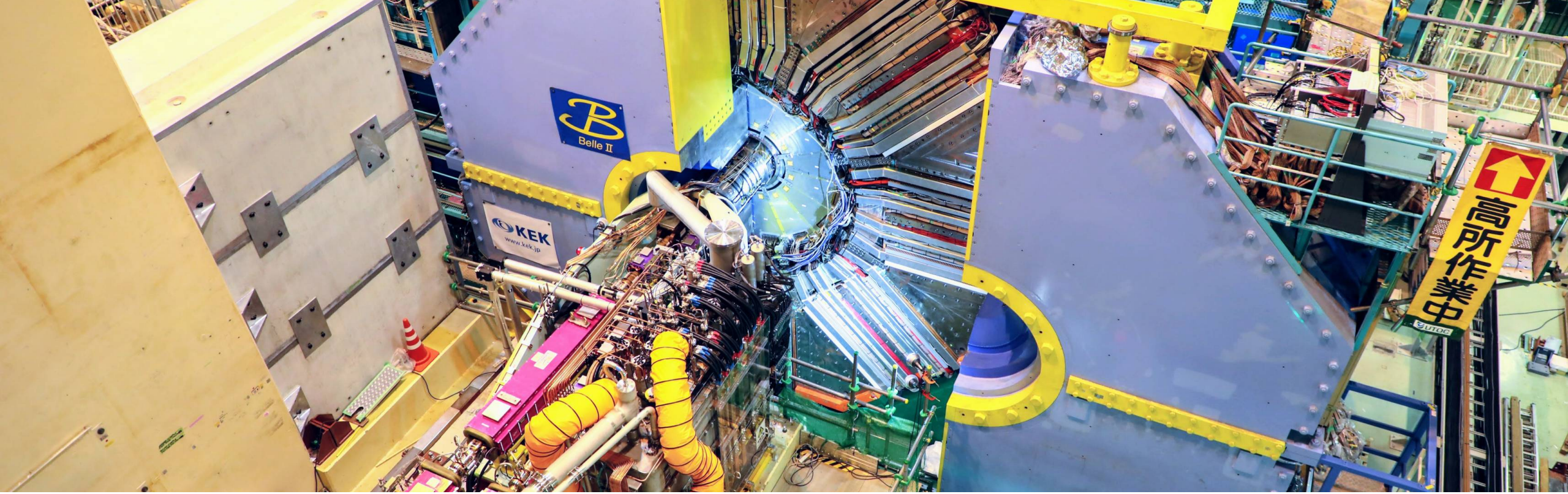


Search for $B^+ \to K^{*+}\tau^+\tau^-$ with hadronic tagging at Belle II

Lennard Damer, Torben Ferber, Pablo Goldenzweig

56th Herbstschule HEP | 04. September 2025

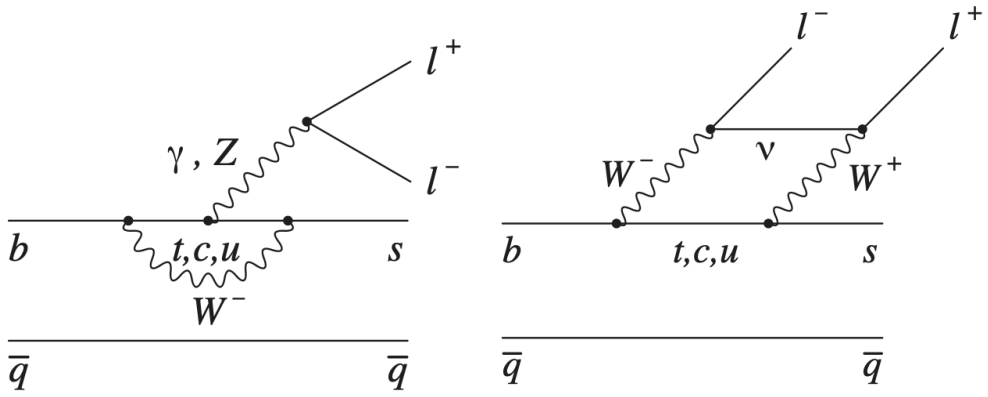
Belle II

Karlsruhe Institute of Technology

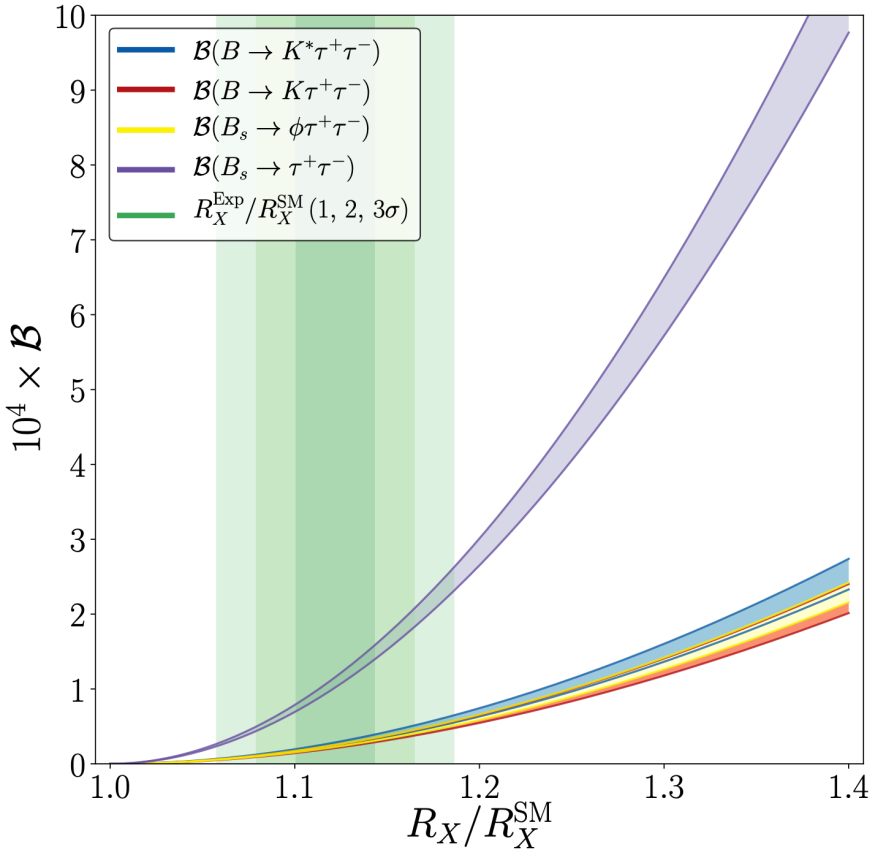
Motivation

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \quad (\ell = e, \mu), \quad R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

- Recent Experiments: Intriguing hints of lepton flavor universality violation in $b \to c\ell\nu$ ratios $R_{D^{(*)}}$ and $R_{J/\psi}$
- FCNC $b \to s\ell^+\ell^-$ involving **third generation** leptons
  - SM: BR $(B^+ \to K^{*+}\tau^+\tau^-) \sim 10^{-7}$
  - NP effects interconnected to $b \to c\ell\nu$ could **enhance** the FCNC process up to **three orders of magnitude**



(Leading order contributions)

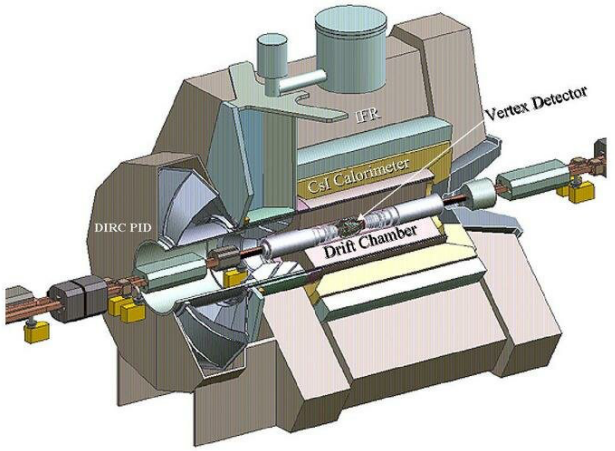


Capdevila, B.: Proceedings of FCPC 2023 [orig. Phys. Rev. Lett. 120, 181802 (2018)]

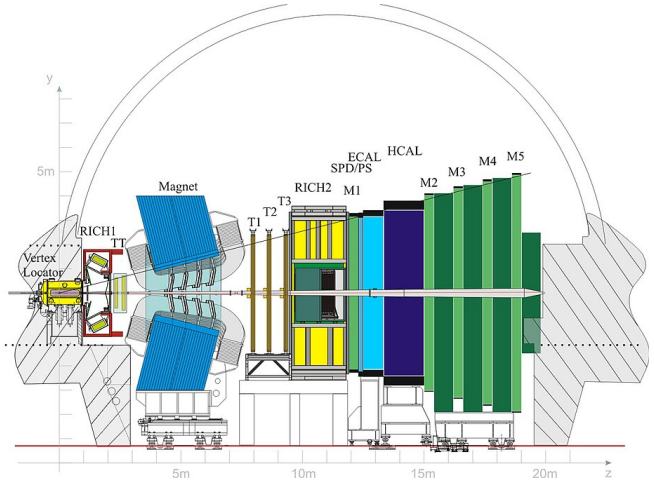
Experimental Landscape

- **Direct Searches** for physics processes
  - **BaBar** [PRL 118, 031802 (2017)]
    - BR $(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ @90 % CI
    - Leptonic τ decays
  - **Belle** [PRD 108, L011102 (2023)]
    - BR $(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ @90 % CL
    - Leptonic τ decay channels and $\tau \to \pi\nu_t$

BaBar



LHCb



- Direct measurement of $C_{9\tau}$
  - **LHCb** [JHEP09(2024)026]
    - Comprehensive analysis of $B^0 \to K^{*0}\mu^+\mu^-$
    - Nonlocal contributions from $B^0 \to K^{*0}[\tau^+\tau^- \to \mu^+\mu^-]$ rescattering
    - $|C_{9\tau}| < 500$ @90 % CL

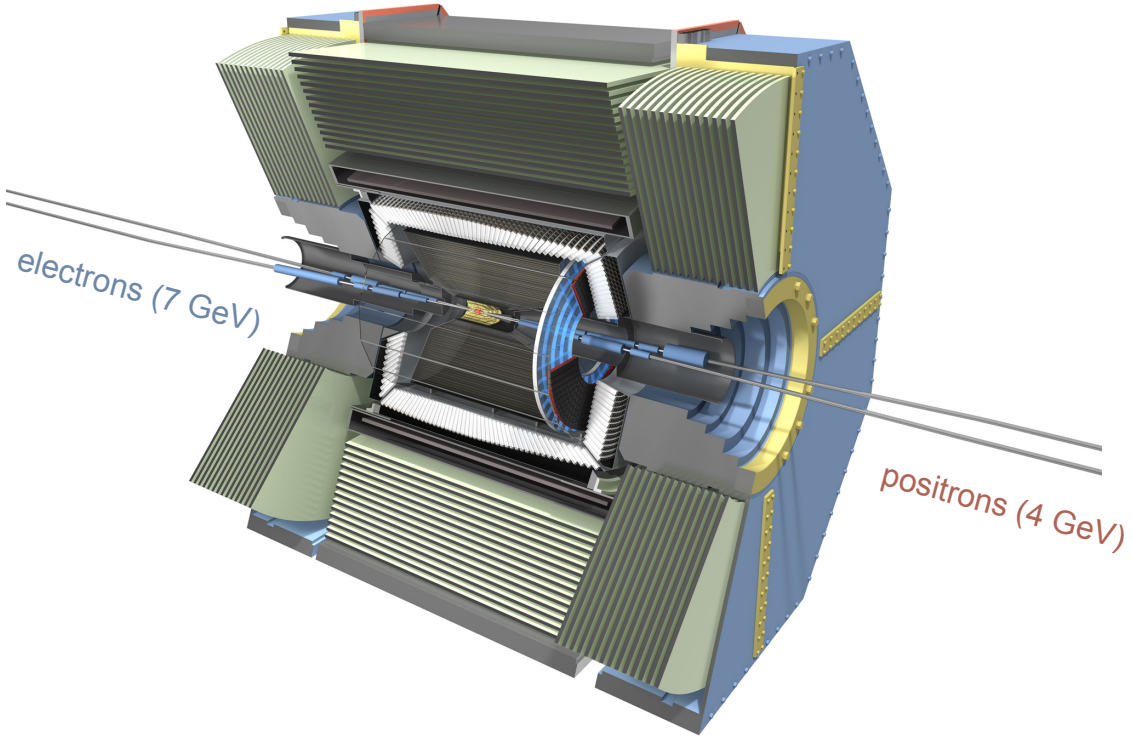
- This overview **focuses** on searching directly for physics processes
- **No significant signal observed** → Most stringent results set by B Factories

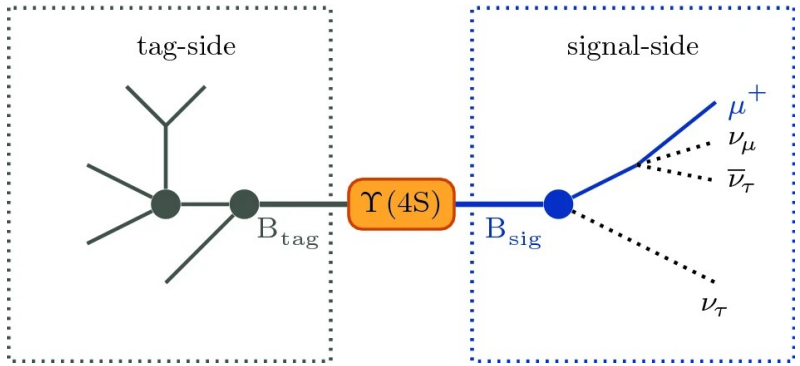
The Belle II Experiment

- **High precision** experiment commissioned at the SuperKEKB accelerator in Tsukuba, Japan
- **B Factory:** e^+e^- collisions at $\Upsilon(4S)$ resonance

- **Analysis specific improvements** over previous B factory generations:
  - Targeted dataset: $50\,\mathrm{ab}^{-1}$ (achieved with world-record inst. luminosity)
  - Improved detector subsystems: Tracking, PID, energy resolution, …
  - Enhanced tagging algorithm FEI

- **Main advantage** compared to LHCb: Clean collision environment, well-known four momentum (beam-energy constrains)





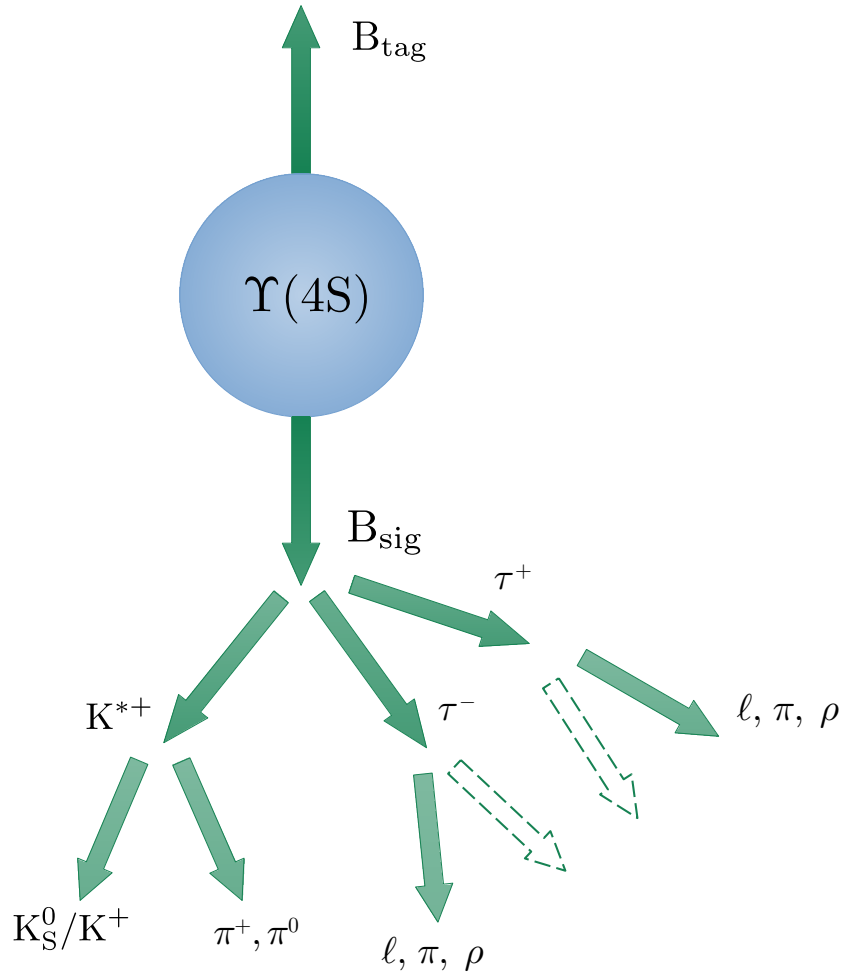
T. Keck, et al. in CSBS, 2019

Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Overview

- **First ever search** for $B^+ \to K^{*+}\tau^+\tau^-$

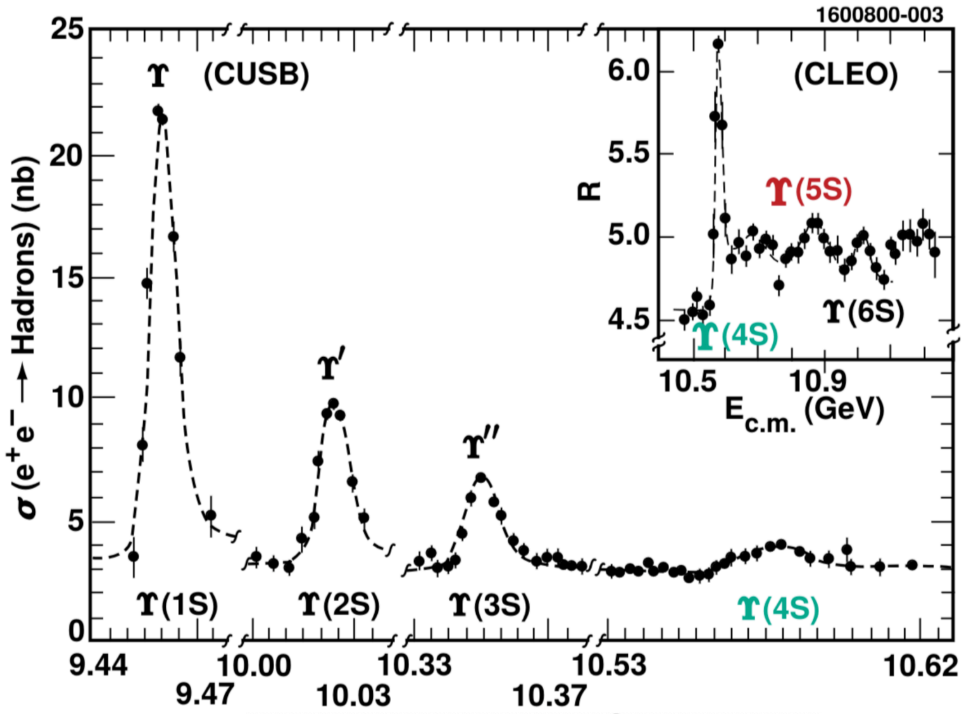
- Reconstruction of $B^+ \to K^{*+}\tau^+\tau^-$ with **hadronic tag** using Run 1 events yielding $365\,\text{fb}^{-1}$ ($\sim 387 \times 10^6$ $B\overline{B}$ pairs)

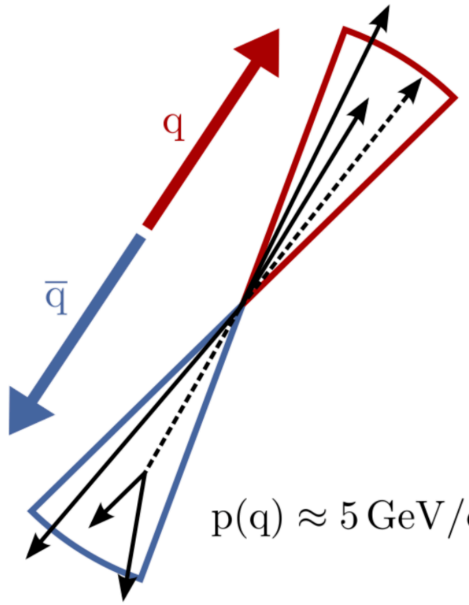
- Reconstruction of K^{*+} via $K^+\pi^0$, $K_S^0\pi^+$
- Reconstruction of $\tau \to$ **1-prong combinations** exclusively in **four signal modes**,
  - Leptonic: $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$
  - Hadronic: $\tau \to \pi\nu$, $\boldsymbol{\tau \to \rho\nu}$

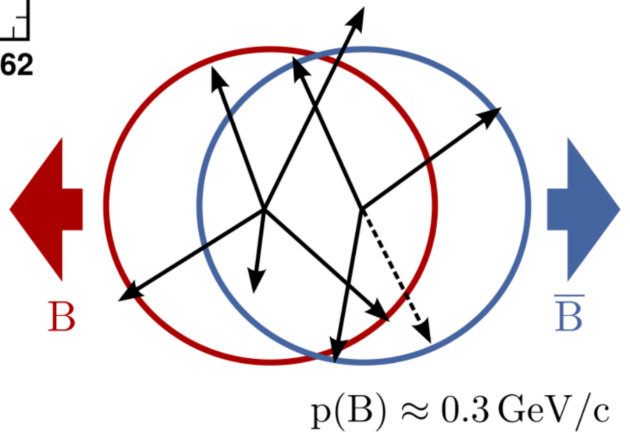


Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Background

- **Main physics background** stem from two distinct sources
  - Light quark pairs: $e^+e^- \to q\overline{q}$
  - Generic $B\overline{B}$ events: Every non-signal $\Upsilon(4S) \to B\overline{B}$ component







- Established event-shape based variables are **outstanding discriminators** (at least for some of the background)

Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Background

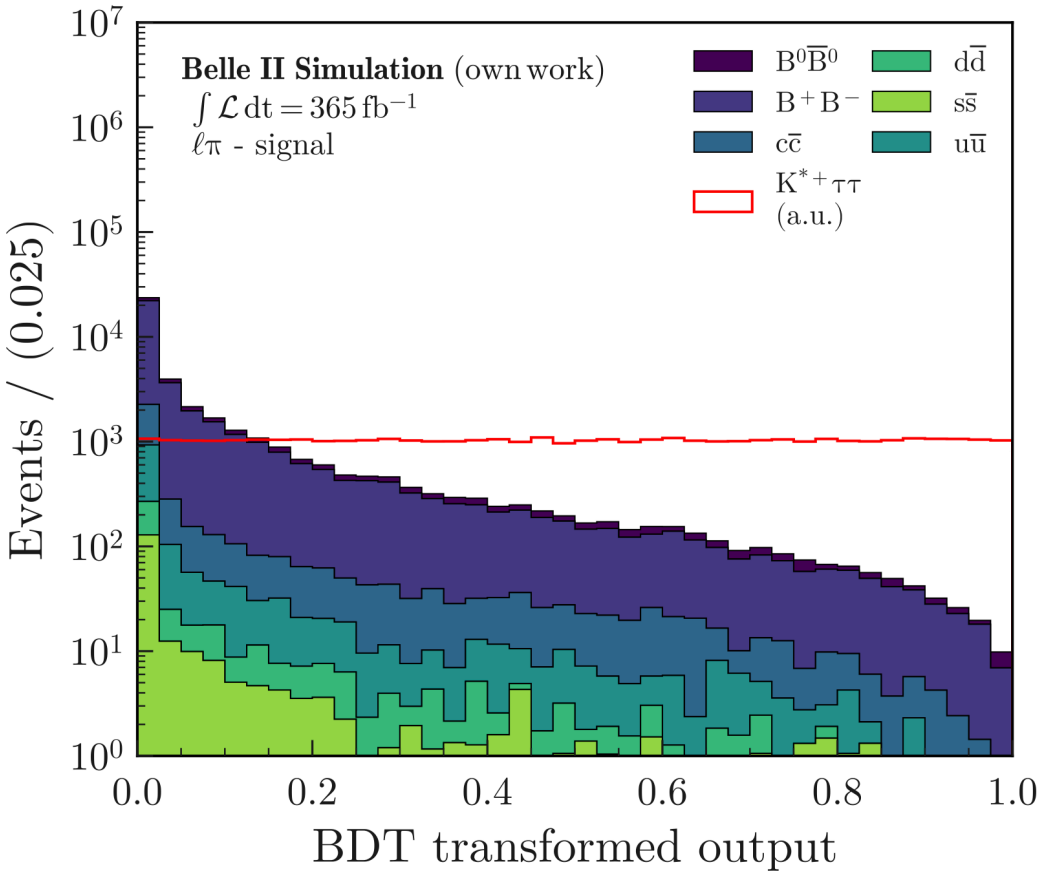
- Multivariate analysis approach is chosen for **optimizing the signal selection**

  → leverages complex correlations of variables (Missing energy, event-shape variables, …)

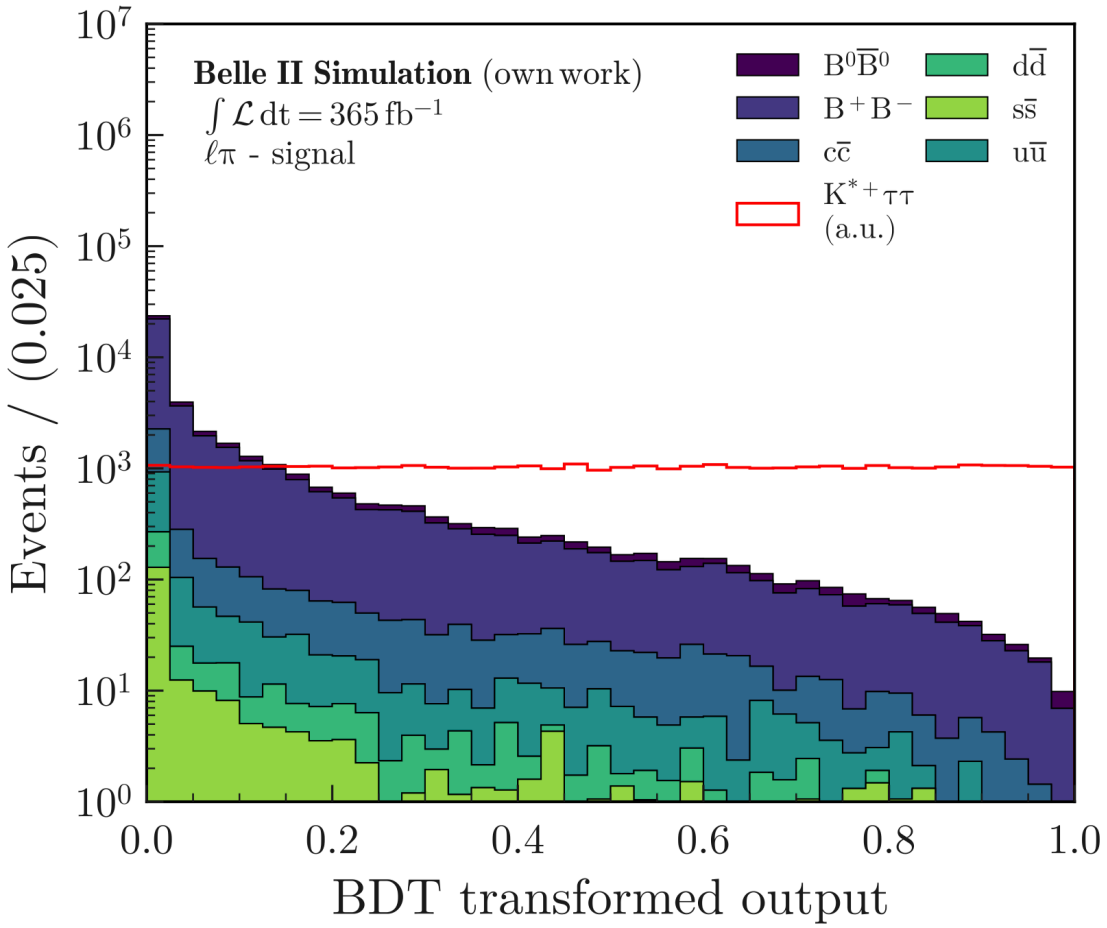
- **Boosted Decision Trees** (BDTs) are employed for each signal channel

  → Robust, interpretable and fast approach

- **Transforming** the BDT output:
  - Empirical cumulative density function (CDF) is determined for signal template and applied to all templates

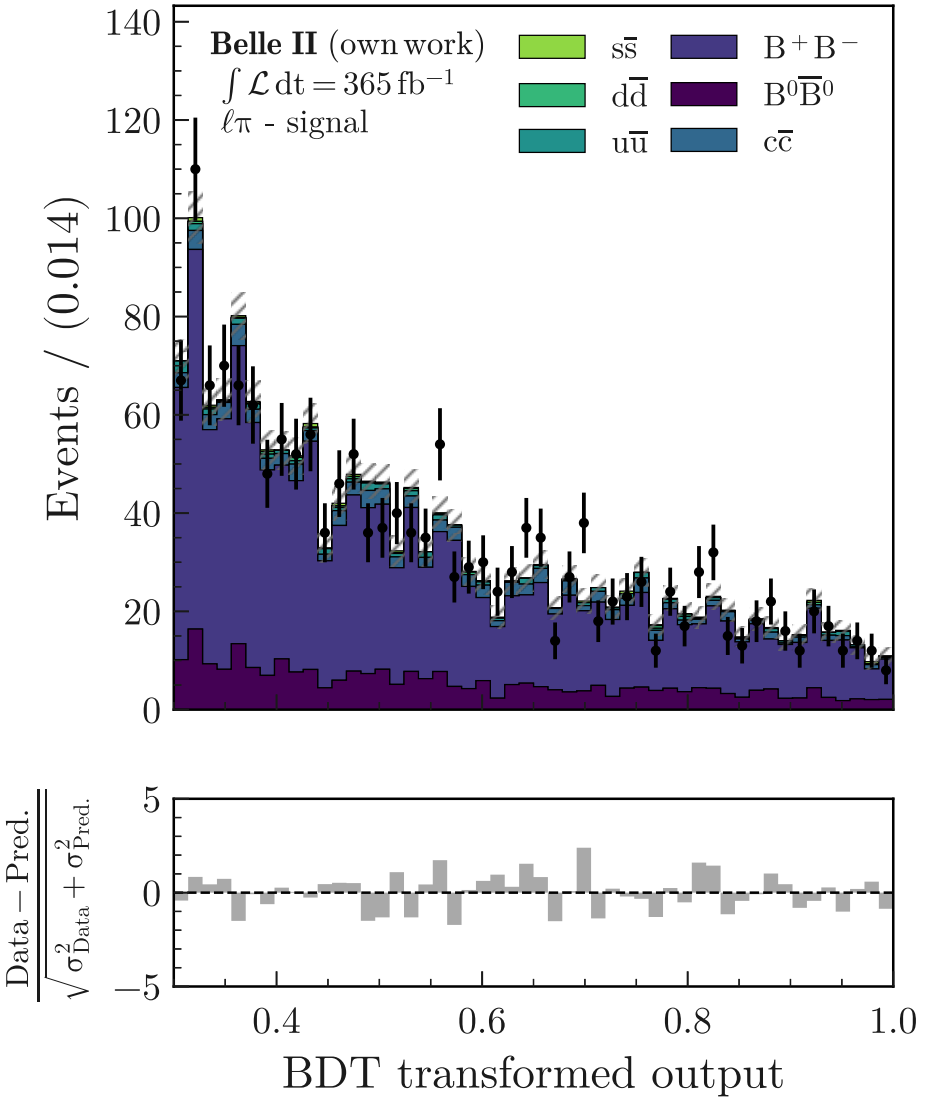


Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Validation



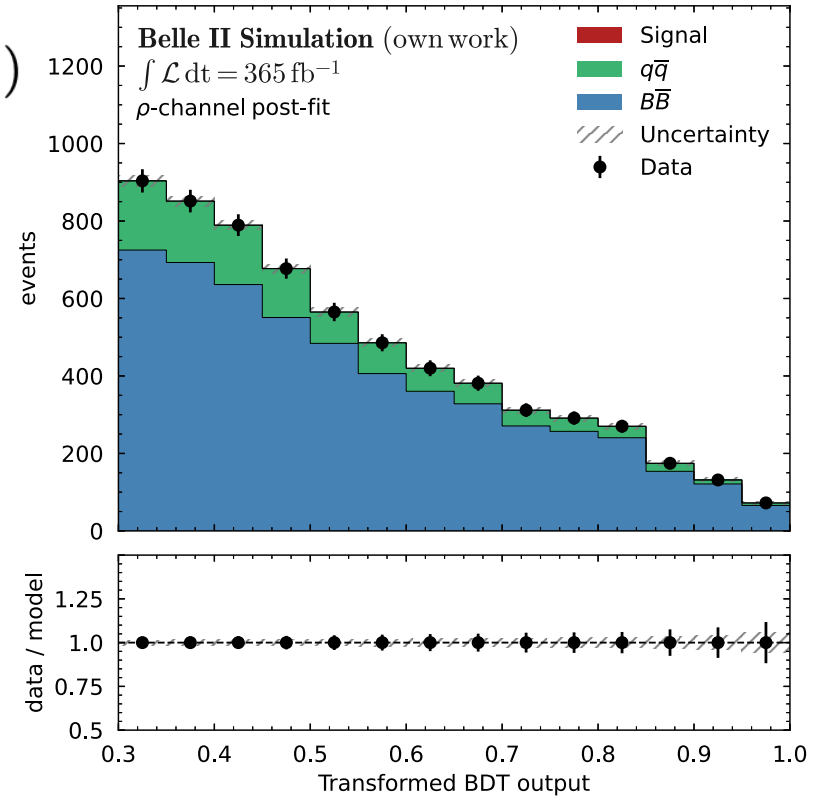
Validation on

control region



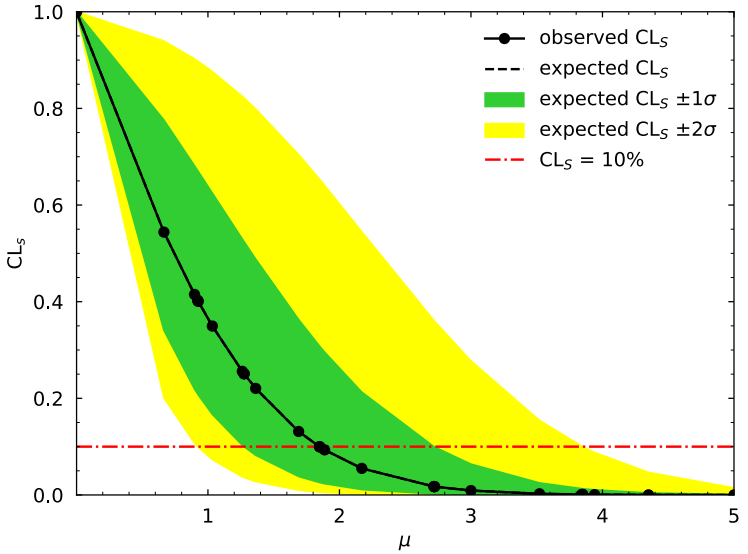
Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Signal Extraction

- **Goal:** Determine $\mathcal{B}(B^+ \to K^{*+}\tau^+\tau^-)$
- **Method:** Binned maximum likelihood fit on transformed BDT output in all channels simultaneously
- Templates:
  - Background: $q\overline{q}$, $B\overline{B}$
  - Signal: $K^{*+}\tau^+\tau^-$
- Estimation of fit sensitivity through **Asimov dataset:**



$$\mathrm{CL}_s \equiv \frac{p_{s+b}}{1-p_b} < \alpha$$

Fit at $\mu = 0$ on **Asimov** data



$$\mathcal{B}(B^+ \to K^{*+}\tau^+\tau^-) < 1.85 \times 10^{-3} \text{ @ 90\% CL}$$

Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Systematics

- Uncertainties on e.g. detector calibrations, theory predictions enter the fit as **nuisance parameters** (extension of the binned likelihood function)

- Impact of a single nuisance parameter estimated in **toy experiment** by a likelihood scan

- **Largest Impact:** Amount of simulated events, propagating into other systematics as well

- **Future prospect:** We will be among the first analyses to include Run 2 data as well, expecting to directly mitigate this effect

Source	Impact on $\mathcal{B}$
Simulated sample size	0.46
FEI calib error	0.13
LeptonID error	0.11
f_{+-}	$^{+0.10}_{-0.11}$
B Counting	0.07
Comb. calib ρ	0.06
Comb. calib $\ell\ell$	0.05
Offres. norm. ρ	0.04
...	
Total combined uncertainty	0.52

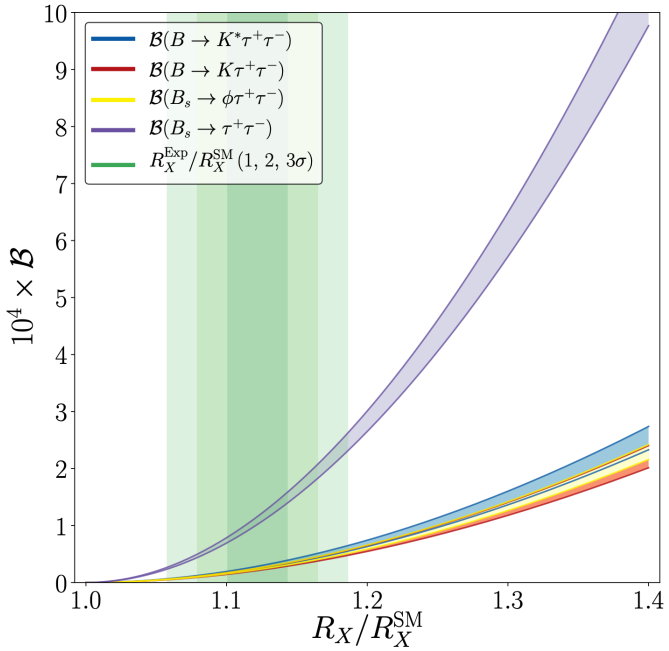
Summary & Outlook

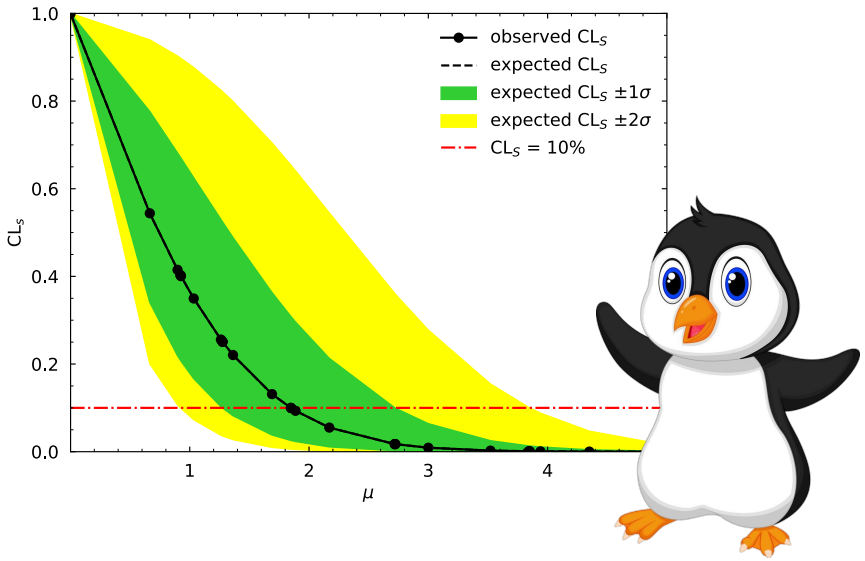
- General theory descriptions of $R_{D^{(*)}}$ and $R_{J/\psi}$ could **enhance** $b \to s\tau^+\tau^-$ transitions $10^{-7} \to 10^{-4}$

- Belle II is **uniquely positioned** for $b \to s\tau^+\tau^-$ searches given the missing energy products

- **First search** for $B^+ \to K^{*+}\tau^-\tau^+$:
  - Reconstruction overview
  - Calibrating & validating on control regions
  - Optimization of BDT-based selection
  - Signal Extraction Method, Systematics

- **Target:** Winter Conferences 2025



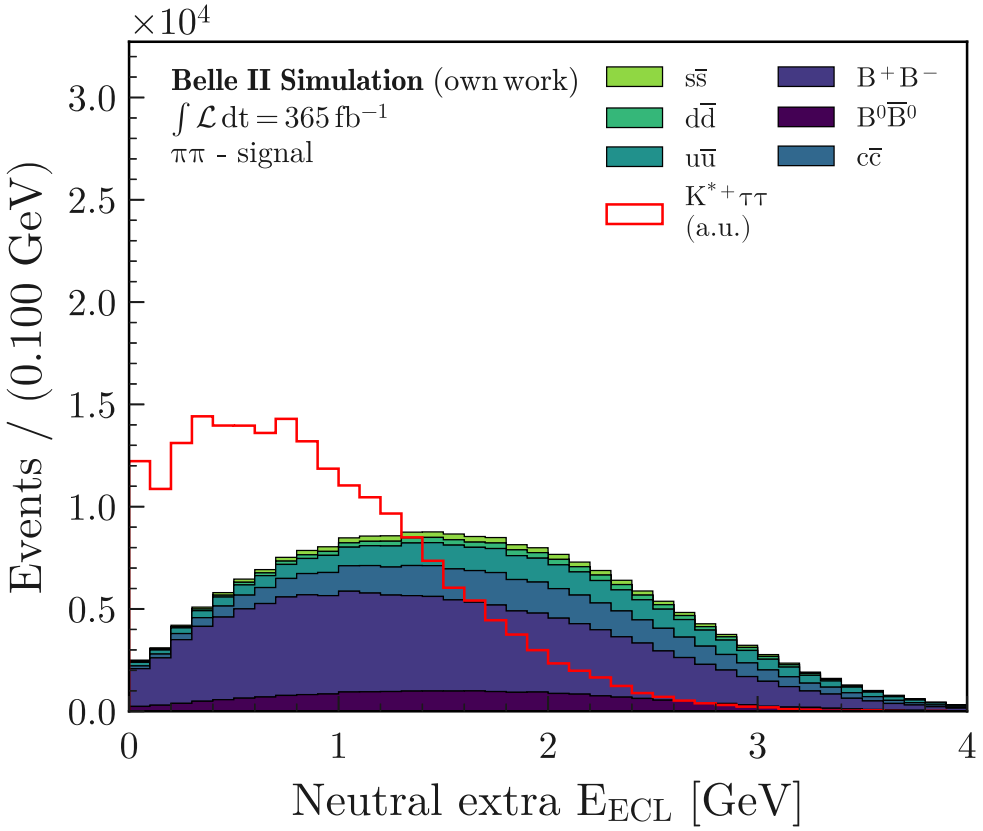


Backup Slides

Search for $B^+ \to K^{*+}\tau^+\tau^-$ - Background

L. Damer, T. Ferber, P. Goldenzweig (KIT)

- **Much more challenging** is the $B\overline{B}$ background
- Given 2-4 neutrinos for signal → no (sharp) kinematic peak
- **Key observable:** Neutral Extra $\mathrm{E_{ECL}}$
  - Residual (neutral) energy after $\Upsilon(4S)$ reconstruction
  - Prone to Data/MC discrepancies as Extra $\mathrm{E_{ECL}}$ is sensitive to entire event description



- Data/MC inconsistencies may bias the end result, **reliable validation is required** (on recorded data)

Background Suppression

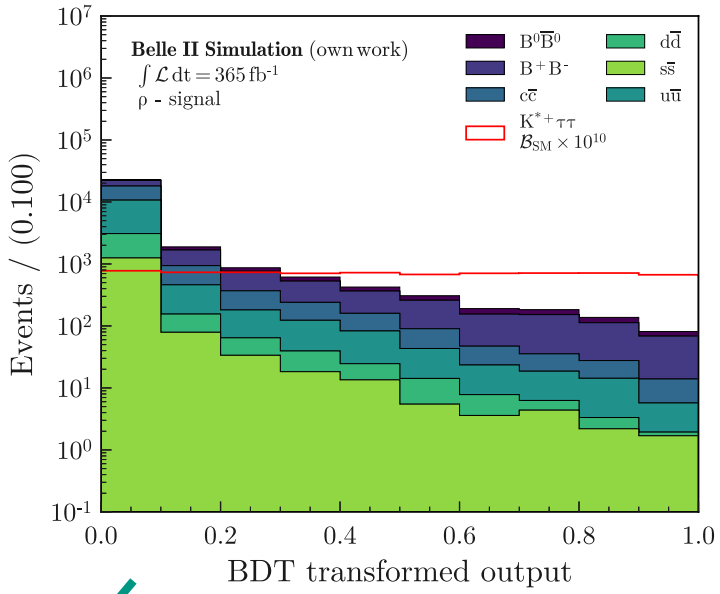
- Individual **BDT-based** event selection is employed in each signal channel
- Exploiting a variety of **event shape** and (missing) **kinematic** variables

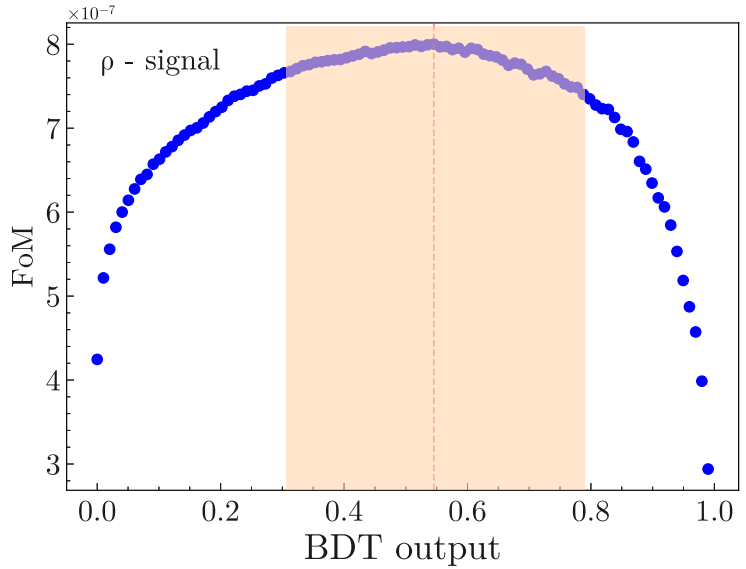
- BDT output is **transformed** and Punzi FOM is computed

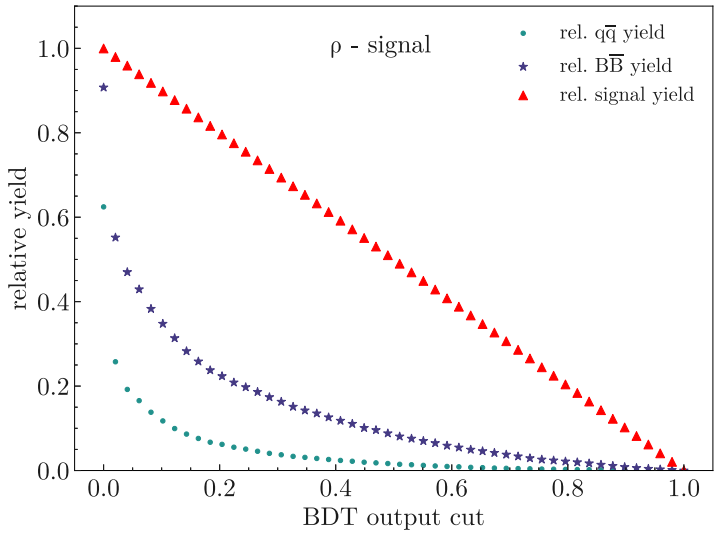
$$\text{FoM} = \frac{\varepsilon}{3/2 + \sqrt{B}}$$

- Global maximum determines **area of the start of the fitting region**

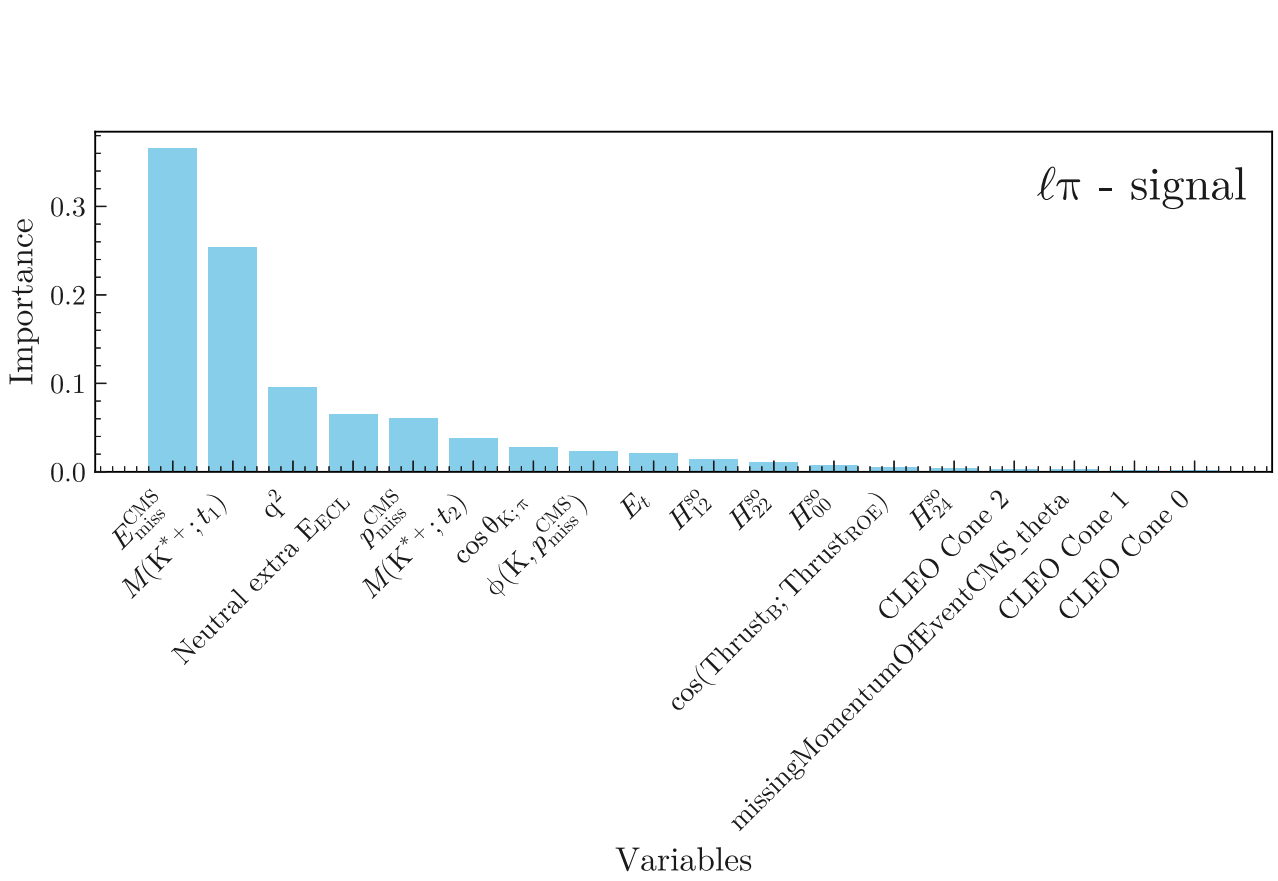
- Fitting region is determined by a **scan-based** approach

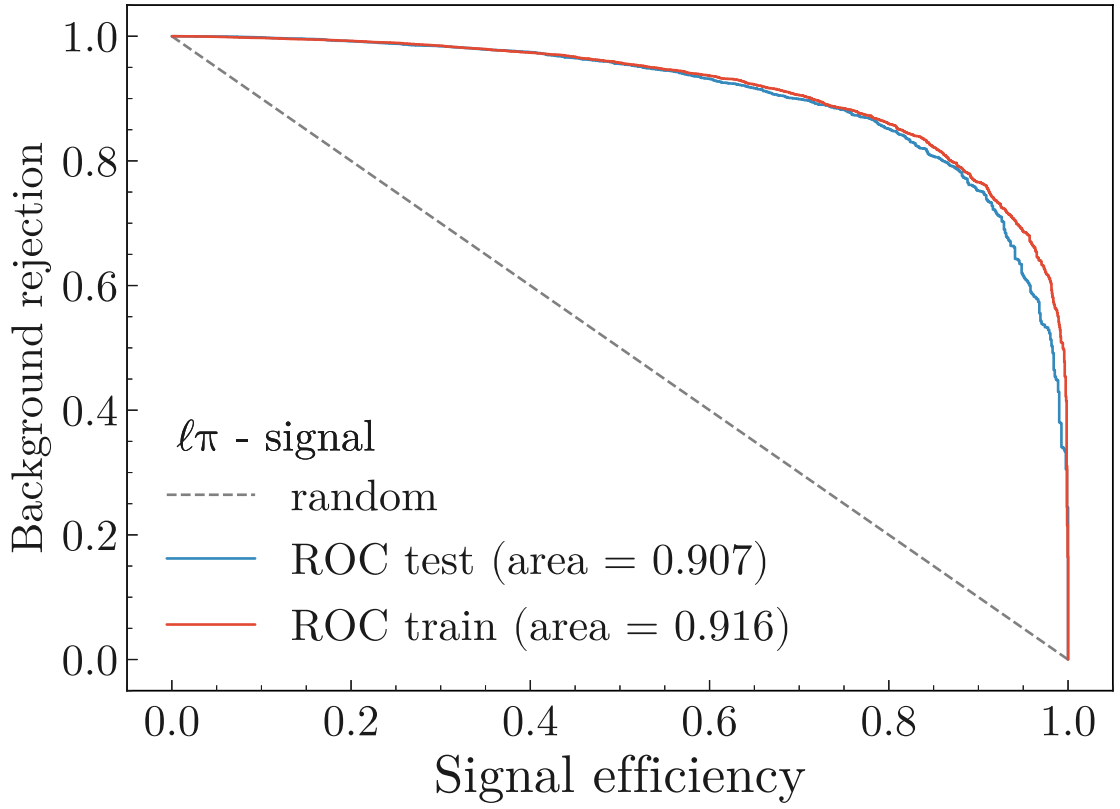






Background Suppression





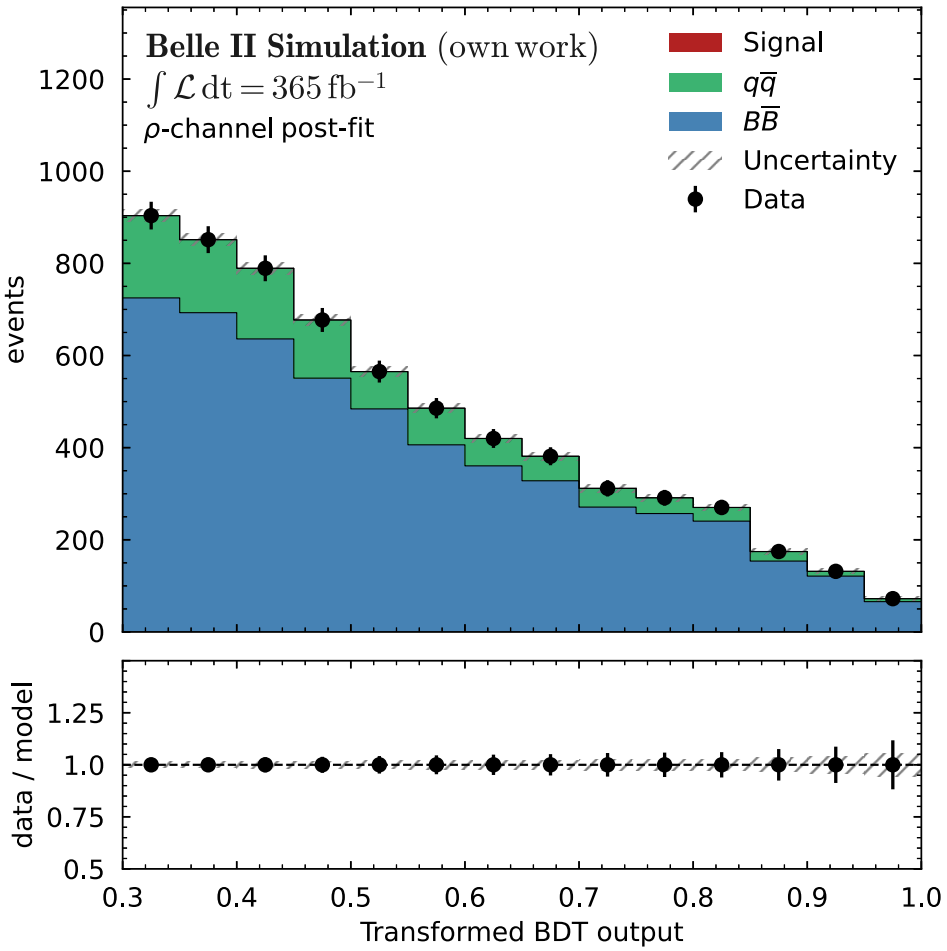
Signal Extraction

- **Goal:** Determine $\mathcal{B}(B^+ \to K^{*+}\tau^+\tau^-)$
- **Method:** Binned template ML fit on transformed BDT output
- Templates (all after preselection, corrections & BDT selection):
  - Background: $q\overline{q}$, $B\overline{B}$
  - Signal: $K^{*+}\tau^+\tau^-$
- Extraction of branching ratio via

$$\mathcal{B}(B^+ \to K^{*+}\tau^+\tau^-) = \frac{N_{\text{Signal}}}{2 \times \varepsilon_{\text{Signal}} \times N_{B^+B^-}}$$

with $\varepsilon_{\text{Signal}} \approx 5 \times 10^{-4}$ and $N_{B^+B^-} \approx 2 \times 10^8$

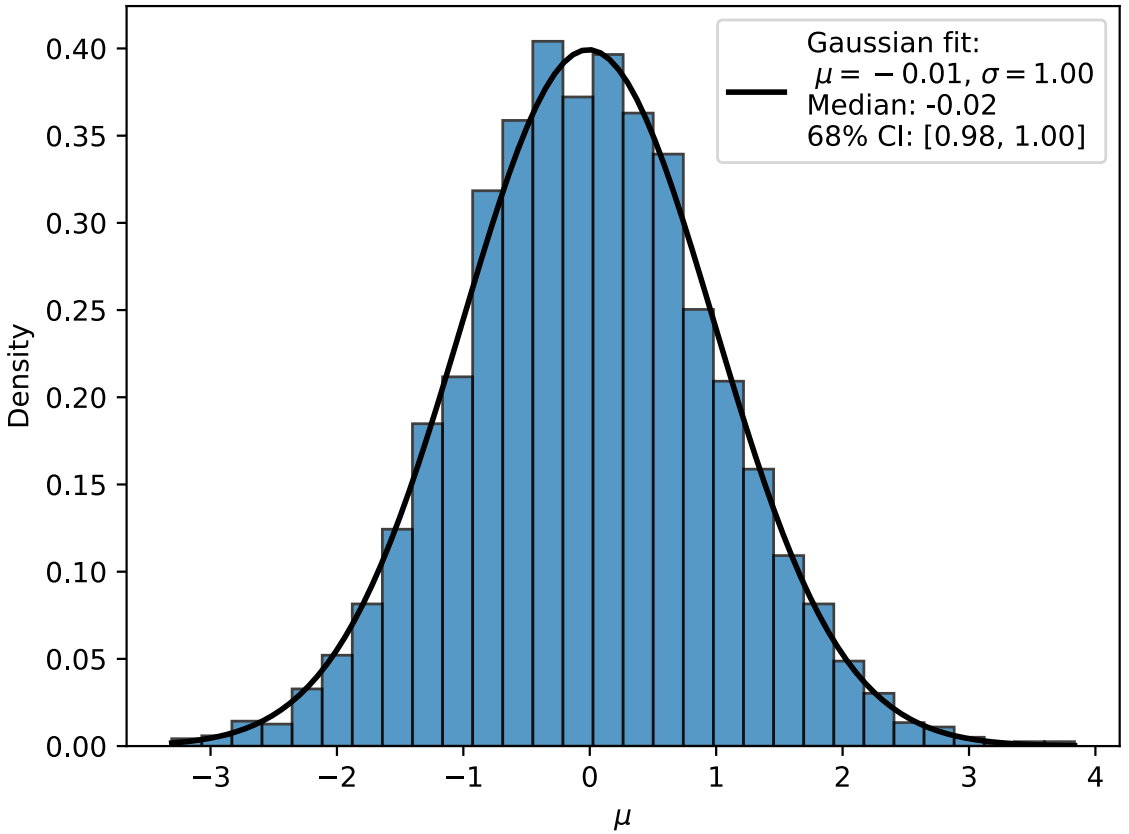
Post-fit distribution at $\mu = 0$ on **Asimov** data



Signal Extraction Bias

- The signal extraction method is **validated** on different signal hypothesis (e.g. SM prediction)
- For each hypothesis, **5k toy samples** are generated from a poisson distribution with mean equal to the expected yields in the bins
- Profile likelihood is not entirely Gaussian (given that the most sensitive bins have the smallest number of expected events)
- Instead, I check the **median** and the **central 68% quantile** of the extracted μ

Pull distribution for SM prediction ($\mu = 0$)



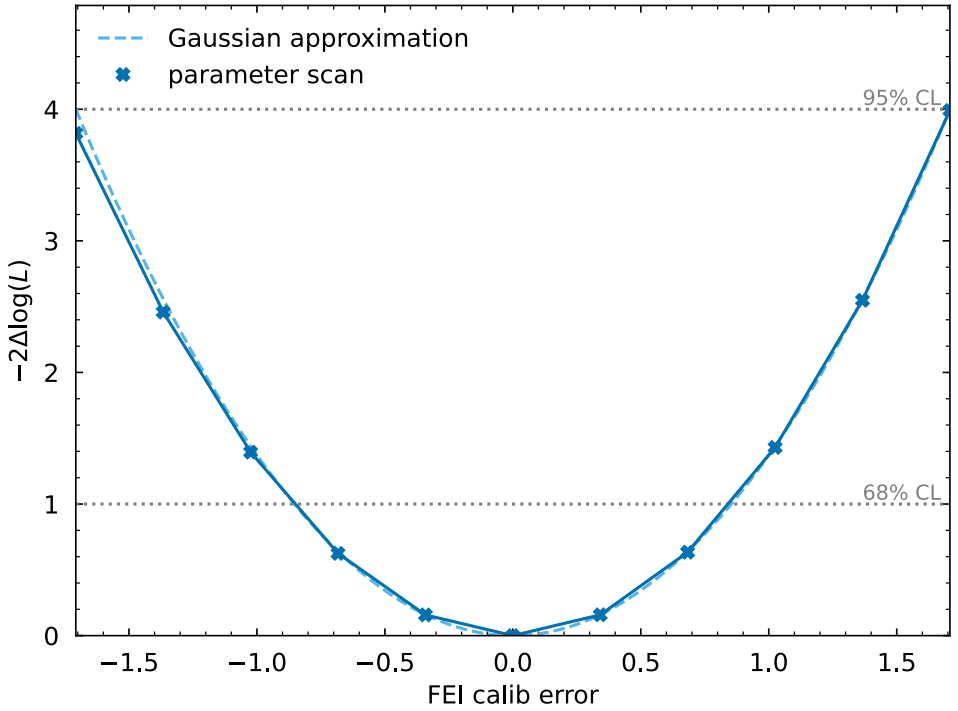
Systematic Components

- Uncertainties on e.g. detector calibrations, theory predictions enter the fit as **nuisance parameters**

- Impact of a single nuisance parameter estimated in **toy experiment** by a likelihood scan

- **Largest Impact:** Amount of simulated events (✱)
  - Solution: Producing more samples

- **2nd largest:** FEI Calibration (✱)
  - Relative high uncertainties on calibration
  - Reason more subtle



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	LeptonID error	0.11
	f_{+-}	$^{+0.10}_{-0.11}$
	B Counting	0.07
	Comb. calib ρ	0.06
	Comb. calib $\ell\ell$	0.05
	Offres. norm. ρ	0.04
	Comb. calib $\pi\pi$	0.03
	HadronID error	0.02
	Offres. norm. $\ell\pi$	0.02
	Comb. calib $\ell\pi$	0.02
	Luminosity	< 0.01
	Offres. norm. $\pi\pi$	< 0.01
	Offres. norm. $\ell\ell$	< 0.01
	Total combined uncertainty	0.52

FEI Calibration

- Algorithm performance mismatch on recorded data and simulation
- **FEI calibration** weights obtained from $B \to X\ell\nu$ and $B \to D\pi$ with combined χ^2 fitting
- **Largest systematic** on calibration factors arise from **uncertainties on** branching fractions ($B \to X\ell\nu$ modes) and **simulation statistics**

Sutcliffe, W. et al.: Internal note, 2023