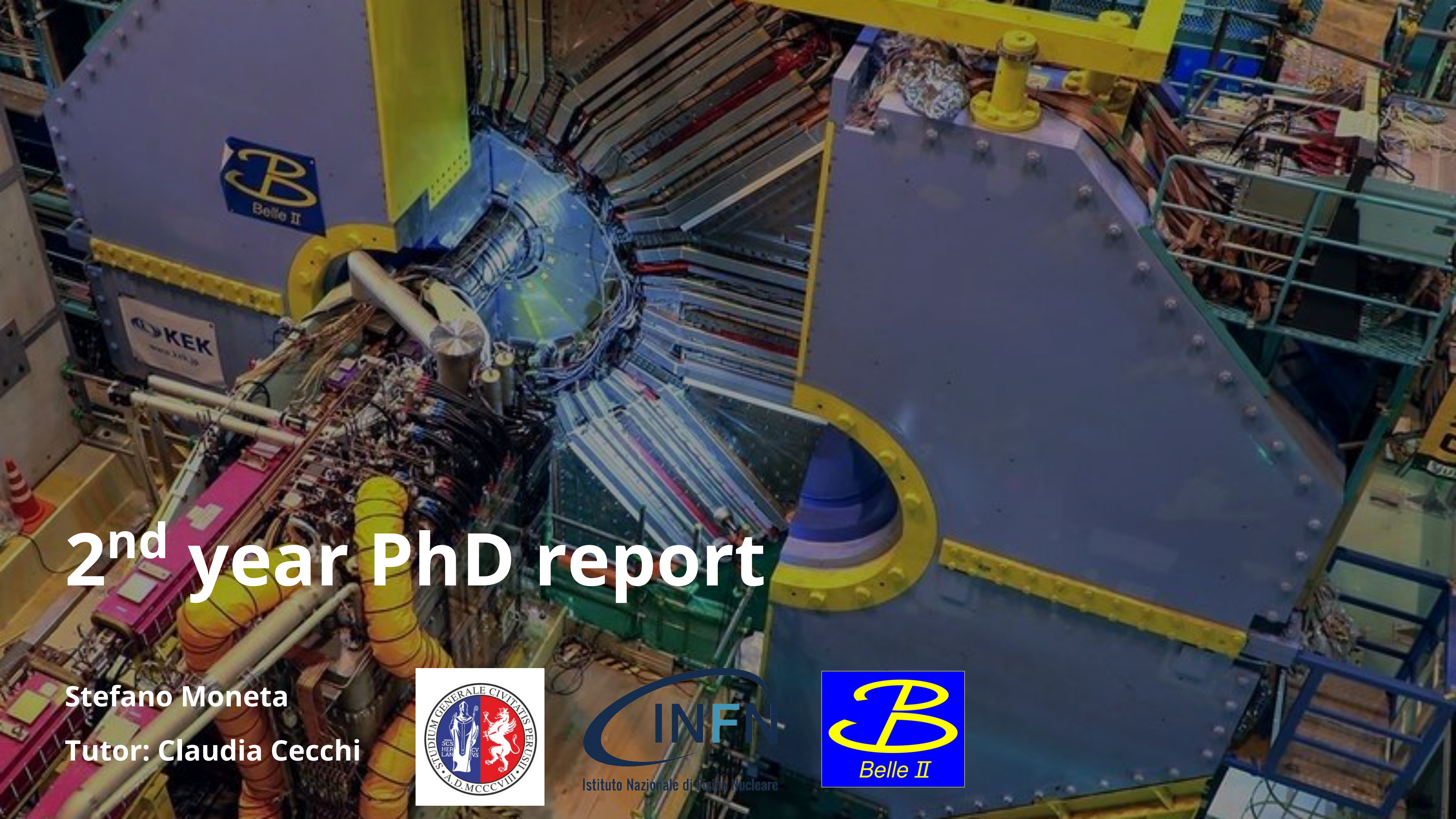


2nd year PhD report

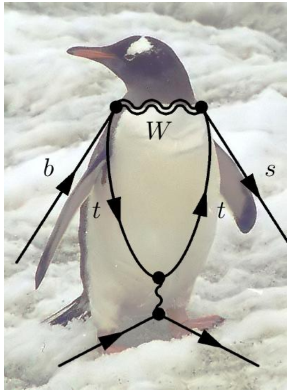
Stefano Moneta

Tutor: Claudia Cecchi

Istituto Nazionale di Fisica Nucleare

Belle II

Recap of 2022 activities



Mostly work on “research side”

- Electroweak penguins B-decays at Belle II
  - $\boldsymbol{B \to K^{*0}\tau\tau}$ **with hadronic tag** (main analyst, PhD thesis)
  - Contribution to $\boldsymbol{B^+ \to K^+\nu\nu}$ **with hadronic tag** (PG group)
  - Several talks at internal Belle II meetings (plenary talk at B2 general meeting in Rome)
- Hardware and calorimetry
  - **Detector maintenance** and **repair** (during shut-down) + **shift** turns (during data-taking)
  - R&D work for possible **calorimeter upgrade**
- Others
  - *XXXIII International School of Nuclear and Subnuclear Physics* "Francesco Romano" (June, 2022, Otranto)
  - Teaching activity at Dipartimento di Matematica (Fisica 2)

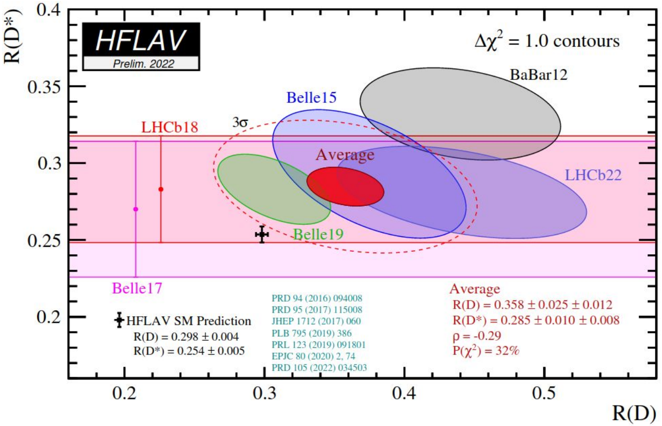
Otranto School

Physics analysis status

Target flavor anomalies

Global tension in semileptonic and $b \to sll$ decays

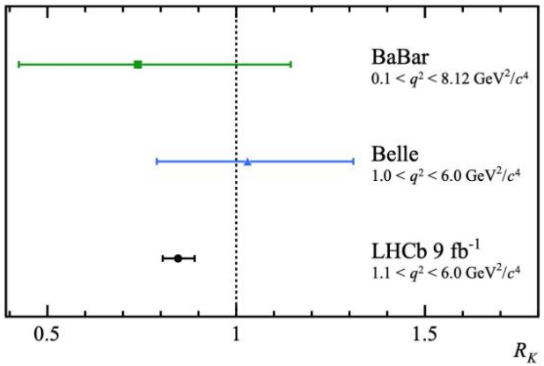
- Belle II can play a major role to study **anomalies** in ***B*-decays**
- B-decays with missing energy expected to be complementary to observed anomalies
    - $B \to K^{*}\tau\tau$, $B^{+} \to K^{+}\nu\nu$



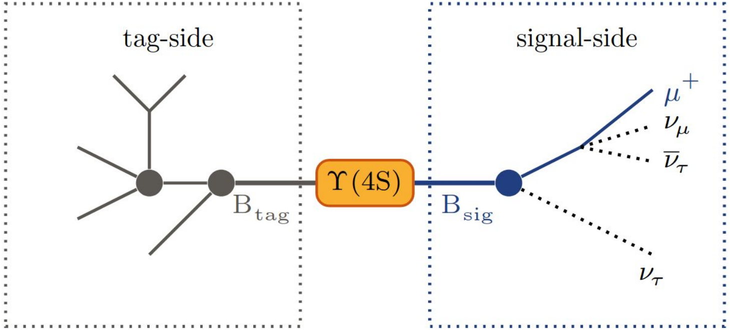
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^{-}\bar{\nu}_{\tau})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^{-}\bar{\nu}_{\ell})}$$

$$(\ell = e, \mu)$$

$$R_K = \frac{\mathcal{B}(B^{+} \to K^{+}\mu^{+}\mu^{-})}{\mathcal{B}(B^{+} \to K^{+}e^{+}e^{-})}$$



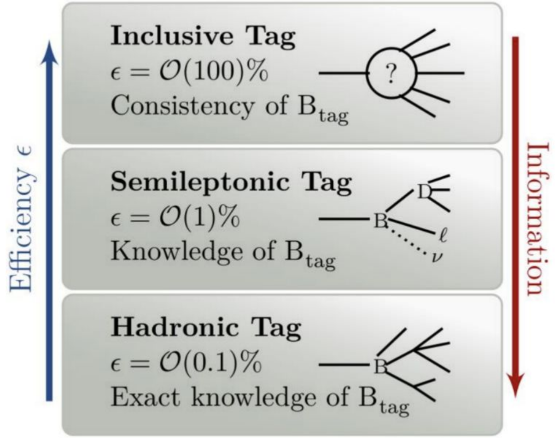
$B\bar{B}$ reconstruction techniques



Measurements of **inclusive B-decays** or with **neutrinos** need knowledge of **initial kinematics**

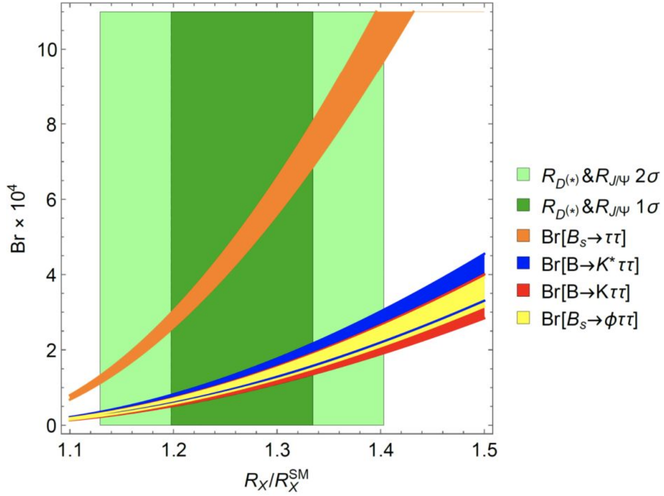
⇒ Information from partner B_{tag} provides insight about signal B_{sig}

- Different possible algorithms to **reconstruct B_{tag} candidates**
- Methods specific to B-factory experiments



Search for $B \to K^* \tau\tau$ decay

- FCNC decay involving **3rd generation** leptons
  - In SM: BR($B \to K^* \tau\tau$) ≃10^{-7}
  - Enhanced by NP models coupling only to 3rd generation or with coupling proportional to particle mass



B. Capdevila, A. Crivellin, S. Descotes-Genon, L. Hofer, et J. Matias, *arXiv:1712.01919*, *PRL 120, 181802*

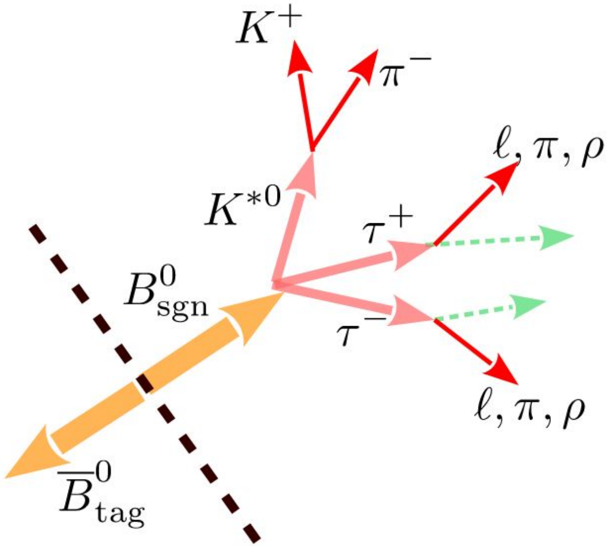
- **Belle** (preliminary) [arXiv] (*)
  - Observed BR($B^0 \to K^{*0} \tau\tau$) < 2.0 ✕ 10^{-3} @90% CL
  - 711 fb^{-1}
  - Hadronic tag (NeuroBayes algorithm)
  - Both τ decay 1-prong (e, μ or π)

(*) not published yet. Expected upper limit is BR < 3.0 ✕ 10–3 @90% CL

Analysis overview

Study **neutral channel** $B^0 \rightarrow K^{*0}\tau\tau$

- B-tag with hadronic Full Event Interpretation (FEI)
- Reconstruct $K^{*0} \rightarrow K\pi$
- Reconstruct all $\tau \rightarrow$ 1-prong combinations
  - $\tau \rightarrow l\nu\nu$, $\tau \rightarrow \pi\nu$ (same as Belle)
  - $\tau \rightarrow \rho\nu$ (new w.r.t. Belle)
- No extra tracks in the rest of event



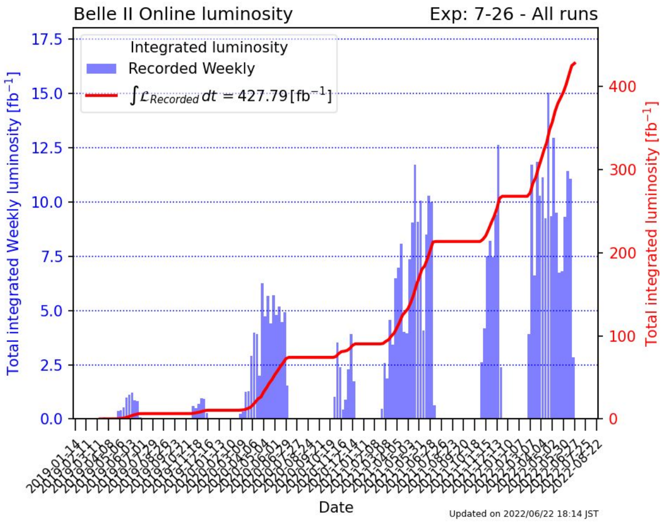
Samples

MonteCarlo (MC)

- 50M signal $B^0 \to K^{*0}\tau\tau$
- 1 ab^{-1} generic background
  - $B\bar{B}$ (neutral + charged)
  - continuum (u,d,s,c)

Data

- Full pre-LS1 (2022) data sample
  - 362 fb^{-1} at Υ(4S)
  - 42 fb^{-1} off-resonance

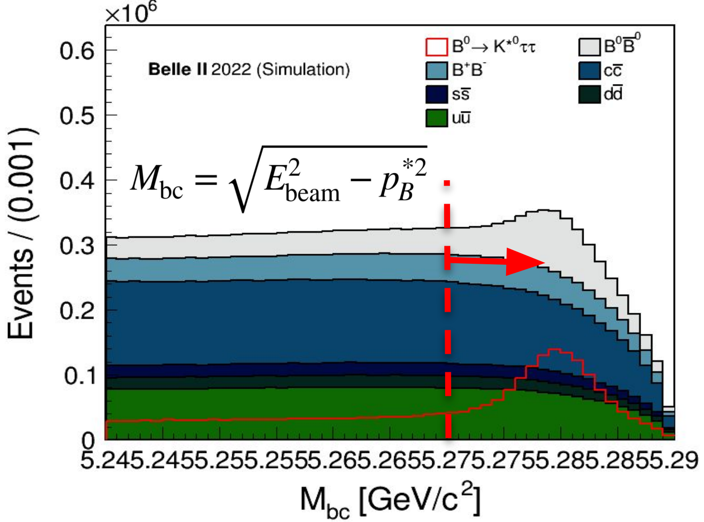


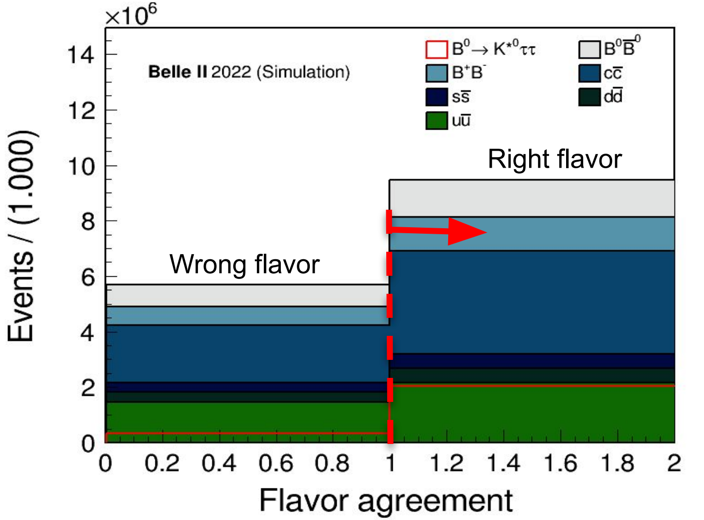
Event preselection

- **M_{bc} > 5.27 GeV**
- **B_{tag} flavor opposite to K^{*0}** (from $K^{\pm}$ sign)

After preselection :

- **$\varepsilon_{sgn} = 2.74 \times 10^{-3}$**
- Reject 75% of background





Background validation

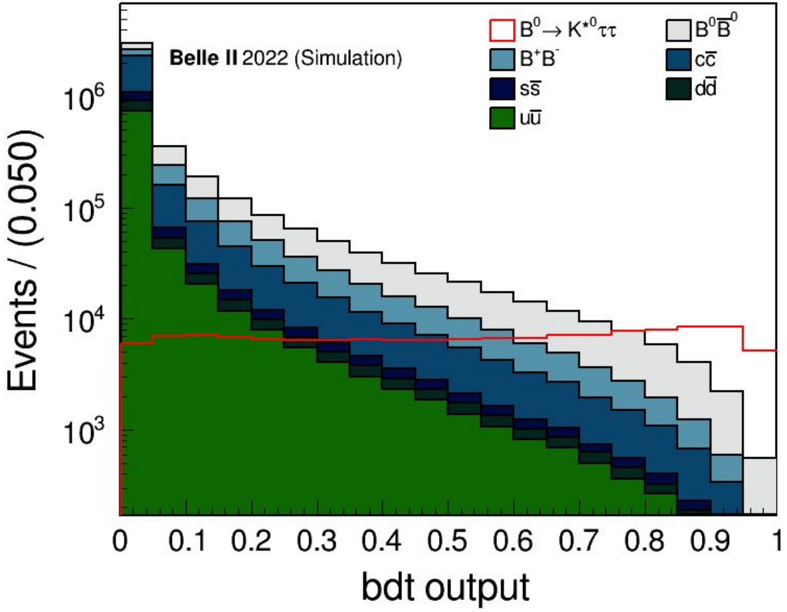
- Υ(4S) sideband to validate peaking background:
  - **sideband** region → wrong flavor reconstructed events
  - Correct **qq** background comparing MC with **off-resonance** data
  - For $B\bar{B}$ background, apply **corrections** to account for different MC/data **FEI efficiency**
- Data/MC = 0.954 ± 0.010 (*)
  - Residual ~5%
  - Need to include charged PID and neutral clusters efficiency corrections

(*) statistical uncertainty only

Signal selection

Train XGBoost **BDT** to discriminate signal against all backgrounds

- Exploit ~30 variables (kinematics, event-shape, vertices, ...)
- Distinguish $\tau\tau$ decay topologies during the training
- Dominant backgrounds are $B\bar{B}$ and ccbar



Upper limit (projections)

Extract upper-limit, assuming different systematics scenarios

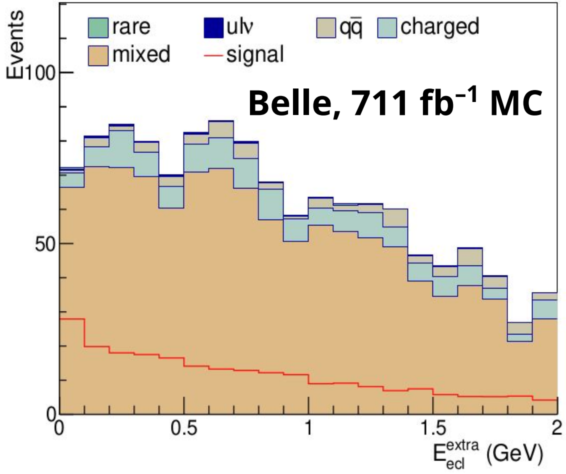
	Bkg systematics	ε_{sgn} x 10^{-5}	Bkg yields (/100 fb^{-1})	**Expected UL BR($B^0 \to K^{*0} \tau\tau$)**
Belle (cut-based)	5%	1.24	21.4	**3.0 x 10^{-3} @711 fb^{-1}**
Belle II (BDT>0.94)	5%	13.6	87.5	**1.1 x 10^{-3} @360 fb^{-1}**
Belle II (BDT>0.96)	10%	7.26	31.2	**1.3 x10^{-3} @360 fb^{-1}**
Belle II (BDT>0.98)	30%	2.23	5.1	**1.7 x10^{-3} @360 fb^{-1}**

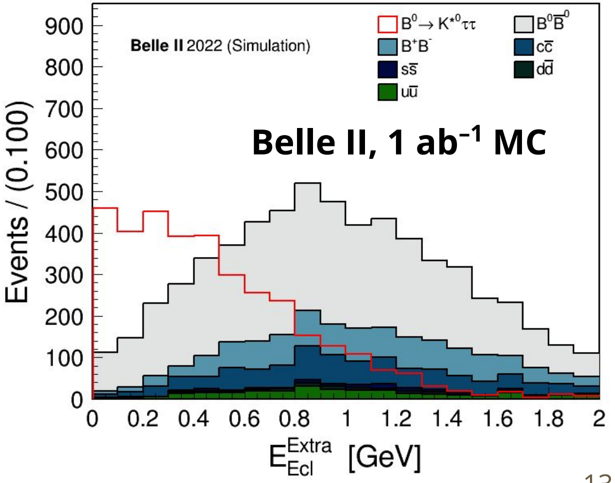
- Optimize BDT cut to cope with higher background uncertainties
- Final strategy is to **fit BDT output** in a wider signal region

Comparison with Belle

The improvement in the expected upper limit w.r.t. Belle, comes from various sources:

- Hadronic **B-tag efficiency** (FEI)
  - ~0.5% vs ~0.2% @Belle
- **BDT** signal selection, instead of cut & count
  - Factor x2 in $\varepsilon_{sgn}/b^{1/2}$ according to Belle II simulation study
- $\tau \rightarrow \rho\nu$ additional decay mode considered
- Better **ECL extra energy** signal/background shape separation



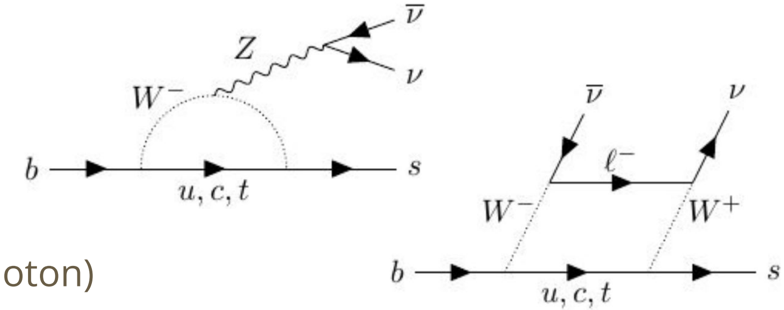


Next analysis steps

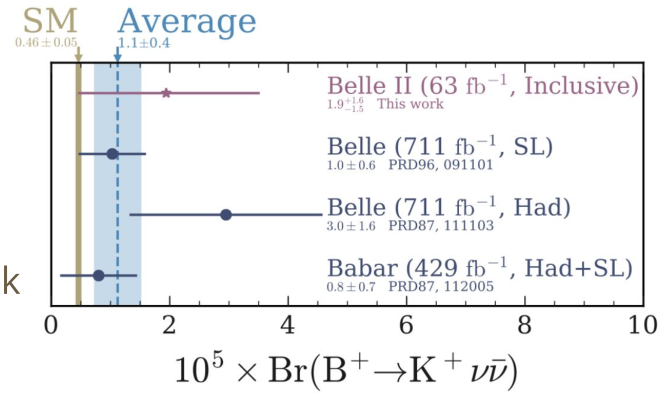
- Finalize validation of backgrounds
- Perform **signal validation** on “embedded” control channel
  - reconstruct B→ K* J/ψ on data, substitute J/ψ with simulated τ-pair
- Upper limit extraction
  - Binned fit in a signal region of BDT output (using pyhf)
  - Optimize BDT cut with Punzi FOM

Some missing steps will be completed in synergy with K$\nu\nu$ analysis
→ see next slides

Search for $B^+ \to K^+\nu\nu$ decay

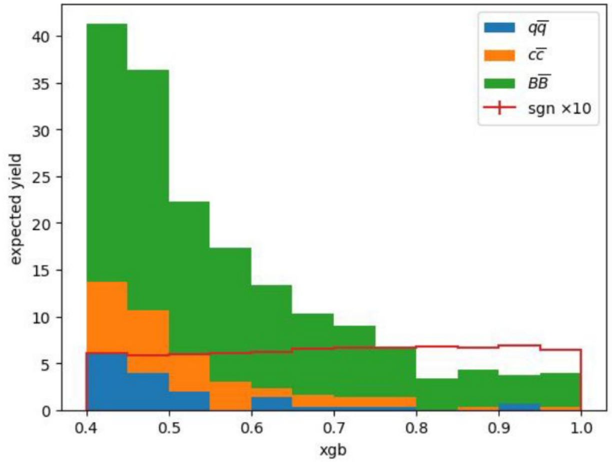


- Analysis unique at B-factories
  - Test SM, complementary to $b \to sll$ anomalies
  - Reliable prediction (no amplitudes with virtual photon)
- Upper limit set by Belle II in 2021 (PRL)
  - Exploit a new **inclusive tag** method
  - Use only 63 fb^{-1} of statistics
  - Expect world-leading result with 2022 data sample
- Combined **inclusive+hadronic tag** analysis for the 2022 data sample (362 fb^{-1})
  - Use hadronic tag analysis (robust method) as cross check for the inclusive one
  - Perugia group involved in this effort



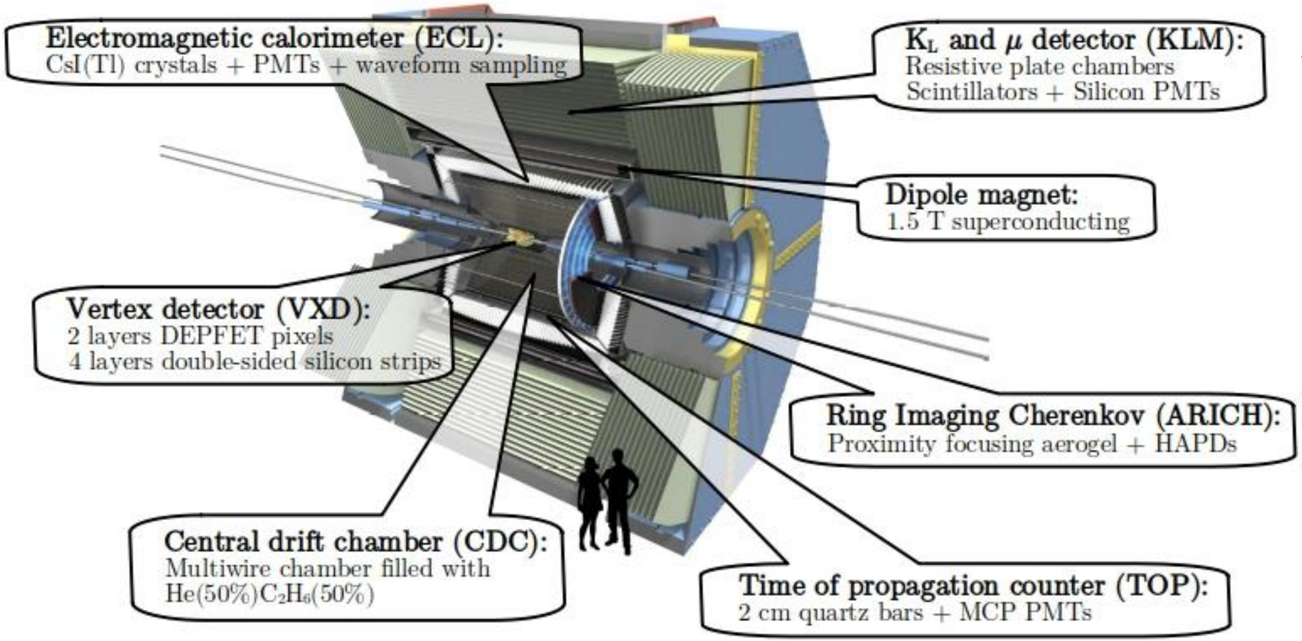
$B^+ \to K^+\nu\nu$ with hadronic tag: overview

- Reconstruct B_{tag} with **hadronic FEI**
- Select K^+ and require no extra tracks/π^0
- Train **XGBoost** to separate signal from background
- **Fit** of **BDT output** signal region
  - Two components (sgn and bkg) in 12 bins
- Set **upper limit**
  - Projection with 400 fb^{-1} (including all systematics)
  - **Expected**: $BR(B+ \to K+\nu\nu) < 1.5 \times 10^{-5}$ @90% C.L.



Hardware and laboratory

Belle II detector

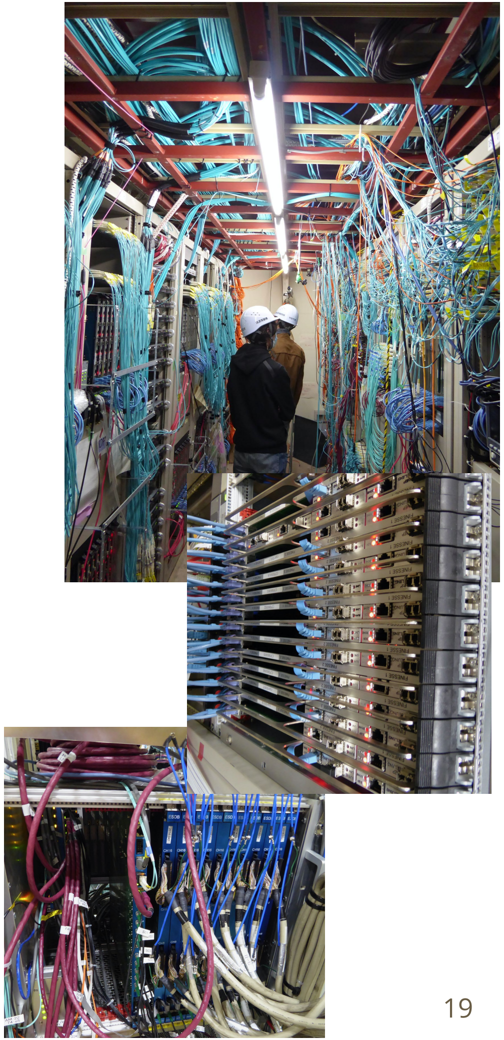


Data-taking stopped for intermediate detector work (**LS1**)

- Upgrade
  - VXD completion
  - new beam pipe
- Maintenance of other sub-detectors
  - PMTs replacement
  - Repair modules
- Will resume running by 2023

Belle II Electromagnetic CaLorimeter (ECL)

- In 2019–2022 data taking period → reached luminosity 5 x 10^{34} $cm^{-2}s^{-1}$
- Target luminosity will be x6 higher
- High level of electromagnetic background → ECL stressed
  - Need to replace some damaged modules
  - Substitute readout system for deal with higher event rate (COPPER → PCIe40)
  - Other minor interventions
  - Open ECL endcaps to access VXD

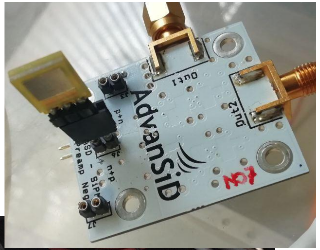


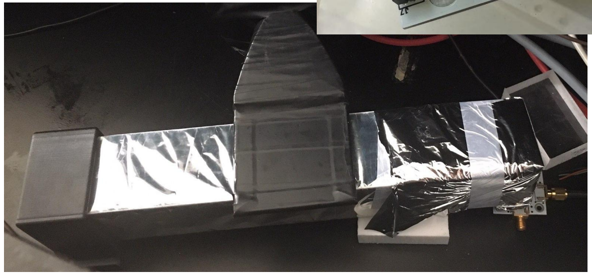
Explore possible calorimeter upgrades

Beam-background can become problematic (particularly in endcaps)

⇒ Faster crystals: pure CsI instead of Tallium-doped CsI

	ρ, g/cm^3	X_0, cm	λ_{em}, nm	$n(\lambda_{em})$	N_{ph}/MeV	τ_d, ns	dL/dT, %/° 20°C
pCsI	4.51	1.85	305	2.0	2000	20/1000	- 1.3
CsI(Tl)	4.51	1.85	550	1.8	52000	1000	0.4





- ~10 times lower light output → need photosensors with internal gain
- Explored two main alternatives:
  - APD → readout with preamplifier + shaper, similar to present Belle II electronics
  - SIPM → no need of signal shaping

Thank you!

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