# Challenges in Semileptonic B Decays

Monday 23 September 2024 - Friday 27 September 2024

# Book of Abstracts

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**Heavy to heavy inclusive** / **1**

# The $q^2$ moments in inclusive semileptonic $B$ decays

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In this talk I will present the calculation of moments of the $q^2$ distribution in inclusive semileptonic $B$ decays with a lower cut on the dilepton invariant mass $q^2$, confirming known results. The theoretical predictions are then used in a global fit to moments of the spectrum of inclusive semileptonic $B$ decays, allowing the extraction of $|V_{cb}|$. The fit includes the recently measured $q^2$ moments, together with moments in the lepton energy and hadronic invariant mass. The uncertainty on the non-perturbative parameters and on $|V_{cb}|$ slightly decreases, yielding to the final value $|V_{cb}| = (41.97 \pm 0.48) \times 10^{-3}$.

**Other** / **2**

# On the potential of Light-Cone Sum Rules without semi-global Quark-Hadron Duality

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The calculation of local form factors involved in the SM predictions of semileptonic $B$-meson decays at low-$q^2$ is a crucial ingredient in the assessment of the $B$-anomalies.
We revisit their calculation in QCD Light-Cone Sum Rule with $B$-meson Light-Cone Distribution Amplitudes. In our strategy, we bypass the semi-global quark-hadron duality (QHD) approximation which usually contributes an unknown and potentially large systematic error to the prediction of form factors.
We trade this improvement for an increased reliance on higher-order contributions in QCD perturbation theory and higher-twist contributions in the light-cone OPE. Unlike the systematic error from QHD, the magnitude of truncation errors is assessable and systematically improvable, hence allowing robust predictions of form factors.

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# Order-$\alpha_s^2$ corrections to the leptonic invariant mass spectrum in $B \to X_c \ell \bar{\nu}$.

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Experimental results for moments of the leptonic $q^2$-spectrum in inclusive semileptonic B-meson decays often involve cuts on $q^2$. Therefore, the spectrum itself (rather than its moments only) needs

to be evaluated on the theoretical side. We present results of our calculation of $\mathcal{O}(\alpha_s^2)$ corrections to this spectrum that have been obtained via a numerical solution to differential equations for the relevant master integrals. Our findings agree with the recently published analytical results of Fael and Herren.

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## A model-independent parameterization of semileptonic B decays with two final-state hadrons

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Semileptonic $B$ decays involving multiple final-state hadrons play a crucial role as backgrounds to studies of lepton flavour universality or recent anomaly observed in $B \to K\nu\nu$. Furthermore, these poorly understood decays constitute sizeable signal components in measurements of inclusive $B \to X_{u/c}\ell\nu$ decays and the subsequent extraction of inclusive $V_{xb}$.

Current theoretical models describing decays such as $B \to D\pi\ell\nu$ or $B \to \pi\pi\ell\nu$ rarely take contributions beyond dominant resonances into account, while neglecting non-resonant components.

In this talk, we present a novel, model-independent parameterization of three-hadron form factors. The challenge is the dependence of the form-factors on two additional variables beyond the usual $q^2$-dependence: they can be chosen to correspond to the invariant mass and the helicity angle of the final state hadron system. Using dispersive methods we derive a systematic expansion in all three kinematic variables, generalizing the standard $z$-expansion, and bound the expansion coefficients through unitarity. Our method treats the two-hadron lineshapes in a model-independent manner using Omnès functions, thus allowing for a data-driven determination of all expansion parameters.

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## Improving our understanding of B -> D pi l nu and B -> pi pi l nu decays

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In this talk, we present studies of two semileptonic decays with two hadrons in the final state. First, we'll discuss $B \to D\pi\ell\nu$ decays that not only constitute a sizeable background for $R(D^{(*)})$ determinations, but also comprise a largely unknown signal component for inclusive $B \to X_c\ell\nu$ decays. The dominant decay chain proceeds through resonant $B \to D^*/D_2^*(\to D\pi)\ell\nu$ decays, but also includes a poorly understood broad component. We study the composition of this broad component

by using our newly developed formalism for $B \to D\pi\ell\nu$ decays, together with experimental spectral measurements, and investigate the plausibility of the two-pole structure in the $D\pi$ S-wave. In addition, we provide recommendations for possible future measurements to systematically improve current understanding of $B \to D\pi\ell\nu$ decays kinematics.

In the second part of the talk we present new results on $B \to \pi\pi\ell\nu$ decays, relevant to studies of $B \to \rho\ell\nu$ and $V_{ub}$ determinations. We discuss the separation of signal P-wave from background S-wave contributions in the $\rho$-region and the use of $e^+e^- \to \pi^+\pi^-$ data to describe the $\rho$-lineshape. In addition, we briefly discuss the inclusion of the leading isospin breaking effects in $B \to \pi\pi\ell\nu$ decays.

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## B->D(*)lnu at BaBar and Lambda_b->Lambda_ctaunu at LHCb

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I will present two sets of results:
1/ legacy BaBar B->D(*)*lnu with l=e/mu, angular analyses. This will cover https://arxiv.org/abs/2311.15071 and an update to: https://arxiv.org/abs/1903.10002, including all lattice B->D* results in a joint BaBar+lattice fit.
2/ Lambda_b -> Lambda_c taunu, for 3-prong hadronic tau, at LHCb. The Run1 R(Lc) analysis is being updated to Run1+2. This includes a separate update to BR(Lambda_b->Lambda_c 3pi), for the normalization mode. I will also discuss possibilities for angular studies in this mode, including both 3-prong Lambda_c->pKpi, and 2-prong Lambda_c -> {pKs, Lambda0pi} modes.

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## Intrinsic Charm and Higher Order $1/m_b$ corrections in inclusive $B \to X_c\ell\bar{\nu}$

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The Heavy Quark Expansion (HQE) has become the major tool to perform precision calculations for inclusive rates and spectra of heavy hadron decays. With this method, the CKM matrix element $V_{cb}$ has been extracted with incredible percent-level precision from moments of the inclusive semileptonic $B \to X_c\ell\bar{\nu}$. The HQE is an expansion in powers of the inverse mass of the heavy quark $1/m_b$ and introduces HQE matrix elements, containing the nonperturbative long-distance effects, which can be extracted from data.

To further increase precision, we have to include even higher order terms in the expansion and therefore we recently pushed the expansion to $1/m_b^5$. We focused specifically on the reparametrization invariant (RPI) dilepton invariant mass $q^2$ moments of the spectrum, which depend on a reduced set of HQE parameters. Specifically, at dimension eight, i.e. $1/m_b^5$, "intrinsic charm" (IC) contributions proportional to $1/(m_b^3 m_c^2)$ enter, which are numerically expected to be sizeable and therefore interesting for improving the theoretical predictions for $B \to X_c\ell\bar{\nu}$.

In this talk, I will discuss how we determine the RPI HQE parameters at $1/m_b^5$ and briefly review how RPI is employed in inclusive $V_{cb}$ determinations. Furthermore, I will show how the "intrinsic

charm" and "genuine" $1/m_b^5$ contribute to the $q^2$-moments of $B \to X_c \ell \bar{\nu}$. Consequently, I will show that the total $1/m_b^5$ contributions may not be as sizeable as initially expected.

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## Determination of Vcb from Exclusive Decays

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We present a determination of Vcb taking into account the most recent data on exclusive decays as well as form factor calculations from lattice QCD. We employ unitarity constraints within the Boyd-Grinstein-Lebed (BGL) parametrization and carefully study their impact on the results. Furthermore, we give updated Standard Model predictions for the lepton-flavor non-universality observables R(D(*)).

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## Investigating Quark Hadron Duality Violation in inclusive semileptonic B → Xc ν l decays

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The Heavy Quark Expansion (HQE) is one of the leading tools for calculating decay rates and kinematic moments of inclusive semi-leptonic B-meson decays. The HQE is an Operator Product Expansion (OPE) in terms of the inverse of the mass of the heavy bottom quark ($1/m_b$). It introduces nonperturbative HQE parameters which can be determined using data. Using the HQE, the CKM matrix element $V_{cb}$ has been extracted at percentage level precision from the moments of inclusive semi-leptonic B meson decays ($B \to X_c \, \overline{\nu} \, l$). The calculations upon which the theoretical estimates rely are done in terms of quarks and gluons. These are, however, not accessible for experiments. Quark Hadron Duality (QHD) allows for a translation of theoretical predictions at the quark level to experimental observables at the hadron level. Since the increased accuracy in HQE predictions up to order of $1/m_b^5$, violation of the QHD may start to become a relevant limit to the achievable precision. When QHD is violated, the OPE upon which the HQE relies stops being a valid expansion. In my talk I will show how we can derive a model for the Quark Hadron Duality Violation (QHDV) and how the violation can enter different kinematic moments of the $B \to X_c \, \overline{\nu} \, l$ decays.

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## Model-independent fits to experimental and lattice data for $B \to D^* \ell \bar{\nu}$ (and other) exclusive decays

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We present an analysis of the exclusive semileptonic decay $B \to D^* \ell \bar{\nu}$ based on the Belle and Belle II data made public in 2023 and considering also a new combination of both data sets by HFLAV, combined with recent lattice-QCD calculations of the hadronic transition form factors by FNAL/MILC, HPQCD and JLQCD. The analysis is based on the form-factor parameterisation by Boyd-Grinstein-Lebed (BGL), determined both in terms of Bayesian and Frequentist statistics, for which we discuss novel strategies. We compare the results of an analysis where the BGL parameterisation is fit only to the lattice data with ones from a simultaneous fit to lattice and experiment, and discuss the resulting predictions for the CKM-matrix element
$Vcb$ as well as other phenomenological observables, such as $R^{\tau/\mu}(D^*)$. We find tensions when comparing the analysis based on different experimental and/or theoretical input, requiring the introduction of a systematic error for our predictions.

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## Kolya and New results on inclusive $V_{cb}$ using $q^2$, $E_\ell$ and $M_X$ spectral moments

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We present a new global fit for inclusive $V_{cb}$ decays based on the Kolya open-source library, utilizing the full available set of spectral moments of semileptonic $B \to X_c \ell \nu$ decays with state-of-the-art precision. Our approach includes a novel prescription to estimate the uncertainty arising from missing higher-order contributions of order $1/m_b^4$ in the heavy quark expansion (HQE). We review various approaches on how to incorporate theoretical uncertainties and correlations, studying their impact on the value of inclusive $V_{cb}$ and HQE parameters.

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## Precision QCD corrections to semileptonic $B$ decays

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In this talk, I will review recent advancements in the calculation of QCD higher-order corrections for semileptonic $B$ decays. Specifically, I will present the next-to-next-to-leading-order corrections to the $q^2$ spectrum of the inclusive decay $B \to X_c l \bar{\nu}_l$, which can be utilized to incorporate the recent measurements of $q^2$ moments by Belle and Belle II into global fits of inclusive semileptonic $B$ decays. Additionally, I will discuss recent results for the third-order corrections to the total width of $b \to u l \bar{\nu}_l$ decays. These corrections are crucial for evaluating the phase-space ratio $C = |V_{ub}/V_{cb}|^2 \Gamma(B \to X_c l \bar{\nu}_l)/\Gamma(B \to X_u l \bar{\nu}_l)$, which appears as normalization factor in the branching ratios of $B$ decays mediated by $b \to s$ transitions, such as $B \to X_s \gamma$ and $B \to X_s l^+ l^-$.

**Other** / **14**

## Streamlining semileptonic analyses

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Semileptonic measurements take a very long time. Particularly at LHCb where the datasets are large and background control is very important and fiddly. Most of these reasons are inherent to the measurements themselves but there are a few aspects which are repeated for each analysis which could be streamlined. This talk will open a broad discussion of how to streamline with a few proposals of potential improvements.

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## $B_{(s)} \to D_{(s)}^{(*)}$ form factors at $calO(1/m_c^2)$

**Authors:** Danny van Dyk[None]; Martin Jung[1]; Marzia Bordone[2]; Nico Gubernari[3]

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We perform a fit of the Isgur-Wise function including $calO(1/m_c^2)$ corrections to the available theoretical and experimental constraints. We include the tensor form factors and the corresponding unitarity bounds for the first time in this framework. We discuss the compatibility between the different constraints. We also compare our results with those of other methods. We present our SM predictions and $V_{cb}$ extractions.

**Other** / **16**

## Implications of SMEFT for semileptonic processes

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The $SU(2)_L \times U(1)_Y$ invariance of the Standard Model Effective Field Theory (SMEFT) predicts multiple restrictions in the space of Wilson coefficients of $U(1)_{em}$ invariant effective lagrangians such as the Low-energy Effective Field Theory (LEFT), used for low-energy flavor-physics observables, or the Higgs Effective Field Theory (HEFT) in unitary gauge, appropriate for weak-scale observables. In this work, we derive and enumerate all such predictions for semileptonic operators up to dimension 6. We find that these predictions can be expressed as 2223 linear relations among the HEFT/LEFT Wilson coefficients, that are completely independent of any assumptions about the alignment of the mass and flavor bases. These relations connect semileptonic $B$ meson decays to a wide array of experimental searches, including high-$p_T$ dilepton searches, top decays, $Z$-pole observables, charged lepton flavor violating observables, non-standard neutrino interaction searches and semileptonic decays of $K$ and $D$ mesons. We illustrate how these relations can be utilized to

impose stringent indirect constraints on several Wilson coefficients that are currently weakly constrained or entirely unconstrained by direct experiments. Moreover, these relations imply that any evidence of new physics in a specific search channel must generally be accompanied by correlated anomalies in other channels.

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## Simultaneous analysis of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ to improve the determination of $|V_{cb}|$.

**Author:** Michele Mantovano[1]

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We propose a simultaneous analysis of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ decays to measure model-independent observables for the determination of $|V_{cb}|$. The $B \to D^*\ell\nu$ decays is partially reconstructed, removing systematic uncertainty on $|V_{cb}|$ from the soft-pion reconstruction. By assuming equality of the semileptonic decay width of $B^0$ and $B^+$ mesons, we can also measure $f_{+-}/f_{00}$, the ratio of the branching fractions of the $\Upsilon(4S)$ decaying into charged and neutral $B\overline{B}$ pairs. From the model-independent observables, $|V_{cb}|$ and the form-factor parameters of both decays can be determined *a-posteriori* assuming any form-factor model and lattice data inputs. Using simulation, we present the potential of this analysis with the current Belle II dataset.

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## Opportunities with Baryons @ LHCb

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Semileptonic b-baryons decays provide powerful probes for testing the Standard Model and for searching for New Physics effects. In this contribution, the LHCb semileptonic measurements with b-baryons will be presented: the status, the analyses ongoing and the prospect for future.

**Other** / **19**

## Exploring CP Violation in Charged Semileptonic Decays

**Author:** Abhijit Mathad[1]

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This talk will focus on the measurement of CP violation in charged semileptonic decays. We will present the current status and prospects of precision measurements of CP asymmetry in B0 and Bs meson systems, which serve as stringent tests of the Standard Model. Additionally, we will explore

the potential for CP asymmetry induced by new physics, emphasizing its role as a powerful null-test of the SM. In this context, we will delve into direct CP violation in semileptonic decays and the investigation of triple product asymmetry in these decays, highlighting their significance in the search for new physics.

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## New physics searches with angular analyses of b-hadron decays

**Author:** Lucia Grillo[1]

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Differential measurements of semileptonic b-hadron decays not only further our understanding of hadronic effects and CKM matrix elements, but are also powerful probes for effects beyond the Standard Model description. An overview of the angular measurements currently pursued at LHCb is presented, including expected New Physics sensitivities and prospects for future measurements.

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## Inclusive $B— > X_u\ell\nu$: Towards NNLO Extractions of $V_{ub}$

**Corresponding Author:** bcapdevila@ifae.es

In this talk, I will present a short overview of inclusive $b \to u$ semileptonic decays, focusing on the current status of the BLNP and GGOU approaches—the two most active frameworks for $V_{ub}$ extractions in recent years. I will delve deeper into the GGOU approach, highlighting our work and status on the NNVub framework, which utilises neural networks for parametrising the required shape functions. I will very briefly discuss the calculation of perturbative power-suppressed corrections. And finally, I will outline our ongoing work on the extraction of NNLO corrections to the fully differential decay distribution.

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## Novel approaches to determine $B^{\pm}$ and $B^0$ meson production fractions

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We propose novel methods to determine the $\Upsilon(4S) \to B^+B^-$ and $\Upsilon(4S) \to B^0\bar{B}^0$ decay rates. The precision to which they and their ratio are known yields at present a limiting uncertainty around 2% in measurements of absolute $B$ decay rates, and thus in a variety of applications, such as precision determinations of elements of the Cabibbo-Kobayashi-Maskawa matrix and flavor-symmetry relations. The new methods we propose are based in one case on exploiting the $\Upsilon(5S)$ datasets, in the other case on the different average number of charged tracks in $B^\pm$ and $B^0$ decays. We estimate future sensitivities using these methods and discuss possible measurements of $f_d/f_u$ at the (HL-)LHC.

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## Combining R(D(*)) measurements at Belle II

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The R(D()) *ratio is an excellent test of Lepton Flavor Universality, that promises to elucidate the nature of potential Beyond the Standard Model physical processes. In this talk, we present the latest R(D())* measurements from the Belle II experiment. Additionally, we explore a likelihood based combination of different analyses relying on orthogonal selections, that goes beyond the combination methodology of HFLAV. We discuss a list of joint systematic uncertainties, that should be decomposed in eigenvariations, relevant for such combinations. We demonstrate a combination using different MC mock analyses implementing the procedure. We also highlight a python based tool that can be used for eigendecompositions of non-trivial systematic uncertainties.

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## Updating inclusive Vub in the factorization framework (aka BLNP)

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In the past two decades significant advances have been made on the perturbative ingredients of the leading-power factorization formula for $B \to X_u \ell \nu$, as well as local parameters in the heavy-quark expansion. An update for partial rates in the "shape-function region" is overdue. The main uncertainty still concerns the leading-power shape function, where we explore novel ideas and generate reliable error estimates. Along the way new lessons were learned that we would like to share and discuss.

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## New developments in B -> D(*) from lattice QCD

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## B -> D*lnu form factors"(BGL truncation)

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## LHCb/Belle II joint measurement of b-> c l nu Wilson Coefficients

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## Measurement of the B -> D*lnu form factor at Belle

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## Recent LHCb results on R(D) and R(D*)

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## New results from LHCb on semitauonic decays"(in particular B -> D**taunu )

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## Inclusive semileptonic Bs0 meson decays via a sum-of-exclusive modes technique

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## Inclusive measurements in charm

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## LQCD results for Vub exclusive

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## B -> pi/rho l nu at Belle II

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## Status of the Bs -> K mu nu analysis in LHCb

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## Inclusive semileptonic decays from Lattice QCD

**Author:** Ryan Kellermann[1]

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We report on the progress in the nonperturbative calculation of the decay rate for inclusive semileptonic decays of charmed and bottomed mesons. We provide an overview on the formalism used to reconstruct the inclusive rate and address the ongoing analysis into understanding the systematic errors associated with the analysis, focusing on the error due to the approximation and finite-volume effects. We further discuss future prospects such as the extension of the formalism towards the determination of moments, such as $q^2$ moments, which can be used for a comparison to experimental data and other theory predictions, such as the OPE.

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## Discussion – Vcb exclusive

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## Discussion – R(D(*)) and LFU in tau

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## Discussion – Vub

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## Discussion – closeout

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## Summary / announcement

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## Welcome

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## B -> Xulnu inclusive at Belle/Belle II

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This talk will review the inclusive B->Xu l nu measurements at Belle and present the status of ongoing activities at Belle II with a focus on the potential improvements in the analysis strategies.