Rare beauty and charm decays: an overview of searches at JSI

G. de Marino* on behalf of the JSI group

4TH JENNIFER2 GENERAL MEETING
Pisa - 2025.4.3

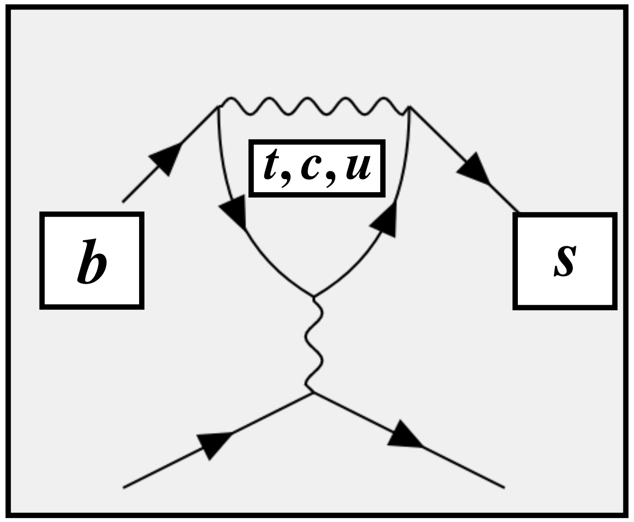
* gaetano.demarino@ijs.si

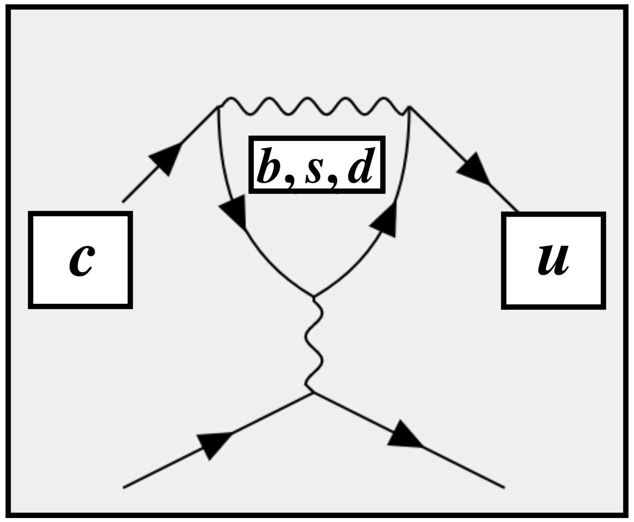
INTRO

- **Rare decays**
  Mediated by flavor changing neutral currents
  Loop, CKM, GIM suppressed $\mathscr{B} < 10^{-5}$
  Ground for testing Standard Model and New Physics

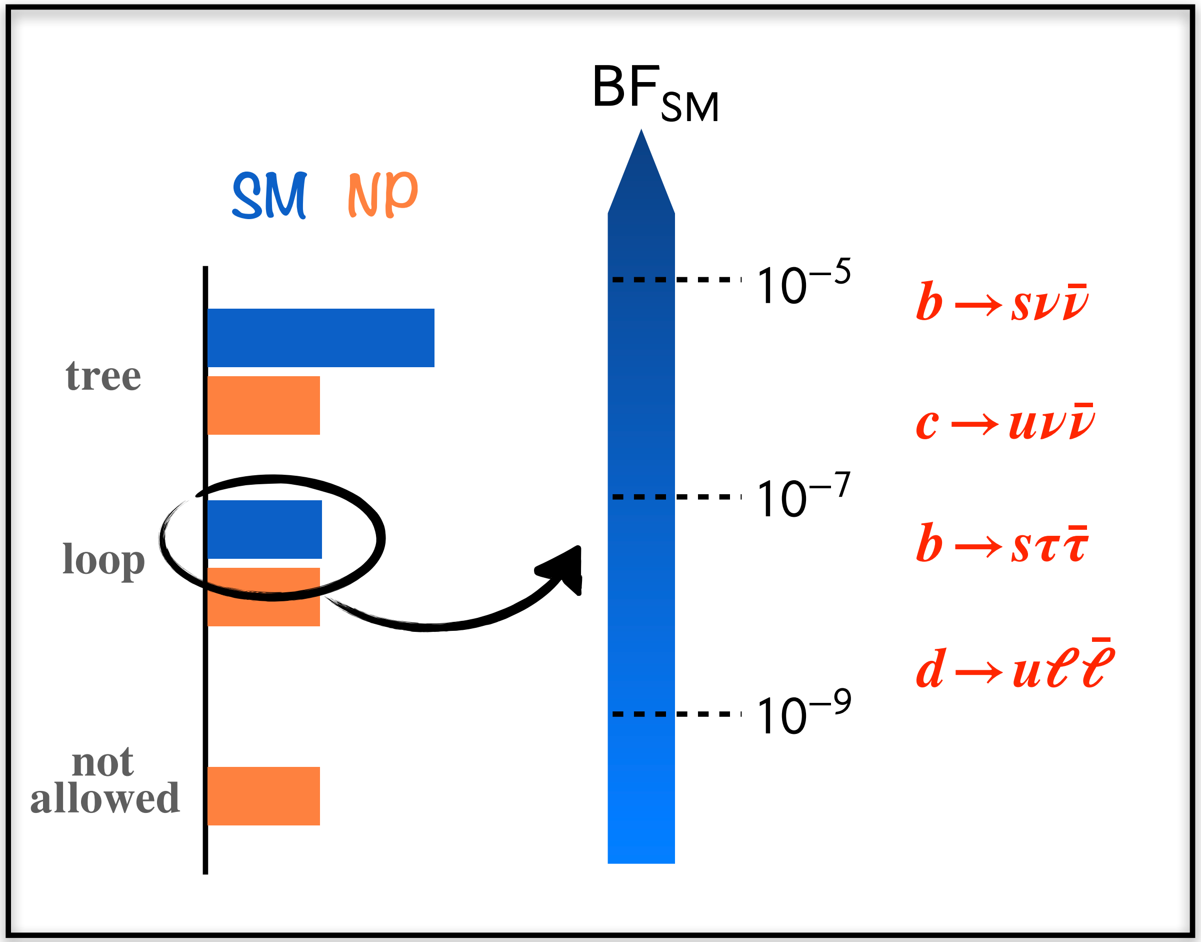
- **Rare beauty-decays** $|\Delta b| = |\Delta s| = 1$
  Large b-mass, richer phenomenology
  Weaker GIM suppression - less rare
  B-anomalies

- **Rare charm-decays** $|\Delta c| = |\Delta u| = 1$
  Stronger GIM suppression - more rare
  Very sensitive to the strong dynamics
  Unique probes of flavor physics in the up-sector





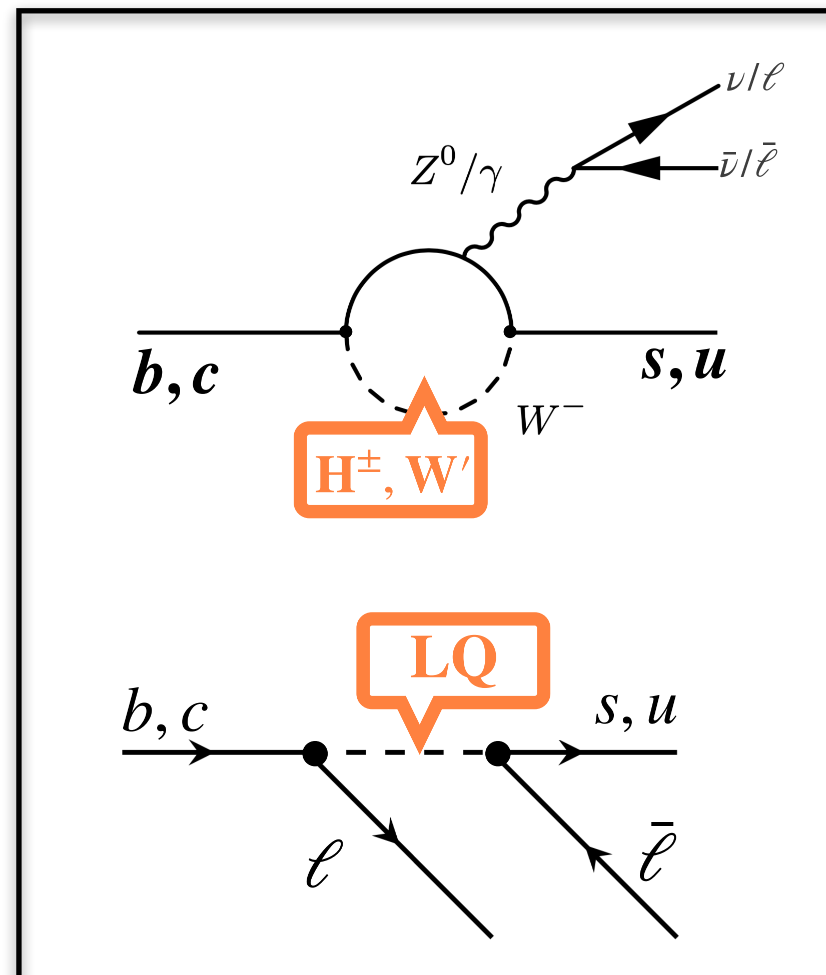
WHY RARE DECAYS



Sizeable alterations/enhancements in FCNC due to NP

New interactions at tree level

Weaker GIM cancellations (new particles in the loop)



NP searches/setting bounds on the NP properties

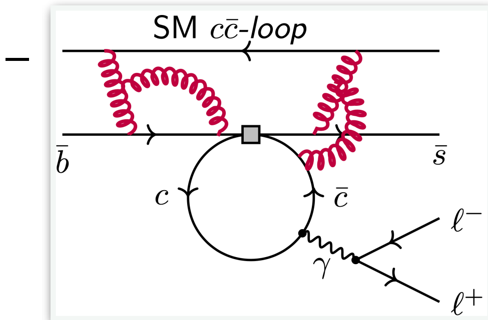
SM has to be described sufficiently well

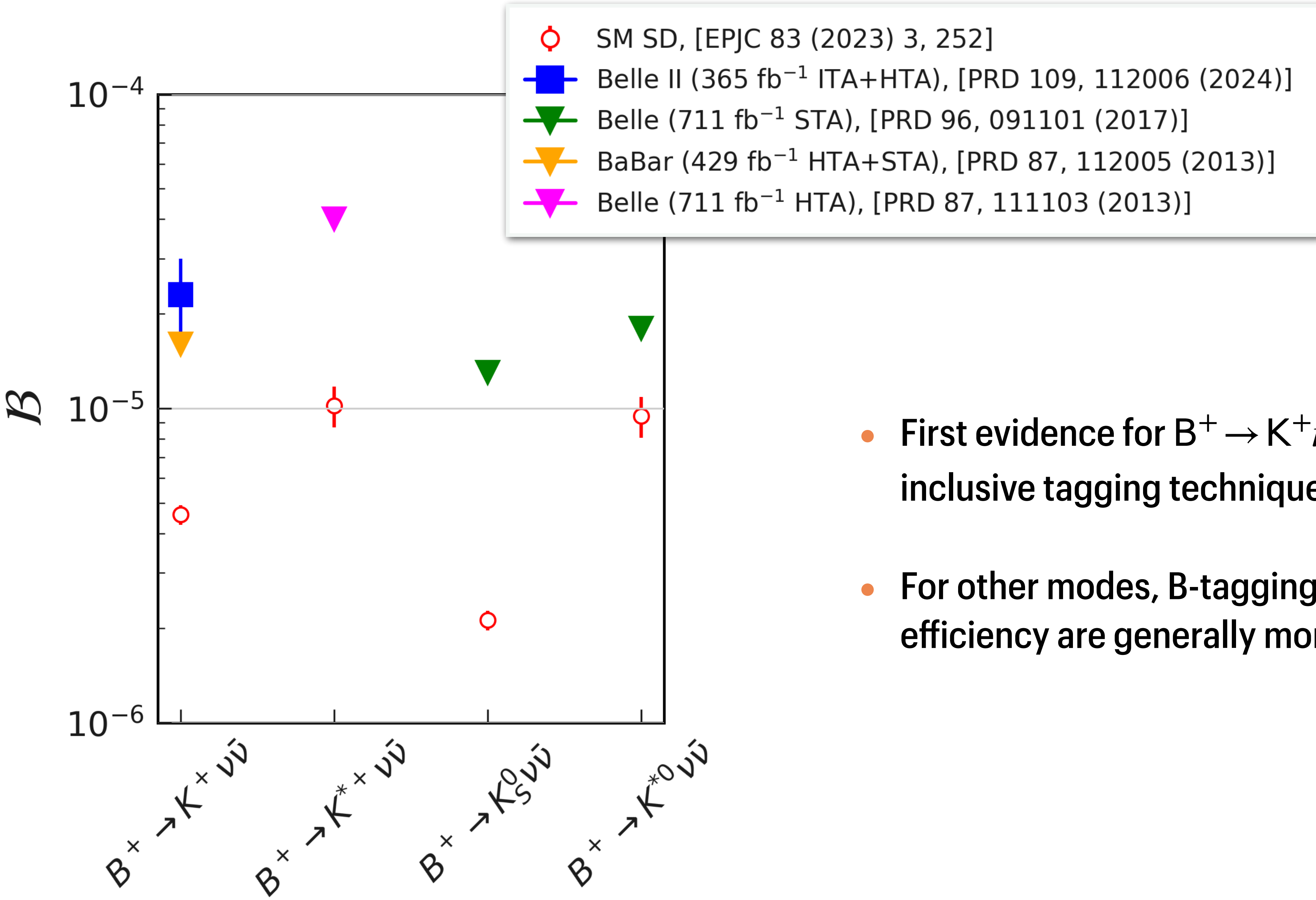
(SM as a background,SM-NP interference)

BEAUTY

$B \to K^{(*)}\nu\bar{\nu}$ SEARCHES

- Precise SM predictions — no hadronic uncertainties for charm annihilation like in $B \to K^{(*)}\ell^+\ell^-$
  Larger ME uncertainties for $B \to K^*$
- **Unique to experiments at e^+e^- machines**

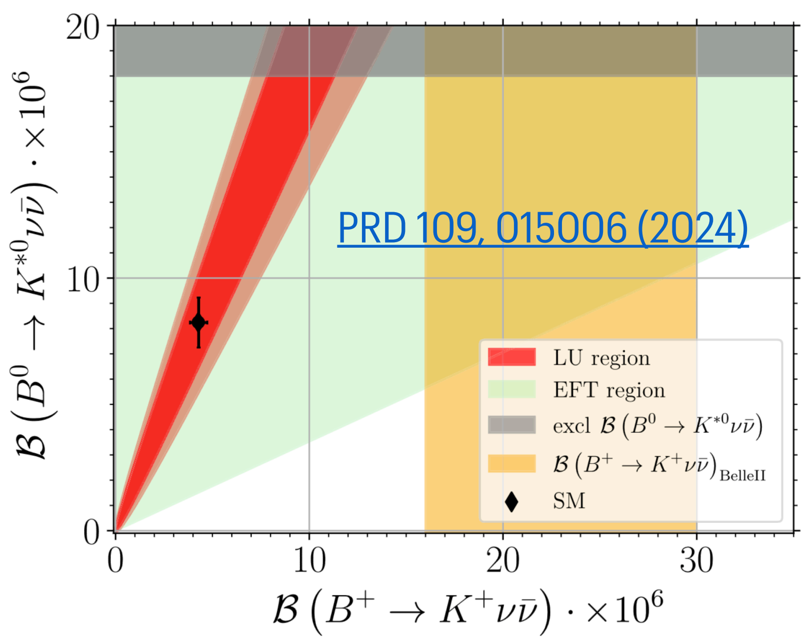




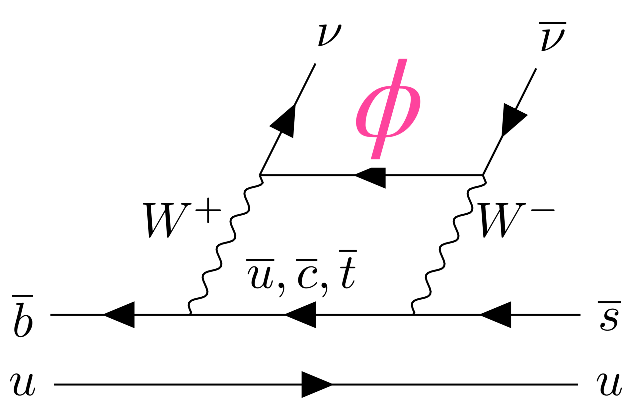
B-tagging	
$B \to X$	ITA
$B \to D\ell\nu$	STA
$B \to Dn\pi$	HTA

- **First evidence for $B^+ \to K^+\nu\bar{\nu}$ at Belle II with Run1 data and inclusive tagging technique (3.5σ from zero, 2.7σ from SM)**
- **For other modes, B-tagging approaches with higher efficiency are generally more sensitive**

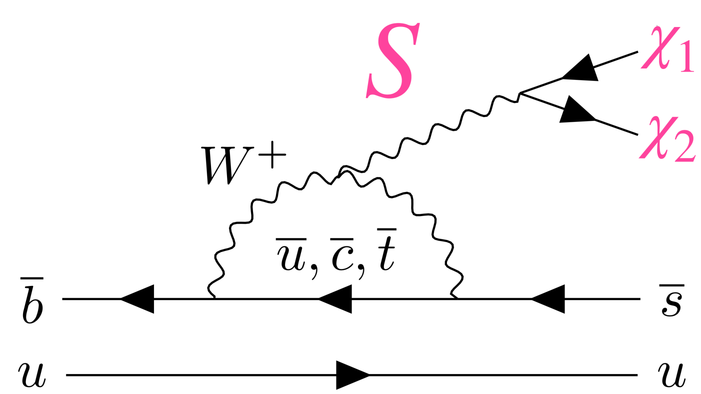
WHAT FOLLOWS $B^+ \to K^+ \nu\bar{\nu}$



Is lepton flavor universality violated?
Multi-TeV-scale? (Correlation to other flavor anomalies)
Light new physics?



LQ, PRD 98, 055003 (2018)
Z', PLB 821, 136607 (2021)



ALPs, EPJC 79 (2019) 5, 369
Axions, PRD 102, 015023 (2020)
Dark scalars, PRD 101, 095006 (2020)

How to corroborate the 2023 result?

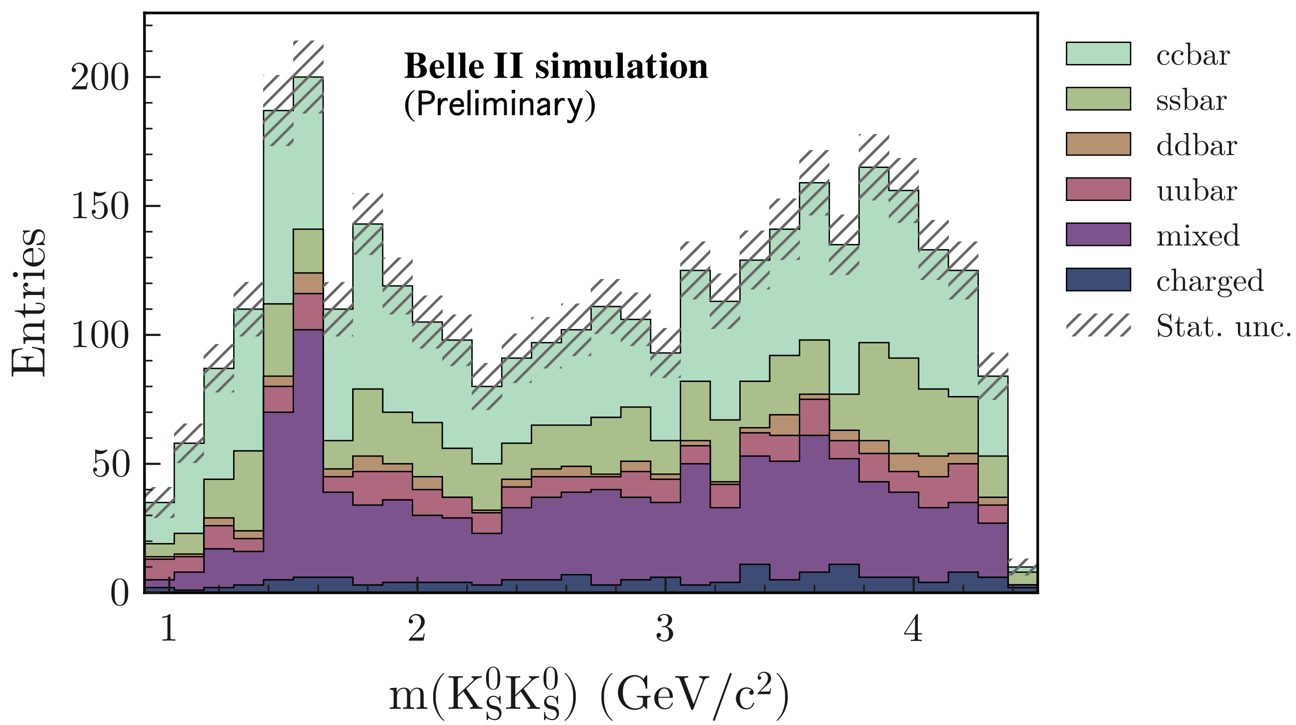
- **Use more data (ITA: stat~syst, with some syst being statistical in nature)**
  - Post- Run1
  - Belle data (see talk @ Jennifer3 kickoff meeting)
- **Additional tagging approaches** (uncertainty SL~ITA)
- **Additional $b \to s\nu\bar{\nu}$ channels with Run1** (NP can couple differently to K, K*)

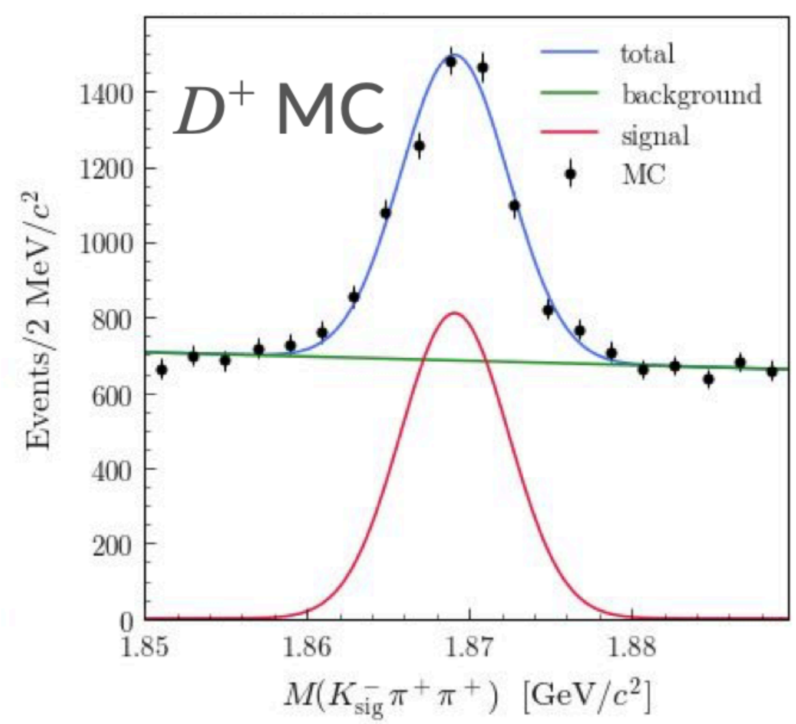
SEARCH FOR $B \to K^{(*)}\nu\bar{\nu}$

Extend the published $B^+ \to K^+\nu\bar{\nu}$ study to $B^0 \to K^0_S(\pi^+\pi^-)\nu\bar{\nu}$ • $B^+ \to K^{*+}(K^0_S\pi^+, K^+\pi^0)\nu\bar{\nu}$ • $B^0 \to K^{*0}(K^+\pi^-)\nu\bar{\nu}$

Challenges

- Combined fit of all channels **cross-feeds, correlation of uncertainties, isospin averages**
- K* modes: Larger multiplicity ↔ fake candidates due to combinatorics
- Different backgrounds for all modes **more control samples needed for validation**
  more charmless B-decays to be studied $K^0_S K^0 \bar{K}^0$ known
  $K^* K^0 \bar{K}^0$ never measured
- Improve the leading syst. uncertainty on the $B\bar{B}$ background by constraining, for example, the $D \to K$ sub-components





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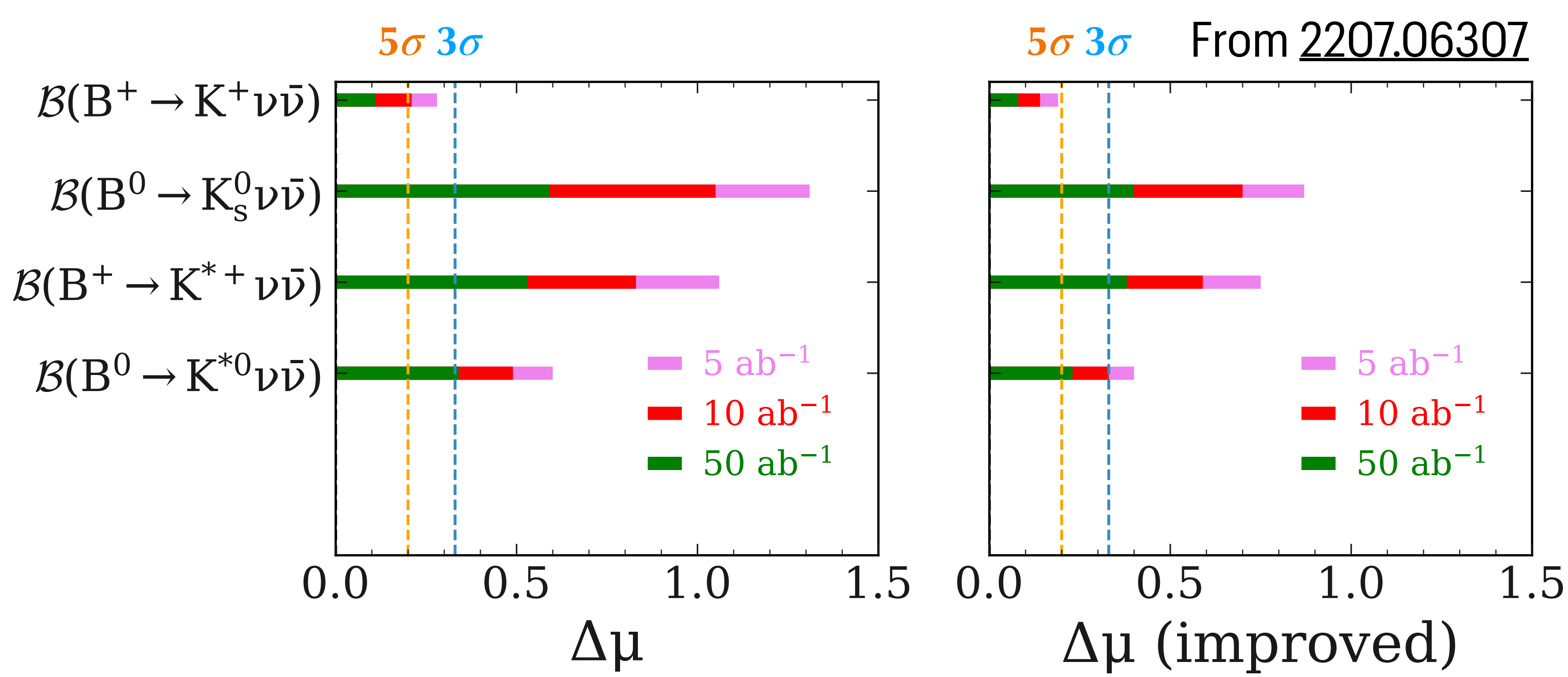
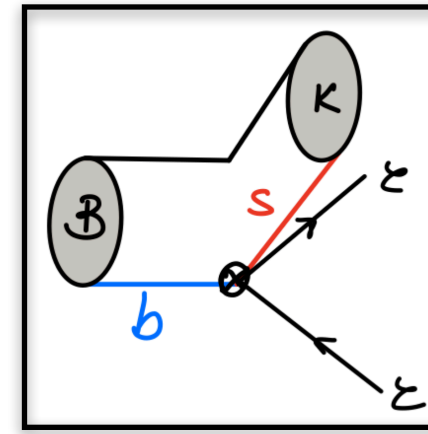
Improved scenario assumes a 50% increase in signal efficiency for the same background level

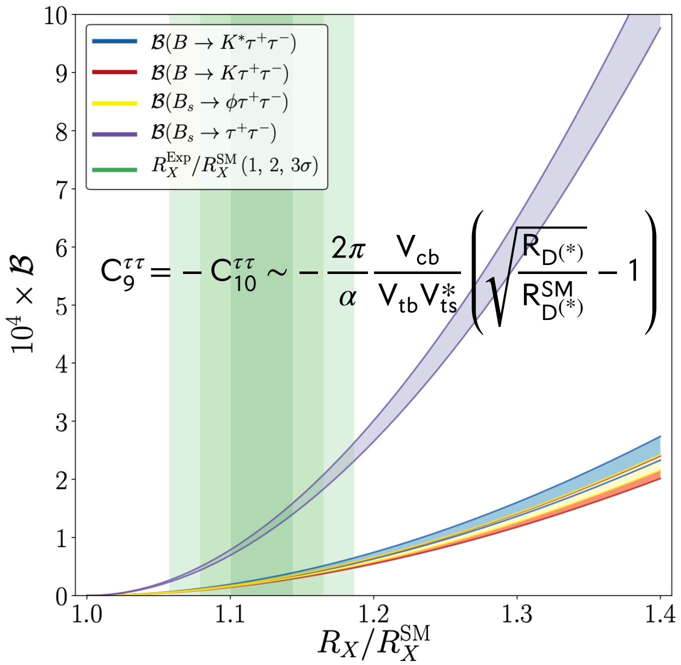
$\Delta\mu$: uncertainty on the signal strength assuming SM

From 2207.06307



MOTIVATION FOR $b \to s\tau\tau$ SEARCHES

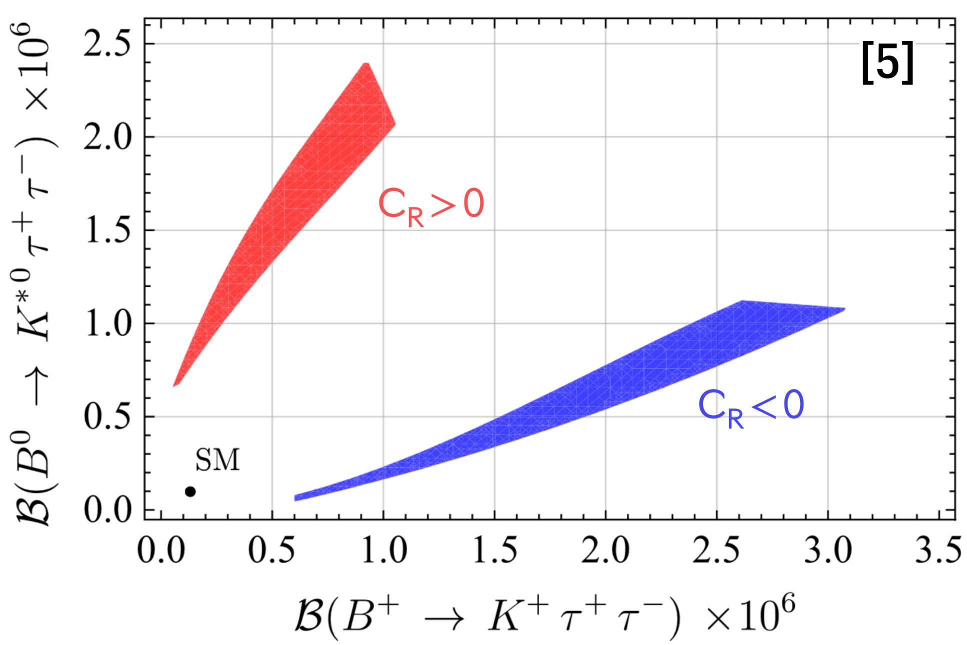


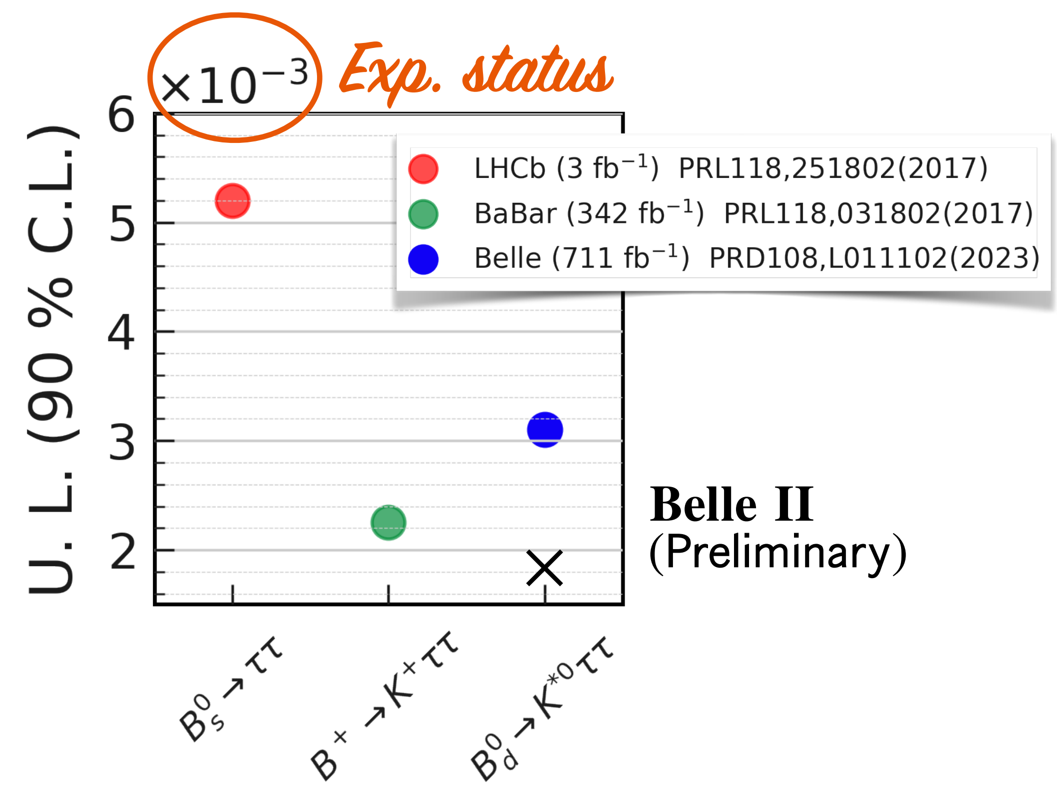


- $\mathscr{B}_{SM} \sim \mathcal{O}(10^{-7})$ [1]
- Correlation with $R_{D^{(*)}}$ [2] → Large enhancements to SM BF $\mathcal{O}(10^2 - 10^3)$ [3]
- Recent $B^+ \to K^+\nu\bar{\nu}$ excess, combined with R_{K^*} constraints, suggest LFUV in τ's [4,5]

$$\frac{\mathscr{B}(B \to K\nu\nu)}{\mathscr{B}(B \to K\nu\nu)^{SM}} = 5.4 \pm 1.5 \text{ (Belle II)}$$

$$\frac{\mathscr{B}(B \to K\tau\tau)}{\mathscr{B}(B \to K\tau\tau)^{SM}} = \frac{\mathscr{B}(B \to K^*\tau\tau)}{\mathscr{B}(B \to K^*\tau\tau)^{SM}} \in [16, 48]$$



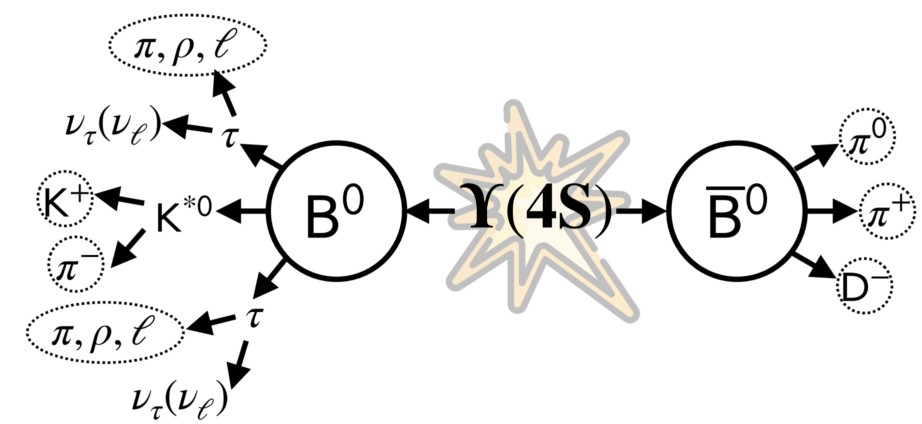


Unique opportunity for Belle II

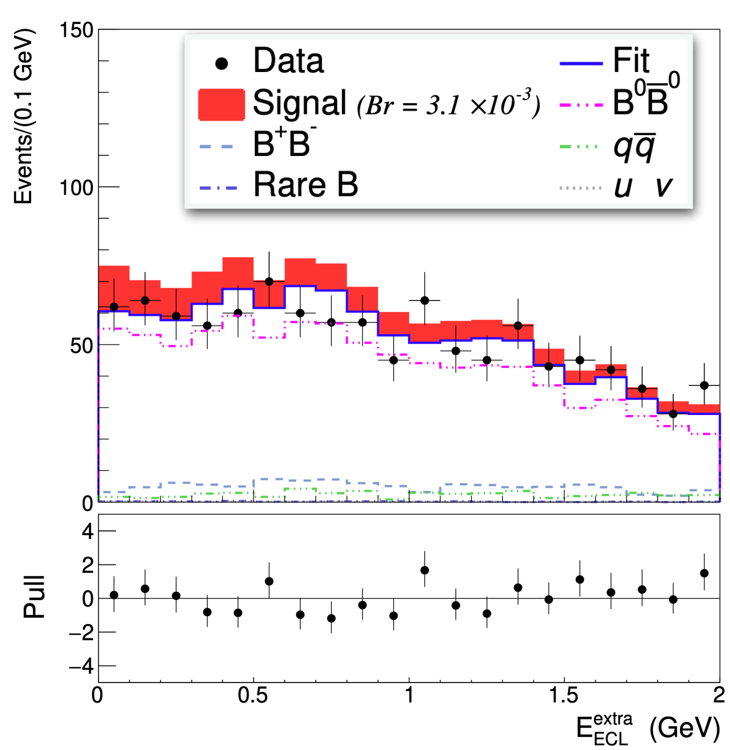
[1] PRD 107, 014511 (2023) [2] PRL 120, 181802 (2018) [3] PRD 105,113007 (2022) [4] PLB 848, 138411 (2023) [5] 2309.00075

$B \to K\tau\tau$ SEARCHES AT BELLE (II): THE CHALLENGES

- Large backgrounds coming from favoured B → D(→ K) decays
  Cut-based → MVA
- Lack of a clear signal signature
  E_{ECL} → BDT output
- Very low efficiencies with exclusive event reconstruction
  Signal side: $\tau \to (\ell\nu, \pi)\nu$ → $+\tau \to \rho\nu$ $\mathscr{B}(\tau \to \rho\nu) \sim 25\,\%$
  Tag side: Full Reconstruction → Full Event Interpretation $\times$ 2 eff .

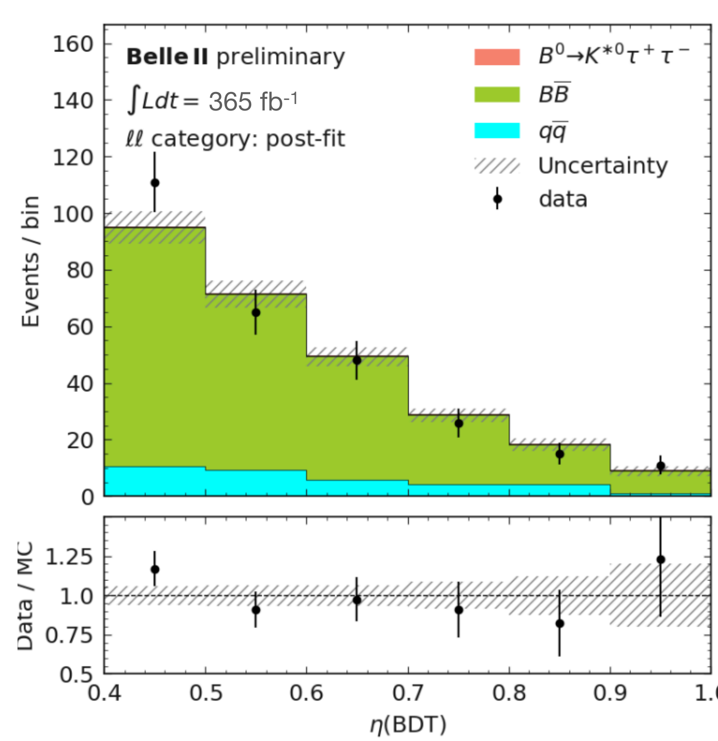


E_{ECL} : Extra energy in the calorimeter



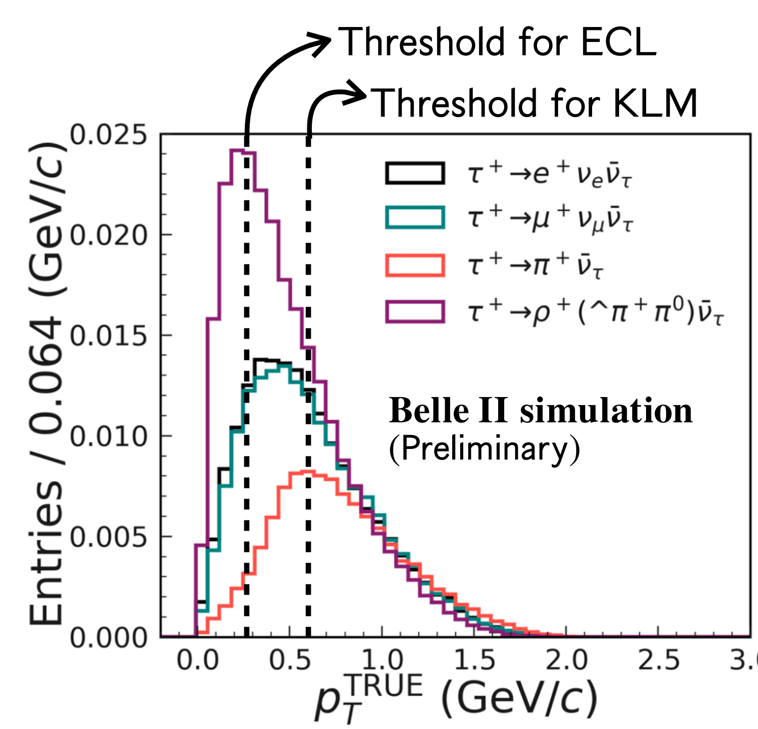
$B^0 \to K^{*0}\tau\tau$ (Belle)

BDT response



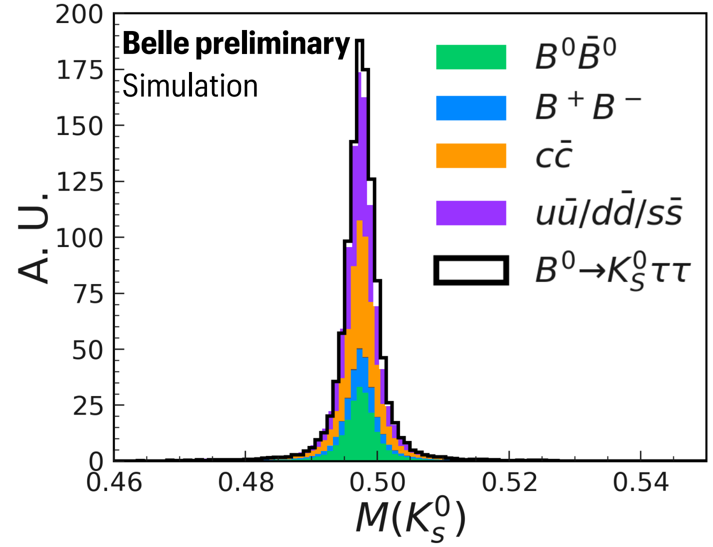
$B^0 \to K^{*0}\tau\tau$ (Belle II)

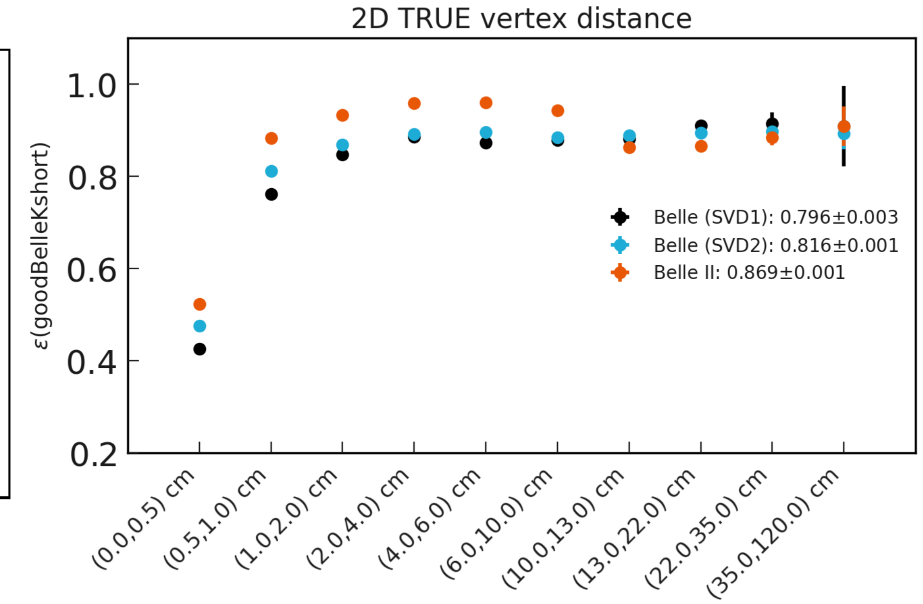
τ daughters momenta



$B \to K^0_S \tau\tau$ SEARCH: THE SPECIFICITIES

Very high K^0_S purity achieved at little signal loss
efficiency is slightly larger in Belle II

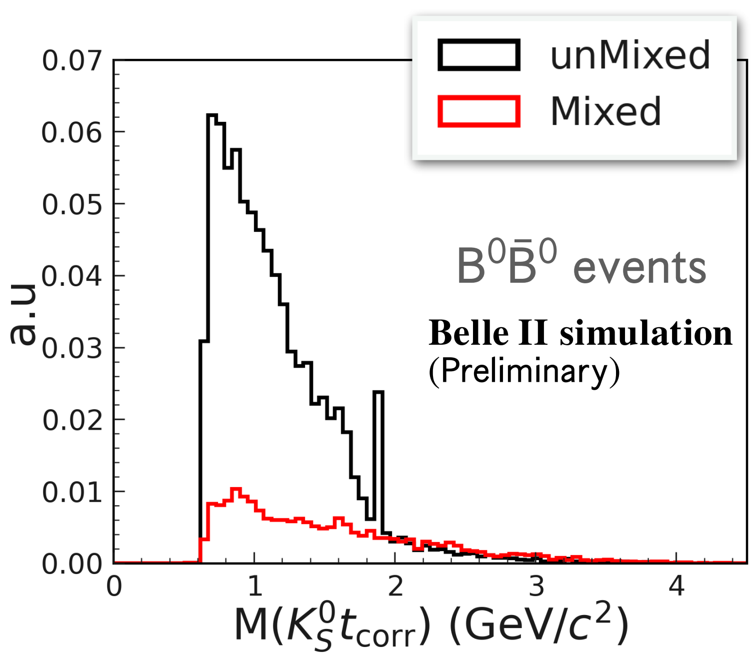


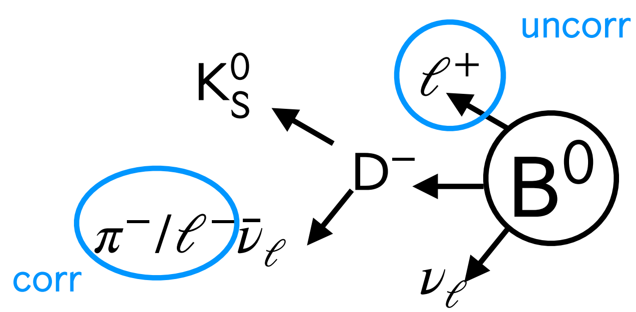


$K^{*0}\tau\tau$: $K^{*0}(K^+\pi^-)t_c^- t_u^+$

$K^0_S\tau\tau$: $K^0_S(\pi^+\pi^-)t_c^? t_u^?$ $\to$ $\bar{B}^0_{tag} K^0_S(\pi^+\pi^-)t_c^- t_u^+$

or $B^0_{tag} K^0_S(\pi^+\pi^-)t_u^- t_c^+$



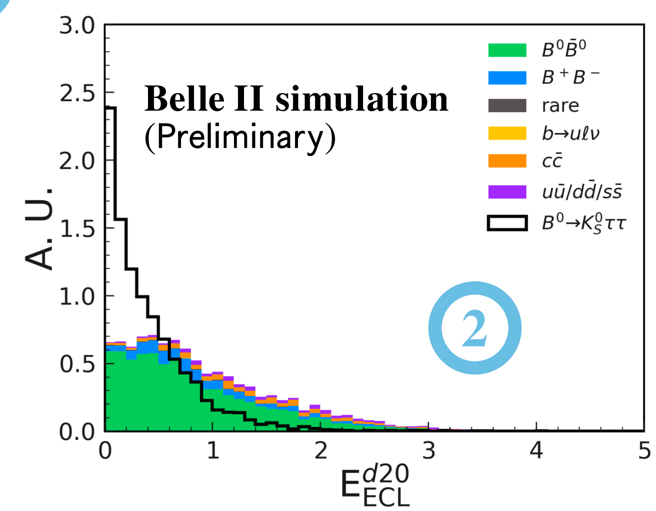


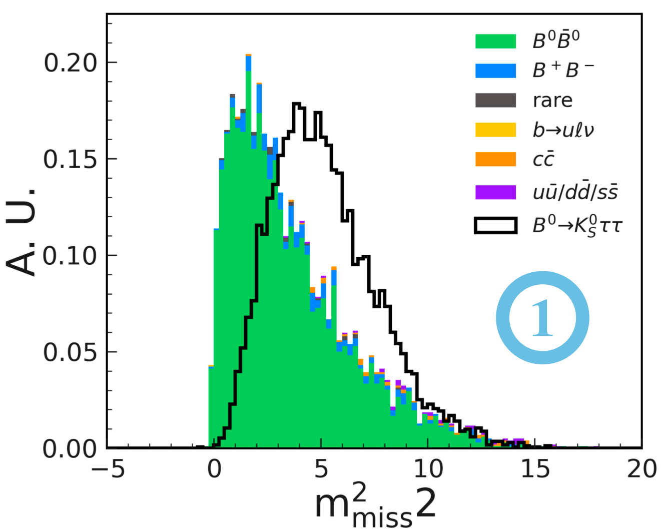
- Final state is not flavor specific (i.e. B^0 or $\bar{B}^0$)
- The `correlated' τ-daughter (t_c) i.e. presumably coming from a D along with the KS, is determined from the flavor of the B_{tag}

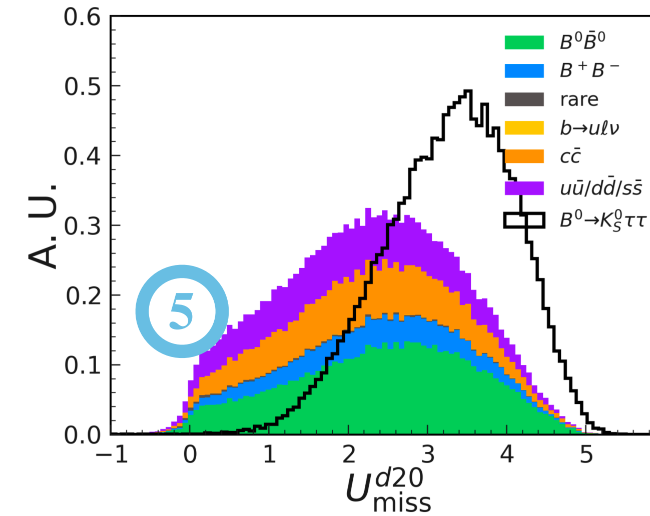
$B \to K_S^0 \tau\tau$ FIT CATEGORIES AND BACKGROUND SUPPRESSION

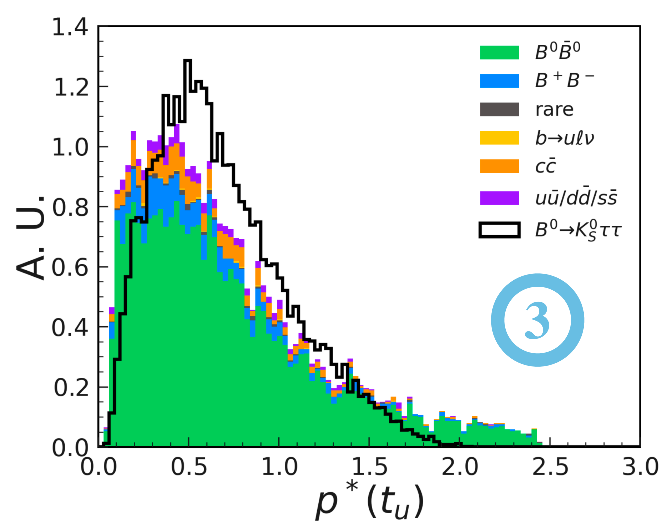
$\tau\bar{\tau}$ final state	Category	
$\mu\ \mu$	$\ell\ell$	1
$e\ \mu$		
$e\ e$		
$\mu\ \rho$	$\rho\ell$	2
$e\ \rho$		
$\mu\ h$	$\ell_c h_u, \ell_u h_c$	3, 4
$e\ h$		
$\rho\ \rho$	$\ell 0$	5
$\rho\ h$		
$h\ h$		

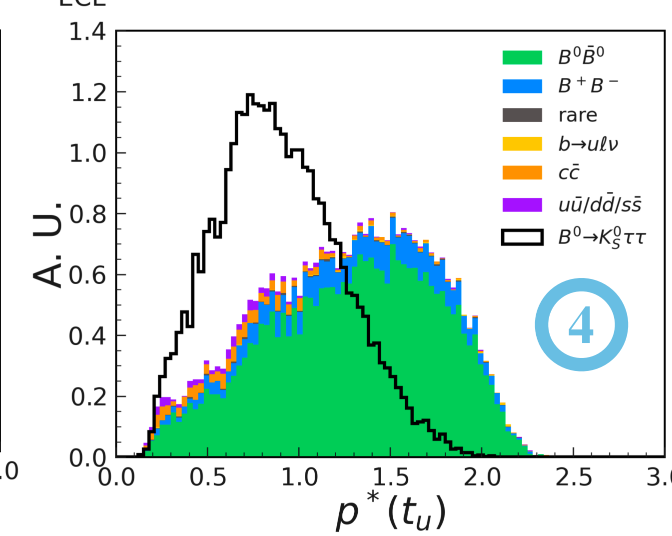
- Fit category based on the τ's decay modes
- Extract the $\mathscr{B}(B^0 \to K_S^0 \tau\tau)$ simultaneously in the 5 categories $\times$ {Belle, Belle II}









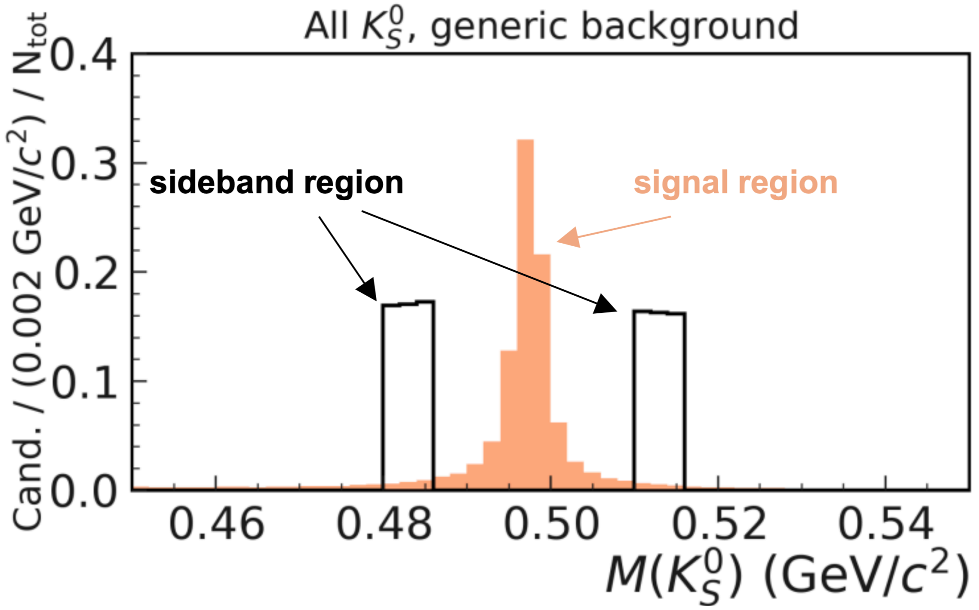


← Purity

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

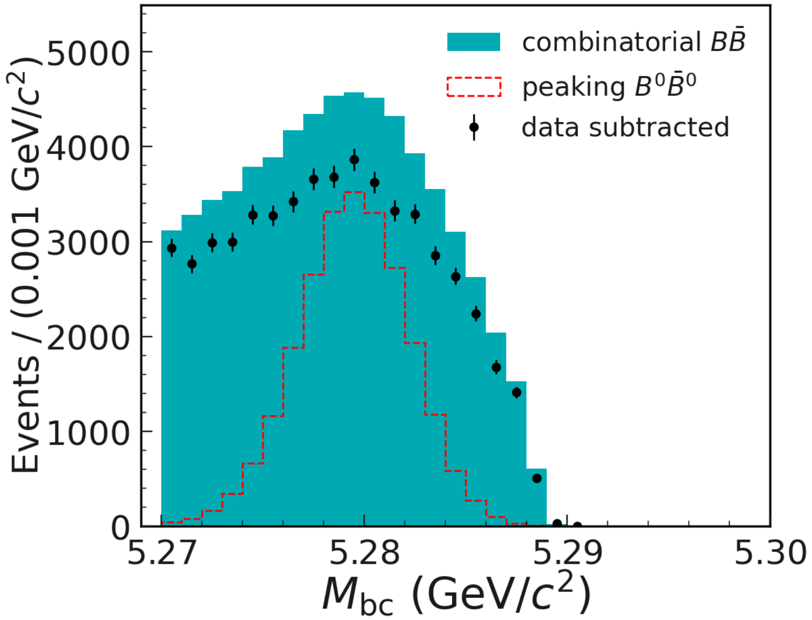
The result is statistically dominated but a careful assessment of the systematic uncertainties is

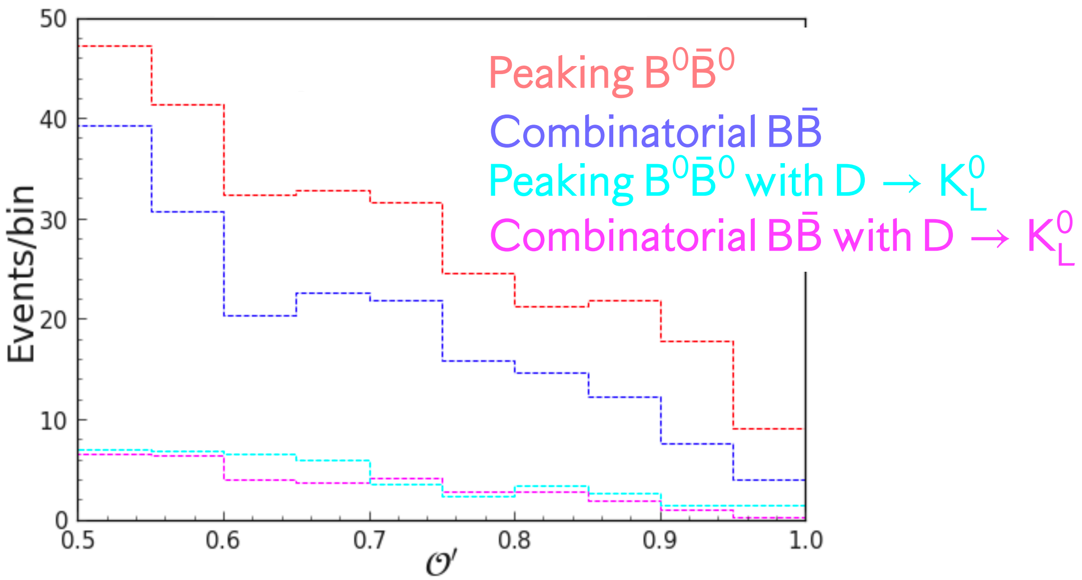
- **background modelling**
  $B\bar{B}$: poorly known B-decays
  $B\bar{B}$, $q\bar{q}$: $D \to K_L^0$ component
  $q\bar{q}$: Normalisation corrections
  $B\bar{B}$: Peaking and non peaking B_{tag}'s



- Other data/MC corrections: lepton ID, π^0, K_S reconstruction

- External inputs: Luminosity, number of $B\bar{B}$ pairs, mixing rate χ_d, neutral B's production





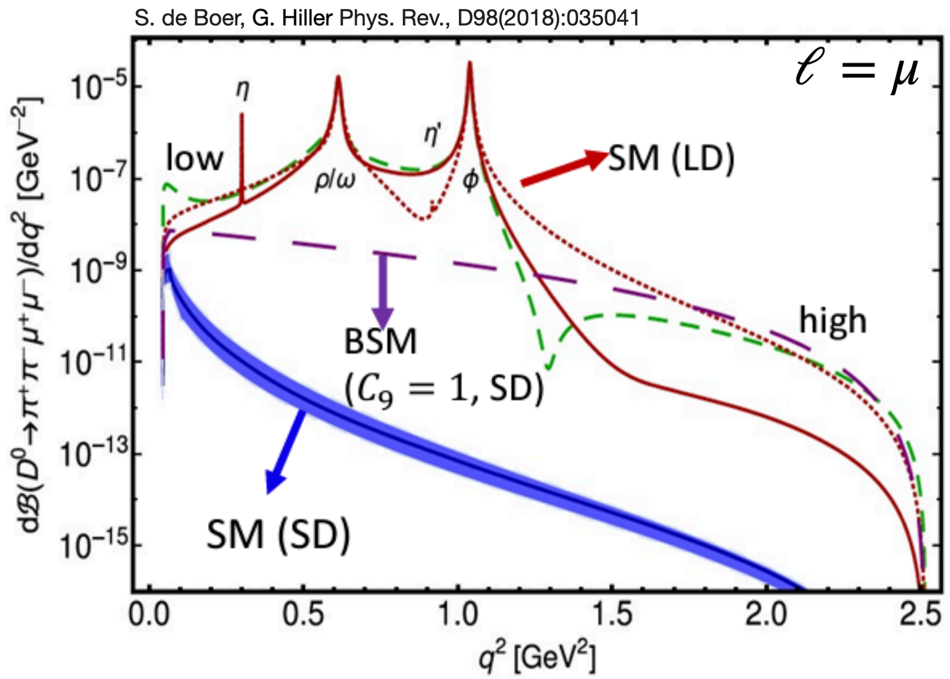
CHARM

NOT ONLY MISSING ENERGY

FCNC $c \to u\ell\ell$ are suppressed processes in the SM

SM long-distance contributions dominate, especially near resonances

BSM contributions maybe visible far from resonances



Current experimental status:

- UL in the non-resonant di-lepton regions
- Some observations in the muon modes and/or at the poles

	Best result	Experiment
$D^+ \to \pi^+e^+e^-$	$<1.1\times10^{-6}$	BaBar (384 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$	$<6.7\times10^{-8}$	LHCb (1.6 fb^{-1})
$D^0 \to K\pi e^+e^-$	$(40.0\pm5.0\pm2.3)\times10^{-7}$ (ρ/ω) $<31\times10^{-7}$ (NR)	BaBar (468 fb^{-1})
$D^0 \to K\pi\mu^+\mu^-$	$(4.17\pm0.12\pm0.40)\times10^{-7}$ (ρ/ω)	LHCb (2 fb^{-1})
$D^0 \to KK\mu^+\mu^-$	$(1.54\pm0.27\pm0.19)\times10^{-7}$	LHCb (2 fb^{-1})
$D^0 \to \pi\pi\mu^+\mu^-$	$(9.64\pm0.48\pm1.10)\times10^{-7}$	LHCb (2 fb^{-1})

Opportunity for Belle II

- + new preliminary results for
  $D^0 \to hh'e^+e^-$ (Belle+Belle II)
  $D^0 \to hhe^+e^-$ (LHCb)

$D^+ \to \pi^+ e^+ e^-$ SEARCH AT BELLE(II)

Challenge

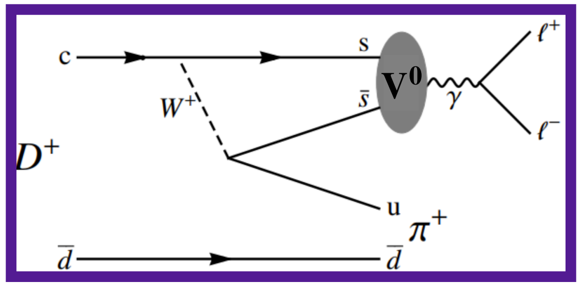
- Very low rates $\mathscr{B}^{SD}_{SM}(D^+ \to X_u^+ e^+ e^-) \simeq 2 \times 10^{-8}$
- Calibration of the *D*-meson production

Strategy

- Simultaneous fit to Belle and Belle II data to $M(\pi^+ e^+ e^-)$ in bins of $M(e^+ e^-)$
- Control channel $D^+ \to \pi^+ \phi(\to e^+ e^-)$ $\mathscr{B}_{SM} = 1.8 \times 10^{-6}$
- Normalisation channel $D^+ \to \pi^+ \phi(\to K^+ K^-)$ (abundant and well known)

$$\frac{Br(D^+ \to \pi^+ e^+ e^-; q^2)}{Br(D^+ \to \pi^+(\phi \to K^+ K^-))} = \frac{N(D^+ \to \pi^+ e^+ e^-; q^2)}{N(D^+ \to \pi^+(\phi \to K^+ K^-))} \frac{\epsilon_{\pi KK}(m^2_\phi)}{\epsilon_{\pi ee}(q^2)} r^{\phi}_{corr}$$

$\mathscr{B} \sim \mathscr{O}(10^{-6})$ (ω, ρ, ϕ)



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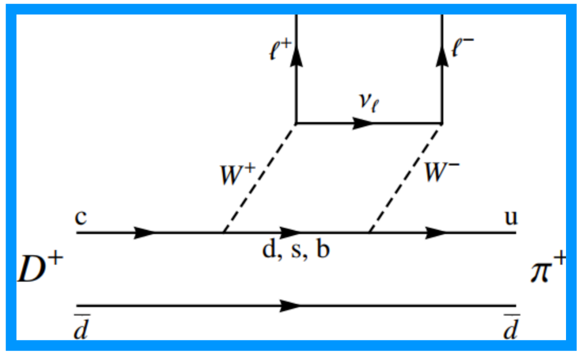

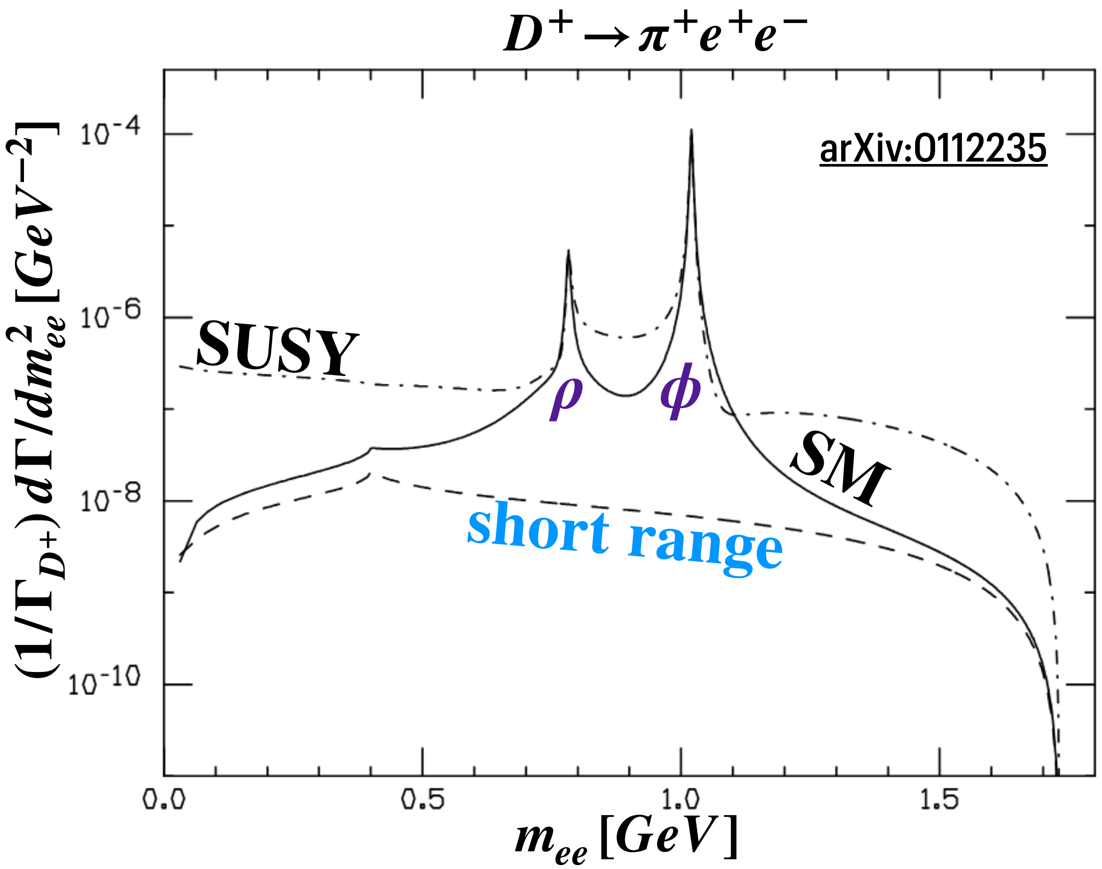

$D^+ \to \pi^+ e^+ e^-$ SEARCH AT BELLE(II)

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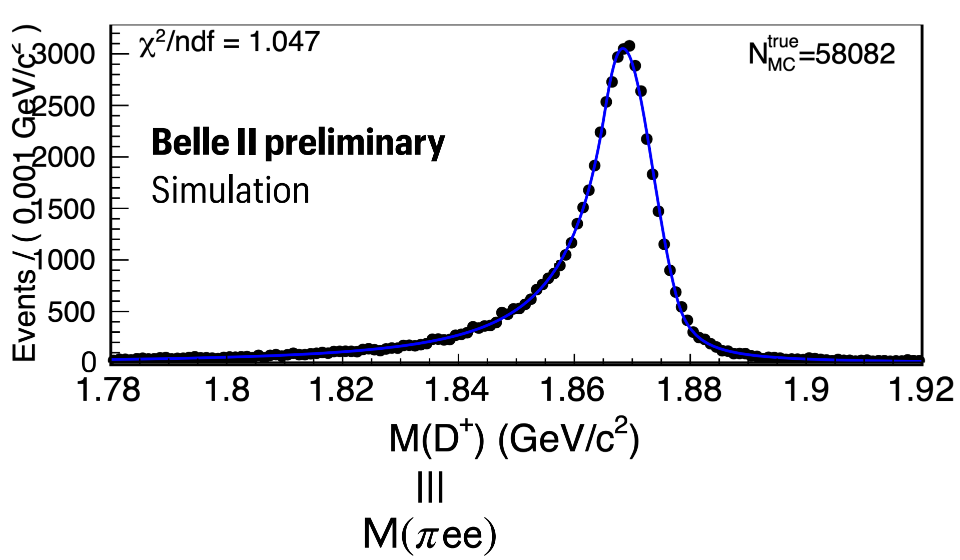
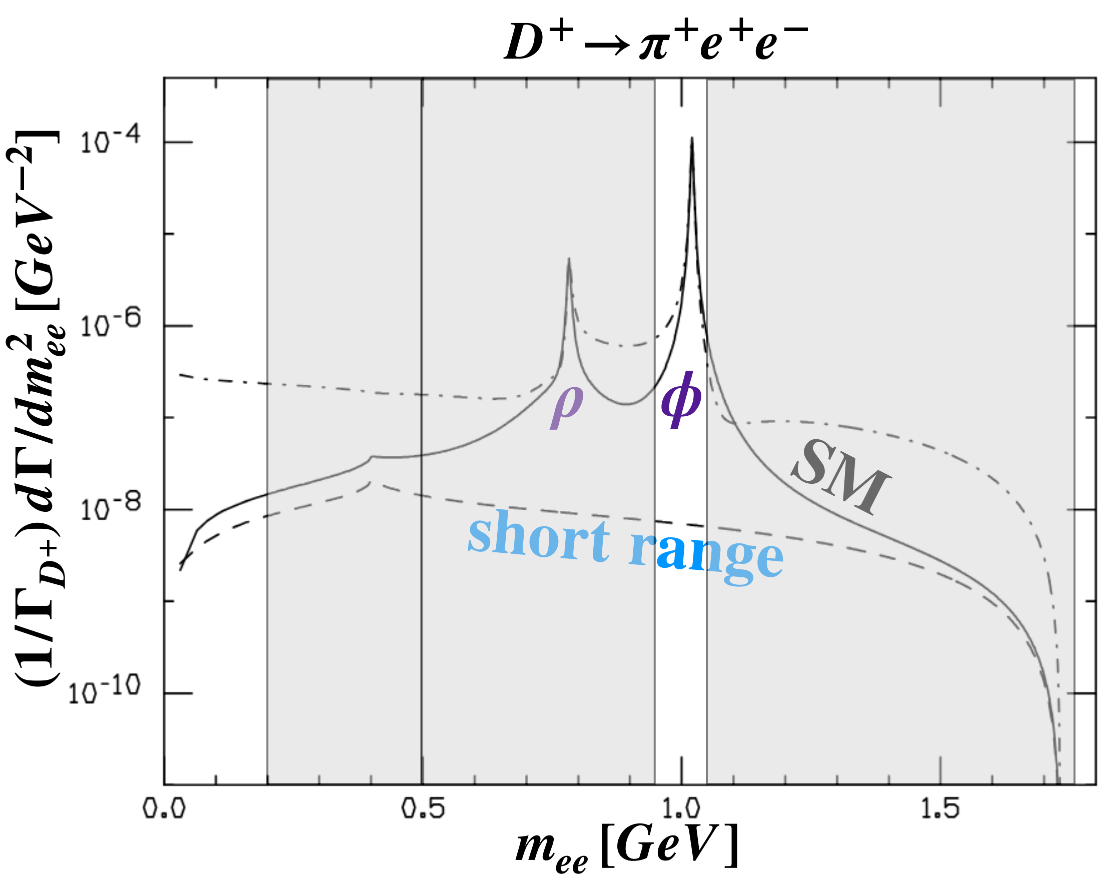


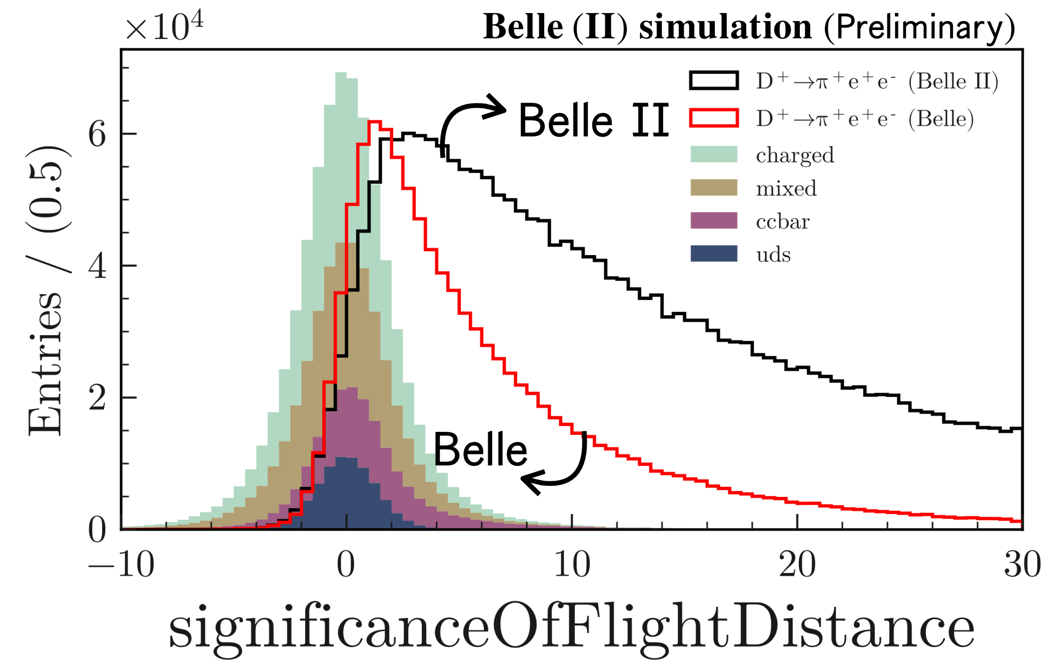


$D^+ \to \pi^+ e^+ e^-$ SEARCH AT BELLE(II)

Random Forest Classifier four the background suppression

Inputs:

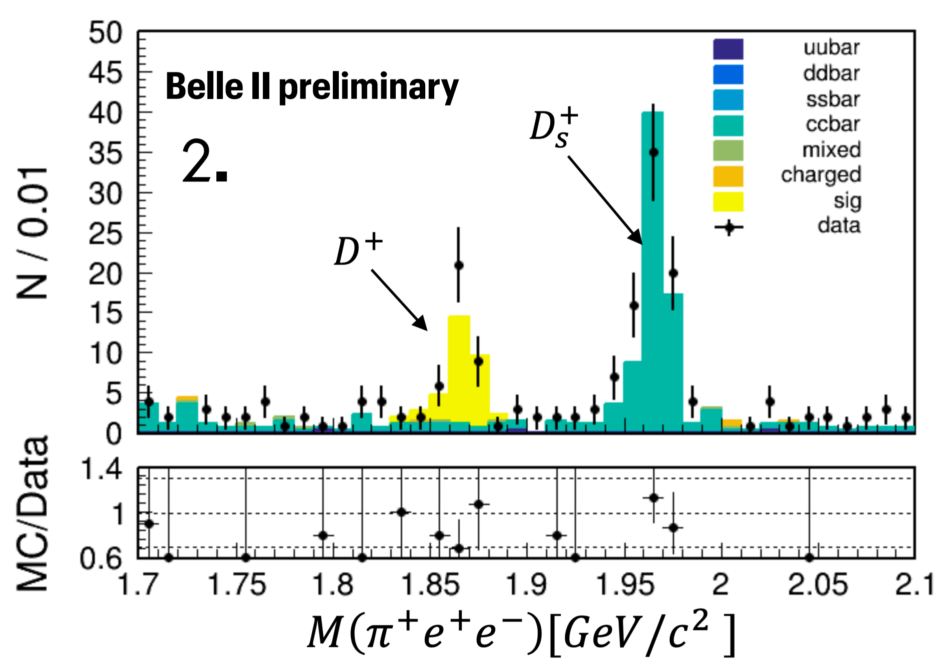
- **Significance of the flight distance**
- Visible energy of the event
- Momentum of D^+
- Cos of the angle between the momentum and the vertex vector of D^+

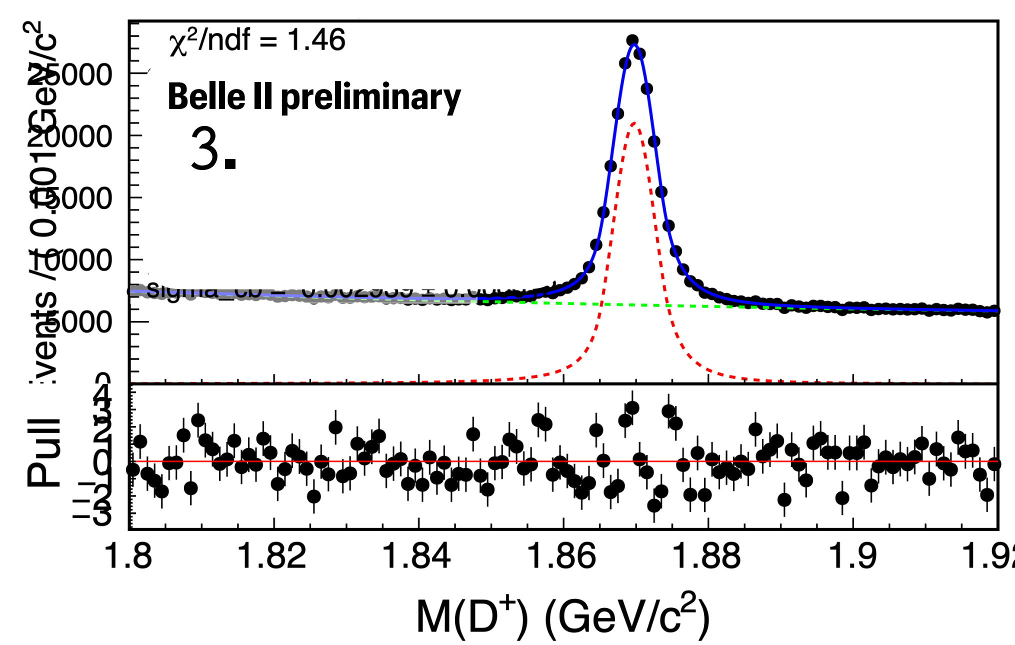


Better vertexing at Belle II

Checklist

1. Fit is unbiased ✅
2. Control channel consistent with PDG ✅
3. RFC calibrated in the normalisation channel ✅





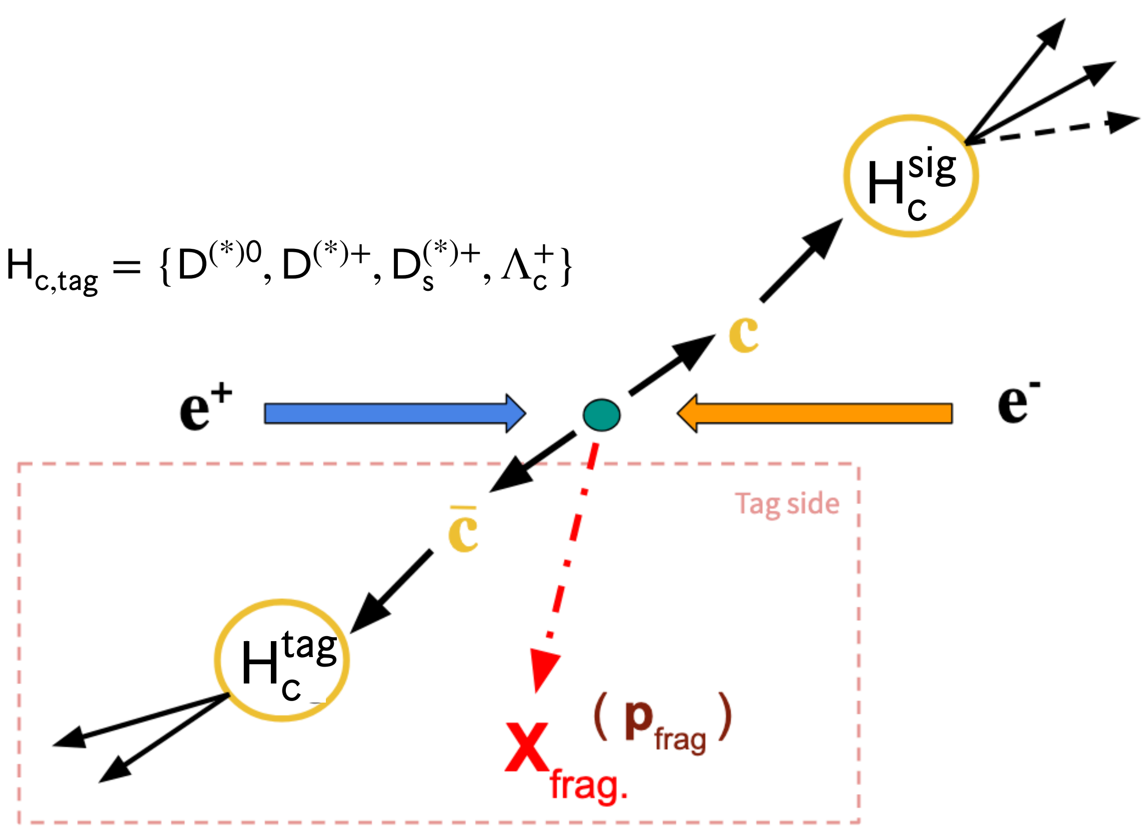
MISSING ENERGY IN CHARM DECAYS

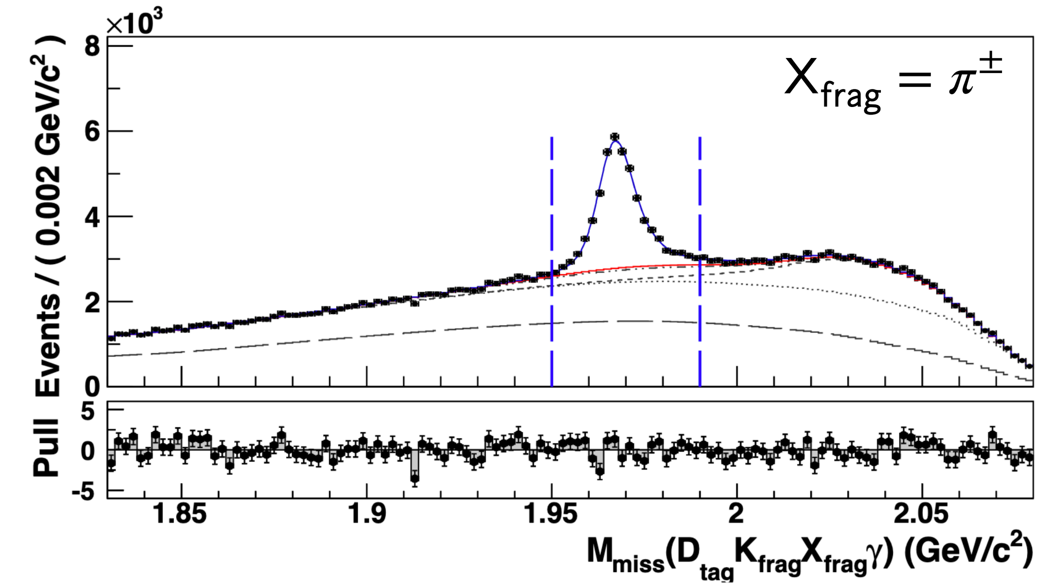
FCNC $c \to u\nu\bar{\nu}$ are also interesting tests of SM and probes of charged lepton flavor violation PRD 103 (2021) 1, 015033 EPJC 82 (2022) 2, 164

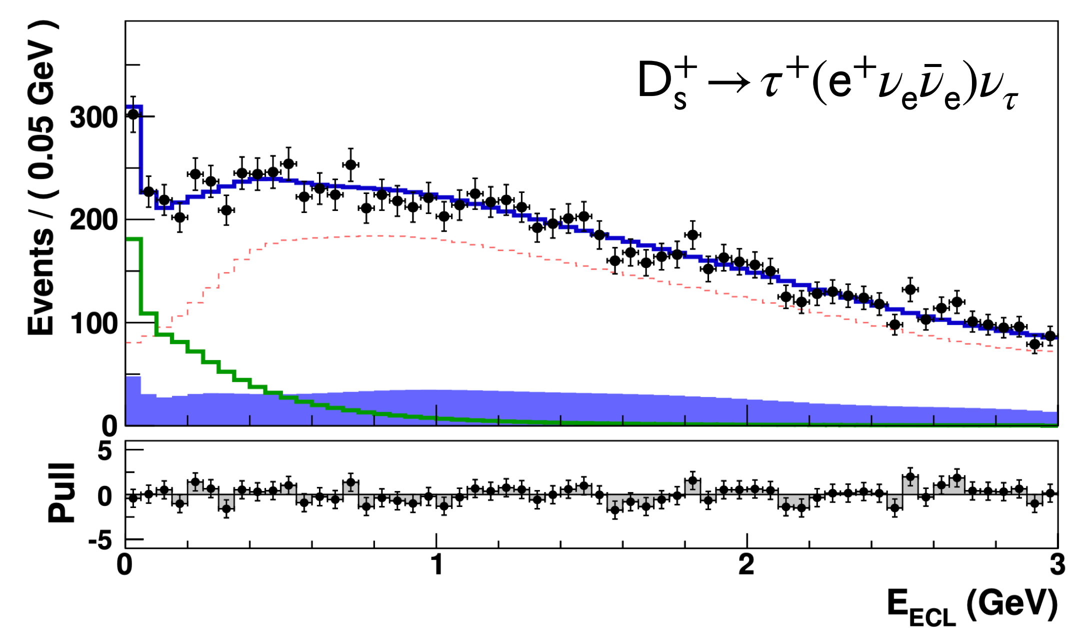
Negligible SM contribution → any signal would be a clear sign of NP

How to detect charm decays with missing energy?

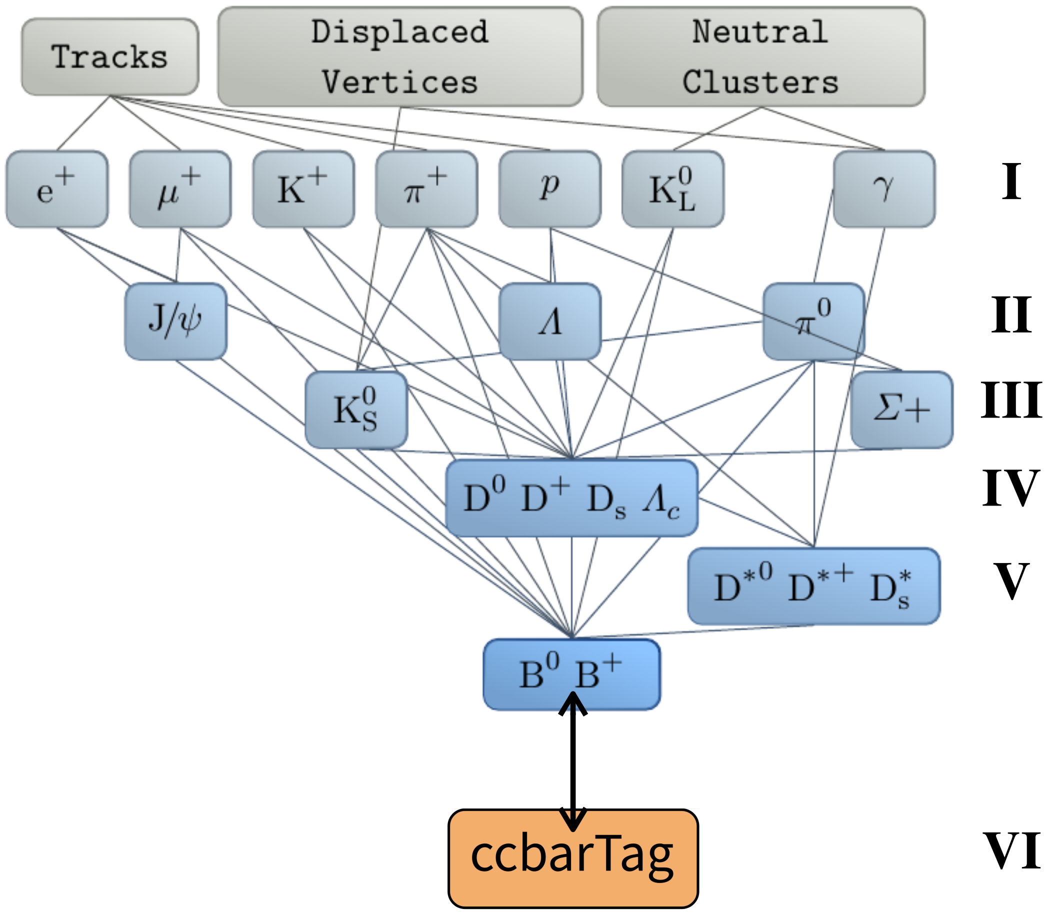
Approach already explored in Ljubljana for $D_s^+ \to \ell^+\nu$ decays: charm tagging JHEP09(2013)139







$c\bar{c}$-TAGGING: SETUP



Adapt the Belle II B-tagging algorithm [1] to charm to replace the cut-based approach with a BDT based one

- Each particle represents a BDT trained on charm events
- The final tag composition (X_{frag}) depend on the target H_c^{sig}
- The quality of the tag is represented by a score $\in[0,1]$

Default

$D^{(*)0}\, p$

$D^{(*)+}\, p\, \pi^-$

$D_s^{(*)+}\, p\, K^-$

+neutrals

$D^{(*)0}\, p\, \pi^0$

$D^{(*)+}\, p\, \pi^-\, \pi^0$

$D_s^{(*)+}\, p\, K^-\, \pi^0$

+charged

$D^{(*)0}\, p\, \pi^+\pi^-$

$D^{(*)+}\, p\, \pi^-\, \pi^+\pi^-$

$D_s^{(*)+}\, p\, K^-\, \pi^+\pi^-$

$D^{(*)0}\, p\, K^+K^-$

$D^{(*)+}\, p\, \pi^-\, K^+K^-$

$D^{(*)0}\, p\, p\, \bar{p}$

+strange

$D^{(*)0}\, \Lambda^0 K^+$

$D^{(*)+}\, \Lambda^0 K^0_S$

$D_s^{(*)+} \Lambda^0$

$D^{*+}\, p\, K^0_S\, K^-$

$D_s^{(*)+}\, p\, K^0_S\, \pi^-$

$D^{(*)+} \Lambda^0 K^+ \pi^-$

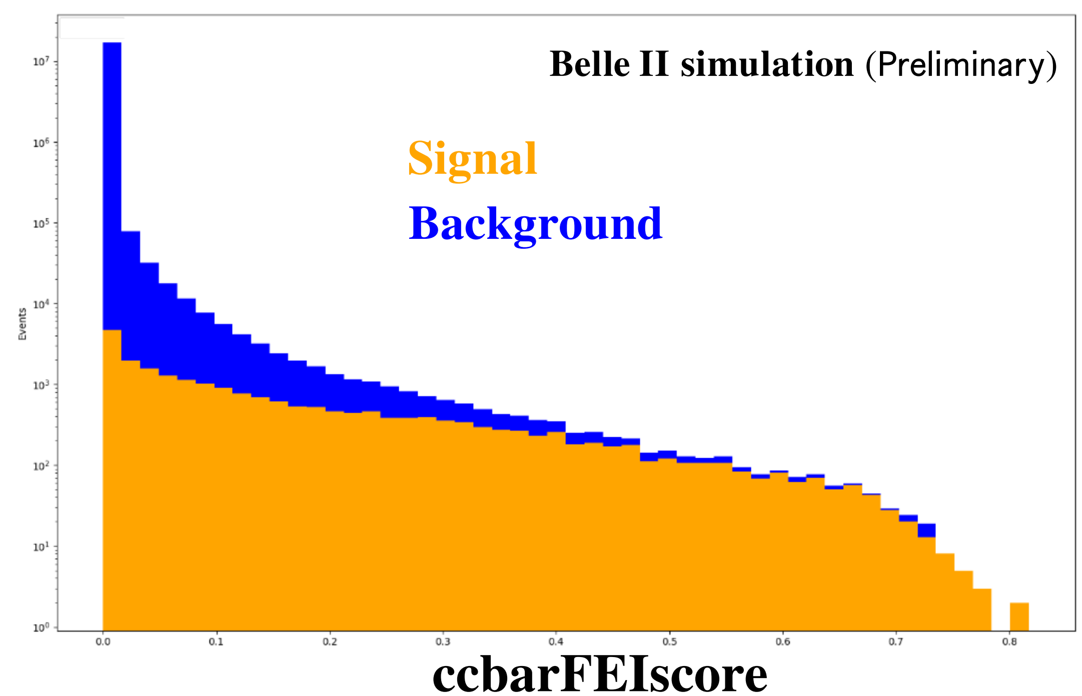
$D^0 \Lambda^0 K^+ \pi^0$

$D^{(*)0} \Lambda^0 K^+ \pi^+ \pi^-$

$D_s^{(*)+} \Lambda^0 \pi^+ \pi^-$

$D^0 \Lambda^0 K^+ \pi^+ \pi^- \pi^0$

$D_s^{(*)+} \Lambda^0 \pi^+ \pi^- \pi^0$

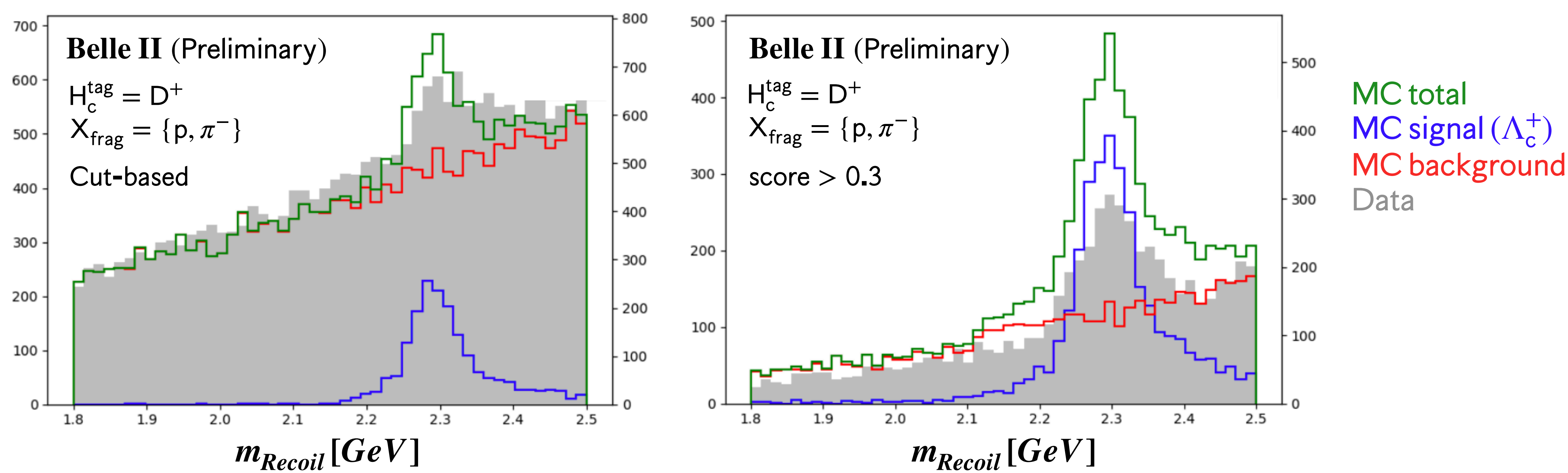


[1] Comput Softw Big Sci 3, 6 (2019)

$c\bar{c}$-TAGGING: TODO

- Calibrate the tagging properties on data
- Compare the performance of the BDT-based method with the cut-based one
- Compare the performance at step V vs. step VI
- Different trainings for Belle and Belle II (different simulation of charm events)
- Measure the impact of ccbarFEI in the context of some branching fraction measurement

- **Make the tool available for the Belle II collaboration to enable/boost many possible searches**
  $D^0 \to inv, \Lambda_c^+ \to \Lambda^0 \ell^+ \nu, ...$

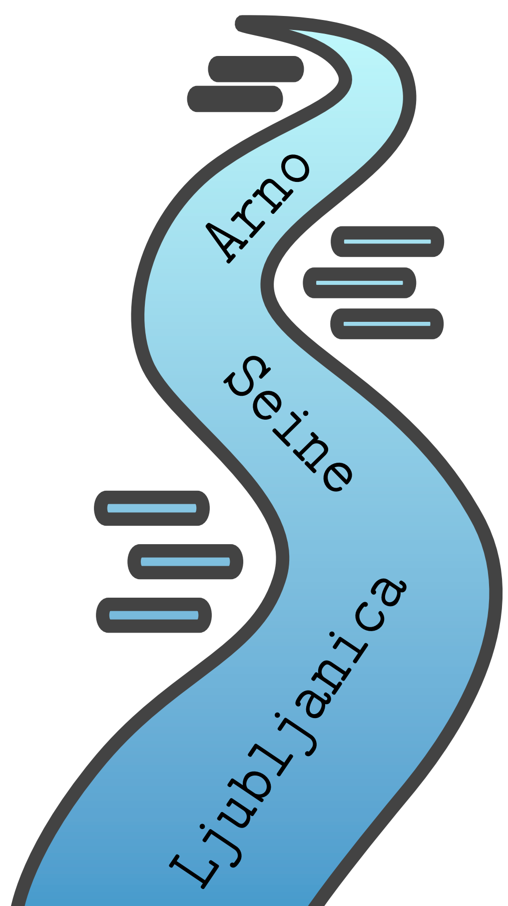


Promising: higher signal efficiency and higher purity

CONCLUSION

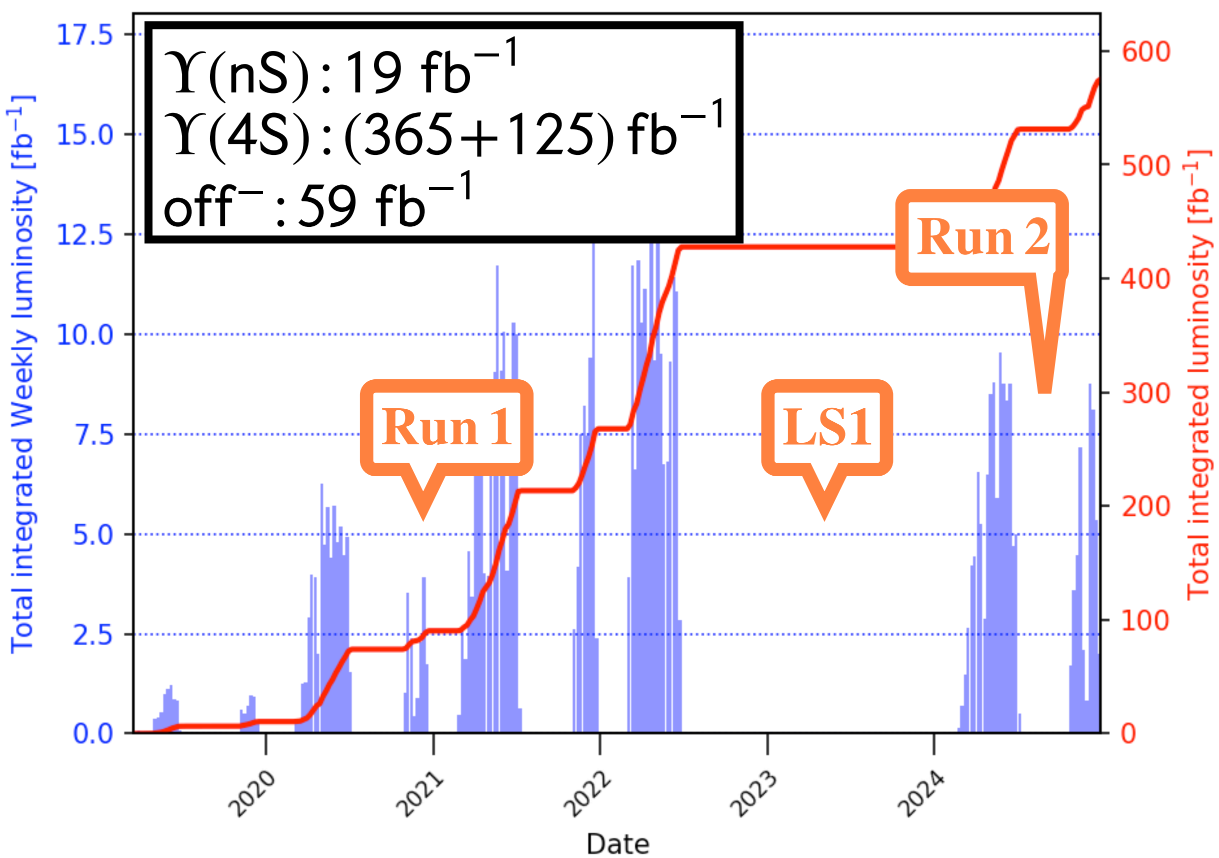
- $B \to K^{(*)} \nu \bar{\nu}$
  Working on providing clarifications on the 2023 evidence
- $B^0 \to K_S^0 \tau^+ \tau^-$
  First search ever to complement other $b \to s\tau\bar{\tau}$ efforts
- $D^+ \to \pi^+ e^+ e^-$
  First search at Belle (II)
- $c\bar{c}$FEI
  New tool for charm decays with missing energy

Thank you for your attention!

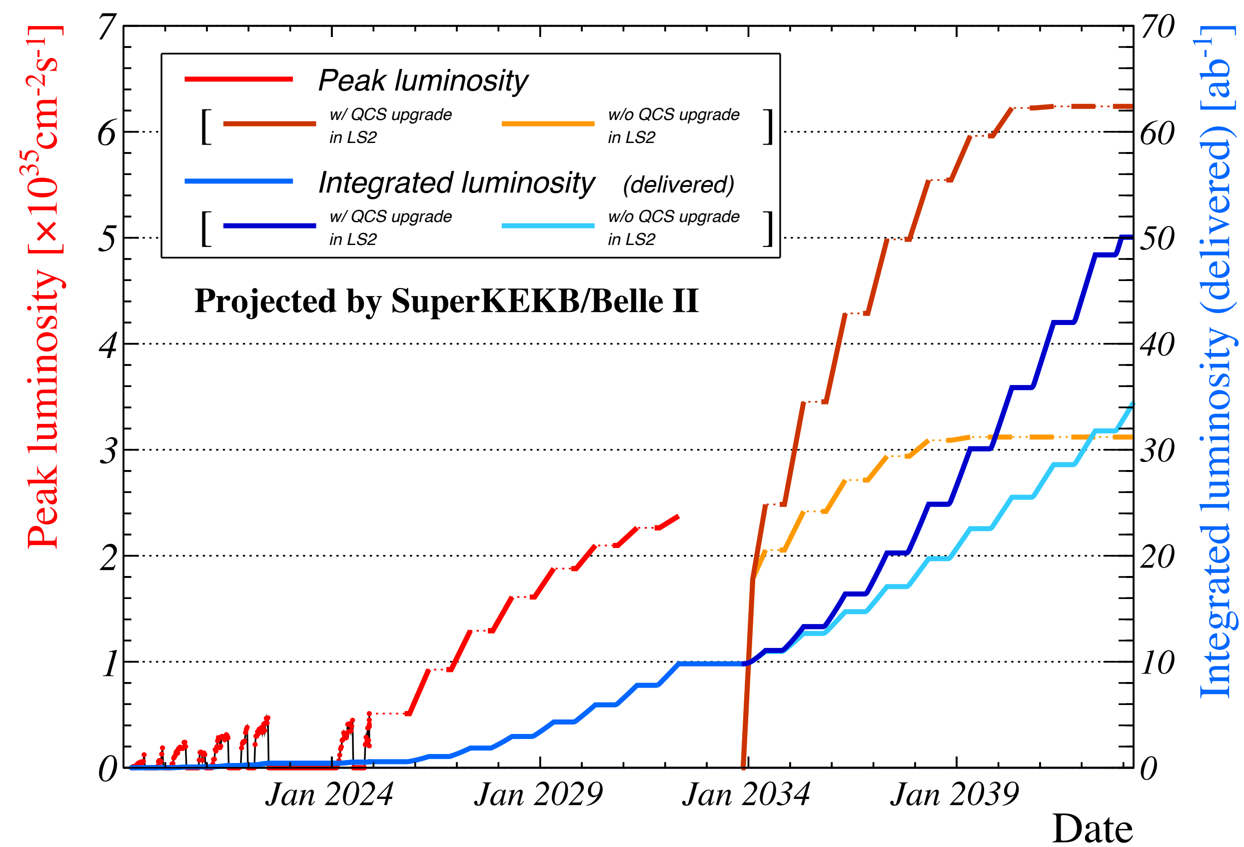


ADDITIONAL MATERIAL

LUMINOSITY INTEGRATED + PROJECTION

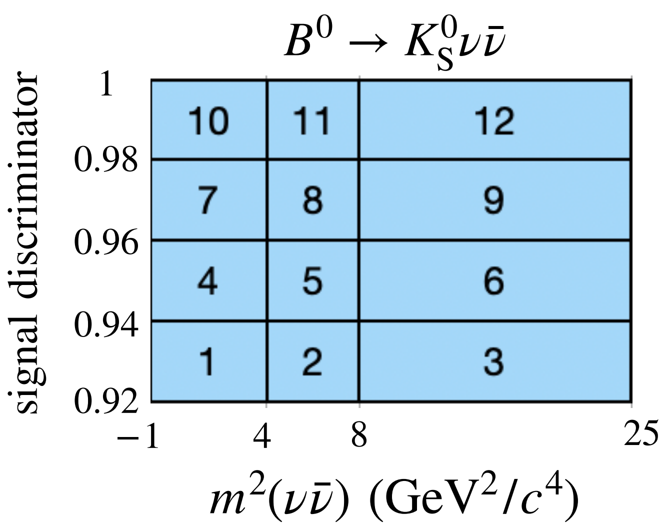


https://www.belle2.org/research/luminosity/



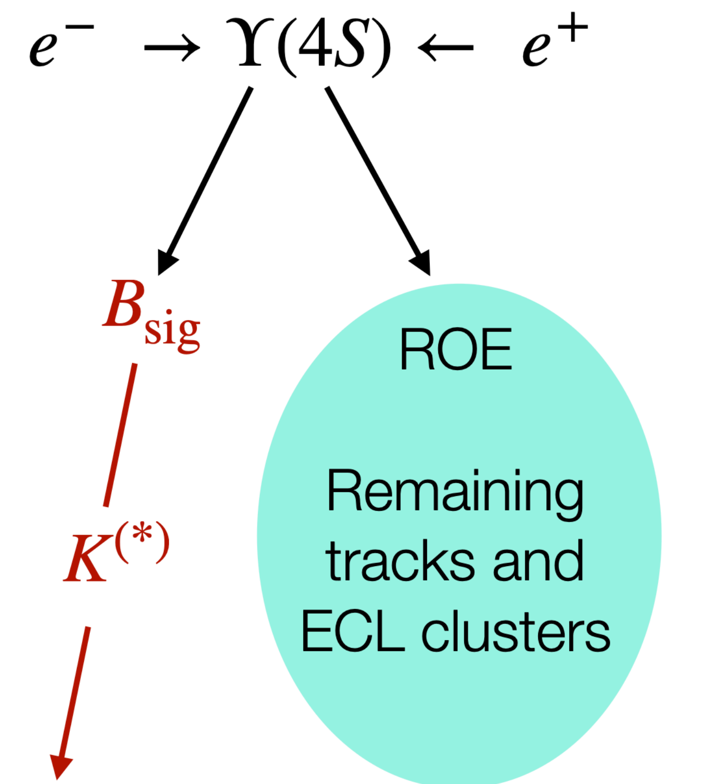
$B^+ \to K^+\nu\bar{\nu}$ SPECIFICS

Combined fit of four channels using PYHF framework in bins of squared di-neutrino invariant mass and classifier output



- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with priors following normal distribution
- Simulation statistical uncertainties are included as nuisance parameters, per each bin and each fit category

Inclusive tag



High efficiency, low purity

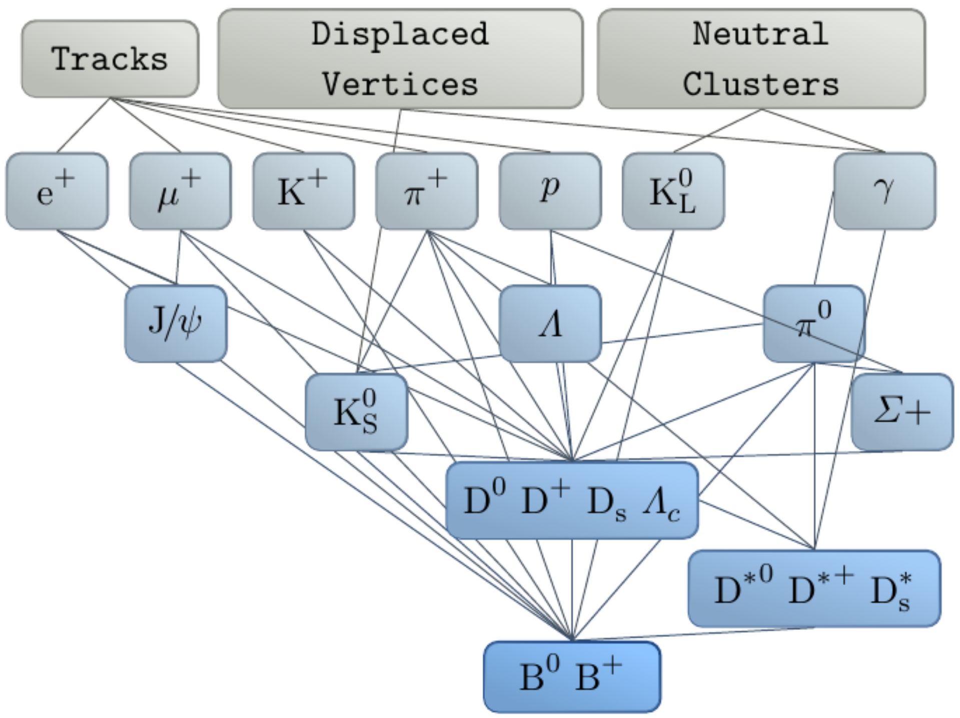
CCBAR TAGGING

D^0 modes	$\mathcal{B}$ [%]
$K^-\pi^+$	3.9
$K^-\pi^+\pi^0$	13.9
$K^-\pi^+\pi^+\pi^-$	8.1
$K^-\pi^+\pi^+\pi^-\pi^0$	4.2
$K_S^0\pi^+\pi^-$	2.9
$K_S^0\pi^+\pi^-\pi^0$	5.4
Sum	38.4

D^+ modes	$\mathcal{B}$ [%]
$K^-\pi^+\pi^+$	9.4
$K^-\pi^+\pi^+\pi^0$	6.1
$K_S^0\pi^+$	1.5
$K_S^0\pi^+\pi^0$	6.9
$K_S^0\pi^+\pi^+\pi^-$	3.1
$K^+K^-\pi^+$	1.0
Sum	28.0

Λ_c^+ modes	$\mathcal{B}$ [%]
$pK^-\pi^+$	5.0
$pK^-\pi^+\pi^0$	3.4
pK_S^0	1.1
$\Lambda\pi^+$	1.1
$\Lambda\pi^+\pi^0$	3.6
$\Lambda\pi^+\pi^+\pi^-$	2.6
Sum	16.8

EXCLUSIVE B-TAGGING AT BELLE II



Full **E**vent **I**nterpretation (**FEI**)

FEI is the algorithm for HAD B_{tag} reconstruction at Belle II [1]

- Mostly $B \to D^{(*)} m\pi^{\pm} n\pi^0$
- ~2x higher efficiency wrt previous algorithms [2]
- Employs BDTs trained on MC $\Upsilon(4S) \to B\bar{B}$ events
- $\mathscr{P}_{FEI}$ used to select best B_{tag}

Main challenges

1. Large data/MC efficiency discrepancies
→ **Improve the modelling of B-decays**

2. Hadronic B-tagging: pure but very low efficiency
→ Add more decay modes
→ New algorithms: Graph Neural Network FEI ACAT2022

[1] Comput Softw Big Sci 3, 6 (2019) [2] NIMA 654 (2011) 432-440

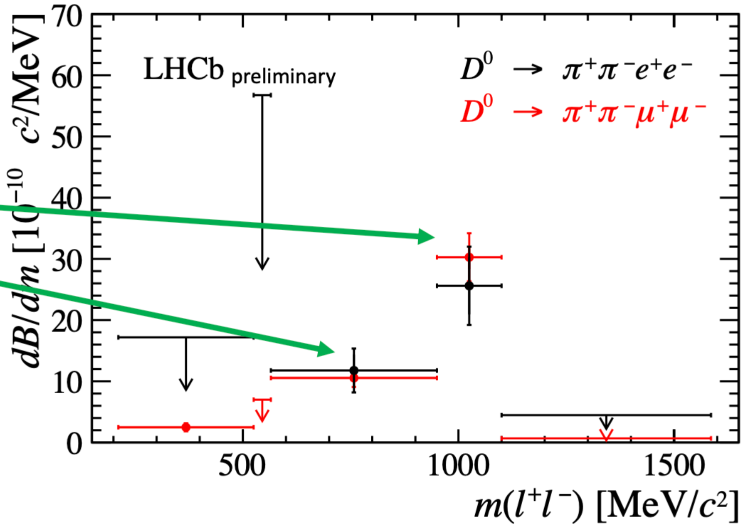
LHCB

Comparison with muon modes

$$\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu}) = (13.3 \pm 1.7 \pm 1.7 \pm 1.8) \times 10^{-7}$$

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

- Integrating over the dielectron mass ranges $D^0 \to \pi^+\pi^-e^+e^-$: compatible within 1.3σ with muon mode
- Similarly in in ρ/ω and φ dilepton mass regions confirming lepton flavour universality at the current level of precision

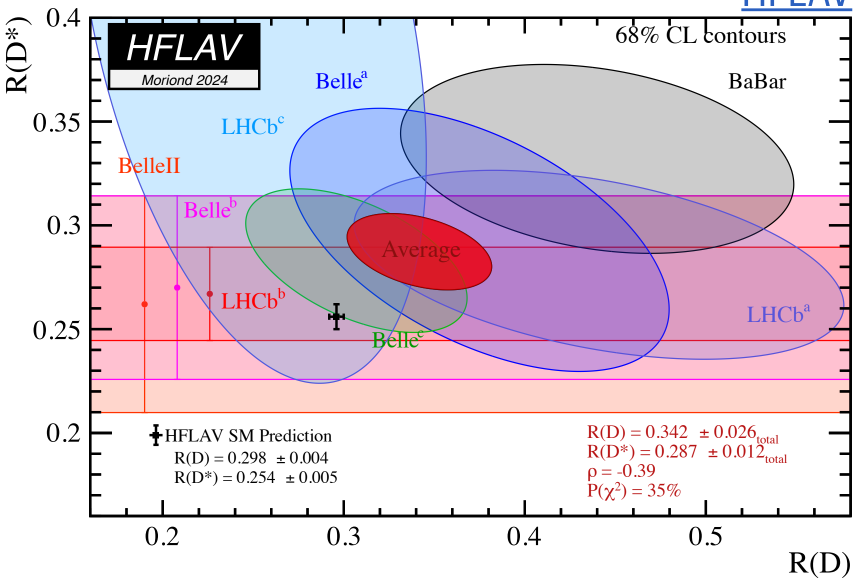


arXiv:2412.09414

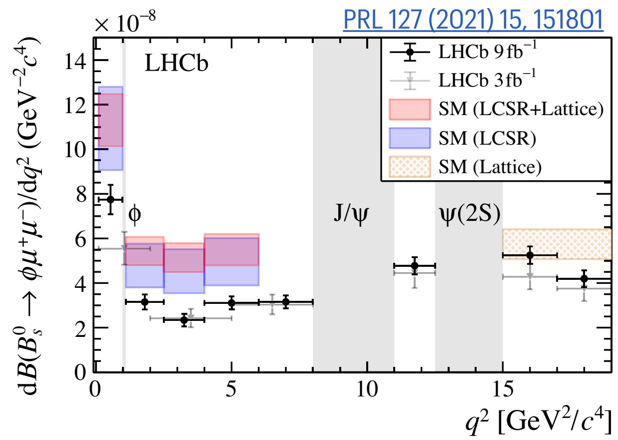
ANOMALIES

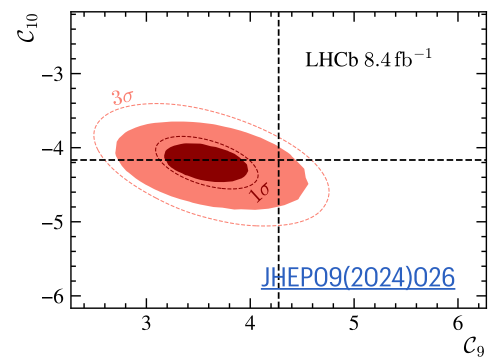
- B-anomalies. Joint explanation?

HFLAV



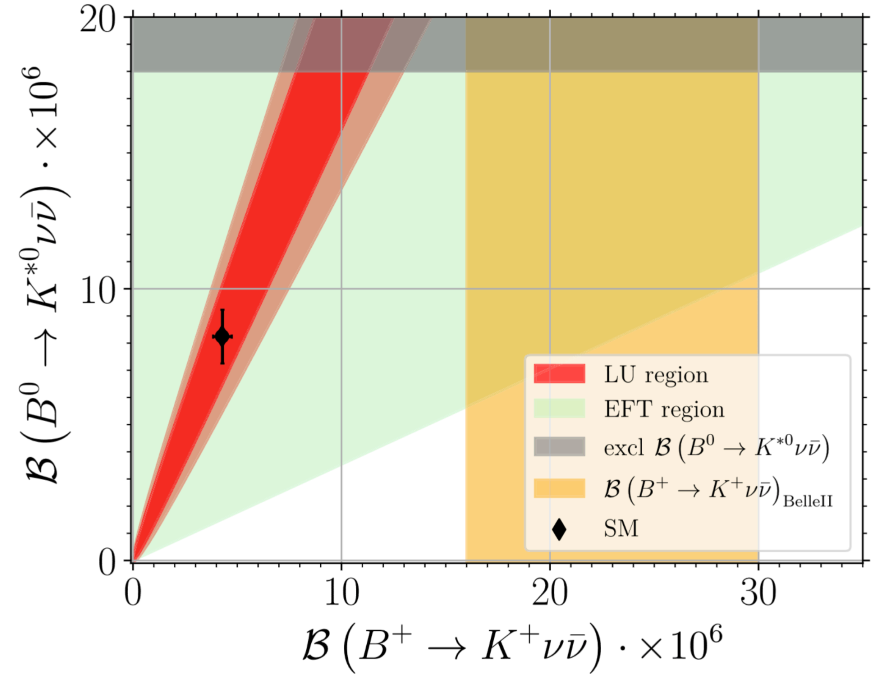
PRL 127 (2021) 15, 151801



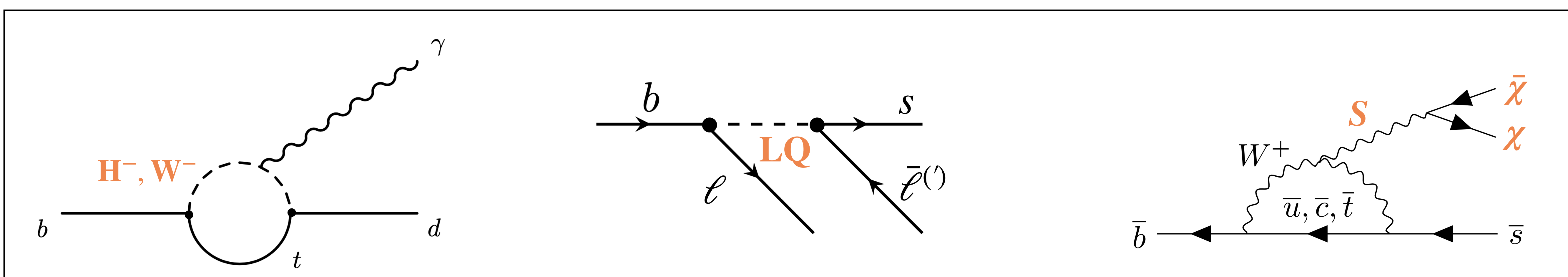


JHEP09(2024)026

PRD 109, 015006 (2024)



- Electroweak and radiative B-meson penguin decays are probes of SM and unique portals to New Physics

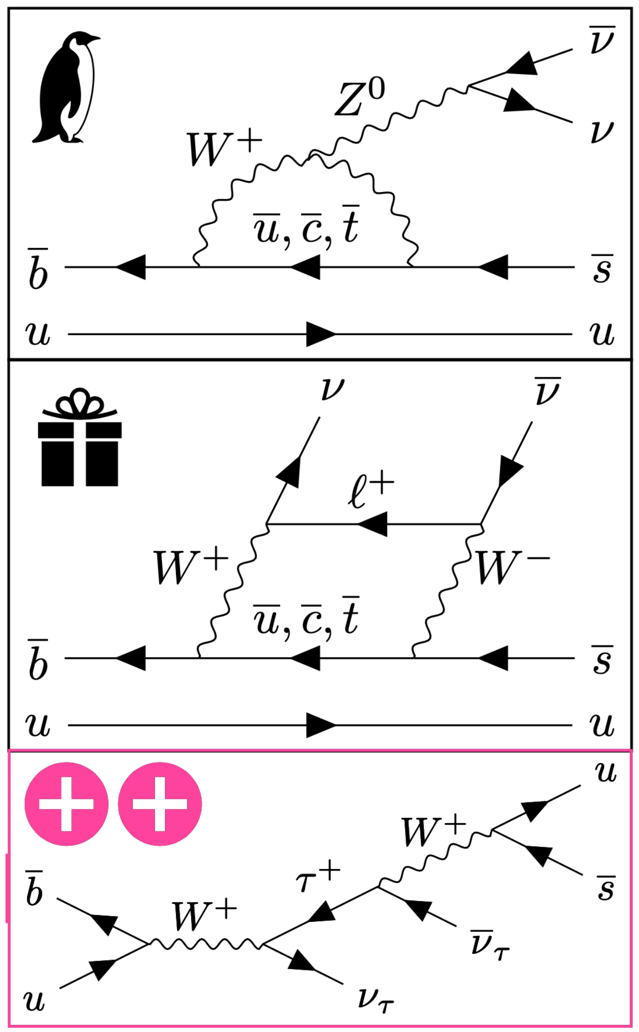


$c \to u\ell^+\ell^-$

https://arxiv.org/pdf/hep-ph/0112235

Decay Mode	Experimental Limit	$\mathcal{B}r_{S.D.}$	$\mathcal{B}r_{L.D.}$
$D^+ \to X_u^+ e^+ e^-$		2×10^{-8}	
$D^+ \to \pi^+ e^+ e^-$	$< 4.5 \times 10^{-5}$		2×10^{-6}
$D^+ \to \pi^+ \mu^+ \mu^-$	$< 1.5 \times 10^{-5}$		1.9×10^{-6}
$D^+ \to \rho^+ e^+ e^-$	$< 1.0 \times 10^{-4}$		4.5×10^{-6}
$D^0 \to X_u^0 e^+ e^-$		0.8×10^{-8}	
$D^0 \to \pi^0 e^+ e^-$	$< 6.6 \times 10^{-5}$		0.8×10^{-6}
$D^0 \to \rho^0 e^+ e^-$	$< 5.8 \times 10^{-4}$		1.8×10^{-6}
$D^0 \to \rho^0 \mu^+ \mu^-$	$< 2.3 \times 10^{-4}$		1.8×10^{-6}
$D^+ \to X_u^+ \nu\bar{\nu}$		1.2×10^{-15}	
$D^+ \to \pi^+ \nu\bar{\nu}$			5×10^{-16}
$D^0 \to \bar{K}^0 \nu\bar{\nu}$			2.4×10^{-16}
$D_s \to \pi^+ \nu\bar{\nu}$			8×10^{-15}
$D^0 \to \gamma\gamma$		3×10^{-11}	few $\times 10^{-8}$
$D^0 \to \mu^+ \mu^-$	$< 3.3 \times 10^{-6}$	10^{-18}	few $\times 10^{-13}$
$D^0 \to e^+ e^-$	$< 1.3 \times 10^{-5}$	$(2.3 - 4.7) \times 10^{-24}$	
$D^0 \to \mu^\pm e^\mp$	$< 8.1 \times 10^{-6}$	0	0
$D^+ \to \pi^+ \mu^\pm e^\mp$	$< 3.4 \times 10^{-5}$	0	0
$D^0 \to \rho^0 \mu^\pm e^\mp$	$< 4.9 \times 10^{-5}$	0	0

$B \to K^{(*)}\nu\bar{\nu}$ SM PREDITICTIONS



[EPJC 83 (2023) 3, 252] **Newest prediction**

Decay	SM total	LD contribution	SD contribution
$B^+ \to K^+\nu\bar{\nu}$	5.22 ± 0.32	0.63 ± 0.06	4.59 ± 0.32
$B^0 \to K^0_S\nu\bar{\nu}$	2.12 ± 0.15	—	2.12 ± 0.15
$B^+ \to K^{*+}\nu\bar{\nu}$	11.27 ± 1.51	1.07 ± 0.10	10.20 ± 1.51
$B^0 \to K^{*0}\nu\bar{\nu}$	9.47 ± 1.40	—	9.47 ± 1.40

$\times 10^{-6}$

SEARCH FOR $c \to u\nu\bar{\nu}$

https://arxiv.org/pdf/2010.02225

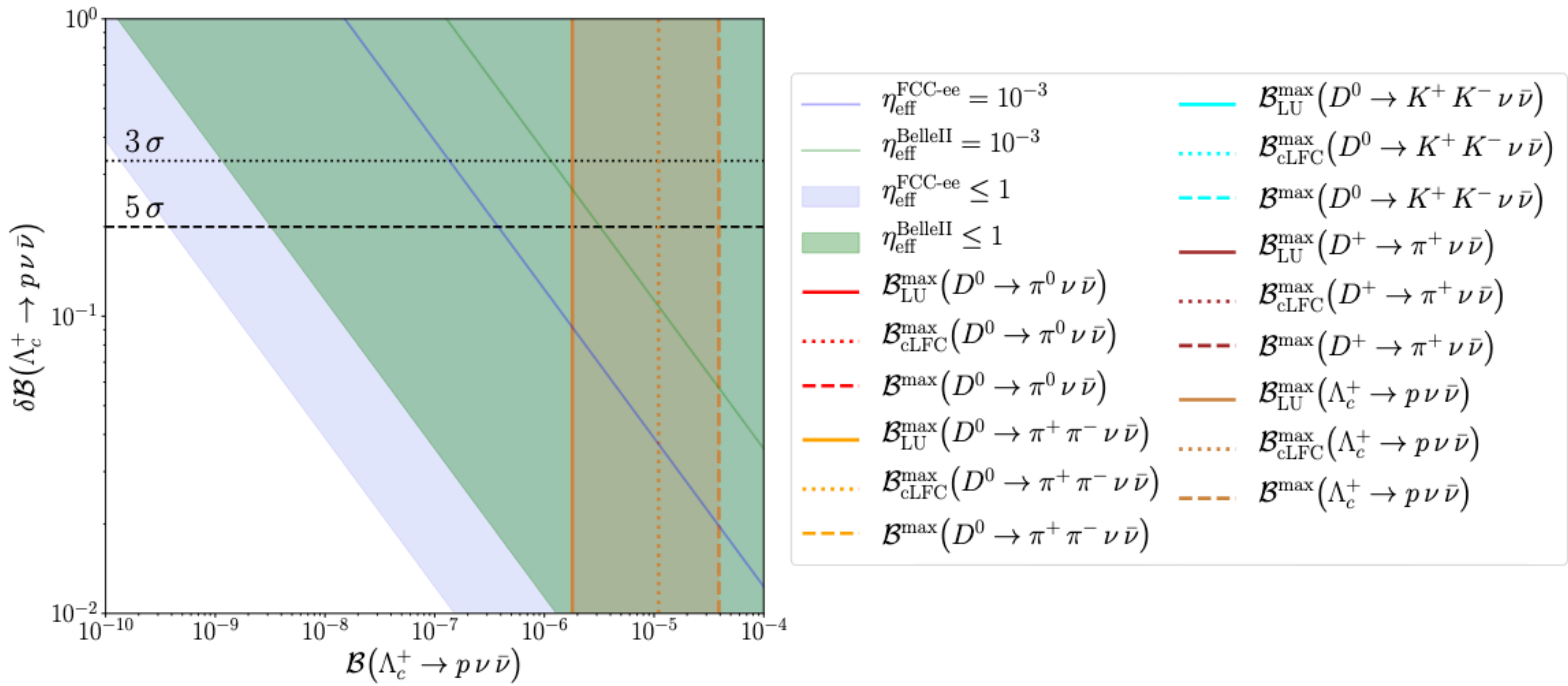


FIG. 1: Relative statistical uncertainty of the branching ratio $\delta\mathcal{B}$ versus the branching ratio $\mathcal{B}$ for decays of the D^0 (upper plot to the left), the D^+ (upper plot to the right) and the Λ_c^+ (lower plot to the left). The shaded areas correspond to the reach for $\eta_{\rm eff} = 1$, whereas the solid tilted lines illustrate the impact of reconstruction efficiencies $\eta_{\rm eff} = 10^{-3}$ for the FCC-ee (lilac) and Belle II (green). Horizontal $3\,\sigma$ (dotted) and $5\,\sigma$ (dashed) black lines correspond to $\delta\mathcal{B} = 1/3$ and $\delta\mathcal{B} = 1/5$, respectively. Vertical lines represent upper limits assuming LU (solid), cLFC (dotted) and generic lepton flavor (dashed) for different modes, given in TABLE III. To improve readability the three lines for each decay mode are grouped together by a shaded band. Upper limits for $D_s^+ \to K^+\,\nu\bar{\nu}$, $\Xi_c^+ \to \Sigma^+\,\nu\bar{\nu}$ and the inclusive modes can be seen in TABLE III.