Rare Beauty and Charm Decays with Missing Energy

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RA2 kick-off Meeting

23.10.2025

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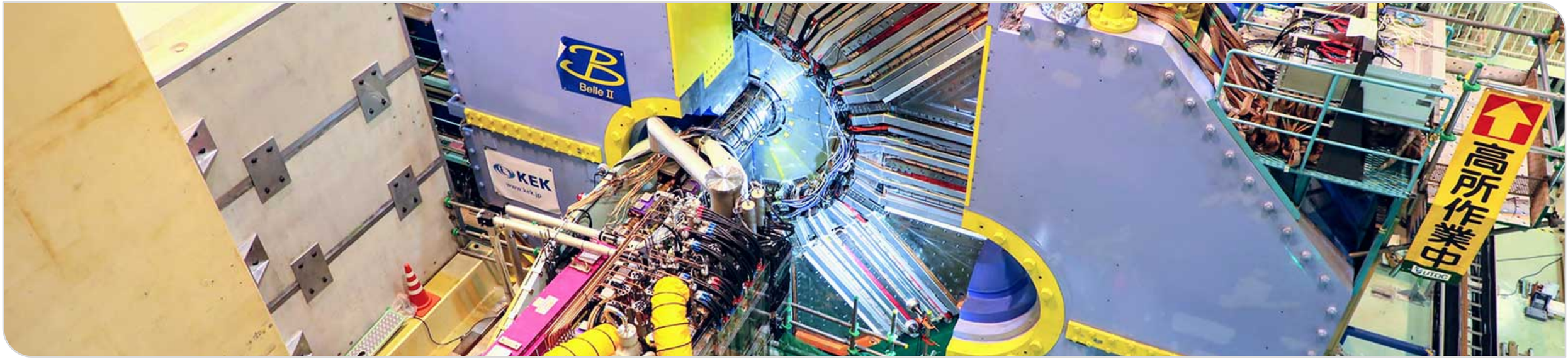


Rare *B*-decays

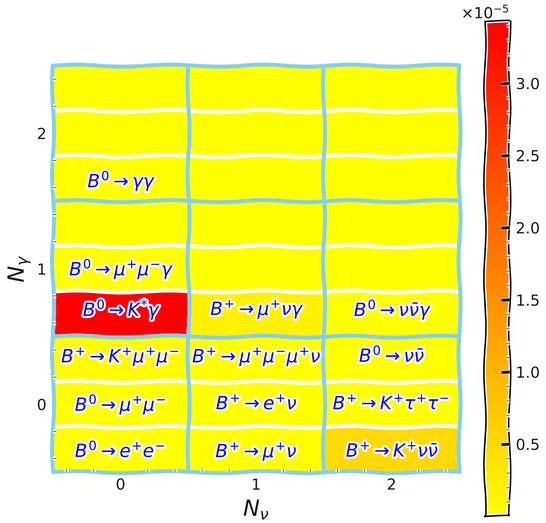
Rare B decays:

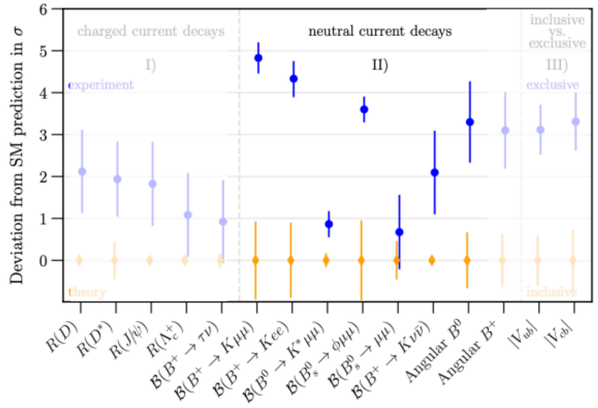
- GIM suppressed flavour changing neutral currents (FCNC)

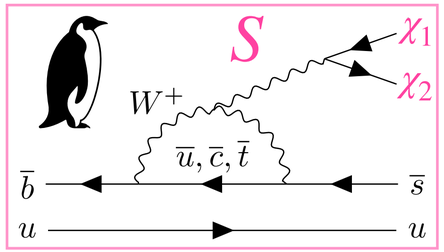
  → $b \to s/d(\gamma)$

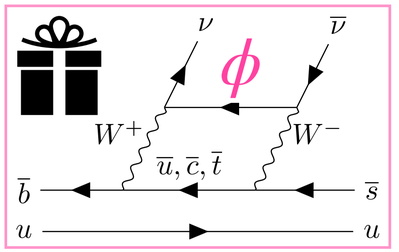
  - forbidden at tree level, allowed at loop level
  - electroweak decays, radiative electroweak decays
  - m_ν^2/M_W^2 suppressed lepton flavour violating decays
- Helicity suppressed purely leptonic decays

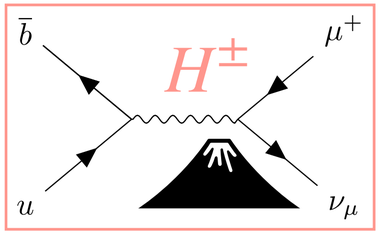
Very sensitive to NP since SM contribution small!

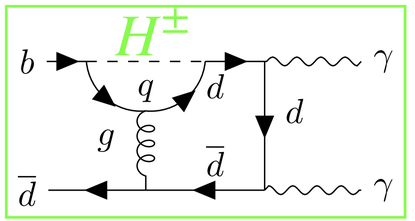


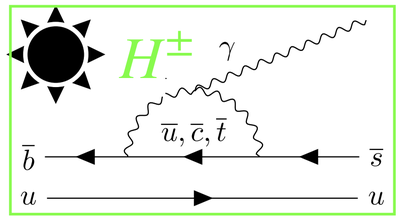


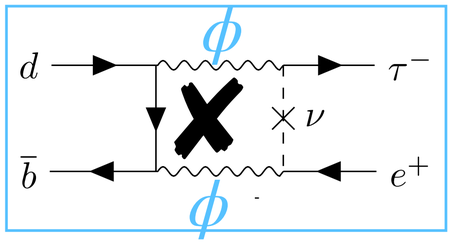








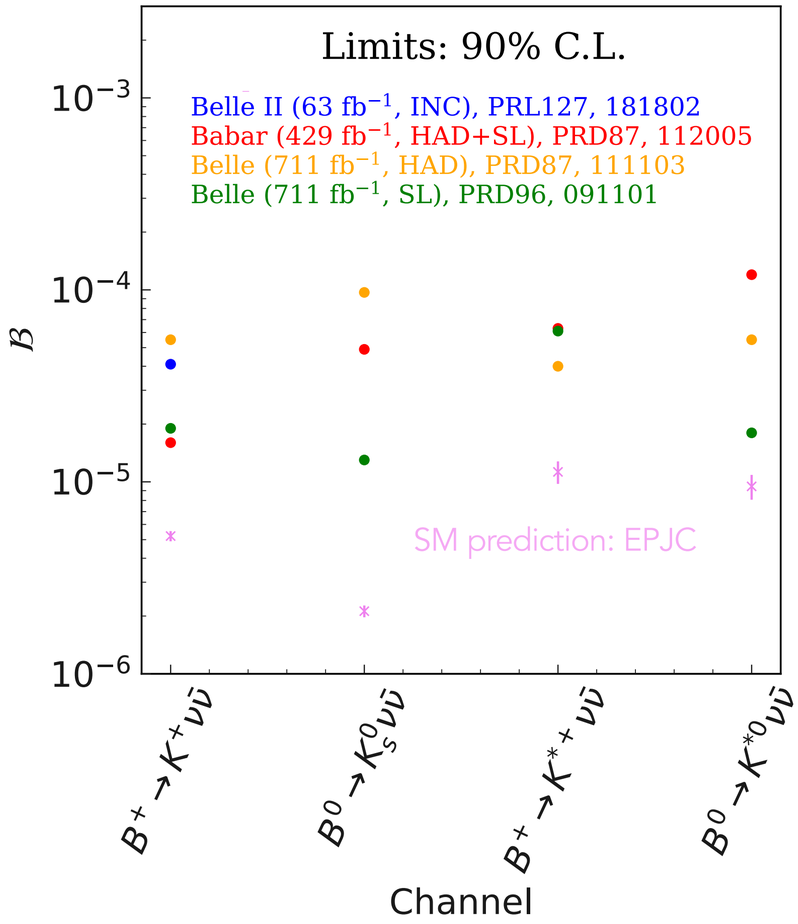




$B \to K^{(*)}\nu\bar{\nu}$ Measurement Overview

Rare B decay with significant missing energy

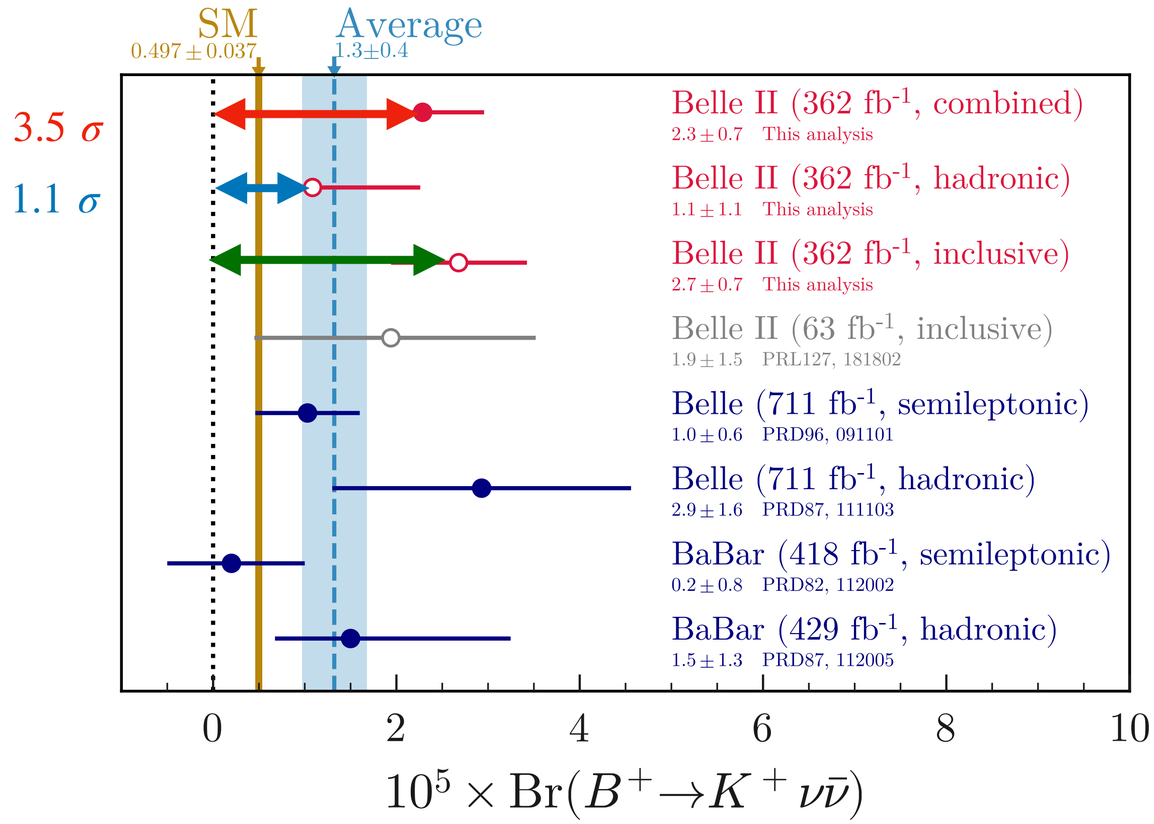
Pre-summer 2023



Post-summer 2023

PRD 109, 112006

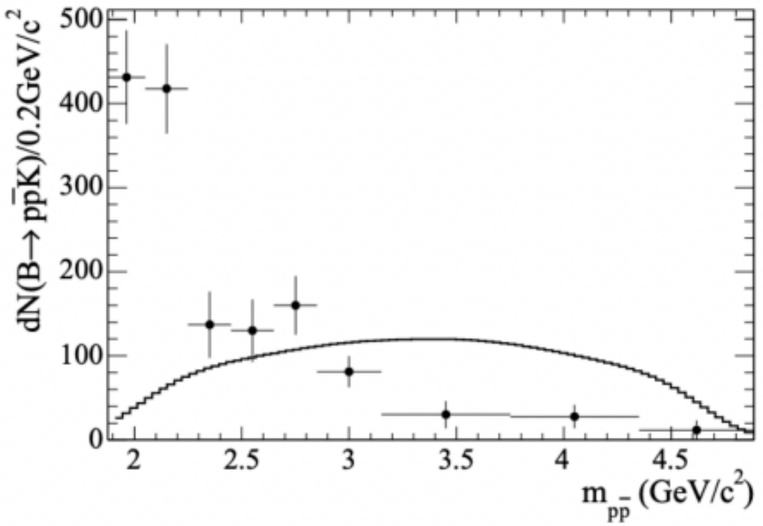
→ first evidence of the $B^+ \to K^+\nu\bar{\nu}$



Ongoing & Future Activities

- **Measurement of all the $B \to K^{(*)}\nu\bar{\nu}$ modes:**
  - $B^+ \to K^{*+}\nu\bar{\nu} : K^{*+} \to K^+\pi^0, K^{*+} \to K_s^0\pi^+$
  - $B^0 \to K^{*0}\nu\bar{\nu} : K^{*0} \to K_s^0\pi^0, K^{*0} \to K^+\pi^-$
  - $B^0 \to K_s^0\nu\bar{\nu}$
- **Public likelihood & reinterpretation under WET ([arxiv:2402.08417], [arxiv:2507.12393]), 2-body hypothesis (light NP)**
- **Possible new avenues within CmF:**
  - $B \to K^{(*)}n\bar{n}$
    - 3-body hadronic decays, $n\bar{n}$ threshold enhancement never observed before
    - important background for the above measurement
    - CP violating effects, isospin relations…
    - Collab with RA1
  - $B \to K^{(*)}/D/p \ldots + X$
    - 2-body dedicated optimised search
    - Collab with RA4

https://arxiv.org/pdf/hep-ex/0507012.pdf



$B^+ \to K^+p\bar{p}$

TABLE II: Branching fractions (in units of 10^{-6}) in the full $M_{p\bar{p}}$ range and below the charm threshold ($M_{p\bar{p}} < 2.85\text{GeV}/c^2$) for the $p\bar{p}K^+$, $p\bar{p}\pi^+$, $p\bar{p}K_S^0$ and $p\bar{p}K^{*+}$ modes. Statistical and systematic errors are quoted.

mode	full $M_{p\bar{p}}$ range	$M_{p\bar{p}} < 2.85\text{GeV}/c^2$
$B^+ \to p\bar{p}K^+$	$5.66^{+0.67}_{-0.57} \pm 0.62$	$4.89^{+0.59}_{-0.55} \pm 0.54$
$B^+ \to p\bar{p}\pi^+$	$3.06^{+0.73}_{-0.62} \pm 0.37$	$1.76^{+0.42}_{-0.37} \pm 0.21$
$B^0 \to p\bar{p}K^0$	$1.88^{+0.77}_{-0.60} \pm 0.23$	$1.56^{+0.52}_{-0.49} \pm 0.19$
$B^+ \to p\bar{p}K^{*+}$	$10.3^{+3.6+1.3}_{-2.8-1.7}$	$6.7^{+2.4+0.9}_{-2.0-1.1}$

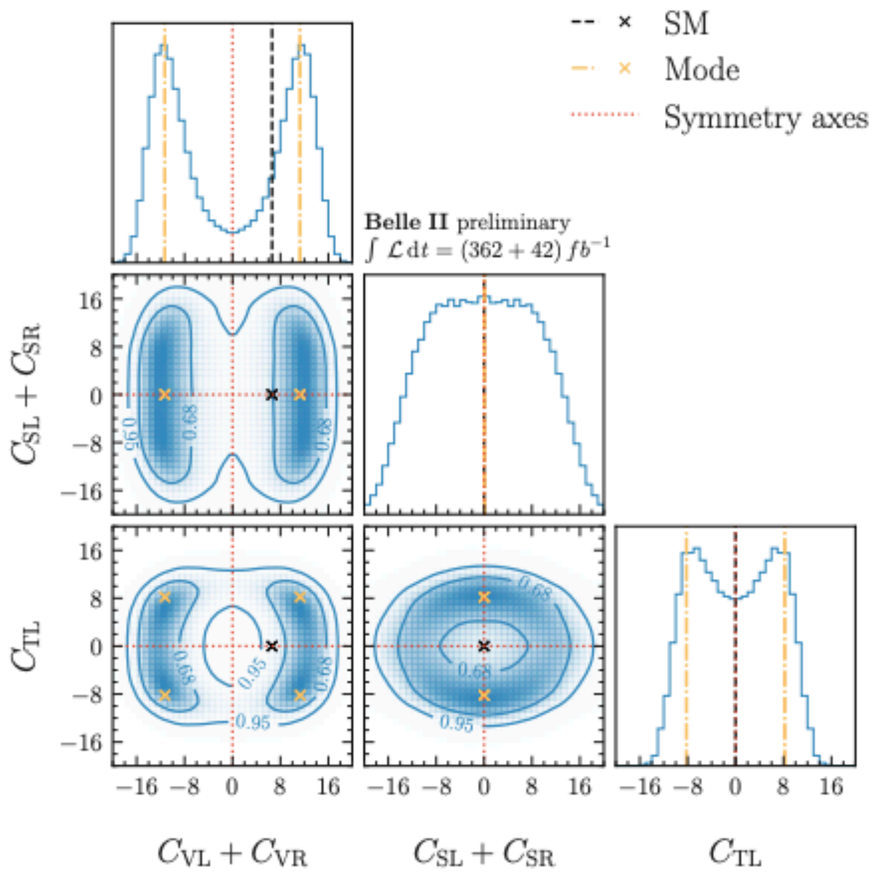
A-propos Reinterpretation

Appendix C: Belle II HEPData reinterpretation inventory

To enable reinterpretation under any NP model with the model-agnostic likelihood [1], the necessary information from Belle II will be published on HEPData [33]. The release will include the following components:

- The SM $B^+ \to K^+ \nu\bar{\nu}$ differential branching fraction as a function of q^2;
- Binned joint number densities:
  - ITA: x-axis: q^2, y-axis: $q^2_{\text{rec}} \times \eta(\text{BDT}_2)$ (flattened), z-axis: events (weighted);
  - HTA: x-axis: q^2, y-axis: $\eta(\text{BDTh})$ (flattened), z-axis: events (weighted);
- `pyhf` combined likelihood in `json` format:
  - Containing templates for signal and background after all selections, binned in $q^2_{\text{rec}} \times \eta(\text{BDT}_2)$ (ITA) and $\eta(\text{BDTh})$ (HTA);
- The code to reproduce the WET reinterpretation results obtained in this analysis.

[arxiv:2507.12393]

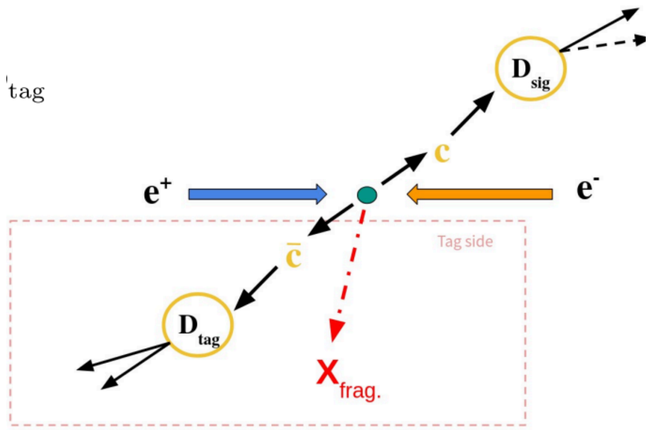


Rare charm-decays with missing energy

Measure $c \to u$ + missing energy (null tests of SM):

- **This avenue is largely experimentally unexplored and CmF perfect platform to study such decays**
  - Charm tagging & FEI @ Belle II provides an interesting sample to study such decays e.g $D \to \pi\nu\bar{\nu}$ …

$D \to F$	A_+ $[10^{-8}]$	A_- $[10^{-8}]$
$D^0 \to \pi^0$	0.9	0
$D^+ \to \pi^+$	3.6	0
$D^0 \to \pi^0\pi^0$	0	0.2
$D^0 \to \pi^+\pi^-$(*)	0	0.4
$D^0 \to X$	2.2	2.2
$D^+ \to X$	5.6	5.6



- Only experimental information so far from $D^0 \to$ invisible (Belle, $\mathcal{C}_{S,P}$) and $D^0 \to \pi^0\nu\bar{\nu}$ (BESIII, $\mathcal{C}_{L,R,S,P}$):

$$\mathcal{B}(D^0 \to \text{invisible}) < 9.4 \times 10^{-5} \quad (90\%\ \text{C.L.}),$$
$$\mathcal{B}(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \times 10^{-4} \quad (90\%\ \text{C.L.}).$$

D^0: 6×10^8 ($\to 10^{11}$)
$D^+_{(s)}$: 10^8 ($\to 10^{10}$)
Λ_c^+: 10^7 ($\to 10^9$) $\mathcal{O}$(1-10%)

  - optimised

Backup

How does it work?

What about charm

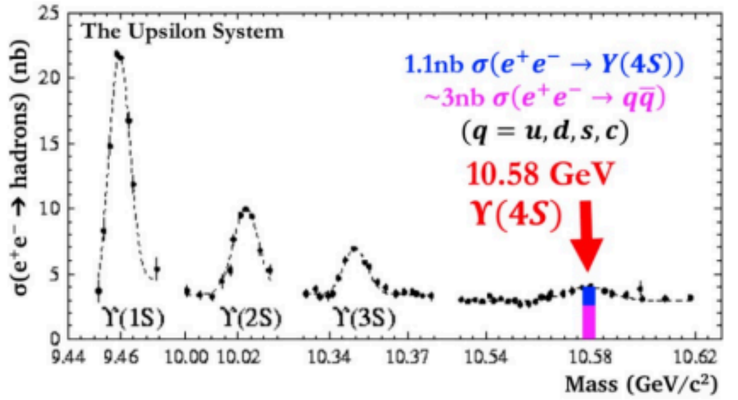
→ @ Belle II charmed hadrons are produced in B decays and in $e^+e^- \to c\bar{c}$ $(\sigma \sim 1.3\text{nb})$

→ while charm from B can also be used for charm studies ccbar events are our interest $e^+e^- \to c\bar{c}$

→ following the B tagging idea let's consider

$$e^+e^- \to c\bar{c} \to X_{\text{tag}} D_{\text{sig}}$$

need to reconstruct



→ if X_{tag} is correctly reconstructed in its RestOfEvent we will find only decay products of $D_{sig} \to f$ along with kinematic constraint $\vec{p}_{D_{sig}} = \vec{p}_{miss}$ $(\vec{p}_{miss} = \vec{p}_{e^+} + \vec{p}_{e^-} - \vec{p}_{X_{tag}})$

→ if we do not put any requirement on RestOfEvent and look at

$M_{miss} = \sqrt{p^2_{miss}}$ $(p_{miss} = p_{e^+} + p_{e^-} - p_{X_{tag}})$ correctly reconstructed events will peak at $M(D_{sig})$

→ the number of peaking events give the total number of D_{sig}'s in the sample (inclusive) which can is then used for absolute branching fraction calculation

Charm FEI

ccbarFEI

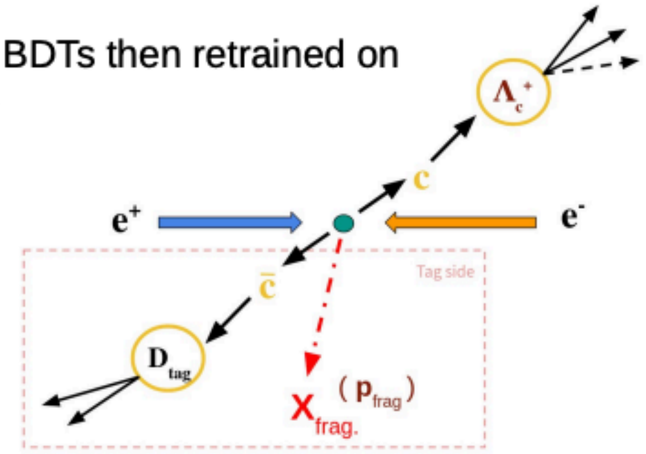
→ FEI is existing tool that is trained to efficiently reconstruct hadronic B decays.

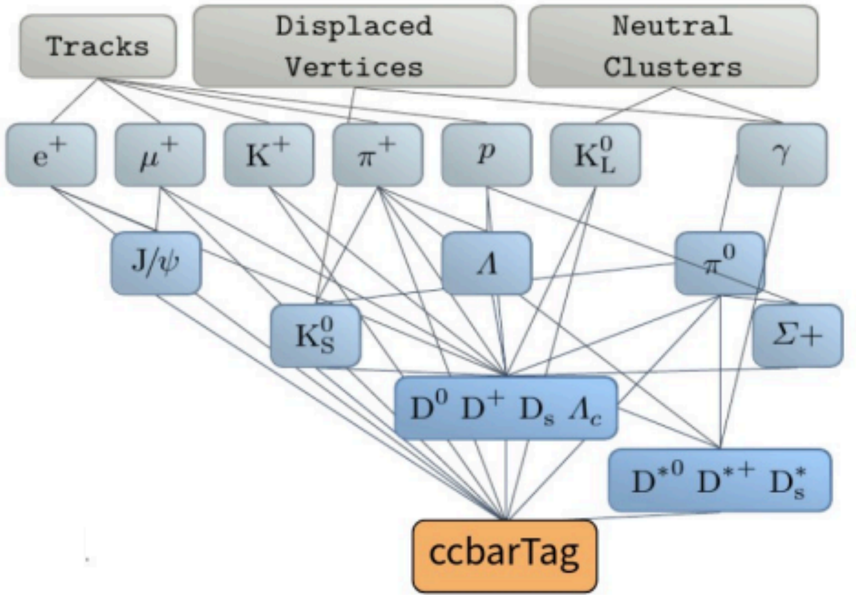
→ in the chain it is already reconstructing various charm states

→ idea of ccbarFEI is to adjust FEI to reconstruct charm tags (the recoil of which is a single $D_{(s)}, \Lambda_c,$ etc.)

→ target B modes in the last step of FEI are replaced with a list of target ccbar tags (specific for $D_{(s)}, \Lambda_c,$ etc. inclusive samples)

→ all stages of BDTs then retrained on ccbar events





Charm Datasets

Experiment	Machine	Operation	C.M.	Luminosity	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	2010-2011 (2021-) 2016-2019 2014+2020	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 ($\rightarrow$ 20) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: 10^7($\rightarrow 10^8$) D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	~ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☺ pure D-beam, almost no background ☹ no CM boost, no time-dept analyses
Belle II	SuperKEKB (e^+e^-)	2019-	10.58 GeV	0.4 ($\rightarrow$ 50) ab^{-1}	D^0: 6×10^8 ($\rightarrow 10^{11}$) $D^+_{(s)}$: 10^8 ($\rightarrow 10^{10}$) Λ_c^+: 10^7 ($\rightarrow 10^9$)	$\mathcal{O}$(1-10%)	☺ clear event environment ☺ high trigger efficiency ☺ good-efficiency detection of neutrals ☺ time-dependent analysis ☹ smaller cross-section than LHCb
BELLE	KEKB (e^+e^-)	1999-2010	10.58 GeV	1 ab^{-1}	D: 10^9 Λ_c^+: 10^8 ★★☆	★★	
LHCb	LHC (pp)	2011,2012 2015-2018 (2022-2025,2029-)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} ($\rightarrow$ 23 $\rightarrow$ 50)	5×10^{12} 10^{13} ★★★★	$\mathcal{O}$(0.1%) ★	☺ very large production cross-section ☺ large boost ☺ excellent time resolution ☹ dedicated trigger required

→ each of experiments has their advantages for different charm studies

→ at present BESIII may be hard to compete in many missing energy measurements

→ nonetheless, even at present (and especially in near future) Belle II has a great potential to produce competitive and leading results (especially with clever ideas and novel reconstruction techniques)