Beauty and Charm Decays with Missing Energy at Belle II

Slavomira Stefkova

RA4 kick-off Meeting

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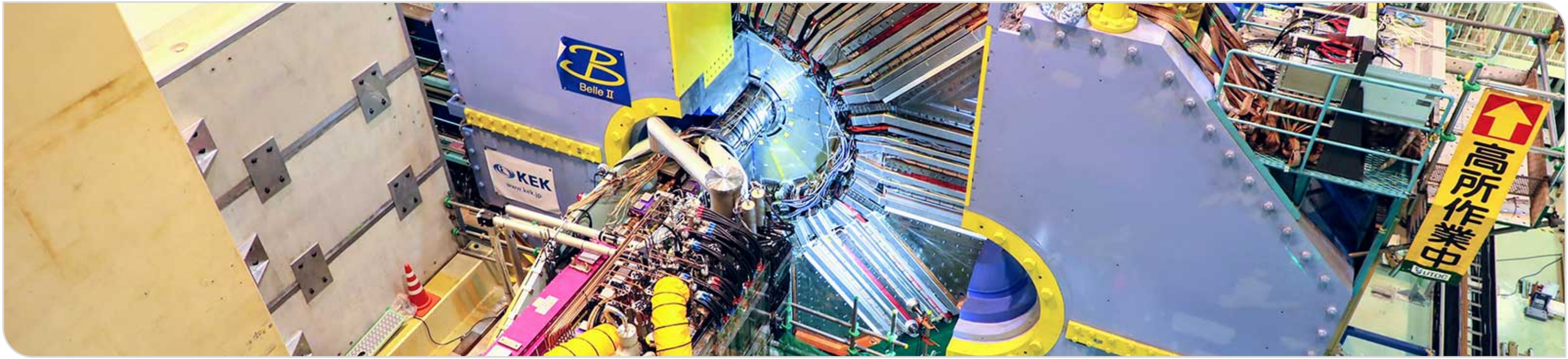
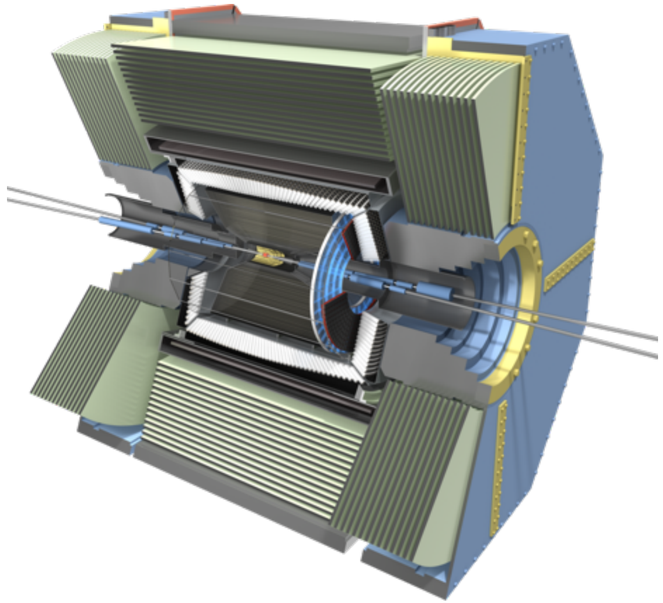


Belle II: Ideal HEP Experiment for Light NP

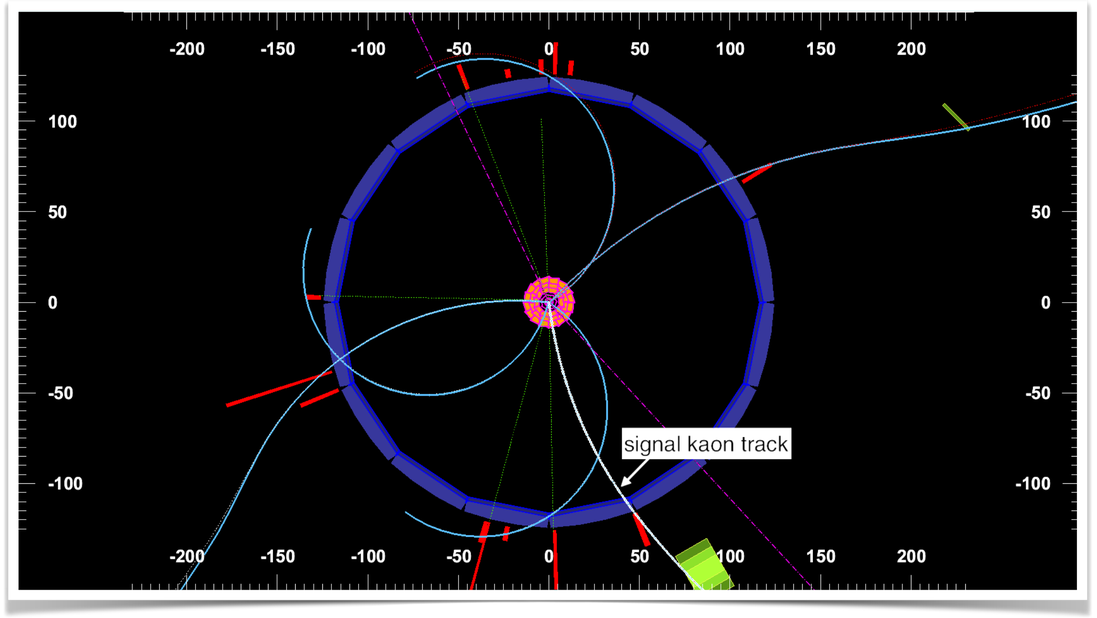


Belle II detector was built for B-decays:

- General purpose detector at asymmetric e^-e^+ SuperKEKB collider @ $\sqrt{s} = 10.58$ GeV
- Running since 2019:
  - collected ~ 500 fb^{-1} → 580 mil. $B\bar{B}$ pairs

Belle II B-events:

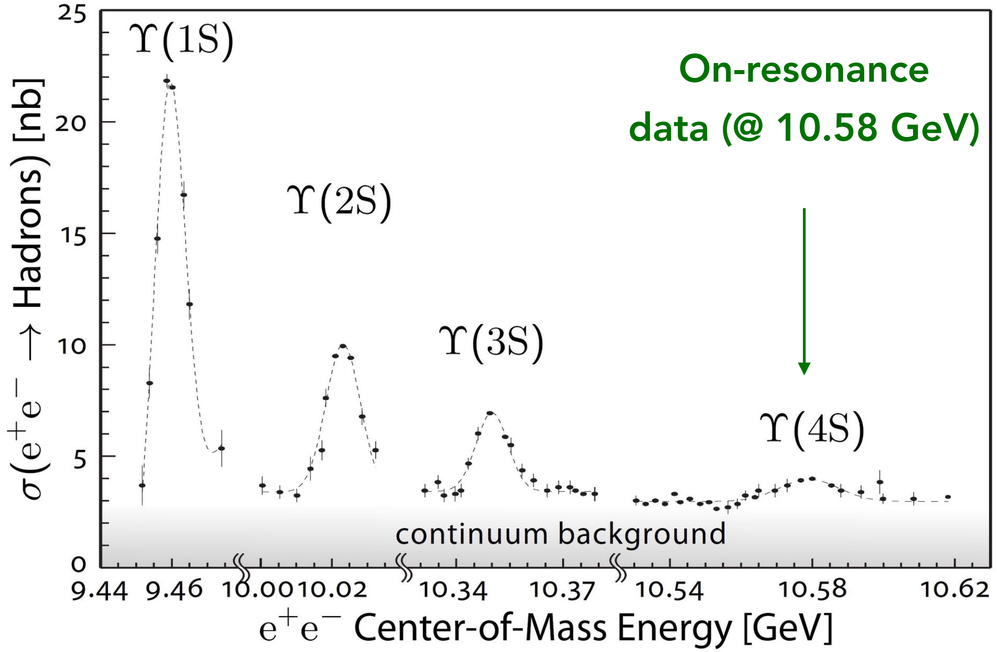
- Very clean environment
- On average: 11 tracks
- Known initial state kinematics
- Near 100% efficiency
- Sensitive to lower energy deposits
- No pile-up



Belle II: Ideal HEP Experiment for Light NP

Light NP can be also search for in continuum (albeit no entanglement) and low-multiplicity samples

$e^+e^- \to$	Cross-section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 0.10



Two Paths for light NP @ Belle II

Low multiplicity resonances/ signatures in e^+e^- collisions

- Direct, e.g $e^+e^- \to a\gamma$

Missing energy decays of beauty and charm hadrons

- Direct, e.g $B \to Ka$
- Indirect, e.g $B \to K\nu\bar{\nu}$

Belle II Light NP Publications (Direct)

Belle II publications:

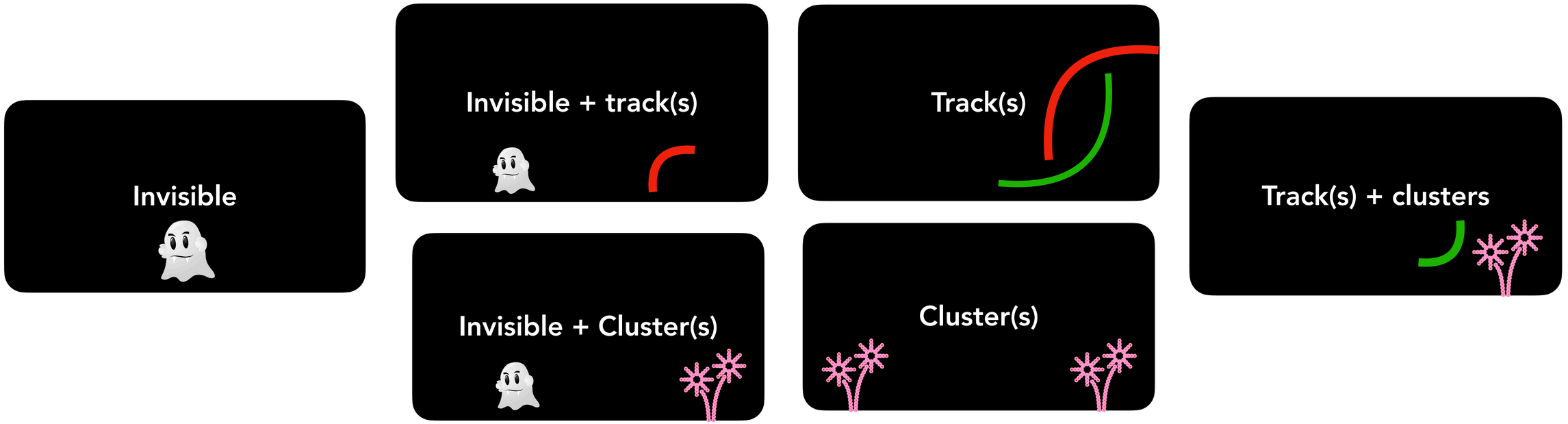
- Search for axionlike particles produced in e^+e^- collisions at Belle II *(PRL 125, 161806 (2020))* $[e^+e^- \to \gamma a \to \gamma\gamma\gamma]$
- Search for an invisibly decaying Z' boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\pm)$ plus missing energy final states *(PRL 124, 141801 (2020))* , *(Phys. Rev. Lett. 130, 231801 (2023))*
- Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment $[e^+e^- \to A'h']$ *((PRL 130, 071804 (2023))*
- Search for a long lived mediator spin-0 mediator in $b \to s$ transitions at the Belle II experiment *(PRD 108, L111104 (2023))* $[B \to KS(S \to x^+x^-, x \in [e, \mu, K, \pi])]$
- Search for a $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events with the Belle II experiment *(PRL 131, 121802 (2023))*
- Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II *(PRD 109, 112015 (2024))*
- Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment *(PRL 135, 131801 (2025))*

Belle pub. in preparation: Search for feebly interacting particles in missing energy B decays at Belle

Belle II Light NP Publications (Indirect in *B*-decays)

- Large number of B-mesons which do not need to be triggered
- Very good charged particle identification (kaons, pions, protons, electrons, muons)
- Very good knowledge about missing energy due to clean environment
- Very good neutral particle identification (photons, pions)

This allows us all to look for light NP with these signatures



we want SM processes to be small and/or well separable as not to be problematic background

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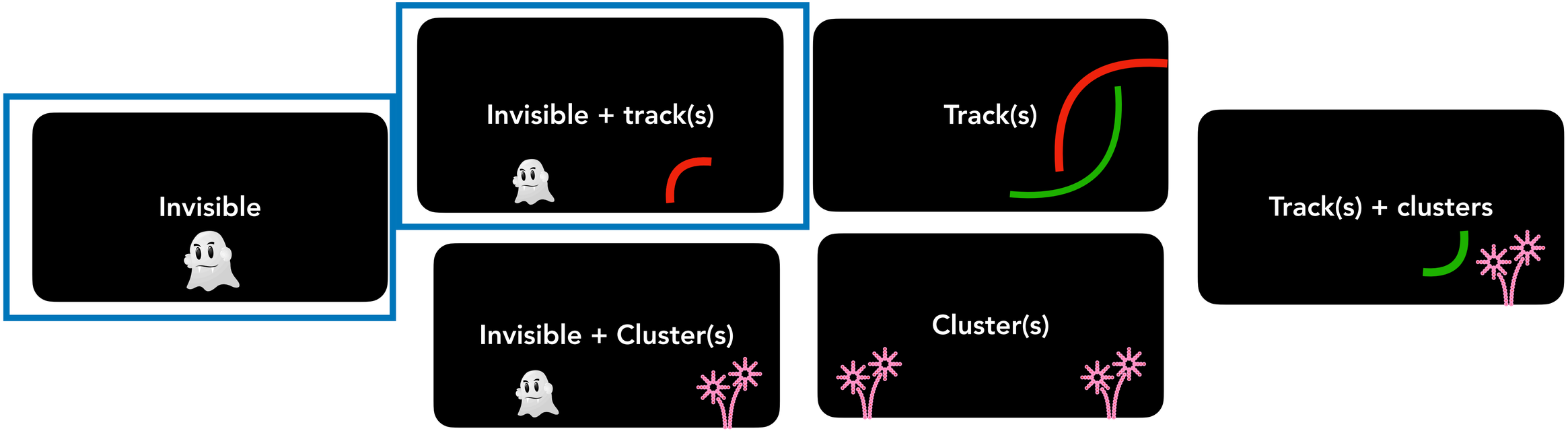

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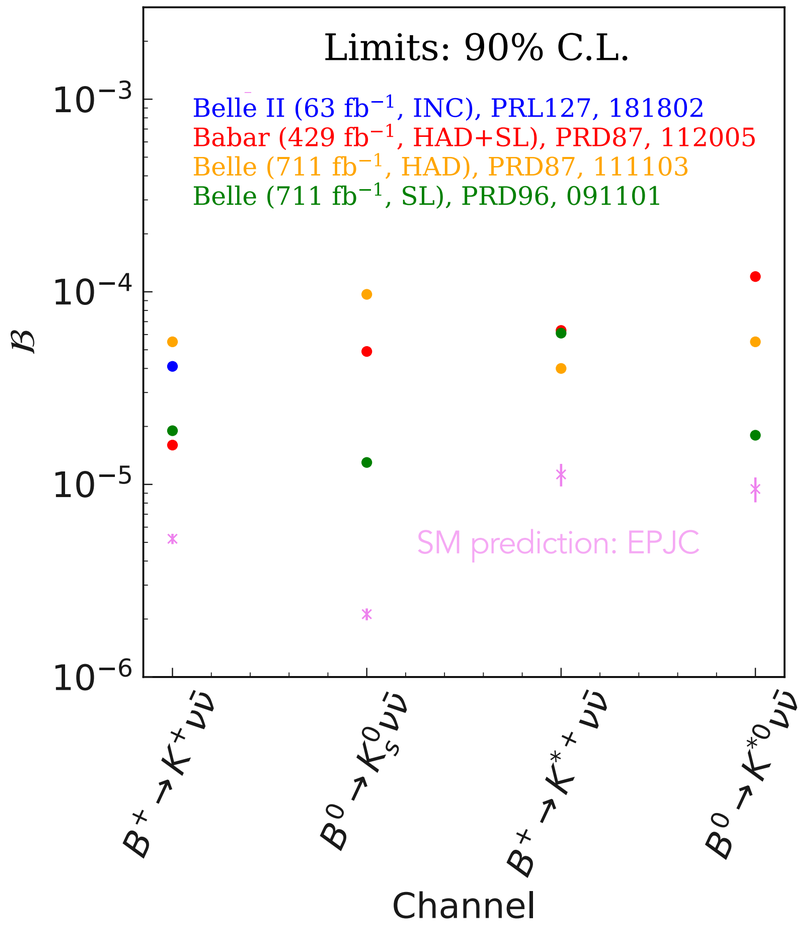
$B \to K^{(*)}\nu\bar{\nu}$ Measurements Overview

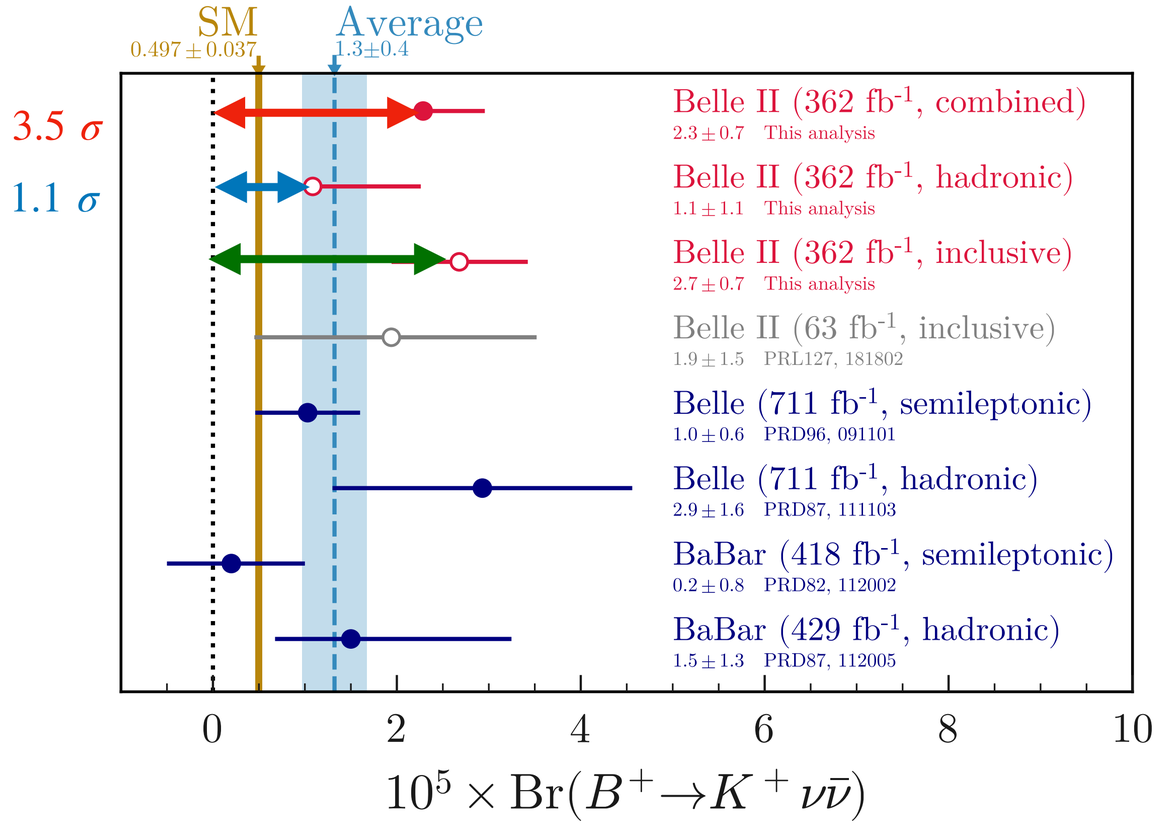
Pre-summer 2023



Post-summer 2023

[PRD 109, 112006 (2024)]

→ first evidence of the $B^+ \to K^+\nu\bar{\nu}$ and only 2.7 σ agreement with SM



Reinterpretation under WET

Published likelihood == statistical model

[PRD 112, 092016, 2025]

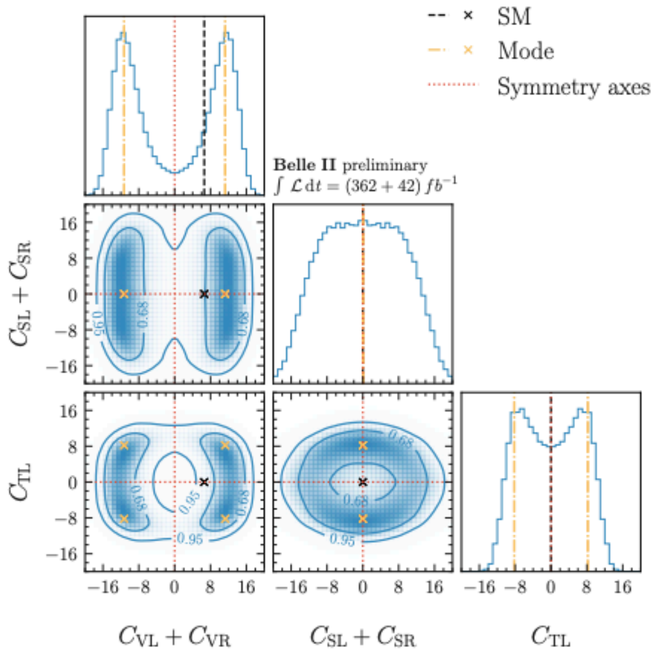
https://www.hepdata.net/record/ins2725943

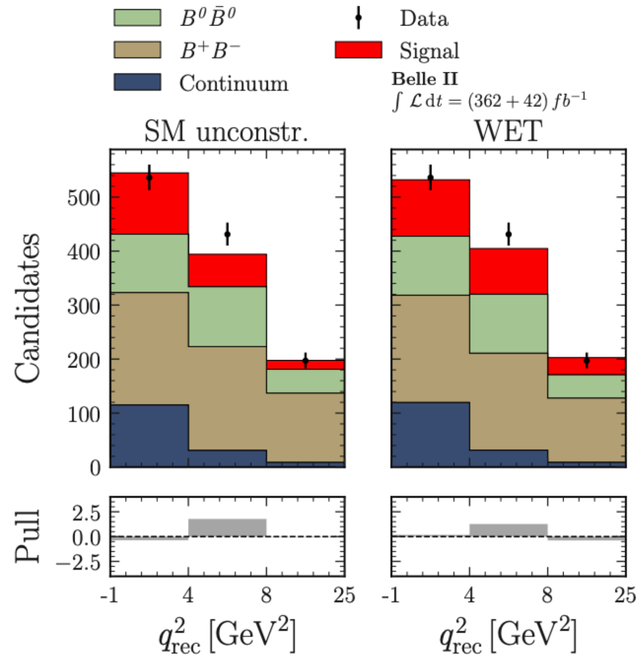
https://www.hepdata.net/record/ins2947386

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.





HEPData

Ongoing & Future Activities

Ongoing activities:

1. **SM measurement of all the $B \to K^{(*)}\nu\bar{\nu}$ modes (*1 postdoc @ Bonn*):**
   - $B^+ \to K^{*+}\nu\bar{\nu} : K^{*+} \to K^+\pi^0, K^{*+} \to K_s^0\pi^+$
   - $B^0 \to K^{*0}\nu\bar{\nu} : K^{*0} \to K_s^0\pi^0, K^{*0} \to K^+\pi^-$
   - $B^0 \to K_s^0\nu\bar{\nu}$
2. **Public likelihood (1 PhD student @ Munich)**
   A. Reinterpretation under WET: [EPJC 84 (2024) 7, 693], [PRD 112, 092016, 2025]
   B. 2-body hypothesis reinterpretation (light NP): WIP
3. **Measurement of hadronic B-meson decays ($B \to Kn\bar{n}$) (*1 Master Thesis @ Bonn; under investigation*)**

Possible new avenues within CmF in collab with RA2 (*1 EXP PhD student requested with Manos/ Thorsten*):

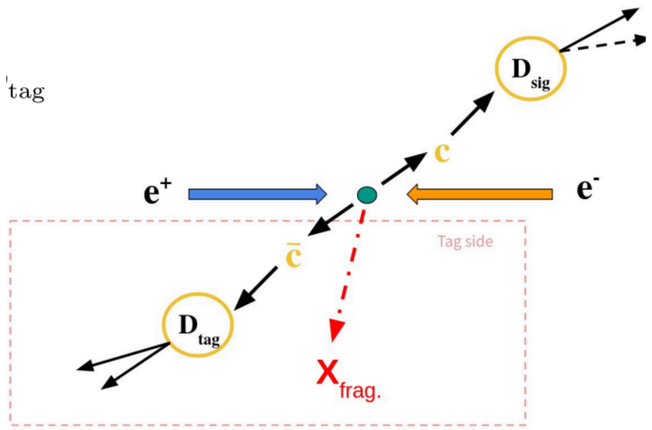
- $B \to K^{(*)}/D/p \ldots + X$ (currently under-funded)
  - 2-body dedicated optimised search
- Reinterpretation of future SM measurements (will be possibly covered in 1)

Rare charm-decays with missing energy

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

- This avenue is largely unexplored, but the dataset is there
  → CmF perfect platform to study such decays ***(1 EXP PhD student requested with Gudrun)*** also w/ RA2
  → interest for FCC as well
- **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



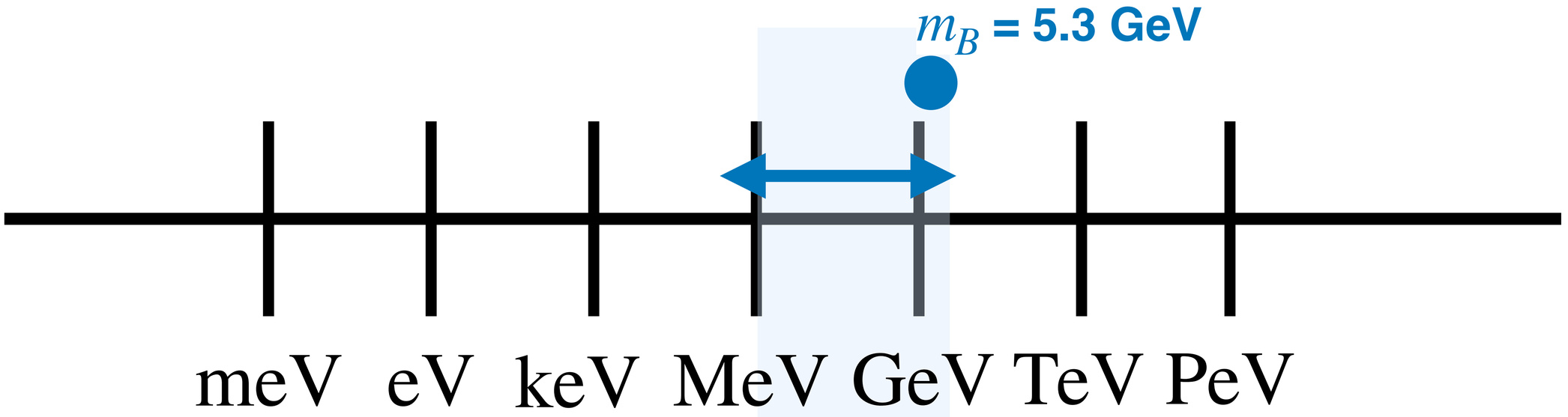
- Only experimental information so far from $D^0 \to$ invisible (Belle, $C_{S,P}$) and $D^0 \to \pi^0\nu\bar{\nu}$ (BESIII, $C_{L,R,S,P}$):

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

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%)

Backup

Searching for Light NP in Belle II



QCD axion

Hidden/Dark Sector

WIMPS

Adapted from arXiv:1707.04591

Rare *B*-decays

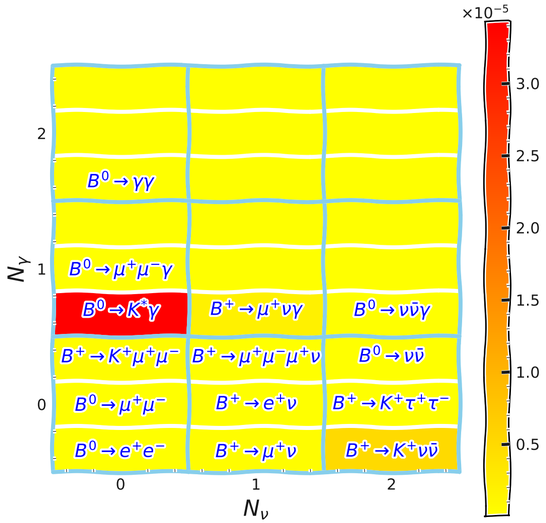
Rare B decays:

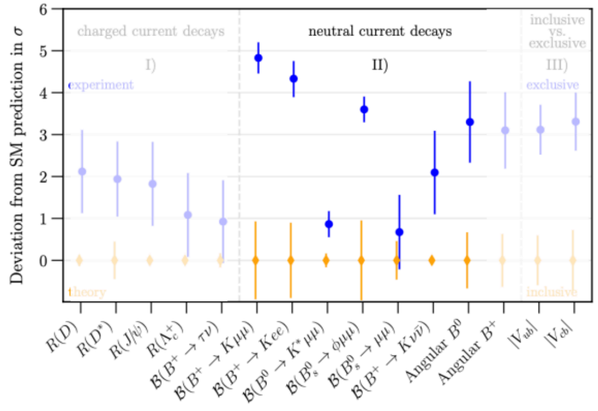
- GIM suppressed flavour changing neutral currents (FCNC)

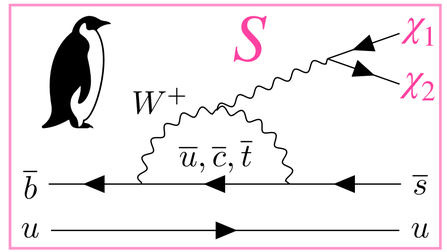
  → $b \to s/d(\gamma)$

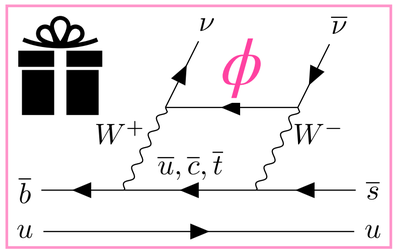
  - forbidden at tree level, allowed at loop level
  - electroweak decays, radiative electroweak decays
  - m_ν^2/M_W^2 suppressed lepton flavour violating decays
- Helicity suppressed purely leptonic decays

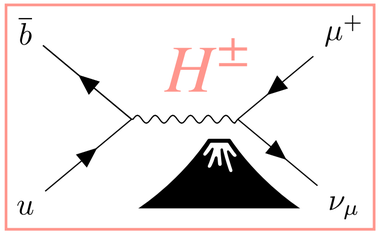
Very sensitive to NP since SM contribution small!

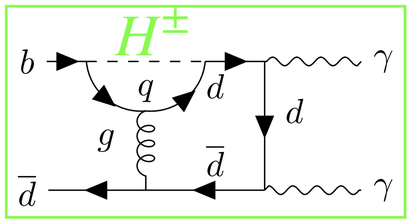


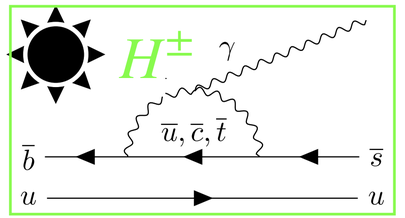


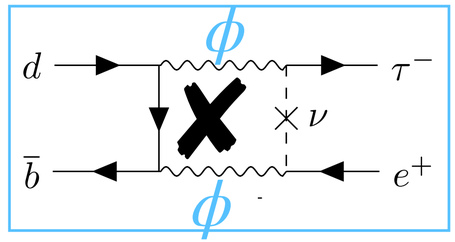












How does it work?

What about charm

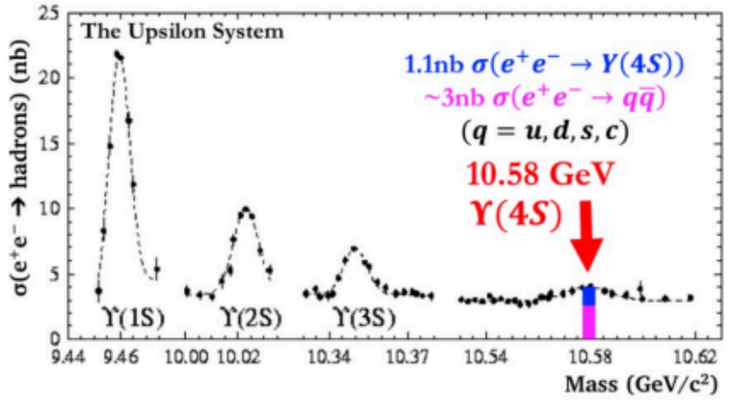
→ @ Belle II charmed hadrons are produced in B decays and in $e^+e^- \to c\bar{c}$ $(\sigma \sim 1.3\text{nb})$

→ 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

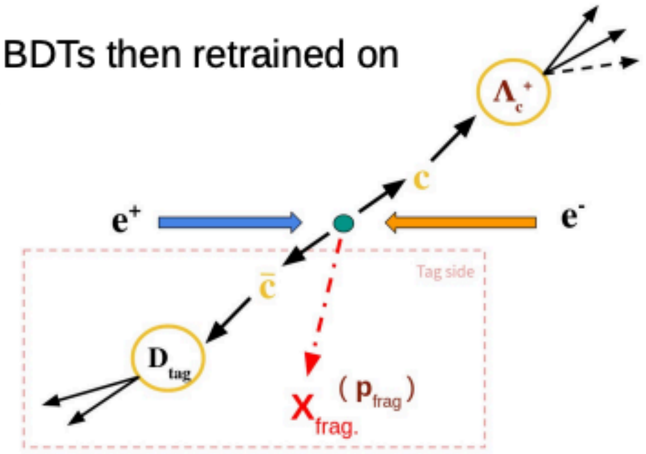
→ FEI is existing tool that is trained to efficiently reconstruct hadronic B decays.

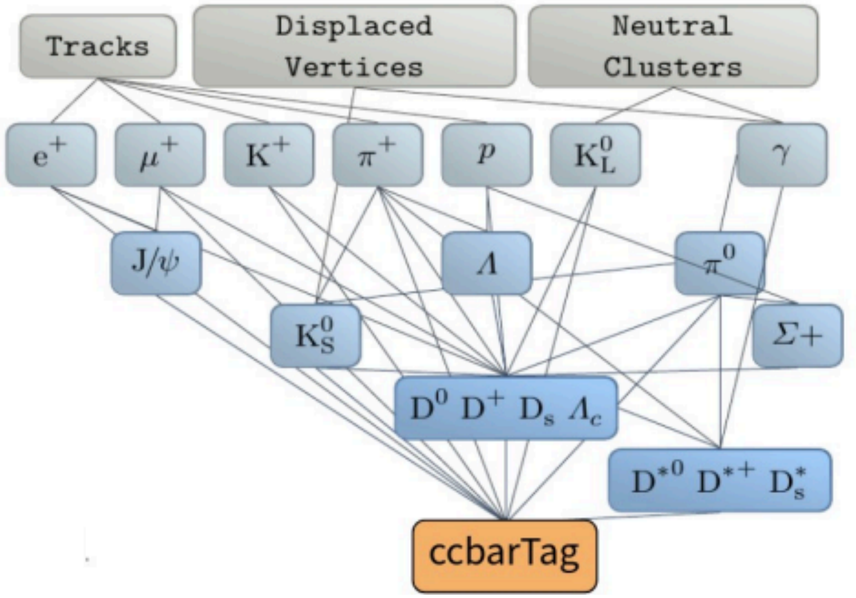
→ in the chain it is already reconstructing various charm states

→ 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)