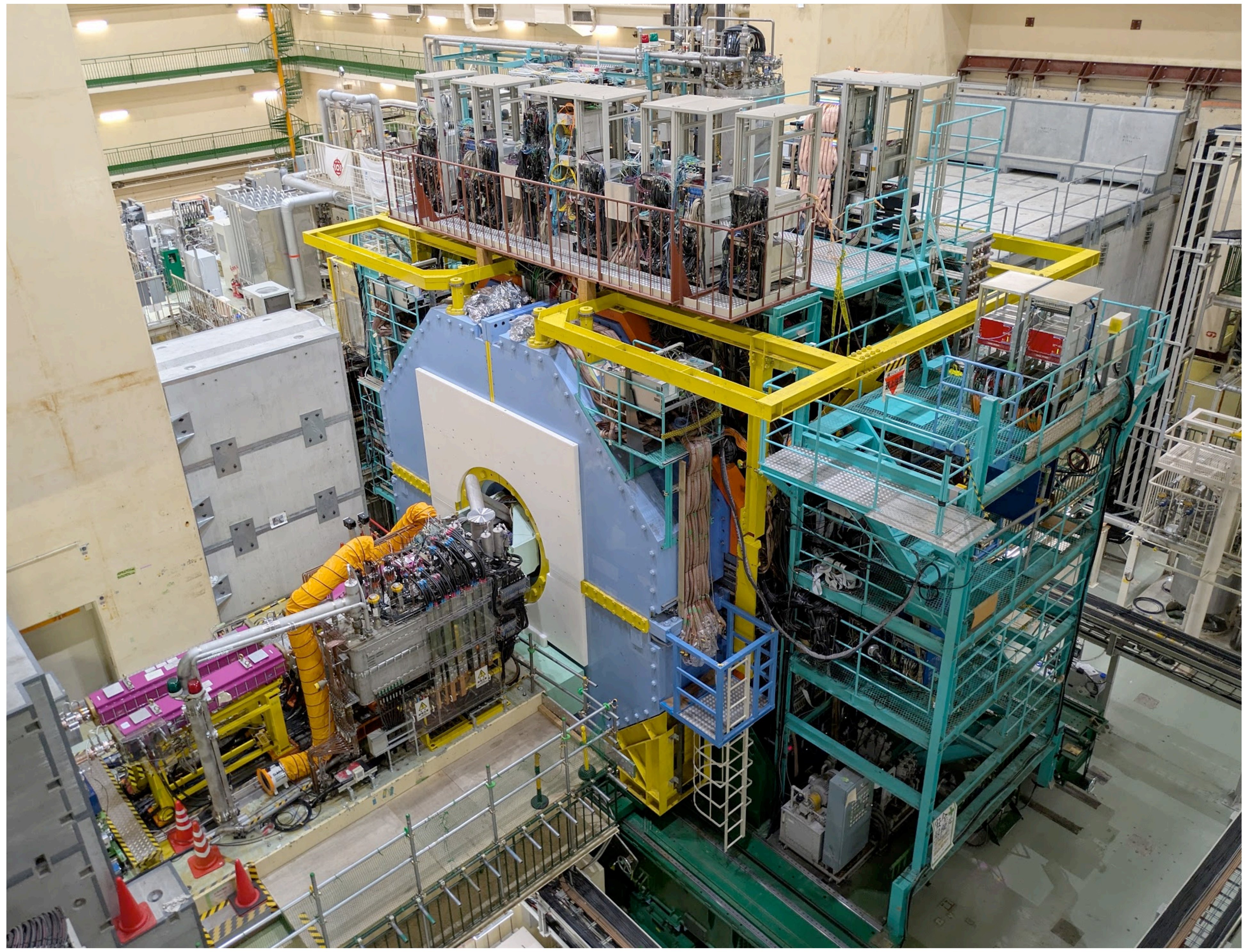
Towards an inclusive reconstruction of prompt Ξ_c and Ω_c baryons, and measurement of their *absolute* decay rates at the Belle II experiment



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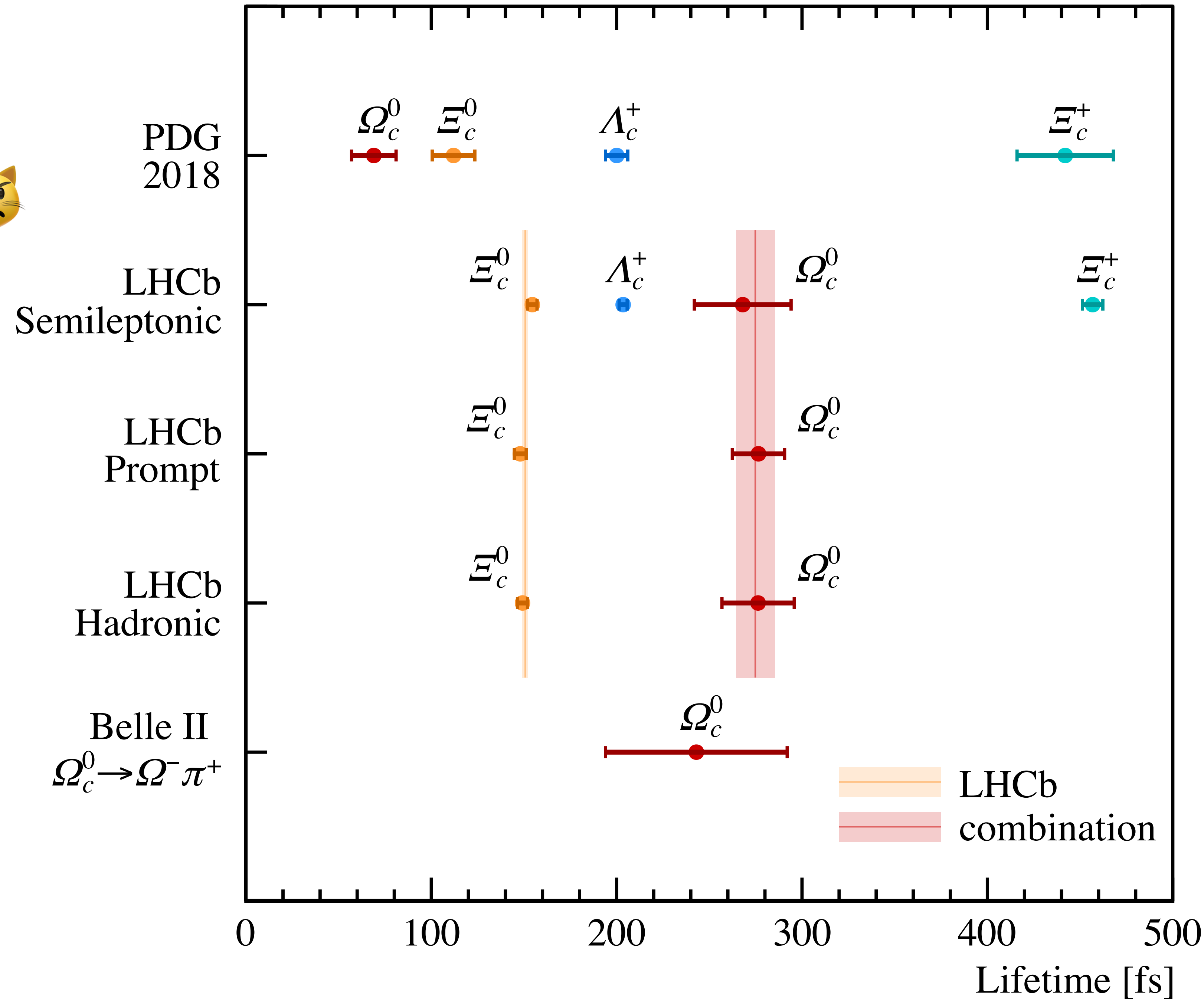
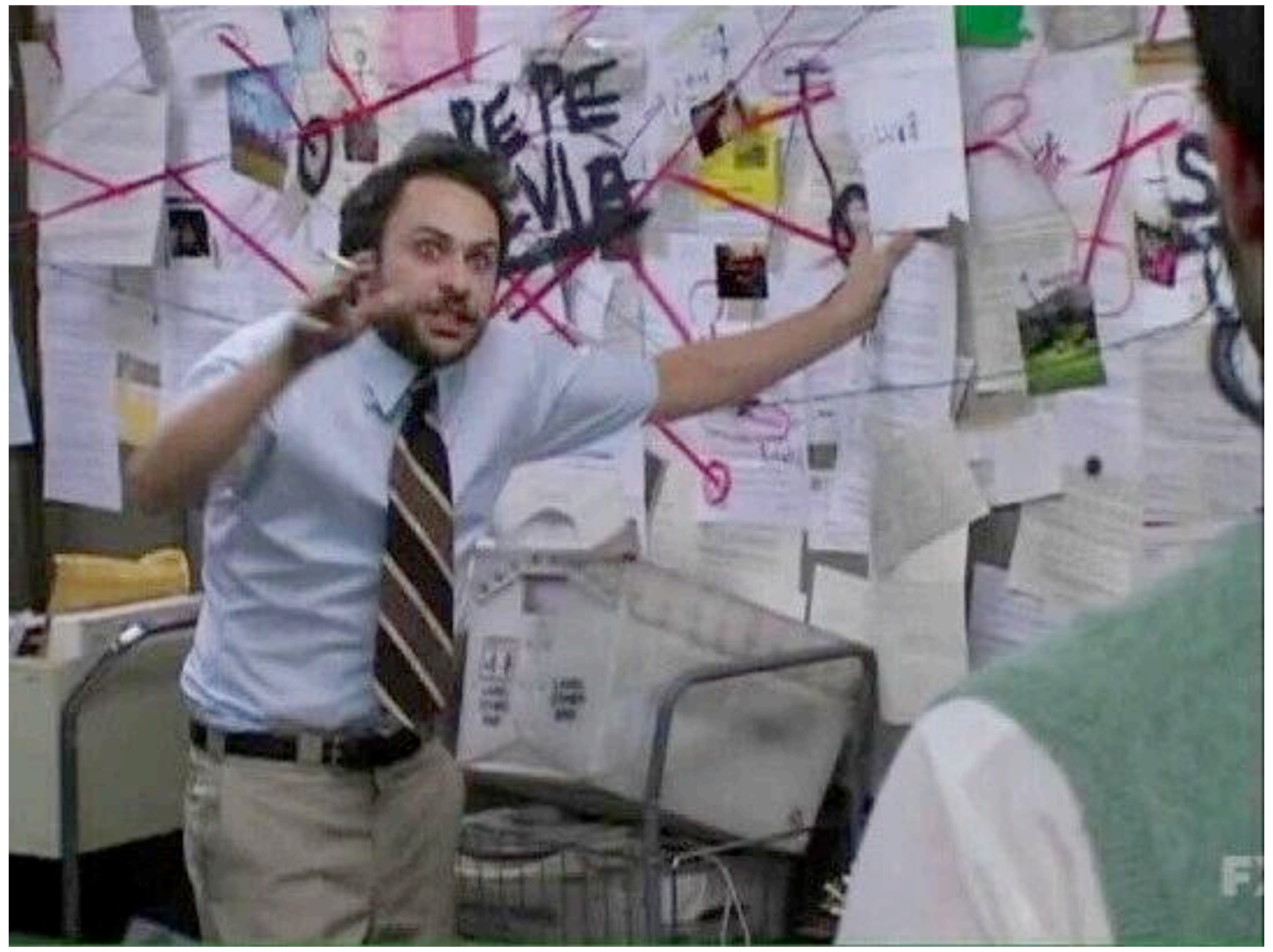
Setting the scene

- **Our world is made of baryons: a good enough reason to study them!**
- There are **four** baryons that contain exactly **one charm quark** and **decay** through the **weak interaction**: $\Lambda_c^+(udc)$; $\Xi_c^+(usc)$, $\Xi_c^0(dsc)$ and $\Omega_c^0(ssc)$
  - Others e.g. $\Sigma_c^0(ddc)$ decay to one of those + pions/photons
  - Out of these four, only the Λ_c^+ is studied satisfactorily well
- Ξ_c^0: absolute decay rates (branching fractions) known to precision of ~18% 😾
  - Not sufficient for precision testing of the Standard Model
  - Lifetime poorly known until recently
- Ξ_c^+: absolute branching fractions known to ~45% 😿
- Ω_c^0: absolute branching fractions not known at all 🙀, but also
  - lifetime was only properly measured a few years ago
  - less than a dozen decay modes known
  - the BF of the decay mode used at LHCb $\Omega_c^0 \to pK^-K^-\pi^+$ never measured even as a relative



Who cares?

- Enter LHCb with its huge datasets of b baryons
  - Interesting for all kinds of BSM searches ($b \to s\ell^+\ell^-$, $b \to c\ell\nu$ etc.)
- How to measure **absolute** rates of b-baryon decays? Need to know their **production rates**
  - How to measure production rates without knowing absolute rates?
  - Trick: theoretically, rates of inclusive semileptonic $b \to c\mu\nu$ decays are ~equal for all b-baryons (heavy-quark expansion)
    - Need to measure the experimental rates of $b \to c\mu\nu$ baryon decays in order to know the production cross-sections!
    - So, we need to measure $\Omega_b \to \Omega_c^{(*)}\mu\nu$ in order to know absolute rate of any other Ω_b decay
      - **But, this is impossible if the branching fractions of Ω_c are unknown!**
- **Poor knowledge of charm-baryon decay rates slows down the b-baryon physics**
- Can Belle II do something about it?



How does one measure an *absolute* decay rate?

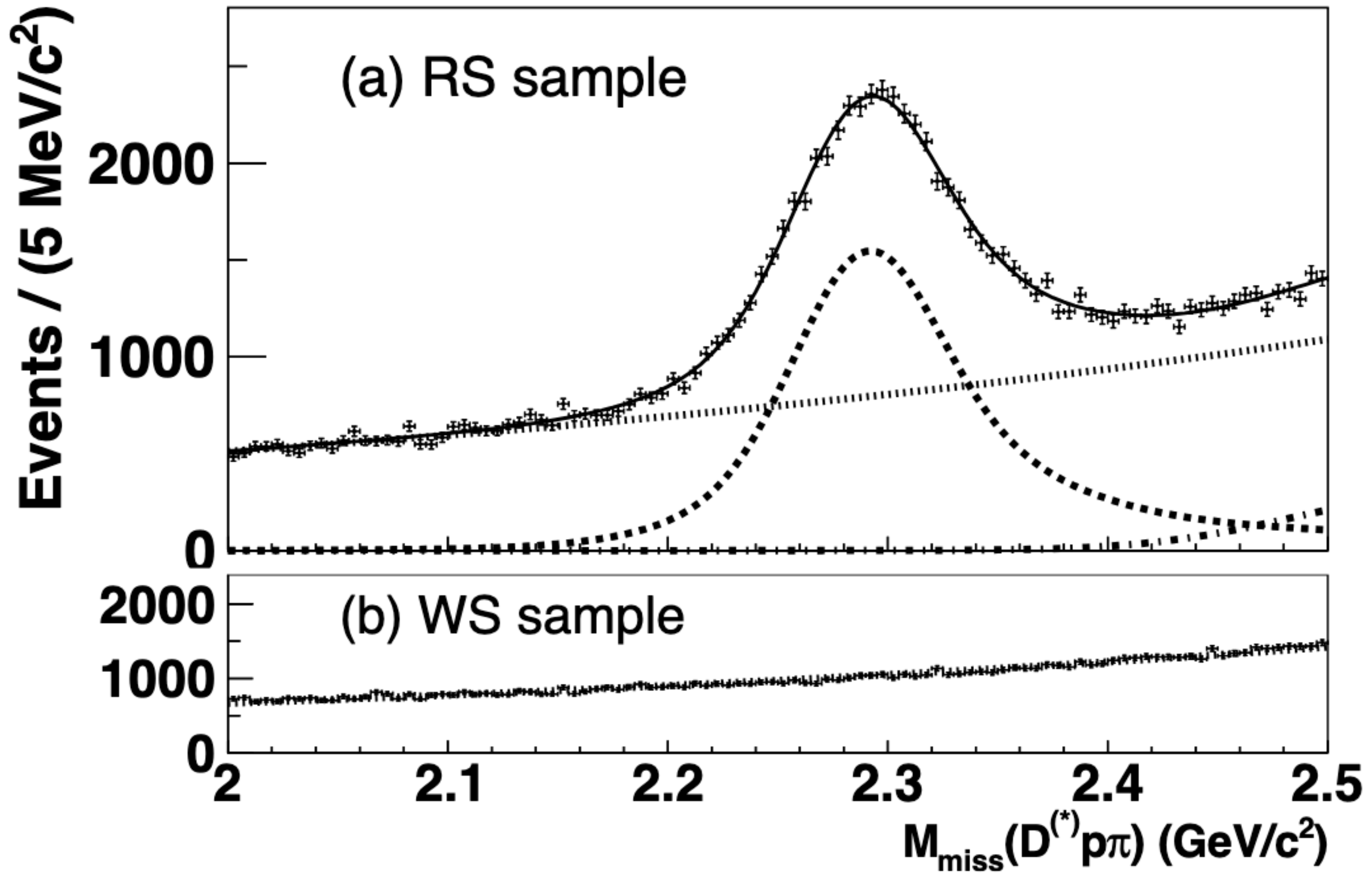
- We need to know:
  - **How many baryons have been produced?**
    - This is tricky
  - **How many, out of those, have decayed to the final state of interest?**
    - This is easy: look for a peak in the invariant mass of its decay products

$$\mathcal{B} = \frac{N_{\text{exclusive \& inclusive}}}{N_{\text{inclusive}} \times \varepsilon_{\text{exclusive}}}$$

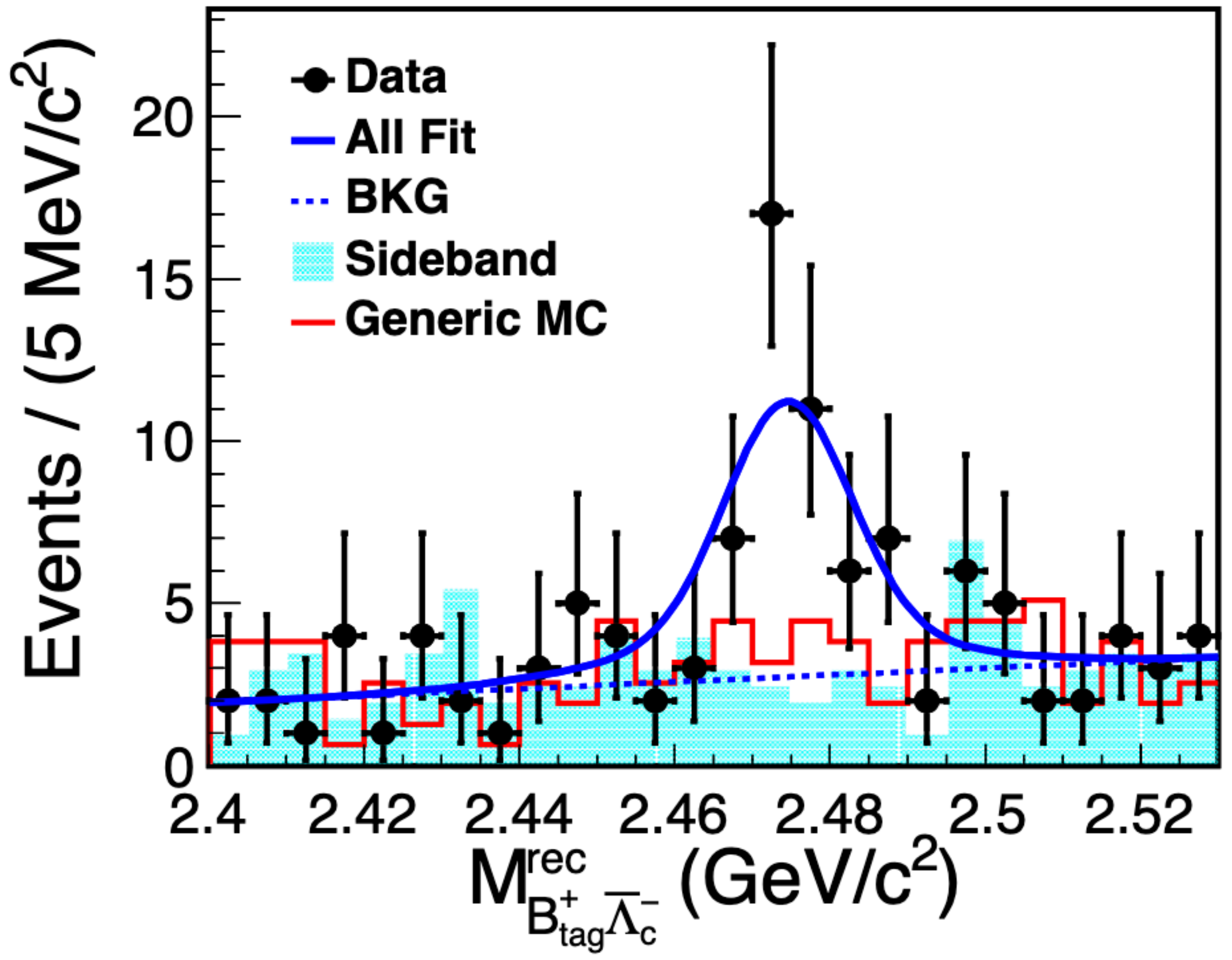
- Problem: charm-baryon production cross-section at Belle II remains unknown!
  - Production mechanisms at Belle II:
    - $e^+e^- \to c\bar{c}$ (1.3 nb) with hadronisation of c quark into a charm baryon (poorly understood)
      - all Belle(II) datasets, not only $\Upsilon(4S)$, can be used
    - or, from B-meson (1.1 nb) decays such as $B \to \Lambda_c \overline{\Xi}_c$ (rare processes)
  - **Use the power of the 4π detector to obtain an inclusive sample of charm baryons, regardless of their production mechanism, by reconstructing all other particles in the event**

La Belle Époque

- Absolute BF measurement for Λ_c^+ at Belle [1312.7826]
  - Use prompt $e^+e^- \to c\bar{c}$ with $c_{tag} \to D^{(*)}p\pi$
  - 36000 inclusively tagged Λ_c^+, out of them 1500 decayed to $pK^-\pi^+$ => BF measured to ~5% precision
  - Note: ~3σ tension between this measurement and BES III result at the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ threshold

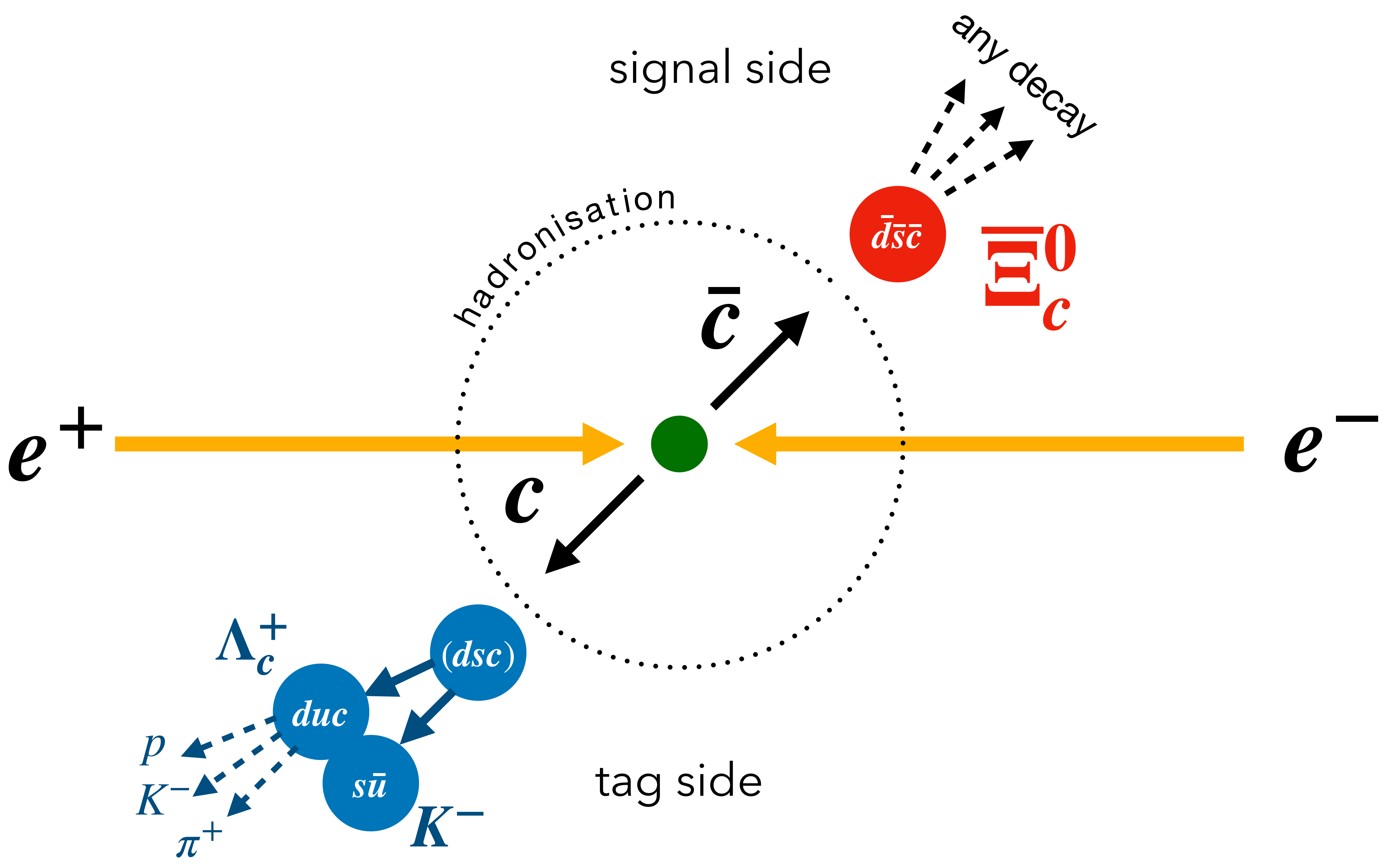


- Absolute BF measurement for Ξ_c^+ [1904.12093] and Ξ_c^0 [1811.09738] at Belle using $\bar{B}^0 \to \bar{\Lambda}_c^-\Xi_c^+$ and $\bar{B}^- \to \bar{\Lambda}_c^-\Xi_c^0$
  - Very low BF: very small tagged dataset (40 Ξ_c^+/ 20 Ξ_c^0 events)
  - But: no need to fully reconstruct the decay in a tagged dataset (B tagging efficiency known)



This talk: the key idea

- Use conservation of baryon number, charm and strangeness in $e^+e^- \to c\bar{c}$
- Step 1: reconstruct dozens of tag-side channels [next slide]
    - Use **missing mass** to measure the ***inclusive*** Ξ_c yield
- Step 2: reconstruct ***exclusively*** the most abundant decay modes of each baryon, and measure their absolute BFs: $\Xi_c^0 \to \Xi^-\pi^+$, $\Xi_c^+ \to \Xi^-\pi^+\pi^+$, $\Omega_c^0 \to \Omega^-\pi^+$
    - Known ratios of other decay modes to these ones will allow to update the PDG for all other decays



Tagging channels

warning: we don't know which one of these hadronisation channels is actually preferred in nature, and whether it is sufficiently clean.

- An incomplete list of possible tagging channels: conserve baryon number, charm, strangeness. Add 1-2 pions to each, if possible.

$\overline{\Xi}_c^0$	$\overline{\Xi}_c^-$	$\overline{\Omega}_c^0$
$\Lambda_c^+ K^-$	$\Lambda_c^+ K^- \pi^+$	$\Lambda_c^+ K^- K_S^0$
$\Lambda_c^+ K_S^0 \pi^-$	$\Lambda_c^+ K_S^0$	$\Lambda_c^+ K_S^0 K_S^0 \pi^-$
$\Sigma_c^+ K^-$	$\Sigma_c^+ K_S^0$	$\Sigma_c^+ K^- K_S^0$
$\Sigma_c^0 K_S^0$	$\Sigma_c^{++} K^-$	$\Sigma_c^0 K_S^0 K_S^0$
$D^{(*)0} \Lambda$	$D^{(*)0} \Lambda \pi^+$	$D^{(*)0} \Xi^0$
$D^{(*)0} \Sigma^0$	$D^{(*)0} \Sigma^0 \pi^+$	$D^{(*)0} \Xi^- \pi^+$
$D^{(*)0} \Sigma^+ \pi^-$	$D^{(*)0} \Sigma^+$	$D^{(*)0} (\Lambda/\Sigma^0) K_S^0$
$D^{(*)0} p K^-$	$D^{(*)0} p K^- \pi^+$	$D^{(*)0} p K^- K_S^0$
$D^{(*)0} p K_S^0 \pi^-$	$D^{(*)0} p K_S^0$	$D^{(*)0} \Sigma^+ K^-$
$D^{(*)+} \Lambda \pi^-$	$D^{(*)+} \Lambda$	$D^{(*)+} \Xi^-$
$D^{(*)+} p K^- \pi^-$	$D^{(*)+} p K^-$	$D^{(*)+} (\Lambda/\Sigma^0) K^-$
$D^{(*)+} p K_S^0 \pi^- \pi^-$	$D^{(*)+} p K_S^0 \pi^-$	$D^{(*)+} p K^- K^-$
$D_s^{(*)+} \Xi^-$	$D_s^{(*)+} \Xi^- \pi^+$	$D_s^{(*)+} \Omega^-$
$D_s^{(*)+} \Xi^0 \pi^-$	$D_s^{(*)+} \Xi^0$	$D_s^{(*)+} \Xi^0 K^-$
$D_s^{(*)+} \Lambda K^-$	$D_s^{(*)+} \Lambda K_S^0$	$\Xi_c^+ K^-$
$D_s^{(*)+} \Omega^- K_S^0$	$D_s^{(*)+} \Omega^- K^+$	$\Xi_c^0 K_S^0$
$\Xi_c^+ \pi^-$	$\Xi_c^0 \pi^+$	Ω_c^0
Ξ_c^0	Ξ_c^+	

Table 2: Dominant decay modes to be considered for the tag-side charm hadrons.

Λ_c^+	D^0	D^+	D_s^+	$\Xi_c^{0/+}$ (for $\overline{\Omega}_c^0$ tag)
$pK^-\pi^+$	$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^-K^+\pi^+$	$\Xi^{-/0}\pi^+$
pK_S^0	$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K_S^0K^+$	$\Xi^{-/0}\pi^+\pi^+\pi^-$
$pK^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^-$	$K_S^0\pi^+$	$K^-K^+\pi^+\pi^0$	$\Xi^{-/0}\pi^+\pi^0$
$\Lambda\pi^+$	$K^-\pi^+\pi^-\pi^+\pi^0$	$K_S^0\pi^+\pi^0$	$K_S^0K^+\pi^+\pi^-$	$\Lambda K^{-/0}\pi^+$
$\Lambda\pi^0\pi^+$	$K_S^0\pi^+\pi^-$	$K_S^0\pi^+\pi^-\pi^+$	$K_S^0K_S^0\pi^+$	$pK_S^0K^{0/-}$
$\Lambda\pi^+\pi^-\pi^+$	$K_S^0\pi^+\pi^-\pi^0$	$K^-K^+\pi^+$	$K^+K_S^0\pi^0$	$pK^-(K^-)\pi^+$

This talk: focus on the inclusive reconstruction of the Ξ_c^0

The absolute BF measurement

- Our **denominator** is the number of events **tagged** by their production mechanism

- Two ways to define our **numerator**:
- (A) Only consider the **tagged events** that are in our denominator, and reconstruct the signal decay of interest inside this dataset.

$$\mathscr{B} = \frac{N_{\text{double tag}}}{N_{\text{single tag}} \times \varepsilon_{\text{exclusive}}}$$

  - Challenge: BF ~1%, so need the size of denominator to be O(10^4) events to reach a stat precision of 10% on our measurements – might be tricky
  - Possible trick: measure a sum of several decays
- (B) **Untagged** reconstruction of a specific signal decay mode. Sufficient statistics.
  - **How to calibrate the tagging efficiency** without knowing the absolute BFs? Systematic challenge.

$$\mathscr{B} = \frac{N_{\text{exclusive}} \times \varepsilon_{\text{single tag}}}{N_{\text{single tag}} \times \varepsilon_{\text{exclusive}}}$$

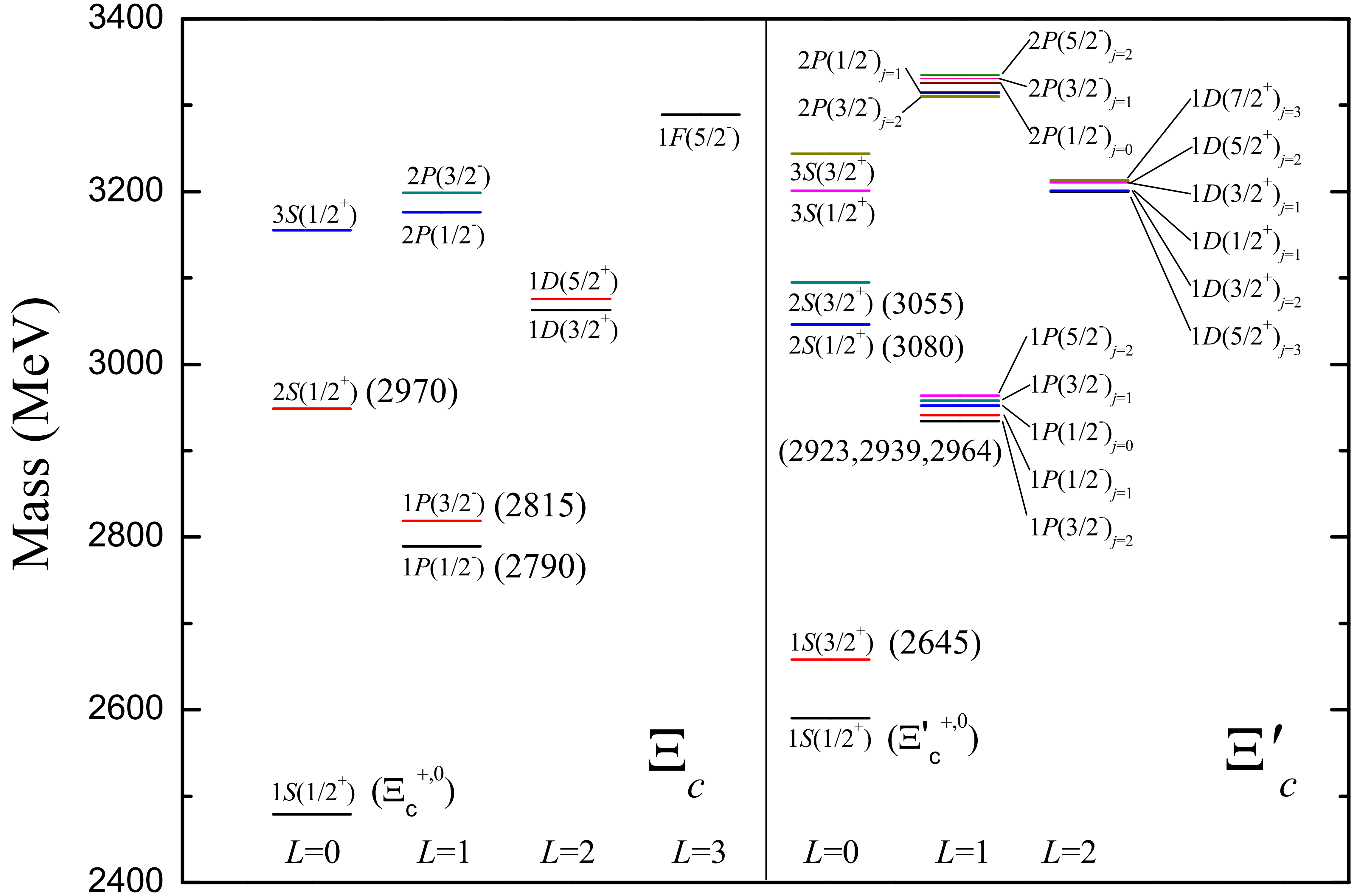
  - not considered in this talk.

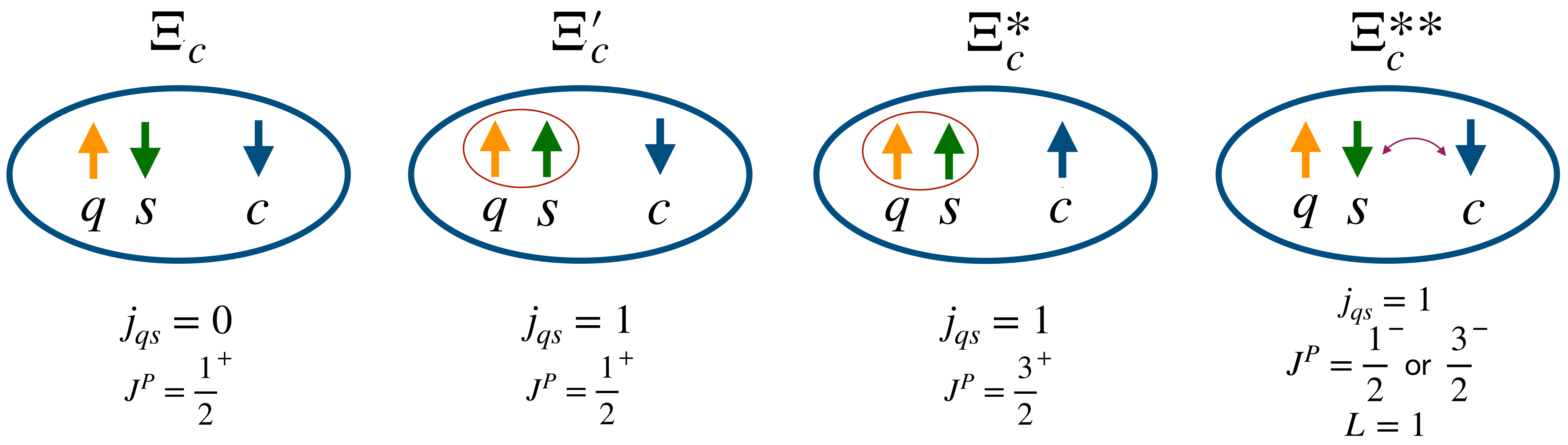
Expected yield

- Using the efficiency-corrected yields of Belle datasets of Λ_c and Ξ_c decays:
  - $\Lambda_c^+ \to pK^-\pi^+$ [2503.04371], efficiency-corrected yield 9.57 million events, $\mathscr{B}_{\mathrm{PDG}}$~6%
  - $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ [2503.17643], efficiency-corrected yield 0.43 million events, $\mathscr{B}_{\mathrm{PDG}}$~3%
  - $\Xi_c^0 \to \Xi^-\pi^+$ [2406.04642], efficiency-corrected yield 0.26 million events, $\mathscr{B}_{\mathrm{PDG}}$~1.4%
  - Summary: prompt Ξ_c cross-section is **about 8…11%** of the Λ_c cross-section
    - Possible worry: signal/background ratio suffers from low cross-section = low signal-to-background ratio

- Inclusive Λ_c yield 36 000 in the Belle paper [1312.7826] (can do better with modern tools) so using the same technique/dataset leads to expected 3000-4000 Ξ_c (once again, can do better)
  - assumes a similar tagging efficiency (could be not true, – tag channels need to have a decent purity)
- Typical branching fractions of the leading decays are a few %: **statistical precision of ~10%** is realistic for Ξ_c
- *Eventually, plan to consider Belle + Belle II for the largest statistical power*
  - *Today's plots – only Belle II simulation*

A side note: what do we expect?



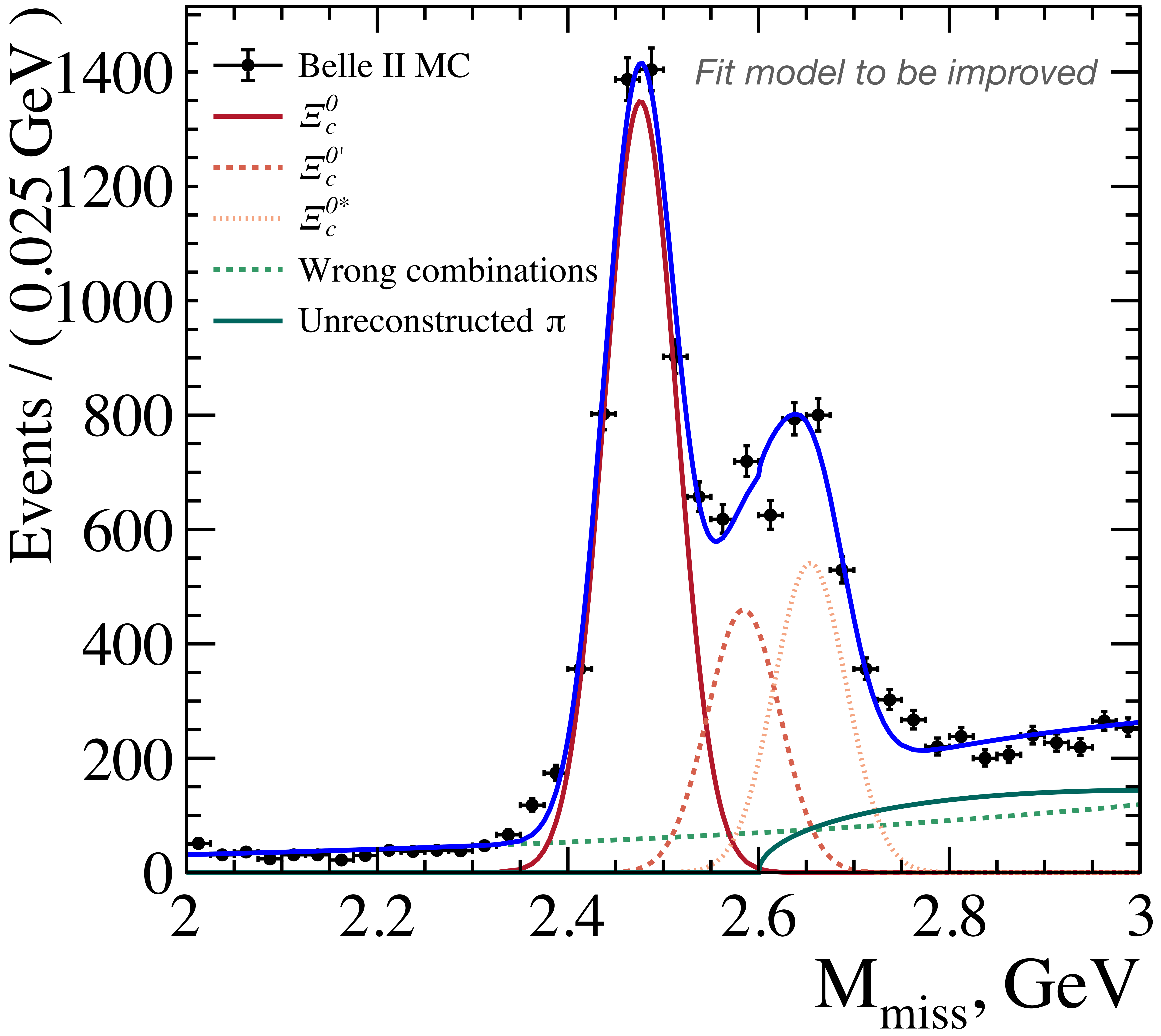


- The tagged dataset will contain not only Ξ_c, *but also its excited states*
- Notably, Ξ_c' and Ξ_c^* with mass splittings only 110 and 175 MeV from the ground state
  - Resolution matters!

Proof of concept: simulation

luminosity corresponds to the Run 1 Belle II dataset

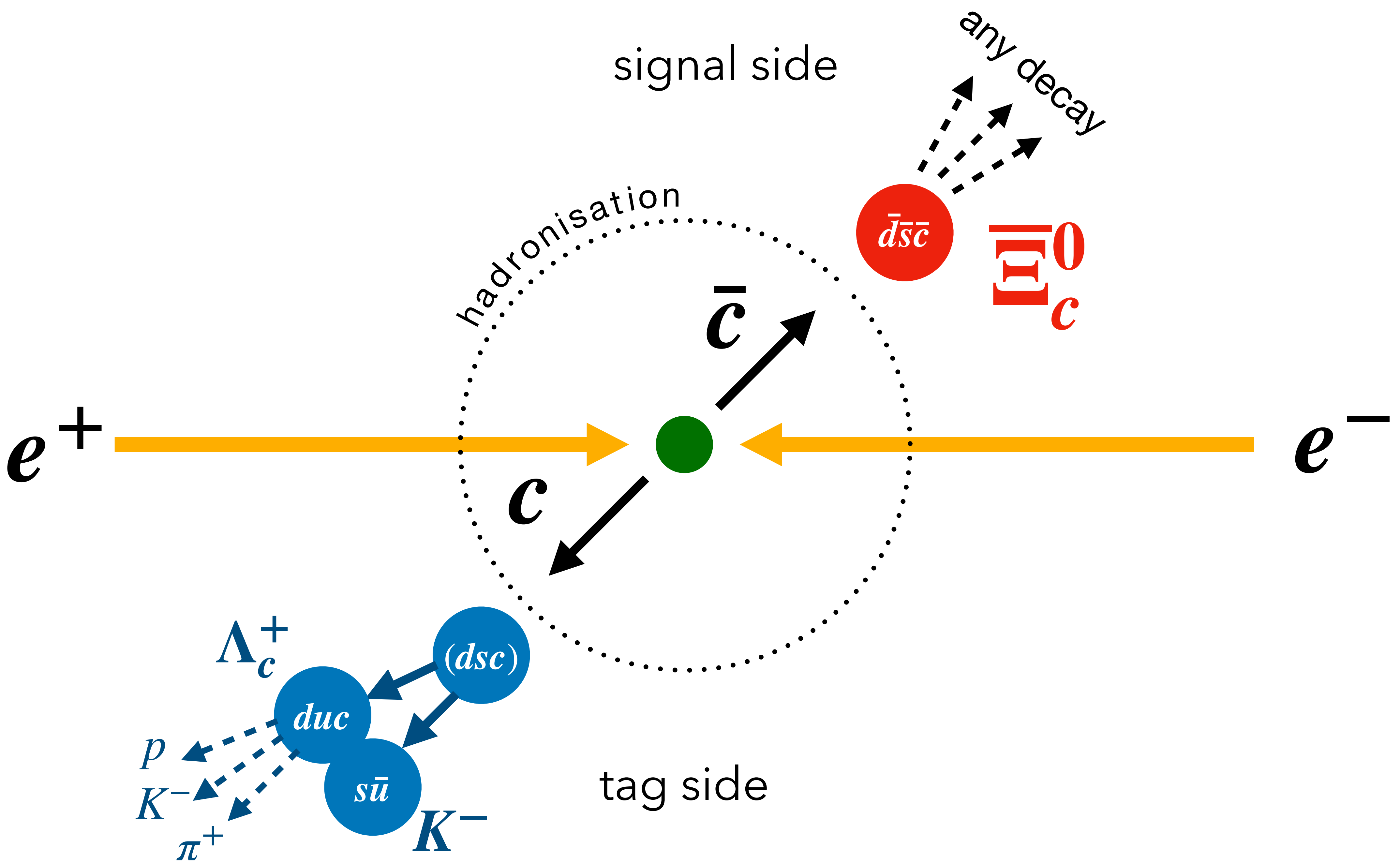
- At first: require that the tag side is reconstructed correctly (truthmatching)
- About 5000 ground-state Ξ_c^0, and ~2000 of each excited state
  - Resolution is OK to distinguish them
- Decent statistical power for our measurement, but:
  - This is simulation: production cross-sections might be too optimistic
    - Note: the Belle dataset not yet included here
  - Background from non-Ξ_c processes not included; suppressing it would lead to lower efficiency

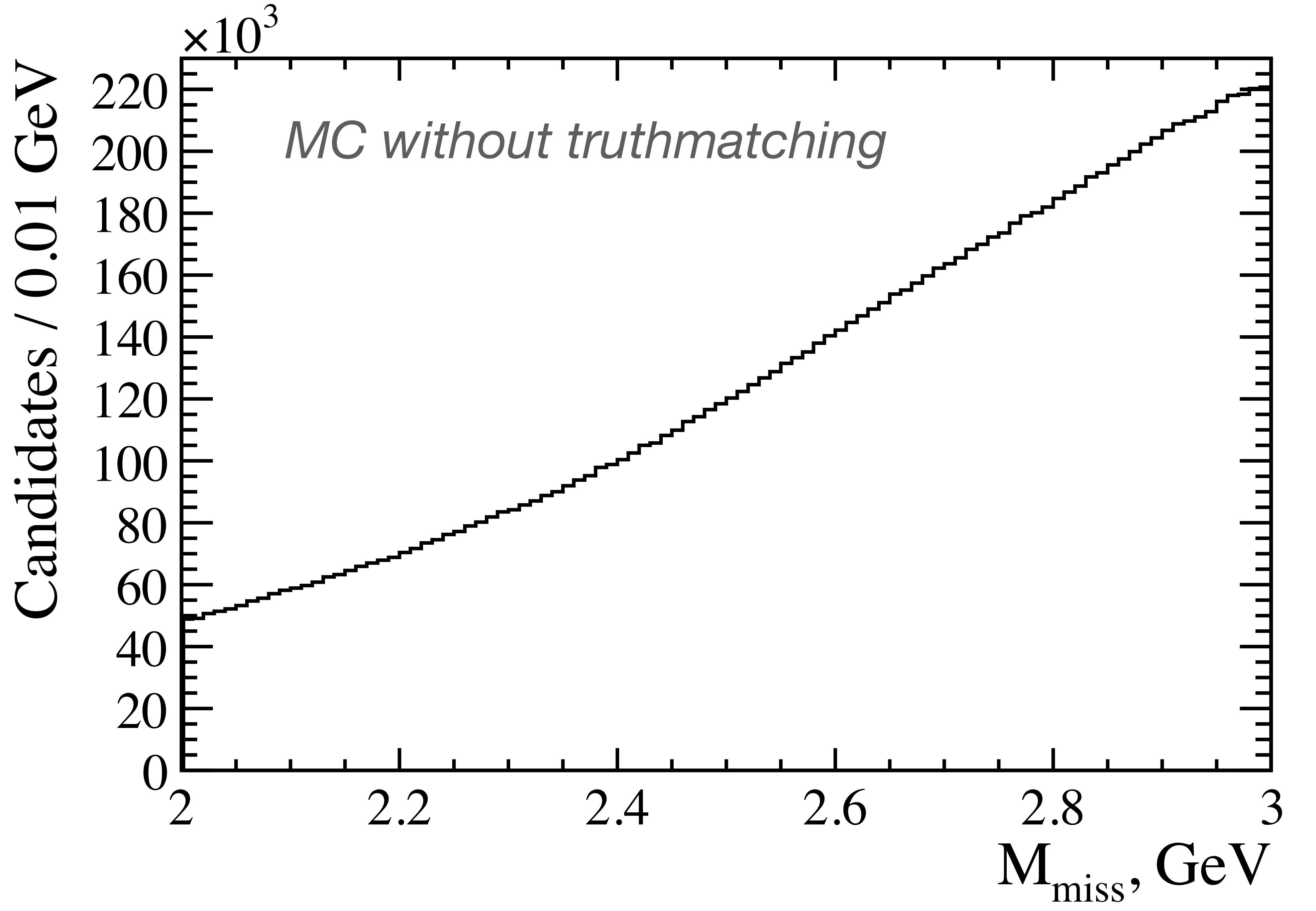


Types of background

- Processes other than $e^+e^- \to c\bar{c}$, such as $e^+e^- \to q\bar{q}$ with light quarks (continuum background)
- Fake tag-side charm hadron candidate: adds to the continuum background
- Misidentified tag-side particles: e.g. $e^+e^- \to \bar{D}^0\Lambda_c^+\bar{p}$ can mimic $e^+e^- \to \bar{\Xi}_c^0\Lambda_c^+K^-$ and produce a peaking background

- Partially reconstructed tag (some tag-side particles left out): bump in the upper sideband
- Over-reconstructed tag (e.g. picking particles from beam background): bump in the lower sideband
  - Had to exclude π^0 from the hadronisation tag system, due to high background levels

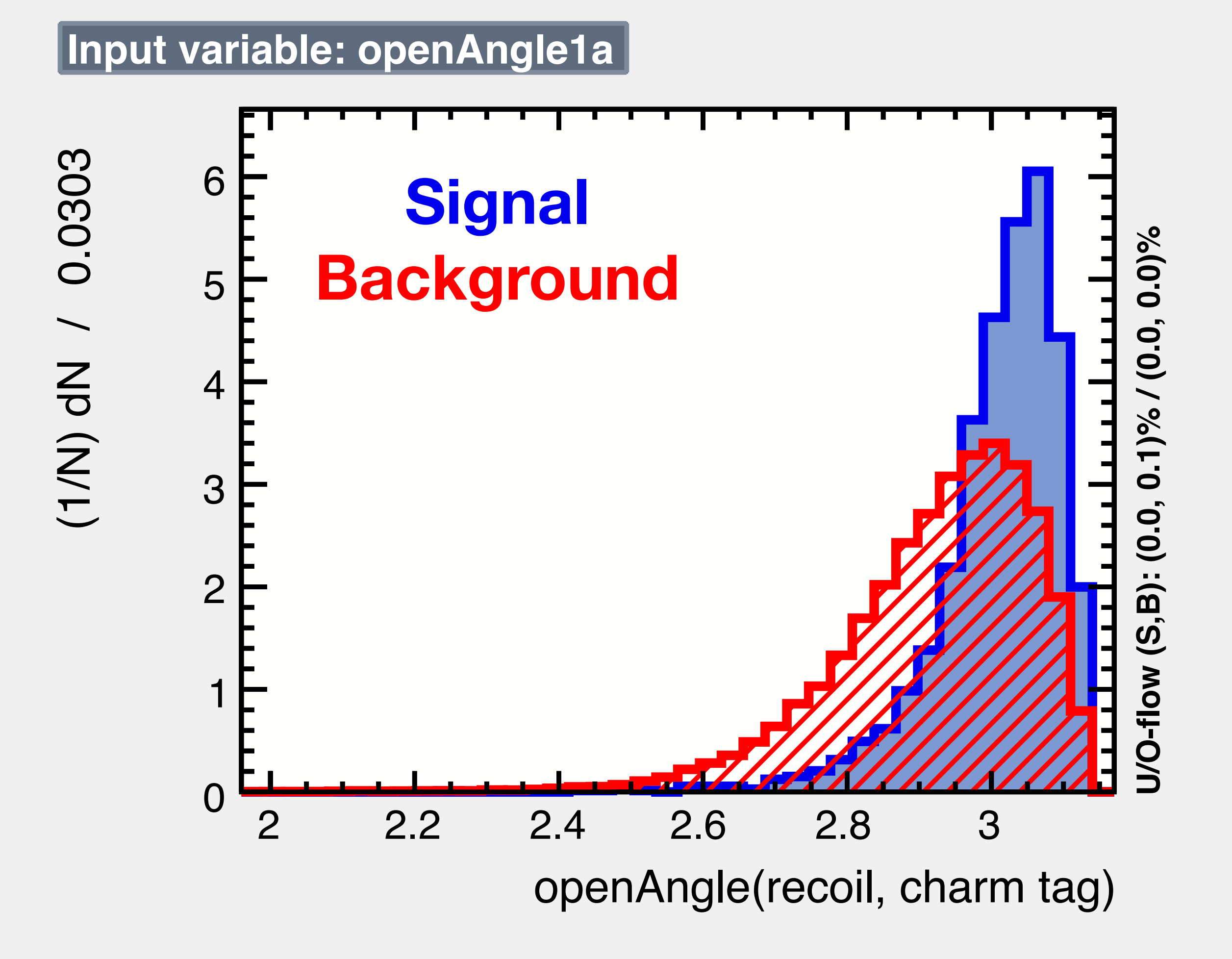




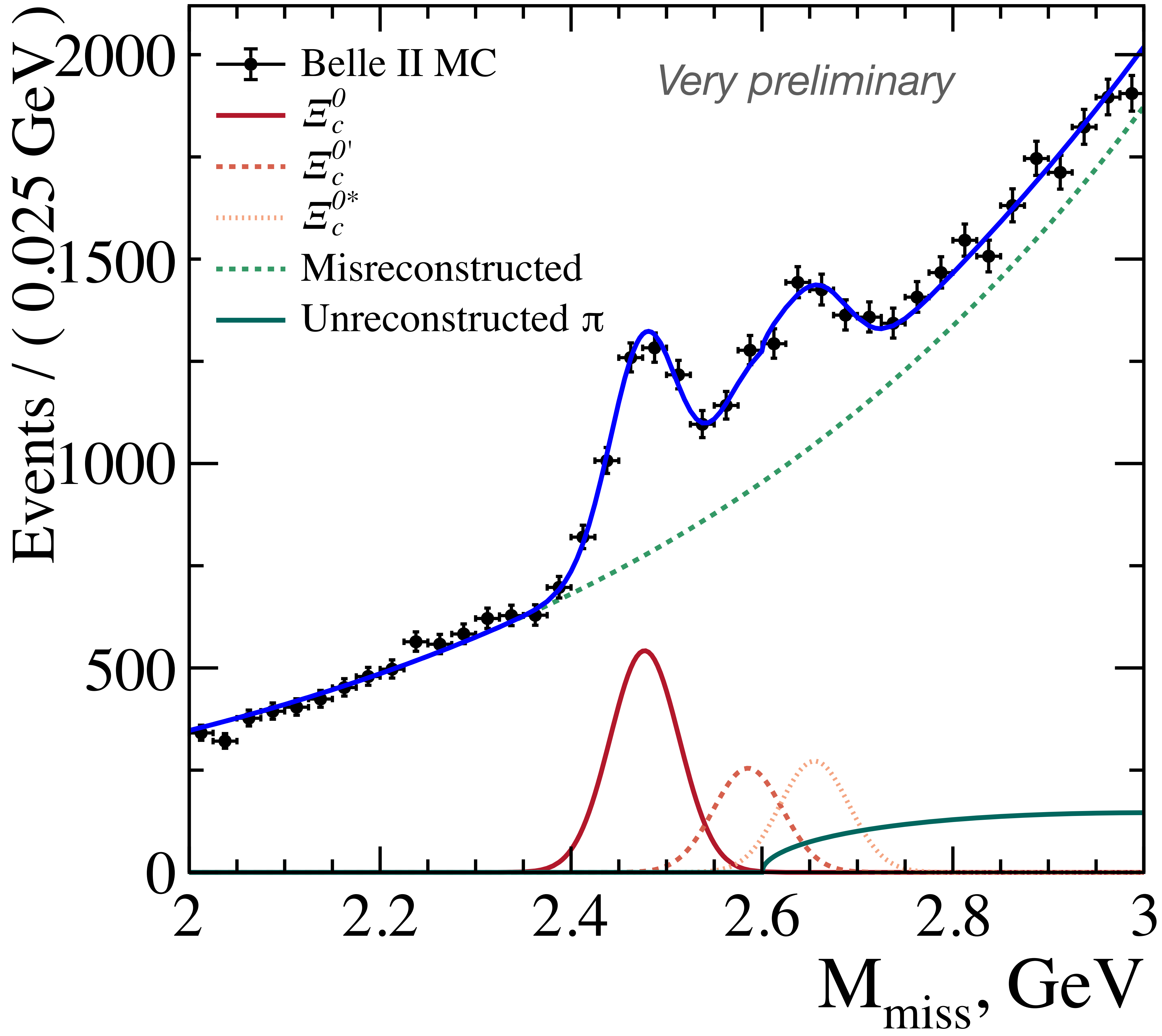
Background suppression

- A BDT classifier aimed at separating properly reconstructed tag from mis-reconstructed tag
  - Use kinematics, displacement and geometry of the tag-side hadrons, as well as the decay-tree-fit χ^2, and the momentum of the recoil (signal-side Ξ_c), etc
  - This suppresses both mis-reconstructed $c\bar{c}$ and the light-quark pairs such as $s\bar{s}$
- Future plans: separate BDT classifiers for each tag category; quantify residual peaking backgrounds

Example input variable: opening angle between the recoil (i.e. signal Ξ_c) and the tag-side charm hadron



Simulated dataset after applying the optimal BDT requirement:



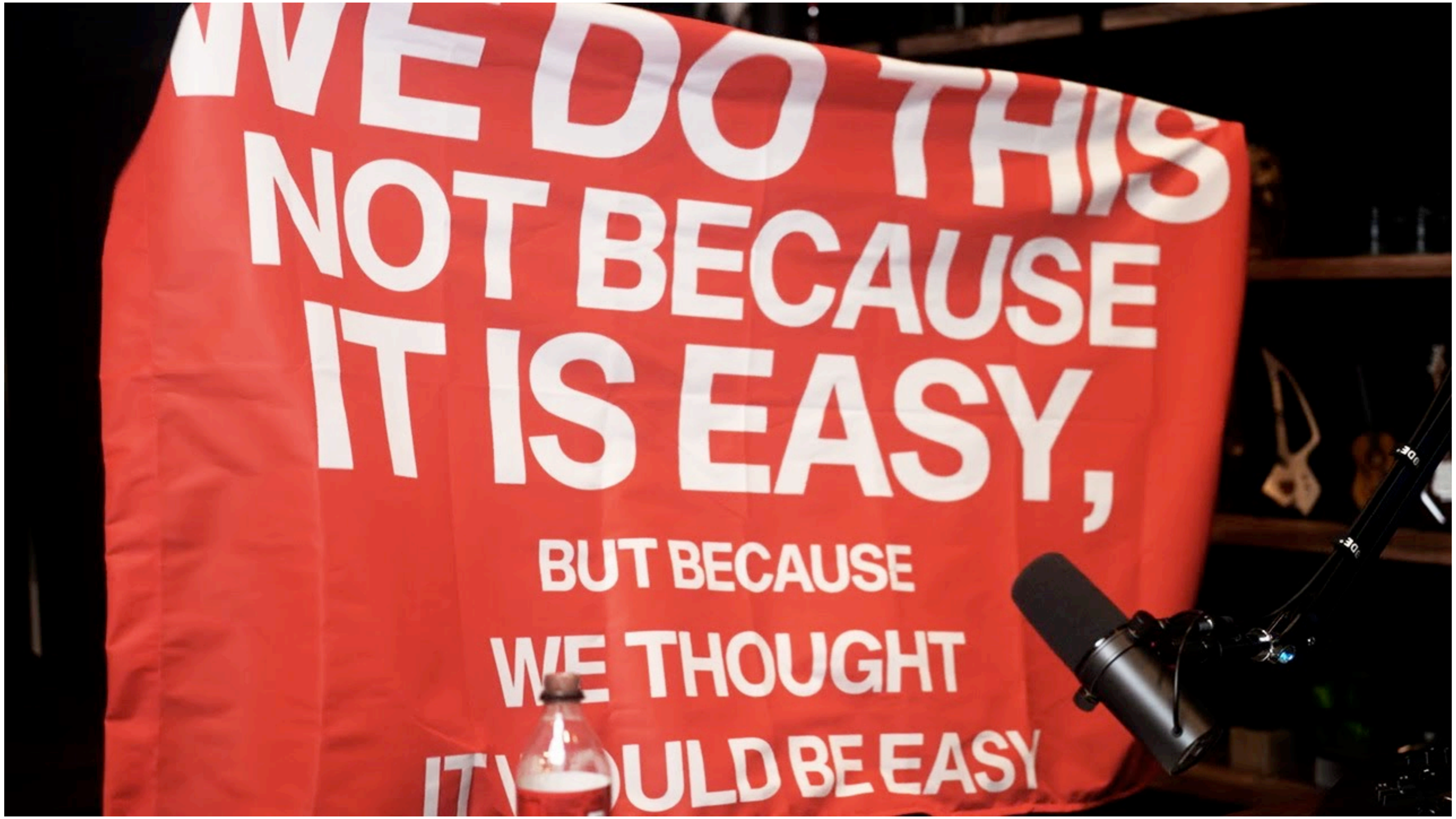
Summary and next steps

- A promising method to deliver world's most precise measurements of the absolute branching fractions of the leading decays of Ξ_c^0, Ξ_c^+ and Ω_c^0 baryons

- Still in early stages; next steps:
  - a more thorough investigation of peaking backgrounds
  - look at data, not just simulation
  - reconstruction of the signal-side decay
  - inclusion of the Belle data

- Possible spin-offs from this method:
  - (inclusive) semileptonic decays of charm baryons: important background for low-mass Drell-Yan measurements at the LHC, and general theoretical interest
  - Inputs to charm-baryon spectroscopy
  - Improved knowledge on charm-baryon fragmentation (e.g. proportion of ground/excited states)
  - etc

End


WE DO THIS
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