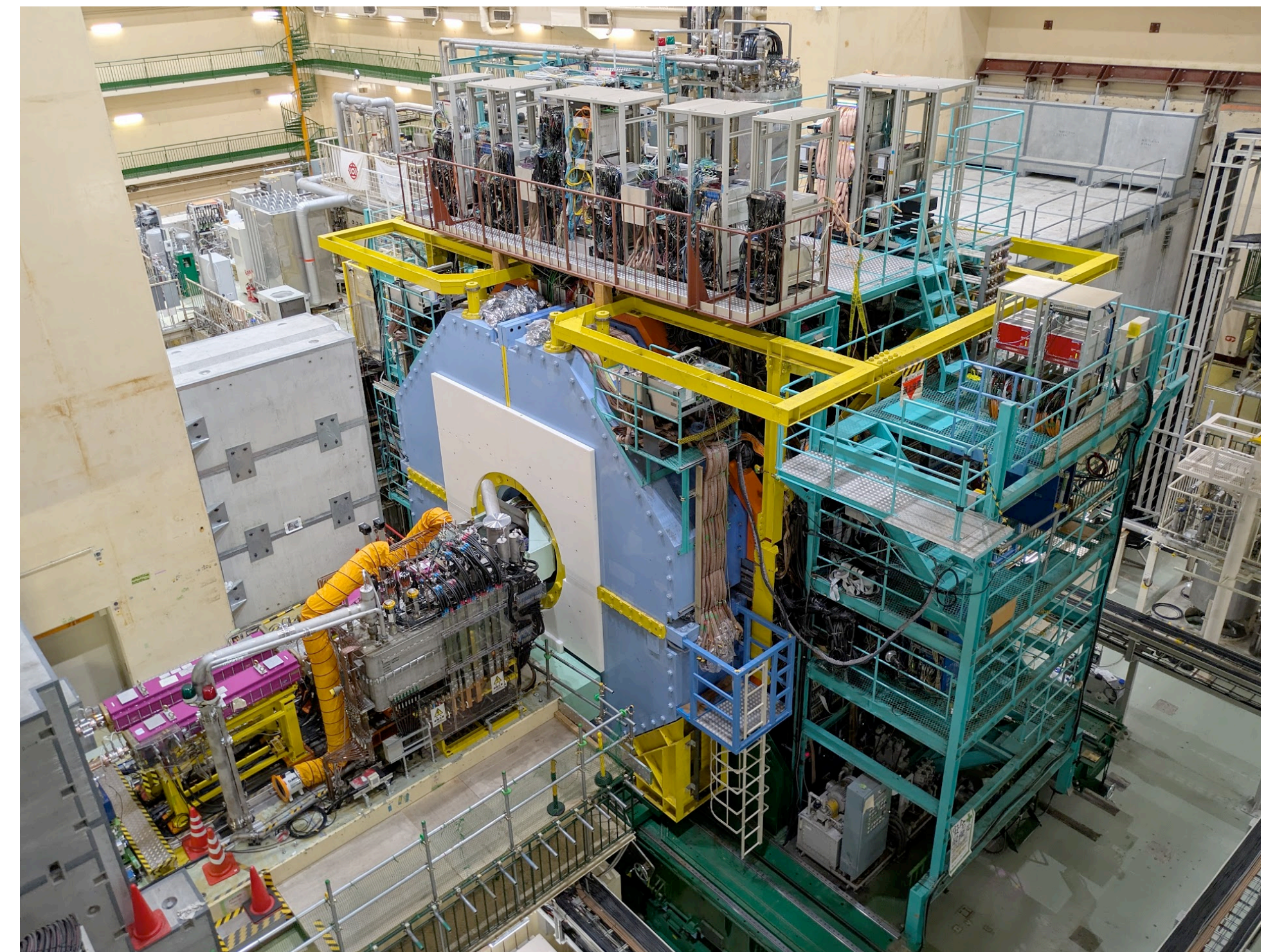


Inclusive reconstruction of charm baryons, and measurement of their *absolute* decay rates at the Belle II experiment

(work in progress)

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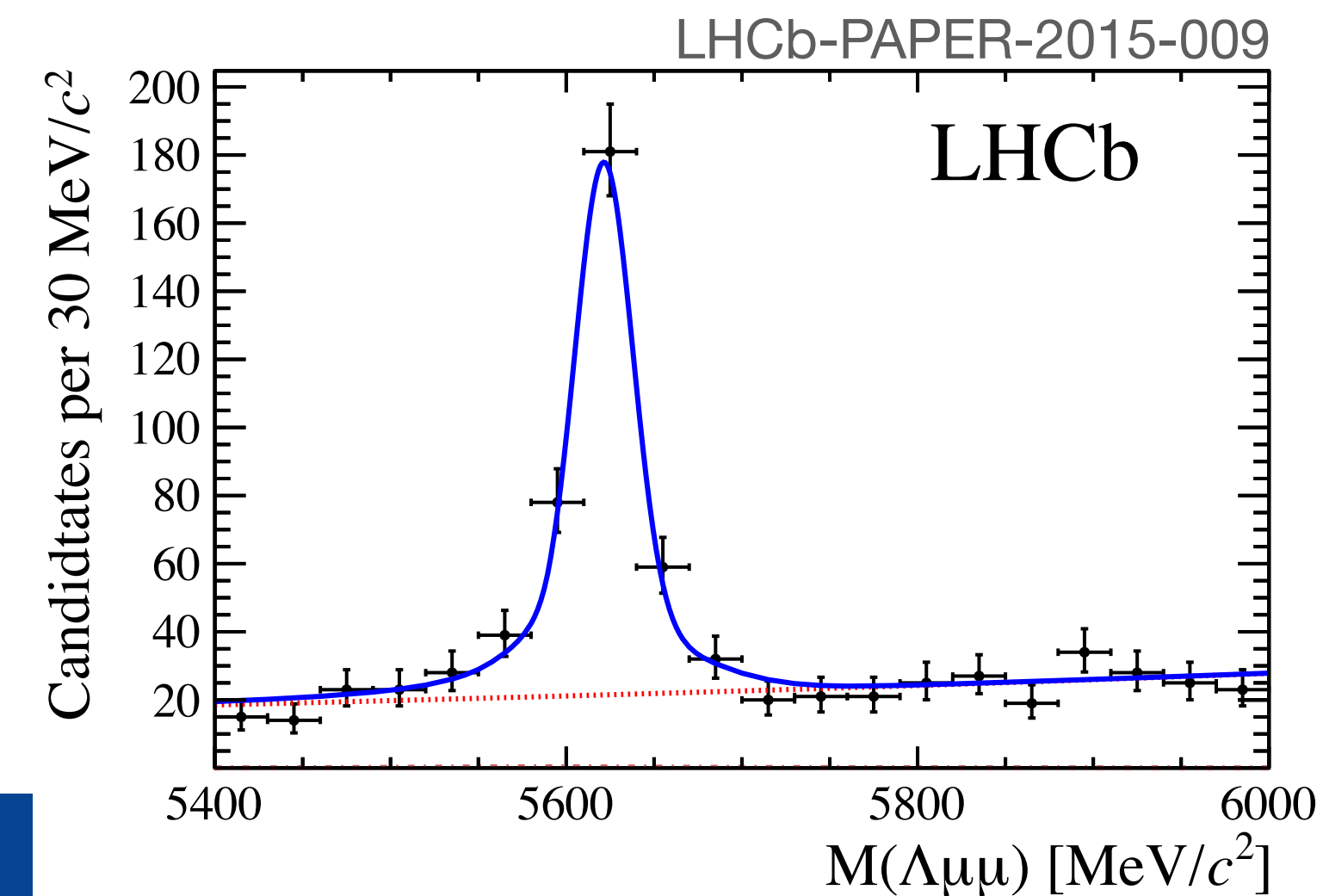
Setting the scene

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- Previous talk: study of the $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$ decay
- But: how does one measure the **rate** of the $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$ decay at LHCb?

$$\Gamma_{70} \quad \Lambda \mu^+ \mu^- \quad (1.08 \pm 0.28) \times 10^{-6}$$

- One needs to know:
 1. How many Λ_b^0 baryons (quark content udb) were produced at LHCb?
 - ???
 - when LHCb started, cross-section was unknown (no previous experiments at 7...13 TeV)
 - how do we measure it?
 2. How many out of them have decayed to the $\Lambda \mu^+ \mu^-$ final state?
 - "easy": just count

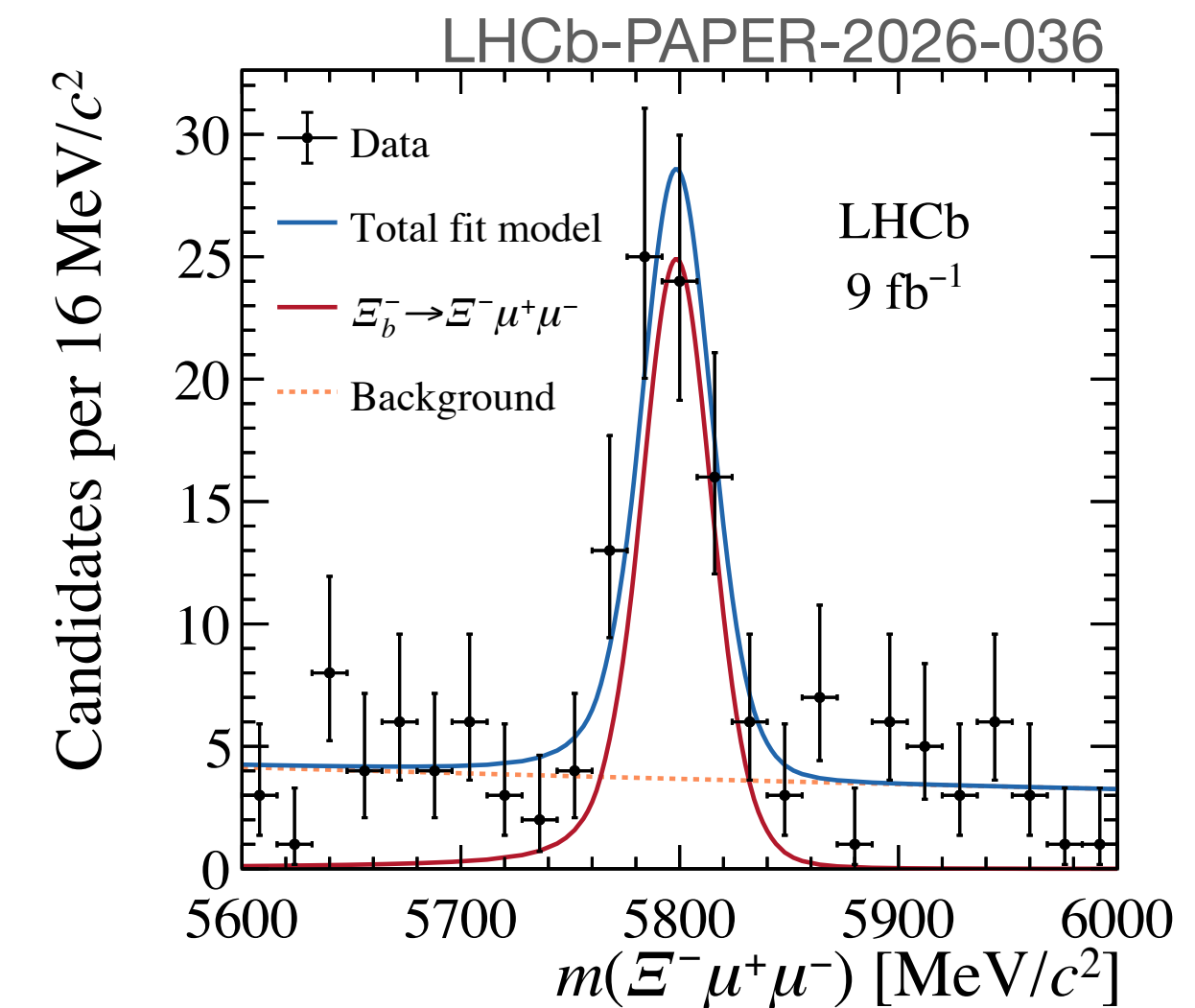


Production cross-sections of b-baryons at LHCb

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- To measure the cross-section of Λ_b^0 , we need to find a way to detect the Λ_b^0
 - At LHCb, the ~only way is to measure its **decay to a specific final state**
 - Very difficult to know the initial state without reconstructing the final state
- If we find a **decay** that has a **reliable theoretical prediction** for its rate, then we can count decays into this final state and infer the cross-section
- A friendly theorist tells us that they can reliably calculate the inclusive $b \rightarrow c\mu^-\bar{\nu}_\mu$ rate, that is: a sum of $\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_{\mu'}$, $\Lambda_b^0 \rightarrow \Lambda_c^{*+}\mu^-\bar{\nu}_{\mu'}$, etc
 - At the quark level, $ud\bar{b} \rightarrow ud\bar{c}\mu^-\bar{\nu}$
 - However: how do we detect Λ_c^+ ? It can decay into hundreds of modes...
 - here we go again...
 - **Luckily, other experiments (Belle II and BES III) have measured the absolute Λ_c^+ decay rates**
- Great! We have measured the Λ_b^0 cross-section!
 - We can now measure absolute rates of Λ_b^0 decays

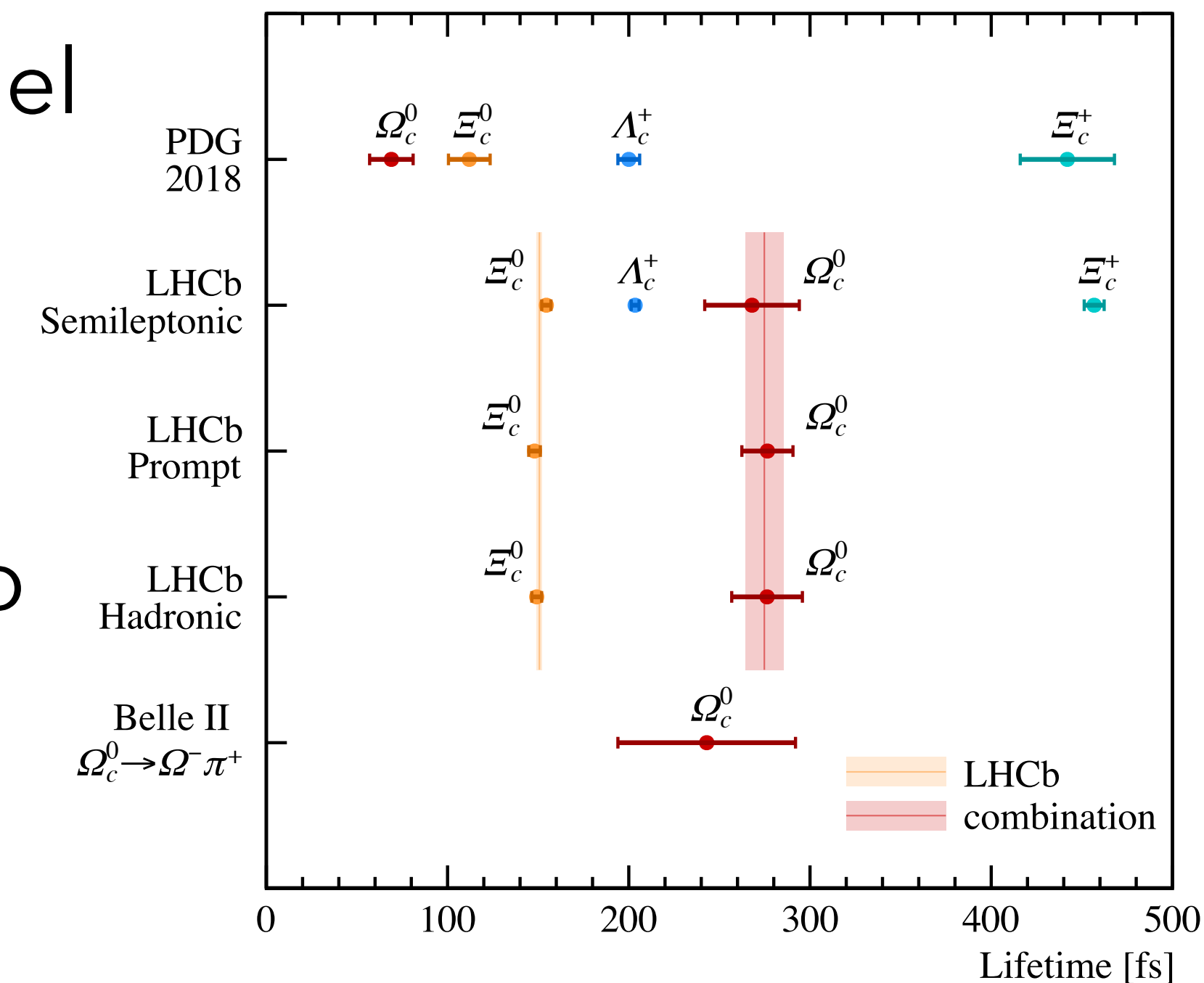
- Λ_b^0 is the simplest b-quark baryon (udb), but there are many others
 - Ξ_b^0 (usb), Ξ_b^- (dsb), Ω_b^- (ssb) have an interesting physics case, too
 - **Absolute rates of their (any!) decays have not been measured**
- Recently, LHCb has observed the rare decay $\Xi_b^- \rightarrow \Xi^- \mu^+ \mu^-$: a SU(3) partner of the $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$
- How to measure its decay rate?
 - For now: assumptions about SU(3) symmetry between Ξ_b^- and Λ_b^0 baryons
 - this is not precise enough, SU(3) breaking may reach 30%
 - Need an independent measurement of the Ξ_b^- cross-section
 - Easy? Same as before... measure using $\Xi_b^- \rightarrow \Xi_c^0 \mu^- \bar{\nu}_\mu$ and $\Xi_b^- \rightarrow \Xi_c^{*0} \mu^- \bar{\nu}_\mu$?
 - Problem: need to reconstruct Ξ_c^0 , and the current precision on Ξ_c^0 decay rates is $\sim 20\%$ (or worse)



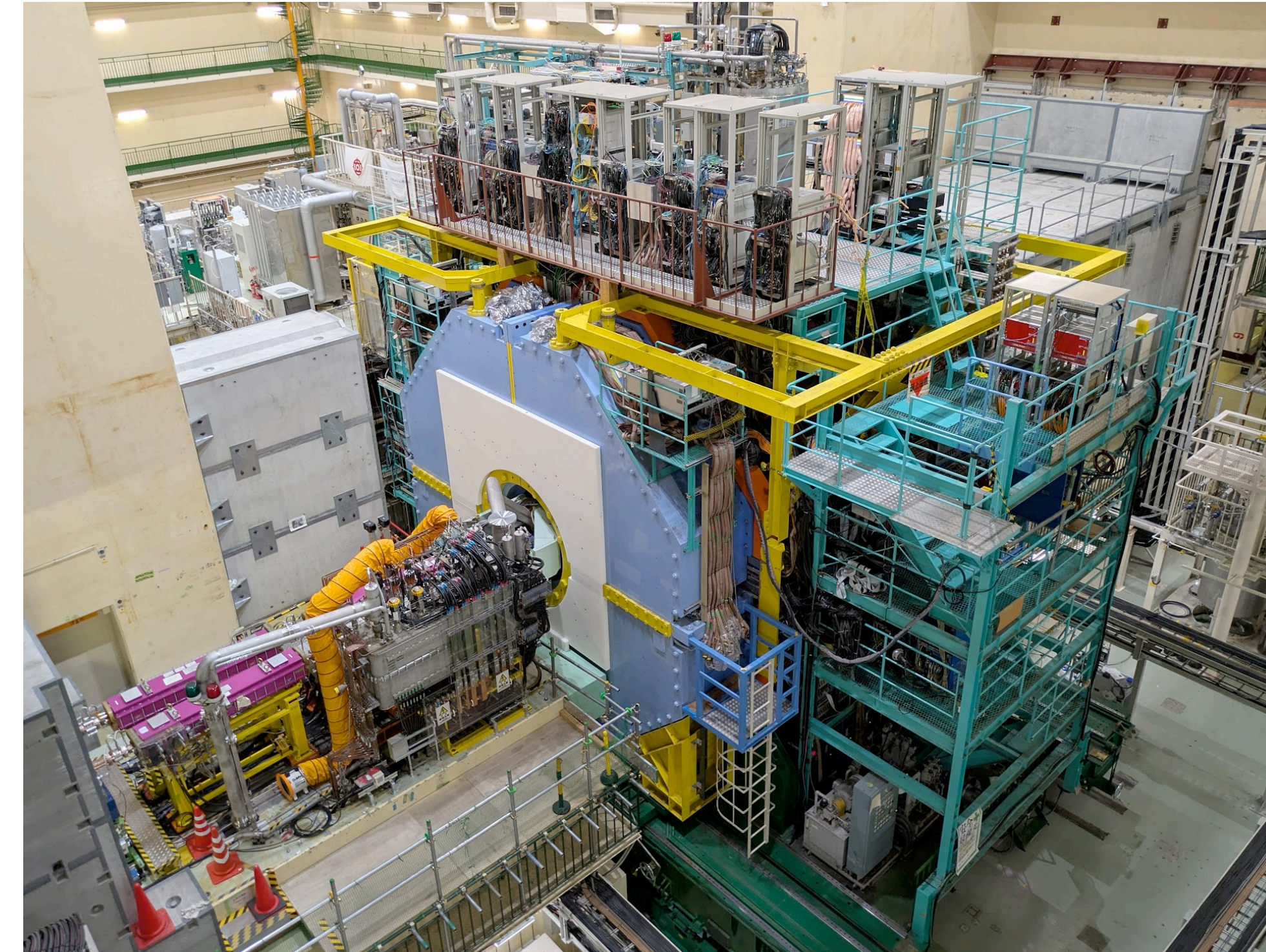
Setting the scene: charm

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- 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 $\Omega_c^0(ssc)$
 - Out of these four, only the Λ_c^+ is studied satisfactorily well
- Ξ_c^0 : absolute decay rates known to precision of $\sim 20\%$
 - Not sufficient for precision testing of the Standard Model
 - Lifetime [total decay width] poorly known until recently
- Ξ_c^+ : absolute branching fractions known to $\sim 45\%$
- Ω_c^0 : absolute branching fractions not known at all, but also
 - lifetime was only properly measured a few years ago
 - only a dozen decay modes known



- **Poor knowledge of charm-baryon decay rates slows down the b-baryon physics**
- Can Belle II do anything about it?
- Experiment introduced yesterday by Roman
 - e^+e^- collisions at 10.58 GeV
 - Not enough to produce b-baryons
 - $e^+e^- \rightarrow c\bar{c}$ production cross-section 1.3 nb
 - additional secondary production from B-meson decays (rare)
- Clean(er) environment compared to LHCb: we know the initial state precisely



How does one measure an *absolute* decay rate?

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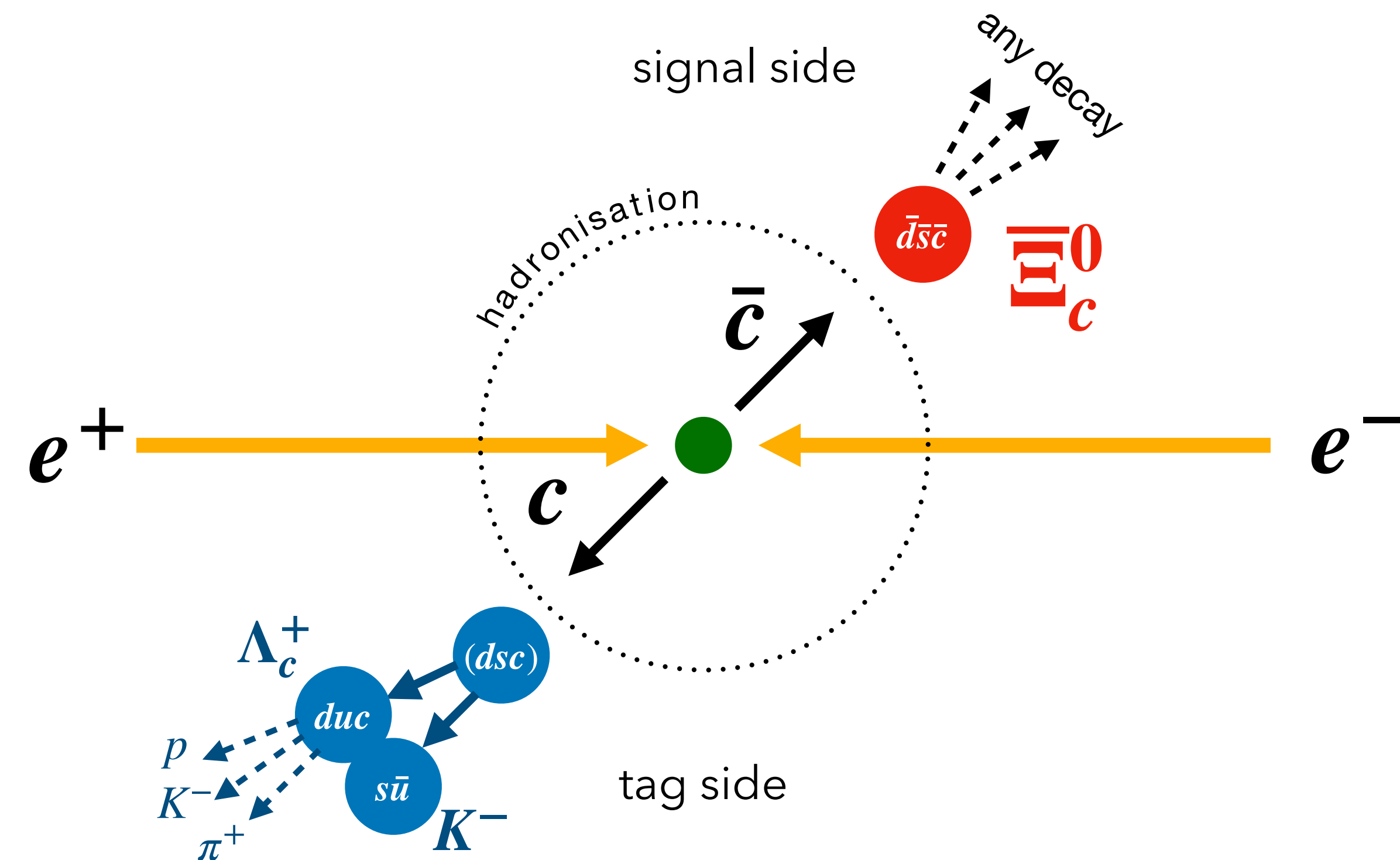
- We need to know:
 - **How many baryons have been produced? [*inclusive*]** $\mathcal{B} = \frac{N_{\text{exclusive \& inclusive}}}{N_{\text{inclusive}} \times \epsilon_{\text{exclusive}}}$
 - This is tricky
 - **How many, out of those, have decayed to the final state of interest? [*exclusive*]**
 - This is easy: a peak in the invariant mass of its decay products
- Problem: charm-baryon production cross-section at Belle II remains unknown!
 - We know the $e^+e^- \rightarrow c\bar{c}$ cross-section but hadronisation of c quark into a charm baryons is poorly understood
- **4π detector: obtain an inclusive sample of prompt charm baryons by reconstructing *all other* particles in the event**

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

The key idea

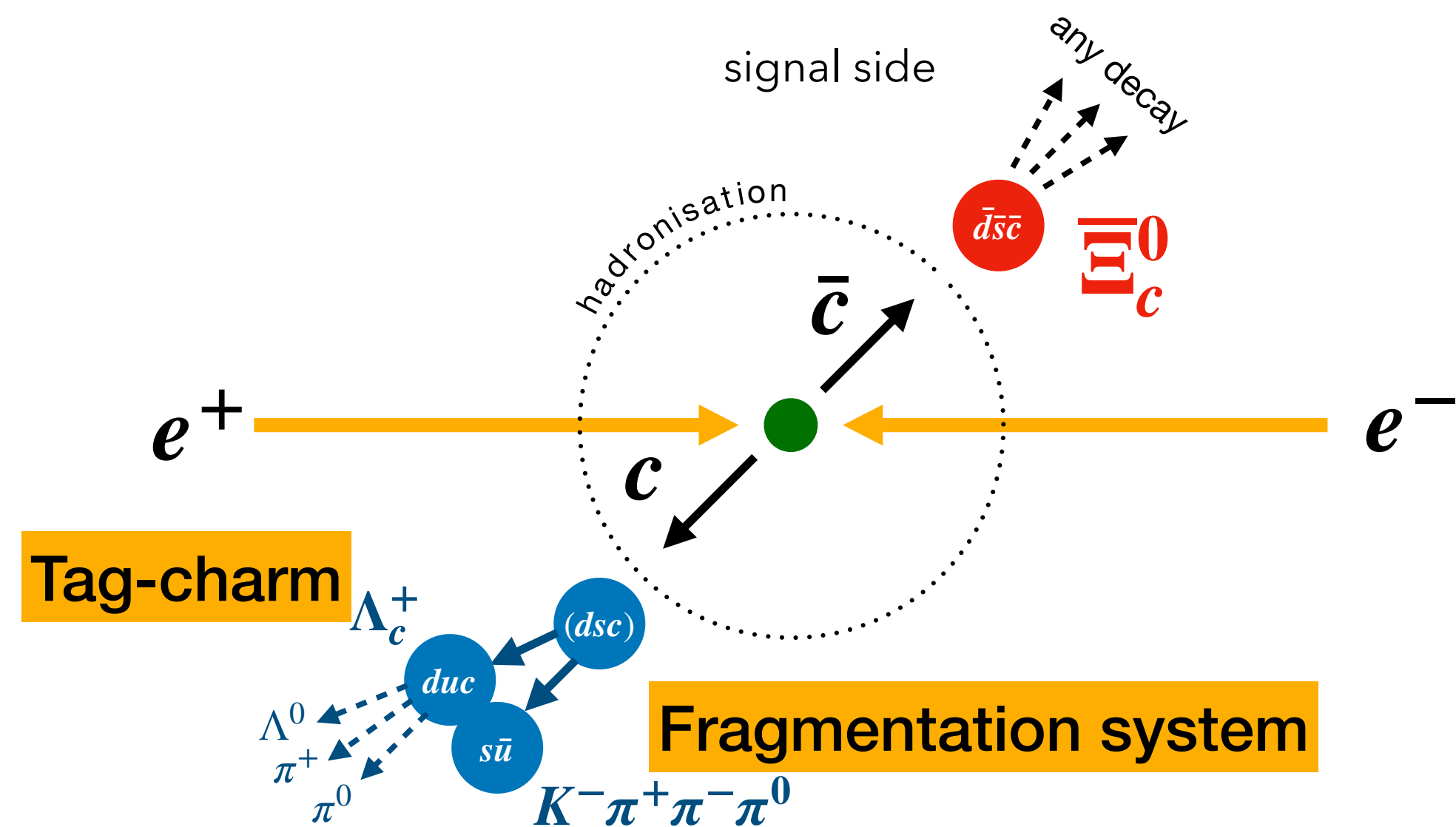
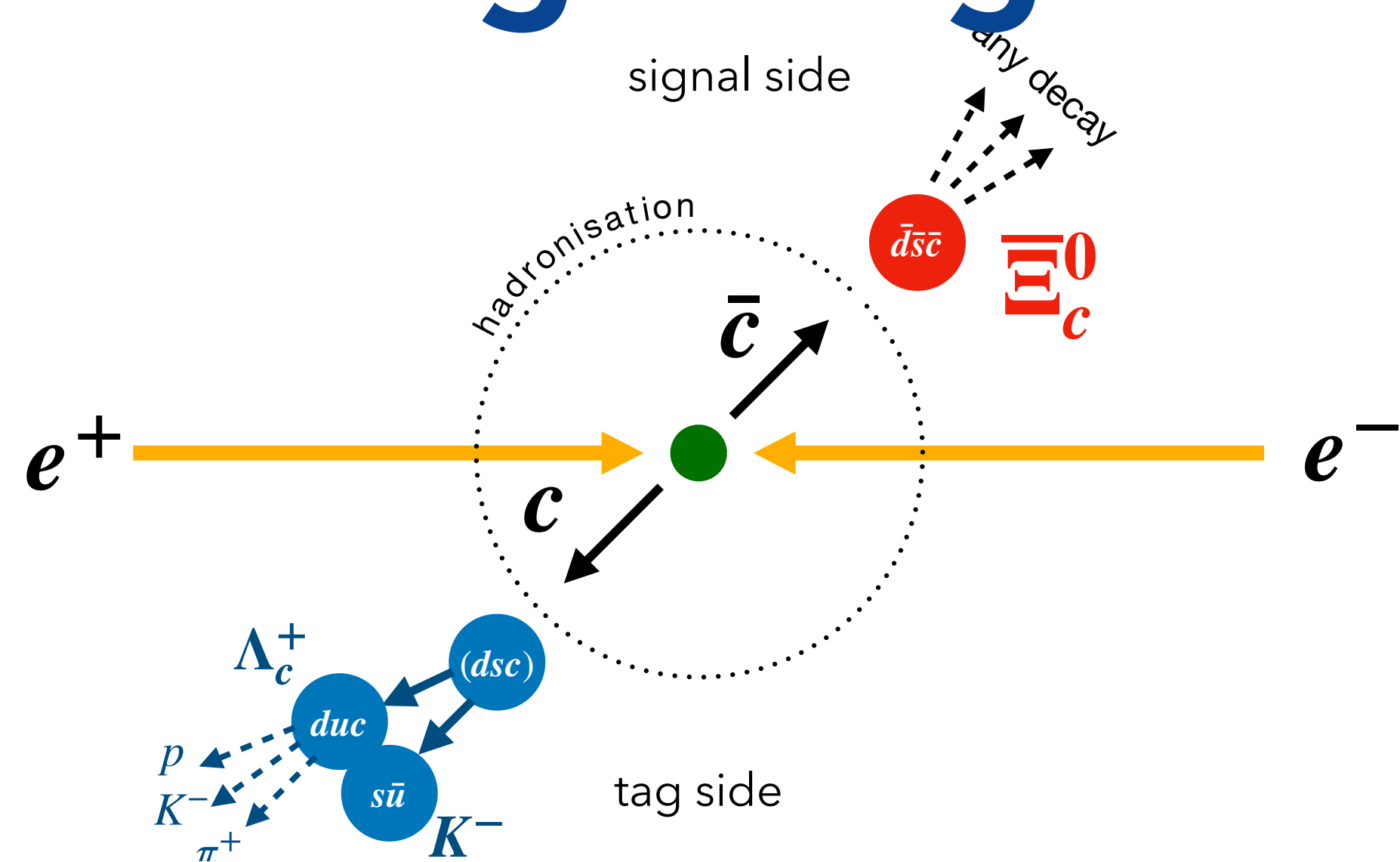
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- Use conservation of baryon number, charm and strangeness in $e^+e^- \rightarrow c\bar{c}$
- Step 1: reconstruct dozens of tag-side channels
 - Use **missing mass** to measure the **inclusive** Ξ_c yield
- Step 2: reconstruct **exclusively** the **most abundant** decay mode of Ξ_c baryon in the "rest of the event", and measure their absolute rates: e.g. $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+ \dots$
 - Known *ratios* of various decay rates will allow to improve knowledge for all other decays

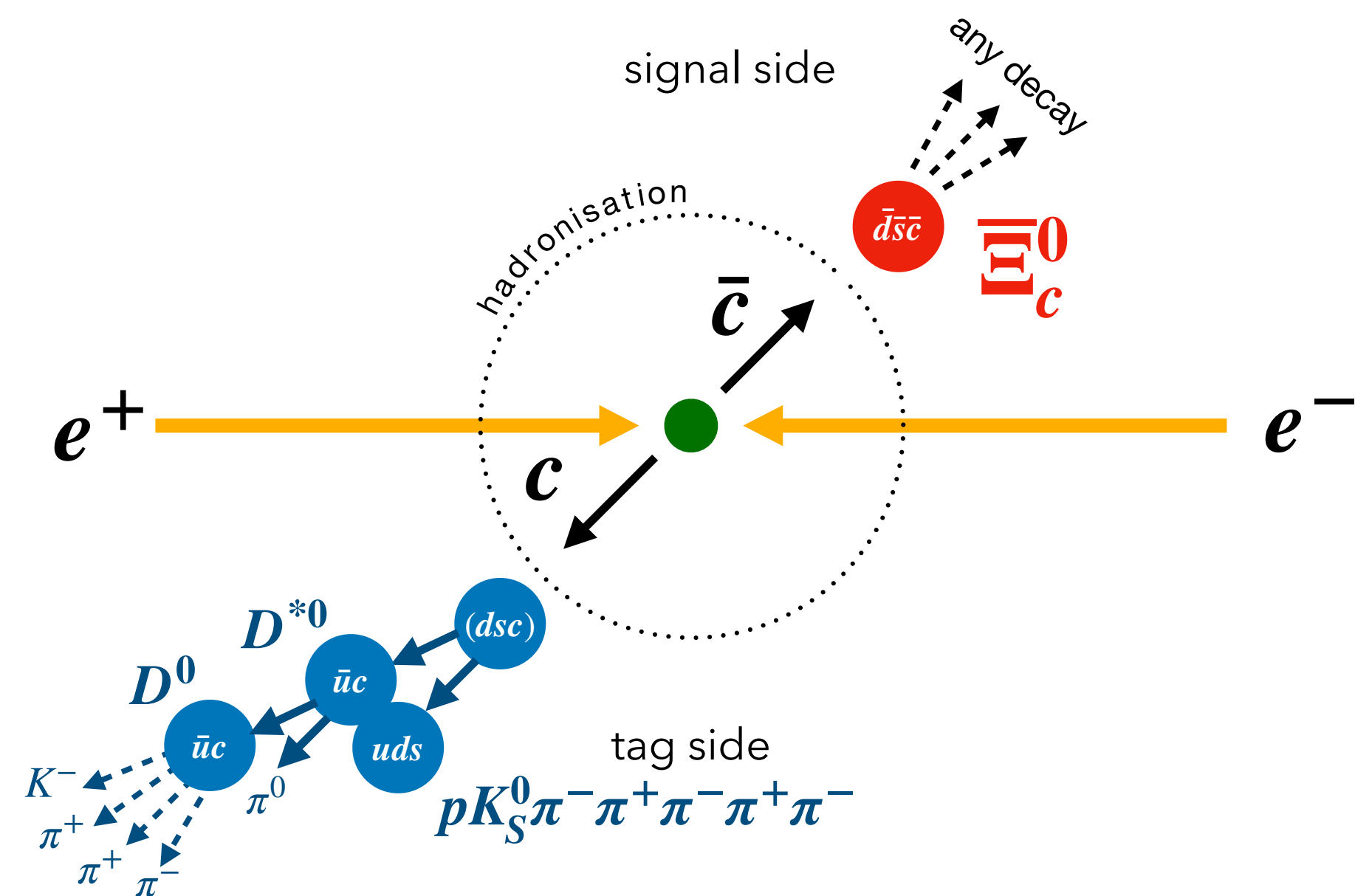
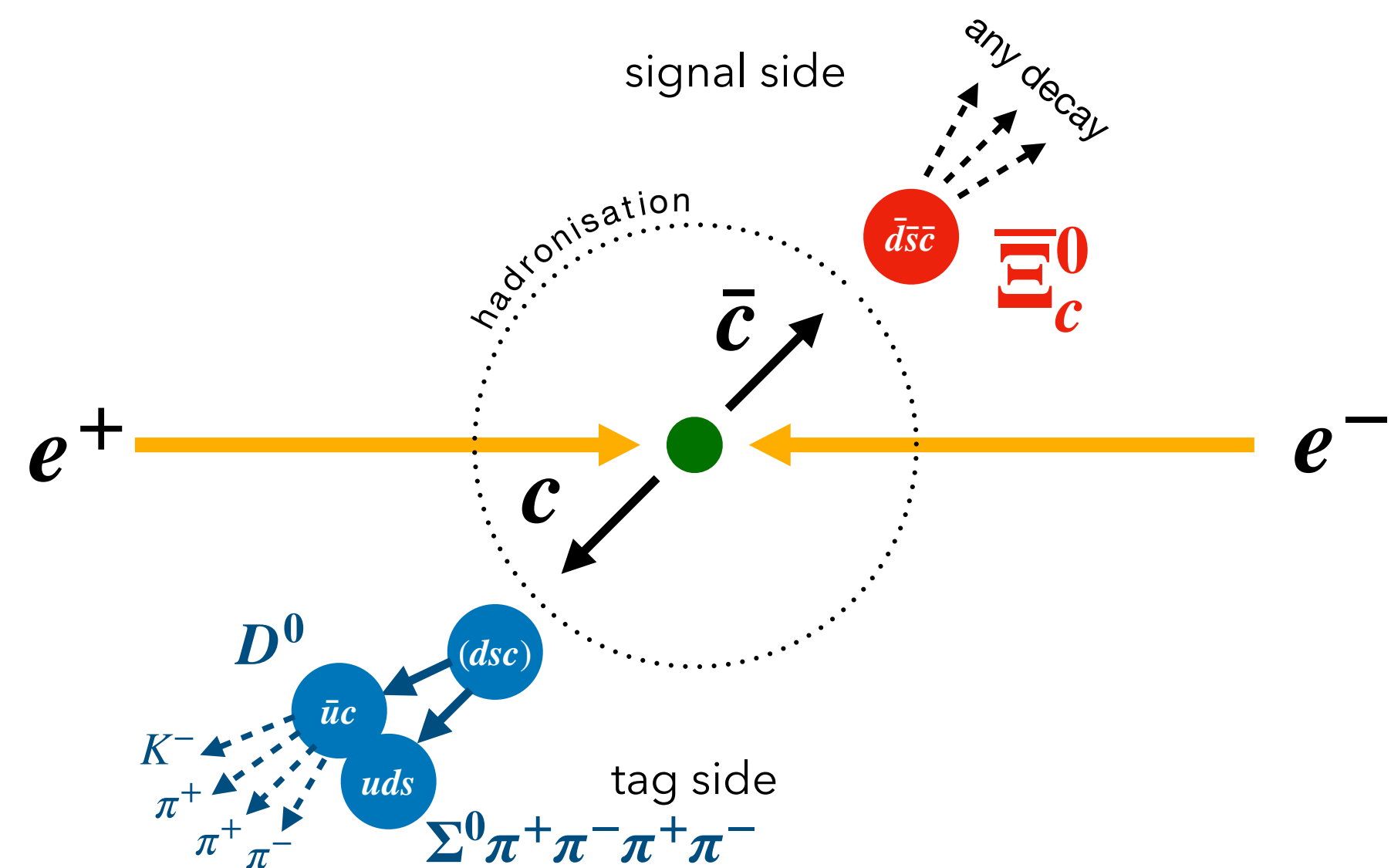


A challenge: fragmentation

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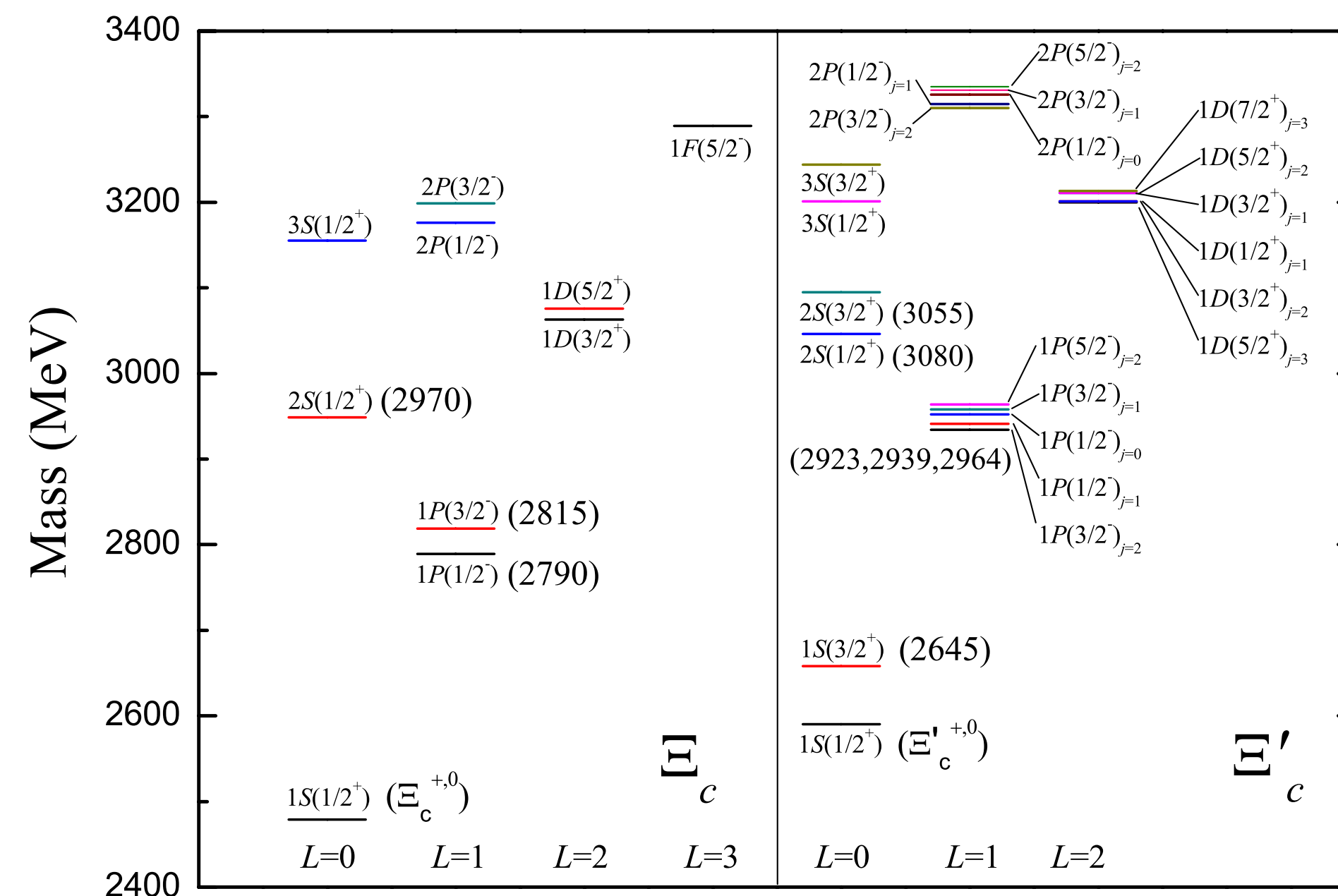
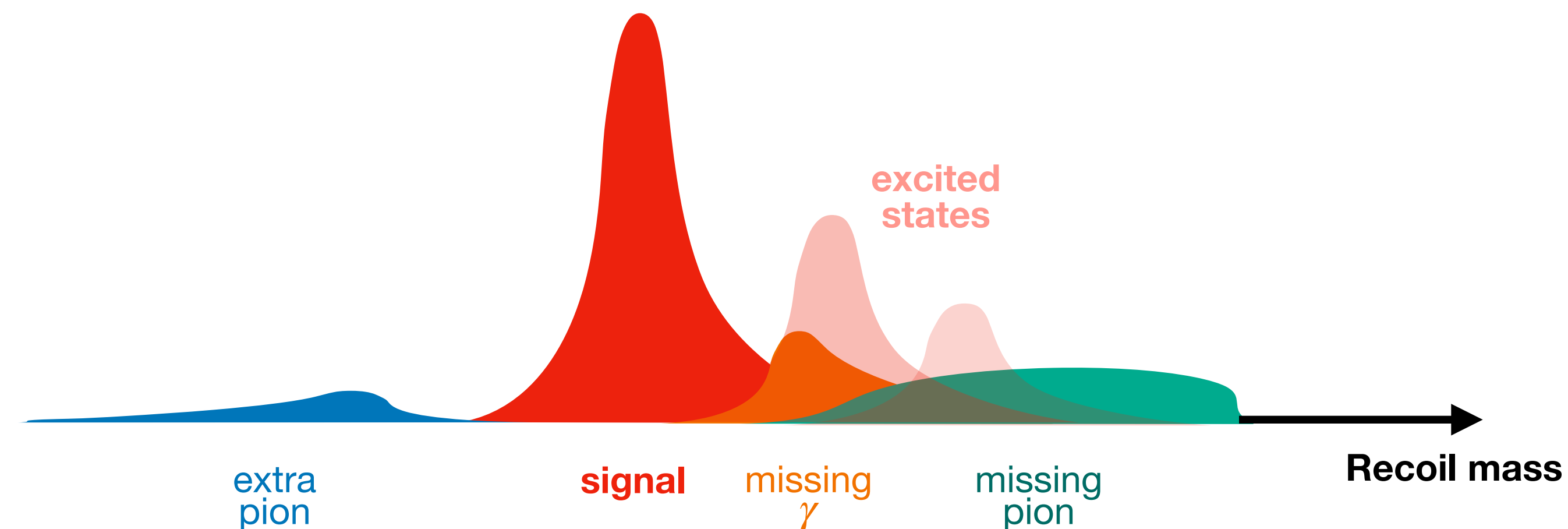


Fragmentation system



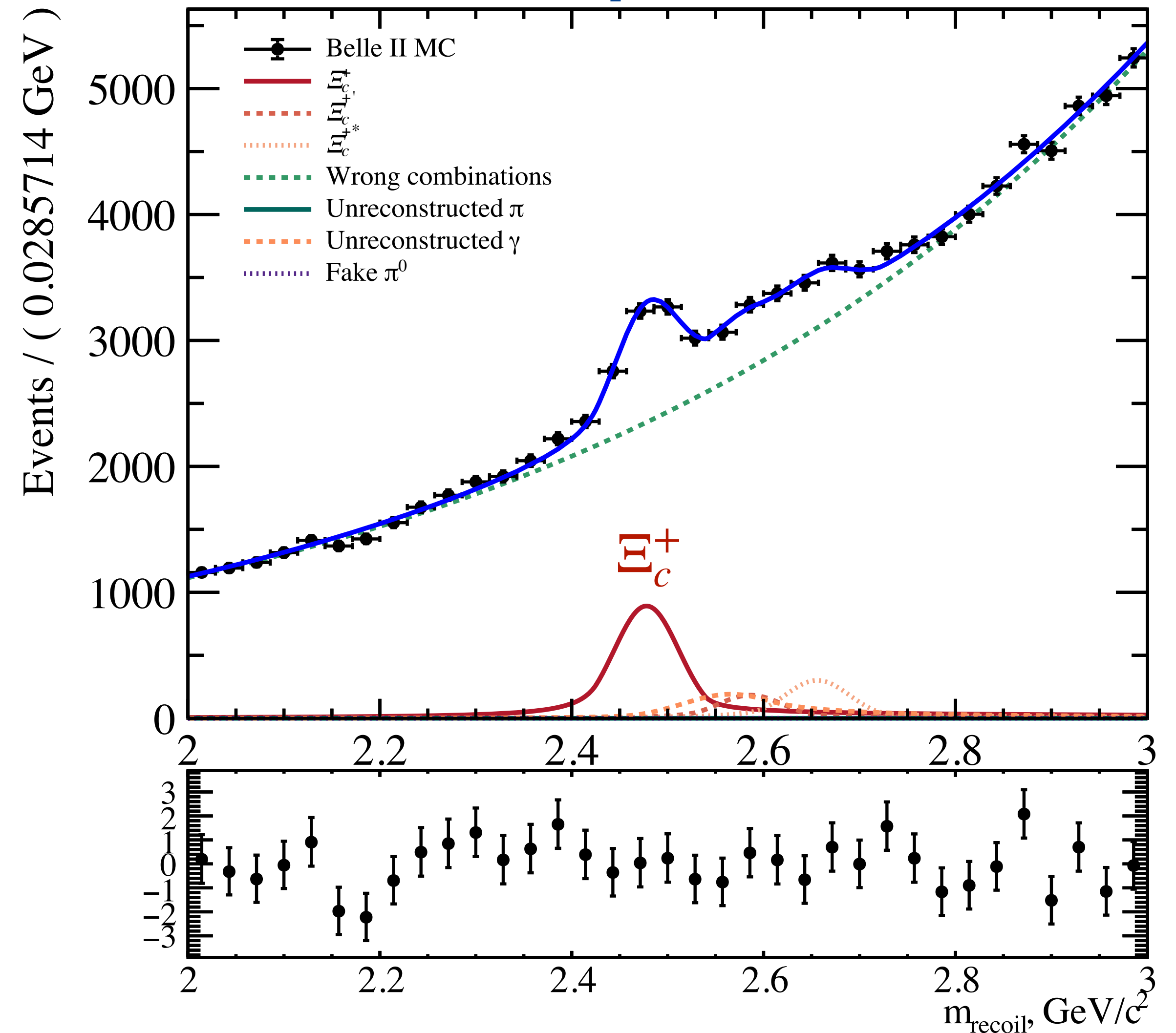
Recoil mass model

- We are sensitive not only to the Ξ_c^+ but also to its excited states



- A clear Ξ_c^+ peak is seen in the recoil-mass distribution
- Summary: we are able to reconstruct Ξ_c^+ from its **production mechanism**, without using any information about its decay!
- We can count how many Ξ_c^+ was produced

Proof of concept with simulation



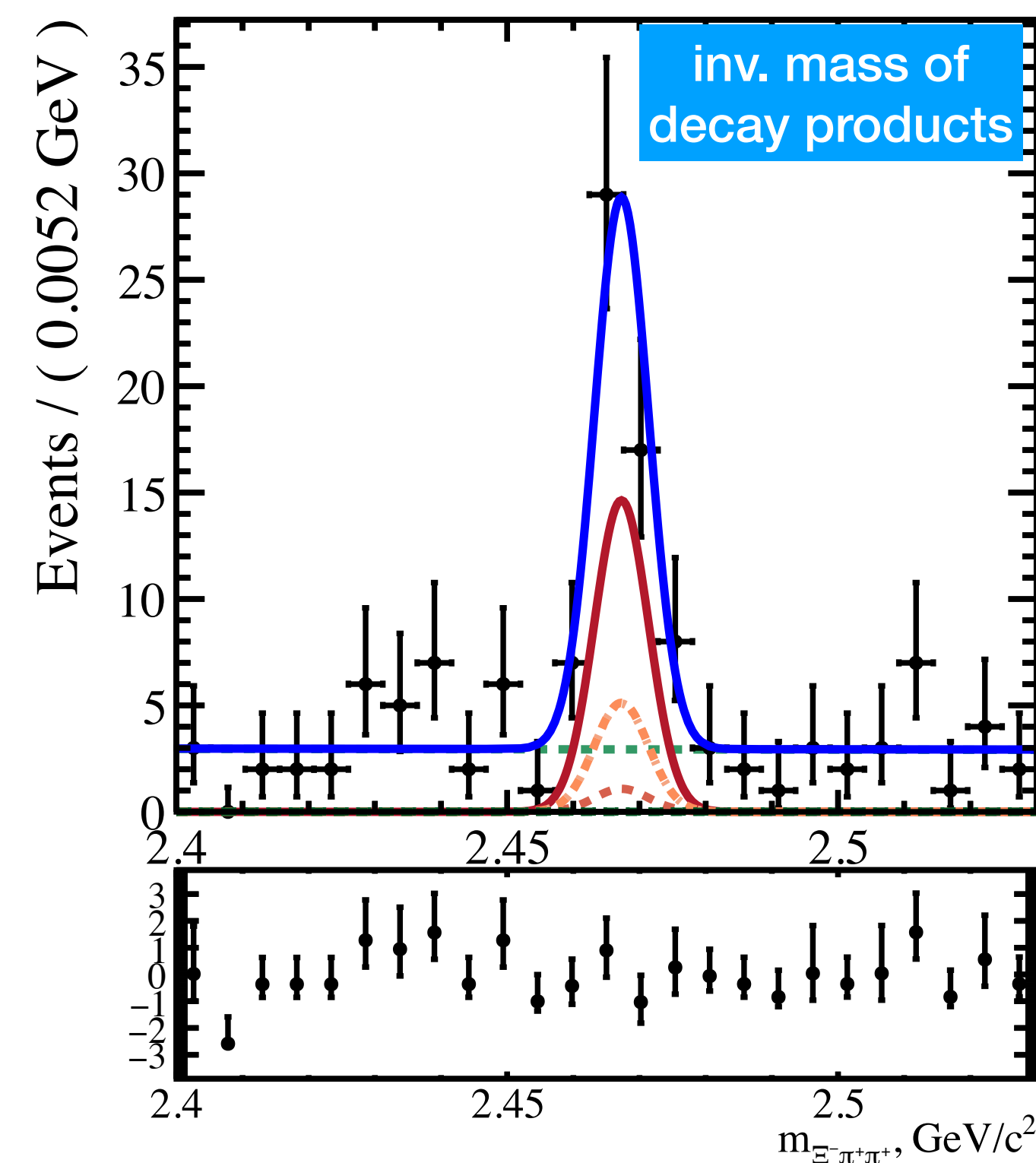
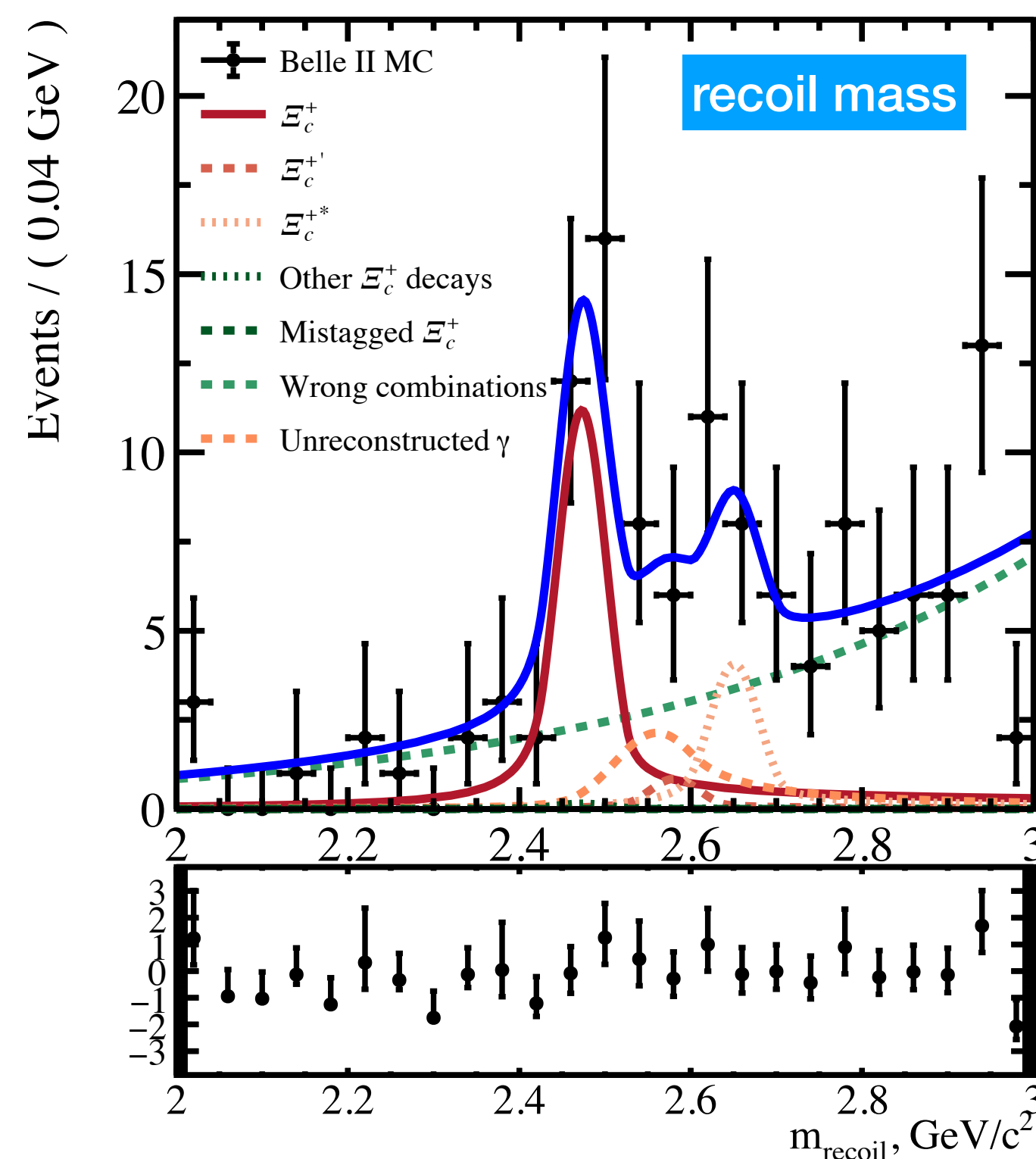
$$\mathcal{B} = \frac{N_{\text{exclusive \& inclusive}}}{N_{\text{inclusive}} \times \epsilon_{\text{exclusive}}}$$

Exclusive selection (WIP)

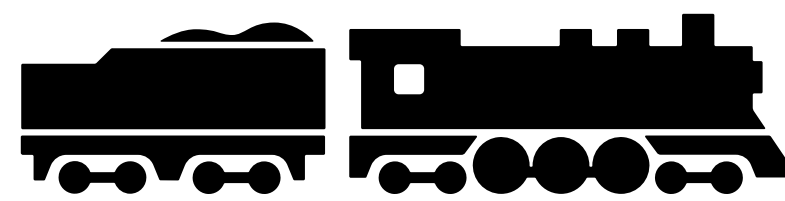
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- Once the **inclusive** dataset is defined, count **exclusive** signal decays **in this dataset**
- Example: reconstruct $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ in the *rest of event*
 - and require 0 remaining tracks in the event
- 2D fit to $M_{recoil} : M_{\Xi^- \pi^+ \pi^+}$ to obtain $N_{\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+}$
- **Studies with simulation very promising**
- **Expected stat. precision on decay rate: 10-15% with existing Belle II data**
- **Results expected during 2027**

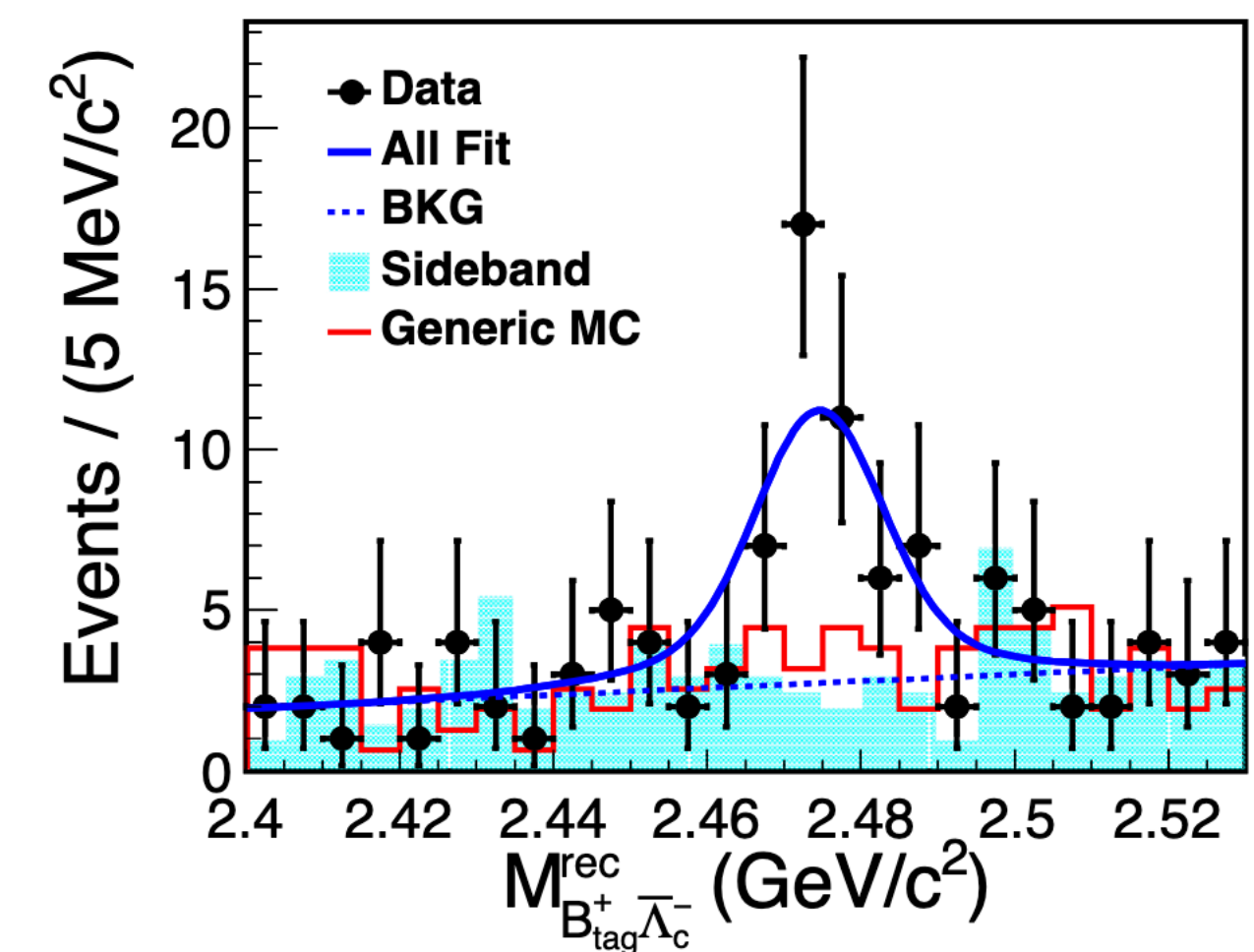
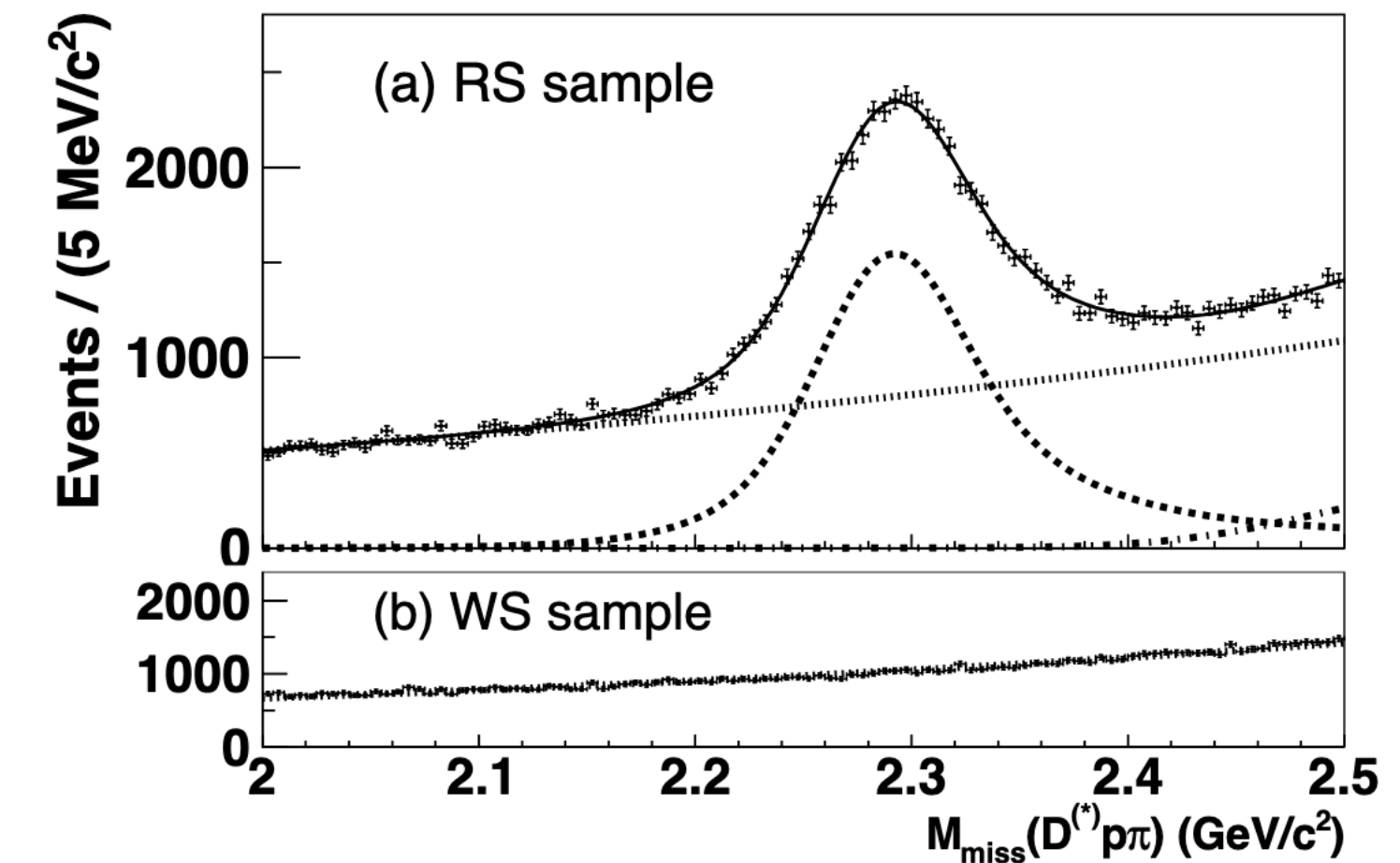
Proof of concept with simulation



- **At Belle II:** we now have an inclusive sample of charm baryons with known 4-momentum of the charm baryon, so we can study:
 - Charm-baryon decays to challenging final states (missing particles)
 - Decays into final states with neutrons or K_L^0
 - Charm-conserving decay $\Xi_c^+ \rightarrow \Lambda_c^+ \pi^0$
 - Semileptonic decays: among other physics cases, background for low-mass Drell-Yan measurements [[2604.11574](#)]
 - $c \rightarrow u \nu \bar{\nu}$
 - Invisible BSM particles (with or without baryon number) [[2602.15936](#), [2512.19794](#)]
 - Relative production rate of ground and excited states, spectroscopy...
 - **Main limitation: statistics**
- **At FCCee:** can use the same idea to perform inclusive reconstruction of charm/beauty hadrons in $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ or $e^+e^- \rightarrow Z \rightarrow c\bar{c}$



- Absolute BF measurement for Λ_c^+ at Belle [[1312.7826](#)]
 - Use prompt $e^+e^- \rightarrow c\bar{c}$ with $c_{tag} \rightarrow D^{(*)}p\pi$
 - 36000 inclusively tagged Λ_c^+ , out of them 1500 decayed to $pK^-\pi^+ \Rightarrow$ BF measured to $\sim 5\%$ precision
- Absolute BF measurement for Ξ_c^+ [[1904.12093](#)] and Ξ_c^0 [[1811.09738](#)] at Belle using $\bar{B}^0 \rightarrow \bar{\Lambda}_c^- \Xi_c^+$ and $\bar{B}^- \rightarrow \bar{\Lambda}_c^- \Xi_c^0$
 - Very low BF: very small tagged dataset (40 Ξ_c^0 / 20 Ξ_c^+ events)
 - But: no need to fully reconstruct the decay in a tagged dataset (B tagging efficiency known)



- Using the efficiency-corrected yields of Belle datasets of Λ_c and Ξ_c decays:
 - $\Lambda_c^+ \rightarrow pK^-\pi^+$ [2503.04371], eff-corrected yield 9.57×10^6 , $\mathcal{B}_{\text{PDG}} \sim 6\%$
 - $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ [2503.17643], eff-corrected yield 0.43×10^6 , $\mathcal{B}_{\text{PDG}} \sim 3\%$
 - $\Xi_c^0 \rightarrow \Xi^-\pi^+$ [2406.04642], eff-corrected yield 0.26×10^6 , $\mathcal{B}_{\text{PDG}} \sim 1.4\%$
 - Summary: prompt Ξ_c cross-section is **about 8...11%** of the Λ_c cross-section
 - NB: S/B ratio suffers from low cross-section
- Inclusive Λ_c yield 36000 in the Belle paper [1312.7826] so using the same technique/dataset leads to expected 3500 Ξ_c
 - assumes a similar tagging efficiency (might be not true)
- *Plan to consider the full Belle II dataset (+Belle?) for the largest statistical power*