Towards measuring $B_c^+ \to \tau^+ \nu_\tau$

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Understanding the decay and its experimental challenges

- This decay has a **well-defined prediction** within the Standard Model (SM)

  $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)_{\text{SM}} = 1.95(9) \times 10^{-2}$

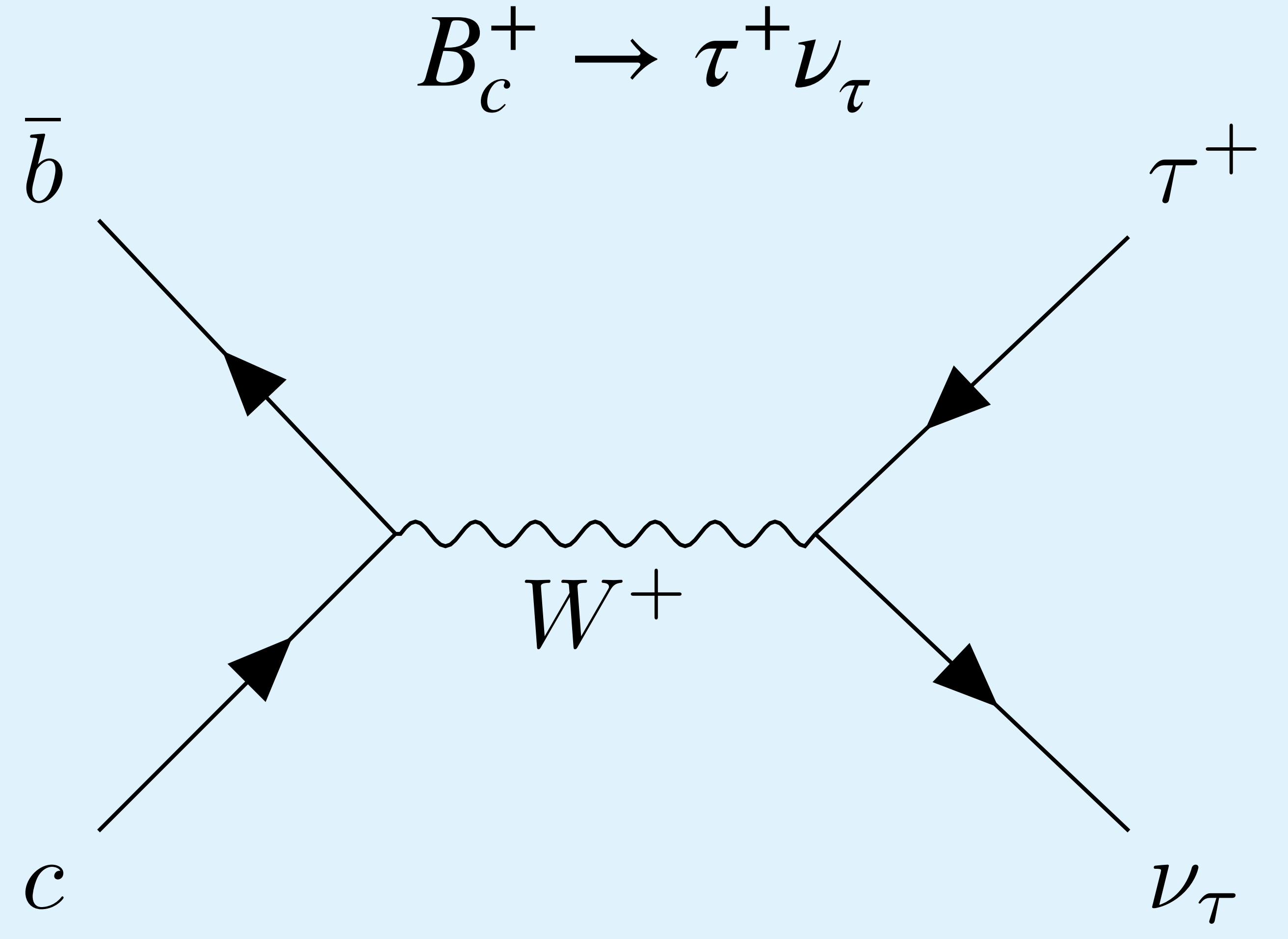
- It has **never observed** experimentally

- Measuring it is challenging because:

  - **Neutrinos** are produced in the decay but cannot be directly detected.

  - The B_c meson and τ lepton have a very **short lifetime**

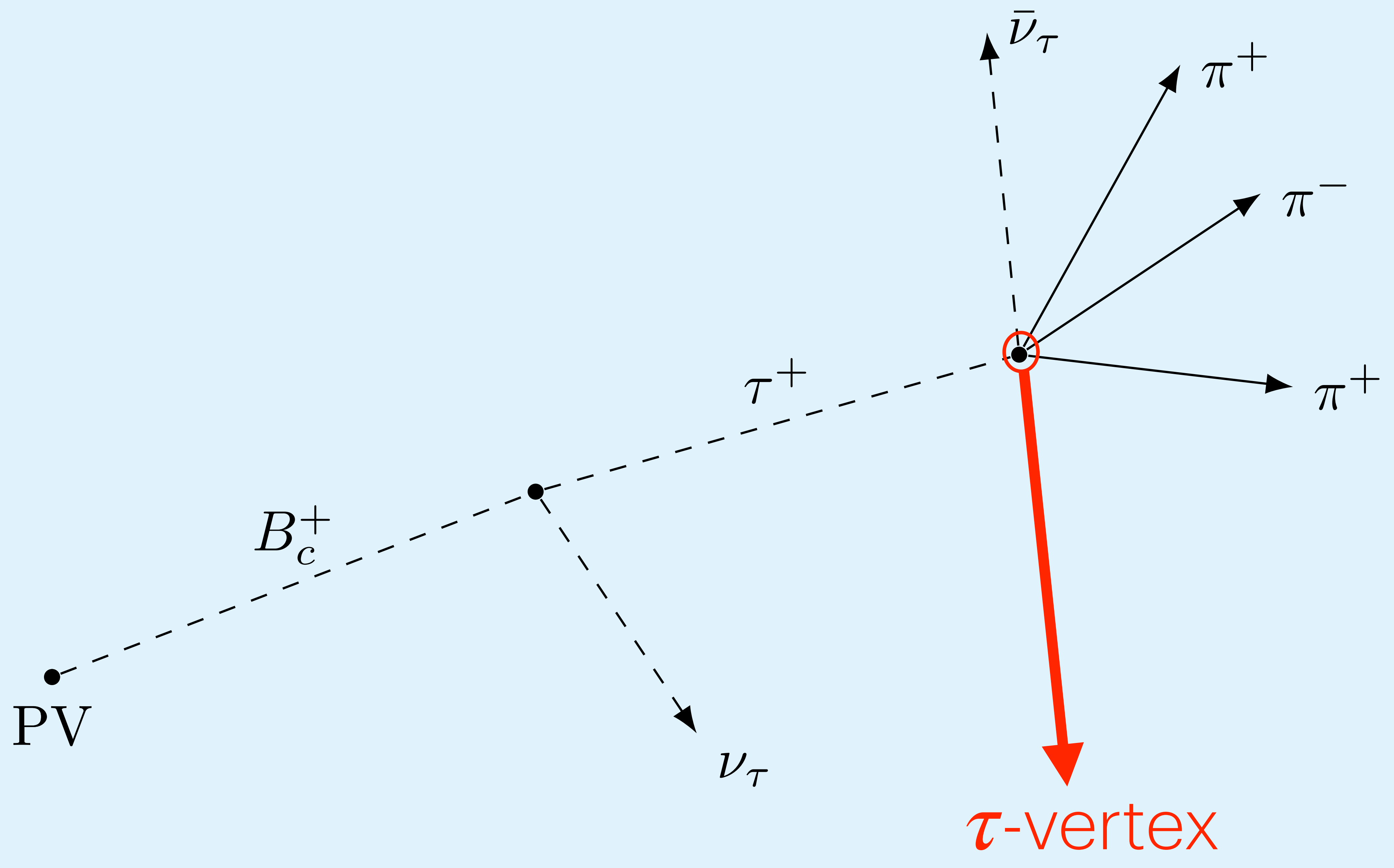
    - $\tau_{B_c} \simeq 0.510$ ps and $\tau_\tau \simeq 290$ fs



How to measure $B_c^+ \to \tau^+\nu_\tau$?

Selecting the decay chain

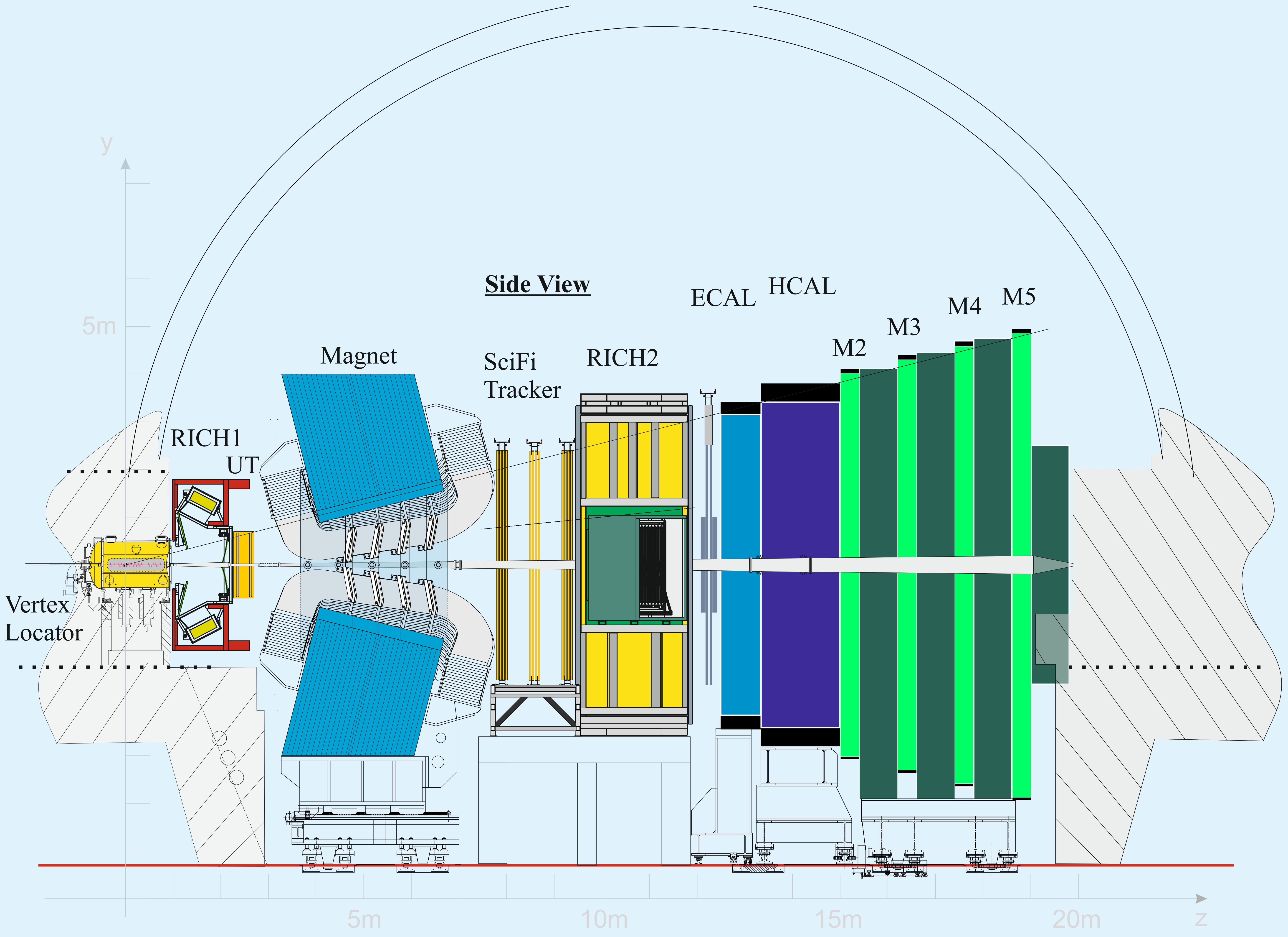
- Decay chain: $B_c^+ \to \tau^+(\to \pi^+\pi^-\pi^+\bar{\nu}_\tau)\nu_\tau$
  - Allows reconstruction of τ **-vertices.**
- Main challenge:
  - High background levels, since several other decays produce the **same visible signature**.



Where to measure $B_c^+ \to \tau^+ \nu_\tau$?

The LHCb Experiment

- Forward spectrometer covering the region **close to the beam line**
- Specialised in **detecting particles** produced **at small angles** to the proton beams
- Optimized for studying hadrons containing b **and** c **quarks**



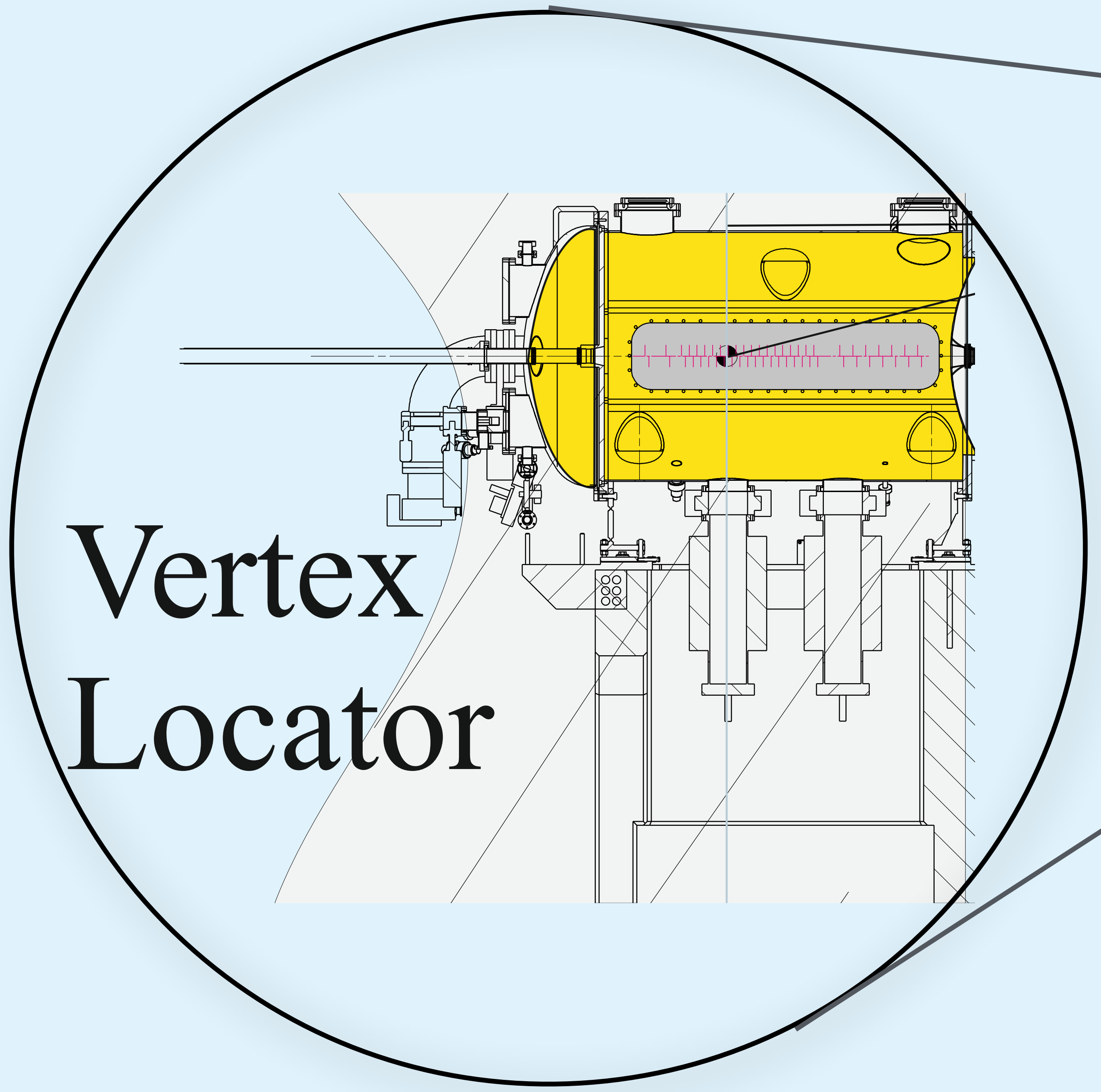
LHCb collaboration, R. Aaij *et al.*, *The LHCb upgrade 1*, JINST **19**. (2024) P05065, arXiv: 2305.10515

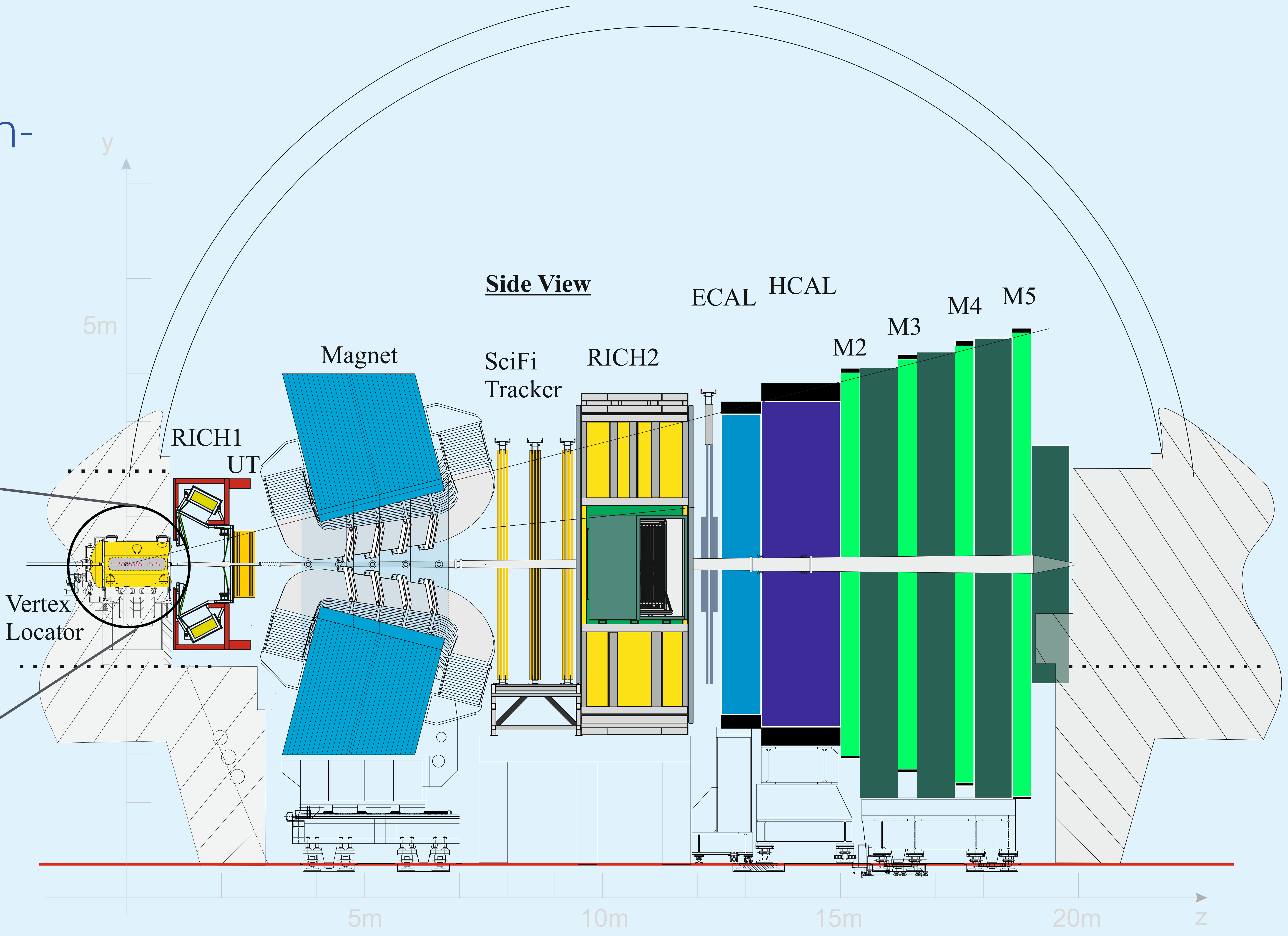
Where to measure $B_c^+ \to \tau^+ \nu_\tau$?

Vertex Locator (VELO) in the LHCb

- Allows **reconstruction** of the proton-proton collision point **(PV) and displaced decay vertices**

- 52 Modules at **5.1 mm** of the beam.





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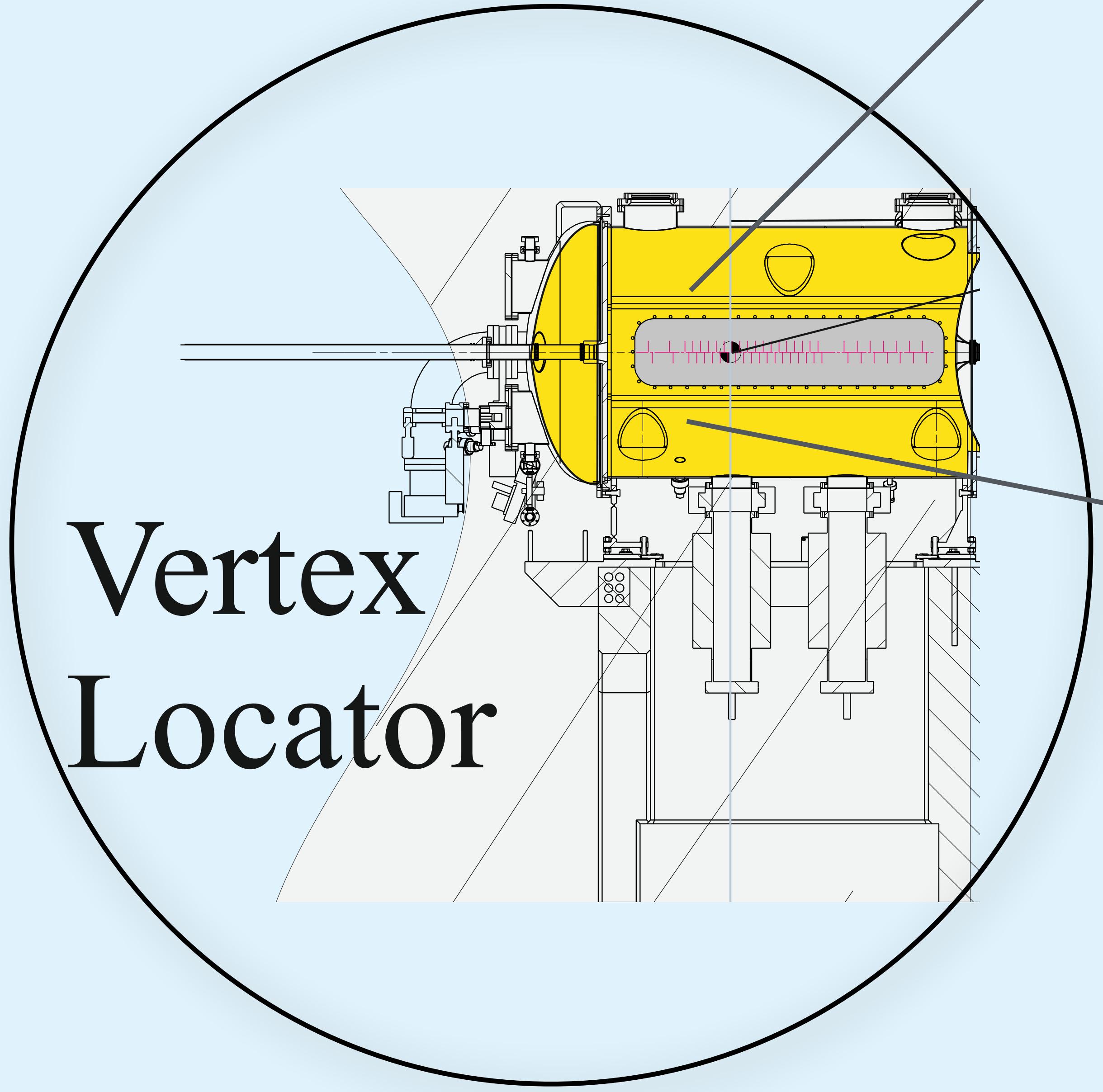

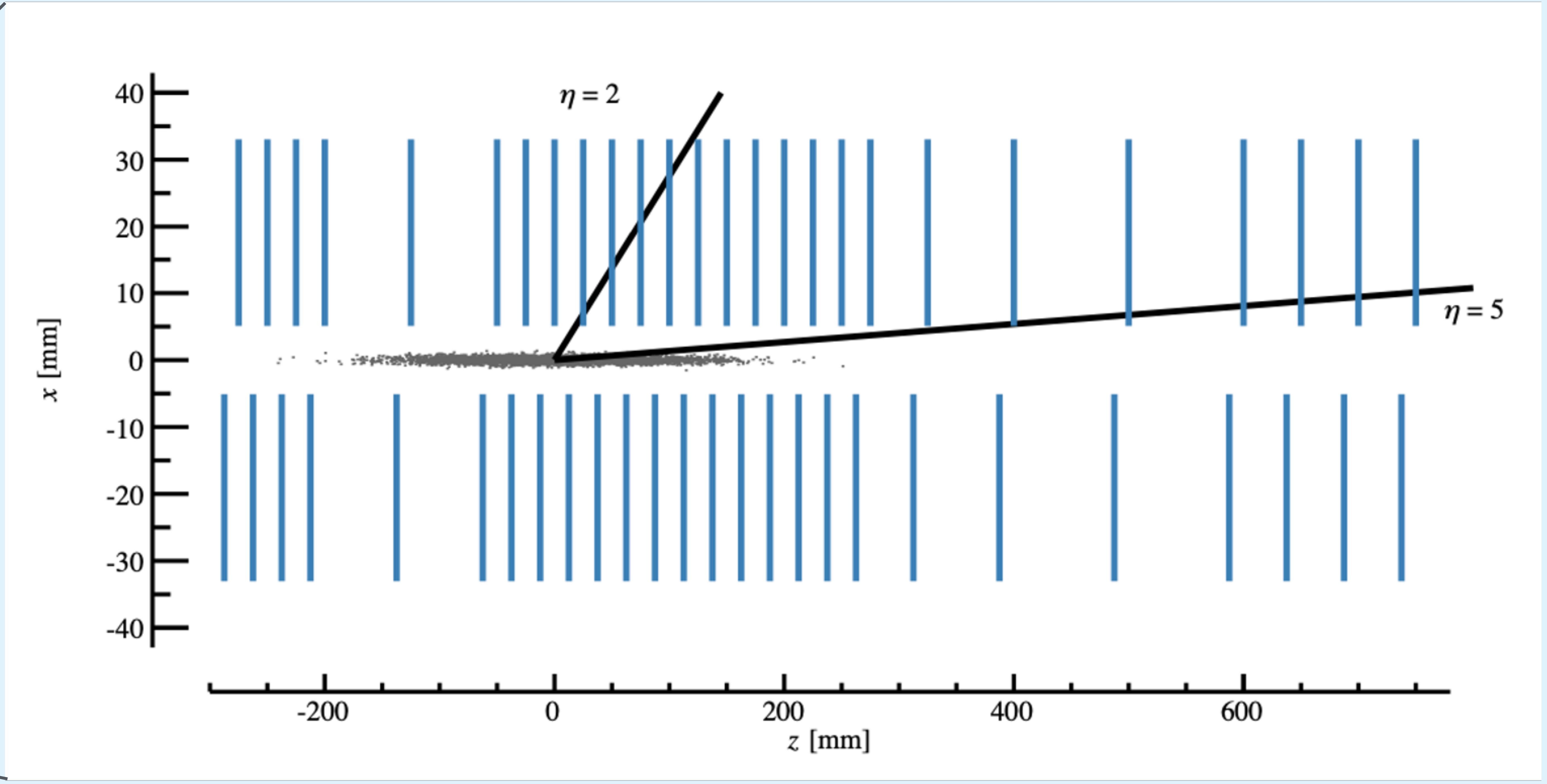

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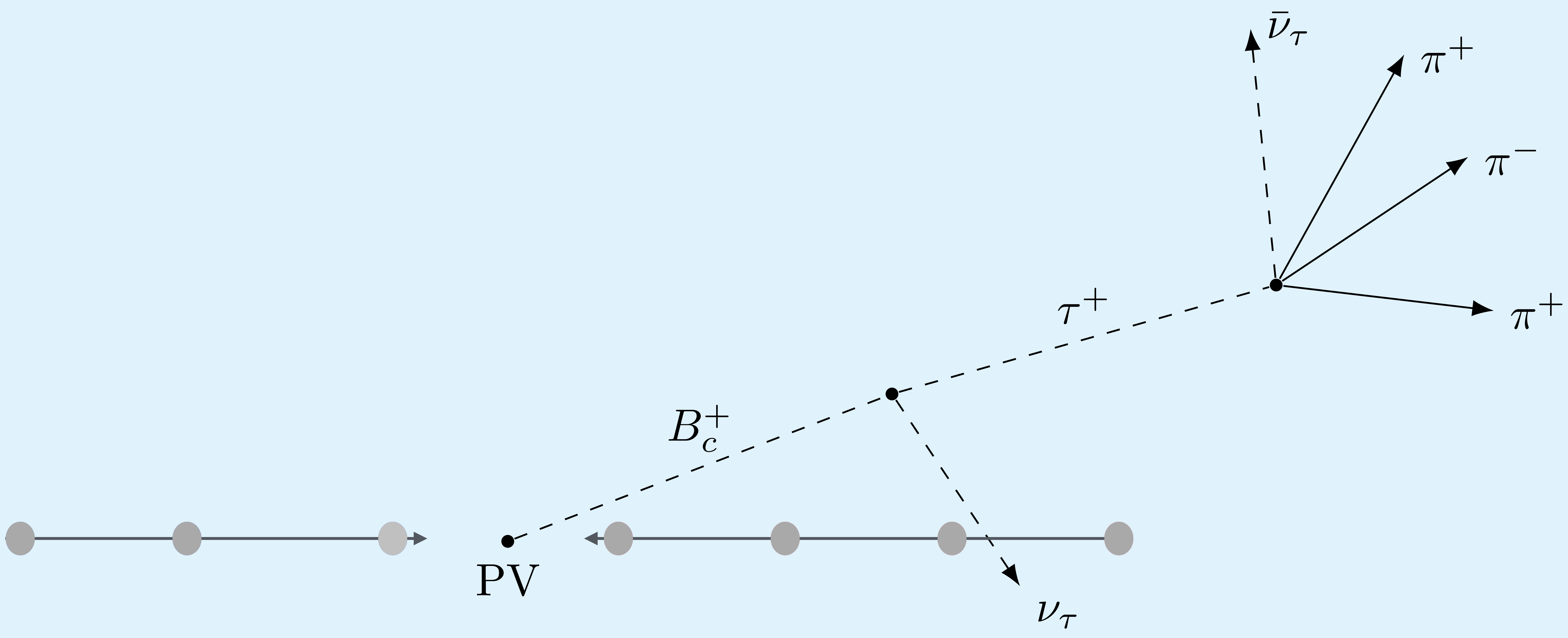
How to measure $B_c^+ \to \tau^+\nu_\tau$?

VELO advantages

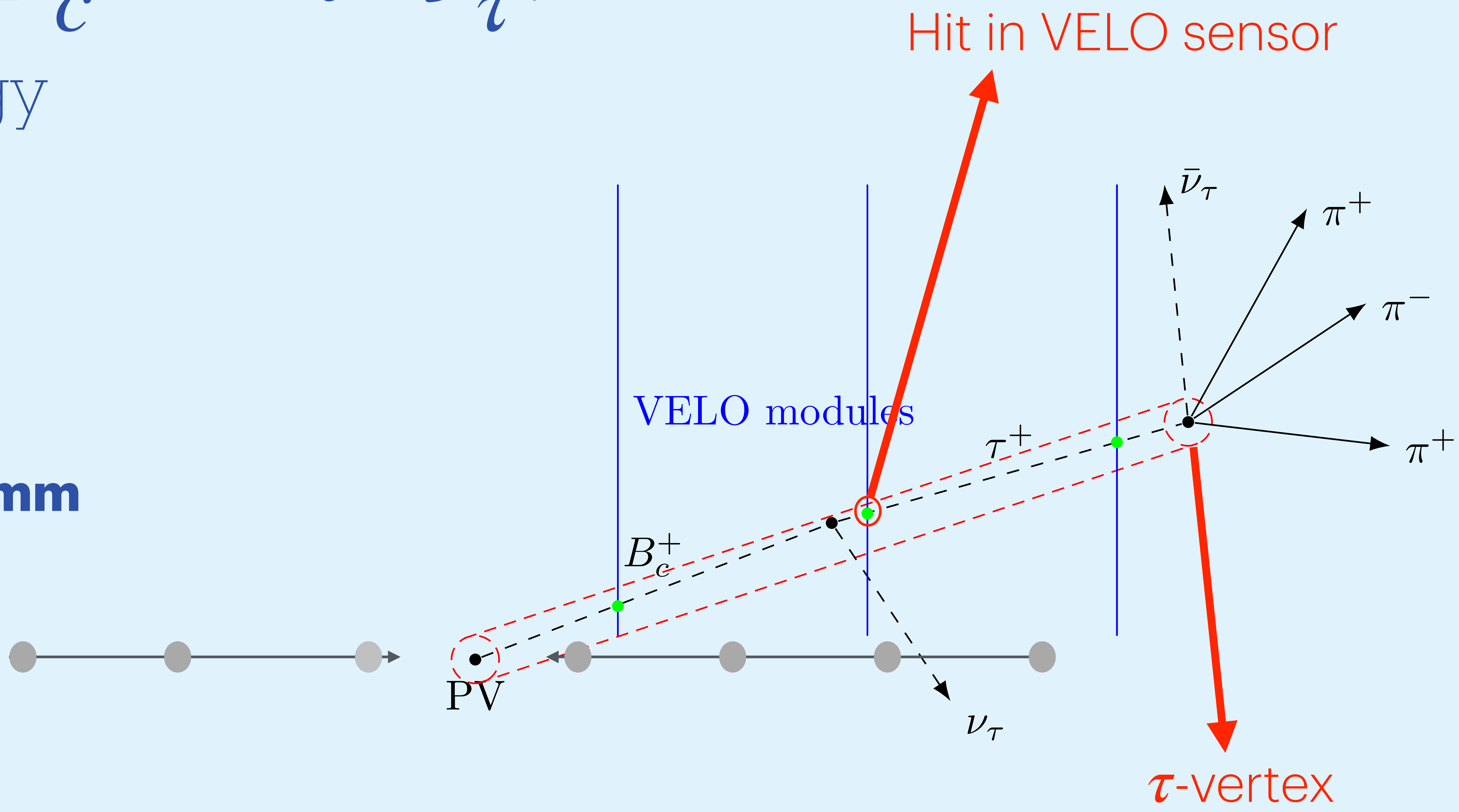
- Located very close to the beam line → **Good vertex resolution**.
- **Registers hits** from charged particles produced in the decay
- Crucial for identifying **displaced vertices** from short-lived particles



How to measure $B_c^+ \to \tau^+ \nu_\tau$?

VELO Hit Selection Strategy

- Define a **cylindrical region** between the **PV** and the τ-vertex
- The cylinder has a **radius of 0.5 mm**
- In each crossed VELO module, select the **closest hit to the cylinder axis**



Measuring branching fractions at LHCb

Normalisation channel for $B_c^+ \to \tau^+ \nu_\tau$

- At LHCb, **absolute branching fractions** cannot be accurately measured.
- Instead it is measured **relative branching fractions**:

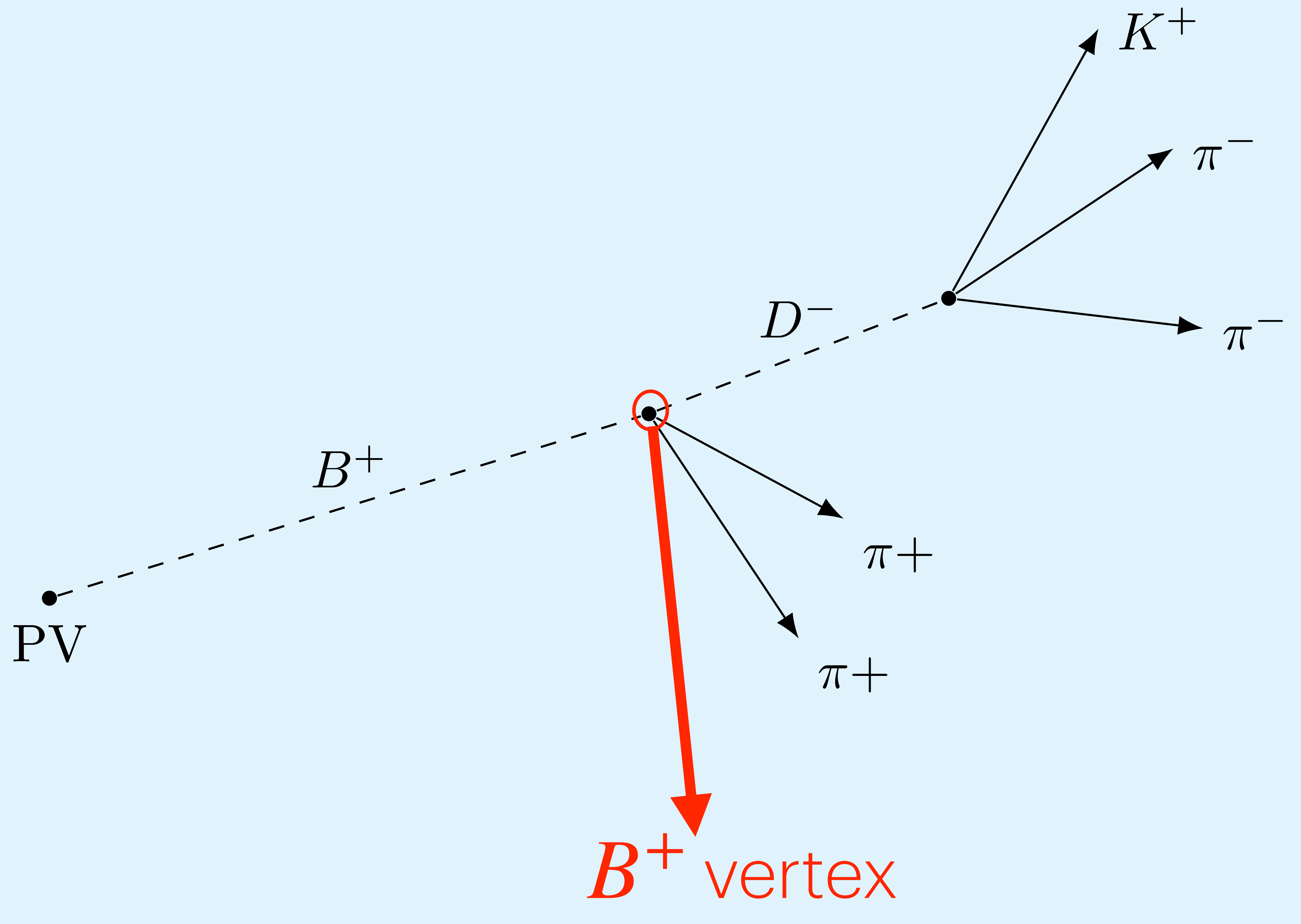
$$\frac{B(B \to X)}{B(B \to Y)} = \frac{N_X/\epsilon_X}{N_Y/\epsilon_Y}$$

With $N_{X,Y}$ the number of observed events and $\epsilon_{X,Y}$ the detection efficiency.

Normalisation channel $B^+ \to D^-\pi^+\pi^+$

How to reconstruct the $B^+ \to D^-\pi^+\pi^+$

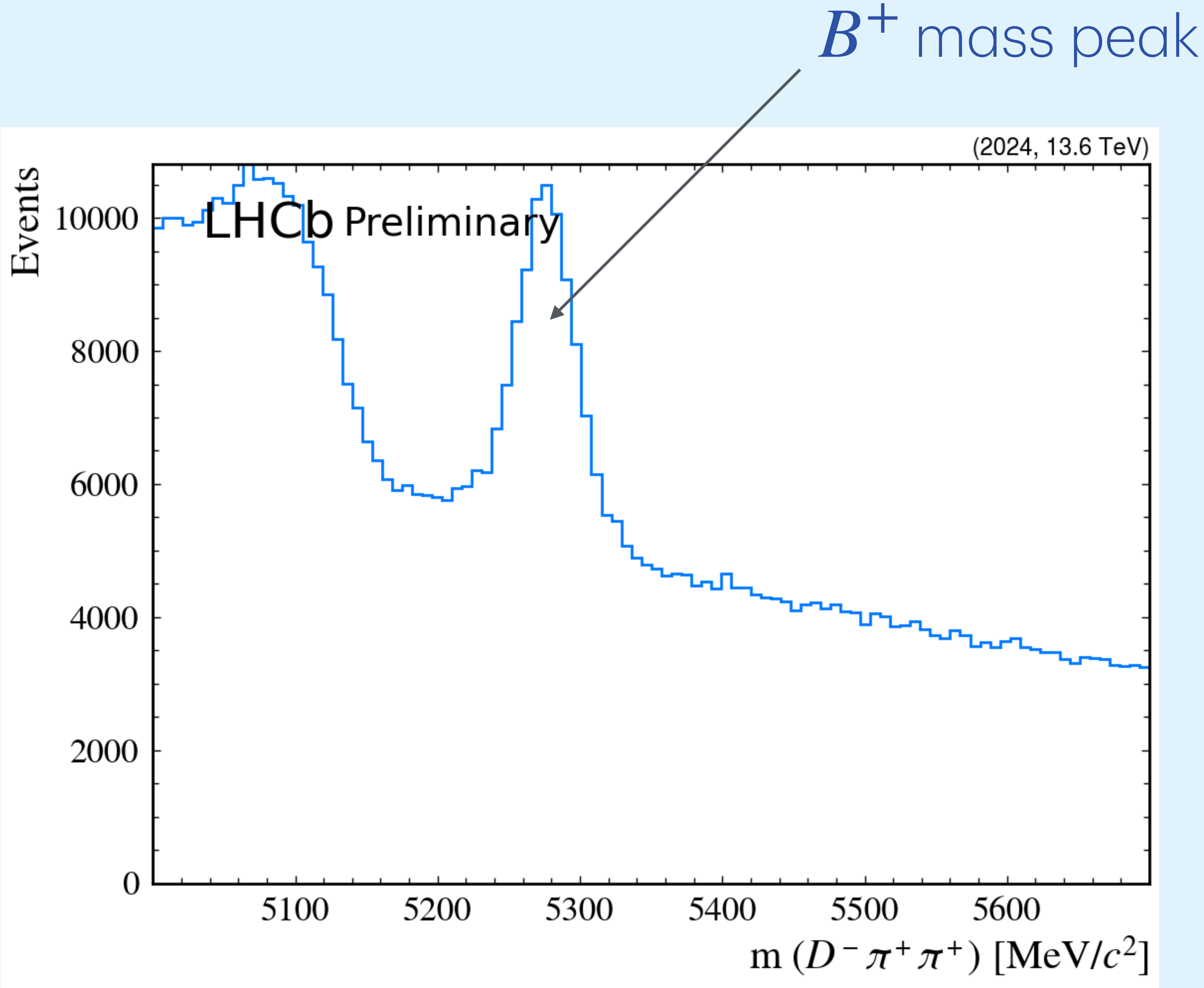
- Decay chain $B^+ \to D^-(\to K^+\pi^-\pi^-)\pi^+\pi^+$
- **Purpose:** Used as a **normalisation channel** to measure relative branching fractions.
- Reconstruction steps:
  - Identify D^- from its decay products K^+ and $\pi^-\pi^-$
  - Combine D^- with two π^+ to reconstruct B^+



Normalisation channel $B^+ \to D^- \pi^+ \pi^+$

First look at the data for $B^+ \to D^- \pi^+ \pi^+$

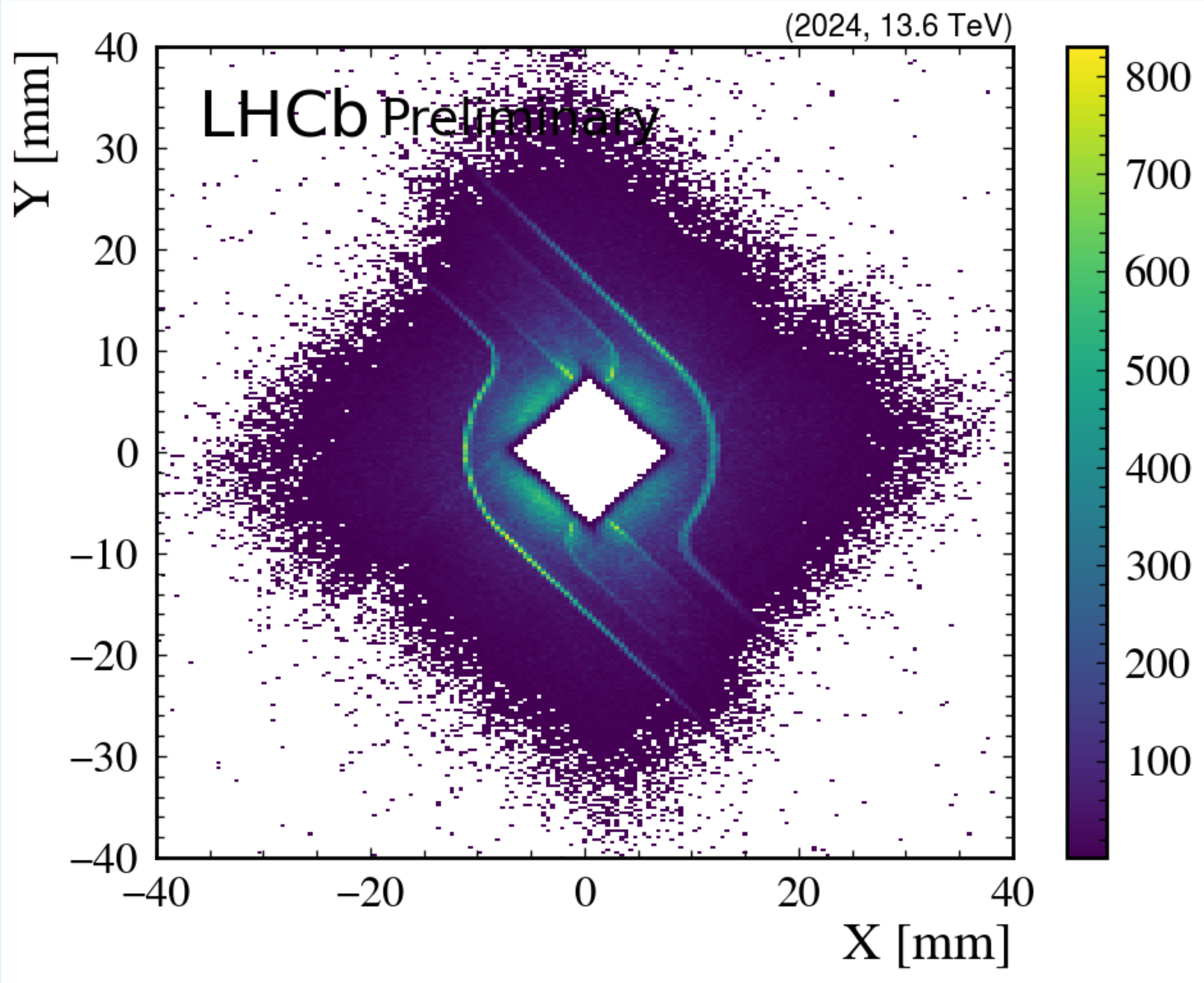
- This decay has been previously measured at LHCb with a **high yield**
- The branching fraction has also been **independently measured** at B-factories.
- B^+ and D^- are relatively **long-lived** particles
- There is a **higher chance** to measure VELO hits



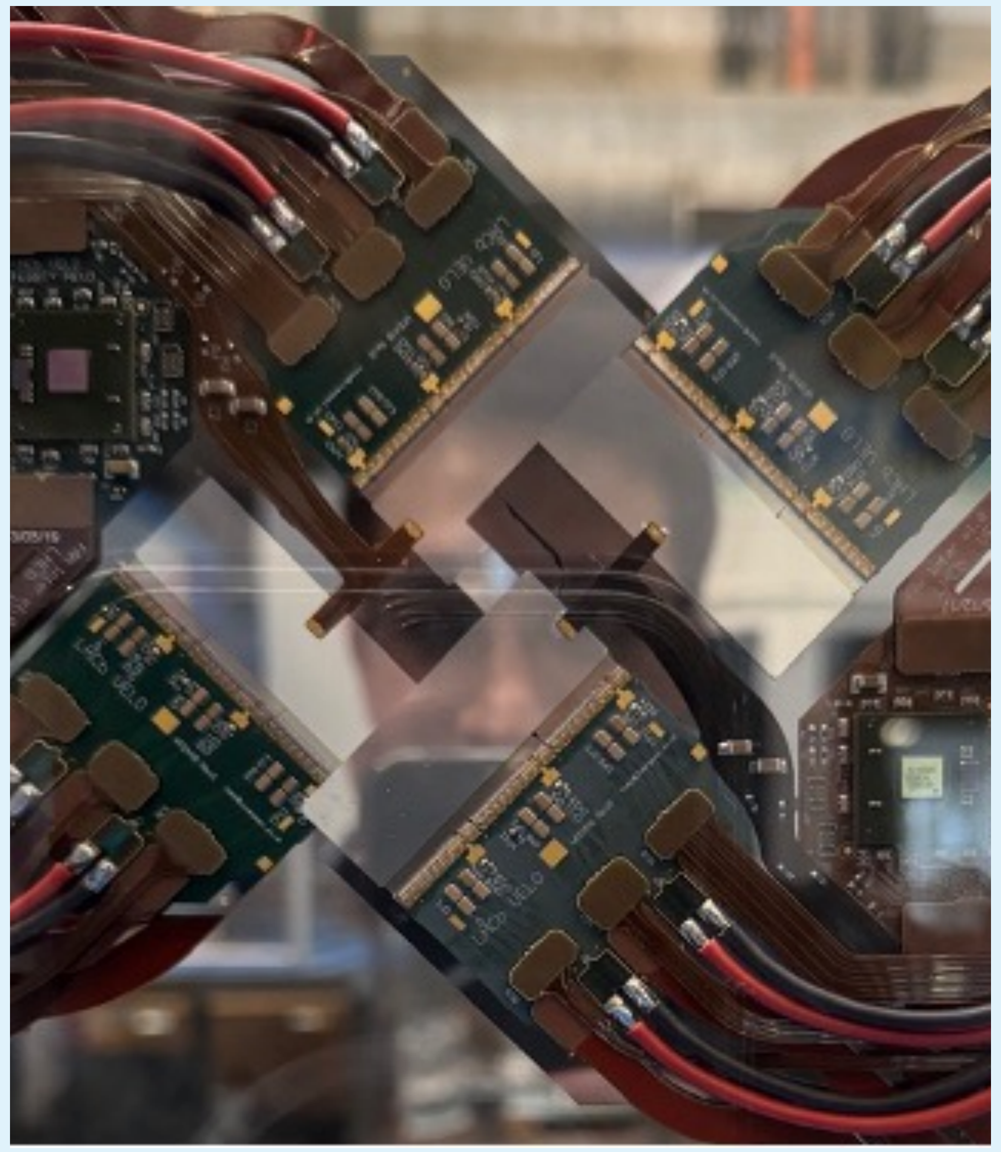
First look at the data of $B_c^+ \to \tau^+\nu_\tau$

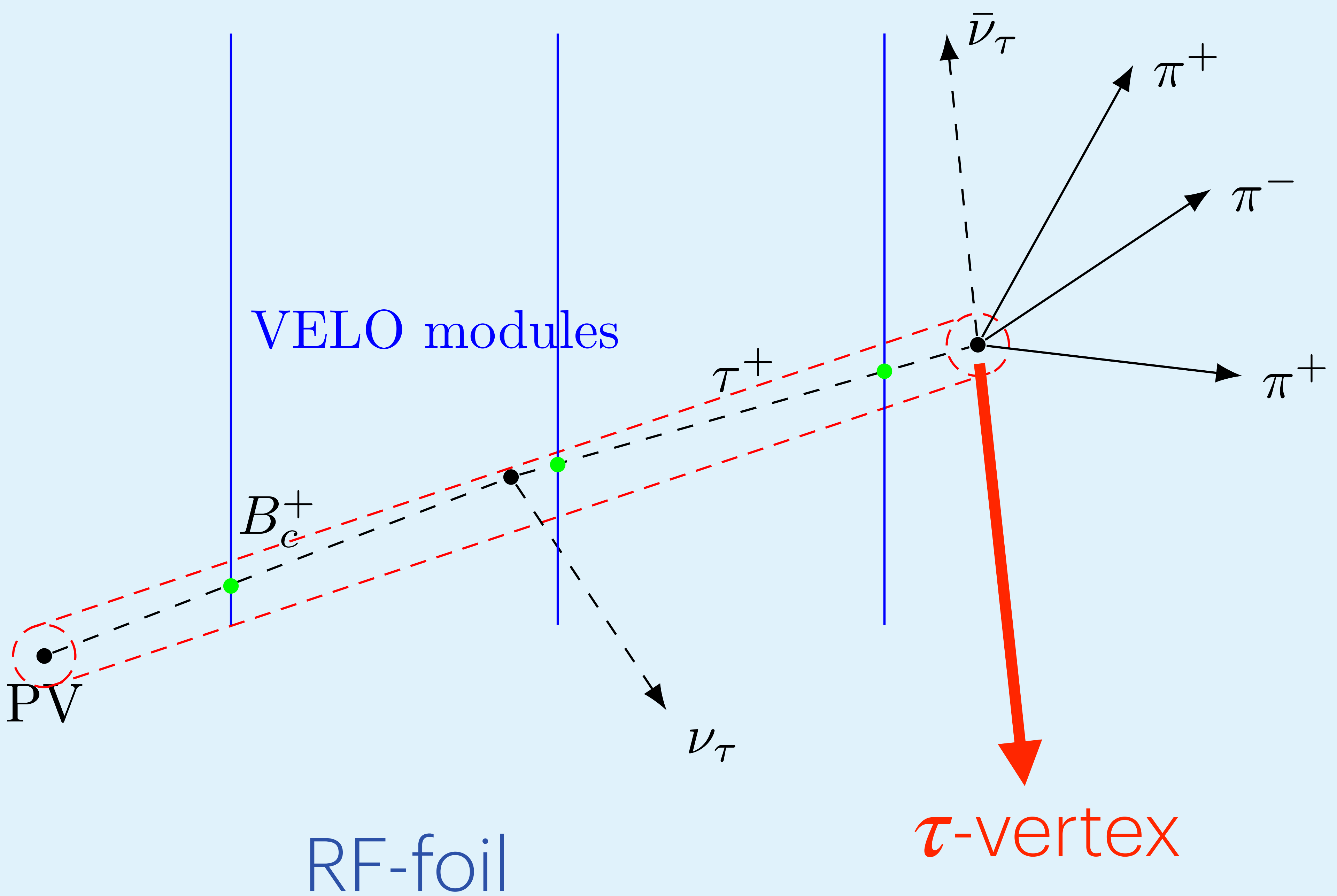
Material interaction background

Observed structure aligns with VELO modules and RF-foil positions

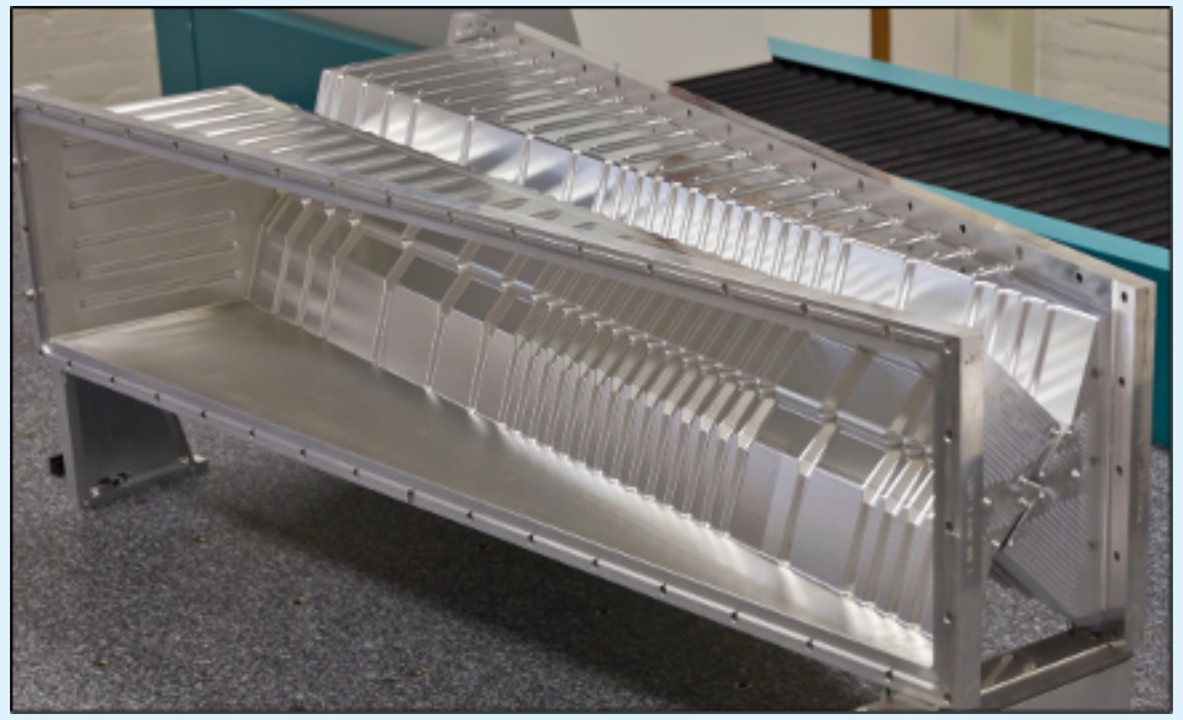


VELO sensors





RF-foil



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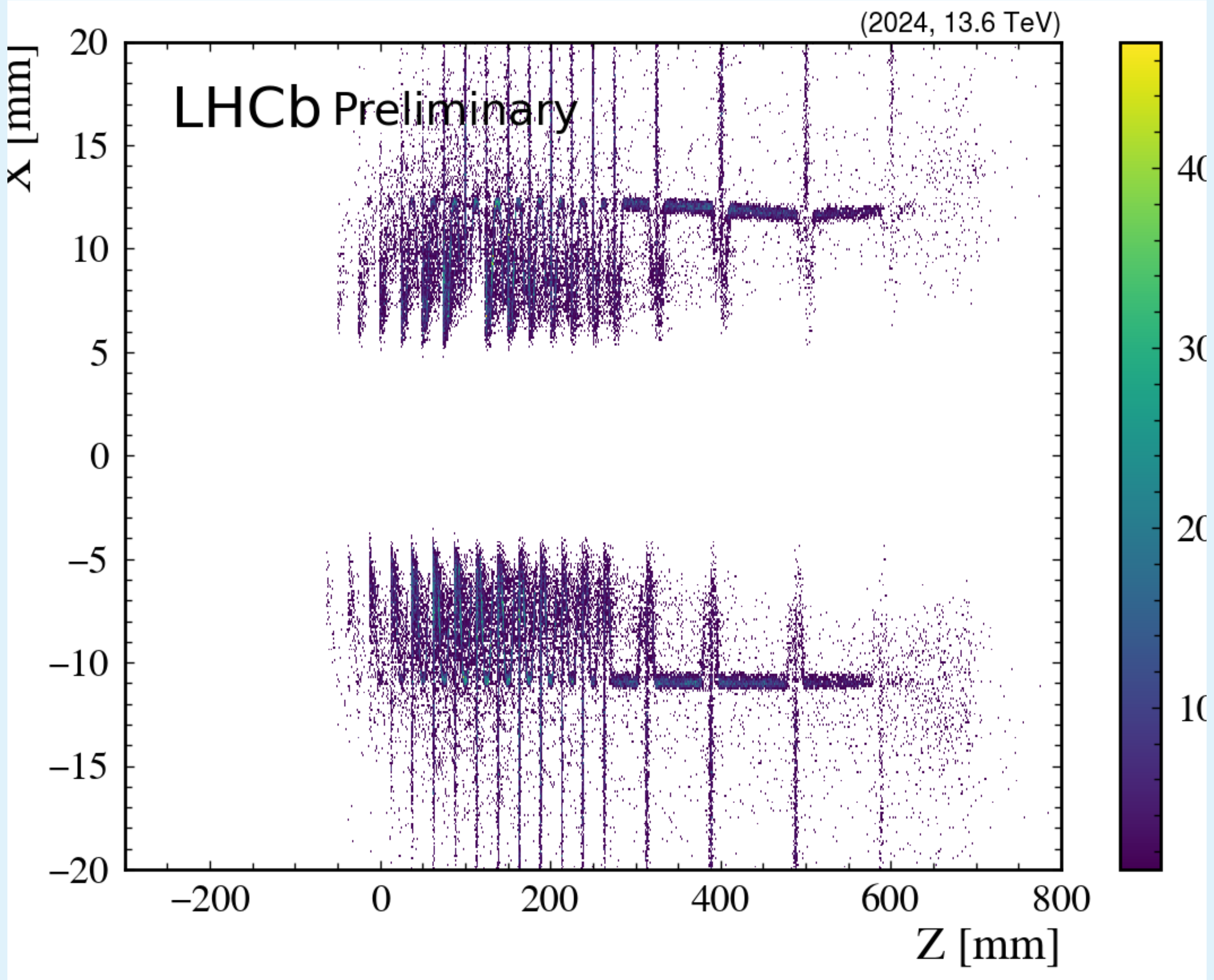

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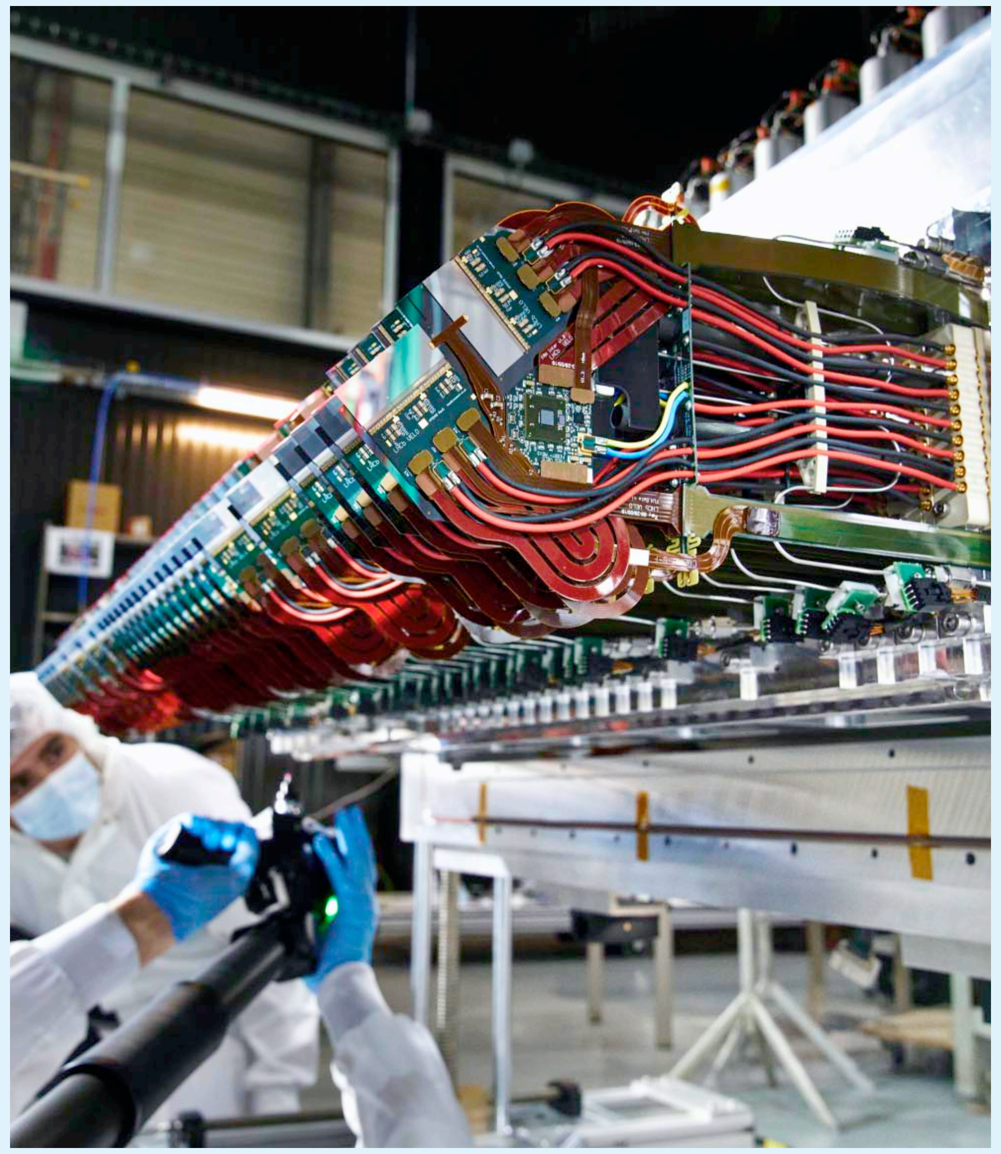
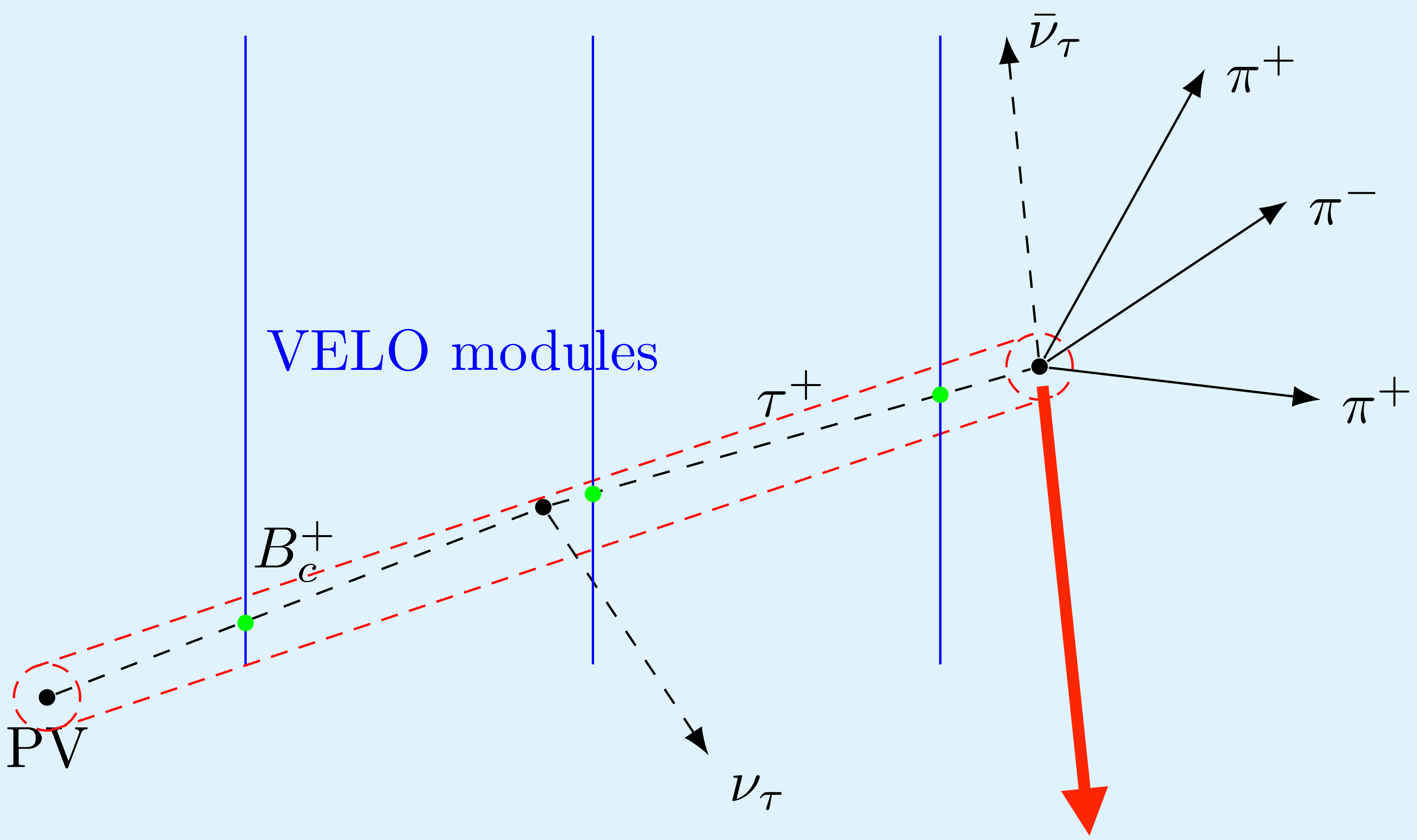
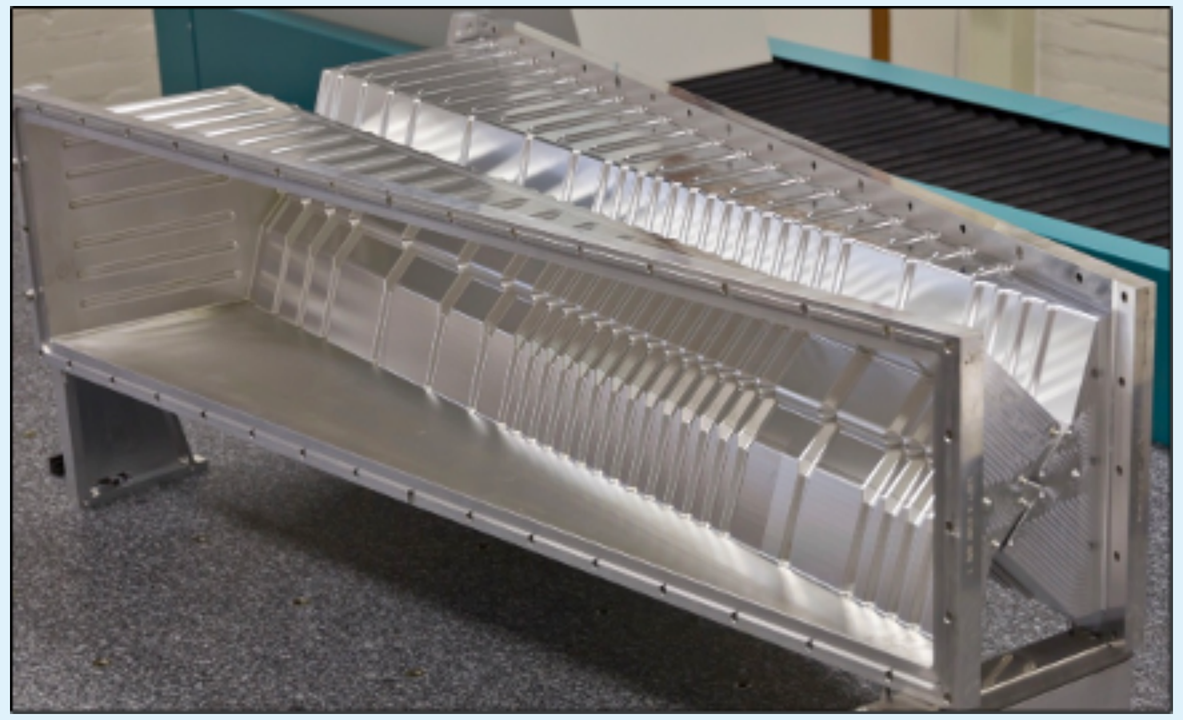




τ-vertex

RF-foil



Material interaction veto

Identifying background from detector material

- Evaluate the **likelihood** that a secondary vertex originates from a hadronic interaction with VELO material. How many **standard deviations** the point is from the closest material surface?
- Use the **distance significance** from the closest material surface:

$$d = \sqrt{\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2 + \left(\frac{\Delta z}{\sigma_z}\right)^2}$$

- The **harmonic mean significance** combines distances to multiple material surfaces

$$H(x_1, x_2, x_3, \ldots, x_n) = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}}$$

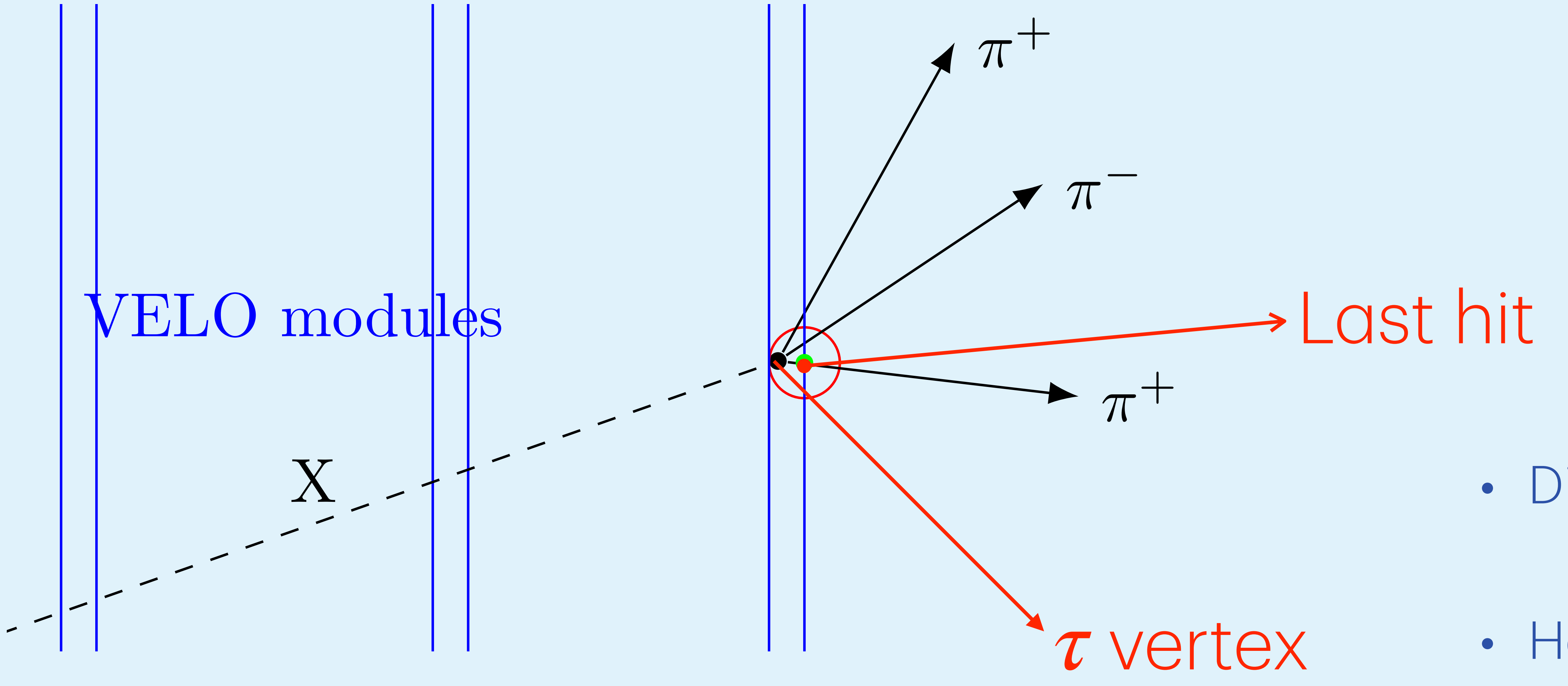
- Vertices with **small significance** are likely from material interactions and can be **vetoed out**

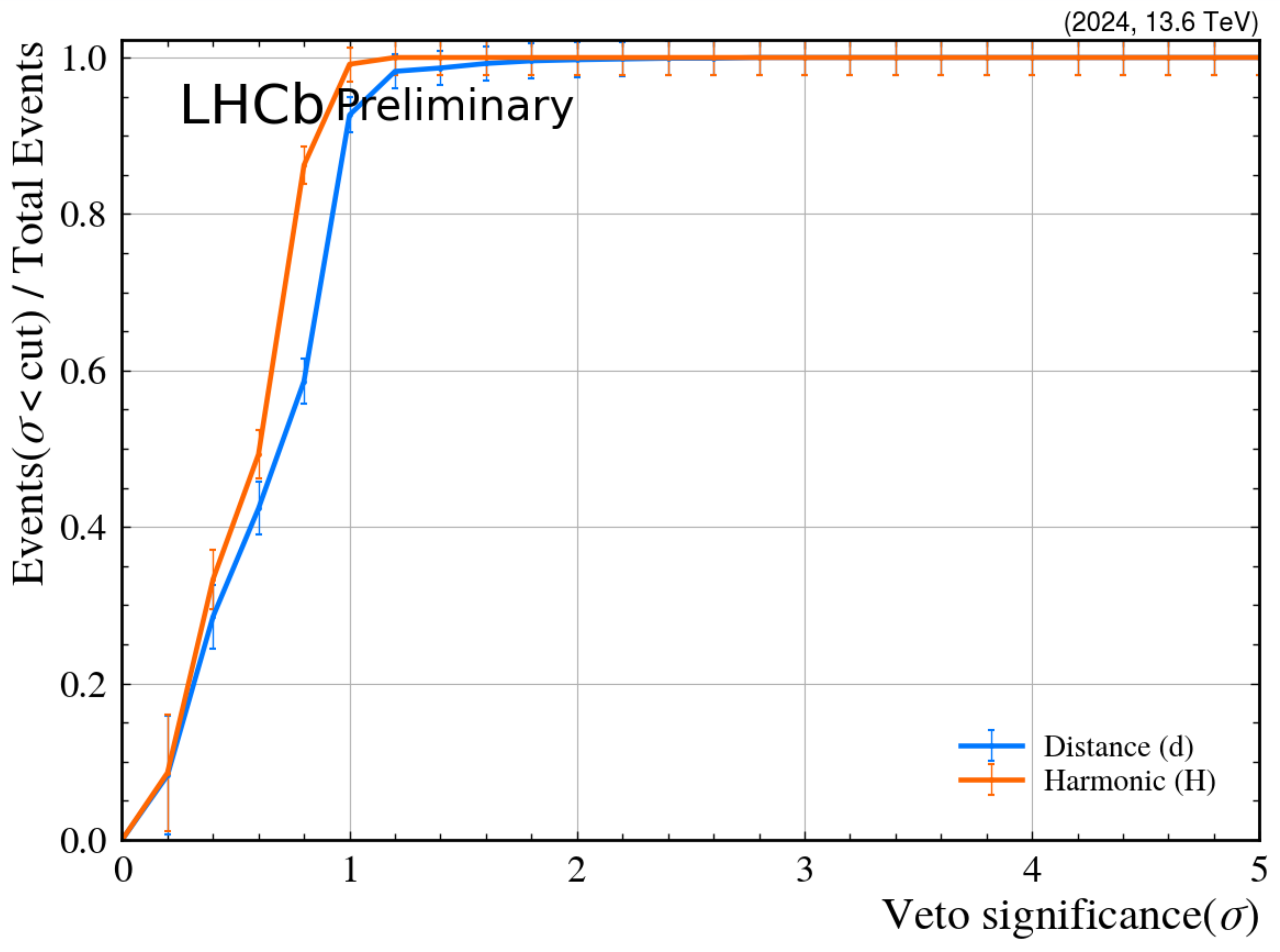
Selecting subsample for veto tool

Identifying likely material interaction events

- Compare the τ **vertex** z position (z_τ) to the **last VELO hit** in the sensor (z_{hit})

- The condition: $z_\tau < z_{\text{hit}}$ selects events likely caused by **material interactions** inside the sensor.





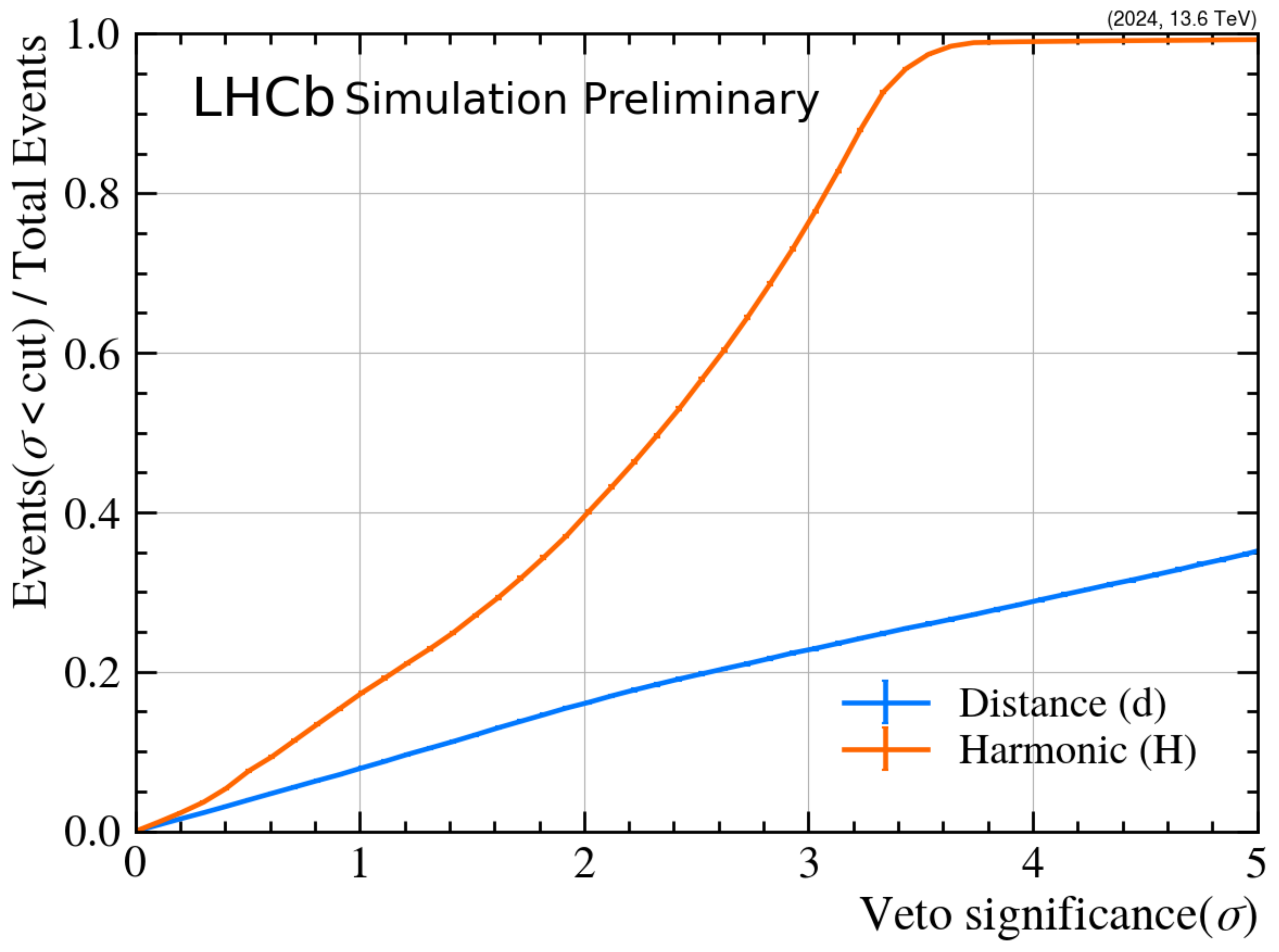
- Distance method: **92.7%** → material interactions (**cut = 1** σ)

- Harmonic method: **99.1%** → material interactions (**cut = 1** σ)

Control channel $B^+ \to D^-\pi^+\pi^+$

Applying veto tool to Monte Carlo data

- Apply veto significance **cut at 1σ**
  - Significance distance **(d)**:
    - $7.9\ \%$ Label events as Material interactions.
  - Harmonic mean distance **(H)**:
    - $17.2\ \%$ Label events as Material interactions.



Conclusions:

- Decay is challenging due to **missing neutrinos** and short lifetime
- Material interaction veto tool **removes background** while preserving signal
- Control channel $B^+ \to D^- \pi^+ \pi^+$ provides insight into **material-related losses**

Outlook:

- Apply veto tool in $B_c^+ \to \tau^+ \nu_\tau$ **Monte Carlo data.**
- Apply veto tool to the full $B_c^+ \to \tau^+ \nu_\tau$ **experimental dataset**
- **Optimize** selection criteria to improve **signal efficiency**

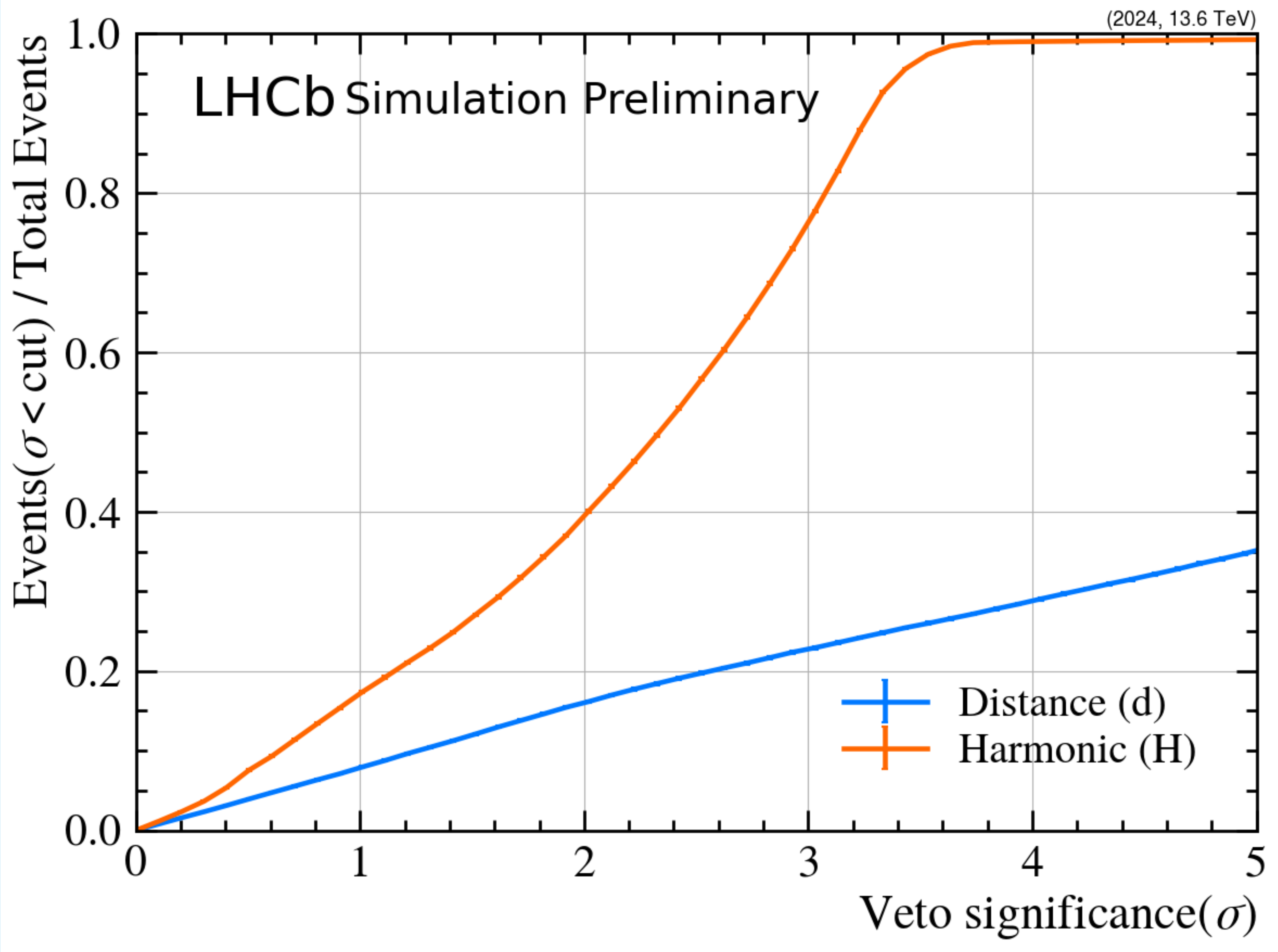
Thank you!

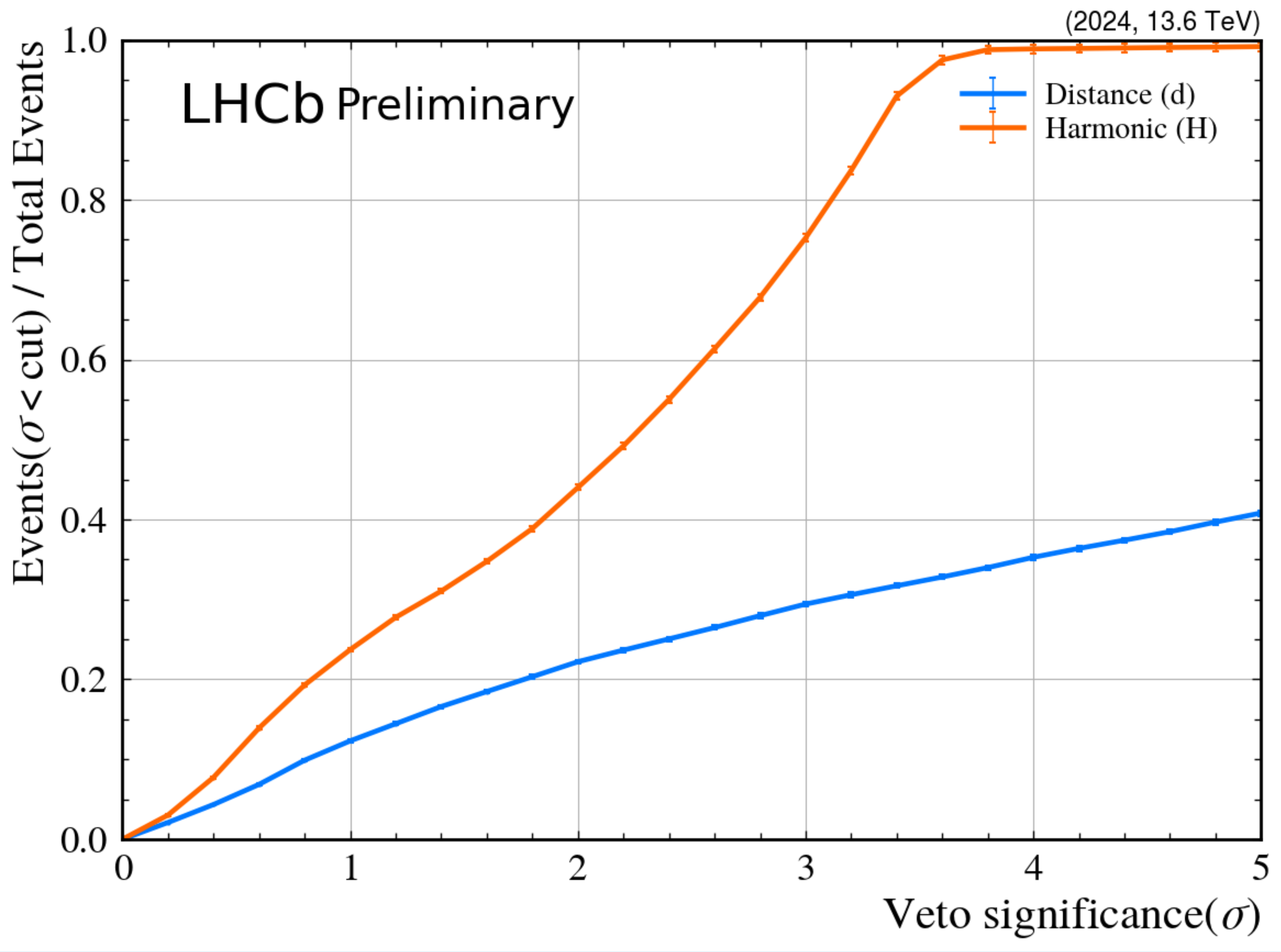
Backup

Control channel $B^+ \to D^-\pi^+\pi^+$

Veto tool in MC and Signal

Comparison of **MC** vs **sWeighted** signal $B^+ \to D^-\pi^+\pi^+$





Lepton flavour unversality

$R(D)$ and $R(D^*)$ anomalies.

$$R(D^{(*)}) = \frac{BR(\bar{B} \to D^{(*)})\tau^- \bar{\nu}_\tau}{BR(\bar{B} \to D^{(*)})\ell^- \bar{\nu}_\ell}$$

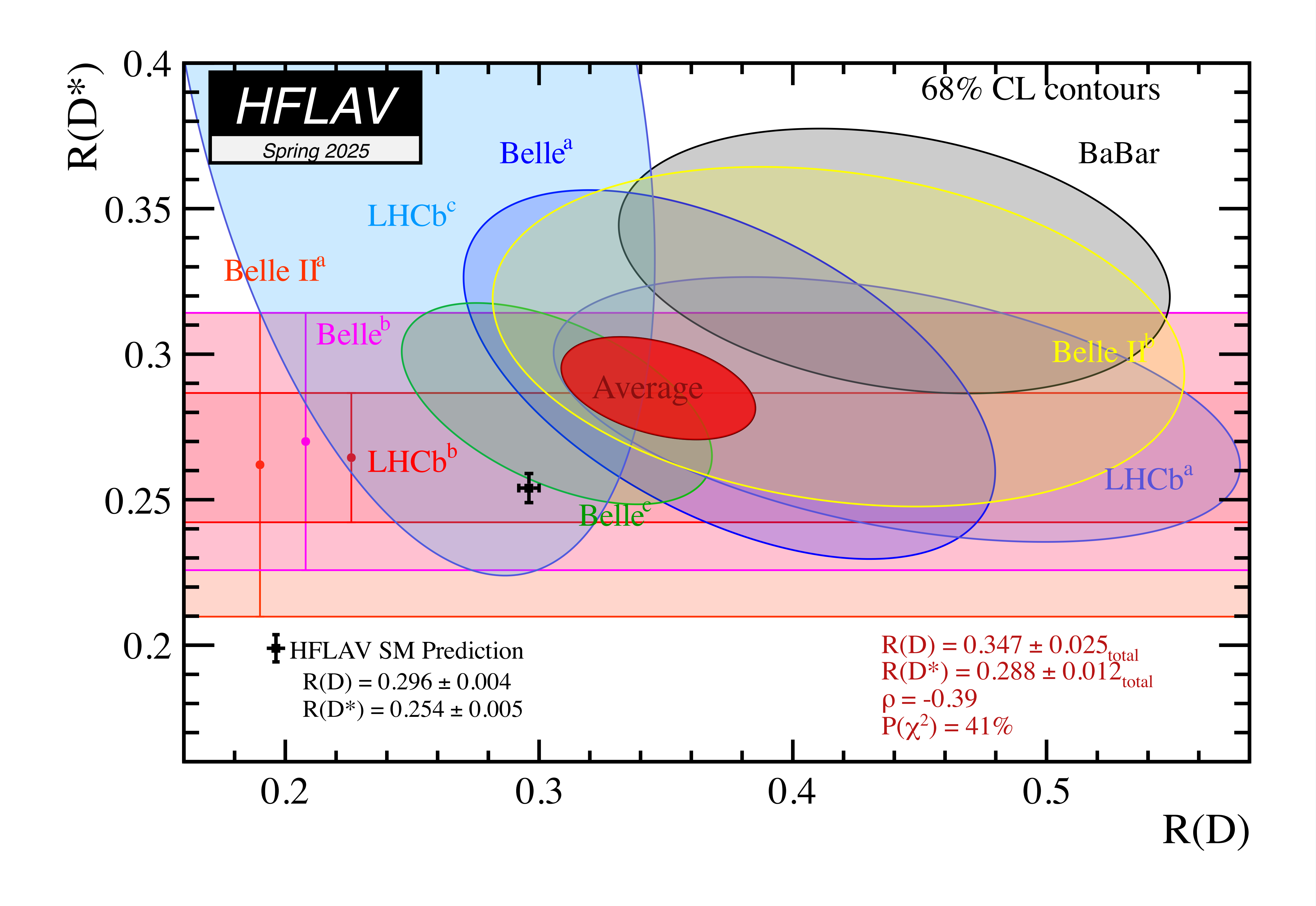
In the **SM**:

$$R(D) = 0.296 \pm 0.004 \qquad R(D^*) = 0.254 \pm 0.005$$

Experimental results differs from SM model preditions:

$$R(D)_{exp} = 0.342 \pm 0.026 \qquad R(D^*)_{exp} = 0.286 \pm 0.012$$

Combine **deviation of** 3.8σ from SM predictions.

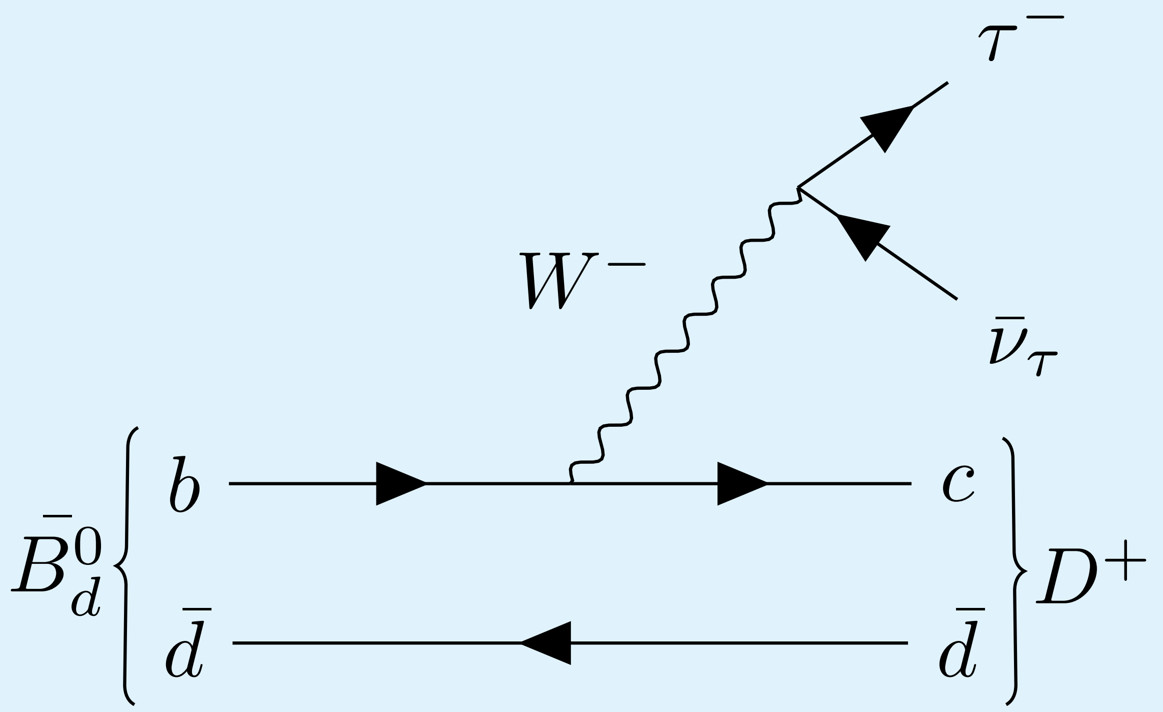


$B_c^+ \to \tau^+\nu_\tau$ Beyond SM

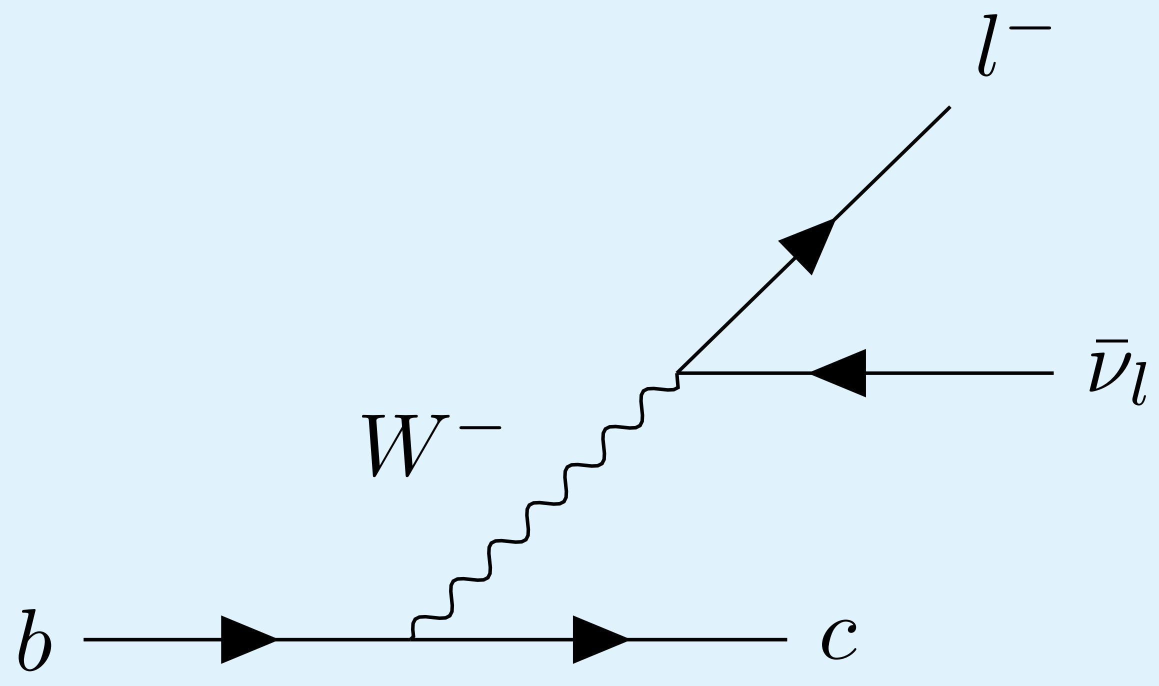
$R(D)$ and $R(D^*)$ anomalies and $B_c^+ \to \tau^+\nu_\tau$

- The underlying $b \to c\ell\nu_\ell$ process in $R(D)$ and $R(D^*)$ anomalies and $B_c^+ \to \tau^+\nu_\tau$ decay is similar.

$\bar{B}_d^0 \to D^+\tau^-\bar{\nu}_\tau$



$b \to c\ell\nu_\ell$



$B_c^+ \to \tau^+\nu_\tau$