Search for $B^+ \rightarrow \pi^+ e^+ e^-$

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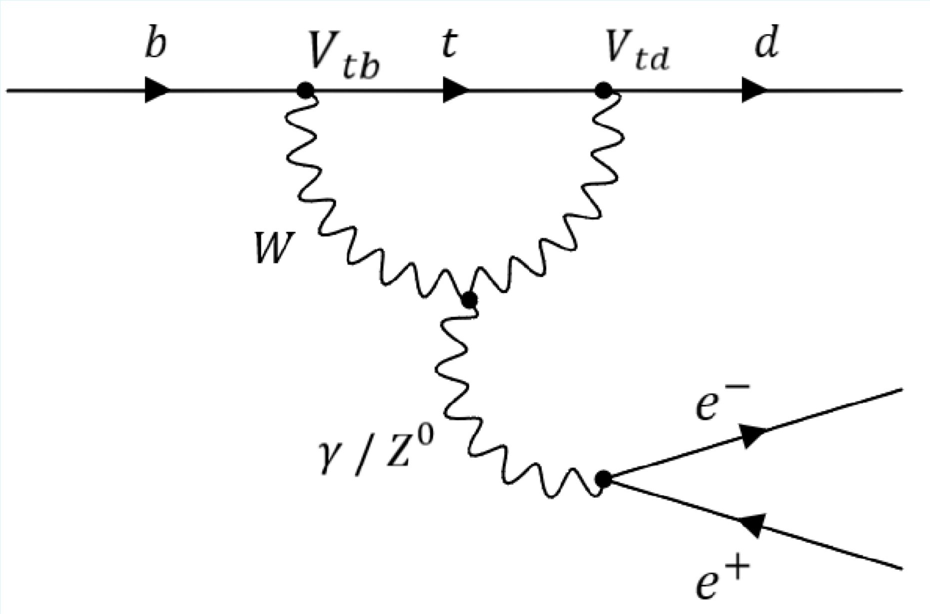
Introduction

The $\mathrm{b} \to \mathrm{d}e^{-}e^{+}$ decay is rare in the standard model $\mathrm{BF_{SM}}(\mathrm{B}^{+} \to \pi^{+}e^{+}e^{-}) \sim 1.8 \times 10^{-8}$, being doubly Cabbibo suppressed, GIM suppressed, and having no tree level diagram. Decay not yet observed, though there is an upper limit from Belle II.

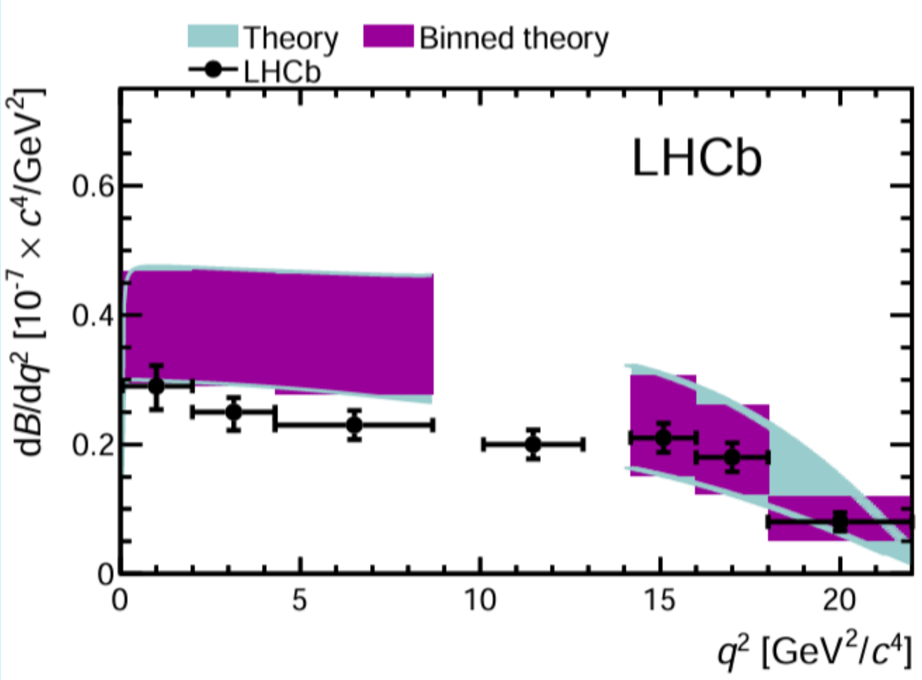
$$\mathrm{BF}(\mathrm{B}^{+} \to \pi^{+}e^{+}e^{-}) < 5.4 \times 10^{-8}$$ [Belle II, Moriond 2024]

Decay is a sensitive probe to interference from tree level NP (Indirect search).

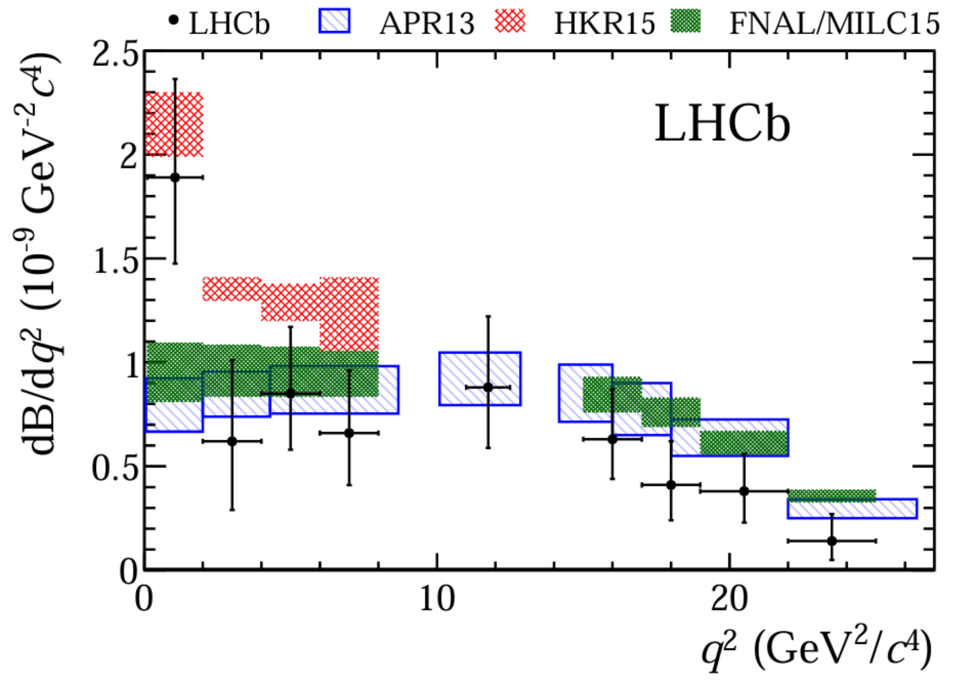


Previous Measurements

- A pattern of measurements of $b \to s\,\ell\ell$ transitions with consistent tensions to the SM.
- $b \to d\,\ell\ell$ is more greatly supressed in the SM, thus sensitive to smaller NP effects.

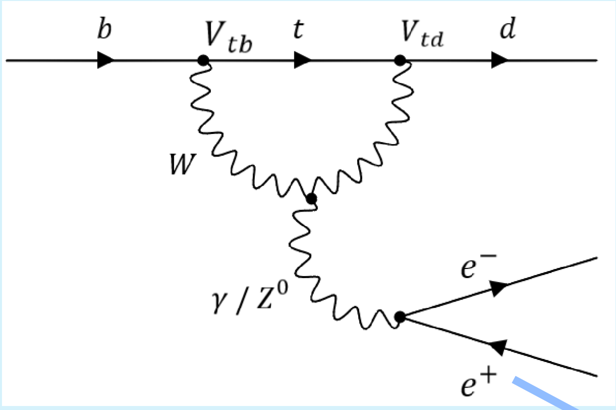


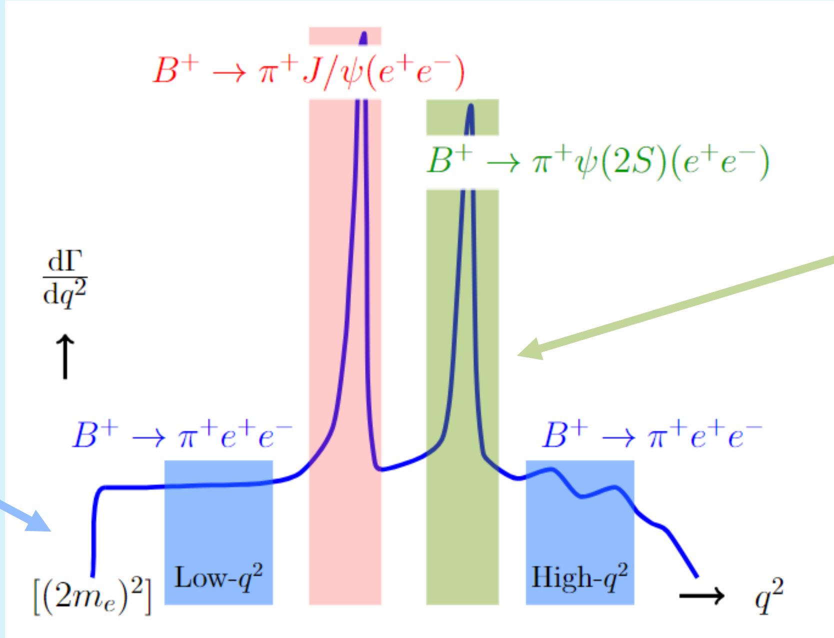
Measurement of $B^+ \to K^+\mu^+\mu^-$ differential branching fraction. [LHCb, arXiv:1209.4284].

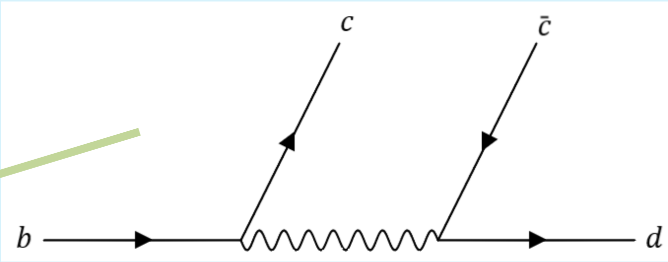


Measurement of $B^+ \to \pi^+\mu^+\mu^-$ differential branching fraction [LHCb, arXiv:1509.00414].

Our Analysis





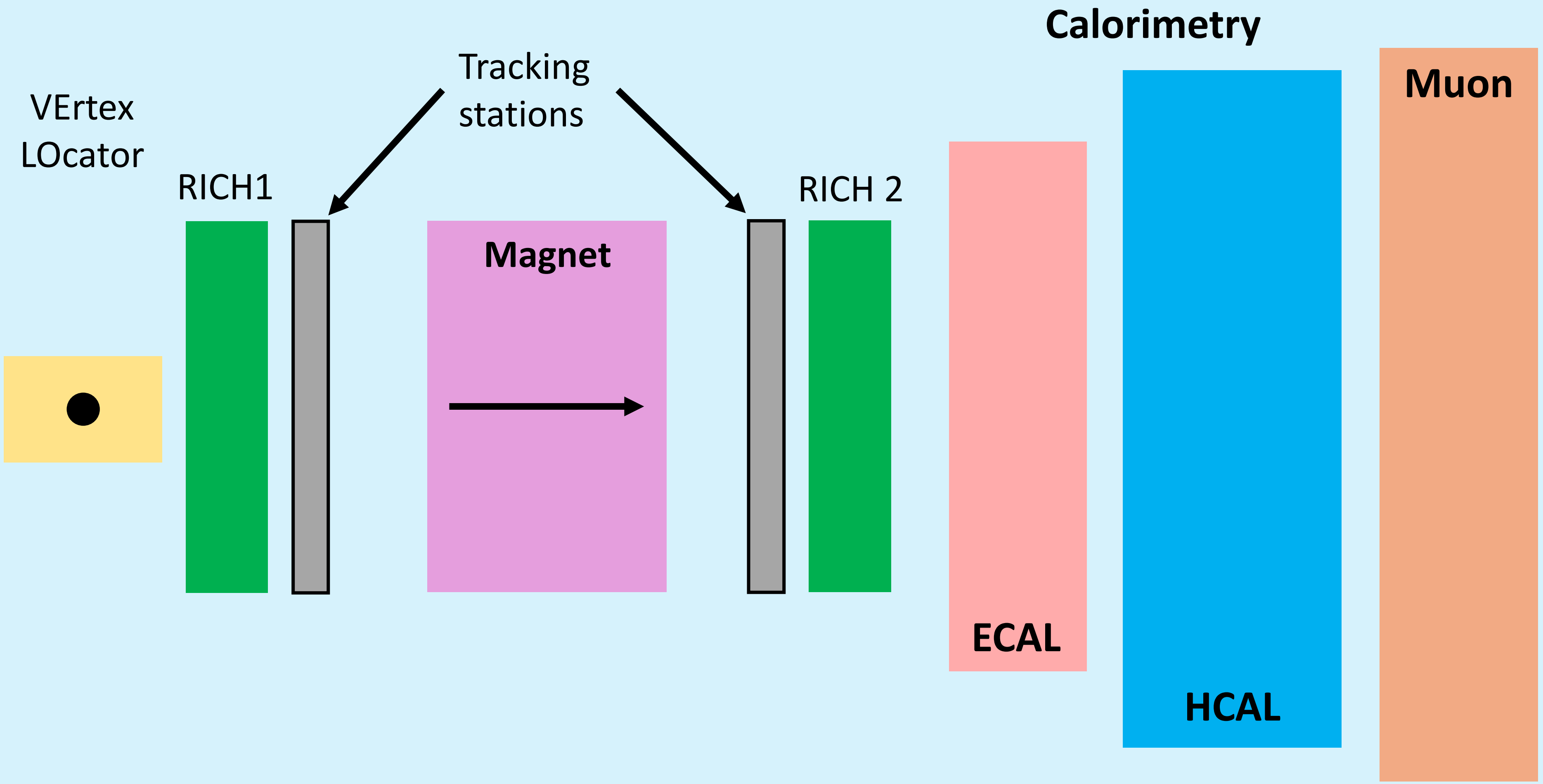


We will report on the rare mode branching fraction $\mathrm{BF}(\mathrm{B}^+ \to \pi^+ e^+ e^-)$, discriminating between this and the resonance processes by the dielectron mass $q^2 = (\ p_{e^-} + p_{e^+}\ )^2$.

Signal region includes High and Low q^2, with the charmonium resonances used as control.

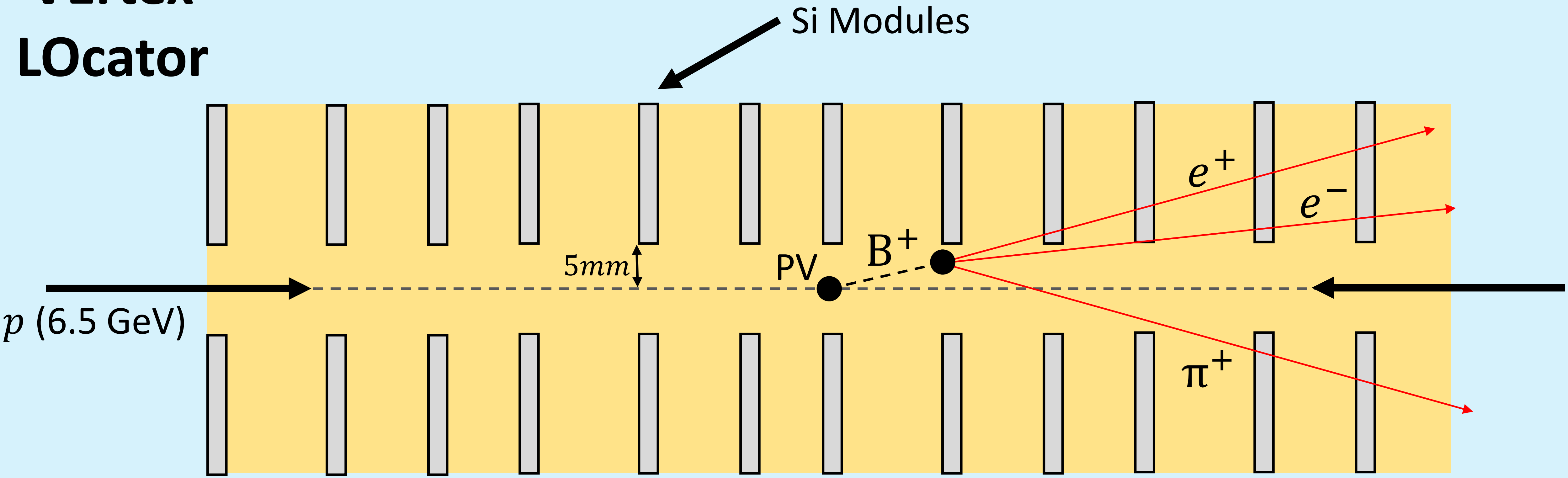
$$\mathrm{N_{SR}}(\mathrm{B}^+ \to \pi^+ \mathrm{e}^+ \mathrm{e}^-) = \mathrm{N_{CR}}(\mathrm{B}^+ \to \mathrm{K}^+ J/\psi(\to \mathrm{e}^+\mathrm{e}^-)) \frac{\mathrm{BF}(\mathrm{B}^+ \to \pi^+ \mathrm{e}^+ \mathrm{e}^-)}{\mathrm{BF}(\mathrm{B}^+ \to \mathrm{K}^+ J/\psi(\to \mathrm{e}^+\mathrm{e}^-))} \frac{\epsilon_{\mathrm{SR}}(\mathrm{B}^+ \to \pi^+ \mathrm{e}^+ \mathrm{e}^-)}{\epsilon_{\mathrm{CR}}(\mathrm{B}^+ \to \mathrm{K}^+ J/\psi(\to \mathrm{e}^+\mathrm{e}^-))}$$

LHCb Detector



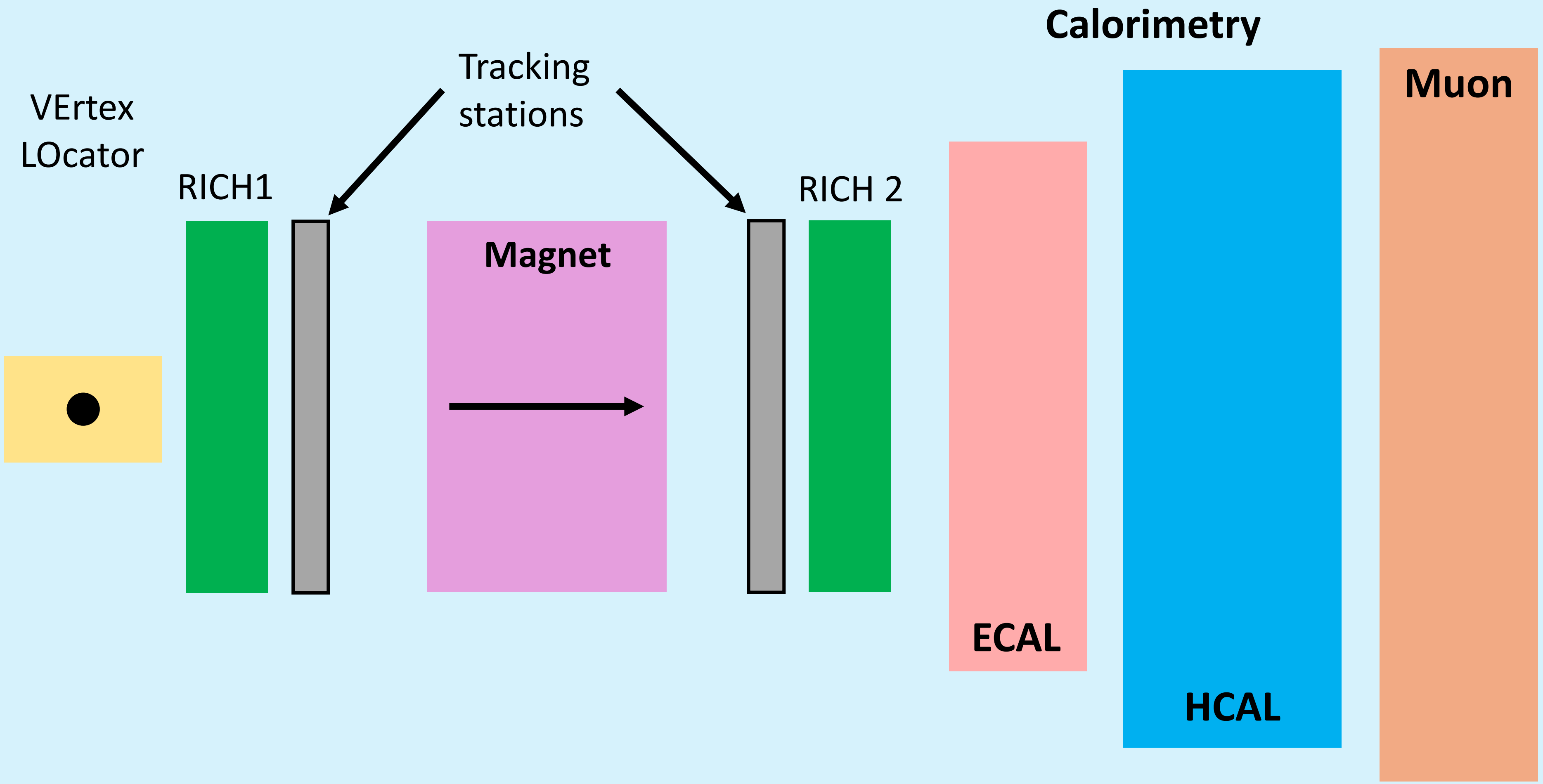
LHCb Detector

VErtex LOcator



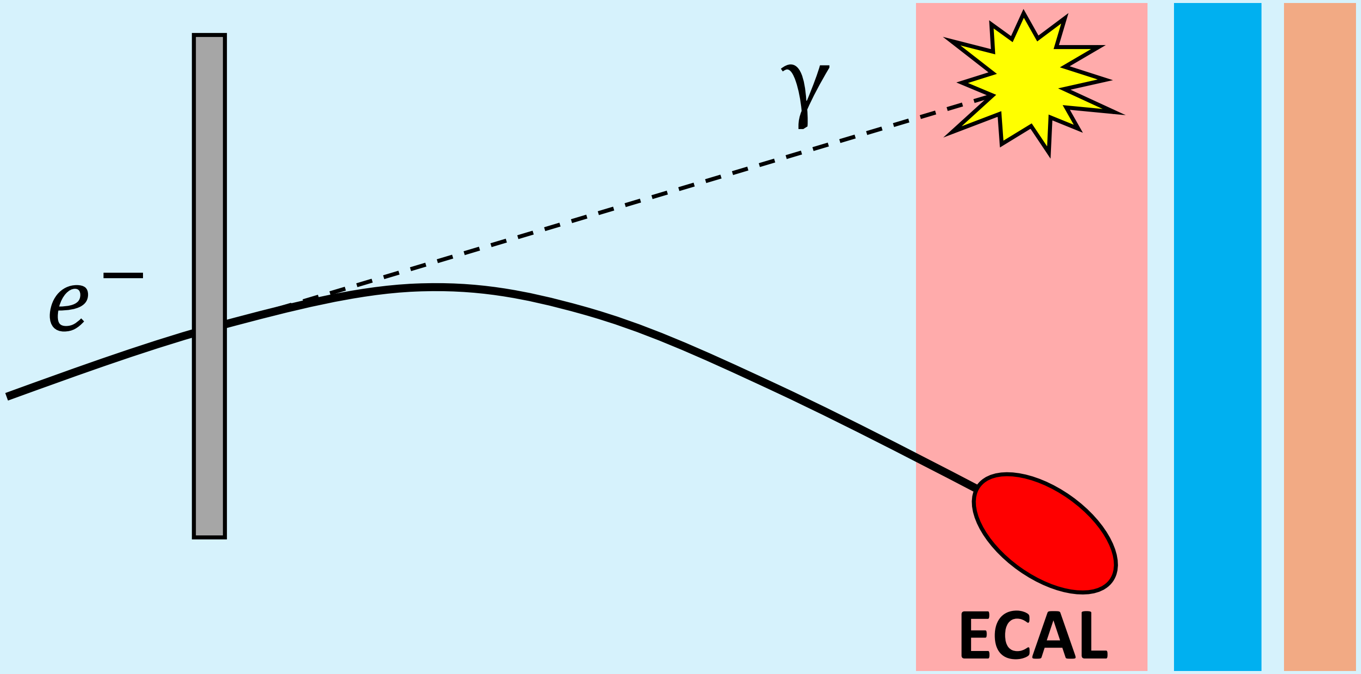
Silicon modules close to the primary vertex allow precise reconstruction of B meson decay vertex.

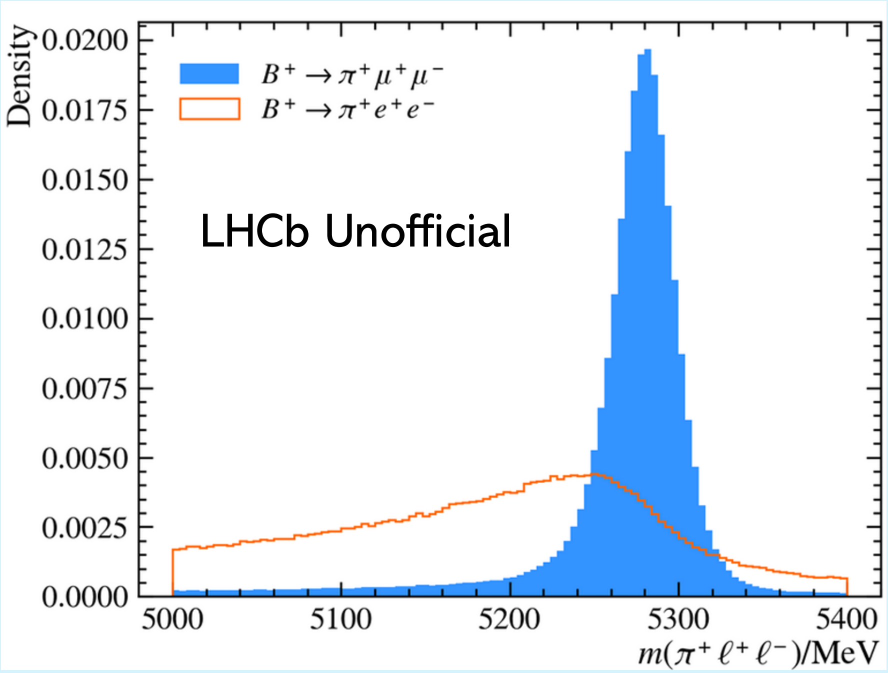
LHCb Detector



LHCb Detector

Bremsstrahlung Recovery

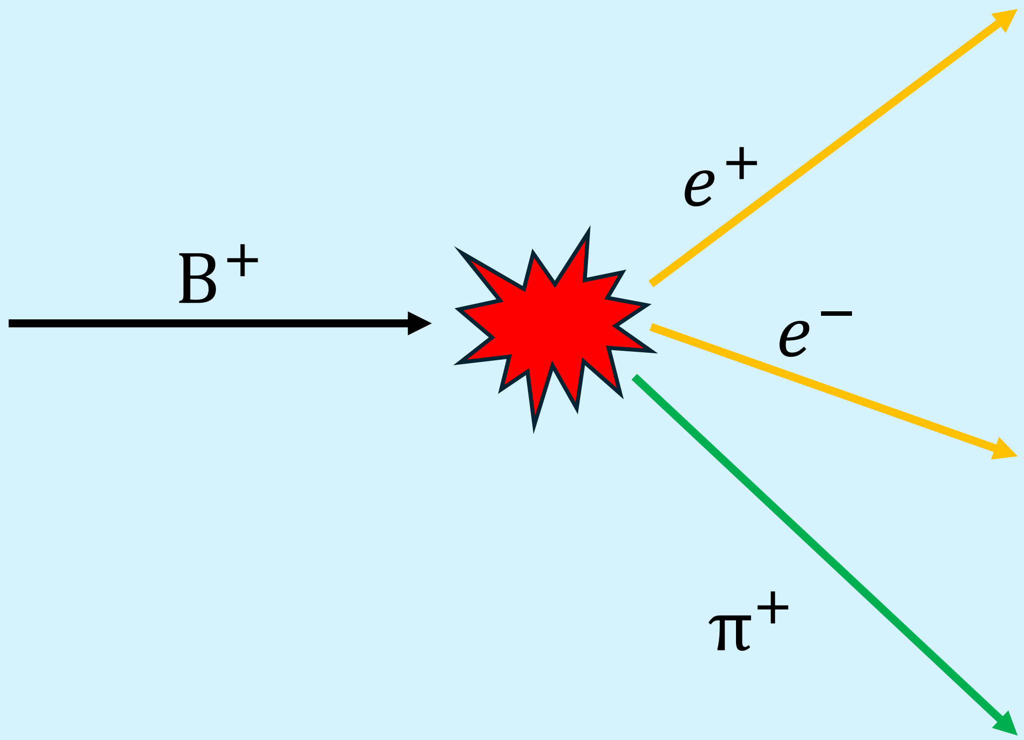




Brem (Bremsstrahlung) photons can be radiated when electrons interact with detector.
Degrades $m(\mathrm{B}^+)$ & p_e resolution:

- May not reconstruct photon / soft photon.
- Calo resolution poorer than tracking.

Signal Reconstruction



Signal Candidate

Extract signal branching fraction by fitting to invariant mass of the B-candidate.

Model physical component shapes and background expectations using calibrated MC.

Challenge of analysis is very rare signal process coupled with abundant and diverse backgrounds

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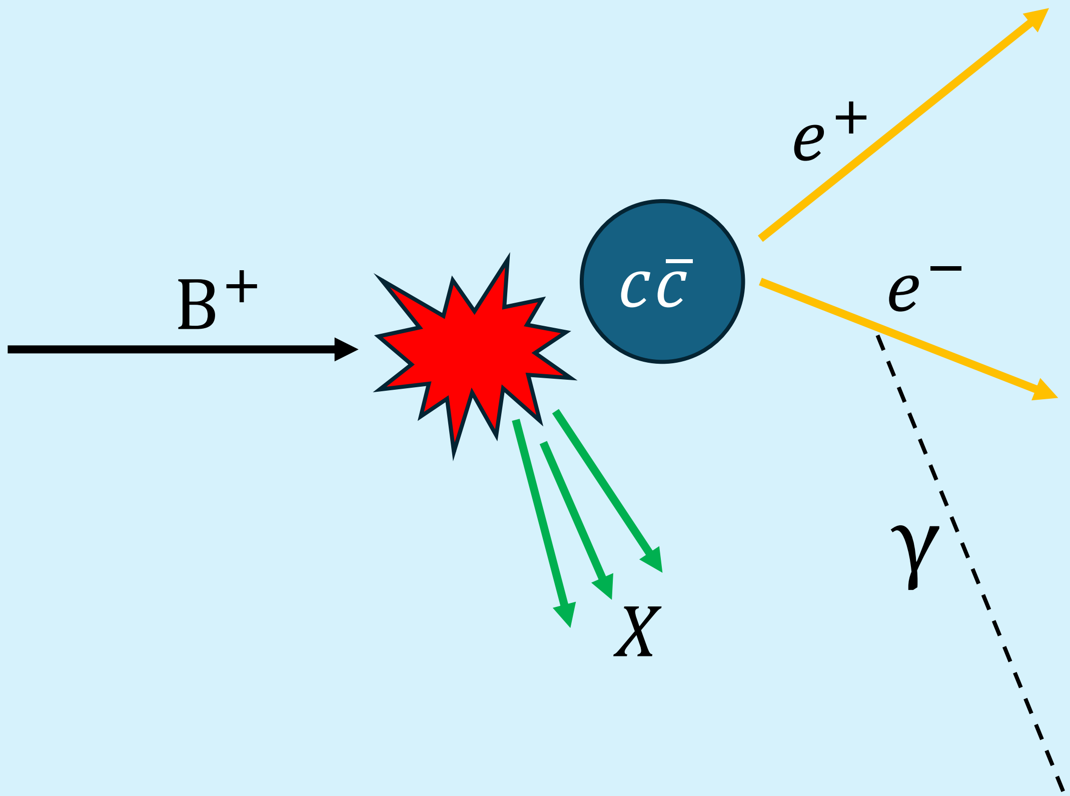
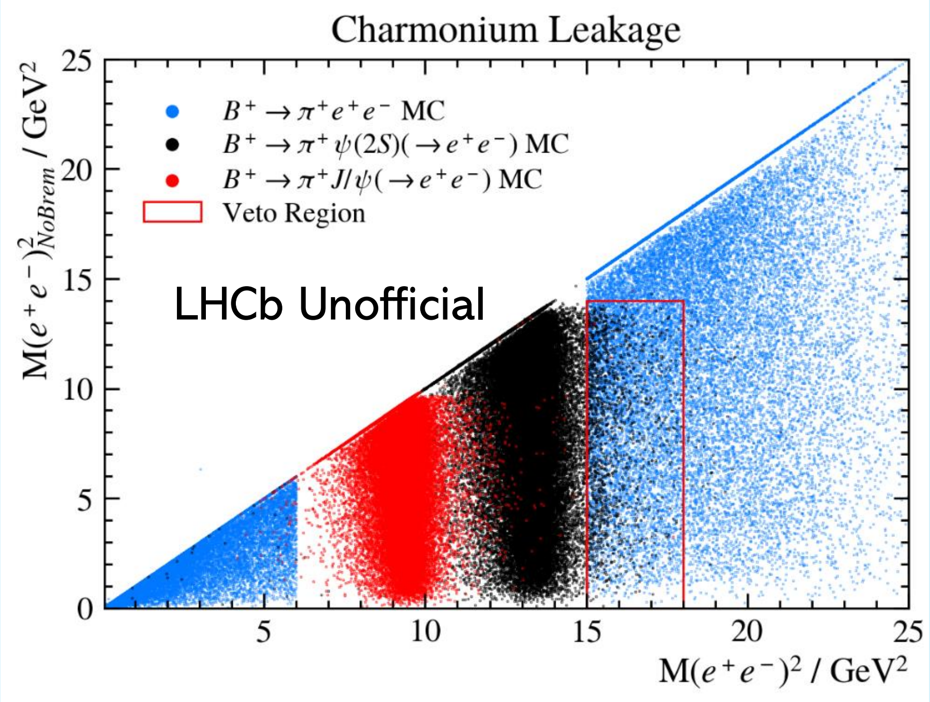
Backgrounds – Charmonium Leakage



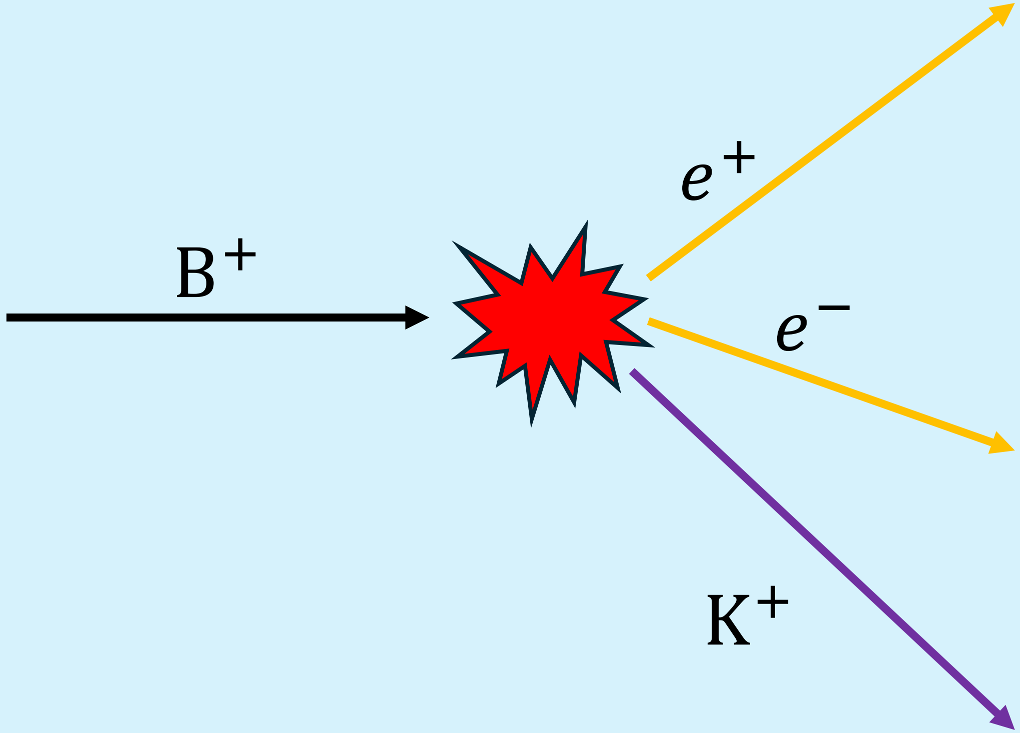
Leakage Background

$$\mathrm{B} \to \mathrm{X}\, J/\psi\, (\to e^+e^-) \text{ or } \mathrm{B} \to \mathrm{X}\, \psi(2\mathrm{S})(\to e^+e^-)$$

- Leakage from charmonium resonances when Brem radiation is mis reconstructed.
- We remove this by applying a veto on the dielectron mass without Brem added.
- Final expectation ≈ 30% of SM signal.



Backgrounds – Kaon MisID



MisID Candidate

Background due to $B^+ \to K^+ e^+ e^-$

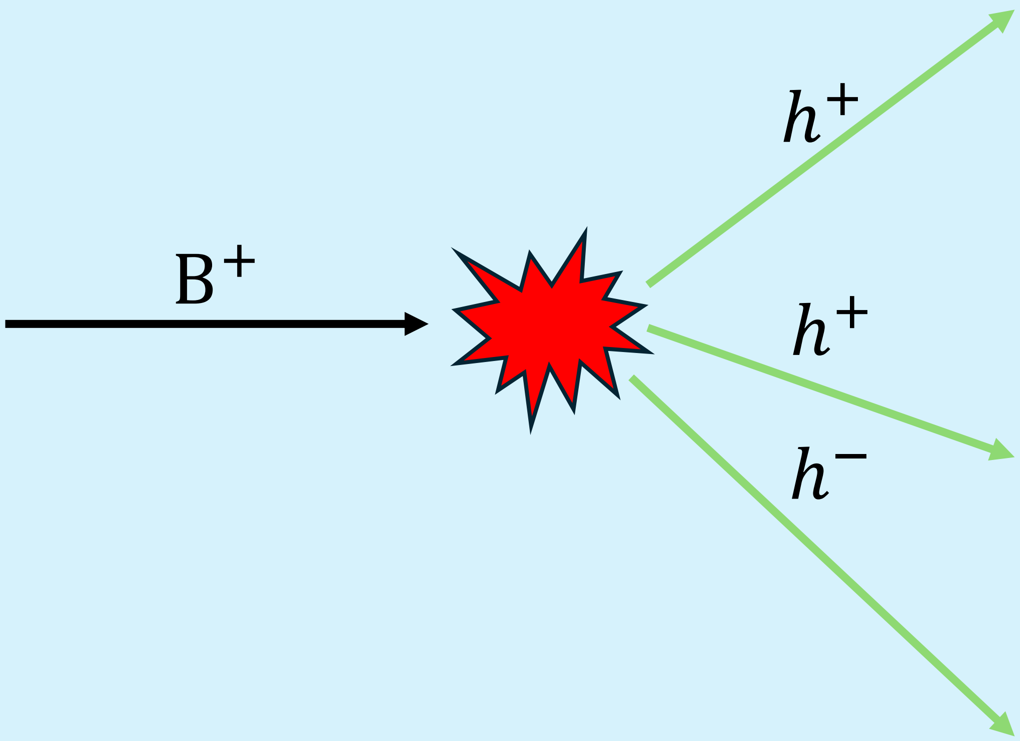
Requires the K^+ is misidentified as π^+, but the background branching fraction is ≈ 25 times greater than signal, following

$$\approx \left|\frac{V_{ts}}{V_{td}}\right|^2$$

We reduce this background by cutting tightly on the pion candidates PID (particle identification) requirements.

Final expectation ≈ 10% of SM signal.

Backgrounds – Electron MisID



Double MisID Background

Background due to $\mathrm{B} \to (3+)\mathrm{hadrons}$

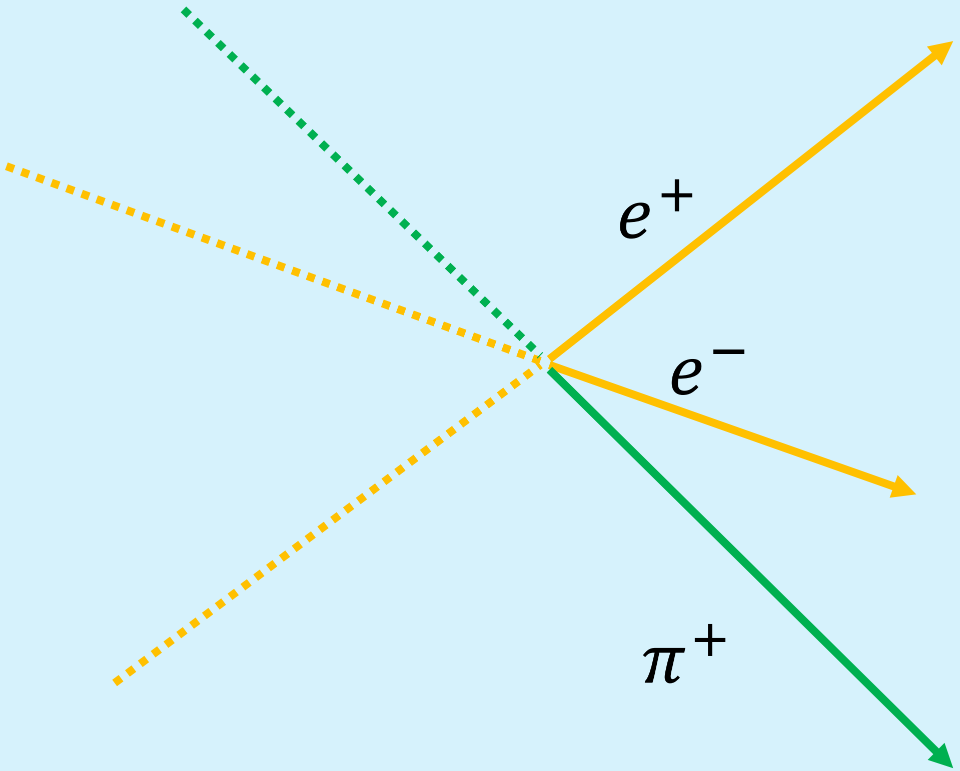
Requires mis-identifying the e^+ & e^- candidates, but background branching fractions $\approx 10^3$ greater than signal.

Remove by applying harsh PID selections on the e^+/e^- candidates.

Final expectation ≈ 10% of SM signal, though peaks under signal.

All these physical backgrounds are small compared to Combinatorial …

Backgrounds – Combinatorial



Combinatorial Background

Combinatorial background is the major background in this analysis.

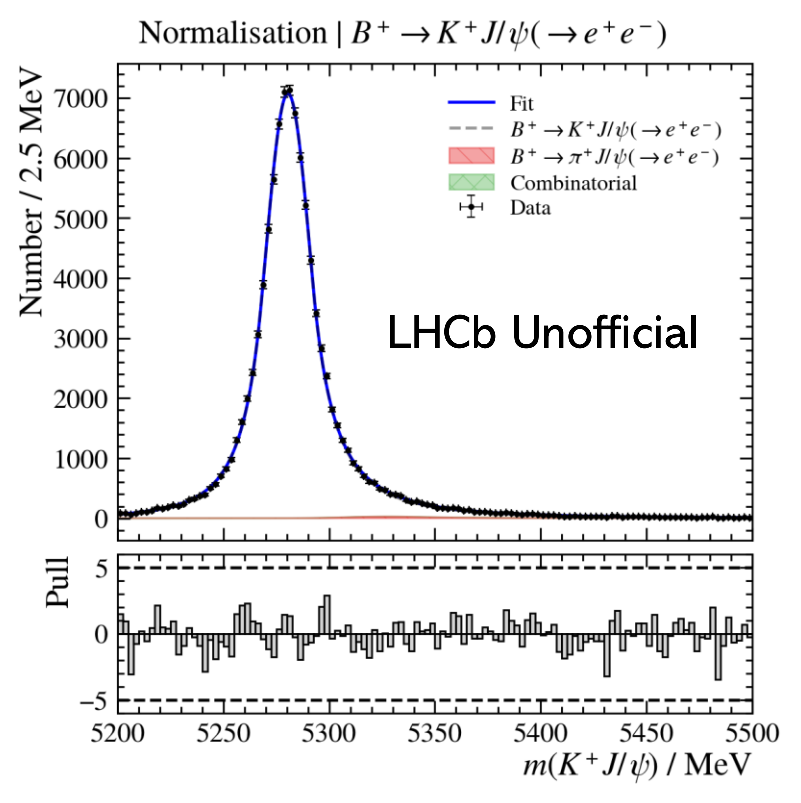
- Abundance of pions from pp collisions.
- Poor electron reconstruction.

Reduced both by PID requirements, as well as dedicated BDT.

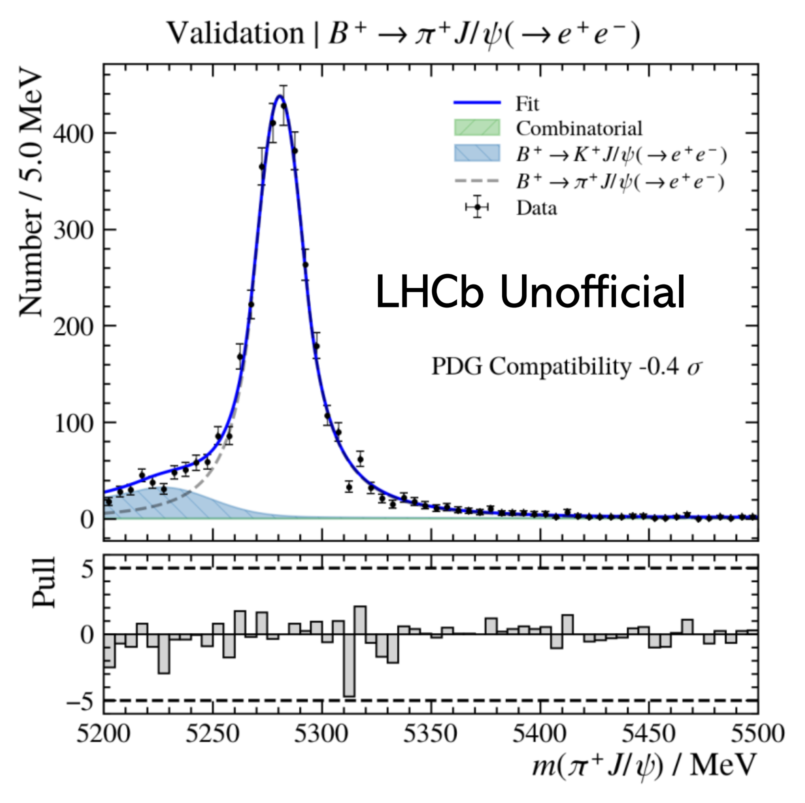
BDT also effective at removing partially reconstructed backgrounds:

$$\mathrm{B} \rightarrow hh(\ldots)\, e^+e^-$$

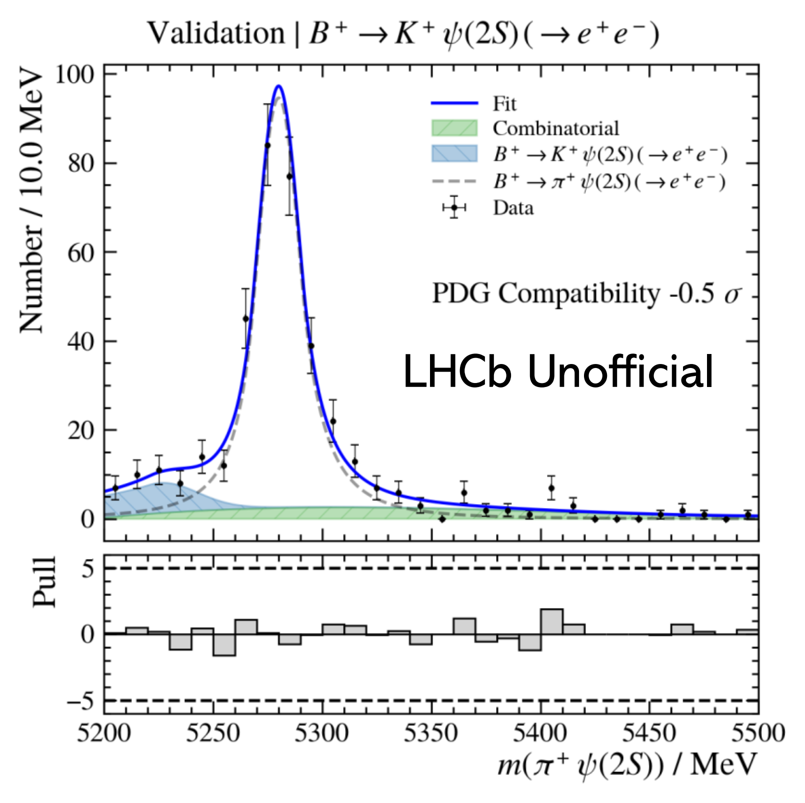
Control & Validation



Fit to the normalisation study to extrapolate.
$N_{CR}(B^+ \to K^+ J/\psi(\to e^+e^-))$



Validation with control mode
$B^+ \to \pi^+ J/\psi(\to e^+e^-)$



Validation with control mode
$B^+ \to \pi^+ \psi(2S)(\to e^+e^-)$

Signal Region

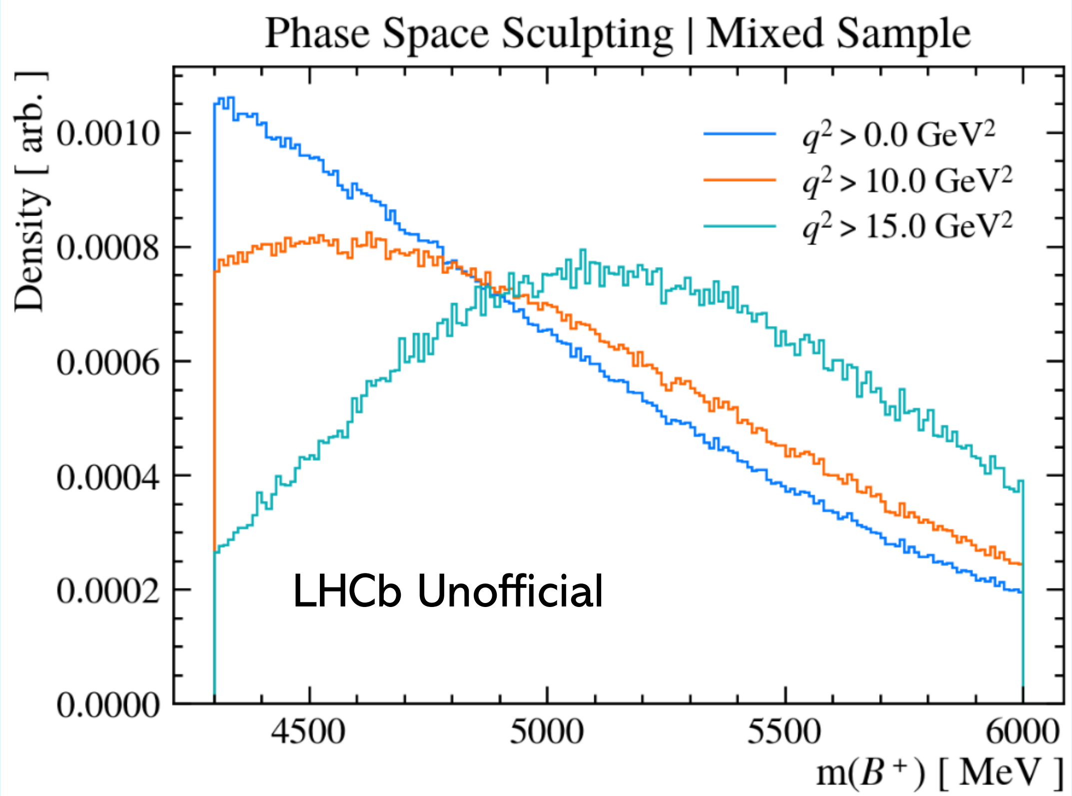
Signal region

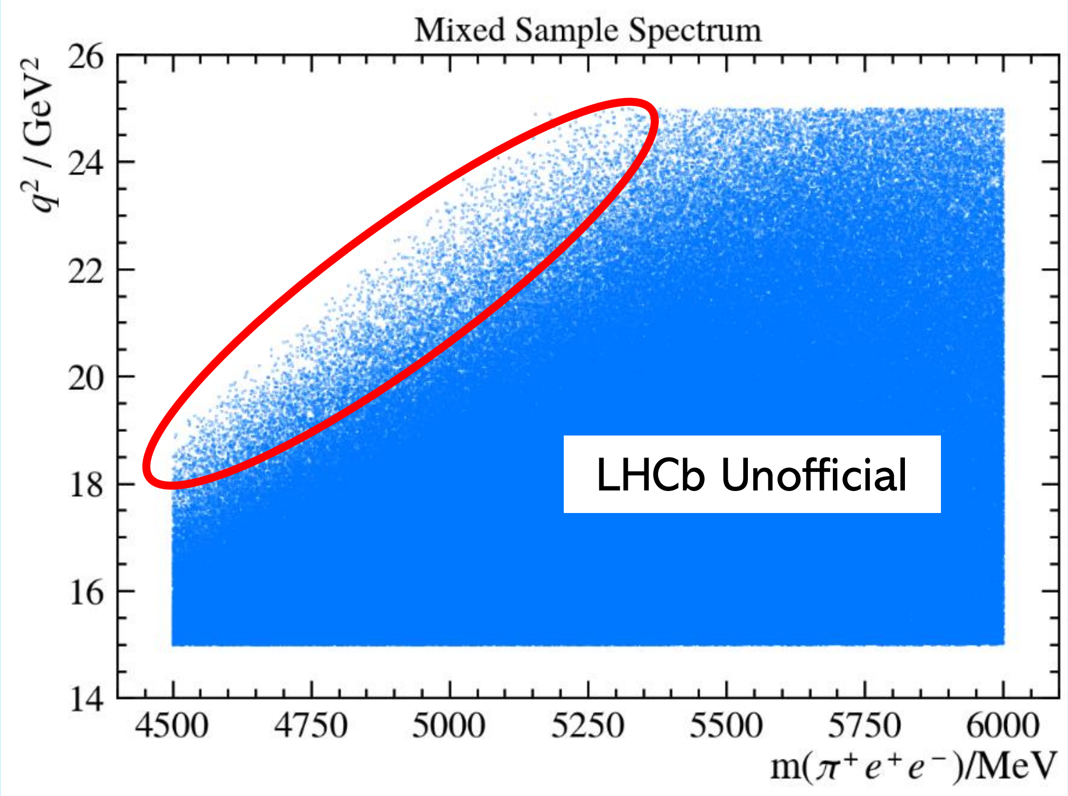
Low-q^2 ⟵ ⟶ High-q^2

For our fit to extract the branching fraction, we split our signal region into High & Low q^2, which are then fit simultaneously.

- Improves sensitivity as signal to background ratio more favourable in Low-q^2.
- Different combinatorial models needed in each region …

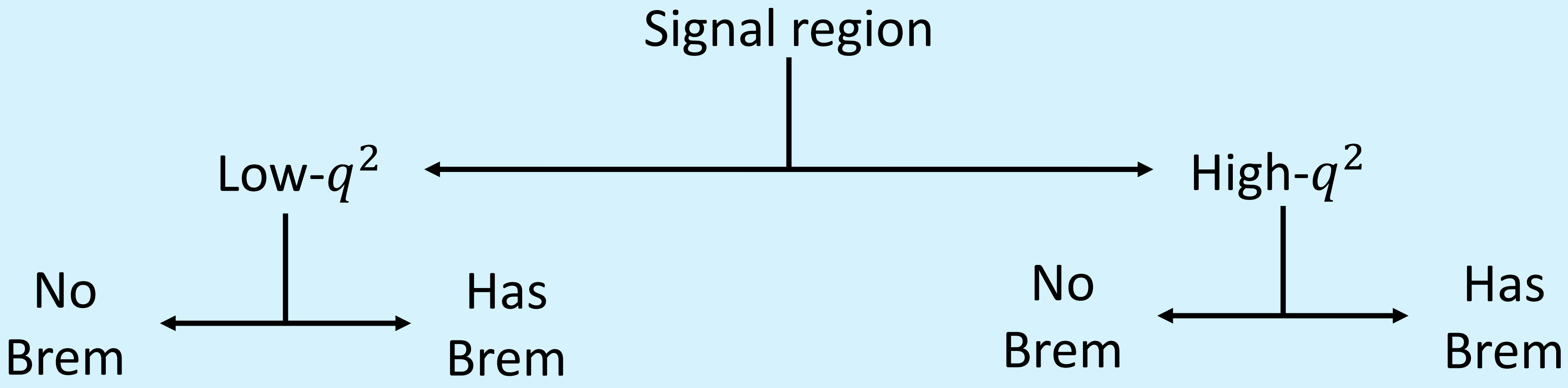
Signal Region – Combinatorial Model





- Observe a non-exponential combinatorial at High-q^2 due to phase-space cut-off.
- We use a phase-space model developed for the LHCb measurement of $\mathrm{R_K}$ at High-q^2.
- Additional sculpting effects are then included to account for warping induced by selections.

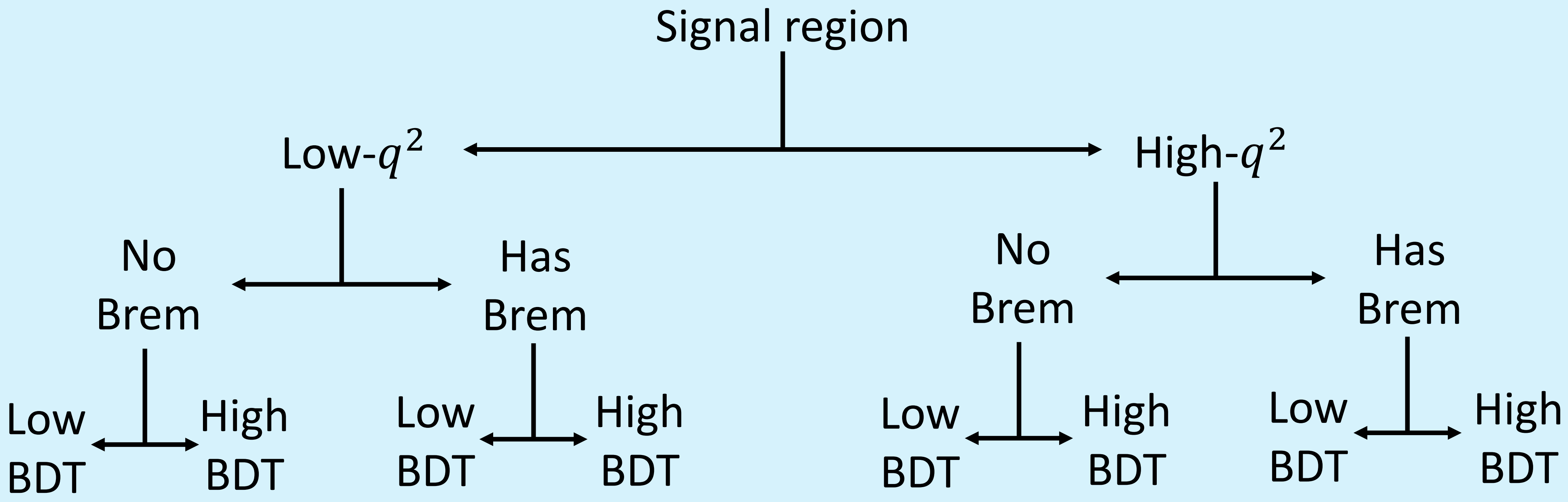
Signal Region



We further separate our signal region data according to Brem category, HasBrem requiring at least one of the e^+/e^- candidates to have an associated Brem photon, this:

- Improves sensitivity, the HasBrem region having a more favourable signal to background ratio.
- Allows us to almost entirely exclude Double MisID from the HasBrem region, since pions far less likely to radiate bremsstrahlung in the detector.

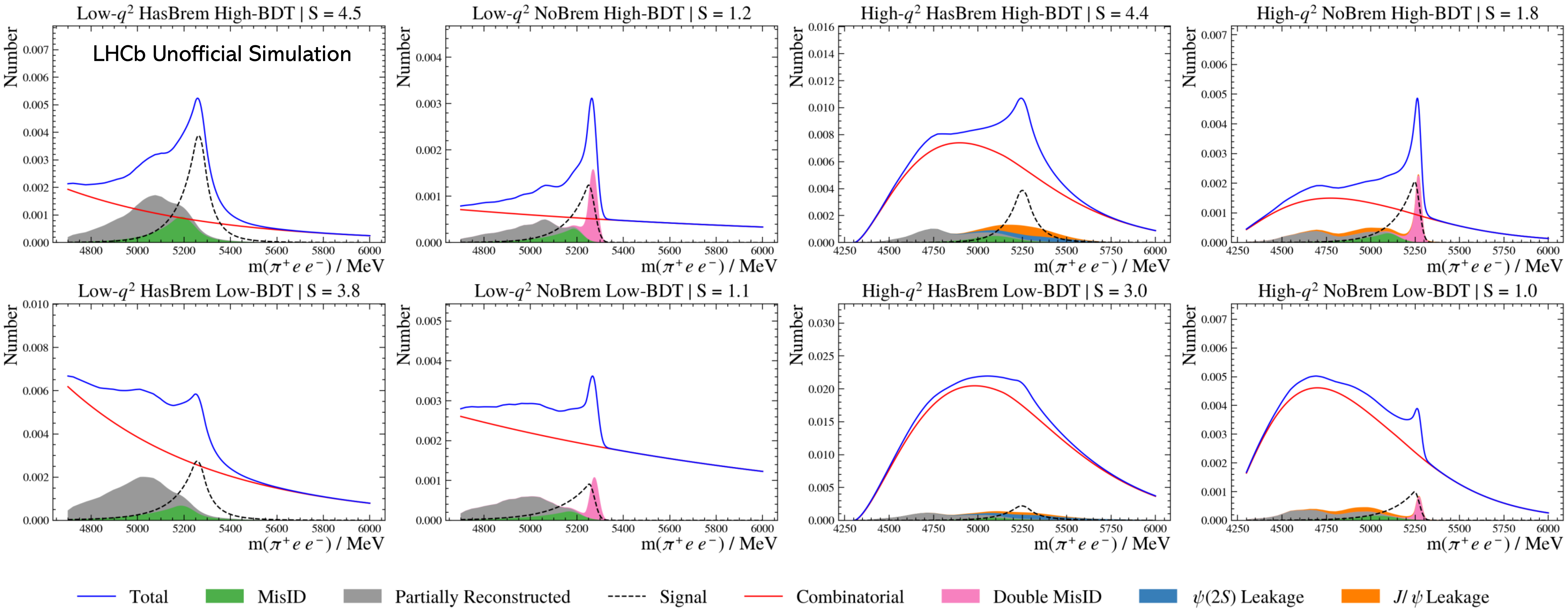
Signal Region



Finally, for each q^2 / Brem region we included 2 bins in BDT (High & Low).

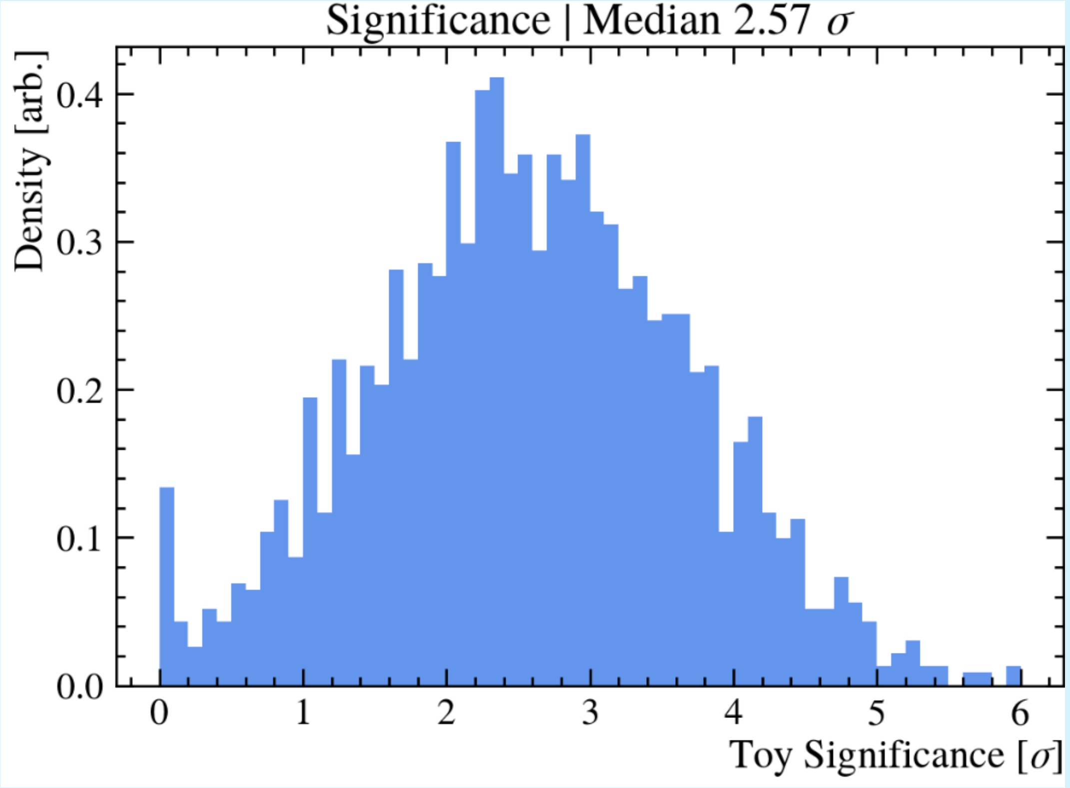
- Recovers some of the signal lost if just included high BDT region.
- Share combinatorial shape parameters between each pair of BDT regions.

Signal Region – Final Model



- We have completed our final signal model, and validated the model using toys.
- A median significance of 2.5 σ expected assuming the standard model.
- **S** here is the expectation number of signal events in that region.

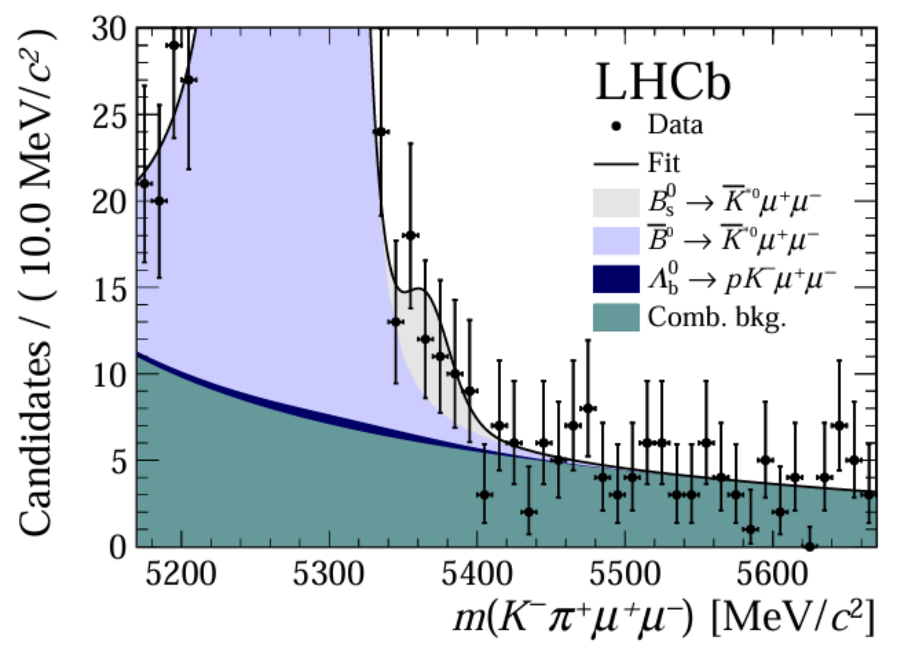
Conclusion

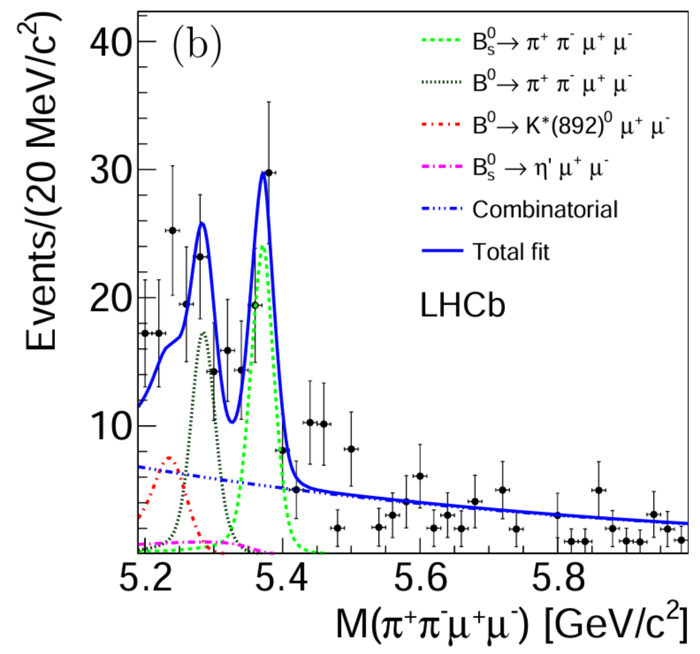


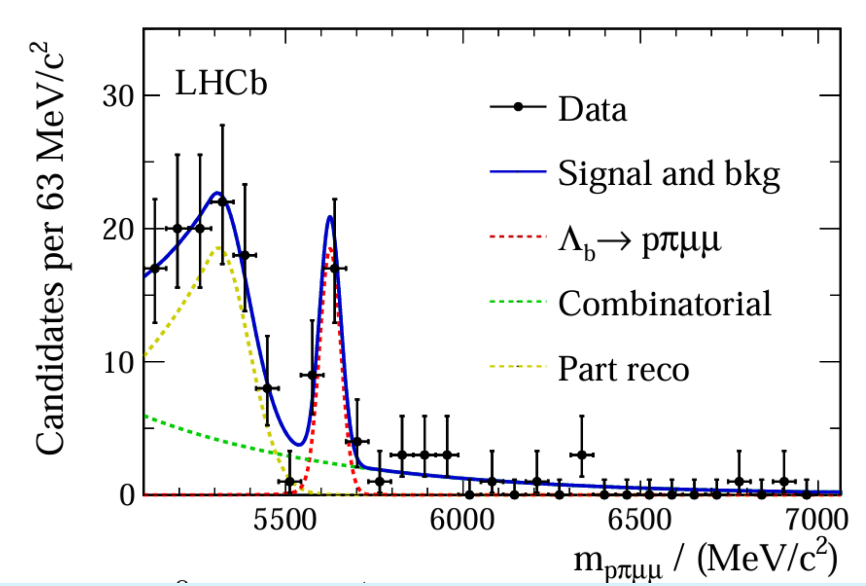
- Analysis is nearly complete, internal review commencing imminently
- Will report BF($B^+ \rightarrow \pi^+ e^+ e^-$), including an upper limit and the likelihood.
- Measurement will improve as more data is taken in Run3 & beyond.

Backup

Backup : Other $b \to d\,\mu^+\mu^-$ measurements at LHCb





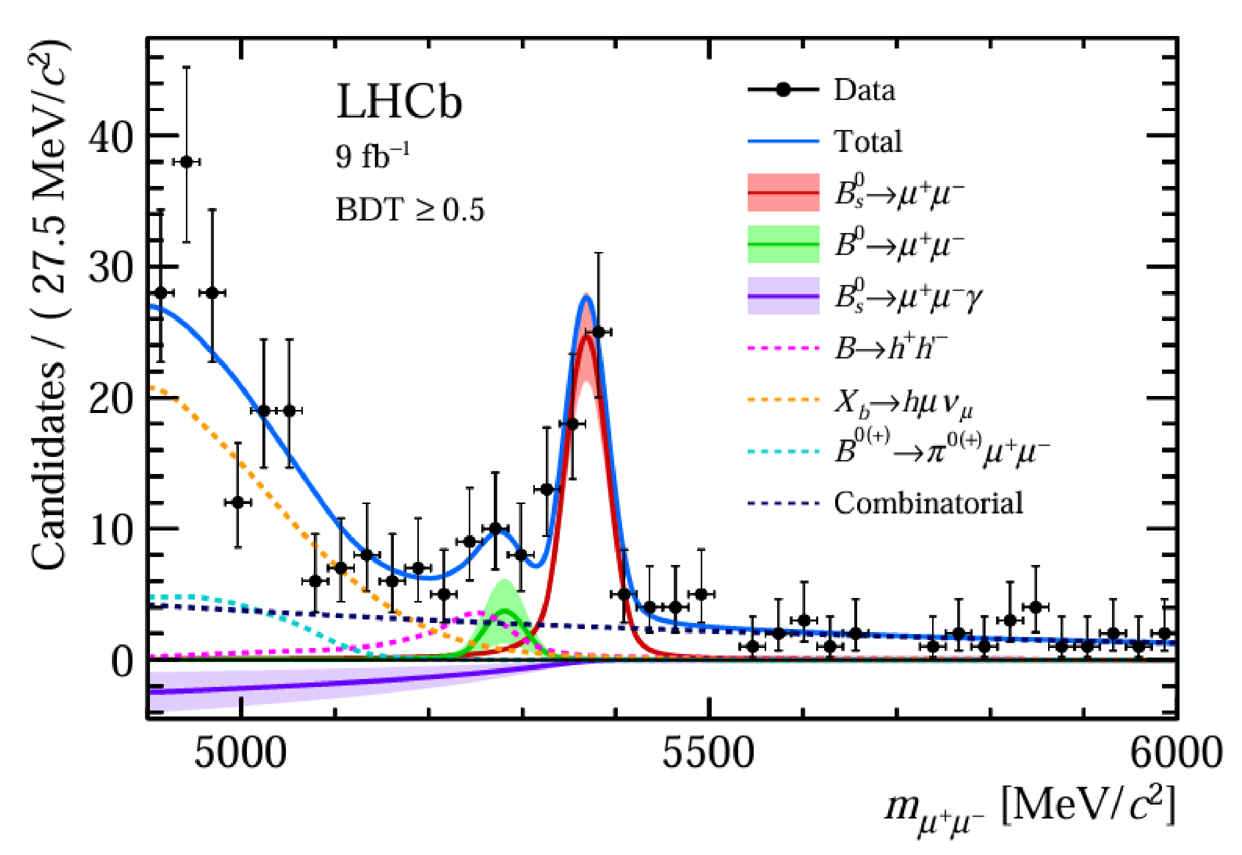


First evidence (significance of 3.4σ) for $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ [LHCb, arXiv:1804.07167].

First evidence (significance of 4.8σ) for $B^0 \to \pi^+\pi^-\mu^+\mu^-$ [LHCb, arXiv:1412.6433].

Observation (significance of 5.5σ) of $\Lambda_b \to p\pi^-\mu^+\mu^-$ [LHCb, arXiv:1701.08705].

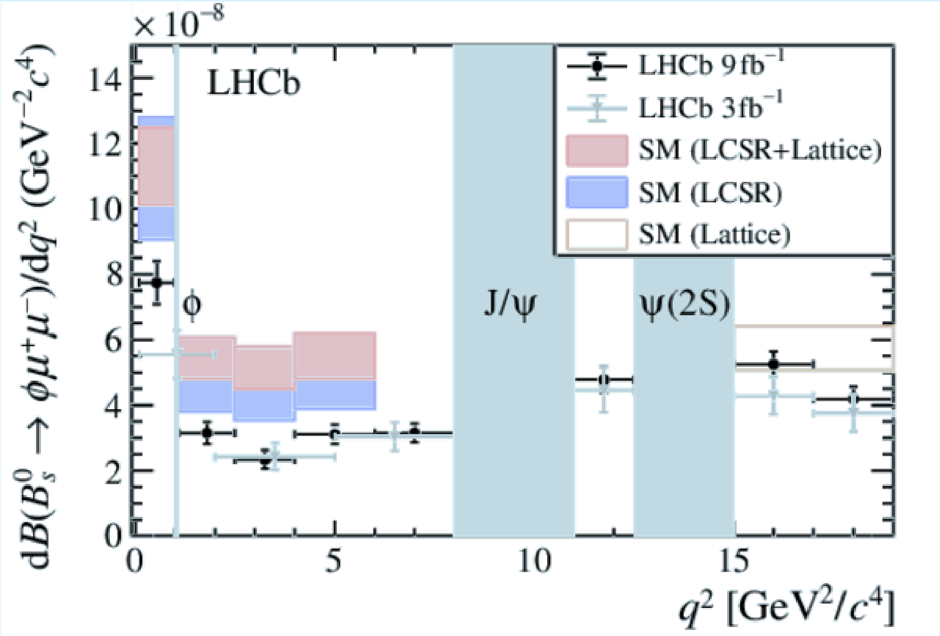
Backup : Operator related processes



Upper limit on $B^0 \to \mu^+\mu^-$
[LHCb, arXiv:2108.09284].

$$\mathrm{BF}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$

Backup : Some b → sll



Measurement of $B_s^0 \to \phi^0\mu^+\mu^-$ differential branching fraction.
Deficit observed of $\sim 3.6\sigma$
[LHCb, arXiv:2105.14007].

Backup : Consistency of flavour anomalies

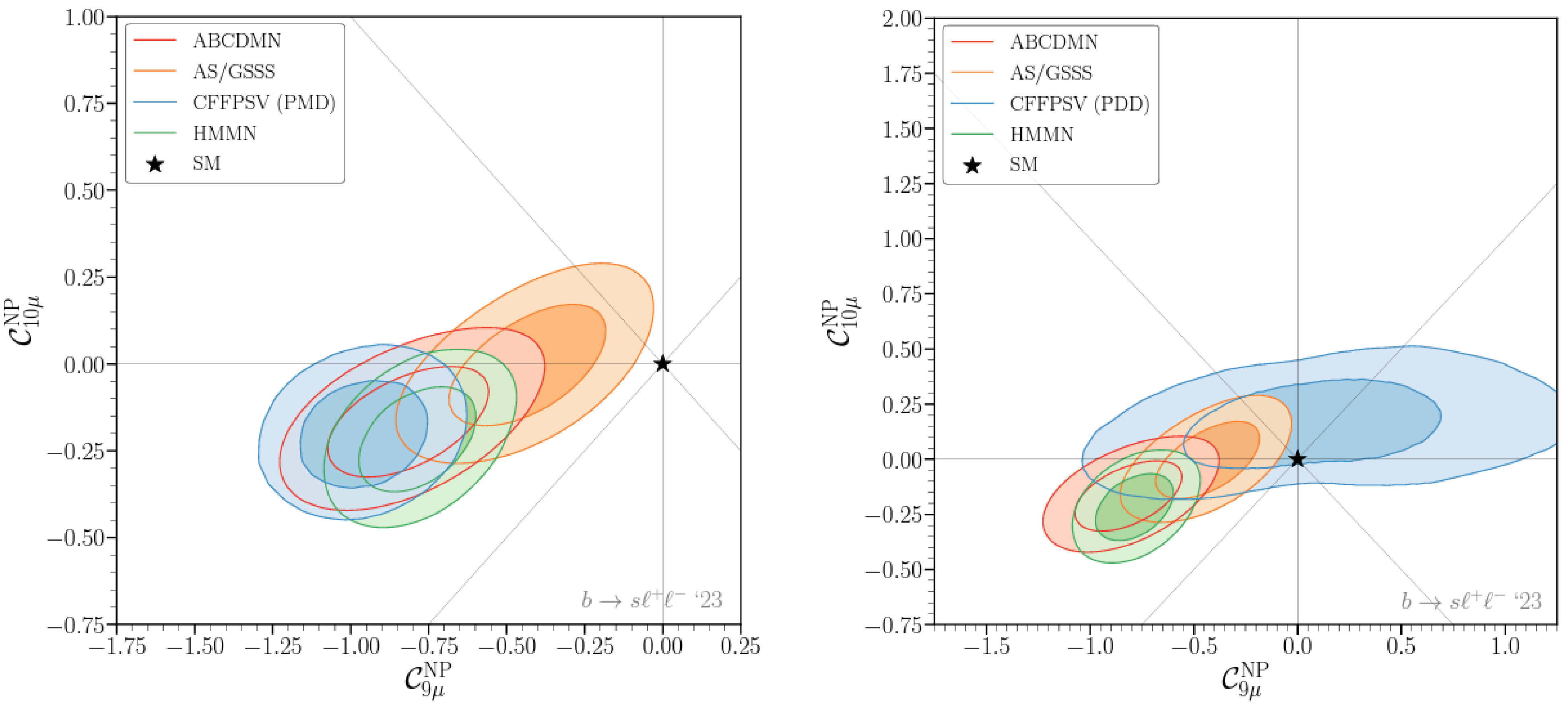
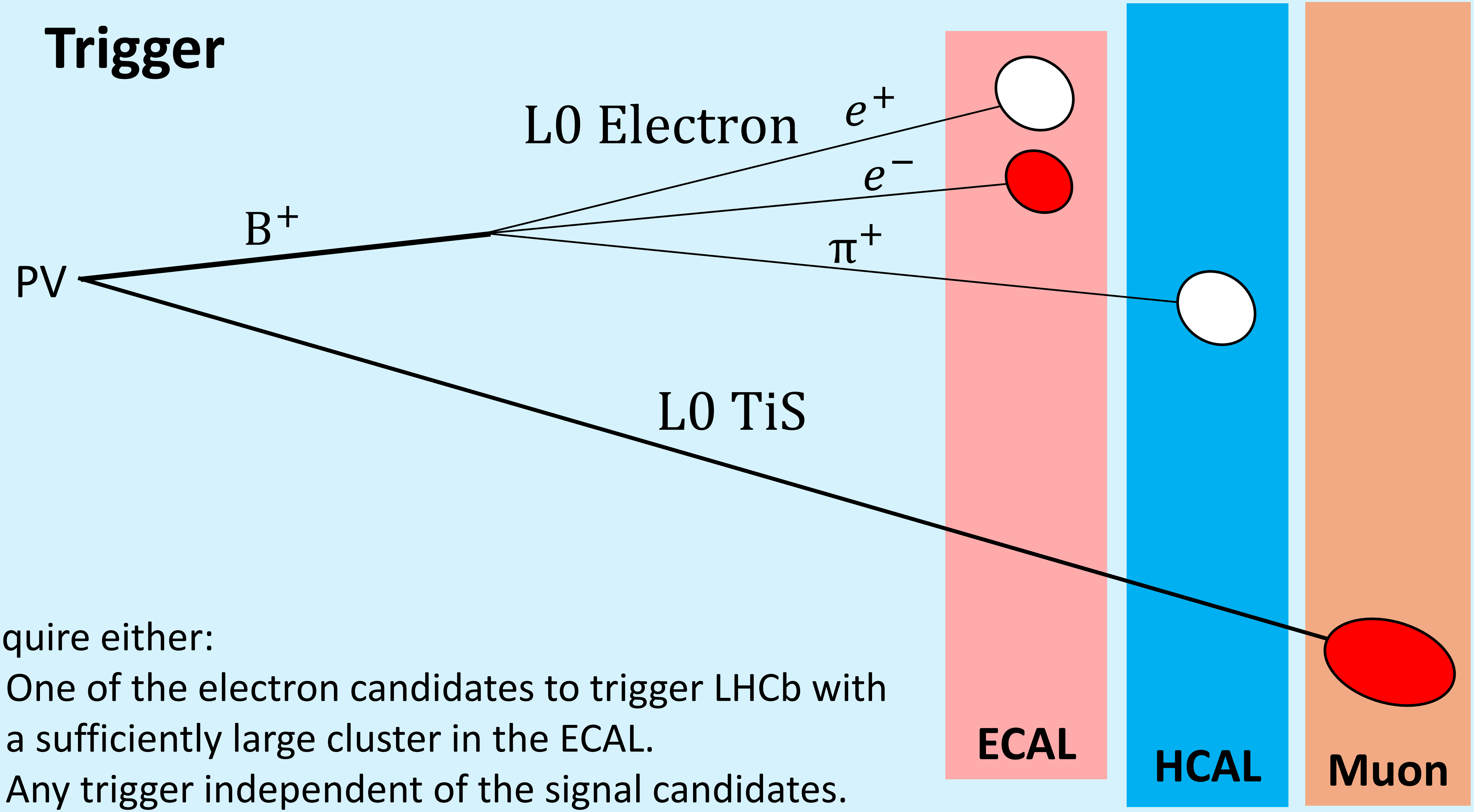


Fig. 3 Comparison of the results of the global fits of the different collaborations in the C_9^μ-C_{10}^μ plane. Note that assuming LFU, the differences would be more pronounced and the significance for NP would be higher. We show the LFV case anyway because the data for comparison is available.

Combination of results [arXiv:2309.01311]

Backup : Trigger

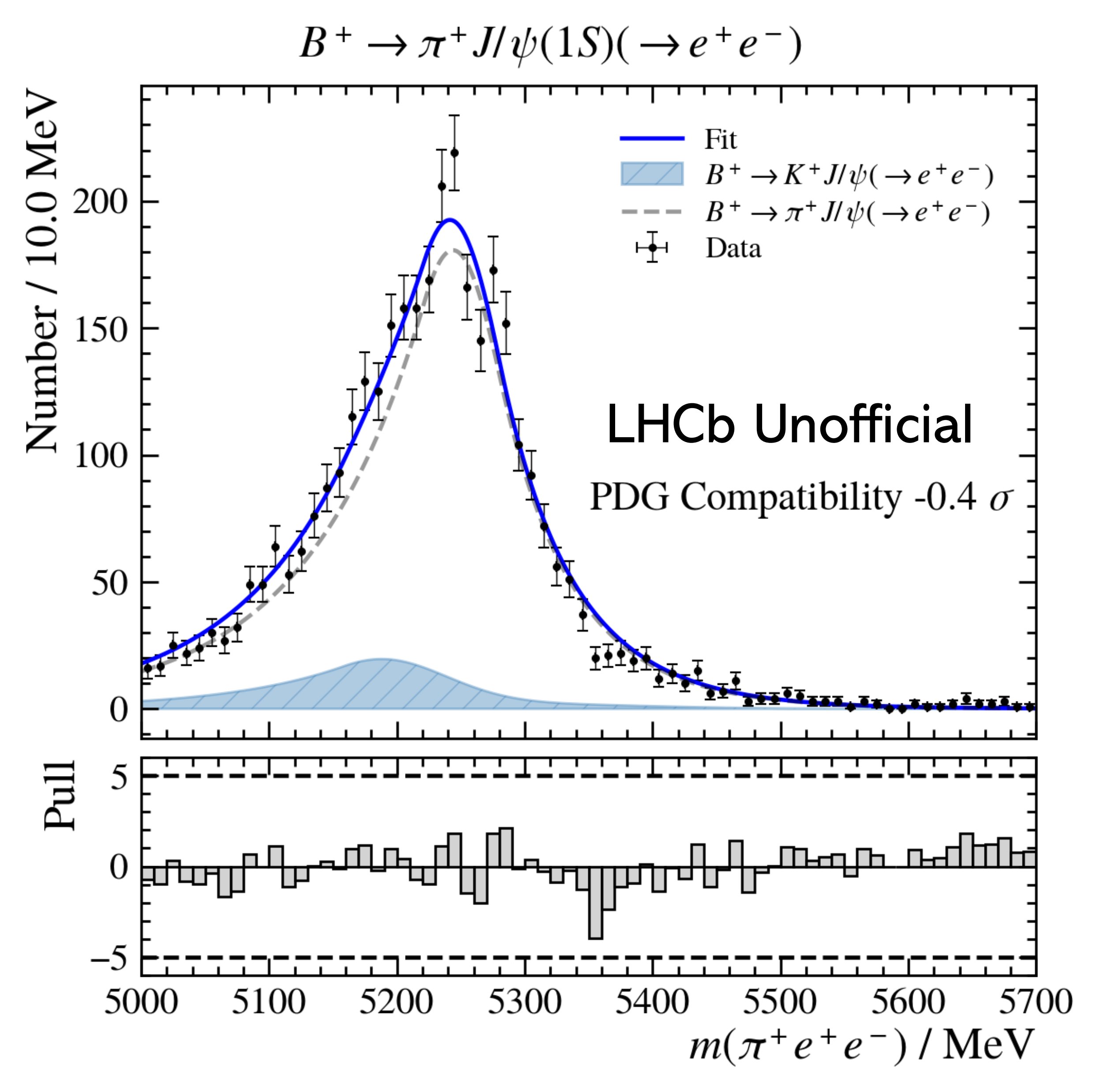
Trigger

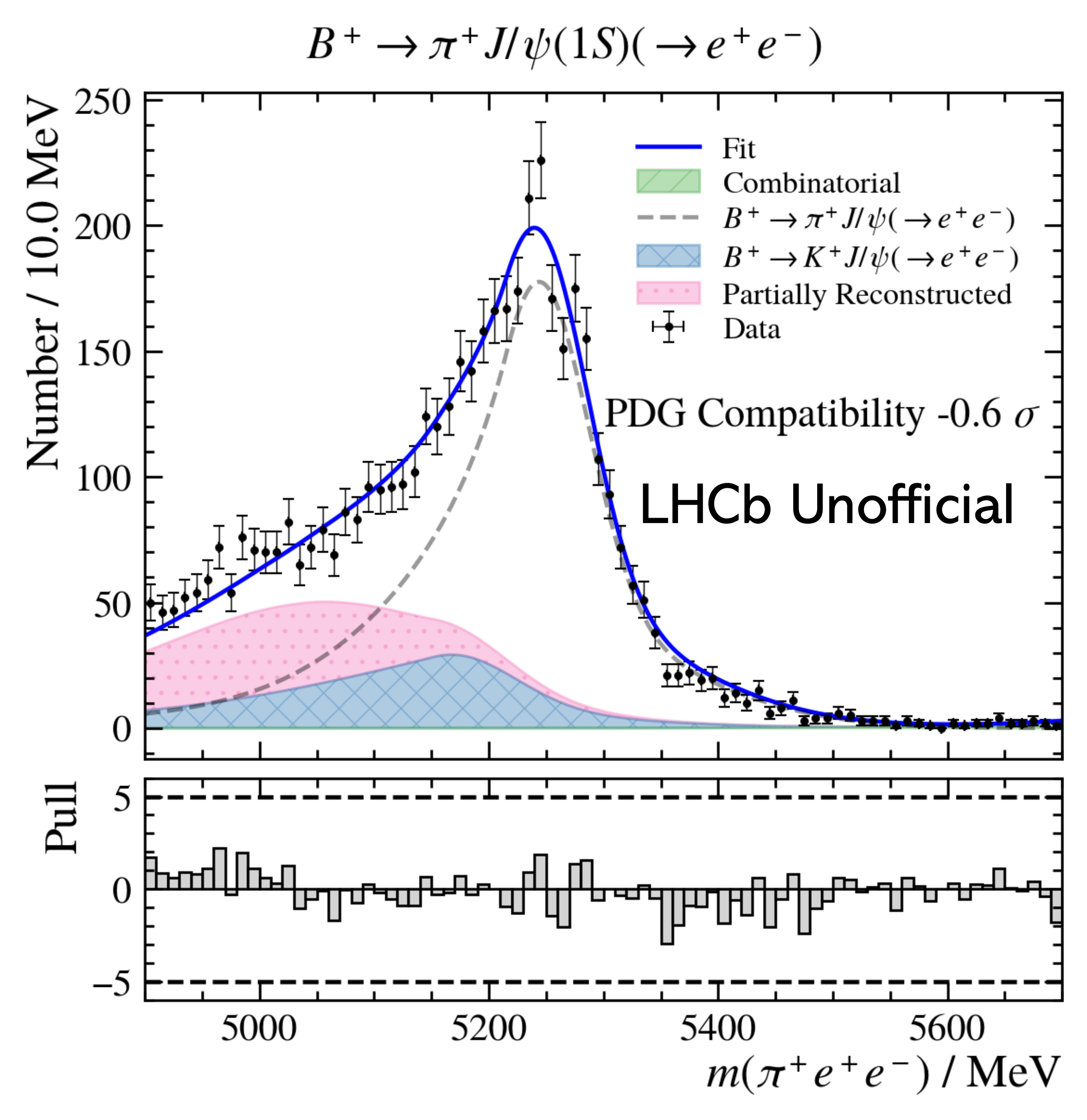


Require either:

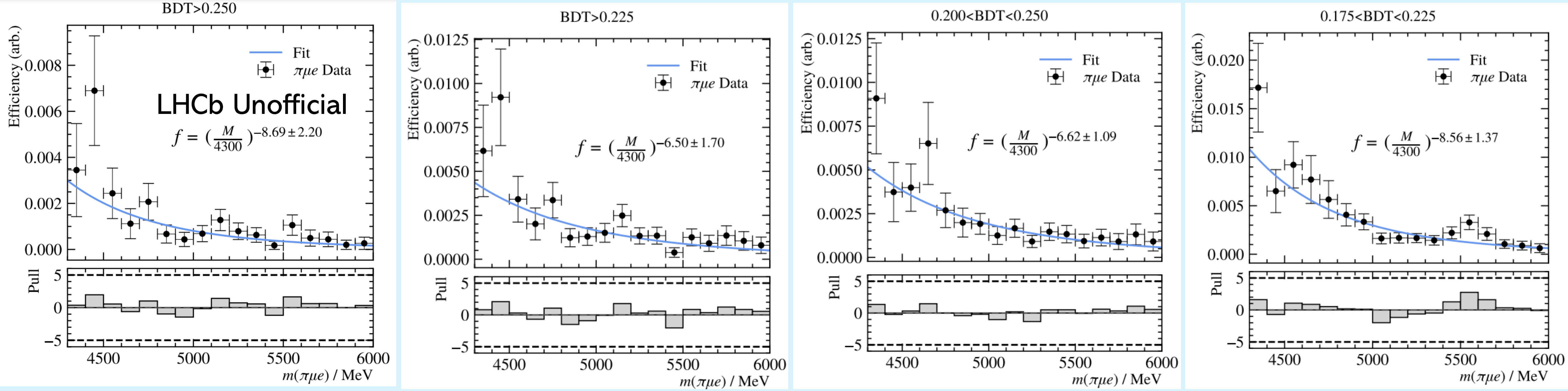
- One of the electron candidates to trigger LHCb with a sufficiently large cluster in the ECAL.
- Any trigger independent of the signal candidates.

Backup : Validation fits to unconstrained B-mass



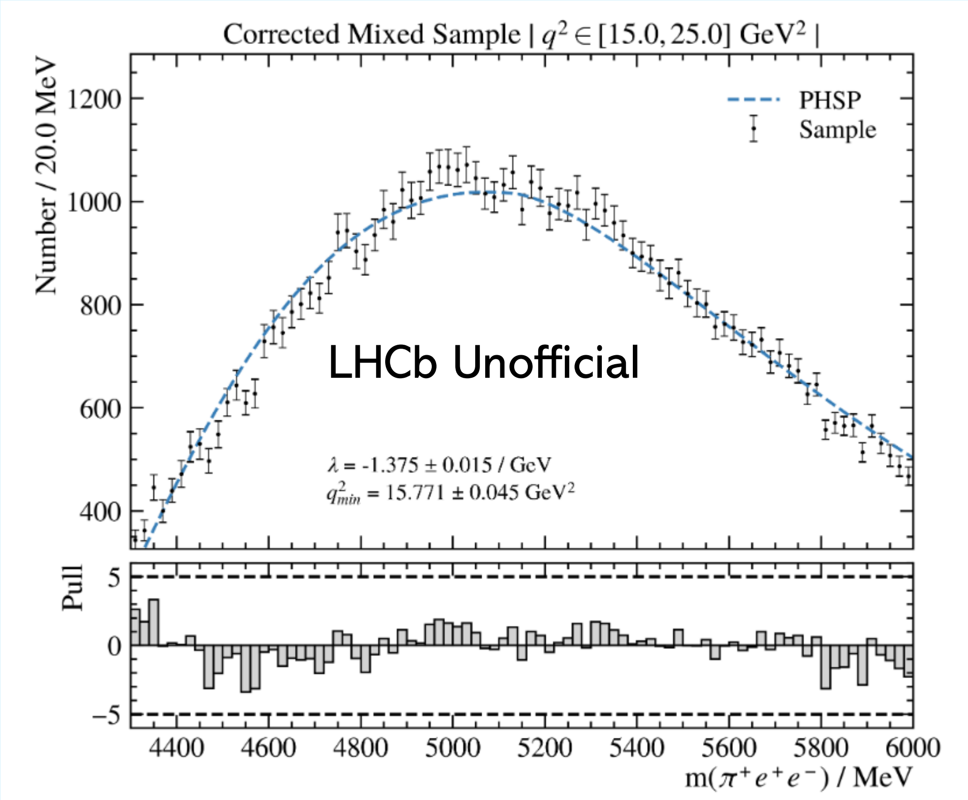


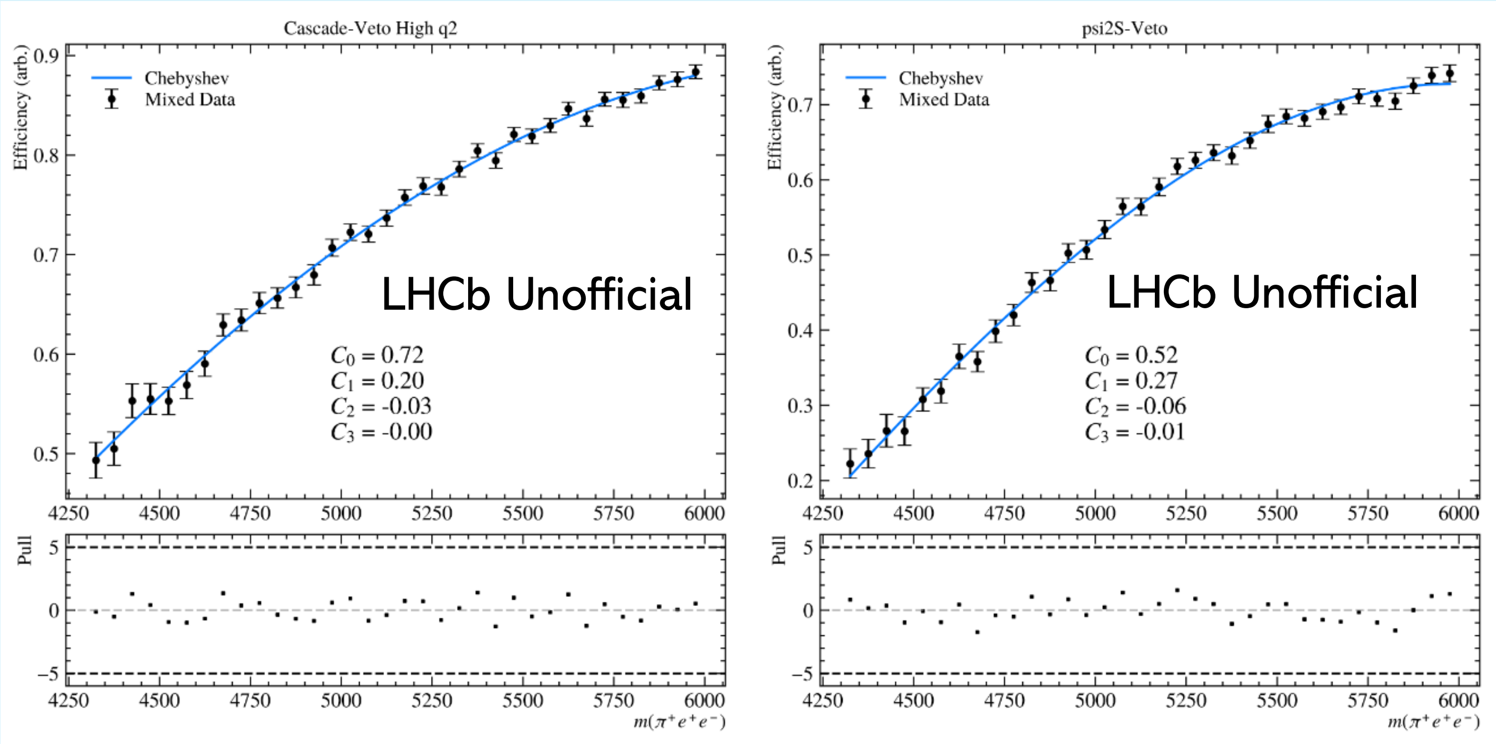
Backup : Sculpting for high-q2 Combinatorial (1)



The BDT Sculpting is computed using a sample of $\pi\mu e$ data as a proxy for combinatorial, where the efficiency is found from the ratio of pass BDT selection and fail, the data corrected to better match BDT response of πee, and the final shape fit to a power law.

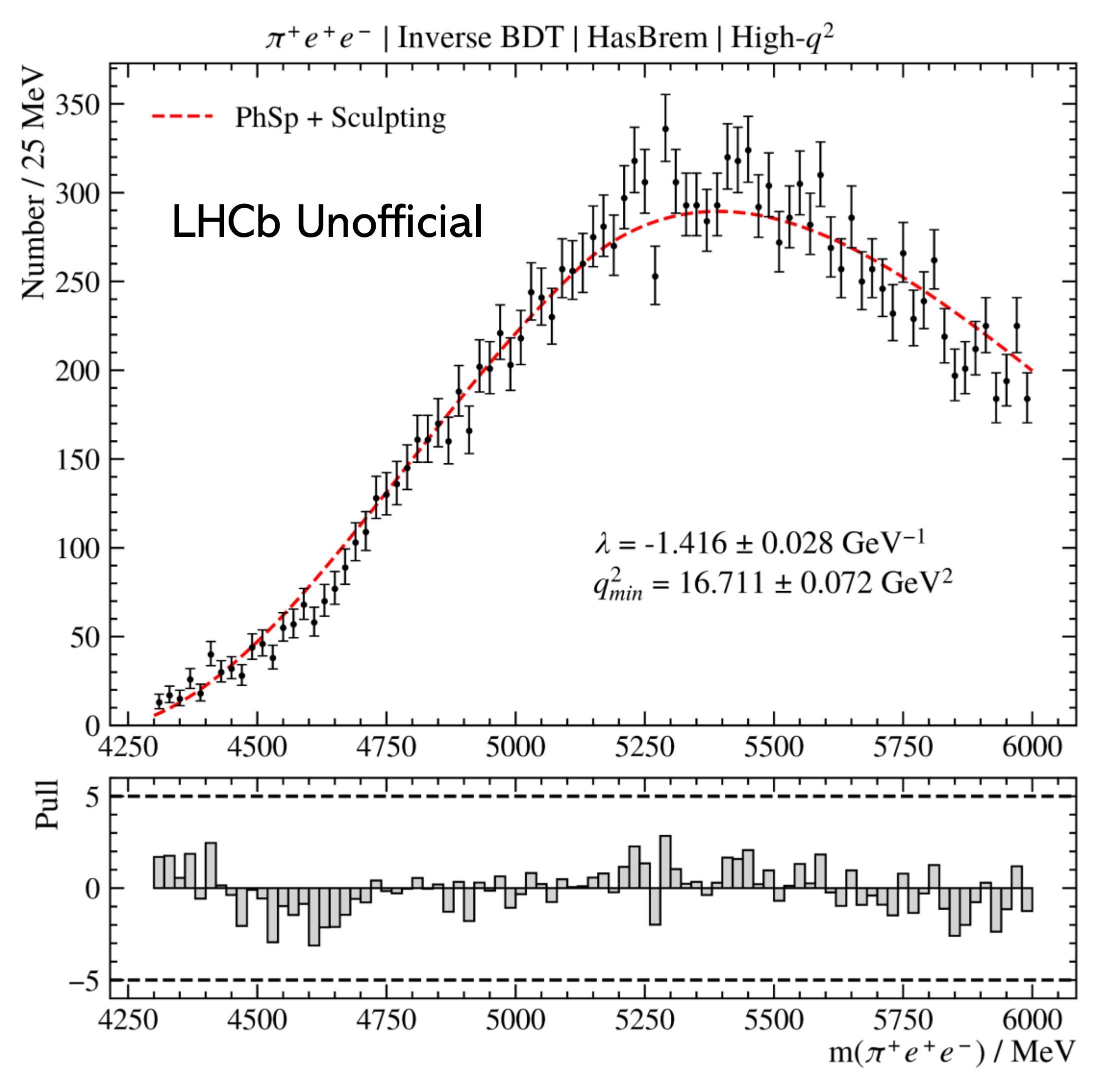
Backup : Sculpting for high-q2 Combinatorial (2)





Sculpting induced by cascade vetoes and the $\psi(2S)$ veto. Shape found by generating a mixed sample, where we create an artificial combinatorial event by picking each candidate (e^+, e^-, π^+) from a different event in the data sample. We can compute for this "Mixed" sample kinematics (B-mass, pT, …), and apply the vetoes.

Backup : Sculpting for high-q2 Combinatorial (2)



Validate model on the BDT rejected sample (combinatorial dominated).

Model has two parameters:

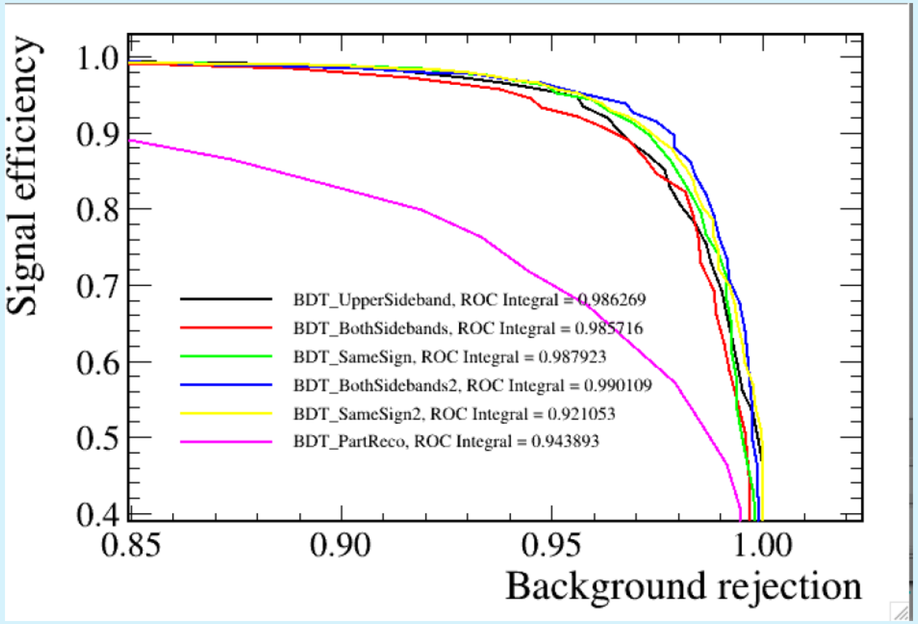
- λ models the underlying energy distribution of the tracks.
- q^2_{min} modulates shape according to the reduced phase space.

Backup : BDT

Combinatorial is the dominant background, and now train the BDT with all other selections pre-applied, specifically PID and q^2 requirements.

BDT inputs (k-fold with k = 5)

B^+	p_T, $\ln \chi^2_{IP}$, $\ln \chi^2_{FD}$, χ^2_{DV}, $DIRA$, $\mathrm{BDT_{iso}}(B_s \to \mu^+\mu^-)$, $\Delta\chi^2_{vtx+1track}$
π^+	p_T, $\ln \chi^2_{IP}$
e^+e^-	$\ln \chi^2_{IP}$, $\ln \chi^2_{FD}$, χ^2_{DV}, $DIRA$, $\max(p_T)$, $\min(p_T)$, $\max(\ln \chi^2_{IP})$, $\min(\ln \chi^2_{IP})$



BDT used is trained with the combined sample of the upper and lower mass sidebands as the background proxy, and weighted signal MC as the signal proxy.

Backup : Efficiencies

For hadrons, w_{PID} histograms from PIDCalib
For electrons use histograms from R_X **Fit&Count**.

Extract using MCStatTools

Use TrackCalib

$$\epsilon = \boxed{\epsilon_{geom}} \times \frac{\sum_{rec} \boxed{w_{kin}^{gen}}}{\sum_{acc} \boxed{w_{kin}^{gen}}} \times \frac{\sum_{sel} \boxed{w_{kin}^{reco}} \cdot \boxed{w_{PID}} \cdot \boxed{w_{L0} \cdot w_{HLT}} \cdot \boxed{w_{track}}}{\sum_{rec} \boxed{w_{kin}^{reco}}}$$

Histograms for w_{kin}^{gen} & w_{kin}^{reco} from R_K.
- Generator corrections in $P_T(B^+) \times \eta(B^+)$.
- Reconstruction correction in $P_T(B^+) \times \eta(B^+)$ and $\chi^2_{DV} \times \chi^2_{IP}(B^+)$

Compute trigger weights using the TIS-TOS method. Apply using Data MC comparison histograms / curves

Backup : Validation