Tests of Lepton Flavour Universality at LHCb

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European Research Council

Established by the European Commission

Why Lepton Flavour Universality?

LFU in $b \to s\ell\ell$ (FCNC) with $\ell = e, \mu, \tau$

- Measurements of branching fraction ratio R_X:

$q^2 = m^2_{(\ell,\ell)}$

$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to X\ell_1^+\ell_1^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to X\ell_2^+\ell_2^-)}{dq^2} dq^2}$$

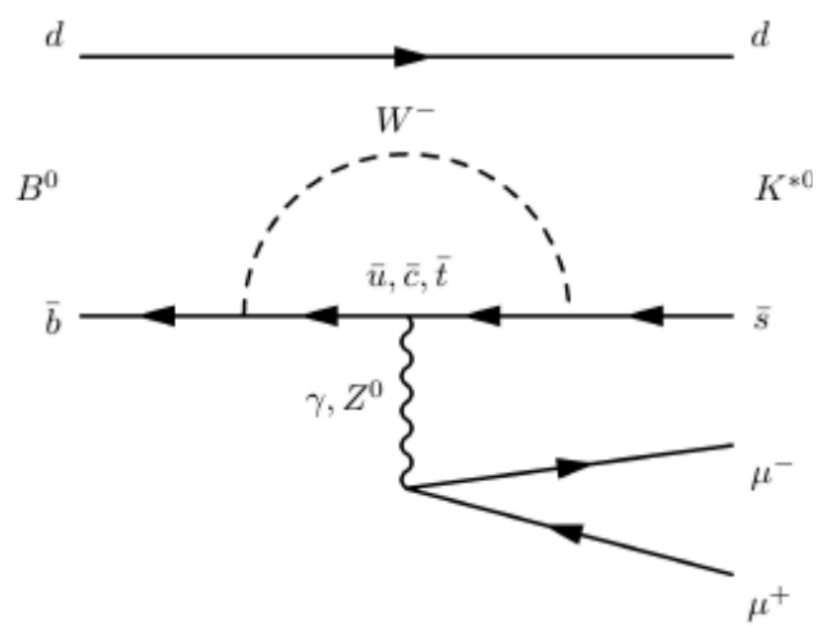
e.x $B = B^0$

e **vs** μ

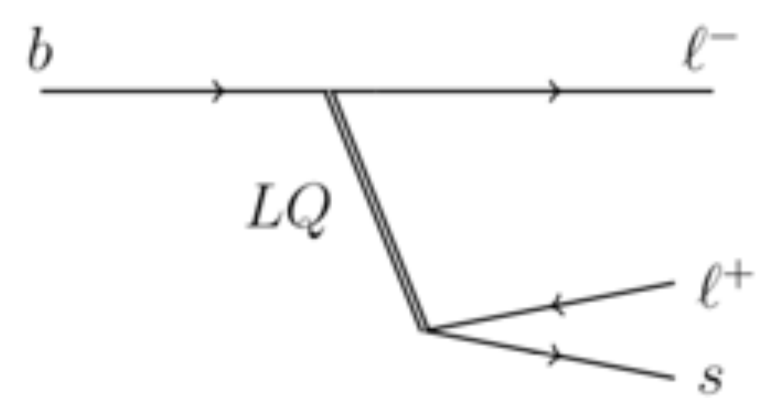
$$R_{K^{*0}} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^0 \to K^{*0}e^+e^-)}{dq^2} dq^2}$$

- Only loop level in the SM (BR ~ 10^{-7})
- Theoretically clean in the SM
- Experimentally accessible

Example $b \to s\ell\ell$ FCNC

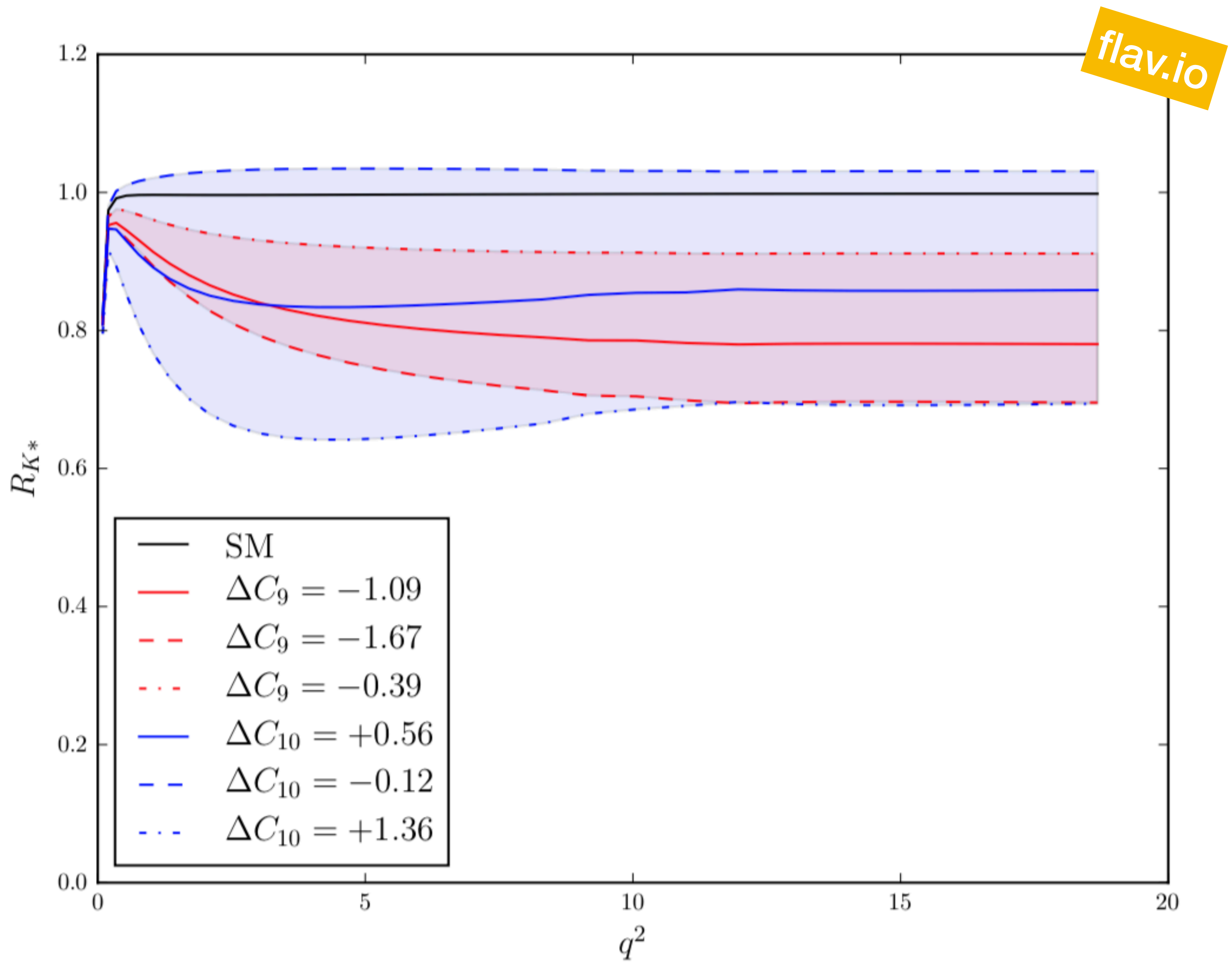


Example NP contributions to $b \to s\ell\ell$



Why Lepton Flavour Universality?

- Several BSM scenarios show dependence of R_X ratios on q^2
- Example: different C_9, C_{10} dependence of R_{K^*} between mid- and high-q^2



Electrons and muons at LHCb

- Electrons and muons interact in significantly different ways with the LHCb detector
- Understanding these differences is essential for correctly interpreting LFU ratio measurements

Muon reconstruction:

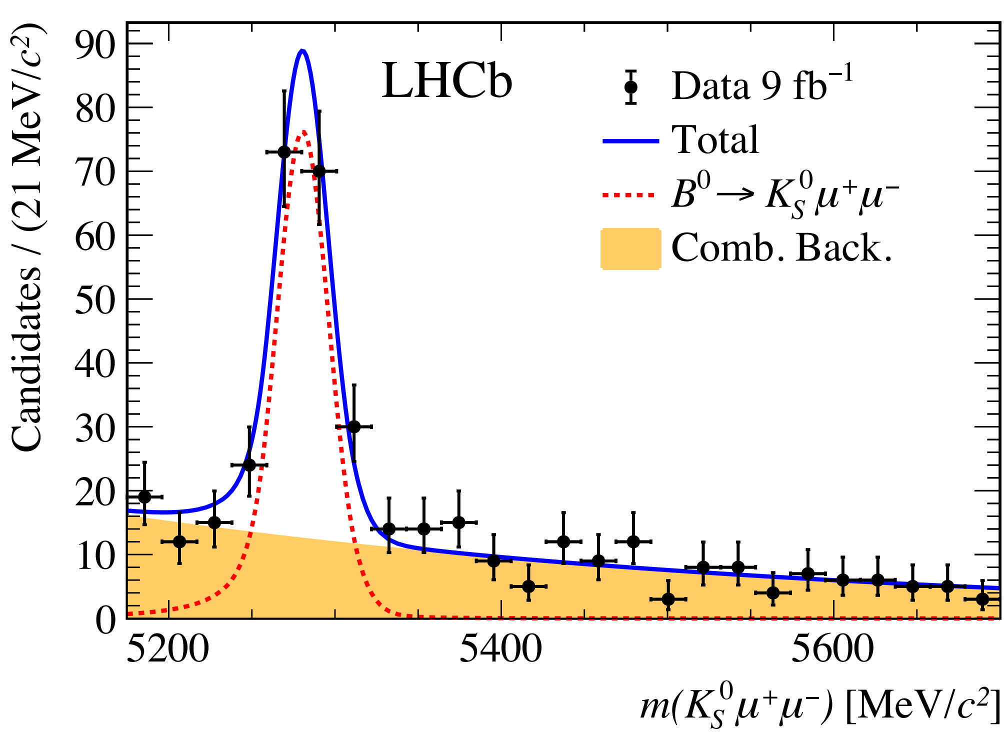
- Hits from muon stations matched to extrapolated tracks
- Momentum measured from the bending of the track

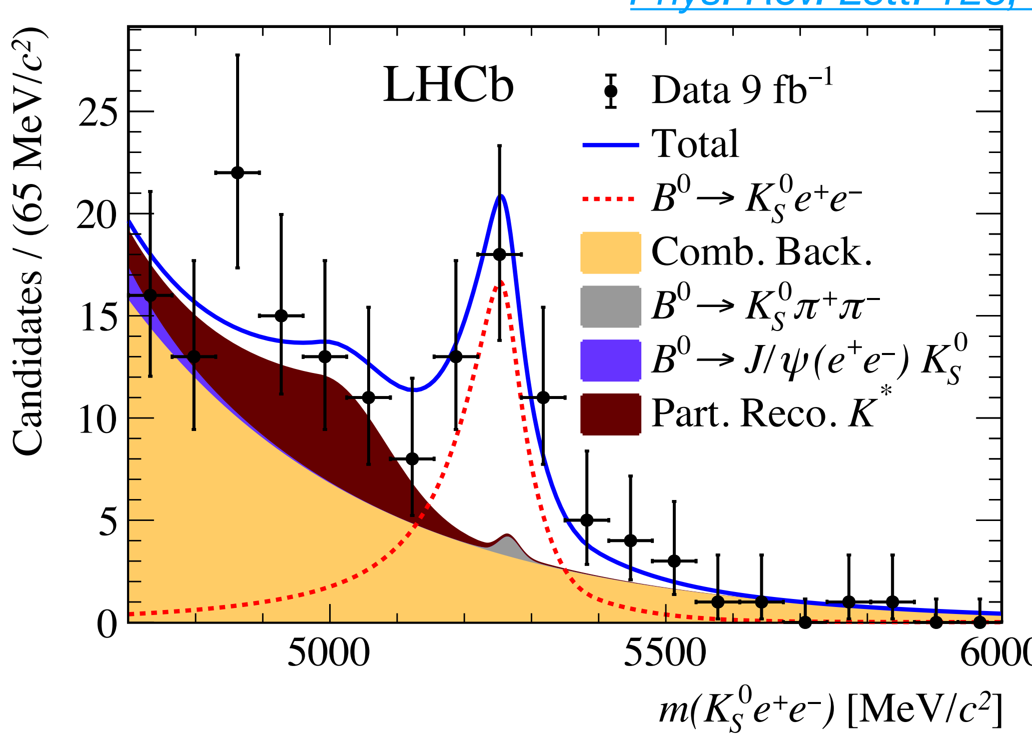
Electron reconstruction:

- Tracks matched to ECAL clusters
- Electrons often emit Bremstrahlung in LHCb
- Momentum measured from the bending of the track + Brem photons

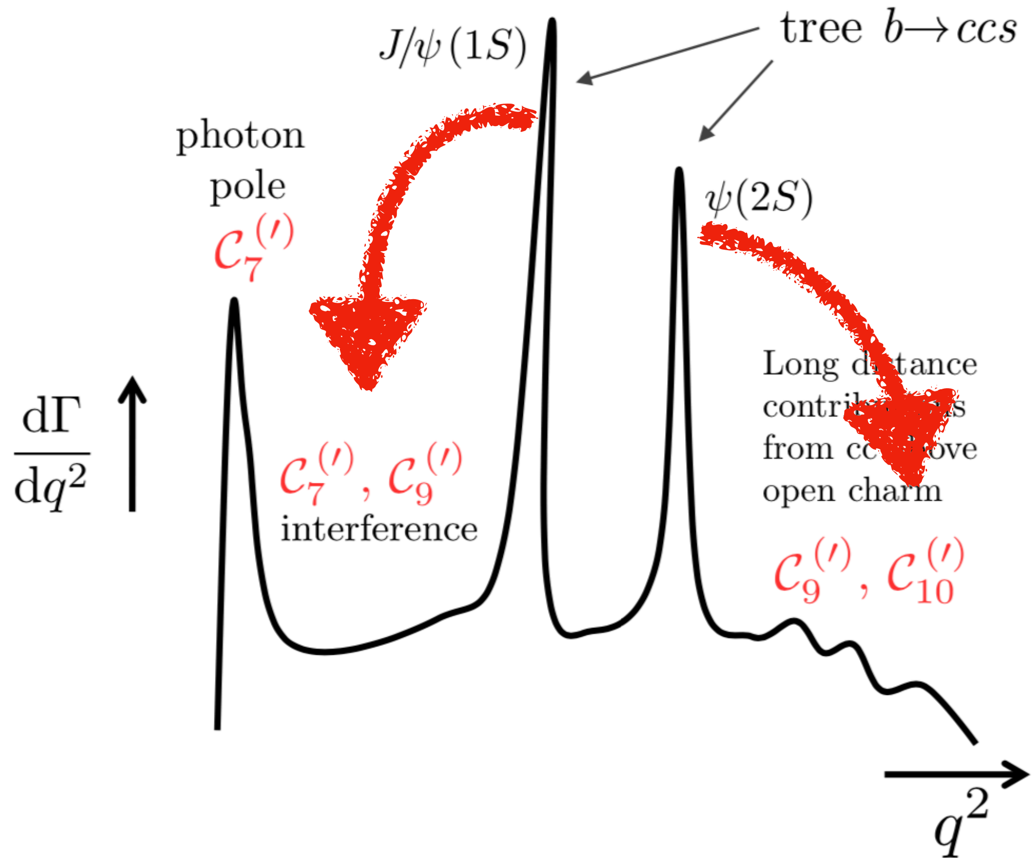
Two main differences:
Recovery procedure of Brem photons not perfect
ECAL has higher occupancy than Muon System → higher hardware trigger thresholds

Phys. Rev. Lett. 128, 191802

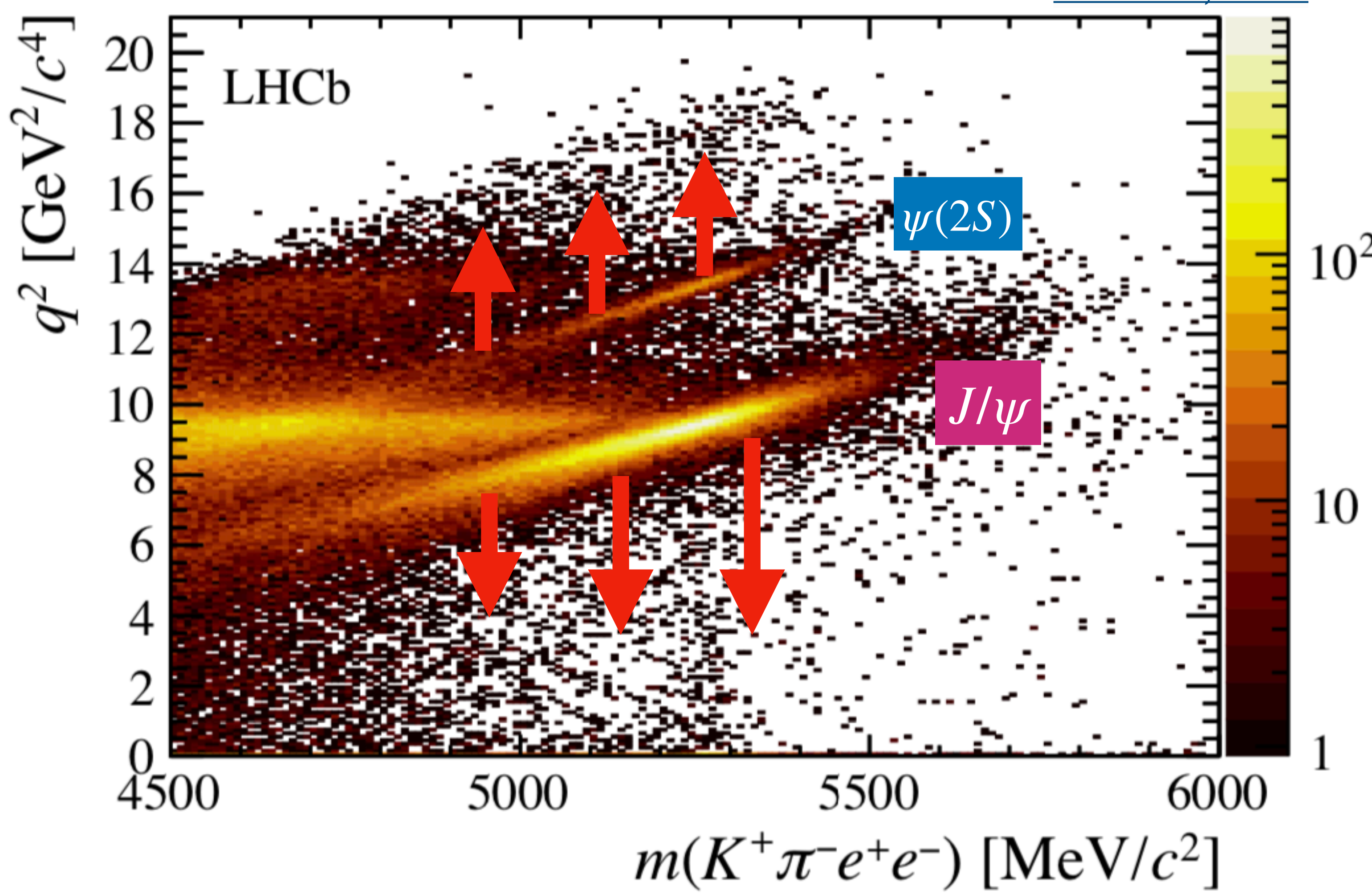




Leakage backgrounds



JHEP 55, 2017



- Two problematic scenarios:
  - If photon is missed → down-ward shift of B-mass
  - If random ECAL cluster is assigned → up - ward shift of B-mass
  - **Migration in and out of bins!**

Analysis strategy

[Nature Physics volume18, pages 277–282 (2022)]

- Use **double ratios** to reduce systematic effects

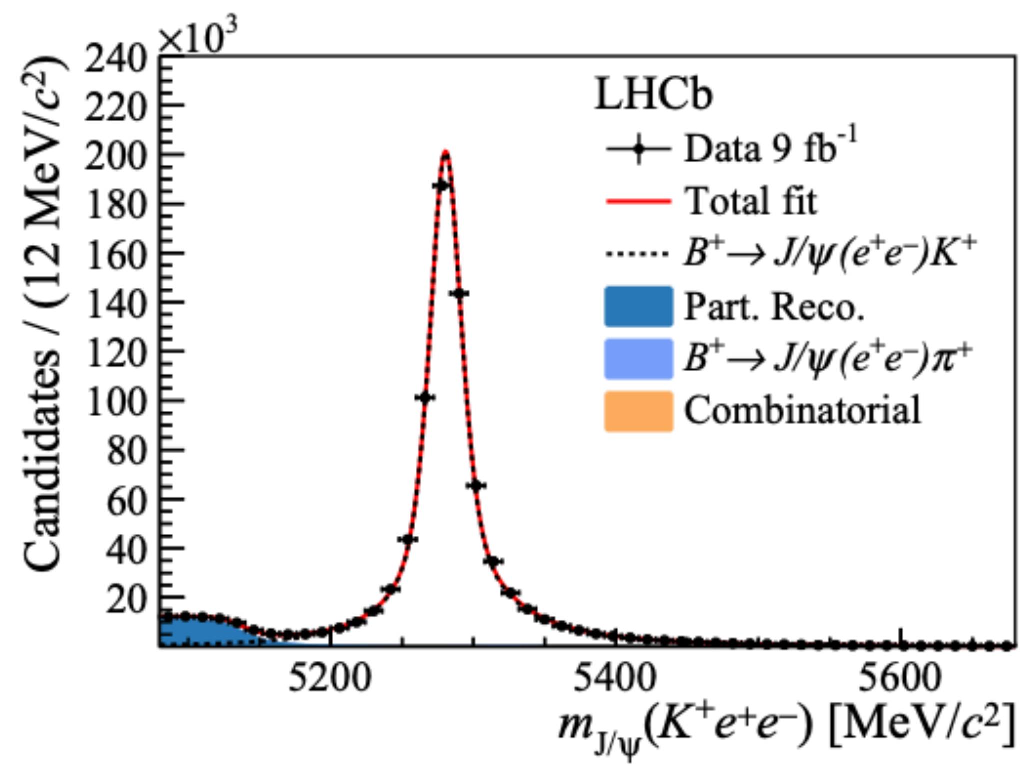
$$R_{K^{*0}} = \frac{\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathscr{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathscr{B}(B^0 \to K^{*0}e^+e^-)}{\mathscr{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- **Selection** as similar as possible between electrons and muons

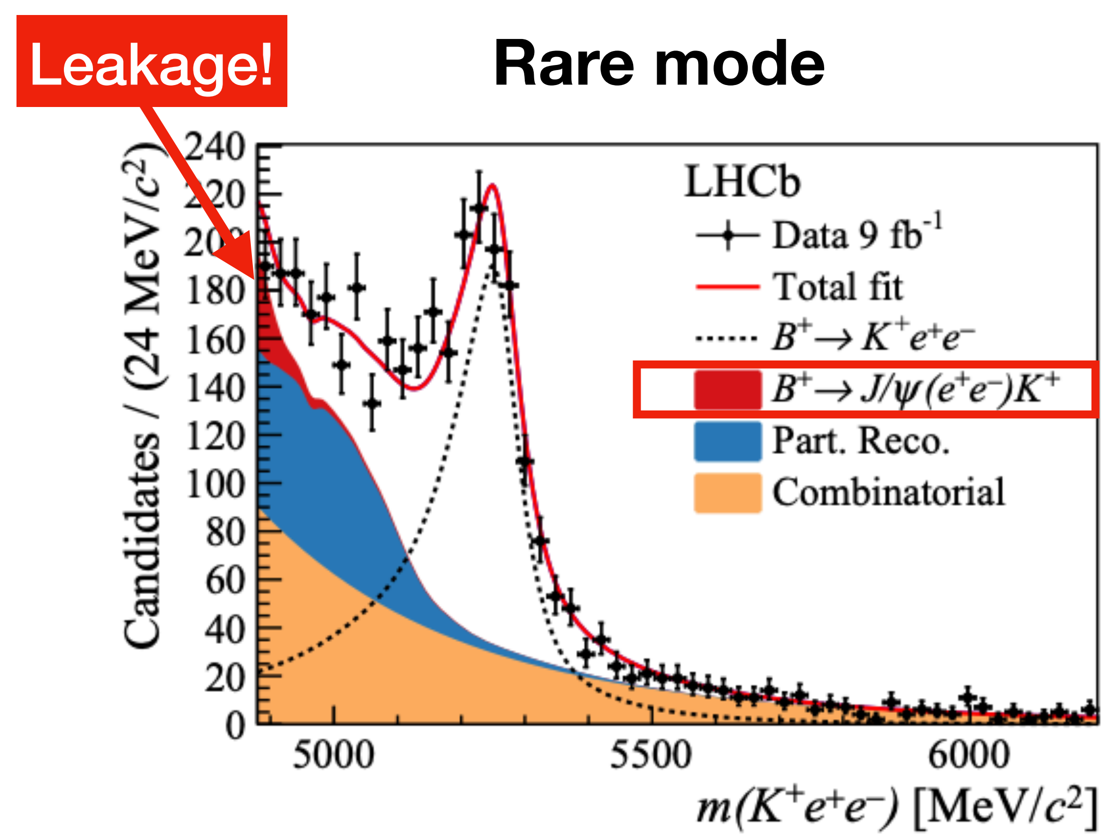
- **Efficiencies:**
  - Mix of simulation and data-driven methods
  - Corrections to simulation in order to achieve good Data/MC agreement

- **Mass fit:**
  - Used to extract the rare and control mode yields
  - Exploit interplay between control and rare modes →can aid in estimation of leakage

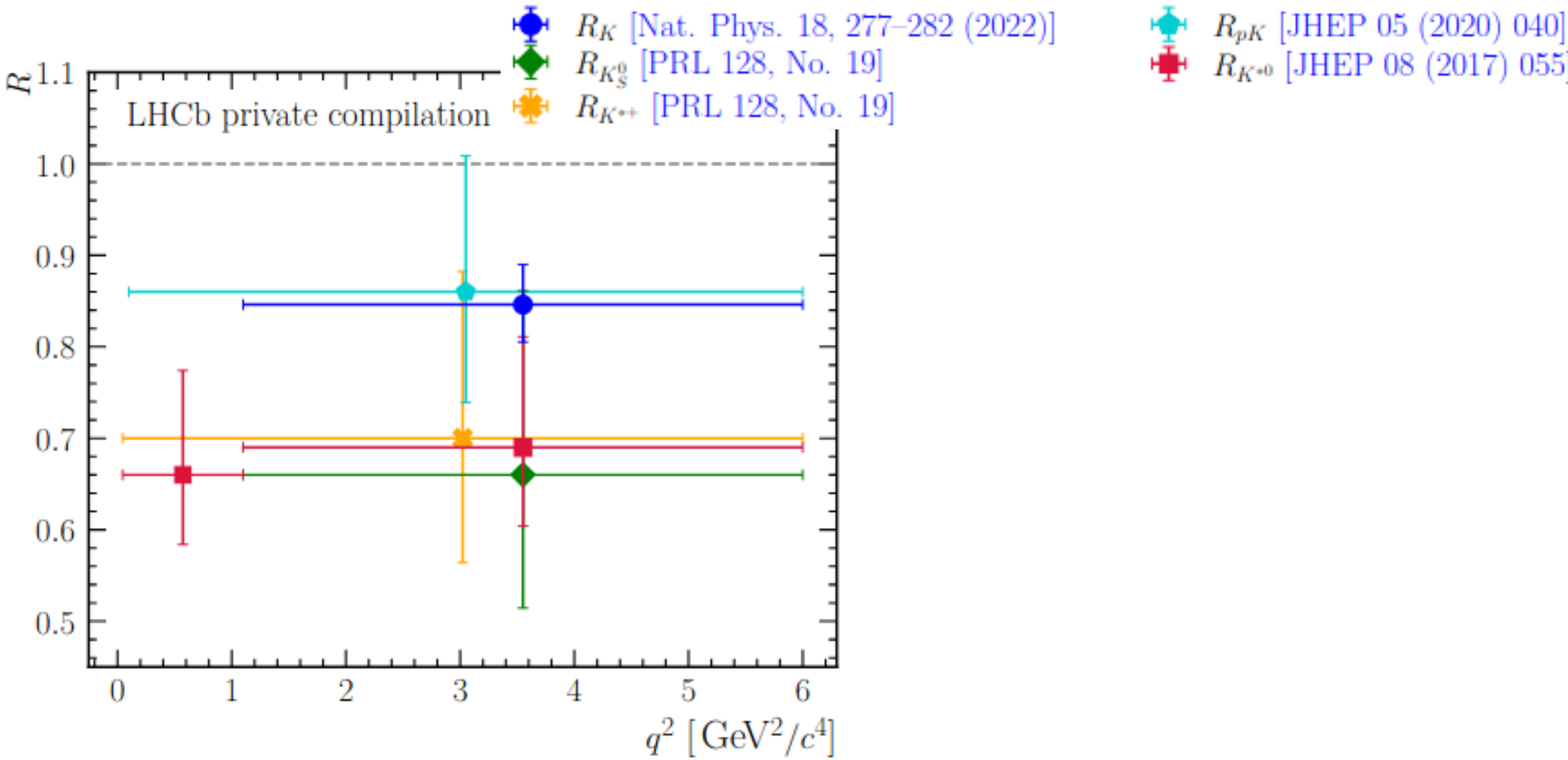
Control mode



Rare mode



Recent LHCb LFU results

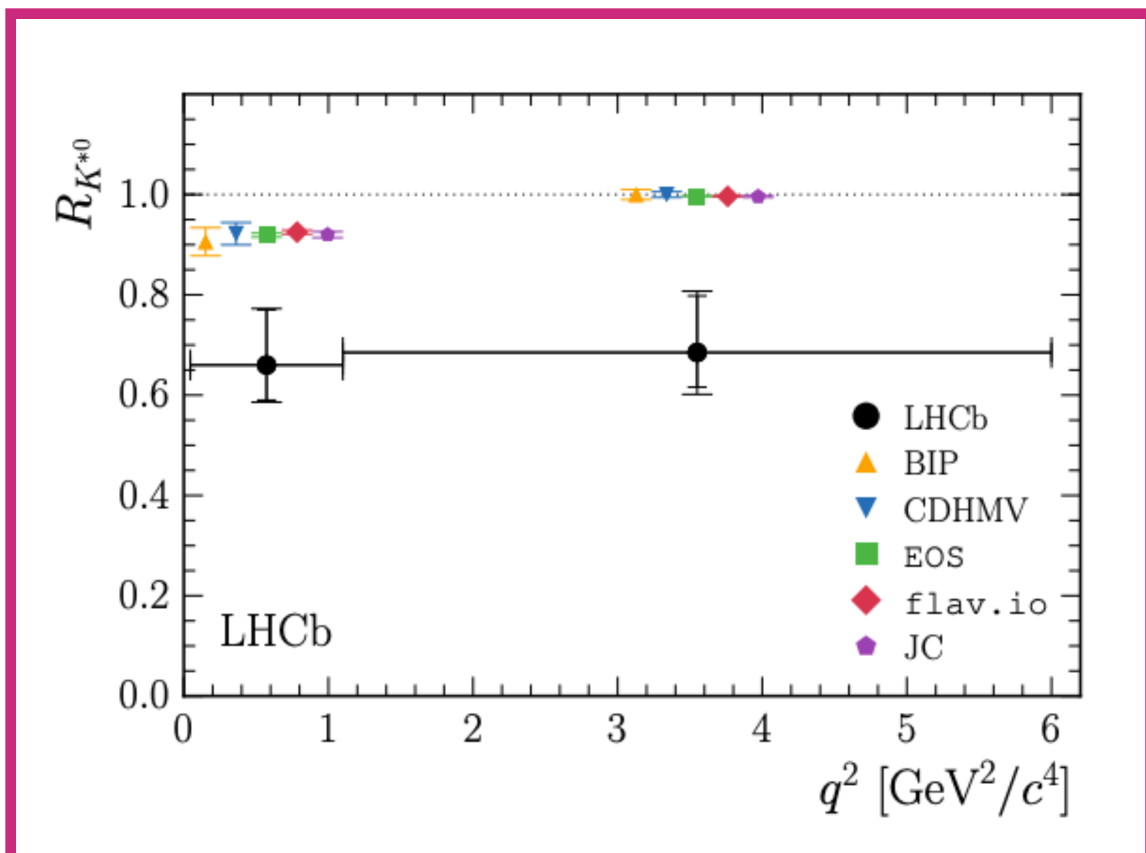


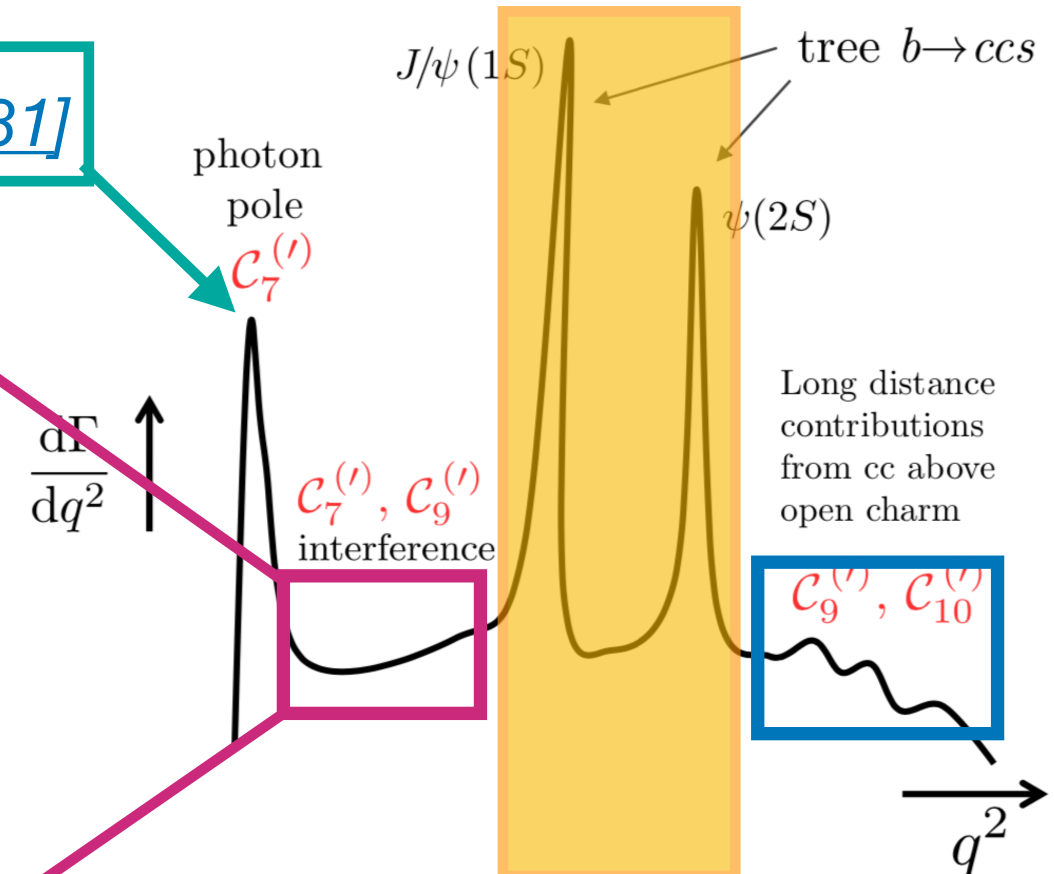
- Measurements of R_K and $R_{K^{*0}}$, but also R_{pK}, $R_{K^{*+}}$ and $R_{K^0_s}$.
- Largest discrepancy seen by Run1+2 analysis R_K (3.1 σ)
- Combined analysis of R_K and $R_{K^{*0}}$ ongoing

Completing the q² spectrum

- Advantages of performing analysis in **bins of q²**:
  - NP could have a dependence in q² - having a differential analysis helps distinguish different BSM scenarios
  - Exclude $c\bar{c}$ **resonances** (SM contributions dominates) - can be used as **control modes** instead

$+\ b \rightarrow s\gamma$ [JHEP 2020, 81]





No LHCb measurement above $q^2 = 6\ GeV^2/c^4$

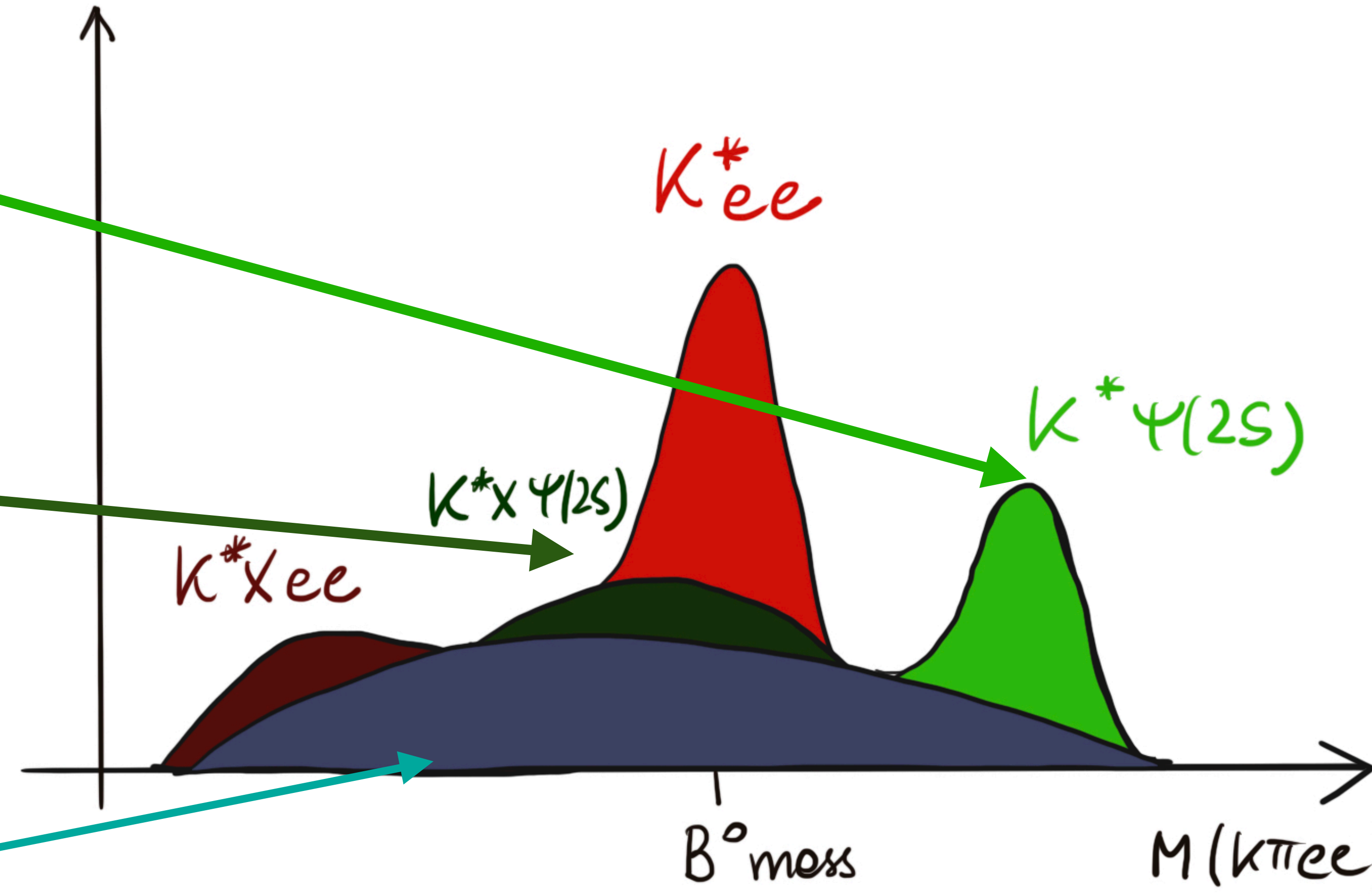
What about higher q^2?

The challenge of the high-q² bin

Challenging background estimation for the electron mode:

- $B^0 \to K^{*0}\psi(2S)(\to ee)$ **leakage** into the rare mode q^2 region due to the Bremsstrahlung photon recovery process

- Hadronic **partially reconstructed** $B \to X(\to YK^*)\psi(2S)$ (where Y is lost) - peaks under the B-mass peak !



- **Combinatorial** background (from combinations of random tracks) sculpted - we're at the kinematic limit

Having a stable mass fit doesn't seem that easy

The challenge of the high-q^2 bin

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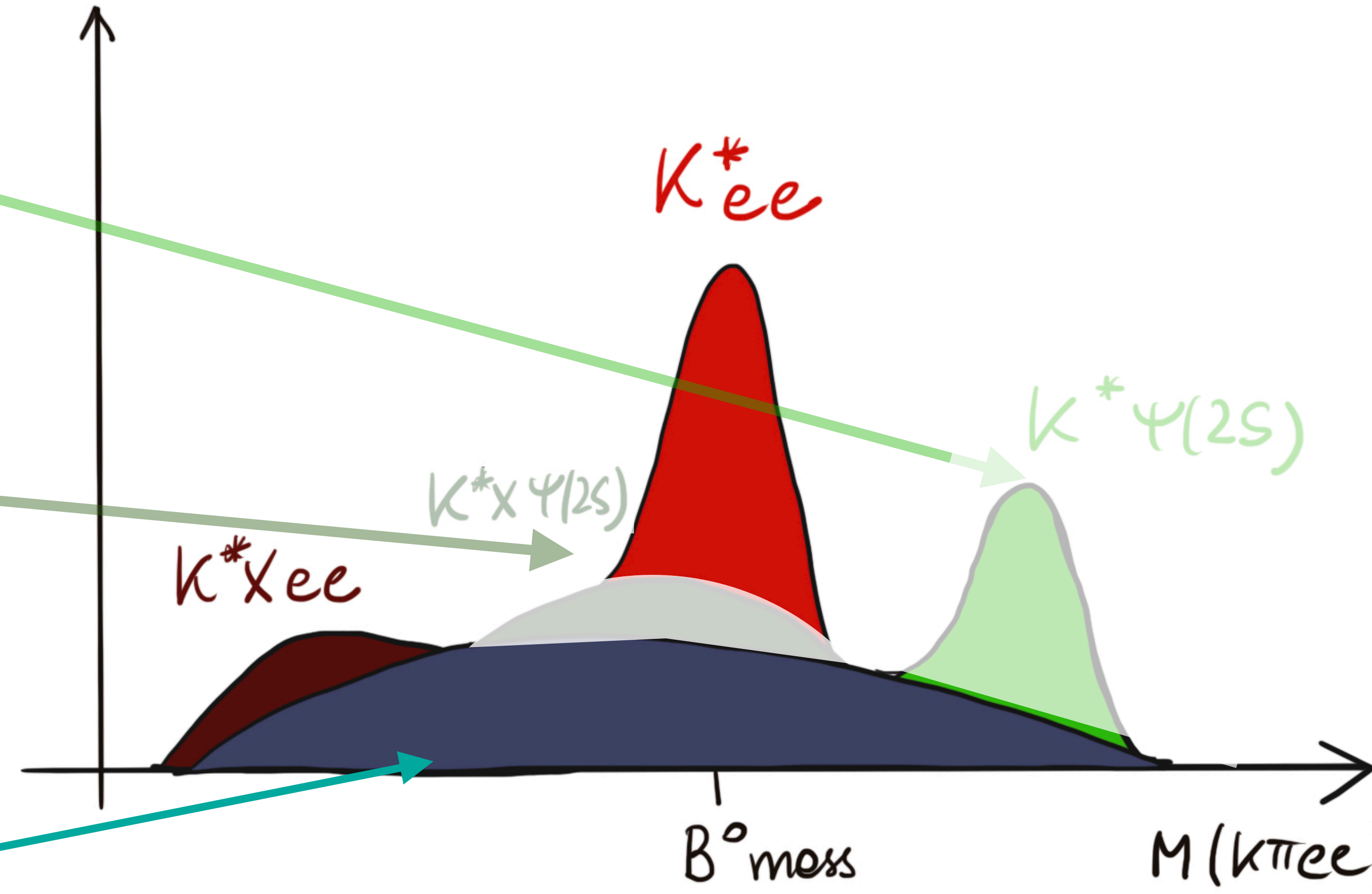

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Overcoming challenges

- Exploring MVA techniques to reduce leakage backgrounds
- Combinatorial estimated from control samples
- Analysis ongoing with encouraging results in the background estimation
- Stay tuned for more details!

Summary

Rare decays and LFU tests

- Rare B decays are unique indirect probes for New Physics
- LFU tests some of the most powerful ones!
- LHCb continues to be a world-leading precision measurement experiment
- New results with the first 2 Runs keep coming out, exploring more difficult signatures
- A whole new run with a fully upgraded detector is starting now…
- So stay tuned for more exciting results!

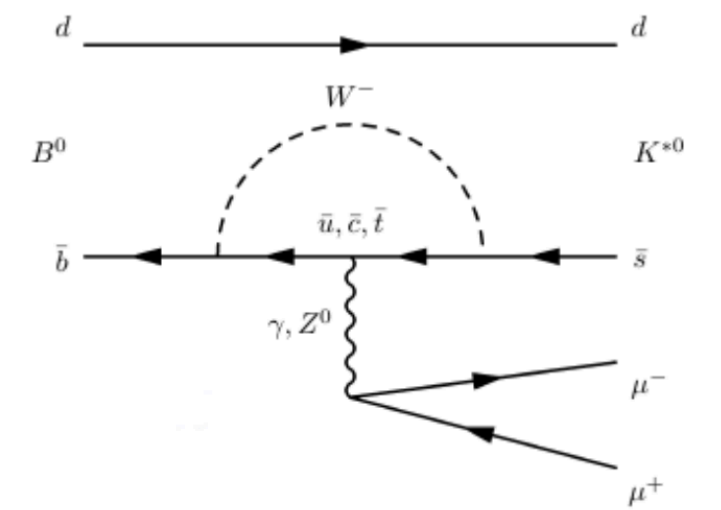
Thank you for your attention!

Backup

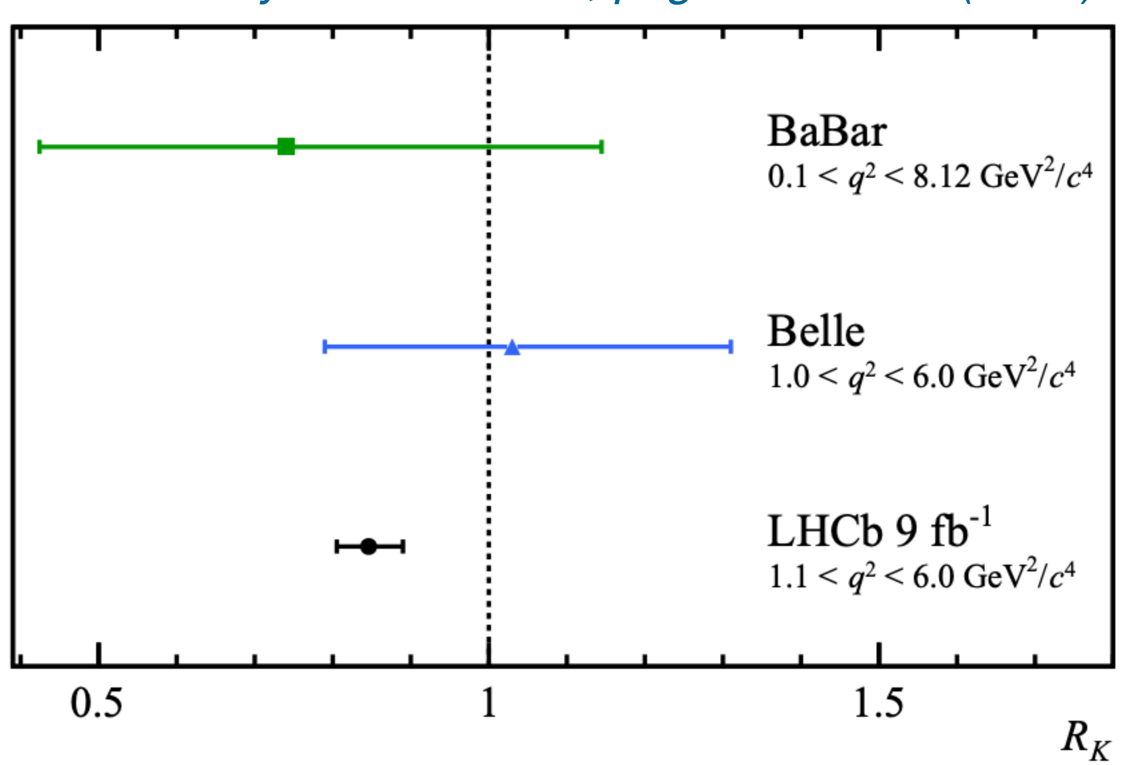
Why we care about rare B decays

- Rare B decays are excellent probes of **Flavour Changing Neutral Current (FCNC)** processes:
  - Not allowed at tree-level in the SM - very rare
  - Sensitive to indirect NP contributions
  - Theoretically clean!
- Coherent pattern of deviations from the SM in several **LFU** measurements and angular observables
- Could also manifest itself as **LFV**
- Complementary measurements from **radiative** and ultra rare **purely leptonic decays** offer important additional information and constraints

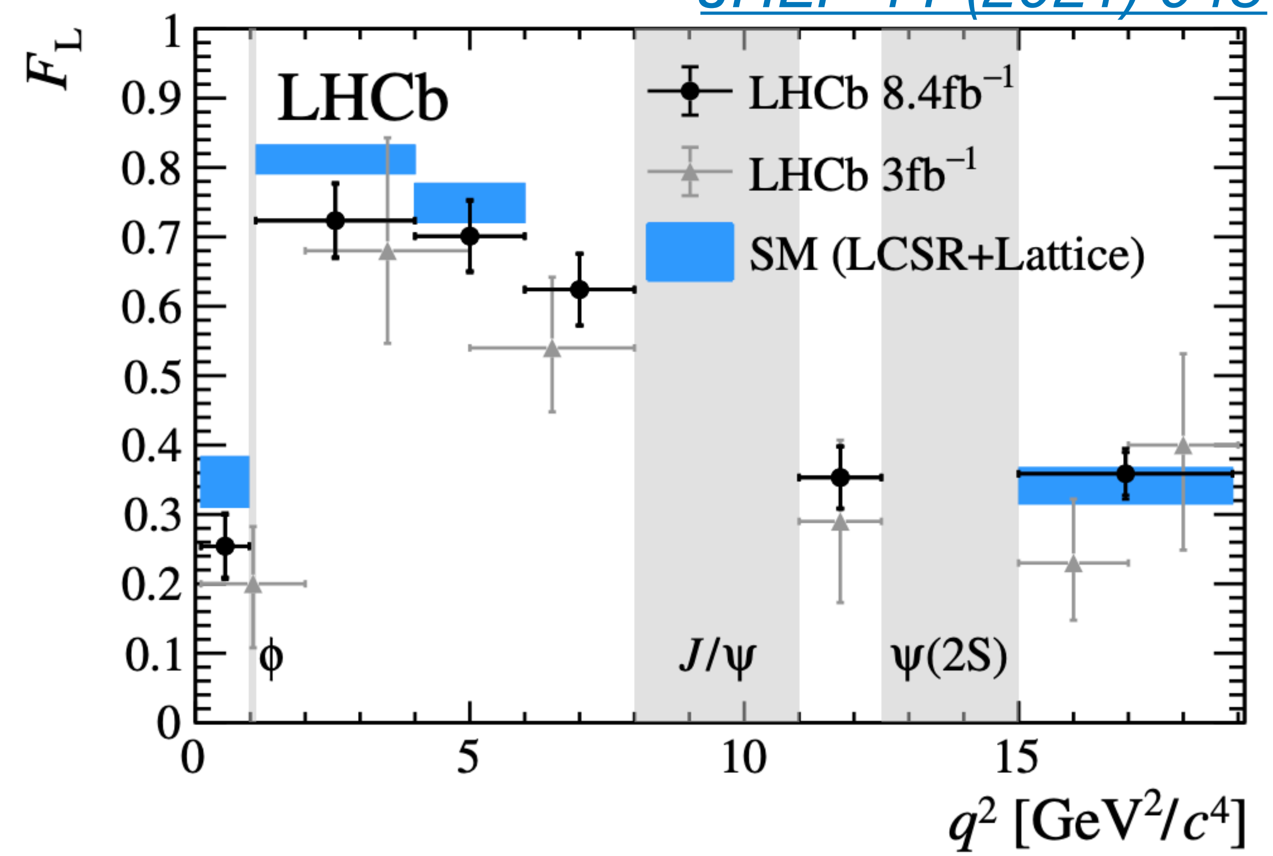
Example $b \to s\ell\ell$ FCNC



Nature Physics volume18, pages 277–282 (2022)

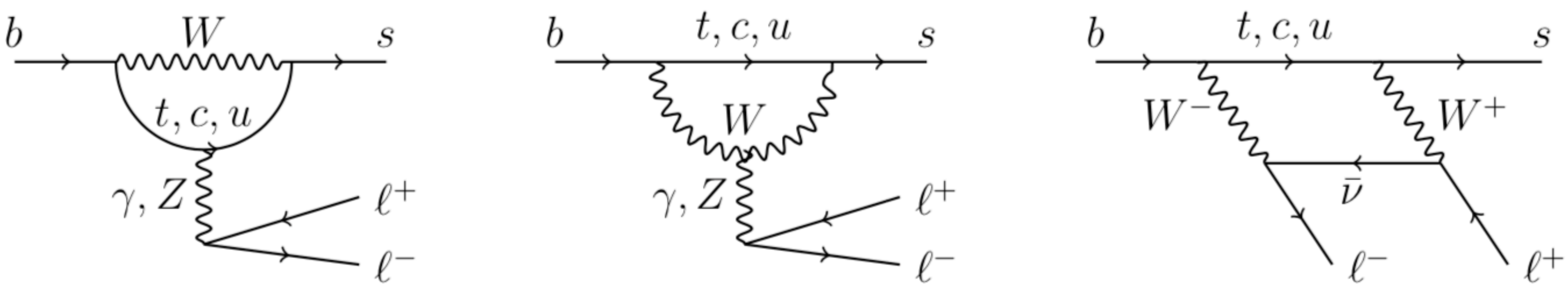


JHEP 11 (2021) 043

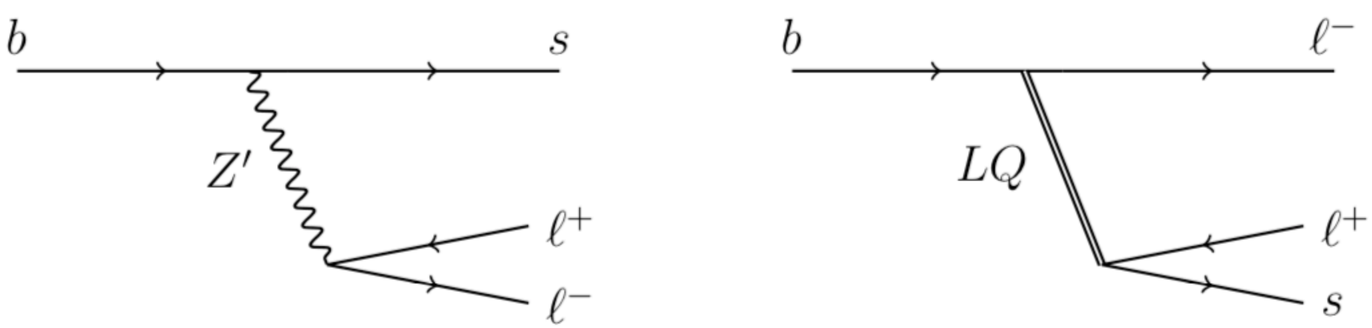


Feynman diagrams for $b \to s\ell\ell$

SM contributions to $b \to s\ell\ell$

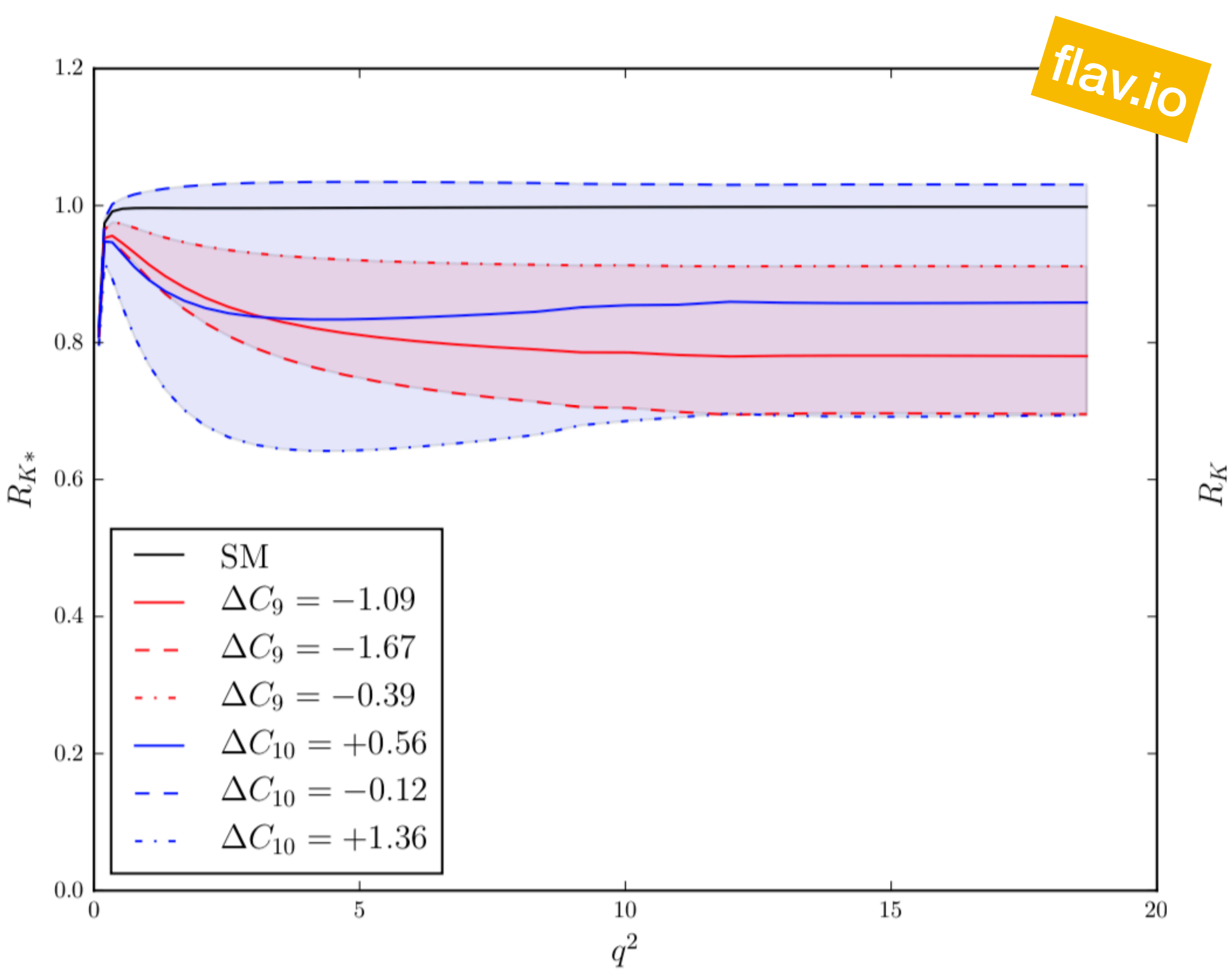


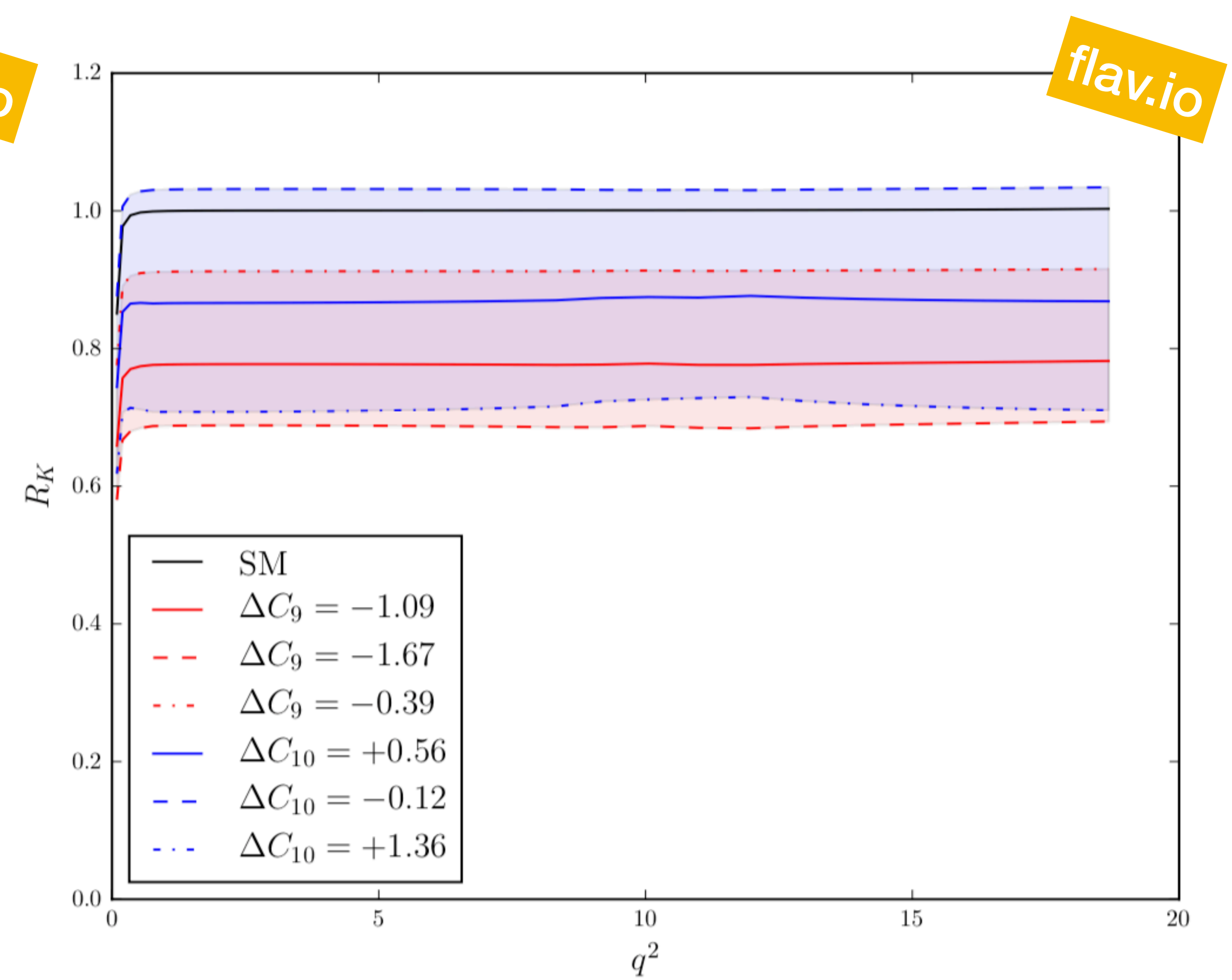
Potential NP contributions to $b \to s\ell\ell$



Sensitivity of R_{K^*}-high q^2 to BSM models

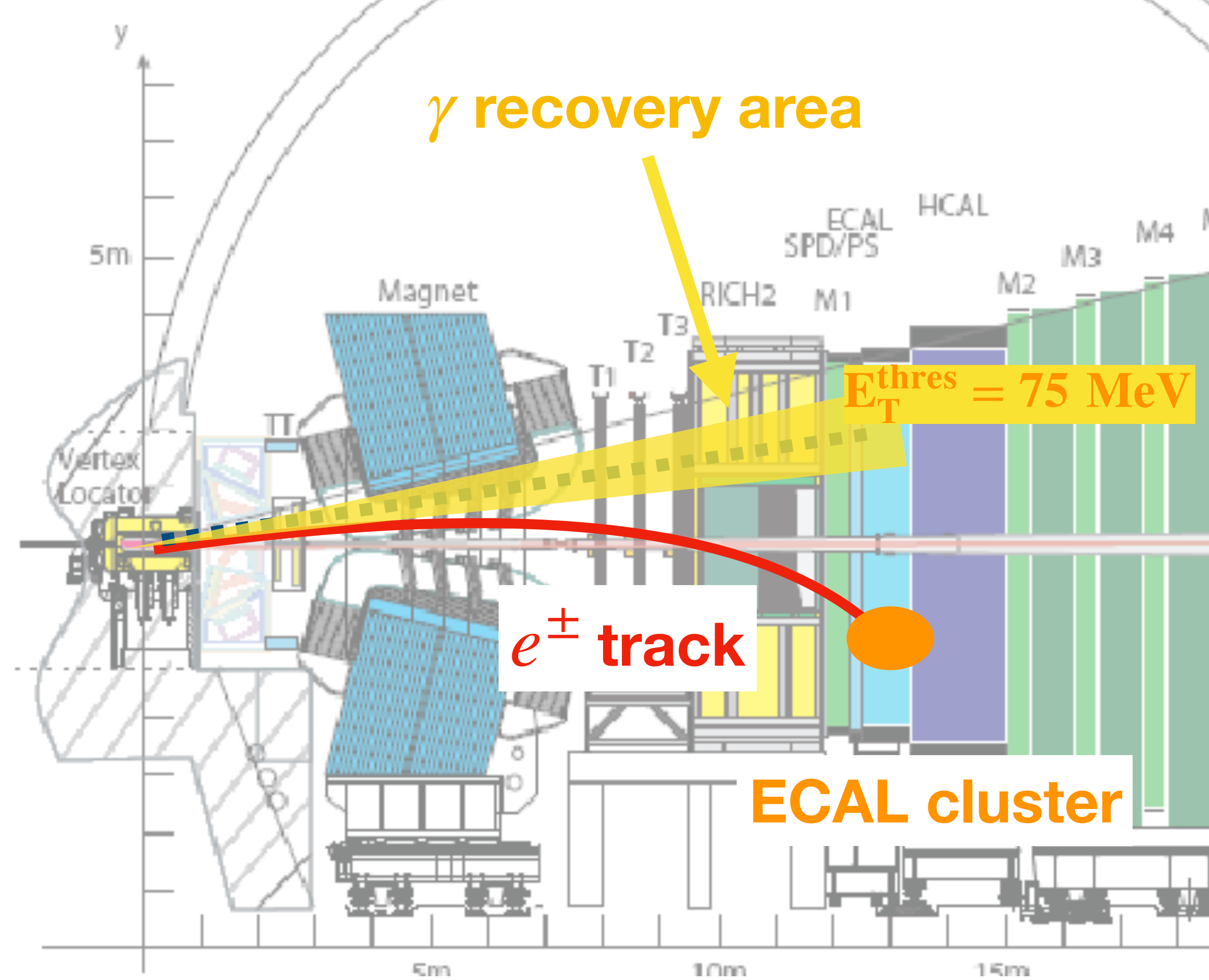
- Several BSM scenarios show dependence of R_{K^*} ratio on q^2
- Different C_9, C_{10} dependence of R_{K^*} between mid- and high-q^2
- No dependence expected in R_K





Bremsstrahlung recovery process

- Material interactions cause electrons to emit Bremsstrahlung photons
- Emission happens often before the magnet → electron momentum measurement is affected!
- **Very frequent at LHCb - most electrons emit one energetic brem before the magnet!**
- Try to find brem photon and add back its energy to the electron
- Recovery efficiency ~ 50%



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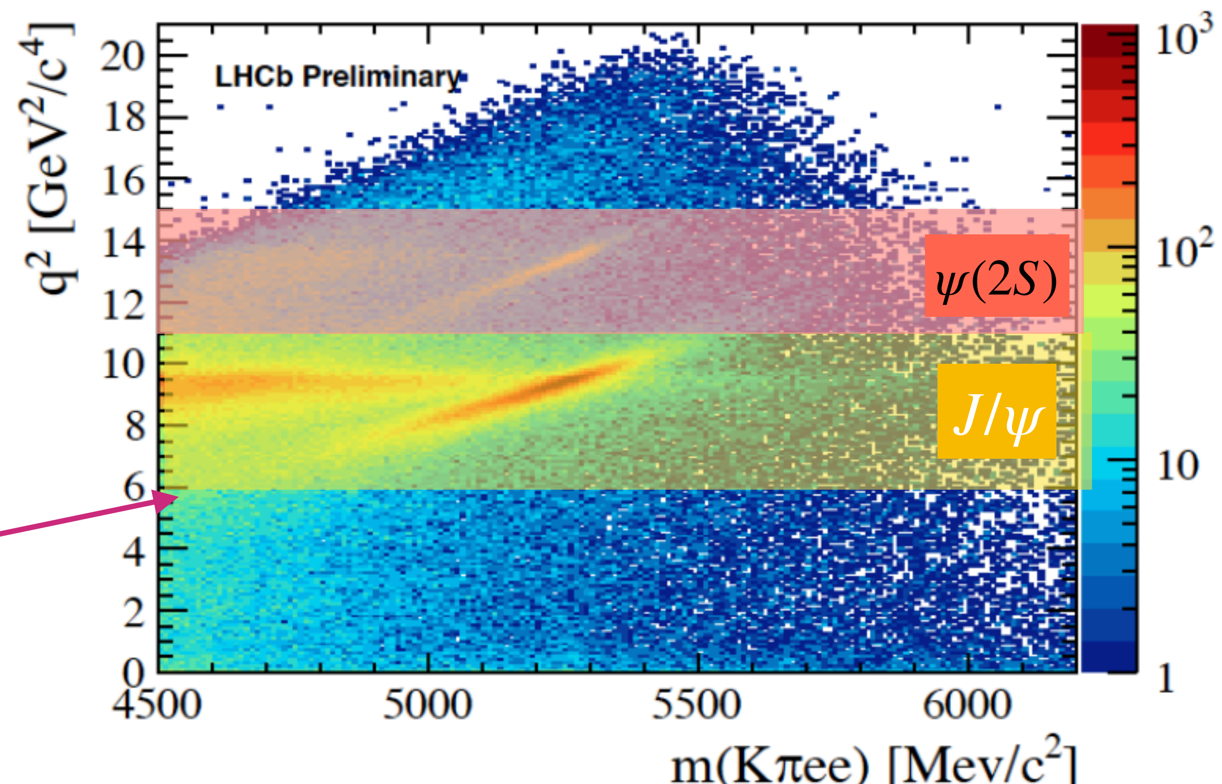
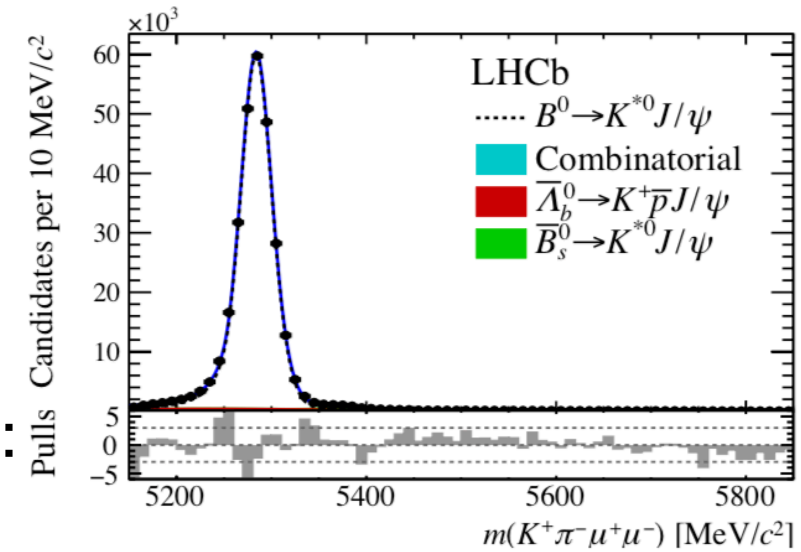
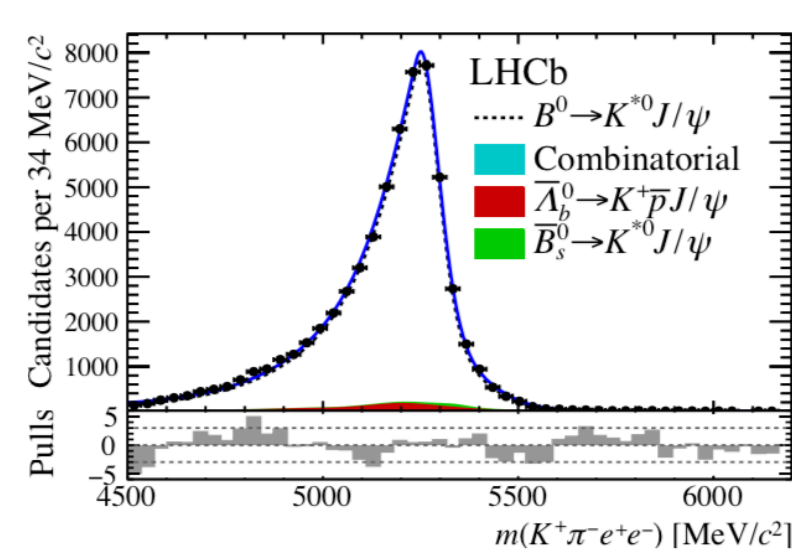


Performance comparison B-factories/LHCb

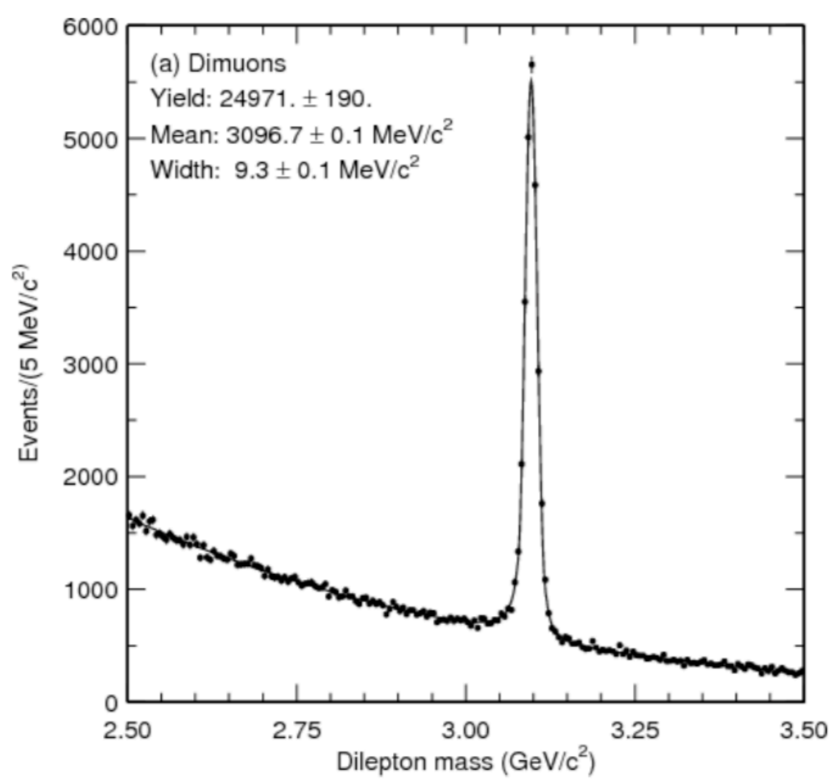
- Larger yields for LHCb
- PID performance similar
- Very different electron response:
  - Belle/BaBar have similar efficiencies for electron/muons
  - LHCb electron efficiency lower because of more Bremsstrahlung and higher trigger thresholds
- B-decays to τ leptons:
  - Belle/BaBar exploit full reco of 2nd B
  - LHCb reco of decay vertices

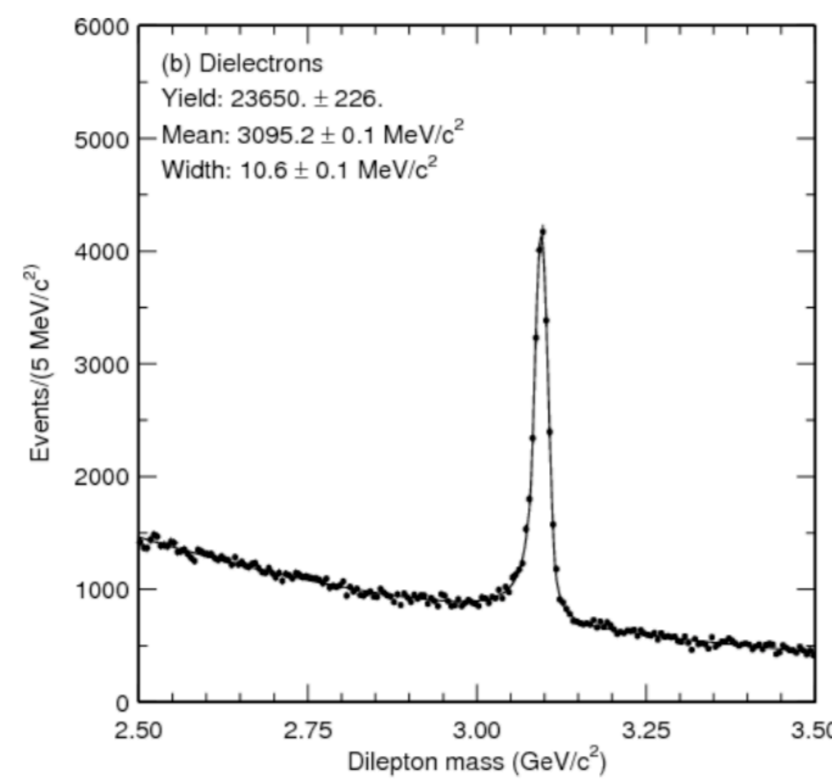
LHCb





Belle





LFU with the LHCb detector

The LHCb experiment at CERN:

- Single-arm spectrometer designed for high-precision flavour physics measurements
- Pseudorapidity range $\eta \in [2,\ 5]$
- Excellent primary and secondary vertex reconstruction
- Highly efficient particle identification
- Excellent momentum and IP resolution