LFU measurements at high q^2

Beyond the flavour anomalies workshop, 4th April 2020

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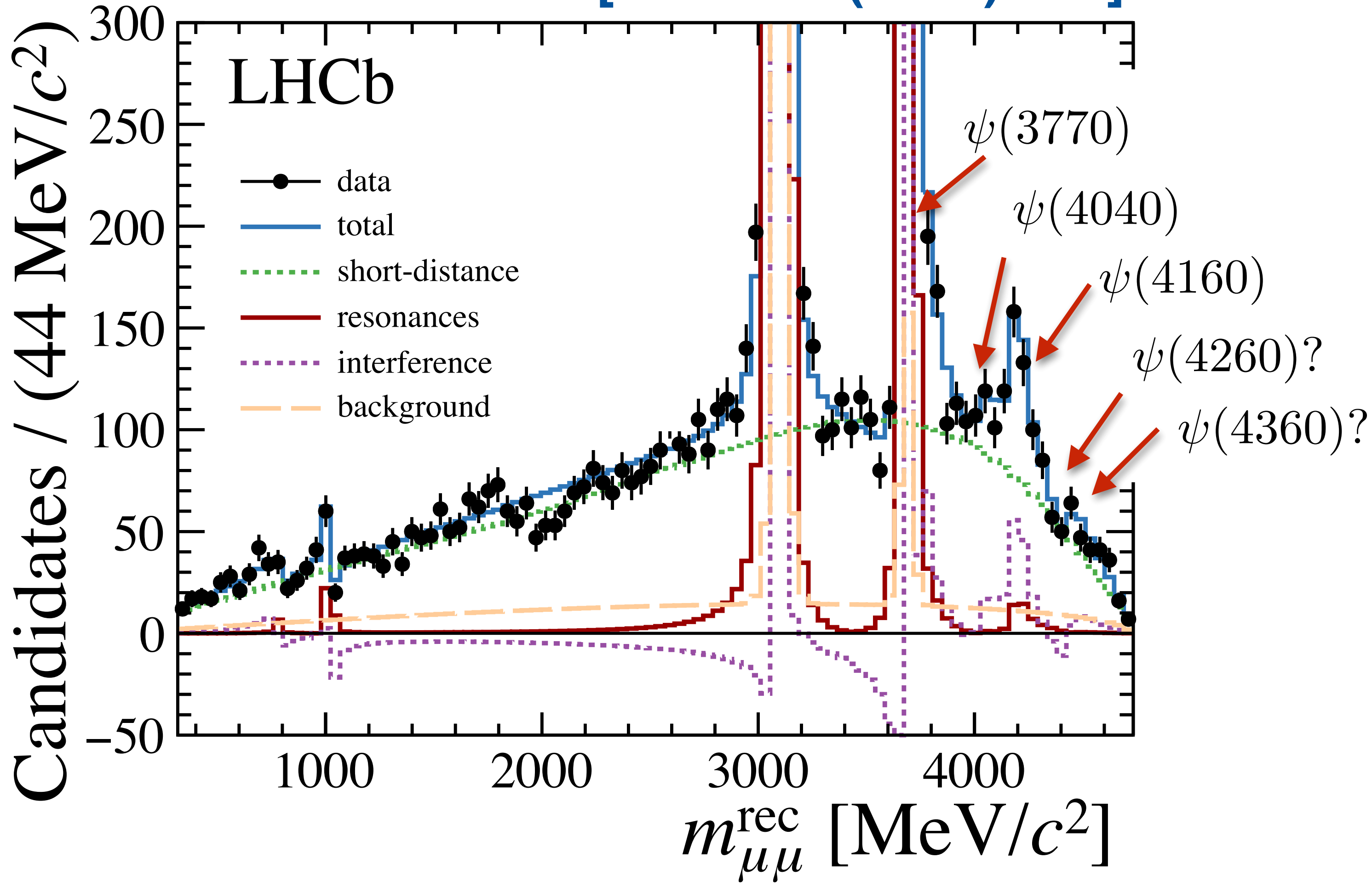
$b \to s\ell^+\ell^-$ at high q^2

- Large number of measurements at high q^2 in different $b \to s\mu^+\mu^-$ decay modes:
  - Branching fractions, angular observables, CP- and isospin-asymmetries.
- See contributions from broad resonances above the open charm threshold in our data.

LHCb [EPJC 77 (2017) 161]



Background subtracted and efficiency corrected dimuon mass distribution of $B^+ \to K^+\mu^+\mu^-$ decays.

Data/theory comparison at high q^2

Experiment

- Several broad charmonium resonances contribute (above the open charm threshold).
- Interference effects are important.
- Pattern is not the same as seen in $e^+e^- \rightarrow$ hadrons.

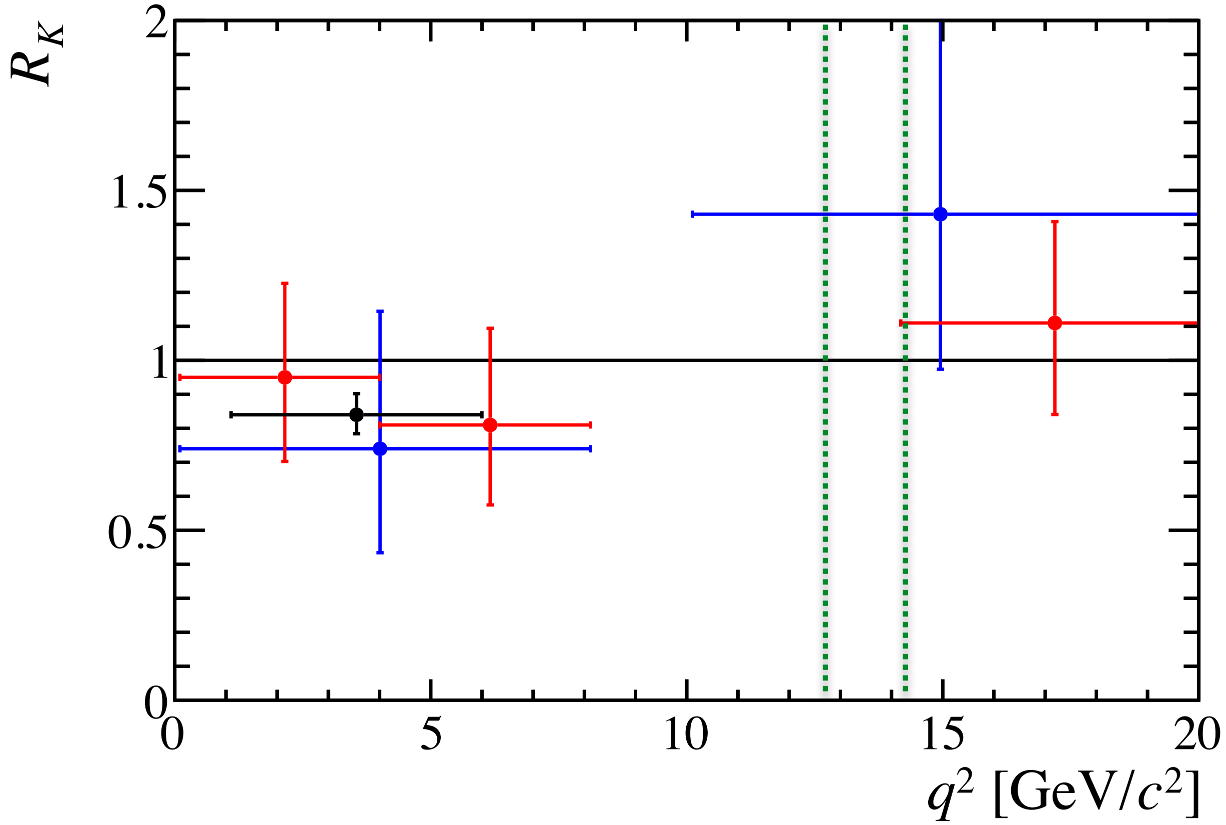
Theory

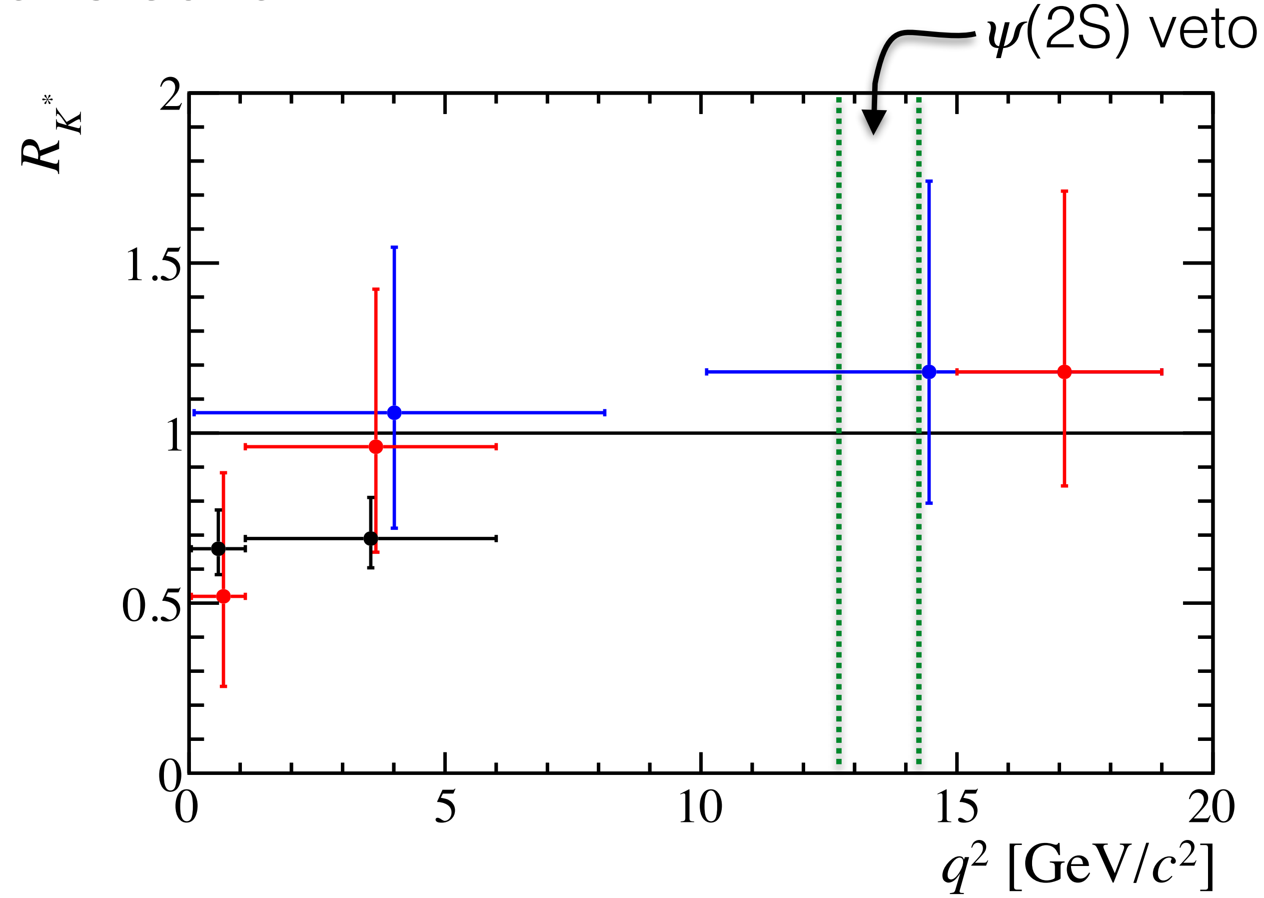
- Calculations typically use a local OPE.
  B. Grinstein and D. Pirjol, [PRD 70 (2004) 114005]
  M. Beylich, G. Buchalla and T. Feldmann, [Eur. Phys. J. C 71,(2011) 1635]
- Expect agreement between data and prediction only in integrated observables (up-to quark-hadron duality violating effects).

Irrelevant for LFU tests? Two exceptions: we need accurate predictions to interpret results in terms of C_9 and C_{10}; and we rely on the distribution to correct experimental results for the migration of events in q^2.

R_K and R_{K^*}

- What LFU measurements do we have so far?





LHCb [PRL 122 (2019) 191801]
BaBar [PRD (2012) 032012]
Belle [EPS-HEP 2019]

LHCb [JHEP 08 (2017) 055]
BaBar [PRD (2012) 032012]
Belle [arXiv:1904.02440]

- Only have measurements from the *B*-factory experiments at large q^2.

R_K and R_{K^*} at Belle II

- Extrapolating current performance to Upgrade II:

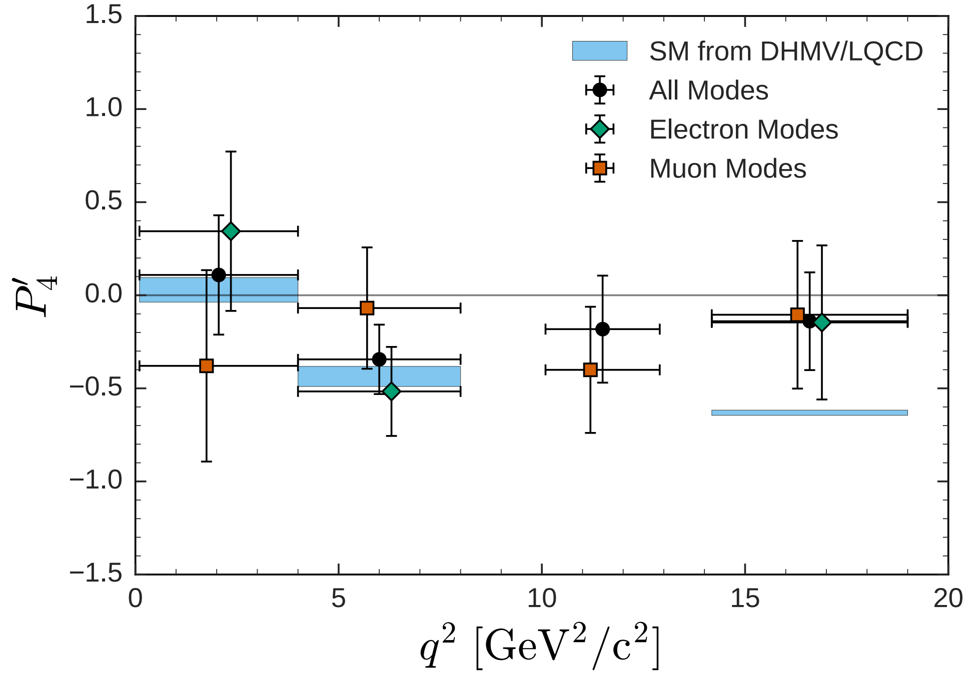
Observable	Belle $[0.7\mathrm{ab}^{-1}]$	Belle II $[5\mathrm{ab}^{-1}]$	Belle II $[50\mathrm{ab}^{-1}]$
R_K $[1.0,6.0]$ GeV$^2/c^4$	28%	11%	3.6%
R_K > 14 GeV$^2/c^4$	30%	12%	3.6%
R_{K^*} $[1.0,6.0]$ GeV$^2/c^4$	26%	10%	3.2%
R_{K^*} > 14 GeV$^2/c^4$	24%	9%	2.8%
R_{X_s} $[1.0,6.0]$ GeV$^2/c^4$	32%	12%	4.0%
R_{X_s} > 14 GeV$^2/c^4$	28%	11%	3.4%

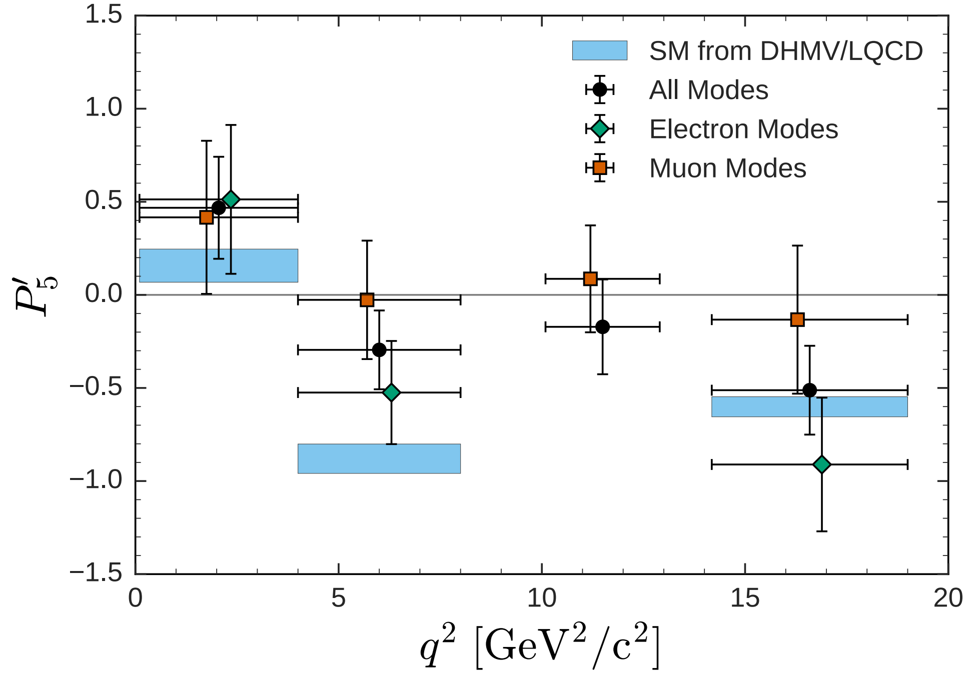
From Belle II physics book **[arXiv:1808.10567]**

Angular observables

- Belle has also made measurements of the optimised angular observables at low- and high-q^2.
  - Measurements with dielectron and dimuon final-states are compatible.
  - 2.6σ tension between P'_5 and SM predictions at low-q^2.

Belle [PRL 118 (2017) 111801]



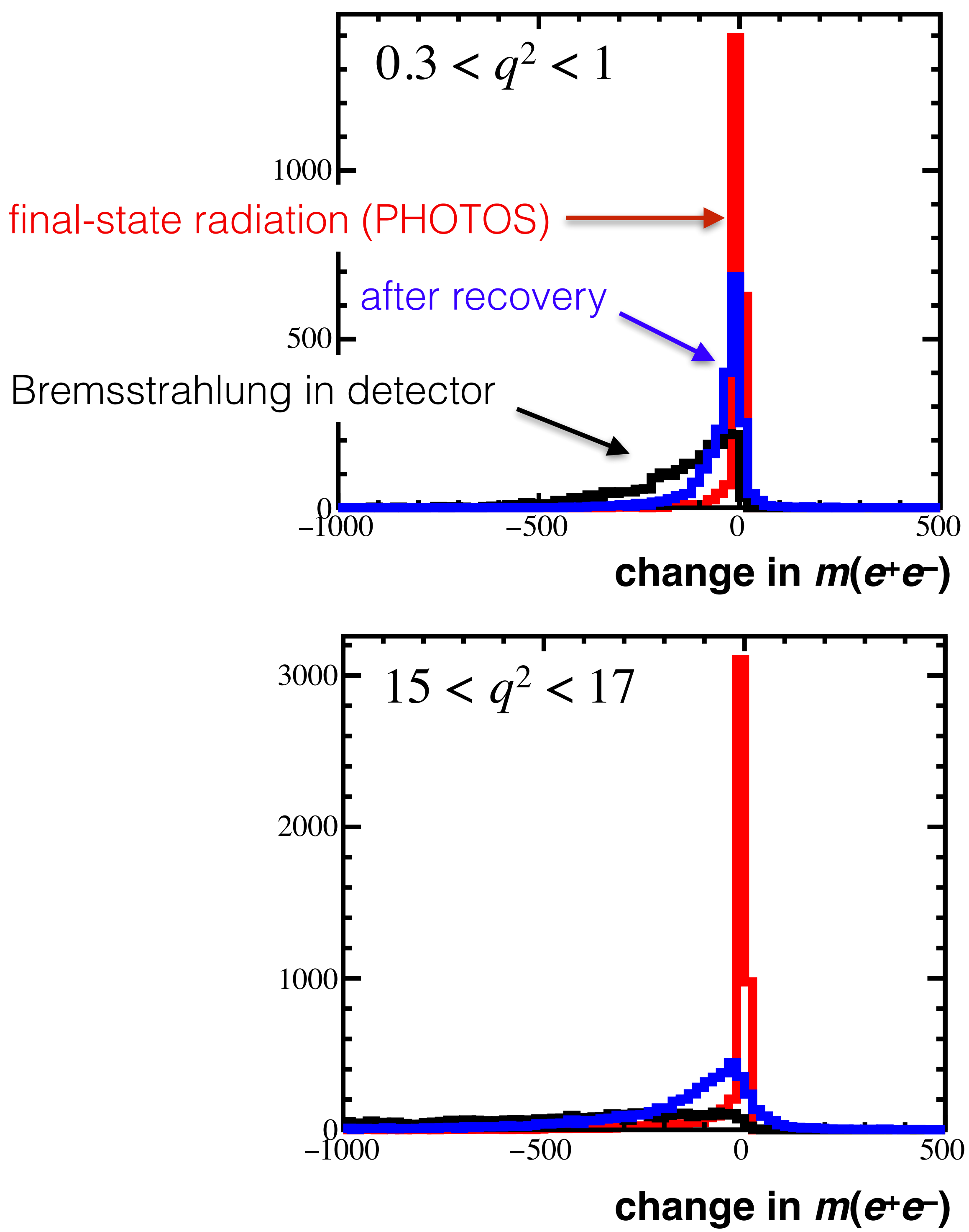


Q Why hasn't LHCb made measurements of R_K, R_{K^*} or R_{pK} at high q2?

A Bremsstrahlung effects are large and this makes the analysis more difficult.

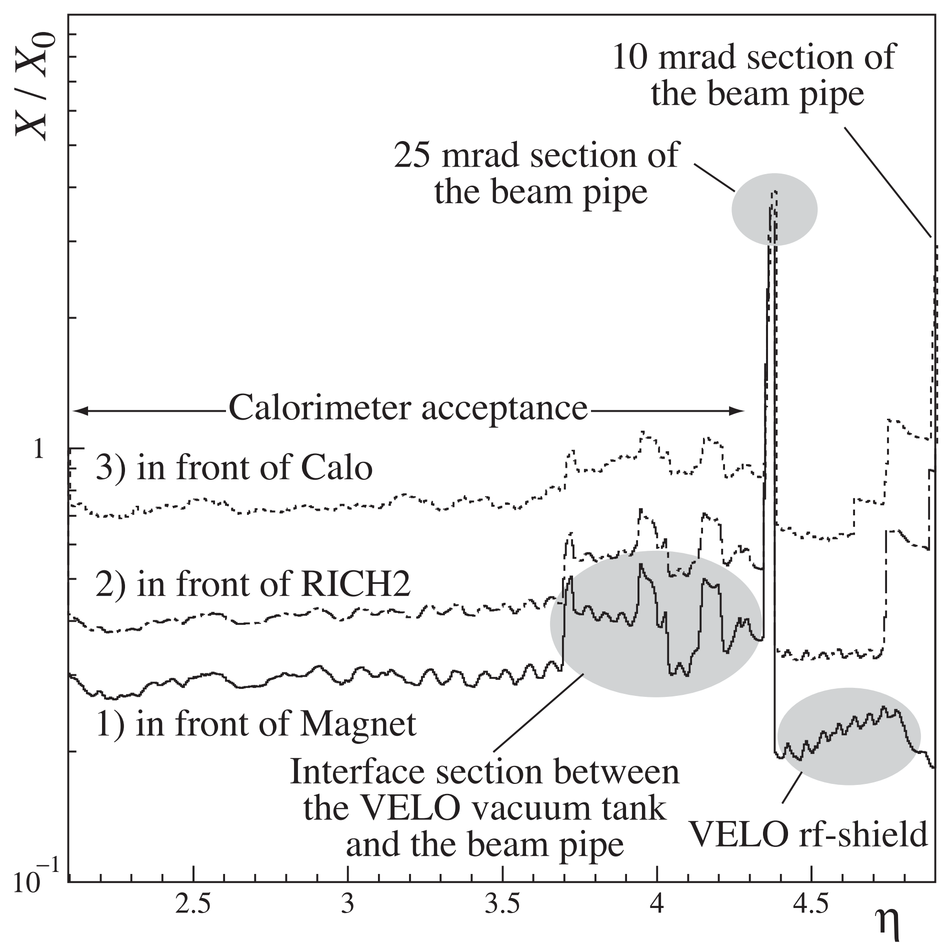
Energy loss in LHCb

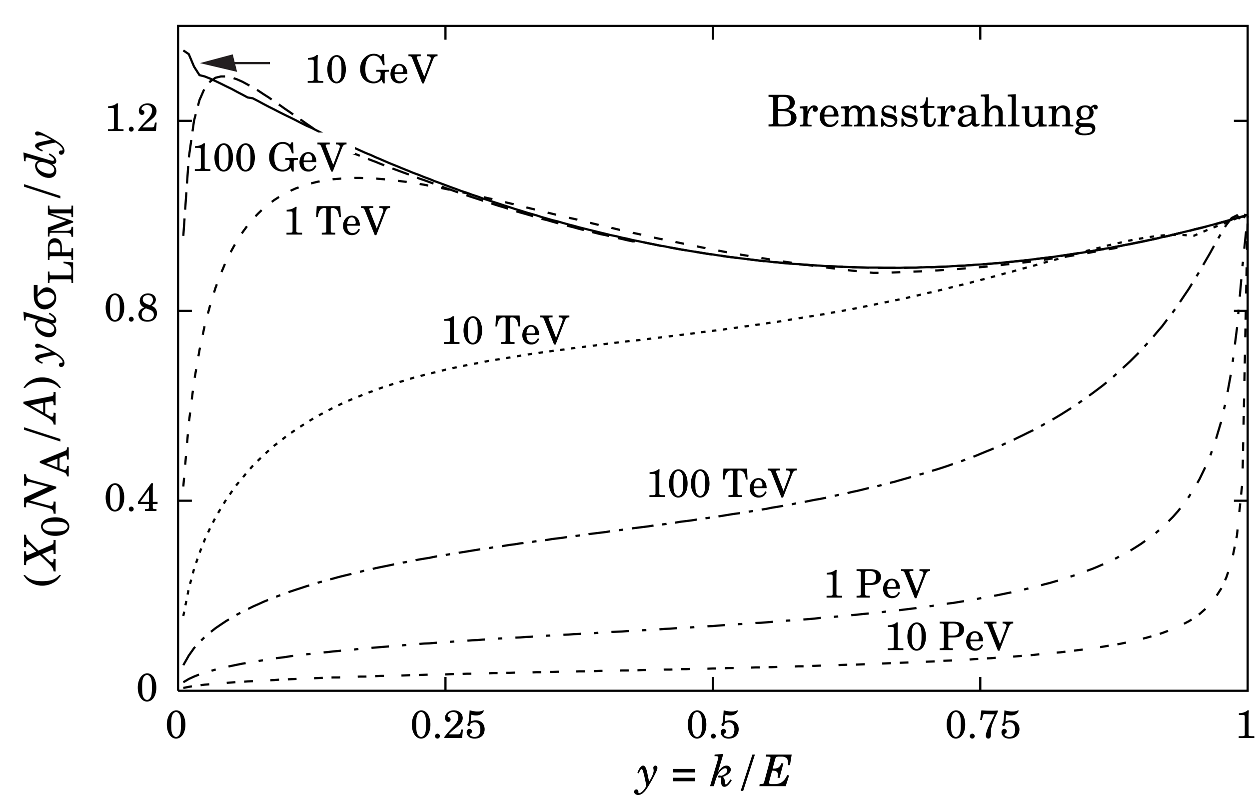
- Dielectron and dimuon final-states look very different in our analyses due to the energy lost by electrons in the detector.
- Bremsstrahlung emission is much more significant than the QED emission considered in the SM calculations. Experimentally we cannot separate the two effects.
- Impact of the energy loss depends on q^2 , with a larger migration at high q^2.
- The signal line shape, and the migration of candidates in q^2 , depends on the underlying q^2 distribution of events within a q^2 bin.



Bremsstrahlung

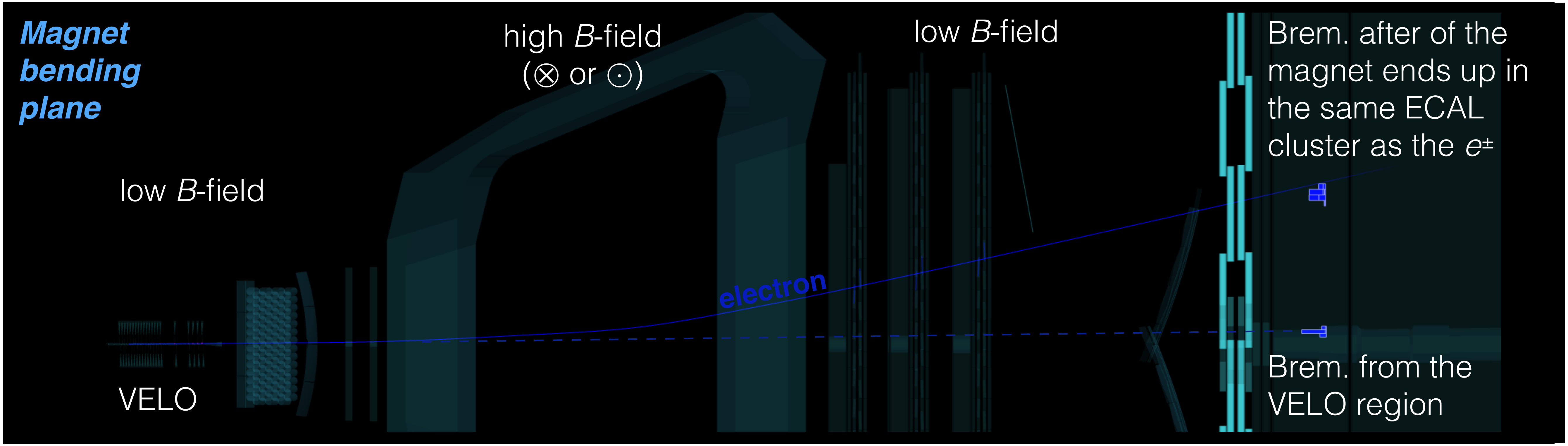
- Depends on material in detector and energy of electrons:





- Unfortunately LHCb is not that lightweight ($e^{\pm}$ see >70% X_0 before ECAL) and the electrons are high energy.

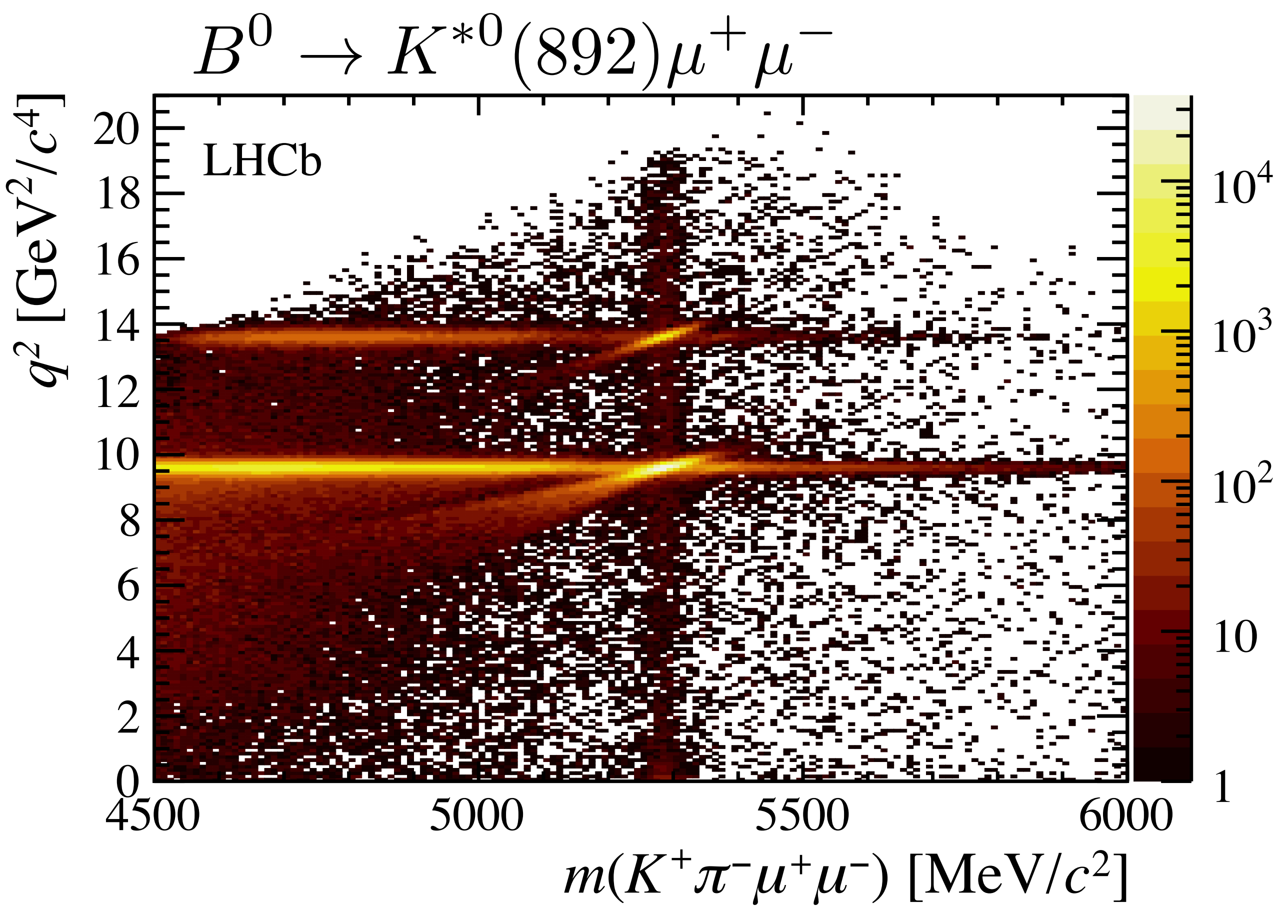
Bremsstrahlung recovery

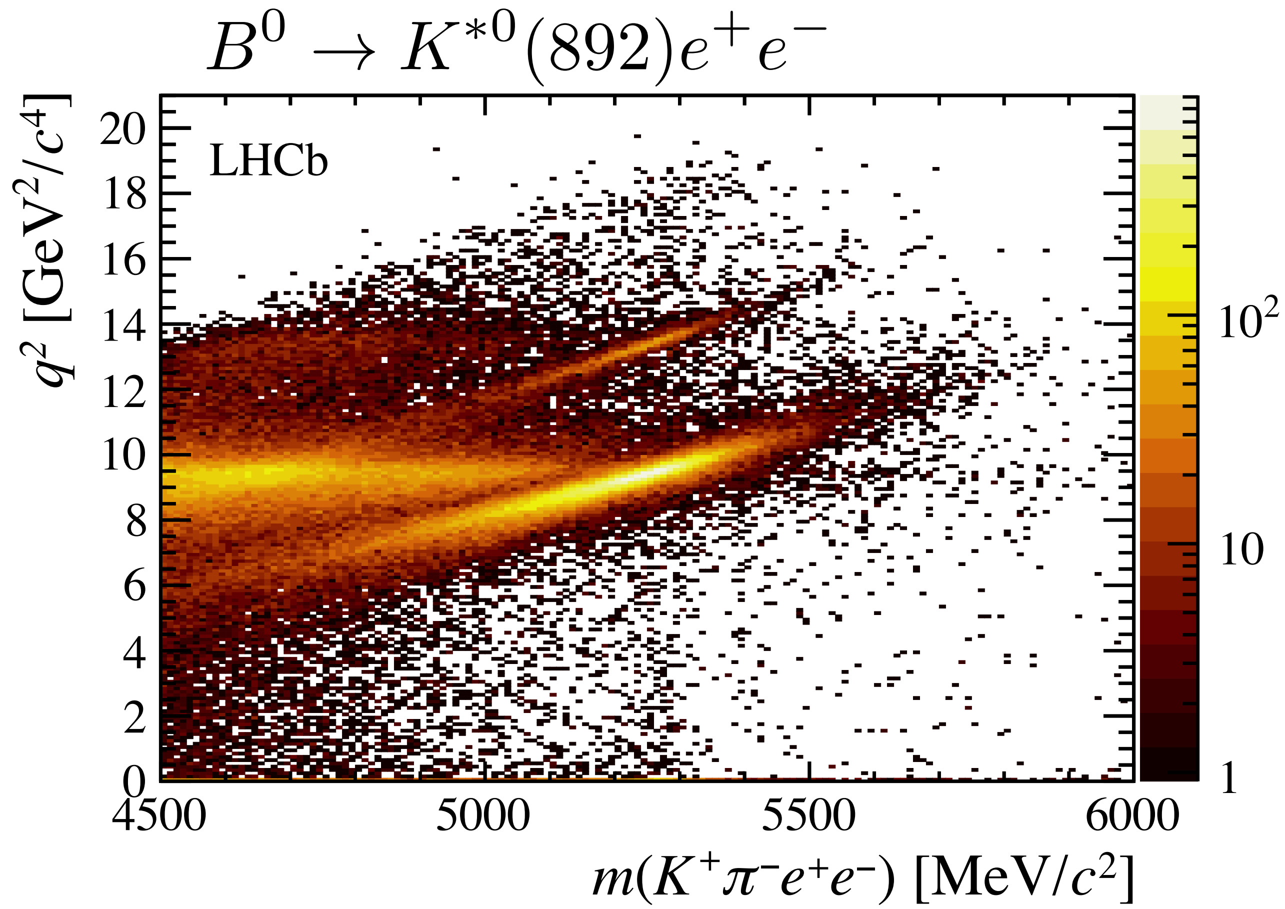


- Large energy loss through Bremsstrahlung in the detector (significant fraction of the $e^{\pm}$ energy).
- Add clusters with $E_T > 75$ MeV/c^2 in the ECAL, within a search window about the track direction, to correct for Bremsstrahlung emission.
- Mass resolution depends on the energy resolution of the calorimeter.

Comparison of dimuon and dielectron final-states

LHCb [JHEP 08 (2017) 055]

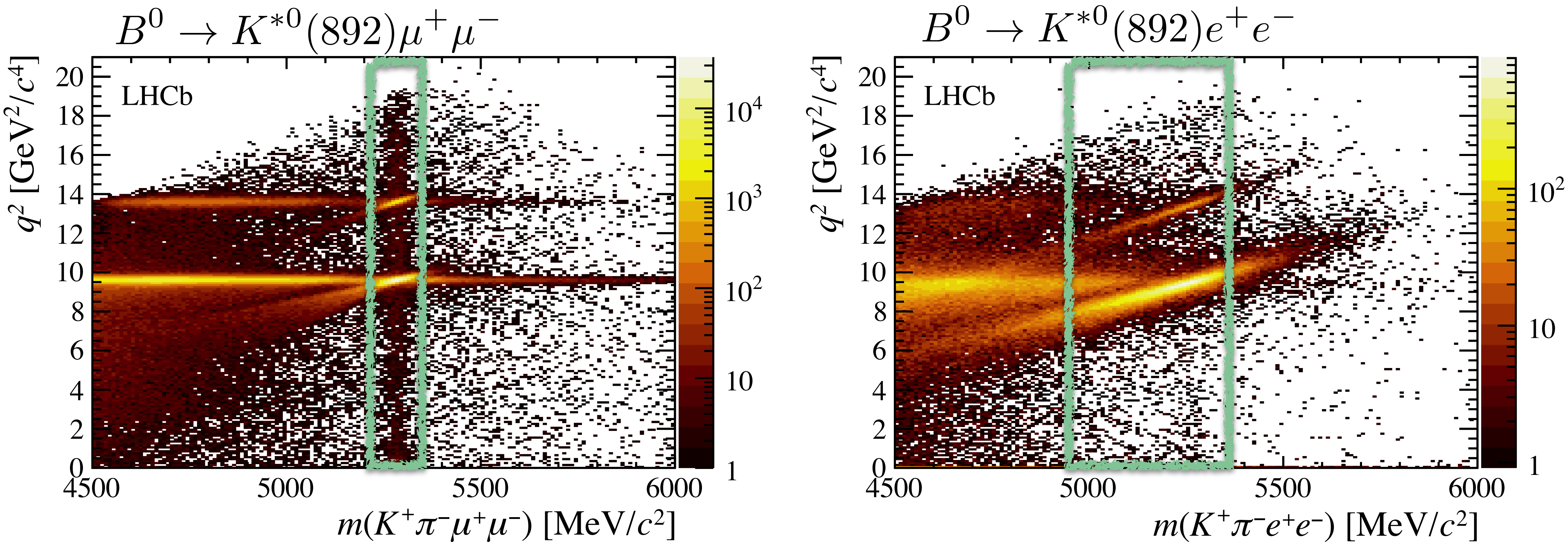




- Even after Bremsstrahlung recovery, we see large differences between dielectron and dimuon final-states.

Comparison of dimuon and dielectron final-states

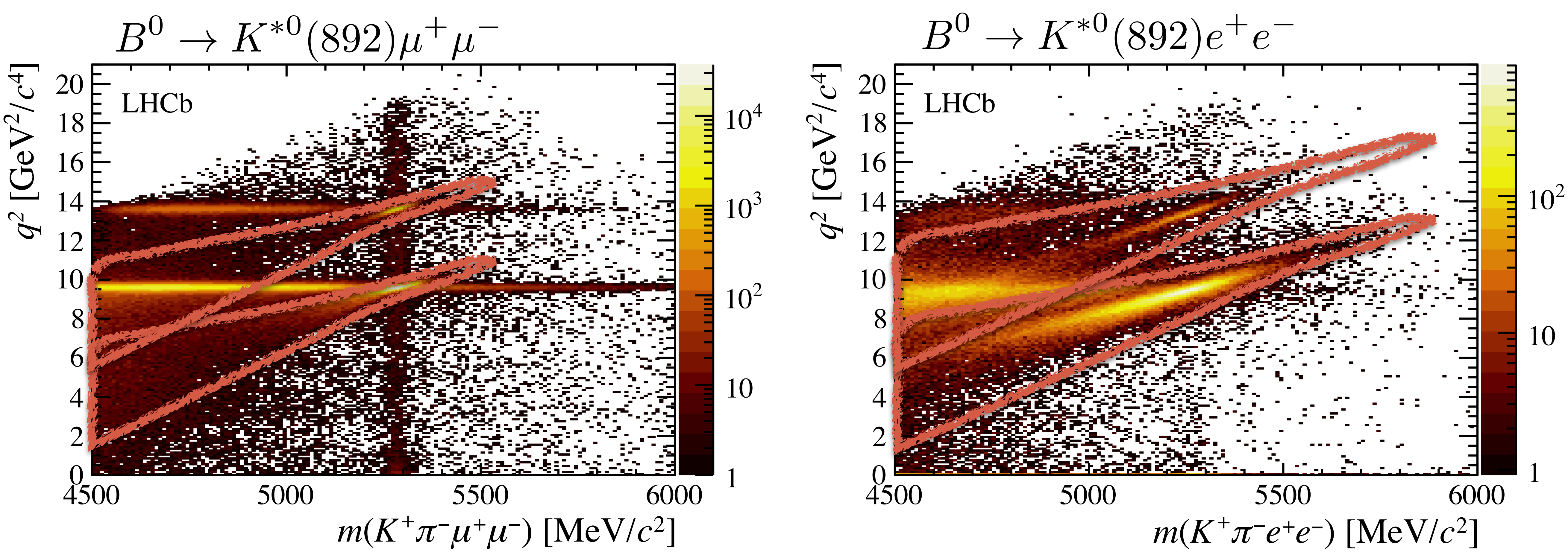
LHCb [JHEP 08 (2017) 055]



- Signal is washed out for dielectron final-states due to imperfect Bremsstrahlung recovery.

Comparison of dimuon and dielectron final-states

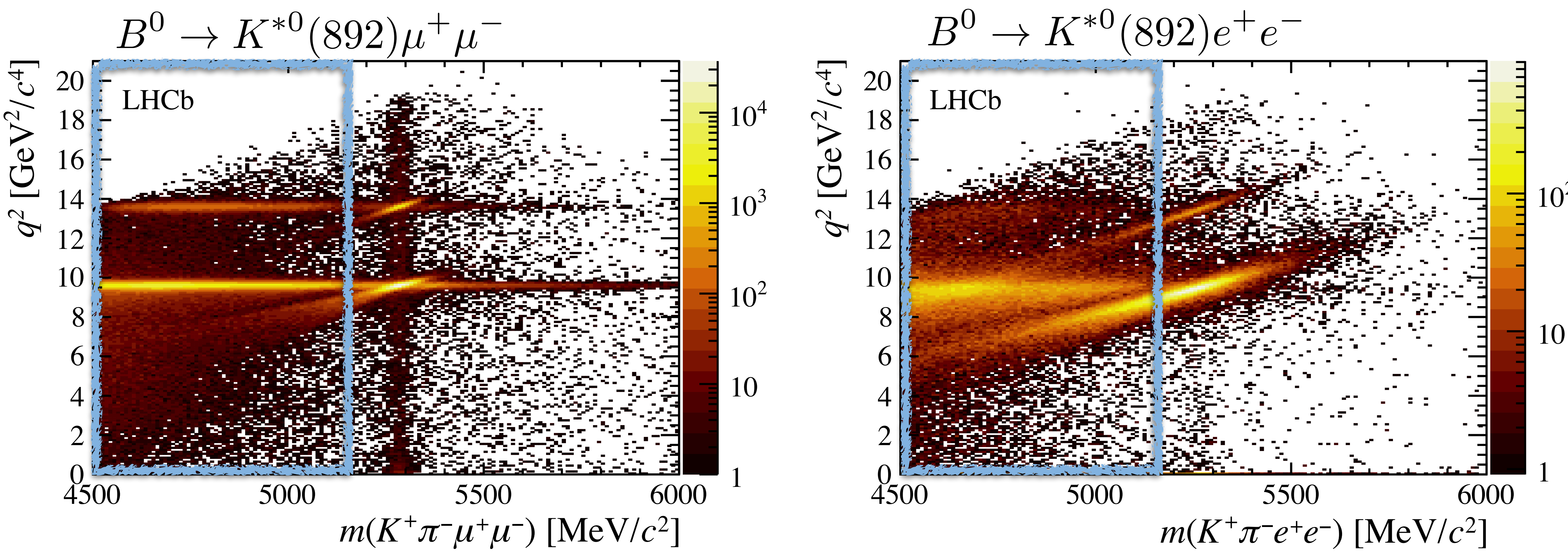
LHCb [JHEP 08 (2017) 055]



- Narrow charmonium resonances have larger tails for dielectron final-states (due to imperfect Bremsstrahlung correction and the energy resolution of the ECAL).

Comparison of dimuon and dielectron final-states

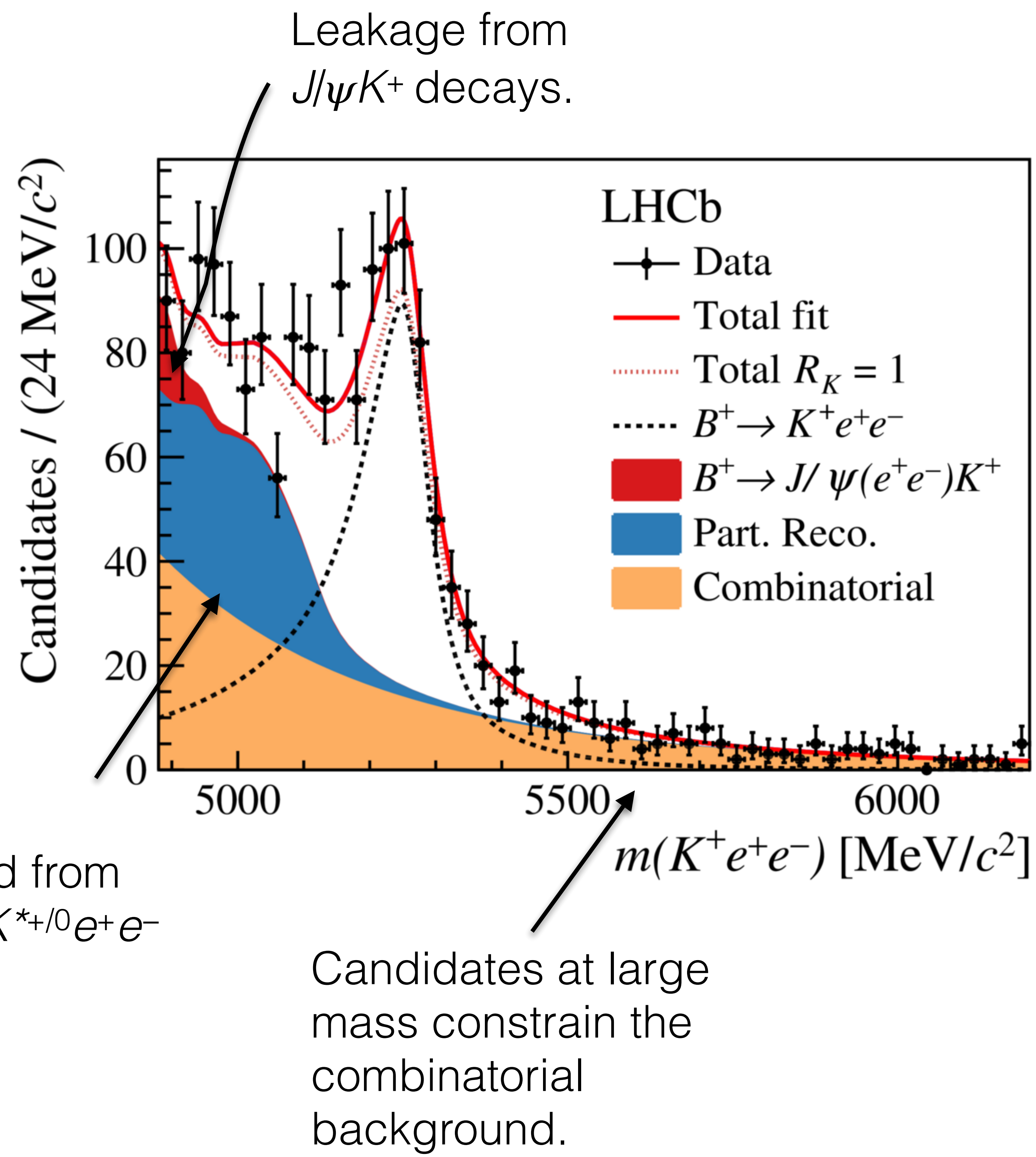
LHCb [JHEP 08 (2017) 055]



- Partially reconstructed backgrounds with missing pions are not well separated from the signal for dielectron final-states.

R_K at low q^2

- Similar contributions are seen in selected $B^+ \to K^+ \ell^+ \ell^-$ candidates.
- Projecting onto the reconstructed B^+ mass for $1.1 < q^2 < 6.0$ GeV$^2/c^4$:

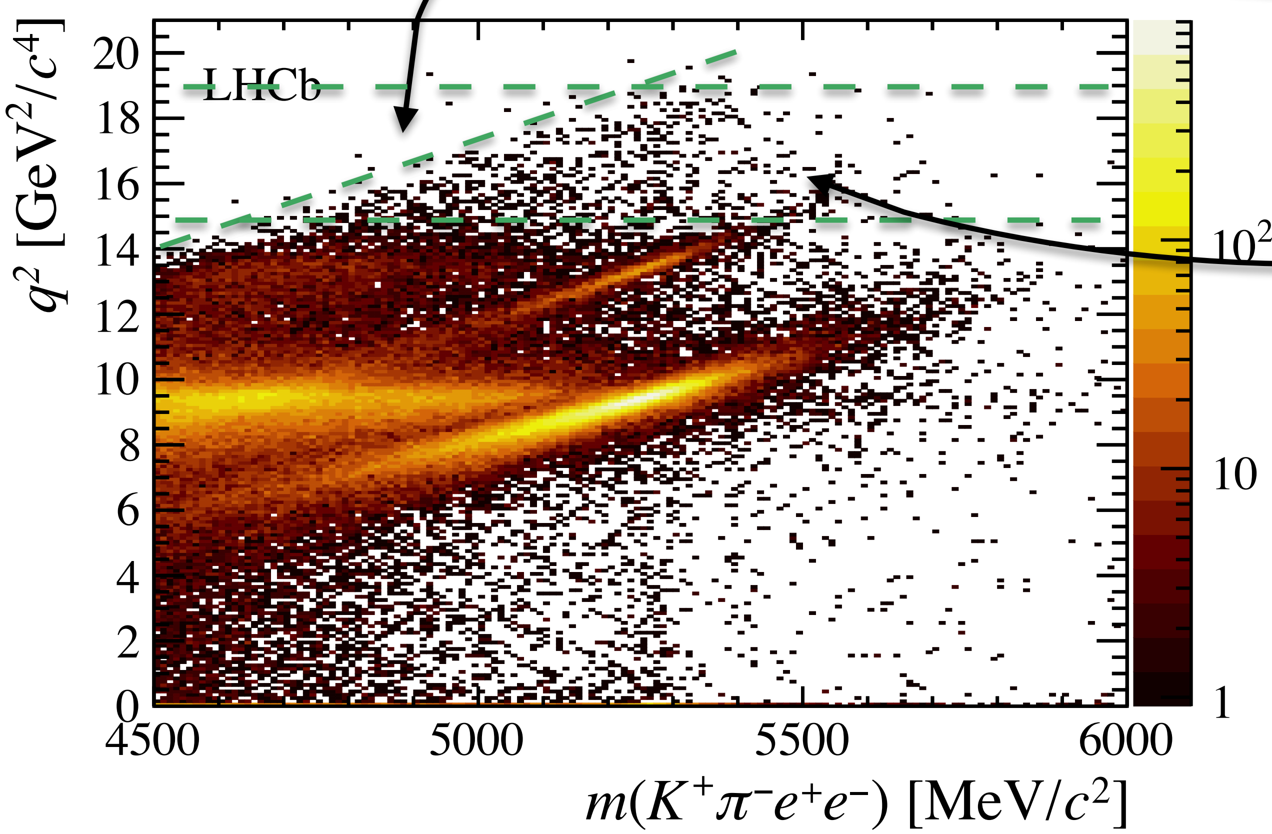


LHCb [PRL 122 (2019) 191801]

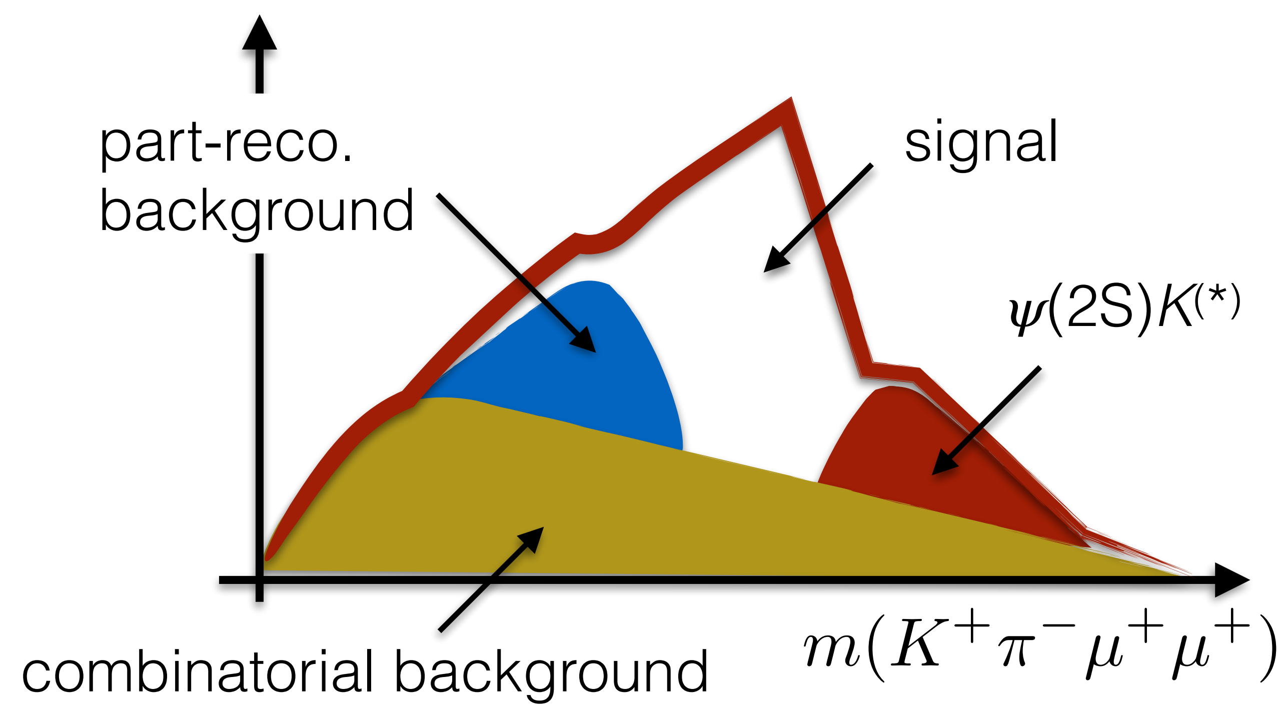
R_K and R_{K^*} at high q^2?

Combinatorial and partially reconstructed backgrounds are sculpted by the available phase space.

Leakage from $\psi(2S)K^{(*)}$ decays.



- At high q^2 it becomes challenging to statistically separate signal from background.



R_K and R_{K^*} at high q^2

- Can we fit in 2D?
  - Features are easy to distinguish by eye in 2D but we don't know the underlying q^2 distribution of the signal or partially reconstructed backgrounds.
- Can we constrain partially reconstructed backgrounds, *e.g.* using the $K^{*0}e^+e^-$ signal to constrain the background to $K^+e^+e^-$?
  - Would require some assumptions, e.g. can we assume isospin symmetry?
- Can we constrain the combinatorial background shape?
  - It's unfeasible to generate enough MC to build a template. We could assume the behaviour is same in the dielectron and dimuon final-states or use same-sign combinations. Unclear how safe these assumptions would be since it depends on the origin of the leptons.

Other processes?

- **$B_s \to \phi\, \ell^+ \ell^-$**
- $\Lambda_b \to pK^- \ell^+ \ell^-$
- $\Lambda_b \to \Lambda \ell^- \ell^-$

❌ suppressed by smaller B_s production fraction ($f_s/f_d \sim 0.26$).

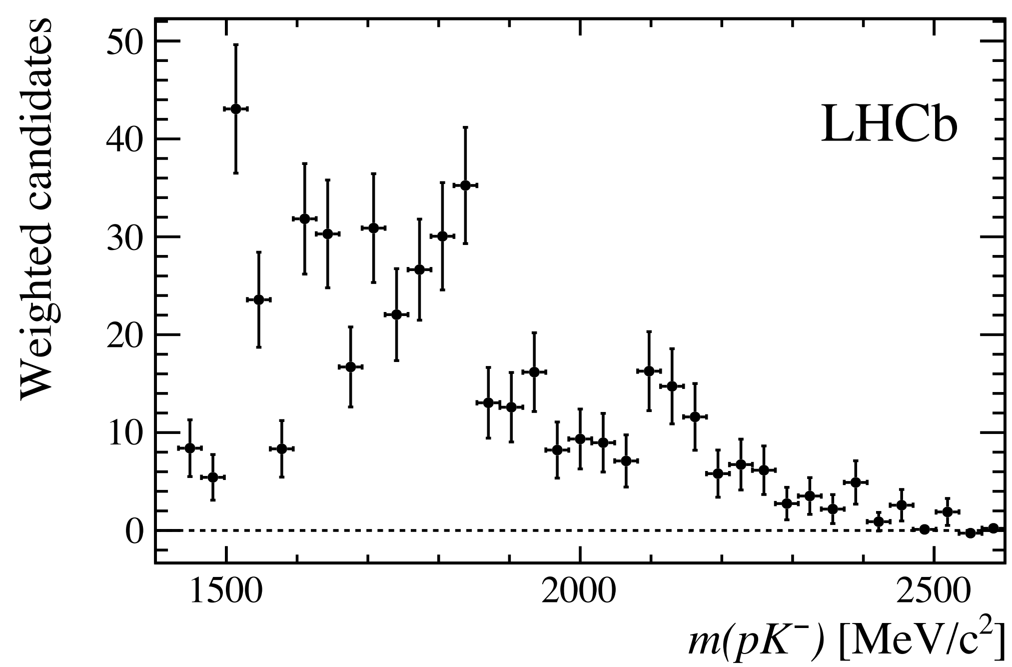
✔ reduced partially reconstructed background (largest source involves a missing kaon and is better separated from the signal).

Other processes?

- $B_s \to \phi \ell^+ \ell^-$
- **$\Lambda_b \to pK^- \ell^+ \ell^-$**
- $\Lambda_b \to \Lambda \ell^- \ell^-$

❌ very little phase space at high q^2.

Background subtracted pK mass distribution of $\Lambda_b \to pK^- \mu^+ \mu^-$ decays in $1.1 < q^2 < 6.0$ GeV$^2/c^4$:



LHCb [arXiv:1912.08139]

See contributions from a large number of Λ^* resonances at large masses.

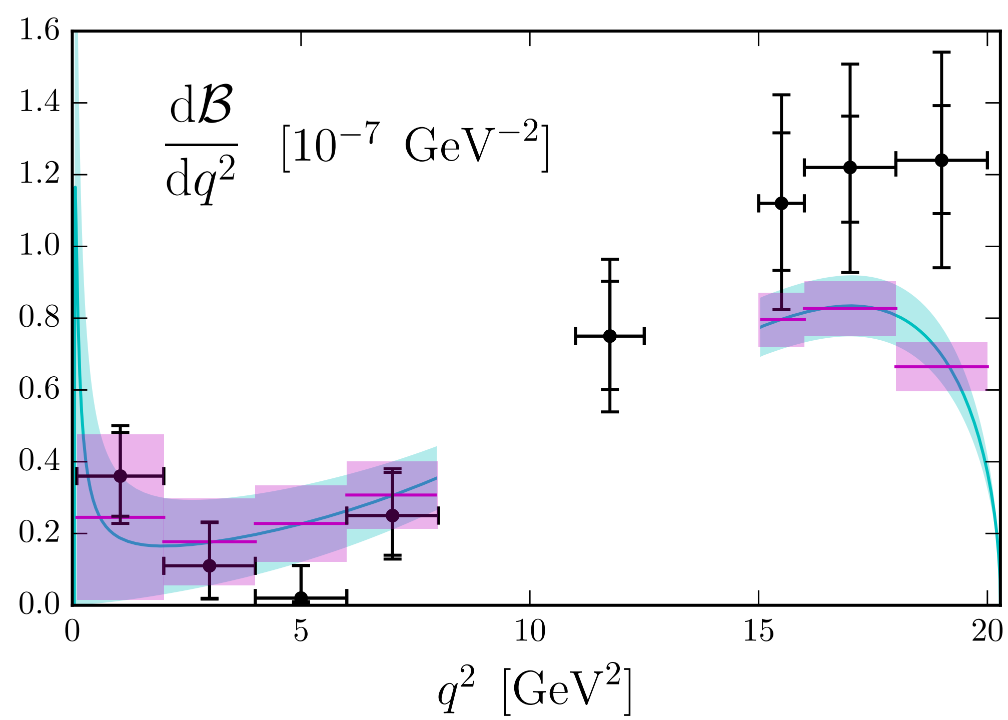
Other processes?

- $B_s \to \phi \ell^+ \ell^-$
- $\Lambda_b \to p K^- \ell^+ \ell^-$
- **$\Lambda_b \to \Lambda \ell^- \ell^-$**

❌ suppressed due to need to reconstruct long-lived Λ baryons.

✔ partially reconstructed backgrounds are suppressed.

✔ signal predominantly expected at large q^2.



Detmold et al. [PRD 93 (2016) 074501]
LHCb [JHEP 06 (2015) 115]