Test of lepton flavour universality in $B^+ \to K^+ l^+ l^-$ decays in high di-lepton invariant mass squared region

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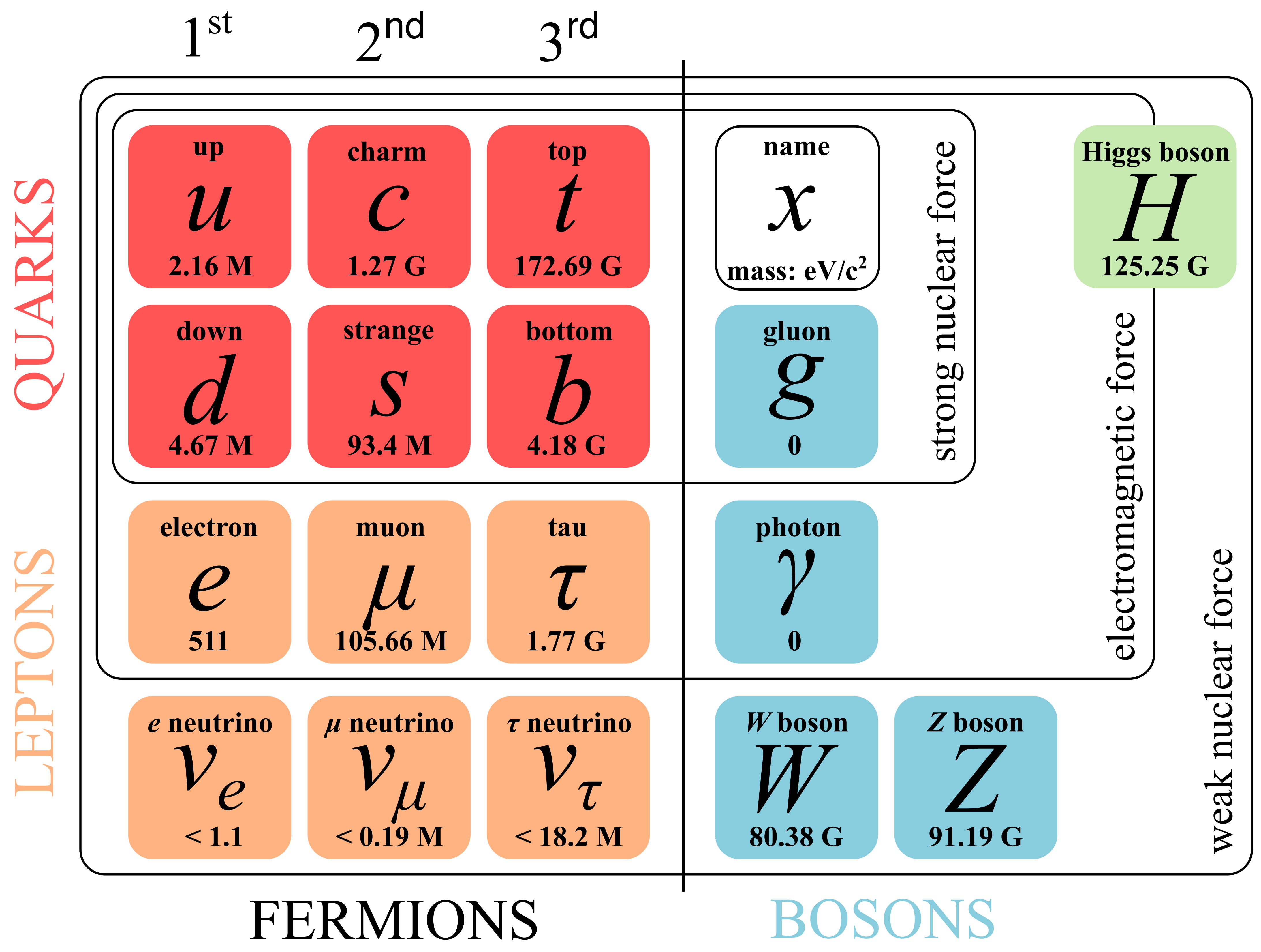
If only there was THE theory

- A theory that:
  - Contains the knowledge of all the elementary blocks
  - Explains the interaction between those elementary particles
  - Works everywhere and all the time

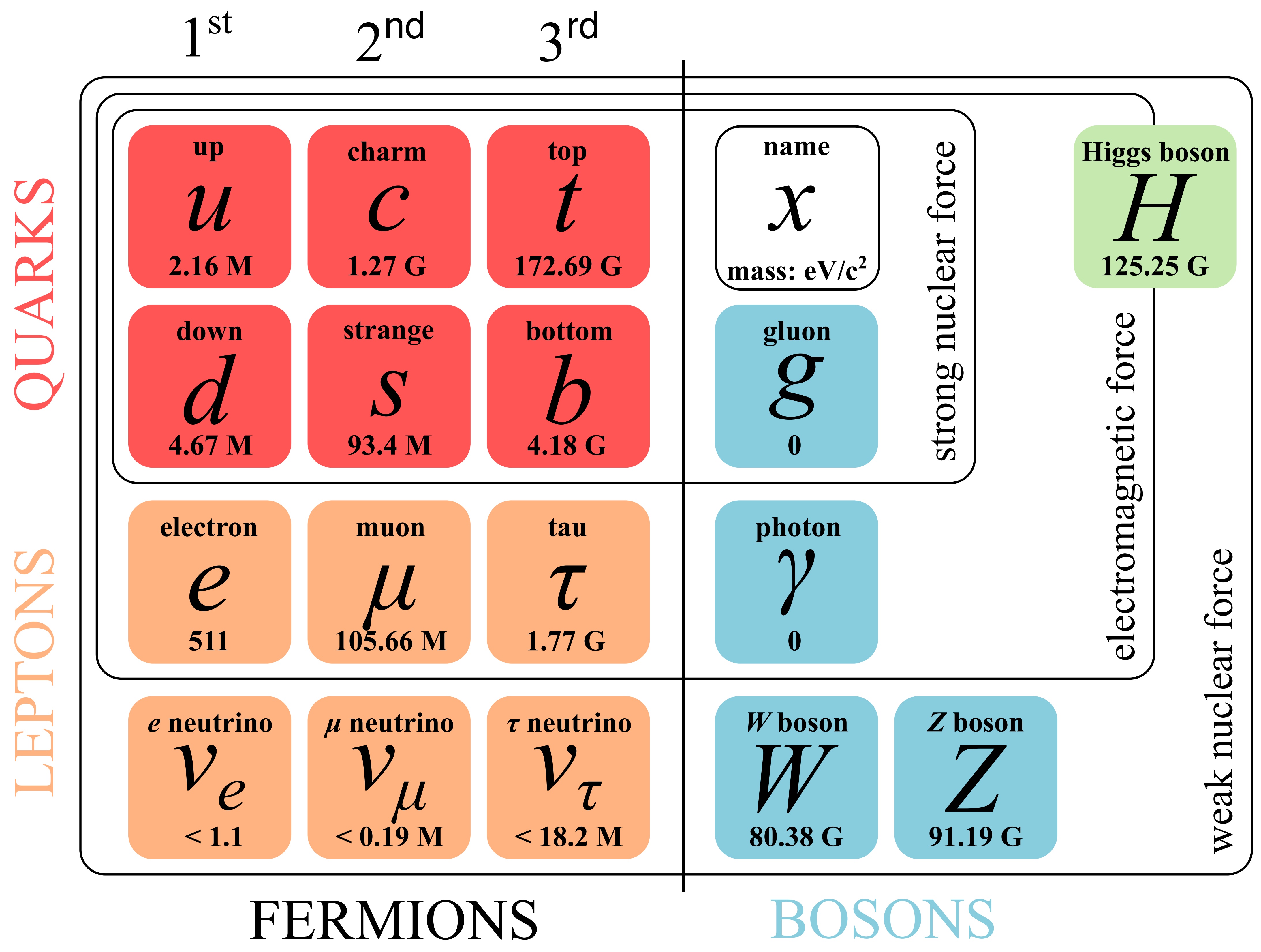
The Standard Model

- The Standard Model (SM) combines
  the vast majority of our knowledge of Particle Physics.



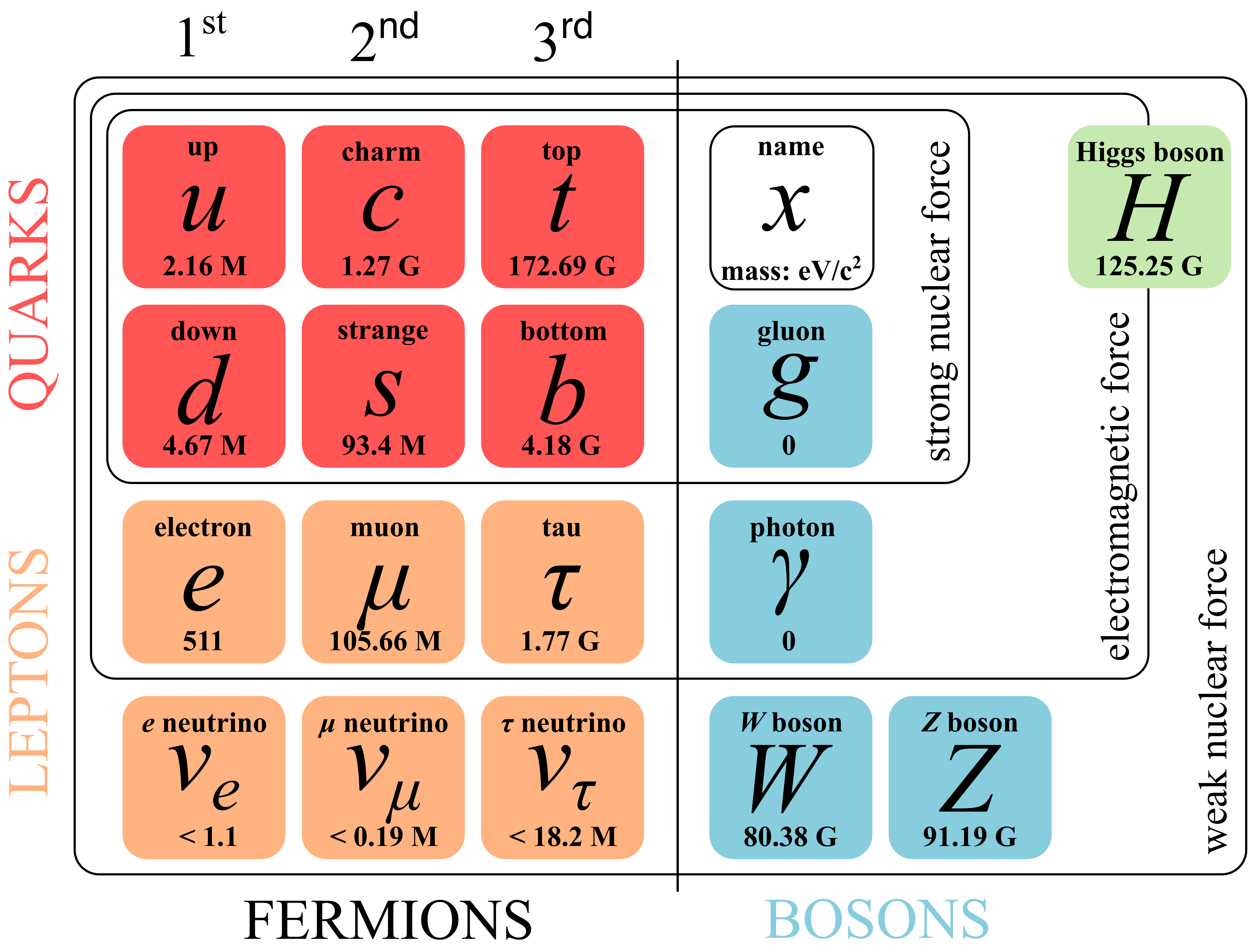
The Standard Model

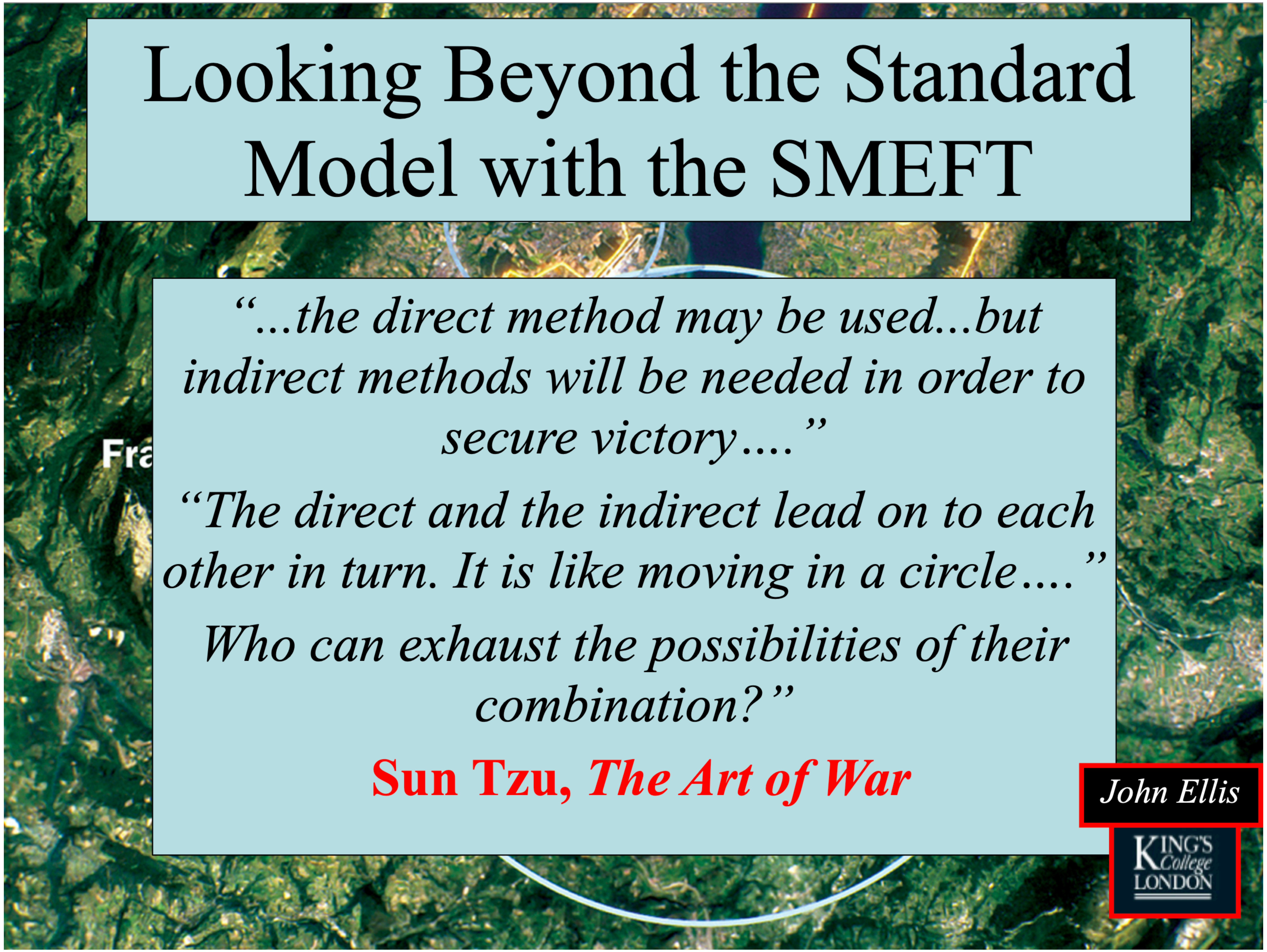
- The Standard Model (SM) combines the vast majority of our knowledge of Particle Physics.
- Luckily, it is **excellent** at explaining an extensive range of physics processes.



The Standard Model

- The Standard Model (SM) combines
  the vast majority of our knowledge of Particle Physics.
- Luckily, it is excellent at explaining an extensive range of physics processes.
- Unfortunately, it **does not explain all** of them and does not answer **ALL** our questions.





Lecture by J. Ellis

Beyond the SM

- The search for New Physics (NP) can be done in a couple of ways:

- Direct searches

  Focus on searches for particles that are **directly** created in high-energy beams

- Indirect searches

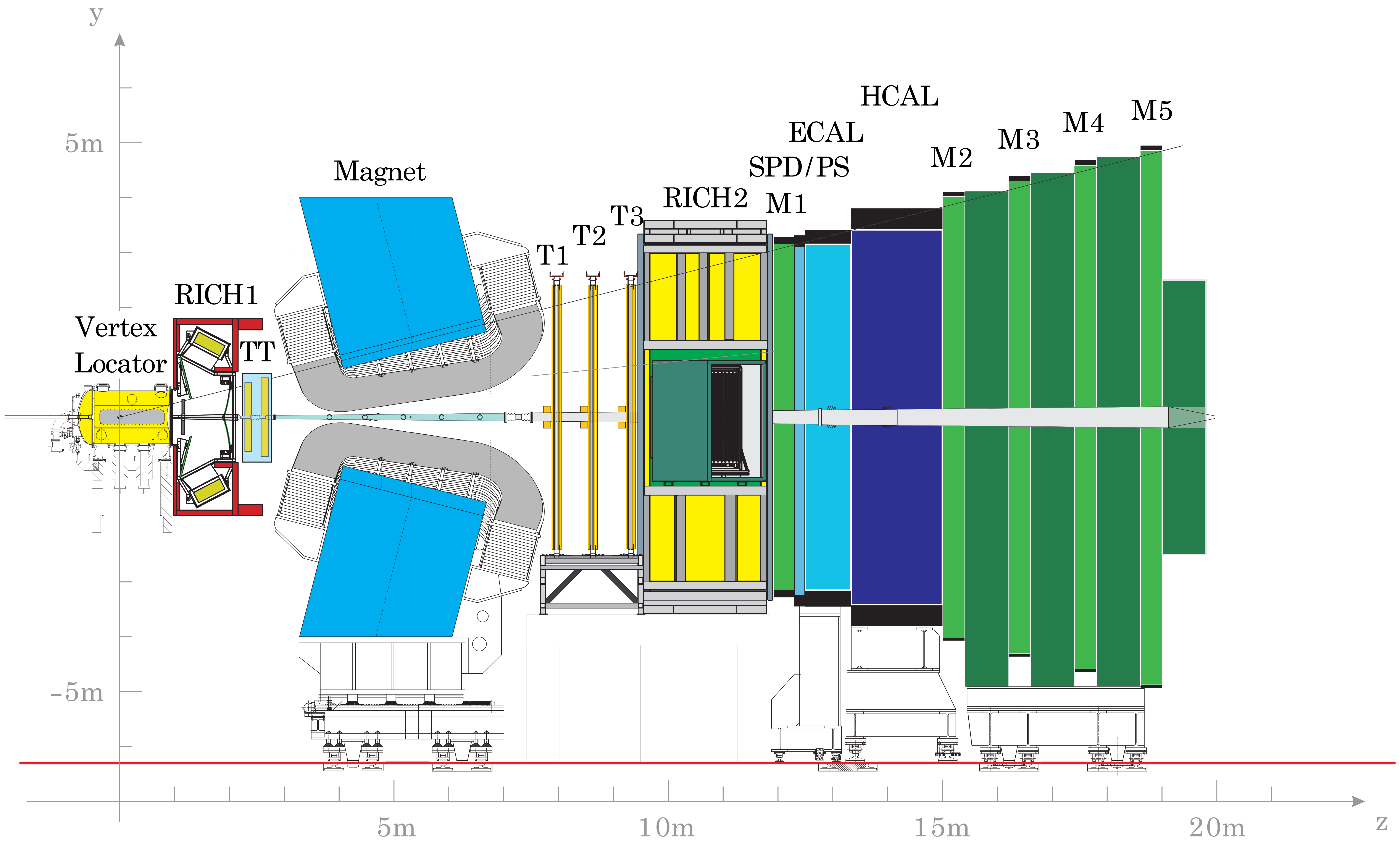
  Focus on searches for **inconsistencies** between experimental results and theoretical predictions

Beyond the SM

- The Large Hadron Collider (LHC) is the perfect place to test the Standard Model:
  - Particle accelerator and collider located in Geneva, Switzerland (and France);
  - Allows to study properties of particles created as a result of proton-proton (and not only) collisions.

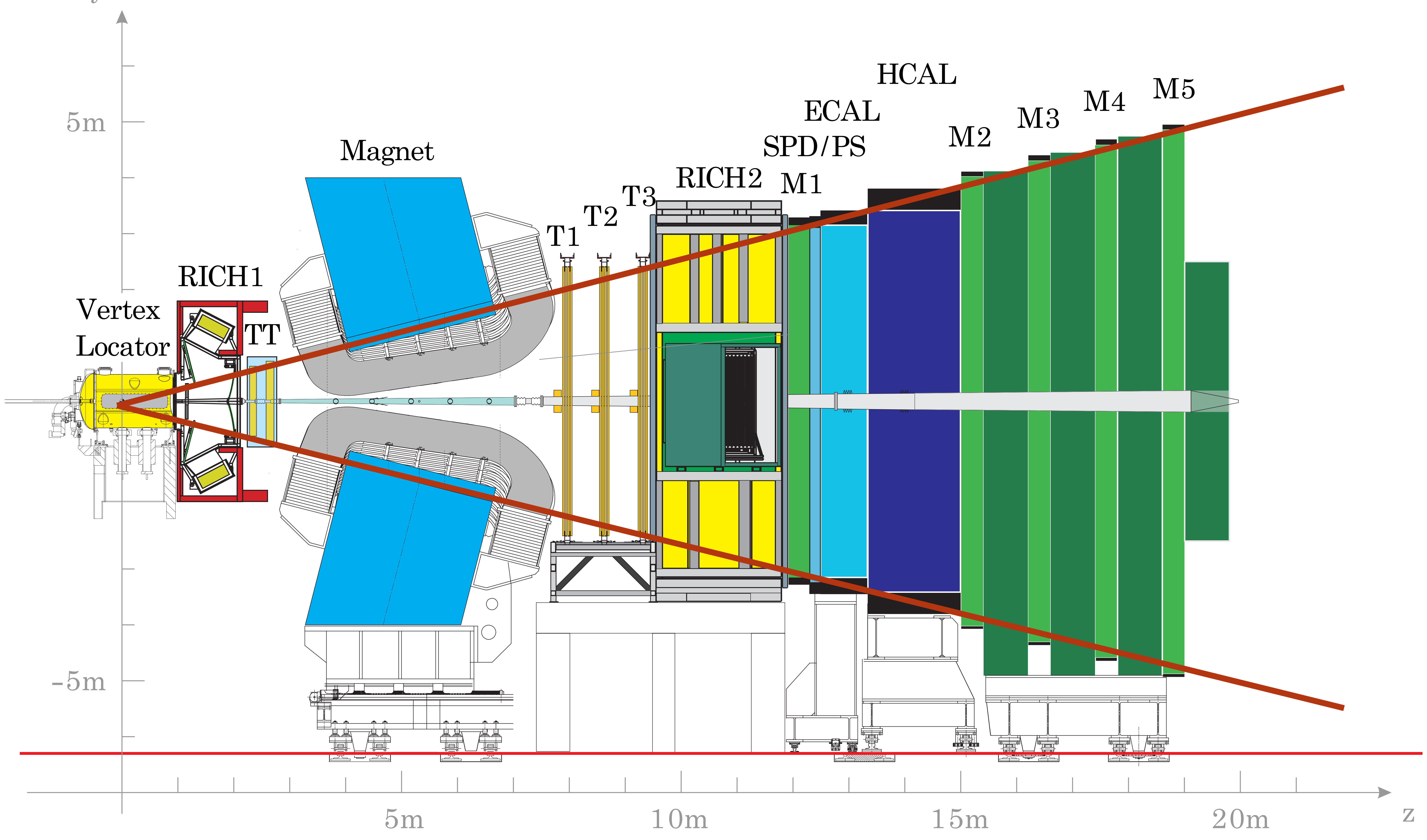
The LHCb experiment

- Exploiting the indirect ways to search for New Physics, LHC**b** is primarily focused on **beauty** quark decays.



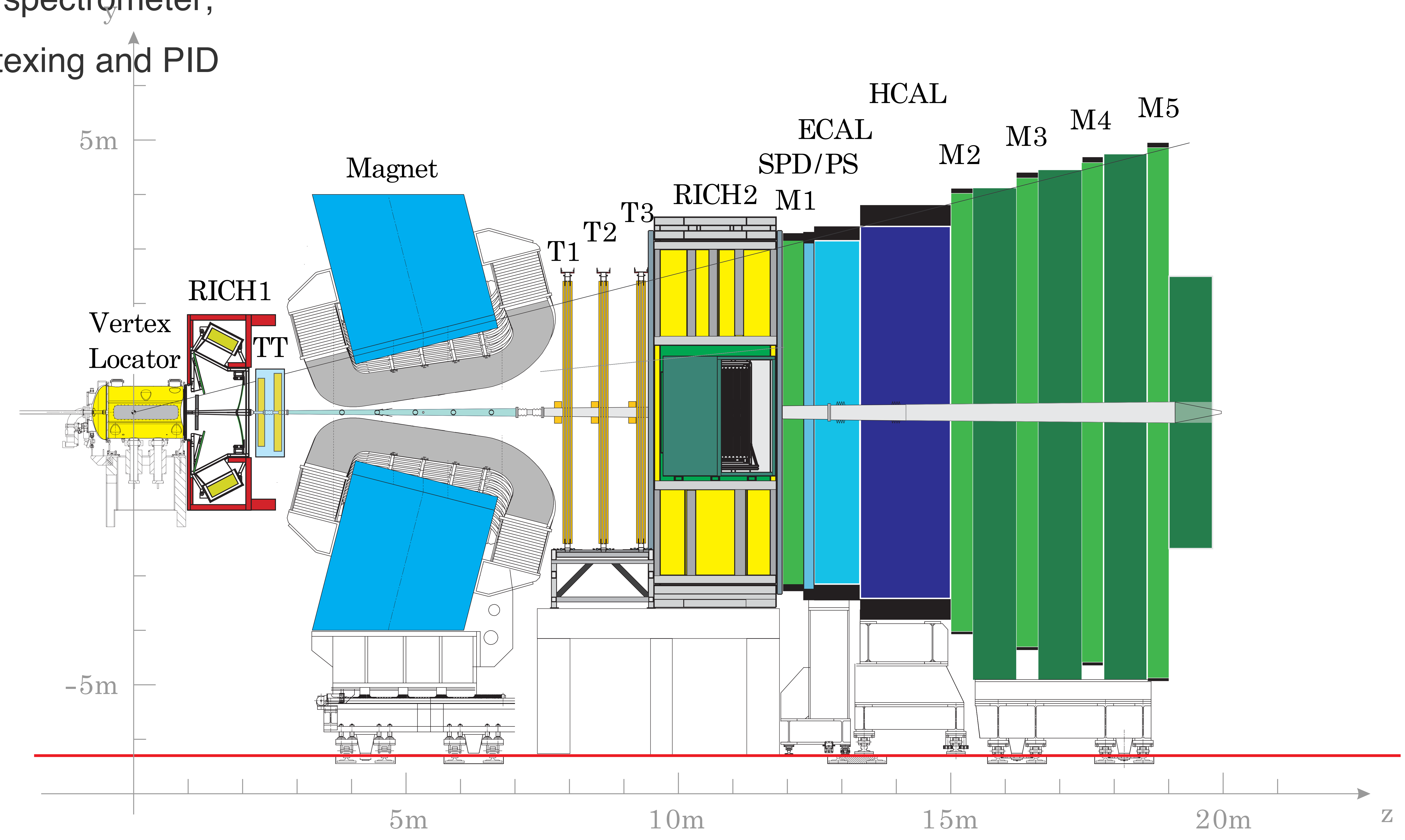
The LHCb experiment

- Exploiting the indirect ways to search for New Physics, LHC**b** is primarily focused on **beauty** quark decays:
  - Forward-arm spectrometer;



The LHCb experiment

- Exploiting the indirect ways to search for New Physics, LHC**b** is primarily focused on **beauty** quark decays:
  - Forward-arm spectrometer;
  - Excellent vertexing and PID



Lepton flavour universality test

- In the Standard Model (SM), the coupling of gauge bosons to leptons is independent of lepton flavour.
  - To test it, the ratio of $B^+ \to K^+ l^+ l^-$ branching fractions (a theoretically clean observable):

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2} dq^2} \cong 1, \quad q^2 \equiv \textit{dilepton invariant mass squared}$$

- Any significant deviation — a hint of New Physics (NP):
  - The latest results show $< 1\sigma$ compatibility with SM [arXiv:2212.09152]

R_K measurements

- The ratio of $B^+ \to K^+ l^+ l^-$ branching fractions R_K as an experimental observable:

$$R_K = \left(\frac{N(B^+ \to K^+ \mu^+ \mu^-)}{\varepsilon(B^+ \to K^+ \mu^+ \mu^-)} \right) \bigg/ \left(\frac{N(B^+ \to K^+ e^+ e^-)}{\varepsilon(B^+ \to K^+ e^+ e^-)} \right)$$

- Problems due to the difference in leptons detection at LHCb.

R_K measurements

- The ratio of $B^+ \to K^+ l^+ l^-$ branching fractions (**a theoretically clean observable**):

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$$= \frac{\left(\frac{N(B^+ \to K^+\mu^+\mu^-)}{\varepsilon(B^+ \to K^+\mu^+\mu^-)}\right) \Big/ \left(\frac{N(B^+ \to K^+e^+e^-)}{\varepsilon(B^+ \to K^+e^+e^-)}\right)}{\left(\frac{N(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}{\varepsilon(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}\right) \Big/ \left(\frac{N(B^+ \to K^+J/\psi(\to e^+e^-))}{\varepsilon(B^+ \to K^+J/\psi(\to e^+e^-))}\right)}$$

- Using a “double ratio” between non-resonant (rare) $B^+ \to K^+ l^+ l^-$ and resonant $B^+ \to K^+ J/\psi(\to l^+ l^-)$ modes allows us to have control over electron/muon differences.

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LFU within 0.4%

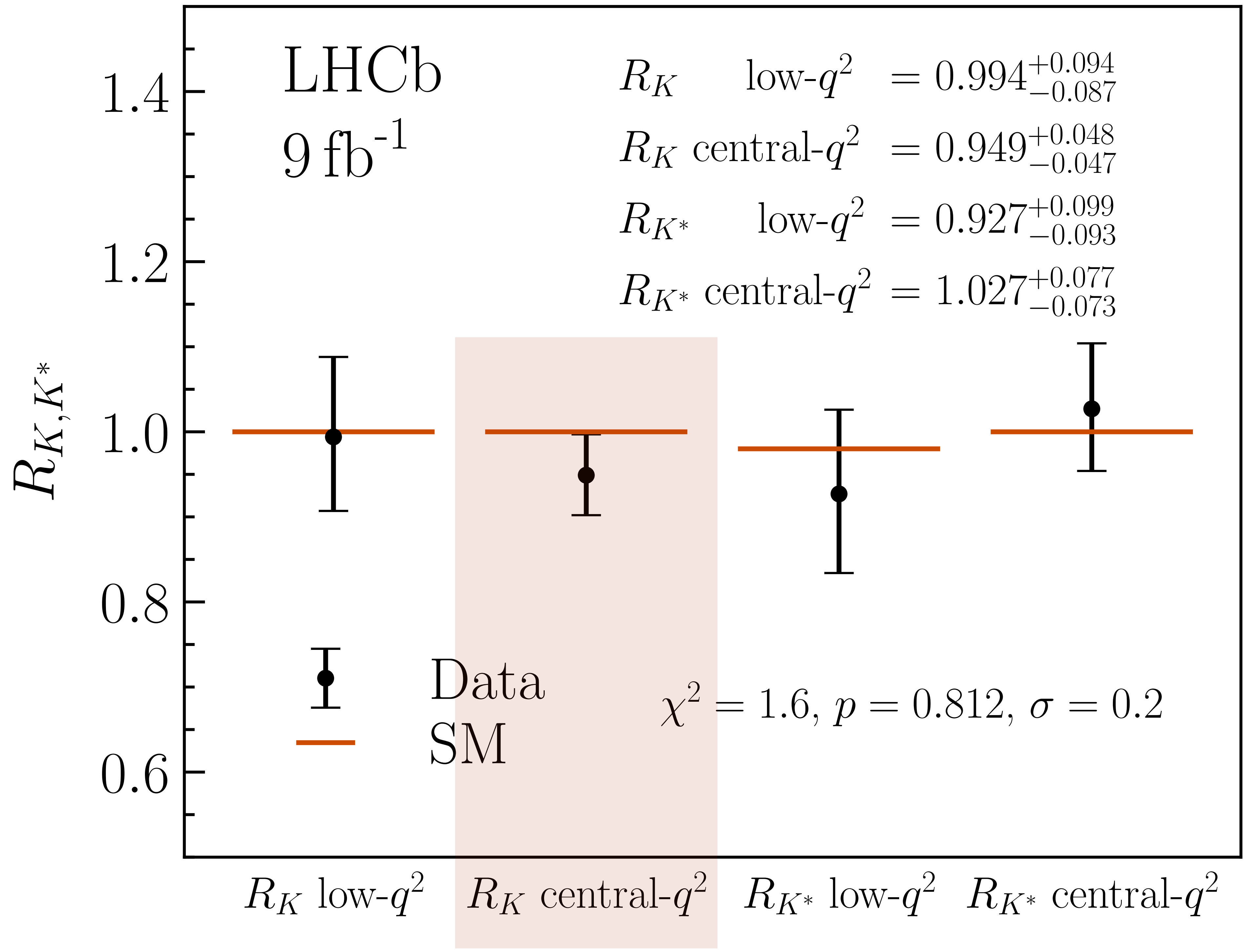
- Using a "double ratio" between non-resonant (rare) $B^+ \to K^+ l^+ l^-$ and resonant $B^+ \to K^+ J/\psi(\to l^+ l^-)$ modes allows us to have control over electron/muon differences.

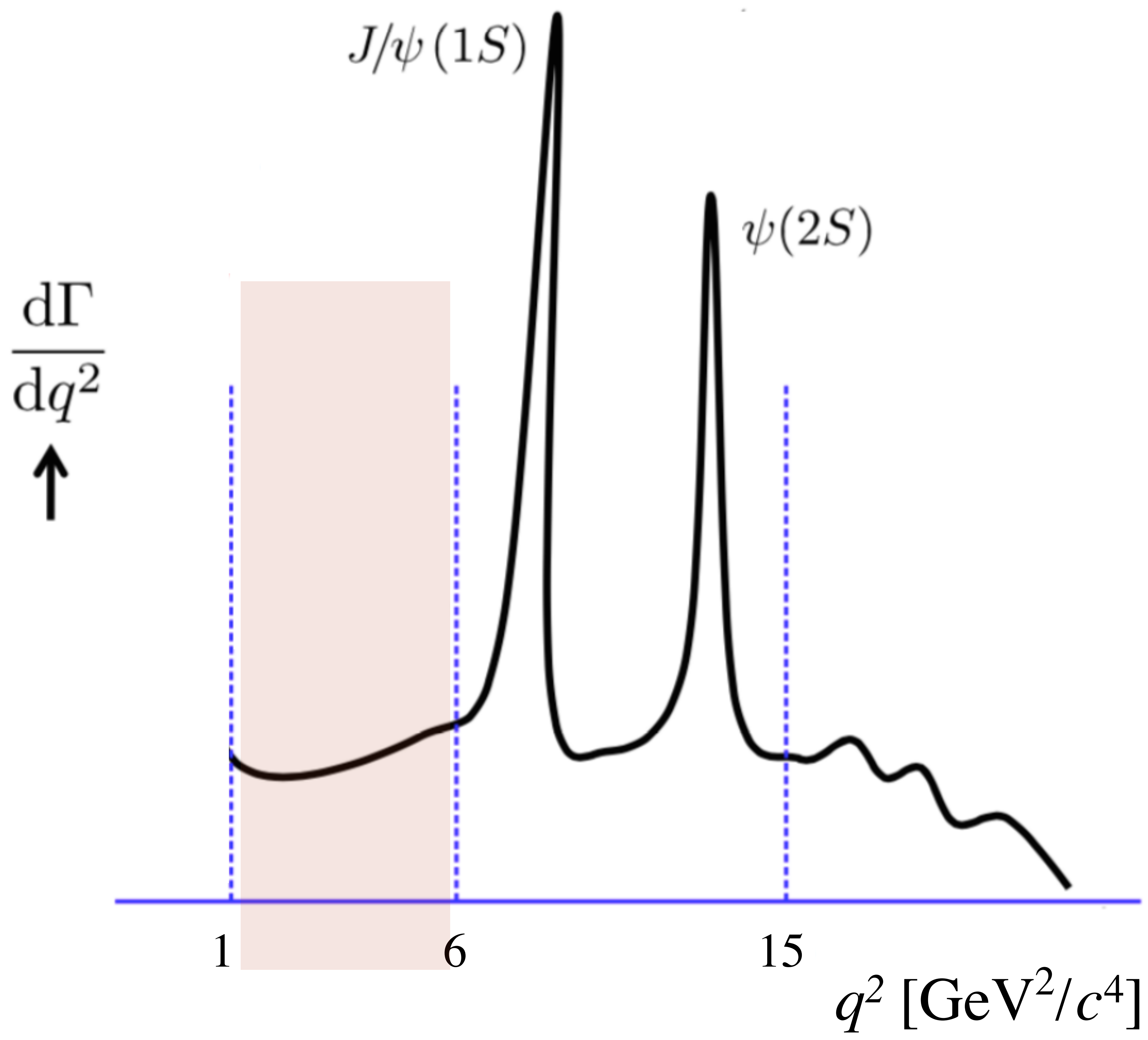
R_K measurements

'Central q^2' measurements ($q^2 \in [1.1\ \mathrm{GeV}^2, 6.0\ \mathrm{GeV}^2]$):

- The latest result points toward compatibility with the Standard Model
- However, the result is **statistically limited**

LHCb [arXiv:2212.09153]

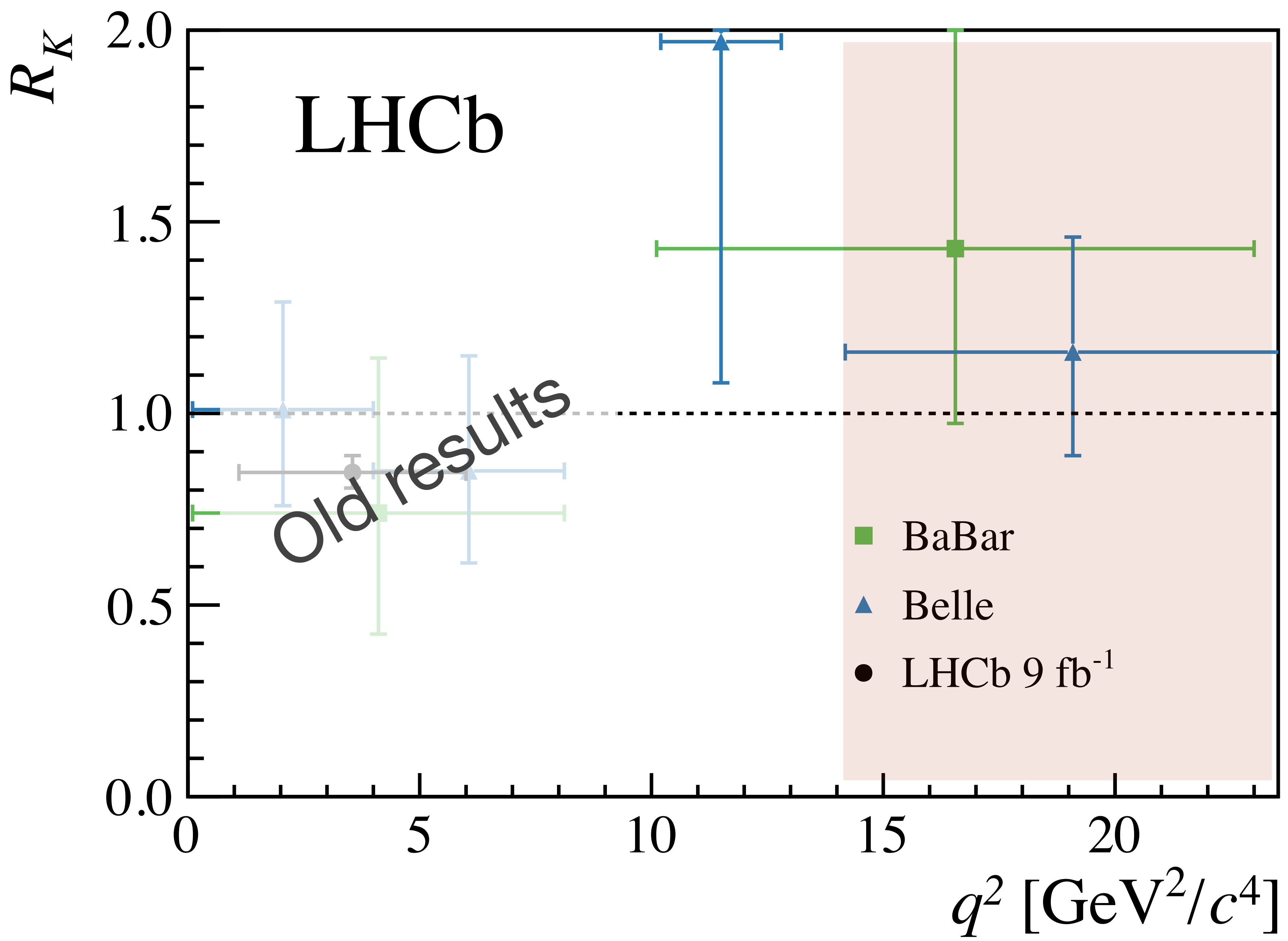


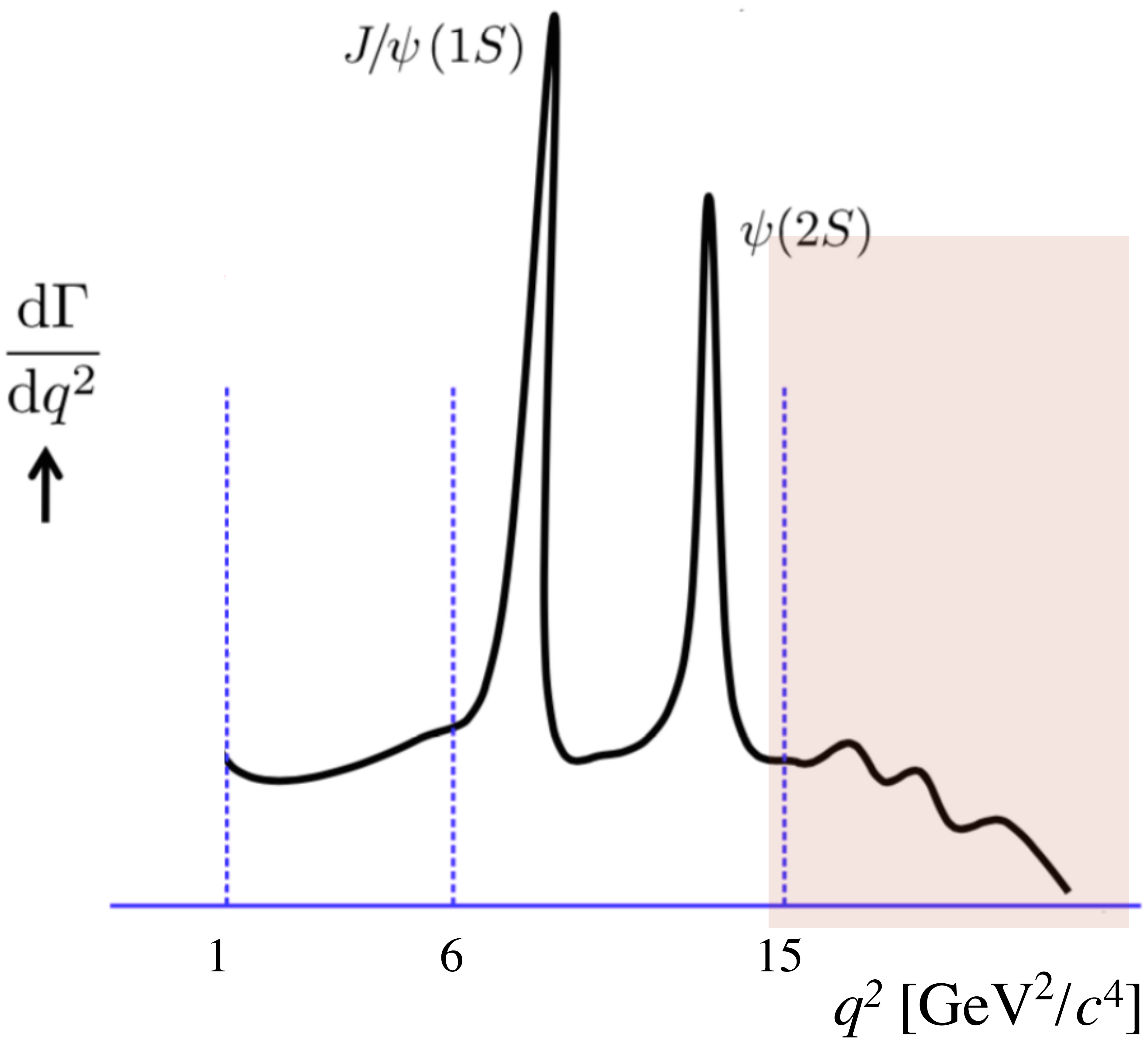


Only have measurements from the *B*-factory experiments at high q^2 (such as Belle and BaBar)

Question: Why hasn't LHCb made measurements of R_K at high q^2 ?

LHCb [arXiv:2103.11769]





R_K measurements

'High q^2' measurements:

- Statistically **independent** measurements with a large yield;

Question: Why hasn't LHCb made measurements of
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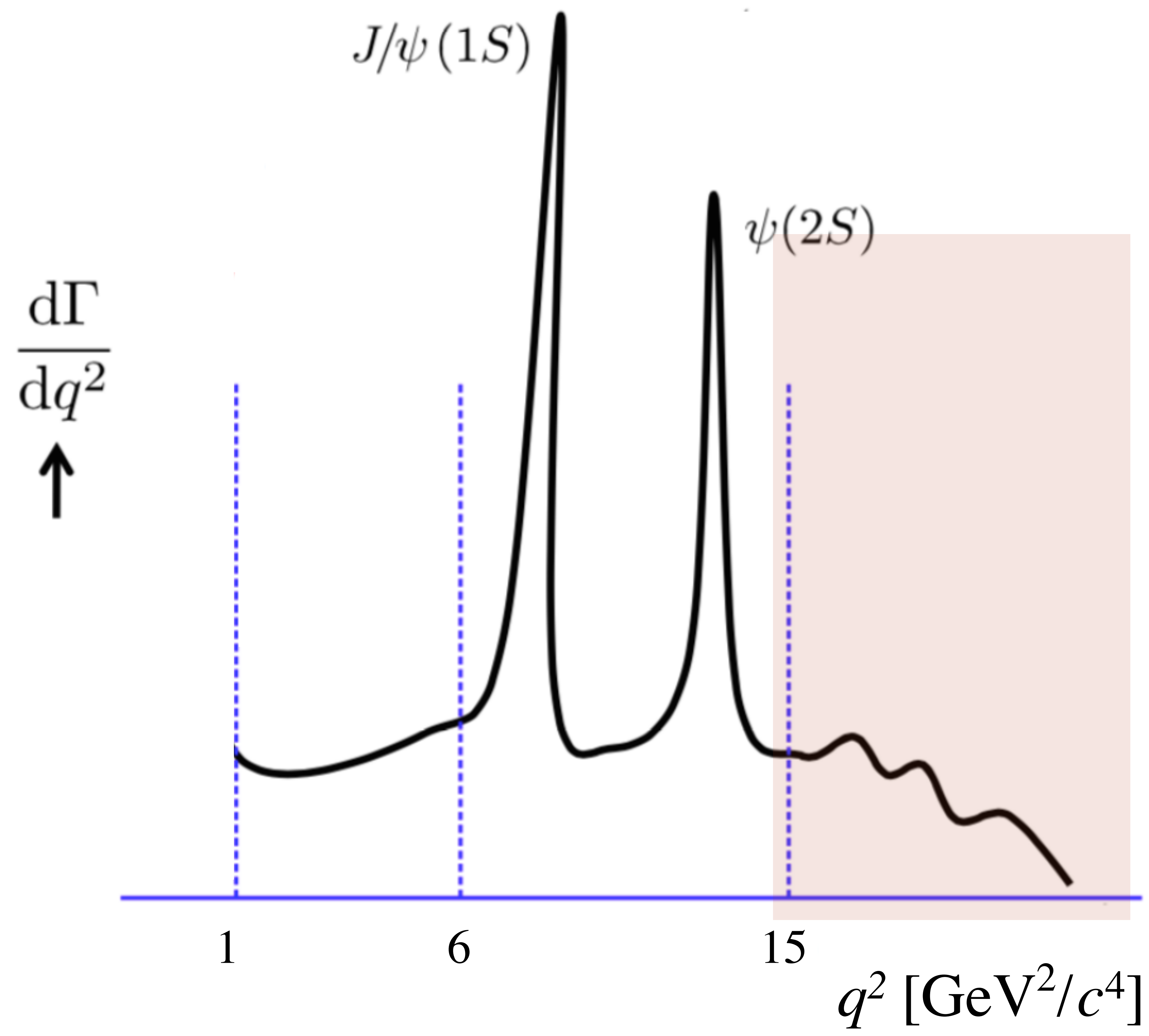


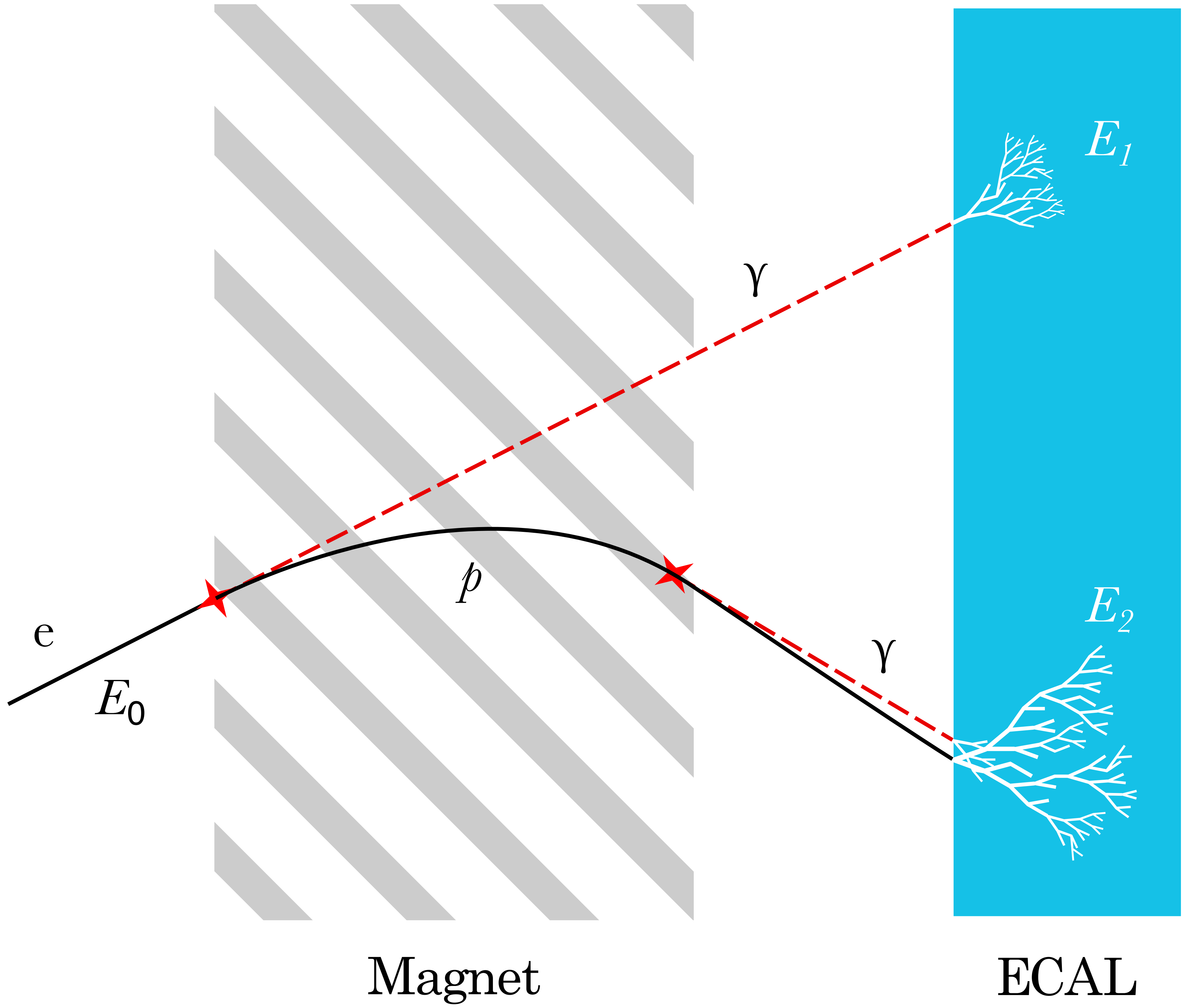
R_K measurements

'High q^2' measurements:

- Statistically **independent** measurements with a large yield;

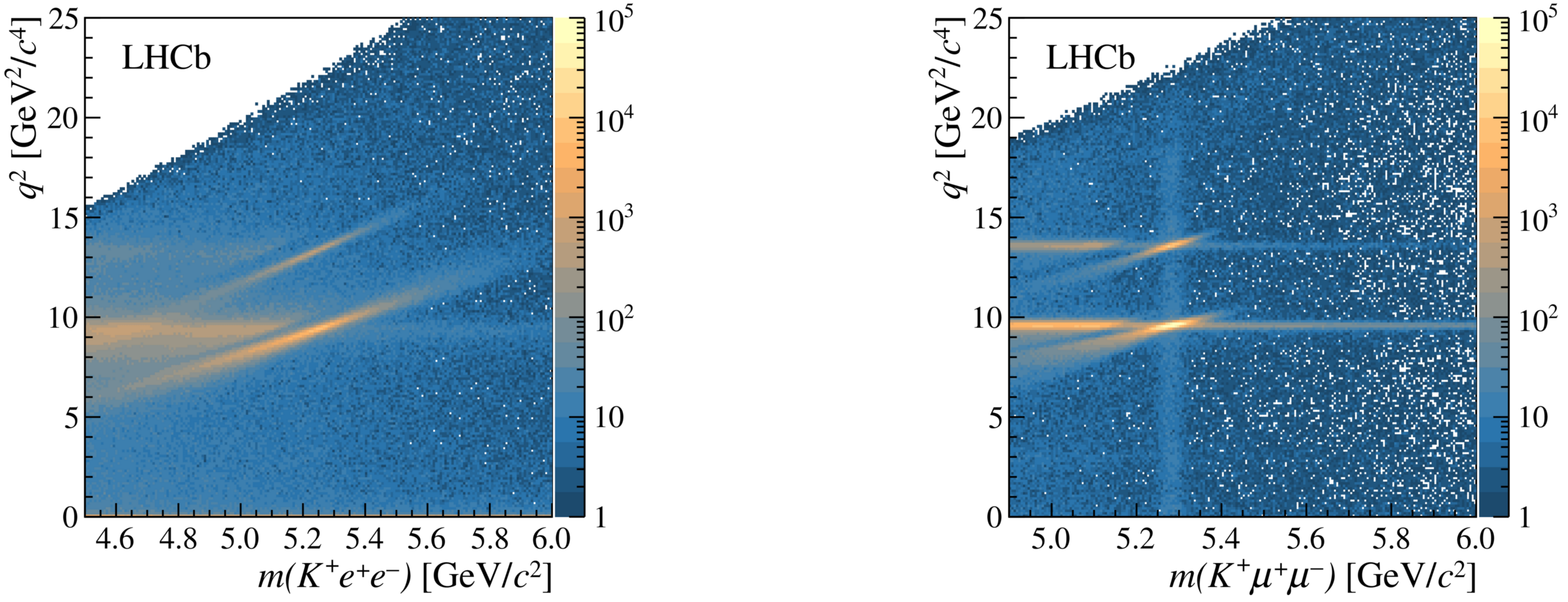
Question: Why hasn't LHCb made measurements of R_K at high q^2 ?

Answer: Bremsstrahlung effects are significant, thus the analysis becomes more difficult to perform.



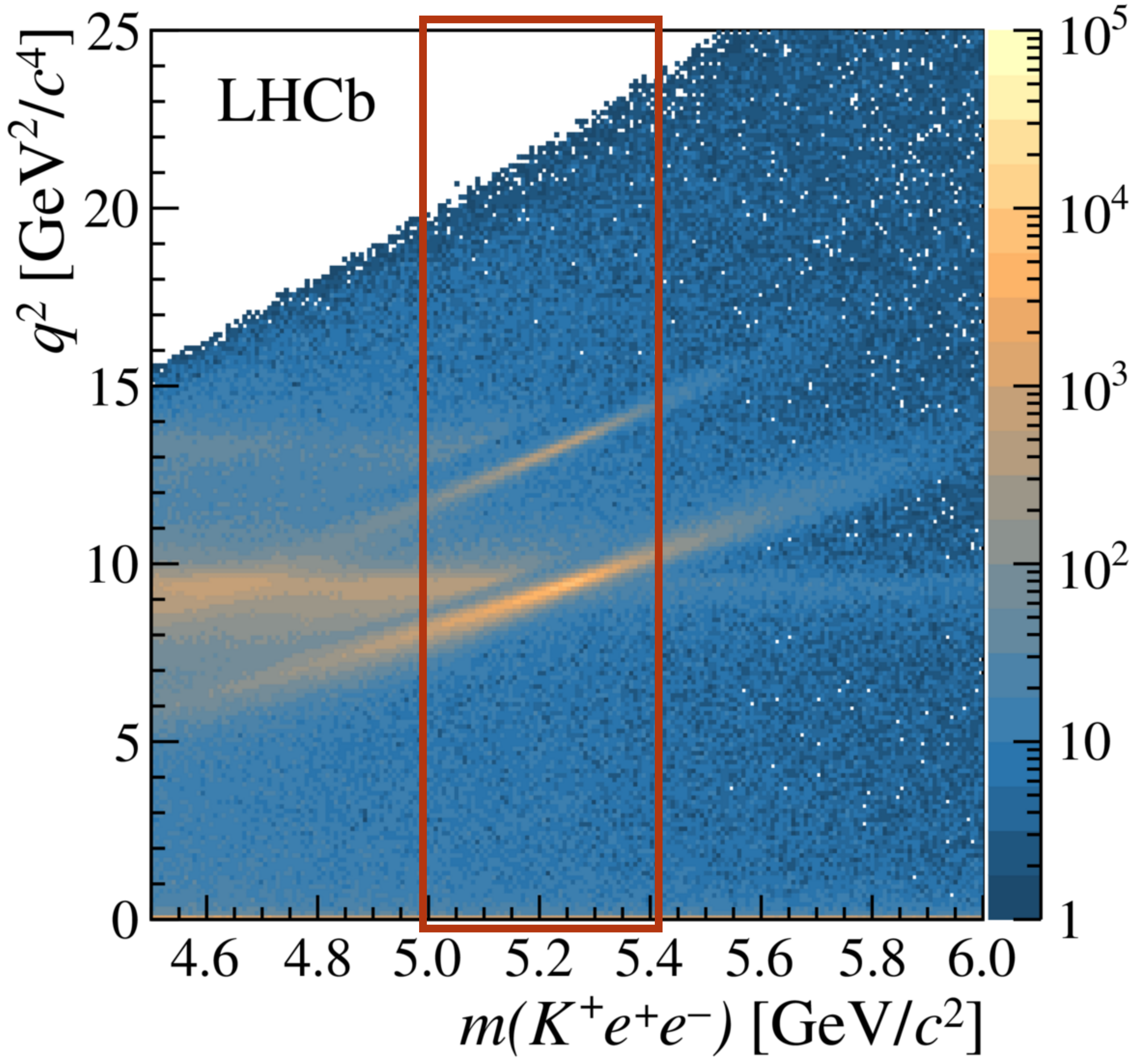
Bremsstrahlung recovery

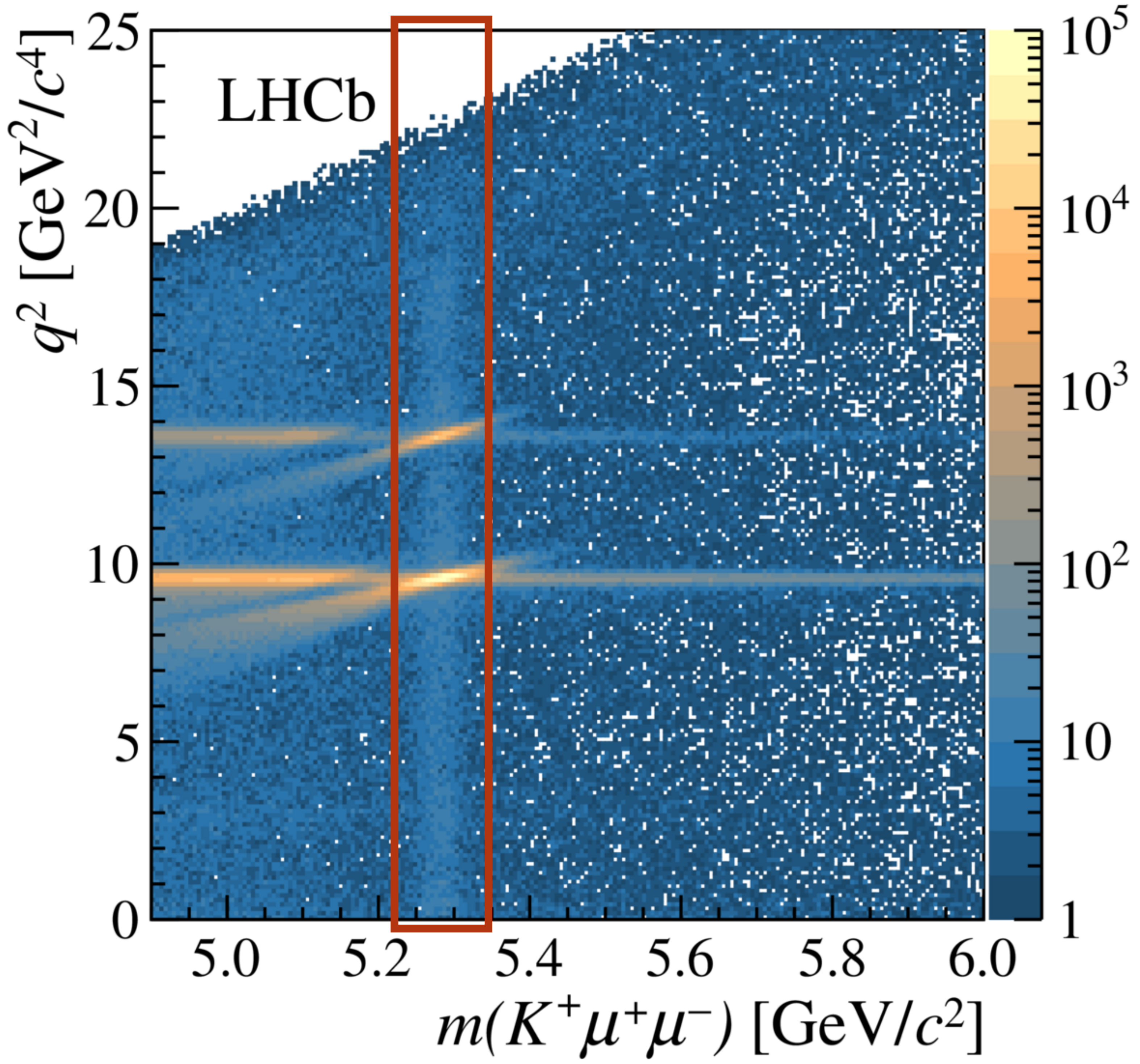
Even after Bremsstrahlung recovery, we see large differences between di-electron and di-muon final states:



Bremsstrahlung recovery

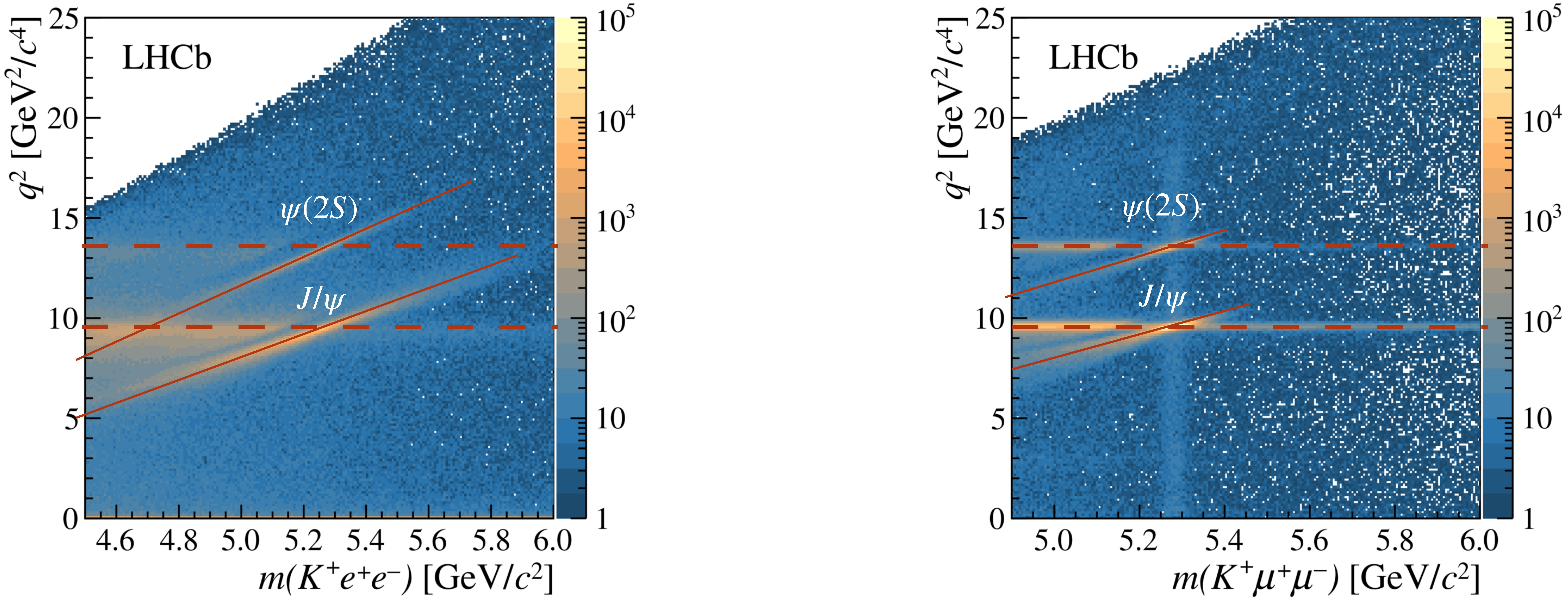
Due to imperfect Bremsstrahlung recovery signal is ‘washed out’ for the electron channel.





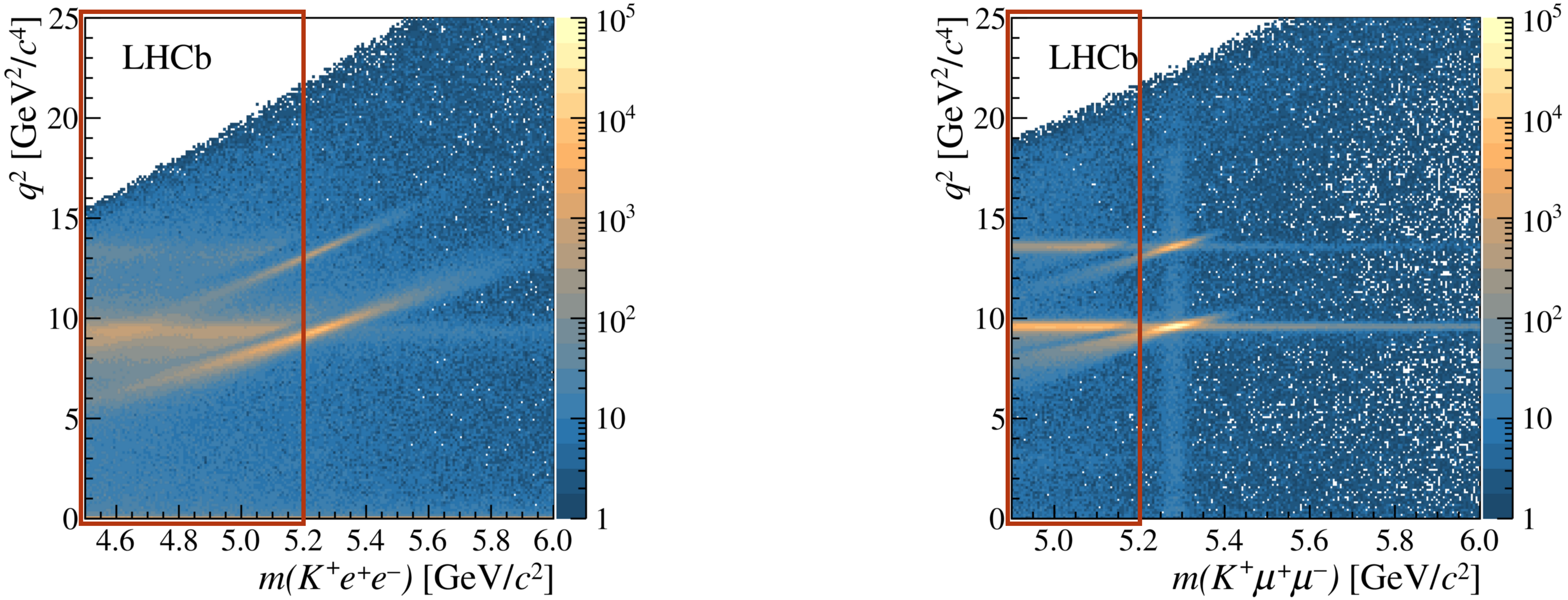
Bremsstrahlung recovery

Narrow charmonium resonances have larger tails for the electron channel due to the imperfect Bremsstrahlung recovery and the energy resolution of the ECAL.

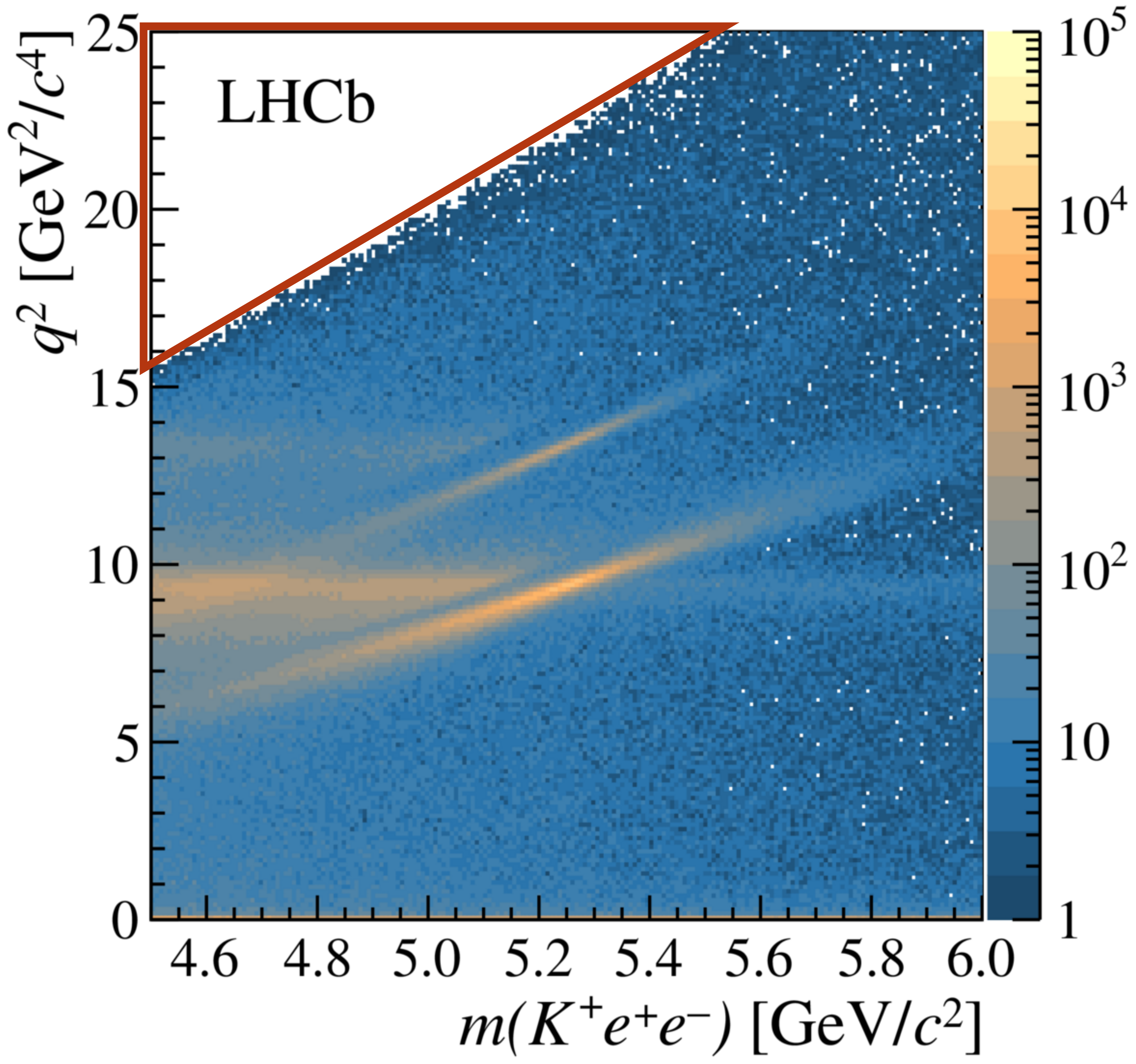


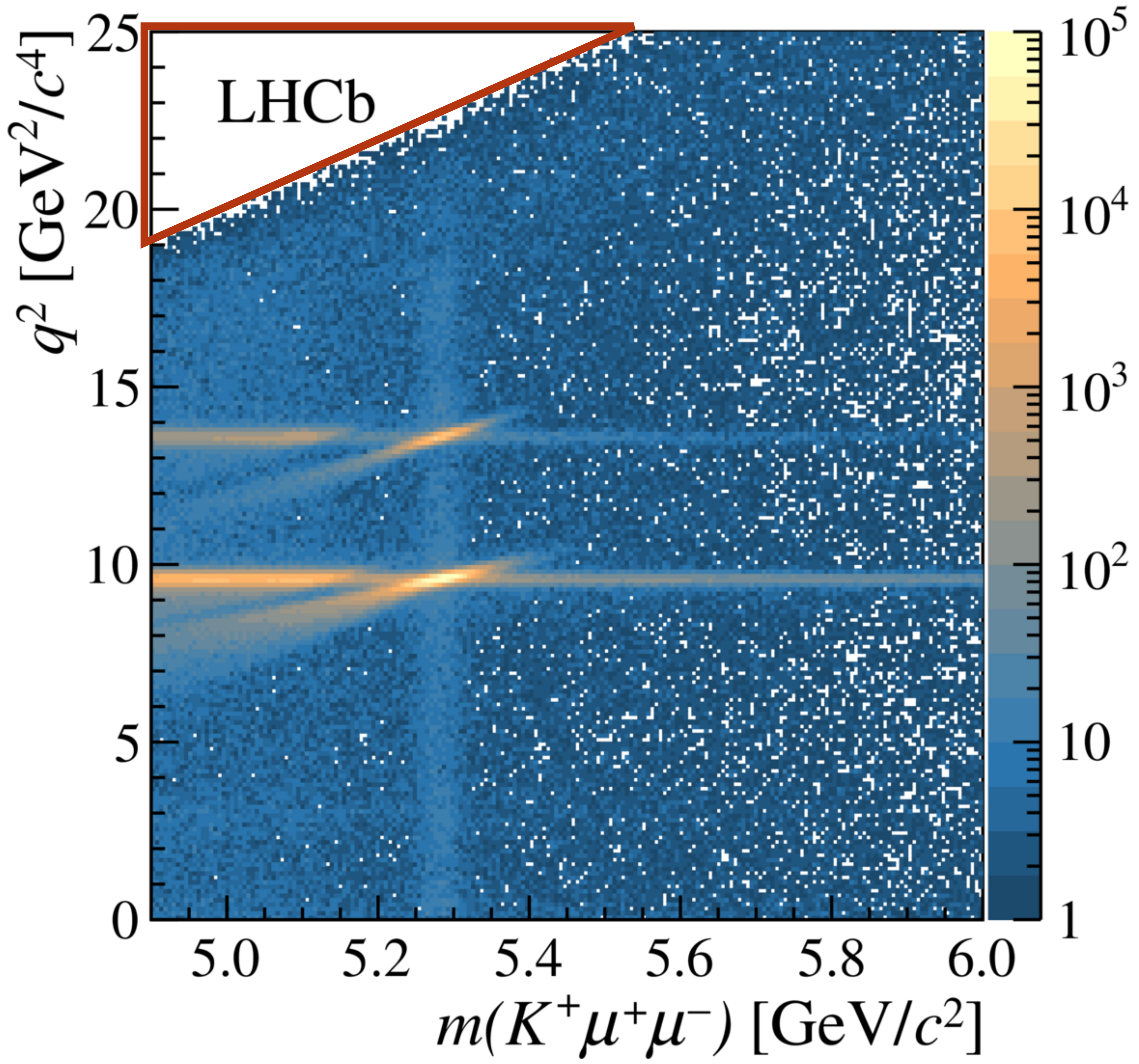
Bremsstrahlung recovery

Partially reconstructed backgrounds are not well separated from the signal for the electron case.



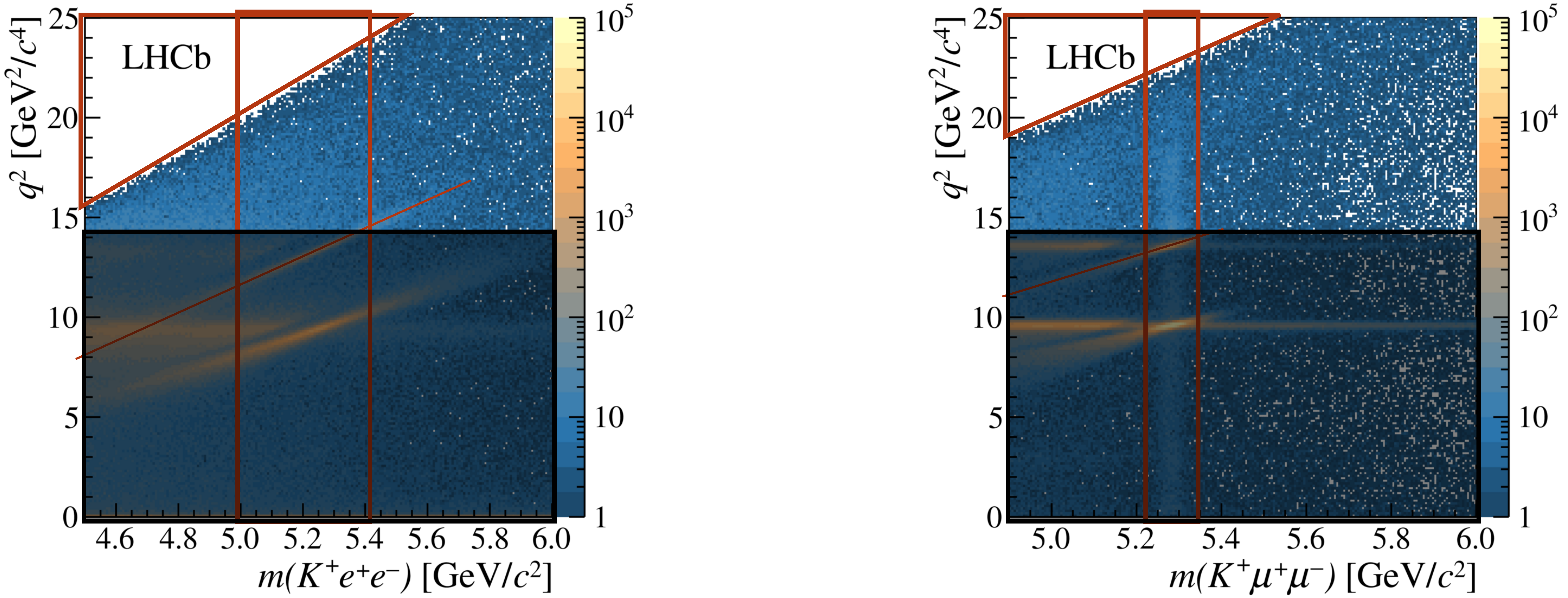
The available phase space distorts combinatorial and partially reconstructed backgrounds.





High q^2 problem

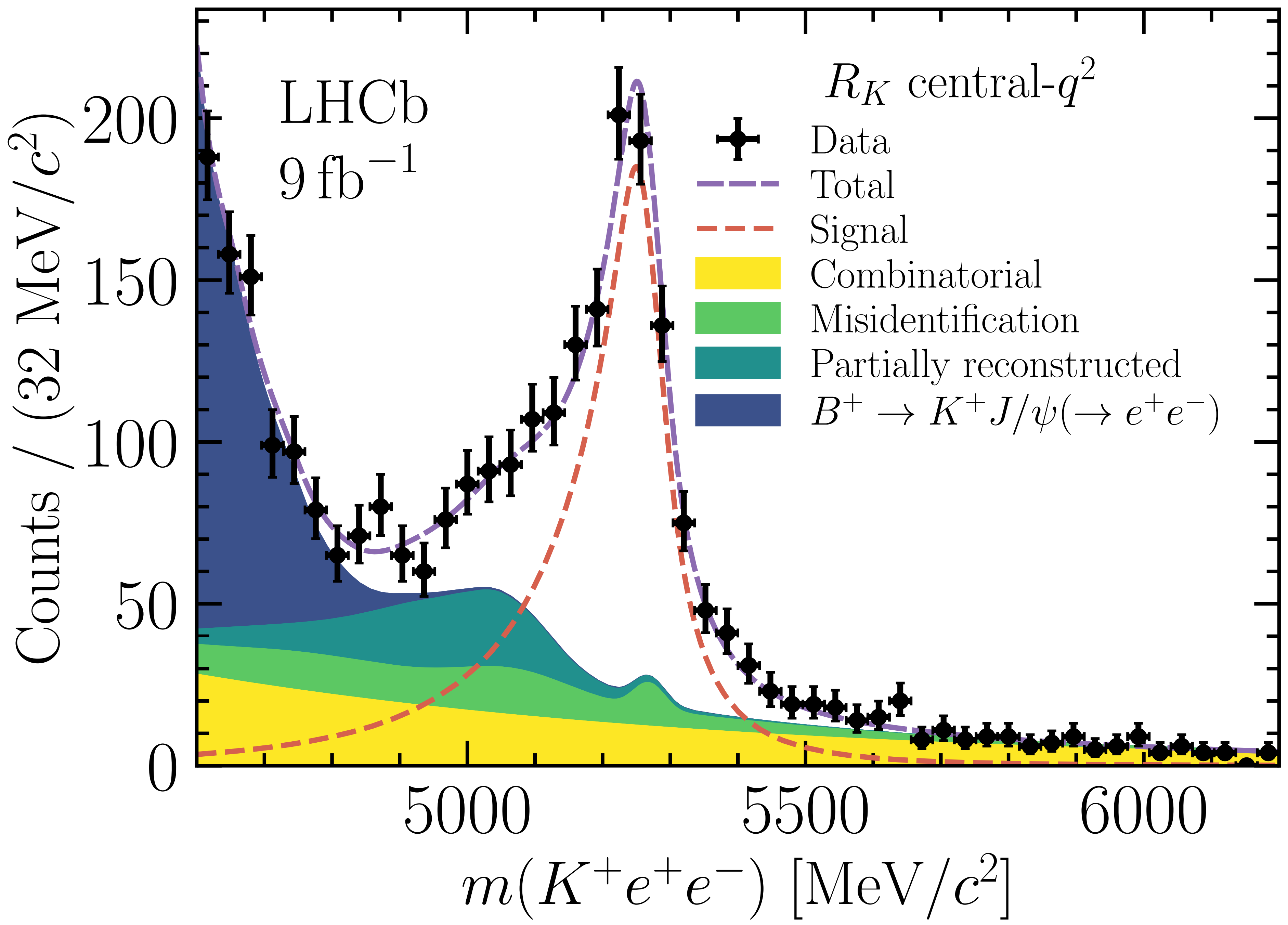
- Di-electron final state is complex due to the $\psi(2S)$ resonance leakage (Bremsstrahlung recovery smears out resonances)
- Di-muon final state is less problematic.



High q^2 problem

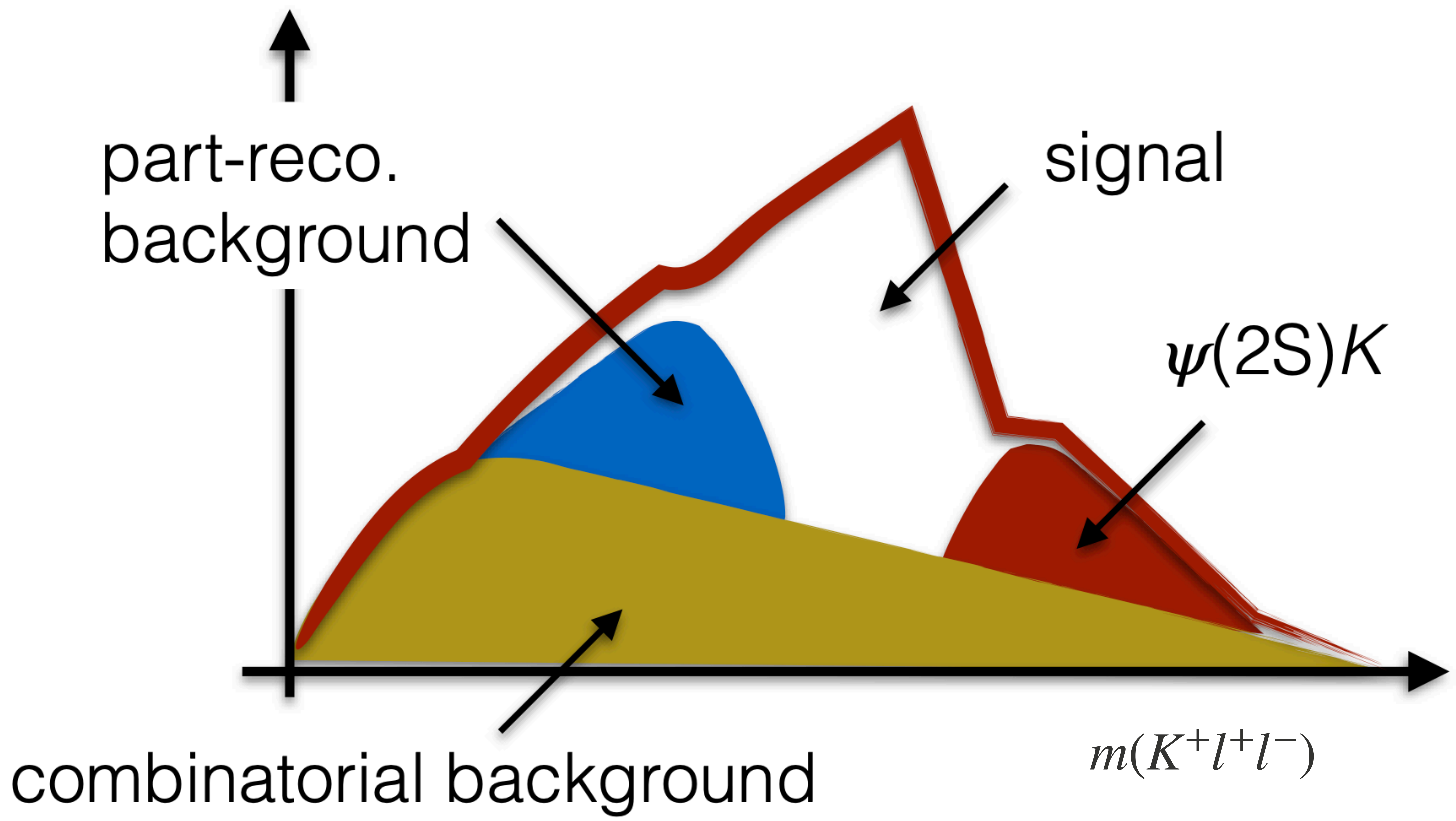
- 'Central q^2' measurements

LHCb [arXiv:2212.09153]



- 'High q^2' measurements:

  It becomes challenging to statistically separate signal from background.



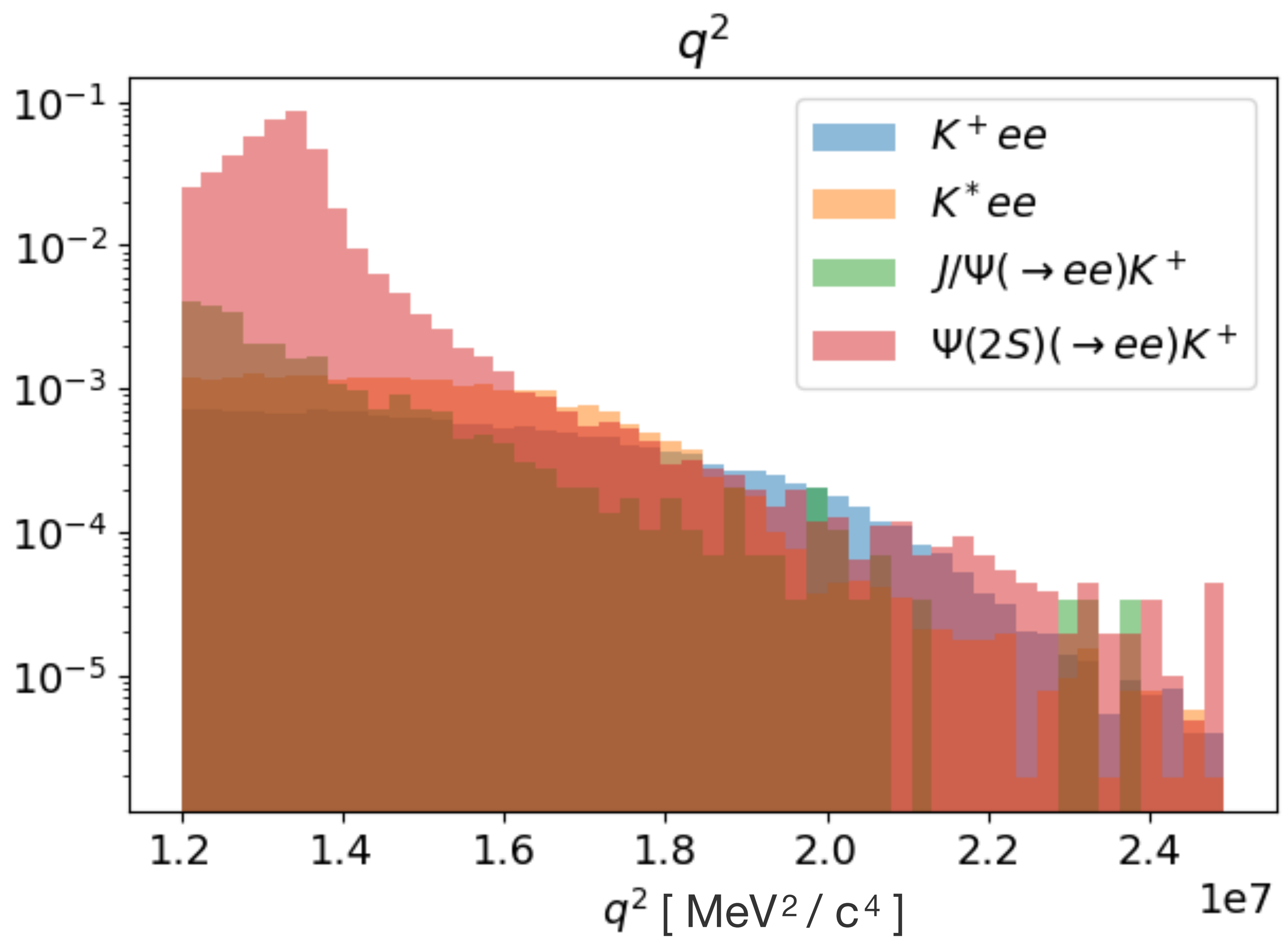
Source

High q^2 problem

Resonances are smeared

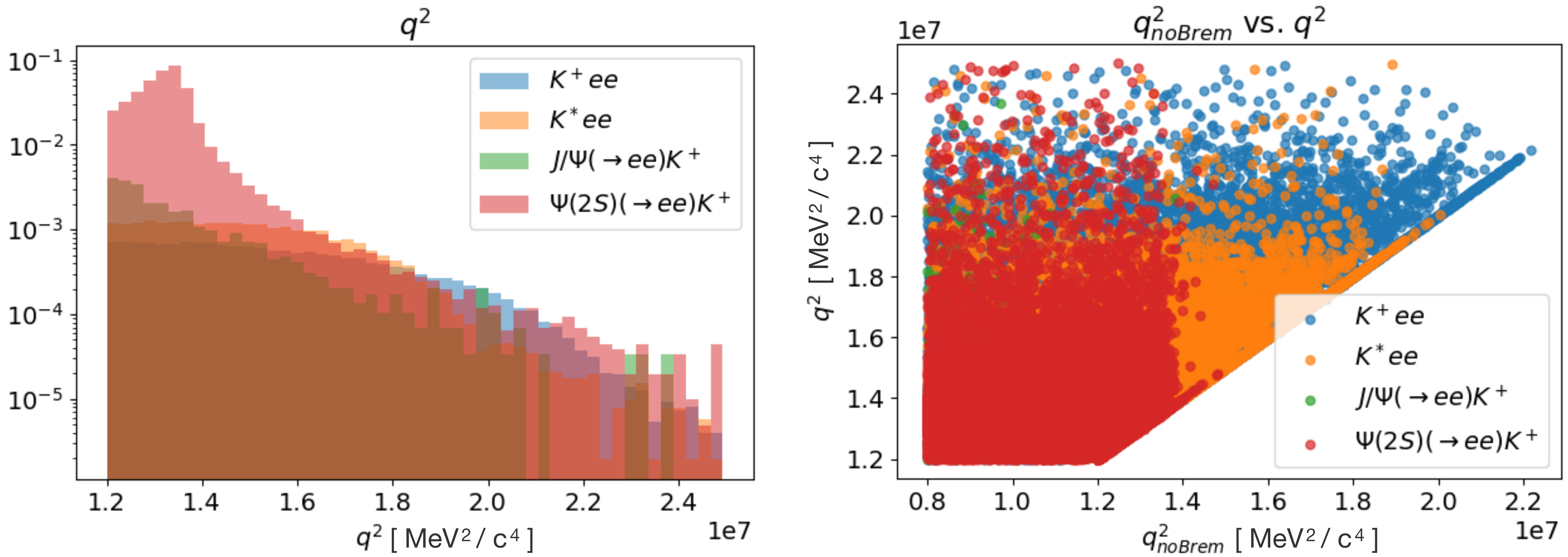
due to the wrong Bremsstrahlung

recovery.



High q^2 solution

Since resonances are smeared due to the wrong Bremsstrahlung recovery:



- $q^2_{no\ Brem.} \equiv$ *dilepton invariant mass (without adding Bremsstrashlung photons) squared*

High q^2 solution

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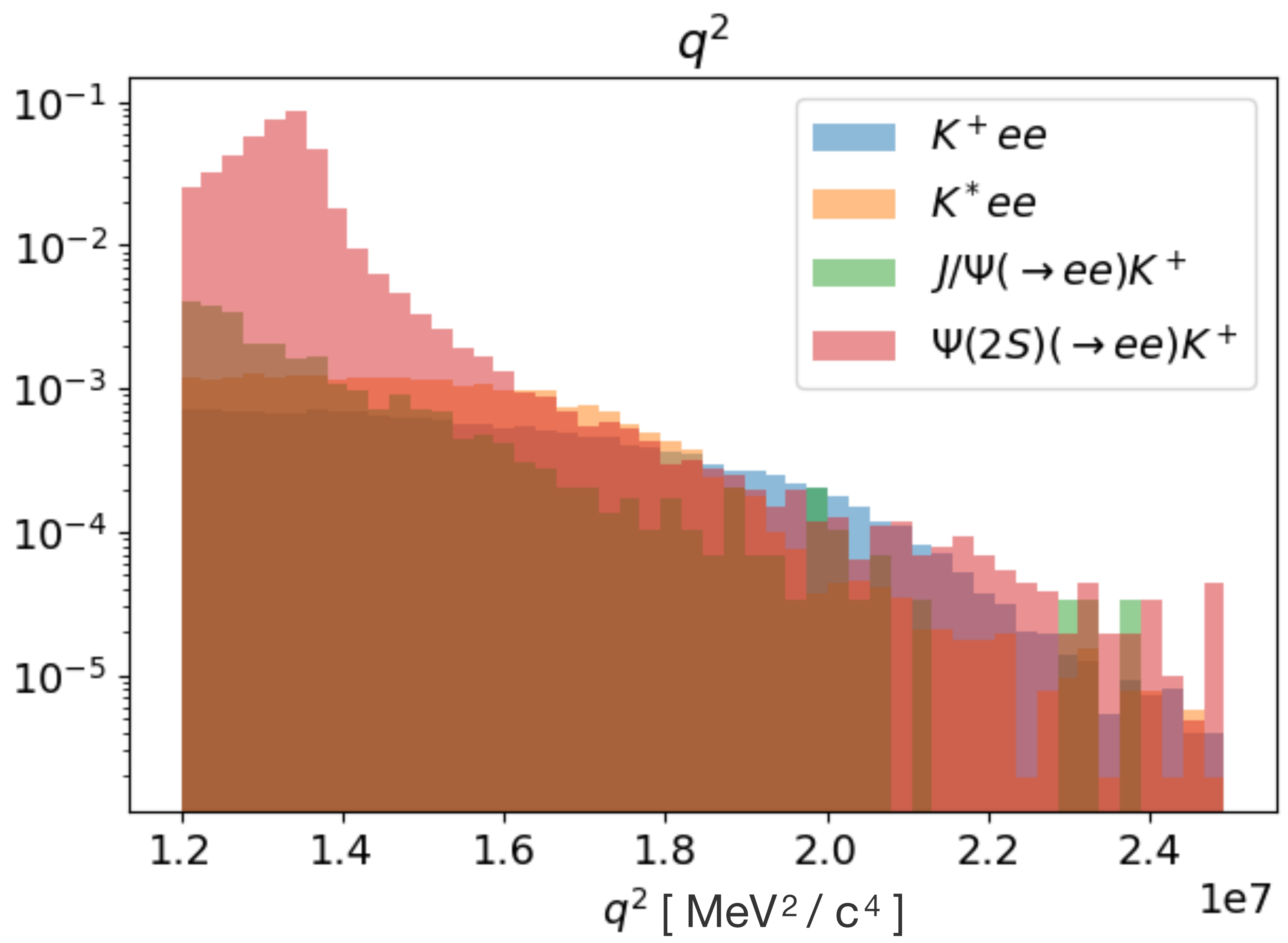
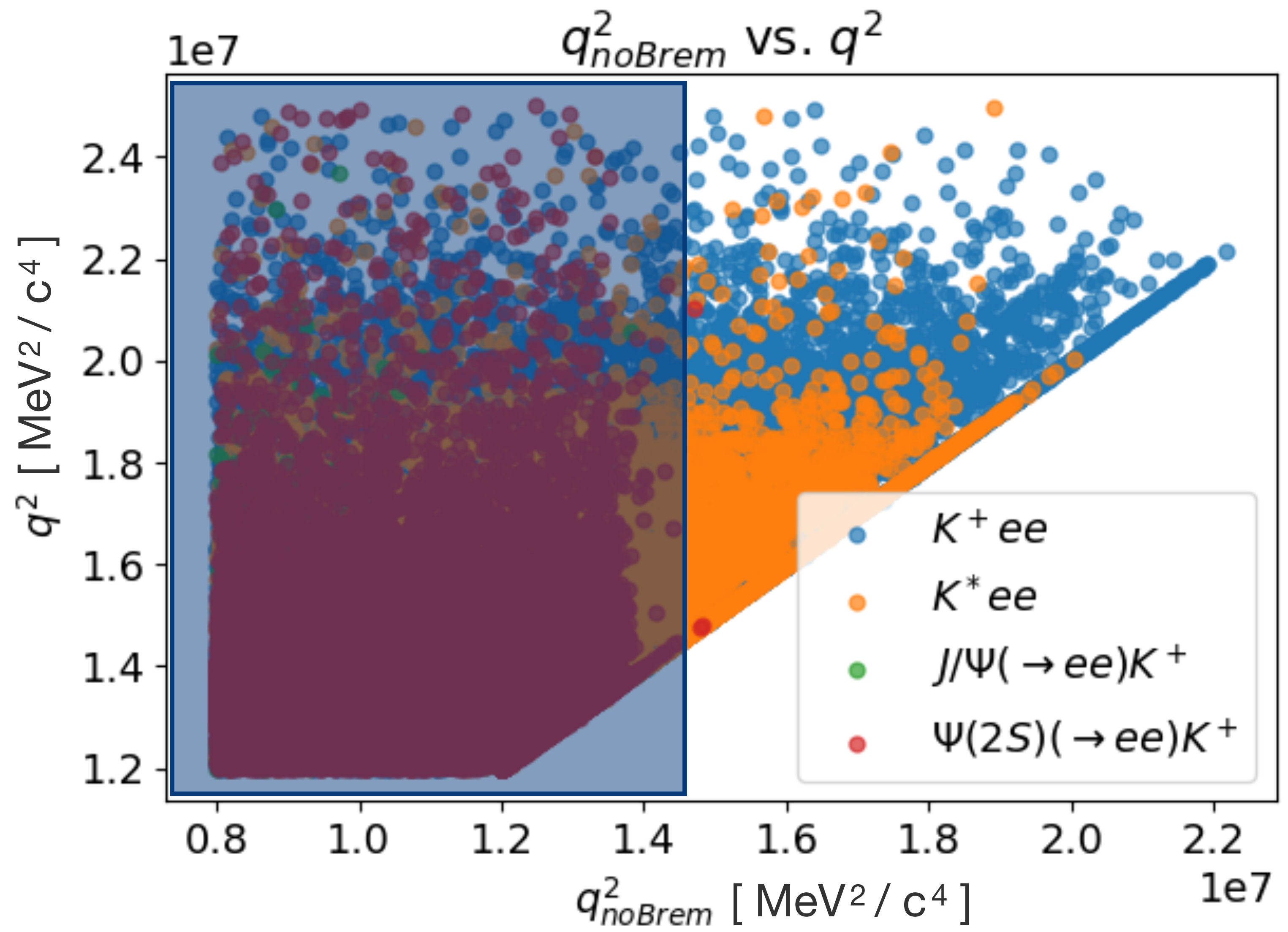
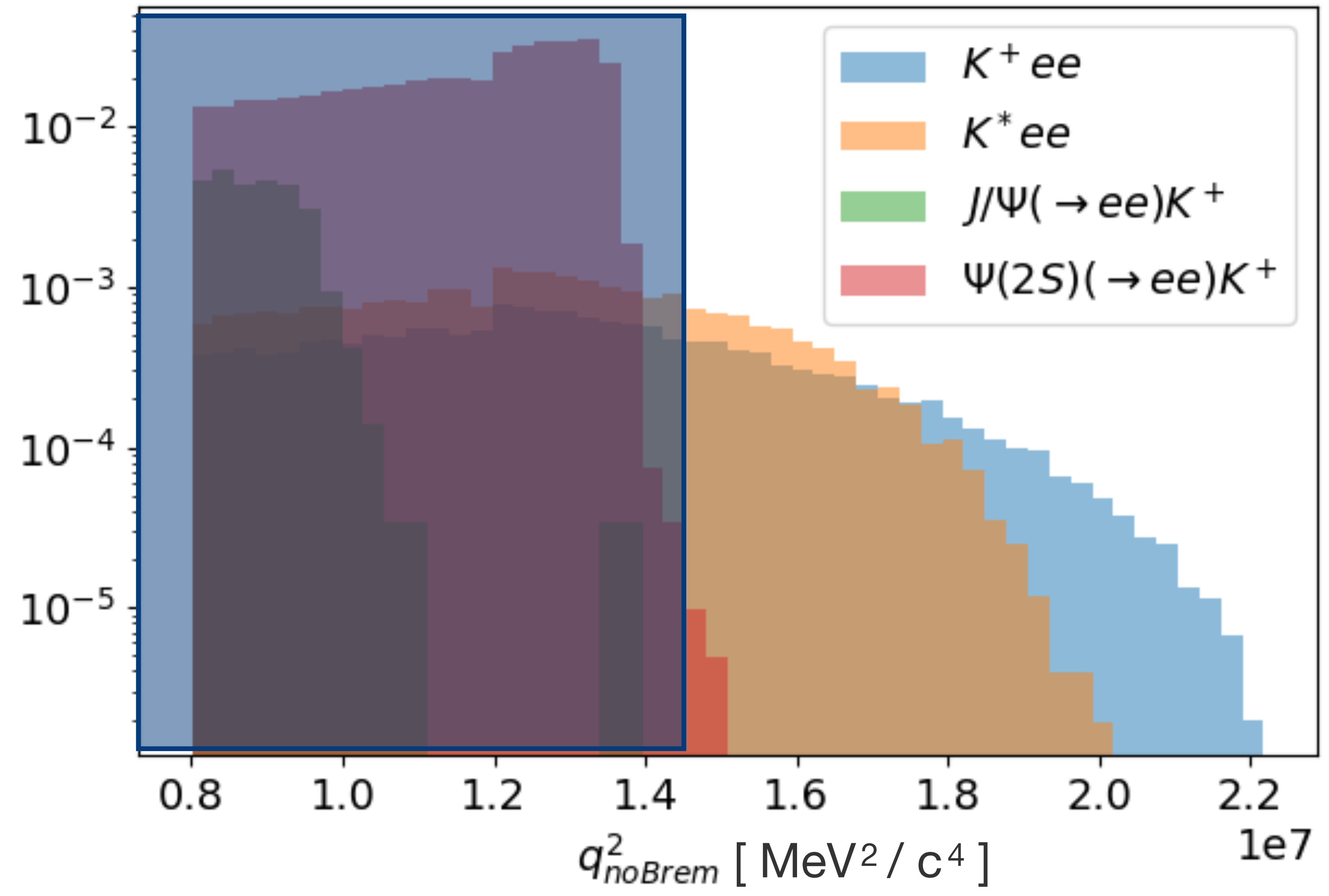


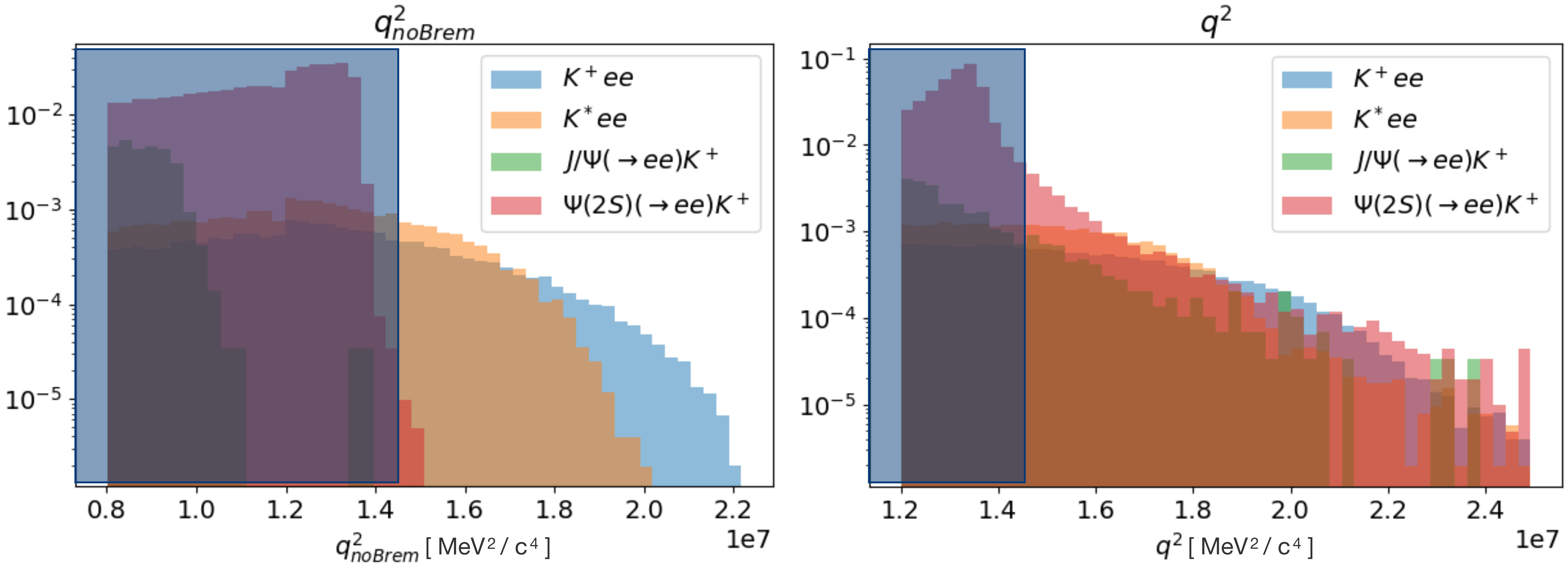


- $q^2_{no\ Brem.}$ is used in order to get rid of the resonance(s)



$q^2_{no\ Brem.}$ cut based signal selection:

- Loose **~ 50%** of signal compared to q^2 cut.



Electron Sensitivity studies

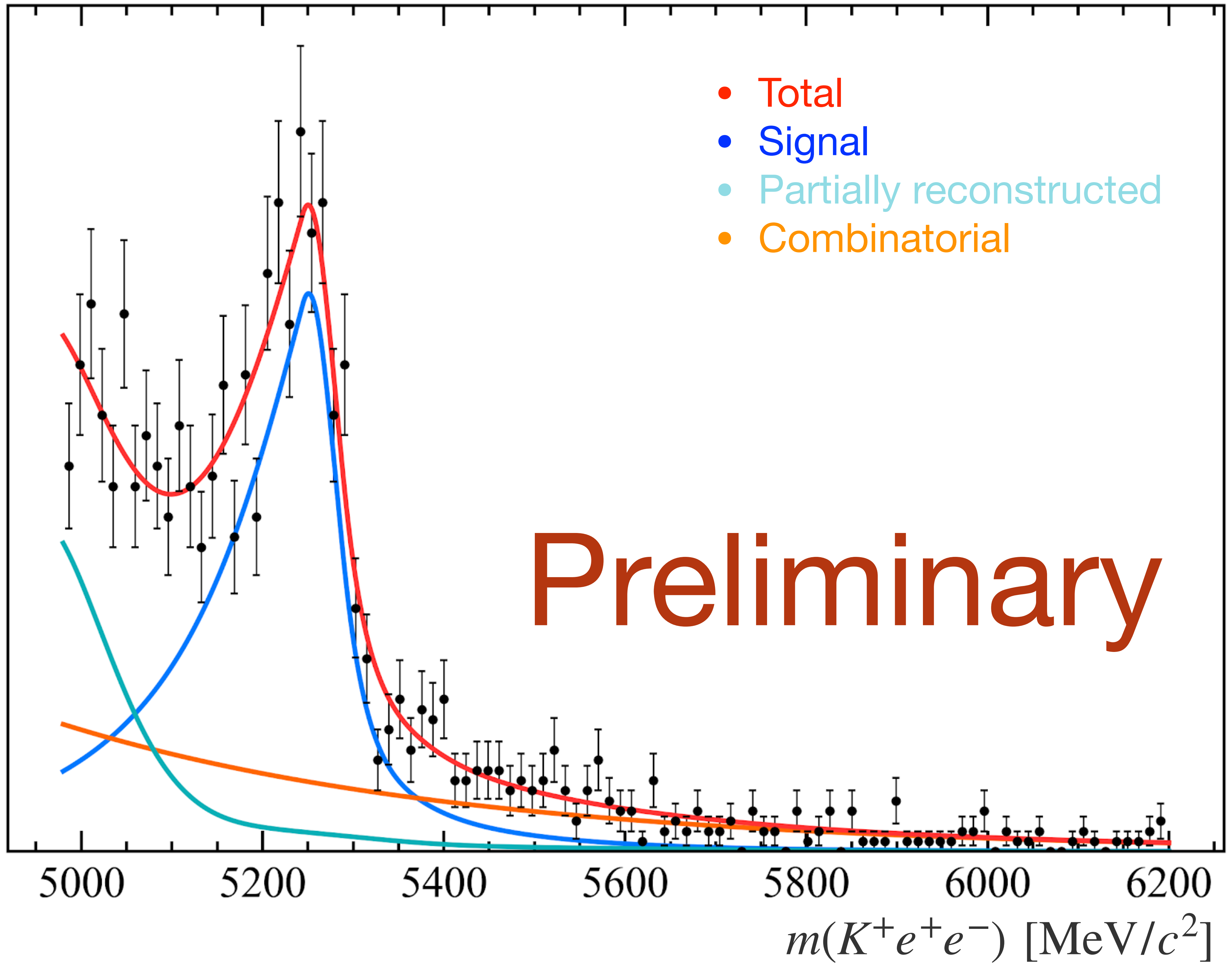
Status: Starting to put different components together

Expect around 800 signal events (~ ½ of Central q^2)

- Signal: sum of 3 DCBs
  - Signal shape parameters fixed from simulation;
  - Brem. fractions are gaussian constrained to the fraction observed in MC;
  - Mean shift and scales are fixed from the simulation;
- Part. Reco.: KDE
- Comb.: Exponential (shape to be studied)

The total model was obtained by summing the PDFs with the relative fraction obtained from the simulation.

Fit to toy model. Run1 + Run2 stats (9 fb^{-1}).



- Full selection and $q^2_{no\ Brem.} > 14\ \mathrm{GeV}^2$
- Hlt and L0 eTOS
- PID cut corrected with weights (DLLe > 4)
- Combinatorial BDT cut and fit range

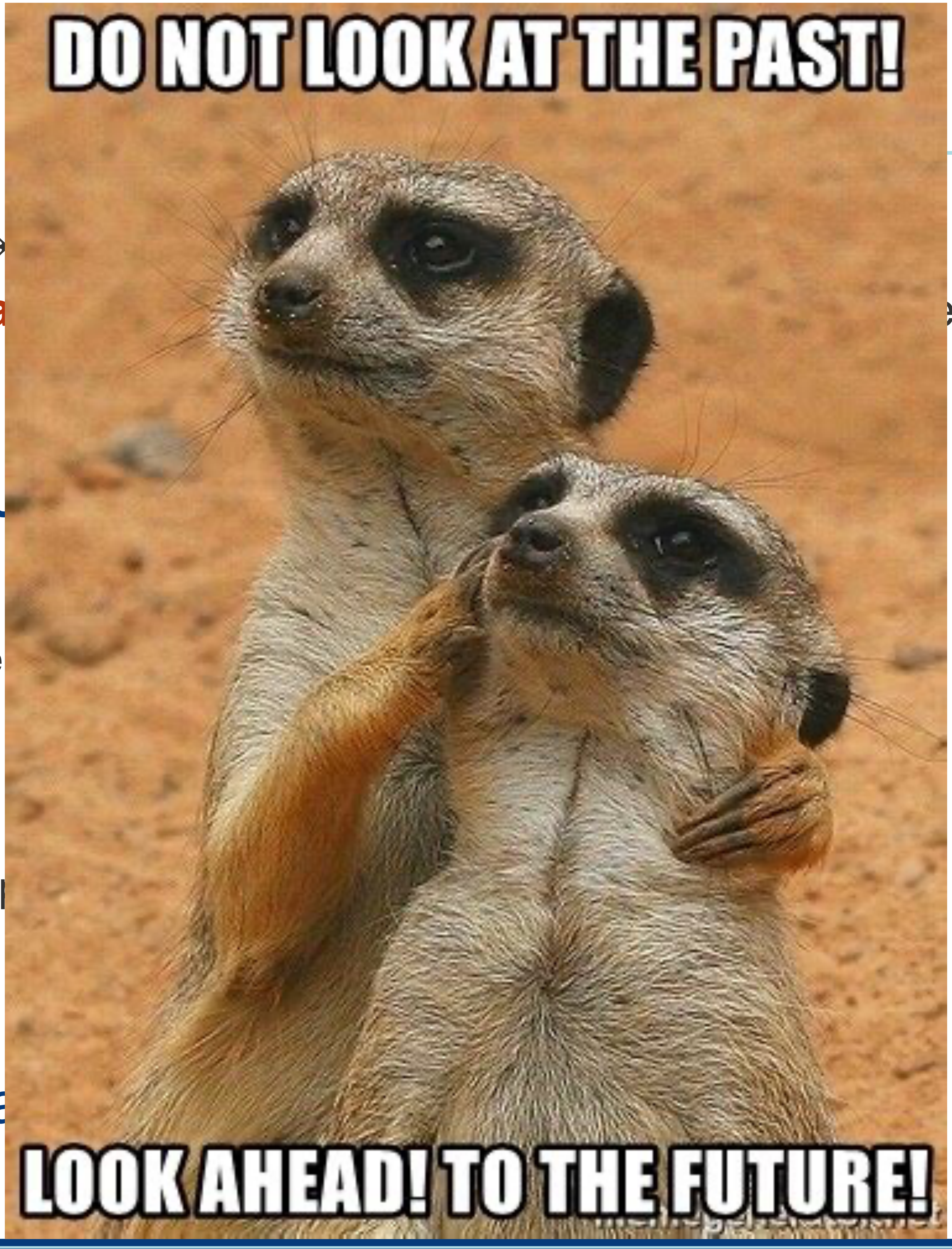
Summary

The latest results in $B^+ \to K^+ l^+ l^-$ decays have been **shown** by LHCb to be consistent with Standard Model, but the result is **statistically limited**. To further investigate further, **more studies** are **required**.

- Measurement of the **LFU ratio** R_K in the **'high q^2'** region:
  - **first** LHCb measurement in this particular region;
  - using the **entire** available dataset (9 fb^{-1});
  - statistically **independent** result;
  - **high** yield;
  - **complementary** phase space;

Work in progress. Stay tuned for further updates :)

Summary

The latest results in $B^+ \to$ 

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  - **first** LHCb measurement
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  - **high** yield;
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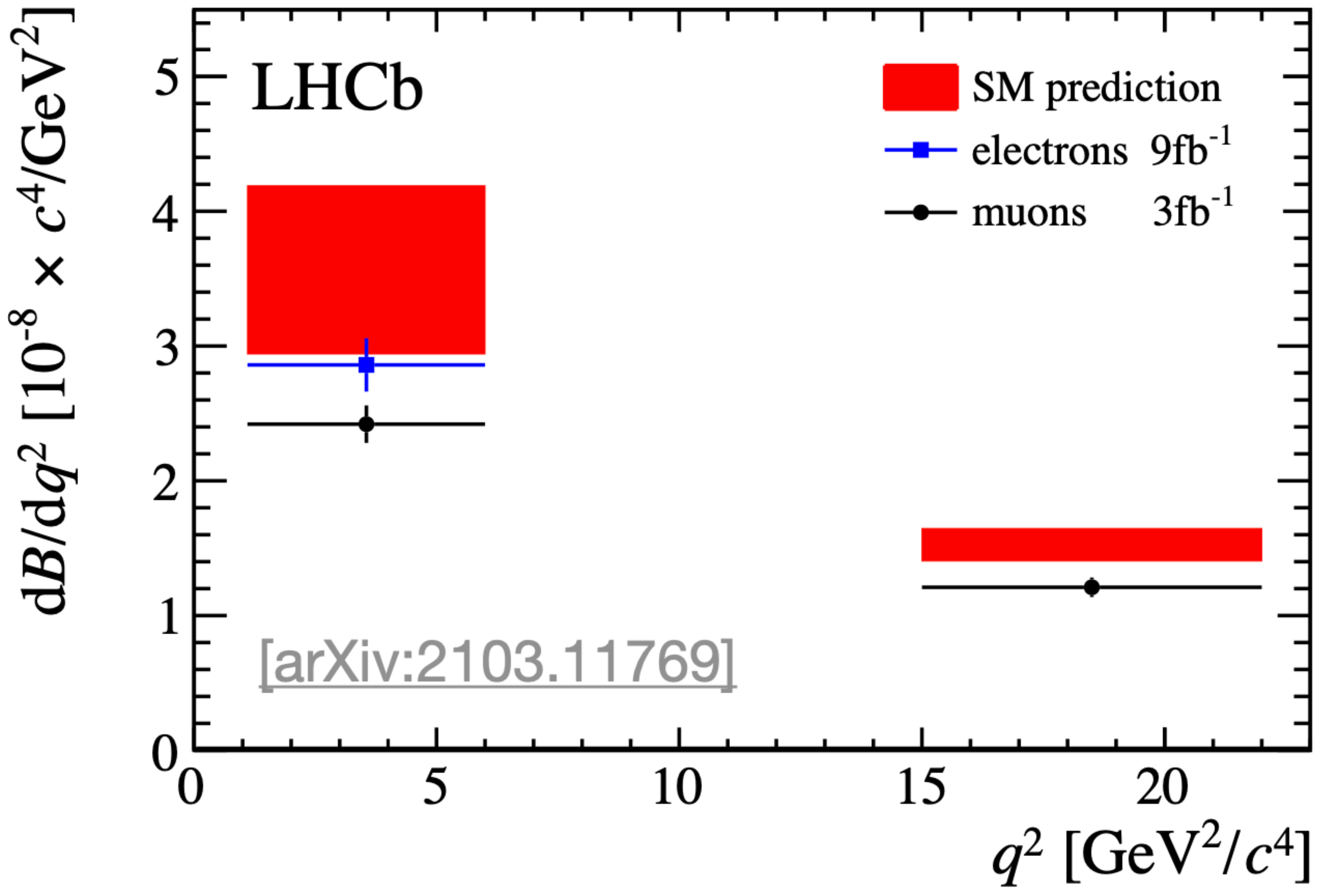
Work in progress. Sta

Thanks for your attention

Combining the measured R_K value with $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ result from [JHEP 06 (2014) 133] gives:

$$\int_{q^2=1.1\ \mathrm{GeV}^2}^{q^2=6\ \mathrm{GeV}^2} \frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2} dq^2 = (28.6^{+1.5}_{-1.4}\ (\mathrm{stat.})\ \pm 1.3\ (\mathrm{syst.})\ ) \times 10^{-9}$$

- Suggesting that electrons are more SM-like than muons.



D. Lancierini (Universität Zürich) talk