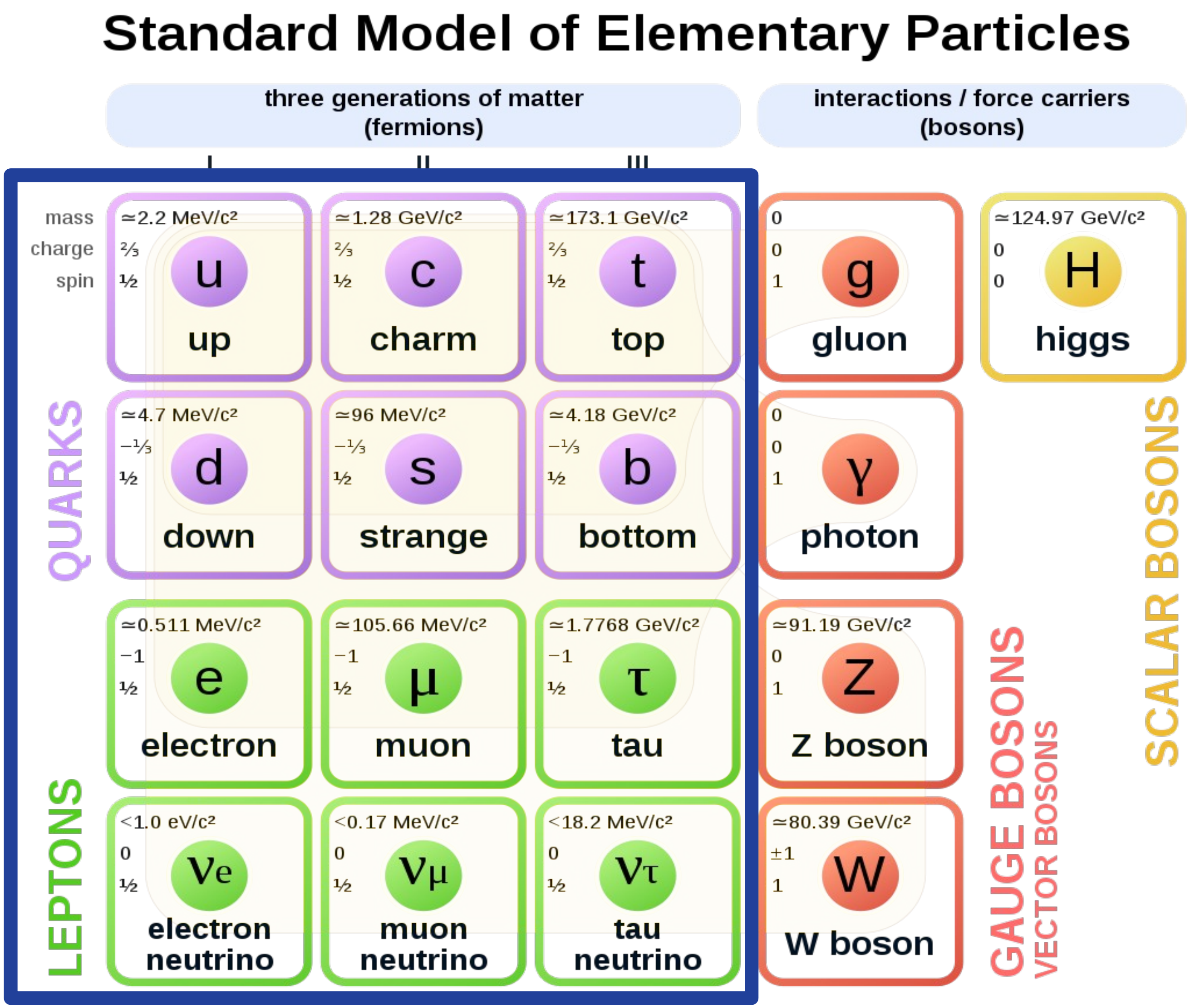
Study of lepton flavour universality in semileptonic B meson decays at LHCb

Anton Poluektov

Aix-Marseille Univ., CNRS/IN2P3, CPPM

Ph. D project by Vlad George DEDU (CPPM, LHCb) supported by IPhU

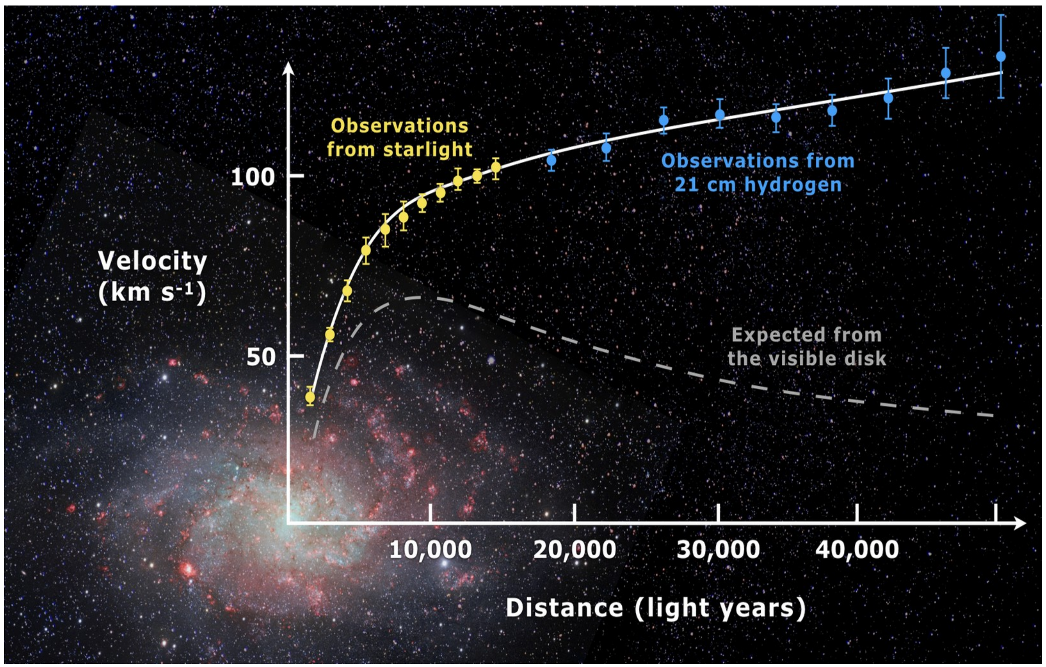


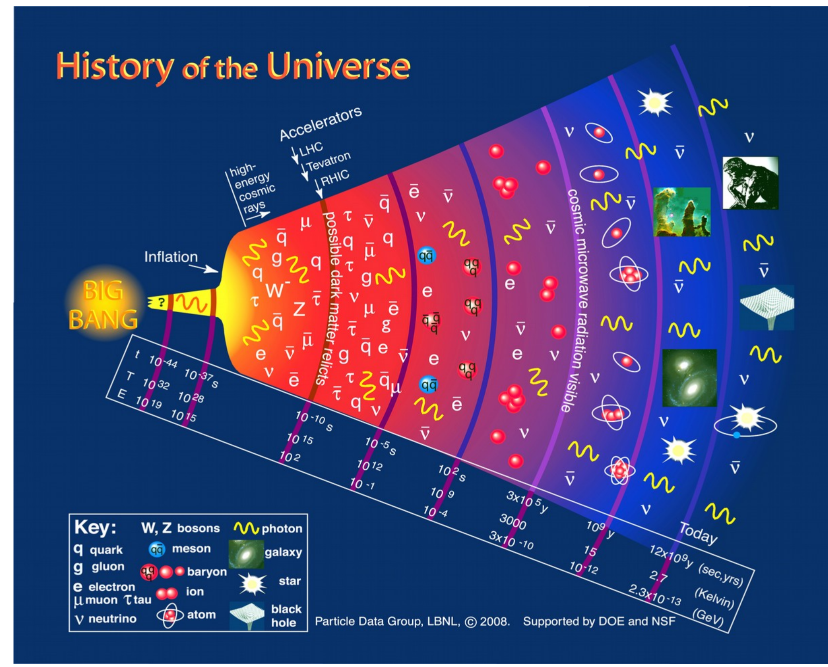
Flavour physics

Study the processes (decays, production) involving hadrons (particles made of quarks) and leptons.

Beyond the Standard Model?

We know that Standard Model is incomplete, for instance:





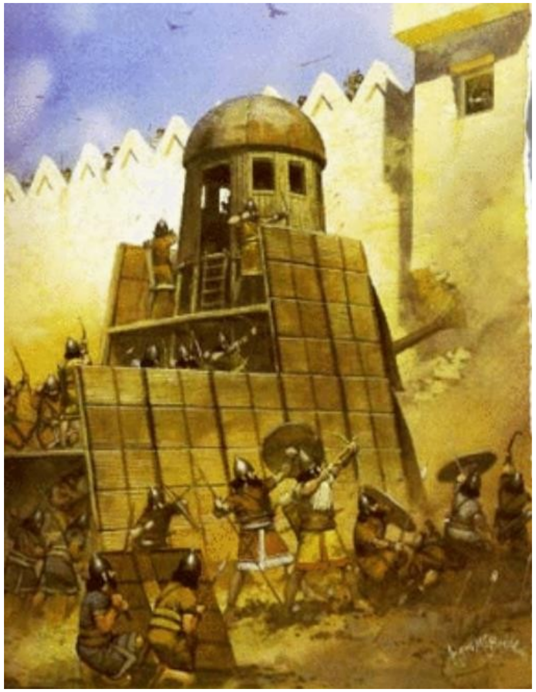
No Dark Matter candidate

Not enough matter/antimatter difference (*CP violation*)

Searches for New Physics

Direct

- Search heavy new particles directly in high-energy collisions



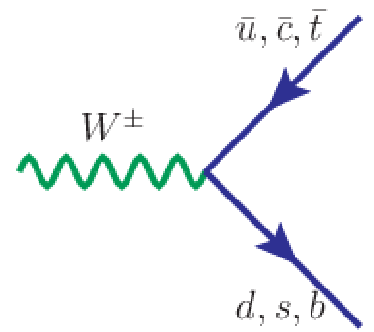
Indirect

- Search for effects of new particles in precise measurements of low-energy processes

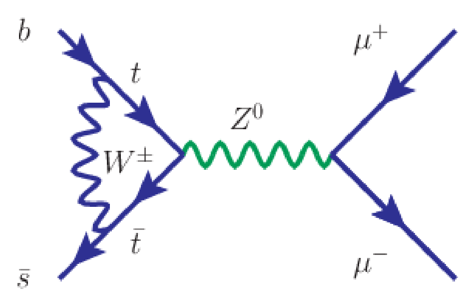
$\Rightarrow$ **Flavour physics approach**

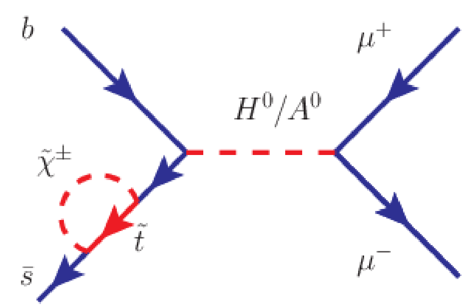
B hadron decays

- Weak decays of hadrons are a sensitive probe for "New Physics"
  - Especially the hadrons containing 3rd-generation *b* ("beauty") quark: B^0 ($b\bar{d}$), B^- ($b\bar{u}$), B_s ($b\bar{s}$), B_c ($b\bar{c}$), Λ_b (bud), *etc.*
- In SM, the only interaction that changes quark flavour is charged weak current:



- Weak decays of hadrons:
  "New Physics" may affect them



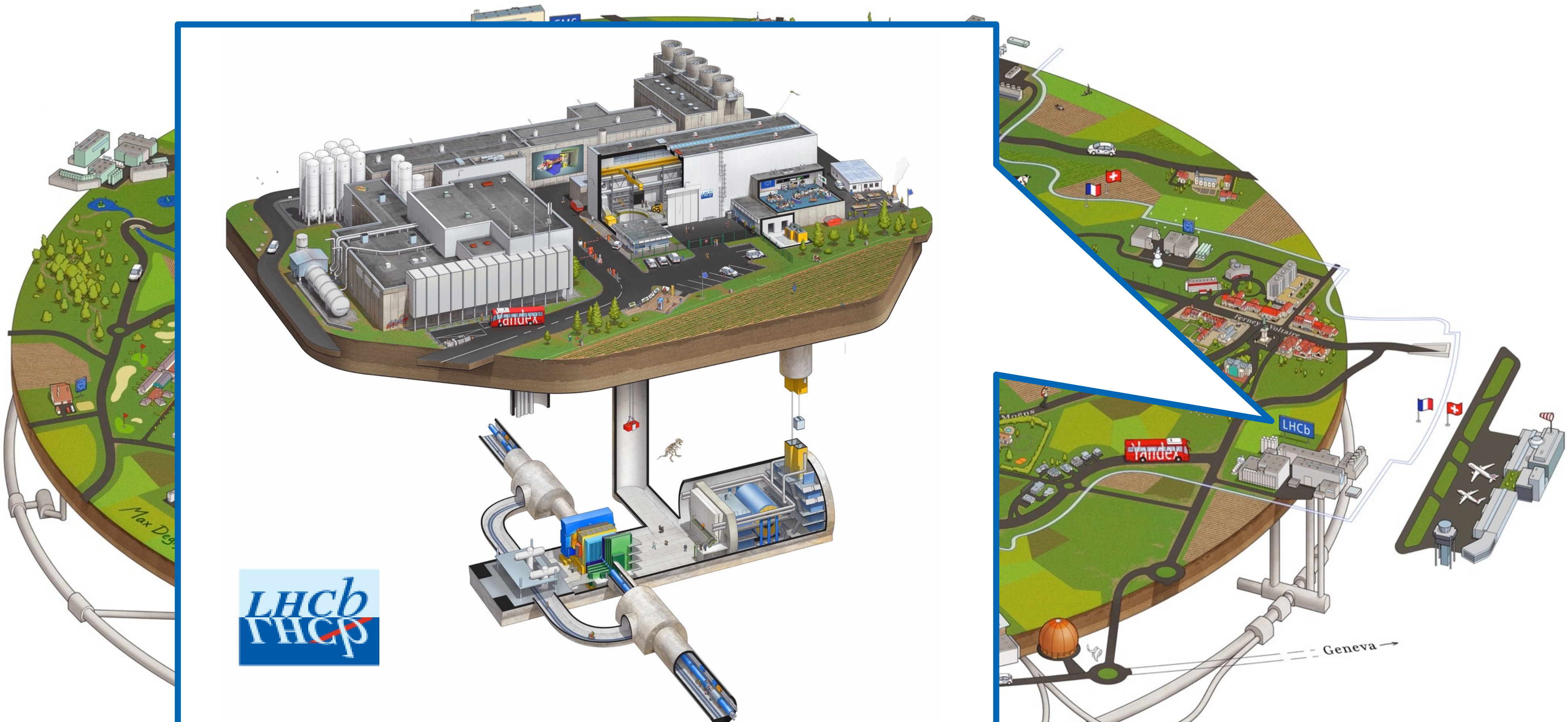


Experimental facilities: LHC

27 km circumference, ~100 m underground, Franco-Swiss border near Geneva

Proton-proton collisions, 13 TeV c.m. energy

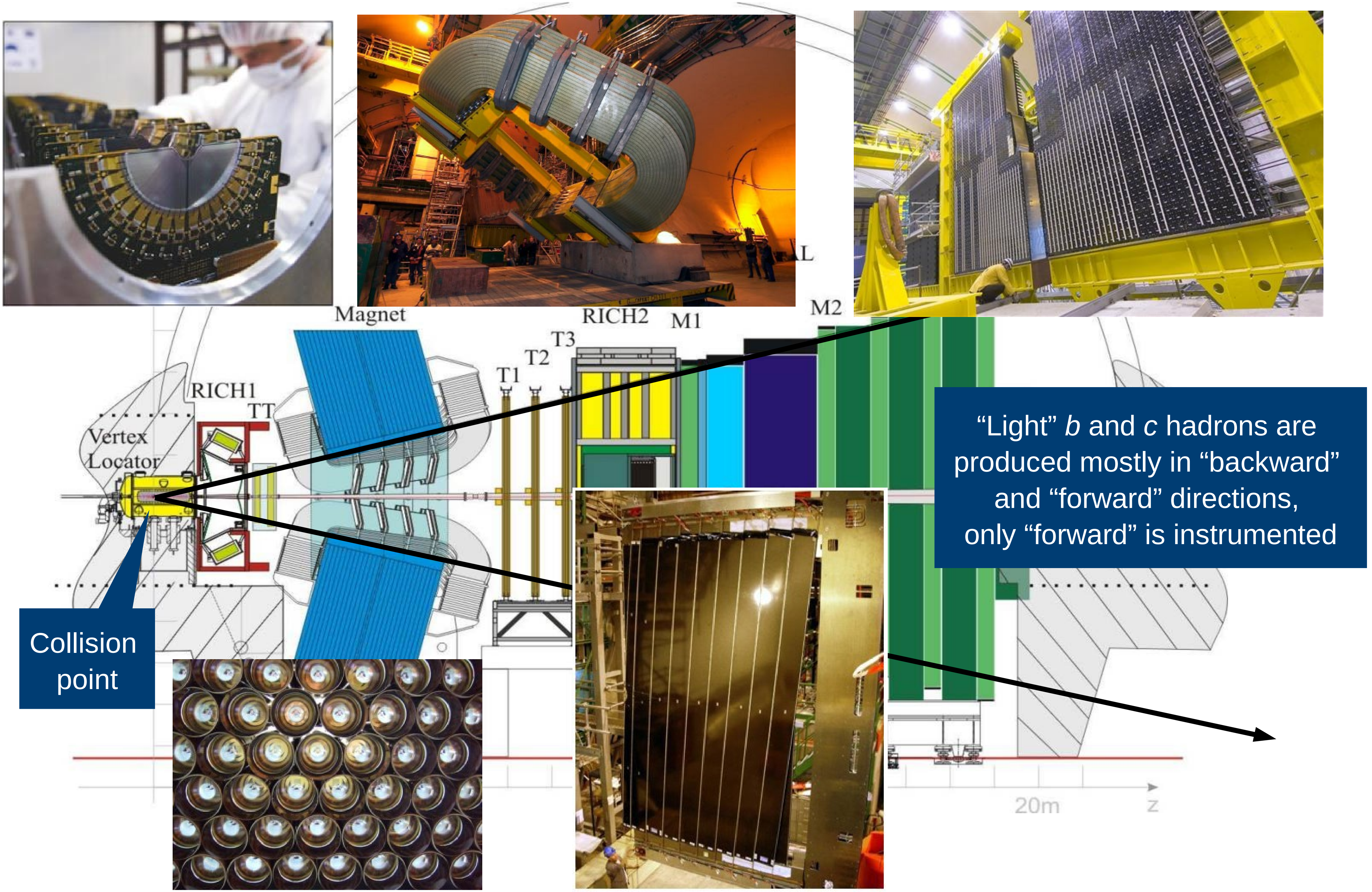
4 big detectors, hundreds of petabytes of data accumulated



Dedicated to flavour physics studies

Mostly *b* and *c* hadron decays

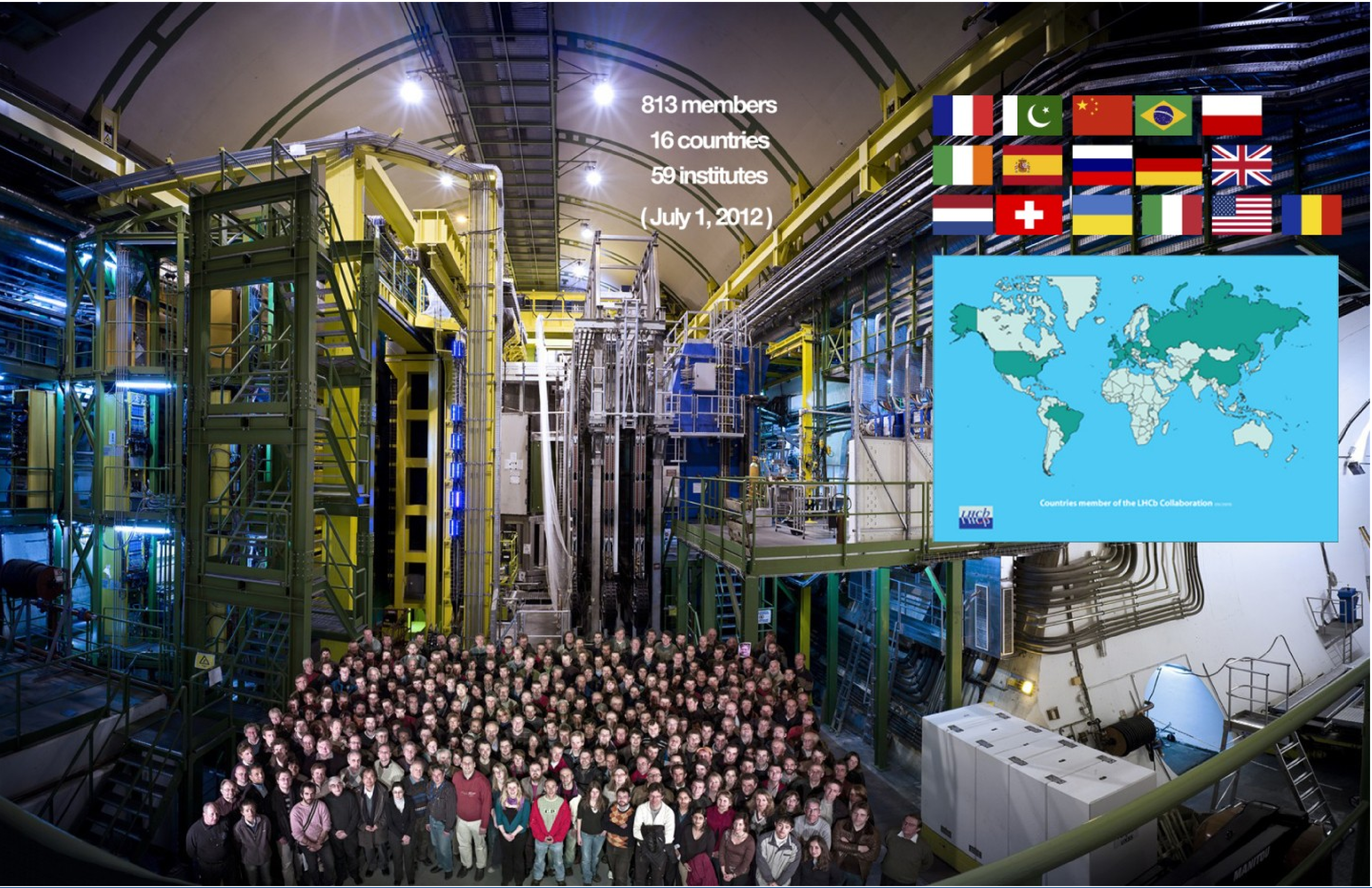
LHCb experiment



"Light" *b* and *c* hadrons are produced mostly in "backward" and "forward" directions, only "forward" is instrumented

Collision point

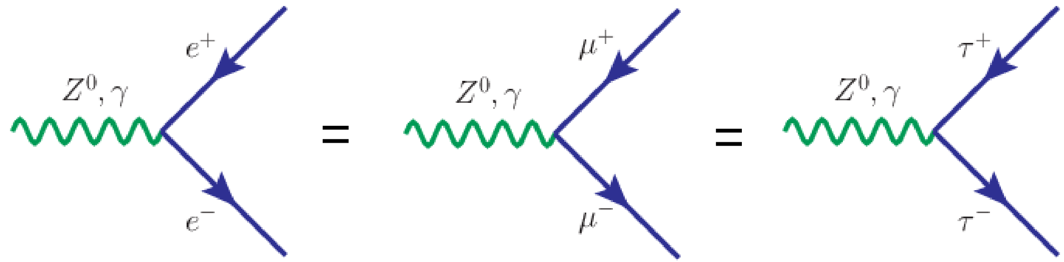
LHCb experiment



Lepton flavour universality: b → sll

Strength of SM electroweak interaction of leptons is the same for all 3 generations:

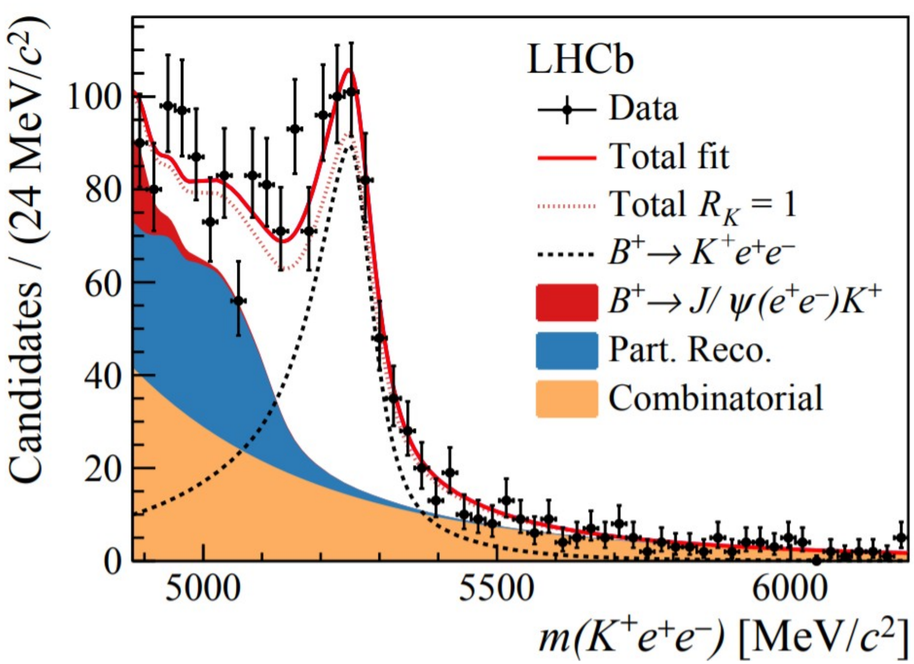
E.g. **neutral weak current**:

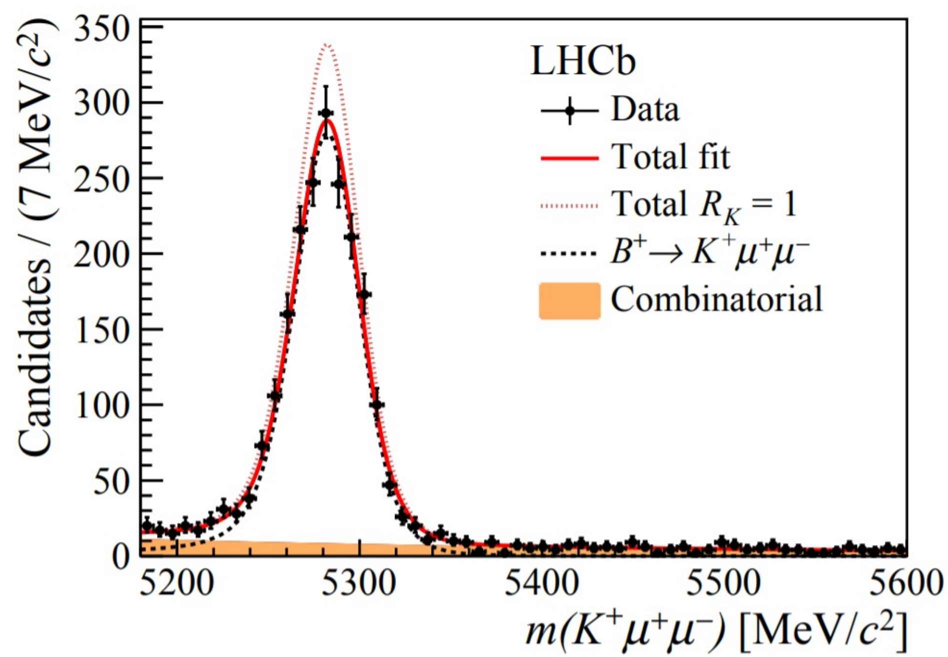


Can be checked by comparing the rates of decay with e^+e^- and $\mu^+\mu^-$ pairs.

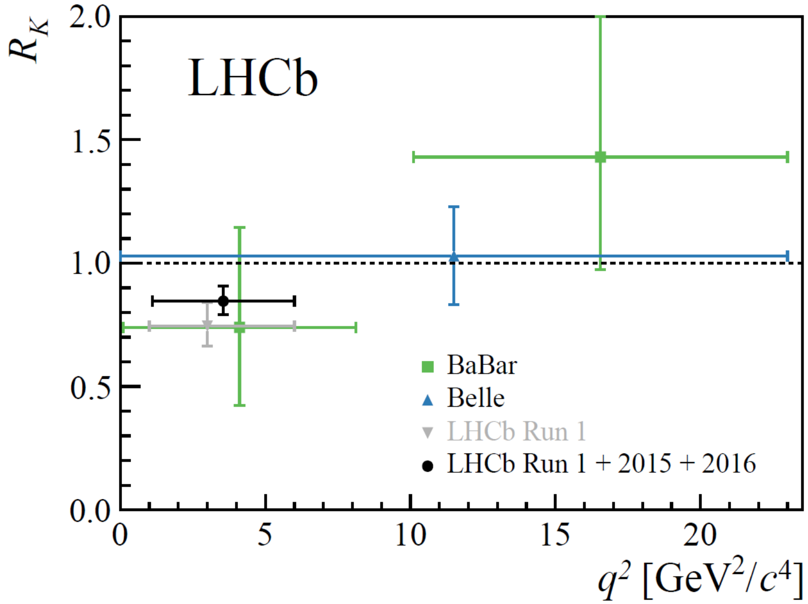
Example: $B^+ \to K^+e^+e^-$ and $B^+ \to K^+\mu^+\mu^-$.

[LHCb, PRL 122, 191801 (2019)]





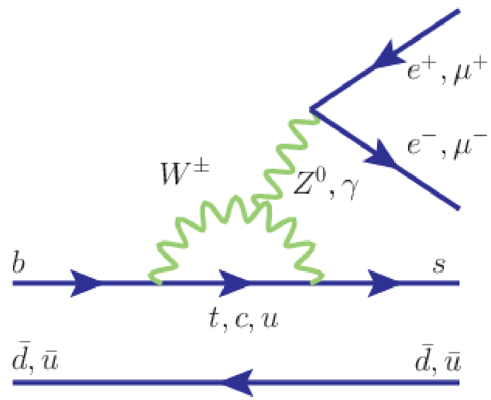
Lepton flavour universality

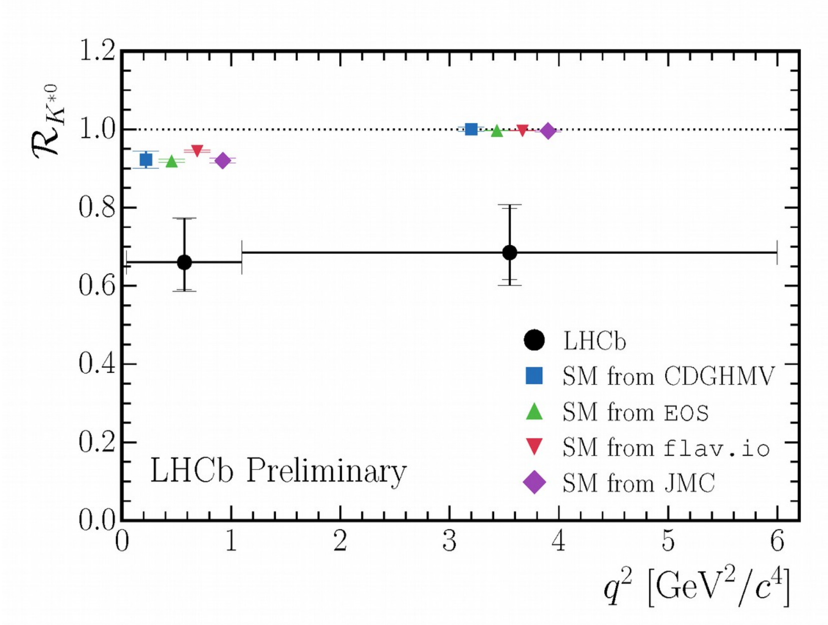


Measuring the ratio $\mathcal{R}_K = \dfrac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$

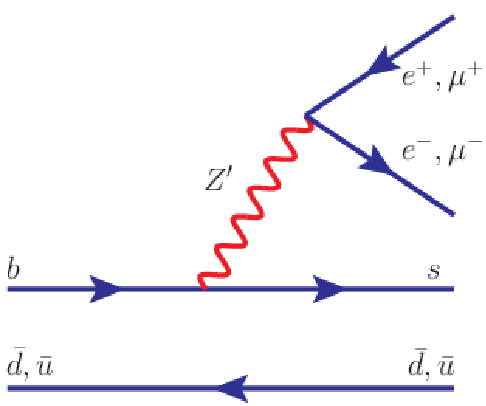
In SM, should be close to 1

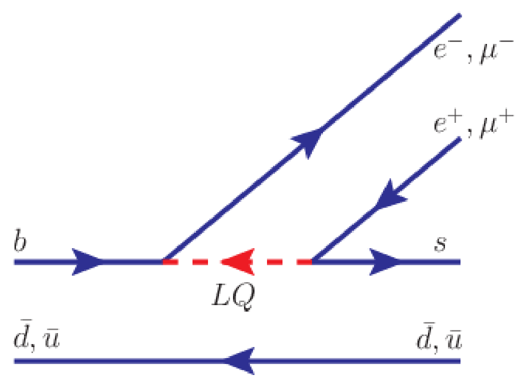
(small correction due to difference of masses)





Possible explanations of deviations from 1:



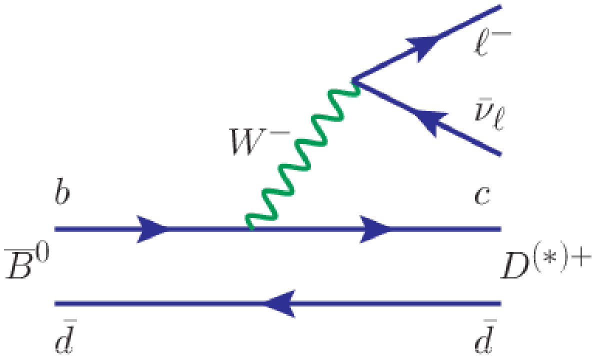


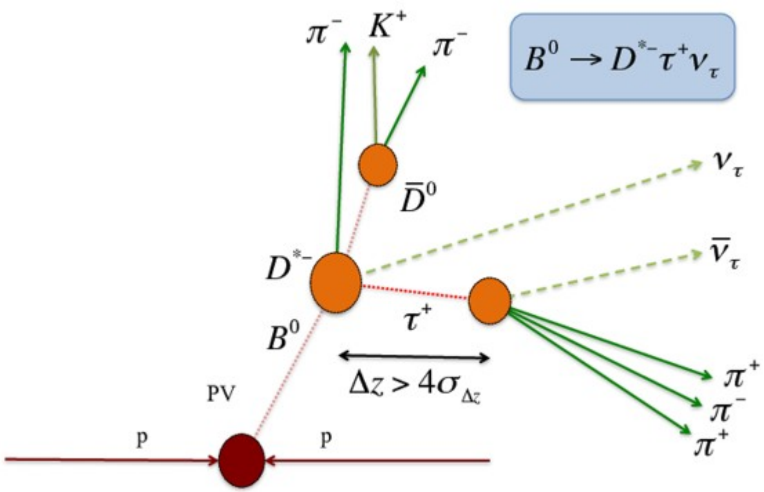
Further tests: $B^0 \to K^{*0}\tau^+\tau^-$, angular distributions, other B hadrons… **A lot of work to do!**

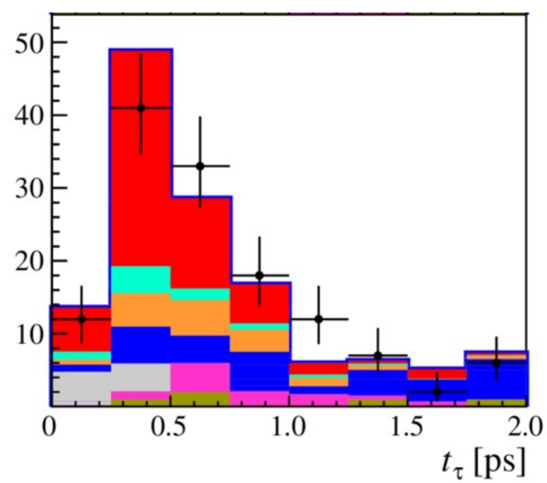
Lepton flavour universality

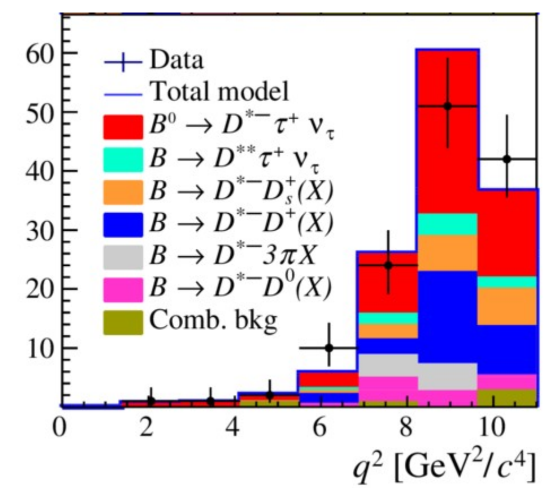
Similar study with **charged weak current:** $R(D^*) = \dfrac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$

- Tricky: neutrinos are not reconstructed
- Use event topology for kinematic constraints
- Use machine learning algorithms trained on simulated signal and backgrounds







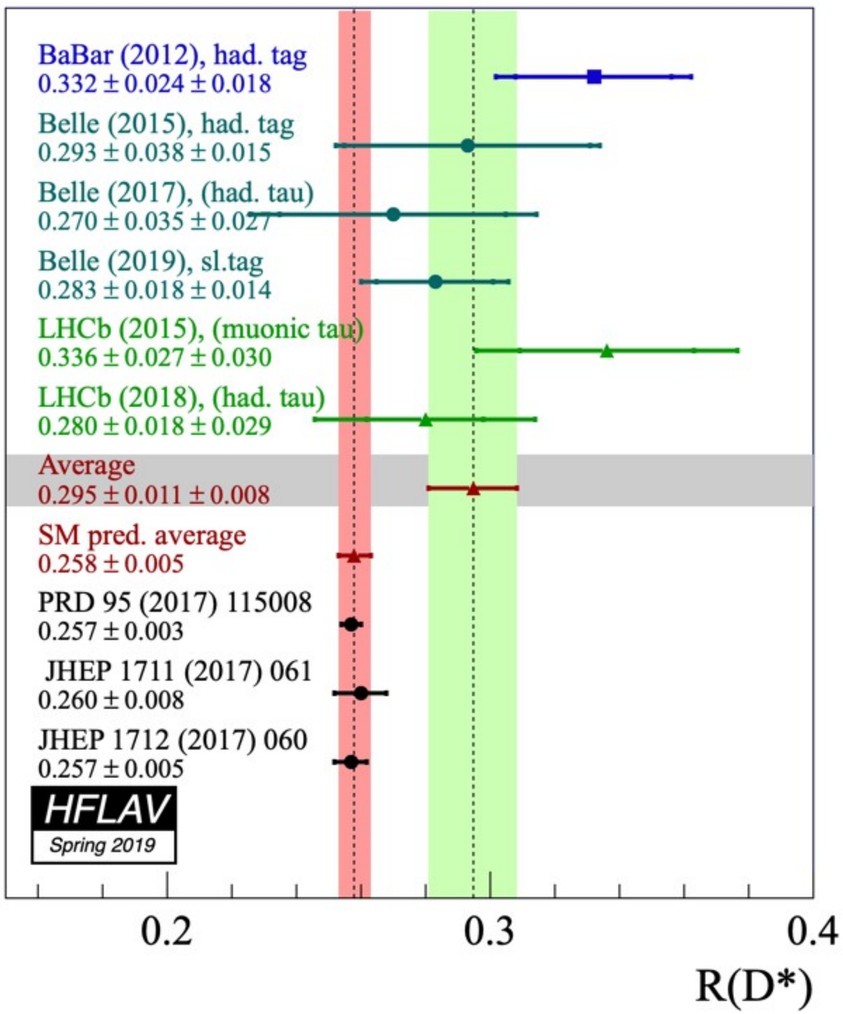


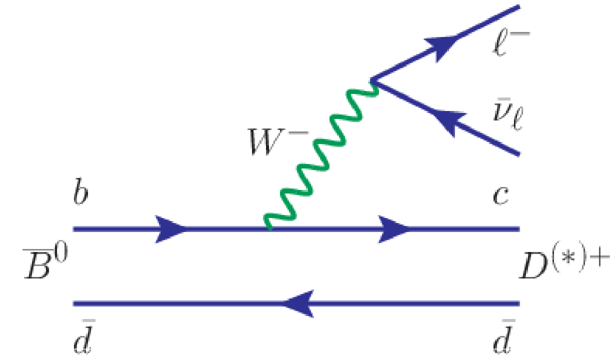
[LHCb, PRL 115, 111803 (2015); PRL 120, 171802 (2018)]

Lepton flavour universality

Similar study with **charged weak current:** $R(D^*) = \dfrac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$

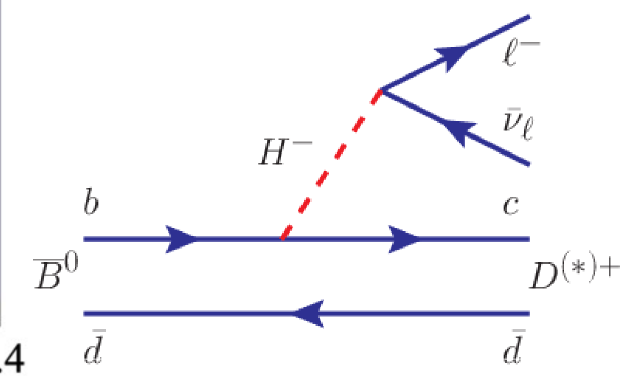
All measurements are systematically **above** SM

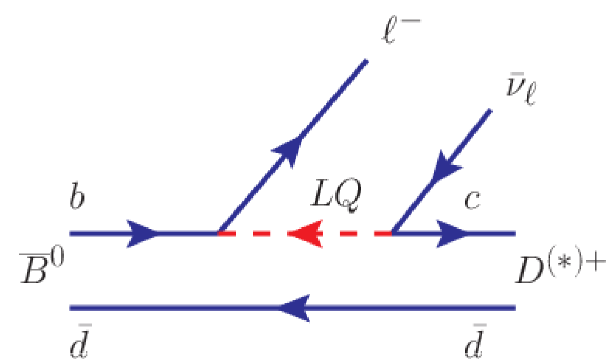




Can be explained by similar “New Physics”

as in $B^0 \to K^{*0}\mu^+\mu^- / e^+e^-$





Further tests: other B hadrons, angular distributions, CP-violating observables…

CP violation in semileptonic decays

- The most general form of New Physics Hamiltonian for $b \to cl\nu$:

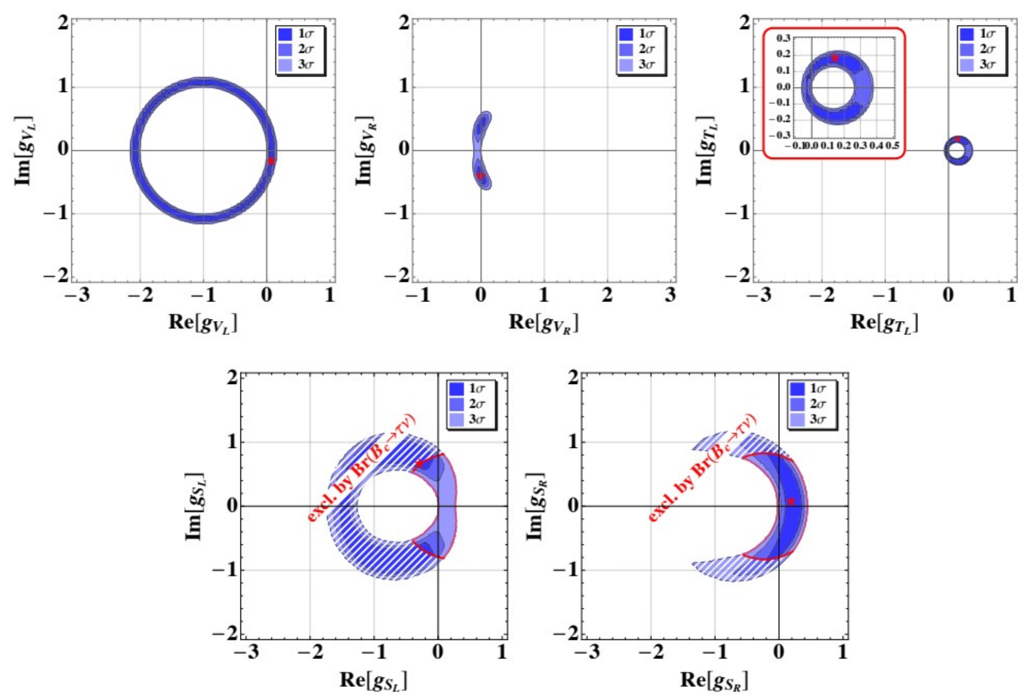
LH vector RH vector

$$\mathcal{H}_{eff} = \frac{G_F V_{cb}}{\sqrt{2}} \Big\{ [(1+g_L)\,\bar{c}\gamma_\mu(1-\gamma_5)b + g_R\,\bar{c}\gamma_\mu(1+\gamma_5)b]\,\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell$$
$$+\ [g_S\,\bar{c}b + g_P\,\bar{c}\gamma_5 b]\,\bar{\ell}(1-\gamma_5)\nu_\ell + g_T\,\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell + h.c. \Big\}$$

Scalar Pseudoscalar Tensor

- g_L, g_R, g_S, g_P, g_T are New Physics couplings (=0 in SM)
- Different NP models (W', LQ, ...) $\Rightarrow$

  different combinations of couplings.



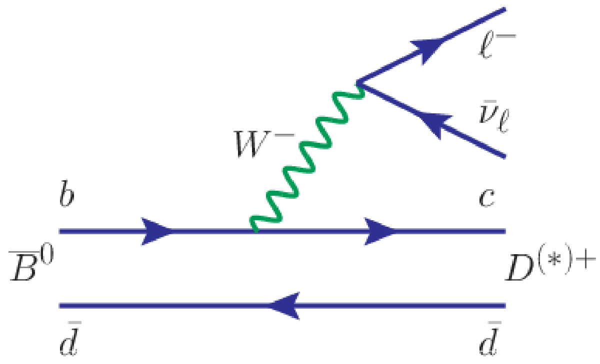
Constraints on g from $R(D^{(*)})$:

CP violation in semileptonic decays

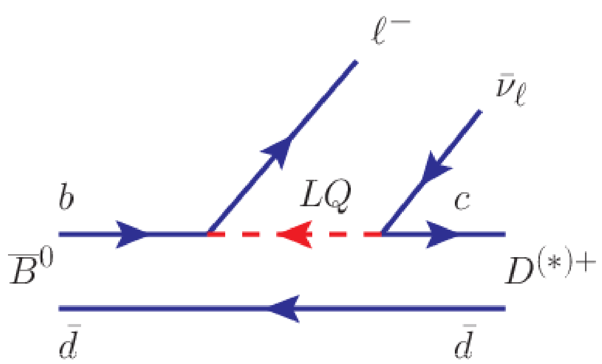
- CP violation: difference between properties of matter and antimatter
- CP violation only enters as the *weak phase* in amplitudes:

  $A \sim e^{\pm i\varphi}$, with $\pm\varphi$ for particles $\leftrightarrow$ antiparticles (*CP conjugation*)

- In experiment, measure $|A|^2 \Rightarrow$ No visible asymmetry if only one amplitude



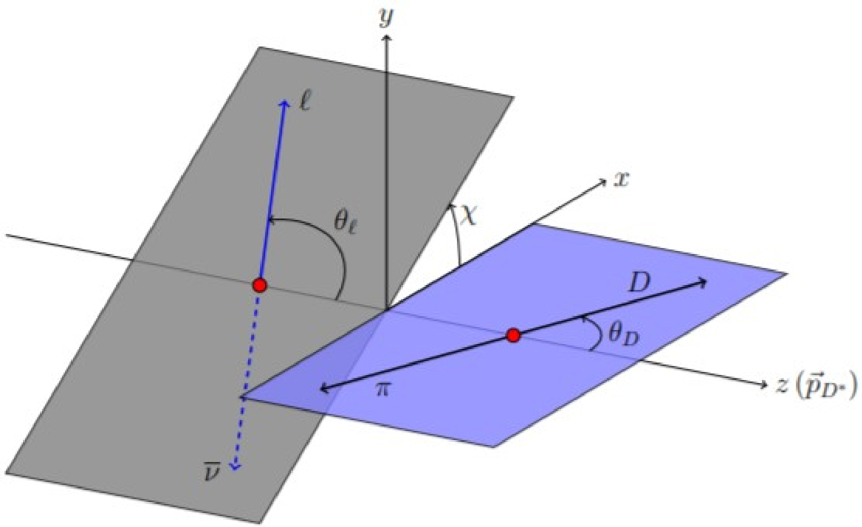
+



- In general, expect CP asymmetry with two amplitudes with different weak phases (e.g. SM and NP)
- However, CP asymmetry cancels out in the total decay probabilities…

Semileptonic B decays to excited charm

- $B \to D^{*} l \nu$ decays : internal degrees of freedom (q^2, Θ_L, Θ_D, χ)



- Angular distribution:

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{9}{32\pi}\Big\{ I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D$$
$$+ \left[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D\right]\cos 2\theta_\ell$$
$$+ \left[I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D\right]\cos\theta_\ell$$
$$+ \left[I_3\cos 2\chi + \boxed{I_9\sin 2\chi}\right]\sin^2\theta_\ell\sin^2\theta_D$$
$$+ \left[I_4\cos\chi + \boxed{I_8\sin\chi}\right]\sin 2\theta_\ell\sin 2\theta_D$$
$$+ \left[I_5\cos\chi + \boxed{I_7\sin\chi}\right]\sin\theta_\ell\sin 2\theta_D\Big\},$$

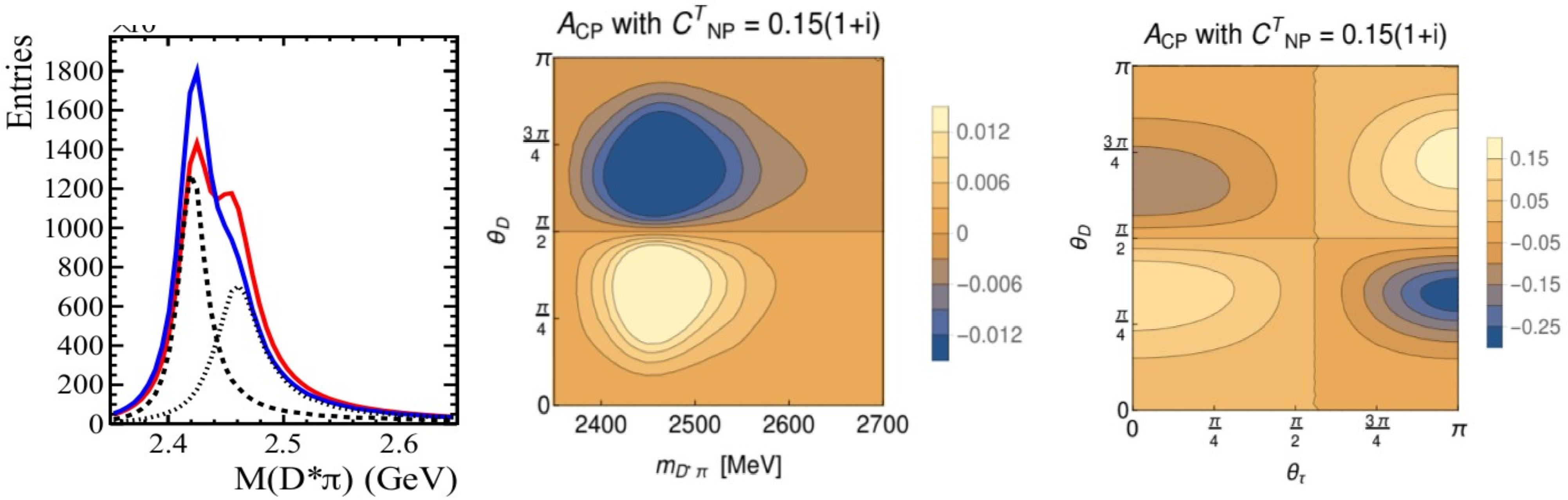
Parity- and

CP-violating terms

[B. Bhattacharya, A. Datta, S. Kamali, D. London, JHEP 05 (2019) 191]

Semileptonic B decays to excited charm

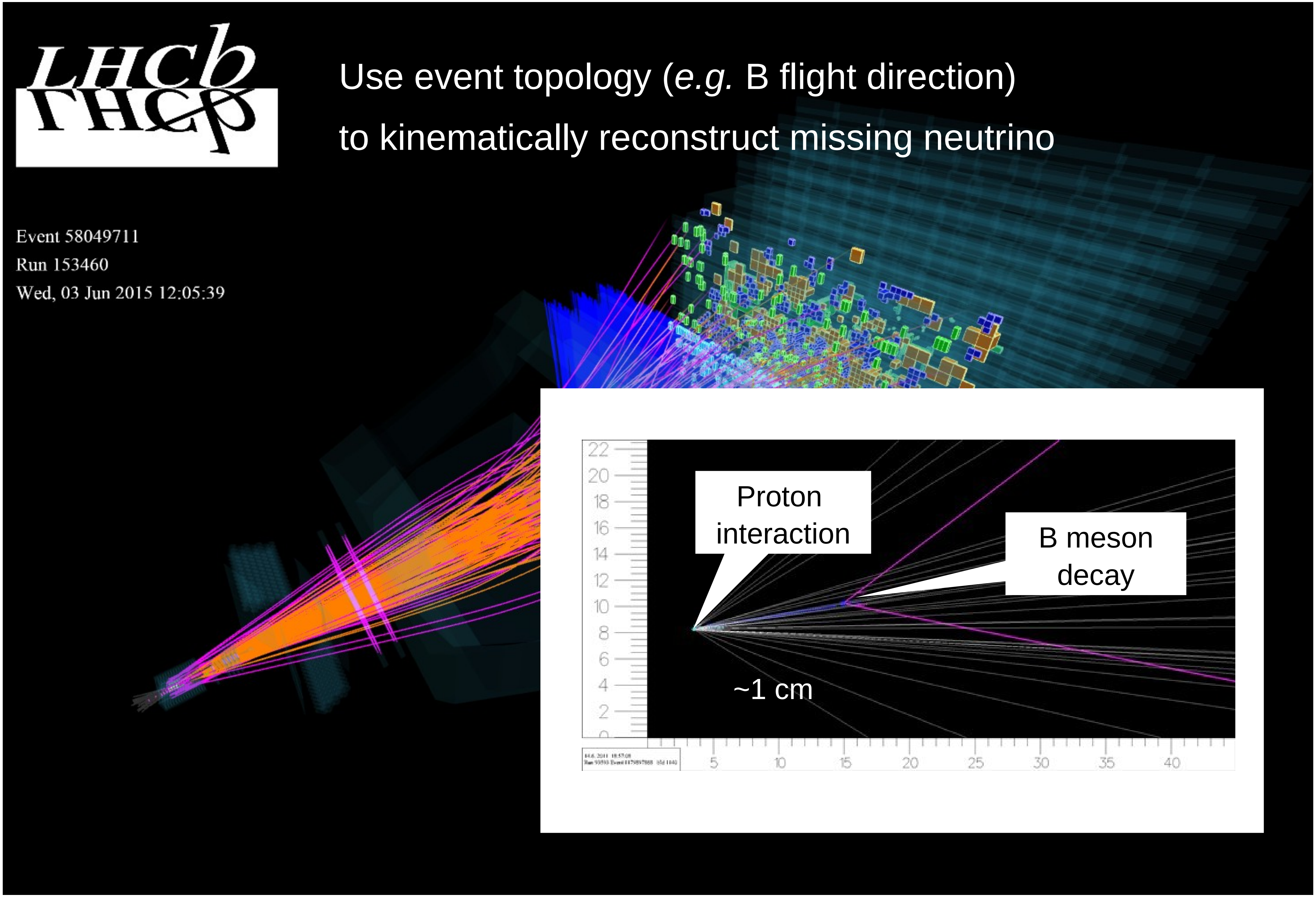
- $B \to D^{**} l\nu$ decays ($D^{**} \to D^{*}\pi$) : even more degrees of freedom
- Additional effect: overlapping D^{**} states with different spins



- Nonzero CP asymmetry even if integrated over some angles

[Aloni, Grossman, Soffer, PRD 98, 035022 (2018)]

LHCb experiment: event topology



Conclusion

- Interesting hints on the effects beyond the Standard Model in current B meson data
  - Hints of lepton flavour violation in neutral and charged current
  - More observables are needed for stronger conclusions and constrain NP models
- Aim to explore CP violation in semileptonic B decays:
  - Complementary to LFV observables.
  - Null test: any $\neq 0$ signal $\Rightarrow$ New Physics
  - More observables to distinguish between NP models
  - Different experimental technique (angular analysis), different systematic uncertainties.
- Only at the start of the long road:
  - (ongoing) Simulation studies of CPV in $B \to D^{*} l\nu$ and $B \to D^{**} l\nu$ decays
  - LHCb data analysis of $B \to D^{(*)*}\mu\nu$
  - (beyond this Ph.D project) Analysis of new (upgraded) LHCb data, $B \to D^{(*)*}\tau\nu$
- Require joint effort on theory (CPT) and experiment (CPPM) sides