New results in LU/LFV tests with LHCb

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on behalf of the LHCb collaboration

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Outline

- Lepton flavour and universality violation
- The LHCb experiment
- LFV searches at LHCb:
  - Search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$
  - Search for $D^0 \to e^{\pm}\mu^{\mp}$
  - Search for $\tau^{\pm} \to \mu^{+}\mu^{-}\mu^{\pm}$
- Tests of lepton flavour universality at LHCb:
  - Measurement of $R(D^*)$
  - Measurement of R_K
- Conclusions

In the Standard Model:

- Couplings of the gauge bosons to leptons are independent of the lepton flavour → BF differences of semileptonic decays in e, μ and τ are only due to phase space and helicity-suppressed contribution

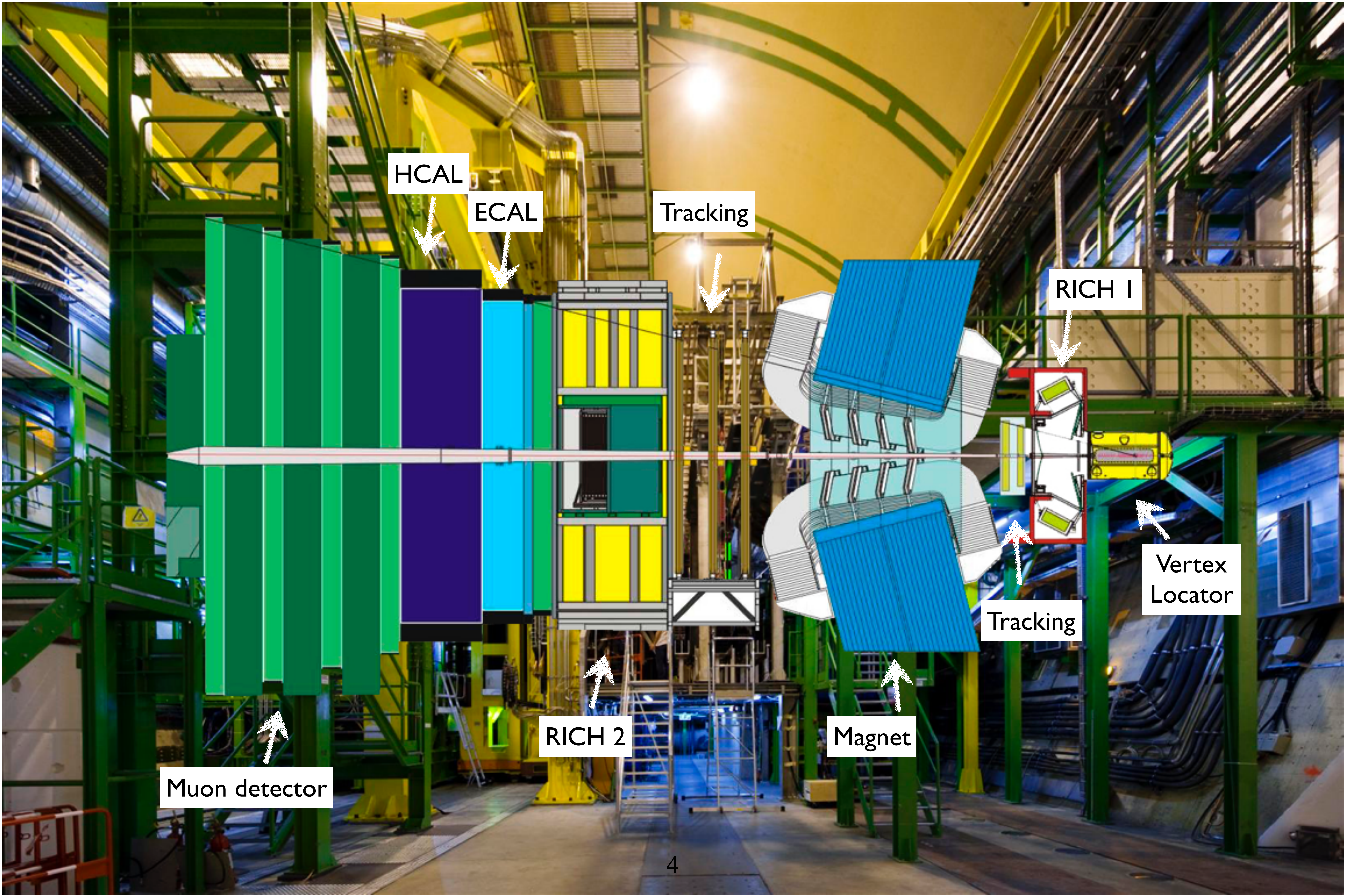
- Lepton flavour violation is allowed in the SM only with massive neutrinos → BF~$\mathcal{O}(10^{-40})$ or smaller

Observation of LFV processes and LFU violations would be a clear sign of new physics

↓

LHCb can play a crucial role in such searches and in putting new limits on BSM theories

The LHCb detector



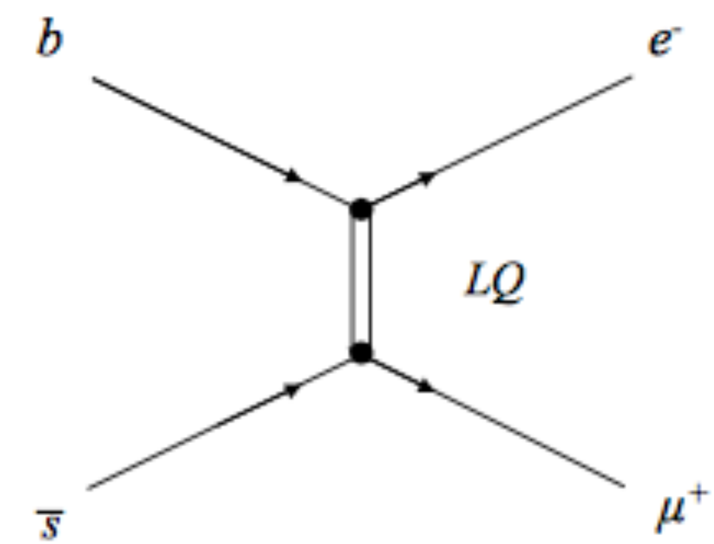
$$B^0_{(s)} \to e^{\pm}\mu^{\mp}$$

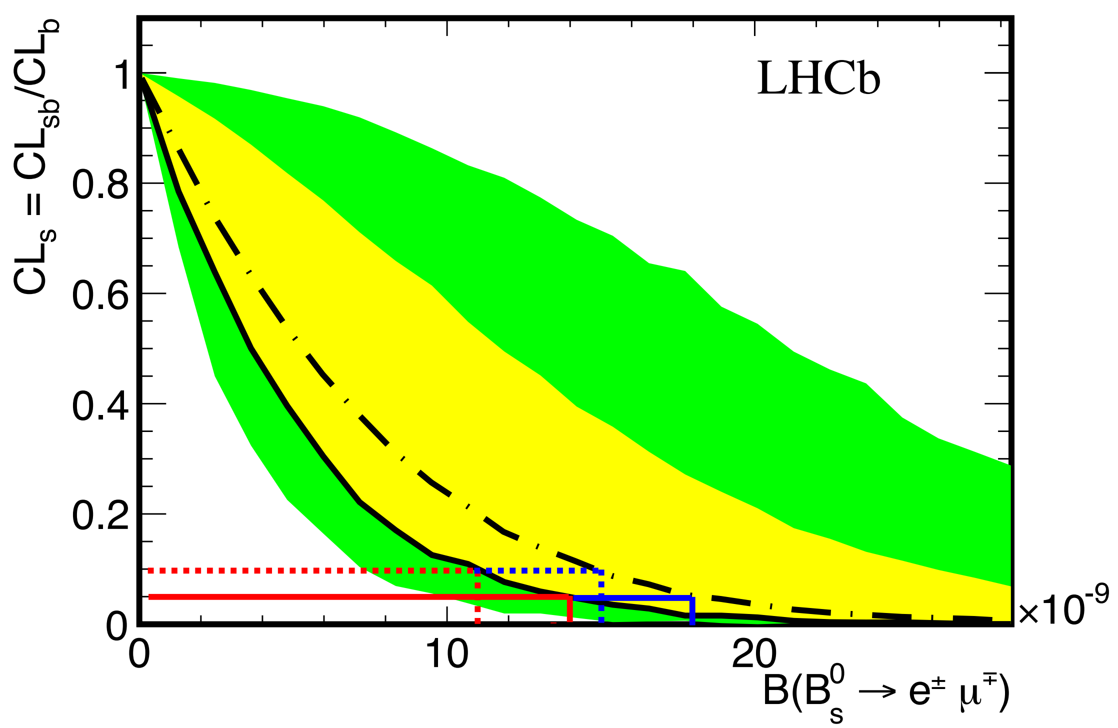
PRL 111, 141801 (2013)

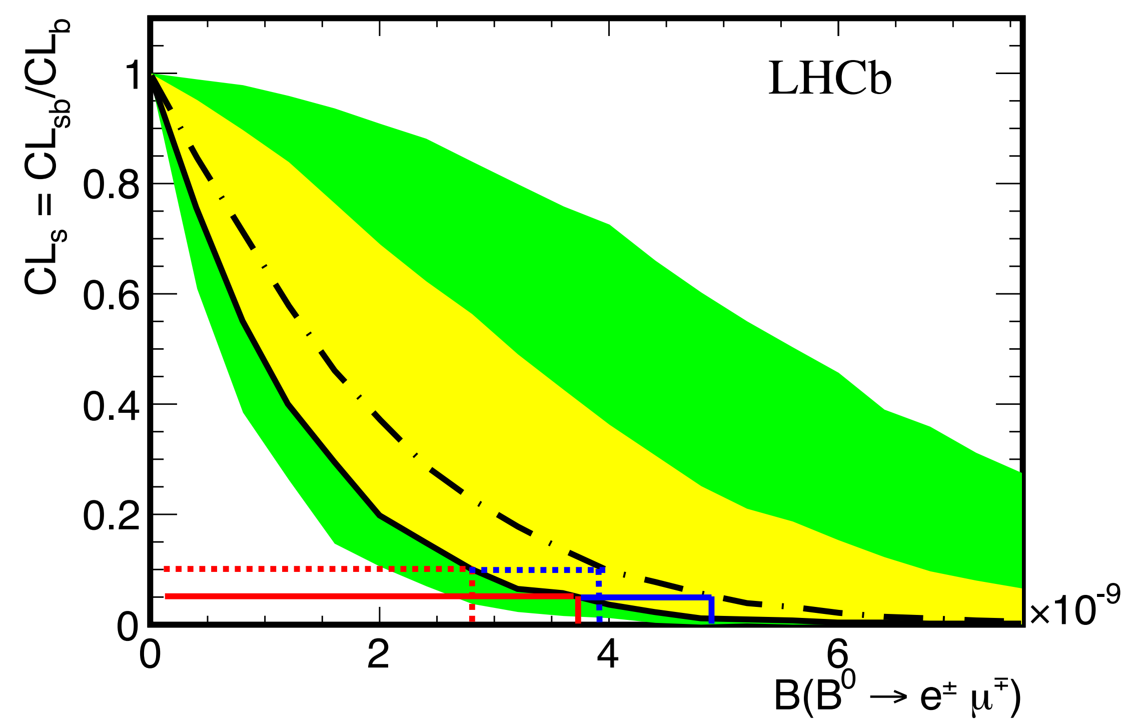
Predicted in BSM theories: heavy singlet Dirac neutrinos, SUSY, Pati-Salam model[1]

Analysis strategy:

- BDT selection
- Simultaneous fit to invariant mass in BDT bins
- normalisation channel $B^0 \to K^+\pi^-$
- CLs method to extract the limit







[1] J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974)

One order of magnitude better than previous best limit from CDF[1]

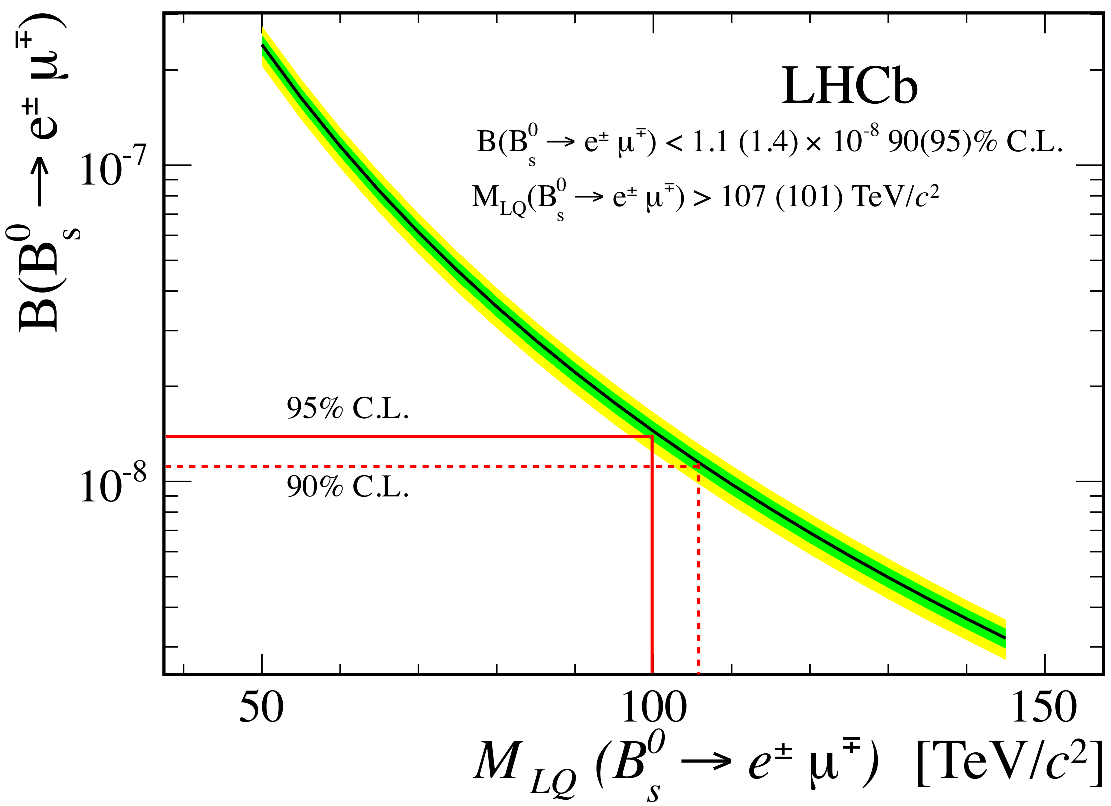
$$\mathcal{B}(B_s^0 \to e^\pm \mu^\mp) < 1.1 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

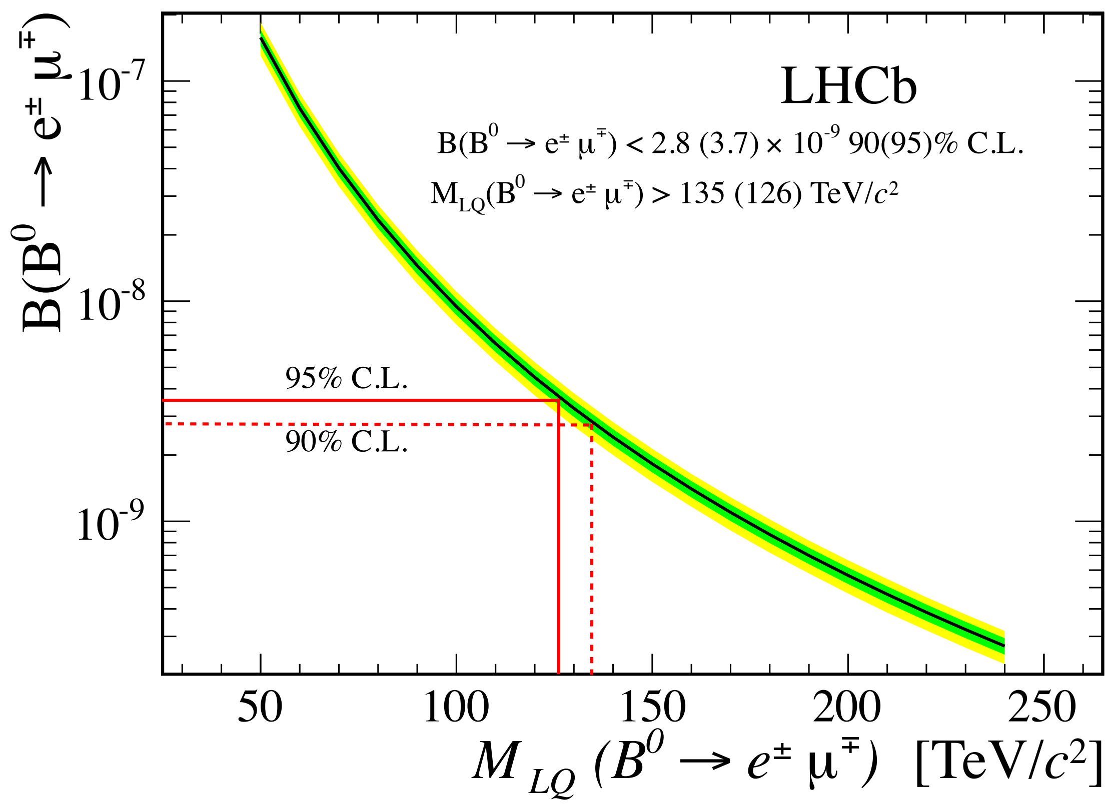
$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 2.8 \times 10^{-9} \text{ at } 90\% \text{ CL}$$

Lower bounds on the leptoquark masses in Pati-Salam model

$$\mathcal{M}_{LQ}(B_s^0 \to e^\pm \mu^\mp) > 107 \text{ TeV/c}^2 \text{ at } 90\% \text{ CL}$$

$$\mathcal{M}_{LQ}(B^0 \to e^\pm \mu^\mp) > 135 \text{ TeV/c}^2 \text{ at } 90\% \text{ CL}$$





[1]T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 102, 201801 (2009).

$$D^0 \to e^{\pm}\mu^{\mp}$$

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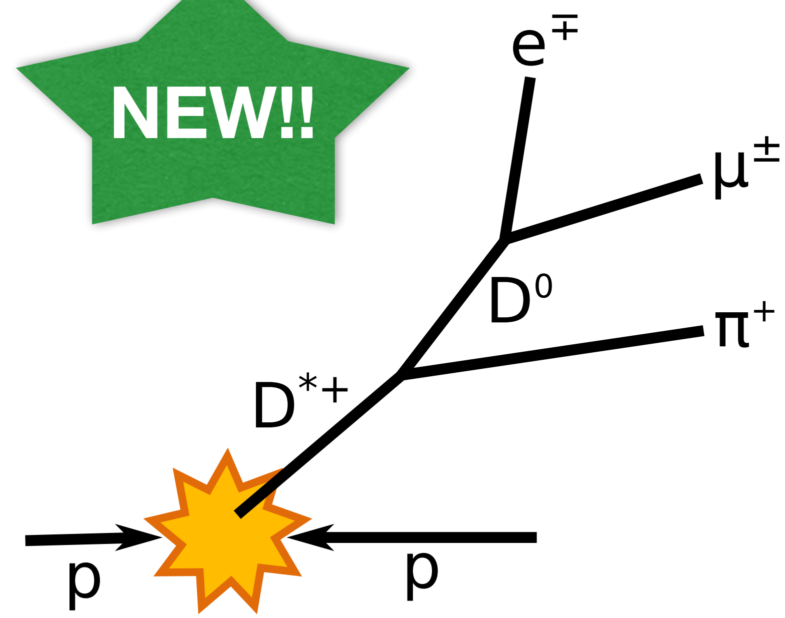
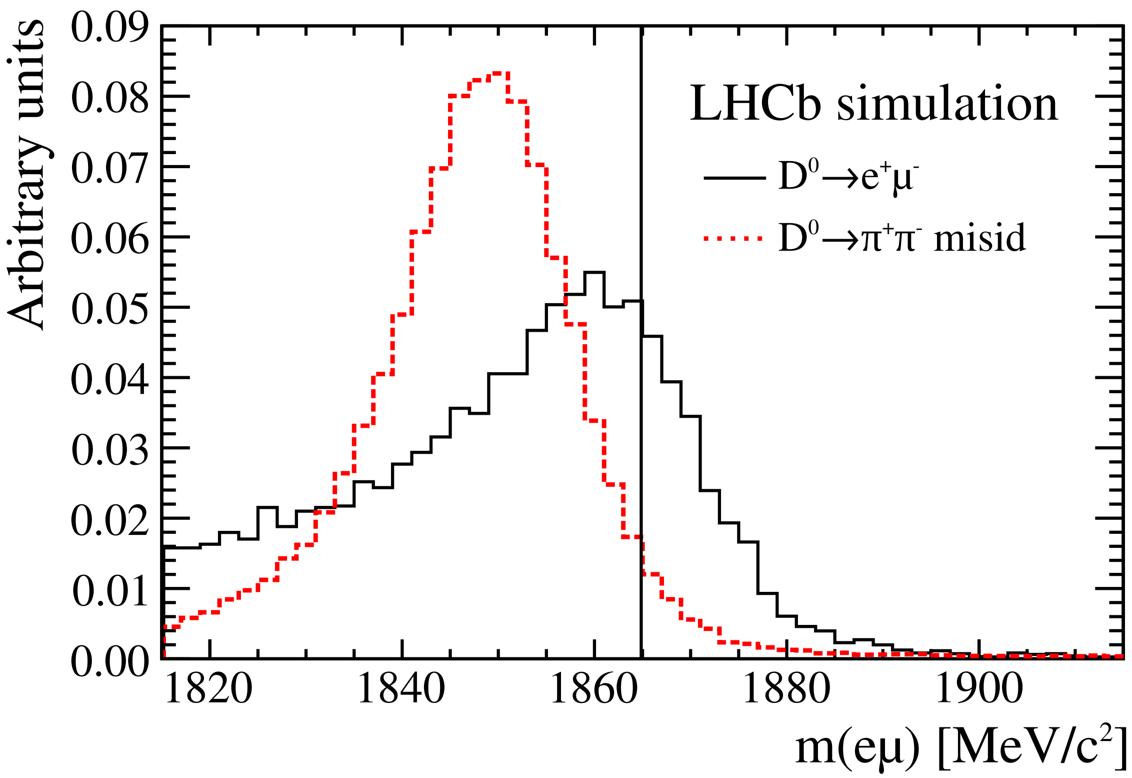
NEW!!

- Forbidden in the SM
- Predicted in various BSM theories[1] (SUSY with RPV, multiple Higgs doublets theory, SM with extra fermions):
  - BF($D^0 \to e^{\pm}\mu^{\mp}$) up to $\mathcal{O}(10^{-6})$



- Best limit previous LHCb:

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 2.6 \times 10^{-7} \text{ at } 90\% \text{ CL}$$ (Belle[2])



Strategy

- Select $D^{*+} \to D^0(\to e^{\pm}\mu^{\mp})\pi^+$ decays
- Normalised to $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

Full Run I statistics used (3 fb^{-1})

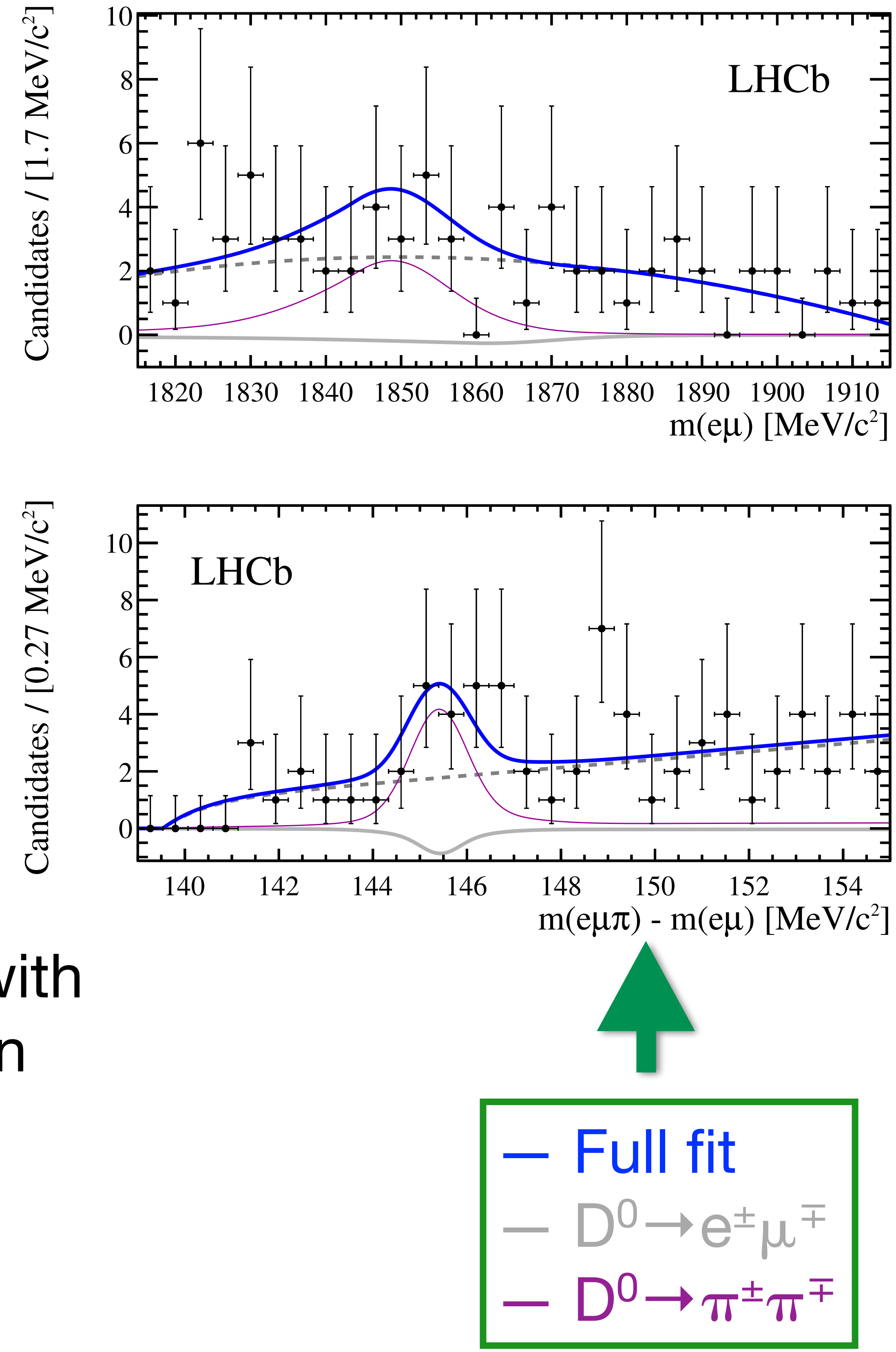
misID $D^0 \to \pi^+\pi^-$: main background

[1] G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa, Phys. Rev. D66 (2002) 014009
[2] Belle collaboration, Phys. Rev. D81 (2010) 091102

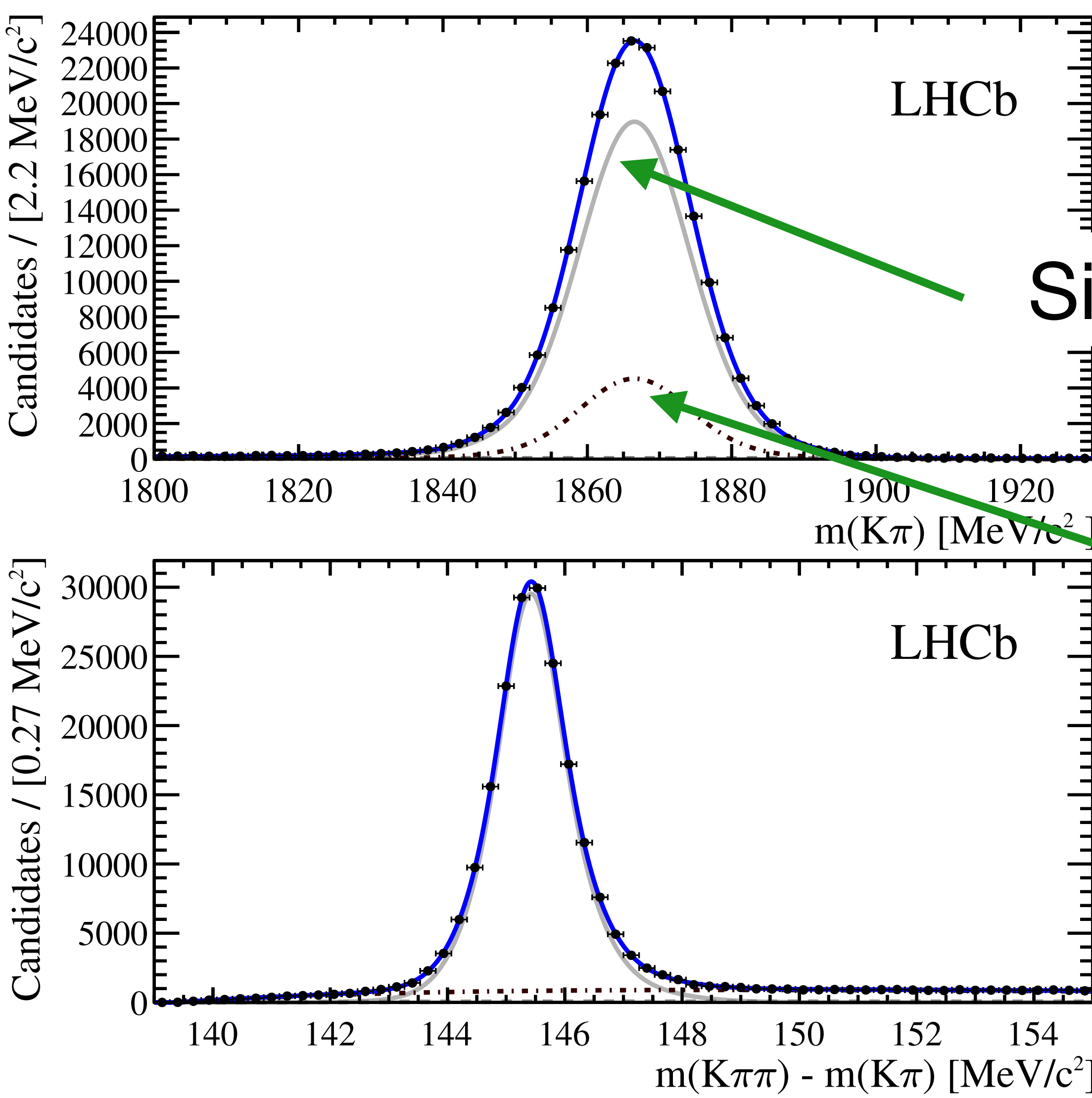
- BDT to separate real D* decays from combinatorial background
- BDT output split in three bins simultaneously fitted
- 2D fit of m(D^0) and Δm=m(D^{*+})-m(D^0)

$$D^{*+} \to D^0(\to e^{\pm}\mu^{\mp})\pi^+$$

(most signal-like bin)



$$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$$



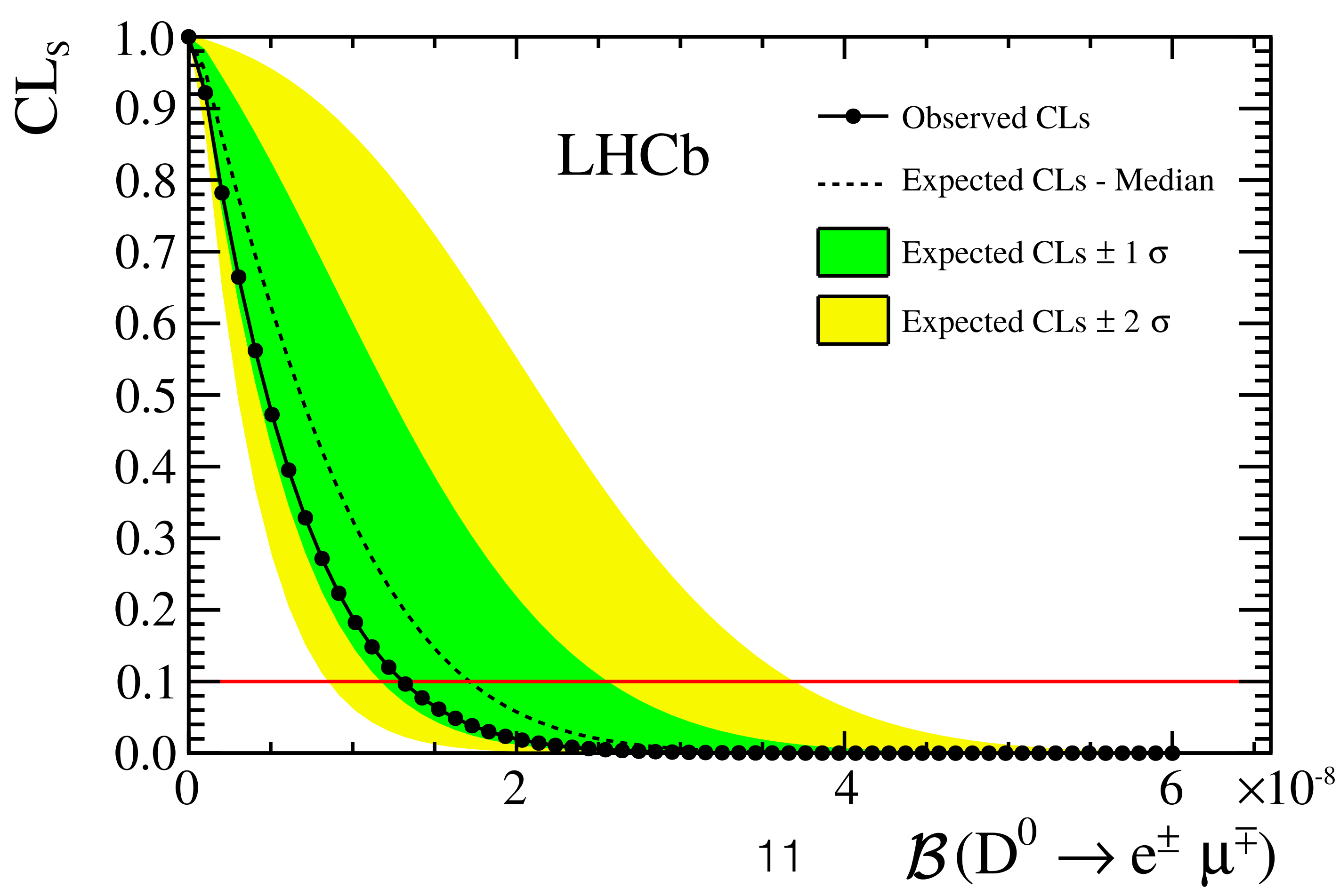
Signal

D^0 events combined with random pion

- No signal observed
- Upper limit with CL_s method, via:

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\pm}) = \frac{N_{e\mu}\epsilon_{e\mu}}{N_{K\pi}\epsilon_{K\pi}} \times \mathcal{B}(D^0 \to K^-\pi^+)$$

$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8}$ at 90% CL (word's best upper limit)



$$\tau^- \rightarrow \mu^+ \mu^- \mu^+$$

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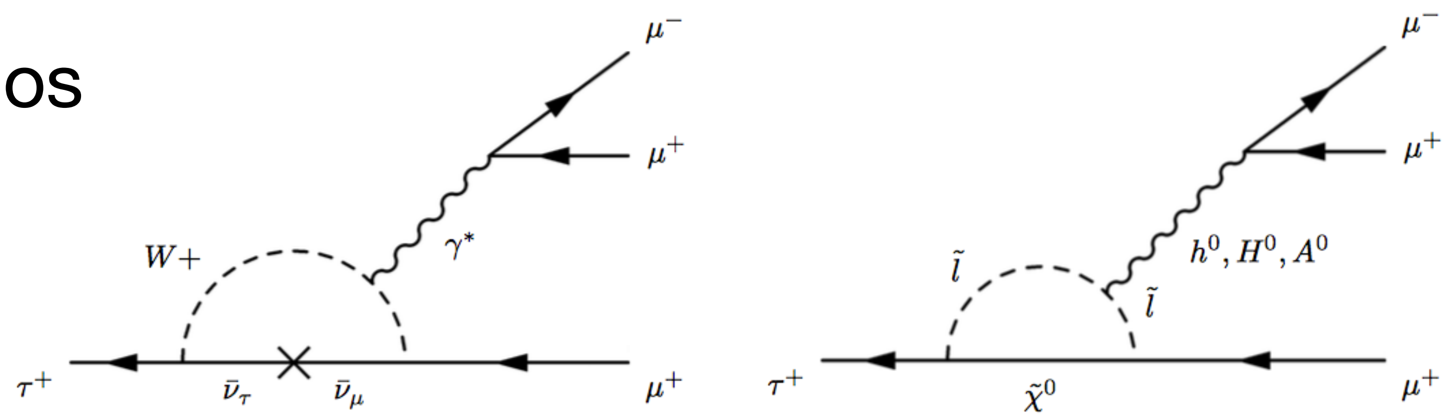
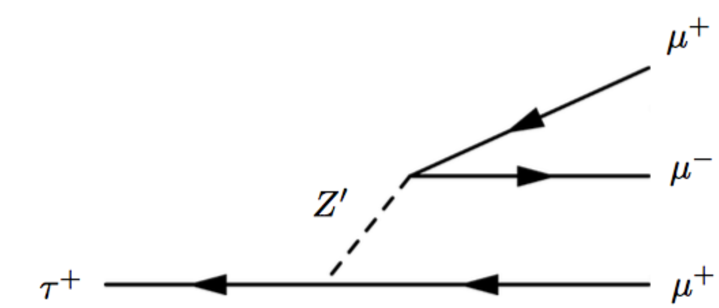
Within the Standard Model:

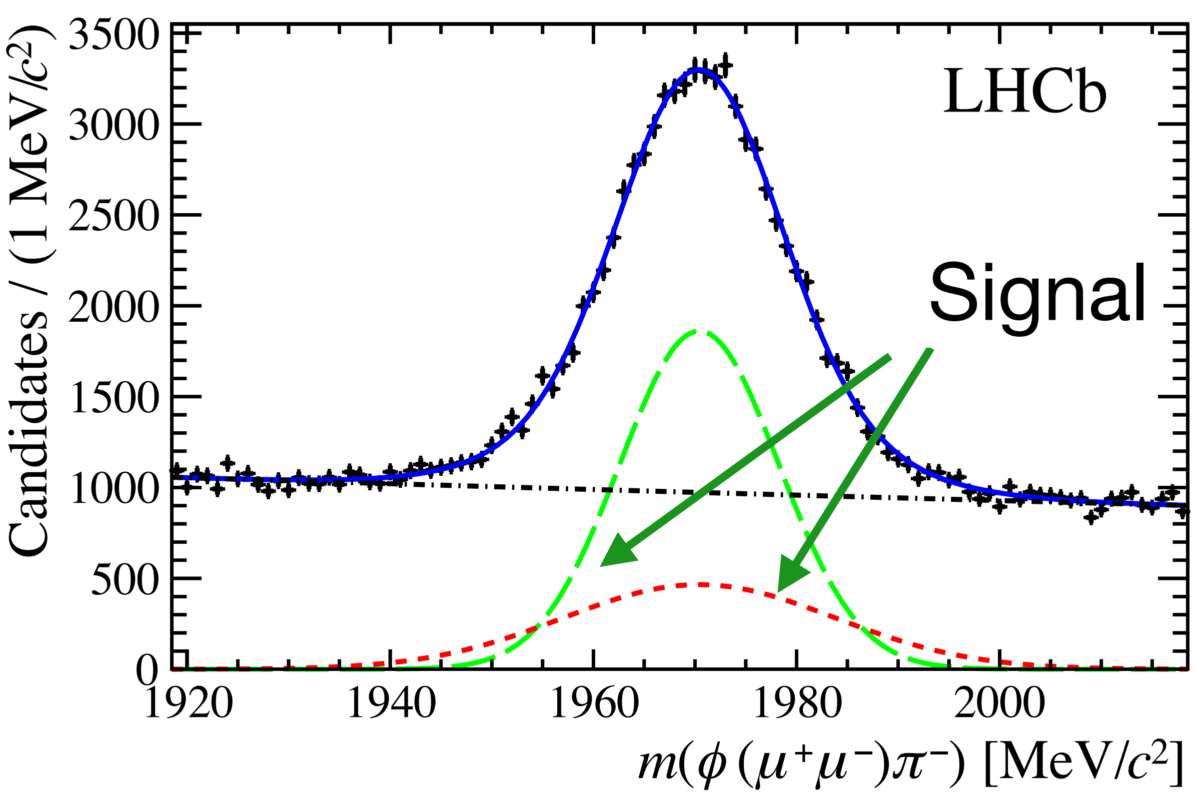
- Allowed with massive neutrinos
- BF extremely low ~ $\mathcal{O}(10^{-40})$



Beyond the Standard Model:

- NP particles in loops increase decay rates
- tree level decays allowed





Large τ production cross section at LHCb (σ ~ 80μb)

Normalisation channel:

$$D_s^- \to \phi(\to \mu\mu)\pi^-$$

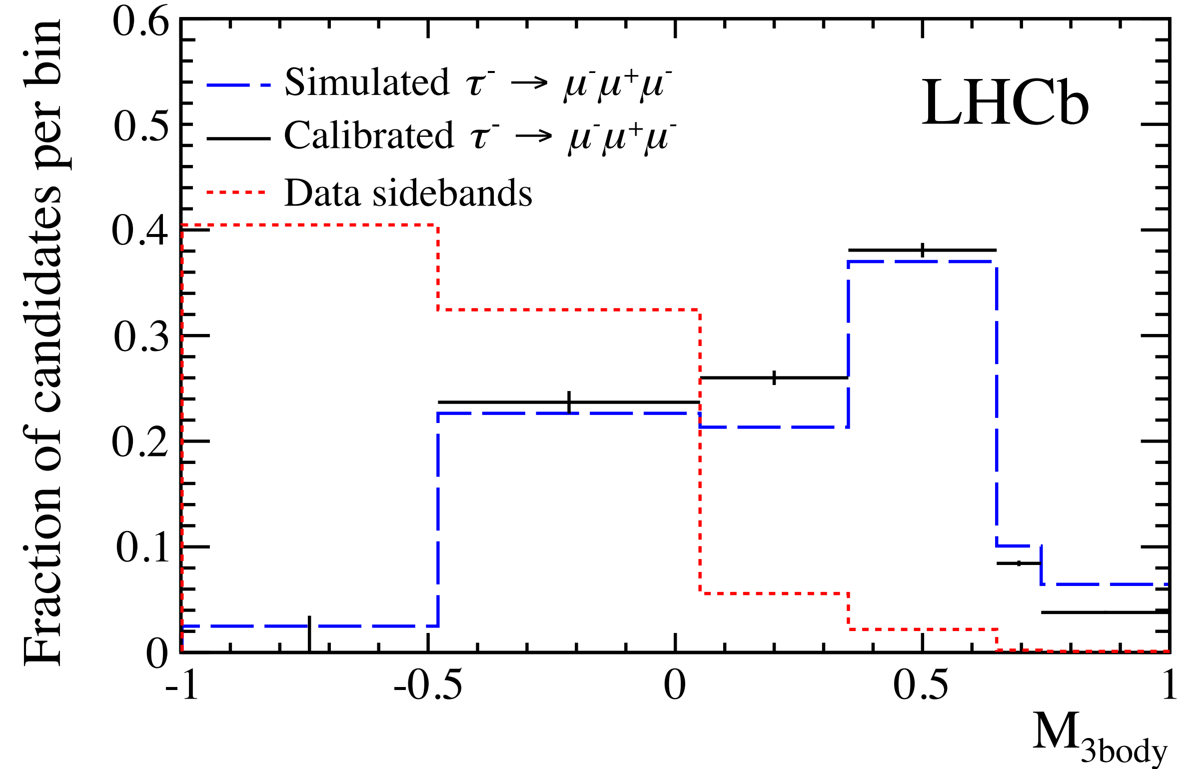
Data set:

- LHCb Run1 data set ($3 fb^{-1}$)

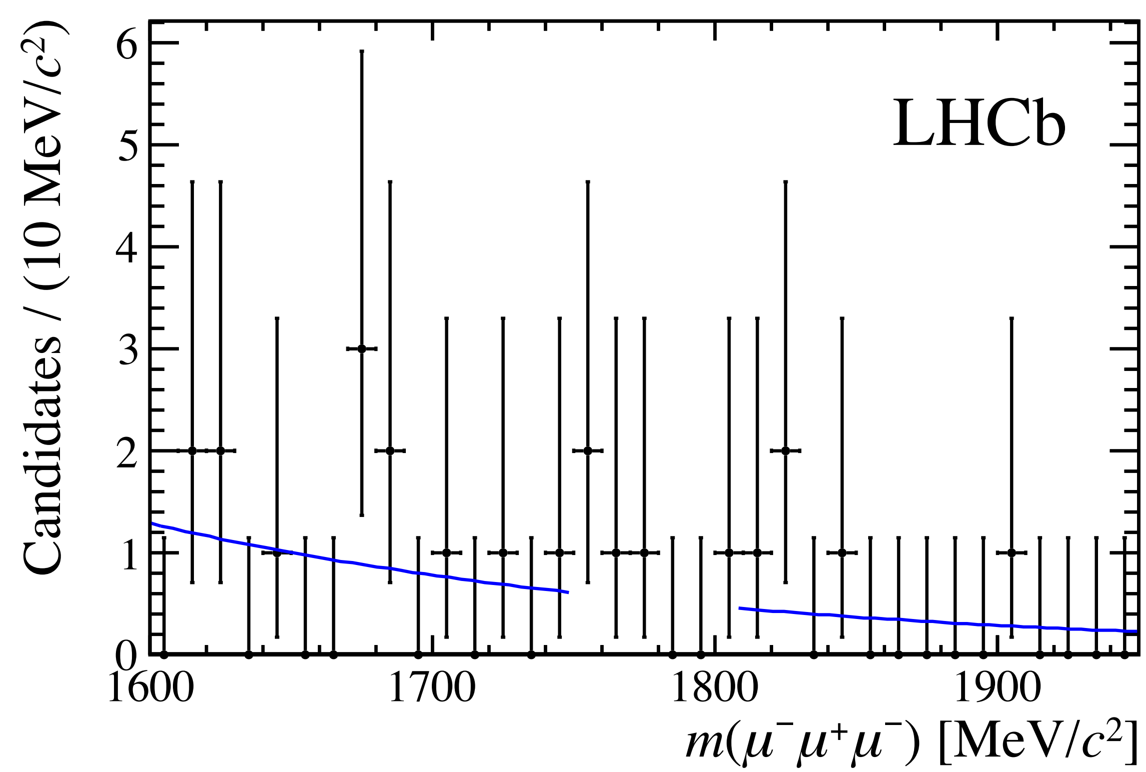
Analysis strategy:

- Cut based preselection
- Background discrimination:
  - MVA for 3-body topological decays
  - MVA for muon identification
  - τ invariant mass
- Simultaneous fit to invariant mass sidebands in bins of M_{3body} and M_{PID}

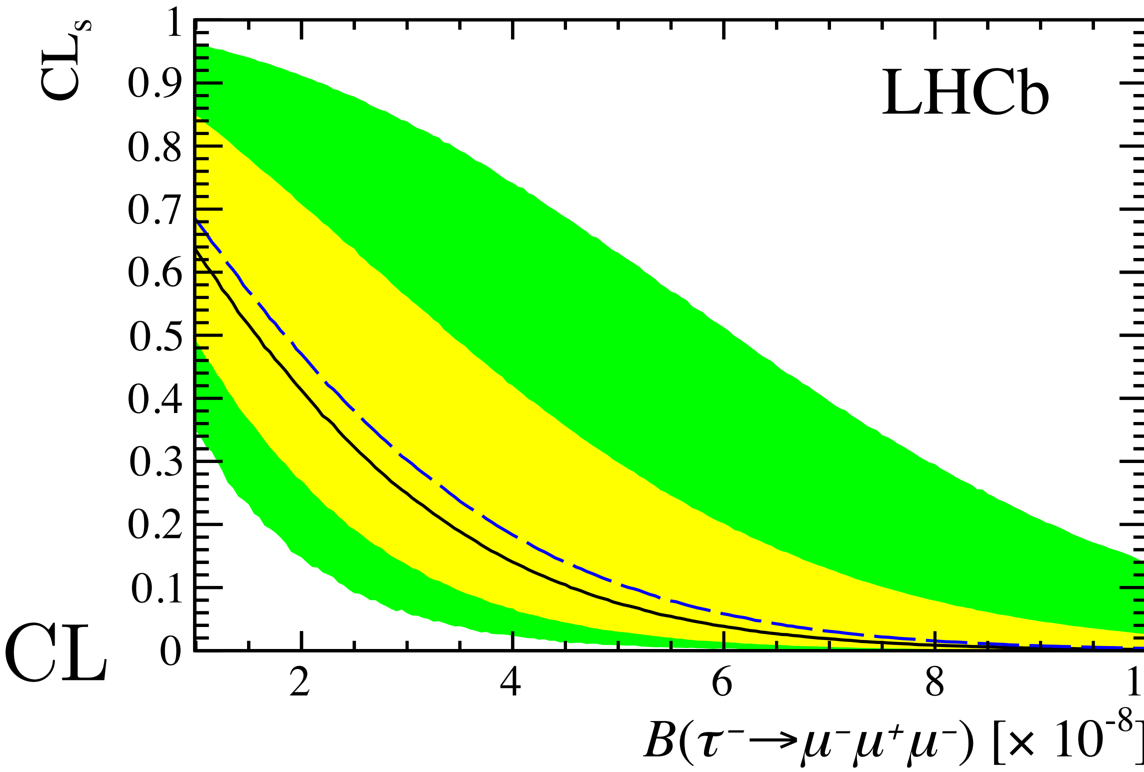
M_{3body} bins:



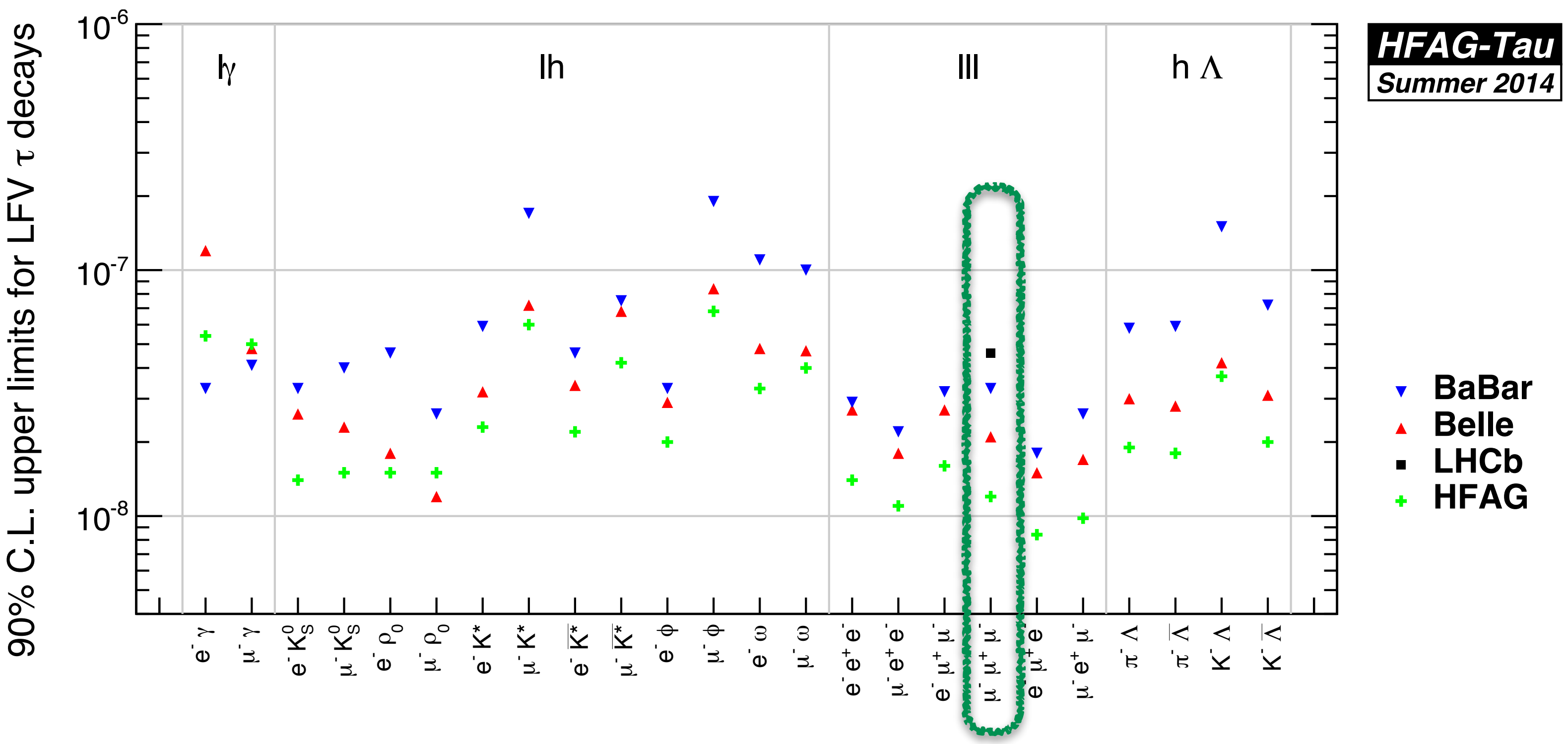
Merged bins:



- No significant excess over the expected background observed
- CL_s method to extract the limit



$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$



Babar[1]:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Belle[2]:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

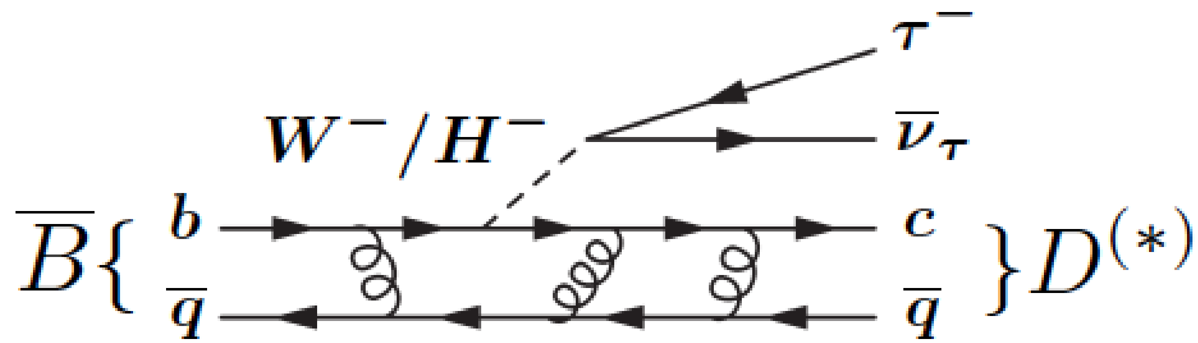
Combined limit improves!

[1] BaBar collaboration, Phys. Rev. D 81 (2010) 111101

[2] K. Hayasaka et al., Phys. Lett. B 687 (2010) 139

$$R(D^*)$$

Objective: measurement of



$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

- SM prediction very clean: 0.252 ± 0.003
- Many NP models foreseen enhanced coupling to the third generation (ex. additional charged Higgs)
- BaBar reported deviations from SM of 2.7σ and 2.0σ for R(D*) and R(D)

Challenges:

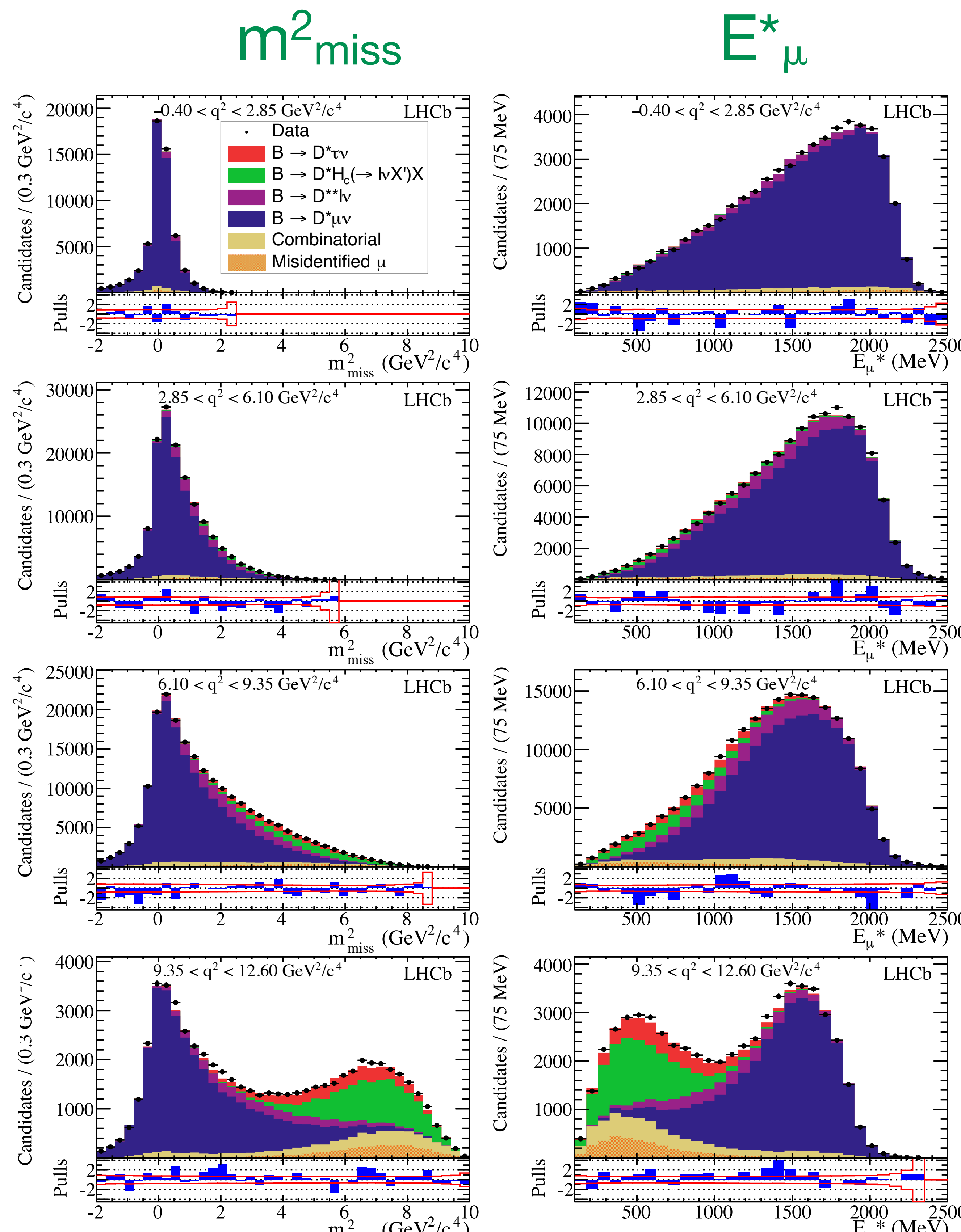
- 3 neutrinos, no narrow peaks to fit ($\bar{B}^0 \to D^{*+}\tau^-(\to \mu^-\nu_\tau\bar{\nu}_\mu)\bar{\nu}_\tau$)
- Main backgrounds: $B \to D^{**}\mu\nu$, $B \to D^* H_C X$ with $H_C \to \mu\nu_\mu X$

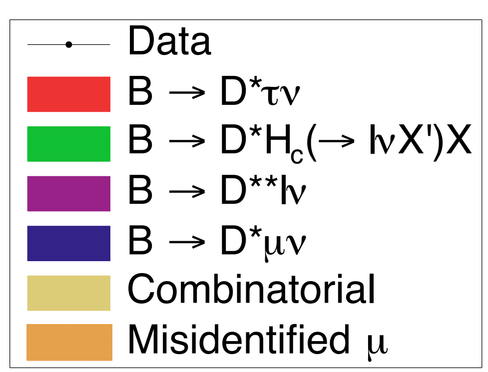
(analysis with $\tau^- \to 3\pi$ in progress)

PRL 115,111883 (2015)

- Same selection procedure for the two channels: $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ + muon
- 3D simultaneous template fit to:
  - $q^2=|p_B-p_D|^2$
  - E^*_μ
  - $m^2_{miss}=|p_B-p_D-p_\mu|^2$
- All uncertainties on the template shapes incorporated in the fit

$$\frac{N(\bar{B}^0\rightarrow D^{*+}\tau^-\bar{\nu}_\tau)}{N(\bar{B}^0\rightarrow D^{*+}\mu^-\bar{\nu}_\mu)} = (4.54\pm0.46)\times10^{-2}$$

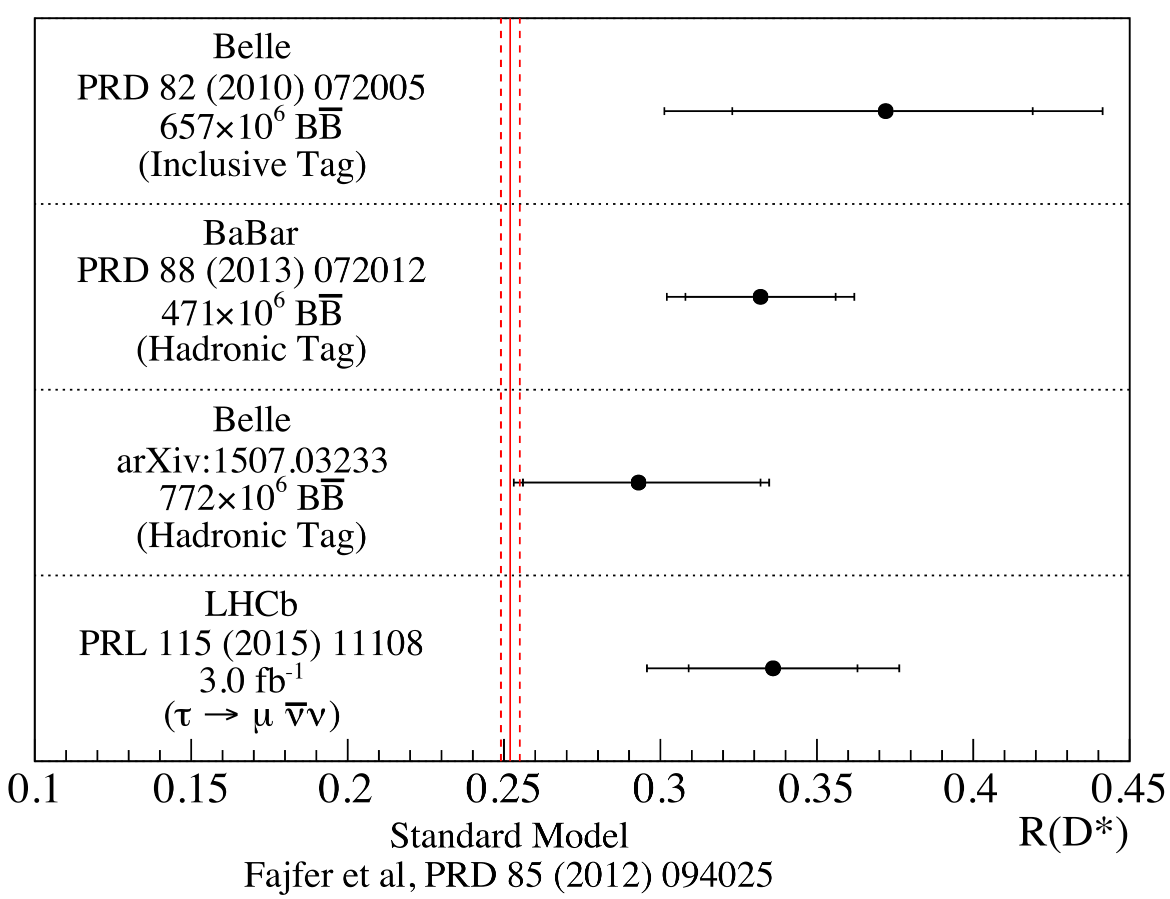


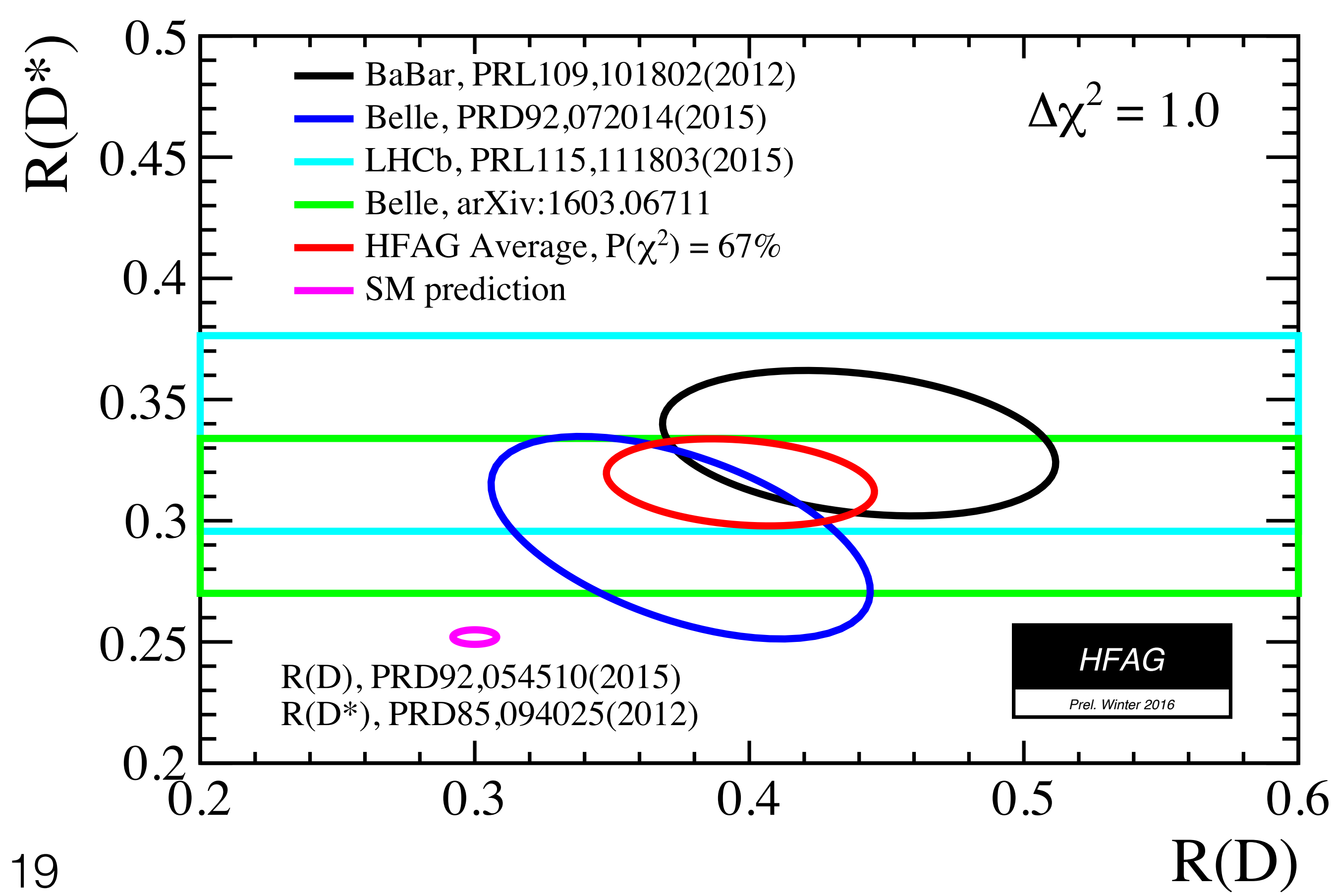


$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

- First measurement at an hadron collider
- 2.1σ larger than the SM expectation
- Good agreement with BaBar and Belle

Current World Average (including the last result by Belle) :4.0σ discrepancy from SM

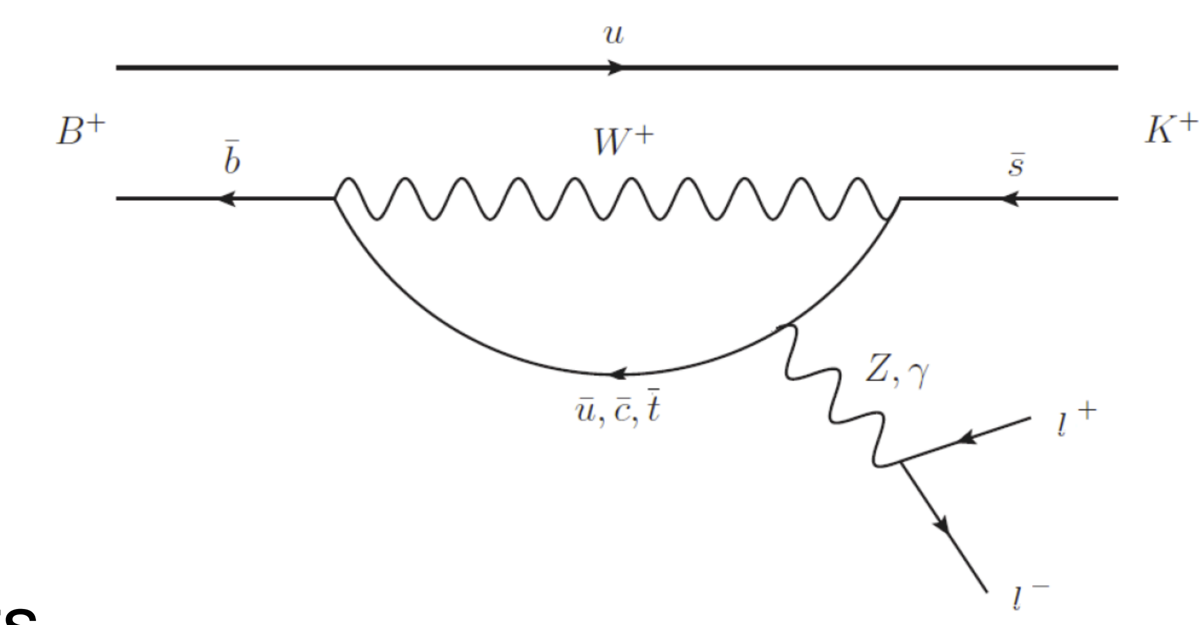




$$R_K$$

Objective: measurement of

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

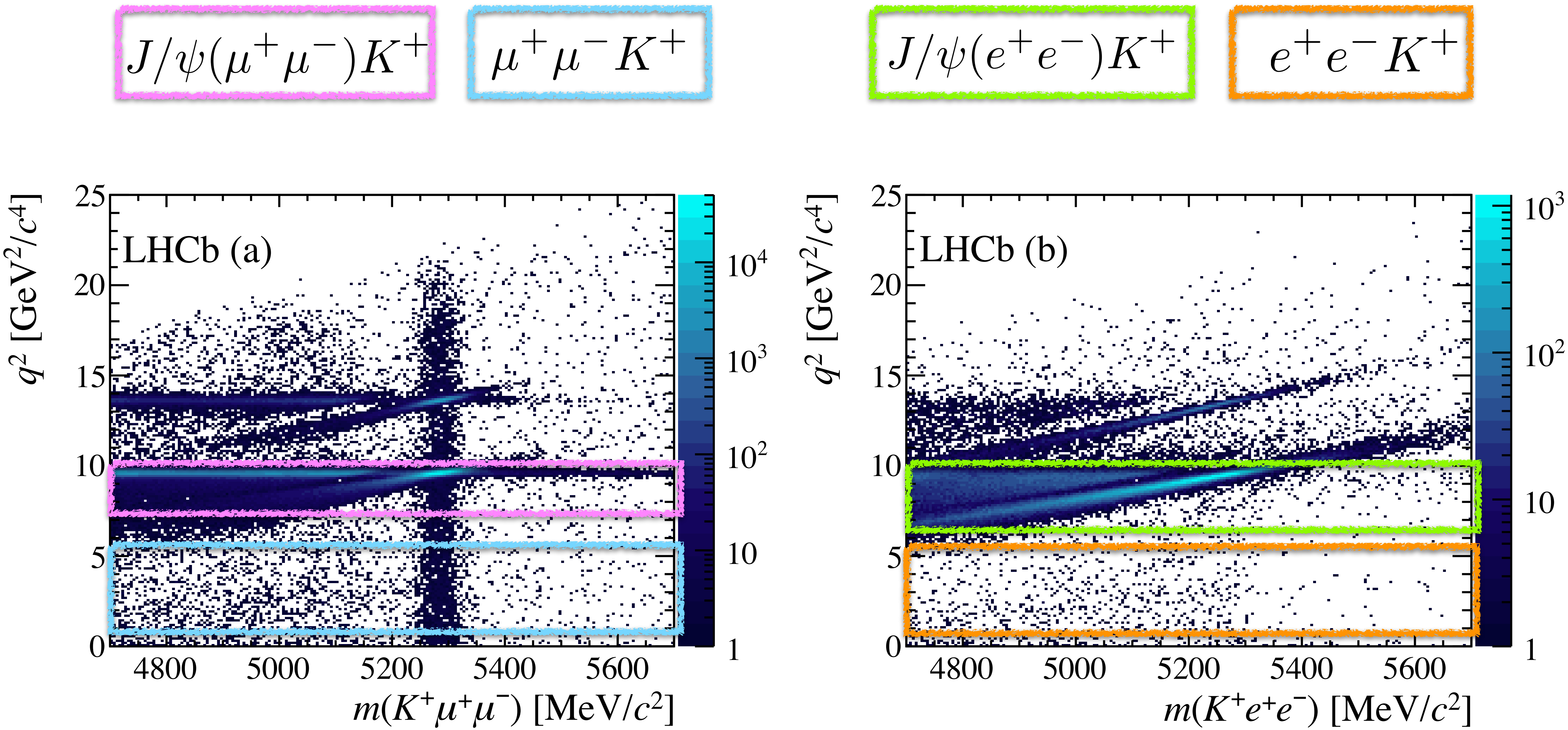


- b→s flavour-changing neutral currents
- Expected to be 1 in the SM (theoretical uncertainty $O(10^{-3})$)
- Highly sensitive to NP (e.g neutral and heavy Z' boson)
- Run I dataset, q^2[1-6] GeV^2/c^4

Measurement relative to $B \to J/\psi(l^+l^-)K$ to reduce systematic uncertainties

$$R_K = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right)\left(\frac{N_{J/\psi(ee)K}}{N_{J/\psi(\mu\mu)K}}\right)\left(\frac{\varepsilon_{Kee}}{\varepsilon_{K\mu\mu}}\right)\left(\frac{\varepsilon_{J/\psi(ee)K}}{\varepsilon_{J/\psi(\mu\mu)K}}\right)$$

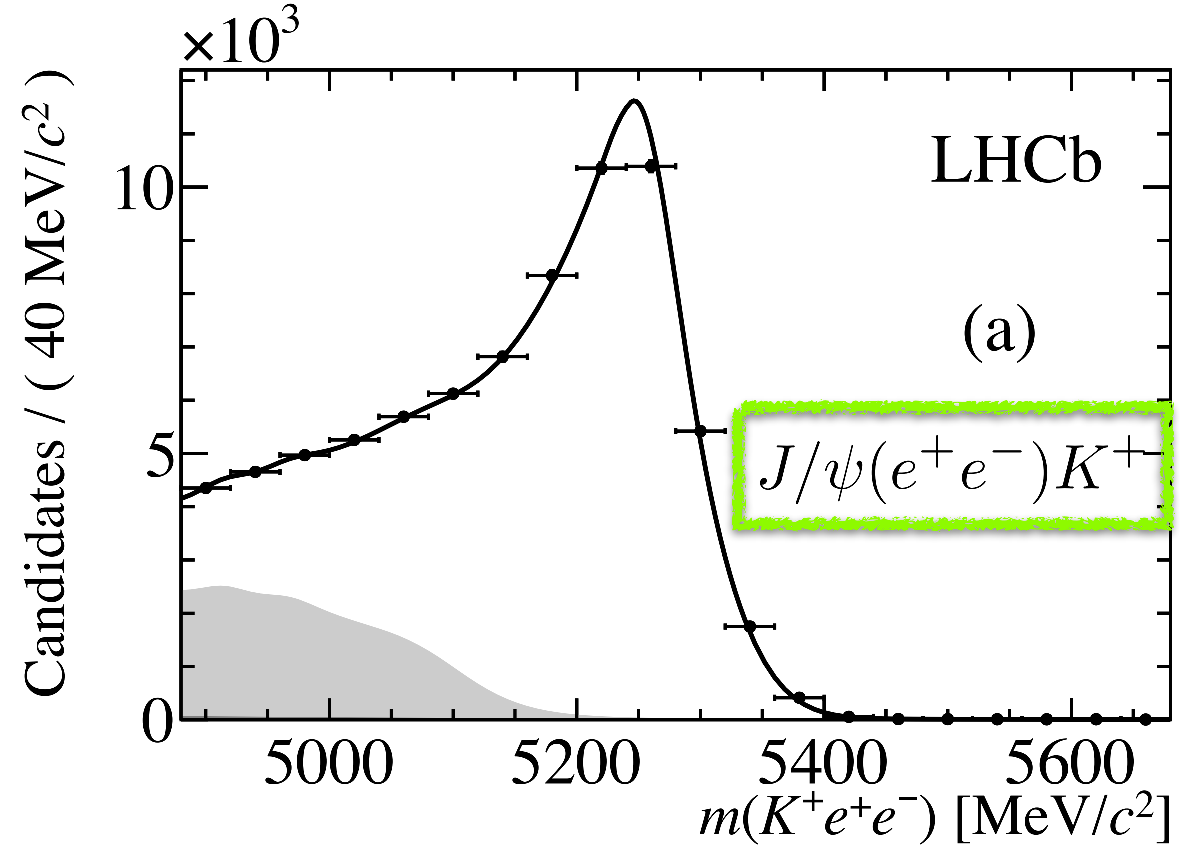
PRL 113, 151601 (2014)

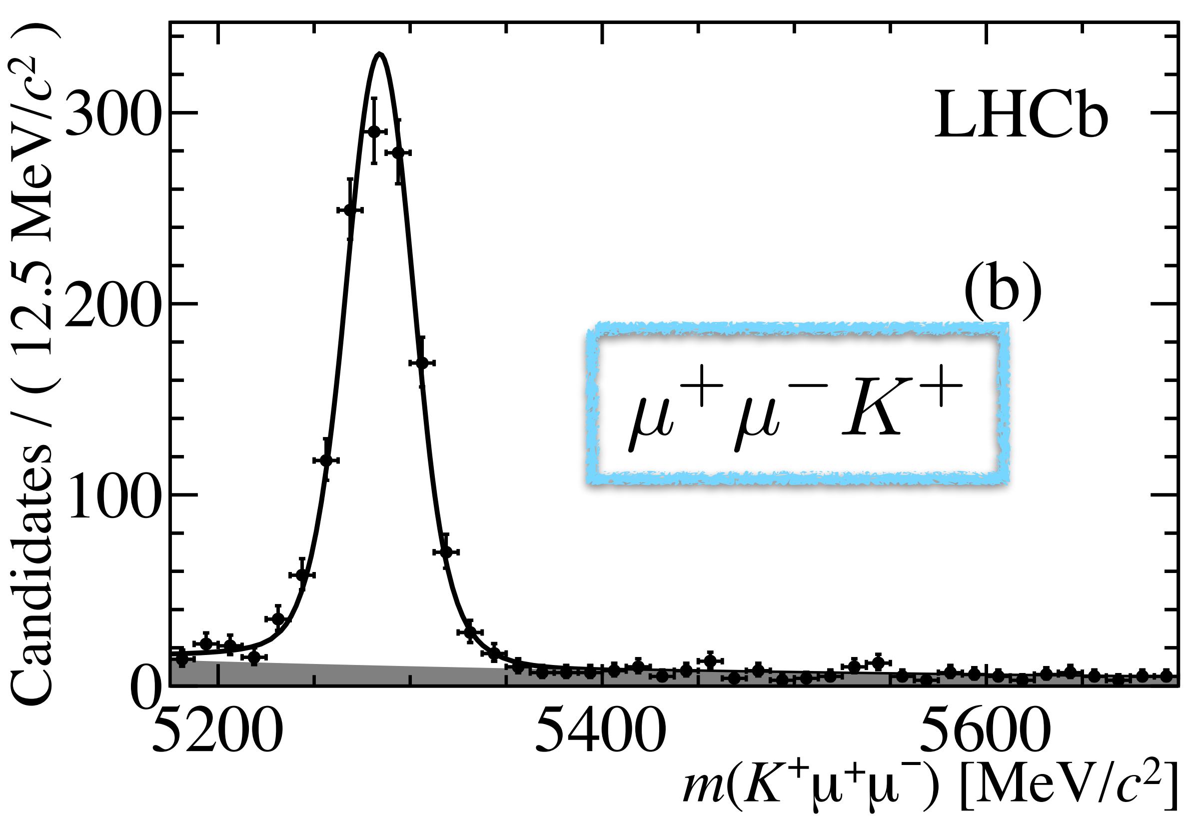


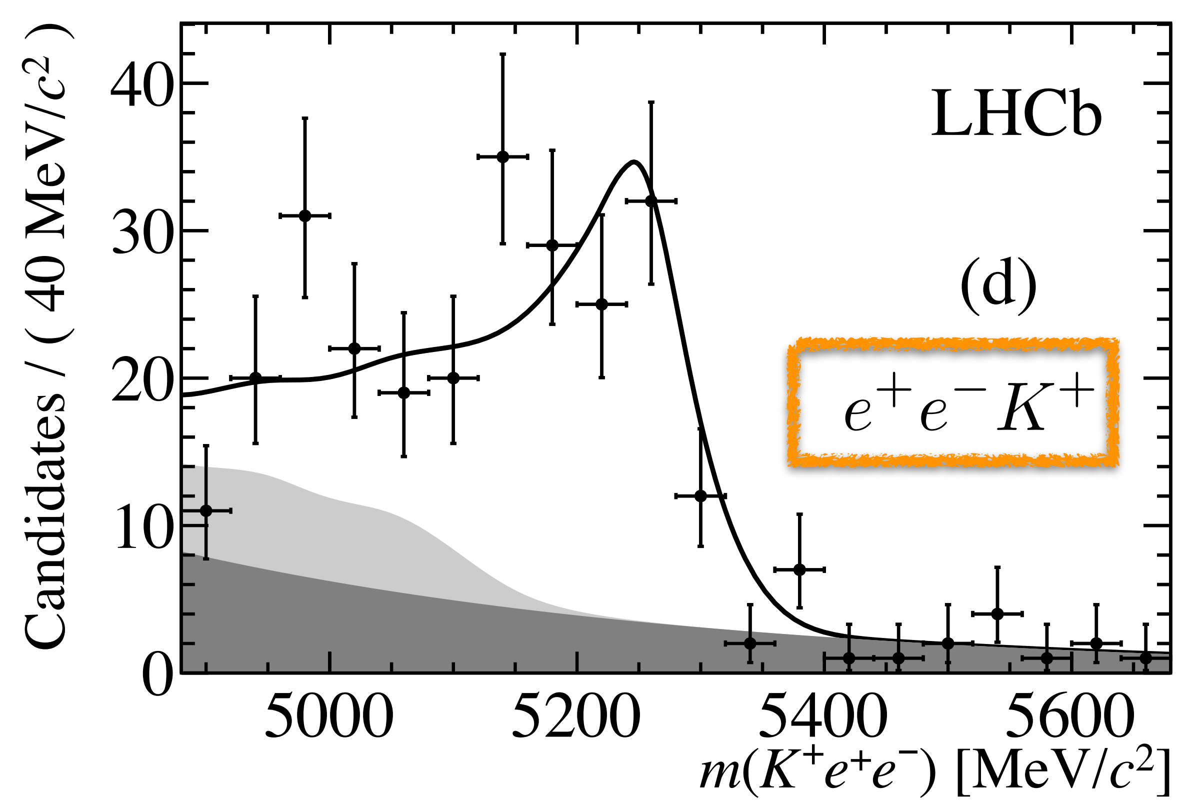
- Diagonal bands due radiative tails
- J/ψ and ψ(2s) peaks

- $B \rightarrow (e^+e^-)K$ events split in three trigger categories
- Bremsstrahlung effects accounted for in the invariant mass shape definition
- Only one category for $B \rightarrow (\mu^+\mu^-)K$ events
- Dominant sources of uncertainties:
  - parametrisation of the J/ψ $(e^+e^-)K$ mass
  - trigger efficiencies estimation

Electron trigger bin





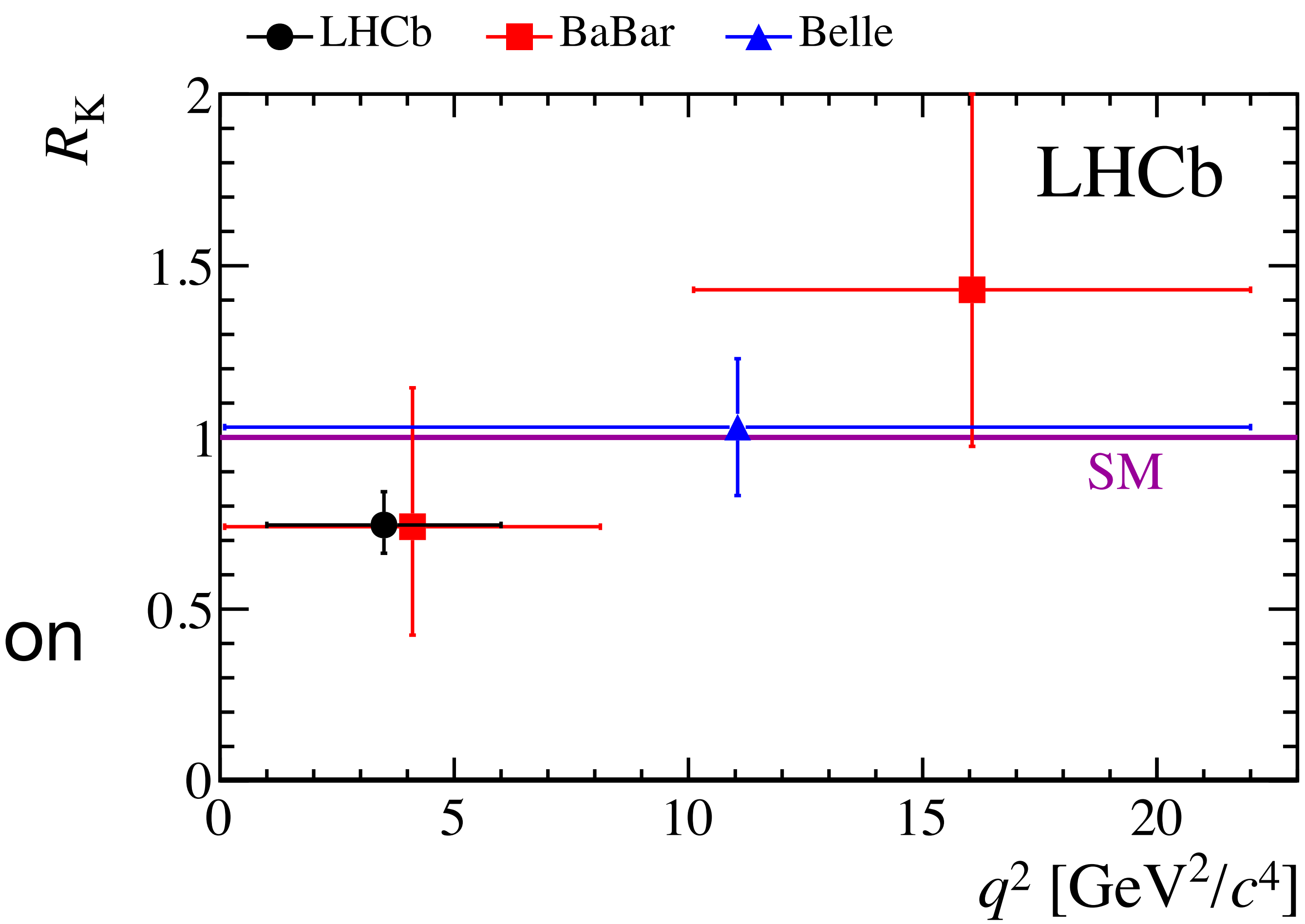


PRL 113, 151601 (2014)

From the combination of the different trigger categories:

$$R(K) = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

- most precise measurement
- compatible at 2.6 σ with SM prediction



Best measurement of the $B \rightarrow e^+e^-K$ branching fraction (compatible with SM predictions):

$$\mathcal{B}(B^+ \rightarrow e^+e^-K^+) = 1.56^{+0.19}_{-0.15}(\text{stat})^{+0.06}_{-0.05}(\text{syst}) \times 10^{-7}$$

Looking forward to RUN II data analysis!

Conclusion

- Test of LU and LFV are crucial for New Physics searches
- LHCb demonstrate to play a crucial role for such studies
  - Best UL for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ set
  - Best UL for $D^0 \to e^{\pm}\mu^{\mp}$ set
  - Most precise measurement of R(D*) and R_K
- Many other analysis currently ongoing in LHCb

Looking forward to new results and to analysis with LHC RUN II data!!