Review of the flavour anomalies at LHCb

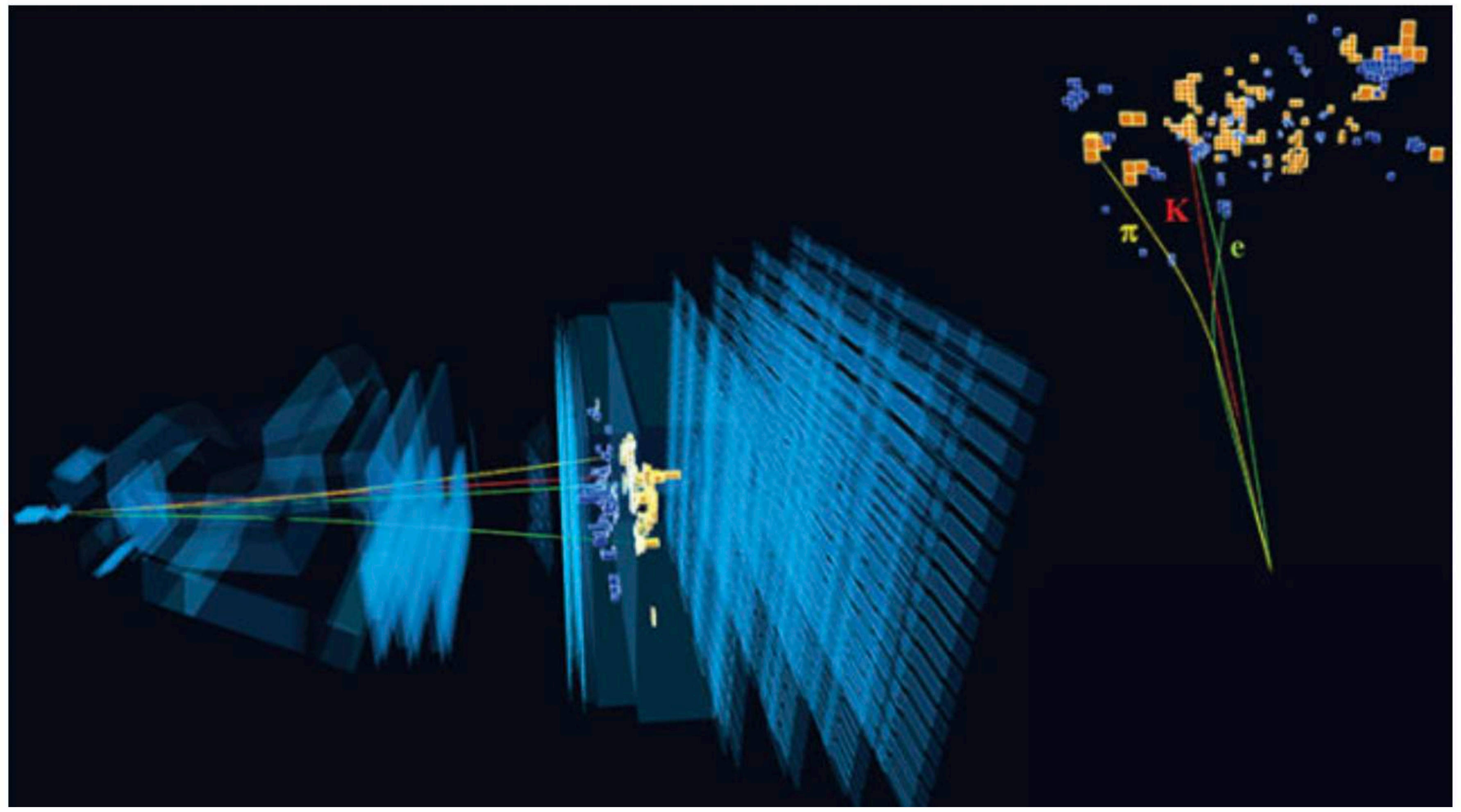
SPS/ÖPG joint meeting, Innsbruck

13:30	【301】Flavour anomalies in b -> sll meson decays: a review - Elena Graverini (EPFL - Ecole Polytechnique Federale Lausanne (CH)) (Room B) hello.pdf
13:45	【302】Lepton flavour universality tests in charged-current b-quark decays - Annarita Buonaura (Universität Zürich (CH)) (Room B) TestsOfLFUinSemiLdecays_CHIPP_2021_ABuonaura.pdf
14:00	【303】Discovering Lepton Flavour Universality Violating New Physics - Andreas Crivellin (Universitaet Zuerich (CH)) (Room B) SPS2021.pdf SPS2021.pptx
14:15	【304】On R_{K} and the global significance of new physics in $b \rightarrow s \ell \ell$ decays - Davide Lancierini (Universitaet Zuerich (CH)) (Room B) [SPS_ÖPG][2021]_Lancierini.pdf
14:30	【305】A new approach in the search for New Physics in b→sl+l- decays - Michele Atzeni (Universitaet Zuerich (CH)) (Room B) MA_SPSOPG_2021.pdf
14:45	【306】Angular analysis of $B^{0} \to K^{*0} e^{+}e^{-}$ decays at LHCb - Zhenzi Wang (Universitaet Zuerich (CH)) (Room B) Zhenzi_Wang_presentation.pdf
15:00	【307】Test of lepton flavour universality in $B^+ \to K^+l^+l^-$ decays in high dilepton invariant mass squared region - Mr Vadym Denysenko (Universitaet Zuerich (CH)) (Room B) rk@highq2-sps-innsbruck.pdf
15:15	【308】Search for New Physics in baryons decay at LHCb - Martina Ferrillo (Universitaet Zuerich (CH)) (Room B) MFerrillo_SPSOPG_Innsbruck_2021.pdf
15:30	【309】Search for Lepton Flavour Universality Violation at CMS - Federica Riti (ETH Zurich (CH)) (Room B) Rjpsi_SPS.pdf
15:45	【310】Highlights from CP-violation in B-decays and Lepton Flavour violation measurements with the ATLAS experiment - Emmerich Kneringer (University of Innsbruck (AT)) (Room B) talk_v4.pdf

Intriguing new result from the LHCb experiment at CERN

The LHCb results strengthen hints of a violation of lepton flavour universality

23 MARCH, 2021



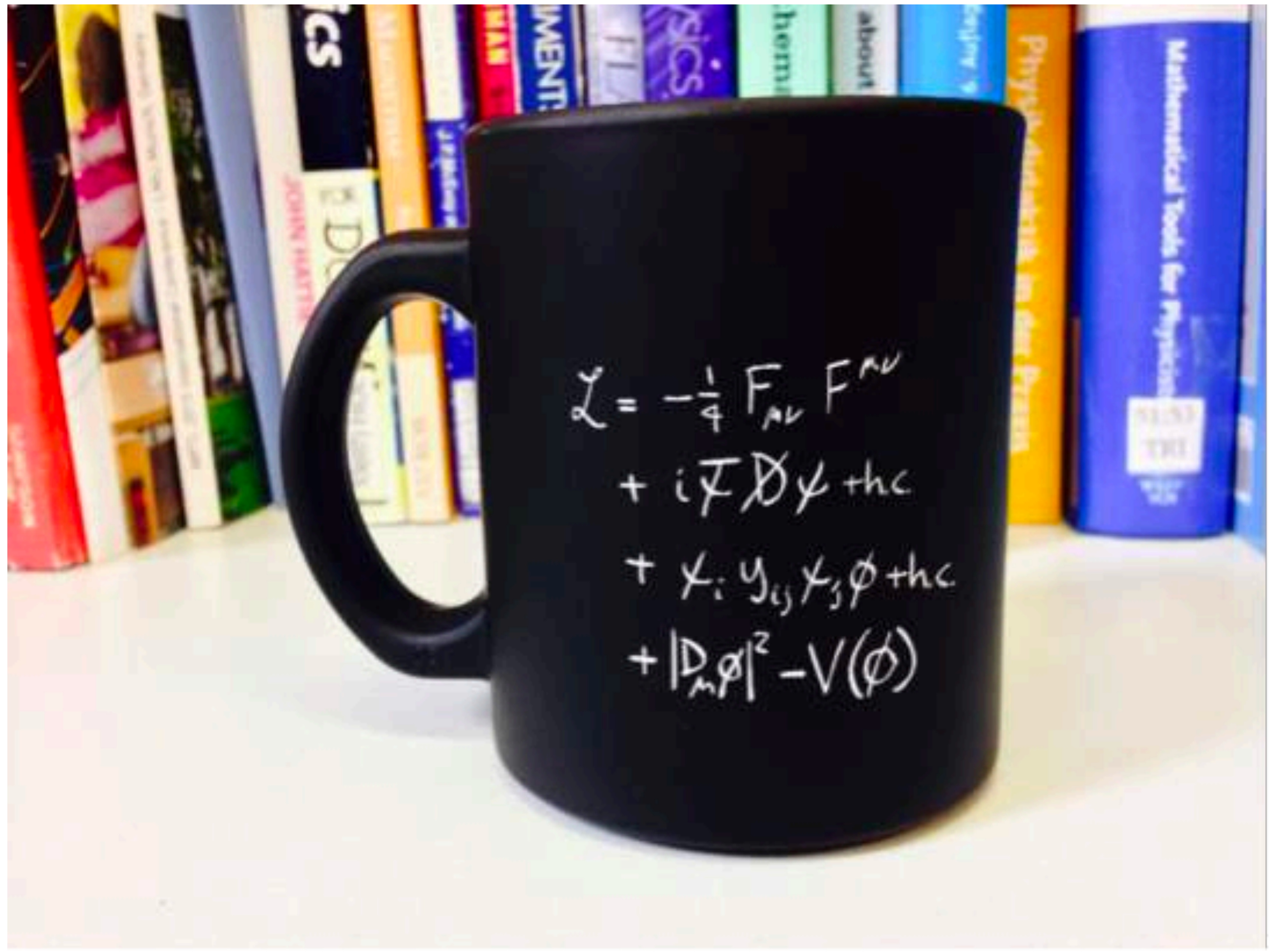
Patrick Owen

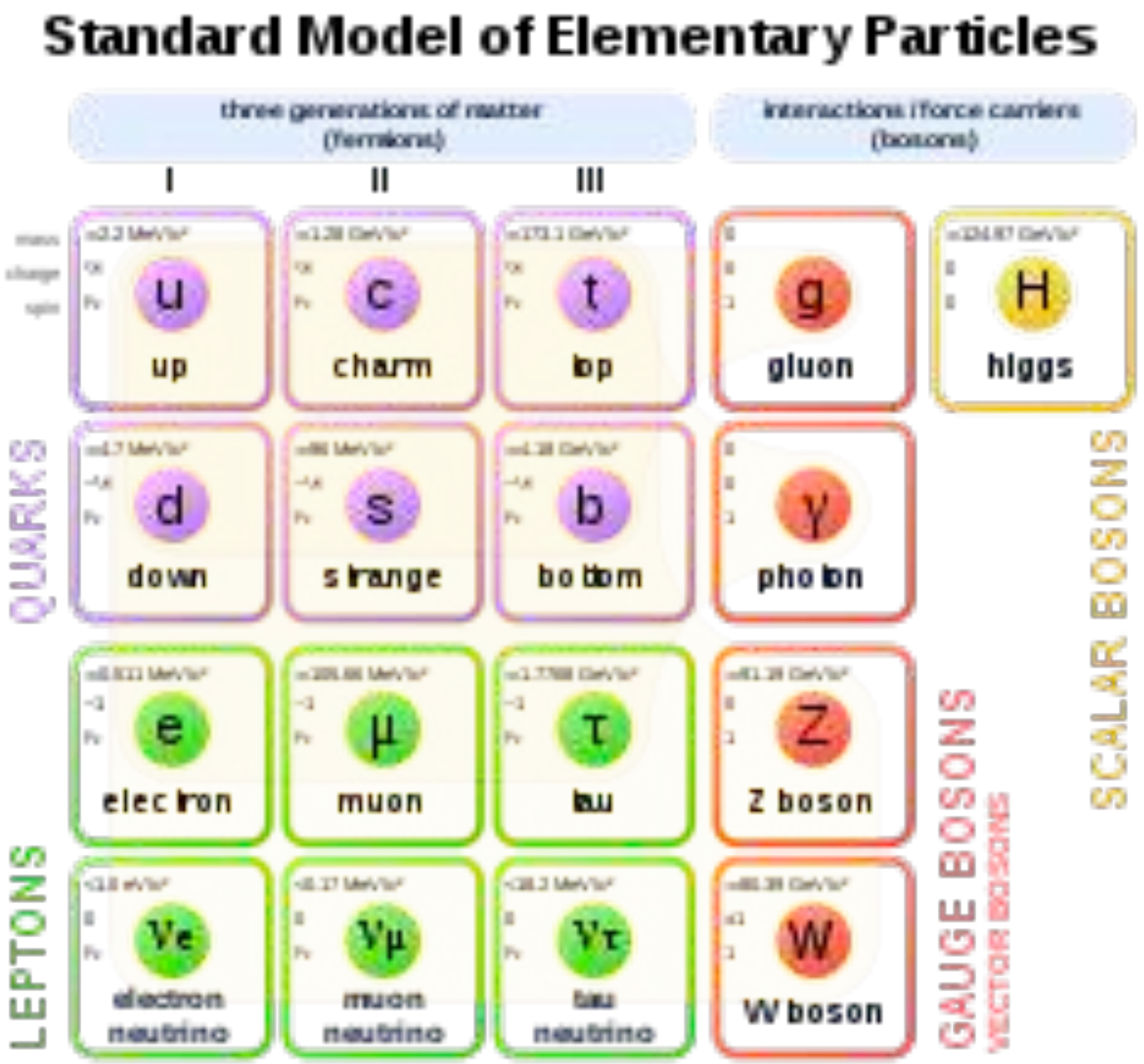
Universität Zürich UZH

02/09/21

The Standard Model

- Vast majority of our knowledge of particle physics encoded in theory known as the Standard Model (SM).





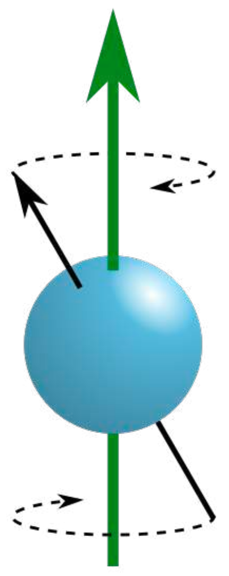
- It describes sub-atomic interactions of fermions via the exchange of force carries (bosons).

The dual state of the Standard Model

- The Standard Model is simultaneously a roaring success and a catastrophic failure.

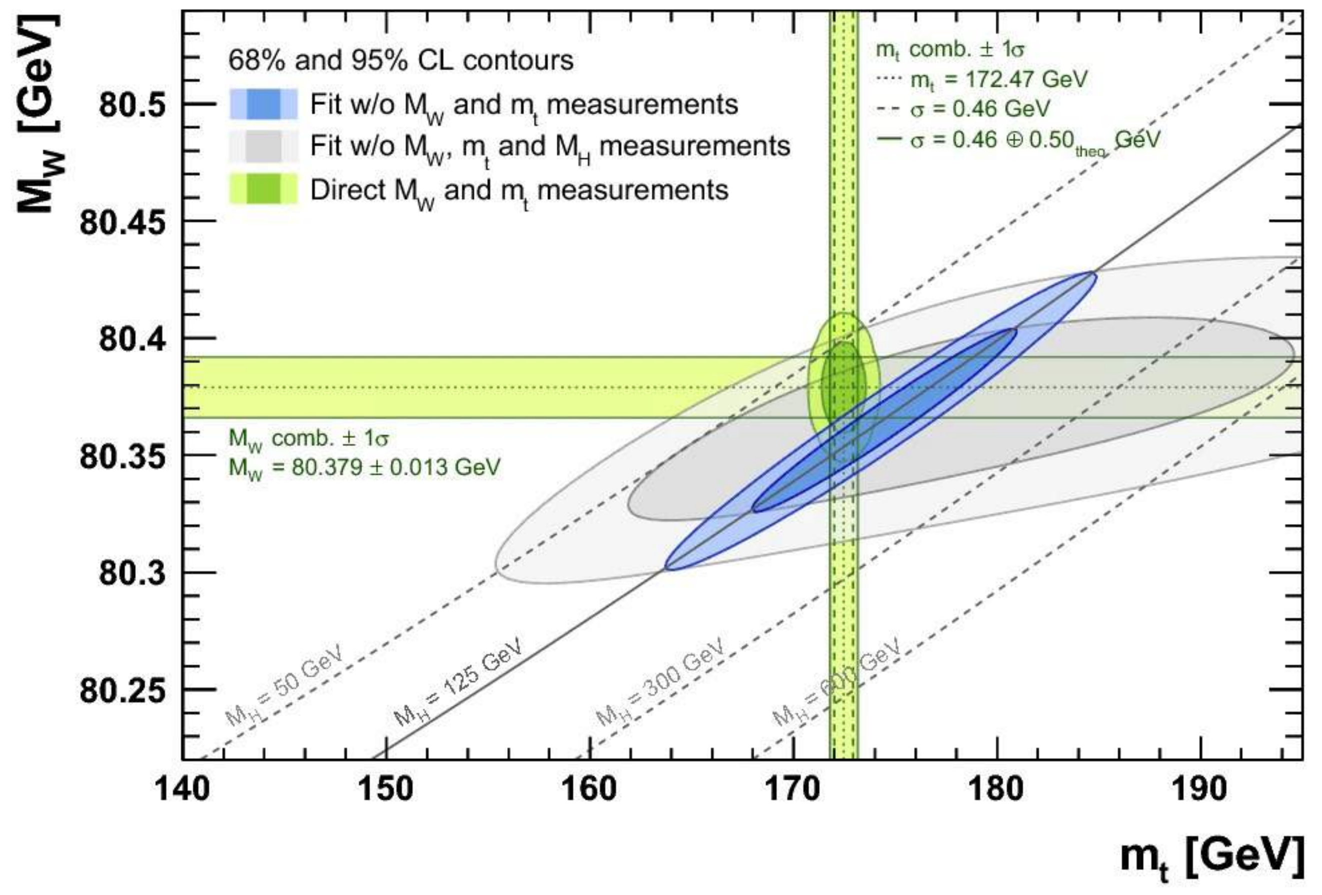
QED verified to 11 decimal places

$$a_e = 0.001\ 159\ 652\ 181\ 643(764) \quad \text{(th)}$$
$$a_e = 0.001\ 159\ 652\ 180\ 73(28) \quad \text{(expt)}$$

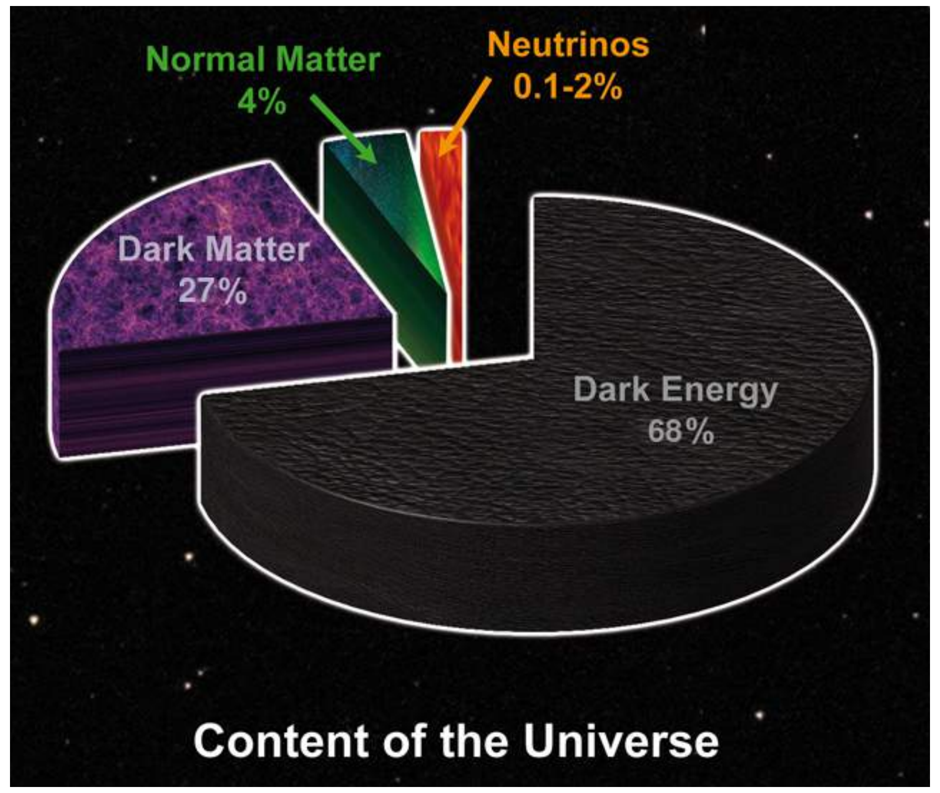


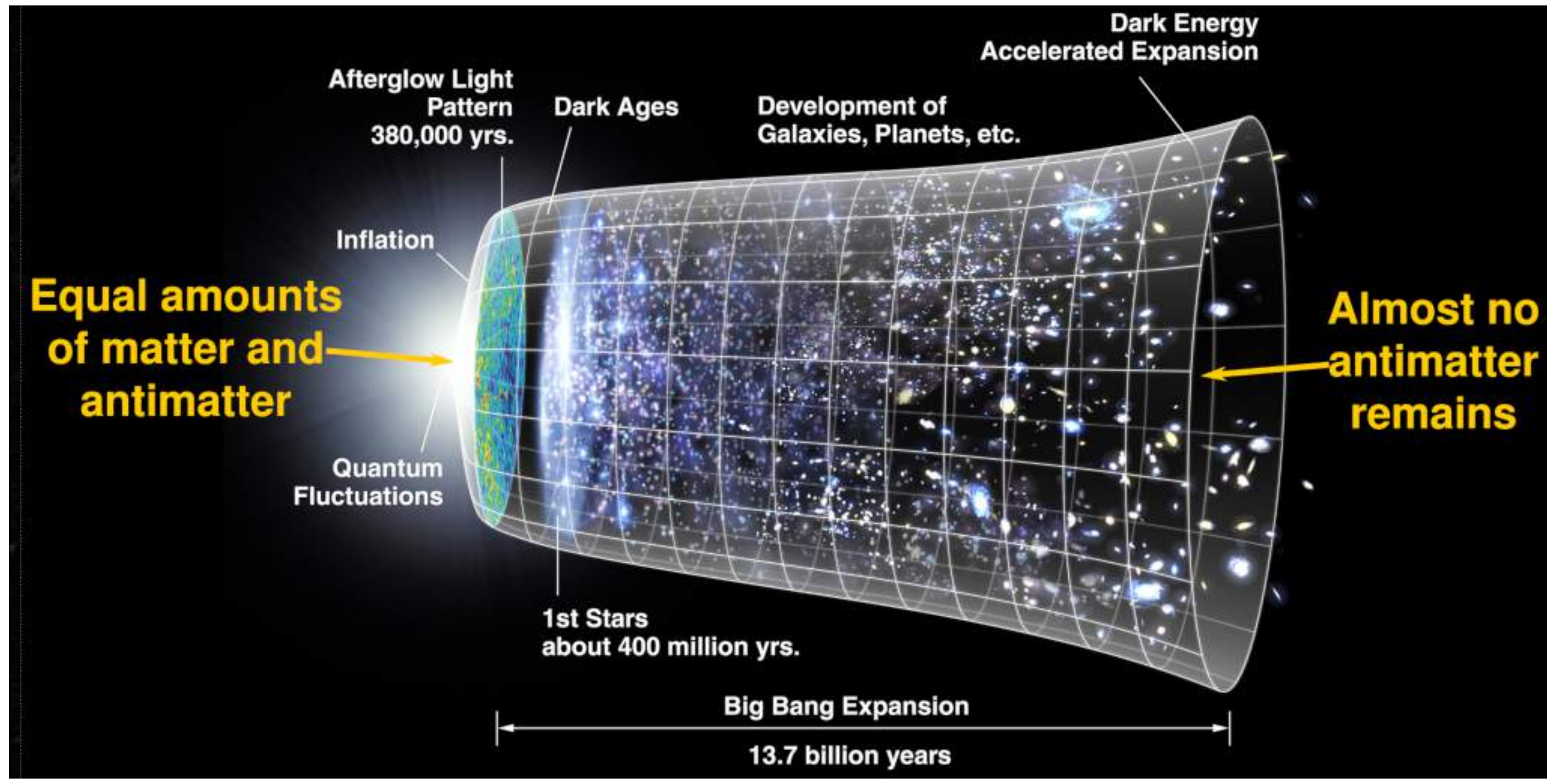
Electroweak theory still consistent under high precision scrutiny

EPJC 78, 675 (2018)



Only small fraction of universe accounted by SM particles.



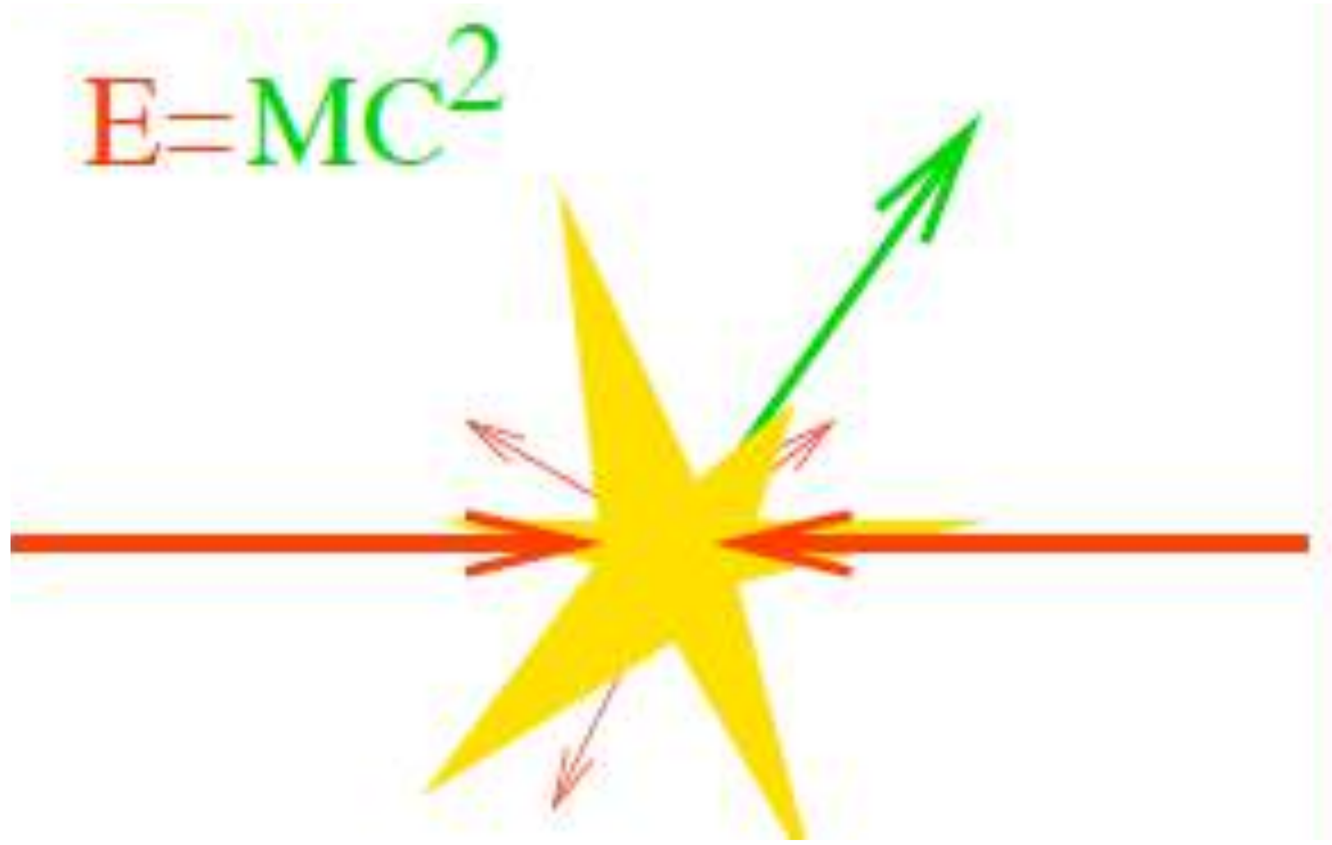


- The search for so-called 'new physics' is therefore highly compelling.

Ways to search for new physics

Direct detection

Search for particles directly produced in high energy beams.



Indirect searches

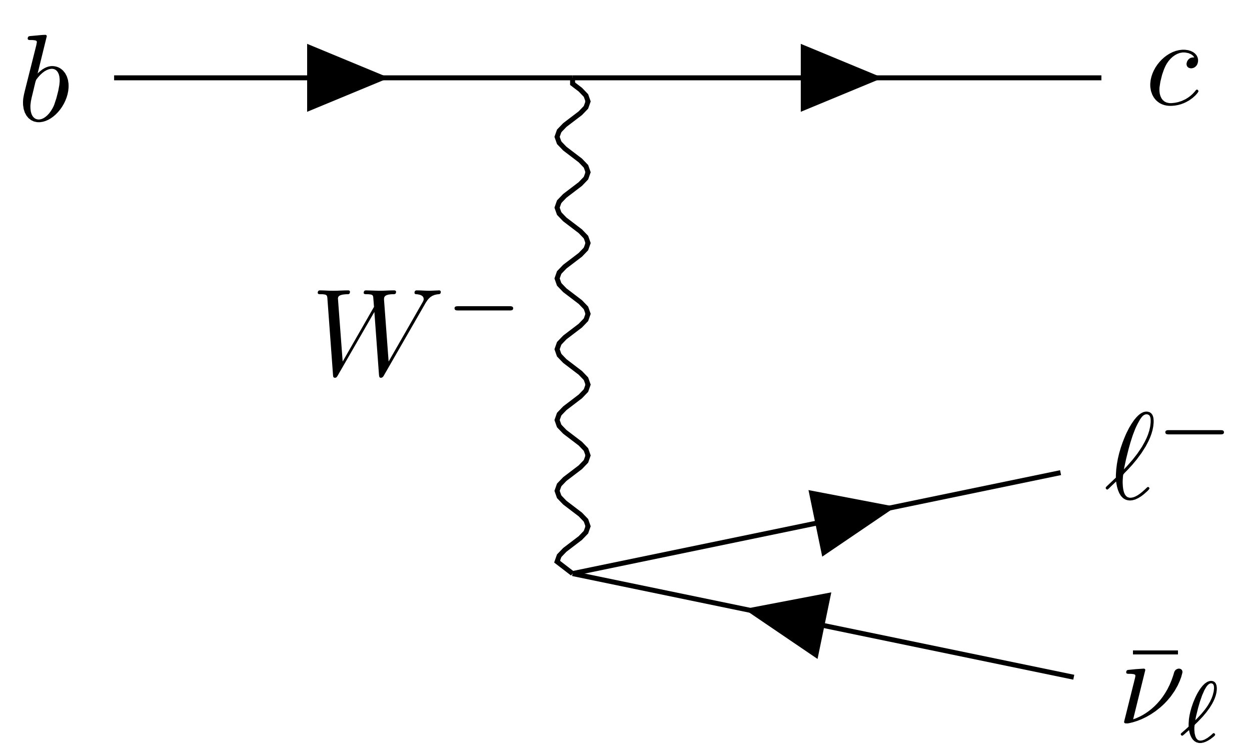
Measure the behaviour of SM particles and compare it to theoretical predictions.

The absence for evidence of new physics in direct searches does not preclude the possibility to find it indirectly.

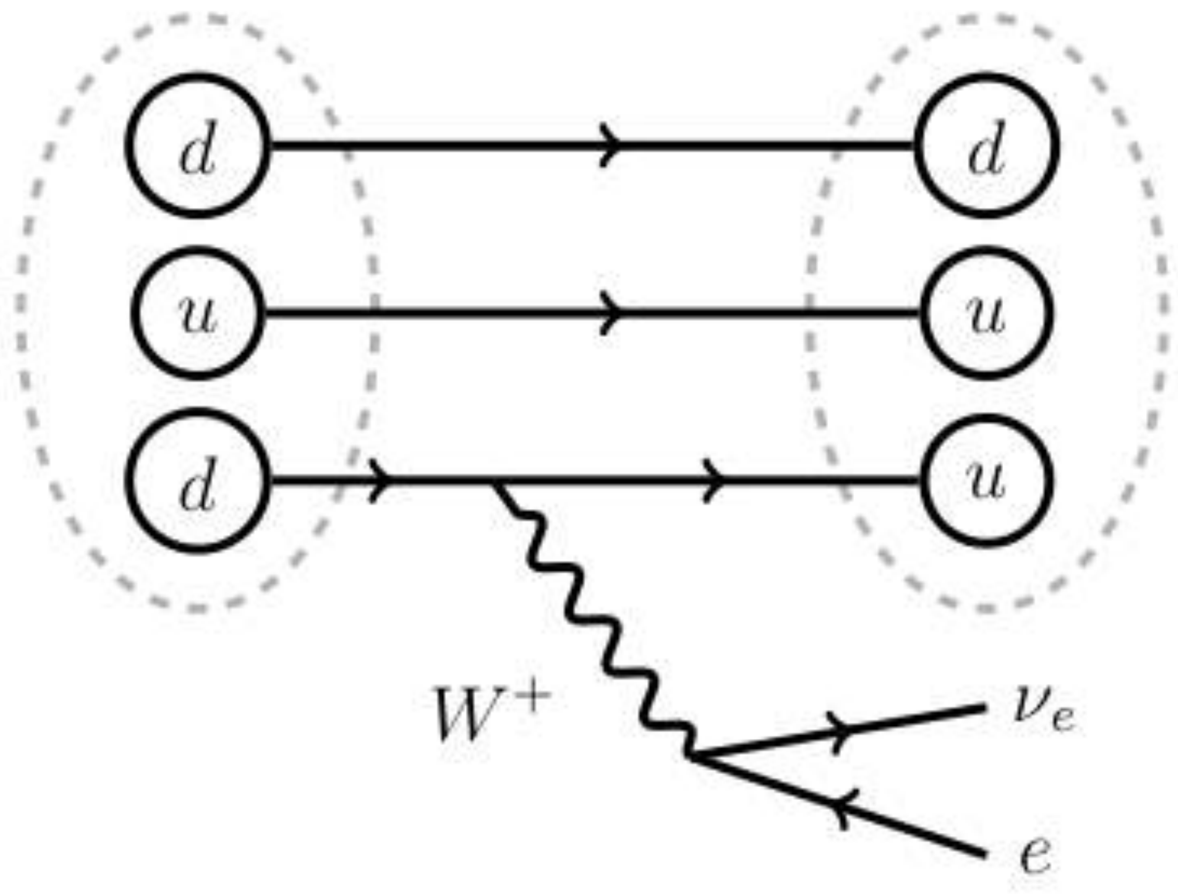
New physics with beauty quarks

- Beauty quarks decay via the weak force.

Beauty quark decay



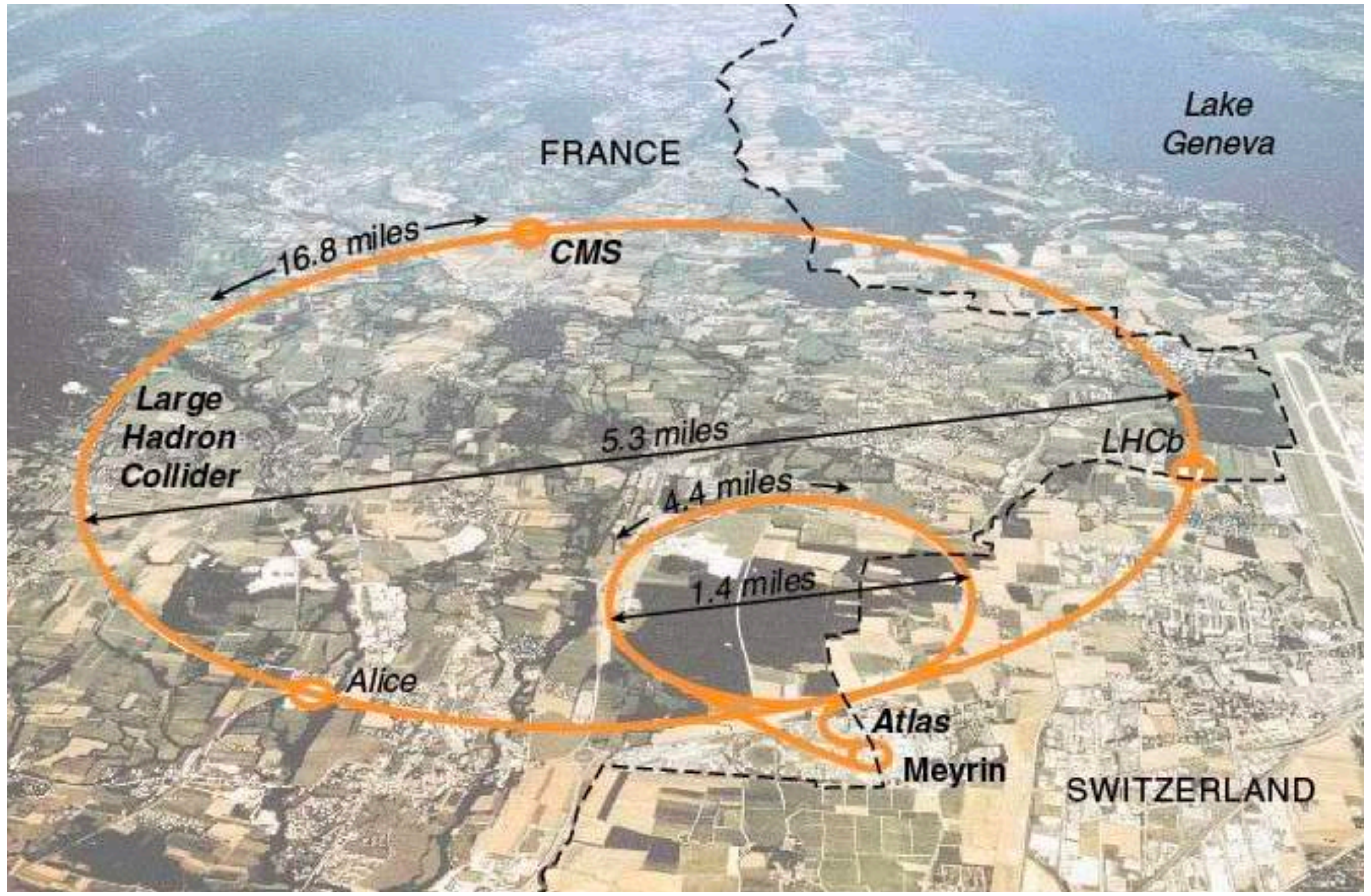
Beta decay

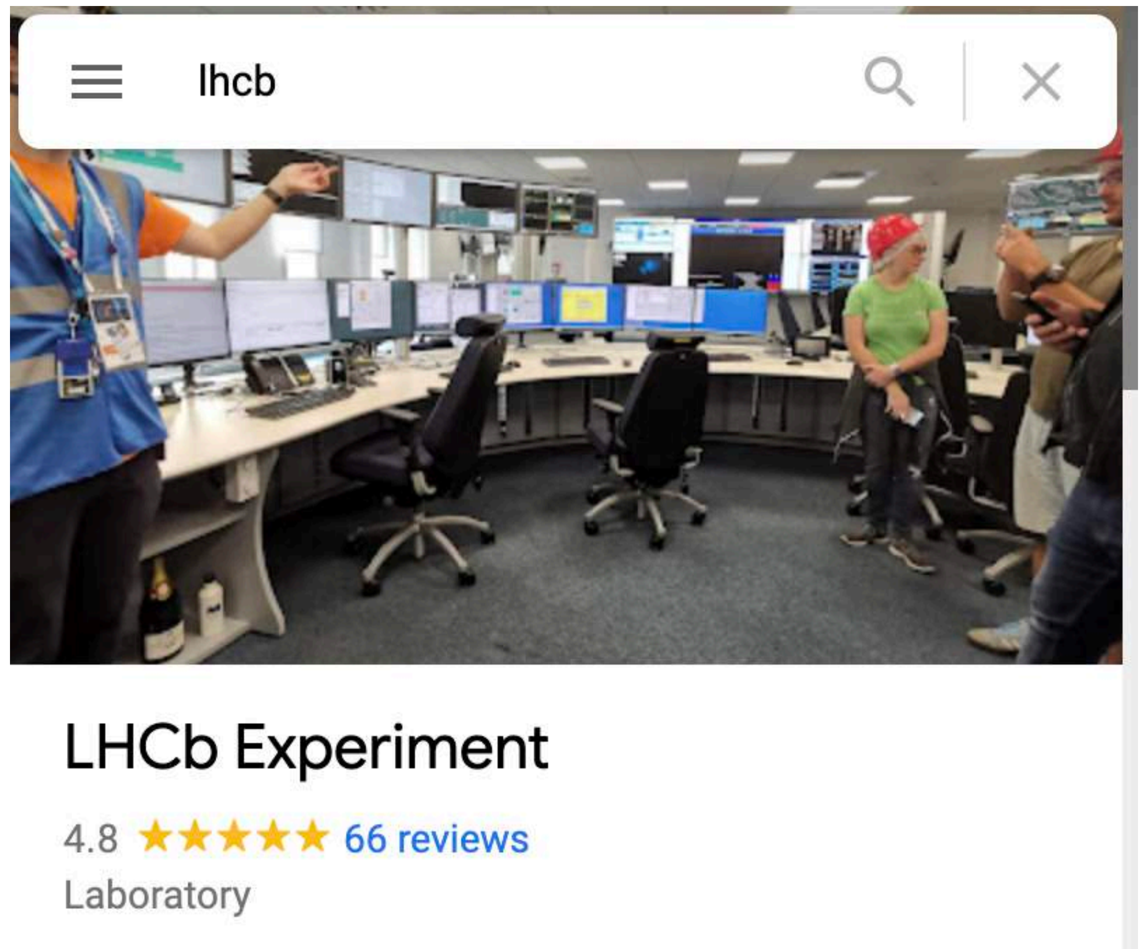


- The W and Z bosons are over 10 times heavier than the initial decaying b-hadron, but still mediate the decay.
    - Measuring beauty quark decays can tell us about new high mass particles.
    - Such particles can change the behaviour of these decays.

The LHCb experiment

- LHCb is the LHC’s dedicated flavour physics experiment.





Your review

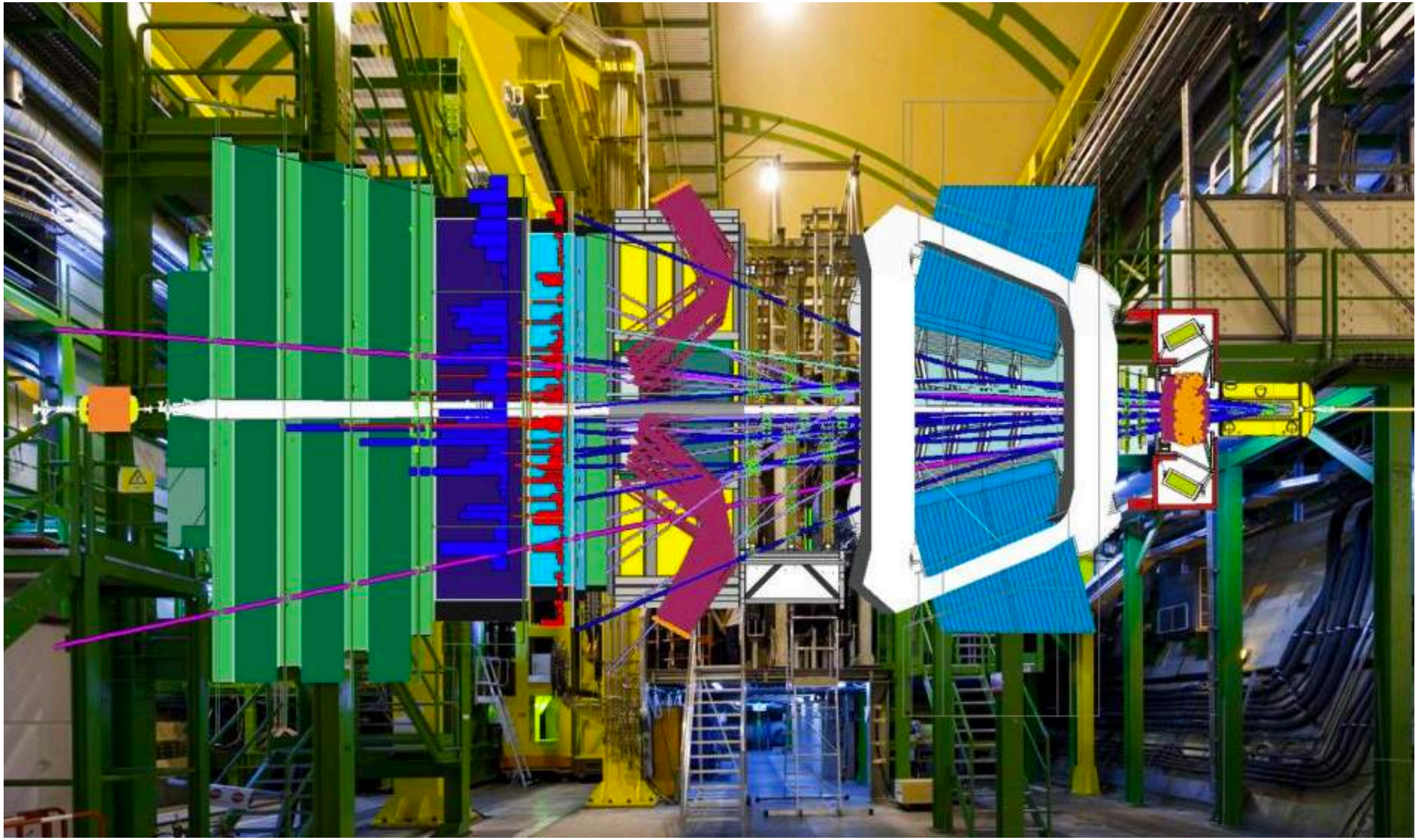
Patrick Owen
10 reviews

★★★★★ 2 years ago

Fantastic experiment ran by fantastic people. 10/10 would recommend to a friend if they fancied doing a bit of flavour physics

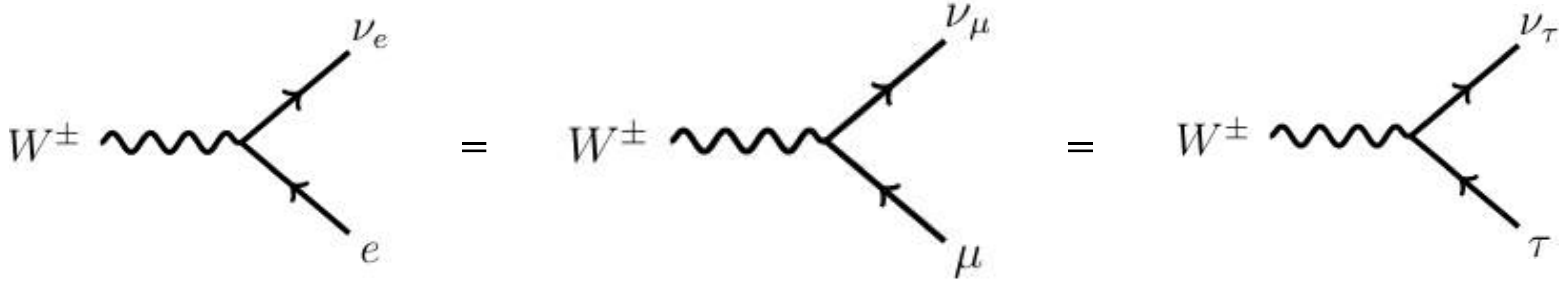
Visited in June 2019

The LHCb experiment



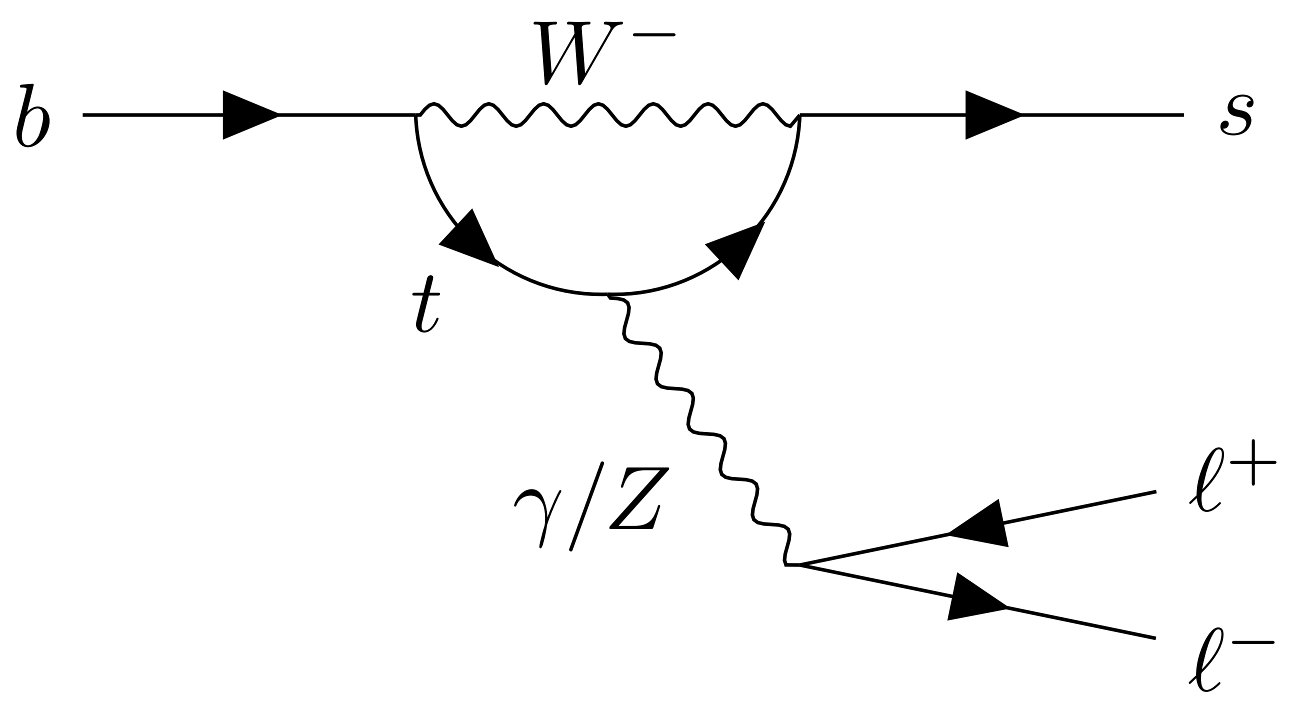
Lepton universality

- Lepton universality is an accidental symmetry in the Standard Model.

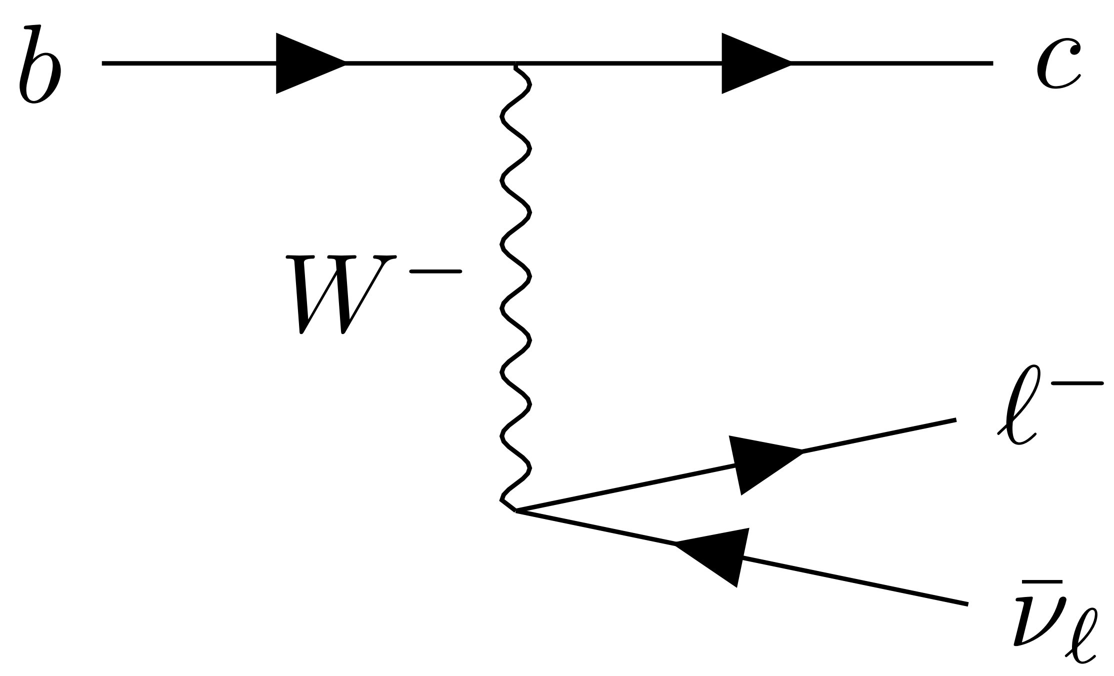


- At LHCb, we want to test it with so-called ‘semileptonic decays’.

Neutral current: BF ~ 10^{-6}



Charged current: BF ~ 10^{-2}



- Compare the decay probabilities (BF) involving different charged lepton types ℓ^-.

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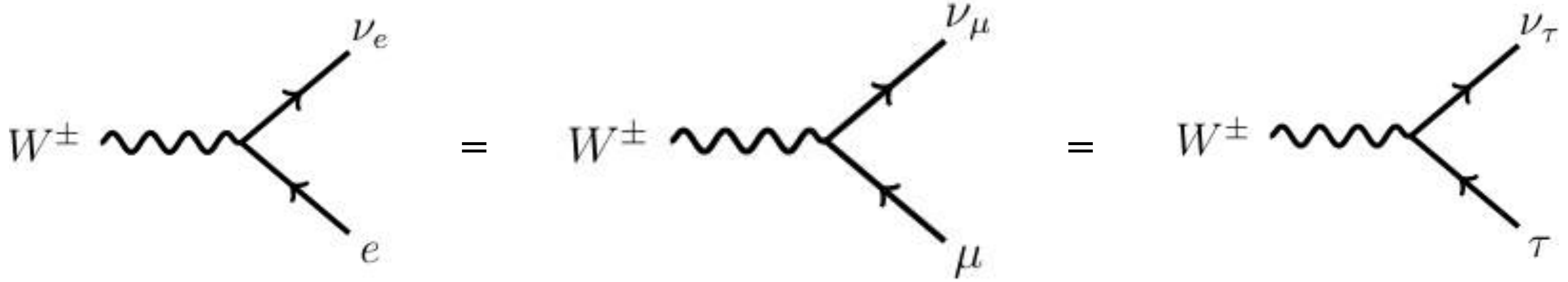

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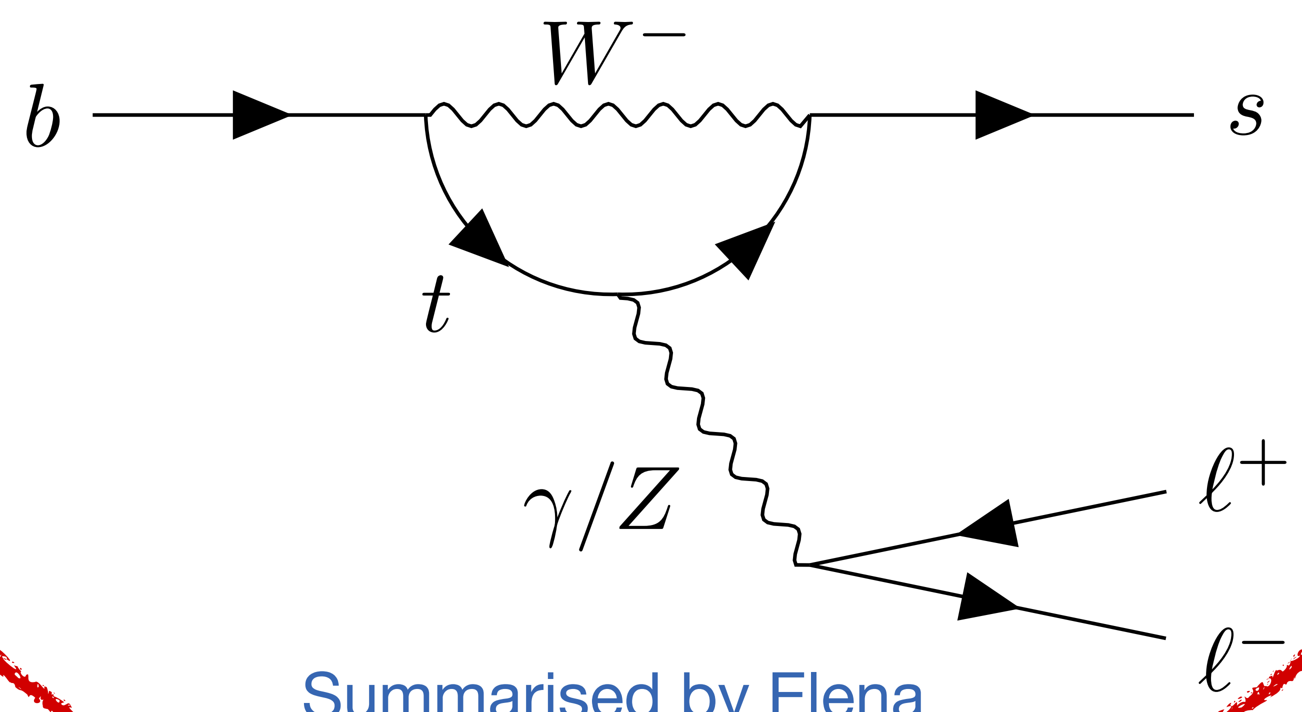
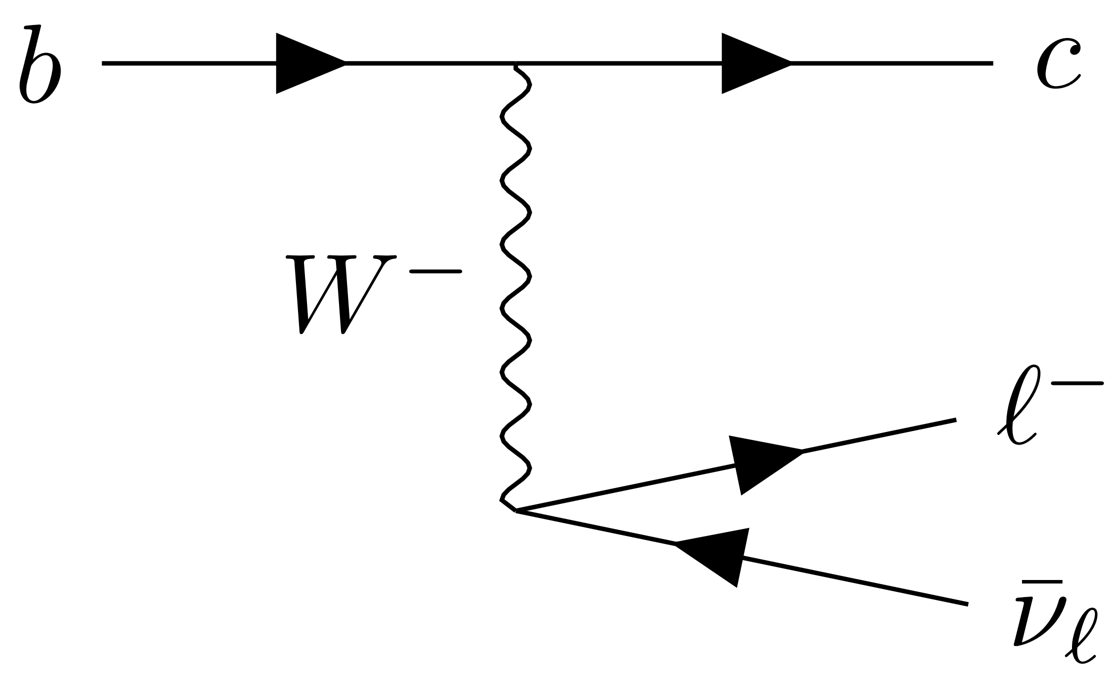


[Summarised by Elena Graverini (EPFL)]

Charged current: BF ~ 10^{-2}

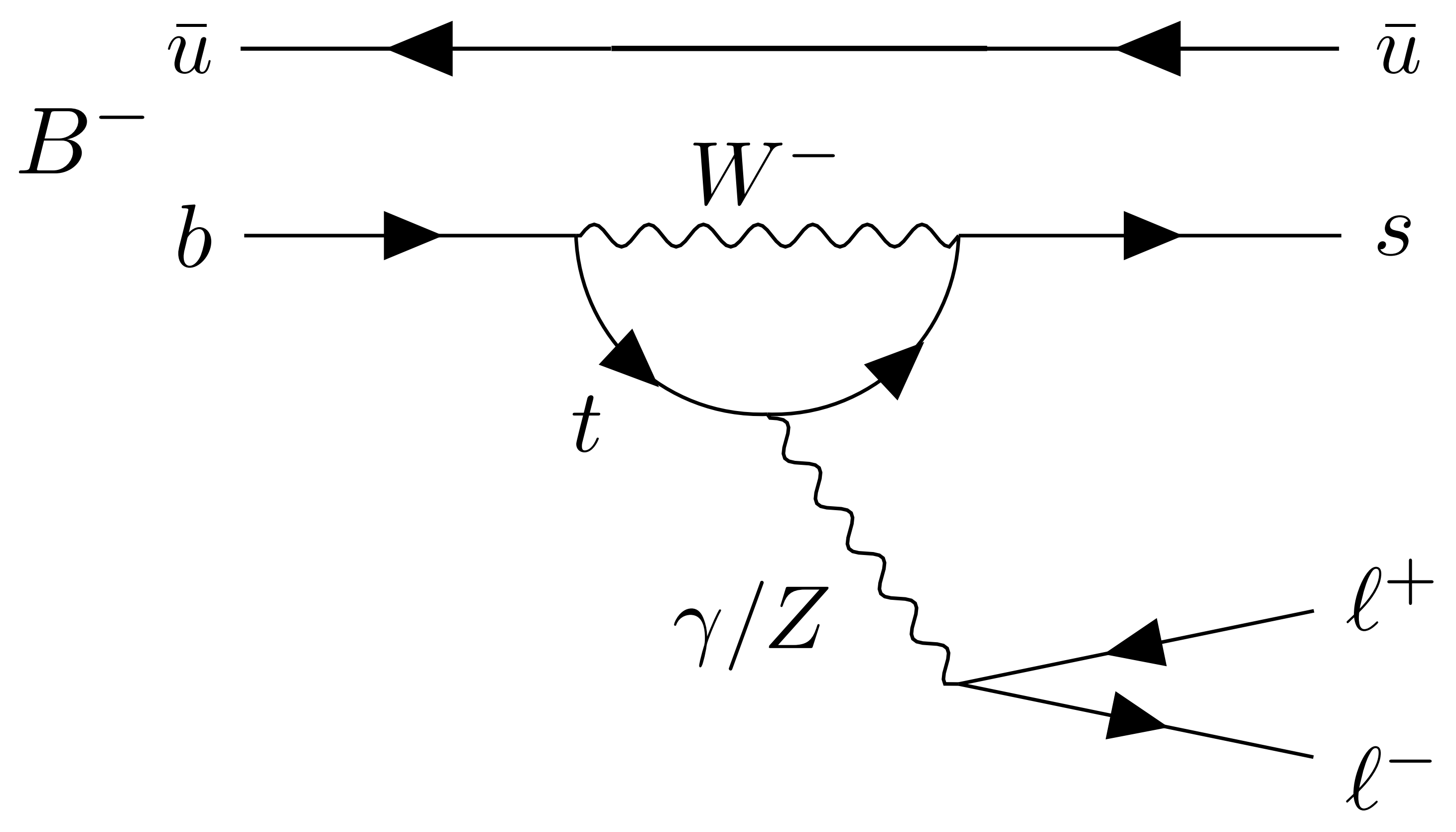


- Compare the decay probabilities (BF) involving different charged lepton types ℓ^-.

The lepton universality ratio R_K

[Discussed by Davide Lancierini (UZH)]

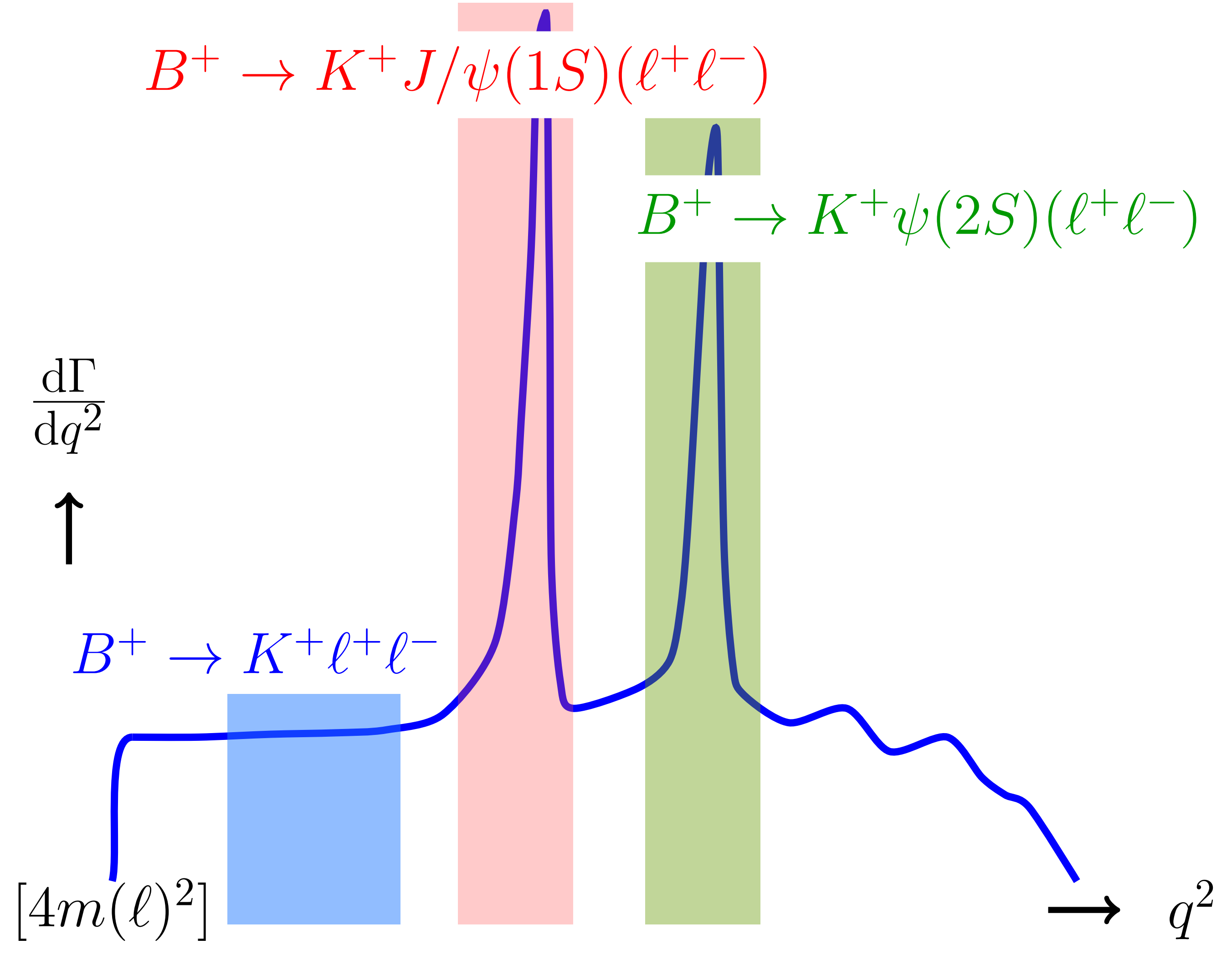
- Quarks never appear by themselves, detect bound states as mesons (qq) or baryons (qqq).



- Take ratio of decay probabilities involving muons and electrons to form R_K.

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

- Important kinematic quantity: $q^2 = m_{\mu\mu}^2$.
- Select signal in the low q^2 region.
- Resonant enhancement from $c\bar{c}$ mesons.



$J/\psi(1S)$ Decay Modes

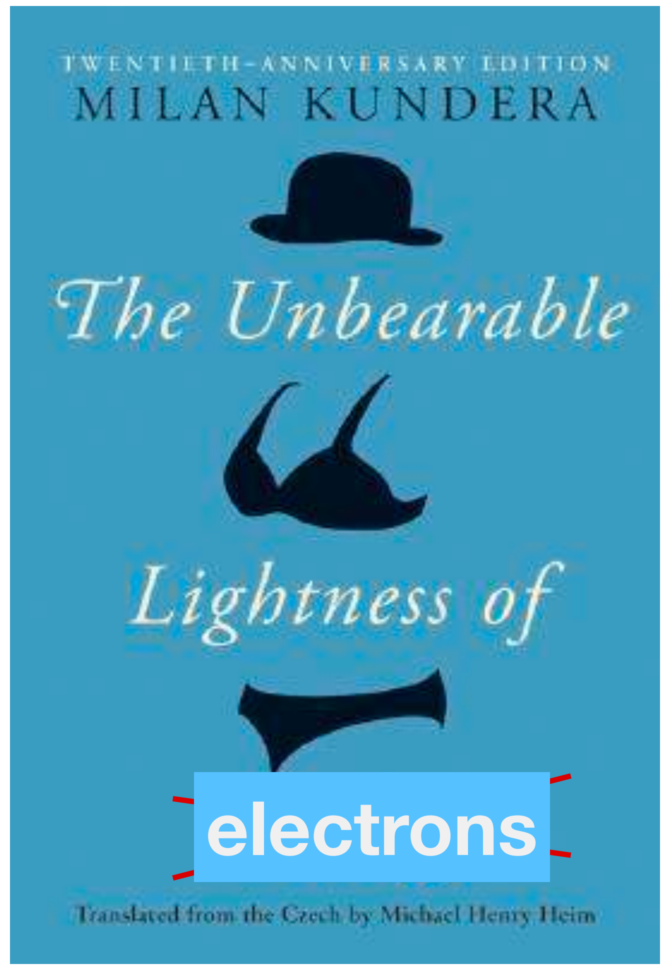
Screenshot from PDG

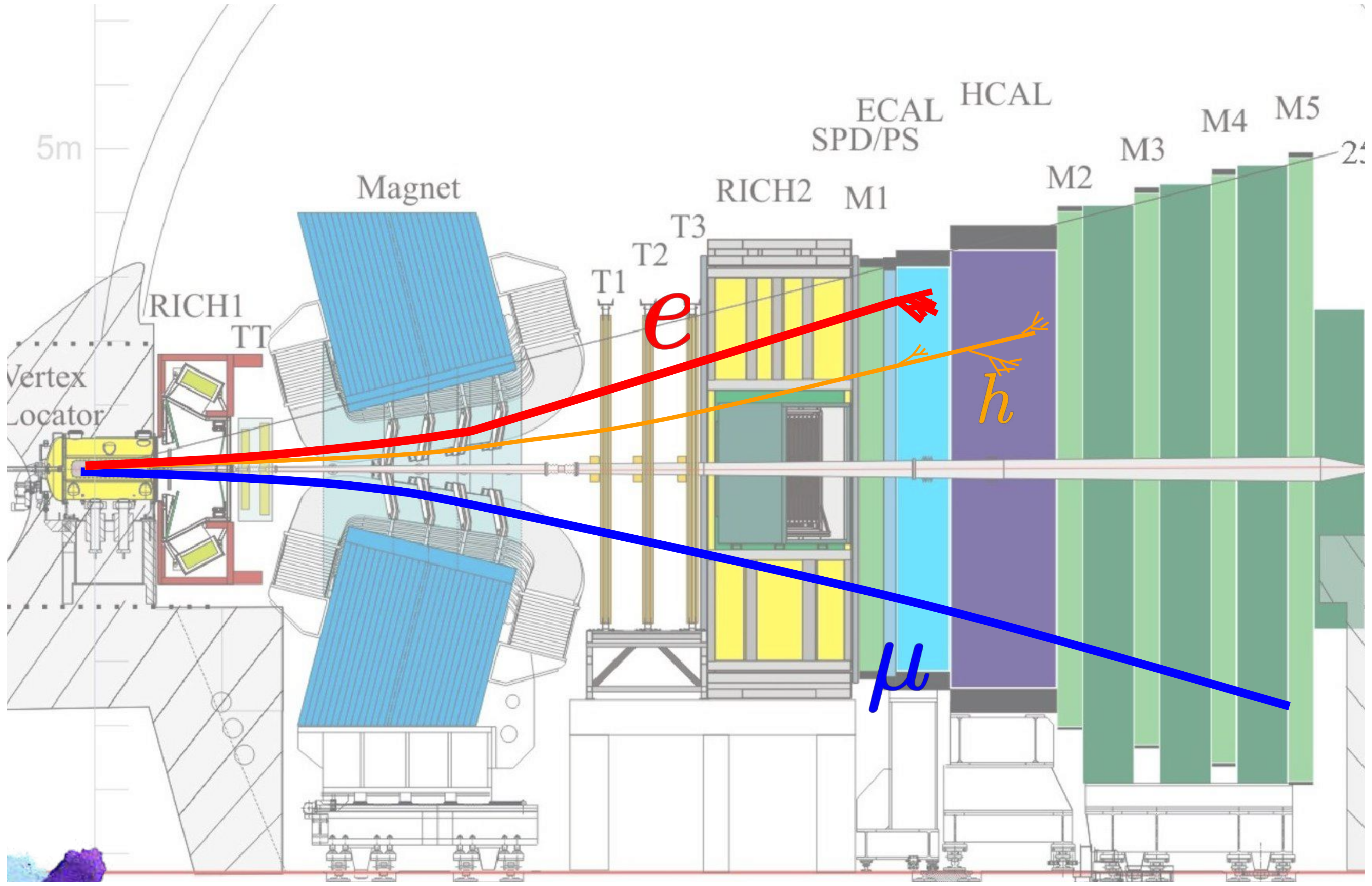
Expand all decays

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_5	e^+e^-	$(5.971 \pm 0.032)\%$		1548
Γ_7	$\mu^+\mu^-$	$(5.961 \pm 0.033)\%$		1545

The unbearable lightness of electrons

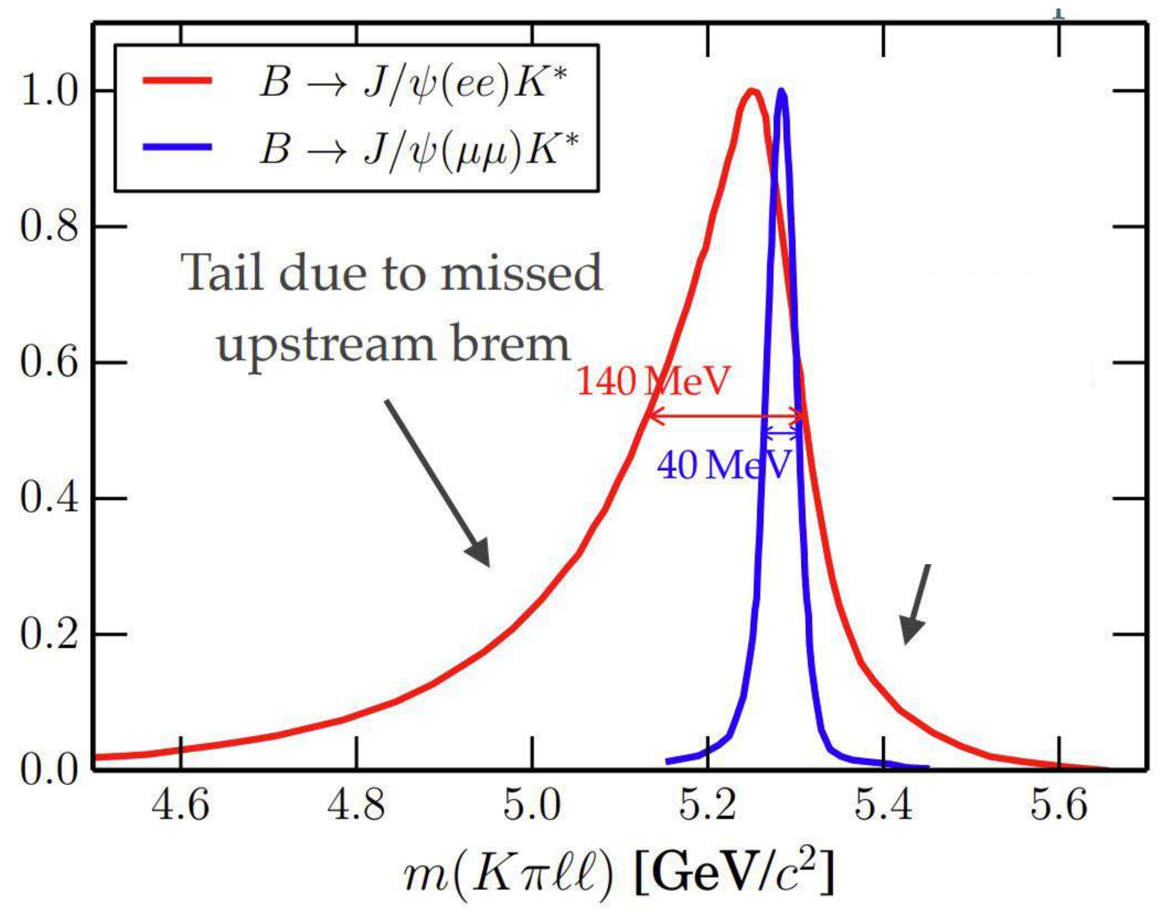
- Electrons are 200 times lighter than muons —> undergo bremsstrahlung more often.

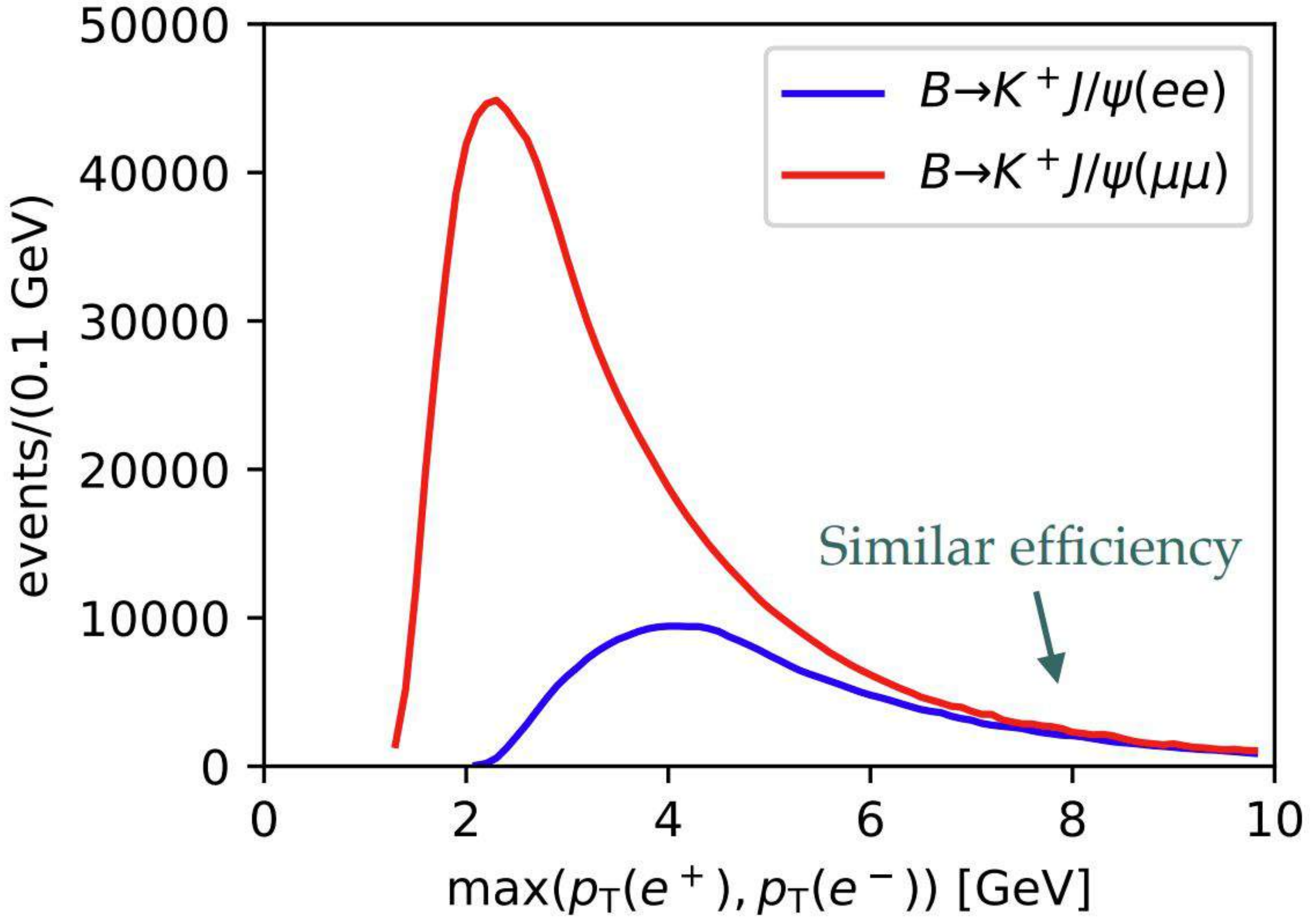




Credit: M. Atzeni

- Two effects from this:
  - Worse mass resolution for electrons.
  - Worse efficiency for electrons.



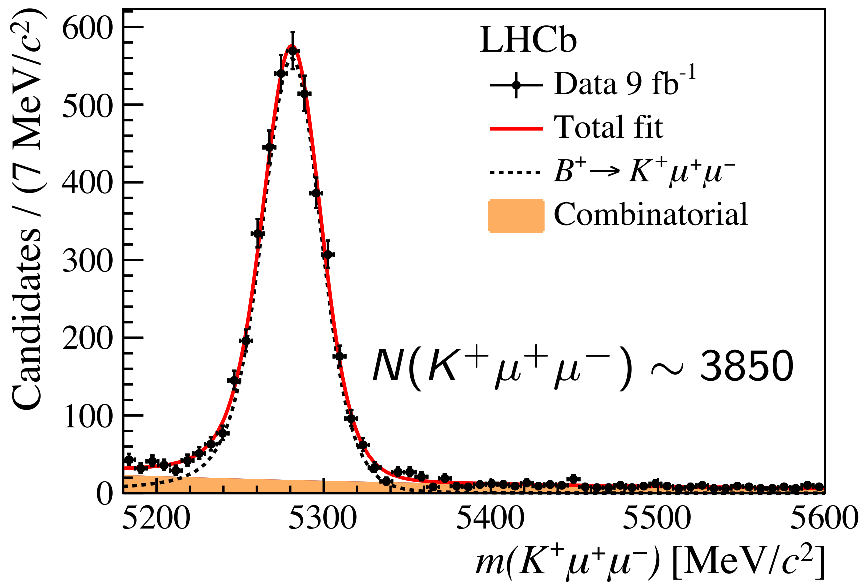


How to control this

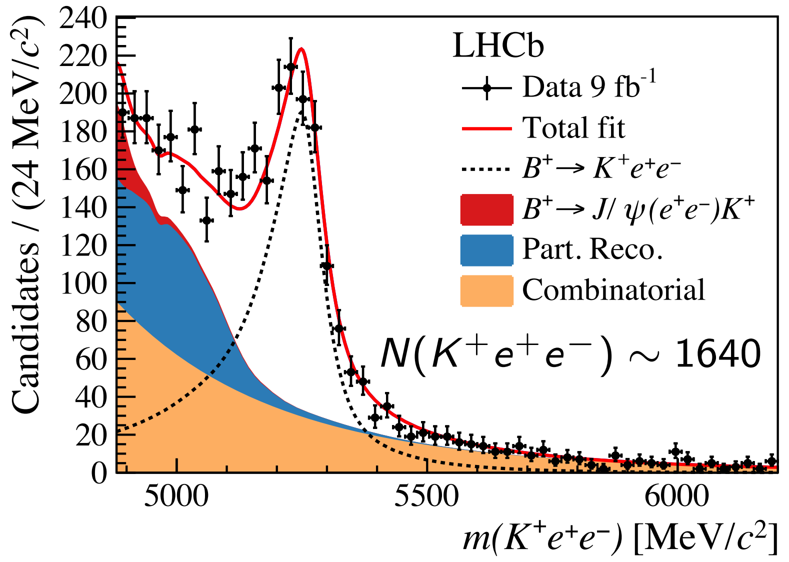
Discussed by Davide Lancierini (UZH)

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

Muons



Electrons



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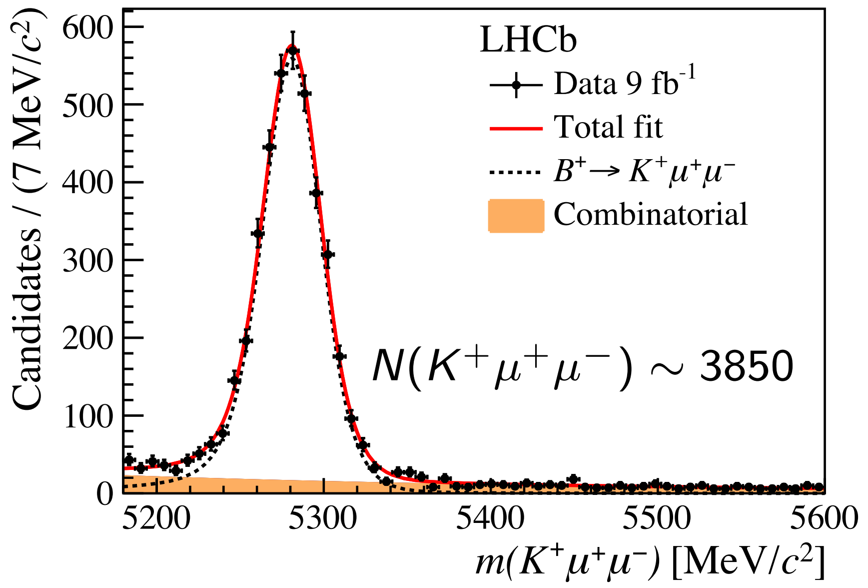
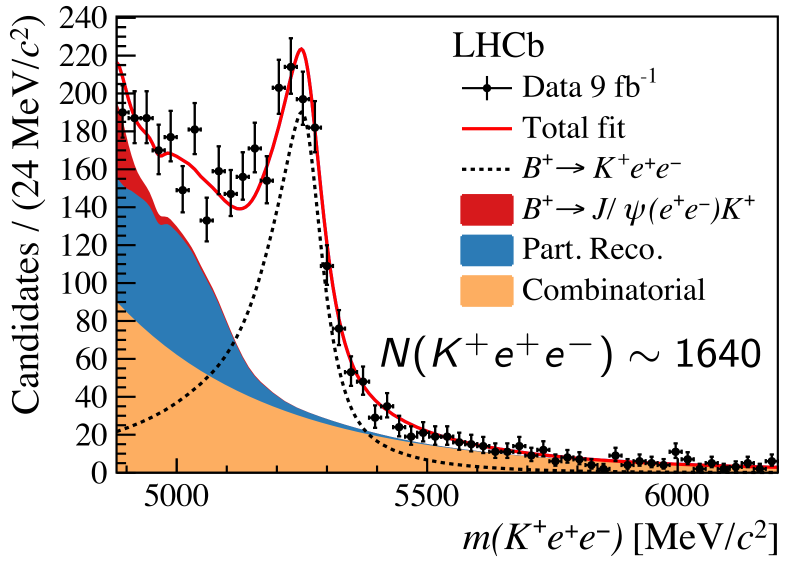
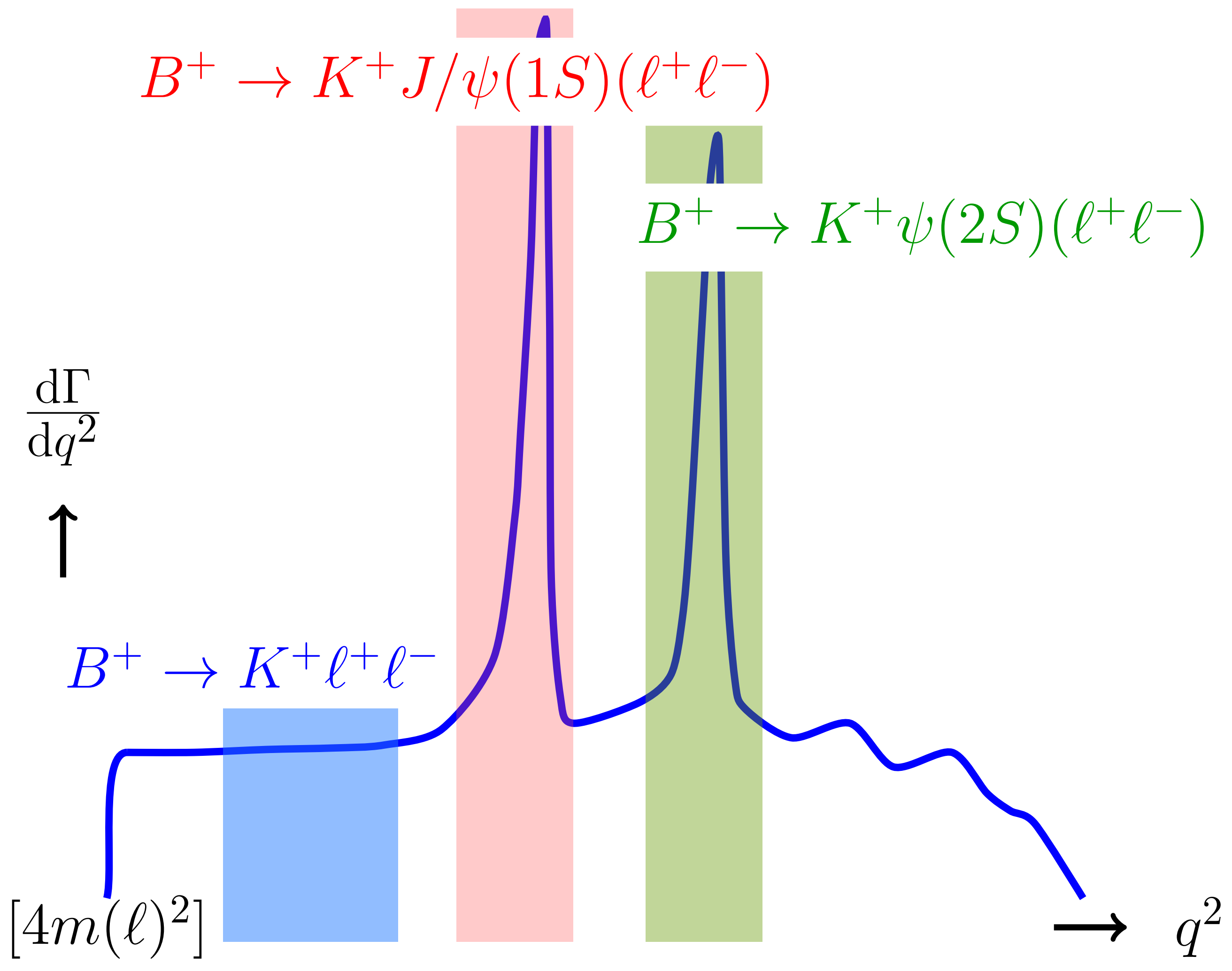
$$\frac{N(B^- \to K^-J/\psi(\mu^+\mu^-))}{N(B^- \to K^-J/\psi(e^+e^-))}\frac{\epsilon^{J/\psi}_{e^+e^-}}{\epsilon^{J/\psi}_{\mu^+\mu^-}}$$

Muons



Electrons





- Only the relative efficiency as a function of q² is needed.
- Stringent cross-check: $r_{J\psi} = \frac{N(B^- \to K^-J/\psi(\mu^+\mu^-))}{N(B^- \to K^-J/\psi(e^+e^-))}\frac{\epsilon^{J/\psi}_{e^+e^-}}{\epsilon^{J/\psi}_{\mu^+\mu^-}} = 0.981 \pm 0.020$

Latest results

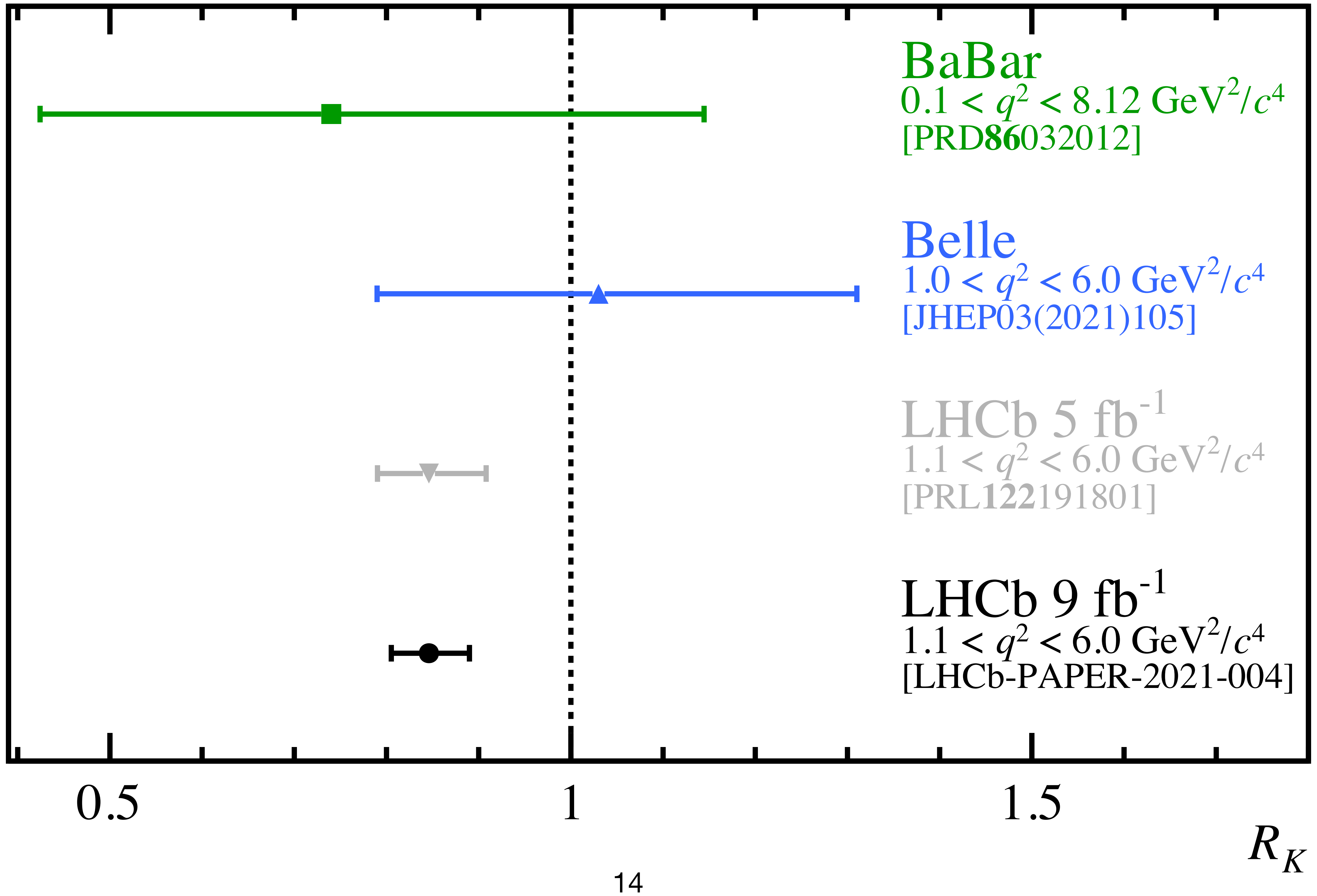
Discussed by Davide Lancierini (UZH)

- Recent update combines the full dataset collected so far by LHCb.

$$R_K = 0.846 \,^{+0.042}_{-0.039}\,(\text{stat})\,^{+0.013}_{-0.012}\,(\text{syst})$$

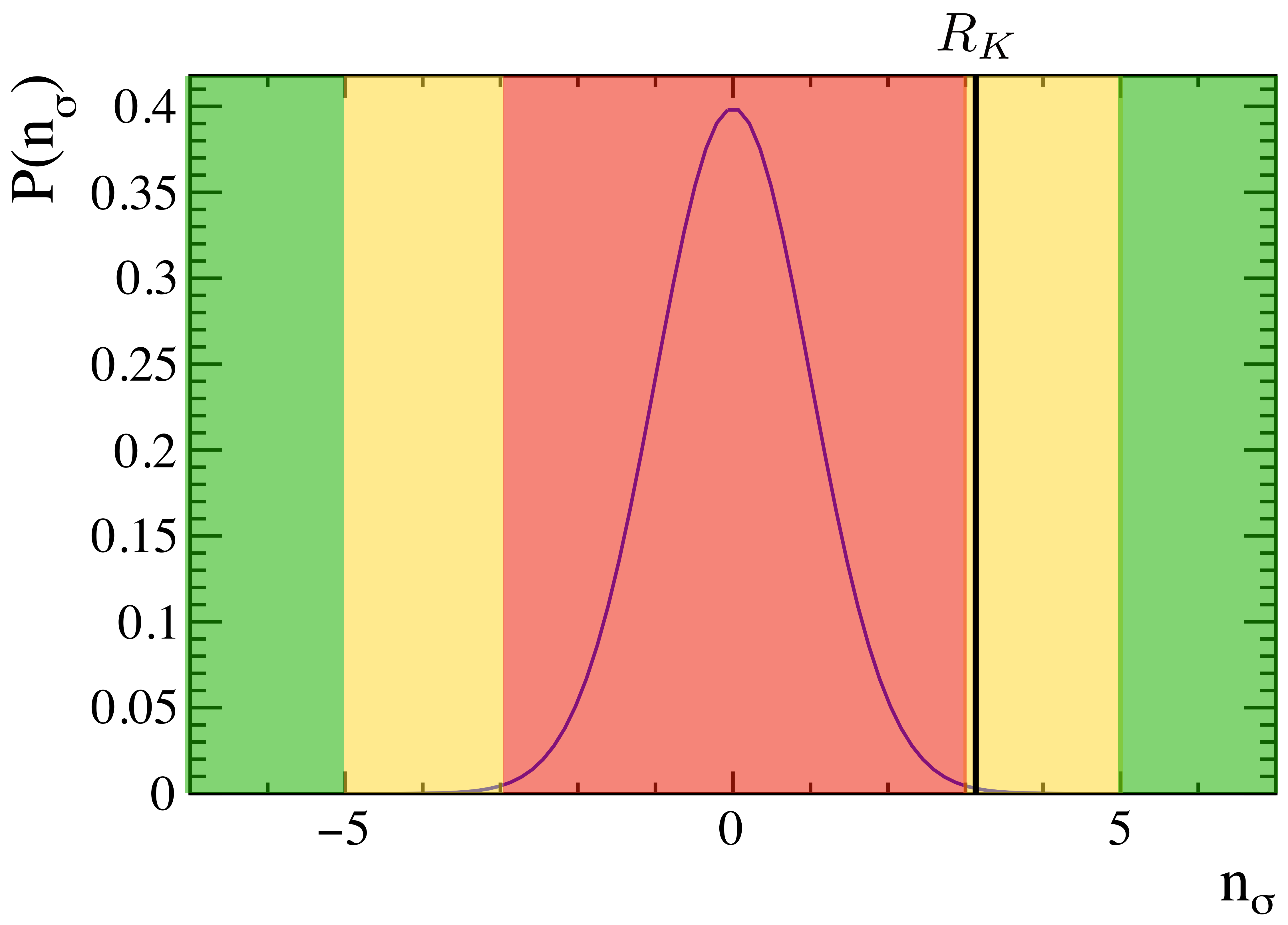
Result statistically dominated due to double ratio cancellation.

- 3.1 standard deviations away from the SM prediction of unity.



Discovery convention in particle physics

- Comparing the likelihood of the null hypothesis to an alternative one.



$n_\sigma < 3$: Cannot reject null hypothesis

$3 < n_\sigma < 5$: 'Evidence'

p-value < 0.2%

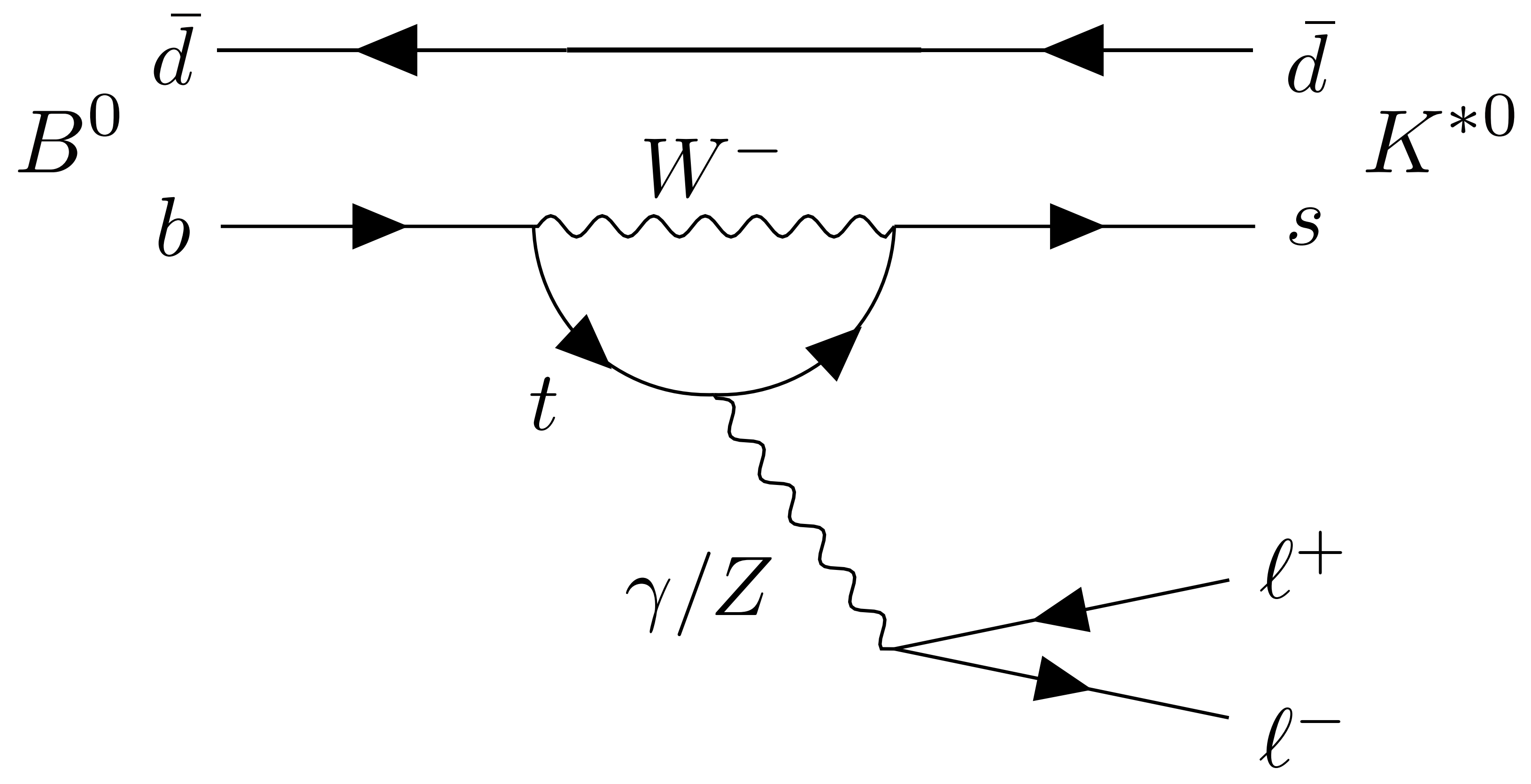
$n_\sigma > 5$: Discovery

p-value < 5×10^{-7}

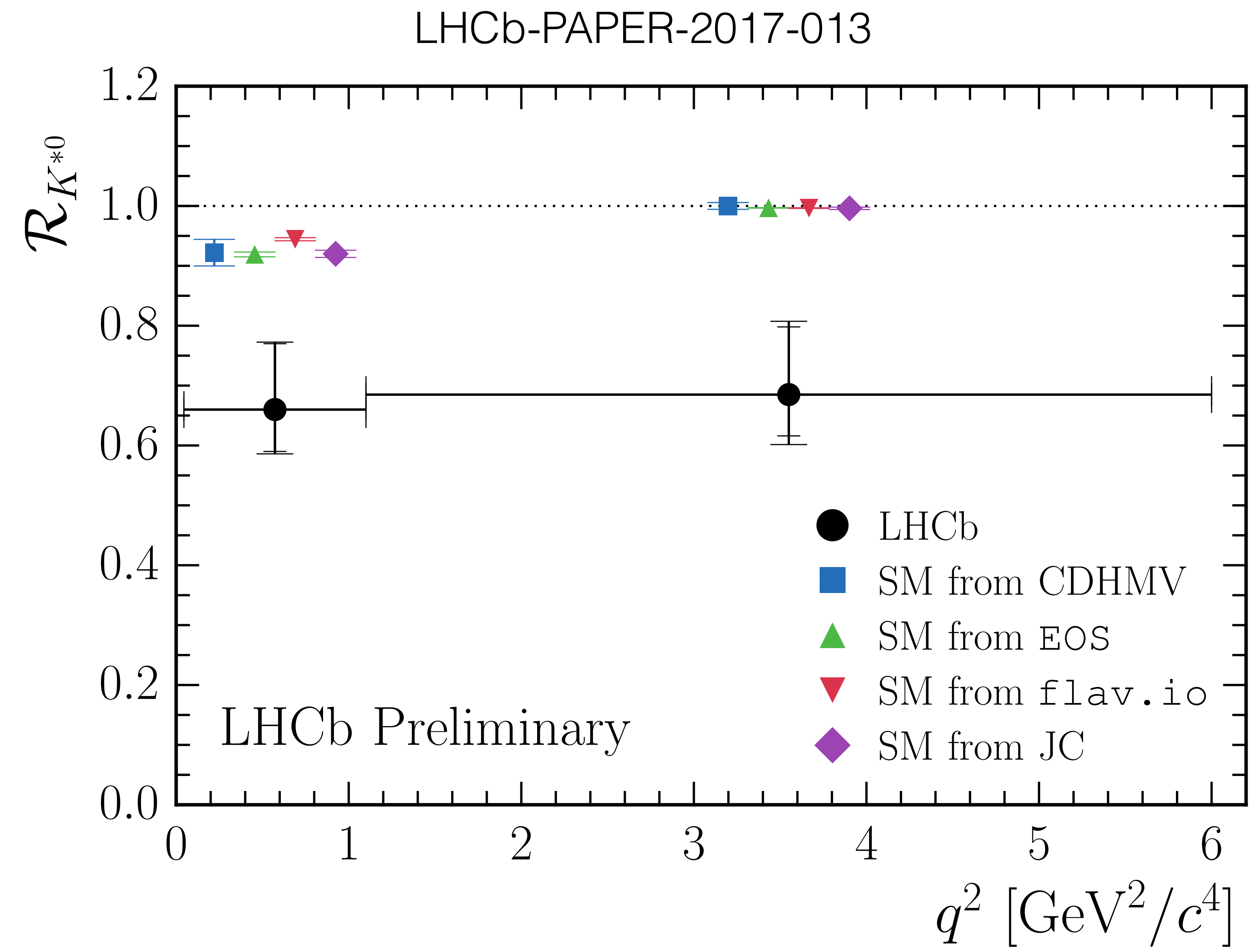
- A significance of 3.1σ is therefore conventionally 'evidence' for lepton universality violation.

The lepton universality ratio R_{K^*}

- We have also tested lepton universality in a closely related mode, $B^0 \to K^{*0}\ell^+\ell^-$



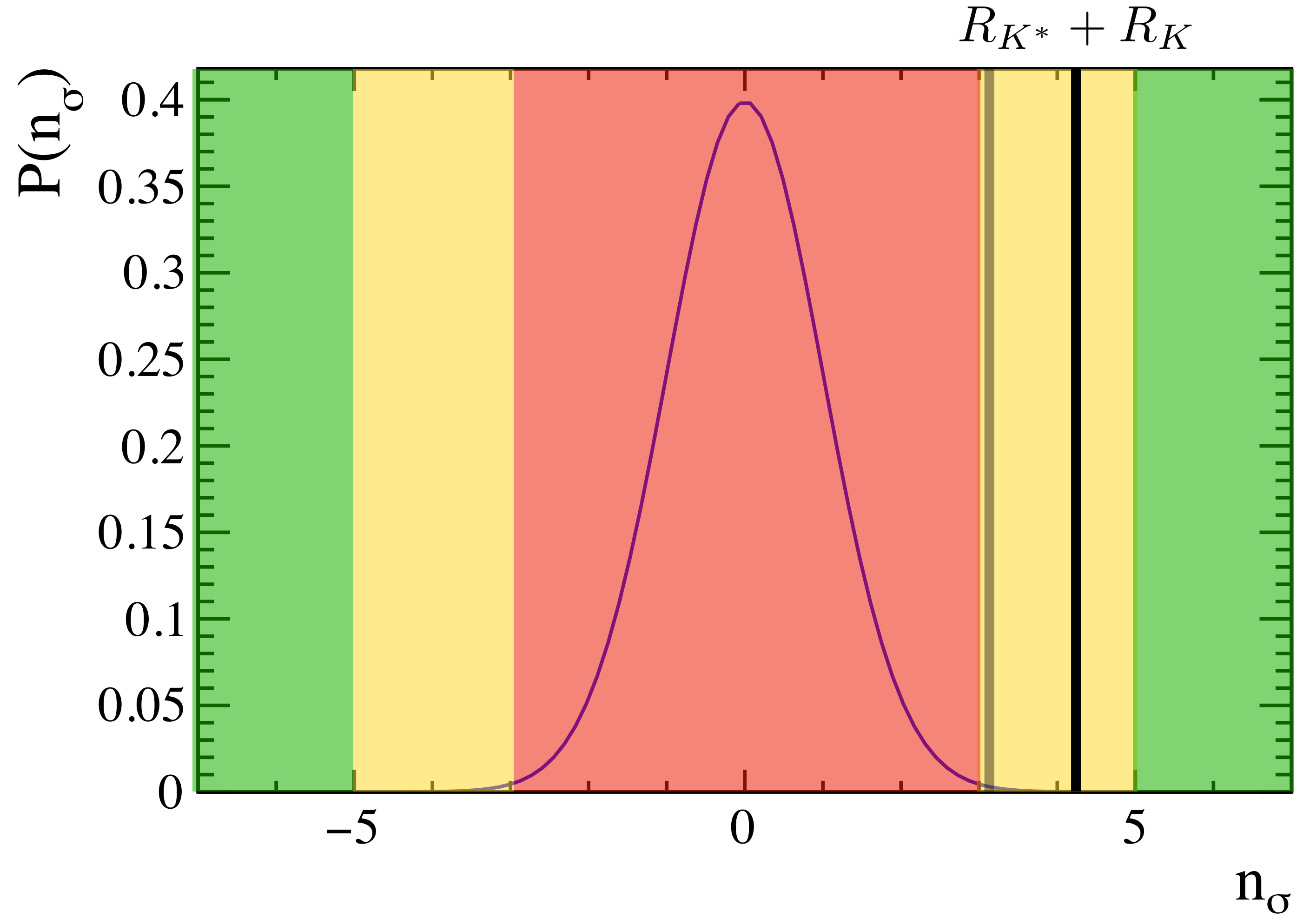
$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$



- Also see deficit of muons compared to electrons in two q^2 regions. Significances 2.2-2.4σ.

- Combined significance ~4.2σ.

- Is there anything else we can measure?

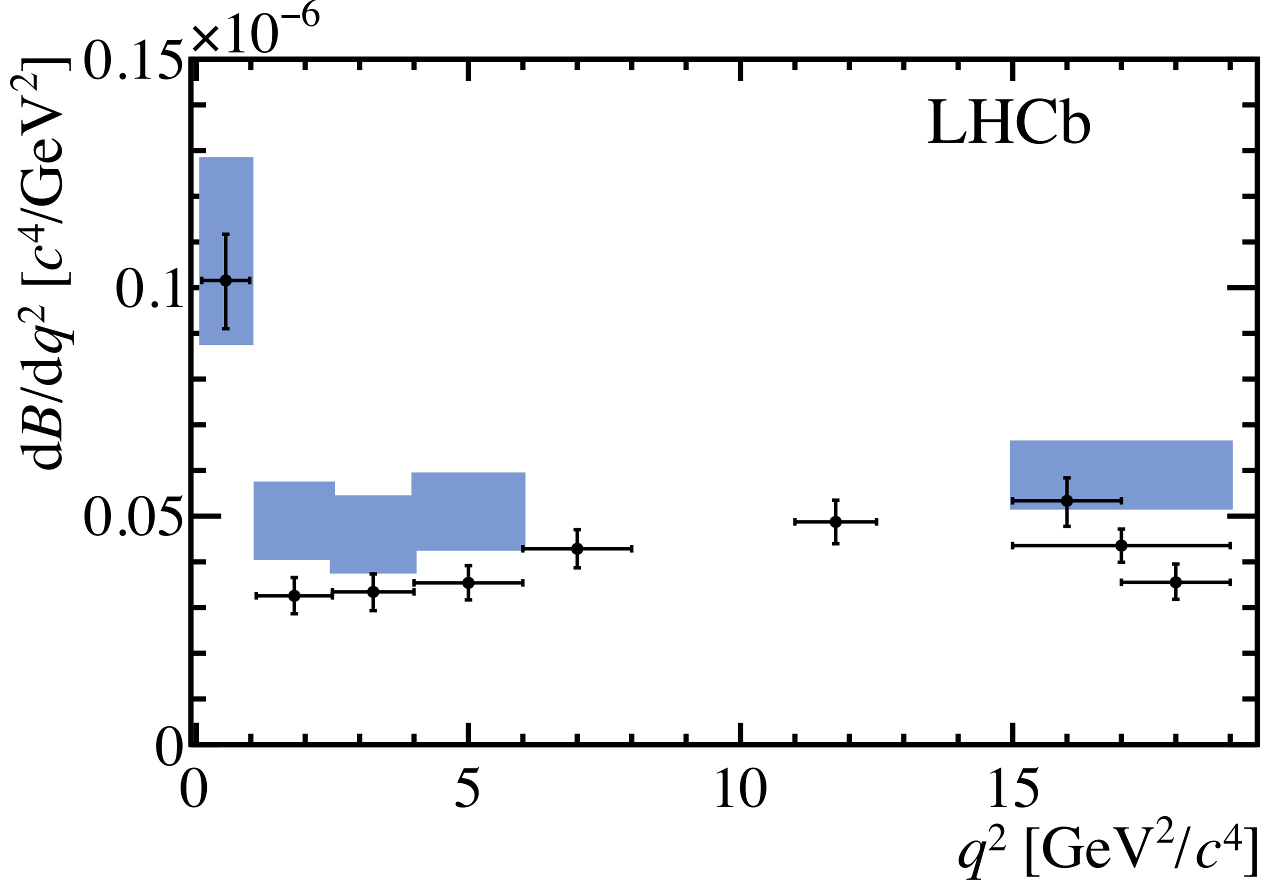


The branching fractions

- Measure the individual branching fractions and compare with SM predictions.

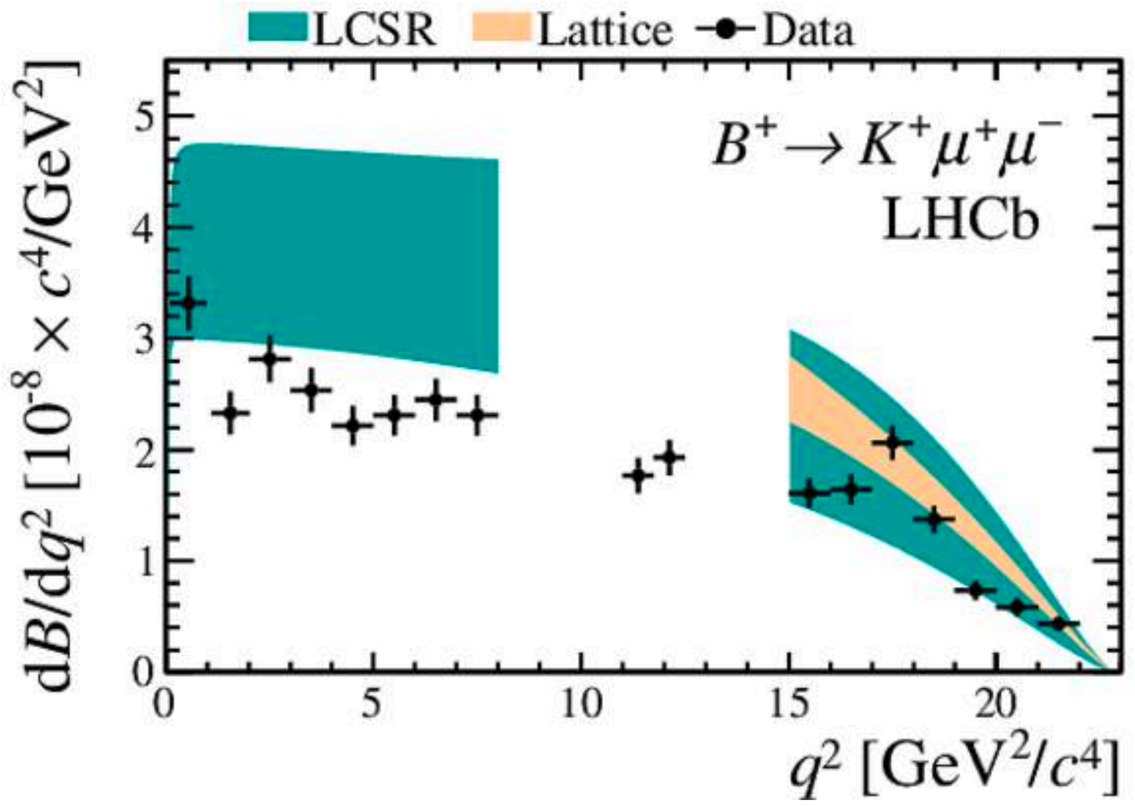
$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104



$B^+ \to K^+\mu^+\mu^-$

JHEP 06 (2014) 133



$B_s^0 \to \phi\mu^+\mu^-$

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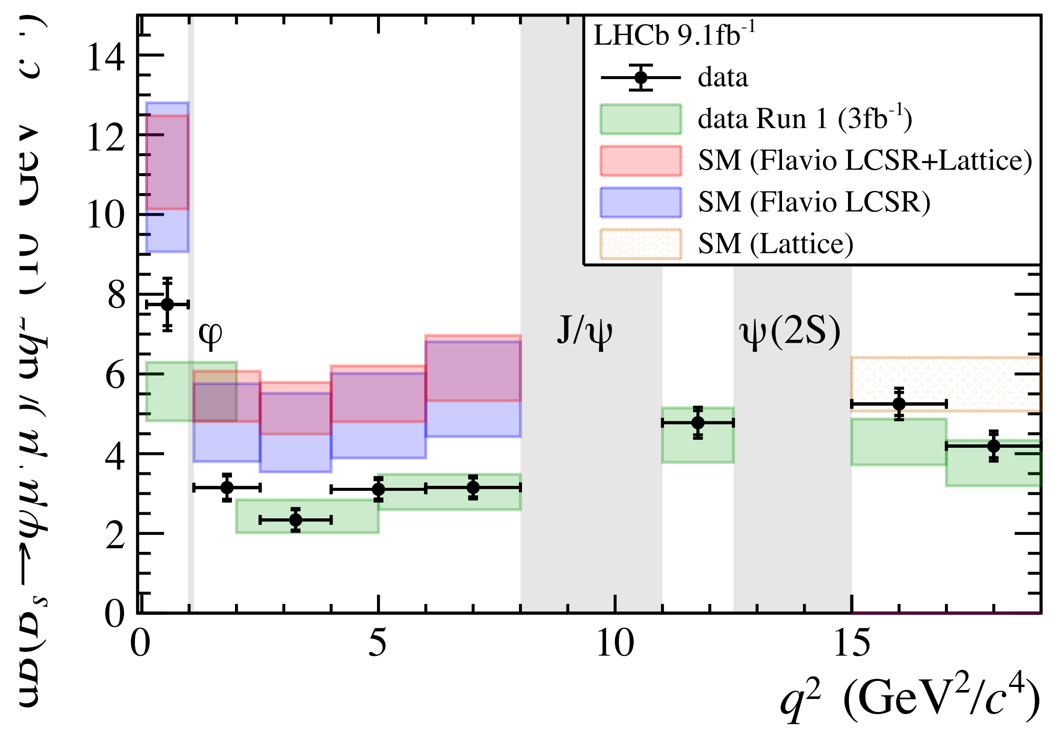
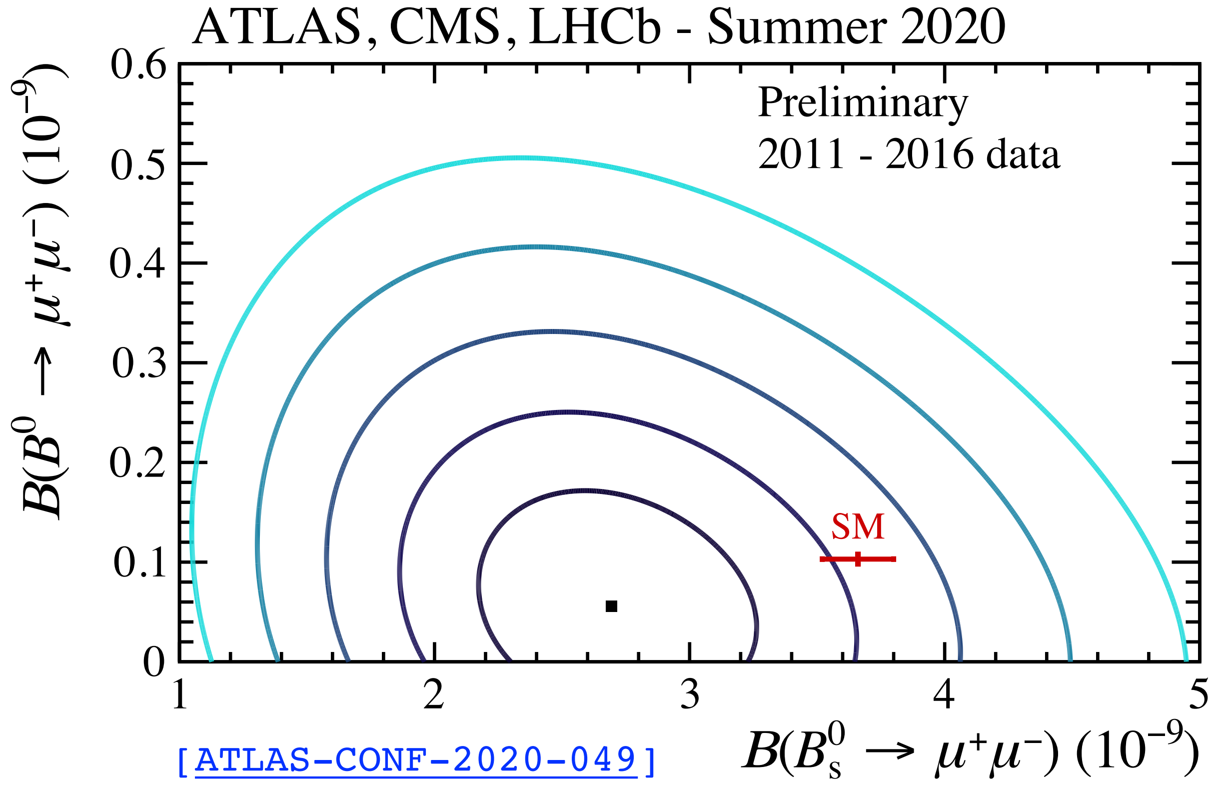


$B_s^0 \to \mu^+\mu^-$

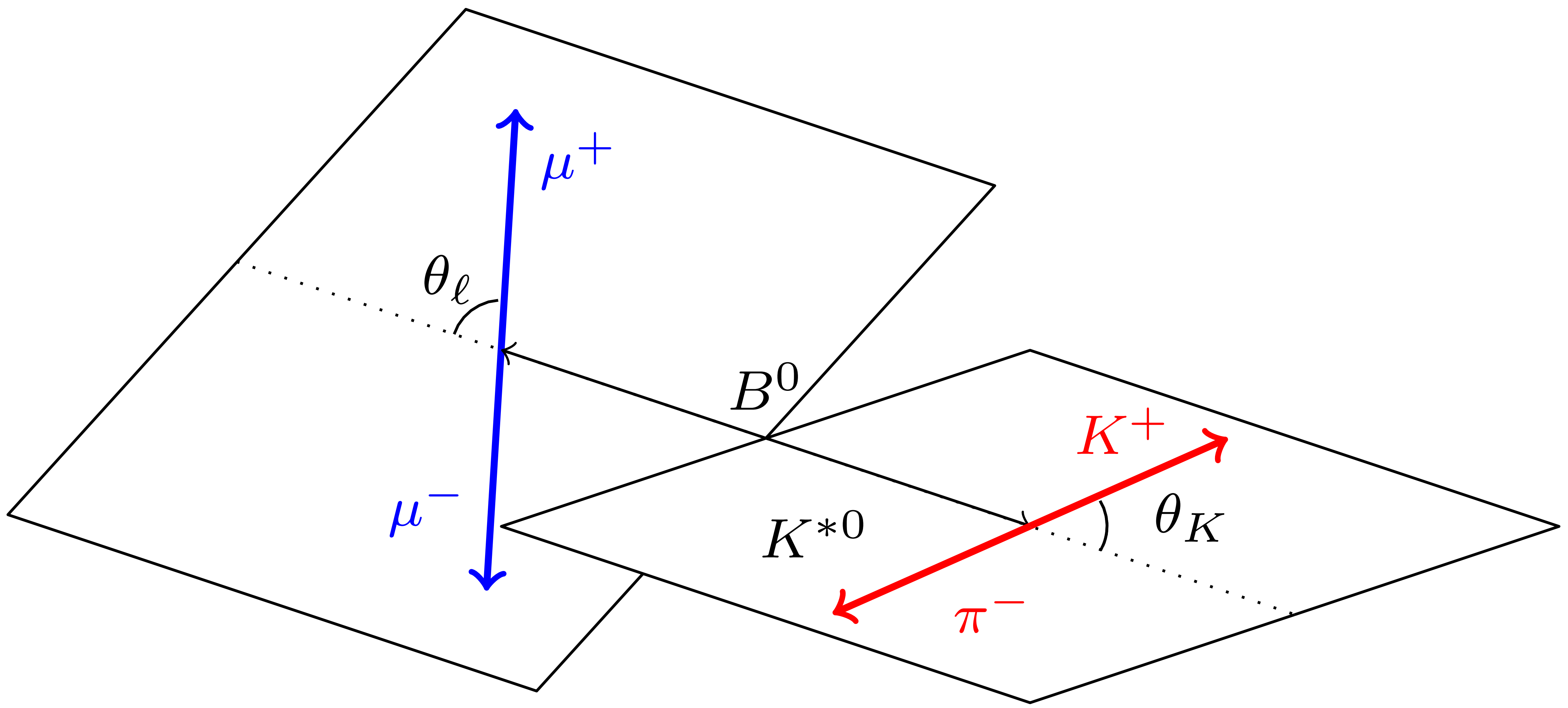


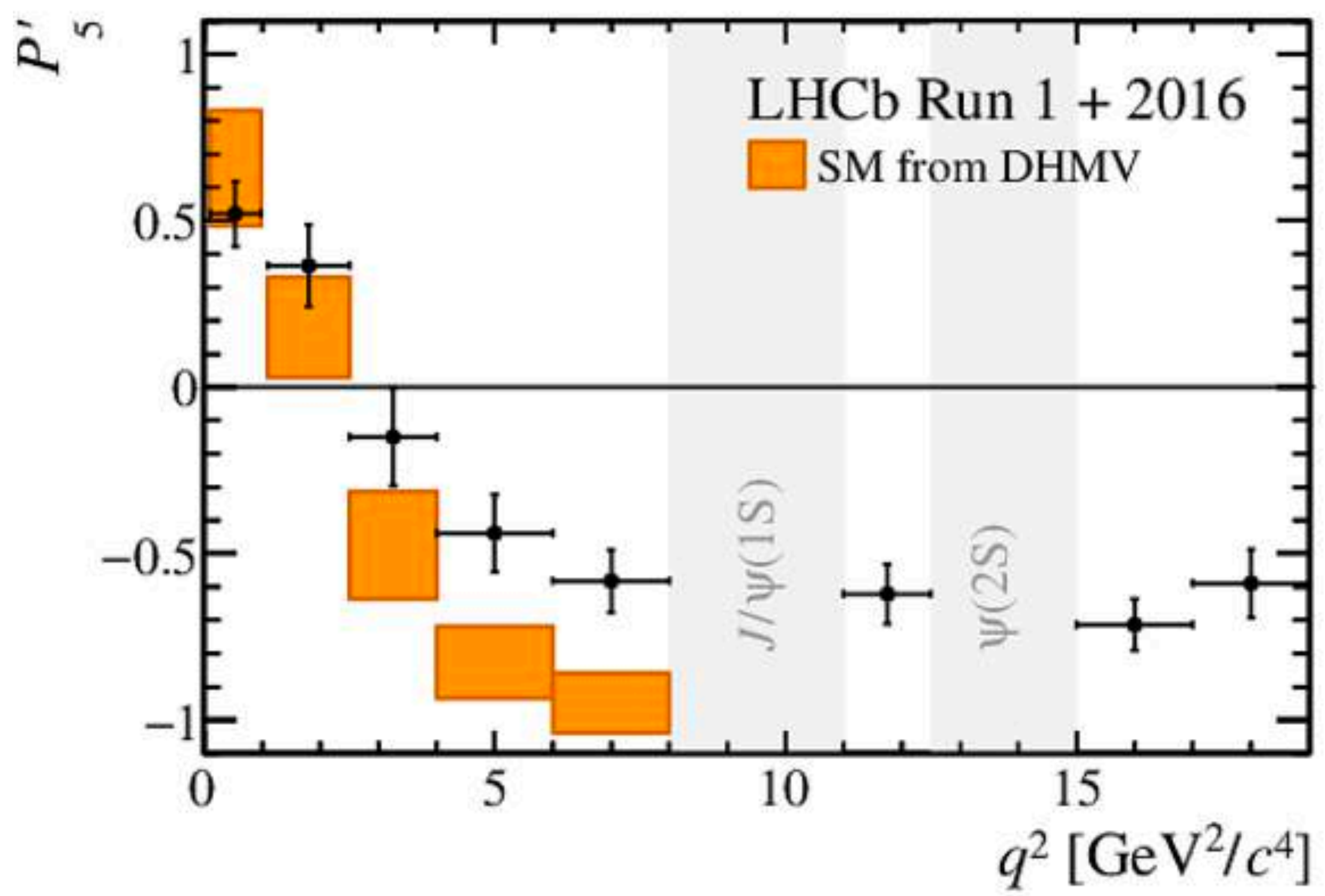
- Theoretical uncertainty now large but a coherent picture emerges: Deficit of muons.

- Could new physics also change the angular distribution as well as the decay rate?

The $B \to K^* \mu^+ \mu^-$ angular analysis

- In addition to decay rates, compare angular distribution and compare with SM.





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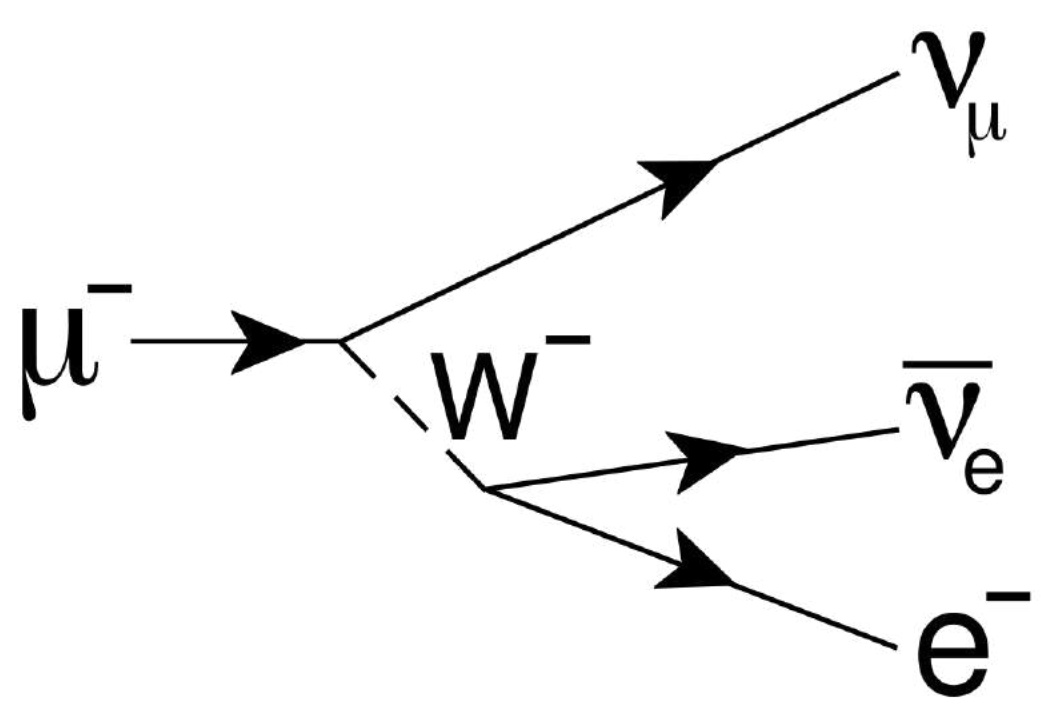
- Discrepancy also seen in the angular distribution.
- Are these anomalies consistent with each other and what is the combined significance?

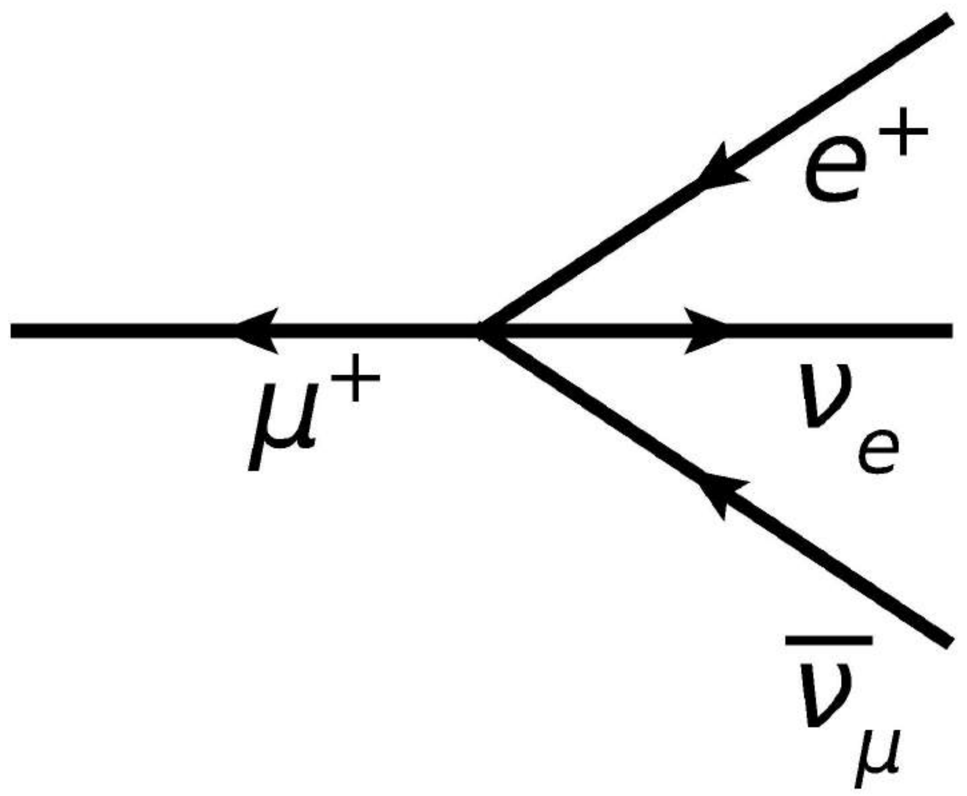
Effective field theories

- We have a general way to connect our observables together via Effective Field Theories (EFTs).
- The idea is a generalisation of Fermi's theory of weak decays:

Full theory



Effective (Fermi) theory



$$\mathcal{M} = \frac{g_L^2}{2}\bar{x}(k_3)\bar{\sigma}_\rho x(p)\frac{1}{q^2 - m_W^2}\bar{x}(k_1)\bar{\sigma}_\rho y(k_2)$$

$$\mathcal{M} \approx -\frac{g_L^2}{2m_W^2}[\bar{x}(k_3)\bar{\sigma}_\rho x(p)][\bar{x}(k_1)\bar{\sigma}_\rho y(k_2)]\left[1 + \mathcal{O}(q^2/m_W^2)\right]$$

- This results in an effective hamiltonian, written as a combination of Wilson Coefficients and operators.

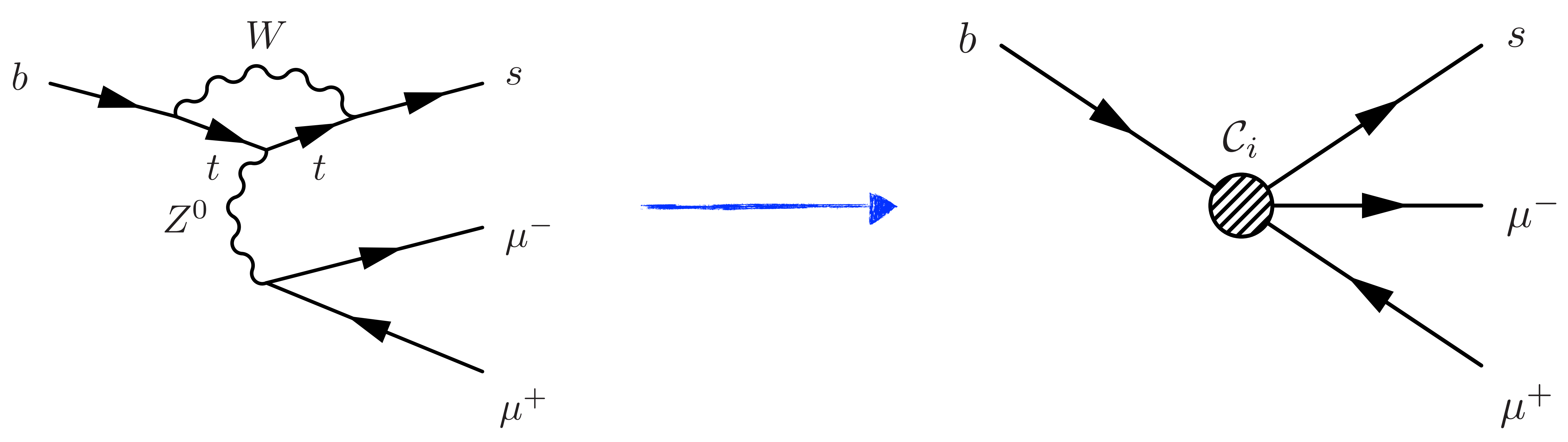
$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\sum_i V_{CKM}^i C_i(\lambda)\mathcal{O}_i(\lambda)$$

- Wilson coefficients (short-distance): evaluated in perturbation theory
- Local operators (long-distance): the corresponding form factor is computed with, e.g., lattice QCD

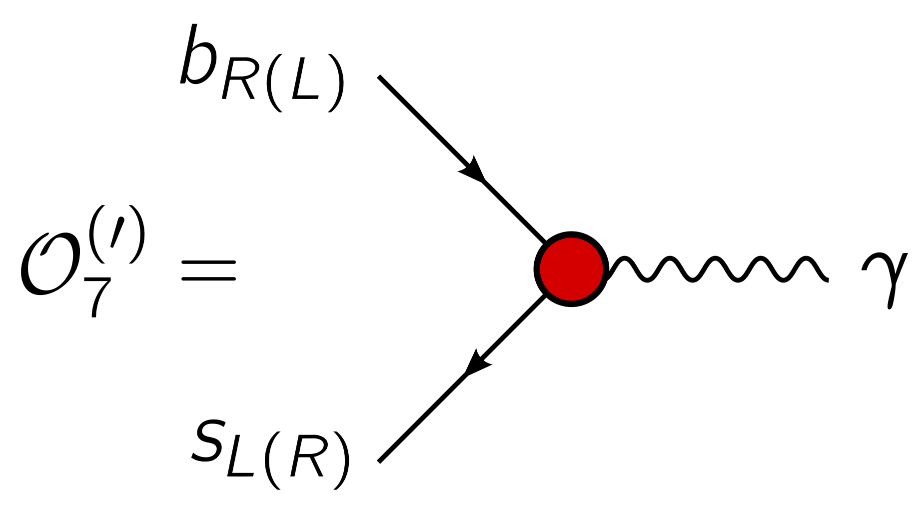
EFTs in heavy flavour physics

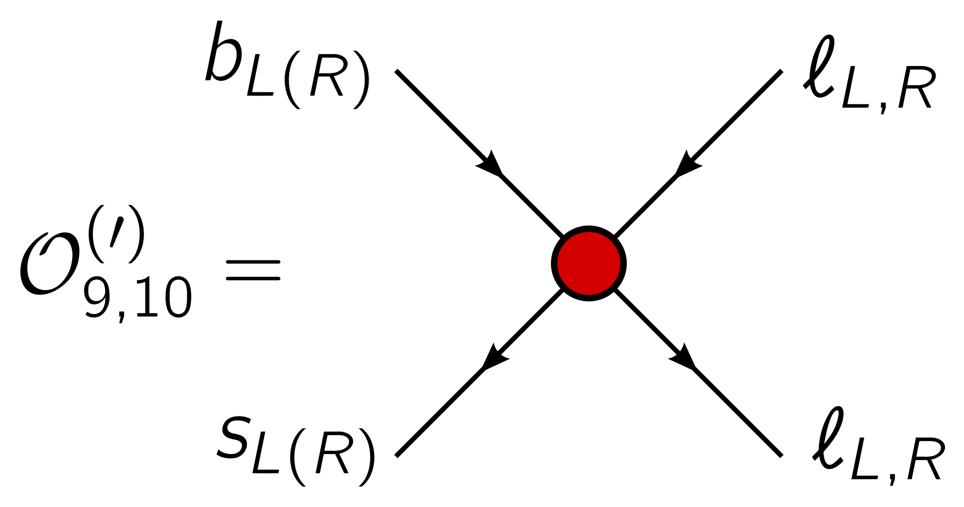
- The EFT we use in heavy flavour physics assumes that NP much heavier than the b mass scale.

Full theory **Effective description**



- Familiar operators:





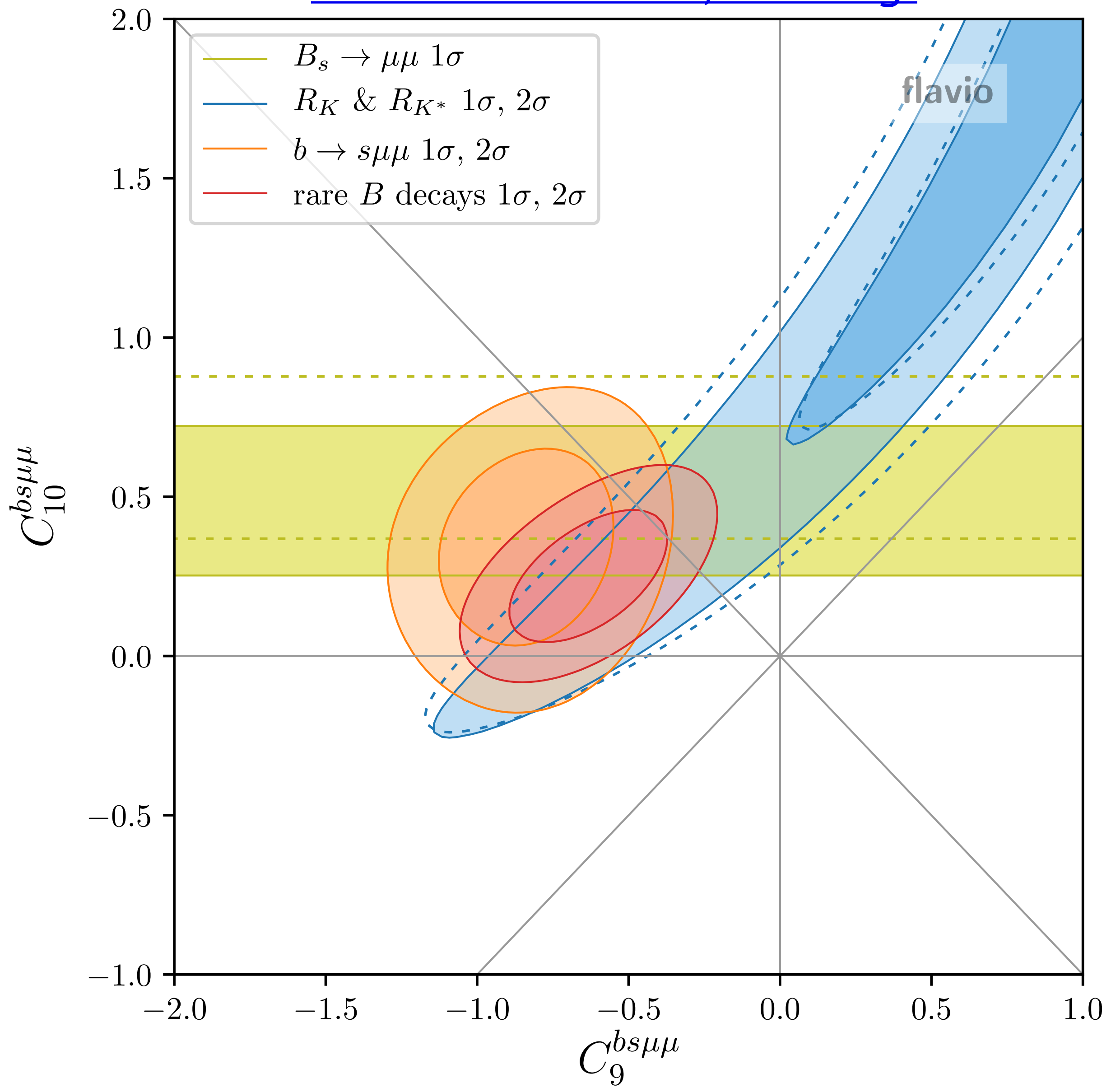
- O_7 gives a long distance contribution to b—>sll via the photon.
- $O_{9,10}$ can be different for different lepton flavours.

- C_9 and C_{10} give the vector and axial-vector couplings to the leptons: Dominant SM semileptonic contribution.

Global $b \to s\ell^+\ell^-$ fits

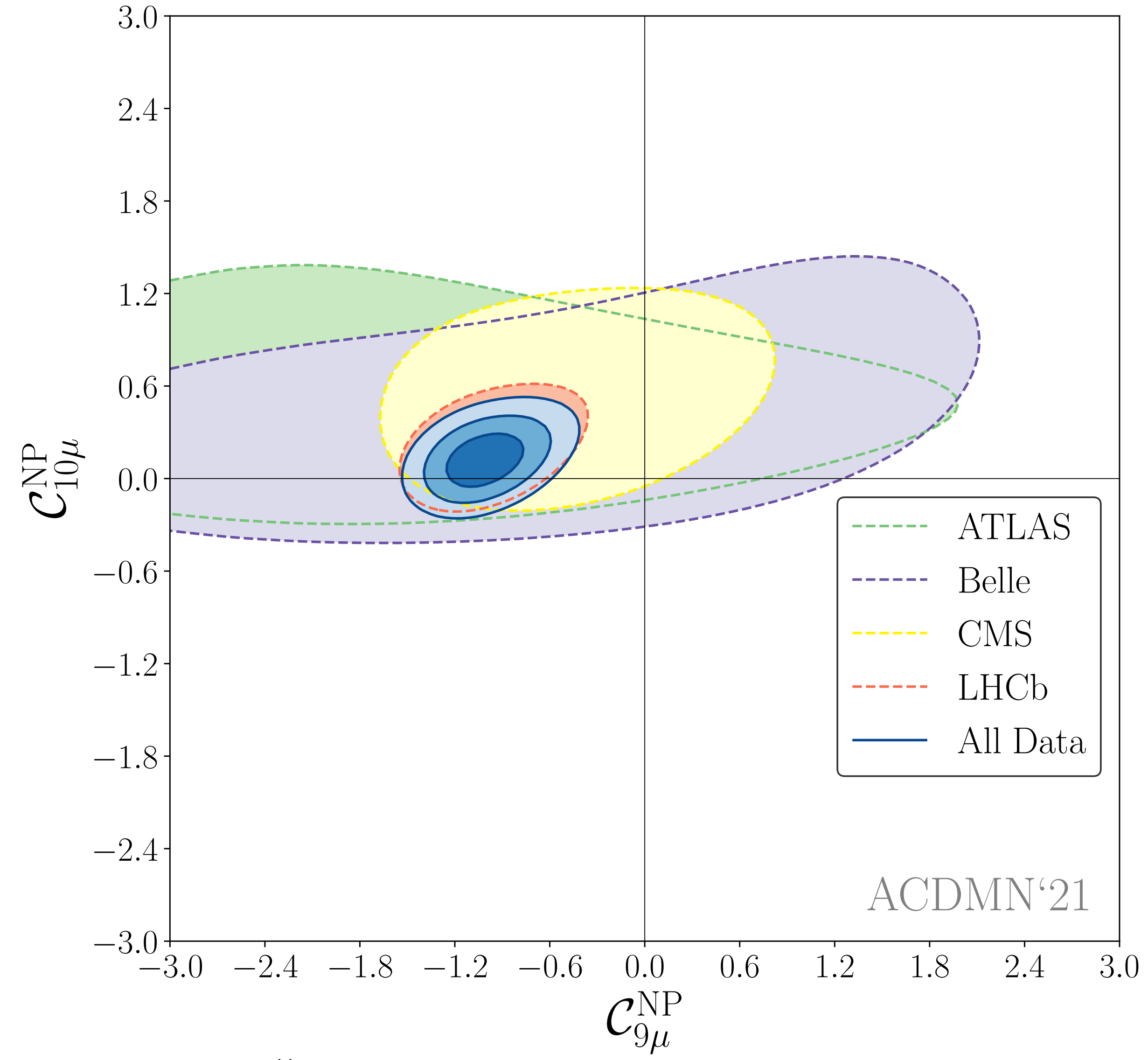
- Global b—>sll fits show that all discrepancies are in consistent within the EFT approach, with significances easily exceeding the conventional 5σ threshold.

W. Altmannshofer, P. Stangl



	Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
NP errors	$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
	$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

M. Algueró et al

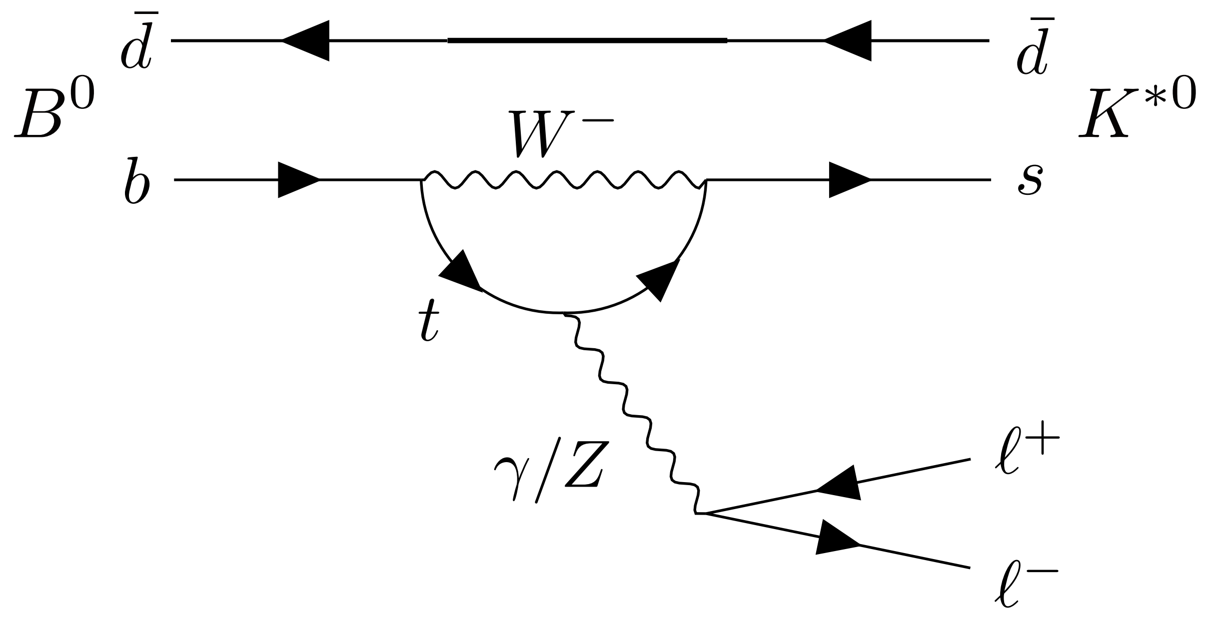


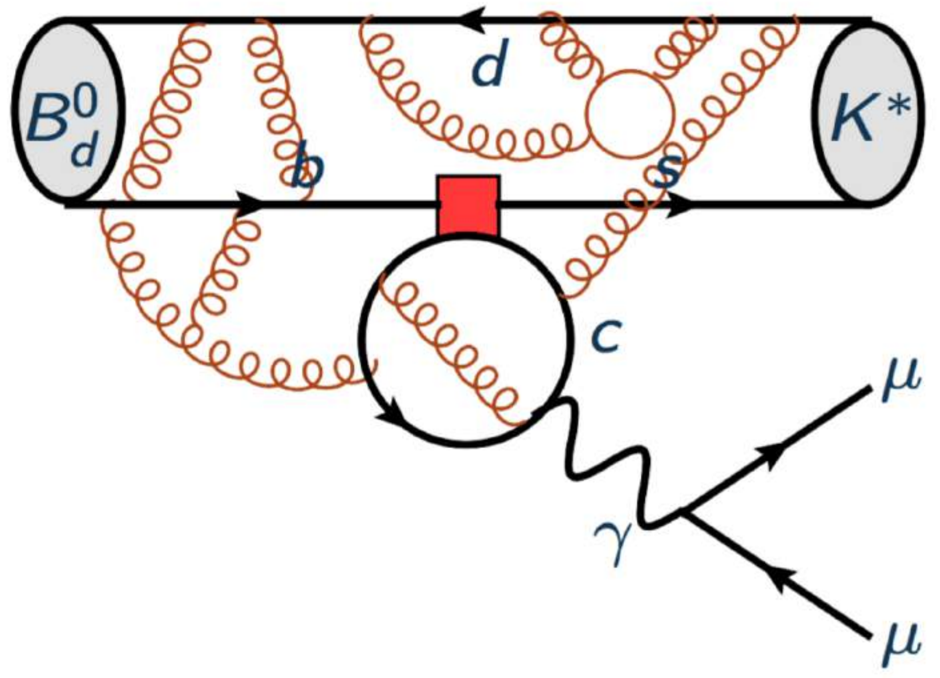
	All			
1D Hyp.	Best fit	$1\ \sigma/2\ \sigma$	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.06	$[-1.20, -0.91]$ $[-1.34, -0.76]$	7.0	39.5 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.44	$[-0.52, -0.37]$ $[-0.60, -0.29]$	6.2	22.8 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	-1.11	$[-1.25, -0.96]$ $[-1.39, -0.80]$	6.5	28.0 %

- No discovery claim from LHCb at this point. Why not?

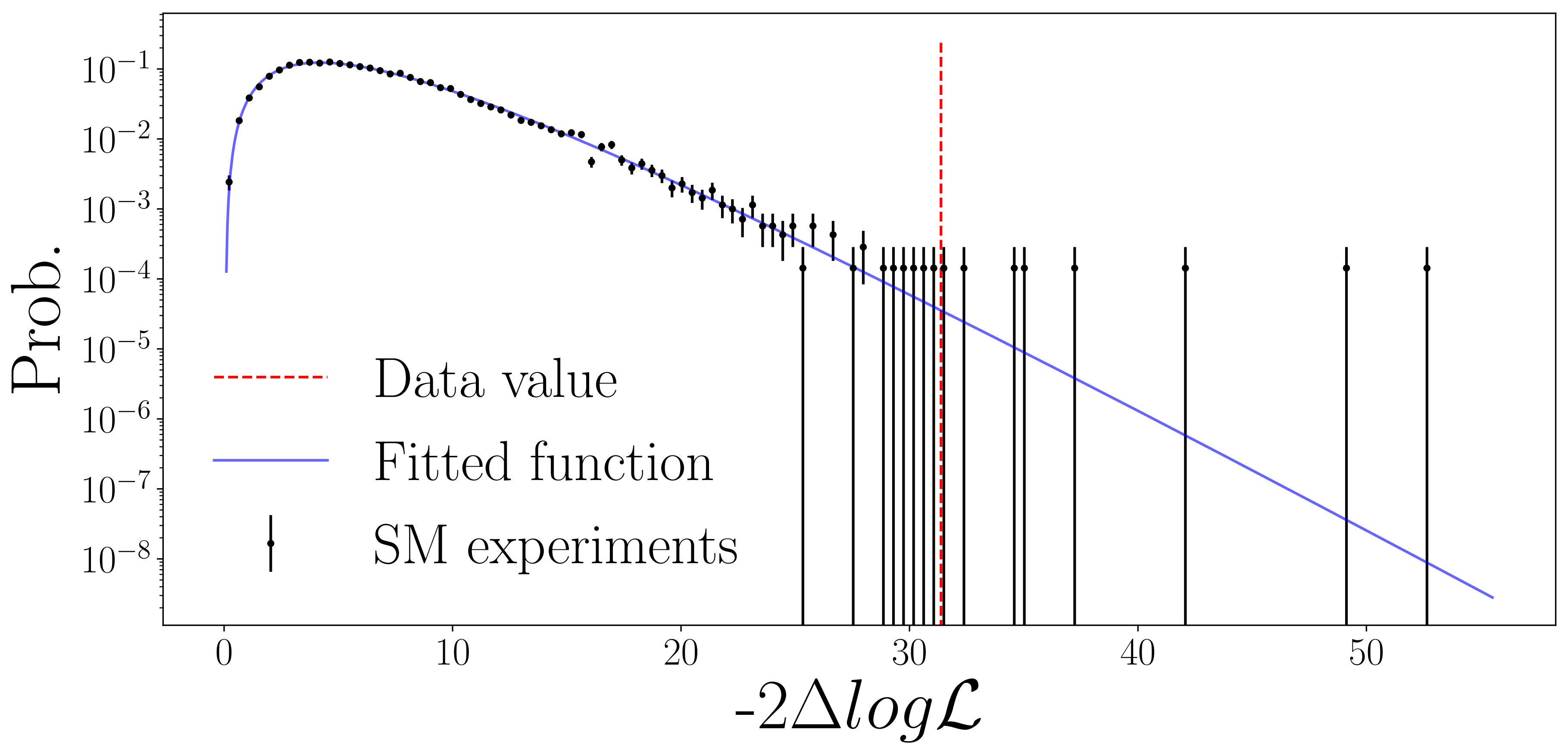
A SM complication

- Also a SM contribution which can negatively interfere with the semileptonic amplitude.
  - Does not affect LFU ratios, but could cause other anomalies we see.





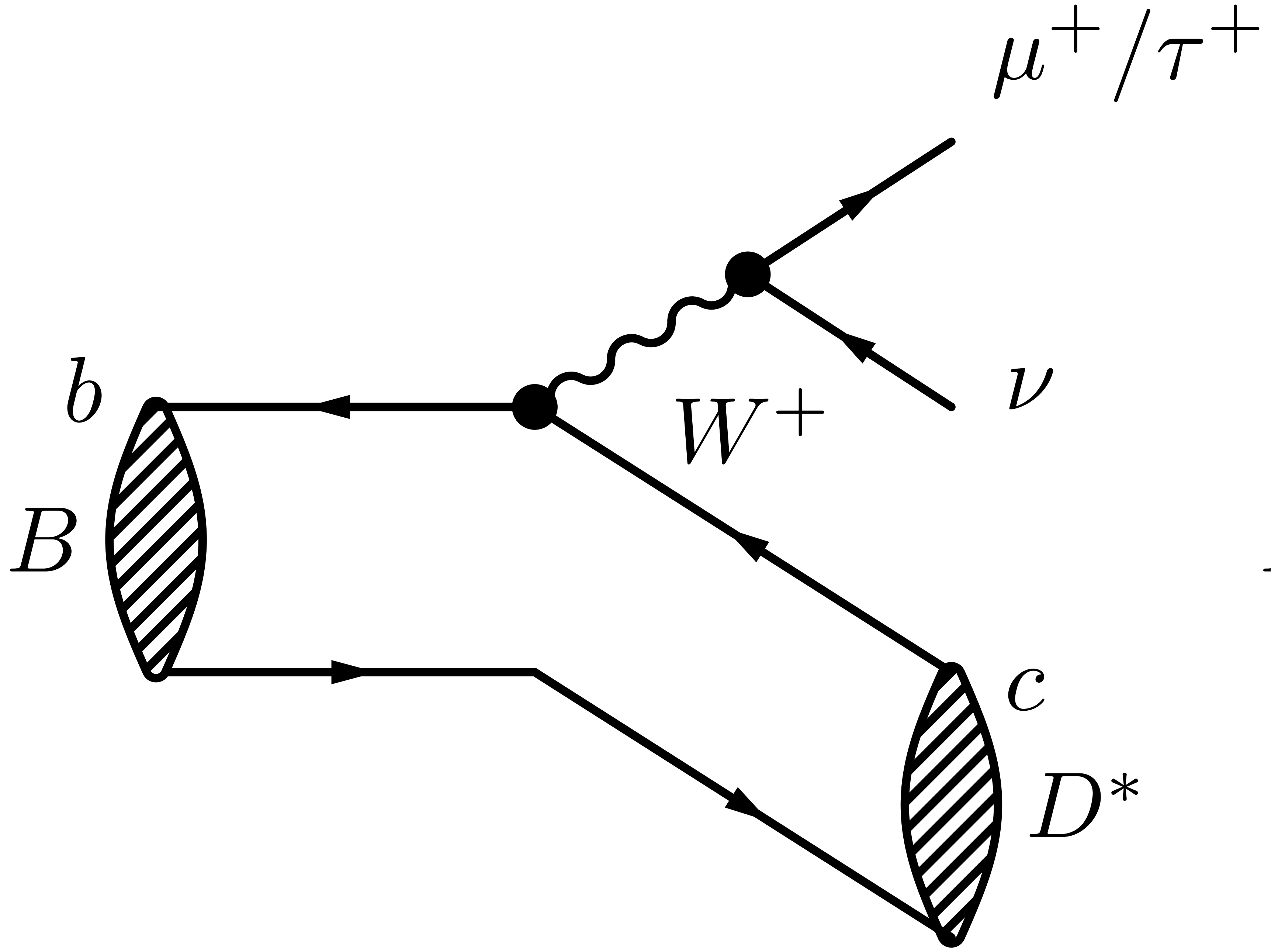
D. Lancierini, G. Isidori, PO, N. Serra



- Try to construct as conservative approach as possible.
  - Hyper conservative hadronic treatment (absorb into SM definition).
  - Test against general NP as possible to take into account the so-called Look-Elsewhere-Effect.
- Global significance is ~4σ, which is not at the discovery threshold but still high.

Summarised by Annarita Buonaura (UZH)

Tree-level $b \to c\ell\nu$ transitions

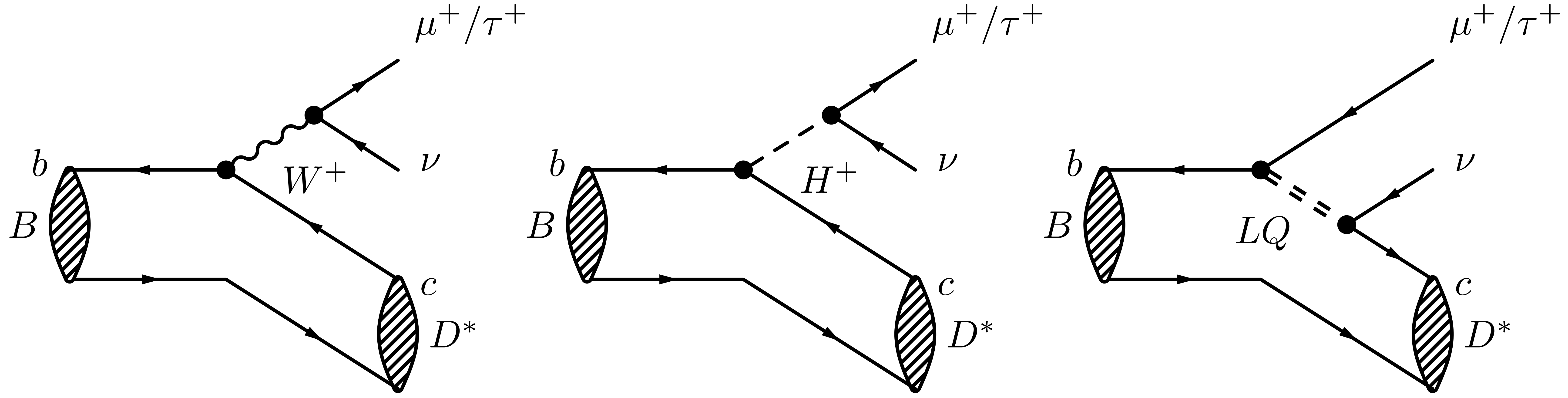


Lepton universality ratio R(D*)

- Now compare tau-leptons with muons/electrons.

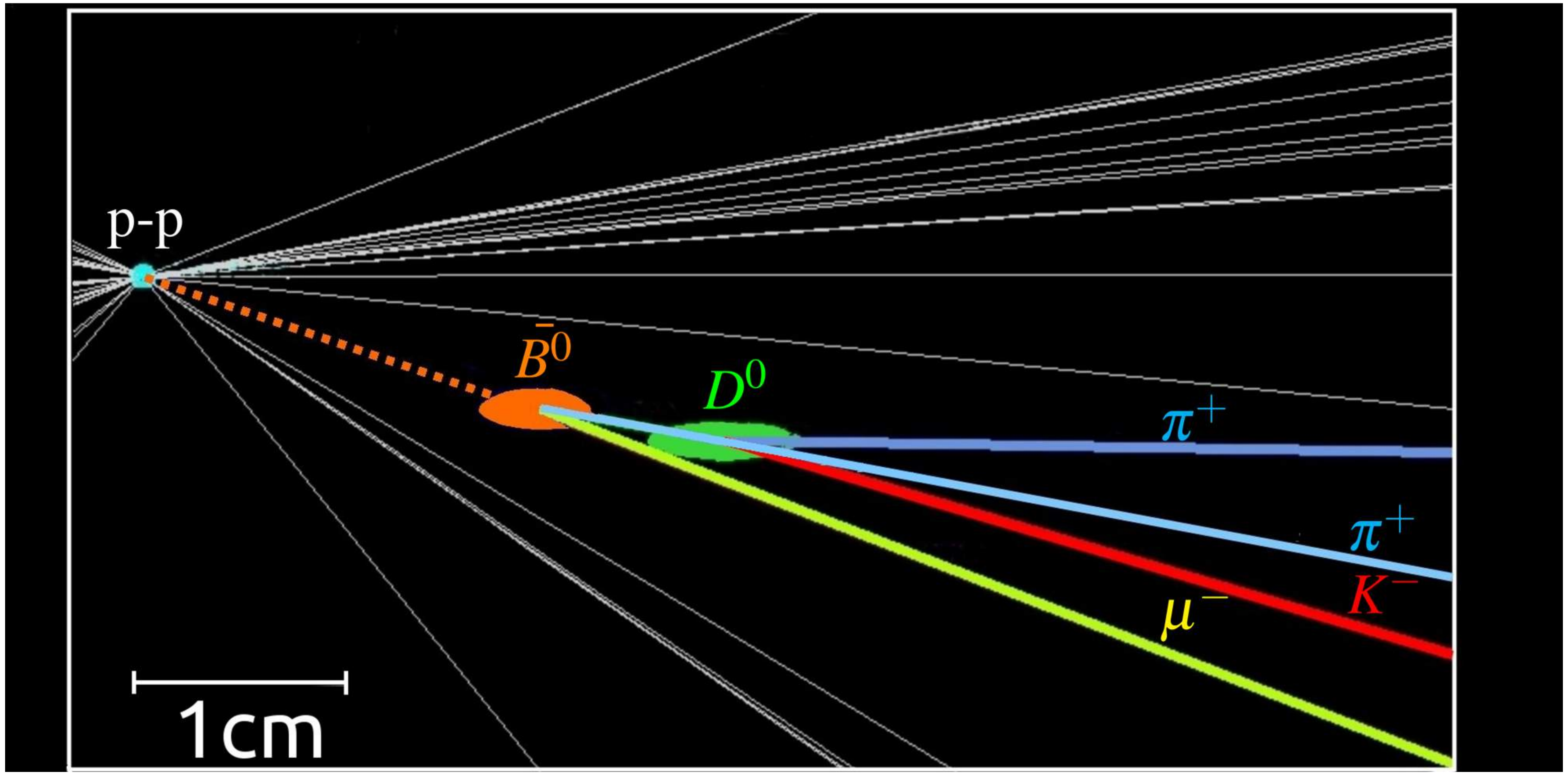
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- R(D*) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs).



The problem with neutrinos at a hadron collider

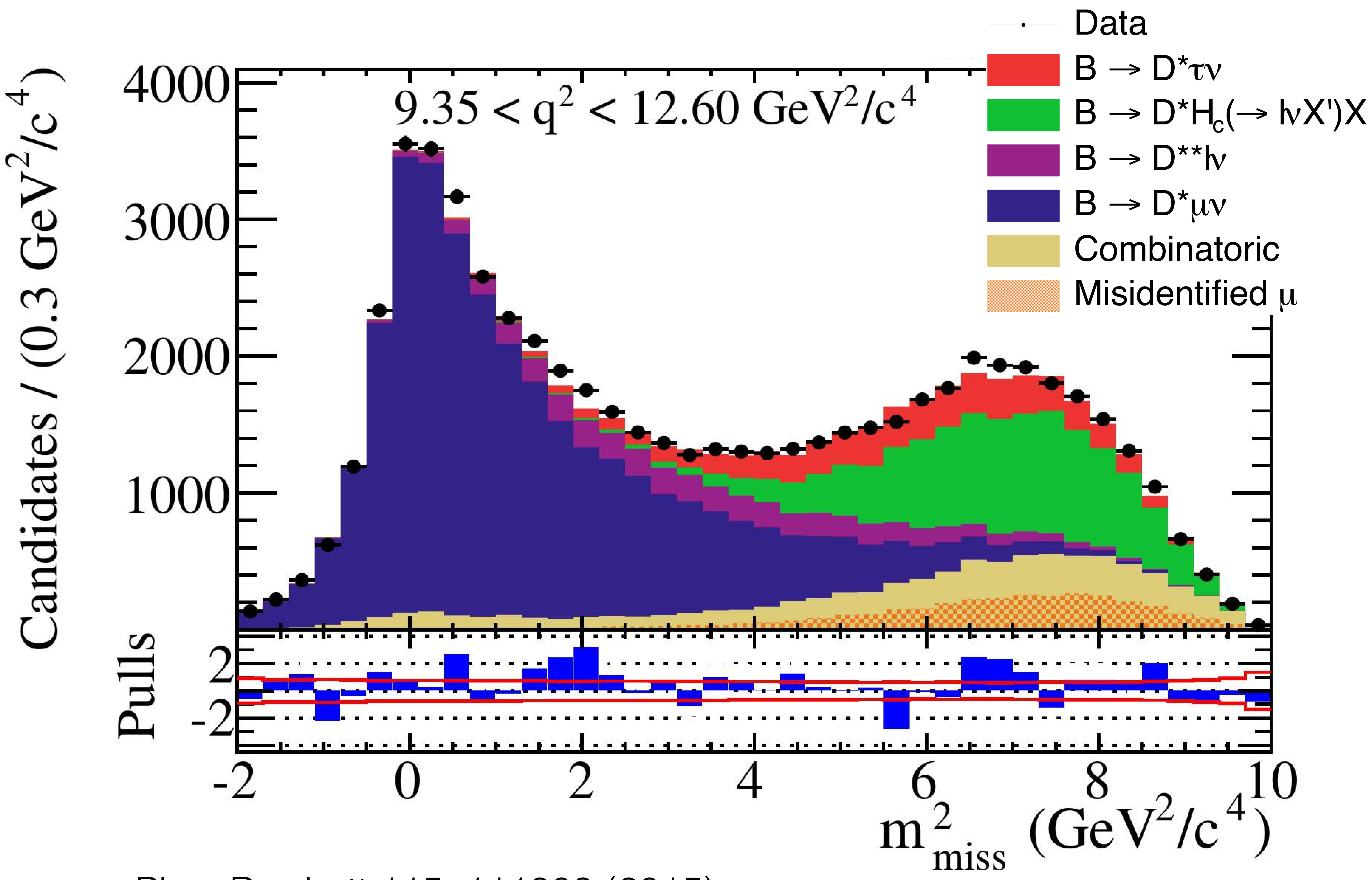
- At least two neutrinos in the final state.
  - No sharp peak to fit in any distribution.



Nature volume 546, pages 227–233

Signal extraction

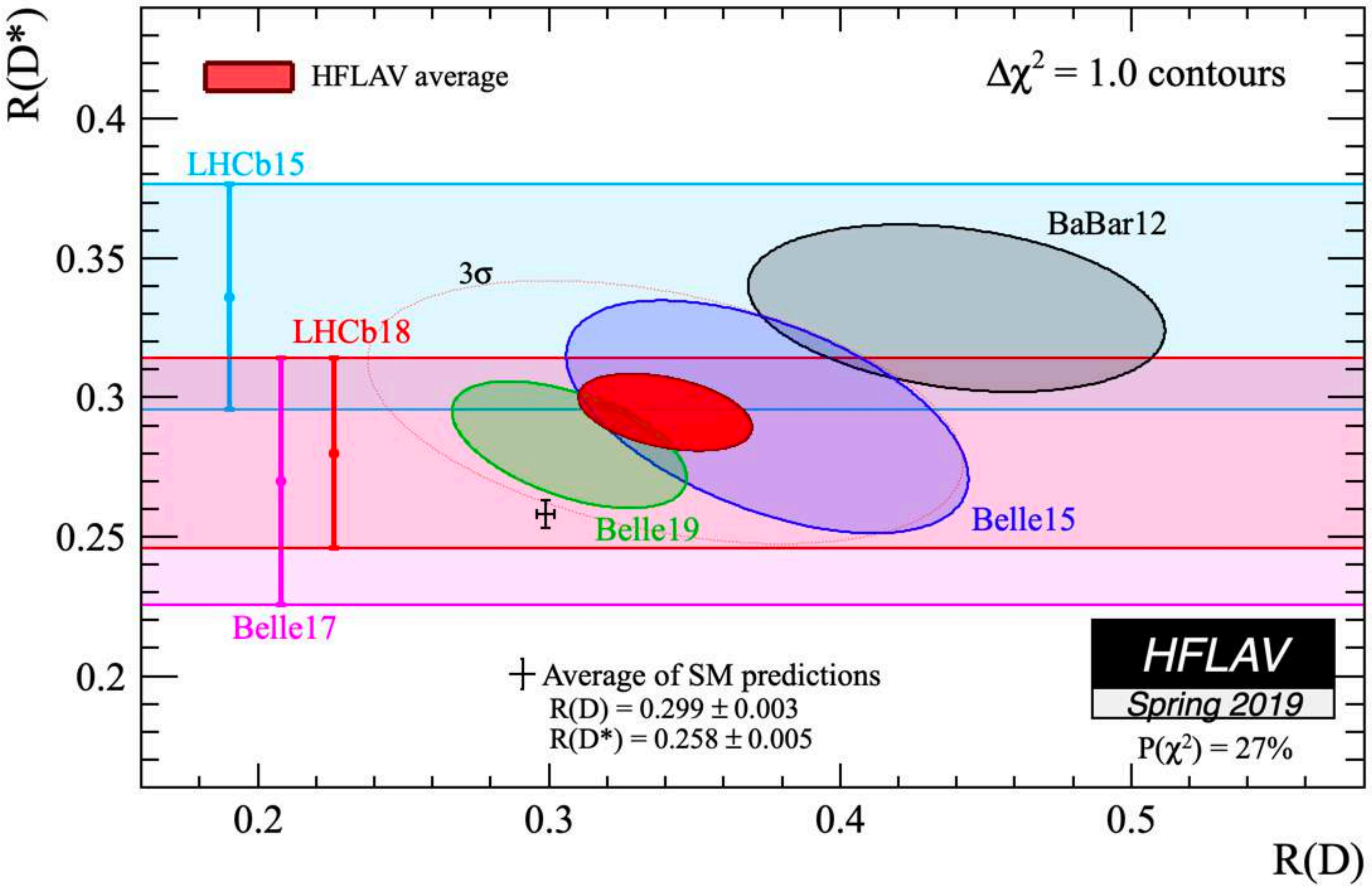
- Fit the missing mass, discriminating between muon and tauonic mode.



Phys.Rev.Lett.115, 111803 (2015)

Hints of an excess

- Three different experiments see an excess in the number of semitauonic candidates.



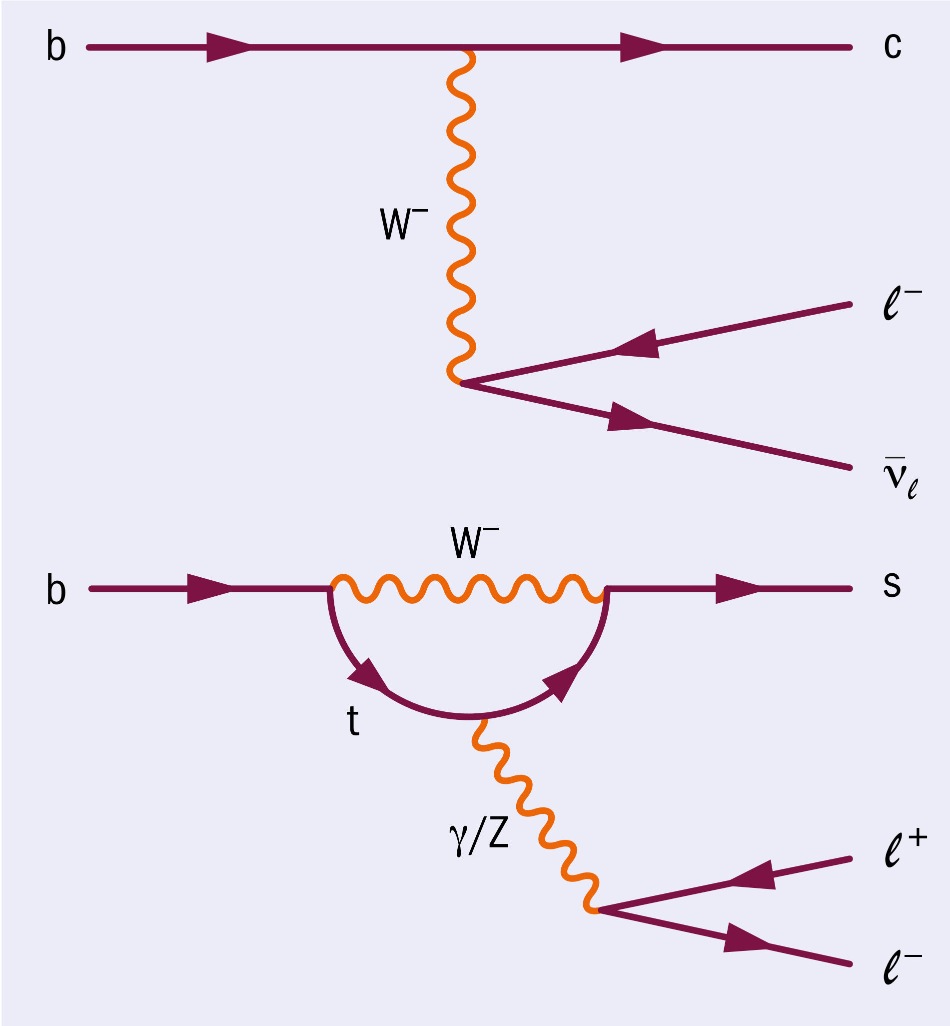
- Combined deviation around 3 σ, strongly motivates new measurements in different decay channels.

What could this all mean?

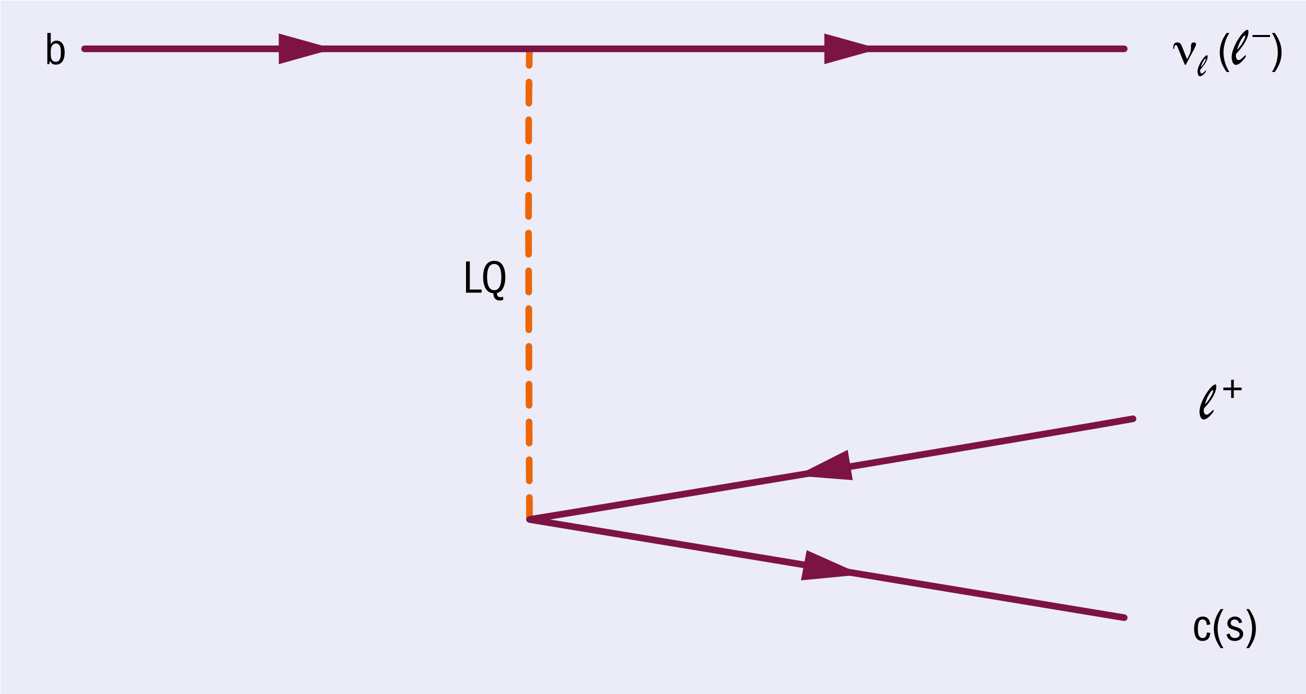
More details in Andreas Crivellin's talk (UZH)

- We have two sets of anomalies in charged and neatral current semileptonic B decays.
- They both point towards a violation of lepton universality.
- Possible to explain both anomalies with a single new particle (leptoquark) of around 2TeV mass.

SM diagrams



New physics diagram



- If these anomalies are confirmed it would mean a new force of Nature.
    - Extraordinary claims need extraordinary evidence..

What's next?

- We have not yet fully exhausted the current dataset at LHCb. Upcoming measurements:
  - Measurement of $R_{K^{(*)}}$ in the high q^2 region. Talk by Vadym Denysenko (UZH)
  - Measurement of new R ratios with different hadron species ($R_{K\pi}$,$R_{K\pi\pi}$,R_{ϕ},R_{D},$R_{J/\psi}$) Talk by Federica Riti (ETH)
  - Angular analysis of $B^0 \rightarrow K^{*0}e^+e^-$ decays. Discussed by Zhenzi Wang (UZH) and by Michele Atzeni (UZH)
  - Lepton universality tests with baryons (Λ_b baryons). Talk by Martina Ferrillo (UZH)
  - Searches for $b \rightarrow s\tau^+\tau^-$ Talk by Martin Andersson (UZH)
  - + many more ..
- Exciting times to be on LHCb!