Lepton Universality Tests in B decay at LHCb

And the strong indication for the LU symmetry breaking

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National Centre for Nuclear Research

High Energy Physics Seminar

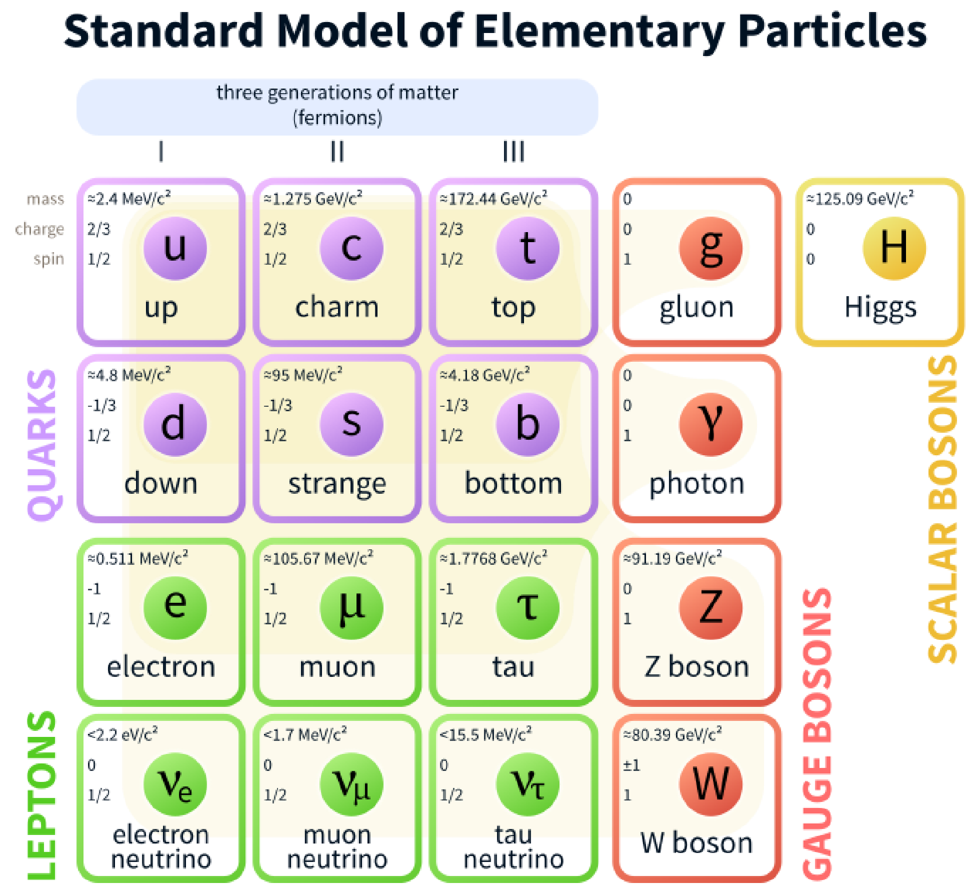
University of Warsaw , 23.04.2021

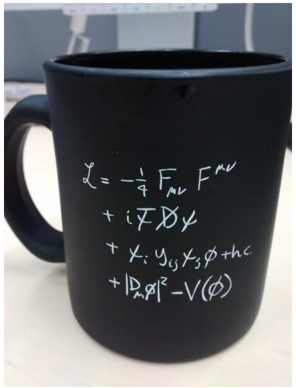
Outline

- ➔ Introduction
- ➔ Lepton flavour universality – problem formulation
- ➔ SM predictions and possible extensions
- ➔ Previous experimental results in B decays
- ➔ Recent LHCb results – strong indication of the LU symmetry breaking
- ➔ Summary & Outlook

Predicted by SM:

- W, Z boson
- gluon
- c and t quarks
- Higgs boson





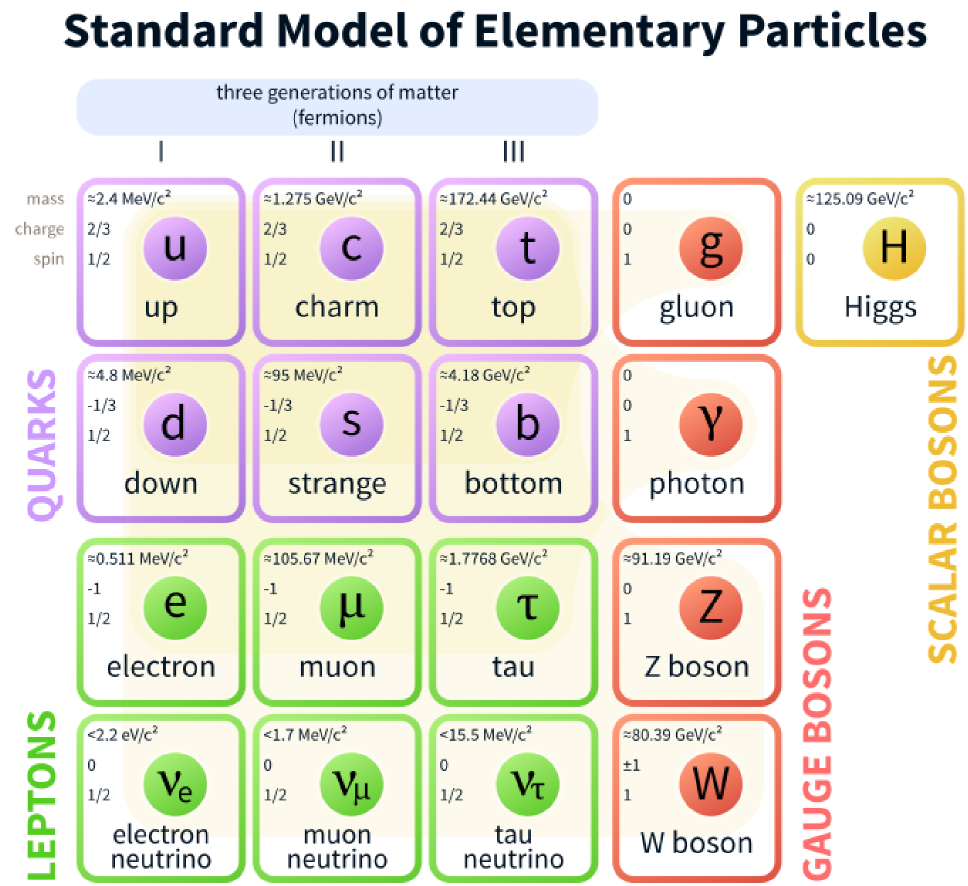
Predicted by SM:

- W, Z boson
- gluon
- c and t quarks
- Higgs boson

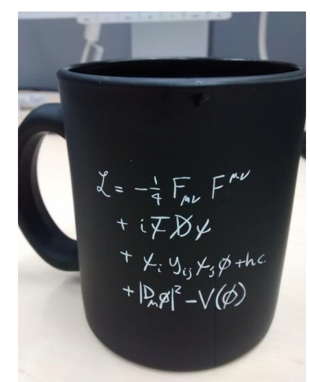
However several unresolved questions:

- Quark mass hierarchy problem
- Matter-antimatter asymmetry
- Dark matter / dark energy
- Neutrino mass

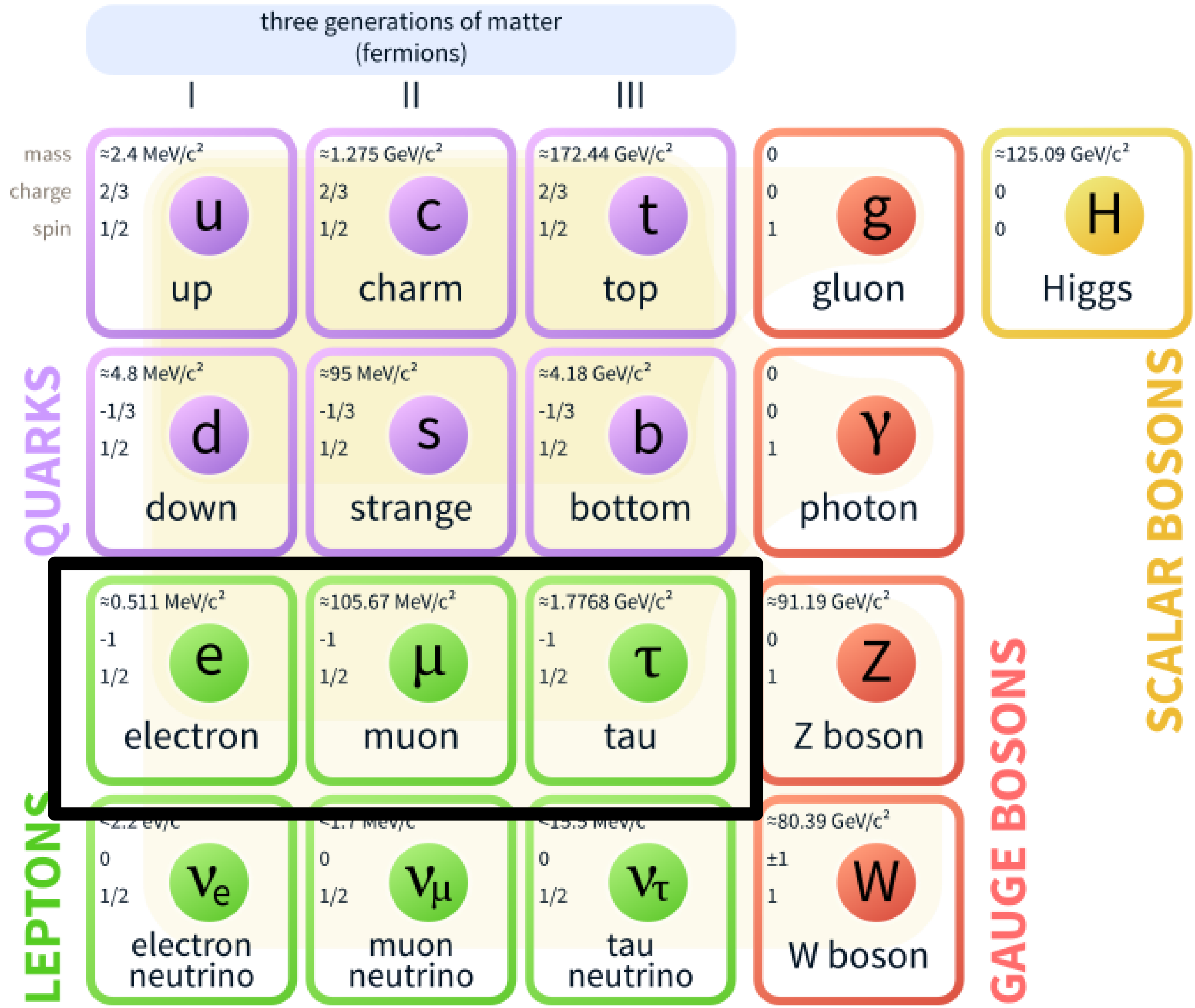
- ...
- How to incorporate gravity forces



Looking for SM "holes" to reveal "hidden" New Physics phenomena



Standard Model of Elementary Particles



Tests of Lepton Universality as New Physics search

charged leptons

electron e^-/e^+

- m = 0.511 MeV/c^2
- lifetime: ∞

muon μ^+/μ^-

- m = 105 MeV/c^2
- lifetime: 2.2 μs

tau τ^+/τ^-

- m = 1777 MeV/c^2
- lifetime: 0.29 ps

- Point-like particles
- Fermions with spin ½
- Undergo electromagnetic and weak interactions

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Lepton Flavour Universality (LU) :
Interactions of the charged leptons with gauge bosons are the same for all three families.

- Accidental symmetry in SM, broken only by the Yukawa interactions
- LU imposes constraints on the lifetimes and decay widths

Previous Experimental tests

Various experimental tests in the past confirming LU validity:

- Many results, performed e.g. at SLAC and LEP
- $Z\to ll$, $W\to l\nu$, $J/\psi\to ll$, $\psi(2S)\to ll$, $\Upsilon\to ll$, $\tau\to l\nu\nu$, $\pi\to l\nu$, $K\to\pi l\nu$
- Comparison of kaon decay rates $K^-\to e^-\bar{\nu}_e$ and $K^-\to\mu^-\bar{\nu}_\mu$

NA62: $R_K = (2.487 \pm 0.013) \times 10^{-5}$ $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ **Phys.Lett. B719 (2013) 326**

- Comparison of weak coupling with precises measurement of μ,τ lifetimes and masses and decay rates of $\tau^-\to e^-\bar{\nu}_e\nu_\tau$ and $\mu^-\to e^-\bar{\nu}_e\nu_\mu$

BESIII: $\left(\frac{g_\tau}{g_\mu}\right)^2 = 1.0016 \pm 0.0042$ **Phys.Rev. D90 (2014) 012001**

- Provided very strong limits on non-universality models

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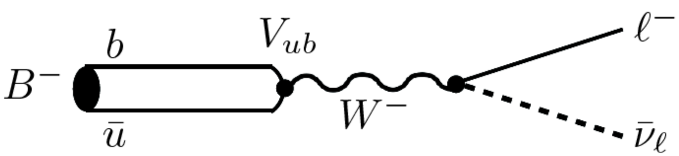
Puzzling results:
Precise studies of B meson decays indicate consistent deviation from SM predictions – excess in τ rate observed by Babar, Belle (e^+e^- colliders), and by LHCb (pp collider)

Tests of LU in B decays

Purely leptonic B decays:

$$B^- \to \ell^- \overline{\nu}_\ell$$



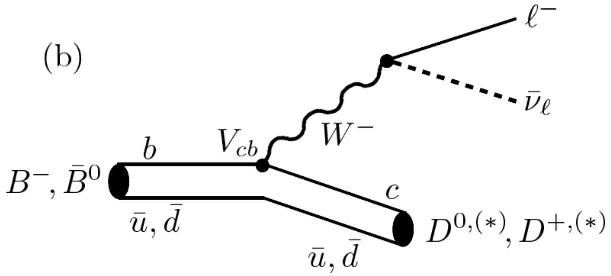
- Branching fraction of tau

Measured by: BABAR and Belle

Semi-leptonic B decays

Charged currents

$$\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell$$

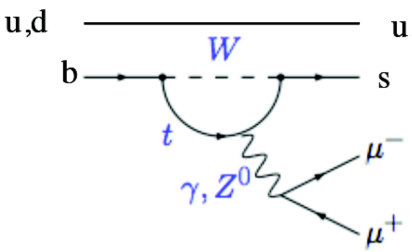


- tau/muon ratio
- R(D), R(D*), R(J/ψ)

Neutral currents

$$B \to K^{(*)} \ell^+ \ell^-$$

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



- Muon/electron ratio
- R(K), R(K*)

Measured by: BABAR, Belle and LHCb

Tests of LU in B decays

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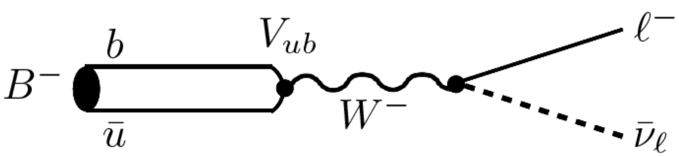

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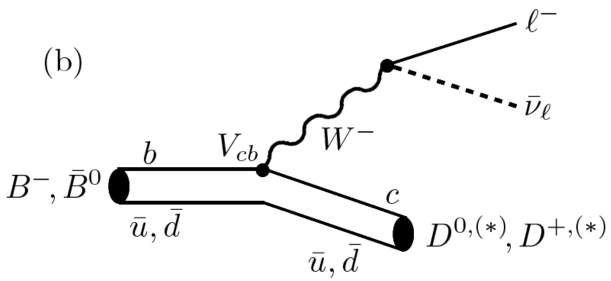

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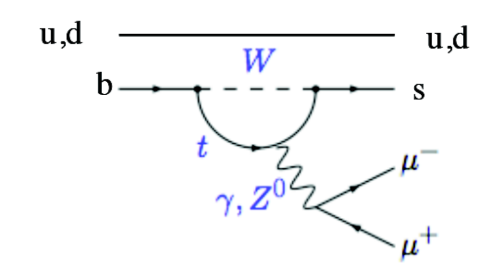


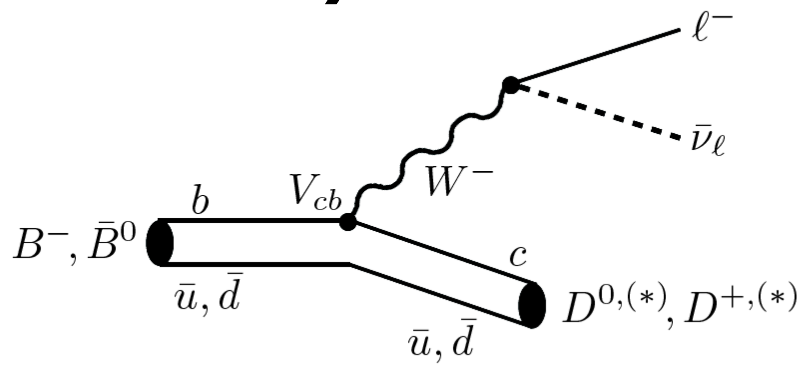
- Muon/electron ratio
- R(K), R(K*)

Measured by: BABAR, Belle and LHCb

SM predictions for B meson decays

SM predictions for semi-leptonic decays (b → c transition)

$$\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell$$



Dependence on lepton mass squared and on q^2

Quark mixing parameter b → c transition

D* three-momentum in B rest frame

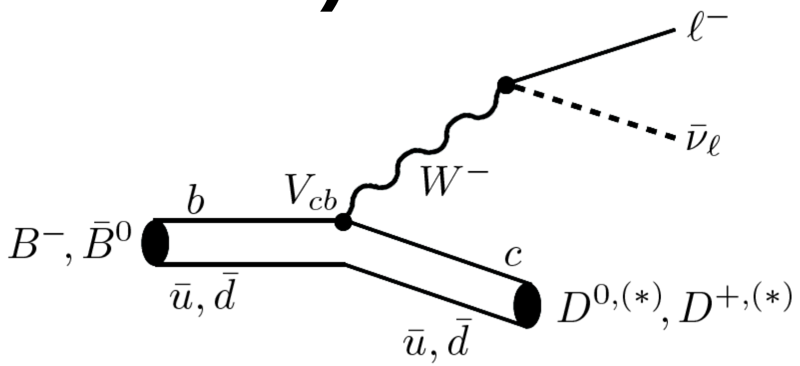
$$\frac{d\Gamma^{SM}(\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell)}{dq^2} = \frac{G_F^2 \, |V_{cb}|^2 \, |p^*_{D^{(*)}}| \, q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \times \left[(|H_+|^2 + |H_-|^2 + |H_0|^2) \left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2} |H_s|^2 \right]$$

universal phasespace factor

Hadronic effects
H_+, H_-, H_0, H_s – helicity amplitudes

SM predictions for semi-leptonic decays (b→ c transition)

$$\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell$$



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$$\frac{\mathscr{B}(\bar{B} \to D\tau^- \overline{\nu}_\tau)}{\mathscr{B}(\bar{B} \to De^- \overline{\nu}_e)}$$

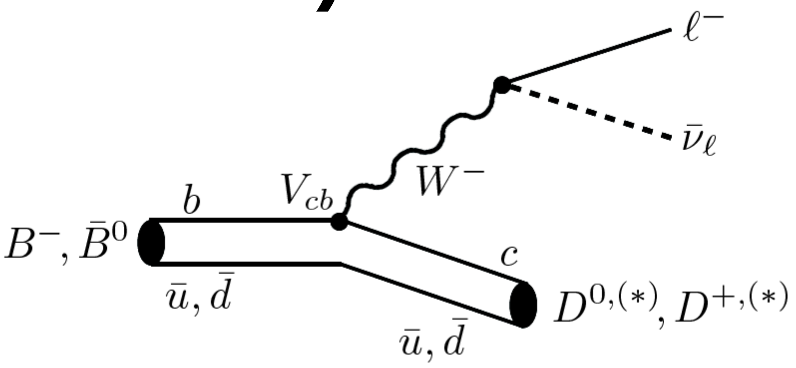
$$\frac{\mathscr{B}(\bar{B} \to D^*\tau^- \overline{\nu}_\tau)}{\mathscr{B}(\bar{B} \to D^*e^- \overline{\nu}_e)}$$

We operate with **R(D)**, **R(D*)** tau/electron (or tau/muon) ratio :

- Remove |Vcb| dependence
- Partial cancellation of theoretical uncertainties (hadronic contributions)
- Partial reduction of experimental errors

SM predictions for semi-leptonic decays (b → c transition)

$$\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell$$



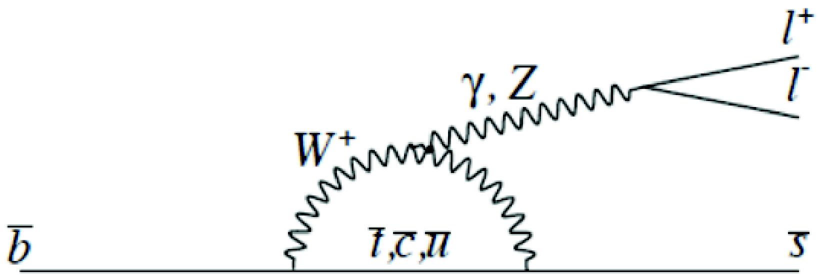
$$\frac{d\Gamma^{SM}(\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell)}{dq^2} = \frac{G_F^2 \, |V_{cb}|^2 \, |p^*_{D^{(*)}}| \, q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \times \left[(|H_+|^2 + |H_-|^2 + |H_0|^2)\left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2}|H_s|^2\right]$$

$$\mathscr{R}_{D^*}^{SM} = \frac{\mathscr{B}(\bar{B} \to D^* \tau^- \overline{\nu}_\tau)}{\mathscr{B}(\bar{B} \to D^* e^- \overline{\nu}_e)} = 0.252 \pm 0.003$$

$$\mathscr{R}_{D}^{SM} = \frac{\mathscr{B}(\bar{B} \to D \tau^- \overline{\nu}_\tau)}{\mathscr{B}(\bar{B} \to D e^- \overline{\nu}_e)} = 0.300 \pm 0.008$$

Bernlocher et al. Phys. Rev. D 95, 115008 (2017)

SM predictions for semi-leptonic (b→ s transition)



$$q^2 = m^2(\ell\ell)$$

$$R_{\mathrm{H}}\left[q^2_{\mathrm{min}}, q^2_{\mathrm{max}}\right] = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to He^+e^-)}{\mathrm{d}q^2}}$$

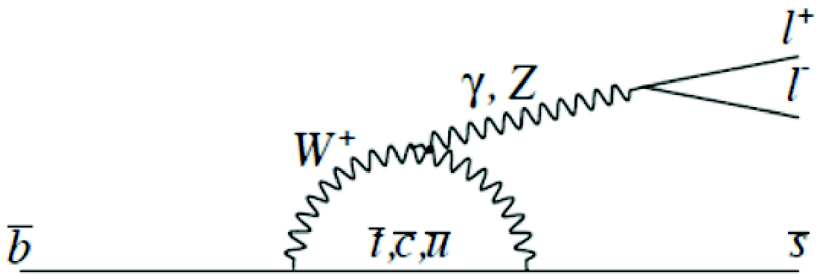
$$H = K, K^*, \phi, ...$$

$R_{SM}(H) = 1 \pm O(10^{-2})$

- QED correction at 10^{-2} level
- Hadronic uncertainties cancels in the ratio (no QCD corrections)

Eur. Phys. J. C76 (2016) 8, 440

SM predictions for semi-leptonic (b→ s transition)



$$q^2 = m^2(\ell\ell)$$

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$H = K, K^*, \phi, \ldots$

$R_{SM}(K) = 1 \pm O(10^{-2})$ from QED corrections

- QED correction at 10^{-2} level
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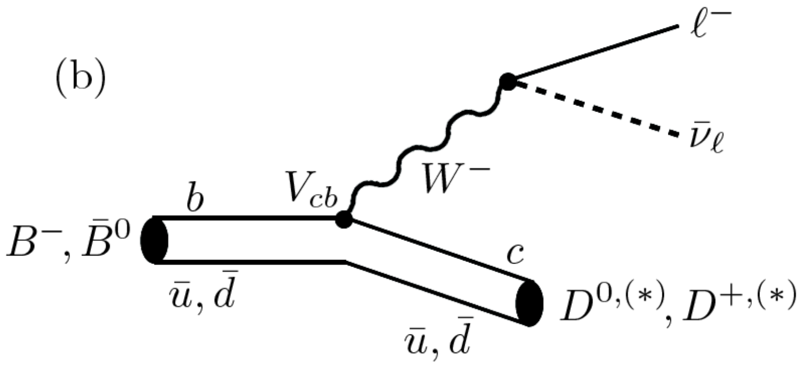
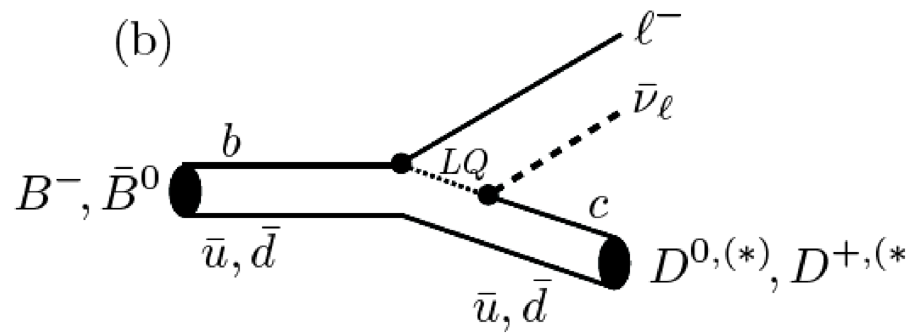
New Physics extension (LeptoQuark)

SM



NP



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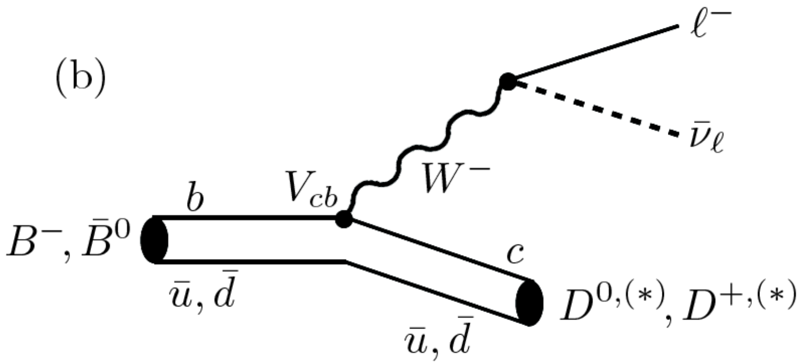

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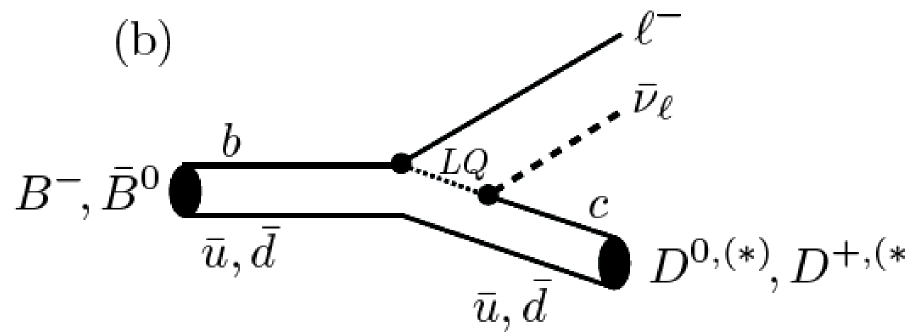
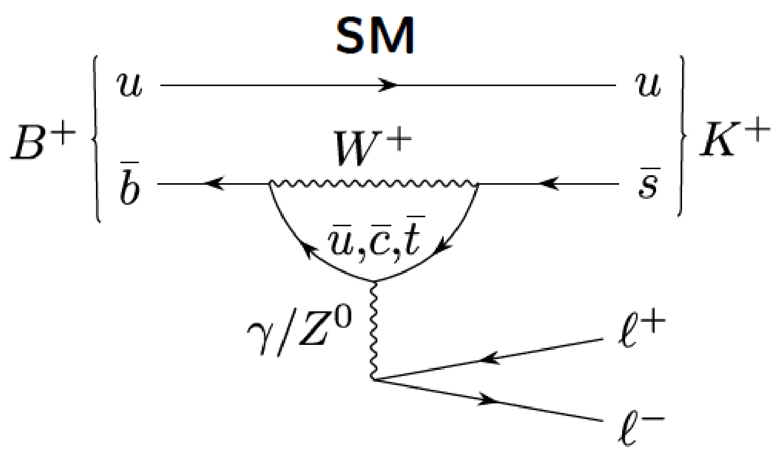
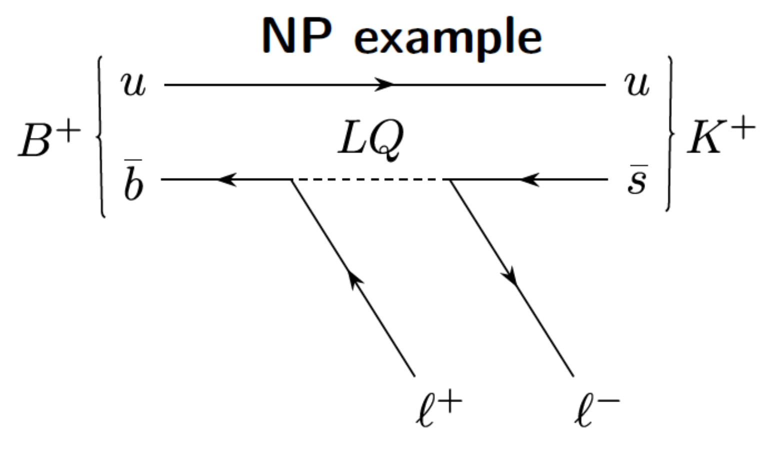






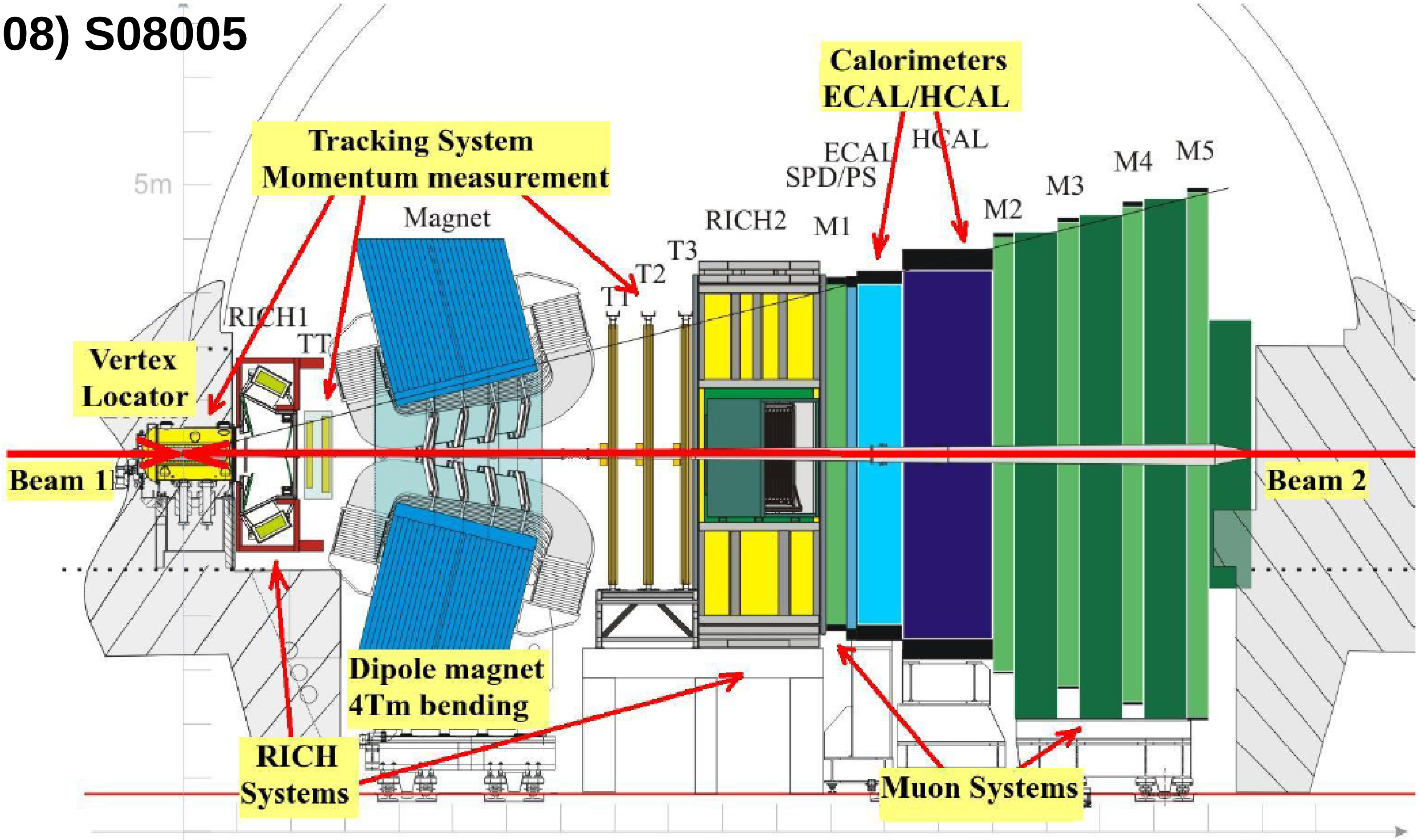
New Physics extensions

- Models predicting Lepto-quark (LQ)
- New gauge boson W'^-
  - more heavy than W^-, couples differently to different leptons
  - Constrained by searches at LHC: $W^- \rightarrow t\bar{b}$, also by muon/tau masses measurement
- Models predicting charged Higgs partner H^- in the minimal extension of SM:
  - Couples differently to different masses
  - Would affect q^2 and angular distribution
- Models with SUSY particles

LHCb experimental results

Large Hadron Collider beauty detector

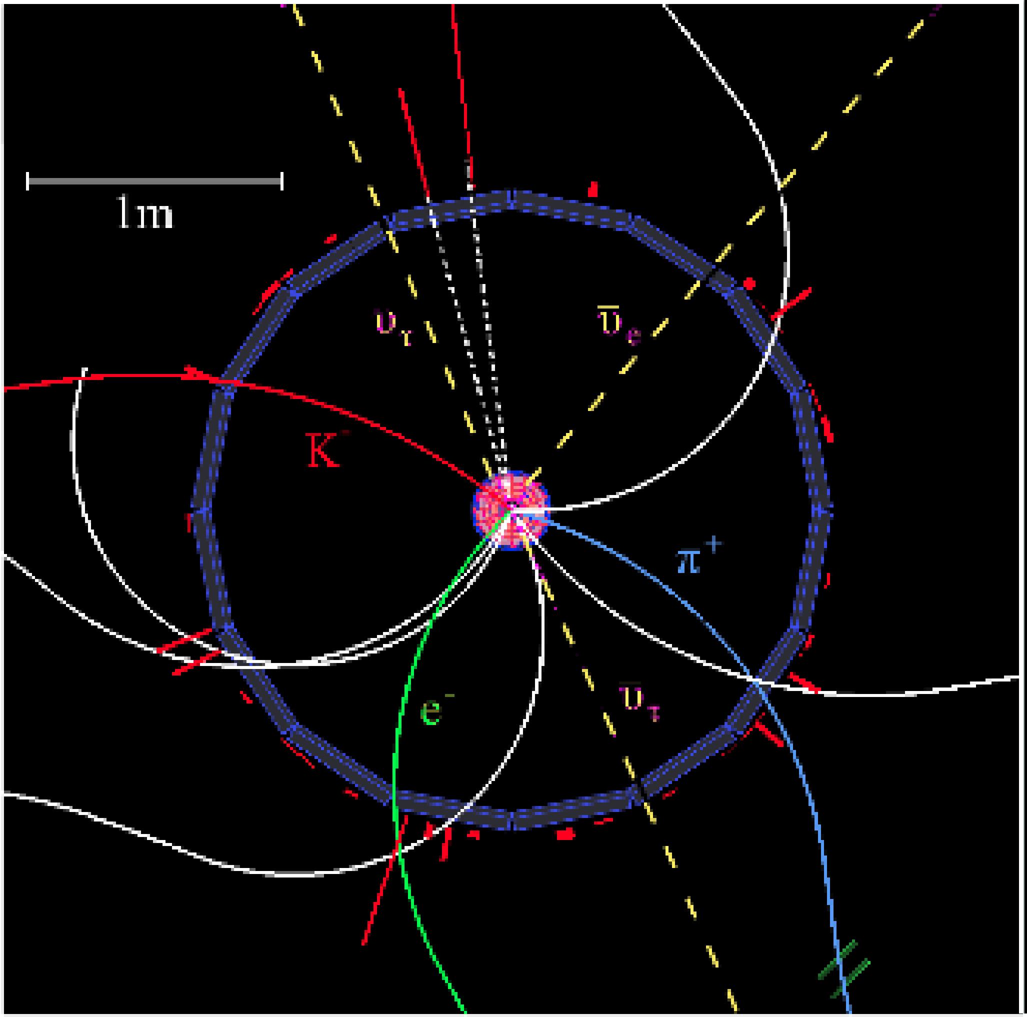
JINST 3 (2008) S08005



- Single-arm forward spectrometer covering range $2 < \eta < 5$ ($10 < \theta < 300$ mrad)
- Momentum resolution $\Delta p/p = 0.5\,\%$ @ 5 GeV/c to 1% @ 200 GeV/c
- Impact parameter resolution: 20 μm from high p_T tracks, **decay time resolution ~45 fs**

Example: B decay

BELLE

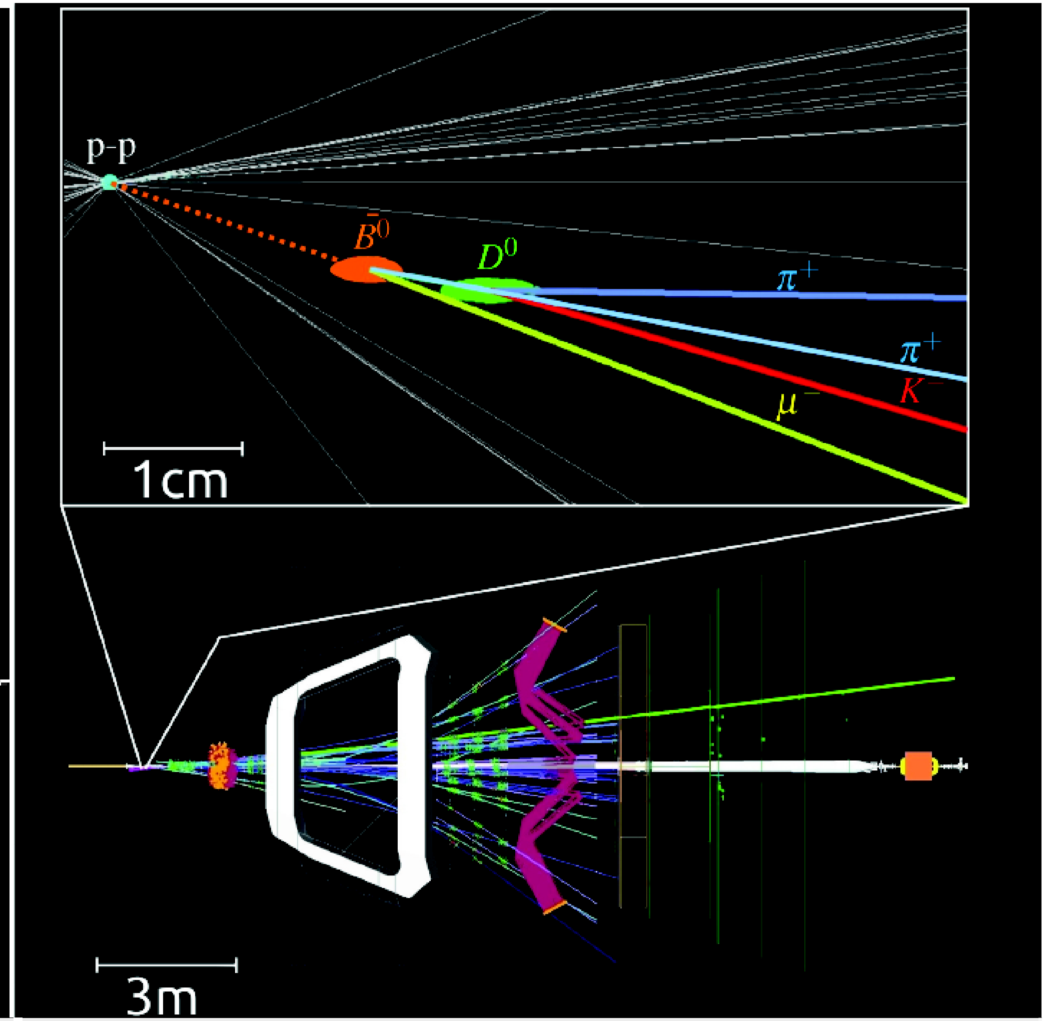


$\Upsilon(4S) \to B^+ B^-$

$B^- \to D^0 \tau^- \nu_\tau$

$D^0 \to K^- \pi^+$ $\tau^- \to e^- \nu_e \nu_\tau$

LHCb

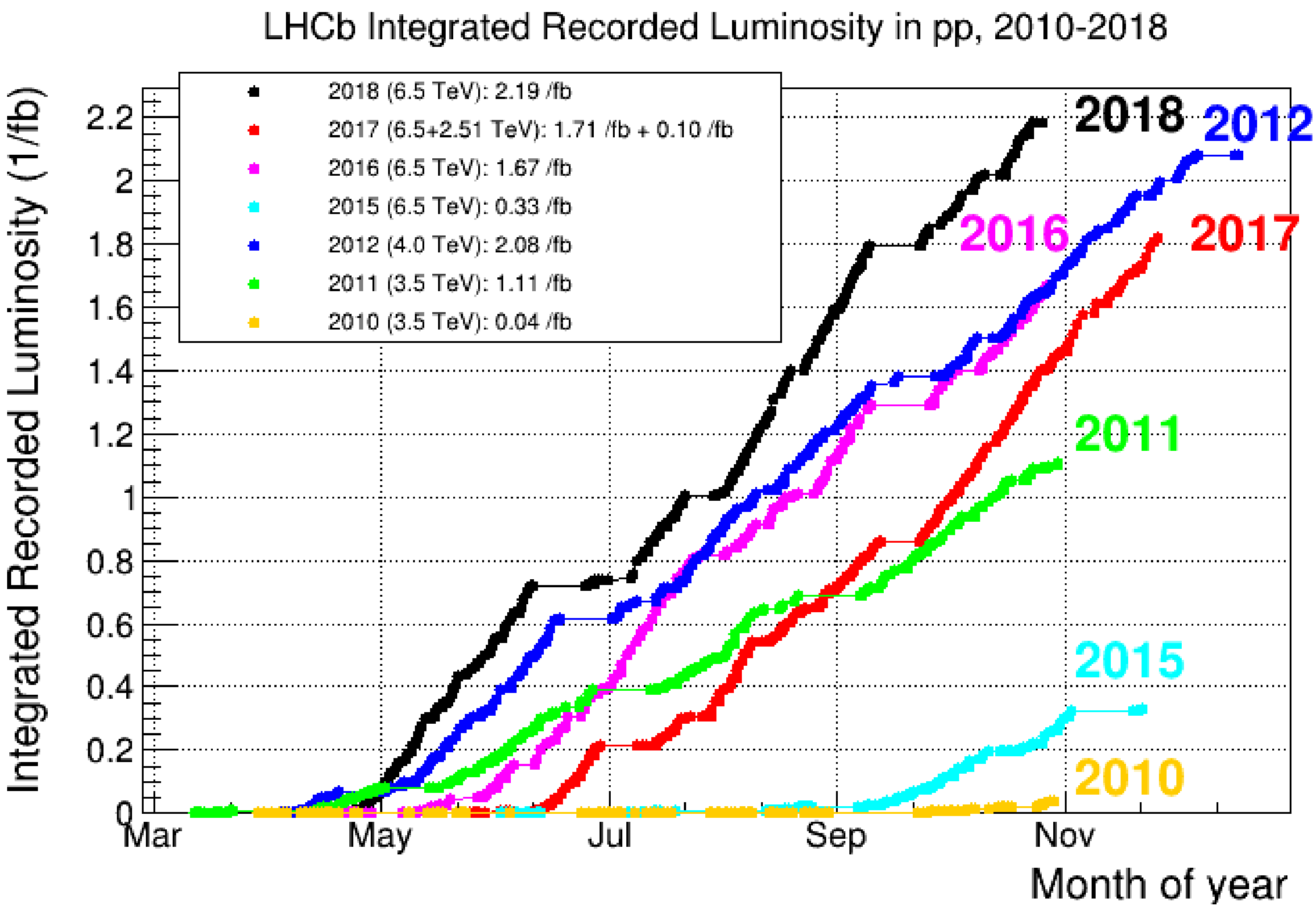


$B^0 \to D^{*+} \tau^- \nu_\tau$

$D^{*+} \to D^0 \pi^+$

$D^0 \to K^- \pi^+$ $\tau^- \to \mu^- \nu_\mu \nu_\tau$

G.Ciezarek et al.,
Nature 546(2017)227



Run I (2011-2012): 3 fb^{-1} @7 and @8 TeV

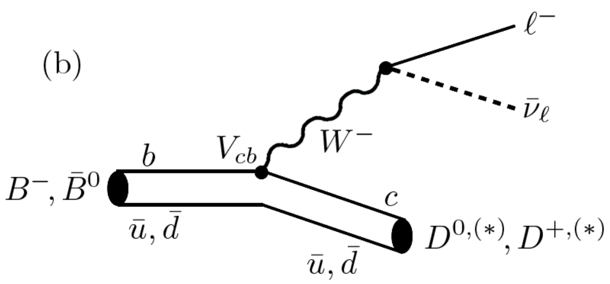
Run II (2015-2018): 6 fb^{-1} @13 TeV

Total sample collected: 9 fb^{-1}

Tests of LU in B decays - recapitulation

Charged currents

$$\bar{B} \to D^{(*)} \ell^- \overline{\nu}_\ell$$



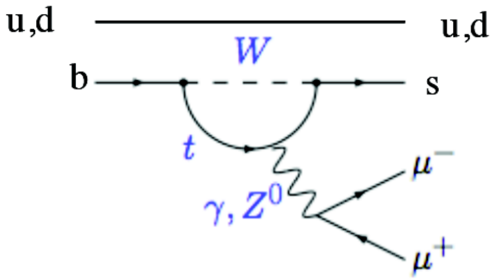
$$R(D^\star) \equiv \frac{\mathcal{B}(B \to D^\star \tau \nu)}{\mathcal{B}(B \to D^\star \mu \nu)}$$

- Large branching fraction (~1.2%)
- SM predictions at level of 2%
- Neutrinos in final state
- Background level

Neutral currents

$$B \to K^{(*)} \ell^+ \ell^-$$

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

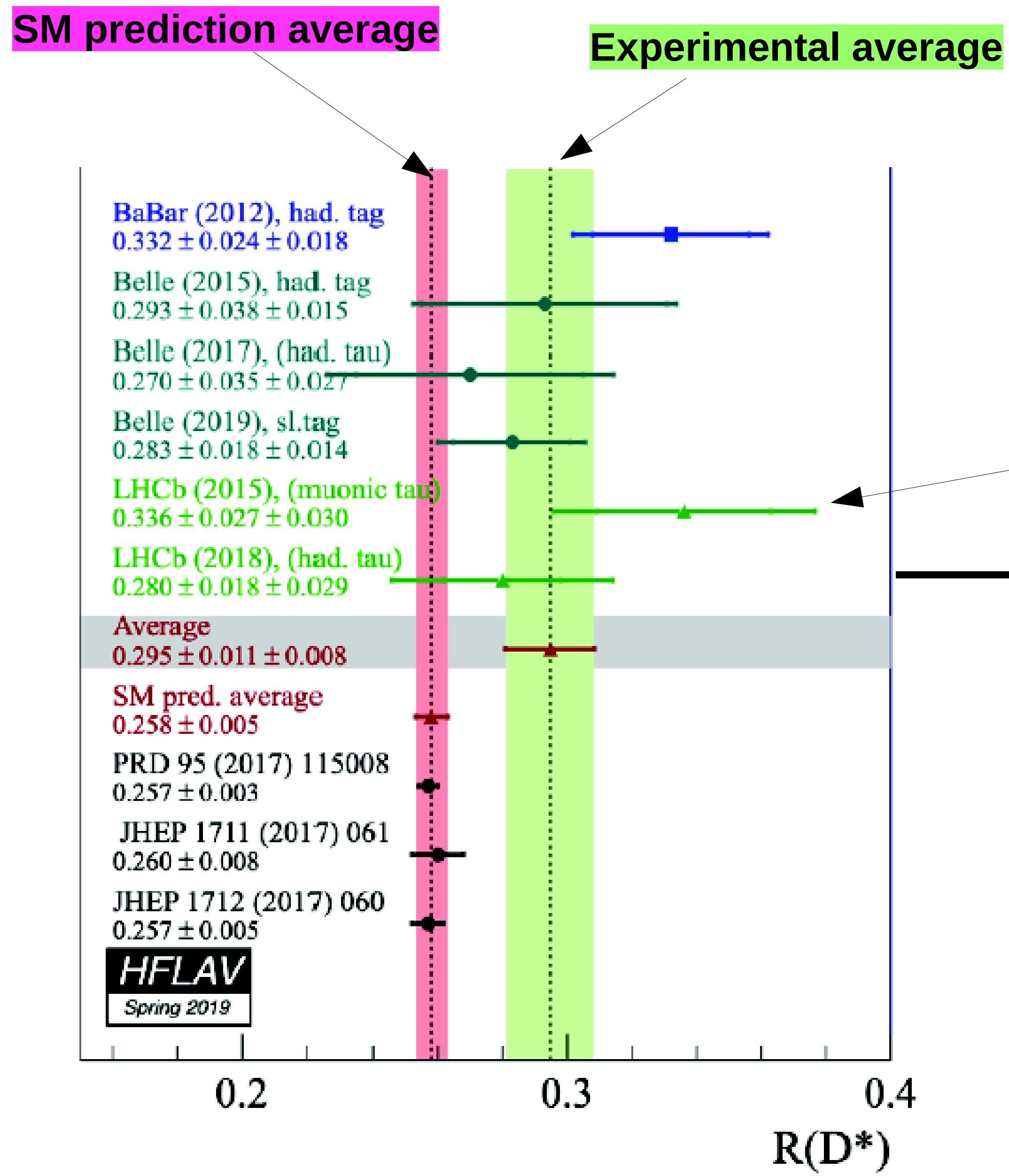


$$R(K) = \frac{B \to K\mu\mu}{B \to Kee}$$

- Rare decay
- SM prediction at 1% level
- Challenge: efficiency control between muon and e

R(D*)

R(D*) measurements



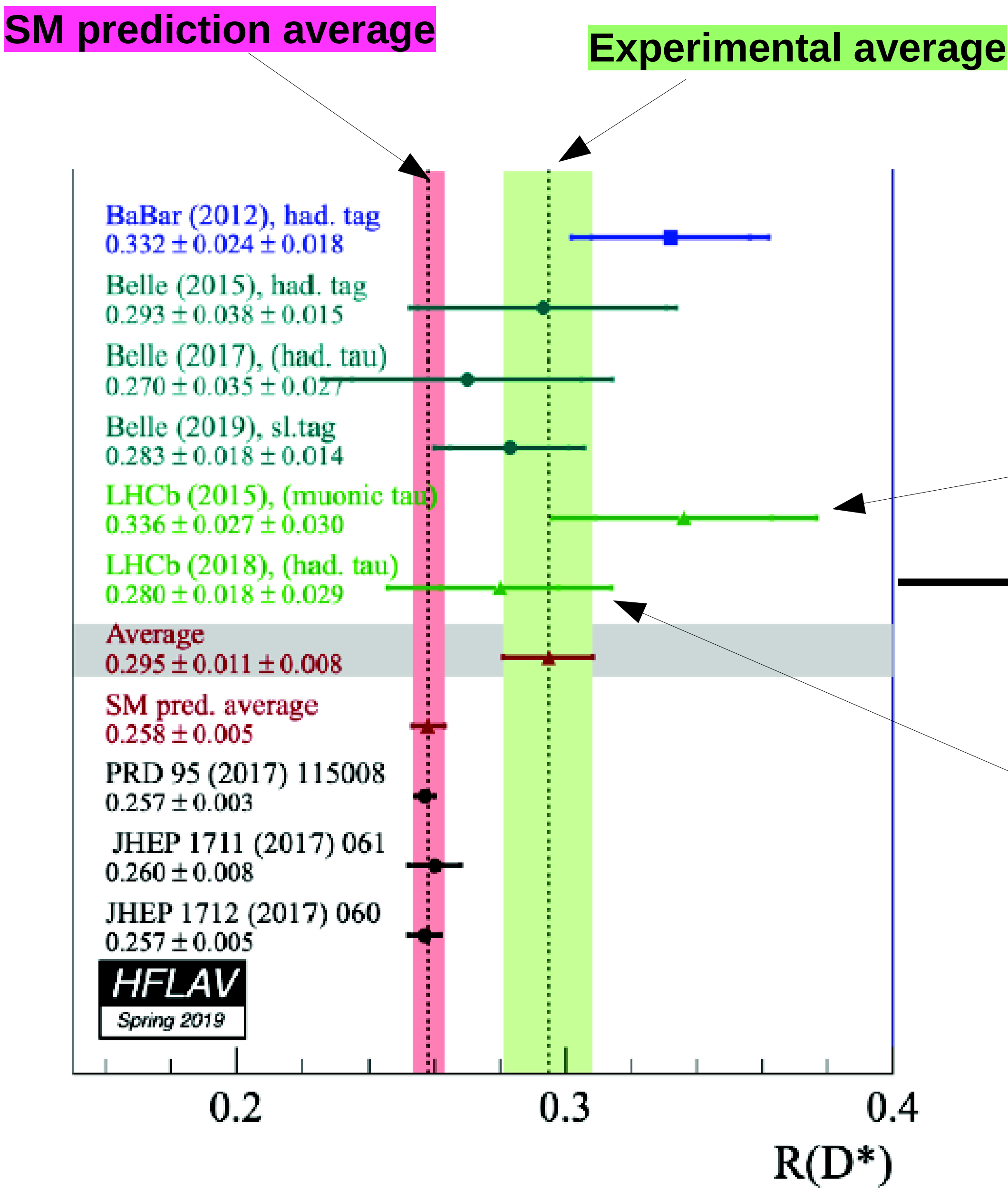
$$R(D^\star) \equiv \frac{\mathcal{B}(B \to D^\star \tau \nu)}{\mathcal{B}(B \to D^\star \mu \nu)}$$

Phys. Rev. Lett. (2015) 111803

R(D*) = 0.336±0.027±0.030

- Compatible with SM prediction at 2.1 σ level

R(D*) measurements



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Phys. Rev. Lett. (2015) 111803

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- Compatible with SM prediction at 2.1 σ level

Phys. Rev. Lett. 120 (2018) 171802

Phys. Rev. D 97 (2018)072013

R(D*) = 0.285±0.018±0.029

- Compatible with SM prediction at 1 σ level

$$R(D^{*-}) = K(D^{*-}) \times \frac{\mathcal{B}(B^0 \to D^{*-} 3\pi)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

$$K(D^{*-}) = \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} \pi^+ \pi^- \pi^+)}$$

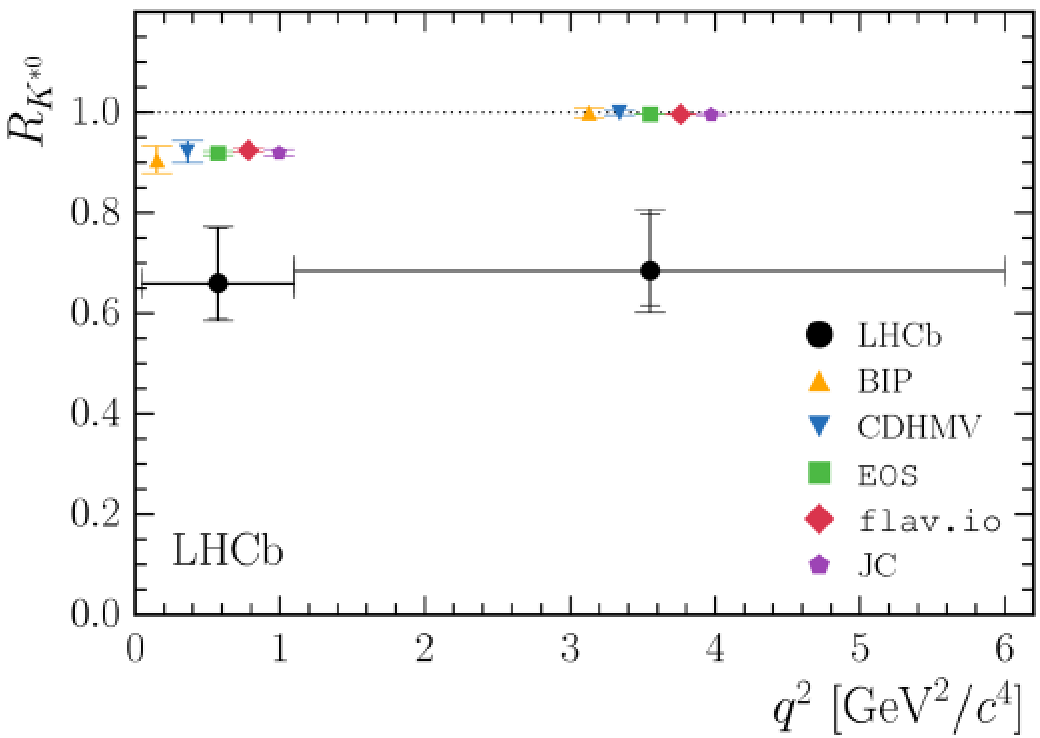
R(K) and R(K*)

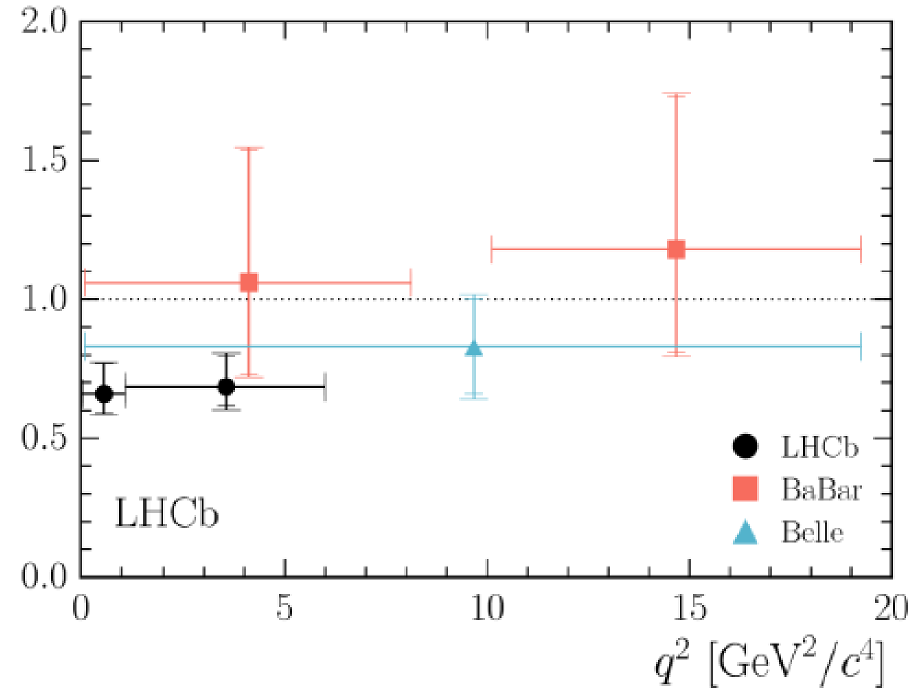
J. High Energ. Phys. (2017) 055

With respect to SM predictions

- Low q^2 bin: 2.1 –2.3 σ
- central q^2 bin: 2.4 – 2.5 σ

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

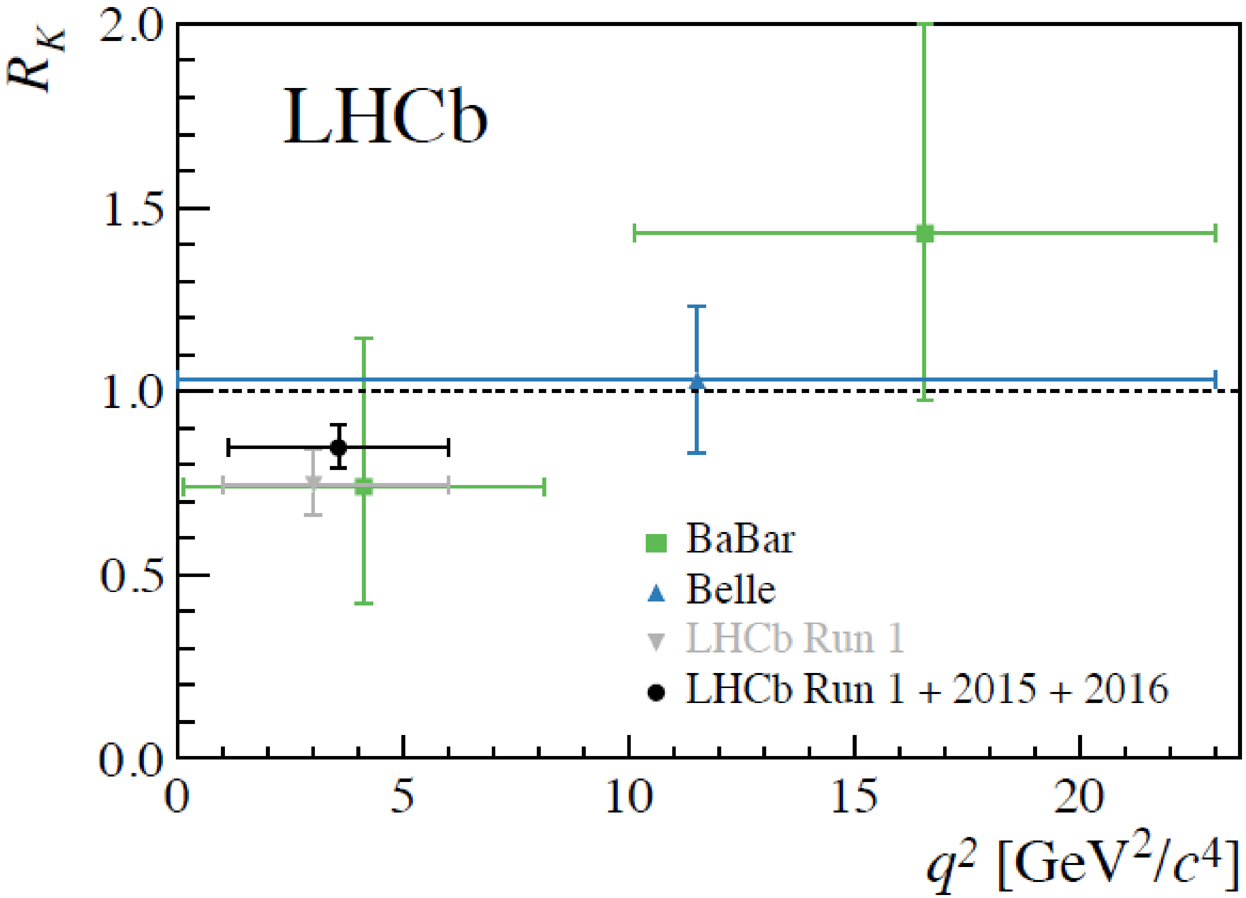




- LHCb sample: 3 fb^{-1}

- BaBar: PRD 86 (2012) 032012
- Belle: PRL 103 (2009) 171801
- LHCb: JHEP 08 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \ \text{GeV}^2/c^4 \\ 0.69\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \ \text{GeV}^2/c^4 \end{cases}$$



BaBar: Phys.Rev.D 86 (2012) 032012

Belle: Phys. Rev. Lett. 103 (2009) 171801

LHCb: Phys. Rev. Lett. 113 (2014) 151601

LHCb2: Phys. Rev. Lett. 122 (2019) 191801

$$B^+ \rightarrow K^+ \ell^+ \ell^-$$

- $R(K)^{SM} = 1$
- Last LHCb result consistent with SM within 2.5 σ
- LHCb sample used: 5 fb^{-1}

Towards LU symmetry breaking
New results on R(K)

New R(K) determination

$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^+ \to K^+ \mu^+ \mu^-\right)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^+ \to K^+ e^+ e^-\right)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

$R_{SM}(K) = 1 \pm O(10^{-2})$

- Repetition of the previous LHCb analysis with the full available data sets

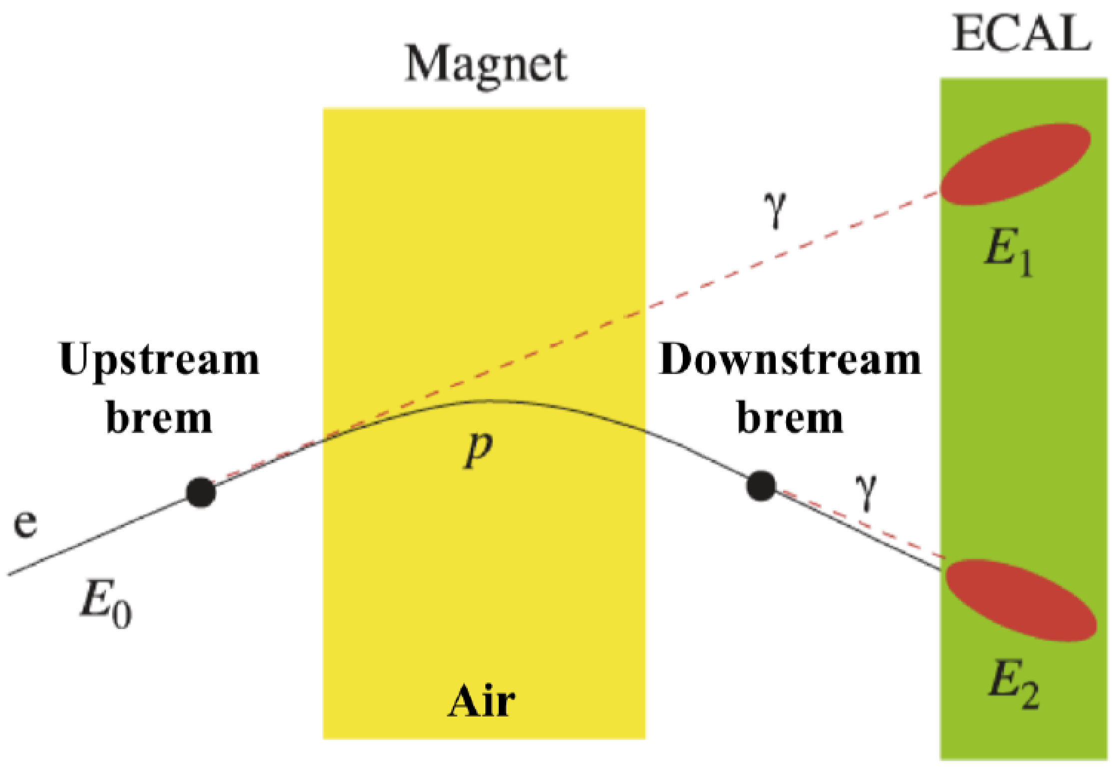
- **Old analysis** based on 5 fb^{-1} sample:
  - Run 1 (2011-2012) 3 fb^{-1}
  - Run 2 (2015-2016) 2 fb^{-1}

Phys. Rev. Lett. 122 (2019) 191801

- **New analysis** based on total 9 fb^{-1}:
  - Adding remaining Run 2 data (2017-2018)
  - Doubling number of B mesons

Experimental challenge with electrons

- Electrons lose a significant fraction of their energy by the bremsstrahlung radiation

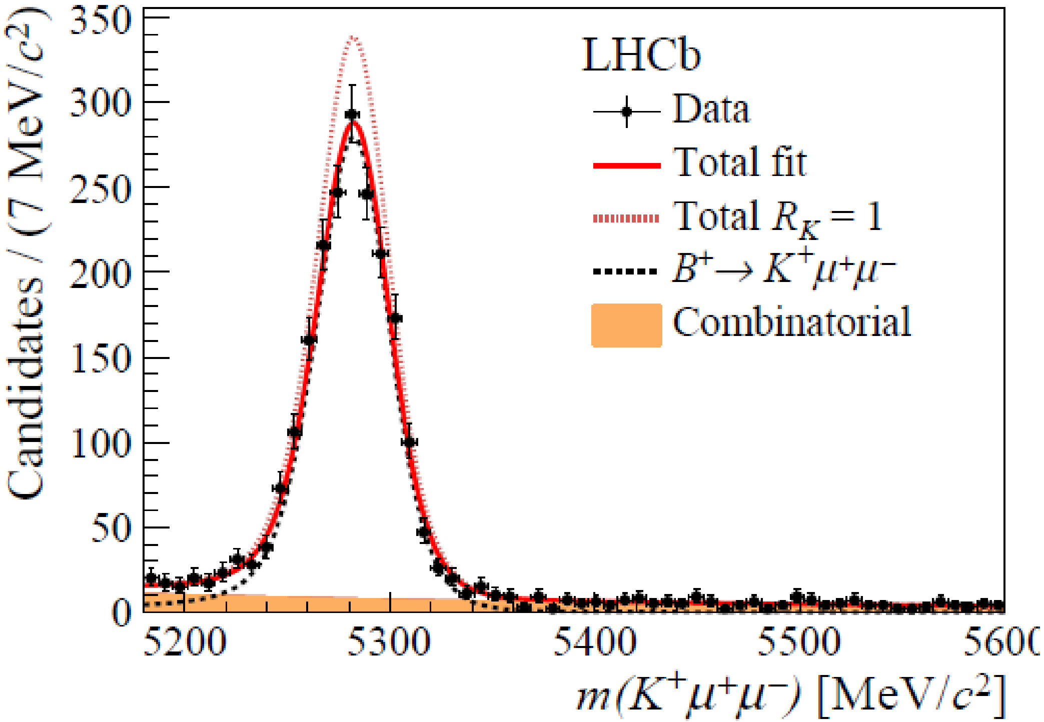


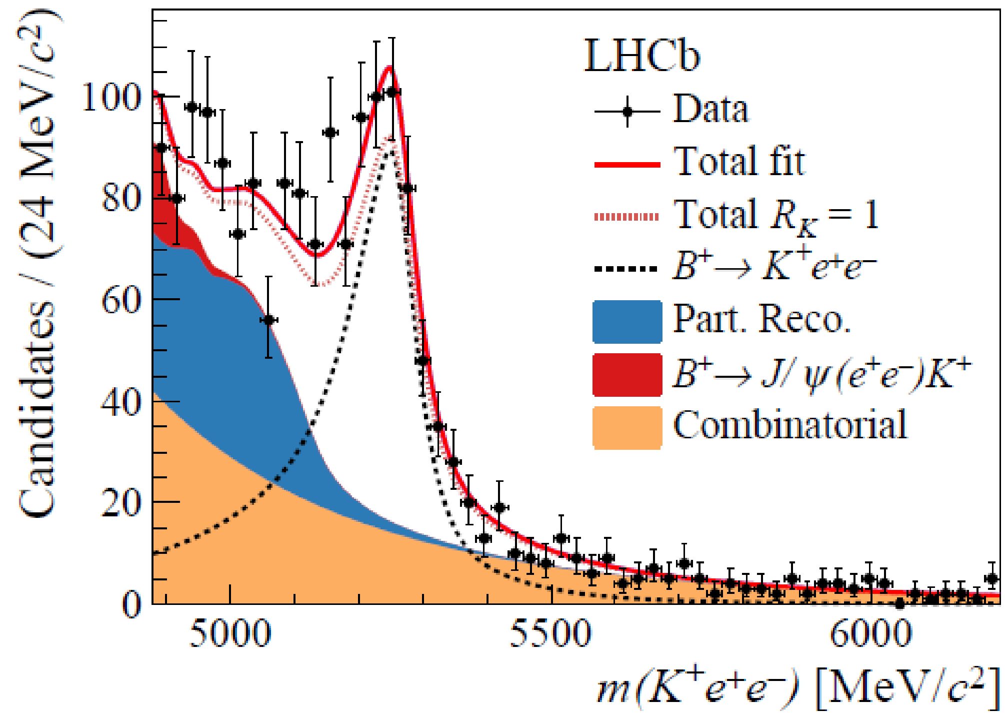
Electron momentum recovery algorithm

(ECAL candidates with E_T > 75 MeV)

Electrons vs muons resolutions

Phys. Rev. Lett. 122 (2019) 191801



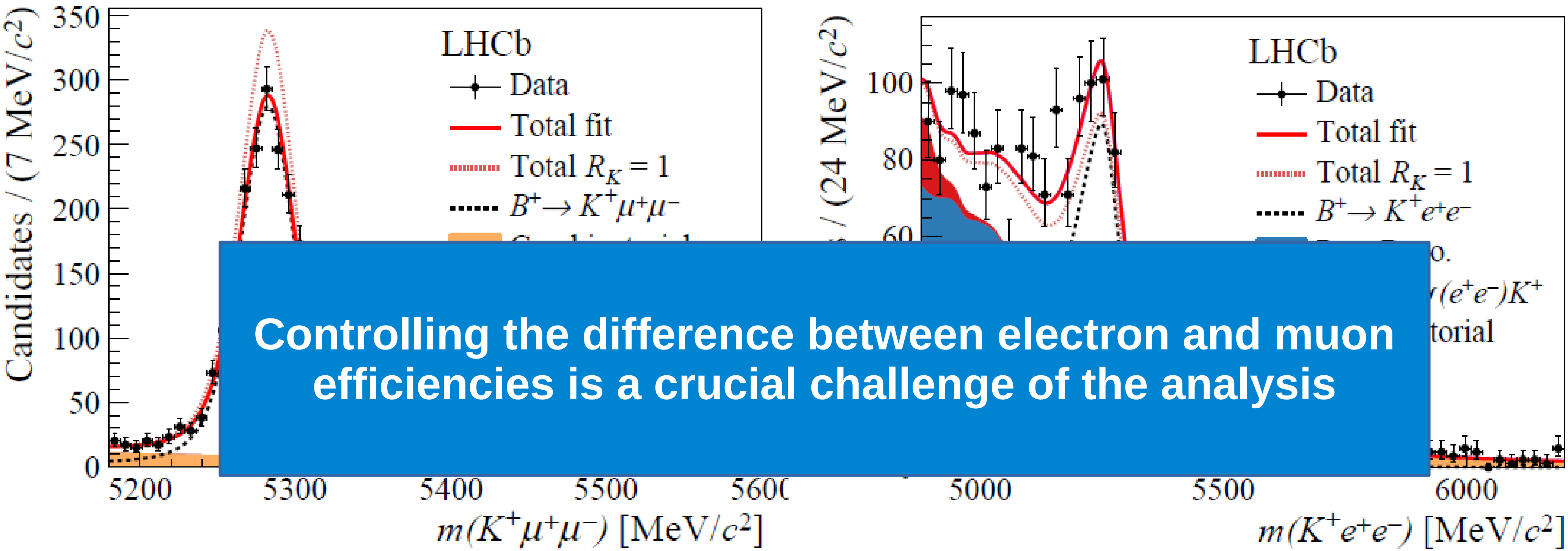


- L0 calorimeter trigger requires higher thresholds for electrons than L0 muon trigger (due to high occupancy)

- Particle identification and tracking efficiency also higher for muons than for electrons.

Electrons vs muons resolutions

Phys. Rev. Lett. 122 (2019) 191801



Controlling the difference between electron and muon efficiencies is a crucial challenge of the analysis

- L0 calorimeter trigger requires higher thresholds for electrons than L0 muon trigger (due to high occupancy)
- Particle identification and tracking efficiency also higher for muons than for electrons.

signal channel: $B^+ \to K^+ \ell^+ \ell^-$

control channel: $B^+ \to K^+ J/\psi(\ell^+ \ell^-)$

$$R_K = \left(\frac{N^{\mu\mu}_{\text{rare}}}{\varepsilon^{\mu\mu}_{\text{rare}}} \Big/ \frac{N^{ee}_{\text{rare}}}{\varepsilon^{ee}_{\text{rare}}} \right) \Bigg/ \underbrace{\left(\frac{N^{\mu\mu}_{\text{control}}}{\varepsilon^{\mu\mu}_{\text{control}}} \Big/ \frac{N^{ee}_{\text{control}}}{\varepsilon^{ee}_{\text{control}}} \right)}_{r_{J/\psi}}$$

$r_{J/\psi}$ **should be close to 1 (!)**

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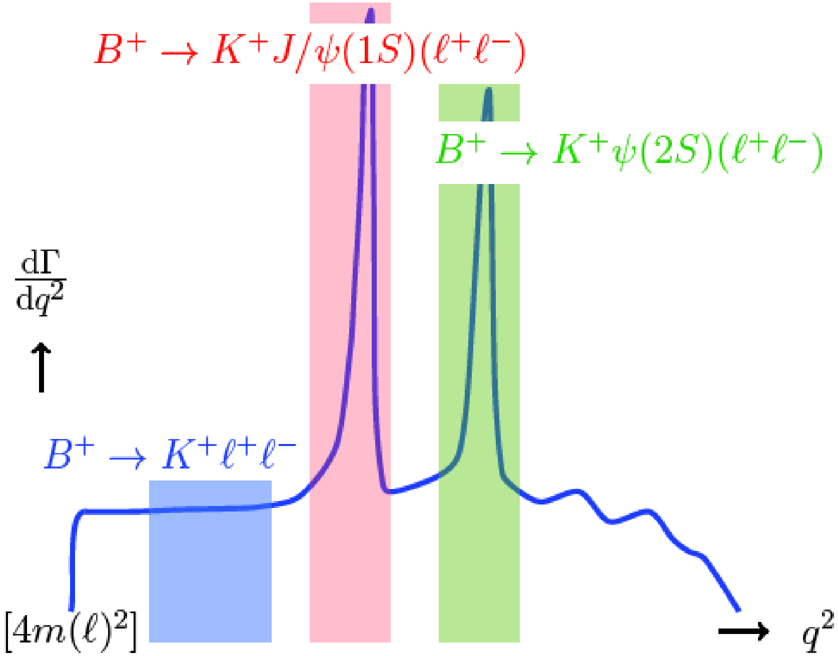
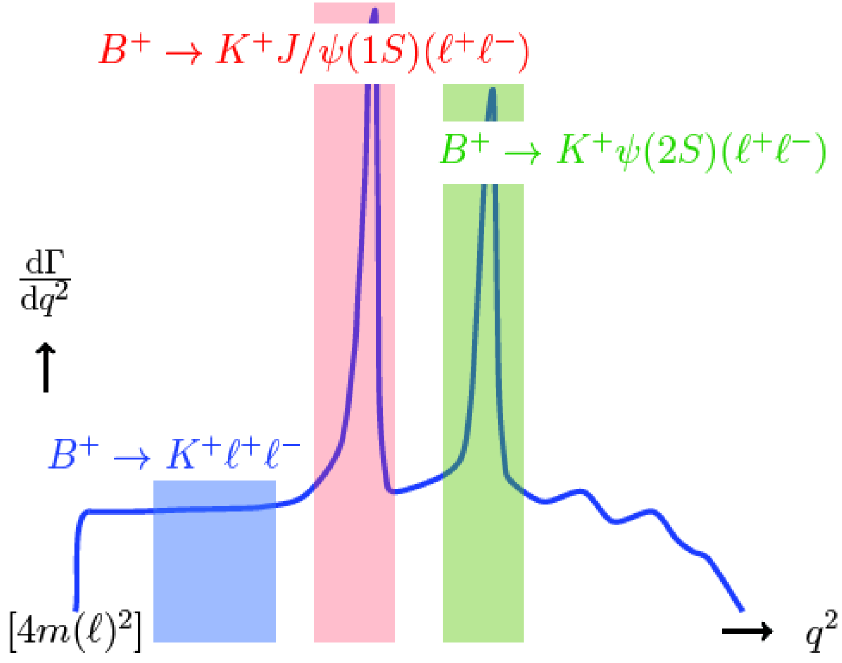


$$R_K = \left(\frac{N^{\mu\mu}_{\text{rare}}}{N^{\mu\mu}_{\text{control}}} \Big/ \frac{\varepsilon^{\mu\mu}_{\text{rare}}}{\varepsilon^{\mu\mu}_{\text{control}}} \right) \Big/ \left(\frac{N^{ee}_{\text{rare}}}{N^{ee}_{\text{control}}} \Big/ \frac{\varepsilon^{ee}_{\text{rare}}}{\varepsilon^{ee}_{\text{control}}} \right)$$

Most of the systematic effects cancels out

- Rare and J/Psi analysis share **the same selections** up to the q^2 cut.
- Yields estimated from the fits to invariant masses of final state particles.
- Efficiencies are determined from MC simulations calibrated with control channels



Measurement of $r_{J/Psi}$

arXiv:2103.11769

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$

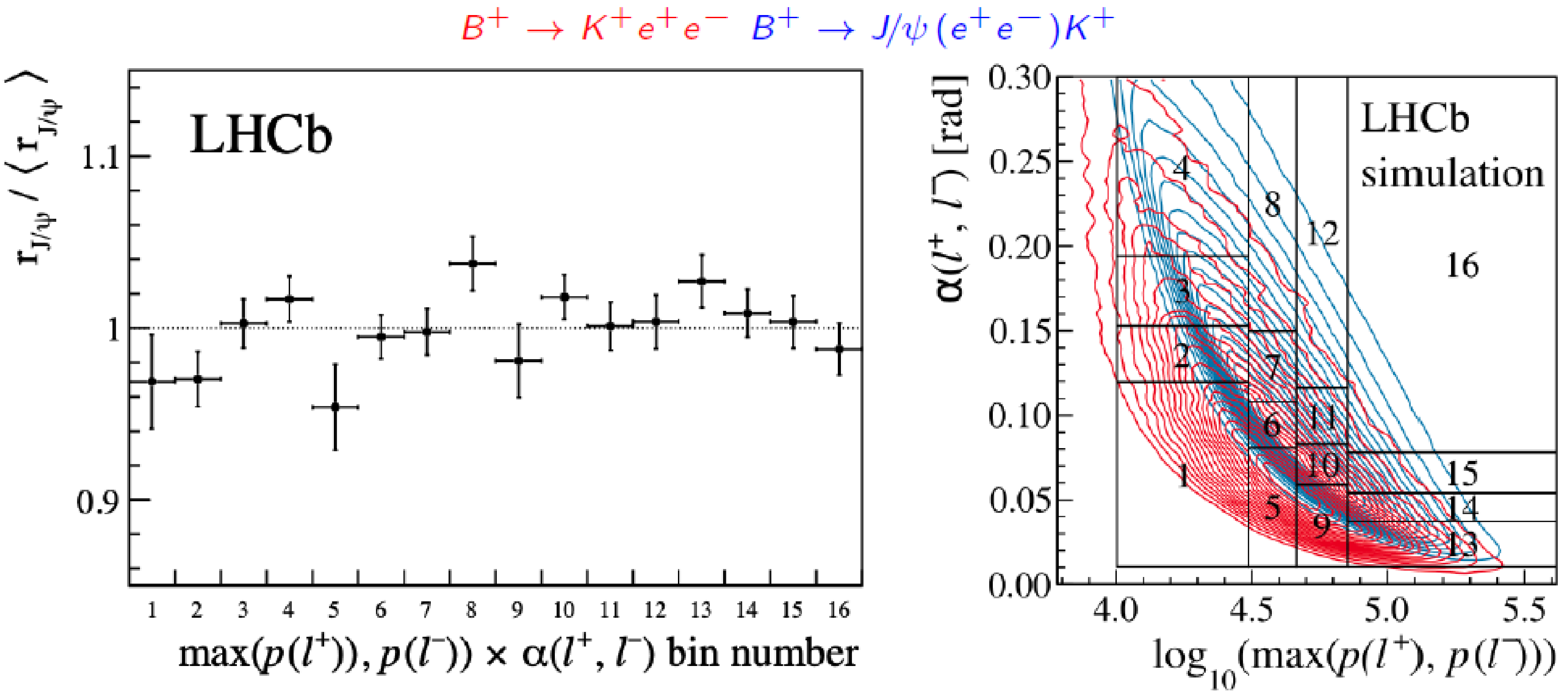
- We expect $r_{J/Psi}$ to be around 1 (from PDG it is within 0.4 %)
- In this case we must control both muon and electron efficiencies

$$r_{J/\psi} = 0.981 \pm 0.020 \;(\mathrm{stat} + \mathrm{syst})$$

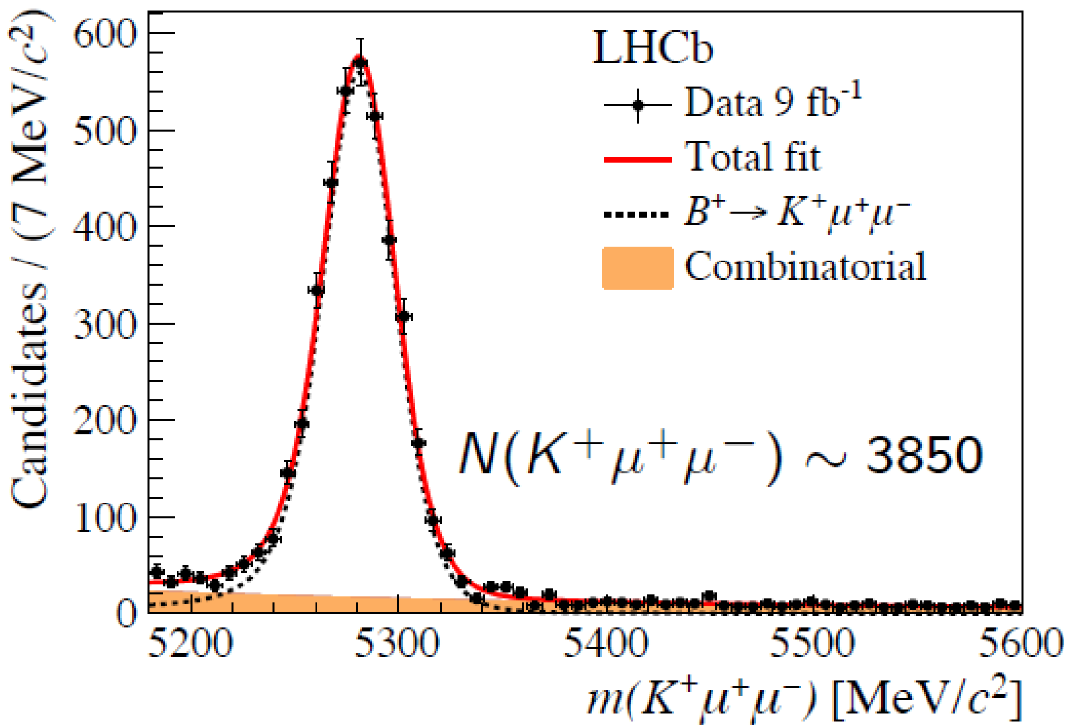
- Cross-checks between different run periods, old and new data set, trigger samples etc.

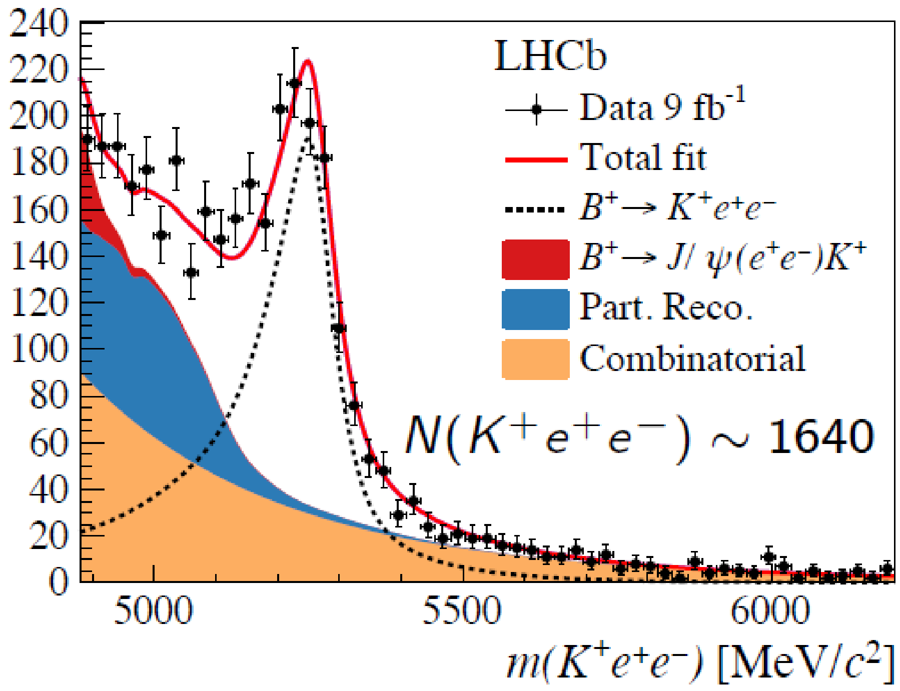
$r_{J/Psi}$ kinematic dependency

arXiv:2103.11769



R(K) extracted from the simultaneous fit to both datasets





- Unbinned maximum likelihood fit
- Correlation between selection efficiencies taken into account
- Shape parameters derived from calibrated simulations
- Systematic effects for chosen signal and background models ~ 1 %

Final R(K) value

arXiv:2103.11769

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

p-value under SM hypothesis = 0.001
3.1 standard deviation from SM prediction!

- Dominant systematic effect → choice of the fit model (~1%)
- Other effects (e.g. calibration, trigger) at permille-level

Final R(K) value

arXiv:2103.11769

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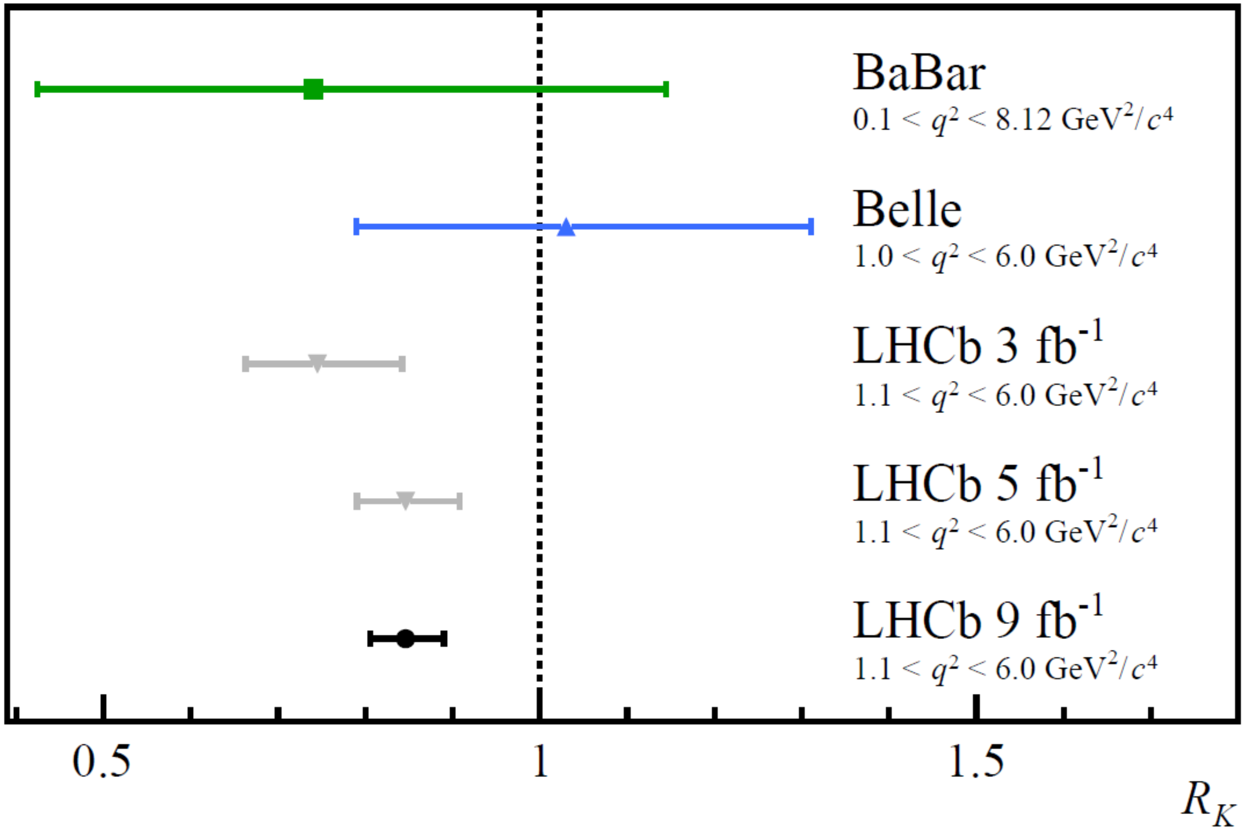
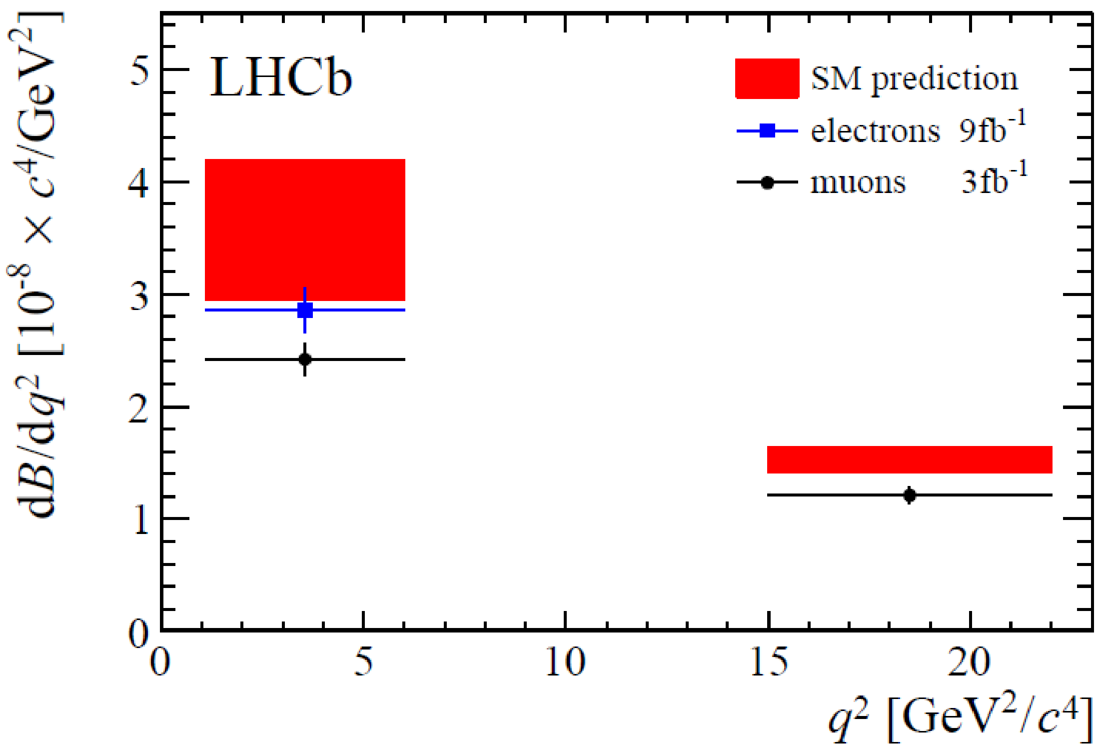


Electron branching fraction

arXiv:2103.11769



- We can combine the R(K) with the previous measurement of muon branching fraction

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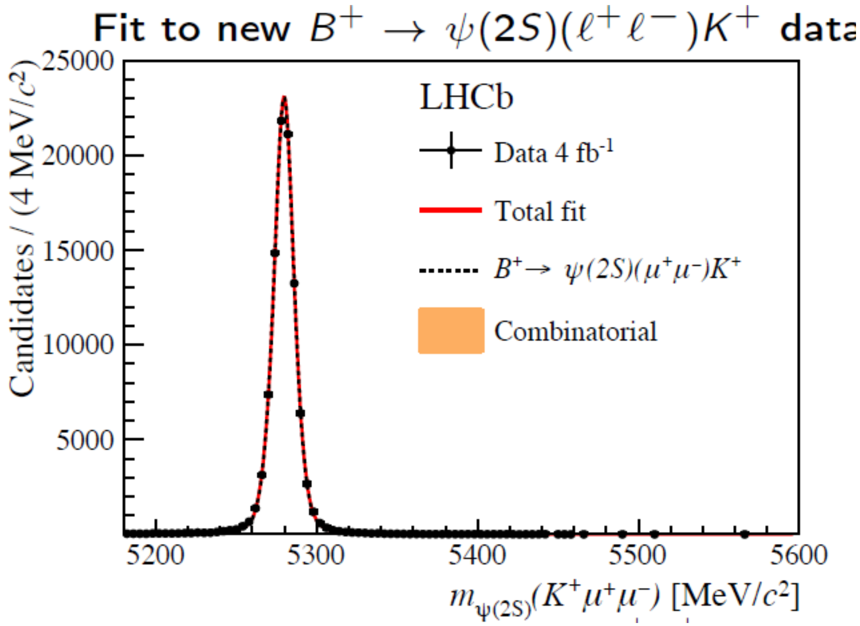
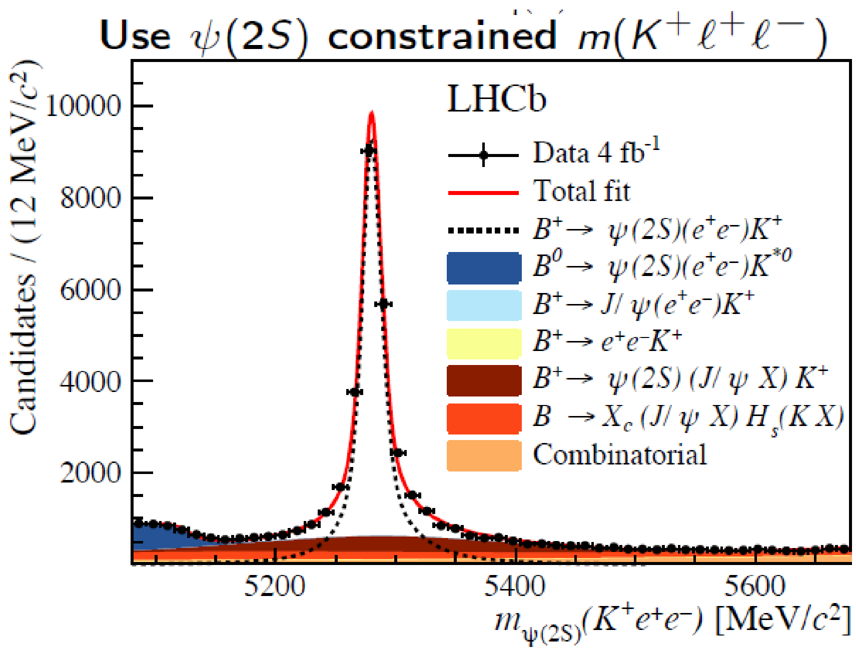
$$\frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2} = (28.6\ ^{+1.5}_{-1.4}(\mathrm{stat})\ \pm 1.4(\mathrm{syst})) \times 10^{-9}\ c^4/\,\mathrm{GeV}^2.$$

arXiv:2103.11769

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

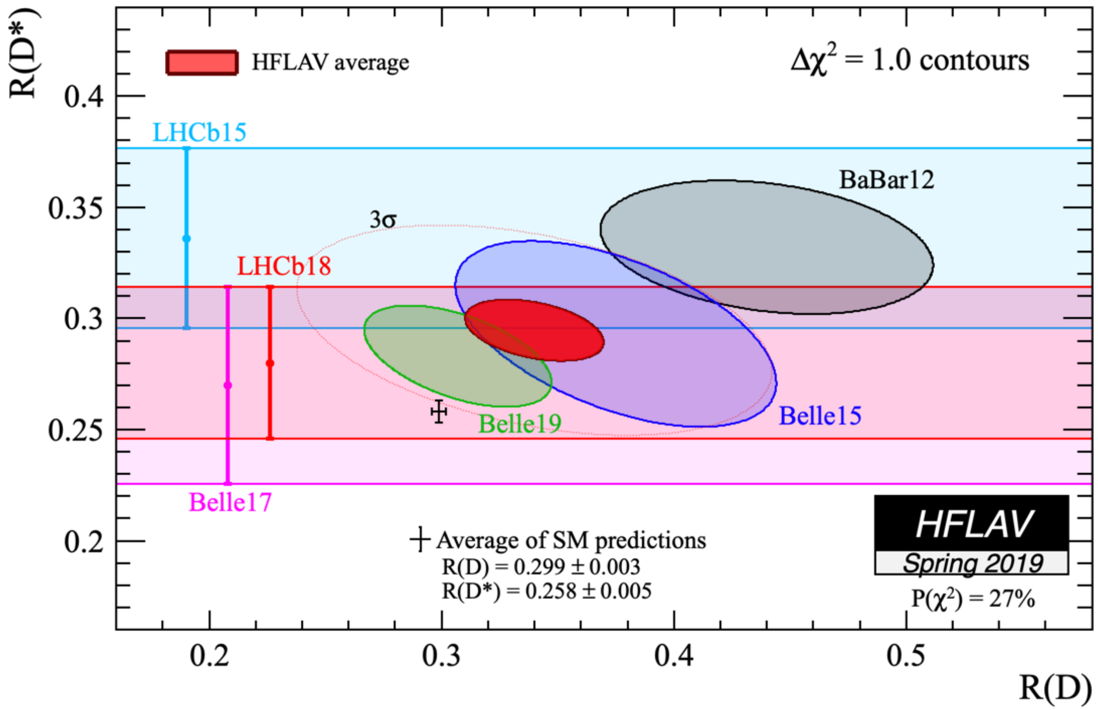


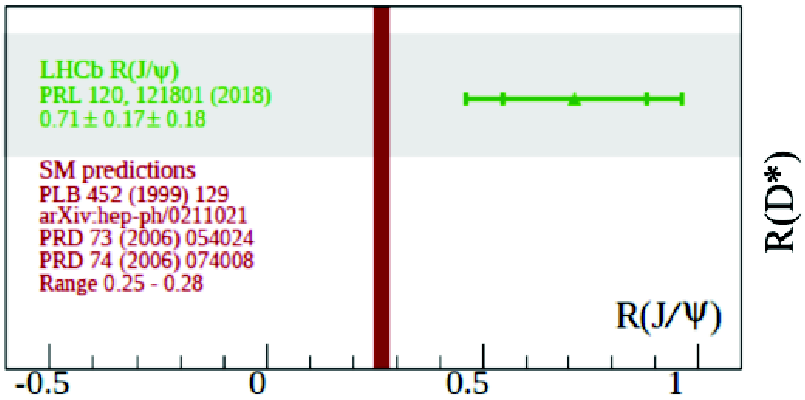


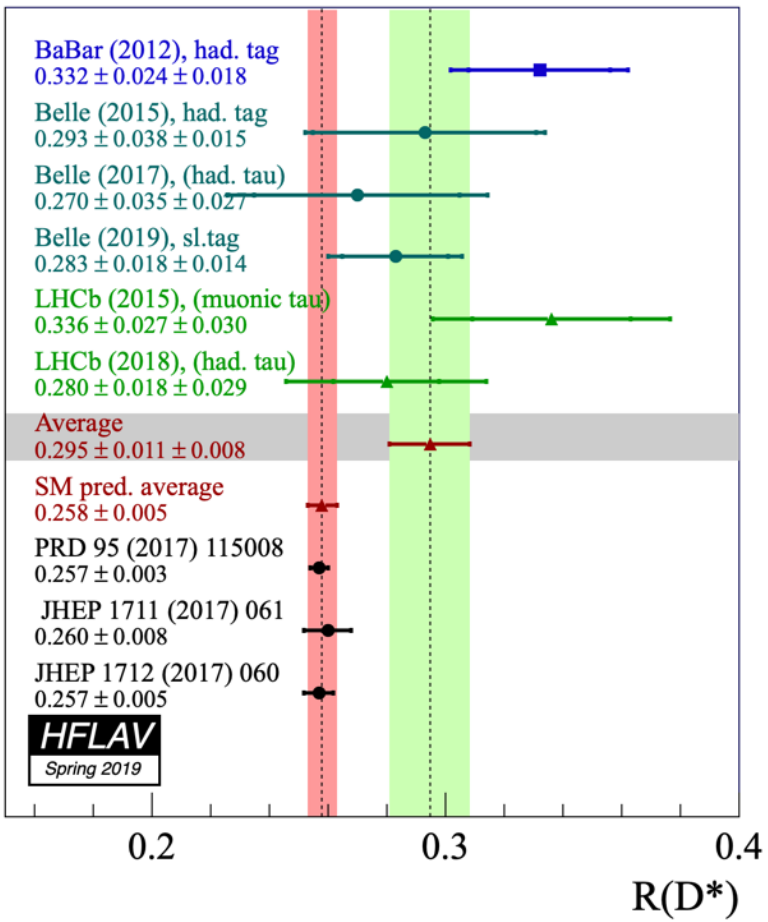
- Independent validation of the double-ratio procedure for q^2 away from J/Psi
- Results compatible with unity:

$$R_{\psi(2S)} = 0.997 \pm 0.011\ (\mathrm{stat} + \mathrm{syst})$$

Results comparison

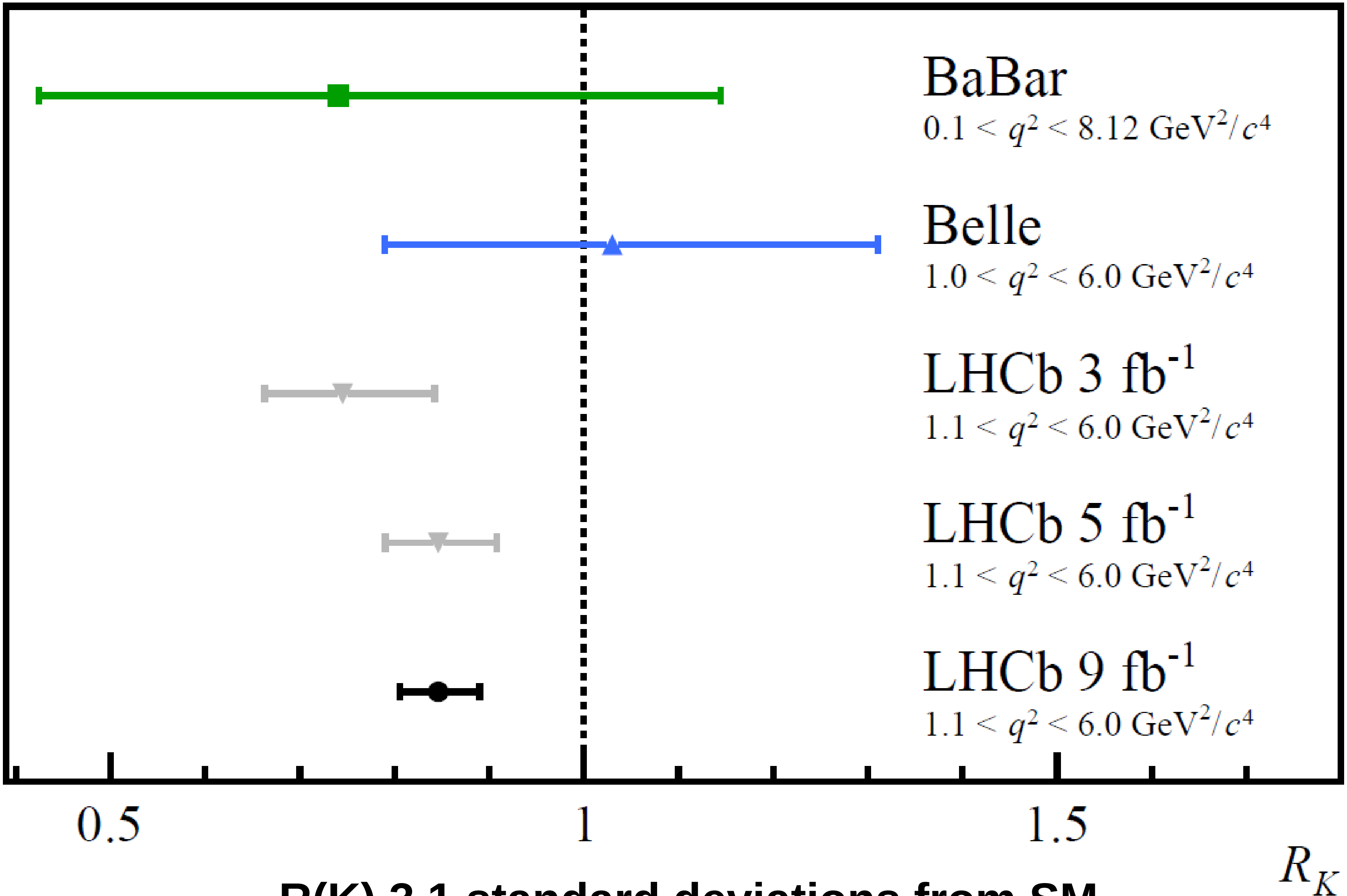






- All measurements consistently shifted from SM predictions:
- R(D*) by 3 sigma
- R(D) by 2.3 sigma

arXiv:2103.11769



R(K) 3.1 standard deviations from SM

Summary and Outlook

PRESENT

- Tensions with the SM predictions are still present in the B decay studies of LU:
  - After latest **LHCb R(D*)** and **R(D)** combined deviation from SM went from **4** to **3 sigma level**
  - Recent **R(K)** LHCb measurement reveals strong indication for **LU symmetry breaking** at **3.1 sigma level**
  - Deviation from SM prediction observed in several other analyses involving angular distributions and branching ratios in $b \rightarrow s\, l^+ l^-$

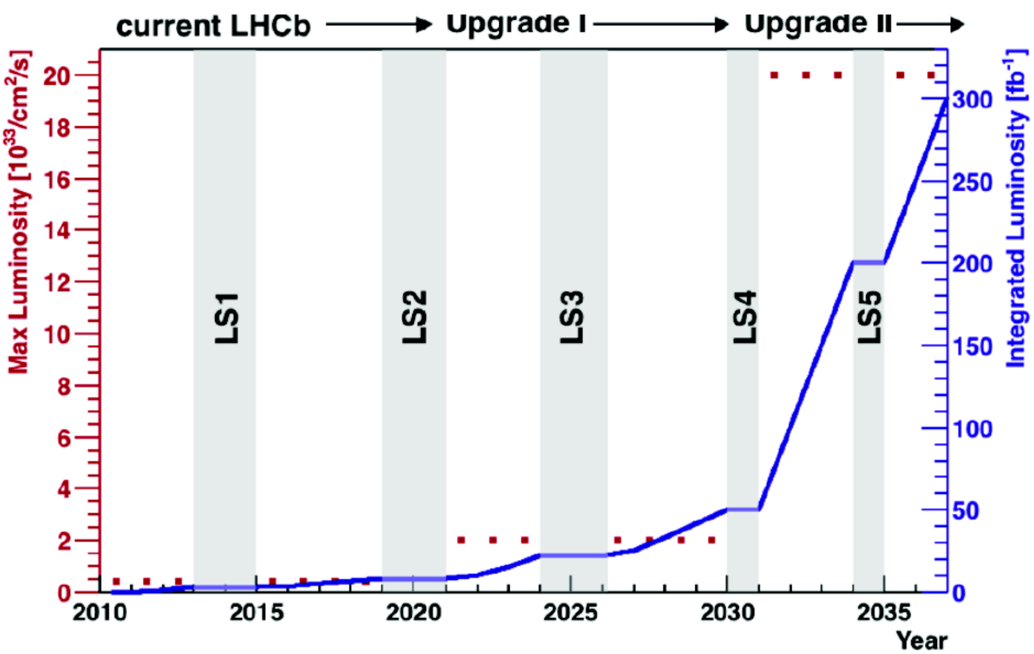
NEAR FUTURE

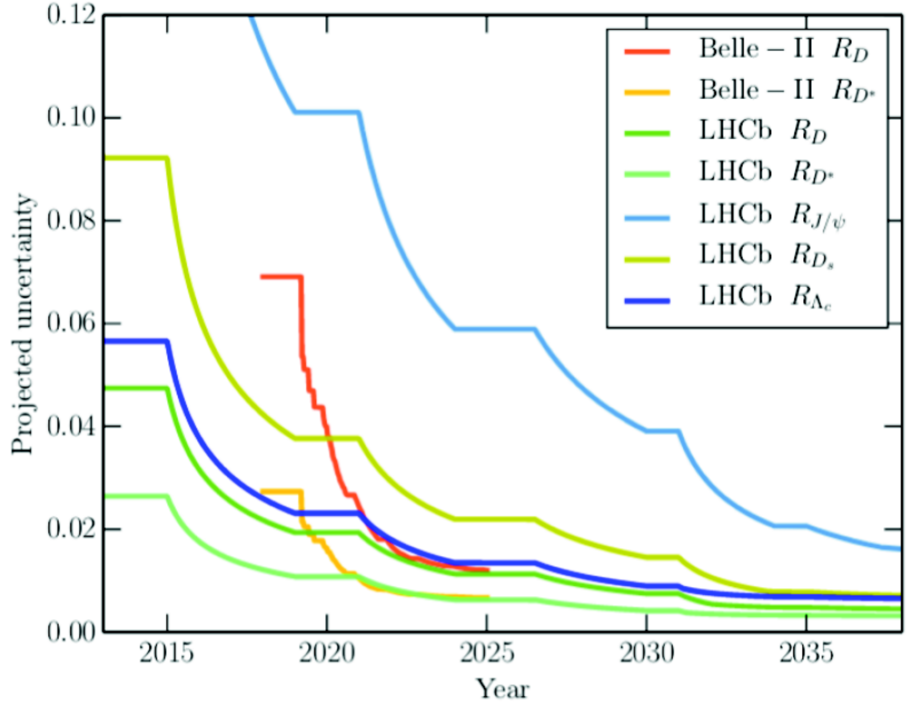
- Several other LHCb results available: R(pK), R(J/Psi)
- Many analyses ongoing:
  - Update of R(pK), R(Φ) , R(K*) ...
  - R(K) and R(K*) at high q^2
  - Angular analyses of $B \rightarrow K^{(*)} e^+ e^-$ and $B \rightarrow K^{(*)} \mu^+ \mu^-$

NEAR FUTURE

- LHCb preparation for Run III (starting next year):
  - Much higher statistics expected
  - Improved triggers (e.g. same trigger for muons and electrons)
- Belle-2 is acquiring the data

FUTURE

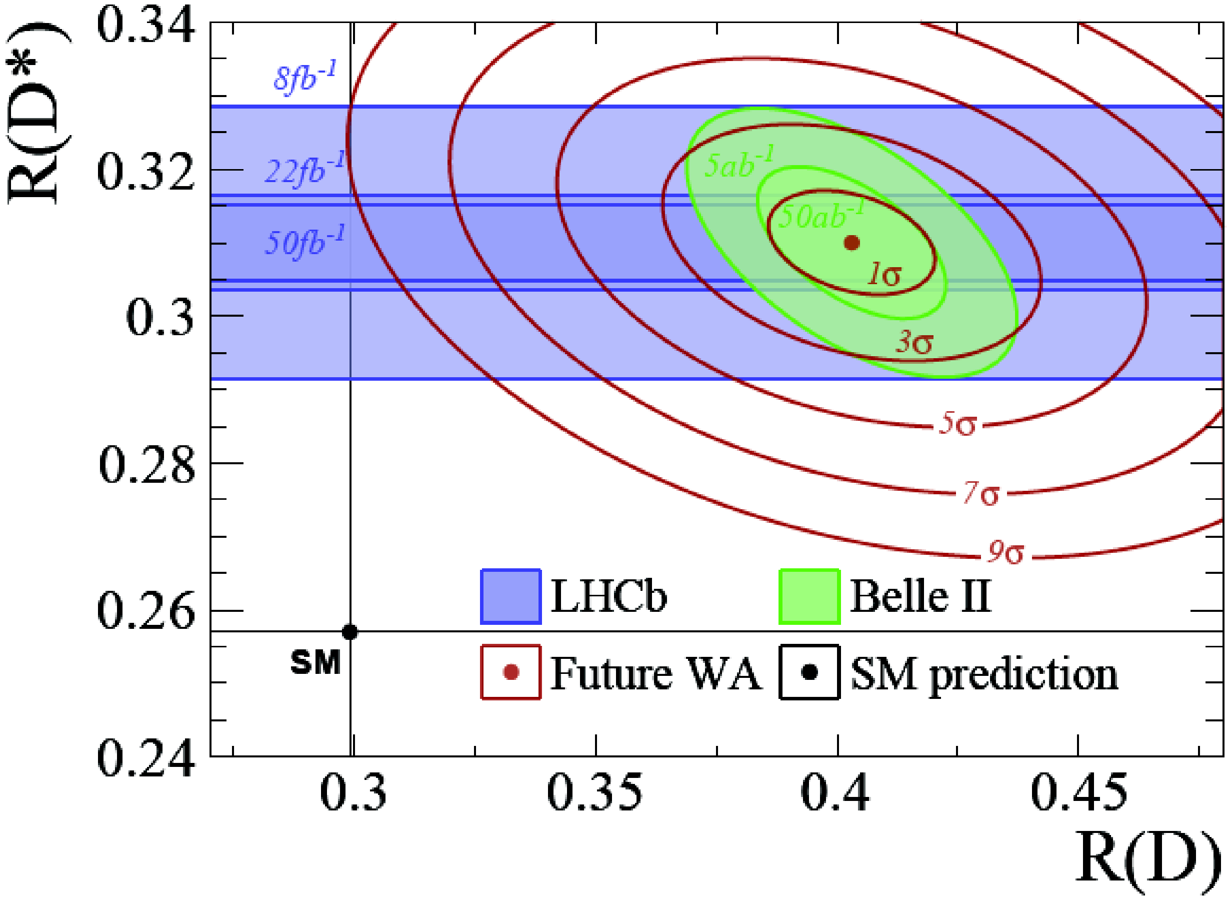




arxiv:1809.06229

Summary and Outlook

FUTURE



arxiv:1709.10308

Thank you for your attention