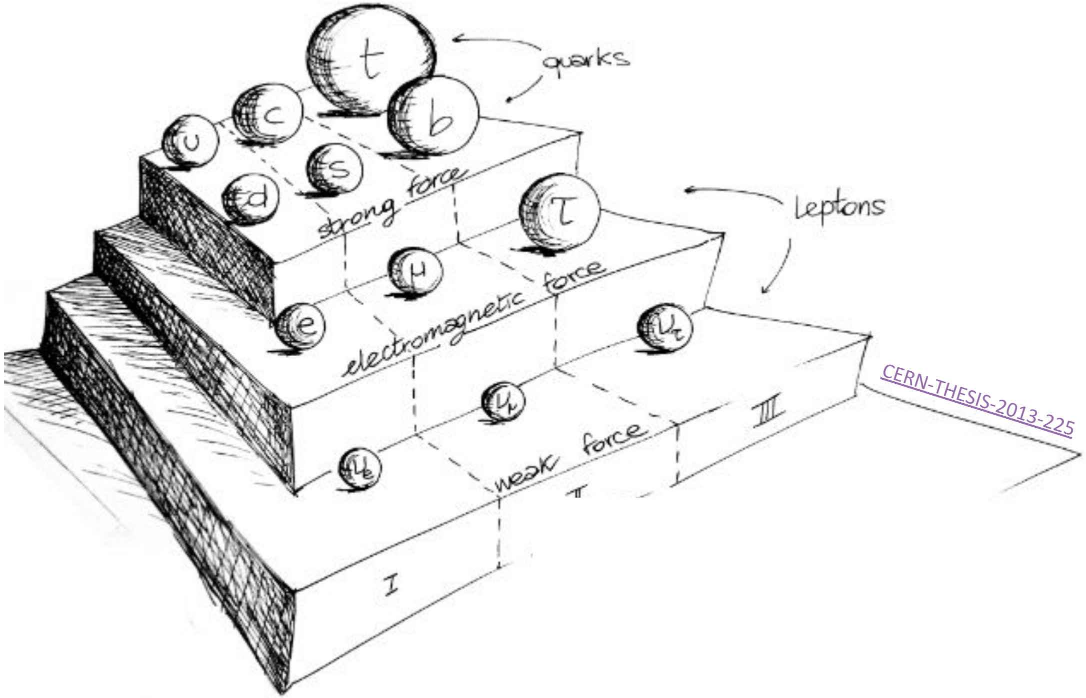
Lepton flavour universality tests in $b \to s\ell\ell$ decays at LHCb experiment

Alice Biolchini,
on behalf of the LHCb collaboration

1st NePSi 23, Pisa

2023 February 16th

Flavour: a very intriguing feature



CERN-THESIS-2013-225

Flavour: a very intriguing feature

Why do generation exists?

Why are there three of them?

Why the fermions hierarchies are the way they are?

Flavour: a very intriguing feature

Why do generation exists?

Why are there three of them?

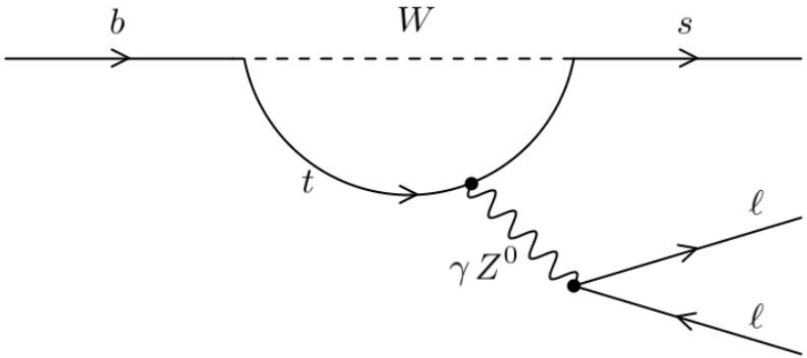
Why the fermions hierarchies are the way they are?

The answer to these questions will open the door to Physics beyond Standard Model

Where to search for the answer?

Flavour of Beauty

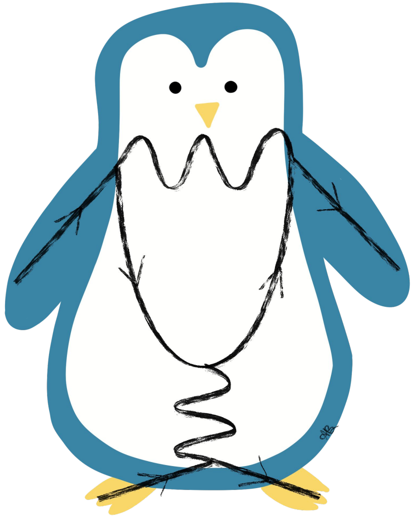
Decays of b-quarks are good laboratory to explore flavour physics.



SM Feynman diagram

Flavour of Beauty

Decays of b-quarks are good laboratory to explore flavour physics.



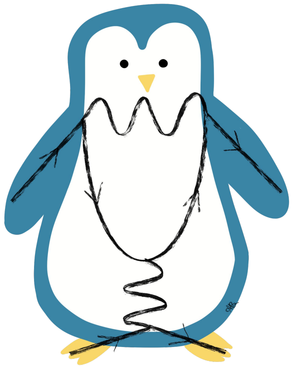
SM Feynman diagram

$\mathcal{B} \sim \mathcal{O}(10^{-6})$

Sensitive to *New Physics* (NP) at the TeV scale

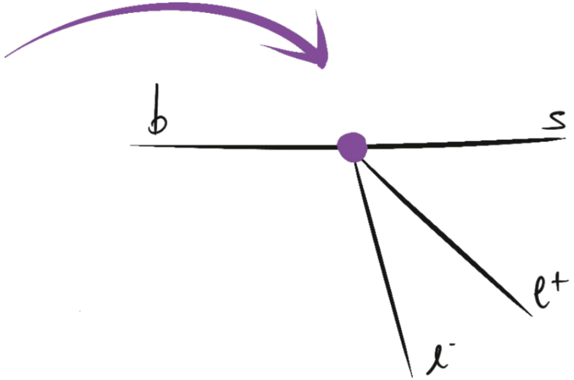
NP can affect the decay rates and angular distributions

Flavour of Beauty

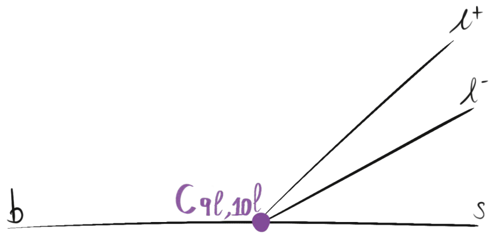


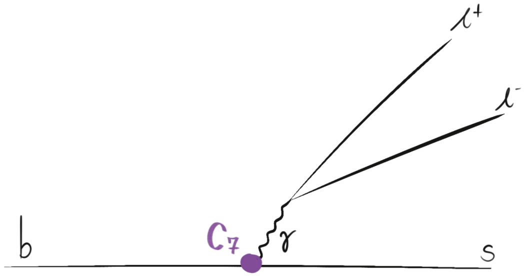
$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \left(C_i^{SM} + \Delta_i^{NP} \right) O_i$$

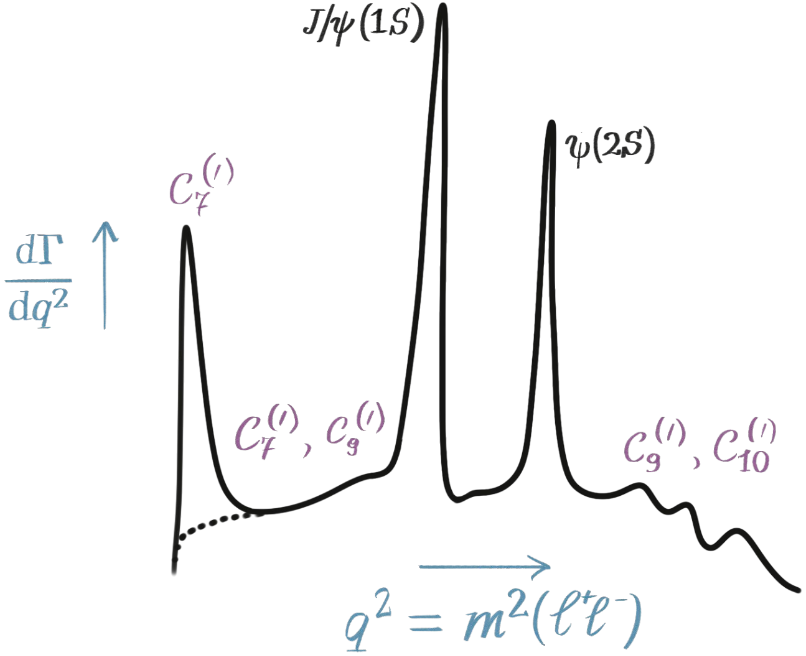
New Physics hiding here?



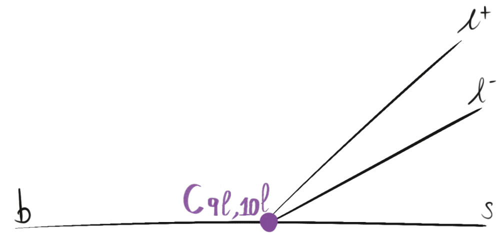
$b \to s\ell^+\ell^-$ decays

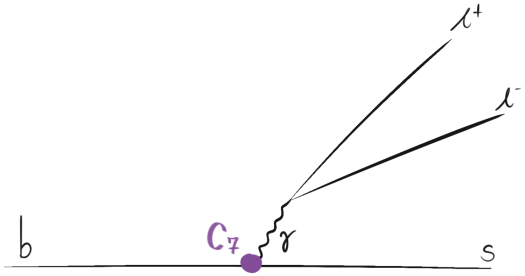


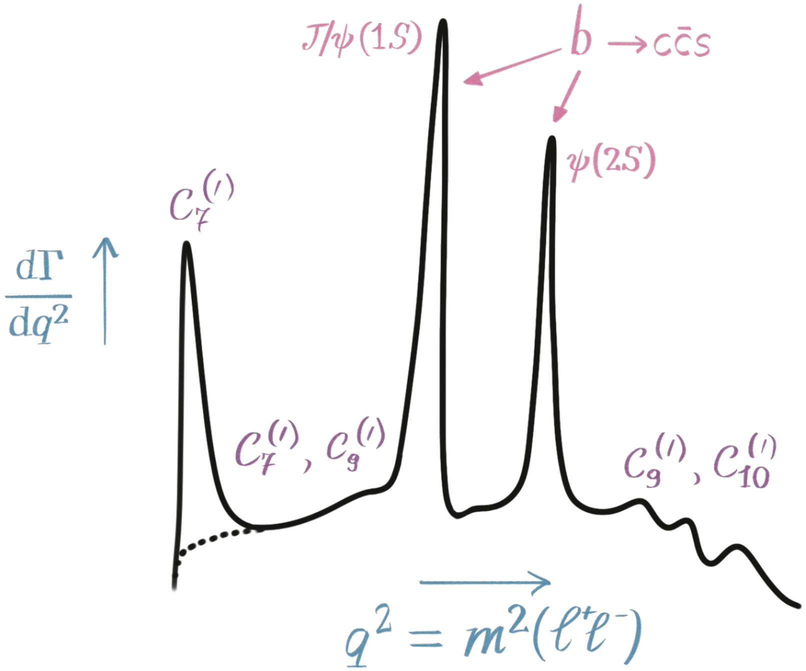




$b \to s\ell^+\ell^-$ decays







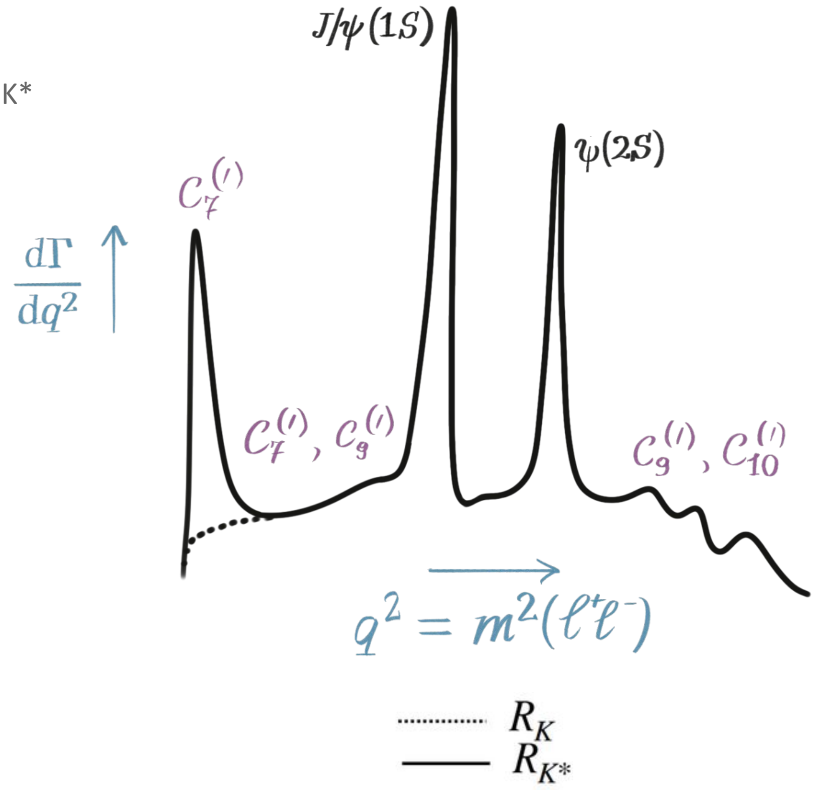
Latest LFU test in $b \to s\ell^+\ell^-$ decays in LHCb

LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

Simultaneous measurement of R_K and R_{K^*}

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

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



LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

R_K and R_{K^*} measurements at LHCb

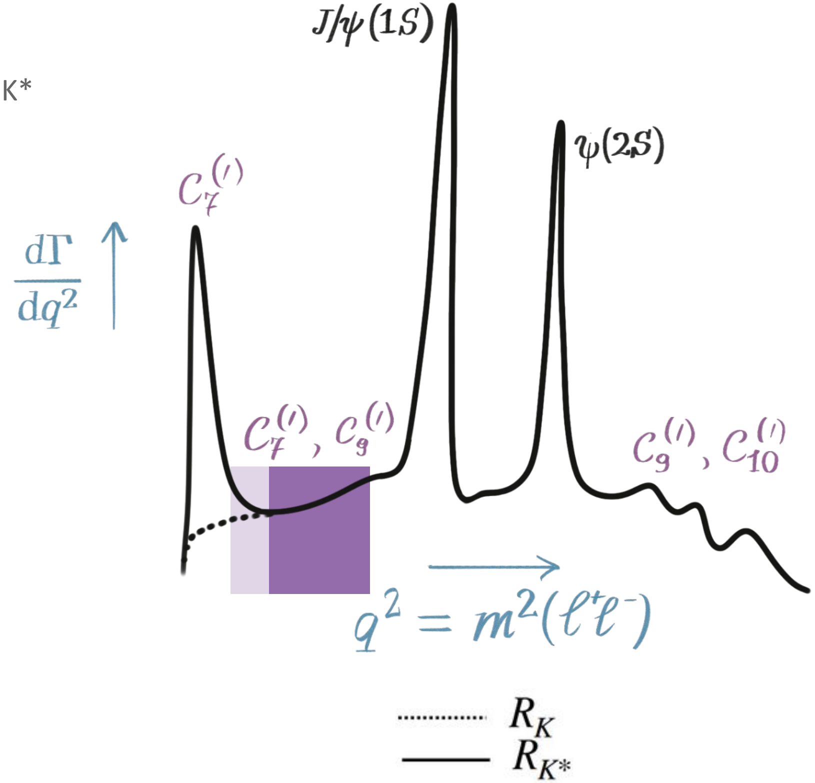
Simultaneous measurement of R_K and R_{K^*}

$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

Ranges of q^2:

low	[0.1 - 1.1] GeV$^2/c^2$
central	[1.1 - 6.0] GeV$^2/c^2$

- Re-analysis of R_K central
  Arxiv(2021)11769



R_K and R_{K*} measurements at LHCb

LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

Simultaneous measurement of R_K and R_{K*}

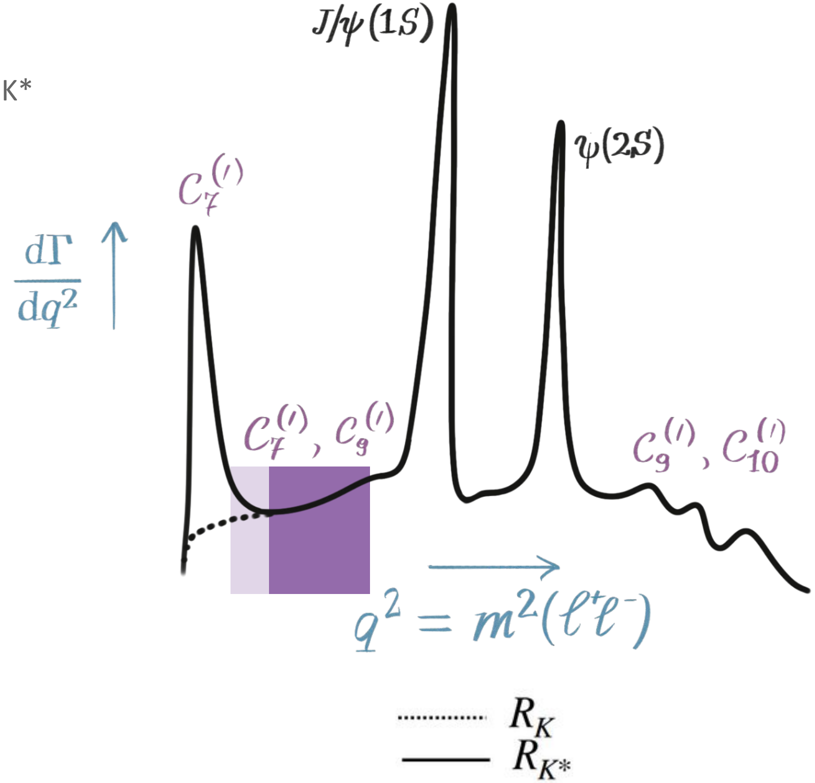
$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

Ranges of q^2:

low	[0.1 - 1.1] GeV^2/c^2
central	[1.1 - 6.0] GeV^2/c^2

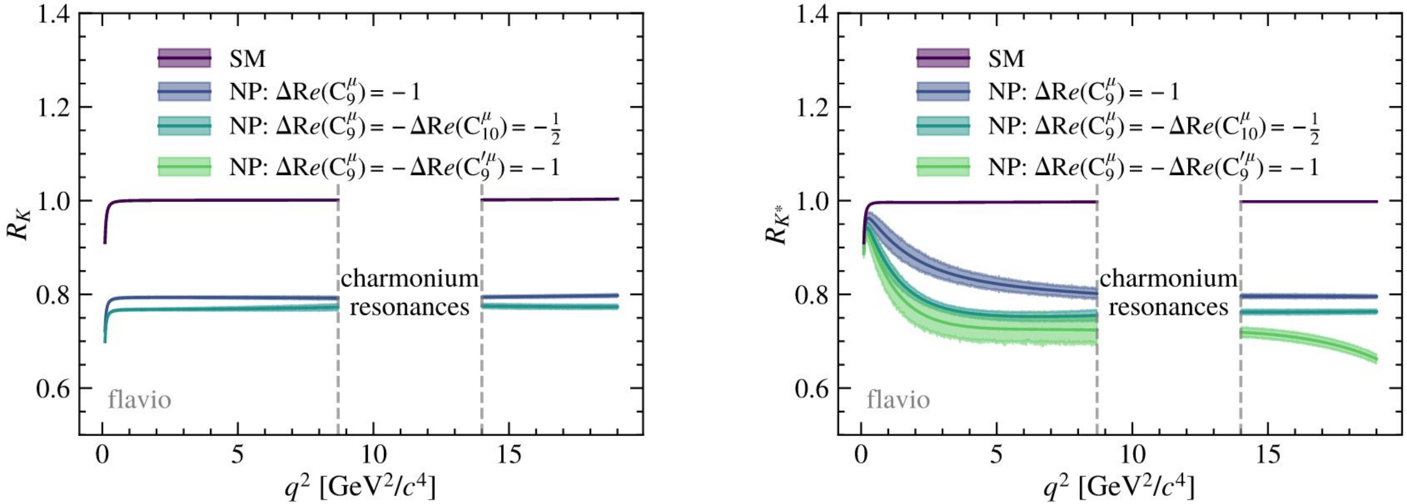
K^{*0} cut:

$m(K^{*0})$ = [792,992] MeV/c^2



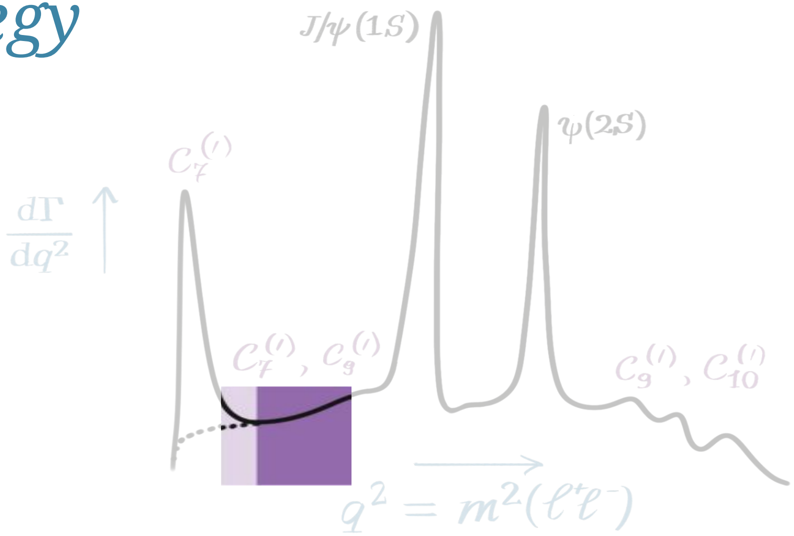
R sensitivity to NP

- R extremely well predicted by SM
  - Form-factor uncertainties cancel out in the ratio



LHCb-PAPER-2022-045

Analysis strategy

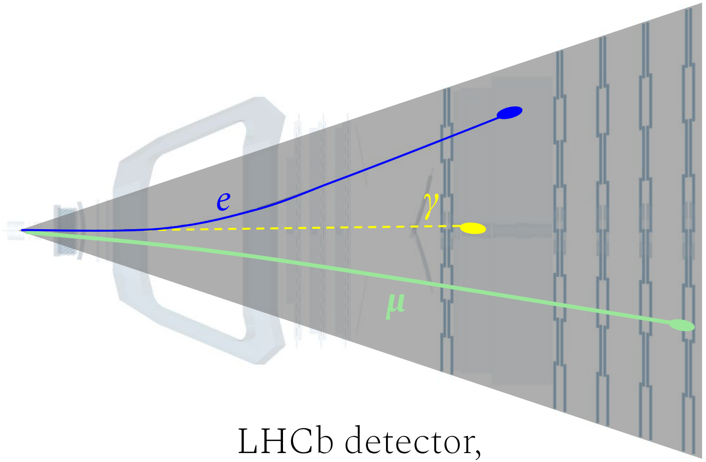


$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}$$

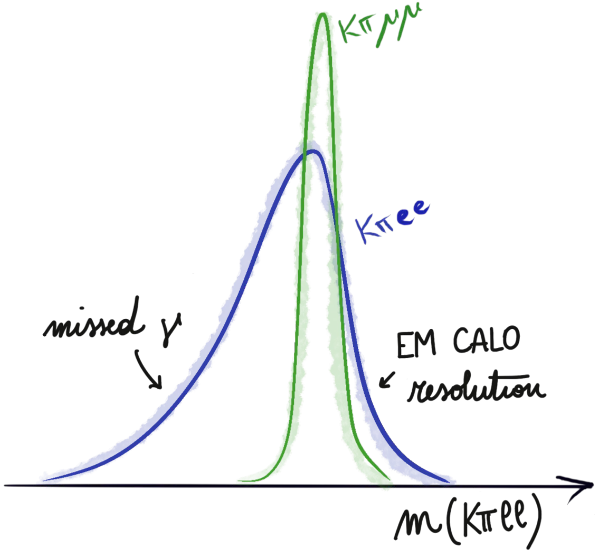
$\mathcal{N}$ yield from mass fit

ε efficiency from MC simulation

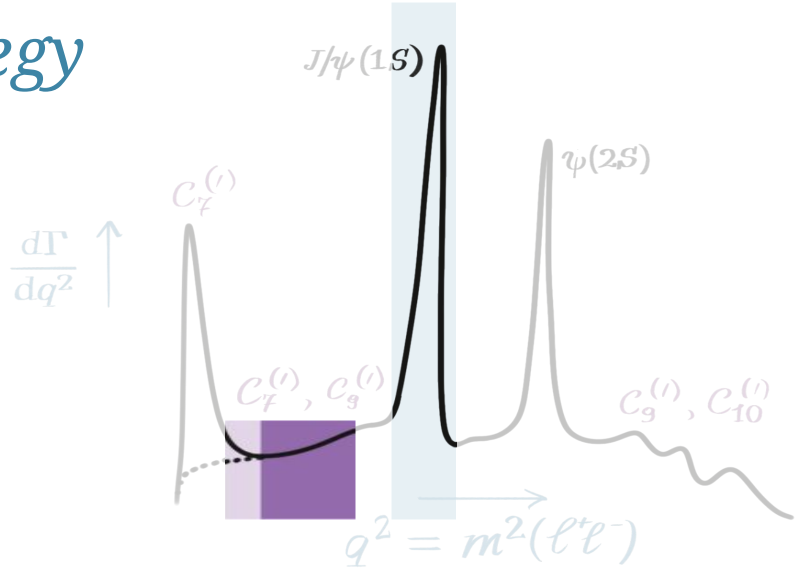
Electron vs muon efficiency



LHCb detector,
upper view



Analysis strategy



$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}$$

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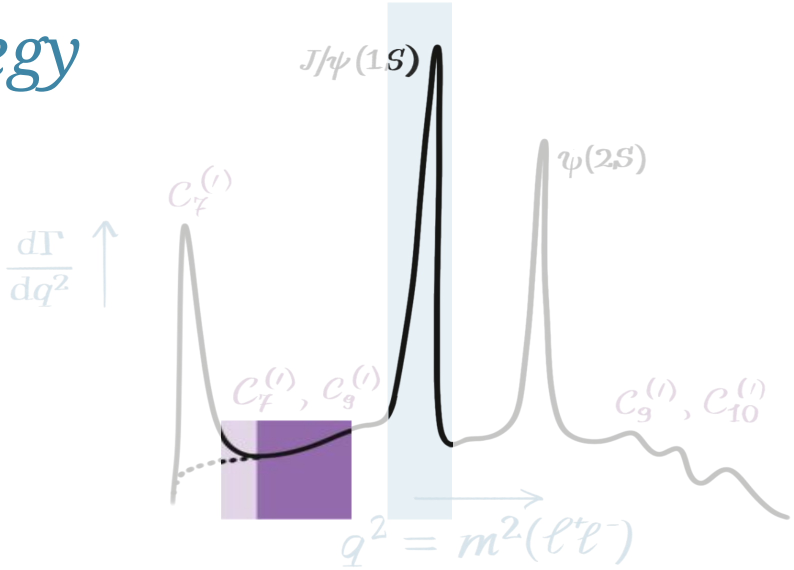

=1 PhysLetB(2014)02.046

$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}$$

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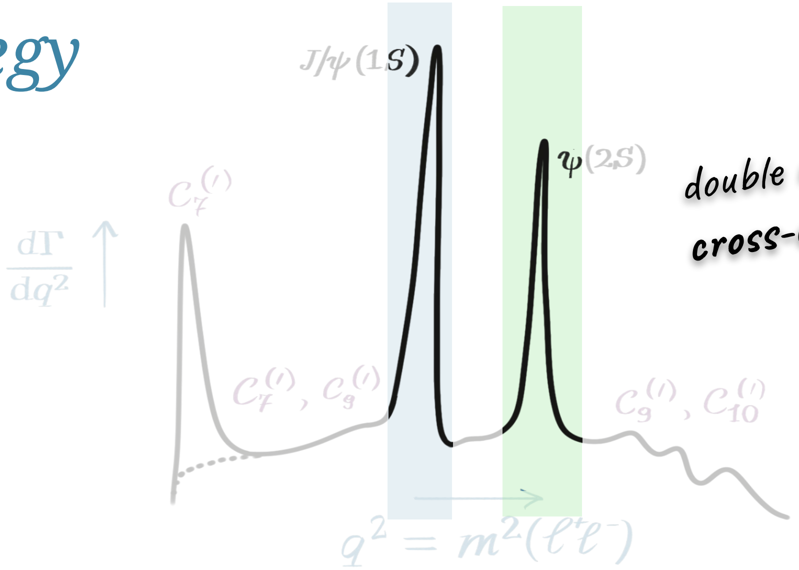

double ratio cross-check

$$R_{\psi(2S)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\psi(2S)(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\psi(2S)(e^+e^-))} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}$$

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ε efficiency from MC simulation

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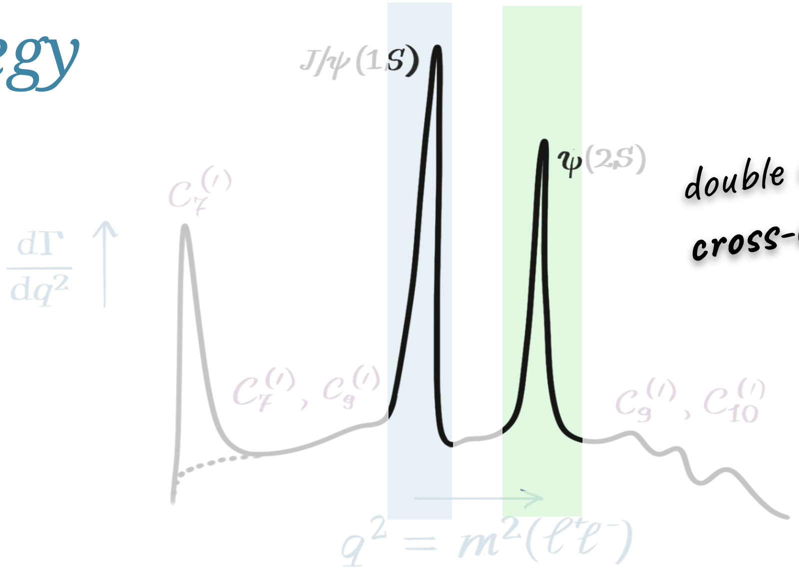

double ratio
cross-check

= 1 PDG2022

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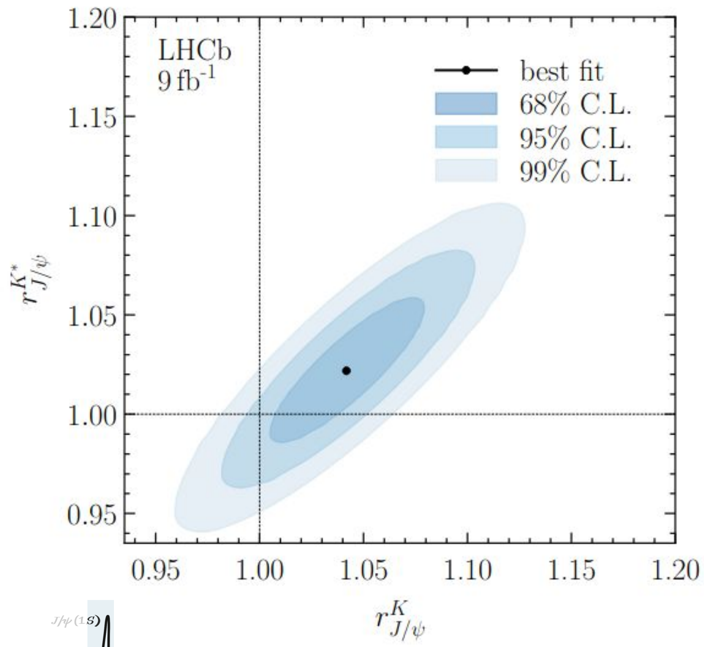
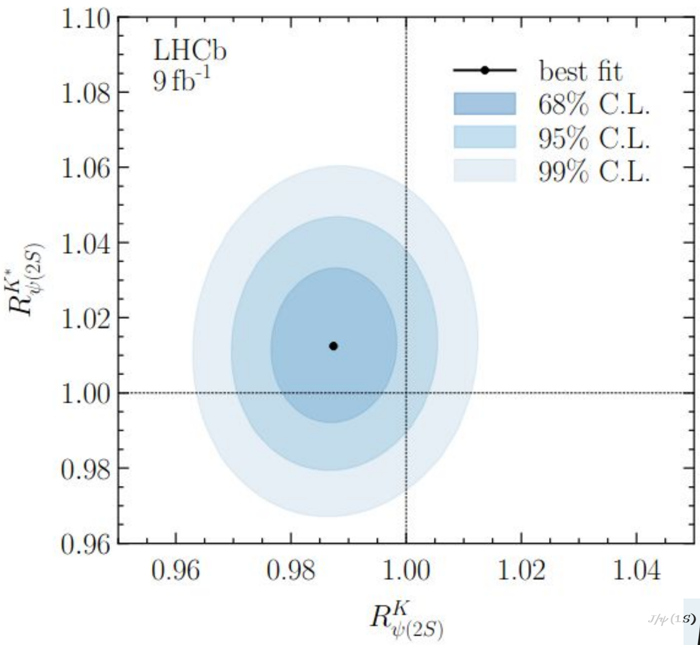
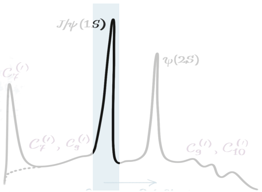
$\mathcal{N}$ yield from mass fit

ε efficiency from MC simulation

Cross-checks results

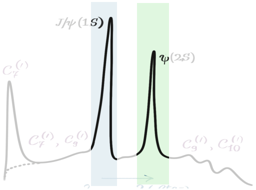






single ratio

double ratio



Final results

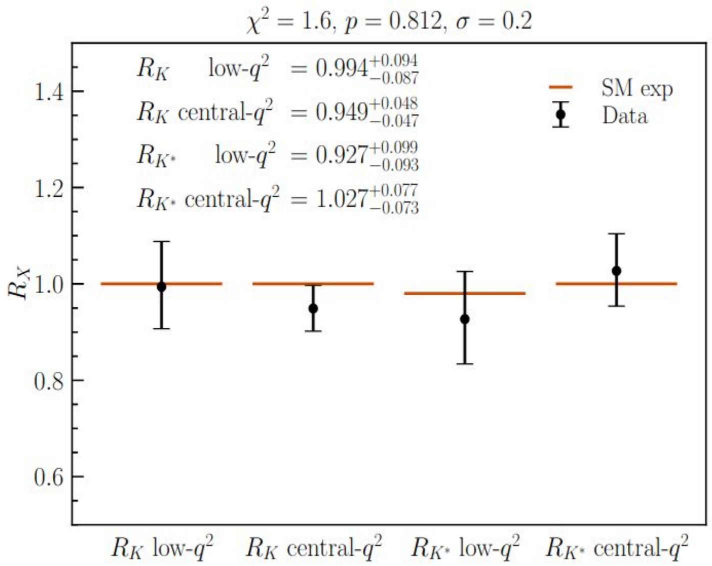
LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

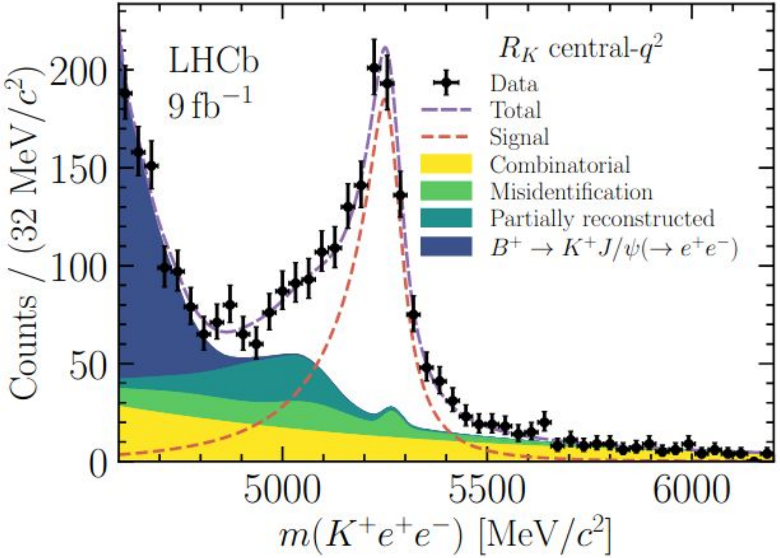
low q²

$$R_K = 0.994\,^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.029}_{-0.027}\,(\text{syst})$$
$$R_{K^*} = 0.927\,^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.036}_{-0.035}\,(\text{syst})$$

central q²

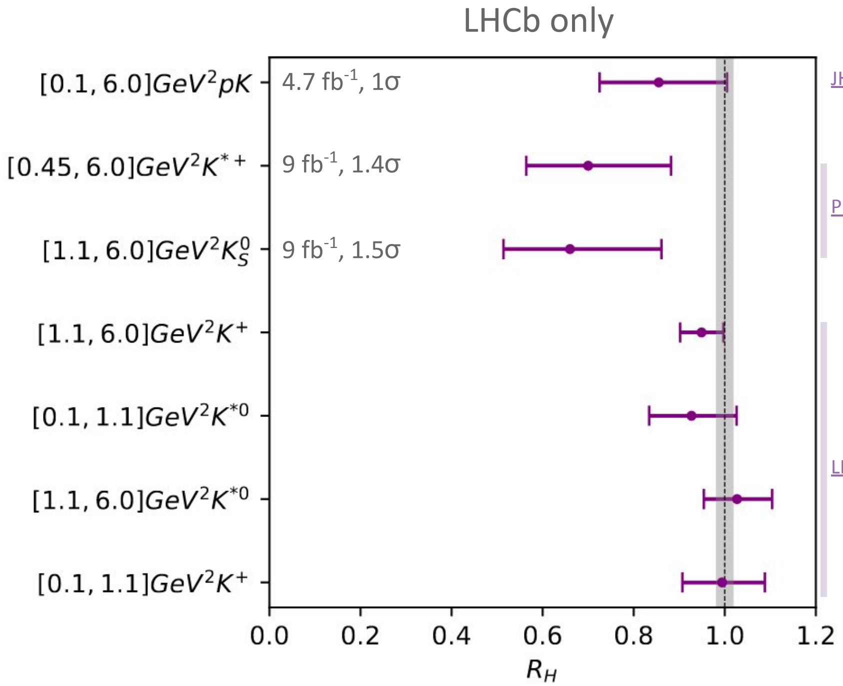
$$R_K = 0.949\,^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.022}_{-0.022}\,(\text{syst})$$
$$R_{K^*} = 1.027\,^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.026}\,(\text{syst})$$





R overview (most recent results)

$$R_H = \frac{\mathcal{B}(b \to s\mu\mu)}{\mathcal{B}(b \to see)}$$



JHEP05(2020)040

PRL 128 (2022) 191802

LHCb-PAPER-2022-045

LHCb measurements of $b \to s\ell^+\ell^-$

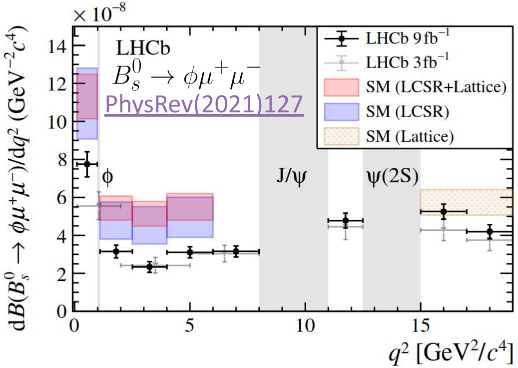
- R measurements
- Angular analyses
- Differential decay rates

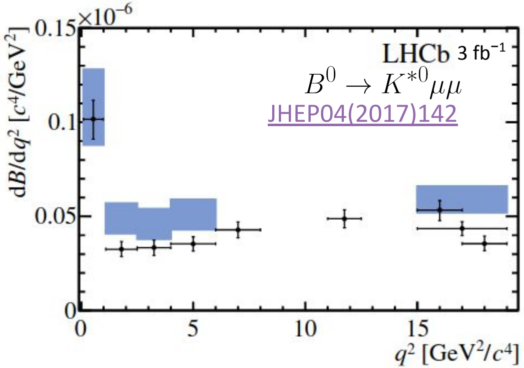
LHCb measurements of $b \to s\ell^+\ell^-$

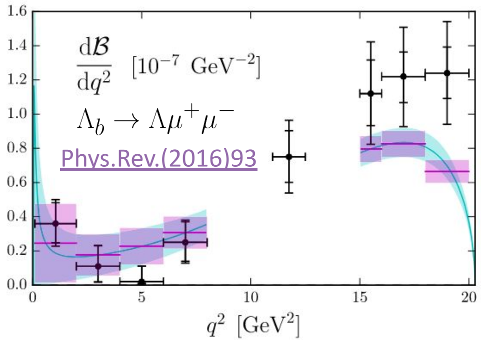
- R measurements
- Angular analyses
- Differential decay rates

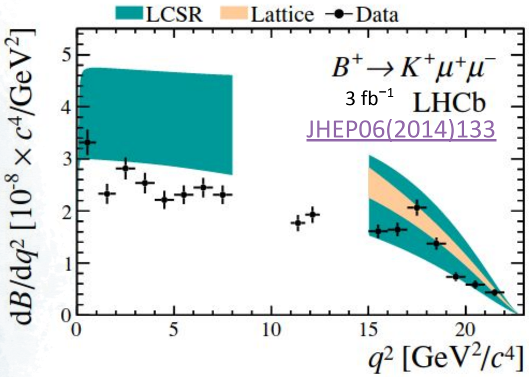
$b \to s\,\mu\mu$

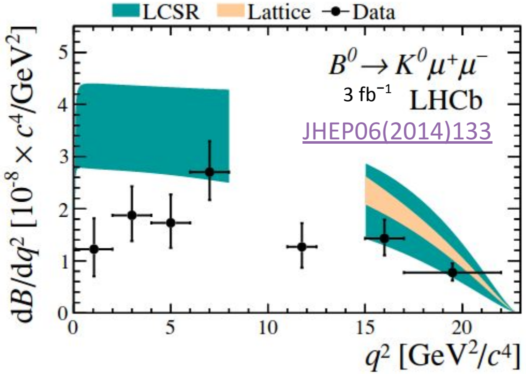
Pattern of anomalies - differential $\mathcal{B}$

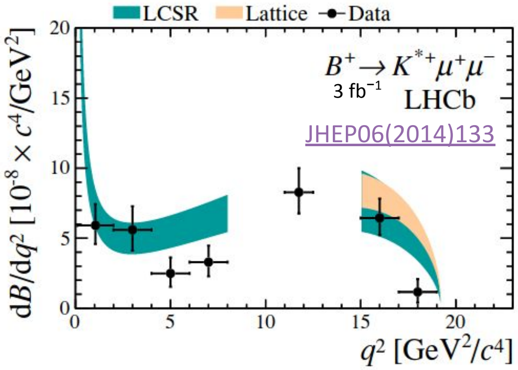




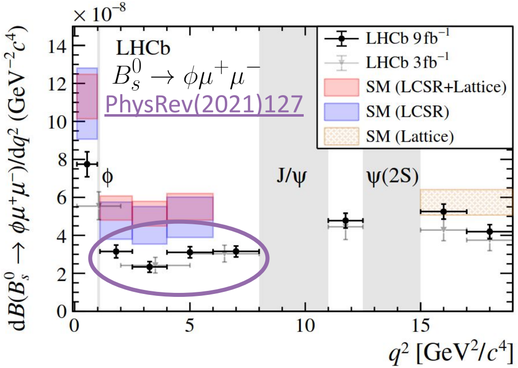


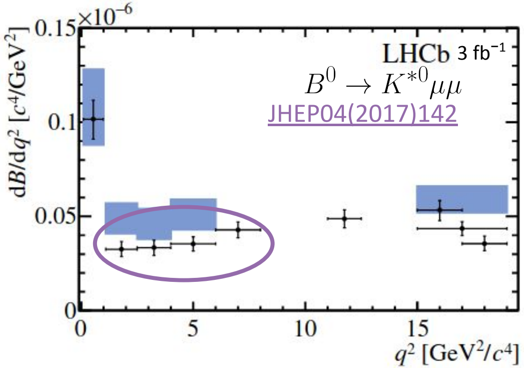


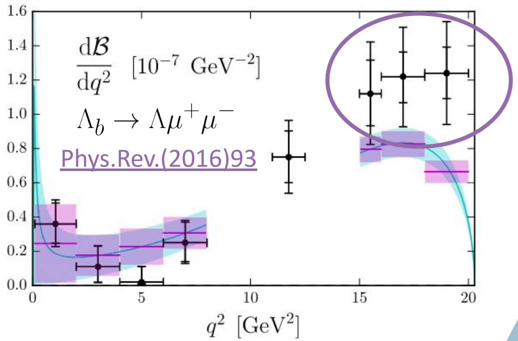


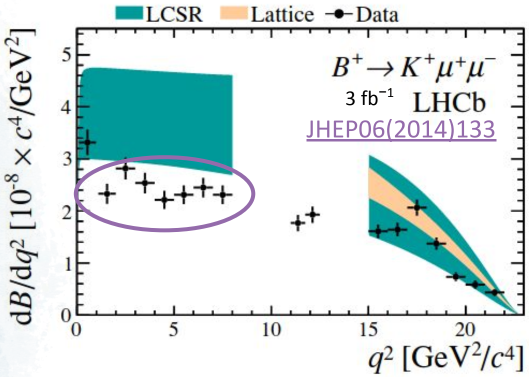


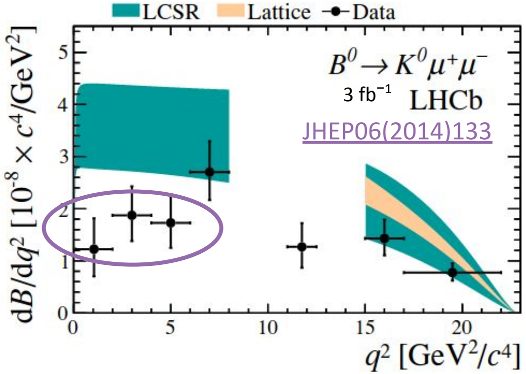
Pattern of anomalies - differential $\mathcal{B}$

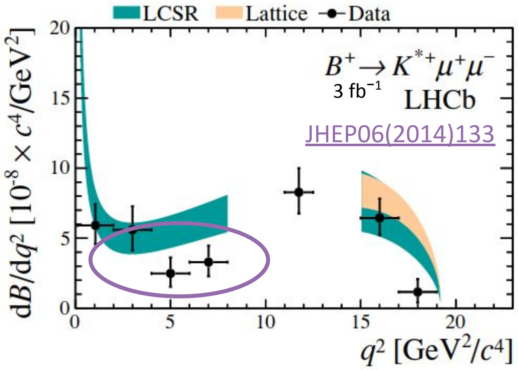








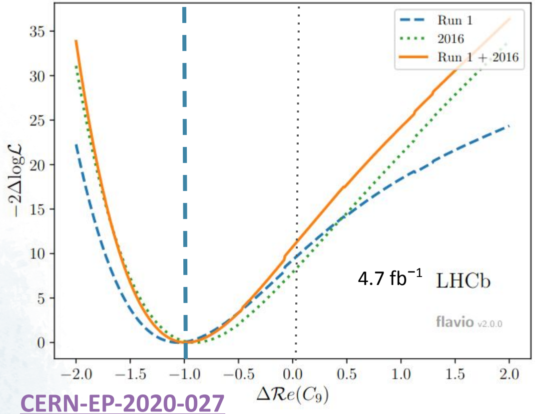




Pattern of anomalies - angular coefficients

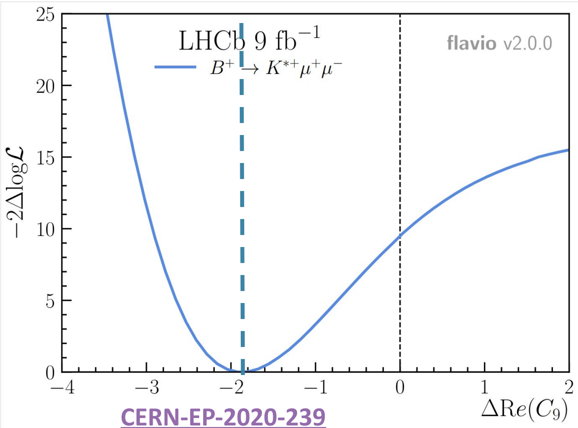
$B^0 \to K^{*0}\mu\mu$ | $B^+ \to K^{*+}\mu\mu$ | $B_s^0 \to \phi\mu^+\mu^-$

SM



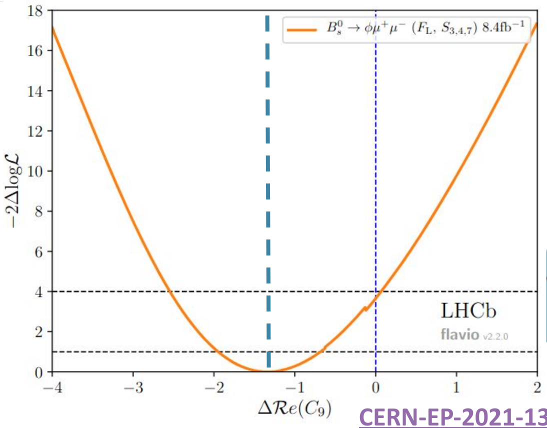
CERN-EP-2020-027
PhysRev(2020)125

SM



CERN-EP-2020-239
PhysRev(2021)126

SM



CERN-EP-2021-138
JHEP11(2021)043

$$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$$

$$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.9$$

$$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.3^{+0.7}_{-0.6}$$

Pattern of anomalies

Philosophy is written in this great book that is constantly open before our eyes (I say the universe),
but it cannot be understood without first learning to understand the language and to know the characters in which it is written.
Without these it is a vain wandering through an obscure labyrinth.

“La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi agli occhi (io dico l’universo), ma non si può intendere se prima non s’impara a intendere la lingua, e conoscer i caratteri, ne’ quali è scritto. [...] ***senza questi è un aggirarsi vanamente per un oscuro labirinto.****”*

Il Saggiatore, Galieo Galilei

The “obscure labyrinth”

Statistical fluctuations

New Physics clues

Human errors-Experimental bias

Missing knowledge-Hadronic effects in SM prediction

~~The “obscure labyrinth”~~

A way out

Statistical fluctuations

New Physics clues

Human errors-Experimental bias

Missing knowledge-Hadronic effects in SM prediction

NEW DATA AND MEASUREMENTS ARE NECESSARY

New measurements with LHCb Run1 + Run2 data

- Measurements in the electron sector - **ongoing**
  - Experimental orthogonal way to test deviations from theory
  - More info on New Physics structure
  - $B^0 \to K^{*0} ee$ angular analysis *(personally working on it)*
- Unbinned angular analysis: $B^0 \to K^{*0}\ \mu\mu$ - **ongoing**
  - Sensitive to interference effect between rare mode ($B^0 \to K^{*0}\ \mu\mu$) and tree level
  - Directly fit for underlying Wilson Coefficients
- Many others analyses ongoing
  - $Bs \to \ell\ell\gamma$ discussed by *Camille Normand* later today (link)
  - Analysis in tau sector (very low efficiency, more data required)

Summary and conclusions

- **Analysis of R_K and R_{K^*}** - ($9fb^{-1}$)
  - Higher signal purity and better statistical sensitivity than previous LHCb LFU test
  - Most precise LFU test in $b \to s\ell\ell$ transitions
  - Compatible with SM
- **Angular analysis and differential branching ratio measurements in decay channel with muons**
  - A pattern of anomalies is visible
- **New measurements using Run1 and Run2 data still to come**
  - Importance of electron sector: NP might be LU
- **Run3 : new and more data will help to disentangle this puzzle**
  - Rare decay measurements are statistically limited

Thanks for your attention.
Any questions?

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Mis-identified background

Developed a **new inclusive data-driven** treatment of misidentified background:

- Fully reco missed ID - peaking stucture
  - $B^{(0,+)} \longrightarrow K^{(*0,+)}h^+h^-$
- Single/double missed ID + missing energy backgrounds- low energy
  - $B^+ \longrightarrow K^+\pi^-(\pi^0,\gamma)X$
  - $B^0 \longrightarrow K^{*0}\pi^-(\pi^0,\gamma)X$

X = any number of other final state particles

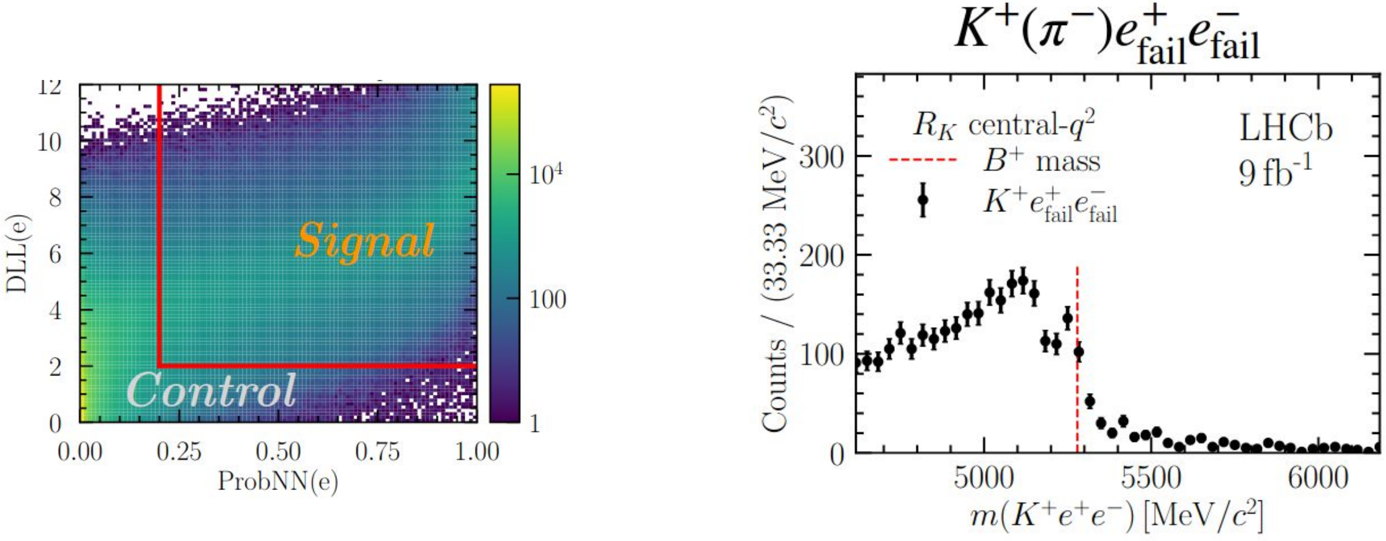
- Single contribution small - Inclusive contribution can be large and different shape from combinatorial background.
- Data-driven ⟶ the systematic associated to this background should scale with number of events collected.

Mis-identified background

LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

Developed a **new inclusive data-driven** treatment of misidentified background:

1. Invert PID requirements on one or both *e* after full selection (control region)

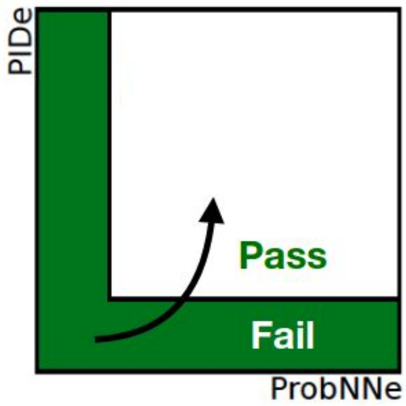


Mis-identified background

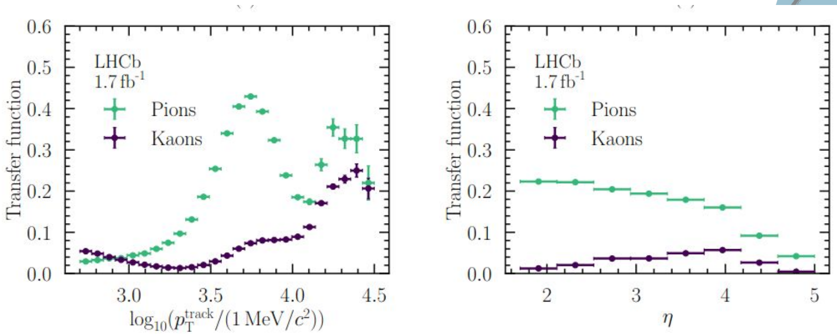
LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

Developed a **new inclusive data-driven** treatment of misidentified background:

1. Invert PID requirements on one or both *e* after full selection (control region)
2. Chosen a calibration Data sample: $D^{*-} \to D^0 (K^+\pi^-)\pi^-$
3. Computed a transfer function in 2D bins (η, $log(p_T)$)



$$w_{fake}(e) = \frac{\varepsilon_{pass}}{\varepsilon_{fail}}$$



Mis-identified background

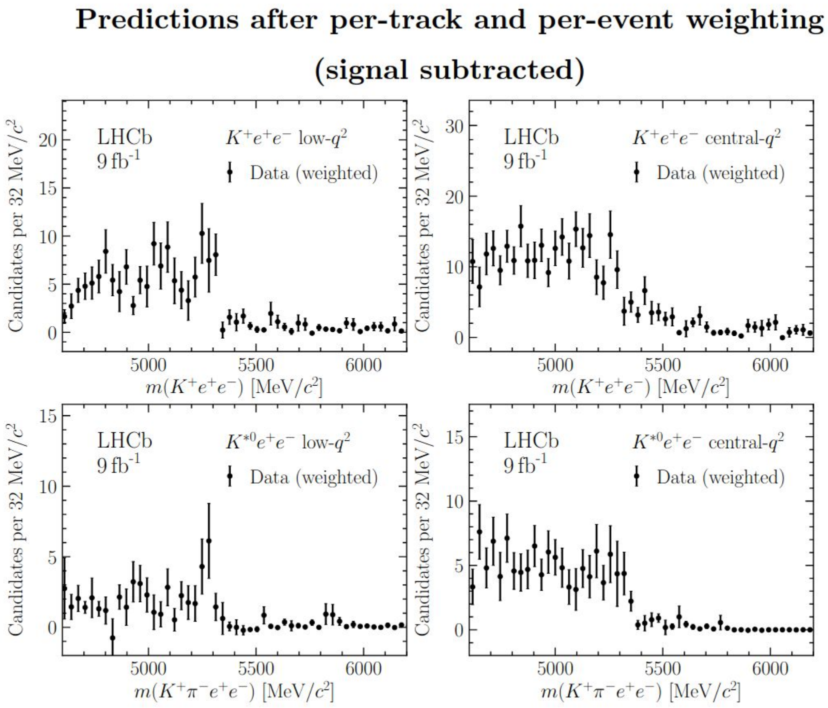
Developed a **new inclusive data-driven** treatment of misidentified background:

1. Invert PID requirements on one or both *e* after full selection (control region)
2. Chosen a calibration Data sample: $D^{*-} \rightarrow D^0 (K^+\pi^-)\pi^-$
3. Computed a transfer function in 2D bins ($\eta, log(p_T)$)
4. Transfer function applied to the data set of interest:
    a. Per-event/per-track weights on e_{fail} to predict background shape and normalisation for e_{pass}
5. Categorised by *pion*- and *kaon*-like electrons in control region based on neural-net kaon ID classifier

Mis-identified background

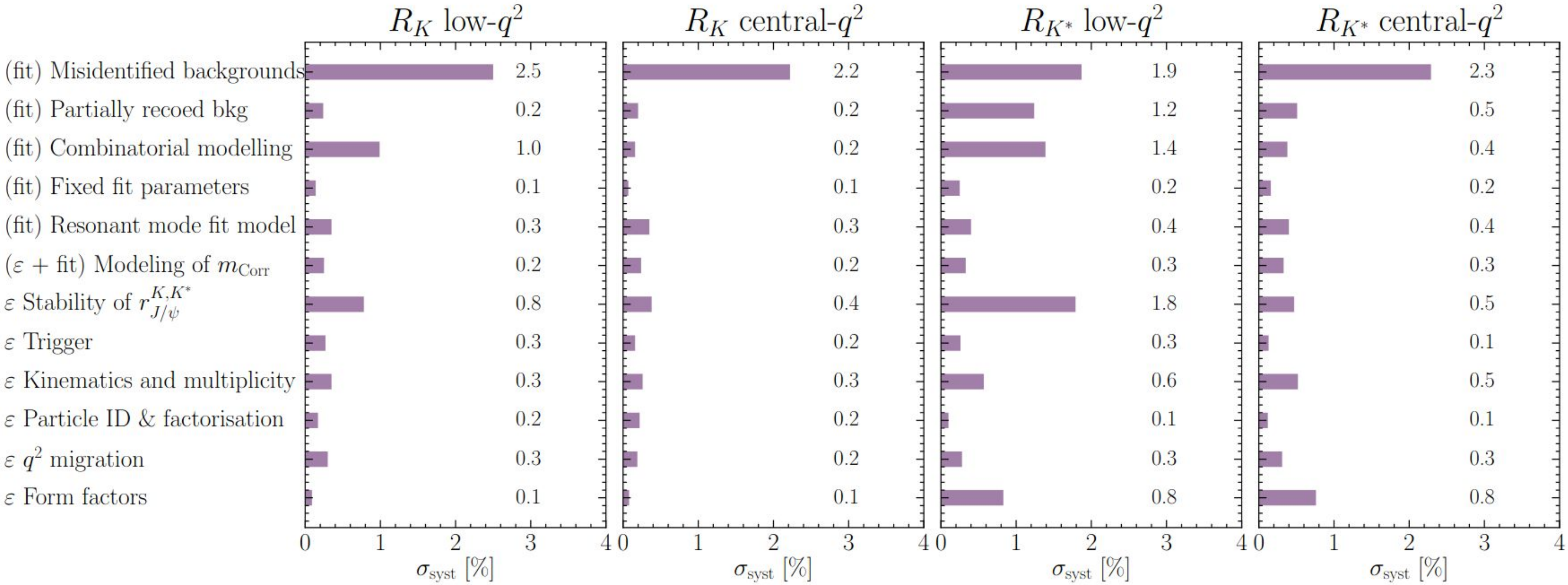
LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

Developed a **new inclusive data-driven** treatment of misidentified background:



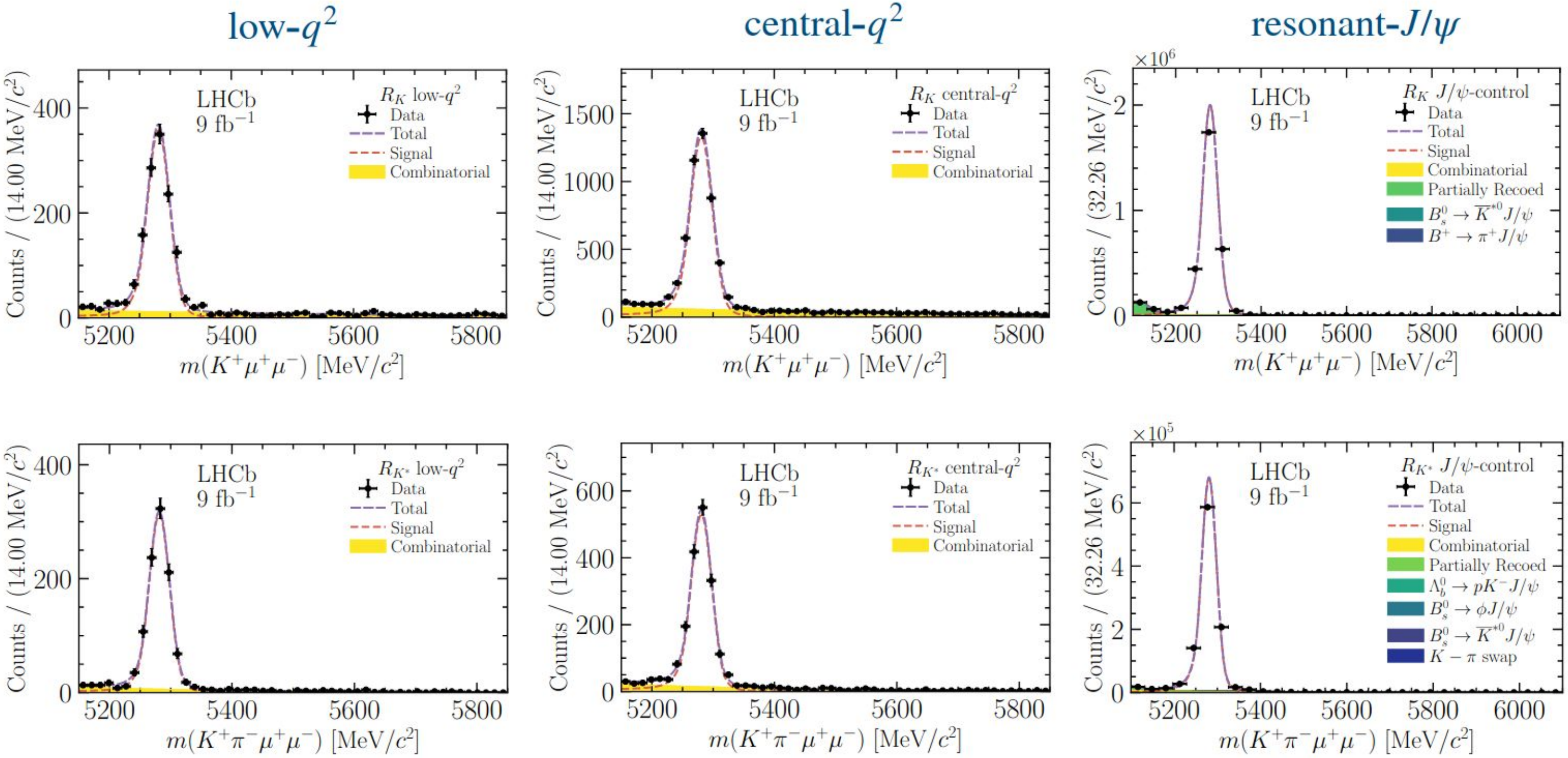
Main Systematics

LHCb-PAPER-2022-045
LHCb-PAPER-2022-046



Simultaneous mass fits - muons

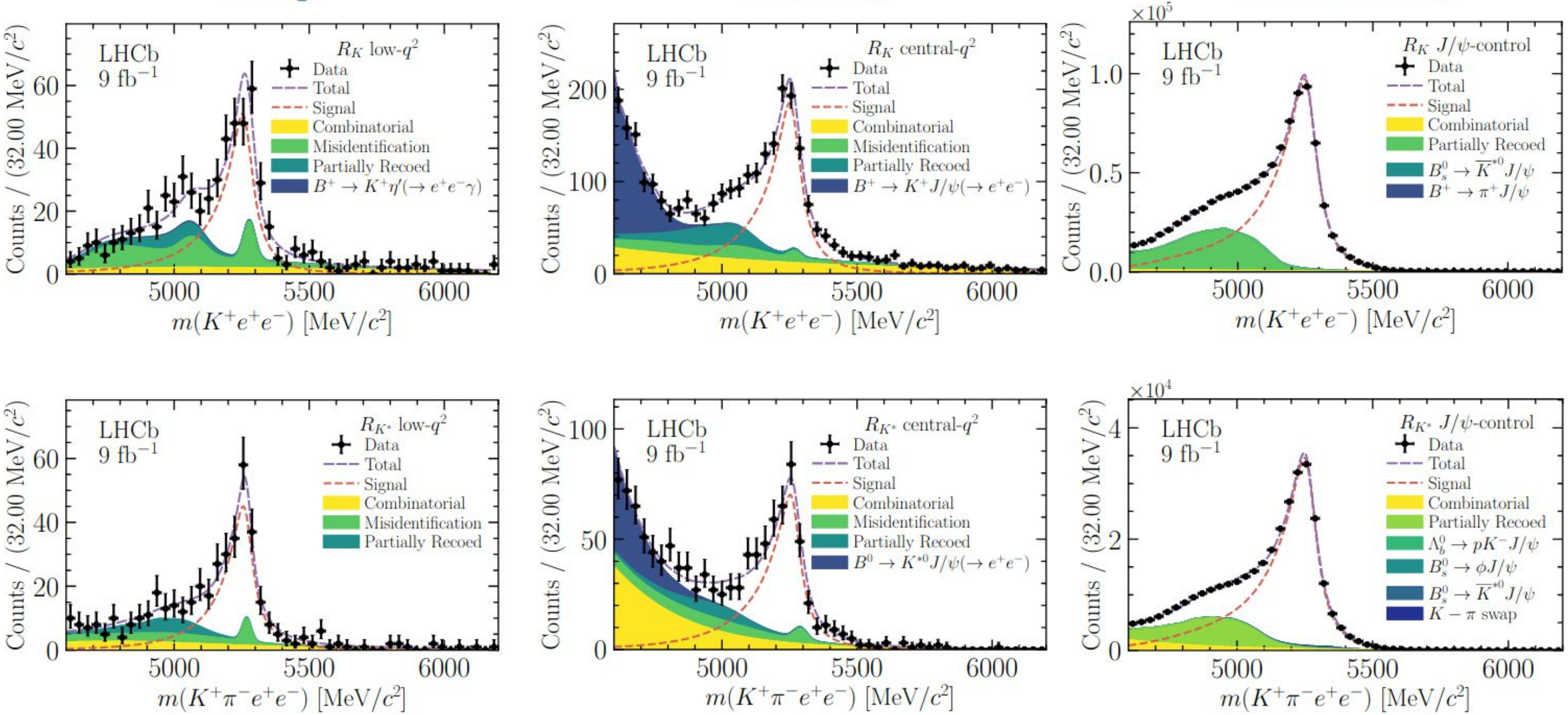
LHCb-PAPER-2022-045
LHCb-PAPER-2022-046



Simultaneous mass fits - electrons

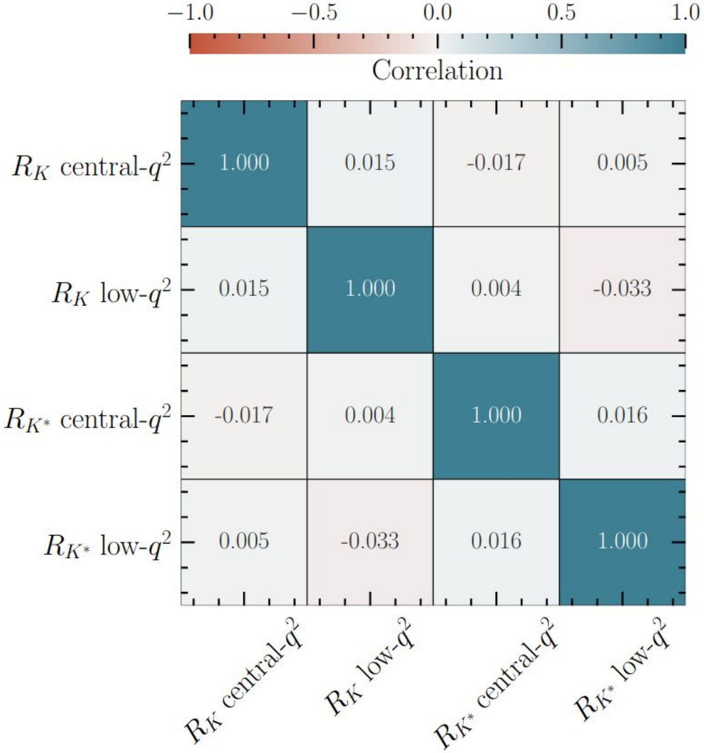
LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

low-q^2 | central-q^2 | resonant-J/ψ

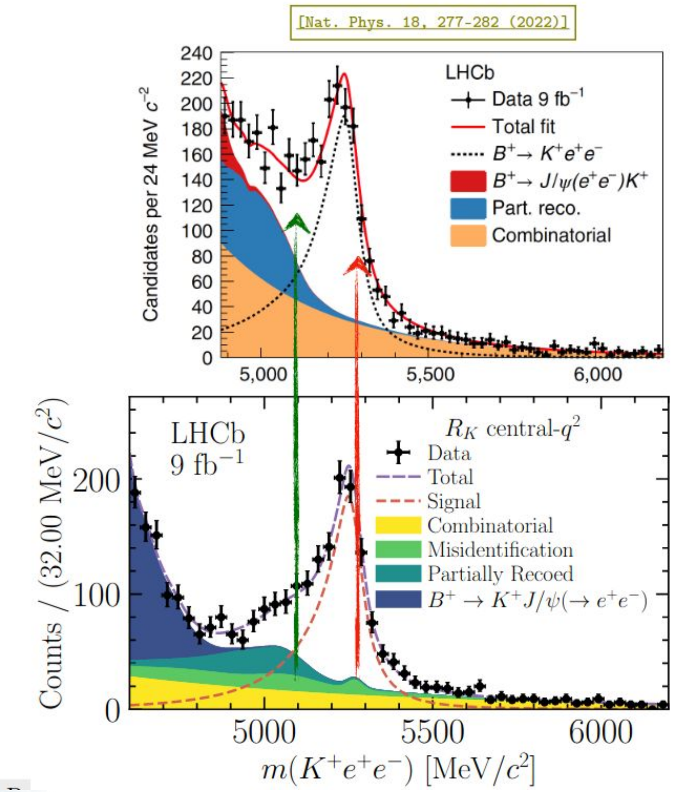


Correlation matrix of the simultaneous fit

LHCb-PAPER-2022-045
LHCb-PAPER-2022-046



Comparison to previous R_K measurements



- Different PID cut used
- Mis-ID rate from $D^{*-} \to D^0(K\pi)\pi$
- With new(previous) analysis requirements

	Sample	$\pi \to e$	$K \to e$
(11+12)	Run 1	1.78 (1.70) %	0.69 (1.24) %
(15+16)	Run 2p1	0.83 (1.51) %	0.18 (1.25) %
(17+18)	Run 2p2	0.80 (1.50) %	0.16 (1.23) %

single-misID	× 1 (Run1) × 2 (Run2)	× 2 (Run1) × 7 (Run2)
double-misID	× 1² (Run1) × 2² (Run2)	× 2² (Run1) × 7² (Run2)

- Shift due to contamination at looser working point : $+\mathbf{0.064}$
- Shift due to not inclusion of background in mass fit: $+\mathbf{0.038}$

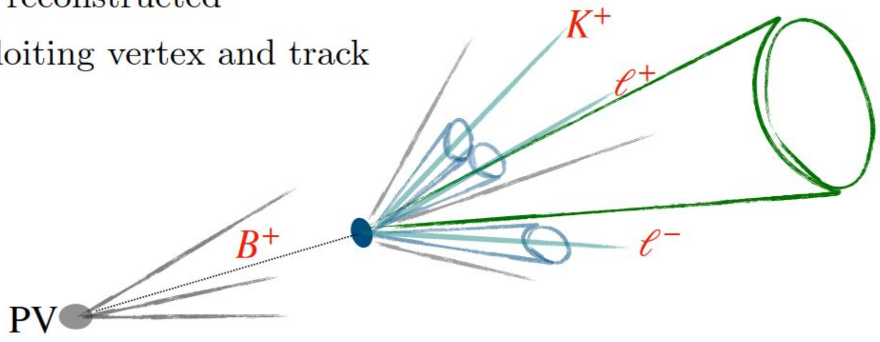
Adds linearly

Slide from CERN seminar

Selection: multivariate analysis

1. $B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-$ **and** $B^{(+,0)} \to K^{(+,*0)}e^+e^-$: suppress combinatorial with multivariate classifier using kinematic and vertex quality information.

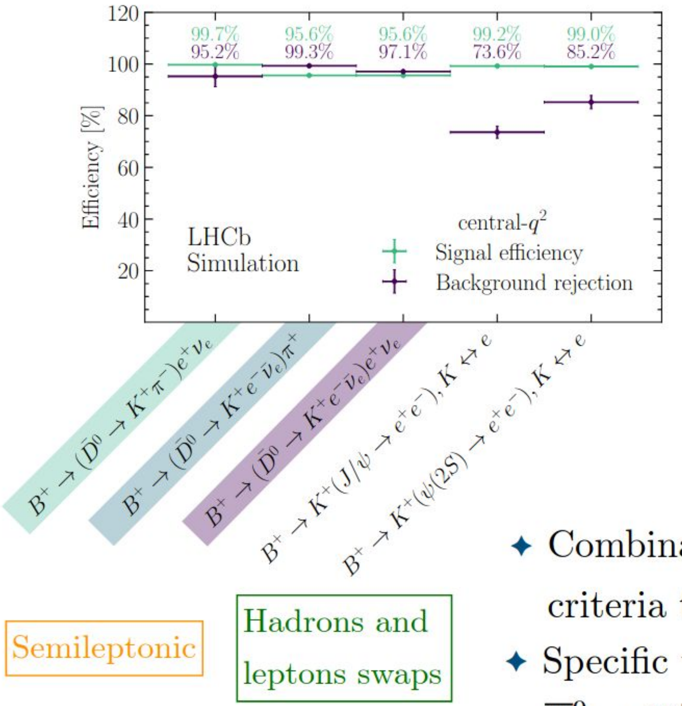
2. $B^{(+,0)} \to K^{(+,*0)}e^+e^-$: dedicated classifier to fight partially reconstructed background, exploiting vertex and track isolation

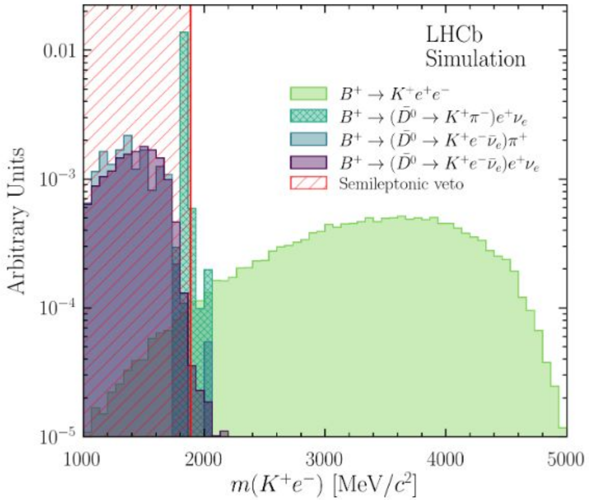


- Optimisation of significance for each mode/q^2 regions and data taking period

Slide from CERN seminar

Selection: veto specific background B^+ mode

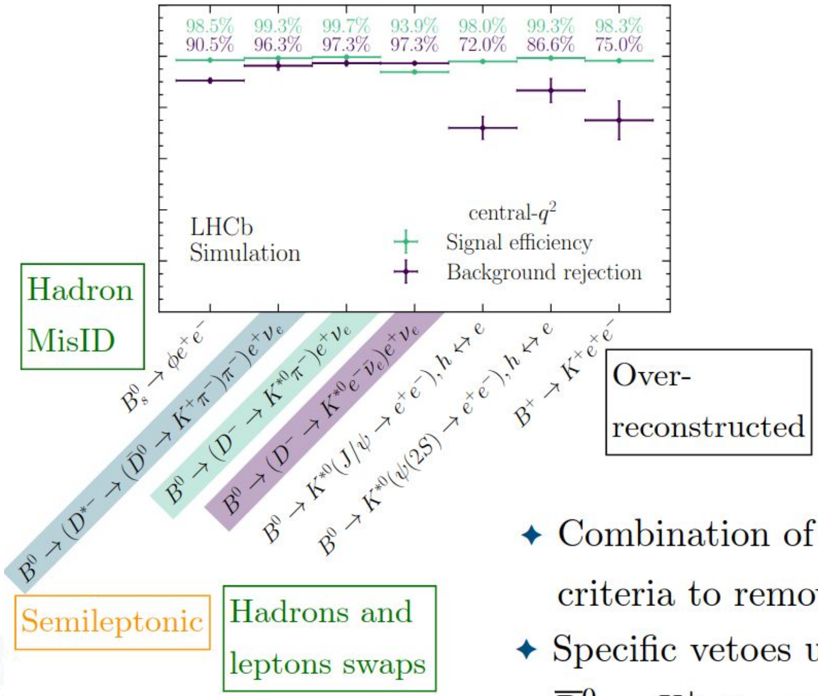


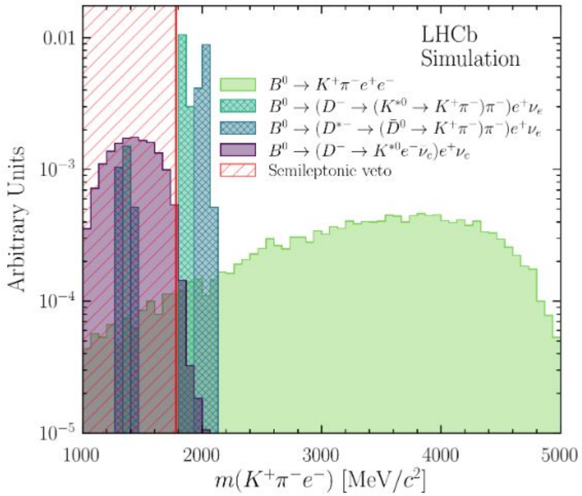


- Combination of efficient kinematic and particle identification criteria to remove background
- Specific vetoes under electron mis-ID hypothesis on $\overline{D}^0 \to K^+\pi^-_{\to e}$

Slide from CERN seminar

Selection: veto specific background B^0 mode





- Combination of efficient kinematic and particle identification criteria to remove background
- Specific vetoes under electron mis-ID hypothesis on $\overline{D}^0 \to K^+\pi^-_{\to e}$ and $D^- \to K^+\pi^-\pi^-_{\to e^-}$

Slide from CERN seminar

MC corrections

Corrections for:

- Particle Identification (PID)
- Tracking (TRK)
- B kinematics and event multiplicity (BKIN&MULT)
- Hardware trigger (L0)
- High level software trigger (HLT)
- B decay vertex reconstruction (RECO)
- q^2 resolution and bin-migration (RES)

Multi-step correction to simulation where $w_i = \dfrac{\varepsilon_{\text{Data}}}{\varepsilon_{\text{Simulation}}}$

$B^{+,0} \to K^{+,*0} J/\psi(\mu^+\mu^-)$: $w_{\text{PID}} \to w_{\text{L0}} \to w_{\text{HLT}}$ ↓

$B^{+,0} \to K^{+,*0} J/\psi(\ell^+\ell^-)$: $w_{\text{PID}} \to w_{\text{TRK}} \to w_{\text{BKIN\&MULT}} \to w_{\text{L0}} \to w_{\text{HLT}} \to w_{\text{RECO}} \to w_{\text{RES}}$

- Two weight chains evaluated: one using $B^+ \to K^+ J/\psi(\ell\ell)$ and one using $B^0 \to K^{*0} J/\psi(\ell\ell)$
- Results evaluated with both chains & shown to be compatible for the first time
- Nominal approach is to use the B^+ chain for B^0 decay channels and vice-versa

Slide from CERN seminar

NP contributions (EFT interpretation)

[Go to Patrick's presentation](#)

[Buchalla, Buras, Lautenbacher, Rev. Mod. Phys.68 (1996) 1125]

$b \to s\ell^+\ell^-$ OPERATORS

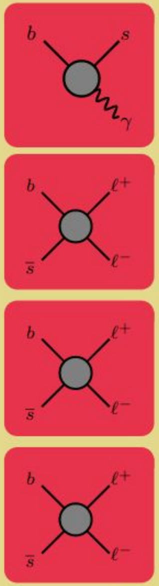
Operator

$\mathcal{O}_{7\gamma}$

$\mathcal{O}_{9V}$

$\mathcal{O}_{10A}$

$\mathcal{O}_{S,P}$



Effective Hamiltonian $\mathcal{H}$

$$A(b \to s\ell\ell) = \langle s\ell\ell \,|\mathcal{H}_{\text{eff}}|\, b\rangle$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$

- Operators $\mathcal{O}_i$: Long-distance effects
- Wilson coefficients C_i: Short-distance effects (masses above μ are integrated out)

New physics can show up in new operators or modified Wilson coefficients

Nikhef

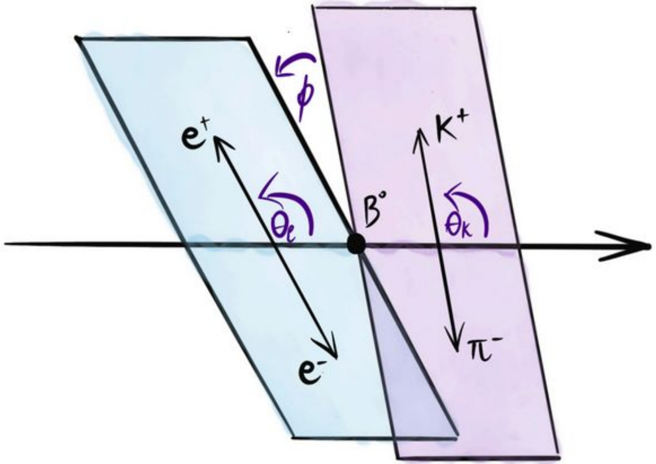
Patrick Koppenburg | Penguin B decays | 19/05/2021 — Santiago [49 / 62]

$B^0 \to K^{*0} ee$ angular analysis

The decay is described by 3 angles (θ_l, θ_K and ϕ)

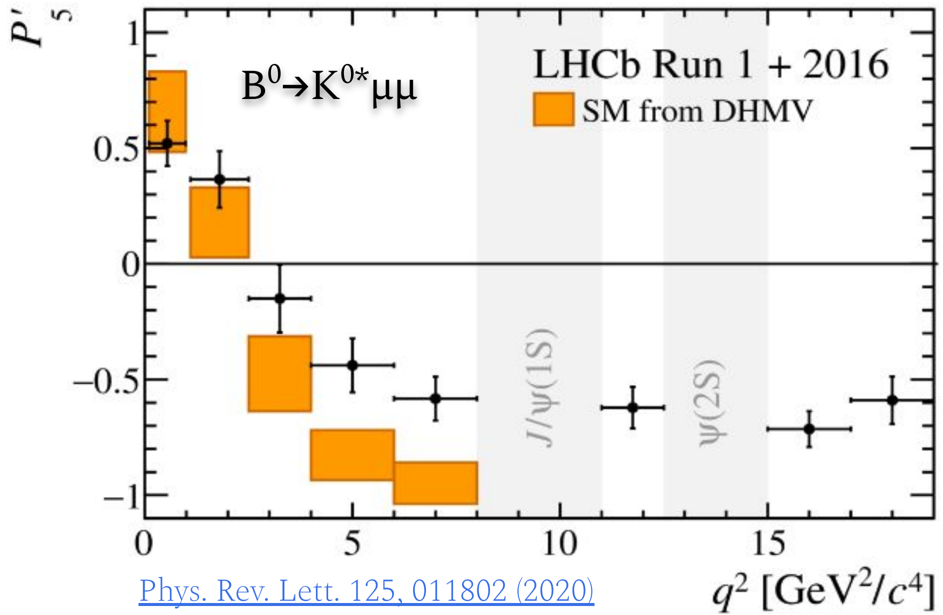
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Angular distribution

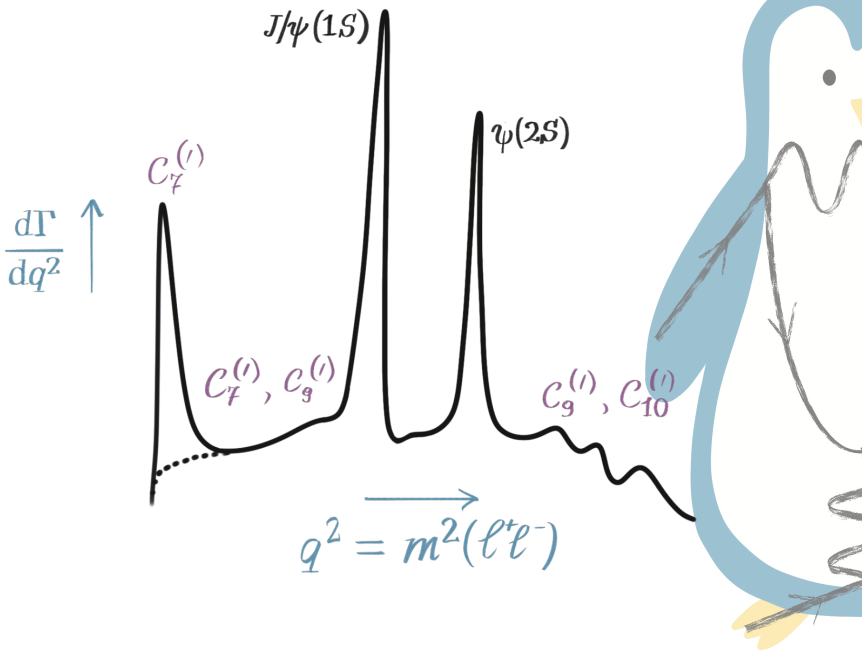


THE GOAL: Measure the coefficients describing the angular distribution

Example: angular coefficients in bin of q^2



[Phys. Rev. Lett. 125, 011802 (2020)](#)



Backup slide: Optimized base P_i'

Theoretically cleaner angular observables:
$B^0 \rightarrow K^{*0}$ form-factor uncertainties largely cancel

$$P_1 = \frac{2S_3}{(1-F_L)} = A_T^{(2)},$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)},$$

$$P_3 = \frac{-S_9}{(1-F_L)},$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}},$$

$$P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}},$$

New theoretical prediction for B→Kll branching ratio

https://arxiv.org/abs/2207.13371

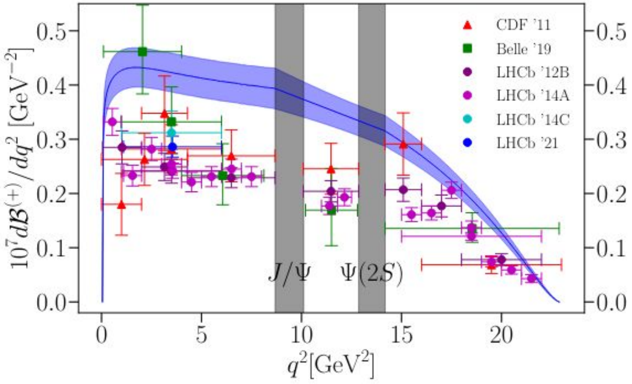


FIG. 3. Differential branching fraction for $B^+ \to K^+\ell^+\ell^-$, with our result in blue, compared with experimental results [15, 16, 18, 19, 21, 23]. Note that Belle '19, and LHCb '14C and '21 have $\ell = e$, whilst otherwise $\ell = \mu$. Horizontal error bars indicate bin widths.

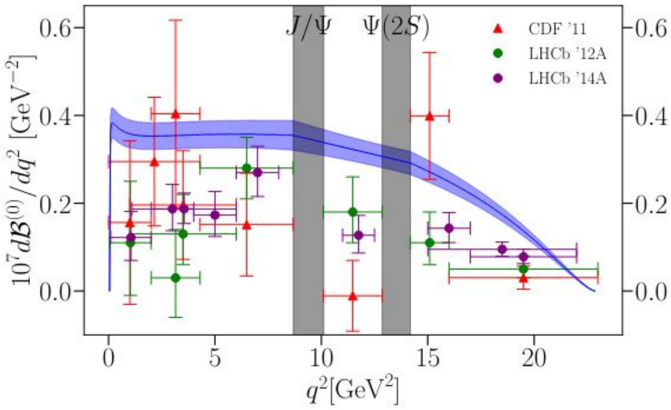


FIG. 4. Differential branching fraction for $B^0 \to K^0\ell^+\ell^-$, with our result in blue, compared with experimental results [16, 17, 19]. All experimental results take $\ell = \mu$. Horizontal error bars indicate bin widths.