Status of Lepton Flavour Universality

Virtual FSP Belle II Germany Meeting

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14.09.2020 Hamburg

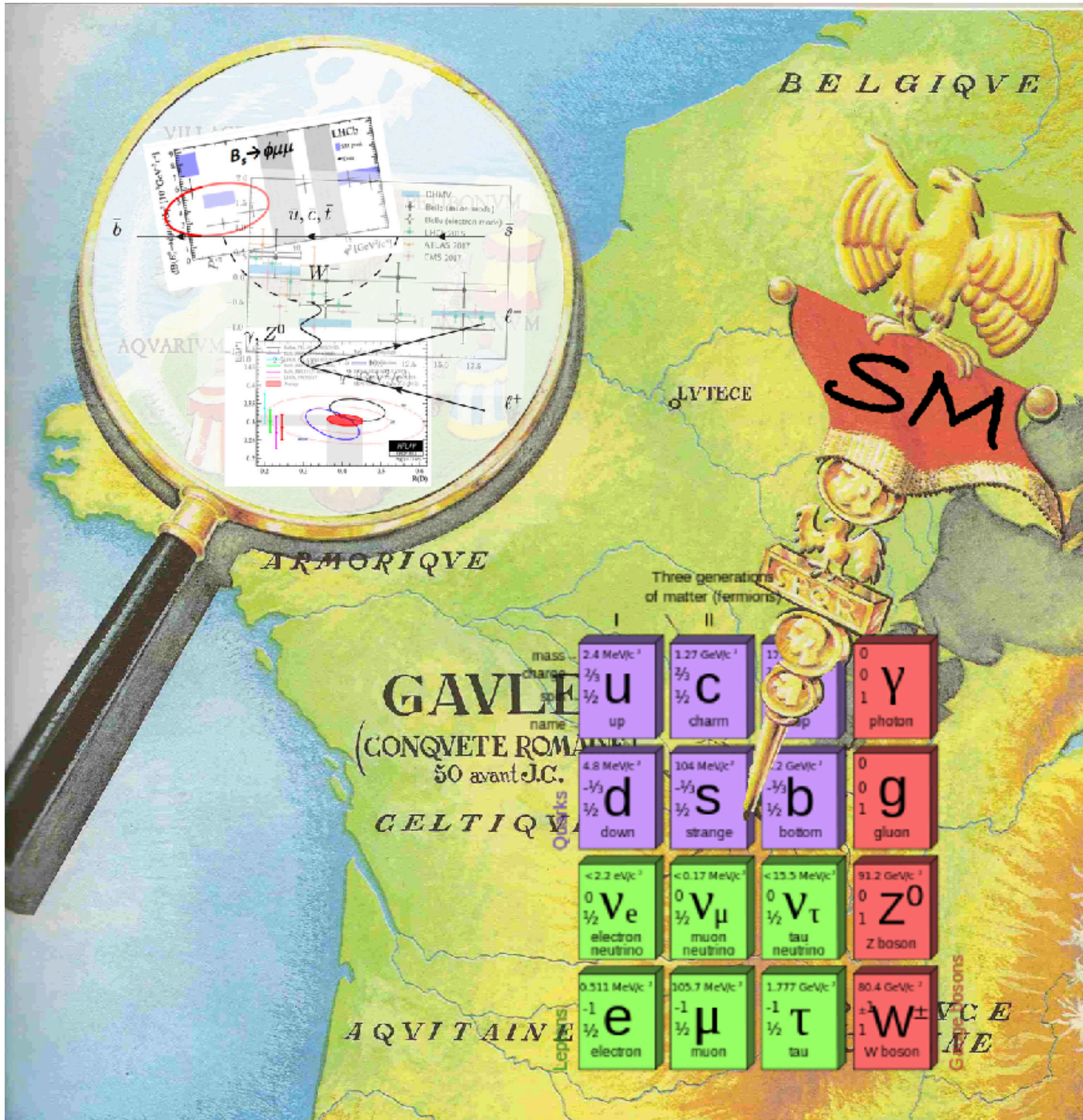
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Motivation

- The Standard Model (SM) is very successful in describing the world at particle level

- Almost all SM predictions seem to fit experimental data precisely… Almost?



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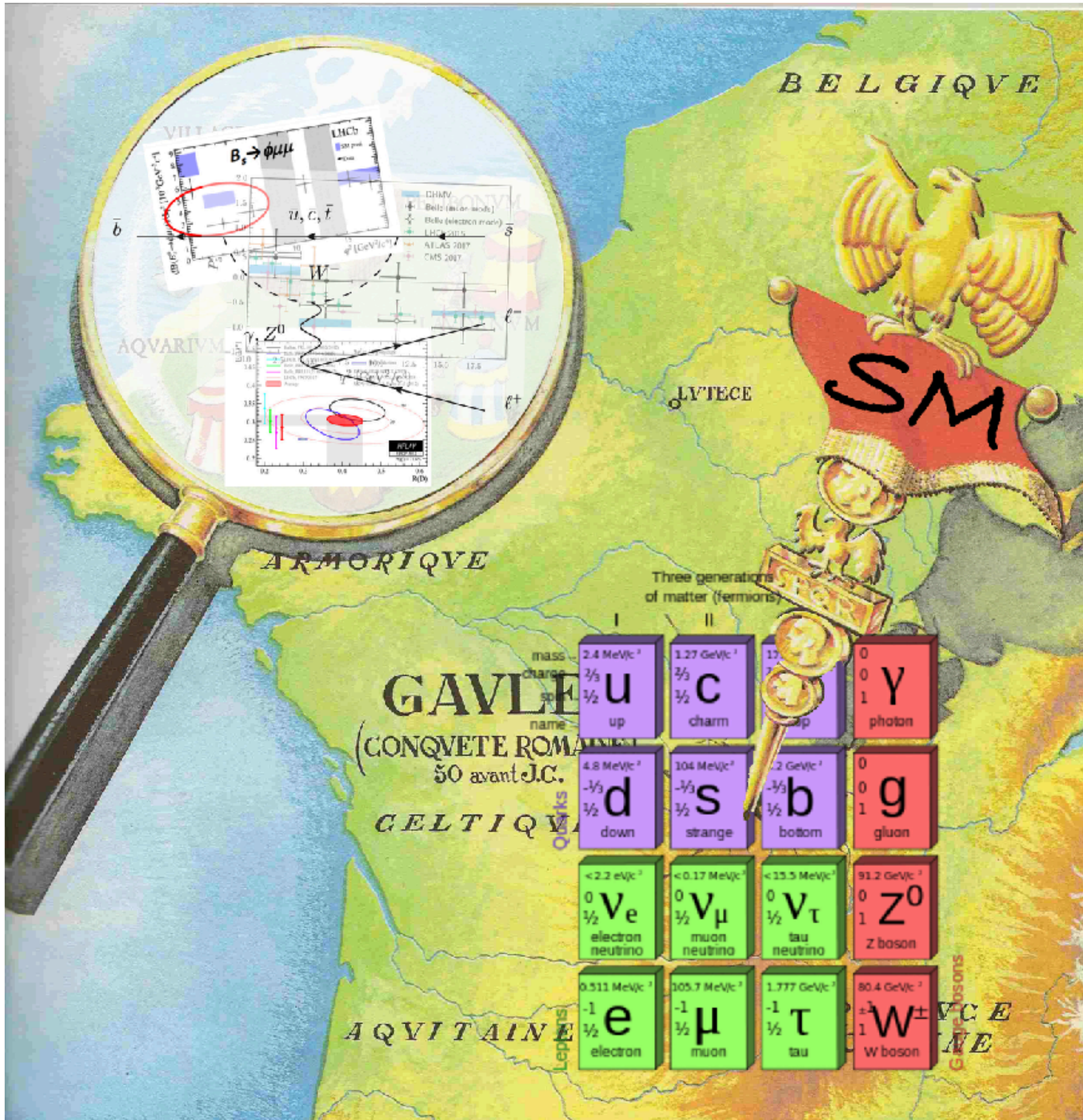
The Flavour Anomalies



The Flavour Anomalies

(maybe only "local" anomalies…)

$> 3.5\sigma$ enhanced $B \to D^{(*)}\tau\nu$ rates

3.3σ suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$

$\sim 3\sigma$ tension between inclusive and exclusive determination of $|V_{ub}|$

$\sim 3\sigma$ tension between inclusive and exclusive determination of $|V_{cb}|$

$> 3\sigma$ anomalies in angular distributions of $B \to K^*\ell\ell$

2.6σ lepton flavor non-universality in $B \to K^{(*)}\mu^+\mu^-$ vs. $B \to K^{(*)}e^+e^-$

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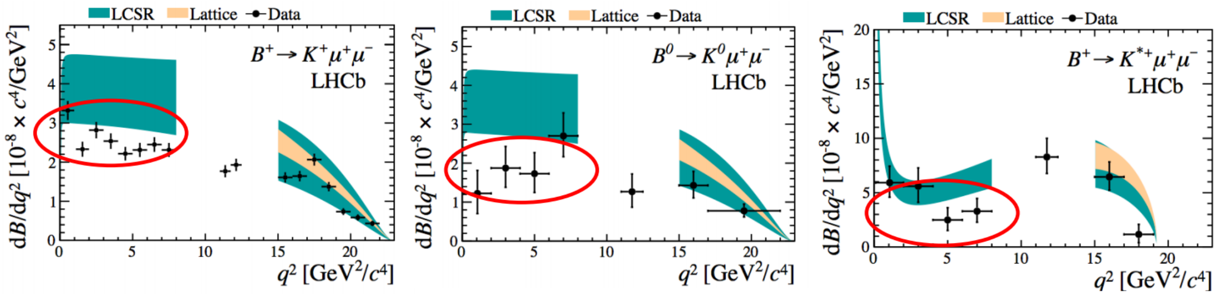

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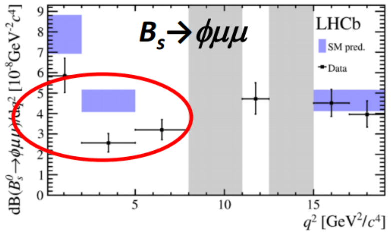

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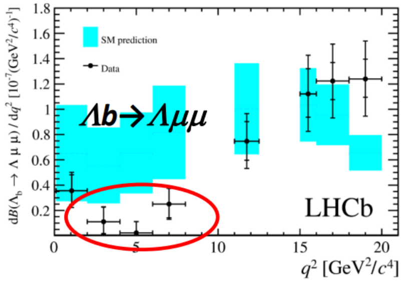

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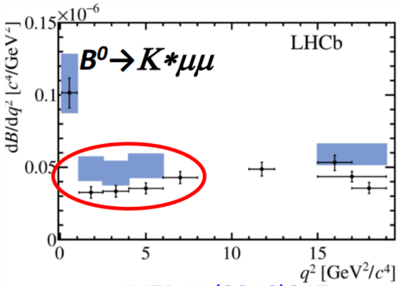

JHEP 11(2016)047
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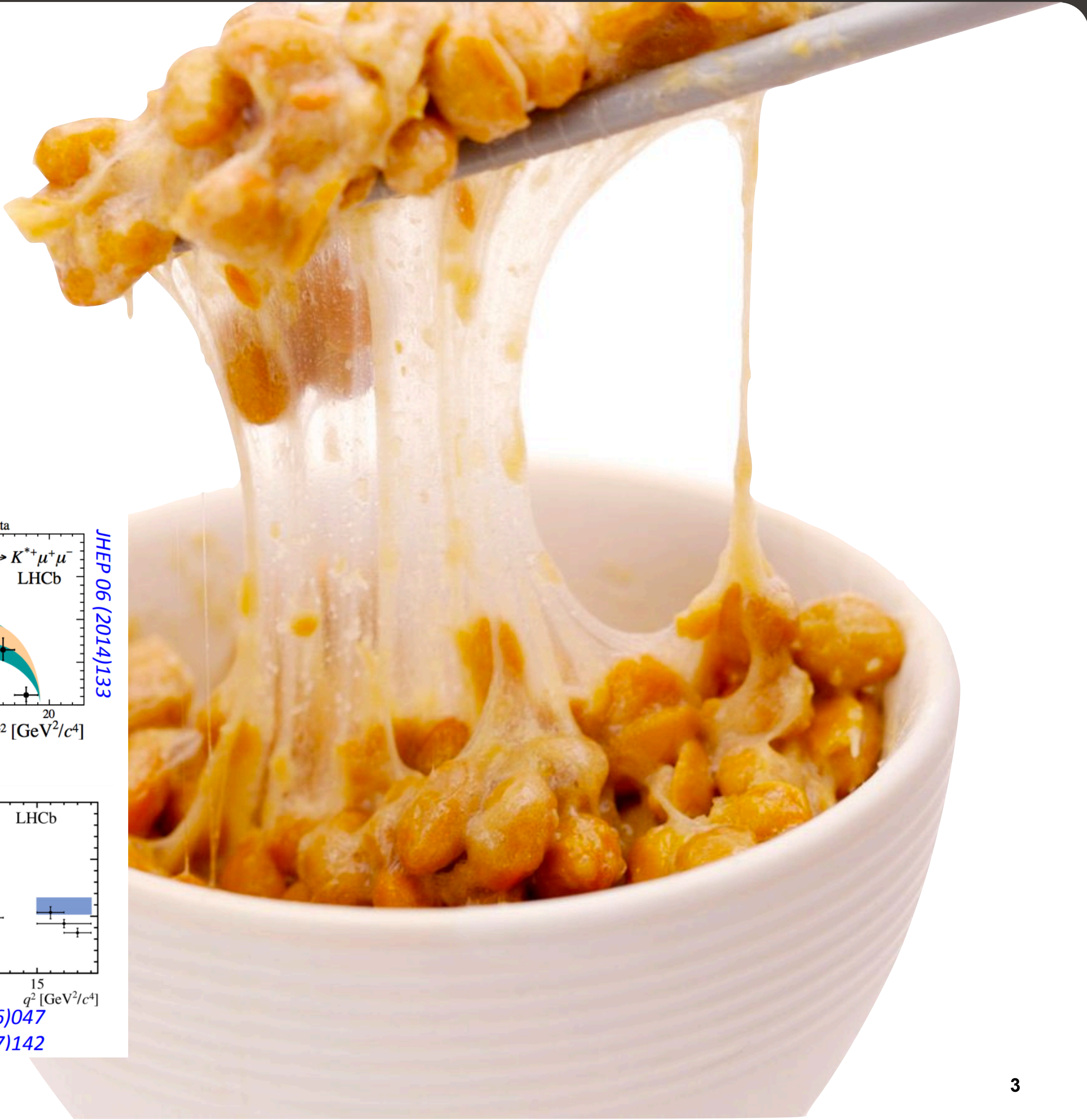

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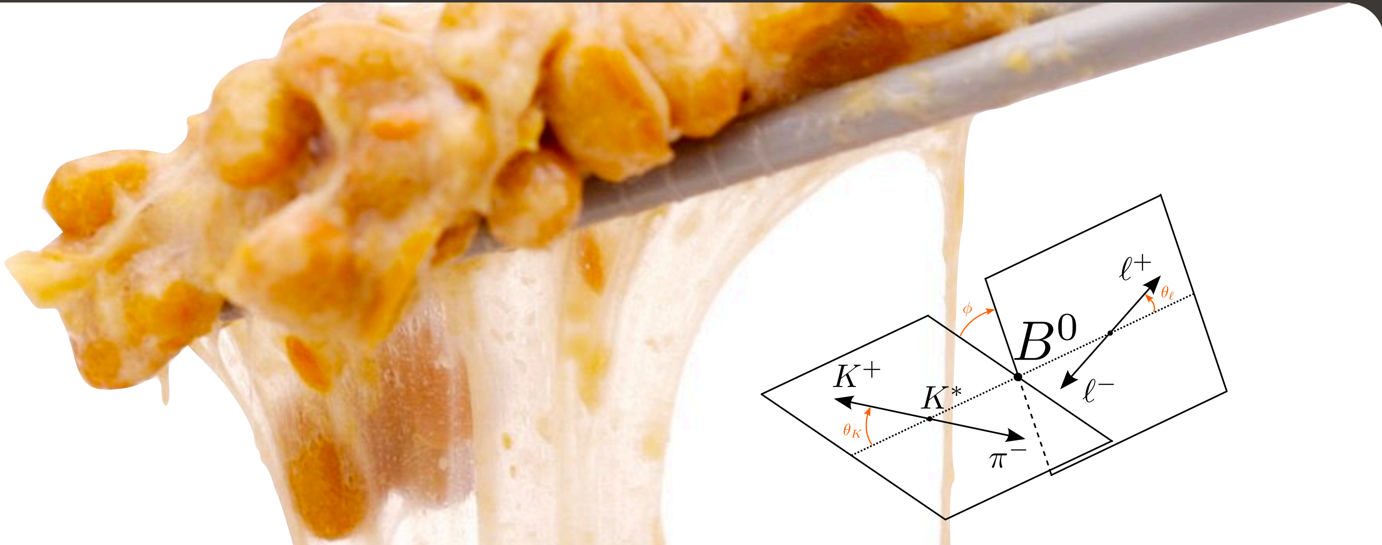

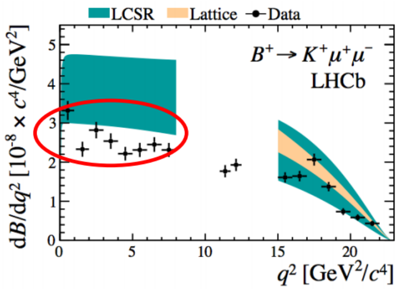

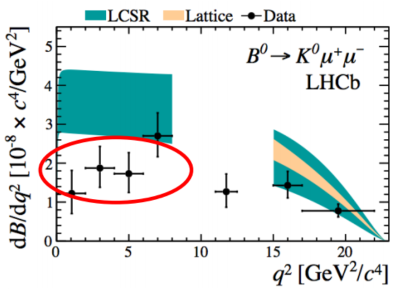

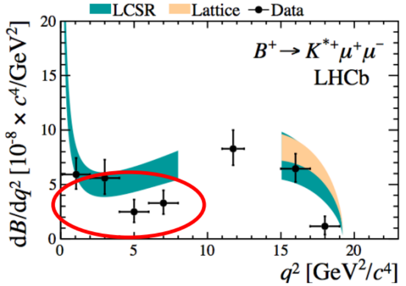

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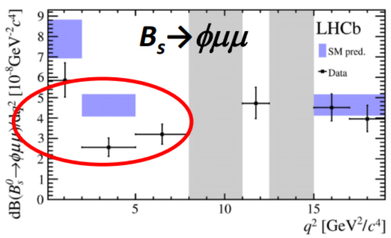

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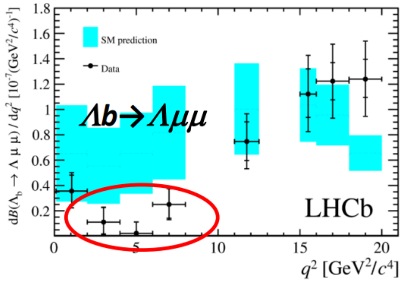

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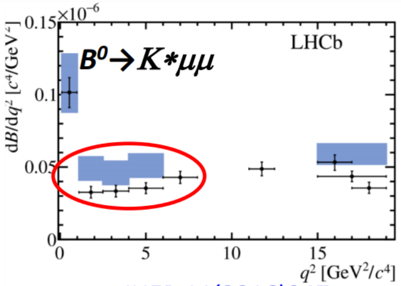

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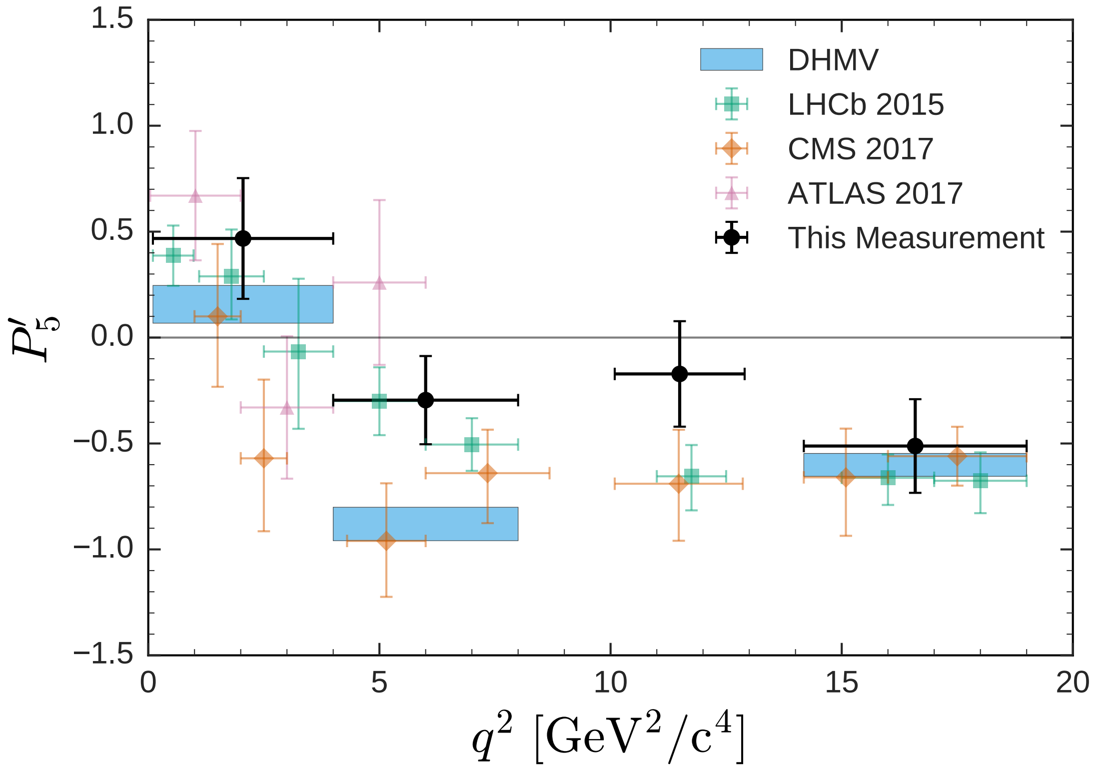
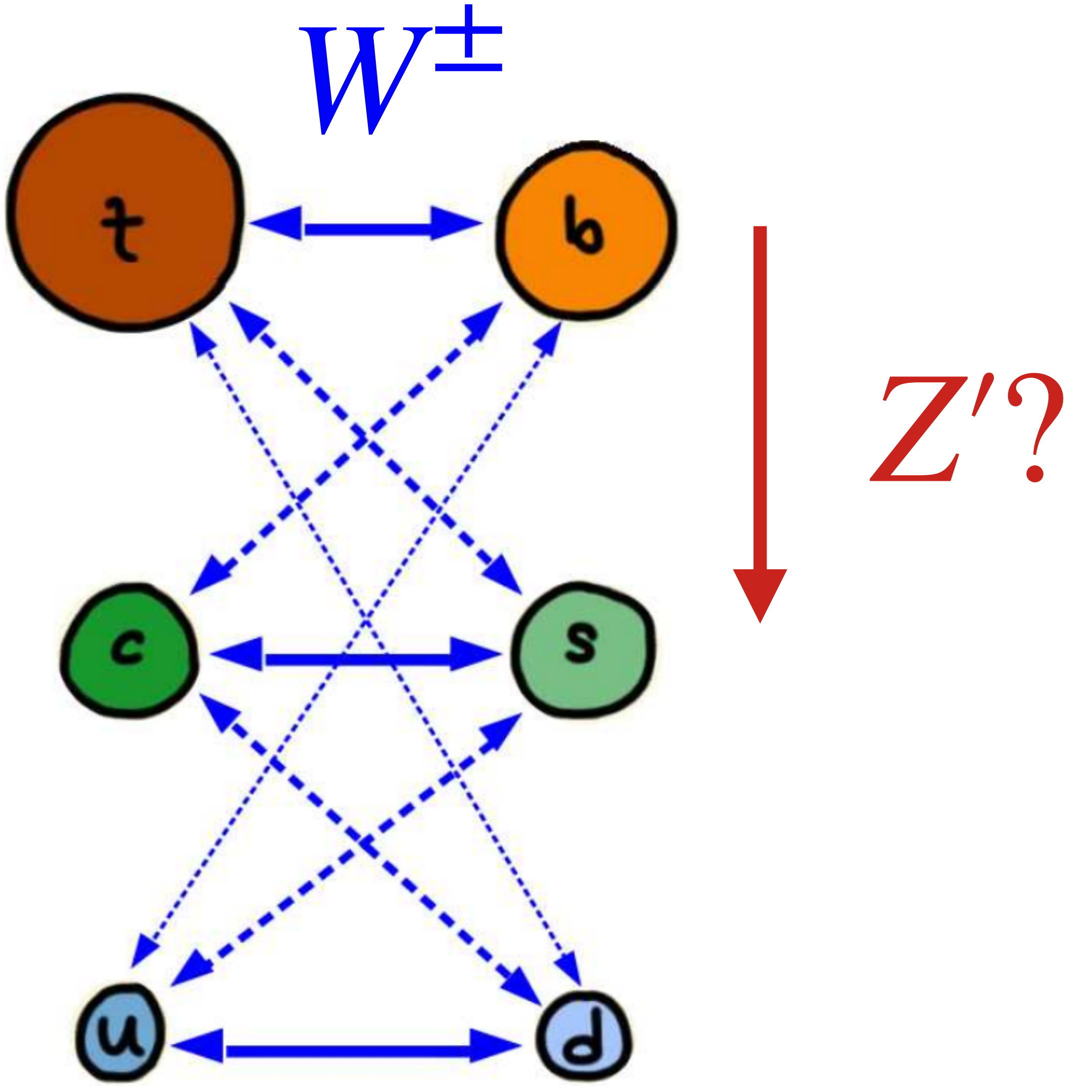
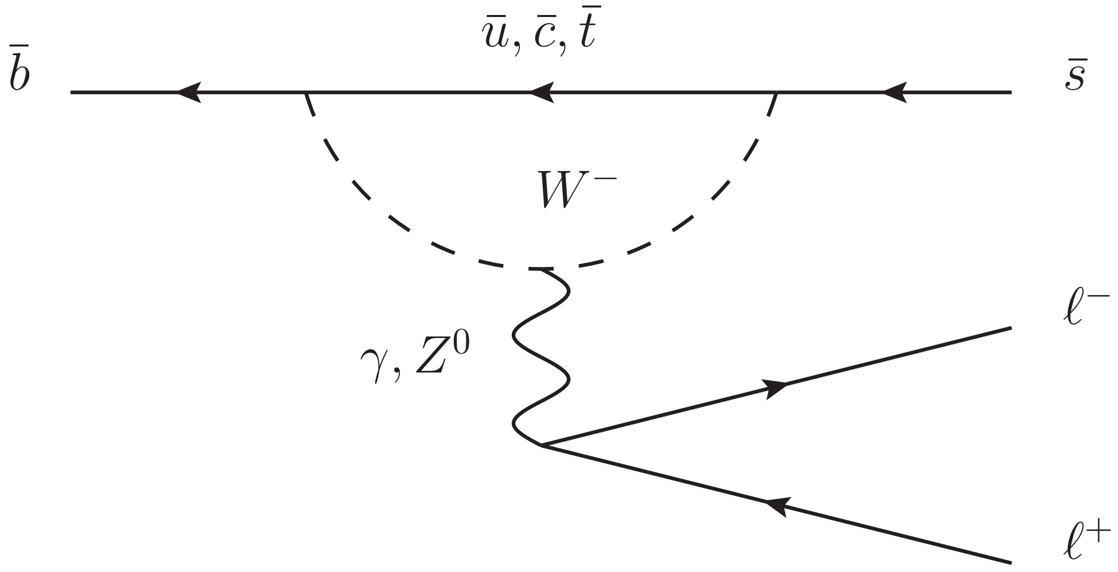


The b→s transition





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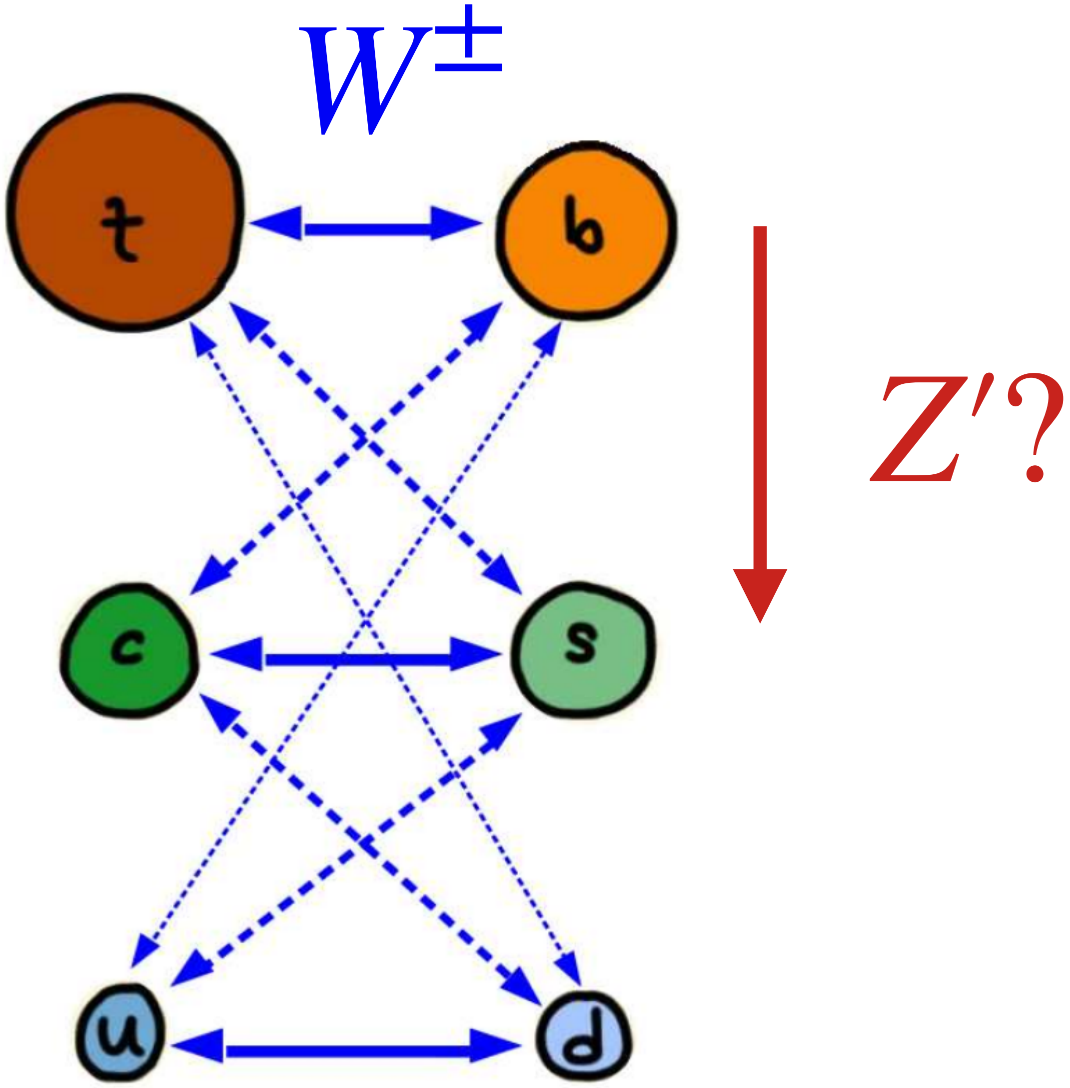
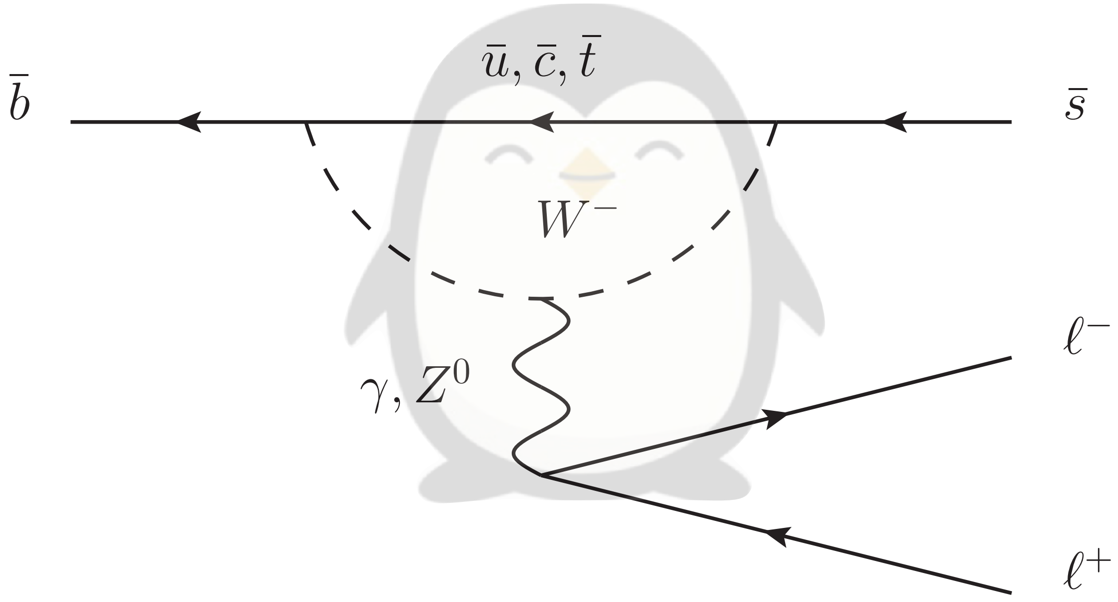
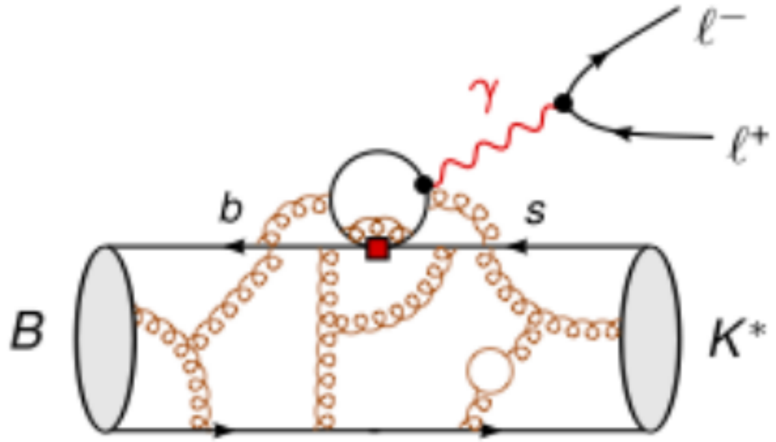


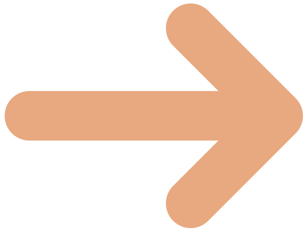


Testing for Lepton Flavour Universality

Smoking gun to overcome theory uncertainties

- Angular observables might have residual uncertainties from form-factors





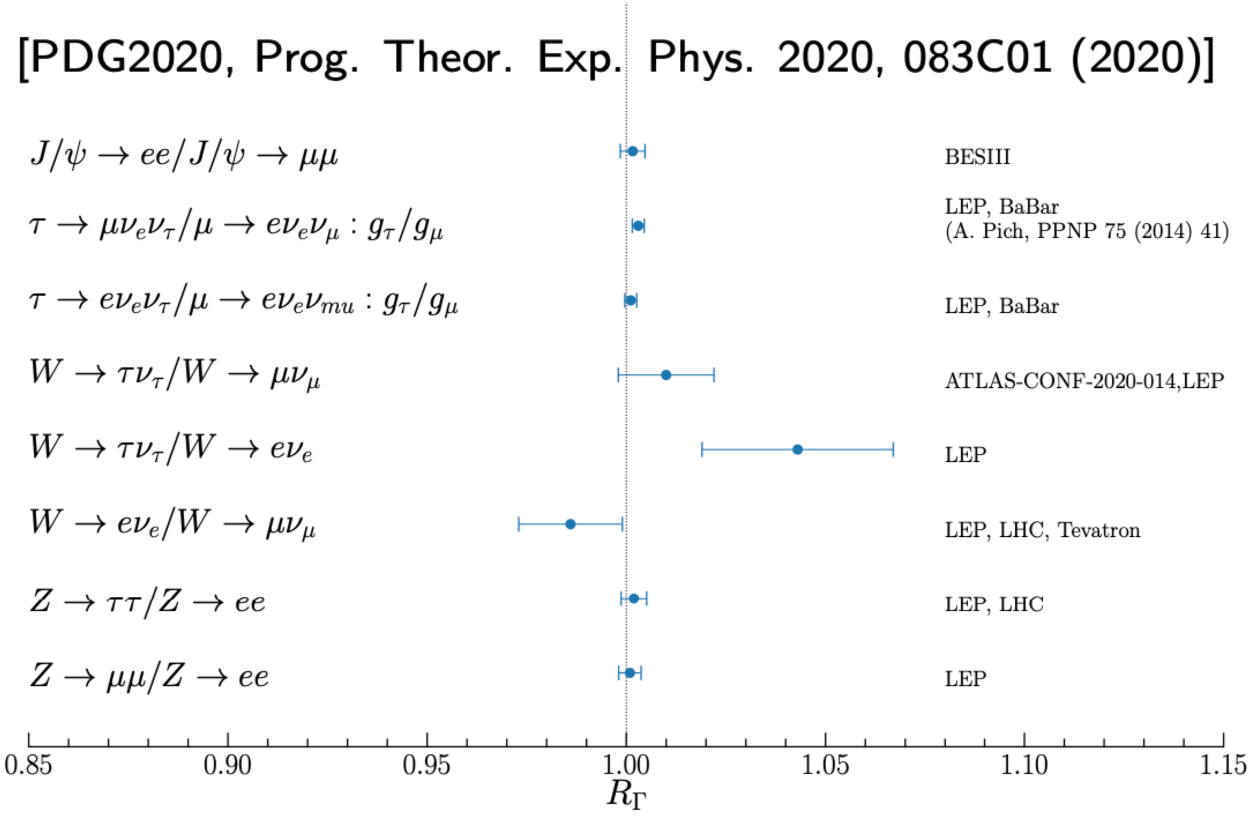
Theoretical cleanness

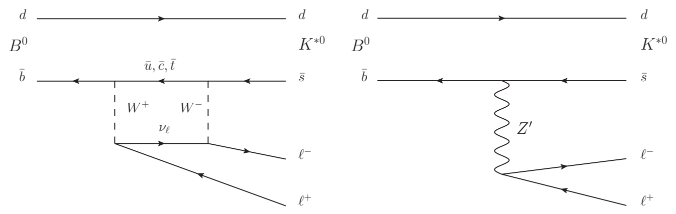
Branching fractions **Angular observables** **LFU tests**

Testing for Lepton Flavour Universality

Smoking gun to overcome theory uncertainties

- All SM forces couple **universal** to the lepton flavour
  - Only differences from mass/phase-space
- Most data seems to support the SM
- NP models can introduce flavour dependent couplings
- Non-universal flavour coupling would be a strong sign for physics beyond the SM





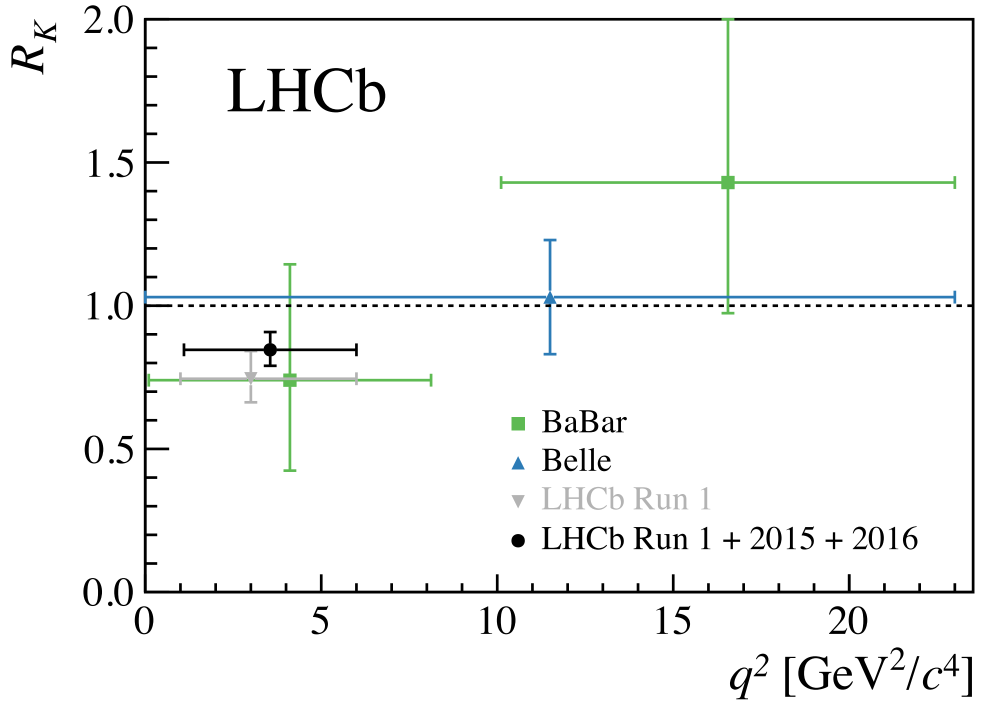
(c) SM example (d) NP example

Most simple approach: Ratio of Branching Ratios

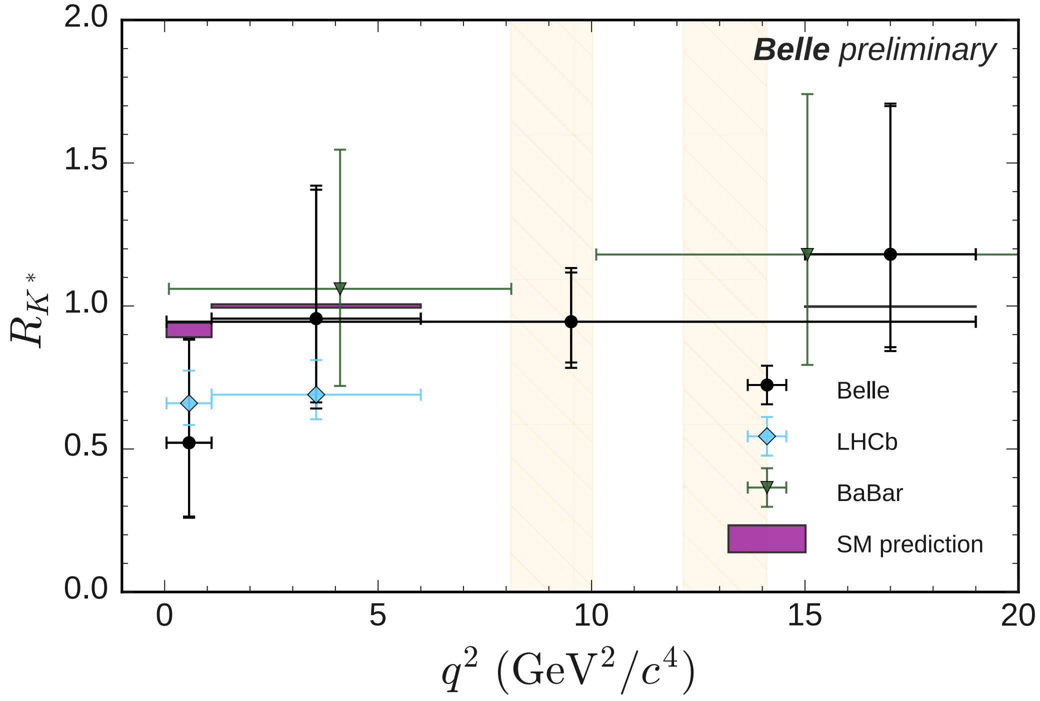
After Moriond

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

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



arXiv:1903.09252



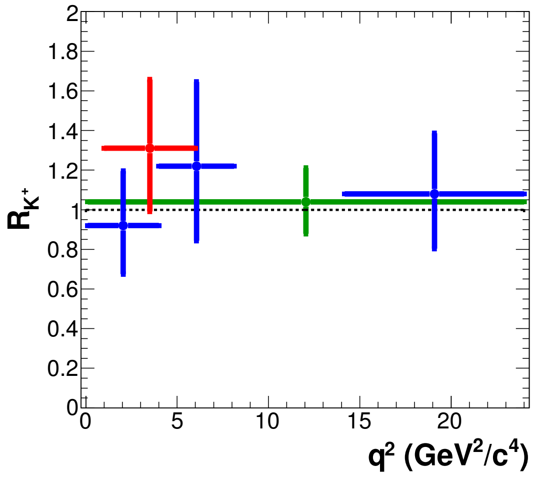
arXiv:1904.02440

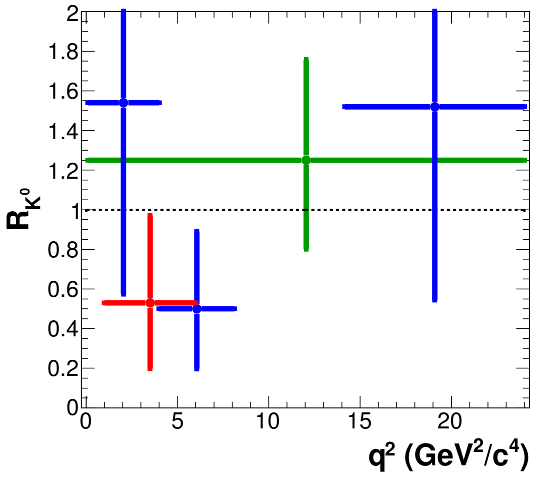
R_K analysis

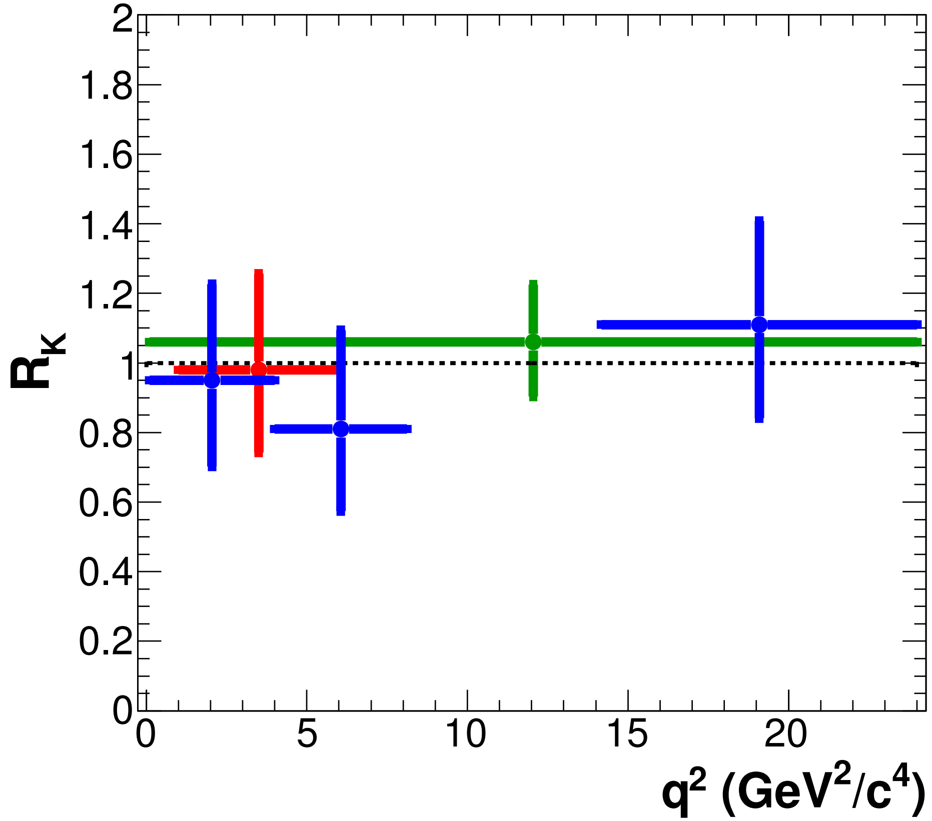
Results for RK

- All measurements in agreement with recent results and SM
- The combined result is the weighted average of the B^+ and B^0 modes

arXiv:1908.01848





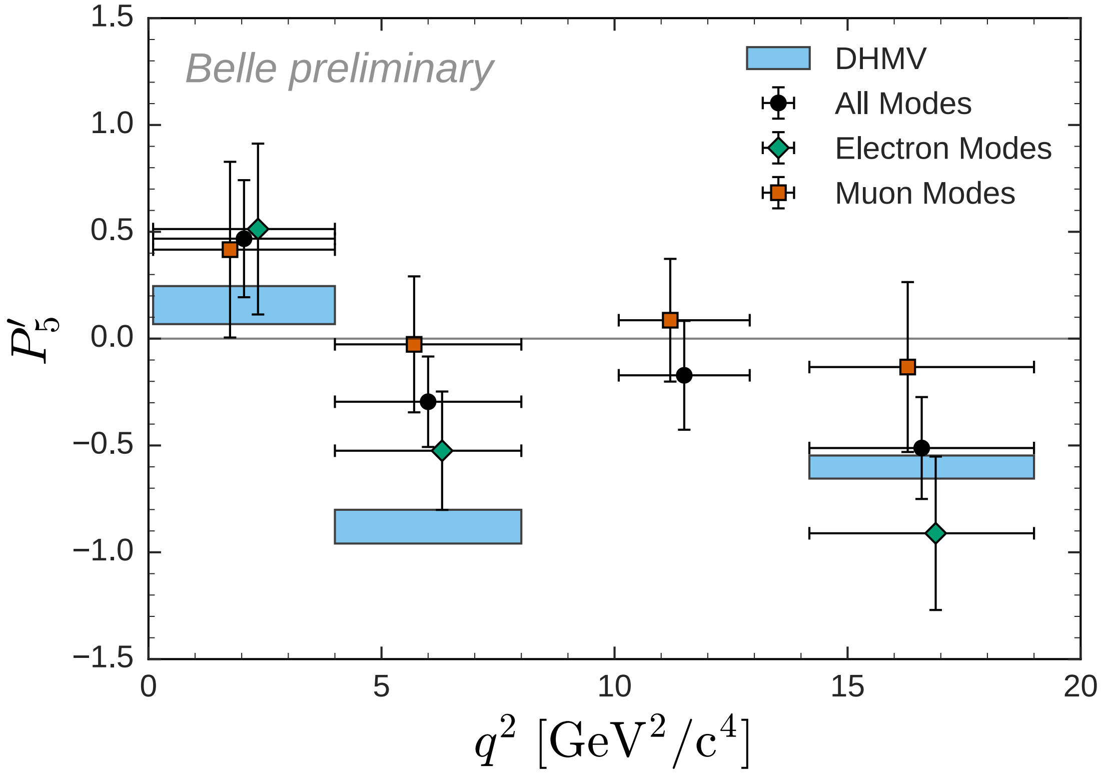


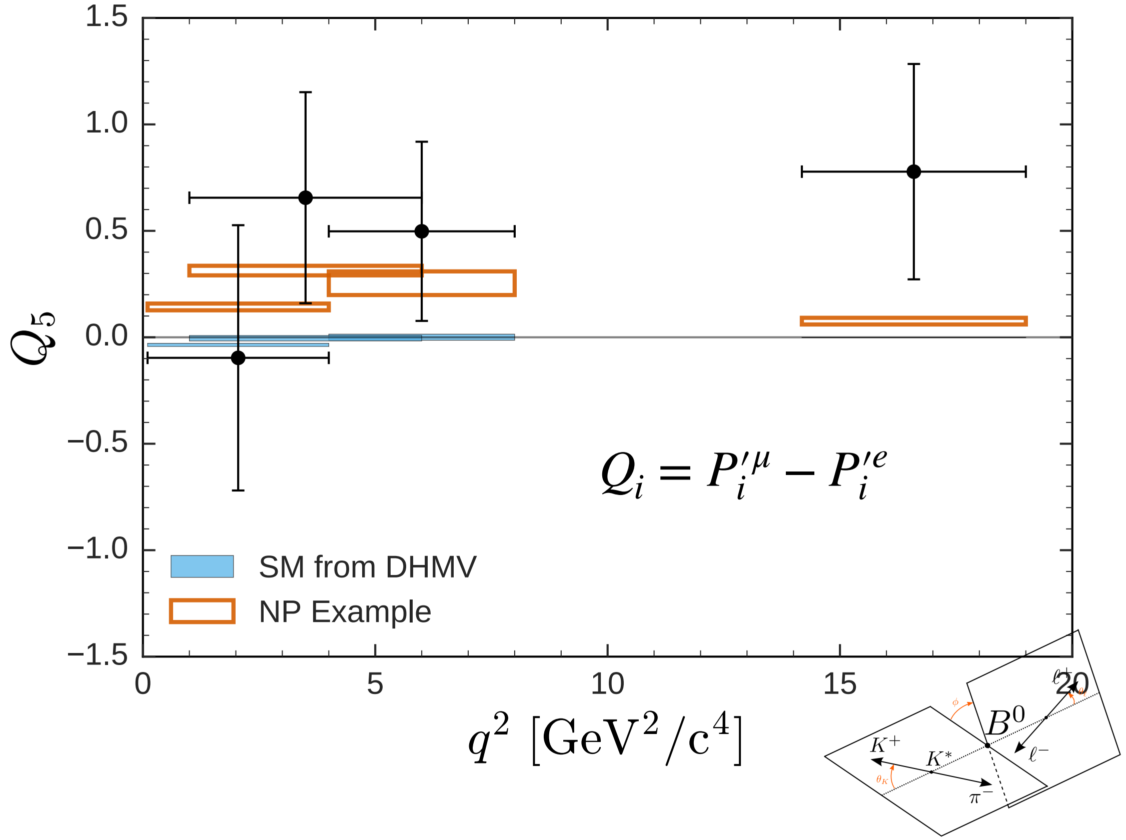
[0.1 , 4.0], [4.0 , 8.12], [1.0 , 6.0], $>$ 14.18 and $>$ 0.1 q^2 bins

Testing for lepton flavour universality in angular observables

Smoking gun to overcome theory uncertainties

- Performing the angular analysis separately for electron an muon modes
- Largest discrepancy in muons mode with 2.6σ while 1.1σ in the electron mode





Overview of the b→sll Puzzle

Combining the results

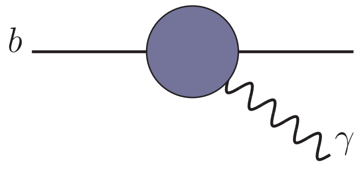
- Effective Hamiltonian approach

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (\underbrace{C_i\mathcal{O}_i}_{\text{left-handed part}} + \underbrace{C_i'\mathcal{O}_i'}_{\text{right-handed part suppressed in SM}})$$

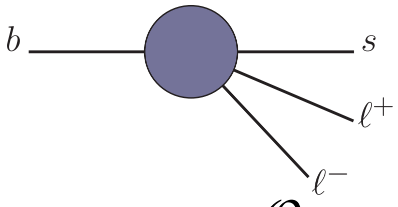
  - Effective Operators O_i
  - Effective Couplings C_i

- Combine measurements and fit for

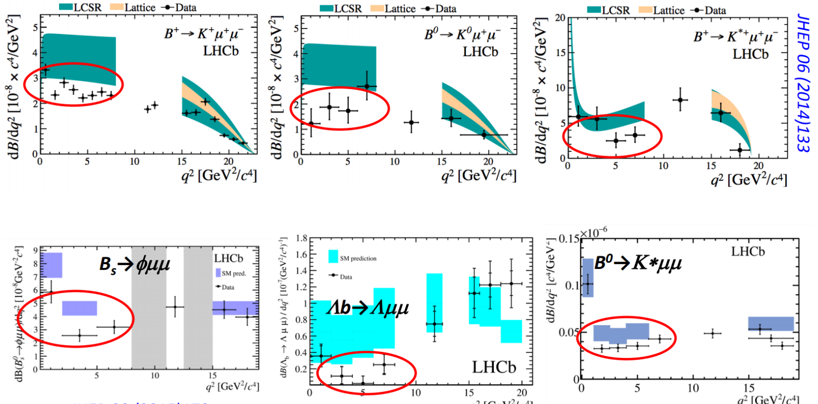
$$\mathcal{C}_9 = \mathcal{C}_9^{\text{SM}} + \mathcal{C}_9^{NP}$$



$\mathcal{O}_7$



$\mathcal{O}_{9,10}$



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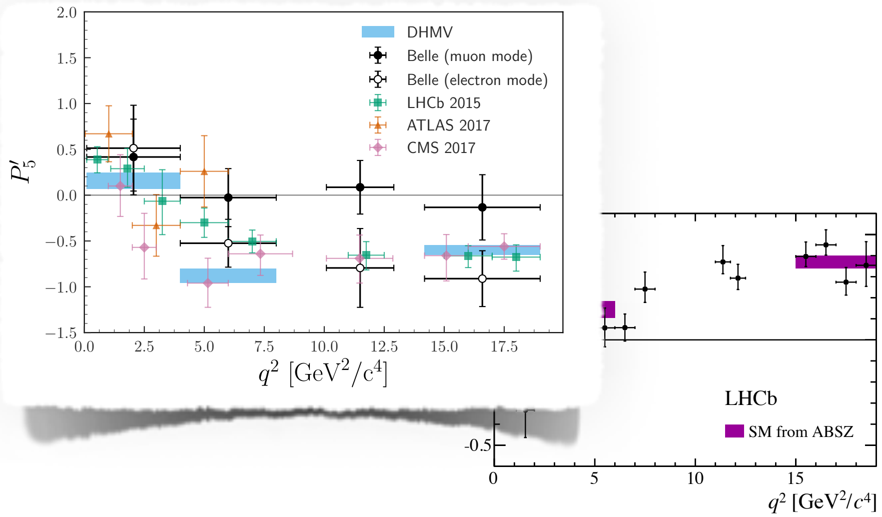
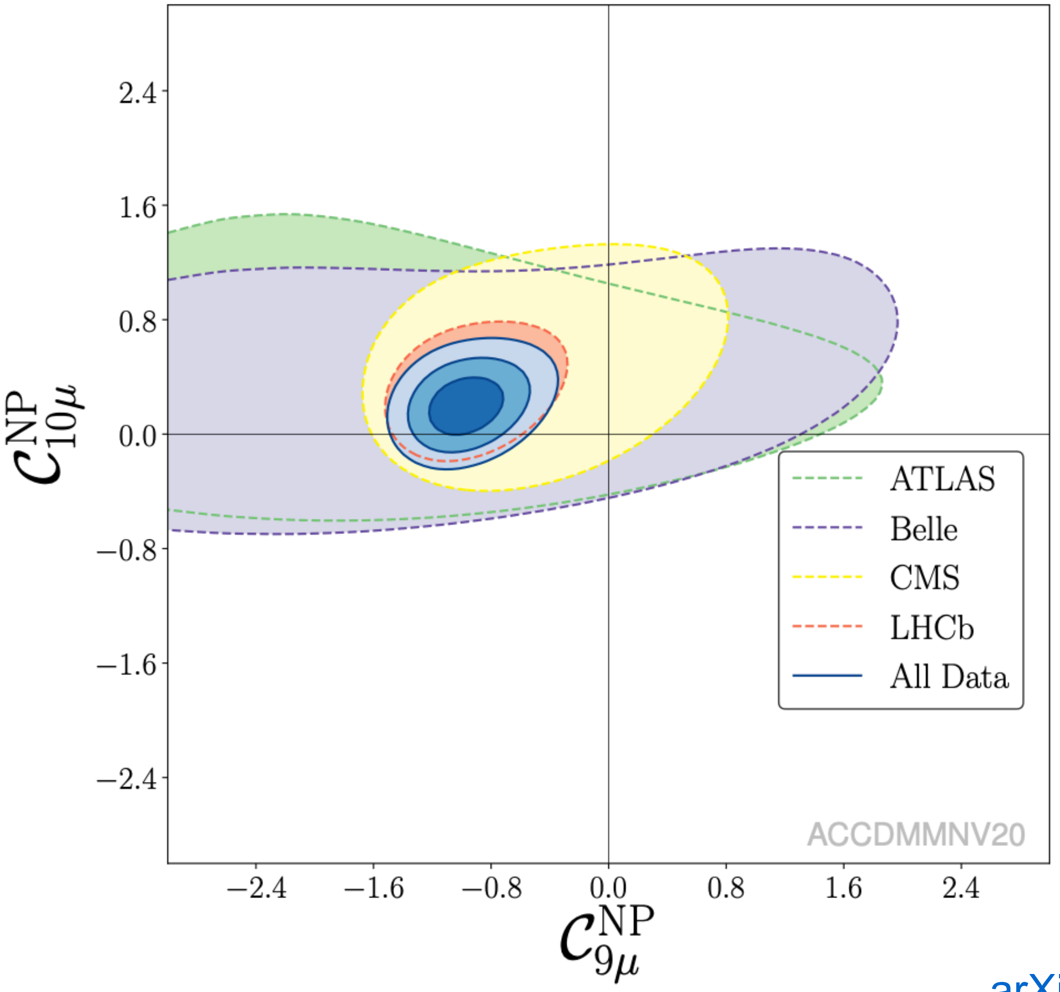
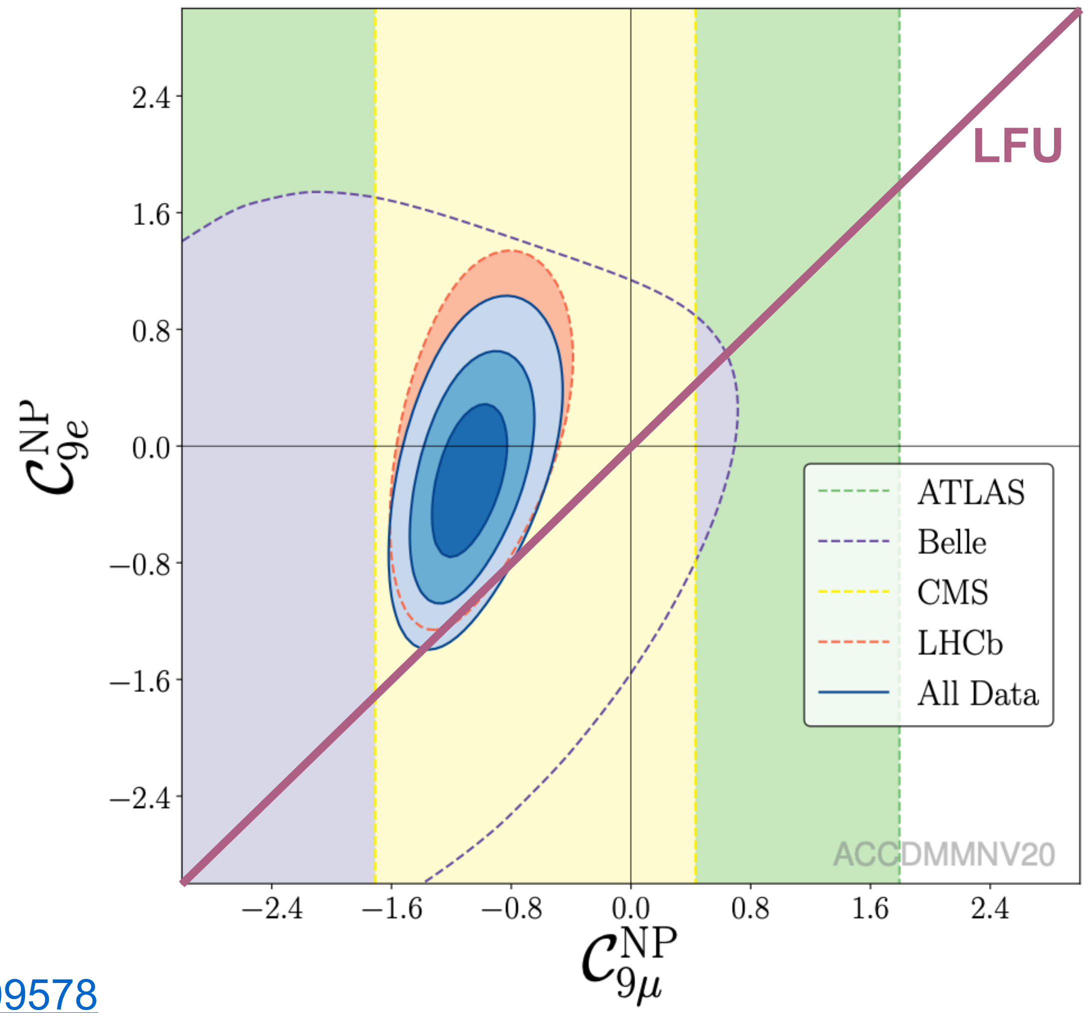


Combined Fit for New Physics

Fit for New Physics

LFU ~3σ pull from SM





arXiv:1903.09578

LFU in tau decays

Discussion

- Most new physics models imply large contributions to the tau modes

- ▶ New Physics may couple to mass of the τ
  $\rightarrow$ enhance sensitivity by $|m_\tau/m_\mu|^2 \simeq 286$
- ▶ Both Z' and leptoquark models predict large enhancements [1704.05340]

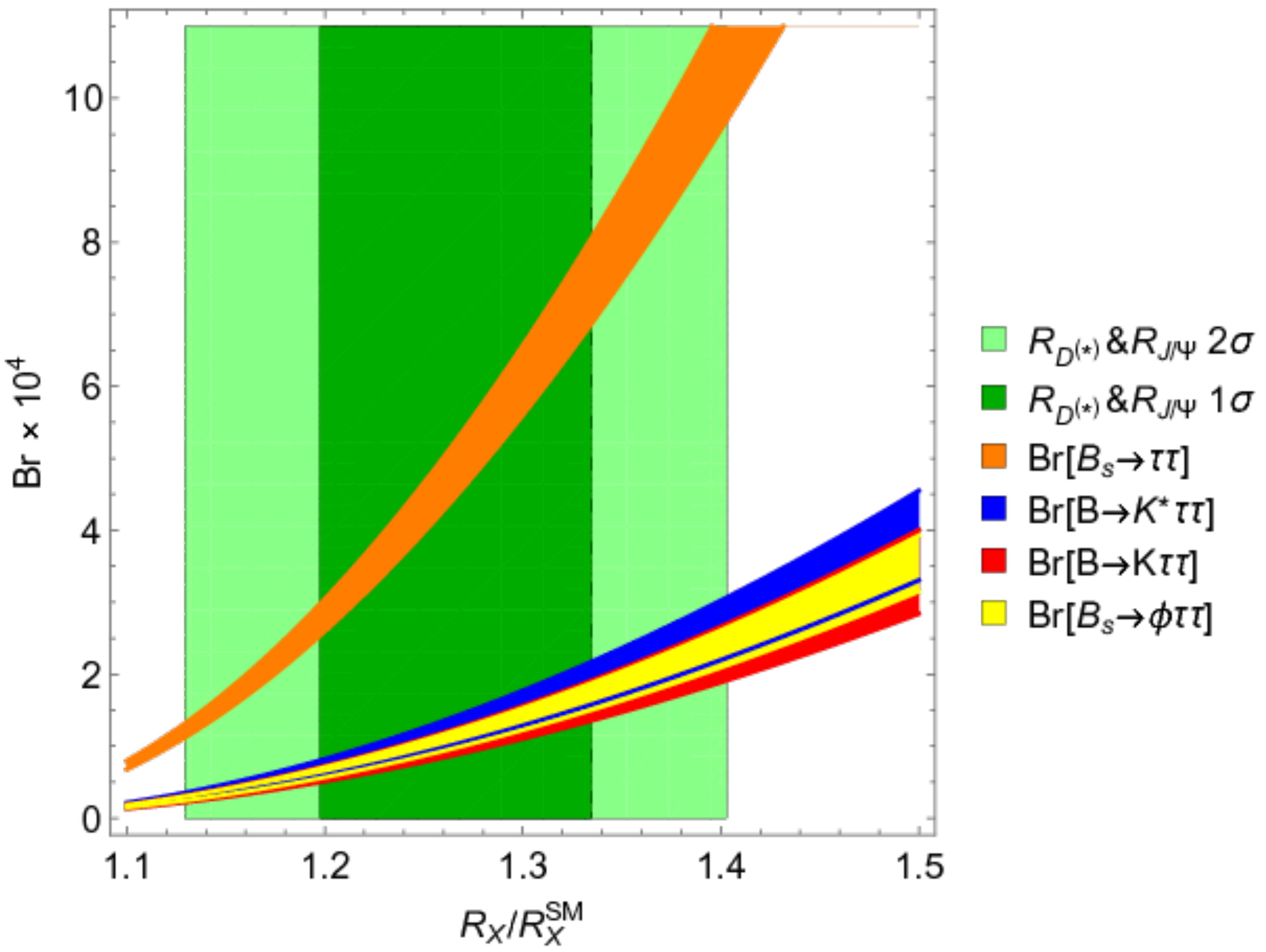
LFU in tau decays

Motivation for B→K⁺$\tau\tau$

- Strong hints for new physics in b→sll decays
- Deviations occur dominantly in muon modes
  - NP couples to mass?
  - **tau modes could be dominant**

- $\mathcal{B}(B^+ \to K^+\tau\tau)^{SM} < 1.44(15) \times 10^{-7}$
- Some models may lead to a strong enhancement
- $\mathcal{B}(B \to K\tau^-\tau^+)^{MLFV} < 2 \times 10^{-4}$
- Only experimental constraints by BaBar with $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at 90% C.L..

Prediction of the b→s$\tau\tau$ branching fraction

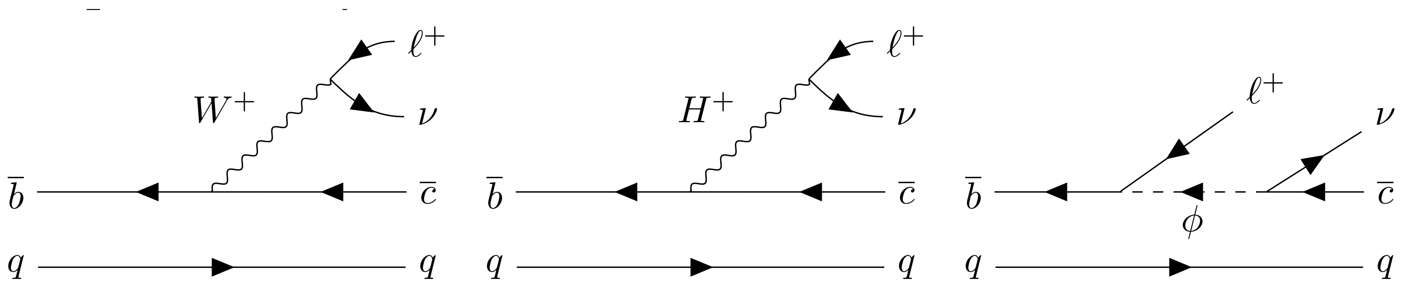


10.1103/PhysRevLett.120.181802

Lepton Flavour Universality in R_{D^*}

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

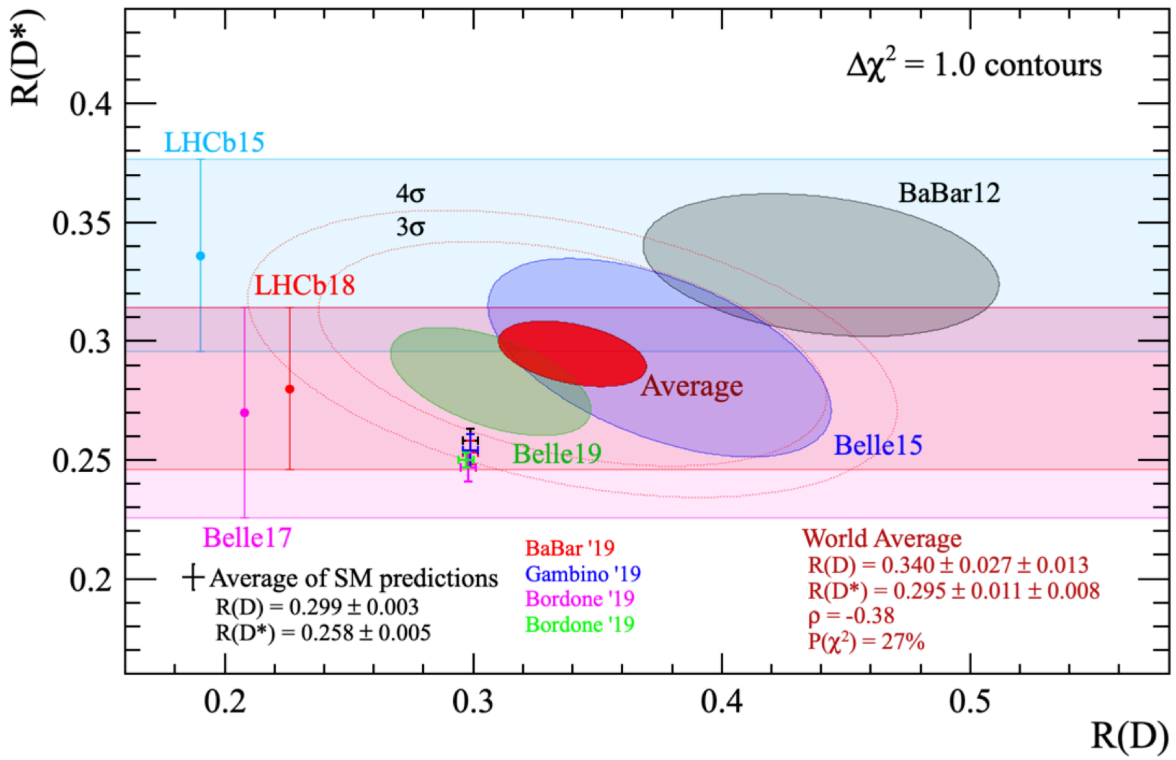
- Tree level decay
- Clean theoretical observable
- Neutrinos in the final state



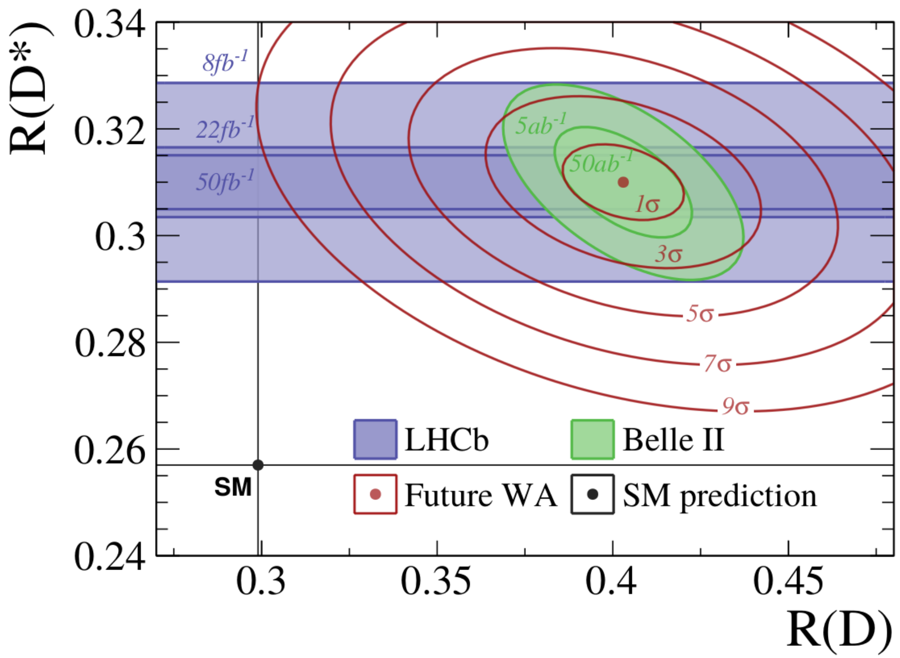
Lepton Flavour Universality in R_{D^*}

Present and Future

Now



Soon



- ~3.1σ tension with SM
- ~30% effect against SM for taus in tree level decays

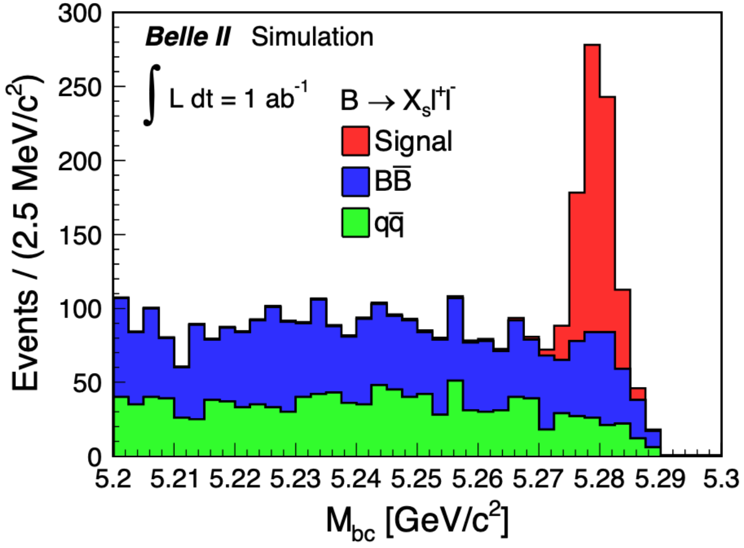
	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

Projections based on Belle SL tag measurement (before 2019)

Belle II Early Physics program

Rediscovery and performance studies

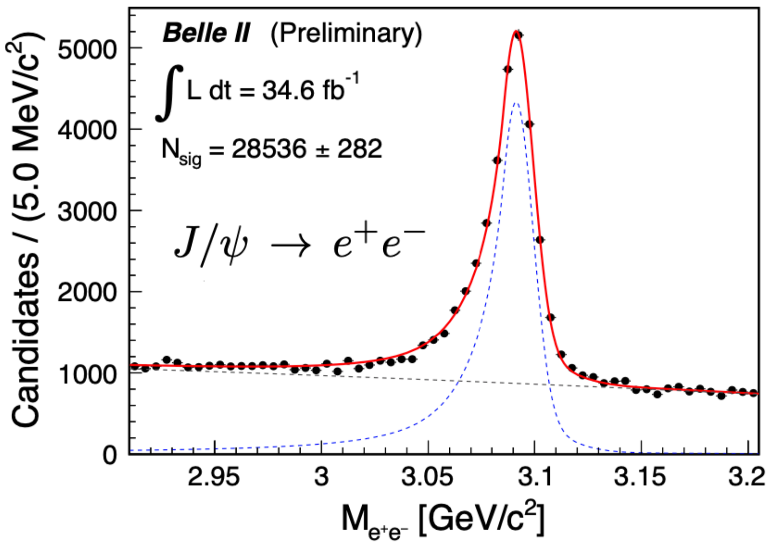
- Validation and performance studies
- Rediscovery for B→XsII and B→K II soon

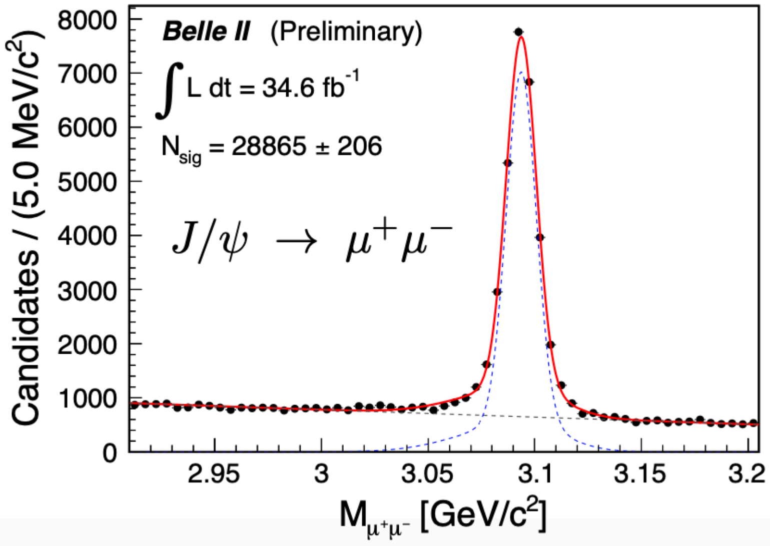


BELLE2-NOTE-PL-2020-007

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ($>$ 14.4 GeV^2)	23%	10%	4.7%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	26%	9.7%	3.1%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	21%	7.9%	2.6%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ($>$ 14.4 GeV^2)	19%	7.3%	2.4%

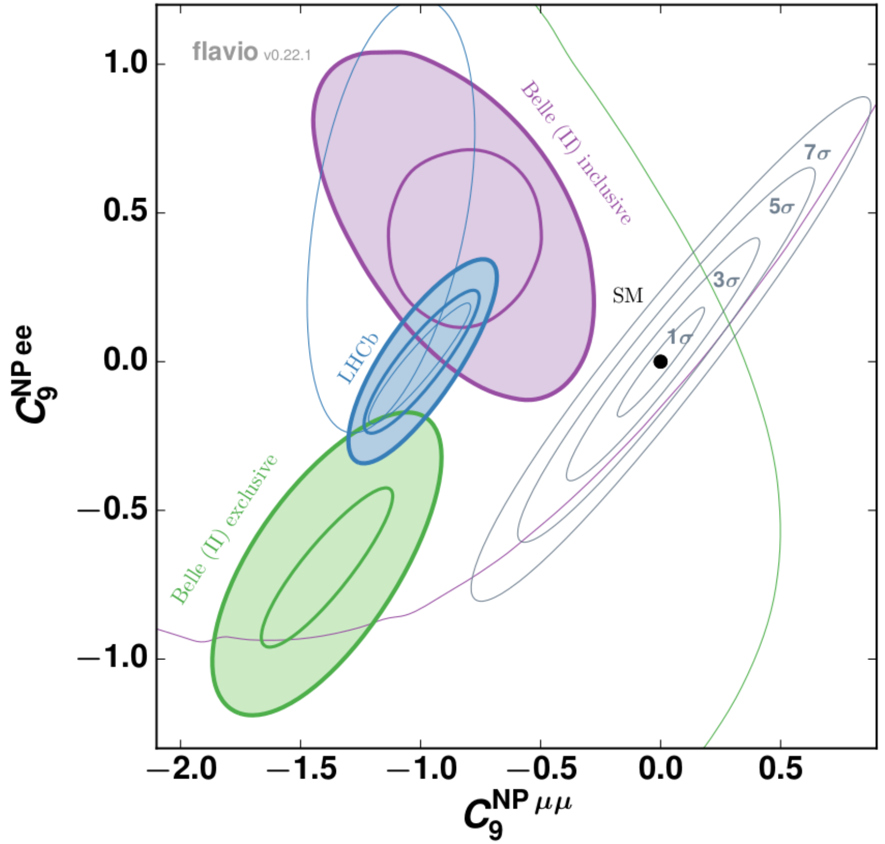
B2TiP





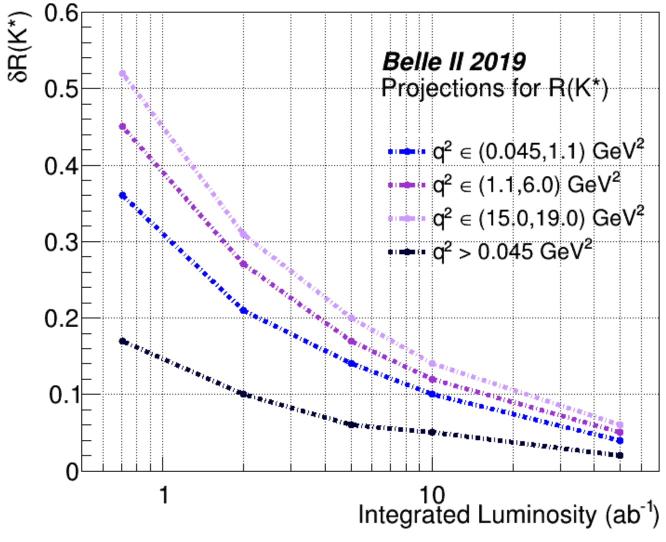
Belle II and LHCb Projections for b→sll

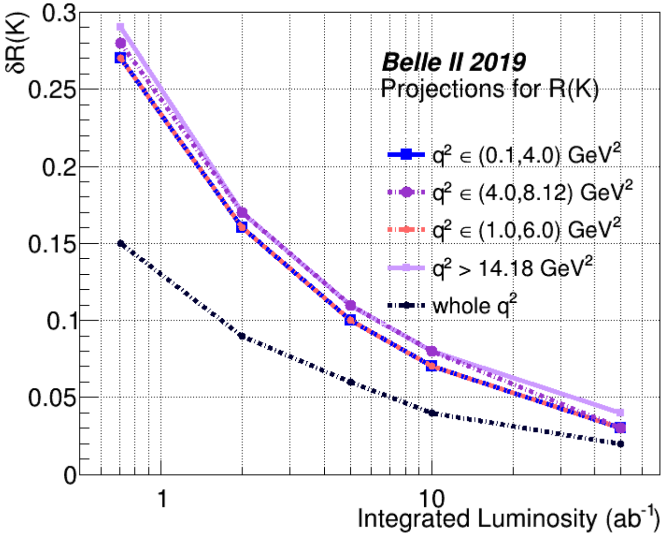
Combined Analysis



J. Albrecht et al., Future prospects for exploring present day anomalies in flavour physics measurements with Belle II and LHCb

Individual Measurements



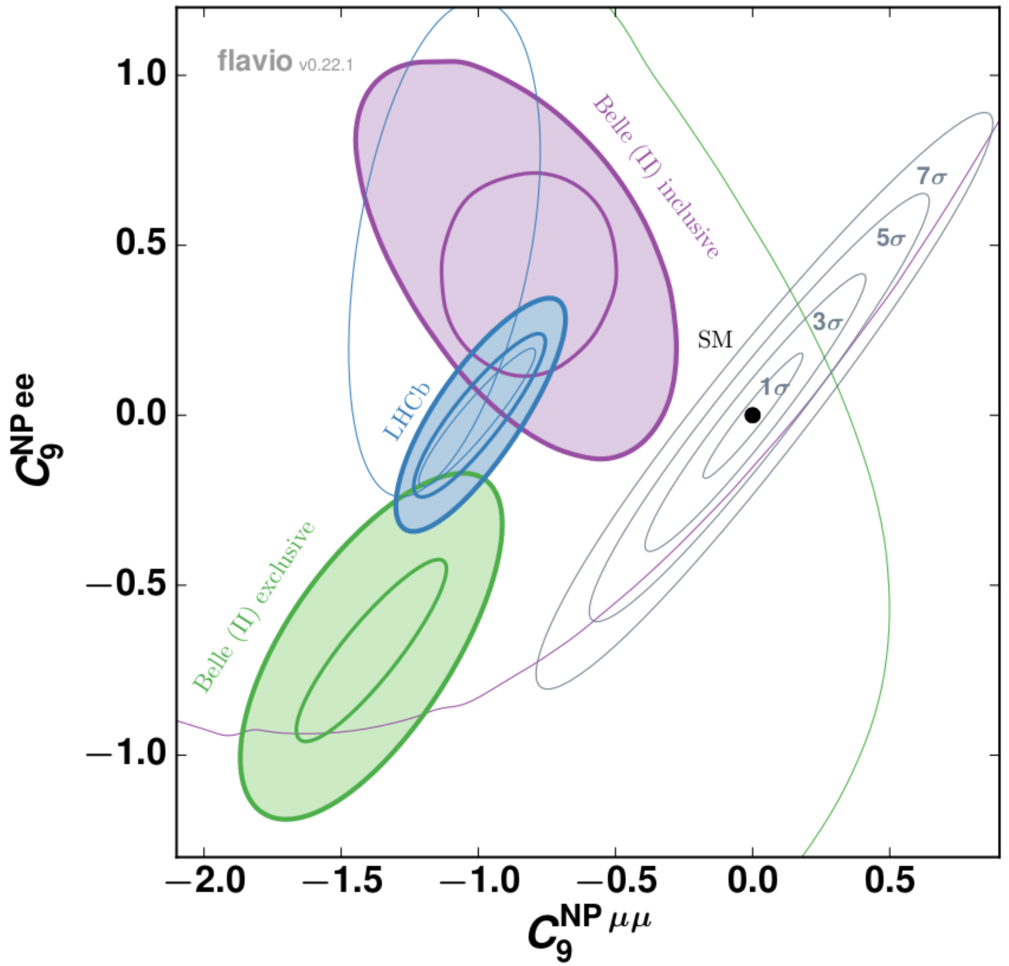


- Already with a few ab^{-1} Belle II might be able to confirm the b->s anomalies
- Belle II has excellent electron momentum resolution and neutrals performance

Summary and Conclusion

Prospects for b→s$\ell\ell$ decays at Belle II

- LFU tests in rare decays provide excellent tests for new physics
- Belle II can probe unique channels and provide an independent validation of the current anomalies
  - Inclusive analyses, full event interpretation, very good electron and neutral particle efficiency
- Discovery of b→s$\tau\tau$ could be in reach of Belle II if anomalies persist
- But not only Belle II also the LHC experiments will be able to shed more light upon the anomalies



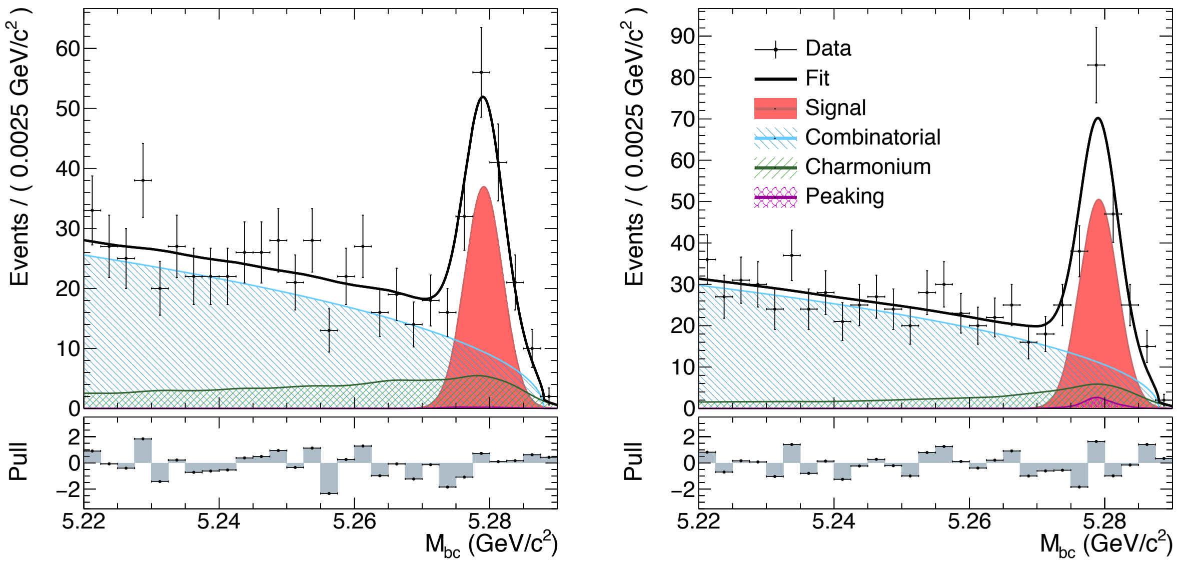
Appendix

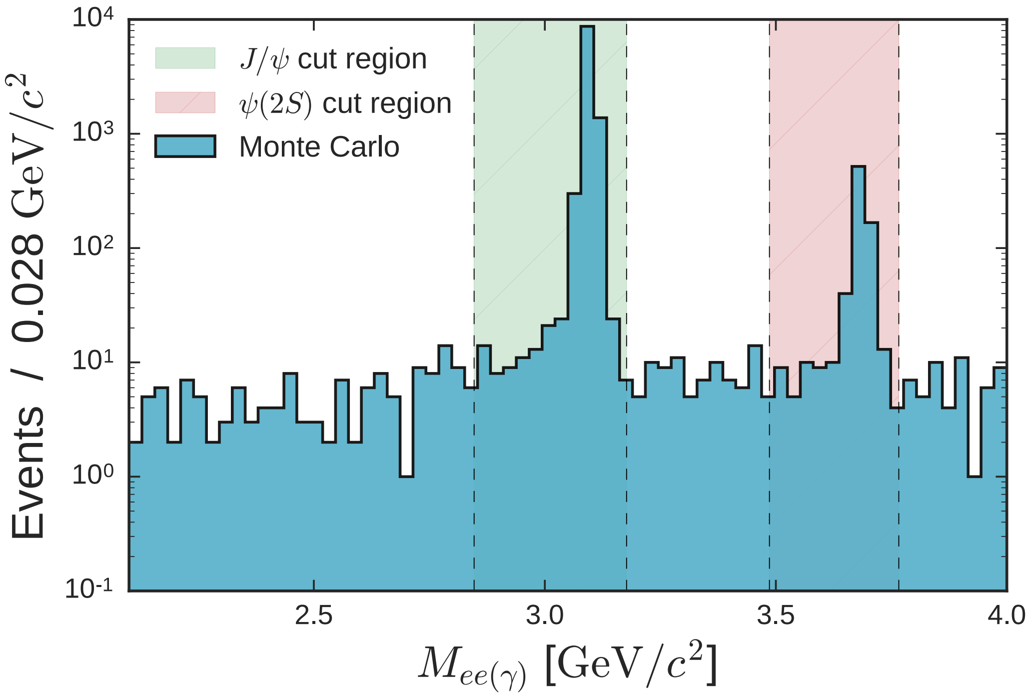
B→K*ll Analysis at Belle

Belle Analysis

- Similar electron and muon performance
- limited statistics
- Neural network based reconstruction in order to maximise efficiency

$$B^+ \to K^{*+}(K^+\pi^0)\ell^+\ell^- \qquad B^0 \to K^{*0}(K_S\pi^0)\ell^+\ell^-$$
$$B^+ \to K^{*+}(K_S\pi^+)\ell^+\ell^- \qquad B^0 \to K^{*0}(K^+\pi^-)\ell^+\ell^-$$





Angular Analysis

Parametrisation of the differential decay rate

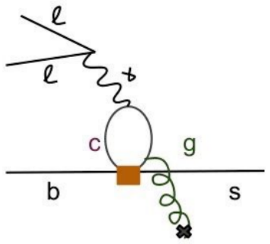
$$\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\sum_{i=1}^{9}(I_i+\bar{I}_i)f_i(\cos\theta_\ell,\cos\theta_K,\phi)$$

- $I_i =$ short distance + long distance

Wilson coefficients:
perturbatively calculable

Form-factors:
non-perturbative estimates
from LCSR, HQET, Lattice …
tremendous effort since past

Non-factorizable
contributions:

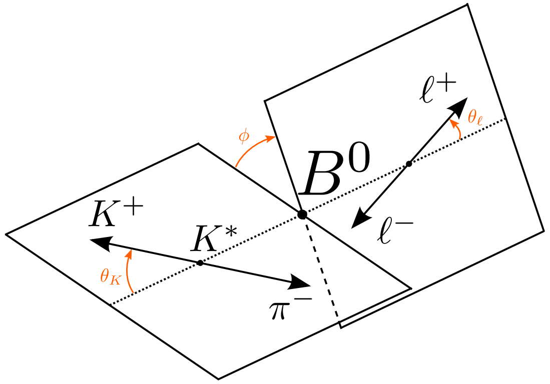


no quantitative computation

Credit: R. Mandal, ICHEP 2016

$$S_i^{(a)} = \frac{I_i^{(a)}+\bar{I}_i^{(a)}}{\mathrm{d}\left(\Gamma+\bar{\Gamma}\right)/\mathrm{d}q^2}$$

$$A_i^{(a)} = \frac{I_i^{(a)}-\bar{I}_i^{(a)}}{\mathrm{d}\left(\Gamma+\bar{\Gamma}\right)/\mathrm{d}q^2}.$$



Angular Analysis

Full expansion of the differential decay rate

"clean" observables

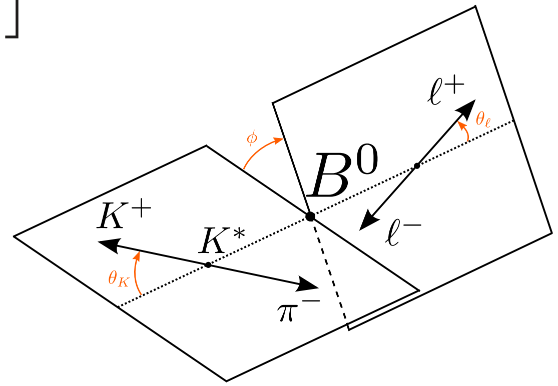
$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}}$$

cancel form-factor uncertainties

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

using definitions of J. High Energy Phys. 01 (2009) 019.

$$S_i^{\mathrm{obs}} = S_i - A_i(\mathcal{A}_{\mathcal{CP}} + \kappa\mathcal{A}_P + A_D)$$

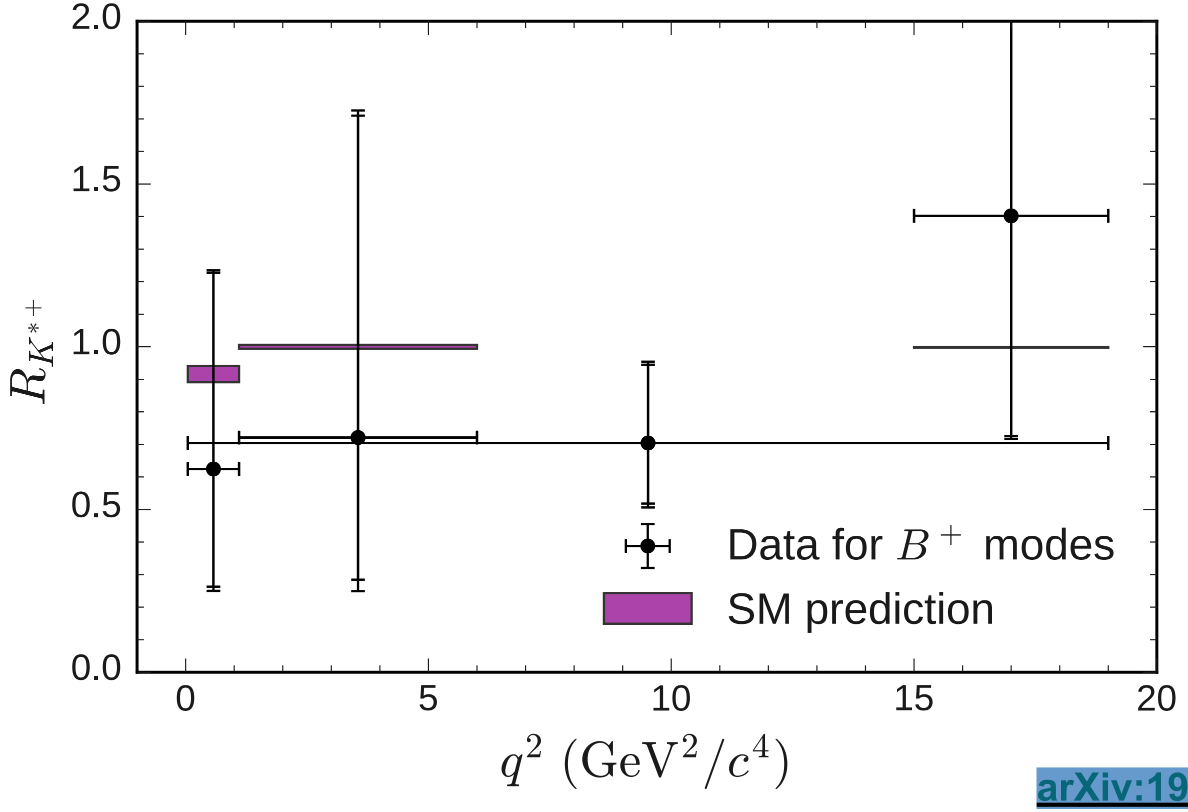


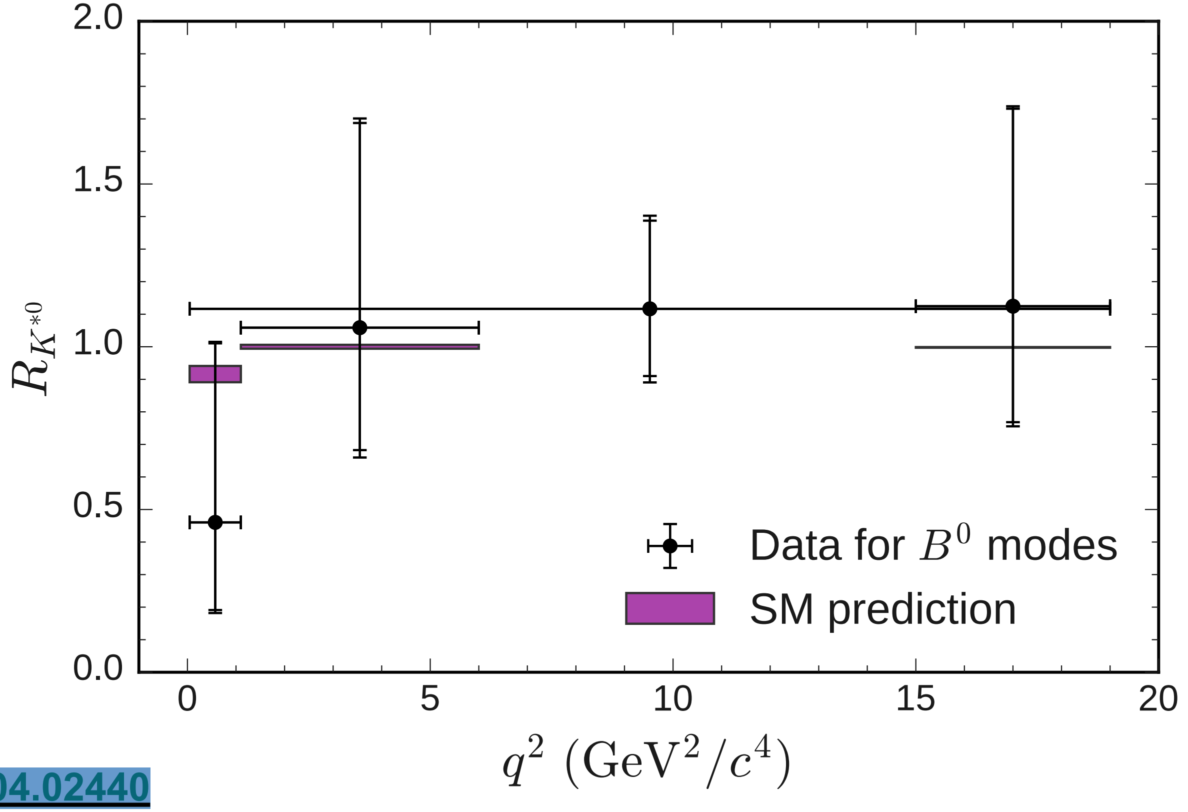
Most simple approach: Ratio of Branching Ratios

The new Belle result

- Separate results B^0 and B^+

SM prediction by: 10.1007/JHEP10(2016)075





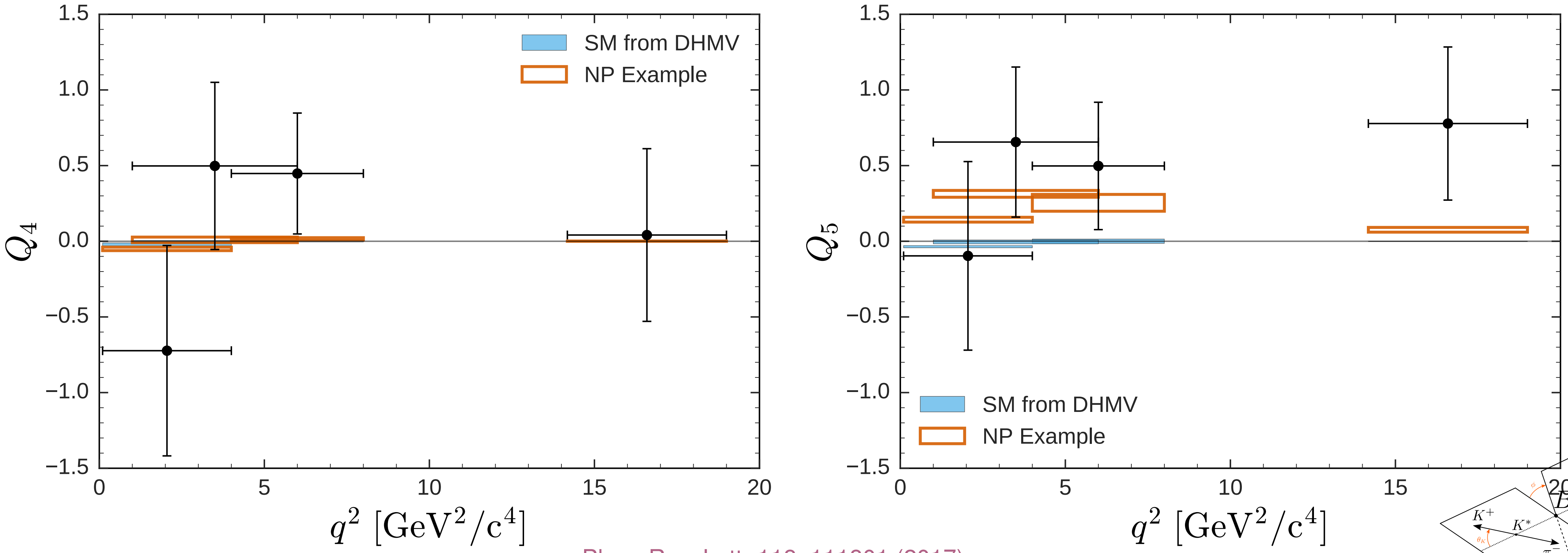
arXiv:1904.02440

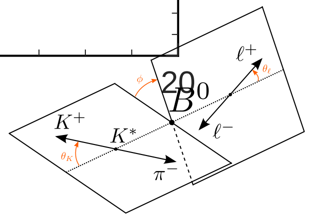
Testing for lepton flavour universality in angular observables

Smoking gun to overcome theory uncertainties

- Testing for LFU can overcome this with very clean observables

$$Q_i = P_i'^{\mu} - P_i'^{e}$$





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