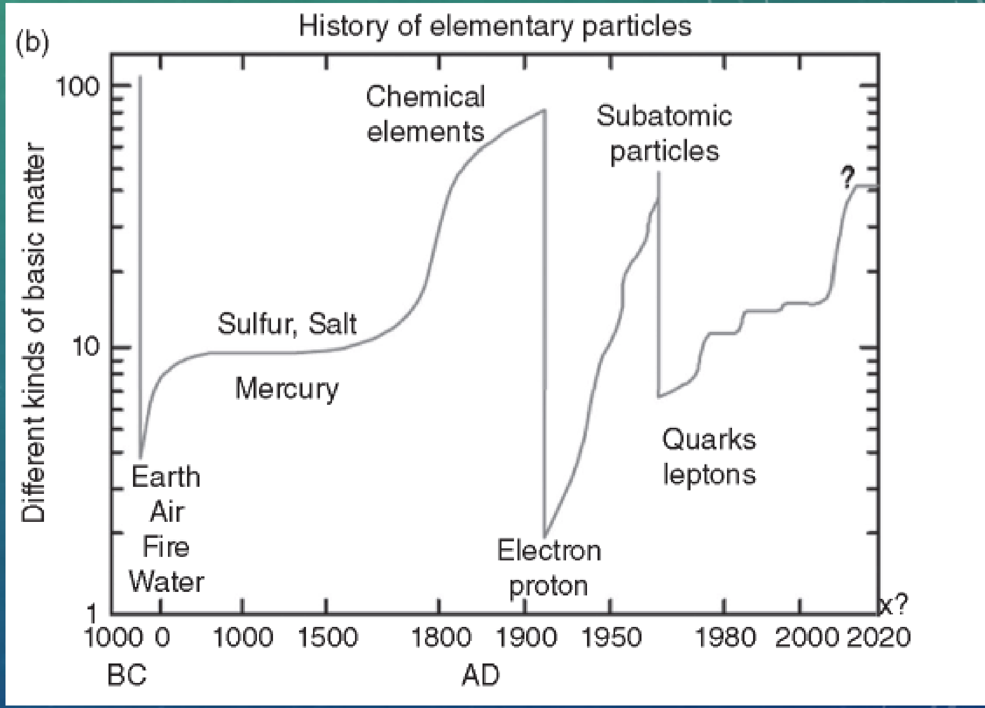
Physics Beyond the Standard Model

Standard Model:

- effective low-energy theory
- it is expected that more fundamental theory exists at higher energies



Searches for Physics Beyond the Standard Model (BSM).

Why Do We Need New Physics?

Several observations cannot be explained within the Standard Model:

- Dark matter exists but no SM particle can account for it.
- Neutrinos have non-zero masses.
- The Universe contains much more matter than antimatter.
- Gravity is absent from the theory.
- The Higgs mass appears unnaturally small.
- Dark energy is unexplained.
- The pattern of particle masses remains mysterious.

The Hierarchy Problem

- Theoretical puzzles concerns the Higgs boson mass.
- Quantum fluctuations contribute corrections to the Higgs mass squared:

$$\delta {m_H}^2 \propto \Lambda^2$$

Λ - energy scale up to which the Standard Model remains valid.

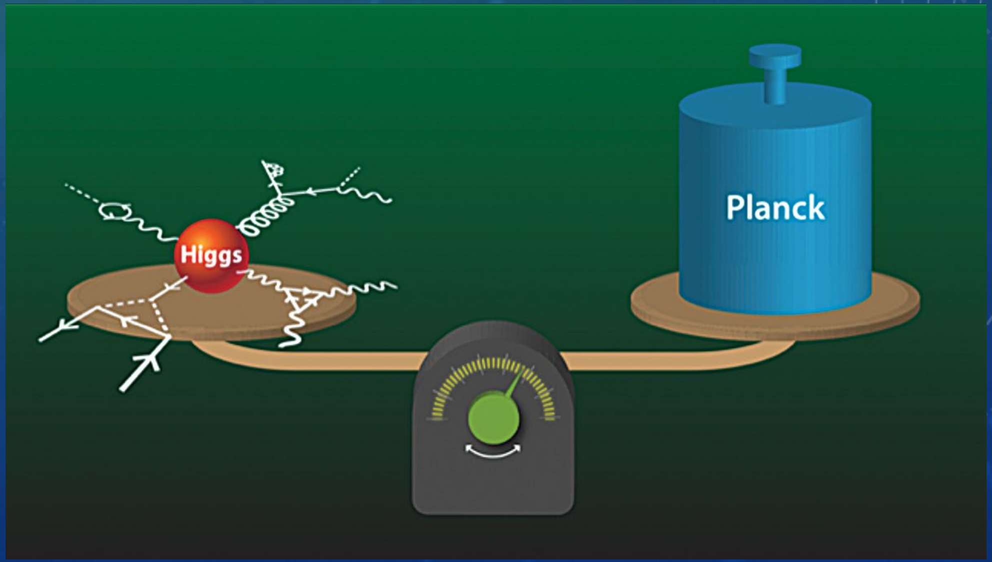
- If Λ is the Planck scale (~10^{19} GeV), quantum corrections become enormous.

The observed Higgs mass is only: m_H = 125 GeV,

why the weak force is so much stronger than gravity?

=> large contributions must cancel almost exactly, requiring extreme fine tuning.

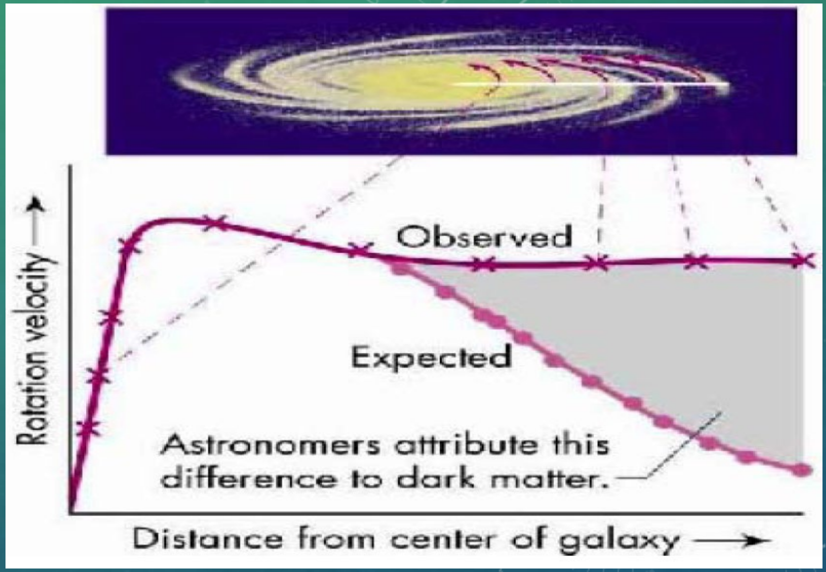
This naturalness problem suggests that **new particles or symmetries** may appear near the TeV scale.



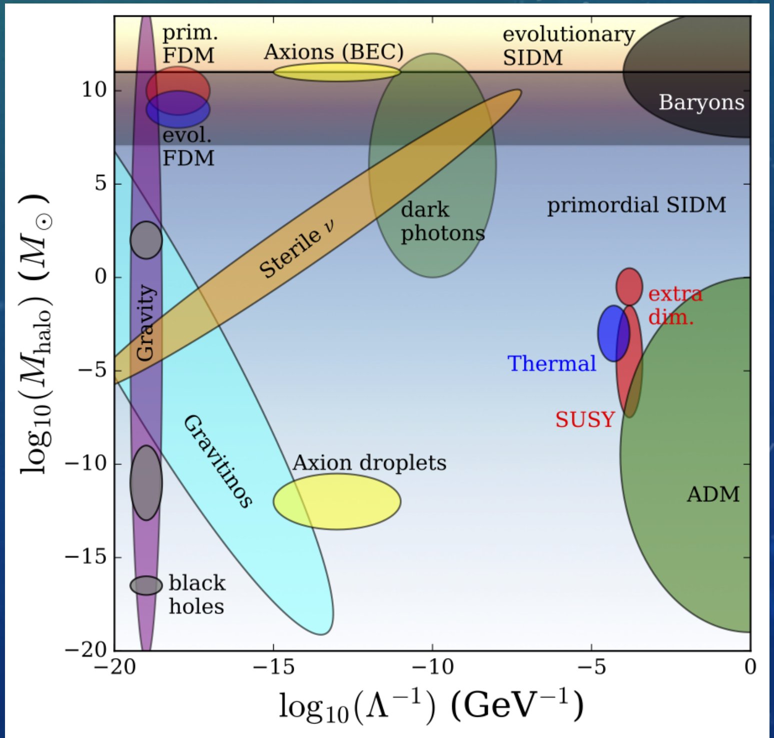
Dark Matter

Astronomical observations indicate that visible matter represents only about 15% of the total matter in the Universe.

- Galaxy rotation curves: Stars orbit galaxies too rapidly to be held together by visible matter alone.
- Gravitational lensing: Mass distributions inferred from light bending exceed visible matter.
- Cosmic Microwave Background: Precision measurements determine the matter density of the Universe.
- Large-scale structure: Galaxy formation requires additional non-luminous matter.



- Dark matter must be:
  - ✓ Electrically neutral
  - ✓ Long-lived
  - ✓ Weakly interacting
  - ✓ Massive
- No Standard Model particle satisfies all these requirements.

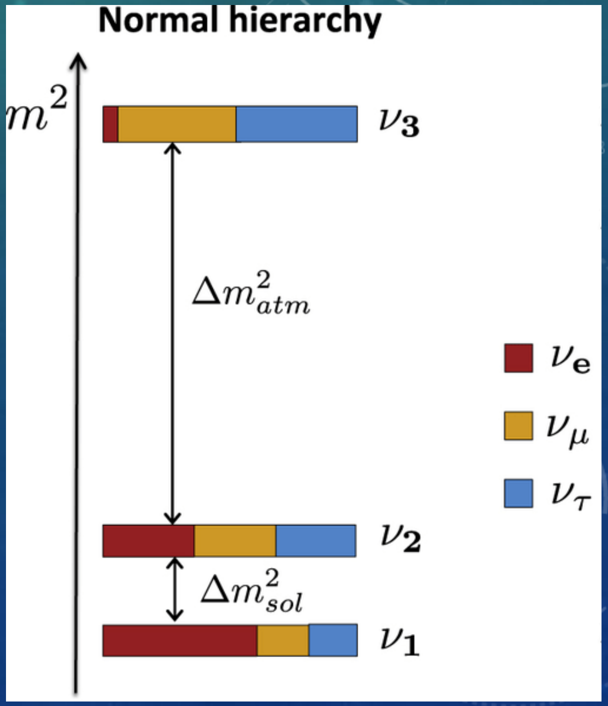


Neutrino masses and oscillations

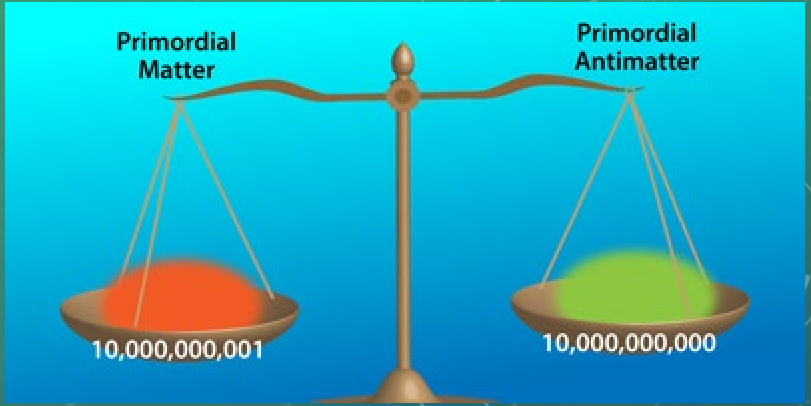
- In the Standard Model, neutrinos are exactly massless because right-handed neutrino fields are absent.
- Experiments studying solar, atmospheric, reactor, and accelerator neutrinos have demonstrated neutrino oscillations.
- Oscillations occur because flavor states are superpositions of mass eigenstates.
- This implies:

$$m_\nu \neq 0$$

- The discovery of neutrino masses is direct evidence that the Standard Model is incomplete.
- Possible explanations include:
  - ✓ Dirac masses with right-handed neutrinos
  - ✓ Majorana masses
  - ✓ Seesaw mechanisms



Matter-Antimatter Asymmetry

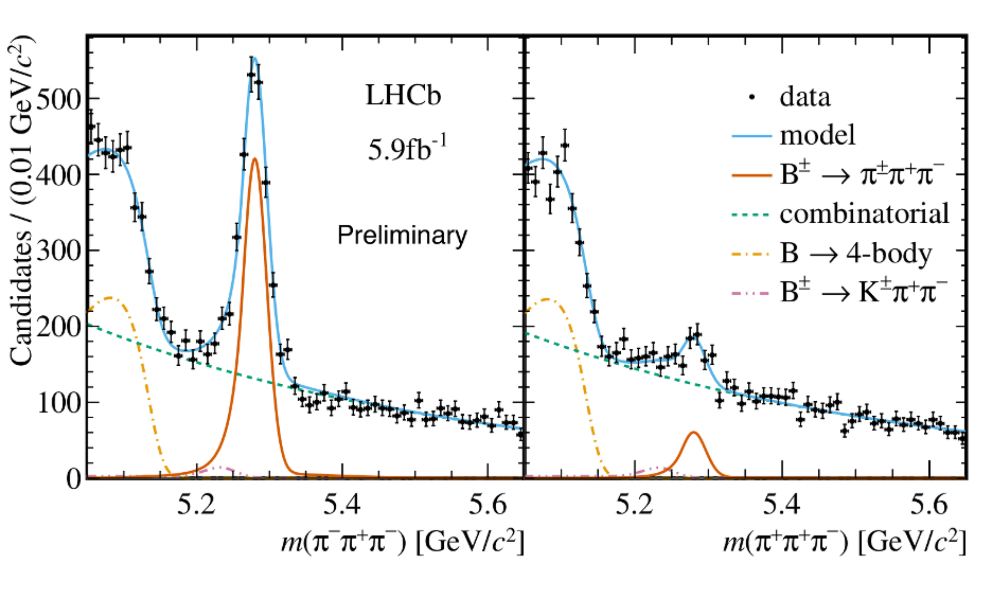


The Universe appears almost entirely composed of matter.

If the Big Bang produced equal amounts of matter and antimatter, they should have annihilated completely.

To generate the observed asymmetry, Sakharov showed that three conditions are required:

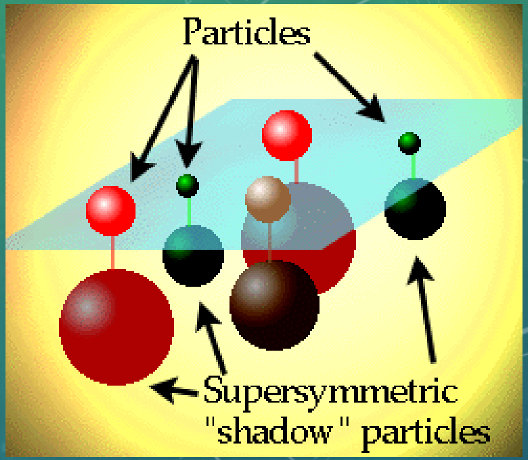
1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium



Although the Standard Model satisfies these conditions in principle, the amount of CP violation is many orders of magnitude too small.

This suggests additional sources of CP violation beyond the Standard Model.

Supersymmetry



Supersymmetry (SUSY) introduces a symmetry relating bosons and fermions (leptoquarks):

$$Q|boson\rangle = |fermion\rangle$$

Every Standard Model particle obtains a superpartner:

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

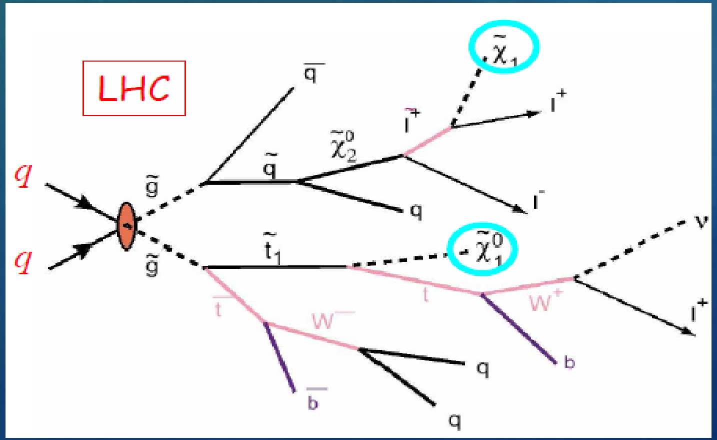
Advantages:

Hierarchy problem: Loop corrections from fermions and bosons cancel.

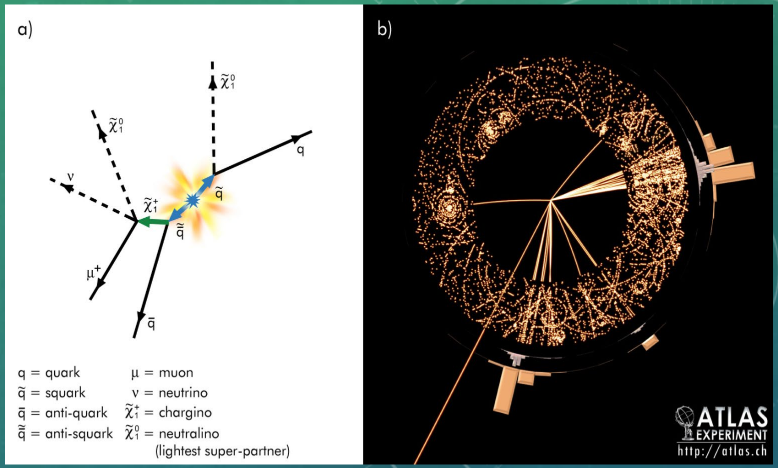
Gauge coupling unification: Couplings meet at approximately 10^{16} GeV.

Dark matter: The lightest supersymmetric particle can be stable and electrically neutral.

Supersymmetry **was** one of the most extensively studied BSM frameworks



Supersymmetry – searches and results



After more than a decade of data:

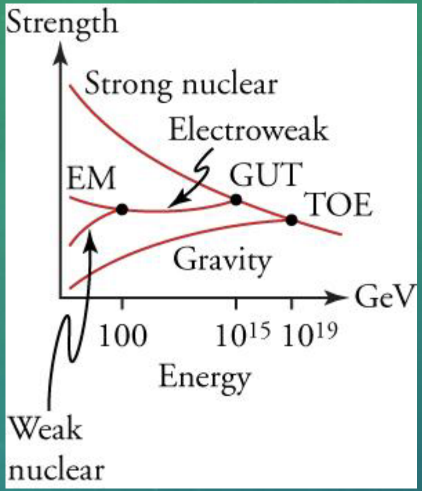
- No squarks observed
- No gluinos observed
- No sleptons observed
- No neutralinos observed

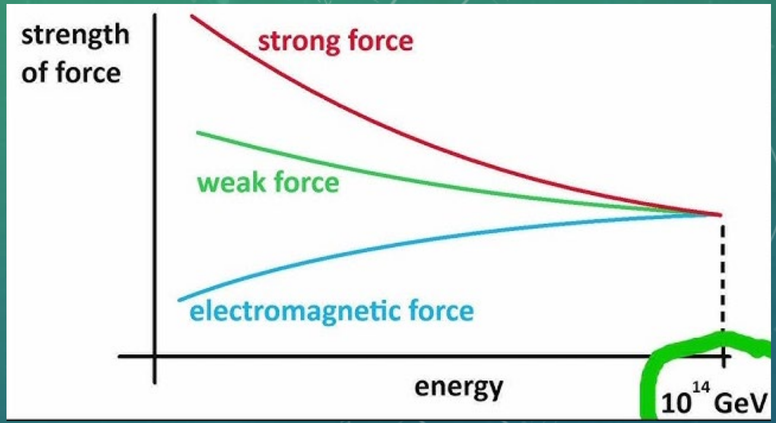
Mass limits now exceed **several TeV** for many models.

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[fb^{-1}]$	Mass limit	
RPV	LFV $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e + \mu$	$2\ e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05
	LFV $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e(\mu) + \tau$	$1\ e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05
	Bilinear RPV CMSSM	$2\ e, \mu$ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	$4\ e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{121}\neq0$
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	$3\ e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$
	$\tilde{g} \to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%
	$\tilde{g} \to \tilde{t}_1 t, \tilde{t}_1 \to bs$	$2\ e, \mu$ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)
	$\tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)
	$\tilde{q}\tilde{q}\gamma, \tilde{q} \to q\tilde{\chi}_1^0$ (compressed)	$1\ \gamma$	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$) = m(c)
	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV
	$\tilde{g}\tilde{g}, \tilde{g} \to qq\tilde{\chi}_1^\pm \to qqW^\pm\tilde{\chi}_1^0$	$1\ e, \mu$	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))
	$\tilde{g}\tilde{g}, \tilde{g} \to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	$2\ e, \mu$	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20
	GGM (bino NLSP)	$2\ \gamma$	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV
	GGM (wino NLSP)	$1\ e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV
	GGM (higgsino NLSP)	$2\ e, \mu$ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV

Grand Unified Theories

- Grand Unified Theories propose that strong, weak, and electromagnetic interactions originate from a single gauge force.
- At very high energies (~10^{16} GeV), the separate couplings merge.





Benefits:

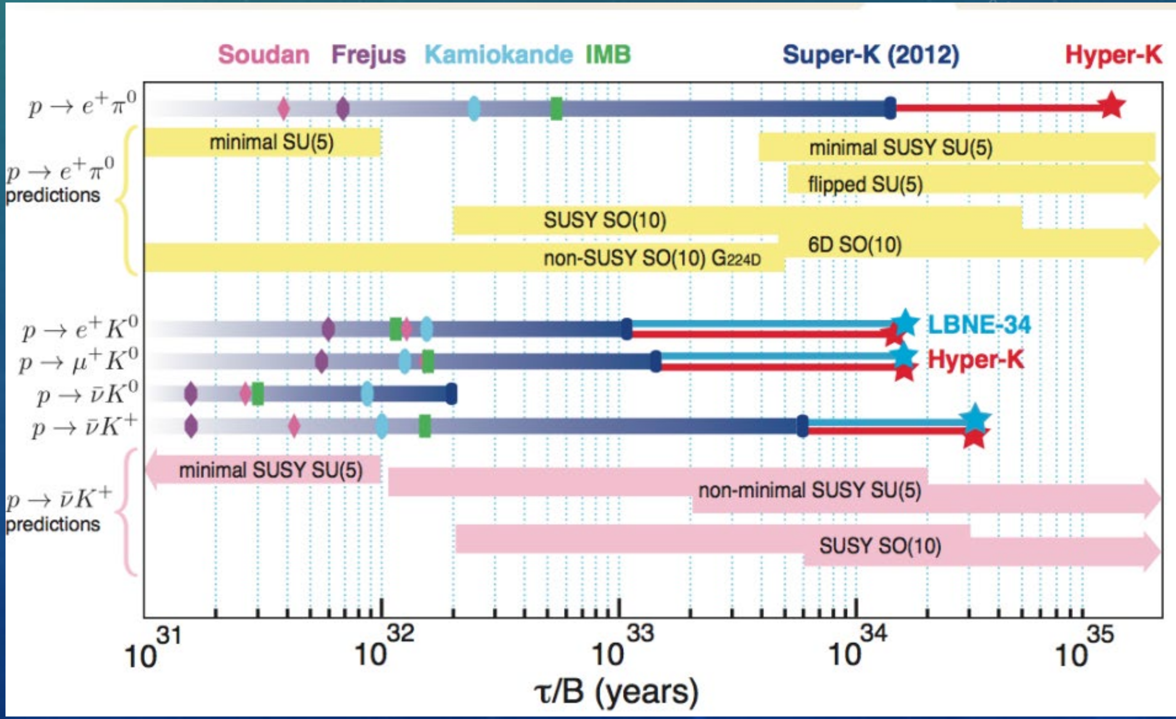
- Unification of interactions
- Explanation of charge quantization
- Natural inclusion of neutrino masses
- Connection to baryogenesis

A key prediction is proton decay:

$$p \rightarrow e^{+} + \pi^{0}$$

Predicted lifetimes are enormous: 10^{31}–10^{36} years

Experiments such as Super-Kamiokande have monitored thousands of tons of water for decades.



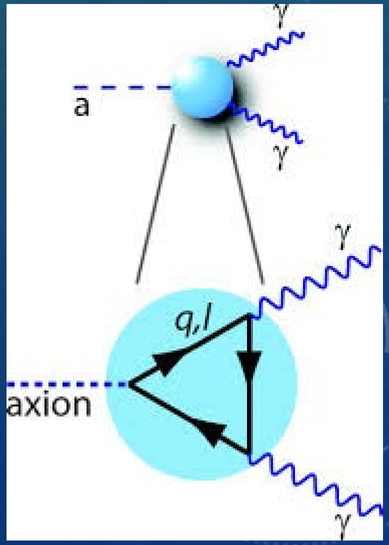
Axions

- Quantum Chromodynamics allows a CP-violating parameter θ.
- If θ were of order 1, QCD would induce a measurable electric dipole moment (EDM) of the neutron.
    - ✓ Experimentally: $\theta < 10^{-10}$

This extreme smallness - strong CP problem.

Peccei and Quinn proposed a new symmetry that dynamically drives θ to zero.

a→γγ



Axion is a hypothetical elementary particle proposed in 1977 by Roberto Peccei and Helen Quinn:

- result of spontaneous breaking of the Peccei–Quinn symmetry,
- spin=0, electric charge=0, colour charge=0, very weak interaction,
- extremely light: $m_a \propto \frac{1}{f_a}$, $10^{-12}\ eV \lesssim m_a \lesssim 10^{-2}\ eV$

Axions are particularly attractive because they naturally provide a dark matter candidate:

- Stable
- Electrically neutral
- Very weakly interacting
- Naturally produced in cosmology
- Predicted independently of dark matter considerations

Extra Dimensions

Theories with extra spatial dimensions attempt to explain the weakness of gravity.

In the ADD (Arkani-Hamed–Dimopoulos–Dvali 1998) model:

- Gravity spreads through additional dimensions (3+n) while Standard Model particles remain confined to a three-dimensional, so in total: (3+n).

Compare two energy scales (hierarchy problem):

- Electroweak scale: ~100 GeV
- Planck scale: ~10^{19} GeV

The enormous difference (17 orders of magnitude) is known as the **hierarchy problem**.

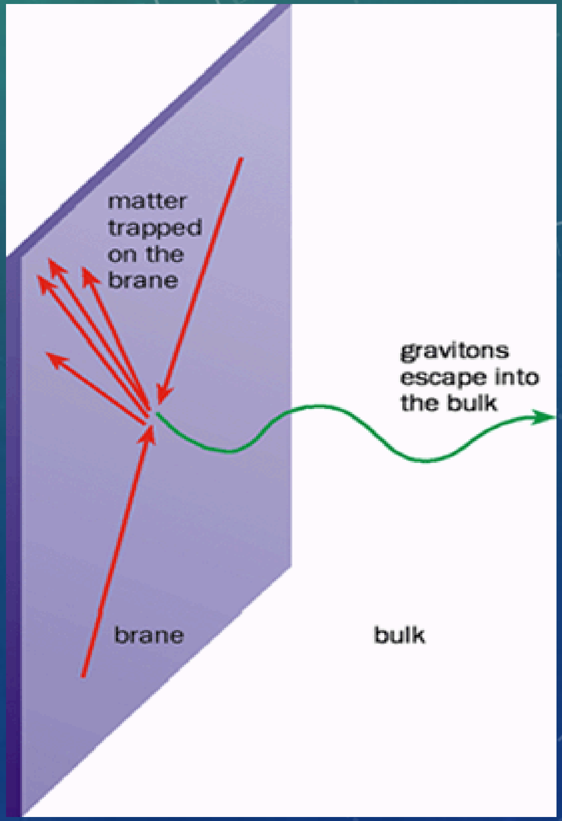
Gravity appears incredibly weak:

- Electromagnetic repulsion between two electrons is about 10^{42} times stronger than their gravitational attraction.

The ADD model proposes that gravity is not intrinsically weak.

Instead:

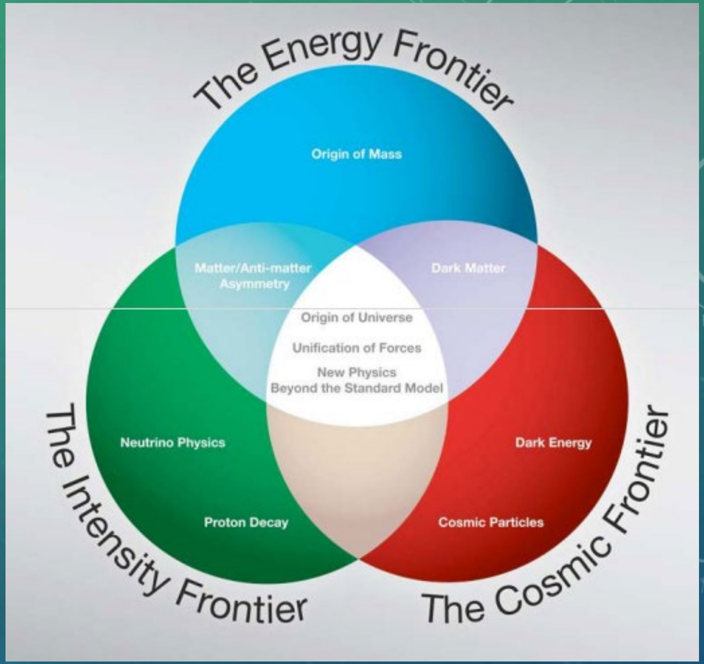
Gravity only appears weak because it spreads into extra spatial dimensions.



Experimental searches

Searches for BSM physics occur on three frontiers.

- Energy Frontier: high-energy colliders.
- Intensity Frontier: rare processes and precision measurements.
- Cosmic Frontier: astrophysical and cosmological observations.

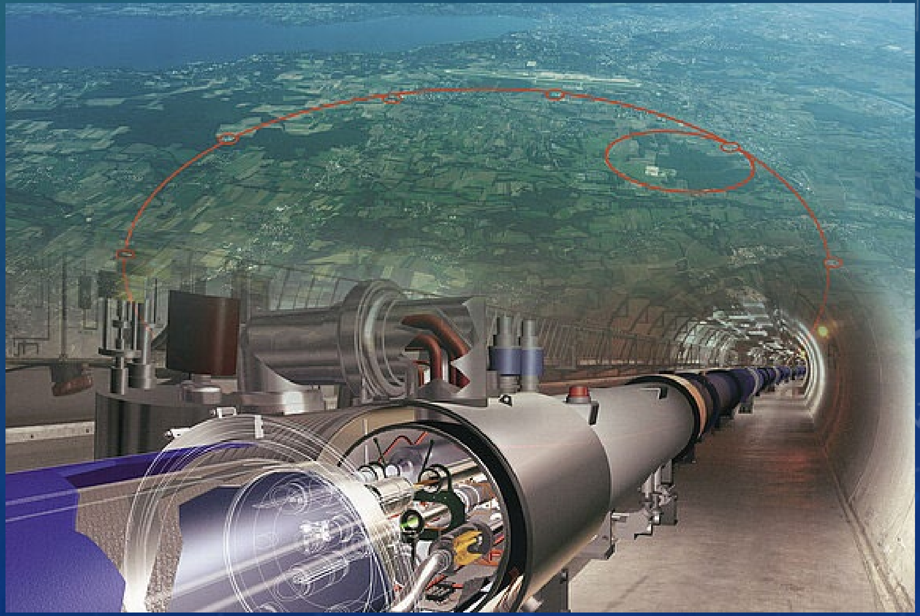


The Large Hadron Collider

The Higgs boson remains a major focus because it may be connected to new physics.

Searches include:

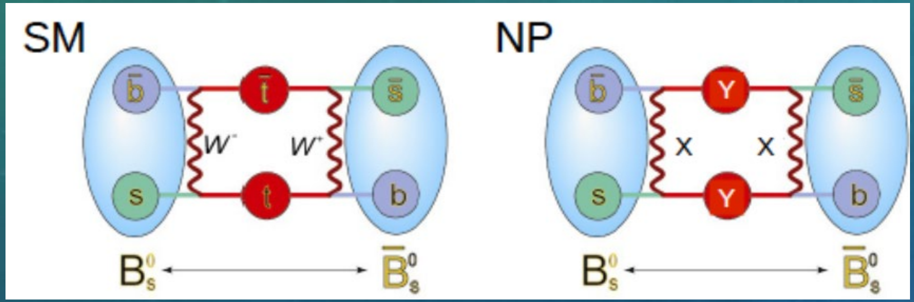
- Supersymmetry
- Heavy gauge bosons (Z’)
- Vector-like fermions
- Dark matter production
- Extra dimensions

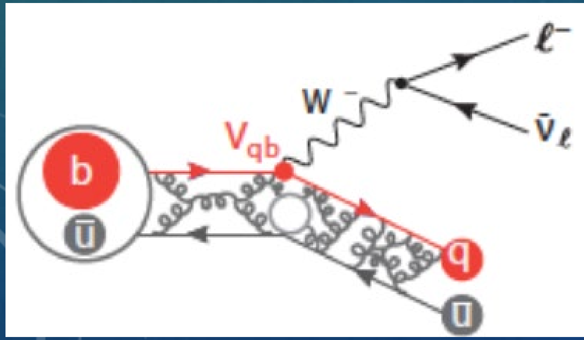


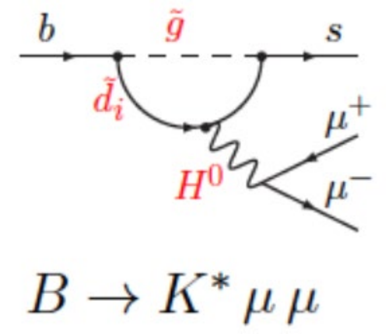
Intensity Frontier - precision physics in rare decays

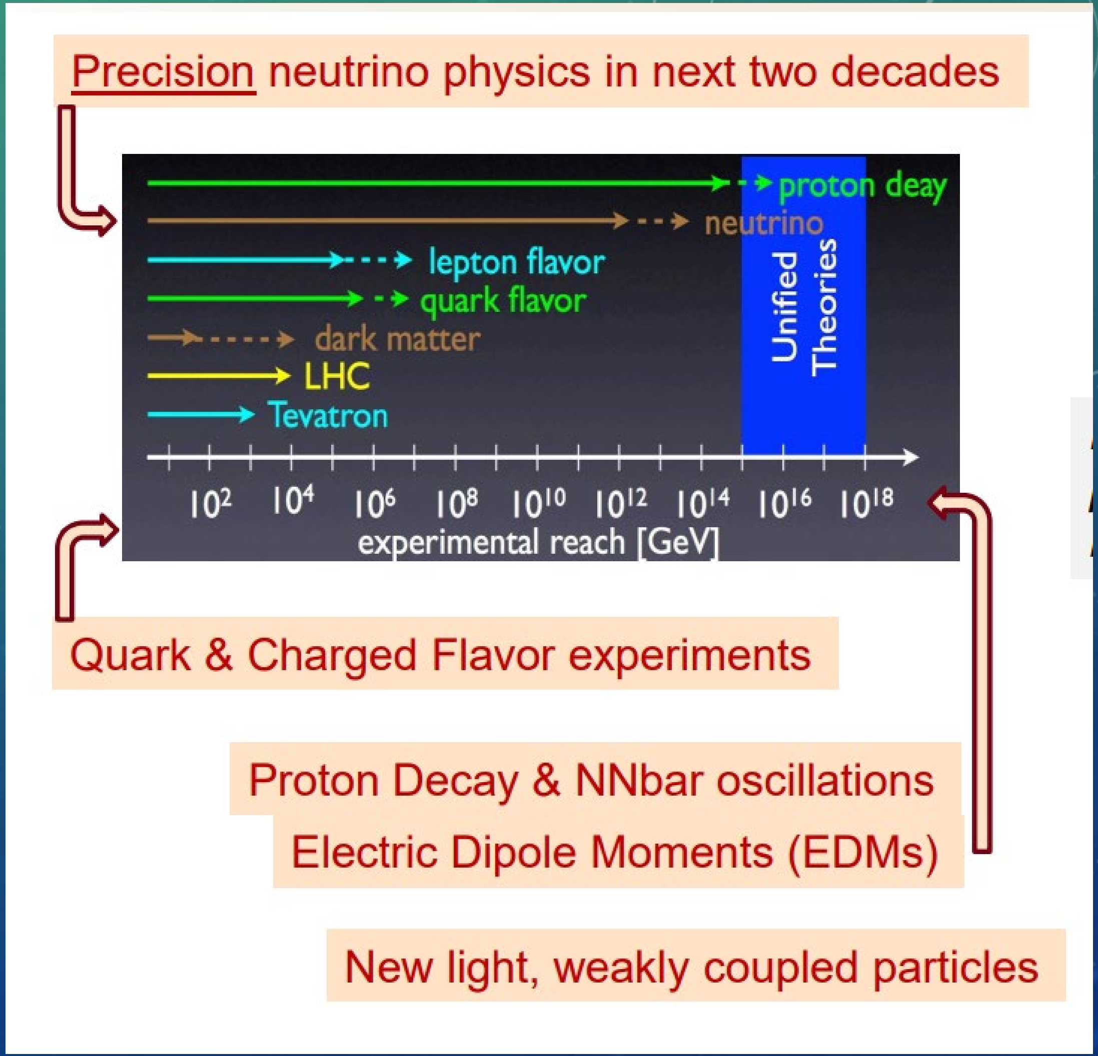
New heavy particles may alter observables through virtual quantum effects.

- Muon anomalous magnetic moment: $a_\mu = (g-2)/2$
- Electric dipole moments
- Rare B meson decays
- Flavor-changing neutral currents
- Precision measurements often probe scales beyond direct collider reach.









B decays –
portal to Physics Beyond the Standard Model
(flavour anomalies)

AGNIESZKA OBŁĄKOWSKA-MUCHA

AGH-UST Faculty of Physics and Applied Computer Science

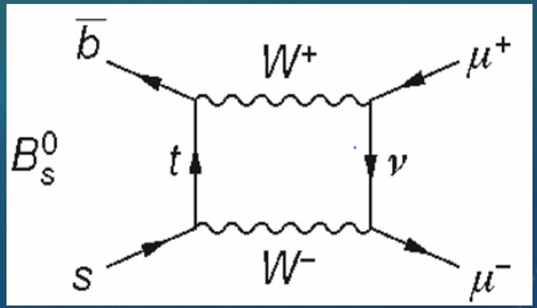
OUTLINE

23 March 2021: Improved measurement of $B_s^0 \to \mu^+\mu^-$ decays LHCB-PAPER-2021-007-001.

23 March 2021: **Test of lepton universality in beauty-quark decays** CERN-EP-2021-042 ; LHCB-PAPER-2021-004

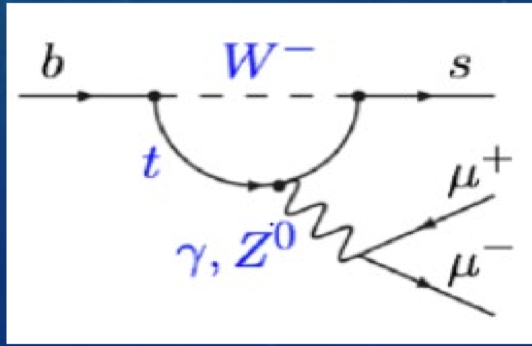
LHCb results and interpretation of flavour anomalies
in b to sll transitions

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



- Purely leptonic flavour-changing neutral current mediated decay
- Clean probe of new physics

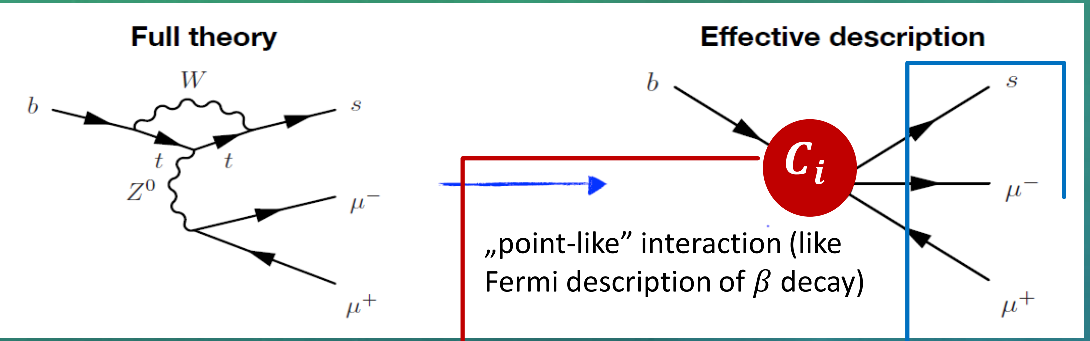
$$B^+ \to K^+ l^+ l^-$$



- Includes hadronic corrections

Effective theory for rare B decays

$b \to s l^+ l^-$ (FCNC) can be described with an „Effective Hamiltonian" where high- and low-energy contributions are factorised ($M_b \ll M_W$)

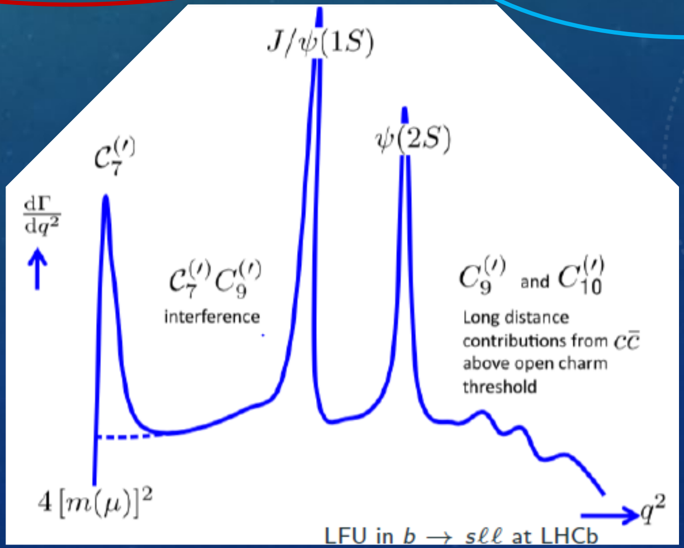


$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

Wilson coefficient (short-distance), evaluated in perturbation theory

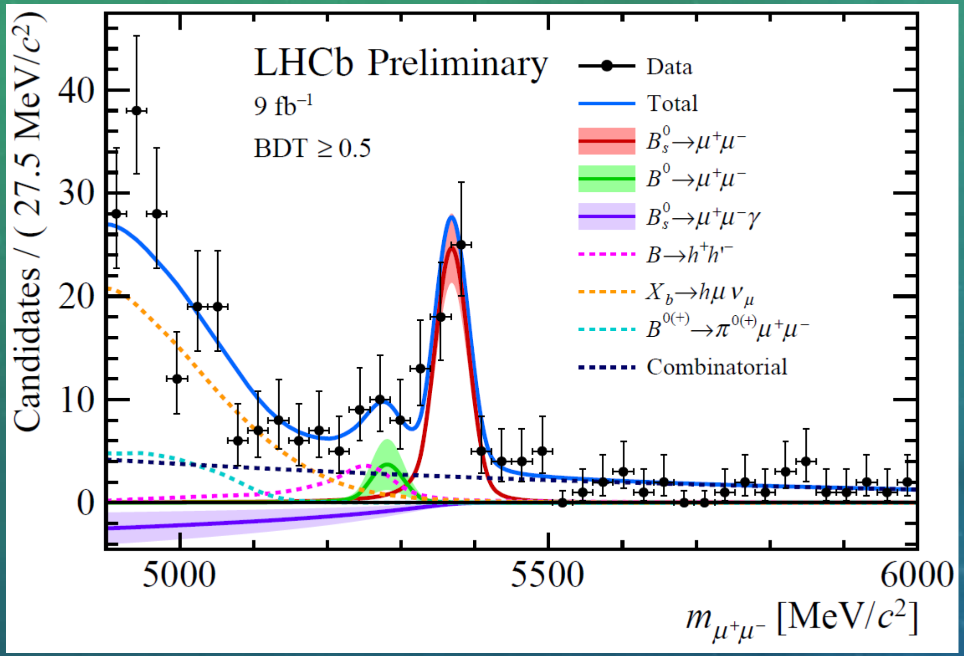
Local operators (long distance), lattice calculations

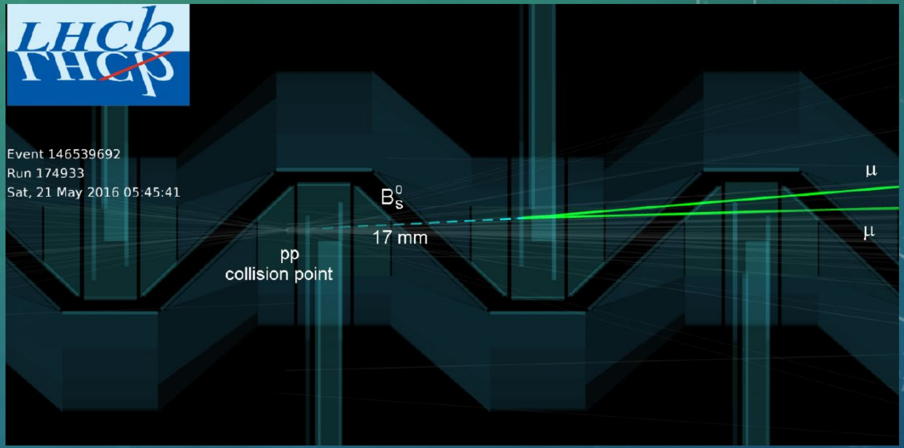
Wilson Coefficient		Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
vector	$\mathcal{C}_9^{(\prime)}$	$(\bar{s}\gamma_\mu P_{R(L)} b)\bar{\mu}\gamma^\mu \mu$
axial-vector	$\mathcal{C}_{10}^{(\prime)}$	$(\bar{s}\gamma_\mu P_{R(L)} b)\bar{\mu}\gamma^\mu \gamma_5 \mu$
scalar	$\mathcal{C}_S^{(\prime)}$	$\bar{s} P_{R(L)} b \bar{\mu}\mu$
pseudo-scalar	$\mathcal{C}_P^{(\prime)}$	$\bar{s} P_{R(L)} b \bar{\mu}\gamma_5 \mu$

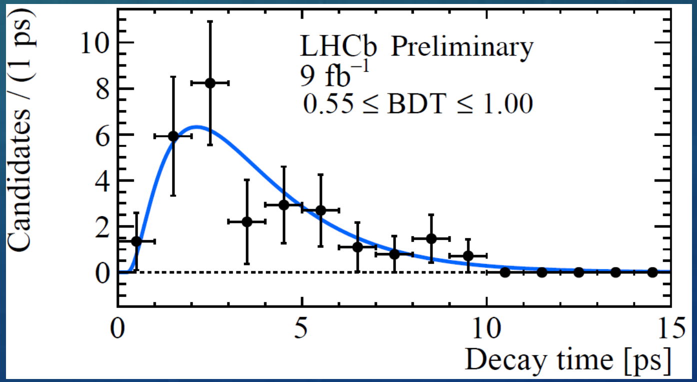


Improved measurement of $B^0_{(s)} \to \mu^+\mu^-$ decays

In the SM, only the heavy and longer-lived B^0_s eigenstate decays to the $\mu^+\mu^-$ final state.







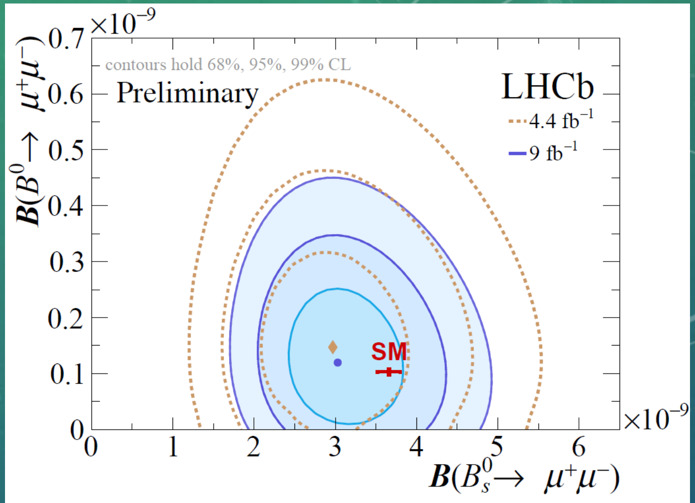
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}\ {}^{+0.15}_{-0.11}\right) \times 10^{-9}\ \ (10.8\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (1.7\sigma)$$

$$\tau_{eff} = 2.07\ \pm 0.29 \pm 0.03\ \text{ps}$$

consistent with both the heavy and light mass eigenstate

Improved measurement of $B^0_{(s)} \to \mu^+\mu^-$ decays



- Important milestone for LHCb and a crucial input for the "flavour anomalies"
- Achieved the most precise single-experiment measurement of $\mathcal{B}(B^0_s \to \mu^+\mu^-)$
- Very clean prediction in the SM:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

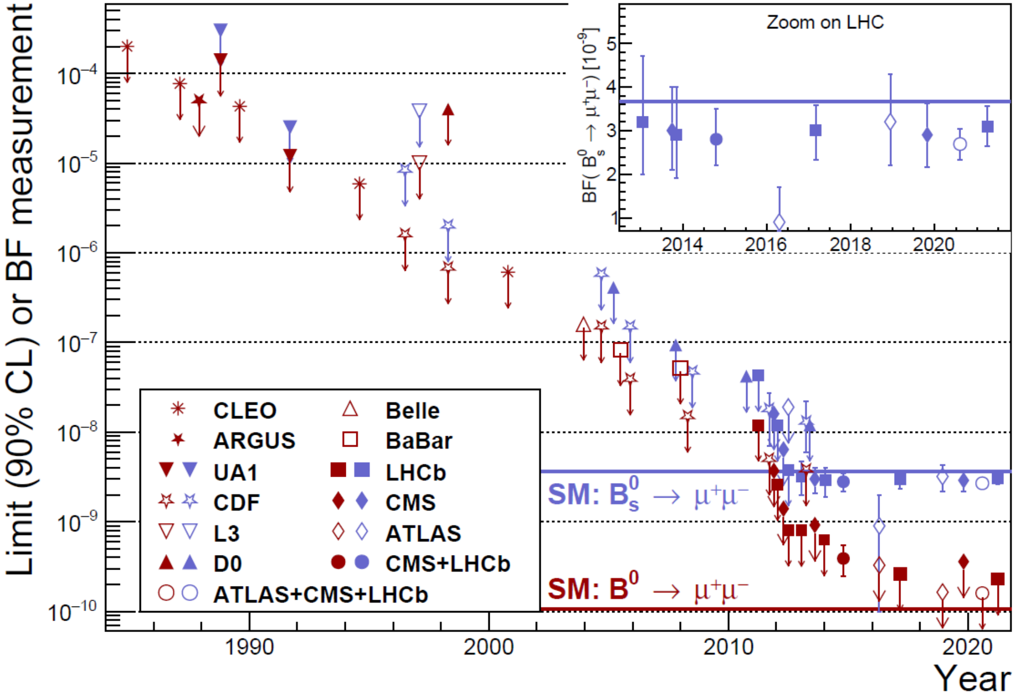
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \times 10^{-10}$$

- BF prediction includes single Wilson coefficient C_{10} and a single hadronic constant
- 2020 combination of ATLAS, CMS, LHCb:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$$

2.1σ away from SM

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}\ {}^{+0.15}_{-0.11}\right) \times 10^{-9} \text{ (LHCb only)}$$



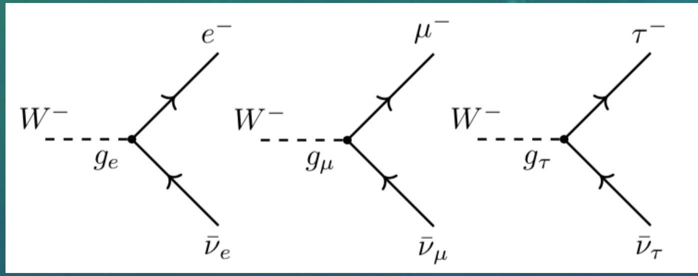
Lepton universality – direct measurements @ LEP 2000

ELSEVIER
Physics Reports
Volume 532, Issue 4, 30 November 2013, Pages 119-244

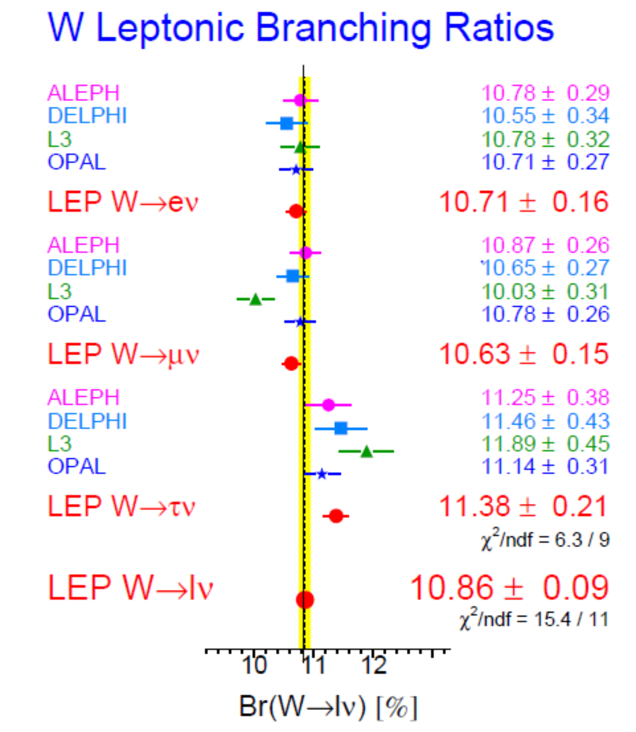
Electroweak measurements in electron–positron collisions at W-boson-pair energies at LEP

The ALEPH Collaboration, The DELPHI Collaboration, The L3 Collaboration, The OPAL Collaboration, The LEP Electroweak Working Group [1]

- SM couplings of charged leptons to gauge bosons are identical
- Very clean and precise measurement at electron collider

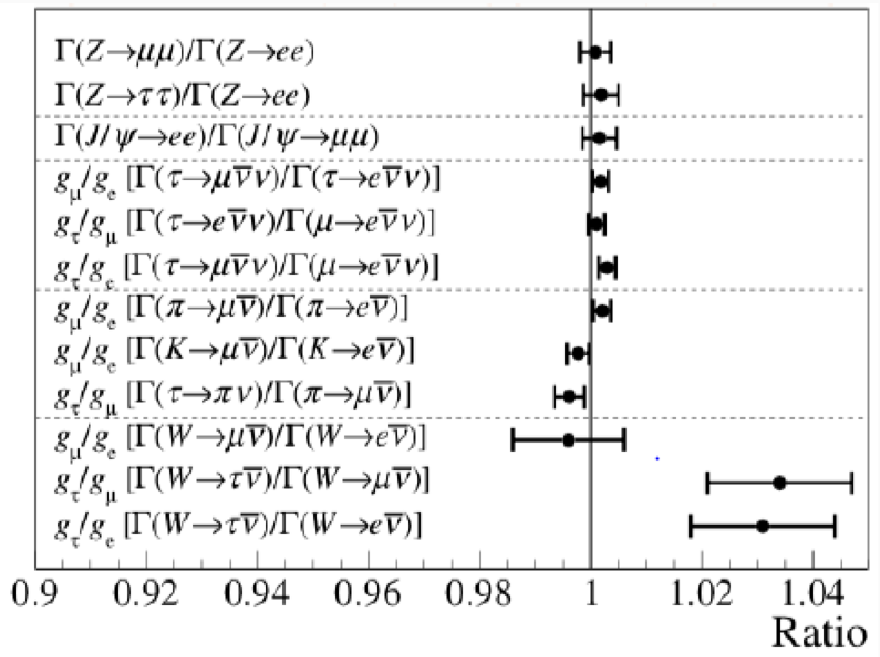


$$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 0.993 \pm 0.019\,,$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 1.063 \pm 0.027\,,$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) = 1.070 \pm 0.026\,.$$

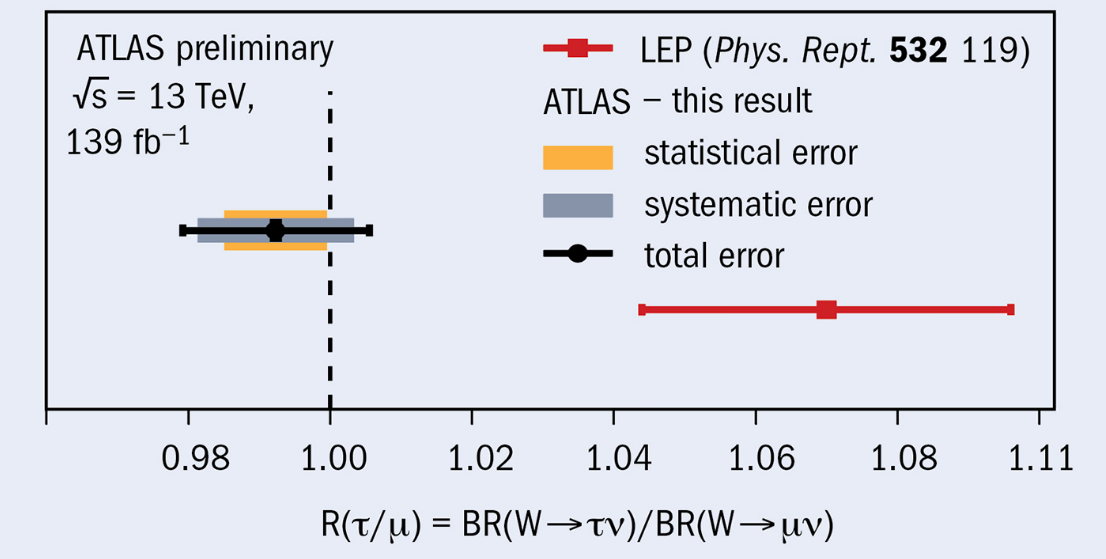


Lepton universality – direct measurements @ LHC 2020

- Extensively probed with $Z^0 \rightarrow l^+l^-$ and $J/\psi \rightarrow l^+l^-$ to sub percent level



ATLAS Collaboration 2020 ATLAS-CONF-2020-014



R(τ/μ) = 0.992 ± 0.013 [± 0.007 (stat) ± 0.011 (syst)]

$$R_K^{(*)} = \frac{\mathcal{B}(B\rightarrow K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\rightarrow K^{(*)}e^+e^-)} \cong 1 \text{ in SM}$$

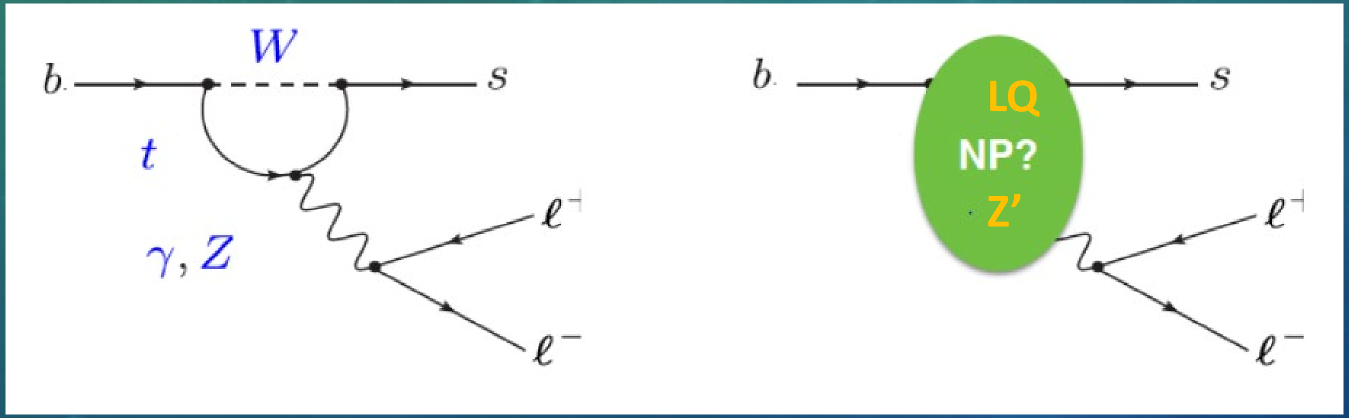
Any significant deviation is a smoking gun for New Physics

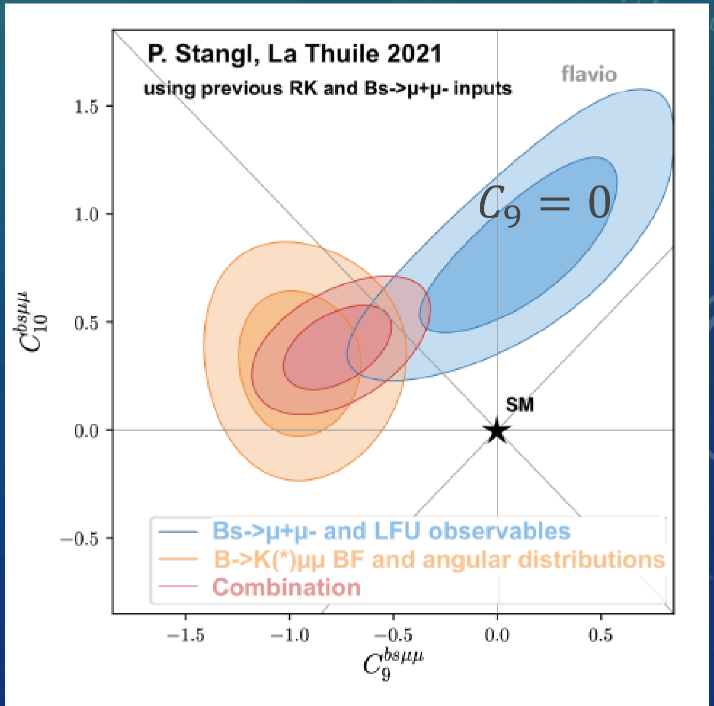
The power of indirect searches

Precision measurements to unveil new particles indirectly:

- 1970 charm quark as an explanation of the suppression of $K^0 \to \mu^+\mu^-$ (before direct discovery of J/ψ)
- 1973 prediction of 3x3 CKM matrix for explanation of CPV in kaons
- 1987 top mass limit from loop contribution in $B^0 - B^0$ mixing

Large mass of b quark and rare decays of B mesons offer a rich phenomenology for **indirect searches of New Physics**





$b \to s l^+ l^-$ are **FCNC** processes – only loop diagram in SM, $BF < 10^{-6}$

Observables are sensitive **to new (virtual) particles**

Flavour Anomalies in $b \to sl^+l^-$

Over the past decade we have observed a coherent set of tensions with SM predictions:

- Branching Fractions:

  $B^0 \to K^*\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\,\mu^+\mu^-$

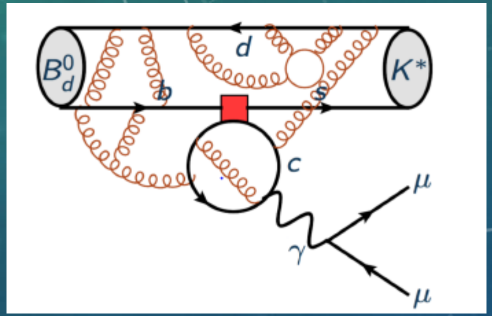
- Angular Analyses:

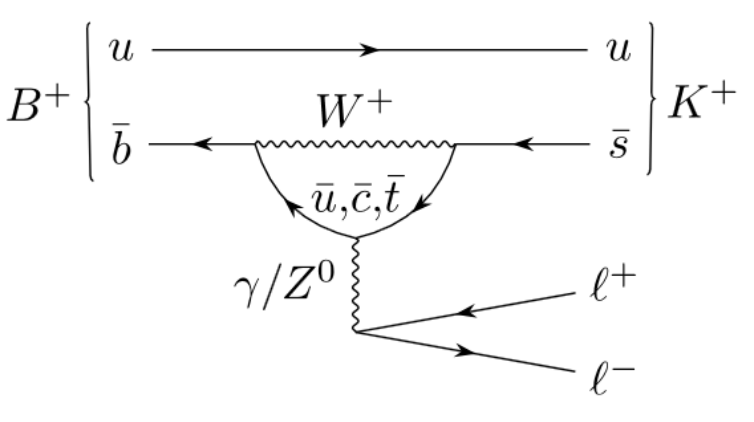
  $B^0 \to K^*\mu^+\mu^-$, $\Lambda_b \to \Lambda\,\mu^+\mu^-$

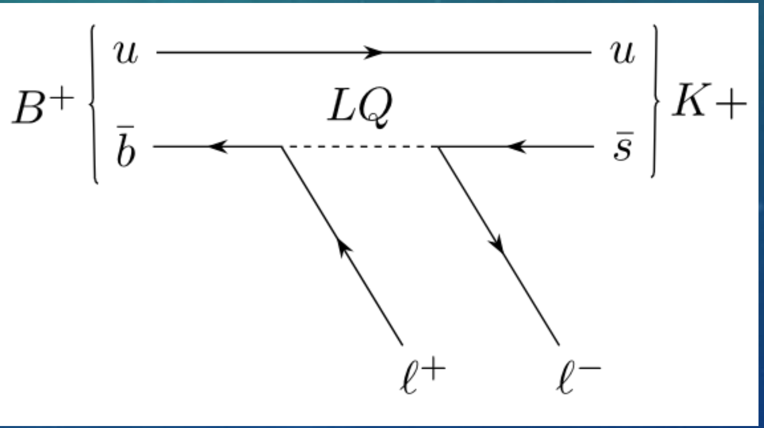
- Lepton Flavour Universality with e/μ ratios:

  $B^0 \to K^*l^+l^-$, $B^+ \to K^+l^+l^-$

Hadronic uncertainties!







BUT

strong force does not couple directly to leptons so decays $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ are identical.

SM predictions with $\mathcal{O}(1\%)$

$b \to sl^+l^-$ contains $b \to s$ transition with a hadron and offer multitude of observables complementary to $B_s^0 \to \mu^+\mu^-$

Test of lepton universality in beauty-quark decays

arXiv:2103.11769
CERN-EP-2021-042
LHCb-PAPER-2021-004
23 March 2021
Nature Physics

The direct observable in rare decays is hardly measurable: $R_K^{(*)} = \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}e^+e^-)}$

Double ratio normalises the rare BF ratio with a control BF ratio:

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

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

$$= 1 \pm \mathcal{O}(10^{-3})$$

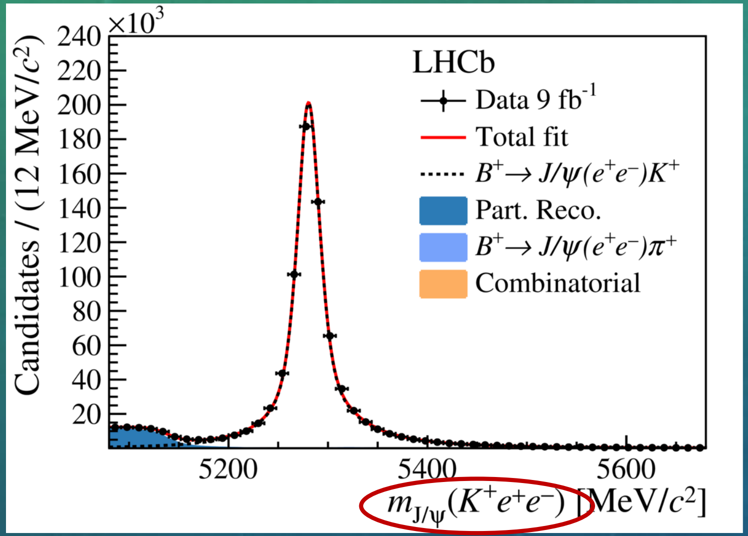
- Experimentally clean: most systematic uncertainties cancel due to double ratio, but controlling efficiencies is vitally important.
- Theoretically clean: hadronic uncertainties cancel, QED effects are small.
- The J/ψ sits in a different q^2 region, but is otherwise identical.

Impact of efficiency on LU measurements

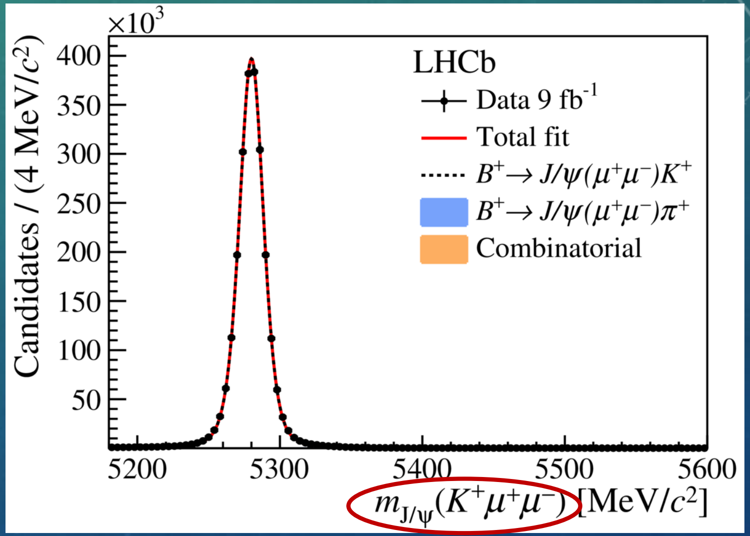
$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))} = 1$$

BUT

electrons and muons exhibits very different detection efficiency:



Yields $\neq$



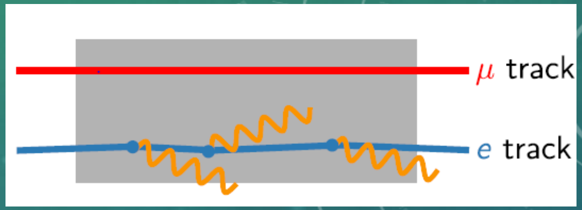
Controlling efficiencies means takes into account:

- bremsstrahlung
- L0 trigger
- Lepton identification

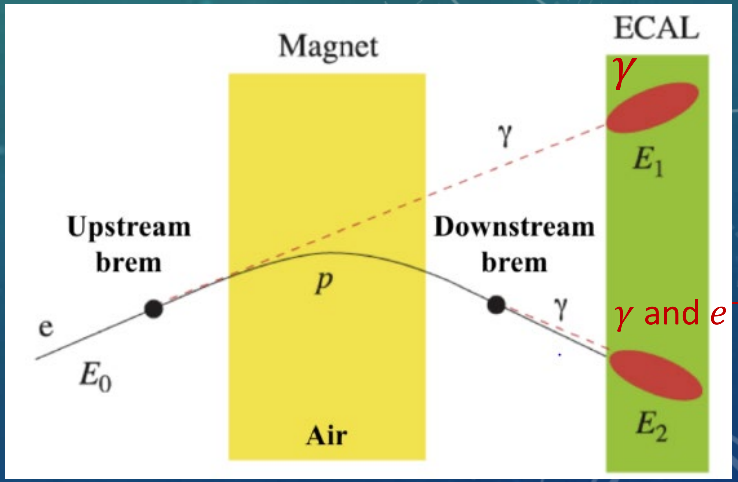
The complexity of this analysis is mostly driven by the differences between muon and electron detection and reconstruction

LHCb-PAPER-2021-004

Bremsstrahlung



- Electron suffer heavy losses from bremsstrahlung (compared to μ) – significantly broader resolution of electron final states.
- Deficit of Energy (up to 20%) is corrected by combining energy deposits from photons (E_T>75 MeV) in small region in the ECAL extrapolated from e track from before the magnet (momentum of matching γ is added to electron track).
- Even after the bremsstrahlung recovery electrons still have degraded mass and q^2 resolution.



L0 Trigger

- L0 calo trigger requires higher thresholds than L0 muon trigger – three exclusive trigger categories are used for e^+e^-

Particle ID

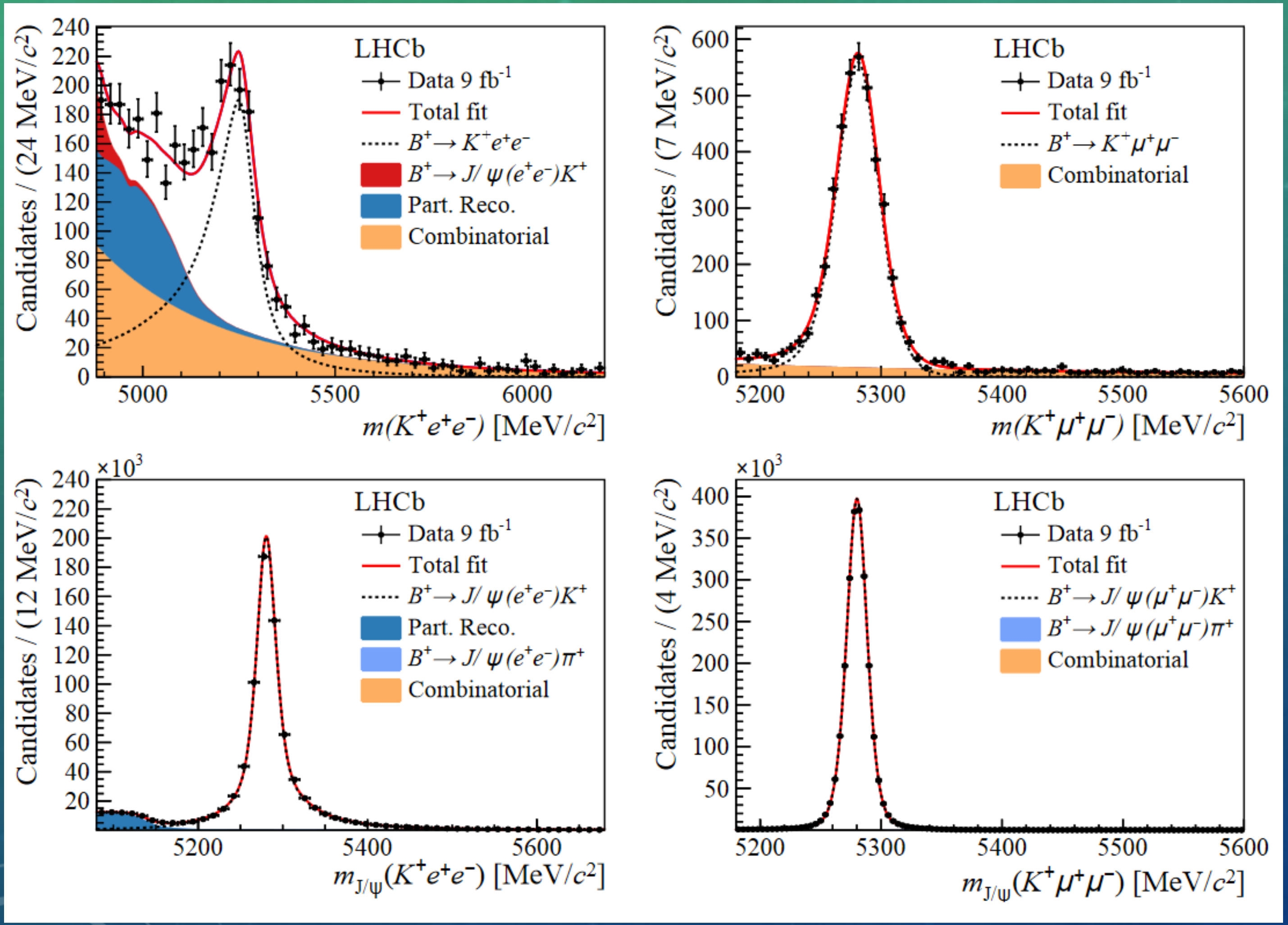
- PID and tracking efficiency larger for muons than electrons.

Yields $B^+ \to K^+ l^+ l^-$ (2021)

LHCb-PAPER-2021-004

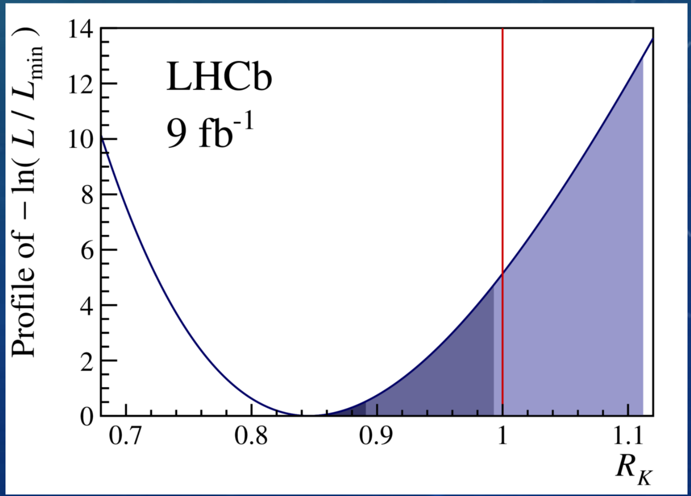
CERN-EP-2021-042
LHCb-PAPER-2021-004
23 March 2021

Nature Physics



Decay mode	Yield
$B^+ \to K^+ e^+ e^-$	$1\,640 \pm 70$
$B^+ \to K^+ \mu^+ \mu^-$	$3\,850 \pm 70$
$B^+ \to J/\psi\,(\to e^+e^-)K^+$	$743\,300 \pm 900$
$B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+$	$2\,288\,500 \pm 1\,500$

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

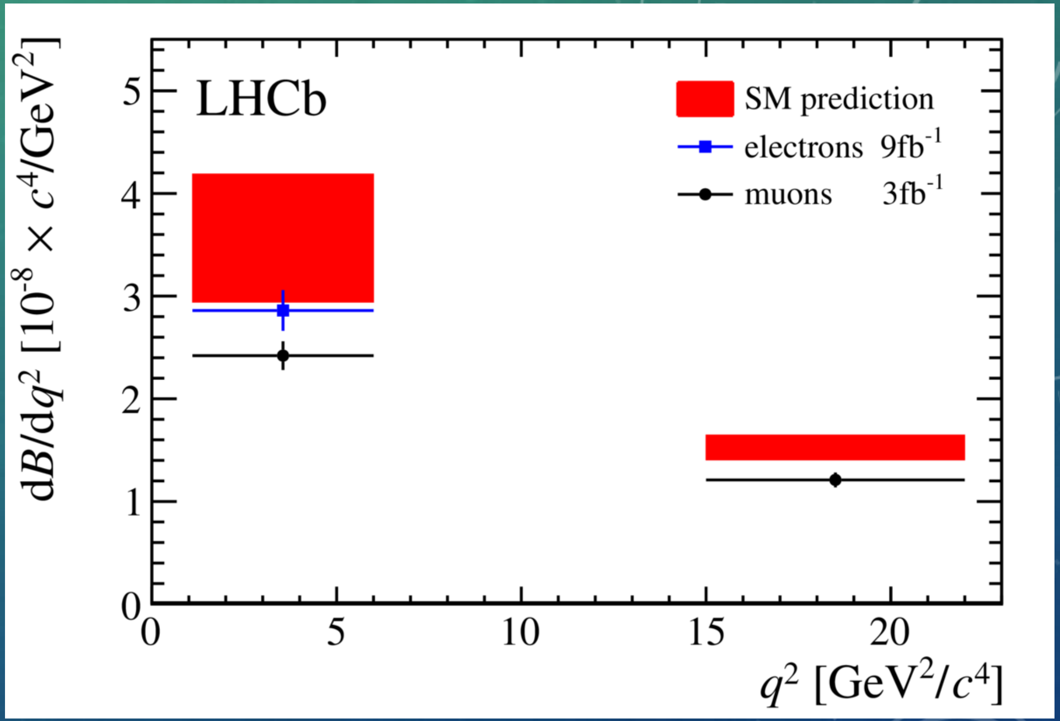


Results

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

p-value under SM hypothesis: 0.0010

evidence of LFU violation at 3.1σ



When combining with $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$, which is below SM [JHEP 06 (2014) 133]:

$$\frac{d\mathcal{B}(B^+\to K^+e^+e^-)}{dq^2} = \left(28.6\ ^{+1.5}_{-1.4}\ (stat) \pm 1.4(syst)\right) \times 10^{-9}\ (GeV/c^2)^{-1}$$

it seems that electrons are more SM-like than muons.

What next? Task for for theorist

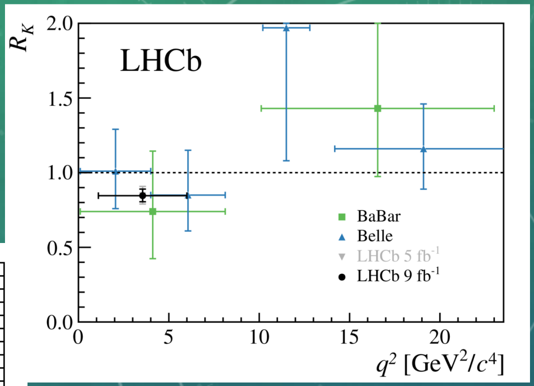
- Updated R_K measurement with a 3.1σ departure from LFU!
- Several LHCb measurements deviate from SM by 2-3 σ
- Start-up of the discussion on flavour anomalies

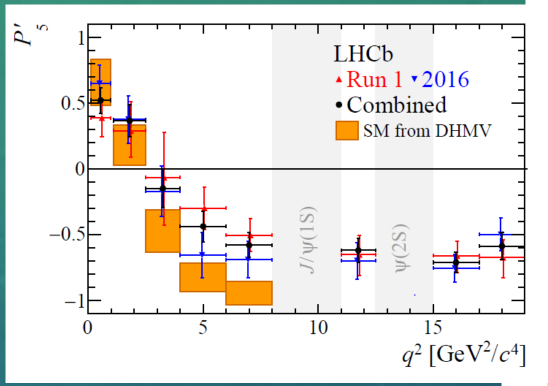
To combine of all LFU observables

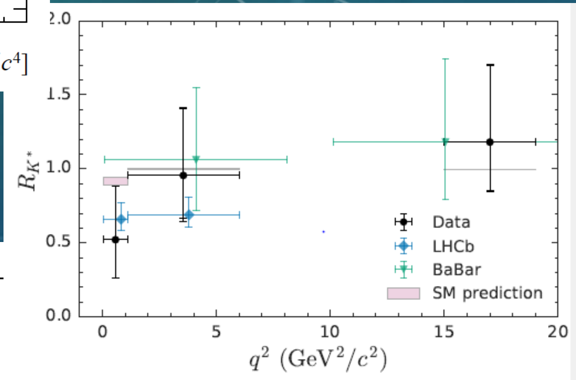
Emerging patterns of New Physics with and without Lepton Flavour Universal contributions:
M. Alguero et al. *Eur.Phys.J.C* 79 (2019) 8, 714
Addendum: Eur. Phys. J. C (2020) **80**: 511

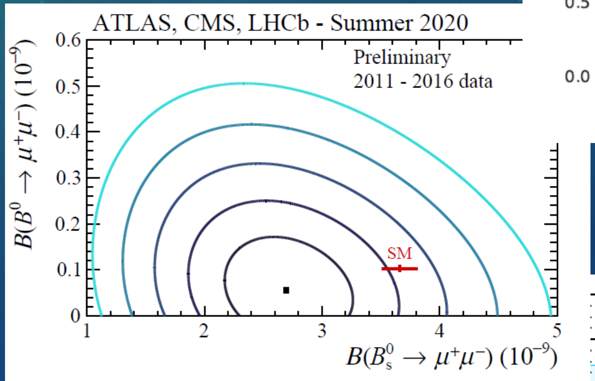
J. Aebischer et al., B-decay discrepancies after Moriond 2019, arXiv:1903.10434
M. Alguero Moriond QCD: Global fits to $b \to sll$ data, link

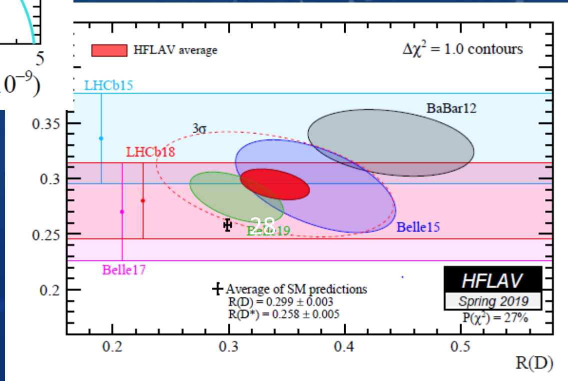
La Thuile 2021 - Les Rencontres de Physique de la Vallée d'Aoste, 10 March 2021:
P. Stangl *Flavour fits*











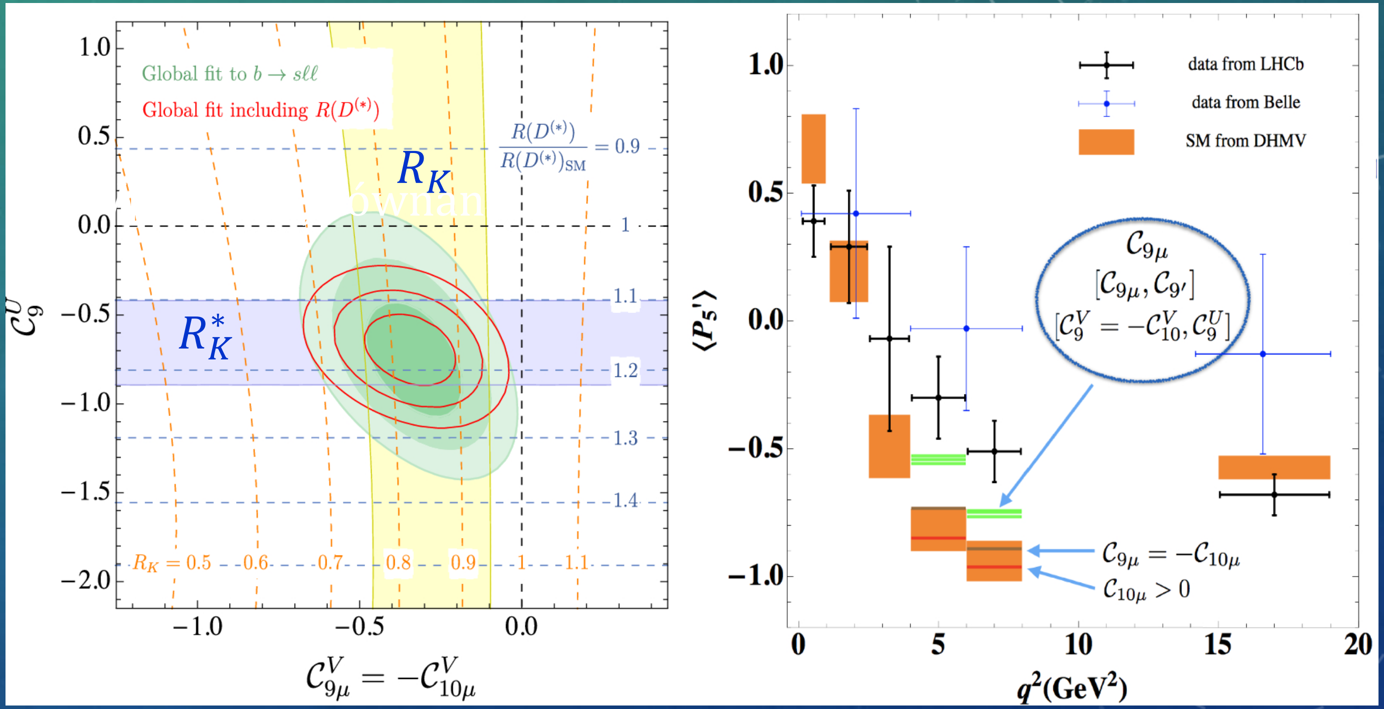
in one model for New Physics interpretation

The model setup

Global likelihood from **smelli** python package for comparing theory predictions to experimental data:

M. Alguero et al. *Eur.Phys.J.C* 79 (2019) 8, 714

J.Aebischer, J.Kumar, P.Stangl, D.M. Straub
A Global Likelihood for Precision Constraints and Flavour Anomalies,
arXiv:1810.07698



- New Physics scenarios:

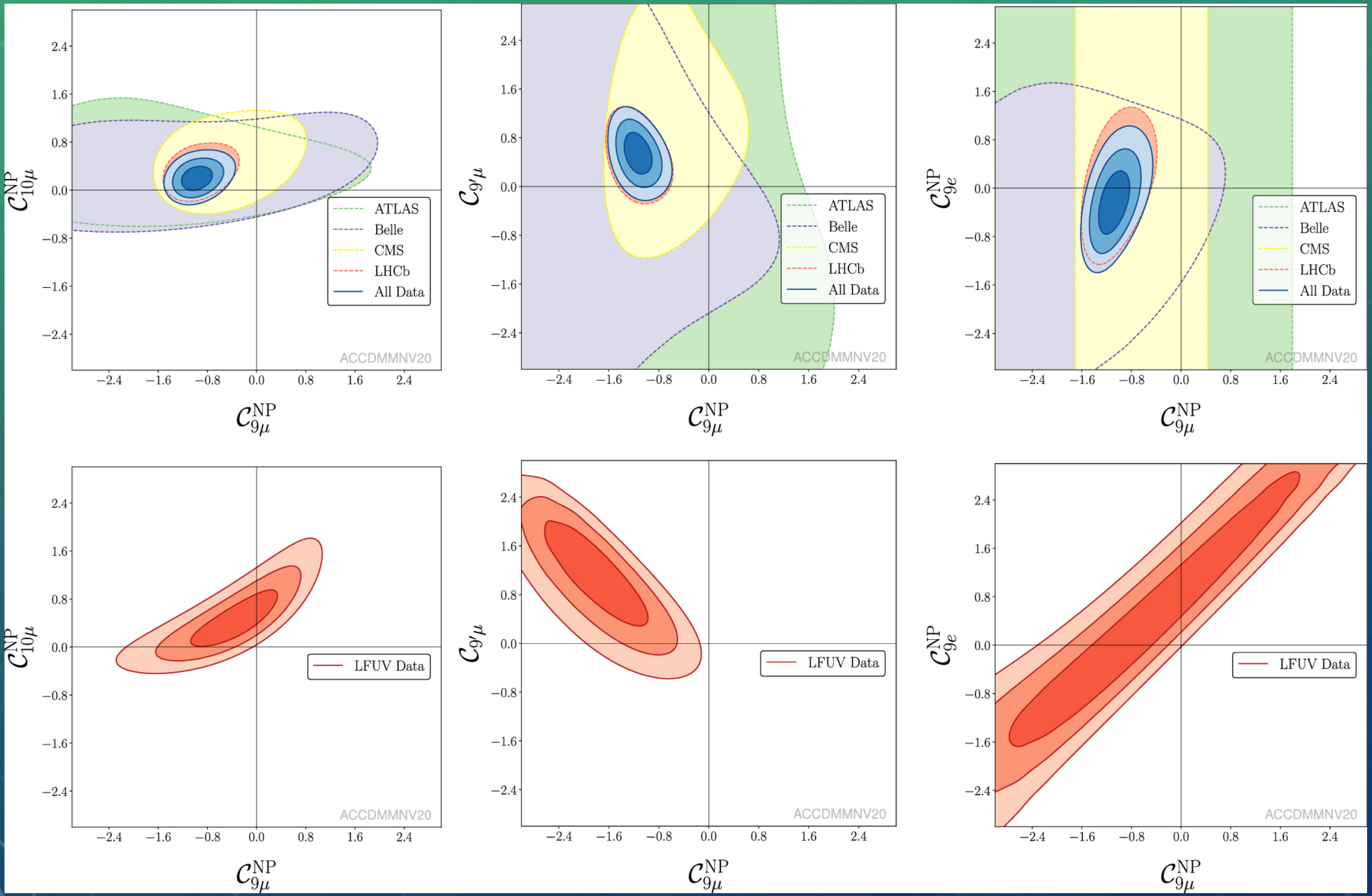
  Weak Effective Theory (WET): NP Wilson coefficients C'_i

  Standard Model Effective Theory (SMEFT) at scale of 4 TeV: NP particles (LQ, Z')

246 obs (Global) + 22 obs (LFUV) from LHCb, Belle, ATLAS, CMS

Emerging patterns of New Physics with and without Lepton Flavour Universal contributions:
M. Alguero et al. *Eur.Phys.J.C* 79 (2019) 8, 714
Addendum: Eur. Phys. J. C (2020) **80**: 511

The model: one Wilson coeficient or more?

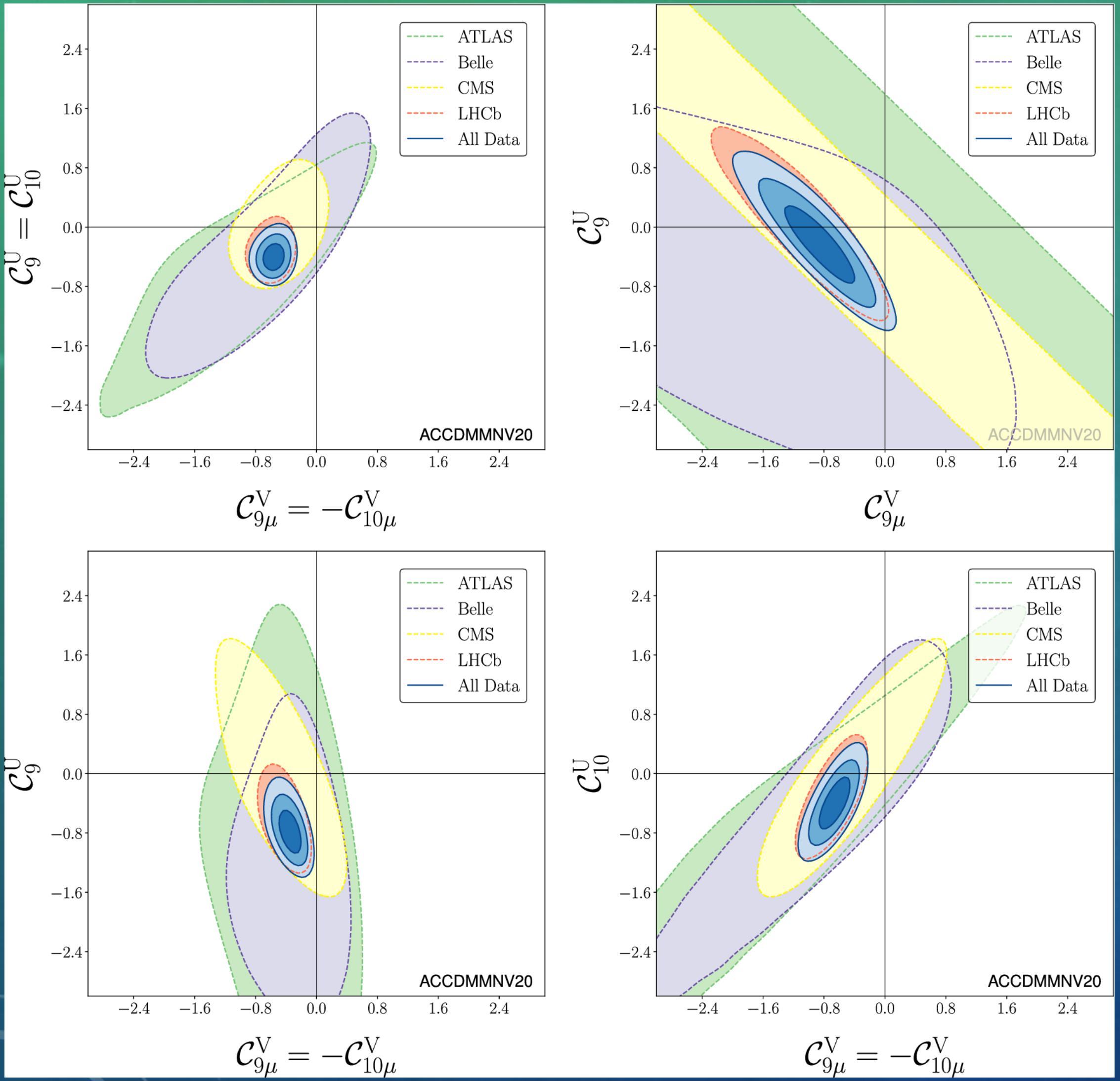


$$B_s \to \mu^+\mu^-$$

$$C_{10\mu} = C_{10\mu}^{SM} + C_{10\mu}^{NP}$$

Emerging patterns of New Physics with and without Lepton Flavour Universal contributions:
M. Alguero et al. *Eur.Phys.J.C* 79 (2019) 8, 714
Addendum: Eur. Phys. J. C (2020) **80**: 511

The model: one Wilson coeficient or more?



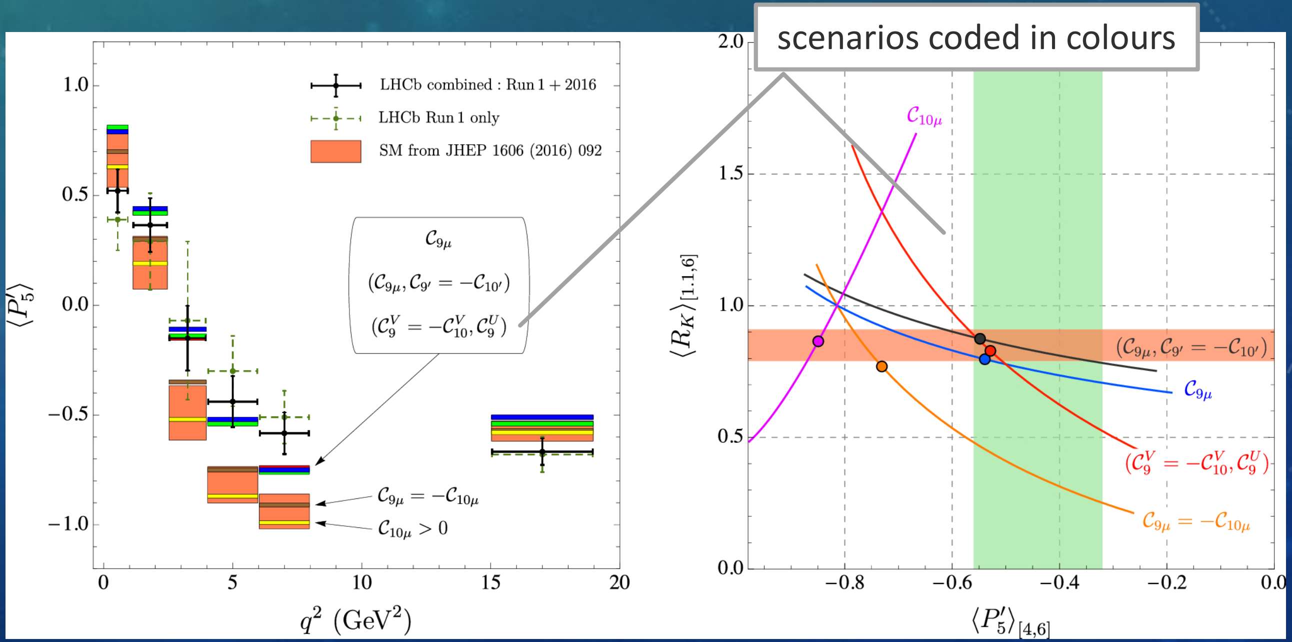
New Physics coefficients:

- Electrons with flavour Universality (U)
- Muons with flavour Universality Violation (UV)

$$C_{ie}^{NP} = C_i^U$$

$$C_{i\mu}^{NP} = C_{i\mu}^V + C_i^U$$

New Physics in muon sector only!



Try it yourself

test your model with global results:
https://github.com/smelli/

jupyter nbviewer

JUPYTER FAQ

Step 1: EFT and basis

Execute this cell and select an EFT and basis

```
In [ ]: widgets.HBox([widget_eft, widget_basis])
```

Step 2: likelihood

execute this cell to initialize the likelihood. This will only take a moment.

```
In [ ]: gl = smelli.GlobalLikelihood(eft=select_eft.value, basis=select_basis.value)
```

Step 3: Wilson coefficients

select a point in EFT parameter space by entering in the text field Wilson coefficient values in the form `name: value`, one coefficient per line (this format is called YAML). The allowed names in the chosen basis can be found in the PDF file linked below.

Example in the SMEFT Warsaw basis:

```
lq1_2223: 1e-9
lq1_3323: 1e-8
lq3_3323: 1e-8
```

```
In [ ]: widgets.VBox([out_basispdf, widgets.HBox([ta_wc, t_scale])])
```

Step 4: parameter point

execute this cell to intialize the `GlobalLikelihoodPoint` object

```
In [ ]: glp = gl.parameter_point(read_yaml(ta_wc.value), float(t_scale.value))
```

Step 5: results!

inspect the likelihood by looking at the numerical value ...

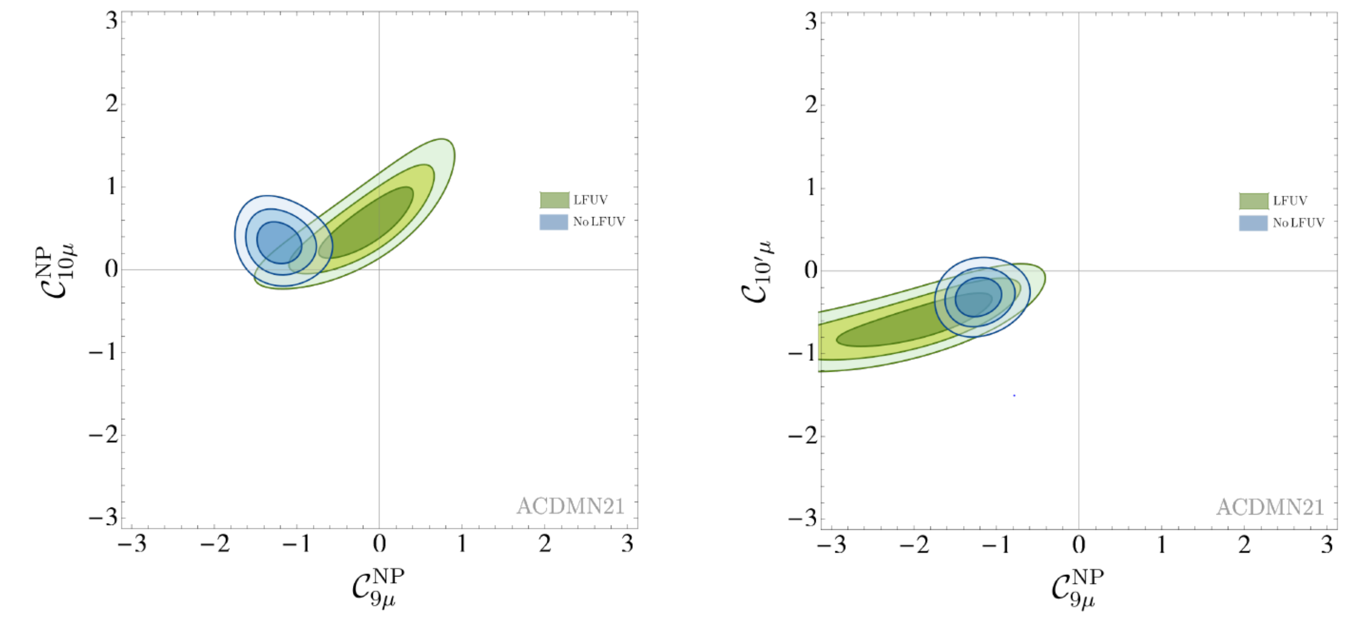
```
In [ ]: glp.log_likelihood_global()
```

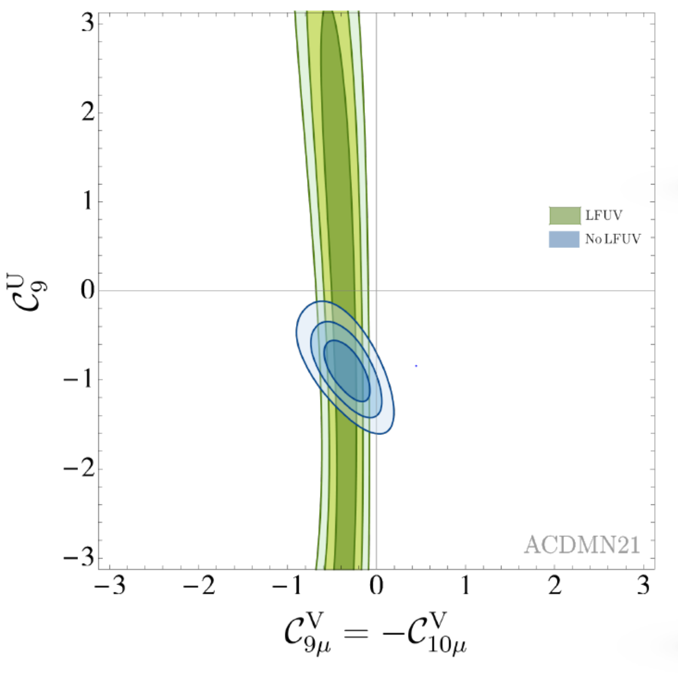
... or inspecting the table of observables

Try it yourself

test your model with global results: https://github.com/smelli/

new fits to $b \to sll$ (Moriond 2021)

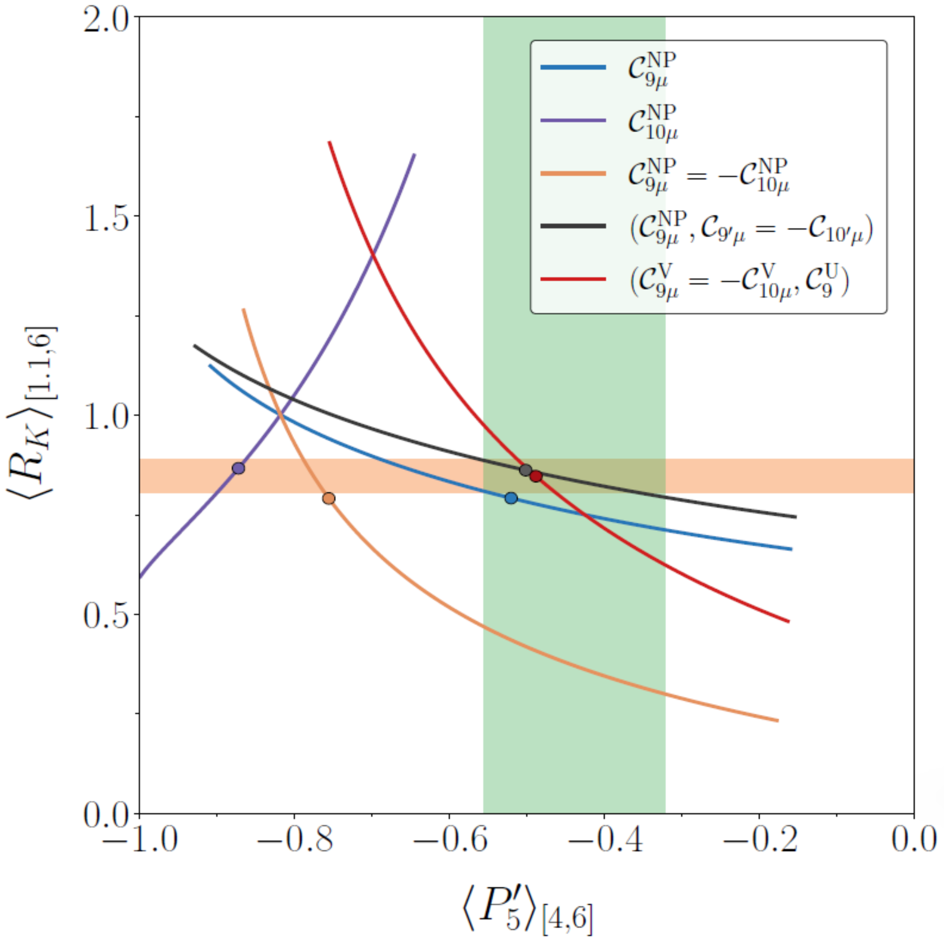




M. Alguero et al. *Eur.Phys.J.C* 79 (2019) 8, 714
Addendum: Eur. Phys. J. C (2020) **80**: 511

Summary

- New result on R_K with more statistic & more precision.
- Increased tension with SM in $B^+ \to K^+ l^+ l^-$ and $B_s^0 \to \mu^+\mu^-$ as a sign of flavour anomalies in $b \to sll$
- R_K is uncorrelated with previous parameters
- Plenty of scenarios with similar significances:
  - Right-Handed Currents $C'_{10\,\mu}$ can explain both $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and R_K with $C'_{10\,\mu} \neq 0$
  - The scenario LFU with coefficients: $\{C_{9\mu}^V = -C_{10\mu}^V, C_9^U\}$ is reinforced and explains tensions between $C_{9\mu}^{NP}$
  - and LFUV fit with $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$
  - $Q_5 = P'_{\mu 5} - P'_{e5}$ new candidate for a discriminator between preferred scenarios
- A consistent model-independent interpretation is possible via modification of $b \to s$ coupling with additional heavy neutral boson or with leptoquarks.
- Other SM extensions: SUSY, Higgs sectors, extra dimensions are also considered.



As seen above:

1) **RHC** such as $\{C_{9\mu}^{\rm NP}, C_{9'\mu} = -C_{10'\mu}\}$ one of favorite scenarios

2) Scenario **LFU** with $\{C_{9\mu}^{\rm V} = -C_{10\mu}^{\rm V}, C_9^{\rm U}\}$ is a good solution

3) $C_{9\mu}^{\rm NP}$ offers quite good solution to both $\langle P_5' \rangle_{[4,6]}$ and $\langle R_K \rangle_{[1.1,6]}$

4) $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP}$ or $C_{10\mu}^{\rm NP}$ clearly fail to explain $\langle P_5' \rangle_{[4,6]}$