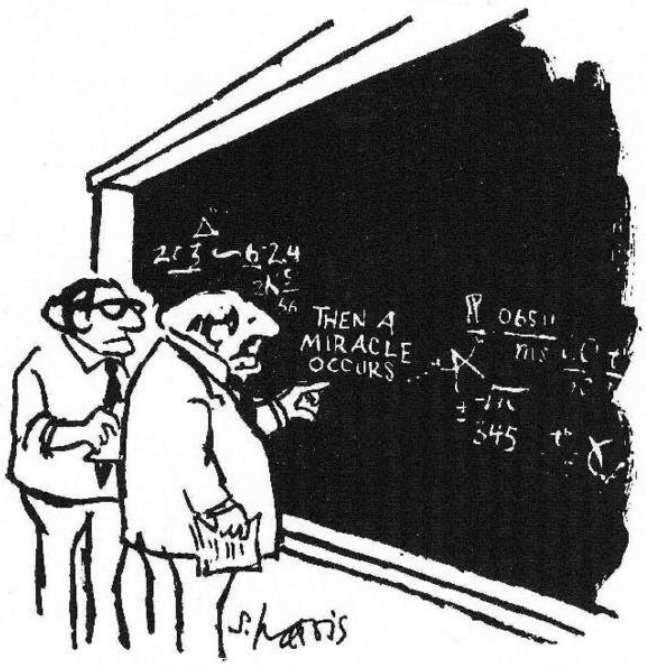
November 28, 2017

Lepton Flavor Universality and Rare *B* Decays

11th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"

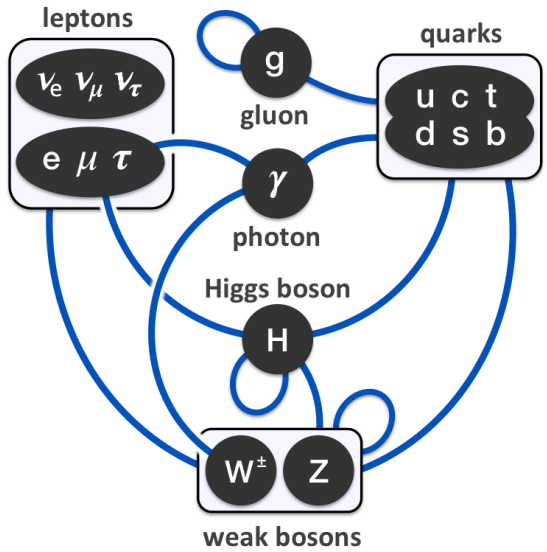
Presented by Simon Wehle

Deutsches Elektronen-Synchrotron



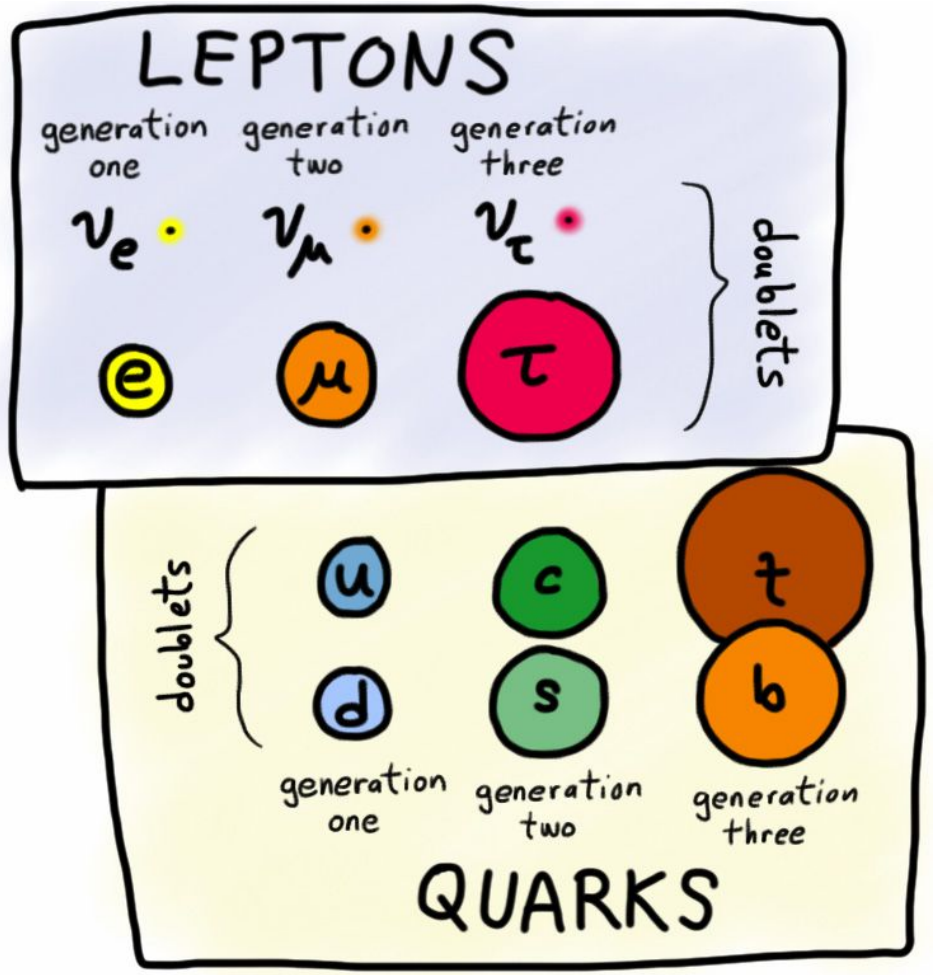
"I think you should be more explicit here in step two."

Design by Philipp Rietz



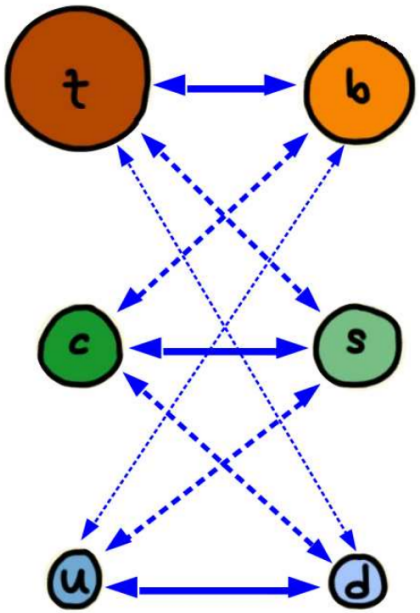
Particle Physics Today

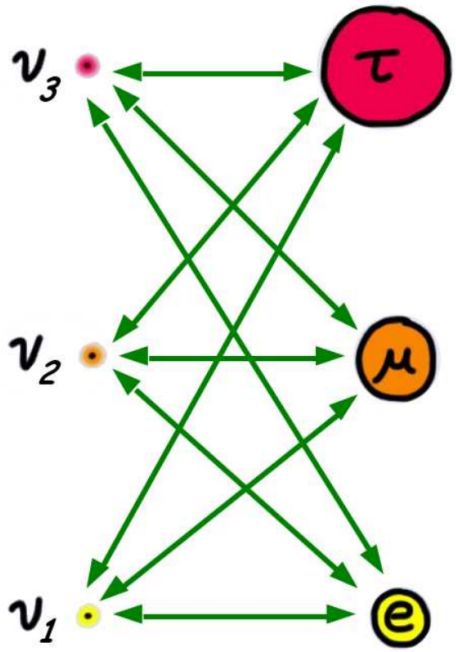
- The Standard Model leaves many questions
- Why do we have three generations of leptons and quarks?
- Hierarchy, masses, 22 free parameters



Credit: W. Altmannshofer, The Flavor Puzzle

Particle Physics Today

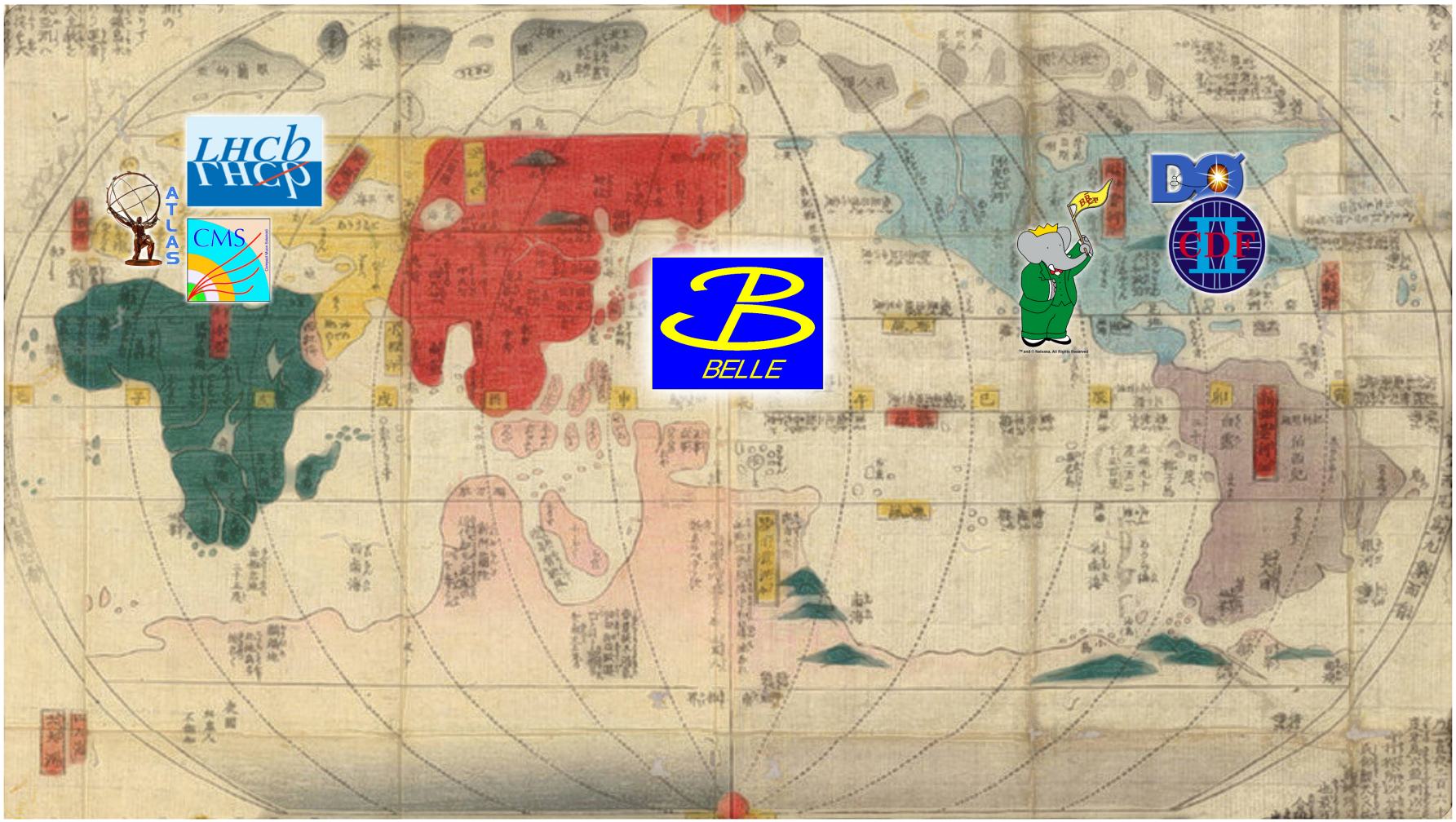




Credit: W. Altmannshofer, The Flavor Puzzle

- Can we find New Physics to understand the structure of the SM ?
- With flavor physics we soon might be a step closer..

Flavor Physics around the World

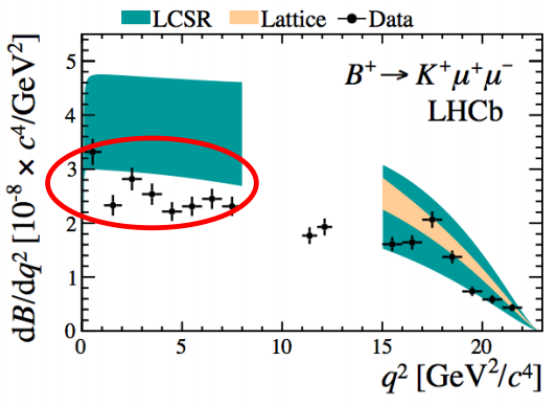


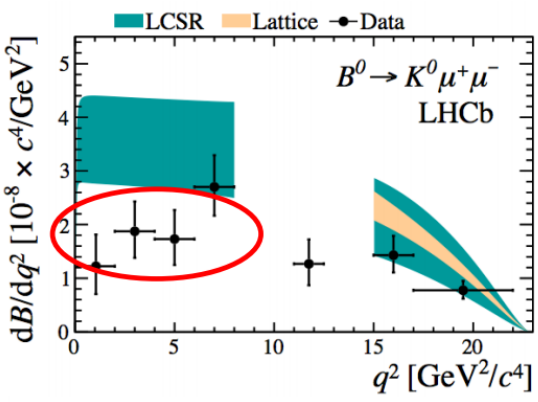
The Flavor Anomalies Overview

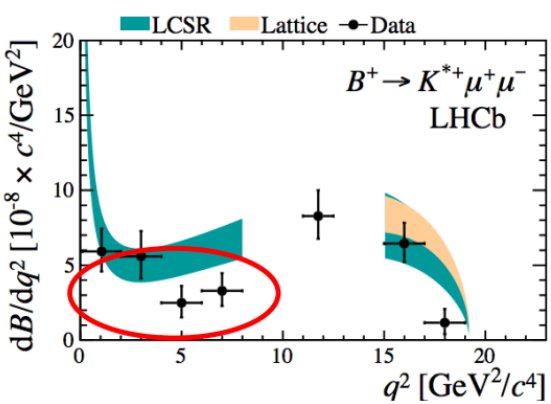
There are actually many tensions with the SM...

$> 3.5\sigma$	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 $\lvert V_{ub}\rvert$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$
$> 3\sigma$	anomalies in angular distributions of $B \to K^*\ell\ell$
2.6σ	lepton flavor non-universality in $B^+ \to K^+\mu^+\mu^-$ vs. $B^+ \to K^+e^+e^-$
2.5σ	lepton flavor non-universality in $B^0 \to K^{*0}\mu^+\mu^-$ vs. $B^0 \to K^{*0}e^+e^-$

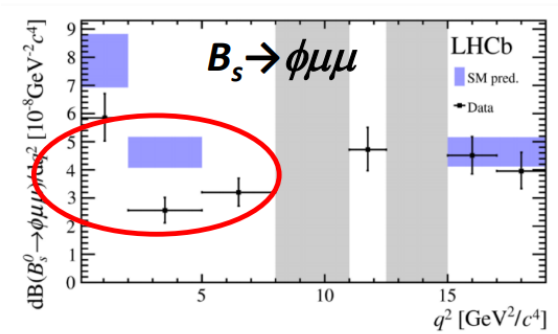
The Flavor Anomalies Overview - Branching Ratios







JHEP 06 (2014)133



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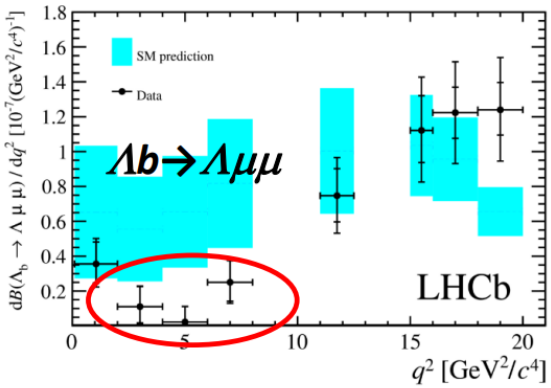

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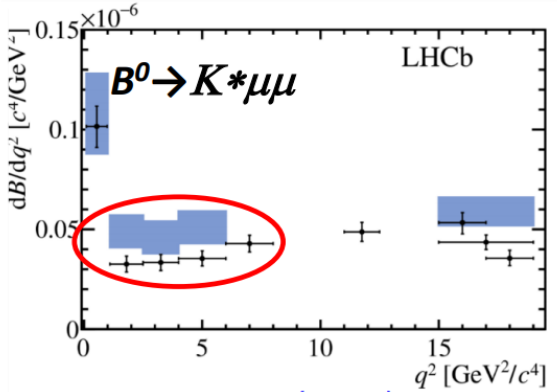
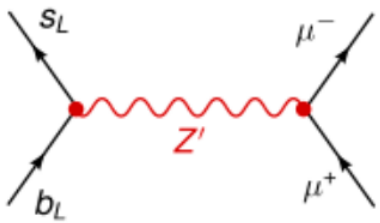


JHEP 11(2016)047
JHEP 04(2017)142

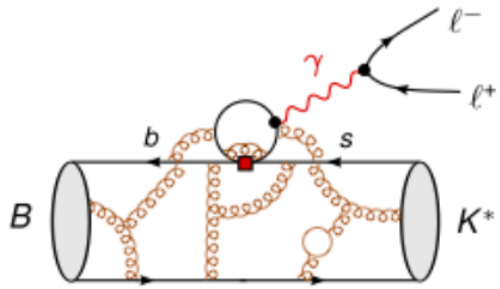
From Justine Serrano EPS2017

Complications - Doubts

Optimist's view point



Pessimist's view point



- Although, overall uncertainty on $b \to s\ell\ell$ form-factors decreased – significance of anomalies increased


e
μ
τ

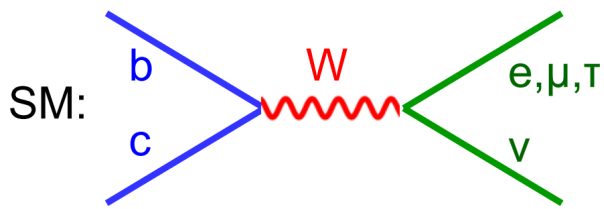
Lepton Flavor Universality

- Fundamental in of the Standard Model
  - Very well tested
- Clean observables
- Only new particles can lead to LFU violation

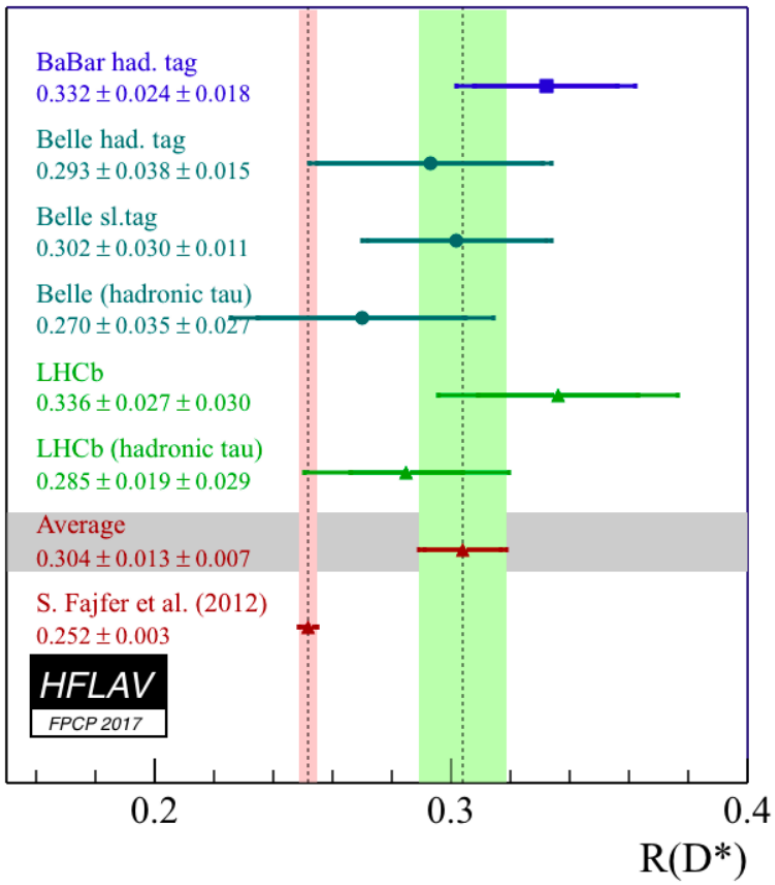
Lepton Flavor Universality in $R_D^{(*)}$

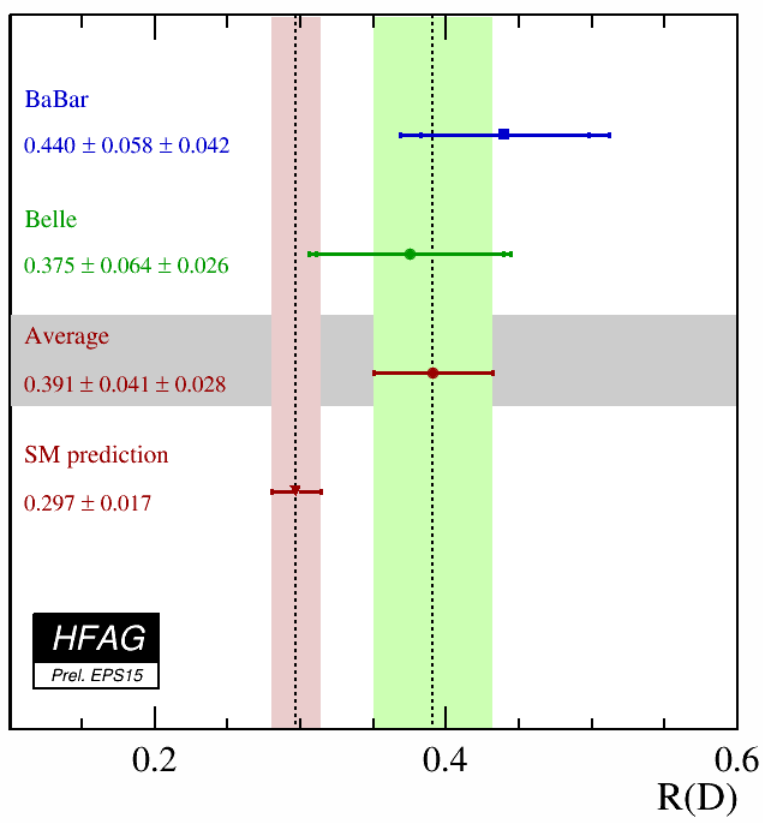
$$R_D^{(*)} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

- Tree level decay
- Theoretically very clean observable
- Neutrinos in final state

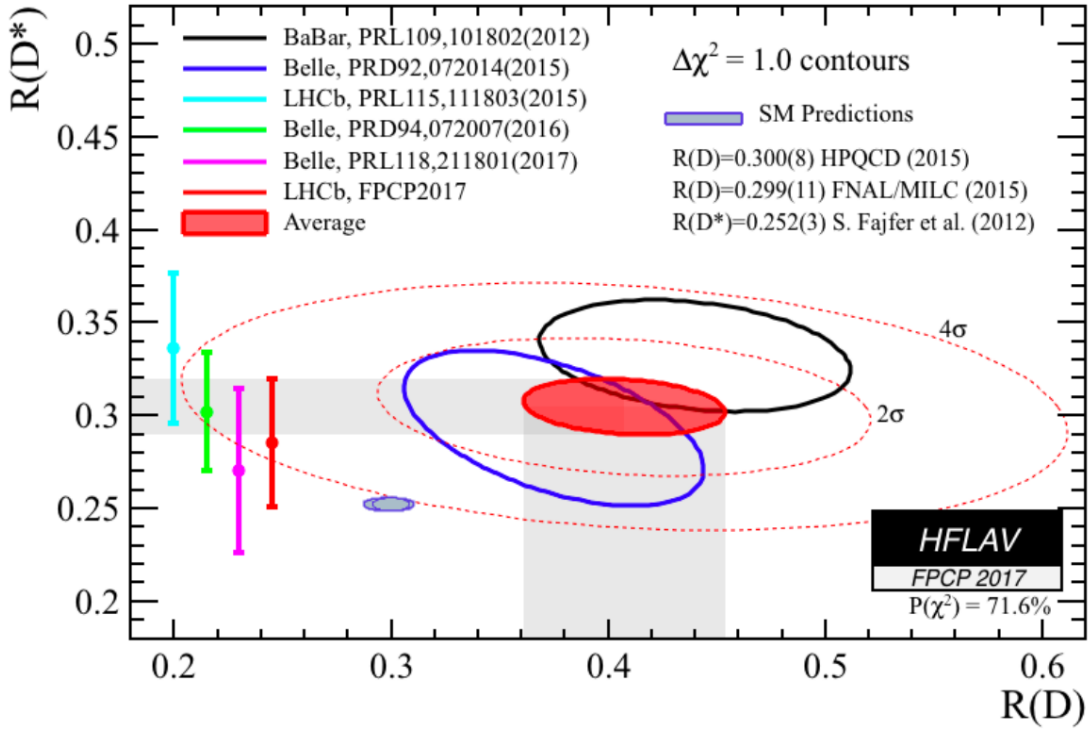


Lepton Flavor Universality in $R_D^{(*)}$





Lepton Flavor Universality in $R_D^{(*)}$

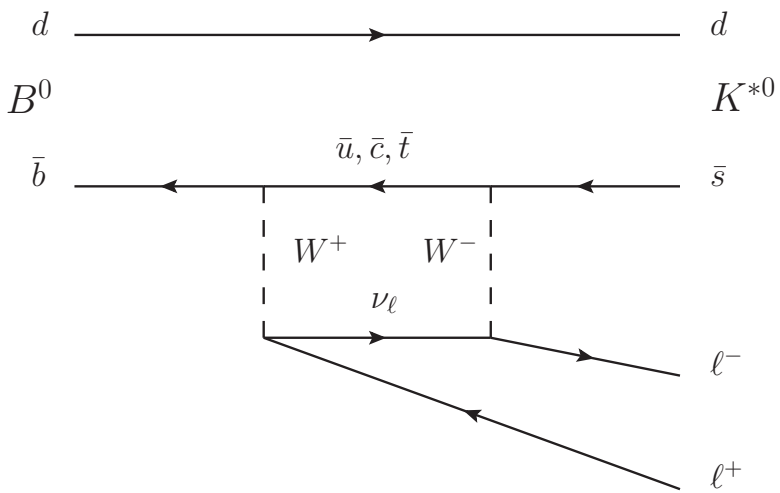


- Tension with SM $> 4\sigma$
- 30% effect against SM for taus in tree level decays

Rare $b \to s$ transitions

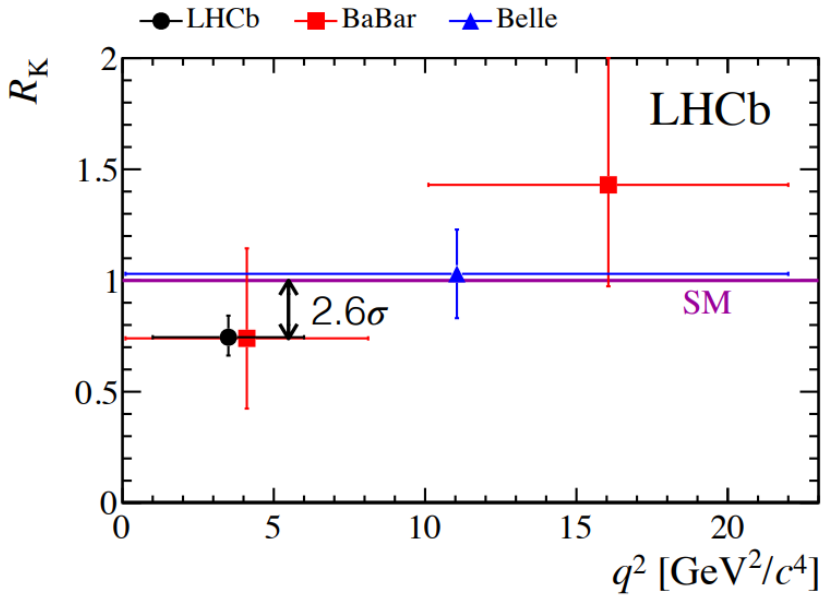
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

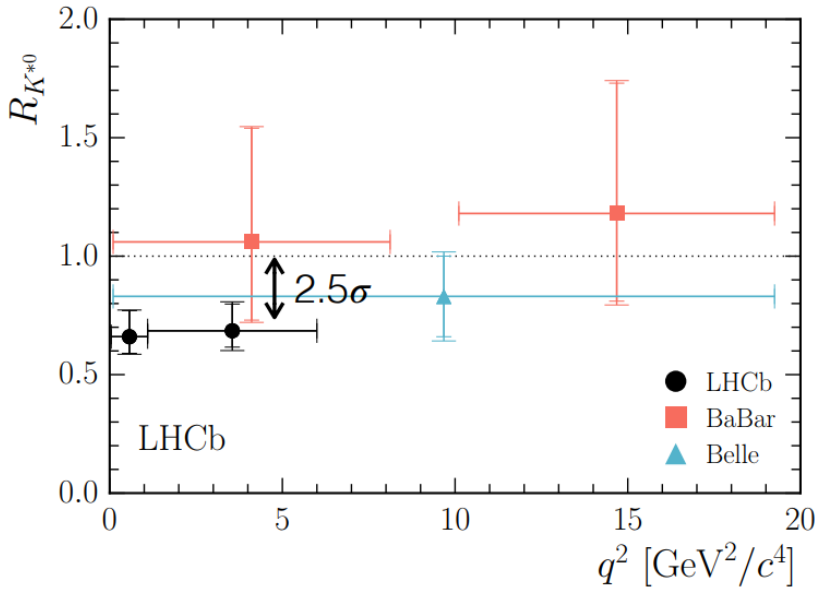
$$R_K^* = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}$$



- Theoretically very clean
- Uncertainties from form factors cancel in the ratio
- Control mode $B \to J/\psi, K^{(*)}$

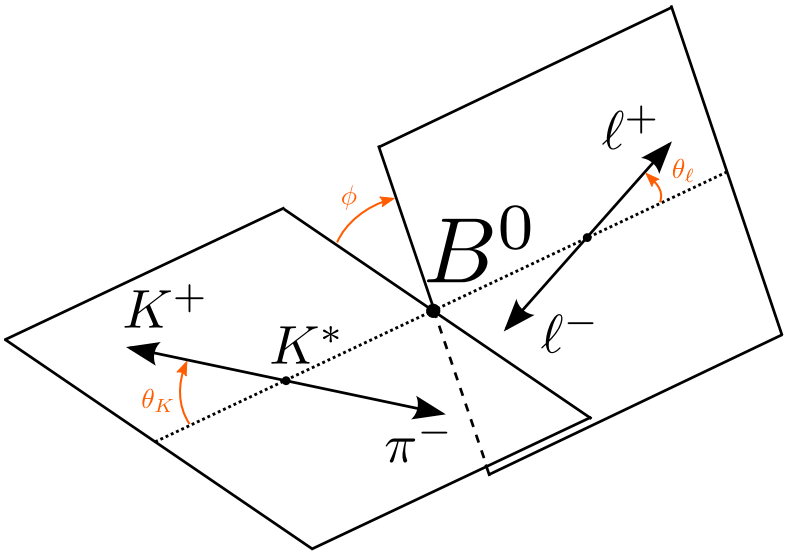
Experimental Results for R_K

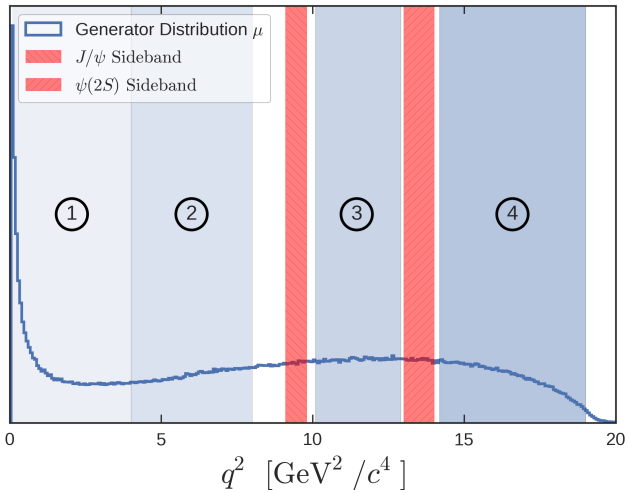




- Consistent experimental results
- Updated Belle result in preparation
  - Possible results for R_K^{*0} and R_K^{*+}
- 25% effect against SM for muons in electroweak penguins

Angular Analysis of $B \to K^* \ell\ell$



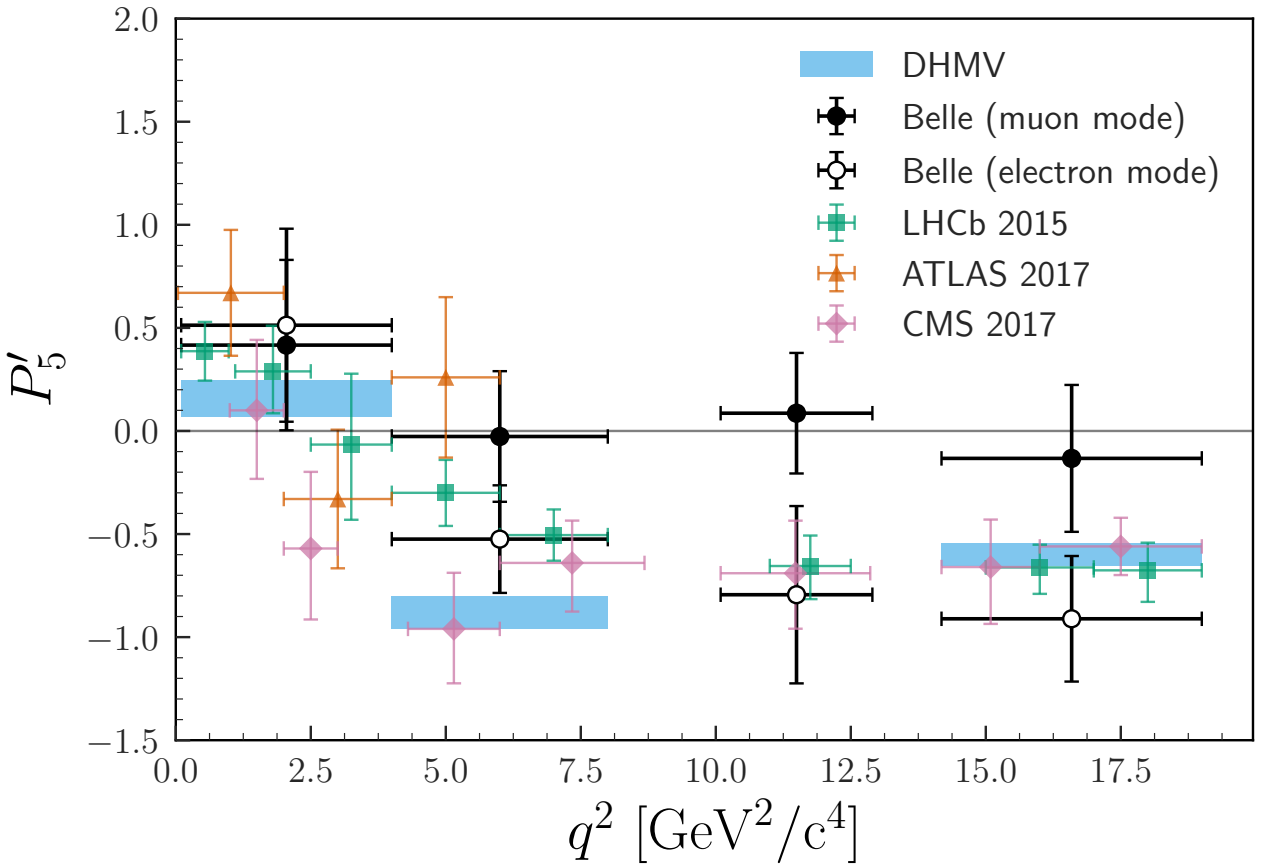


The observables are depended on $q^2 = M^2_{\ell^+\ell^-}$

The differential decay rate for $B \to K^* \ell^+ \ell^-$ can be written as

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

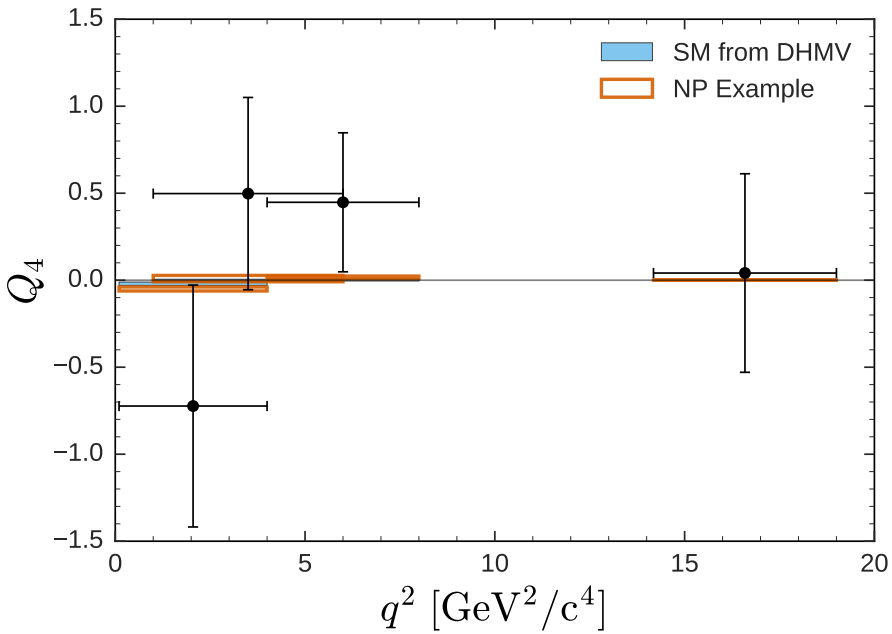
Result P_5' - Result for Combined Data

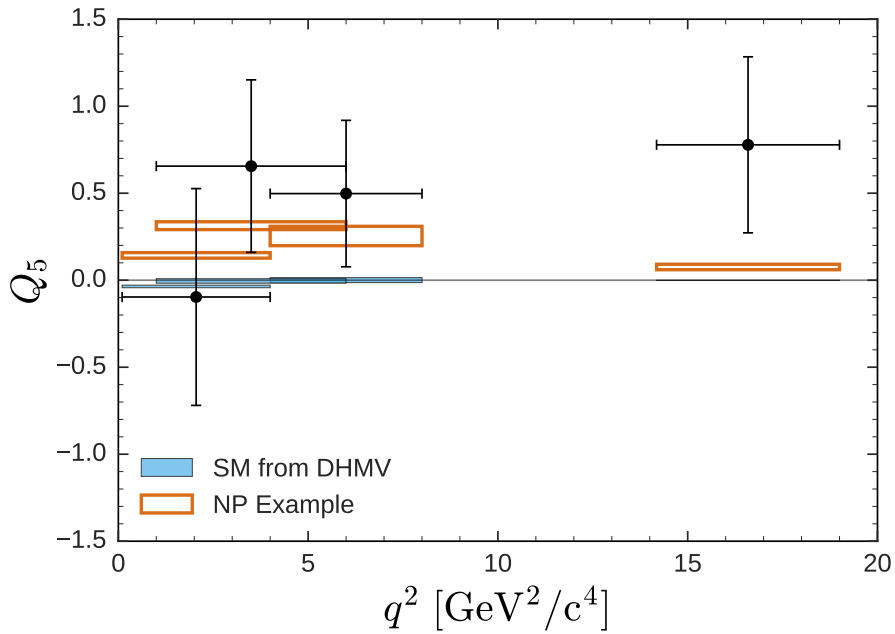


- Measurements are compatible with the SM
- Similar central values for the P_5' anomaly with 2.5σ tension

Lepton Flavor Universality in Angular Observables

- Test lepton flavor universality
- Observables $Q_i = P_i^\mu - P_i^e$, JHEP 10, 075 (2016)
- Deviation from zero very sensitive to NP





- Published recently in Phys. Rev. Lett. 118, 111801 (2017)

Effective Hamiltonian Approach

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i\mathcal{O}_i + C_i'\mathcal{O}_i')$$

left-handed part

right-handed part suppressed in SM

i=7 : photon

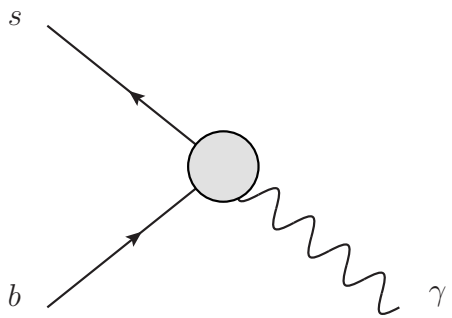
i=9 : vector current

i=10 : axial-vector current

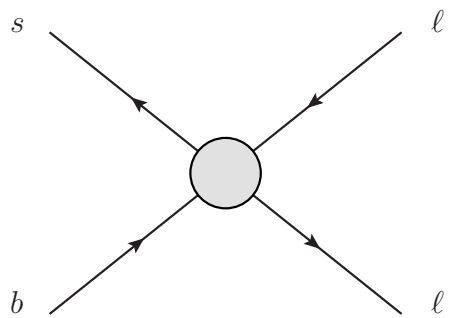
i= S,P : scalar, pseudo scalar operators

- The $b \to s\ell\ell$ decay can be described by an effective field theory
- Model independent description:

$$\mathcal{H}_{eff} \propto \sum_i \left(C_i^{SM} + C_i^{NP}\right) \cdot O_i$$

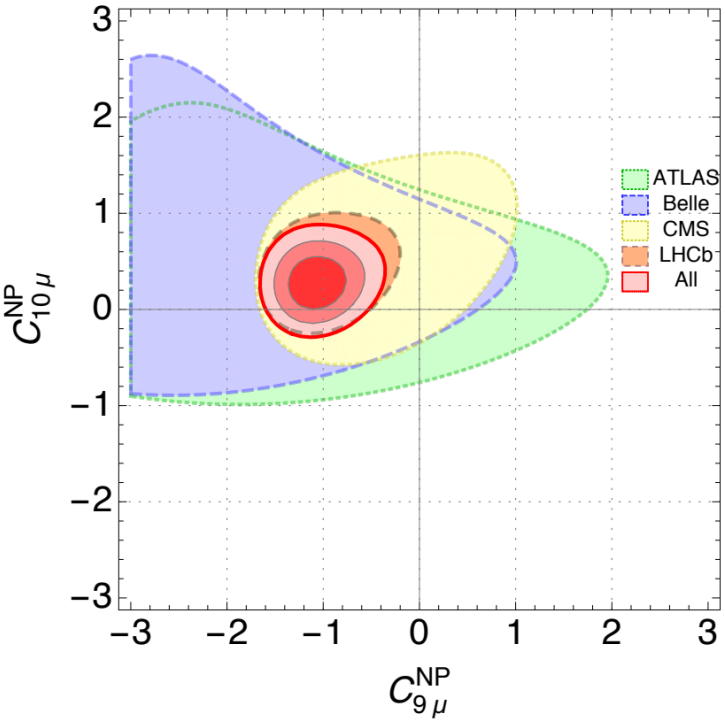


(a) $\mathcal{O}'_7$

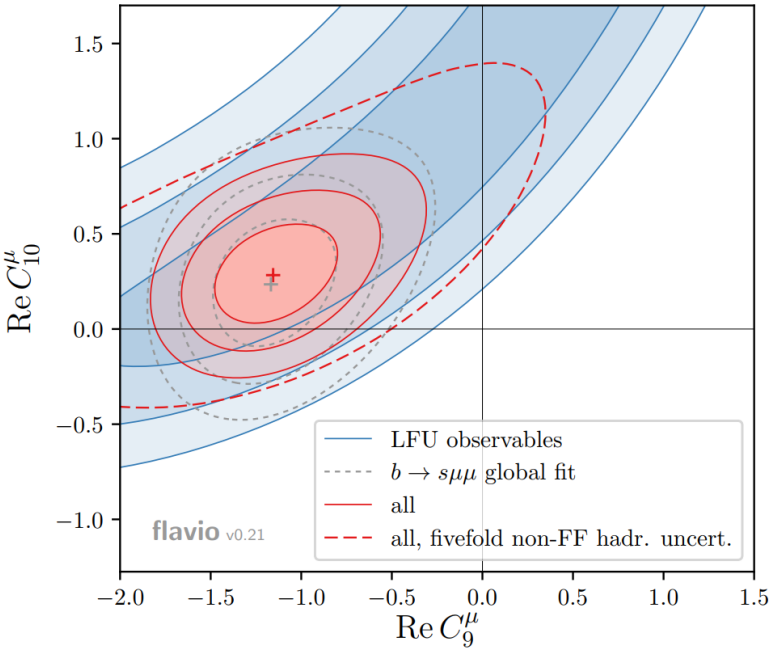


(b) $\mathcal{O}'_9$ and $\mathcal{O}'_{10}$

Fits for New Physics in Wilson Coefficients



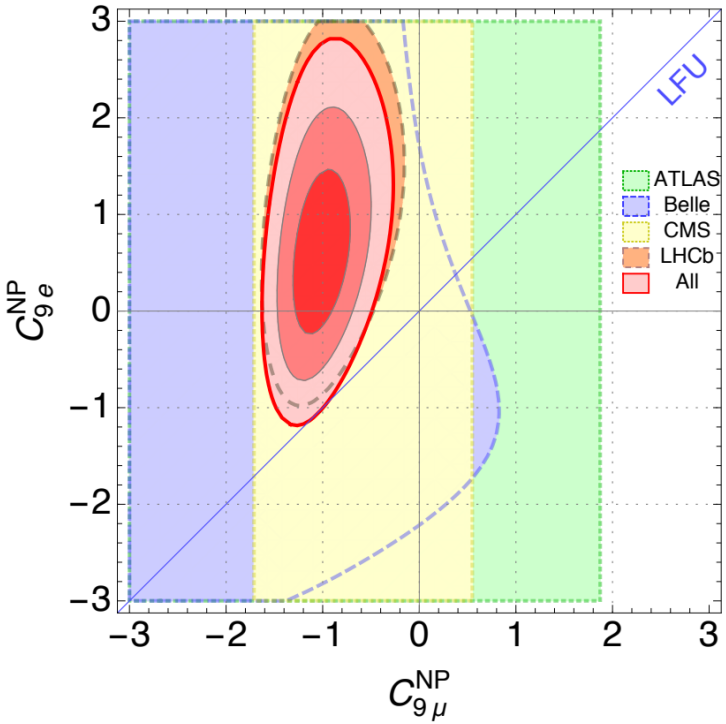
1704.05340



Phys. Rev. D 96, 055008 (2017)

- Many theorists perform global fits of $\mathcal{O}(150)$ measurements
- Pull for the SM at the level of 4.4-5 σ

Fits for Lepton Flavor Universality



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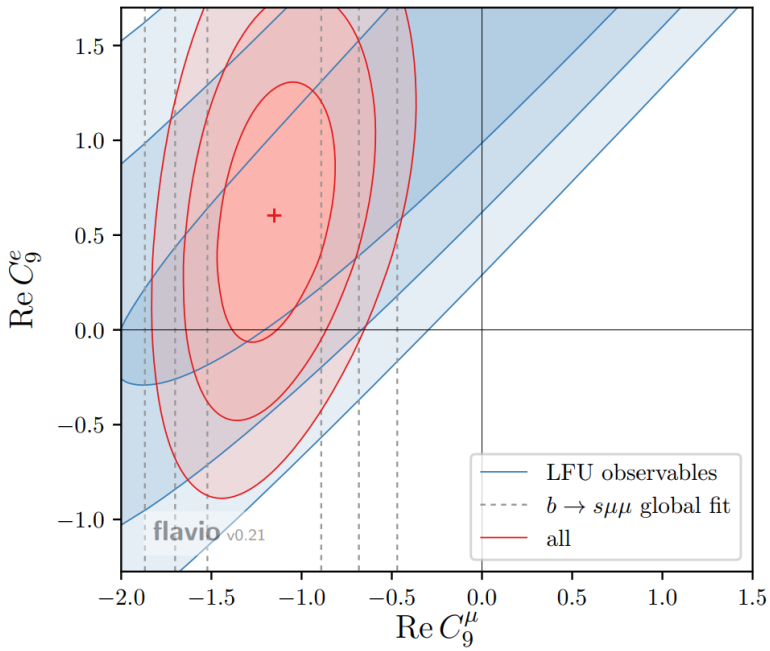
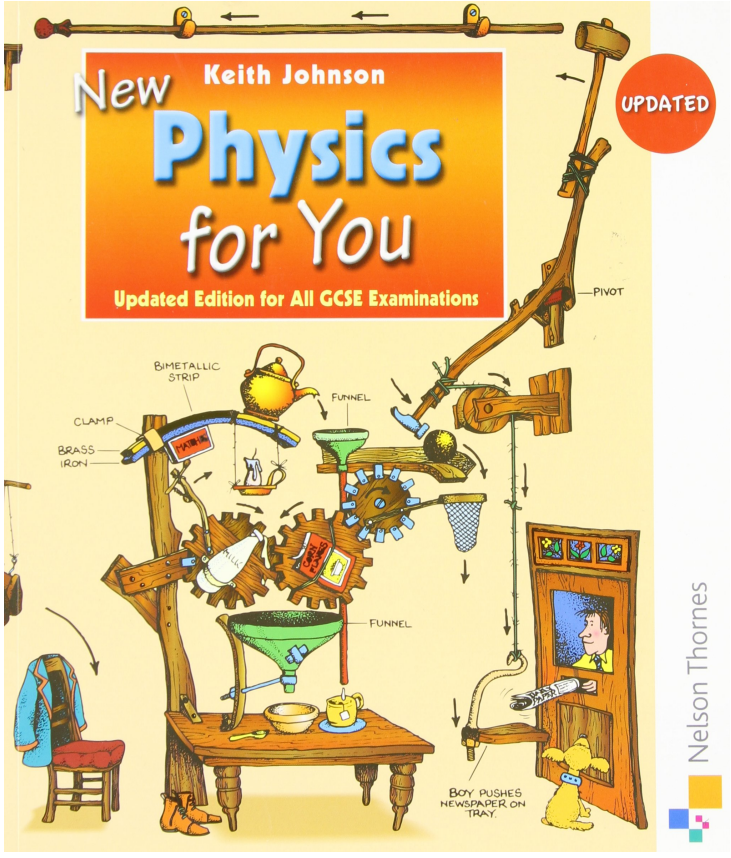


Phys. Rev. D 96, 055008 (2017)

- Lepton Flavor Non Universality favored with $> 3\sigma$

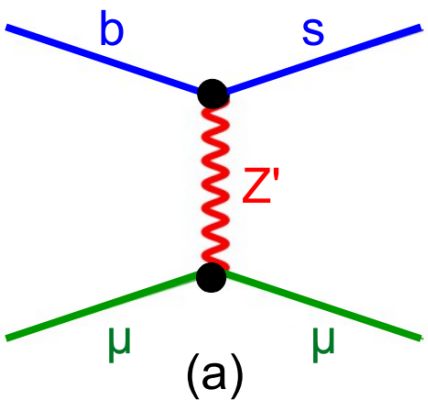
Did we find new Physics?

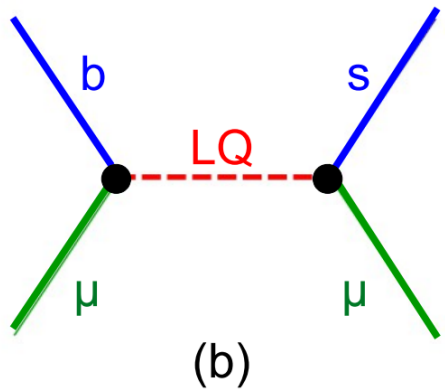
What does it mean?



Did we find new Physics?

- The anomalies are difficult to explain at once
- Two models are favored:





- Both cases may enhancement $b \to s\tau\tau$
- LQ: large enhancement of $b \to s\mu\tau$

Motivation for $b \to s\tau\tau$ at Belle

Motivation

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

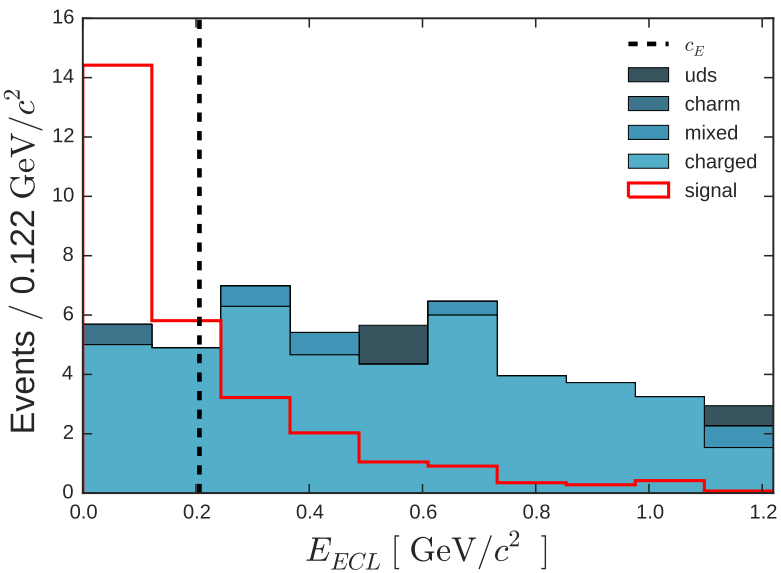
The $B^+ \to K^+\tau^+\tau^-$ Decay

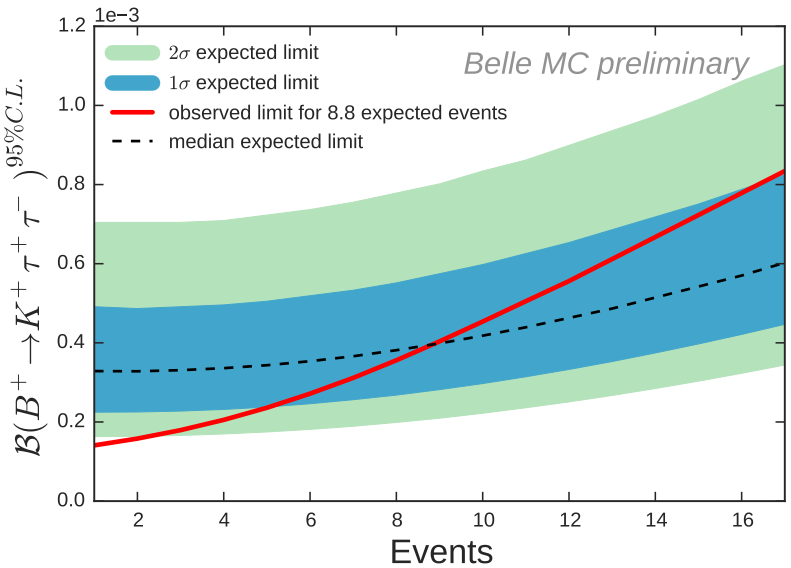
- $\mathcal{B}(B^+ \to K^+\tau\tau)^{SM} < 1.44(15) \times 10^{-7}$
- Some models may lead to a strong enhancement
- $\mathcal{B}(B \to K\tau^-\tau^+)^{MLFV} < 2 \times 10^{-4}$

  Alonso, R., Grinstein, B. & Camalich, J.M. J. High Energ. Phys. (2015) 2015
- Only experimental constraints by BaBar with $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at 90% C.L..

Simulation for $B^+ \to K^+\tau^+\tau^-$ at Belle

- Signal is Identified in calorimeter energy related observable E_{ECL}
- All systematic uncertainties are calculated
- Expected upper limit: $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 3.17 \times 10^{-4}$ at 90% C.L. on MC

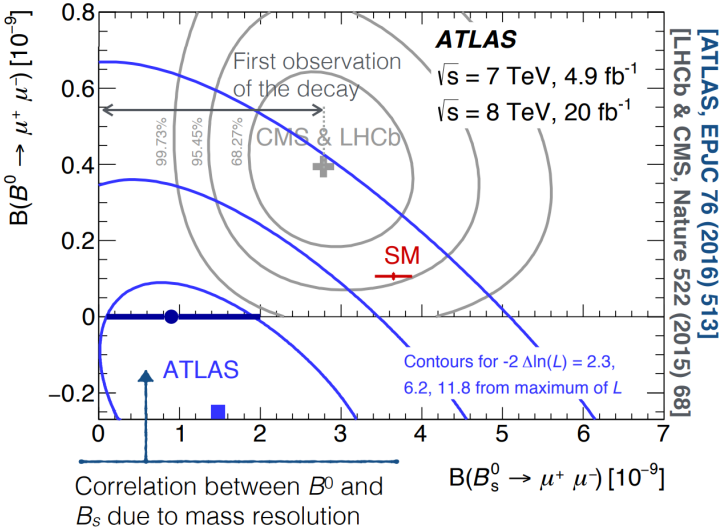




Important recent Measurements

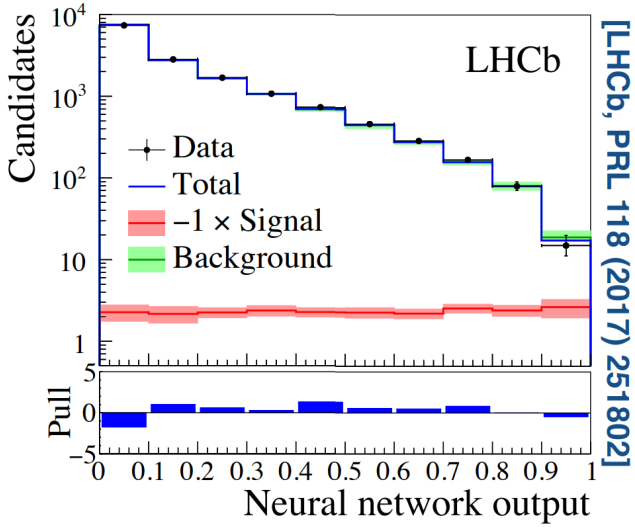
$B_{d,s} \to \mu\mu$

- Golden mode to study at LHC(b)
- LHCb: Single experiment observation of $B_s^0 \to \mu^+\mu^-$ with more than 7σ
- Powerful probe of models with enhanced (pseudo)scalar interactions



$B_{d,s} \to \tau\tau$

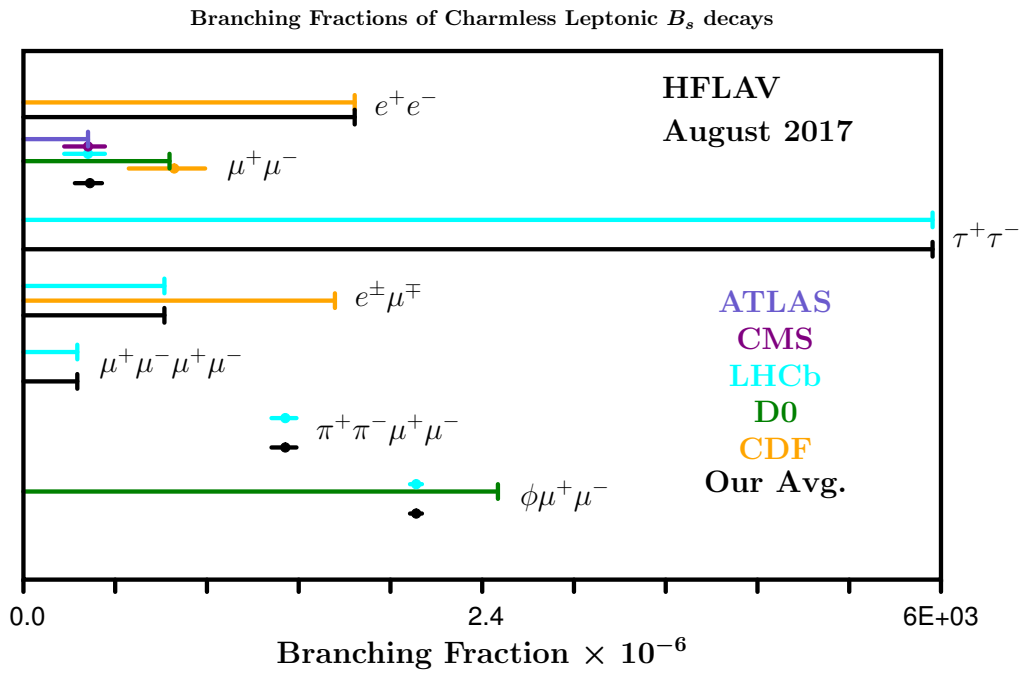
- LHCb measurement using $\tau \to \pi^-\pi^+\pi^-\nu_\tau$
- $\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} (95\%\mathrm{CL})$
- $\mathcal{B}(B_d^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} (95\%\mathrm{CL})$



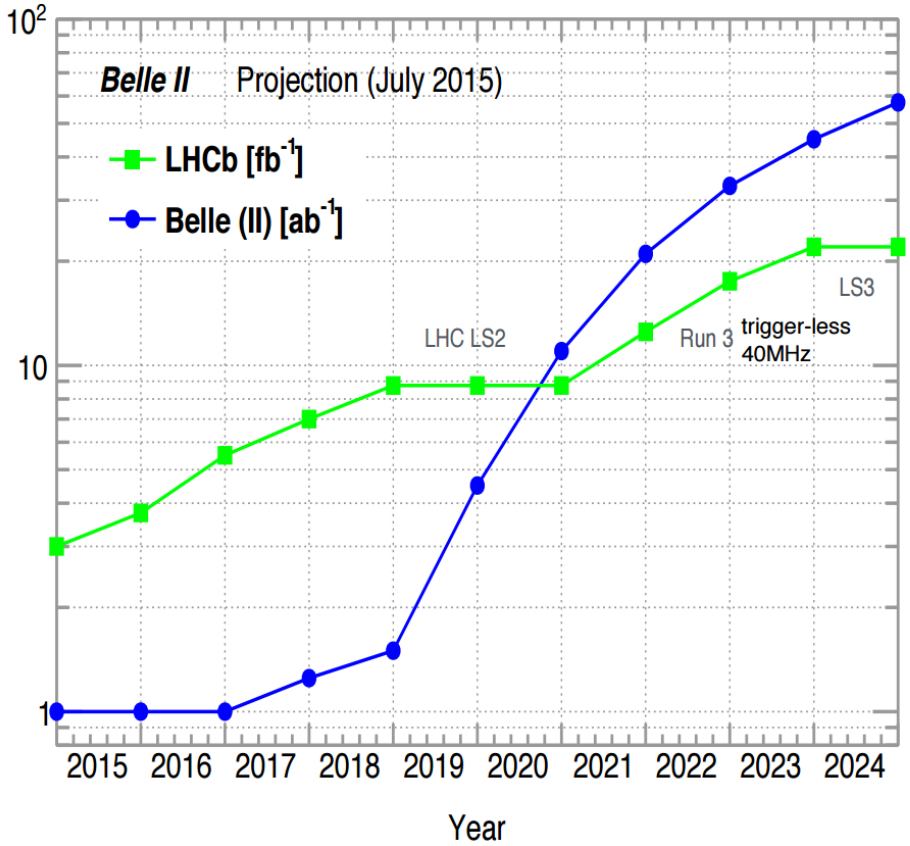
Important Measurements Wish-List

B_s^0

1. $B_s \to \phi e^+ e^-$
2. $B \to K^{(*)} \tau\tau$
3. $B \to K^{(*)} \mu\tau$
4. $B \to K^{(*)} \nu\nu$
5. $B_s \to \ell^+ \ell^-$
6. $B_s \to \ell^{+\prime} \ell^-$
7. ...



The next Generation of Flavor Factories



- B_s System
  CPV in $J/\psi\phi$, $\phi\phi$,
  CPV in Mixing
- $B \to \mu\mu$

B_s & charged tracks

- CKM phase γ in $B \to DK$
- CPV in B_d
- $B \to X_s$ ll (exclusive)
- $B \to X\gamma$ (exclusive)
- Charm physics
- Semi-leptonic B decays

- τ - physics: LFV
- $B \to D, D^* \tau\nu$

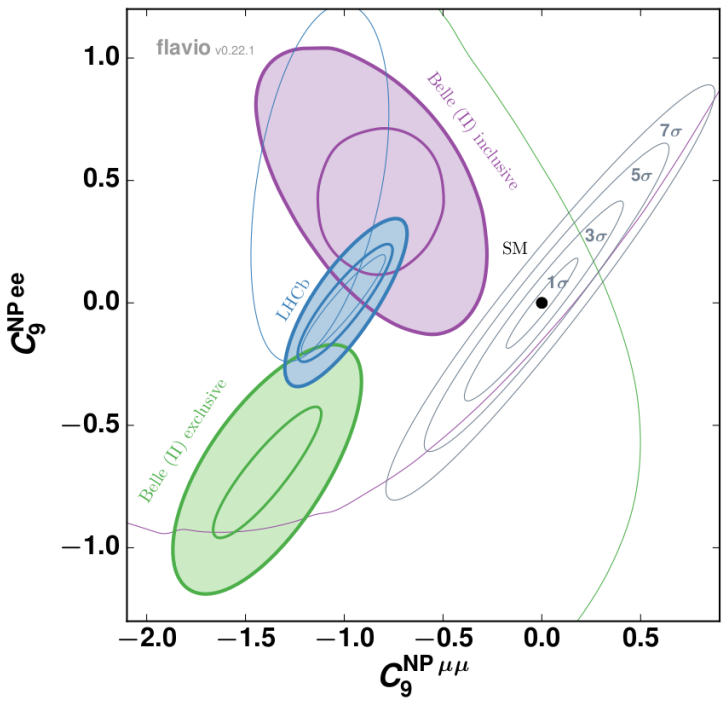
Important cross checks

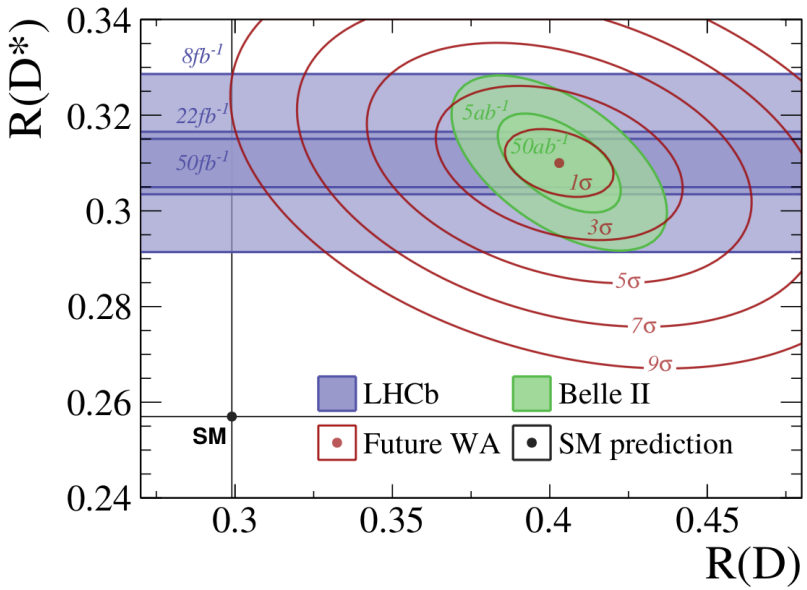
- $B \to X_s$ ll (inclusive)
- $B \to X\gamma$ (inclusive)
- $B \to \tau\nu, \mu\nu$
- $B \to K^*\nu\nu$, $B \to \nu\nu$

inclusive & neutrals

Slide adapted from J.Albrecht, DESY Seminar 25.10.16

Belle 2 and LHCb Projections





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

- Both Belle II and LHCb can individually verify the flavor anomalies

Next Generation of Experiments

- Both LHCb and Belle II have their strength and weaknesses
- We need to have a confirming experiment!

Conclusion

- We can find new physics
- In not too distant future

If there is new physics in the flavor sector, we will find it!

Next Generation of Experiments

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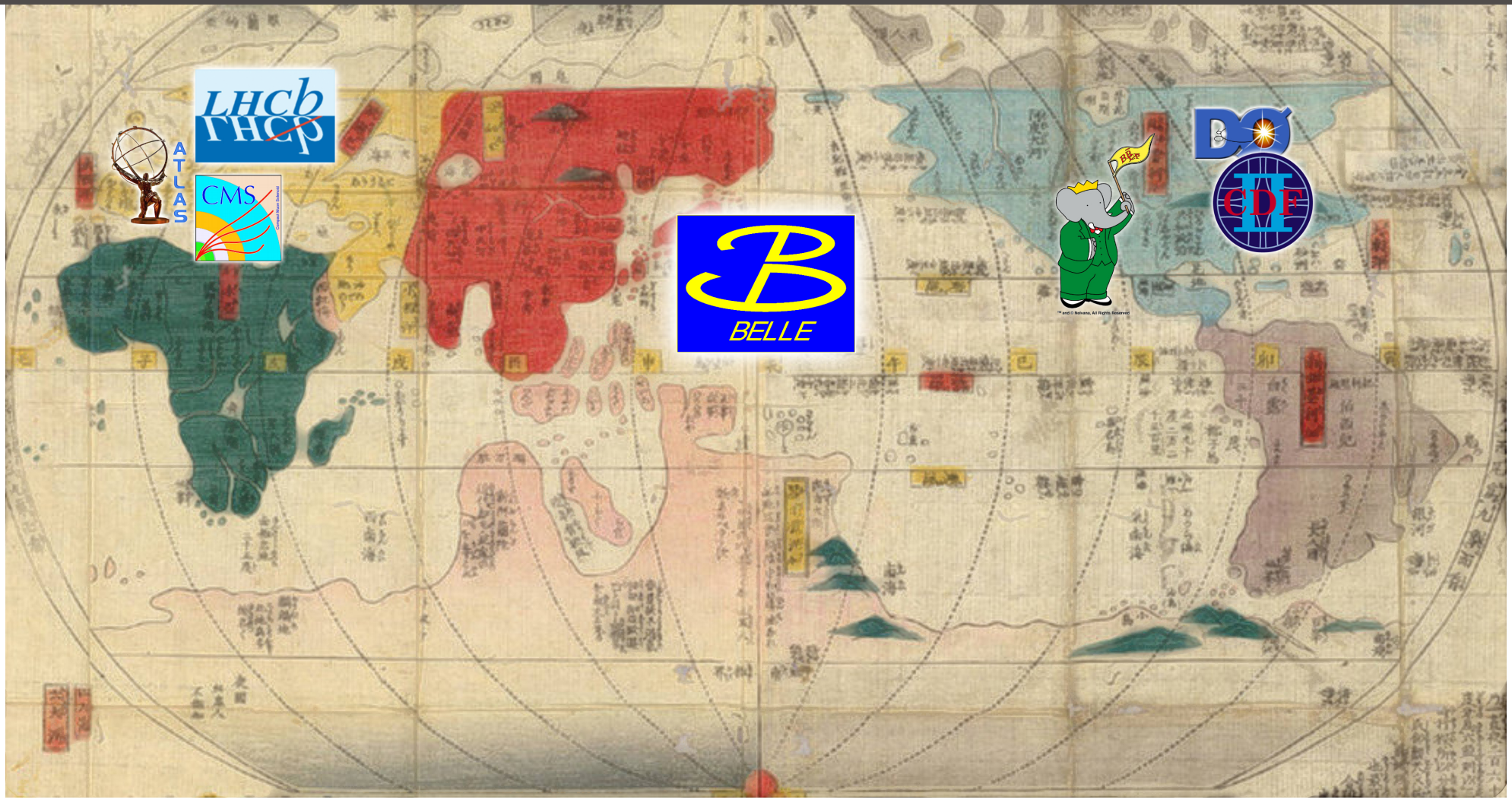

Thank you!