Probing New Physics With Experiment E36 at J-PARC

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for the TREK Collaboration

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J-PARC

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New Physics beyond the Standard Model

Big questions

- *Baryogenesis:* Asymmetry of matter and anti-matter in universe
- Dark matter
- Dark energy etc.

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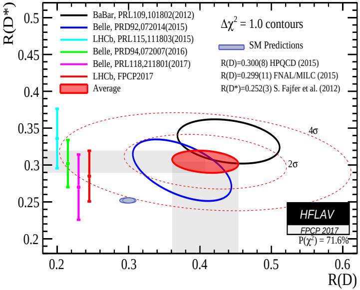
In the world of *weak interactions* do *electrons*, *muons* and *tauons* behave the same way?

Lepton universality violation?

$\mu - \tau$

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

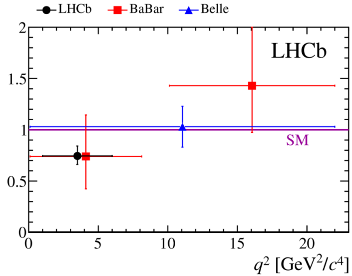


HFLAV average of combined $R(D)$ and $R(D^*)$ is 4.1σ from the SM prediction

Lupato (PANIC 2017)

$\mu - e$

$$R_K[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to K \mu^+ \mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to K e^+ e^-)}{dq^2}}$$



$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \text{ (sys)}$$

2.6σ deviation!

Lepton universality violation?

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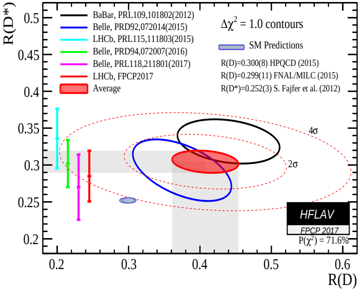

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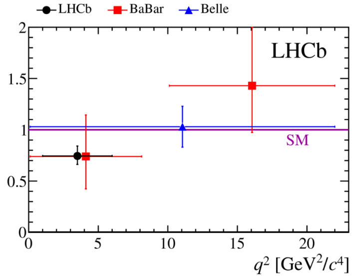

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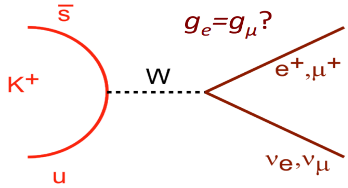
Lepton non-universality is the flagship for physics beyond the Standard Model

Outline

Lepton universality in K^+ decays



2-body decay of K^+

$$\Gamma(K_{l2}) = g_l^2 \left(\frac{G^2}{8\pi}\right) f_K^2 m_K m_l^2 \left[1 - \left(\frac{m_l^2}{m_K^2}\right)\right]^2$$

Lepton universality in K^+ decays

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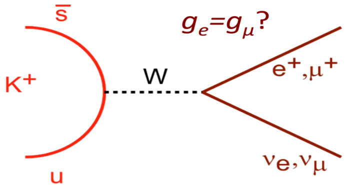

Decay width ratio of electronic (K_{e2}) and muonic ($K_{\mu 2}$) decay modes

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta_r)$$

Lepton universality in K^+ decays

2-body decay of K^+

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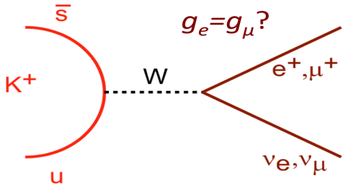

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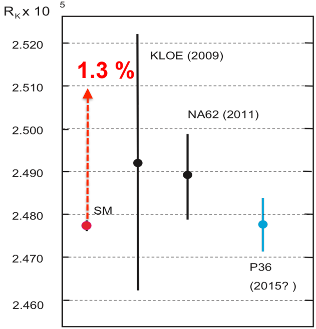
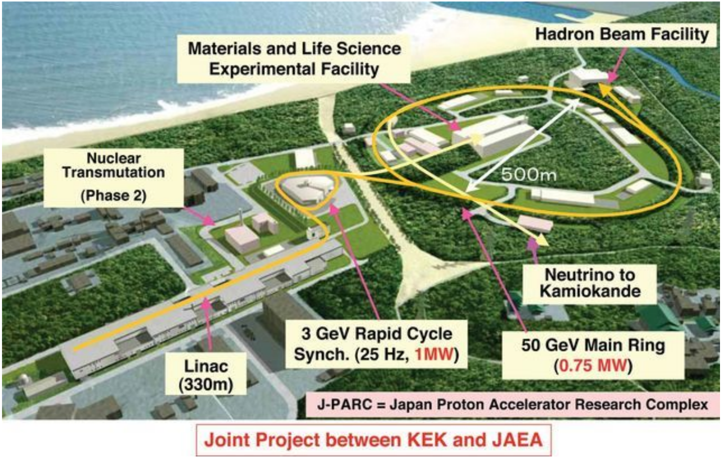
- Hadronic *form factors* cancel
- Strong *helicity* suppression of electronic channel enhances sensitivity to effects beyond SM
- SM prediction is highly precise: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

- **Highly precise SM value**
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$ (with $\delta_r = -0.036$), $\delta R_K/R_K = 0.04\%$
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)
- **KLOE @ DAΦNE (in-flight decay)**
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
  F. Ambrosino et al., Eur. Phys. J. C64, 627 (2009)
- **NA62 @ CERN-SPS (in-flight decay)**
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
  C. Lazzeroni et al., PLB719, 105 (2013)
- **World average (2012)**
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$
- **Systematics:**
  - In-flight-decay experiments: kinematics overlap
  - E36 stopped K^+: detector acceptance and target
  - E36 complementary to in-flight experiments
- **E36 goal:** $\delta R_K / R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst) [0.25% total]



M. Kohl (ICHEP 2016)

Bird's eye view of J-PARC



Timeline of TREK/E36

TREK: Time Reversal Experiment with Kaons

December 2014

- Installed detector components

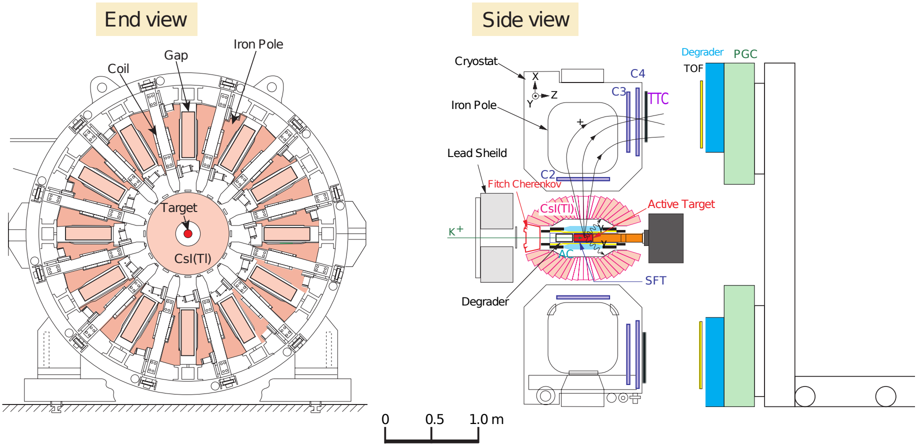
February - June 2015

- Completed installation of C3 & C4
- Cabling
- Detector maintenance

September - December 2015

- Physics run
- Data taking

E36 detector geometry



Stopped K^+ method
K1.1BR beamline
K^+ stopping target

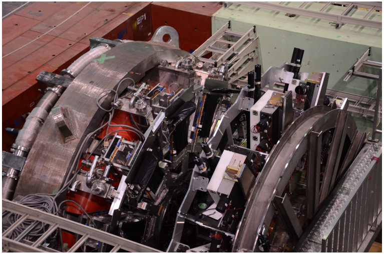
Momentum measurement
MWPC (C2, C3, C4)
Spiral fiber tracker (SFT)
Thin trigger counter (TTC)

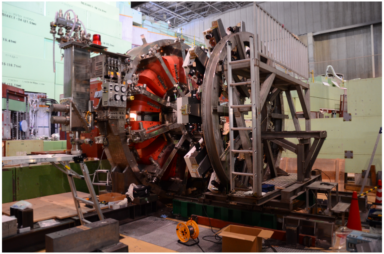
Particle ID
TOF
AC
PGC

Gamma ray
CsI(TI)

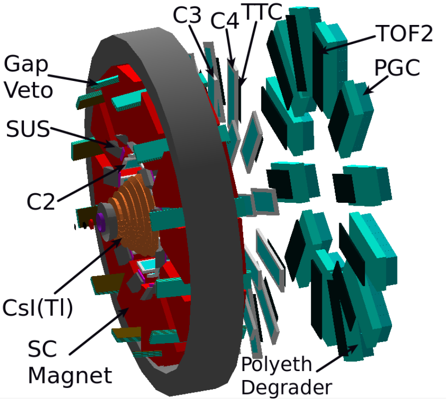
Outline

Geant4 generated geometry



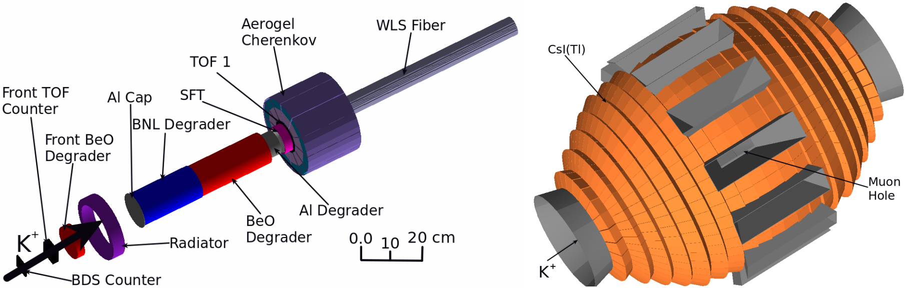


- Detector Assembly



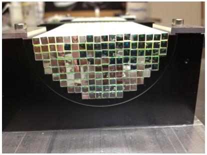
- Geant4 E36 detector

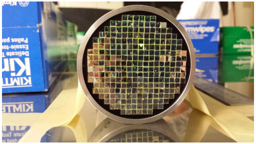
Central Detector

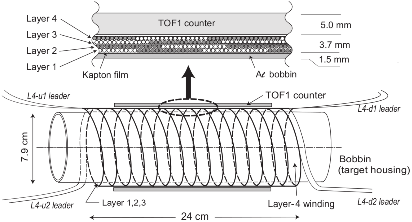


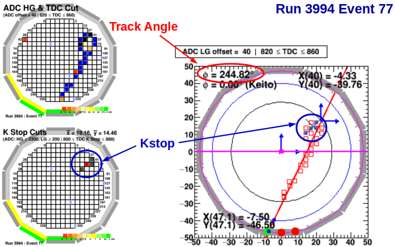
- Central Detector

Target and spiral fiber tracker (SFT)





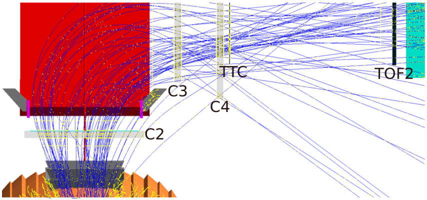


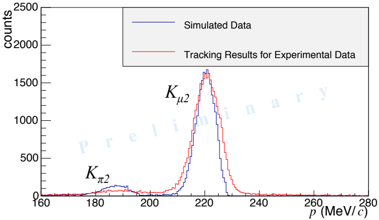


- Determine the K^+ stopping position
- Determine the lepton track length
- Segmented target in conjunction with the SFT yields transverse and longitudinal information

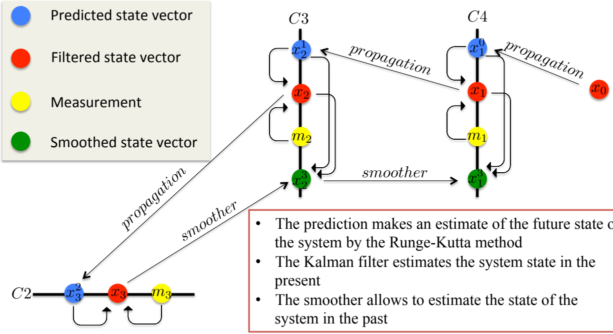
Outline

Tracking: momentum reconstruction and Kalman Filter





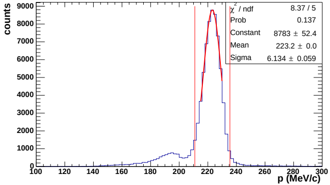
Kalman Filter

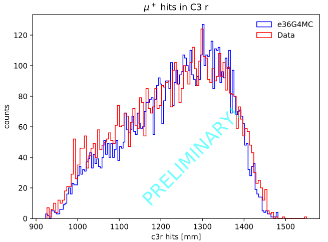


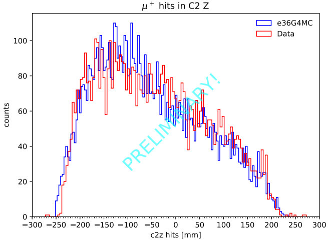
- The prediction makes an estimate of the future state of the system by the Runge-Kutta method
- The Kalman filter estimates the system state in the present
- The smoother allows to estimate the state of the system in the past

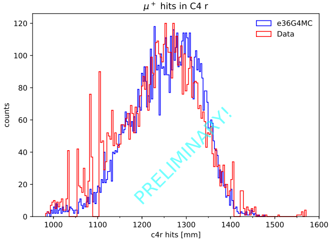
(T. Cao)

$K^+ \to \mu^+ \nu_\mu \; (p_{\mu^+} = 236 \text{ MeV}/c)$









- Trigger on Target $\otimes$ TOF1 $\otimes$ TTC $\otimes$ TOF2
- $z = 2.5cm$ and $x = y = 0.0cm$ $\sigma_z = 8.75cm$, $\sigma_{x,y} = 0.15cm$

Particle identification systems

Preliminary PID results

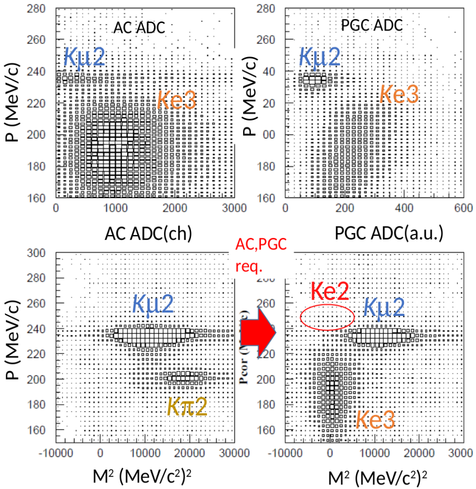
- e^+ are selected by aerogel cherenkov (AC), lead-glass counter (PGC) and TOF detectors
- PID will be performed by combing all three detectors

$K_{\mu 2}$: $K^+ \to \mu^+ \nu_\mu$

$K_{\pi 2}$: $K^+ \to \pi^+ \pi^0$

K_{e2}: $K^+ \to e^+ \nu_e$

K_{e3}: $K^+ \to \pi^0 e^+ \nu_e$



Outline

1. Preliminaries
   - Lepton universality in K^+ decays
   - Detector geometry
2. Simulation and real geometry
   - Central detector system
3. Tracking & PID systems
   - Kalman Filter, magnetic field etc.
   - $K_{\mu 2}$ hit profile
   - PID systems
4. Closing
   - $K_{\pi 2}$ tracks

Summary and Remarks

- The TREK/E36 experiment has been run and decommissioned
- Data analysis is currently ongoing
- Currently working on improving the energy-loss in Geant4 and tracking packages
- Very good agreement between Geant4 and experimental data for $K_{\mu 2}$ hit distribution
- Expect preliminary results by the fall

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Lepton non-universality is the flagship for BSM physics

Collaboration

Approximately 30 collaborators

Spokespeople:
M. Kohl, S. Shimizu

CANADA
University of British Columbia
Department of Physics and Astronomy
TRIUMF

USA
University of South Carolina
Department of Physics and Engineering
Iowa State University
College of Liberal Arts & Sciences
Hampton University
Department of Physics

JAPAN
Osaka University
Department of Physics
Chiba University
Department of Physics
High Energy Accel. Research Organization (KEK)
Institute for Particle and Nuclear Studies

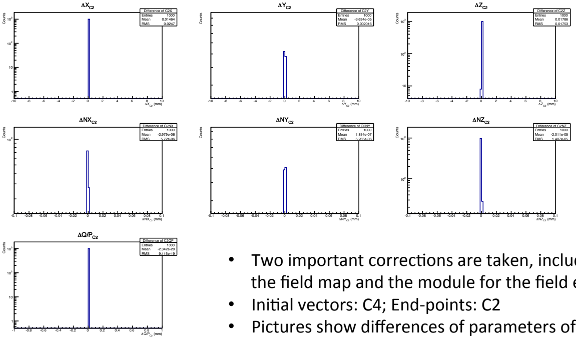
RUSSIA
Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)


ありがとうございました
(Thank You)

Back up slides

Tracking: propagation with G4 and reconstruction with Kalman Filter

Use *geantinos* as the primary particle
Propagate through magnetic field and compare the results



Geantinos propagate in the field without any physics.

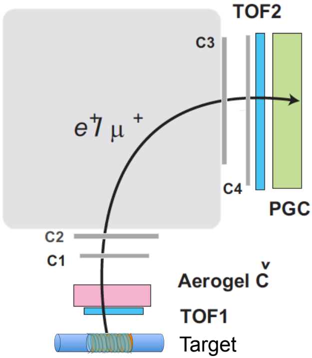
- Two important corrections are taken, including the setup of the field map and the module for the field evaluation.
- Initial vectors: C4; End-points: C2
- Pictures show differences of parameters of state vectors at C2 extracted from two packages
  - ✓ Magnetic field map is consistent with each other
  - ✓ Evaluation of magnetic field is consistent with each other

Runge-Kutta methods are consistent

T. Cao

PID with:

- TOF
- Aerogel Č
- Lead glass

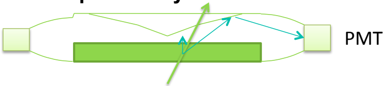


TOF

Flight length	250 cm
Time resolution	<100 ps
Mis-ID probability	7×10^{-4}

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%



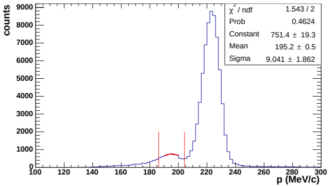
Lead glass (PGC)

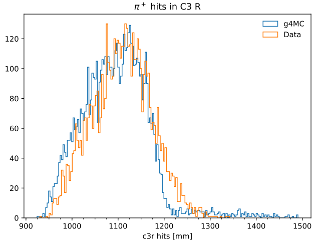
Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

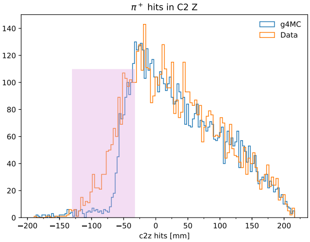
$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

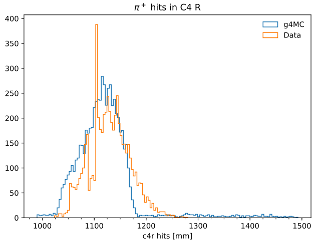
M. Kohl (ICHEP 2016)

$K^+ \to \pi^+\pi^0 \; (P_{\pi^+} = 205 \text{ MeV}/c)$









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Possible New Physics that violate $\mu - e$ universality

Proposed NP models

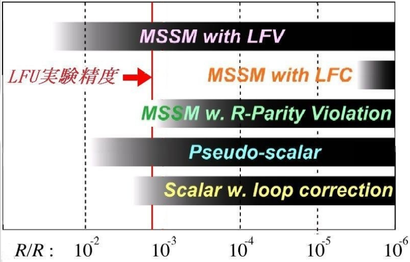
- MSSM with R-parity violation
- Pseudo-scalar interaction
- Scalar with loop Correction
- MSSM with LFV for K_{e2}

SUSY effects

- Charged Higgs H^+ mediated LFV SUSY
  $\rightarrow$ Large effect but strong constraints from

  $$B_s \rightarrow \mu^+ \mu^-$$

  J. Girrbach and U. Nierste, arXiv:1202.4906



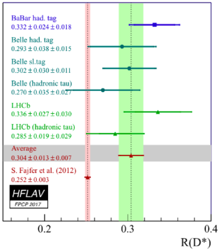
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \mu \nu)}$$

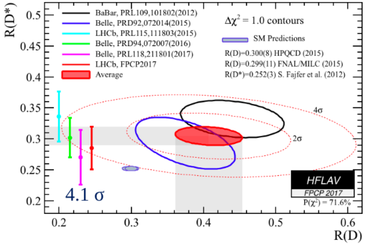
Combined measurement of $R(D^*)$

- $R(D^*)_{Hadronic} = 0.285 \pm 0.019(stat) \pm 0.025(syst) \pm 0.014(ext)$
- $R(D^*)_{Muonic} = 0.336 \pm 0.027(stat) \pm 0.030(syst)$

LHCb$_{ave}$: $R(D^*) = 0.306 \pm 0.027$ $\to$ 2.1σ above the SM prediction

HFLAV world$_{ave}$: $R(D^*) = 0.304 \pm 0.015$ $\to$ 3.4 σ above the SM





Lupato (PANIC 2017)

HFLAG average of combined $R(D)$ and $R(D^*)$ is 4.1σ from the SM prediction

Lepton non-universality in the $e - \mu$ sector

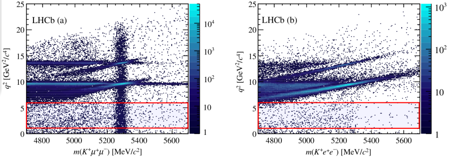
$$R_K[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to K\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to Ke^+e^-)}{dq^2}}$$

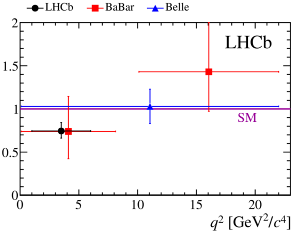
- SM prediction: $R_K^{SM} = 1 + 0(10^{-2})$
- Signal: $1 < q^2 < 6$ GeV^2

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036\ (\mathrm{sys})$$

2.6σ deviation!

$q^2 = m^2_{ll}$





Lupato (PANIC 2017)

Lepton non-universality is the flagship for physics beyond the Standard Model