Measurements of lepton flavor universality at LHCb

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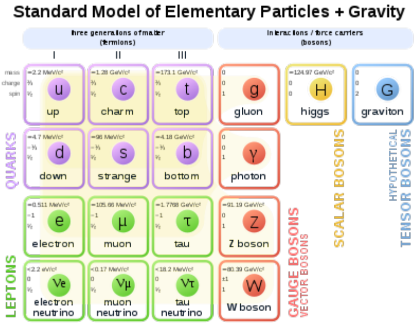
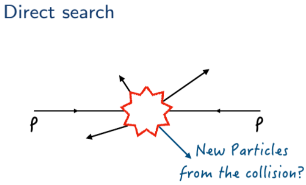
Lepton flavor universality in the SM

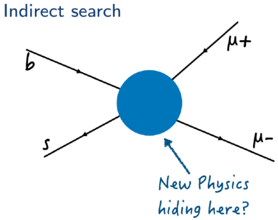


- Electroweak gauge bosons couple with equal strength to the three generations of leptons - LFU (accidental symmetry - not the consequence of a gauge symmetry)
- LFU broken only by Yukawa interactions - 3 generations differ only by mass

Are there undiscovered particles that may cause LFU?

Direct vs. Indirect searches





- Use full energy of collision for production of new particle
- Direct observation of new particle in eg. invariant mass distribution of decay products
- ATLAS/CMS used this method to find the Higgs

- NP can enhance rate of SM suppressed/ forbidden decays or change angular distributions
- Search for discrepancies between SM prediction and precise measurement of observables
- Access higher mass scales through virtual contributions to decays

Testing LFU in the SM

Compare the same observable for processes where only the lepton flavour differs

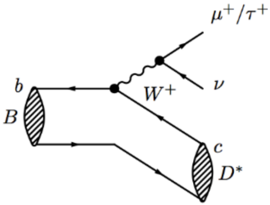
- Differences in kinematic/topological observables eg. an angular analysis
- Differences in decay rates eg. ratio of branching fractions

What decays should we look at to have the best sensitivity to new LFU violating effects?

Flavor changing charged currents

Flavour changing charged currents (FCCC) like $b \to cl^+\nu_l$

- Tree-level semileptonic decays - missing neutrino energy
- Theoretically clean
- Branching fractions of a few % - high statistics
- BSM theories predict greatly enhanced coupling to 3rd generation - compare τ to e or μ
- Sensitive to NP contributions up to masses of 1 TeV

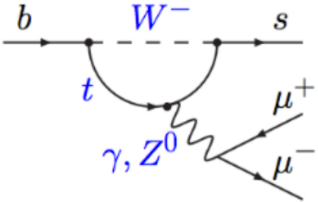


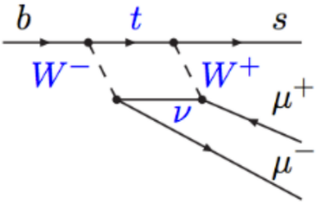
Flavor changing charged current

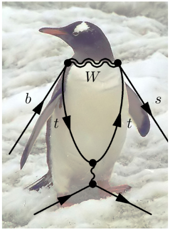
Flavor changing neutral currents

Flavour changing neutral currents (FCNC) like $b \to s l^+ l^-$

- Only occur via loops in SM - subject to large hadronic uncertainties
- Strongly suppressed in SM - branching fractions $\mathcal{O}(10^{-7})$
- NP, heavier particles can enter loops as virtual particles
- Sensitive to NP contributions up to masses of 100 TeV!





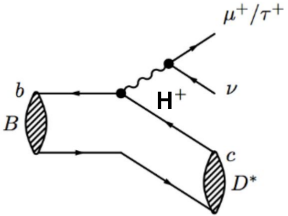


SM electroweak penguin and electroweak box

Models supporting LFU

For LFU we need new particles that couple differently to lepton generations

- Additional fields
  - 2 Higgs Doublet Model
- Extensions to gauge group
  - Extra U(1) - Z' with non-universal couplings
  - GUTs with Leptoquarks
- Larger frameworks
  - SUSY (MSSM)



Charged Higgs in 2HDM. Higgs coupling mass dependent

Models supporting LFU

For LFU we need new particles that couple differently to lepton generations

- Additional fields
  - 2 Higgs Doublet Model
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  - Extra U(1) - Z' with generation-dependent couplings
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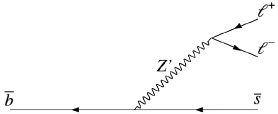

Neutral boson introduced through extra U(1) gauge symmetry. Allows FCNC at tree level

Models supporting LFU

For LFU we need new particles that couple differently to lepton generations

- Additional fields
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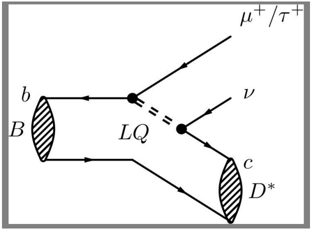


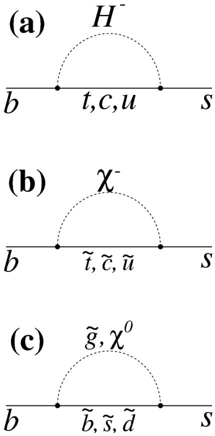
LQ carry both lepton and baryon number. Predict large leptoquark couplings between 3rd generation quarks and leptons

GUT: Grand Unified Theories are extensions of the SM with larger symmetry groups. Candidate groups for a GUT model must contain the SM group as a subgroup

Models supporting LFU

For LFU we need new particles that couple differently to lepton generations

- Additional fields
  - 2 Higgs Doublet Model
- Extensions to gauge group
  - Extra U(1) - Z' with non-universal couplings
  - with Leptoquarks
- Larger frameworks
  - SUSY (MSSM)



SUSY charged Higgs, squarks, charginos, gluinos

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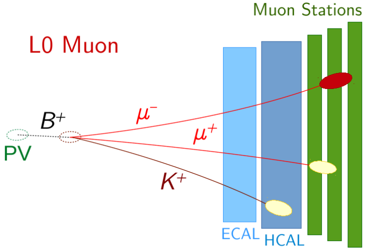
Reconstruction leptons at LHCb - muons

Easy

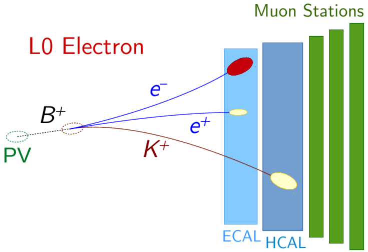
- Stable particles
- No significant Bremsstrahlung
- Only particles to reach muon chambers at end of detector - clean signature to trigger on



Reconstruction leptons at LHCb - electrons

Harder

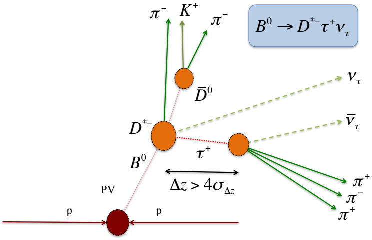
- Radiate Bremsstrahlung at a rate 10^8 times greater than muons greatly complicating reconstruction (even after Brem recovery)
- Much lower trigger efficiency
  - Electrons identified in Calorimeter. Higher occupancy means higher trigger thresholds
- PID and track reconstruction efficiencies lower



Reconstruction leptons at LHCb - taus

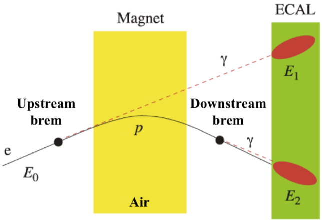
Hardest

- Not stable - lifetime approx. 10^{-12}s
- Have to reconstruct as hadronic or semileptonic decay with neutrinos $\tau \to \pi\pi\pi\nu$ or $\tau \to \mu\nu\nu$
- Neutrinos $\to$ missing mass $\to$ poorly resolved signal peak



Bremsstrahlung recovery for electrons

LHCb tries to recover the energy lost by electrons through Bremsstralung
- If electron radiates photon after magnet
  - momentum measured correctly through track curvature in magnetic field
  - photon hits same ECAL cells as electron measuring energy correctly
- If electron radiates photon before magnet
  - wrong momentum determined
  - photon hits different ECAL cells as electron - wrong energy determined



Brem recovery - search for neutral clusters with $E_T > 75$ MeV in region of ECAL defined by extrapolation of electron track

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LFU measurements - the $R(X)$ family

FCCC - tree level

- $R(D^*)$
- $R(J/\psi)$

FCNC - loop level

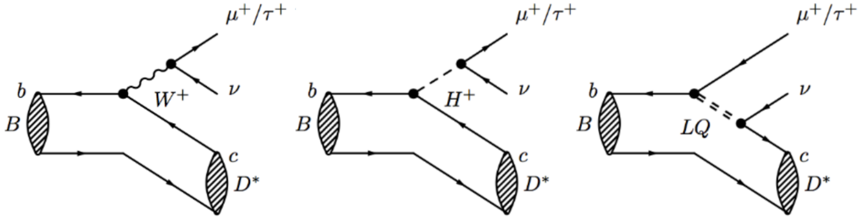
- $R(K)$
- $R(K^{*0})$

LHCb is in a unique position to access decays of all b-hadron species

$R(D^*)$

$$R(D^*)^{SM} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*0}\tau^-\bar{\nu_\tau})}{\mathcal{B}(\bar{B}^0 \to D^{*0}\mu^-\bar{\nu_\mu})} = 0.252 \pm 0.003$$

- Precise SM theory estimate due to cancellation of uncertainties associated with strong interaction in B to D^* transition
- SM value differs from unity due to phase-space effects
- Sensitive to NP particles that preferentially couple to 3rd generation of leptons

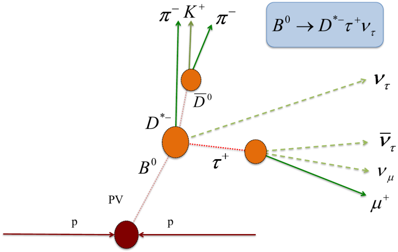


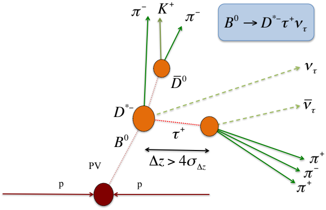
SM BSM BSM

$R(D^*)$

$$R(D^*)^{SM} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*0}\tau^-\bar{\nu_\tau})}{\mathcal{B}(\bar{B}^0 \to D^{*0}\mu^-\bar{\nu_\mu})} = 0.252 \pm 0.003$$

- Precise SM theory estimate due to cancellation of uncertainties associated with strong interaction in B to D^* transition
- SM value differs from unity due to phase-space effects
- Sensitive to NP particles that preferentially couple to 3rd generation of leptons
- Tau reconstructed in leptonic or hadronic mode

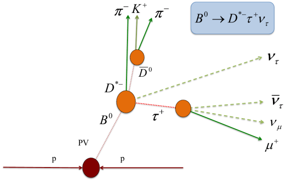


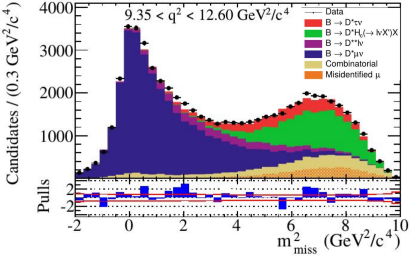


$R(D^*)$ - leptonic mode

- For leptonic mode identical visible final state for $\bar{B}^0 \to D^{*0}\tau^-\bar{\nu_\tau}$ and $\bar{B}^0 \to D^{*0}\mu^-\bar{\nu_\mu}$
- Exploit kinematic distributions resulting from $\mu - \tau$ mass different and extra neutrinos in τ decay

$$m^2_{miss} = (p^\mu_B - p^\mu_B - p^\mu_D - p^\mu_\mu)^2$$

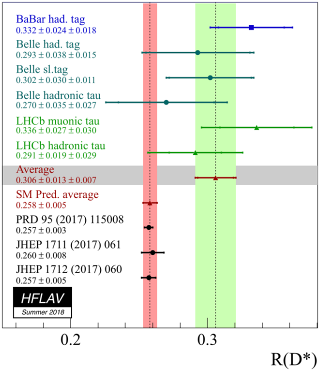




Hadronic mode much harder... substantial background from $B \to D^{*-}3\pi X$

$R(D^*)$

$R(D^*)^{lep} = 0.336 \pm 0.027 \pm 0.030$ $\qquad$ $R(D^*)^{had} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$



Three independent experiments, 6 individual measurements all lie above SM prediction

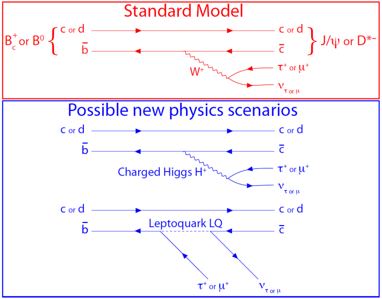
$R(D^*)$ world average 3σ above SM prediction

$R(J/\psi)$

$R(J/\psi)$ is complementary to $R(D^*)$ - change in spectator quark

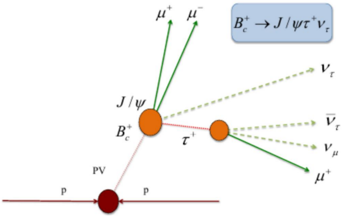
$$R(J/\psi)^{SM} = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^-\bar{\nu_\tau})}{\mathcal{B}(B_c^+ \to J/\psi\mu^-\bar{\nu_\mu})} = 0.252 \pm 0.003$$

- Again sensitive to NP particles that preferentially couple to 3rd generation of leptons
- Only leptonic mode so far

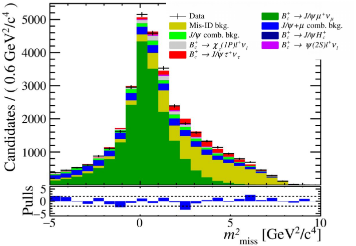


- Identical visible final state - 3 muons
- Exploit distinct kinematic distributions resulting from $\mu - \tau$ mass different and extra neutrinos in τ decay

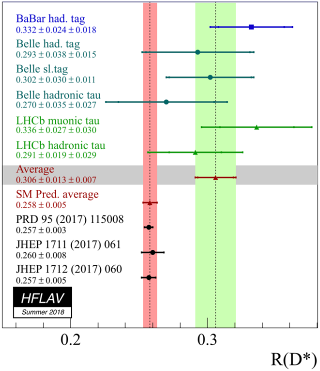
$$m_{miss}^2 = (p_B^\mu - p_B^\mu - p_D^\mu - p_\mu^\mu)^2$$

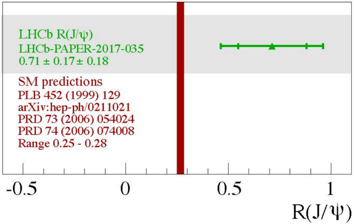


$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$
(2σ tension with SM)



$R(J/\psi)$



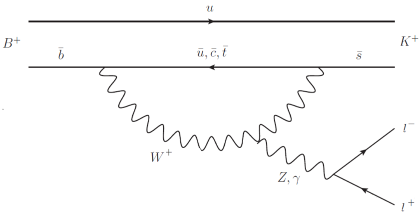


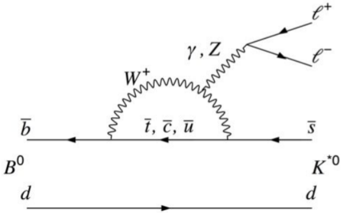
$R(D^*)$ leptonic, $R(D^*)$ hadronic, $R(J/\psi)$ are different decays with different efficiencies/systematics - all show deviation from SM in same direction

$R(K^{(*0)})$

$R(K)$ and $R(K^{(*0)})$ differ only by the spectator quark involved

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



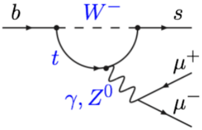


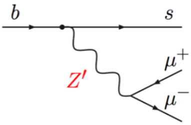
The following corresponds to $R(K)$ but the principles are very similar for $R(K^{*0})$

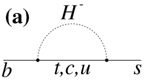
$R(K^{(*0)})$

$$R(K)^{SM} = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1 \pm 0.01$$

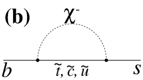
- Precise SM theory estimate due to cancellation of hadronic uncertanties
- Sensitivity to NP at both tree-level (Z', LQ) and from heavy NP particles entering loops



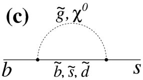




SUSY charged Higgs



SUSY chargino



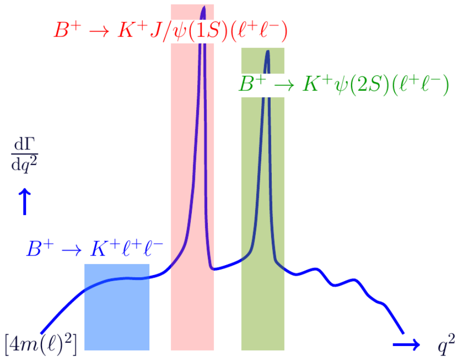
SUSY gluino/neutralino

Note: Although some of the SUSY particles would not cause LFU, as part of these BF ratio measurements we also report the single BF results, albeit with larger systematic errors. These heavy SUSY particles would enhance BF above their SM predictions

$R(K^{(*0)})$

$R(K)$ performed in specific regions of phasespace

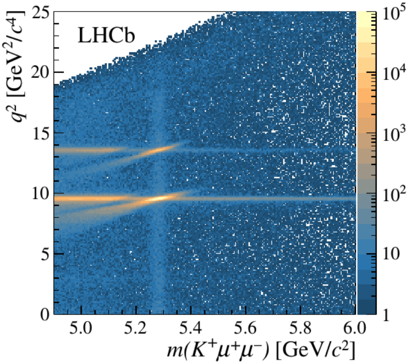
- Charmonium resonances dominate $B^+ \to K^+ l^+ l^-$ final state
- Select dilepton invariant mass range (q^2) 1-6 GeV

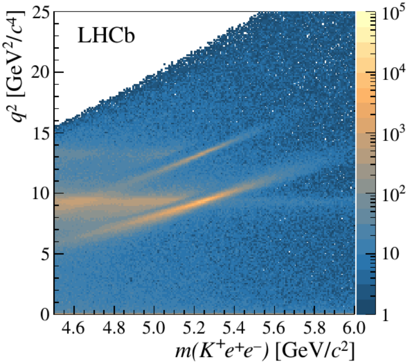


Resonant and nonresonant separated in q^2

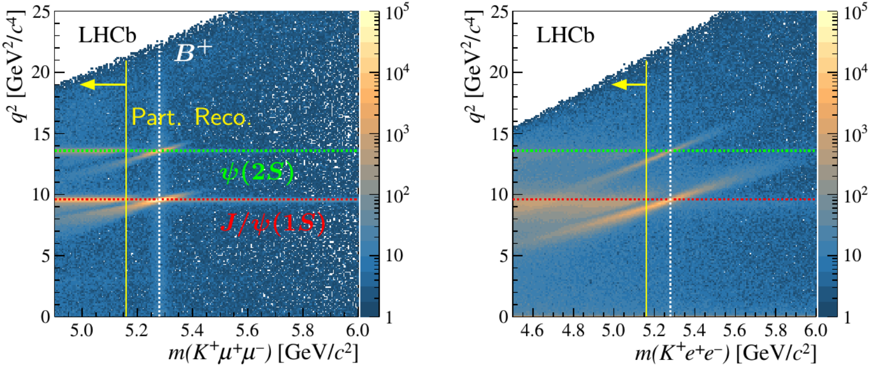
$R(K^{(*0)})$

Bremsstrahlung (even after Brem recovery) means poorer resolution of electron channels - long radiative tail. Easily seen in 2D plot of B candidate mass and q^2





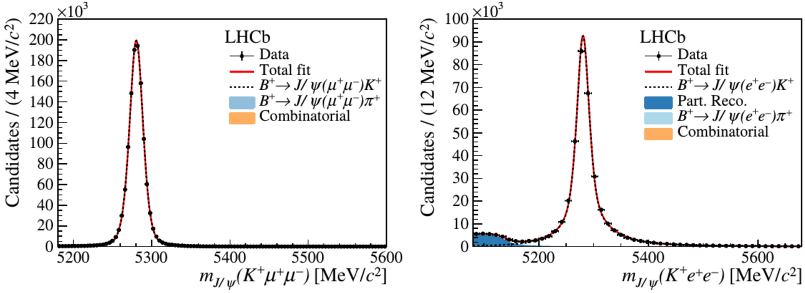
This makes it difficult to separate from partially reconstructed background



$R(K^{(*0)})$

Fitting to resonant modes -

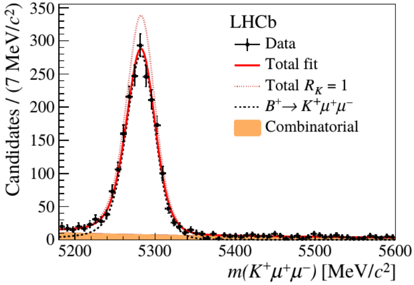
- Muon channel - simple mass cut to remove partially reconstructed background. Nicely separated in B candidate mass
- Electron channel - small radiative tail $->$ have to fit wider mass range. Saved here by mass constraint on J/ψ which negates effect of Bremsstrahlung

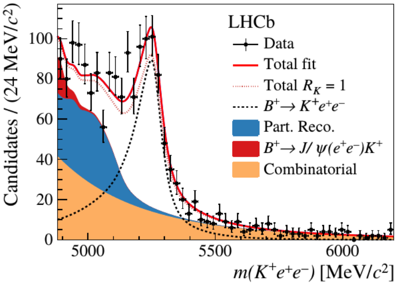


$R(K^{(*0)})$

Fitting to nonresonant modes -

- Muon channel - more challenging due to lower statistics
- Electron channel - cannot use J/ψ mass constraint. Very large radiative tail means signal overlaps with partially reconstructed background and even resonant mode that leaks into q^2 region

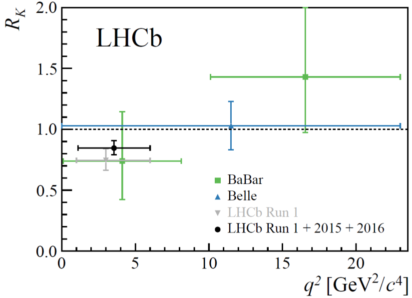


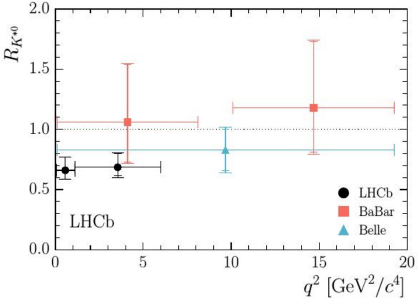


$R(K^{(*0)})$

$R(K) = 0.846^{+0.090}_{-0.054}\,^{+0.014}_{-0.016}$
2.5σ tension with SM

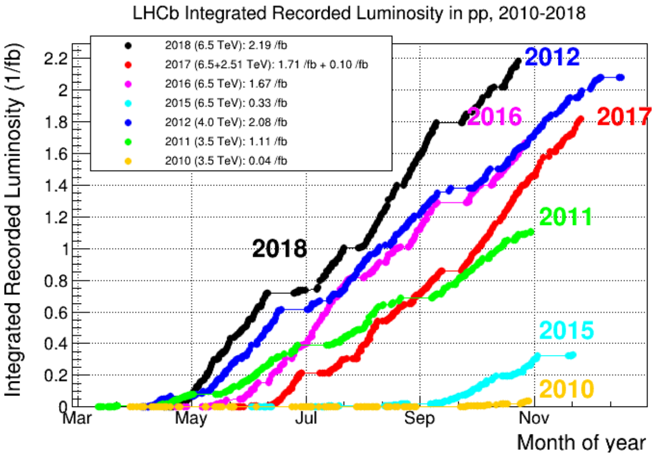
$R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05$
2.1-2.5σ tension with SM



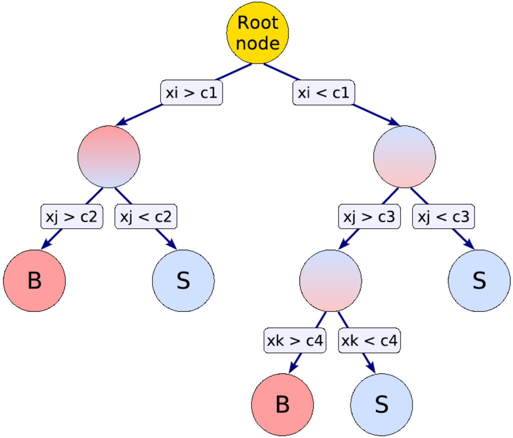


Both $R(K)$ and $R(K^{*0})$ show tensions in the same direction

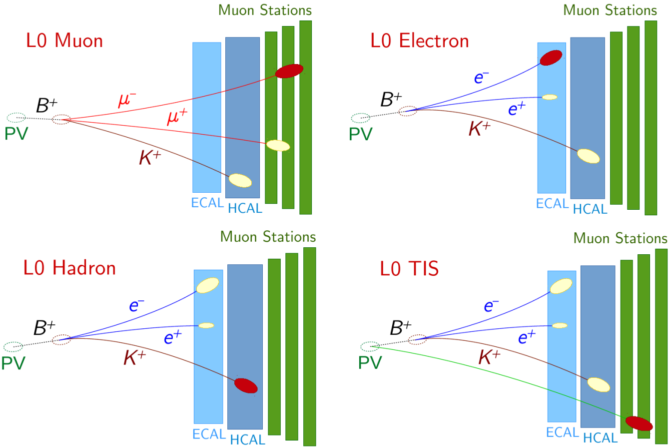
LHCb datasets



Boosted decision trees



$R_{K^{(*)}}$ triggers


L0 Muon
Muon Stations
B^+
PV
μ^-
μ^+
K^+
ECAL
HCAL
L0 Electron
Muon Stations
B^+
PV
e^-
e^+
K^+
ECAL
HCAL
L0 Hadron
Muon Stations
B^+
PV
e^-
e^+
K^+
ECAL
HCAL
L0 TIS
Muon Stations
B^+
PV
e^-
e^+
K^+
ECAL
HCAL