Milano Bicocca University

LEPTON FLAVOUR UNIVERSALITY AT THE LHCB EXPERIMENT

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Symmetries in indirect searches for New Physics

- Symmetries play an important role in physics
  - Standard Model: $SU(3) \times SU(2) \times U(1)$ (local) gauge invariance

- Symmetries also imply conservation rules

The most beautiful theorem in physics:

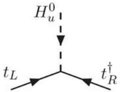
To each continuous symmetry of a system (...) corresponds a conserved quantity.

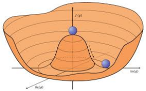
- Putting under stress conservation laws and the symmetries they stem from is one of the most powerful tools that we have in the indirect search for new physics
  - This catches a lot of the investigations done at LHCb: testing symmetries, trying to track down small deviations from their predictions, measuring asymmetries...

Lepton Flavour Universality: what is it?

Quarks world

- When the Higgs field choses a ground state, mass terms arise.

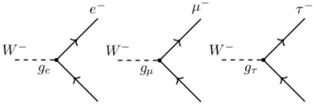


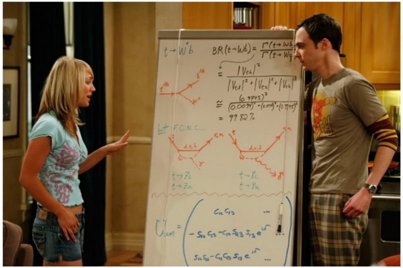


- Diagonalizing the mass terms, you obtain non diagonal interaction terms with charged gauge bosons ($W^{\pm}$)

Leptons world

- Neutrinos are massless in the Standard Model
- This lets you diagonalize simultaneously the mass and interactions terms





Lepton Flavour universality: Accidental symmetry of the standard model that predicts the equality of the couplings of the leptons with the force carrier particles

$$g_e = g_\mu = g_\tau$$

LEP tests, a non exhaustive list

- Lepton flavour universality was tested at the LEP (e^+e^-) collider in various ways.
- The partial widths of the $Z \to \ell\ell$ decays have been found to be all compatible with each other
- Using leptonic decays of the τ lepton: $\frac{\Gamma(\tau \to e\nu\nu)}{\Gamma(\mu \to e\nu\nu)} \to \frac{g_\tau}{g_\mu} = 1.0004 \pm 0.0022$
- At LEPII has been tested with decays of on-shell W bosons

Table 5.5
Summary of W branching fractions derived from W-pair production cross-sections measurements up to 207 GeV centre-of-mass energy.

	Lepton non-universality			Lepton universality
Experiment	$\mathcal{B}(W \to e\overline{\nu}_e)$ (%)	$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$ (%)	$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$ (%)	$\mathcal{B}(W \to \text{hadrons})$ (%)
ALEPH	10.78 ± 0.29	10.87 ± 0.26	11.25 ± 0.38	67.13 ± 0.40
DELPHI	10.55 ± 0.34	10.65 ± 0.27	11.46 ± 0.43	67.45 ± 0.48
L3	10.78 ± 0.32	10.03 ± 0.31	11.89 ± 0.45	67.50 ± 0.52
OPAL	10.71 ± 0.27	10.78 ± 0.26	11.14 ± 0.31	67.41 ± 0.44
LEP	10.71 ± 0.16	10.63 ± 0.15	11.38 ± 0.21	67.41 ± 0.27
χ^2/dof		6.3/9		15.4/11

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$$\frac{2\mathcal{B}(W \to \tau\nu)}{\mathcal{B}(W \to \mu\nu) + \mathcal{B}(W \to e\nu)} = 1.066 \pm (0.025)\ (2.6\sigma)$$

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Take Home Message

Lepton Flavour Universality has been extensively tested with leptonic decays of leptons and gauge bosons with very high precision

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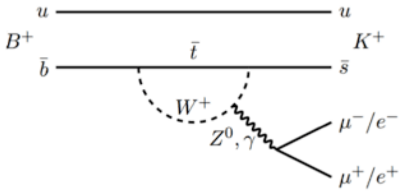
The renewed interest in Lepton Flavour Universality

- Recently some deviations from the SM prediction of LFU emerged in semileptonic B decays.

Neutral current decays

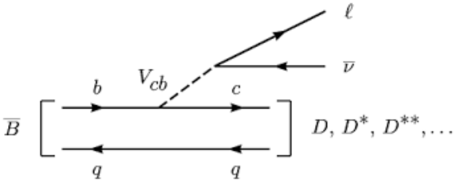


- Testing $e - \mu$ universality

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

- Loop induced (second order in perturbation theory), very rare decays $\mathcal{B}\ \mathcal{O}(10^{-6})$
- Sensitivity to new physics up to about 50 TeV

Charged current decays



- Testing $\tau - \mu$ universality

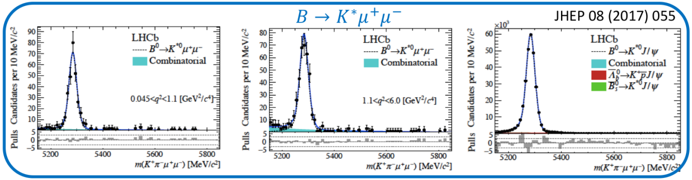
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

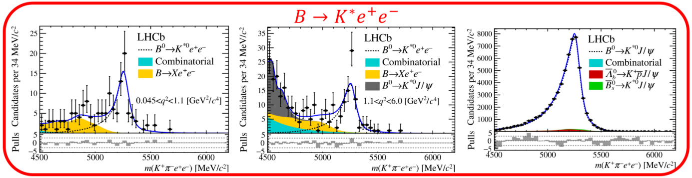
- Tree, very high transition rate processes, $\mathcal{B}\mathcal{O}(\%)$
- Very precisely predicted, $\mathcal{O}(\%)$ accuracy
- Sensitivity to new physics up to about 1 TeV

Lepton Flavour universality in neutral current decays

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})\ (SM)$$

- One of the golden channels for the search of NP effects
  - Suppressed transitions
  - Clean decay signature





Low q^2 *central q^2* *J/ψ*

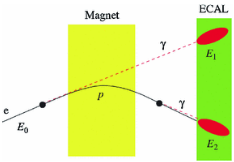
- The measurement is, in reality

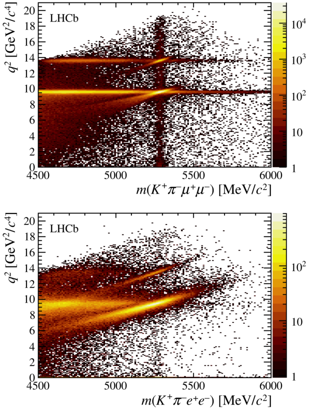
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- and the ratio of the resonant mode is checked to be unity

The detector is not lepton flavour universal

- The challenge lies in the fact that the detector is not lepton flavour universal in its response
- The electrons, being lighter, emit more Bremmstrahlung photons when accelerated by the magnet
- This affects the resolution of the peak with electrons





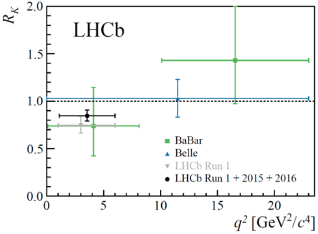
- Controlling the radiative tail is far from simple
- The double ratio check is just one of the many tests
- Many other tests are performed on this important result

Change log

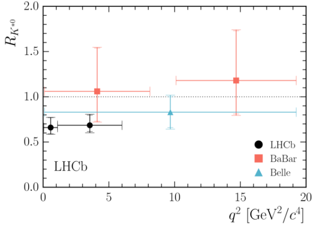
Since the "Deinotherium" version, the following major changes have been made:

Results so far

R_K



R_{K*}



decay	q^2 range $[GeV^2/c^4]$	Value
$B^0 \to K^{*0}\ell^+\ell^-$	0.045 - 1.1	$0.66^{+0.11}_{-0.03} \pm 0.05$
$B^0 \to K^{*0}\ell^+\ell^-$	1.1 - 6.0	$0.69^{+0.11}_{-0.07} \pm 0.05$
$B^+ \to K^+\ell^+\ell^-$	1.1 - 6.0	$0.846^{+0.060+0.016}_{-0.054-0.014}$
$\Lambda_b^0 \to pK^-\ell^+\ell^-$	0.1 - 6.0	$0.86^{+0.14}_{-0.11} \pm 0.05$

- This year we also measured R_{pk}, using decays of b-baryons
- All results are found to be smaller than the SM expectation at low q^2

Lepton Flavour universality in charged current decays

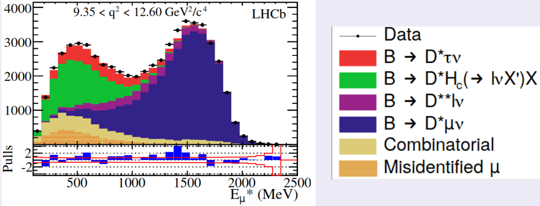
$$R(D^*) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

- Two decays of the τ lepton are exploited at the LHCb experiment

Decay Mode	Branching ratio (%)
$\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$	17.39 ± 0.04
$\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$	9.00 ± 0.06

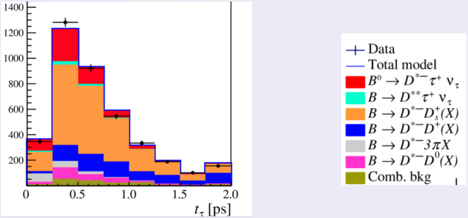
$\tau \to \mu\nu\nu$

- Signal and normalizations have the same final state
- Very similar kinematics between signal and normalization mode, good for systematics

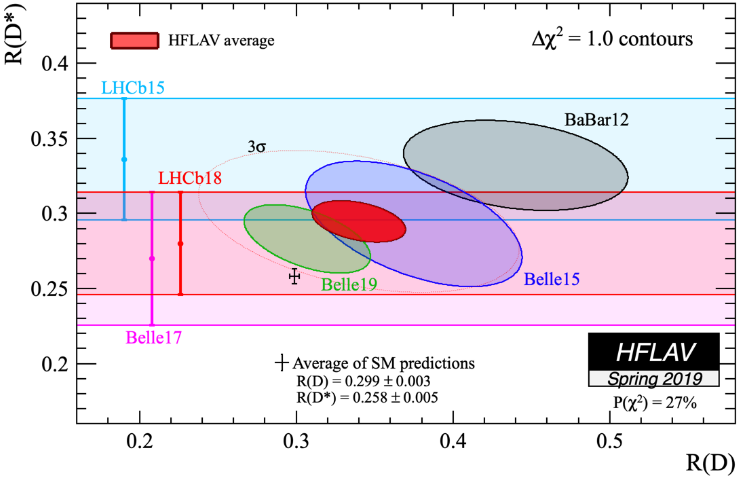


$\tau \to 3h$

- The lifetime of the τ permits the reconstruction of the τ vertex
- The signal is normalized to a similar hadronic final state, then external measurements are used



The status of the art as of today



- Tension of the world average of 3σ with respect to SM prediction
- The combination is performed on 6 results coming from 3 different experiments: Belle, BaBar and LHCb

Our analysis

- No measurement using D ground states has been performed at hadron colliders

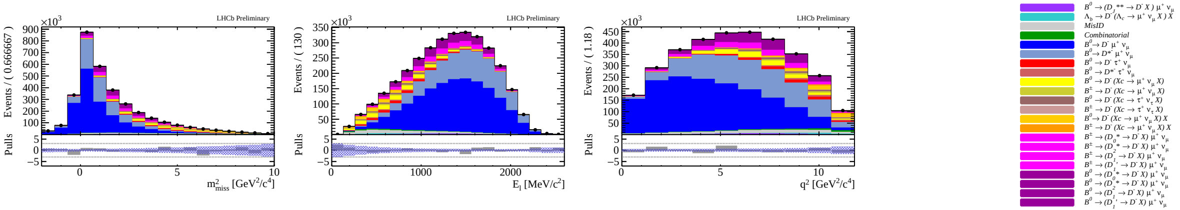
- In our group we are performing a measurement of the $R(D^+)$ parameter

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

- $\tau \to \mu \nu \nu$
- $D \to K \pi \pi$

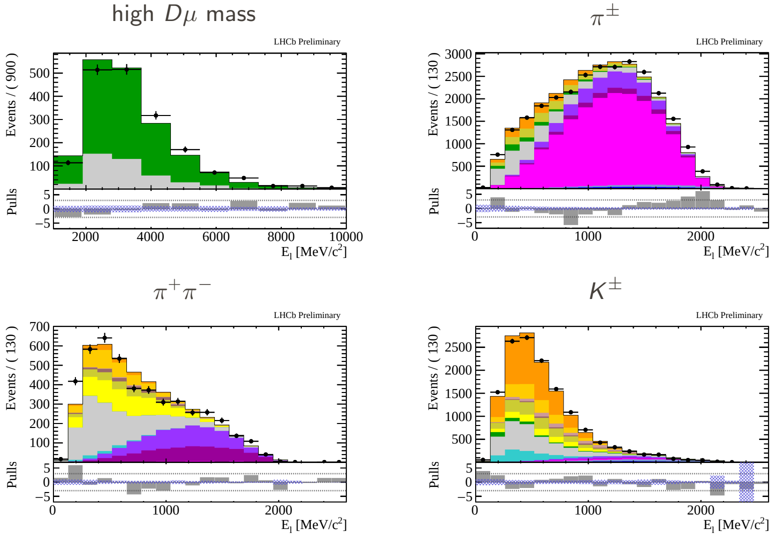
- Additional contributions coming from $D^* \to D^+ \pi^0$, with unreconstructed π^0
- Simultaneous measurement of the $R(D^+)$ and $R(D^*)$ parameter
- The physics backgrounds are estimated using MC simulations

- Signal and normalization, having the same final state, are separated from the backgrounds with a fit to three B rest frame variables



- **What are the main challenges of the analysis?**

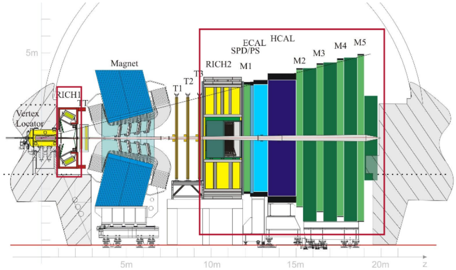
Background levels: an excercise in understanding the backgrounds



- The signal is required to be isolated from the presence of other tracks in the event.
- Inverting these requirements, it is possible to define control regions in data enriched in the presence of specific backgrounds
- These regions are fit simultaneously to the signal to derive corrections to the MC models

The amount of data to fit: we need of faster MC simulations

- The analysis is performed on 2015 + 2016 data samples ($\approx 3M$ events to be fit in the signal region)
- One of the highest source of systematic uncertainties in previous measurements: MC statistics
- In order to not be limited by this, we need $\mathcal{O}(10^9)$ MC events being simulated

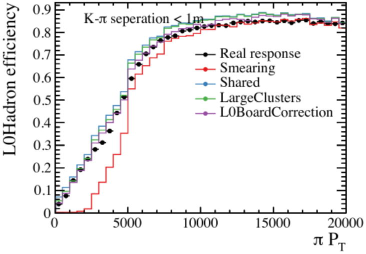


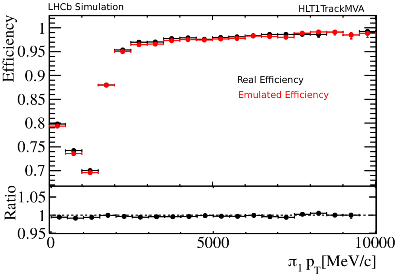
- Each event weights $\mathcal{O}(100)$ kB on disk
- It takes around minutes for each event to be simulated...
- When simulating events, most of the time is spent in the detector response simulation
  - Calorimeters
  - RICH
- With the full simulation it would take us one year of production
- **We need Faster MC**

- A few approaches emerged in the collaboration:
- Our way: **Tracker Only simulation**

Emulating our way out

- Emulating only the tracker response, you miss out on a lot of features
  - RICH information (used for particle identification)
  - Calo information (used at the trigger stage)
- The PID information is already present in calibration samples provided centrally by the collaboration
- Our group has been greatly involved in the emulation of the trigger response using information provided offline

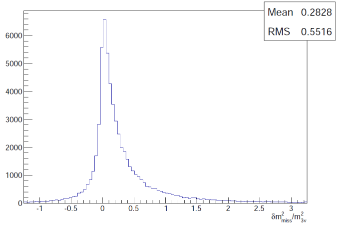




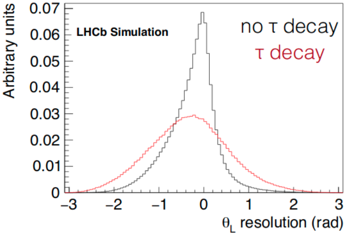
- We have developed tools to emulate the trigger response, which now agrees at the $\mathcal{O}(0.5\%)$ with the information provided by the Full Simulation
- These tools are now available for usage by the whole collaboration

What is in the pipeline at LHCb?

- Up to now only ratios of Branching fractions, under the Standard Model hypothesis have been measured
- Angular variables are more sensitive to NP effects
- It can be interesting to measure Wilson coefficients in a model independent way
- Can we do the usual way? subtract background and unfold detector resolution?



(a) m^2_{miss} resolution



- **Technical challenge**:
  - The momentum of the B is not known (main production mechanism is $gg \to b\bar{b}$, unkown neutrinos' momentum)
  - Approximation: neutrinos' momentum collinear to the B decay (20% resolution on the fit variables)
  - Unfolding this angular resolution is not very ideal, especially with the level of backgrounds
- **Physics challenge**:
  - Backgrounds are affected by the same physics
  - You cannot subtract assuming the SM for backgrounds, and then analyze the signal under different hypotheses

Bicocca proposal: Forward Folding

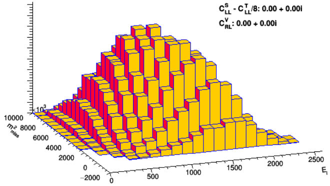
- Generating many MC samples in different physics configurations is literally impossible
- Our proposal: Instead of unfolding detector from physics, **forward fold physics inside the detector resolution**

- Our group is closely collaborating with the developers of a tool called **Hammer**
- The idea behind this tool: linear expansion, the best friend of a physicist
  - The matrix element is expanded until it is linear in Wilson coefficients and hadronic parameters (Form Factor parameters)

$$\mathcal{M} = \sum_{\alpha,i} c_i FF_\alpha \mathcal{A}_{i,\alpha}$$

Helicity Amplitude Module
for Matrix Element Reweighting

- The reweighting needed to go from one modelto the other is fast, only linear operations



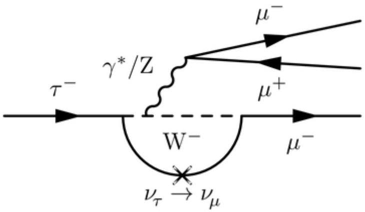
- Our group has developed an interface to this tool that enables to inject this tool directly into the fit
- We are already deploying it in our analysis to propagate systematic uncertainties due to the choice of the form factors models
- **This work can be used to set the stage for New Physics angular analyses in $b \to c\ell\nu$ decays, measuring Wilson coefficients directly from data**

Other lines of research @ Bicocca

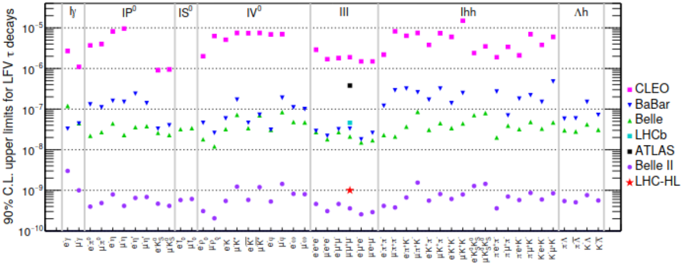
- Intriguing results seem to be pointing towards Lepton Flavour Non universality in decays involving quarks and leptons
- Another quantity that is conserved in the standard model is the total lepton number

$$N_\tau = N(\tau^-) + N(\nu_\tau) - N(\tau^+) - N(\bar{\nu}_\tau)$$

- This conservation law is deeply linked with the neutrinos research!
- In fact decays like $\tau \to 3\mu$ are prohibited in the Standard Model, but allowed if we assume neutrinos are massive
  - but we do know they are massive!
- Branching fractions heavily suppressed, 10^{-40} or below
- Any observation of the decay would be a clear sign of new physics



$\tau \to 3\mu$



- LHCb performed the first search for $\tau \to 3\mu$ at an hadron collider on RunI data
  - $\mathcal{B}(\tau \to 3\mu) < 4.6 \times 10^{-8}$ 90% CL
- Now also the CMS group (S. Malvezzi, Luca Guzzi) is performing the search at CMS, with τ coming from W decays.

- The Bicocca LHCb group is now updating the measurement with the full RunII dataset
- It is being considered as one of the possible measurements for the Upgrade detector phase
  - Other LFN violating B-decays: $B \to e\mu$, $B \to \tau\mu$, $B \to K\mu e$, $B \to K\mu\tau$

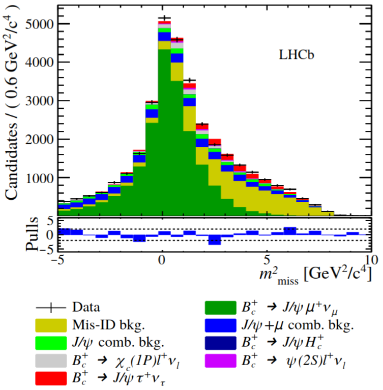
Conclusions

- Bicocca is very active in indirect searches of Physics beyond the Standard Model through lepton flavour universality and lepton number violation
- I have given you the idea of the effort and the level of complexity that needs to go into high precision indirect searches of New Physics
- The results of the analysis performed by our department can have huge impact on physics
- **Stay Tuned! And hope with us that the hints are real!**

Thanks for your attention!

Other decay modes

- Other decay modes are under investigation at LHCb to test lepton flavour universality in charged current decays



$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi \tau \nu)}{\mathcal{B}(B_c \to J/\Psi \mu \nu)}$$

- First observation of the $B \to J/\Psi \tau \nu$ decay, with significance of 3σ
- Backgrounds composition is completely different from the analyses with B^0
- Other analyses are in the pipeline, with both decays of the τ lepton
- $R(\Lambda_c)$, $R(\Lambda_c^*)$, $R(D^{0/+})$