Lepton Flavour Universality violation Review of experimental results and prospects

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LHCb

With many thanks to Simone Bifani

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Lepton Flavour Universality
a key ingredient of the standard model

- In the SM, the charged and neutral current interactions must respect **Lepton Flavour Universality**

⇒ Equal couplings of the W and Z bosons to

  ○ **electrons, muons and taus**

- For the Z boson, this has been checked at the 2 per mill accuracy at LEP
- For the W boson, the τ BR is 2.8 σ above <e,μ> which are equal to 2 per mil precision

$$\left.\frac{\mathcal{B}(W\to\tau\nu_\tau)}{[\mathcal{B}(W\to e\nu_e)+\mathcal{B}(W\to\mu\nu_\mu)]/2}\right|_{\mathrm{LEP}} = 1.077\pm0.026,$$

- Arxiv : hep-ph/0607280

Where to look for LFU

- In rare K decays
  - πee, πμμ (known το 6%) hadronic effects
- In rare D decays
  - K(*)ee, K(*)μμ (only limits) hadronic effects
- In B decays

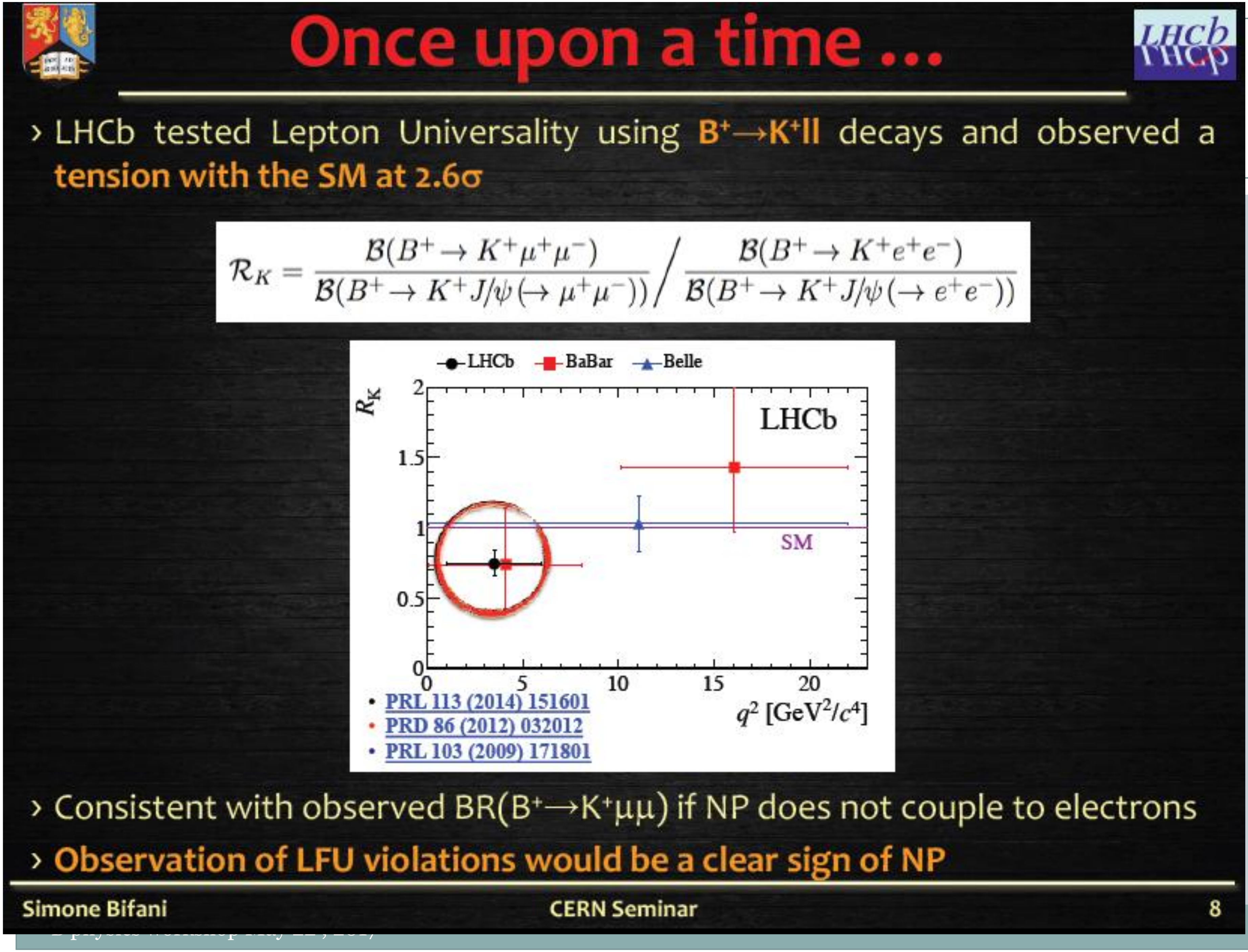
  The only possibility to look for e/mu/tau comparison
  - **At tree level in Charged current interactions**
  - **in supressed neutral current reactions**
  - Can also to be searched for, in annihilation reactions

  $B \to \tau\nu$ vs $B \to \mu\nu$ (BELLE-II)
- D_s,$D^+ \to \tau\nu$ D_s,$D^+ \to \mu\nu$, (hadronic corrections)

Semileptonic Vub decays b->uτν probe the same vertex as the annihilation (LHCb) $B^+ \to pp\tau\nu$, $\Lambda_b \to p\tau\nu$)

The criterium for a good LFU

- Very robust theoretical prediction
- Experimental precision in the same ball park
- High sensitivity to new physics (involving third family of quarks and/or leptons)



Once upon a time …

- LHCb tested Lepton Universality using **$B^+ \to K^+ll$** decays and observed a **tension with the SM at 2.6σ**

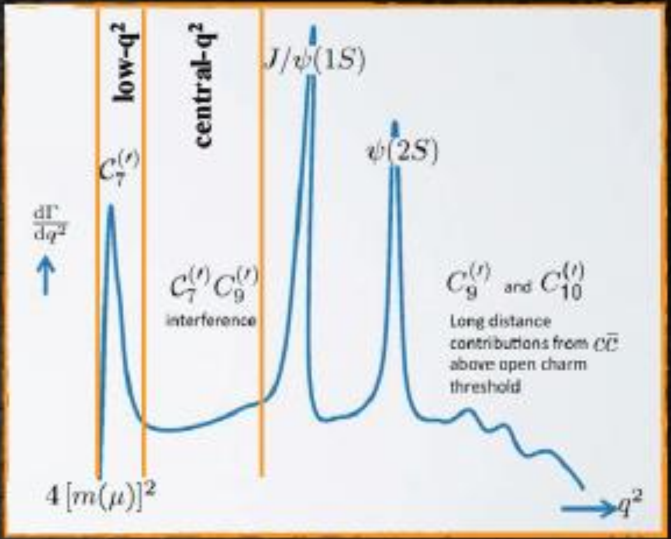
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))}$$

- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Consistent with observed BR($B^+ \to K^+\mu\mu$) if NP does not couple to electrons
- **Observation of LFU violations would be a clear sign of NP**

Today ...

- Test of LFU with **$B^0 \to K^{*0}\mu\mu$** and **$B^0 \to K^{*0}ee$, $R_{K^{*0}}$**

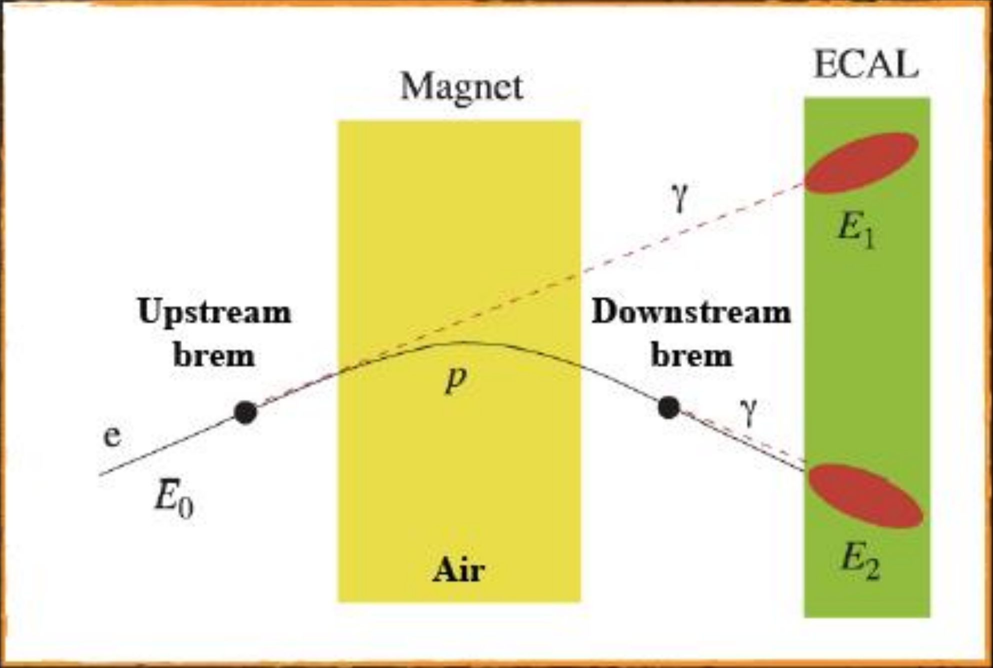


- **Two regions of q^2**
  - Low [0.045-1.1] GeV^2/c^4
  - Central [1.1-6.0] GeV^2/c^4
- Measured relative to **$B^0 \to K^{*0}J/\psi(ll)$** in order to reduce systematics
- K^{*0} reconstructed as **$K^+\pi^-$** within 100MeV from the $K^*(892)^0$
- **Blind analysis** to avoid experimental biases
- Extremely challenging due to significant differences in the way μ and e "interact" with the detector
  - Bremsstrahlung
  - Trigger

Bremsstrahlung – I

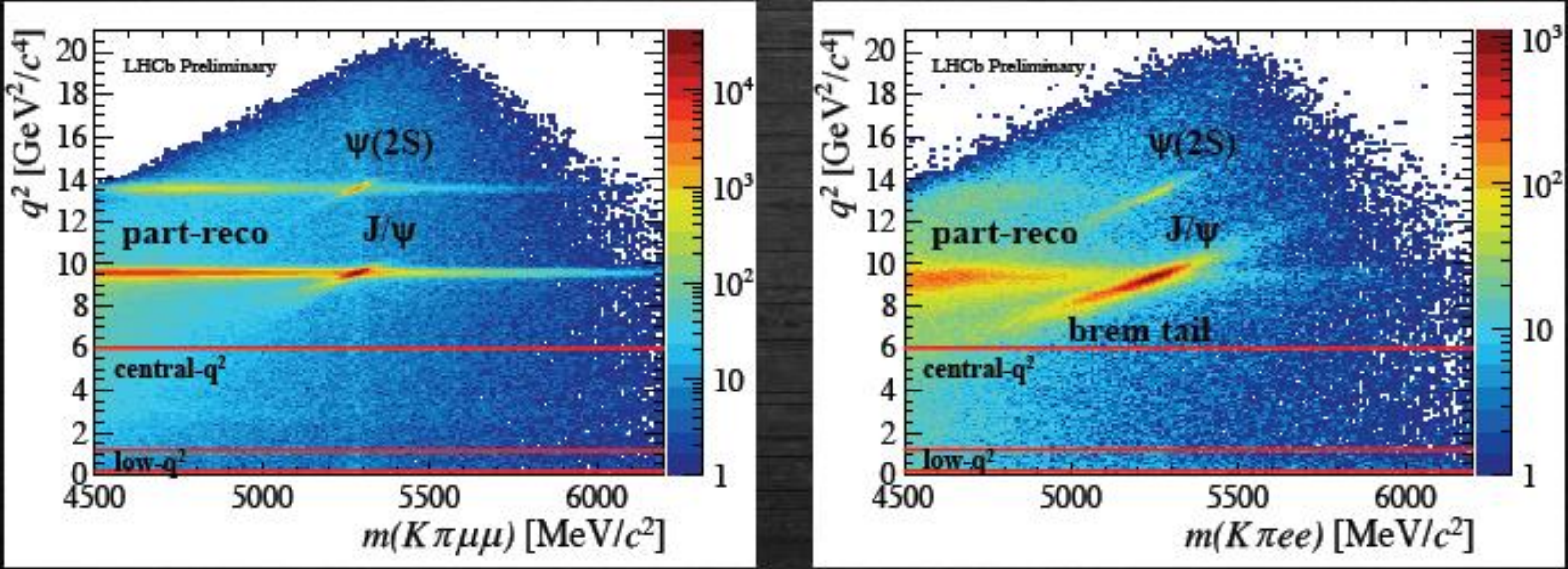
- Electrons emit a large amount of bremsstrahlung that results in degraded momentum and mass resolutions

- **Two types of bremsstrahlung**
  - **Downstream of the magnet**
    - photon energy in the same calorimeter cell as the electron
    - momentum correctly measured
  - **Upstream of the magnet**
    - photon energy in different calorimeter cells than electron
    - momentum evaluated after bremsstrahlung



Bremsstrahlung – II

- A **recovery procedure** is in place to improve the momentum reconstruction
- Events are categorised depending on the number of recovered photon clusters
- Incomplete recovery due to
  - Energy threshold of the bremsstrahlung photon ($E_T > 75$ MeV)
  - Calorimeter acceptance
  - Presence of energy deposits mistaken as bremsstrahlung photons



- Incomplete recovery causes the reconstructed B mass to shift towards lower values and events to migrate in and out of the q² bins

Corrections to Simulation

- Four-step procedure largely based on tag-and-probe technique

1. **Particle identification**
   - PID response of each particle species tuned using dedicated calibration samples
2. **Generator**
   - Event multiplicity and B^0 kinematics matched to data using $B^0 \rightarrow K^{*0} J/\psi(\mu\mu)$ decay
3. **Trigger**
   - Hardware and software trigger responses tuned using $B^0 \rightarrow K^{*0} J/\psi(ll)$ decays
4. **Data/MC differences**
   - Residual discrepancies in variables entering the MVA reduced using $B^0 \rightarrow K^{*0} J/\psi(ll)$ decays

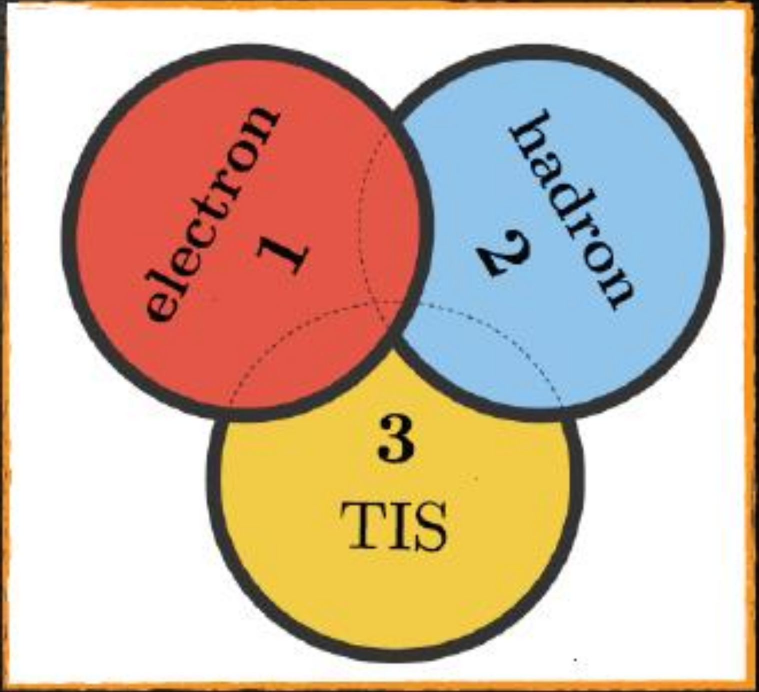
- After tuning, very good data/MC agreement in all key observables

Trigger

› Trigger system split in hardware (L0) and software (HLT) stages

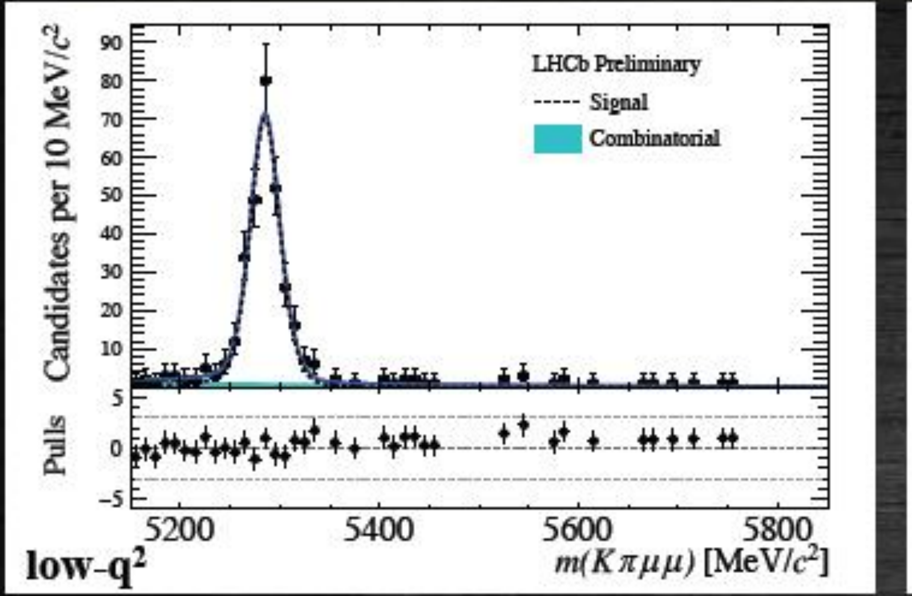
› Due to higher occupancy of the calorimeters compared to the muon stations, hardware thresholds on the electron E_T are higher than on the muon p_T (**L0 Muon**, p_T>1.5,1.8 GeV)

› To partially mitigate this effect, **3 exclusive trigger categories** are defined

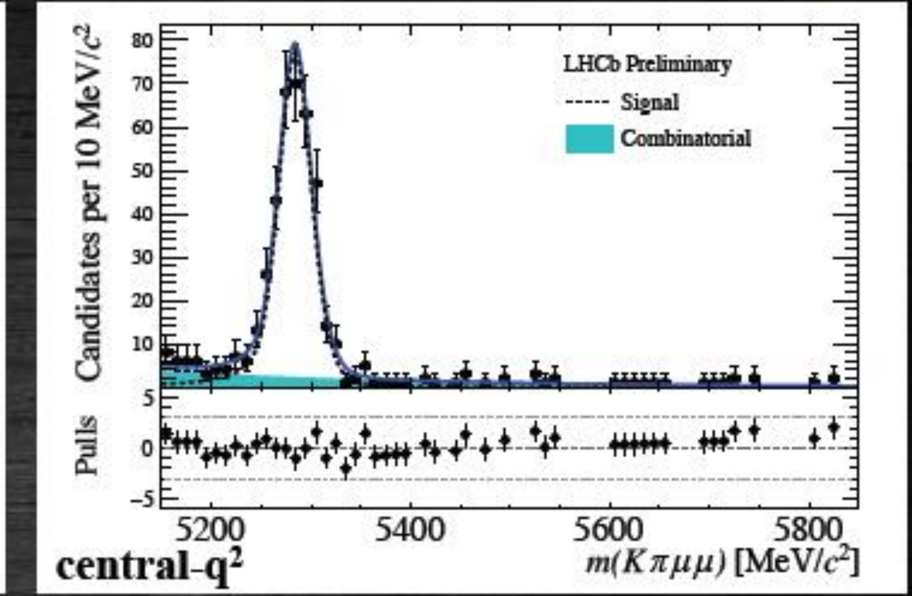


- » **L0 Electron**: electron hardware trigger fired by clusters associated to at least one of the two electrons (E_T > 2.5 GeV)
- » **L0 Hadron**: hadron hardware trigger fired by clusters associated to at least one of the K^{*0} decay products (E_T > 3.5 GeV)
- » **L0 TIS**: any hardware trigger fired by particles in the event not associated to the signal candidate

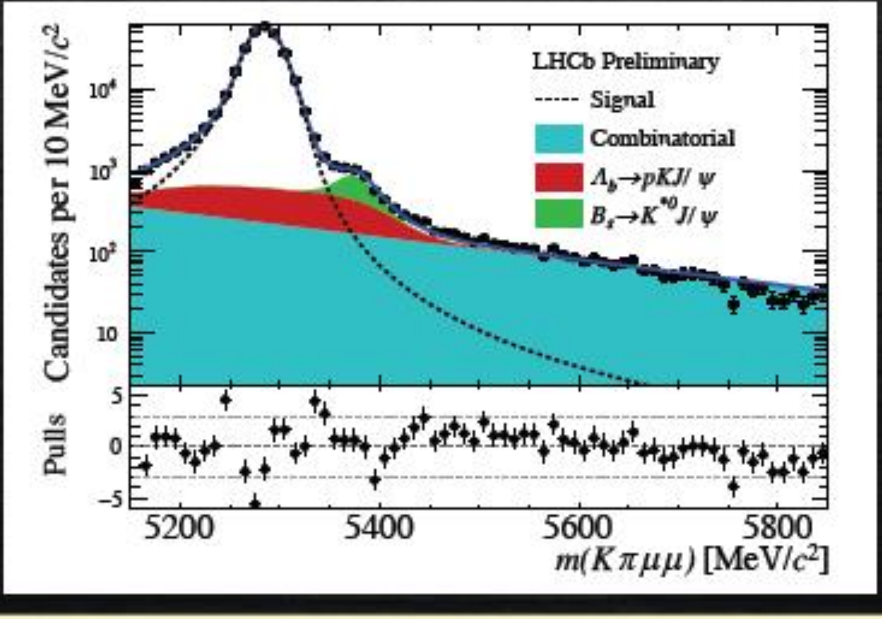
Fit Results – μμ

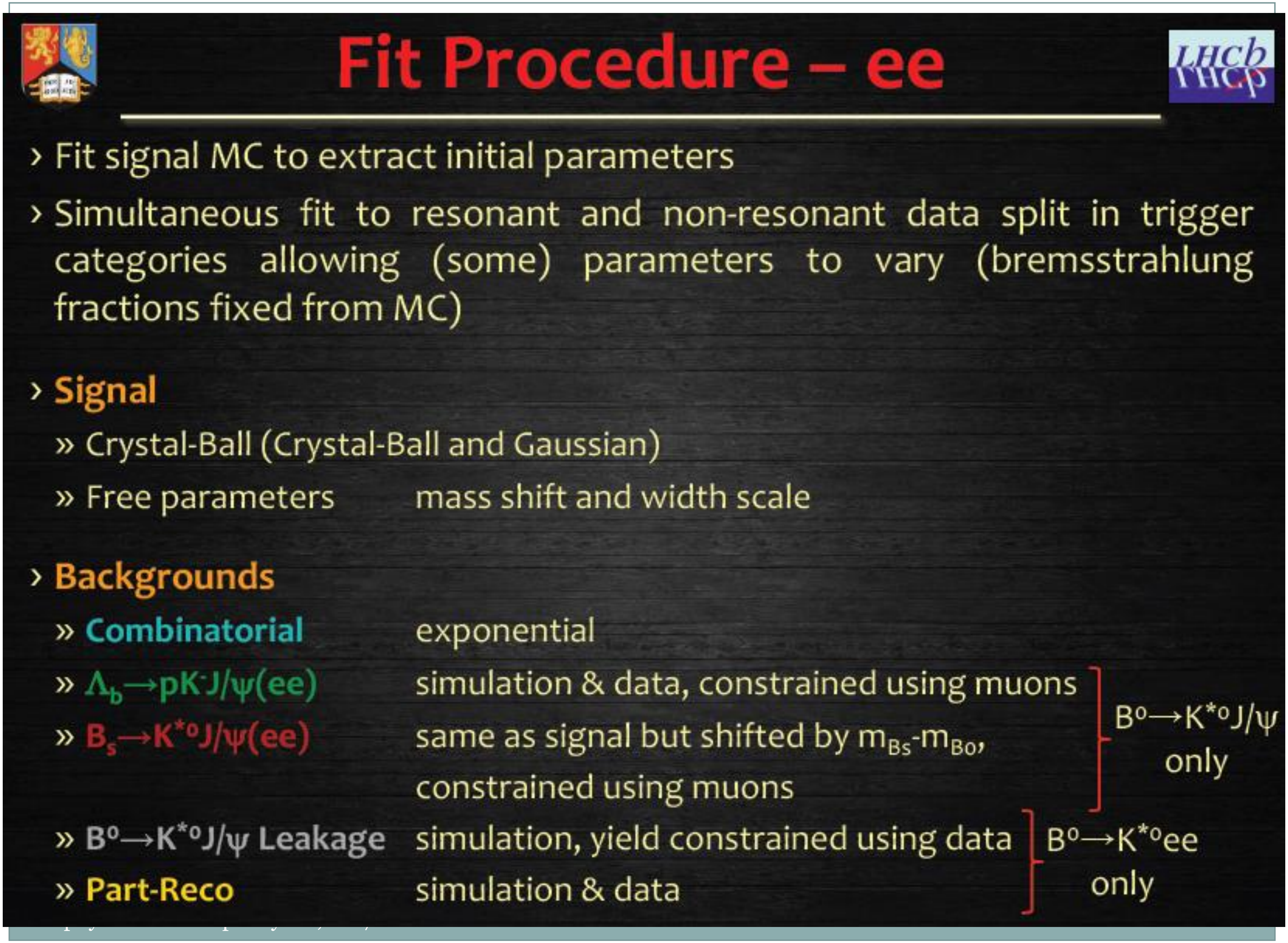


low-q^2



central-q^2



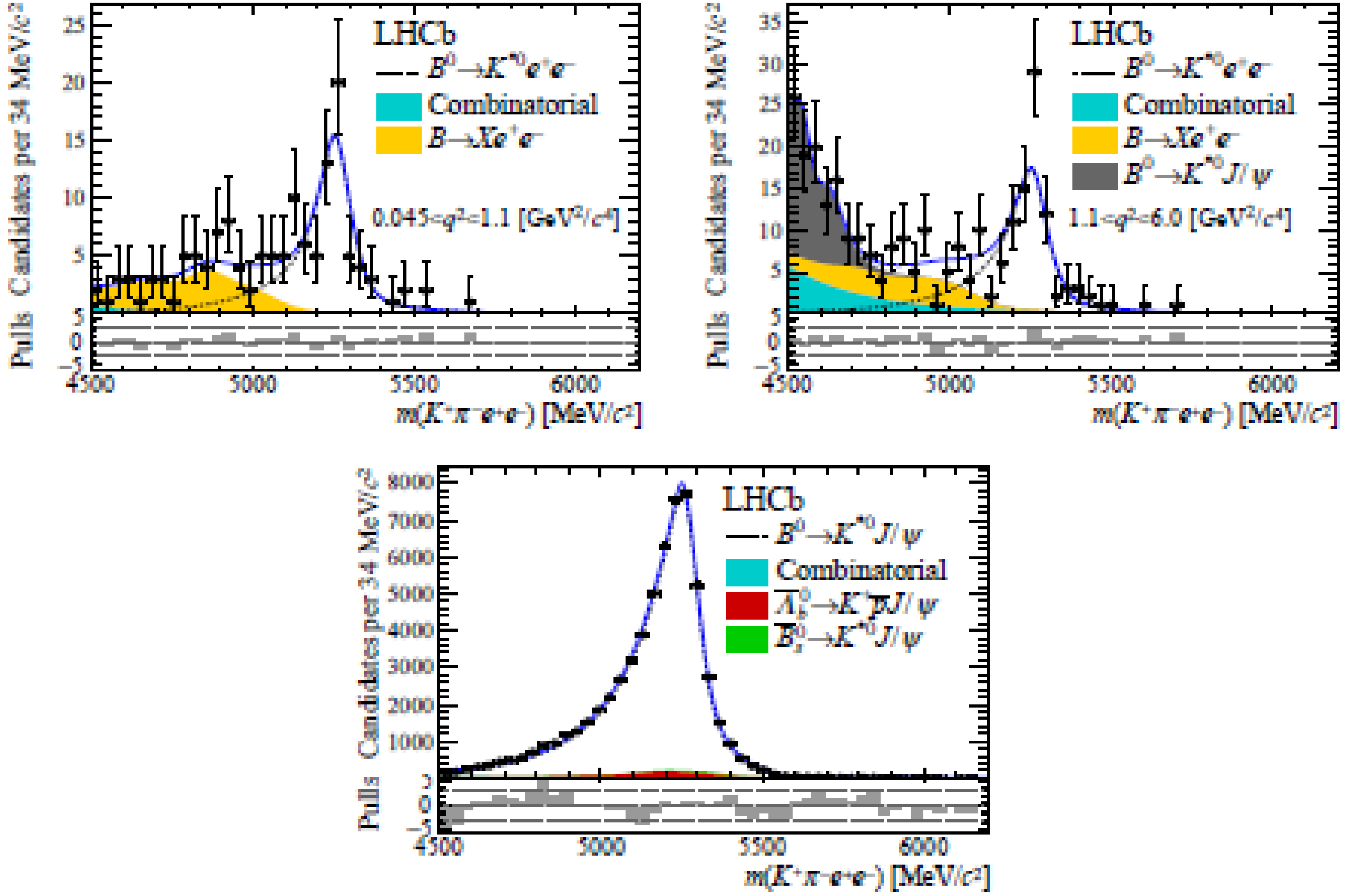


Fit Procedure – ee

- Fit signal MC to extract initial parameters
- Simultaneous fit to resonant and non-resonant data split in trigger categories allowing (some) parameters to vary (bremsstrahlung fractions fixed from MC)
- **Signal**
  - Crystal-Ball (Crystal-Ball and Gaussian)
  - Free parameters — mass shift and width scale
- **Backgrounds**

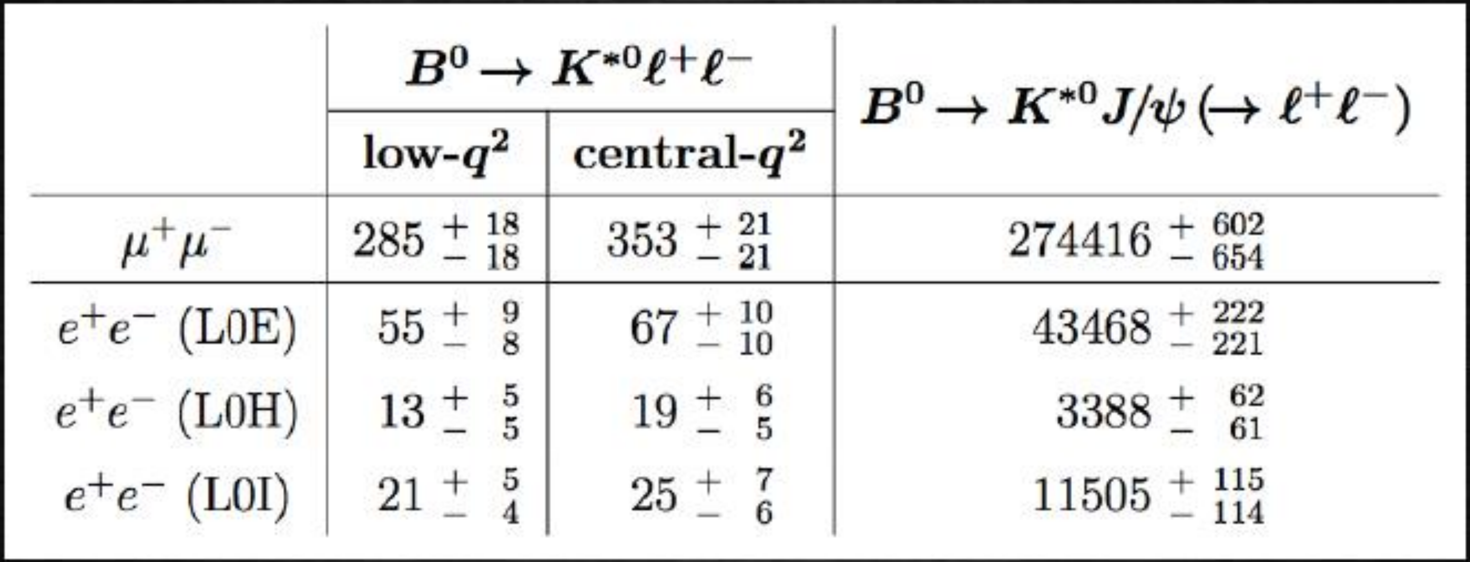
» **Combinatorial**	exponential	
» $\Lambda_b \rightarrow pK^- J/\psi(ee)$	simulation & data, constrained using muons	$B^0 \rightarrow K^{*0} J/\psi$ only
» $B_s \rightarrow K^{*0} J/\psi(ee)$	same as signal but shifted by m_{Bs}-m_{B0}, constrained using muons	
» $B^0 \rightarrow K^{*0} J/\psi$ **Leakage**	simulation, yield constrained using data	$B^0 \rightarrow K^{*0} ee$ only
» **Part-Reco**	simulation & data	

LHCb preprint hep-ex arXiv:1705.05802



Yields

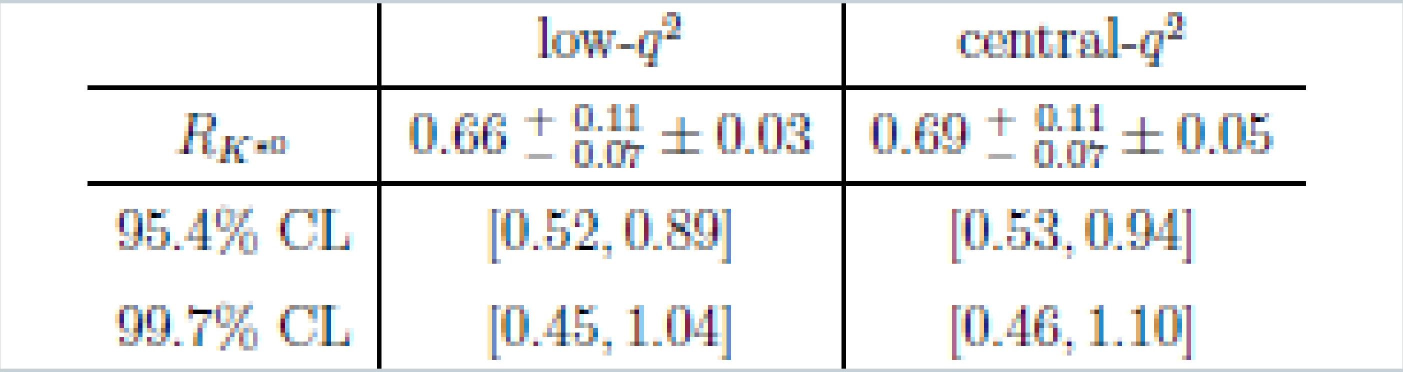
- Precision of the measurement driven by the statistics of the electron samples



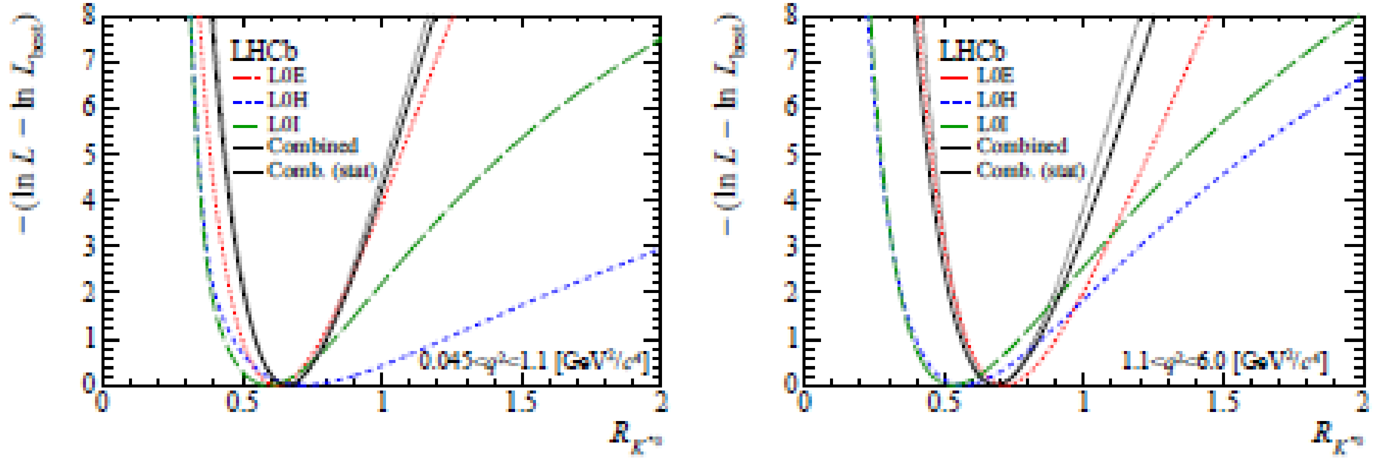
	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0}J/\psi(\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285\,^{+18}_{-18}$	$353\,^{+21}_{-21}$	$274416\,^{+602}_{-654}$
e^+e^- (L0E)	$55\,^{+9}_{-8}$	$67\,^{+10}_{-10}$	$43468\,^{+222}_{-221}$
e^+e^- (L0H)	$13\,^{+5}_{-5}$	$19\,^{+6}_{-5}$	$3388\,^{+62}_{-61}$
e^+e^- (L0I)	$21\,^{+5}_{-4}$	$25\,^{+7}_{-6}$	$11505\,^{+115}_{-114}$

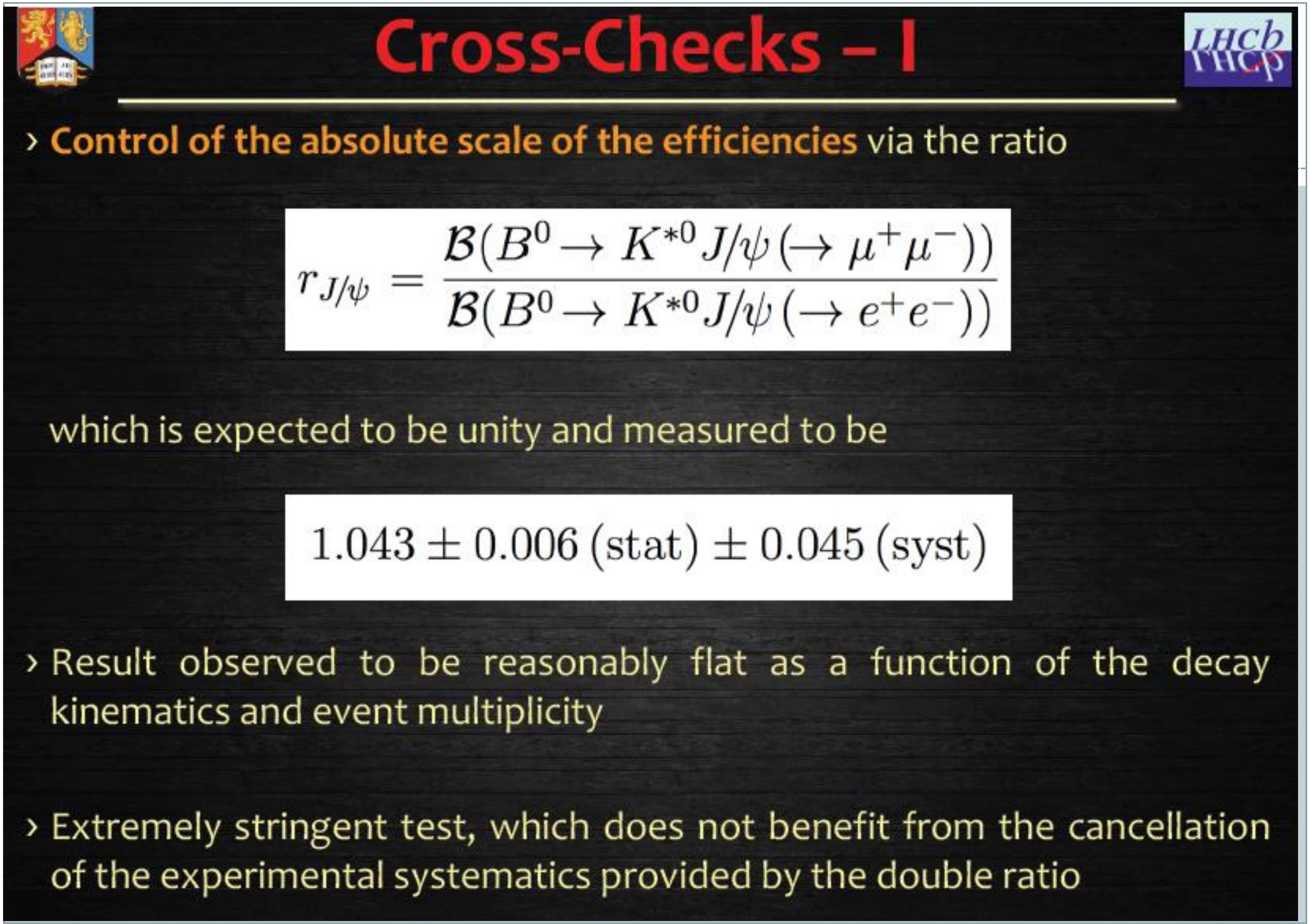
- In total, about 90 and 110 $B^0 \to K^{*0}ee$ candidates at low- and central-q^2, respectively

LHCb results on R(K*)



	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66 \, ^{+\, 0.11}_{-\, 0.07} \pm 0.03$	$0.69 \, ^{+\, 0.11}_{-\, 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$





Cross-Checks – I

- **Control of the absolute scale of the efficiencies** via the ratio

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

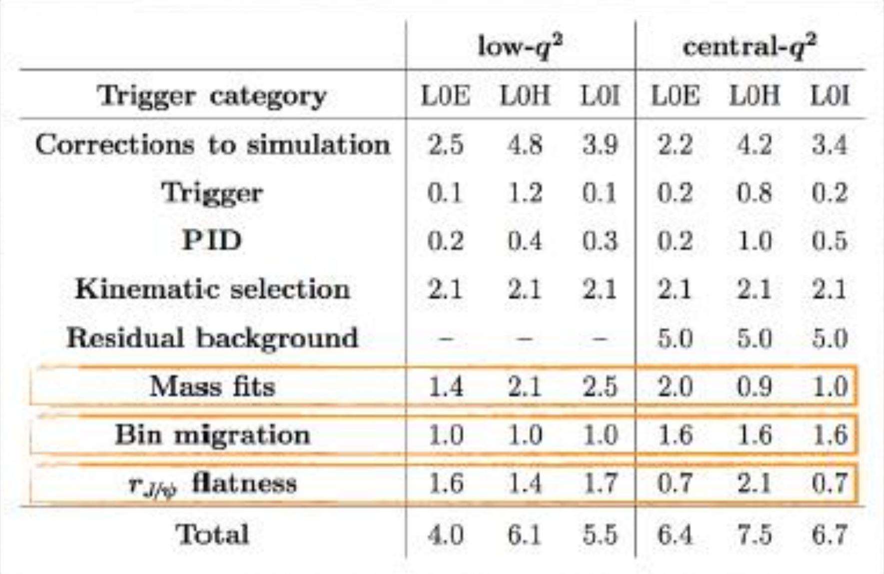
which is expected to be unity and measured to be

$$1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

- Result observed to be reasonably flat as a function of the decay kinematics and event multiplicity
- Extremely stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio

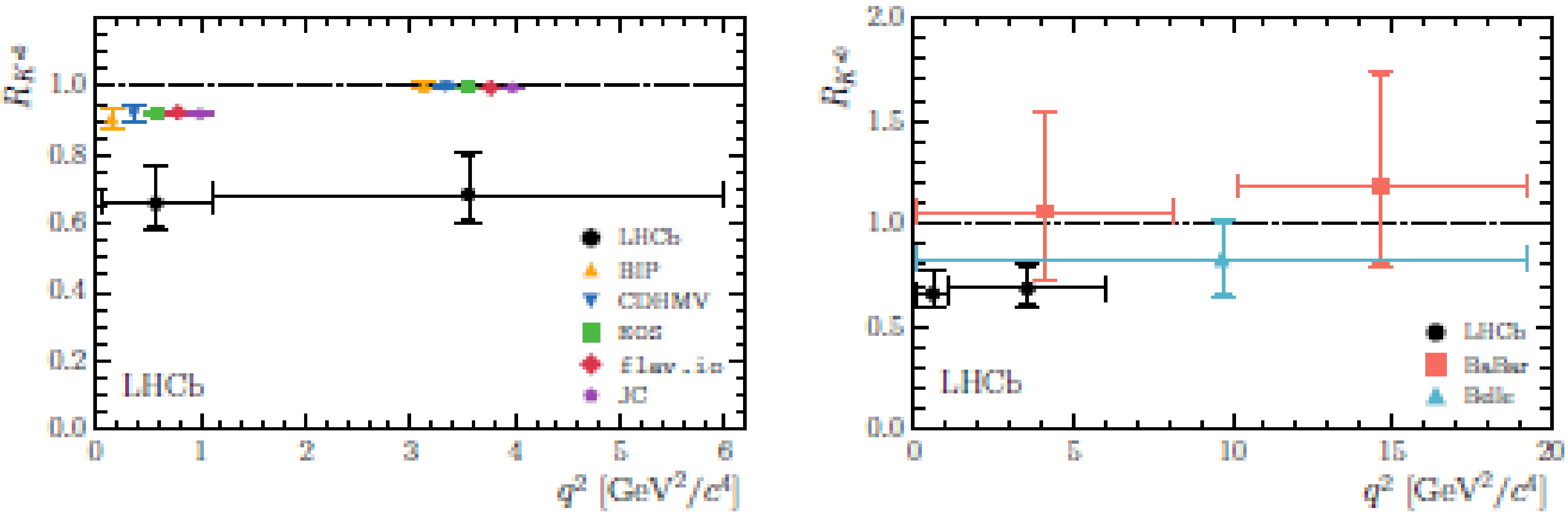
Systematics – III

- **Mass fit:** a systematic uncertainty is determined by running pseudo-experiments with different descriptions of the signal and background fit models
- **Bin migration:** the effect of the model dependence and description of the q^2 resolution in simulation are assigned as a systematic uncertainty
- **$r_{J/\psi}$ flatness:** the ratio is studied as a function of several properties of the event and decay products, and the observed residual deviations from unity are used to assign a systematic uncertainty

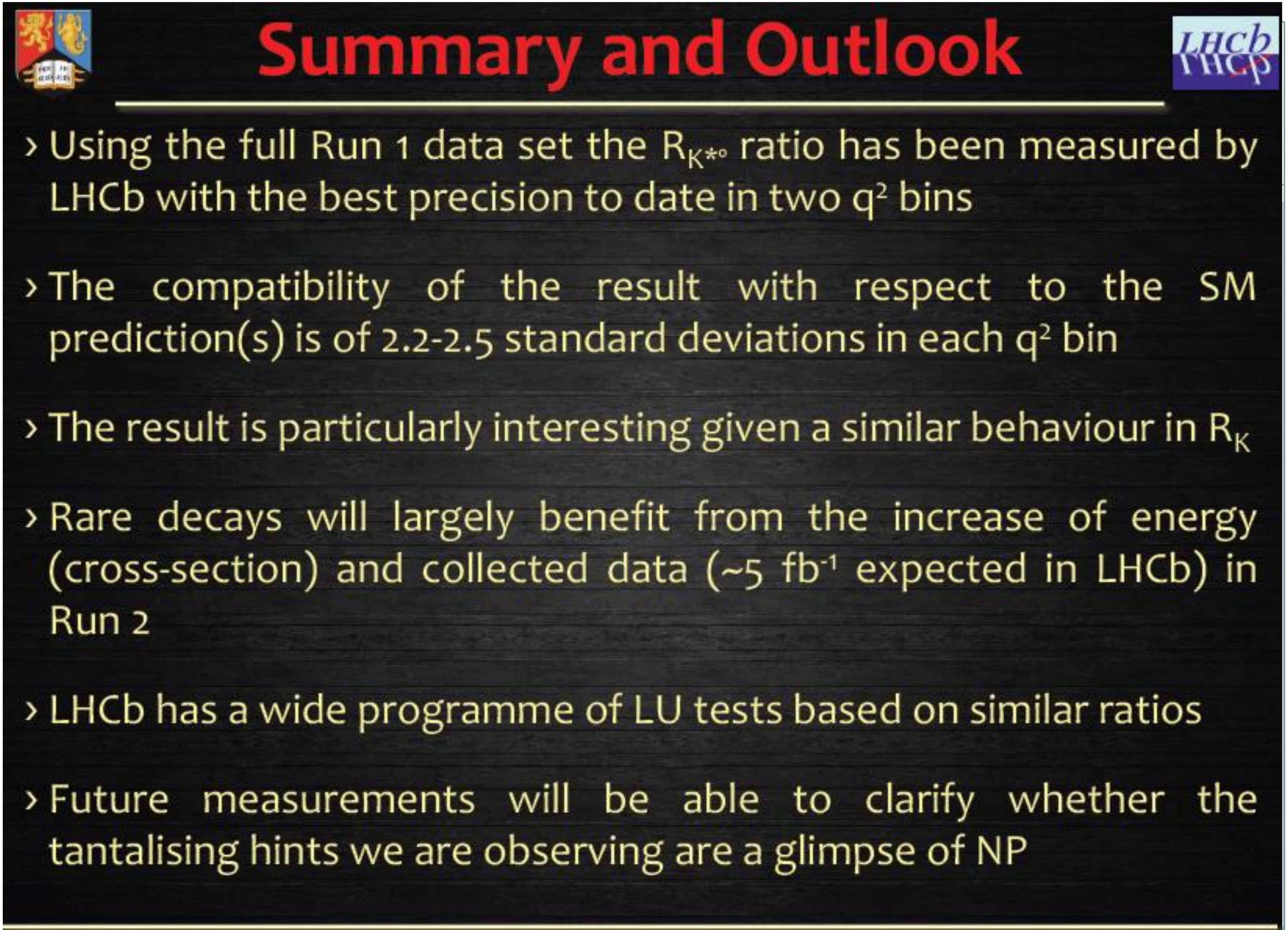


	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ flatness	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

Results – II



- The compatibility of the result in the **low-q²** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q²** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations



Summary and Outlook

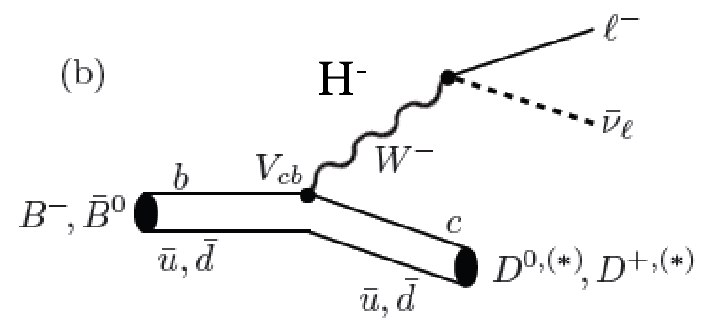
- Using the full Run 1 data set the $R_{K^{*0}}$ ratio has been measured by LHCb with the best precision to date in two q^2 bins
- The compatibility of the result with respect to the SM prediction(s) is of 2.2-2.5 standard deviations in each q^2 bin
- The result is particularly interesting given a similar behaviour in R_K
- Rare decays will largely benefit from the increase of energy (cross-section) and collected data (~5 fb^{-1} expected in LHCb) in Run 2
- LHCb has a wide programme of LU tests based on similar ratios
- Future measurements will be able to clarify whether the tantalising hints we are observing are a glimpse of NP

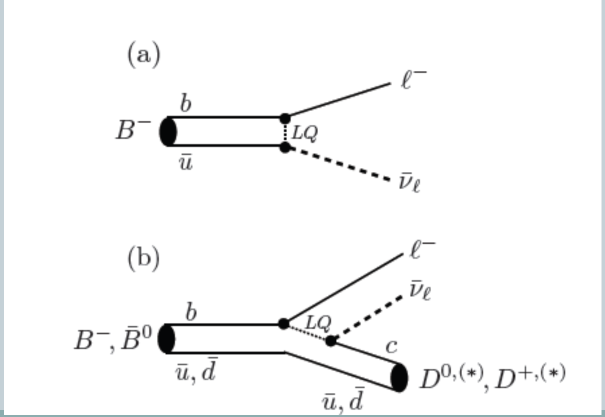
Why semitauonic decays are interesting?

- As tree level decays, they combine the advantages :
  - Very precise prediction from SM :R(D*) known to 2% precision, using

    $R(D^*) = BR(B \rightarrow D^*\tau\nu / BR\text{-}B \rightarrow D^*\mu\nu)$
  - Abundant channel $BR(B^o \rightarrow D^*\tau\nu)$=1,24%, one of the largest individual BR
  - Sensitivity to new physics: (simplest realization) A charged Higgs will automatically couple more to the τ . LFU violation can also occur through other mechanisms (leptoquarks,..)
- They offer several hadronisation implementations:
  - $D^*, D^o, D^+, D_s, \Lambda_c, J/\psi$
  - Differing not only by various properties of the spectator particle but also

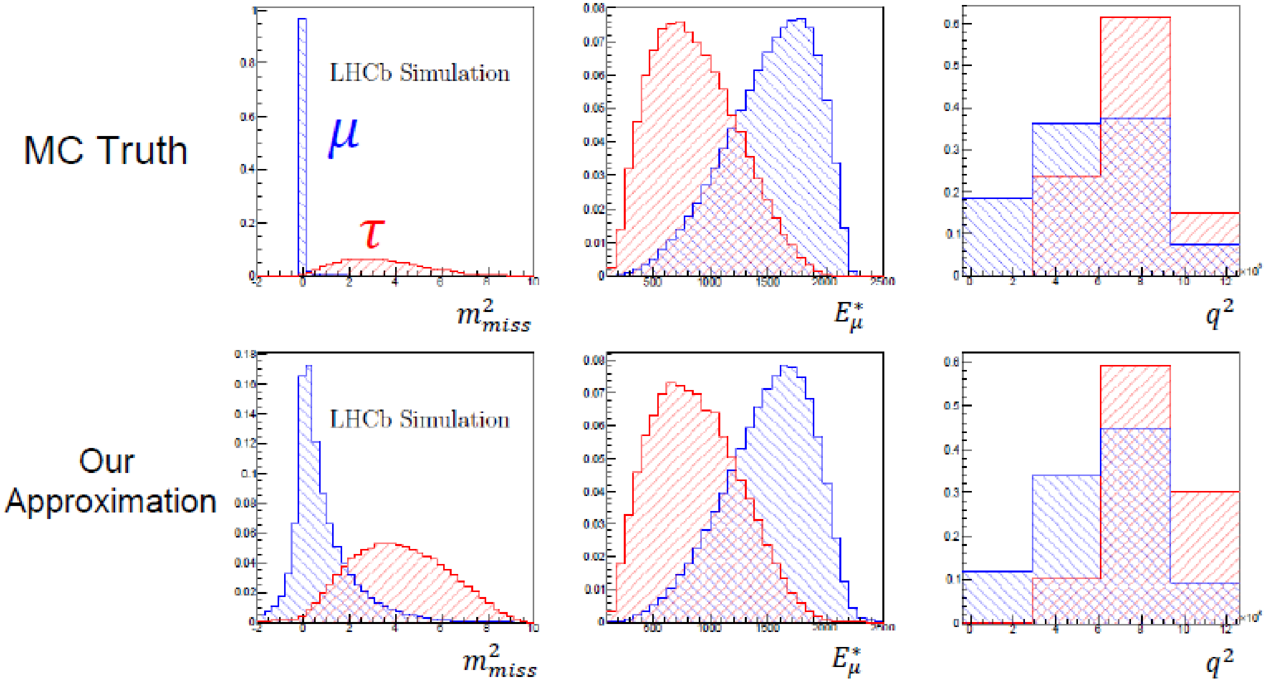
  its spin 0 (D^o, D^+, D_s), 1 (D^* and J/ψ) and ½ (Λ_c!!)





R(D*) with τ →μνν

PRL 115 111803 (2015)



Using the known B flight direction, approximate the B momentum using $\gamma\beta_{z,vis}=\gamma\beta_{z,B}$:

- Estimate gives ~ 18% resolution on B momentum, but preserves shapes of already-broad distributions of to m^2_{miss}, E^*_μ and q^2
- 3d MC-template based binned fit to m^2_{miss} vs E^*_μ in coarse q^2 bins

Fit Result

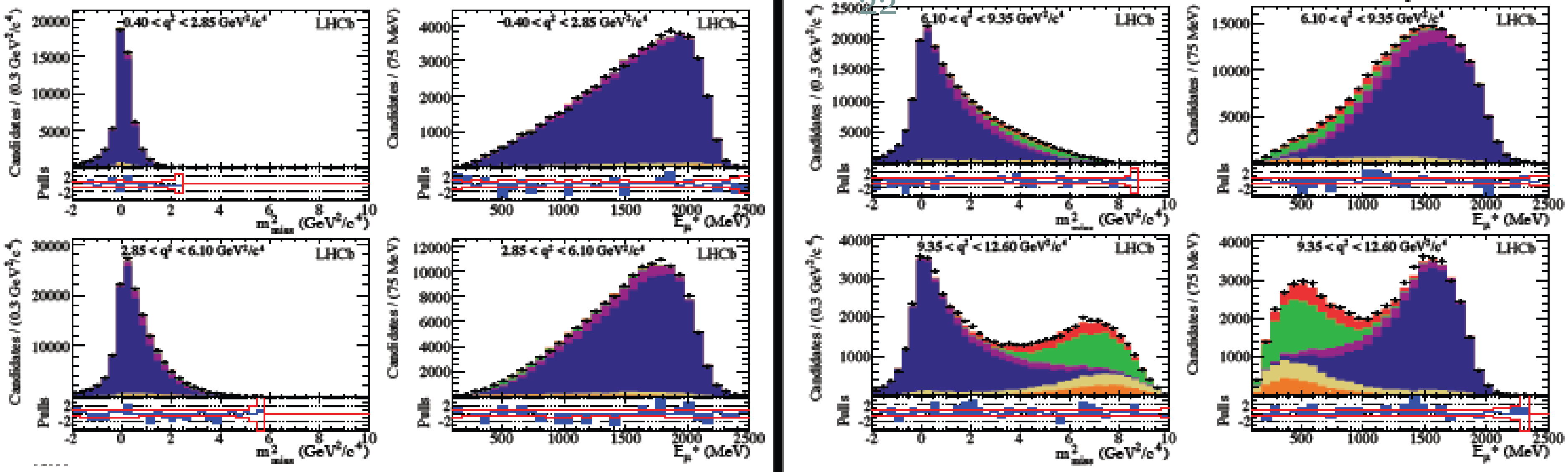
PRL 115 111803 (2015)

Low q^2

m^2_{miss} E^*_μ

High q^2

m^2_{miss} E^*_μ

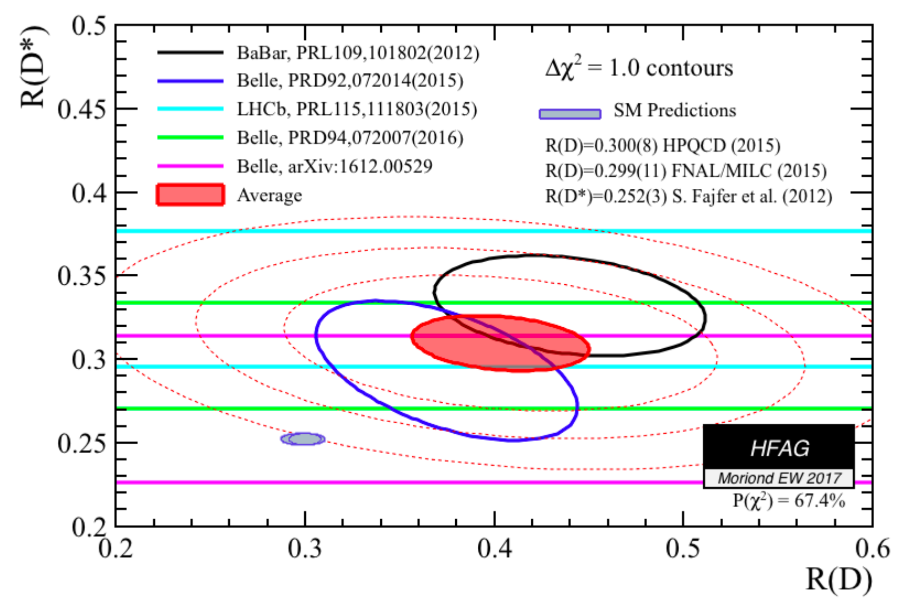


- Shown above: signal fit to "signal" data passing isolation selection
- Result $\frac{N_\tau}{N_\mu} = (4.32 \pm 0.37)\times 10^{-2}$, $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- $N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363{,}000 \pm 1600$

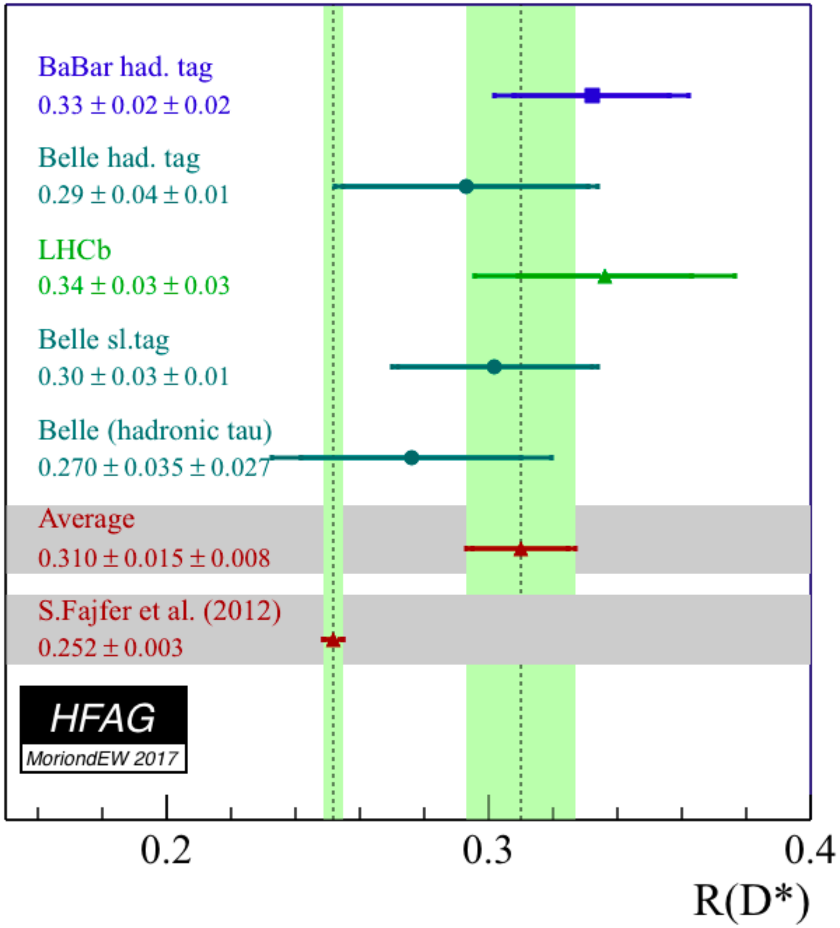
● Data
🟥 $B \to D^*\tau\nu$
🟩 $B \to D^*H_c\,(\to l\nu X')X$
🟪 $B \to D^{**}l\nu$
🟦 $B \to D^*\mu\nu$
🟨 Combinatoric
🟧 Misidentified μ

R(D*) status today

3.3 σ (goes to 3.1 σ if theor. error goes to 0.007)



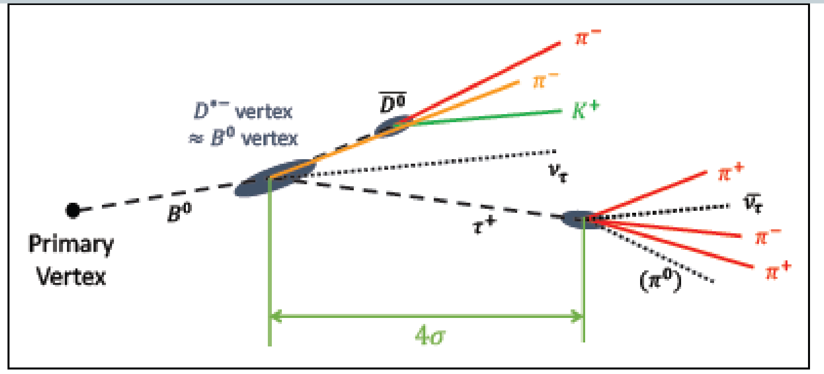
http://www.slac.stanford.edu/xorg/hfag/semi/index.html



If WA is correct, 22% of the D*τν events are mediated by new physics!

New ! R(D*) using τ hadronic decays in 3π
Unusual features of this analysis

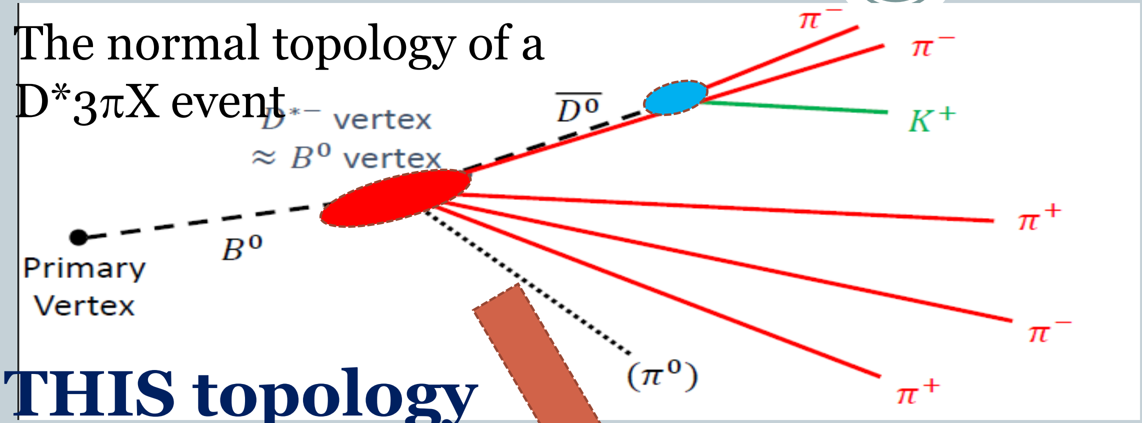
- A semileptonic decay without (charged) lepton !!:
  - Amusing but more importantly ZERO background from normal semileptonic decays!!!!



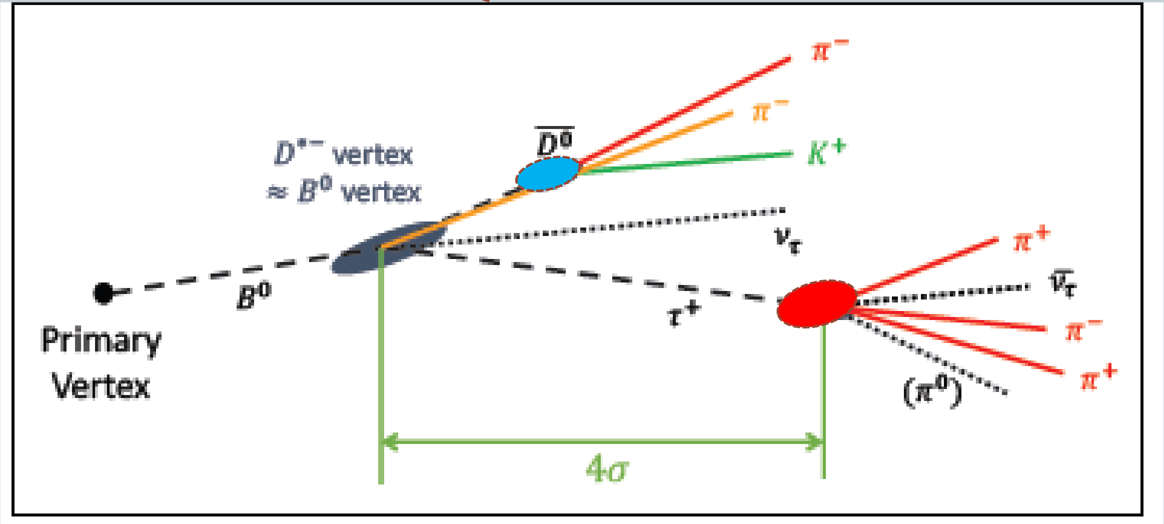
- The background leads to nice mass peaks and not the signal !!!
  - Amusing but more importantly provides key handles to control the various backgrounds
- Only 1 neutrino emitted at the τ vertex
  - The complete event kinematics can be reconstructed with reasonable precision
- But very large potential background from « bread and butter » D*3π X decays; 100 times larger than the signal : A trick must be found!!

The detached vertex method

The normal topology of a D*3πX event



THIS topology for D*τν events



The 4σ requirement kills the D*3πX background by ~10^3: **the road to the treasure is open ☺!!!**

The second gate : the double charm background

The second gate consists of B^o decays where the 3π vertex is transported away from the B^o vertex by a charm carrier: D_s, D^+ or D^o (in that order of importance)

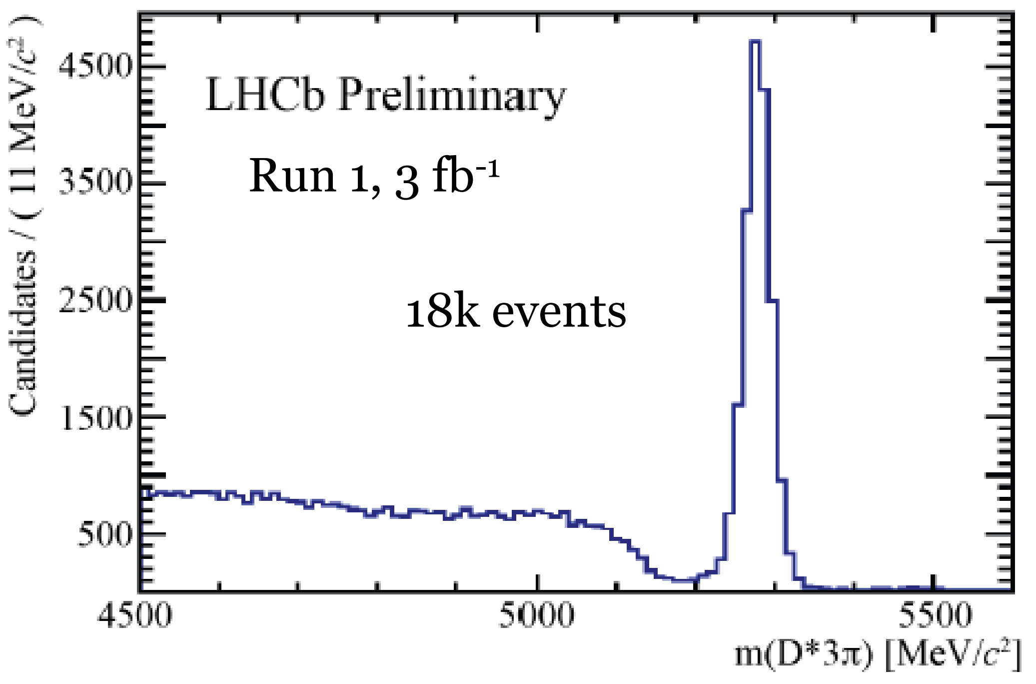
- This gate is thinner :
  - Double Charm→$3\pi X$ ~10 x signal

LHCb has three very good weapons to blow this gate away:

3π dynamics
Neutral isolation
Background partial reconstruction

Importance of the normalization channel $B^0 \rightarrow D^* 3\pi$

- Normalization as similar as possible to the signal to cancel production yield, BR uncertainties and systematics linked to trigger, PID, first selection cuts



- Absolute BR recently measured by BABAR with a precision of 4.3%

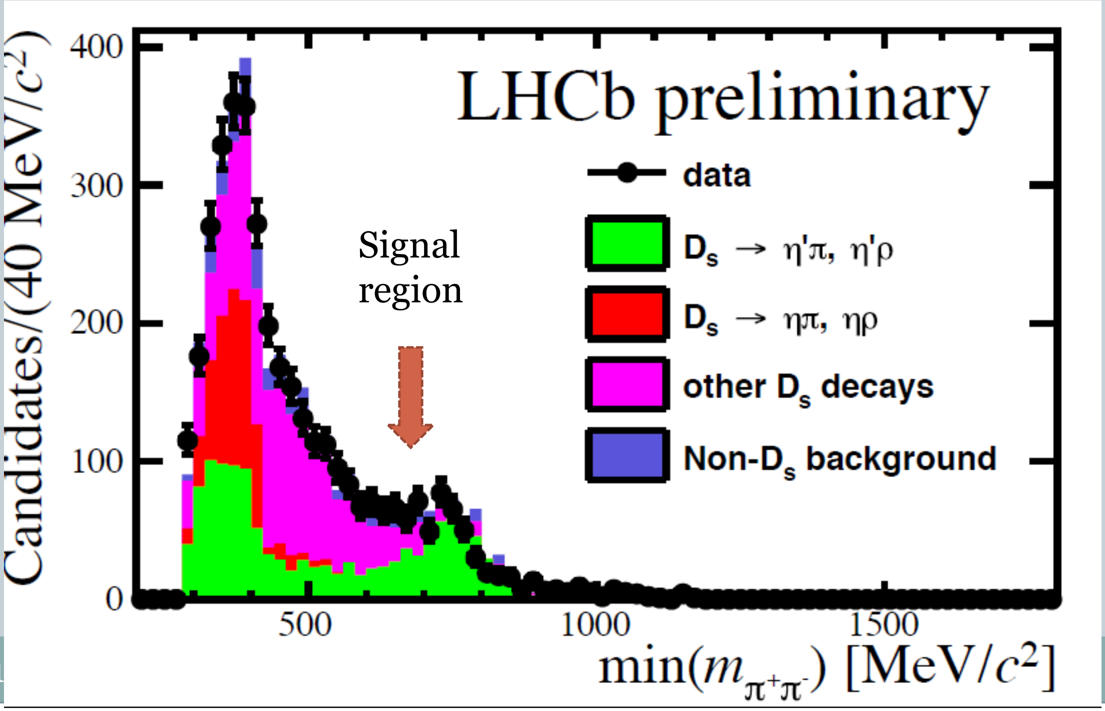
(**Phys.Rev. D94 (2016) no.9, 091101**)

The importance of the « D_s-o-meter »

- The D_s meson is the highest background since the W decays dominantly in D_s and the D_s is a very rich source of 3π +X final states.
- At low mass, only η and η’ (red,green) contributions are peaking

$\eta \rightarrow \pi^+\pi^- \pi^\circ$ and $\eta' \rightarrow \eta \pi^+\pi^-$ ⇨ $M_{\pi+\pi-}$ <415 MeV

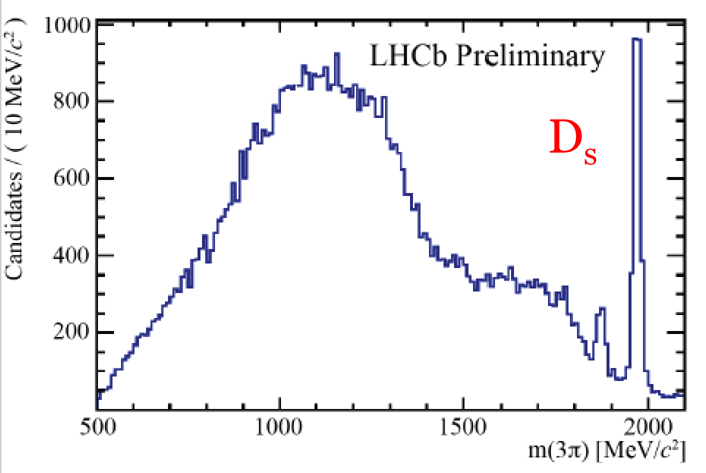
- At the ρ mass where the signal lives ($\tau \rightarrow a_1 ; a_1 \rightarrow \rho\pi$), only η’ contributes ($\eta' \rightarrow \rho\gamma$)
- Using the low BDT region, one constraints the D_s decay model to be used at high BDT



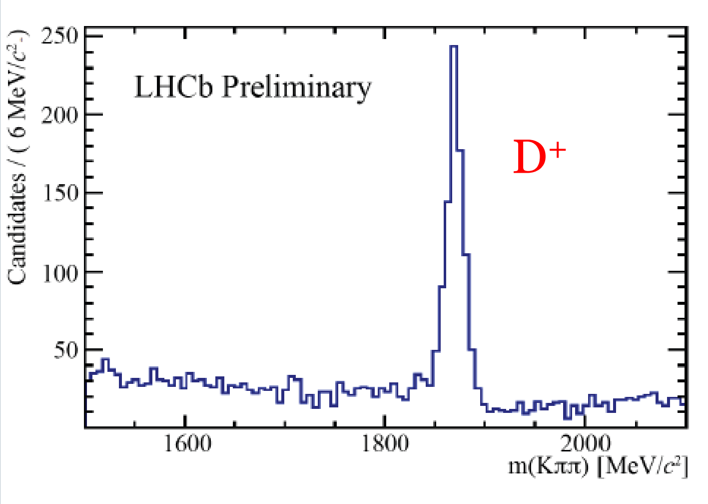
The anti-D_s BDT

- A BDT is constructed to get rid of the D_s background. It contains the following variables:
  - 3π dynamics : min($m_{\pi\pi}$), max($m_{\pi\pi}$),
  - B dynamics: D*3π mass
  - Partial reconstruction: the 4 constraints from the 2 lines of flight allows to reconstruct fully the event in the background hypothesis (no neutrinos)
  - Neutral isolation : energy in a cone around the 3π direction
  - Very D_s enriched at low BDT, good purity for signal at high BDT
- Opens the gate for search for BSM inside the events in addition to yields measurements

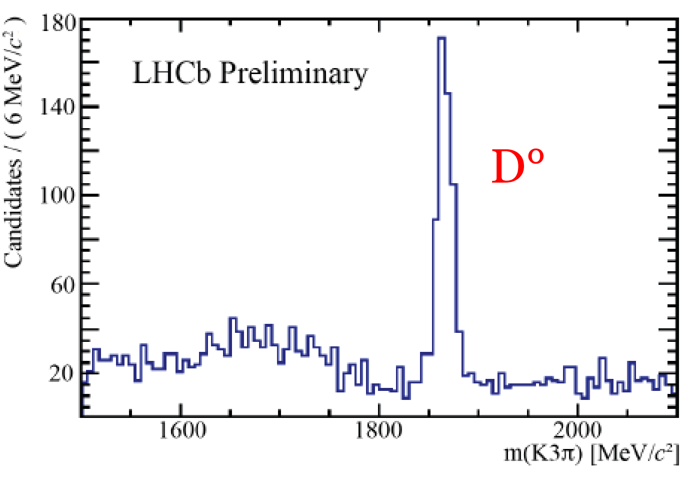
The control channels D_s, D°, and D^+



$\pi\pi\pi$ mass in detached topology

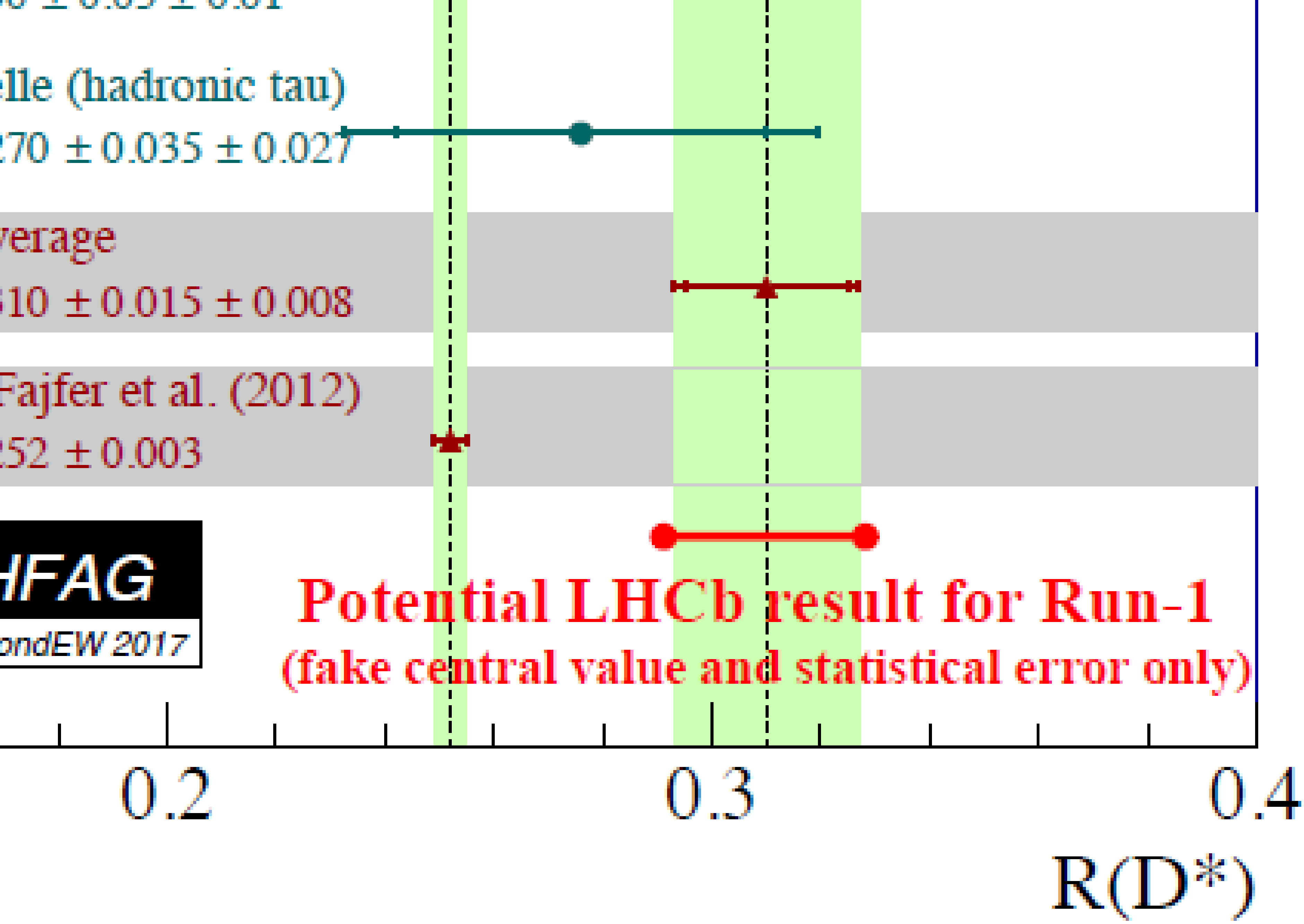


D^+ peak : Anti-PID cut



Run 1, 3 fb^{-1}

D° to K 3π peak : Antisolation cut



Potential LHCb result for Run-1

(fake central value and statistical error only)

Systematic uncertainties

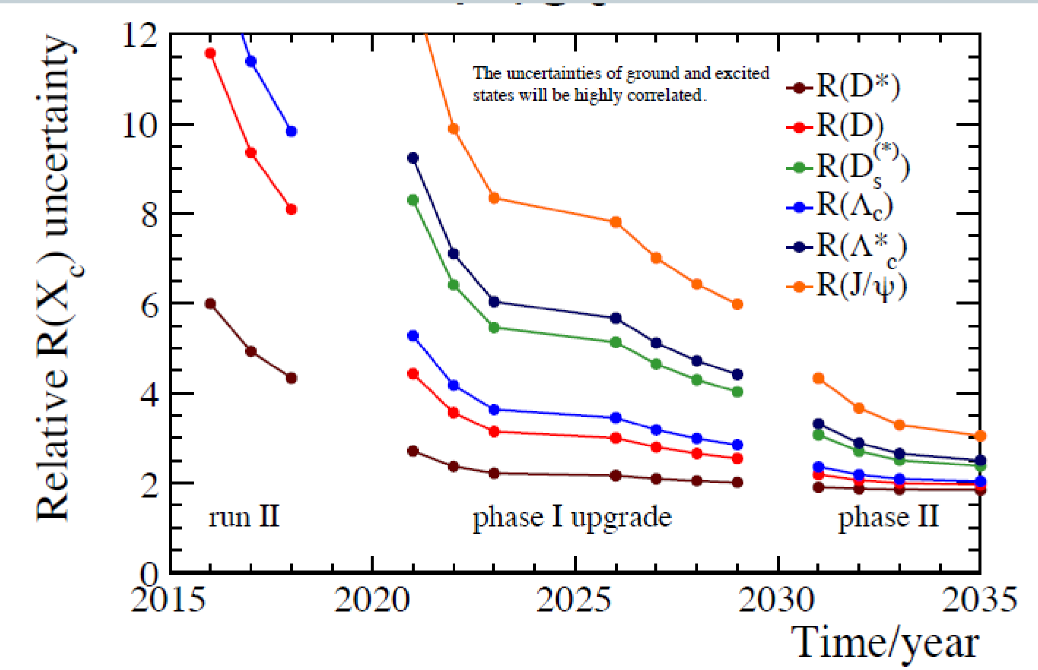
- External
  - 4,3 % from BR(B°→D*3π) PDG 2016
  - 2% from BR(B°→D*μν)
- Internal
  - MC statistics
  - D_s,D^+,D° backgrounds
  - Prompt B° backgrounds
  - Stripping, Trigger
  - FF and τ decay model

In red : can be reduced with help from other experiments (BELLE, BES,..)

- Expected overall to be larger than statistical error for the first publication (soon to come)
- Room for progress exists on a longer timescale on both internal and external sources!

Conclusion and Perspectives

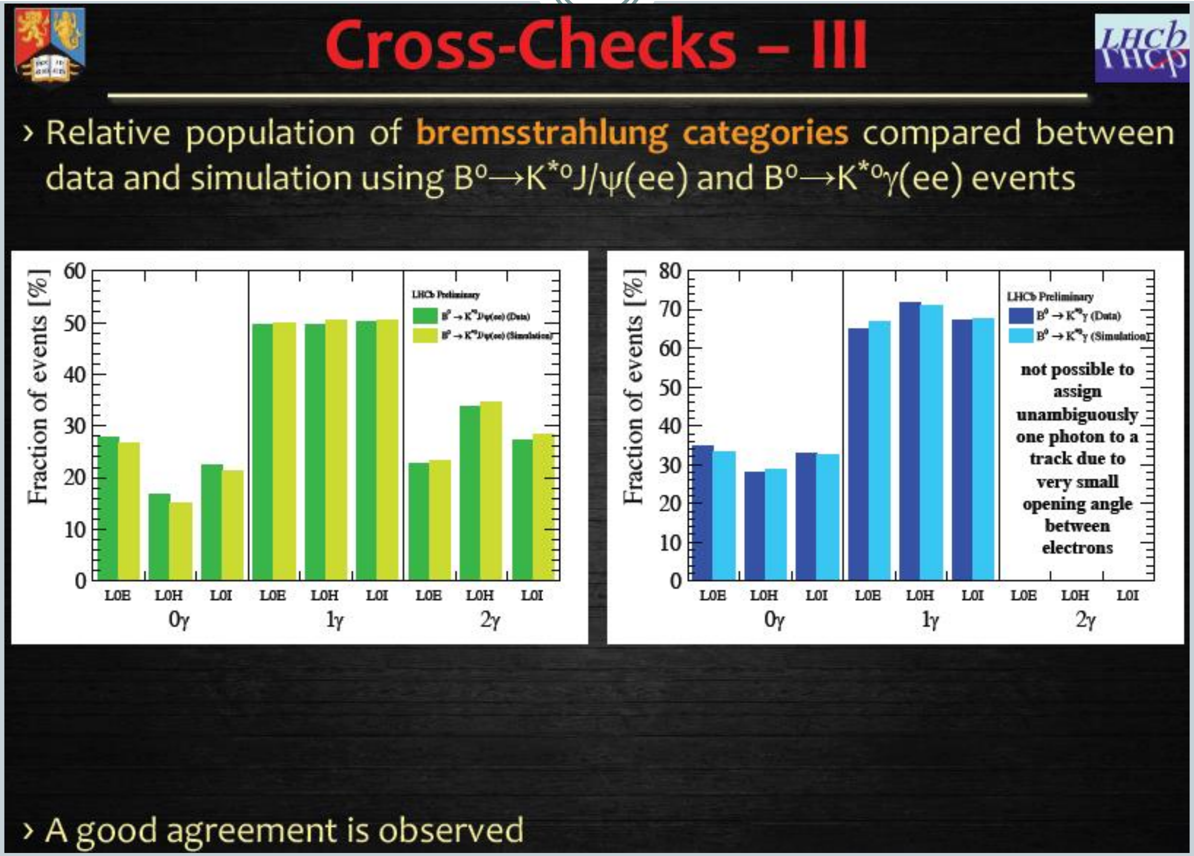
- Semitauonic B decays are a great tool to discover new physics : high SM precision, high rate and high sensitivity
- The exceptional LHCb capability to separate secondary and tertiary vertices open up the best road to study **the semi-tauonic decays of all B particles** , thanks to a new method based on **3 prongs τ decays**.
- The **statistical precision on Run1 should be around 6.7%**, the best achieved so far for a single measurement.
- The very successfull RunII data taking in 2015-2016 leads to **a quadrupling of the data set**
- High statistics and high purity samples to search for BSM effects in the event observables



The uncertainties of ground and excited states will be highly correlated.

Conclusion

- Lepton Flavour universality violation appears to be nowadays the most promising road towards Beyond Standard Model Physics
- LHCb will be the major player in the next 5 years
  - It will improve its present measurements by a very significant factor in the next 2 years
  - It will add measurement of the various R() in all hadronization channels $\Lambda_b \rightarrow \Lambda ee$
  - $R(\Lambda_c)$, $R(J/\psi)$
  - Intra-event searches with high purity samples
- The technique s used for R(D*) will also apply to searches for direct LFV such as $B \rightarrow K\mu\tau$
- From 2020 onwards, BELLE-II will add more data
- More precision in $BR(W \rightarrow \tau\nu)$ is also required (LHC (?), ILC..)



Cross-Checks – III

- Relative population of **bremsstrahlung categories** compared between data and simulation using $B^0 \to K^{*0} J/\psi(ee)$ and $B^0 \to K^{*0}\gamma(ee)$ events

- A good agreement is observed