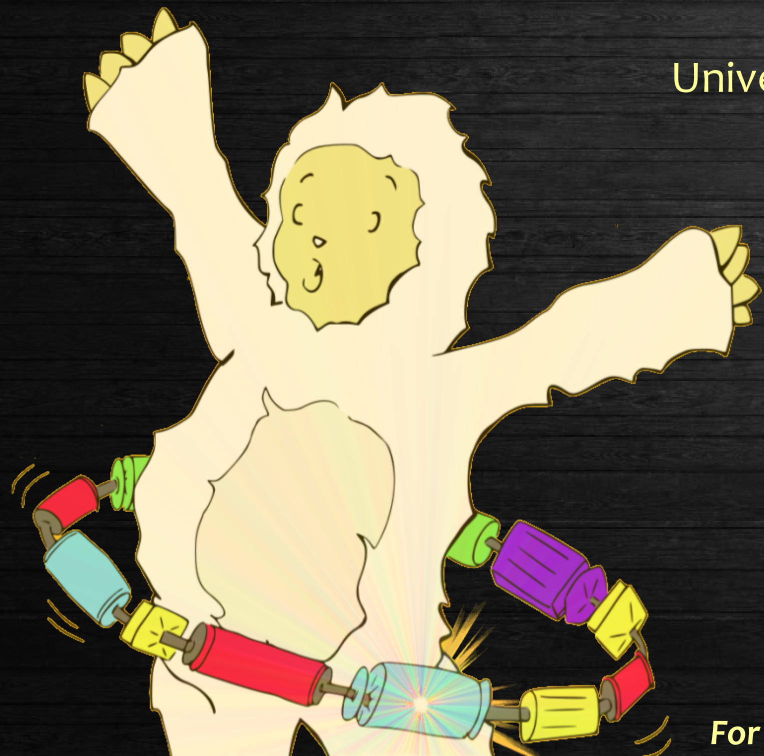
Lepton Universality Violation
An Experimental Perspective

Simone Bifani
University of Birmingham (UK)



YETI 2018 - Flavours and Resonances
What has the LHC done for us?

7th - 10th January 2018

For a theoretical review please attend tomorrow's lecture by Prof. Svjetlana Fajfer

Introduction

- Recent measurements of b-quark transitions manifest intriguing **hints of Lepton Universality violation**
  - Tests with tree-mediated **$b \to c l \nu$** transitions
  - Tests with loop-mediated **$b \to s l l$** transitions

- **Lepton Universality**
  - **Electroweak couplings of leptons to gauge bosons are independent of their flavour** (i.e. interactions of charged leptons differ only because of their different masses)
  - **Not a fundamental symmetry of the Standard Model**

- **Today**
  - How are these measurements made?
  - Are we seeing the first hints of physics Beyond the Standard Model?
  - When/how can we confirm or rule out these deviations?

Lepton Universality Tests in Other Sectors

Gauge Sector

› LEP [PR 427 (2006) 257, PR 532 (2013) 119]

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

$$\mathcal{B}(W \to \mu\overline{\nu}_\mu) \,/\, \mathcal{B}(W \to e\overline{\nu}_e) = 0.993 \pm 0.019$$

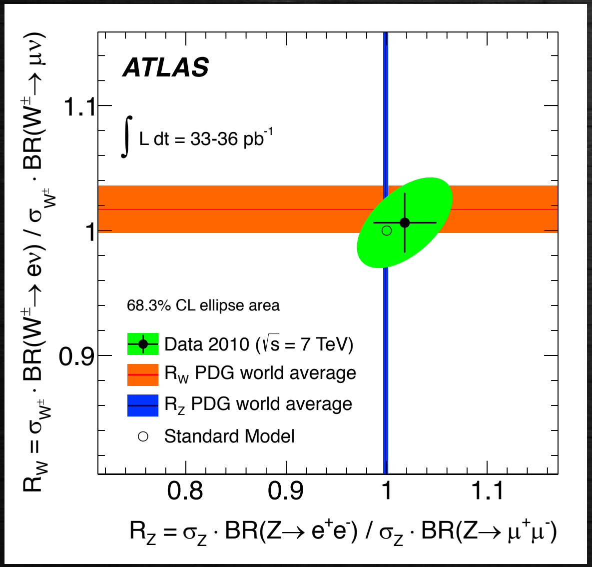
$$\mathcal{B}(W \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(W \to e\overline{\nu}_e) = 1.063 \pm 0.027$$

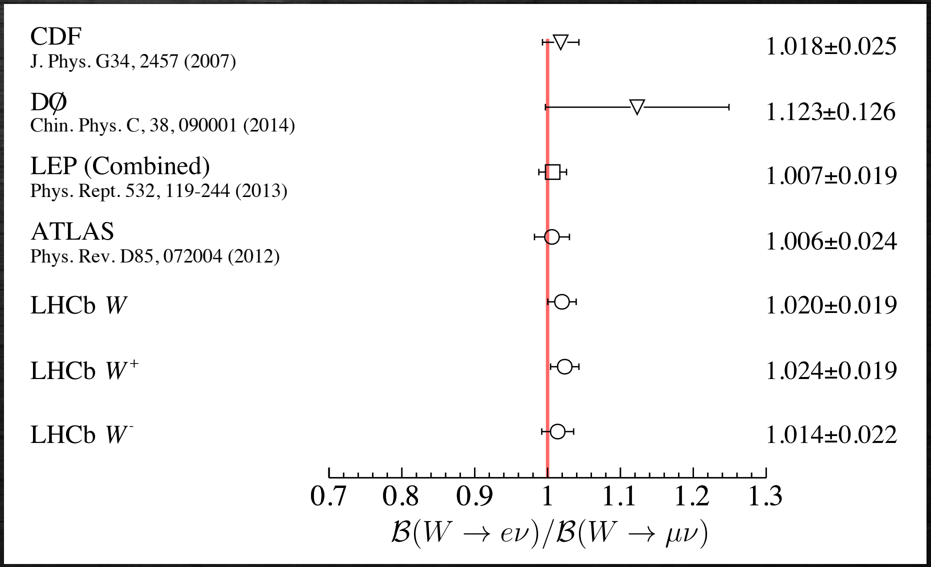
$$\mathcal{B}(W \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(W \to \mu\overline{\nu}_\mu) = 1.070 \pm 0.026$$

$$2\mathcal{B}(W \to \tau\overline{\nu}_\tau) \,/\, (\mathcal{B}(W \to e\overline{\nu}_e) + \mathcal{B}(W \to \mu\overline{\nu}_\mu)) = 1.066 \pm 0.025$$

2.6s deviation

› LHC [PRD 85 (2012) 072004, JHEP 10 (2016) 030]





Light Mesons

› **PIENU** [PRL 115 (2015) 071801]

$$R_{e/\mu} = \Gamma(\pi \to e\nu(\gamma))/\Gamma(\pi \to \mu\nu(\gamma))$$

» SM = $(1.2352 \pm 0.0002) \times 10^{-4}$

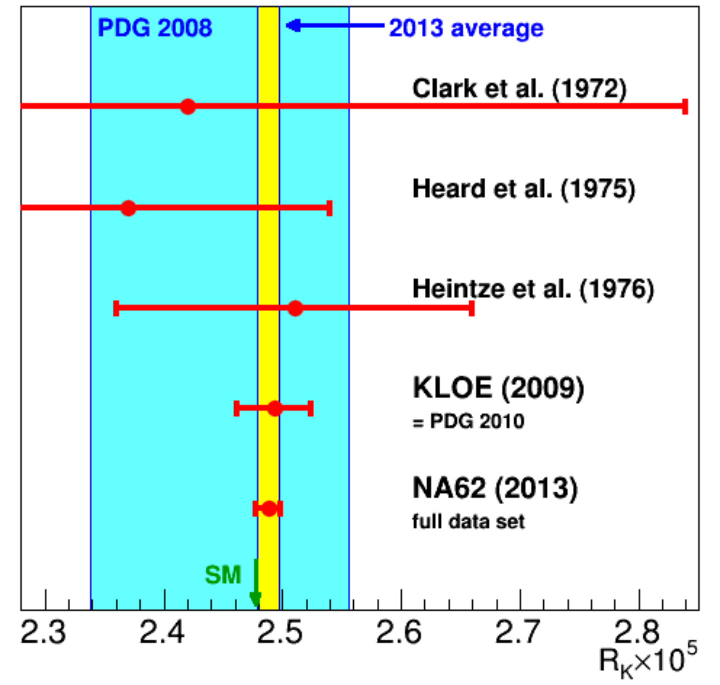
» Exp = $(1.2344 \pm 0.0023_{stat} \pm 0.0019_{syst}) \times 10^{-4}$

› **NA62** [PLB 719 (2013) 326]

$$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$$

» SM = $(2.477 \pm 0.001) \times 10^{-5}$

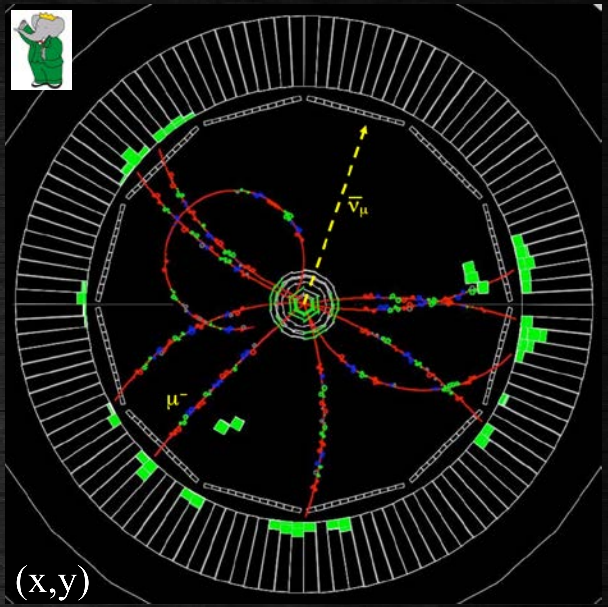
» Exp = $(2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$

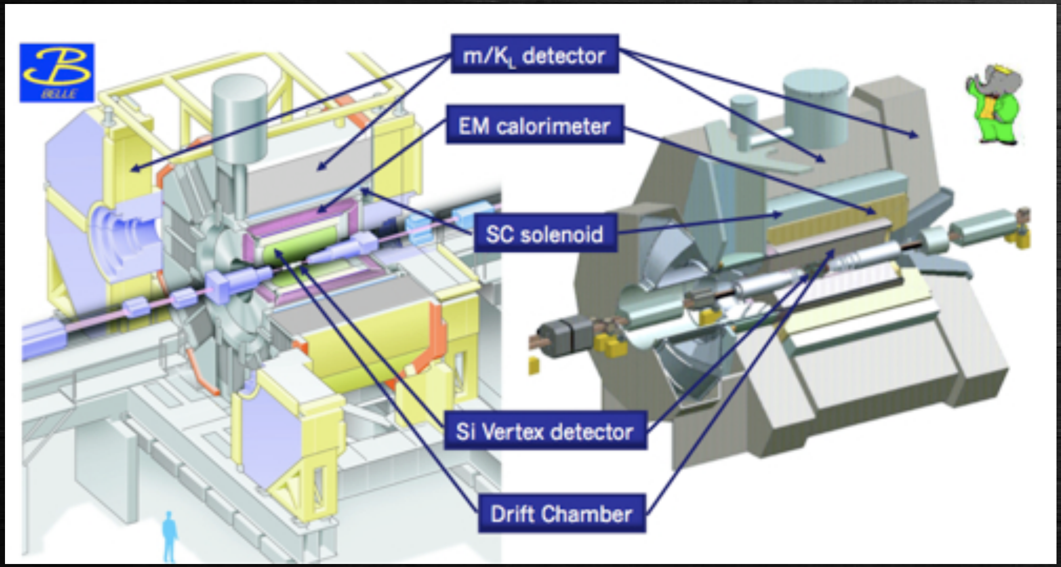


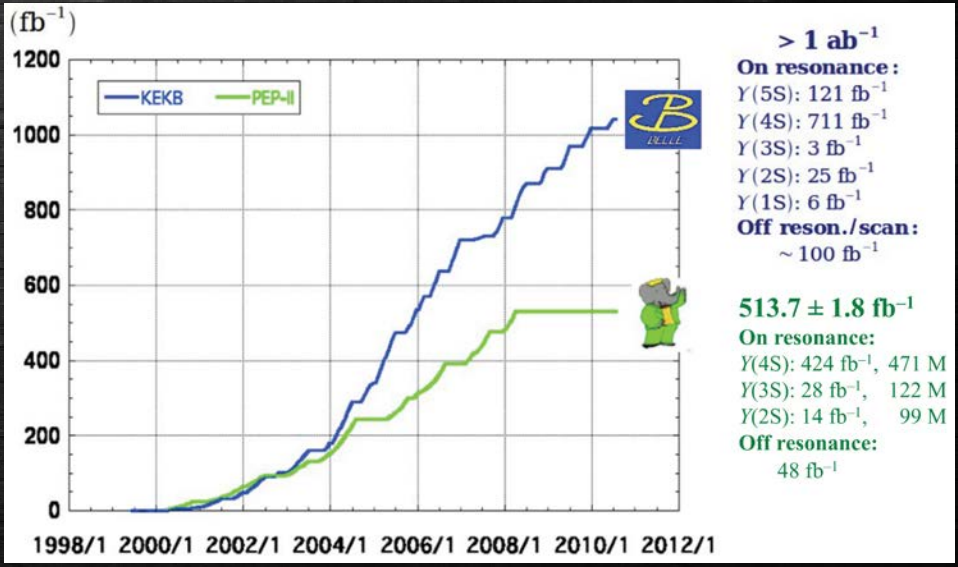
Lepton Universality in B Decays

B-Factories

- PEP-II and KEKB
  - **e^+e^- collisions** at $\Upsilon(4S)$ resonance (BB threshold)
  - Small cross-section $\sigma_{BB} \sim 10^{-9}$ b
  - **Initial state known** (e^+e^- collision energy)
  - **Very clean BB production** (no underlying event)
  - **BaBar** and **Belle** hermetic detectors
  - Large luminosity collected (~1.1 ab^{-1} at $\Upsilon(4S)$)



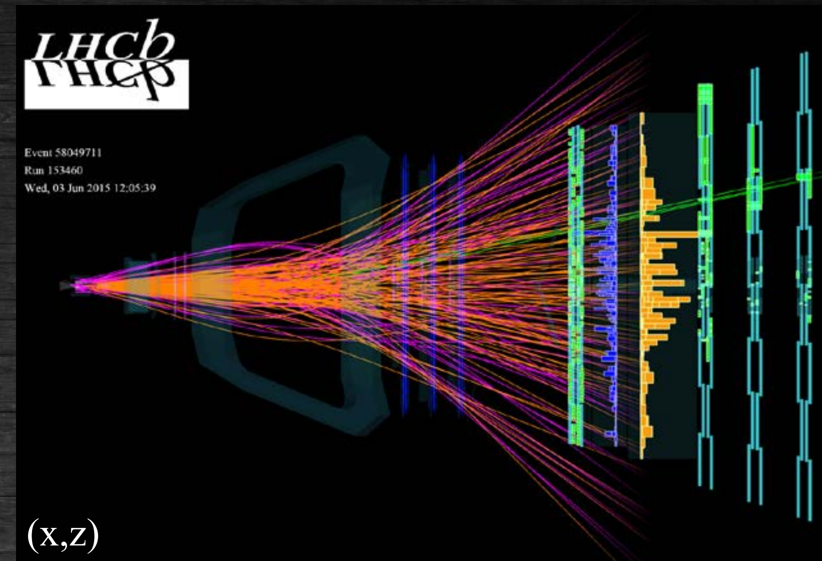


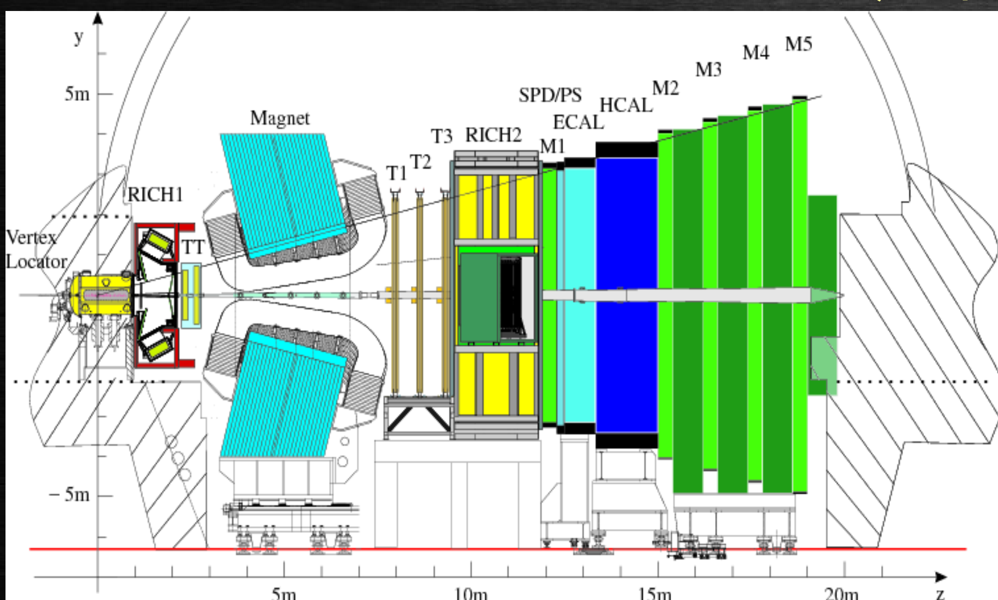


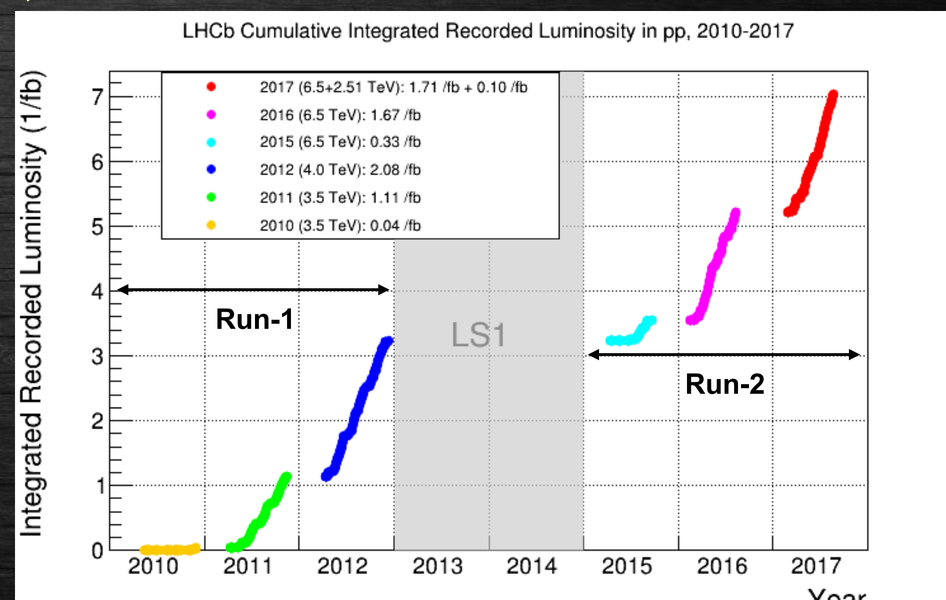
Hadron Collider

› **LHC**

- » **pp collisions** at 7-14 TeV
- » **Huge cross-section** σ_{bb} ~0.3-0.6 × 10^{-3} b but $\sigma_{inelastic}$ ~200 σ_{bb}
- » Initial state unknown (partons)
- » Very boosted b-hadrons
- » bb production peaks at small angle → **LHCb** instrumented forward ($2<\eta<5$)







Detector Performance

- Key detector performance for Lepton Universality tests

  - **μ ID (misID) efficiency**
    - BaBar ~75 (1-2) %
    - Belle ~90 (2) %
    - LHCb >95 (1-2) %

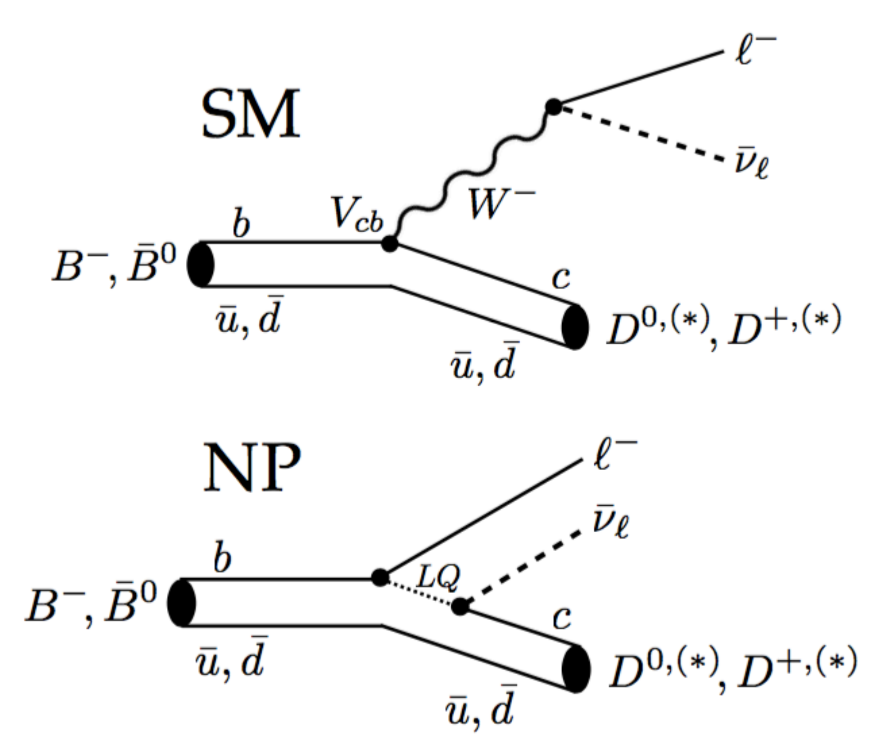
  - **e ID (misID) efficiency**
    - BaBar&Belle ~90 (0.2-0.3) %
    - LHCb ~90 (3-5) %

  - **Trigger efficiency**
    - BaBar&Belle ~100 %
    - LHCb >90 (60-70) % for μ(e)

Lepton Universality in Trees

Lepton Universality in Trees

› **Flavour-Changing Charged-Current** quark-transitions



› BSM physics can couple to 3rd generation

› Sensitive to **charged Higgs, W' boson** and **Leptoquarks**

› Measure **τ/e or τ/μ**
- » Hadronic uncertainties largely cancel
- » Precise predictions (1-3%)

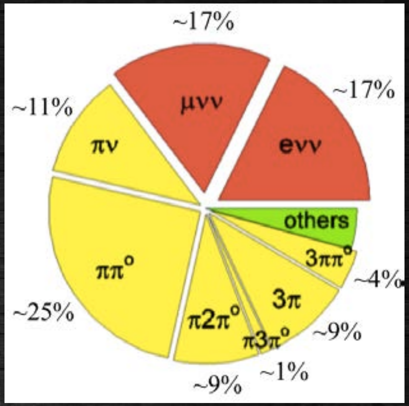
$$\mathcal{R}_D^{SM} = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to De^-\bar{\nu}_e)} = 0.300 \pm 0.008$$

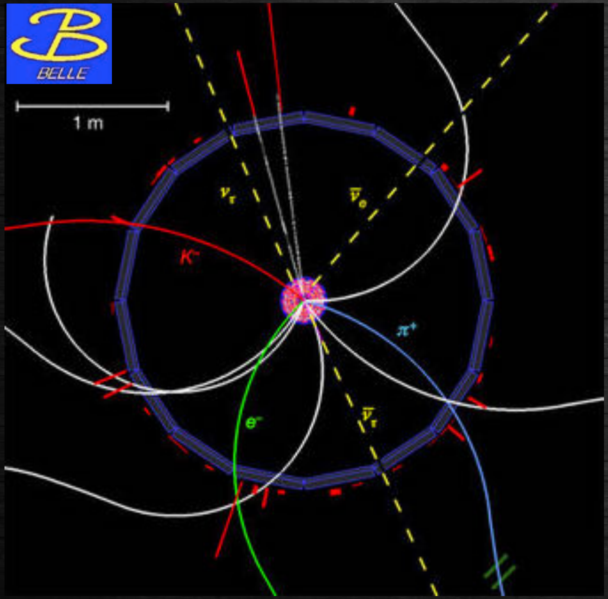
$$\mathcal{R}_{D^*}^{SM} = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*e^-\bar{\nu}_e)} = 0.252 \pm 0.003$$

*not unity because of phase-space effects due to different lepton masses

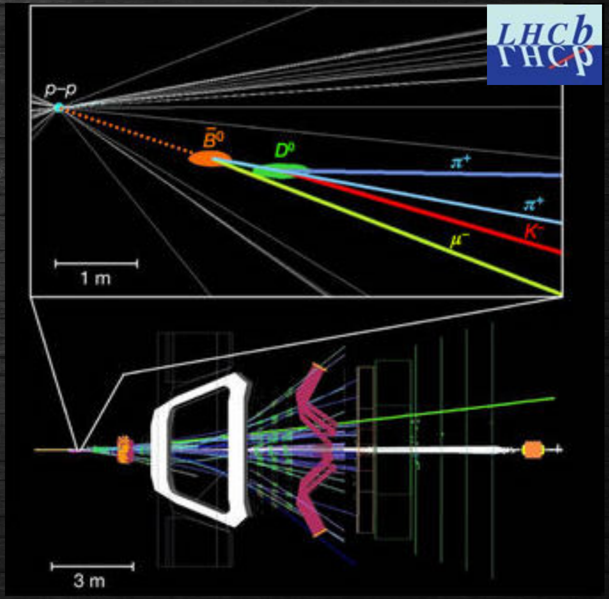
Tau

- **Heaviest lepton** in the SM
  - m_τ ~1.78 GeV (~15x m_μ)
  - lifetime ~0.3 ps
- **Large variety of decay modes**
- **One or more neutrinos** in the final state





$B^- \to D^0[K^-\pi^+]\tau^-\nu$ with $\tau^- \to e^-\nu\nu$
$B^+ \to$ 5 charged tracks

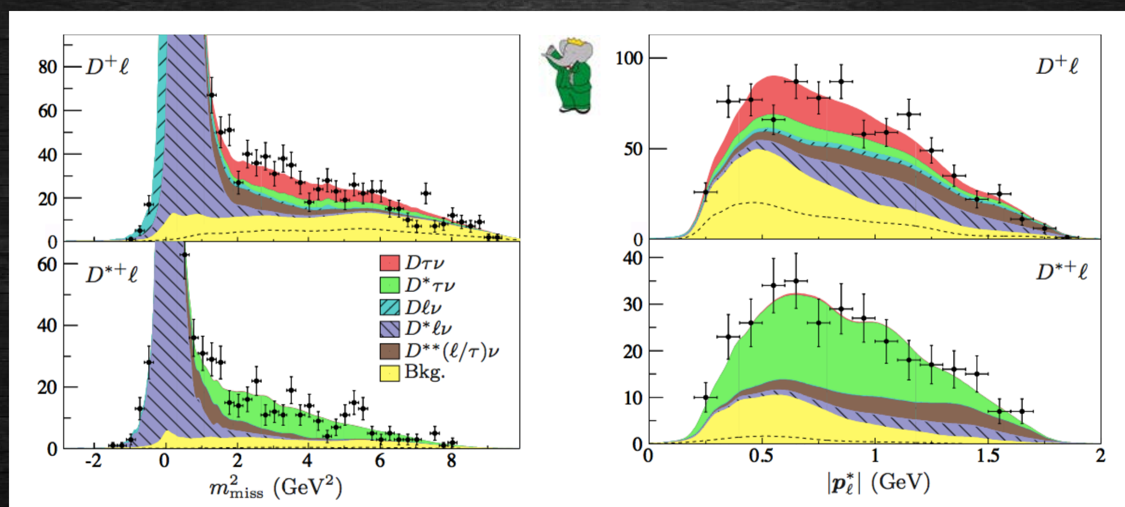


$\bar{B}^0 \to D^{*+}\tau^-\nu$ with $\tau^- \to \mu^-\nu\nu$
and $D^{*+} \to D^0[K^-\pi^+]\pi^+$

$R(D^{(*)})$ – BaBar

- Hadronic tag of the other B [PRD 88 (2013) 072012]
- Technique
  - **Beam constraints** to isolate signal
  - Tau reconstructed via **$\tau \to e\nu\nu$** and $\tau \to \mu\nu\nu$
  - **Charged and neutral hadrons** and D→2,3h
  - 2D fit to m^2_{miss} and p_l

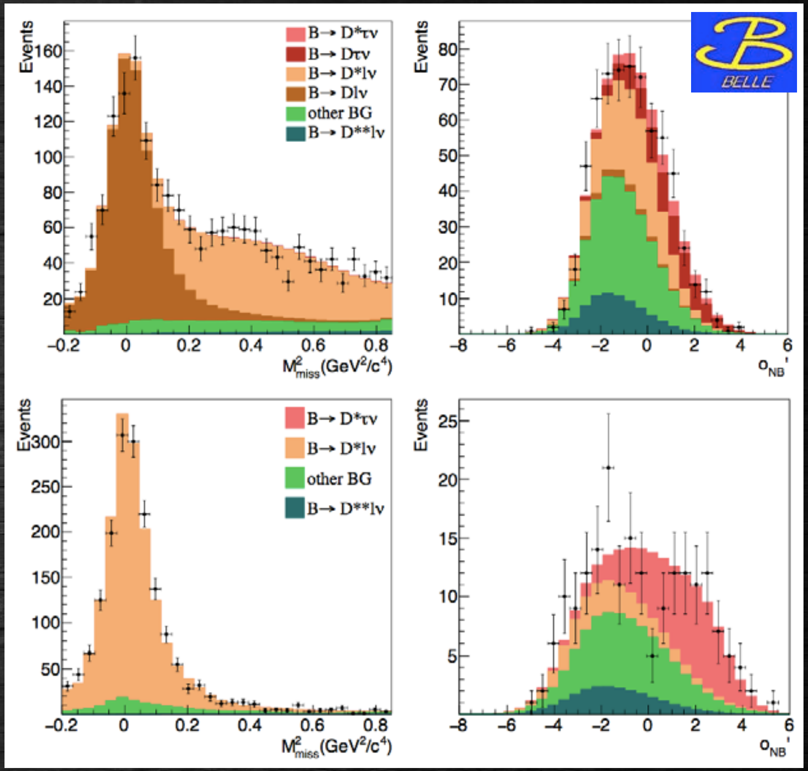
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$



- **Precision of ~16(9)%** on $R(D^{(*)})$
- Systematic uncertainties ~10(5)% mainly from shapes

$R(D^{(*)})$ – Belle

- Hadronic [PRD 92 (2015) 072014] and semileptonic [PRD 94 (2016) 072007] tag of the other B
- Technique
  - » **Beam constraints** to isolate signal
  - » Tau reconstructed via **$\tau \to e\nu\nu$** and $\tau \to \mu\nu\nu$
  - » **Charged and neutral hadrons** and $D \to 2,3h$
  - » 2D fit to m^2_{miss} and kinematic NN output



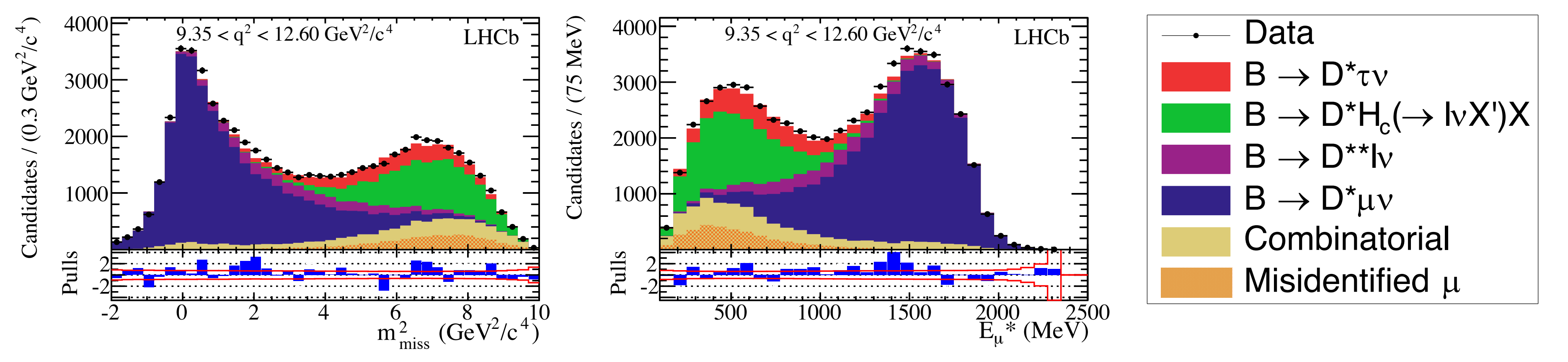
- **Precision of**
  - » **~18(14)%** on $R(D^{(*)})$ with h-tag
  - » **~11%** on $R(D^*)$ with sl-tag

- Measured also $R(D^*)$ using $\tau \to h\nu$ with a precision of ~17% [PRL 118 (2017) 211801]

R(D*) – LHCb

- Measurement thought not to be possible at LHCb
  - No info on initial state and non-hermetic detector
- Technique [PRL115 (2015) 111803]
  - Tau reconstructed via $\tau \to \mu\nu\nu$
  - **Only charged hadrons** ($D^{*+} \to D^0(K^- \pi^+)\pi^+$)
  - Selection designed to not bias the $D^{*+}\mu$ system
  - 3D fit to (q^2, m^2_{miss}, E_μ^*)

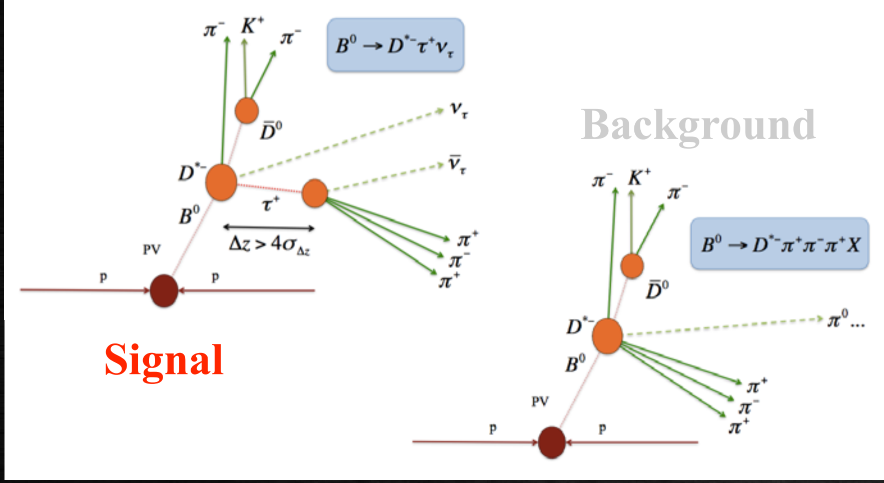
$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

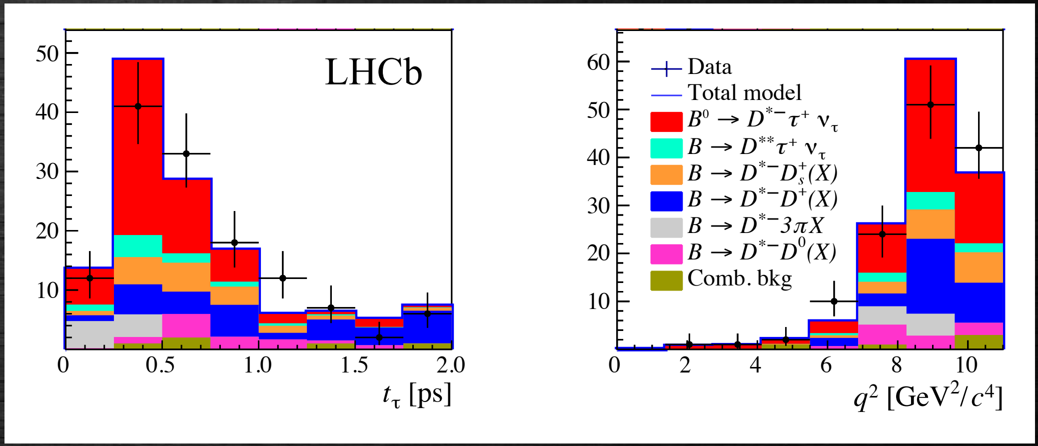


- **Precision of ~12%** using 3fb⁻¹
- Dominant systematics due to size of simulated samples for templates

R(D*) – LHCb

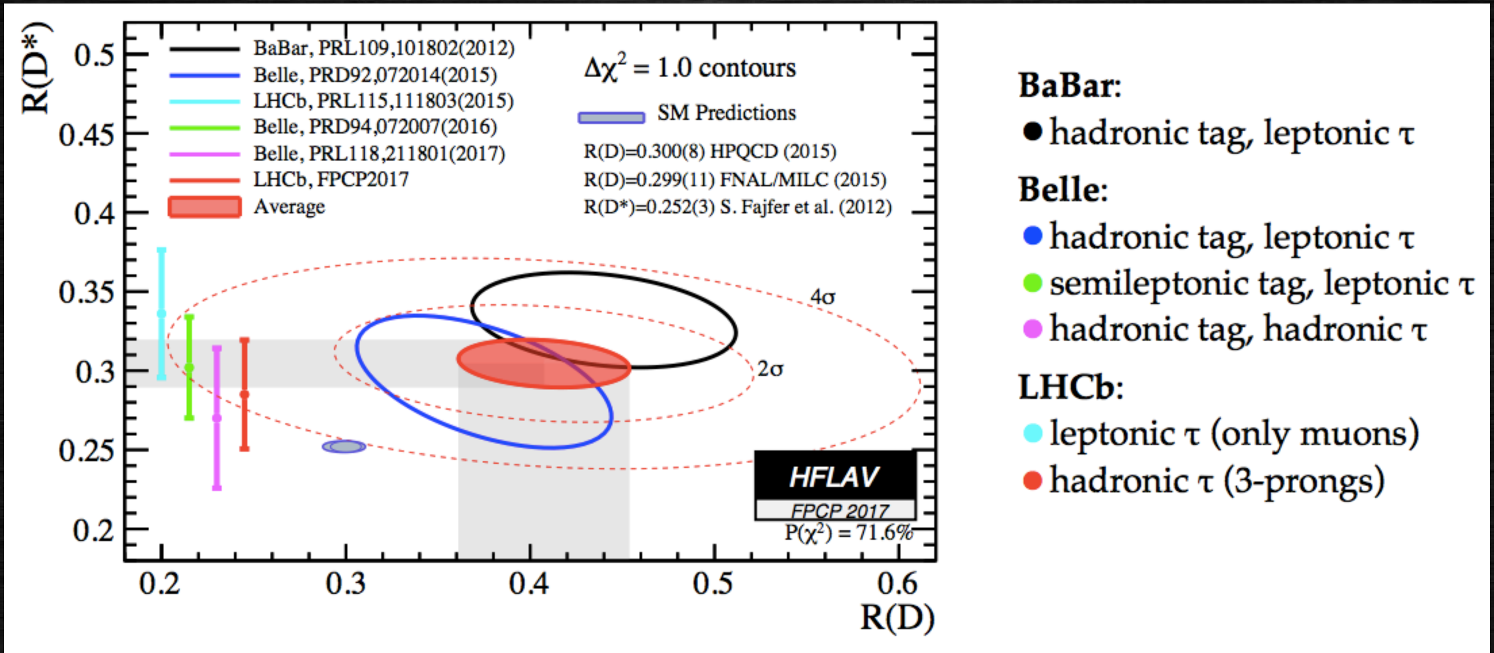
- Technique [arXiv:1708.08856]
  - Tau reconstructed via $\tau \to 3\pi\nu$
  - **Only charged hadrons** ($D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\tau^+ \to \pi^+\pi^+\pi^-\nu$)
  - Normalise to $B \to D^{*-}\pi^+\pi^+\pi^-$ and use $BR(B \to D^*\mu\nu)$ from B-factories
  - **Exploit τ lifetime** to reduce part-reco background
  - 3D fit to (q^2, τ decay time, BDT)





- **Precision of ~13%** (~7% due to $BR(B \to D^*\mu\nu)$) using 3fb^{-1}
- Dominant systematics due to size of simulated samples for templates

$R(D^{(*)})$ – Global Picture



› **Combined significance of ~4σ**

› Results consistent using **different experimental apparatuses**

  » B-factories with ee@10GeV and LHCb with pp@8TeV

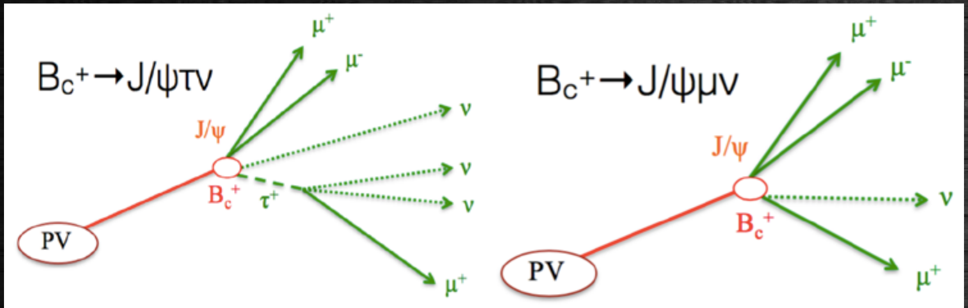
› Results consistent using **different analysis techniques**

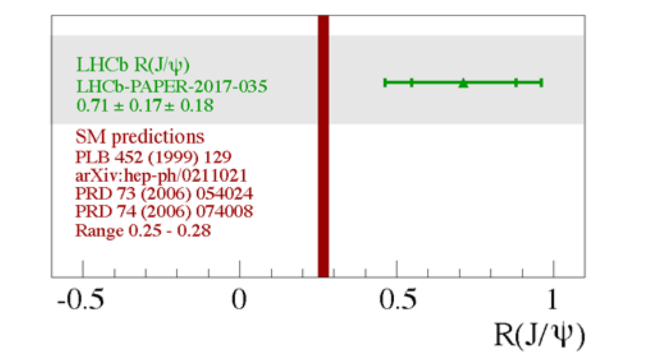
  » Expect systematics to be largely orthogonal

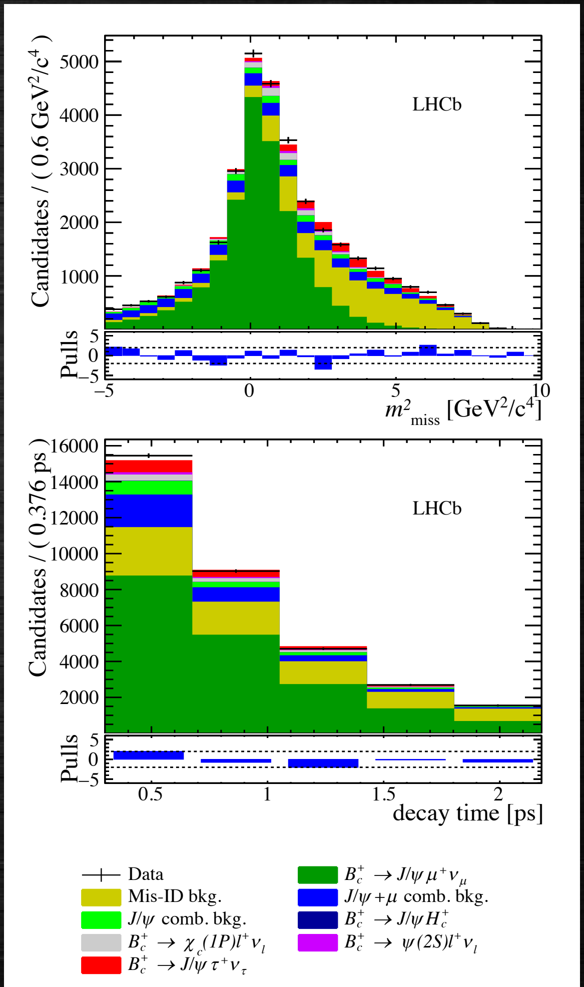
R(J/ψ) – LHCb

- Charmed B decays [arXiv:1711.05623]
  - Similar technique to R(D*)
  - Tau reconstructed via $\tau \to \mu\nu\nu$
  - 3D fit to (q^2, E_μ^*), m^2_{miss} and B_c decay time

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$





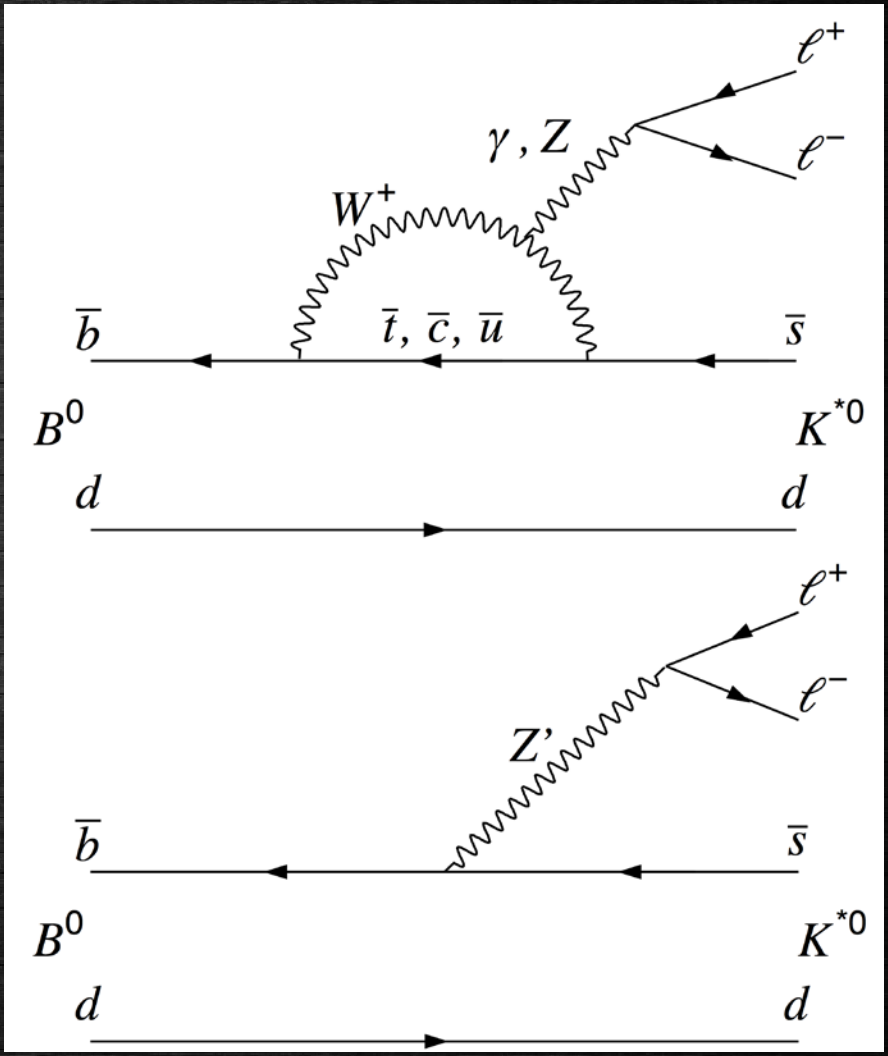


- **Precision of ~35%** using 3fb⁻¹
- **Compatible with the SM at ~2σ**

Lepton Universality in Loops

Lepton Universality in Loops

- **Flavour-Changing Neutral-Current** quark-transitions
- Only allowed at loop level in the SM
- New Particles can
  - Enhance/suppress decay rates
  - Introduce new sources of CP violation
  - Modify the angular distribution of the final-state particles
- Sensitive to **Z' boson** and **Leptoquarks**
- Measure **μ/e** (τ inaccessible at present)
  - Expected to be unity in SM
  - Hadronic uncertainties largely cancel



Theoretical Framework

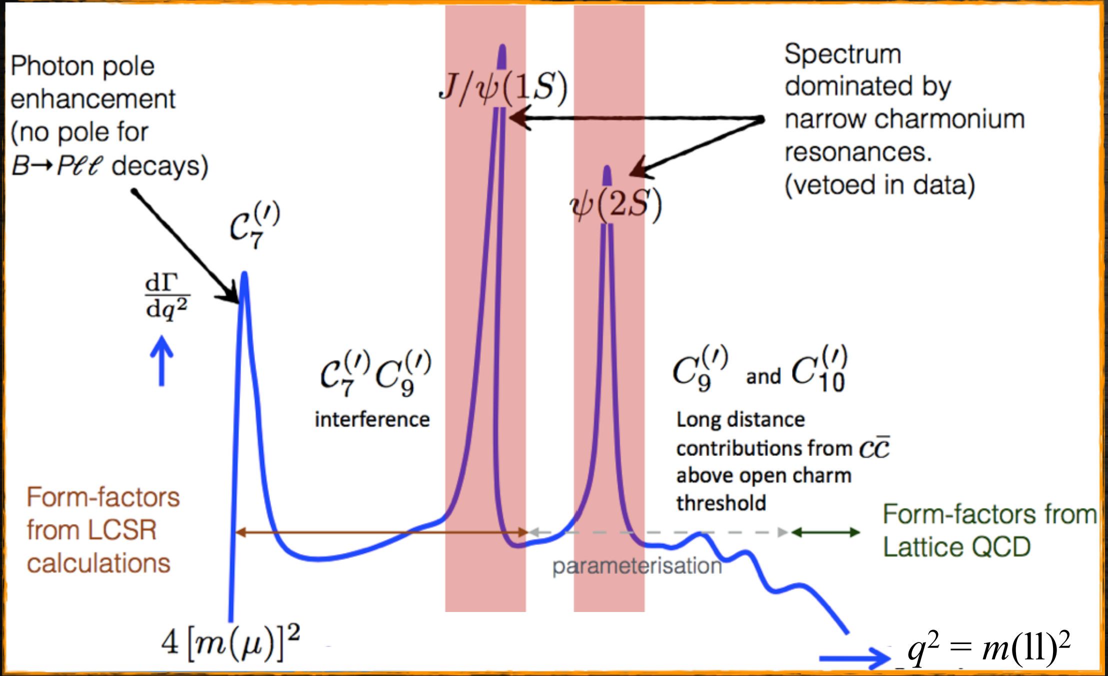
› FCNC **effective Hamiltonian** described by Operator Product Expansion

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right-handed part suppressed in SM}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

» C_i (**Wilson coefficients**): perturbative, short-distance physics, sensitive to E>Λ_{EW}

» O_i (**Operators**): non-perturbative, long-distance physics, depend on hadronic FF



Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

What Have We Done So Far?

› Extensive studies at LHCb in three main areas

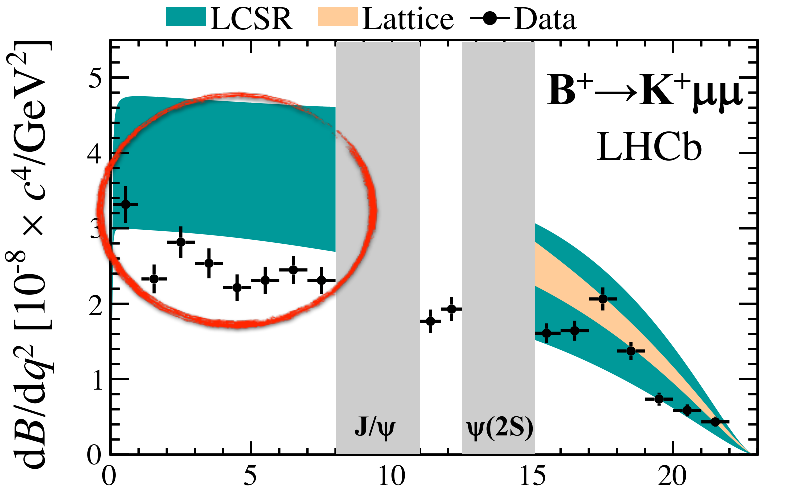
1. **Differential branching fractions**
   » Large hadronic uncertainties in theory predictions

2. **Angular analyses**
   » Define observables with smaller theory uncertainties

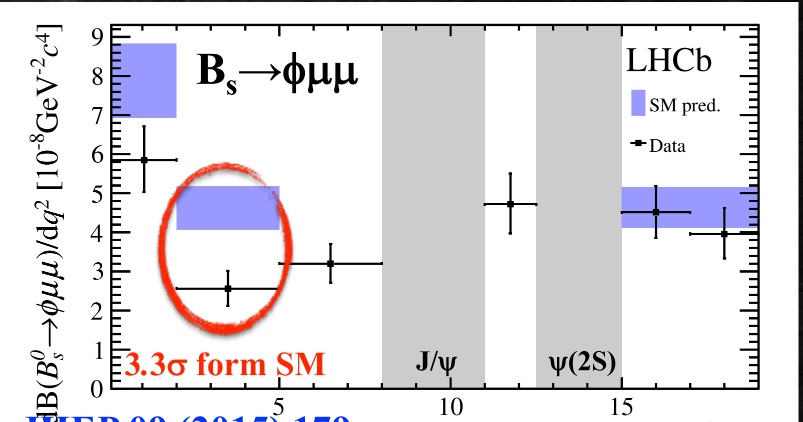
3. **Branching fraction ratios**
   » Large cancellation of hadronic uncertainties in theory predictions

Differential Branching Fractions

› Results **consistently lower than SM predictions**



JHEP 06 (2014) 133



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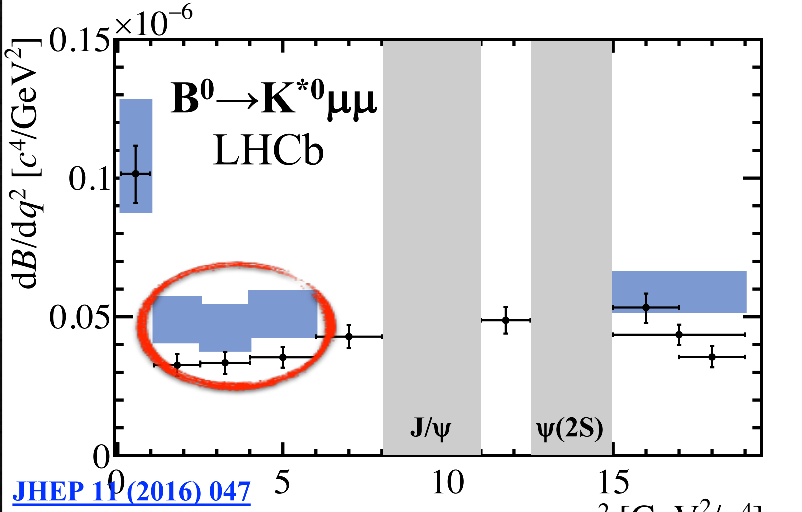

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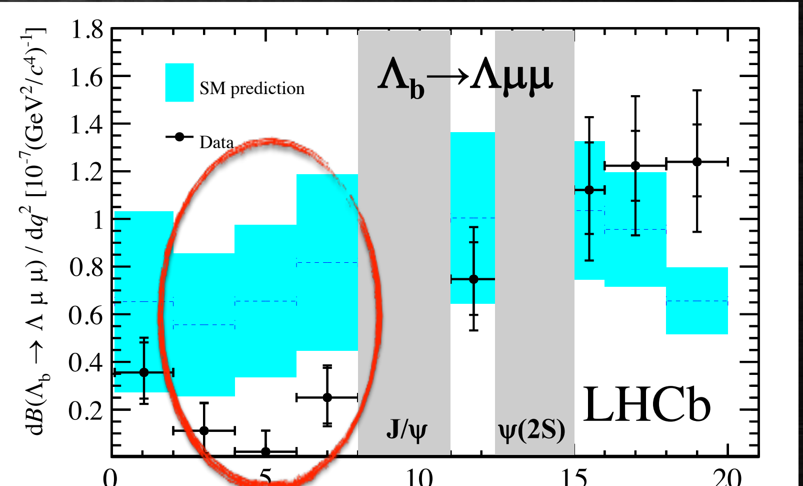
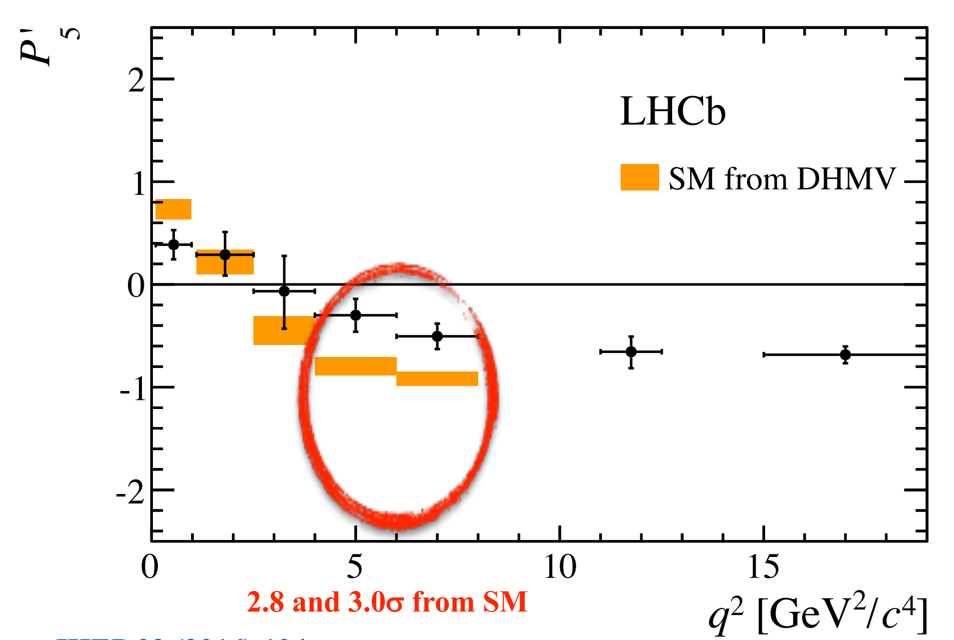
JHEP 04 (2017) 142



JHEP 06 (2015) 115

Angular Analyses

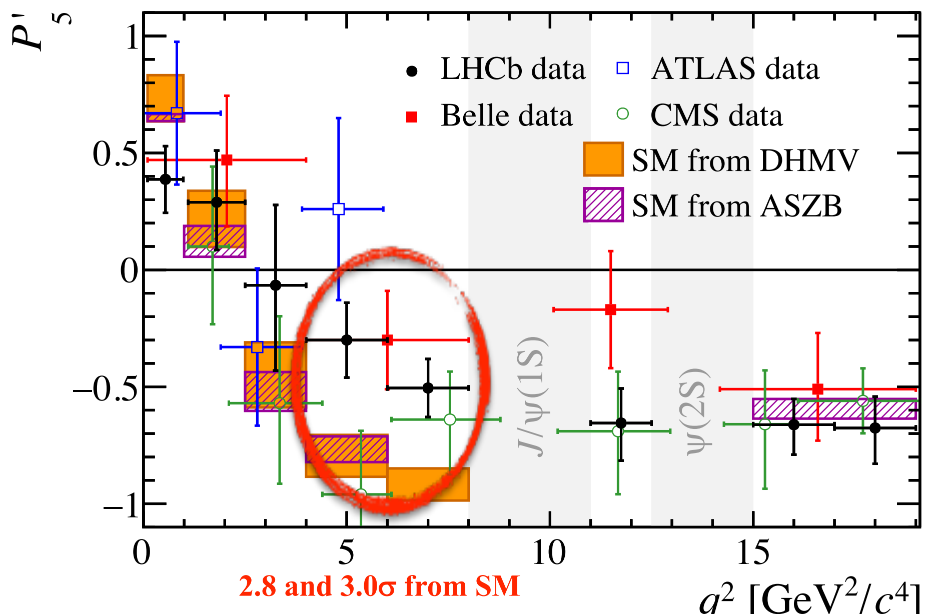
- $B^0 \to K^{*0}(K^+\pi^-)\mu\mu$ provides an excellent laboratory
  - System described by **three angles** and the **di-lepton invariant mass squared**
  - Complex angular distribution with many observables **sensitive to different types of BSM physics**
  - Can construct **less form-factor dependent ratios of observables**



- JHEP 02 (2016) 104

Angular Analyses

- **BaBar** and **Belle** data samples are clean but have limited statistics
  - Even Belle-II is not expected to surpass LHCb
- **CMS** and **ATLAS** have large samples but these events are hard to trigger, less clean and worse mass resolution
  - Sensitivity not (yet) competitive with LHCb



- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- arXiv:1710.02846

Branching Fraction Ratios

- Provides powerful **tests of Lepton Universality**
  - Experimental systematics are reduced
  - Largest residual theoretical uncertainty due to QED corrections (1-2%) [EPJC 76 (2016) 440]

- **Measure μ/e**
  - Expected to be unity in the SM

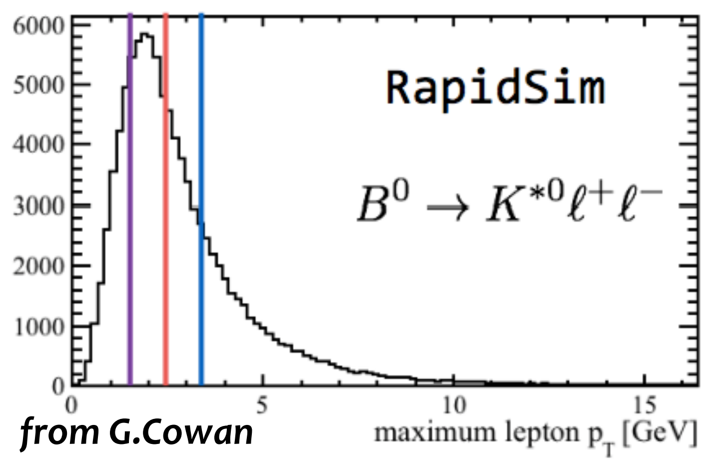
$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

- **Tests at B-factories are not very sensitive**
- **LHCb has much better sensitivity but electrons are challenging** (e.g. trigger, bremsstrahlung, resolution, modelling)

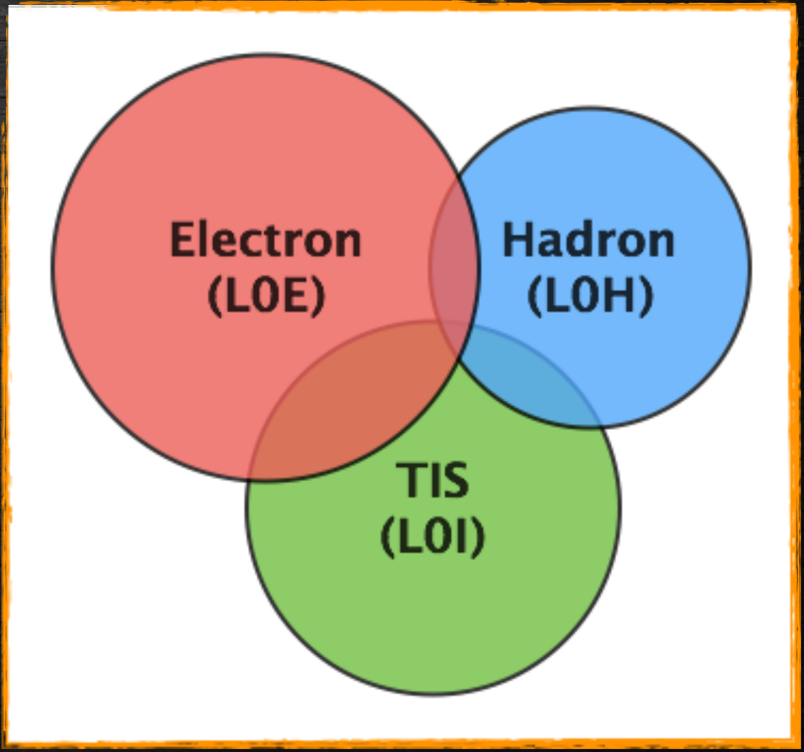
$$\varepsilon_{reco}(B^0\to K^{*0}J/\psi(\mu\mu)) \sim 5 \times \varepsilon_{reco}(B^0\to K^{*0}J/\psi(ee))$$

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 electron E_T are higher than on muon p_T (**L0 Muon**: $p_T > 1.5$-1.8 GeV)
- To mitigate this effect, electron sample selected using **3 exclusive trigger categories**
  - **L0 Electron**: $E_T > 2.5$-3.0 GeV
  - **L0 Hadron**: $E_T > 3.5$ GeV
  - **L0 TIS**: triggers fired by other particles

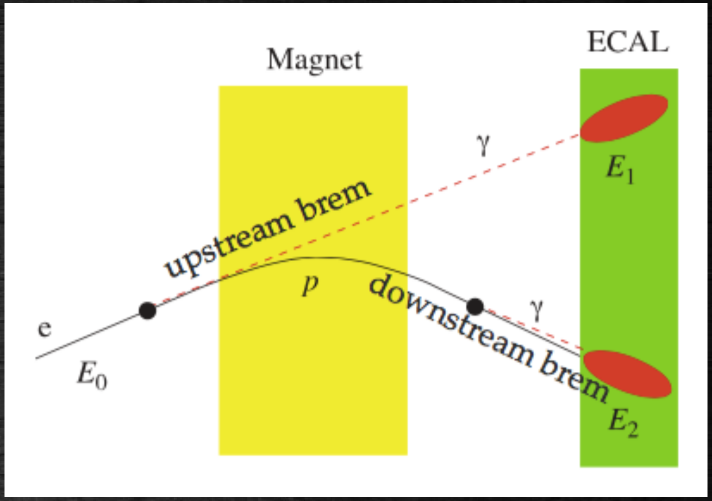


from G.Cowan



Bremsstrahlung

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



› If emitted **before the dipole magnet**

» Affects momentum measurement

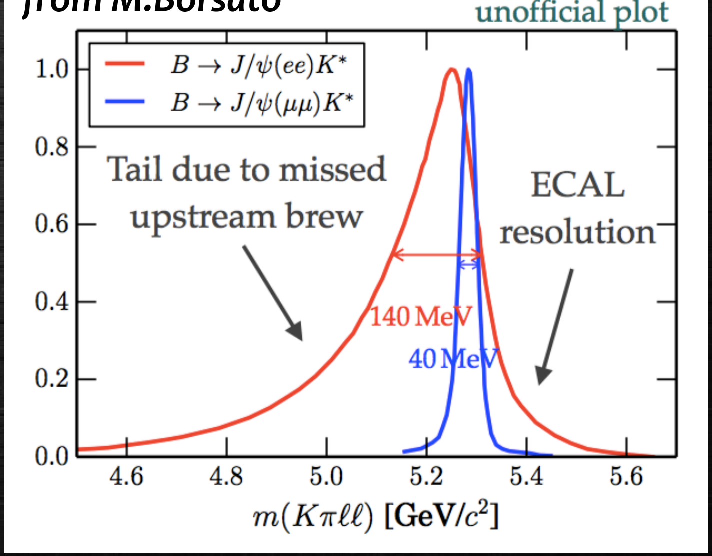
» Does not affect calorimeter PID

› **Recovery procedure** in place to search for brem-like deposits in the calorimeter

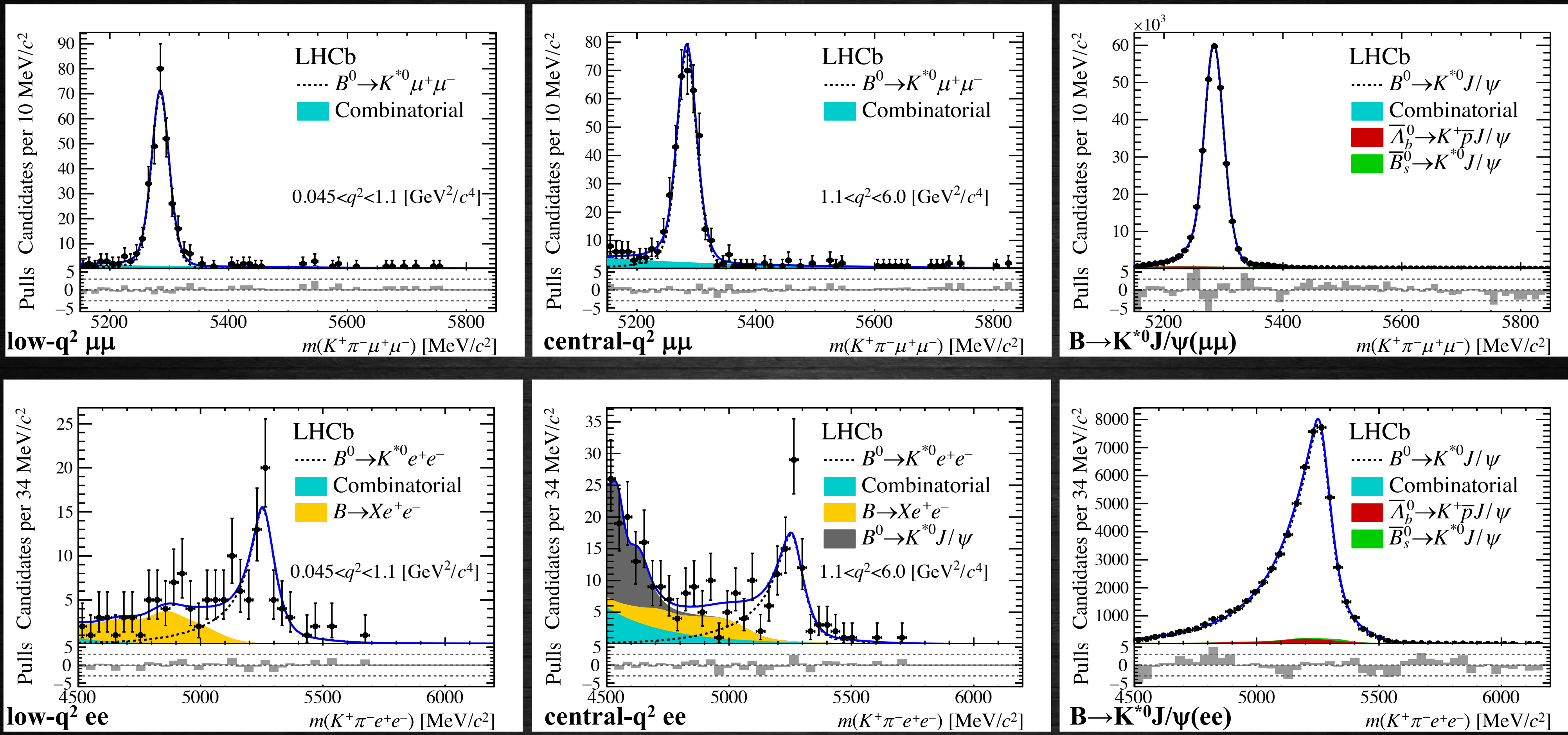
» Limited efficiency but well reproduced in simulation

» Calorimeter resolution (1-2%) worse than spectrometer (~0.5%)

from M.Borsato



Resolution



- Pollution from **partially-reconstructed decays** in the electron sample
  - Decays of **higher K resonances** with one or more decay products in addition to a Kπ pair that are not reconstructed
  - **Decays with neutrinos**

Modelling

- **Tuning of the simulation** with tag-and-probe data-driven techniques
  - Generated B kinematics and event multiplicity
  - Trigger and Particle Identification response
  - Data/MC reconstruction differences

- **Control of the absolute efficiency scale** tested via single ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$

Compatible with unity and independent of the decay kinematics

- Further checks performed by measuring the ratios

$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

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

Compatible with the expectations

- Measurement performed as double ratio to $B \to K^{(*)} J/\psi(ll)$ mode

R(K) – LHCb

› Test of LU with **$B^+ \to K^+ ll$** decays

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

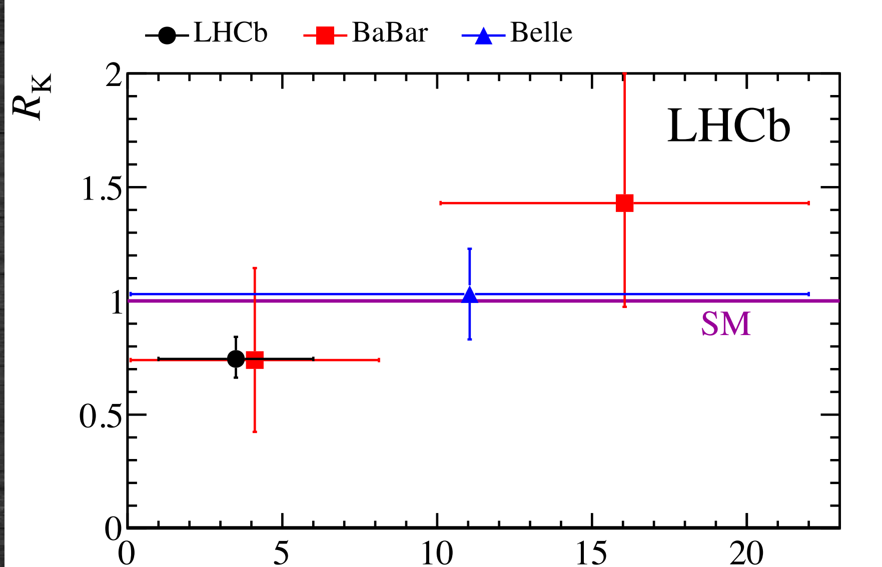
› **One region of q^2**

» Central [1.0-6.0] GeV^2/c^4

› About 1200 (250) $B^+ \to K^+ \mu\mu$ ($B^+ \to K^+ ee$) candidates

› **Precision of ~13%** using $3fb^{-1}$

› Largest systematic uncertainty from trigger and mass modelling



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

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

› Compatibility **with the SM at ~2.6σ**

R(K*) – LHCb

› Test of LU with $B^0 \to K^{*0}(K^+\pi^-)ll$ decays

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

› **Two regions of q^2**

» Low [0.045-1.1] GeV^2/c^4

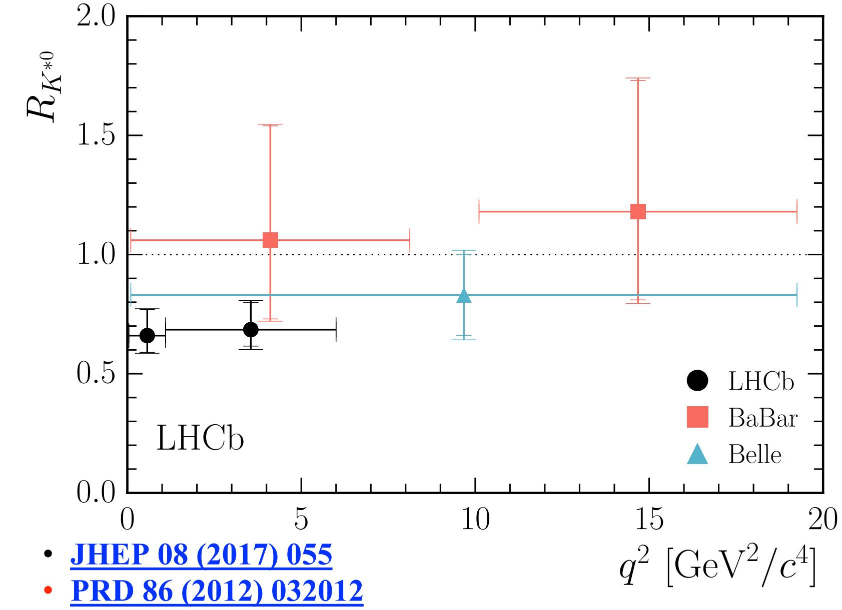
» Central [1.1-6.0] GeV^2/c^4

› About 290 (90) and 350 (110) $B^0 \to K^{*0}\mu\mu$ ($B^0 \to K^{*0}ee$) candidates at low- and central-q^2, respectively

› **Precision of ~17%** using $3fb^{-1}$

› Largest systematics from trigger and mass modelling

› Compatibility **with the SM at 2.1-2.5σ**

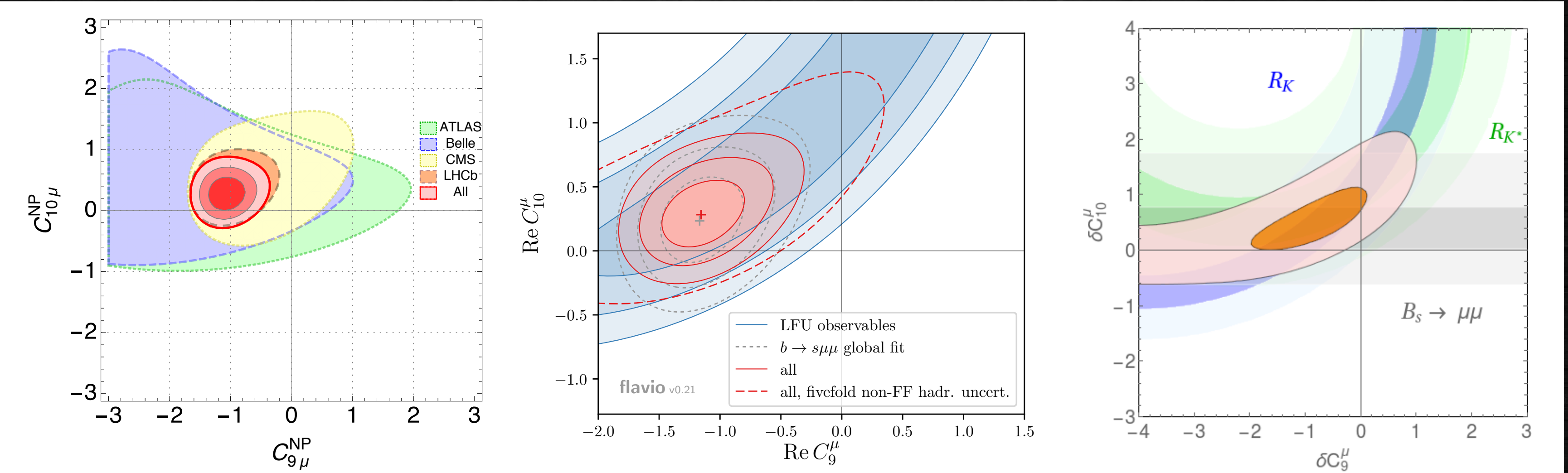


- JHEP 08 (2017) 055
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

$$R_{K^{*0}} = \begin{cases} 0.66\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \ GeV^2/c^4 \\ 0.69\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \ GeV^2/c^4 \end{cases}$$

Global Fits

- Several attempts by independent groups to interpret results by performing **global fits to the data**

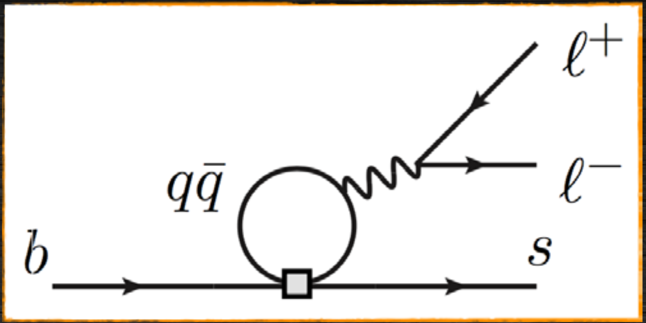


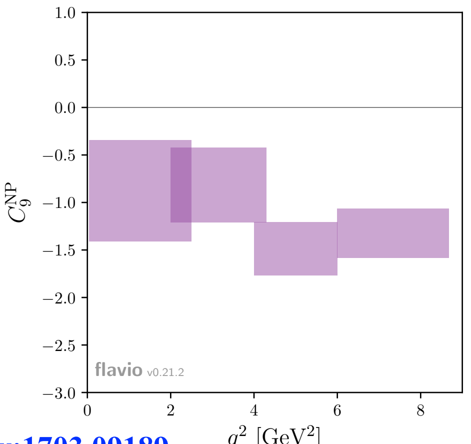
arXiv:1704.05340 arXiv:1704.05435 arXiv:1704.05446

- Take into account O(100) observables from different experiments, including b→μμ, b→sll and b→sγ transitions
- **Coherent pattern** that requires an additional contribution wrt the SM to accommodate the data
- Preference for **BSM physics in C_9 with a significance of 3-5σ**

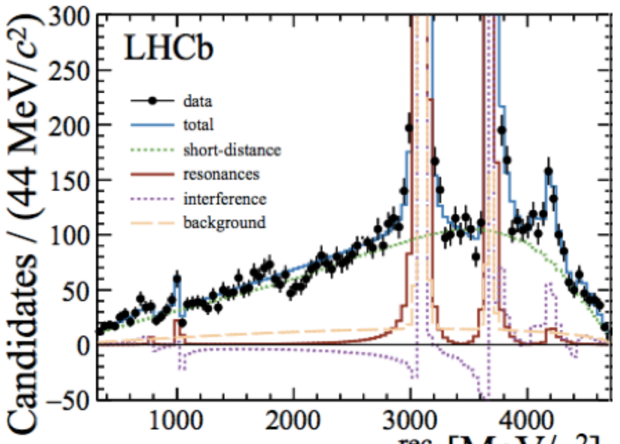
Controlling Charm Loops

› Or is this a **problem with the understanding of contributions from charm loops?**





arXiv:1703.09189



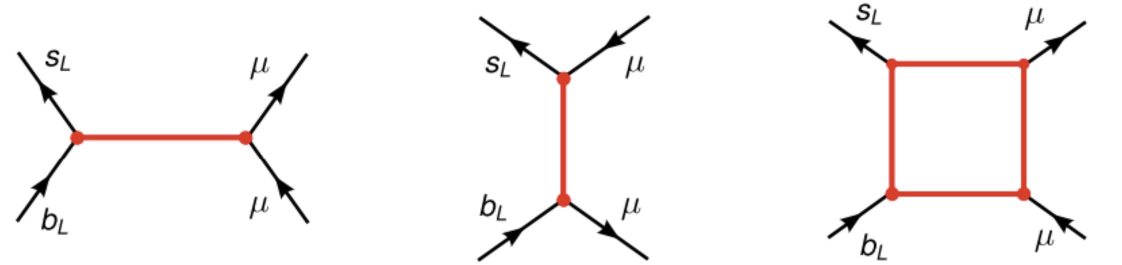
EJPC 77 (2017) 161

› Global fits in bins of **q²** indicate **no dependence**

› Measurement of **interference** between penguin and cc from data indicates this is **small**

Is it a Z', a Leptoquark or … ?

› **Plethora of models** to accommodate the flavour anomalies

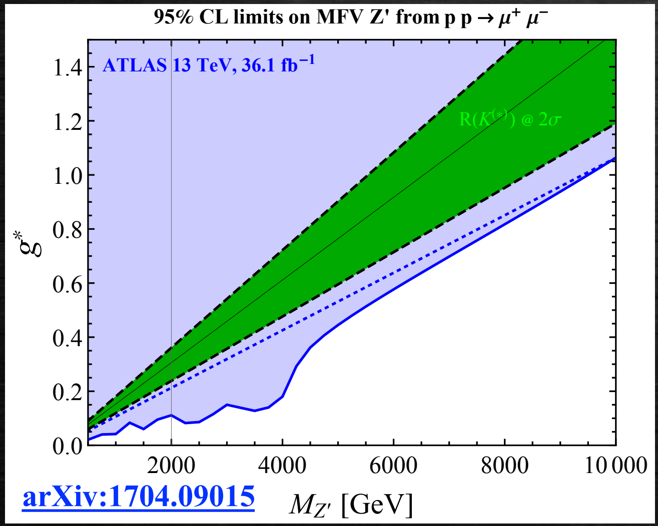


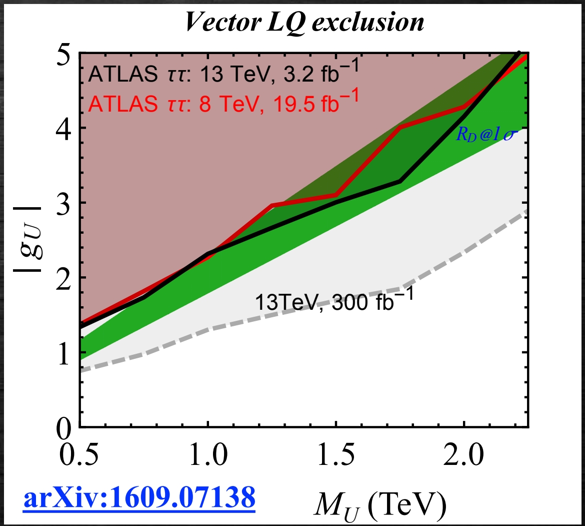
- Z'
- $SU(2)_L$ singlet or triplet

- Leptoquark
- Spin 0 or 1

- New scalars/vectors, also leptoquarks possible

› Direct searches provides complementary information to B decays





A Glimpse into the Future

Future Experiments

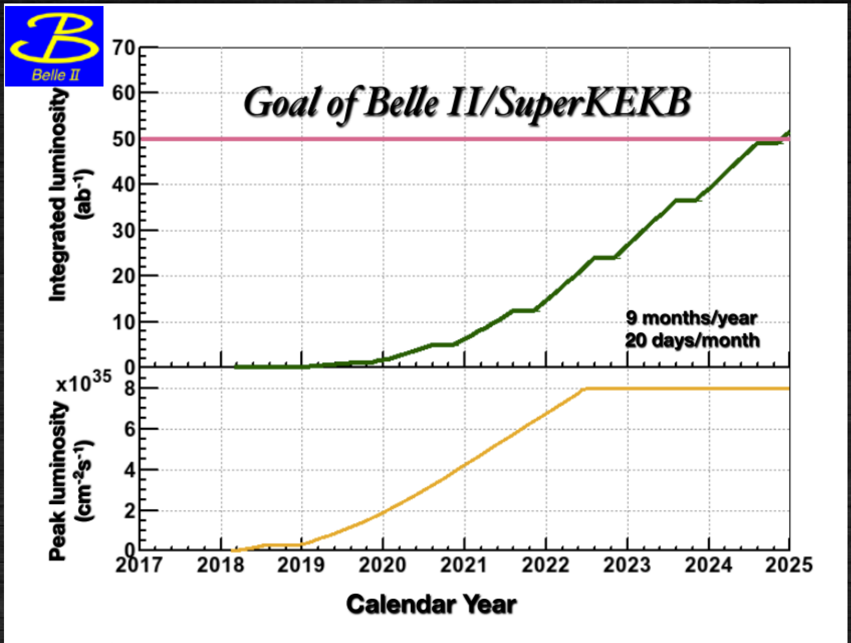
- The **Belle-II** and **LHCb Upgrade(s)** experiments are best suited to the study of flavour physics in the next decade

- Their **complementary characteristics** will provide unique opportunities to perform tests of Lepton Universality (and much more)

- The data collected will yield the **world's largest sample** of b-hadron decays and will boost measurements of their properties to an unparalleled precision

Belle-II

› Designed to study B mesons at the ϒ resonances



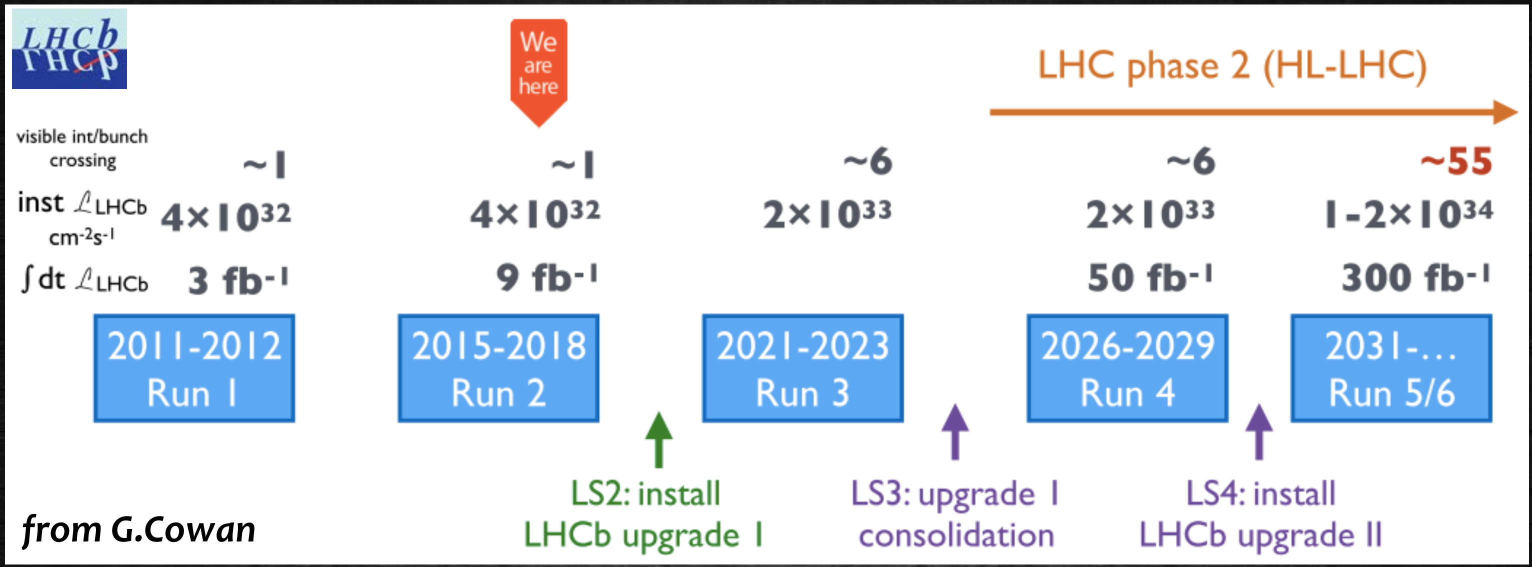
› **Second generation B-Factory** which builds upon the Belle experience

› Main data taking in 2019 with 40x increase in instantaneous luminosity wrt KEKB and collect **~50ab^{-1} by 2025** (~50 × 10^9 BB events)

› **Belle-II will dominate measurements of final states with missing energy, multiple photons and of inclusive decays**

LHCb Upgrade(s)

› Designed to study heavy-flavour in pp collisions



› **Upgrade-I** during LS2 to run at 5x larger instantaneous luminosity and collect **~50fb^{-1} by 2029** (~90 × 10^{12} bb pairs) [CERN-LHCC-2012-007]

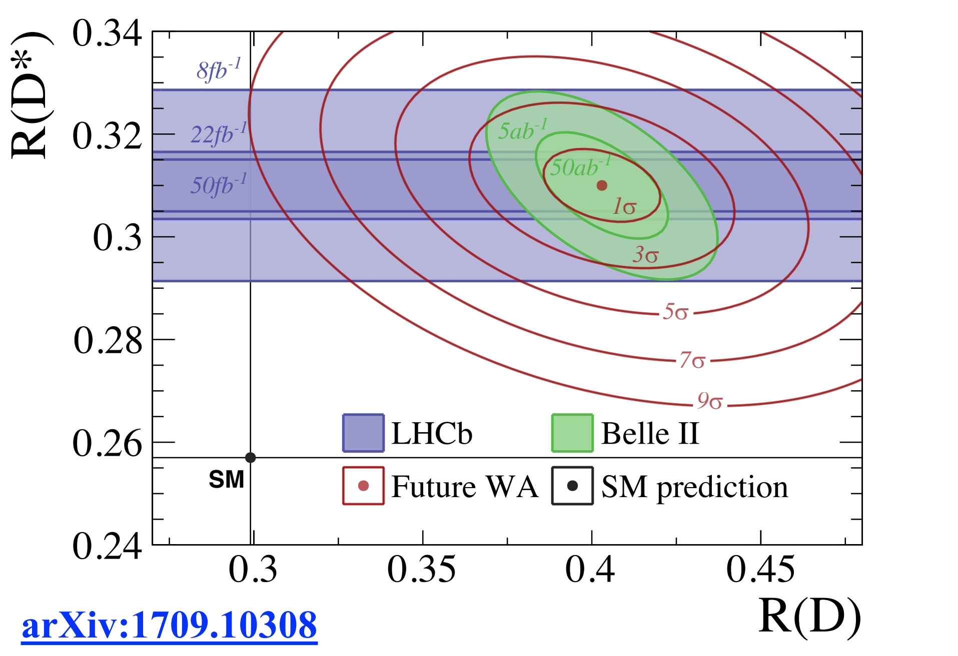
› EoI for **Upgrade-II** during LS4 to take full advantage of the flavour physics opportunities at the HL-LHC [CERN-LHCC-2017-003]

› **LHCb can access all b-hadron species and will dominate measurements of final states with all charged particle**

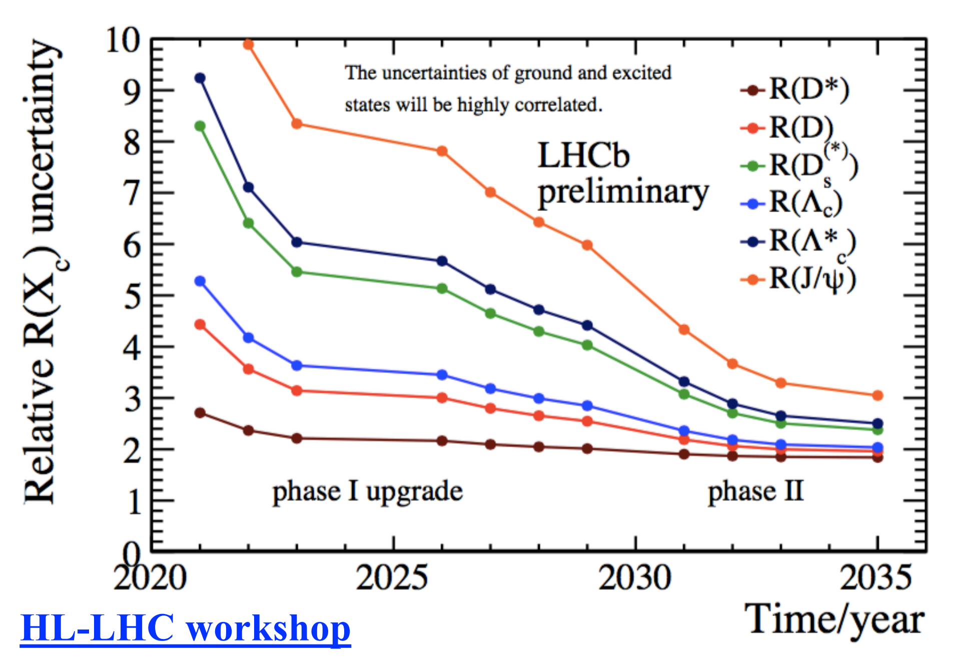
Future – R(D$^{(*)}$)

Measurement	SM prediction	Current World Average	Current Uncertainty	Projected Uncertainty Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1}	LHCb 22 fb^{-1}	LHCb 50 fb^{-1}
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310 \pm 0.015 \pm 0.008)$	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%

arXiv:1709.10308



arXiv:1709.10308



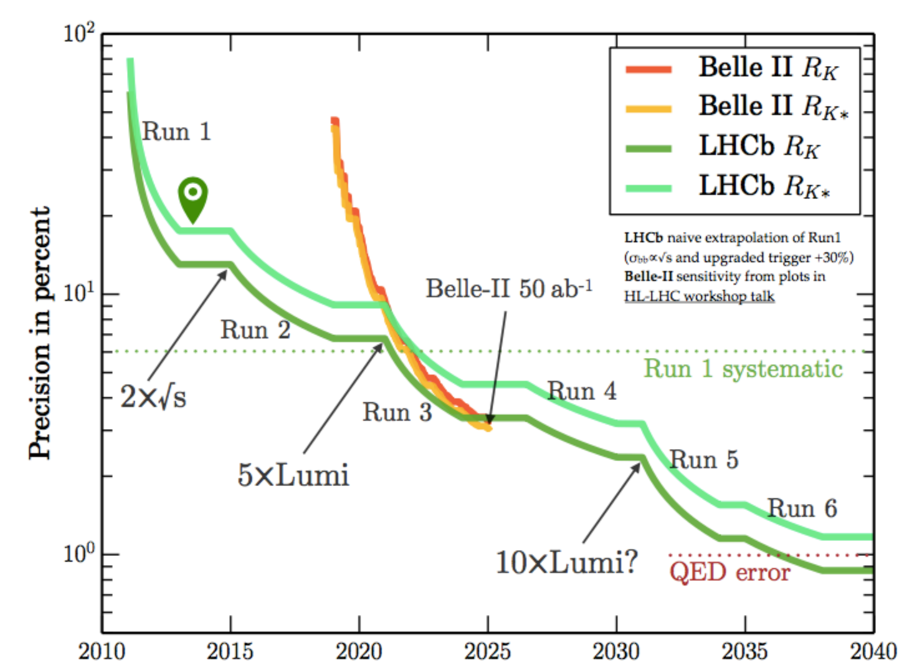
HL-LHC workshop

*projected uncertainties not including improvements in detectors and algorithms

Future – R(K$^{(*)}$)

Observable	q^2 interval	Extrapolations $5\,\text{ab}^{-1}$	$50\,\text{ab}^{-1}$
arXiv:1709.10308			
$R(K)$	$1.0 < q^2 < 6.0\,\text{GeV}^2$	11%	3.6%
$R(K)$	$q^2 > 14.4\,\text{GeV}^2$	12%	3.6%
$R(K^*)$	$1.1 < q^2 < 6.0\,\text{GeV}^2$	10%	3.2%
$R(K^*)$	$q^2 > 14.4\,\text{GeV}^2$	9.2%	2.8%

Observable	q^2 interval	Measurement $3\,\text{fb}^{-1}$	Extrapolations $8\,\text{fb}^{-1}$	$22\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$
$R(K)$	$1.0 < q^2 < 6.0\,\text{GeV}^2$	$0.745^{+0.090}_{-0.074} \pm 0.036$	0.046	0.025	0.016
$R(K)$	$15.0 < q^2 < 22.0\,\text{GeV}^2$	-	0.043	0.023	0.015
$R(K^*)$	$0.045 < q^2 < 1.1\,\text{GeV}^2$	$0.66^{+0.11}_{-0.07} \pm 0.03$	0.048	0.026	0.017
$R(K^*)$	$1.1 < q^2 < 6.0\,\text{GeV}^2$	$0.69^{+0.11}_{-0.07} \pm 0.05$	0.053	0.028	0.019
$R(K^*)$	$15.0 < q^2 < 19.0\,\text{GeV}^2$	-	0.061	0.033	0.021

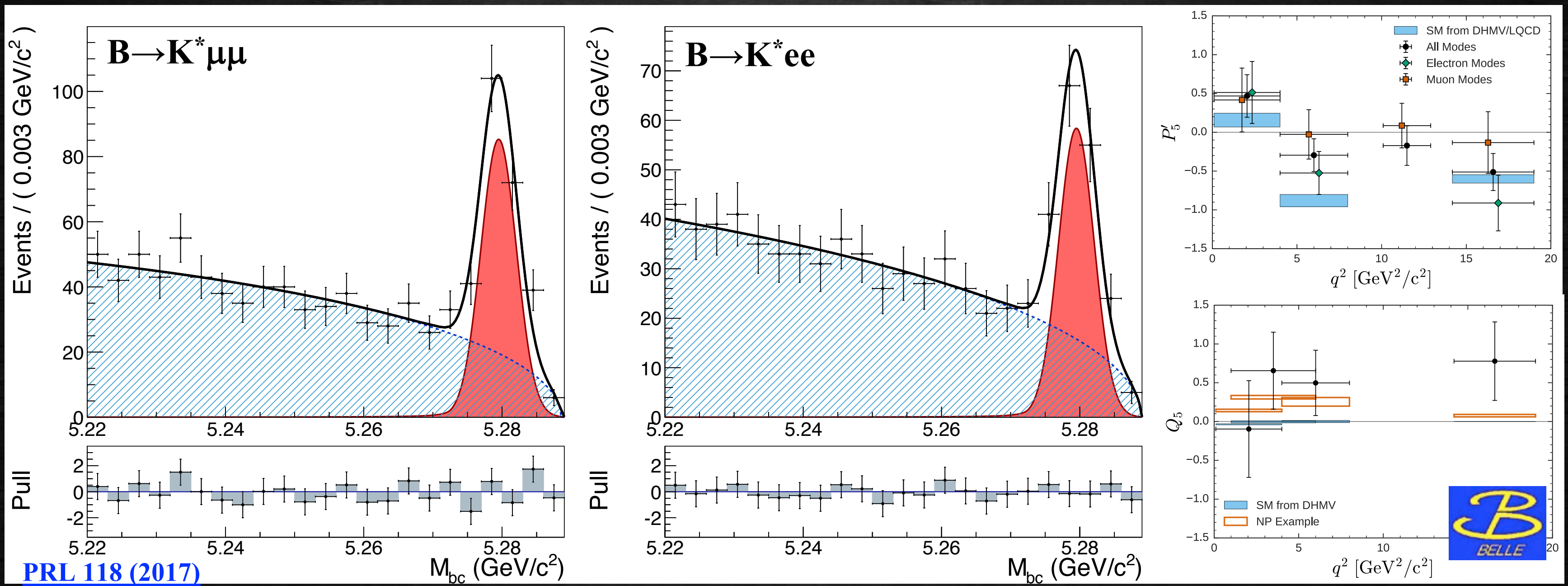


from M.Borsato

› But also R(ϕ), R(Λ$^{(*)}$) and b→dll transitions

Future – Angular Observables

- Detector response much more similar between muons and electrons at B-factories than LHCb
- Easier to test Lepton Universality using angular observables at Belle-II



Summary

- **Interesting set of anomalies observed in b-hadron decays**
- **Tree-mediated $b \to c l \nu$ transitions**
  - Challenging analyses involving neutrinos
  - Coherent effects from different experiments and with different techniques
- **Loop-mediated $b \to s l l$ transitions**
  - Challenging analyses involving electrons (LHCb)
  - Coherent effects with deviations seen in $b \to s \mu \mu$

- **If taken together this is probably the largest "coherent" set of BSM effects in the present data**

- **No unambiguous LU violation yet but we will know soon**
  - New/update analyses with LHCb Run2 data expected soon
  - Belle-II and LHCb Upgrade(s) will reach unprecedented sensitivity