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Instituto Galego de Física de Altas Enerxías
EXCELENCIA MARÍA DE MAEZTU

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UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Lepton Flavour Universality tests with semileptonic b-hadron decays

Antonio Romero Vidal
antonio.romero@usc.es

Instituto Galego de Física de Altas Enerxías (IGFAE)
Universidade de Santiago de Compostela, Spain

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Outline

Introduction

- Standard Model and CKM matrix
- Old measurements in Flavour Physics
- Lepton Flavour Universality (LFU)

LHCb detector

Results with $b \longrightarrow s\ell^{+}\ell^{-}$

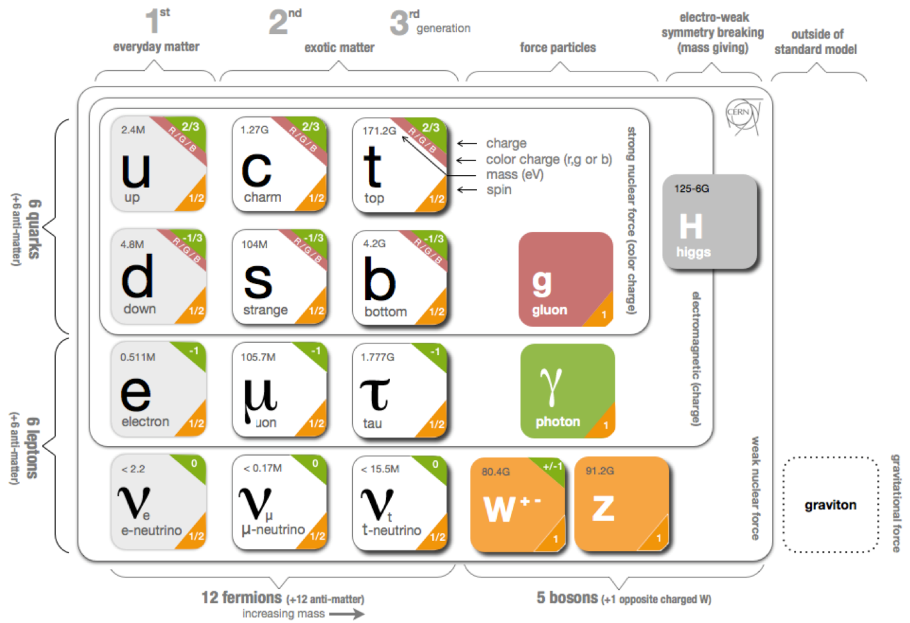
- Branching fractions
- Angular analysis (P'_5)
- LFU tests (R_K)
- Prospects

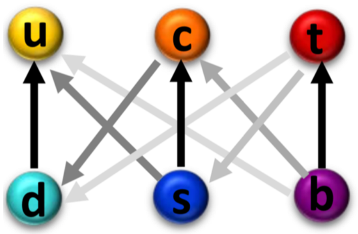
Results with $b \longrightarrow c\ell\nu_{\ell}$

- LFU tests with $b \longrightarrow c\tau\nu_{\tau}$ (R_{D^*} and $R_{J/\psi}$)
- Prospects

Conclusions

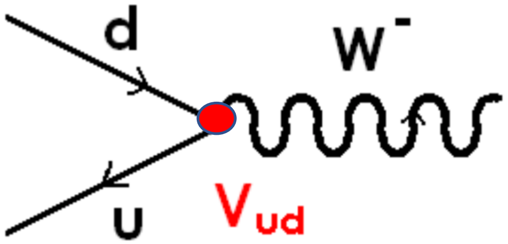
Standard Model and CKM matrix





$$V_{\rm CKM} = \begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{pmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix}$$

- In the Standard Model (SM), quarks and leptons are divided in **3 families** (or generations).
- Interactions described by the exchange of **gauge bosons**: photon (EM), W/Z (weak), gluon (strong).
- **Flavour Physics**: study of transitions between quarks of different flavour.
  - described by the **CKM matrix** ⇒ mediated by a **W boson** in the SM.

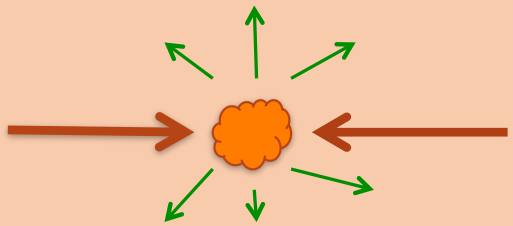


- Transitions between quarks of different families suppressed: $|V_{tb}|\sim 1$, $|V_{cb}|\sim 0.04$, $|V_{ub}|\sim 0.004$.
- However, SM does not account for:
  - Matter/antimatter asymmetry in the Universe.
  - Dark matter.
  - Dark energy.
- The SM must be a **low-energy effective theory**.

Search for NP: direct vs indirect approaches

High energy (direct) approach

- Energy in particle collisions large enough to create new **real** particles.
- Particles appear as "peaks" in a given distribution.
- Approach followed by **ATLAS** and **CMS**.

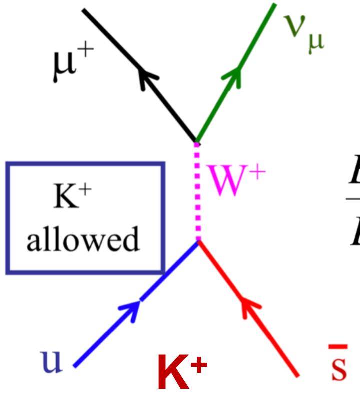


High precision (indirect) approach

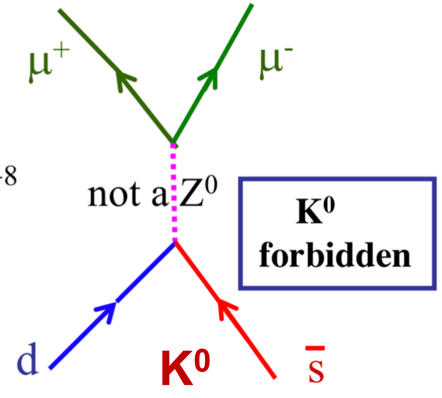
- Precision of the measurements high enough to detect New Physics (NP) effects due to **virtual** particles.
- Indirect measurements can access **higher energy scales**.
- Approach followed by **LHCb** and **B-factories**.

Flavour physics in the past: GIM mechanism

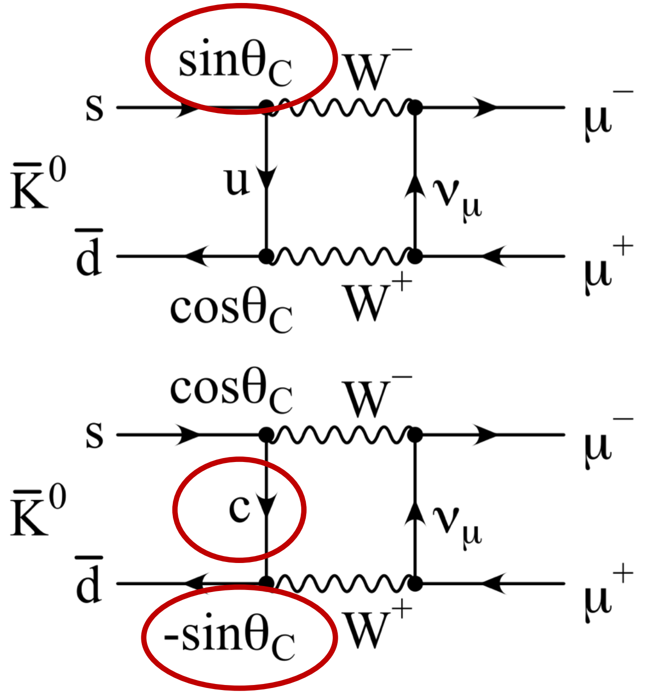
- In the past, flavour physics lead to several **indirect** discoveries:
  - Branching fraction of leptonic K decay **BR($K^0 \to \mu^+\mu^-$)** very suppressed .



$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times 10^{-9}}{0.64} \approx 10^{-8}$$



cancellation between loop diagrams



(exact cancellation in the massless quark limit)

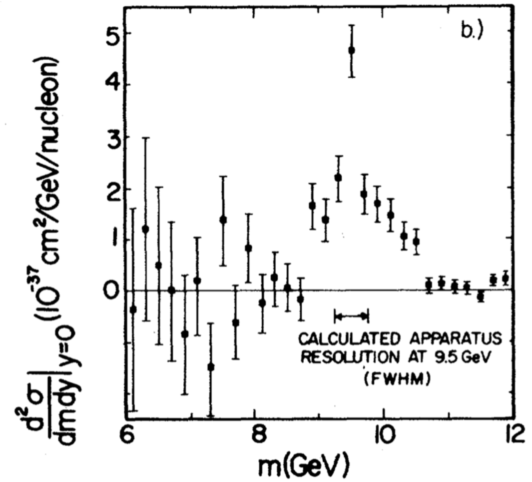
  - **1970**: Glashow, Iliopoulos and Maiani proposed a solution (**GIM** mechanism, only 3 quarks (u,d,s) known at the time) [PRD 2, 1285 (1970)]:
    - Flavour Changing Neutral Currents (**FCNC**) **forbidden in the SM at tree level** .
    - FCNC suppressed: only through **loop** diagrams.
    - **Prediction of the charm quark ⇒ Observed in 1973 (J/ψ).**

      [PRL 33, 1404, (1974) & PRL 33, 1406(1974)]

Flavour physics in the past: CPV and B^0 mixing

- **1964**: observation of (indirect) **CP violation (CPV) in kaons** :
$K^0_L(CP=-1)\longrightarrow\pi^+\pi^-(CP=+1)$ [PRL 13, 138 (1964)]

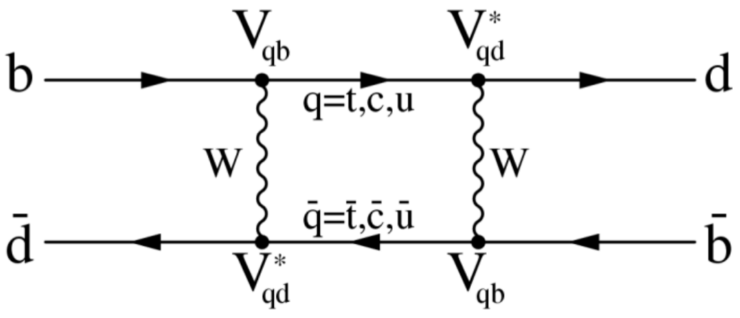
  ⇒ **1973**: **Kobayashi** and **Maskawa** demonstrated that this could be explained if there are **at least 3 generations** of quarks [PTP 49, 2 (1973) 652-657] ⇒ **bottom quark discovered in 1977** [PRL 39, 252 (1977)] .



$\Upsilon(1S)\longrightarrow\mu^+\mu^-$
mass ~ 9.5 GeV/c²

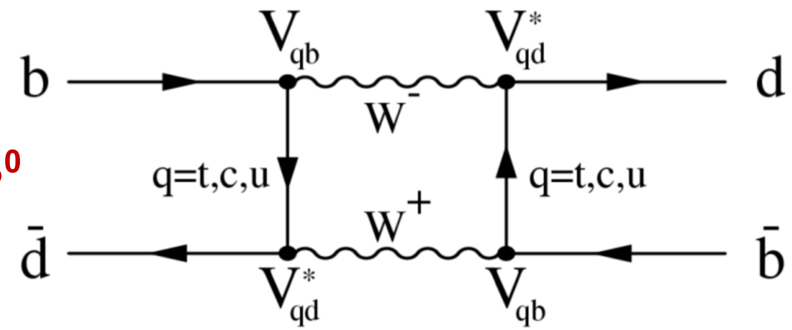
- **1987**: Observation of **$B^0-\bar{B}^0$ meson mixing** (property for which a neutral meson (**B^0**) transform (oscillates) into its antiparticle (**$\bar{B}^0$**) over time) [ARGUS collaboration, PLB 192, 1-2, 245-252] .

B^0



$\bar{B}^0$

B^0



$\bar{B}^0$

ARGUS measured $\Delta m_B \approx 0.00002\cdot\left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1} \approx 0.5\mathrm{ps}^{-1}$

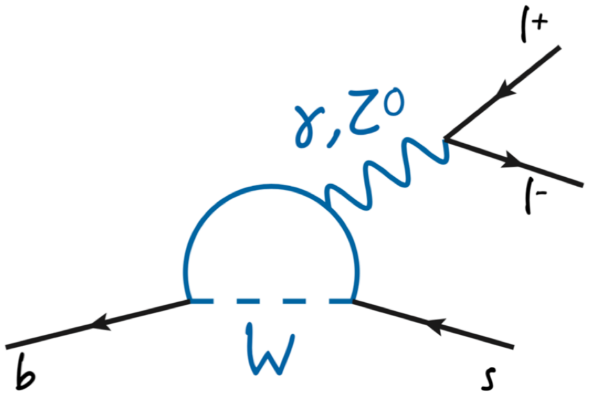
high frequency ⇒ first hint of the high mass of the top quark, discovered in 1995.

Present: B anomalies

- In recent years, some interesting set of tensions with the SM predictions have arisen:

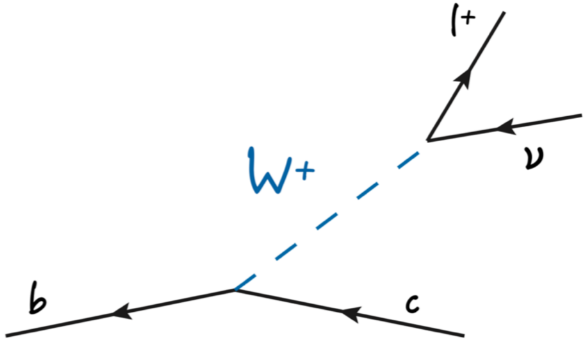
1. In **$b \longrightarrow s\ell^+\ell^-$** transitions (**loop**, FCNC):

    - **Branching fractions** of $b \longrightarrow s\mu^+\mu^-$ decays.
    - **Angular observables** of $b \longrightarrow s\mu^+\mu^-$ decays.
    - **Lepton Flavour Universality (LFU) tests** in **μ/e** ratios.



2. In **$b \longrightarrow c\ell^+\nu_\ell$** transitions (**tree**, FCCC):

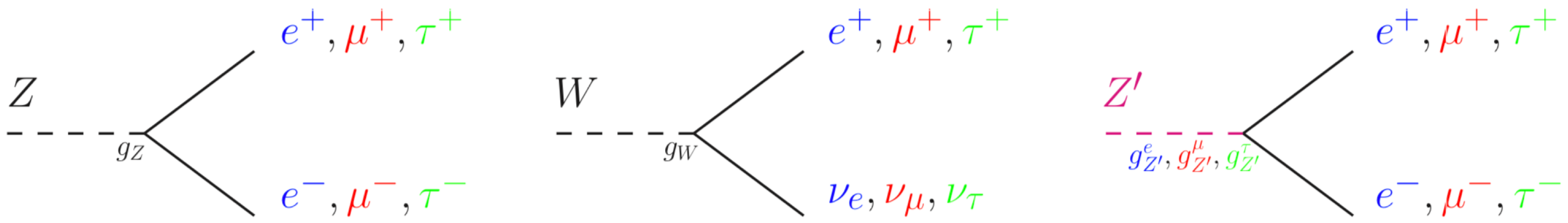
    - **Lepton Flavour Universality tests** in **τ/μ** ratios.



- In this talk: experimental situation.

Lepton Flavour Universality

- In the SM, couplings of the gauge bosons to charged leptons are universal (**Lepton Flavour Universality, LFU**).
- Branching fractions involving e, μ and τ differ only due to their **different masses** (phase space and helicity suppressions)
- Some extensions of the SM predict new particles that can break LFU, i.e. **Z'**, **W'**, **leptoquarks** …

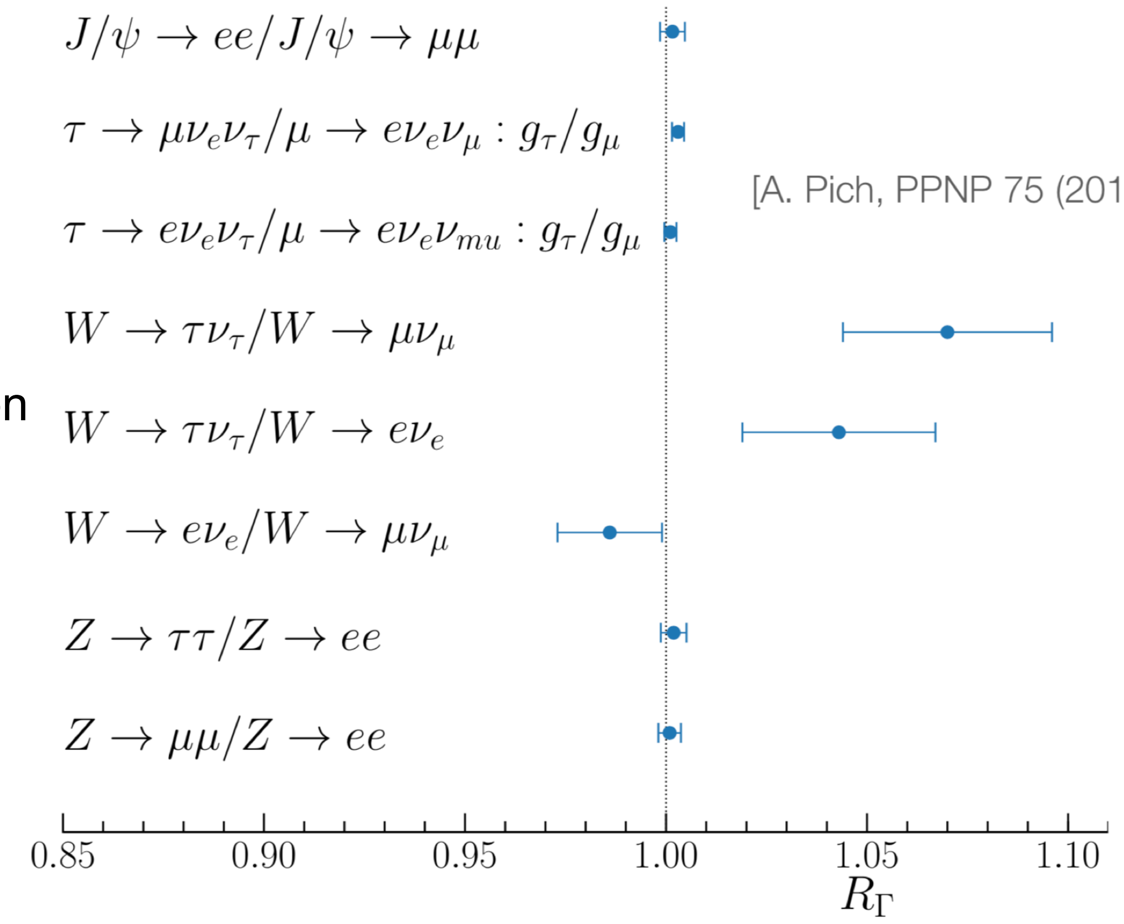


- Any significant deviation of LFU is a **clear sign of NP**.

Testing LFU

- Thoroughly tested in the past:
  - **Electroweak sector**: $Z \rightarrow \ell^+\ell^-$ and $W^+ \rightarrow \ell^+\nu_\ell$.
  - **Pseudoscalar mesons**: semileptonic decays of π, K and D mesons.
  - **Purely leptonic decays**: $\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$ and $\tau^- \rightarrow e^- \nu_e \nu_\tau$.
  - **Quarkonia decays**: $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$.

[PDG, PRD98, 030001 (2018)]

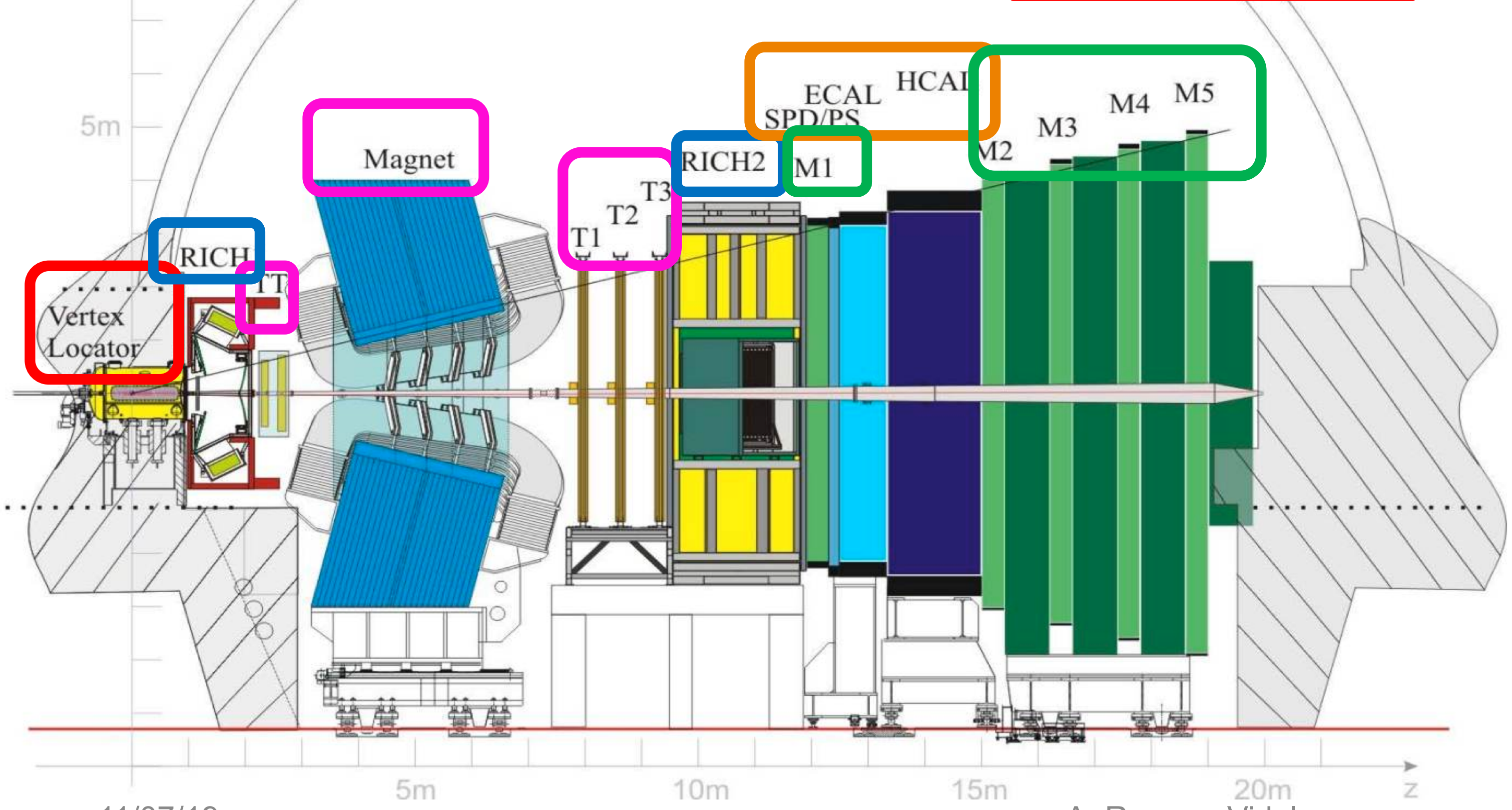


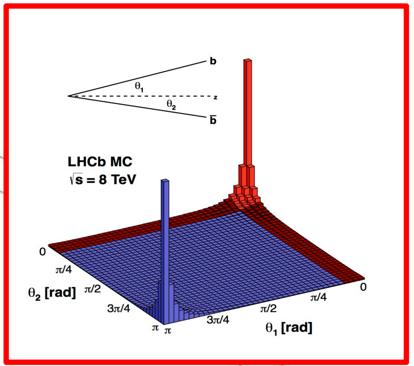
[A. Pich, PPNP 75 (2014) 41]

- **W** coupling to $\tau\nu_\tau$ in tension with SM at **2.6σ** level (precision needs to be improved).

- In recent years, some interesting set of tensions with the SM predictions have arisen in the B sector:
  - In **$b \rightarrow s\ell^+\ell^-$** transitions ($R_K$, R_{K^*} , BR's, angular distributions …)
  - In **$b \rightarrow c\tau\nu_\tau$** transitions ($R_D$, R_{D^*} and $R_{J/\psi}$)

The LHCb detector





- In pp collisions **b/$\overline{\textbf{b}}$** pairs produced with very small opening angle. **LHCb** detector is a **forward** spectrometer.

- Vertex detector (VELO):
  - Excellent vertex resolution: 20μm resolution on impact parameter.
  - Decay time resolution ~45ps.

- Tracking system (plus a 4T magnet):
  - Momentum resolution $\Delta p/p$~0.4%−0.6%

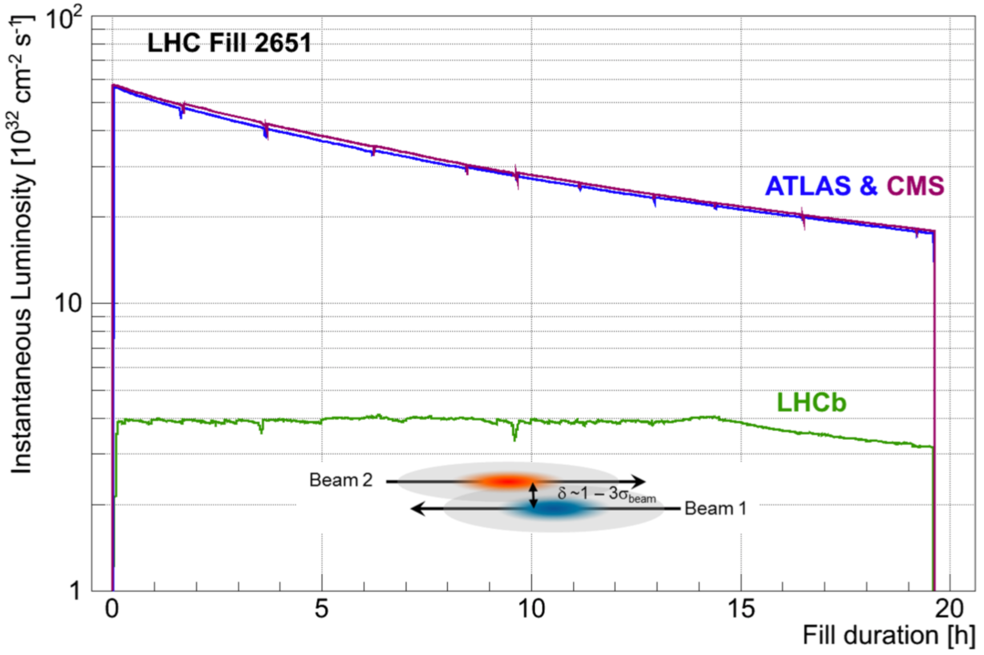
- RICH detectors:
  - Excellent K/π/p separation.

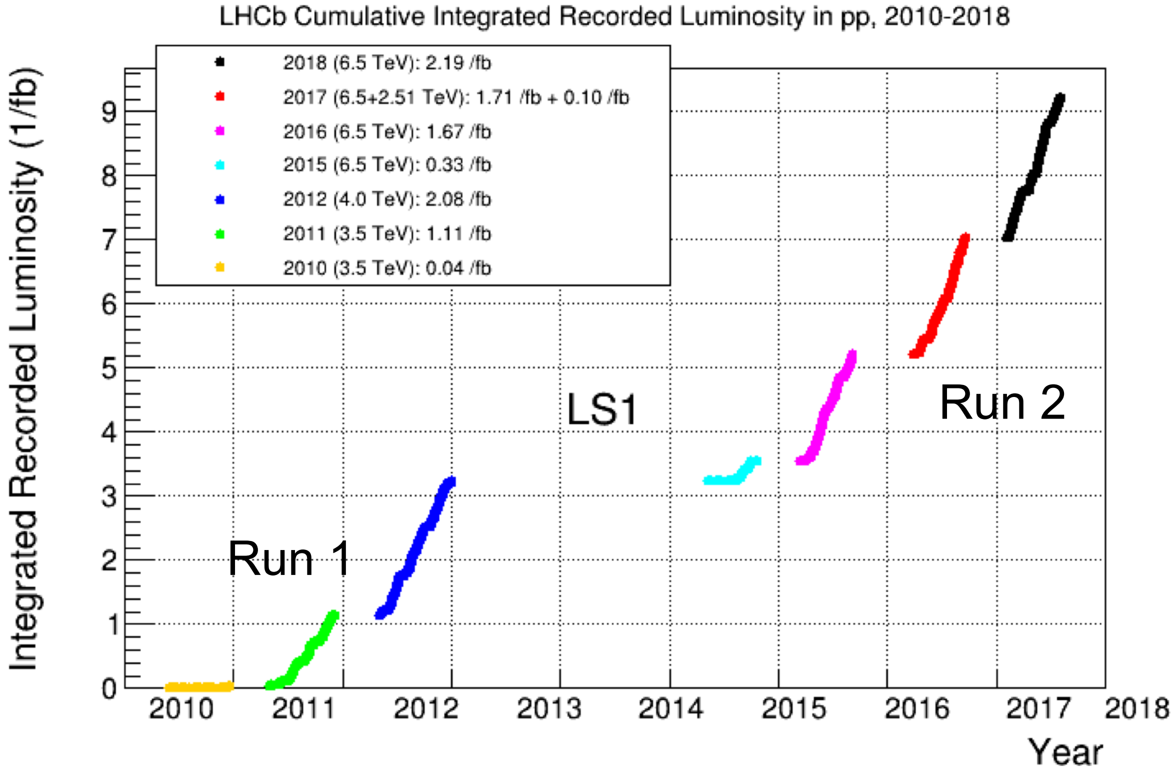
- Calorimeter systems:
  - Energy measurement (i.e: π^0, γ) .

- Muon system:
  - Very high efficiency for muons.

Detector operation

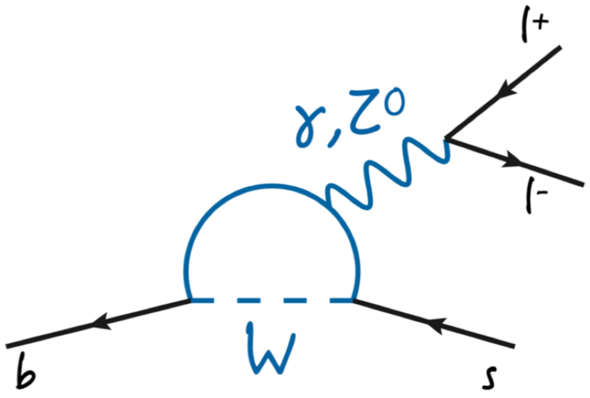
- LHCb designed to run at **lower instantaneous luminosity** $\mathcal{L}$ than ATLAS and CMS.
- Mean number of interactions per bunch crossing ~1.
- pp **beams displaced** to reduce $\mathcal{L}$.





- **3 fb^{-1}** of pp collisions at **7-8 TeV** in **Run 1** (2011+2012)
- **6 fb^{-1}** of pp collisions at **13 TeV** in **Run 2** (2015-2018)
- **9 fb^{-1}** in total at the end or Run 2.

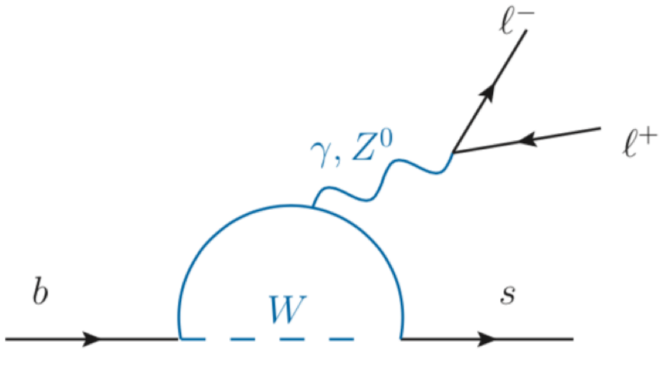
Measurements of loop $b \longrightarrow s\ell^+\ell^-$ transitions



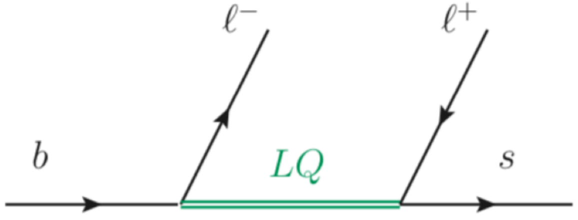
Flavour Changing Neutral Currents: $b \longrightarrow s\mu^+\mu^-$

- Flavour Changing Neutral Currents (FCNC) suppressed in the SM:

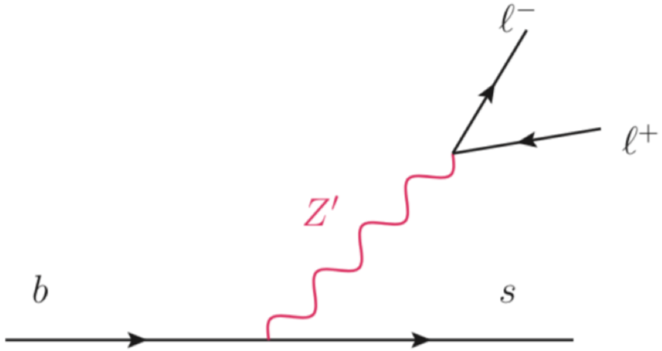
  1. only occur at **loop** level.
  2. **GIM** suppressed.
  3. left-handed **chirality**.



- This is not necessarily true in a NP scenario.

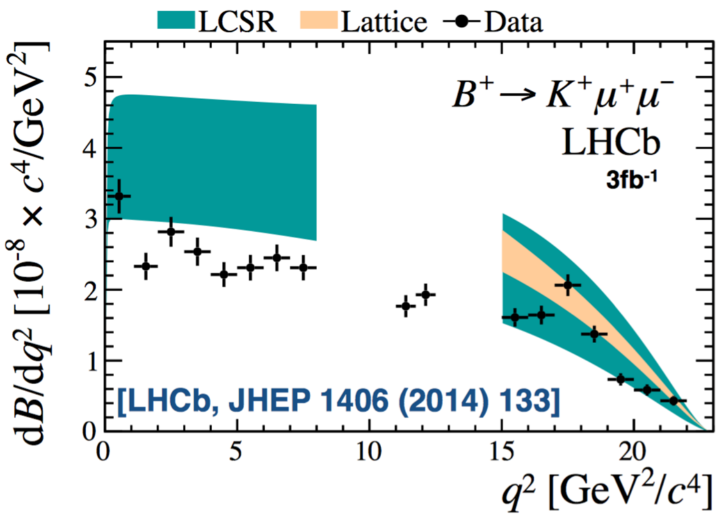


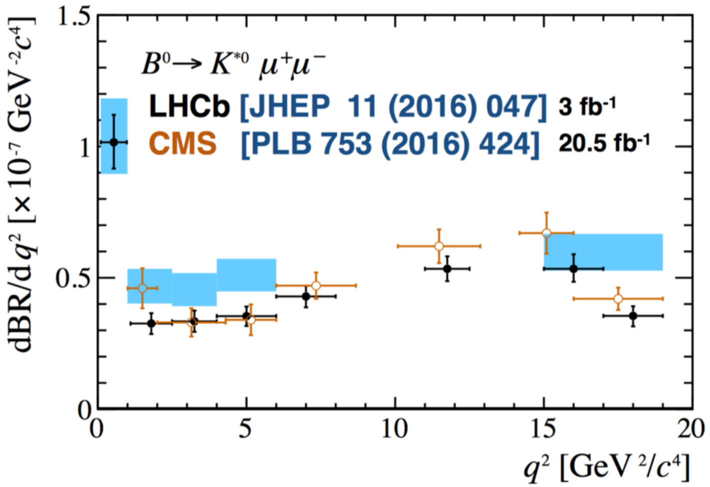
- Important to study different kind of observables (BR's, angular observables and LFU tests) with different sensitivities to NP.

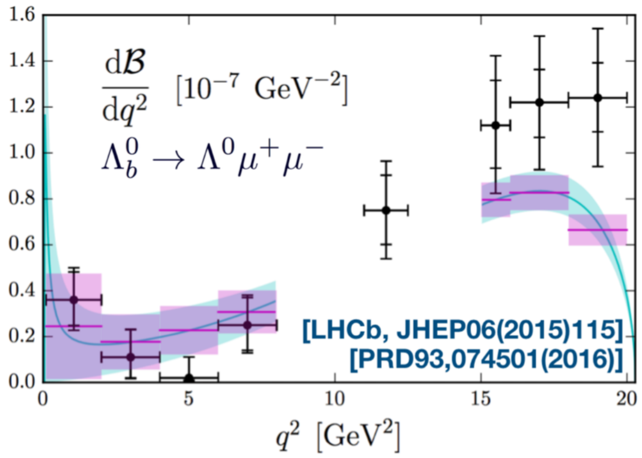


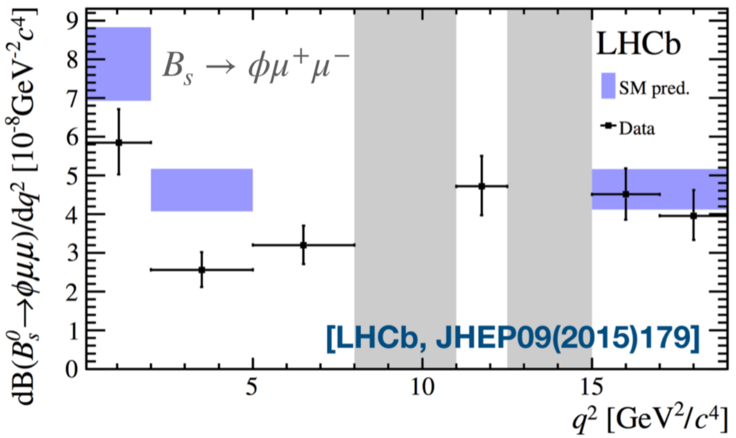
$b \longrightarrow s\mu^+\mu^-$ branching fractions

- Several measurements performed in different b-hadron decays: **$B^+ \longrightarrow K^+\mu^+\mu^-$, $B^0 \longrightarrow K^{*0}\mu^+\mu^-$, $\Lambda_b^0 \longrightarrow \Lambda^0\mu^+\mu^-$, $B_s^0 \longrightarrow \phi\mu^+\mu^-$** , by different experiments.







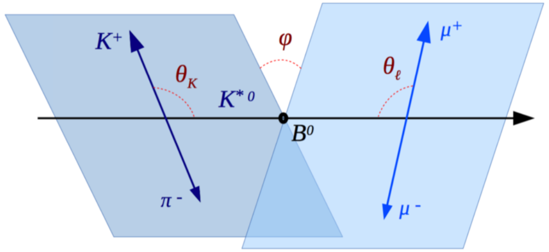


- Branching fractions consistently below the SM prediction **at low q^2**$=m^2(\ell^+\ell^-)$ for several processes.
- Considerable uncertainty in the SM prediction.

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- $B^0 \to K^{*0}\mu^+\mu^-$ is a $b \to s\mu^+\mu^-$ transition: excellent place to search for NP in FCNC process.
- Rates, angular distributions and asymmetries sensitive to NP.
- Experimentally very clean signature.
- Decay described by **three angles** and di-muon invariant mass squared **q^2** (with parameters depending on q^2: $\mathbf{F_L, A_{FB}, S_i}$) .
- Many observables with clean theoretical predictions (i.e. **$P'_{4,5,8}$** : partial cancellation of hadronic uncertainties) [JHEP 1204(2012) 104] .
- **LHCb finds in P_5' a deviation from the SM prediction at the level of 3.4σ .**

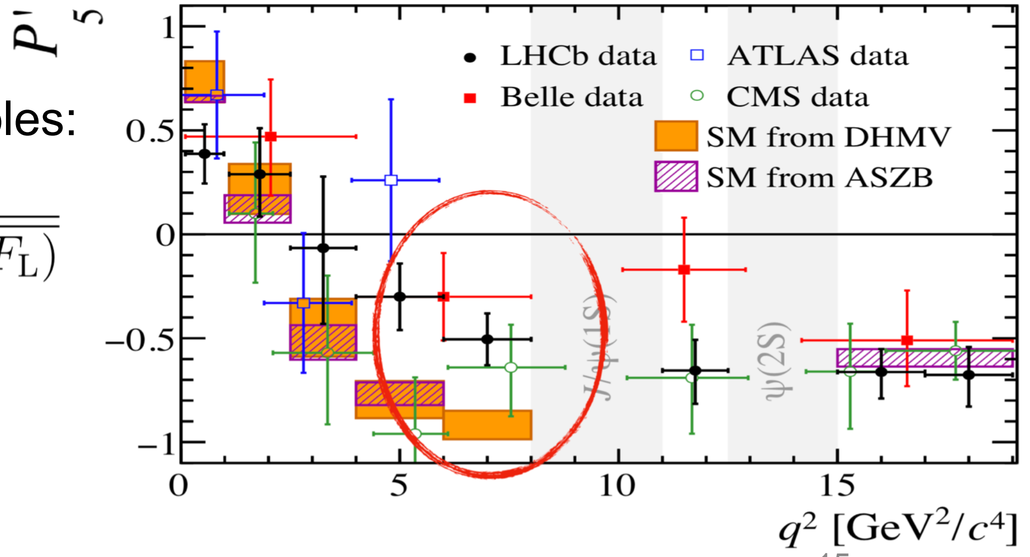
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



Optimized observables:

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

$q^2 = m^2(\mu^+\mu^-)$



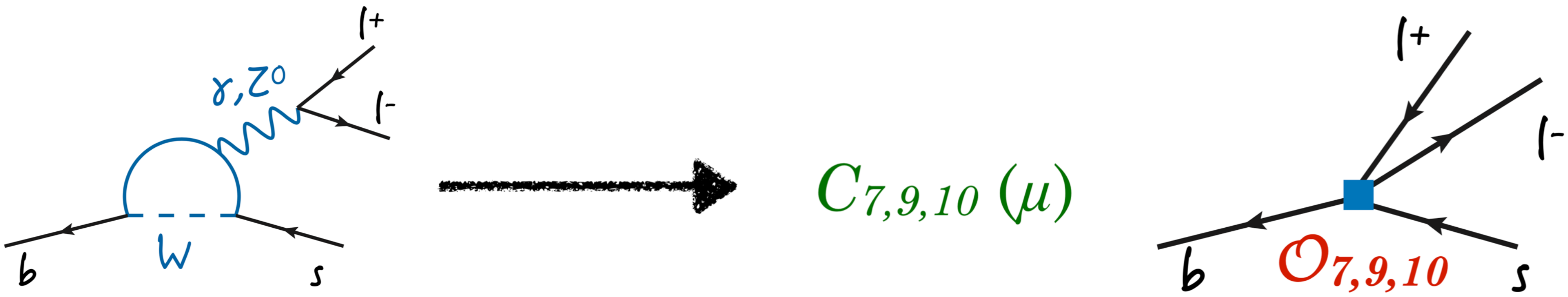
[JHEP 02 (2016) 104]

Theoretical framework: Effective Field Theory

- **Effective Field Theory (EFT)** can describe $b \to s\ell^+\ell^-$ transitions in terms of an **effective Hamiltonian** that describes the full theory **at low energies (μ)** .

$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

- **$C_i(\mu)$** : Wilson coefficients (perturbative, short-distance physics, sensitive to **$E>\mu$**).
- **$\mathcal{O}_i(\mu)$** : Local operators (non-perturbative, long-distance physics, sensitive to **$E<\mu$**).



- Contributions from NP will **modify the measured values** of the Wilson coefficients present in the SM **or introduce new operators**.

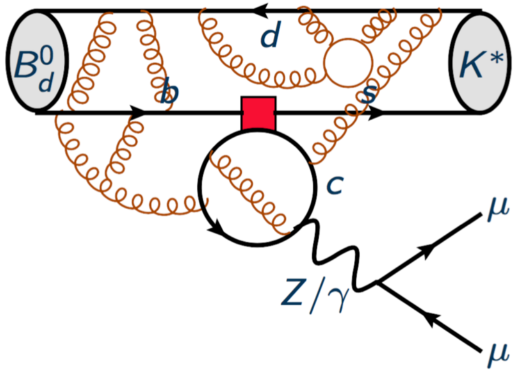
Global fits to $b \longrightarrow s\mu^+\mu^-$ observables

- A large number of measurements performed in $b \longrightarrow s\ell^+\ell^-$ and $b \longrightarrow s\gamma$ transitions are used as input in a **global fit**.

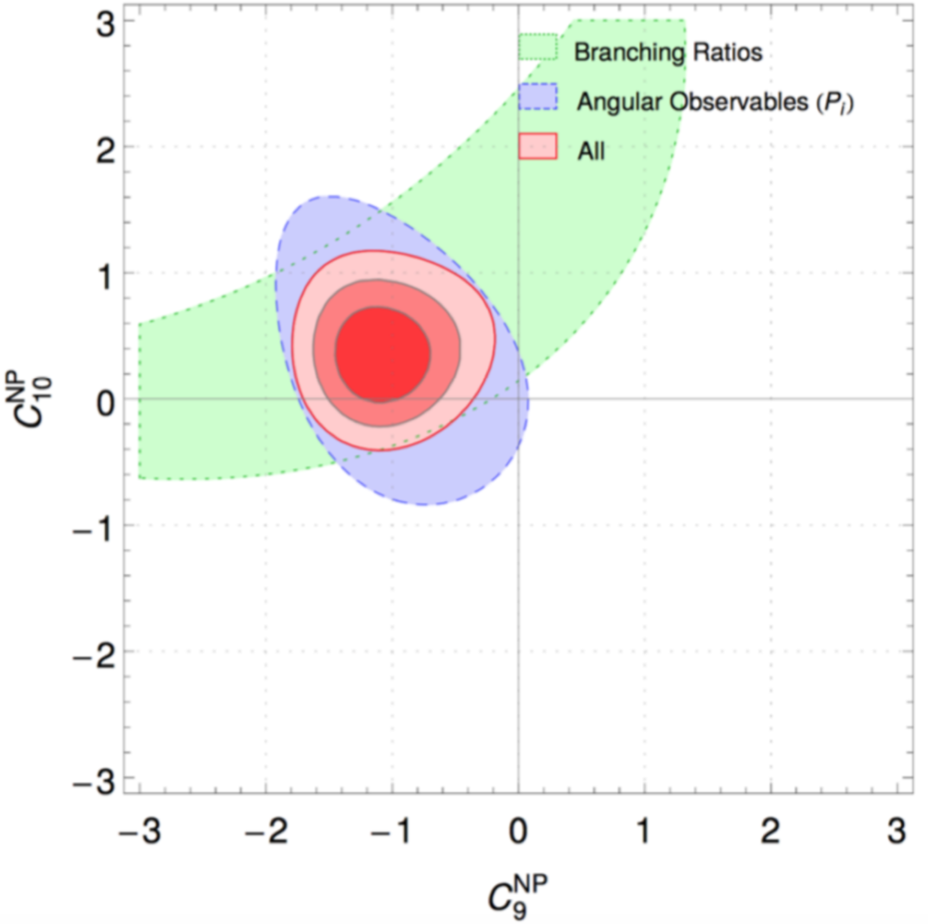
$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

- Wilson coefficients split as $\mathbf{C_i = C_i^{SM} + C_i^{NP}}$ with i=7,9,10,7',9',10'. Primed $\mathbf{C_i'}$: right handed currents, suppressed in the SM.

- Best fit prefers a non-zero value for the vector coupling $\mathbf{C_9^{NP}}$ (or $\mathbf{C_9^{NP}}$ and axial-vector $\mathbf{C_{10}^{NP}}$)
  - … could QCD effects mimic vector-like NP contribution?



[JHEP 06 (2016) 092]



[W. Altmannshofer et al. Phys. Rev. D96 (2017) 055008,
B. Capdevila et al. JHEP 01 (2018) 093, T. Hurth et al. Phys. Rev. D96 (2017) 095034,
G. DAmico et al. JHEP 09 (2017) 010, L.-S. Geng et al. Phys. Rev. D96 (2017) 093006,
M. Ciuchini et al. Eur. Phys. J. C77 (2017) 688,
S. Jäger and J. Martin Camalich, Phys. Rev. D93 (2016) 014028 and many others]

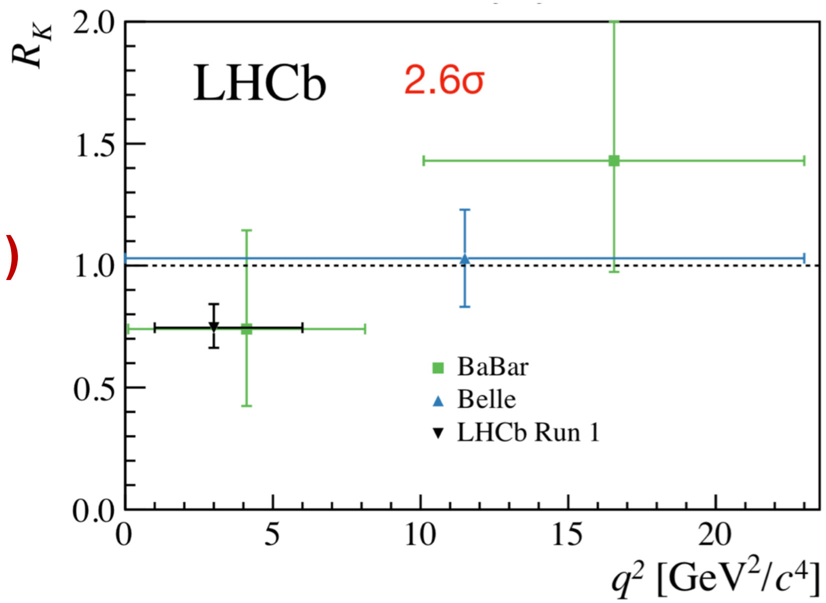
Lepton flavour universality in $b \longrightarrow s\mu^+\mu^-$ decays

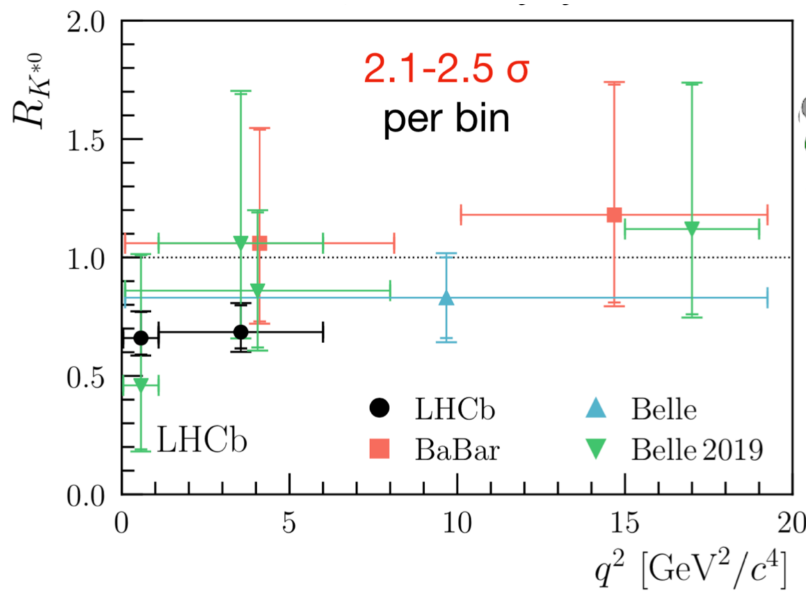
- Ratios of muons/electrons are **extremely well predicted** in the SM:
  - Hadronic uncertainties of $\mathcal{O}(10^{-4})$ ([JHEP 0712 (2007) 040]).
  - QED uncertainties of $\mathcal{O}(10^{-2})$ ([EPJC 76 (2016), 8, 440]).
- Any significant deviation from 1 is a clear sign of NP.

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{SM}{\cong} 1$$

(similar definition for R_{K^*})

LHCb
Run 1 (3fb^{-1})

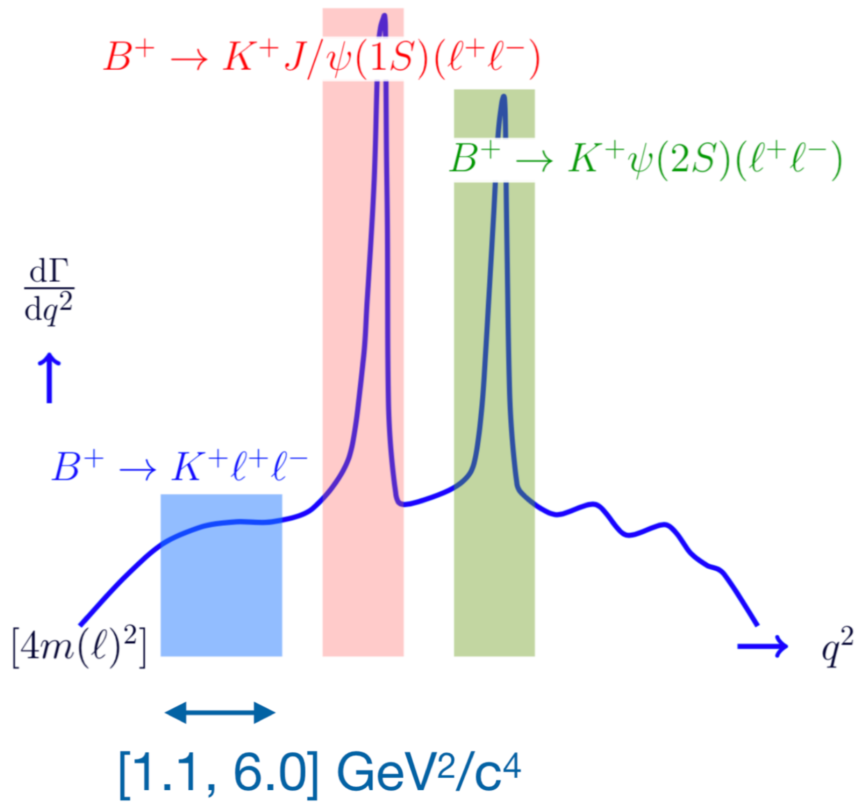




[LHCb, PRL 113 (2014) 151601] [BaBar, PRD 86 (2012) 032012] [Belle, PRL 103 (2009) 171801]
[LHCb, JHEP 08 (2017) 055] [Belle, arXiv:1904.02440]

New measurement of R_K at LHCb

- In total, this update uses ~twice as many B's as previous analysis.
  - Re-optimized analysis of **Run 1** dataset (**3fb^{-1}**).
  - Added 2015 and 2016 datasets from **Run 2** (**2fb^{-1}**).
- Details of the analysis:
  - Electrons and muons behave very differently in the LHCb detector due to larger Bremsstrahlung for electrons.
    - Worse **mass** and **q^2 resolution**.
    - Lower reconstruction **efficiency**.
  - Measurement performed as a **double ratio** between **$B^- \to K^- \ell^+ \ell^-$** and **$B^- \to K^- J/\psi(\to \ell^+ \ell^-)$** modes to cancel most systematics.



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

(**$R_{J/\psi} = 1$**)

[PRL 122 (2019) 191801]

Bremsstrahlung

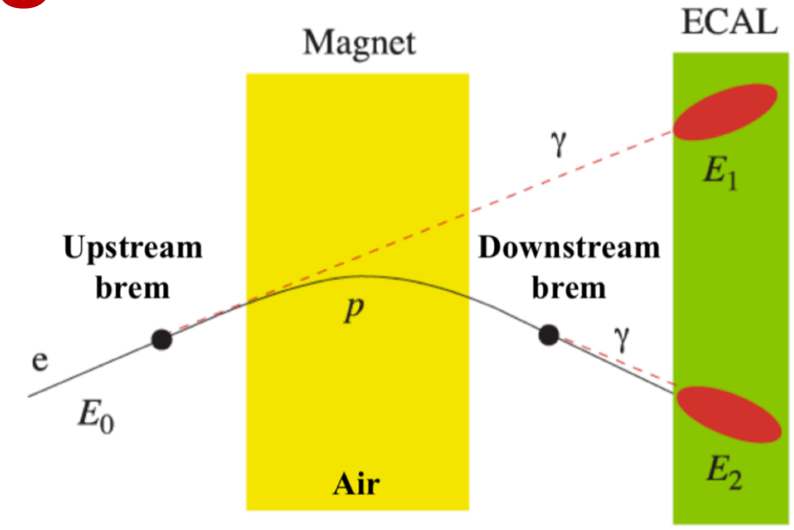
- Electrons lose a fraction of their energy through **Bremsstrahlung** radiation.

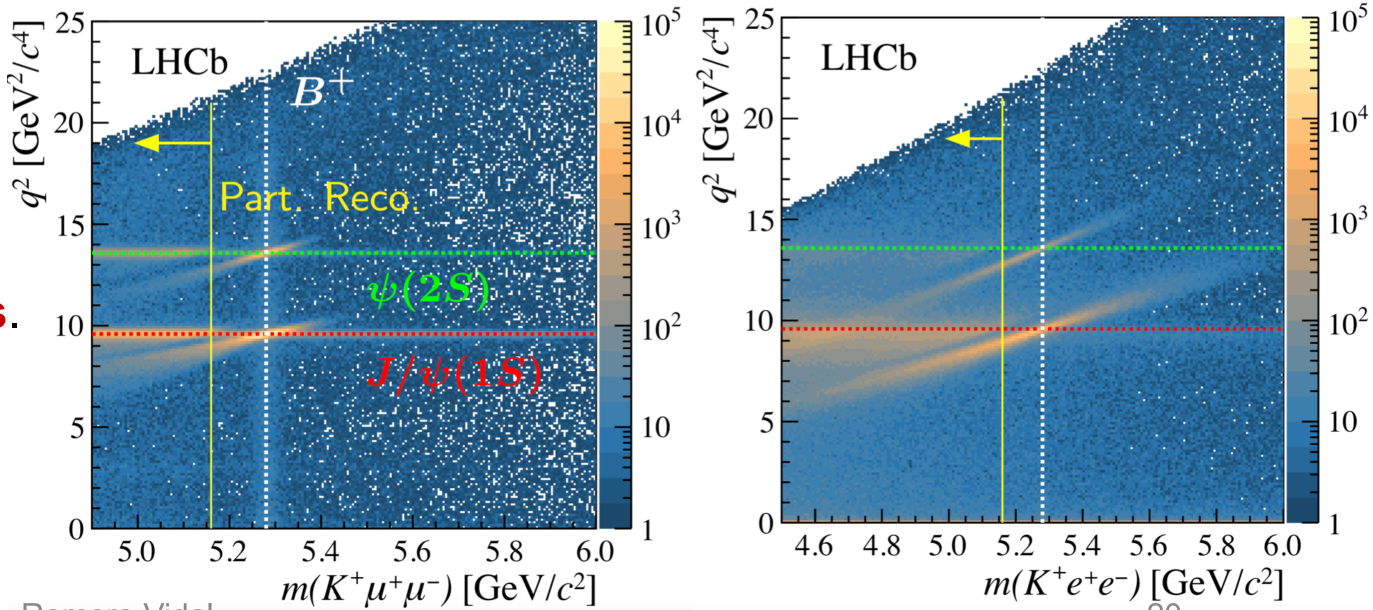
- Bremsstrahlung **recovery procedure** to improve momentum measurement for electrons.
  - Look for photon **clusters** in the **calorimeter** (E_T>75 MeV) compatible with electron direction.

- Even after bremsstrahlung recovery, electrons still have degraded momentum and mass/q^2 resolution.

- Very different trigger signatures: lower trigger efficiency for electrons.
  - **Muons** identified by **muon detectors**.
  - **Electrons** rely on signal in the **calorimeters**: higher occupancy ⇒ **higher trigger thresholds**.

- **Critical aspect** of the analysis: get the **differences** between electrons and muons fully under control.





R_K systematics and cross-checks

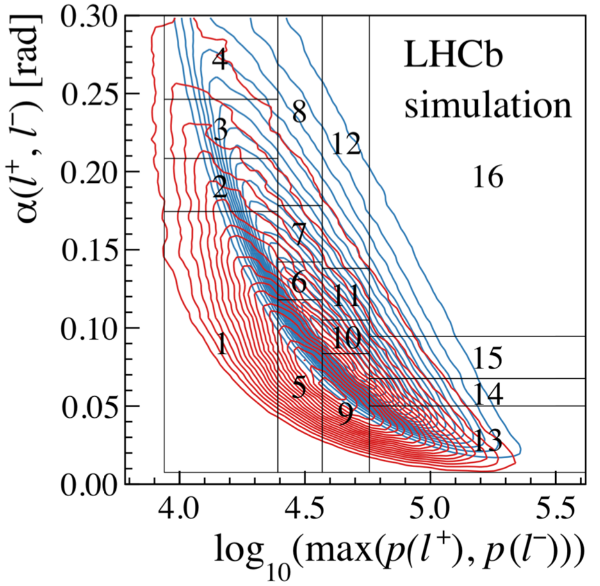
- **Efficiencies** computed using **simulation** carefully **calibrated** using **control channels** selected from data:
  - Applied corrections due to B^+ kinematics, particle-ID, trigger efficiency…
  - **Small systematic** due to good **cancellation** in double ratio.
- Numerous **cross-checks** to ensure good understanding of the efficiencies, i.e check:

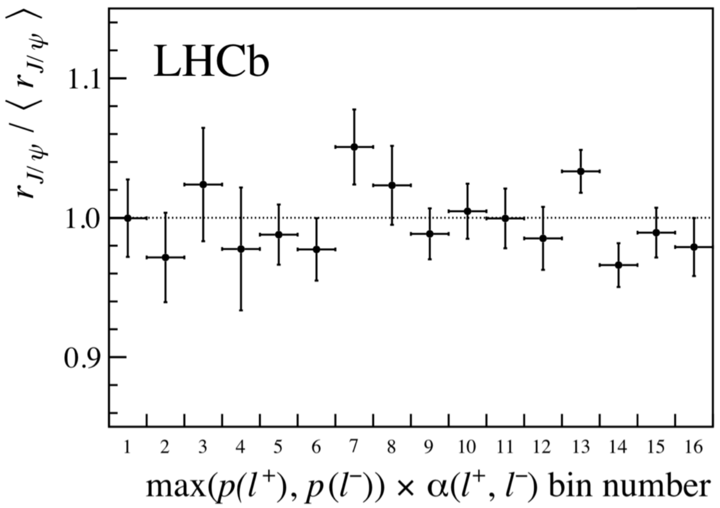
$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1$$

$$r_{J/\psi} = 1.014 \pm 0.035\,(\text{stat} + \text{syst})$$

- Checked that **efficiencies are understood in all kinematic regions** $\Longrightarrow$ **$R_{J/\psi}$ flat** for all variables examined.
- Cross-checks done independently for **Run 1** and **Run 2** samples and **excellent agreement** found.

(α: angle between leptons)





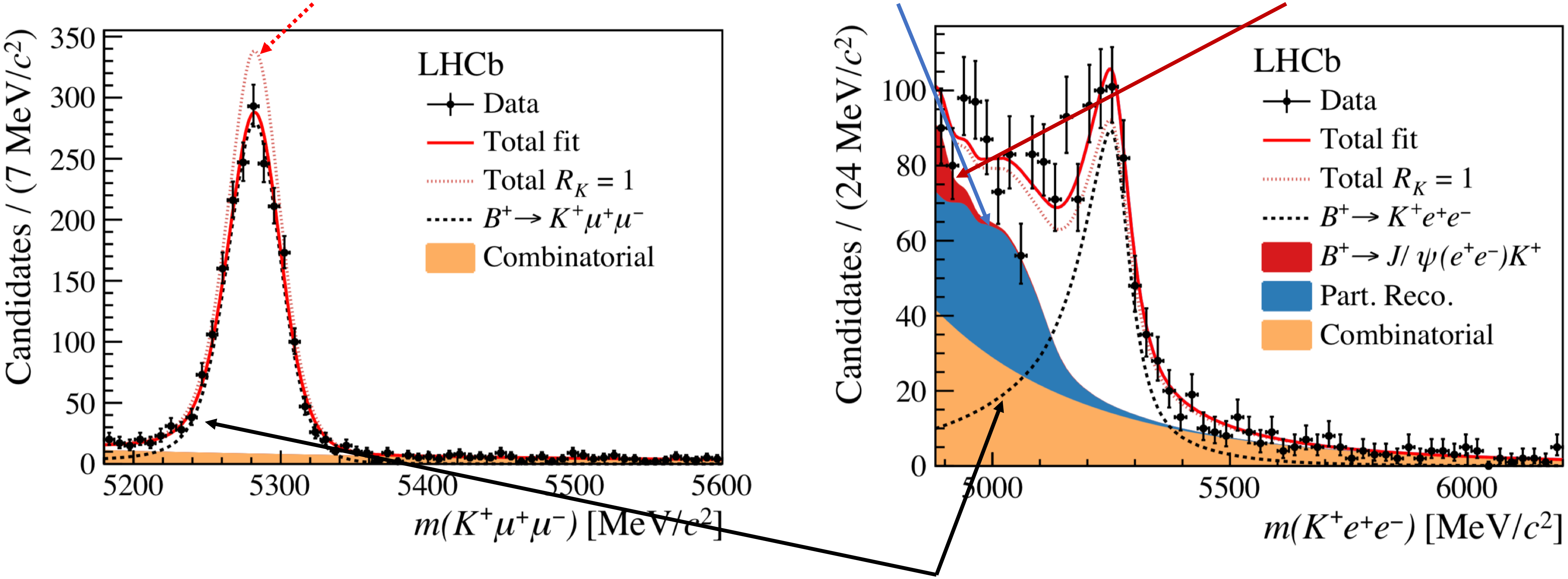
[PRL 122 (2019) 191801]

R_K simultaneous fit

Expectation from observed $B^- \to K^- e^+ e^-$ yield and R_K=1

Partially reconstructed background, mainly $B \to K^* e^+ e^-$

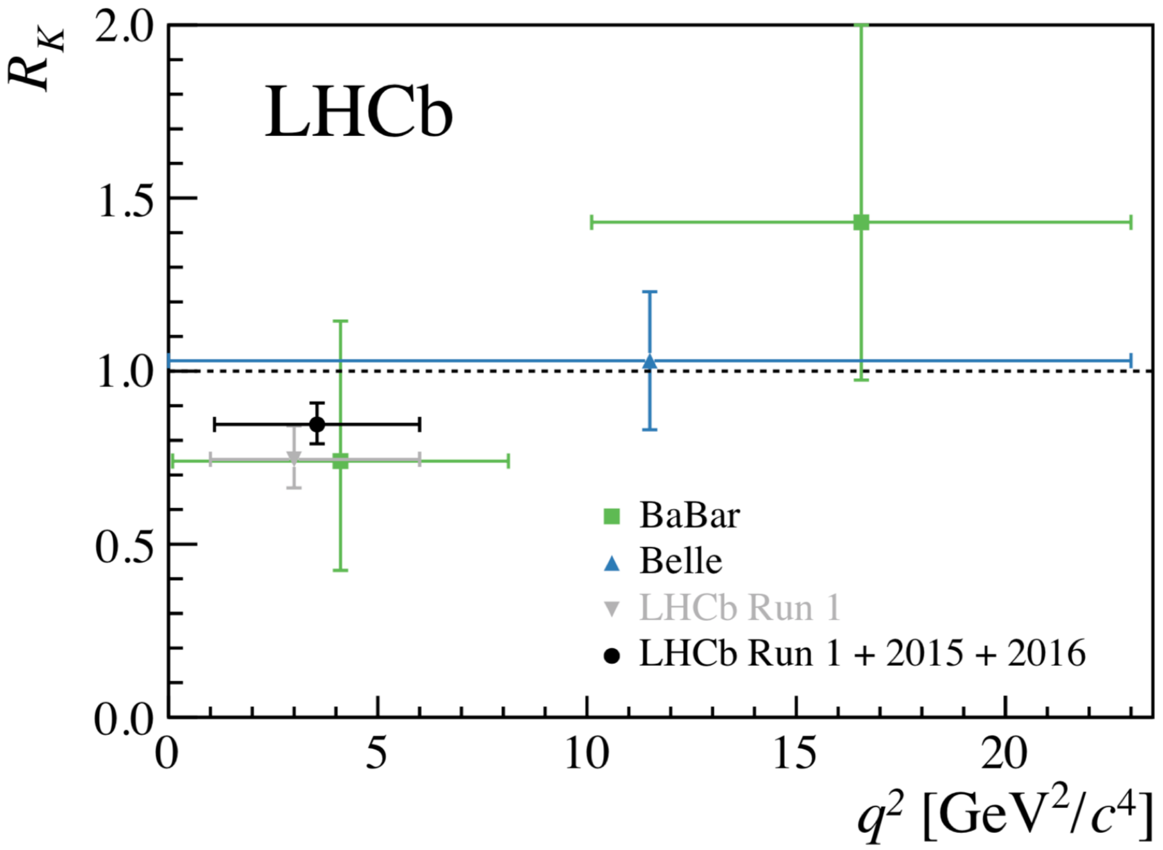
Leakage from $B^- \to K^- J/\psi(\to e^+ e^-)$ constraint from the fit to resonant mode



- Different signal shape between muons and electrons (different x-scales!):
  - worse mass resolution (recovered photons)
  - longer radiative tails (bremsstrahlung)

[PRL 122 (2019) 191801]

New R_K result



- Using **Run 1** (2011+2012) data:

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

compatible with SM expectation at **2.6σ**.

- **Re-analysing** 2011+2012 data and **adding** 2015+2016:

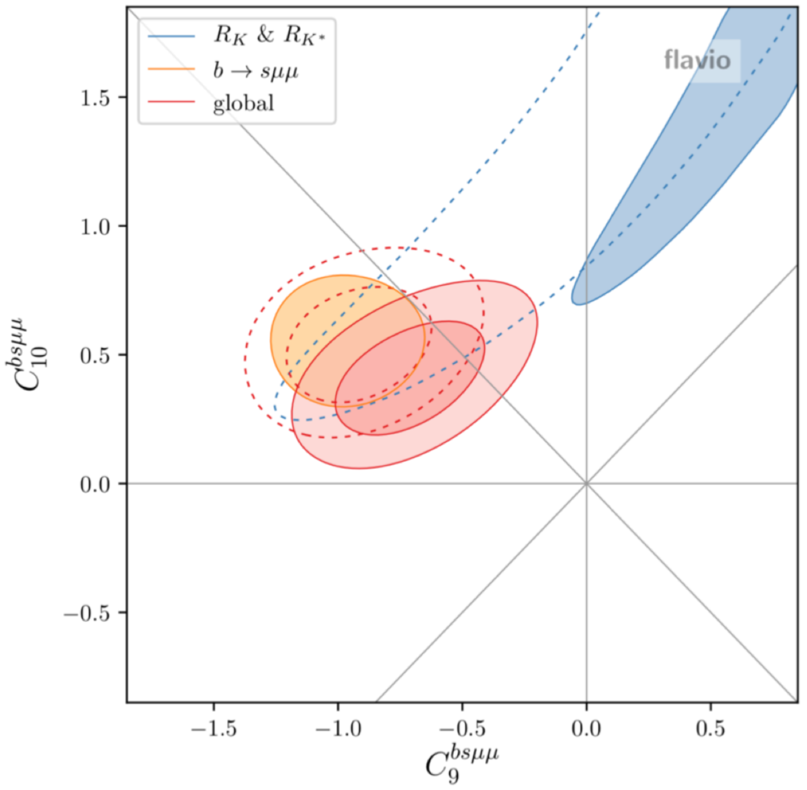
$$R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.014}_{-0.016}\,(\text{syst})$$

compatible with SM expectation at **2.5σ**.

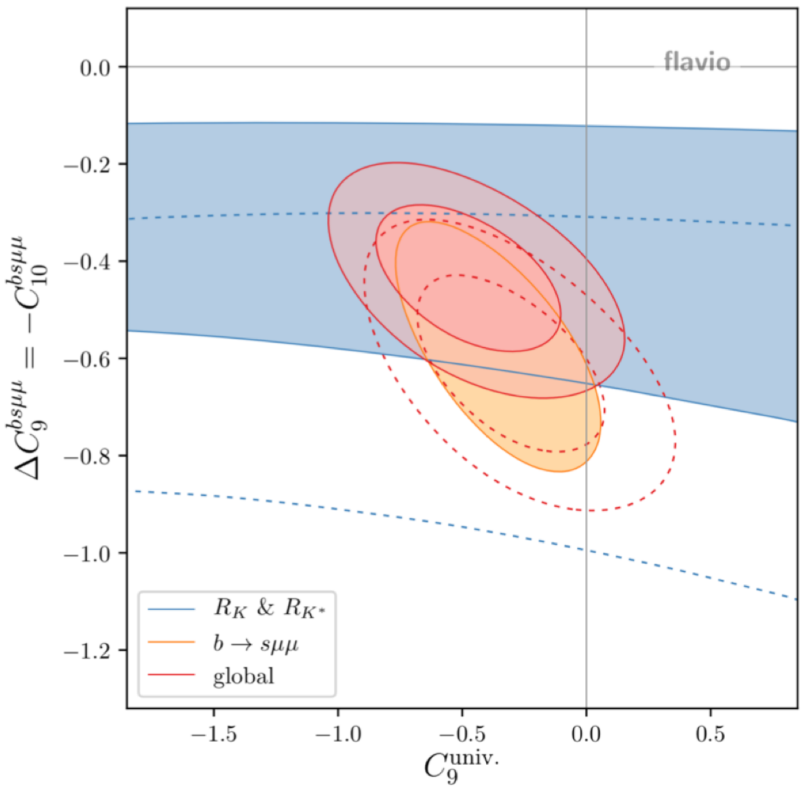
- **Systematic small** due to good cancellation in double ratio:
  - Uncertainty on the **model shape**.
  - Calibration of B^+ **kinematics** and **trigger** efficiency.

Impact on global fits

model independent fit



fit assuming **LFU** and **C_9=−C_{10}**



[J. Aebischer et al., arXiv:1903.10434]

- Best fit point still in tension with the SM.
- Worse compatibility between R_K (R_{K^*}) and other $b \longrightarrow s\mu^+\mu^-$ observables.
- Muonic NP: best fit closer to the SM, **C_9=−C_{10}** still preferred.
- Adding **LFU NP**: slight preference for universal shift in **C_9**.

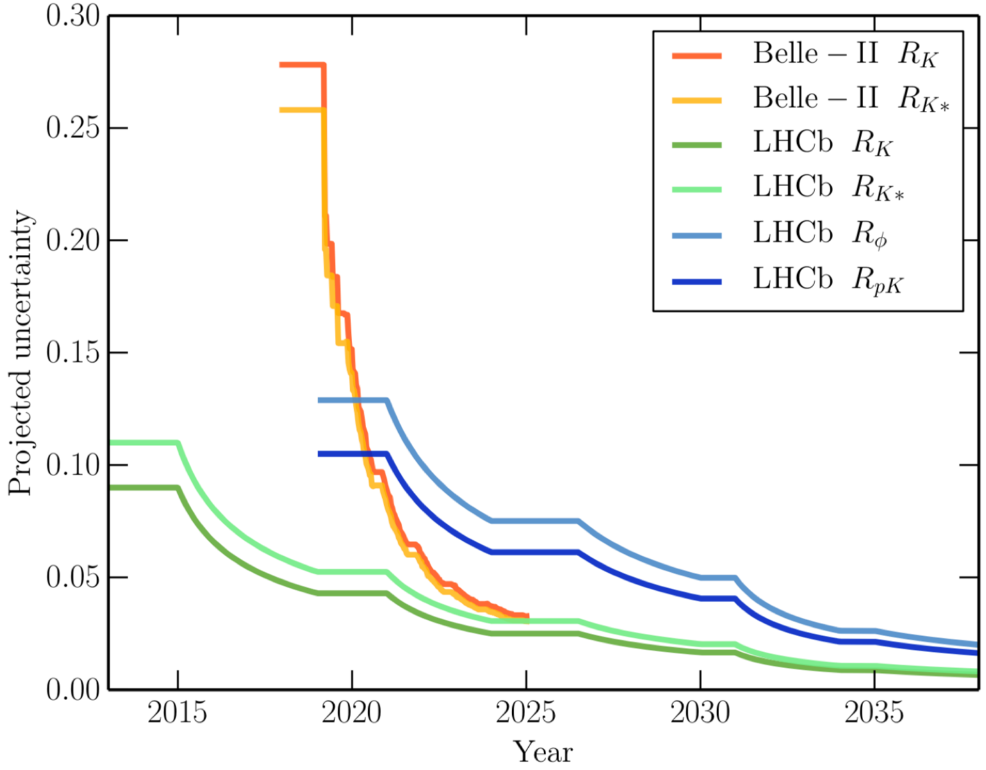
Before new R_K measurement.
After new R_K measurement.

[M. Algueró et al., arXiv:1903.09578, A. K. Alok et al., arXiv:1903.09617, M. Ciuchini et al., arXiv:1903.09632, Guido D'Amico et al., arXiv:1704.05438, and more]

Prospects on $b \to s\ell^+\ell^-$

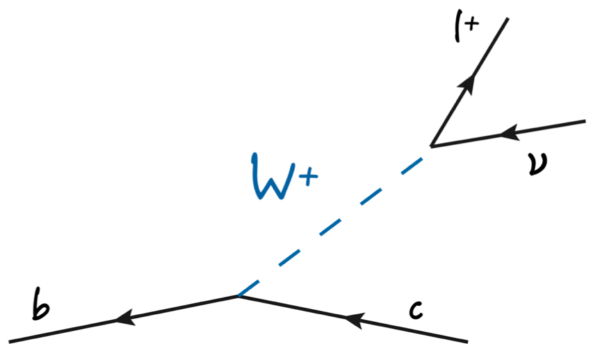
- **LHCb full Run 2** dataset ~4 times number of B's available in Run 1.
  - **Updates** of R_K and R_{K^*} and **other** LFU ratios: R_Φ, R_{pK} …
  - **Angular analyses** of $b \to s\ell^+\ell^-$ transitions also underway
- **CMS** has collected a sample of **~10^{10} B** decays.
  - With an effective low p_T electron reconstruction, should get a very competitive number of $B^+ \to K^+e^+e^-$ candidates.
  - Expected **systematics** will be **different** to those at LHCb, i.e. no trigger effect and very different material distribution.
- **ATLAS** pursuing a similar strategy.
- **Belle II** already started data-taking this year.

Evolution of uncertainties vs year



[J.Phys. G46 (2019) no.2, 023001]

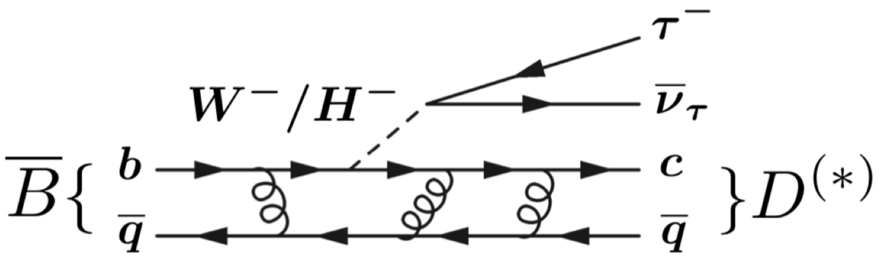
Measurements of tree b⟶$c\tau\nu_\tau$ transitions



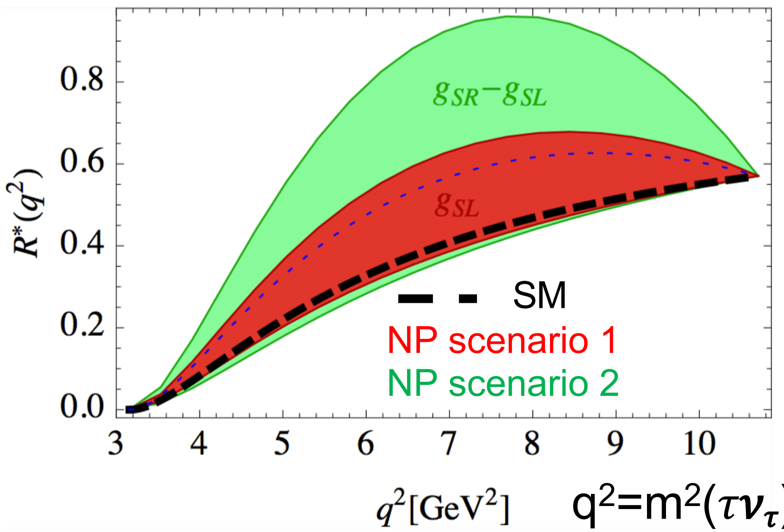
LFU in semitauonic B decays

- In some NP scenarios, new particles couple preferentially to the third family ⇒ important to study **semileptonic** B decays into this family (τ).

- Comparison between **semitauonic** (τ) and **semimuonic** (μ) decays sensitive to NP, which could **modify branching fractions and angular distributions**.



[PRD 85 094025 (2012)]



$q^2=m^2(\tau\nu_\tau)$

- Perform **LFU** test through: $R(D^{(*)}) = \frac{\mathcal{B}(B^0 \to D^{(*)}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)}\mu\nu)}$

- $R(D^{(*)})$ very **clean SM prediction** due to partial cancellation of hadronic form-factors uncertainties in the ratio. **Deviation from 1** due to the different lepton masses (i.e. phase space…)

- Observation of violation of LFU would be a sign for NP.

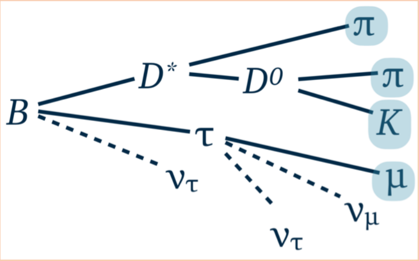
	$R(D)_{SM}$	$R(D^*)_{SM}$
PRD94 (2016) 9, 094008	0.299 ± 0.003	
PRD95 (2017) 11, 115008	0.299 ± 0.003	0.257 ± 0.003
JHEP 1711 (2017) 061		0.260 ± 0.008
JHEP 1712 (2017) 060	0.299 ± 0.004	0.257 ± 0.005

Reconstruction of tau decays

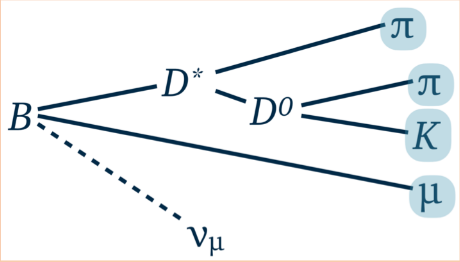
Leptonic decays

- Signal and normalisation channels share the **same visible final state**.

signal



normalisation



- Part of the **systematics cancel in ratio**.
- Important **background** from inclusive semileptonic decays (**$B \longrightarrow D^{**}\ell\nu(X)$**), with many unknowns (form-factors, BR's…)

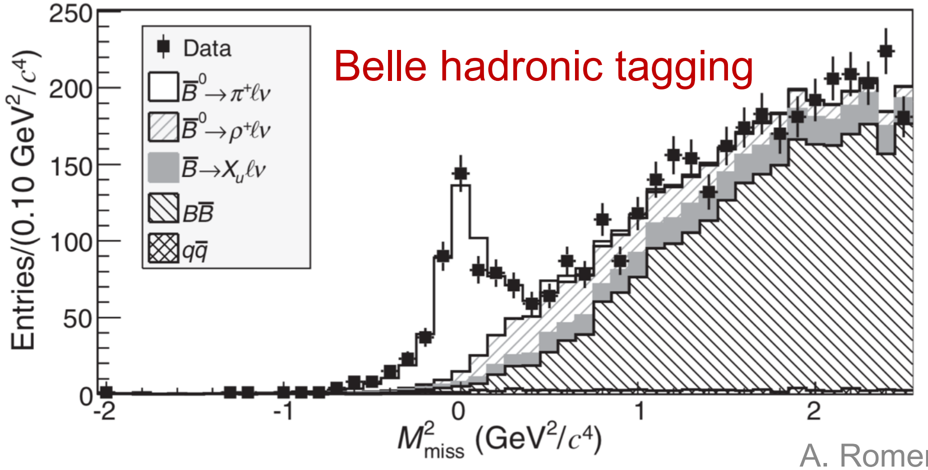
Hadronic decays

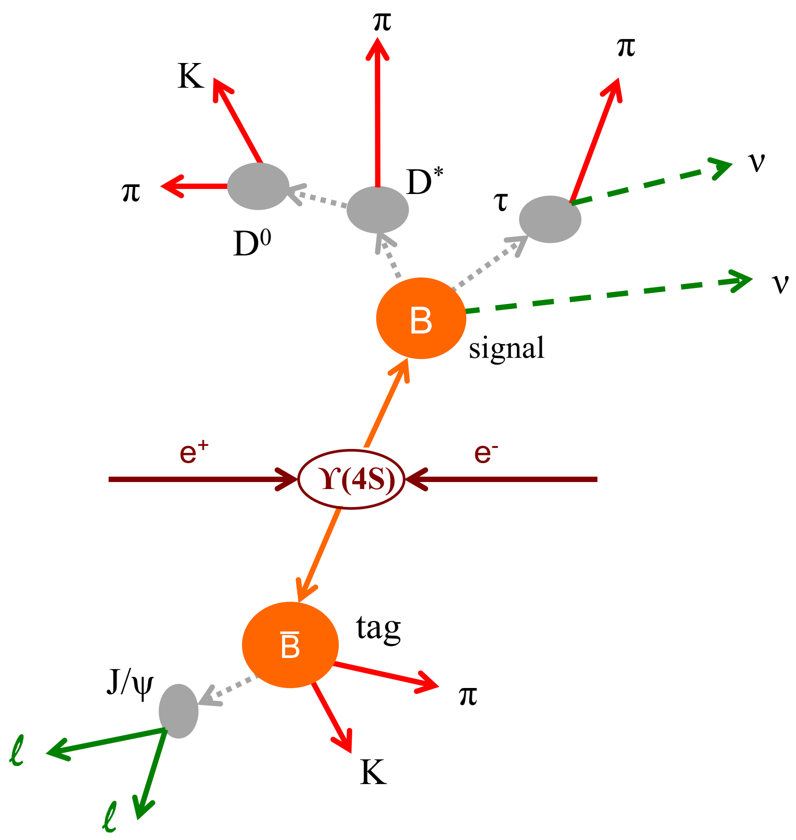
- No background from inclusive semileptonic decays.
- **Visible final state is not the same**. Systematics (at LHCb) do not cancel in the ratio ⇒ measure with respect to other decay with similar final state.

tau decay	BR(%)	Used by
leptonic		
$\tau^- \longrightarrow \mu^- \nu_\mu \nu_\tau$	17.39 ± 0.04	B-factories and **LHCb**
$\tau^- \longrightarrow e^- \nu_e \nu_\tau$	17.82 ± 0.04	B-factories
hadronic		
$\tau^- \longrightarrow \pi^- \pi^0 \nu_\tau$	25.49 ± 0.09	Belle
$\tau^- \longrightarrow \pi^- \nu_\tau$	10.82 ± 0.05	Belle
$\tau^- \longrightarrow \pi^- \pi^+ \pi^- \nu_\tau$	9.02 ± 0.05	**LHCb**
$\tau^- \longrightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	4.49 ± 0.05	**LHCb**

Semitauonic B decays at B-factories

- At B-factories (Belle(II) and BaBar), **e^+/e^-** collisions producing **$\Upsilon(4S) \to B\bar{B}$**. e^+ and e^- with different energies to produce **boosted B's**.
- **B-tagging** allows to constrain the momentum of the **B-signal:**
  - **Hadronic B-tag**: precise measurement of $p_{B,sig}$. Good determination of q^2 and m_{miss}^2 (**eff. ~0.3%**)
  - **SL B-tag**: weaker constraint on p_B (**eff. ~1%**)
- The **missing mass** (neutrinos) can be measured with high precision.





B-factories vs LHCb

B-factories	LHCb

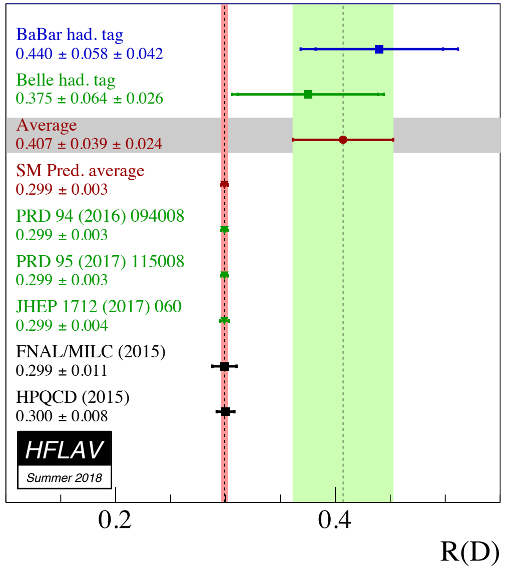
B-factories

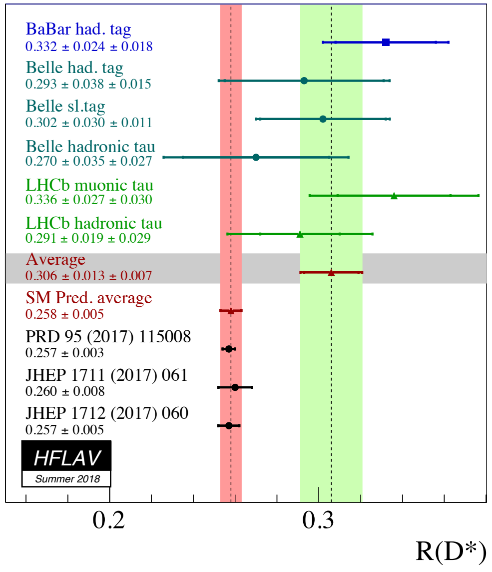
- B momentum is known ($\Upsilon(4S) \to B\bar{B}$)
- B-tag algorithms use the other B in the event:
  - **Hadronic** B-tag: 0.3% efficient, very pure: all **backgrounds are fully reconstructed**.
  - **SL** B-tag: 1% efficient, **less pure**.
- Charm mesons reconstructed in multiple decay modes:
  - $D^{*-} \to D^0\pi^-$, $D^+\pi^0$.
  - $D^{*0} \to D^0\pi^0$.
  - $D^0 \to K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+$, $K_S^0\pi^+\pi^-$, $K_S^0\pi^0$, $K_S^0K^+K^-$, K^+K^-, $\pi^+\pi^-$. (30% of D^0 BR's)
  - $D^+ \to K^-\pi^+\pi^-$, $K_S^0\pi^+\pi^0$, $K_S^0\pi^+\pi^-\pi^+$, $K_S^0\pi^+$, $K^-K^+\pi^+$, $K_S^0K^+$. (22% of D^+ BR's)

LHCb

- Use the **B flight direction** to measure transverse component of missing momentum.
- Cannot measure longitudinal component, so use some **approximation** to access rest frame variables.
- Until now only used $D^{*-} \to D^0\pi^-$ with $D^0 \to K^-\pi^+$ for R(D*) measurements.
- Studies using Λ_b^0, B_c^+ and B_s^0 hadrons only possible at the **LHC** (not produced at B-factories).

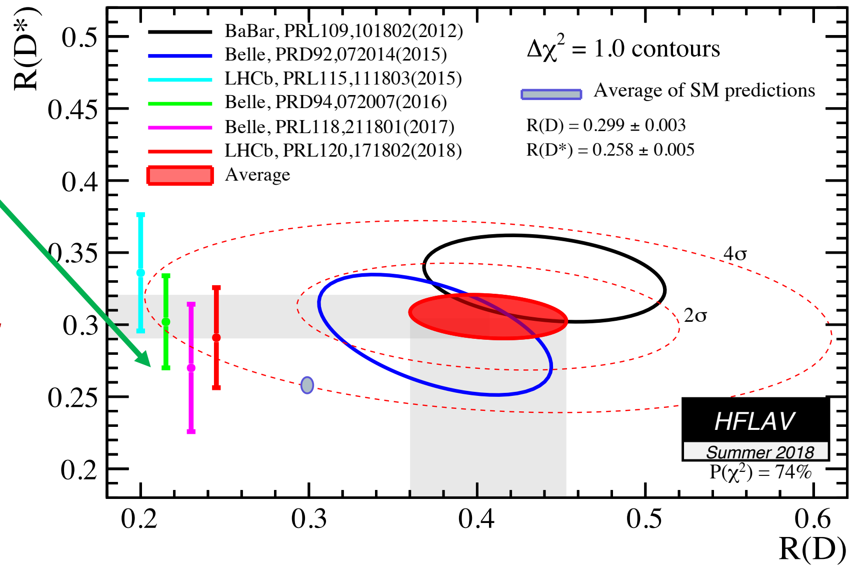
Status of R(D) and R(D*) measurements

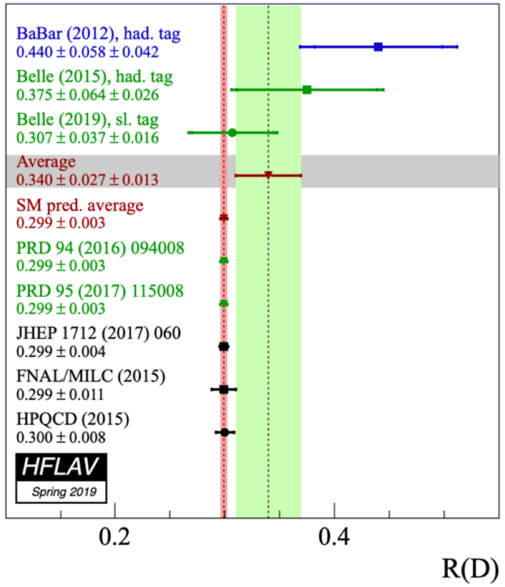


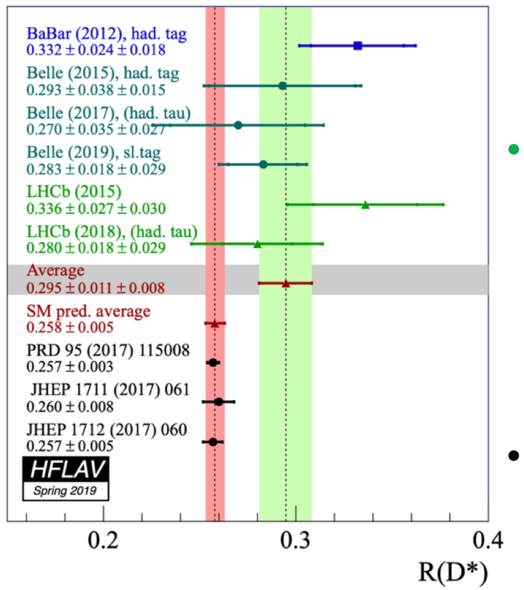


⇐ Summer 2018 ⇒

- Old measurement of R(D*) by Belle using SL B-tagging.
- Tension with SM **3.8σ**

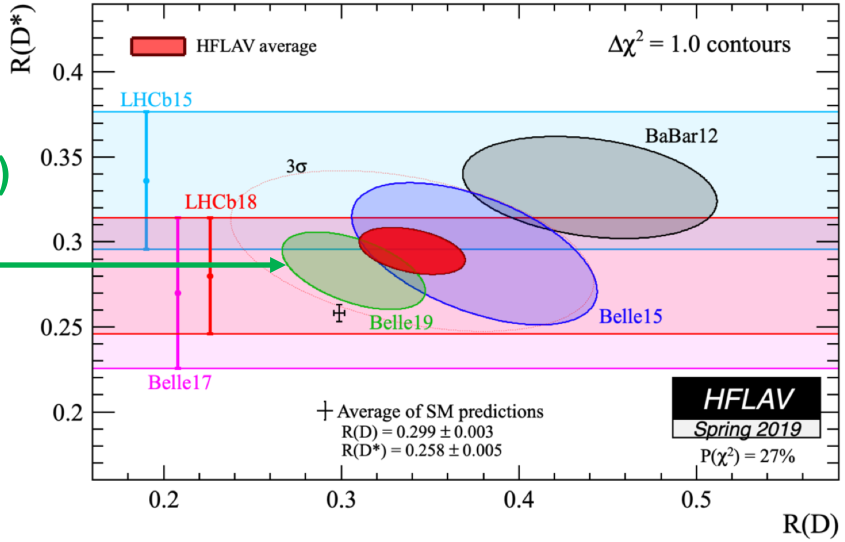






⇐ Spring 2019 ⇒

- **New (simultaneous) measurement of R(D) and R(D*) by Belle using SL B-tagging.**
- Tension with SM decreased to **3.1σ**



Semitauonic measurements at LHCb

Muonic tau decays

- Measurement using $\tau^-\to\mu^-\nu_\mu\nu_\tau$ decays.
- **3 neutrinos** present in $B^0\to D^{*-}\tau^+\nu_\tau$
- Important **contributions** from exclusive **$B^0\to D^{*-}\mu^+\nu_\mu$** (normalisation) and inclusive **$B\to D^{*-}\mu^+\nu_\mu X$** decays, i.e. $(D^{**}\to D^*\pi\pi)$.
- Important contribution from **doubly-charmed** $B\to D^{*-}D(X)$ decays with $D\to X\mu^+\nu_\mu$.
- **R(D*) directly measured** from the same data sample $(D^{*-}\mu^+)$.

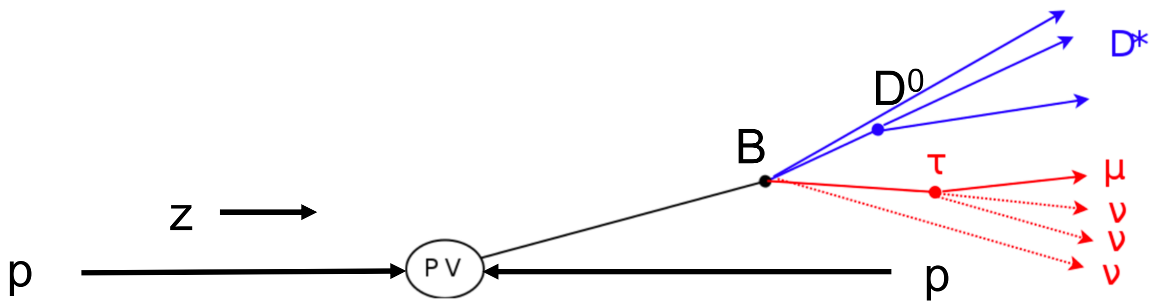
Published analyses use only Run 1 data (3fb^{-1})

Hadronic tau decays

- Measurement using $\tau^-\to\pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ decays.
- **Only 2 neutrinos** present in $B^0\to D^{*-}\tau^+\nu_\tau$
- **tau vertex is known** (3π vertex). This gives access to the **tau decay time**, which can be used to discriminate between signal and background.
- **No** contamination from **semileptonic** $B\to D^{*-}\mu^+\nu_\mu(X)$ decays.
- **Large** contribution from **doubly-charmed** $B\to D^{*-}D(X)$ decays with $D\to\pi^+\pi^-\pi^+X$.
- **Measure BR($B^0\to D^{*-}\tau^+\nu_\tau$)** with respect to, i.e. $B^0\to D^{*-}\pi^+\pi^-\pi^+$. Then, use WA BR($B^0\to D^{*-}\mu^+\nu_\mu$) to obtain R(D*).

R(D*) at LHCb using $\tau^- \to \mu^- \nu_\mu \nu_\tau$ decays

- At the **LHC**, B momentum **cannot be constrained** from beam energy (no ϒ(4S)→B$\bar{\text{B}}$ decay as in B-factories).

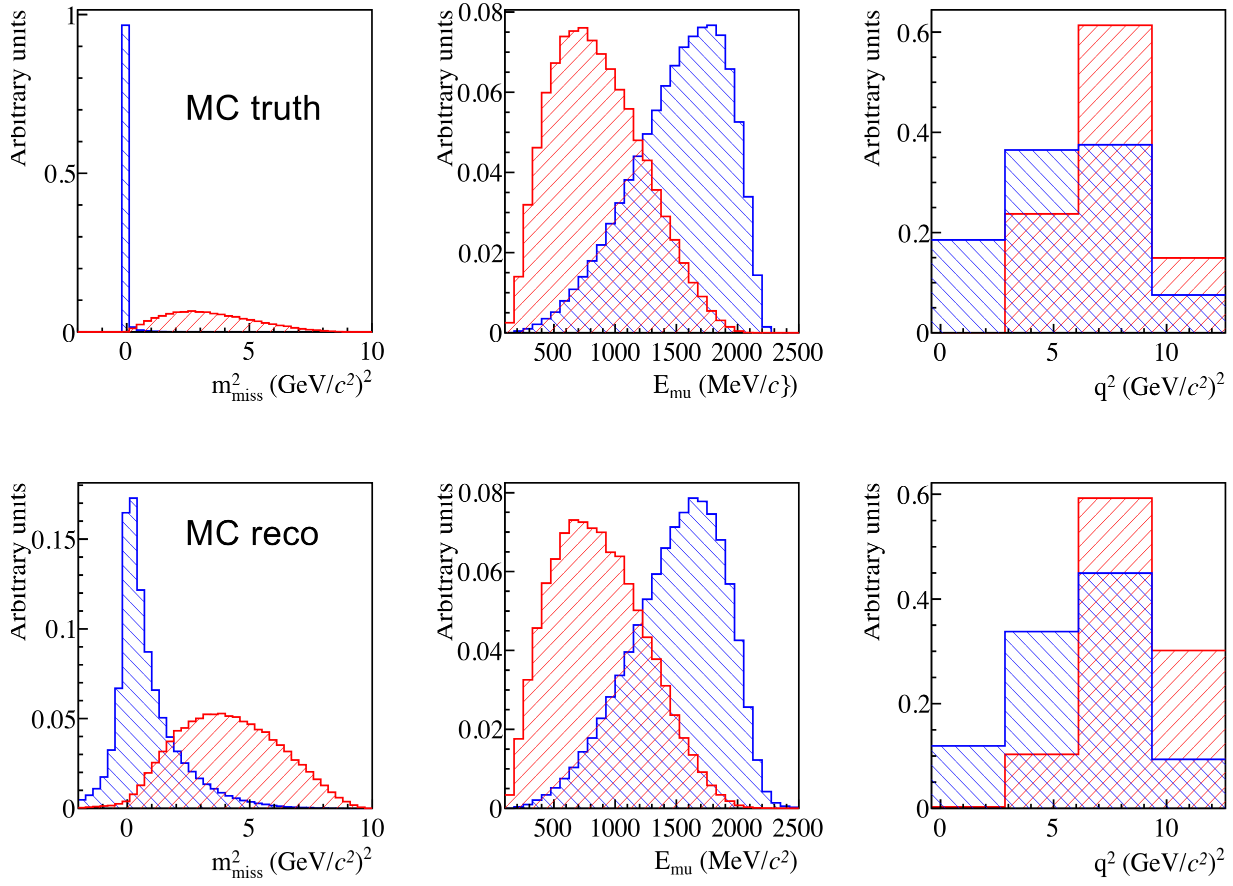


- **Approximation** used to estimate B momentum: B boost along z >> boost of decay products in B rest frame:

$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

- **~18% resolution on p_B** still good enough to preserve signal and background discrimination.

- 3D template fit to **m^2_{miss}** , **E_μ*** and **q^2 (=$m^2(\tau^-\nu_\tau)$)**.

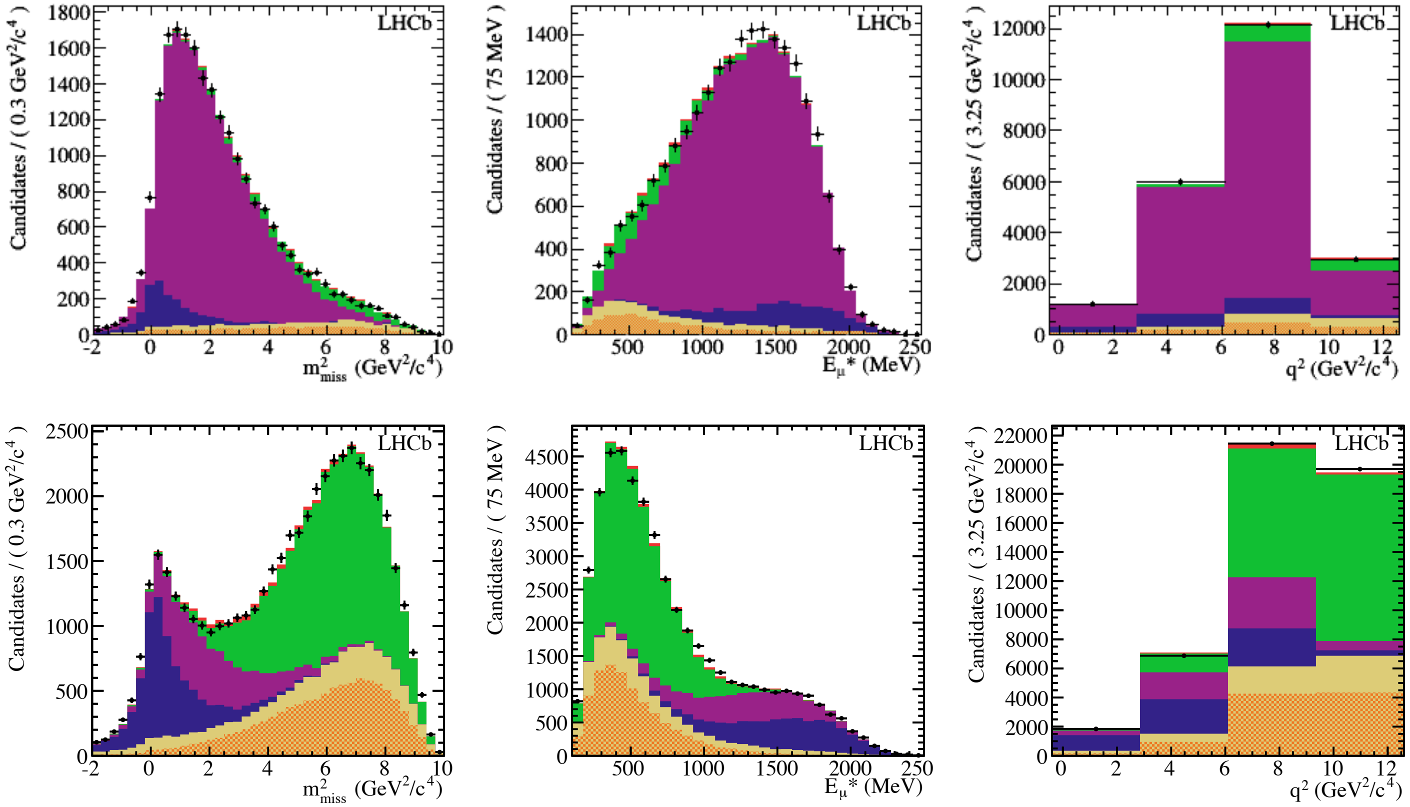


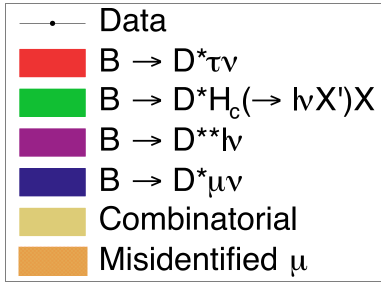
Muonic R(D*): Fit model

- $B^0 \to D^{*-}\mu^+\nu_\mu$. Normalisation mode.
- $B^0 \to D^{*-}\tau^+\nu_\tau$. Signal.
- Inclusive semileptonic $B \to D^{*-}\mu^+\nu_\mu X$ (and $B \to D^{*-}\tau^+\nu_\tau X$).
- Doubly-charmed $B \to D^{*-}D(\to X\mu^+\nu_\mu)X'$.
- Combinatorial $D^0\pi^-$ and $D^{*-}\mu^+$ background.
- $h \to \mu$ mis-identification.

Control samples fits to constrain background shapes

- Control samples created adding extra **pions** and **kaons** pointing to B vertex.
- **MC re-weighted** to match data.



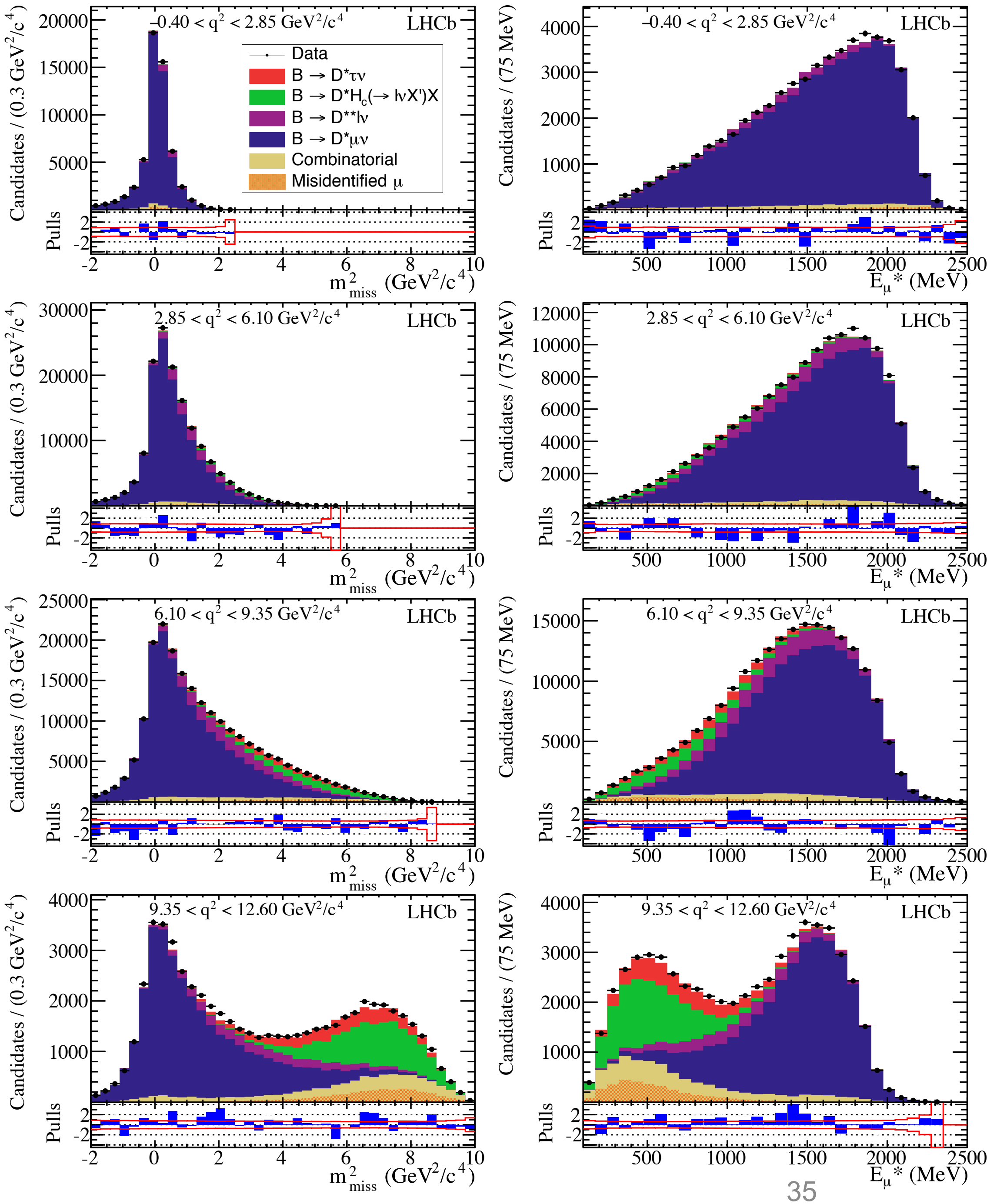


Muonic R(D*): results

- Projections of (left) m^2_{miss} and (right) E_μ^* in bins of increasing q^2 from top to bottom.
- **Signal clearly visible in highest q^2 bin**. Note different y scales, most signal actually in second-highest q^2 bin.
- **Systematics** dominated by the **size of simulation** sample and **$h \to \mu$** mis-ID. Expected to be reduced in future analyses.
- 3D template fit to m^2_{miss}, E_μ^* and q^2 gives:

R(D*) = 0.336 ± 0.027(stat) ± 0.030(syst)

- Result is **2.1σ** above SM ($R(D^*)_{SM} \approx 0.26$).

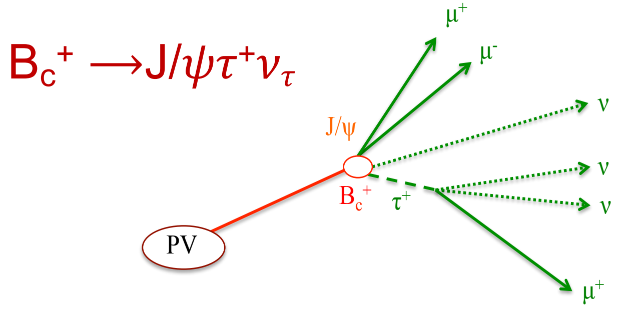


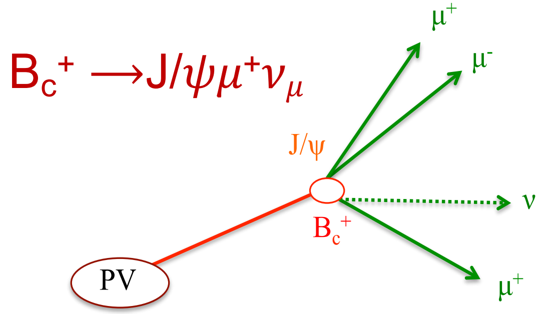
R(J/ψ) at LHCb using $\tau^-\longrightarrow\mu^-\nu_\mu\nu_\tau$ decays

- **LFU test** through the measurement of: $$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)}$$

- This measurement only possible at the LHC (B_c^+ not produced at B-factories).

- B_c^+ **form-factors** not known precisely ⇒ Theoretical prediction not precise. R(J/ψ) predicted to be in **range [0.25,0.28]** ([PLB452 (1999) 129], [arXiv:hep-ph/0211021], [PRD73 (2006) 054024], [PRD74 (2006) 074008])





- Improvements in form-factors calculation needed.

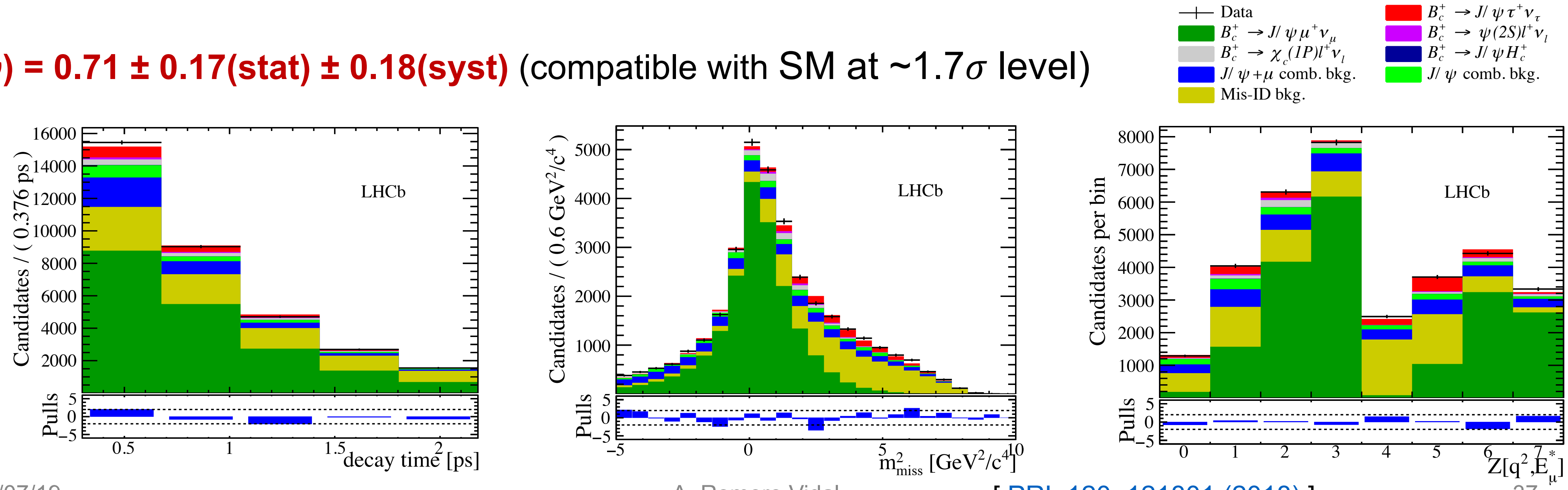
- Same reconstruction method as in muonic R(D*) analysis: $\tau^-\longrightarrow\mu^-\nu_\mu\nu_\tau$ decays. ⇒ $$(p_{B_c})_z = \frac{m_{B_c}}{m(J/\psi\mu)} \times (p_{J/\psi\mu})_z$$

- Main backgrounds:
  - **$B_c^+\longrightarrow J/\psi\mu^+\nu_\mu$** (normalisation mode), **$B_c^+\longrightarrow\psi(2S)\mu^+\nu_\mu$** and **$B_c^+\longrightarrow J/\psi D(\longrightarrow X\mu^+\nu_\mu)X'$** .
  - Hadron **mis-identified** as a muon.
  - **Combinatorial** background (J/ ψ and μ not from same B)

R(J/ψ) results

- **B_c^+ decay time** used in addition to **q^2**, **m_{miss}^2** and **E_μ*** in fit model (q^2 and E_μ* combined in a single variable, Z) in a **3D template fit**.
- Form-factors constrained from a control sample enriched in normalisation decays.
- **Systematics** dominated by the knowledge of the **form-factors** and **size of simulation** samples.
- **First evidence** of the decay $B_c^+ \longrightarrow J/\psi\tau^+\nu_\tau$ (**3σ**).

⇒ **R(J/ψ) = 0.71 ± 0.17(stat) ± 0.18(syst)** (compatible with SM at ~1.7σ level)



[PRL 120, 121801 (2018)]

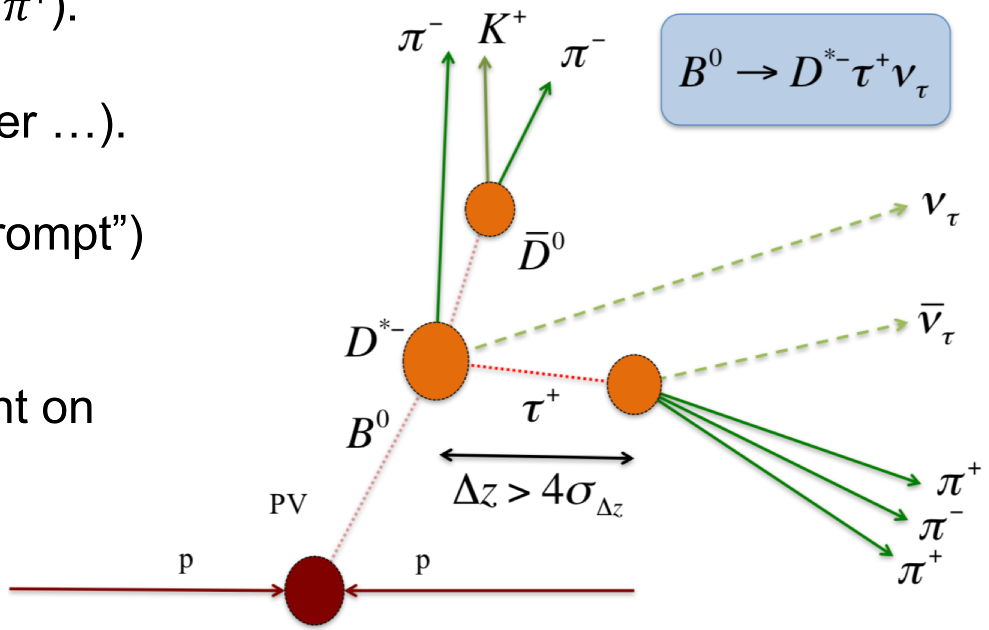
R(D*) using hadronic $\tau^- \longrightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

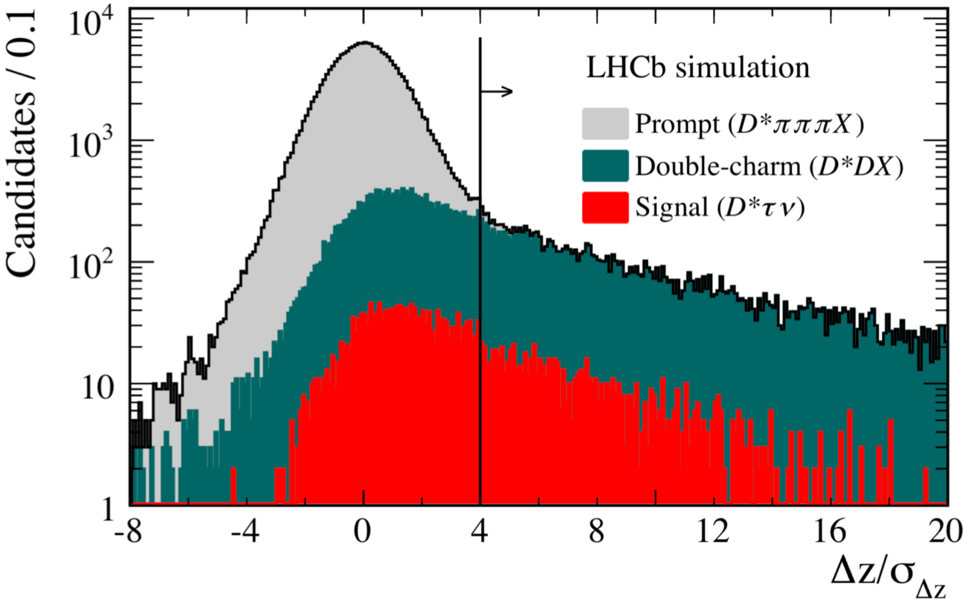
~4% precision

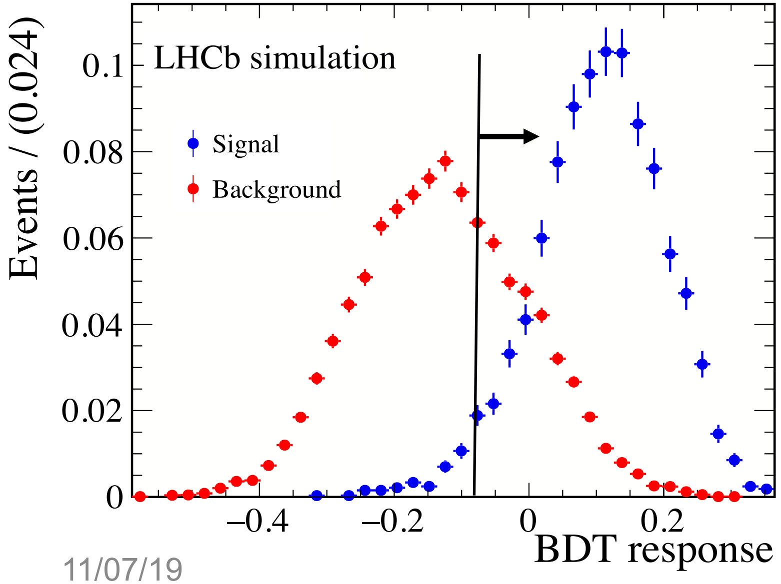
~2% precision

- Signal and normalisation share **same visible final state** ($D^{*-}\pi^+\pi^-\pi^+$).
- Most of the systematic uncertainties cancel in the ratio (PID, trigger …).
- Use **topology** of the decay to suppress large $B \longrightarrow D^{*-}\pi^+\pi^-\pi^+X$ ("prompt") background (where the 3 pions come from the B vertex).
- Minimum distance **Δz** between B^0 and τ vertices **>4σ**: 35% efficient on signal and reduces prompt background by a factor >100.
- Possible due to the **excellent LHCb vertex resolution**.



Selection





- After **$\Delta z>4\sigma$** cut, most of the remaining background is due to **doubly-charmed** B decays (comparable **lifetime** of the charm D mesons and the tau).
  - **$B\to D^{*-}D_s^+X$** : ~ 10 x **signal**
  - **$B\to D^{*-}D^+X$** : ~ 1 x **signal**
  - **$B\to D^{*-}D^0X$** : ~0.2 x **signal**

- Largest background due to **$B\to D^{*-}D_s^+X$** decays with inclusive **$D_s^+\to\pi^+\pi^-\pi^+X'$** decays.
  - Use a multivariate analysis algorithm (Boost Decision Tree, **BDT**) to suppress them.
  - Remaining background still large: **modelling of the D_s^+** (and D^0 and D^+) using data control samples.

- BDT trained with background MC vs signal MC, including:
  - 3π dynamics (i.e. $m(\pi^+\pi^-)$ …),
  - $D^{*-}3\pi$ dynamics (i.e $m(D^{*-}3\pi)$ …),
  - Deposit energy in the electromagnetic calorimeter.

- **BDT cut** applied to suppress main $B\to D^{*-}D_s^+X$ background.

Signal reconstruction

- Due to the presence of 2 neutrinos in the final state:

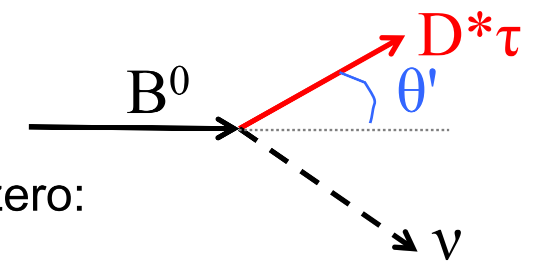
  - **2 solutions for $|p_\tau|$** due to the missing neutrino from the tau decay.

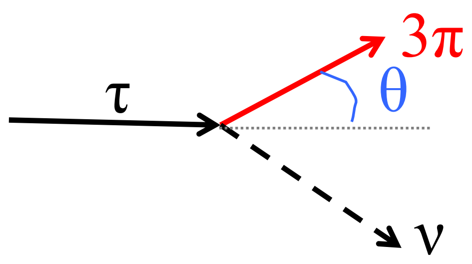
$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2\cos^2\theta)}$$

  - **2 solutions for $|p_B|$** due to the missing neutrino from the B decay.

$$|\vec{p}_{B^0}| = \frac{(m_{D*\tau}^2 + m_{B^0}^2)|\vec{p}_{D*\tau}|\cos\theta' \pm E_{D*\tau}\sqrt{(m_{B^0}^2 - m_{D*\tau}^2)^2 - 4m_{B^0}^2|\vec{p}_{D*\tau}|^2\sin^2\theta'}}{2(E_{D*\tau}^2 - |\vec{p}_{D*\tau}|^2\cos^2\theta')}$$

  ⇒ 4-fold ambiguity





- **Approximation**: Set the argument of the 2 squared roots to zero:

$$\theta_{max} = \arcsin\left(\frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau|\vec{p}_{3\pi}|}\right) \qquad \theta'_{max} = \arcsin\left(\frac{m_{B^0}^2 - m_{D*\tau}^2}{2m_{B^0}|\vec{p}_{D*\tau}|}\right)$$

- Possible to reconstruct rest frame variables such as **tau decay time** and **q^2**.

- These variables have negligible biases, and sufficient resolution to preserve **good discrimination** between signal and background.

The $D_s^+ \to \pi^+\pi^-\pi^+X$ decay model: low-BDT fit

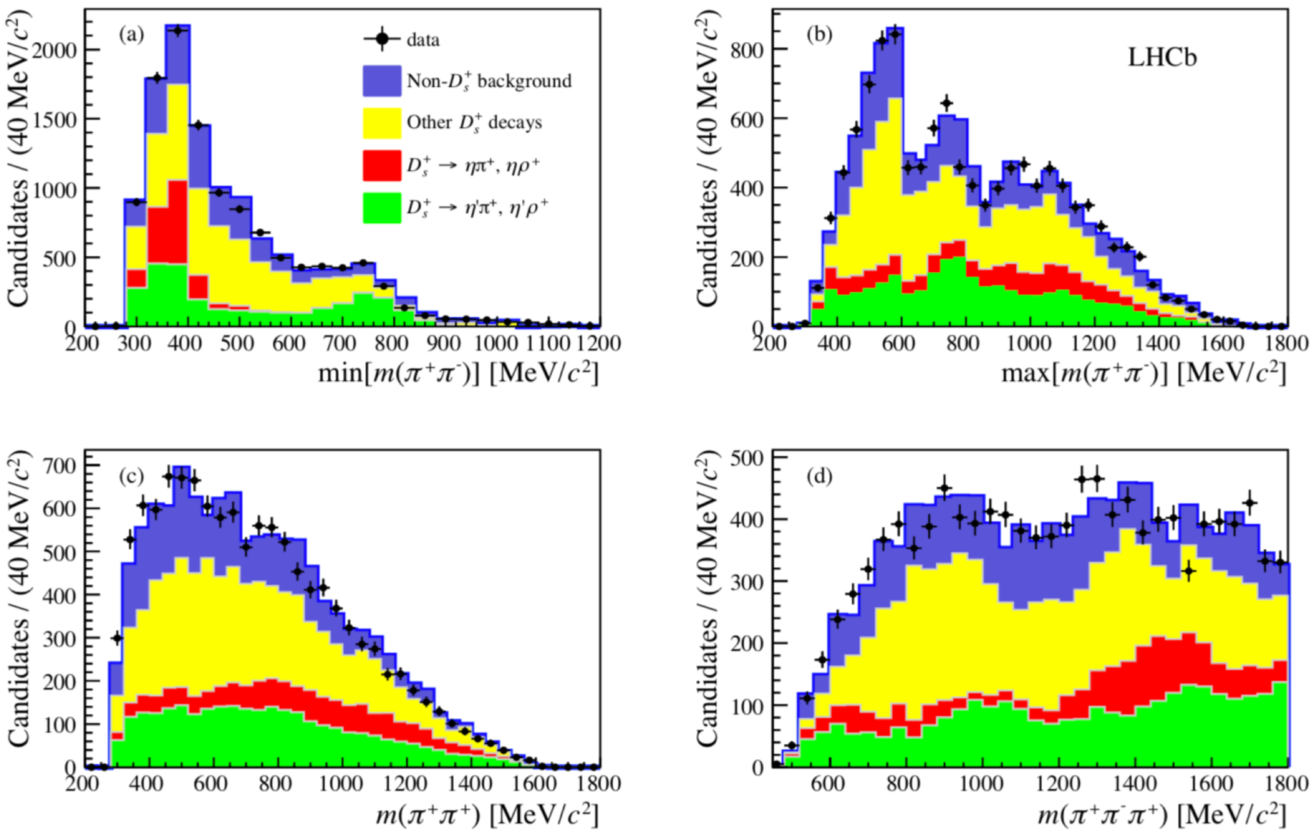
- Events removed by the BDT cut are used to **model the inclusive $D_s^+ \to \pi^+\pi^-\pi^+X$** decay.

- Low BDT region (not used for signal extraction) is used to measure the D_s composition.
  - D_s decay modes with 3 pions + neutrals not very well measured.
  - $D_s \to 3\pi$ is only 1/15 of the inclusive $D_s \to 3\pi X$.

- Model obtained from **simultaneous fit** to:
  - Min[m($\pi^+\pi^-$)], Max[m($\pi^+\pi^-$)], m($\pi^+\pi^+$) and m(3π).

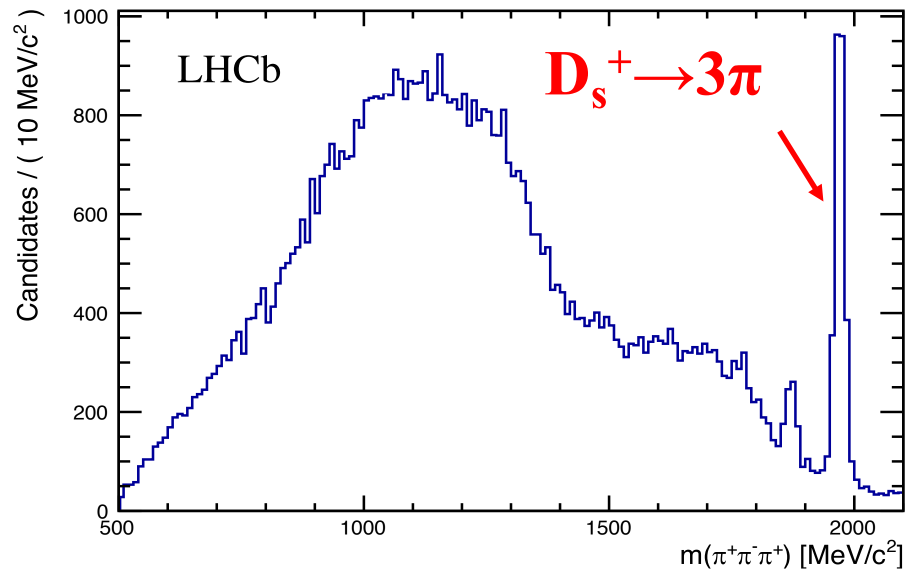
- Fit components:
  1. **$\eta\pi^+$, $\eta\rho^+$**,
  2. **$\eta'\pi^+$, $\eta'\rho^+$**,
  3. **Other components including**: $\omega\pi^+$, $\omega\rho^+$, $\phi\pi^+$, $\phi\rho^+$, $K^0 3\pi$, $\eta 3\pi$, $\eta' 3\pi$, $\omega 3\pi$, $\phi 3\pi$.
  4. **Non-D_s component**.

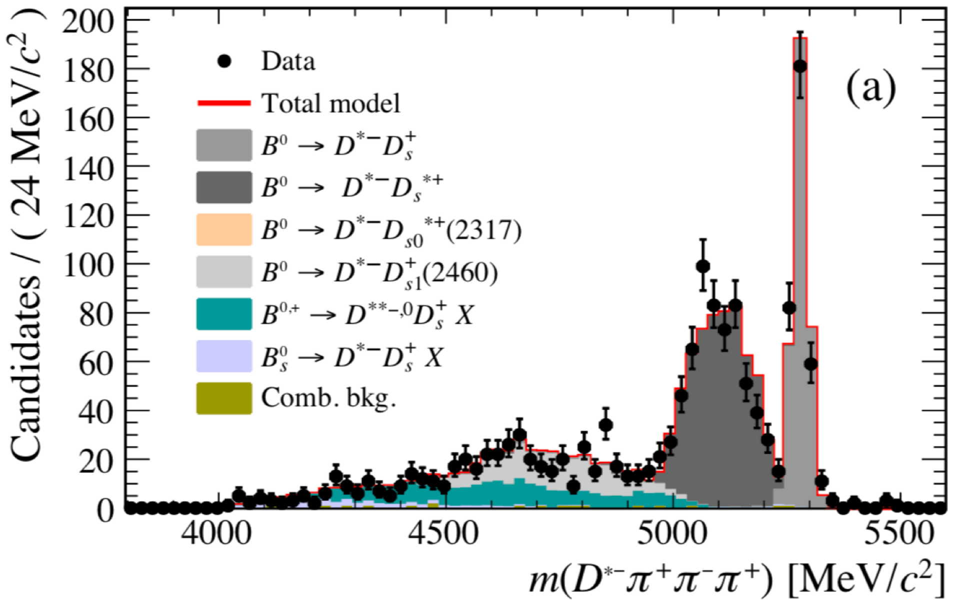
- Fit results are used to **describe the D_s model at high BDT** (signal sample).



The B⟶D*⁻DX control samples

- Different **control samples** are used to improve the description of background **B⟶D*⁻DX** components:
  - **$D_s^+ \to 3\pi$**
  - $D^0 \to K3\pi$ (kaon recovered by isolation tools)
  - $D^+ \to K^-\pi^+\pi^+$ (mis-ID kaon/pion)
- Monte Carlo corrected using data-driven approach.
- A **pure $B \to D^{*-}D_sX$** control sample obtained by selecting exclusive $D_s \to 3\pi$ decays.
- Allows to measure the different **$B \to D^{*-}D_s^+X$** contributions from a **fit to $m(D^{*-}D_s^+)$**.
- Uncertainties in the fit parameters **propagated** to final analysis.
- Similar strategy followed for **$B \to D^{*-}D^+X$** and **$B \to D^{*-}D^0X$** decays.



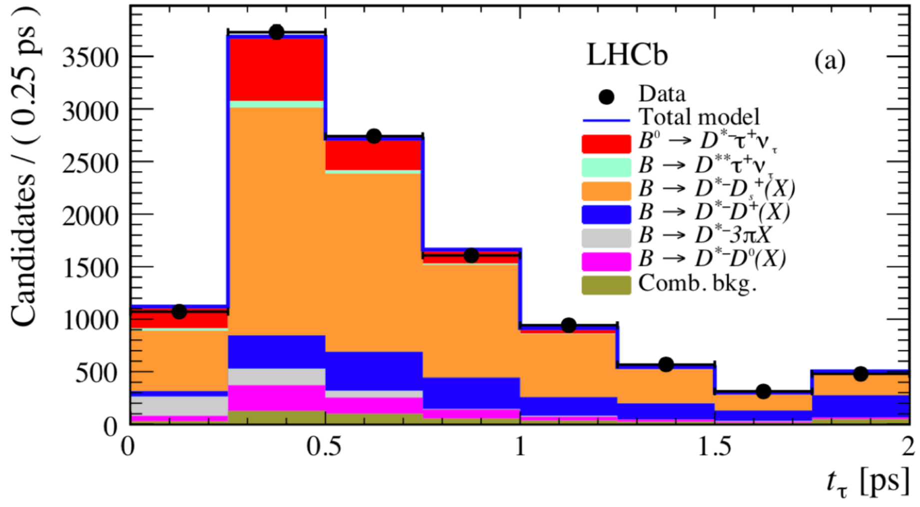


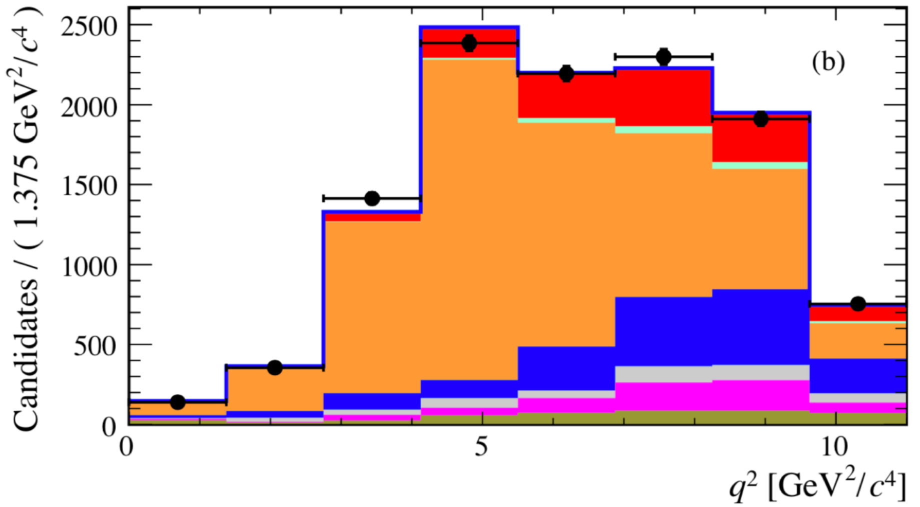
3D template fit

- 3D binned fit to data in (**q^2, τ decay time, BDT**) with (8,8,4) bins.

- Model:
  1. **Signal $B^0 \to D^{*-}\tau^+\nu_\tau$**: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ratio constrained according to known BF's). Free in the fit.
  2. **$B \to D^{**}\tau\nu_\tau$.** Fixed to the expected yield, 11% of signal (assign syst. uncertainty).
  3. Doubly-charmed B decays:
     a) **$B \to D^{*-}D_s^+X$.** Includes $B^0 \to D^{*-}D_s^+$, $B^0 \to D^{*-}D_s^{*+}$, $B^0 \to D^{*-}D_{s0}^{*+}$, $B^0 \to D^{*-}D_{s1}$, $B_s^0 \to D^{*-}D_s^+X$, $B \to D^{**}D_s^+X$. Shape constrained from control sample.
     b) **$B \to D^{*-}D^0X$.** Yield constrained from control sample.
     c) **$B \to D^{*-}D^+X$.** Free in the fit.
  4. **Prompt $B \to D^{*-}3\pi X$.** Yield constrained from control sample.
  5. **Comb. background.** Yield constrained from control sample.

⇒ $BR(B^0 \to D^{*-}\tau\nu) = (1.42 \pm 0.094(stat) \pm 0.129(syst) \pm 0.054(ext))\%$
⇒ $R(D^*) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(ext)$

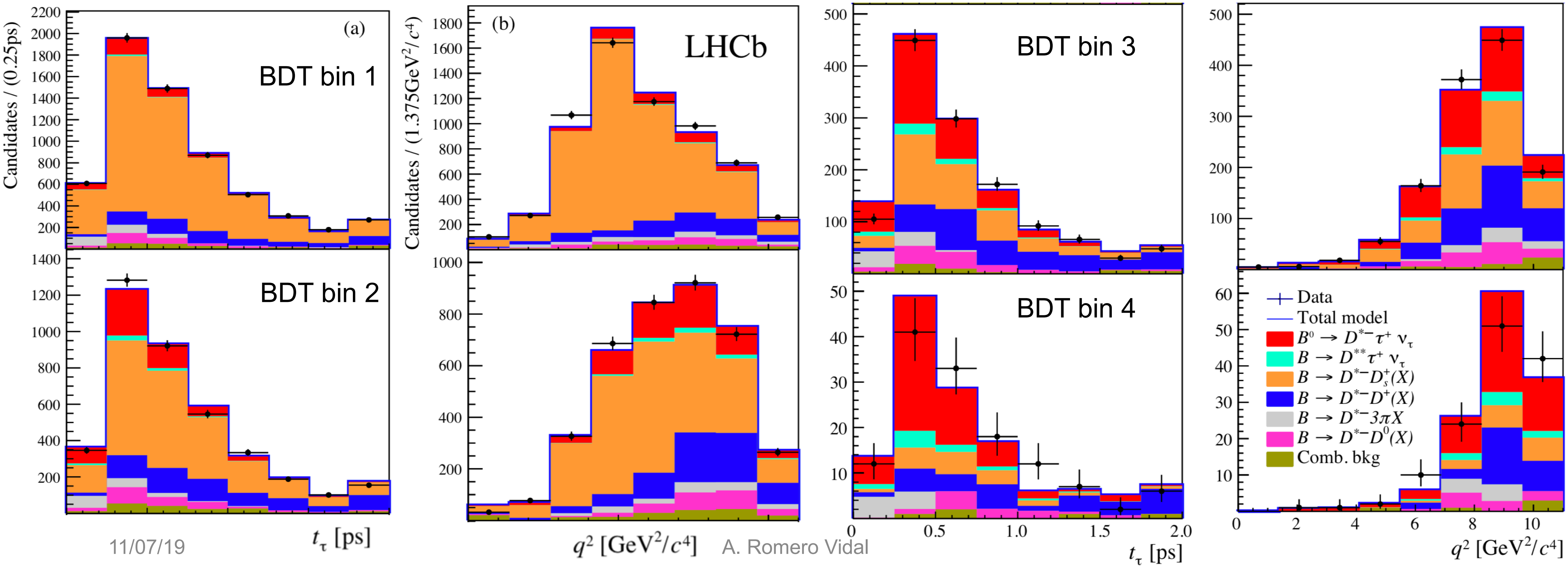




- **1σ** agreement with the SM ($R(D^*)_{SM} \approx 0.26$).

Fit projections in BDT bins

- Quality of the fit good in all bins of BDT.
  - Plots ordered from lowest BDT (bin 1) to highest BDT (bin 4)
  - High signal purity at high BDT.



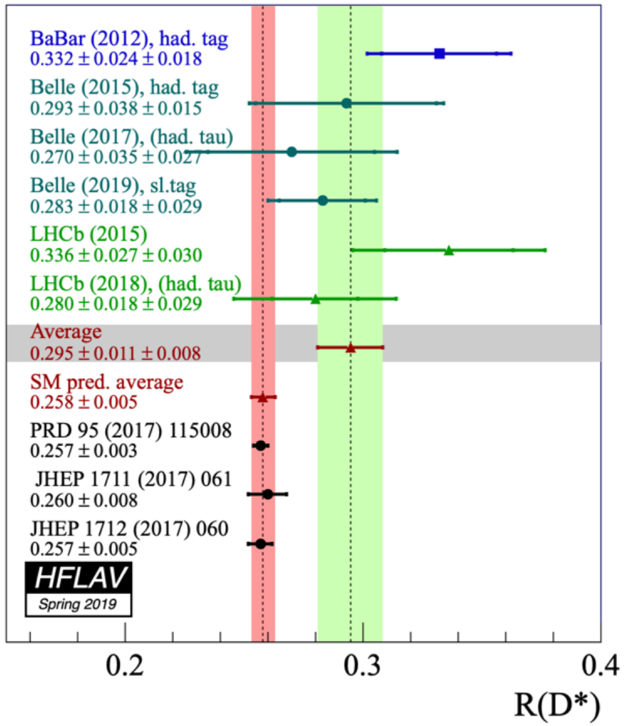
Systematic uncertainties

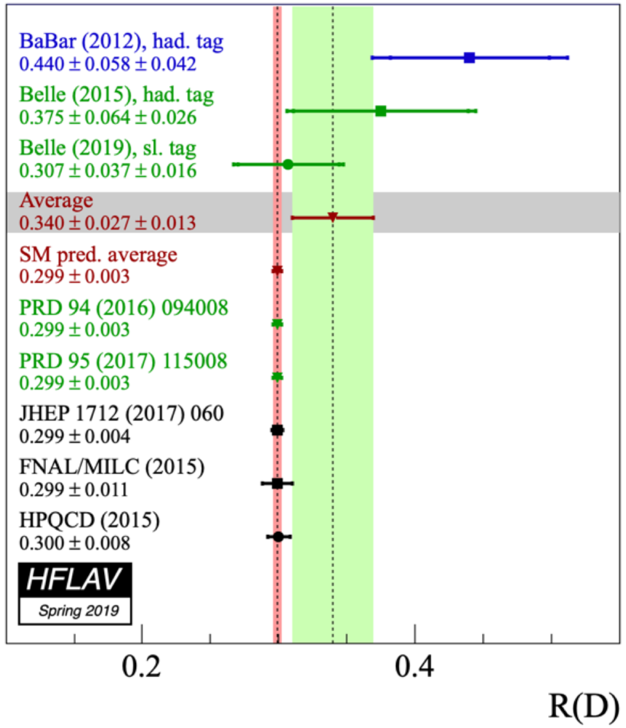
Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

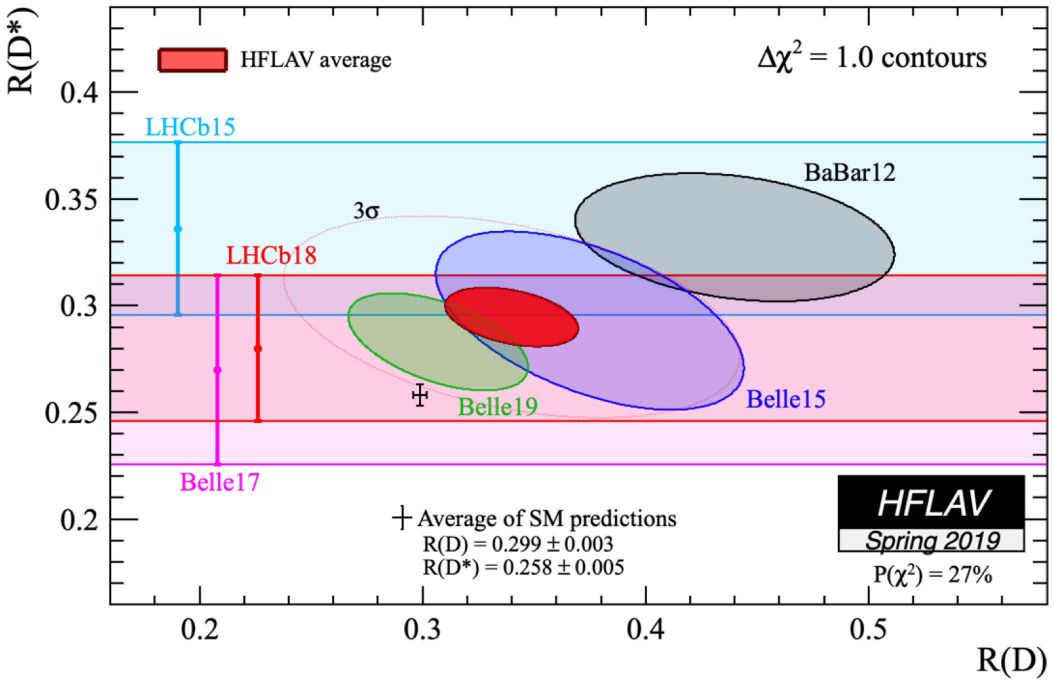
These errors will be reduced with more data.

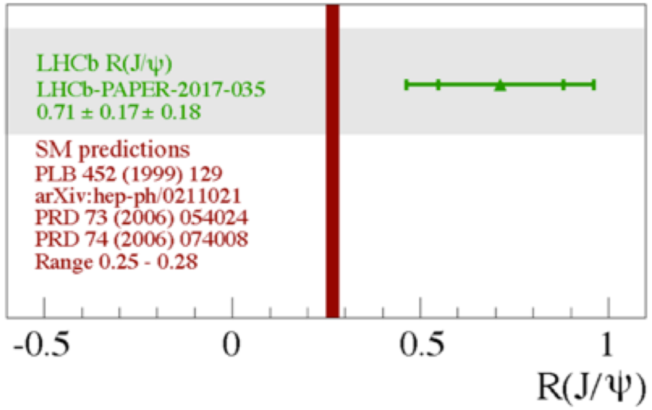
New external measurements can help to reduce this uncertainty!!!

Summary on $R(X_c)$





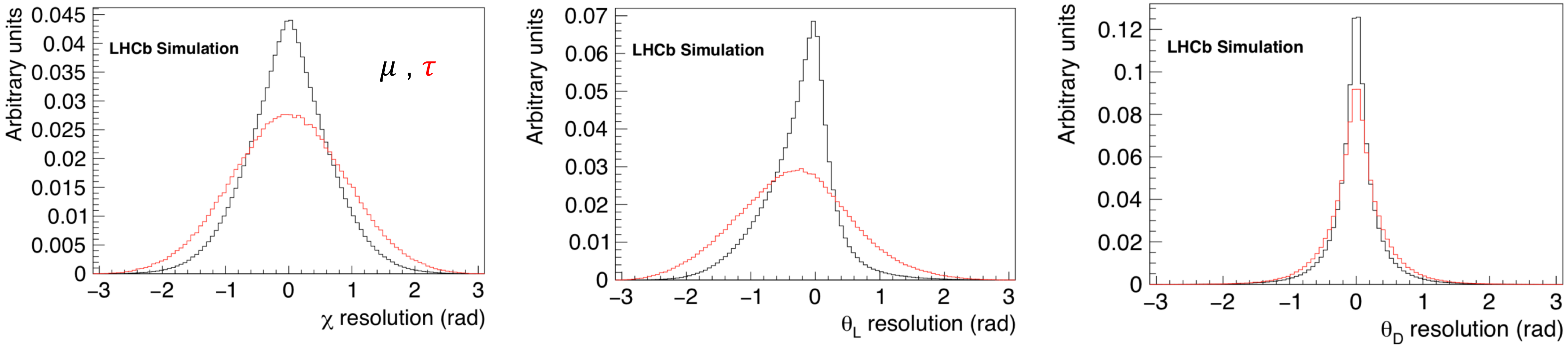




- R(D)/R(D*) combination BaBar/Belle/LHCb at 3.1σ from the SM.

Future: Angular analyses

Resolutions using leptonic tau reconstruction:

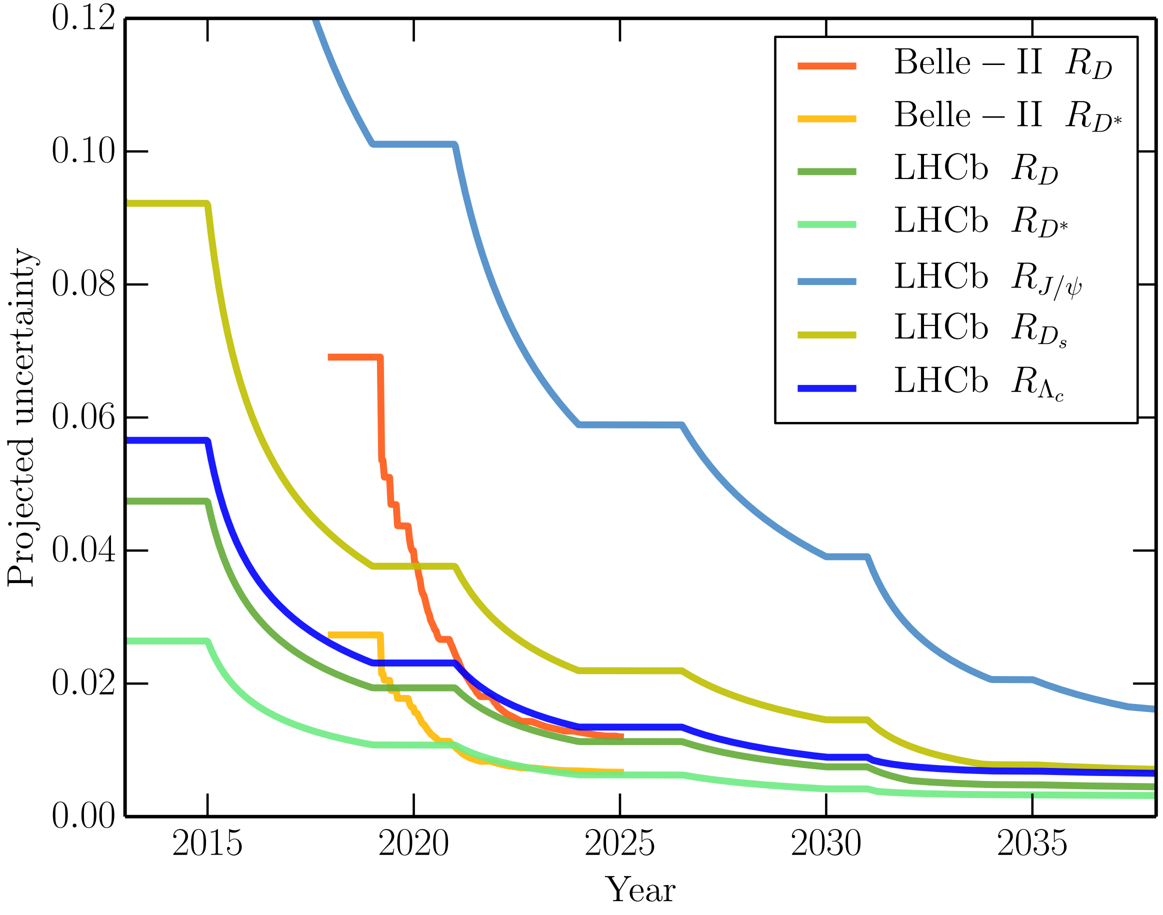


- A future step is to look at the **angular distributions** in $B^0 \to D^{*-}\tau^+\nu_\tau$, very sensitive to NP contributions.
- Resolution in the D* **polarisation** angle good enough to measure D* polarisation.
- Resolution in **χ and θ_L not so good**, but some sensitivity is expected. This is compensated by the huge amount of statistics (to be) collected by LHCb.
- Prospects on the precision of angular analyses still to be studied.

LHCb prospects on $R(X_c)$

- LHCb can perform tests of LFU not accessible at Belle II:
  - **$R(\Lambda_c^{(*)})$, $R(J/\psi)$, $R(D_s^{(*)})$.**
- Precision in $R(X_c)$ about 2-3% at the end of the Upgrade II.
- Sensitivity to angular observables need to be studied.

- Production fractions and efficiencies used to extrapolate the uncertainties.



[J.Phys. G46 (2019) no.2, 023001]

Conclusions

- Intriguing **anomalies** found in measurements of B-hadron decays:
  - loop-level **$b \longrightarrow s\ell^+\ell^-$** transitions.
  - tree-level **$b \longrightarrow c\ell^+\nu_\ell$** transitions.
- **Lepton Flavour Universality** tests are theoretically clean probes for New Physics.
- Precision in measurements still needs to improve to provide a definite picture.
- Upcoming measurements using **Run 2** full statistics will help to resolve the current situation.
- Ongoing and future experiments **upgrades** and the start-up of **Belle II** open the door to many improvements in precision, so interesting times are ahead.

BACKUP

Future: R(D) vs R(D*) with hadronic tau decays

- Hadronic R(D*) measurement performed using $B^0 \to D^{*-} 3\pi$ as normalisation mode.

- $B^0 \to D^{*-} 3\pi$ branching fraction measured with ~4% precision (PDG).

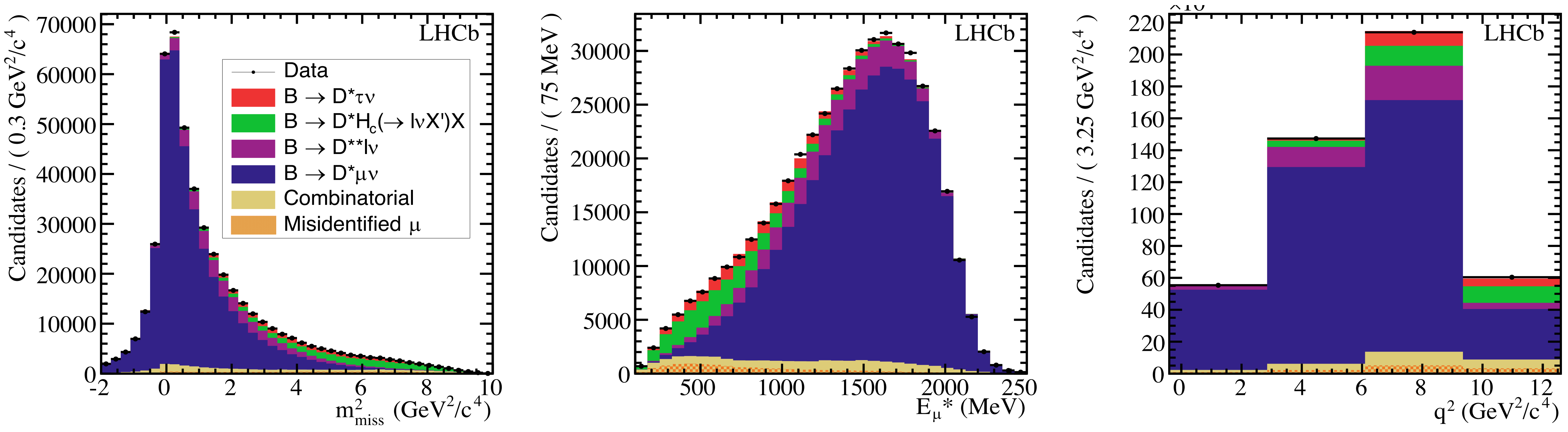
- For R(D) measurement ($B^- \to D^0 \tau^+ \nu_\tau$), an alternative normalisation mode needed:

  - **$B^- \to D^0 3\pi$** poorly measured (**37%**)
  - **$B^- \to D^0 D_s^+$** measured with **10%** precision. In addition, $D_s^+ \to 3\pi$ measured with **5%** precision.
  - **Need improvements in these branching fractions: Belle II, BES III**.

- In the **LHCb Upgrade-I**, the use of **software trigger** will allow to measure R(D$^{(*)}$) combining muonic and hadronic tau decays.

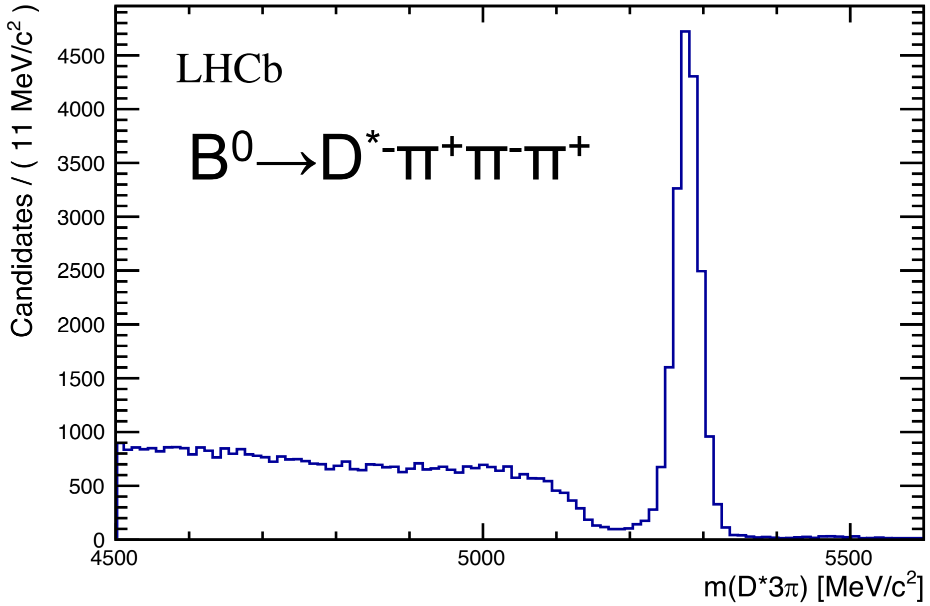
Decay	Branching fraction (PDG)	Precision
$B^0 \to D^- 3\pi$	$(6.0 \pm 0.7) \times 10^{-3}$	11.7%
$B^0 \to D^- D_s^+$	$(7.2 \pm 0.8) \times 10^{-3}$	11.1%
$B^0 \to D^{*-} 3\pi$	$(7.21 \pm 0.29) \times 10^{-3}$	4.0%
$B^0 \to D^{*-} D_s^+$	$(8.0 \pm 1.1) \times 10^{-3}$	13.8%
$B^- \to D^0 3\pi$	$(5.6 \pm 2.1) \times 10^{-3}$	37.5%
$B^- \to D^0 D_s^+$	$(9.0 \pm 0.9) \times 10^{-3}$	10.0%
$B^- \to D^{*0} 3\pi$	$(1.03 \pm 0.12) \times 10^{-3}$	11.6%
$B^- \to D^{*0} D_s^+$	$(8.2 \pm 1.7) \times 10^{-3}$	20.7%
$D_s^+ \to 3\pi$	$(1.09 \pm 0.05) \times 10^{-2}$	4.6%

R(D*) muonic: fit projection



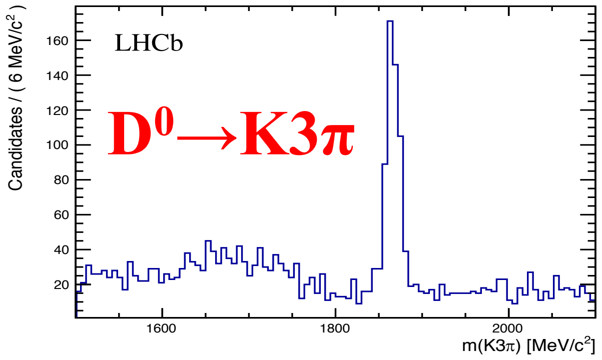
The normalisation mode

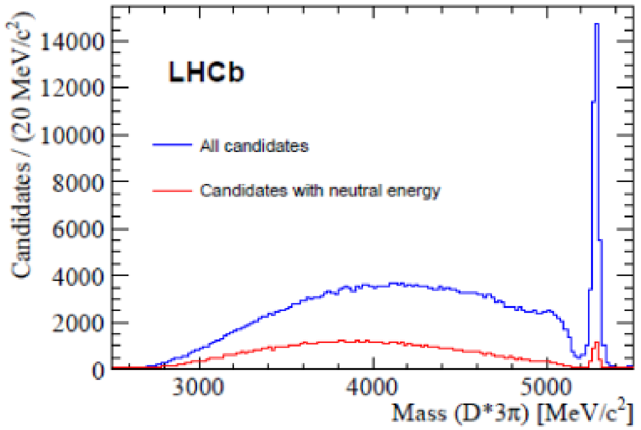
- Normalization channel as similar as possible to the signal → $B^0 \to D^{*-}\pi^+\pi^-\pi^+$.
- This cancels production yield, BR uncertainties and systematics linked to trigger, PID and selection.
- In PDG 2014, BR($B^0 \to D^{*-}\pi^+\pi^-\pi^+$) known with 11% precision.
- New BaBar measurement 4.3% (stat+syst) precision. [Phys. Rev. D94 (2016) 091101]
- In this analysis ~17000 events (1% precision)

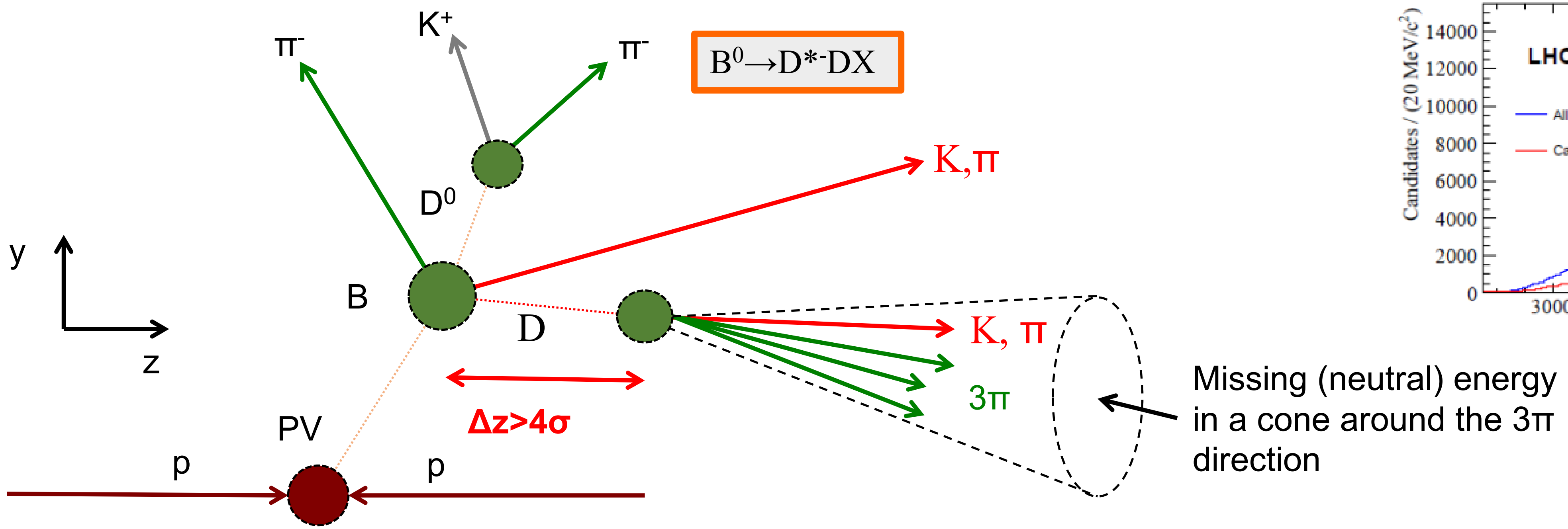


Isolation

- Signal candidates are required to be well isolated.
- Events with extra particles pointing to the B and/or tau vertices are vetoed.

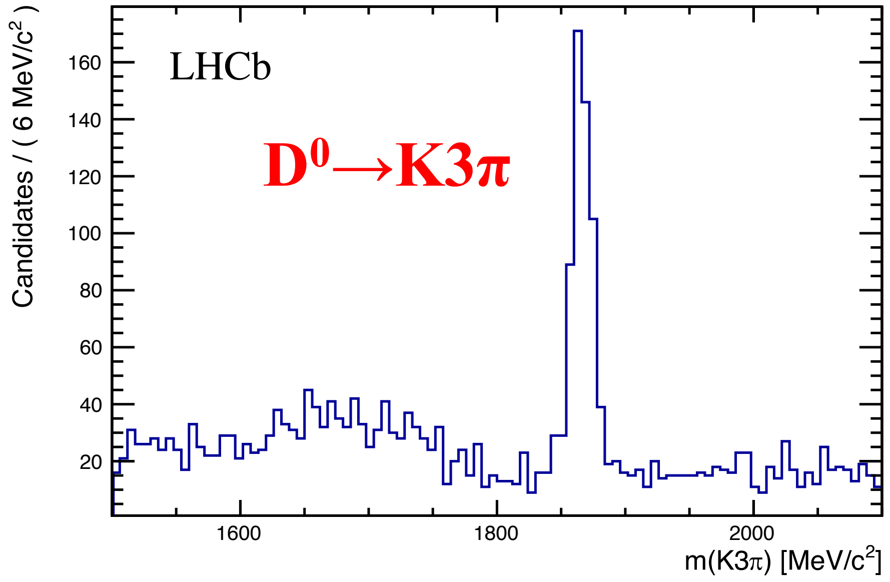


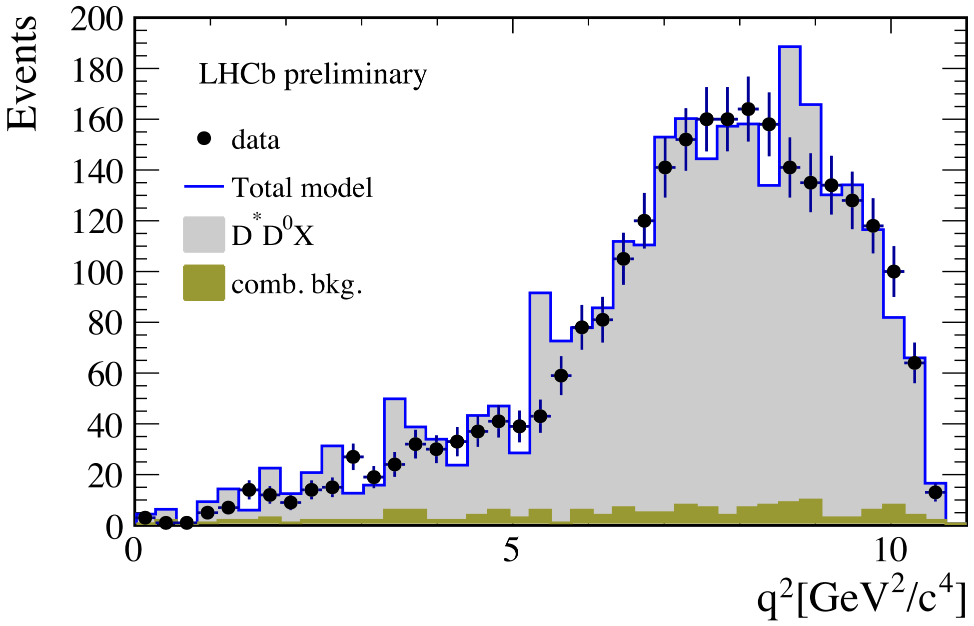




D^0 control sample

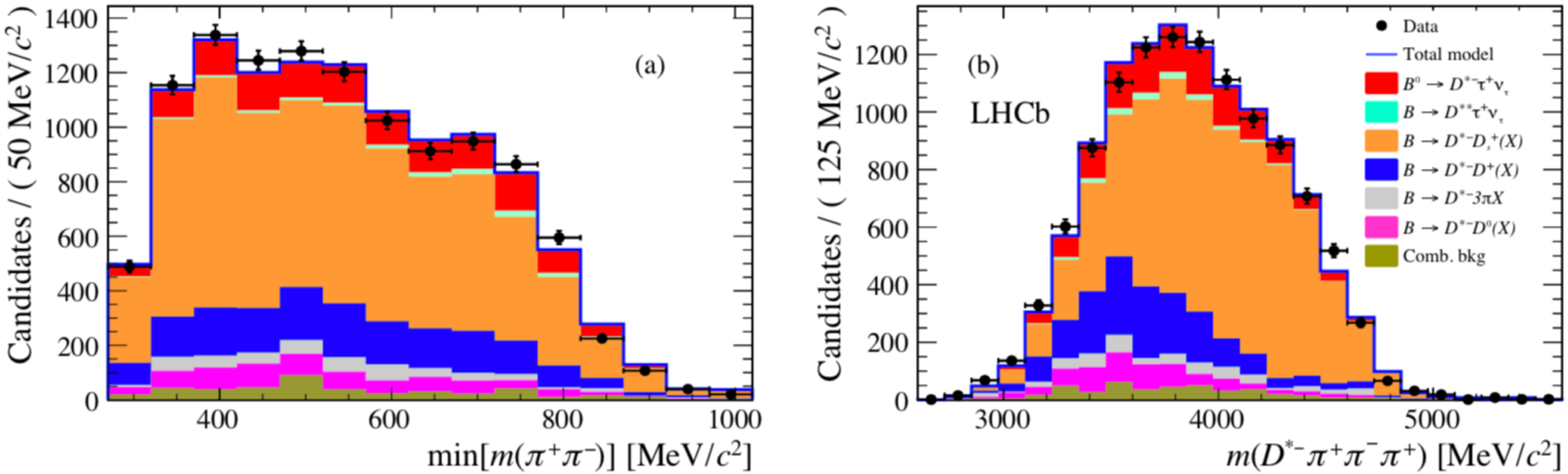
- $X_b \to D^* D^0 X$ decays can be isolated by selecting exclusive $D^0 \to K3\pi$ decays (kaon recovered using isolation tools).
- A correction to the q^2 distributions is applied to the Monte Carlo to match data.





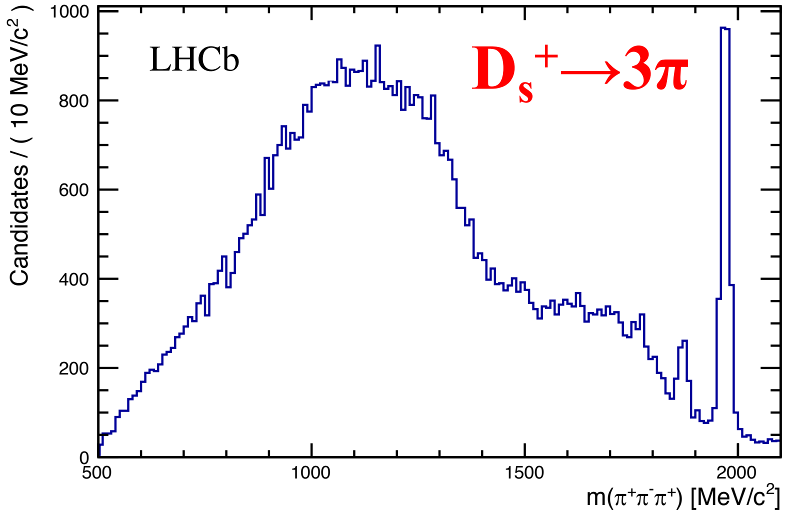
Fit projections on M(D*3π) and min[M(2π)]

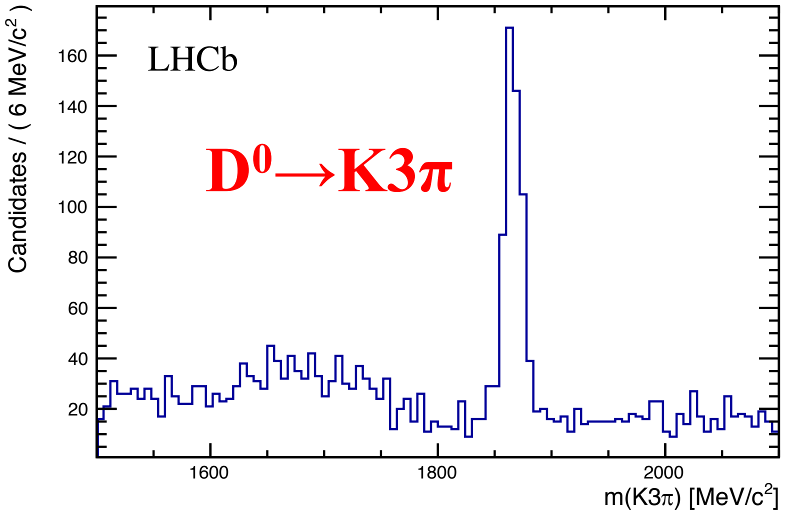
- Important variables in the BDT.

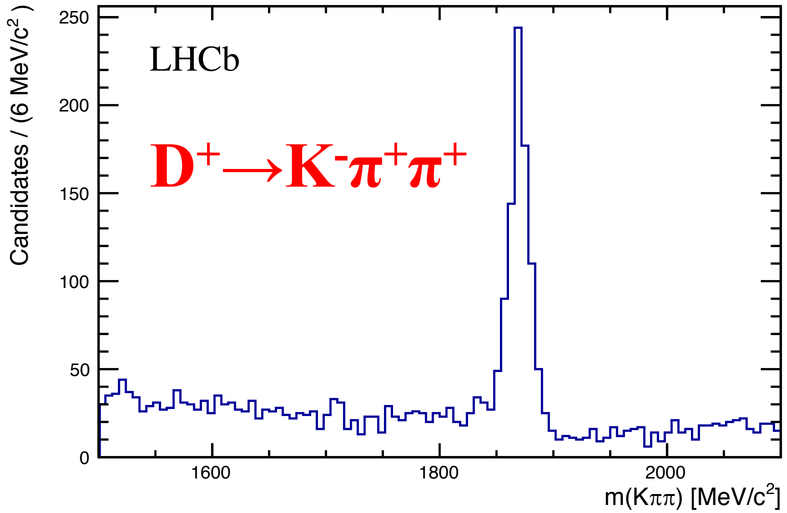


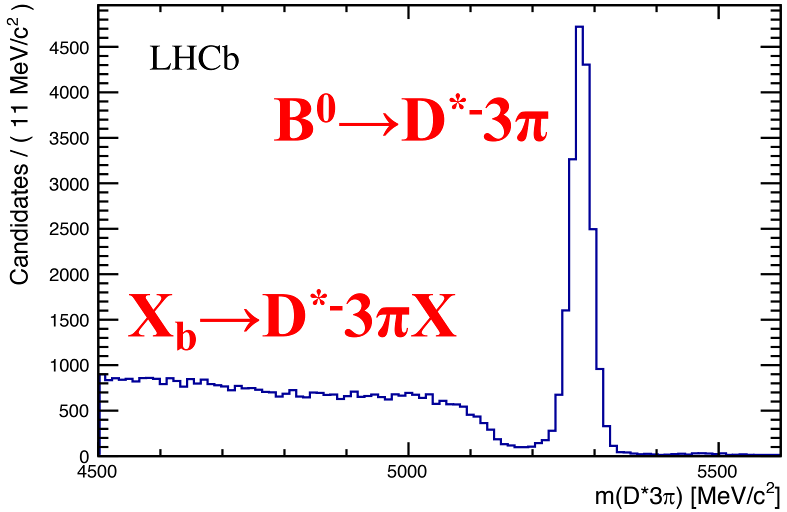
- Excellent agreement with data.

Control samples





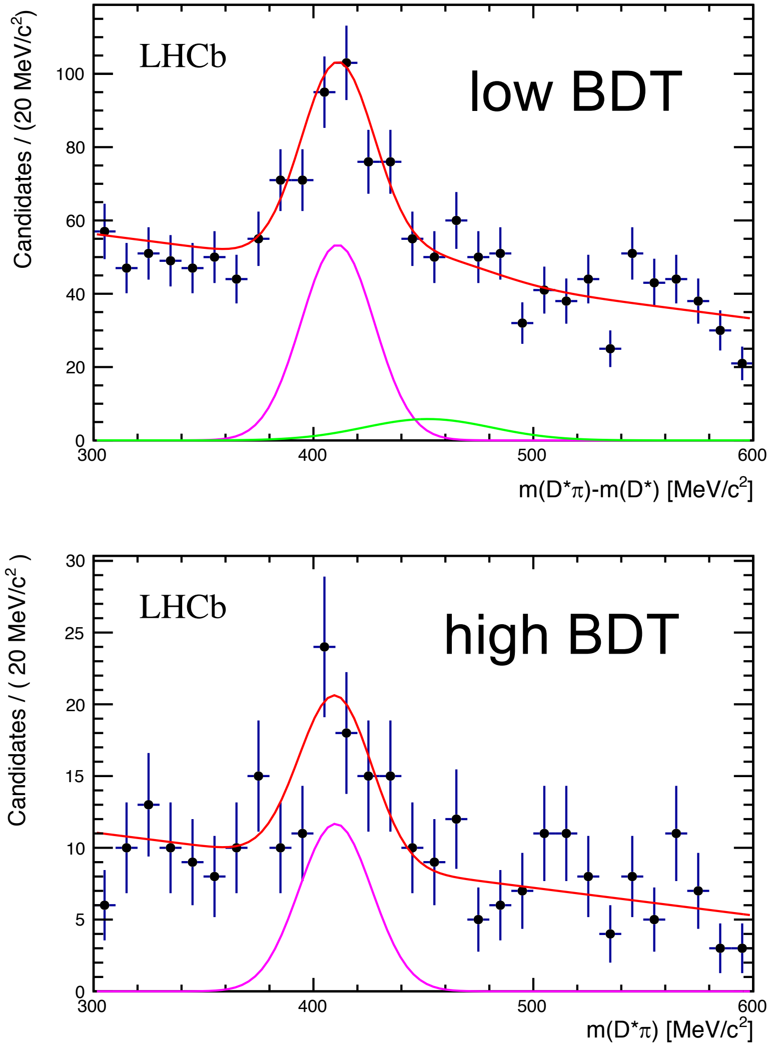




- Different control samples are used to study background components:
  - $D_s^+ \to 3\pi$
  - $D^0 \to K3\pi$ (kaon recovered by isolation tools)
  - $D^+ \to K^-\pi^+\pi^+$ (mis-ID kaon/pion)
- Monte Carlo corrected using data-driven approach.

Additional cross-checks: B→D**τν

- $B^0 \to D^{**}\tau\nu$ and $B^+ \to D^{**0}\tau\nu$ constitute potential feed-down to the signal.
- $D^{**}(2420)^0$ is reconstructed using its decay to $D^{*+}\pi^-$ as a cross-check.
- The observation of the $D^{**}(2420)^0$ peak allows to compute the $D^{**}3\pi$ BDT distribution and to deduce a $D^{**}\tau\nu$ upper limit. This upper limit is consistent with the theoretical prediction.
- Subtraction in the signal of 0.11 ± 0.04 due to $D^{**}\tau\nu$ events leading to a systematic uncertainty of 2.3%.



Belle II prospects on R(D) and R(D*)

[arXiv:1808.10567]

- Improve the precision on R(D) and R(D*) to the 2-3% level.
- Better control on backgrounds like $B \longrightarrow D^{**}\ell\nu$, very important for these measurements.
- Perform measurements of τ and D* polarisation.

Belle II projection:

	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

(First uncertainty statistical and second systematic