

# Searching for $B \rightarrow \tau^+ \tau^-$ Decays

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## LHC Mission Objectives

- ✓ Search for the Higgs boson
- ✗ Search for evidence of Beyond the Standard Model Physics

## Two Complementary Strategies

### Direct Searches (Energy Frontier):

Search for new on-shell resonances

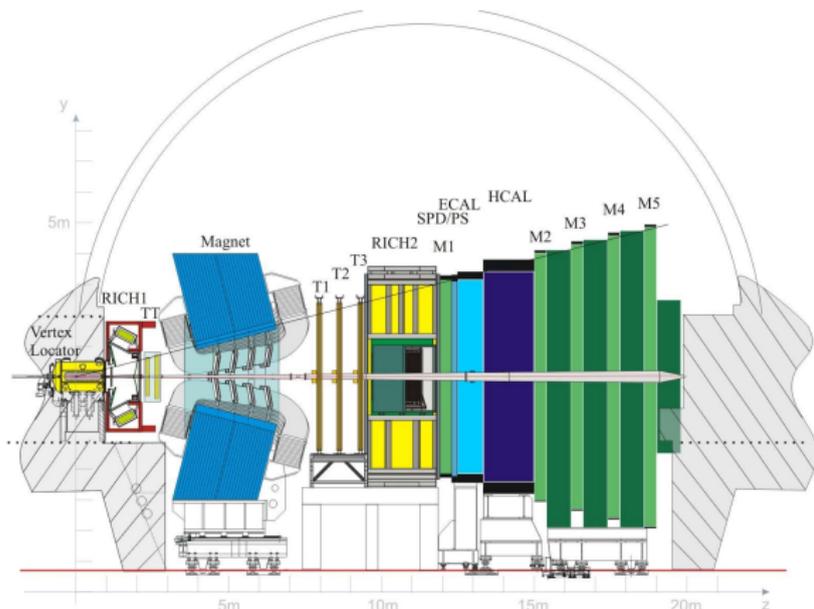
- ▶ *Bump*-hunting
  - ▶ + Missing energy
  - ▶ +  $x$  leptons +  $y$  jets + ...

### Indirect Searches (Precision Frontier):

Search for anomalies in SM quantities

- ▶ Higgs Sector
- ▶ (Heavy) Flavour Sector
  - ▶ CP Violation & CKM Matrix
  - ▶ **Rare Decays**

# The LHCb Detector



Forward arm spectrometer to study b- and c-hadron decays

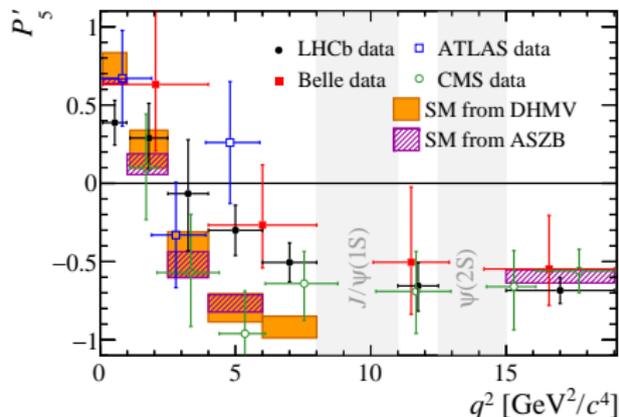
- ▶ Pseudo-rapidity coverage:  $2 < \eta < 5$

- ▶ Good impact parameter resolution to identify secondary vertices:  
 $(15 + 29/p_T) \mu\text{m}$
- ▶ Invariant mass resolution:  
 $8 \text{ MeV}/c^2$  ( $B \rightarrow J/\psi X$ )  
 $22 \text{ MeV}/c^2$  ( $B \rightarrow hh$ )
- ▶ Excellent particle identification:  
95 %  $K$  ID efficiency  
(5 %  $\pi \rightarrow K$  mis-ID)
- ▶ Versatile & efficient trigger for b- and c-hadrons and forward EW signals

# Puzzling Tensions in $b \rightarrow sl^+l^-$ Transitions

$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

- ▶ Angular Observable  $P'_5$

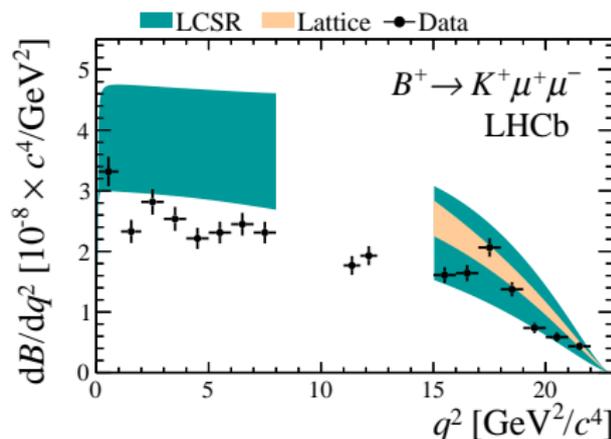


LHCb, JHEP02 (2016) 104, arxiv:1512.04442

- ▶ Tension:  $3.4\sigma$
- ▶ Discussion on  $c\bar{c}$ -contributions

$$B^+ \rightarrow K^+ \mu^+ \mu^-$$

- ▶ Differential branching fractions



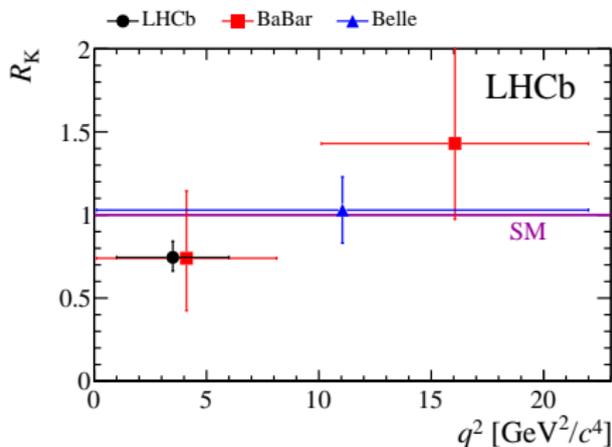
LHCb, JHEP06 (2014) 133, arxiv:1403.8044

- ▶ Similar effects in  $B^0 \rightarrow K^0 \mu^+ \mu^-$  and  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$

# Puzzling Tensions in $b \rightarrow sl^+l^-$ Transitions

$$B^+ \rightarrow K^+ l^+ l^-$$

$$\blacktriangleright R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \stackrel{\text{SM}}{\rightarrow} 1$$



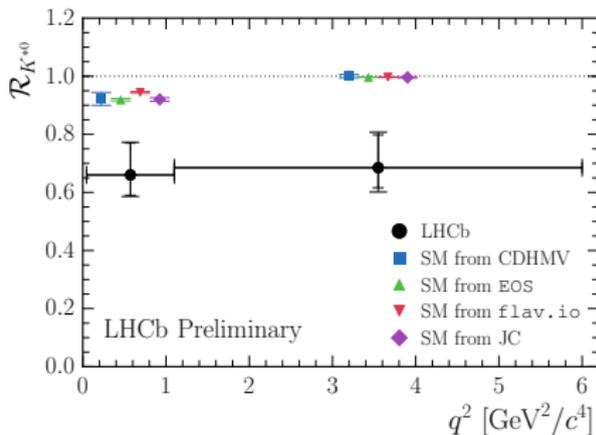
LHCb, PRL 113 (2014) 151601, arxiv:1406.6482

- ▶ Tension:  $2.6\sigma$
- ▶ Test of Lepton Universality

$$B^0 \rightarrow K^{*0} l^+ l^-$$

**NEW!**

$$\blacktriangleright R_{K^*} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$$



LHCb, LHCb-PAPER-2017-013

- ▶ Tensions:  $2.2\sigma$  and  $2.5\sigma$
- ▶ Test of Lepton Universality

- ▶ Model-independent approach: **Effective Hamiltonian**

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{j=u,c} \underbrace{V_{jd}^* V_{jb}}_{\text{CKM Elements}} \left[ \sum_k \underbrace{C_k}_{\text{Wilson Coefficient}} \underbrace{\mathcal{O}_k}_{\text{Operator}} + C'_k \mathcal{O}'_k \right] \quad (1)$$

G. Buchalla *et al.*, RMP 68 (1996) 1125, arxiv:9512380[hep-ph]

## Ingredients:

- ▶ **Coupling constants & CKM elements**
- ▶ **Wilson coefficients** contain all **perturbative short-distance effects**
  - ⇒ Can be calculated within perturbation theory
  - ⇒ Are the free parameters when fitting to the data
- ▶ **Operators** contain all **non-perturbative long-distance effects**
  - ▶ Electromagnetic operator  $\mathcal{O}_7^\gamma$ , important for  $b \rightarrow s\gamma$  decays
  - ▶ Semileptonic ops  $\mathcal{O}_9$  (vector) and  $\mathcal{O}_{10}$  (axial-vector), important for  $b \rightarrow sll$  decays
  - ▶ Primed operators have mirrored (L  $\leftrightarrow$  R) chirality

# Hints for New Physics?

- ▶ Best fit model has Wilson coefficient

$$C_9^{\text{NP}} \approx -1 \quad (4 \text{ to } 5\sigma)$$

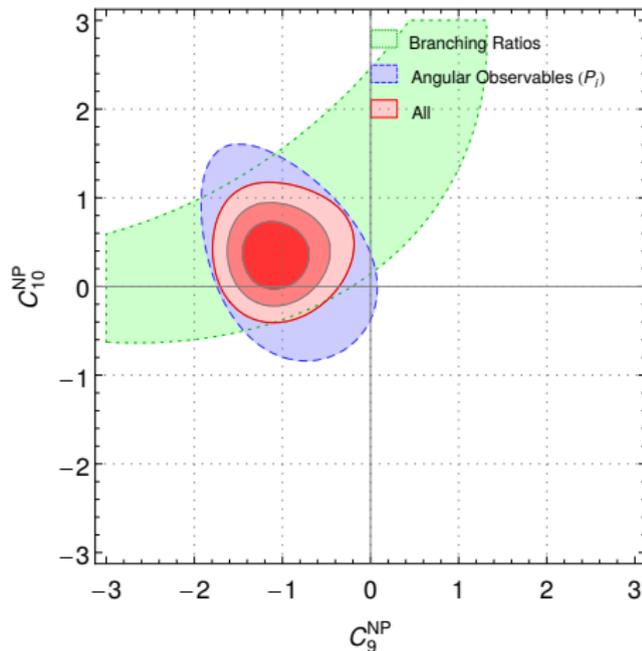
- ▶ Suggests **lepton universality violation**

- ▶ What can explain this?

- 1 Statistical fluctuations
- 2 Not-yet-understood SM effects
- 3 New Physics

- ▶ Way forward?

- ▶ Increase the statistics
- ▶ Additional observables
- ▶ **Additional decay channels**



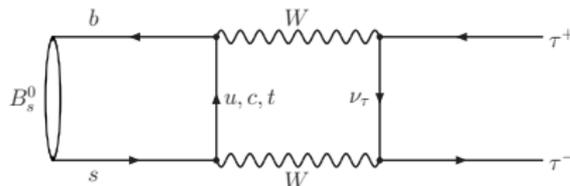
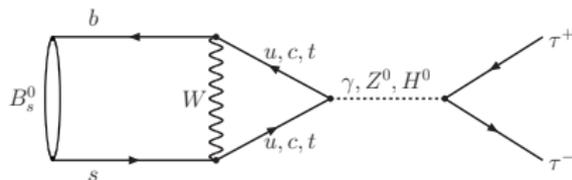
S.Descotes-Genon *et al.*, JHEP 06 (2016) 092  
arxiv:1510.04239

Search for  $B_s^0 \rightarrow \tau^+ \tau^-$  and  $B^0 \rightarrow \tau^+ \tau^-$

# Standard Model Decay



- ▶ Flavour Changing Neutral Current
- ▶ **Forbidden at Tree level**
- ⇒ Loop suppressed
- ▶ Sensitive to **new physics** contributions



- ▶ Purely leptonic final state makes it **theoretically very clean**
- ▶ Calculated up to NLO EW and NNLO QCD corrections

$$B(B_s^0 \rightarrow \tau^+ \tau^-) \stackrel{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7} \quad (2)$$

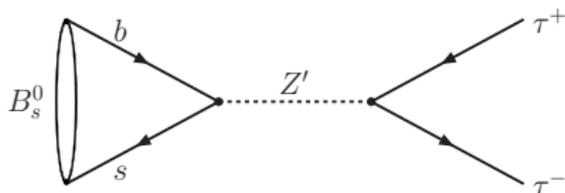
$$B(B^0 \rightarrow \tau^+ \tau^-) \stackrel{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8} \quad (3)$$

Bobeth *et al.*, PRL 112 (2014) 101801, arxiv:1311.0903

## New Physics Models

- ▶ New tree level processes ( $Z'$ ,  $W'$ , ...)
- ▶ Additional loop contributions (leptoquarks, 2HDM, ...)
- ▶ Branching fraction can be as large as a %

R. Alonso, [arxiv:1505.05164](https://arxiv.org/abs/1505.05164)



## Experimental Picture

- ▶ Previous best limit:

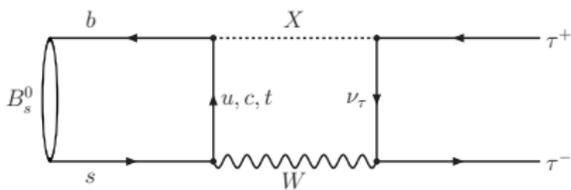
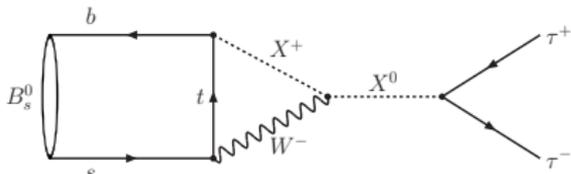
$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 4.1 \times 10^{-3} \quad @ 90\% \text{ C.L.}$$

BaBar, PRL 96 (2006) 241802, [arxiv:hep-ex/0511015](https://arxiv.org/abs/hep-ex/0511015)

- ▶ No direct limit on  $B_s^0 \rightarrow \tau^+ \tau^-$
- ▶ Indirect constraint  $\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 3\%$

C. Bobeth and U. Haisch, APP B44 (2013) 127

[arxiv:1109.1826](https://arxiv.org/abs/1109.1826)



# Reconstructing the $\tau$

## Available Options:

- ▶ Largest Decay Channels

$$\mathcal{B}(\tau^- \rightarrow \pi^- \pi^0 \nu_\tau) = 25.49 \pm 0.09 \%$$

$$\mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau) = 17.82 \pm 0.04 \%$$

$$\mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) = 17.39 \pm 0.04 \%$$

$$\mathcal{B}(\tau^- \rightarrow \pi^- \nu_\tau) = 10.82 \pm 0.05 \%$$

$$\rightarrow \mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau) = 9.31 \pm 0.05 \% \leftarrow$$

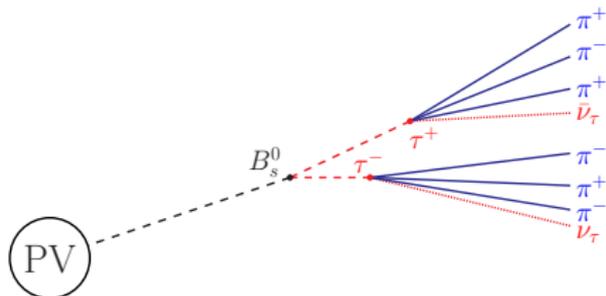
$$\mathcal{B}(\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau) = 9.26 \pm 0.10 \%$$

## LHCb's Choices

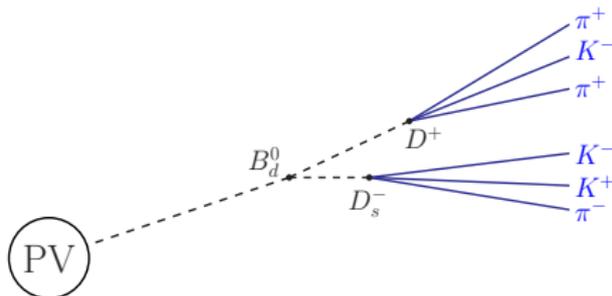
- ▶ Challenging to reconstruct electrons and  $\pi^0$  (and limited efficiency)
  - ▶ Abundant pions
  - ▶ Only covers  $2 < \eta < 5 \Rightarrow$  always missing energy
- $\Rightarrow$  Reduced signal efficiency

# Experimental Signature

$$\underline{B_s^0 \rightarrow \tau^+(\rightarrow 3\pi)\tau^-(\rightarrow 3\pi)}$$



$$\underline{B^0 \rightarrow D^+(\rightarrow \pi^+ K^- \pi^+) D_s^-(\rightarrow K^- K^+ \pi^-)}$$



## Challenges

- 1 2 missing neutrinos
    - ▶ No narrow (mass) peak to fit, no mass sidebands to exploit
    - ▶ Cannot differentiate  $B_s^0$  from  $B^0$
  - 2 6 pions
    - ▶ Low efficiency
    - ▶ Large combinatorial background
- ⇒ **Need special tools!**



## 1 Neutral isolation variables

- ▶ Quantify neutral activity ( $\pi^0$ ,  $\gamma$ , ...) in a cone around the  $B$  candidate

## 2 Track isolation variables

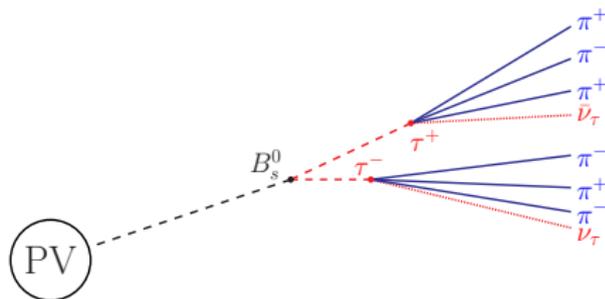
- ▶ Aims to identify tracks that belong to the same  $b$ -hadron decay as the 6 pions
- ▶ Based on a BDT trained on simulated signal and  $b$ -hadron background

## 3 Vertex isolation variables

- ▶ Aims to identify tracks that make a good quality vertex with selected pions or  $\tau$
- ▶ Based on a BDT trained on simulated signal and  $b$ -hadron background

## Constraints

- ▶  $B$  origin vertex ( $pp$  collision)
- ▶  $\tau$  decay vertices  
(advantage of  $3\pi$  decay mode)
- ▶ Momentum conservation at  $B$  and  $\tau$  decay vertices
- ▶ Masses for the  $B$ ,  $\tau$  and  $\nu_\tau$



## Strategy

- ▶ Combine constraints in Lorentz invariant way  $\Rightarrow$  Leads to a **fourth order polynomial**
- ▶ Roots provide analytic **solutions for the  $\tau$  momenta**
- ▶ 1 unknown degree of freedom remaining in calculation  
 $\rightarrow$  asymmetry ( $\theta$ ) of the triangle  $PV \leftrightarrow SV(\tau^+) \leftrightarrow SV(\tau^-)$

## Limitations

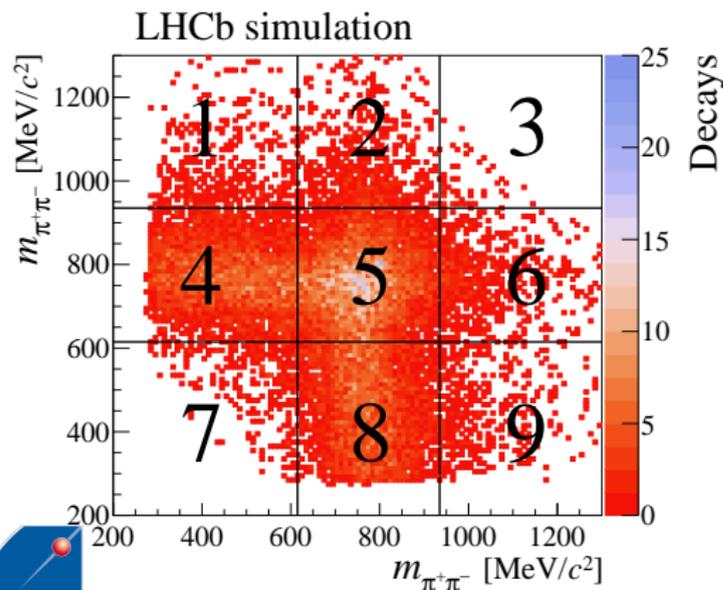
- ▶ Approximations required for  $\theta$
- ▶ Experimental resolution
- $\Rightarrow$  Majority of cases **no purely real solution** can be found: limits applicability
- ▶ Use **intermediate results** to discriminate signal and background

## Intermediate Resonances

- ▶ Predominantly proceeds through

$$\tau^- \rightarrow a_1(1260)^- \nu_\tau \rightarrow \rho(770)^0 \pi^- \nu_\tau .$$

- ▶ Exploit this in analysis



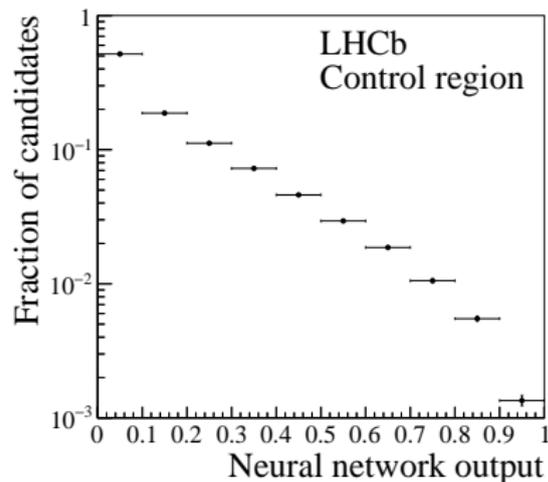
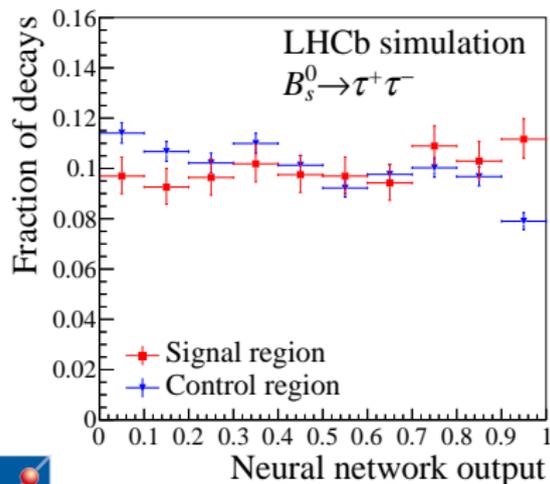
### Subsamples:

- ▶ Signal Region [SR]:  
( $\tau^+ \in 5$ ) & ( $\tau^- \in 5$ )
- ▶ Signal-Depleted Region:  
( $\tau^+ \in 1, 3, 7, 9$ ) || ( $\tau^- \in 1, 3, 7, 9$ )
- ▶ Control Region [CR]:  
( $\tau^\pm \in 4, 5, 8$ ) & ( $\tau^\mp \in 4, 8$ )

### Selection:

- ▶ Cut-based loose selection
- ▶ Two-stage neural network
- ▶ Optimise size of SR

- ▶ Perform a 1-dimensional histogram fit to the **output of a neural network**
- ▶ Output is remapped such that **signal is flat**
- ▶ The Signal templates are taken from simulation
- ▶ The Background template is taken from **data** control region



Events:

Signal: 16%  $B_s^0 \rightarrow \tau^+ \tau^-$  Simulation versus 7% data

Sig.-Depleted: 13%  $B_s^0 \rightarrow \tau^+ \tau^-$  Simulation versus 37% data

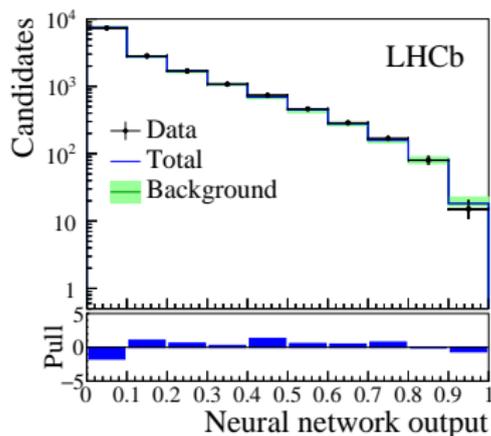
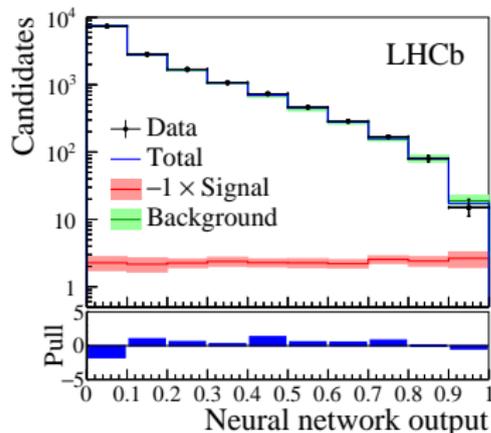
Control: 58%  $B_s^0 \rightarrow \tau^+ \tau^-$  Simulation versus 47% data

- ▶ ...so the data control region might also contain signal.

Model:

$$\mathcal{N}_{\text{data}}^{\text{SR}} = s \times \underbrace{\hat{\mathcal{N}}_{\text{sim}}^{\text{SR}}}_{\text{Sig PDF}} + f_b \times \underbrace{\left( \mathcal{N}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon_{\text{CR}}}{\epsilon_{\text{SR}}} \times \hat{\mathcal{N}}_{\text{sim}}^{\text{CR}} \right)}_{\text{Bkg PDF}}$$

- ▶  $s$ : signal yield (free parameter)
- ▶  $f_b$ : scaling factor for background template (free parameter)
- ▶  $\epsilon_i$ : efficiencies, taken from simulation
- ▶  $\hat{\cdot}$ : indicates normalised distributions

Background-Only ModelNominal Fit Model

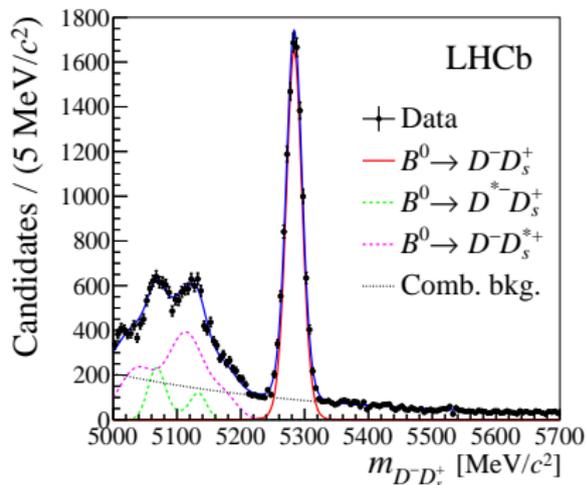
$$s = N_{\tau^+\tau^-}^{\text{obs}} = -23_{-53}^{+63} \text{ (stat)}_{-40}^{+41} \text{ (syst)}$$

- ▶ Compatible with the background-only hypothesis
- ▶ In good agreement with expectations from pseudo-experiments

$$N_{\tau^+\tau^-}^{\text{toy, SM}} = 0_{-40}^{+62} \text{ (stat)}_{-42}^{+40} \text{ (syst)}$$

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) = \alpha^s \times N_{\tau^+ \tau^-}^{\text{obs}}$$

- ▶ Assume all signal comes from  $B_s^0 \rightarrow \tau^+ \tau^-$   
i.e. ignore  $B^0 \rightarrow \tau^+ \tau^-$  completely
- ▶ Determine  $\alpha^s$  using  $B^0 \rightarrow D^- D_s^+$  normalisation mode



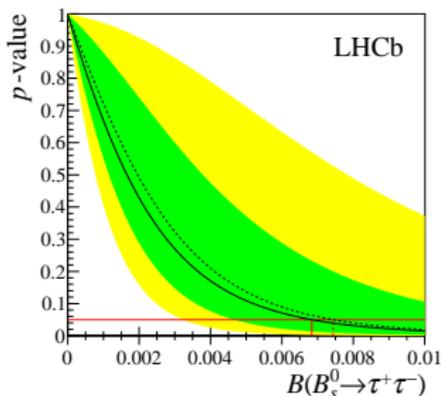
$$\alpha^s = \frac{\epsilon^{D^- D_s^+} \times \mathcal{B}(B^0 \rightarrow D^- D_s^+) \times \mathcal{B}(D^+ \rightarrow \pi^+ K^- \pi^+) \times \mathcal{B}(D_s^+ \rightarrow K^+ K^- \pi^+)}{N_{D^- D_s^+}^{\text{obs}} \times \epsilon^{\tau^+ \tau^-} \times [\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau)]^2} \times \frac{f_d}{f_s}$$

- ▶ Fit to data, Efficiencies from simulation, External Input

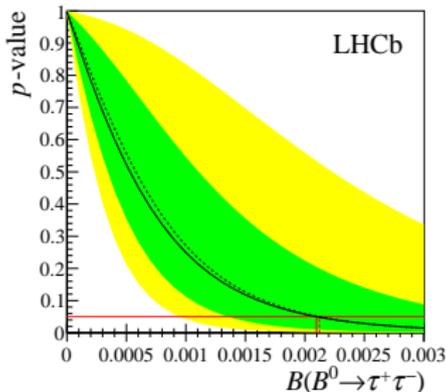
$$\alpha^s = (4.07 \pm 0.70) \times 10^{-5} \quad \rightarrow \quad N_{\tau^+ \tau^-}^{\text{SM}} = 0.019$$

$$\alpha^d = (1.16 \pm 0.19) \times 10^{-5} \quad \rightarrow \quad N_{\tau^+ \tau^-}^{\text{SM}} = 0.002$$

$$\underline{B_s^0 \rightarrow \tau^+ \tau^-}$$



$$\underline{B^0 \rightarrow \tau^+ \tau^-}$$



## Branching Fraction Limit (CL<sub>s</sub> Method)

- ▶ First limit on  $B_s^0 \rightarrow \tau^+ \tau^-$

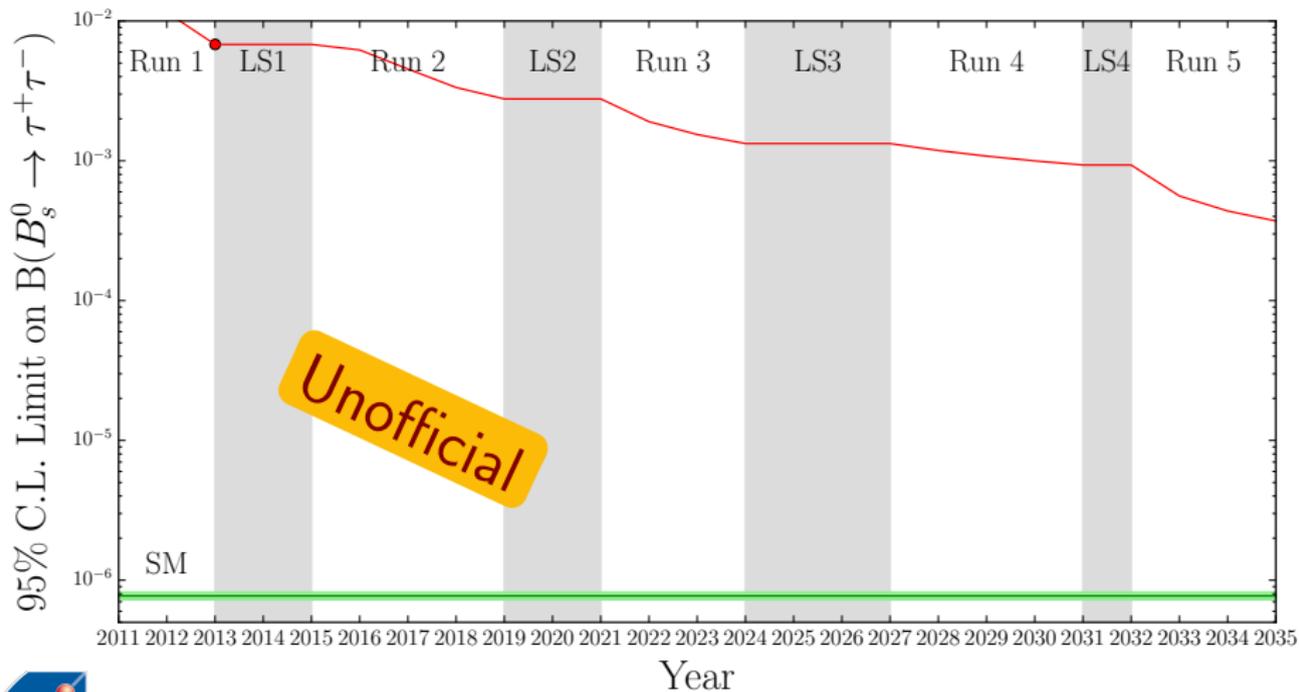
$$B(B_s^0 \rightarrow \tau^+ \tau^-) < 5.2 (6.8) \times 10^{-3} \quad @ 90 (95) \% \text{ C.L.}$$

- ▶ Improved limit for  $B^0 \rightarrow \tau^+ \tau^-$

$$B(B^0 \rightarrow \tau^+ \tau^-) < 1.6 (2.1) \times 10^{-3} \quad @ 90 (95) \% \text{ C.L.}$$

# Future Improvements for $B_s^0 \rightarrow \tau^+ \tau^-$ ?

- ▶ Only scaling with luminosity



- ▶ Tensions in  $b \rightarrow sl^+\ell^-$  transitions motivate studies of decays involving  $\tau$  leptons
- ▶ The search for  $B \rightarrow \tau^+\tau^-$  decays at LHCb is challenging, but possible
- ▶ First limit on the  $B_s^0 \rightarrow \tau^+\tau^-$  branching ratio

$$\mathcal{B}(B_s^0 \rightarrow \tau^+\tau^-) < 6.8 \times 10^{-3} \quad @ 95 \% \text{ C.L.}$$

- ▶ Improved limit on the  $B^0 \rightarrow \tau^+\tau^-$  branching ratio

$$\mathcal{B}(B^0 \rightarrow \tau^+\tau^-) < 2.1 \times 10^{-3} \quad @ 95 \% \text{ C.L.}$$