

Exclusive $b \rightarrow s\tau^+\tau^-$ Decays from LHCb

Kristof De Bruyn

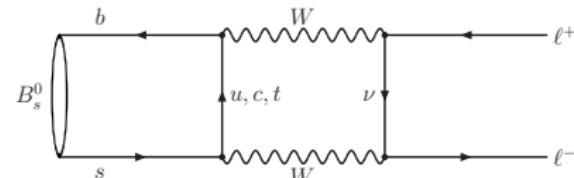
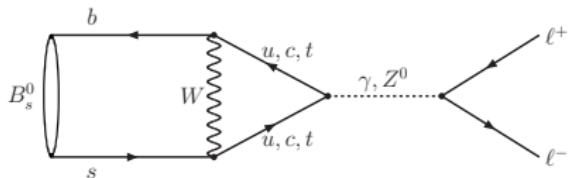
On behalf of the LHCb collaboration and the CPPM LHCb group

Current Trends in Flavor Physics
GDR Intensity Frontier
Paris – March 29th, 2017



$b \rightarrow s\ell^+\ell^-$ Transitions

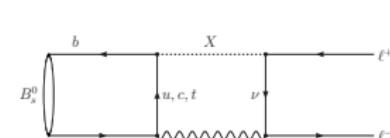
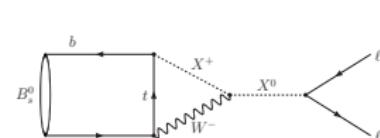
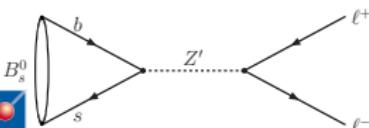
Standard Model



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

Beyond the SM Theories

- ▶ Z'/W' models, leptoquarks, 2HDM, ...



Search for the Rare Decays $B \rightarrow \ell^+ \ell^-$

Standard Model

- ▶ Theoretically clean quantity → accurate SM prediction
→ include NLO EW + NNLO QCD corrections
- ▶ In the SM, only difference between the channels is due to **helicity suppression**

	$B \rightarrow e^+ e^-$	$B \rightarrow \mu^+ \mu^-$	$B \rightarrow \tau^+ \tau^-$
B^0	$(2.48 \pm 0.21) \times 10^{-15}$	$(1.06 \pm 0.09) \times 10^{-10}$	$(2.22 \pm 0.19) \times 10^{-8}$
B_s^0	$(8.54 \pm 0.55) \times 10^{-14}$	$(3.65 \pm 0.23) \times 10^{-9}$	$(7.73 \pm 0.49) \times 10^{-7}$

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

Experimental Picture

	$B \rightarrow e^+ e^-$	$B \rightarrow \mu^+ \mu^-$	$B \rightarrow \tau^+ \tau^-$
B^0	$< 8.3 \times 10^{-8}$ @90% C.L.	$< 3.4 \times 10^{-10}$ @95% C.L.	$< 4.1 \times 10^{-3}$ @90% C.L.
B_s^0	$< 2.8 \times 10^{-7}$ @90% C.L.	$(3.0 \pm 0.7) \times 10^{-9}$	—

CDF, PRL 102 (2009) 201801, arxiv:0901.3803

LHCb, LHCb-PAPER-2017-001, arxiv:1703.05747

BaBar, PRL 96 (2006) 241802, arxiv:hep-ex/0511015

The Latest Results on $B_s^0 \rightarrow \mu^+ \mu^-$

LHCb-PAPER-2017-001, arxiv:1703.05747

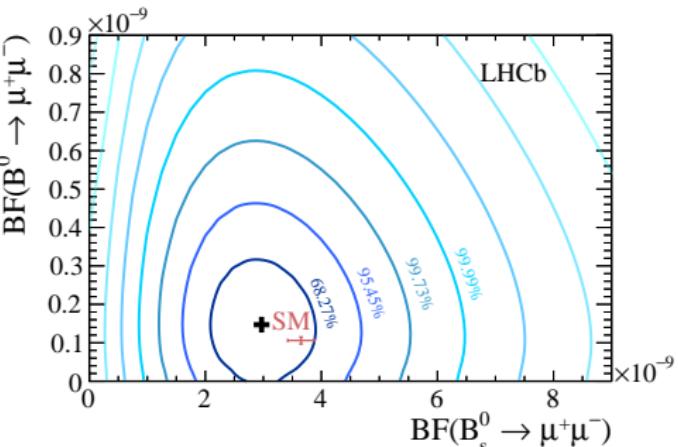
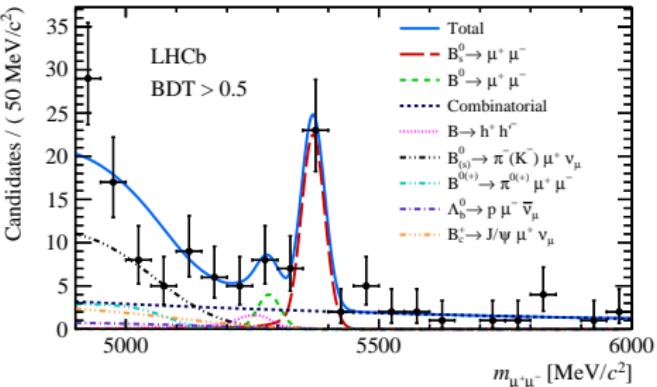
Updated Analysis

- ▶ 3 fb^{-1} Run 1 + 1.4 fb^{-1} of Run 2
- ▶ Improved selection:
 - ▶ Signal isolation
 - ▶ BDT classifier
 - ▶ PID requirements
- ▶ First measurement of $B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime

Branching Fractions

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6(\text{stat})^{+0.3}_{-0.2}(\text{syst})) \times 10^{-9} \quad [7.8\sigma]$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} \quad @ 95\% \text{ C.L.} \quad [1.6\sigma]$$



Search for the Rare Decays $B \rightarrow \tau^+ \tau^-$

τ Decay Modes

- ▶ Modes with electrons or π^0 more challenging for LHCb
- ▶ Most promising:
 - 1 $\mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) = (17.39 \pm 0.04)\%$
 - 2 $\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau) = (9.31 \pm 0.05)\%$
- ▶ Reduces signal efficiency

Current LHCb Analysis

- ▶ Reconstructed both τ s in hadronic $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ mode
- Can reconstruct the τ decay vertices
- Exploit decay geometry to approximately reconstruct the B and τ properties

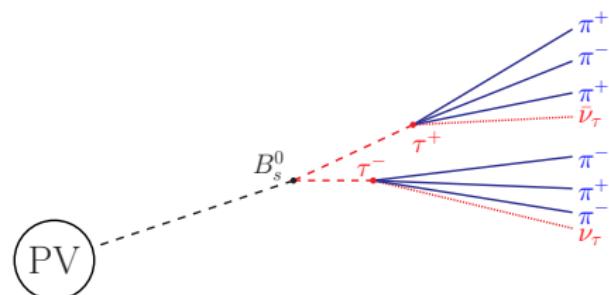


Analytic Reconstruction Method for $B \rightarrow \tau^+ \tau^-$

A. Morda, CERN-THESIS-2015-264

Constraints

- ▶ B origin vertex (pp collision)
- ▶ τ decay vertices
- ▶ Momentum conservation at the B and τ decay vertices
- ▶ Masses for the B , τ and ν_τ



Strategy

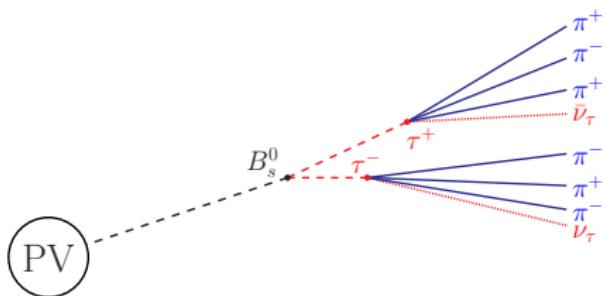
- ▶ Combine constraints in Lorentz invariant way \Rightarrow Leads to a fourth order polynomial
- ▶ Roots provide analytic solutions for the τ momenta
- ▶ 1 unknown degree of freedom remaining in calculation
 \rightarrow asymmetry (θ) of the triangle $PV \leftrightarrow SV(\tau^+) \leftrightarrow SV(\tau^-)$

Limitations

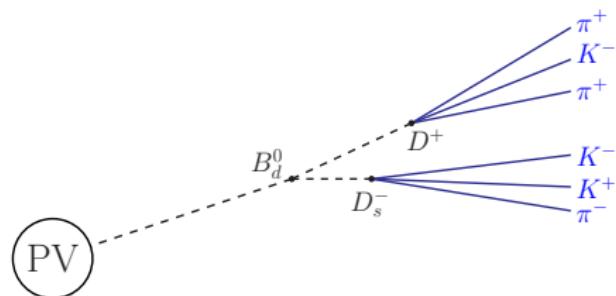
- ▶ Approximations required for θ
- ▶ Experimental resolution
-  \Rightarrow Majority of cases no purely real solution can be found: limits applicability
- ▶ Use intermediate results to discriminate signal and background

Experimental Signature

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



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



Challenges

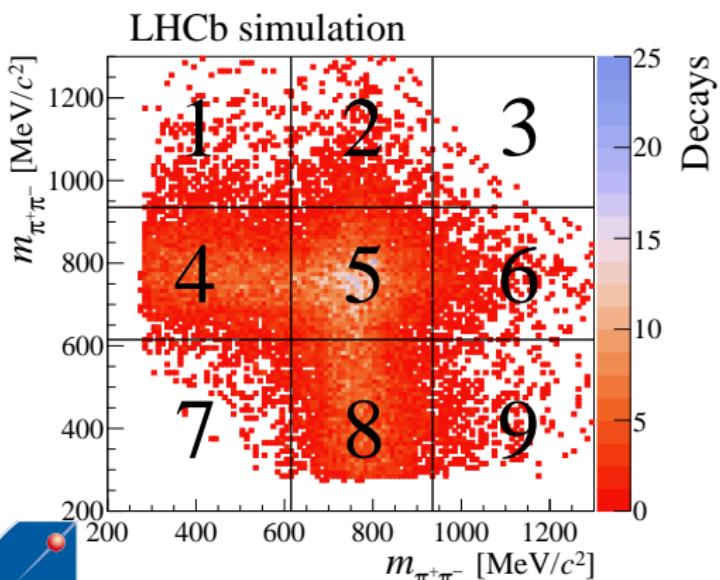
- 1** 2 missing neutrinos
 - ▶ No narrow (mass) peak to fit
 - ▶ Cannot differentiate B_s^0 from B^0
- 2** 6 pions = large combinatorial background
 - ▶ Use isolation variables to suppress background

Intermediate Resonances

- Predominantly proceeds through

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

- Exploit this in analysis



Subsamples:

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

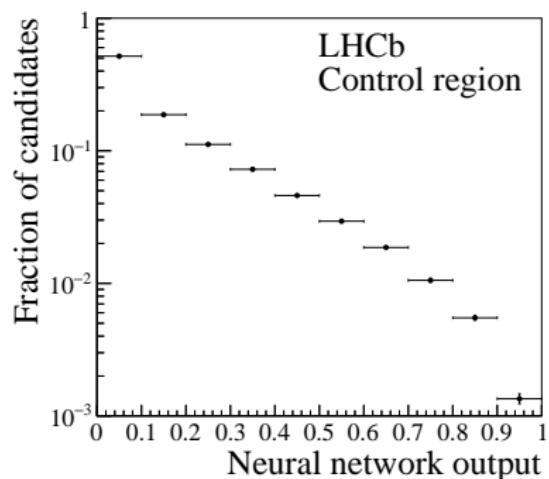
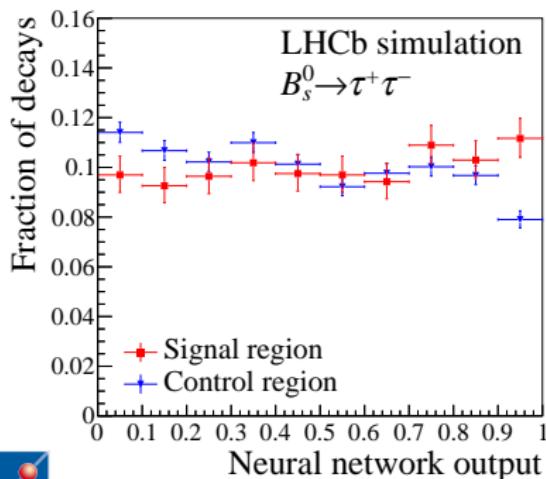
Selection:

- Cut-based loose selection
- Two-stage neural network

Fit Strategy

LHCb-PAPER-2017-003, arxiv:1703.02508

- ▶ 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



Fit Model

LHCb-PAPER-2017-003, arxiv:1703.02508

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:

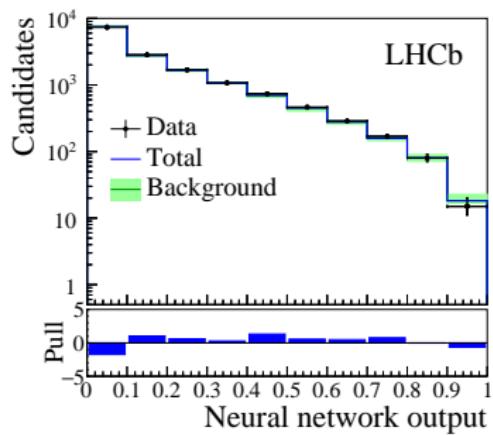
$$\mathcal{N}_{\text{data}}^{\text{SR}} = s \times \hat{\mathcal{N}}_{\text{sim}}^{\text{SR}} + f_b \times \left(\mathcal{N}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon_{\text{CR}}}{\epsilon_{\text{SR}}} \times \hat{\mathcal{N}}_{\text{sim}}^{\text{CR}} \right)$$

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

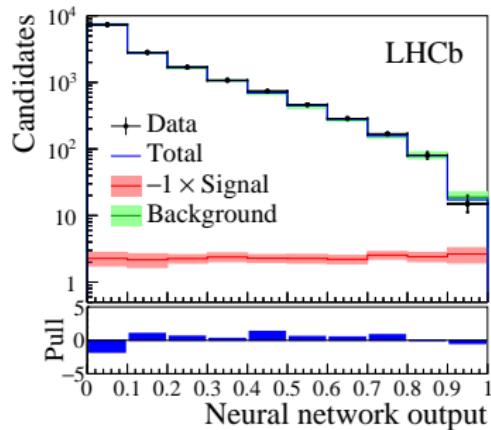
Fit to Data

LHCb-PAPER-2017-003, arxiv:1703.02508

Background-Only Model



Nominal Fit Model



$$N_{\tau^+\tau^-}^{\text{obs}} = s = -23 \pm 71$$

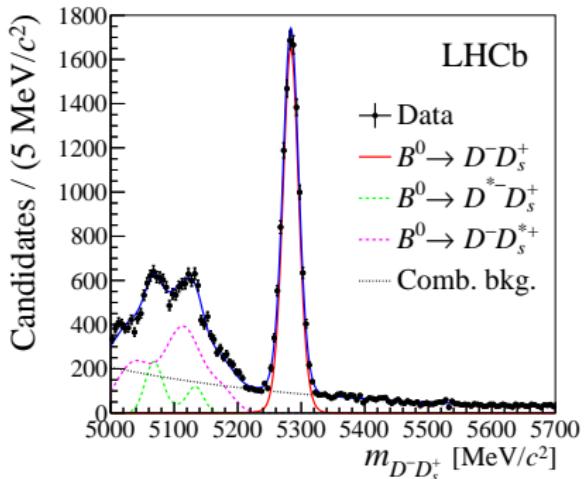
- ▶ Compatible with the background-only hypothesis
- Set an upper limit

From Yield to Branching Ratio

LHCb-PAPER-2017-003, arxiv:1703.02508

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

- ▶ Assume all signal comes from $B_s^0 \rightarrow \tau^+ \tau^-$
i.e. ignore $B^0 \rightarrow \tau^+ \tau^-$ completely
- ▶ Determine α^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

$$\alpha^s = (4.07 \pm 0.70) \times 10^{-5}$$

→

$$N_{\tau^+ \tau^-}^{\text{SM}} = 0.019$$

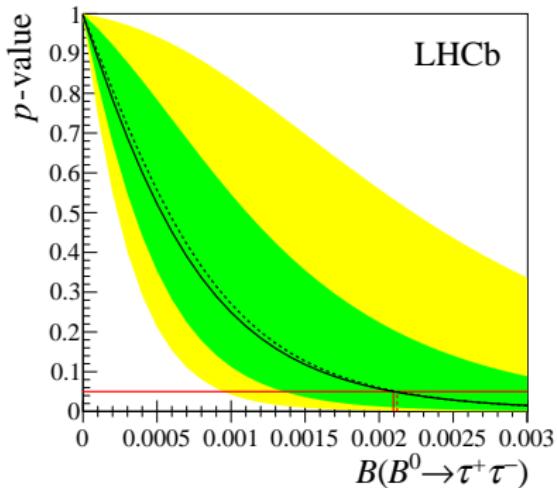
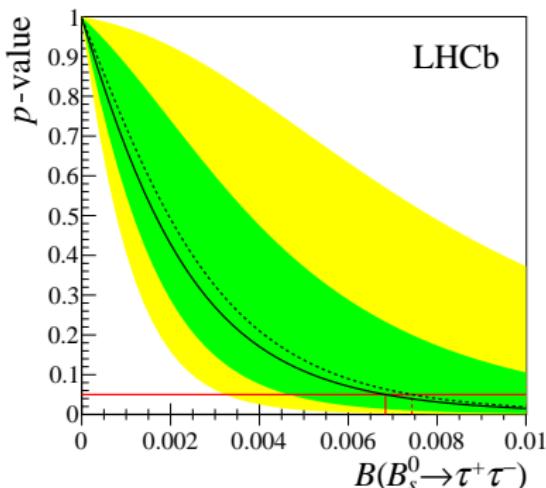
$$\alpha^d = (1.16 \pm 0.19) \times 10^{-5}$$

→

$$N_{\tau^+ \tau^-}^{\text{SM}} = 0.002$$

Branching Fraction Limit

LHCb-PAPER-2017-003, arxiv:1703.02508

 $B_s^0 \rightarrow \tau^+ \tau^-$ $B^0 \rightarrow \tau^+ \tau^-$ Branching Fraction Limit (CL_s Method)

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 6.8 \times 10^{-3} \text{ @ 95 % C.L.}$$
$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 2.1 \times 10^{-3} \text{ @ 95 % C.L.}$$

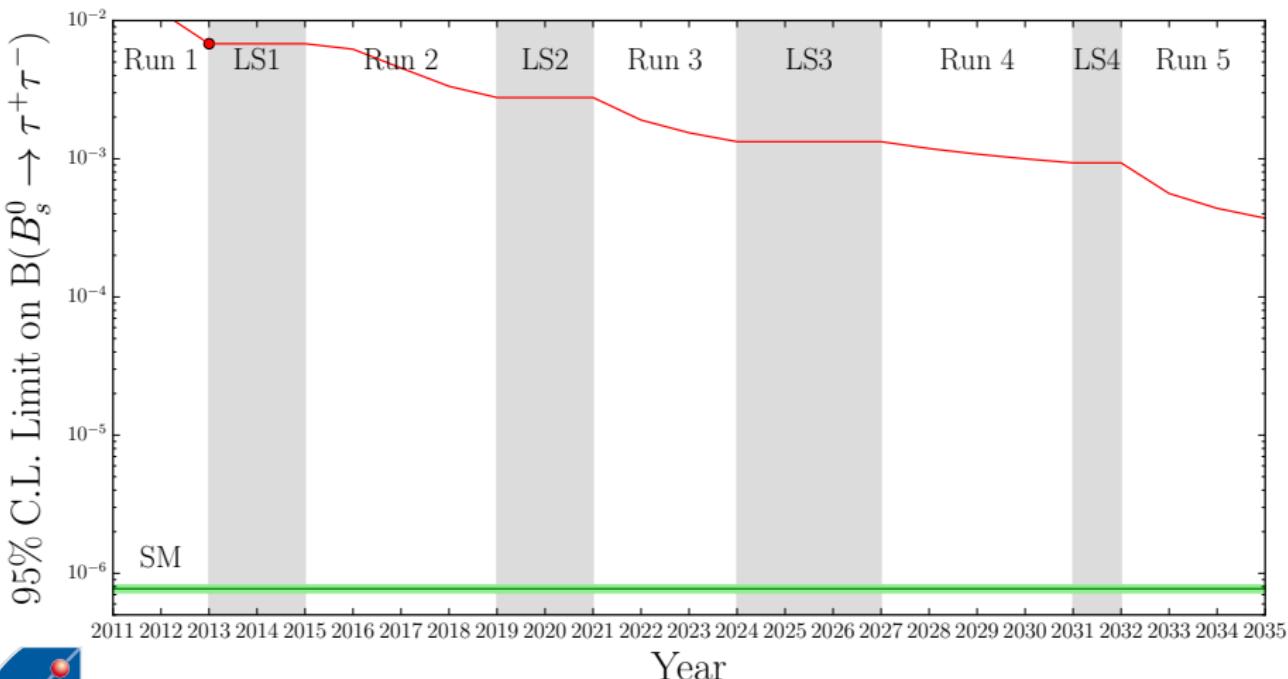


Prospects and Other Ongoing Analyses

**CPPM**

What Can We Expect for $B_s^0 \rightarrow \tau^+ \tau^-$?

- ▶ Only scaling with luminosity



What Can We Expect for $B_s^0 \rightarrow \tau^+ \tau^-$?

Further Improvements are Needed!

- 1 Additional τ decay modes: $B_s^0 \rightarrow \tau^\pm (\rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau) \tau^\mp (\rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)$
 - ▶ Larger efficiency (Due to $\mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)$)
 - ▶ Single Dalitz plane, only one τ decay vertex known
 - ▶ Different background composition

⇒ Sensitivity is worse than $B_s^0 \rightarrow \tau^\pm (\rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau) \tau^\mp (\rightarrow \pi^- \pi^+ \pi^- \nu_\tau)$ mode
- 2 Increase selection efficiency (?)
- 3 Wishlist: Further develop analytic reconstruction method (?)

Other Ongoing Analyses: $B \rightarrow \tau^\pm \mu^\mp$

- ▶ Forbidden in the Standard Model: Lepton Flavour Violating mode
- ▶ Strongly enhanced in many New Physics models
 - $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) \sim \mathcal{O}(10^{-6})$ in Z' models
 - A. Crivellin *et al.*, PRD 92 (2015) 054013, arxiv:1504.07928
- ▶ Best limit: $\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) < 2.2 \times 10^{-5}$ @ 90 % C.L.
 - BaBar, PRD 77 (2008) 091104, arxiv:0801.0697
- ▶ No limit for $B_s^0 \rightarrow \tau^\pm \mu^\mp$

Experimental Status

- ▶ Reconstruct in $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ mode
 - Use kinematic constraints to analytically reconstruct the B mass
 - Better performance than for $B_s^0 \rightarrow \tau^+ \tau^-$
- ▶ Large background from semileptonic decays
- ▶ Aim for similar sensitivity as BaBar
- ▶ Hope to have a result by summer

Other Ongoing Analyses: $B^0 \rightarrow K^{*0} \tau^+ \tau^-$

- ▶ Current analysis aim = branching ratio measurement/limit
- ▶ Standard Model expectation $\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \tau^-) \sim \mathcal{O}(10^{-7})$
C. Bobeth et al., JHEP 1201 (2012) 107, arxiv:1111.2558
- ▶ No experimental limits yet
- ▶ When observed:
 - ▶ Can provide another Lepton Flavour Universality test
 - ▶ An angular analysis would complement the studies of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Experimental Status

- ▶ Simultaneously exploring the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ and $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ modes
- ▶ Initial studies: $B^0 \rightarrow K^{*0} \tau(\rightarrow 3\pi\nu)\tau(\rightarrow \mu\nu\nu)$ more sensitive than
 $B^0 \rightarrow K^{*0} \tau(\rightarrow 3\pi\nu)\tau(\rightarrow 3\pi\nu)$



Conclusion

LHCb-PAPER-2017-003, arxiv:1703.02508

- ▶ Searches for $B \rightarrow \tau X$ decays at LHCb are 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

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

- ▶ Work in progress:
 - ▶ $B \rightarrow \tau^\pm \mu^\mp$
 - ▶ $B^0 \rightarrow K^{*0} \tau^+ \tau^-$
 - ▶ Searching for improvements for $B \rightarrow \tau^+ \tau^-$



CENTRE DE PHYSIQUE DES
PARTICULES DE MARSEILLE

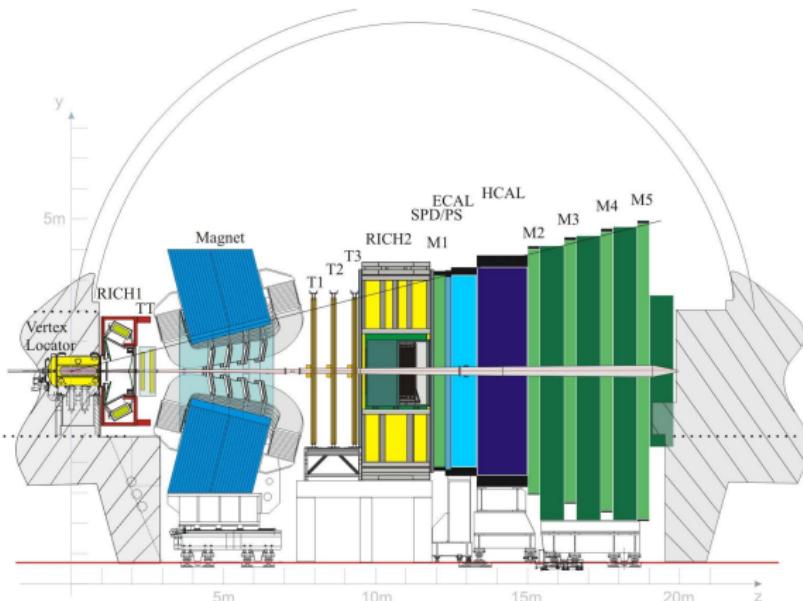
CPPM

Supplementary Material

**CPPM**

The LHCb Detector

JINST 3 (2008) S08005



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

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

- ▶ Good impact parameter resolution to identify secondary vertices: $(15 + 29/\rho_T) \mu\text{m}$
- ▶ 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