Search for the Rare Decay $B^0_s \to \tau^+\tau^-$

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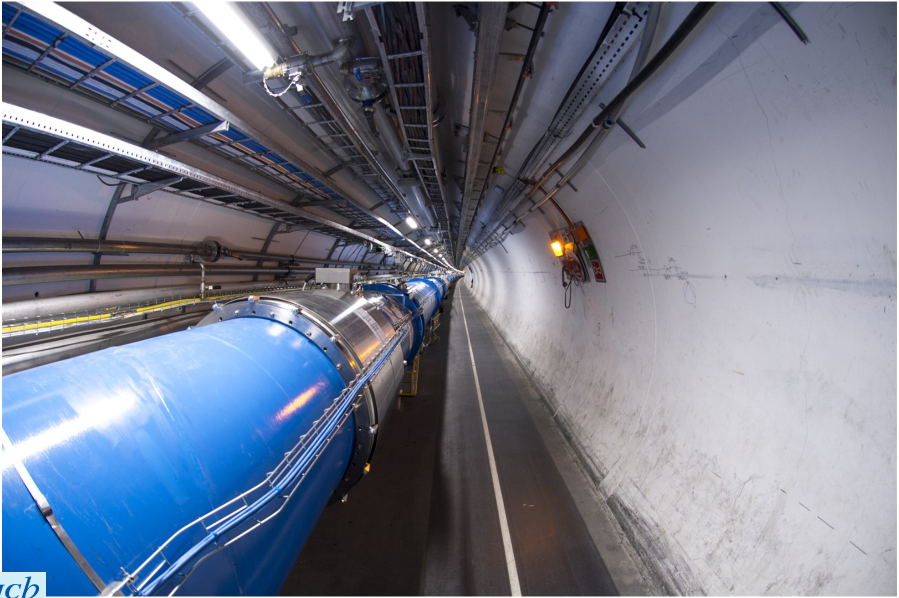
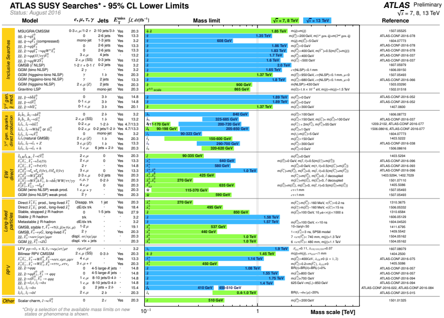
CPPM Seminar
November 21th, 2016

The Large Hadron Collider

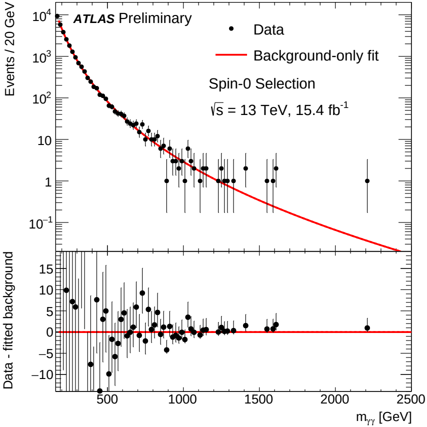


Where is New Physics Hiding?

No Direct Signs for SUSY or Exotica



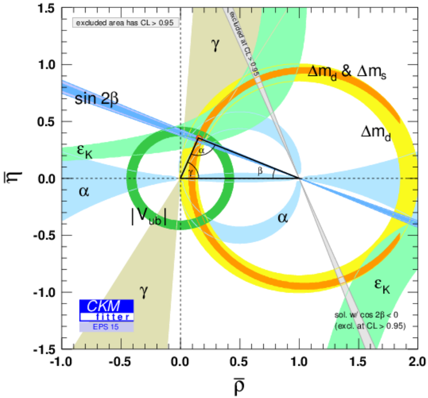
No More 750 GeV Diphoton Excess



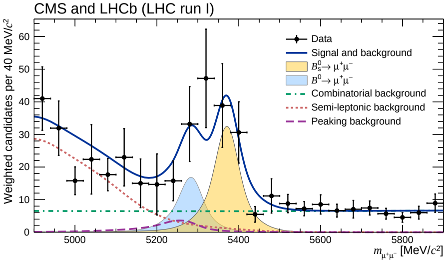
Is this the Era of Flavour Physics?

- Searching for anomalies with precision measurements of SM parameters

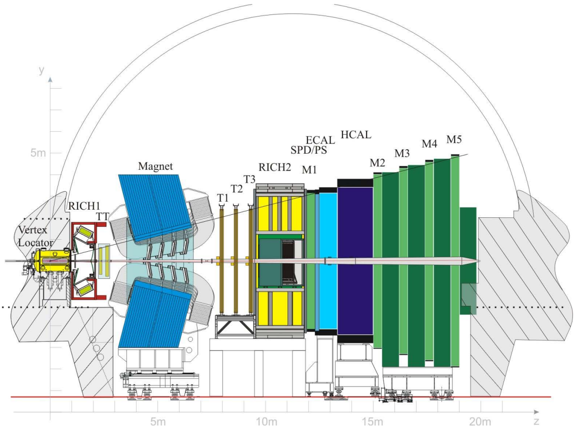
Constraining the CKM Matrix



Searches and Studies of Rare Decays



The LHCb Detector

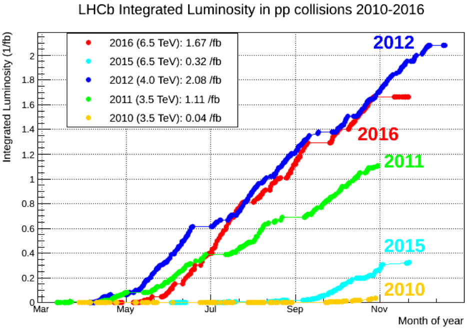


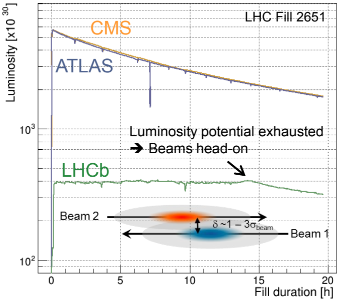
Forward arm spectrometer to study b- and c-hadron decays

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

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

LHCb Data Sample

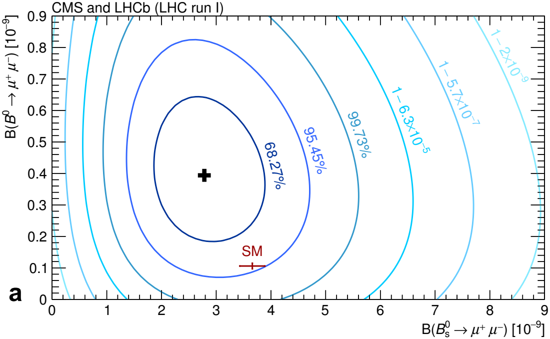




- LHCb uses luminosity levelling
- Average number of interactions per bunch crossing: 1.1

Puzzling Tensions in $b \to s\ell\ell$ Transitions

Puzzling Tensions in $b \to s\ell\ell$ Transitions: $B^0_{(s)} \to \mu^+\mu^-$



Branching Fractions

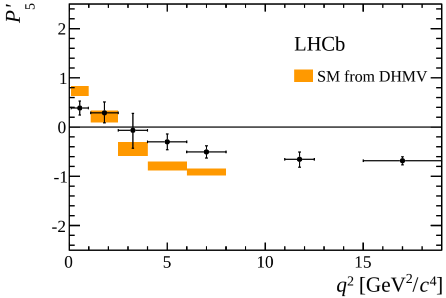
Observable	SM Prediction	Measurement	Tension
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$(3.66 \pm 0.23) \times 10^{-9}$	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$	1.2σ
$\mathcal{B}(B^0_d \to \mu^+\mu^-)$	$(1.06 \pm 0.09) \times 10^{-10}$	$(3.9^{+1.6}_{-1.4}) \times 10^{-10}$	2.2σ
$\frac{\mathcal{B}(B^0_d \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)}$	$0.0295^{+0.0028}_{-0.0025}$	$0.14^{+0.08}_{-0.06}$	2.3σ

CMS+LHCb, Nature 522 (2015), arxiv:1411.4413

Puzzling Tensions in $b \to s\ell\ell$ Transitions: $B^0 \to K^{*0}\mu^+\mu^-$

Angular Observables

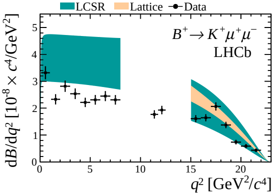
- Measured 7 angular observables + 7 CP asymmetries + polarisation fractions
- Including the famous "P_5'"
- Global fit of data give a 3.4σ deviation from the SM



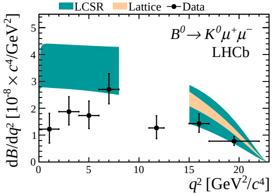
LHCb, JHEP 02 (2016) 104, arxiv:1512.04442

Puzzling Tensions in $b \to s\ell\ell$ Transitions: Differential Branching Fractions

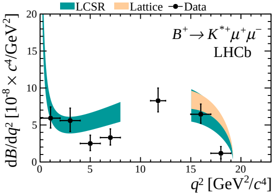
$B^+ \to K^+\mu^+\mu^-$



$B^0 \to K^0\mu^+\mu^-$



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



LHCb, JHEP 06 (2014) 133, arxiv:1403.8044

- Individually consistent ...
- but all favour lower values than their respective Standard Model predictions

Puzzling Tensions in $b \to s\ell\ell$ Transitions: R_K

Test of Lepton Universality

- Definition

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \xrightarrow{SM} 1 \pm \mathcal{O}\left(10^{-4}\right)$$

C. Bobeth *et al.*, JHEP 07 (2007) 040, arxiv:0709.4174

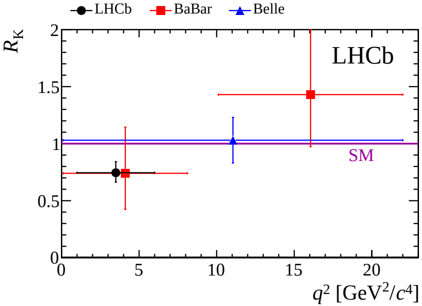
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

- Measured in the range

$$1 < q^2 < 6\ \text{GeV}^2/c^4$$

(q^2 momentum transfer to lepton system)

- 2.6σ deviation from the SM



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

Effective Field Theory Framework

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

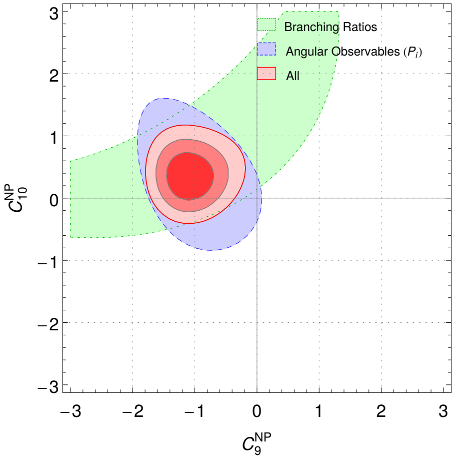
G. Buchalla *et al.*, RMP 68 (1996) 1125, arxiv:9512380[hep-ph]

Ingredients:

- Coupling Constants
- Wilson Coefficients contain all perturbative short-distance effects
  - ⇒ Can be calculated with 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 $b \to s\gamma$ decays
  - Semileptonic ops $\mathcal{O}_9$ (vector) and $\mathcal{O}_{10}$ (axial-vector), important for $b \to s\ell\ell$ decays

Things Start to Add Up ...

- Best fit model has Wilson coefficient
  $C_9^{\text{NP}} \approx -1$ (4 to 5σ)
- What can explain this?
  1. Statistical fluctuations
  2. Not-yet-understood SM effects
  3. New Physics
- Strong case for
  - violation of lepton universality
  - studying other $b \to s\ell\ell$ transitions
  - eagerly awaiting LHCb Run 2 updates



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

Test of Lepton Universality: $R(D^{(*)})$

- Definition

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu)}$$

- In the SM, only difference between $\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau$ and $\bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu$ is due to dependence on the lepton mass
- Theoretically clean quantity $\to$ accurate SM prediction

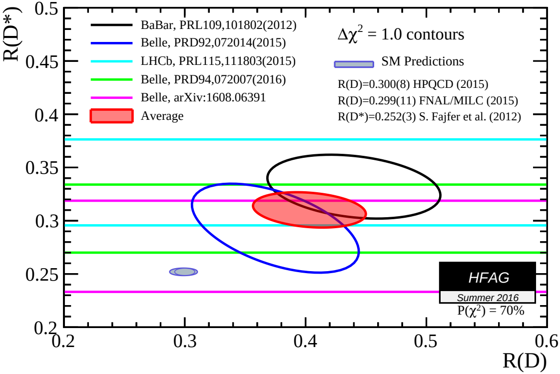
$$R(D^*) \overset{\text{SM}}{=} 0.252 \pm 0.003$$

$$R(D) \overset{\text{SM}}{=} 0.300 \pm 0.008$$

S.Fajfer *et al.*, PRD85 (2012) 094025, arxiv:1203.2654

H.Na *et al.*, PRD92 (2015) 054410, arxiv:1505.03925

Experimental Picture on $R(D^{(*)})$

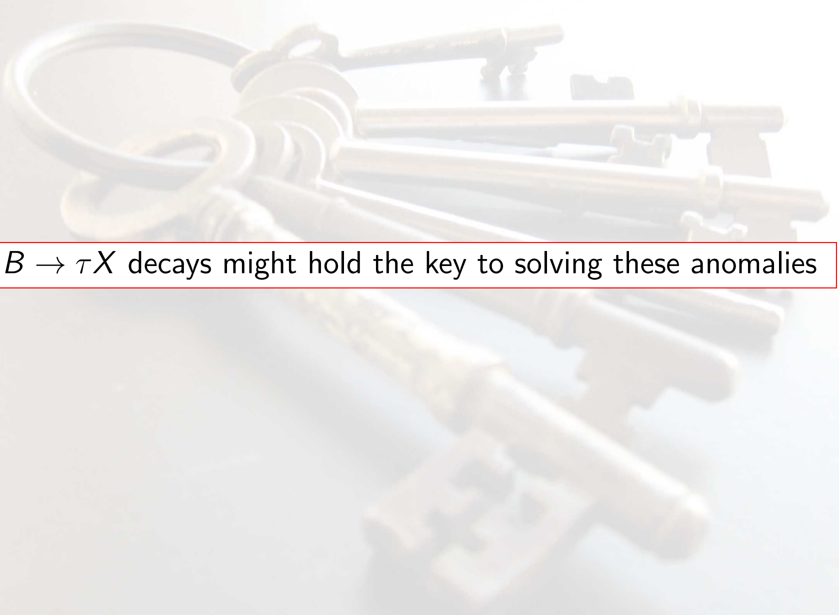


Experimental Average:

$$R(D^*) = 0.310 \pm 0.015\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$R(D) = 0.403 \pm 0.040\,(\text{stat}) \pm 0.024\,(\text{syst})$$

- 3.9σ deviation from SM

Heavy Flavour Averaging Group



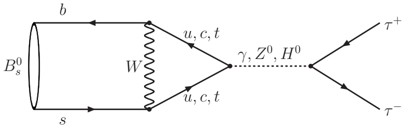
$B \to \tau X$ decays might hold the key to solving these anomalies

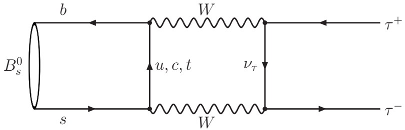
$B^0_{(s)} \to \tau^+\tau^-$ Analysis

Standard Model Decay

- Flavour Changing Neutral Current
- Forbidden at Tree level

⇒ Loop suppressed





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

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) \overset{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7} \quad (2)$$

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

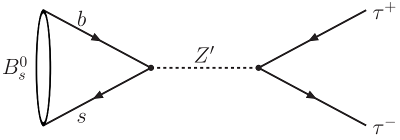
Bobeth *et al.*, PRL 112 (2014) 101801, arxiv:1311.0903

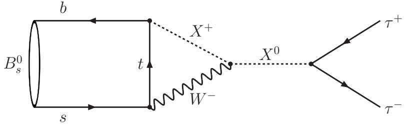
. . . and Beyond

New Physics Models

- New tree level processes (Z', . . .)
- Enhanced loop contributions (leptoquarks, charged Higgs, . . .)
- Branching fraction can be as large as a %

R. Alonso, arxiv:1505.05164





Experimental Picture

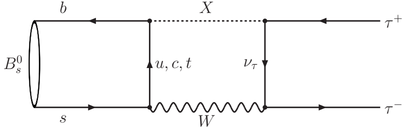
- Current best (and only) limit:

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

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

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

C. Bobeth and U. Haisch, APP B44 (2013) 127
arxiv:1109.1826



Reconstructing the τ

Largest Decay Channels

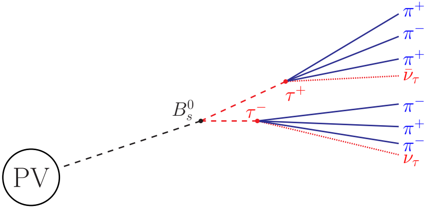
$$\mathcal{B}(\tau^- \to \pi^-\pi^0\nu_\tau) = 25.49 \pm 0.09\ \%$$
$$\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 17.82 \pm 0.04\ \%$$
$$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) = 17.39 \pm 0.04\ \%$$
$$\mathcal{B}(\tau^- \to \pi^-\nu_\tau) = 10.82 \pm 0.05\ \%$$
$$\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau) = 9.31 \pm 0.05\ \%$$
$$\mathcal{B}(\tau^- \to \pi^-\pi^0\pi^0\nu_\tau) = 9.26 \pm 0.10\ \%$$

For LHCb

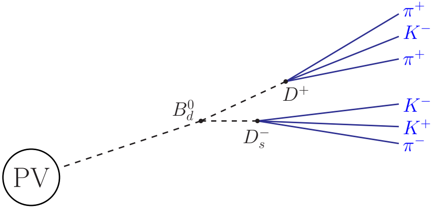
- Abundant pions
- Difficult to reconstruct π^0
- Limited efficiency for electrons
- Only covers $2 < \eta < 5$ $\Rightarrow$ always missing energy

Experimental Signature

$B^0_s \to \tau^+(\to 3\pi)\tau^-(\to 3\pi)$



$B^0 \to D^+(\to \pi^+K^-\pi^+)D^-_s(\to K^-K^+\pi^-)$



Challenges

1. 2 missing neutrinos
   - No narrow (mass) peak to fit, no mass sidebands to exploit
   - Cannot differentiate B^0_s from B^0
2. 6 pions
   - Low efficiency
   - Large combinatorial background

Sketching our Starting Situation

pp Collissions $\xrightarrow{\text{Trigger}}$ Raw Event $\xrightarrow{\text{Reconstruction}}$ Offline Data

Yields in data

- 3 fb^{-1} of data from Run 1
- 18 million events
- 124 million candidates (av. 6.8 per event)

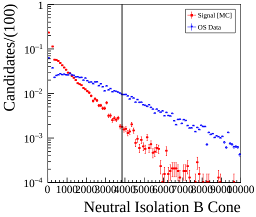
Signal Efficiencies

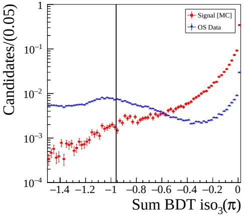
- Geometrical Acceptance: 3%
- Trigger + Reconstruction: 0.76%
- Total: 0.023%
- Expect about 0.2 SM events

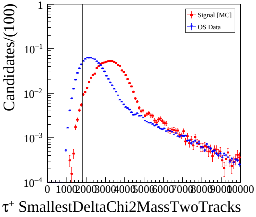
$\Rightarrow$ need some special tools

Custom Tools: Isolation Variables

1. Neutral isolation variables
   - Count neutral objects in a cone around the B candidate
2. Track isolation variables
   - BDT-based, aiming to identify tracks coming from the same decay chain
3. Vertex isolation variables
   - Combine signal tracks making a τ candidate with other tracks in the event, refit vertex, and check for improvement







Custom Tools: Decay Chain Reconstruction

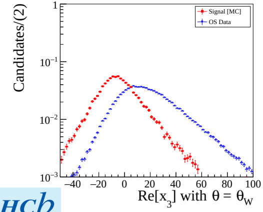
Ideal Scenario

- Goal: Obtain an analytic solution for the τ momenta
- How: B decay plane is spanned by the PV and the known τ decay vertices

$\to$ Advantage of the $B^0_s \to \tau^+(\to 3\pi)\tau^-(\to 3\pi)$ decay mode

Realistic Scenario

- Detector resolution spoils the accuracy of the method (solutions are not always purely real)
- Do not succeed in our main goal, but ...
- Intermediate steps of calculation are very valuable features to differentiate beween signal and bkg

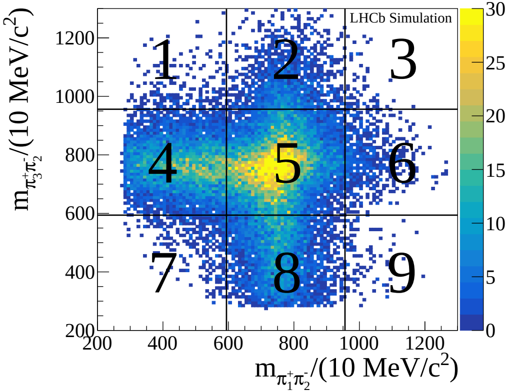


- Method developed by Alessandro Mordà & Jérôme Charles (See Alessandro's Thesis or this talk)

Custom Tools: Intermediate Resonances

- Exploit τ decay chain

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



Subsamples:

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

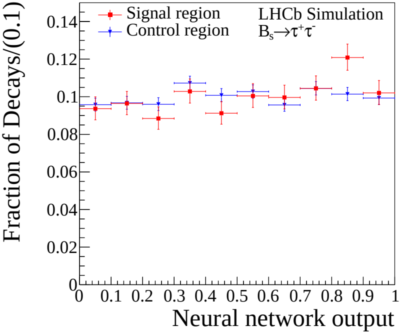
Analysis in a Nutshell

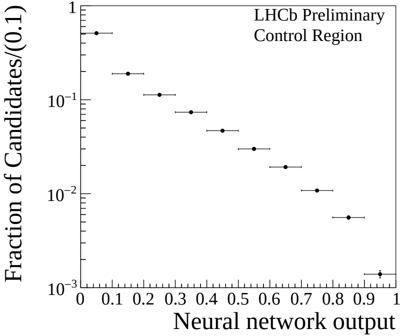
1. Cut-based loose selection: Remove obvious background, keep high signal efficiency
2. Two-stage Neural Network
3. Optimise signal search window
4. Perform 1D histogram fit to output distribution of the second Net
5. Convert likelihood fit to branching ratio limit using CLs method

- Analysis is optimised for $B^0_s \to \tau^+\tau^-$
- But we also put a limit on $B^0 \to \tau^+\tau^-$

Fit Strategy

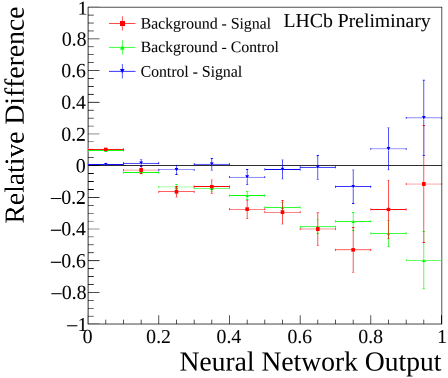
- Perform a 1-dimensional histogram fit to the output of a neural network
- Output is remapped such that signal is flat and $\in [0, 1]$
- The Signal templates are taken from simulation
- The Background template is taken from the data, using the Control Region





Background Model

- How representative is the control region for the background in the signal window?



- Blinded Analysis
- Extensive cross-checks on data
- Studied both exclusive and inclusive MC background samples

Fit Model

Events:

Signal: 17% $B^0_s \to \tau^+\tau^-$ Simulation versus 4.8% data

Background: 11% $B^0_s \to \tau^+\tau^-$ Simulation versus 44% data

Control: 55% $B^0_s \to \tau^+\tau^-$ Simulation versus 41% data

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

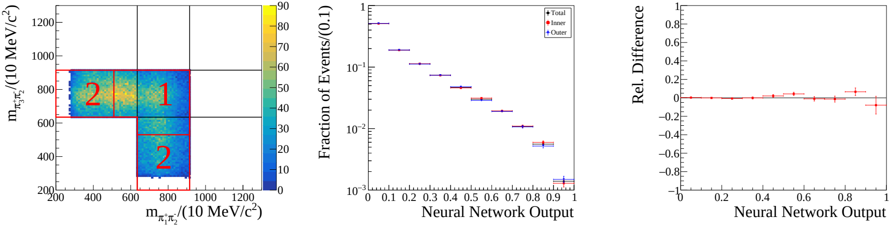
Model:

$$\mathrm{NN}^{\mathrm{SR}}_{\mathrm{data}} = s \times \widehat{\mathrm{NN}}^{\mathrm{SR}}_{\mathrm{sim}} + f_b \times \left(\mathrm{NN}^{\mathrm{CR}}_{\mathrm{data}} - s \cdot \frac{\epsilon_{\mathrm{CR}}}{\epsilon_{\mathrm{SR}}} \times \widehat{\mathrm{NN}}^{\mathrm{CR}}_{\mathrm{sim}}\right)$$

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

Systematic Uncertainties on the Background Template

Step 1 | Step 2 | Step 3



Procedure:

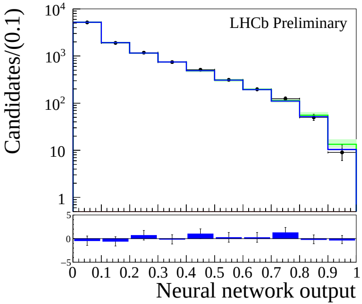
1. Split the control region into an inner and outer region (equal statistics)
2. Compare the NN output of both regions
3. Calculate the relative difference (= relative systematic uncertainty)

Fit to Data

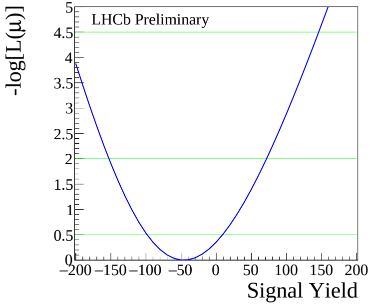
LHCb, LHCb-CONF-2016-011

Nominal Fit Model

Total Bkg



Profile Likelihood



$$N^{\text{obs}}_{\tau^+\tau^-} = s = -46 \pm 51$$

- Compatible with the background-only hypothesis

From Yield to Branching Ratio

LHCb, LHCb-CONF-2016-011

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) = \alpha_s \cdot N^{\text{obs}}_{\tau^+\tau^-} \; ,$$

- Assume all signal comes from $B^0_s \to \tau^+\tau^-$, i.e. ignore $B^0 \to \tau^+\tau^-$ completely
- Determine α_s using $B^0 \to D^- D^+_s$ normalisation mode

$$\alpha_s = \frac{\epsilon^{D^- D^+_s} \cdot \mathcal{B}(B^0 \to D^- D^+_s) \cdot \mathcal{B}(D^+ \to \pi^+ K^- \pi^+) \cdot \mathcal{B}(D^+_s \to K^+ K^- \pi^+)}{N^{\text{obs}}_{D^- D^+_s} \cdot \epsilon^{\tau^+\tau^-} \cdot [\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)]^2} \cdot \frac{f_d}{f_s}$$

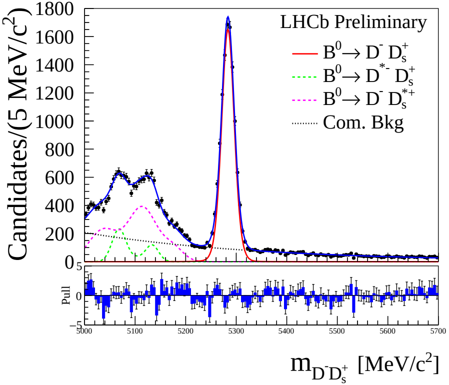
- Fit to data, Efficiencies from simulation, External Input

$$\alpha_s = (3.16 \pm 0.43) \times 10^{-5} \quad \to \quad N^{\text{SM}}_{\tau^+\tau^-} = 0.0245 \pm 0.0037 \qquad (4)$$

$$\alpha_d = (0.94 \pm 0.16) \times 10^{-5} \quad \to \quad N^{\text{SM}}_{\tau^+\tau^-} = 0.0024 \pm 0.0004 \qquad (5)$$

- (Model-dependent result based on EvtGen simulation of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$)

Normalisation Mode



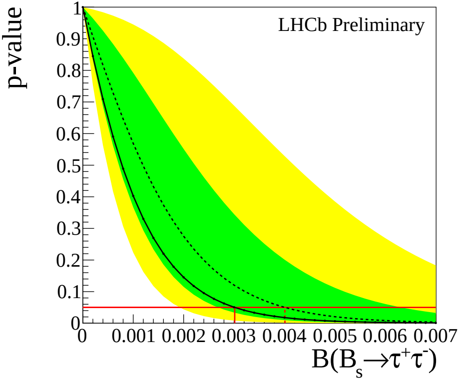
- Same Trigger + Reconstruction settings

$\rightarrow$ minimise systematic uncertainty on efficiency ratio

- Very clean

Branching Fraction Limit

LHCb-CONF-2016-011



- First limit!

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 2.4(3.0) \times 10^{-3} \quad @\, 90(95)\,\%\ \text{C.L.}$$

- Model-dependent result based on `EvtGen` simulation of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

$B^0 \to \tau^+\tau^-$

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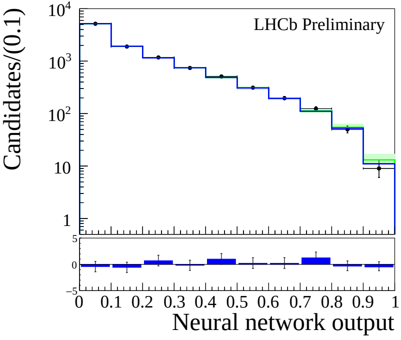
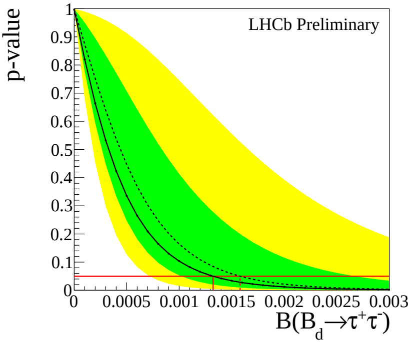
Likelihood Fit



Limit



- Factor 4 improvement w.r.t. BaBar

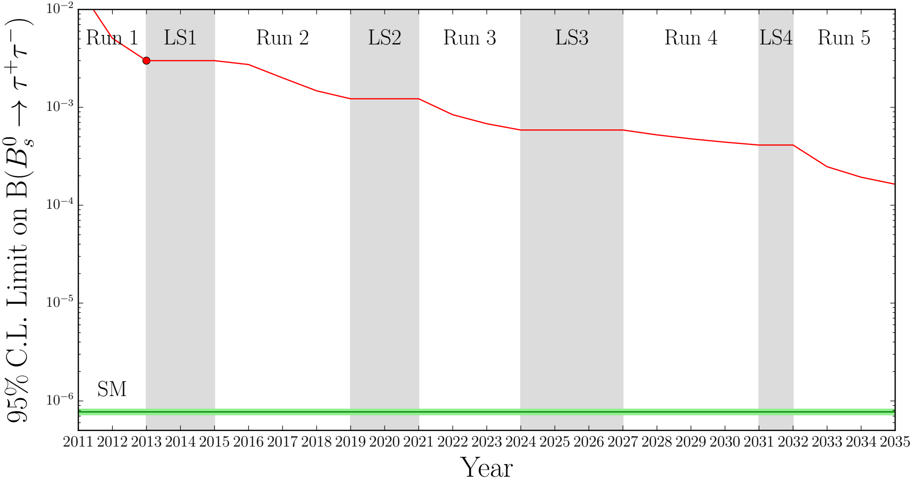
$$N^{\text{obs}}_{\tau^+\tau^-} = -39 \pm 65$$

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.0(1.3) \times 10^{-3} \quad @\,90(95)\,\%\ \text{C.L.}$$

- Model-dependent result based on `EvtGen` simulation of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

Prospects

Looking Forward: Unofficial Prospects for $B^0_s \to \tau^+\tau^-$



- More work is needed to reach the SM value.

Looking Forward: Other τ Analyses at CPPM

- Search for $B_s^0 \to \tau^+(\to 3\pi)\tau^-(\to 3\pi)$
  [Kristof, Justine, Julien, Giampiero, (Alessandro)]

- Search for the LFV decay $B_s^0 \to \tau^\pm\mu^\mp$
  [Joan, Julien, Giampiero]

- Search for $B^0 \to K^{*0}\tau^+\tau^-$
  [Andrey, Giampiero]

- Explore alternative τ decay paths for $B_s^0 \to \tau^+\tau^-$
  [Cédric, Justine]

- Search for the LFV decay $B^0 \to K^{*0}\tau^\pm\mu^\mp$
  [Justine + LPNHE]

Conclusion

- Tensions in $b \to s\ell\ell$ transitions motivate studies of LFV and LUV
- Very interesting to study decays involving τ leptons
- Searched for the rare decay $B^0_s \to \tau^+\tau^-$ in the $B^0_s \to \tau^+(3\pi)\tau^-(3\pi)$ final state
- Likelihood fit

$$N^{\text{data}}_{\tau^+\tau^-} = -46 \pm 51$$

- First limit on the $B^0_s \to \tau^+\tau^-$ branching ratio

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 2.4(3.0) \times 10^{-3} \quad @\, 90(95)\,\%\ \text{C.L.}$$

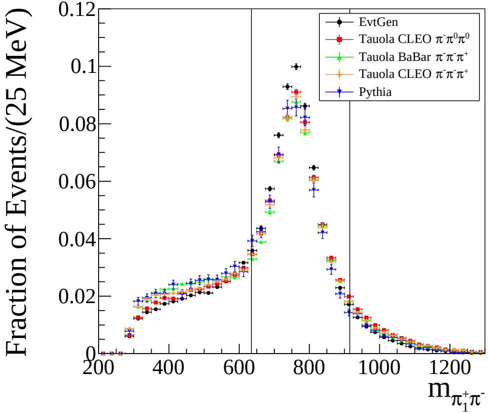
- Factor 4 improvement on $B^0 \to \tau^+\tau^-$ limit

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.0(1.3) \times 10^{-4} \quad @\, 90(95)\,\%\ \text{C.L.}$$

- Work ongoing to study dependence on the τ decay model

Back Up

τ Decay Models



EvtGen TauHadNu: Tuned to $\tau^- \to \pi^-\pi^0\nu_\tau$ [CLEO]

Tauola "CLEO" tune: Tuned to $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ [CLEO]

Tauola "BaBar" tune: Tuned to $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ [BaBar]

Tauola "CLEO intricate" tune: Tuned to $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ [CLEO] + isospin