On the possibility of measuring $\mathcal{B}(B_s \to \tau\tau)$ @ LHCb

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Flavor of New Physics in $b \to s$ transitions

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Outlook

- **Motivations**
- **Challenges**
- **Some ideas**
- **Conclusions**

$B_s^0 \to \tau\tau$: motivations

No evidence of huge New Physics (NP) effects in $B_s \to \mu\mu$, but some hints that NP could manifest in processes involving the 3^{rd} generation...

Observable	Discrepancy wrt SM
$\frac{\mathcal{B}(B\to D(D^\star)\tau\nu_\tau)}{\mathcal{B}(B\to D(D^\star)\ell\nu_\ell)}\vert_{\ell=\mu,e}$	3.4σ
A^b_{SL} like-sign dimuon asymmetry	3.9σ

- $B_s^0 \to \tau\tau$ a good candidate where to look for NP effects even if these are absents in other $B^0_{(s)}$ decays [Dighe *et al*, arXiv:1207.1324v2]:
  - In SM we have [Bobeth *et al.*, arXiv:1311.0903v1] :

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B_d^0 \to \tau^+\tau^-) = (2.22 \pm 0.04) \times 10^{-8}$$

  - respecting all the constraints on other B_s^0 decays it might be as large as 15%
  - in models with a flavor depending Z' coupling it might be up to 5%
  - in models with scalar Leptoquark it might be up to 0.3%
- Current status:
  - $\mathcal{B}(B_d^0 \to \tau^+\tau^-) < 4 \cdot 10^{-4}$ @ 90% CL by BaBar
  - $\mathcal{B}(B_s^0 \to \tau^+\tau^-)$ has **not yet been constrained**

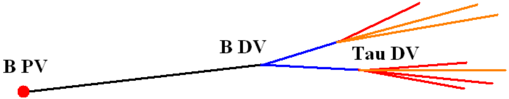
Challenging issues

τ have a very short lifetime $\Longrightarrow$ we must reconstruct them from their daughter particles

But...

- at least one neutrino for each τ decay (1 for hadronic or 2 for leptonic channels) $\Rightarrow$ at least **2 unreconstructable neutrinos** and so...
- we cannot completely reconstruct the two τ momenta, hence neither $\tau^{\pm}$ invariant mass nor the decay topology
- a $B^0_{(s)} \to \mu\mu$-like analysis (*i.e.* 2D classification geometry $\otimes$ invariant mass) is not straightforward

B_s
τ
visible (charged) tracks
ν & neutral tracks



The τ decay final states

Two possible τ decay modes are used:

- **both $\tau \to 3\pi\,\nu_\tau$ (covered here !)**

- only 2 neutrinos
- 2 3-prong vertexes
- reconstruction of the decay plane: kinematic constraints & partial neutrino momentum reconstruction
- needs 6-charged tracks in the detector acceptance
- $\mathcal{B}(\tau \to 3\pi\,\nu_\tau) = 9.31\%$
- $\mathcal{B}(\mathbf{B_s} \to$ **final state**$) \simeq \mathbf{6.7 \times 10^{-9}}$

- $\tau \to \mu\,\nu_\mu\,\nu_\tau$, $\tau \to 3\pi\,\nu_\tau$

- 3 neutrinos
- only one 3-prong vertex
- unreconstructable decay plane: approximate (partial) reconstruction of the missing ν-momentum still possible
- "only" 4 charged tracks in the detector acceptance $\oplus$ higher trigger efficiency
- $\mathcal{B}(\tau \to \mu\,\nu_\mu\,\nu_\tau) = 17.41\%$
- $\mathcal{B}(\mathbf{B_s} \to$ **final state**$) \simeq \mathbf{1.25 \times 10^{-8}}$

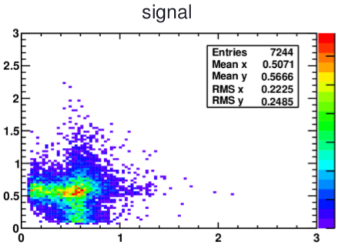
Same effective $\mathcal{B}$ as $B_s \to \mu\mu$!

The $\tau \to 3\pi\,\nu_\tau$ decay chain

The $\tau \to 3\pi\,\nu_\tau$ decay proceeds through the a_1 and ρ resonances, *i.e.*

$$\tau^\pm \to a_1^\pm \nu \to \rho^0 \pi^\pm \nu \to \pi^+\pi^-\pi^\pm \nu$$

- it helps to improve the τ selection
- makes possible to define control regions in the Dalitz plane



Sources of background - $\tau \to 3\pi\nu$

The following kind of background can fake the $\tau \to 3\pi\nu$ decay:

- **combinatorial τ** : 3 random π tracks forming a common displaced vertex
  - characterized using a sample of "dataSS", *i.e.* $B_s \to \tau^{\pm}\tau^{\pm}$ (nonphysical) events
  - this sample contains true particles (τ & $D^{(\star)}_{(s)}$)
  - look at the region in the Dalitz plane outside the resonances structures
- **true particles**: prompt $D^{(\star)}_{(s)} \to 3\pi X$ misidentified as $\tau \to 3\pi\nu$

	Mass (MeV)	lifetime (10^{-15} s)	Spin
τ	1776	290	1/2
D	1869	1040	0^-
D_s	1968	500	0^-

Use of Dalitz plane may improve the rejection of D_s (depending on the resonances it goes through) but not of the D, because it proceeds through the same resonances of the τ.

Sources of background - $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

The following processes could appear very similar to the $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$ signal:

- **2 "combinatorial" τ**
- **2 true τ coming from 2 semileptonic $B_{(s)}$ decays**
- **1 or 2 $D_{(s)}^{(\star)}$ from 2 hadronic or semileptonic $B_{(s)}$ decays**

- studied using the sample of "dataSS" using all the Dalitz plane

- resonant: one hadronic or semileptonic $B_{(s)}$ decay with misID $D_{(s)}^{(\star)}$ (due to $D_{(s)}^{(\star)} \to \tau\nu_\tau X$)

- Monte Carlo generated samples for some of the resonant modes:

Decay chain	$\mathcal{B}$	$\mathcal{B}/\mathcal{B}_{sig}$
$B^0 \to D3\pi,\ D \to 3\pi\pi^0$	7.23×10^{-5}	1.19×10^4
$B^0 \to D^\star 3\pi,\ D^\star \to D\pi^0,\ D \to 3\pi\pi^0$	2.42×10^{-5}	3.98×10^3
$B^0 \to D^\star 3\pi\pi^0,\ D^\star \to D\pi^0,\ D \to 3\pi\pi^0$	6.10×10^{-5}	1.00×10^4
$B^0 \to D^\star \omega\pi,\ D^\star \to D\pi^0,\ D \to 3\pi\pi^0,\ \omega \to 2\pi\pi^0$	8.94×10^{-6}	1.47×10^3
$B_s \to D_s\tau\nu,\ D_s \to \tau\nu,\ \tau \to 3\pi\nu$	4.70×10^{-6}	7.01×10^2
$B_s \to D_s 3\pi,\ D_s \to \tau\nu$	3.28×10^{-5}	5.40×10^3
$B^+ \to D^\star 3\pi\pi^0,\ D^0 \to K3\pi$	1.45×10^{-3}	2.38×10^5
$B^+ \to D^\star 3\pi\pi^0,\ D^0 \to K3\pi\pi^0$	7.56×10^{-2}	1.24×10^7
$B^0 \to D\tau\nu,\ D \to \tau\nu$	1.14×10^{-7}	1.87×10^1
$B^0 \to D\tau\nu,\ D \to 3\pi\pi^0$	1.15×10^{-5}	1.89×10^3

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

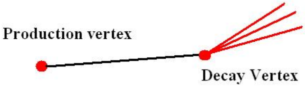
In the events we select we know the following quantities:

- B origin vertex
- 3d sides of triangle $\overrightarrow{w}_\pm$
- 4-momenta $p^\mu_\pm$ of $(3\pi)_\pm$ system

Let's assume that the pattern we observe is generated by a $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$ chain.

Can we reconstruct two τ candidates momenta?

Preliminar example. 1D case:



- τ production and decay vertexes are known $\Rightarrow$ τ flight direction is known
- 4 unknowns: the p^μ_τ momentum components
- the norm of the τ momentum is defined up to a twofold ambiguity
- technique used for the τ momentum reconstruction in the $H \to \tau\tau$ searches

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

What about the case with 2 τ, when their production point is not known?

In this case we have to fix 2 4-vectors p^{μ}_{+}, p^{μ}_{-} $\Rightarrow$ 8 unknowns

A first attempt was suggested in Anne Keune's doctoral thesis (reported also in [LHCb-INT-2011-039]):

expressing the 2 τ momenta in cartesian coordinates in 3D space (**non covariant** approach) and imposing:

- B, τ, ν mass constraints
- momentum conservation in $B_s \to \tau\tau$ & planarity of the decay

the solution of the problem is (one of) the root of a 8^{th} **degree polynom**.

Still some issues:

- no analytic solutions
- numerical instability
- no more than 4 solutions: why?
- no variables related to the invariant mass: only the B_s & $\tau_{\pm}$ decay time

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

We propose a slightly different approach, differing from the previous one in the following point:

- keep **manifest Lorentz-covariance**
- **different choice of unknown** momenta

Let's define:

$$W^\mu_\pm \equiv (w^0_\pm, \vec{w}_\pm) \tag{1}$$

and

$$W \equiv (W^\mu_+, W^\mu_-) \quad , \quad P \equiv (p^\mu_+, p^\mu_-) \tag{2}$$

We have that (from momentum conservation in $B \to \tau\tau$ and 4-velocity definition)

$$W = H \cdot P \tag{3}$$

with

$$H \equiv \begin{pmatrix} \hat{\tau_B} + \hat{\tau_+} & \hat{\tau_B} \\ \hat{\tau_B} & \hat{\tau_B} + \hat{\tau_-} \end{pmatrix} = \hat{\tau_B} \cdot \begin{pmatrix} 1 + t_+ & 1 \\ 1 & 1 + t_- \end{pmatrix} \tag{4}$$

being $\hat{\tau}_i \equiv \frac{\tau_i}{m_i}$ and $t_\pm \equiv \frac{\hat{\tau}_\pm}{\hat{\tau}_B}$.

H is Lorentz-invariant!

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

H is a real 2×2 symmetric matrix. Let's diagonalize it:

$$H = R(\theta) \cdot D_\lambda \cdot R^{-1}(\theta) \tag{5}$$

being

$$D_\lambda \equiv \hat{\tau}_B \cdot \begin{pmatrix} \lambda_+ & 0 \\ 0 & \lambda_- \end{pmatrix} \quad , \quad R(\theta) \equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

3 parameters in total: $(\theta, \lambda_+, \lambda_-)$. What is their physical "meaning" ?

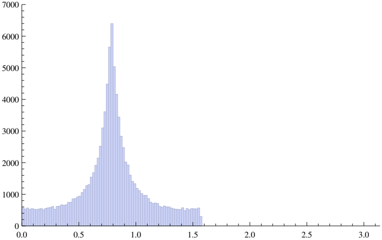
Let's look at some **limit case**:

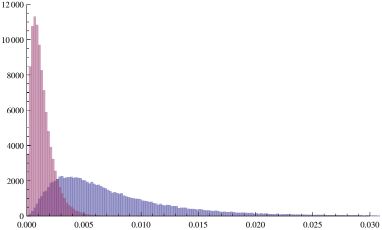
- if $t_+ = t_- \equiv \delta$ we have $(\theta = \frac{\pi}{4}, \lambda_+ = 2 + \delta, \lambda_- = \delta)$
- if $\delta = 0$ H is not invertible: both τ are created and decay at the *same* moment $\Rightarrow$ no triangle
- if $t_+ \neq t_-$ we have $\cos(\theta) \simeq \cos(\frac{\pi}{4}) + \mathcal{O}(t_+ - t_-)$

θ is a measure of the asymmetry of the triangle in the proper time dimension of each τ

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

Distribution of the θ angle for Monte Carlo generated signal events





Distribution of the 2 eigenvalues λ_+ & λ_- for Monte Carlo generated signal events

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

Using the "rotated" sides & momenta

$$\tilde{W} \equiv R^{-1}(\theta) \cdot W \quad , \quad \tilde{P} \equiv R^{-1}(\theta) \cdot P \tag{6}$$

and imposing

- mass-shell condition for $p_\pm$
- the constraint on the direction of $\vec{\tilde{p}}_\pm$
- the constraint on $(p^\mu \cdot p_\mu^{(3\pi)})_\pm$

we end up with a system of **2 equations of 2^{nd} degree in two unknowns x & y** (the norm of $\vec{\tilde{p}}_\pm$) to be solved as a function of the parameter θ:

$$\begin{cases} P_\theta^{(2)}(x,y) = 0 \\ Q_\theta^{(2)}(x,y) = 0 \end{cases}$$

Two possibility to solve this system:

- solve for $x(\theta)$ & $y(\theta)$ and fix θ using the constraint on $p_+^\mu \cdot p_{-\mu}$.
- substitute θ with its average value $\overline{\theta} = \frac{\pi}{4}$ (*i.e.* same decay time of the 2 τ) $\Longleftarrow$

Signal reconstruction for $B_s \to \tau\tau \to (3\pi\nu)(3\pi\nu)$

Solving the previous system we end up with an equation on x in the form

$$A \cdot x^4 + B \cdot x^3 + C \cdot x^2 + Dx + E = 0 \quad (7)$$

where A, B, C, D, E are functions of the observables and the average value $\overline{\theta}$.

- being a 4^{th} degree polynom solutions are analytical
- for signal events there must exist at least one real positive solution
- even if, due to
  - detector resolution
  - approximation $\theta \to \overline{\theta}$
  - γ-radiation in the final state

  eq.(7) doesn't have real solutions, imaginary solutions and quantities related to them could still help to discriminate signal *vs* background
- the coefficients A, B, C, D, E could already be used as discriminating variables
- also the discriminants from which depends the existence of real positive solutions of (7)

Aspects to improve:

- find the optimal set of variables to be used for sig-bkg discrimination
- find a better approximation of the θ angle as a function of measurables quantities

Conclusions

- A lot of work going on to set un upper limit on the $\mathcal{B}(B_s \to \tau\tau)$
- Only a part of the effort devoted to this search has been presented today.
  - definition and optimization of topological & geometrical variables
  - development of new tools for the topological reconstruction of each events
  - development of Multi Variate Analysis selection chain
- The measure is really challenging and requires a good understanding both of the combinatorial background and of the resonant decays
  - all the $3.1f^{-1}$ collected during the Run I of LHC is being analyzed
  - an upper limit of $\mathcal{O}(10^{-3})$ should be reachable with the current dataset
  - to improve this limit the crucial point is the understanding of the exclusives modes
- LHCb is the only experiment which will be able to perform this kind of measurement in the coming 20 years
  - Belle II will not have enough statistics
  - the general purpose LHC experiments (CMS & ATLAS) do not have a dedicated trigger

Thanks for your attention !