Beyond the Standard Model invisible particle searches in τ lepton decays

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Motivation

Observed phenomena:

- Matter - antimatter asymmetry
- Neutrino masses
- Dark matter

↓

Physics Beyond the SM

↓

Searches for new physics

Motivation

Where to look for BSM Physics?

Differences from the SM

New particles

- Axionlike particles
- Z' gauge boson
- Dark photons

τ sector:
LFV decays such as $\tau \to l\alpha$

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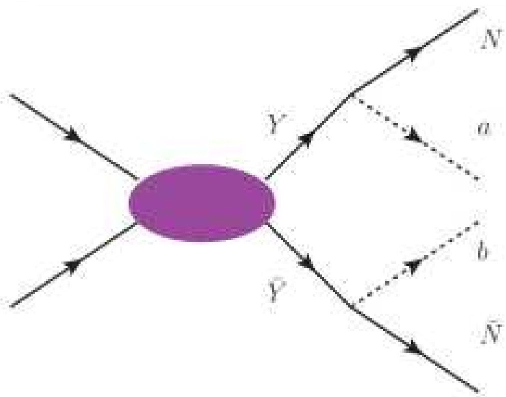
Motivation

Previous Methods

How to look for BSM Physics?



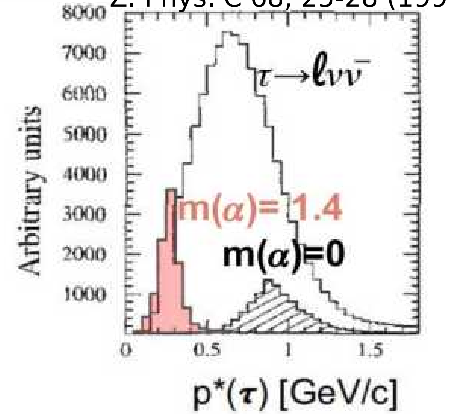
$Y\bar{Y} \rightarrow (a+N)(b+\bar{N})$

Suitable for lepton colliders.

Issue: require both, Y and $\bar{Y}$, decays to include the BSM invisible particle, and as consequence a large data sample to be able to perform a sensible study.

10.1103/PhysRevD.90.114029
10.1103/PhysRevLett.108.181805
10.1103/PhysRevD.95.075037

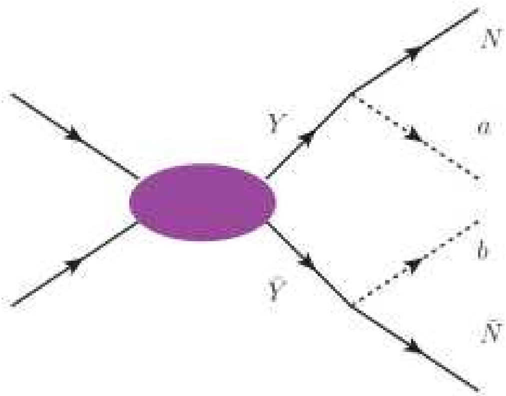
Z. Phys. C 68, 25-28 (1995)



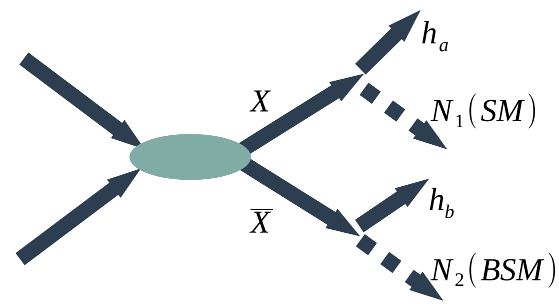
$\tau \rightarrow l \; \alpha$

Spectrum of the lepton in the τ pseudo rest frame.
Issue:
Overlap of kinematic region with the bkg distribution: low discrimination power.
Approximate the boost direction: smearing effect.

Our proposal



$$Y\bar{Y} \rightarrow (a+N)(b+\bar{N})$$



$$X\bar{X} \rightarrow (h_a+N_1)(h_b+N_2)$$

h_a, h_b: visible final state particles.

N_1, N_2: particles that evade detection.

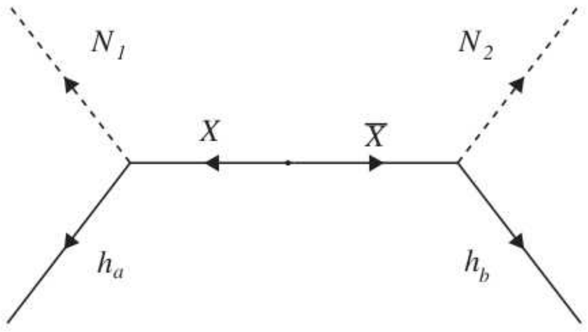
This generalization allows to study XX pair decays with BSM processes in one decay, and SM processes with missing particle in the complementary decay (such as τ lepton decays).

This the increase the possibility of a BSM particle production compared to requiring a double creation of the unknown particle.

Our proposal

Kinematic constraints

$X\bar{X} \to (h_a + N_1)(h_b + N_2)$



At CMS energy $\sqrt{s}$

$$p_a = (E_a, \vec{p}_a)$$
$$p_b = (E_b, \vec{p}_b)$$
$$p_1 = (E_1, \vec{p}_1)$$
$$p_2 = (E_2, \vec{p}_2)$$

The kinematic equations:

$$q^\mu = p_a^\mu + p_b^\mu + p_1^\mu + p_2^\mu, \ \mu = 0,1,2,3$$

$$p_{1,2}^2 = m_{1,2}^2$$

$$(p_a + p_1)^2 = (p_b + p_1)^2 = m_X^2$$

After some algebra:

$$A_1(\mu_X^2 - \mu_1^2)^2 + A_2(\mu_X^2 - \mu_2^2)^2 + A_3(\mu_X^2 - \mu_1^2)(\mu_X^2 - \mu_2^2) + B_1(\mu_X^2 - \mu_1^2) + B_2(\mu_X^2 - \mu_2^2) + C_1\mu_1^2 + D_1 \leqslant 0$$

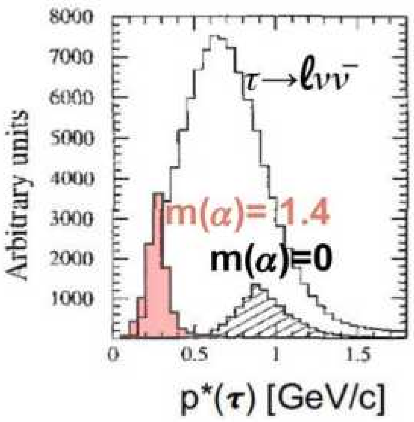
μ_i is the normalized mass of the i-th particle.

Summarize the available kinematics information of the decay $X\bar{X} \to (h_a + N_1)(h_b + N_2)$

Use case

Search for the lfv decay $\tau \to l\,\alpha$.

ARGUS



$\tau \to l\ \alpha$

Z. Phys. C 68, 25-28 (1995)

Challenges:
- Same detector signature of the BSM signal and the lνν SM process.
- Estimate the τ rest frame: introduce an smearing effect,

From our main result we can construct other methods to perform this search.
Consider the process:

$(e^+e^- \to \tau^+\tau^-) \to (\tau^+ \to \pi^+\pi^-\pi^+\nu)(\tau^- \to e^-\alpha)$

In this case:
$\mu_1 = \mu_\alpha$, $\mu_2 = \mu_\nu = 0$ and $\mu_X = \mu_\tau$
We have:

$$A_0(\mu_\alpha^2)^2 + B_0\mu_\alpha^2 + C_0 \leq 0$$

Hence:

$$M_{min}^2 \leqslant m_\alpha^2 \leqslant M_{max}^2$$

Where:

$$M_{min}^2 = (\sqrt{s})^2\left(\frac{-B_0 - \sqrt{(B_0^2 - 4A_0C_0)}}{2A_0}\right)$$

$$M_{max}^2 = (\sqrt{s})^2\left(\frac{-B_0 + \sqrt{(B_0^2 - 4A_0C_0)}}{2A_0}\right)$$

New discriminating variables

Use case

Search for the lfv decay $\tau \rightarrow l\,\alpha$.

To study the performance of our new variables at the energies of the Belle II experiment, we simulate:

$$e^+ e^- \rightarrow \tau^+ \tau^+$$

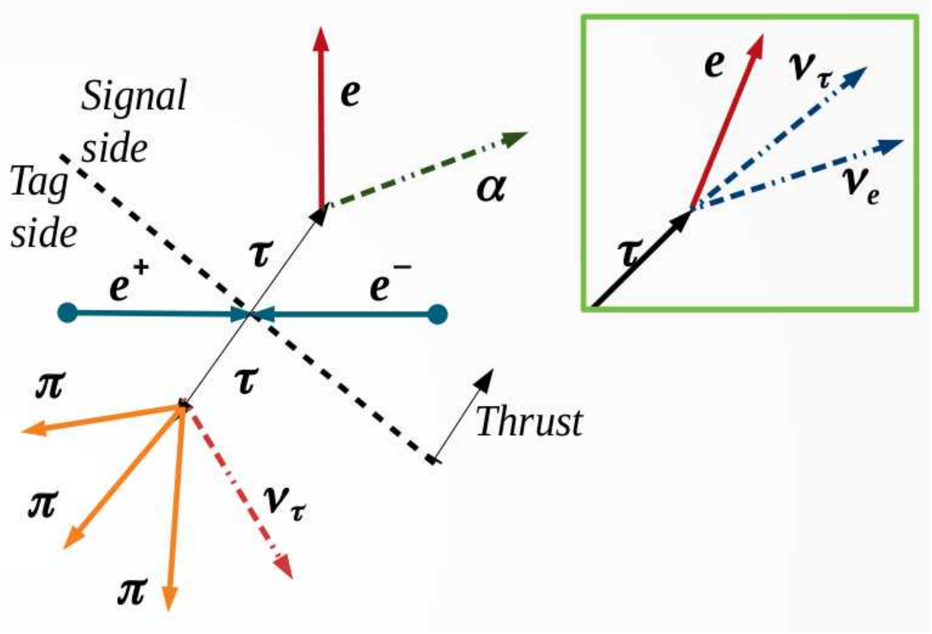
$$e^+ e^- \rightarrow q\bar{q}$$

at

$$\sqrt{(s)} = 10.58\,GeV$$

PYTHIA 8 and *ROOT*

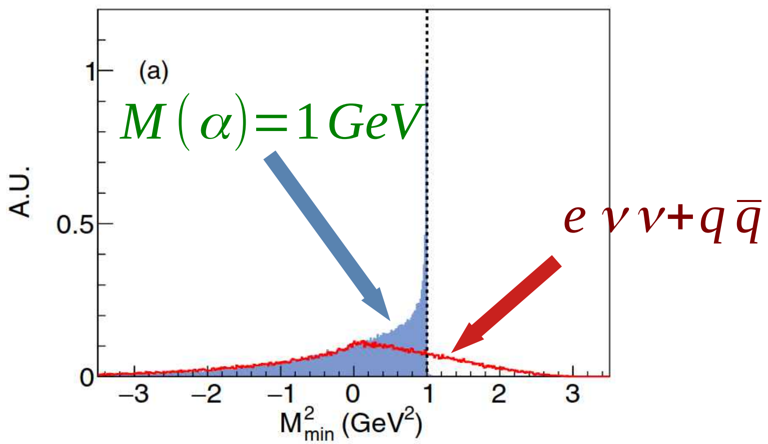
The number of expected events was estimated acording to the cs reported by Belle II.

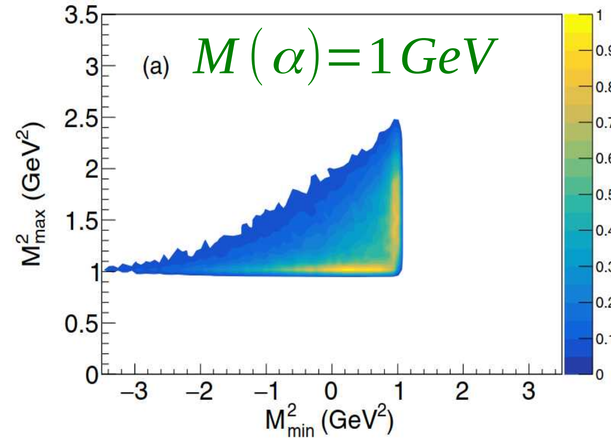


Event selection

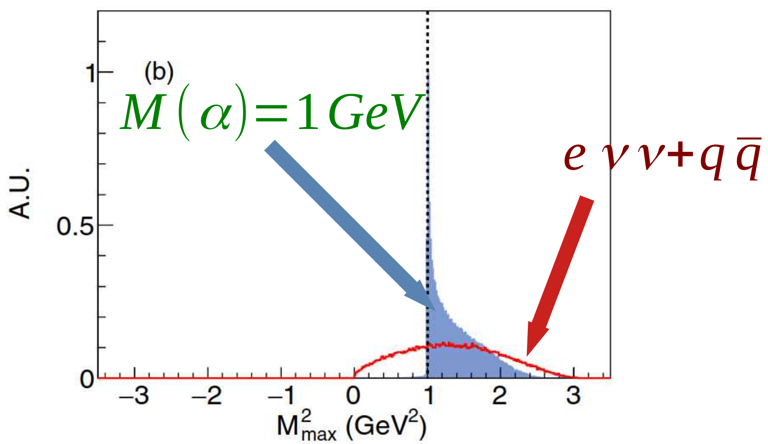
3 x 1 prong events
4 tracks in the event

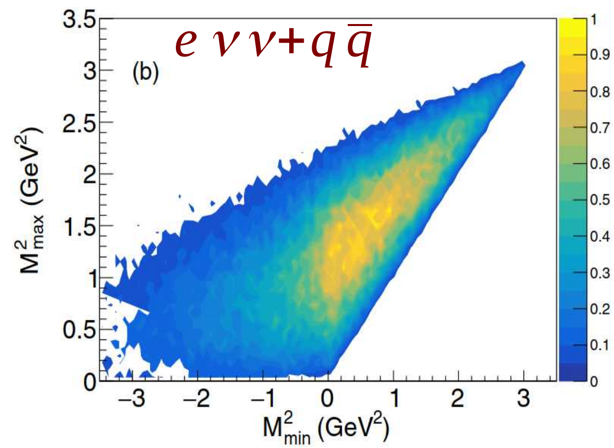
Use case





No direct correlation





Correlation

The signal production is set to an equal number of background events.

The striking differences between signal and background distributions will allow us to disentangle them.

Use case

Relative production measurement

Physical processes

Signal channel: $\tau \rightarrow e\,\alpha$
Normalization channel: $\tau \rightarrow e\,\nu\,\nu$
Background $\tau^{+}\tau^{-}$ and $q\,\bar{q}$
Our data can be modeled as:

$$f(x)=\frac{N_{\nu}\mu\frac{\epsilon_{\alpha}}{\epsilon_{\nu}}S_{\alpha}(x)+N_{\nu}S_{\nu}(x)+N_{b}B(x)}{N_{\nu}\mu\frac{\epsilon_{\alpha}}{\epsilon_{\nu}}+N_{\nu}+N_{b}}$$

where:

$$\mu=\frac{BR(\tau\rightarrow e\,\alpha)}{BR(\tau\rightarrow e\,\nu\,\nu)} \qquad (\text{what we want to measure})$$

Discriminating variables: $M_{min}^{2}, M_{max}^{2}, M_{min}^{2}\times M_{max}^{2}$.

Use case

Relative production measurement

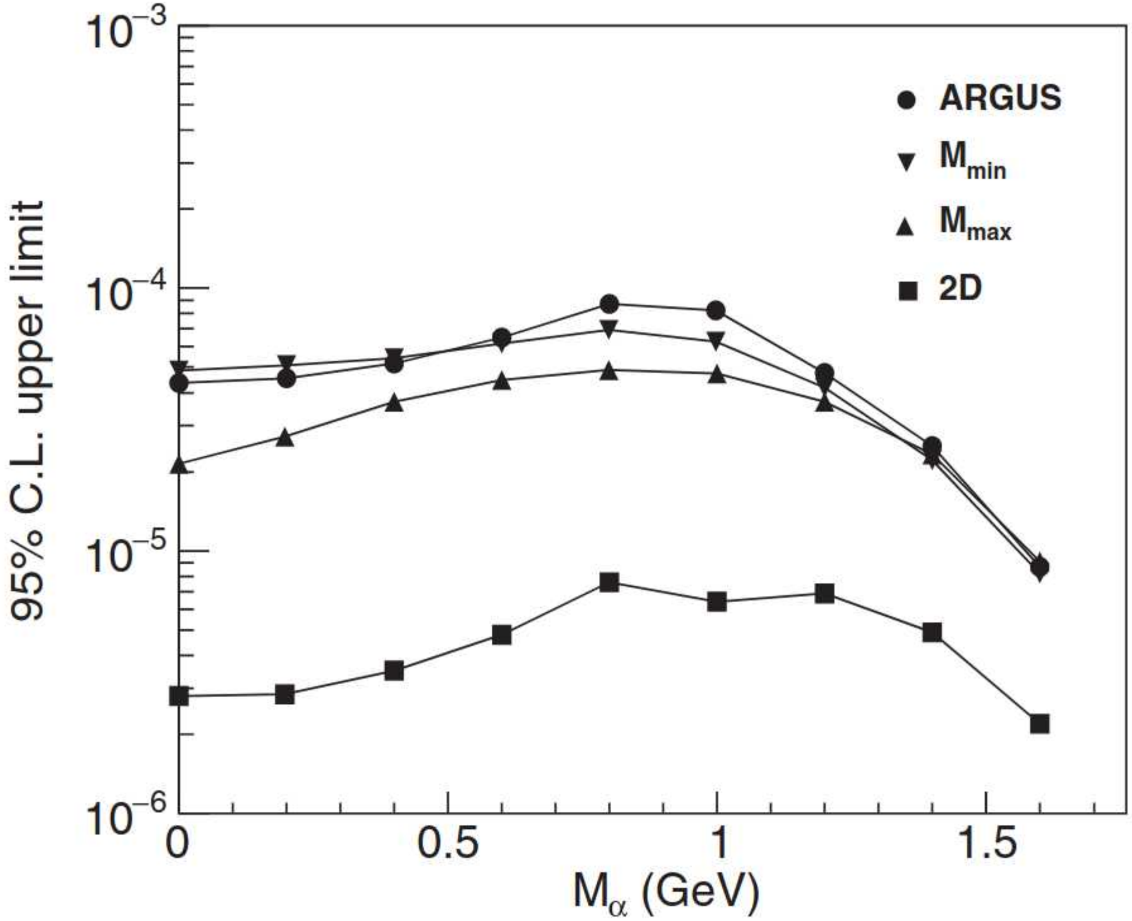
We compare the performance of 4 different methods by estimating an ul on the relative production μ at $95 C.L.$

- -The ARGUS method: $x = 2 E_l / m_\tau$
- -The M^2_{min}
- -The M^2_{max}
- - $M^2_{min} \times M^2_{max}$

For this we simulate a bkg only data set corresponding to $50\, ab^{-1}$.

Use case

Results

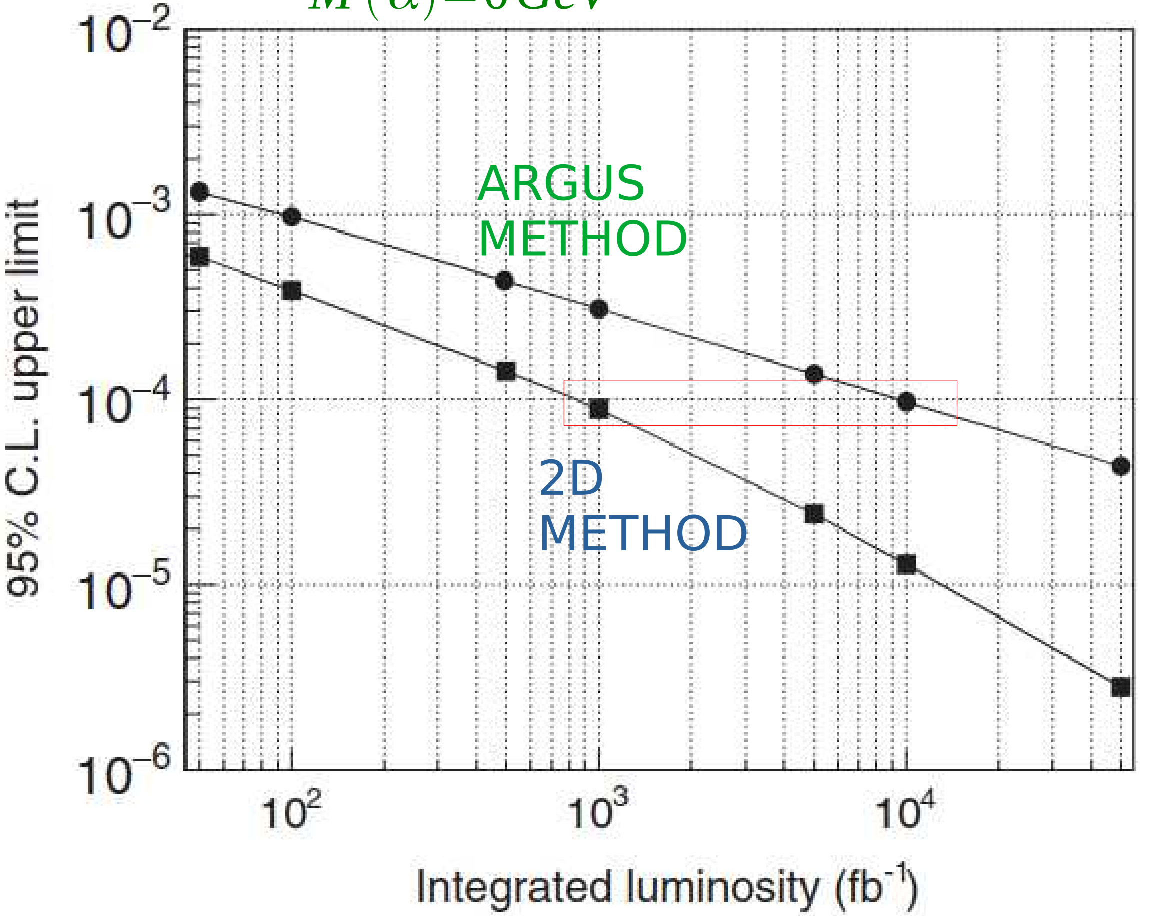


- $M(\alpha) = 0 - 1.6\,GeV$
- The performance of the $1D$ methods is similar.
- The $2D$ method produces a much better result than any of the other three methods alone.

Use case

Results

$M(\alpha)=0\,GeV$



Ul at 95% C.L. on μ as function of the integrated luminosity.

For L=50 ab^{-1} an ul one order of magnitude better could be set with the 2D method as compared with the ARGUS method.

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Conclusions

- We studied the kinematics of pair decays for a well known center-of-mass energy when in each decay one of the produced particles escapes detection.

- As result, we propose new variables with a better statistical discriminating power (as compared with the commonly used ARGUS method) to search for BSM invisible particles in τ lepton decays.

New method for beyond the Standard Model invisible particle searches in tau lepton decays

E. De La Cruz-Burelo, A. De Yta-Hernandez, and M. Hernandez-Villanueva
Phys. Rev. D **102**, 115001 – Published 1 December 2020

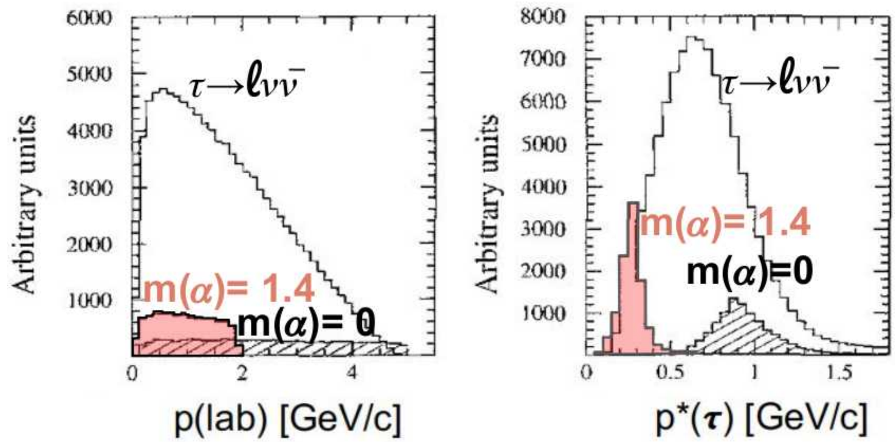
- Status of the $\tau \rightarrow l \alpha$ analysis @ Belle II on Friday during the τ session by Thomas (Tau physics prospects at Belle II).

Backup

Search for the LFV decay channels :

$\tau \rightarrow e\,\alpha$ and $\tau \rightarrow \mu\,\alpha$

being α a BSM unobservable particle.



Previous measurements

→ *Mark III* $(85,\ 9.4\,pb^{-1})$

→ *ARGUS* $(95,\ 472\,pb^{-1})$

Study the momentum spectrum of the lepton in the τ pseudo rest frame. Here the lepton momentum distribution is shaped as a peak with a position depending on the α mass.

Fit the distribution and set an upper limit on $Br(\tau\rightarrow l\,\alpha)/Br(\tau\rightarrow l\,\nu\,\bar{\nu})$.