Search for LFV $\tau \to \ell\alpha$ process in 1x1-prong topology using a novel technique at Belle II

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Overview

- Motivation
- State-of-the-art
- Search strategy
- Sensitivity study
- Data/MC – control channel

Motivation

Where to look for BSM physics?

Clear differences with the predictions of the SM

New particles

- Axion-like particles
- Z’ gauge bosons
- Dark matter particles

τ sector:
LFV decay

Motivation

- New invisible NPGB
- Could potentially solve several discrepancies in the SM
    - Mass structure of charged leptons
    - Neutrino oscillations
    - Strong CP problem
- DM candidate

State-of-the-art

Channel	Belle II (3x1 topology) UL ($\times 10^{-4}$)
Electron	(1.96 – 17.4)
Muon	(1.21 – 21.2)

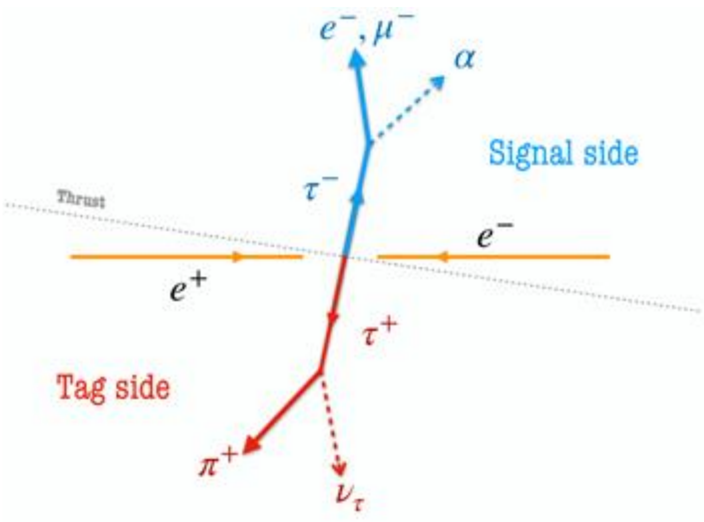
Phys. Rev. Lett. 130, 181803-Belle II

The standard model of particle physics successfully describes the electromagnetic, weak, and strong interactions and classifies all known elementary particles. However, phenomena such as neutrino oscillations, long-standing discrepancies between expectations and observations such as the muon magnetic-moment anomaly, and indirect evidence of dark matter clearly indicate that the standard model is incomplete. Many extensions of the standard model that attempt to incorporate these phenomena require new bosons that are candidates for dark matter or that explain the muon's anomalous magnetic moment [1].

Decays of τ leptons into final states involving light, beyond-the-standard-model bosons that are not directly detectable (invisible) are predicted in models with, e.g., axionlike particles [2–5]. These bosons are collectively referred to as α in this work. A direct search in $\tau^- \to \ell^- \alpha$, where ℓ^- indicates e^- or μ^-, can probe theories beyond the standard model with high sensitivity (charge-conjugated decays are implied throughout). This process was previously searched for by the MARK III [6] and ARGUS [7] collaborations. The current best upper limits on the $\tau^- \to \ell^- \alpha$ branching fractions, relative to the corresponding standard-model leptonic decays, are $\mathcal{B}(\tau^- \to e^- \alpha)/\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau) < (6 - 36) \times 10^{-3}$ and $\mathcal{B}(\tau^- \to \mu^- \alpha)/\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) < (3 - 34) \times 10^{-3}$ at the 95% confidence level (C.L.), where the range indicates their dependence on the α mass in the (0–1.6) GeV/c^2 [7] range.

Lepton Alpha search: Reconstruction

- **Signal side**: τ decay into ℓ+*invisible*
- **Tag side:** τ decay into π+*neutrino*



Event requirements and selection cuts

Track selection

- Originated from the interaction point (IP):
  - |*dz*| < 0.05 m and |*dr*| < 0.01 m
  - good tracks = 2

Gamma list

- -0.8660 < *cosTheta* < 0.9563 (in the CDC acceptance)
- E > 0.2 GeV
- *clusterNHits* > 1.5
- All photons with efficiency correction

-PhotonEfficiencyDataMCRatio_Run1MC15rd_April2024

π0's list

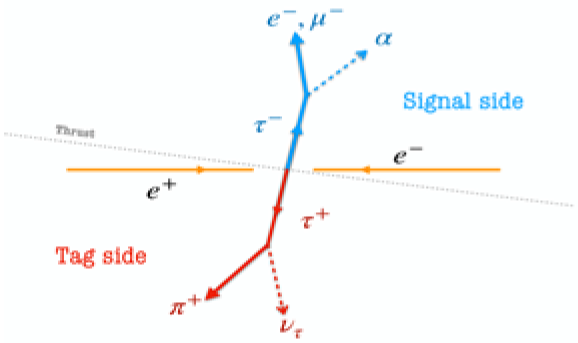
- same as gammas
- 0.115 < M < 0.152
- Correct the efficiency is a pending task

Electron channel

- signal side: $\tau^{\pm} \to e^{\pm} + \alpha$
  - *pid_BDT_e* > 0.9
  - $N_{\gamma}^{sig} = 0$
  - $N_{\pi_0}^{sig} = 0$
- tag side:
  - *pionID* > 0.9
  - $N_{\gamma}^{tag} = 0$
  - $N_{\pi_0}^{tag} = 0$

Muon channel

- signal side: $\tau^{\pm} \to \mu^{\pm} + \alpha$
  - *muonID_noSVD* > 0.9
  - $N_{\gamma}^{sig} = 0$
  - $N_{\pi_0}^{sig} = 0$
- tag side:
  - *pionID* > 0.9
  - $N_{\gamma}^{tag} = 0$
  - $N_{\pi_0}^{tag} = 0$



Mmin and *Mmax* variables

$$M_{min}^2 = \left(\sqrt{s}\right)^2 \left(\frac{-B_0 - \sqrt{B_0^2 - 4A_0 D_0}}{2A_0}\right),$$

$$M_{max}^2 = \left(\sqrt{s}\right)^2 \left(\frac{-B_0 + \sqrt{B_0^2 - 4A_0 D_0}}{2A_0}\right).$$

$$\begin{aligned}
A_1 &= |\mathbf{b}|^2, \\
A_2 &= |\mathbf{a}|^2, \\
A_3 &= 2(\mathbf{a}\cdot\mathbf{b}), \\
B_1 &= 2(\mathbf{b}\cdot\mathbf{H}), \\
B_2 &= 2(\mathbf{a}\cdot\mathbf{H}), \\
C_1 &= 4|\mathbf{a}\times\mathbf{b}|^2, \\
D_1 &= \mathbf{H}\cdot\mathbf{H} - 4|\mathbf{a}\times\mathbf{b}|^2\left(\frac{1}{2} - z_a\right)^2.
\end{aligned}$$

$$\begin{aligned}
A_0 &= A_1, \\
B_0 &= -B_1 + C_1 - (2A_1 + A_3)\mu_\tau^2, \\
C_0 &= (A_1 + A_2 + A_3)\mu_\tau^4 + (B_1 + B_2)\mu_\tau^2 + D_1.
\end{aligned}$$

$$\mathbf{H} \equiv \left(z_b^2 - z_b - |\mathbf{b}|^2 - 2\mathbf{a}\cdot\mathbf{b}\right)\mathbf{a} + \left(z_b^2 - z_b + |\mathbf{a}|^2\right)\mathbf{b},$$

"Measuring masses in semi-invisible final states at electron-positron colliders"
Qian-Fei Xiang, Xiao-Jun Bi, Qi-Shu Yan, Peng-Fei Yin, and Zhao-Huan Yu

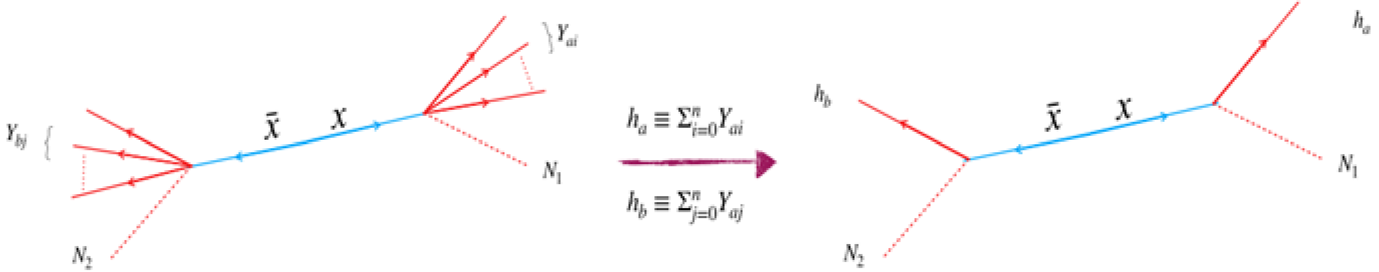
PhysRevD.95.075037

"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

"Measurement of the mass of the tau lepton in semi-invisible final states in the Belle II collaboration"
J. A. Colorado-Caicedo

BELLE2-MTHESIS-2023-007



Mmin and *Mmax* variables

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PhysRevD.95.075037

article searches in

nandez-Villanueva

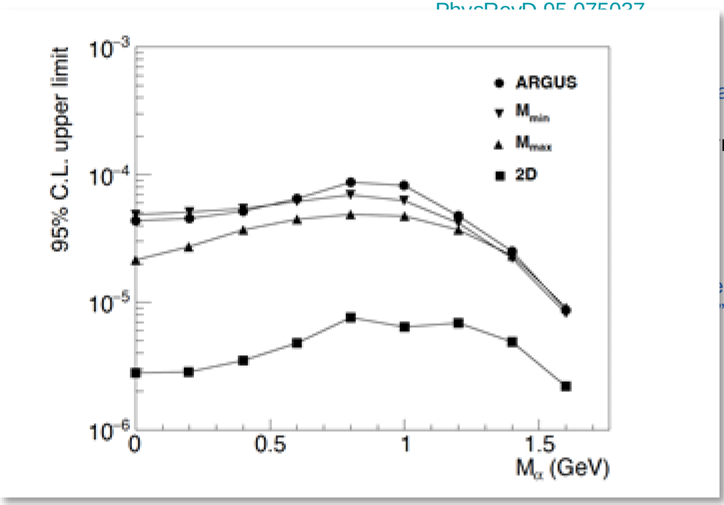
emi-invisible

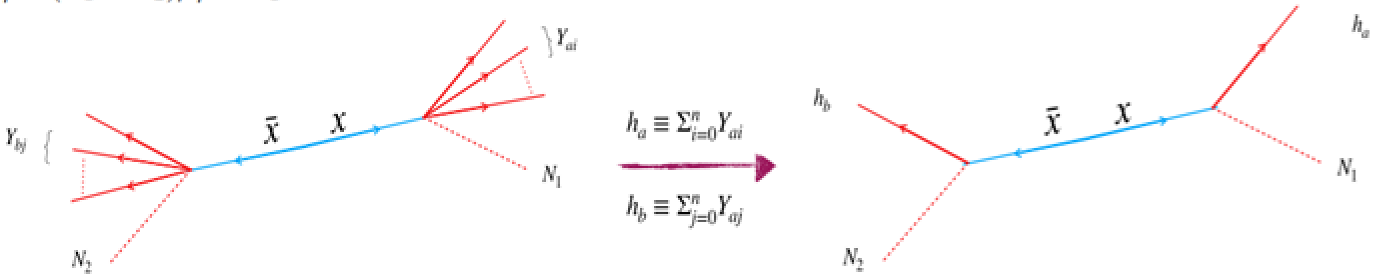
$$M^2_{min} = \left(\sqrt{s}\right)^2 \left(\frac{-B_0 - \sqrt{B_0^2 - 4A_0D_0}}{2A_0}\right),$$

$$M^2_{max} = \left(\sqrt{s}\right)^2 \left(\frac{-B_0 + \sqrt{B_0^2 - 4A_0D_0}}{2A_0}\right).$$

$$A_1 = |\mathbf{b}|^2,$$
$$A_2 = |\mathbf{a}|^2,$$
$$A_3 = 2(\mathbf{a}\cdot\mathbf{b}),$$
$$B_1 = 2(\mathbf{b}\cdot\mathbf{H}),$$
$$B_2 = 2(\mathbf{a}\cdot\mathbf{H}),$$
$$C_1 = 4|\mathbf{a}\times\mathbf{b}|^2,$$
$$D_1 = \mathbf{H}\cdot\mathbf{H} - 4|\mathbf{a}\times$$

$$A_0 = A_1,$$
$$B_0 = -B_1 + C_1 - (2A_1 + A_3)\mu_\tau^2,$$
$$C_0 = (A_1 + A_2 + A_3)\mu_\tau^4 + (B_1 + B_2)\mu_\tau^2 + D_1.$$





Selection cuts based on Simulated Annealing

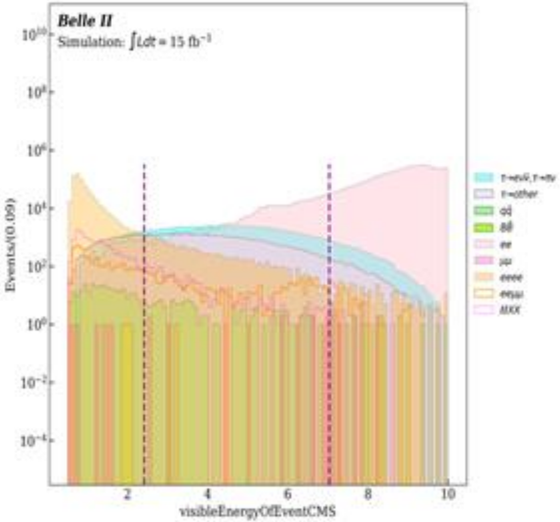
We optimized with $\tau \rightarrow \ell(e,\mu)\nu\nu$ as our "signal", due to the lack of a precise model for the decay $\tau \rightarrow \ell\alpha$.

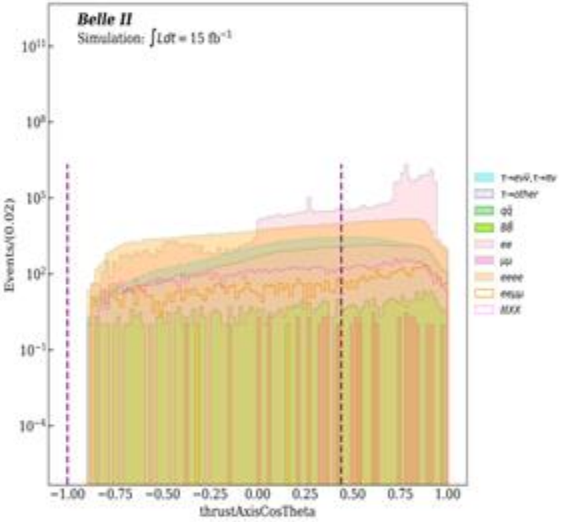
- 10 variables were used to extract the best cuts using the following FOM

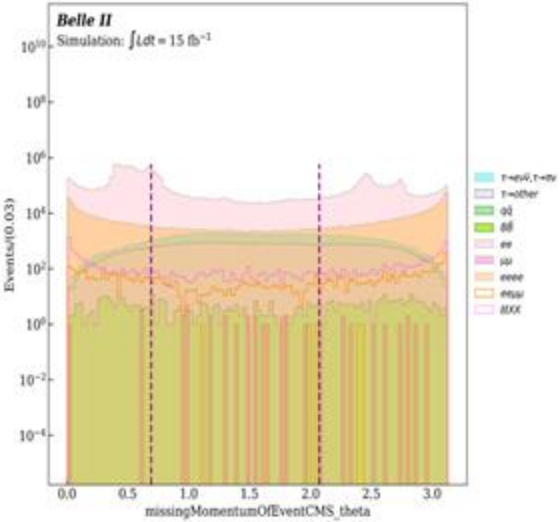
$$\frac{N_{sig}}{\sqrt{N_{sig} + 100(N_{bkg})}} \longrightarrow$$ *Purity-focused optimization**

*Another optimization with FOM = S/(S+B)^(1/2) was made, we stayed with the better performance

Selection cuts (e-channel)

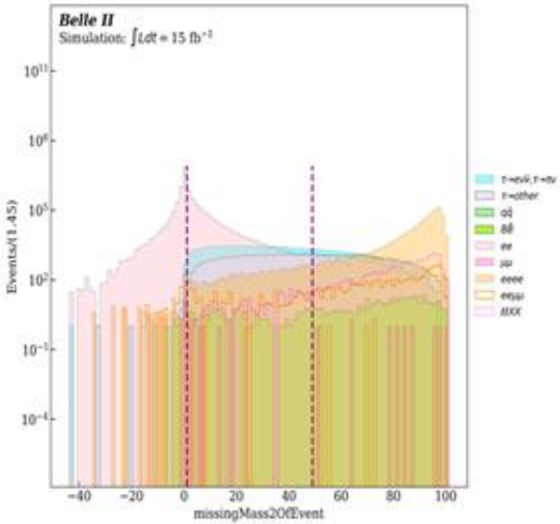


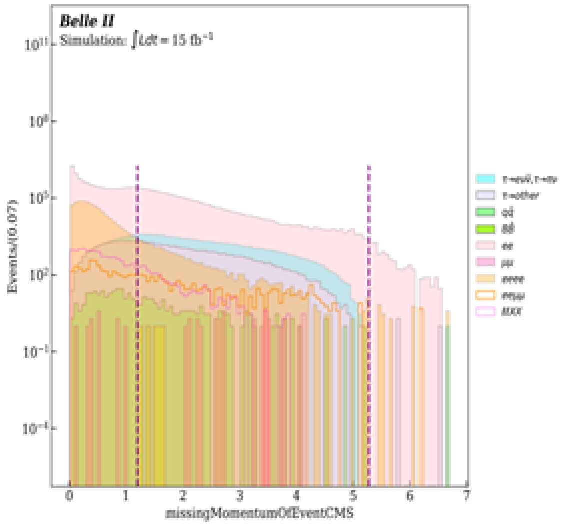




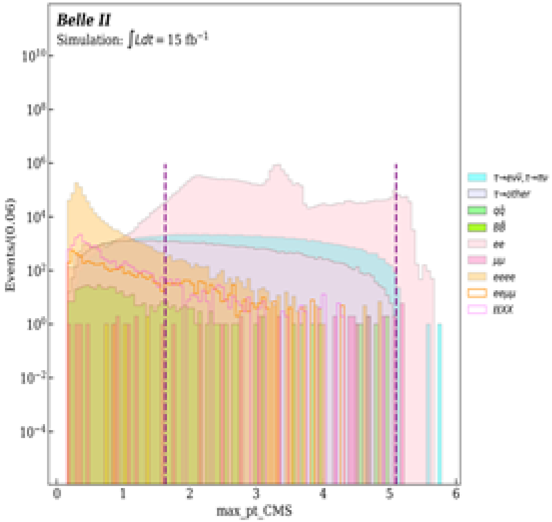
Luminosity: 15/fb

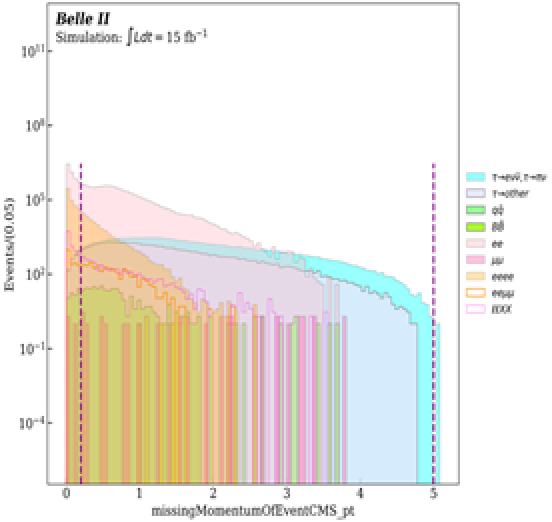
(Sample -> Events)
SM -> 118226
tau -> 59003
qqbar -> 446
mixed+charged -> 5
ee -> 10994800
eeee -> 624400
eemumu -> 4476
mumu -> 114
llXX -> 12528

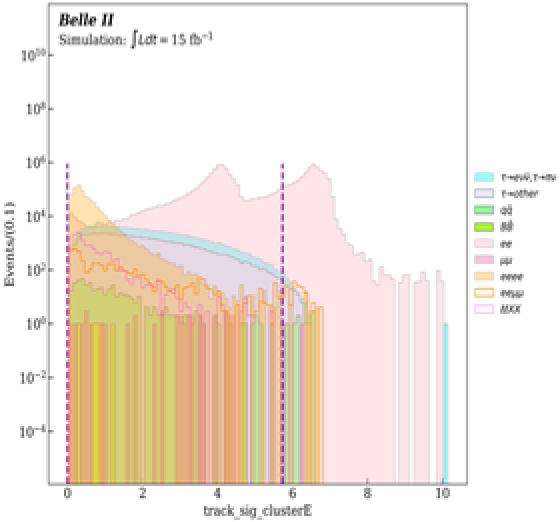




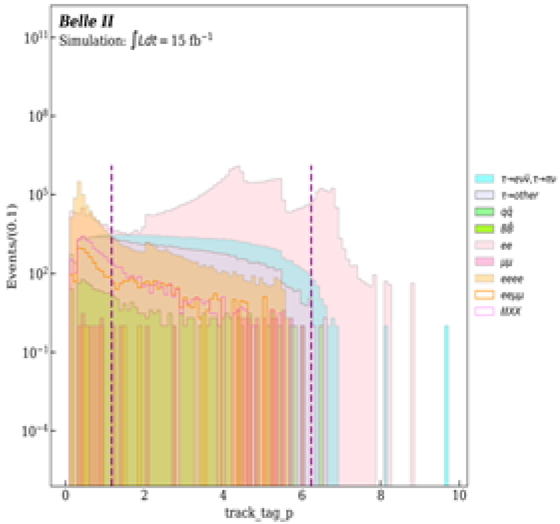
exp20_bucket26_v1

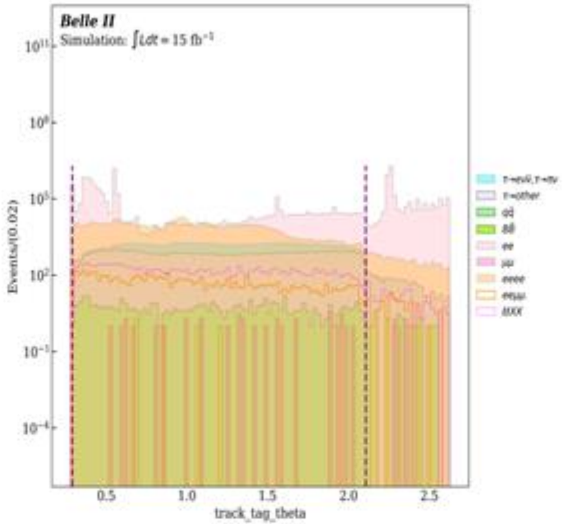






Luminosity: 15/fb
after cuts
(Sample -> Events)
SM -> 25610
tau -> 6768
qqbar -> 4
mixed+charged -> 0
ee -> 40
eeee -> 0
eemumu -> 8
mumu -> 0
llXX -> 64





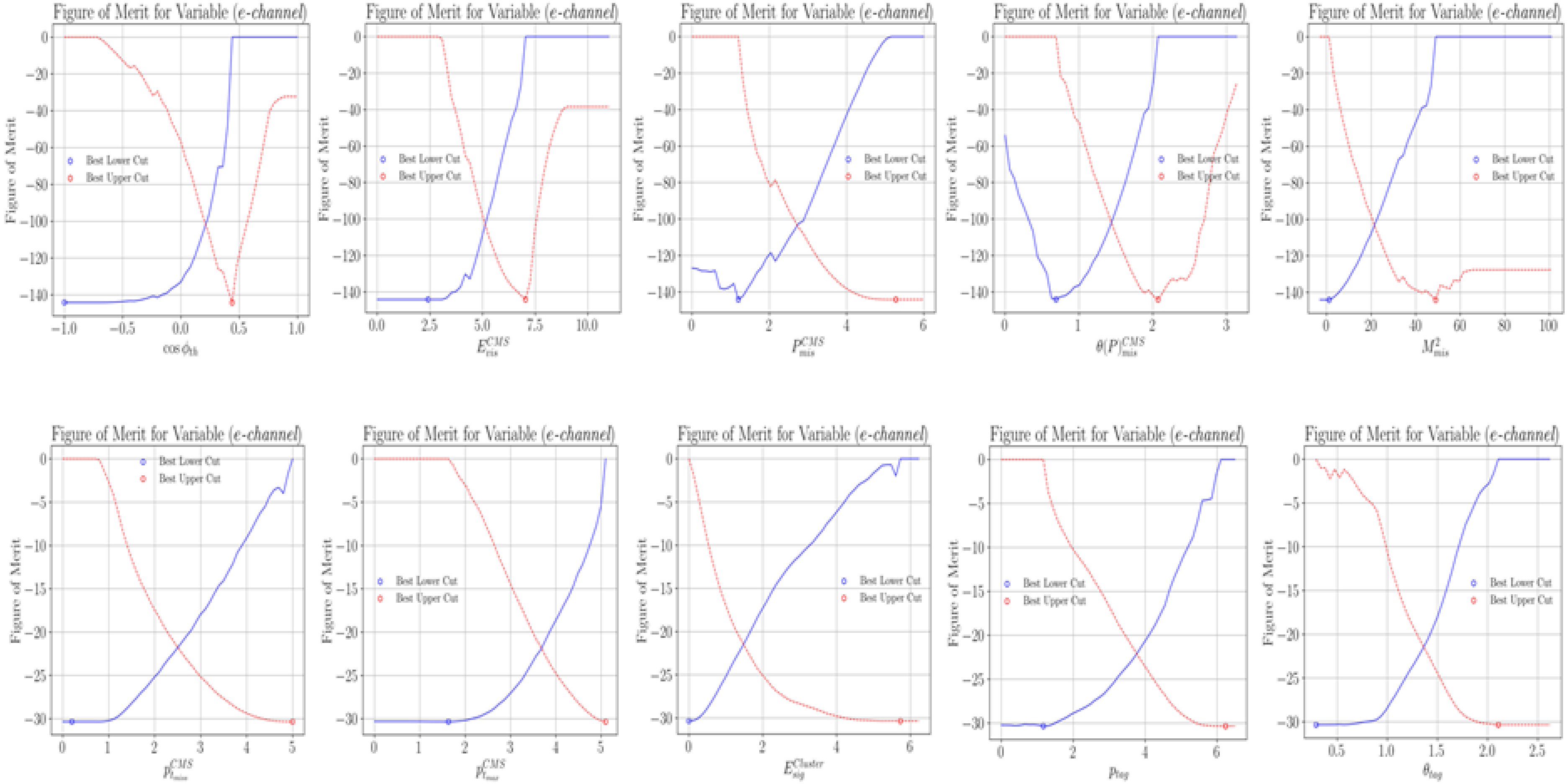
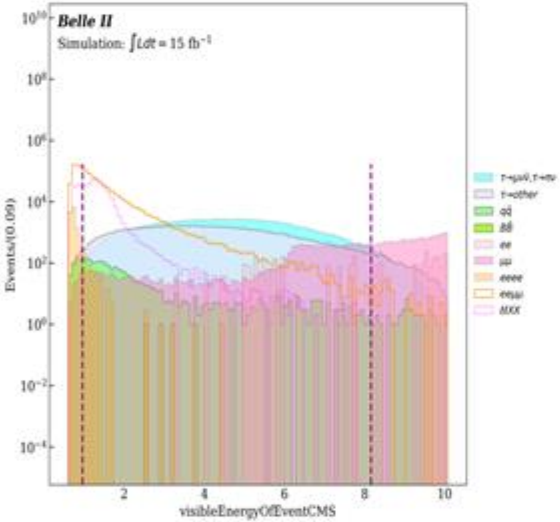
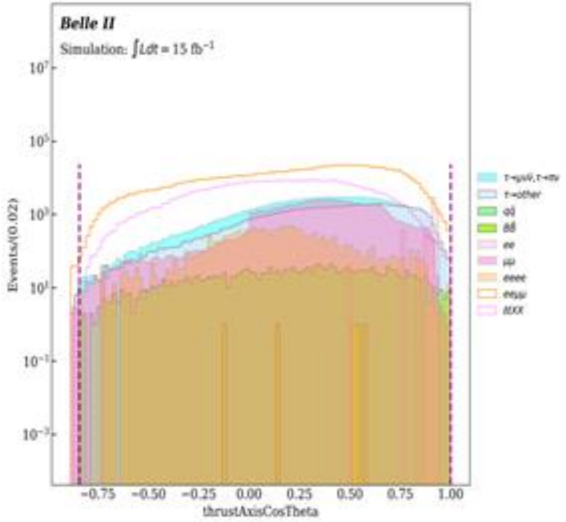
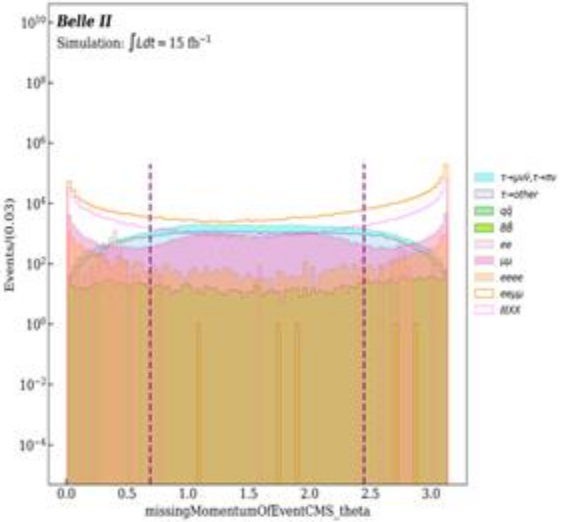


Figure of Merit for Variable (e-channel)
Figure of Merit
Best Lower Cut
Best Upper Cut
$\cos\phi_{th}$
E_{vis}^{CMS}
P_{mis}^{CMS}
$\theta(P)_{mis}^{CMS}$
M_{mis}^2
$p_{l_{min}}^{CMS}$
$p_{l_{max}}^{CMS}$
$E_{sig}^{Cluster}$
p_{tag}
θ_{tag}

Selection cuts (μ-channel)

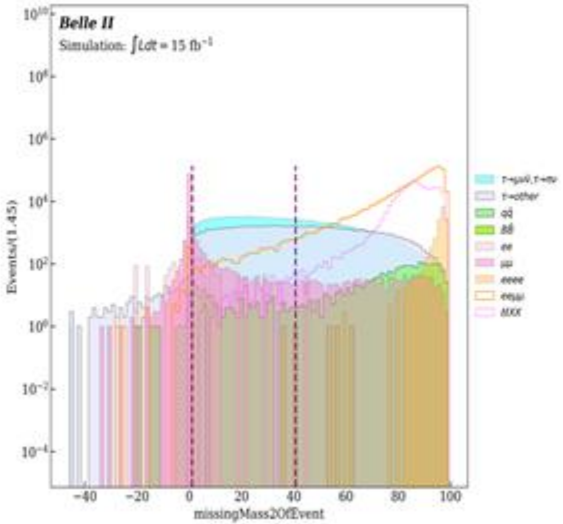


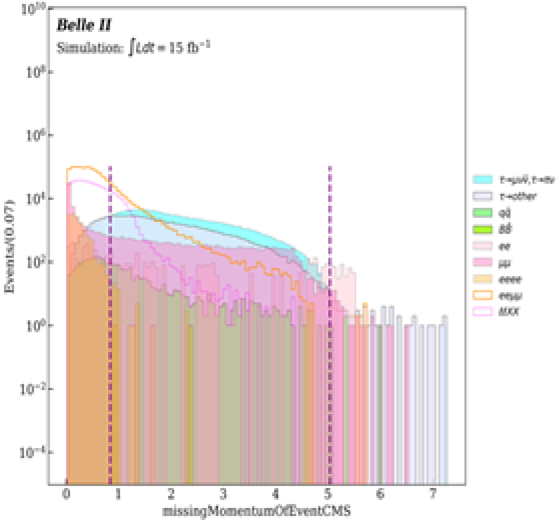


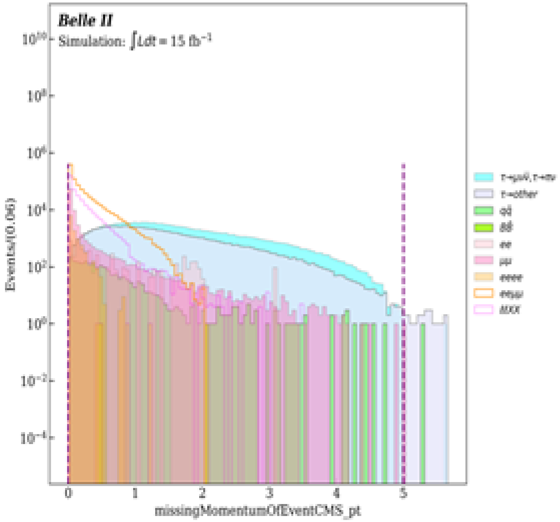


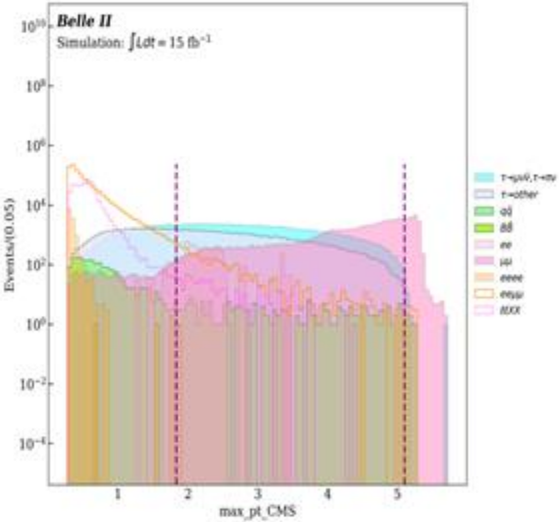
Luminosity: 15/fb

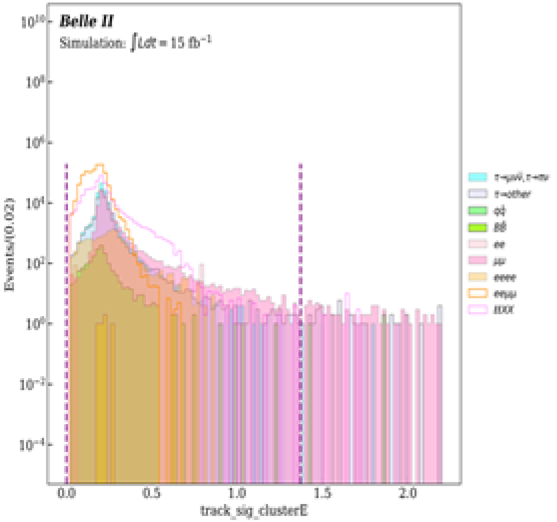
(Sample -> Events)
SM -> 125581
tau -> 79716
qqbar -> 2400
mixed+charged -> 5
ee -> 5360
eeee -> 13824
eemumu -> 1048740
mumu -> 81566
llXX -> 408196



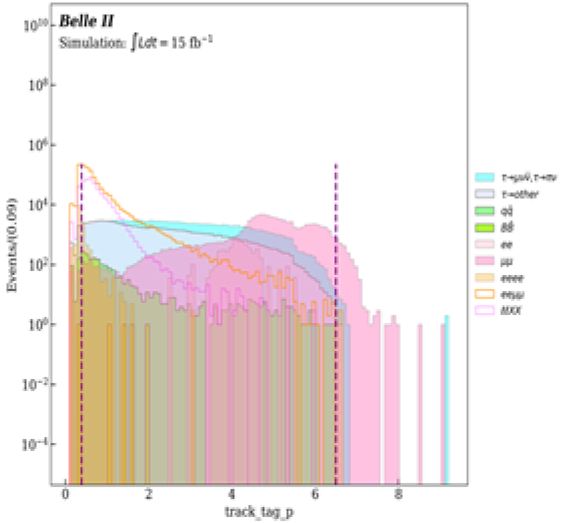


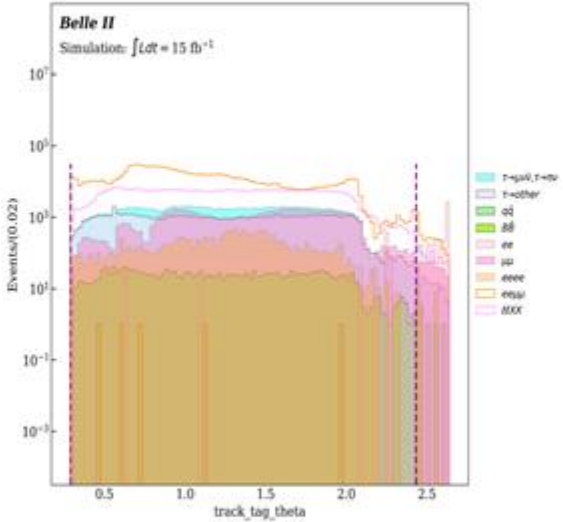






Luminosity: 15/fb
after cuts
(Sample -> Events)
SM -> 56677
tau -> 23838
qqbar -> 44
mixed+charged -> 0
ee -> 0
eeee -> 0
eemumu -> 56
mumu -> 70
llXX -> 156





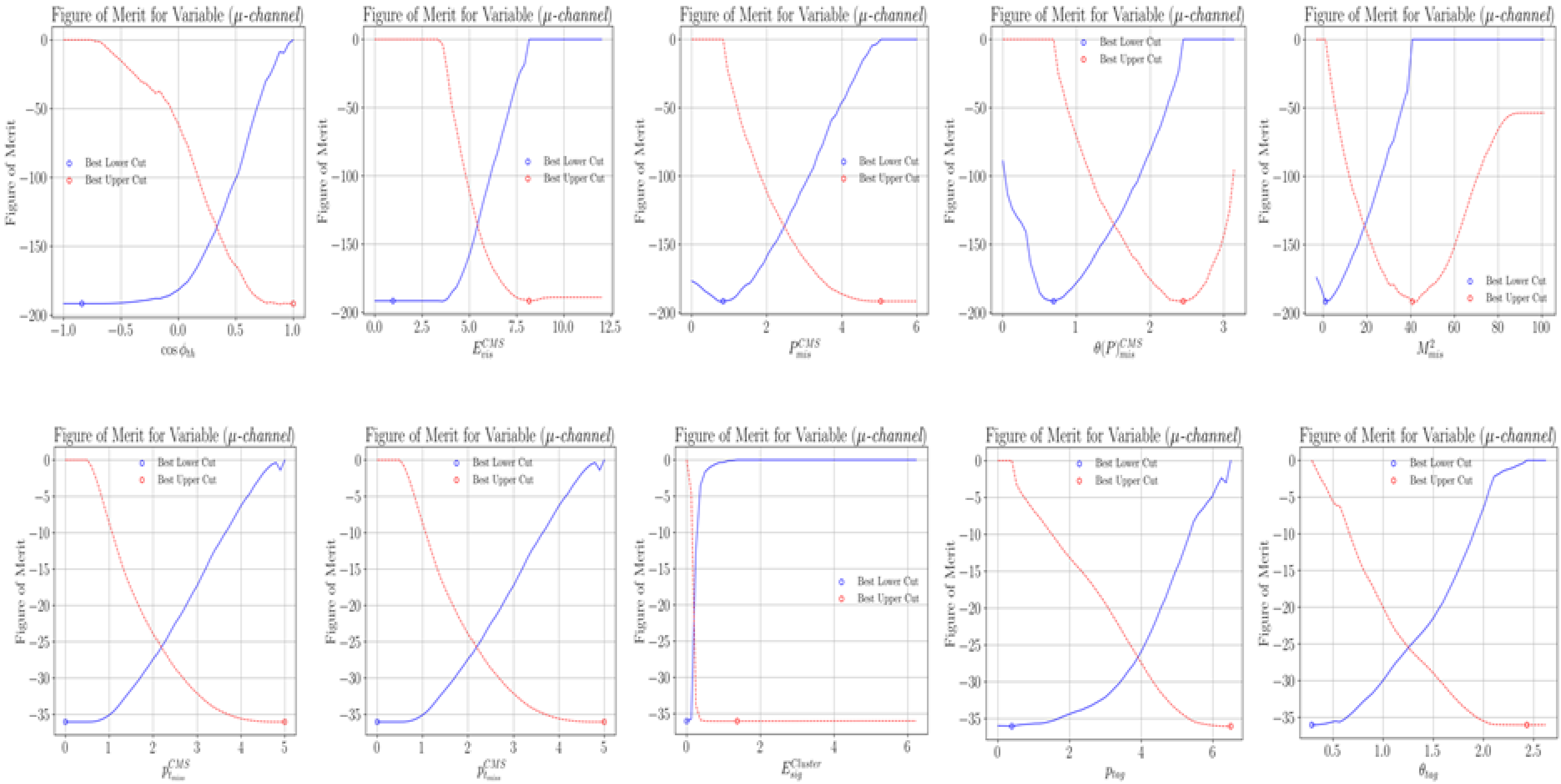
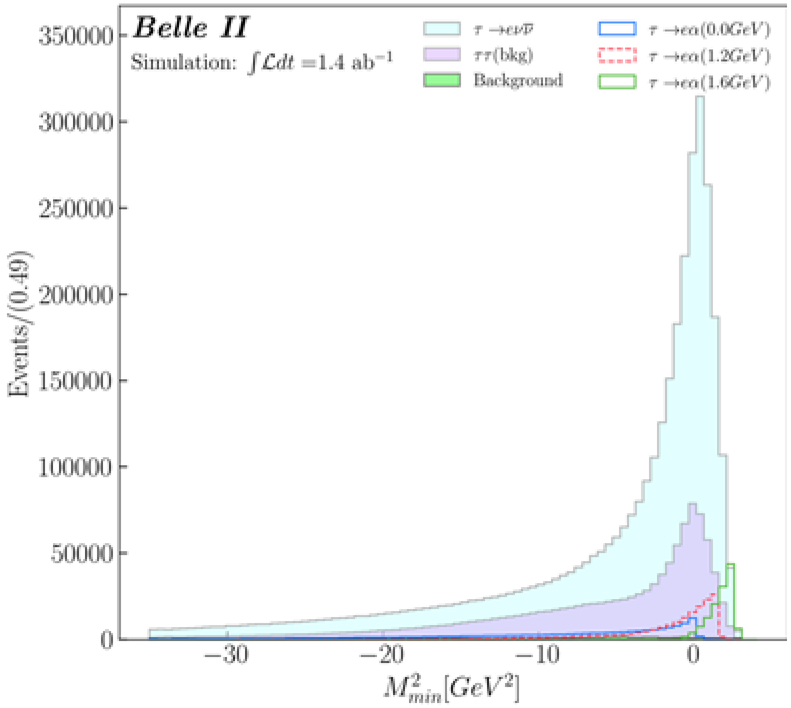
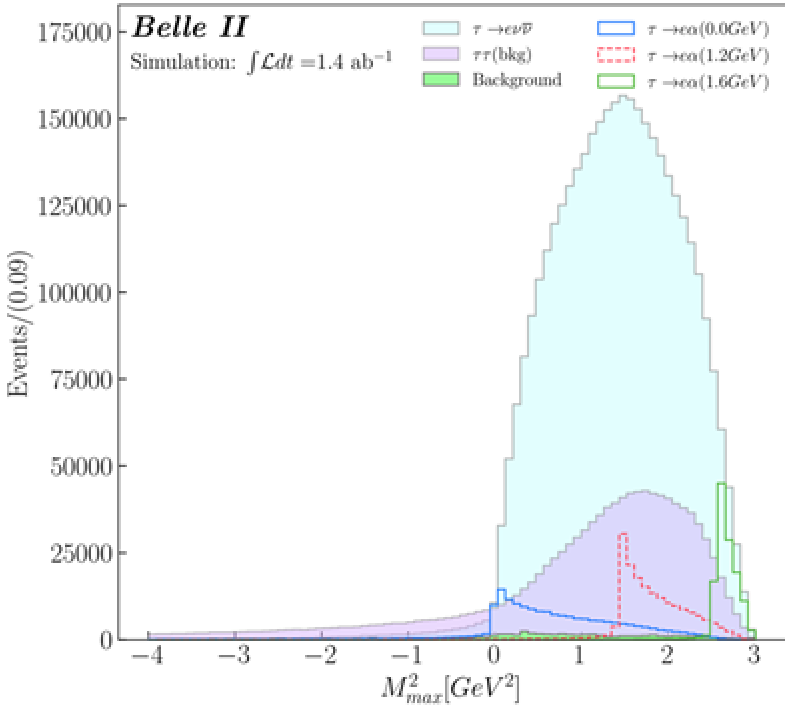


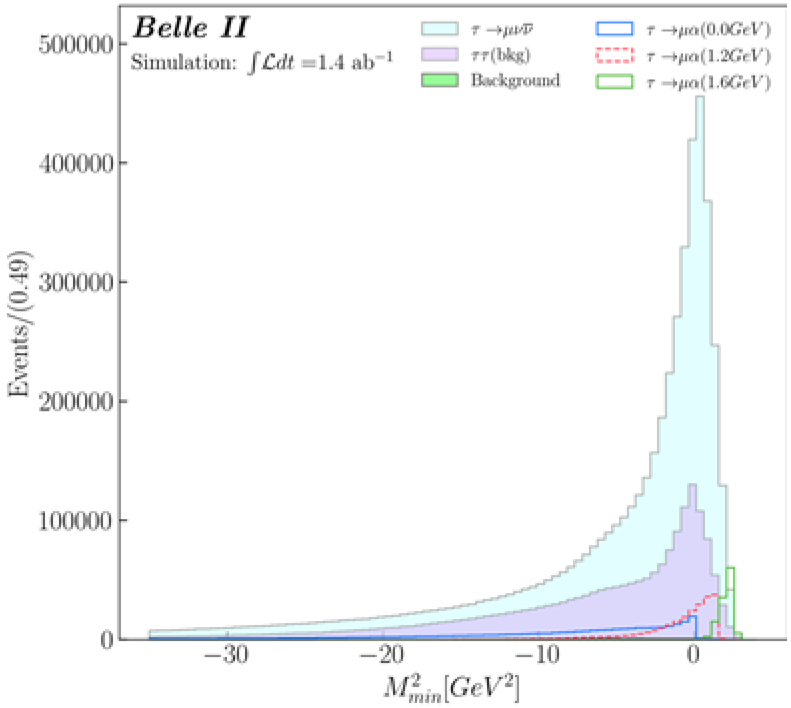
Figure of Merit for Variable (μ-channel)
Figure of Merit
Best Lower Cut
Best Upper Cut
cos φ_th
E_vis^CMS
P_mis^CMS
θ(P)_mis^CMS
M_mis^2
p_t_miss^CMS
E_sig^Cluster
p_tag
θ_tag

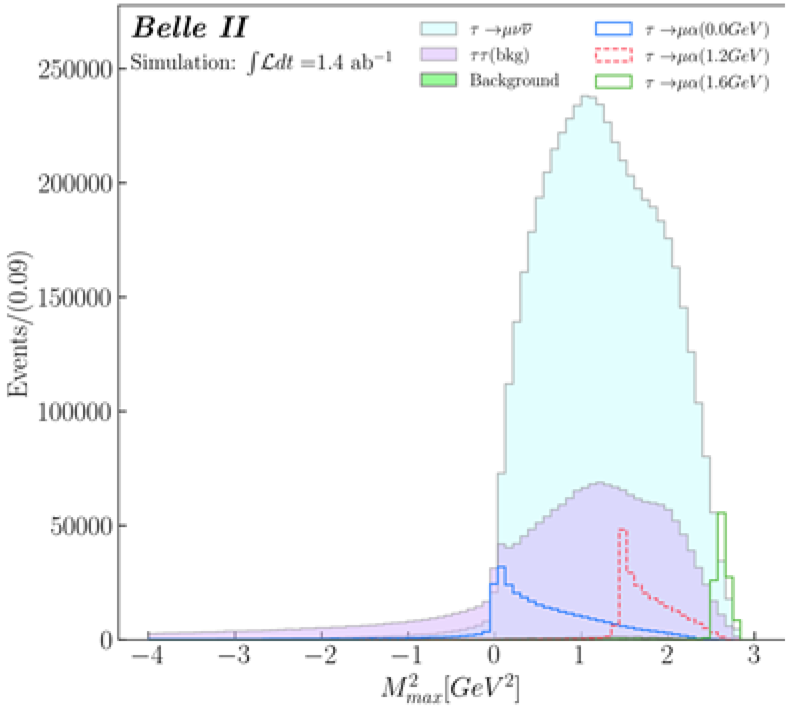
Mmin and *Mmax* Distributions (e-channel) - MC15rd



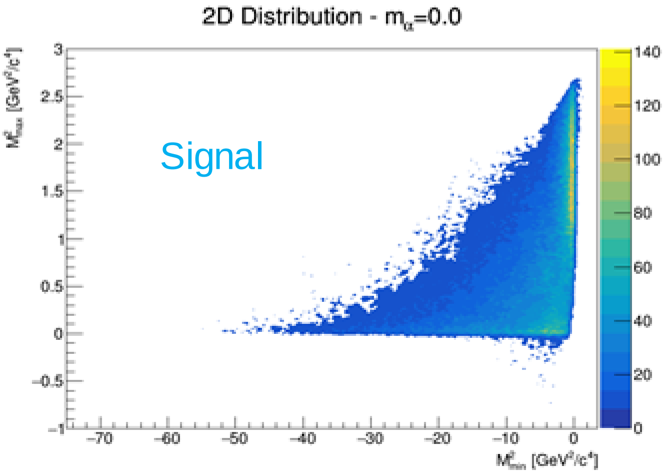


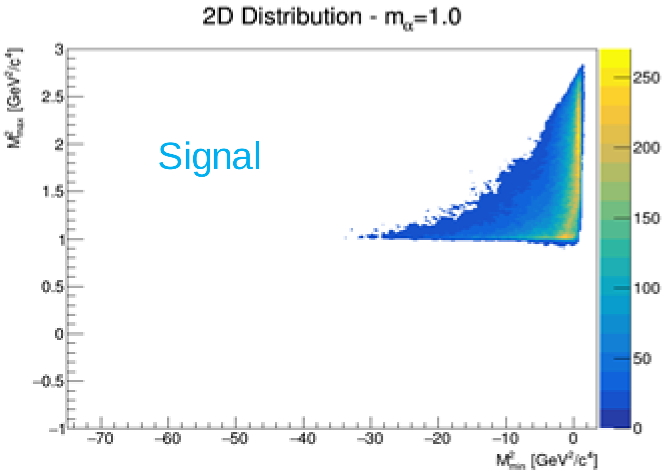
Mmin and *Mmax* Distributions (μ-channel) - MC15rd

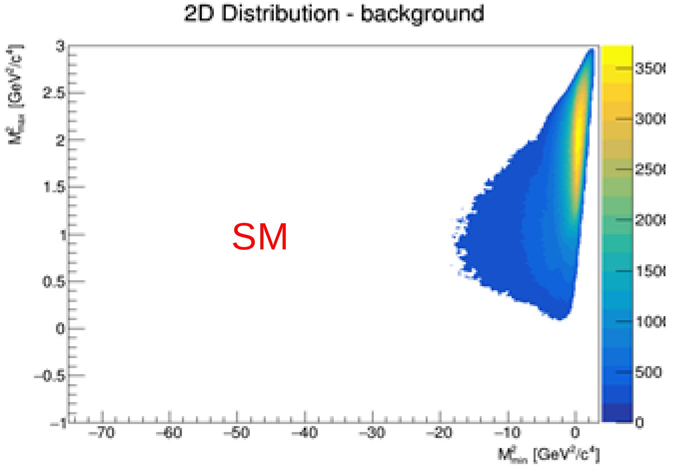




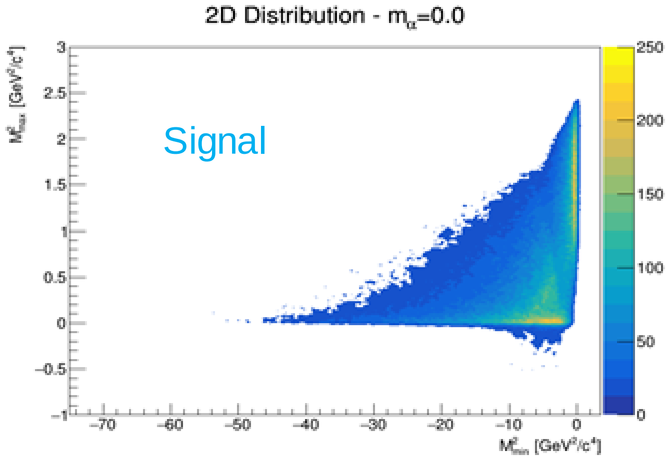
2D distributions (e-channel)

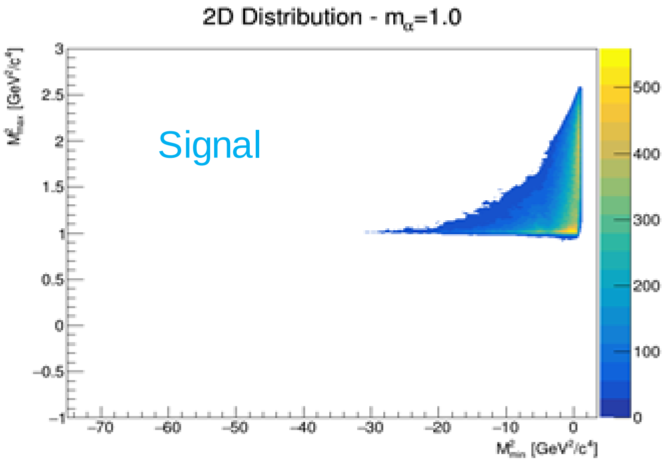


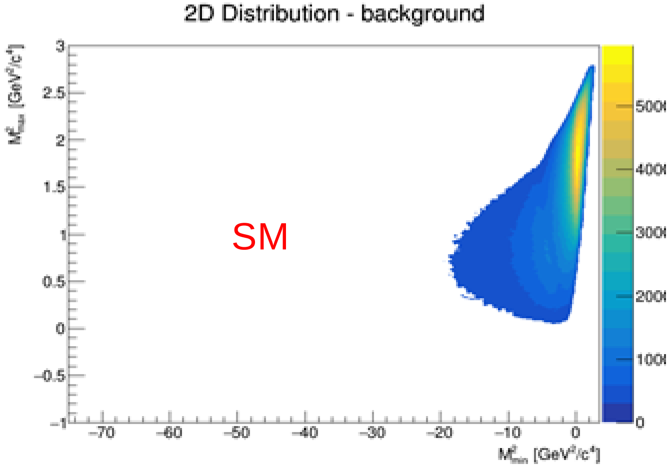




2D distributions (μ-channel)







Upper Limit Estimation

We used the following PDF

$$F(x,y) = \frac{\epsilon_\alpha}{\epsilon_{l\nu\nu}} \times R \times f_\alpha(x,y) + N_{SM} \times f_{SM}(x,y) + N_{bkg} \times f_{bkg}(x,y)$$

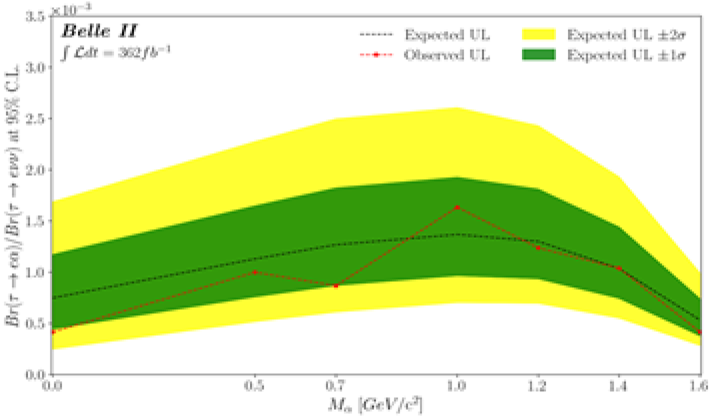
where $R \equiv \frac{Br(\tau \to l\alpha)}{Br(\tau \to l\nu\nu)} = \frac{\epsilon_{SM}}{\epsilon_\alpha}\frac{N_\alpha}{N_{SM}}$, $N_{bkg} = N_{\tau bkg} + N_{other}$ and $f_{bkg}(x,y)$ is constructed with the histogram of the remaining tau decays and the remaining background (qqbar, lowmulti, etc.). We determined upper limits with the asymptotic CLs technique, implemented in the RooStats package.

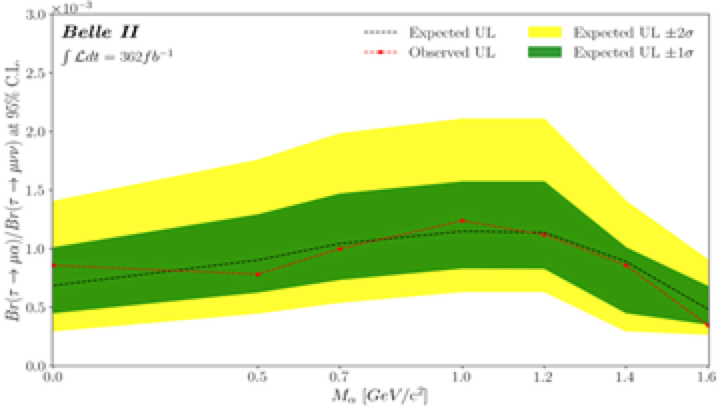
UL estimation

2D Method - Luminosity scaled to 362/fb

M_α $[GeV/c^2]$	UL at 95% CL* $(\times 10^{-3})$
0.0	0.748
0.5	1.113
0.7	1.268
1.0	1.370
1.2	1.300
1.4	1.035
1.6	0.533

$[GeV/c^2]$	UL at 95% CL* $(\times 10^{-3})$
0.0	0.685
0.5	0.903
0.7	1.043
1.0	1.148
1.2	1.139
1.4	0.891
1.6	0.485





UL in the branching ratio ($Br(\tau \to \ell\alpha)$)

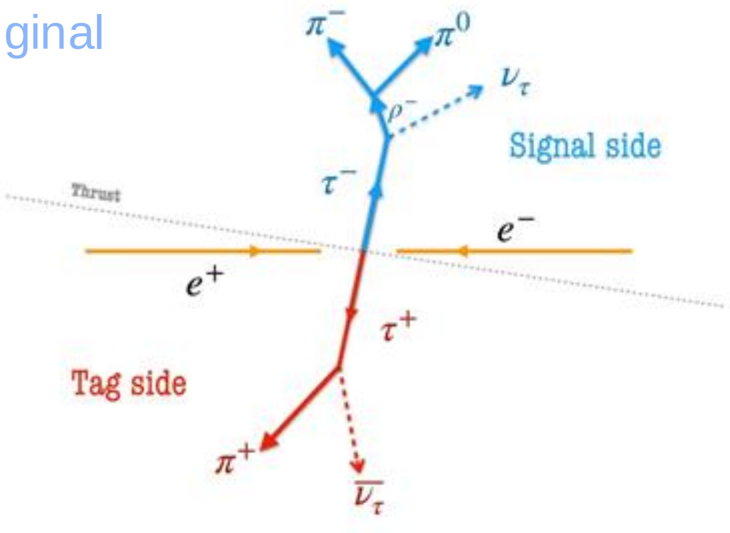
Channel	Belle II (3x1) – 62.8/fb $(x10^{-4})$	Belle II (1x1) – 362/fb $(x10^{-4})$
Electron	(1.96 – 17.4)	(0.9 – 2.4)
Muon	(1.21 – 21.2)	(0.8 – 2.6)

Data/MC using a control channel

Control channel

Using the same selection criteria from the original channels in the analysis, except by

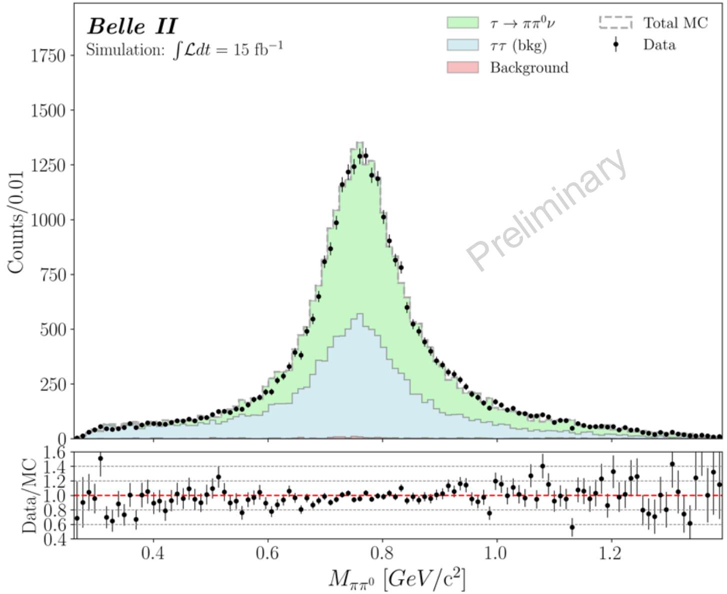
- signal side: $\tau^{\pm} \to \rho^{\pm}\nu_{\tau}$
  - *pionID* > 0.9
  - $N_{\gamma}^{sig} \leq 2$
  - $N_{\pi^0}^{sig} = 1$
- tag side: $\tau^{\pm} \to \pi^{\pm}\nu_{\tau}$
  - *pionID* > 0.9
  - $N_{\gamma}^{tag} = 0$
  - $N_{\pi^0}^{tag} = 0$



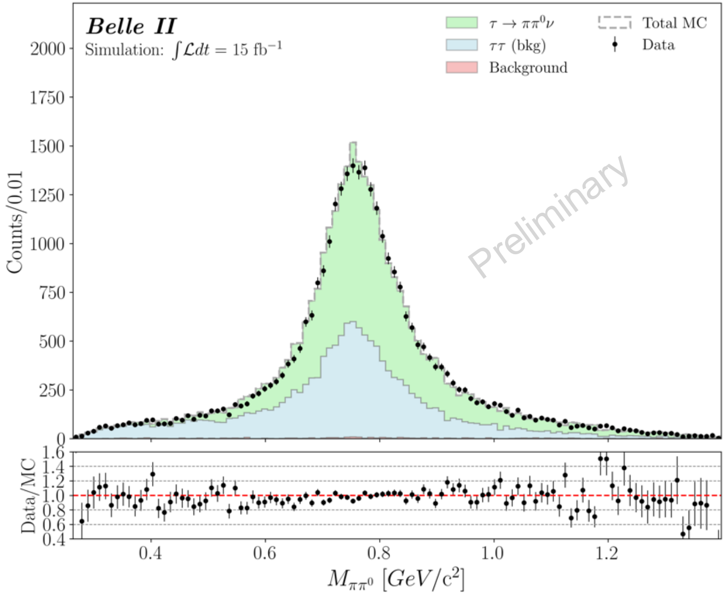
Data/MC comparison

Note: Applying corrections
- π^0
- πID
- Triggers

Electron case

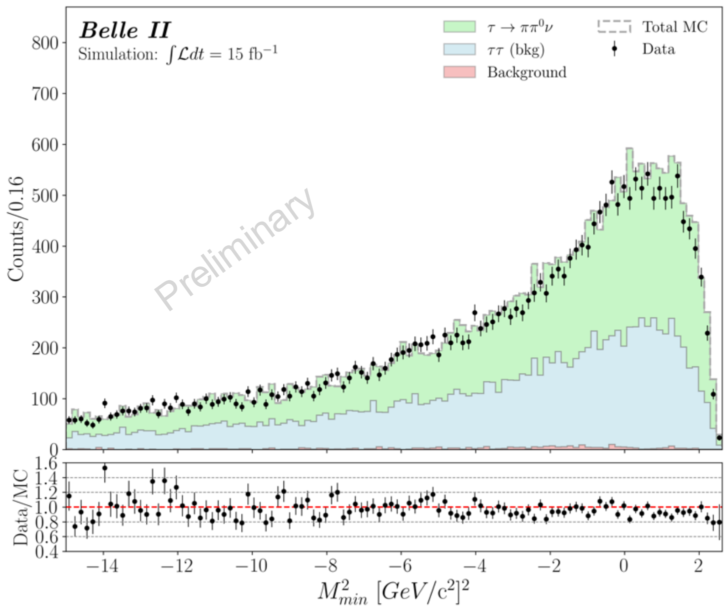


Muon case

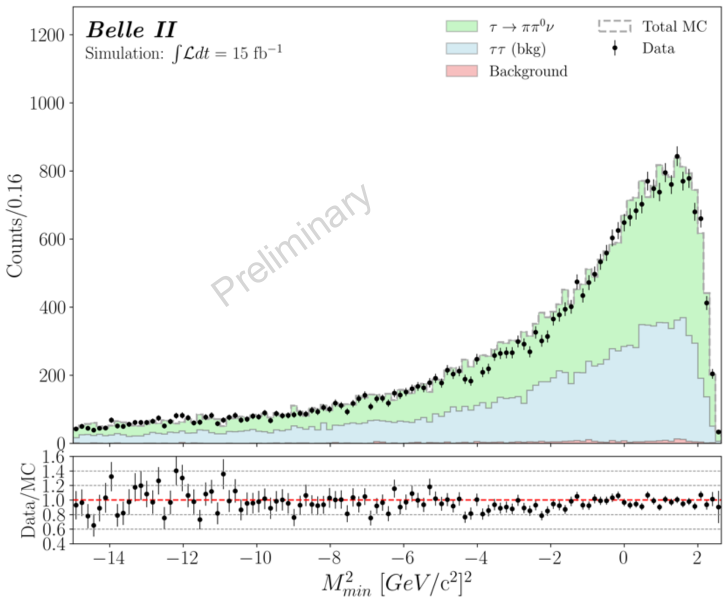


Data/MC comparison

Electron case

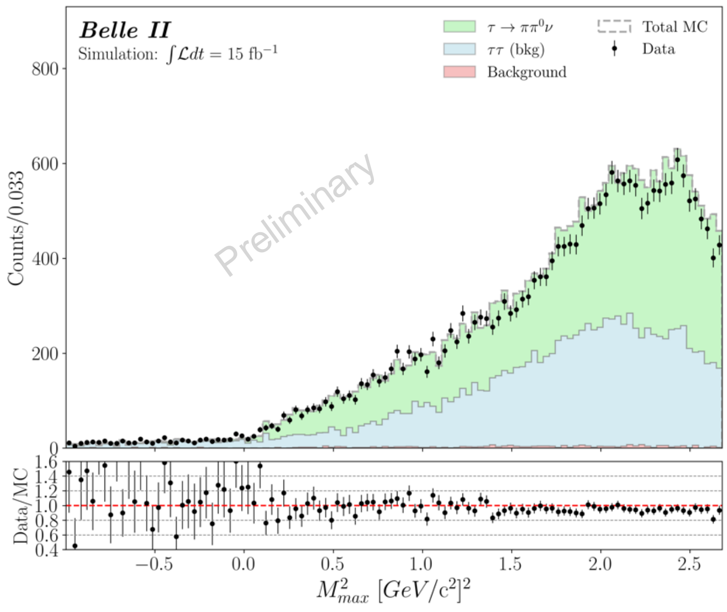


Muon case

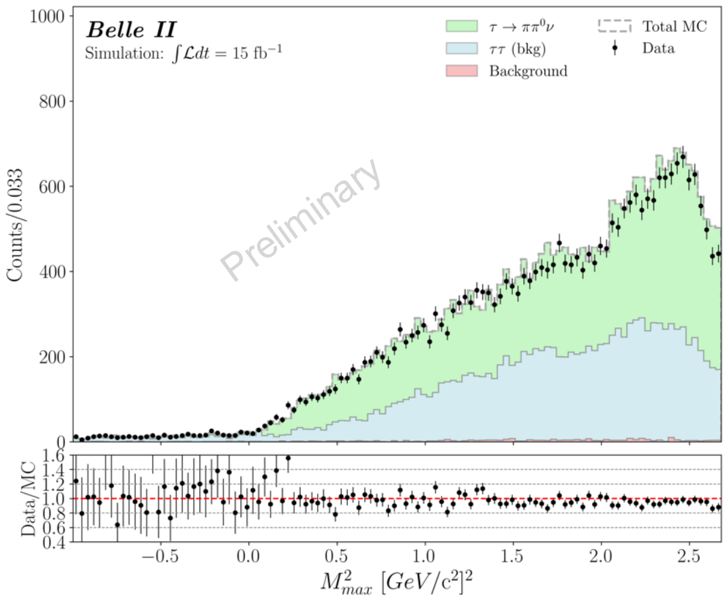


Data/MC comparison

Electron case



Muon case



Summary

- Our results (w/o systematics) are more restrictive than previous Belle II results.
    - ULs on Br are arranged in $(0.9 - 2.4)\times10^{-4}$ and $(0.8 - 2.6)\times10^{-4}$ for the electron and muon channels respectively.

- The Data/MC comparison was made in a control channel.
    - A good agreement is observed in the Data/MC (shape).

Backup

Differences between approaches

Belle

- A data luminosity of 792/fb is used
- 3 different tags are used (*1-prong* (leptonic, hadronic) + *3-prong*).
- The pseudo-rest frame method is used as a discriminant variable.
- UL computed using likelihood fits - 10K Toy MC
- The POI is the number of signal events

$$\mathcal{B}(\tau \to \ell\alpha) = \frac{N_s}{2N_{\tau\tau}\epsilon}$$

This study

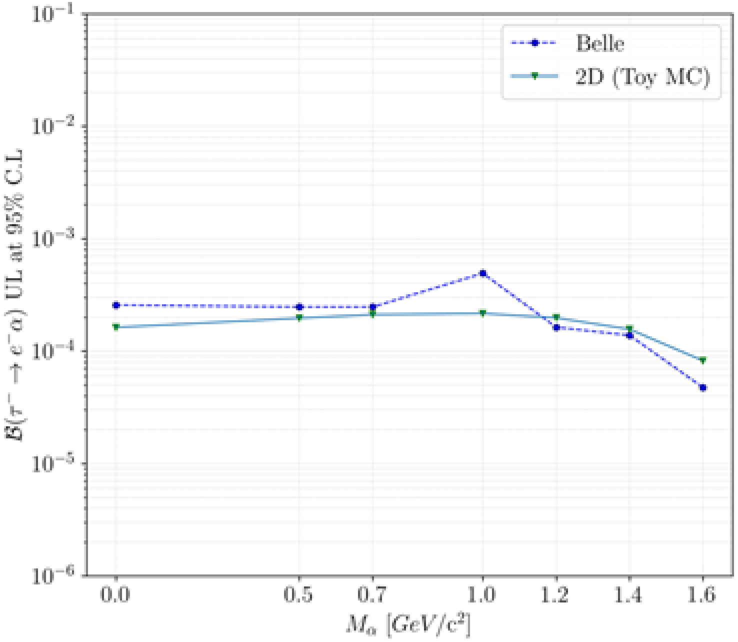
- A pseudo-data luminosity of 362/fb is used
- Only 1-prong is used as tag
- 2D method (Mmin2, Mmax2)
- Asymptotic CLs is used to compute the ULs
- The POI is the ratio of branching fractions

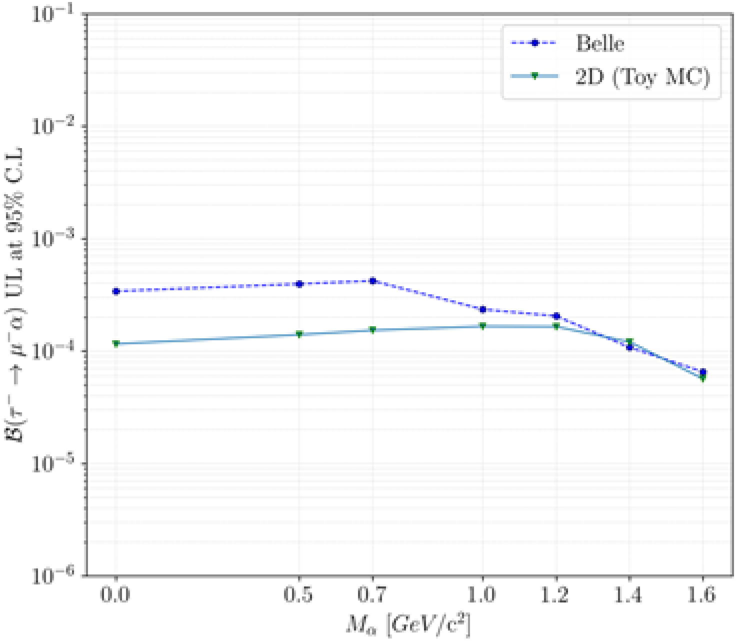
$$\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$$

As Belle did …

In order to do a comparison, the PDF was modified. Now, the number of signal events is set as POI, 10K pseudo-experiments were generated and POI is extracted from the fits. A gaussian UL at 95% C.L was estimated.

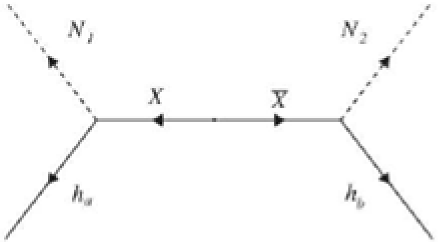
UL at 95% C.L. using Toy MC





Kinematic constraints

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



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:

$$\boxed{\begin{aligned} &A_1(\mu_X^2 - \mu_1^2)^2 + A_2(\mu_X^2 - \mu_2^2)^2 \\ &+ A_3(\mu_X^2 - \mu_1^2)(\mu_X^2 - \mu_2^2) \\ &+ B_1(\mu_X^2 - \mu_1^2) + B_2(\mu_X^2 - \mu_2^2) \\ &+ C_1\mu_1^2 + D_1 \leqslant 0 \end{aligned}}$$

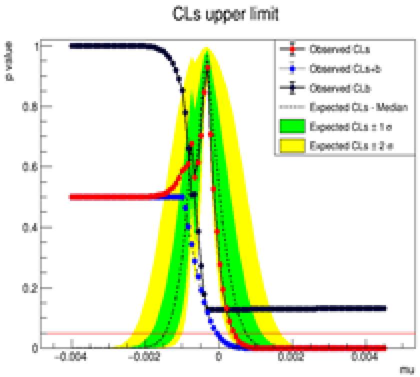
μ_i is the normalized mass of the i-th particle.

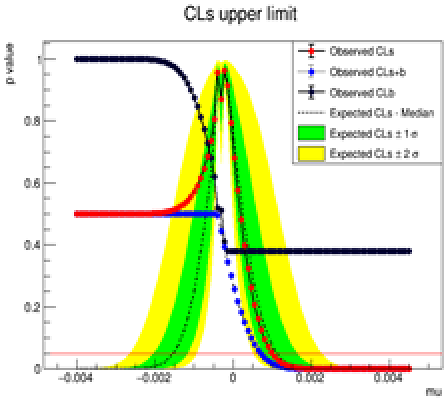
$$A_1 = |\mathbf{b}|^2,$$
$$A_2 = |\mathbf{a}|^2,$$
$$A_3 = 2(\mathbf{a} \cdot \mathbf{b}),$$
$$B_1 = 2(\mathbf{b} \cdot \mathbf{H}),$$
$$B_2 = 2(\mathbf{a} \cdot \mathbf{H}),$$
$$C_1 = 4|\mathbf{a} \times \mathbf{b}|^2,$$
$$D_1 = \mathbf{H} \cdot \mathbf{H} - 4|\mathbf{a} \times \mathbf{b}|^2 \left(\frac{1}{2} - z_a\right)^2.$$

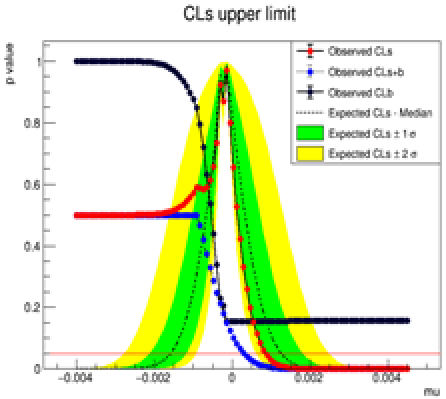
$$\mathbf{H} \equiv \left(z_b^2 - z_b - |\mathbf{b}|^2 - 2\mathbf{a} \cdot \mathbf{b}\right)\mathbf{a} + \left(z_a^2 - z_a + |\mathbf{a}|^2\right)\mathbf{b}.$$

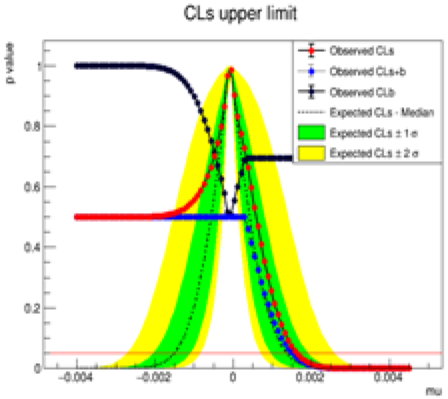
We summarized all the available kinematic information of the process

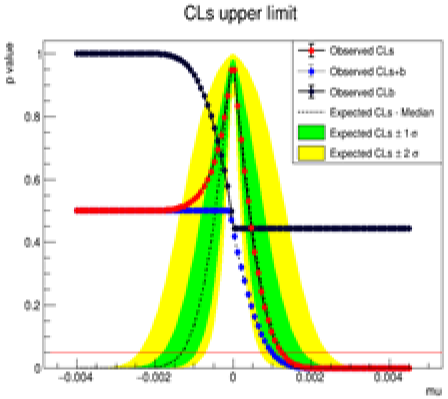
Brazilian plots e-channel

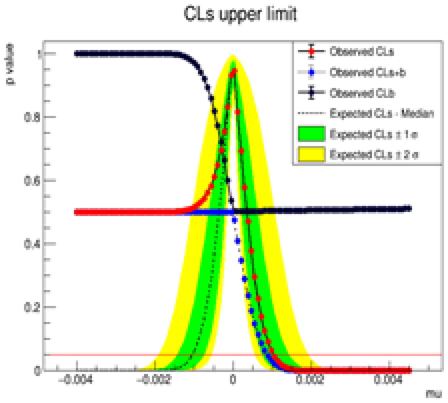


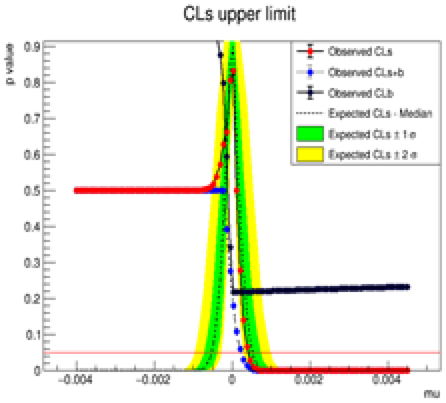












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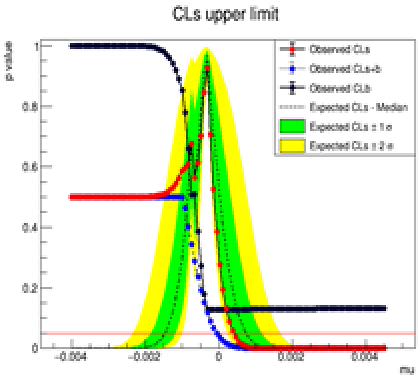
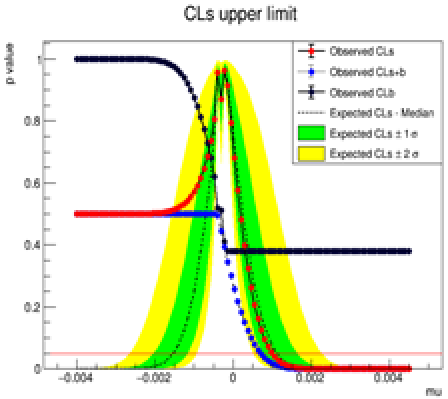
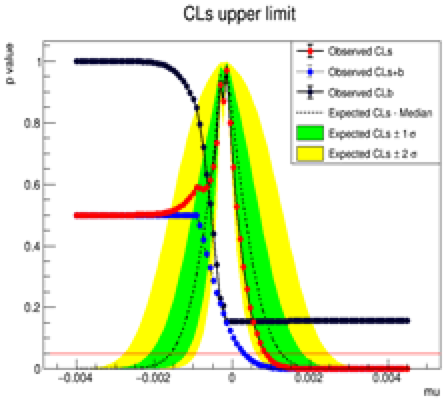
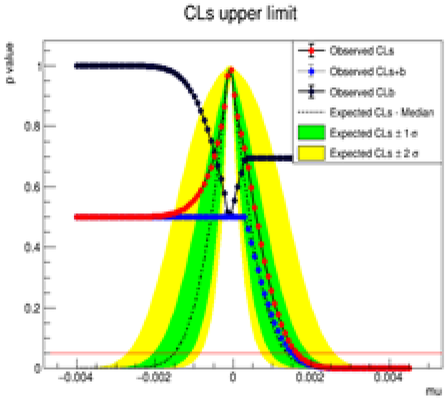
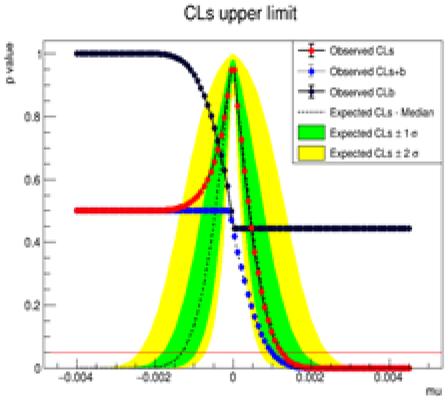
Brazilian plots μ-channel

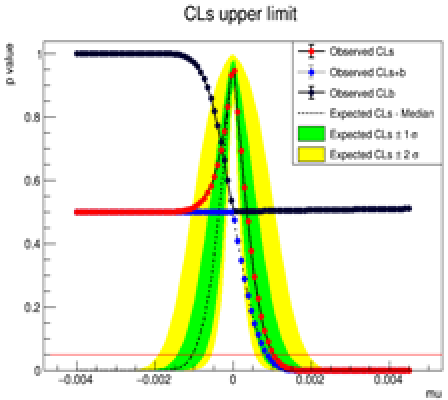


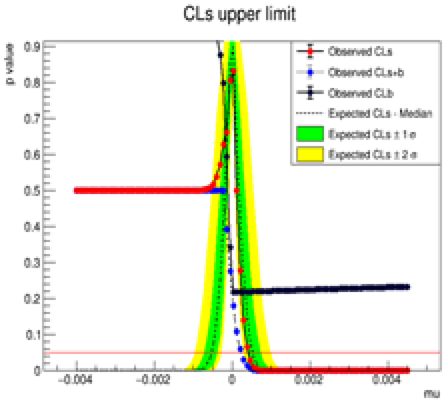




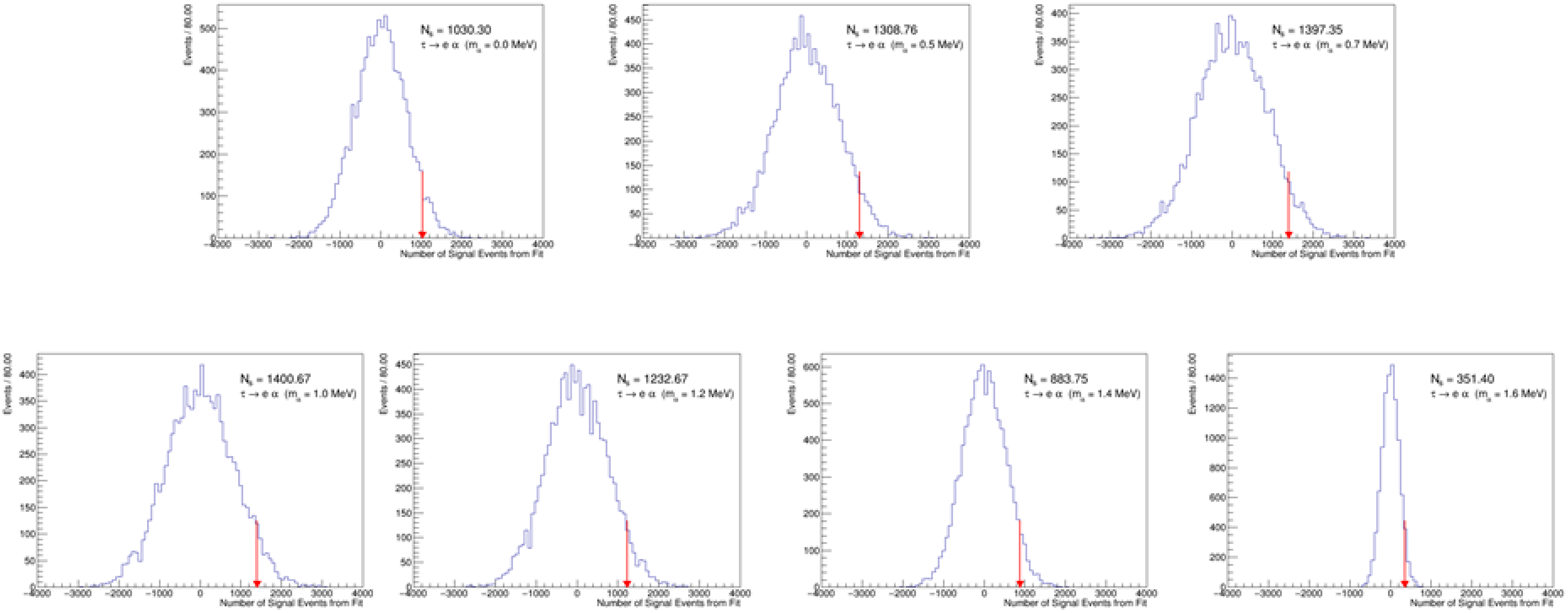




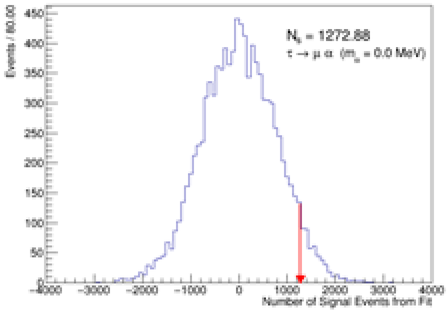


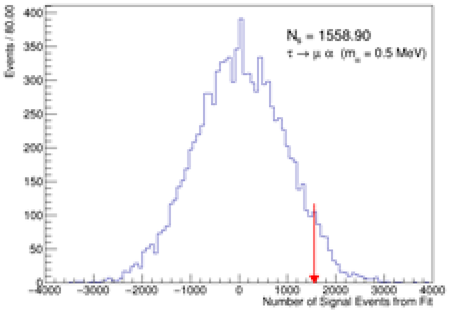


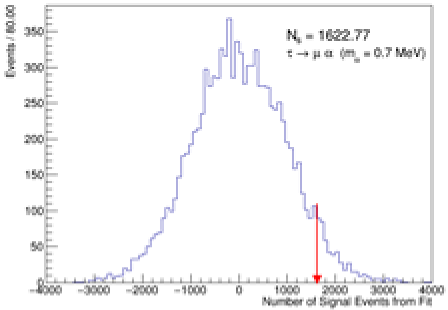
Toy MC POI distribution

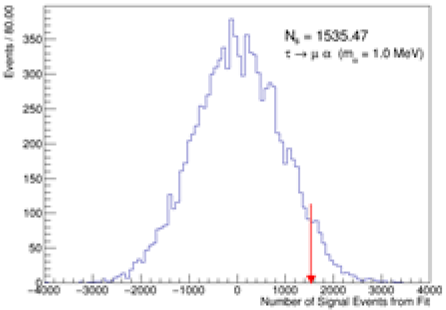


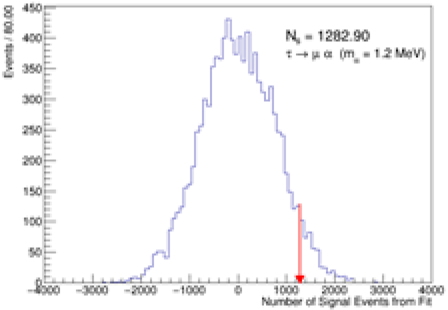
Toy MC POI distribution

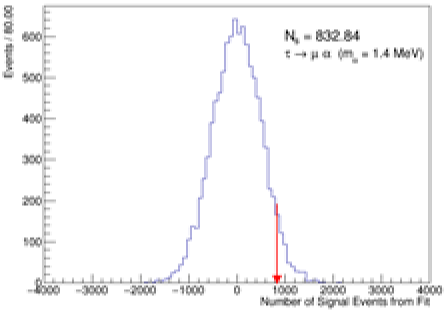


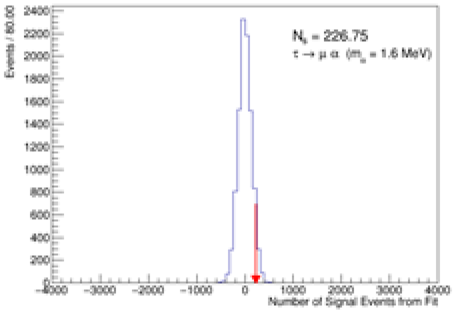












Skim study

After apply the optimization cuts and *pionID09* as wp. Comparing the different efficiencies without and with the skims

	$\tau \to e\alpha$ search		$\tau \to \mu\alpha$ search	
	No skim	TauGeneric skim	No skim	TauGeneric skim
Samples	Efficiencies (%)		Efficiencies (%)	
$m_\alpha = 0.0$	8.16	7.96	14.31	14.29
$m_\alpha = 0.5$	8.56	8.44	14.55	14.54
$m_\alpha = 0.7$	8.52	8.46	13.89	13.88
$m_\alpha = 1.0$	8.49	8.44	12.28	12.21
$m_\alpha = 1.2$	8.32	8.27	10.42	10.34
$m_\alpha = 1.4$	7.73	7.69	9.25	9.18
$m_\alpha = 1.6$	5.84	5.80	5.36	5.30
$\tau^+\tau^- \to e\nu\nu, \pi\nu$	6.80	6.75	-	-
$\tau^+\tau^- \to \mu\nu\nu, \pi\nu$	-	-	9.82	9.79

Event Reconstruction

- Signal (New 10M events MC15rd):
  - $\tau \rightarrow e+\alpha$: sig_mcPDG = ∓11, genMotherPDG =∓15, tag_mcPDG = ∓211
  - $\tau \rightarrow \mu+\alpha$: sig_mcPDG = ∓13, genMotherPDG =∓15, tag_mcPDG = ∓211
- Background:

MC samples	Luminosity (1/fb)
$\tau\tau$	1444
u(u)	1444
d(d)	1444
s(s)	1444
c(c)	1444
Charged	1444
Mixed	1444
Low multiplicity	
$\mu\mu(\gamma)$	1444
ee(γ)	36.1
ee$\mu\mu$	361.0
eeee	361.0
eekk	361.0
ee$\pi\pi$	361.0
eepp	361.0