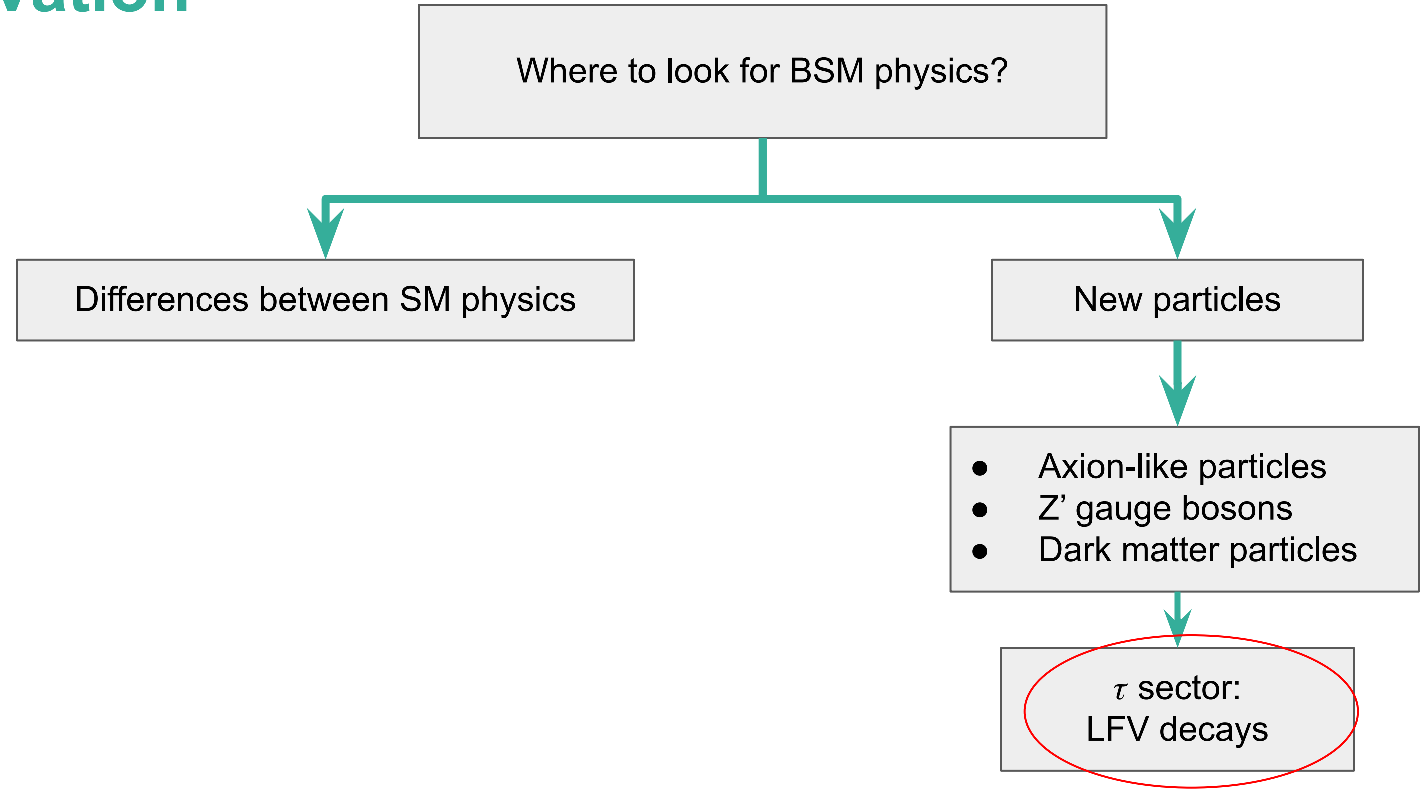
Exploring invisible particles: In a search of “Beyond Standard Model” in τ decays

Johan A. Colorado Caicedo
In collaboration with
Eduard De La Cruz Burelo

johan.colorado@cinvestav.mx

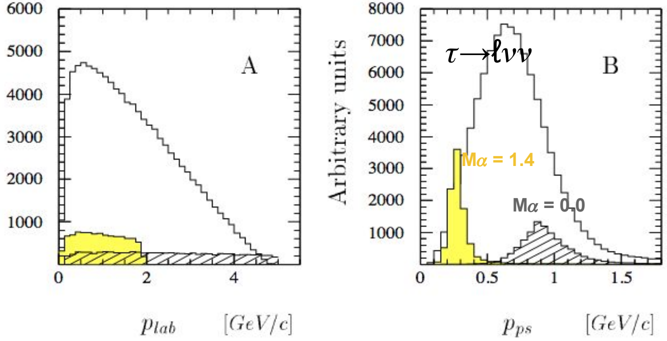
Motivation


Where to look for BSM physics?
Differences between SM physics
New particles
Axion-like particles
Z' gauge bosons
Dark matter particles
τ sector:
LFV decays

How to look for BSM physics?

Previous methods to study decays with missing energy in colliders

ARGUS



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

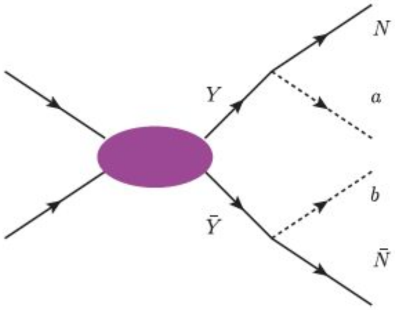
as signal (1 prong): $\tau\to\ell\alpha$ as tag (3 prong): $\tau\to(3h)\nu$ or $\tau\to(3h)\pi^0\nu$

- pseudo-rest frame distribution.

Issue:
Overlap in the kinematic region with background distribution: low discriminant power
Approximate the boost direction: smearing effect

[Phys. Rev. D 90, 114029]

[Phys. Rev. D 95, 075037]



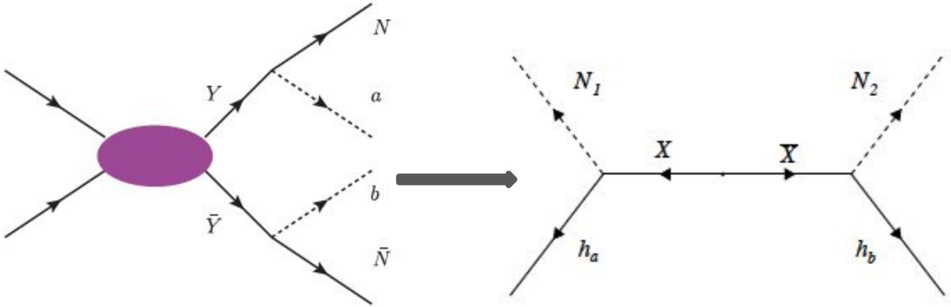
$Y\tilde{Y}\to(a+N)(b+\tilde{N})$

Suitable for leptonic colliders

Issue:
It is necessary $Y\tilde{Y}$ pairs, only one detectable particle in each side and one invisible particle also: a large data sample to be able to perform a sensitivity study

johan.colorado@cinvestav.mx

Our method



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

ha, hb: could be a bunch of detectable particles

Phys. Rev. D 102, 115001

N1, N2: couple of particles that evade the detector

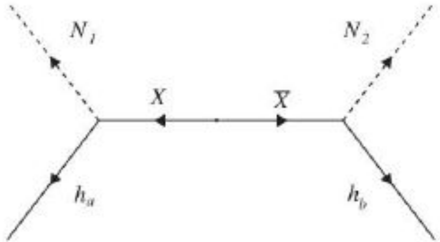
This generalization allows to study XX pair decays with BSM processes in one decay, and SM processes with missing particle in the complementary decay (such as the τ lepton decays).

This could be to increase the possibility of a BSM particle production compared with the requirement of a double creation of the unknown particle.

johan.colorado@cinvestav.mx

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:

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

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

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

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

We summarized all the available kinematic information of the process

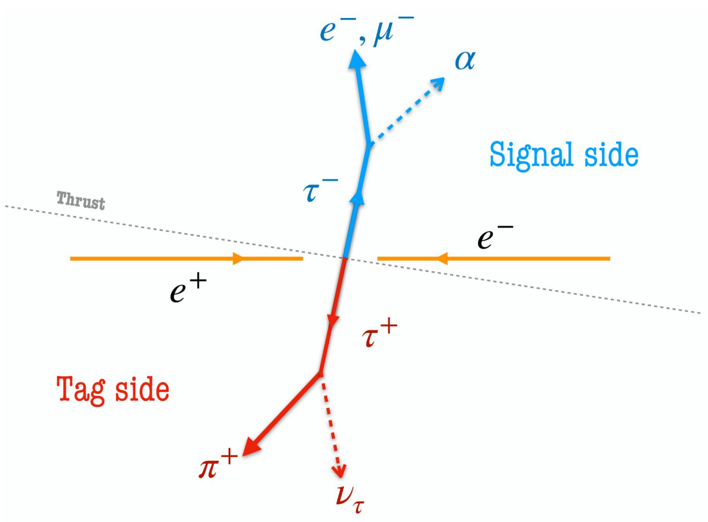
johan.colorado@cinvestav.mx

Cinvestav

Our case

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

  - ➔ The Branching of 1x1-prong is significant
  - ➔ ($\mathcal{B}(\tau \to \pi\nu) \sim 10.8$ and $\mathcal{B}(\tau \to e\nu\nu) \sim 17.8$)



johan.colorado@cinvestav.mx

Cinvestav

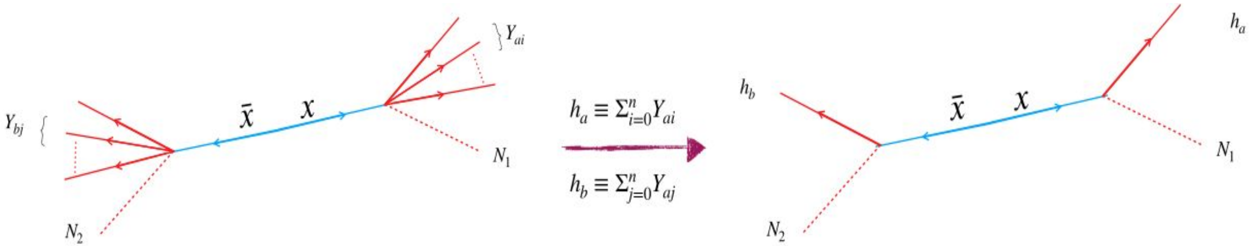
Mmin and *Mmax* variables

Discriminant variables

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

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

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



"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

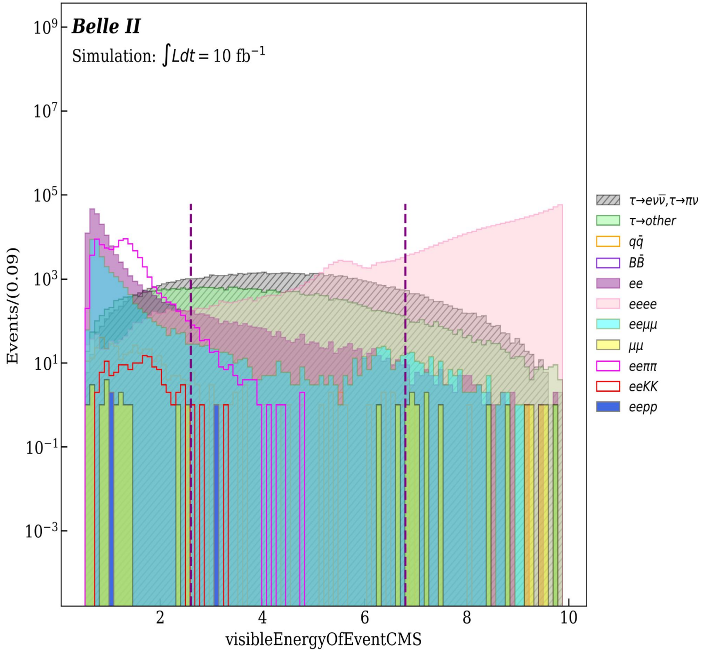
"Measurement of the mass of the tau lepton in semi-invisible final states in the Belle II collaboration"
J. A. Colorado-Caicedo
BELLE2-MTHESIS-2023-007

Cleaning the signal zone

Optimizing with the SM irreducible background ($\tau \to \ell \nu \boldsymbol{\nu}$) using a purity FOM in a simulated annealing algorithm.

$$\frac{N_{sig}}{\sqrt{N_{sig} + 100(N_{bkg})}}$$

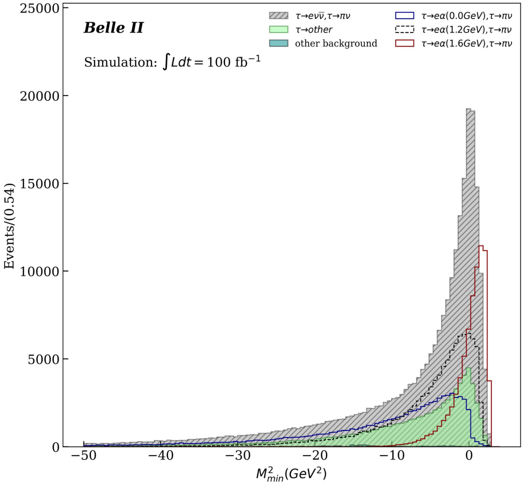
→ *Purity-focused optimization**

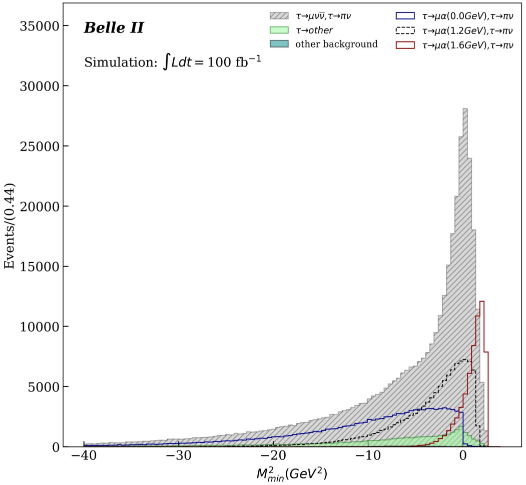


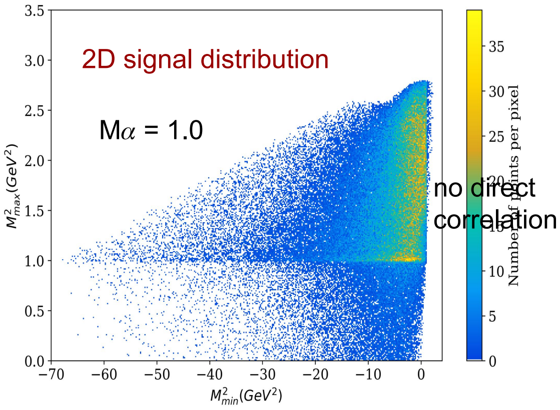
*Another optimization with FOM = S/(S+B)^(1/2) was made, we stayed with the better performance

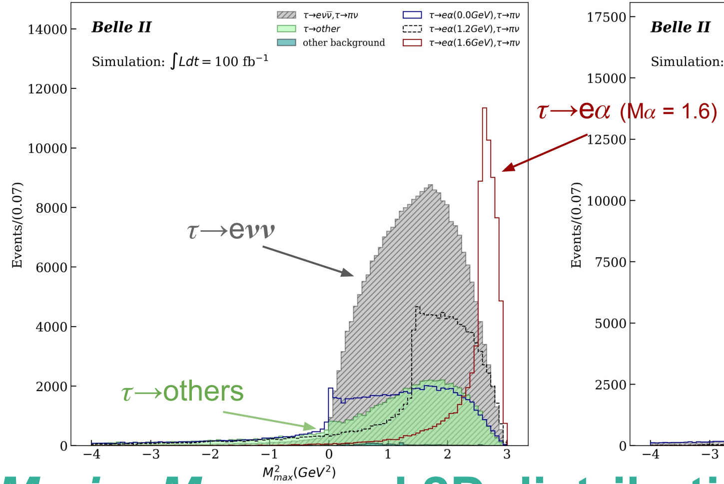
johan.colorado@cinvestav.mx

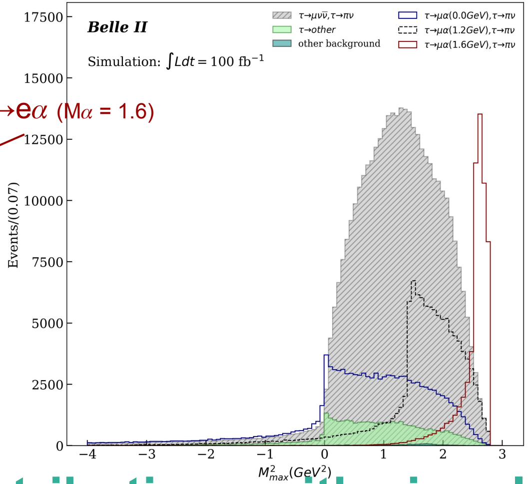
e-channel | *μ-channel*

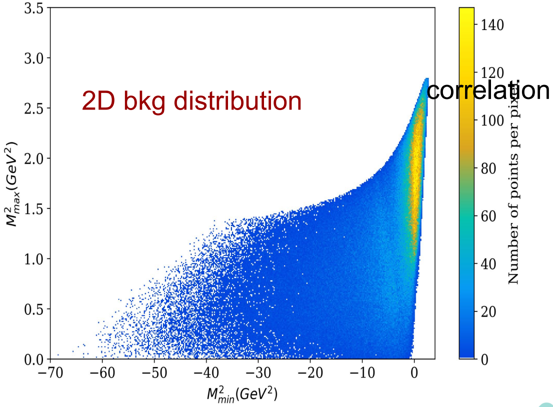












Mmin, *Mmax* and 2D distributions with signal component

johan.colorado@cinvestav.mx

Upper Limit Estimation

We used the following PDF

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

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 $f_{bkg}(x)$ is constructed with the histogram of the remaining tau decays and the background remaining (qqbar, lowmulti, etc.). And we determined upper limits with the asymptotic CLs technique, implemented in the RooStats package.

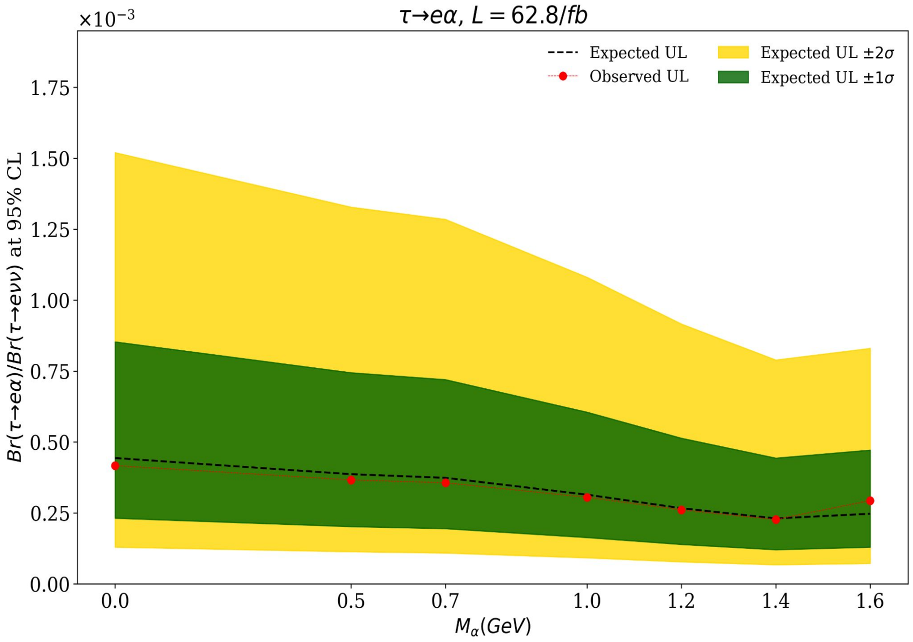
johan.colorado@cinvestav.mx

Cinvestav

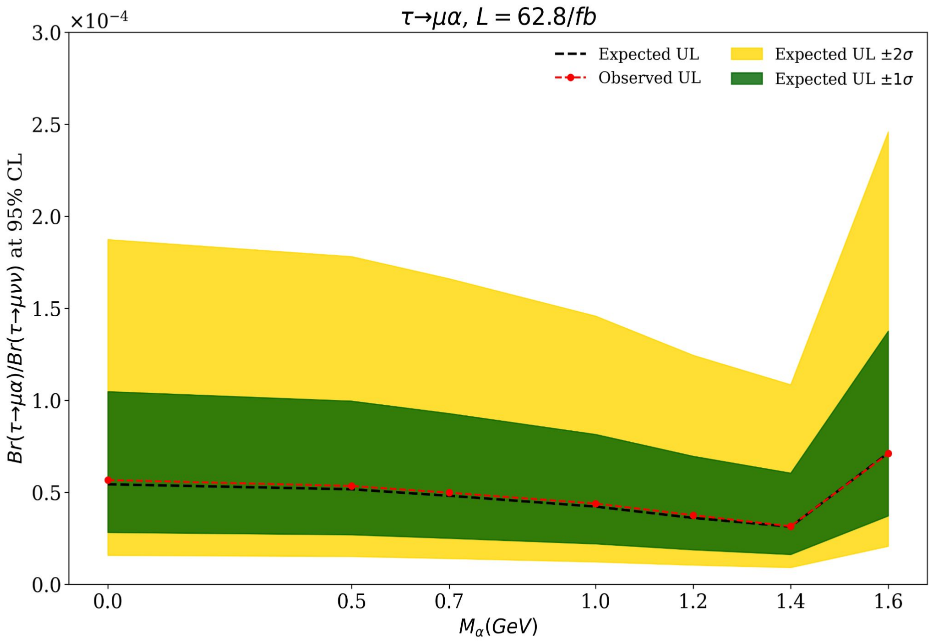
UL estimation with the purity cuts

UL with 2D method to different α masses - 62.8/fb

e-channel



μ-channel

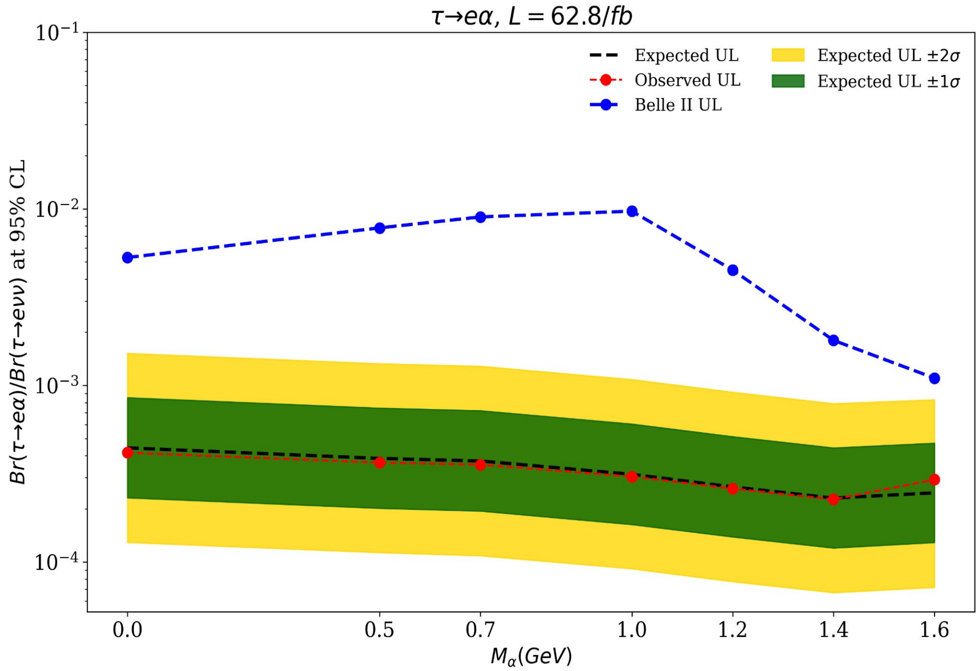


johan.colorado@cinvestav.mx

Cinvestav

UL estimation with the purity cuts (e-channel)

Comparison with previous study - 62.8/fb



Central values at 95% CL, upper limits for the branching-fraction ratios $\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ for various masses of α boson

M_α $[GeV/c^2]$	UL at 95% CL* $(\times 10^{-3})$	UL at 95% CL* $(\times 10^{-3})$
0.0	5.30	0.416
0.5	7.80	0.366
0.7	9.00	0.356
1.0	9.70	0.305
1.2	4.50	0.260
1.4	1.80	0.226
1.6	1.10	0.293

*Phys. Rev. Lett. 130, 181803

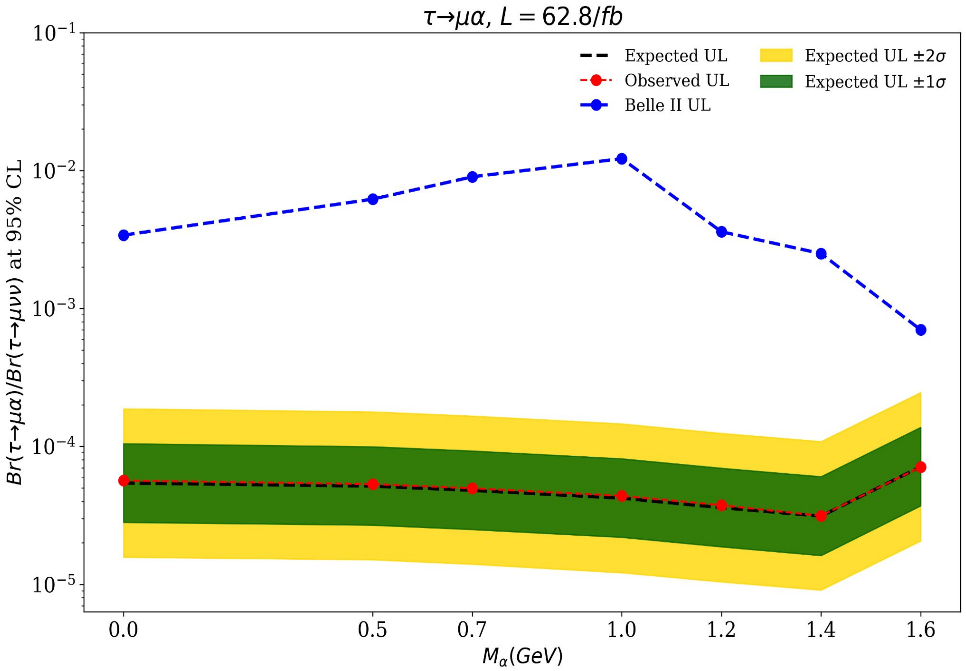
*UL's found by us using 2D method

johan.colorado@cinvestav.mx

Cinvestav

UL estimation with the purity cuts (μ-channel)

Comparison with previous study - 62.8/fb



Central values at 95% CL, upper limits for the branching-fraction ratios $\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ for various masses of α boson

M_α $[GeV/c^2]$	UL at 95% CL $(\times 10^{-3})$	UL at 95% CL* $(\times 10^{-3})$
0.0	3.40	0.057
0.5	6.20	0.053
0.7	9.00	0.050
1.0	1.22	0.044
1.2	3.60	0.037
1.4	2.50	0.031
1.6	0.70	0.071

*Phys. Rev. Lett. 130, 181803

*UL's found by us using 2D method

johan.colorado@cinvestav.mx

Cinvestav

In summary

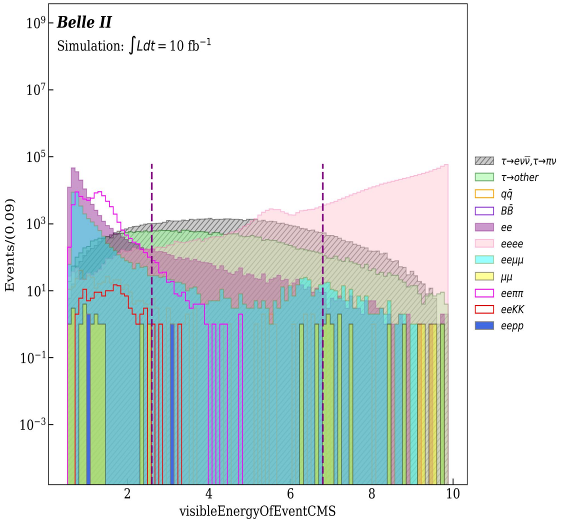
- In the recent Belle II paper for 3x1-prong topology it was achieved upper limits on the branching-ratio fraction $\mathcal{B}(\tau \to e\alpha)/\mathcal{B}(\tau \to e\nu\bar{\nu})$ ranging in $(1.1 - 9.7) \times 10^{-3}$ and on $\mathcal{B}(\tau \to \mu\alpha)/\mathcal{B}(\tau \to \mu\nu\bar{\nu})$ in the range $(0.7 - 12.2) \times 10^{-3}$ at 95% CL. CLs limits are 2.2 to 14 times more stringent than ARGUS collaboration
- Our MC estimations (without systematics) in the 1x1-prong topology for 62.8/fb are $(2.26 - 4.16) \times 10^{-4}$ and $(3.1 - 7.1) \times 10^{-5}$ for the electron and the muon channel respectively. Our limits are 4.9 to 23.3 and 22.6 to 171.8 times more stringent than the previous Belle II study.
- At this level these two different estimations could be in the worst worst case (including systematics) at least comparables and they could be combined to estimate a better upper limit.

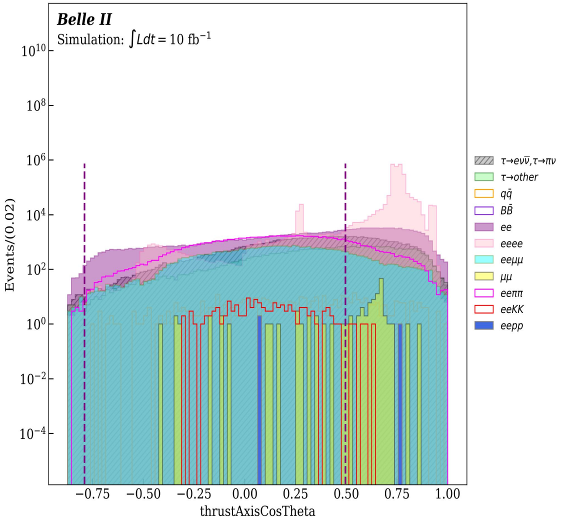
¡Muchas gracias!

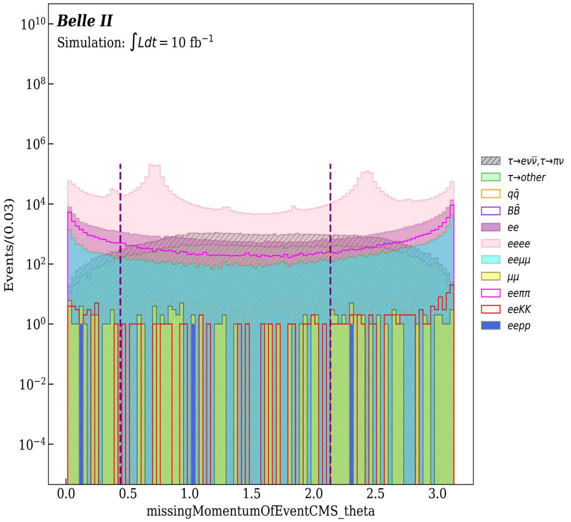
johan.colorado@cinvestav.mx

Back up

Selection cuts (e-channel)

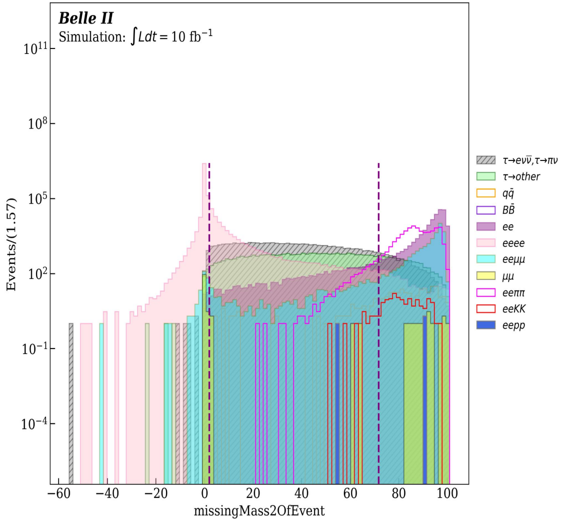


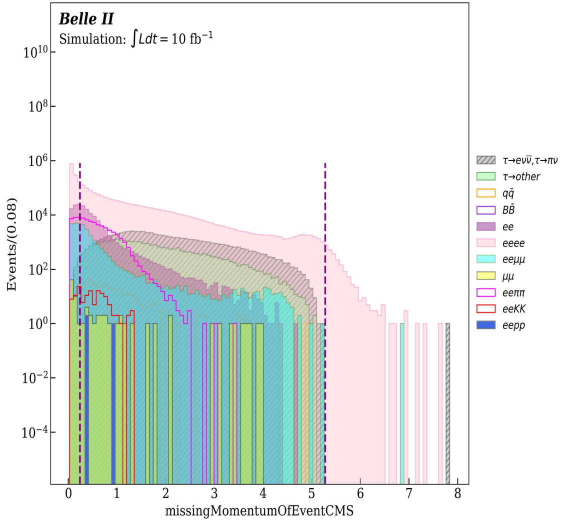


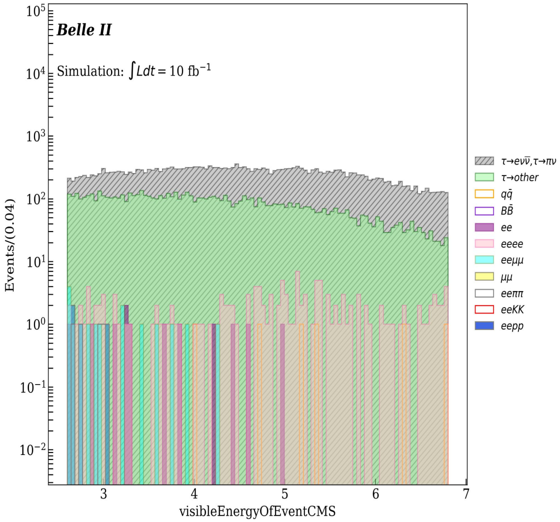


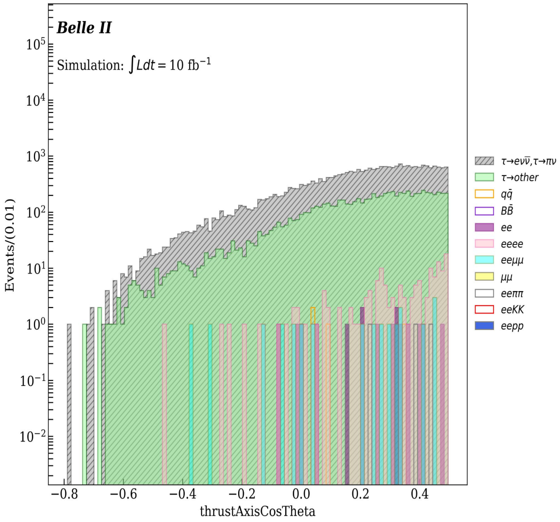
Luminosity: 10/fb:100/fb

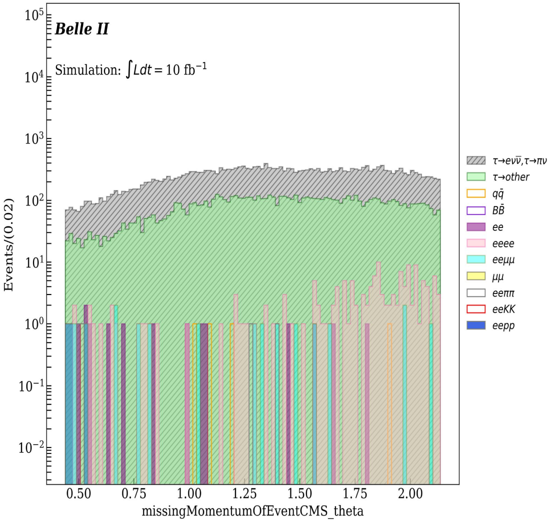
(Sample -> Events)
SM -> 66818
tau -> 28932
qqbar -> 403
mixed+charged -> 1
ee -> 2745305
eeee -> 148972
eemumu -> 29429
mumu -> 114
eepipi -> 73360
eeKK -> 134
eepp -> 3





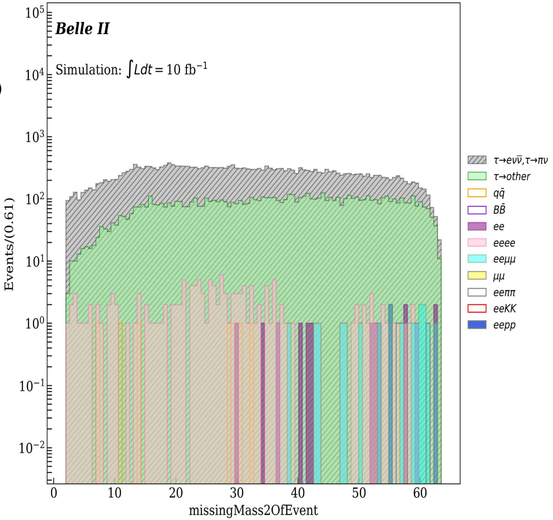


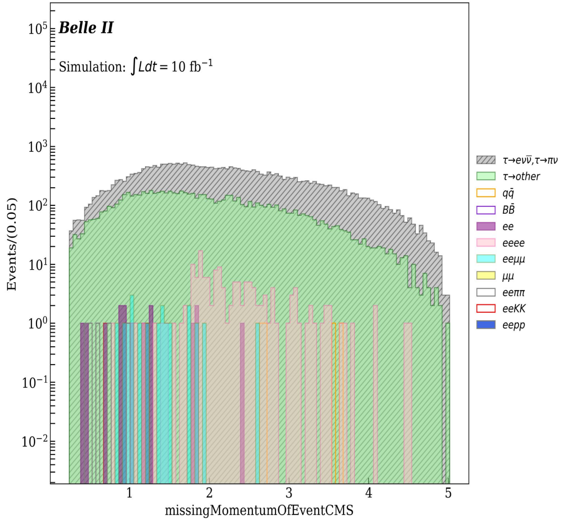




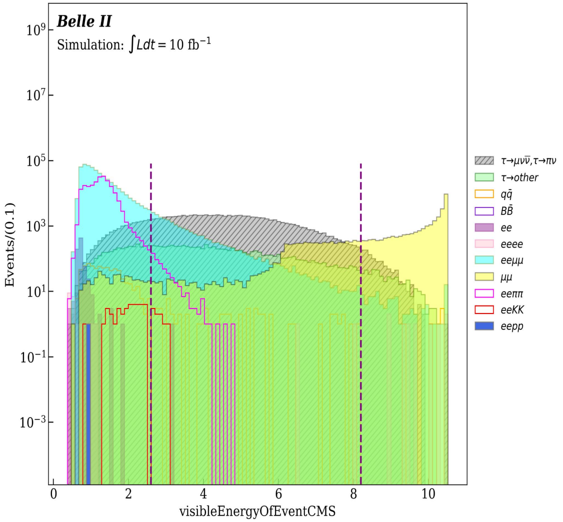
Luminosity: 10/fb:100/fb

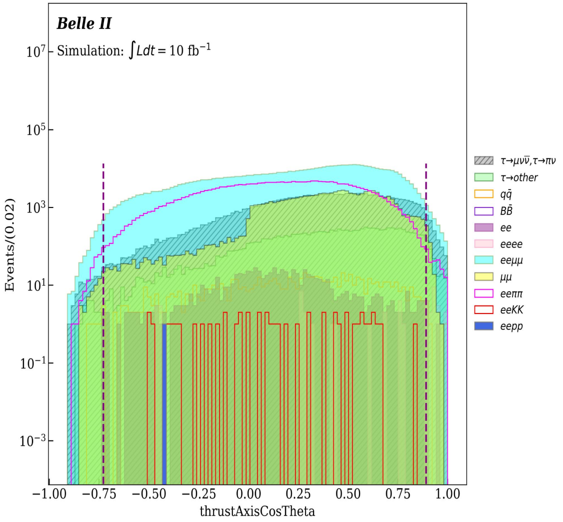
(Sample -> Remaining Events)
SM -> 25186
tau -> 7418
qqbar -> 8
mixed+charged -> 0
ee -> 99
eeee -> 26
eemumu -> 26
mumu -> 0
eepipi -> 4
eeKK -> 0
eepp -> 0

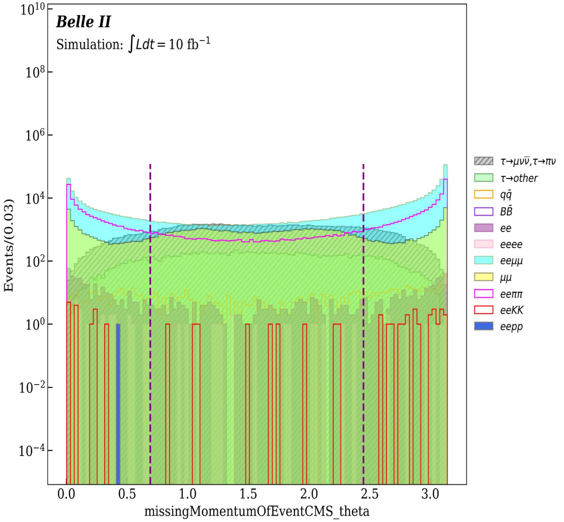




Selection cuts (μ-channel)

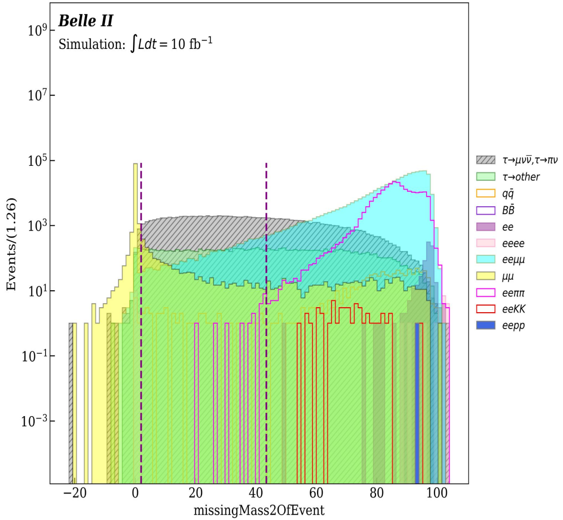


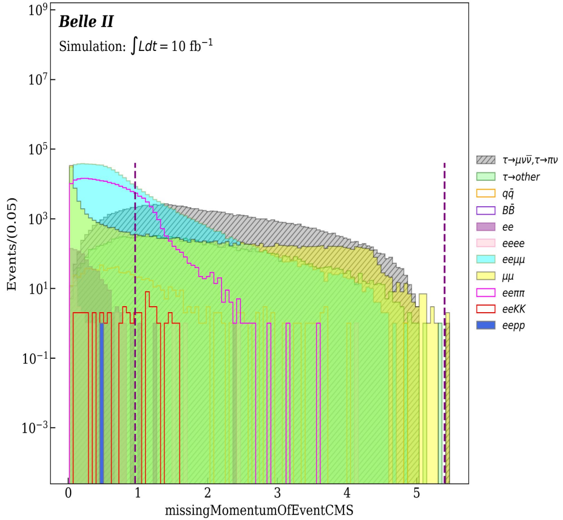


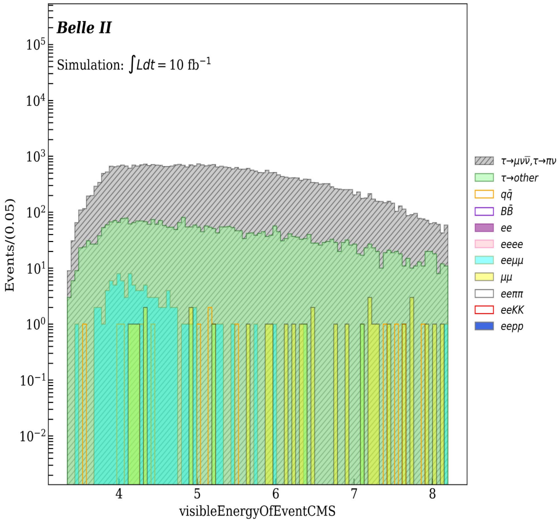


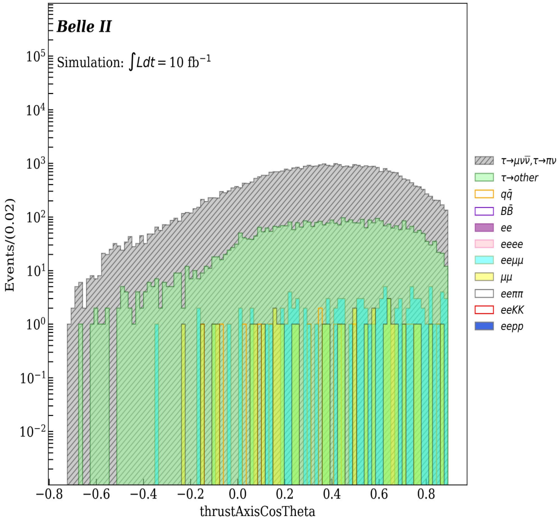
Luminosity: 10/fb:100/fb

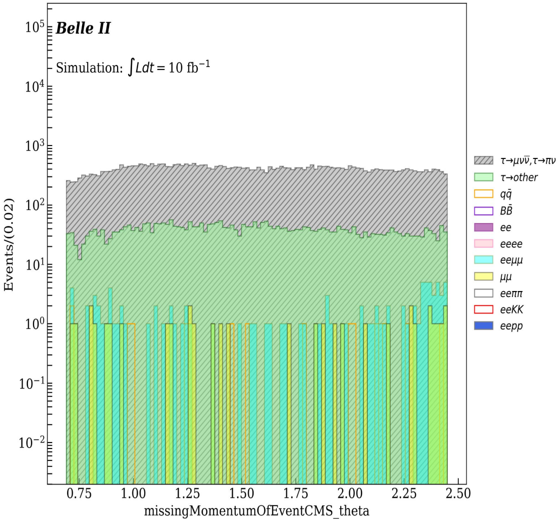
(Sample -> Events)
SM -> 95772
tau -> 12012
qqbar -> 761
mixed+charged -> 0
ee -> 49
eeee -> 734
eemumu -> 556163
mumu -> 84246
eepipi -> 217331
eeKK -> 47
eepp -> 1





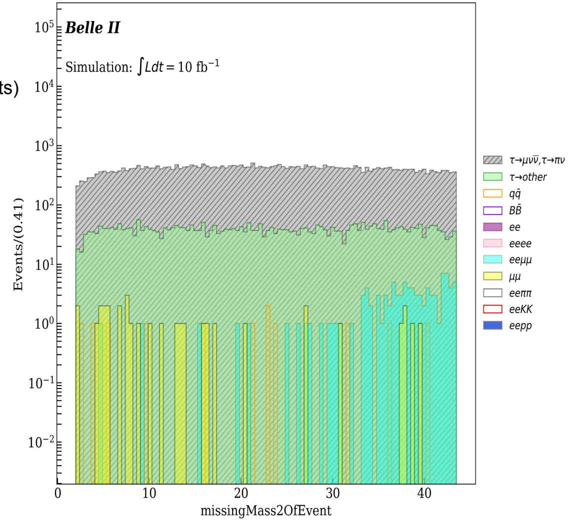


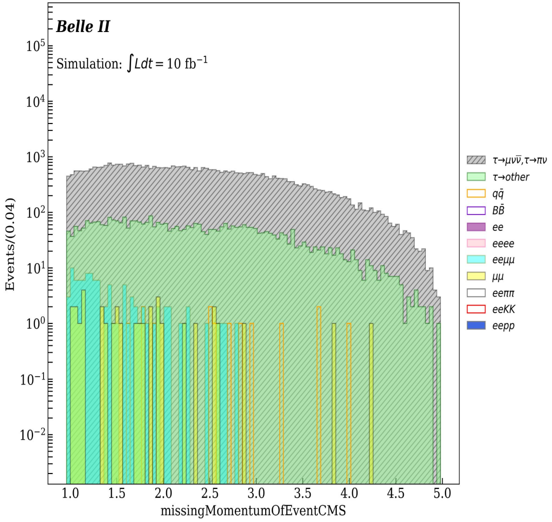




Luminosity: 10/fb:100/fb

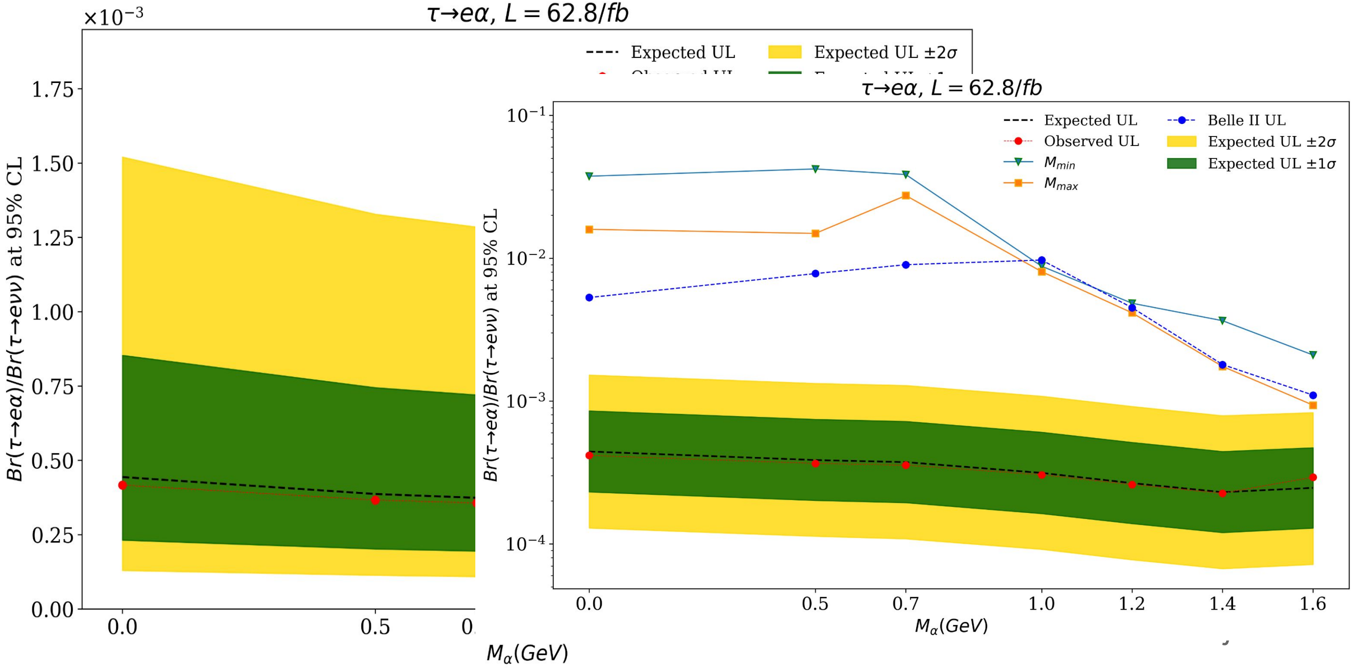
(Sample -> Remaining Events)
SM -> 38380
tau -> 3269
qqbar -> 14
mixed+charged -> 0
ee -> 0
eeee -> 0
eemumu -> 82
mumu -> 27
eepipi -> 4
eeKK -> 0
eepp -> 0





UL estimation with the purity cuts (e-channel)

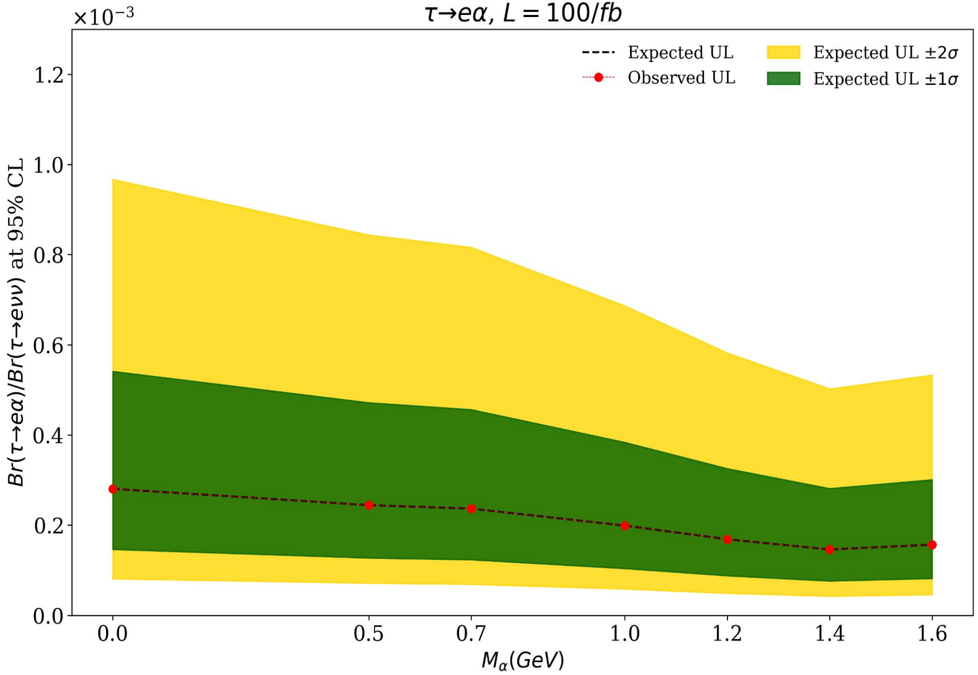
UL with 2D method to different α masses - 62.8/fb



1D methods comparison, we can see a better agreement in large masses

UL estimation with the purity cuts (e-channel)

UL with 2D method to different α masses - 100/fb



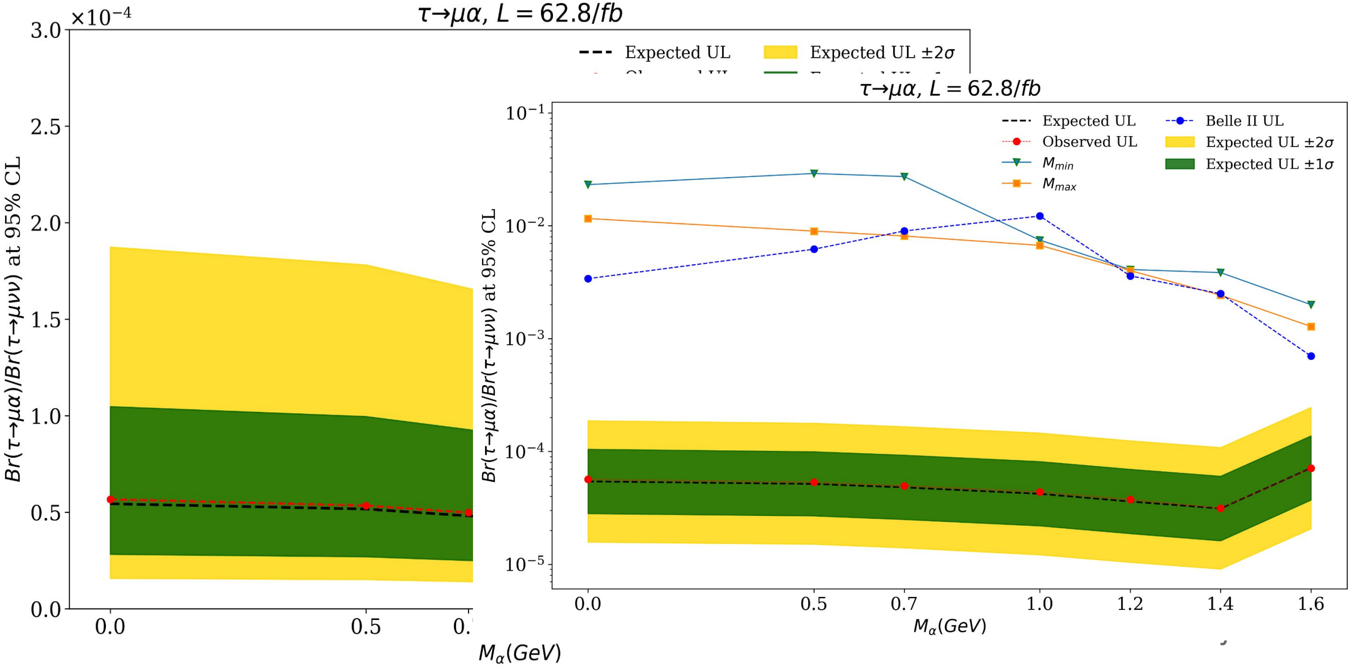
M_α $[GeV/c^2]$	UL at 95% CL $(\times 10^{-4})$
0.0	2.80
0.5	2.44
0.7	2.36
1.0	1.99
1.2	1.69
1.4	1.46
1.6	1.57

UL's found by us using 2D method

johan.colorado@cinvestav.mx

UL estimation with the purity cuts (μ-channel)

UL with 2D method to different α masses - 62.8/fb



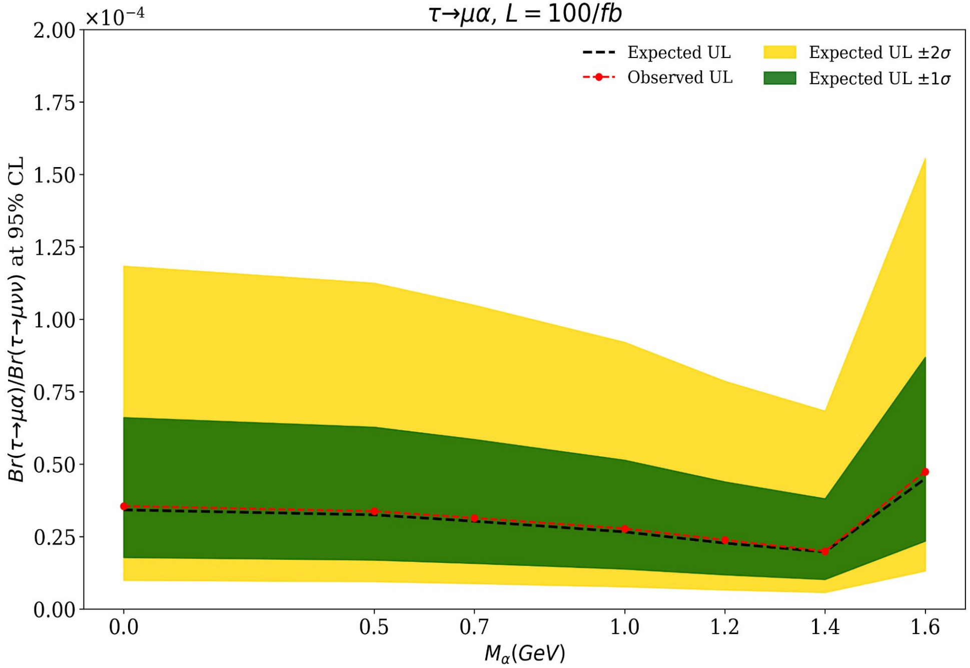
1D methods comparison, we can see a better agreement in large masses

...rado@cinvestav.mx

Cinvestav

UL estimation with the purity cuts (μ-channel)

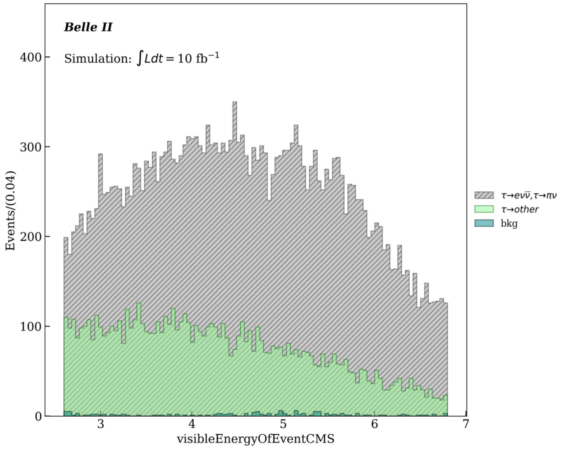
UL with 2D method to different α masses - 100/fb

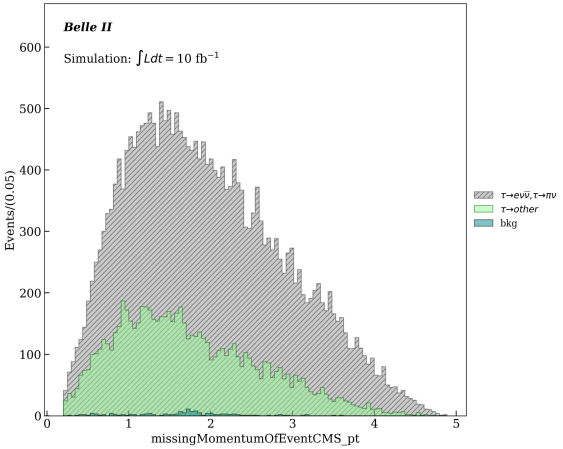


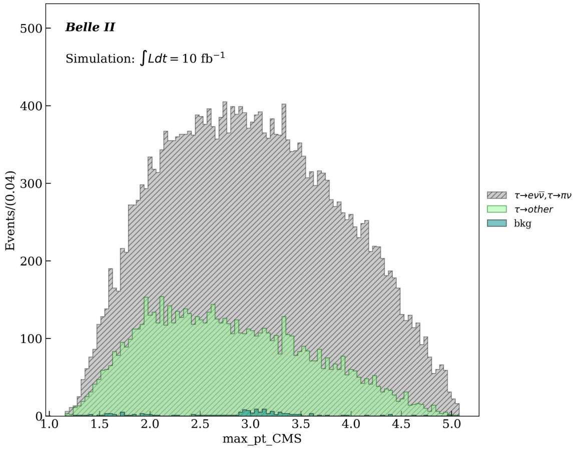
M_α $[GeV/c^2]$	UL at 95% CL $(\times 10^{-5})$
0.0	3.50
0.5	3.40
0.7	3.10
1.0	2.80
1.2	2.40
1.4	2.00
1.6	4.70

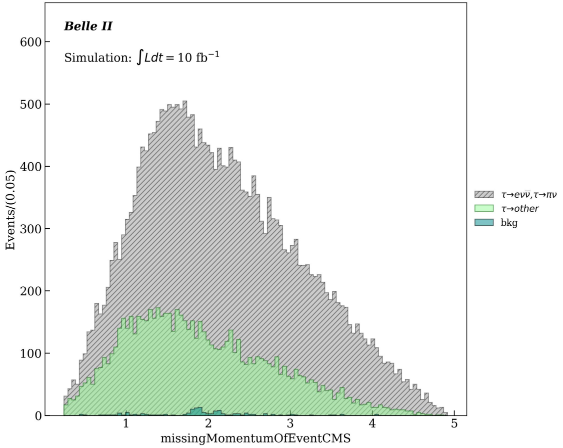
UL's found by us using 2D method

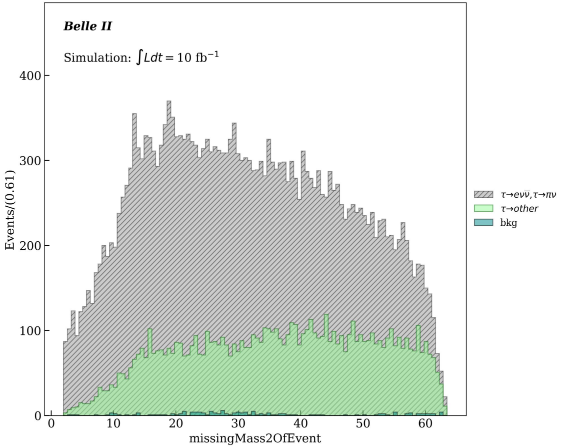
MC study background rejection - τ→eνν

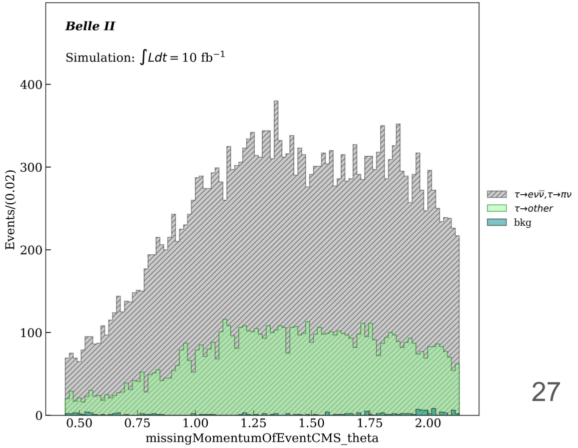




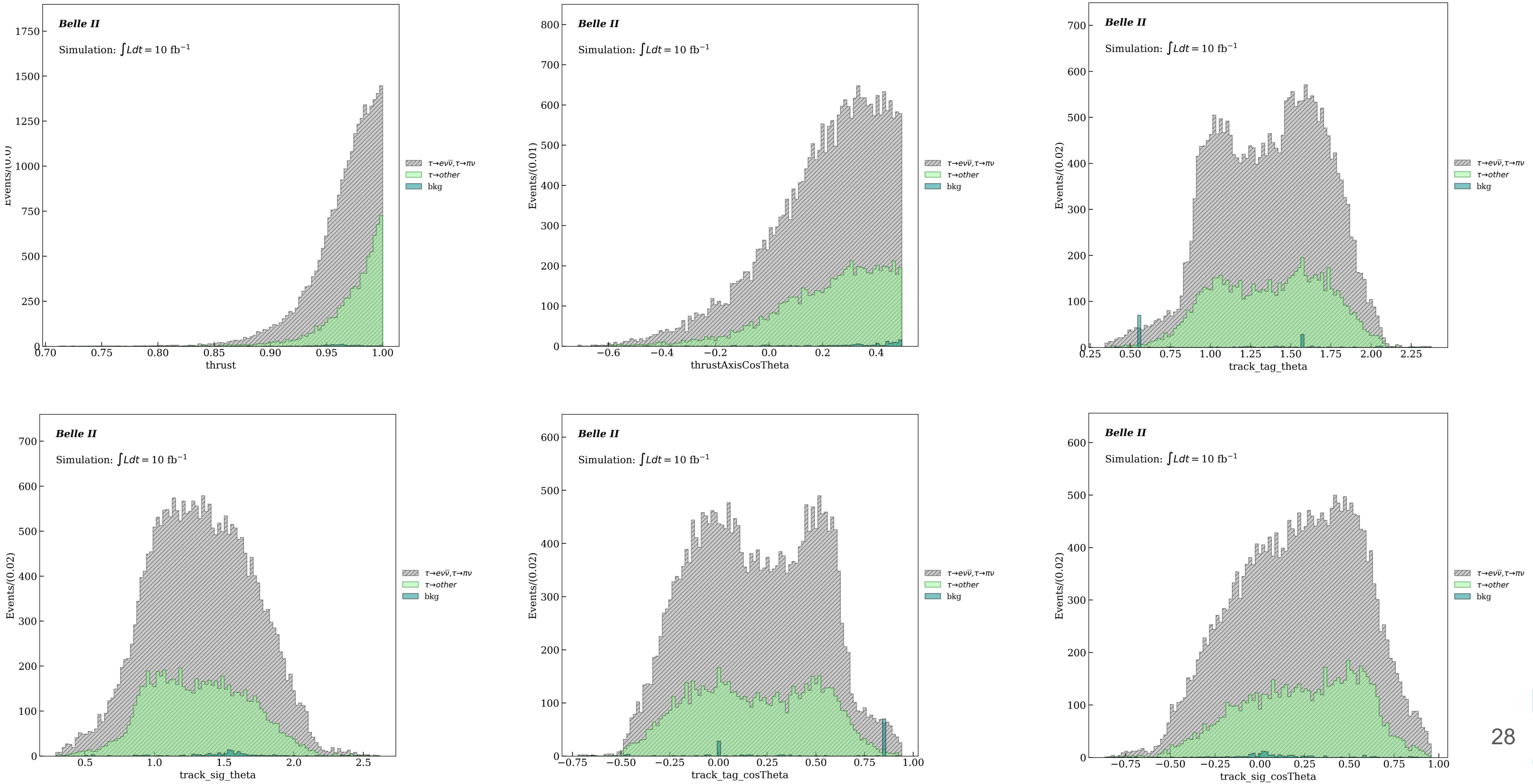


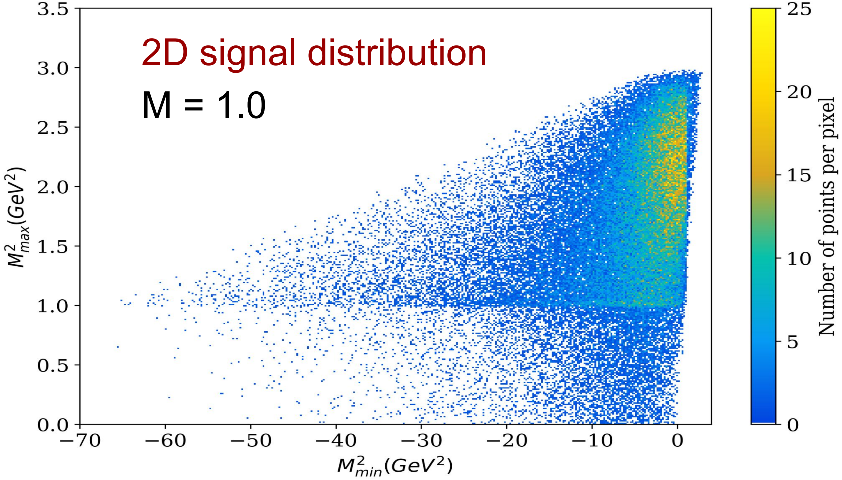


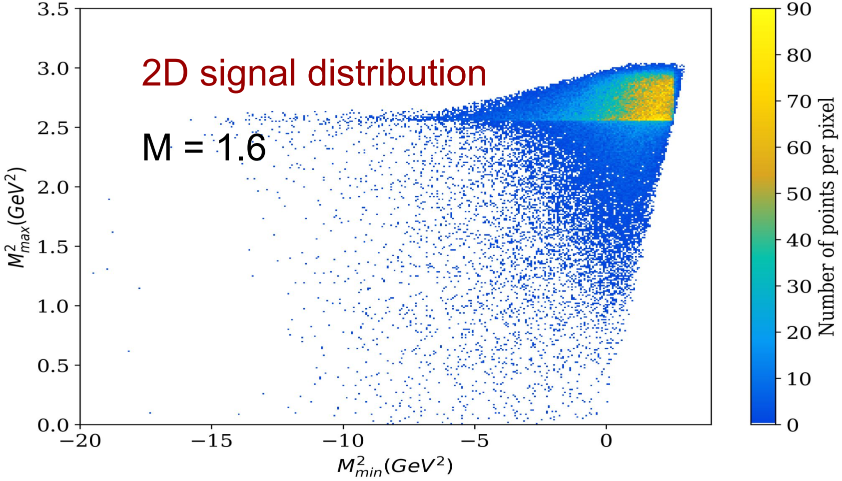


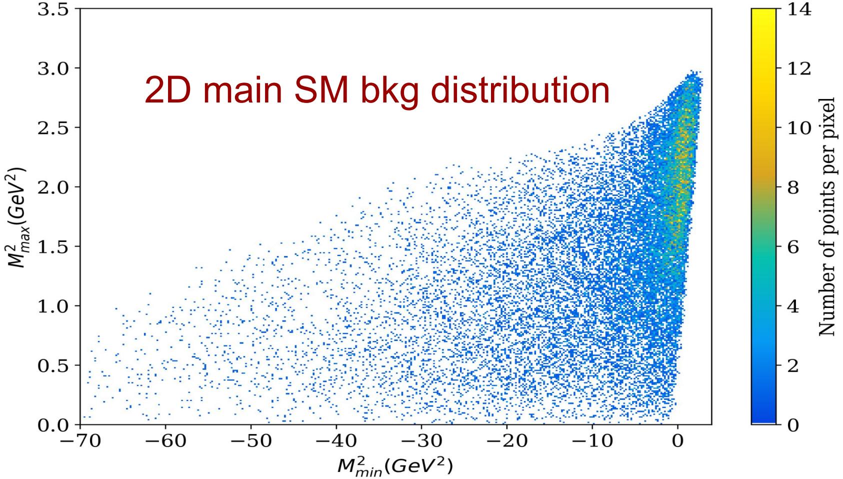


MC study background rejection - $\tau \to e\nu\nu$

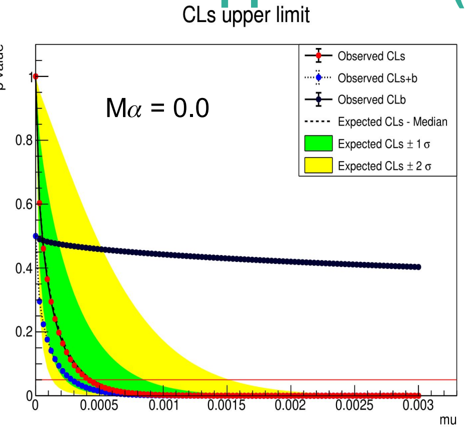


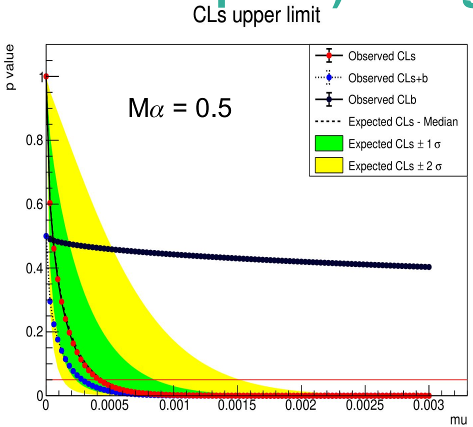

2D signal distribution
M = 1.0
$M^2_{max}(GeV^2)$
$M^2_{min}(GeV^2)$
Number of points per pixel

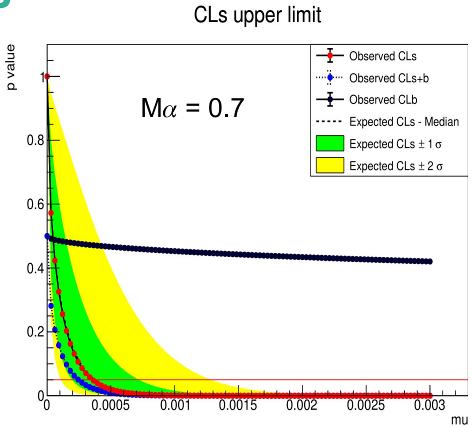

2D signal distribution
M = 1.6
$M^2_{max}(GeV^2)$
$M^2_{min}(GeV^2)$
Number of points per pixel

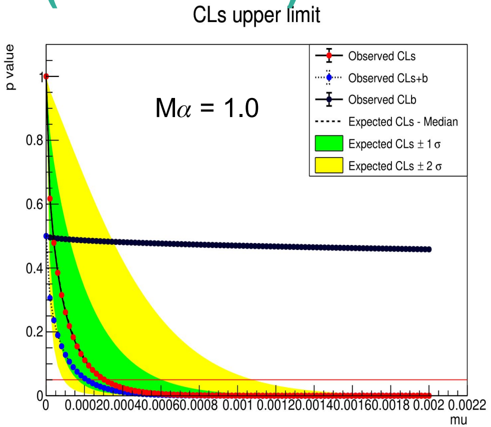

2D main SM bkg distribution
$M^2_{max}(GeV^2)$
$M^2_{min}(GeV^2)$
Number of points per pixel

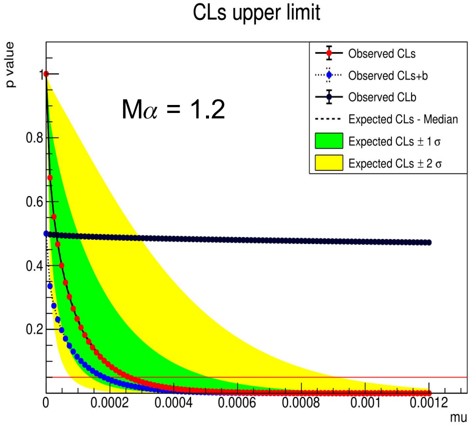
CLs upper limit (Brazilian plots) using 2D method to 62.8/fb (e-channel)

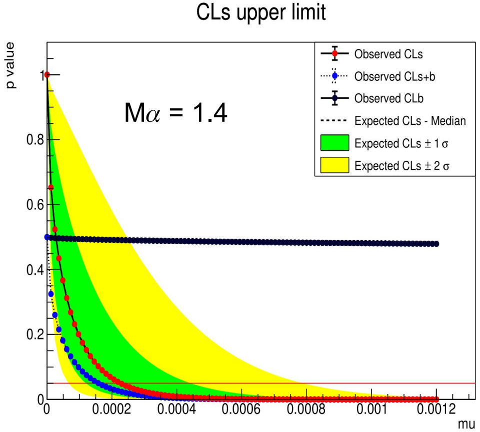


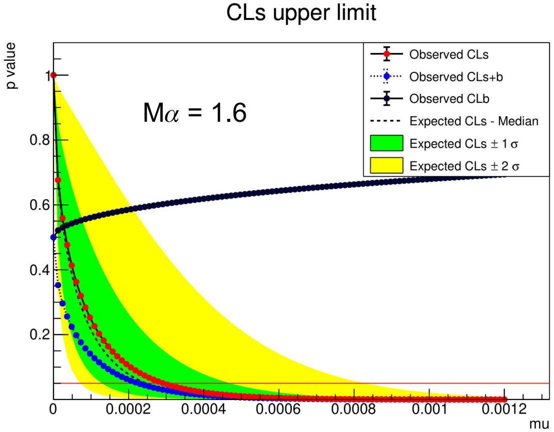












johan.colorado@cinvestav.mx

Cinvestav