Search for $\tau \rightarrow l\alpha$ decays at Belle II

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Cinvestav

XXXV REUNIÓN ANUAL DE LA DIVISIÓN PARTÍCULAS Y CAMPOS

DPC-SMF

Belle II

Motivation

Observed phenomena:
-Matter – antimatter asymmetry
Of the universe
-Neutrino masses
-Dark matter
...

→ Physics beyond the SM

→ Searches for new physics

→ NP models containing:
-Axionlike particles
-Z' gauge bosons
-Dark photons

→ LFV tau lepton decays including invisible BMS particles:

$$\tau \rightarrow l \ \alpha$$

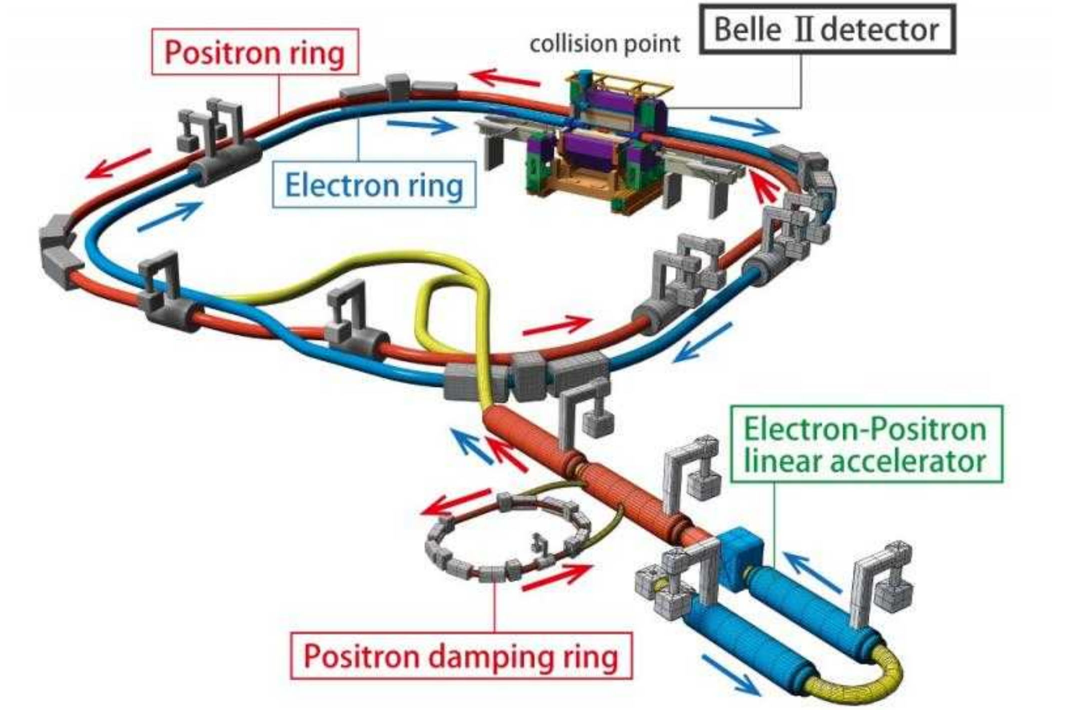
Outline

- → The Belle II colaboration
  - → Accelerator
  - → Detector
  - → Physics
- → Our search
- → Conclusions & Perspectives

SuperKEKB

SuperKEKB (High Energy Accelerator Research Organzation, Tsukuba, Japan)

- E_{CM} = 10.58 GeV
- HER: 7 GeV
- LER: 4 GeV
- Target
  - $\mathcal{L} = 8 \times 10^{35}\ cm^{-2}s^{-1}$ (40xKEKB)
  - $L = 50ab^{-1}$(50xKEKB)
- B-factory: $e^{-}e^{+} \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$(~96%)



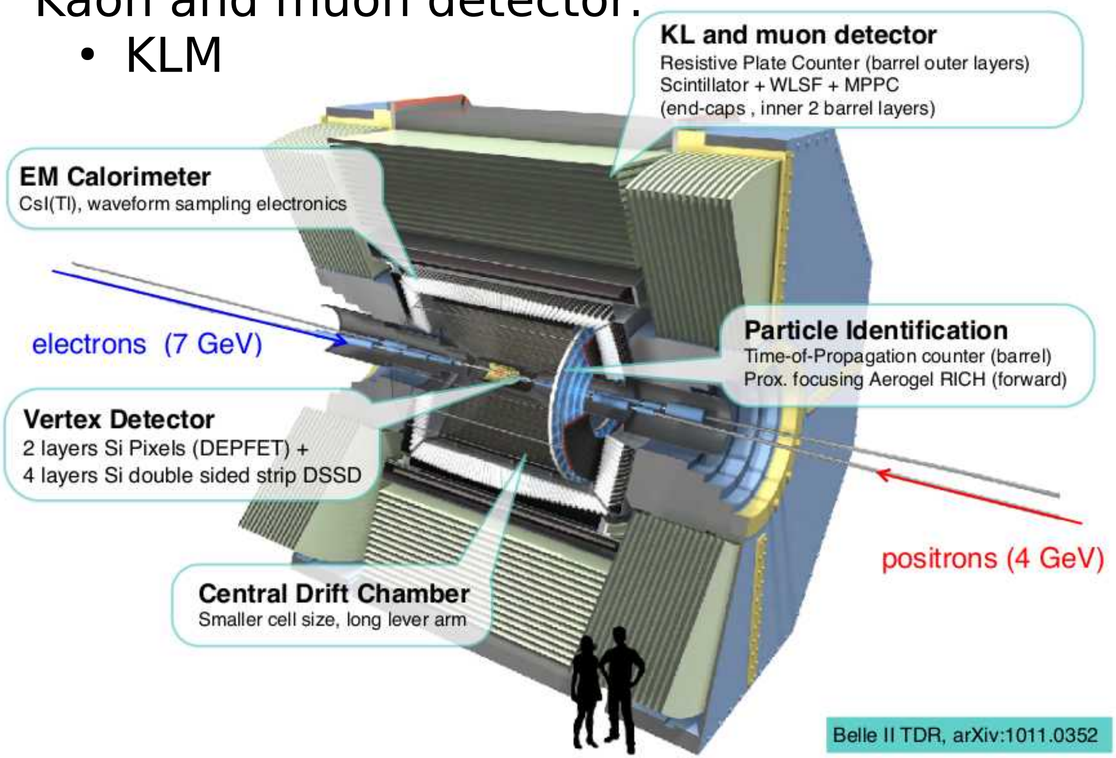
https://www-superkekb.kek.jp/

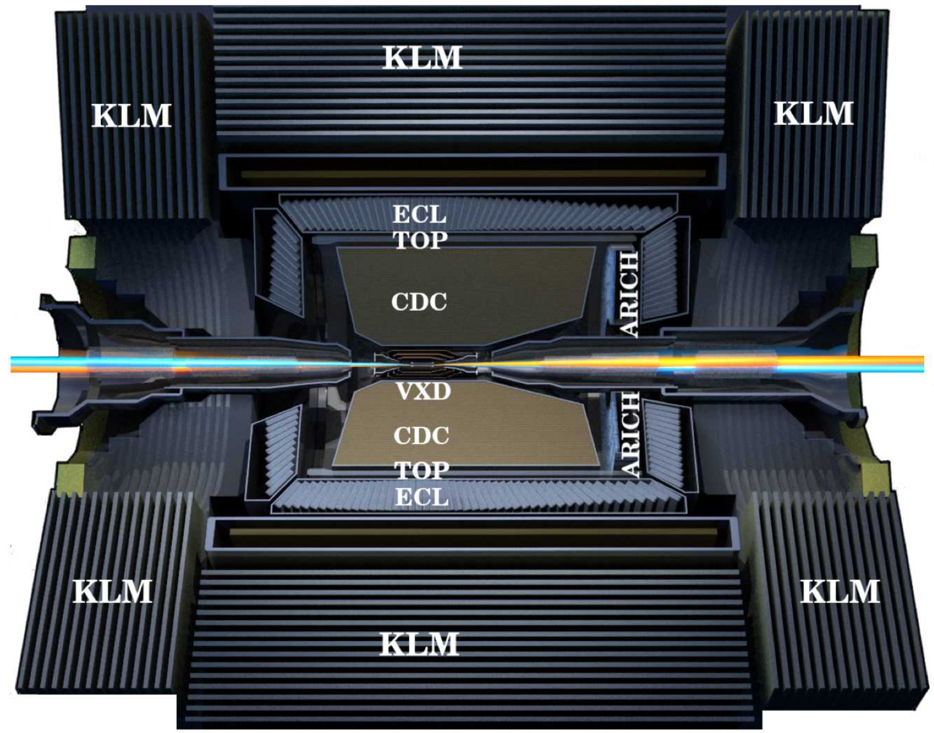
Belle II at SuperKEKB

Tracking system:
- PXD
- SVD
- CDC

Particle ID system:
- TOP (barrel)
- ARICH (forward endcap)

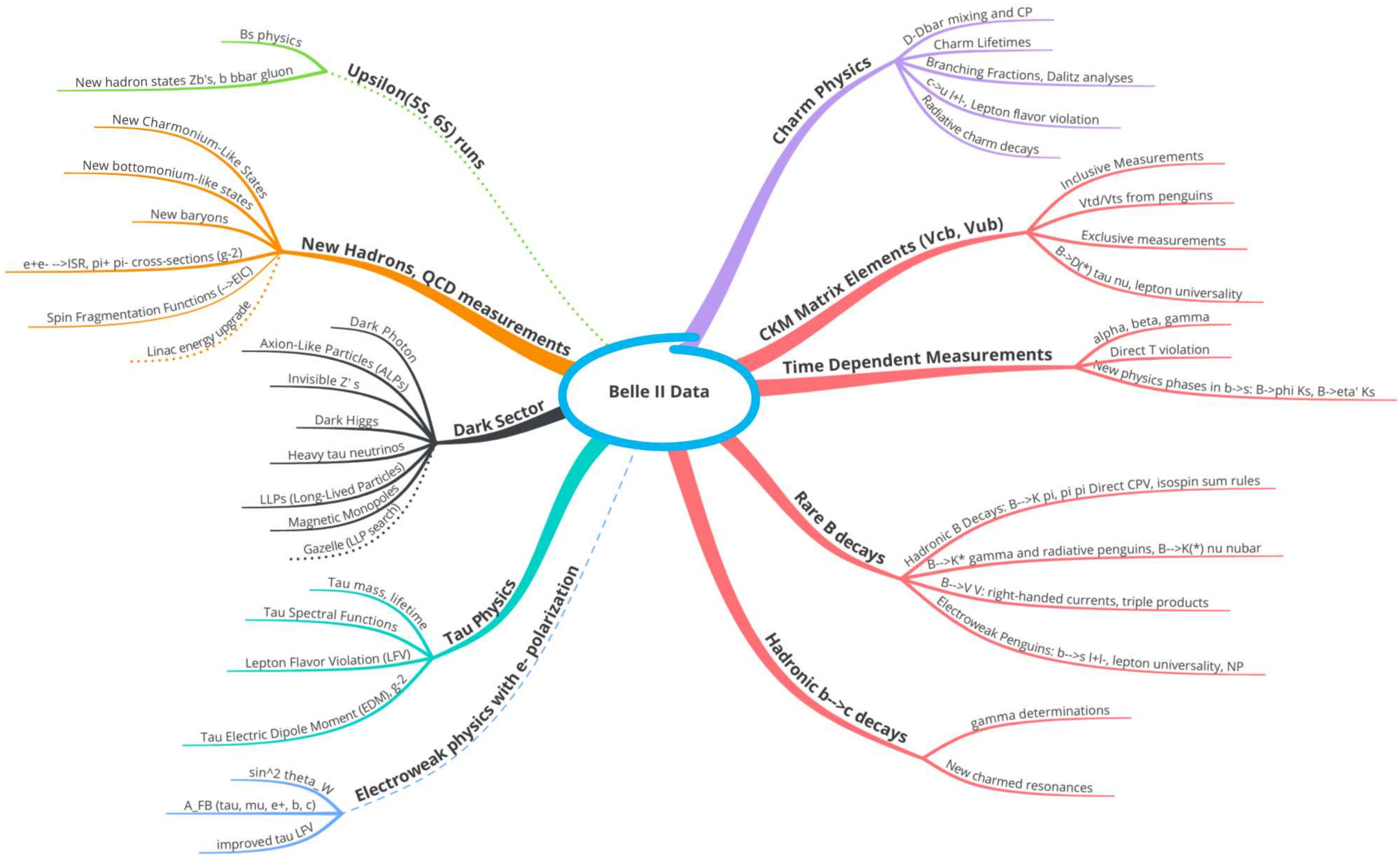
Kaon and muon detector:
- KLM





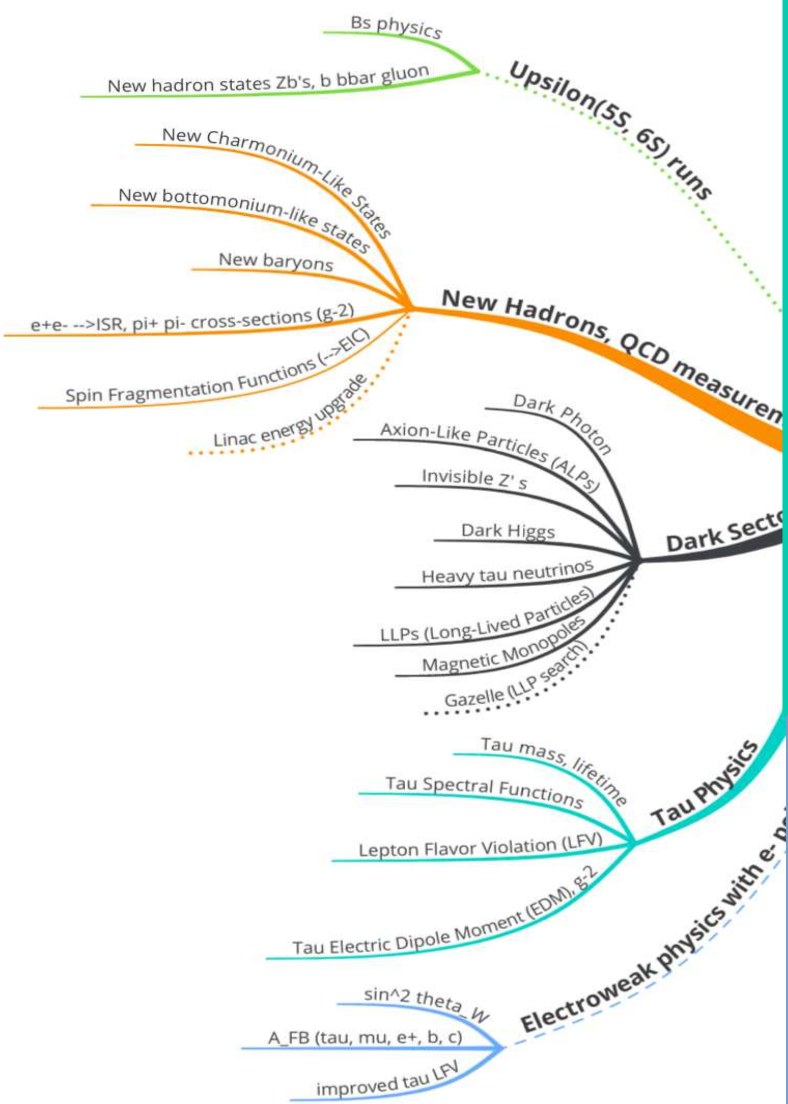
Belle II Technical Design Report:
https://arxiv.org/pdf/1011.0352.pdf

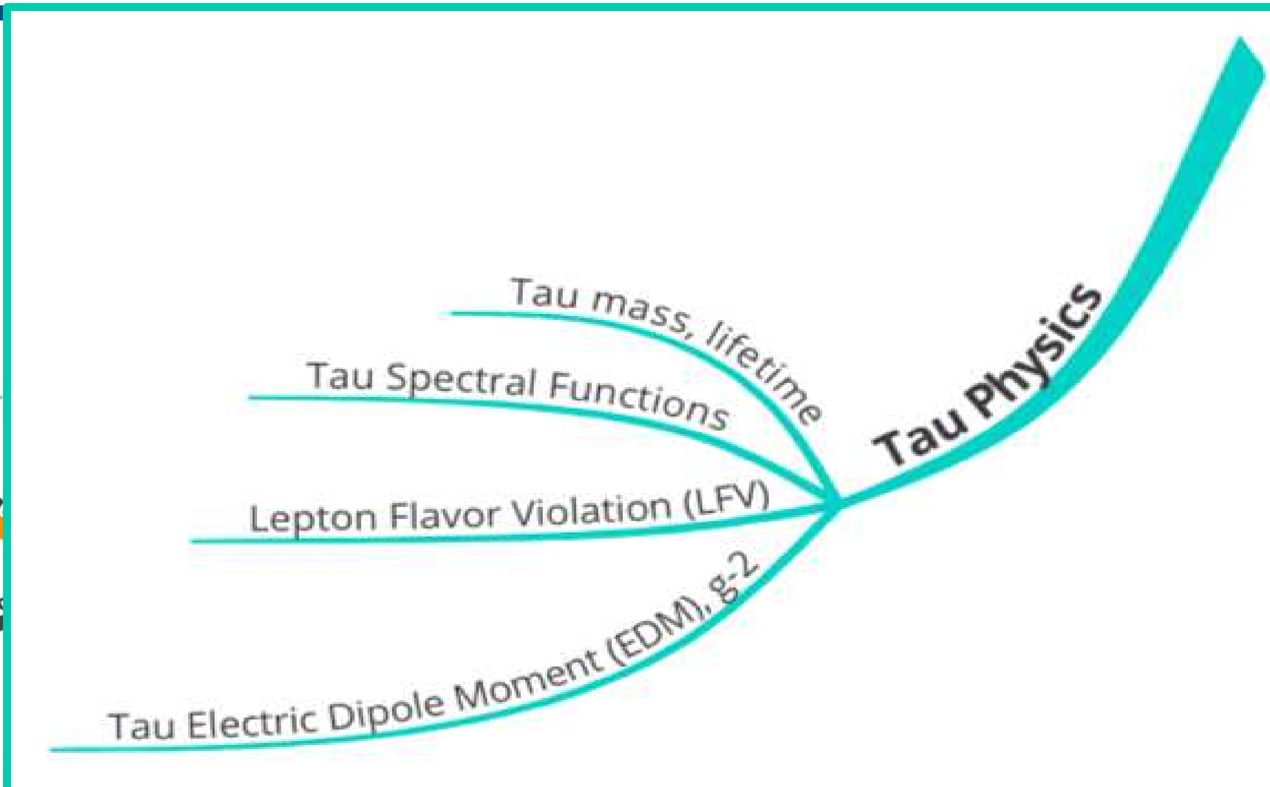
Physics at SuperKEKB – Belle II



The Belle II Physics Book:
https://arxiv.org/pdf/1808.10567.pdf

τ - Physics at SuperKEKB – Belle II





E_{CM} = 10.58 GeV

B–factory: $\sigma(e^- e^+ \rightarrow \Upsilon(4S))$ = 1.05 nb

τ–factory: $\sigma(e^- e^+ \rightarrow \tau^- \tau^+)$ = 0.92 nb

Belle and BaBar achieved many results in τ physics:

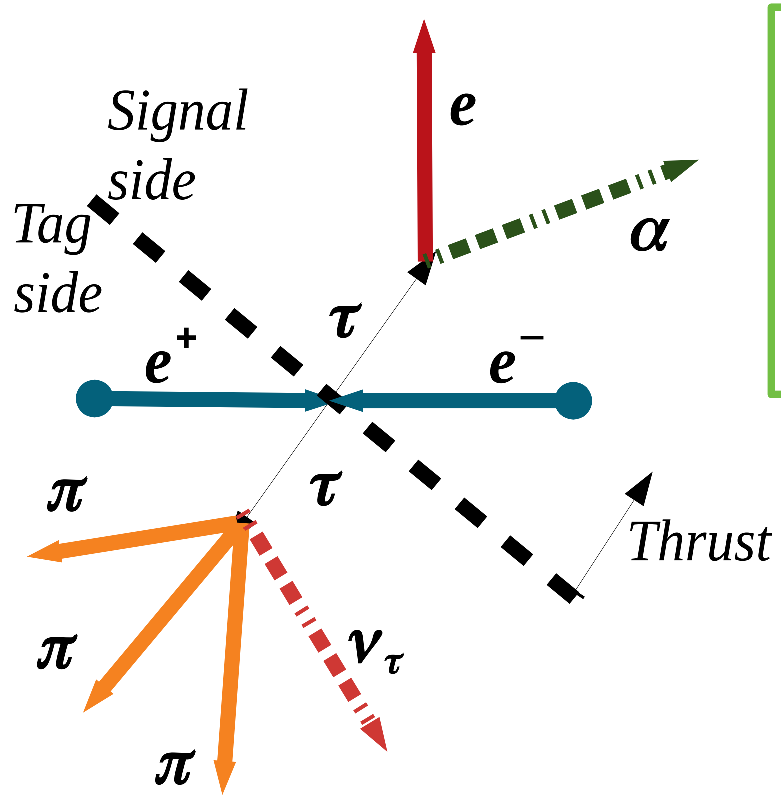
Mass, Br, LFV & LNV, etc.

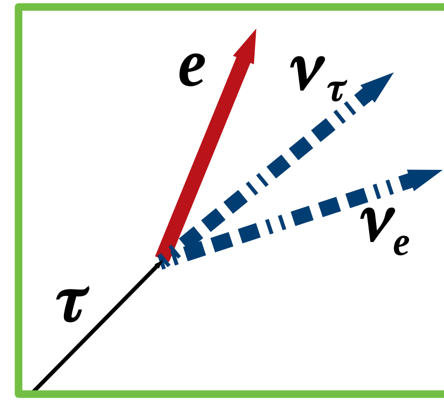
Our search

Event selection

4 tracks in the event

***Thrust*: signal and tag sides**
→1 track in the signal side
→3 tracks in the opposite side





Dominant bkg: $\tau \rightarrow e \nu \bar{\nu}$

We can not suppress it

We optimize in favor of it

$$ee \rightarrow \tau(\rightarrow 3\text{-}prong)\,\tau(\rightarrow e)$$

Cut based optimization

Figure of merit:

$$FOM = \frac{S}{\sqrt{S+B}}$$

$$V_{thrust} = \frac{\sum_i |\vec{p_i}^{\,cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p_i}^{\,cm}|}$$

Our search

Event selection

$$\varepsilon = \frac{N_{sel}}{N_{gen}}$$

$$Purity = \frac{S}{S+B}$$

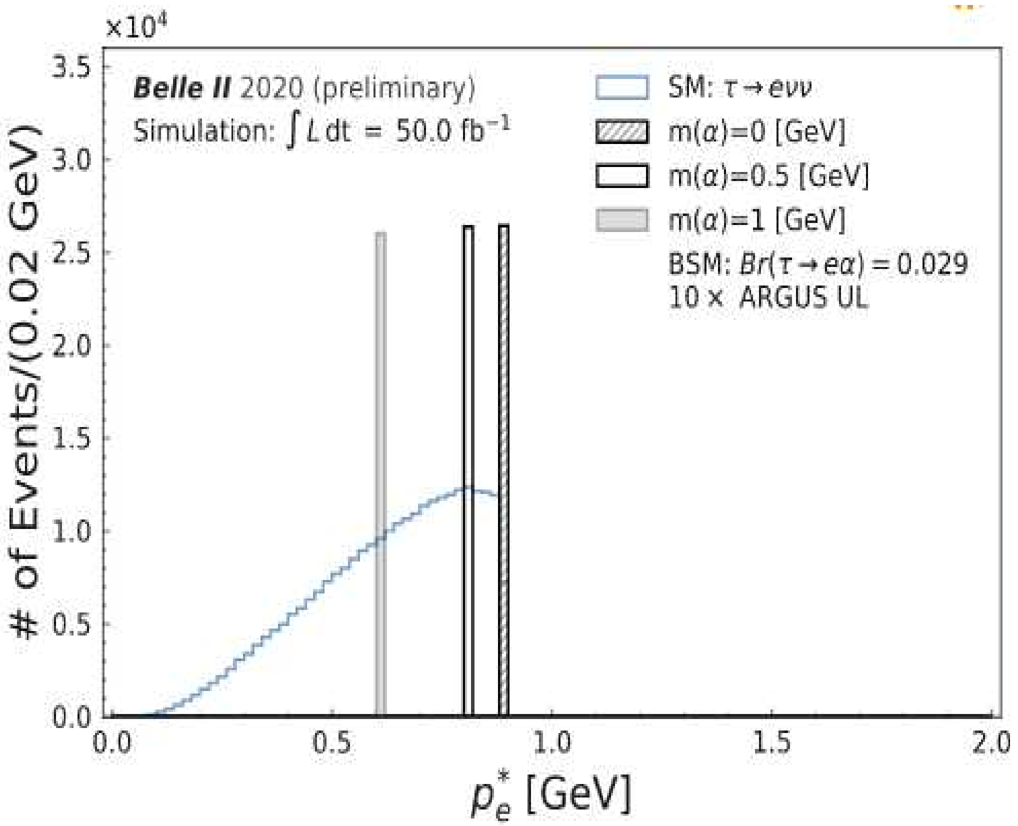
Sample	Efficiency	Purity
$e\nu\nu$	14.82%	95.22%
$M(\alpha) = 0$	16.0%	
$M(\alpha) = 0.5$	15.99%	
$M(\alpha) = 0.7$	15.96%	
$M(\alpha) = 1.0$	15.81%	
$M(\alpha) = 1.2$	15.64%	
$M(\alpha) = 1.4$	15.05%	
$M(\alpha) = 1.6$	13.01%	

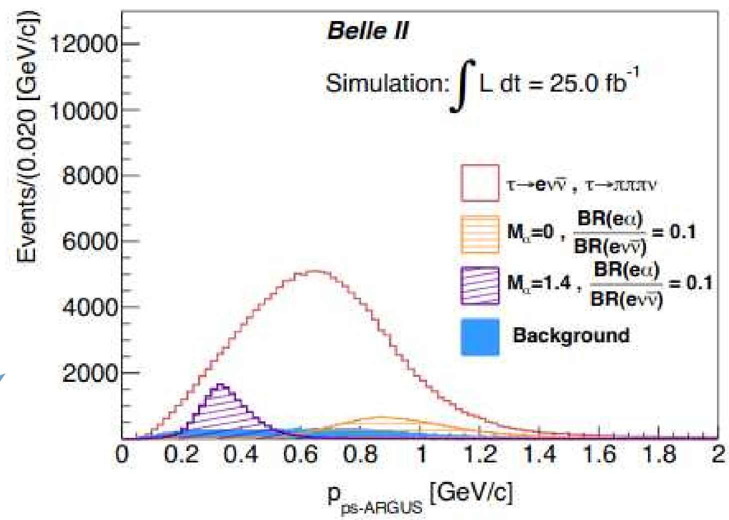
Sample	Efficiency	Purity
$\mu\nu\nu$	17.88%	91.05%
$M(\alpha) = 0$	19.65%	
$M(\alpha) = 0.5$	19.44%	
$M(\alpha) = 0.7$	19.43%	
$M(\alpha) = 1.0$	18.84%	
$M(\alpha) = 1.2$	18.11%	
$M(\alpha) = 1.4$	16.55%	
$M(\alpha) = 1.6$	11.59%	

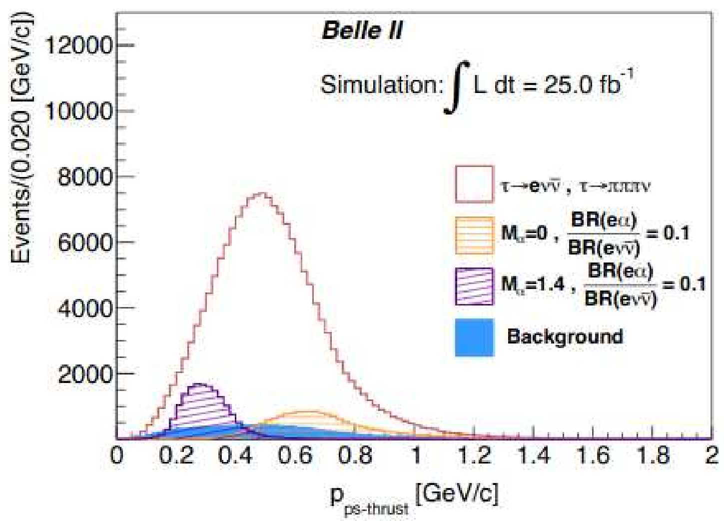
Our search

τ rest frame

τ pseudo rest frame







Our search

A new approach

Search for $\tau \rightarrow$ *lepton+invisible*

$m_\nu = 0, \; m_\alpha$

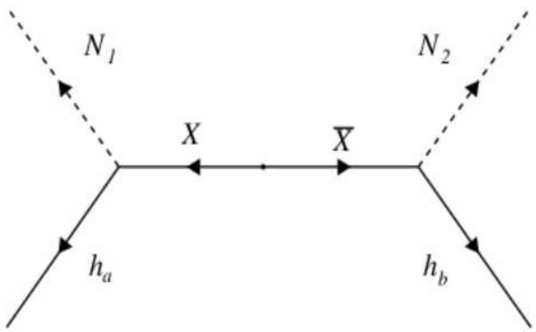


FIG. 1. $X\bar{X}$ production topology in the center-of-mass frame. Each X decays to a detectable product h and an invisible particle N that escapes undetected.

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

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

$$M_{min}^2 \leq m_\alpha^2 \leq M_{max}^2,$$

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

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

New method for beyond the Standard Model invisible particle searches in tau lepton decays.
Phys. Rev. D 102, 115001

Our search

Statistical model

Template-based approach

The $\tau \to e\,\alpha$ branching ratio is given by: $Br(sig) = \dfrac{N_{sig}}{2\,L\,\sigma(e^- e^+ \to \tau^- \tau^+)\,Br(tag)\,\varepsilon}$

Using $\tau \to e\,\nu\,\bar{\nu}$ as normalization channel

$$poi \overset{\text{def}}{=} \frac{N_{e\,\alpha}}{N_{e\,\nu\,\nu}} \frac{\varepsilon^{e\,\nu\,\nu}}{\varepsilon^{e\,\alpha}} = \frac{Br(\tau \to e\,\alpha)}{Br(\tau \to e\,\nu\,\nu)}$$

Our data can be modeled as:

$$F(x) = \frac{\varepsilon^{e\,\alpha}}{\varepsilon^{e\,\nu\,\nu}} N_{e\,\nu\,\nu}\, poi\; f_{e\,\alpha}(x) + N_{e\,\nu\,\nu} f_{e\,\nu\,\nu}(x) + N_{bkg} f_{bkg}(x)$$

Discriminating variables: $x = \dfrac{2\,E_l}{m_\tau},\;\; M^2_{min},\;\; M^2_{max}$

Our search

Upper limit estimation

$\boldsymbol{CL_s}$**:** Modified frequentist method

$$CL_s \equiv \frac{CL_{s+b}}{CL_b}$$

CL_{s+b}: confidence level observed for the signal + bkg hypothesis

CL_b: confidence level observed for the bkg-only hypothesis

Asymptotic CL_s formulation : fast

<u>Goal</u> : Given a MC dataset, estimate the upper limit on poi at $95\%\,cl$

Eur. 638 Phys. J. C 71, 1554 (2011)

Our search

Preliminary results

→ Results for the estimation of the upper limit at 95 % cl assuming an integrated luminosity of $25\,fb^{-1}$ within the early phase III conditions.

→ Test (bkg only) dataset, equivalent to $25\,fb^{-1}$:

$\tau\tau,\ B\bar{B},\ q\bar{q},\ low\,multiplicity.$

→ Since this is a template based analysis, we use the equivalent to $100\,fb^{-1}$ from MC samples to obtain the templates.

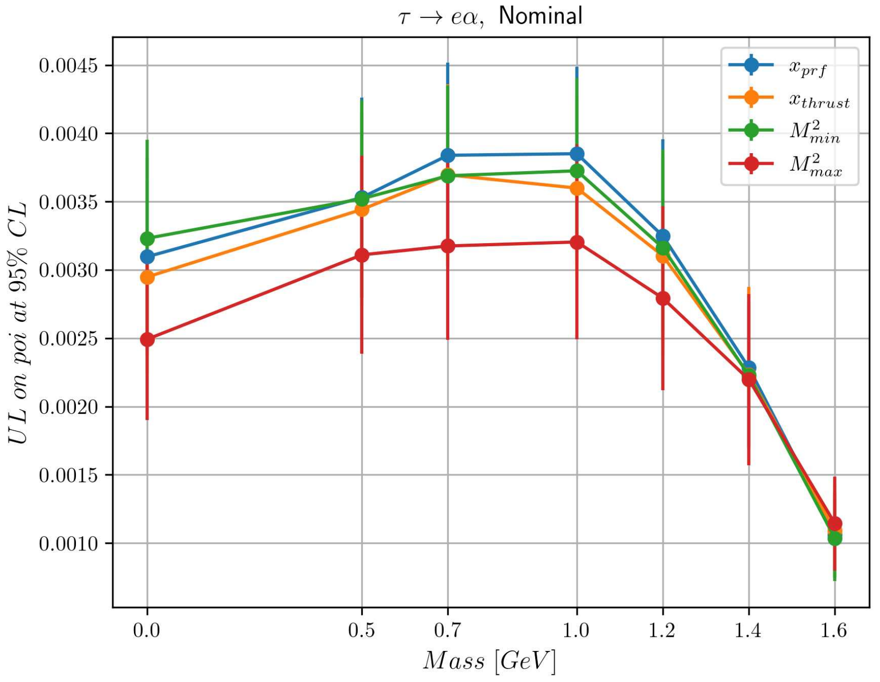
→ Signal simulation:

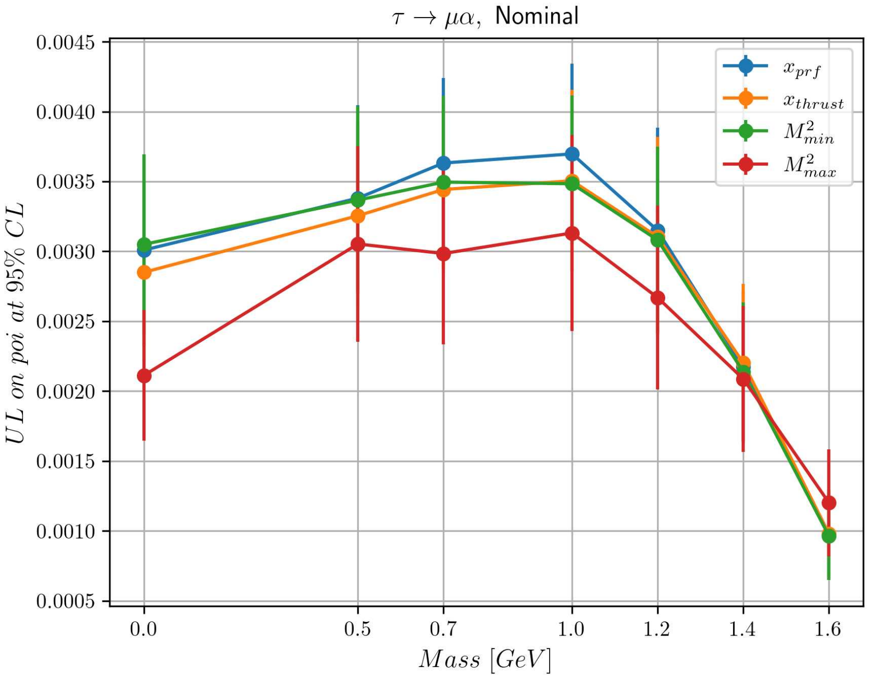
$\tau \rightarrow l\alpha$: 10^7 events at $M(\alpha)=0,\ 0.5,\ 0.7,\ 1,\ 1.2,\ 1.4,\ 1.6\ GeV.$

Our search

Preliminary results

Nominal results: using the asymptotic CLs ROOT implementation





Checks:
Bayesian estimation
Non-asymptotic CLs estimation

Conclusions & perspectives

- Framework for the search of the decay channel $\tau \rightarrow l\,\alpha$
  - Selection: cut based
  - Implementation of new searching variables
  - Different ul estimation methods (crosschecks)

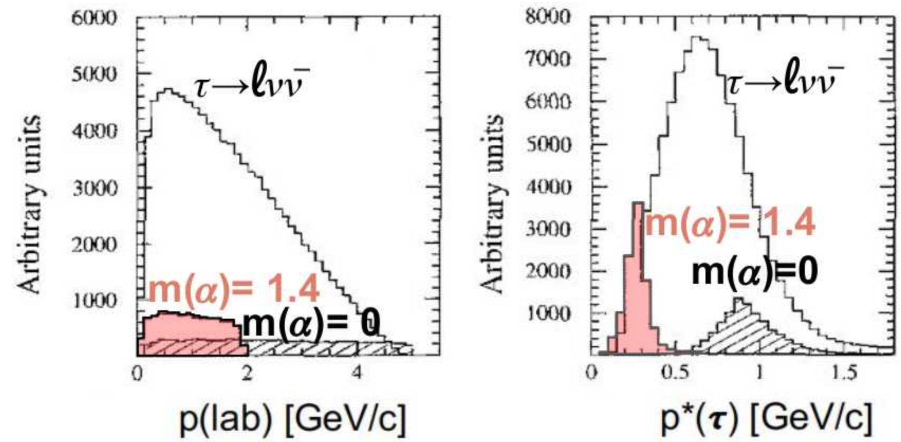
- Ongoing studies
  - Systematic uncertainties
  - Unblinding methodology

Backup

Search for the LFV decay channels :

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

being α a BSM unobservable particle.

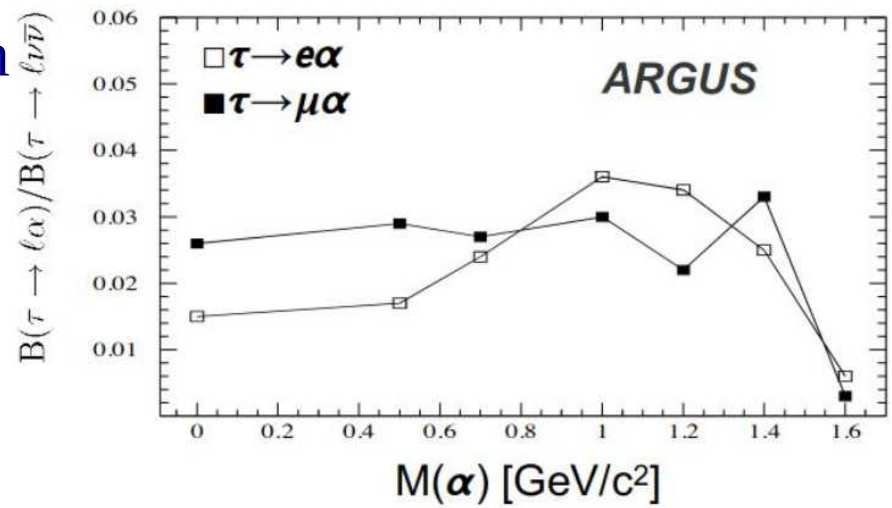


Previous measurements

→ $Mark\ III\ \left(85,\ 9.4\,pb^{-1}\right)$

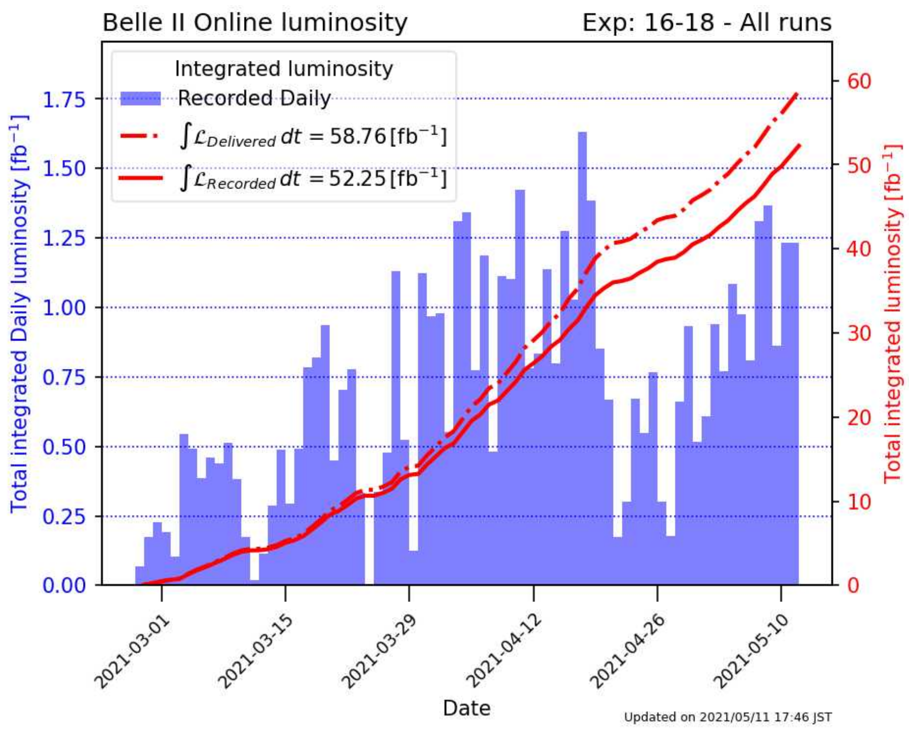
→ $ARGUS\ \left(95,\ 472\,pb^{-1}\right)$

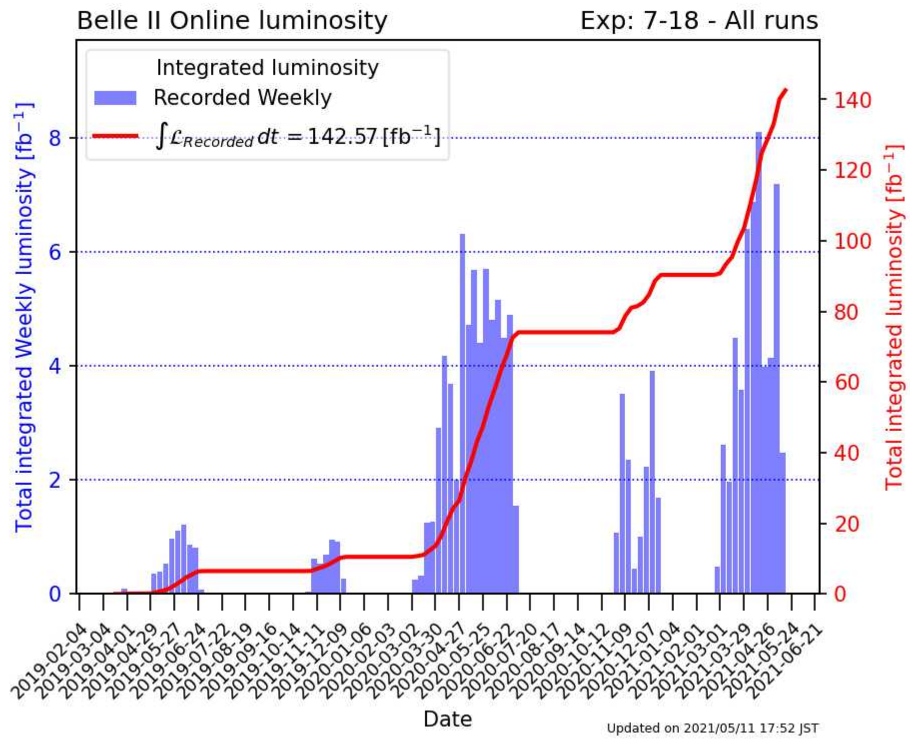
Study the momentum spectrum of the lepton in the τ pseudo rest frame. Here the lepton momentum distribution is shaped as a peak with a position depending on the α mass.



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

SuperKEKB: luminosity status





Integrated luminosity per day for the current run period

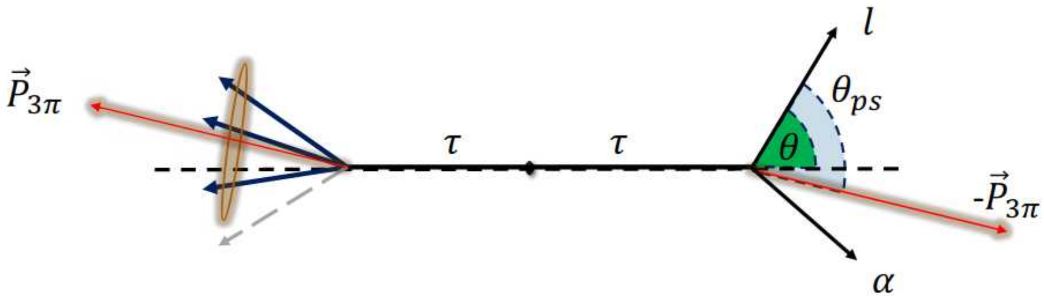
Total recorded integrated luminosity

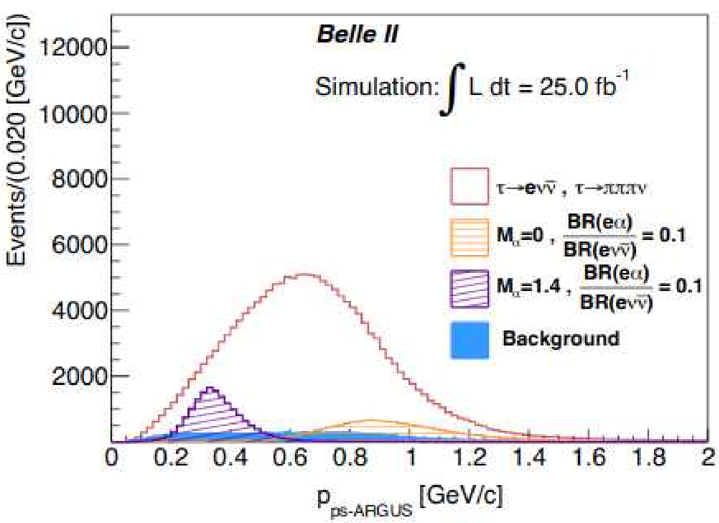
Our search

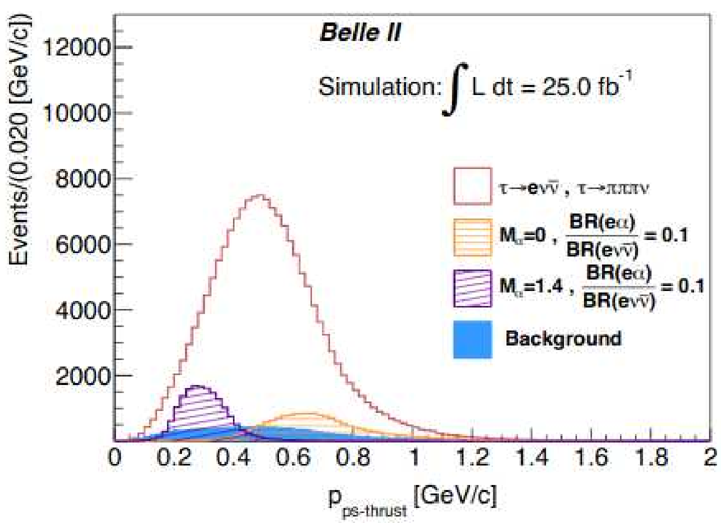
τ pseudo rest frame

In the τ rest frame the momentum of the lepton l, in the decay $\tau \to l\,\alpha$, will peak with a position depending on the α mass.
We do not know the direction of flight of the τ in order to boost to its r.f.
Lets aproximate .

ARGUS method
Direction of the τ:
$\vec{e}_\tau \simeq \vec{e}_{3-prong}$
Energy of the τ:
$E_\tau \simeq E_{CMS}/2$
Boost the lepton l to the τ p.r.f.



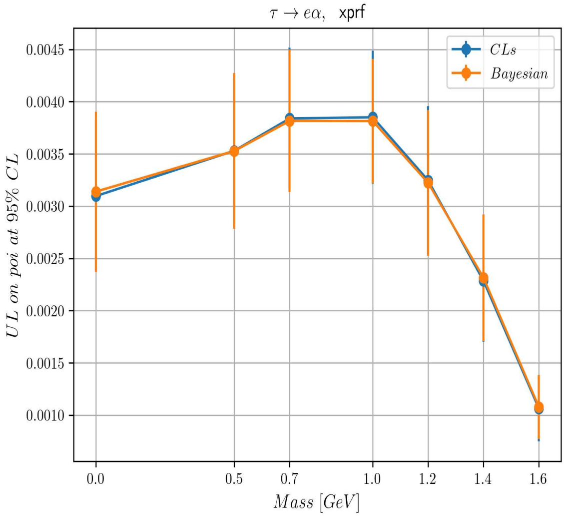


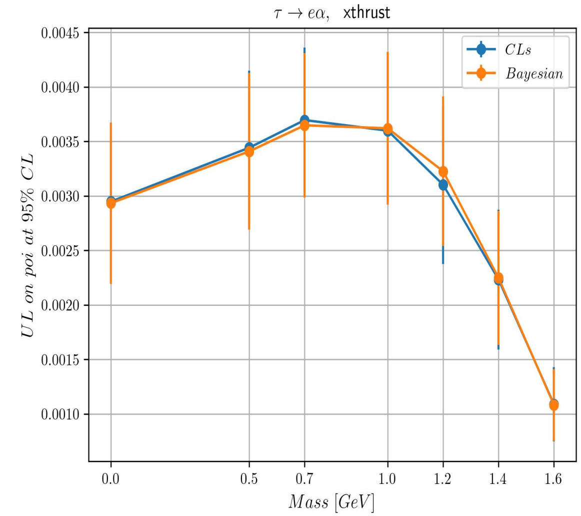


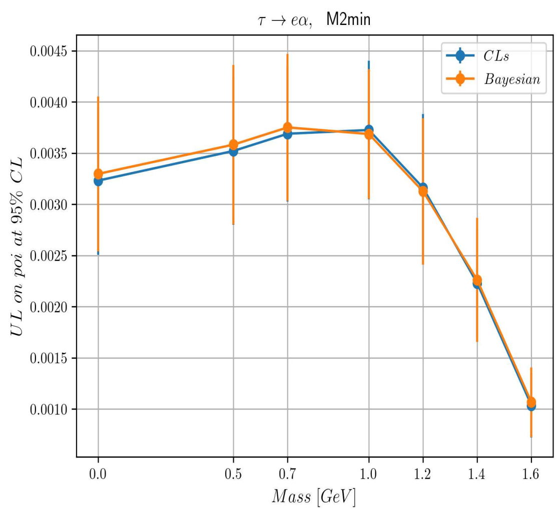
Thrust method
Direction of the τ:
$\vec{e}_\tau \simeq \vec{e}_{thrust}$
Energy of the τ:
$E_\tau \simeq E_{CMS}/2$
Boost the lepton l to the τ p.r.f.

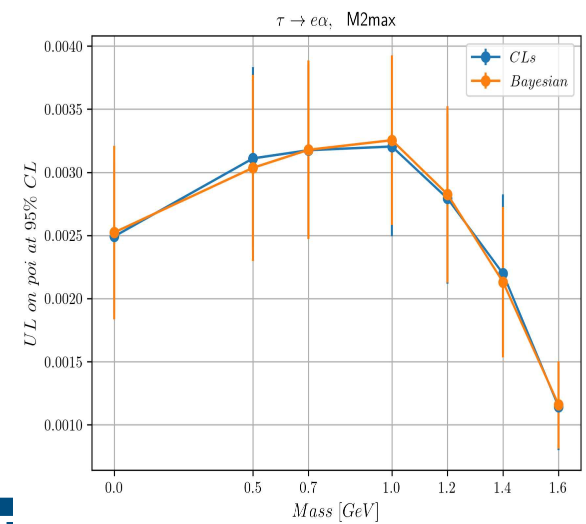
$e-channel$

Nominal results: MCMC bayesian vs asymptotic CLs (ROOT implementations)



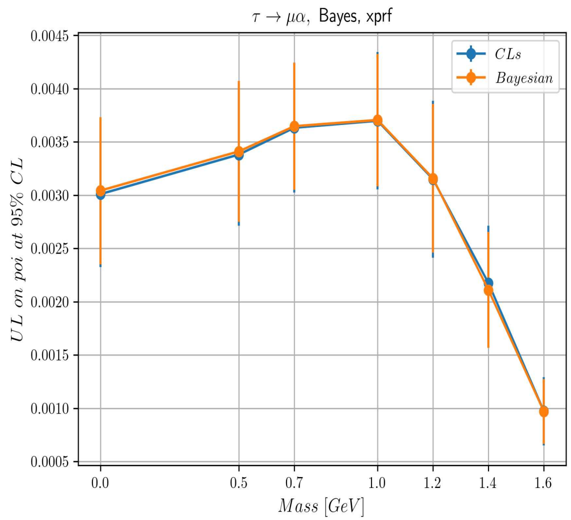


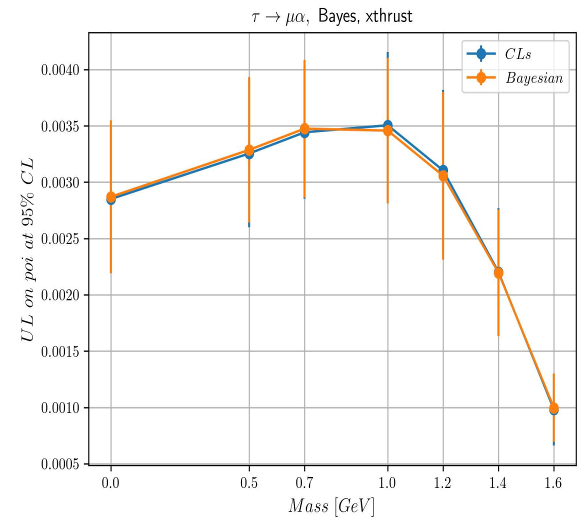


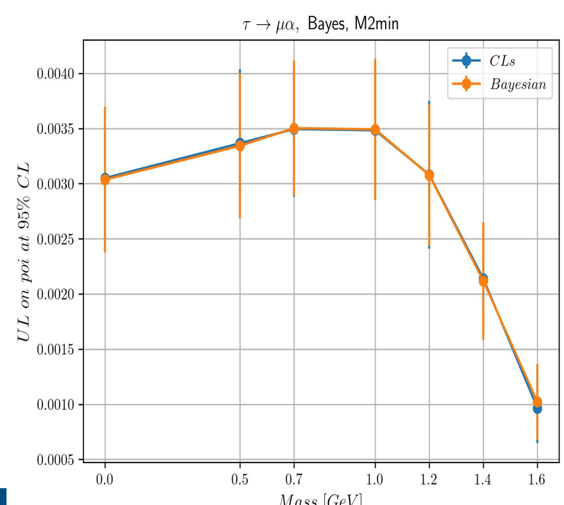


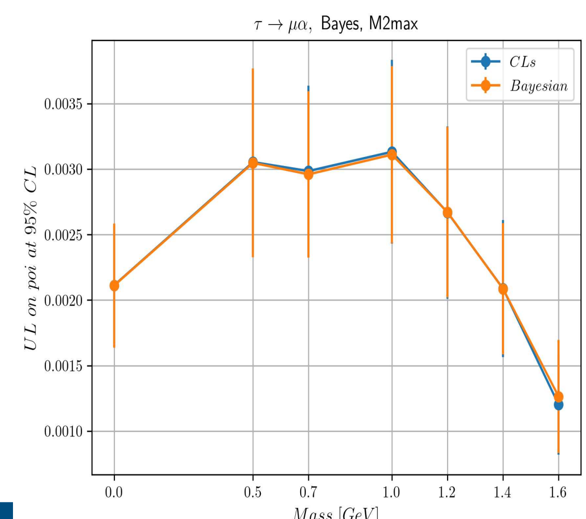
$\mu-channel$

Nominal results: MCMC bayesian vs asymptotic CLs (ROOT implementations)

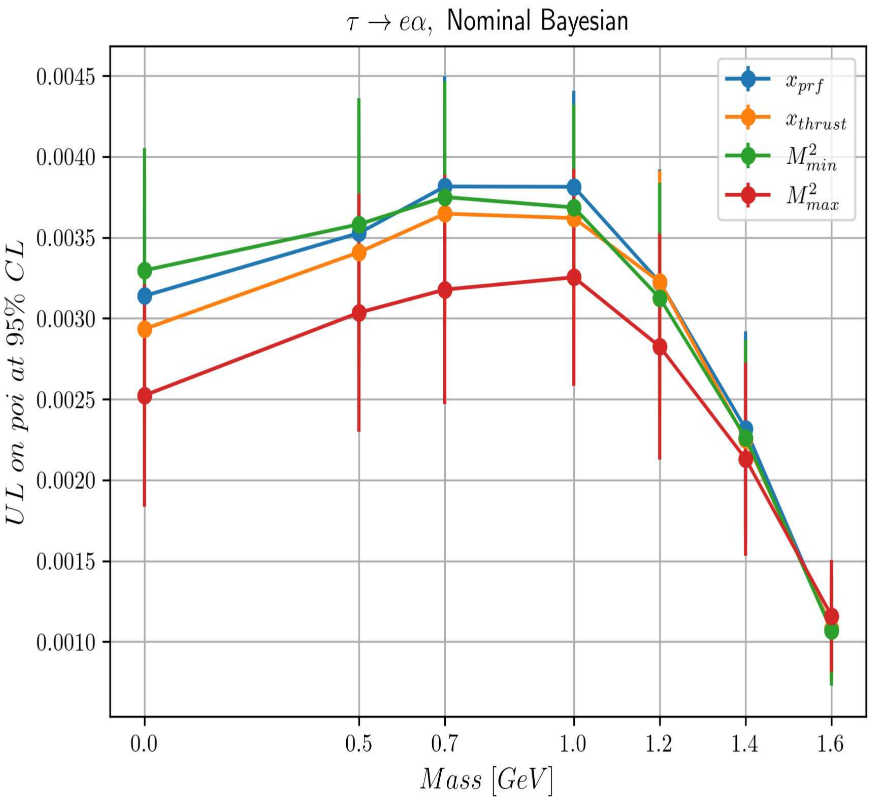


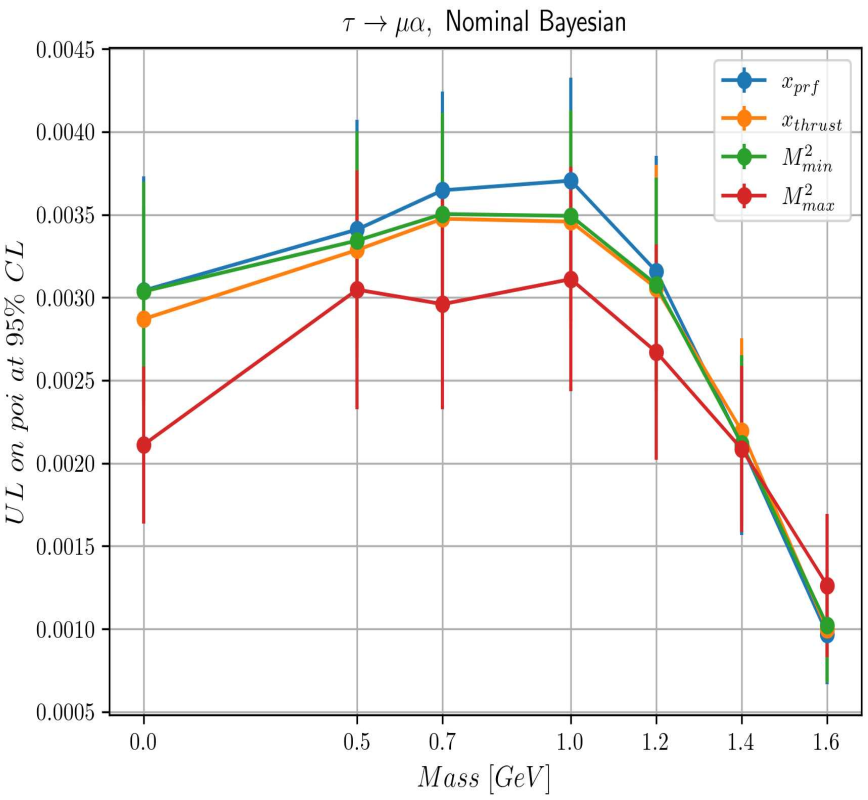






Nominal results: using the MCMC bayesian (w a uniform prior) ROOT implementation





Our search

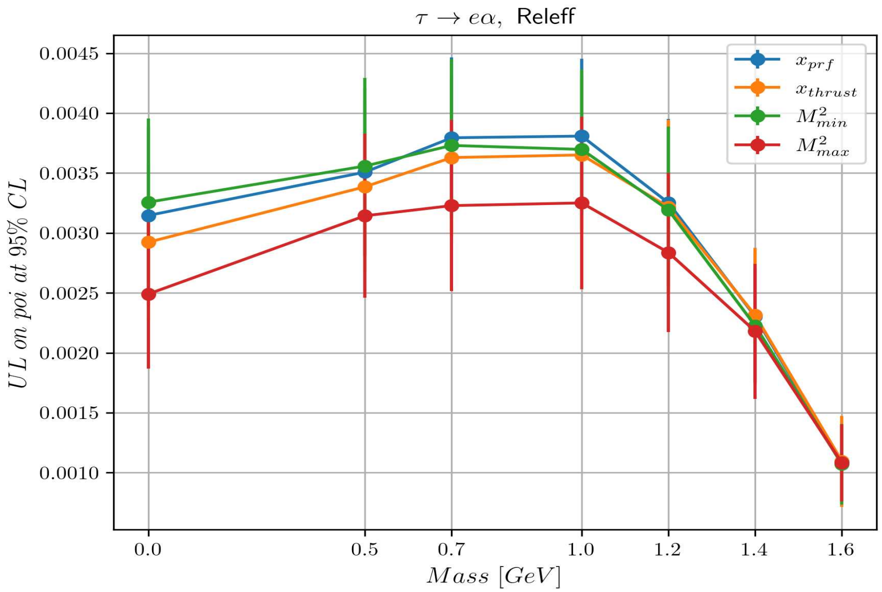
Preliminary results

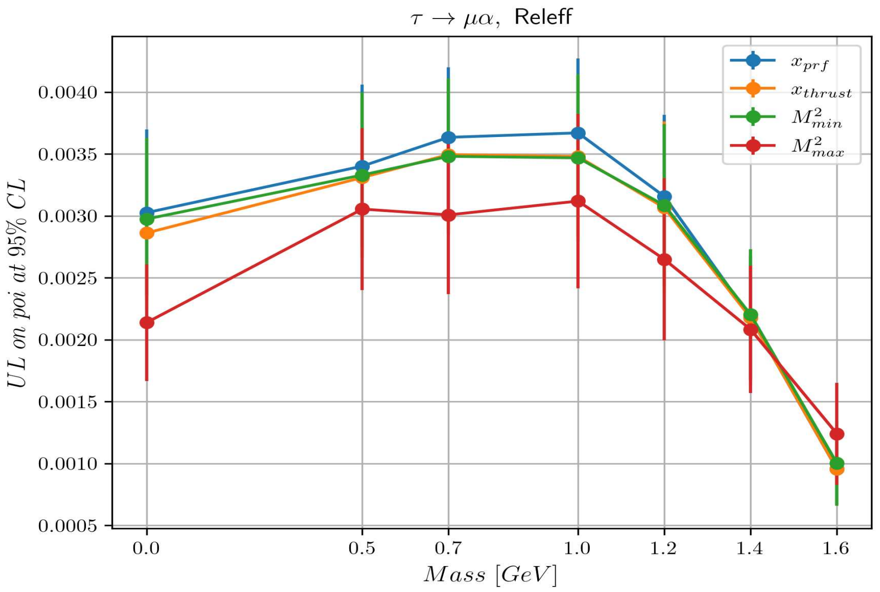
Systematic uncertainties

Rel eff

$$\sigma_{\frac{\varepsilon^{e\alpha}}{\varepsilon^{e\nu\nu}}} = 0.3\%$$

$$F(x) = \boxed{\frac{\varepsilon^{e\alpha}}{\varepsilon^{e\nu\nu}}} N_{e\nu\nu}\, poi\, f_{e\alpha}(x) + N_{e\nu\nu} f_{e\nu\nu}(x) + N_{bkg} f_{bkg}(x)$$





Our search

Preliminary results

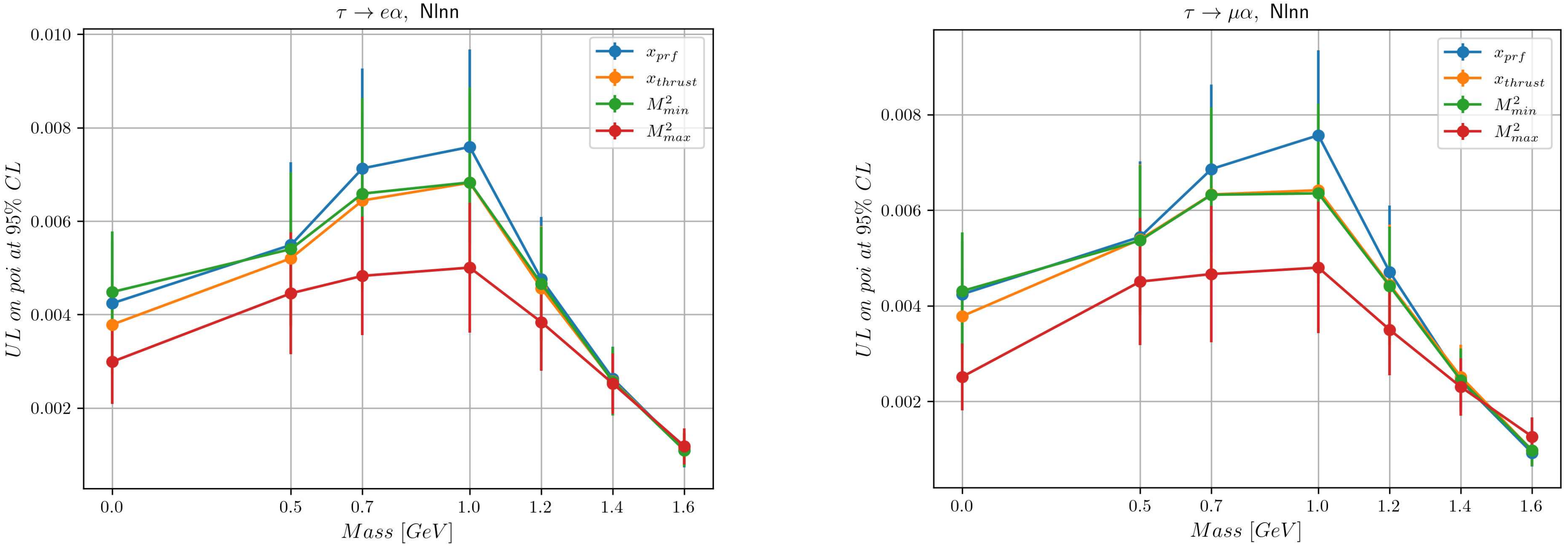
Systematic uncertainties

$\sigma_{N_{e\nu\nu}}$

$N_{\tau\to e\nu\nu} = 2L\sigma Br(tag)Br(\tau\to e\nu\nu)\varepsilon$

$\sigma_{N_{\tau\to e\nu\nu}} = 1.6\%$

$$F(x) = \frac{\varepsilon^{e\alpha}}{\varepsilon^{e\nu\nu}} N_{e\nu\nu}\, poi\, f_{e\alpha}(x) + N_{e\nu\nu} f_{e\nu\nu}(x) + N_{bkg} f_{bkg}(x)$$



Our search

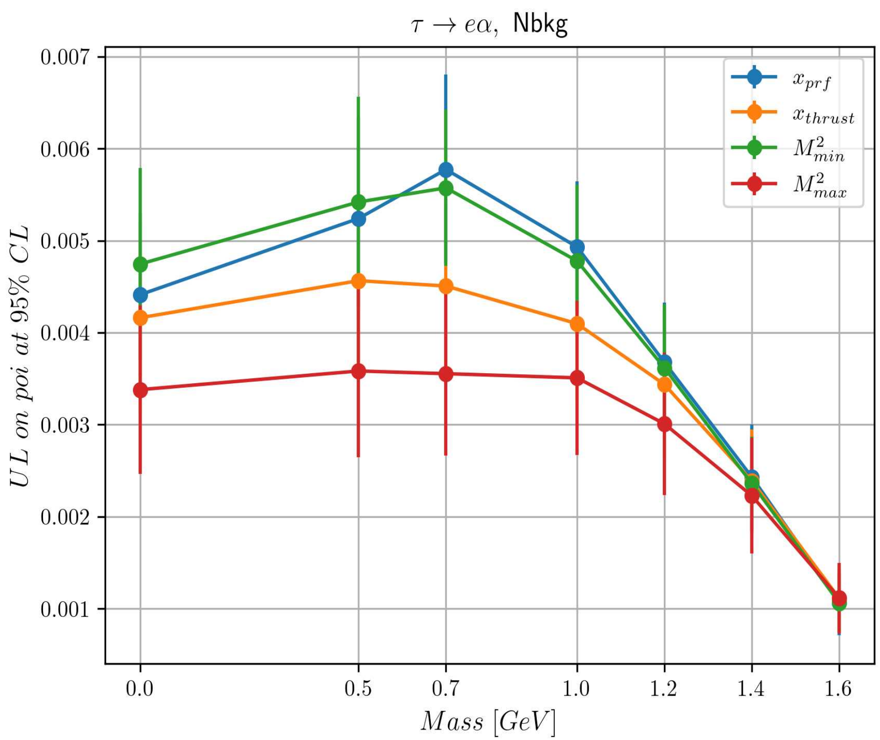
Preliminary results

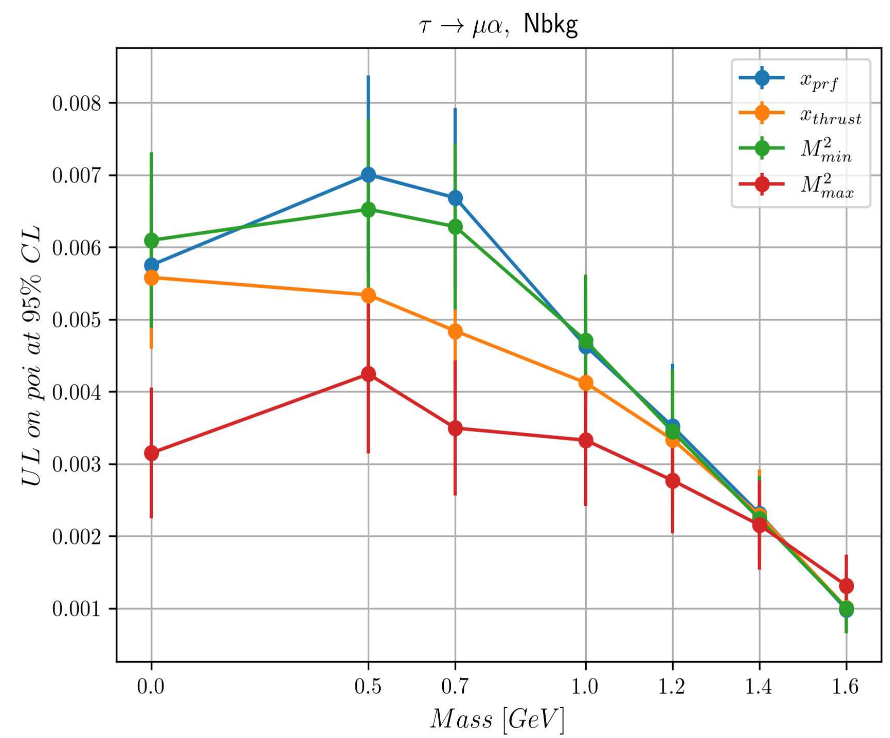
Systematic uncertainties

$\sigma_{N_{bkg}}$

$\sigma_{N_{bkg}} = 10.0\,\%$

$$F(x) = \frac{\varepsilon^{e\,\alpha}}{\varepsilon^{e\,\nu\,\nu}} N_{e\,\nu\,\nu}\, poi\, f_{e\,\alpha}(x) + N_{e\,\nu\,\nu} f_{e\,\nu\,\nu}(x) + \boxed{N_{bkg}}\, f_{bkg}(x)$$





Our search

Preliminary results

Systematic uncertainties

Trigger

$$F(x) = \frac{\varepsilon^{e\alpha}}{\varepsilon^{e\nu\nu}} N_{e\nu\nu}\, poi\, f_{e\alpha}(x) + N_{e\nu\nu} f_{e\nu\nu}(x) + N_{bkg} f_{bkg}(x)$$