τ Physics at Belle II

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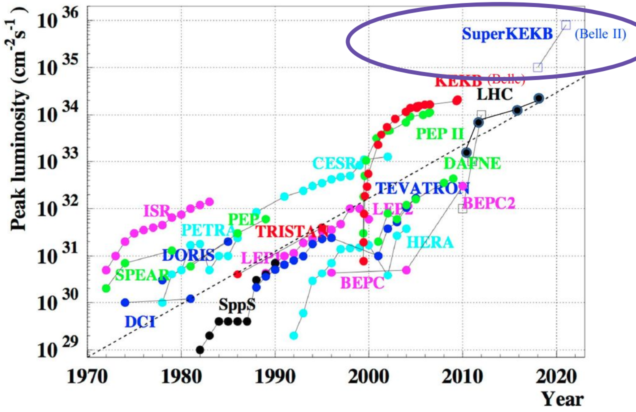
Belle II

Belle II experiment



The Belle experiment operated from 1998 to 2010, at KEK, Japan.

- KEKB was a 3 km circular collider of asymmetric electron–positron beams. (B-factory).
- In 2009 it reached an instantaneous luminosity of $2.11 \times 10^{34} cm^{-2} s^{-1}$.

In 2018, **LHC** set the world record on instantaneous luminosity of **2.14×10^{34} cm^{-2} s^{-1}**.

The Belle II experiment is a major upgrade of Belle.

- The SuperKEKB accelerator is designed to increase the instantaneous luminosity 40 times larger than Belle.
- Last June 15th, SuperKEKB reached an instantaneous luminosity of **2.22×10^{34} cm^{-2} s^{-1},** reclaiming the **world's highest luminosity record**.

- Belle II, the first *super* B-Factory experiment, is designed to find New Physics (NP) beyond the Standard Model (SM) of particle physics. Physics prospects have been documented in the Belle II Physics Book.

- There are 1047 active members from 119 institutes and 26 countries in the Belle II collaboration; among them, **Cinvestav,** UAS and UNAM in **Mexico**.

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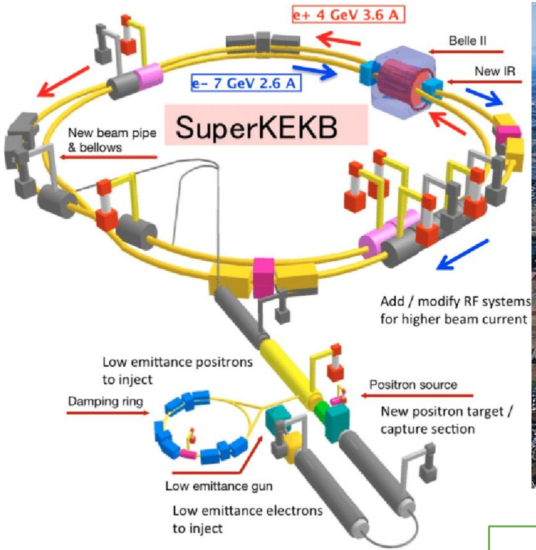
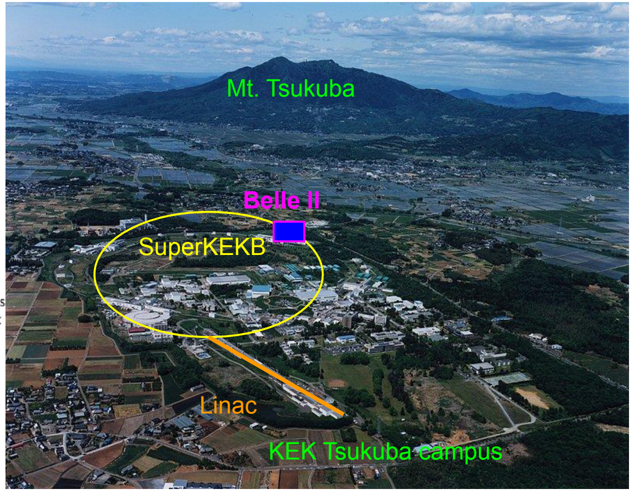
SuperKEKB

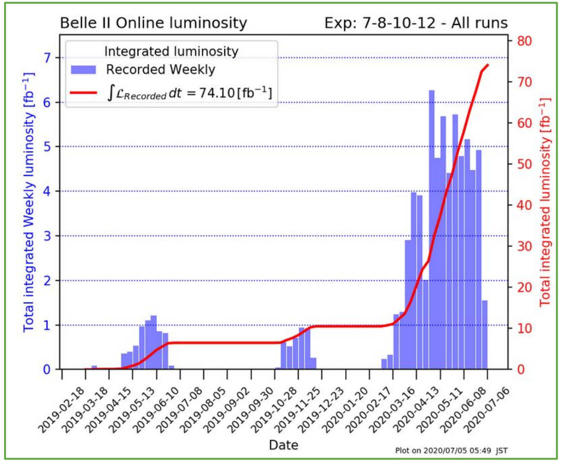
Electron-positron asymmetric beams collider:

- CMS energy $\sqrt{s} \approx m_{\Upsilon(4S)} \approx 10.58$ GeV
  → Super B-factory.
- Nano beams scheme.
- Increased beam current (x 2 Belle)
- Luminosity of 8×10^{35} cm^{-2} s^{-1}
  → luminosity frontier.

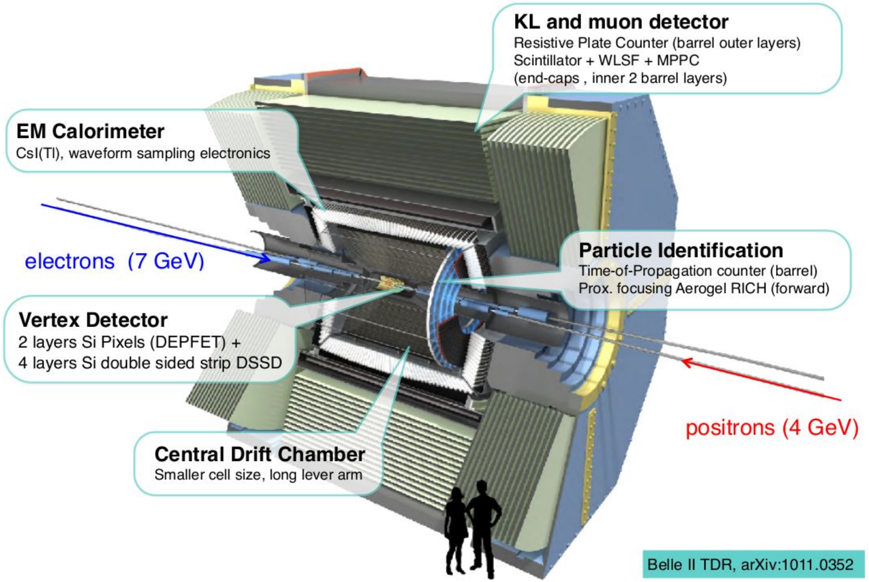




	Electron (HER)	Positron(LER)
Energy(GeV)	7	4
Current(A)	2.6	3.6
βy^*(mm)	0.30	0.27



Belle II detector



Solenoid: 1.5 T

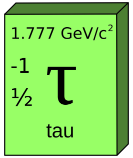
Upgrades with new technologies in:

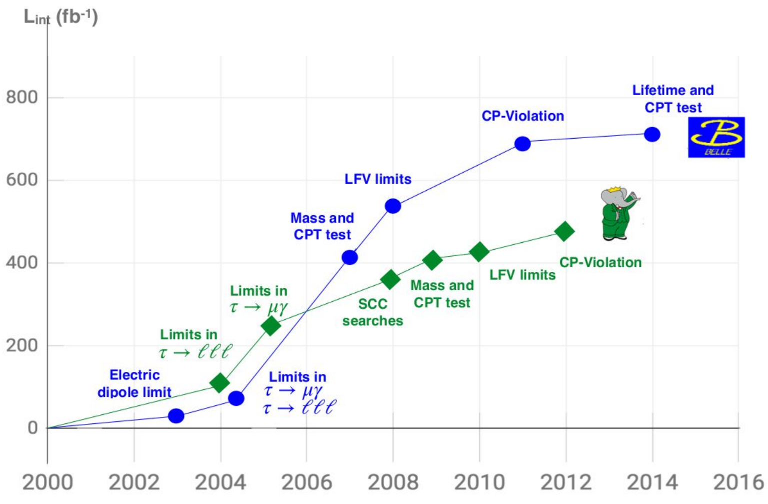
- Tracking system
- TOP counter
- Trigger and DAQ system
- Software Belle 2

Remarks:

- First physics run: End of 2018.
- **We have managed to maintain the operation of Belle II and SuperKEKB during the COVID-19 emergency.**
- Total Integrated luminosity, so far: 74.10 fb^{-1}.
- Current situation: summer shutdown since July 1st.

τ physics at Belle II





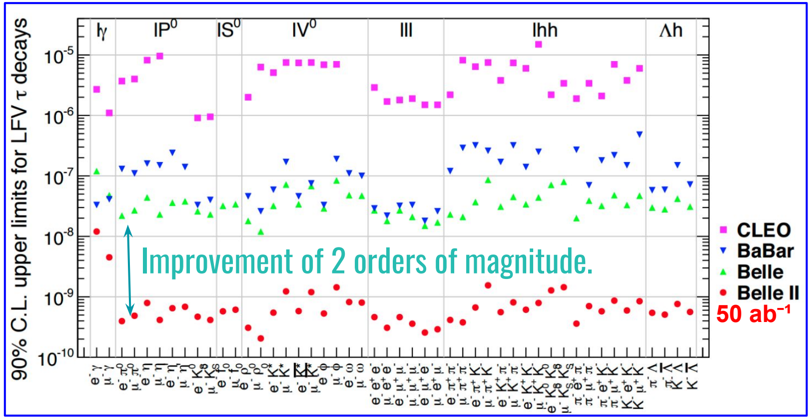
Why do we study τ's at Belle II ?

- Belle II produce as many τ leptons as B mesons:
  - $\sigma(e^+e^- \to B\bar{B}) = 1.05$
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.919$

} **τ factory**

⟶ The Belle II experiment will offer fantastic possibilities to study τ physics with high precision.

B-factories have provided many interesting results in τ lepton physics. Belle II will update and improve these results.



Studies of the τ lepton is an extremely convenient tool to:

- Search for NP (LFV & LNV).
- Determine SM basic parameters.
- Do precise tests of EW interactions.

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Ongoing studies of τ physics at Belle II

Some examples:

- Mass measurement
  (**Cinvestav**,DESY,MISSISSIPPI)

LFV:

- ➢ $\tau \rightarrow \ell + \gamma$ (**Cinvestav**,DESY)
- ➢ $\tau \rightarrow \ell + \alpha$ (**Cinvestav**,DESY, MPP)
- ➢ $\tau \rightarrow 3\ell$ (**Cinvestav**,DESY)
- ➢ $\tau \rightarrow \ell + V^0$ (ρ,ω,ϕ,K^{0*})

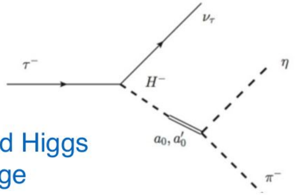
- $\tau \rightarrow K_S \pi \nu$

CP violation

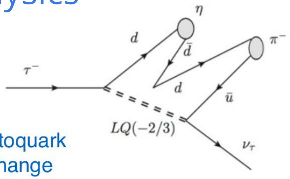
$$A_\tau = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S^0 \bar{\nu}_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S^0 \bar{\nu}_\tau)}$$

- $\tau \rightarrow \eta \pi \nu$

$\eta \pi \nu$ New physics



Charged Higgs exchange



Leptoquark exchange

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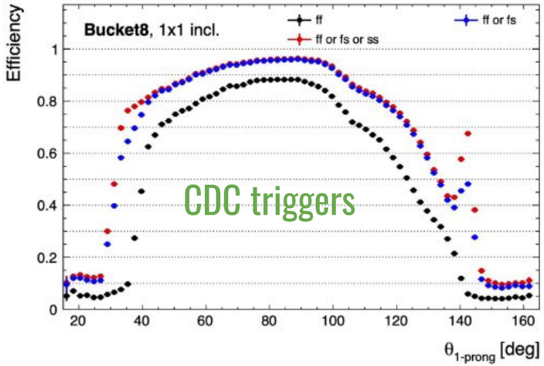
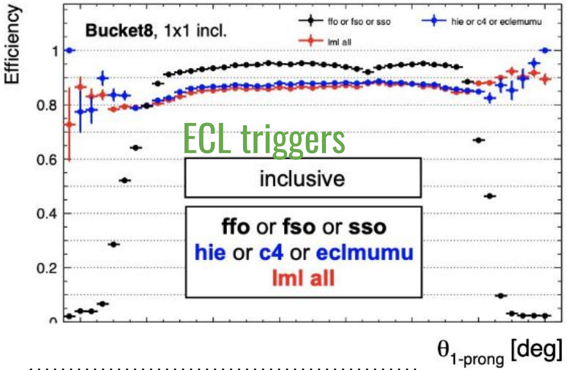
Ongoing studies of τ physics at Belle II

Performance studies:

- Efficiency studies.
  - ECL and CDC triggers performance in $e^+e^- \to \tau^+\tau^-$ events.
  - 1x3 and 1x1 topology studies.
- Tracking studies.
  - Reconstruction efficiency.
    - 1x3 topology.
  - Fake tracks studies.
    - 4-5 tracks.

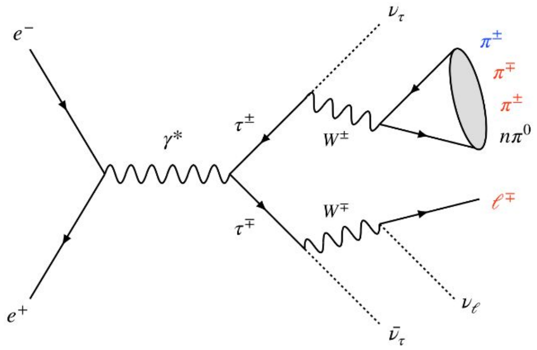




BELLE2-NOTE-PH-2020-006

$$\epsilon_{track} \cdot A = \frac{N_4}{N_3 + N_4}$$

$$r_{fake} = \frac{N_5}{N_4 + N_5}$$



Both results will be presented in ICHEP 2020.

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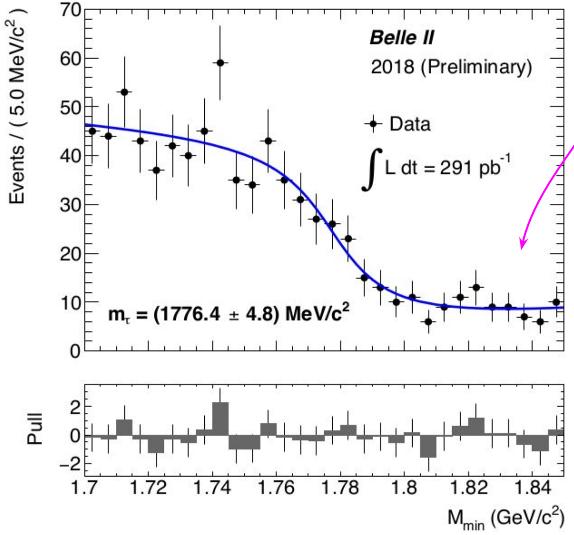
τ mass measurement

$$\frac{\Gamma(\mu \to e\nu\bar{\nu})}{\Gamma(\tau \to e\nu\bar{\nu})} \sim \left(\frac{g_\mu}{g_\tau}\right)^2 \frac{m_\mu^5}{m_\tau^5}$$

→ Accuracy of lepton universality measurements.

The measurement is performed in the decay mode $\tau \to 3\pi\nu$ (3x1 prong topology), using a pseudomass technique developed by the ARGUS collaboration:

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$

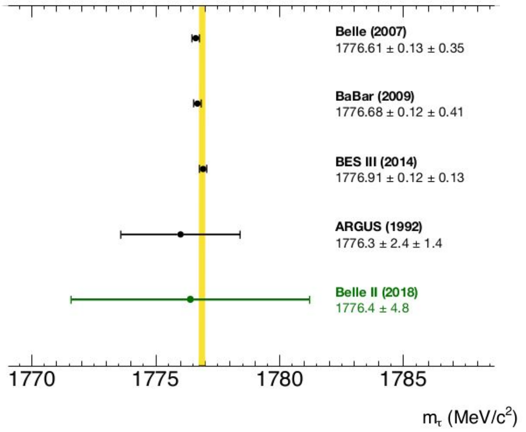


* The distribution of the pseudomass is fitted to a empirical edge function to estimate τ lepton mass.

Results:

- Current best fit from Belle:
  - 1776.61 ± 0.13 ± 0.35 MeV/c²
- Bes III:
  - 1776.91 ± 0.12 ± 0.13 MeV/c²
- Belle II from early data:
  - 1776.4 ± 4.8 (stat) MeV/c²

Dominated by systematics.



→The update of this measurement is completed and it is under review.

τ mass measurement (update)

“Blind analysis” method

- ★ Measurement performed with an integrated luminosity of 8.76 fb^{-1} (x30 more statistics than previous Belle II preliminary result).
- ★ Detailed studies of systematic uncertainties have been performed and are expected to be lower than in previous measurement by Belle (2007).

Sources of systematics uncertainties:

- Estimator bias
- Momentum shift due to the B-field map → will be recalculated using data after unblinding.
- Mass dependence of bias
- Trigger efficiency → will be calculated using the data after unblinding.
- Beam energy → dominant in Belle.
- Fit function
- Fit window
- Initial parameters → ***negligible.***
- Background processes → ***negligible.***
- Decay model → ***negligible.***
- Tracking efficiency → ***negligible.***

BELLE2-NOTE-PH-2020-001

Unblinding process ongoing and results will be presented in ICHEP 2020.

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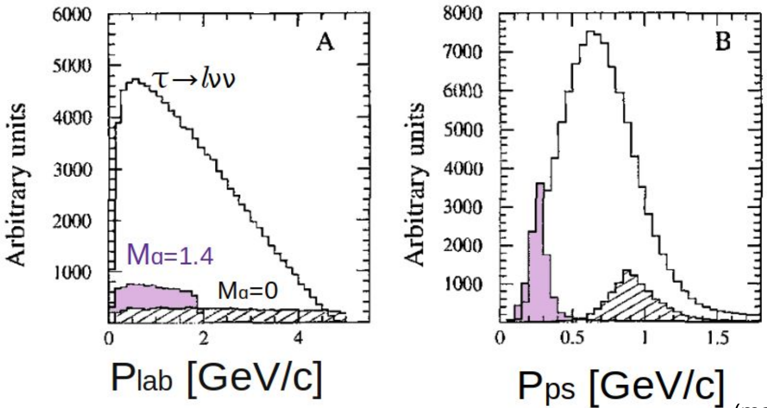
LFV $\tau \rightarrow \ell + \alpha$

- **α** is assumed to be an invisible (undetected) long-lived massive BSM boson.
- Previous studies by Mark III (9.4 pb^{-1}) and ARGUS (476 pb^{-1}).

ARGUS:

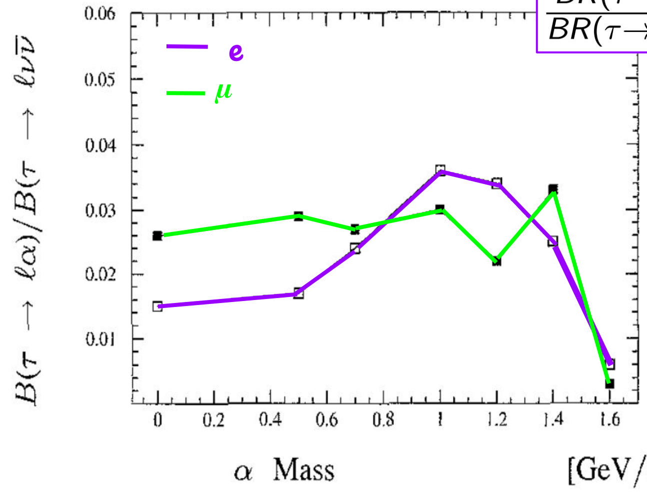
- Fit the distribution of the momentum spectrum of the lepton in the "**τ** pseudo rest frame" and set an upper limit on $\frac{BR(\tau \rightarrow l\alpha)}{BR(\tau \rightarrow l\nu\bar{\nu})}$.



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

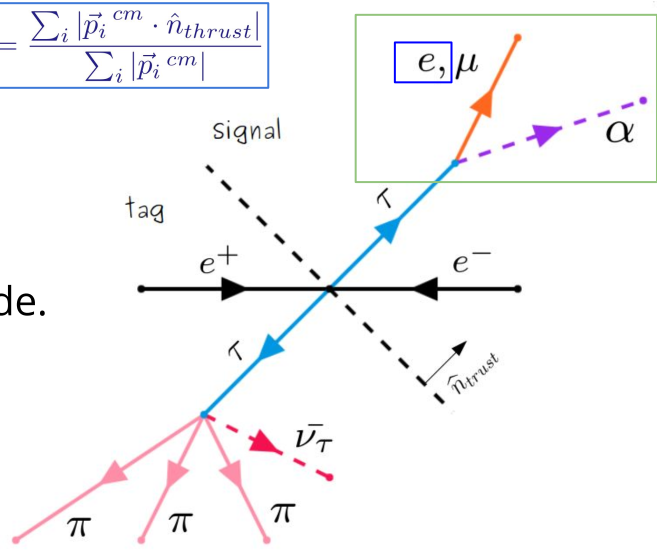
(massless assumption)

$$\frac{BR(\tau \rightarrow e\alpha)}{BR(\tau \rightarrow e\nu\bar{\nu})} < 1.5\%$$



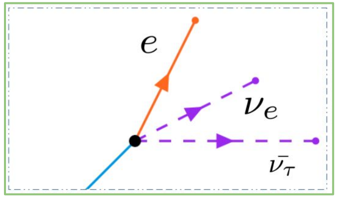
LFV $\tau \to \ell + \alpha$

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



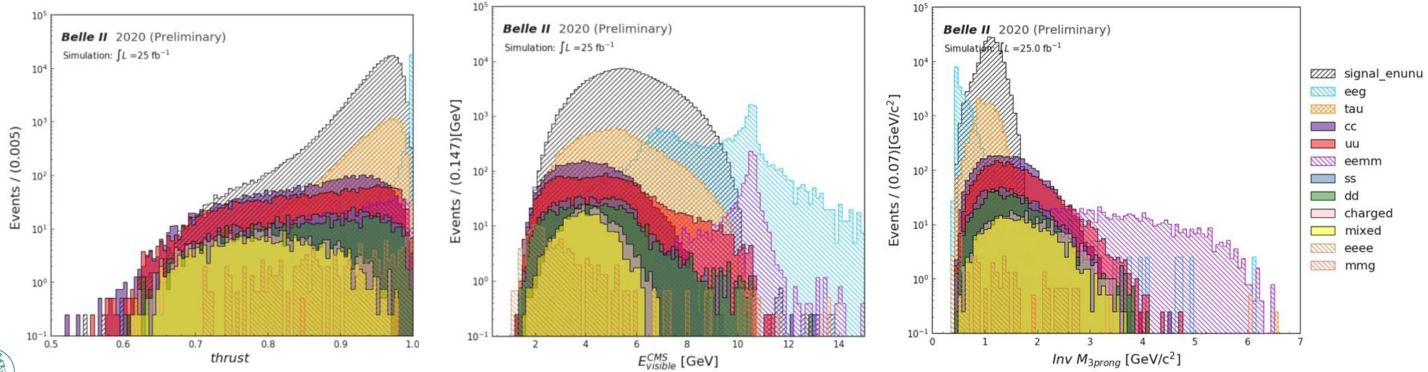
- Preselection: 3x1 prong topology.
  - Requires 4 good tracks.
  - Common vertex for the 3 pion candidates in the tag side.
- Background suppression ($\tau \to e\nu\nu$):

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



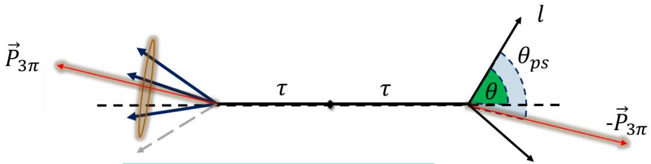
0.8 < thrust < 0.99
2.0 < visibleEnergyOfEventCMS <9.9
0.48 < $M_{3\pi}$ < 1.66

	Efficiency	Purity
$e\nu\nu$	13.36%	92.47%



LFV $\tau \rightarrow \ell + \alpha$

Pseudo-rest frame:



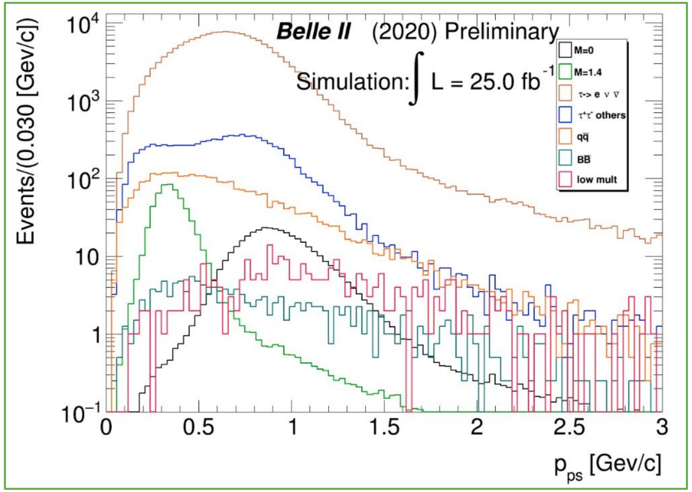
BELLE2-NOTE-PH-2019-015

Electron boosted to the "$\boldsymbol{\tau}$ pseudo-rest" frame using:

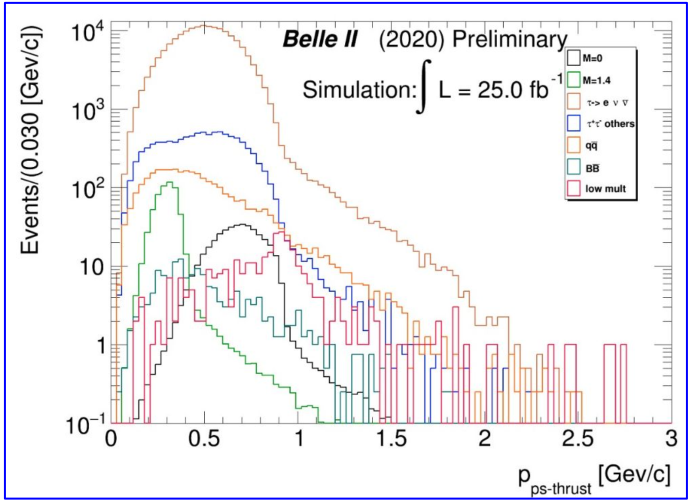
$$\vec{e}_{\tau} \simeq \vec{e}_{3-prong} \qquad \vec{e}_{\tau} \simeq \vec{e}_{thrust}$$

$$E_{\tau} \approx E_{CMS}/2$$

LOG SCALE



Using the direction of the 3-pion system.



Using the direction of the thrust vector.

Cinvestav DESY. MAX PLANCK INSTITUTE FOR PHYSICS

LFV $\tau \rightarrow \ell + \alpha$

$$Br(sig) = \frac{N^{obs}}{2L_{int}\sigma(e^+e^- \rightarrow \tau^+\tau^-)Br(tag)\epsilon^{signal}}$$

BELLE2-NOTE-PH-2019-009

M_α	Argus	Belle II	
		Argus-like	Thrust
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

Using $\tau \rightarrow e\nu\nu$ as normalization channel:

$$\frac{Br(\tau \rightarrow e\alpha)}{Br(\tau \rightarrow e\nu\nu)} = \frac{N^{obs,e\alpha}}{N^{obs,e\nu\nu}} \frac{\epsilon^{e\nu\nu}}{\epsilon^{e\alpha}} = poi$$

Data model:

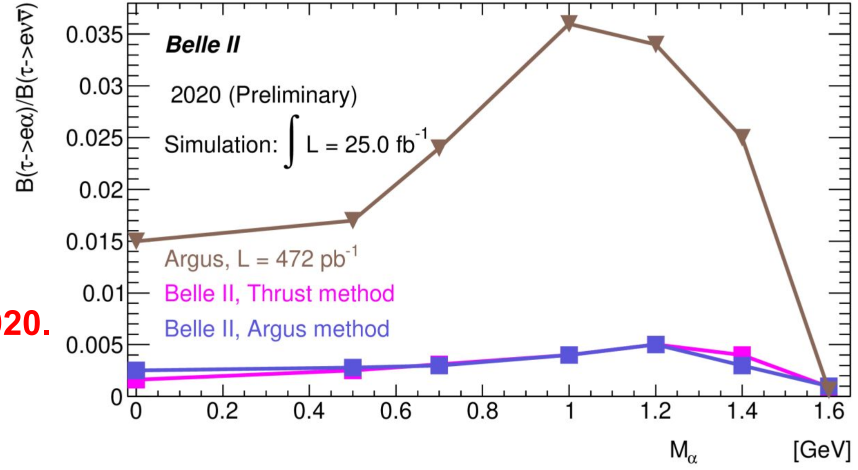
$$F(x) = N^{obs,e\alpha} f_{e\alpha}(x) + N^{obs,e\nu\nu} f_{e\nu\nu} + N^{obs,other} f_{other(x)}$$

$$= poi \frac{\epsilon^{e\alpha}}{\epsilon^{e\nu\nu}} N^{obs,e\nu\nu} f_{e\alpha}(x) + N^{obs,e\nu\nu} f_{e\nu\nu} + N^{obs,other} f_{other(x)}$$

CL_s:

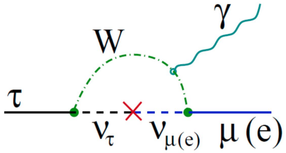
- Modified frequentist approach.
- **Asymptotic** approximation.
- Upper limit at 95% C.L.

More detailed results will be presented in ICHEP 2020.



Cinvestav DESY. MAX PLANCK INSTITUTE FOR PHYSICS

LFV $\tau \to \ell + \gamma$



μ channel

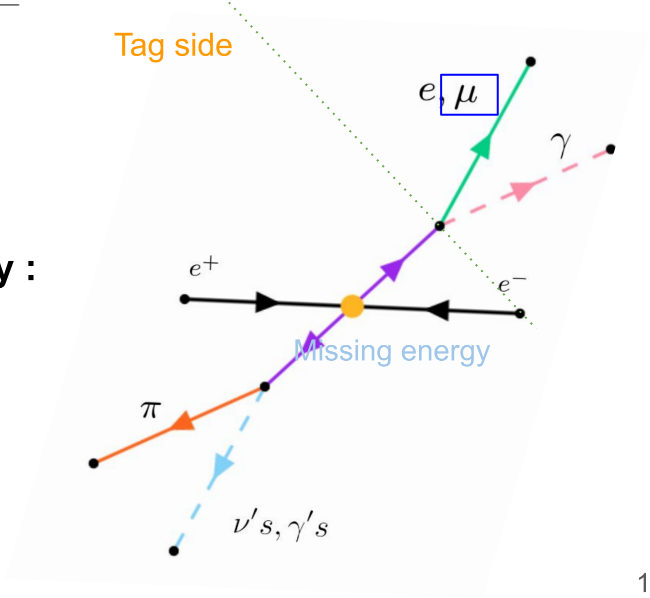
Very suppressed within the SM (including ν masses) → $\mathcal{B}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi} \mid \Sigma U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \mid^2 \sim 10^{-45}$

Previous upper limits on its BR($\tau \to \ell + \gamma$):

Analysis	Data sample	$\mathcal{B}(\tau \to \mu\gamma)$
BELLE (2008)	535 fb^{-1}	$< 4.5 \times 10^{-8}$
BABAR (2009)	9.6×10^8 τ	$< 4.4 \times 10^{-8}$

Modelo	$\tau \to \mu\gamma$
SM + osc. ν	10^{-45}
SUSY Higgs	10^{-10}
Little Higgs	10^{-10}
SM + heavy ν_R	10^{-9}
Non-universal Z'	10^{-9}
SUSY SO(10)	10^{-8}

Reconstruction of 1x1 prong topology :



Some BSM scenarios can be tested by Belle II

LFV $\tau \to \ell + \gamma$

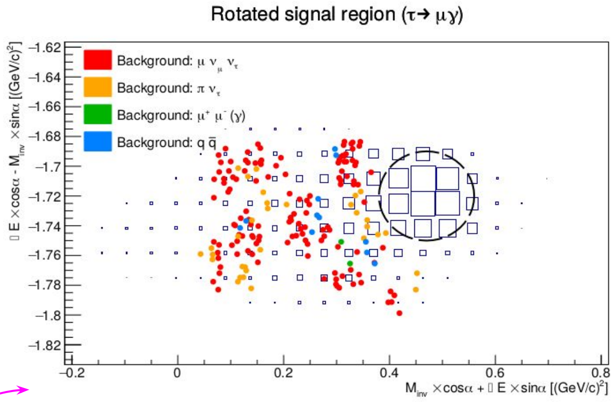
[Belle II Physics Book](#)

In order to evaluate the signal yield:

$$M_{\tau^-} \equiv M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2}$$

$$\Delta E = E_{\mu\gamma}^{CM} - E_{beam}^{CM}$$

$$R = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$



Analysis	Data sample	$\mathcal{B}(\tau \to \mu\gamma)$
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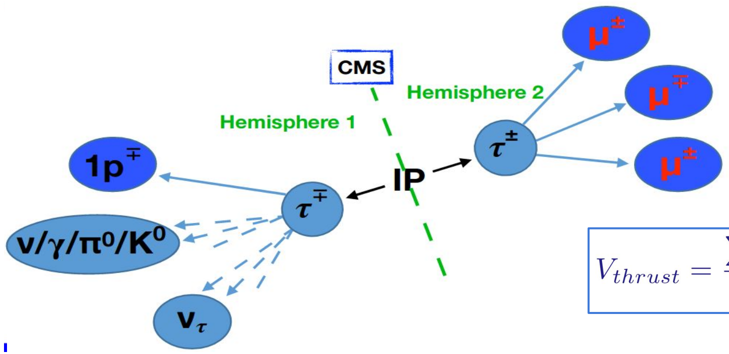
BABAR (2009)	9.6×10^8 τ	$< 4.4 \times 10^{-8}$
BELLE II (Book 2018)	MC	$< 2.726 \times 10^{-8}$
BELLE2-NOTE-PH-2019-001	MC9 (1 ab^{-1})	$< 2.883 \times 10^{-8}$

With a BKG free selection we a sensitivity improvement of about two orders of magnitude can be expected in Belle II . (50 ab^{-1})

- In early 2019, we performed a cross check of these results with large simulated samples.
- Currently, we are updating the analysis with improved reconstruction and simulation tools.
- A more realistic beam background has been overlaid in simulations (using real events).
- Trigger performance studies and corrections are ongoing.
- New estimations of the expected upper limit will be released soon! 😀

LFV $\tau \to 3\,\ell$

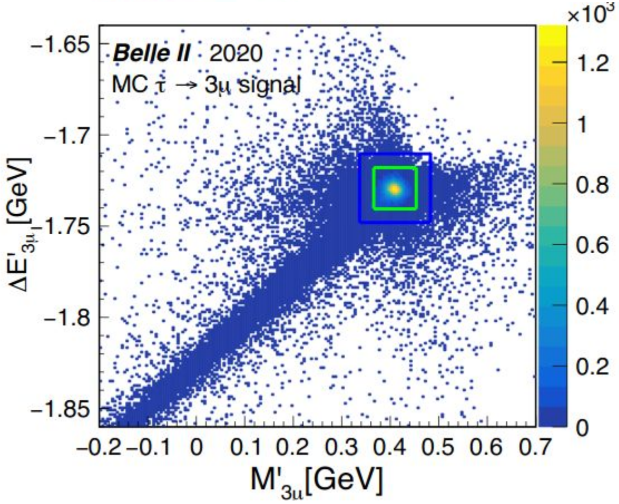


$$V_{thrust} = \frac{\sum_i |\vec{p_i}^{\,cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p_i}^{\,cm}|}$$

Signal yield:

$$\begin{matrix} M'_{3\mu} \\ \Delta E'_{3\mu} \end{matrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} M_{3\mu} \\ \Delta E_{3\mu} \end{pmatrix}$$

with $\theta \simeq 77^{\circ}$



Limit comparison: BaBar → $3.3{\cdot}10^{-8}$ Still very
Belle II → $1.4{\cdot}10^{-8}$ preliminary!

500fb^{-1}

★ Additional studies of SM and LFV channels with 3 leptons:

➢ Considering the allowed combinations between e and μ leptons.

- $\tau \to 3\,\ell$
- $\tau \to 3\,\ell\,\nu's$

} $\mu\mu e,\, ee\mu,\, \ldots$

Summary

- The Belle II experiment is suitable to study tau physics.
- A brief overview of tau physics at Belle II experiment was presented, focusing on the studies were CINVESTAV group is involved, and the results that will be presented in ICHEP 2020.
- Different studies can be performed with the data accumulated so far: 74.10 fb^{-1}.
  - Improvements of SM basic parameters $\rightarrow \tau$ mass measurement.
  - Searches of NP on LFV channels $\rightarrow$ $\tau \rightarrow \ell + \alpha$.
  - Performance studies.
- The upcoming data taking for the next years will lead us to:
  - Improved tau physics measurements.
  - Searches for new physics scenarios.

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BACKUP

CP violation in τ decays

The first CP asymmetry measurement in τ decay has been done by using the decay rate difference between $\tau^+ \to \pi^+ K_S \bar{\nu}_\tau$ and $\tau^- \to \pi^- K_S \nu_\tau$:

$$\mathcal{A}_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}$$

This CP asymmetry is non-zero in SM due to the $K^0 - \overline{K}^0$ mixing.

The SM prediction yields: $\mathcal{A}_\tau^{\mathrm{SM}} \simeq 2\mathrm{Re}(\epsilon) \simeq (0.36 \pm 0.01)\%$

Babar collaboration result: $\mathcal{A}_\tau = (-0.36 \pm 0.23 \pm 0.11)\%$

→ 2.8 σ away from the SM expectation.

Similar CP violation for D mesons:

$$\mathcal{A}_D = \frac{\Gamma(D^+ \to \pi^+ K_S) - \Gamma(D^- \to \pi^- K_S)}{\Gamma(D^+ \to \pi^+ K_S) + \Gamma(D^- \to \pi^- K_S)} = (-0.41 \pm 0.09)\%$$

$$A_\tau = -A_D$$

much more precise

An improved on the measurement is one of the first priorities at Belle II.

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