"Tau Physics Prospects at Belle II"

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on behalf of the Belle II collaboration

The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

23-28 August 2021

SuperKEKB

Electron-positron asymmetric beams collider:

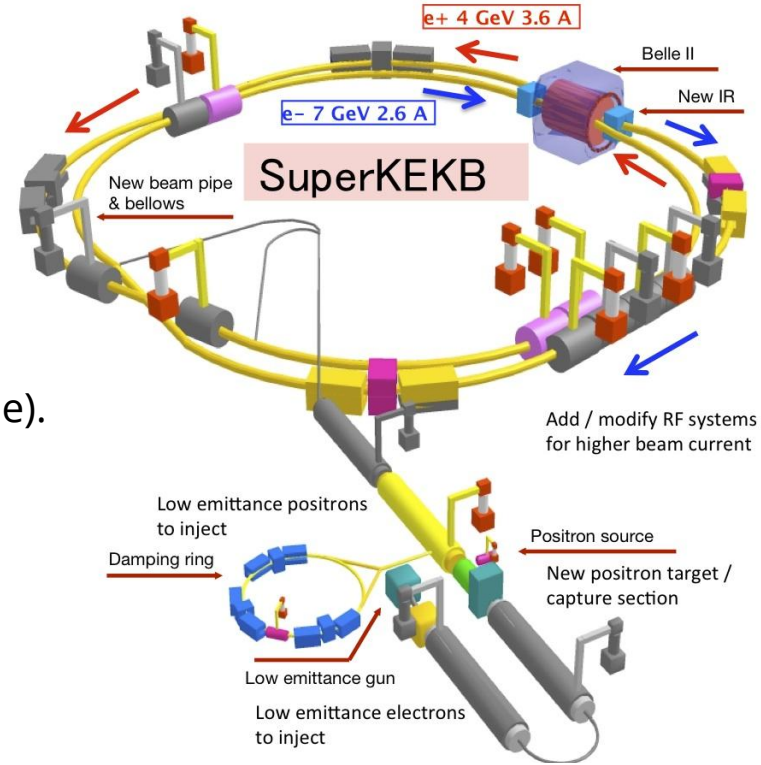
- CMS energy $\sqrt{s} \approx m_{\Upsilon(4S)} \approx 10.58$ GeV
- Target instantaneous luminosity of 6.5×10^{35} cm^{-2} s^{-1} (x30 KEKB)
- Target integrated luminosity 50 ab^{-1} (x50 Belle).

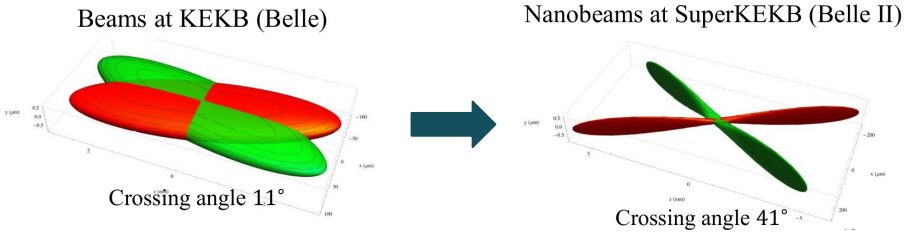
Higher luminosity requires:

- Narrow beams at IP (Nanobeams)
- Increased beam current (x2 Belle)
- Detector works with higher beam background and trigger rates.

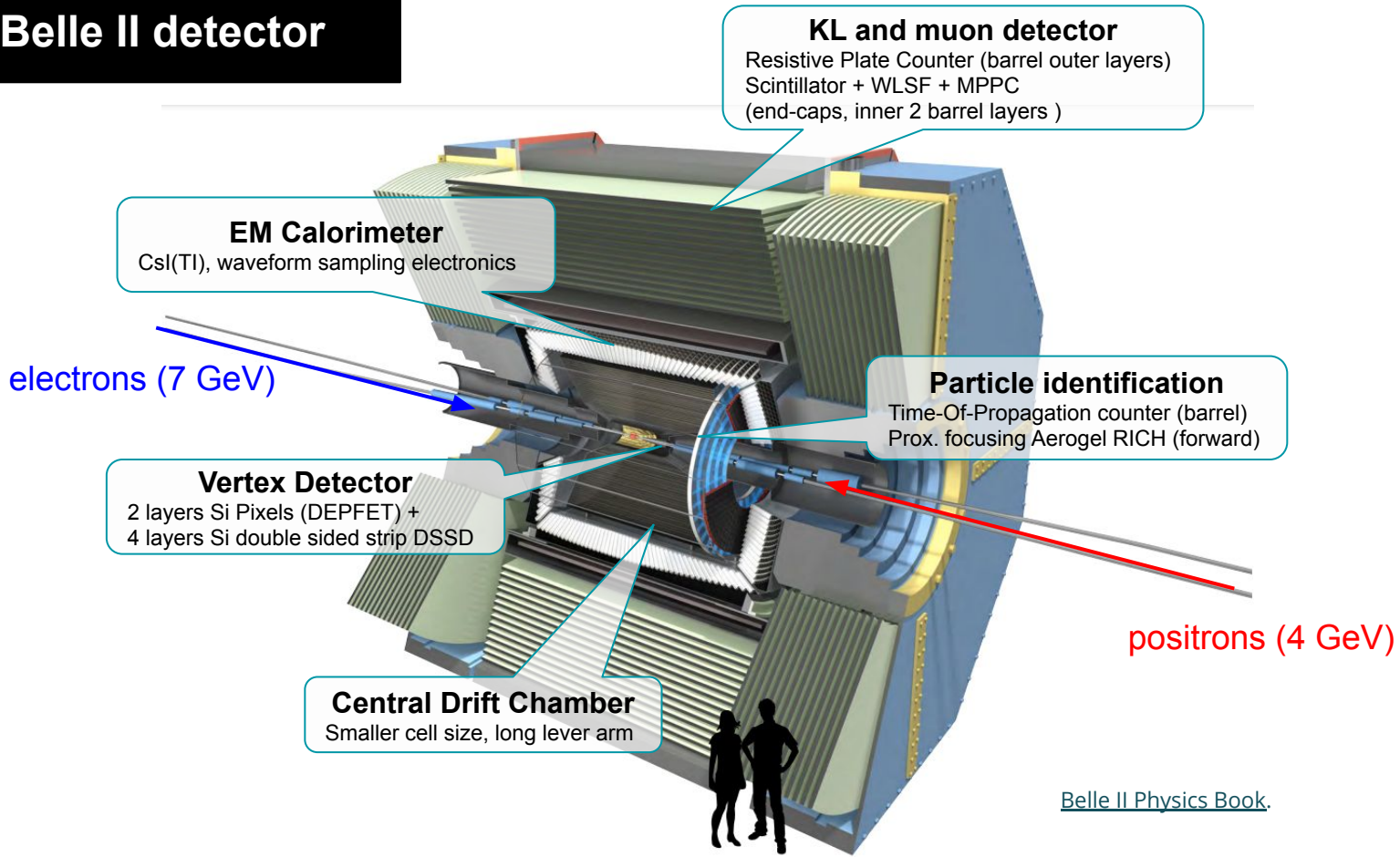
$\sigma(e^+e^- \to BB) = 1.05$

$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \to$ **τ factory!**





The Belle II detector

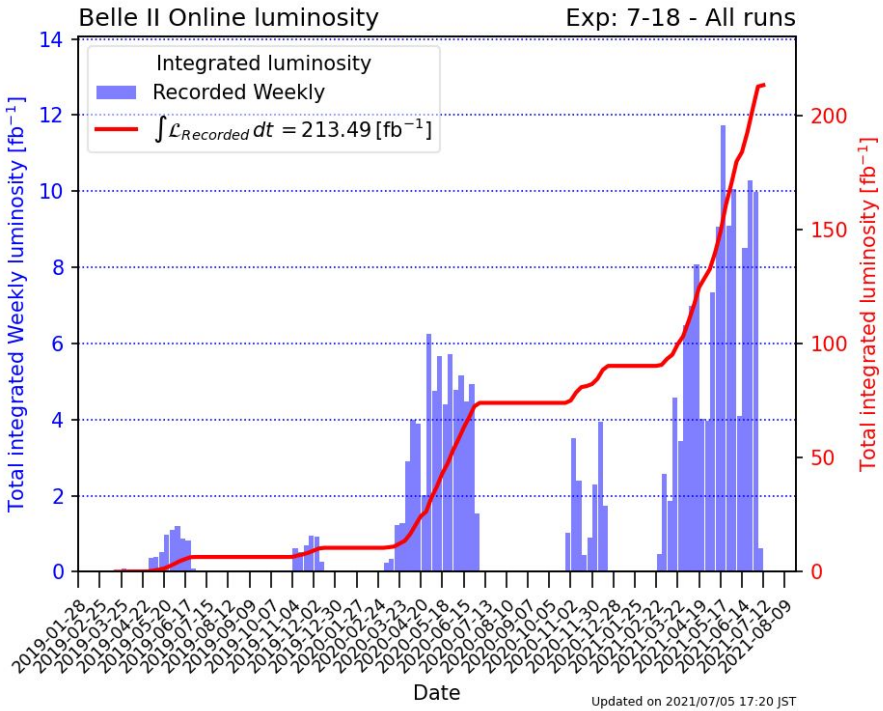


Belle II Physics Book.

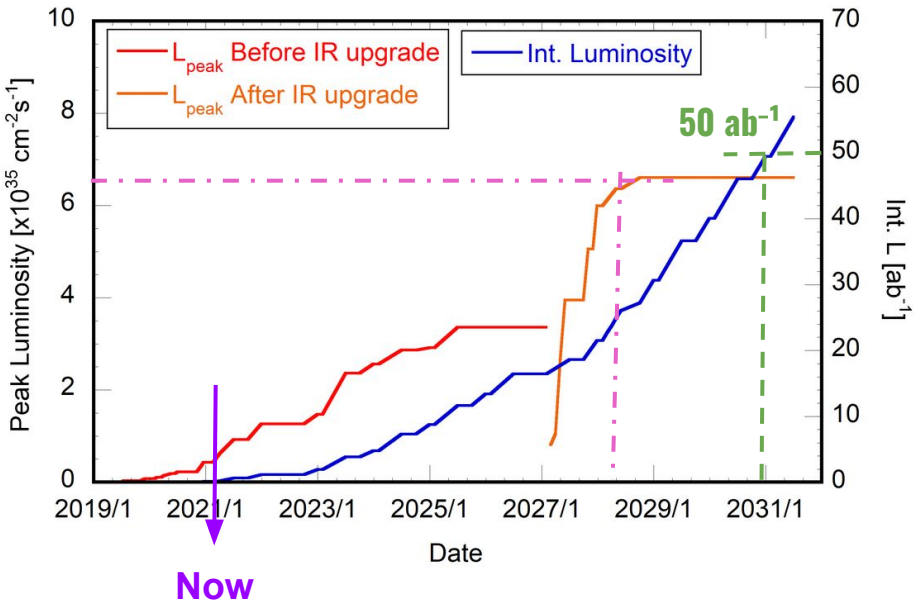
\+ **Trigger**, **DAQ** and **GRID** system.

Luminosity status and projections

- First e^+e^- collision: April 2018.
- Phase 3 data: **>** 210 fb^{-1} collected so far.



- **Luminosity projection** for the coming years.



$L = 3.1 \times 10^{34}\ cm^{-2}\ s^{-1}$

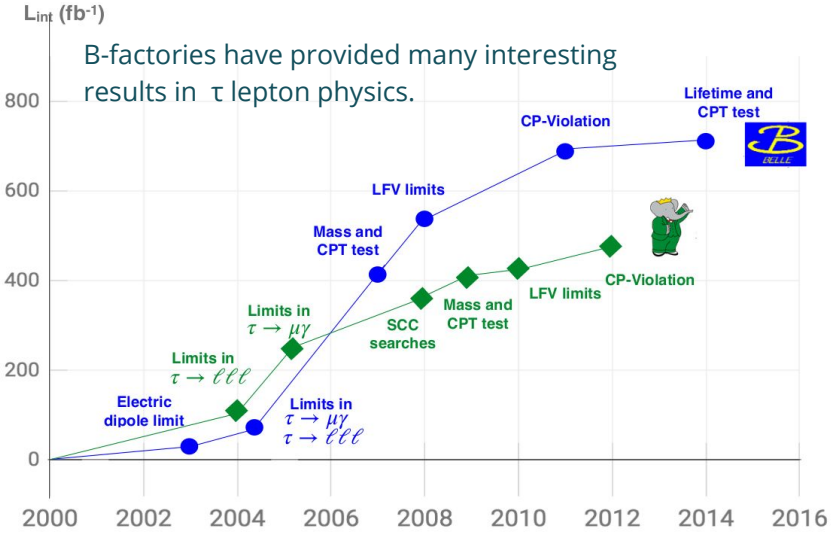
Tau Physics at Belle II

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

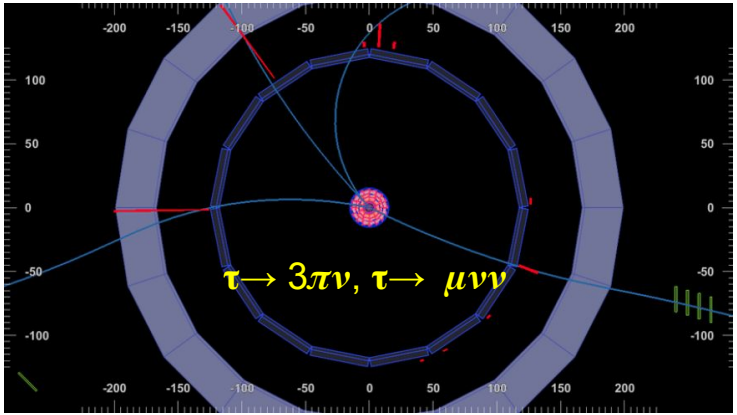
- Search for NP (LFV & LNV).
- Determine SM basic parameters (lifetime, m_τ).
- Do precise tests of EW interactions.

Clean environment

- Low background, high resolution.



τ reconstruction:



Wide physics program is documented in the Belle II Physics Book.

You can also take a look at the other Belle II talks at this conference! 😊

Tau mass measurement

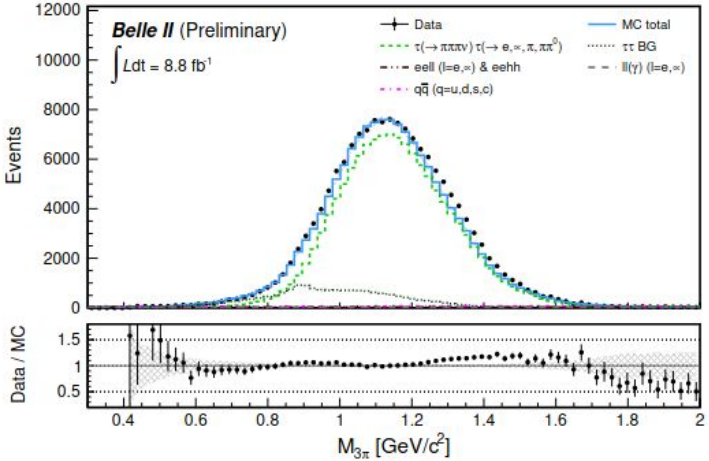
$$B_{\tau l}^{SM} \propto B_{\mu e} \cdot \frac{\tau_\tau}{\tau_\mu} \cdot \frac{m_\tau^5}{m_\mu^5}$$ ⬅ Accuracy of lepton universality measurements.

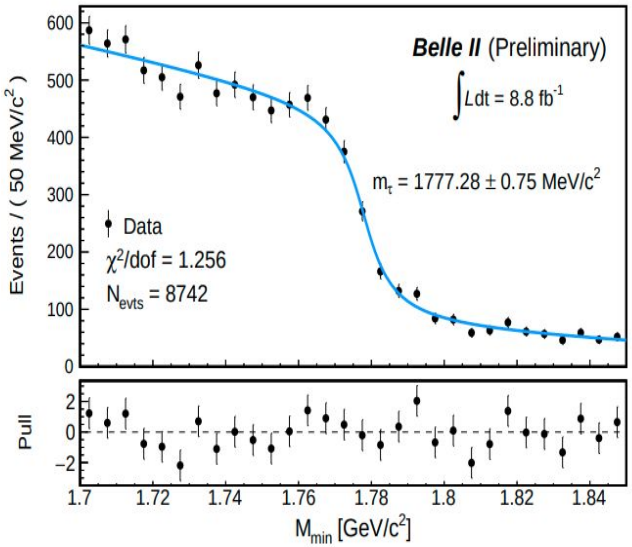
The measurement is performed in the decay mode $\tau \to 3\pi\nu$ (3x1 prong topology), using a pseudomass technique developed by the ARGUS collaboration:

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

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

$$F(M_{min}, \vec{P}) = (P_3 + P_4 \cdot M_{min}) \cdot tan^{-1}[(M_{min} - \mathbf{P_1})/P_2] + P_5 \cdot M_{min} + 1$$





m_τ = 1777.28 ± 0.75 (stat) ± 0.33 (syst) MeV/c²

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$ 0.01

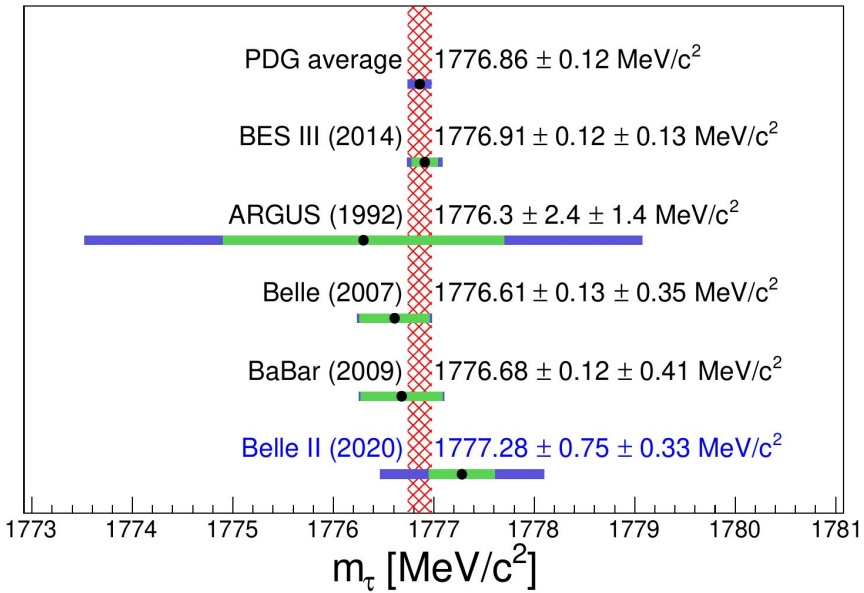
to be reduced

Public Belle II note
→arxiv.2008.04665

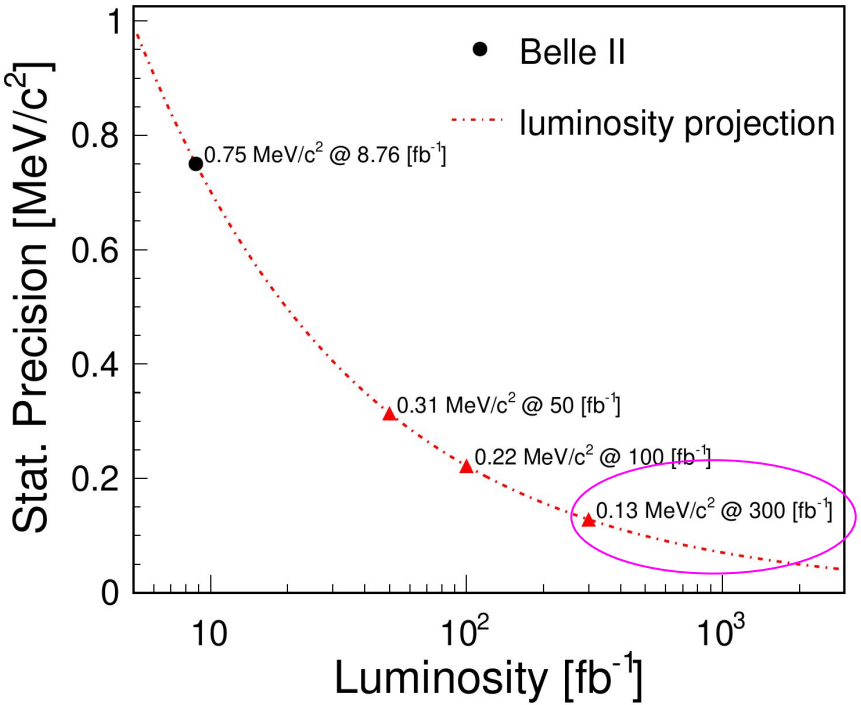
Tau mass measurement

The goal is achieve the best m_τ precision among pseudomass measurements.

arxiv.2008.04665



Belle II have compatible results with previous experiments and comparable sys. errors with previous B factories BaBar and Belle.

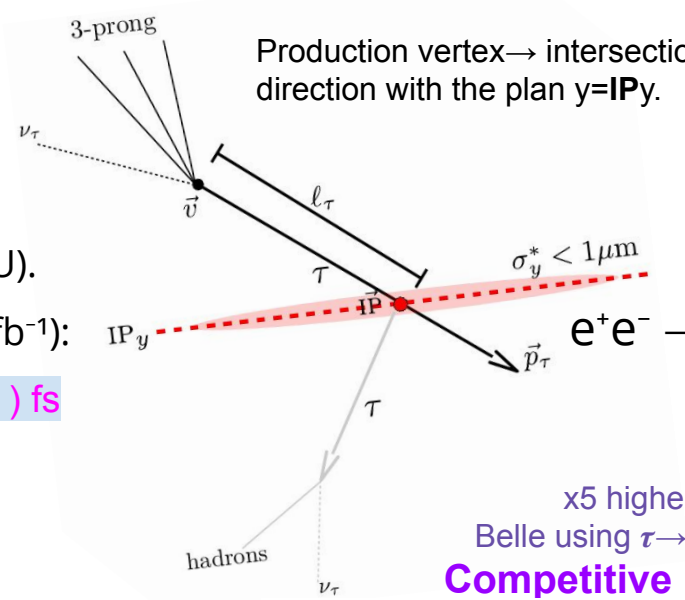


~300 fb^{-1} statistical precision as Belle/BaBar.

Tau lifetime

- Important parameter in the SM.
- Test of the lepton flavor universality (LFU).
- World best measurement by Belle (711 fb^{-1}):

τ_τ = (290.17 ± 0.53(stat) ± 0.33(sys)) fs



Production vertex→ intersection of the $\vec{p}_t$ direction with the plan y=**IP**y.

3x1 topology

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

- $\rho(\pi\pi^0)\nu$
- $\pi\pi\pi\nu$

x5 higher efficiency than Belle using $\tau \rightarrow 3\pi\nu$ x $\tau \rightarrow 3\pi\nu$ topology.

Competitive results at 150 fb^{-1}!

Measurement strategy:

- **Proper decay time** distribution.

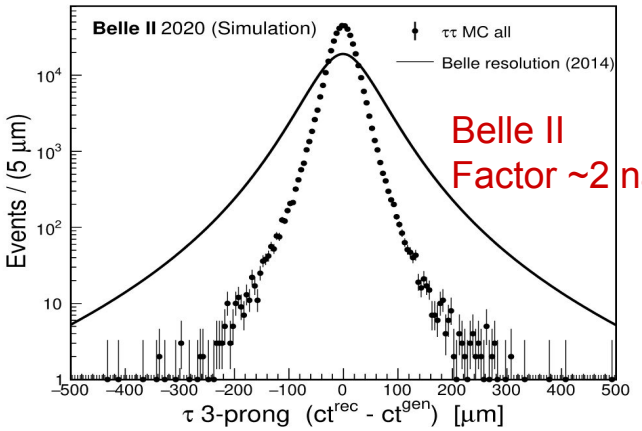
$$p(t,\tau_\tau) = \frac{1}{\tau_\tau} e^{-\frac{t}{\tau_\tau}} \cdot R(t)$$

Proper time resolution

- Proper time related to the decay length and the momentum.

$$t = \frac{l_\tau}{\beta\gamma c} = l_\tau \frac{m_\tau}{p_\tau c}$$

l_τ and p_τ to be reconstructed from measurements.



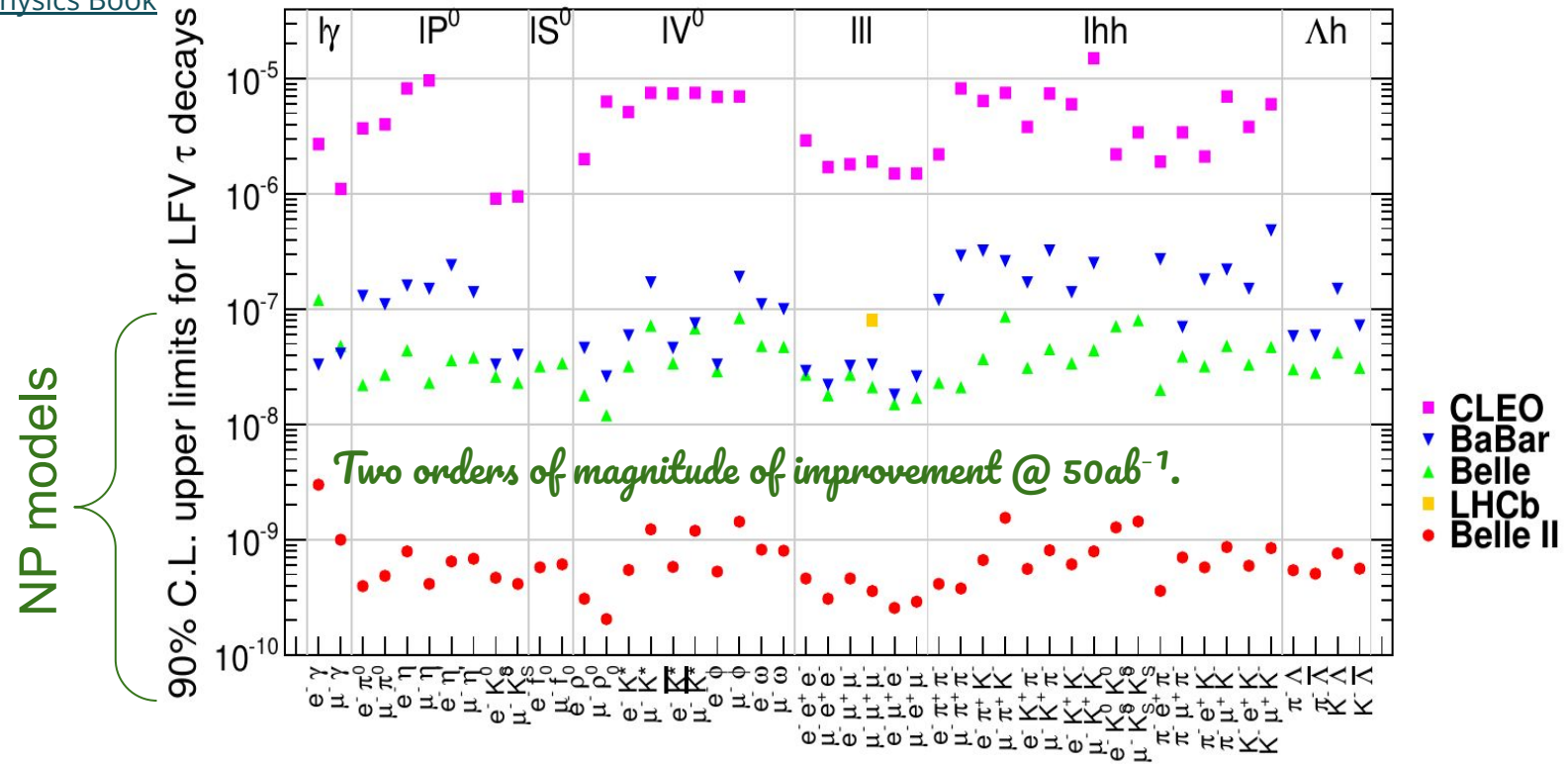
Belle II
Factor ~2 narrower.

Epiphany conference talk

Lepton Flavor Violation

LFV is strongly suppressed within the SM.
Any observation of LFV is clear signal for New Physics!

Belle II Physics Book



τ is the heaviest charged lepton ⇨ Large variety of leptonic and semi-leptonic decays to search for LFV(LNV).

$\tau \to \ell + \gamma,\ \tau \to 3\,\ell$

Golden channels

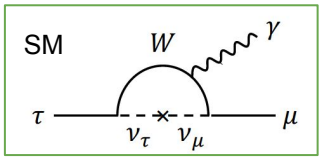
Full reconstructed

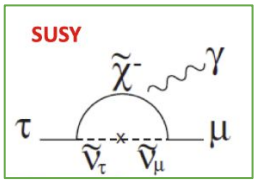
$e^+e^- \to \tau^-\tau^+$

- $\mu\gamma$, $\mu\mu\mu$ (LFV mode)
- 1 prong + missing(ν,γ)

In SM LFV is highly suppressed Br ~ O(10^{-54})

$$\mathcal{B}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi} \left| \Sigma U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \right|^2$$





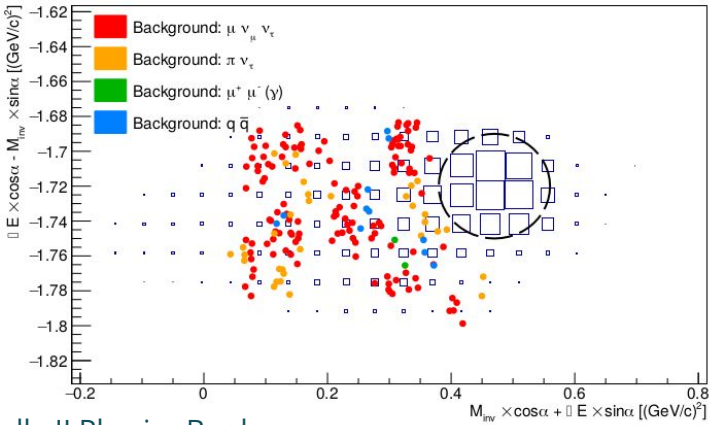
NP model predictions: O(10^{-10}-10^{-8}).

Strategy:

- $M^{\mu\gamma}_{inv} = \sqrt{E^2_{\mu\gamma} - P^2_{\mu\gamma}}$
- $\Delta E = E^{CM}_{\mu\gamma} - E^{CM}_{beam}$

$$\begin{pmatrix} M'_\tau \\ \Delta E' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} M_\tau \\ \Delta E \end{pmatrix}$$

Rotated signal region ($\tau \to \mu\gamma$)



Belle II Physics Book

Belle II Physics Book.

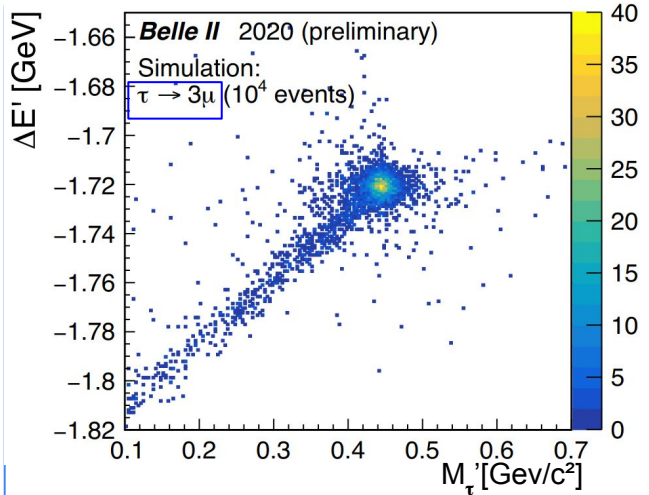
BKG free selection w/ 1 ab^{-1}.

BR($\tau \to \mu + \gamma$) < 2.72 x 10^{-8}

Improvement ~Belle limit/2.

(no sys. unc. included)

$\tau \to \mu\mu\mu$ **same strategy as** $\tau \to \mu\gamma$.



Belle: 2.1 x 10^{-8} (782fb^{-1}).

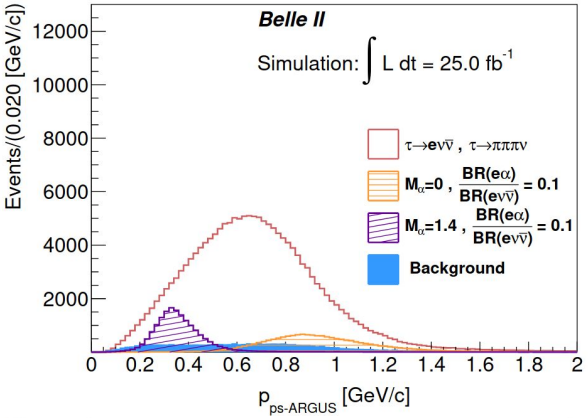
Belle II: ~10^{-10}.

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

$\tau \to 3\pi\nu$, $\tau \to \ell+\alpha$ (3x1 topology)

BELLE2-NOTE-PL-2020-018

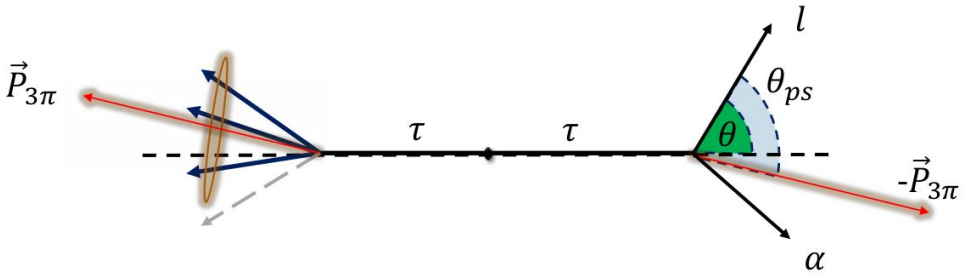
- α is assumed to be an invisible (undetected) long-lived massive BSM boson.
- Previous studies by Mark III (9.4 pb^{-1}) and ARGUS (476 pb^{-1}).

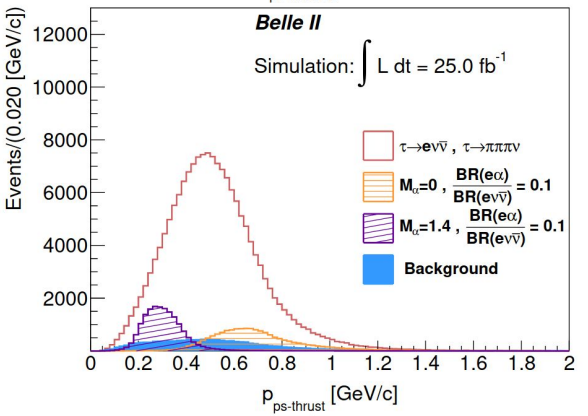


ARGUS:

➔ Search for 2 body decay in τ rest frame will manifest as a peak.

➔ cannot access τ rest frame directly due to neutrino.





"τ pseudo rest frame" :

$$E_\tau \approx E_{CMS}/2 \quad + \quad \begin{cases} \vec{e}_\tau \simeq -\vec{e}_{3-prong} \text{ (ARGUS)} \\ \vec{e}_\tau \simeq \vec{e}_{\hat{n}_{thrust}} \end{cases}$$

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

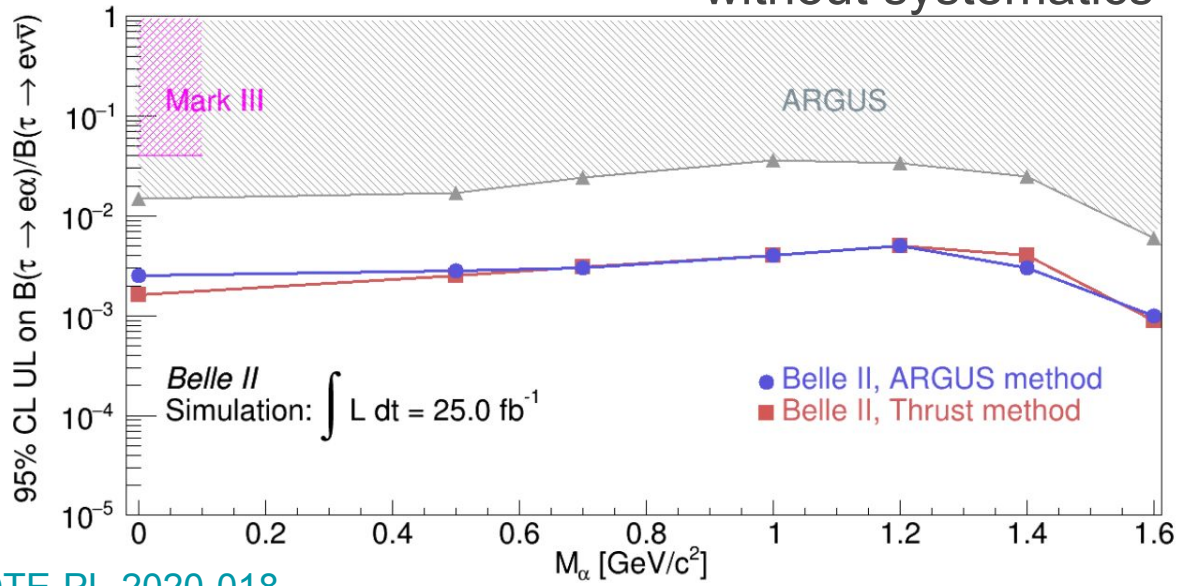
LFV $\tau \to \ell + \alpha$

- Upper limit estimation for $\frac{BR(\tau \to l\alpha)}{BR(\tau \to l\nu\bar{\nu})}$
- Using a Frequentist method: CLs method.

Fit on the x_{prf} lepton spectrum for the hypothesis SM and SM+NP.

$$x_{prf} = \frac{2 \cdot E_l}{m_\tau}$$

without systematics



Considerable improvement for 25fb^{-1}.

Right now finishing the study with all the systematics included!!😀

BELLE2-NOTE-PL-2020-018

Summary

- Belle II is not only a B factory, it is also a τ factory.
- Large data collected so far (>210fb^{-1}) with the final goal of 50 ab^{-1}.
- Very rich physics program of SM precisions measurements and New Physics with τ's.

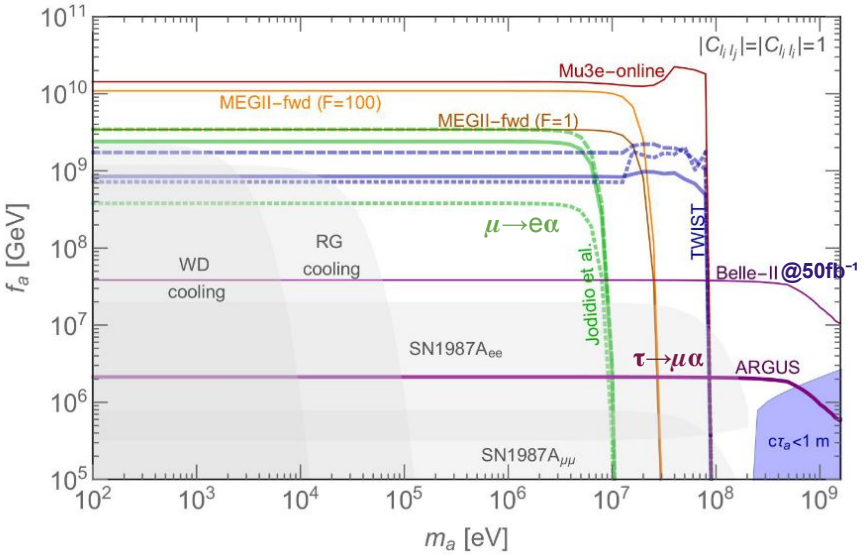
- Many ongoing τ studies, where competitive results are expected.
  - τ mass measurement (systematics already comparable to Belle/BaBar).
  - τ lifetime (x5 higher efficiency than Belle).
  - $\tau \rightarrow l + \alpha$ (Final results coming soon).
  - Near future: Test of LFU, LFV($\tau \rightarrow l + \gamma$, $\tau \rightarrow 3\,l$), CP violation, electric dipole moment , ...

More exciting results coming in the future!

Backup

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

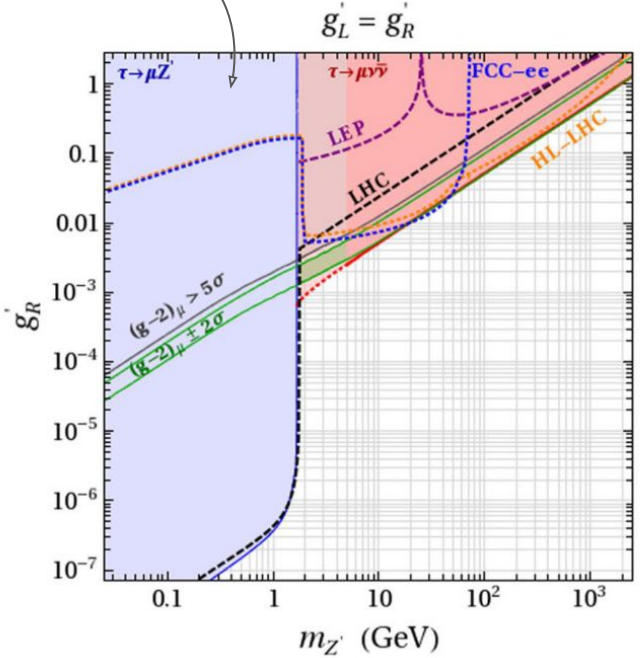
Models axion-like particles (ALP).
Exploring regions of parameter space not reachable by other experiments.



P3H-20-024, TTP20-025

Models giving rise a Z' boson.
Searches for τ→μ+(missing energy) can constrain the Z' parameter space (g'_R).

ARGUS



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