Tau physics prospects at Belle II

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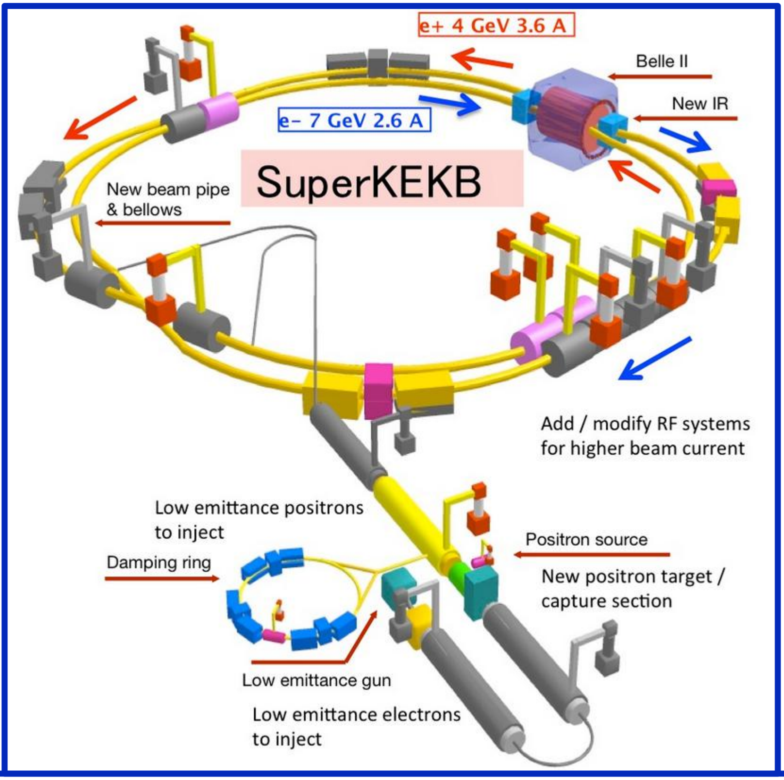
on behalf of the Belle II collaboration

Phenomenology 2021 Symposium - 24/05/2021

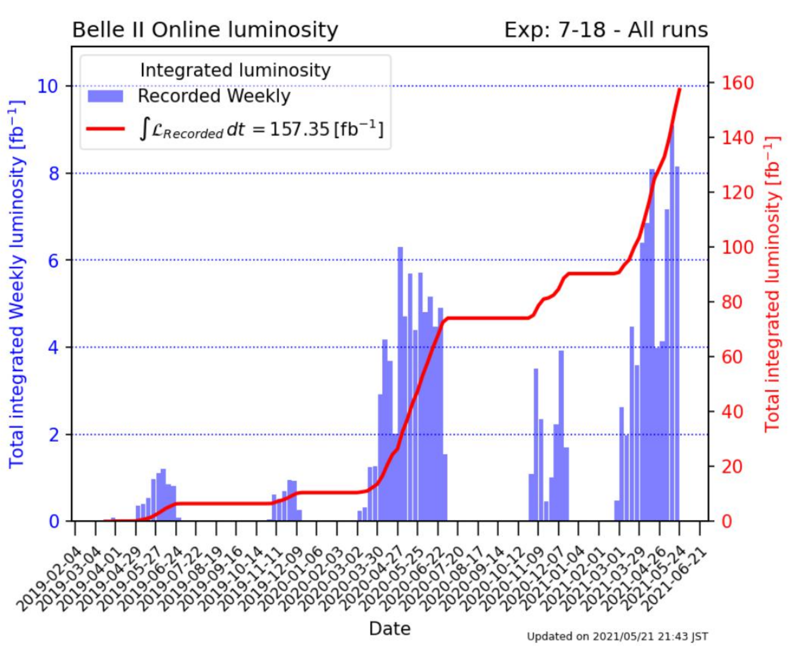
SuperKEKB and status of Belle II

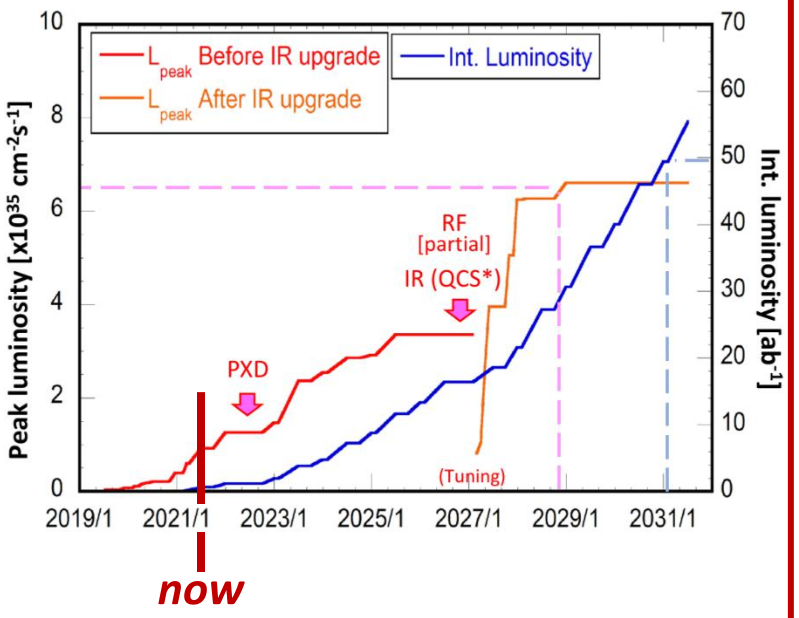


Electron (7 GeV) - **Positron** (4 GeV) collider.

$$e^+e^- \to \Upsilon(4S)[10.58\ \mathrm{GeV}] \to \boldsymbol{B\overline{B}}\ (\boldsymbol{\sigma = 1.1\ \mathrm{nb}})$$

$$e^+e^- \to \boldsymbol{\tau^+\tau^-}\ (\boldsymbol{\sigma = 0.9\ \mathrm{nb}})$$

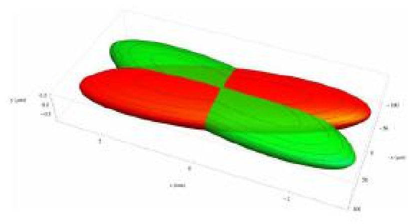




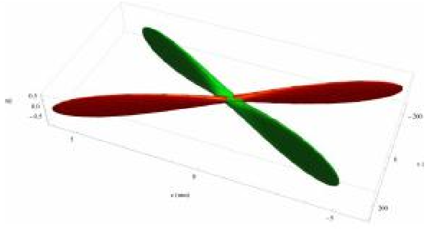
Targeted peak luminosity: $\boldsymbol{6\times10^{35}\ \mathrm{cm^{-2}\ s^{-1}}}$

Today: ~ 160 $\mathrm{fb^{-1}}$ of data collected | Goal: $\boldsymbol{50\ \mathrm{ab^{-1}}}$

Higher beam currents
Lower beam size
} **30x** KEKB peak luminosity

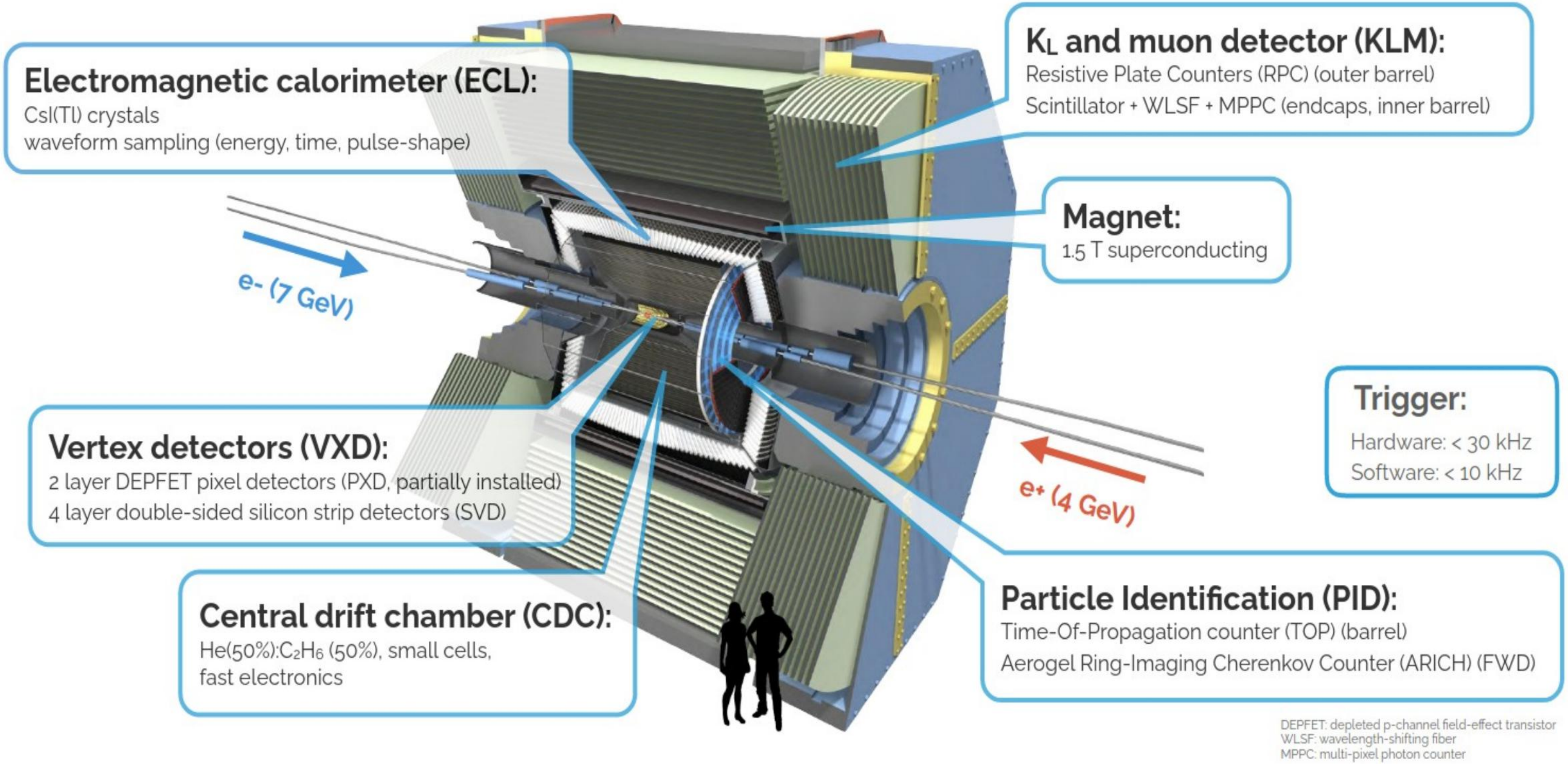


KEKB Interaction region beam overlap

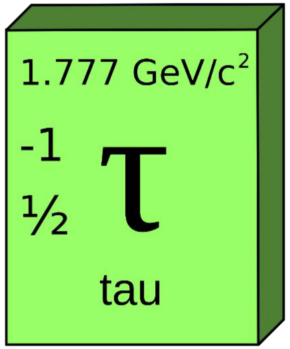


SuperKEKB Interaction region beam overlap

Belle II detector



Motivations for tau studies



The large tau production cross section allows us to study tau physics with high precision, as a probe of new physics or a test of the standard model.

Tau studies at Belle II:

- Lepton flavour violating (LFV) decays: $\tau \to l\gamma$, lll, lhh, lV^0…
- LFV decay with new particles: $\tau \to l+\alpha$,
- Tau electric dipole moment,
- CP violation: $\tau \to K_s \pi \nu$,
- Tau mass measurement,
- Tau lifetime measurement,
- Michel parameters determination,
- V_{us} and α_s determinations,
- ...

Direct New Physics (NP) searches

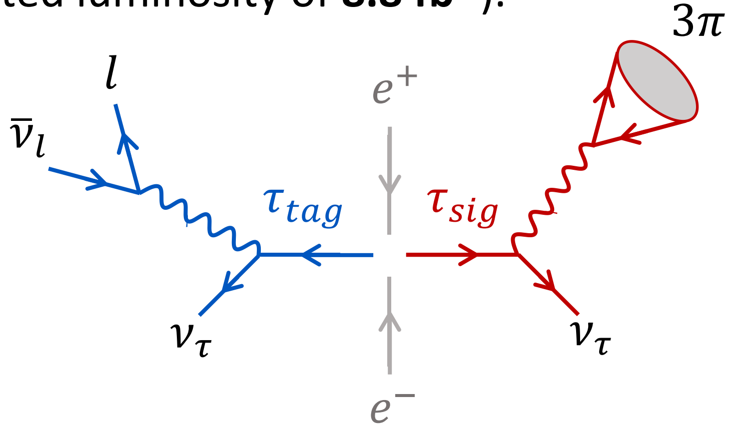
Precise test of the Standard Model (SM)
Indirect NP searches

Motivations:

- LFV decays: testing predictions from SUSY, little Higgs models, leptoquark models, etc.,
- $\tau \to l+\alpha$: related to axion-like particles and dark matter studies (cf. backup slides),
- Tau mass and lifetime: tests of leptonic universality depend on these parameters and their accuracies...

Tau mass measurement (Preliminary)

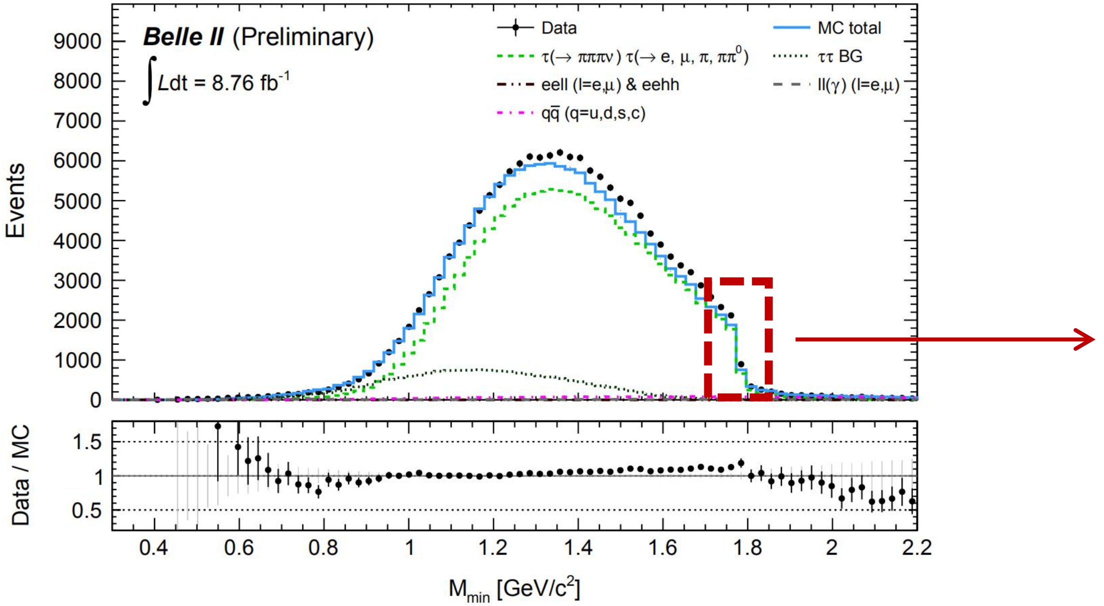
- **Tau mass measurement** analysis performed using Belle II early Phase 3 data (integrated luminosity of **8.8 fb^{-1}**).

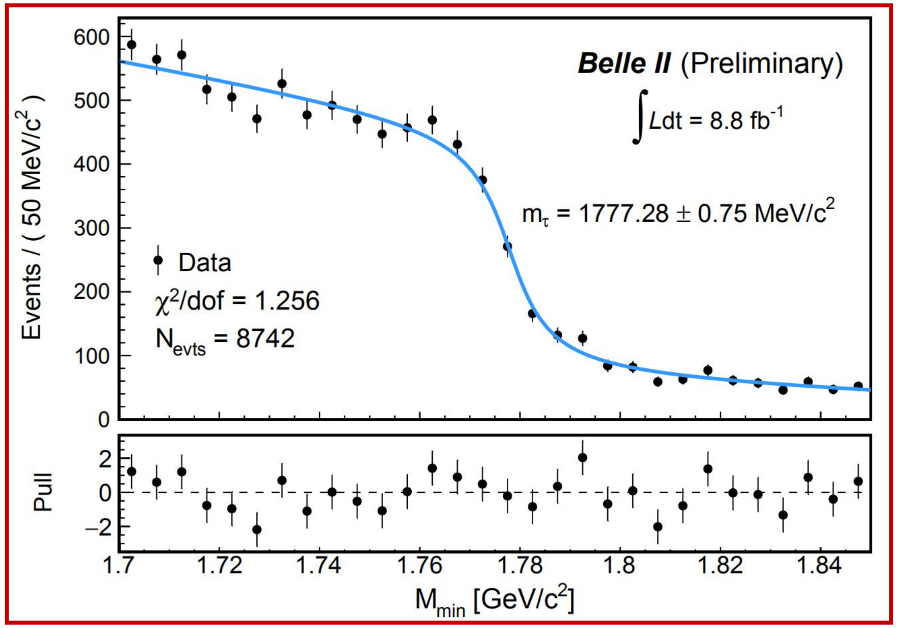


- **[τ→3πν]** + [τ→1-prong] events are selected and the tau mass is measured following the pseudomass technique developed by the ARGUS collaboration:

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

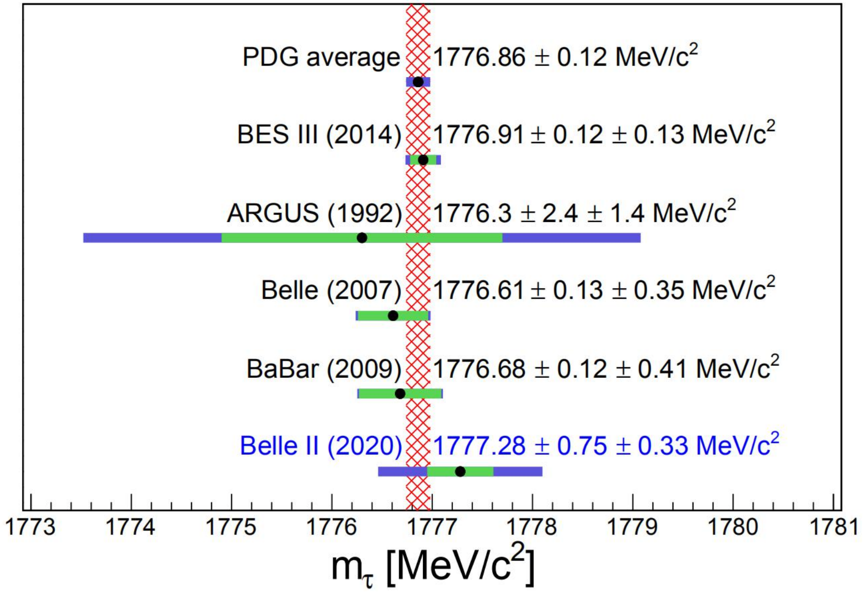
- The tau mass is extracted by fitting the pseudomass to an empirical edge function.



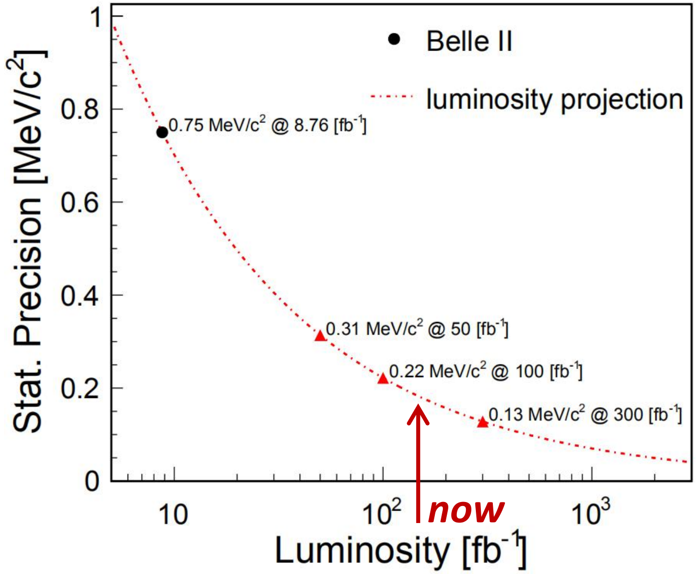


Tau mass measurement (Preliminary)

- Current best fit by Belle (414 fb^{-1}):
  $1776.61 \pm 0.13_{stat} \pm 0.35_{syst}$ MeV K. Belous et al, Phys. Rev. Lett. 99, 011801 (2007)
- More precise measurement done by BES III near τ pair production threshold:
  $1776.91 \pm 0.12_{stat} \pm 0.13_{syst}$ MeV M. Ablikim et al, Phys. Rev. D 90 012001 (2014)
- **Preliminary** result from Belle II early Phase 3 data:
  $m_\tau = 1777.28 \pm 0.75_{stat} \pm 0.33_{syst}$ MeV BELLE2-CONF-PH-2020-010
  → Consistent with previous measurements, improvable statistical uncertainty, systematic error similar to Belle but could be reduced in the future.



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	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01



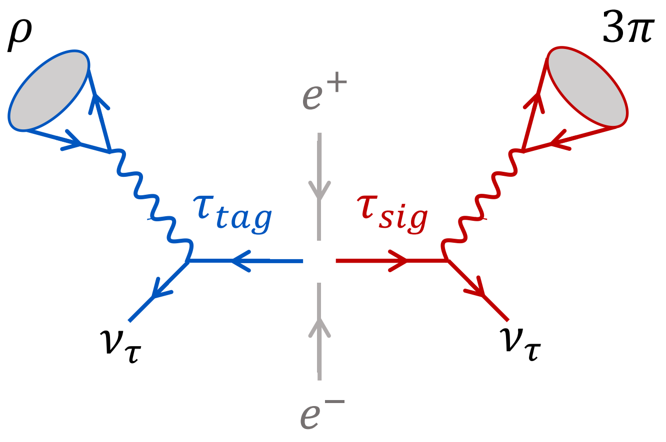
Tau lifetime measurement

- **Tau lifetime** is measured thanks to the relation:

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

ℓ_τ = decay length in lab. frame
p_τ = momentum in lab. frame
t = proper decay time

→ the challenge consists in measuring precisely ℓ_τ and p_τ.



- Events corresponding to **[τ→3πν]** + [τ→ρν] are selected, the measurement is done on the 3-prong τ.

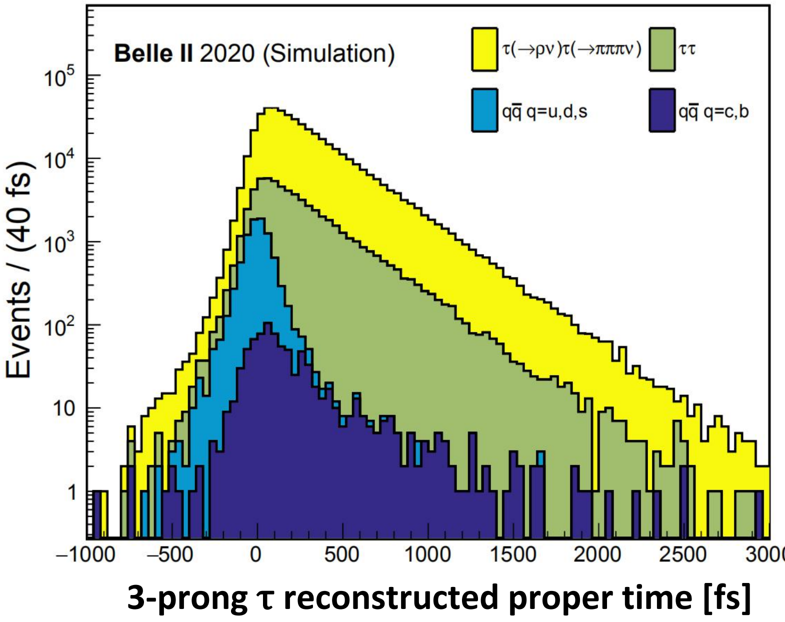
- The proper time is fitted with the convolution of an exponential distribution and a resolution function: and the lifetime τ_τ is extracted from there.

$$p(t;\ \tau_\tau) = \frac{1}{\tau_\tau} e^{-\frac{t}{\tau_\tau}} * \mathcal{R}(t)$$

- World-best measurement comes from Belle (711 fb^{-1}):

τ_τ = 290.17 ± 0.53_{stat} ± 0.33_{syst} fs K. Belous et al, Phys. Rev. Lett. 112, 031801 (2014)

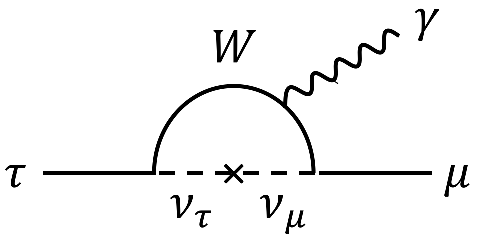
- Belle II's study on simulation done with 200 fb^{-1}: τ_τ = 287.2 ± 0.5_{stat} fs
  generated τ_τ = 290.2 ± 0.4_{stat} fs



Belle II already competitive at ~ 150 fb^{-1} (5× more events than in Belle study)

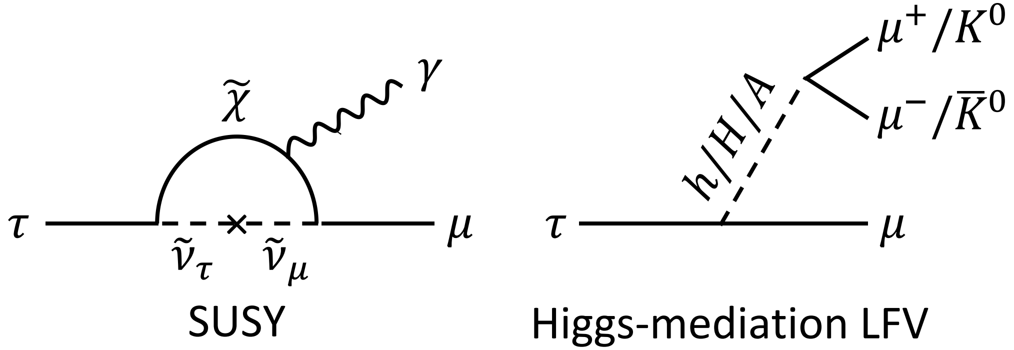
Tau lepton flavour violation

- **Lepton flavour violation** is heavily suppressed in the SM (extended with neutrino masses).
- Many NP models allow LFV at scales that can be probed by particle physics experiments.
- In tau physics, the "golden modes" are τ→μγ and τ→3μ, but a lot more are also studied (lγ, lll, lhh, lV⁰...).

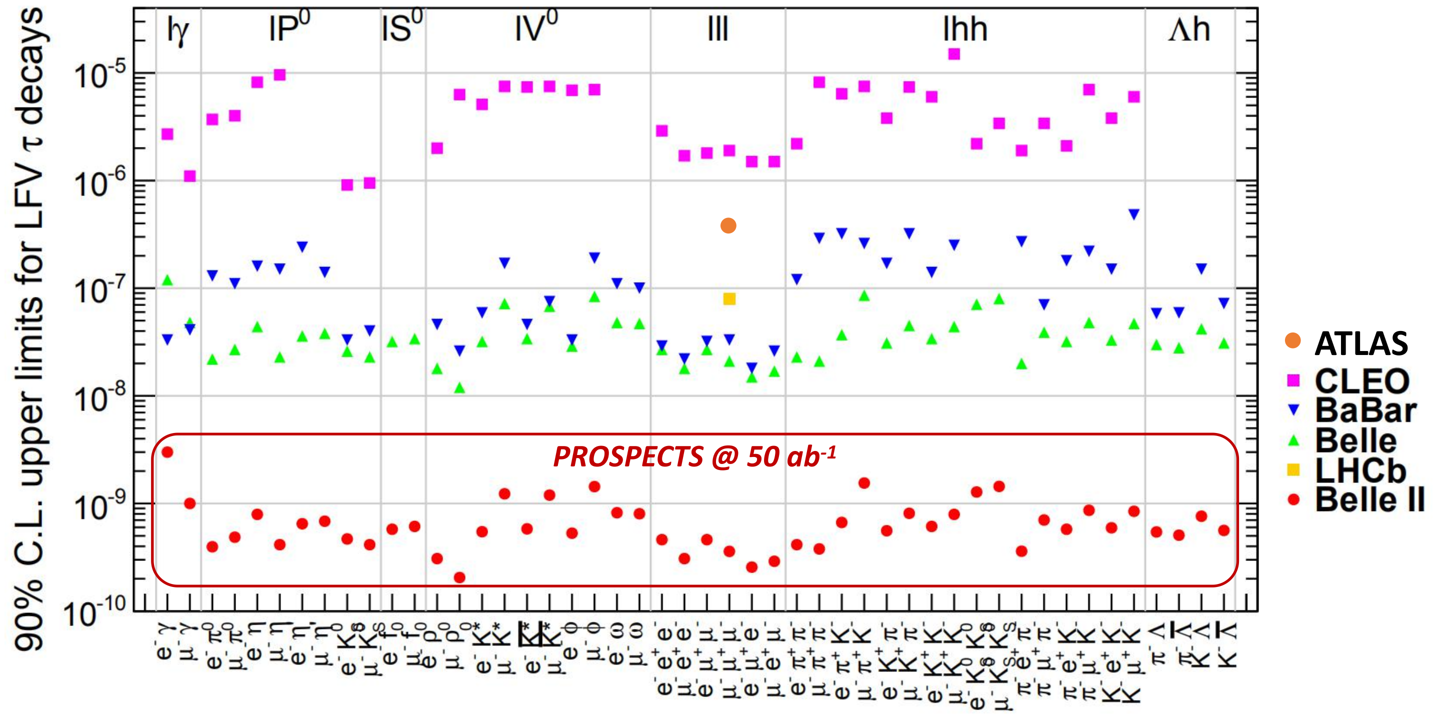


Br ~ $\mathcal{O}(10^{-54})$

NP models: **Br ~ $\mathcal{O}(10^{-10})$-$\mathcal{O}(10^{-7})$**



Improvement of 2 orders of magnitude expected for Belle II!

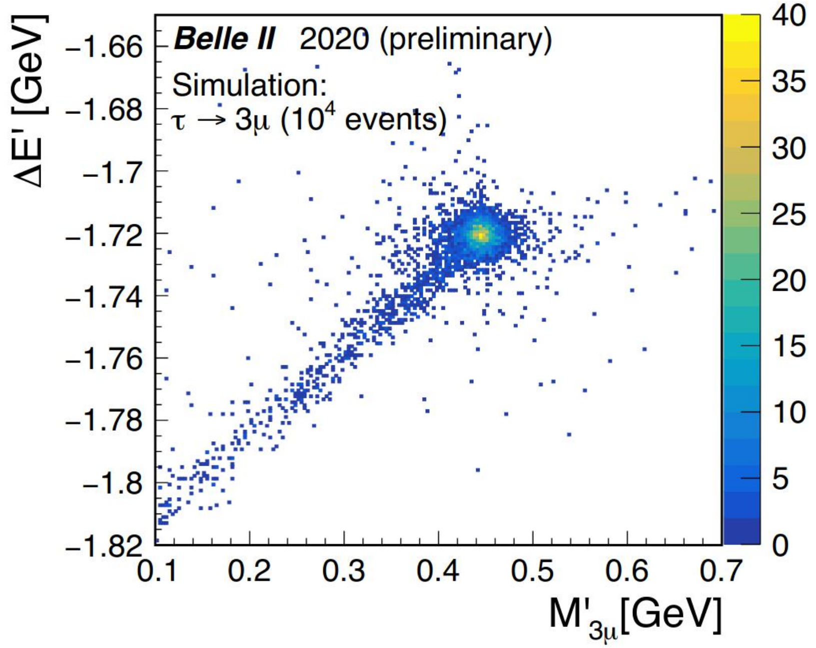


The Belle II Physics Book, Prog. Theor. Exp. Phys. (2019), 123C01

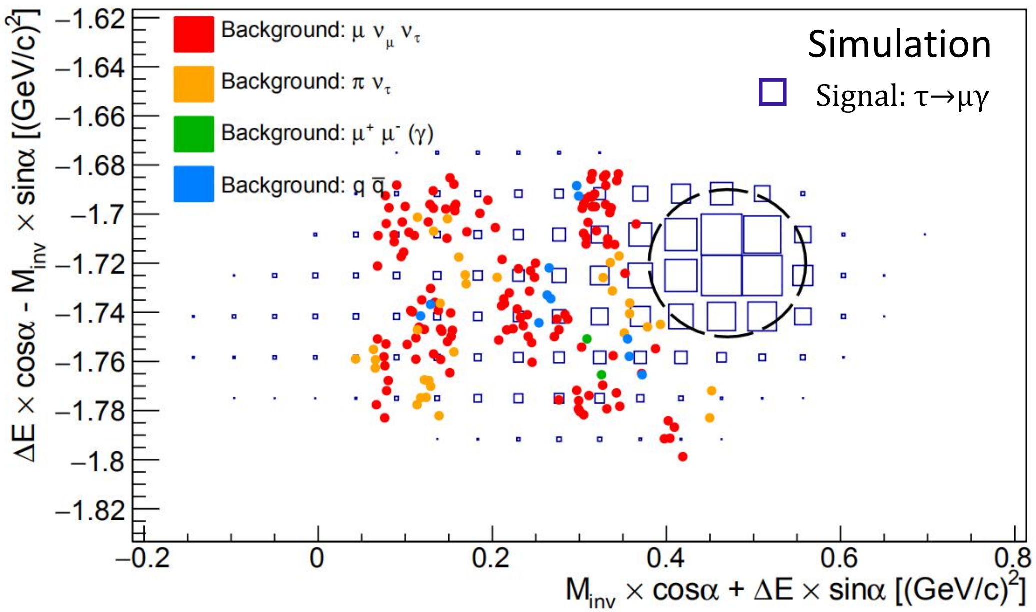
Tau lepton flavour violation

- The signal is looked for within the M_τ-ΔE space ($\Delta E = E_\tau - E_{beam}$), in an optimised region defined around the signal peak in simulation.
- Usually the signal region is rotated to get rid of the correlations: $\begin{pmatrix} M'_\tau \\ \Delta E' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} M_\tau \\ \Delta E \end{pmatrix}$
- Background is evaluated from side bands. Some channels require a more thorough background suppression strategy (e.g. $\tau\to\mu\gamma$ is much more contaminated than $\tau\to 3\mu$).

Rotated signal region ($\tau\to 3\mu$, signal events only)

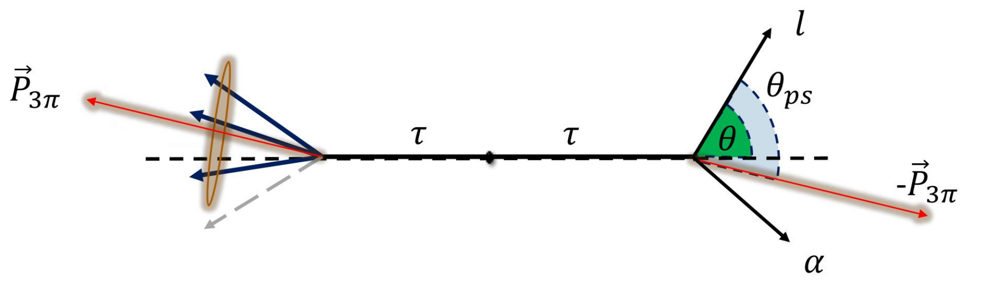


Rotated signal region ($\tau\to\mu\gamma$)



LFV decay τ→l+α (invisible)

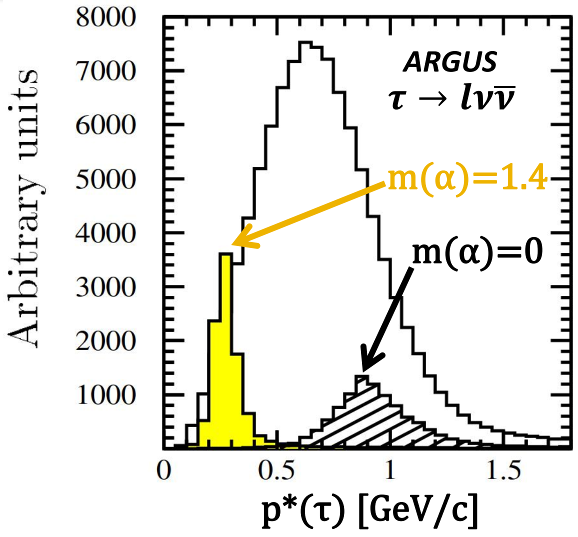
- Search for LFV two-body decay **τ→l+α**, l=e/μ and **α** being an invisible particle.
- The opposite τ decays as τ→3πν. Due to the missing energy from neutrino, we approximate: $E_\tau \approx E_{CMS}/2, \quad \vec{p}_\tau \approx \vec{p}_{3\pi}$
- Signal manifests as a **peak in the τ momentum in pseudo-rest frame**, stacking on the **τ→lνν** background.



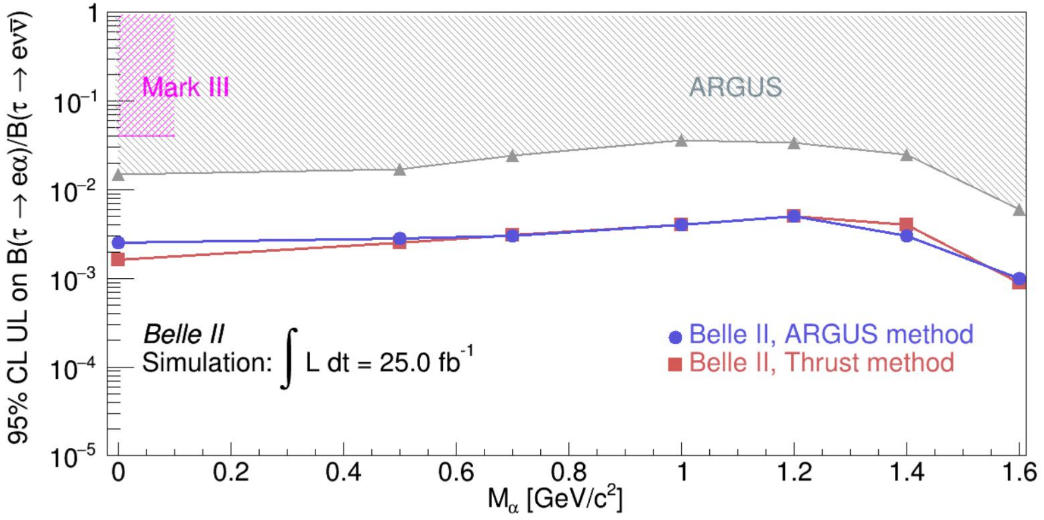
- Full spectrum is fitted with (SM) and (SM+NP) expectations and respective likelihoods are compared.
- Latest results are from:
  - ARGUS (472 pb^{-1})
  - MARK III (9.4 pb^{-1})

Belle II is already competitive with respect to ARGUS.

H. Albrecht et. al. (ARGUS), Z.Phys. C68 (1995) 25-28



BELLE2-NOTE-PL-2020-018



Summary

- The Belle II experiment is currently collecting data with a final goal of 50 ab^{-1} by ~ 2031.
  → ~ 5×10^{10} τ pairs, much larger sample than in previous B-factories.

- This amount of data will enable researchers to perform analyses probing new physics or testing with high precision the parameters of the standard model with respect to τ particles.

- Some analyses are already progressing well:

  - *Tau mass measurement*: $m_\tau = 1777.28 \pm 0.75 \pm 0.33$ MeV (with a small set of data),

  - *Tau lifetime measurement*: already competitive w.r.t. Belle,

  - *Lepton flavour violating decays*: $\tau\to\mu\gamma$ & $\tau\to3\mu$, $\tau\to l+\alpha$...

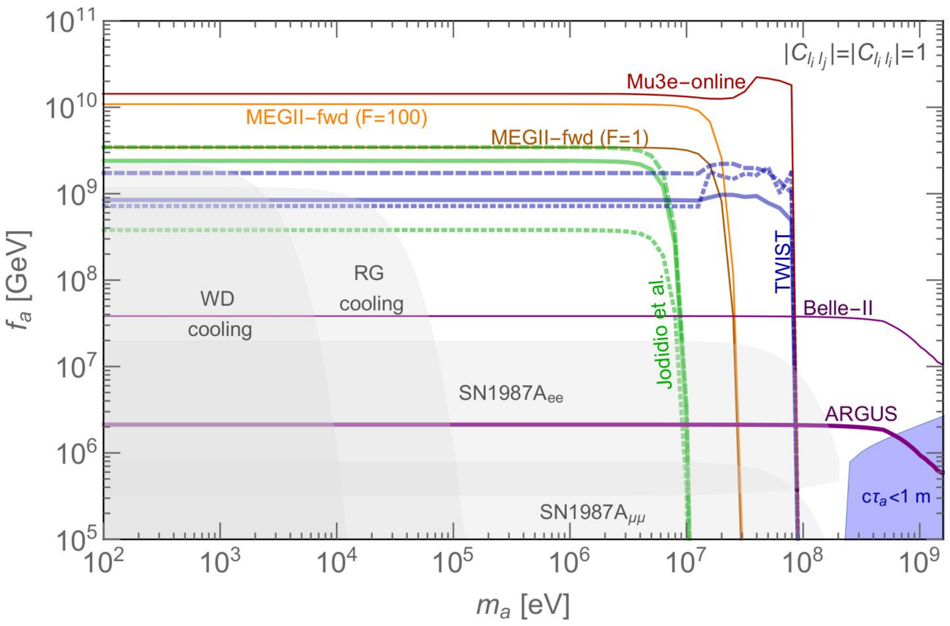
- Many other analyses are ongoing or in preparation (electric dipole moment, CP violation, hadronic currents...).

Backup

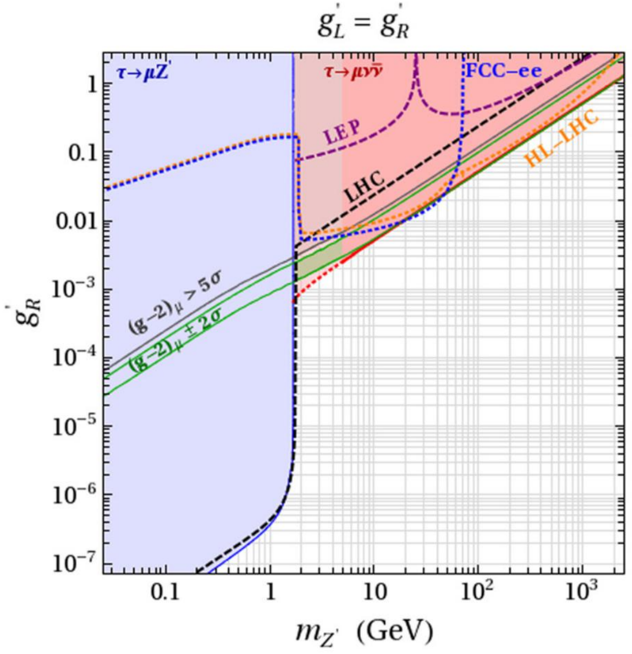
τ→l+α: Links to ALP and Z'

Future results from **τ→l+α** searches at Belle II might put boundaries on several NP models, for example:

- Models with axion-like particles, where Belle II should be able to put a stronger constraint on f_a (decay constant in effective Lagrangian) than the bound from ARGUS, in particular for high ALP masses.
- Models giving rise to a Z' boson, that could address issues like the $(g-2)_\mu$ anomaly or in dark matter phenomenology. Searches for τ→μ+(missing energy) can constrain the Z' parameter space (g'_R: right-handed coupling).



L. Calibbi et al., P3H-20-024, TTP20-025



W. Altmannshofer et al., Phys.Lett. B762 (2016) 389-398

CP violation in $\tau \to K_s \pi \nu$

- A **decay rate asymmetry** is expected in $\tau \to K_s \pi \nu$ according to the SM because the K_s is subject to CP violation:

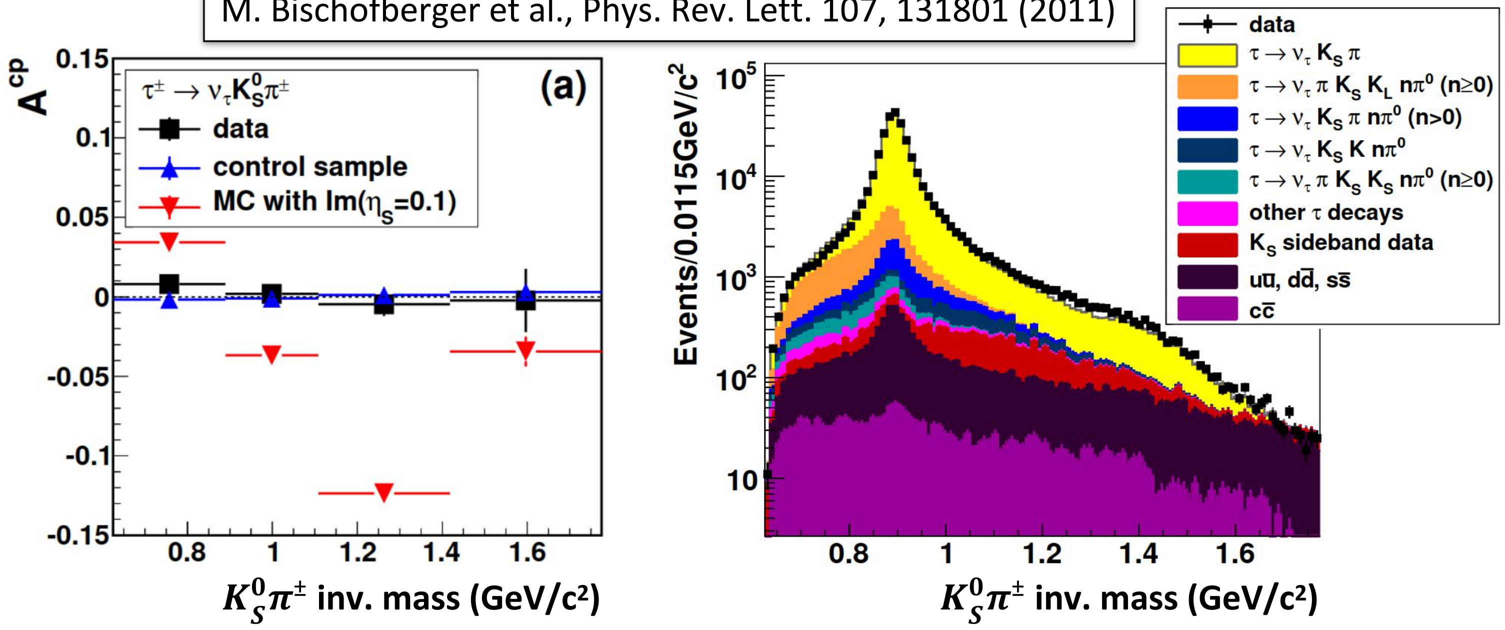
$$\mathcal{A}_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

- The SM predicts: $\mathcal{A}_\tau^{SM} \approx (0.36 \pm 0.01)\%$ I. I. Bigi and A. I. Sanda, Phys. Lett. B 625, 47 (2005)
- ... while BaBar has measured: $\mathcal{A}_\tau^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\%$ J. P. Lees et al., Phys. Rev. D 85, 031102 (2012)

→ **2.8σ** discrepancy w.r.t. the SM.

A measurement of the decay rate asymmetry is a priority for Belle II, which should improve the precision by a factor ~ 8 at 50 ab^{-1}.

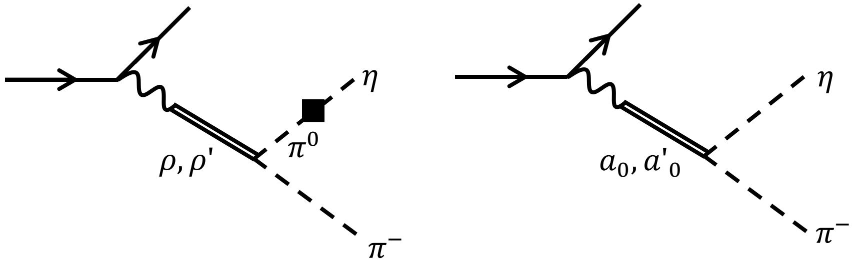
M. Bischofberger et al., Phys. Rev. Lett. 107, 131801 (2011)



Second-class hadronic currents: $\tau \to \pi\eta\nu$

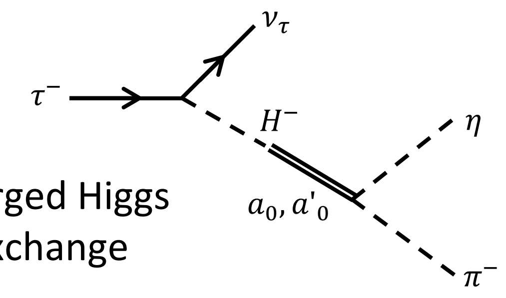
- **Second-class hadronic currents** violate G-parity, still present in the SM because of the charge and mass differences between *up* and *down* quarks, but heavily suppressed.

- **$\tau \to \pi\eta\nu$** is a SCC, therefore it is a potential probe for new physics.

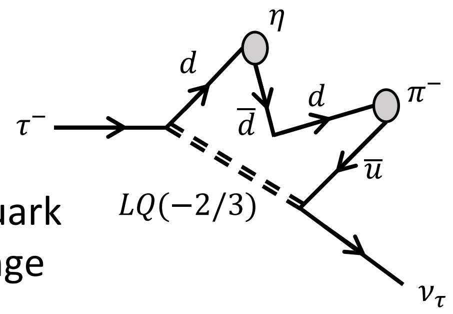


- The SM predicts: $\mathrm{Br}(\tau \to \pi\eta\nu) \sim 10^{-5}$ — A. Pich, Phys. Lett. B 196, 561 (1987)

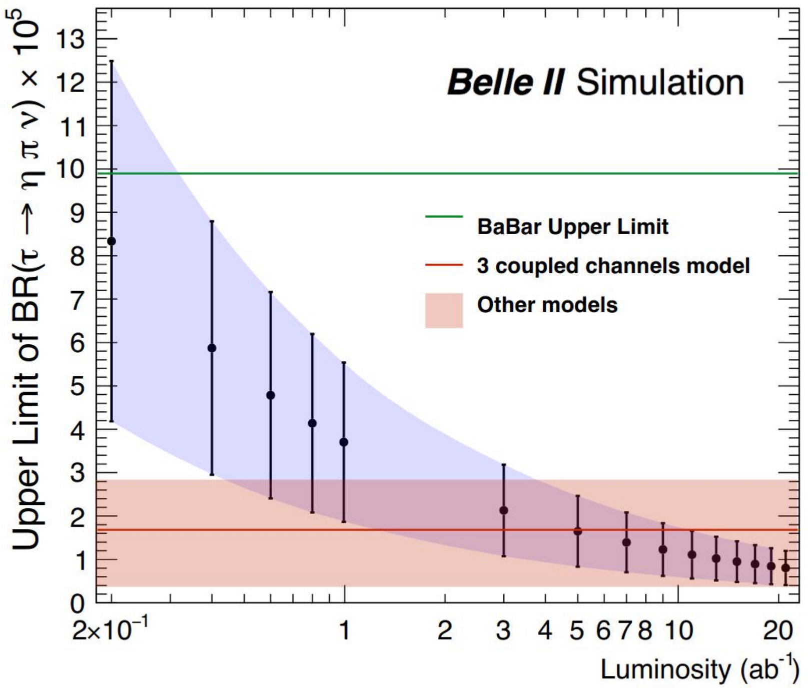
- Upper limits from two previous experiments:
  - BaBar (470 fb^{-1}): $\mathrm{Br}(\tau \to \pi\eta\nu) < 9.9 \times 10^{-5}$
    K. Hayasaka, PoS EPS-HEP2009, 374 (2009)
  - Belle (670 fb^{-1}): $\mathrm{Br}(\tau \to \pi\eta\nu) < 7.3 \times 10^{-5}$
    P. del Amo Sanchez et al., Phys. Rev. D 83, 032002 (2011)



Charged Higgs exchange



Leptoquark exchange



Other topics

Michel parameters:

- 4 parameters ρ, η, ξ and δ (combinations of coupling constants in four-lepton point interaction Lagrangian), experimentally accessible in decay $\tau \to l \nu_l \nu_\tau$.
- Belle II expected to improve statistical uncertainties at 50 ab^{-1} by one order of magnitude w.r.t. Belle ($10^{-3} \to 10^{-4}$).

Electric and magnetic dipole moments of the τ:

- Evaluating some observables that are proportional to the EDM and getting maximal sensitivity by combining results from multiple τ decay modes. Belle II expected to gain in precision by a factor 40: $|\mathrm{Re}, \mathrm{Im}(d_\tau)| < 10^{-18} - 10^{-19}$.
- $g - 2$ can be evaluated similarly but sensitivity is expected to be worse than that of the τ EDM.

Measurements of V_{us} and α_s:

- Determinations of the CKM matrix element and the strong coupling constant at the tau mass (+ running to the Z mass) with the help of inclusive hadronic τ decays and observable: $R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau \,\mathrm{hadrons}^-(\gamma))}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e(\gamma))}$

More details in:

The Belle II Physics Book, Prog. Theor. Exp. Phys. (2019), 123C01