Tau physics prospects at Belle II

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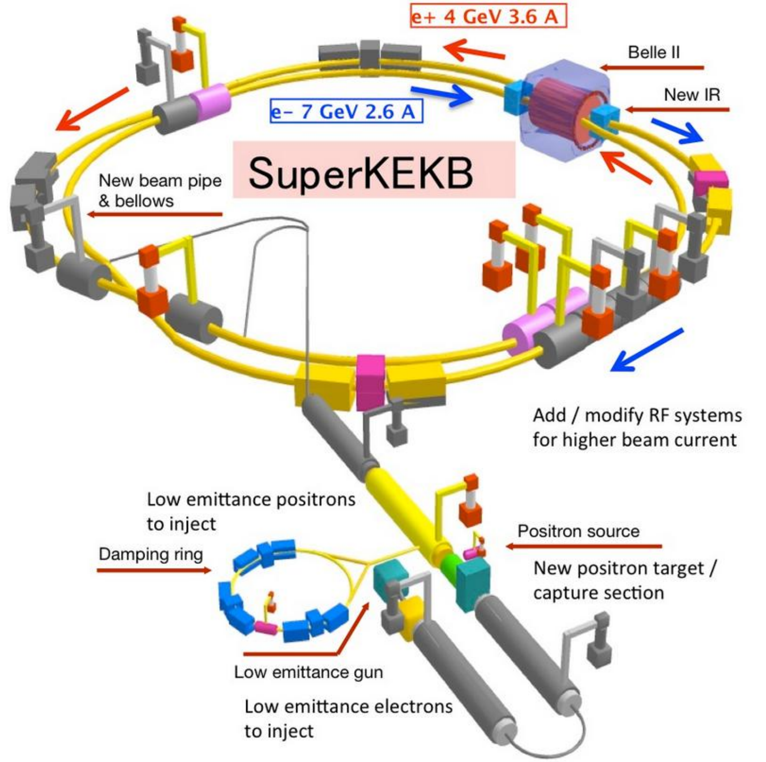
on behalf of the Belle II collaboration

Phenomenology 2021 Symposium - 24/05/2021

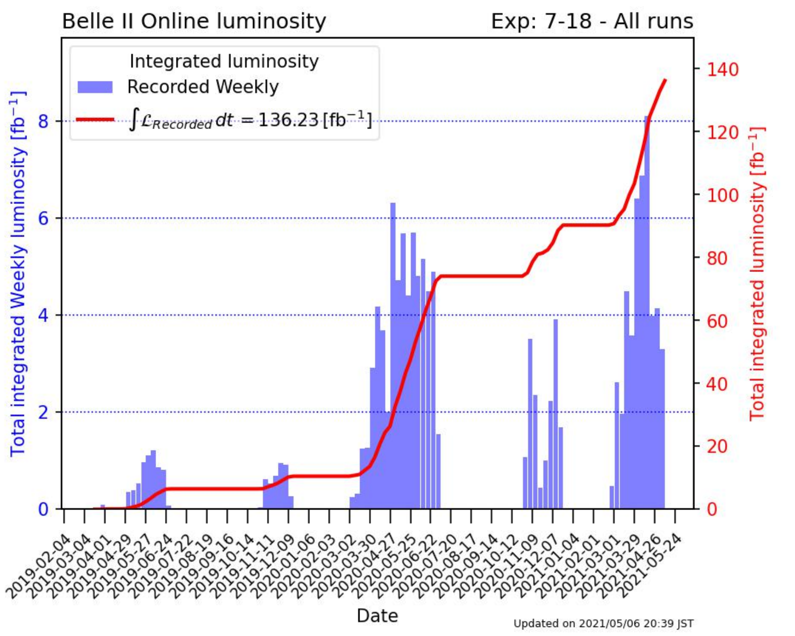
SuperKEKB and status of Belle II

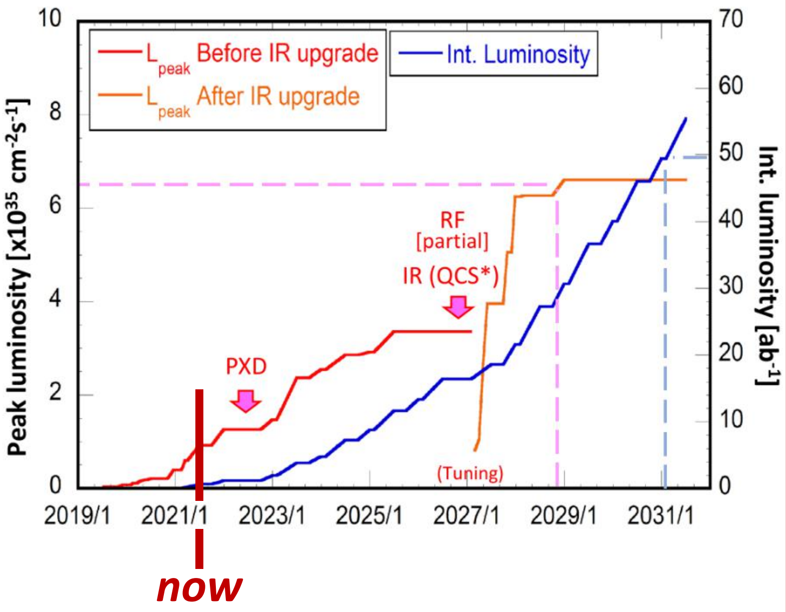


Electron (7 GeV) - **Positron** (4 GeV) collider.

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

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

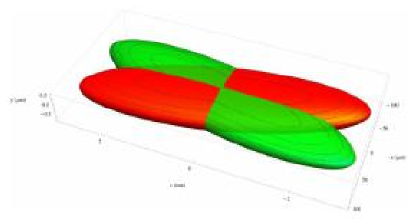




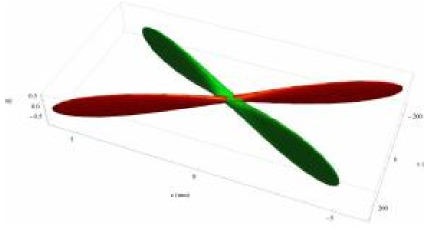
Peak luminosity: $\mathbf{6 \cdot 10^{35}\ cm^{-2}\ s^{-1}}$

Today: ~ 136 fb^{-1} of data collected | Goal: $\mathbf{50\ ab^{-1}}$

Current ↗
Beam size ↘
} **30x** KEKB peak luminosity

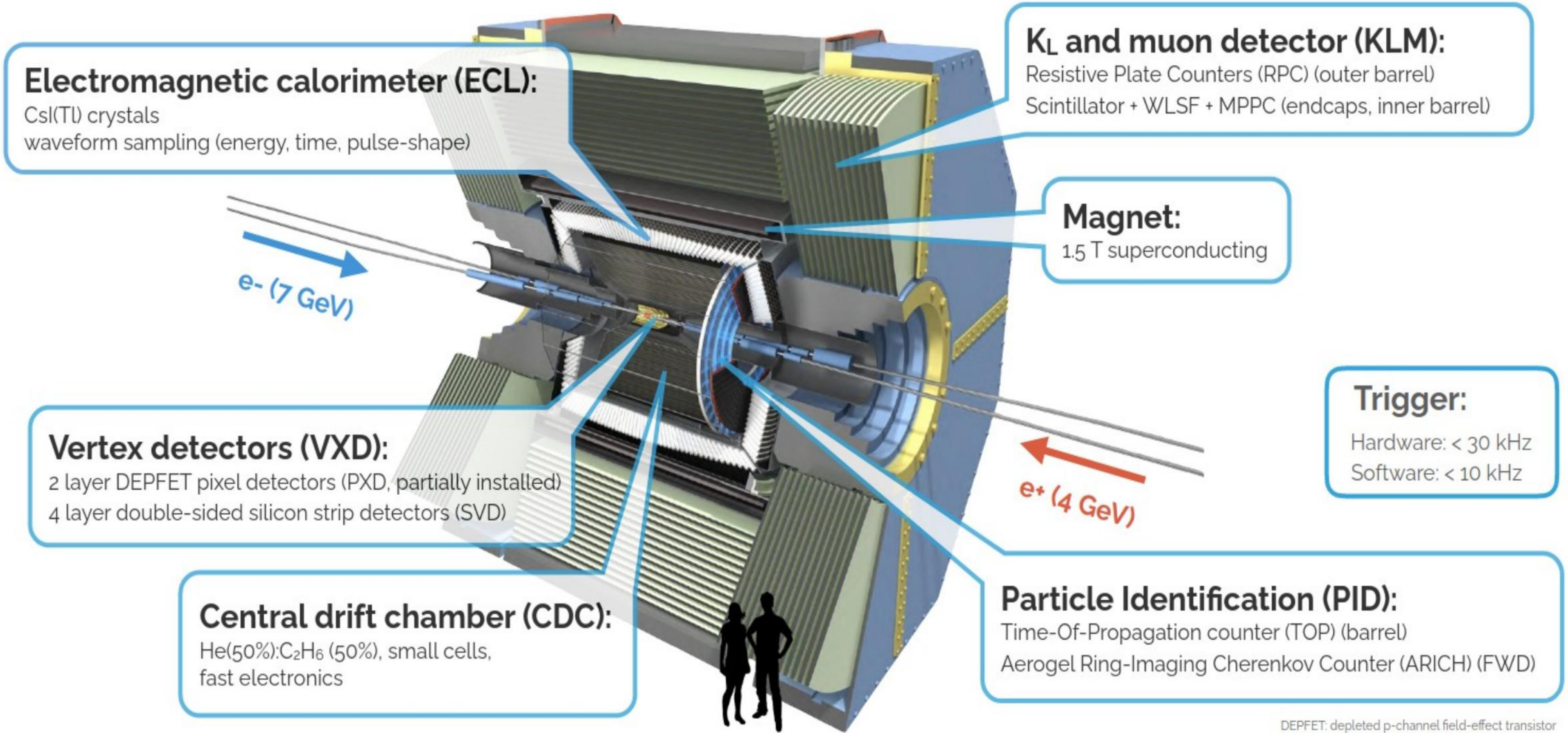


KEKB Interaction region beam overlap



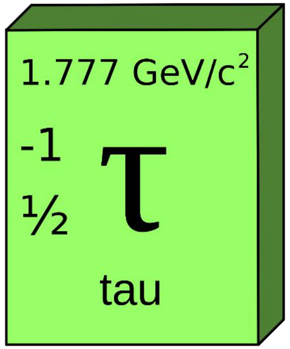
SuperKEKB Interaction region beam overlap

Belle II detector



DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

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 and lifetime measurements,
- Michel parameters determination,
- Search for second-class hadronic currents: $\tau \to \pi \eta \nu$,
- V_{us} and α_s determinations,
- ...

New Physics (NP) searches (first four items)

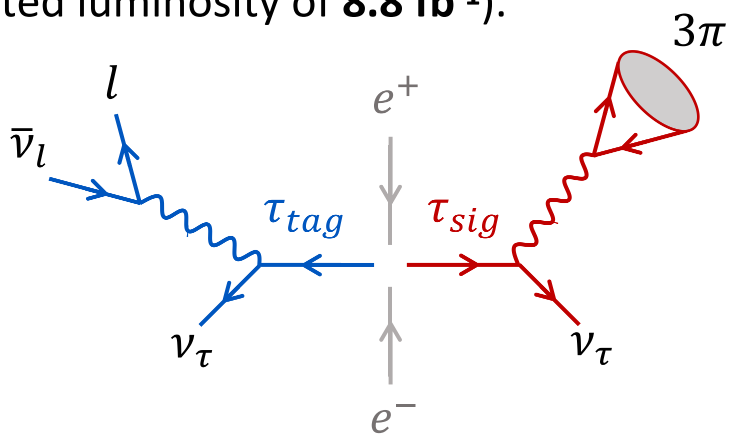
Precise test of the Standard Model (SM) (remaining items)

Motivations:

- LFV decays: testing predictions from SUSY, little Higgs models, leptoquark models, etc.,
- Tau mass: tests of leptonic universality depend on the tau mass value and its accuracy,
- ...

Tau mass measurement (Preliminary)

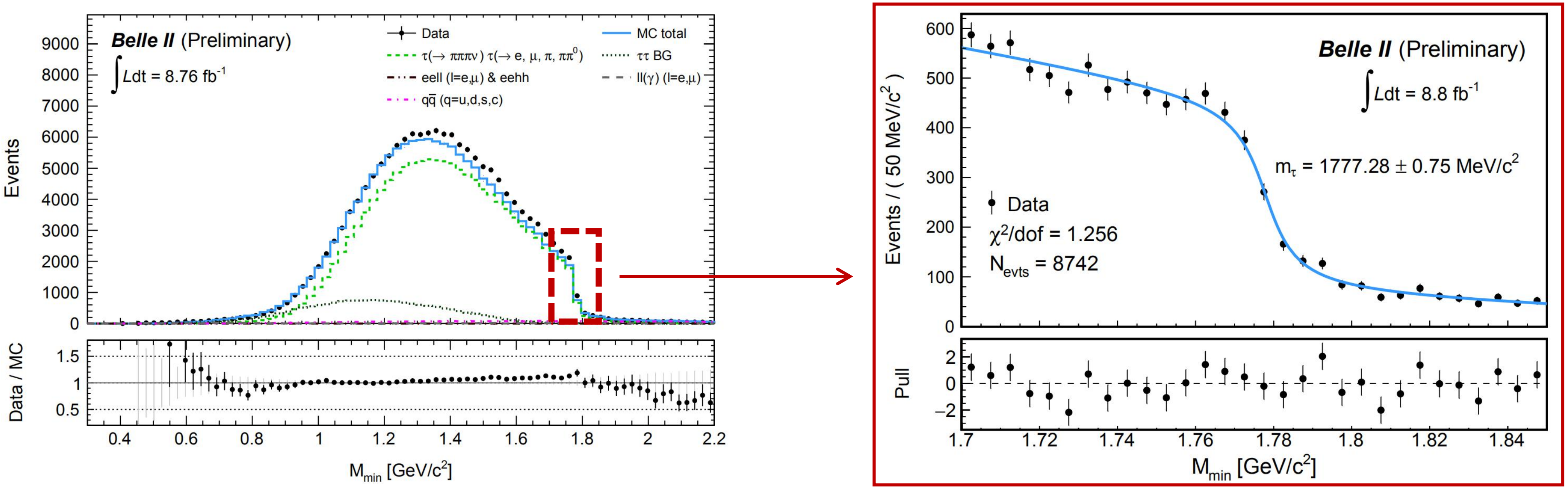
- **Tau mass measurement** analysis performed using Belle II early Phase 3 data (integrated luminosity of **8.8 fb^{-1}**).



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

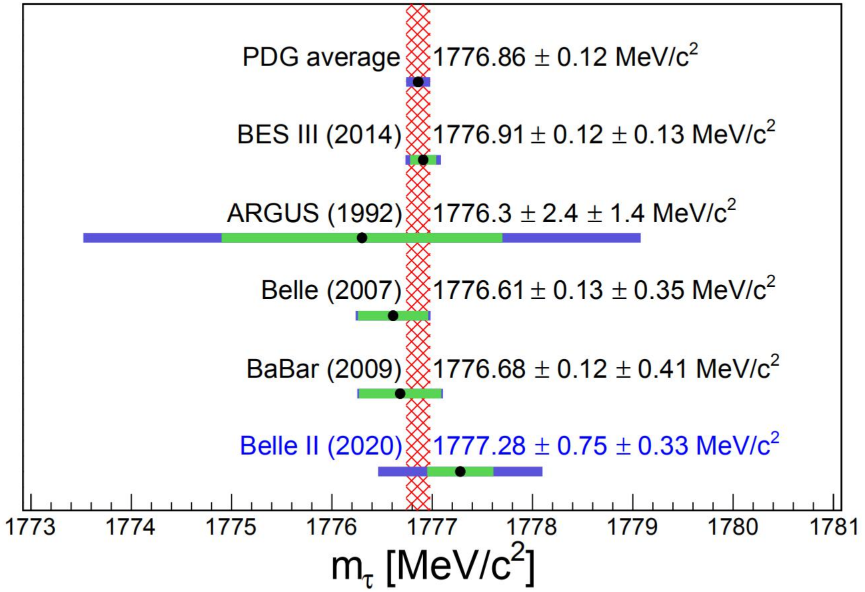
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$

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

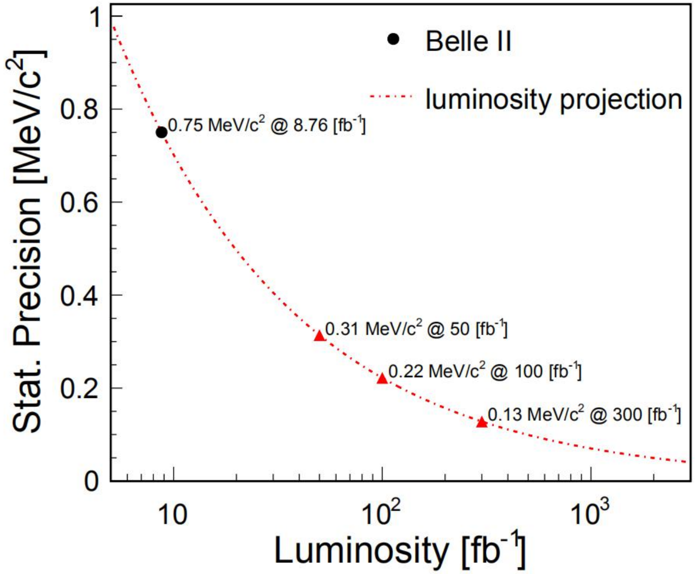


Tau mass measurement (Preliminary)

- Current best fit by Belle (414 fb^{-1}):
  1776.61 ± 0.13 ± 0.35 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 ± 0.12 ± 0.13 MeV M. Ablikim et al, Phys. Rev. D 90 012001 (2014)
- **Preliminary** result from Belle II early Phase 3 data:
  m_τ = 1777.28 ± 0.75 ± 0.33 MeV BELLE2-CONF-PH-2020-010
  → Consistent with previous measurements, improvable statistical uncertainty, systematic error similar to Belle.

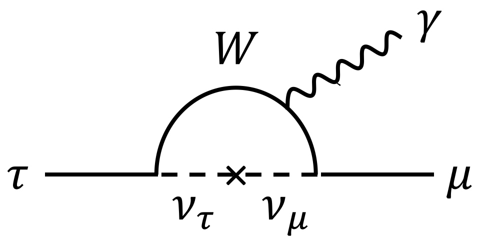


Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$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



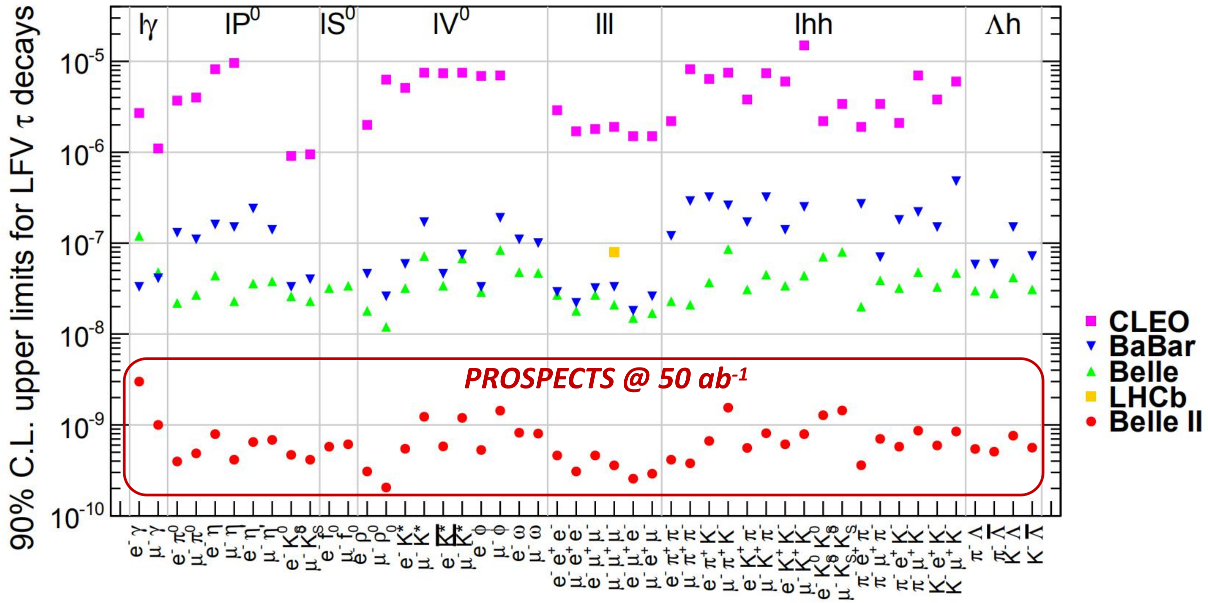
Tau lepton flavour violation

- **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…).



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

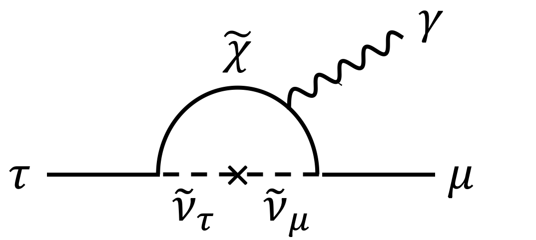
Improvement of 2 orders of magnitude expected for Belle II!



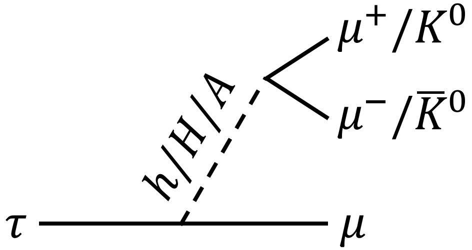
The Belle II Physics Book, Prog. Theor. Exp. Phys. (2019), 123C01

NP models:

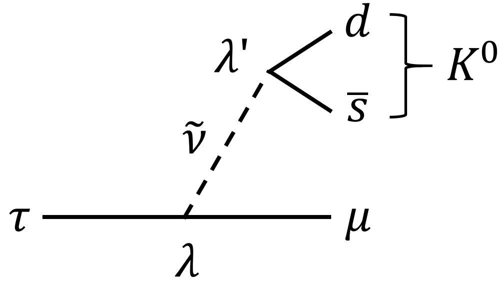
$Br \sim \mathcal{O}(10^{-10})$-$\mathcal{O}(10^{-7})$



SUSY



Higgs-mediation LFV

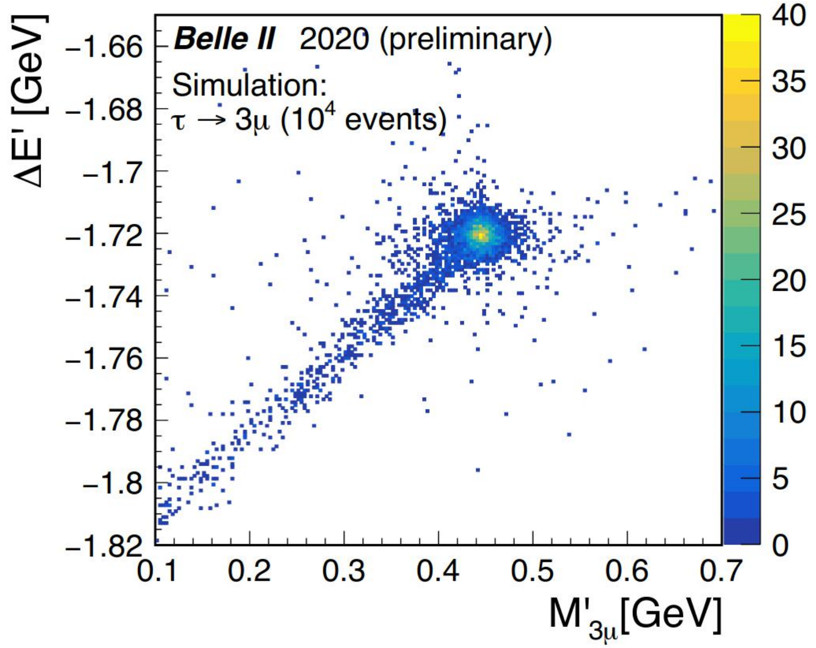


R-parity violation

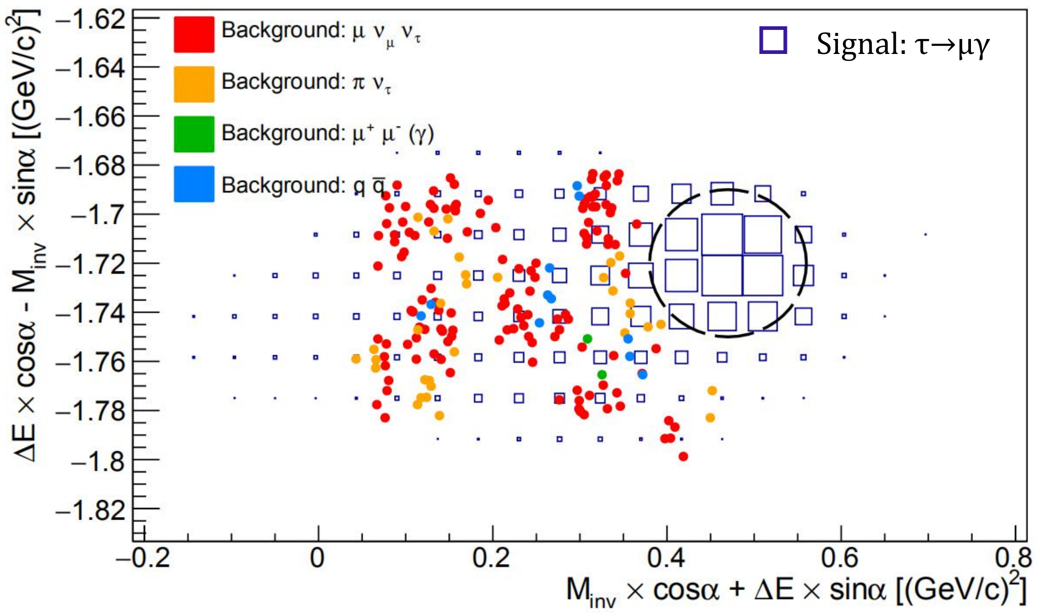
Tau lepton flavour violation

- 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)

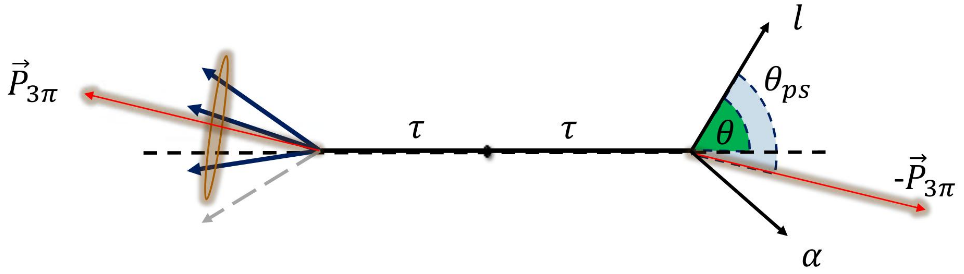


Rotated signal region ($\tau \to \mu\gamma$)



LFV decay τ→l+α (invisible)

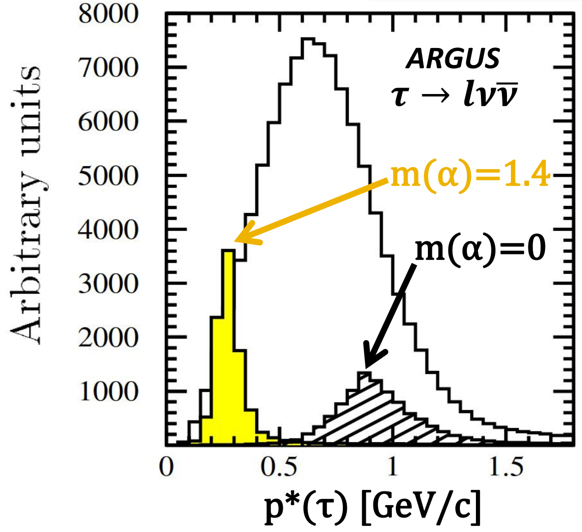
- Search for LFV two-body decay **τ→l+α**, l=e/μ and **α** being an invisible particle (Goldstone boson in new physics models).
- The paired τ decays as τ→3πν. Due to the missing energy from neutrino, we approximate: $E_\tau \approx E_{CMS}/2, \quad \vec{p}_\tau \approx \vec{p}_{3\pi}$
- LFV decay manifests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

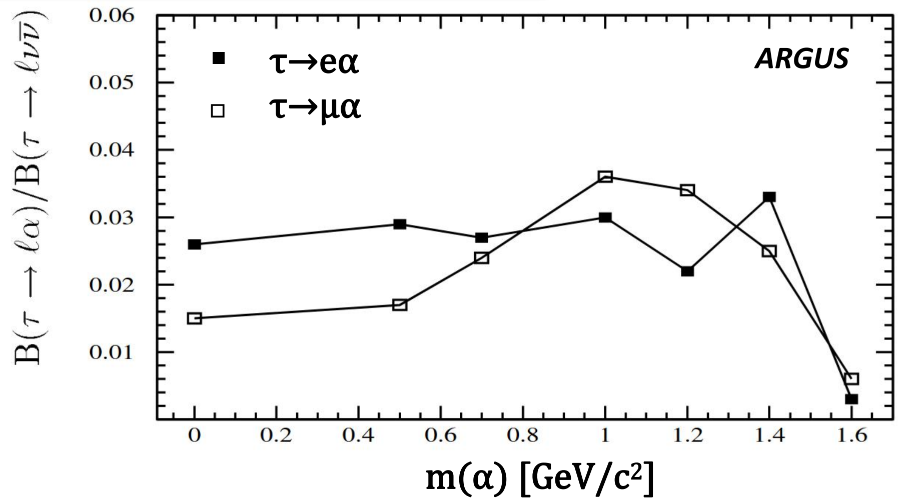


- Full spectrum is fitted with (SM) and (SM+NP) expectations and respective likelihoods are compared.
- Latest results are from:
  - ARGUS (472 pb^{-1})
  - MARK III (9.4 pb^{-1})

Belle II is already competitive with respect to ARGUS.

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





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_τ = 1777.28 ± 0.75 ± 0.33 MeV (with a small set of data),

  - Lepton flavour violating decays: $\tau\rightarrow\mu\gamma$ & $\tau\rightarrow3\mu$, $\tau\rightarrow l+\alpha$...

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

Backup

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

Belle II

- 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: →

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

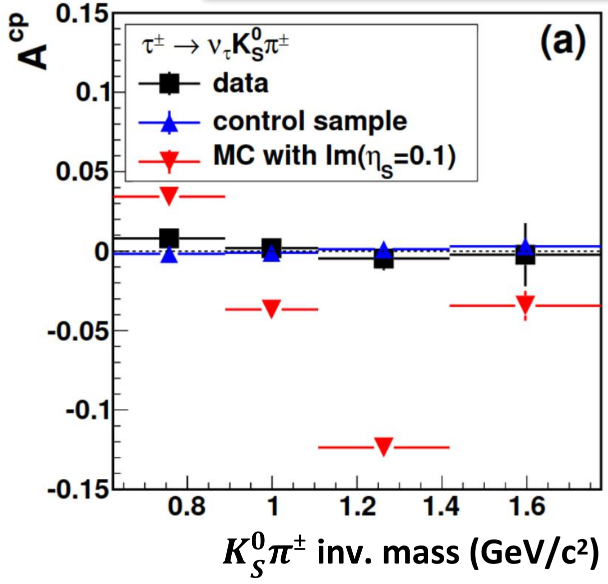
- The SM predicts: $\mathcal{A}_\tau^{SM} \approx (0.36 \pm 0.01)\%$ I. I. Bigi and A. I. Sanda, Phys. Lett. B 625, 47 (2005)

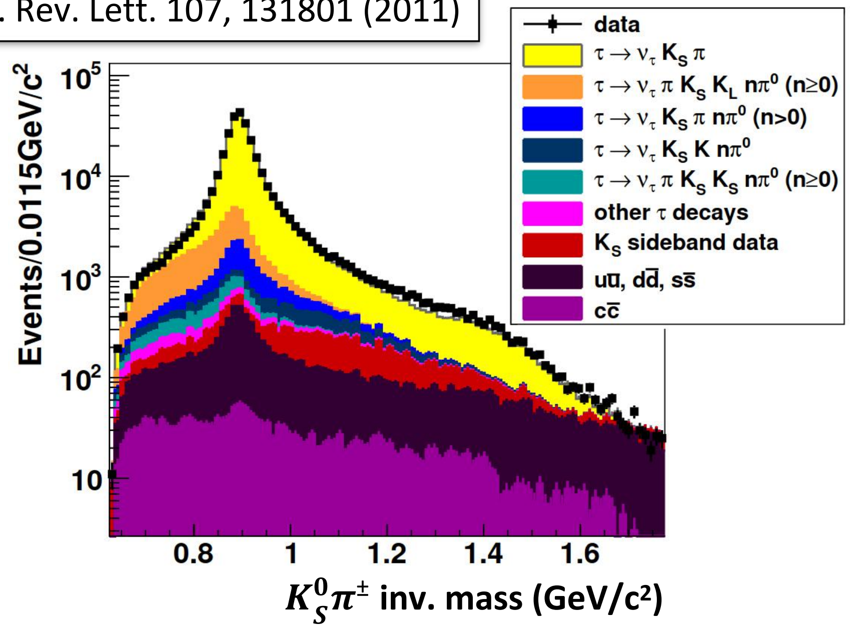
- ... while BaBar has measured: $\mathcal{A}_\tau^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\%$ J. P. Lees et al., Phys. Rev. D 85, 031102 (2012)

  → **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}.

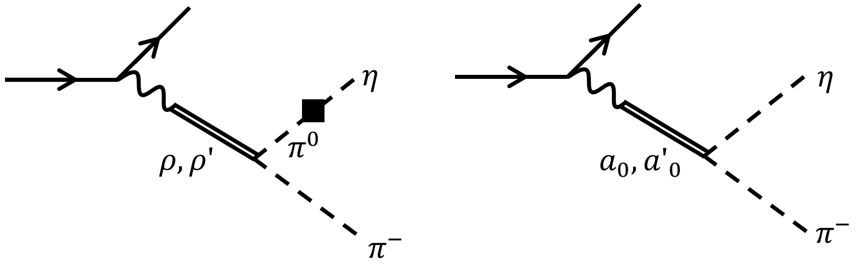
M. Bischofberger et al., Phys. Rev. Lett. 107, 131801 (2011)



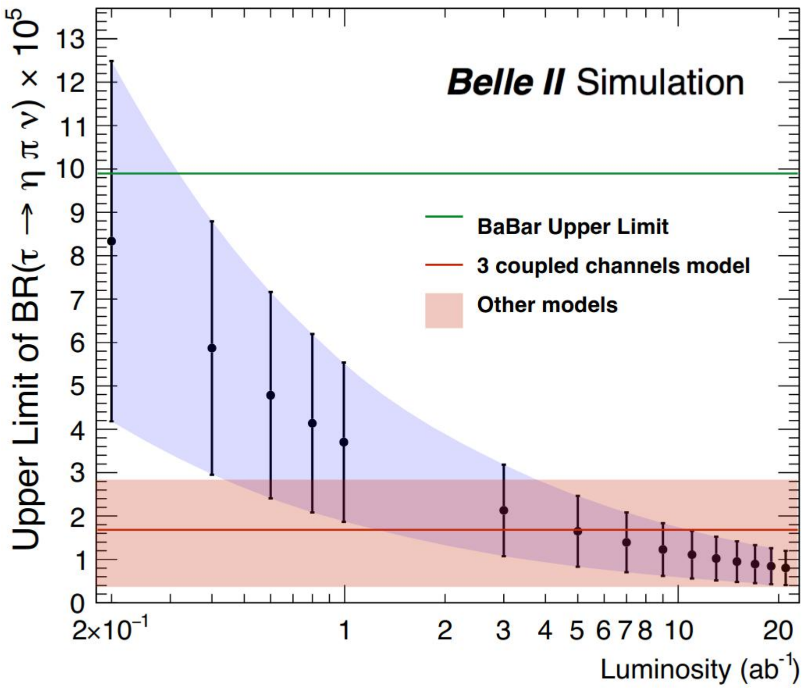


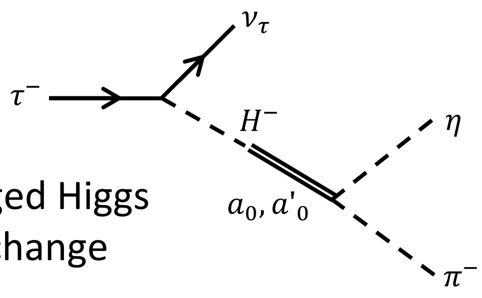
Second-class hadronic currents: τ→πην

- **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.

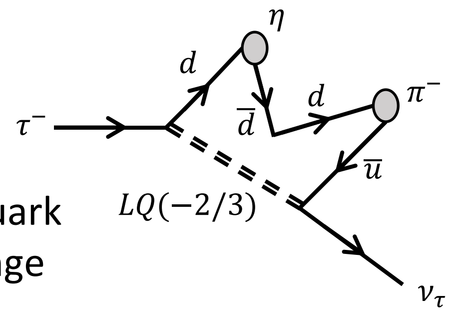


- **τ→πην** violates G-parity, therefore it is a potential probe for new physics.
- The SM predicts: $\mathrm{Br}(\tau \to \pi\eta\nu) \sim 10^{-5}$ A. Pich, Phys. Lett. B 196, 561 (1987)
- Upper limits from two previous experiments:
  - BaBar (470 fb^{-1}): $\mathrm{Br}(\tau \to \pi\eta\nu) < 9.9 \times 10^{-5}$
    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

Belle II

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