Tau physics program at Belle II

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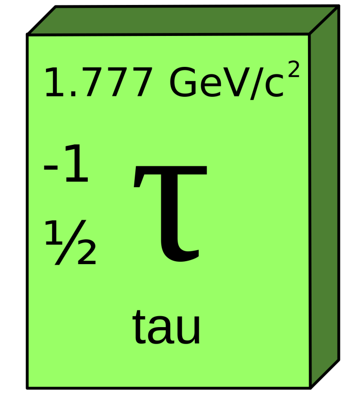
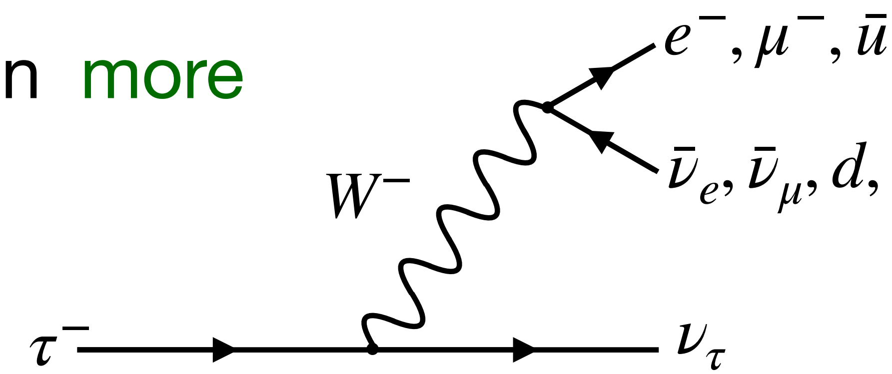
on behalf of the Belle II collaboration

The 2023 International Workshop on the High Energy Circular Electron-Positron Collider

Introduction: why τ lepton?



- τ lepton is the heaviest lepton in the Standard Model (SM) with both leptonic and hadronic decay modes
- Larger mass compared to muon makes τ lepton more sensitive to some models of New Physics (NP)



List of available studies:

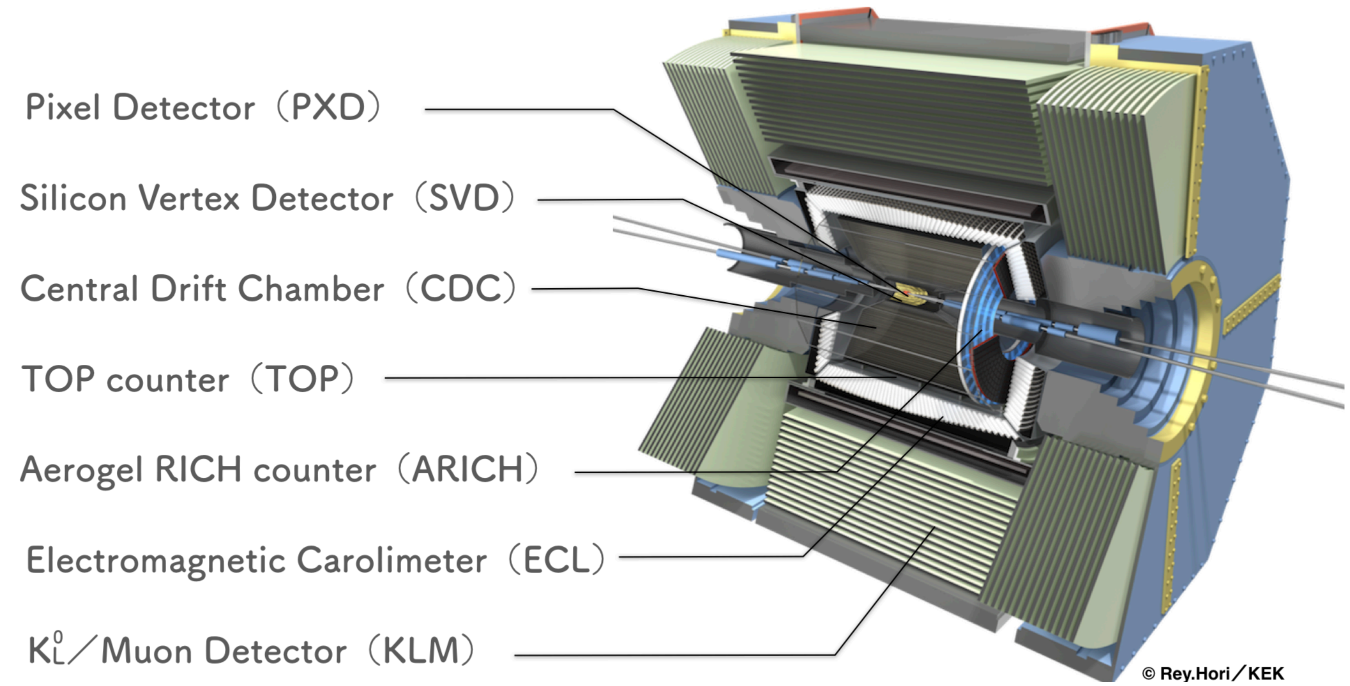
- Precise measurements of properties with CPT tests:
  - Mass
  - Lifetime
  - Electric and Magnetic DM
- Study of pure leptonic decays
  - Lepton flavor universality (LFU)
  - Michel parameters
- Study of hadronic decays
  - QCD at 1 GeV
  - LFU
  - CP violation (CPV)
- Direct search for New Physics
  - Lepton flavor violation (LFV)
  - Invisible particles

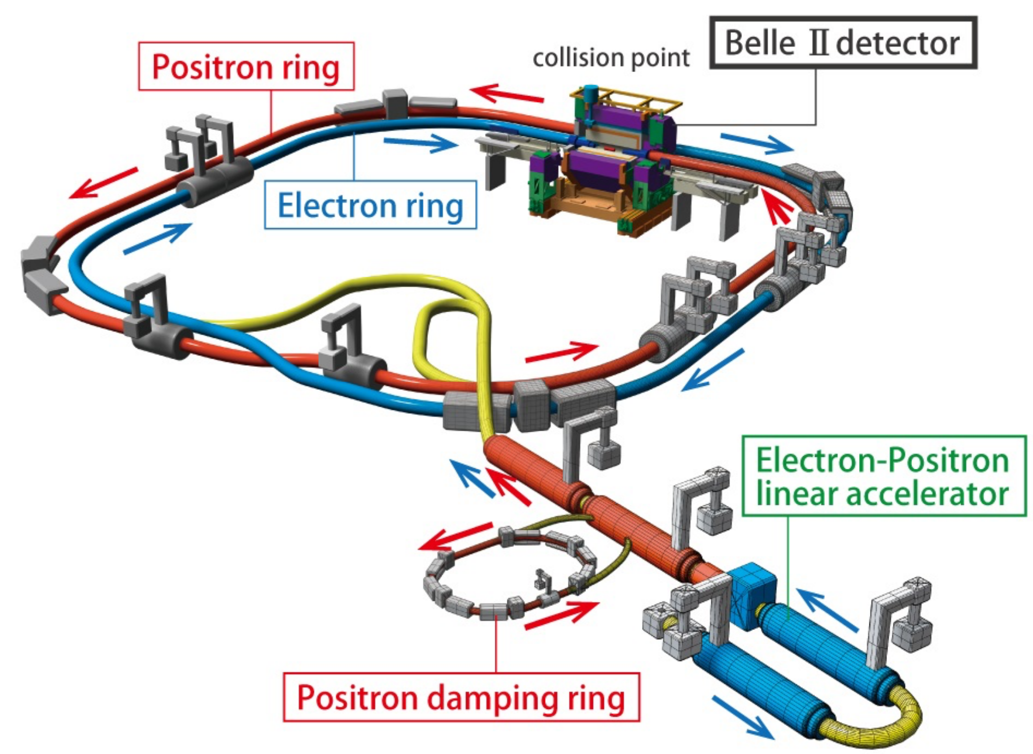
Belle II as a τ factory

- e^+e^- colliders outperform hadron machines in τ physics due to undetectable neutrinos in the final state
- Existing experiments:
  - BES III and KEDR (limited in statistics compared to Belle II)
  - *B*-factories Belle and BaBar (Belle II ancestors) are perfect for the τ lepton studies due to unprecedented tagged $\tau^+\tau^-$ data samples (for the time being, they surpass the Belle II statistics of $\mathscr{L} = 424\,\mathrm{fb}^{-1}$)
- Belle II expects integrated luminosity of $\mathscr{L} = 50\,\mathrm{ab}^{-1}$ (FL) providing 46×10^9 $\tau^+\tau^-$-pairs
- Significant improvements on the trigger for low-multiplicity events

The Future belongs to Belle II

[PTEP 2019 (2019) 12, 123C01]





Mass of the τ lepton

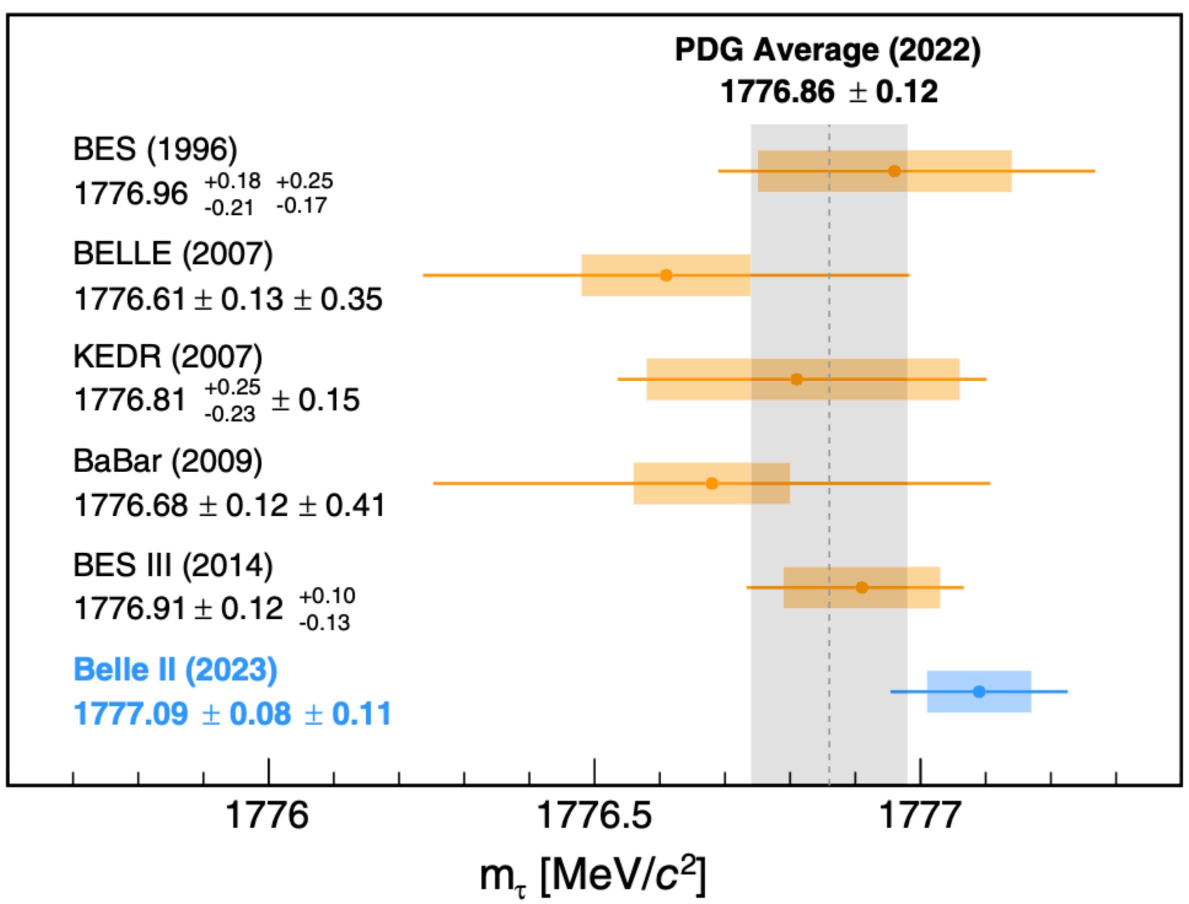
Precision is needed for LFU and $\alpha_s(m_\tau)$

Phys.Rev.D 108 (2023) 032006

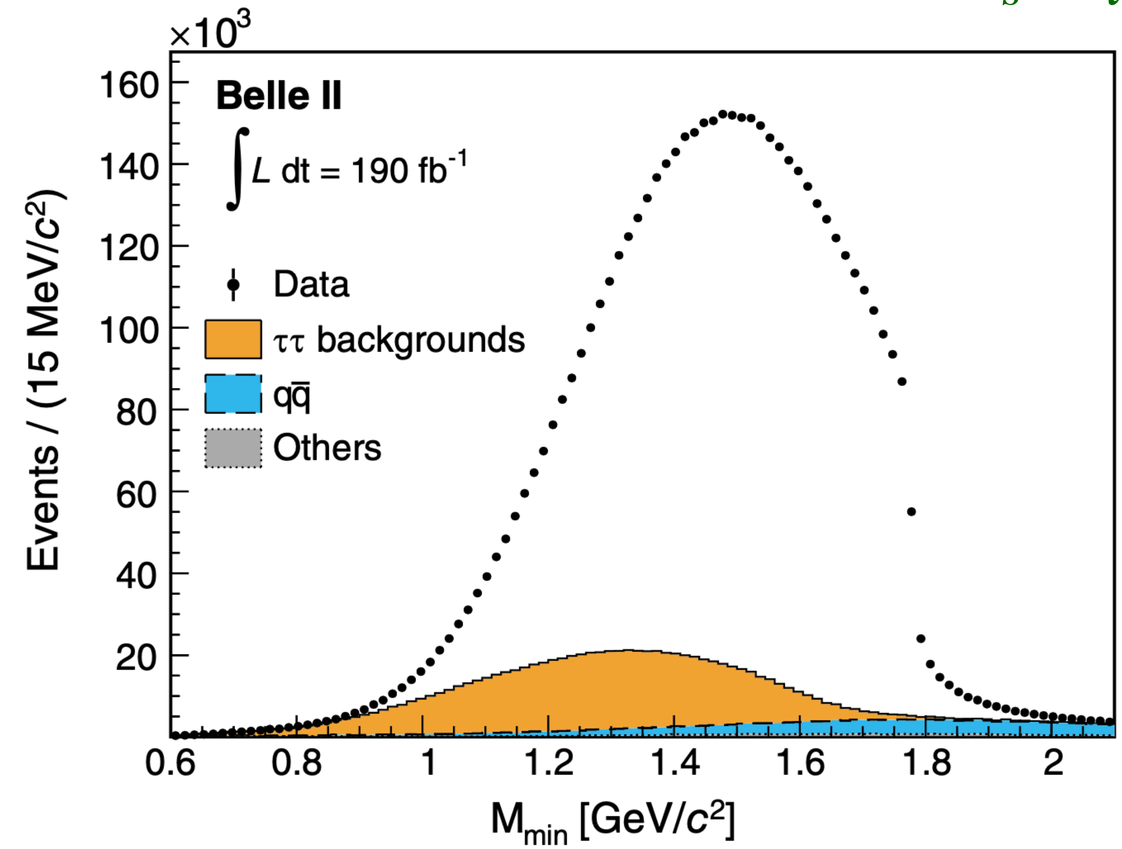
- Belle II in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ ($\mathscr{L} = 190\,\mathrm{fb}^{-1}$)
- Pseudomass method

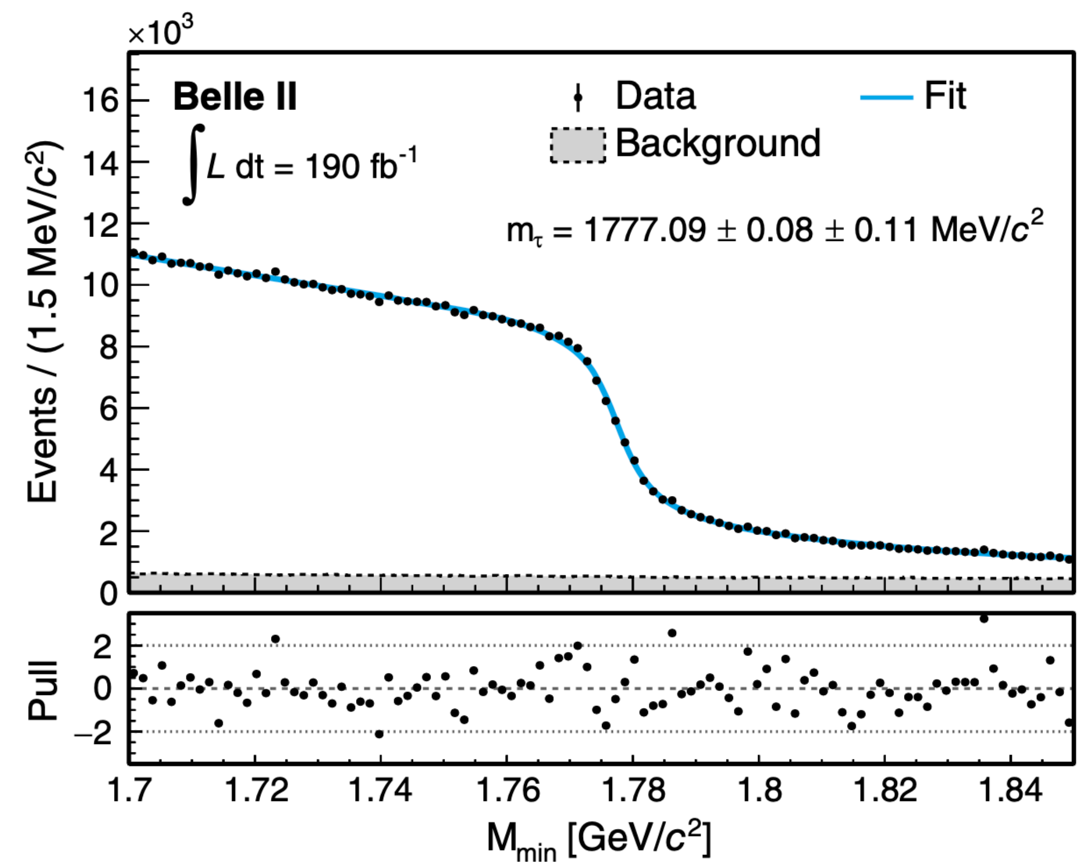
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

Accuracy in $\sqrt{s}$ and p is the key to precision



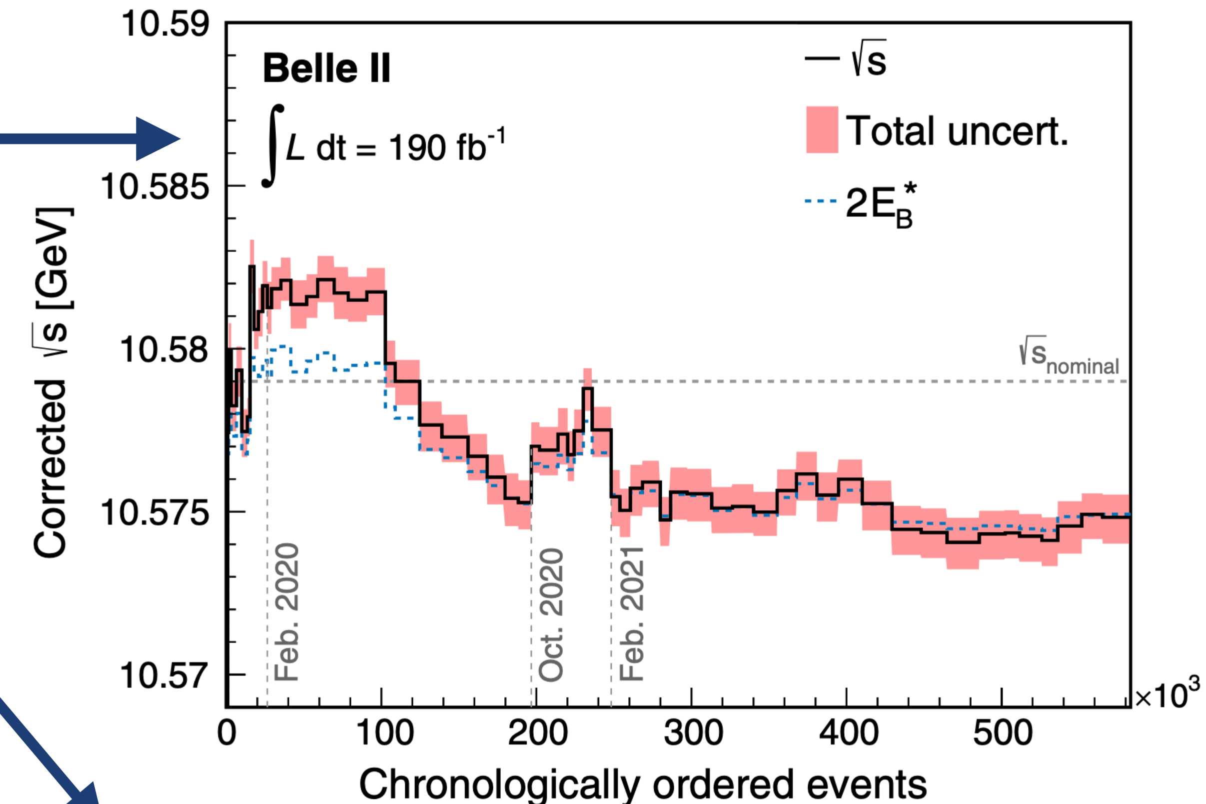
Belle II provides World's most precise result



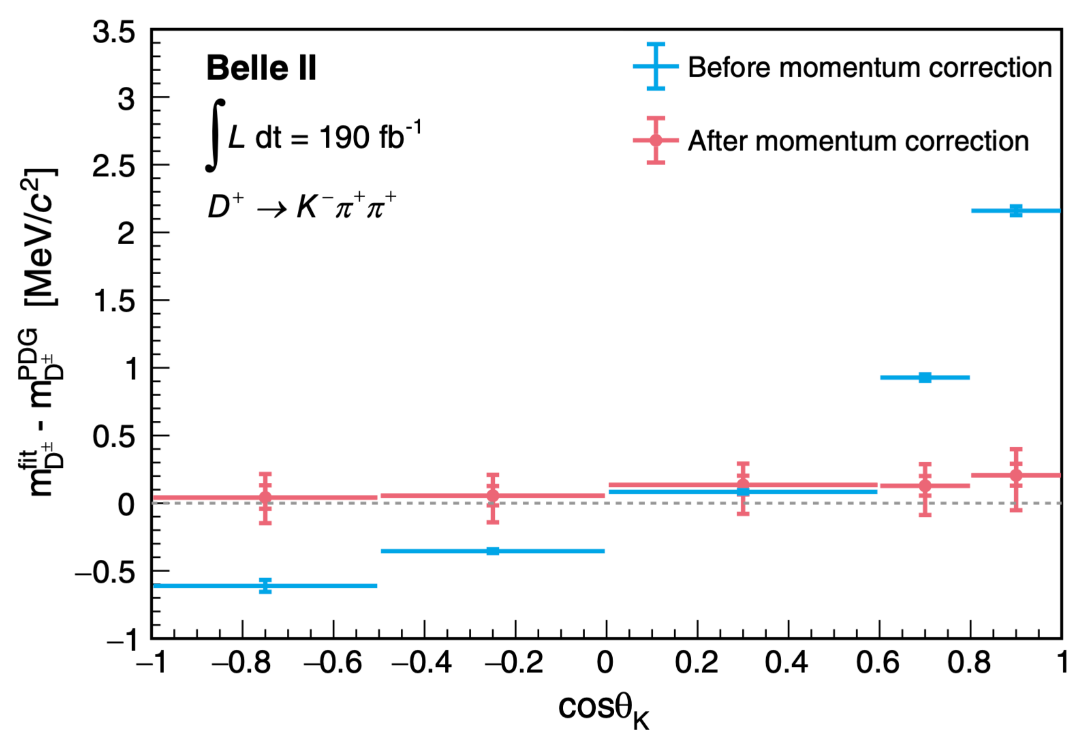


Mass of the τ lepton (2)

- Systematics is crucial in this study
- Beam energy calibration using hadronic $B\bar{B}$-pair decays and $e^+e^- \to B\bar{B}$ cross section
- Charged-particle momentum correction using $D^0 \to K^-\pi^+$ sample with cross-checks in $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$, and $J/\psi \to \mu^+\mu^-$

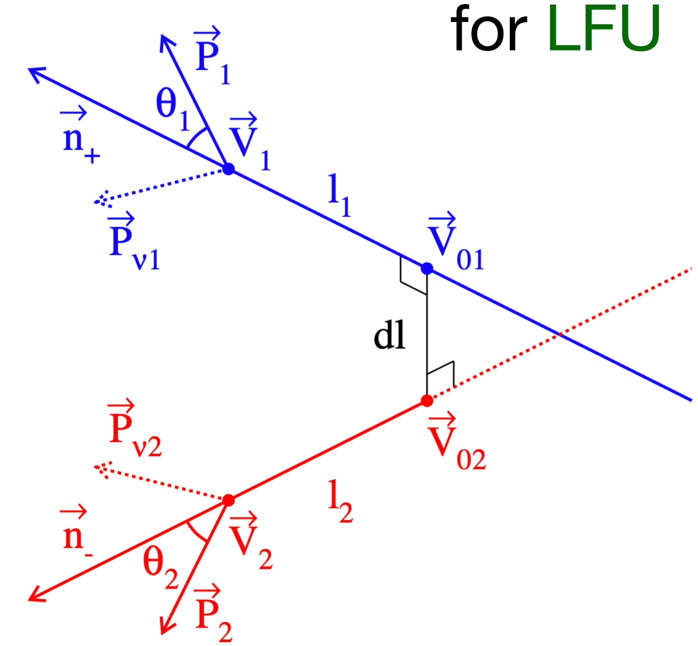


Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	$\leq$ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11



Lifetime of the τ lepton

Precision is needed for LFU

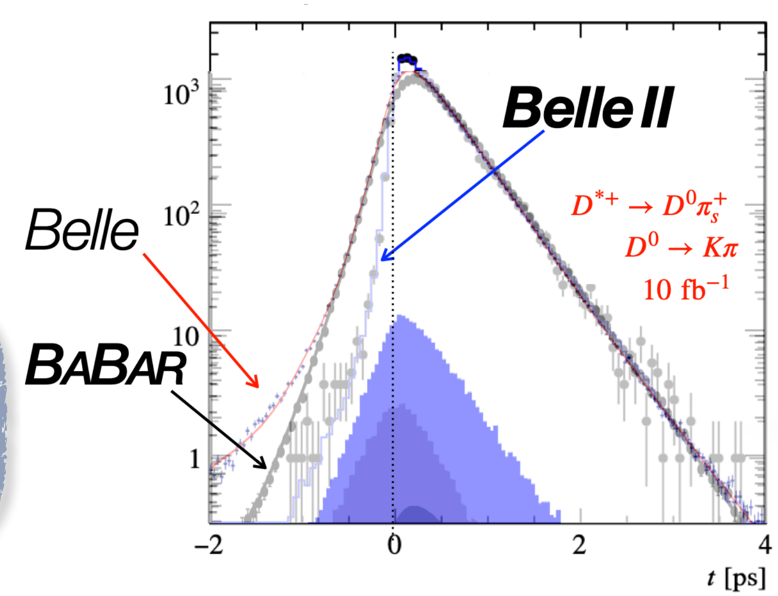


- Boost of the τ lepton in the Laboratory frame is required
- The most precise measurement is done by Belle using $\mathscr{L} = 711\ \mathrm{fb}^{-1}$ in $e^+e^- \to \tau^+\tau^- \to (\pi^+\pi^-\pi^+\bar{\nu}_\tau, \pi^+\pi^-\pi^-\nu_\tau)$:
  $[290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst})] \times 10^{-15}$ s
- The CPT invariance was tested for the first time:
  $|\langle\tau_{\tau^+}\rangle - \langle\tau_{\tau^-}\rangle| / \langle\tau_\tau\rangle < 7.0 \times 10^{-3}$ (90 % CL)

Source	$\Delta\langle\tau\rangle$ (μm)
SVD alignment	0.090
Asymmetry fixing	0.030
Beam energy, ISR and FSR description	0.024
Fit range	0.020
Background contribution	0.010
τ-lepton mass	0.009
Total	0.101

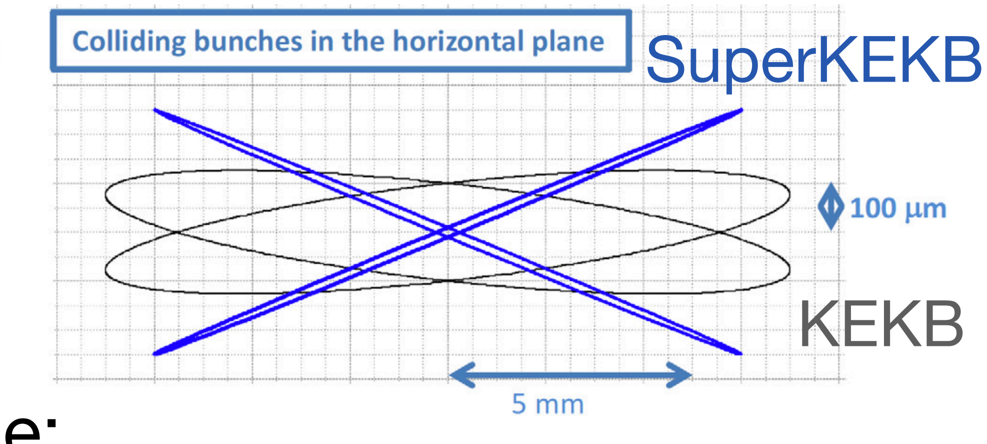
Phys.Rev.Lett. 112 (2014) 031801

- Statistical uncertainty is dominant, and the main systematics source is SVD alignment
- The result can be improved by Belle II with more statistics and better vertex detector



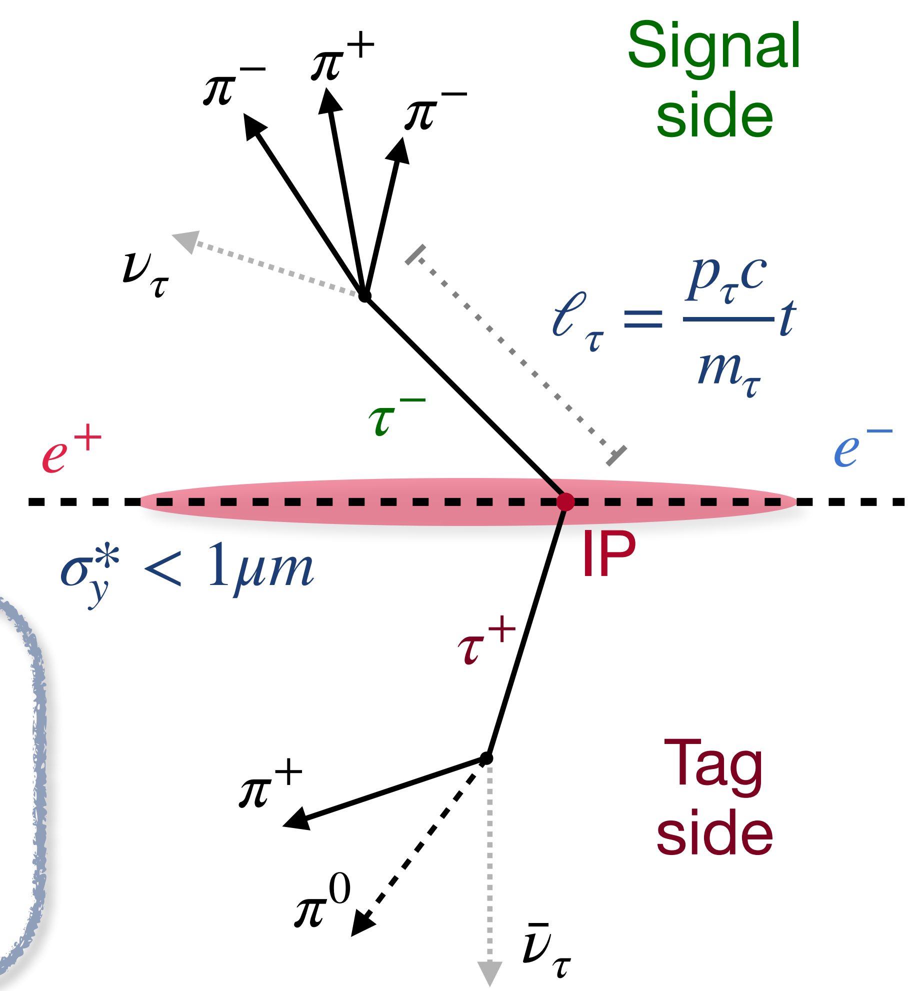
x2 better time resolution (visible at $t < 0$)

Lifetime of the τ lepton: new approach



Nucl.Instrum.Meth.A 907 (2018) 188-199

- SuperKEKB uses nanobeam collision scheme: constraint to the beam-spot can be done
- Second τ-lepton can be reconstructed in one-prong decay mode $\tau^+ \to \rho^+ \bar{\nu}_\tau$: increase in statistics compared to $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$ due to higher branching fraction
- One neutrino mode is still needed for the τ lepton momentum reconstruction
- Competitive results can be obtained with current statistics soon (check the talk by Stefano Moneta at the XXVII Cracow EPIPHANY Conference on Future of particle physics)



EDM and MDM

[1] JHEP 04 (2022) 110
[2] 2207.06307 [hep-ex]
[3] Eur.Phys.J.C 35 (2004) 159-170
[4] JHEP 10 (2019) 089

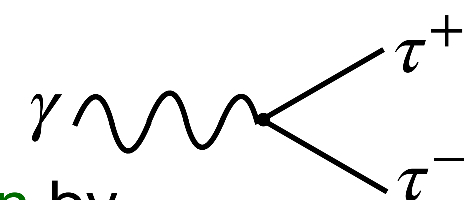
- General expression of the $\tau\tau\gamma$ vertex can be parametrized as follows:

$$-ir\bar{u}(p')\left\{F_1(q^2)\gamma^\mu + iF_2(q^2)\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau} + F_3(q^2)\gamma^5\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau}\right\}u(p)\varepsilon_\mu(q)$$

$$F_1(0) = 1 \qquad F_2(0) = \frac{g_\tau - 2}{2} \equiv a_\tau$$

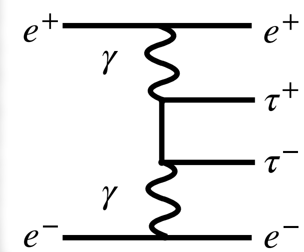
$$F_3(0) = -\frac{2m_\tau d_\tau}{e_\tau}$$

- d_τ – EDM, a_τ – MDM



- In the SM, the first is forbidden by T-invariance, and the second is $a_\tau^{\text{SM}} = 117721(5) \times 10^{-8}$

MDM measurement by DELPHI [3]



Two photon approach is used

$$-0.052 < a_\tau < 0.013\ (95\ \%\ \text{CL})$$

- For EDM, matrix element can be written as $M^2 = M^2_{\text{SM}} + \Re(d_\tau)M^2_{\Re} + \Im(d_\tau)M^2_{\Im} + |d_\tau|^2 M^2_{d^2}$

Belle II (FL) expects $|a_\tau^{\text{NP}}| < 2 \times 10^{-5}$ [4]

EDM measurement by Belle ($\mathscr{L} = 833\ \text{fb}^{-1}$) [1]

Optimal observables are used $O_{\Re} = \frac{M^2_{\Re}}{M^2_{\text{SM}}}, \quad O_{\Im} = \frac{M^2_{\Im}}{M^2_{\text{SM}}}$

$$-1.85 \cdot 10^{-17} < \Re(d_\tau) < 6.1 \cdot 10^{-18}\ e\text{cm}\ (95\ \%\ \text{CL})$$

$$-1.03 \cdot 10^{-17} < \Im(d_\tau) < 2.3 \cdot 10^{-18}\ e\text{cm}\ (95\ \%\ \text{CL})$$

Mode	$\text{Re}(d_\tau)(10^{-17}\ e\text{cm})$	$\text{Im}(d_\tau)(10^{-17}\ e\text{cm})$
$e\mu$	$-3.2 \pm 2.5 \pm 3.6$	$0.6 \pm 0.4 \pm 1.8$
$e\pi$	$0.7 \pm 2.3 \pm 4.8$	$2.4 \pm 0.5 \pm 2.2$
$\mu\pi$	$1.0 \pm 2.2 \pm 4.3$	$2.4 \pm 0.5 \pm 2.6$
$e\rho$	$-1.2 \pm 0.8 \pm 1.0$	$-1.1 \pm 0.3 \pm 0.6$
$\mu\rho$	$0.7 \pm 1.0 \pm 2.2$	$-0.5 \pm 0.3 \pm 0.8$
$\pi\rho$	$-0.6 \pm 0.7 \pm 1.0$	$0.4 \pm 0.3 \pm 1.2$
$\rho\rho$	$-0.4 \pm 0.5 \pm 0.9$	$-0.3 \pm 0.3 \pm 0.4$
$\pi\pi$	$-2.2 \pm 4.3 \pm 5.2$	$-0.9 \pm 0.9 \pm 1.2$

Belle II (FL) expects $|\Re, \Im(d_\tau)| < 10^{-18} - 10^{-19}$ [2]

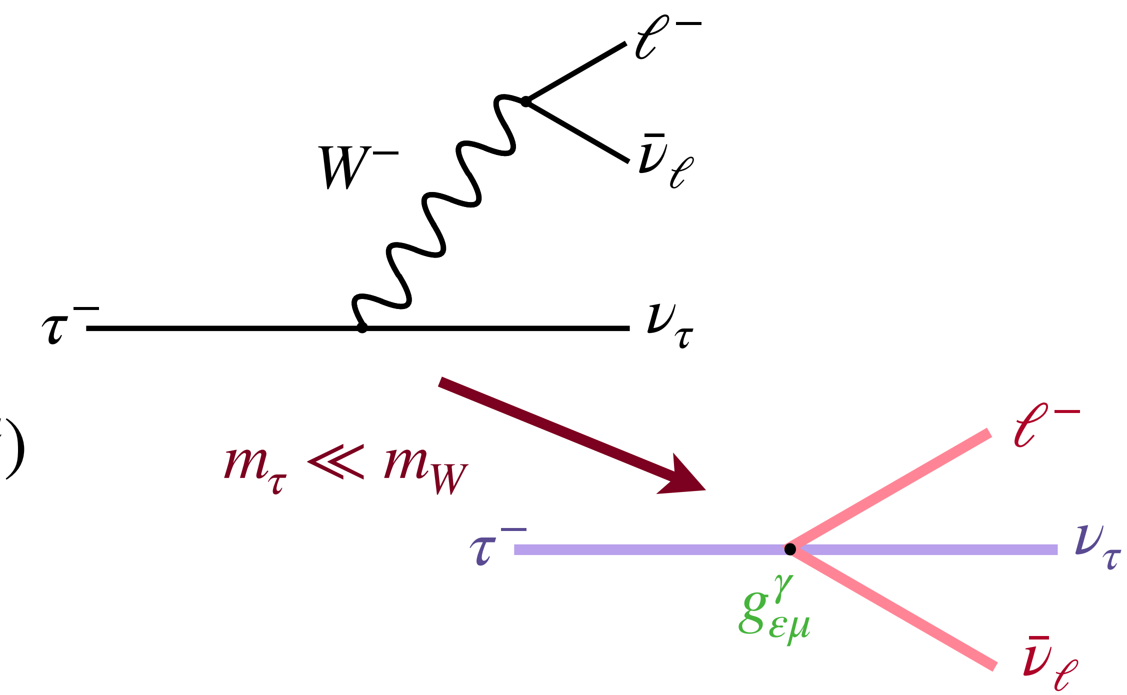
Leptonic decays: Michel parameters

- Michel parameters (MP) of a lepton decay are bilinear combinations of coupling constants arising in the most general expression for the decay matrix element

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma = S,V,T \\ \varepsilon,\mu = R,L}} g^{\gamma}_{\varepsilon\mu} \langle \bar{\ell}_{\varepsilon} | \Gamma^{\gamma} | ((\nu_\ell)_\alpha) \rangle \langle (\bar{\nu}_\tau)_\beta | \Gamma_\gamma | \tau_\mu \rangle$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \frac{1}{\sqrt{2}}\sigma^{\mu\nu} = \frac{i}{2\sqrt{2}}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$$

Scalar Vector Tensor



- Michel parameters describe the Lorentz structure of the charged currents interaction in the theory of weak interaction and can be used to test the SM
- Deviations can be caused by anomalous coupling with the W-boson, new gauge or charged Higgs bosons, presence of massive neutrinos
- The only nonzero term in the SM theory of weak interaction: $g^V_{LL} = 1$

Leptonic decays: Michel parameters (2)

- Differential decay width of τ lepton integrated over neutrino momenta:

$$\frac{d^2\Gamma}{dx\,d\cos\theta} = \frac{m_\tau}{4\pi^3} W_{\ell\tau}^4 G_F^2 \sqrt{x^2 - x_0^2}\,\Big(F_{IS}(x) \pm F_{AS}(x) P_\tau \cos\theta + F_{T_1}(x) P_\tau \sin\theta \zeta_1 + F_{T_2}(x) P_\tau \sin\theta \zeta_2 + (\pm F_{IP}(x) + F_{AP}(x) P_\tau \cos\theta)\zeta_3\Big)$$

$$W_{\ell\tau} = \max E_\ell = \frac{m_\tau^2 + m_\ell^2}{2m_\tau},\ x = \frac{E_\ell}{\max E_\ell},\ x_0 = \frac{m_\ell}{\max E_\ell},\ P_\tau = |\boldsymbol{P}_\tau|$$

Nucl.Part.Phys.Proc. 287-288 (2017)

Functions parameters:

$F_{IS}(x) : \rho, \eta;$

$F_{AS}(x) : \xi, \xi\delta;$

$F_{IP}(x) : \xi', \xi, \xi\delta;$

$F_{AP}(x) : \xi'', \rho, \eta'';$

$F_{T_1}(x) : \xi'', \rho, \eta, \eta'';$

$F_{T_2}(x) : \alpha'/A, \beta'/A$

PTEP 2022 (2022) 083C01

MP (SM)	$\tau \to e\nu_e\nu_\tau$	$\tau \to \mu\nu_\mu\nu_\tau$
$\rho\,(0.75)$	0.747 ± 0.010	0.763 ± 0.020
$\eta\,(0)$	0.013 ± 0.020	0.094 ± 0.073
$\xi\,(1)$	0.994 ± 0.040	1.030 ± 0.059
$\xi\delta\,(0.75)$	0.734 ± 0.028	0.778 ± 0.037
$\xi'\,(1)$	NM	0.22 ± 1.03

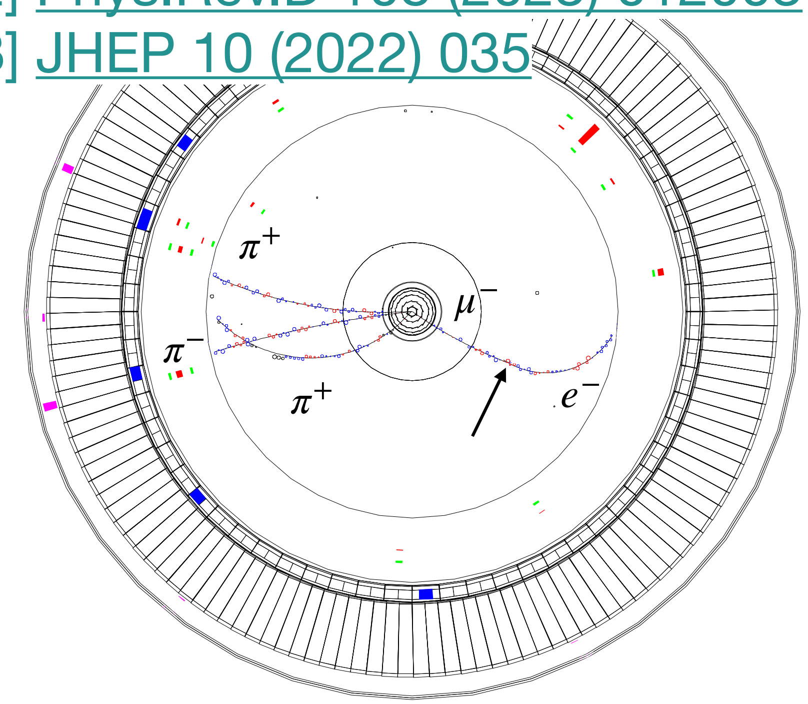
For MP ρ, η, ξ, and $\xi\delta$, Belle has already achieved statistical uncertainty of an order 10^{-3}, but systematics is around 10^{-2}

At Belle II (FL), statistical uncertainties will be of the order 10^{-4}, and the systematic errors will be the dominant one

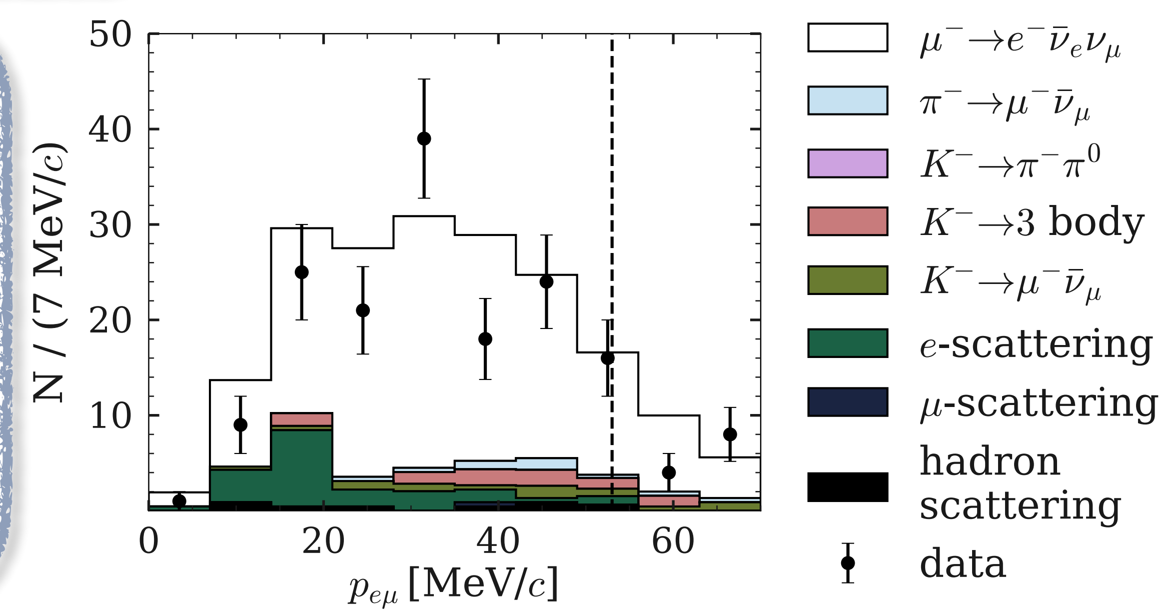
Measurement of the MP ξ' in the $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decay

- The method is based on the muon decay-in-flight reconstruction in the tracker as a kink
- The information about muon spin can be inferred from the daughter electron direction in the muon rest frame due to *P*-violation in the decay
- The first measurement was performed by the Belle collaboration ($\mathscr{L} = 988\,\mathrm{fb}^{-1}$) [1, 2]: $\xi' = 0.22 \pm 0.94(\mathrm{stat}) \pm 0.42(\mathrm{syst})$

[1] Phys.Rev.Lett. 131 (2023) 021801
[2] Phys.Rev.D 108 (2023) 012003
[3] JHEP 10 (2022) 035



- With enlarged CDC, special kink reconstruction algorithm, and record integrated luminosity, Belle II (FL) can improve the statistical uncertainty up to $\sigma_{\xi'} \approx 7 \times 10^{-3}$ [3]
- Systematics can be controlled at the same level with various data samples with kinks



Radiative and five-body leptonic τ decays

- Radiative and five-body leptonic τ-decays provide information about Michel parameters that describe daughter lepton polarization in $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$
- Their understanding is also crucial for LFV studies as they are main background

Radiative leptonic τ-decay

$$\frac{d\Gamma(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma)}{dE_\ell \, d\Omega_\ell \, dE_\gamma \, d\Omega_\gamma} = \left(A_0 + \bar{\eta} A_1\right) + \left(\vec{B}_0 + \xi\kappa \vec{B}_1\right) \cdot \vec{S}_\tau$$

$$\xi\kappa = -1/4(\xi + \xi') + 2/3\xi\delta$$
$$\bar{\eta} = 4/3\rho - 1/4\xi'' - 3/4$$

Belle collaboration measured $\xi\kappa(e) = -0.4 \pm 1.2$, $\xi\kappa(\mu) = 0.8 \pm 0.6$, and $\bar{\eta}(\mu) = -1.3 \pm 1.7$ ($\mathscr{L} = 711\ \text{fb}^{-1}$) PTEP 2018 (2018) 2, 023C01

Belle II can repeat with better precision!

Five-body leptonic τ-decay

Belle estimations for $\mathscr{L} = 700\ \text{fb}^{-1}$

Mode	SM Br	Measured	Expected N	Systematics
$\tau^- \to e^- e^+ e^- \bar{\nu}_e \nu_\tau$	$4.21(1) \times 10^{-5}$	$(1.8 \pm 1.5) \times 10^{-5}$	$1300\ (r_s = 47\%)$	$(6-12)\ \%$
$\tau^- \to \mu^- e^+ e^- \bar{\nu}_e \nu_\tau$	$1.984(4) \times 10^{-5}$	$< 3.2 \times 10^{-5}\ (90\%)$	$430\ (r_s = 50\%)$	$(8-13)\ \%$
$\tau^- \to e^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau$	$1.247(1) \times 10^{-7}$	NM	$8\ (r_s = 37\%)$	$(36-72)\ \%$
$\tau^- \to \mu^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau$	$1.183(1) \times 10^{-7}$	NM	$4\ (r_s = 16\%)$	$(36-72)\ \%$

JHEP 04 (2016) 185 J.Phys.Conf.Ser. 912 (2017) 1

Hadronic decays

- Hadronic decays of τ lepton are unique laboratory to determine $\alpha_s(m_\tau)$, m_s, and V_{us}
- They also can be used for the lepton universality tests: $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to K^- \nu_\tau$ decays are analogous to $\pi^- \to \mu^- \bar{\nu}_\mu$ and $K^- \to \mu^- \bar{\nu}_\mu$

$$R_{\tau/P} = \frac{\Gamma(\tau^- \to P^- \nu_\tau)}{\Gamma(P^- \to \mu^- \bar{\nu}_\tau)} = \left| \frac{g_\tau}{g_\mu} \right|^2 \frac{m_\tau^3}{2 m_P m_\mu^2} \frac{(1 - m_P^2/m_\tau^2)^2}{(1 - m_\mu^2/m_P^2)^2} (1 + \delta R_{\tau/P})$$

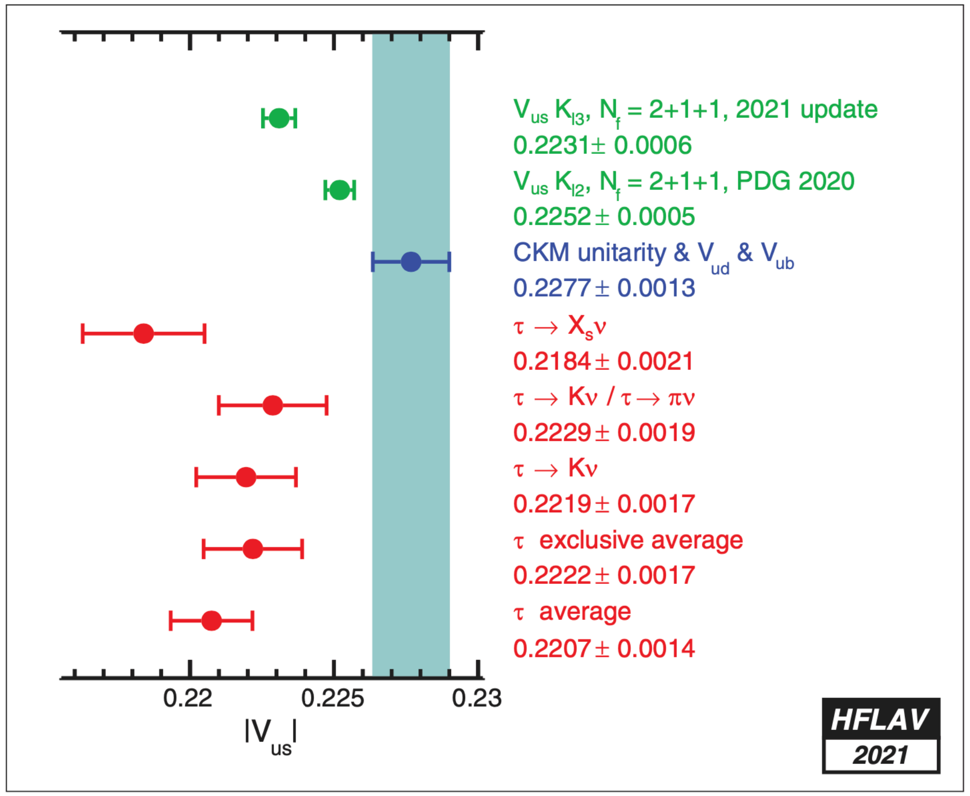
$$\boxed{|g_\tau/g_\mu|_\pi = 0.9959 \pm 0.0038 \quad |g_\tau/g_\mu|_K = 0.9855 \pm 0.0075}$$

- Determination of $|V_{us}|$

$$\frac{|V_{us}| f_K}{|V_{ud}| f_\pi} = \frac{m_\tau^2 - m_\pi^2}{m_\tau^2 - m_K^2} \sqrt{\frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)} \frac{1 + \delta R_{\tau/\pi}}{1 + \delta R_{\tau/K}} \frac{1}{1 + \delta R_{K/\pi}}}$$

$$\boxed{|V_{us}| = 0.2229 \pm 0.0019} \qquad |V_{us}|_{\text{unitarity}} = 0.2277 \pm 0.0013$$

Phys.Rev.D 107 (2023) 052008



Belle II can measure $\Gamma(\tau^- \to \pi^- \nu_\tau)$ and $\Gamma(\tau^- \to K^- \nu_\tau)$ that has not been done at *B*-factories before

Hadronic decays (2)

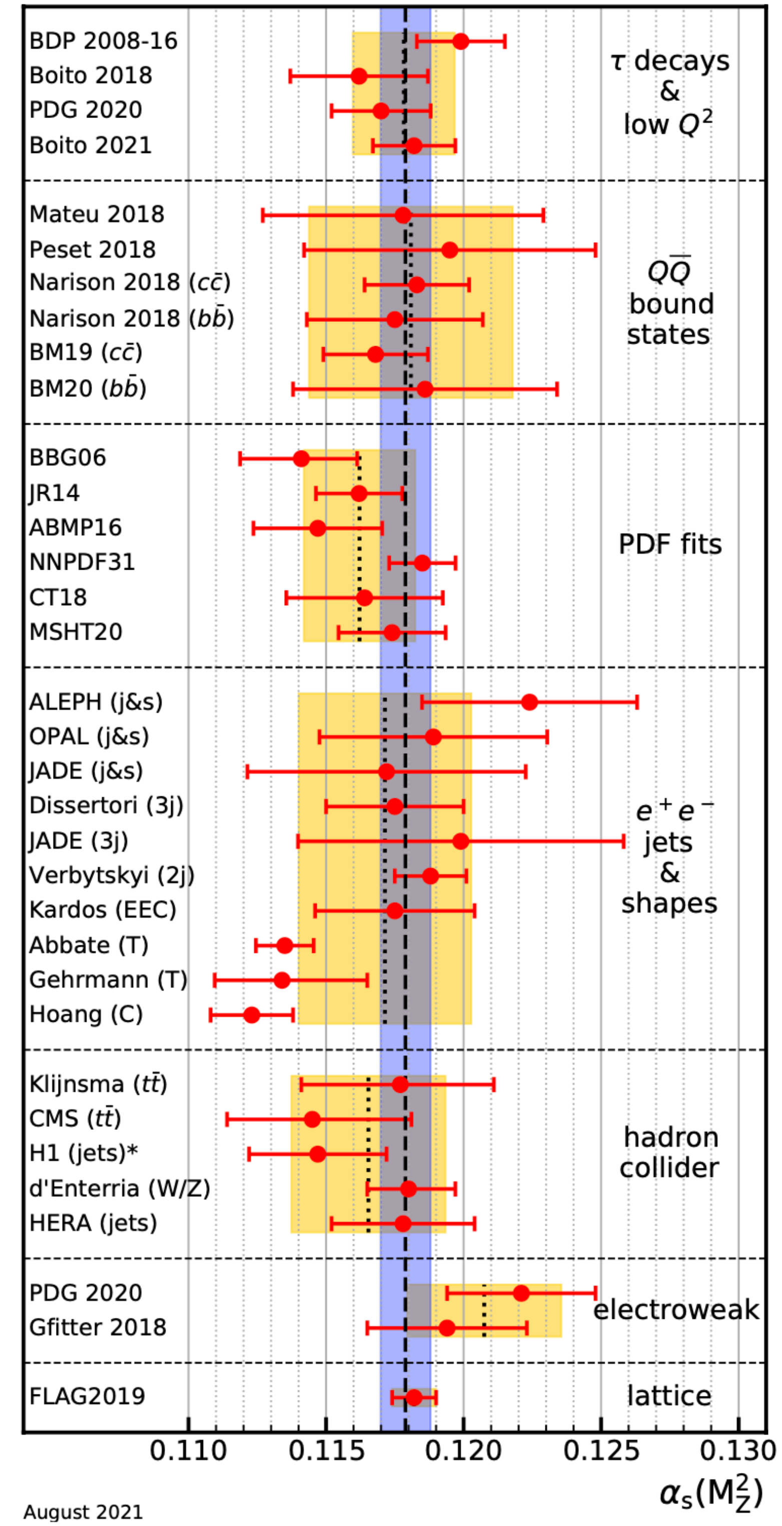
- More precise knowledge of already measured hadron modes is desirable for more accurate determination of α_s and for other studies, where these modes play the role of background

- Higher statistics of Belle II will also allow for observation of various hadron modes not accessible in the previous-generation *B*-factories

- Studies of hadronic modes of τ lepton can be used in the theoretical calculation of the hadronic contribution in the $a_\mu \equiv (g_\mu - 2)/2$

- Belle II can confirm or resolve current deviation of $a_\mu^{\text{had}}(\tau) = (703.0 \pm 4.4) \cdot 10^{-10}$ from $a_\mu^{\text{had}}(e^+e^-) = (692.3 \pm 4.2) \cdot 10^{-10}$

PTEP 2022 (2022) 083C01



CP violation

- No CPV is observed in the charged leptons sector (in the SM, it is predicted only in quarks sector)

- The most promising modes for the studies: $\tau^- \to K^-\pi^0\nu_\tau$, $\tau^- \to K_S^0\pi^-\nu_\tau$, $\tau^- \to K_S^0\pi^-\pi^0\nu_\tau$, $\tau^- \to (\rho\pi)^-\nu_\tau$, $\tau^- \to (\omega\pi)^-\nu_\tau$, and $\tau^- \to (a_1\pi)^-\nu_\tau$

The first measurement of the CP asymmetry was performed by BaBar in $\tau^- \to \pi^- K_S^0 \nu_\tau$:

Phys.Rev.D 85 (2012) 031102

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

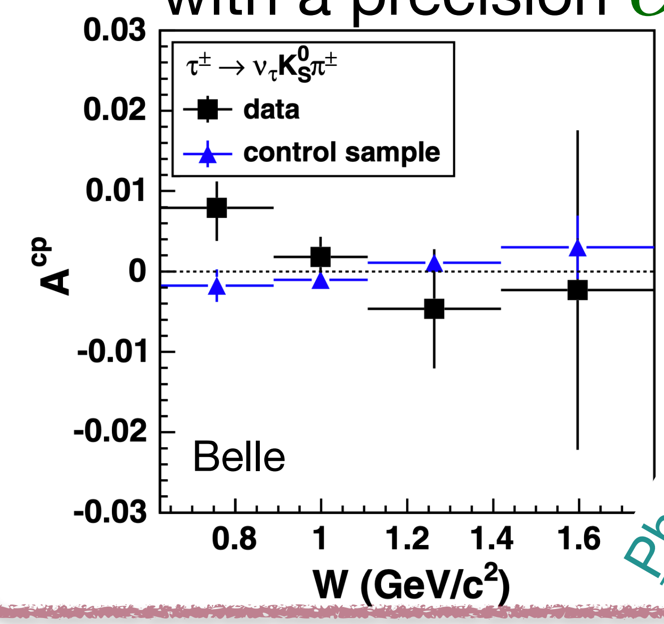
$$A_\tau^{\mathrm{SM}} = (0.36 \pm 0.01)\,\%$$

$$A_\tau = (-0.36 \pm 0.23 \pm 0.11)\,\%$$

- It is also possible to use a modified asymmetry with differential distributions integrated over a limited volume in the phase space with a specially selected kernel (done by Belle)

- More complicated and most powerful method is to use unbinned maximum likelihood fit in the full phase space (not done at *B*-factories)

A^{CP} is compatible with zero with a precision $O(10^{-3})$



Phys.Rev.D 107 (2011) 131801

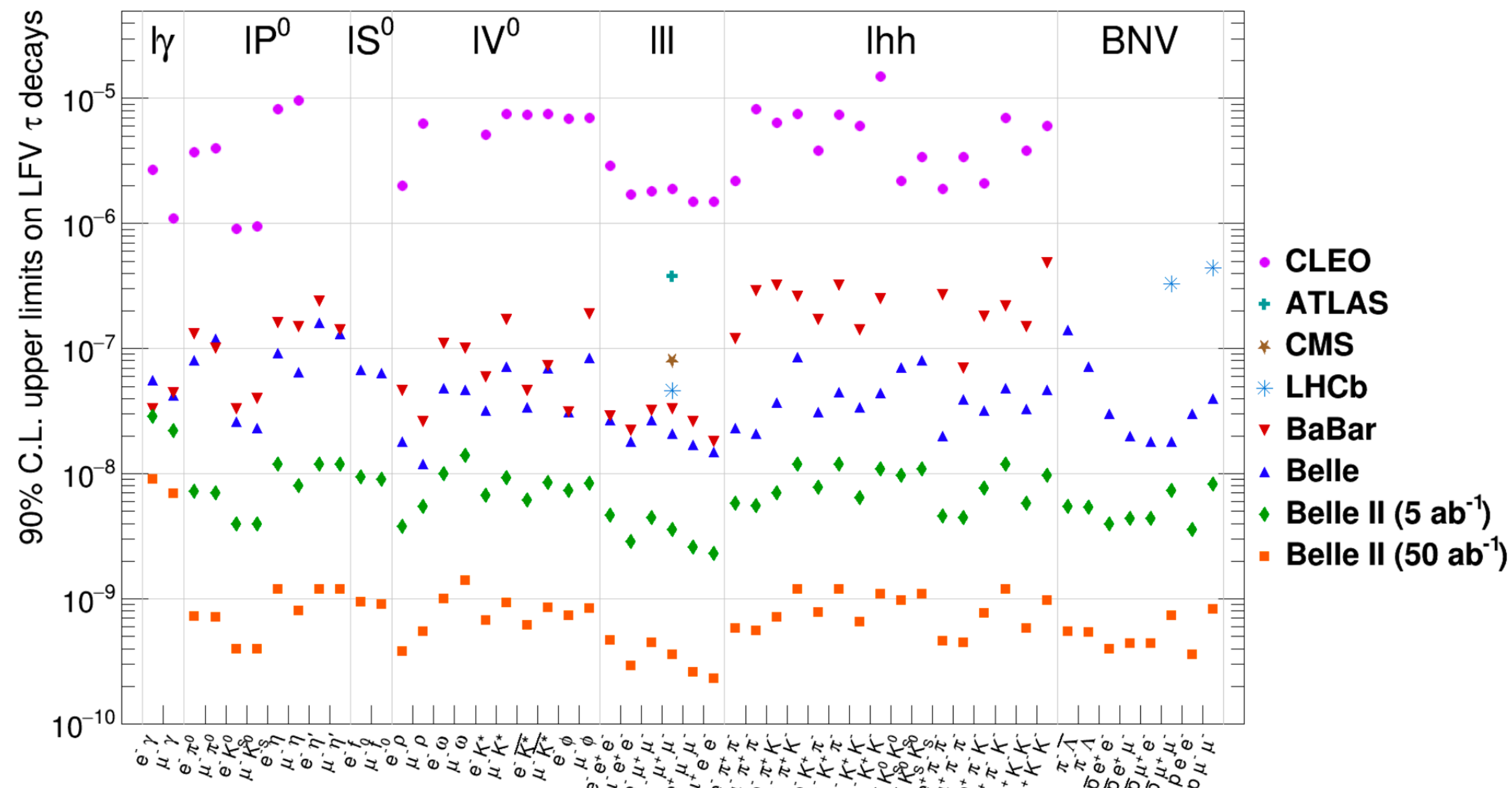
Belle II (FL) can approach the sensitivity level of 10^{-4}

Charged Lepton Flavor Violation in τ decays

2203.14919 [hep-ph]

- Decays $\tau \to \ell\gamma$, $\tau \to \ell\ell\ell^{(\prime)}$, $\tau \to \ell h$ ($\ell, \ell' = e, \mu$ and h is a hadron system), and modes with baryons in the final state are sensitive to New Physics

- Different NP models predict branching fractions of such decays at the level 10^{-7}-10^{-10} (in the SM, $\sim 10^{-53}$ or even forbidden)



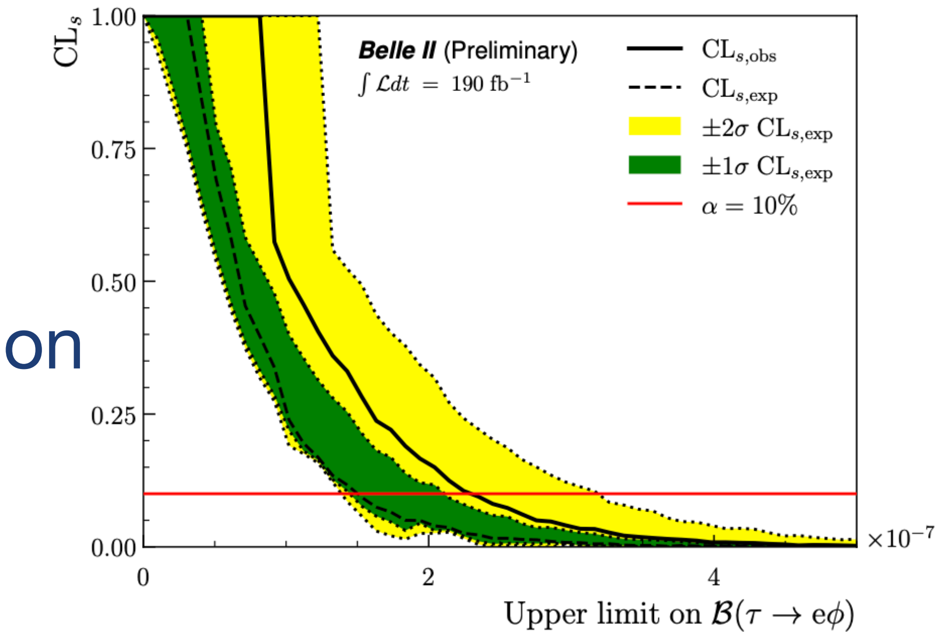
90% CL upper limits for measurements and extrapolation for Belle II from Belle results with respect to $5\,\text{ab}^{-1}$ and $50\,\text{ab}^{-1}$

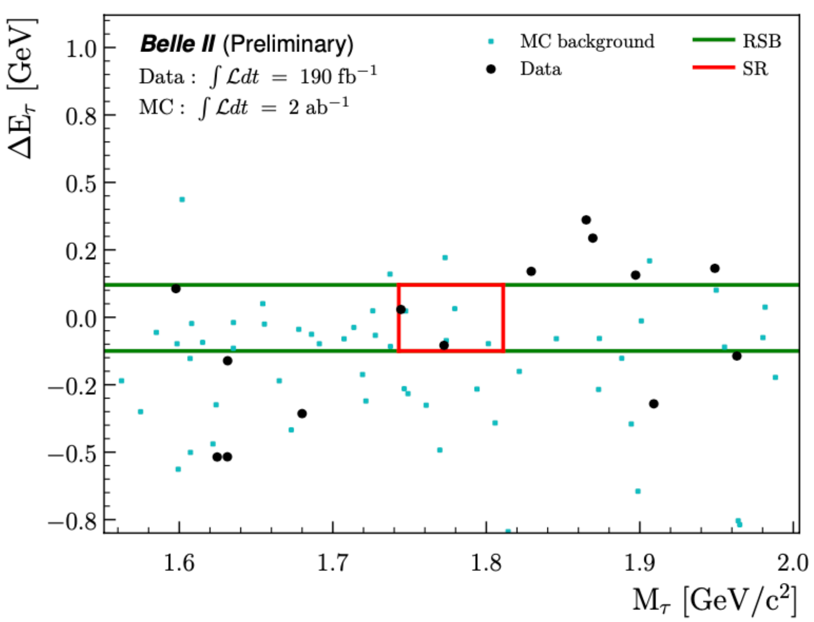
- In the zero-background scenarios, Belle II will improve Belle results linearly with the integrated-luminosity increase (assuming the same analysis efficiency)

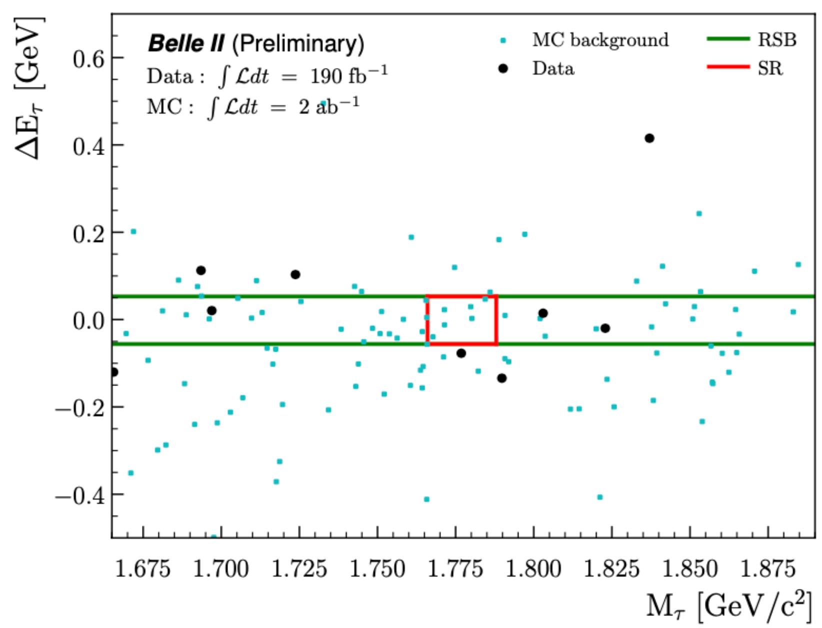
LFV: first result from Belle II

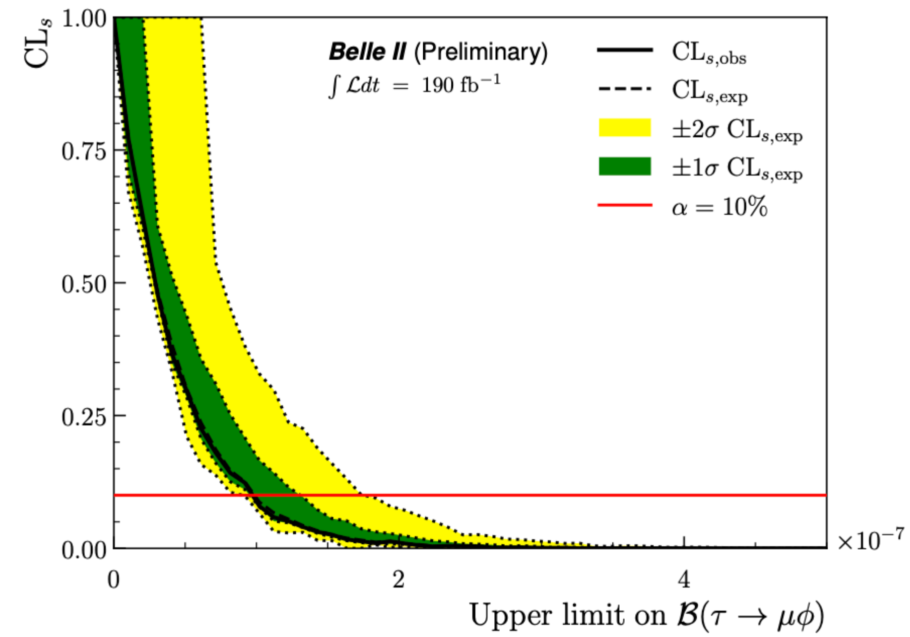
- Search for LFV $\tau^- \to \ell^- \phi$ decays ($\mathscr{L} = 190\,\mathrm{fb}^{-1}$)
- For the first time, untagged approach is used
- Background is suppressed using BDT
- Twice the final signal efficiency improve for muon mode compared to previous studies
- Background is controlled by sidebands in data

2305.04759 [hep-ex]









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Belle

$$\mathscr{B}(\tau^- \to e^-\phi) < 2.0 \times 10^{-8}\,(90\,\%\,\mathrm{CL})$$
$$\mathscr{B}(\tau^- \to \mu^-\phi) < 2.3 \times 10^{-8}\,(90\,\%\,\mathrm{CL})$$

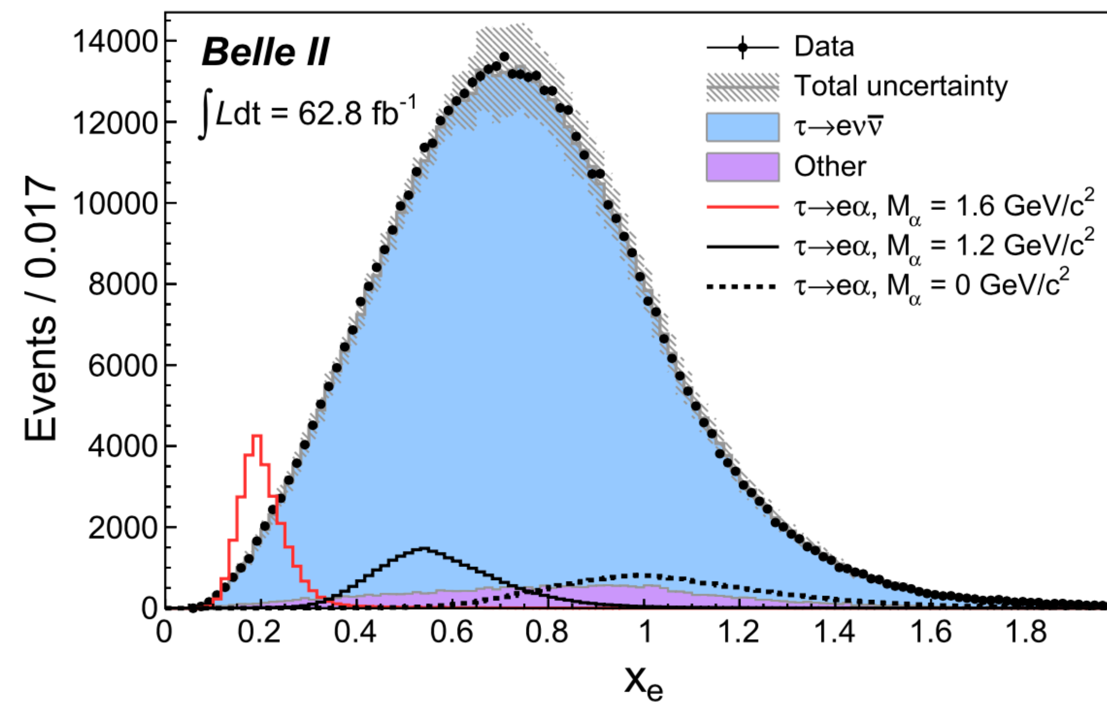
Belle II

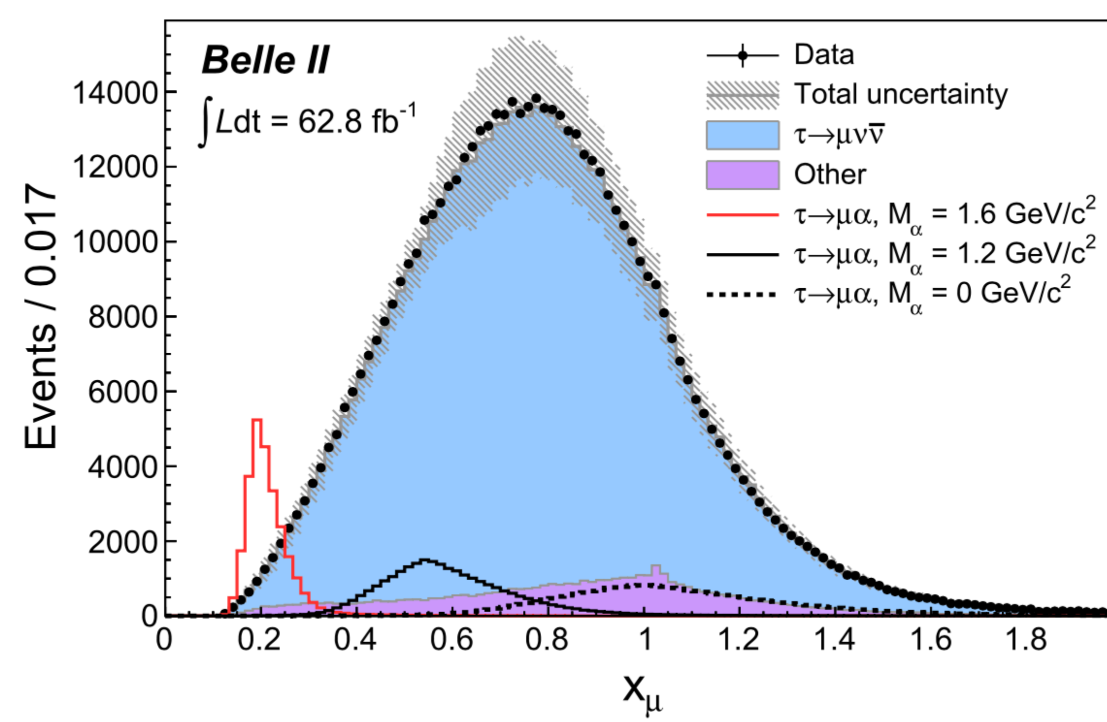
$$\mathscr{B}(\tau^- \to e^-\phi) < 23 \times 10^{-8}\,(90\,\%\,\mathrm{CL})$$
$$\mathscr{B}(\tau^- \to \mu^-\phi) < 9.7 \times 10^{-8}\,(90\,\%\,\mathrm{CL})$$

Search for LFV with Invisible boson

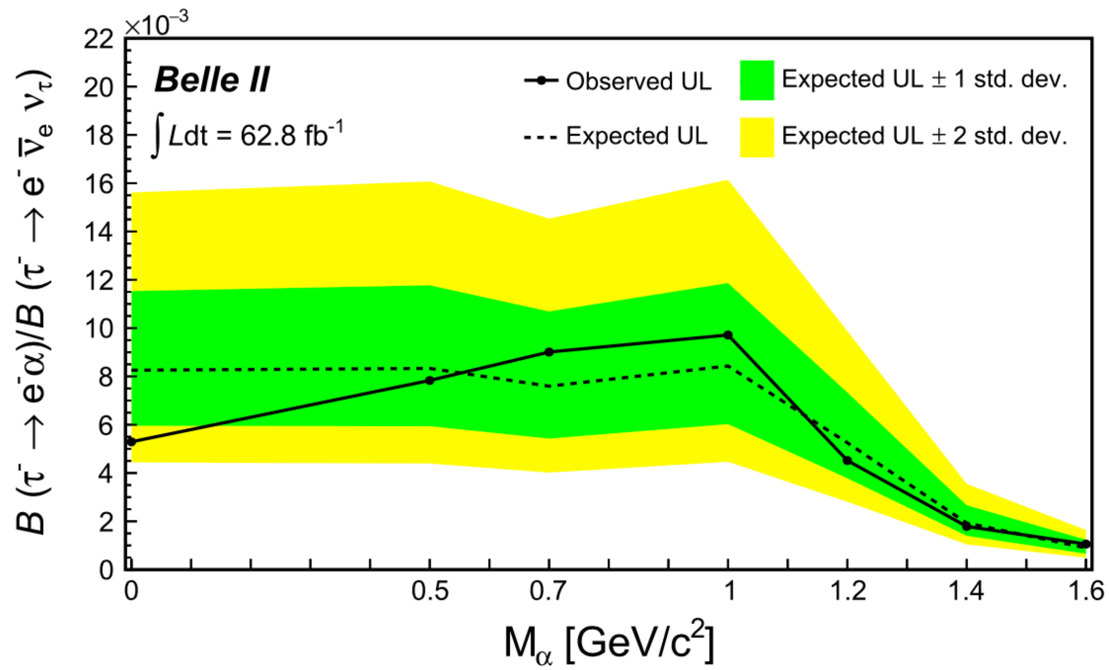
[Phys.Rev.Lett. 130 (2023) 181803]

- Search for LFV $\tau^- \to \ell^- \alpha$ decays, where α is invisible spin-0 boson ($\mathscr{L} = 62.8\,\mathrm{fb}^{-1}$)
- Predicted in models with axionlike particles
- Second τ lepton is reconstructed in $\tau^+ \to h^+ h^- h^+ \bar{\nu}_\tau$ decay mode ($h = \pi, K$)
- Pseudo τ rest frame is used ($\overrightarrow{p}_\tau \sim -\overrightarrow{p}_{3h} / |\overrightarrow{p}_{3h}|$)
- Looked for as an excess above $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ spectrum
- $x_\ell = 2E_\ell / m_\tau$

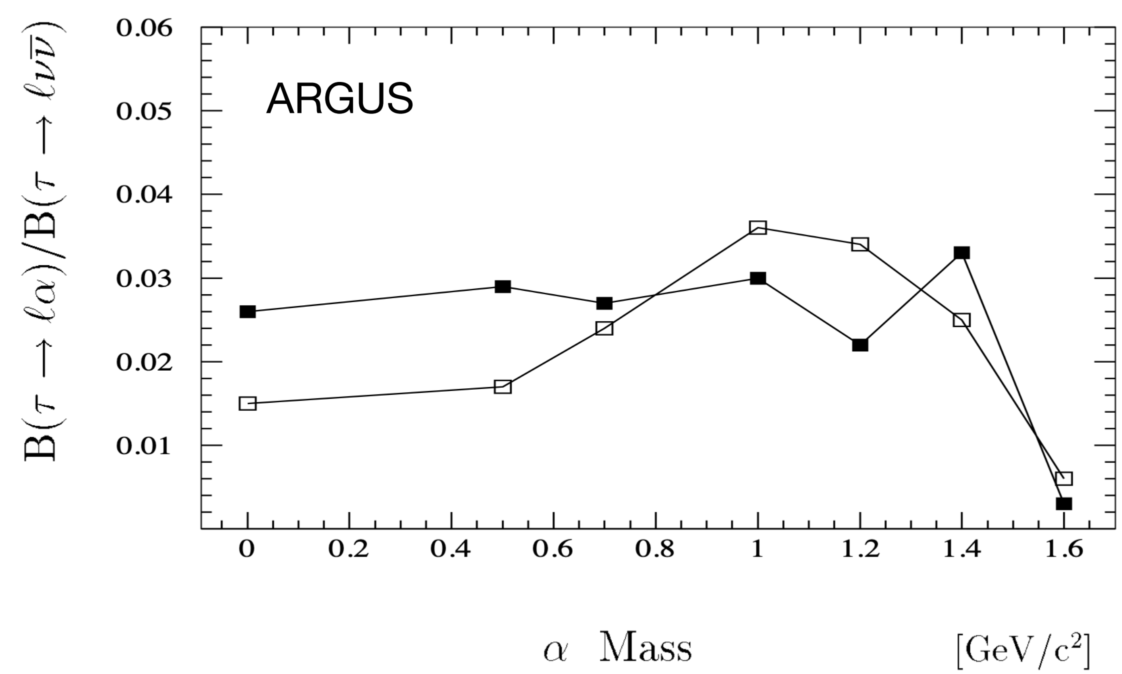


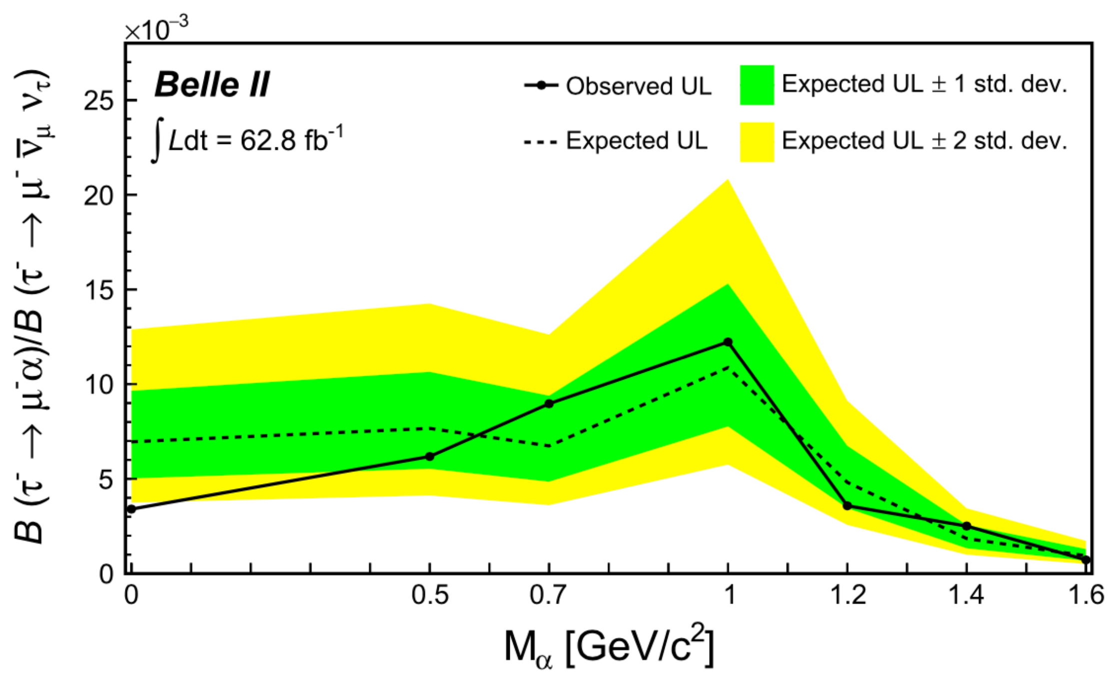


Search for LFV with Invisible boson (2)



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





For massless particle

Argus
$\mathscr{B}(\tau \to e\alpha) < 26 \cdot 10^{-3}$ (95 % CL)
$\mathscr{B}(\tau \to \mu\alpha) < 15 \cdot 10^{-3}$ (95 % CL)

Belle II
$\mathscr{B}(\tau \to e\alpha) < 5.3 \cdot 10^{-3}$ (95 % CL)
$\mathscr{B}(\tau \to \mu\alpha) < 3.4 \cdot 10^{-3}$ (95 % CL)

2.2-14 times more stringent than the best previous bounds

Conclusions

- Although Belle II is still in the beginning of its operation, it has already provided the community with competitive results and new methods applications (τ lepton mass measurement, search for LFV decays $\tau^- \to \ell^- \alpha$ and $\tau^- \to \ell^- \phi$)
- τ physics plays a significant role in the overall program of the Belle II experiment
- It opens up an opportunity to repeat all the measurements done by Belle and BaBar with higher precision and to conduct new studies, not available for the previous generation
- The systematics become the dominant source of uncertainty in many analysis
- By the end of operation, Belle II will accumulate unprecedented number of $\tau^+\tau^-$-pairs, which makes it, without any questions, the Super τ-factory

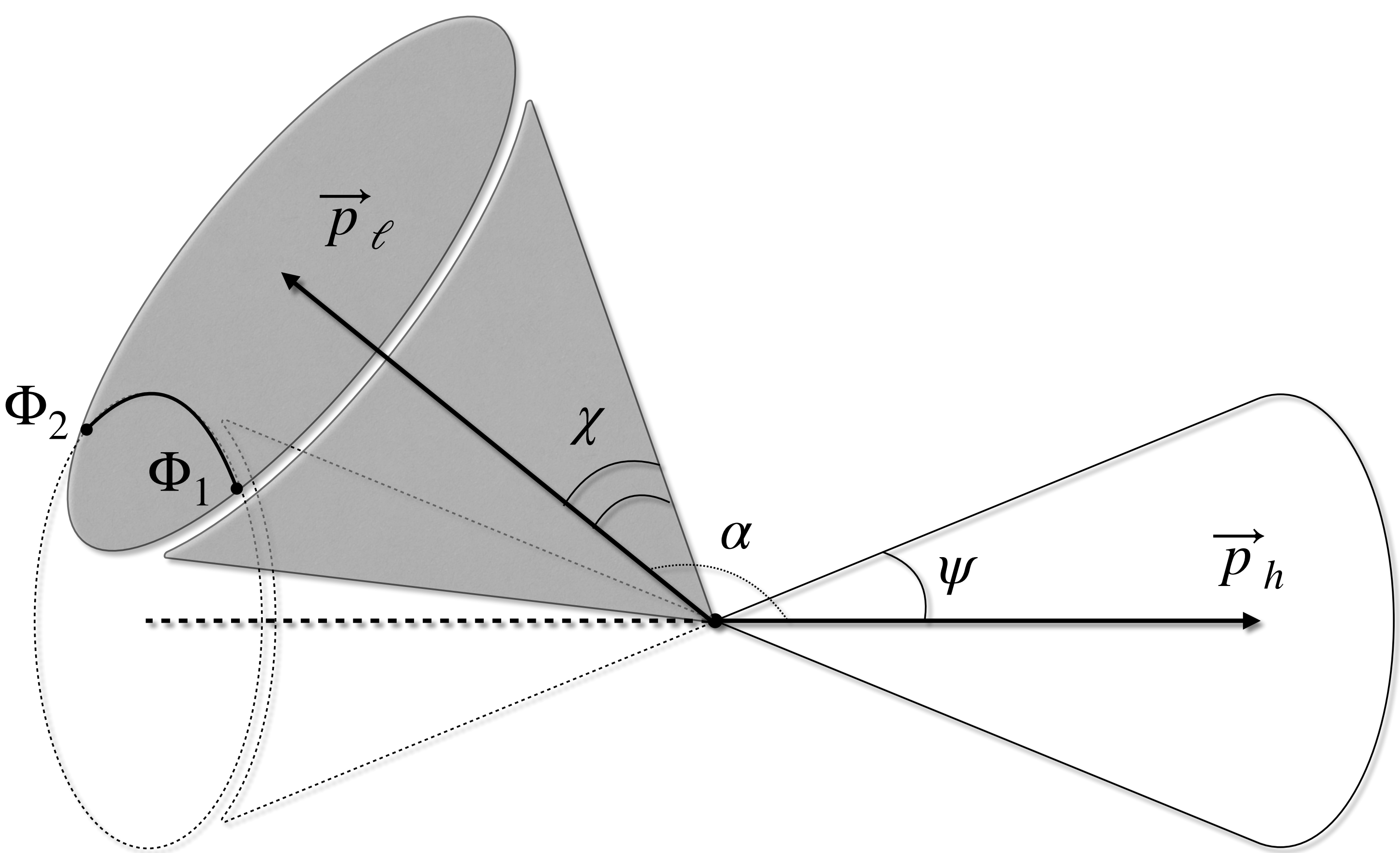
Let's wish the Belle II experiment flourish and prosperous path to the new discoveries!

Thank you for attention!

Backup

τ lepton momentum reconstruction at Belle II

- The momentum of the τ lepton produced in $e^+e^- \to \tau^+\tau^-$ is impossible to reconstruct due to presence of undetectable neutrinos
- Precise knowledge of center-of-mass energy, back-to-back production of $\tau^+\tau^-$-pair, and zero mass (to a high extent) of neutrinos allows to restrict the possible directions of $\tau^+\tau^-$-pair (up to initial-state radiation)



$$\frac{2E_\tau E_\ell - M_\tau^2 - m_\ell^2}{2p_\tau p_\ell} \le \cos\chi \le \frac{E_\tau E_\ell - M_\tau m_\ell}{p_\tau p_\ell}$$

$$\cos\psi = \frac{2E_\tau E_h - M_\tau^2 - m_h^2}{2p_\tau p_h}$$

$$\Phi_1 = \pi + \arcsin\left(\frac{\cos\psi\cos\alpha + \cos\chi}{\sin\psi\sin\alpha}\right)$$

$$\Phi_2 = 2\pi - \arcsin\left(\frac{\cos\psi\cos\alpha + \cos\chi}{\sin\psi\sin\alpha}\right)$$

τ lepton polarization at Belle II

- The beams at Belle II are not polarized, so average τ lepton polarization is zero. Nevertheless, spins of τ leptons are correlated in $e^+e^- \to \tau^+\tau^-$:

$$\frac{d\sigma(e^+e^-(w^-) \to \tau_{\text{sig}}(\vec{s}_{\text{sig}})\tau_{\text{tag}}(\vec{s}_{\text{tag}}))}{d\Omega_\tau} = \frac{\alpha^2\beta}{64E^2}\left[A_0 + D_{ij}(\vec{s}_{\text{sig}})_i(\vec{s}_{\text{tag}})_j\right]$$

$$A_0 = 1 + \cos^2\theta_\tau + \frac{\sin^2\theta_\tau}{\gamma^2} \qquad D_{ij} = \begin{pmatrix} \left(1+\frac{1}{\gamma^2}\right)\sin^2\theta_\tau & 0 & \frac{1}{\gamma}\sin 2\theta_\tau \\ 0 & -\beta^2\sin^2\theta_\tau & 0 \\ \frac{1}{\gamma}\sin 2\theta_\tau & 0 & 1+\cos^2\theta_\tau - \frac{\sin^2\theta_\tau}{\gamma^2} \end{pmatrix}$$

- One can use tagging τ lepton as a spin analyzer with the decay mode $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$. This mode has the largest branching fraction (around $25\,\%$), and it is also well-studied

Leptonic differential decay width parametric functions definition

$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$F_{AS}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 3 - \frac{x_0^2}{2}\right)\right]$$

$$F_{IP}(x) = \frac{1}{54}\sqrt{x^2 - x_0^2}\left[-9\xi'\left(2x - 3 + \frac{x_0^2}{2}\right) + 4\xi\left(\delta - \frac{3}{4}\right)\left(4x - 3 - \frac{x_0^2}{2}\right)\right]$$

$$F_{AP}(x) = \frac{1}{6}\left[\xi''\left(2x^2 - x - x_0^2\right) + 4\left(\rho - \frac{3}{4}\right)\left(4x^2 - 3x - x_0^2\right) + 2\eta'' x_0(1-x)\right]$$

$$F_{T_1}(x) = -\frac{1}{12}\left[2\left(\xi'' + 12\left(\rho - \frac{3}{4}\right)\right)(1-x)x_0 + 3\eta(x^2 - x_0^2) + \eta''(3x^2 - 4x + x_0^2)\right]$$

$$F_{T_2}(x) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left(3\frac{\alpha'}{A}(1-x) + \frac{\beta'}{A}(2 - x_0^2)\right)$$

MP parameters through coupling constants

$$\rho = \frac{3}{4} - \frac{3}{4}\left[\left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right) + \Re\left\{g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR}\right\}\right]$$

$$\eta = \frac{1}{2}\Re\left\{g^V_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right) + g^V_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right) + \left(g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right)\right\}$$

$$\xi = 4\Re\left\{g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL}\right\} + \left(|g^V_{LL}|^2 - |g^V_{RR}|^2\right) + 3\left(|g^V_{LR}|^2 - |g^V_{RL}|^2\right)$$
$$+5\left(|g^T_{LR}|^2 - |g^T_{RL}|^2\right) + \frac{1}{4}\left(|g^S_{LL}|^2 - |g^S_{RR}|^2 + |g^S_{RL}|^2 - |g^S_{LR}|^2\right)$$

$$\xi\delta = \frac{3}{16}\left(|g^S_{LL}|^2 - |g^S_{RR}|^2 + |g^S_{RL}|^2 - |g^S_{LR}|^2\right) + \frac{3}{4}\left(|g^V_{LL}|^2 - |g^V_{RR}|^2 - |g^T_{LR}|^2\right.$$
$$\left. + |g^T_{RL}|^2 + \Re\left\{g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL}\right\}\right)$$

MP parameters through coupling constants (2)

$$\xi' = -\left[3\left(|g^T_{RL}|^2 - |g^T_{LR}|^2\right) + \left(|g^V_{RR}|^2 + |g^V_{RL}|^2 - |g^V_{LR}|^2 - |g^V_{LL}|^2\right)\right.$$
$$\left. + \frac{1}{4}\left(|g^S_{RR}|^2 + |g^S_{RL}|^2 - |g^S_{LR}|^2 - |g^S_{LL}|^2\right)\right]$$

$$\xi'' = 1 - \frac{1}{2}\left(|g^S_{RL}|^2 + |g^S_{LR}|^2\right) + 2\left(|g^V_{RL}|^2 + |g^V_{LR}|^2 + |g^T_{RL}|^2 + |g^T_{LR}|^2\right)$$
$$+4\Re\left\{g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR}\right\}$$

$$\eta'' = \frac{1}{2}\Re\left\{3g^V_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right) + 3g^V_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right) - \left(g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right)\right\}$$

$$\frac{\alpha'}{A} = \frac{1}{2}\Im\left\{g^V_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right) - g^V_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right)\right\}$$

$$\frac{\beta'}{A} = \frac{1}{4}\Im\left\{g^V_{RR}g^{S*}_{LL} - g^V_{LL}g^{S*}_{RR}\right\}$$

Five-body leptonic τ-decays branching fractions

J.Phys.Conf.Ser. 912 (2017) 1

$$BR_{\rm exp}^{\tau^-\to e^-e^+e^-\bar\nu_e\nu_\tau} = BR_{\rm SM}^{\tau^-\to e^-e^+e^-\bar\nu_e\nu_\tau}\{[Q_{LL} + (1.051\pm0.036)Q_{LR} + (-0.2053\pm0.1431)B_{LR} + L\leftrightarrow R] + (0.2416\pm0.0002)I_\alpha + (0.8606\pm0.0001)I_\beta\}.$$

$$BR_{\rm exp}^{\tau^-\to \mu^-e^+e^-\bar\nu_\mu\nu_\tau} = BR_{\rm SM}^{\tau^-\to \mu^-e^+e^-\bar\nu_\mu\nu_\tau}\{[Q_{LL} + (1.220\pm0.049)Q_{LR} + (-0.8717\pm0.1957)B_{LR} + L\leftrightarrow R] + \underline{(181.3\pm0.1)I_\alpha + (104.4\pm0.1)I_\beta}\}.$$

$$BR_{\rm exp}^{\tau^-\to e^-\mu^+\mu^-\bar\nu_e\nu_\tau} = BR_{\rm SM}^{\tau^-\to e^-\mu^+\mu^-\bar\nu_e\nu_\tau}\{[Q_{LL} + (1.226\pm0.001)Q_{LR} + (-0.8456\pm0.0001)B_{LR} + L\leftrightarrow R] + (0.2253\pm0.0001)I_\alpha + (0.5231\pm0.0001)I_\beta\}.$$

$$BR_{\rm exp}^{\tau^-\to \mu^-\mu^+\mu^-\bar\nu_\mu\nu_\tau} = BR_{\rm SM}^{\tau^-\to \mu^-\mu^+\mu^-\bar\nu_\mu\nu_\tau}\{[Q_{LL} + (1.216\pm0.005)Q_{LR} + (-0.8459\pm0.0005)B_{LR} + L\leftrightarrow R] - (18.00\pm0.01)I_\alpha + (197.3\pm0.1)I_\beta\}.$$

- Underlined part is the most sensitive to Michel parameters: $I_\alpha = 2(\alpha + i\alpha')/A$ and $I_\beta = -2(\beta + i\beta')/A$. Here $\eta = (\alpha - 2\beta)/A$ and $\eta'' = (3\alpha + 2\beta)/A$
- Here an alternative Michel-like parametrization from Phys.Lett.B 173 (1986) 102-106 is used