Tau and Low Multiplicity at Belle and Belle II

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on behalf of the Belle II collaboration

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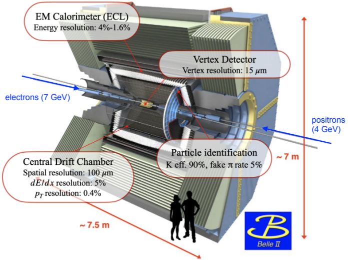
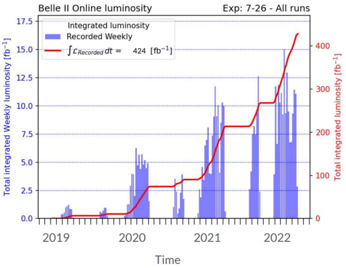
58th Rencontres de Moriond
QCD & High Energy Interactions

March 21, 2024

- B factories offer clean environment to study τ and low-multiplicity physics
  - Well defined initial state
  - No pile up
  - Hermetic detectors allows precise determination of missing energy $\&$ momentum
- Belle II operates since 2018:
  - Excellent particle identification
  - High efficiency neutral reconstruction
  - Dedicated low multiplicity triggers
- Finished run1 data-taking in 2023:
  - 424 fb^{-1} on tape
  - **362 fb^{-1}** @ $\Upsilon(4S)$

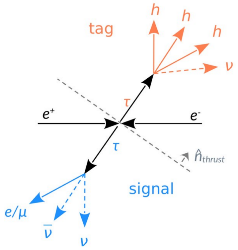


[Belle II TDR: arXiv:1011.0352]

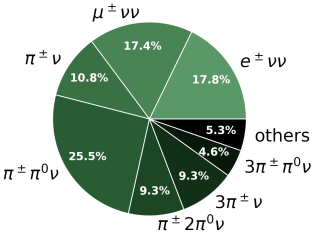


- $\sigma(ee \to bb) \simeq 1.1$ nb
- $\sigma(ee \to \tau\tau) \simeq 0.9$ nb
  - ↪ Belle II is not just B factory, but also τ factory!
  - ▶ $\sim 4 \cdot 10^8$ τ pairs recorded in run1 data
- $\tau\tau$ events are characterized by low track multiplicities and large missing energies
- Identify τ events by reconstructing thrust axis
  - ▶ Separate into hemispheres

$$V_{\text{thrust}} \overset{\max}{=} \frac{\sum_i |\vec{p}_i^{\,\text{CM}} \cdot \hat{n}_{\text{thrust}}|}{\sum_i |\vec{p}_i^{\,\text{CM}}|}$$



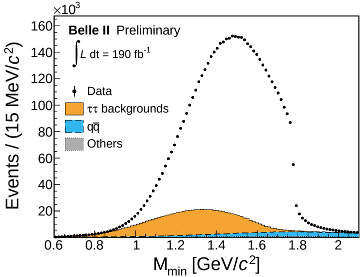
  - ▶ Use one side to tag by reconstructing 1-prong or 3-prong decays
  - ▶ Reconstruct signal on other hemisphere



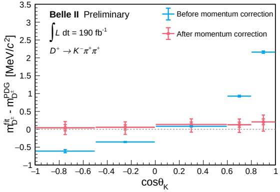
[Phys. Rev. D 108, 032006]

- Precise determination of m_τ with $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ in $\mathcal{L} = 190\ \mathrm{fb}^{-1}$
  - Fundamental parameter, important input e.g. for LFU tests
- Pseudomass method:

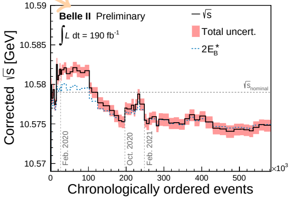
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} < m_\tau$$



- Challenge:
  - High accuracy in p and $\sqrt{s}$
  - p : calibrate track momentum correction with $D^0 \to K^-\pi^+$
  - $\sqrt{s}$: calibrate using B decays

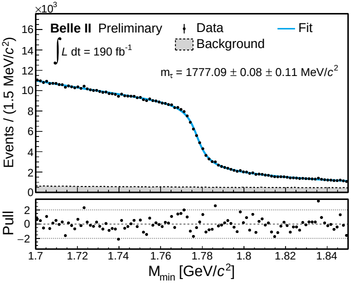


$D^0 \to K^-\pi^+\pi^+$ validation



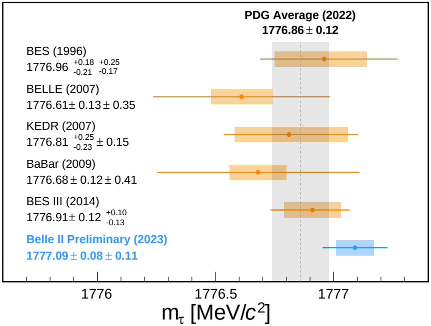
τ mass measurement

[Phys. Rev. D 108, 032006]



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	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

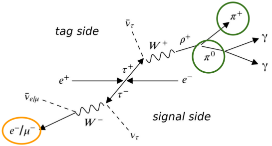
- Measure $m_\tau = 1777.09 \pm 0.08 \pm 0.11 \mathrm{MeV}/c^2$
- World's most precise measurement!



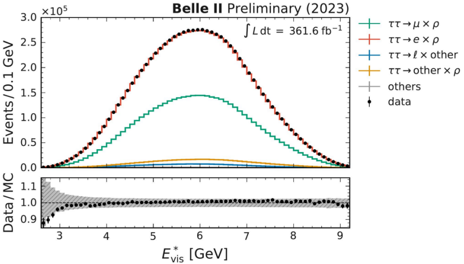
Lepton flavor universality in τ decays

- Measurement of lepton flavor universality:

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} \overset{SM}{=} 0.9726$$



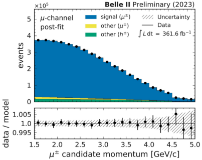
- 1-prong decays on tag side:
  - Require one charged hadron and at least one π^0
  - Large branching ratio, low backgrounds, high trigger efficiency

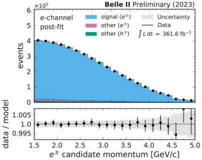


- Suppress backgrounds using BDT
- Combined $e - \mu$ sample: 94% purity at 9.6% signal efficiency
- Main backgrounds:
  - $\sim 3.3\%\ e^+e^- \to \tau^+\tau^-$ with $\pi^\pm$ faking lepton
  - $\sim 2.3\%\ e^+e^- \to \tau^+\tau^-$ with wrongly reconstructed tagside
  - $0.2\%\ e^+e^- \to e^+e^-\tau^+\tau^-$

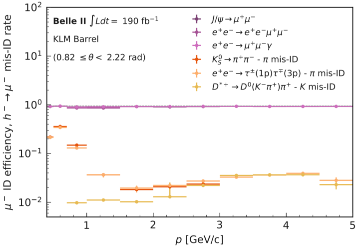
Lepton flavor universality in τ decays

- Extract signal yields with binned maximum likelihood fit in p_ℓ using `pyhf`





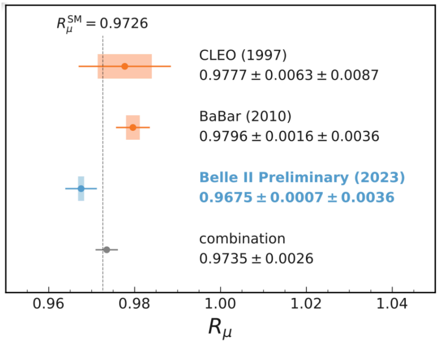
- Challenge in this analysis: careful treatment of leading particle identification (PID) systematic
  - Restrict to region least impacted by PID unceratinties:
    - $0.82 < \theta_\ell < 2.13$
    - $1.5 < p_\ell < 5.0$ GeV
  - Obtain correction factors and uncertainties from correlation factors
  - PID Efficiency:
    - $J/\psi \to \ell^+\ell^-$, $e^+e^- \to e^+e^-\ell^+\ell^-$, and $e^+e^- \to \ell^+\ell^-(\gamma)$
    - e efficiency 99.7 %, μ efficiency 93.9%
  - PID fake rates:
    - $K_S^0 \to \pi^+\pi^-$ and $\tau \to \pi\pi\pi\nu$
    - π faking e: 0.9 %, π faking μ 3.1%



↪ Implement PID uncertainty as nuisance parameter on fit templates

Lepton flavor universality in τ decays

- Measure $R_\mu = 0.9675 \pm 0.0007 \pm 0.0036$
- World's most precise measurement of $\mu - e$ universality in τ!
- Consistent with SM expectation within 1.4σ



Source	Uncertainty [%]
Charged-particle identification:	
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Trigger	0.10
Imperfections of the simulation:	
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Size of the samples	
Simulated samples	0.06
Luminosity	0.01
Charged-particle reconstruction:	
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Total	0.37

- PID makes up 0.32% of total 0.37% systematic uncertainty

- τ lepton flavour violation decay modes:

$\tau \to \ell\ell\ell$

$\tau \to \ell K_s, \Lambda h$

$\tau \to \ell V^0(\to hh')$

$\tau \to \ell P^0\ (\to \gamma\gamma)$

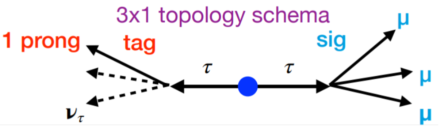
$\tau \to \ell hh'$

$\tau \to \ell\gamma$

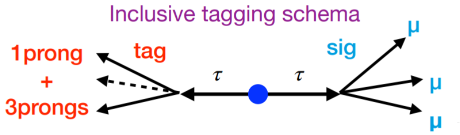
↪ Golden channel: $\tau \to \mu\mu\mu$
  - Experimentally the most accessible
  - Branching ration in ν mixing SM: $10^{-53} \sim 10^{-56}$
  - Enhanced in new physics models

- Inclusive 1prong + 3prong tag at Belle II
- Signal efficiency $\varepsilon_{sig} = 20.42 \pm 0.06\%$
  - $\sim\ 300\%$ increase over Belle!

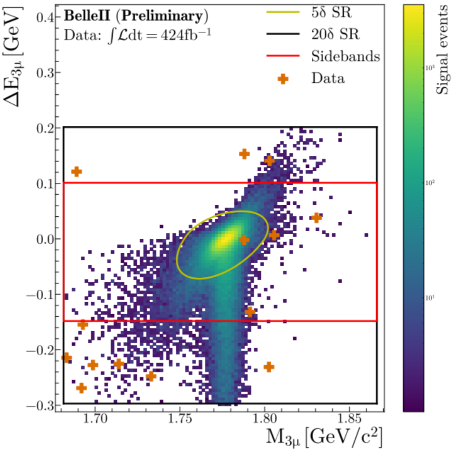
Belle:



Belle II:



Search for τ to three muons

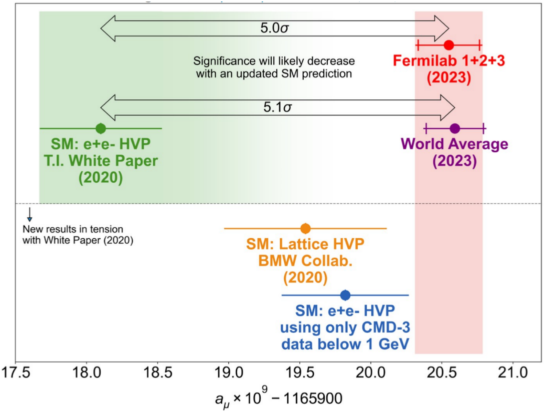


- Large background subtraction using $\Delta E_{3\mu} = E_{\tau,sig} - E_{beam}$ and $M_{3\mu}$
- Observed 1 event in the signal region
  - Expected $0.5^{+1.4}_{-0.5}$ background events

$$\text{UL@90\%CL} : \mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$$

- More stringent limit than Belle with $\sim 50\%$ of data sample!

$(g-2)$ of the muon



- Tension between theoretical prediction of the muon magnetic anomaly

$$a_\mu = \frac{(g-2)_\mu}{2} = a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{QCD}}$$

- Tension reduces to $\sim 1\sigma$ with newly included data:
  - $a_\mu^{\mathrm{HVP,LO}}$ from lattice QCD
  - π form-factor from CMD-3 in $a_\mu^{\mathrm{HVP,LO}}$

$(g-2)$ of the muon

$$a_\mu = \frac{g-2}{2} = a_\mu^{EW} + a_\mu^{QED} + a_\mu^{QCD}$$

Hadron-contribution

$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$

Leading order HVP-term

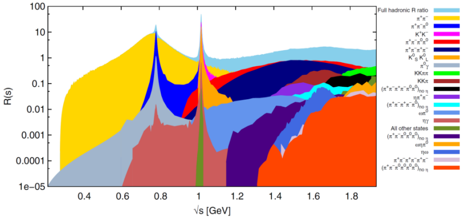
$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} \frac{ds}{s} R(s) K(s)$$

HVP = hadron vacuum polarization; 82% of a_μ^{QCD}, HLBL = light-by-light; 18%

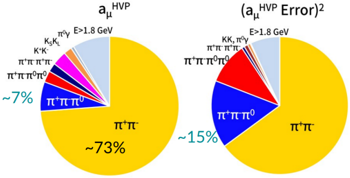
$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

- Belle II can provide $e^+e^- \to \text{hadrons}$ cross sections to improve predictions
  - Largest contribution $e^+e^- \to \pi^+\pi^-$ analysis currently ongoing
  - Second largest contribution $e^+e^- \to \pi^+\pi^-\pi^0$ presented today

Measured R-ratio



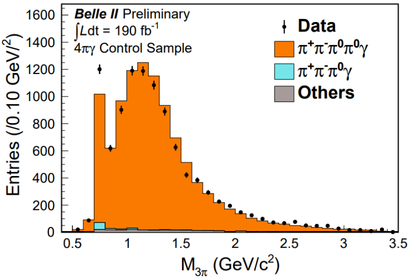
(a) The hadronic R-ratio.



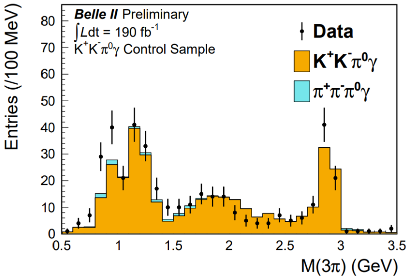
New for Moriond 2024!

- Reconstruct $e^+e^- \to \pi^+\pi^-\pi^0$ decays in $\mathcal{L} = 190\ \text{fb}^{-1}$
- Measure at different $\sqrt{s}$ by using ISR technique
  - Reconstruct ISR photon
  - Pion invariant mass range from 0.62 to 3.5 GeV
- Effectively suppress background by using kinematic fit:
  - Constrain sum of $\pi^+\pi^-\pi^0\gamma_{ISR}$ momenta to e^+e^- beam momentum
- Validate main backgrounds in control samples:

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$



$e^+e^- \to K^+K^-\pi^0\pi^0\gamma$



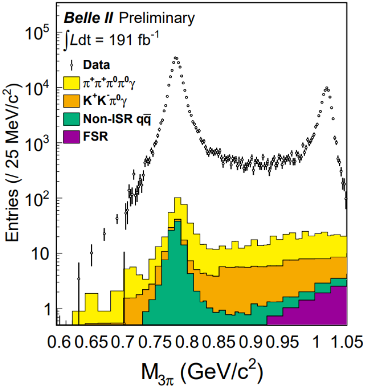
$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

New for Moriond 2024!

- Major analysis challenge is handling π^0 efficiency
  - Evaluate efficiency using partial reconstruction of ω resonance decays:

$$\varepsilon_{\pi^0} = \frac{N(\text{Full reconstruction of } \gamma_{ISR}\, \pi^+\pi^-\pi^0)}{N(\text{Partial reconstruction of } \gamma_{ISR}\, \pi^+\pi^-)})$$

  - Determines π^0 efficiency up to 1% $\to$ systematic uncertainty
- Fit $M_{\gamma\gamma}$ in each bin of $M_{3\pi}$:



- Integrate over 3π cross section from 0.62 to 1.8 GeV:

$$a^{3\pi}_{\mu,0.62\text{-}1.8} \times 10^{10} = 49.02 \pm 0.23(\text{stat.}) \pm 1.07(\text{syst.})$$

- 6.7% higher than global fit with 2.6σ significance

$\hookrightarrow$ Slightly smaller anomaly

- Leading systematics π^0 efficiency and generator

Summary

Results
$m_\tau = 1777.09 \pm 0.08 \pm 0.11 \mathrm{MeV/c^2}$
$R_\mu = 0.9675 \pm 0.0007 \pm 0.0036$
$\mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8} (90\% \mathrm{CL})$
$a_{\mu,0.62\text{-}1.8}^{3\pi} \times 10^{10} = 49.02 \pm 0.23(\mathrm{stat.}) \pm 1.07(\mathrm{syst.})$

- Belle II is providing leading precision in τ and low multiplicity measurements
  - Precision measurements of τ properties
  - Studies of standard model parameters
  - Searches for beyond SM physics
- Improvements on multiple frontiers
  - Results with $362\mathrm{fb}^{-1}$ of run1 data
  - Improved analysis techniques and reduced systematics

Run 2 started on February 20, 2024!

Backup