Amplitude Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ at Belle (II)

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τ Physics at Belle and Belle II

- Precision studies of the weak interaction
- τ lepton properties potentially sensitive to Beyond Standard Model physics
- Unique and clean environment to study hadronic decays
- Precision measurement of τ requires τ factory
  - Belle : $900\,\mathrm{M}$ τ pairs produced ($\mathcal{L} \approx 1\,\mathrm{ab}^{-1}$)
  - Belle II: $400\,\mathrm{M}$ τ pairs produced ($\mathcal{L} \approx 0.4\,\mathrm{ab}^{-1}$)

[Particle Zoo]

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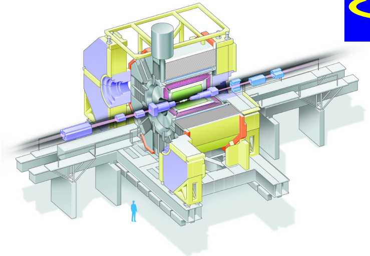
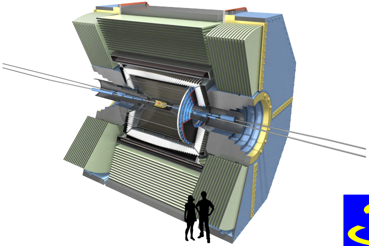
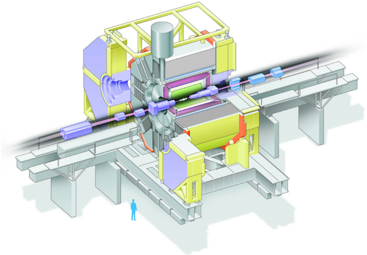




τ Physics at Belle and Belle II

- The Belle (II) detector
  - High-precision tracking
  - Efficient particle identification
  - Reconstruction of neutral particles
- Production of τ pairs in e^+e^- collisions
  - Clean events; Large boost of τ
  - Known initial conditions
- Study of hadron resonances in weak τ decays complementary to other studies, e.g. in diffractive or photo production



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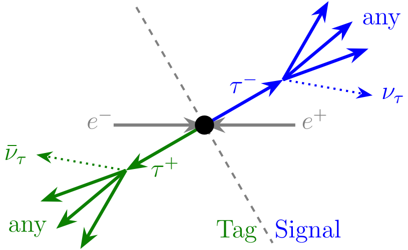

e^+e^- center-of-mass frame

Partial-Wave Analysis of $\tau^{\mp} \to \pi^{\mp}\pi^{\mp}\pi^{\pm} \overset{(-)}{\nu_{\tau}}$ at Belle

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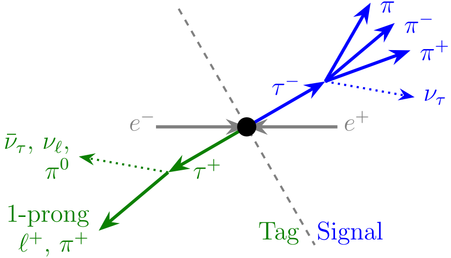
- $\tau^\mp \to \pi^\mp\pi^\mp\pi^\pm \overset{(-)}{\nu}_\tau$ unique laboratory for hadron spectroscopy
- $\mathcal{B}(\tau^\mp \to \pi^\mp\pi^\mp\pi^\pm \overset{(-)}{\nu}_\tau) \approx 9\,\%$
  - Belle: 55×10^6 events
- 3π system dominated by a_1 resonances
  - ➥ Study of $a_1(1420)$ observed by COMPASS
- Studied to far only by ARGUS and CLEO in partial-wave analysis [PLB 349 (1995) 576], [PRD 61 (1999) 012002]



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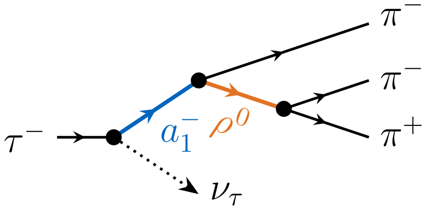


Partial-Wave Analysis Formalism

- Amplitude for τ helicity λ

$$^{\lambda}\mathcal{A} = {}^{\lambda}\ell_{\mu}\, J^{\mu}$$

- Decompose hadronic current into partial waves

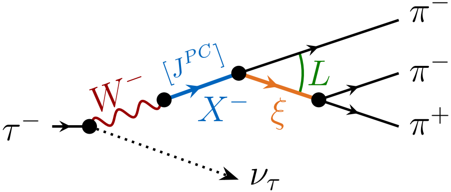
$$J_{\mu} = \sum_{a} c_a\, J_a^{\mu}$$

  - J_a^{μ} calculated using relativistic tensor formalism and the isobar model [EPJC 81 (2021) 1073]
  - Labeling: $J^{P}[\xi\pi]_{L}$

- Intensity for unpolarized τ

$$I = \frac{1}{2}\sum_{\lambda}\left|{}^{\lambda}\ell_{\mu}\, J^{\mu}\right|^2 = \sum_{a,b} c_a\,[c_b]^*\, J_a^{\mu}\,[J_b^{\nu}]^*\, L_{\mu\nu}$$

- Fit I to data in independent narrow $m_{3\pi}$ bins to measure partial-wave amplitudes $c_a(m_{3\pi})$



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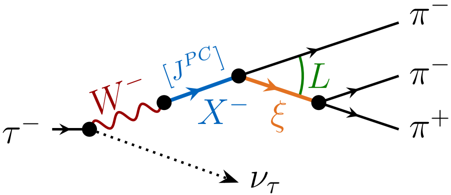

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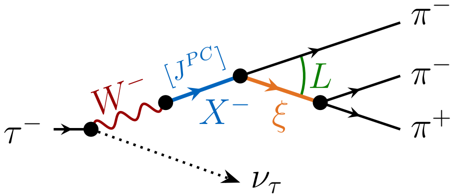

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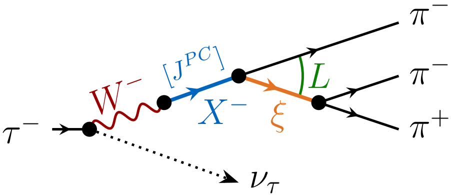


Partial-Wave Analysis Formalism

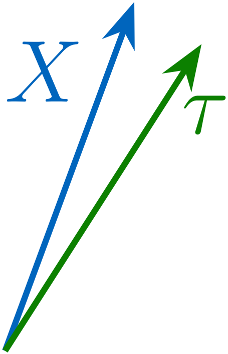
Unknown τ Direction

[Z. Phys. C 76 (1997) 15]

- Cannot measure ν_τ momentum
  - ➥ Cannot measure the τ momentum, needed to calculate $L_{\mu\nu}$
- τ energy in e^+e^- center-of-mass system known
  - ➥ Constrain the τ momentum up to one unknown angle α
- Marginalize the intensity over this unknown angle

$$\bar{I} = \int \mathrm{d}\alpha \, I = \sum_{a,b} c_a \, [c_b]^* \, J_a^\mu \, [J_b^\nu]^* \, \bar{L}_{\mu\nu}$$

- Need to pre-calculate and store $N_{\text{wave}} \times N_{\text{wave}}$ matrix $M_{ab} = J_a^\mu \left[J_b^\nu\right]^* \bar{L}_{\mu\nu}$ for each event



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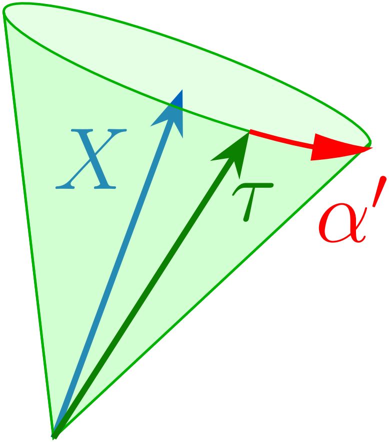

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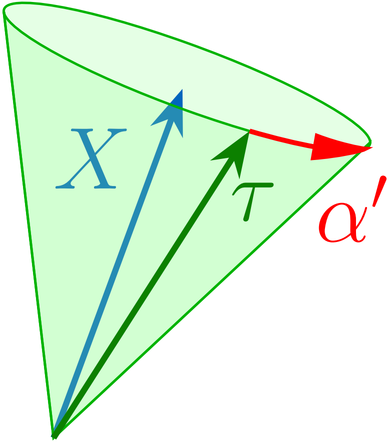

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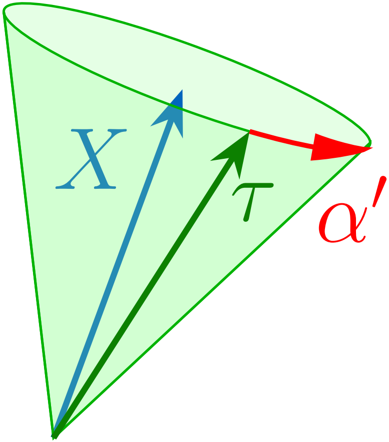

Partial-Wave Analysis Formalism

Unknown τ Direction

- Decompose $\bar{L}_{\mu\nu}$ into 4 4-vectors

$$\bar{L}_{\mu\nu} = \sum_i^4 {}^i v_\mu \left[{}^i v_\nu \right]^*$$

- Write marginalized intensity

$$\bar{I} = \sum_i^4 \sum_{a,b} \left[c_a \, {}^i v_\mu J_a^\mu \right] \left[c_b \, {}^i v_\nu J_b^\nu \right]^*$$

- Group all pre-calculable quantities into

$${}^i\Psi_a = {}^i v_\mu J_a^\mu$$

allows to write the marginalized intensity in the simple form

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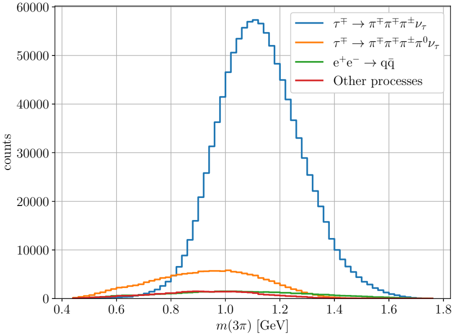
Background Treatment

- Overall small background of 18 %
  - $\tau^{\mp} \to \pi^{\mp}\pi^{\mp}\pi^{\pm}\pi^{0}\overset{(-)}{\nu_{\tau}}$ 12 %
  - $e^{+}e^{-} \to q\bar{q}$ 4 %
- Modeling background in partial-wave decomposition
  - Requires high-dimensional pdf of background distribution

- Realistic background simulation at Belle
- Parameterize background pdf using a neural network
- Include background pdf with fixed shape per $m_{3\pi}$ bin
- Study remaining leakage by performing partial-wave decomposition of simulated background sample
  - ➥ Small background leakage into partial waves



$q\bar{q} = u\bar{u},\, d\bar{d},\, c\bar{c}$

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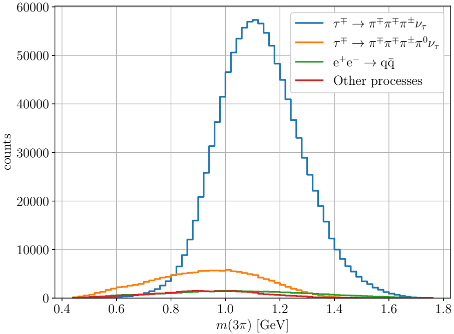

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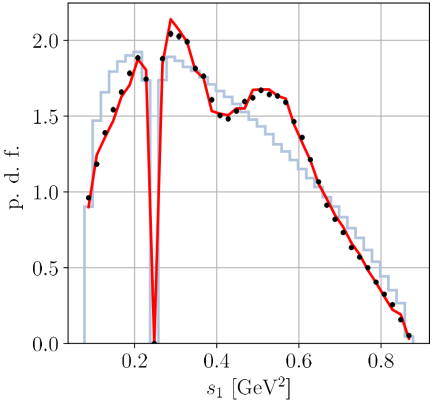

$s_1 = m^2_{\pi^-\pi^+}$

phase-space, Simulated background, Neural Network

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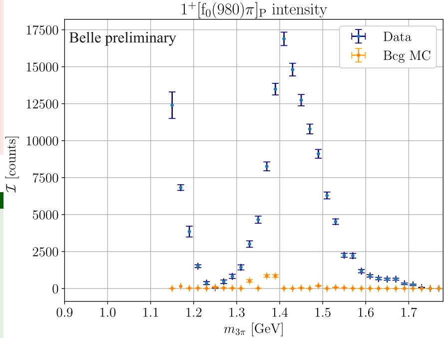


Wave Set

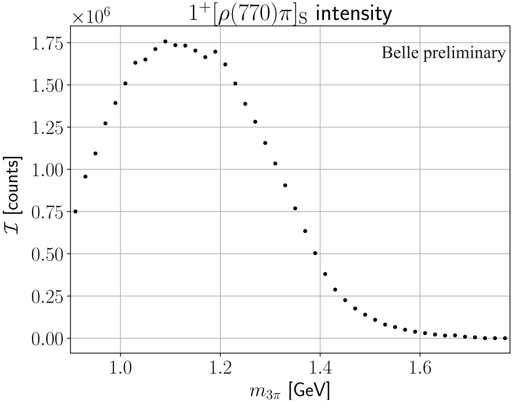
$$J_\mu = \sum_a c_a \, J_a^\mu$$

- Fit 17 partial waves to the data
- 10 waves representing $J^P = 1^+$
  - Various ρ, f_0, f_2, and ω decay modes
- 4 waves representing $J^P = 0^-$
  - $\rho(770)$, f_0 and $f_2(1270)$ decay modes
- 3 waves representing $J^P = 1^-$
  - $\rho(770)$, $f_2(1270)$, $\omega(782)$ decay modes
- CLEO used only 7 waves representing only $J^P = 1^+$

$a_1(1260)$

$1^+[\rho(770)\pi]_S$

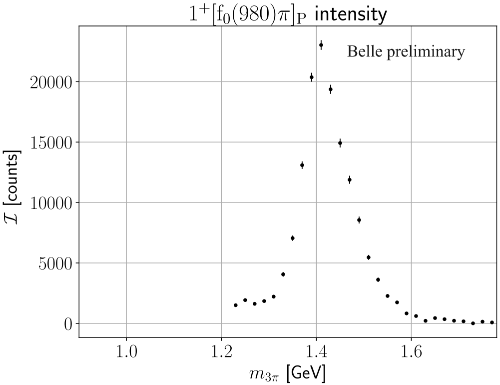
- Dominant partial wave
- Broad $a_1(1260)$-like signal



$a_1(1420)$

$1^+[f_0(980)\pi]_P$

- Narrow peak at about 1.4 GeV$/c^2$
- Accompanied by rise in relative phase
- Similar to $a_1(1420)$ signal observed by COMPASS in same partial wave



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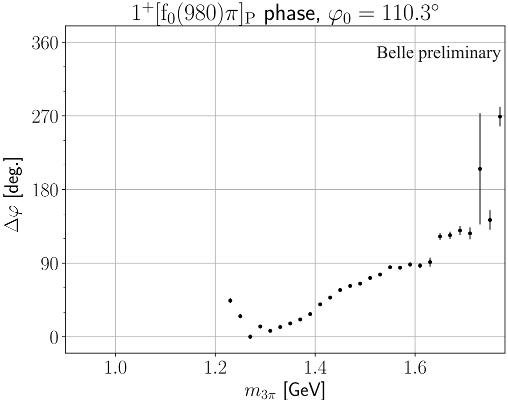
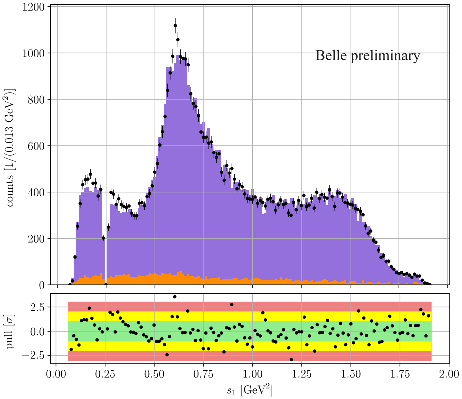


$1^{-}[\omega(782)\pi]_{P}$ Wave

- 0.77 GeV/c^2 $m_{\pi^-\pi^+}$ region not well described by $\rho(770)$ only
  - ➡ Additional narrow structure
  - ➡ Potential $\omega(782)$ contribution from G-parity violating $\omega(782) \to \pi^-\pi^+$ decay
- Modeled by including $1^{-}[\omega(782)\pi]_{P}$ wave
  - $G \cdot P \cdot (-1)^J = +$ for first class currents
  - $[\omega(782)\pi]$ system has $G = +$
    - ➡ $P = -$ for $J = 1$ state
    - ➡ ρ-like state
- Broad bump in intensity at about 1.4 GeV/c^2
- Similar yield and shape as CLEO measurement of $\tau^- \to \omega(782)\pi^-\nu_\tau$ with $\omega(782) \to \pi^-\pi^+\pi^0$ [PRD 61 (2000) 072003]



Data points,
Simulated background,
Simulated signal without $\omega(782)$

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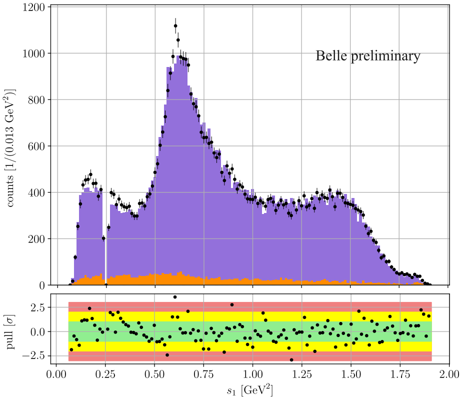

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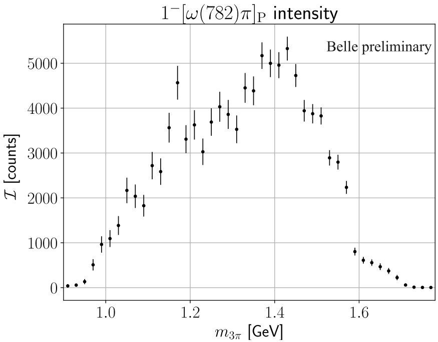

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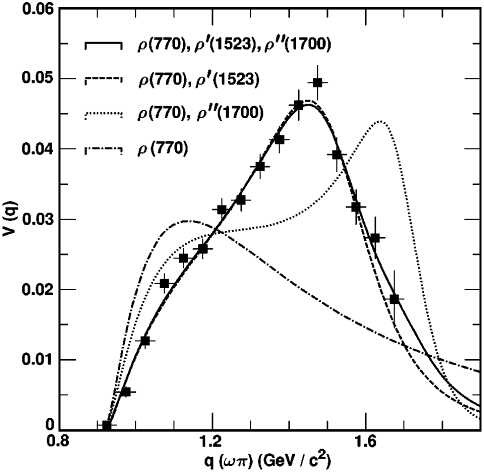
  - $[\omega(782)\pi]$ system has $G = +$
    - ➥ $P = -$ for $J = 1$ state
    - ➥ ρ-like state
- Broad bump in intensity at about 1.4 GeV$/c^2$
- Similar yield and shape as CLEO measurement of $\tau^- \to \omega(782)\pi^-\nu_\tau$ with $\omega(782) \to \pi^-\pi^+\pi^0$ [PRD 61 (2000) 072003]



Measuring the Amplitude of Isobar Resonances

- Conventional PWA: Parameterize lineshape of ξ by fixed amplitude
- Freed-isobar analysis: Measure the ξ line shape by
  - Replacing fixed parameterization by step-wise constant function
- Free multiple isobar line shape simultaneously to avoid bias, e.g. $[\pi\pi]_P$ and $[\pi\pi]_S$ amplitudes
  - ➥ Mathematical ambiguities in the partial-wave decomposition (zero modes) [PRD 97 (2018) 114008]
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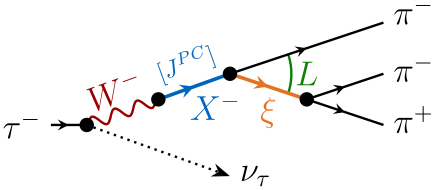

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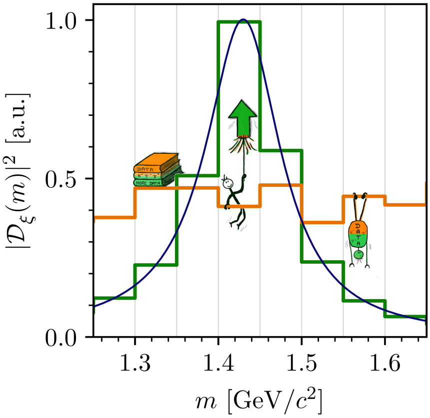

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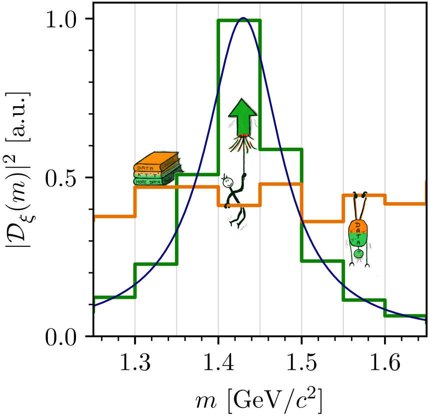

Measuring the Amplitude of Isobar Resonances

$[\pi\pi]_P$ amplitudes from $J^P = 1^+$ partial wave

- $G_{\pi\pi} = +\ \Rightarrow\ \rho$-like state
- Clear peak from $\rho(770)$ resonance

$[\pi\pi]_P$ amplitudes from $J^P = 1^-$ partial wave

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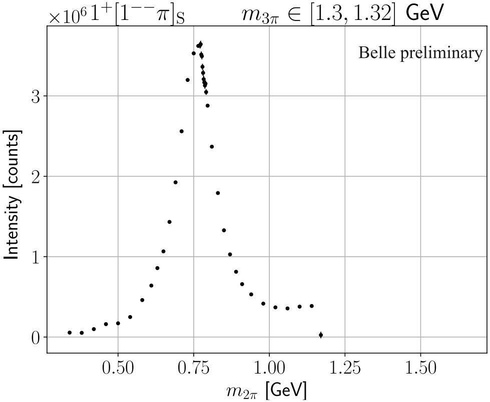
- Clear peak from $\omega(782)$ resonance
  - ➡ Verifies observation of G violation $\omega(782) \to \pi^-\pi^+$ decay



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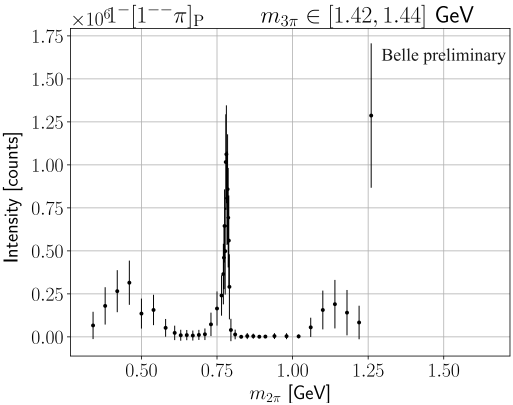

Prospects for Belle II

Belle II finished first run of data taking 2022

- Measured about 426 fb^{-1}
    - About BaBar data set; $1/2$ Belle data set
- World-record luminosity of $4.71 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
- Many physics results published or in the pipeline
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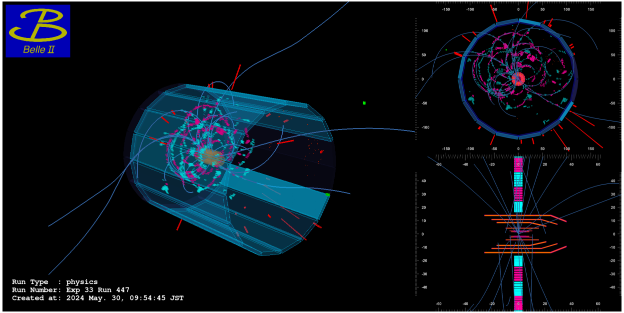

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Run Number: Exp 33 Run 447
Created at: 2024 May. 30, 09:54:45 JST
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SuperKEKB Operation Status

Live Event Display

Prospects for Belle II

Ongoing spectroscopy analyses at Belle II

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[LA THUILE 2024]

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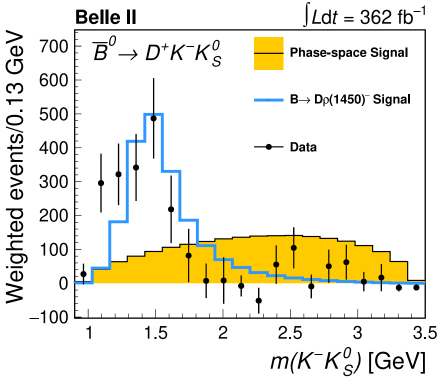

Summary and Outlook

- Many opportunities for spectroscopy at Belle (II): hadronic τ and B decays
- Analysis formalism and background modeling challenging
- Precision measurements in $\tau^\mp \to \pi^\mp\pi^\mp\pi^\pm \overset{(-)}{\nu_\tau}$ decays
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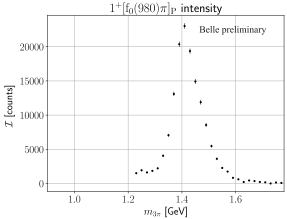
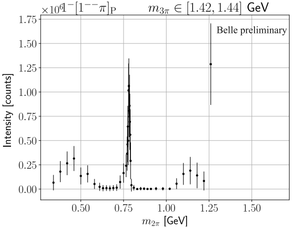
  - Amplitudes of $\pi^-\pi^+$ subsystem: ρ, ω, $[\pi\pi]_S$
- Even larger sample from Belle II will allow us to study also rare decays





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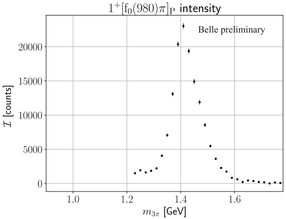

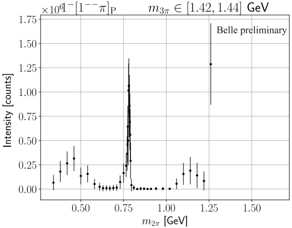

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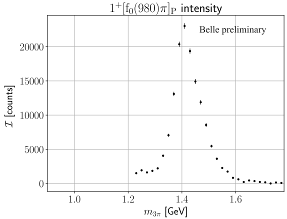

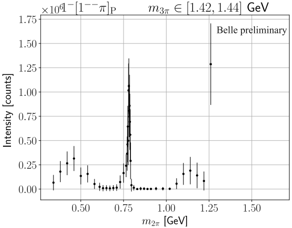

Backup

Outline

Belle II

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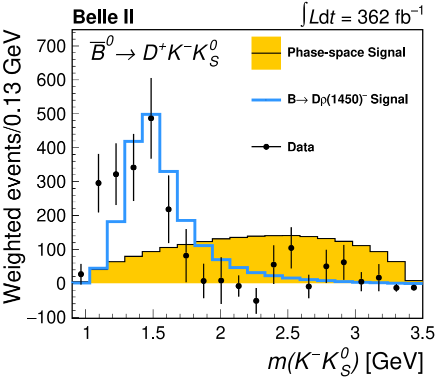

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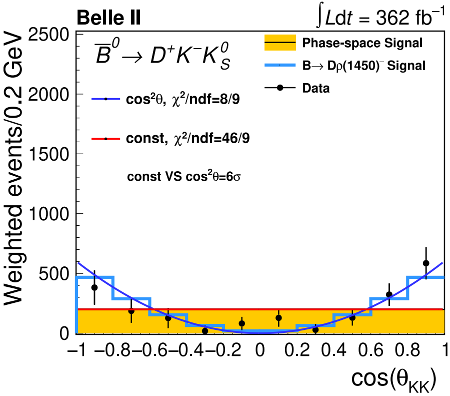

Partial-Wave Decomposition of $\tau^\mp \to \pi^\mp\pi^\mp\pi^\pm \overset{(}{\overline{\nu}}\overset{)}{_\tau}$ at Belle

Wave Set

Belle Wave Set

- $1^+[\rho(770)\pi]_S$
- $1^+[\rho(770)\pi]_D$
- $1^+[\rho(1450)\pi]_S$
- $1^+[\rho(1450)\pi]_D$
- $1^+[f_2(1270)\pi]_P$
- $1^+[f_2(1270)\pi]_F$
- $1^+[\sigma\pi]_P$
- $1^+[f_0(980)\pi]_P$
- $1^+[f_0(1500)\pi]_P$
- $1^+[\omega(782)\pi]_S$

- $0^-[\rho(770)\pi]_P$
- $0^-[f_2(1270)\pi]_D$
- $0^-[\sigma\pi]_S$
- $0^-[f_0(980)\pi]_S$

- $1^-[\rho(770)\pi]_P$
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Wave Set

[PRD 61 (1999) 012002]

CLEO Wave Set

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