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

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Max Planck Institute for Physics

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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 laboratory to study hadronic decays
- Precision measurement of τ requires τ factory
  - Belle : 900 M τ pairs produced ($\mathcal{L} \approx 1\,\mathrm{ab}^{-1}$)
  - Belle II: 400 M τ pairs produced ($\mathcal{L} \approx 0.4\,\mathrm{ab}^{-1}$)

[Particle Zoo]

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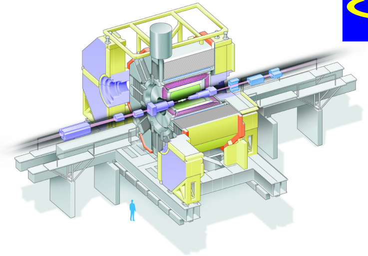
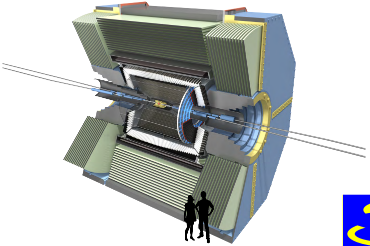
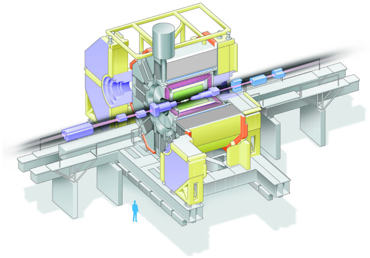




- The Belle (II) detector
  - High-precision tracking
  - Efficient particle identification
  - Reconstruction of neutral particles
- Production of τ pairs in e^+e^- collisions
  - Clean events; Large boost of τ
  - Known initial conditions
- Study of hadron resonances in weak τ decays complementary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



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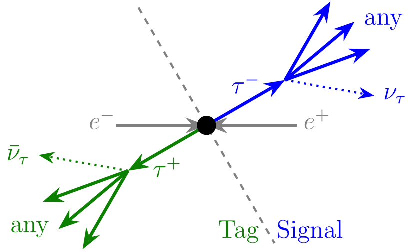
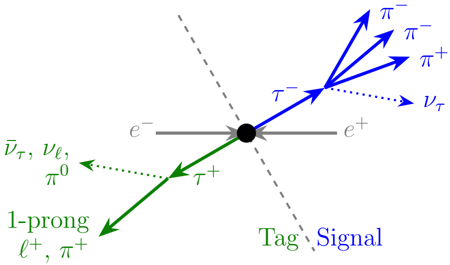


Partial-Wave Analysis of $\tau^{\mp} \rightarrow \pi^{\mp}\pi^{\mp}\pi^{\pm}\overset{(}{\overline{\nu_\tau}}\overset{)}{}$ at Belle

- $\tau^{\mp} \to \pi^{\mp}\pi^{\mp}\pi^{\pm} \overset{(-)}{\nu_\tau}$ 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 resonance
  - ➥ Study of $a_1(1420)$ observed by COMPASS
- Studied to far only by CLEO in partial-wave analysis [PRD 61 (1999) 012002]



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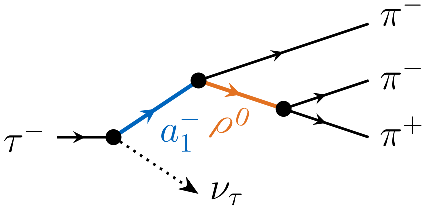


- Amplitude for τ helicity λ

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

- Decompose hadronic current into partial waves

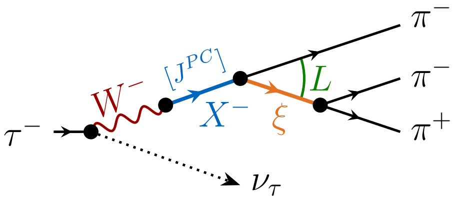
$$J_{\mu} = \sum_{a} c_a\, J_a^{\mu}$$

  - 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 independently narrow $m_{3\pi}$ bins to measure partial-wave amplitudes $c_a(m_{3\pi})$



Partial-Wave Analysis Formalism

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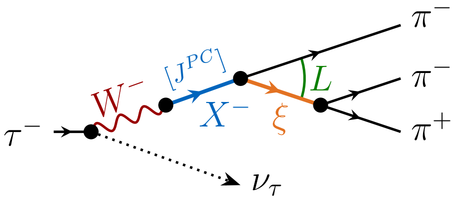

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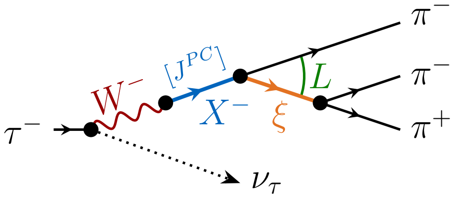

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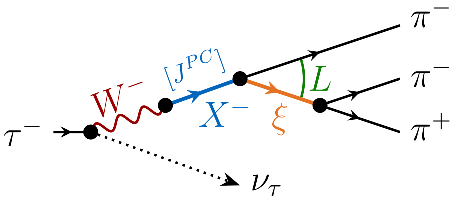
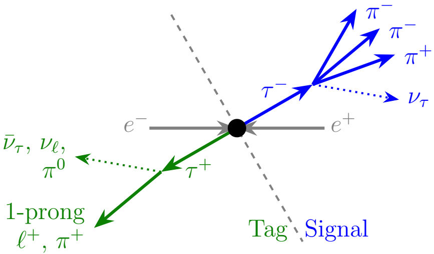


- Cannot measure ν_τ momentum
  - ➥ Cannot measure the τ momentum, needed to calculate $L_{\mu\nu}$
- τ energy in e^+e^- center-of-mass system known
  - ➥ Constraint the τ momentum up to one unknown angle α
- Marginalize the intensity over this unknown angle

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

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



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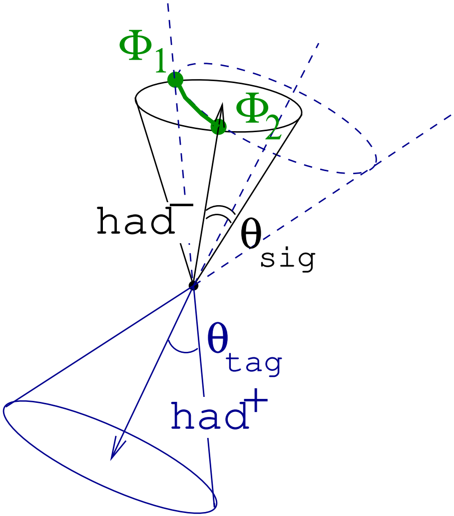

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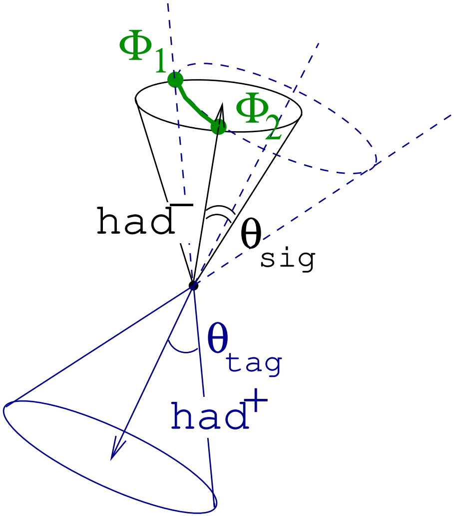

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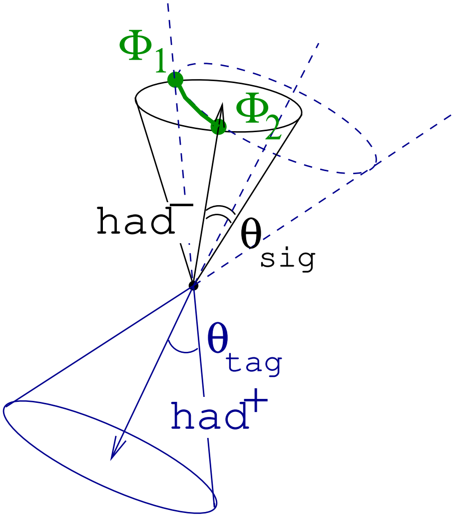

- Decompose $\bar{L}_{\mu\nu}$ into 4 4-vectors

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

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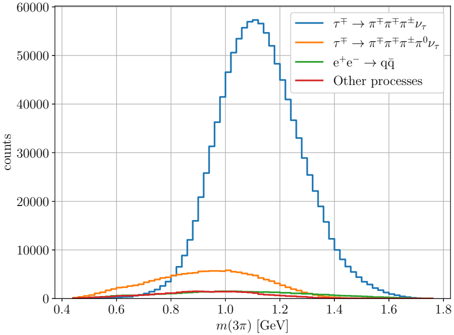
- Overall small background of 18 %
  - $\tau^{\mp} \to \pi^{\mp}\pi^{\mp}\pi^{\pm}\pi^{0}\overset{(-)}{\nu_{\tau}}$ 12 %
  - $e^{+}e^{-} \to q\bar{q}$ 4 %
- Modeling background in partial-wave decomposition
  - Requires high-dimensional pdf of background distribution

- 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



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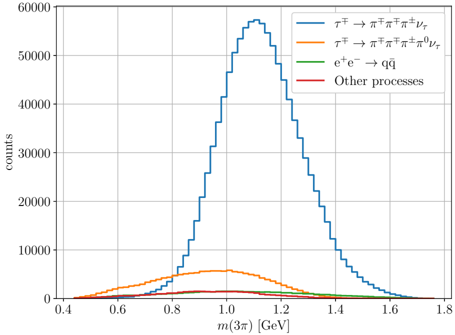

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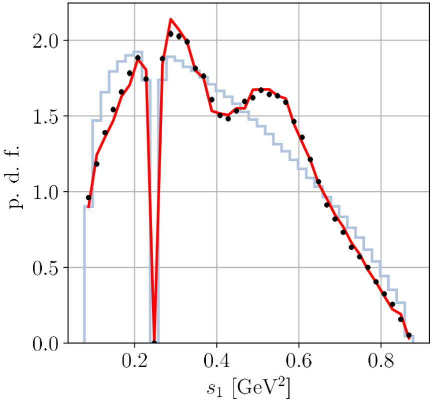

phase-space, Simulated background, Neural Network

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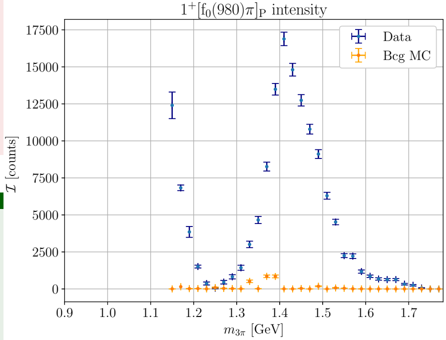


Wave Set

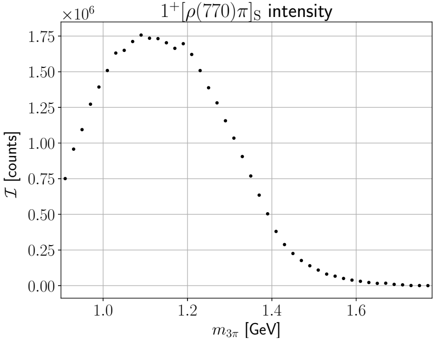
$$J_\mu = \sum_a c_a \, J_a^\mu$$

- Fit 16 partial waves to the data
- 9 waves representing $J^P = 1^+$
  - Various ρ, f_0 and f_2 decay modes
- 4 waves representing $J^P = 0^-$
- 3 waves representing $J^P = 1^-$
- CLEO used only 7 waves representing only $J^P = 1^+$

$a_1(1260)$

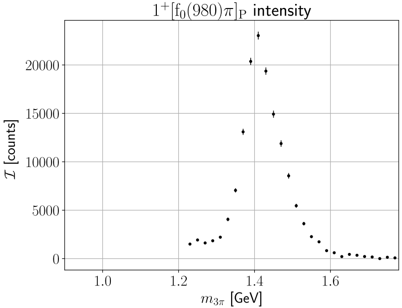
$1^+[\rho(770)\pi]_S$

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



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

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



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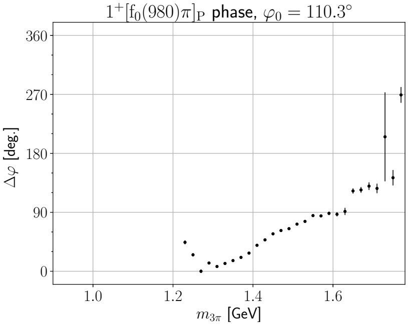
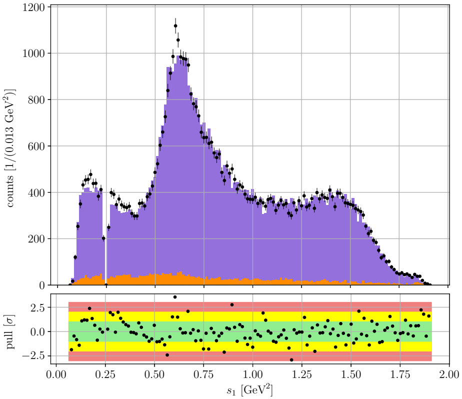


$1^{-}[\omega(782)\pi]_P$ Wave

- 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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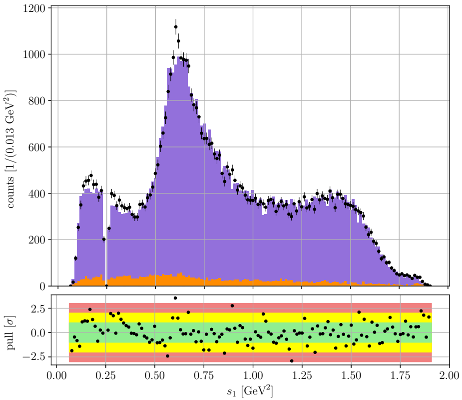

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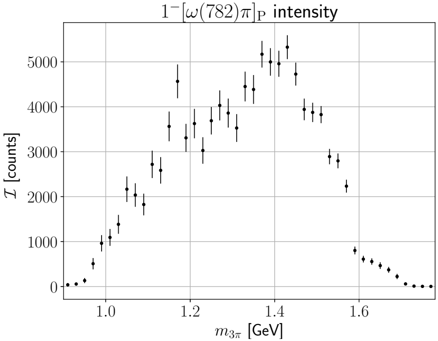

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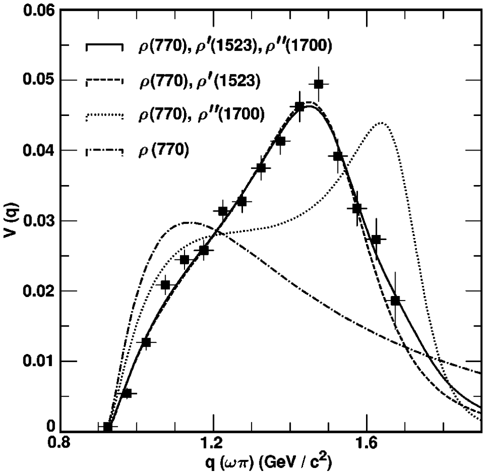
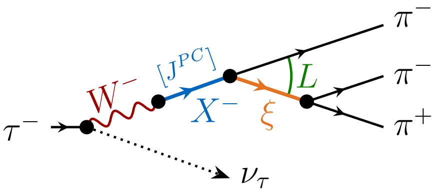


- Conventional PWA: Parameterize lineshape of ξ by fixed amplitude
- Freed-isobar analysis: Measure the ξ line shape by
  - Replacing fixed parameterization by step-wise constant function
- Free multiple isobar line shape simultaneously to avoid bias, e.g. $[\pi\pi]_P$ and $[\pi\pi]_S$ amplitudes
  -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



Measuring the Amplitude of Isobar Resonances

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- Freed-isobar analysis: Measure the ξ line shape by
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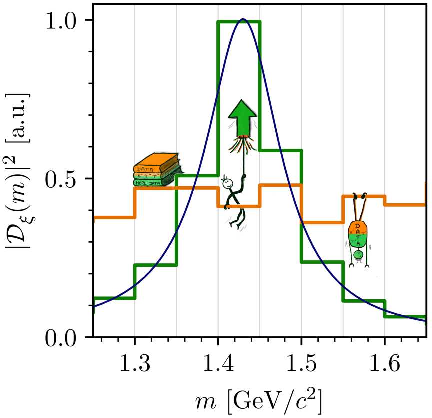
- Free multiple isobar line shape simultaneously to avoid bias, e.g. $[\pi\pi]_P$ and $[\pi\pi]_S$ amplitudes
  - ➡ Mathematical ambiguities in the partial-wave decomposition (zero modes) [PRD 97 (2018) 114008]
  - ➡ Requires external input to resolve them



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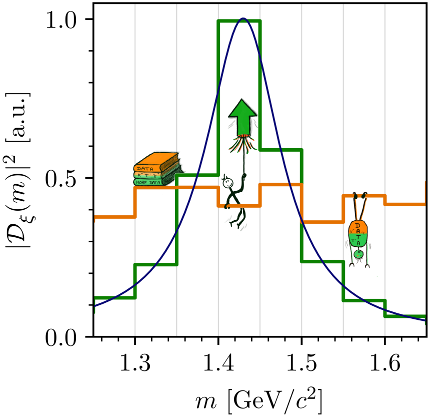

$[\pi\pi]_P$ amplitudes from $J^P = 1^+$ partial wave

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

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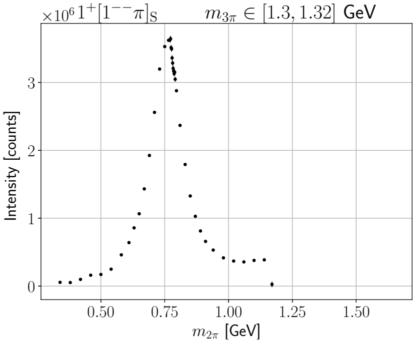
  - ➥ Verifies observation of G violation $\omega(782) \to \pi^-\pi^+$ decay



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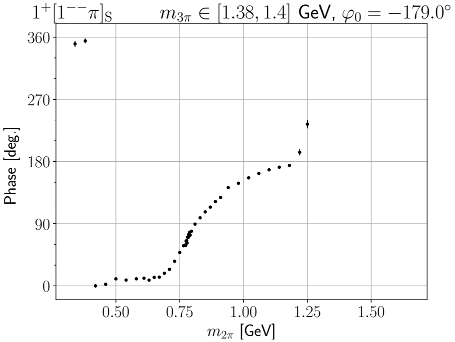

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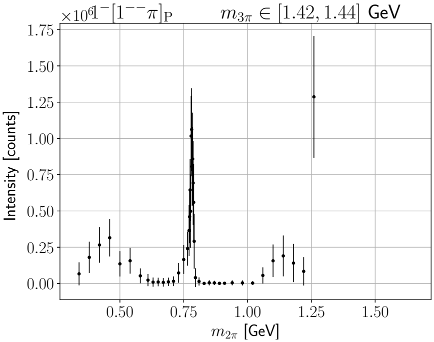

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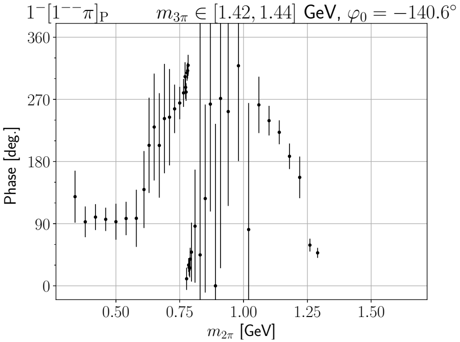

Prospects for Belle II

Belle II finished first run of data taking 2022

- Measured about $426\,\text{fb}^{-1}$
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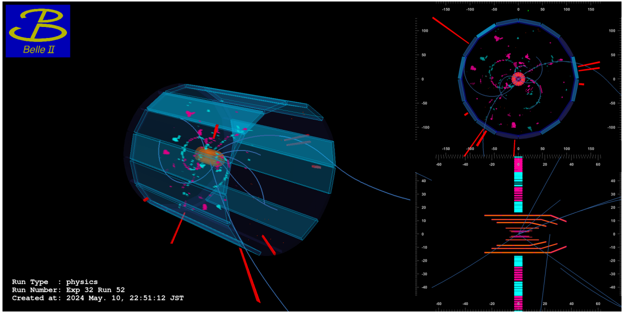

SuperKEKB Operation Status
Live Event Display

Prospects for Belle II

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- Partial-wave analyses of $\tau^{\mp} \to h^{\mp} h^{\mp} h^{\pm} \overset{(-)}{\nu_{\tau}}$
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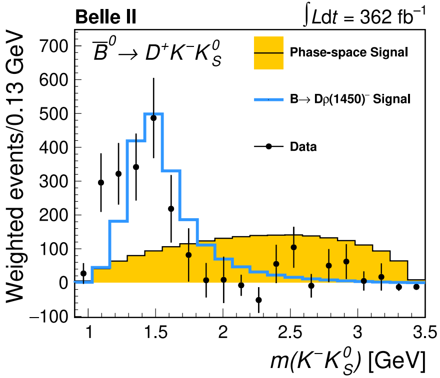

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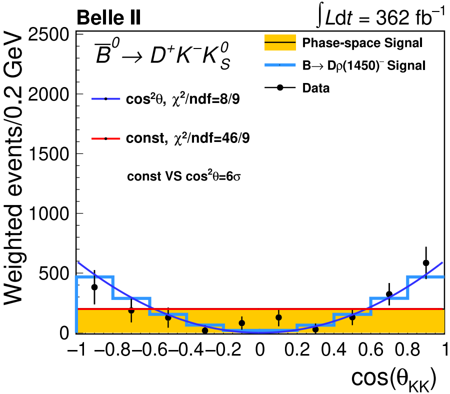

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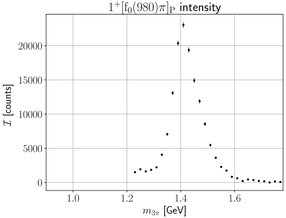

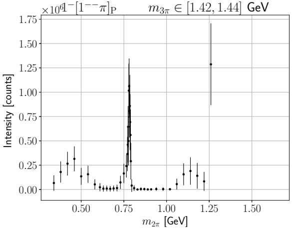

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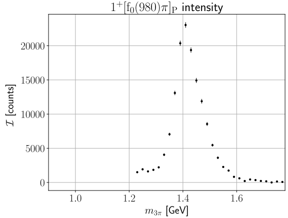

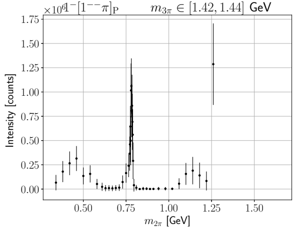

Summary and Outlook

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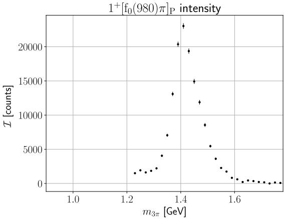

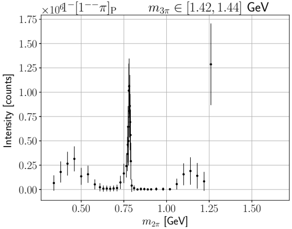

Backup

Outline