Belle II

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Max Planck Institute for Physics

Project Review
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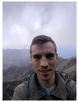
The Belle II Group at the MPP

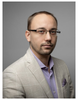
- **Director:** Allen Caldwell
- **Project Leader:** Hans-Günther Moser
- **Fellow:** Stephan Paul
- **Emeritus:** Christian Kiesling

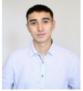


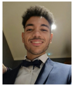

- **2 Postdocs:** Sagar Hazra, Stefan Wallner; Boqun Wang, Thibaud Humair, Fabian Krinner
- **5 Doctoral Candidates:** Markus Reif*, Philipp Leitl*, Justin Skorupa, Oskar Tittel, Martin Bartl; Felix Meggendorfer, Benedikt Wach, Thomas Kraetschmar, Lukas Bierwirth
- **11 Students:** Godo Kurten, Ceren Ay, Maximilian Hattenbach, Simeon Hamurcu, Franz Jackl, Vanessa Geier, Kilian Brückner, Adrian Liese, Claudia Perez-Orive, Erik Gräter, Gustav Cordes; Xavier Simó, Okan Eren, Yingming Yang, Arina Katscho, Yannik Fausch, Lars von der Werth, Timo Forsthofer, Simon Hiesl
- **Technical Support:** Ullrich Leis, Sven Vogt, Enrico Rochser, David Kittlinger, Miriam Modjesch, Markus Fras, Stefan Horn, Carina Schlammer, Werner Haberer





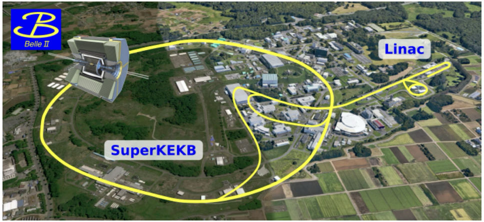


The Belle II Experiment

- Experiment at SuperKEKB (Tsukuba/Japan)
  - e^+e^- collider at $E_{\mathrm{CM}} = 10.58\,\mathrm{GeV}/c^2$
- Successor of the Belle experiment (1999–2010)
- Belle II goals:
  - $50\times$ Belle data-sample size
- Run 1 (2019–2022)
  - World-record luminosity: $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - Collected about $1/2\times$ Belle data-sample size
    $1\times$ BaBar data-sample size
- Run 2 started spring 2024
  - Upgraded detector
- Belle II consists of various subdetectors for tracking, particle identification, calorimetry



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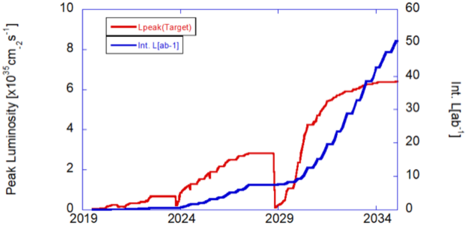

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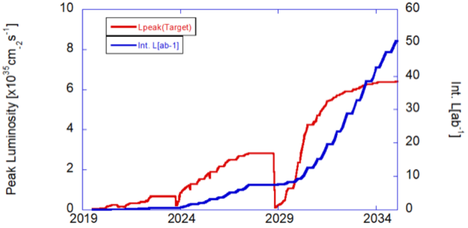

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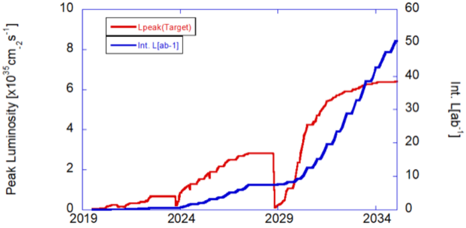

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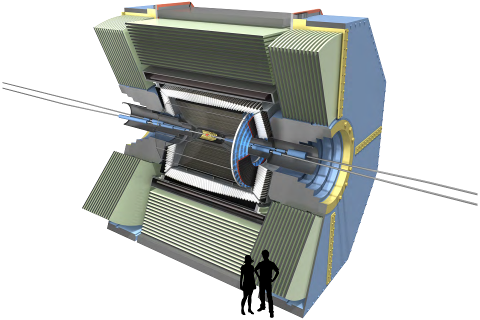
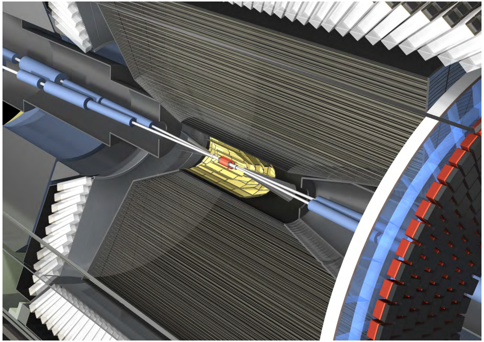


Contributions to the Pixel Vertex Detector

[H.G. Moser, P. Leitl, et al.]

- Pixel Vertex Detector for precise decay-vertex reconstruction
  - Two layers of monolithic "all-silicon" DEPFET modules
    - Novel development
    - No additional structures in acceptance region
  - 75 µm thin sensors with 7.68 million pixels
  - Impact parameter resolution 15 µm
- Assembly
  - Sensors + ASICS developed and produced at Max Planck Halbleiterlabor
  - Kapton mounting + ladder gluing at MPP
  - Module testing, characterizing, and optimizing at MPP
  - System testing at DESY
- PXD1 (1 layer + 2 ladders) successfully operated during Run 1
- PXD2 (full 2 layers) installed for Run 2



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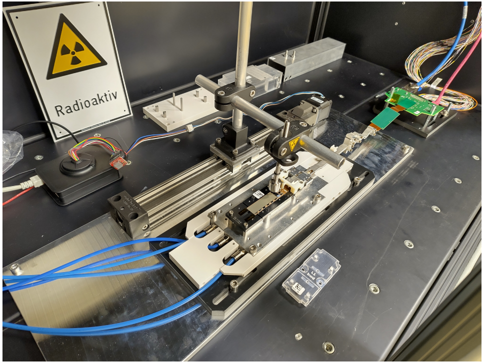

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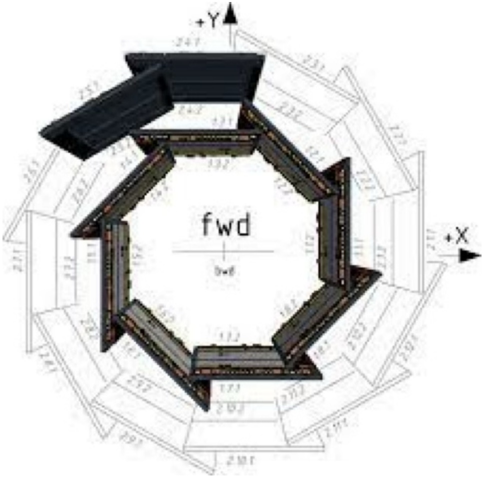

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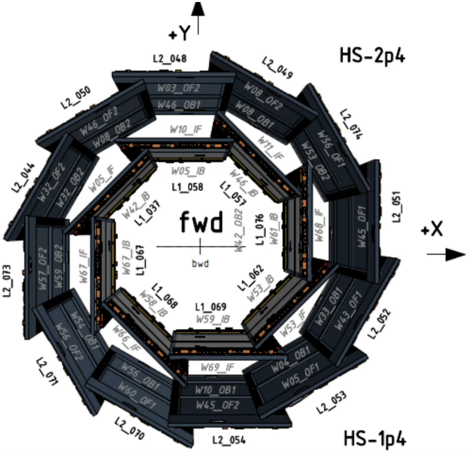

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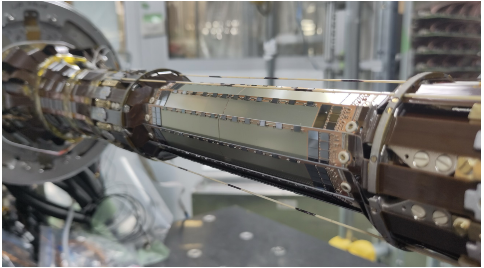

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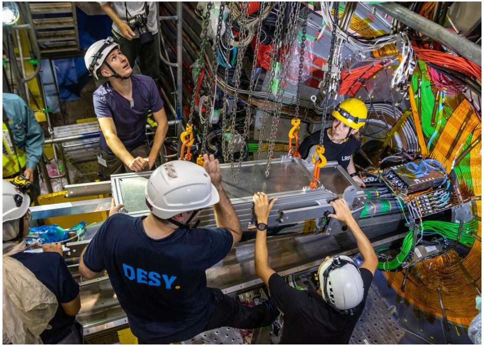
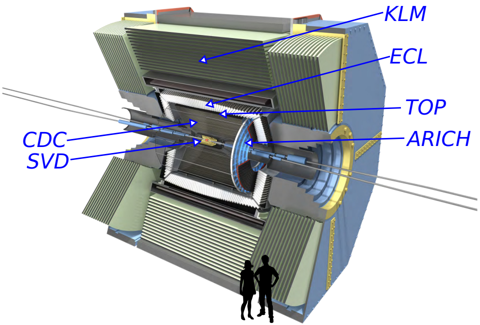


Contributions to Particle Identification

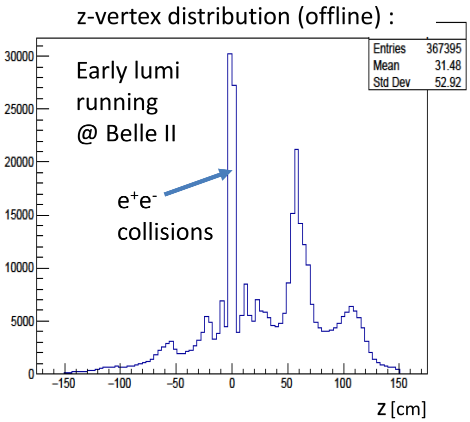
- Information from various subdetectors must be combined to identify species of charged particles
- Conventional approach based on likelihoods is imperfect
- Developed novel neural-network based approach to combine subdetector information
- For example, improvement in π identification efficiency by up to 20 %
- Becoming the standard particle identificaciton approach at Belle II



Contributions to the Trigger

[C. Kiesling, F. Meggendorfer, T. Forsthofer, S. Hiesl, et al.]

- Track trigger challenging due to beam background
  - Background tracks not from interaction point
  - Higher luminosity $\Rightarrow$ higher background
- Requires information on z position at L1 trigger to reduce trigger rate
- Developed neural network to form neural track
  - Part for every track trigger at Belle II
  - Further improvements ongoing
- Trigger on events with a low number of charged particles challenging
  - Interesting for τ physics, for dark-matter searches, ...
  - Use neural tracks to trigger on a single track
    - ➡ Outperforms multi-track triggers
- Development of trigger for vertices displaced from the interaction point



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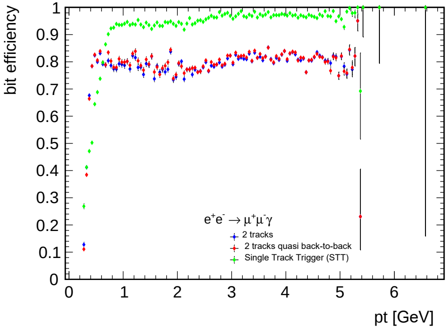

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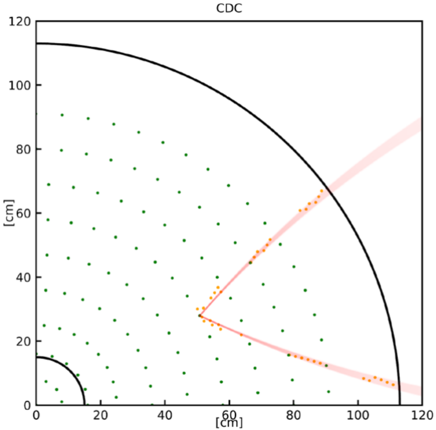
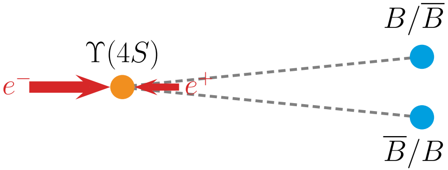


Measurement of CP Violation in B^0 Decays

- B^0 mesons are produced in pairs
  - Flavor-specific decay of tag $\overline{B}^0$ fixes flavor of signal B^0 at t_1
- Signal B^0 oscillates and decays at $t_2 = t_1 + \Delta t$
- Time dependent CP violating asymmetry between B^0 and $\overline{B}^0$ decays

$$f_{CP}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} [1 + q(S_{CP} \sin(\Delta m_d \Delta t) - C_{CP} \cos(\Delta m_d \Delta t))]$$

- Requires precises measurement of Δt by measuring displacement between decay vertices



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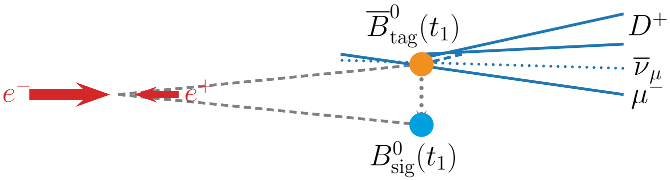

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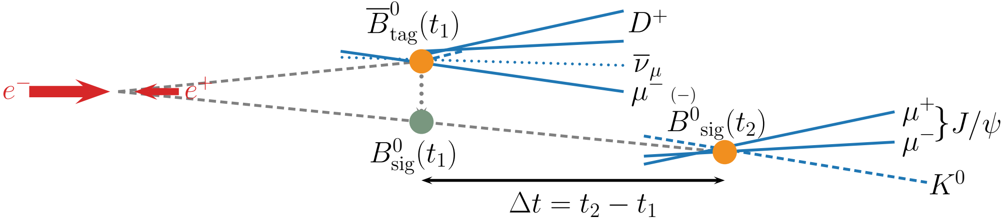

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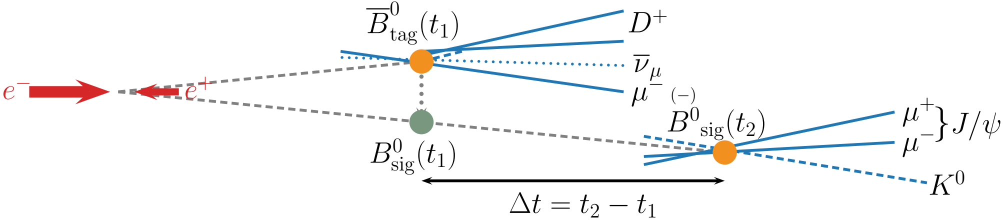

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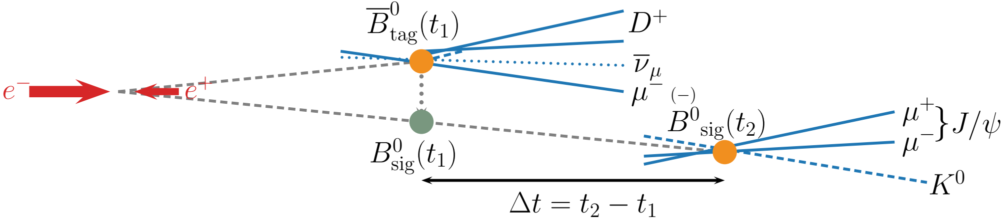

Measurement of CP Violation in B^0 Decays

[T. Humair, O. Tittel, et al.]

$B^0 \to J/\psi K_S^0$

- Golden channel: $B^0 \to J/\psi K_S^0$
  - $S_{CP} = \sin(2\beta)$
  - $C_{CP} \approx 0$
- Analysis on full Run 1 Belle II sample [PRD 110 (2024) 012001]
  - $S_{CP} = \quad 0.724 \pm 0.035 \pm 0.014$
  - $C_{CP} = -0.035 \pm 0.026 \pm 0.012$
- Improved precision compared to Belle for same sample size
- Comparable precision as BaBar measurement

Measurement of CP Violation in B^0 Decays

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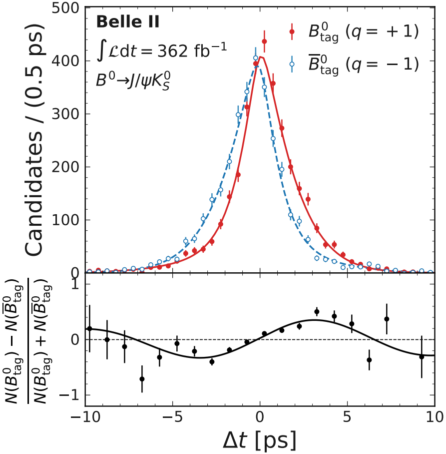
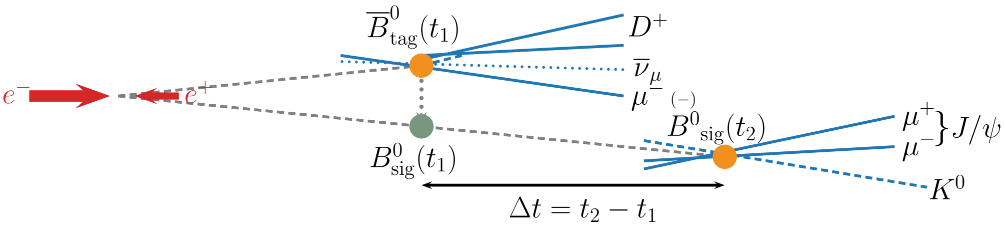


- The $B^0/\overline{B}^0$ oscillations can be measured by identifying the flavor of tag and signal B to be the same
- Fully entangled system

$$P_{\mathrm{E}}(B^0B^0,\,\overline{B}^0\,\overline{B}^0) = \frac{1}{4}\Gamma e^{-\Gamma|\Delta t|}[1 - 1\cos(\Delta m\Delta t)]$$

- Spontaneous Disentanglement
  - If entanglement breaks down (spontaneously or time dependent), time dependence is altered



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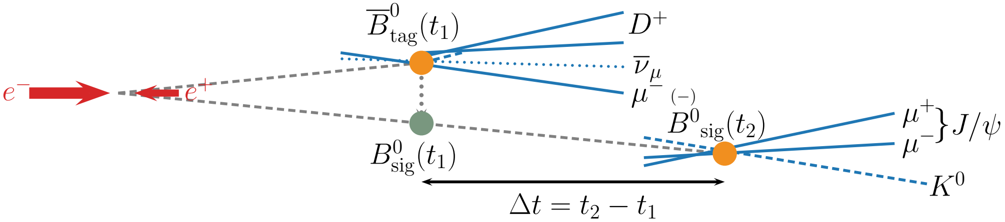

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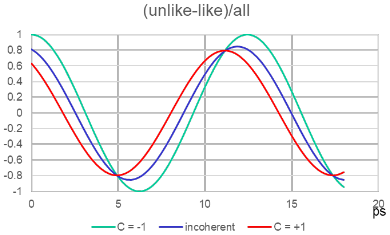
$$P_{\mathrm{SD}}(B^0B^0, \overline{B}^0\,\overline{B}^0) = \frac{1}{4}\Gamma e^{-\Gamma|\Delta t|}[1 - \frac{\Gamma^2\Delta m^2}{2\Gamma^2+2\Delta m^2}\cos(\Delta m\Delta t) + \frac{\Gamma\Delta m}{2\Gamma^2+2\Delta m^2}\sin(\Delta m|\Delta t|)]$$



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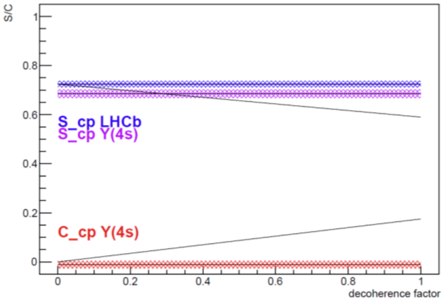
  - May explain deviation between S_{CP} measurement from LHCb and B-factories
- Test Entanglement in $B^0 \to D^-\pi^+$ decays
  - ✓ Event selection and resolution function from Δm measurement
  - ✓ Modified time dependence
  - ✓ Signal MC studies
  - ⌛ Background
  - ⌛ Sensitivity tests, bias, systematics



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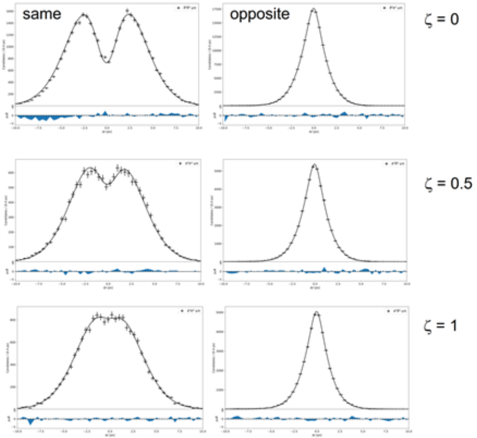
  - ✓ Event selection and resolution function from Δm measurement
  - ✓ Modified time dependence
  - ✓ Signal MC studies
  - ⌛ Background
  - ⌛ Sensitivity tests, bias, systematics



- So far, all B-factory analyses assume 100 % entanglement. Deviations (few %) would lead to systematic errors $\sin(2\beta)$
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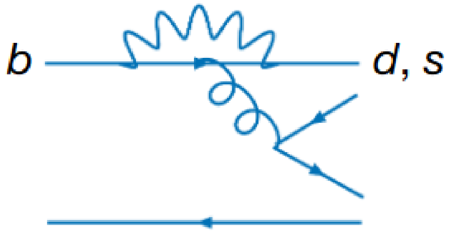
Entanglement in $\Upsilon(5S) \to B\bar{B}^{(*)}$

- Possibility to measure absolute decay times
  - ➥ Discriminate different entanglement mechanisms
- More options due to separable $C = -1$ and $C = +1$ states
- Higher energy and $B^* \to B\gamma$ transitions may lead to disentanglement

- B meson decays to final states without charm quarks proceed via $b \to s$ transitions
- Rare in the Standard Model $\Rightarrow$ sensitive to New Physics
- Combination of asymmetries in isospin-related $B \to K\pi$ decays offers Standard Model null test [PLB 627 (2005) 82]

$\mathcal{A}^{CP}_{K^+\pi^-}$



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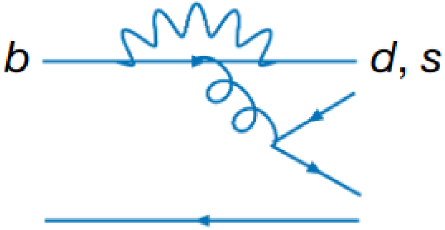

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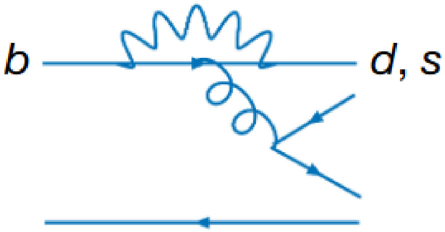
$$\mathcal{A}^{CP}_{K^+\pi^-} + \mathcal{A}^{CP}_{K^0\pi^+} \frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^+\pi^0} \frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^0\pi^0} \frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$



- Three of the four decay channels analyzed at MPP
- Result $-0.03 \pm 0.13 \pm 0.05$

  [PRD 109 (2024) 012001]
- Consistent with Standard Model prediction
  - Theory precision $\mathcal{O}(0.01)$

- Goal: Test isospin sum rule also for $B \to K^*\pi$ decays
- K^* further decays to $K\pi$ $\Rightarrow$ $B \to K\pi\pi$ decays
- Challenge: Other contributions to $B \to K\pi\pi$ decays

$$\begin{aligned} B &\to K^*\pi &&\to K\pi\pi \\ &\to \rho K &&\to K\pi\pi \\ &\to \dots &&\to K\pi\pi \end{aligned}$$

- Very short lifetime of intermediate states (K^*, ρ)
  - ➡ Different decay chains interfere which each other
  - ➡ Measuring branching fractions and CP asymmetries of $B \to K^*\pi$ contribution requires partial-wave analysis (Dalitz-Plot analysis)
    - Modeling full phase-space distribution of $K\pi\pi$ final state

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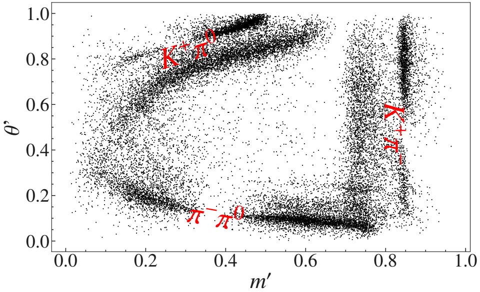
Measuring Asymmetries in $B \to K^*\pi$ Decays

- Rich structure in phase-space distribution (Daliz-Plot) representing different decay chains
- All four isospin-related $B \to K^*\pi$ decays
  - $B^0 \to K^{*+}\pi^-$
  - $B^0 \to K^{*0}\pi^0$
  - $B^+ \to K^{*+}\pi^0$
  - $B^+ \to K^{*0}\pi^+$

  can be obtained by analyzing two final states
  - $B^0 \to K^+\pi^-\pi^0$
  - $B^+ \to K_S^0\pi^+\pi^0$
- Monte Carlo input-output studies yield consistent results



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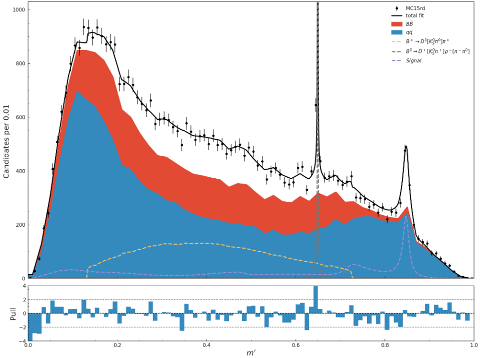

Search for Exotic Heavy Mesons in $B \to J/\psi K\pi$ Decays

[M. Bartl, S. Wallner, et al.]

- Meson resonance structure in multi-body hadronic B decays allows us to study meson resonances
- $J/\psi h$ system, e.g. $J/\psi K$, potentially contains exotic non-$q\bar{q}'$ meson resonances
- Partial-wave analysis of $B \to J/\psi\pi K$ decays just started
  - Also important input to $b \to s\ell\ell$ anomaly searches
- Challenge: Higher dimensionality of phase-space distribution due to spin of J/ψ

Hadron Spectroscopy

- Multi-body hadronic τ decays provide clean environment to study light mesons
- Partial-wave analysis necessary to isolate resonance contributions and identify their quantum numbers
- $\tau^{\mp} \to \pi^{\mp}\pi^{\mp}\pi^{\pm} \overset{(-)}{\nu_\tau}$ dominated by a_1-like mesons
  - High precision measurement of $a_1(1260)$ parameters
  - Confirmation of $a_1(1420)$ signal observed by COMPASS
- Partial-wave formalism established
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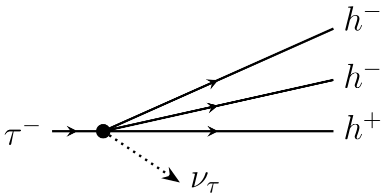

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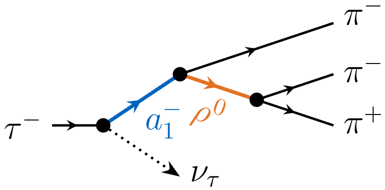

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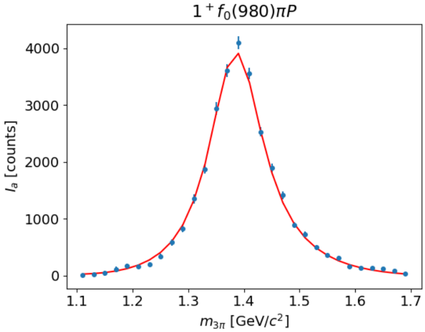

Fit Result; Input Model

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Search for Lepton-Flavor Violation

- Search for lepton-flavor violating $\tau^- \to \ell^- \alpha$ decay without ν_τ

  [PRL 130 (2023) 181803]

Summary

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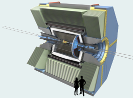
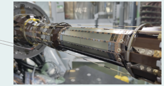
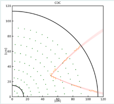
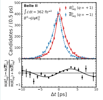
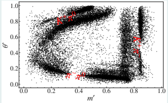
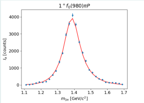
- Development and production of the DEPFET pixel detector
  - Main German contribution to the Belle II detector lead by MPP
- MPP contributes to trigger and particle-identification performance of Belle II
- Run 1 data taking finished
  - 58 publications
  - World leading results
- Broad physics program with strong contribution from MPP
  - Flavor physics and *CP* violation
  - Entanglement
  - τ physics
  - Hadron spectroscopy
- Data sample will increase by a factor of 100 in the next decade
  - ➥ Unique physics opportunities

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