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for the COMPASS Collaboration

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Technische Universität München,
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DPG Frühjahrstagung 2012
Mainz, 19.03.2012
Gruppenbericht HK 8.1
The COMPASS Physics Program

**Goal**
- Study non-perturbative regime of QCD
- Probe structure and dynamics of hadrons

**Very low \(Q^2\):**
- Chiral dynamics
  - \(\pi\) and \(K\) em. polarizabilities
  - \(\pi\gamma^*\) reactions (Primakoff)

**Intermediate \(Q^2\):**
- Spectroscopy
  - Mass spectrum of hadrons
  - Gluonic excitations

**Large \(Q^2\):**
- Nucleon structure
  - Helicity, transversity PDFs
  - Generalized PDFs

HK 23.1 J. M. Friedrich

Plenary Talk: PV III F. Nerling
1. The experimental setup

2. Search for spin-exotic mesons
   - PWA of $\pi^- \pi^+ \pi^-$ from $\pi^-$ diffraction
   - PWA of $\pi^- \eta$ and $\pi^- \eta'$ from $\pi^-$ diffraction
   - PWA of $\pi^- \pi^+ \pi^- \pi^+$ from $\pi^-$ diffraction

3. Search for scalar glueballs
   - PWA of $\pi^+ \pi^-$ from central production
Outline

1 The experimental setup

2 Search for spin-exotic mesons
   - PWA of $\pi^- \pi^+ \pi^-$ from $\pi^-$ diffraction
   - PWA of $\pi^- \eta$ and $\pi^- \eta'$ from $\pi^-$ diffraction
   - PWA of $\pi^- \pi^+ \pi^- \pi^+ \pi^-$ from $\pi^-$ diffraction

3 Search for scalar glueballs
   - PWA of $\pi^+ \pi^-$ from central production
Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- > 1 PByte/year
The COMPASS Experiment at the CERN SPS

Experimental Setup

Fixed-target experiment
- Two-stage spectrometer
- Large acceptance over wide kinematic range
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Hadron spectroscopy
- 190 GeV/c secondary hadron beams
  - $h^{-}$ beam: 97% $\pi^{-}$, 2% $K^{-}$, 1% $\bar{p}$
  - $h^{+}$ beam: 75% $p$, 24% $\pi^{+}$, 1% $K^{+}$
- Various targets: $\ell H_{2}$, Ni, Pb, W

190 GeV/c secondary hadron beams

190 GeV/c secondary hadron beams
The experimental setup
Search for spin-exotic mesons
Search for scalar glueballs

The COMPASS Experiment at the CERN SPS
Experimental Setup

NIM A 577, 455 (2007)

Spectrometer upgrades for 2008 run
- Recoil proton detector (RPD)
- Beam particle identification
- Electromagnetic calorimetry
- Tracking at forward angles

Hadron spectroscopy

- 190 GeV/c secondary hadron beams
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   - PWA of $\pi^-\pi^+\pi^-$ from $\pi^-$ diffraction
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   - PWA of $\pi^+\pi^-$ from central production
The experimental setup
Search for spin-exotic mesons
Search for scalar glueballs

PWA of $\pi^− \pi^+ \pi^−$ from $\pi^−$ diffraction
PWA of $\pi^− \eta$ and $\pi^− \eta'$ from $\pi^−$ diffraction
PWA of $\pi^− \pi^+ \pi^− \pi^+$ from $\pi^−$ diffraction

Mesons in the Constituent Quark Model

Spin-parity rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative orbital angular Momentum $\vec{L}$ and total spin $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- Forbidden $J^{PC}$: $0^{--}$, $0^{+-}$, $1^{-+}$, $2^{+-}$, $3^{--}$, ...

QCD allows for states beyond the CQM

- Hybrids $|q\bar{g}\rangle$, glueballs $|g\bar{g}\rangle$, multi-quark states $|q^2\bar{q}^2\rangle$, ...
- Physical mesons: superposition of all allowed basis states
- “Exotic” mesons have quantum numbers forbidden for $|q\bar{q}\rangle$
  - Particularly interesting: $J^{PC}$-exotic states
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PWA of $\pi^-\pi^-\pi^-\pi^+$ from $\pi^-$ diffraction

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Hadron Spectroscopy with COMPASS
Mesons in the Constituent Quark Model

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Production of Hadrons in Diffractive Dissociation

- Soft scattering of beam hadron off nuclear target (remains intact)
  - Beam particle is excited into some intermediate state $X$
  - $X$ decays into $n$-body final state

- High $\sqrt{s}$ and low $t$: Pomeron exchange dominates strong interactions
- Rich spectrum: large number of overlapping and interfering states
- Goal: use kinematic distribution of final-state particles to
  - Disentangle all resonances $X$
  - Determine their mass, width, and quantum numbers

- Method: partial-wave analysis (PWA)
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Diffractive Dissociation of $\pi^-$ into $\pi^- \pi^+ \pi^-$ Final State

Isobar model: $X^-$ decay is chain of successive two-body decays

- "Wave": unique combination of isobar and quantum numbers
- Full wave specification (in reflectivity basis): $J^{PC} M^\epsilon [\text{isobar}] L$

Fit model: $\sigma(m_X, \tau) = \sigma_0 \left| \sum_{\text{waves}} T_{\text{wave}}(m_X) A_{\text{wave}}(m_X, \tau) \right|^2$

- Transition amplitudes $T_{\text{wave}}(m_X)$ determined from multi-dimensional fit to final-state kinematic distributions taking into account interference effects
Diffractive Dissociation of $\pi^-$ into $\pi^- \pi^+ \pi^-$ Final State

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PWA of $\pi^- \pi^+ \pi^- \pi^+$ from $\pi^-$ diffraction

**PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$**

- 190 GeV/c negative hadron beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
- Liquid hydrogen target
- Recoil proton measured by RPD
- Kinematic range $0.1 < t' < 1.0 \ (GeV/c)^2$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

World's largest $3\pi$ data set: **96 M events**

- Challenging analysis
  - Needs precise understanding of apparatus
  - Model deficiencies become visible
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$\pi^- \pi^+ \pi^-$ invariant mass distribution
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PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

World’s largest 3$\pi$ data set: **96 M events**

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$\pi^- \pi^+ \pi^-$ invariant mass distribution

Dalitz plot for $\pi_2(1670)$ region

**COMPASS**

COMPASS 2008
$\pi^- p \rightarrow \pi^- \pi^+ p$
$0.1 \text{ GeV}^2c^2 < t' < 1.0 \text{ GeV}^2c^2$
w/o acceptance correction

$\text{Im}_3 \pi < 0.130 (\text{GeV}/c^2)$

$\pi^- p \rightarrow \pi^- \pi^+ p$
$0.1 \text{ GeV}^2c^2 < t' < 1.0 \text{ GeV}^2c^2$
w/o acceptance correction

preliminary

preliminary

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Hadron Spectroscopy with COMPASS
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

\[
\begin{align*}
\pi^-(1260) & \quad \left( a_1(1260) \right) \\
\pi^+(1670) & \quad \left( \rho^- \pi^+ \right)
\end{align*}
\]
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

1$^+ + 0^+ [\rho \pi] S : a_1(1260)$

COMPASS 2008
$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

Mass of $\pi^- \pi^+ \pi^- System (GeV/c^2)$

Events/(5 MeV/c^2)

$\pi_1(1260)$

$\pi_2(1320)$

$\pi_3(1670)$

COMPASS 2008
$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

Mass of $\pi^- \pi^+ \pi^- System (GeV/c^2)$

Events/(20 MeV/c^2)

$1^+ + 0^+ [\rho \pi] S$

preliminary
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

1$^{++}$ 0$^+$ $[\rho \pi] S : a_1(1260)$

2$^{++}$ 1$^+$ $[\rho \pi] D : a_2(1320)$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

\[\pi^- \pi^+ \pi^-\] invariant mass spectrum

1\(^{++}\) 0\(^{+}\) $[\rho \pi] S : a_1(1260)$

2\(^{-+}\) 0\(^{+}\) $[f_2 \pi] S : \pi_2(1670)$

2\(^{++}\) 1\(^{+}\) $[\rho \pi] D : a_2(1320)$
**PWA of** \( \pi^- p \rightarrow \pi^- \pi^+ \pi^- p \)

\( \pi^- \pi^+ \pi^- \) invariant mass spectrum

- Data described by **model consisting of 52 waves**
  + **Incoherent isotropic background**
- **Isobars:** \((\pi \pi)_S\)-wave, \(f_0(980), \rho(770), f_2(1270), f_0(1500)\)
  and \(\rho_3(1690)\)

\[ 2^{-+} 0^+ \ [f_2 \pi] S : \pi_2(1670) \]

\[ 1^{++} 0^+ \ [\rho \pi] S : a_1(1260) \]

\[ 2^{++} 1^+ \ [\rho \pi] D : a_2(1320) \]

PWA of \( \pi^- \pi^+ \pi^- \) from \( \pi^- \) diffraction

PWA of \( \pi^- \eta \) and \( \pi^- \eta' \) from \( \pi^- \) diffraction

PWA of \( \pi^- \pi^+ \pi^- \pi^+ \pi^- \) from \( \pi^- \) diffraction

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**COMPASS Data**

Isobars:
- \((\pi \pi)_S\)-wave, \(f_0(980), \rho(770), f_2(1270), f_0(1500)\)
- \(\rho_3(1690)\)

Understanding of small waves is work in progress

Significant contributions from Deck-like processes

\( t' \)-dependence of partial-wave amplitudes important
The experimental setup
Search for spin-exotic mesons
Search for scalar glueballs

PWA of $\pi^- \pi^+ \pi^-$ from $\pi^-$ diffraction
PWA of $\pi^- \eta$ and $\pi^- \eta'$ from $\pi^-$ diffraction
PWA of $\pi^- \pi^+ \pi^- \pi^+ \pi^-$ from $\pi^-$ diffraction

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**PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$**

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

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  + incoherent isotropic background
- **Isobars:** $(\pi \pi)_S$-wave, $f_0(980)$, $\rho(770)$, $f_2(1270)$, $f_0(1500)$ and $\rho_3(1690)$

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Significant contributions from Deck-like processes
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PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

$2^{-+} 0^+ [f_2 \pi] S : \pi_2(1670)$

$2^{-+} 0^+ \pi_2(1670)$

COMPASS 2008
$\pi^p \rightarrow \pi^\pi^\pi^p$
$0.1 \text{ GeV}^2/c^2 < t < 1.0 \text{ GeV}^2/c^2$

420 000 events
Pb target
Selection of exclusive events with 3 charged tracks + 2 photons

- $\eta$ reconstructed from $\eta \rightarrow \pi^+ \pi^- \pi^0$
- $\eta'$ reconstructed via $\pi^+ \pi^- \eta$ decay with $\eta \rightarrow \gamma \gamma$

$\gamma \gamma$ mass distribution
PWA of $\pi^- p \to \pi^- \eta p$ and $\pi^- \eta' p$

Selection of exclusive events with 3 charged tracks + 2 photons

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$\gamma\gamma$ mass distribution

$\pi^- \eta$ mass distribution
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Selection of exclusive events with 3 charged tracks + 2 photons
- $\eta$ reconstructed from $\eta \rightarrow \pi^+ \pi^- \pi^0$
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$\pi^+ \pi^- \eta$ mass distribution

$\pi^- \eta$ mass distribution

COMPASS 2008
$\pi p \rightarrow \pi \pi \pi^+ \eta p$

w/o acceptance correction

preliminary

COMPASS 2008
$\pi^+ \eta (\pi \pi^+ \pi^0)p$

w/o acceptance correction

preliminary
The experimental setup
Search for spin-exotic mesons
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PWA of $\pi^- p \rightarrow \pi^- \eta p$ and $\pi^- \eta' p$

Selection of exclusive events with 3 charged tracks + 2 photons

- $\eta$ reconstructed from $\eta \rightarrow \pi^+ \pi^- \pi^0$
- $\eta'$ reconstructed via $\pi^+ \pi^- \eta$ decay with $\eta \rightarrow \gamma \gamma$

$\pi^- \eta'$ mass distribution

$\pi^- \eta$ mass distribution

COMPASS 2008
$\pi p \rightarrow \pi^- \eta' (\pi^+ \pi^- \gamma \gamma) p$

COMPASS 2008
$\pi p \rightarrow \pi^- \eta (\pi^+ \pi^- \pi^0) p$

preliminary
PWA of $\pi^- p \rightarrow \pi^- \eta' p$

Spin-exotic $1^{-+} 1^+$

- $1^{-+} 1^+$ is dominant wave
- Slight phase motion w.r.t. $2^{++} 1^+$
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PWA of $\pi^- p \rightarrow \pi^- \eta' p$

Spin-exotic $1^{-+} 1^+$

$2^{++} 1^+ - 1^{-+} 1^+$

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PWA of $\pi^- p \rightarrow \pi^- \eta p$

**Spin-exotic $1^- + 1^+$**

- $1^- + 1^+$ much smaller
- $2^{++} 1^+$ is dominant wave
- Slight phase motion of $1^- + 1^+$ w.r.t. $2^{++} 1^+$

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**COMPASS 2008**

$\pi p \rightarrow \pi \eta p$
PWA of $\pi^- p \rightarrow \pi^- \eta p$

Spin-exotic $1^{-+} 1^+$

$2^{++} 1^+ : a_2(1320)$

$1^{-+} 1^+ - 2^{++} 1^+$

- $1^{-+} 1^+$ much smaller
- $2^{++} 1^+$ is dominant wave
- Slight phase motion of $1^{-+} 1^+$ w.r.t. $2^{++} 1^+$
PWA of $\pi^- p \to \pi^- \eta p$ and $\pi^- \eta' p$

Work in progress

- Resonance interpretation of $1^{-+} 1^+$ requires understanding of resonance structure of $2^{++} 1^+$ wave
- First mass-dependent fits (HK 8.2 T. Schlüter)
- Final goal: combined analysis of both channels
PWA of $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

First mass-dependent analysis of this channel

- **Light-meson frontier:** access to mesonic states in 2 GeV/$c^2$ region
- Little information from previous experiments

Data from pilot run

- Pb target
- Recoil not measured
- Kinematic range $t' < 5 \cdot 10^{-3}$ (GeV/$c$)$^2$
PWA of $\pi^-\text{Pb} \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-\text{Pb}$

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PWA of $\pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

Fit model

- Complicated isobar structure
  - Large number of possible waves
  - Data exhibit no dominant waves
- Exploration of model space using evolutionary algorithm based on goodness-of-fit criterion
  - 284 waves tested
  - Also provides estimate for systematic uncertainty from fit model
- Best model: 31 waves + incoherent isotropic background
- Isobars
  - $(2\pi)^0$ isobars: $(\pi\pi)_{S-\text{wave}}, \rho(770)$
  - $(3\pi)^\pm$ isobars: $a_1(1260), a_2(1320)$
  - $(4\pi)^0$ isobars: $f_0(1370, 1500), \rho'(1450, 1700), f_1(1285), f_2(1270)$
    - Only few information available for $(4\pi)^0$ isobars
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PWA of $\pi^- \mathrm{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \mathrm{Pb}$

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PWA of $\pi^- \text{ Pb } \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{ Pb}$

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PWA of $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

COMPASS 2004
$\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

width (GeV/c²)

mass (MeV/c²)

$\pi(1300)$
$a_1(1900)$
$\pi_2(2100)$
$a_1(2200)$
$\pi_2(1670)$
$\pi_2(1880)$
$\pi(1800)$

HK 8.4 S. Neubert

PRELIMINARY
Proof of Principle: First mass-dependent full five-body PWA

- Rather simplistic fit model
  - Spin-density sub-matrix of 10 waves described using 7 resonances + background terms
  - Parameterization by sum of relativistic constant-width Breit-Wigners
  - Mixing and coupled-channel effects neglected
  - Multi-peripheral processes (Deck-effect) not taken into account
- Good description of data

Work in progress

- Much more data on tape
  - Proton target, kinematic range $0.1 < t' < 1$ (GeV/c)$^2$
- Improvement of fit models
Proof of Principle: First mass-dependent full five-body PWA

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   - PWA of $\pi^{-}\pi^{+}\pi^{-}$ from $\pi^{-}$ diffraction
   - PWA of $\pi^{-}\eta$ and $\pi^{-}\eta'$ from $\pi^{-}$ diffraction
   - PWA of $\pi^{-}\pi^{+}\pi^{-}\pi^{+}\pi^{-}$ from $\pi^{-}$ diffraction

3. Search for scalar glueballs
   - PWA of $\pi^{+}\pi^{-}$ from central production
Search for glueballs

- Mesonic state with no valence quarks
- Lattice QCD simulations predict lightest glueball to be scalars
  - Strong mixing with conventional scalar mesons expected
  - Difficult to disentangle
- Pomeron-Pomeron processes well-suited to study scalar mesons

PWA of \( p p \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}} \)
The experimental setup
Search for spin-exotic mesons
Search for scalar glueballs

PWA of $p p \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}}$

**Selection of central events:**

- Cut $m(p_{\text{fast}} \pi^\pm), m(p_{\text{slow}} \pi^\pm) > 1.5 \text{ GeV/c}^2$

**Preliminary**

COMPASS 2009
$p p \rightarrow p_1 \pi^+ \pi^- p_2$,
$W33 (~30\% \text{ of 2009})$

Not acceptance corrected
The experimental setup
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PWA of $pp \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}}$

Selected central events

$\chi_F$ distribution

$\pi^+ \pi^-$ invariant mass
The experimental setup
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PWA of $\pi^+\pi^-$ from central production

PWA of $pp \rightarrow p_{\text{fast}}\pi^+\pi^- p_{\text{slow}}$

COMPASS 2009
$pp \rightarrow p_{t}\pi^+\pi^- p_{s}$
Proof of concept

- Analysis similar to previous experiments (WA102)
  - Comparable results
- Simplistic fit model
  - Angular information of the two proton scattering planes not taken into account
- 8 different mathematically ambiguous solutions
  - Additional constraints needed to select physical solution
- Next step: mass-dependent fit
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PWA of $\pi^+ \pi^-$ from central production

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COMPASS has acquired world’s largest data sets for many channels

- **Main focus on search for** $J^{PC}$-exotic mesons
  - Pilot run: significant $J^{PC} = 1^{-+}$ signal consistent with $\pi_1(1600)$ seen in $\pi^-\pi^+\pi^-$ data on Pb target
  - Detailed study of $\pi^-\pi^+\pi^-$ final state
    - Full two-dimensional analysis in $m_{\pi^-\pi^+\pi^-}$ and $t'$
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  - $\eta\pi^-$ and $\eta'\pi^-$ data similar to previous experiments
    - Mass-dependent fits underway
  - First full $\pi^-\pi^+\pi^-\pi^+\pi^-$ PWA
    - $\pi(1800)$ and $\pi_2(1670)$ seen
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    - Results similar to previous experiments
  - Further analyses
    - $K^-$ diffractive into $K^-\pi^+\pi^-$
    - $(\pi\pi K\bar{K})^-$, …
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**References**

- PRL 104 (2010) 241803
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