From Pions to Kaons - Hadron Spectroscopy from COMPASS to AMBER

Mathias Wagner
on behalf of the COMPASS collaboration
and COMPASS++/AMBER

HISKP, Bonn University

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at the IWHSS19 Aveiro

supported by BMBF
Motivation

The COMPASS experiment

$3\pi$ PWA

Freed-isobar analysis

Exotic $\pi_1(1600)$

RF-separated kaon beam

Conclusion & outlook
Why Hadron Spectroscopy?
Motivation

[To be published in Progress in Particle and Nuclear Physics]

Hadron Spectroscopy from COMPASS to AMBER (4/30)

Mathias Wagner (Uni Bonn, HISKP)

QM not assigned

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Motivation

[To be published in Progress in Particle and Nuclear Physics]

Hadron Spectroscopy from COMPASS to AMBER (4/30)
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[To be published in Progress in Particle and Nuclear Physics]

Hadron Spectroscopy from COMPASS to AMBER
The COMPASS Experiment
The COMPASS Experiment

- Secondary hadron beam, mostly $\pi^-$ ($\sim 97\%$)
  - $E_{\text{beam}} = 190$ GeV
  - Liquid hydrogen target (40 cm)
  - $\pi^- + p \rightarrow \pi^- + \pi^- + \pi^+ + p$
  - $\pi^- + p \rightarrow \eta'(\pi^0) + \pi^- + p$

[COMPASS, NIM A779, 69-115 (2015)]
COMPASS

$3\pi$ PWA
Isobar model: $X^- \rightarrow \pi^- + \xi^0 \rightarrow \pi^- + \pi^+ + \pi^-$

Data binned in 100 $m_{3\pi}$ and 11 $t' = |t| - |t|_{\text{min}}$ slices

PWA with 88 waves [COMPASS, PRD 95, 032004 (2017)]

**Diagram:**
- **P:** Pomeron
- **X:** Resonance with $J^{PC}$
- **\(\xi\):** Isobar

**Graph:**
- Events / (5 MeV/c²)
- $m_{3\pi}$ [GeV/c²]
- Peaks at $a_1(1260)$, $a_2(1320)$, $\pi_2(1670)$
Isobar model: $X^- \rightarrow \pi^- + \xi^0 \rightarrow \pi^- + \pi^+ + \pi^-$

Data binned in 100 $m_{3\pi}$ and 11 $t' = |t| - |t|_{\text{min}}$ slices

PWA with 88 waves [COMPASS, PRD 95, 032004 (2017)]
Naming scheme:

\[ I^G(J^{PC}) M^\varepsilon \xi \pi L \]

- \( I^G = 1^- \)
- \( J \leq 6, M \in \{0, 1, 2\} \)
- \( PC = ++ \) for \( J \geq 1 \),
  \( PC = -- \) for \( J \geq 0 \)
- 80 waves \( \varepsilon = + \)
- \( L \leq 6 \)
- Isobars \( \xi \):
  \( (\pi\pi)_S, \rho(770), f_0(980), f_2(1270), f_0(1500), \rho_3(1690) \)
  fixed shape (Breit-Wigner)
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\( 1^-(1^-+)1^+ \rho\pi P\)-wave!

We have access to exotic mesons
Maximize the likelihood function:

\[ \mathcal{L} = \frac{N_e^N}{N!} \exp(-N_e) \prod_{k=1}^{N} \frac{I(\tau_k)}{N_e}, \]

\[ N_e = \int I(\tau) \zeta(\tau) d\tau, \]

with \( \tau = (s_0, m_{3\pi}^2, t, \Omega_X, m_{2\pi}^2, \Omega_\xi) \)
Maximum-Likelihood Fit

- Maximize the likelihood function:
  \[ L = \frac{N_e^N}{N!} \exp(-N_e) \prod_{k=1}^{N} \frac{l(\tau_k)}{N_e}, \]  \[ N_e = \int l(\tau) \eta(\tau) d\tau, \]
  with \( \tau = (s_0, m_{3\pi}^2, t, \Omega_X, m_{2\pi}^2, \Omega_\xi) \)

- Define intensity function (strongly simplified!):
  \[ I(\tau) = |A(\tau)|^2 = \left| \sum_{JMLS} A_{LS}^{JM}(\tau) \right|^2 \]
  with the amplitude \( A \) separated in partial waves (\( J^{PC} M^\varepsilon \xi \pi L \)):
  \[ A_{LS}^{JM}(\tau) = F_{LS}^{JM}(s_0, m_{3\pi}^2, t) \cdot \psi_{LS}^{JM}(m_{2\pi}^2, \Omega_X, \Omega_\xi) \]
  const per (\( m_{3\pi}, t' \))-bin
Maximize the likelihood function:

\[ L = \frac{N_e^N}{N!} \exp(-N_e) \prod_{k=1}^{N} \frac{I(\tau_k)}{N_e}, \quad N_e = \int I(\tau)\zeta(\tau)d\tau, \]

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\[ A_{LS}^{JM}(\tau) = F_{LS}^{JM}(s_0, m_{3\pi}^2, t) \cdot f_S^\xi(m_{2\pi}^2)Z_{LS}^{JM}(\Omega_{GJ}, \Omega_H) \]
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- Extract the spin density matrix
  \[ \rho^{(JM)(J'M')}_{(LS)(L'S')} = F_{LS}^{JM} \left( F_{L'S'}^{J'M'} \right)^* = \begin{pmatrix}
  l_{w1} & \Phi_{w1}^{w2} & \cdots \\
  (\Phi_{w1}^{w2})^* & l_{w2} & \cdots \\
  \vdots & \vdots & \ddots
\end{pmatrix} \]
Fit of $m_{3\pi}$-Dependence (Example)

Example: $a_2(1320)$
- $2^{++}1^+ \rho \pi D$
- $2^{++}2^+ \rho \pi D$
- $2^{++}1^+ f_2(1270)\pi P$

$$\rho = \begin{pmatrix} I_{w1} & \Phi_{w1}^{w2} & \Phi_{w1}^{w3} \\ \Phi_{w1}^{w2} & I_{w2} & \Phi_{w2}^{w3} \\ \Phi_{w1}^{w3} & \Phi_{w2}^{w3} & I_{w2} \end{pmatrix}$$

[COMPASS, PRD 98 (2018) 092003]
Fit of $m_{3\pi}$-Dependence (Example)

Example: $a_2(1320)$
- $2^{++}1^+\rho\pi D$
- $2^{++}2^+\rho\pi D$
- $2^{++}1^+f_2(1270)\pi P$

Parametrized by relativistic Breit-Wigner

$$\rho = \left( \begin{array}{ccc} I_{w1} & \Phi^{w2}_{w1} & \Phi^{w3}_{w1} \\ I_{w2} & \Phi^{w3}_{w2} & \Phi^{w3}_{w2} \end{array} \right)$$

Good approximation if isolated resonance

[COMPASS, PRD 98 (2018) 092003]
Resonance Parameters

\[ \pi, a_1, \pi_1, a_2, \pi_2, a_4 \]

Mass and width [MeV/c^2]

[COMPASS, PRD 98 (2018) 092003]

- previous measurements
- COMPASS
- decay width
- color: different excitations
COMPASS

Freed-Isobar Analysis
Basic Idea

- Not only slices in $m_{3\pi}$ and $t'$, but also in $m_{2\pi}$

[F. Krinner]
Basic Idea

Freed-Isobar Analysis

- Not only slices in $m_{3\pi}$ and $t'$, but also in $m_{2\pi}$
- Keep $F$ and $f$ as free complex fit parameters

$$A_{LS}^{JM}(\tau) = F_{LS}^{JM}(s_0, m_{3\pi}^2, t) \cdot f_\xi (m_{2\pi}^2) Z_{LS}^{JM}(\Omega_{GJ}, \Omega_{H})$$

fixed per $(m_{3\pi}, t', m_{2\pi})$-bin

- Freed partial waves include $[\pi\pi]_{0^{++}}, [\pi\pi]_{1^{--}}, [\pi\pi]_{2^{++}}$
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- Freed partial waves include $[\pi\pi]_{0^{++}}, [\pi\pi]_{1^{--}}, [\pi\pi]_{2^{++}}$

What do we gain from this?

- Less model dependence during the PWA
- Enables to fit $2\pi$ spectrum
- Study rescattering effects → collab. with C. Hanhart, B. Kubis
π₁(1600)

Freed-Isobar Analysis

0.326 < t' < 1.000 (GeV/c)²
0.30
0.69
0.89
0.79
0.326 < t' < 1.000 (GeV/c)²

0.5 1.0 1.5 2.0 2.5
m₃π [GeV/c²]

0 15000
30000
45000
60000
75000
90000
105000

0
1
2
3
Intensity [Events/(GeV/c²)]
×10⁶

1.58 < m₃π < 1.62 GeV/c²
1−+1+[ππ]₁−−πP

Corrected zero mode
Full range
Fixed shape

Preliminary

Hadron Spectroscopy from COMPASS to AMBER (15/30)
Mathias Wagner (Uni Bonn, HISKP)
Signal not an artifact of fixed isobar shape!
COMPASS

Exotic $\pi_1(1600)$
Signals in $\eta\pi$ and $\eta'\pi$

Two pseudo scalars $\sim$ waves with odd $L$ are spin-exotic

The $\pi_1$ is a puzzle!

Hexotic $\pi_1(1600)$

$\eta\pi$ P-wave

@1400?

$\eta'\pi$ P-wave

@1600?

But: Fit not stable, strongly model dependent!

[COMPASS, PLB 740 (2015) 303]
Coupled-Channel Analysis

Exotic $\pi_1(1600)$

Improvement over simple Breit-Wigner fit:
- Unitary model ($K$-matrix approach)
- $\eta\pi$ and $\eta'\pi$ coupled-channel ($N/D$ formalism)
- Analytic (extract pole positions)
Coupled-Channel Analysis

Exotic $\pi_1(1600)$

Improvement over simple Breit-Wigner fit:
- Unitary model ($K$-matrix approach)
- $\eta \pi$ and $\eta' \pi$ coupled-channel ($N/D$ formalism)
- Analytic (extract pole positions)

$D$-wave with $a_2$ and $a'_2$

[JPAC, PRL 122, 042002 (2019)]
Improvement over simple Breit-Wigner fit:
- Unitary model (K-matrix approach)
- $\eta \pi$ and $\eta' \pi$ coupled-channel ($N/D$ formalism)
- Analytic (extract pole positions)

$P$-wave with $\pi_1$

[JPAC, PRL 122, 042002 (2019)]
Result: [JPAC, PRL 122, 042002 (2019)]

- 2 poles in $D$-wave: $a_2$ and $a'_2$
- Only 1 pole in $P$-wave: $\pi_1$!

<table>
<thead>
<tr>
<th>Poles</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_2(1320)$</td>
<td>1306.0 ± 0.8 ± 1.3</td>
<td>114.4 ± 1.6 ± 0.0</td>
</tr>
<tr>
<td>$a'_2(1700)$</td>
<td>1722 ± 15 ± 67</td>
<td>247 ± 17 ± 63</td>
</tr>
<tr>
<td>$\pi_1$</td>
<td>1564 ± 24 ± 86</td>
<td>492 ± 54 ± 102</td>
</tr>
</tbody>
</table>
COMPASS

Meson Spectrum of Excited Kaons
Meson Spectrum of Excited $K$


- included into PDG
- need confirmation
Already from 2008/2009 run:

- $K^- + p \rightarrow K^- \pi^+ \pi^- + p_{\text{recoil}}$
- Only 2.5% $K^-$ fraction in beam
- Results from 2008-data consistent with previous experiments
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- $K^- + p \rightarrow K^- \pi^+ \pi^- + p_{\text{recoil}}$
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**Comparison $\pi\pi$ for $K \leftrightarrow \pi$:**

**COMPASS: $K^- \pi^+ \pi^-$**

**COMPASS: $\pi^- \pi^- \pi^+$**

Mathias Wagner (Uni Bonn, HISKP)
**K at COMPASS**

Already from 2008/2009 run:

- \( K^- + p \rightarrow K^- \pi^+ \pi^- + p_{\text{recoil}} \)
- Only 2.5 % \( K^- \) fraction in beam
- Results from 2008-data consistent with previous experiments

**Comparison \( K\pi \):**

![Graph showing comparison between COMPASS and WA03 (CERN) for \( K\pi \) production](preliminary)
Already from 2008/2009 run:

- $K^{-} + p \rightarrow K^{-}\pi^{+}\pi^{-} + p_{\text{recoil}}$
- Only 2.5% $K^{-}$ fraction in beam
- Results from 2008-data consistent with previous experiments

**Comparison $K\pi\pi$:**
COMPASS++/AMBER
Apparatus for Meson and Baryon Experimental Research

Improve our knowledge of the spectrum of excited Kaons
What do we need?

- Clean, high-intensity $K$ beam
- 10x more statistics than currently available
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- Clean, high-intensity $K$ beam
- 10x more statistics than currently available

What do we gain?
- Improved precision
- Access to higher-mass kaon states
- PWA in $(m, t)$-bins
- Freed-isobar analysis → study $K\pi$
- Will revolutionize the $K$-spectrum!
**What do we need?**
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- Freed-isobar analysis → study $K\pi$
- Will revolutionize the $K$-spectrum!

**How can we achieve this?**
COMPASS++/AMBER

RF-Separated Kaon Beam
First employed at CERN in the 1960s

Two dipole RF-cavities at frequency $f$ and phase $\varphi$

Different particles at same beam momentum have phase difference:

$$\Delta \Phi = 2\pi \frac{Lf}{c} \left( \frac{m_1^2 - m_2^2}{2p^2} \right)$$

$$\Delta \Phi_{\rho\pi} = 2\pi \quad \Rightarrow \quad \Delta \Phi_{K\pi} \approx \pi/2$$
Choice of $p$

RF-Separated Kaon Beam

Beam line limit $L = 1.1$ km yields $p_{\text{max}} \sim 75$ GeV/c (for fixed $f$) \(
\leadsto\text{high enough forward boost, recoil proton angle sufficiently large}\)
Pions:
- $3\pi$ PWA improved mass and width parameters
- Freed-isobar analysis further removes model dependence from PWA, independent of the isobar shape
- Enables fits to $2\pi$ subsystems, rescattering effects
- Coupled-channel analysis of $\eta^{(')}\pi$ yields precise $\pi_1(1600)$ pole position $\Rightarrow$ Puzzle solved!

Kaons:
- Limited data set of $K^- + p \rightarrow K^-\pi^+\pi^- + p_{\text{recoil}}$
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–003
SPSC-I-250
January 28, 2019
Letter of Intent:
A New QCD facility at the M2 beam line of the CERN SPS*
COMPASS++ †/AMBER ‡

* email: NQF-M2@cern.ch
† COrmon Muon Proton Apparatus for Structure and Spectroscopy
‡ Apparatus for Meson and Baryon Experimental Research

RF-separated $K$ beam for spectroscopy
- Only way to achieve a high-intensity $K$ beam
- Same quantum leap as for $\pi$ expected
- Knowledge exists for $\pi$, can easily be adapted to $K$
- Nowhere else possible at this high intensity and energy
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RF-separated $K$ beam will also give insight in:
- Kaon valence-quark distribution
  (Drell-Yan $\rightarrow$ Marco Meyer, yesterday 12:10)
- Separation of valence- and sea-quark contribution
  ($K^\pm$ cross-section asymmetry $\rightarrow$ Yann Bedfer, today 15:00)
- Study of gluon content inside the kaon via $J/\Psi$ and prompt photon production
- Kaon polarizability (Primakoff)

Also possible: RF-separated $\bar{p}$ beam
- Spin structure of the nucleon
- Drell-Yan with high-intensity antiproton beam
Thank you for your attention!
Back-Up
$\pi(1300)$?

[COMPASS, PRD 98 (2018) 092003]
$a_1(1420)$ - Triangle Singularity
$a_1(1420)$ - Triangle Singularity

**$f_0\pi P$ - intensity**

- Mass-independent fit
- $t' = 0.100-0.113$ (GeV/c)$^2$
- BW-model
- $\Delta$-model
- Signal
- Background

**$\rho\pi S - f_0\pi P$ - phase**

Intensity / (20 MeV) $P - intensity\pi_0 f\pi_0$$P - phase\pi_0 S - f\pi_\rho$

Relative phases (deg)

$\Delta$ signal

Background

Preliminary
Maximum-Likelihood Fit

Probability to measure $N$ events:

$$P(N; N_e) = \frac{N_e^N}{N!} \exp(-N_e)$$

with expected events

$$N_e = \int I(\tau) \zeta(\tau) \, d\tau$$

with the kin. variables chosen as $\tau = (s_0, m_{3\pi}^2, t, \Omega_{GJ}, m_{2\pi}^2, \Omega_H)$.

Probability to find measured event at given kinematics:

$$P_k(\tau_k) = \frac{I(\tau_k)}{N_e}$$

Maximize likelihood: $\mathcal{L} = \frac{N_e^N}{N!} \exp(-N_e) \prod_{k=1}^{N} \frac{I(\tau_k)}{N_e}$

Or minimize: $-\log \mathcal{L} = \int I(\tau) \zeta(\tau) \, d\tau - \sum_{k=1}^{N} \log \left( I(\tau_k) \right)$

acceptance with MC

real data
simpler: angular dependence $\rightarrow$ spherical harmonics

$J = L$, $P = (-1)^L$, $C = +1 \quad \Rightarrow \quad J^{PC} = 1^{--}, 2^{++}, (3^{--}), 4^{++}, ...$

giving access to $\pi_1, a_2, (\pi_3)$ and $a_4$
N/D formalism:

\[ A_i^J(s) \sim \sum_k n_k^J(s) \left[ D_J(s)^{-1} \right]_{ki} \]

\[ n_k^J \text{ effective expansion in Chebyshev polynomials} \]

\[ D_J = \begin{pmatrix} \eta\pi \to \eta\pi & \eta\pi \to \eta'\pi \\ \eta'\pi \to \eta\pi & \eta'\pi \to \eta'\pi \end{pmatrix} \]

containing right-hand cuts constrained by unitarity
\[ D^J_{ki}(s) = \left[ K^J(s)^{-1} \right]_{ki} - \frac{s}{\pi} \int_{s_k}^{\infty} ds' \frac{\rho N^J_{ki}(s')}{s'(s' - s - i\epsilon)} \]

effective description of left-hand singularities via

\[ \rho N^J_{ki}(s') = \delta_{ki} \frac{\lambda^{J+1/2}(s', m_{\eta^{'}}^2, m_\pi^2)}{(s' + s_L)^{2J+1+\alpha}} \]

\((s_L = 1 \text{ GeV}^2, \alpha = 2)\) and standard \(K\)-matrix parametrization

\[ K^J_{ki}(s) = \sum_R \frac{g^J_k R g^J_i R}{m_R^2 - s} + c^J_{ki} + d^J_{ki}s \]

2 poles in \(D\)-wave, 1 pole in \(P\)-wave (\(c\) and \(d\) are symmetric)

pole in \(K \sim\) zero in \(D \sim\) pole in \(a\)
[JPAC, PRL 122, 042002 (2019)]
Comparison $\pi_1(1600)$

Weighted Average
1317.1$^{+1.5}_{-1.6}$ MeV/c$^2$ (Error scaled by 3.5)

PDG

[To be published in Progress in Particle and Nuclear Physics]
Comparison $a_2(1320)$

[To be published in Progress in Particle and Nuclear Physics]