Experimental spectroscopy

Precision and Exotics

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JLab Users Group
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Introduction

- Quantum Chromodynamics (QCD)
  - Degrees of freedom: quarks and gluons
  - Rich spectrum of bound states predicted
  - Outstanding questions remain e.g., What is the nature of confinement?
- New understanding gained by studying spectrum of bound QCD states
  - Recent progress in understanding hadron spectrum driven by large, high-quality data sets
  - New theoretical tools key for accurately interpreting this data
QCD and Hadron Spectroscopy

- Idea: study QCD through spectrum of bound states
  - Static properties of known hadrons well described by first-principals calculations
  - Modern experiments provide unprecedented data sets to push boundaries of our knowledge
- Open questions:
  - What is the origin of confinement?
  - Which color-singlet states exist in nature?
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QCD and Hadron Spectroscopy

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  - Modern experiments provide unprecedented data sets to push boundaries of our knowledge
- Open questions:
  - What is the origin of confinement?
  - Which color-singlet states exist in nature?
  - Do gluonic degrees of freedom manifest themselves in the bound states that we observe?
Meson Quantum Numbers

Mesons are arranged in groups of 9 ("nonets") with same $J^{PC}$

$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

- **Gluonic field excitation** → "constituent gluon" ($J^{PC} = 1^{-+}$)

- **"Normal" Meson**
  - Allowed $J^{PC}$: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{+-}, ...$
  - Forbidden $J^{PC}$: $0^{--}, 0^{+-}, 1^{-+}, 2^{--}, ...$

- **"Hybrid" Meson**
  - Allowed $J^{PC}$: $0^{--}, 0^{+-}, 1^{--}, 1^{+-}, 2^{--}, 2^{+-}, ...$

Hybrid–Meson mass splitting $\sim 1.0$ – 1.5 GeV
Light Meson Spectrum from Lattice QCD

Meson Mass (MeV)

negative parity

positive parity

exotic

lightest hybrids

J^PC=

0++ 1++

2++ 3++ 4++

Exotics QN mesons are “smoking gun” for existence of hybrid mesons

To determine hybrid meson properties, need to study full spectrum of these states.

• Search by BES for resonances in $J/\psi \to \gamma \eta'\pi^+\pi^-$ in $e^+e^-$ annihilation
  • Structure seen near $2M(p)$
  • Understanding evolves as more data collected

BES II: PRL 95, 262001 (2005)

$X(1835)$

$J^{PC} = 0^-$

$58 \times 10^6 J/\psi$
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• Search by BES for resonances in $J/\psi \rightarrow \gamma \eta^\prime \pi^+ \pi^-$ in $e^+e^-$ annihilation
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  • More data reveals more complexity, more sophisticated analysis required

BESIII: PRL 106, 072002 (2011)

BESII: PRL 95, 262001 (2005)

$X(1835) \quad J^{PC} = 0^-$

$58 \times 10^6 \quad J/\psi$

BESIII: PRL 117, 042002 (2016)

1.1 $\times 10^9 \quad J/\psi$

$225 \times 10^6 \quad J/\psi$
Precision and Spectroscopy: BES III & J/ψ → γ η′π⁺π⁻

- Search by BES for resonances in J/ψ → γ η′π⁺π⁻ in e⁺e⁻ annihilation
  - Structure seen near 2M(p)
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BESIII: PRL 117, 042002 (2016)

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X(1835) JPC = 0⁻

58x10^6 J/ψ

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225x10^6 J/ψ
Evidence for exotic light-quark mesons

- Many searches, strongest evidence for $\pi_1$ in $\eta'\pi$ and $\rho\pi$ P-waves
- Resonance character not conclusively established

**COMPASS: $\pi_1 \rightarrow \eta \pi / \eta'\pi$**

- D-wave in $\eta'\pi$

\[a_2(1320)\]
\[a_2'(1700)\]

Extract resonance parameters with unitary reaction model

**COMPASS: PLB 740, 303 (2015)**

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2018)
Evidence for exotic light-quark mesons

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COMPASS: $\pi_1 \rightarrow \eta\pi / \eta'\pi$

P/D-wave in $\eta\pi/\eta'\pi$ (preliminary)

COMPASS: PLB 740, 303 (2015)

A. Szczepaniak, MESON 2018
Evidence for exotic light-quark mesons

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$\pi_1 \rightarrow \rho\pi$

420k $\pi^- \pi^- \pi^+$ events

COMPASS: PRL 104, 241803 (2010)

50M $\pi^- \pi^- \pi^+$ events

COMPASS: PRD 95, 032004 (2017)
Evidence for exotic light-quark mesons

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\[ 0.724 < t' < 1.000 \text{ (GeV/c)}^2 \]

\[ m_{3\pi} \text{ [GeV/c}^2 \text{]} \]

\[ 0.100 < t' < 0.113 \text{ (GeV/c)}^2 \]

\[ m_{3\pi} \text{ [GeV/c}^2 \text{]} \]

\[ \pi^-p \rightarrow \pi^-\pi^-\pi^+p \text{ (COMPASS 2008)} \]

COMPASS: PRL 104, 241803 (2010)

COMPASS: PRL 104, 241803 (2010)

420k $\pi^-\pi^-\pi^+$ events

\[ \Delta\phi - \delta\phi \text{ [deg]} \]

\[ [\text{GeV/c}^2] \]

\[ [\text{GeV/c}^2] \]

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Evidence for exotic light-quark mesons

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COMPASS: 190 GeV $\pi\pi$ on Pb

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$50M \pi^-\pi^-\pi^+$ events

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arXiv:1802.05913
Evidence for exotic light-quark mesons

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- Resonance character not conclusively established

\[ a_1(1420) \rightarrow f_0(980) \pi ? \]

50M $\pi\pi\pi^+$ events

Describe non-$q\bar{q}$ candidate as triangle singularity

M. Mikhasenko, HADRON 2017

PRD 95, 032004 (2017)
Hadron Spectroscopy is Moving Forward Worldwide!

Moving into the high-precision era…

…collecting comprehensive data with orders of magnitude larger than previously available.
Hadron Spectroscopy at JLab

- Unique capability at JLab: hadron production with intense beams of electrons and photons

**GlueX**

- Photon beam with linear polarization
- Large acceptance and PID optimized for amplitude analysis

**CLAS12**

- Electron and photon beams with linear and circular polarization
- PID over large momentum range
Hadron Spectroscopy at JLab

• Unique capability at JLab: hadron production with intense beams of electrons and photons

**GlueX**

• Commissioning: 2015–6
• Physics started 2017, GlueX-I 80% done
• DAQ rate: 400–700 MB/s
• Over 2.5 PB raw data to tape

**CLAS12**

• Commissioning: 2017-8
• Physics started March 2018
• DAQ rate: 600 MB/s
• Over 800 TB raw data to tape
Meson Photoproduction

- Photon couples to exchanged QN via VMD, generates mesons with wide variety of $J^{PC}$
  - All expected hybrids can be produced!

\[ \gamma \rightarrow (\rho,\omega,\phi) \]

\[ X \rightarrow P(0^{++}), \pi(0^{-+}), \rho(1^{--}), \ldots \]

\[ P, n, \ldots \]

\[ \rho, \eta_1 \]

\[ \omega, \eta_1 \]

\[ \rho, \pi_1, \omega \]

- Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes
Meson Photoproduction

- Photon couples to exchanged QN via VMD, generates mesons with wide variety of $J^{PC}$
  - All expected hybrids can be produced
- Variety of hybrid decays expected:
  - $\pi_1 \rightarrow \rho \pi$, $\pi b_1$, $\pi f_1$
  - $\eta_1 \rightarrow \eta f_2$, $\eta a_2$, $\eta f_1$
- Little existing photoproduction data. Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes
Multiple states are produced which decay to the same set of particles and interfere.

- Need to understand photon beam characteristics and have detailed detector model.
- Improved theoretical models for amplitudes also needed, work closely with JPAC and others.
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

Opportunistic measurements & New Ideas

Understand production mechanisms

Current Efforts

Measure cross sections

Amplitude Analysis

Identify known mesons

Search for exotics

Theoretical Models (JPAC, ....)
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

- Understanding production mechanisms necessary to determine $J^{PC}$ of mesons in amplitude analyses, look at simplest reactions first.
- Beam asymmetry $\Sigma$ yields information on production mechanisms.
- Combining data taken with different beam polarization cancels most acceptance effects.

\[ \Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2} \]

Exchange $J^{PC}$
- $1^{--}$: $\omega, \rho$
- $1^{+-}$: $b, h$

\[ \frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p \]

JPAC: Mathieu et al., PRD 92, 074013
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0 / \eta$

- First step towards study of photoproduction amplitudes using 2016 data
- $\Sigma \approx 1$ indicates vector exchange dominates at this energy
- First $\eta$ measurement at this energy
- Constrains background to baryon resonance production at lower energies [e.g. arXiv:1708.07779]

Beam Asymmetries: $\gamma p \rightarrow p + \eta / \eta'$

- Initial studies of $\eta$ and $\eta'$ beam asymmetries using 2017 data and additional decay modes
  - Production is consistent with vector exchange dominance
  - Expect similar mechanism for exotics
  - Full GlueX-I data will provide a factor 5 more events
  - Program of production amplitude studies is well underway

Statistical uncertainties only
Beam Asymmetries: $\gamma p \rightarrow \pi^- \Delta^{++}$

- Charged pseudoscalar beam asymmetry has more complicated $t$-dependence.
- Preliminary results use order of magnitude more data than previous measurements.

**SLAC (16 GeV)**

Phys. Rev. D 20, 1553 (1979)

**GLUEX**

Preliminary

$\gamma p \rightarrow \pi^- \Delta^{++}$ ($\sim 8.5$ GeV)

Asymmetry $\Sigma$ vs. $\sqrt{-t}$ (GeV/c)

Asymmetry $\Sigma$ vs. $-t$ (GeV$^2$)

- Natural exchange favored (e.g. $\rho, a_2$)
- Unnatural exchange favored (e.g. $\pi$)

B.G Yu (Korea Aerospace U.), arxiv:1611.09629v5 (16 GeV)
J. Nys (JPAC), arxiv: 1710.09394v1 (8.5 GeV)

$\pm 7\%$ norm. uncertainty
Spin Density Matrix Elements (SDMEs): $\gamma p \rightarrow p + \omega$

- SDMEs measure the transfer of polarization from the photon to the vector meson
  - Require understanding of detector acceptance
- Two matrix elements are particularly sensitive to exchange particle in $\omega$ polarization transfer
  - Pomeron: $+1/2$ and $-1/2$
  - Pion: $-1/2$ and $+1/2$
- We observe around $+0.35$ and $-0.35$
- $\gamma p \rightarrow p + \phi$ and $p + \rho$ also under analysis
**Light Meson Spectrum from Lattice QCD**

- **negative parity**
  - $J^{PC} = 0^{--}$
  - $J^{PC} = 1^{--}$
  - $J^{PC} = 2^{--}$

- **positive parity**
  - $J^{PC} = 1^{++}$
  - $J^{PC} = 2^{++}$
  - $J^{PC} = 3^{++}$

- **exotic**
  - $J^{PC} = 1^{+-}$
  - $J^{PC} = 0^{+-}$
  - $J^{PC} = 2^{+-}$

---

Meson Mass (MeV)

*HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)*
Spectroscopy Prospects: $\gamma p \rightarrow p + \pi^+ \pi^-$

SLAC: $\gamma p \rightarrow \pi^+ \pi^- p$
$E_{\text{beam}} = 20 \text{ GeV}$

$\rho'$?


$m_{\pi^+ \pi^-} [\text{GeV}/c^2]$

- Take fresh look at $\pi^+ \pi^-$ photoproduction
  - Using two-orders of magnitude more data than SLAC
  - Enhancements seen with $M > 1 \text{ GeV}$
  - Moment / amplitude analysis underway
- $K^+ K^-$ photoproduction also being studied

$E_{\text{beam}} \sim 9 \text{ GeV}$

$f_2(1270)$?

$\rho'$?

$\rho(770)$

$m_{\pi^+ \pi^-} [\text{GeV}/c^2]$
Work Towards Vector Meson Production Cross Sections

- Vector meson production cross sections provide important benchmarks
  - Require understanding of efficiencies and photon flux
  - Comparison with previous measurements
  - Photon energy and t dependence gives more insight into production mechanisms
- Very preliminary “Work In Progress” shows similar beam energy dependence to previous measurements
Spectroscopy Prospects: $\gamma p \rightarrow p + \pi^0 \eta$

- $\pi\eta / \pi\eta'$ promising channels for early hybrid searches
- With 20% of GlueX-I data, we see several well-known mesons
- Statistics are competitive with previous experiments

$\gamma p \rightarrow p + \pi^0 \eta, \eta \rightarrow \gamma\gamma$

$a_0(980)$

$\pi^0\eta$ mass

Counts / 10 MeV

$a_2(1320)$

$\pi^- p \rightarrow \eta\pi^0 n$

$E852$

S. Dobbs — JLab UG 2018 — June 20, 2018 — Experimental spectroscopy: Precision and Exotics
Spectroscopy Prospects: $\gamma p \to p + \pi^0 \eta$

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$\gamma p \to p + \pi^0 \eta, \eta \to \gamma \gamma$

$a_0(980) \quad a_2(1320)$

$\gamma p \to \Delta^{++} + \pi^- \eta, \eta \to \gamma \gamma$

$a_0(980) \quad a_2(1320)$

$M(\pi^- \eta)$ (GeV/c$^2$)

$M(\pi^+ \pi^- \pi^0 \pi^0)$ (GeV/c$^2$)
Spectroscopy Prospects: $\gamma p \rightarrow p + \eta \pi^+ \pi^-$

- Large sample of multiparticle decays collected as well
- Example: $\eta \pi^+ \pi^-$ can have contributions from $\eta_1$ and $b_1$ hybrids
- Will analyze with models built from experience with 3-body reactions

Contributions from:

1. $\gamma p \rightarrow p a_2^\pm \pi^\mp$
2. $\gamma p \rightarrow p f_2 \eta$
3. $\gamma p \rightarrow p \rho \eta$

[Graph showing mass distribution]
Prospects for Cascade Spectroscopy

- The Cascade \((ssd, ssu)\) spectrum is poorly known — nothing new since 1988!
- LQCD predicts rich spectrum, many narrow states
- CLAS observed photoproduction of ground states
- Production of excited cascades via a forward-going kaon?

\[ \gamma + p \rightarrow K^+ K^+ (\Xi^-, \Xi^{-*} \rightarrow \Xi^0 \pi^-) \]

<table>
<thead>
<tr>
<th>State</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Xi(1320))</td>
<td>(1/2)^+</td>
</tr>
<tr>
<td>(\Xi(1530))</td>
<td>(3/2)^+</td>
</tr>
<tr>
<td>(\Xi(1690))</td>
<td></td>
</tr>
<tr>
<td>(\Xi(1820))</td>
<td>(3/2)^-</td>
</tr>
<tr>
<td>(\Xi(1950))</td>
<td></td>
</tr>
<tr>
<td>(\Xi(2030))</td>
<td></td>
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</tbody>
</table>
Hunting for Excited Cascades

- GlueX can reconstruct these multi-step reactions
- Full GlueX-I data opens door for more detailed studies
- Searches in CLAS12 by Very Strange Group

\[ \Xi^-(1320) \]

\[ \Xi^-(1820)? \]
Summary

• Exciting time for light mesons! Confronting opportunities and challenge of new experiments is leading to new understanding.

• Entering era of large precision data
  • Unprecedented photoproduction data being collected by 12 GeV JLab experiments
  • Close collaboration between experiment and theory crucial for progress in understanding these data

• Hunt for hybrid mesons and other exotics at GlueX is on!
  • Many other opportunistic measurements being made: Cascade spectroscopy, J/ψ, B-boson, …
  • Expect many exciting results from CLAS12 as well!
• 2016: ~80 hours of physics-quality commissioning data
• 2017: Start of data taking, ~8 times more data than 2016 (20% of GlueX-I)
The GlueX Experiment: Photon Beam

- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
  - Photon linear polarization $P_\gamma \sim 40\%$ in peak
  - Design intensity of $10^8 \gamma/s$ in peak
**Sidebar: Experiment and Theory Working Hand-in-Hand**

**D-wave in $\pi p \rightarrow p \eta \pi$**

![Graph showing D-wave transition]

Extract resonance parameters with unitary reaction model

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2018)

**$a_1(1420) \rightarrow f_0(980) \pi$**

![Graph showing $a_1(1420)$ transition]

Describe non-qq candidate as triangle singularity

M. Mikhasenko et al. [JPAC and COMPASS Collaborations], in preparation
Angular Correlations in $\gamma p \rightarrow p + 4\gamma$

- Production near $\cos \theta \sim 1$ corresponds to meson production
- Stronger signal in $\eta'\pi^0$ than $\eta\pi^0$
Evidence for exotic light-quark mesons

\[ \pi_1 \rightarrow \eta' \pi \]

E852: 18 GeV π on p

PRL 86, 3977 (2001)

\[ \pi_1 \rightarrow \rho \pi \]

COMPASS: 190 GeV π on Pb

PRL 104, 241803 (2010)
Evidence for exotic light-quark mesons

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Evidence for exotic light-quark mesons

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam Momentum (GeV/c)</th>
<th>Reaction</th>
<th>Resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAMS</td>
<td>32, 38, 100</td>
<td>$\pi^- p \rightarrow \pi^0 \eta n$</td>
<td>$\pi_1(1400)$</td>
</tr>
<tr>
<td>KEK</td>
<td>6.3</td>
<td>$\pi^- p \rightarrow \pi^- \eta p$</td>
<td>?</td>
</tr>
<tr>
<td>E852</td>
<td>18</td>
<td>$\pi^- p \rightarrow \pi^- \eta(\prime) p$</td>
<td>$\pi_1(1400/1600)$</td>
</tr>
<tr>
<td>Crystal Barrel</td>
<td>Annihilation</td>
<td>$\bar{p} n \rightarrow \pi^- \pi^0 \eta$</td>
<td>$\pi_1(1400)$</td>
</tr>
<tr>
<td>VES</td>
<td>37</td>
<td>$\pi^- p \rightarrow \pi^- \eta(\prime) p$</td>
<td>$\pi_1(1600)$?</td>
</tr>
<tr>
<td>COMPASS</td>
<td>190</td>
<td>$\pi^- p \rightarrow \pi^- \eta(\prime) p$</td>
<td>?</td>
</tr>
<tr>
<td>CLAS</td>
<td>5.5</td>
<td>$\gamma p \rightarrow \pi^- \eta \Delta^{++}$</td>
<td>(not published)</td>
</tr>
</tbody>
</table>

Exchange | Exotic Final States
---|---
$\bar{p}$ | $0^{++}$ | $b, h, h'$ | $2^{--}, 0^{+-}$
$\pi^0$  | $0^{--}$ | $b_2, h_2, h'_2$ | $2^{+-}$
$\pi^\pm$ | $0^{--}$ | $\pi^\pm_1$ | $1^{--}$
$\omega$ | $1^{--}$ | $\pi_1, \eta_1, \eta'_1$ | $1^{--}$
Many broad, overlapping states. Overpopulation of states?
Progress requires multiple channels, amplitude analysis…
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

**Exchange $J^{PC}$**

- $1^-\cdot\cdot\cdot: \omega, \rho$
- $1^+-\cdot\cdot\cdot: b, h$

\[
\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}
\]

JPAC: Mathieu et al., PRD 92, 074013

- Understanding production mechanisms necessary to determine $J^{PC}$ of mesons in amplitude analyses
- Beam asymmetry $\Sigma$ yields information on production mechanisms
How Do We Make Mesons?

- Production in Hadron Decays: BES, BaBar, Belle, CLEO, …
  - Simple initial state
  - Clean event samples
  - Small sample size

\[ \chi, \eta, \omega, \phi, \ldots \]
How Do We Make Mesons?

- Production in Hadron Decays: BES, BaBar, Belle, CLEO, …
  - Simple initial state
  - Clean event samples
  - Small sample size
- Hadroproduction (π, K beams): COMPASS, E852, VES, …
  - Large event samples, more complicated initial state
  - Need more sophisticated models of reaction

\[
\pi^- \rightarrow P \rightarrow X^- \rightarrow \pi^-, \pi^+, \pi^-
\]

\[P \rightarrow p \rightarrow p_{\text{recoil}}\]
How Do We Make Mesons?

- Production in Hadron Decays: BES, BaBar, Belle, CLEO, …
  - Simple initial state
  - Clean event samples
  - Small sample size
- Hadroproduction ($\pi$, K beams): COMPASS, E852, VES, …
  - Large event samples, more complicated initial state
  - Need more sophisticated models of reaction
- Photoproduction: CLAS12, GlueX, …
  - Large event samples, wide range of QN produced
    - Polarization gives extra info for amplitude analyses
  - Need to understand production mechanisms
Light Meson Spectroscopy at COMPASS

- Study of light meson spectrum $M \approx 2$ GeV using diffractive $\pi p$ scattering
  - $\pi^- \pi^+ \pi^-$
  - $\eta \pi^-$, $\eta' \pi^-$
  - ...
- Large data set of $\sim 50$ M exclusive $\pi^- + p \rightarrow \pi^- \pi^+ \pi^- + p_{\text{recoil}}$ events
- Partial wave decomposition using 88 waves: largest set to date
- Performed $t$-resolved analysis

- **Resonance model fit**
  - Modeling $M(\pi^-\pi^+\pi^-)$ dependence of partial waves
    - Resonant + non-resonant contributions, 11 ground + excited states
  - Simultaneous fit to 14 partial waves: largest model so far
  - Extensive systematic studies

Talk by S. Wallner, Wed. 9:00
$\pi^- \pi^+ \pi^-$ at COMPASS: Spin-density matrix of resonance fit

$0.724 < t' < 1.000$ (GeV/c)$^2$

$0.100 < t' < 0.113$ (GeV/c)$^2$

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

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

$t'$ bins
\( \pi^- \pi^+ \pi^- \) at COMPASS: Results (triangles) and PDG (circles)

Center of the boxes represents the mass, height of the boxes the width of the states. The different colors show ground and excited states. The circles represent the latest measurements according to [PDG 2014], the triangles the results of this analysis.
\[ \pi^- \pi^+ \pi^- \text{ at COMPASS: } J^{PC} = 2^{-+}: \pi_2(1670), \pi_2(1880), \pi_2(2005) \]

- Clear peak in \( f_2(1270) \pi S \) decay, described by \( \pi_2(1670) \) resonance
- Peak in \( f_2(1270) \pi D \) decay at higher masses, described mainly by \( \pi_2(1880) \)
- Potential \( \pi_2(2005) \) signal strongest in \( \rho(770) \pi P \) decay