The Search for Exotic Matter in the Light-Meson Sector

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Thomas Jefferson National Accelerator Facility

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Jefferson Lab, Newport News, VA

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Constituent Quark Model

Light Mesons

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- $|q\bar{q}\rangle$ states, with $q = u$, d, or s
- Organized in SU(3)$_{\text{flavor}}$ nonets

Quantum numbers

- Total intrinsic spin $\vec{S} = \vec{s}_1 \oplus \vec{s}_2$; $S = 0$ or 1
- Relative orbital angular momentum $\vec{L}$ and $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} \oplus \vec{S}$
- Parity: $P = (-1)^{L+1}$
- Charge conjugation: $C = (-1)^{L+S}$
- Forbidden J^{PC} combinations: 0^{--}, even^{+-}, odd^{-+}

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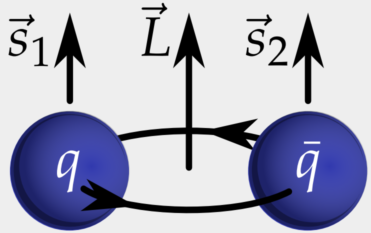

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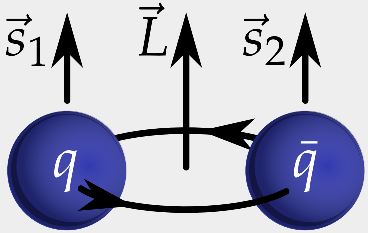

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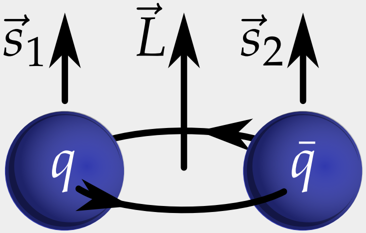
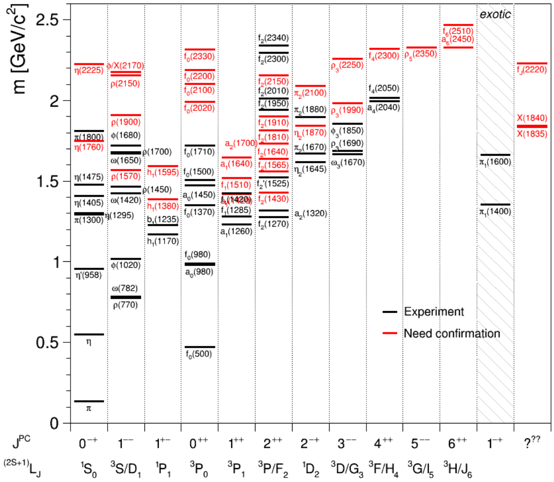


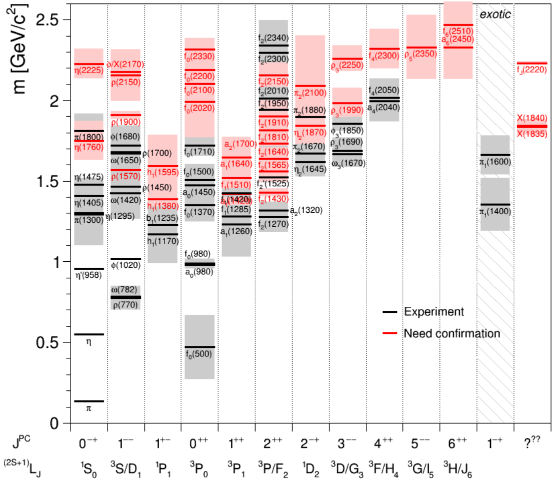


[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim$ 2 GeV/c^2 need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - States with same J^{PC} overlap and mix

Spectrum of Light Non-Strange Mesons

Light-Meson Frontier



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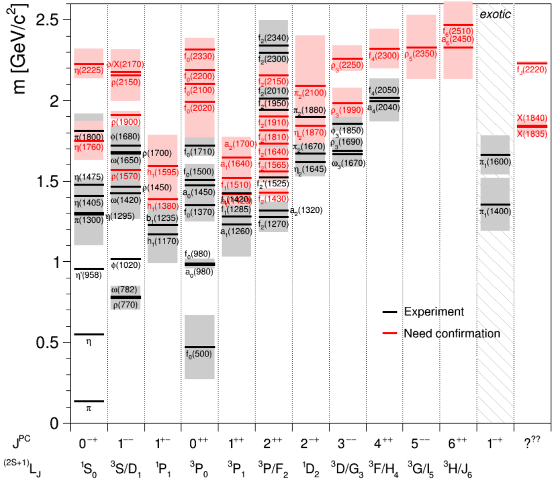

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Goal: precision measurement

- Confirm higher excitations
- Complete $\mathrm{SU(3)}_{\mathrm{flavor}}$ nonets
- Search for exotic states

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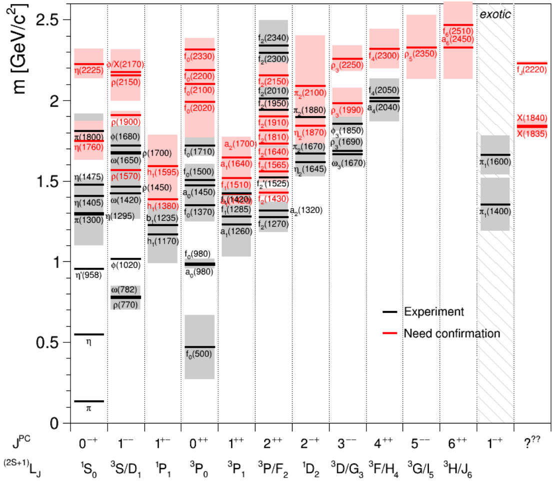

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Goal: precision measurement

- Input for theory and phenomenology
- Understand QCD at low energies, e.g. nature of confinement

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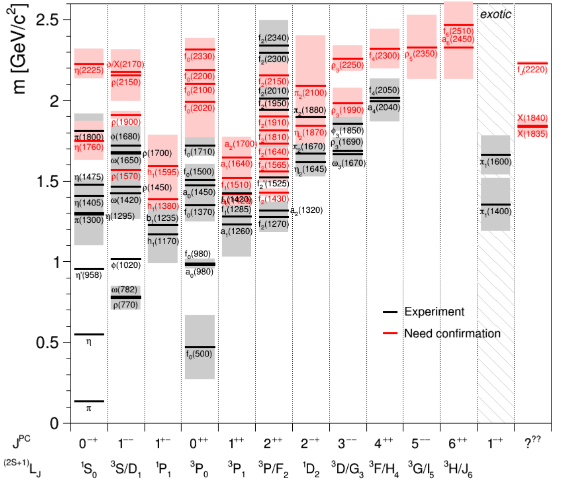

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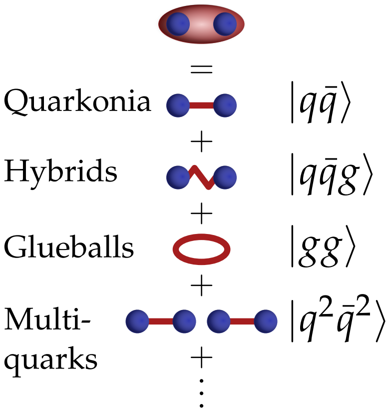
Analyses driven by

- High-quality data
- Advancements in analysis techniques
- More rigorous theoretical PWA models



QCD permits additional color-singlet mesonic configurations

Physical mesons

- Linear superpositions of *all* allowed basis states
- Configuration mixing
- Disentanglement of contributions difficult
  - Detailed and accurate information about couplings to production and decay channels required

Manifestly exotic mesons

- Quantum numbers forbidden for $|q\bar{q}\rangle$ states
- Flavor-exotics: flavor quantum numbers
- Spin-exotics: J^{PC} quantum numbers

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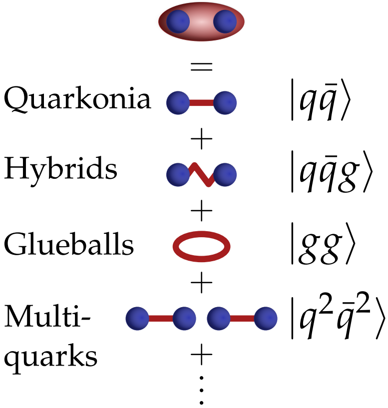

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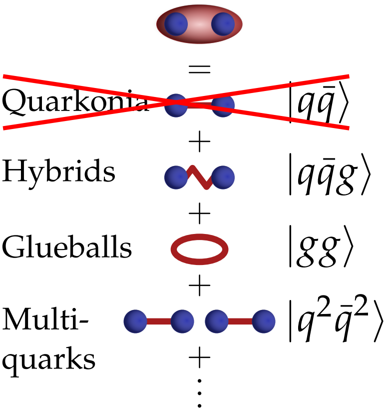

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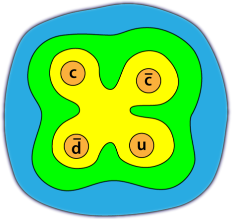
- Charged $|c\bar{c}\rangle$- and $|b\bar{b}\rangle$-like states
- E.g. $Z_c^{\pm}(3900) \to J/\psi + \pi^{\pm}$

T_{cc}

- Doubly charmed mesons
- $T_{cc}(3875)^+ \to D^0 + D^0 + \pi^+$

$T_{\psi\psi}$

- States with 4 heavy quarks
- $X(6900) \to J/\psi + J/\psi$



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Exotic Mesons

Heavy-Quark Sector: Clear Evidence for Four-Quark States

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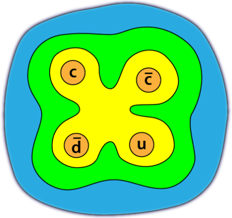

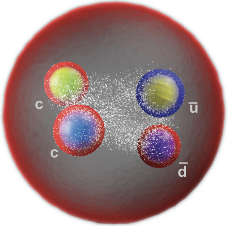

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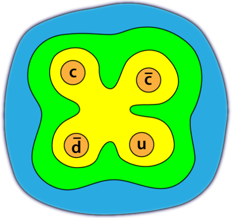

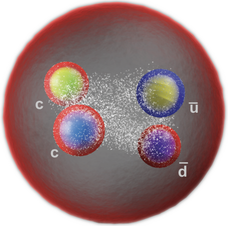

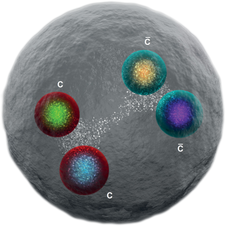

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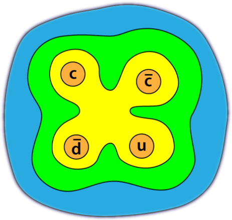

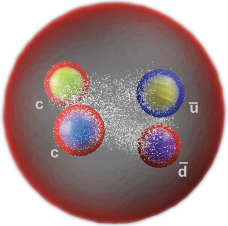

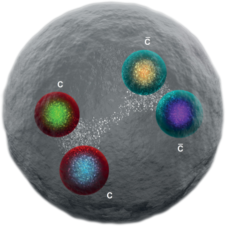

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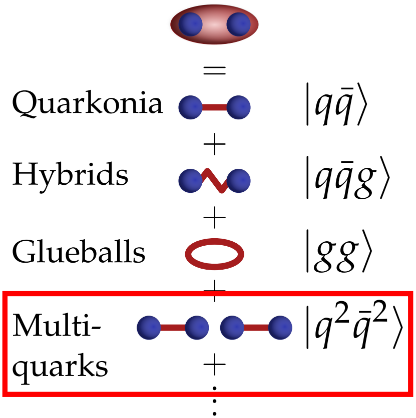
Exotic light mesons with ordinary quantum numbers

- Assignment of some SU(3)$_{\text{flavor}}$ $|q\bar{q}\rangle$ nonets difficult
  - E.g. lightest isoscalar $J^{PC} = 0^{++}$ nonet $a_0(980)$, $K_0^*(700)$, $f_0(500)$, $f_0(980)$ could be four-quark states
  - Evidence for supernumerary states w.r.t. quark-model expectation, e.g. excited f_0 states $\Longrightarrow$ glueball candidates
- Claims model-dependent; non-$q\bar{q}$ nature difficult to establish

Light mesons with exotic quantum numbers

- Finding them would be unambiguous proof for existence of non-$q\bar{q}$ states
- So far no flavor-exotic signals
- Efforts concentrate on spin-exotic mesons



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Light-Quark Sector: Experimental Situation Less Clear

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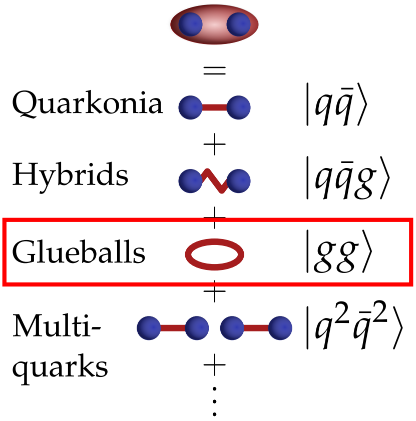

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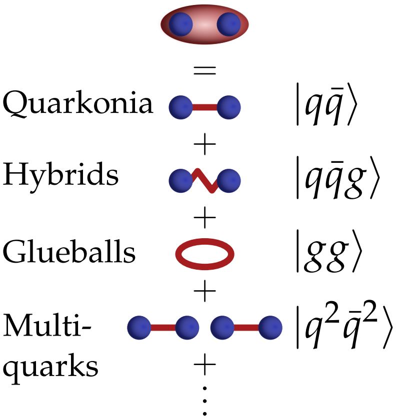

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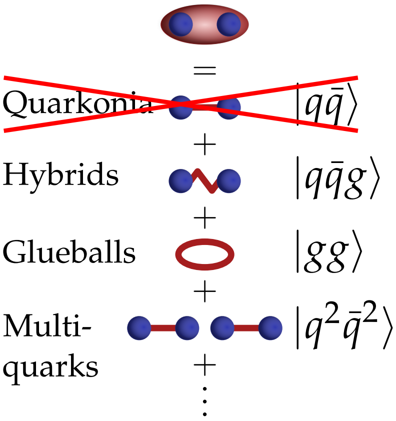

- High towers of excited states similar to quark model
- Additional hybrid-meson supermultiplet
- Lightest hybrid state is isovector with exotic $J^{PC} = 1^{-+}$
- First prediction for partial widths of 1^{-+} state
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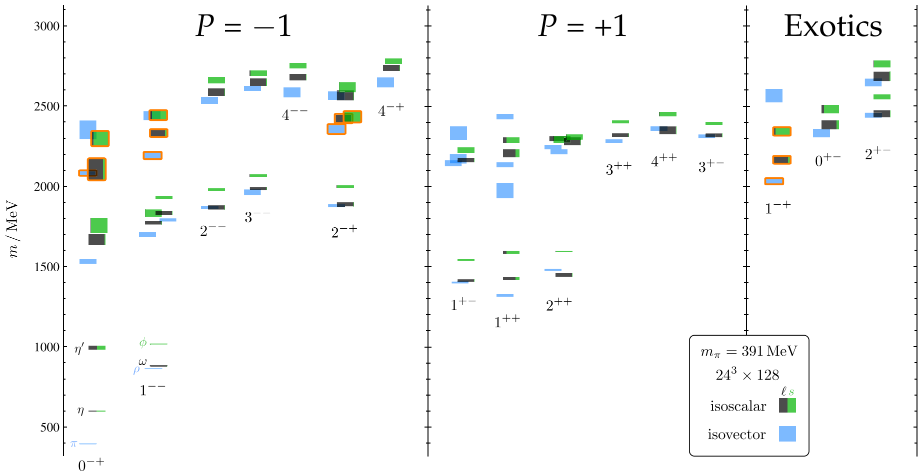

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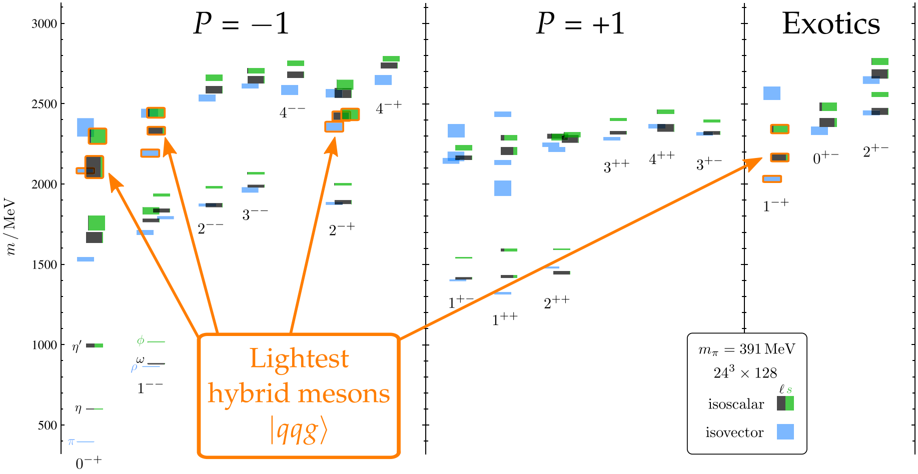

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Light Non-Strange Spectrum from Lattice QCD

State-of-the-Art Calculation with $m_\pi = 391$ MeV/c^2

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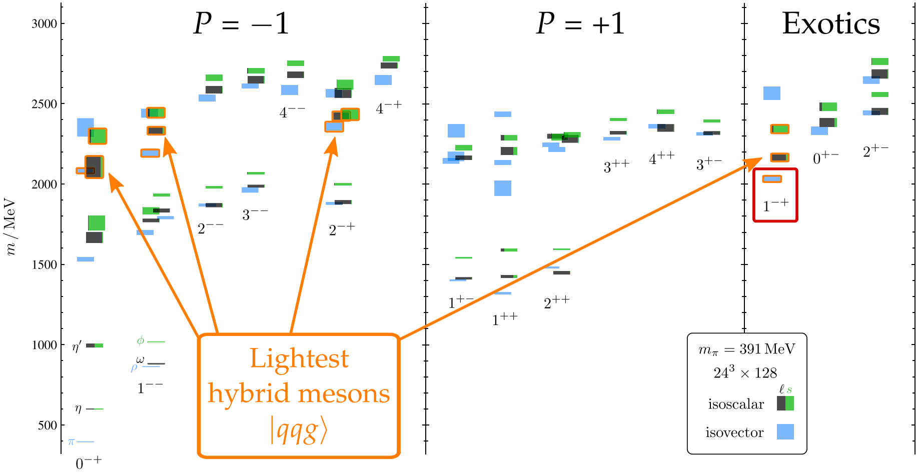

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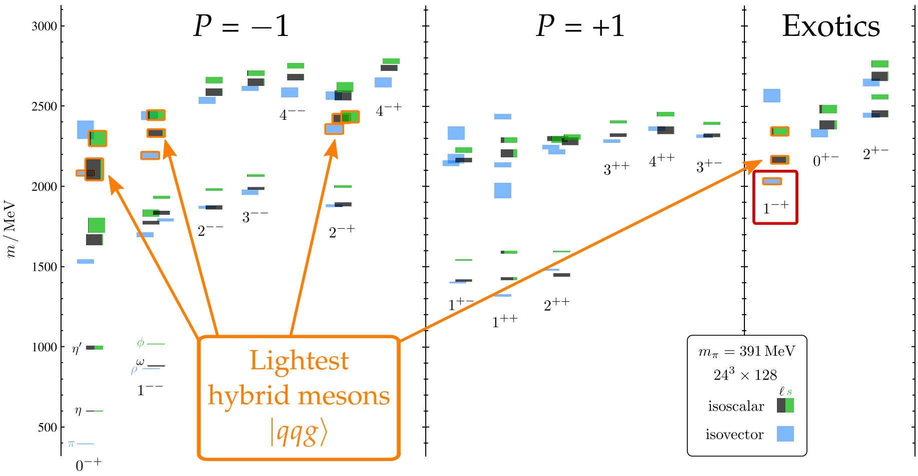

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- *Nearly 35 years ago:* first observation of a spin-exotic π_1 state with $I^G(J^{PC}) = 1^-(1^{-+})$ in $\pi^- p \to \pi^0 \eta n$ at 100 GeV/c by GAMS
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- Since then many experiments reported signals
- Seemingly large body of evidence from
  - Various production mechanisms
  - Several decay channels
- 3 states listed by PDG, all with $I^G(J^{PC}) = 1^-(1^{-+})$:
  - $\pi_1(1400)$ established: $m_0 = 1354 \pm 25\,\text{MeV}/c^2$, $\Gamma_0 = 330 \pm 35\,\text{MeV}/c^2$
  - $\pi_1(1600)$ established: $m_0 = 1661\,^{+15}_{-11}\,\text{MeV}/c^2$, $\Gamma_0 = 240 \pm 50\,\text{MeV}/c^2$
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- But:
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Spin-Exotic Light Mesons

Experimental Candidates

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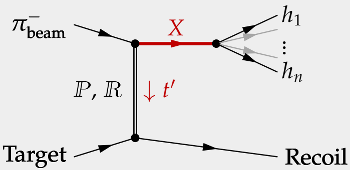
1. π scattering off nucleon or nuclear targets
2. $\bar{p}$-N annihilation at rest or in flight
3. Heavy-meson decays



Excited mesons appear as short-lived intermediate states X

- Decay into multi-body hadronic final state
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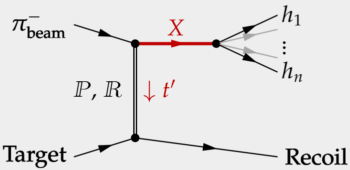

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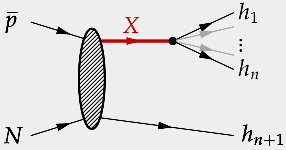

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2. $\bar{p}$-N annihilation at rest or in flight
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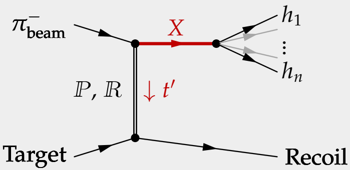

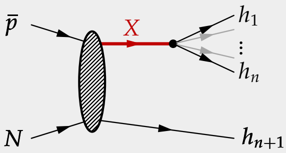

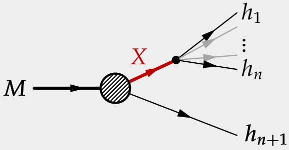

Excited mesons appear as short-lived intermediate states X

- Decay into multi-body hadronic final state
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Spin-Exotic Light Mesons
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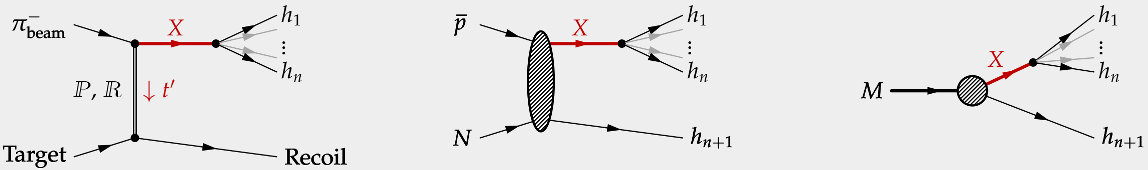

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Ansatz: Factorization of production and decay

- Kinematics of n-body final state defined by its mass m_n and multi-dimensional phase-space variables τ_n

$$\mathcal{I}(m_n, \tau_n) = \frac{\mathrm{d}N(m_n, \tau_n)}{\mathrm{d}m_n \; \mathrm{dLIPS}_n(m_n, \tau_n)} \propto \left| \sum_i^{\text{waves}} \mathcal{T}_i(m_n) \, \Psi_i(m_n, \tau_n) \right|^2$$

- *Simplest case:* all amplitudes are fully coherent
- Decay amplitudes $\Psi_i(m_n, \tau_n)$
  - $|\Psi_i(m_n, \tau_n)|^2$ describes τ_n distribution of partial wave i for given m_n
  - i defines all quantum numbers
  - $\Psi_i(m_n, \tau_n)$ calculable using spin formalism (usually helicity formalism)
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  - Dalitz plot analysis: all $\mathcal{T}_i(m_n)$ are modeled in terms of resonances and $\mathcal{I}(m_n, \tau_n)$ is fit to data

Partial-Wave Analysis (PWA) Method

Model Measured Intensity Distribution

Jefferson Lab
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- Partial-wave amplitudes $\mathcal{T}_i(m_n) \Longrightarrow$ **interesting physics**
  - Scattering experiments use two-step approach:
    1. Fit $\mathcal{I}(\tau_n)$ in narrow m_n bins $\Longrightarrow$ extract m_n dependence of $\mathcal{T}_i$
       no assumptions about resonance content of n-body system
    2. Resonance-model fit of $\mathcal{T}_i(m_n)$ for selected subset of waves

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Common challenges of this approach

- Model selection: Which resonances/partial waves should be included in model?
- Isobar model: subsystems of n-body final state with $n > 2$ are dominated by resonances
  - Which isobar resonances to include? Which parametrizations to use? Which parameter values?
- ...

- Seen by BNL E852, Crystal Barrel, GAMS, KEK E179, and VES in
  - π scattering
  - $\bar{p}$-N annihilation

Puzzling properties of the $\pi_1(1400)$

- Observed nearly exclusively in $\eta\pi$ decay mode
- Too light compared to lattice QCD calculation and most model predictions
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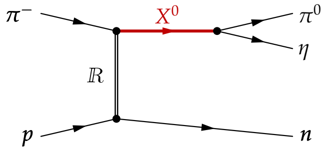
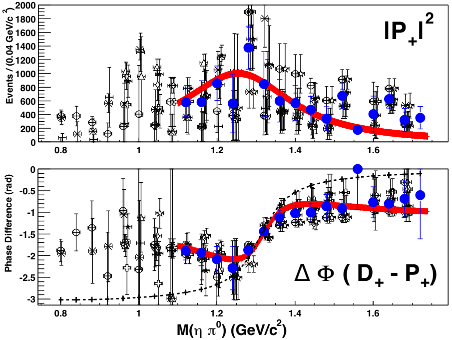
Example: $\pi^- p \to \eta\pi^0 n$ at 18 GeV/c





BNL E852, PLB **657** (2007) 27

Spin-Exotic Light Mesons

The $\pi_1(1400)$

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Thomas Jefferson National Accelerator Facility

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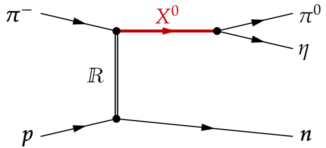

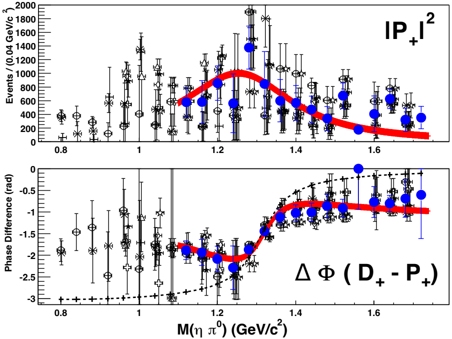

BNL E852, PLB **657** (2007) 27

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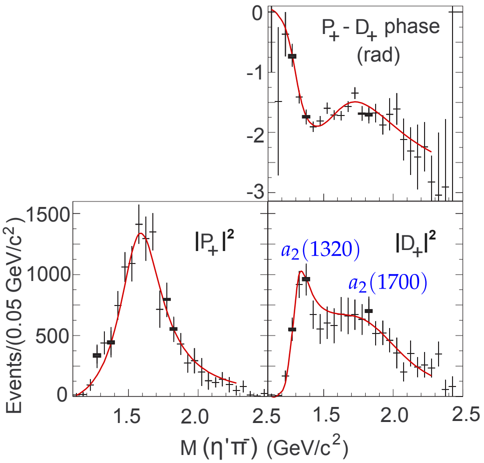

BNL E852, PRL **86** (2001) 3977

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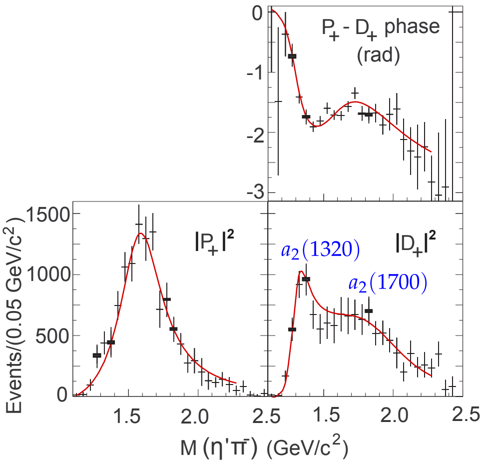

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Spin-Exotic Light Mesons

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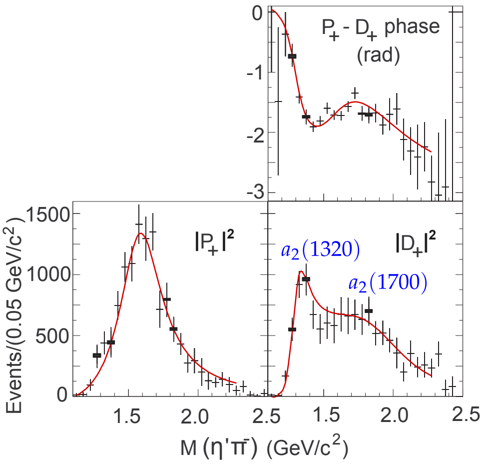

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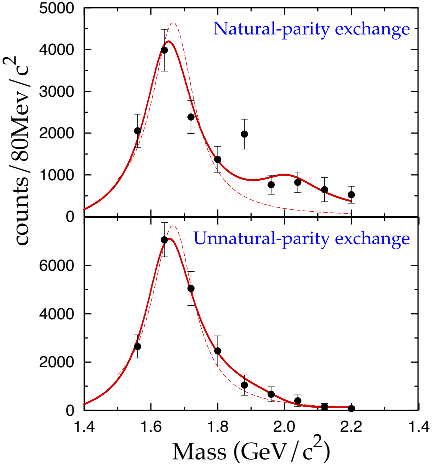
BNL E852: $\pi^- p \to \omega(782)\pi^0\pi^- p$ at 18 GeV/c



BNL E852, PRL **94** (2005) 032002

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

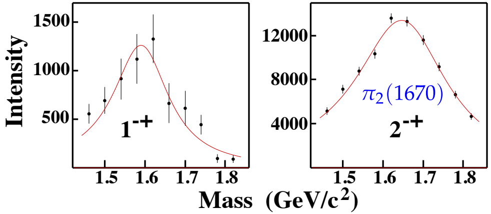
Jefferson Lab
Thomas Jefferson National Accelerator Facility

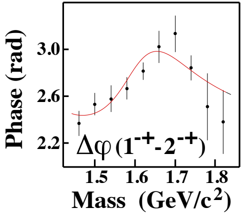
- One of the deepest puzzles surrounding the π_1s

$\pi_1(1600) \to \rho(770)\pi$ first claimed by BNL E852

- 0.25×10^6 events in $0.05 < t' < 1.0\,(\text{GeV}/c)^2$
- PWA model with 21 waves
- Pronounced peak at $1.6\,\text{GeV}/c^2$ in 1^{-+} intensity
- Accompanied by phase motion w.r.t. other waves
- Resonance-model fit using Breit-Wigner amplitudes
- *Conclusion:* observation of $\pi_1(1600) \to \rho(770)\pi$

BNL E852: $\pi^- p \to \pi^-\pi^-\pi^+ p$ at $18\,\text{GeV}/c$





BNL E852, PRL **81** (1998) 5760 BNL E852, PRD **65** (2002) 072001

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

Analysis of BNL E852 Data by Dzierba *et al.*

- 5.6×10^6 events in $0.08 < t' < 0.53\,(\text{GeV}/c)^2$ ($20\times$ larger sample)
- PWA with 36 waves performed independently in 12 t' bins
- Peak at $1.6\,\text{GeV}/c^2$ in 1^{-+} intensity disappeared
  - Peak in E852 analysis: leakage from $\pi_2(1670)$
  - Important 2^{-+} waves were missing in 21-wave set
- *Conclusion:* No evidence for $\pi_1(1600) \to \rho(770)\pi$
- But:
  - Phase motions of 1^{-+} wave nearly unchanged
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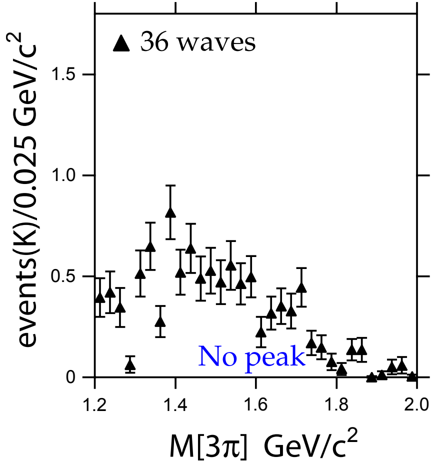
$\pi^- p \to \pi^-\pi^-\pi^+ p$ and $\pi^-\pi^0\pi^0 p$ at $18\,\text{GeV}/c$



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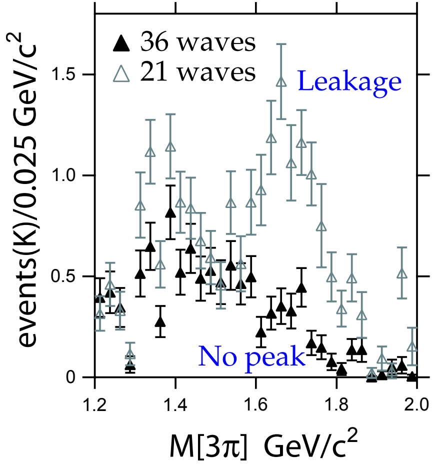

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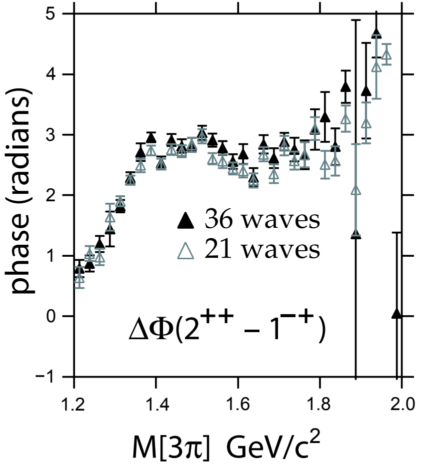


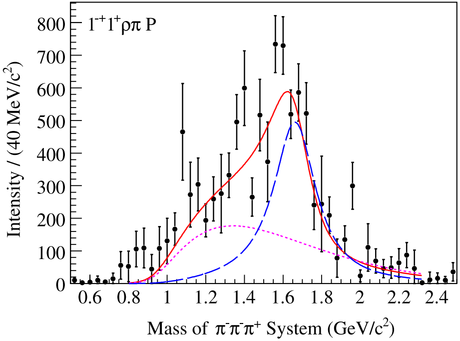
Dzierba *et al.*, PRD **73** (2006) 072001

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Pb-Target Data

- 0.42×10^6 events in $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- PWA model with 42 waves
  - Similar to 36-wave set used by Dzierba *et al.*
- Enhancement at $1.6\,\text{GeV}/c^2$ in 1^{-+} intensity
- Resonance-model fit using Breit-Wigner amplitudes
- *Conclusion:* observation of $\pi_1(1600) \to \rho(770)\pi$

$\pi^-\text{Pb} \to \pi^-\pi^-\pi^+\text{Pb}$ at $190\,\text{GeV}/c$



COMPASS, PRL **104** (2010) 241803

How to explain these seemingly contradictory experimental findings?

Caused by inconsistent data or by model dependence of the PWA?

$\Longrightarrow$ Study high-precision COMPASS data on $\pi^- p \to \pi^-\pi^-\pi^+ p$

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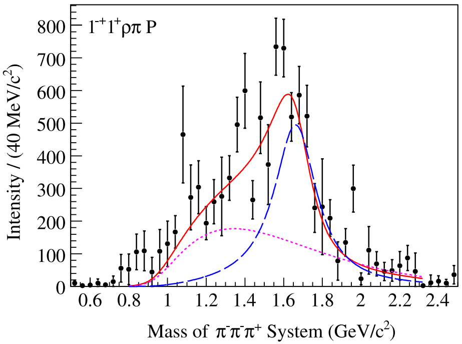

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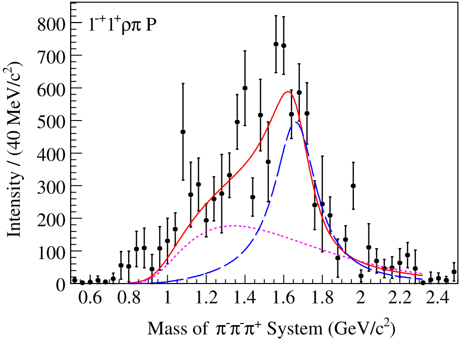

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The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Proton-Target Data

- $\pi^- p \to \pi^- \pi^- \pi^+ p$ at 190 GeV/c
- 46×10^6 events in $0.1 < t' < 1.0$ (GeV/c)^2
- PWA performed independently in 11 t' bins
  - PWA with **21 waves** in $0.1 < t' < 1.0$ (GeV/c)^2
    $\Longrightarrow$ artificial peak at 1.6 GeV/c^2 in 1^{-+} intensity
    consistent with BNL E852 analysis
  - PWA with **36 waves** in t' bin around 0.2 (GeV/c)^2
    $\Longrightarrow$ peak at 1.6 GeV/c^2 disappears
    consistent with analysis by Dzierba *et al.*
  - PWA with **88 waves** in $0.1 < t' < 1.0$ (GeV/c)^2
    - No peak at 1.6 GeV/c^2
    - Consistent with VES data on π^- Be $\to \pi^- \pi^- \pi^+$ Be at 37 GeV/c
  - Phase motion not very sensitive to PWA model

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

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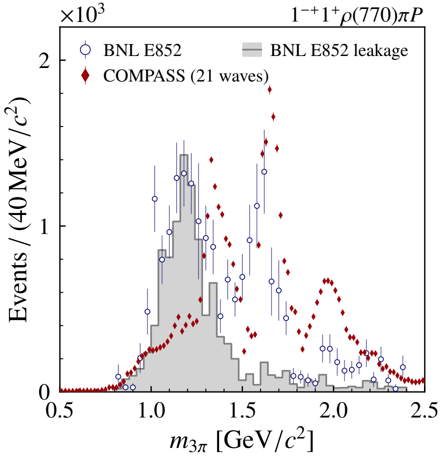
  - Phase motion not very sensitive to PWA model



COMPASS, PRD **105** (2022) 012005

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Proton-Target Data

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- $\pi^- p \to \pi^-\pi^-\pi^+ p$ at 190 GeV/c
- 46×10^6 events in $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- PWA performed independently in 11 t' bins
    - PWA with **21 waves** in $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
      $\Longrightarrow$ artificial peak at 1.6 GeV/c^2 in 1^{-+} intensity
      consistent with BNL E852 analysis
    - PWA with **36 waves** in t' bin around 0.2 (GeV/c)^2
      $\Longrightarrow$ peak at 1.6 GeV/c^2 disappears
      consistent with analysis by Dzierba *et al.*
    - PWA with **88 waves** in $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
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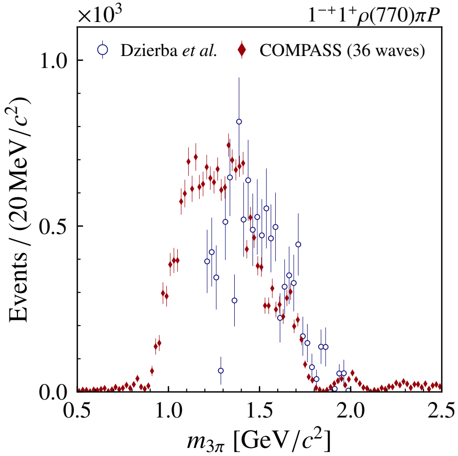

COMPASS, PRD **105** (2022) 012005

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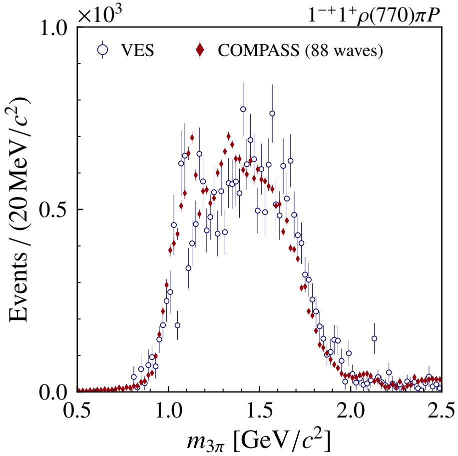

COMPASS, PRD **105** (2022) 012005

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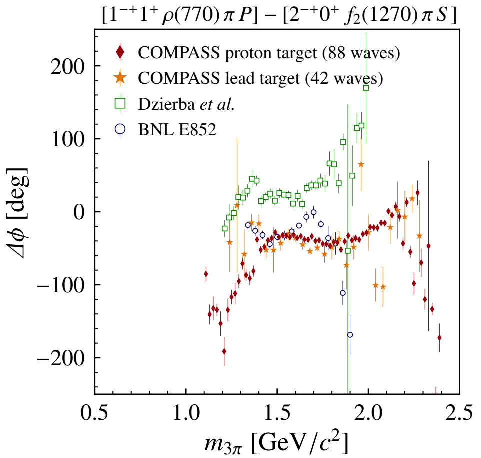

COMPASS, PRD **105** (2022) 012005

- Shape of 1^{-+} intensity distribution changes dramatically with t'
- Low t': broad distribution
- High t': peak at 1.6 GeV/c^2

Resonance-model fit

- *Novel approach:* fit 11 t' bins simultaneously enforcing the same resonance parameters in all t' bins
- Low t': saturated by non-resonant component
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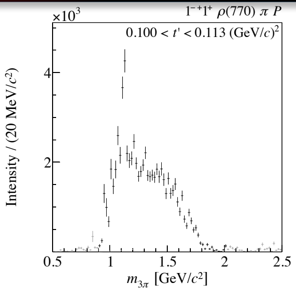

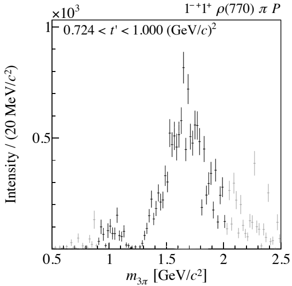

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Proton-Target Data

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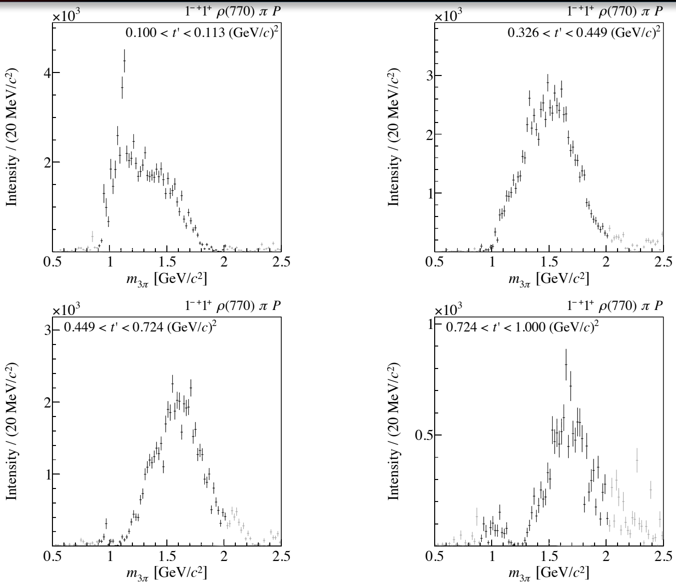

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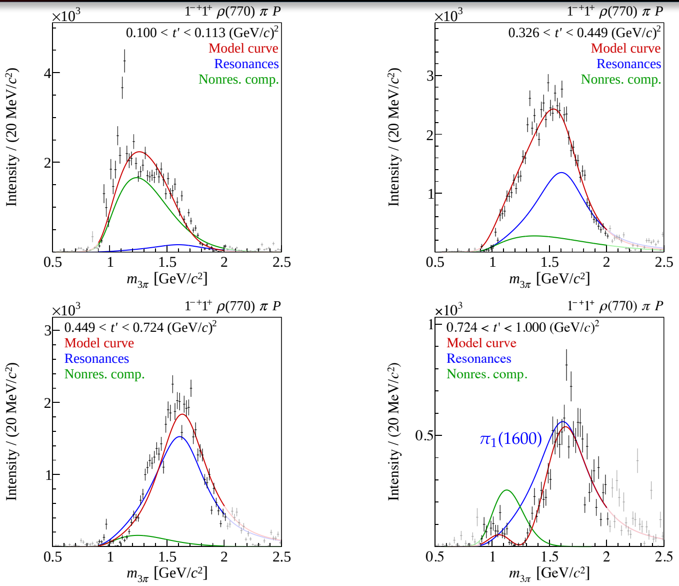
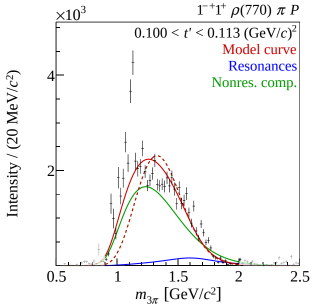


The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Proton-Target Data

Lowest t' bin

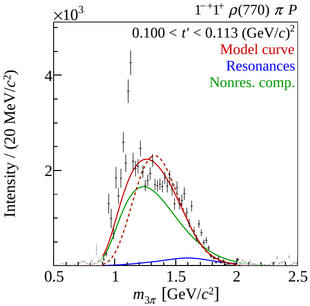


- Data at high t' cannot be described without $\pi_1(1600)$ component (dashed curves)

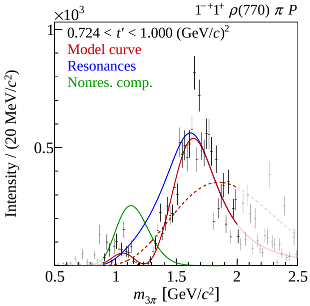
t'-resolved analysis solves longstanding controversy

- $\pi_1(1600)$ masked by non-resonant component for $t' \lesssim 0.5\,(\text{GeV}/c)^2$
- Not observable by Dzierba *et al.* because analysis was limited to $t' < 0.53\,(\text{GeV}/c)^2$

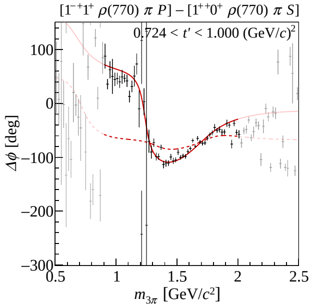
Lowest t' bin



Highest t' bin



COMPASS, PRD **98** (2018) 092003



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The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Proton-Target Data

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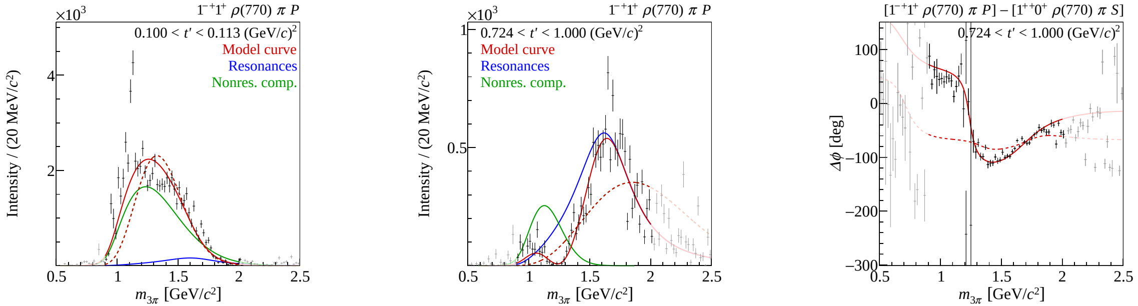
Lowest t' bin | Highest t' bin | COMPASS, PRD **98** (2018) 092003



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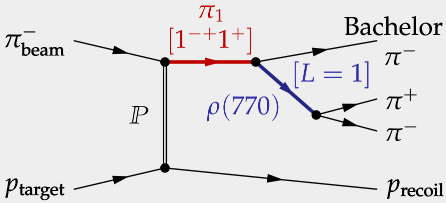
Model Dependence of the $\pi_1(1600)$ Signal?

COMPASS Proton-Target Data



- Conventional PWA requires complete knowledge of isobar amplitude
    - Employed parametrization for amplitudes of $\rho(770)$ isobar might deviate from data
- *Novel technique:* **“freed-isobar” PWA** Krinner *et al.*, PRD **97** (2018) 114008
    - Replace fixed isobar parametrizations by step-like functions
    - Extract $\pi^-\pi^+$ isobar amplitude with well-defined J^{PC} from data
    - Greatly reduces model dependence

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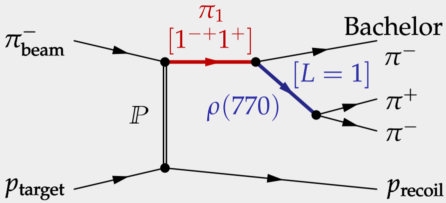

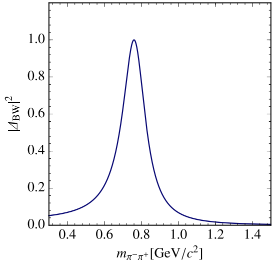

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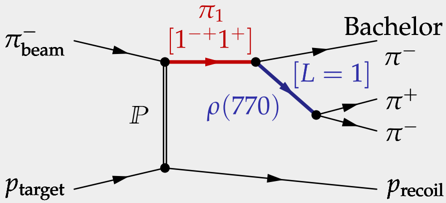

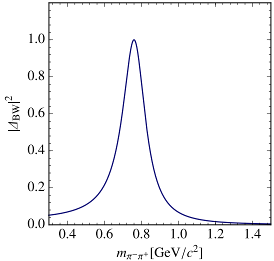

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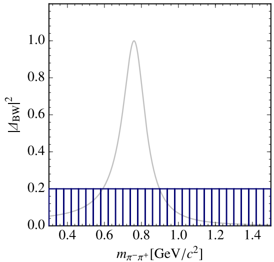

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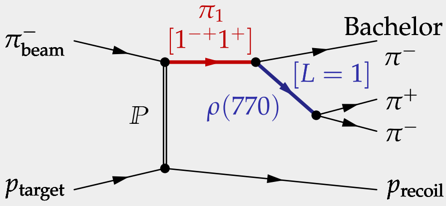

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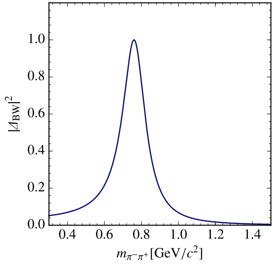

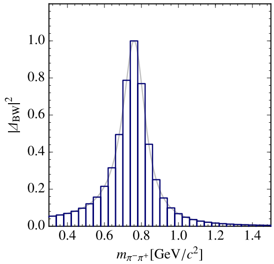

$\pi^-\pi^+$ Amplitude in $1^{-+} \to [\pi\pi]_{1^{--}} + \pi^-$

$0.326 < t' < 1.000\ (\text{GeV}/c)^2$ COMPASS, PRD **105** (2022) 1012005

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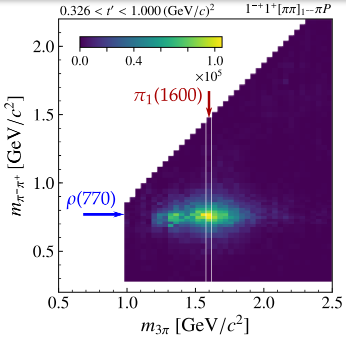

- Intensity peak at $m_{3\pi} \approx 1.6\,\text{GeV}/c^2$ and $m_{\pi^-\pi^+} \approx 0.8\,\text{GeV}/c^2$
- Clear $\rho(770)$ signal: peak in intensity + circular structure in Argand diagram

- $\rho(770)$ parametrization used in conventional PWA (gray line) agrees fairly well with measured amplitude of $\pi^-\pi^+$ subsystem

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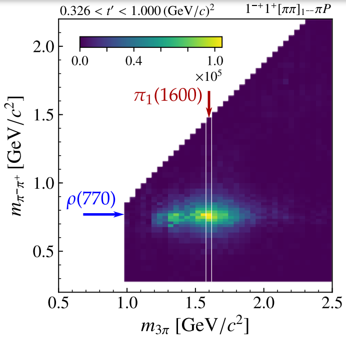
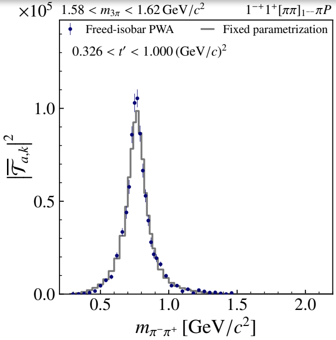
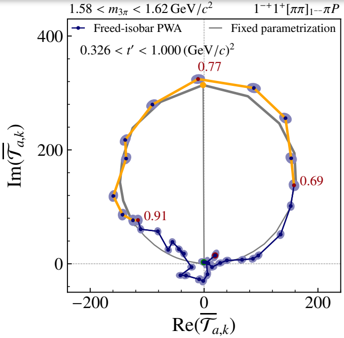
$0.326 < t' < 1.000\,(\text{GeV}/c)^2$ COMPASS, PRD **105** (2022) 1012005







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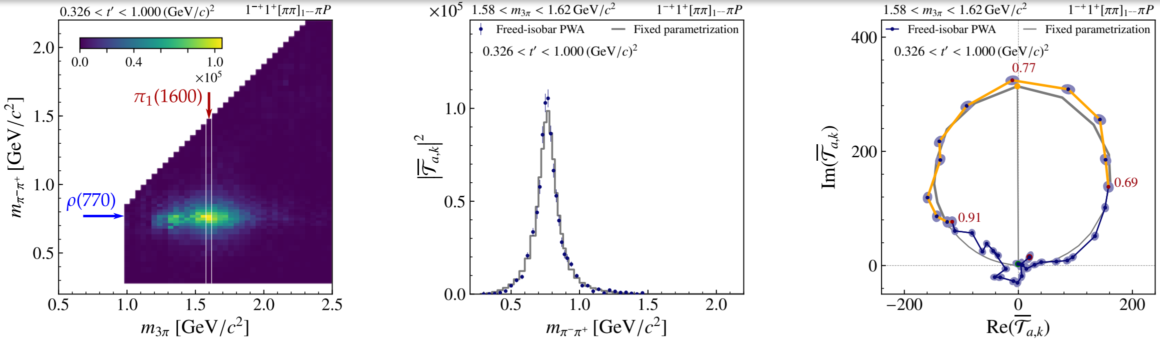

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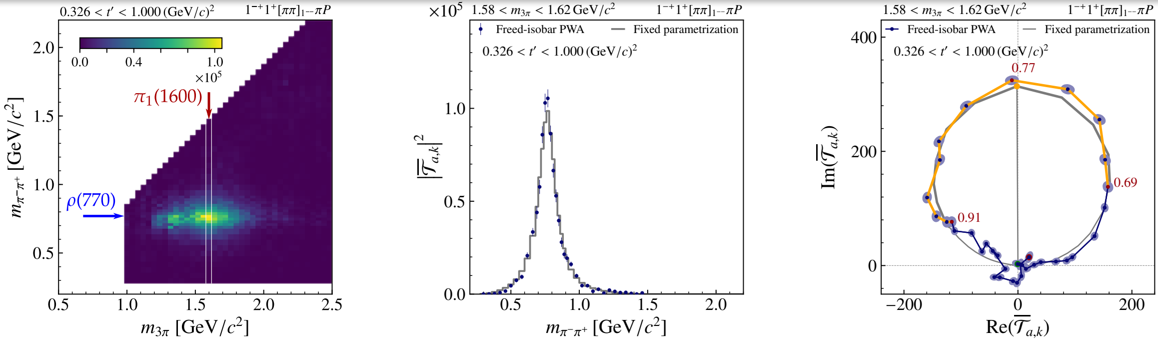
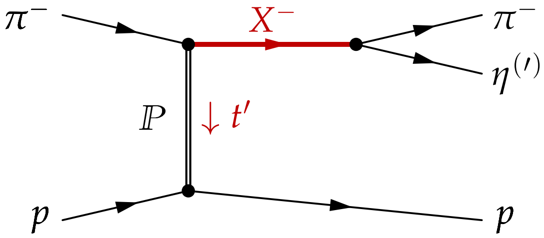


Freed-isobar PWA confirms $\pi_1(1600) \to \rho(770)\pi$

The π_1 in $\eta\pi$ and $\eta'\pi$

COMPASS Data



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

- 190 GeV/c π^- beam
- Studied range $0.1 < t' < 1.0$ (GeV/c)^2
  - 116 000 $\pi^-\eta$ events with $\eta \to \pi^-\pi^0\pi^+$
  - 39 000 $\pi^-\eta'$ events with $\eta' \to \pi^-\pi^0\eta$ and $\eta \to \gamma\gamma$
- PWA model: partial waves with spins from 1 to 6 and natural-parity exchange

The π_1 in $\eta\pi$ and $\eta'\pi$

JPAC Coupled-Channel Analysis of COMPASS Data

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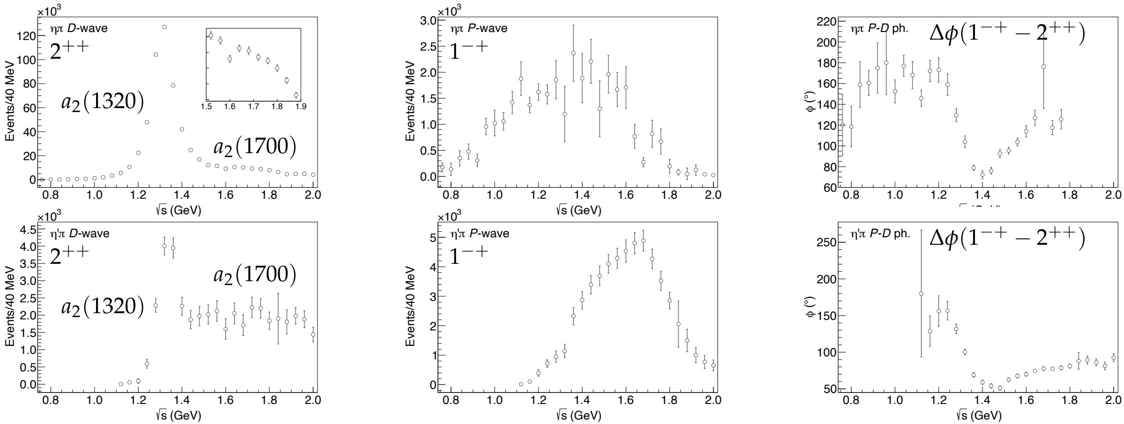
Thomas Jefferson National Accelerator Facility

$\eta\pi$:

$\eta'\pi$:



Rodas *et al.* [JPAC], PRL **122** (2019) 042002 COMPASS, PLB **740** (2015) 303

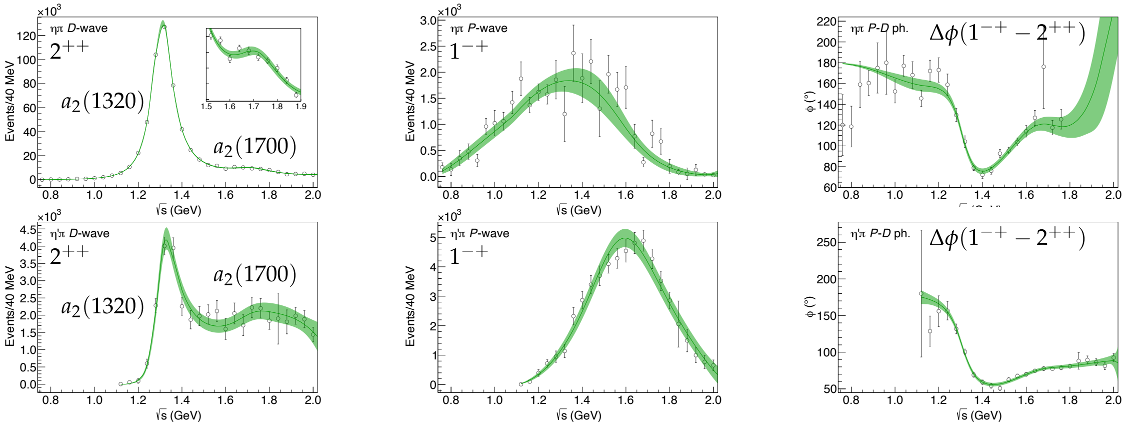
- Partial-wave amplitudes from COMPASS analysis
- D-wave with $a_2(1700)$ signal needs to be well understood

The π_1 in $\eta\pi$ and $\eta'\pi$

JPAC Coupled-Channel Analysis of COMPASS Data

$\eta\pi$:

$\eta'\pi$:



Rodas *et al.* [JPAC], PRL **122** (2019) 042002

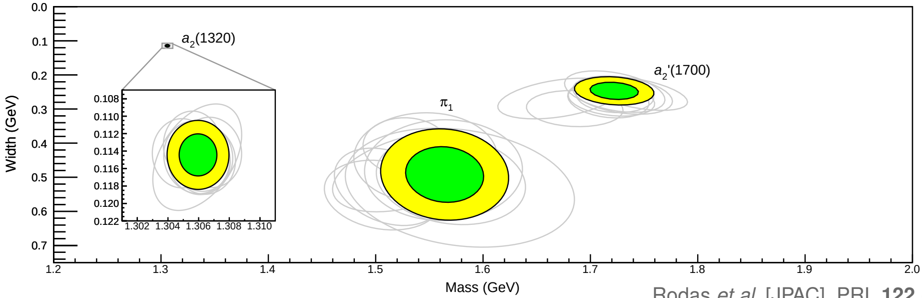
COMPASS, PLB **740** (2015) 303

Fit by JPAC

- Analytical and unitary model based on S-matrix principles

The π_1 in $\eta\pi$ and $\eta'\pi$

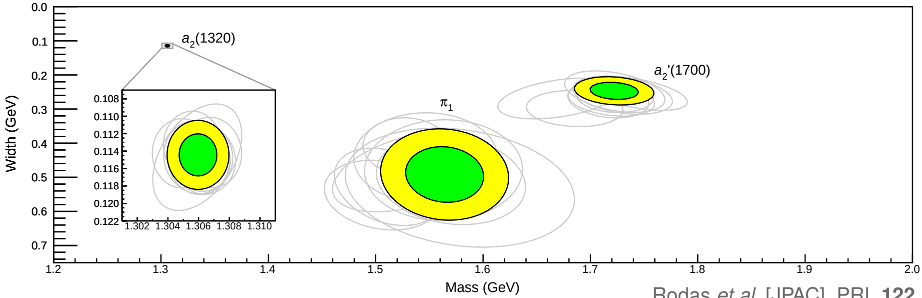
JPAC Coupled-Channel Analysis of COMPASS Data



Rodas *et al.* [JPAC], PRL **122** (2019) 042002

Only **single pole** required to describe peaks at 1.4 and 1.6 GeV/c^2 in 1^{-+} waves

- $m_0 = 1564 \pm 24\,(\text{stat.}) \pm 86\,(\text{sys.})\,\text{MeV}/c^2$, $\Gamma_0 = 492 \pm 54\,(\text{stat.}) \pm 102\,(\text{sys.})\,\text{MeV}/c^2$
- Consistent with $\pi_1(1600)$
- Confirmed by Kopf *et al.* in similar analysis including in addition Crystal Barrel data on $\bar{p}p \to \pi^0\pi^0\eta$, $\pi^0\eta\eta$, and $K^+K^-\pi^0$ as well as $\pi\pi$ scattering data Kopf *et al.*, EPJC **81** (2021) 1056



Rodas *et al.* [JPAC], PRL **122** (2019) 042002

Only **single pole** required to describe peaks at 1.4 and 1.6 GeV/c^2 in 1^{-+} waves

- Raises doubts about existence of $\pi_1(1400)$ as separate resonance
- Suggests simpler and more plausible picture: only 1 state, the $\pi_1(1600)$, below 2 GeV/c^2
- Would solve longstanding puzzle of two π_1 states with puzzling properties
- Would remove discrepancy of $\pi_1(1400)$ with lattice QCD and most model calculations

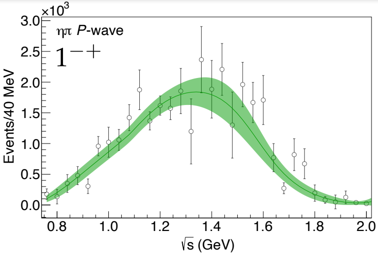
The $\pi_1(1600)$: Three Sides of the Same Coin

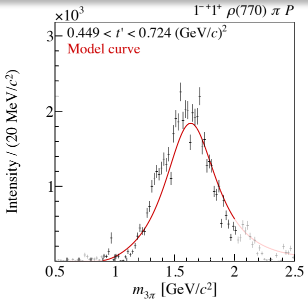
COMPASS Proton-Target Data

$\eta\pi$

t' range

$[0.1, 1.0]$ (GeV/c)^2





3π

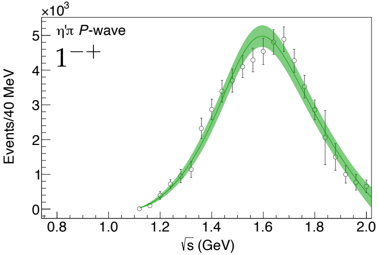
t' range

$[0.449, 0.724]$ (GeV/c)^2

$\eta'\pi$

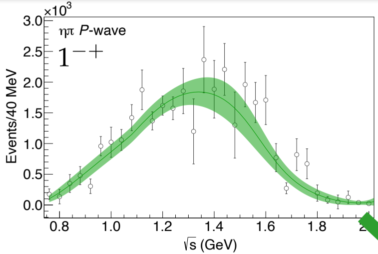
t' range

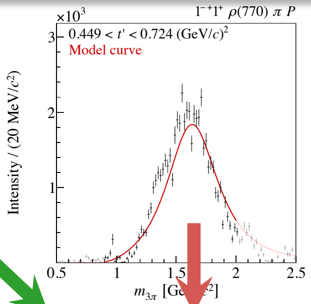
$[0.1, 1.0]$ (GeV/c)^2



- Distribution in $\rho(770)\pi$ similar to $\eta'\pi$

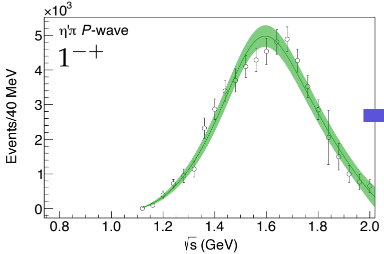
$\eta\pi$
t' range
$[0.1, 1.0]$ (GeV/c)^2

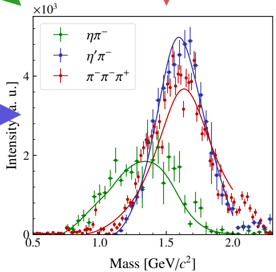




3π
t' range
$[0.449, 0.724]$ (GeV/c)^2

$\eta'\pi$
t' range
$[0.1, 1.0]$ (GeV/c)^2





- Distribution in $\rho(770)\pi$ similar to $\eta'\pi$

Remaining Puzzles

Spin-exotic $1^{-+}1^{+}\rho(770)\,\pi\,P$ Wave from $\pi\gamma$ Interactions

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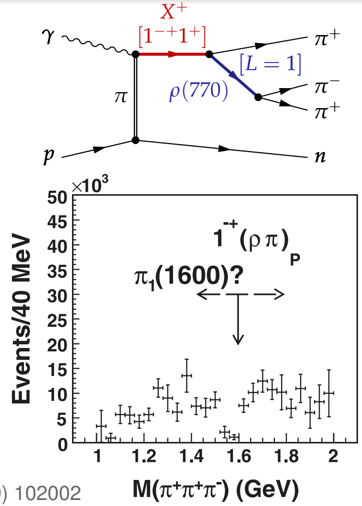
Thomas Jefferson National Accelerator Facility

- Observation of $\pi_1(1600) \to \rho(770)\pi \Longrightarrow$ should see $\pi\gamma \to \pi_1(1600)$

CLAS

COMPASS



CLAS, PRL **102** (2009) 102002

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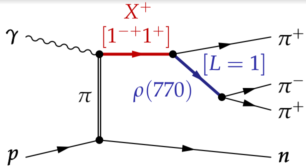
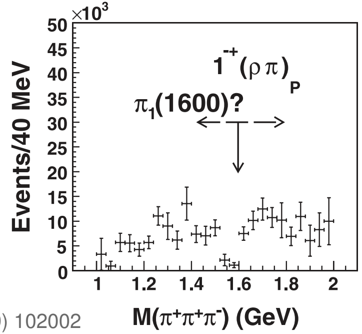
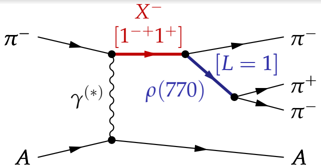
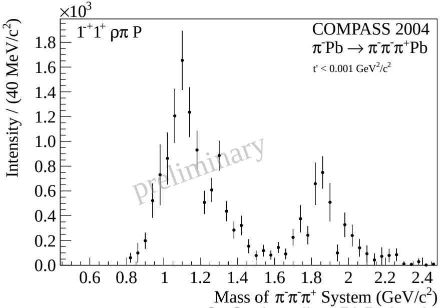




CLAS, PRL **102** (2009) 102002

COMPASS





S. Grabmüller, PhD thesis (2009) TU Munich

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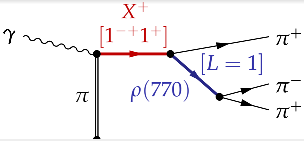
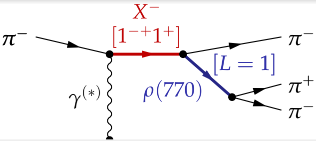
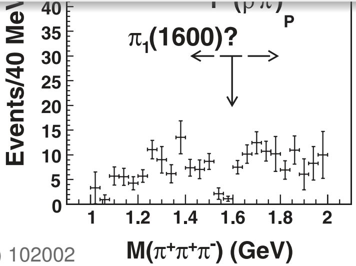


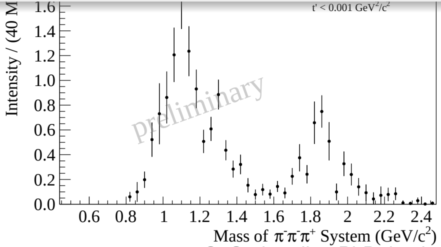


COMPASS

- No signal or destructive interference of $\pi_1(1600)$ with non-resonant component?

Will be studied by GlueX and MesonEx @ CLAS at Jefferson Lab





CLAS, PRL **102** (2009) 102002

S. Grabmüller, PhD thesis (2009) TU Munich

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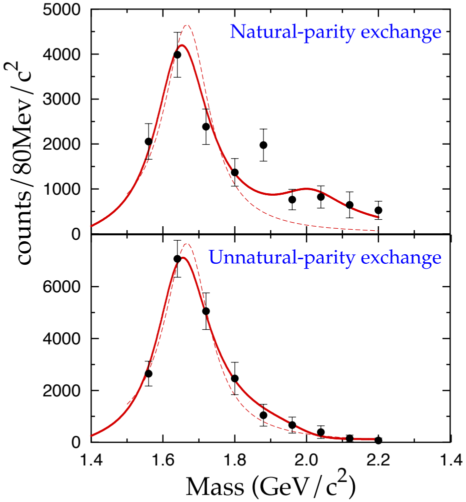
Pion diffraction

- Production via natural-parity exchange expected to be dominant
- BNL E852 observed also unnatural-parity exchange production of $\pi_1(1600)$ in $b_1(1235)\pi$

- Can be verified using COMPASS data for same reaction at 190 GeV/c
- 720 000 events (5× BNL E852)
- PWA work in progress

$\pi^- p \to \omega(782)\pi^0\pi^- p$ at 18 GeV/c



BNL E852, PRL **94** (2005) 032002

Remaining Puzzles

Unnatural-Parity Exchange Production of $\pi_1(1600)$ in $b_1(1235)\pi$

Pion diffraction

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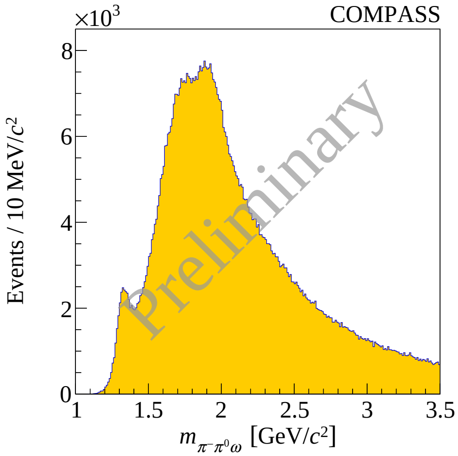


A Recent Surprise Reported by BESIII

Observation of $J/\psi \to \gamma\eta_1(1855)$ with $\eta_1(1855) \to \eta\eta'$

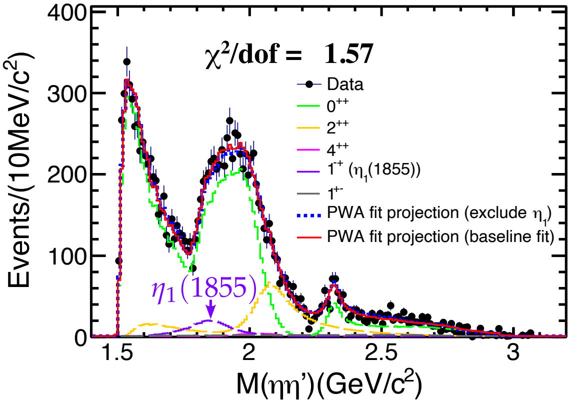
- Dalitz-plot analysis of 15 000 $\gamma\eta\eta'$ events
- Isoscalar resonance with $J^{PC} = 1^{-+}$ required with statistical significance $> 19\sigma$
  - Parameters:

$$m_0 = 1855 \pm 9\,(\text{stat.})\,^{+6}_{-1}\,(\text{sys.})\ \text{MeV}/c^2$$

$$\Gamma_0 = 188 \pm 18\,(\text{stat.})\,^{+3}_{-8}\,(\text{sys.})\ \text{MeV}/c^2$$

$\Longrightarrow \eta_1(1855)$

- First step towards establishing $SU(3)_{\text{flavor}}$ partner states of $\pi_1(1600)$
- Needs confirmation by other experiments



BESIII, PRL **129** (2022) 192002
BESIII, PRD **106** (2022) 072012

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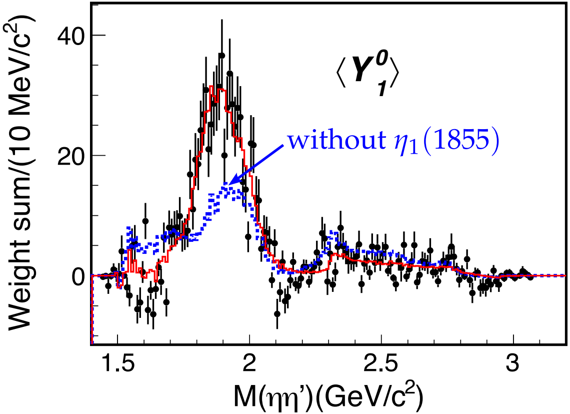

BESIII, PRL **129** (2022) 192002
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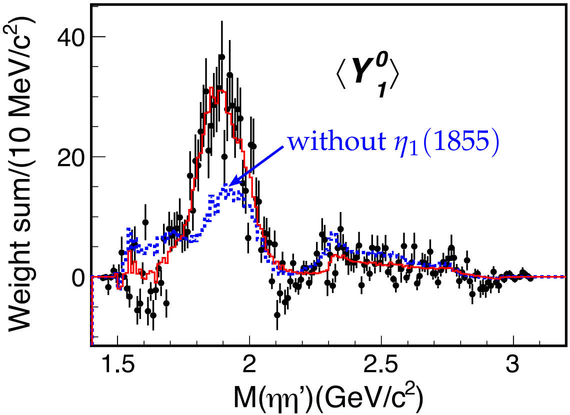

BESIII, PRL **129** (2022) 192002
BESIII, PRD **106** (2022) 072012

Resolved many puzzles and confusing experimental results surrounding the π_1 states

using

- high-precision experimental data
- novel analysis techniques
- advanced theoretical models

Recent results favor simpler and more plausible picture

- Instead of two states, $\pi_1(1400)$ and $\pi_1(1600)$, with hard to explain properties only the $\pi_1(1600)$ remains as a firmly established state
- However, some puzzles remain to be solved
- Currently, most likely interpretation of $\pi_1(1600)$ is a hybrid state

Spin-Exotic Light Mesons

The dust of more than 30 years of research is starting to settle

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Spin-Exotic Light Mesons

The dust of more than 30 years of research is starting to settle

Having established that $\pi_1(1600)$ exists is only the starting point

- In order to proof its hybrid nature, we have to
  - study its production and decay properties with more detail and higher precision
  - search for its radial excitations, i.e. confirm BNL E852 claims of $\pi_1(2015) \rightarrow b_1(1235)\pi$ and $f_1(1285)\pi$
  - establish its $\text{SU}(3)_\text{flavor}$ partner states, i.e. confirm BESIII claim of $\eta_1(1855)$, find other $\eta_1^{(\prime)}$ and K^*
- In addition, search for spin-exotic states with $J^{PC} \neq 1^{-+}$

World-wide effort

- Running or planned experiments at all major accelerator labs
- Leveraging the high precision of current and future data requires
  - More advanced statistical methods, e.g. model selection, uncertainty estimation/propagation
  - More realistic PWA models
    - Amplitudes that incorporate constraints from fundamental physical principles
    - Detailed models for production reactions and final-state interactions
  - Close collaboration of theorists and experimentalists

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Part II

Backup Slides

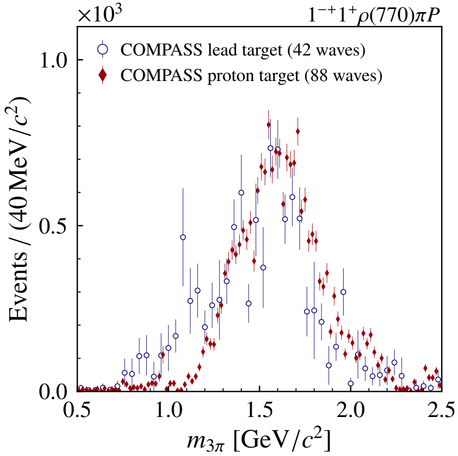
7. COMPASS proton-target data
   - The $\pi_1(1600)$ in the freed-isobar PWA
   - Model for the Non-Resonant Component in the 1^{-+} wave

The $\pi_1(1600) \to \rho(770)\pi$ Controversy

COMPASS Proton-Target Data

Jefferson Lab
Thomas Jefferson National Accelerator Facility

- $\pi^- p \to \pi^-\pi^-\pi^+ p$ at 190 GeV/c
- 46 × 10^6 events in $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$
- PWA with **88 waves** in $0.449 < t' < 0.724\,(\mathrm{GeV}/c)^2$
  - Peak at 1.6 GeV/c^2
  - Consistent with COMPASS intensity obtained from 42-wave PWA of Pb-target data in $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$



COMPASS, PRD **105** (2022) 012005

Comparison with Conventional PWA

Coherent Sum over full $m_{\pi^-\pi^+}$ Range

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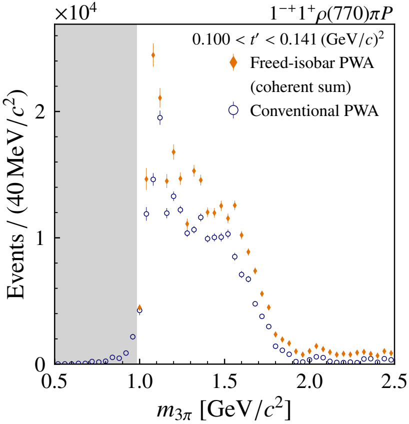
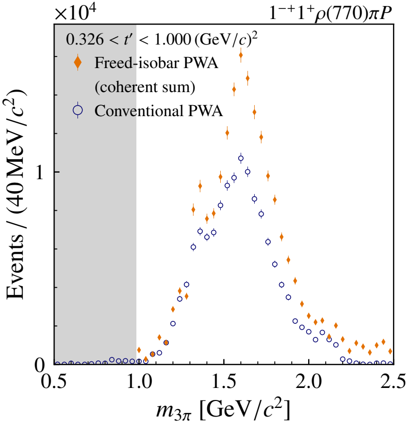
Thomas Jefferson National Accelerator Facility

Lowest t' bin



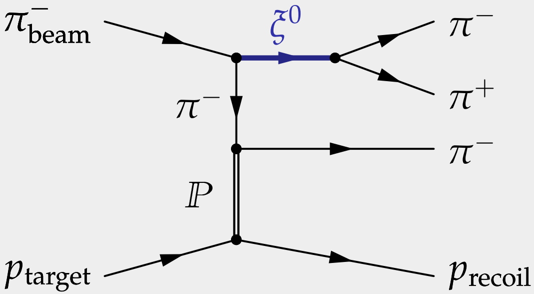
Highest t' bin



COMPASS, PRD **105** (2022) 012005

- Freed-isobar PWA confirms existence of $\pi_1(1600) \to \rho(770)\pi$

Dominant non-resonant component: Deck effect



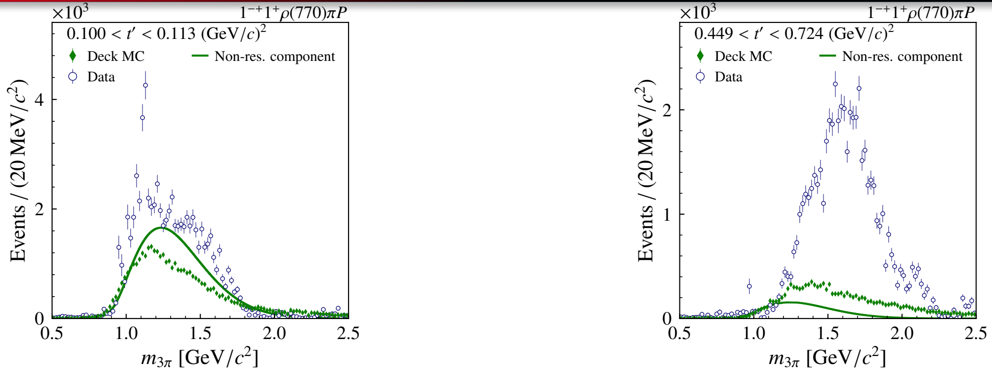
- MC pseudodata generated according to simple model for Deck amplitude

  based on ACCMOR, NPB **182** (1981) 269

  - Upper vertex: amplitude from $\pi\pi$ scattering up to F-wave — Hyams *et al.*, NPB **64** (1973) 134
- Partial-wave decomposition using same 88-wave set as for real data

Model for the Non-Resonant Component

Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave



COMPASS, PRD **105** (2022) 012005

- Deck intensity normalized to intensity of non-resonant component in resonance-model fit for $t' \lesssim 0.5\,(\mathrm{GeV}/c)^2$
  - Similar shape of mass spectra for $t' \lesssim 0.5\,(\mathrm{GeV}/c)^2$
  - Different shape at high t'